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- Vijay Kadam [Assistant]

List of Participants

Name	Affiliation
Eric Adelberger	University of Washington, USA
Rana Adhikari	Cal Tech, USA
Suhail Ahmad	Jamia Millia Islamia University, India
Moumita Aich	IUCAA, India
P. Ajith	Cal Tech, USA
Ujjaini Alam	Los Alamos, USA
Amna Ali	Jamia Miliia Islamia University, India
Bruce Allen	MPI Gravitationphysik, Germany
Gareth Amery	University of KwaZulu-Natal, South Africa
Rizwan Ansari	IUCAA, India
Frederico Arroja	Ewha Womans University, South Korea
Abhay Ashtekar	Penn State, USA
Kumar Atmjeet	University of Delhi, India
Abhishek Atreya	IOP, India
Luca Baiotti	Osaka University, Japan
Y. Bala Murali Krishna	Indian Science Writers Association, India
Debades Bandyopadhyay	SINP, India
Fernando Barbero	IEM, Spain
Sukratu Barve	CMS, India
Rupal Basak	TIFR, India
Soumen Basak	University of Paris, France
Rudranil Basu	SN Bose Centre, India
Yumnam Bembem Devi	Manipur University, India
Pijushpani Bhattacharjee	SINP, India
Srijit Bhattacharjee	SINP, India
Dipankar Bhattacharya	IUCAA, India
Pinaki Bhattacharya	Jadavpur University, India
Swastik Bhattacharya	HRI, India
J. R. Bond	CITA, Canada
Sukanta Bose	Washington State University, USA
Francois Bouchet	IAP, France
Marco Bruni	University of Portsmouth, UK
Luke Butcher	Cambridge, UK
Rong-Gen Cai	Institute of Theoretical Physics, China
Marie-Noelle Celerier	Meudon, France
Sukanya Chakrabarti	Florida Atlantic Uniersity, USA
Manoneeta Chakraborty	TIFR, India
Shuvendu Chakraborty	Seacom Engineering College, India
Ningombam Chandrachani Devi	Jamia Miliia Islamia University, India

Name	Affiliation
Tzu-Ching Chang	CITA, Canada
V. Chellathurai	IUCAA, India
Pravabati Chinganbam	IIA, India
S. M. Chitre	CBS, India
Marina Cortes	LBNL, USA
Carlos Filipe Da Silva Costa	INPE, Brazil
Naresh Dadhich	IUCAA, India
Mihalis Dafermos	DAMTP, UK
Santanu Das	IUCAA, India
Sudeep Das	UC Berkeley, USA
Sudipta Das	Visva-Bharati, India
Suratna Das	TIFR, India
Patrick Das Gupta	University of Delhi, India
Ghanashyam Date	IMSc, India
Justin David	IISc, India
Adam Day	IOP Publishing, UK
Ujjal Debnath	BESU, India
Josue De Santiago Sanabria	UNAM, Mexico
Walter Del Pozzo	Nikhef. Netherlands
Ashok Deshpande	TIFR, India
Umananda Dev Goswami	Dibrugarh University, India
Sanjeev Dhurandhar	IUCAA, India
Amol Dighe	TIFR, India
Suresh Doravari	Cal Tech, USA
Olivier P. Dore	JPL, USA
Gustavo Dotti	Cordoba, Argentina
Margaret D'Souza	TIFR, India
John Ellis	King's College, UK
Stephen Fairhurst	Cardiff University, UK
Brendan Foster	Foundational Questions Institute, USA
Anne Franzen	Utrecht, Netherlands
Joshua Frieman	Fermilab, USA
Ryuichi Fujita	RRI, India
Koyel Ganguly	St. Xavier's College, Kolkata, India
Abhik Ghosh	IIT Kharagpur, India
Shaon Ghosh	Washington State University, USA
Suman Ghosh	IISER Thiruvananthapuram, India
Sushant Ghosh	Jamia Miliia Islamia University, India
Tuhin Ghosh	IUCAA, India
Jinn-Ouk Gong	CERN, Switzerland
Gabriela Gonzalez	Lousiana State University, USA
A. Gopakumar	TIFR, India
Gaurav Goswami	IUCAA, India

Name	Affiliation
Rituparno Goswami	University of Capetown, South Africa
Gabriel Govender	University of KwaZulu-Natal, South Africa
Julien Grain	University of Paris, France
Samuel Gralla	University of Maryland, USA
Pierre Gratia	University of Chicago, USA
Pathik Guha	Anand Bazar Patrika, India
Sarbari Guha	St. Xavier's College, Kolkata, India
Tapomoy Guha Sarkar	HRI, India
Anuradha Gupta	TIFR, India
Gaveshna Gupta	Jamia Miliia Islamia University, India
Rajalakshmi Gurumurthy	TIFR, India
Yuan Ha	Temple University, USA
Sudan Hansraj	University of KwaZulu-Natal, South Africa
Tomohiro Harada	Rikkyo University, Japan
Dhiraj Kumar Hazra	HRI, India
Suraj Hegde	Bengaluru, India
Steven Hergt	Friedrich-Schiller University, Germany
Gilbert Holder	McGill University, USA
Gary Horowitz	UCSB, USA
Jim Hough	University of Glasgow, UK
Ngangbam Ibohal	Manipur University, India
Ningombam Ibotombi Singh	Manipur University, India
Stephane Ilic	Universite Paris-Sud, France
Bala Iyer	RRI, India
Shobha Jagtap	TIFR, India
Deepak Jain	University of Delhi, India
Rajeev Kumar Jain	University of Geneva, Switzerland
Sanjay Jhingan	Jamia Miliia Islamia University, India
Charles Jose	IUCAA, India
Nidhi Joshi	Jamia Miliia Islamia University, India
Pankaj S. Joshi	TIFR, India
Narayan K.	CMI, India
Arun K. G.	CMI, India
Rakesh Kabir	University of Delhi, India
Nishikant Kadam	TIFR, India
Vijay Kadam	TIFR, India
Laishram Kapil	Manipur University, India
Manoj Kaplinghat	UC Irvine, USA
Sayan Kar	IIT Kharagpur, India
Mansi Kasliwal	Cal Tech, USA
Laxman Katkar	Shivaji University, India
David Keitel	AEI, Germany
Ajit Kembhavi	IUCAA, India

Name	Affiliation
Udayraj Khanal	Tribhuvan University, Nepal
Robert Kirshner	Harvard, USA
Sergey Klimenko	University of Florida, USA
Sanved Kolekar	IUCAA, India
Eiichiro Komatsu	University of Texas at Austin, USA
Atanu Kumar	SINP, India
Devaky Kunneriath	Astronomical Institute, Czech Republic
Fabien Lacasa	University of Paris-Sud, France
Alok Laddha	Penn State, USA
Luis Lehner	Perimeter Institute, Canada
Tjonnie Li	Nikhef, Netherlands
Yen-Ting Lin	ASIAA, Taiwan
Eric Linder	UC Berkeley, USA
Kinjalk Lochan	TIFR, India
Sunil Maharaj	University of KwaZulu-Natal,South Africa
Debasish Majumdar	SINP, India
Subhabrata Majumdar	TIFR, India
Suman Majumdar	IIT Kharagpur, India
Daniele Malafarina	TIFR, India
Gautam Mandal	TIFR, India
Felipe Marin	Swinburne University of Technology, Australia
Nairwita Mazumder	Jadavpur University, India
Shiraz Minwalla	TIFR, India
Chandra Mishra	RRI, India
Priti Mishra	TIFR, India
Sanjit Mitra	IUCAA, India
Sourav Mitra	HRI, India
Anupreeta More	KICP Chicago, USA
Subhendra Mohanty	PRL, India
Surhud More	KICP Chicago, USA
Amitabha Mukherjee	University of Delhi, India
Arunava Mukherjee	TIFR, India
Shinji Mukohyama	IPMU, Japan
Marcello Musso	Abdus Salam ICTP, Italy
Sharvari Nadkarni-Ghosh	SN Bose Centre, India
Yasusada Nambu	Nagoya University, Japan
Roshina Nandra	Cambridge, UK
Gaurav Narain	IMSc, India
D. Narasimha	TIFR, India
Jayant Narlikar	IUCAA, India
Priyamvada Natarajan	Yale, USA
Akhilesh Nautiyal	HRI, India
William Nelson	Penn State, USA

Name	Affiliation
Samaya Nissanke	Cal Tech, USA
Ernesto Nungesser	AEI, Germany
Anne Marie Nzioki	University of Capetown, South Africa
Seiju Ohashi	Kyoto University, Japan
T. Padmanabhan	IUCAA, India
Isha Pahwa	Delhi University, India
Archana Pai	IISER Thiruvananthapuram, India
N. Panchapakesan	Delhi, India
Maria Allessandra Papa	MPI Gravitationphysik, Germany
Aseem Paranjape	Abdus Salam ICTP, Italy
Rajesh Parwani	National University of Singapore
Kishor Patil	B. D. College of Engg., India
Mandar Patil	TIFR, India
P. James E. Peebles	Princeton, USA
Valeria Pettorino	SISSA, Italy
Dmitri Pogosyan	University of Alberta, Canada
Anirudh Pradhan	Hindu P. G. College, India
Jayanti Prasad	IUCAA, india
A. R. Prasanna	Ahmedabad, India
Reinhard Prix	MPI Gravitationphysik Hannover, Germany
Kangujam Priyokumar Singh	Manipur University, India
Raghavan Rangarajan	PRL, India
Anais Rassat	EPFL, Switzerland
Sourya Ray	CECS, Chile
Subharthi Ray	University of KwaZulu-Natal, South Africa
Satyanarayan Ray Pitambar Mohapatra	University of Massachusetts, USA
Snehal Rebello	Hindustan Tmes, India
David Reitze	Cal Tech, USA
Pablo A. Rosado	MPI Gravitationphysik Hannover, Germany
Graziano Rossi	KIAS, Korea
Aditya Rotti	IUCAA, India
Carlo Rovelli	Marseille, France
Sheila Rowan	University of Glasgow, UK
Dibakar Roychowdhury	SN Bose Centre, India
Anirban Saha	West Bengal State University, India
Varun Sahni	IUCAA, India
P. K. Sahoo	BITS Hyderabad, India
Satyabrata Sahu	TIFR, India
Hiromi Saida	Daido University, Japan
Mairi Sakellariadou	King's College, London
Mohammad Sami	Jamia Miliia Islamia University, India
Prakash Sarkar	IUCAA, India

Name	Affiliation
B. S. Sathyaprakash	Cardiff University, UK
Seema Satin	IMSc, India
P. S. Saumia	IOP, India
Bernard Schutz	AEI, Germany
Anjan Ananda Sen	Jamia Millia Islamia University, India
Anand Sengupta	University of Delhi, India
Arman Shafieloo	Ewha Womans University, Korea
S. Shankaranarayanan	IISER Thiruvananthapuram, India
Pankaj Sharan	Jamia Millia Islamia, India
Ranjan Sharma	P. D. Women's College, India
Masaru Shibata	YITP, Japan
Chandra Prakash Singh	Delhi Technological University, India
Suprit Singh	IUCAA, India
Tejinder Singh	TIFR, India
Navin Sivanandam	Cape Town, South Africa
Tristan Smith	UC Berkeley, USA
Rafael Sorkin	Perimeter Institute, Canada
Tarun Souradeep	IUCAA, India
L. Sriramkumar	IIT Chennai, India
Angom Sumati Devi	Manipur University, India
Sanasam Surendra Singh	Manipur University, India
Sumati Surya	RRI, India
Jacek Tafel	Institute of Theoretical Physics, Poland
Maunel Tessmer	Friedrich-Schiller-University, Germany
Itzadah Thongkool	HRI, India
Kip Thorne	Cal Tech, USA
Rakesh Tibrewala	IMSc, India
Ramesh Tikekar	Pune, India
Tommaso Treu	UC Santa Barbara, USA
Pranjal Trivedi	University of Delhi, India
Sandip Trivedi	TIFR, India
C. S. Unnikrishnan	TIFR, India
Sanil Unnikrishnan	IUCAA, India
Mauri Valtonen	Tuorla Observatory, Finland
Chris Van Den Broeck	Nikhef, Netherlands
Madhavan Varadarajan	RRI, India
Nijo Varghese	Cochin University of Science and Technology, India
Cenalo Vaz	University of Cincinnati, USA
Filippo Vernizzi	IPT, France
Francesca Vidotto	Marseille, France
Alexander Vikman	CERN, Switzerland
Salvatore Vitale	Nikhef, Netherlands
Ram Gopal Vishwakarma	Zacatecas, Mexico

Name	Affiliation
C. V. Vishveshwara	Bengaluru, India
Spenta Wadia	TIFR, India
Kameshwar C. Wali	Syracuse, USA
David Wands	University of Portsmouth, UK
Neils Warburton	University of Southampton, UK
John T. Whelan	Rochester Institute of Technology, USA
Stan Whitcomb	Cal Tech, USA
Moslem Zarei	Isfahan University of Technology, Iran

Keynote Addresses

Keynote Address

Kip Thorne
350 – 17 Caltech, Pasadena, CA 91125, USA.
kip@caltech.edu

Black hole research: A new golden age

We are entering a new “golden age” of research on black holes. This golden age has been triggered by numerical simulations, aided by a new way to visualize the full vacuum Riemann curvature tensor. This new visualization uses “tendex and vortex lines” that embody the gravitoelectric and gravitomagnetic parts of the vacuum Riemann tensor, in the same way as electric and magnetic field lines embody electromagnetism's electric and magnetic fields. These tools have revealed nonlinear, dynamical structures around colliding black holes, for example, six vortexes of twisting space attached to generic, merging black hole horizons. The golden age will culminate with gravitational wave observatories probing these nonlinear structures, and probing other aspects of the nonlinear dynamics of curved spacetime.

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Keynote Address

Jim Peebles
Princeton University, USA.
pjep@Princeton.EDU

The natural science of cosmology

The relativistic hot big bang ΛCDM cosmology passes a tight network of independent tests that probe the universe from many directions. This impressive success does not mean ΛCDM is the final theory for cosmology after baryogenesis, but rather that if there is a better theory it will predict a universe that is much like ΛCDM. The many surprises along the path to the present standard cosmology do not inspire confidence that we have the final theory. Indeed, we can be sure our thinking will be affected, perhaps deeply, by progress of research on a broad variety of topics, from establishing the physics of the very early universe to improving tests of gravity physics on scales from the laboratory to the universe, establishing the properties of dark matter, unraveling the puzzles of dark energy, and understanding galaxies at high redshift and in our immediate neighborhood.

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Plenary Talks

Plenary Talk

Eric G. Adelberger
Emeritus Professor of Physics, CENPA, Box 354290, University of Washington, Seattle, WA 98195 – 4290, USA.
eric@npl.washington.edu

Tests of gravity from the solar system scale down to the separations smaller than the diameter of a hair

The speaker will summarize the recent developments in testing the gravitational inverse-square law at a variety of length scales, ranging from the size of the lunar orbit down to length scales smaller than the diameter of a human hair. Precise tests of the equivalence principle comparing the acceleration of a variety of materials toward attractors ranging from the earth and its local topography to galactic dark matter will also be reviewed.

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Plenary Talk

Dipankar Bhattacharya
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India.
dipankar@iucaa.ernet.in

Observational evidence of relativity in and around compact stars

Precision measurements of multi-wavelength spectra and intensity variations of radiation received from neutron star and black hole sources are enabling astronomers to measure relativistic effects in these regions of strong gravity. New experiments are being planned to significantly improve the accuracy of these measurements. This talk will review the progress made in this area in recent years and outline the road ahead.

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Plenary Talk

J. Richard Bond
Canadian Institute for Advanced Research in Cosmology and Gravity Program, Canadian Institute for Theoretical Astrophysics, 60 St. George Street, University of Toronto, Toronto, ON M5S 3H8, Canada.
bond@cita.utoronto.ca

Probing the cosmic theory of early and late universe physics

The universe is fundamentally quantum and statistical, a many-paths/many-worlds information-theoretic random-field story that now pervades all discussions in cosmic theory. This lecture uses Cosmic Information Theory and Analysis (CITA) as a unifying theme to explore our ideas of how the universe morphed from a smooth Hubble-patch within a vast and wild landscape into the ephemeral cosmic web we observe, with focus on early inflation, including preheating, and late inflation (aka dark energy). Particular topics will include: Gravity waves from the inflation epoch (with comments on optimal CMB sky coverage for fixed observing time to constrain GW-induced B-modes of polarization), the acceleration trajectory approach to inflation and current and forecasted constraints on gently-broken and radically-broken scale invariance, isocurvature modes, the delivery of almost all of the entropy in the universe through a preheating "shock-in-time", gently-broken and radically-broken Gaussianity of primordial curvature fluctuations and its constraints, and physically-motivated parameterizations for dark energy equation of state trajectories and their current and forecasted constraints.

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Plenary Talk

Francois Bouchet
Institut d'Astrophysique de Paris, CNRS and UPMC – Sorbonne Universites, Paris, France.
bouchet@iap.fr

Cosmic microwave background anisotropies: Status and prospects

One of the prime tools to make progress in fundamental physics and cosmology is the study of the cosmic microwave background (CMB) anisotropies. Indeed, it binds together the constraints on the main ingredients for the evolution of the universe, from the properties of the initial condition for structure formation to the cosmic census. The speaker will review the current experimental knowledge, describe the on-going Planck satellite project, and describe its early results regarding the relevant foregrounds, in particular the Sunyaev-Zeldovich effect and the cosmic infrared background fluctuations. He will also describe some of the expectations of what Planck will tell us on the CMB and cosmology.

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Plenary Talk

Mihalis Dafermos
DAMTP, UK.
M.Dafermos@dpmms.cam.ac.uk

The black hole stability problem

The speaker will review recent progress on the black hole stability problem in general relativity.

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Plenary Talk

John Ellis
CERN, Geneva, and King's College, London, UK.
John.Ellis@cern.ch

Particle physics and cosmology in light of the LHC?

Many topics in LHC physics touch upon aspects of cosmology. For example, the Higgs Boson may be related to theories of inflation and dark energy, and supersymmetry or other TeV-scale physics may provide dark matter and/or modify nucleogenesis, LHC studies of matter-antimatter differences may elucidate baryogenesis, and relativistic heavy-ion collisions may reveal the nature of the plasma that filled the universe when it was a microsecond old.

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Plenary Talk

Gary Horowitz
UC, Santa Barbara, USA.
gary@physics.ucsb.edu

Using general relativity to study superconductivity

It has recently been shown that in addition to describing black holes, gravitational waves, and other gravitational phenomena, general relativity can also describe aspects of nongravitational physics including condensed matter. This is a result of a remarkable gauge/gravity duality that has emerged from string theory. The speaker will explain this surprising development and illustrate it by showing how general relativity can reproduce aspects of superconductivity. This novel approach may eventually yield new insight into the known high temperature superconductors.

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Plenary Talk

Robert P. Kirshner
Harvard University, USA.
robert.kirshner@gmail.com

Exploding stars and the accelerating universe

Observations of exploding stars halfway across the universe show that the expansion of the universe is speeding up. We attribute this to a pervasive “dark energy” whose properties we would like to understand. This work was recently honoured by the 2011 Nobel Prize in Physics to Perlmutter, Schmidt and Riess. In this talk, the speaker will show the most recent evidence from supernovae, CMB fluctuations, and galaxy clustering. The present state of knowledge on dark energy is completely consistent with a modern version of the cosmological constant, but with a ridiculously low value. He will discuss ways to use infrared observations to make the supernova measurements with better accuracy and higher precision. Finally, he will discuss how improved supernova measurements plus the matrix of evidence from other observations, can help us to understand whether modifications to general relativity or a time-varying component of dark energy can be ruled out.

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Plenary Talk

Luis Lehner
Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, ON N2L 2Y5, Canada.
llehner@perimeterinstitute.ca

Membranes and black holes: From jets to cosmic censorship

Analogies between black holes and membranes have long been exploited to understand certain properties of black holes. This talk will review two dynamical scenarios: Jets induced by black holes and the final fate of unstable black strings, where the analogy sheds light into the dynamics and hints of further interesting behaviour. Consequences on observational prospects and cosmic censorship will be discussed.

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Plenary Talk

Shiraz Minwalla
Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India.
minwalla@theory.tifr.res.in

Fluid dynamics from gravity

The speaker will review the map between long wavelength solutions of gravity with a negative cosmological constant, and the equations of fluid dynamics (relativistic generalizations of the Navier Stokes equations). He will review further the extensions of this map to gravitational duals of charged fluid dynamics and superfluid dynamics, and discuss the concrete lessons from this map for fluid dynamics, and speculate about possible lessons about gravity.

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Plenary Talk

Priyamvada Natarajan
Department of Astronomy and Physics, Yale University, 260 Whitney Avenue, New Haven, CT 06511, USA.
priyamvada.natarajan@yale.edu

The formation of the first black holes in the universe

Black holes are the most enigmatic objects in the universe, although it appears now that they are ubiquitous and inhabit the centres of most galaxies in the universe. In fact, the observed local demography of black holes in galactic nuclei suggests that they are supermassive. The first black holes are expected to have formed from the remnants of the first stars at very early times. However, the discovery of supermassive black holes that power quasars as early as 2 Gyrs after the big bang requires alternate channels to form more massive seed black holes. We proposed a new mechanism that involves the direct collapse of massive pre-galactic gas disks and thereby, makes massive early seeds to alleviate this problem. The speaker will present the latest results from the theoretical investigation of these models, including state of the art numerical simulations of the formation process, and outline the new tantalizing observational evidence that appears to support such a mechanism.

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Plenary Talk

Bernard F. Schutz
Max Planck Institute for Gravitational Physics, Albert Einstein Institute, D – 14424 Potsdam, Germany.
bernard.schutz@aei.mpg.de

Gravitational waves: Astronomy for the 21st century

Advanced ground-based detectors will almost certainly make the first detections of gravitational waves within the next few years. With a worldwide network of five sensitive detectors, we will be able to count on spectacular science returns: mass functions for neutron stars and black holes, tight constraints on physics at nuclear densities, insight into the mechanism of short gamma-ray bursts, highly accurate measurements of the Hubble flow out to $z \sim 0.2$, tests of strong-field relativity, measurements of the speed of gravitational waves, constraints on extra scalar gravitational fields, tests of the cosmic censorship hypothesis. Further, sensitivity improvements, and then the construction of third-generation detectors like the Einstein Telescope, offer much more than this. The opening of the low-frequency window with a space-based detector like LISA or eLISA will bring all our galaxy's compact binary systems under scrutiny and will reveal how the massive black hole population of the universe got started and grew. The ultra-low frequency window explored by pulsar timing can give further information about the supermassive black hole population. And these are the scientific outcomes we can predict; what we can't predict will be guaranteed to be even more interesting!

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Plenary Talk

Masaru Shibata
YITP, Japan.
shibata@ea.c.u-tokyo.ac.jp

Coalescence of binary neutron stars and black hole-neutron star binaries

Coalescenece of binary neutron stars and black hole-neutron star binaries is one of the most promising sources for ground-based gravitational wave detectors such as LIGO, VIRGO, and LCGT. It is also a possible candidate for the central engine of short-gamma ray bursts, and an invaluable experimental field for exploring neutron star matter. To theoretically clarify the inspiral and merger processes of these compact binaries and gravitational waves emitted, numerical relativity simulation is the unique approach. In this talk, the speaker will report a variety of their acquaintances obtained from the latest numerical relativity simulations. He will focus, in particular, on how merger process proceeds, the properties of the possible outcomes that may be the central engine of short gamma-ray bursts, and how neutron star properties are obtained from gravitational waves detected in the near future.

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Plenary Talk

Rafael Sorkin
Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, ON N2L 2Y5, Canada.
rsorkin@perimeterinstitute.ca

Geometry from order and number: Causal sets

Among the various ideas put forward in the search for a theory of quantum gravity, the causal set hypothesis is distinguished by its logical simplicity and by the fact that it incorporates the assumption of an underlying spacetime discreteness organically and from the very beginning. After presenting the problem of quantum gravity in general, the speaker will precise the causal set programme and touch on some old and some recent developments.

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Plenary Talk

David Wands
ICG, Portsmouth, UK.
David.Wands@port.ac.uk

Primordial non-Gaussianity from inflation

Inflation in the very early universe provides a simple model for the origin of structure in the universe from initial quantum fluctuations. The fluctuations in a free field have a Gaussian random distribution, but interactions and non-linearities in the field equations can give rise to a non-Gaussian distribution of primordial density perturbations. The speaker will discuss how different sources of non-linearities can lead to different types of non-Gaussianity, and how they may be revealed by observations of the cosmic microwave background and/or large-scale structure in galaxy surveys.

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Plenary Talk

Stan Whitcomb
Caltech, USA.
stan@ligo.caltech.edu

Laser interferometer gravitational wave detectors: Advancing toward a global network

A new generation of gravitational wave detectors based on precision laser interferometry over long baselines should yield the first detections of these predicted waves in the next five years. The required sensitivity equivalent to displacements of ~ 10 - 19 m over multikilometre baselines put these detectors among the most precise optical instruments ever. To move the field from simply detecting gravitational waves to using them to probe questions in both astronomy and physics will require an expansion of the current network based in the US and Europe. A recently started project in Japan and a proposed project in India offer the best hopes for completing the global network.

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W1

Classical General Relativity and Gravitational Waves

Coordinators : Sukanta Bose and Sanjay Jhingan

W1 (T): Classical General Relativity and Gravitational Waves

P. Ajith
LIGO Laboratory and Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA.
ajith@caltech.edu

Addressing the spin question in gravitational wave searches: Spin distributions of compact binary populations

P. Ajith, and Marc Favata

Astrophysical spin distributions of inspiralling compact binaries, which are prime sources of gravitational waves (GWs) for the interferometric GW detectors, are poorly understood. If the spins are misaligned with the orbital angular momentum, the general-relativistic 'spin-orbit' and 'spin-spin' coupling will cause the spins and the angular momentum to precess. This will produce significant complexity in the observed GW signal, deteriorating our ability to detect these signals. This talk will characterize the expected detectability of compact binary populations with different spin distributions (considering the general-relativistic evolution of the binaries over large time scales) in the frequency band of advanced ground-based interferometric detectors. This will help us to formulate search strategies for spinning binaries as well as to make statements about astrophysical spin distributions based on GW observations.

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W1 (T): Classical General Relativity and Gravitational Waves

Bruce Allen
Max Planck Institute for Gravitational Physics, Callinstrasse 38 30167, Hannover, Germany.
bruce.allen@aei.mpg.de

The Einstein@Home search for new neutron stars

Einstein@Home is a volunteer distributed computing project with more than a quarter-million participants. The speaker will describe the current status of its search for new neutron stars, using data from radio telescopes and gravitational wave observatories. He will also talk about the first Einstein@Home discoveries, of new radio pulsars found in data from Arecibo Observatory and other telescopes.

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W1 (P): Classical General Relativity and Gravitational Waves

Gareth Amery

School of Mathematical Sciences, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa.
AmeryG1@ukzn.ac.za

Exact solutions for isometric embeddings of pseudo-Riemannian manifolds

Jothi Moodley, and Gareth Amery

Embeddings into higher dimensions are of direct importance in the study of higher dimensional theories of our universe, in high-energy physics, and in classical general relativity. Theorems have been established that guarantee the existence of local and global co-dimension-1 embeddings between pseudo-Riemannian manifolds, particularly, for Einstein embedding spaces. A technique has been provided to determine solutions to such embeddings. However, general solutions have not yet been found and most known explicit solutions are for embedded spaces with relatively simple Ricci curvature. Motivated by this, we consider isometric embeddings of 4-dimensional pseudo-Riemannian spacetimes into 5-dimensional Einstein manifolds. We apply the technique to treat specific 4D cases of interest in astrophysics and cosmology (including the global monopole exterior and Vaidya-de Sitter-class solutions), and provide novel physical insights into, for example, Einstein-Gauss-Bonnet gravity. Since difficulties arise in solving the 5D equations for given 4D spaces, we also investigate which embedded spaces admit bulks with a particular metric form. These analyses help to provide insight to the general embedding problem.

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W1 (T): Classical General Relativity and Gravitational Waves

Luca Baiotti

ILE, Osaka University, 2 – 6 Yamadaoka, Suita, Osaka 565 – 0871, Japan.
baiotti@ile.osaka-u.ac.jp

Gravitational waves from simulations of binary neutron stars

Luca Baiotti, L. Rezzolla, M. Shibata, T. Damour, B. Giacomazzo, and Nagar A.

The speaker will present their latest results on three-dimensional general-relativistic simulations of binary neutron-star coalescence and merger, and of the subsequent

formation and evolution of the merged object (black hole or hyper-massive neutron star) surrounded by a possibly massive self-gravitating disc. He will focus, in particular, on the gravitational radiation from this system and on its detectability.

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W1 (P): Classical General Relativity and Gravitational Waves

Rudranil Basu

S.N. Bose National Centre for Basic Sciences, Block – JD, Sector – III, Salt Lake, Kolkata 700098, India.
rudranil@bose.res.in

Local symmetries of non-expanding horizons

Rudranil Basu, Ayan Chatterjee, and Amit Ghosh

Local symmetries of a non-expanding horizon have been investigated in the first order formulation of gravity in 4-dimensions. When applied to a spherically symmetric horizons, only a U(1) subgroup of the Lorentz group survives as residual local symmetry that one can make use of in constructing an effective theory on the horizon. We also study the local symmetries for 3-dimensional gravity with a Barbero-Immirzi like parameter in a covariant framework.

Reference

arXiv: 1101.2724

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W1 (T): Classical General Relativity and Gravitational Waves

Luke Butcher

Kavli Institute for Cosmology, C/o. Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK.
lmb62@cam.ac.uk

Localising the energy and momentum of linear gravity

Although there is little doubt that gravitational waves exist and carry energy as they propagate, it has been notoriously difficult to explain where in spacetime this energy resides. The speaker will motivate and derive a new framework for localising

the energy and momentum of the linearised gravitational field, based on the local exchange of energy-momentum between matter and gravity. The gauge ambiguity of the description is removed, mostly as a natural consequence of the derivation, and partly by considering the energy-momentum transferred onto an infinitesimal detector. He will also show that this gravitational energy-density is always positive, and never flows faster than light.

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W1 (P): Classical General Relativity and Gravitational Waves

Carlos Filipe Da Silva Costa
INPE Divisao de Astrofisica Av. dos, Astronautas 1758, 12227 – 010 Sao Jose, dos Campos SP, Brazil.
filipe.dasilva@das.inpe.br

Spherical gravitational wave detectors: Mario Schenberg and MiniGRAIL

(For the Gravitation Group)

Both detectors, Mario Schenberg (Brazil) [1], and MiniGRAIL (Netherlands) [2], share the same principle of detection and almost the same features. Spherical detectors present the possibility of multichannel analysis and the determination of gravitational wave direction and polarization. Mario Schenberg has done a commissioning run in 2006. Since then, its transducers have been redesigned to improve the sensibility. A new run is planned until the end of the year. The author will present the new status, and also present the data analysis techniques that are or going to be investigated: low latency analysis, direction detection [3, 4], Bayesian techniques and a study for periodic signals. These techniques are presently tested on simulated data.

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W1 (P): Classical General Relativity and Gravitational Waves

Patrick Das Gupta
Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India.
patrick@srb.org.in

Gravitational waves in the presence of a dynamical four-form

A dynamical four-form arises naturally in the theory of general relativity, and it leads to a Chern-Simons extension of gravitation in (3+1)-dimensions. The evolving four-form in Einstein-de Sitter universe acts as a source of dark energy responsible for the observed accelerated expansion. The present work studies the propagation of gravitational waves, taking into account the back-reaction from the dynamical four-form. Constraints on the coupling constants appearing in the Lagrangian density for the four-form, from future LIGO experiments, have been investigated.

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W1 (P): Classical General Relativity and Gravitational Waves

Suresh Doravari
Caltech, USA.
doravari_s@ligo.caltech.edu

Third harmonic resonant side band extraction and interferometer control at the Caltech 40 m prototype

Suresh Doravari, Kiwamu Izumi, Jenne Driggers, Jameson Rollins, Steve Vass, Koji Arai, and Rana Adhikari

The Caltech 40 metre prototype interferometer has recently been upgraded to implement several control schemes, which are going to be used in the aLIGO. The interferometer is currently configured as a dual recycled Fabry-Perot Michelson interferometer (DRFPMI) and employs third harmonic resonant side band signal extraction for sensing controlling its various degrees of freedom. We have also implemented arm length stabilization (ALS) using green beams from auxiliary frequency doubled NPRO's placed at the end of each arm. This poster summarizes these schemes, and describes how they are used in setting up and operating the 40m DRFPMI.

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Gustavo Dotti
FaMAF, Universidal Nacional de Cordoda, Argentina.
gdotti@famaf.unc.edu.ar

Instabilities in super extreme Kerr spacetime and black hole interiors

Scalar, spinor and Maxwell fields, as well as gravitational perturbations propagating in super-extreme Kerr spacetime or the stationary Kerr black hole interior, are shown to exhibit axially symmetric modes that grow exponentially in time. There is at least one such mode for each harmonic number greater than a minimum value that depends on the spin of the field. The existence of these modes is shown to be related with the "time machine" region of Kerr spacetime, where the axial Killing vector field is timelike. Difficulties to treat the evolution-from-data problem and to determine if the unstable behaviour is generic will be commented.

References

1. G. Dotti, R.J.Gleiser and I.F. Ranea-Sandoval, Instabilities in super extreme Kerr spacetime and black hole interiors (in preparation).
2. G. Dotti and R.J. Gleiser, Class. Quant. Grav., **27**, 185007 (2010) [arXiv:1001.0152 [gr-qc]].
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W1 (P): Classical General Relativity and Gravitational Waves

Ryuichi Fujita
Theoretical Physics, Raman Research Institute, Sir C.V. Raman Avenue, Sadashiva Nagar, Bangalore 560080, India.
draone@rri.res.in

Gravitational waves from extreme mass ratio inspirals to the 14th post-Newtonian order

We derive gravitational waveforms needed to compute the 14th post-Newtonian (14 PN) order energy flux, i.e., v^{28} beyond Newtonian approximation, where v is the

orbital velocity of a test particle, in a circular orbit around a Schwarzschild black hole. We exhibit clearly the convergence of the energy flux in the PN expansion and suggest the fitting formula, which can be used for more general case. The phase difference between the 14 PN waveforms and numerical waveforms after two years inspiral becomes about 10^{-7} for $\mu M = 10^{-4}$ and 10^{-3} for $\mu M = 10^{-5}$, where μ and M are the masses of a compact object and a supermassive black hole at the centers of galaxies respectively. The 14 PN expressions will lead to the parameter estimation comparable to numerical waveforms for extreme mass ratio inspirals, which are one of the main targets of Laser Interferometer Space Antenna.

Reference

http://arxiv.org/abs/1104.5615.

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W1 (P): Classical General Relativity and Gravitational Waves

Shaon Ghosh

Department of Physics and Astronomy, Washington State University, P.O. Box 642814, Pullman, WA 99164 – 2814, USA.
shaonghosh@mail.wsu.edu

Searching for short duration gamma ray bursts in ligo with large sky position uncertainties

Shaon Ghosh, and Sukanta Bose

Short duration gamma ray bursts (GRB) are one of the prime candidates for discovery of gravitational waves. The advantages of these types of source are two fold. Firstly, being compact binary coalescence type source, the wave forms are known beforehand, and secondly, we have external verification of an actual event through electromagnetic counterpart. Conventional short GRB search pipeline treats the source coordinates and time as precisely known quantity. But observatories giving us the sky position alerts for the GRB have finite sky localization ability. The error in the sky position information will result in to reduction in the signal recovery, and hence, will damage the performance and efficiency of the search process. With this in mind, we developed a new search technique that attempts at resolving this issue. We develop this technique in which the search is done over a patch of sky instead on one specified point and then we maximize the signal to noise ratio for all the points in that patch. We also discuss how this technique might give us some added benefits even if the sky position of the object

is perfectly known, due to the fact that the interferometers have different noise power spectral densities, the templates that we construct for matched filtering will be different.

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W1 (T): Classical General Relativity and Gravitational Waves

Sushant Ghosh

Centre for Theoretical Physics, Jamia Millia Islamia, New Delhi 110025, India.
sgghosh@gmail.com

Inhomogeneous dust collapse in 5 D Einstein-Gauss-Bonnet gravity

Sushant G. Ghosh, and Sanjay Jhingan

The low-energy expansion of supersymmetric string theory suggests that the leading correction to Einstein action is given by Gauss-Bonnet invariant. In 5D, we have found exact spherically symmetric Lemaitre-Tolman-Bondi (LTB) solutions for the marginally bound case to Gauss-Bonnet extended Einstein equations (5D-LTB-EGB). This describes gravitational collapse of spherically symmetric inhomogeneous dust in a 5D spacetime in EGB gravity. It turns out that the presence of the coupling constant of the Gauss-Bonnet terms $\alpha > 0$ completely changes the casual structure of the singularities from the analogous general relativistic case. The gravitational collapse of inhomogeneous dust in the five-dimensional Gauss-Bonnet extended Einstein equations leads to formation of a massive, but weak, timelike singularity, which is forbidden in general relativity. Interestingly, this is a counter example to three conjectures, viz., cosmic censorship conjectures, hoop conjecture, and Seifert's conjecture. In the general relativistic case, a naked singularity will form only when M_0 takes a sufficiently small value, and therefore, turning on the Gauss-Bonnet term worsens the situation from the viewpoint of cosmic censorship conjecture (CCC). It is also seen here that the Gauss-Bonnet term modifies the time of formation of singularities, and the time lag between singularity formation and apparent horizon formation, in contrast to the 5D dust models. Indeed, the time for the occurrence of the central shell focusing singularity for the collapse is increased as compared to the autologous 5D-LTB case.

References

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W1 (P): Classical General Relativity and Gravitational Waves

Achamveedu Gopakumar
Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India.
gopu@tifr.res.in

Gravitational wave phasing for spinning compact binaries

Achamveedu Gopakumar, and Gerhard Schaefer

We provide a prescription to obtain temporally evolving gravitational wave (GW) polarization states for spinning compact binaries in inspiraling circular and eccentric orbits, while restricting the spin effects to the leading order spin-orbit coupling. The new ingredient in our approach is to employ the total orbital angular momentum to describe the orbit rather than using its Newtonian counterpart as usually followed in the literature. We compare our approach with existing prescriptions for both the quasi-circular and quasi-eccentric inspirals and point out differences.

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W1 (P): Classical General Relativity and Gravitational Waves

Gabriel Govender
University of KwaZulu-Natal, School of Mathematical Sciences, Private Bag X54001, Durban 4000, South Africa.
govenderg@ukzn.ac.za

Generalised junction conditions for radiating star

G. Govender, S. D. Maharaj, and M, Govender

We construct the general junction condition on the surface of a dissipating star. Our investigation shows that the exterior region of the star must be a superposition of pressureless null dust and a null string fluid. Our result is applied to a particular physical model.

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W1 (T): Classical General Relativity and Gravitational Waves

Samuel Gralla

University of Maryland, College Park, MD 20742-4111, U.S.A.
sgralla@uchicago.edu

Why do spinning black hole binaries bob and kick?

S. Gralla, A. Harte, and R. Wald

Numerical simulations of binary black holes with spin have revealed some surprising behavior: for anti-aligned spins in the orbital plane, one sees (1) an up-and-down "bobbing" of the entire orbital plane at the orbital frequency, and (2) a velocity kick, roughly in the direction of the bobbing motion at merger. We show that this type of bobbing is in fact ubiquitous in relativistic mechanics, occurring independently of the type of bodies or force holding them in orbit. The cause can be identified as a spin correction to the naive center of mass of a body; the effect is analogous to Thomas precession and is "purely kinematical" in the same way. Since a kick requires the release of field momentum, it is instead very dependent on the type of force holding bodies in orbit. In a mechanical analog (spinning balls connected by a string), there is bobbing but can be no kick. In an electromagnetic analog, one should be able to tune the kick independently of the bobbing. In the gravitational case, the spin parameter happens to control both bobbing and kick, making separate tuning impossible and giving the appearance of causation. We conclude that the bobbing is caused by a purely kinematical effect of spin, and the kick should not be viewed its post-merger continuation.

Reference

Phys. Rev. D, **81**, 104012 (2010).

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Sarbari Guha
Department of Physics, St. Xavier's College, 30 Mother Teresa Sarani, Kolkata 700016, India.
srayguha@yahoo.com

Gravity in five-dimensional warped product spacetimes with time-dependent warp factor

Sarbari Guha, and Pinaki Bhattacharya

We have considered gravity in a 5-dimensional warped product spacetime with a time-dependent warp factor and time-dependent extra dimension. The braneworld is described by a spatially flat FRW-type metric. The five-dimensional field equations have been constructed and solved and the status of the energy conditions have been examined. In the low energy regime, we have considered a stabilized bulk and have analyzed the cosmological behaviour of the corresponding universe. In the high energy regime, the bulk is assumed to be sourced by a scalar field. The field equations have been solved to obtain desirable solutions, pertaining to viable energy conditions.

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2. International Journal of Theoretical Physics, 2011 (accepted for publication)

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Anuradha Gupta
Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India.
arg@tifr.res.in

Compact binaries in hyperbolic orbit encounters

Compact binaries in hyperbolic orbit (hyperbolic encounter) are plausible sources of gravitational waves (GWs) for ground based and space-based detectors and produce burst of GWs. We model the GWs from these encounters using post-Newtonian (PN) approximation to general relativity. We compute fully 1 PN accurate

GWs polarization states evolving under 1 PN-accurate orbital dynamics using a quasi-Keplerian approach. Efforts to extend the dynamics to fully 2.5 PN-accurate level is outlined.

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W1 (P): Classical General Relativity and Gravitational Waves

Rajalakshmi Gurumurthy
Gravitation Group, Department of High Energy Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India.
g.raji@tifr.res.in

Short range force measurement employing prototypes of interferometric gravity wave detectors

G. Rajalakshmi, and C. S. Unnikrishnan

We propose an experiment to measure Casimir force between parallel mirrors, using highly sensitive gravitational wave detectors as displacement sensors. The finite temperature effects of the Casimir force would be detectable with a sensitivity of better than 1%. The experiment will also provide constraints for theoretical models suggesting deviation to gravity in the sub-mm regime.

Reference

Class. Quant. Grav., **27**, 215007 (2010).

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W1 (P): Classical General Relativity and Gravitational Waves

Sudan Hansraj
School of Mathematical Sciences, University of KwaZulu – Natal, Howard College Campus, King George V Avenue, Durban 4041, South Africa.
hansrajs@ukzn.ac.za

Perfect fluid spacetimes conformally related to the schwarzschild exterior metric

We present the most general perfect fluid spacetime conformal to the non-conformally flat Schwarzschild exterior metric, and prove that such metrics are

necessarily static, and exhibit the line element explicitly. Such conformally Ricci-flat perfect fluid spacetimes are rare, and the only other attempt is by van den Bergh (1985) who presented vorticity free solutions albeit not explicitly. We analyze this solution for physical plausibility, and demonstrate that it satisfies the most elementary requirements, including the causality criterion.

Reference

General Relativity and Gravitation (To appear).

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W1 (T): Classical General Relativity and Gravitational Waves

Tomohiro Harada
Department of Physics, Rikkyo University, Toshima, Tokyo 171-8501, Japan.
harada@rikkyo.ac.jp

High velocity collision of particles around a rapidly rotating black hole

Tomohiro Harada, and Masashi Kimura

We derive a general formula for the center-of-mass (CM) energy for the near-horizon collision of two general geodesic particles around a Kerr black hole. We find that if the angular momentum of the particle satisfies the critical condition, the CM energy can be arbitrarily high. We then apply the formula to the collision of a particle orbiting an innermost stable circular orbit (ISCO) and another generic particle near the horizon and find that the CM energy is arbitrarily high if we take the maximal limit of the black hole spin. In view of the astrophysical significance of the ISCO, this implies that particles can collide around a rapidly rotating black hole with a very high CM energy without any artificial fine-tuning. We next apply the formula to the collision of general inclined geodesic particles and show that, in the direct collision scenario, the collision with an arbitrarily high CM energy can occur near the horizon of maximally rotating black holes, not only at the equator but also on a belt centered at the equator between latitudes pm 42.94°. This is also true in the scenario through the collision of a last stable orbit particle. This strongly suggests that if signals due to high-energy collision are to be observed, such signals will be generated primarily on this belt.

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Suraj Hegde
No. 107, I Floor, Saptha Residency, S.B.M. Colony, K.S.R.T.C. Layout, Chikkalasandra, Bangalore 560061, India.
physicsshegde@gmail.com

Analytical theory for optical black hole analogs

Suraj Hegde, and C.V. Vishveshwara

Advances in transformation optics and analog gravity have led to systems that mimic aspects of gravity like black holes. We develop a general analytical formalism for such systems with static optical media based on the wave equation for propagation of electromagnetic waves in inhomogeneous medium in flat spacetime. Its similarity to the wave equation in spherically symmetric spacetimes leads to the analogy between the metric of a curved spacetime, and the permittivity and/or permeability of the medium in flat spacetime. In geometrical optics limit, we obtain similar Eikonal equations in both cases, which lead to ray trajectories in the medium similar to gravitational geodesics. Thus, we formulate spherically symmetric optical spacetimes corresponding to black holes including Schwarzschild, and apply it to specific case of Narimanov-Kildishev optical black hole (Applied Phys. Lett., **95**, 041106, 2009).

We discuss effective potential and quasinormal modes (QNM) of such optical black holes. QNM and curved light paths manifestly characteristic phenomena of black holes, and are functions of refractive index, a quantity controllable through experiments. One can, thus, investigate such gravitational phenomena with simple table-top experiments, using varying refractive index medium to bend the light rays and metamaterials to absorb the incident light.

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Steven Hergt
Friedrich-Schiller University Jena, Physikalisch-Astronomische Fakultat, Theoretical Physics Institute, Max-Wien-Platz 1, D-07743 Jena, Thuringia, Germany.
steven.hergt@uni-jena.de

On the comparison of results regarding the post-Newtonian approximate treatment of the dynamics of extended spinning compact binaries

Steven Hergt, Jan Steinhoff, Johannes Hartung, and Gerhard Schaefer

We review the results obtained during the last year, concerning the conservative post-Newtonian dynamics of a system consisting of two extended spinning compact objects in general relativity with focus on spin interaction. The results are either given as a fully reduced Hamiltonian, calculated by using the canonical ADM approach to the constrained dynamics on a 3+1 decomposed spacetime or as a not fully reduced effective potential calculated within the effective field theory approach. Comparison between the various Hamiltonians and the corresponding effective potentials is made. Therefore, a variable transformation is derived from an effective action, which transforms the frame pertaining to the covariant spin supplementary condition to the canonical one. The Hamiltonians and potentials in question comprise all the next-to-leading-order ones linear and quadratic in spin as well as the next-to-next-to-leading-order spin-orbit and spin(1)-spin(2) Hamiltonians.

References

1. arXiv:1002.2093.
2. arXiv:1104.3079.
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W1 (P): Classical General Relativity and Gravitational Waves

Sanjay Jhingan
Centre for Theoretical Physics, Jamia Millia Islamia, Jamia Nagar, New Delhi 110025, India.
sanjay.jhingan@gmail.com

Depletion of energy from naked singular regions during gravitational collapse

Sanjay Jhingan, and Sukratu Barve

A distinguishable and observable physical property of naked singular regions of the spacetime formed during a gravitational collapse has important implications for both experimental and theoretical relativity. We examine here whether energy can escape physically from naked singular regions to reach either a local or a distant observer within the framework of general relativity. We find that in case of imploding null dust collapse scenarios, field outgoing singular null geodesics including the Cauchy horizon can be immersed between two Vaidya spacetimes as null boundary layers with non vanishing positive energy density. Thus, energy can be transported from the naked singularity to either a local or a distant observer. An example illustrating that similar considerations can be applied to dust models is given.

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W1 (T): Classical General Relativity and Gravitational Waves

Arun K. G.
Chennai Mathematical Institute, Plot H1, SIPCOT IT Park, Pudur P.O., Siruseri 603103, India.
kgarun@cmi.ac.in

Possible bounds on vector modes of generic metric theories of gravity using gravitational waves observations

A generic metric theory of gravity has six modes of gravitational wave polarization: two tensor modes, two vector modes, and two scalar modes. We put forward a physically motivated gravitational waveform in Fourier domain for vector modes in terms of two parameters, one which captures the relative amplitude of the vector mode with respect to the tensor mode (α), and the other a dipole term in the phase (β). We then use this two parameter representation to discuss the typical bounds on them using 'single detector' GW measurements. We find that the best bound

would come from the observations of supermassive black hole binaries by the proposed LISA interferometer, which may bound the amplitude parameter α to $\sim 10^{-4}$ and the β at the level of 10^{-7}. Second generation ground-based interferometers such as AdvLIGO, and third generation detectors like Einstein Telescope may put a bound of 10^{-2} and 10^{-3} for α and 10^{-6} and 10^{-4} for dipole parameter β, respectively.

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W1 (P): Classical General Relativity and Gravitational Waves

Laishram Kapil
Department of Mathematics, Manipur University, Imphal 795003, India.
laishramkapil@gmail.com

Hawking radiation from Reissner-Nordstrom-Vaidya black hole by using Hamilton Jacobi method

Ng. Ibohal, and L. Kapil

The black hole thermodynamics can be derived successfully on the apparent horizon. The first law of black hole thermodynamics can be constructed at the new supersurface, which has a small deviation from the apparent horizon if a relativistic perturbation is applied to the apparent horizon, and a similar calculation can also lead to a purely thermal spectrum, which corresponds to a modified temperature from the former. When the event horizon is thought of as a deviation from the apparent horizon, the expression of the characteristic position and temperature are consistent with the previous result, which asserts that thermodynamics should be built on the event horizon. It is concluded that the thermodynamics should be constructed exactly on the apparent horizon, while the event horizon thermodynamics is just one of the perturbations near the apparent horizon.

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Sayan Kar
Department of Physics and Meteorology, and Centre for Theoretical Studies, Indian Institute of Technology, Kharagpur 721302, India.
sayan@iitkgp.ac.in

Confinement and focusing of geodesics in warped spacetimes

Sayan Kar, Suman Ghosh, Hemwati Nandan, and Anirvan DasGupta

We first explore certain characteristic features of test particle trajectories in five dimensional, warped bulk geometries with a single thick brane. After an overview of such spacetimes, we begin our analysis of timelike geodesic motion [1]. The geodesic equations, which reduce to a first order autonomous dynamical system, are solved using analytical and numerical methods. We demonstrate how a growing (decaying) warp factor leads to oscillatory (runaway) trajectories, suggesting confinement (deconfinement) [1]. Next, we move on to the kinematics of geodesic congruences [2]. The evolution of the kinematical variables (expansion, rotation and shear) along geodesic flows are obtained using analytical and numerical approaches, with particular emphasis on the required conditions and occurence of geodesic focusing [2]. Finally, we analyse geodesics and geodesic flows for two-brane models [2] and conclude by briefly mentioning a recently proposed class of two-brane models - the slanted warped extra dimensions [3] - for which, possible future directions of research related to our work, are outlined.

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3. D. Hernandez, and M. Sher, Phys. Letts. B, **698**, 403 (2011).

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W1 (T): Classical General Relativity and Gravitational Waves

Mansi Kasliwal
Carnegie-Princeton Fellow, Caltech, USA
mansi@astro.caltech.edu

The transient electromagnetic sky

The transient electromagnetic (EM) sky is quite dynamic. The speaker will begin with a discussion of the EM false positives on gravitational wave (GW) localization scales. Next, she will discuss how the GW sensitivity limitation to the local universe can be leveraged to overcome the poor localization challenge. In order to design an effective search strategy for an EM counterpart, she presents two ongoing efforts with the Palomar Transient Factory: (i) building a complete catalog of nearby galaxies, (ii) systematically completing the inventory of transients in the local universe. This will help to identify, follow-up and unambiguously associate an EM counterpart with the GW signal in a timely manner.

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W1 (P): Classical General Relativity and Gravitational Waves

David Keitel
Albert Einstein Institute, Max Planck Institute for Gravitational Physics, Callinstrasse 38 30167, Hannover, Germany.
david.keitel@aei.mpg.de

An F-statistic based multi-detector veto for detector artifacts in searches for continuous gravitational waves

D. Keitel, R. Prix, M.A. Papa, P. Leaci, and M. Siddiqi

Continuous gravitational waves (CW) are expected from spinning neutron stars with non-axisymmetric deformations. They are predicted to be very weak and retrievable only by integration over long observation times. One of the standard methods of CW data analysis is the multi-detector F-statistic. In a typical search, the F-statistic is computed over a range in frequency, spin-down and sky position, and the candidates with highest F values are kept for further analysis. However, this detection statistic is susceptible to a class of noise artifacts, strong monochromatic lines in a single detector. By assuming an extended noise model - standard Gaussian noise plus single-detector lines - we can use a Bayesian odds ratio to derive a generalized detection statistic, the line veto (LV) statistic. In the absence of

lines, it behaves similarly to the F-statistic, but it is much more robust against line artifacts. In the past, ad-hoc post-processing vetoes have been implemented in searches to remove these artifacts. Here, we provide a systematic framework to develop and benchmark this class of vetoes. We present our results from testing this LV-statistic on simulated data. Furthermore, we plan to use it on the current Einstein@Home distributed computing analysis of LIGO S6 data.

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W1 (T): Classical General Relativity and Gravitational Waves

Tjonnie Li
National Institute for Subatomic Physics (Nikhef), Science Park, 105 1098 XG, Amsterdam, The Netherlands.
tgfli@nikhef.nl

Coalescing binary neutron stars and black holes as laboratories for testing general relativity

T.G.F. Li, W. Del Pozzo, S. Vitale, C. Van Den Broeck, J. Veitch, K. Grover, and A. Vecchio

Coalescences of binary neutron stars and/or black holes are amongst the most likely gravitational wave signals to be observed in ground based interferometric detectors. Apart from the importance of their detection, they will also provide us with the very first empirical access to the genuinely strong field dynamics of general relativity (GR). We present a Bayesian data analysis pipeline aimed to detect arbitrary deviations from GR, irrespective of their detailed nature. The pipeline tests the consistency of the measured gravitational wave phase coefficients in the inspiral regime with the predictions made by GR. Sources in the Advanced LIGO/Virgo detectors will have too low a signal-to-noise ratio (SNR) for all of these coefficients to be measured together. Instead, we introduce a framework in which, for a single source, one performs a number of tests on a limited number of coefficients, which are more sensitive at low SNR. The results of these can be collected to construct an odds ratio quantifying the extent of a possible deviation from GR. Information from multiple sources can then be combined in a straightforward fashion. In order to demonstrate the workings of the pipeline, we show preliminary results obtained by analysing simulated waveforms containing small deviations from GR.

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W1 (T): Classical General Relativity and Gravitational Waves

Sunil Maharaj
School of Mathematical Sciences, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa.
maharaj@ukzn.ac.za

New models with heat flow and Lie symmetries

We study shear-free spherically symmetric spacetimes with heat flow. The Lie symmetry generators for the governing field equation are obtained, which enables us to map the equation into itself. In this way, we can generate a new solution to the field equations if a particular solution is known. All known solutions of Einstein equations with heat flow can, therefore, produce infinite families of new solutions. By considering combinations of the Lie infinitesimal generators, two other new classes of exact solutions are found.

Reference

A. M. Msomi, K. S. Govinder, and S. D. Maharaj, accepted for publication in Gen. Rel. Grav.

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W1 (T): Classical General Relativity and Gravitational Waves

Daniele Malafarina
Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India.
daniele.malafarina@polimi.it

Static configurations from gravitational collapse

Pankaj S. Joshi, Daniele Malafarina, and Ramesh Narayan

We investigate here how equilibrium configurations that result as the final state of gravitational collapse from regular initial conditions can develop within Einstein's theory of gravity. We show that the equilibrium geometries generated by this method form a subset of static solutions to the Einstein equations, and that they can either be regular or develop a naked singularity at the center. When a singularity is present, there are key differences in the properties of stable circular orbits relative to those around a Schwarzschild black hole with the same mass.

Therefore, if an accretion disk is present around such a naked singularity it could be observationally distinguished from a disk around a black hole.

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W1 (T): Classical General Relativity and Gravitational Waves

Chandra Kant Mishra
Theoretical Physics Group, Raman Research Institute, Sadashiv Nagar, Bangalore 560080, India.
chandra@rri.res.in

Nonspinning inspiralling compact binaries in quasi circular orbits: 2.5 PN linear momentum loss and associated recoil

Chandra Kant Mishra, K. G. Arun, and Bala R. Iyer

Anisotropic emission of gravitational waves (GWs) from inspiralling compact binaries leads to the loss of linear momentum by the system in the form of GWs. As a consequence, these system will experience a recoil and may eventually be ejected from their hosts. In the present work, the loss rate of linear momentum from a nonspinning binary system of black holes in quasi-circular orbit have been investigated. We have used the multipolar post-Minkowskian approximation method to compute the expression for the linear momentum flux at the 2.5 post-Newtonian (PN) order. We then use this expression to compute the recoil velocity accumulated during the inspiral phase of binary evolution, and give a formula for the recoil velocity as a function of the separation between the two BHs in the binary system. Going beyond the inspiral phase, the contribution to the recoil velocity at the end of the plunge phase has also been computed.

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W1 (P): Classical General Relativity and Gravitational Waves

Priti Mishra
A 272, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India.
priti@tifr.res.in

Quadrupolar gravitational back-reaction and flat galaxy rotation curves

Priti Mishra, and T. P. Singh

Using a Scalar-Tensor-Vector-Gravity [STVG] theory, Moffat and collaborators have shown that the incorporation of the scalar and vector gravity components modifies Newtonian gravity by the inclusion of a Yukawa type potential. This modification can be used, along with two parameters [a mass scale and a length scale], to fit the flat rotation curves of more than a hundred galaxies. The STVG theory is, thus, suggested as an alternative to dark matter in galaxies. We show that precisely the same result as that of Moffat can be obtained by considering the gravitational back-reaction of ordinary matter in a galaxy, at the quadrupole approximation, in classical general relativity.

Reference

arXiv:1108.2375 [astro-ph.GA]

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W1 (T): Classical General Relativity and Gravitational Waves

Sanjit Mitra
Jet Propulsion Laboratory, M/S. 169 – 327, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.
Sanjit.Mitra@jpl.nasa.gov

Probing a stochastic gravitational wave background using a network of laser interferometric detectors

Gravitational wave (GW) astronomy aims to probe different kinds of sources; Stochastic Gravitational Wave Background (SGWB) is one of the most interesting ones. The universe is expected to have an SGWB generated by unmodeled/unresolved astrophysical and cosmological sources. Statistically

isotropic cosmological SGWB has already caught lot of attention, as it is a direct probe of slow roll inflation. On the other hand, anisotropic SGWB, generated by unmodeled/unresolved astrophysical sources in the nearby universe, dominates the background by several orders of magnitude and can provide important information about the nearby universe not accessible to electro-magnetic astronomy. A gravitational wave radiometer algorithm is well suited for probing SGWB. We present a general analysis framework to efficiently probe SGWB in any given basis using a network of detectors. We study the performance of a network using different figures of merit. Simplicity of this method leads to results which are relatively straightforward to compute, yet provide vital understanding of the overall network performance.

References

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2. E. Thrane, et al., Phys. Rev. D, **80**, 122002 (2009).
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W1 (P): Classical General Relativity and Gravitational Waves

Arunava Mukherjee
Department of Astronomy and Astrophysics, School of Natural Sciences, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India.
arunava@tifr.res.in

Recent observations of extremely strong gravity phenomena and its interesting consequences

Einstein's GR is the best theory of gravity, while tested and confirmed, with exquisite precision in weak to moderate fields. But till date, it has not yet been tested by direct observation, e.g., of the motion of particles in the gravitational field comparable to that at a few Schwartzschild radius near a compact object, where the gravitational binding energy is of the order of rest mass. The extreme predictions of GR are the existence of event horizons, i.e., black holes, the existence of an inner radius within which no stable orbits exist, existence of Kerr spacetime, strong dragging of inertial frames, and general-relativistic precession at rates similar to the orbital motion itself. Since testing these predictions is not possible at any terrestrial laboratories, the only possible hope is to look at the astrophysical objects. Measuring the spins of black holes and existence of near extremal Kerr black holes are very exciting recent discoveries. One of the principal motivations for studying the low-mass x-ray binaries is the unique window that accretion onto neutron stars and black holes provides on the physics of strong gravity. Moreover, some alternate theory of gravity that differs from GR should potentially be tested around these astrophysical objects. The author will present some of these observational results of current x-ray observations.

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W1 (T): Classical General Relativity and Gravitational Waves

Samaya Nissanke
Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA.
samaya@tapir.caltech.edu

Localizing compact binary inspirals on the sky using ground-based gravitational wave interferometers

Samaya Nissanke, Jonathan Sievers, Neal Dalal, and Daniel Holz

The inspirals and mergers of compact binaries are among the most promising events for ground-based gravitational wave (GW) observatories. The detection of electromagnetic (EM) signals from these sources would provide complementary information to the GW signal. It is, therefore, important to determine the ability of GW detectors to localize compact binaries on the sky, so that they can be matched to their EM counterparts. We use Markov Chain Monte Carlo techniques to study sky localization using networks of ground-based interferometers. Using a coherent-network analysis, we find that the Laser Interferometer Gravitational Wave Observatory (LIGO)-Virgo network can localize 50% of their detected neutron star binaries to better than 50 deg^2 with a 95% confidence interval. The addition of the Large Scale Cryogenic Gravitational Wave Telescope (LCGT) and LIGO-Australia improves this to 12 deg^2. Using a more conservative coincident detection threshold, we find that 50% of detected neutron star binaries are localized to 13 deg^2 using the LIGO-Virgo network, and to 3 deg^2 using the LIGO-Virgo-LCGT-LIGO-Australia network. Our findings suggest that the coordination of GW observatories and EM facilities offers great promise.

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W1 (T): Classical General Relativity and Gravitational Waves

Ernesto Nungesser
Max-Planck-Institute for Gravitational Physics, Am Muehlenberg 1 D – 14476, Golm, Germany.
ernesto.nungesser@aei.mpg.de

Late-time asymptotics of some Bianchi A spacetimes with collisionless matter

The late-time behavior of Bianchi spacetimes with a non-tilted fluid is well understood. Sometimes it is of advantage to use kinetic theory to describe the matter content of the universe. In particular, collisionless matter is often used in astrophysics and has some nice mathematical properties. We will present results concerning the late-time behavior of some expanding Bianchi A spacetimes with this kind of matter. The results imply in particular that collisionless matter is well approximated by the Einstein-dust system.

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W1 (T): Classical General Relativity and Gravitational Waves

Seiju Ohashi
Department of Physics, Kyoto University, Kitashirakawa-oiwake, Sakyoku, Kyoto 606-8502, Japan.
ohashi@tap.scphys.kyoto-u.ac.jp

Spherical collapse of inhomogeneous dust cloud in the Lovelock theory

Seiju Ohashi, Tetsuya Shiromizu, and Sanjay Jhingan

We study gravitational collapse of spherically symmetric inhomogeneous dust cloud in the Lovelock theory without cosmological constant. We show that the final fate of gravitational collapse in this theory depends on the spacetime dimensions. In odd dimensions, the naked singularities formed are found to be massive. In the even dimensions, on the other hand, the naked singularities are found to be massless. We also show that the curvature strength of naked singularity is independent of the spacetime dimensions in odd dimensions. However, it depends on the spacetime dimensions in even dimension.

Reference

arXiv:1103.3826.

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W1 (P): Classical General Relativity and Gravitational Waves

Archana Pai
Indian Institute of Science Education and Research, CET Campus, Thiruvananthapuram 695016, India.
archana@iisertvm.ac.in

Tests of post-Newtonian theory using singular value decomposition in parameter estimation

Archana Pai, and K. G. Arun

Phasing formula of non-spinning compact binaries is fully characterized by the two component masses. If two of the post-Newtonian (PN) phasing coefficients are independently measured, the masses can be estimated. Future gravitational wave observations could measure many of the 8 independent PN coefficients calculated to date. These additional measurements can be used to test the PN predictions of the underlying theory of gravity. Since all of these parameters are functions of the two component masses, there is strong correlation between the parameters when treated independently. We use Singular Value Decomposition to obtain a new set of parameters, which significantly improves the accuracy with which PN theory can be tested.

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Maria Alessandra Papa
Max Planck Institut f. Gravitationphysik, Callinstrasse, 38 30167 Hannover, Germany.
maria.alessandra.papa@aei.mpg.de

Deep searches for continuous gravitational wave signals

M. Alessandra Papa, et al.

The speaker will review the latest results, and open challenges in blind searches for continuous gravitational wave signals.

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W1 (T): Classical General Relativity and Gravitational Waves

Mandar Patil
Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India.
mandarp@tifr.res.in

Naked singularities as particle accelerators

Mandar Patil, and Pankaj Joshi

We discuss the particle acceleration by Kerr naked singularities. We show that the particles with moderate energies at infinity, following a geodesic motion in the background of the Kerr naked singularity can collide and interact with arbitrarily large unbound center of mass energies, provided the deviation of the Kerr spin parameter from unity is small. We discuss two cases, where particles move and collide in equatorial plane and along the axis of symmetry of the Kerr spacetime. We show that the acceleration mechanism we proposed is generic and avoids various extremely severe fine-tuning issues encountered in a related process in the background of extremal blackholes. We briefly talk about the curious thought collider physics experiment that can be set up along the axis of symmetry of Kerr spacetime to probe beyond standard model physics at arbitrarily large energies. We also discuss the possible astrophysical implications of the particle acceleration process in terms of dark matter annihilation around the galactic central supermassive objects, assuming that it can be modeled as a Kerr naked singularity.

References

1. arxiv/1103.1082.
2. arxiv/1103.1083.

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W1 (P): Classical General Relativity and Gravitational Waves

Reinhard Prix
Albert Einstein Institute, Max Planck Institute for Gravitational Physics, Callinstrasse 38 30167, Hannover, Germany.
Reinhard.Prix@aei.mpg.de

Bayesian detection methods for continuous gravitational waves

In recent years, Bayesian methods have proved increasingly useful in the search for continuous gravitational waves (CWs), both for improving existing detection methods, as well as for developing new methods, such as a detection statistic for transient CWs and veto methods for detector "line" artifacts. The author will report on recent progress on using this framework to develop improved methods for CW searches over large parameter spaces, which need to take account of the additional constraint of finite available computing power.

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W1 (T): Classical General Relativity and Gravitational Waves

Satyanarayan Ray Pitambar Mohapatra
Department of Physics, University of Massachusetts – Amherst, Amherst, MA 01003, USA.
satya@physics.umass.edu

Detectability of binary black hole merger signals in ground based gravitational wave detectors

(For the NINJA Collaboration, the LIGO Scientific Collaboration, and the Virgo Collaboration)

Binary black hole mergers are one of most important astrophysical sources that could be detected in a ground based gravitational wave detector, like the Laser Interferometer Gravitational Wave Observatory (LIGO). There are several data

analysis algorithms, which have carried out searches or are capable of detecting the gravitational wave signals from binary black hole mergers. Numerical INJection Analysis (NINJA) project has brought together several numerical relativity groups; producing the best available, state of the art binary black hole merger waveforms and several gravitational wave data analysis groups; using wide varieties of algorithms to study the detectability, and estimate the source parameters from these gravitational wave signals. In this talk, preliminary results from different search algorithms on NINJA waveforms will be presented, detectability of binary black hole merger signals in different search algorithms will be compared and then the outlook for detection in the advanced generation gravitational wave detectors will be discussed.

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W1 (P): Classical General Relativity and Gravitational Waves

Sourya Ray
CECS, Chile
ray@cecs.cl

Birkhoff's theorem in higher derivative theories of gravity

We present a class of higher derivative theories of gravity, which admit Birkhoff's theorem (in vacuum). In particular, we explicitly show that in this class of theories, although generically the field equations are of fourth order, under spherical (plane or hyperbolic) symmetry, all the field equations reduce to second order and have exactly the same or similar structure to those of Lovelock theories, depending on the spacetime dimensions and the order of the Lagrangian.

Reference

Class. Quant. Grav., **28**, 175007 (2011), arXiv:1104.1205 [gr-qc].

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W1 (P): Classical General Relativity and Gravitational Waves

Pablo Antonio Rosado Gonzalez
Albert Einstein Institute, Max Planck Institute for Gravitational Physics, Callinstrasse 38 30167, Hannover, Germany.
pablo.rosado@aei.mpg.de

Gravitational wave background from binary systems

The gravitational wave background produced by binary systems (containing white dwarfs, neutron stars, stellar mass black holes or massive black holes) is presented over the frequencies of all existing and planned detectors. Besides, a realistic prediction of the level of background, upper and lower limits are given to account for the uncertainties in some astrophysical parameters, such as binary coalescence rates. The unresolvable part of the background (often called confusion noise or stochastic background) is distinguished from the resolvable one (that could be subtracted out of the data). For that, we introduce the overlap function, which is a generalization of the duty cycle. The latter has been often used in the literature, in some cases leading to incorrect results. One interesting result concerns all current and planned ground-based detectors (including the Einstein Telescope). In their frequency range, the background of binaries is only sporadically present and resolvable. In other words, there is no stochastic background of binaries for ground-based detectors.

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W1 (P): Classical General Relativity and Gravitational Waves

Anand Sengupta
Department of Physics and Astrophysics, University of Delhi, North Campus, Delhi 110007, India.
asengupta@physics.du.ac.in

Cosmology with the network of advanced gravitational wave detectors

Anand Sengupta, P. Ajith, and K.G. Arun

Over the next few years, a network of advanced broadband gravitational wave detectors are expected to begin operation. These detectors are expected to have an order of magnitude improvement in sensitivity at the 10 - 1000 Hz frequency band, thereby, improving the chances of detecting gravitational waves from

astrophysical sources by almost three orders of magnitude. Coalescing black-hole binaries are of particular interest in this context for at least two important reasons: not only are their waveforms well modeled by theory making them likely candidates for detection, but the inherent nature of the sources make them the equivalent of “standard candles”. This allows one to probe the fundamental properties of our universe in a novel way. We explore the improvement in source reconstruction for such systems using a network of four advanced gravitational wave detectors, including a hypothetical one in the Indian subcontinent called ‘IndIGO’. We also study the ramifications thereof in the determination of cosmological parameters.

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W1 (P): Classical General Relativity and Gravitational Waves

Pankaj Sharan
Department of Physics, Jamia Millia Islamia, New Delhi 110025, India.
pankajsharan@gmail.com

Variational principle in the extended phase space formalism

Using a recent variational formalism in the extended phase space for fields proposed by the author (arxiv: 1104.5095v1, arxiv: 1105.2696v1), it is shown that the requirement of invariance under arbitrary local inertial frames implies a coupling of torsion to a 3-form of matter fields on the one hand, and to Einstein 3-form on the other. The variational principle allows only those field configurations for which torsion is zero, and Einstein field equations are satisfied.

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Ranjan Sharma
Department of Physics, P.D. Women's College, Club Road, Jalpaiguri 735101, India.
rsharma@iucaa.ernet.un

Spacetime inhomogeneity and gravitational collapse

Ranjan Sharma, and Ramesh Tikekar

The problem of obtaining a realistic description of the interior spacetime of a stellar body, collapsing under its own gravity accompanied with heat flux and predicting its future evolution within the framework of Einstein's theory of relativity has received considerable attention. We investigate the evolution of the collapse of an inhomogeneous stellar configuration, which begins to collapse from a curvature singularity with infinite mass and size, and explore the possibilities of evolution of anisotropy as the collapse proceeds considering two different spacetime backgrounds for the evolution of the collapse. In particular, we examine the impact of inhomogeneous nature on the collapse by comparison with the homogeneous and isotropic description of a collapsing configuration, which follows as a special class in our set up. We also investigate the evolution of collapse of an inhomogeneous distribution of matter without flowing radiation on the background of spacetime, which is deviation from the standard Robertson-Walker spacetime.

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W1 (T): Classical General Relativity and Gravitational Waves

Jacek Tafel
Institute of Theoretical Physics, Department of Physics, University of Warsaw, Hoza 69 00-681, Warsaw, Poland.
tafel@fuw.edu.pl

Static, spherically symmetric black holes with scalar field

It is known (see for e.g., M. Wyman 1981, Phys Rev **D24**, 839) that 4-dimensional static spherically symmetric metric with a scalar massless field ϕ contains neccessarily naked singularity. An analysis (Christodolou, 1987, Commun. Math. Phys. **109**, 613) shows that time evolution of an initial data for spherically symmetric metric and a massless scalar may lead to formation of black holes or it can end

with a flat metric and trivial scalar field. Numerical confirmation of this behavior was obtained by Goldwirth and Piran (1987, Phys. Rev. **D36**, 3575) and Choptuik (1993, Phys. Rev. Lett. **70**, 9). The speaker will discuss the static case with a non-trivial potential V(ϕ), which is not fixed at the beginning. From the field equations, he derives metric, scalar field and the potential in terms of a single function f of the radial coordinate r, and then the conditions on f, which guarantee asymptotical flatness of the metric and existence of an event horizon surrounding all singularities. These conditions restrict a possible shape of the potential V. As an example, he considers a modification of the Schwarzschild solution with unchanged global structure. Metric, scalar field and potential V are presented. The scalar field can play a role of a time under horizon. This property can be important in the loop quantum gravity.

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W1 (P): Classical General Relativity and Gravitational Waves

Manuel Tessmer
Friedrich-Schiller-Universitat Jena, Theoretisch-Physikalisches Institut, Max-Wien-Platz 1, 07743 Jena, Germany.
m.tessmer@uni-jena.de

Full-analytic time Fourier-domain gravitational waveforms from inspiralling eccentric compact binaries through 2PN

Manuel Tessmer, and Gerhard Schaefer

We provide full-analytic gravitational wave forms for inspiralling eccentric compact binaries of arbitrary mass ratio in the time Fourier domain for the case of vanishing spins. In our prescription, the semi-analytical property of recent descriptions, i.e., the demand of inverting the higher-order Kepler equation numerically, but keeping all other computations analytic, is avoided. Therefore, a fully analytical inversion formula of the Kepler equation in harmonic coordinates is provided, as well as the analytic time Fourier expansion of trigonometric functions of the eccentric anomaly in terms of sines and cosines of the mean anomaly. Tail terms are not considered. The calculation is, by construction, straightforwardly expandable to the case of spinning compact binaries with spins that are aligned with the orbital angular momentum vector.

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Ramesh Tikekar
Professor of Mathematics (Retired), E – 49, Ganga Vishnu Heights, Samarth Path, Karve Nagar, Pune 411052, India.
tikekar@iucaa.ernet.in

Spherical fluid collapse with radiation on inhomogeneous spacetime background

The evolution of the collapse of an inhomogeneous spherical distribution of matter in the presence of outflow of electromagnetic radiation is examined on the background of the spacetime obtained by introducing an inhomogeneous perturbation in the Robertson Walker spacetime. The physical 3-space of this spacetime has geometry of 3-spheroid, 3-pseudo spheroid or 3-paraboloid for appropriate choice of RW parameter k. The set up is used to study the inhomogeneous collapse subsequent to loss of equilibrium of static compact stars with content in the form of anisotropic matter or charged perfect fluid. The homogeneous dust collapse model on FRW background of Oppenheimer-Snyder, its generalizations in the presence of radiation describing (a) homogeneous collapse of a fluid given by Vaidya and (b) the inhomogeneous collapsing fluid model on the background of spheroidal Vaidya-Tikekar spacetime given by Vaidya-Patel, follow on appropriate choice of parameters. Explicit collapse models for different K in the three classes of geometries corresponding to RW parameter $k = 1, 0, -1$ have been considered to study the various stages in the evolution of collapse. The restriction $0 < K < 1$, in the Vaidya-Patel model does not arise in this general approach and the analysis holds for all $K < 1$.

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C.S. Unnikrishnan
Gravitation Group, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India.
unni@tifr.res.in

The design and characteristics of the TIFR gravitational wave prototype detector

Unnikrishnan, C. S., and Rajalakshmi, G.

We will describe the design and main characteristics of the optical interferometer that is in its initial development stages at the Tata Institute of Fundamental Research, Mumbai. With aimed displacement sensitivity below 10^{-17} m/sqrt (Hz) above 200 Hz, and a potential limit that is 30 times lower, the prototype gravitational wave detector incorporates several aspects of advanced GW detectors.

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Mauri Valtonen
Tuorla Observatory, 21500 Piikkio, Finland.
mvaltonen2001@yahoo.com

Black hole binary OJ287 as a testing platform for general relativity

M. Valtonen, A. Gopakumar, R. Hudec, J. Polednikova, S. Mikkola, A. Sillanpää, L. Takalo, C. Villforth, K. Wiik, H. Lehto, T. Savolainen, and S. Ciprini

The quasar OJ287 has a long optical light curve, extending from 1891 up today. It shows a prominent 12 yr cycle of double peaks with 60 yr modulation. It has been suggested that it is a binary black hole system with a 12 yr period. The double peaks arise from the impacts of the secondary on the accretion disk, while the 60 yr modulation comes from the Kozai cycle in the disk. This picture has been confirmed by optical brightness and polarization monitoring, by observations of the rotation of the radio jet by more than 90 degrees, and by spectral energy distribution studies using ground based telescopes together with the XMM-Newton telescope. In OJ287, for the first time, it is possible to study the second order post-Newtonian terms of general relativity in a binary system. At present, we show that the no-hair theorem of black holes is correct at 30% level of accuracy. This test can be considerably improved during the next two optical outbursts, in December 2015

and in July 2019. The last one is more difficult: it requires observations from a telescope in space, which must be located rather far from the Earth.

References

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W1 (P): Classical General Relativity and Gravitational Waves

Nijo Varghese
Department of Physics, Cochin University of Science and Technology, Kochi 682022, India.
nijovarghesen@gmail.com

Behaviour of massive scalar field around a black hole in Horava gravity

Nijo Varghese, and V. C. Kuriakose

The evolution of massive scalar field is studied in the background of Kehagias-Sfetsos (KS) [1] black hole in deformed Horava-Lifshitz (HL) [2] gravity by time domain integration method [3]. We observed in the time domain picture that the behaviour of quasinormal ringdown(QNM) phase in the evolutions process is significantly deviated from the Schwarzschild case. The QNM phase lasts for a longer time in HL theory before the late time tail dominates. Also, the QNMs of massive field calculated from the numerically integrated data shows that they have a higher oscillation frequency and a lower damping rate than the Schwarzschild spacetime case. The ringdown frequency increases with a lower damping rate as the HL parameter increases. We also study the late time relaxation of field in the intermediate and asymptotic range and verified that behaviours of field in these phases are independent of the HL parameter, and is identical to the Schwarzschild case.

References

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3. C. Gundlach, R. H. Price, and J. Pullin, Phys. Rev. D, **49**, 883 (1994).

Ram Gopal Vishwakarma
Unidad Academica de Matematicas, Universidad Autonoma de Zacatecas C.P. 98068, Zacatecas, ZAC Mexico.
rvishwa@mate.reduaz.mx

Pressure in the relativistics representation of matter

One of the most novel aspects of the modern theories of gravitation (for example, general relativity) is the prediction that not only the energy density but the pressure too gravitates. This is purely a relativistic effect resulting from the covariant character of the theories. However, this prediction has never been tested directly in any experiment so far. We analyze critically this issue on theoretical front, and to our surprise, we find that the relativistic formulation of matter, given by the energy-stress tensor, suffers from some fundamental inconsistencies and paradoxes. There already exists the longstanding Tolman paradox related with the gravitational effect of pressure. However, the Tolman paradox has not received much attention, as it involves the gravitational energy, which is a controversial subject. The author discovers some new paradoxes, which do not involve any gravitational energy, and establishes beyond doubts that the relativistic representation of matter is suffering from subtle inherent inconsistencies in its basic formulations. Corrections are discovered, which lead to the long-sought-after equality of the gravitational and inertial masses, which are otherwise different in general relativity. The consequences of the corrected theory would be revolutionary.

Reference

Astrophys. Space Sci., **321**, 151, (2009) [arXiv:0705.0825], and the additional recent works.

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W1 (P): Classical General Relativity and Gravitational Waves

Salvatore Vitale
Nikhef Science Park, 105 1098 XG, Amsterdam, The Netherlands.
svitale@nikhef.nl

Effect of detectors calibration errors on parameter estimation of gravitational waves from inspiral compact binaries

The new generation of gravitational waves detectors will begin to collect data in ~2015, with a sensitivity that should allow for weekly detections, opening a new era of Astronomy and Astrophysics. Those detectors will be affected by calibration errors that may lead to a wrong estimate of the source parameters, and may reduce or deteriorate the amount of physical information we can extract from a detection. In this work, we analyze and quantify the effects of calibration errors on Bayesian parameter estimation for gravitational signals coming from compact coalescing binary systems. We show how the estimation of the system masses, and distance is only lightly affected, while the reconstructed position of the source can suffer from serious biases, making it hard to find possible electromagnetic or neutrino counterpart. The final aim of this work is to give recommendations to the calibration teams of LIGO and Virgo on the maximum level of calibration errors we can deal with in the advanced detector era.

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W1 (P): Classical General Relativity and Gravitational Waves

Niels Warburton
Department of Mathematics, University of Southampton, University Road, Southampton SO17 1BJ, UK.
n.warburton@soton.ac.uk

A fast frequency-domain algorithm for gravitational self-force: Eccentric orbits in Schwarzschild spacetime

N.Warburton, S. Akcay, and L. Barack.

State-of-the-art computations of the gravitational self-force (GSF) on mass particles in black hole spacetimes [Phys. Rev. D, **81**, 084021 (2010)] involve numerical evolution of the metric perturbation equations in the time-domain, and are computationally expensive. We present a new computation strategy, based on a frequency-domain treatment of the perturbation equations, which offers

considerable computational saving. The essential components of our method are (i) a Fourier-harmonic decomposition of the Lorenz-gauge metric perturbation equations and a numerical solution of the resulting coupled set of ordinary equations with suitable boundary conditions; (ii) a generalized version of the method of extended homogeneous solutions [Phys. Rev. D, **78**, 084021 (2008)] used to circumvent the Gibbs phenomenon that would otherwise hamper the convergence of the Fourier mode-sum at the particle's location; and (iii) standard mode-sum regularization, which finally yields the physical GSF as a sum over regularized modal contributions. We present a working code that implements this strategy to calculate the Lorenz-gauge GSF along eccentric geodesic orbits around a Schwarzschild black hole.

Reference

Phys. Rev. D, **83**, 124026 (2011).

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W1 (T): Classical General Relativity and Gravitational Waves

John Whelan
Rochester Institute of Technology, School of Mathematical Sciences and Center for Computational Relativity and Gravitation, 85 Lomb Memorial Drive, Rochester, NY 14623, USA.
john.whelan@astro.rit.edu

Directed searches for continuous gravitational waves

(For the LIGO Scientific Collaboration, and the Virgo Collaboration)

Deformed rotating neutron stars should generate gravitational waves in the frequency band of ground-based detectors such as LIGO and Virgo. Neutron stars observed as pulsars can be attacked with targeted gravitational wave searches, which use the known rotation frequency to perform a fully-coherent template-based search. The speaker will describe strategies for directed searches, in which the sky position of a (confirmed or suspected) neutron star is known, but no rotational ephemeris exists. Such searches can be used to search for gravitational waves from objects such as supernova remnants (e.g., SN1987A), and low-mass X-ray binaries (e.g., Scorpius X-1).

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John Whelan
Rochester Institute of Technology, School of Mathematical Sciences and Center for Computational Relativity and Gravitation, 85 Lomb Memorial Drive, Rochester, NY 14623, USA.
john.whelan@astro.rit.edu

Treatment of calibration uncertainty in multi-baseline cross-correlation searches for gravitational waves

John T. Whelan, Emma L. Robinson, Joseph D. Romano, and Eric Thrane

Residual uncertainty in the calibration of gravitational wave (GW) detector data leads to systematic errors, which must be accounted for in setting limits on the strength of gravitational wave signals. When cross-correlation measurements are made using data from a pair of instruments, as in searches for a stochastic GW background, the calibration uncertainties associated with the two instruments can be combined into an uncertainty associated with the pair. With the advent of multi-baseline gravitational wave observation (e.g., networks consisting of multiple detectors such as the LIGO observatories and Virgo), a more sophisticated treatment is called for. We describe how the correlations between calibration factors associated with different pairs can be taken into account by marginalizing over the uncertainty associated with each instrument.

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W2

Cosmology

Coordinators : Eiichiro Komatsu and L. Sriramkumar

W2 (P) : Cosmology

Moumita Aich
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India
moumita@iucaa.ernet.in

WMAP-7 SI-violation detections due to Weak Lensing of CMB

Statistical isotropy (SI) has been one of the simplifying assumptions in cosmological model building. With experiments like WMAP and PLANCK this assumption is being rigorously tested. Signals of SI violation have been tested for in the WMAP 7 year data and a significant quadrupolar detection has been claimed. The modifications to the correlation function due to lensing have been largely ignored in the context of isotropy violation studies. Lensing will induce signals which mimic isotropy violation even in an isotropic universe. This might be able to explain the WMAP detection of SI violation.

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W2 (P): Cosmology

Ujjaini Alam
Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA.
ujjaini@lanl.gov

Non-parametric reconstruction of dark energy equation of state from diverse datasets

Ujjaini Alam, Tracy Holsclaw, Salman Habib, Katrin Heitmann, Dave Higdon, Herbie Lee, and Bruno Sanso

The nature of dark energy - the unknown energy component causing the accelerated expansion of the universe - poses one of the most fundamental questions in physics today. A major aim of ongoing and upcoming cosmological surveys is to measure its equation of state w(z). Since w(z) is not directly accessible to measurement, powerful reconstruction methods are needed to extract it reliably. We introduce a new reconstruction method for w(z) based on Gaussian process modeling. This can capture nontrivial time-dependencies in w(z) and yields controlled and unbiased error estimates. In this talk, the speaker outlines the reconstruction of w(z) from a diverse set of measurements: BAO, CMB, SNe Ia data. We find that current observations are in good agreement with a cosmological constant. In addition, we explore nontrivial behavior of w(z) by analyzing simulated data, assuming high-quality future observations. We find that BAO measurements by themselves already lead to remarkably good reconstruction, and that the combination of different high-quality probes allows us to reconstruct w(z) with small error bounds. This method may also be used to predict optimal survey strategies for obtaining maximal information on the nature of dark energy.

Reference

http://lanl.arxiv.org/abs/1104.2041.

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W2 (T): Cosmology

Amna Ali
Centre for Theoretical Physics, Jamia Millia Islamia, Jamia Nagar, New Delhi 110025, India.
amnaalig@gmail.com

Modified gravity a la Galilean: Late time cosmic acceleration and observational constraints

Amna Ali, Radouane Gannouji, and M. Sami

We examine the cosmological consequences of fourth order Galilean gravity. We carry out detailed investigations of the underlying dynamics and demonstrate the stability of one de Sitter phase. The stable de Sitter phase contains a Galilean field π, which is an increasing function of time. Using the required suppression of the fifth force, supernovae, BAO and CMB data, we constrain parameters of the model. We find that the π matter coupling parameter β is constrained to small numerical values such that $\beta < 0.02$. We also show that the parameters of the third and fourth order in the action (c3, c4) are not independent and with reasonable assumptions, we obtain constraints on them. We investigate the growth history of the model and find that the sub-horizon approximation is not allowed for this model. We demonstrate strong scale dependence of linear perturbations in the fourth order Galilean gravity.

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W2 (P): Cosmology

Rizwan ul Haq Ansari
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India.
rizwan@iucaa.ernet.in

Perturbations in dark energy models with evolving speed of sound

Rizwan Ul Haq Ansari, and Sanil Unnikrishnan

The behavior of perturbation in scalar field dark energy and its consequent effect on the cold dark matter (CDM) power spectrum is well understood to be governed by the equation of state (EOS) parameter and the effective speed of sound (ESS) of dark energy. We investigate whether dark energy models whose ESS are epoch dependent leaves any distinct imprints on the large scale CDM power spectrum. In particular, we compare the cases where the ESS is decreasing with time with those where it increases. The CDM power spectrum is found to be generically suppressed in these cases as compared to the Λ CDM model. The degree of suppression at different length scales can, in principle, reflect the evolving nature of the ESS of dark energy. It is also shown that the effect of different evolution of ESS for a given evolution of EOS parameter of dark energy on the CDM power spectrum is significant only at the intermediate scales (around $k \sim 0.01$ h/Mpc). At scales much smaller and larger than the Hubble radius, it is the evolution of EOS parameter of dark energy which governs the degree of suppression of CDM power spectrum with respect to the Λ CDM model.

Reference

http://arxiv.org/abs/1104.4609.

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Soumen Basak
Laboratoire AstroParticule et Cosmologie 10, rue Alice Domon et Leonie Duquet, 75205 Paris Cedex 13, France.
basak@apc.univ-paris7.fr

A needlet ILC analysis of WMAP 7-year temperature data

Soumen Basak, and Jacques Delabrouille

The angular power spectrum of cosmic microwave background (CMB) is very sensitive to the values of different cosmological parameters, which primarily describes the fundamental properties of the universe. This is why, a key goal of the CMB community is to measure the true CMB temperature anisotropies in the sky. The WMAP satellite has already provided high resolution maps of the sky in five frequency bands ranging from 23 to 94 GHz. These maps, however, contain uncorrelated noise and a mixture of emissions from various astrophysical origins, superimposed on CMB emission. We would like to present the estimation of angular power spectrum of true CMB from these multi-frequency observations of WMAP using a model-independent method by removing foreground signals and noise as much as possible. The method used is an implementation of a internal linear combination (ILC) of the WMAP channels with minimum error variance on a frame of spherical wavelets called needlets, allowing localized filtering in both pixel space and harmonic space. Implementation of ILC on needlet frame allows to vary the ILC weights independently in different angular scales of CMB. We have obtained a low foreground CMB power spectrum at the resolution of W channel of WMAP, which can be used for future scientific studies, particularly for accurate determination cosmological parameters.

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W2 (T): Cosmology

Marco Bruni
Institute of Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth PO1 3FX, UK.
marco.bruni@port.ac.uk

Relativistic effects and large scale structure: Post-Newtonian dynamics

At a time when galaxy surveys and other observations are reaching unprecedented sky coverage and precision it seems timely to investigate the effects of general relativistic non-linear dynamics on the growth of structures and on observations. Indeed, there is a gap in the way we theoretically investigate the Universe: on the largest scales we assume an homogeneous isotropic background, on top of which we consider relativistic perturbations to study effects produced in the early universe, e.g. in the CMB. On the other hand, structure formation is investigated in the non-linear regime through a purely Newtonian approach, using N-body simulations as main tool. In this talk the speaker will present a new post-Newtonian formalism where Einstein equations are truncated to include the first post-Newtonian order, resulting in a set of non-linear equations that reduce to those of standard Newtonian cosmology at small scales and, when linearized, coincide with those of first order scalar relativistic perturbation theory. Thus this formalism provides a single framework to investigate structure formation, from the smallest Newtonian scales to scales of order of the Hubble radius and beyond.

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W2 (T): Cosmology

Sukanya Chakrabarti
Department of Physics, Florida Atlantic University, 777 Glades Avenue, Boca Raton, FL 3343, USA.
schakra1@fau.edu

A new probe of the distribution of dark matter in galaxies

While the cold-dark matter paradigm has been very successful in reproducing the large scale distribution of galaxies, there are a number of problems this model faces on galactic scales. The missing satellites problem, i.e., the over abundance of CDM sub-structure in simulations relative to observations of local group dwarfs,

raises questions about the applicability of this paradigm on galactic scales. The speaker describes a new method, which she calls Tidal Analysis, that allows one to quantitatively characterize galactic satellites from analysis of observed disturbances in outer gas disks without requiring knowledge of their optical light (Chakrabarti, and Blitz 09; Chakrabarti, and Blitz 2011; Chakrabarti, Bigiel, Chang, and Blitz 2011; Chang, and Chakrabarti 2011). This method may be able to address the missing satellites problem, which is an outstanding problem in cosmology today. She will also describe an observationally motivated probe of the concentration parameter of dark matter halos, which is a fundamental parameter in modeling galaxies. Future tests of the CDM paradigm will lie in how well it does in describing galaxy evolution. The method of Tidal Analysis can offer important insight in this regard, as it takes advantage of observed disturbances in the extended atomic hydrogen gas disks of galaxies, which are the largest and most sensitive tracers of satellite interactions and the gravitational potential well in galaxies.

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W2 (P): Cosmology

Ningombam Chandrachani Devi
Centre for Theoretical Physics, Jamia Millia Islamia, Jamia Nagar, New Delhi 110025, India.
chandrachani@gmail.com

Evolution of spherical over density in thawing dark energy models

N. Chandrachani Devi, and Anjan A Sen

The spherical collapse model, which has a long history in cosmology, is a simple and a fundamental tool for understanding how a small spherical patch of over density forms a bound system via gravitational instability. We study the general evolution of spherical over-densities for thawing class of dark energy models. We model dark energy with scalar fields having canonical as well as non-canonical kinetic energy. For non-canonical case, we consider models, where the kinetic energy is of the Born-Infeld form. We consider various potentials like linear, inverse-square, exponential as well as PNGB-type. We also consider the case when dark energy is homogeneous as well as the case when it is inhomogeneous and virializes together with matter. The study shows that models with linear potential, in particular, with Born-Infeld type, kinetic term can have significant deviation from the ΛCDM model in terms of density contrast at the time of virialization. Although, this is a simplified approach to study the nonlinear evolution of matter over densities inside the cluster, and is not applicable to actual physical situation, it gives some

interesting insight into the nonlinear clustering of matter in the presence of thawing class of dark energy models.

Reference

arXiv:1003.4094v2.

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W2 (T): Cosmology

Tzu-Ching Chang
CITA, Canada.
tcchang@asiaa.sinica.edu.tw

21-cm Cosmology

Hydrogen is the most abundant element in the universe, and in its neutral phase (HI) radiates at a wavelength of 21-cm. The redshifted 21-cm line can potentially probe a significant fraction of the universe, shedding light on astrophysical processes and fundamental physics. At redshifts around unity, 21-cm follows large-scale structure and can be used to measure the baryon acoustic oscillation signature, constraining the properties of dark energy. The speaker will describe the current effort in the measurements of the 21-cm power spectrum at redshifts around one, utilizing the Green Bank Telescope (GBT), and discuss prospects for future 21-cm surveys.

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W2 (T): Cosmology

Pravabati Chingangbam
Indian Institute of Astrophysics, Koramangala, 2nd Block, Bangalore 560034, India.
prava@iiap.res.in

Search for non-Gaussianity in the CMB with geometrical and topological quantities

Pravabati Chingangbam, and Changbom Park

We use Minkowski functionals and Betti numbers to study non-Gaussianity in the CMB. We present the theoretically expected behaviour of these quantities using Gaussian and non-Gaussian simulations. Further, we study how they behave for galaxy foreground maps obtained from WMAP data and analyze the extent to which residuals of these contaminants can bias the quest for non-Gaussian deviations in the 'true' CMB signals.

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W2 (T): Cosmology

Marina Cortes
Lawrence Berkeley National Laboratory 1, Cyclotron Road, MS 050-5004 Berkeley, CA 94704, USA.
mvinhas@yahoo.com

On the prior dependence of constraints on tensor-to-scalar ratio

Marina Cortes, Andrew R. Liddle, and David Parkinson

We investigate the prior dependence of constraints on cosmic tensor perturbations. Commonly imposed is the strong prior of the single-field inflationary consistency equation, relating the tensor spectral index nT to the tensor-to-scalar ratio r. Dropping it leads to significantly different constraints on nT, with both positive and negative values allowed with comparable likelihood, and substantially increases the upper limit on r, on scales $k = 0.01$ Mpc^{-1} to 0.05 Mpc^{-1}, by a factor of ten or more. Even if the consistency equation is adopted, a linear prior on r, on one scale does not correspond to a linear one on another; constraints, therefore, depend on the pivot scale chosen. We assess this size of this effect and determine the optimal scale for constraining the tensor amplitude, both with and without the consistency relation.

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W2 (P): Cosmology

Santanu Das
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India.
santanud@iucaa.ernet.in

Leakage of power from dipole to higher multipoles due to non-circular WMAP beam

In cosmic microwave background radiation, it has been postulated by many researchers that the power at the low multipoles is not of the primordial origin, and it is only an observation effect coming from the scan procedure adapted in the WMAP satellite. The dipole, which is almost 550 times higher than the quadrupole, can get transferred to the higher l's causing the low power at high l's. It had been postulated that this power transfer can be caused by the non-circular beam shape of the WMAP satellite. Therefore, to study the effect of the non-circular beam on power transfer from dipole to higher multipoles, simulation is carried out. It is seen that the power from the dipole can get transferred to the higher multipoles due to the non-circular beam. The amount of the power transfer depends on the eccentricity of the non-circular beam, and the shape higher multipoles caused by power transfer dependents on the relative orientation of the two beams.

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W2 (T): Cosmology

Sudeep Das
Berkeley Center for Cosmological Physics, Department of Physics, University of California, Berkeley, CA 94709, USA.
sudeep.das@berkeley.edu

A new view of the cosmic microwave background with ACT

Over the coming decade, tiny fluctuations in temperature and polarization of the Cosmic Microwave Background (CMB) will be mapped with unprecedented resolution. These new arc-minute resolution observations are shedding new light on the physics of the early universe and the neutrino sector. These observations are also allowing to measure the gravitational lensing of the CMB by intervening large scale structure. CMB lensing will probe the growth of structure over cosmic time, helping constrain the total mass of neutrinos and the behaviour of dark energy. In the first part of the talk, the speaker will review the recent progress made with

Atacama Cosmology Telescope, and in the second part, he will discuss the first internal detection and the scientific potential of the CMB lensing signal.

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W2 (P): Cosmology

Walter Del Pozzo
Nikhef Science Park, 105 1098 XG, Amsterdam, The Netherlands.
walterdp@nikhef.nl

Precision measurements of the Hubble constant with gravitational waves

Walter Del Pozzo, and Alberto Vecchio

The precise measurement of the Hubble constant H_0 is the foundation of the current cosmological paradigm. Because of the correlation between H_0 and the remaining cosmological parameters, a precise measurement of H_0 is critical, in view of future high redshift surveys. Second generation interferometers are expected to deliver a wealth of gravitational waves (GW) events up to a redshift of about 0.3. Being free of the systematics affecting electromagnetic measurements, GW offer the possibility of an independent measurement of H_0 with great accuracy. Here, we present a method based on Bayesian inference aimed at estimating H_0 with a few percent accuracy. In contrast to earlier work, we do not require the precise identification of the putative optical counterpart, but we include all the potential hosts consistent with the recovered sky position and distance posterior distributions. We show that with 50 GW events, Advanced LIGO and Advanced Virgo will yield a measurement of H_0 with an uncertainty of few percents.

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Olivier P. Dore
JPL, USA.
Olivier.P.Dore@jpl.nasa.gov

Planck early measurements of the cosmic infrared background anisotropies

Since, it reached the Lagrange point L2 in August 2009, Planck has been observing the sky at frequencies ranging from 30 to 857 GHz, measuring not only the cosmic microwave background, but also everything else in the universe that radiates at these frequencies. The first scientific results from Planck cover a wide range of galactic and extragalactic astrophysics, including clusters, extragalactic radio sources, spinning and thermal dust in the milky way and cosmic infrared background (CIB).

The CIB is the far-infrared relic emission from galaxies formed throughout cosmic history. It appears as a cosmological, diffuse, background light. Being produced by the star heated dust within high redshift galaxies, it carries a wealth of information about the processes of star formation therein. Besides, the fluctuations detected in this background light trace the large-scale distribution of star-forming galaxies and, to some extent, the underlying distribution of the dark matter halos in which galaxies reside.

Using six regions of the low galactic dust emission with a total area of about 140 deg^2, Planck measured the angular power spectra of CIB anisotropies on angular scales ranging from half a degree to a few arcminutes at 217, 353, 545 and 857 GHz. At all these frequencies, we detect with high significance the clustering of high redshift dusty star-forming galaxies. Combining a new dusty galaxy parametric evolution model with a galaxy clustering model, we obtain a good fit to our data. The speaker will discuss various aspects of these measurements and highlight the unique insights we expect to obtain from them in the coming years, combining Planck and other far-infrared measurements.

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W2 (P): Cosmology

Abhik Ghosh
Centre for Theoretical Studies, Old Building, Indian Institute of Technology, Kharagpur 721302, India.
abhik@phy.iitkgp.ernet.in

Characterizing the diffuse foregrounds for redshifted 21-cm HI signal: GMRT 150 MHz observation

Abhik Ghosh, Jayanti Prasad, Somnath Bharadwaj, Sk. Saiyad Ali, and Jayaram N. Chengalur

We have detected fluctuations in the galactic diffuse emission on scales greater than 10 arcmin at 150 MHz, in galactic latitude area of $l=151.80^o$ and $b=13.89^o$. The total intensity power spectrum shows two clearly different behaviours as a function of the angular scale. At large angular scales, there is a power-law behaviour, with power decreasing at increasing angular scale. This behaviour is typical of the galactic diffuse emission observed at higher frequencies and higher angular resolutions. We have noticed that in the image made by discarding the short baselines contains no diffuse emission, therefore, we expect the power spectrum to be dominated by point sources at high l (angular modes) values. The power spectrum of the total intensity diffuse emission was fitted by a power-law down to $l = 619$: $C_l= 402.11 \times (1000/l)^{2.11+/-0.49}$ mk^2. The slope is within the range of slopes [–2, –3] found by all the previous measurements at higher frequencies.

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W2 (P): Cosmology

Tuhin Ghosh
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India.
tuhin@iucaa.ernet.in

Characterisation of CMB foregrounds

Tuhin Ghosh, Anthony Banday, Tess Jaffe, Clive Dickinson, and Tarun Souradeep

CMB foreground is an important topic of research in CMB data analysis. Understanding CMB foreground helps in extraction of cosmological information in much more reliable manner and also helps in understanding the physics of emission processes (synchrotron, free-free, dust, etc.), which dominates at microwave frequencies. The author will present the spacial, spectral and statistical

characterisation of CMB foreground. Spacial characterisation is done in pixel space to capture the morphology of foregrounds, and is performed by cross-correlating with external template maps and to extract the physical properties of different foreground emission like spectral index variation over different regions of sky. Statistical characterisation of CMB foreground is done in needlet space to capture its statistical properties.

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W2 (P): Cosmology

Rituparno Goswami
Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch 7701, South Africa.
Rituparno.Goswami@uct.ac.za

On the shear-free perturbations of FLRW universe

Anne Marie Nzioki, Rituparno Goswami, Peter K.S. Dunsby, and George F. R. Ellis

We show that if the matter congruence of a barotropic perfect fluid in an almost homogeneous and isotropic universe is shear-free, then it must be either expansion-free or rotation-free. This result, not being true in the Newtonian cosmology, proves that the linearized solutions, believed to result in standard local Newtonian theory, does not always give the usual behaviour of Newtonian solution.

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W2 (P): Cosmology

Tapomoy Guha Sarkar
Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211019, India.
topomoy@hri.res.in

The cross-correlation of 21-cm signal and the Lyman-alpha forest: A cosmological probe

Tapomoy Guha Sarkar, Somnath Bharadwaj, Tirthankar Roy Choudhury, and Kanan Datta

We present the cross-correlation of the redshifted 21-cm emission from neutral hydrogen in the post-reionization era with the Lyman-alpha forest as a new probe of

the large scale matter distribution in the redshift range z = 2 to 3. Though the two signals originate from different astrophysical systems, they are both expected to trace the underlying dark matter distribution on large scales. The multi frequency angular power spectrum is used to quantify the cross-correlation. Statistical properties of the angular cross-correlation power spectrum estimator are investigated. The estimator is found to be unaffected by the discrete quasar sampling, which only affects the noise in the estimate. Considering a quasar survey with high angular density, like the upcoming BOSS, we find that it will be possible to measure the cross-correlation at a higher level of precision than the 21-cm auto-correlation power spectrum using the same 21-cm observations. Further, we also investigate the imprint of the BAO features in the cross-correlation power spectrum as a probe of cosmology. We also discuss the feasibility of detection of BAO with futuristic data sets.

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W2 (T): Cosmology

Gil Holder

Rutherford Physics Building, McGill University, 3600 rue University, Montreal, QC H3A 2T8, Canada.
holder@physics.mcgill.ca

Gravitational lensing of the CMB and the South Pole Telescope

Gil Holder, and the SPT collaboration

Small-scale CMB measurements have a wealth of cosmological information, including non-Gaussianities induced by gravitational lensing. The speaker will report on recent measurements of the gravitational lensing signature using the South Pole Telescope (SPT), and discuss prospects for measuring neutrino masses and other fundamental physics with upcoming measurements, including Planck, and the recently completed SPT temperature survey, as well as for upcoming instruments like SPT-Pol.

References

1. Shirokoff, et al. 2011 (arXiv:1012.4788).
2. Wlliamson, et al. 2011 (arXiv:1101.1290).
3. Keisler, et al. 2011 (in prep).
4. van Engelen, et al. 2011 (in prep).

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Stephane Ilic
Institut d'Astrophysique Spatiale, Universite Paris-Sud, Batiment 120 – 121, F – 91405 Orsay, France.
stephane.ilic@ias.u-psud.fr

CMB/CIB cross-correlation for ISW detection

The author will present the results of their recent work on the cross-correlation between the cosmic infrared and microwave background anisotropies due to the integrated Sachs-Wolfe effect in the LCDM cosmology. We describe the CIB anisotropies using a linearly biased power spectrum valid on the angular scales of interest. We derive the theoretical power spectrum of the CMB-CIB cross-correlation for different instruments and frequencies. While our cross-spectra show similarities with usual CMB/galaxies cross-correlations, using the CIB instead has a higher potential due to the intrinsically deeper range of redshifts probed, and a larger fraction of the sky common with the CMB. We assess the detectability of the ISW signal by an SNR analysis, and obtain significances as high as 6 or 7 σ in the ideal case of noiseless, full-sky maps. We identify the optimal frequency for detection among those used by present experiments. We further study realistic cases accounting for noise including astrophysical contaminants and instrumental noise: the results depend strongly on the dominant noise term and go from 2 to 5 σ. Interestingly, the joint use of all available frequencies in the cross-correlation does not improve significantly the total SNR, due to the high level of correlation of the CIB maps at different frequencies. Finally, possible extensions to dynamical models of dark energy will be also discussed.

Reference

Ilic, et al. 2011, MNRAS in press.

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Deepak Jain
Department of Physics and Electronics, Deen Dayal Upadhyaya College (University of Delhi), Karampura, Shivaji Marg, New Delhi 110015, India.
djain@ddu.du.ac.in

Observational cosmology and the cosmic distance duality relation

Remya Nair, Sanjay Jhingan, and Deepak Jain

We study the validity of cosmic distance duality relation between angular diameter and luminosity distances. To test this duality relation we use the latest Union2 Supernovae Type Ia (SNe Ia) data for estimating the luminosity distance. The estimation of angular diameter distance comes from the samples of galaxy clusters (real and mock) and FRIIb radio galaxies. We parameterize the distance duality relation as a function of redshift in six different ways. Our results rule out some of the parameterizations significantly.

Reference

arXiv:1102.1065.

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Charles Jose
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India.
charles@iucaa.ernet.in

Weighing neutrinos using high redshift galaxy luminosity functions

Laboratory experiments measuring neutrino oscillations, indicate small mass differences between different mass eigenstates of neutrinos. The absolute mass scale is, however, not determined, with at present the strongest upper limits coming from astronomical observations rather than terrestrial experiments. The presence of massive neutrinos supresses the growth of perturbations below a characteristic mass scale, which leads to a decreased abundance of collapsed dark matter halos. We show that this effect can significantly alter the predicted luminosity

function (LF) of high redshift galaxies. In particular, we demonstrate that a stringent constraint on the neutrino mass can be obtained using the galaxy LF at $z = 4$ and our semi-analytic structure formation models. Combining the constraints from the WMAP7 data with the LF data at $z = 4$, we limit the sum of the masses of 3 degenerate neutrinos to be < 0.52 eV at the 95 % CL. The additional constraints using the prior on Hubble constant strengthens this mass limit to be < 0.28 eV at the 95 % CL. This limit is a factor ~ 4 improvement compared to the constraint based on the WMAP7 data alone, and as stringent as other known limits from cosmology. The method presented here provides a complementary probe of neutrino mass and can be repeated over a range of redshifts to tighten this limit.

Reference

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W2 (T): Cosmology

Nidhi Joshi
Centre for Theoretical Physics, Jamia Millia Islamia, Jamia Nagar, New Delhi 110025, India.
niidhi.joshi@gmail.com

Statistics of statistical anisotropy measures

Nidhi Joshi, Aditya Rotti, and Tarun Souradeep

Gaussianity of temperature fluctuations in the cosmic microwave background (CMB) implies that the statistical properties of the temperature field can be completely characterized by its two point correlation function. We expand this two point correlation function in terms of bipolar spherical harmonics and then analytically find out the moments, and the distribution of the coefficients of expansion using characteristic function approach. Looking for significant deviations from zero for bipolar spherical harmonic coefficients derived from observed CMB maps forms the basis of the strategy used to detect isotropy violation. In order to quantify "significant deviation", we need to know the distributions of these coefficients. Bipolar spherical harmonic coefficients are linear combination of elements of harmonic space covariance matrix, and hence, assuming the independence of the terms, we find out characteristic function of each of these coefficients. It turns out that for few cases, we have analytical form of moments up to any order and the distribution. We would further like to comment that this method

is not completely applicable to all bipolar coefficients due to the absence of assumed independence of terms in these cases.

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W2 (T): Cosmology

Manoj Kaplinghat
Department of Physics and Astronomy, UC, Irvine, USA.
mkapling@uci.edu

Fermi-LAT constraints on WIMP dark matter

Satellite galaxies of the milky way are among the most promising targets for dark matter searches in gamma rays. A joint likelihood analysis of 10 satellite galaxies with 24 months of data of the Fermi Large Area Telescope reveals no dark matter signal. For the first time, using gamma rays, we are able to rule out models with the thermal cross section (~ 3e-26 cm^3s^{-1} for a purely s-wave cross section), without assuming additional astrophysical or particle physics boost factors.

Reference

arXiv: 1108.3546.

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W2 (P): Cosmology

Fabien Lacasa
Institut d'Astrophysique Centre, Universitaire d'Orsay, Batiment 120 – 121, 91405 Orsay Cedex, France.
fabien.lacasa@ias.u-psud.fr

Non-Gaussianity of point-sources foregrounds

The measurement of the power spectrum of CMB anisotropies has lead to the standard LCDM cosmology. Going beyond order 2 has gained in interest as primordial non-Gaussianity (NG) may discriminate the models of the primordial perturbation generation, but the understanding of the observed NG with high angular resolution needs to account for the NG of foregrounds. We focus on the NG due to radio (RS) and infrared (IR) sources in the frequency range of the CMB.

We propose a simple, accurate way to infer the bispectrum from the power spectrum of point-sources considering different independent populations, with or without clustering. We obtain the configuration and frequency dependence of the IR and RS bispectra. The IR bispectrum peaks in the squeezed limit and the clustering of sources enhances it by orders of magnitude on large scales. The IR bispectrum dominates that of RS on large scales at 150 GHz, and at all multipoles at 350 GHz and higher frequencies. We compute the bias on the local NG parameter fnl induced by IR and RS. The positive bias due to RS is strongly reduced by masking detectable sources. The form of the IR bispectrum mimics the 'local' one on large scales. The IR yields an important negative bias for Planck resolution at high frequencies. Most of the signal being due to the faint IR clustered sources, the bias is not reduced by masking above a realistic flux cut and may even be increased by reducing the shot-noise.

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W2 (T): Cosmology

Yen-Ting Lin
Institute of Astronomy and Astrophysics, Academia Sinica, 11 F of Astronomy-Mathematics Building, AS/NTU. No. 1, Roosevelt Road, Sec. 4, Taipei, Taiwan.
ytl@asiaa.sinica.edu.tw

A WISE-Chandra view of baryon content evolution in galaxy clusters

Yen-Ting Lin, Adam Stanford, Peter Eisenhardt, Alexey Vikhlinin, Ben Maughan, and Andrey Kravtsov

We study the relationship between two major baryonic components in galaxy clusters, namely the galaxies, and intracluster medium (ICM), using 94 clusters that span the redshift range 0.0 – 0.6, with accurately measured total and ICM mass from 'Chandra' observations, and stellar mass derived from 'Wide-Field Infrared Survey Explorer', and 'Two-Micron All-Sky Survey'. This allows us to trace the evolution of cluster baryon content in a self-consistent fashion. We find that the ICM mass--total mass scaling relation evolves according to the self-similar model, while there is no evidence for redshift evolution in the stellar mass-total mass relation. This suggests that the clusters acquire their gas and galaxy contents in different ways.

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W2 (P): Cosmology

Suman Majumdar
Centre for Theoretical Studies, Indian Institute of Technology, Kharagpur 721302, India.
mid.suman@gmail.com

Matched filter detection of ionized bubbles in simulated redshifted 21-cm maps of epoch of reionization

Suman Majumdar, Somnath Bharadwaj, T. Roy Choudhury, and Kanan K. Datta

Detection of ionized bubbles around quasars in redshifted 21-cm maps is possibly one of the most direct probe of reionization. Following the formalism developed by Choudhury, Haehnelt, and Regan (2009), which is a set of numerical simulations based on Zel'dovich approximation, a particle mesh N-body code, friends-of-friends algorithm and excursion set formalism, we generate redshifted 21-cm maps of reionization epoch. We then include a quasar in the simulation box at the location of the most massive halo and use the visibility based matched filter technique developed by Datta, Bharadwaj, and Choudhury (2007) to study the detectability of this quasar generated ionized bubble, while taking into account the fluctuations in neutral hydrogen distribution as well as the impact of smaller ionized bubbles around generated by other stellar sources. We also incorporate the anisotropy due to finite light travel time in the apparent shape of a growing ionized bubble around a quasar (as predicted by the previous work, Majumdar, Bharadwaj, Datta, and Choudhury (2011)), by stacking snapshots of simulated 21-cm maps at different stages of bubbles growth, and observe its impact on the bubble detection technique.

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W2 (T): Cosmology

Felipe Marin
Centre for Astrophysics and Supercomputing, Mail Number H 39, Swinburne University of Technology, P.O. Box 218, Hawthorn, Victoria 3122, Australia.
fmarin@astro.swin.edu.au

High-order clustering of WiggleZ galaxies

Felipe Marin, and the WiggleZ Team

High-order statistics are a useful and complementary tool for measuring the clustering of galaxies. Containing information of clustering as a function of scale, and morphology of large scales, these statistics allow us to measure the non-linear bias of galaxies with respect to dark matter, which provides constraints on cosmological and galaxy population models. We present results of the high-order clustering measured in the WiggleZ spectroscopic galaxy survey at a mean redshift of $z = 0.6$, the highest redshift, where these measurements have been made to date. Using N-body simulations and analytic predictions of the clustering of dark matter, we estimate the linear and non-linear bias terms, from where we obtain constraints on cosmological parameters such as σ_8 and the growth rate, and explore the feasibility of detecting primordial non-Gaussianity imprints in the large-scale structure.

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W2 (P): Cosmology

Sanjit Mitra
Jet Propulsion Laboratory, M/S. 169 – 327, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.
Sanjit.Mitra@jpl.nasa.gov

Effect of asymmetric beams in CMB experiments: Importance and remedy

Precise measurement of the Cosmic Microwave Background (CMB) anisotropies can accurately constrain many cosmological models and parameters. Over the last decade, measurements of CMB anisotropy has spearheaded the remarkable transition of cosmology into a precision science. Nevertheless, much more information about the universe remains to be extracted from CMB anisotropy, specially from polarization. Extracting maximum amount of science out of these

high-resolution-low-noise data-rich experiments also pose a stiff challenge to current analysis techniques. Every possible systematic effect has to be studied and, if significant, must be accounted for, in the analyses to extract accurate scientific results. The effect of asymmetric beams is one of the most important and challenging systematic effects in the current and future CMB missions. We have developed and implemented a very fast pixel based method to account for this effect in the Planck mission. This poster will broadly describe the effect of asymmetric beams in scanning CMB experiments and the method to account for it in Planck data analyses.

References

1. S. Mitra, et al., Astrophys. J. Suppl., **193**, 5 (2011).
2. P. A. R. Ade, et al., arXiv:1101.2048 (2011).
3. S. Mitra, et al., MNRAS, **394**, 1419 (2009).

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W2 (P): Cosmology

Sourav Mitra
Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211019, India.
smitra@hri.res.in

Joint QSO – CMB constraints on reionization history

Based on the work by Mitra, Choudhury, and Ferrara (2010), we obtain model-independent constraints on reionization from cosmic microwave background (CMB) and QSO absorption line data by decomposing the function $N_{ion}(z)$ (the number of photons entering the IGM per baryon in collapsed objects) into its principal components. The main addition in this work is that for the CMB data set, we explicitly include the angular power spectra C_l for TT, TE and EE modes in our analysis, which seem to contain somewhat more information than taking the electron scattering optical depth τ_{el} as a single data point. Using Markov Chain Monte Carlo methods, we find that all the quantities related to reionization can be severely constrained at $z < 6$, whereas a broad range of reionization histories at $z > 6$ are still permitted by the current data sets. With currently available data from WMAP7, we constrain $0.080 < \tau_{el} < 0.112$ (95% CL), and also conclude that reionization is 50% complete between $9.0 < z(Q_{HII} = 0.5) < 11.8$ (95% CL), and is 99% complete between $5.8 < z(Q_{HII} = 0.99) < 10.4$ (95% CL). With the forthcoming PLANCK data on large-scale polarization (ignoring effect of foregrounds), the $z > 6$

constraints will be improved considerably, e.g., the 2-σ error on τ_{el} will be reduced to 0.009 and the uncertainties on z (Q_{HII} = 0.5), and z (Q_{HII} = 0.99) would be $\sim$ 1 and 3 (95% CL), respectively. For more stringent constraints on reionization at z > 6, one has to rely on data sets other than CMB. Our method will be useful in such case, since it can be used for non-parametric reconstruction of reionization history with arbitrary data sets.

Reference

MNRAS, **413**, 3, 1569.

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W2 (T): Cosmology

Anupreeta More
Kavi Institute for Cosmological Physics, The University of Chicago, 5640 S. Ellis Avenue, Chicago, IL 60637, USA.
anupreeta@kicp.uchicago.edu

The SL2S arcs sample

A. More, R. Cabanac, S. More, M. Limousin and J-P. Kneib

We present the Strong Lensing Legacy Survey - ARCS (SARCS) sample compiled from the final T0006 data release of the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) covering a total area of 172 deg^2. We adopt a semi-automatic method to find gravitational arcs in the survey that makes use of the ARCFINDER algorithm of Alard (2006) to find candidate lensed arcs. This list is pruned by visual inspection and ranking to form the final SARCS sample. Our sample consists of 127 lens candidates with arc radii ≥ 2" within the unmasked area of 156 deg^2. This list also includes some serendipitously discovered lenses from the CFHTLS fields, which the algorithm did not detect. In total, we find 54 candidates as promising lenses. Owing to the large area and depth of the CFHTLS, we have a large lens sample, for the first time, probing mass scales that are intermediate to cluster and galaxy lenses. We compare the observed image separation distribution (ISD) with theoretical models. A two-component density profile for the lenses, which accounts for both the central galaxy and the dark matter component is required by the data to explain the observed ISD. Unfortunately, current uncertainties are large enough to accommodate models both with and without adiabatic contraction. We also detect a systematic alignment of the giant arcs from our sample with the major axis of the baryonic component as expected.

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Surhud More
Kavi Institute for Cosmological Physics, The University of Chicago, 5640 S. Ellis Avenue, Chicago, IL 60637, USA.
surhud@kicp.uchicago.edu

Galaxy-dark matter connection: A cosmological perspective

Surhud More, Frank van den Bosch, and Marcello Cacciato

The statistical properties of dark matter distribution in the universe are crucially dependent on the parameters used to describe cosmology. The distribution of galaxies in the universe traces the distribution of dark matter. Therefore, observations of galaxies can provide important information about the cosmological parameters. However, this requires an accurate knowledge of how the galaxy distribution is biased with respect to the dark matter distribution. We have developed a unique statistical tool, the conditional luminosity function (CLF) which can be used to specify how galaxies occupy dark matter halos and consequently specify the galaxy bias. The CLF can be used to predict various observable properties of the galaxy distribution. The speaker shall focus on the abundance of galaxies, their clustering strength and the galaxy-galaxy lensing signal around them and present constraints on cosmological parameters such as Ω_m, σ_8, and sum of neutrino masses obtained from a combination of these observable properties.

References

1. Cacciato, et al. (2009).
2. More, et al. (2009, 2011).

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W2 (P): Cosmology

Sharvari Nadkarni-Ghosh
S.N. Bose National Centre for Basic Sciences, Block JD, Sector III, Salt Lake, Kolkata 700098, India.
nsharvari@gmail.com

Extending the domain of validity of Lagrangian perturbation theory

Sharvari Nadkarni-Ghosh, and David F. Chernoff

Lagrangian Perturbation Theory (LPT) has been widely used to model the non-linear growth of large-scale structure, analytically. However, it is known that the Lagrangian series fails to converge when applied to spherical voids. This work examines this issue from first principles, and introduces the novel method of Lagrangian re-expansions. The method shows that LPT should be treated like a finite difference approximation, whose error can be controlled by fine tuning the order and/or the number of time-steps. The LPT based scheme is versatile and has advantages over simulations in two limits: cases where numerical shot noise may interfere with accuracy, and cases where time is a premium.

Reference

MNRAS, **410**, 1454 (2011).

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W2 (P): Cosmology

Roshina Nandra
Churchill College, Storeys Way, Cambridge CB3 0DS, UK.
rn288@mrao.cam.ac.uk

The interplay between cosmological expansion and massive objects

Roshina Nandra, Anthony N. Lasenby, and Michael P. Hobson

The author will present a tetrad-based procedure for solving Einstein's field equations for spherically-symmetric systems, and use it to derive metrics describing a point mass m in a spatially-flat, open and closed expanding universe. In the spatially-flat case, a simple coordinate transformation relates our metric to

McVittie's, but for open and closed universes, we believe McVittie to be incorrect. In the closed case, our metric possesses an image mass at the antipotal point of the universe. The author will present the derived invariant fully general-relativistic expressions for the force required to hold a test particle at rest relative to m. In the spatially-flat case, the Newtonian limit of this force consists of the usual m/r^2 inwards component and a cosmological component proportional to r, that is directed outwards (inwards) when the expansion of the universe is accelerating (decelerating). This is used together with the geodesic equations, to calculate the locations of maximum possible, and stable circular orbits respectively. These indicate that galaxies/clusters have definite edges, whose predicted locations agree well with observation. Finally, the author will generalise the results to (a) incorporate mass accretion, and (b) describe the interior of the object.

References

1. arXiv:1104.4458.
2. arXiv:1104.4447 (currently under review at MNRAS).

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W2 (P): Cosmology

Anne Marie Nzioki

Astrophysics, Cosmology, and Gravity Centre, Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch 7701, Cape Town, South Africa.
anne.nzioki@gmail.com

A geometrical approach to strong gravitational lensing in f(R) gravity

Anne Marie Nzioki, Peter K. S. Dunsby, Rituparno Goswami, and Sante Carloni

We present a framework for the study of lensing in spherically symmetric spacetimes within the context of f(R) gravity. Equations for the propagation of null geodesics, together with an expression for the bending angle are derived for any f(R) theory, and then applied to an exact spherically symmetric solution of R^n gravity. We find that for this case, more bending is expected for R^n gravity theories in comparison to GR, and is dependent on the value of n and the value of distance of closest approach of the incident null geodesic.

Reference

Phys. Rev. D, **83**, 024030 (2011).

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W2 (P): Cosmology

Isha Pahwa
(University of Delhi), H. No. 284/1, Ward No. 4, Krishna Colony, Near Old Bus Stand, Rohtak 124001, Haryana.
ishapahwa1@gmail.com

Higher dimensional cosmological models - An alternative explanation for late time cosmic acceleration

Einstein equations are solved for a homogeneous, anisotropic 1 + 3 + D dimensional universe. We study the late time acceleration of the universe in this model. The content of the universe is assumed to be such that it exerts zero pressure in visible dimensions and in extra dimensions, the equation of state is $P = w/\rho^{\gamma}$. The parameters of the model are fixed by comparing with observational data on supernovae. We show that late time acceleration occurs in the universe with q0 and z_{tr} being approximately − 0.46 and 0.76 respectively.

Reference

arXiv:1104.1925 [gr-qc].

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W2 (T): Cosmology

Aseem Paranjape
Abdus Salam ICTP, Strada Costiera, 11, 34151 Trieste, Italy.
aparanja@ictp.it

Random walks, moving barriers and the large scale structure

A. Paranjape, T. Y. Lam, and R. K. Sheth

Our understanding of the statistics of the large scale structure (LSS) of the universe has been influenced a great deal by the excursion set formalism - the study of (one-

dimensional) random walks and their first passage of a given barrier. After a brief introduction to excursion sets, the speaker will discuss some recent results in understanding the behaviour of random walks with correlated steps, in the presence of "moving" barriers. This work builds on an almost forgotten result due to Peacock, and Heavens (1990), which will also be discussed. In particular, while the effects of correlations between steps are known to be small when the formalism is applied to study collapsed dark matter halos, the speaker will argue that these effects are instead crucial in predicting the distribution of underdense regions or voids in the LSS.

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W2 (T): Cosmology

Valeria Pettorino
SISSA, Via Bonomea 265, 34136 Trieste, Italy.
pettorin@sissa.it

Interacting dark energy: Impact on CMB and structure formation

Valeria Pettorino, C. Wetterich, L. Amendola, and M. Baldi.

The speaker will illustrate the case of interacting dark energy, that is, to say cosmologies in which dark energy evolution is coupled to other species in the universe (cold dark matter, neutrinos or extensions of general relativity like scalar-tensor theories). After briefly introducing coupled quintessence models, the speaker, in particular, will focus on the effects that such an interaction has on CMB and structure formation, and will show how the presence of an effective attractive force stronger than gravity, and mediated by the dark energy scalar field can lead to an increase in the ISW effect and to the formation of very large scale structures of the order of 100 Mpc, as it happens in growing neutrino cosmologies. We carry out the analysis at both linear and non linear levels showing both constraints from CMB and results from N-body simulations.

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W2 (T): Cosmology

Dmitri Pogosyan
Department of Physics, University of Alberta, 4 – 183 CCIS, Edmonton, AB T6G 2E1, Canada.
pogosyan@ualberta.ca

Geometrical statistics of non-Gaussian cosmological fields

We present a general formalism: how standard geometrical statistics, such as Minkowski functionals and number density of extrema as well as the less standard ones, such as properties of the skeleton of the random field can be calculated via Gram-Charlier like expansion to an arbitrary order. Applications to mildly non-linear 3D density field of forming large scale cosmic structure or 2D field of CMB temperature are discussed.

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W2 (P): Cosmology

Jayanti Prasad
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India.
jayanti@iucaa.ernet.in

Cosmological parameter estimation using Particle Swarm Optimization

Jayanti Prasad, and Tarun Souradeep

Obtaining best fit cosmological parameters from observational data sets is an important exercise in current cosmological research. In Bayesian formalism, it involves finding the global maximum of likelihood function in a multi-dimensional parameter space. So far, Markov-Chain Monte Carlo methods (MCMC), which are stochastic methods, have been commonly used for parameter estimation. The beauty of stochastic methods is that the computational cost grows logarithmically in place of exponentially with the dimensionality of parameter space. MCMC methods give full joint probability distribution (posterior) from which best fit parameters, error bars, and two dimensional contour plots can be obtained after marginalization. We demonstrate here the application of another stochastic method, named Particle Swarm Optimization (PSO) for parameter estimation from WMAP seven years data. We find that there is a good agreement between the

values of best fit parameters obtained from PSO and publically available code COSMOMC, however, there is slight disagreement between error bars.

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W2 (T): Cosmology

Graziano Rossi
Korea Institute for Advanced Study (KIAS), 85 Hoegiro (Cheongnyangni-dong 207-43), Dongdaemun-gu, Seoul 130-722, Republic of Korea.
graziano@kias.re.kr

Halo shapes in the cosmic web

Studying and quantifying the triaxial morphology of dark matter halos is the first necessary step to understand the properties of galaxies. In turn, the formation of dark matter halos affects the properties of the galaxies hosted by the halos. Triaxiality also has a number of observationally relevant implications, such as the nonlinear clustering of halos and dark matter, the distribution of voids, the formation and evolution of galaxies, and their relation to the cosmic web. The speaker will present a new model which allows one to study the shapes of dark matter halos, and even the distribution of voids, and will provide simple physical explanations for some empirical fitting formulae obtained from numerical studies, and show results of the comparison with simulations. The speaker will also discuss how the morphology of dark halos is related to the underlying topology of the cosmic web, with particular attention to the role of the gravitational potential field.

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W2 (P): Cosmology

Prakash Sarkar
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India.
sarkar@iucaa.ernet.in

The luminosity, colour and morphology dependence of galaxy structures in the Sloan Digital Sky Survey

Prakash Sarkar, Biswajit Pandey, and Somnath Bharadwaj

It is possible to visualize the cosmic web as an interconnected network of one dimensional filaments, two dimensional sheets and three dimensional volume filling

structures, which we refer to as clusters. We consider the local dimension D, defined through $N(R) = A R^D$, where N(R) is the galaxy number count within a sphere of comoving radius R, centered on a particular galaxy, as a tool to locally quantify the shape in the neigbourhood of different galaxies along the cosmic web. We expect $D \sim 1$, 2 and 3 for a galaxy located in a filament, sheet and cluster respectively. We have analysed the cosmic web using local dimension in a LCDM N-body simulations [1] and to a three dimensional volume limited galaxy sample from the Sloan Digital Sky Survey Data Release Six [2]. We now want to test for luminosity, colour and morphology dependence of the galaxy structures (filaments, sheets and clusters) in three dimensional volume of SDSS data.

References

1. MNRAS Lett., **394**, 1, L66, (arXiv:0812.1800).
2. MNRAS (arXiv:1105.4469) (Submitted).

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W2 (T): Cosmology

P.S. Saumia
Institute of Physics, Sachivalay Marg, Sainik School P.O., Bhubaneswar 751005, India.
saumia@iopb.res.in

Probing the anisotropic expansion history of the universe with cosmic microwave background

Ranjita K. Mohapatra, P. S. Saumia, and Ajit M. Srivastava

We propose a new technique to detect any anisotropic expansion stage in the history of the universe starting from the inflationary stage to the surface of last scattering from the CMBR data. We argue that any anisotropic expansion in the universe would deform the shapes of the primordial density perturbations and this deformation can be detected in a shape analysis of superhorizon fluctuations in CMBR. Using this analysis we obtain the constraint on any previous anisotropic expansion of the universe to be less than 50 %.

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W2 (T): Cosmology

Anjan Anand Sen
Centre for Theoretical Physics, Jamia Millia Islamia, Jamia Nagar, New Delhi 110025, India.
anjsen@gmail.com

Deviation from ΛCDM: Pressure parametrization

Most parametrizations for dark energy involve the equation of state w of the dark energy. We choose the pressure of the dark energy to parametrize. As $p =$ constant essentially gives a cosmological constant, we use the Taylor expansion around this behavior, $p = -p_0 + (1 - a)p_1 + ...$, to study the small deviations from the cosmological constant. In this model, the departure from the cosmological constant behaviour has been modeled by the presence of extra K-essence fields, while keeping the cosmological constant term untouched. The model is similar to assisted inflation scenario, in a sense that for any higher order deviation in terms of Taylor series expansion, one needs multiple K-essence fields. We have also tested this model with the recent observational data coming from Supernova type Ia measurements, the baryon oscillations peak (BAO) and the gas mass fraction of the galaxy clusters inferred from X-ray observations and obtain constraints for our model parameters.

Reference

Phys. Rev. D, **77**, 043508 (2008).

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W2 (P): Cosmology

Arman Shafieloo
Institute for the Early Universe, No. 611, International Education Building, Ewha Woman's University, Seoul, Korea.
arman@ewha.ac.kr

The crossing statistic: Dealing with unknown errors in the dispersion of type Ia supernovae

Arman Shafieloo, Timothy Clifton, and Pedro Ferreira

We propose a new statistic that has been designed to be used in situations, where the intrinsic dispersion of a data set is not well known: 'The Crossing Statistic'. This statistic is in general less sensitive than 'χ^2' to the intrinsic dispersion of the data, and hence, allows to make progress in distinguishing between different models using goodness of fit to the data, even when the errors involved are poorly understood. The proposed statistic makes use of the shape and trends of a model's predictions in a quantifiable manner. It is applicable to a variety of circumstances, although we consider it to be especially well suited to the task of distinguishing between different cosmological models using type Ia supernovae. We show that this statistic can easily distinguish between different models in cases where the 'χ^2' statistic fails. We also show that the last mode of Crossing Statistic is identical to 'χ^2', so that one can consider it as a generalization of 'χ^2'.

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W2 (T): Cosmology

Tristan Smith
University of California, Berkeley 2806, Regent St. Apt. A, Berkeley, CA 94705, USA.
tlsmith@berkeley.edu

Constraints on neutrino interactions using cosmological observations

Tristan L. Smith, Sudeep Das, and Oliver Zahn

Observations of the cosmic microwave background (CMB) and large-scale structure (LSS) provide a unique opportunity to explore the fundamental properties of neutrinos. We report on the first constraint to the cosmic neutrino background (CNB) rest-frame sound speed, c^2_{eff}, using the most recent CMB and LSS data. Additionally, we report the improved constraints to the CNB viscosity parameter, c^2_{vis}. For standard neutrinos, these parameters both equal 1/3. Using current data,

we find that the standard CNB is ruled out at the 99 % confidence level (C.L.) with $c^2_{eff} = 0.30_{-0.026}^{+0.027}$ and $c^2_{vis} = 0.44^{+0.27}_{-0.21}$ (95 % C.L.) for three neutrino species. Fundamentally, these constraints allow us to quantify the extent to which neutrinos are non-interacting around the time of the formation of structure in the CMB. We also discuss how constraints to these parameters from the current and future observations (such as the Planck satellite) allow us to explore the fundamental properties of any anomalous radiative energy density beyond the standard three neutrinos.

Reference

arXiv:1105.3246.

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W2 (P): Cosmology

Itzadah Thongkool
Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211019, India.
ithongkool@gmail.com

How delicate are the f(R) gravity models with disappearing cosmological constant?

I. Thongkool, M. Sami, and S. Rai Choudhury

We consider stability of spherically symmetric solutions in f(R) gravity model, proposed by Starobinsky. We find that the model suffers from a severe fine tuning problem when applied to compact objects like neutron stars. The problem can be remedied by introducing a cut off on the mass of the scalar degree of freedom present in the model. A new mass scale associated with neutron stars density is then required for the stabilities of f(R) gravity solutions inside relativistic stars.

References

1. http://arxiv.org/abs/0908.1693.
2. Phys. Rev. D, **80**,127501.

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Tommaso Treu
Department of Physics, University of California, Santa Barbara, CA 93106 – 9530, USA.
tt@physics.ucsb.edu

Cosmology from gravitational time delays

Tommaso Treu, Sherry Suyu, and Matt Auger

Strong gravitational lenses, where the background source is variable in time and the foreground deflector is a massive galaxy, can be used very effectively as cosmic "standard-rods" to measure the geometry and content on the universe (Treu 2010). Specifically, gravitational time delays constrain primarily the Hubble constant, and - in combination with other techniques - the equation of state of dark energy, flatness of the universe, and neutrino masses. The speaker will illustrate the recent advances in modelling techniques and data quality, that have enabled a 7% measurement of the Hubble constant from a single gravitational lens (Suyu, et al. 2010) as well as constraints on the equation of state of dark energy and flatness comparable to those obtained with the best probes. A measurement of the Hubble constant with absolute precision of 3 - 4% is in progress (Suyu, et al. 2011). The speaker will show the first results and their implications, and will conclude by discussing the bright prospects of gravitational time delays as cosmographic probe.

References

1. Suyu, et al., Astrophysical Journal,**711**, 201 (2010).
2. Treu Tommaso, Annual Reviews of Astronomy and Astrophysics, **48**, 87 (2010).

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W2 (P): Cosmology

Pranjal Trivedi
C – 11, University Flats, 29 – 31, Chhatra Marg, University of Delhi, North Campus, Delhi 110007, India.
ptrivedi@physics.du.ac.in

CMB non-Gaussianity sourced by primordial magnetic fields

Pranjal Trivedi, Kandaswamy Subramanian, and T. R. Seshadri

An interesting possibility for the origin of large-scale magnetic fields in the universe is a primordial cosmological magnetic field. Perturbations due to magnetic fields (both energy density and stress) are non-linear at lowest order in the field, and can contribute significant non-Gaussianity to the CMB. We calculate a CMB bispectrum of $\sim 10^{-16}$ due to the scalar anisotropic stress passive mode. This is a million times greater than the CMB bispectrum calculated previously, induced by the magnetic energy density mode. The WMAP7 limits for f_{NL} allow us to place an order of magnitude stronger upper limit to the strength of the primordial magnetic field, redshifted to the current epoch, of 2 nanoGauss. Both the bispectrum amplitude and magnetic field limits are only weakly dependent on the assumed epoch of magnetic field generation, and we assume a scale-invariant magnetic energy spectrum. We have also calculated the CMB non-Gaussianity from the magnetic tensor mode bispectrum sourced by the gravity waves produced by a primordial magnetic field. This tensor passive mode CMB bispectrum is $\sim$ 50 times larger than the scalar passive bispectrum, allowing us to set a tighter upper limit of 1 nanoGauss on the primordial magnetic field strength.

Reference

Phys. Rev. D, **82**, 123006 (2010) [arXiv:1009.2724v1], and another paper in preparation.

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W2 (P): Cosmology

Sanil Unnikrishnan
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India.
sanil@iucaa.ernet.in

Dark energy versus f(R) theories of modified gravity

Sanil Unnikrishnan, Shruti Thakur, and T. R. Seshadri

We show that if f(R) theory of modified gravity is to drive the late time accelerated expansion of the universe as if it is due to dark energy in Einstein's GR with a constant equation of state parameter w, the density parameter of matter will be close to that in GR if and only if w is close to -1. Further, this result also demonstrates that the total duration of matter domination decreases significantly as w deviates from minus one. For those models where w is epoch dependent, the deviation of density parameter of matter from the GR value is larger in f(R) models, which mimics freezing dark energy model than those models which mimic thawing dark energy.

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W2 (T): Cosmology

Filippo Vernizzi
Institut de Physique Theorique, CEA Saclay, 91191 gif-sur-Yvette cedex, France.
filippo.vernizzi@cea.fr

Structure formation with clustering quintessence

The speaker will present a study of large-scale structure formation in the presence of a scalar field dark energy with zero speed of sound. This model is motivated by stability properties of the field. After a short review on the phenomenology of clustering quintessence in linear perturbations, the speaker will discuss the nonlinear aspect, and will compute the bispectrum of the density field and show that it is modified by the clustering of quintessence at low redshift, which can potentially be used to detect or rule out this model. Further, the speaker will discuss the nonlinear regime using the spherical collapse model. Quintessence contributes to the mass of virialized objects, which represents an observational signature for future galaxies and cluster surveys.

References

1. With Emiliano Sefusatti, arXiv:1101.1026.
2. With Paolo Creminelli, Guido D'Amico, Jorge Norena, and Leonardo Senatore, JCAP, **1003**, 027 (2010).
3. With Paolo Creminelli, Guido D'Amico, and Jorge Norena, JCAP, **0902**, 018 (2009).

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W3

Quantum Gravity and Early Universe

Coordinators : Justin David and Shinji Mukohyama

Suhail Ahmad
Jamia Millia Islamia, Jamia Nagar, New Delhi 110025, India.
suhail.dream@gmail.com

Sub-leading corrections to black hole entropy formula in black holes (convergences and divergences)

We are finding subleading corrections to the entropy correction formula. The first term appears to be generic to all approaches, whether strings loops or other approaches. In BTZ scenario, with the presence of Chern-Simon terms, how will the correction turn out to be, and correlating it with semiclassical analysis, whereby, we also get correction to Bekenstein result in various scenarios like Schwarzschild-Kerr-Newman, etc.

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Frederico Arroja
Institute for the Early Universe, Ewha Womans University, 11 – 1 Daehyun-dong, Seodaemun-gu, 120 – 750 Seoul, South Korea.
arrojaf@ewha.ac.kr

Large and strong scale dependent bispectrum in single field inflation from a sharp feature in the mass

Frederico Arroja, Antonio Romano, and Misao Sasaki

We study an inflationary model driven by a single scalar field with a step in its mass modeled by an Heaviside step function. We present an analytical approximation for the mode function of the curvature perturbation, obtain the power spectrum analytically and compare it with the numerical result. We show that, after the scale set by the step, the spectrum contains damped oscillations that are well described by our analytical approximation. We also compute the dominant contribution to the bispectrum in the equilateral and the squeezed limits and find new shapes. In the equilateral and squeezed limits, the bispectrum oscillates and it has a linear growth envelope towards smaller scales. The bispectrum size can be large depending on the model parameters.

Reference

e-Print: 1106.5384 [astro-ph.CO].

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W3 (P): Quantum Gravity and Early Universe

Kumar Atmjeet
26 – D, BG – 3 Paschim Vihar, New Delhi 110063, India.
atmjeet2@gmail.com

Cosmological magnetogenesis

The origin of cosmic magnetic field is still a mystery. Observations have verified the presence of μ-gauss field in galaxy clusters and intergalactic medium. There is enough motivation to look into the primordial origin of magnetic field. The primordial generation of magnetic field requires the breaking of conformal invariance of Maxwell's theory. A variety of mechanisms to generate primordial magnetic fields have been proposed. A brief overview of those models will be presented. Other models are also proposed which are within the framework of the standard model with an inflationary phase. Models such as bouncing cosmology, to generate the primordial magnetic field, which are beyond the inflationary framework, are also discussed. The nature of the power-spectrum of magnetic fields when the dynamics of the inflaton field does not obey the slow-roll approximation is also discussed.

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W3 (T): Quantum Gravity and Early Universe

Abhishek Atreya
Institute of Physics, Sachivalaya Marg, Bhubaneswar 751005, India.
atreya@iopb.res.in

Baryon inhomogeneities in early universe due to CP violating quark scattering from QCD Z(3) domains

Abhishek Atreya, Anjishnu Sarkar, and Ajit M. Srivastava

We investigate the possibility of generation of baryon inhomogeneties in the quark-gluon plasma phase in the early universe due to CP violating scattering of quarks

and antiquarks from moving Z(3) domain walls. CP violation, here, is spontaneous in nature, and arises from the nontrivial profile of the background gauge field (A0) between different Z(3) vacua. We calculate the spatial variation for A0 across the Z(3) interface from the profile of the Polyyakov loop L(x) for the Z(3) interface, and determine the reflection of quarks and antiquarks using the Dirac equation. Our results show that the reflection coefficients of quarks and antiquarks can differ by a large amount. We discuss the implications of this for baryon inhomogeneity generation from collapsing large Z(3) walls (which can arise in the context of certain low energy scale inflationary models).

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W3 (T): Quantum Gravity and Early Universe

Fernando Barbero
Instituto de Estructura de la Materia, CSIC Serrano 123, 28006 Madrid, Spain.
fbarbero@iem.cfmac.csic.es

Detailed black hole state counting in loop quantum gravity

Ivan Agullo, J. Fernando Barbero G., Enrique F. Borja, Jacobo Diaz-Polo, and Eduardo J. S. Villase

We give a detailed description of the computation of black hole entropy in loop quantum gravity by employing the most recently introduced number theoretic and combinatorial methods. The use of these techniques allows us to perform a detailed analysis of the precise structure of the entropy spectrum for small black holes, showing some relevant features that were not discernible in previous computations. The ability to manipulate and understand the spectrum up to the level of detail that we describe is a crucial step towards a full understanding of the behavior of black hole entropy.

References

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2. arXiv:1101.3662.

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Srijit Bhattacharjee
Saha Institute of Nuclear Physics, Sector 1, Block AF, Bidhan Nagar, Kolkata 700064, India.
srijit.bhattacharjee@saha.ac.in

Gauge invariant coupling of fields to torsion: A string inspired model

Srijit Bhattacharjee, and Ayan Chatterjee

In a consistent heterotic string theory, the Kalb-Ramond field, which is the source of spacetime torsion, is augmented by Yang-Mills and gravitational Chern-Simons terms. When compactified to 4 dimensions and in the field theory limit, such additional terms give rise to interactions with interesting astrophysical predictions, like rotation of plane of polarization for electromagnetic and gravitational waves. On the other hand, if one is also interested in coupling 2- or 3-form (Abelian or non-Abelian) gauge fields to torsion, one needs another class of interaction. In this talk, we shall discuss this interaction, and offer some astrophysical and cosmological predictions. We explicitly calculate the Coleman-Weinberg potential for this theory. We also comment on the possibility of such terms in loop quantum gravity where, if the Barbero-Immirzi parameter is promoted to a field, acts as a source for torsion.

Reference

Phys. Rev. D, **83**, 106007 (2011).

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Shuvendu Chakraborty
Seacom Engineering College, JL – 2: Jaladhulagori, Via Andul Mouri, Howrah, Kolkata 711302, India.
shuvendu.chakraborty@gmail.com

Higher dimensional cosmology with normal scalar field and tachyonic field

Shuvendu Chakraborty, and Ujjal Debnath

We have considered N-dimensional Einstein field equations, in which four-dimensional spacetime is described by a FRW metric and that of extra dimensions by an Euclidean metric. We have supposed that the higher dimensional anisotropic universe is filled with only normal scalar field or tachyonic field. Here, we have found the nature of potential of normal scalar field or tachyonic field. From graphical representations, we have seen that the potential is always decreases with field φ increases.

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W3 (T): Quantum Gravity and Early Universe

Suratna Das
Theoretical Physics Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India.
suratna@prl.res.in

Effects of radiation on primordial non-Gaussianity

Suratna Das, and Subhendra Mohanty

The simple single field slow-roll model of inflation predicts tiny primordial non-Gaussianity, ensuring the nearly Gaussian distribution of the primordial fluctuations, which is in accordance with the present observations. Such tiny non-Gaussianity is beyond the range of detection by any present or forthcoming CMB observations. This simple scenario changes if one takes into account the effect of radiation prior to, during (Warm) or after (Thermal) inflation, which enhances the primordial non-Gaussianity detectable by present or future experiments. The speaker will discuss the effect of radiation on primordial non-Gaussianity.

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W3 (T): Quantum Gravity and Early Universe

Guido D'Amico

Center for Cosmology and Particle Physics, Mayer Hall of Physics, New York University, 4 Washington Place, New York, NY 10003, USA.
gda2@nyu.edu

The (not so) squeezed limit of the primordial 3-point function

Paolo Creminelli, Guido D'Amico, Marcello Musso, and Jorge Norena

We prove that, in a generic single-field model, the consistency relation for the 3-point function in the squeezed limit receives corrections that vanish quadratically in the ratio of the momenta, i.e., as $(k_L/k_S)^2$. This implies that a detection of a bispectrum signal going as $1/k_L^2$ in the squeezed limit, that is suppressed only by one power of k_L compared with the local shape, would rule out all single-field models. The absence of this kind of terms in the bispectrum holds also for multifield models, but only if all the fields have a mass much smaller than H. The detection of any scale dependence of the bias, for scales much larger than the size of the haloes, would disprove all single-field models. We comment on the regime of squeezing that can be probed by realistic surveys.

Reference

http://arxiv.org/abs/1106.1462.

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W3 (T): Quantum Gravity and Early Universe

Josue De Santiago Sanabria

Departamento de Fisica, Instituto Nacional de Investigaciones Nucleares (ININ), Apartado Postal 18 – 1027, Col. Escandon, Mexico DF 11801, Mexico.
josue@ciencias.unam.mx

Generalizing a unified model of dark matter, dark energy, and inflation with a noncanonical kinetic term

Josue De Santiago, and Jorge L. Cervantes Cota

In this model, the kinetic term of the Lagrangian accounts for the dark matter and dark energy, and at early epochs, a quadratic potential accounts for slow roll

inflation. The speaker will demonstrate that the model is viable at the background and linear perturbation levels.

Reference

Phys. Rev. D, **83**, 063502 (2011).

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W3 (P): Quantum Gravity and Early Universe

Ujjal Debnath
Department of Mathematics, Bengal Engineering and Science University, Shibpur, Howrah 711103, India.
ujjal@iucaa.ernet.in

Thermodynamics in Vaidya spacetime

We have considered the Vaidya spacetime in null radiating fluid with perfect fluid in higher dimension and have found the solutions for barotropic fluid, polytropic fluid, and variable modified Chaplygin gas models. We have shown that the Einstein's field equations can be obtained from unified first law, i.e., field equations and unified first law are equivalent. The first law of thermodynamics has also been constructed by unified first law. From this, the variation of entropy function has been derived on the horizon. The variation of entropy function inside the horizon has been derived using Gibb's law of thermodynamics. So the total variation of entropy function has been constructed at both apparent and event horizons. If we do not assume the first law, then the entropy on both the horizons can be considered by area law and the variation of total entropy has been found at both the horizons. Also, the validity of generalized second law (GSL) of thermodynamics has been examined at both apparent and event horizons by using the first law and using the area law separately.

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W3 (T): Quantum Gravity and Early Universe

Anne Franzen
University Utrecht, Leuvenlaan 4 3584 CE, Utrecht, The Netherlands.
a.t.franzen@uu.nl

Scalar waves in Kerr background

Anne Franzen, Gerard 't Hooft, and Igor Khavkine

We investigate the propagation of scalar waves through the full region of Kerr spacetime. Imposing appropriate boundary conditions in each region will lead to expressions for the associated propagators. The region reaching from the inner horizon to minus infinity will turn out to be delicate, since it contains a ring singularity as well as closed timelike curves. Eventually, matching the propagators of each region across the horizons is expected to lead to an expression of a global propagator.

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W3 (P): Quantum Gravity and Early Universe

Suman Ghosh
School of Physics, Indian Institute of Science Education and Research, Computer Science Building, College of Engineering, Thiruvananthapuram 695016, India.
suman.ghosh@iisertvm.ac.in

Higher-order field derivatives and deviations from entropy-area law

Suman Ghosh, and S. Shankaranarayanan

It is now established that the entanglement entropy of canonical scalar fields evaluated by integrating over certain degrees of freedom leads to area-law. One of the weaknesses of the above procedure is that the discretized Hamiltonian of the scalar field is independent of the lattice size. However, theoretical arguments suggest that when the lattice size is close to the Planck scale, then the above description of canonical scalar field fails and higher-order field derivatives play a crucial role. We introduce a class of higher-derivative terms to the canonical scalar field and study the effects of these terms on the entropy-area relation. Our results show how the strength of the higher-derivative term leads to deviation from the area-law, and provide a physical insight into the roles of degrees of freedom far away from the horizon.

W3 (T): Quantum Gravity and Early Universe

Jinn-Ouk Gong
Theory Division, CERN, CH – 1211, Geneva 23, Switzerland.
jinn-ouk.gong@cern.ch

Multi-field inflation: Formulation, effective theory and phenomenology

Ana Achucarro, Jinn-Ouk Gong, Gonzalo A. Palma, and Subodh P. Patil

The absence of the relevant inflaton in the standard model of particle physics demands that inflation be described in the context of the speculative high energy theories, where plenty of scalar fields, which can contribute to the inflationary dynamics exist. Further, in multi-field system, we can obtain interesting observational signatures, which deviate from the predictions of the single field models of inflation and can be detected in near future. Thus, we have both theoretical and phenomenological motivations to study multi-field inflation. The speaker will describe, starting from the general multi-field Lagrangian, how to obtain higher order action of cosmological perturbations easily, and systematically in a covariant manner, and then give the effective single field description by integrating out the heavy isocurvature modes, which leaves distinctive observational signatures. Especially, we find correlated features in the power spectrum and bispectrum of the curvature perturbation, which can be a strong support of multi-field inflation.

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W3 (T): Quantum Gravity and Early Universe

Gaurav Goswami
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India.
gaurav@iucaa.ernet.in

Features in scalar primordial power spectrum and their consequences

Gaurav Goswami, and Tarun Souradeep

We argue in favour of the existence of features in the scalar Primordial Power Spectrum (PPS), and then answer what do such features say about the era of cosmic inflation. We present general characteristics of models, which lead to very sharp features in PPS. We comment about reconstruction of the inflationary

potential that is consistent with sharp features in PPS, and how the existence of such features could be closely related to other observable consequences of inflation such as primordial non-Gaussianity.

Reference

Gaurav Goswami, and Tarun Souradeep, Phys. Rev. D, **83**, 023526 (2011).

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W3 (T): Quantum Gravity and Early Universe

Julien Grain

Institut d'Astrophysique Spatiale, CNRS/University Paris 11 Centre, Universitaire d'Orsay, Batiment 120 – 121, 91405 Orsay Cedex, France.
julien.grain@ias.u-psud.fr

The primordial universe as a potential probe of loop quantum cosmology

J. Grain, A. Barrau, T. Cailleteau, and J. Mielczarek

Loop quantum cosmology is a promising attempt to apply loop quantum gravity ideas to the universe as a whole. The speaker will describe some possible observational features. First, he will explain how the primordial tensor power spectrum is modified, even in a standard inflation, through both holonomy and inverse-volume corrections, and then, will show how the bounce leaves specific footprints on the primordial power spectrum. This leads to potentially relevant features in the cosmic microwave background B-modes. Finally, he will present the work in progress on the construction of an anomaly-free algebra for holonomy corrected vector and scalar perturbations.

References

1. arXiv: 1106.3744.
2. Phys. Rev. D, **82**, 123520 (2010).
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W3 (P): Quantum Gravity and Early Universe

Yuan K. Ha
Department of Physics, Temple University, Philadelphia, PA 19122, USA.
yuanha@temple.edu

An underlying theory for gravity

A new direction to understand gravity has recently been explored by considering classical gravity to be a derived interaction from an underlying theory. This underlying theory would involve new degrees of freedom at a deeper level, and it would be structurally different from classical gravitation. It may conceivably be a quantum theory or a non-quantum theory. The relation between this underlying theory and Einstein's gravity is similar to the connection between statistical mechanics and thermodynamics. We discuss the meaning of quantum gravity in this context and the lack of any quantum nature of spacetime in current observations.

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W3 (T): Quantum Gravity and Early Universe

Dhiraj Kumar Hazra
Department of Physics, Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211019, India.
dhiraj@hri.res.in

On the discriminating power of f_{nl}

Dhiraj Kumar Hazra, L. Sriramkumar, and Jerome Martin

The WMAP seven year data constrains the primordial non-Gaussianity parameter f_{nl} to be (21 +/- 140) in the equilateral limit and at 68% confidence level. Such a large mean value will rule out inflationary models described by the canonical scalar fields, provided one restricts to models that lead to a nearly scale invariant primordial spectrum. Models that generate features in the scalar power spectrum are also known to lead to large levels of non-Gaussianity. We numerically evaluate the non-Gaussianity parameter f_{nl} (in the equilateral limit) in a variety of models that lead to features in the inflationary scalar power spectrum. We consider different inflationary models that lead to very similar features, and investigate if f_{nl} can help us discriminate between the models. We first, study scenarios that lead to a sharp cut off in the scalar power spectrum at large scales, followed by oscillations, as it

occurs, say, when there is a brief period of departure from inflation. We also study models that lead to a burst of oscillations, as is generated when a step is introduced in the inflaton potential. We find that certain differences in the background dynamics-reflected in the behaviour of the slow roll parameters-can lead to a reasonably large difference in the f_{nl} generated by the models.

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W3 (T): Quantum Gravity and Early Universe

Rajeev Kumar Jain
Department of Theoretical Physics and Center for Astroparticle Physics, University of Geneva, 24 Quai Ernest-Ansermet, Ch – 1211 Geneva 4, Switzerland.
rajeev.jain@unige.ch

Can slow roll inflation induce relevant helical magnetic fields?

Ruth Durrer, Lukas Hollenstein, and Rajeev Kumar Jain

The speaker shall discuss the generation of helical magnetic fields in single field inflation induced by an axial coupling of the electromagnetic field to the inflaton. In slow roll inflation, such a coupling always leads to a blue spectrum of the magnetic fields with $P_B \sim k$. Moreover, even a short deviation from slow roll does not result in strong modifications to the shape of the spectrum. He shall also discuss the subsequent evolution of the spectrum during the inverse cascade and viscous damping of the helical magnetic fields in the radiation era after inflation. Although, the power is transferred from small to large scales, the magnetic fields generated in this scenario are too weak to provide the seeds for the observed fields in galaxies and clusters; except for low scale inflation with very strong axial coupling, a case where the perturbative treatment of the theory may break down.

Reference

http://iopscience.iop.org/1475-7516/2011/03/037/

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Sanved Kolekar
IUCAA, Post Bag 4, Ganeshkhind, Pune University Campus, Pune 411007, India.
sanved@iucaa.ernet.in

Action for gravity: An emergent perspective

From an emergent gravity paradigm perspective, we highlight some aspects of the action for gravity. Firstly, the Einstein-Hilbert action and its natural generalizations (like the Lanczos-Lovelock action) can be separated into a bulk and a surface term, with a specific "holographic" relationship between the two, so that either term can be used to extract information about the other. With a new particular separation, we show that the surface term becomes Wald entropy on a horizon, and the bulk term is the energy density (which is the ADM Hamiltonian density for Einstein gravity). We show that this new pair also obeys a holographic relationship, and give a thermodynamic interpretation to this relation, that the holographic nature of the action allows us to relate the descriptions of the same system in terms of two different thermodynamic potentials. Secondly, we explore an action for the dynamics of null surfaces, which on extremizing w.r.t. the null normals, lead to a Navier-Stokes like equation governing the evolution of the geometry of the null surface. These can be shown to imply the Einstein field equations. We show that the action can be interpreted as describing an on-shell local entropy density of the spacetime.

References

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2. S. Kolekar, and T. Padmanabhan (in preparation).

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Alok Laddha
Davey Laboratory, Pennsylvania State University, State College, PA 16801, USA.
oranjok@gmail.com

Constraint algebra in loop quantum gravity

Constraint algebra of canonical gravity is not a true Lie algebra. As entire dynamical content of the theory is encoded in the constraints, an anomaly free representation of this algebra is one of the core issues in loop quantum gravity. We summarise the main results obtained in this direction and some of the more recent ongoing efforts.

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Kinjalk Lochan
Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India.
kinjalk@tifr.res.in

Extension of trace dynamics to spacetime

K. Lochan, and T. P. Singh

Trace dynamics is a classical dynamical theory of non-commuting matrices, which has been developed by Stephen Adler and collaborators as a fundamental basis for deriving quantum theory from first principles, and for explaining quantum to classical transition as a dynamical process. However, the theory treats spacetime as a classical input, to be provided by an external classical spacetime geometry. This limitation of the theory, should be removed, if possible. We suggest a way to remove this limitation, by constructing a non-commutative special relativity, in which space and time coordinates are included in the theory as fundamental degrees of freedom rather than external parameters, and yet Poincare invariance is preserved. We attempt to see if classical spacetime is an emergent description.

Reference

Kinjalk Lochan and T. P. Singh, Phys. Lett. A 375 (2011) 3747 [arXiv:1109.0300]

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Amitabha Mukherjee
Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India.
amimukh@gmail.com

Scalar field theory with a time-dependent potential and its application to cosmology

Rakesh Kabir, and Amitabha Mukherjee

The theory of a real scalar field with an arbitrary potential plays an important role in cosmology, particularly in the context of inflationary scenarios. However, in most applications the potential is treated as independent of time, whereas in an evolving universe – for example, before the onset of inflation – the potential is actually likely to be changing with time. As pointed out by Berry in the context of single-particle quantum mechanics, the existence of multiple time scales can lead to results that are qualitatively different from those obtained with a static potential. The talk will report on some preliminary investigations in a scalar field theory with a double-well potential that depends explicitly on time. The transition rate per unit volume for the decay of the false vacuum is found to depend strongly on time. Some implications for cosmology are discussed.

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Marcello Musso
ICTP, Strada Costiera 11, 34151 Trieste, Italy.
musso@ictp.it

Galilean symmetry in the effective theory of inflation: New shapes of non-Gaussianity

Paolo Creminelli, Guido D'Amico, Marcello Musso, Jorge Norena, and Enrico Trincherini

We study the consequences of imposing an approximate Galilean symmetry on the effective theory of inflation, the theory of small perturbations around the inflationary background. This approach allows us to study the effect of operators with two derivatives on each field, which can be the leading interactions due to non-renormalization properties of the Galilean Lagrangian. In this case, cubic non-Gaussianities are given by three independent operators, containing up to six

derivatives, two with a shape close to equilateral and one peaking on flattened isosceles triangles. The four-point function is larger than in models with small speed of sound and potentially observable with the Planck satellite.

References

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2. arXiv:1011.3004.

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W3 (T): Quantum Gravity and Early Universe

Yasusada Nambu
Department of Physics, Graduate School of Science, Nagoya University, Chikusa, Nagoya 464 – 8602, Japan.
nambu@gravity.phys.nagoya-u.ac.jp

Classical and quantum correlations of scalar field in the inflationary universe

Yasusada Nambu, and Yuji Ohsumi

We investigate classical and quantum correlations of a quantum field in the inflationary universe using a particle detector model. By considering the entanglement and correlations between two comoving detectors interacting with a scalar field, we find that the entanglement between the detectors becomes zero after their physical separation exceeds the Hubble horizon. Furthermore, the quantum discord, which is defined as the quantum part of total correlation, approaches zero on super horizon scale. These behaviours support appearance of classical nature of the quantum fluctuation generated during the inflationary era.

Reference

arXiv:1105.5212 (gr-qc).

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W3 (P): Quantum Gravity and Early Universe

Gaurav Narain
Institute of Mathematical Sciences, IV Cross Road, CIT Campus, Taramani, Chennai 600113, India.
gaunarain@gmail.com

Analogue of Wilson-Fisher fixed point in quantum gravity

Gaurav Narain, and Roberto Percacci

We use functional renormalization group techniques to study the RG flow of scalar field theory coupled to gravity in three dimensions. We find an analogue of Wilson-Fisher fixed point in the system considered. We also compute the anomalous dimension of the scalar field at this fixed point.

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W3 (T): Quantum Gravity and Early Universe

K. Narayan
Chennai Mathematical Institute, Plot H1, SIPCOT IT Park, Padur P.O., Siruseri 603103, India.
narayan@cmi.ac.in

Cosmological singularities in string theory

The speaker will describe attempts to understand cosmological singularities in string theory, through (1) holographic approaches involving time-dependent generalizations of AdS/CFT, and analyzing gauge theories subjected to time-dependent sources [based on arXiv:0602107 [hep-th] and follow-up work with Sumit Das, Sandip Trivedi and others], and (2) analyses of worldsheet string spectra and propagation in the vicinity of null cosmological singularities [based on arXiv:1012.0113 [hep-th] and preceding work].

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W3 (T): Quantum Gravity and Early Universe

Akhilesh Nautiyal
Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211019, India.
akhilesh@hri.res.in

Warm natural inflation

Hiranmaya Mishra, Subhendra Mohanty, and Akhilesh Nautiyal

In warm inflation models, there is the requirement of generating large dissipative couplings of the inflaton with radiation, while at the same time, not de-stabilising the flatness of the inflaton potential due to radiative corrections. One way to achieve this without fine tuning unrelated couplings is by supersymmetry. We show that if the inflaton and other light fields are Pseudo-Nambu-Goldstone Bosons, then the radiative corrections to the potential are suppressed and the thermal corrections are small as long as the temperature is below the symmetry breaking scale. In such models, it is possible to fulfill the contrary requirements of an inflaton potential, which is stable under radiative corrections and the generation of a large dissipative coupling of the inflaton field with other light fields. We construct a warm inflation model, which gives the observed CMB-anisotropy amplitude and spectral index, where the symmetry breaking is at the GUT scale.

Reference

arXiv:1106.3039v1 [hep-ph].

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William Nelson
Institute of Gravitation and the Cosmos, 104 Davey Laboratory # 258, The Pennsylvania State University, University Park, PA 16802 – 6300, USA.
nelson@gravity.psu.edu

Inhomogeneities in loop quantum cosmology

Abhay Ashtekar, Ivan Agullo, and William Nelson

The era of precision cosmology has allowed us to precisely determine many of the cosmological parameters, in particular, via the CMB. Confronting loop quantum cosmology with these observations provides us with a powerful test of the theory. For this to be possible, we need a detailed understanding of the generation and evolution of inhomogeneous perturbations during the early, quantum gravity, phase of the universe. The speaker will describe how the dynamics of the background loop quantum cosmological model impacts the scalar and tensor power spectra of the CMB. In particular, the stimulated creation of perturbations due to the non-static nature of the background results in significant corrections to the power spectra that are, in principle, observable.

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Rajesh Parwani
Department of Physics, National University of Singapore, Kent Ridge, Singapore.
parwani@nus.edu.sg

Nonlinear quantum cosmology: Nonperturbative effects

R. Parwani, and S.N. Tarih

We update our previous analysis of an information-theoretically motivated nonlinear Wheeler-deWitt (WDW) equation, in the minisuperspace scheme, for flat Friedmann-Robertson-Walker (FRW) universes with a cosmological constant Λ. The nonlinear WDW equation, is in the form of a difference-differential equation. Numerical solutions show that for weak nonlinearity, the results are in agreement with a previous perturbative study, which found the original big bang to be screened by a barrier in the effective potential, leading to the quantum creation of a universe through tunneling. However, in this non-perturbative study, we also observe some new features, such as a nonzero minimum and maximum size to the

quantum universe. We also discuss the $\Lambda = 0$ case, and finally suggest applications to realistic inflationary potentials.

References

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2. L.H. Nguyen, and R. R. Parwani, AIP Conf. Proc. 1115, 180 (2009) (arXiv:0902.2844).

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W3 (T): Quantum Gravity and Early Universe

Raghavan Rangarajan
Theoretical Physics Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India.
raghavan@prl.res.in

Non-Gaussian fluctuations of the inflaton and constancy of correlations of zeta outside the horizon

Namit Mahajan, and Raghavan Rangarajan

We point out that the non-Gaussianity arising from cubic self interactions of the inflaton field is proportional to ξ N_e ,where $\xi \sim V'''$, and N_e is the number of e-foldings from horizon exit till the end of inflation. For scales of interest $N_e = 60$, and for models of inflation such as new inflation, natural inflation and running mass inflation, ξ is relatively large. Therefore, the contribution from self interactions should not be outrightly ignored, while retaining other terms in the non-Gaussianity parameter f_{NL}. But the N_e dependent term seems to imply the growth of non-Gaussianities outside the horizon. Therefore, we discuss the issue of the constancy of correlations of the curvature perturbation, ξ outside the horizon. We then calculate the 3-point function of the inflaton fluctuations using the canonical formalism, and further obtain the 3-point function of ξ_k. We find that the N_e dependent contribution to f_{NL} from self interactions of the inflaton field is cancelled by contributions from other terms associated with non-linearities in cosmological perturbation theory.

Reference

Phys. Rev. D, **83**, 043510 (2011).

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Carlo Rovelli
Centre de Physique Theorique de Luminy, Aix-Marseille University CPT – CNRS, Case 907, Luminy, F – 13288 Marseille, France.
rovelli@cpt.univ-mrs.fr

Loop quantum gravity

The speaker will review the present state, successes and difficulties of the loop approach to gravity. The first public presentation of loop quantum gravity was given 24 years ago, here in Goa.

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Dibakar Roychowdhury
Department of Theoretical Sciences, S.N. Bose National Centre for Basic Sciences, Sector III, Block JD, Salt Lake, Kolkata 700098, India.
dibakar@bose.res.in

Thermodynamics of Hawking-Page phase transition in AdS black holes

Rabin Banerjee, Sujoy Kumar Modak, and Dibakar Roychowdhury

The Hawking-Page phase transition, originally observed for the Schwarzschild Anti-de-Sitter black hole, has continued to generate considerable interest over the last few decades. Two outstanding problems associated with this transition remain. First, the nature of the phase transition is not clearly spelt out. Secondly, its generalisation to other black holes, where the critical temperature, critical mass, etc. have been explicitly computed, as was done by Hawking and Page, is lacking. We have resolved all these points. Importantly, we have provided a completely standard thermodynamical approach, which should interest a general group of physicists.

Reference

S.W. Hawking, and D.N. Page, Comm. Math. Phys., **87**, 577 (1983).

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Anirban Saha
Department of Physics, West Bengal State University, Berunanpukuria P.O., Malikapur, North 24 Parganas, Barasat 700126, West Bengal.
anirban@iucaa.ernet.in

Upper-bound of the time-space noncommutative parameter from gravitational quantum well experiment

The idea of noncommutative (NC) spacetime, where the coordinates x^μ satisfy the noncommutative algebra $[x^\mu, x^\nu] = \theta^{\mu\nu}$, has gained prominence in the recent literature. Apart from studying the formal aspects of the NC geometry, certain possible phenomenological consequences have also been investigated. A part of the endeavour is spent in finding the order of the NC parameter, and in exploring its connection with observations. A particular piece of this scenario is the quantum well problem, which has emerged in recent GRANIT experiments by Nesvizhevsky, et al., who detected the quantum states of the neutrons trapped in earth's gravitational field. We construct a field theoretic model of this gravitational well system in a NC spacetime. Analysis of this NC model from a second quantised platform, enables to study the effect of time-space noncommutativity in the gravitational well scenario, which is hitherto unavailable in the literature. The corresponding first quantized theory reveals a leading order perturbation term of noncommutative origin. Latest experimental data are used to estimate an upper bound on the time–space noncommutative parameter. The results are found to be consistent with the order of magnitude estimations of other NC parameters reported earlier.

Reference

Eur. Phys. J. C, **51**, 199 (2007).

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W3 (P): Quantum Gravity and Early Universe

Pradyumn Kumar Sahoo
Department of Mathematics, BITS – Pilani Hyderabad Campus, Jawahar Nagar, Shameerpet Mandal, R.R. District, 500078, India.
sahoomaku@rediffmail.com

Plane symmetric domain walls and cosmic strings in bimetric theory

P. K. Sahoo, and B. Mishra

The field equations for thick domain walls and cosmic strings are solved for plane symmetric space time in Rosen's bimetric theory of gravitation. Various physical and geometrical properties of the models have also been discussed.

References

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W3 (T): Quantum Gravity and Early Universe

Hiromi Saida
Daido University, Takiharu-cho 10 – 3, Minami-ku, Nagoya 457 – 8530, Japan.
saida@daido-it.ac.jp

Universal property of quantum gravity implied by uniqueness theorem of Bekenstein-Hawking entropy

Contents are made of three steps. First, the speaker shows the uniqueness theorem of Bekenstein-Hawking entropy. Proof is constructed in the framework of axiomatic thermodynamics, without using any existing model of quantum gravity. Second, he clarifies the intrinsic property of Hilbert space of ordinary quantum mechanics, which justifies the Boltzmann formula so as to give "unique" entropy. This property is the central basis for the consistency of quantum statistical

mechanics with ordinary thermodynamics. Third, combine the steps: Suppose that BH entropy, which is unique shown in step 1, is given by Boltzmann formula. This implies that the property of quantum mechanics shown in step 2 is shared by the underlying quantum gravity. From this, we find the suggestion that the potential of gravitational interaction, at short length scale such as Planck scale, is bounded below. Furthermore, under some physical requirement, the gravity at Planck length becomes repulsive, in order to let the thermal equilibrium of black hole can exist under a suitable setting. This suggestion on underlying quantum gravity is universal in the sense that no existing model of quantum gravity is used in all the above discussions.

Reference

Feature paper invited by J. Bekenstein to special issue "BH Thermodynamics" in the journal "Entropy".

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W3 (T): Quantum Gravity and Early Universe

Mairi Sakellariadou
Department of Physics, King's College, University of London, Strand, London WC2R 2LS, UK.
Mairi.Sakellariadou@kcl.ac.uk

Non-commutative spectral geometry

In the first part, the speaker will present the phenomenological and cosmological consequences , while in the second one, issues like the quantization of the theory and relation between doubling the algebra and gauge theories will be discussed.

References

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W3 (T): Quantum Gravity and Early Universe

S. Shankaranarayanan
Indian Institute of Science Education and Research, CET Campus, Thiruvananthapuram 695016, India.
shanki@iisertvm.ac.in

Entanglement entropy in all dimensions

S. Shankaranarayanan, Samuel Braunstein, and Saurya Das

Hawking radiation and Bekenstein-Hawking entropy are the two robust predictions of a yet unknown quantum theory of gravity. Any theory, which fails to reproduce these predictions is certainly incorrect. However, a clear understanding of the microscopic degrees of freedom giving rise to this entropy is still lacking. It is important to explore all possible avenues. One proposal, which stands out for its simplicity and generality is entanglement entropy. In this talk, we show that the entanglement of modes across the horizon in higher dimensions is proportional to higher dimensional area. We also discuss generic subleading corrections that lead to in all dimensions. We examine implications of our results.

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W3 (P): Quantum Gravity and Early Universe

Chandra Prakash Singh
Department of Applied Mathematics, Delhi Technological University, Bawana Road, Delhi 110042, India.
cpsphd@rediffmail.com

Viscous FRW model with particle creation in the early universe

We discuss the dynamical effects of bulk viscosity and particle creation on the early evolution of the Friedmann-Robertson-Walker model in the framework of open thermodynamical systems. We consider cosmological model with bulk viscosity and particle creation as separate irreversible processes. Exact solution of the Einstein field equations are obtained by using the “gamma-law” equation of state $p = (\gamma - 1)\rho$, where the adiabatic parameter γ varies with scale factor of the metric. We consider the cosmological model to study the evolution of the universe as it goes from an inflationary phase to a radiation-dominated era in the presence of bulk viscosity and particle creation. Analytical solutions are obtained for particle number density and entropy for all models. It is seen that, by choosing appropriate

functions for particle creation and bulk viscous coefficient, the models exhibit singular and non-singular beginnings.

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W3 (P): Quantum Gravity and Early Universe

Navin Sivanandam
Theory Group, The University of Texas at Austin, University Station, C1608, Austin, TX 78712 – 0269, USA.
navin.sivanandam@gmail.com

Adiabaticity and non-Gaussianity

Joel Meyers, and Navin Sivanandam

Extending the analysis of [1011.4934] beyond the bispectrum, we explore the superhorizon generation of local non-Gaussianities and their subsequent approach to adiabaticity. Working with a class of two field models of inflation with potentials amenable to treatment with the δN formalism, we find that, as is the case for f_{NL}^{local}, the local trispectrum parameters τ_{NL} and g_{NL} are exponentially damped toward values which are slow roll suppressed if the fluctuations are driven into an adiabatic mode by a phase of effectively single field inflation. We argue that general considerations should ensure that a similar suppression will hold for the local forms of higher point correlations as well.

References

1. arXiv:1011.4934.
2. arXiv:1104.5238, and work in progress.

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Sanasam Surendra Singh
Department of Mathematics, Manipur University, Canchipur, Imphal 795003, India.
ssuren_mu@rediffmail.com

Particle creation in cosmology with varying speed of light

N. Ibotombi Singh, and S. Surendra Singh

We investigate the behaviour of the particle creation in the Einstein's field equations with a variable speed of light and variable energy density in the context of open thermodynamical systems, where the particle creation gives rise to a supplementary negative creation pressure in addition to the thermodynamic pressure. The dynamical behaviour of the cosmological models has been investigated.

References

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Sumati Surya
Raman Research Institute, Sir C.V. Raman Avenue, Sadashiva Nagar, Bangalore 560080, India.
ssurya@rri.res.in

Markov chains with causal sets

Sumati Surya, David Rideout, Rafael Sorkin, and Joe Henson

We present evidence for a phase transition in a model of 2D causal set quantum gravity, which is characterised by a dimensionless non-locality parameter. The transition is between a continuum phase and a crystalline phase, characterised by a set of covariant observables. For a fixed size of the causal set, the transition temperature decreases monotonically with the non-locality parameter. Plotted as a function of the critical temperature v/s the non-locality parameter, the line of phase

transitions asymptotes to the infinite temperature axis, suggesting that the continuum phase survives the analytic continuation. We discuss the implications of these results for 2D quantum gravity.

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W3 (T): Quantum Gravity and Early Universe

Rakesh Tibrewala
Institute of Mathematical Sciences, CIT Campus, Taramani, Chennai 600113, India.
rtibs@imsc.res.in

Modified constraint algebra in LQG and spacetime interpretation?

Classically, in the Hamiltonian formulation of general relativity, the constraint algebra, which generates gauge transformations, is equivalent to spacetime covariance. Quantum gravity effects can modify the constraints, leading to a modified constraint algebra. Requirement that the algebra be closed, restricts the possible corrections of the constraints. In LQG, inverse triad corrections lead to an effective Hamiltonian constraint, which can lead to a modified constraint algebra. It, then, becomes important to ask whether the constraint algebra still corresponds to spacetime diffeomorphism. We provide examples to show that, in the context of spherically symmetric spacetimes, with modified algebra, such a correspondence does not hold. In such a scenario, the notion of black hole horizon, which is based on spacetime notions, also needs to be reconsidered. We provide a possible modification to the classical horizon condition, which leads to consistent results. We also provide example for the case, where the inverse triad corrections do not modify the constraint algebra such that a spacetime picture is valid, and which leads to a mass threshold for black holes and small corrections to Hawking temperature.

Reference

Martin Bojowald, George M. Paily, Juan D. Reyes, and Rakesh Tibrewala, arXiv:1105.1340.

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Madhavan Varadarajan
Raman Research Institute, Sir C.V. Raman Avenue, Sadashiva Nagar, Bangalore 560080, India.
madhavan@rri.res.in

The diffeomorphism constraint operator in loop quantum gravity

A. Laddha, and M. Varadarajan

We construct the smeared diffeomorphism constraint operator at finite triangulation from the basic holonomy- flux operators of loop quantum gravity (LQG), evaluate its continuum limit on the Lewandowski- Marolf habitat, and show that the action of the continuum operator provides an anomaly free representation of the Lie algebra of diffeomorphisms of the 3- manifold. Our work provides the first hints in LQG of a conceptual similarity with the so called "mu- bar" scheme of loop quantum cosmology. We expect our work to be of use in the construction of an anomaly free quantum dynamics for LQG.

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Cenalo Vaz
Department of Physics, University of Cincinnati, Cincinnati, OH 45242, USA.
Cenalo.Vaz@uc.edu

Quantum gravitational collapse

Quantum effects are widely expected to play an important role in describing black holes and naked singularities, and more generally in determining the outcome of gravitational collapse during its final stages. We will outline a canonical quantization of the LeMaitre-Tolman-Bondi models, which describe the collapse of inhomogeneous, non-rotating dust. Although, there are many models of gravitational collapse, this particular class of models stands out for its simplicity, and the fact that both black holes and naked singularity end states may be realized on the classical level, depending on the initial conditions. We solve the Wheeler-DeWitt equation exactly after regularization on a spatial lattice, and discuss some consequences of the quantization. The solutions describe Hawking radiation, and provide an elegant microcanonical description of black hole entropy, but they also

raise some very interesting questions concerning the nature of gravity's fundamental degrees of freedom.

References

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W3 (T): Quantum Gravity and Early Universe

Francesca Vidotto
Centre de Physique Theorique (CPT), Case 907, Luminy, F – 13288 Marseille EU, France.
vidotto@cpt.univ-mrs.fr

Spinfoam cosmology

In loop quantum gravity, it is possible to compute transition amplitudes between cosmological states. In the semiclassical limit, these have been proved to lead to Friedmann dynamics, also for non-trivial case, such as De Sitter space. The speaker will review this approach to cosmology, discussing opportunities, and open issues.

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W3 (T): Quantum Gravity and Early Universe

Alexander Vikman
University of Geneva, Switzerland.
alexander.vikman@cern.ch

Non-canonical scalar field theories with kinetic gravity braiding

We present a standard hydrodynamical description for non-canonical scalar field theories with kinetic gravity braiding. In particular, this picture applies to the simplest Galileons and k-essence. The fluid variables not only have a clear physical meaning, but also drastically simplify the analysis of the system. The fluid carries charges corresponding to shifts in field space. This shift-charge current contains a spatial part responsible for diffusion of the charges. Moreover, in the incompressible limit, the equation of motion becomes the standard diffusion equation. The fluid is indeed imperfect because the energy flows neither along the field gradient nor along the shift current. The fluid has zero vorticity, and is not dissipative: there is no entropy production, the energy-momentum is exactly conserved, the temperature vanishes and there is no shear viscosity. Still, in an expansion around a perfect fluid, one can identify terms which correct the pressure in the manner of bulk viscosity. We conclude by formulating the non-trivial conditions for the thermodynamic equilibrium of this imperfect fluid.

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W3 (T): Quantum Gravity and Early Universe

Moslem Zarei
Department of Physics, Isfahan University of Technology, Isfahan 84156 – 83111, Iran.
m.zarei@cc.iut.ac.ir

Gauge vector fields at the preheating stage

We consider a model of inflation with U(1) gauge fields and charged scalar with a time-dependent gauge kinetic coupling. We study the preheating at the end of inflation with a symmetry breaking potential. It is assumed that inflaton is decaying to relativistic components, and there is also a transport coefficient including the electric conductivity, which modifies the dynamics of gauge field. Then using the continuity equation of such multi-component system, we drive the equation of motion of inflaton and gauge fields. For the case of symmetry breaking potential,

we numerically study the evolution of fluids and then the behaviour of equation of state of system. We also consider an inflation model with vector and scalar inflaton fields. We show that in the presence of vector fields, inflation is stopped for a moment and then is driven. This phenomenon during inflation is investigated by CMB data analysis.

Reference

R. Emami, H. Firouzjahi, S. M. Sadegh Movahed, and M. Zarei, JCAP. **1102**, 005 (2011), arXiv:1010.5495v2 [astro-ph.CO].

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Mini-Sessions

I. Gravity as an Emergent Phenomenon
Coordinator: T. Padmanabhan

Recent research suggests that gravity could be an emergent phenomenon like elasticity or fluid mechanics. Such an idea is fairly old – possibly dating back to Sakharov – and different researchers have tried to interpret, and implement this idea in different ways. This mini-session will examine the evidence for such a paradigm, some of the approaches, their current status and open issues. It will consist of a few short presentations with some time made available for open discussion.

Speakers

Rong-Gen Cai

Shiraz Minwalla

T. Padmanabhan

Rafael Sorkin

Kip Thorne

II. Dark Energy
Coordinator: Varun Sahni

The Dark Energy session will focus on observational and theoretical aspects of an accelerating cosmology. It will cover future surveys including DES, non-Einsteinian approaches to cosmic acceleration and the affect of inhomogeneities on cosmological inferences of dark energy. It will also include an open discussion on various aspects of the accelerating Universe and dark energy.

Speakers

Marie-Noelle Celerier

Joshua Frieman

Eric Linder

III. Gravitational Wave Astronomy
Coordinator: B.S. Sathyaprakash

Gravitational wave detectors have quadrupolar antenna patterns with a wide sky coverage. Even a single detector would be sensitive to a third of the sky, but their ability to resolve a transient source is very poor. A global network of three or more detectors is essential to fully reconstruct the incident radiation and extract the best possible science. Since the current network of two detectors (LIGO) in the US, two in Europe (Virgo and GEO600) and Japan (LCGT) are roughly coplanar and don't fully exploit the global baseline that could, in principle, significantly improve the measurement of the source's parameters. The mini session will discuss the advantages of extending the global network, in particular of building a detector in India or Australia with regard to improvements in the angular resolution of the network, enhanced accuracy in the estimation of the source's distance, polarization of the waves, and the inclination of the binary with respect to the line of sight.

Speakers

Stephen Fairhurst

Sergey Klimenko

Chris Van Den Broeck

Evening Lectures

Abhay Ashtekar
IGPG, USA. (ashtekar@gravity.psu.edu)

The big bang and the quantum

Jayant V. Narlikar
IUCAA, India. (jvn@iucaa.ernet.in)

ICGC – 87: As I see today

C. V. Vishveshwara
Bangalore, India. (saruvishu@gmail.com)

ICGCs – A cartoon chronicle