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MATHEMATICS FOR THE PEOPLE, A CONVERSATION WITH MICHAEL JORDAN

Michael I. Jordan is Pehong Chen Distinguished Professor in the Department of Electrical Engineering and Computer Science and the Department of Statistics at the University of California, Berkeley. He has made foundational contributions in several fields, such as cognitive science, machine learning, and computer science. Prof. Jordan spoke to Debdutta Paul on his recent visit to ICTS-TIFR.

Here are excerpts:

What is machine learning or artificial intelligence about as a subject?

Well, it's really just this blend of statistics and computer science. In my recent career I also bring in economics — it's kind of a part of it. How do you connect producers, consumers, or people who have something to offer others? So, machine learning is, in some sense, not new. It's statistical principles about how I take

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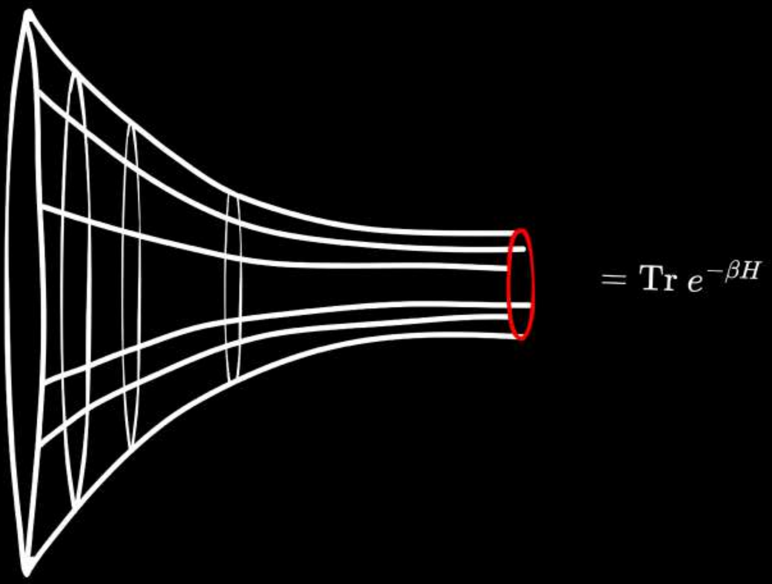

NEW INSIGHTS ON EXTREMAL BLACK HOLES FROM JT GRAVITY

GUSTAVO J. TURIACI

Black Holes and Quantum Gravity

General relativity and quantum mechanics are the most successful theories describing the real world, each verified in very different regimes. Put together, the two theories seem incompatible. Two physical phenomena arise for which reconciling these theories is crucial. The first is the big bang. The second concerns black holes, the topic of this article.

A general result from string theory, the leading example of a theory of quantum gravity, is that a black hole behaves as a quantum system from the point of view of an observer that remains outside of it. This conjecture is behind the developments of holography and AdS/CFT dualities [1-3], which have been extensively tested in the past decades. Assuming that black holes in our world are described by quantum systems, it is indispensable to investigate the rules of quantizing gravity necessary to reproduce such behavior.

A first observation is the success of the 'gravitational path integral' (GPI) pioneered by Gibbons and Hawking [4]. According to this proposal, we first analyze the region exterior to the black hole where gravity is weak and decide which observable we want to study. An example is the black hole thermal partition function or the time dependence of correlation functions between probes sent to the black hole. This choice determines a boundary condition far from the black hole, and one then integrates over all smooth spacetimes and matter configurations near the black hole consistent with the given boundary conditions.

In quantum mechanics the path integral is equivalent to the Hilbert space approach. In gravity this is not so trivial: there are multiple situations where the GPI is in apparent tension with the interpretation of the black hole as a quantum system with discrete microstates. Upon closer inspection, most of these discrepancies are removed by a more complete evaluation of the GPI. In this article we will explain one example concerning near-extremal black holes, understood thanks to developments in Jackiw-Teitelboim (JT) gravity [5-7] which is amenable to quantization.

Extremal Black Holes

In asymptotically flat four spacetime dimensions, black hole geometries are described by only a few measurable parameters: the mass M, the angular momentum $\vec{J}$ and the charge Q[1]. This is the 'no-hair theorem' of black holes. But these parameters are not all independent from each other. For a given value of $J = |\vec{J}|$ and Q, there is a minimal possible mass, the 'extremal mass' $M_{\text{ext}}(Q, J)$ such that[2]

$$M \geq M_{\text{ext}}(J, Q) = \begin{cases} \frac{|Q|}{\sqrt{G_N}}, & \text{For } J = 0. \\ \\ \sqrt{\frac{cJ}{G_N}}, & \text{For } Q = 0. \end{cases} \qquad [2.1]$$

A black hole saturating this bound is called *extremal*, and black holes that are close to saturating it are *near-extremal*. As we tune the mass of the black hole below M_{ext}, the event horizon disappears leaving behind a naked singularity. This could hardly be called a black hole, and the singularity would represent a lack of predictability of the theory, thus ruling out all solutions with $M < M_{\text{ext}}$ as unphysical. The conjecture that all singularities are protected by event horizon is the 'cosmic censorship conjecture.'

Black holes have few isometries (meaning transformations that leave the geometry invariant). For generic values of $(M, Q, \vec{J})$ they correspond to time translations and rotations around the $\vec{J}$ axis. The first reason that near-extremal black holes are interesting is that a powerful new symmetry emerges near the horizon: scale invariance. Extremal black holes develop a long throat near the horizon corresponding to 2d Anti-de Sitter space along the time and radial directions, AdS_2, fibered over the angular directions, see Fig. 1. AdS_2 is special since it is invariant under simultaneous rescalings of the time and radial coordinate. This isometry is actually enhanced to the full conformal group $\mathrm{SL}(2, \mathbb{R})$. Several aspects of the dynamics of near-extremal black holes are controlled by this emergent symmetry, which is softly broken close to extremality.

The second reason near-extremal black holes are special is the following. To make the conjecture that black holes are quantum systems precise, we need to separate a spacetime region that we identify with the black hole quantum system from the environment. This separation becomes the sharpest near extremality - the black hole quantum system describes the AdS_2 throat.

A final reason concerns Hawking radiation [8]. Black holes are thermal objects and radiate at a temperature T that depends on M, Q and J in a known way. In the near-extremal limit the temperature is low and vanishes at extremality. Therefore, while generic black holes evaporate, near-extremal ones do so very slowly. (Of course, other effects might also lead to instabilities such as superradiance or Schwinger pair production near the horizon that produce a discharge of the black hole.) These features make an understanding of black hole microstates in this regime more likely.

Two Puzzles

Near-extremal black holes are quite subtle. We shall describe two puzzles about them which were raised long time ago, but only recently addressed.

First, extremal black holes have the minimal possible mass given (Q, J), and have zero temperature. They would therefore correspond to the ground state(s) of the putative quantum system describing them. Another property characterizing them is their large entropy! The Bekenstein-Hawking entropy, as derived from a classical analysis of the gravitational path integral, is proportional to the area A of the event horizon measured in units of the Planck length $\ell_{\text{Pl}} = \sqrt{G_N \hbar / c^3}$. This is a very large quantity for macroscopic objects such as a black hole. At extremality even though $T = 0$ the area of the event horizon remains large

$$S_{\text{ext}} = k_B \, \frac{A_{\text{ext}}}{4\ell_{\text{Pl}}^2} = k_B \, \frac{\pi\sqrt{Q^4 + 4c^2 J^2}}{c\hbar}. \qquad [3.1]$$

For illustration, an extremal black hole with the same spin-to-mass-ratio as M87 has $S_{\text{ext}}/k_B \sim 10^{70}$. Such a large zero-temperature entropy violates Nernst's third law of thermodynamics. In one of its formulations, this law claims that the entropy of a system must vanish in the zero temperature limit. This is not a theorem, but a phenomenological observation: the statistical mechanics interpretation of the entropy at zero temperature is as a ground state degeneracy which in the absence of any symmetry is expected to be small. According to classical black hole thermodynamics, the quantum system that describes a near-extremal black hole has an extensive number of ground states, with respect to the number of

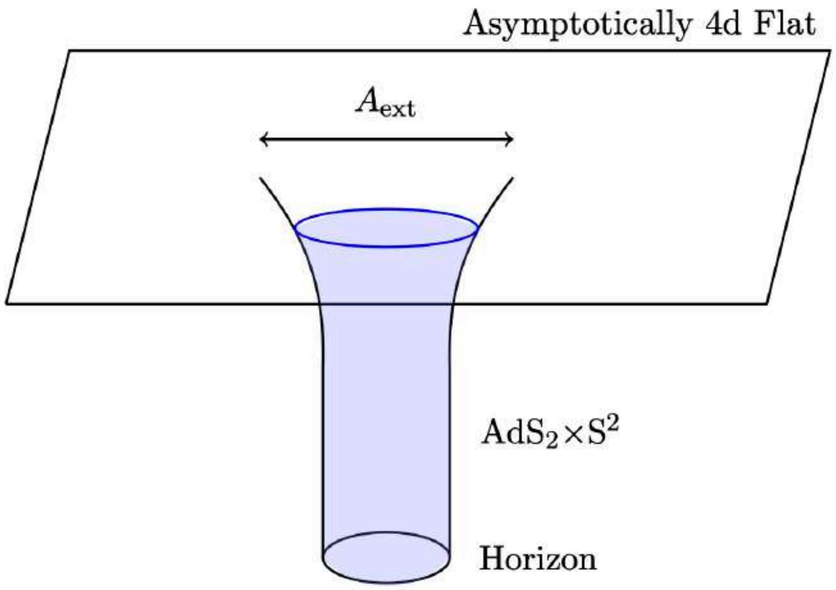

Figure 1: Spatial geometry of a near-extremal black hole. The throat is shown in blue. At the bottom of the $AdS_2 \times S^2$ throat (shaded region) is the event horizon. The dynamics in this region is described by Jackiw-Teitelboim gravity coupled to matter. Exterior to the blue line is the asymptotically flat spacetime.

1: We work in units where the Coulomb force between two charges at a distance d is $F = Q^2/d^2$. 2: The extremal mass for arbitrary charges is more complicated and not particularly enlightening $M_{\text{ext}}(J, Q) = \frac{\sqrt{2}cJ}{\sqrt{G_N}\sqrt{\sqrt{Q^4+4c^2J^2}-Q^2}}$

degrees of freedom $N \sim O(S_{\text{ext}})$, and therefore violates the third law without any good reason. This issue was emphasized by Page [9].

The second puzzle was first raised by Preskill, Schwarz, Shapere, Trivedi and Wilczek in 1991 [10], and further elaborated by Maldacena, Michelson and Strominger in 1998 [11]. The thermal treatment of the black hole is appropriate if the emission of a typical quantum of radiation does not change the temperature by a substantial amount. Preskill *et al*. realized this property is lost for near-extremal black holes when the temperature becomes low enough. The temperature change upon emission of a Hawking quanta is given by

$$\frac{\delta T}{T} = \frac{k_B}{c^2} \left| \left(\frac{\partial T}{\partial M} \right)_{Q,J} \right|, \qquad [3.2]$$

When the right-hand-side becomes order one, the thermal description breaks down. This happens for temperatures lower than[3]

$$T_{\text{breakdown}} = \frac{\pi c^3 \hbar}{G_N M_{\text{ext}}} \frac{1}{S_{\text{ext}}} = \frac{\pi \hbar^2}{\ell_{\text{Pl}}^2 M_{\text{ext}}} \frac{1}{S_{\text{ext}}}. \qquad [3.3]$$

For macroscopic black holes, this is extremely small $T_{\text{breakdown}} \sim O(1/S_{\text{ext}})$. For a black hole with the same spin-to-mass-ratio as M87 it is of order $T_{\text{breakdown}} \sim 10^{-120} K$. Examples from string theory suggested that there is a gap of order $E_{\text{breakdown}} = k_B T_{\text{breakdown}}$ in the energy spectrum of near-extremal black holes, although there was no calculation in gravity supporting this claim. This gap would be too large, power-law suppressed in the entropy, while for a chaotic system such as the black hole spectrum, gaps are expected to be exponentially small in S_{ext}. What would cause such a large gap?

Both puzzles are resolved when we take the gravitational path integral seriously. When evaluating it, there are certain gravitational modes that become very light at low temperatures. Their quantum fluctuations therefore cannot be ignored and the classical picture that lead to these two puzzles is strongly modified. This was realized recently thanks to developments in Jackiw-Teitelboim gravity, which we explain next.

Jackiw-Teitelboim Gravity: A Resolution

The geometry of near-extremal black holes develops a long throat described by an AdS_2 space fibered over the angular coordinates of S^2. As an illustration, if one wants to study scattering of a probe off the black hole, it is natural to treat the throat and the exterior region separately. In the exterior region the probe is far from the black hole and gravity is weak. When the probe reaches the throat, the interaction with the black hole is important and the AdS_2 description becomes useful. The dynamics of gravity and matter on $AdS_2 \times S^2$ can be conveniently described as a 2d theory on AdS_2 as follows (see for example [12-14])

- **JT gravity:** This is a 2d theory of dilaton-gravity that describes the dynamics of spherically symmetric fluctuations of the AdS_2 metric, and spherically symmetric fluctuations of the total area of the transverse sphere S^2. From the 2d point of view, the latter mode is a scalar field called the 'dilaton.'
- **2d Matter:** There are two types of 2d matter fields that arise from the higher-dimensional theory. The first corresponds to spherically symmetric modes of light matter that were already present in four dimensions. The second corresponds to modes with non-trivial angular dependence coming either from higher dimensional light matter or from the higher dimensional metric itself. In 2d both sets of fields are described in the same way.

The matter content that appears in 2d can be quite complicated. Since the size of the sphere $S^2$is of the same order of magnitude as the size ofAdS_2, modes with non-trivial angular dependence cannot be integrated out since they are not heavy - we are left in 2d with a large number of light fields. The simplification instead arises because interactions between JT gravity and light matter become very simple[4] and even solvable [15-17]!

A non-trivial fact understood only recently (thanks to developments in condensed matter systems such as the Sachdev-Ye-Kitaev models [18] is that JT gravity has two coupling constant that should be considered independent. The first is G_N which is the obvious one: gravity is weak when Newton's constant G_N is small. The second one is the temperature itself [19-22]. Quantum effects become large when the temperature is low and small when the temperature is high. The transition derived from the JT gravity description of the higher dimensional black hole is at precisely the same scale $T_{\text{breakdown}}$ identified by Preskill *et al*.

Intuitively, quantum effects captured by JT gravity arise from a mode that become light at extremality: time-dependent fluctuations of the length of the throat. As the temperature is lowered quantum fluctuations are less and less suppressed. Besides characterizing this mode, recent developments in JT gravity explain how to quantize it exactly! This is true even in the presence of matter. We illustrate this for $J = 0$. The quantum-corrected near-extremal entropy (for $k_B T \ll \hbar c / \sqrt{A_{\text{ext}}}$) becomes [23-27].

$$\frac{S(T)}{k_B} \approx \underbrace{\frac{A_{\text{ext}}}{4\ell_{\text{Pl}}^2} + \frac{4\pi^2 T}{T_{\text{breakdown}}}}_{\text{Classical Bekenstein-Hawking entropy}}$$
$$+ \underbrace{\underbrace{\left(\frac{-n_S - 62 n_V - 11 n_F - 964}{180} \right)}_{= c_{\log}} \log \left(\frac{A_{\text{ext}}}{4\ell_{\text{Pl}}^2} \right) + \underbrace{\frac{3}{2} \log \left(\frac{T}{T_{\text{breakdown}}} \right)}_{\text{JT mode}}}_{\text{Quantum Corrections}} \qquad [4.1]$$

The first two terms come from classical gravity. The last two arise from quantum corrections to the GPI. The temperature-independent correction gets contributions from all fields and depends on the number of 4d light scalars n_S, vectors n_V, and Dirac fermions n_F.Its evaluation was pioneered by Sen [28-29]. Importantly, the last term is the only temperature-dependent quantum correction and comes from JT gravity alone making it universal.

These considerations address the puzzle raised by Preskill *et al*.: regardless of how small G_N is, when the temperature is low enough the quantum effects from the JT mode will be unavoidably large. When $T \lesssim T_{\text{breakdown}}$, the log-T correction dominates over the classical linear-in-Tcontribution. Since quantum corrections are large, the classical analysis is no longer applicable. This also addresses the first puzzle. The quantum-corrected entropy becomes order one for $T \sim T_{\text{breakdown}} \exp\left(-\frac{A_{\text{ext}}}{4\ell_{\text{Pl}}^2}\right)$. At such ultra-low

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[3] For now, the order one coefficient in $T_{\text{breakdown}}$ is arbitrary.

[4] In more detail, the matter couples minimally to the 2d metric but to leading order does not couple to the dilaton. This simplification is crucial.

temperatures other non-perturbative corrections can compete with the black hole and the actual ground state can be quite complicated. The important conclusions are that (i) the prediction from gravity is consistent with an order one number of ground states and (ii) the ground state is not at all described by an extremal black hole since the classical description is completely lost.

In the real world the electron exists with a small enough mass-to-charge-ratio which allows charged extremal black holes to decay. This effect should then be included in the GPI as well as the quantum effects we focused on. As emphasized by the 'weak gravity conjecture' [30] this implies that there is no truly stable ground state of a charged black hole.

It is instructive to present the density of black hole microstates, shown in Fig. 2A. In terms of the energy above extremality $E = Mc^2 - M_{\text{ext}}c^2$, the density of states $\rho(E)$, defined through the partition function by $Z(T) = \int dE\, \rho(E)\, e^{-\frac{E}{k_B T}}$, is given by

[4.2]

$$\rho(E) \approx e^{\frac{A_{\text{ext}}}{4\ell_{\text{Pl}}^2} + c_{\log} \log(\frac{A_{\text{ext}}}{4\ell_{\text{Pl}}^2})} (E_{\text{breakdown}})^{-1} \sinh\left(\sqrt{\frac{8\pi^2 E}{E_{\text{breakdown}}}}\right)$$

$$\approx e^{\frac{A_{\text{ext}}}{4\ell_{\text{Pl}}^2} + c_{\log} \log(\frac{A_{\text{ext}}}{4\ell_{\text{Pl}}^2})} (E_{\text{breakdown}})^{-1} \times \begin{cases} e^{\sqrt{\frac{8\pi^2 E}{E_{\text{breakdown}}}}}, & E \gg E_{\text{breakdown}} \\ \sqrt{\frac{8\pi^2 E}{E_{\text{breakdown}}}}, & E \ll E_{\text{breakdown}} \end{cases}$$

[4.3]

While for $E \gg E_{\text{breakdown}}$ the density of states grows exponentially with energy, consistent with the classical Bekenstein-Hawking entropy, the density of states vanishes at extremality. At energies $E \sim E_{\text{breakdown}} \exp\left(-\frac{A_{\text{ext}}}{4\ell_{\text{Pl}}^2}\right)$ non-perturbative corrections are expected.

The conclusions are universal and only depend on the pattern of symmetry breaking of a near-extremal black hole. The JT mode is equivalent to the Schwarzian theory, the Goldstone mode that arises from the breaking of conformal invariance by finite temperature effects. We expect this near-extremal spectrum to be valid in full generality, although A_{ext} and $T_{\text{breakdown}}$ can depend on the model. This mode also controls quantum corrections to matter correlators and the dynamics.

String theory has provided several examples of specific black holes and their quantum systems, in the context of supergravity. When the extremal black hole preserves supersymmetry we can count microstates and compare with the S_{ext}, an approach initiated by Strominger and Vafa in 1996 [31] see also the review [32]. In asymptotically flat 4d supergravity, this occurs when $J = 0$. This raises two questions that were never addressed until now: Why should we trust the classical formula for the entropy at extremality? Can we reliably identify a Hilbert space of extremal black holes if gaps between states are not visible semiclassically? Again, we resort to the GPI and the JT gravity formulation. When supersymmetry is present at extremality, new fermionic light modes that modify the quantum corrections to the spectrum appear. JT gravity is generalized to JT supergravity and the result [33] is shown in Fig. 2 (b). While the gravity theory is only changed by the inclusion of fermions, the quantum corrected spectrum is now completely different! There is a gap given, to leading order in small G_N expansion, by

[4.4]

$$E_{\text{gap}} = \tfrac{1}{8} E_{\text{breakdown}}(J=0) = \frac{c^4\hbar^2}{8G_N^{1/2}|Q|^3}$$

and the large ground state degeneracy now survives

[4.5]

$$\frac{S(T)}{k_B} \approx \frac{\pi Q^2}{c\hbar} + c_{\log} \log\left(\frac{\pi Q^2}{c\hbar}\right) + O(1) + O(e^{-E_{\text{gap}}/k_B T})$$

(This does not violate the third law since the degeneracy is protected by supersymmetry.) The first line contains temperature independent corrections to the ground state entropy while the second line the leading temperature-dependent correction. Extremal black holes therefore do exist, only when supersymmetric. It is still an open question to elucidate the gravitational description of these supersymmetric black hole microstates. As an example, surprisingly, in some cases the GPI when combined with supersymmetric localization reproduces exactly the ground state entropy [34-36] and not only the large charge limit implicit in eqn. (4.5)

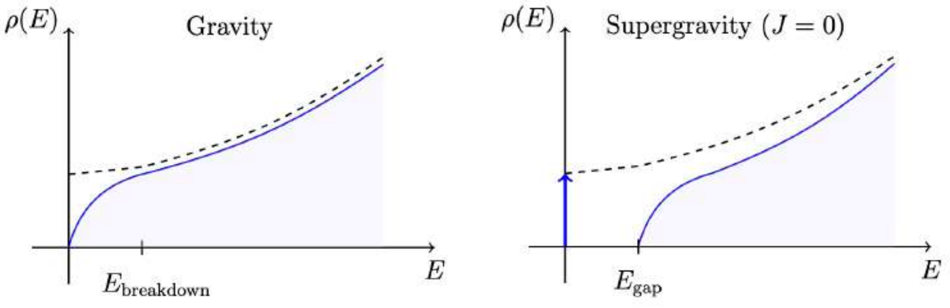

Figure 2: (a) Density of states for a near-extremal black hole with fixed Q and J, as a function of $E = (M - M_{\text{ext}})c^2$. The dashed line is the classical prediction from gravity. The blue line is the quantum corrected one which strongly deviates from the dashed line as extremality is approached. There is no gap visible in this approximation, and extremal black holes disappear. This spectrum also qualitatively applies to supergravity when $J \neq 0$. (b) In supergravity, if the extremal limit preserve some supersymmetries (which happens when $J = 0$) the quantum corrected spectrum displays a gap and the extremal black holes survive with their large classical entropy S_{ext}, justifying microstate counting in string theory.

To conclude, JT gravity played a crucial role in uncovering the correct spectrum of near-extremal black holes. It has also provided a fruitful solvable model of quantum gravity that has clarified various quantum aspects of black hole physics such as quantum chaos, the relation with random matrix models, and the evaluation of the entropy of Hawking radiation for an evaporating black hole.

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Gustavo J. Turiaci is a postdoctoral fellow at the Institute for Advanced Study, Princeton.

BETWEEN THE SCIENCE

SUBHRO BHATTACHARJEE and MANAS KULKARNI have been selected for the Indian National Science Academy (INSA) Medal for Young Scientists 2022.

RAJESH GOPAKUMAR's publication (in collaboration with Lorenz Eberhardt and Mathias Gaberdiel) titled, "The Worldsheet Dual of the Symmetric Product CFT," received the 2023 ICBS Frontiers of Science Award.

RAMA GOVINDARAJAN was awarded the Archana Sharma Memorial Lecture Award 2022 by the National Academy of Sciences, India (NASI), in recognition of her distinguished contributions to science.

ICTS graduate student BHANU KIRAN was selected for an Institut Henri Poincaré (IHP)-Centre International de Mathématiques Pures et Appliquées (CIMPA) fellowship.

PRAYUSH KUMAR was awarded the NASI Young Scientist Platinum Jubilee Award for 2022.

STHITADHI ROY has been awarded a new Max Planck Partner Group. Sthitadhi will head this partnership with his counterpart Roderich Moessner from MPIKS, Dresden.

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MATHEMATICS FOR THE PEOPLE, A CONVERSATION WITH MICHAEL JORDAN

Michael I. Jordan at ICTS-TIFR. Photo credit: Harsh Kumar Khatwani

partial knowledge about the world and try to infer what's out there like a scientist would do. These are complementary fields. Computer science has been more about how you programme a computer, how you ensure it works. How does it follow certain algorithmic steps and do things? I was more concerned about the internal world of the computers, that everything was correct and right inside. And statistics is more about the outside world: What's happening in the outside world? How do I gather evidence about that and try to make decisions about that? You glue the two together, and that's a powerful combination. In some sense, that is really what machine learning is. But it's also a little bit more of an engineering field. Because statistics focus mostly on scientific inference and trying to help scientists discover things. The Higgs-Boson discovery, for example, use statistics to decide if you *did* discover it or not. And machine learning has a little bit more of a computer science and engineering flavour. How do we build systems that automatically analyse data in various domains [to] help us make our own decisions? Also, things like automatic self-driving cars will use machine learning, and they try to figure out what's in the world with statistics. And but they do it rapidly and, and do it on a very large scale. So it's more of an engineering system and less of a science system.

Can you tell us about one problem that excites you now?

Yeah, sure. As I alluded to earlier, whilst historically machine learning has been about statistics and computer science together [with] algorithms that make statistical inference, I've been more interested recently in economic models being brought to bear and being part of that whole story. So why economics? Well, when you think about where data comes from, who it benefits, and how it is used, you really want to think about a big network. You know, companies collect large amounts of data, often collect them from cell phones or from other sources that individual people have produced. So that's more like a market. You want to think about the people being agents and main players in that — they should opt-in, they should decide they want to participate. Any contribution they make with their data, which might be something they write or create, should be valued and part of the opt-in process. So there are ideas in economics that definitely talk that kind of language. One such idea I'm interested in right now is something called contract theory or principal-agent model, where there's one entity, maybe a human, maybe not, maybe an organisation that wants to accomplish some task. There's some other entity and agent that has more knowledge about how to achieve that task. And they kind of want to cooperate. The principal's got to incentivise the agent, who only accepts if it's in their interest. If you now think about data in this world, the principal wants to incentivise the agent to provide data. So their data becomes an economic good. And people, in fact, often create data at great expense, or based on their knowledge, and so on. So this model allows the data to be treated as an economic good, traded, aggregated, and used for various purposes. The mathematics is interesting. And the implications, [and] the use cases are really interesting. That's the area I'm most interested in right now.

In your recent Infosys-ICTS Turing lectures, you talked about social intelligence. What are your thoughts on how ML/AI researchers and policymakers perceive 'social intelligence' today?

I didn't really use that word, but it is a nice word. It's a nice phrase, [by which] I mean systems, [let's say] that bring food into Bangalore every day somehow have social intelligence. They are social. People make individual decisions — I'm going to bring tomatoes over here because I've got tomatoes, and you don't. Everybody's making simple local decisions, but the overall effect is that enough food arrives for all the people in the city every day. It's not always efficient, but it's pretty good. That's an intelligent system, and it's a social system. So to be part of what AI should be is to mimic that kind of system. And classical AI didn't think that way. It was more about mimicking the individual human and trying to be as smart as a human. That's a different goal. I like this more social goal. So if you put the two together, the computer is now part of the overall social system, and it knows things, and maybe it's better in some ways than humans in some things but not in other things. Then the overall system could be better and more effective for everybody. But you've got to have it clear that your goal here is to have high social welfare and have the system work for people.

Do you think researchers and policymakers look at it that way, or is there a need for change?

Not enough. I mean, right now, there's too much mystique about machine learning and AI. Some people think it can just sort of solve all the world's problems all by itself. Some people fear it because it feels like it's going to do things that take away things from what humans do. There's a lot of misunderstanding about what it can and can't do, and just not a lot of thoughtfulness about it. It's true that there are certain kinds of things they can do that are going to take away some jobs. There are also, especially in this social intelligence model, new jobs [that] can be created and ways to think about that. And to me, there's not enough discussion about that and to me those are the real problems. It's not really about — Are robots going to take over and kill humans? All that kind of science fiction discussions. To me, it's more interesting and important to think about: Okay, what kind of jobs are at risk? How fast is that going to happen? Are there other kinds of jobs that are going to be created? How can we incentivise that? How can we make sure this is fair? How can we ensure that everybody participates and it's not just a small power set? And there is some discussion about that, but just not enough. You don't see most articles in the newspaper [talking] about those kinds of issues. It's always about the more exotic fears and dreams.

Some scientists fear that this is the time for meta-principles. Science has been conducted through observations, extracting principles or laws from them. Given that we have machine learning now — was that a limitation? Do we really need laws? Or is the concept of science itself being challenged by ML and AI?

I totally disagree. I mean, laws can be local and contextual. I think we're used to laws being, *F equals m-a*, or [the] law of gravitation, that it applies everywhere, for everything. And that was important and beautiful. But there are also laws that only apply to certain ecological niches, or in certain kinds of species, certain kinds of social interactions, or even certain kinds of fluids and certain kinds of physical systems. And maybe they don't have the vast reach and power of *F equals m-a* or [the] law of gravitation. But they're super interesting and exciting to work on. And there are scientific ideas to be discovered there. And observations are needed, and thinking is needed. Thinking about the immune system of a human — how that works. It's very rich and complicated. And there are principles required to understand it. It's not some crazy system; it's got principles. So there's lots of science, and it just becomes a little more contextual. And I think that's actually valuable. Studying genomics, for example. Genomics allowed us to see that DNA is composed of lots of genes, and each gene has its role. Instead of just worrying about a big law for all genes, whatever that might mean, you try to think, what does each gene do? How does that gene participate with other genes to make an organism function? So these are all more contextual stories, but they're, to me, just as interesting and powerful and important as the principles that the early physicists and biologists came up with.

And it's still valid to continue making principles and developing principles?

Absolutely, unquestionably. Otherwise, you really can't predict, you can't have a notion of stability, you can't also try to build a system that behaves in a desired way. It's definitely not just the machine that takes over, or we write down a list of things we don't understand. It is about the simplified abstractions that allow us to reason and make some sense of our world.

Coming to the applications of machine learning: ML/AI are used as tools in science. For example, in your talk earlier this week, you mentioned AlphaFold. There's the Event Horizon Telescope, and you mentioned other astronomy projects. What is its role in automating science in the future?

I don't really know. That's a little far beyond my scope of knowledge. The word "automating" — I'm not sure exactly what that means. I mean, I do think that human curiosity is always going to drive things and human insight. That [if] something is important [it] really requires seeing what all the consequences of that are and see what could change, and doing 'What if?' experiments and all. And I think humans will be, for the rest of our lifetimes, at least, really good at that relative to what machines are. So, smart humans will be able to use these machines in new ways — have a bigger scope than they had, just like computers can solve partial differential equations (PDEs) that we can't solve that helped science. Similarly, here, I think it's going to drive innovation, and it's going to drive possibilities we didn't think of, and some part of that will be more automatic, just like the PDE solution was a little more automated, but [it] doesn't mean we're just going to push a button and the computer will solve our science problems for us. I just don't think we're aspiring to that. I don't think it's realistic. I think it'll just allow humans to think a little bit more broadly, and maybe a little more carefully, maybe have their ideas have [a] broader scope. Think a little more about safety issues, fairness issues, and things that weren't on the table.

In this context, what is the future role of scientists? Should they be adaptable to the changes?

I don't think it's that different from when a telescope came. Instead of the role of a scientist walking outside with your eyes and you look at stars, now you build a better telescope, and you think about what more things? Could I measure the infrared? Could I measure this and that? And then the machine helps [you] see things you could have never seen. And you envisage how you could use that in new ways. And I think, conceptually, it's not that different. Yeah, AI is still really subservient to the human. I think that's going to be true for quite some time. The 'automatic scientist is an AI' — I still think that's kind of science fiction. It's not clear why we would do it. Little by little, yes, it'll become a little more automatic. But I think it'll maybe drive us faster to open up new questions that we didn't even think about before. Someone was talking about chess playing. At some point, the computer got better than humans in chess, okay? But that didn't mean that all interest in chess went away. In fact, I think it's been quite the opposite. Humans have seen the computer play. They say, "Well, that's interesting. I never thought about that." And then they think about the consequences. And they try it out, and they get pleasure. And in, it's still a way to help humans grow by playing chess. So just the fact that there exists an entity that could do something automatically doesn't mean humans won't want to do it themselves.

How do we go about training people for the science ecosystem, as well as for the industrial work, the changing job market, especially in a country like India? How do we collectively evolve and adapt to AI for the positive?

I don't think you have to ask me. I think the 20-year-olds will figure that out. Honestly, a 20-year-old still needs to learn mathematics; they need to learn sciences; they need to learn something about humanities; they learn to be an evolved person. They may not have to learn as much programming because these systems can do a lot more programming for you. That's fine. Maybe learning all the details of [the] syntax of a programming language — you could do it, but it's not necessary. Well, they can do other things. When you see a 20-year-old playing around with ChatGPT, they very quickly understand what it can do, what it can't do. They play around with it and get some value from it. And they can learn. And we just have to remind them, that's not the end of the story, that there are other principles to investigate it and use it now to investigate those principles, and think about medicine, and think about commerce, and think about agriculture and all those things. The computer is not going to solve those things for you. But if you are clever at using the computer, you could help contribute to that. So yes, in some ways, it hasn't changed — [you need to] understand mathematics, understand human history, understand biology and physics and all. Mathematics should also include statistics, as I've alluded to. Many previous generations didn't do much statistics, or treated it just as a mathematical exercise. That's just changed. Statistics is very much not just a mathematical exercise; it's really analysing data and making inferences with it. And people need to be more empowered to do that. And think for themselves in the data analyses.

Now that you mention ChatGPT, I have to ask this question. What are your thoughts on this new phenomenon that has taken the world by storm?

I already alluded to it. I mean, because it's human data, we already had a fair amount of clarity that machine learning could make great predictions and things like supply chains or recommendation systems. The backbone of many companies has been machine learning for quite some time now, and they're pretty good. When it became language data, and it's really doing these things that look like only humans could have done that, that's definitely surprising. And the architectures because they can scale. They can take in trillions of pieces of data. It is rather amazing how fluent it can be. But it is also true that you have to build things around it. You can't just take the output of this system as the truth. It doesn't know the truth. So there has to be work around it to build a better-engineered system. Instead of just outputting the name of the Prime Minister of India as x, well, maybe in the data, it was a certain name, and now it's changed! ChatGPT doesn't know that. So instead of having ChatGPT say the name, it might say 'Prime Minister of India', and then you go look it up in a database, and someone maintains the database. So there are systems around ChatGPT that will help it do the right thing, say the right thing, be more context-aware, and so on. So that's like in any engineering field, you take a powerful tool, and you build around it to make it more approachable, more usable, more safe. So ChatGPT itself is fluent but could be dead wrong in many situations. That's not just fixed by having more data. That's fixed also by thinking about what to build around it.

What are your final thoughts on these topics that you engage with — for the general public, for school students interested in the topic, as well as for ICTS researchers?

I would be more excited than fearful right now. It *does* change certain things. An example for a student is the essays that you have to write in high school and college. A teacher who ignores the fact that ChatGPT is good at writing essays will not be a good teacher. They're not going to be helping the student very much. But a teacher who says, "Okay, let's embrace it, it does exist, let a student start with a ChatGPT-generated essay, and show me what they're starting with, and then they help correct it. Tell me what they could do to make it better. And then I'm going to tell them what they could have done. And I'm going to work with them to sort of see that." Because a human-written essay on something that's really written well, we can sort of tell. It communicates in a certain way. There's depth, [and] there's a human experience coming through. So teachers can help with that. They don't have to help as much with all the grammar issues and fluency issues. Just like the calculator helped us not to worry about all the algorithms [with which] we're adding and subtracting. There were some people who said, "That's terrible; it's ruining children's minds." I don't think so. I think that the calculator allowed us to say, "Okay, arithmetic is handled over there. I can now use it in new ways." Similarly, here the essay can be written, it's not too bad, [and] it sounds pretty good. It gets you started. Maybe you think, "Okay, I like that. But I would do it a little bit differently." And again, a teacher can help you with that process. And now you take it and reshape it, and so on. Similarly, for artistic things, it's not that DALL-E or whatever ChatGPT-like image generators are going to take over art. But they're a good starting place. Someone could say, "I want to have a scene with a mountain in the back and a horse in the foreground." It draws, and it comes out looking like that; it's pretty impressive. But the human will rarely just look at it and say, "I'm done." They'll say, "I would like to do this and change this-and-this in this way." And partly, it'll just be going back to ChatGPT and working with it. But that could that'll start to become a very creative act. I can imagine younger people not just being content with just pushing buttons. Good teachers will themselves learn how to do that, [and] they will engage with it. And they will learn this and [the] best practices and things they can teach students. It's going to be a demanding process for teachers to embrace it and not fight it. But rather, it's real, use it, and find new ways to help students engage with it, not be fearful, but also not be intimidated.

Read the full interview at https://blog.icts.res.in/blog/conversation-michael-jordan-mathematics-people

ICTS HOSTS SUMMER SCHOOL FOR WOMEN IN PHYSICS

SUPURNA SINHA

This summer ICTS-TIFR held a Summer School for Women in Physics (SSWP). The School ran along-side a Summer School for Women in Mathematics and Statistics (SSWMS) which enabled the participants of both Schools to interact. The school was held during May 29, 2023 to June 9, 2023. This year the SSWP was a pilot version which was restricted to participants from within Karnataka. We intend to expand the scope of this school to include participants from all over India in 2024. The SSWP was centered around a few demos and experiments. The idea was to get the participants to ask questions based on the observations they made during the course of the demos or while doing the experiments.

Summer School for Women in Physics participants

The first day started with a set of soap film demos which set the tone for the rest of the School. It was clear that the participants started actively thinking about the observations they made during the demos. We invited questions and many of the participants came to the board and explained their points of view to the rest of the participants. The participants were engaged in experiments during the morning half of each day and the afternoon half was devoted to discussions on theoretical aspects of the experiments and some problem solving based on the themes of the experiments. The participants were divided into five groups and they named their groups after five pioneering women scientists. The division into groups enabled greater interaction between participants from different parts of Karnataka.
There were experiments on soft matter (reversibility experiment at low Reynolds numbers, osmosis, Brownian motion etc.), sound (Doppler effect, measurement of the speed of sound, Chladni plates etc.), oscillations and waves (Kapitza pendulum, coupled pendula, Faraday waves, Lissajous figures etc.) and experiments related to Climate Change (role of humidity in heating up the atmosphere, for instance). One of the ICTS PhD students had a session on Climate Change with the participants of SSWP.

There were a few special talks given by experts in various fields in the evenings. The topics ranged between Magnetohydrodynamics, Infinite Series, Cloud formation and so on. These were attended by participants of both Schools (SSWP and SSWMS). There were a few sessions where the participants interacted with a few ICTS faculty members in the evening. There were also a couple of unstructured open ended interactions late at night where the participants discussed Physics with some of the organisers. Apart from Science we also felt that a cultural program where all the participants would come together and participate would induce greater interaction between the participants. Participants from both Schools (SSWP and SSWMS) came together and there was a wonderful event at the Chandrasekhar Auditorium, ICTS where the participants showcased their talents ranging between visual arts, poetry, dance, singing and instrumental music. It was a memorable event for everybody.

We look forward to similar summer schools in the coming years.

For more details see https://www.icts.res.in/program/swp

THE ICTS-RRI MATH CIRCLE

JOSEPH SAMUEL

Math Circles are communities which encourage and nurture mathematical talent in children. The idea goes back to Bulgaria (1907) and the Soviet Union (1930 s). Over the years, math circles have spread over the globe. TIFR in Mumbai has started Math Circles India, which has been functioning online. This brief note describes an in-person local chapter in Bangalore organised to attract mathematically inclined children. This activity has been running since January 2023.

Mathematics can be fun and engaging. As with chess and music, mathematical talent often manifests very early. We hope to spot and nurture such talent in children of school going age by having them interact with researchers in a friendly setting. These events are held on second and fourth Saturdays at the Raman Research Institute in Bengaluru. Participation is by invitation only. To receive an invitation, children can take on one of the math challenge (https://www.icts.res.in/sites/default/files/mci-online-challenge.pdf) questions and send in a solution, in their own handwriting to show their interest in joining. The activity consists of guided problem solving in a fun setting, with lots of discussion, collaboration and exchange of ideas. The facilitators will only help the discussion along, not teach and direct. They may provide occasional hints when the discussion stalls. In the ICTS-RRI Maths Circle, we are less concerned with speed and performance than with enjoyment and exploration.

Here is a sample question: On an infinite plane, every point is coloured either red, blue or green. Show that there must be two points, exactly one inch apart, of the same colour.

MY NEXT GOAL IS TO PENETRATE THE DARK AGES OF THE UNIVERSE, SAYS JOE SILK

Joe Silk is a renowned astrophysicist. He is currently professor of physics at the Institut d'astrophysique de Paris, Universite Pierre et Marie Curie and Homewood Professor of Physics and Astronomy at Johns Hopkins University, USA. He is also an Emeritus Fellow of New College, Oxford and a Fellow of the Royal Society. In 2011, he was awarded the Balzan Prize for his contributions to the study of the early Universe. Prof. Silk spoke to Debdutta Paul on his recent visit to ICTS-TIFR.

How do you explain your field of research to a high school student interested in physics and mathematics?

The field of research I work in is cosmology, generally speaking, and that's a study of the universe. More specifically, it starts off with looking at the universe, seeing that it's full of galaxies and asking the question: Where do the galaxies come from? How do they originate? What was there before the galaxies? And how far back can we go in time?

Can you explain in detail any one of the questions that you're studying?

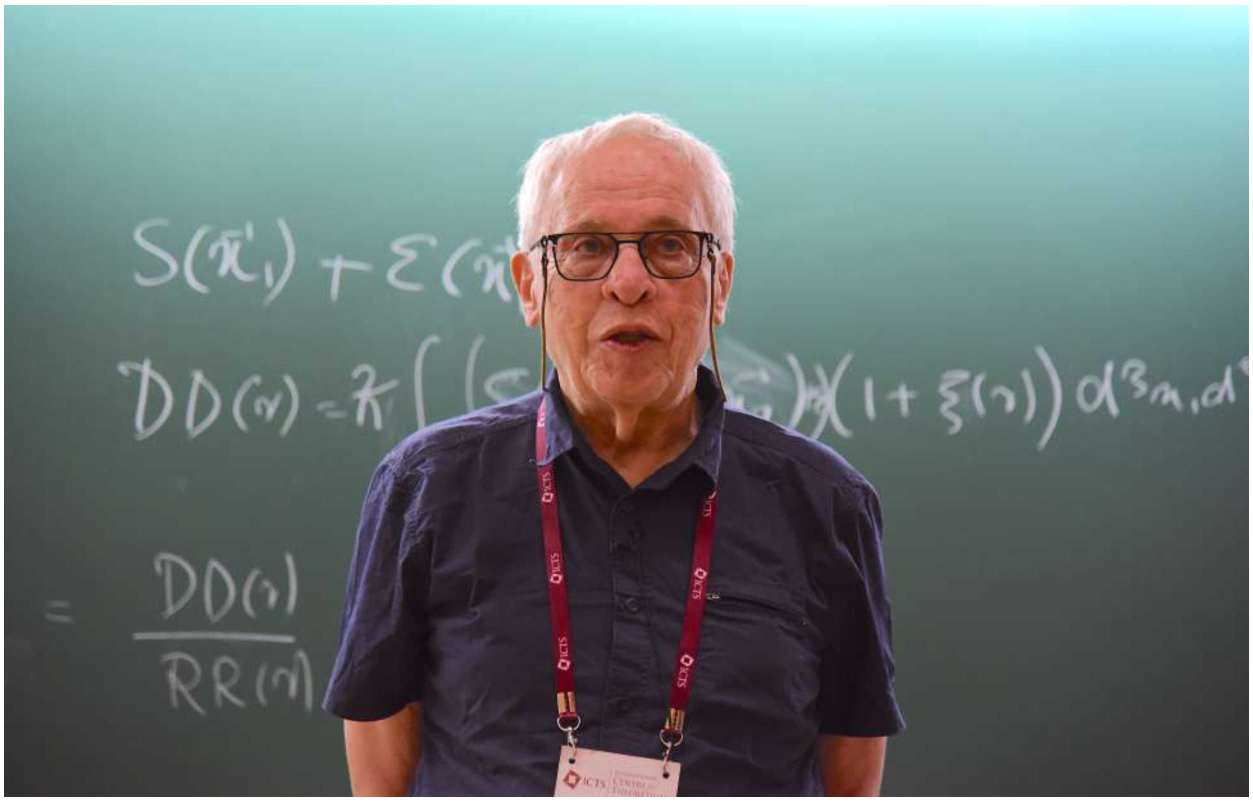
One of the main questions is the origin of the galaxies. Let me try to put that in perspective. The universe began in a gigantic primordial ball of fire, intense radiation, which cooled down since that explosion occurred. We call that explosion the Big Bang. Now, because it's so hot, it's very difficult for anything to condense out of that expansion. But as the radiation cools down, eventually condensation occurs. That's partly because the radiation cools down rapidly enough so that it becomes as cold as three degrees kelvin. That's what we measure in fossil radiation that we view as the cosmic microwave background. But before then, the ordinary matter in the universe is more important. It has a stronger influence on gravity than radiation. The intensity of radiation has expanded away, and the matter then controls the gravity. That means there are areas which are slightly denser than the average, and they have a slight advantage. Their gravity is stronger, they tend to collapse, and eventually form the seeds of galaxies much later as time goes on. So I figured out how to trace these seeds back in time and view them as slight fluctuations, hot spots if you like, in the cosmic microwave background radiation.

Can you tell us about your journey in this particular field of research starting from how you came into it to where you are working today?

I began as an undergraduate in mathematics. I spent three years getting my degree at Cambridge University. Towards the end of those three years, I started wondering what I should apply my mathematics to. I experimented with a few things professionally, such as becoming an actuary, for example. I did an internship for that. I found it very boring. And then by chance, I stumbled into a lecture, which I wasn't officially supposed to attend. I sat at the back and heard a brilliant lecturer talk about Einstein and gravity and something called Mach's principle, which is a mixture of philosophy and physics. This expedition captivated me, and I decided to learn more, and eventually chose cosmology as my major interest in research.

What are some of the open questions in cosmology today?

One of the questions that we've heard for many years now, and have really got no nearer to answering, is - what is the nature of dark matter? We know from observations that 90 per cent of galaxies consist of something that we can't see directly. It is mostly in the outer parts of galaxies and so must interact fairly weakly with ordinary matter. So we conjecture that it's some form of weakly interacting particle. We search for these particles in particle colliders, for example. We do experiments that look for these particles, which can penetrate ordinary matter more easily because they're weakly interacting, deep underground. We search in laboratories deep underground. We haven't found any evidence for these particles yet. So that's why it continues to be a very, very big



Joe Silk at ICTS-TIFR. Photo credit: S. Shantaraj

puzzle... an outstanding question. Many searches are going on. We're building bigger and better experiments. So far, there's no indication when we'll be successful, if ever.

In cosmology seminars, talks, and presentations, we keep hearing about the Hubble tension. What is your opinion on that?

Well, the Hubble constant is the rate of expansion of the universe and we measure it by looking around us and measuring the rate of expansion of the distribution of galaxies, space if you like, from the redshift of the spectrum that gives us the expansion rate. Now, it's complicated because you need some precise distance calibrator to get a precise velocity. Also the average velocity of the galaxy itself is not good enough, because galaxies have a random motion as well. And what we're trying to do is decipher the underlying overall flow, the expansion flow of the universe, the expansion of space. We do that by seeking out what we call distance calibrators. They're like standard candles, yardsticks if you like, things that you can measure distance with. And these, of course, are varieties of very bright stars. They may be variable stars called Cepheid stars. If you look a bit further away, the targets of choice are supernovae - exploding stars, which are also very good distance calibrators. We combine these together, pushing further out to the universe, and measure a certain rate of expansion where we think we're more or less in some quiescent part of the expansion of the Universe not perturbed too much by local objects, such as galaxy clusters. At the same time, we use the cosmic microwave background as our anchor in the distant universe. From studying the fluctuations in that background radiation, we can actually infer a distance scale, because those fluctuations are predicted to have a certain scale, and will be too large or too small, depending on hofar away they were. By correcting for this uncertainty in distance, we can infer the scale of the Universe — what it should be from the microwave background. There's a problem here - when we look at the microwave background, we work on our parameters, we figure out what the missing link is, in terms of the expansion of the Universe, that's one parameter we get from the sky basically and we compare that with the local value from the variable stars and the supernovae, and it's not the same. That's the source of the Hubble tension. The difference is only a few per cent, but it's very persistent. And the precision of our measurements is such that we think it's a very real discrepancy. That's the Hubble tension.

In the ICTS-Infosys Chandrasekhar Lecture, you talked about precise measurements carried out by proposed experiments on the far side of the moon. How and why will these measurements yield new information about cosmology?

The basic goal in the cosmology I want to do next is to penetrate the Dark Ages. That's long before there were any galaxies or stars, very far away in the early universe. That's the equivalent of a redshift of 50, that is, the wavelengths are stretched out by a factor of 50 due to the expansion. Now, the only things in the dark ages are hydrogen clouds, because they're the building blocks of the later galaxies. To look for these hydrogen clouds is to measure them by using the 21-centimetre line of atomic hydrogen, which is produced when the electron spin flips in a hydrogen atom. When spins are antiparallel of electron relative to the proton, the energy is very slightly lower. So the spin flip is excited by absorbing background radio waves at a very precise wavelength, and we see this as absorption against the diffuse radio background. And so you can see these cooler clouds as shadows against the background radiation. However, because they're so far away in the early Universe, the absorbing radiation is highly redshifted. So from 21 centimetres, it stretches out all the way to 10 metres. And that corresponds to a very low frequency, indeed, a frequency so low, or wavelength so long if you like, that it's almost impossible to do these experiments on Earth. Because of the Earth's ionosphere which deflects these waves, it stops seeing them from so far away, basically, and gives us all sorts of extra noise. It turns out that the far side of the Moon is the best place to do this experiment in the nearby Universe. In fact, it's said to be the most radio-quiet region in the entire inner solar system. And that's because not only is there no ionosphere around the Moon to give you radio noise, but also the far side is shielded completely from the Earth. And that means there is no radio interference from the Earth from our cell phones or TV or whatever. So that's why it's such a perfect place to do low-frequency radio astronomy.

What will you learn from these measurements about the early universe, the hypothesis of inflation, and about dark matter and dark energy?

So the goal is to learn something about inflation. That's the major goal of these experiments on the far side of the Moon. And the way we'll do that is the following. Inflation occurred in the first instance of the universe, 10 to the power of minus 36 seconds after the Big Bang. It produced a dramatically huge expansion of the universe, and then rapidly settled down to a more normal expansion rate. But during that brief instant of very accelerated early expansion and the settling down to the usual expansion rate, a field of gravitational waves was generated. And those waves of course redshifted to a very low frequency, but they leave a tiny imprint on the microwave background. This is because gravitational waves shear matter as they pass through it by a very tiny amount. They leave this shear signal on the microwave background, which is unique to the passage of gravity waves. We can measure this as tiny twists in the fluctuations in the background radiation. It's a non-compressive mode of polarisation, a shearing mode of polarisation, that's the signal of gravity waves. So with the cosmic microwave background, we've been trying very hard to look for this signal. It turns out that it's really difficult to find. It's very, very weak. But above all, the inflation models don't give you any definite prediction. They tell you what is possible, but they don't tell you what is guaranteed. So we've had to think of an alternative way to get a definitive result on testing inflation. And that definitive result comes about because inflation generates the fluctuations from which all the structures are made today, it's one of the great successes of the theory. But in generating those fluctuations, it leaves slight twists and turns. We call this non-Gaussianity, non-randomness in the pattern of the fluctuations in the sky. And so we will use the enormous amount of information we have in the low-frequency radio waves from all these early clouds to try to detect this deviation from Gaussianity in these primordial fluctuations. We can see this in the very low frequency radio, effectively. And so that's how we'll test inflation because inflation is guaranteed to produce these deviations from Gaussianity.

A couple of weeks back, we also heard about the proposal to have gravitational wave detectors on the Moon, the LGWA. Coming back to India today, how important do you think is LIGO-India in the LIGO collaboration? And will it be useful if it comes up in say, the next 10 years?

LIGO-India is very timely. Right now we have three functioning experiments: two in the US, one in Italy, and a fourth one in Japan is about to come up. Adding a fifth detector in India will be a great improvement. That's because, with these experiments in different parts of the globe, you can greatly improve the localisation on the sky of the gravity wave sources. India's great distance from the other observatories means we'll be able to pinpoint much more accurately where the sources are coming from. That's really important. Even if it will take us 10 years to get there, that's still fine, there'll be no competition. And that will be a wonderful contribution to the field. The reason that the Moon will provide an important addition to gravity wave telescopes that will probably occur on roughly the same timescale, maybe a few years later, is the following. These gravity waves from far away, from merging black holes, pass by us. They shake the interferometer, the telescope, one that eventually will be LIGO-India; currently, it is LIGO and Virgo. We measure the resulting signals at a certain frequency corresponding to the speed at which the waves (at the speed of light if you like because gravity travels at the speed of light) can traverse a few kilometres — that's the length of the arm of the interferometer, the beam as it were. So that's your measuring rod and the vibrations in it give you the signal that you measure in these gravity wave detectors. Now the Moon is some 8000 kilometres across. And so when a gravity wave passes there, it shakes the Moon very, very slightly. And so that gives you a vibration on a scale that's not four kilometres, or 40 kilometres (which will be the new generation of ground-based telescopes after LIGO-India actually, but that's projected), but something much, much longer, and therefore a frequency that's much, much slower. And that is really, really nice because if we had gravitational wave telescopes on the Moon, we could then measure a frequency range that corresponds to black holes coming together. They move slowly at first, gradually speeding up, so we can measure their approach as they are produced as the black holes begin to merge together. So it's a very important missing link in our understanding of how black holes merge. We would see their approach. We can do that very simply on the Moon because all we need to do is to put seismometers — very, very precise seismometers — on the Moon. Now, Apollo did that 50 years ago, and they measured the first lunar quakes. These new seismometers, much more precise, will measure the tiny, tiny vibrations of the Moon from passing gravity waves. So a few of those installed on the Moon will be a wonderful new telescope, a futuristic one, but one that we'll be able to build in perhaps 20 years' time and complement all the other gravitational wave telescopes we have.

You have studied the possibility that dark matter is made up of a large number of tiny asteroid-mass black holes. What attracts you to this scenario over other possible explanations of dark matter? And how can the theory be tested?

The problem with dark matter is that we haven't found it yet. We have been looking desperately for weakly interacting particles, and if they existed, they should be produced in collisions, high energy collisions of known particles, you'll see events with missing energy or missing momentum. But we haven't seen those yet. And so we're being forced to think of different possibilities. So one of those is a black hole. Because we know they exist, we've measured black holes. We have even imaged very massive black holes. Black holes are dark, so they're ideal for dark matter. The problem is, if the black holes are, say, produced by dying stars a few times the mass of the Sun, then we can set very strong limits on how many of those there are from basically their merger rate and the gravity waves they produce. And there simply are not enough. We also have other types of experiments, looking for dark things passing in front of nearby stars. All of these say that most black holes are one per cent of the dark matter. Also dark matter can't consist of very massive black holes, they wouldn't be dark, they'd be glowing as they'd inevitably be accreting ambient gas. So you have to say, well, maybe it's not black holes produced astrophysically like the mass of the Sun, but they could be much smaller. In principle, primordial black holes could be really, really small because the universe was very dense very early on. If regions collapsed today, they would make enormous black holes, but early on, they would make microscopic black holes. So the question then is... what masses of black holes could you imagine that could be the dark matter? Well, they can't be too small. Because if you made the black holes less than roughly the mass of a small kilometre size asteroid, actually, about a billion tons or 10 to the power of 15 grams to give you a number, then they would undergo a process discovered by Stephen Hawking called evaporation. And so they would disappear, they couldn't be the dark matter. And if they were about a hundred million times more massive than that, they would deflect the light too much when they are in between us and nearby stars. We would see light deflections and the process that we call lensing, or microlensing, would allow them to be detected. So there's a narrow range, not so narrow really, it's between asteroid mass and lunar mass basically, so that's a respectable range of mass, where we could hide the black holes. They wouldn't deflect the light from stars, they wouldn't Hawking-evaporate, and they'd be stable. If they were produced in the early universe, they would be the dark matter today. And the reason why we think this is an interesting option is because if you go back early enough in the universe when these were made, they could be very rare events early on. You could make, you know, very tiny fractions of these at the time, as a fraction of the energy density of the universe. What happens is the radiation all expands away, but the black holes are left behind. So the tiniest numbers at the beginning, amounting to fractions of a billion or whatever, compared to the density of energy then, could be the dark matter today. So that's the attractive part of the hypothesis. Rare events can make them — events that just involve gravity, so it's not a great mystery. We're not inventing new particles. It is a little bit unusual in the sense that our theory didn't predict these, but we can tweak the theory to make them and they could be the dark matter.

And how do we test them?

How do we test these primordial black holes? Well, our best hope is that they would actually collect where the dark matter is, they are the dark matter. And in the centre of a galaxy where there often lurks a supermassive black hole, we know that there will be lots of these tiny black holes around it, as the black hole itself grew from smaller beginnings. Early on, far away in the past, those tiny black holes, the dark matter, would cluster around the massive central black hole. Many of them would fall in and give you some gravity waves. And that will result in something detectable. Although you probably couldn't see individual gravity wave events from the falling into the black hole, you would imagine sort of a stochastic background, as ripples in the gravity waves in the background sea of gravity waves. And that would be a vital clue.

One last question. You give a lot of presentations to various audiences. What do you think is the role of scientists in outreach to the non-science audience?

Well, I think scientists basically especially those, well all of us really, but mostly those doing experiments, but even the theorists too — who ask the general public for funding, I mean, basically, to do our research. You know, we need computers, we need to build experimental telescopes. Those can be very, very expensive. And I think the only way to communicate this to the policymakers who make the budgets is to get across the excitement of doing science, and why we really have to lift our eyes to the horizon and go for very, very ambitious things that are, you know, at the core of science and exploration and discovery. And it's via outreach that we have to communicate these needs and hopefully, our politicians will listen and fund our research. That's the driver.

PROGRAMS

Machine Learning for Health and Disease

24 July-4 August 2023 ✦ *Organizers* — Gautam Menon, Leelavati Narlikar, Uma Ram, Ponnusamy Saravanan and Rahul Siddharthan

Summer School on Gravitational-Wave Astronomy

24 July-4 August 2023 ✦ *Organizers* — Parameswaran Ajith, K. G. Arun, Bala R. Iyer, Prayush Kumar

Introduction to Precision Measurements and Quantum Metrology

10-21 July 2023 ✦ *Organizers* — Subhadeep De, Saikat Ghosh, Arup Kumar Raychaudhuri, Kasturi Saha, Bijaya Kumar Sahoo, Anil Shaji

Modern Trends in Harmonic Analysis

26 June-7 July 2023 ✦ *Organizers* — Jotsaroop Kaur, Saurabh Shrivastava

Periodically and Quasi-Periodically Driven Complex Systems

12-23 June 2023 ✦ *Organizers* — Jonathan Keeling, Manas Kulkarni, Aditi

Summer School for Women in Mathematics and Statistics

29 May-9 June 2023 ✦ *Organizers* — Siva Athreya, Rhythm Grover, Dootika Vats

Dualities in Topology and Algebra

15-26 May 2023 ✦ *Organizers* — Samik Basu, Anita Naolekar, Rekha Santhanam

Largest Cosmological Surveys and Big Data Science

1-12 May 2023 ✦ *Organizers* — Shadab Alam, Girish Kulkarni, Subha Majumdar, Surhud More, Aseem Paranjape, Tirthankar Roy Choudhury

Less Travelled Path to the Dark Universe

13-24 March 2023 ✦ *Organizers* — Arka Banerjee, Subinoy Das, Koushik Dutta, Raghavan Rangarajan, Vikram Rentala

Probabilistic Methods in Negative Curvature

27 February-10 March 2023 ✦ *Organizers* — Riddhipratim Basu, Anish Ghosh, Subhajit Goswami, Mahan MJ

Vortex Moduli

6-17 February 2023 ✦ *Organizers* — Nuno Romão, Sushmita Venugopalan

Turbulence: Problems at the Interface of Mathematics and Physics

16-27 January 2023 ✦ *Organizers* — Uriel Frisch, Konstantin Khanin, Rahul Pandit

Topics in High Dimensional Probability

2-13 January 2023 ✦ *Organizers* — Anirban Basak, Riddhipratim Basu

DISCUSSION MEETINGS

Data Science: Probabilistic and Optimization Methods

3-7 July 2023 ✦ *Organizers* — Vivek Borkar, Sandeep Juneja, Praneeth Netrapalli, Devavrat Shah

Mathematical modeling of Climate, Ocean, and Atmosphere Processes

26-30 June 2023 ✦ *Organizers* — Jim Thomas, Ashwin K Seshadri, Aman Gupta

Gravitational-Wave Open Data Workshop

16-17 May 2023 ✦ *Organizers* — Bala Iyer, Mukesh Kumar Singh, Prayush Kumar, Uddeepta Deka, Parameswaran Ajith

Inaugural meeting of Asian-Oceanian Women in Mathematics

24-28 April 2023 ✦ *Organizers* — Rukmini Dey, Sanoli Gun, Purvi Gupta, Hyang-Sook Lee, Polly Sy, Melissa Tacy

Lunar Gravitational-Wave Detection

17-20 April 2023 ✦ *Organizers* — Parameswaran Ajith, Jan Harms, Andrea Maselli, Rajesh Nayak, P. Sreekumar

Topics in Hodge Theory

20-25 February 2023 ✦ *Organizers* — Indranil Biswas, Mahan Mj

Second Preparatory School on Population Genetics and Evolution

20-24 February 2023 ✦ *Organizers* — Deepa Agashe, Kavita Jain

8th Indian Statistical Physics Community Meeting

1-3 February 2023 ✦ *Organizers* — Ranjini Bandyopadhyay, Abhishek Dhar, Kavita Jain, Rahul Pandit, Samriddhi Sankar Ray, Sanjib Sabhapandit, Prerna Sharma

Physics Teachers Training Program – Quantum Mechanics

9-13 January 2023 ✦ *Organizers* — Raghavan Rangarajan, SVM Satyanarayana, M Sivakumar

LECTURE SERIES

INFOSYS-ICTS CHANDRASEKHAR LECTURES

The Future of Cosmology

1-2 May 2023 ✦ *Speaker* — Joseph Silk *(The Institut d'Astrophysique de Paris, France and Johns Hopkins University, USA)*

INFOSYS-ICTS RAMANUJAN LECTURES

Critical Phenomena Through the Lens of the Ising Model

9-13 January 2023 ✦ *Speaker* — Hugo Duminil-Copin *(Institut des Hautes Études Scientifiques, France & University of Geneva, Switzerland)*

INFOSYS-ICTS TURING LECTURES

An Alternative View on AI: Collaborative Learning, Incentives, Social Welfare, and Dynamics

4 July 2023 ✦ *Speaker* — Michael I. Jordan *(University of California, Berkeley, USA)*

DISTINGUISHED LECTURES

A Century after Heisenberg: Discovering the World of Simultaneous Measurements of Noncommuting Observables

19 July 2023 ✦ *Speaker* — Carlton M. Caves *(University of New Mexico, USA)*

The History of Gravitational Lensing in Cosmology

10 May 2023 ✦ *Speaker* — Nick Kaiser *(Département de Physique, ENS Paris)*

The Ubiquity of Logarithmically Correlated Fields and Their Extremes

5 January 2023 ✦ *Speaker* — Ofer Zeitouni *(Weizmann Institute of Science, Israel & New York University, USA)*

ABDUS SALAM MEMORIAL LECTURES

The Future of the Indian Space Programme

18 April 2023 ✦ *Speaker* — S. Kiran Kumar *(Vikram Sarabhai Professor at ISRO and Member of the Space Commission, Govt of India)*

CENTENNIAL TRIBUTE TO AMAL RAYCHAUDHURI

This was a special lecture series conducted as a centennial tribute to Amal Kumar Raychaudhuri. The lecture series provided a brief overview of topics relevant to current research on General Relativity.

Advanced General Relativity: A Centennial Tribute to Amal Kumar Raychaudhuri

24, 27, 31 March, 3, 7, 10, 15, 17, 21, 24, 28 April 2023 ✦ *Speaker* — Sunil Mukhi *(Adjunct Professor, ICTS- TIFR, Bengaluru)*

SPECIAL ICTS KOLMOGOROV SYMPOSIUM

On the occasion of A.N. Kolmogorov's 120th birth anniversary, a symposium was held on 25 April 2023. The symposium featured online talks by leading researchers in the fields where Kolmogorov had an impact on in its early stages.

The speakers were Hao Wu (*Tsinghua University*), Samriddhi Sankar Ray (*ICTS-TIFR*), Prahladh Harsha (*TIFR, Mumbai*), Amit Apte (*ICTS-TIFR, on lien at IISER Pune*), Alison Etheridge (*Oxford University*), Riddhipratim Basu (*ICTS-TIFR*) and S.R.S. Varadhan (*Courant Institute of Mathematical Sciences, NYU*) and K.R. Parthasarathy (*Indian Statistical Institute*).

OUTREACH

KAAPI WITH KURIOSITY

Conway's Tangles
2 July 2023 ✦ *Speaker* — Michael Lacey *(Georgia Institute of Technology)* ✦ *Venue* — J. N. Planetarium, Bangalore

Is Clay a Solid or a Liquid?
17 June 2023 ✦ *Speaker* — Ranjini Bandyopadhyay *(Raman Research Institute, Bengaluru)*

What's the Matter with Primordial Black Holes?
14 May 2023 ✦ *Speaker* — Ravi K. Sheth *(University of Pennsylvania, USA)*

Opportunities for Breakthrough Science With Lunar Exploration
16 April 2023 ✦ Speaker — Jan Harms *(Gran Sasso Science Institute, Italy)*

What is Natural Selection (And Why it is Not 'Survival of the Fittest')?
26 March 2023 ✦ *Speaker* — Amitabh Joshi *(JNCASR, Bengaluru)*

VIGYAN ADDA

Some Tales of Universality from the World of Probability
13 July 2023 ✦ *Speaker* — Riddhipratim Basu *(ICTS-TIFR)*

Dynamics of Quantum Entanglement
2 February 2023 ✦ *Speaker* — Sthitadhi Roy *(ICTS-TIFR)*

Participants in the Asian-Oceanian Women in Mathematics at ICTS-TIFR

The Summer School for Women in Mathematics and Statistics

ICTS

International Centre *for* Theoretical Sciences

Tata Institute of Fundamental Research

ICTS Permanent Address
Survey No. 151, Shivakote village, Hesaraghatta Hobli, North Bengaluru, India 560089
Website www.icts.res.in

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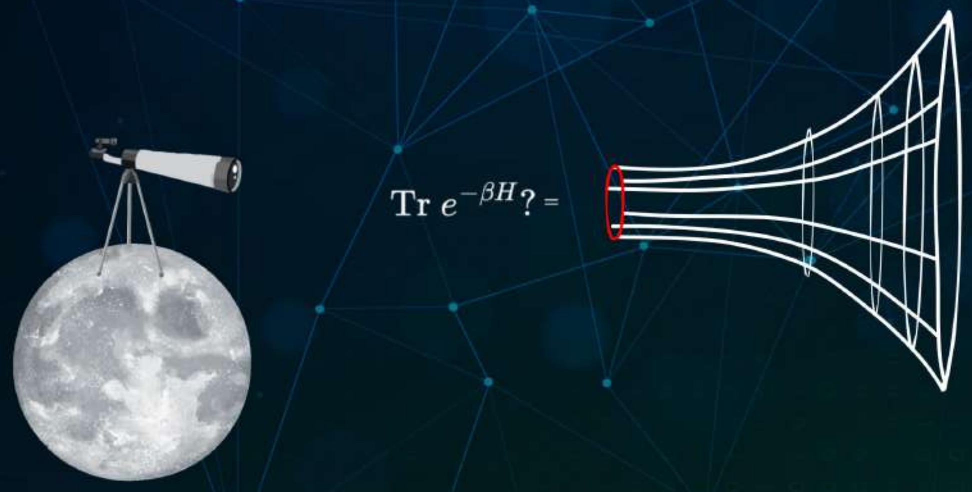

Editor: Ananya Dasgupta
Designer: Roshni Samuel