



Big Bang, Black Holes and Gravitational Waves

Illustrations of Paradigm Shifts in Fundamental Science

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Institute for Gravitation & the Cosmos



Setting the stage: The goal of this talk

- A rather general discussion on the theme “*paradigm shifts in basic science*” –illustrated by examples drawn from my expertise- to bring out three points.
- First, what is now considered as commonplace knowledge, was not at all so a just few decades ago. In fact most of the scientific community at the time was thinking in an almost opposite direction. (Courage!)
- Second, precisely because they are so startling at first, dramatic paradigm shifts take decades to get settled and become the new common pool of knowledge. (Patience!)
- Third, factors driving or slowing the process are quite varied; it is not a matter of simple logical steps, as is made to appear in retrospect! (Maturity!)



Organization

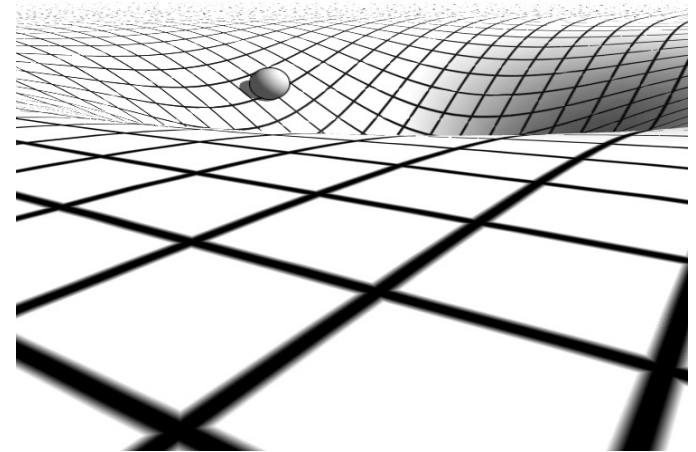
- Prelude: General Relativity
- Birth of modern cosmology & the Big Bang
- Warping of space-time & Black Holes
- Ripples on space-time: Gravitational Waves
- Summary

Space, Time and Gravity

- Most of the familiar ideas come from the Newtonian paradigm: space and time an inert backdrop/arena/stage on which things happen. Gravity a force between massive bodies. **Universality!**
- Paradigm reigned for over 200 years but was shattered by Einstein's general relativity. Space and time fused into a 4-d continuum. Its geometry is a **physical & dynamical** entity, just like matter. It can be acted upon and it reacts. A radical shift in description of reality. Furthermore, this shift is absolutely essential when gravity is strong. **Even greater universality!**

Gravity fuses with Space-Time Geometry

- Space-time no longer an inert background or stage.
- Gravitational field is encoded in the very geometry of space-time: Possible because gravity is omnipresent and non-discriminating, like geometry.
- Matter tells space-time how to curve. Space-time tells matter how to move.
- Geometry intertwined with matter via Einstein's equations.



Discovery of General Relativity

“During the last month, I experienced one of the most exciting and most exacting times of my life, true enough also one of the most successful.
....

Now the marvelous thing which I experienced was the fact that not only did Newton's theory result as first approximation but also the perihelion of mercury ($43''$ per century) as second approximation.
....



Einstein to Sommerfeld
November 28, 1915

On General Relativity

It is as if a wall which separated us from the truth has collapsed. Wider expanses and greater depths are now exposed to the searching eye of knowledge, regions of which we had not even a pre-sentiment.

...Hermann Weyl



When Henry Moore visited the University of Chicago some years ago, I had the occasion to ask him how one should see sculptures: from afar or from nearby. Moore's response was that *the greatest sculptures can be viewed –indeed should be viewed—from all distances since new aspects of beauty will be revealed in every scale*. Moore cited structures of Michelangelo as examples. In the same way, the general theory of relativity reveals strangeness in the proportion at any level in which one may explore its consequences.

...Subramanyan Chandrasekhar

Side Remark: But does it matter in practical terms?

- Why care about all these abstract ideas? For GR to be relevant, conditions have to be so extreme.
- Not really. Both special and general relativity effects critical for GPS! If ignored, within 2 minutes, the GPS localization errors will grow to ~23M; airplanes to fail to land on runways!!
- What may seem like fantasy today is often *essential* for tomorrow's technology, if grounded in solid fundamental science.
- **Fundamental laws of Nature always matter!**



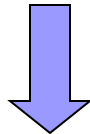
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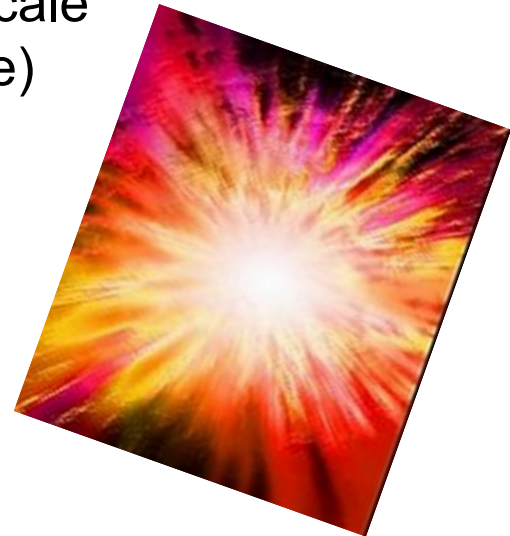
2. Cosmology

Application of GR to the Universe As a Whole

- Evolution of Geometry: Einstein's Equations
(Space-time Curvature) = $8\pi G$ (Matter stress-energy)
AND
- Observations: Homogeneity and Isotropy on large scale
(the grandest realization of the Copernicus Principle)

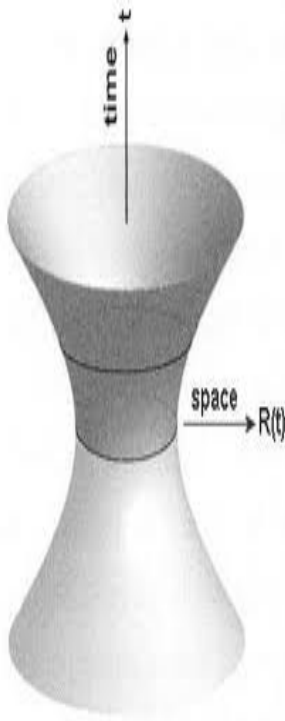


- Geometry must be **Dynamical**,
Related to Matter via Einstein's Eqs.
- Standard Picture: Universe began with a
Primordial Explosion ~13.8 Billion years ago
Paradigm Shift!



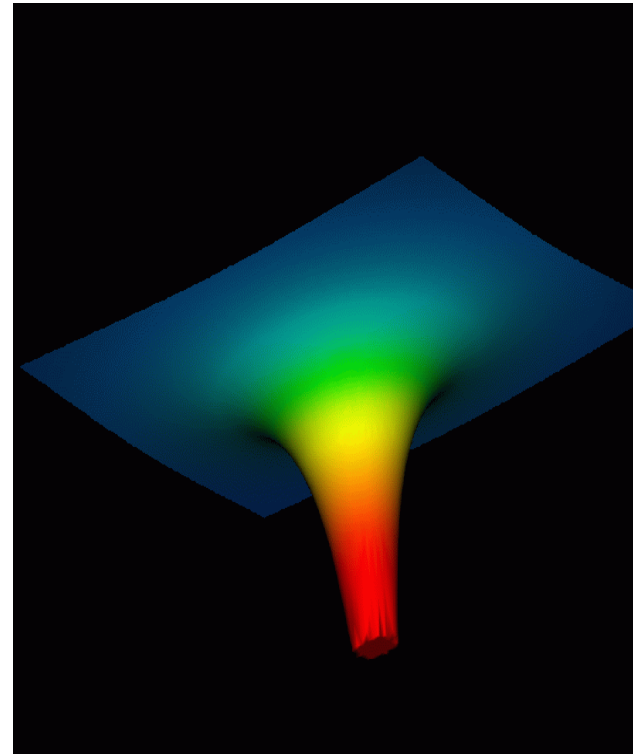
The Issue of the Beginning: Curious History

Einstein (1917)
de Sitter (1917)
Eternal Universes



No beginning or end;
No singularity

Friedmann (1921-24)
Lemaitre (1926-65)
Finite Beginning



Big Bang! The space-time continuum
tears and classical physics stops!

The Big Bang: Twists and Turns

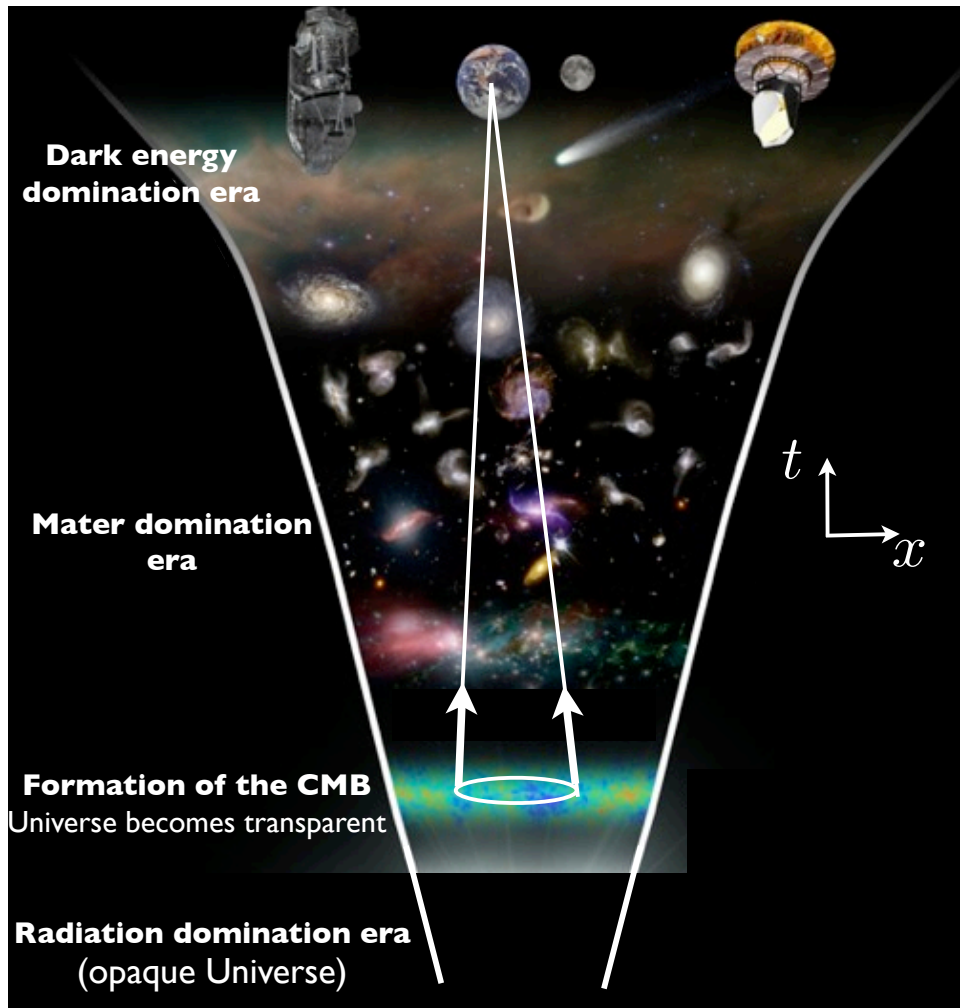
- 1930: In a January RAS Meeting, Eddington:
“Shall we put a little motion into Einstein’s world of inert matter or a little matter into de Sitter Premium Mobile?”
- Hubble’s discovery. Conclusion: Universe is expanding! (1929-31).
- Lemaitre’s seminal role (1929-31)
(Hubble law now renamed: Hubble-Lemaitre law)
Gamow, Pope Pius XII & Lemaitre (1951)
- Philosophical/Aesthetic Preferences
Soviet program: Lifshitz, Khalatnikov (late 50s ...)
Steady State: Hoyle, Narlikar Bondi, Gold, Sciama (till 70s)
(Cyclic Universe: Dicke, Sakharov, Weinberg, Wheeler, ...)



A Paradigm Shift

- The idea of a Big Bang continued to remain outside mainstream physics and astronomy for decades largely due to aesthetic and philosophical preferences of leading thinkers. This changed because of two discoveries:
- **Nucleosynthesis was understood:** Gamow, Alpher, Herman (1948-65: Early universe essential as an oven for cooking light elements)
- **Cosmic Micro-wave Background: CMB** Dicke, Peebles, Roll, Wilkinson (1965 onwards: Relic or primordial radiation left over from when radiation decoupled from matter.)

Cosmic Microwave Background



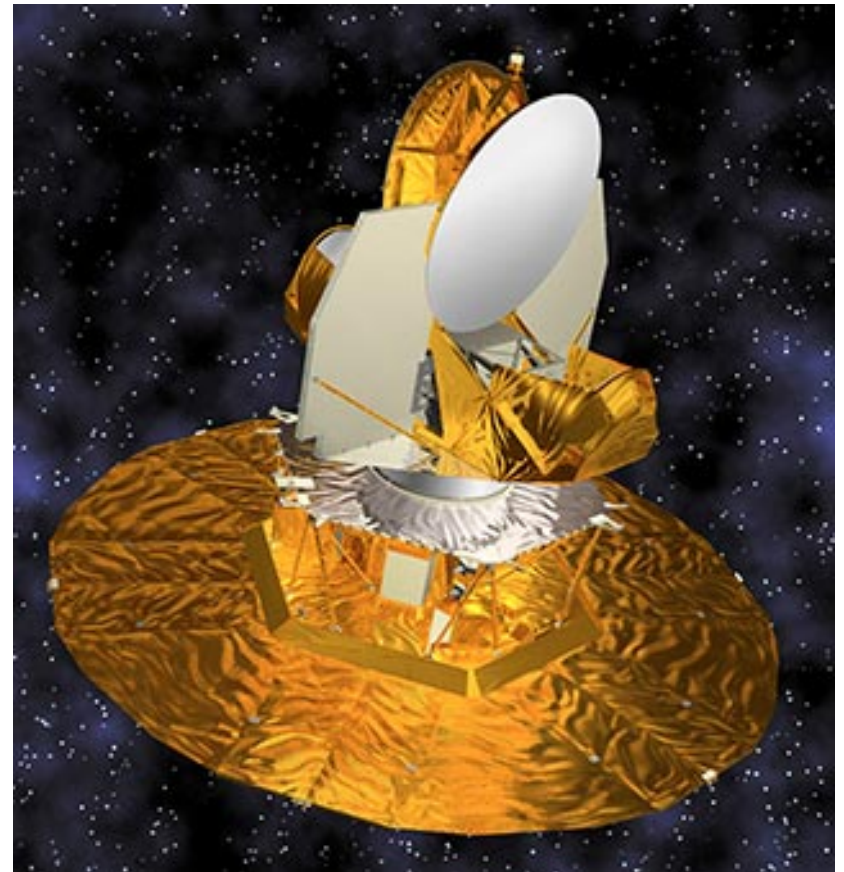
Snapshot of the universe when it was 380,000 years young!

Spectacular success over the last two decades: Powerful interplay between theory and high precision observations especially through space missions, COBE; WMAP & PLANCK

COBE & WMAP (Image Credits: NASA)

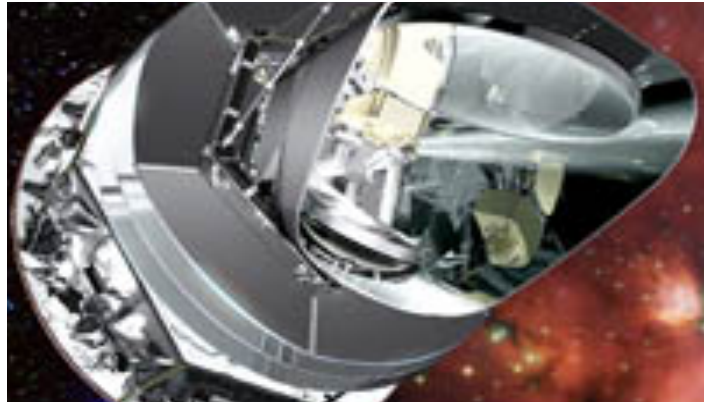


Cosmic Microwave
Background Explorer
(launched in 1989)



Wilkinson Microwave
Anisotropy Probe
(launched in 2001)

Planck Satellite (launched 2009)

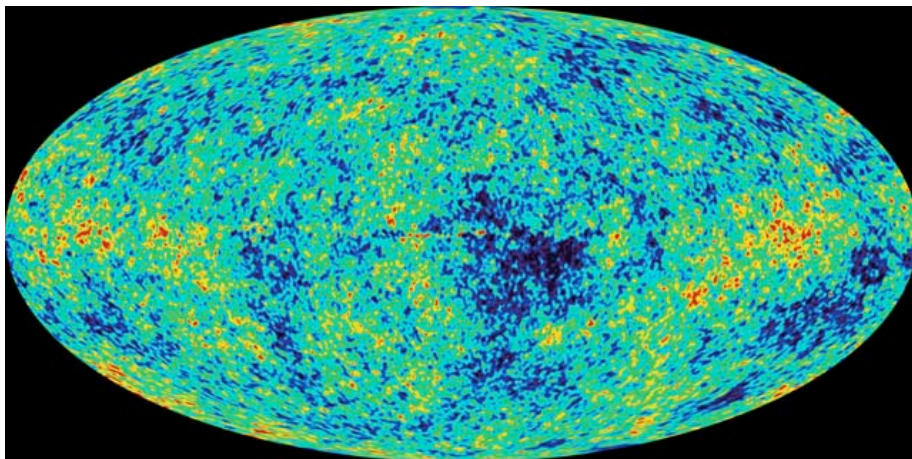
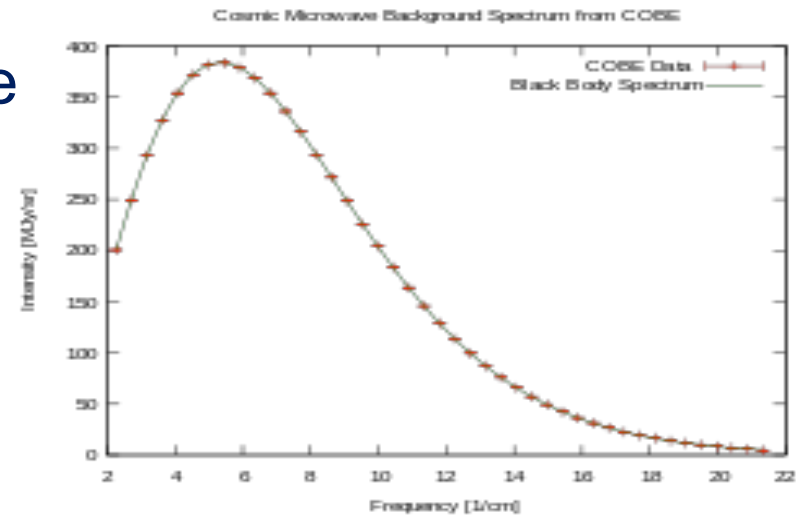


Astronomers released the latest and most exquisite baby picture yet of the universe on Thursday, one that showed it to be 80 million to 100 million years older and a little fatter than previously thought, with more matter in it and perhaps ever so slightly lopsided. **NY Times, March 21st, 2013 headline**

Final data release: Summer 2018

Cosmic Microwave Background

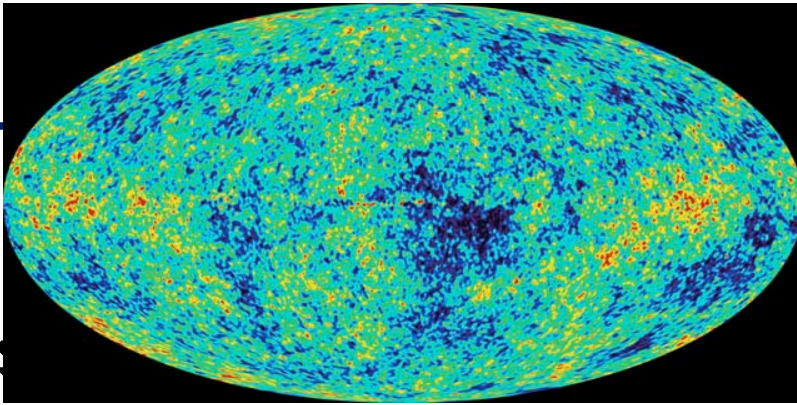
When it was 380,000 years young, the Universe was extremely homogeneous as Lemaitre had envisaged. Perfect black body with temperature of 2.73K as seen today.



(Image credits: NASA)

But tiny inhomogeneities
of 1 part in 100,000.

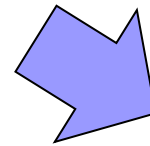
Cosmic Microwave Background



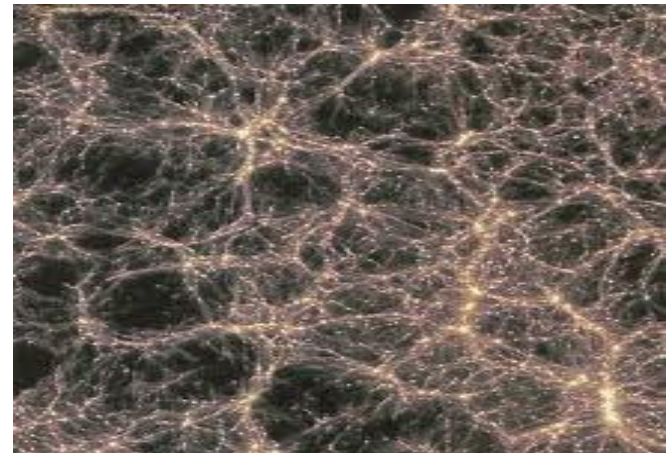
TINY inhomogeneities seen in CMB when the universe was 380,000 years young grow obeying general relativity...

Triumph of General Relativity!

In human terms: from the snapshot of a baby 1 day after birth, providing an accurate profile at age 100!

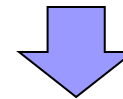


...Into the complex large scale structure of the universe seen now, 13.8 billion years later.



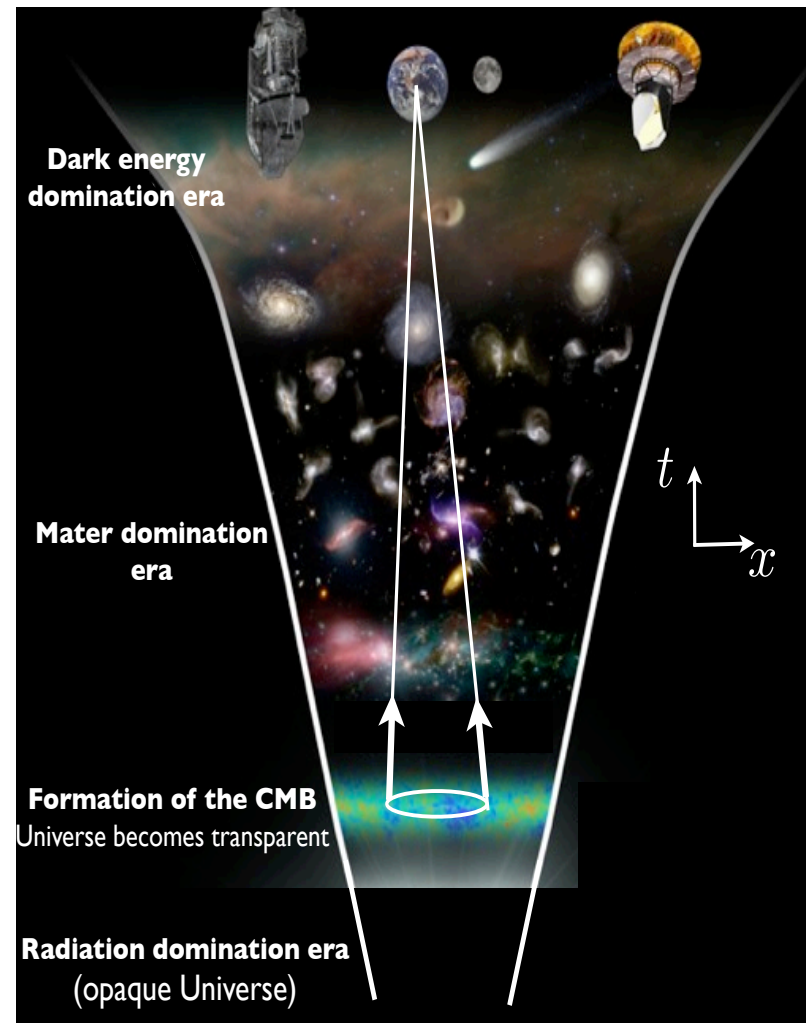
Origin of Inhomogeneities in the CMB?

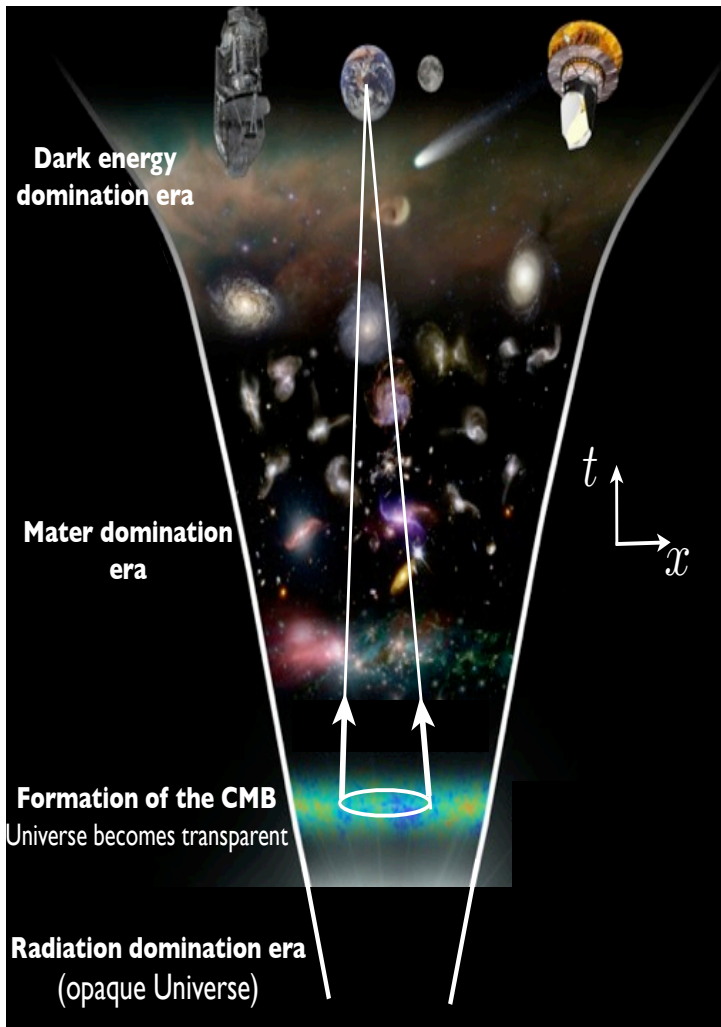
- **Inflation:** Soon after the Big Bang the universe underwent a phase of rapid expansion. At the onset of this phase universe was completely homogeneous EXCEPT for the **ever present vacuum fluctuations** which cannot be gotten rid of even in principle! (Mukhanov & Chibisov; Guth,...)
- The vacuum fluctuations are shown to grow in time to produce exactly the inhomogeneities seen in the CMB.



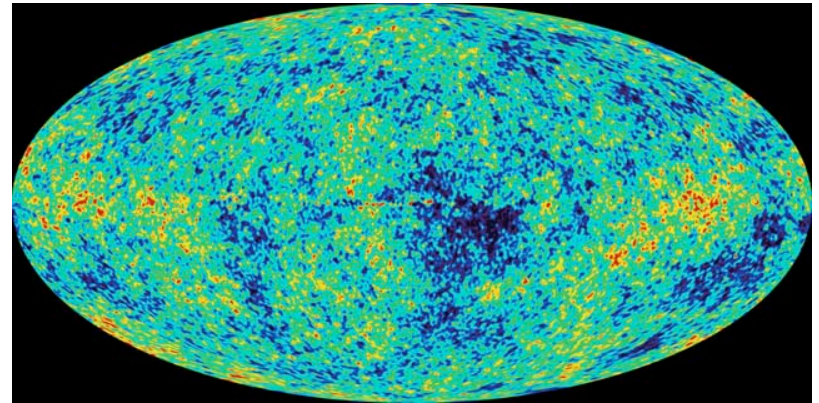
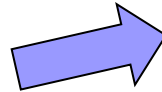
The origin of the observed large scale structure: **Vacuum Fluctuations!**

Again, a paradigm shift



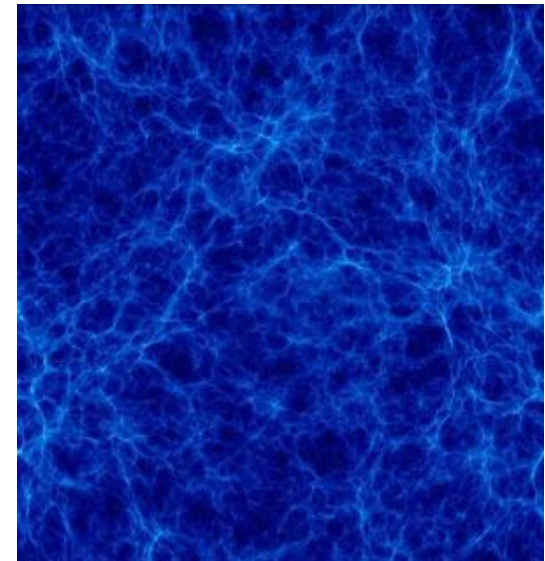


QFT on a
classical
FLRW
space-
time



Classical
gravity

The origin of the
Cosmic Structure:
**Quantum
Nothingness!**

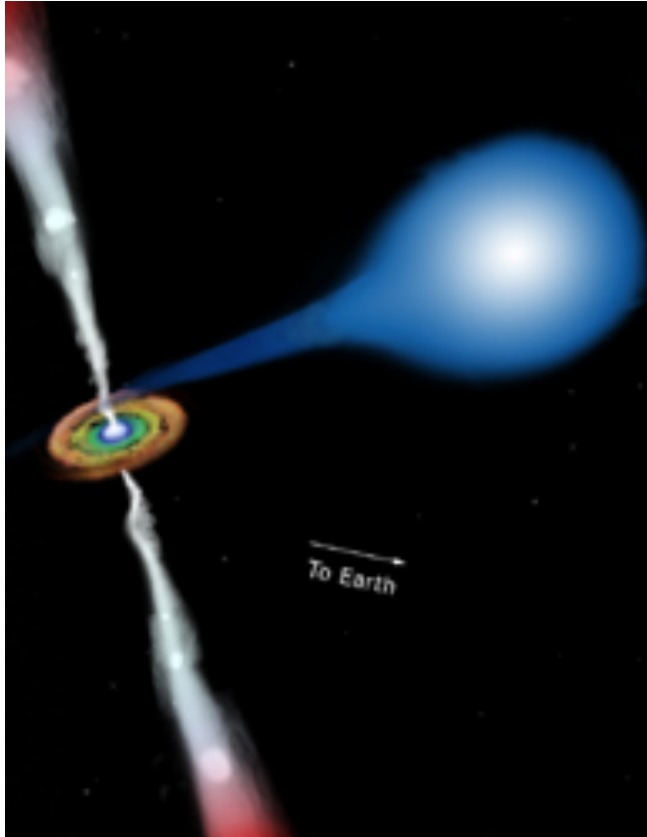




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Black Holes: End of Space & Time

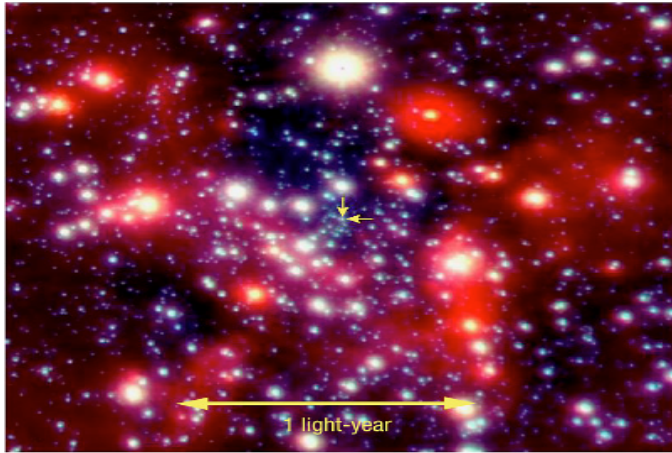


“Region of space-time from which even light can never escape.”

Now black holes are widely recognized as the engines that drive the most energetic phenomena in astrophysics. But this was not always so: Again, the subject has a **very curious history!**

A small \sim few M_{\odot} mass black hole gobbling up a nearby star

Our Own Black Hole: sgr A*



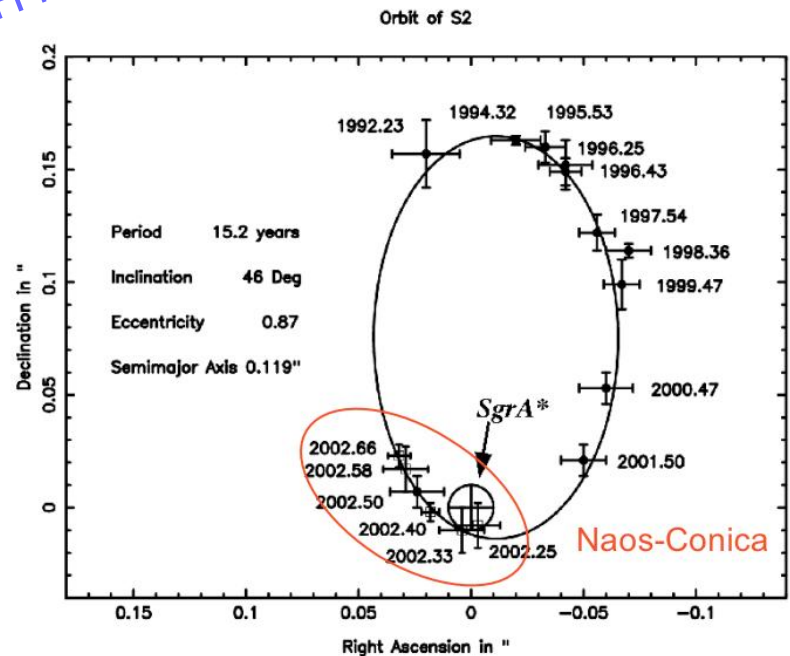
The Centre of the Milky Way
(VLT YEPUN + NACO)

ESO PR Photo 23a/02 (9 October 2002)

© European Southern Observatory



Sagittarius A*, ~ 4 Million M_{\odot} BH in the Center of the Milky Way





Amazingly, predictions appeared over 230 years ago! Based on Newton's law of Gravitation

“ If there should exist in Nature ... any [such] bodies we could have no information from sight; yet if any other luminous bodies should happen to revolve around them we might still perhaps from the motions of these revolving bodies infer the existence of the central ones with some degree of probability, as this might afford a clue to some of the apparent irregularities of the revolving bodies, which would not be easily explicable on any other hypothesis. ”

John Mitchell Phil. Trans. R. Soc. (Lon) (1784)

“A luminous body of the same density as earth, whose diameter is 250 times larger than that of the sun, can by its attractive power prevent its light rays from reaching us, and consequently, largest bodies in the universe could remain invisible to us.

There exist, in the immensity of space, opaque bodies as considerable in magnitude, and perhaps equally as numerous as stars.’ ’



M Le Marquis de Laplace/ Peter Simon Laplace
Exposition du systeme du Monde, Part II (1798/1799)

In spite of these fascinating conclusions, the reasoning was conceptually flawed! Since all speeds are relative in Newtonian physics, it predicts that we should be able to see black holes by reflected light (just as we see the moon)!

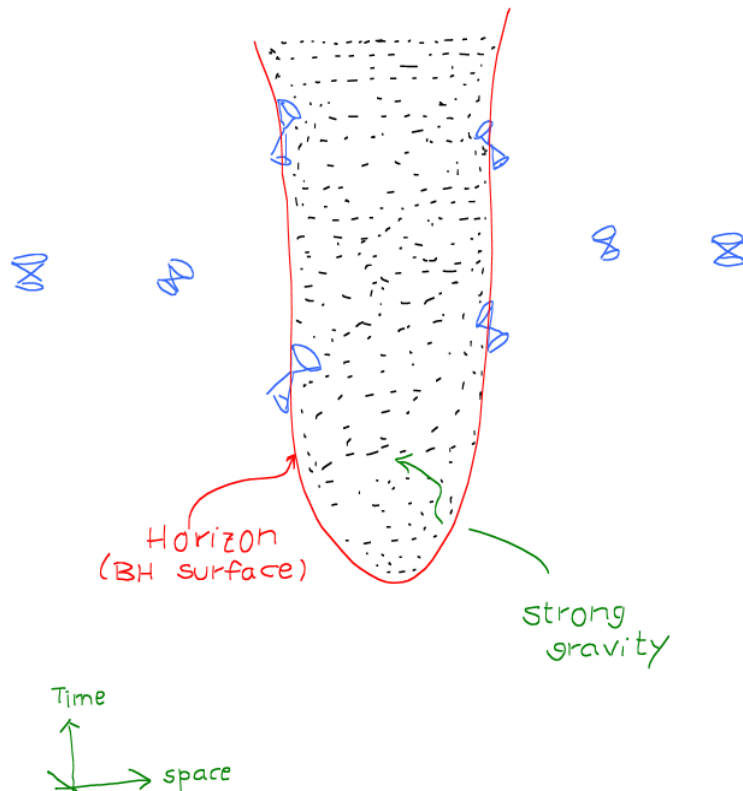
Need: Both an absolute of speed of light and gravity



General relativity!

In GR one can have regions in which light is trapped in an absolute sense, irrespective of who observes.

Curved space-time essential!



Curious History of Black Holes in GR

- The simplest black hole solution discovered by Schwarzschild while serving on the front during WWI. But a clear black hole interpretation had to await several decades both because leading researchers did not understand the interplay between geometry and physics well.
- Chandrasekhar's Discovery (1931-35): Fate of heavy stars
- Oppenheimer & Snyder (1939): Gravitational collapse to a Black hole in general relativity.
- General reluctance in accepting the idea that stars more massive than the Chandrasekhar limit have no equilibrium configuration once they exhaust their nuclear fuel. Astronomers preferred a serene, calm universe, not a violent one. And there was a quirk of history: the 1939 paper of O & S appeared the same day as Bohr and Wheeler's paper on nuclear fission. Also the day when Hitler invaded Poland!

Prominent Examples of the reluctance

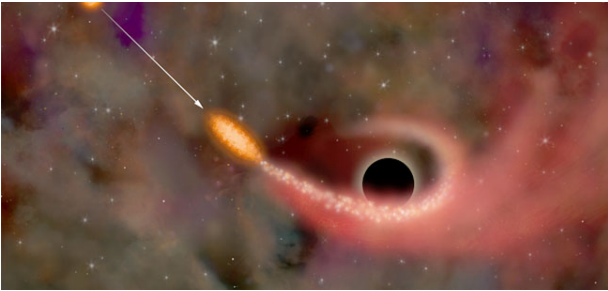
- The Chandrasekhar-Eddington episode:

“Various accidents may intervene to save the star. But I want more protection than that. I think there should be a law of Nature to prevent the star from behaving in this absurd way!” — A. Eddington, 1931

- Einstein: Ann. Math. XI, 922–936 (1939): Impossibility of formation of a black hole through gravitational collapse! Oppenheimer-Snyder paper just a few months later! Bergmann: No mention of BHS in the influential 1942 book.

- Late seventies: Widespread belief that black holes were mathematical solutions with no physical significance in both physics and astronomy communities.

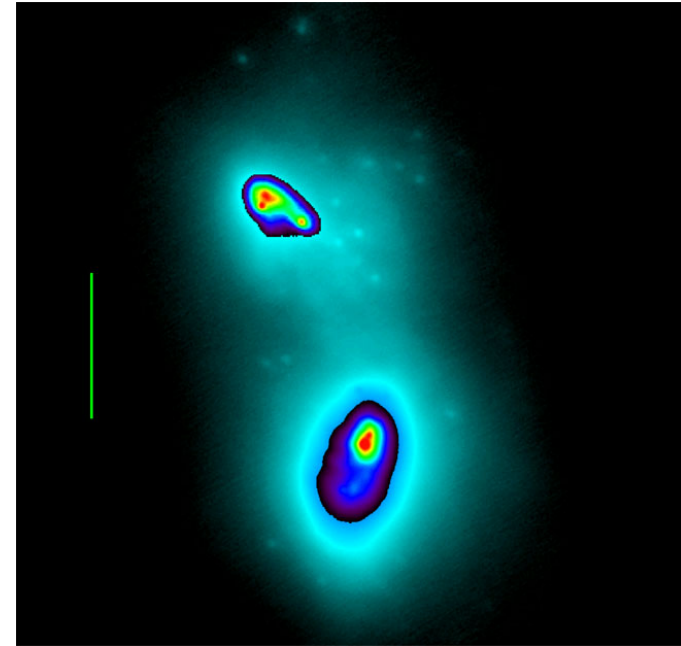
Now: BHs routinely invoked as engines driving the most energetic explosions in the universe



Black hole accretion: X ray image



Gamma ray burst; in a few blinding seconds, more energy is emitted than what a thousand suns do in their life time!



A Black hole merger

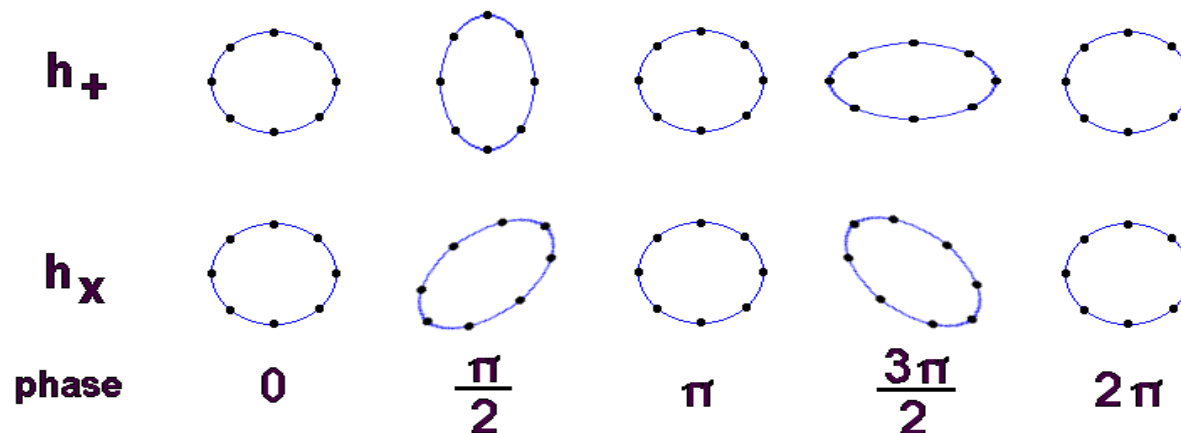


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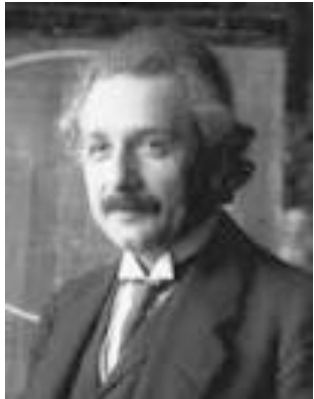
Ripples on space-time: Gravitational waves

- Einstein: 1916: Just as time-changing electric dipole produce electromagnetic waves (x rays, visible light, infrared, radio waves...), in general relativity, time-changing quadrupole produce gravitational waves.



Gravitational Waves: Curious History

- Great confusion until 1960s whether gravitational waves exist in full, non-linear general relativity or if they are artifacts of the (weak field) approximation Einstein made in 1916.



Einstein



Nathan Rosen



H.P. Robertson

Surprisingly, Einstein himself contributed to this confusion. In a letter to Max Born, he wrote in 1936:

“Together with a young collaborator I arrived at the interesting result that gravitational waves **do not exist**

though they had been assumed to be a certainty in the first approximation. This shows that **non-linear gravitational wave field equations tell us more or, rather, limit us more than we had believed up to now.**”

Resolution of the confusion



Hermann Bondi



Roger Penrose

Reality of gravitational waves in full, non-linear general relativity was firmly established only in the 1960s through systematic theoretical analysis by Bondi, Penrose and others



Russell Hulse

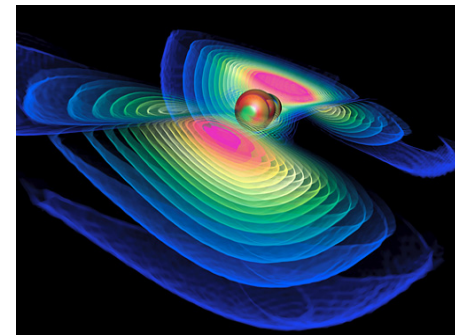


Joe Taylor

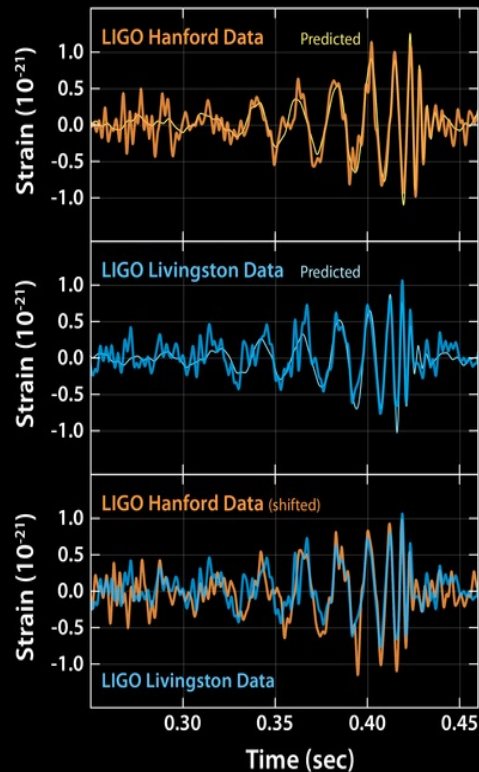
On the observational side, it was established by the careful observations by Russell Hulse and Joseph Taylor of a binary pulsar system in the 1970s-1990s period (1993 Nobel Prize).

Novel Cosmic Messengers

- Why such indirect methods of detection? Gravitational waves are ripples in space-time geometry and space-time geometry is extremely rigid. The effective Young's modulus of space-time (at 10^3 Hertz) is $\sim 10^{25}$ times that of rubber and $\sim 10^{22}$ times that of steel (B. Sathyaprakash) ! Only extremely violent events can shake space-time geometry sufficiently to create effects observable.
- But such events do occur: black hole collisions, supernovae explosions, gamma ray bursts. Gravitational waves provide detailed 'images' that we cannot obtain from conventional astronomy: We have a brand new window on the universe, that we could not even dream of in Newtonian gravity!

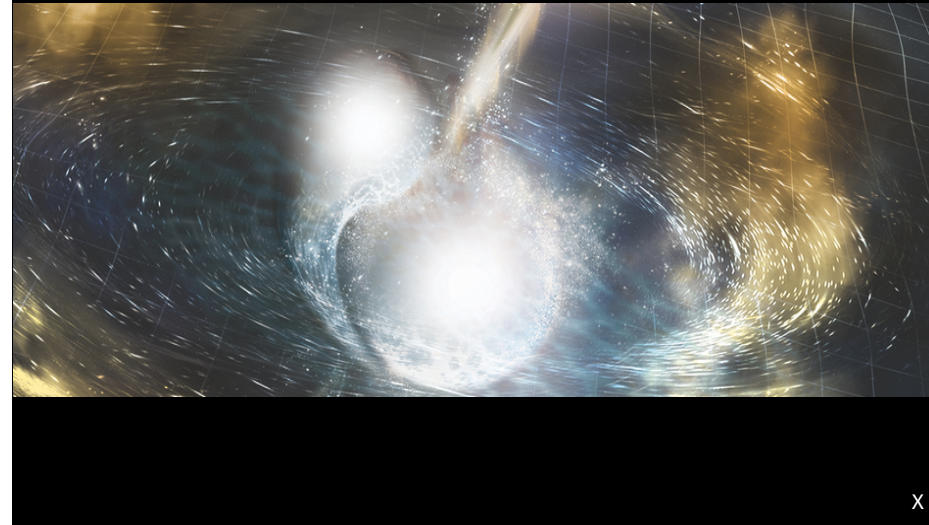


Direct detections on earth: Triumph of Human ingenuity.



BBH Merger event 150924
Loud! Occurred the first day the
advanced detector was turned on!!
Four subsequent BH-BH mergers.

GW170817: DISCOVERY OF INSPIRALLING BINARY NEUTRON STARS



Binary neutron star merger event 170817
Followed by ~70 em observatories.
Resolved the decades long mystery of
Short hard GRBs



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Summary

- I presented a few examples of paradigm shifts in fundamental physics/Astronomy.

“The physicists succeeded magnificently, but in doing so, revealed the limitation of intuition, unaided by mathematics; an understanding of Nature, they discovered, comes hard. The cost of scientific advance is the humbling recognition that reality is not constructed to be easily grasped by the human mind.”



Consilience, The unity of Knowledge
Edward O. Wilson.

- Paradigm shifts illustrate the **audacity** of the human race to see way beyond what is directly perceived.

Lessons

- Paradigm shifts I used offer some lessons for young researchers working at the cutting edge of science:
- First, what is now considered as commonplace knowledge, was not at all so just a few decades ago. In fact most of the scientific community at the time was thinking in an almost opposite direction. (Courage!)
- Second, precisely because they are so startling at first, dramatic paradigm shifts take decades to get settled and become the new common pool of knowledge. (Patience!)
- Third, factors driving or slowing the process are quite varied; it is not a matter of simple logical steps, as is made to appear in retrospect! (Maturity!)

(All three exemplified in Prof. S. Chandrasekhar!)