100 Years of General Relativity
A global perspective

Abhay Ashtekar

Physics Department &

The Institute for Gravitation & the Cosmos

The Pennsylvania State University

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Institute for Gravitation & the Cosmos

A bird's eye view of the discovery & the deep impact of General Relativity

Will be able to focus only on classical GR and, furthermore, only provide an impressionist portrait.

- Einstein's Revolution
- Birth of modern cosmology & the Big Bang:
- Warping of space-time & Black Holes
- Ripples on space-time: Gravitational Waves
- Summary

Einstein's Revolution: 1907 -1915

- The 1907 realization: Tension between the Newtonian Paradigm and the loss of absolute time in Special Relativity.
- Resolution: A new theory of space, time and gravitation?
- 1913: Planck visits Einstein in Zurich.

"*As an older friend, I must advise you against it, for, in the first place you will not succeed, and even if you succeed, no one will believe you.*"

---Planck to Einstein

- *Solution: 1915* General Relativity

Discovery of General Relativity

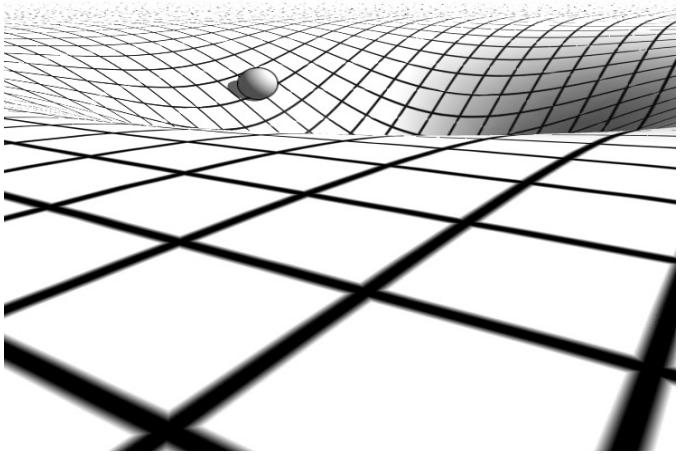
"During the last month, I experienced one of the most exciting and most exacting times of my life, true enough also one of the most successful. ….

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

Einstein to Sommerfeld
November 28, 1915

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.



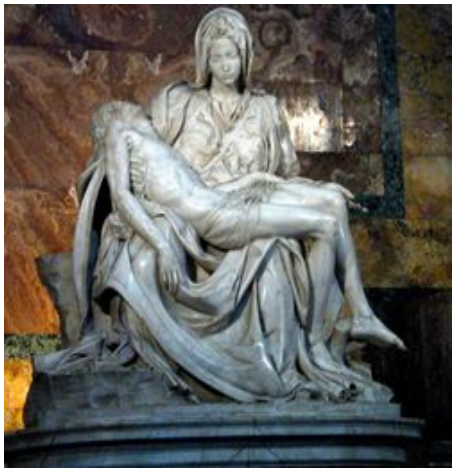
- Matter tells space-time how to curve. Space-time tells matter how to move.

- Geometry intertwined with matter via Einstein's equations.

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

THE *NEW YORK TIMES*, MONDAY, NOVEMBER 10, 1919

LIGHTS ALL ASKEW IN THE HEAVENS

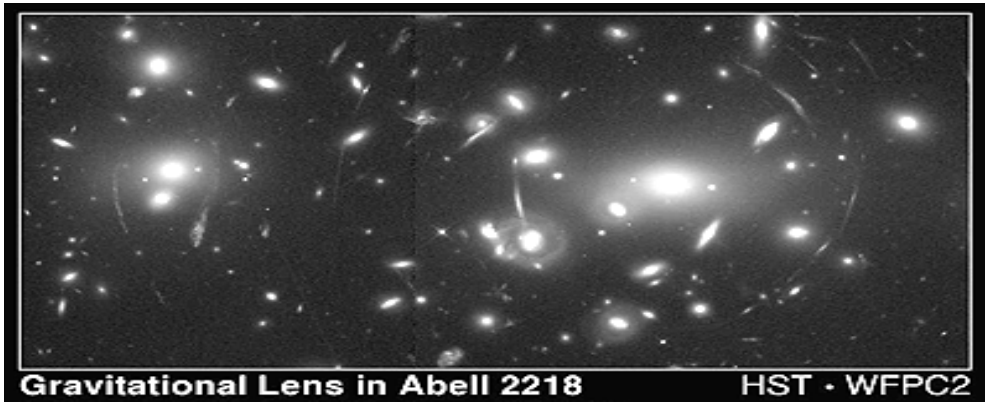
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be *but Nobody Need Worry*.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend it, Said Einstein When His Daring Publishers Accepted it.



What use is it ? Does it matter?

- Why care? Conditions have to be so extreme.
- Not really. Both special and general relativity effects critical for GPS! If ignored, within 2 minutes, the GPS accuracy will fail to be sufficient for today's airplanes 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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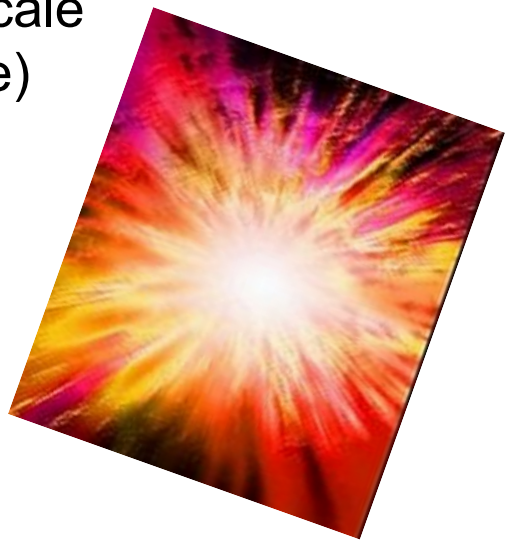
Cosmology
Application of GR to the Universe As a Whole

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

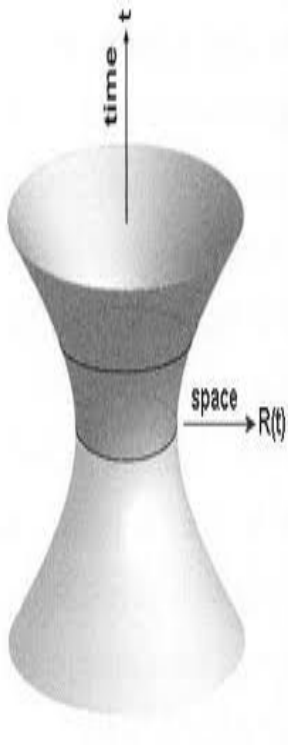


- Geometry must be **Dynamical**,
  Related to Matter via Einstein's Eqs.

- Standard Picture: Universe began with a
  Primordial Explosion ~13.8 Billion years ago

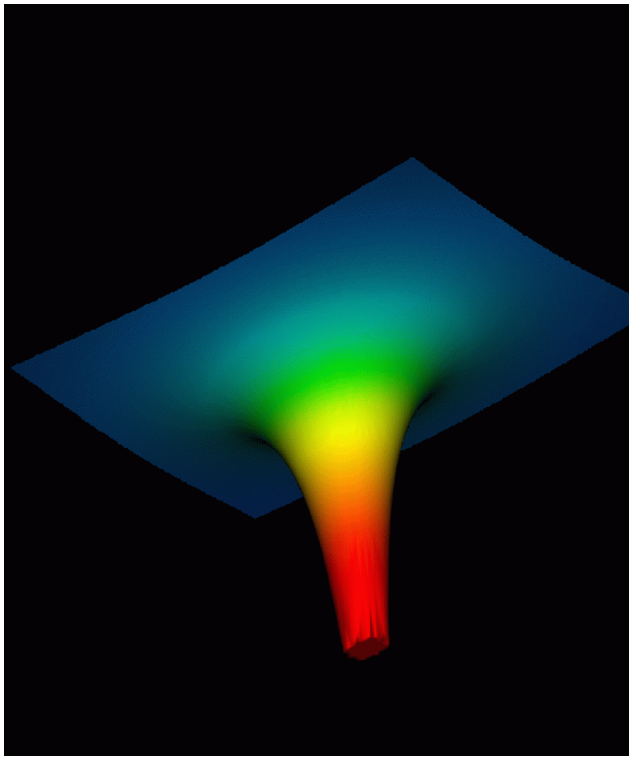
The Issue of the Beginning: Curious History

Einstein (1917)
de Sitter (1917)
Eternal Universes



No beginning or end;
No singularity

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



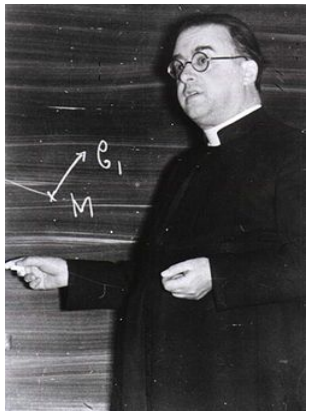
Big Bang! The space-time continuum tears and classical physics stops!

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)

  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, …)

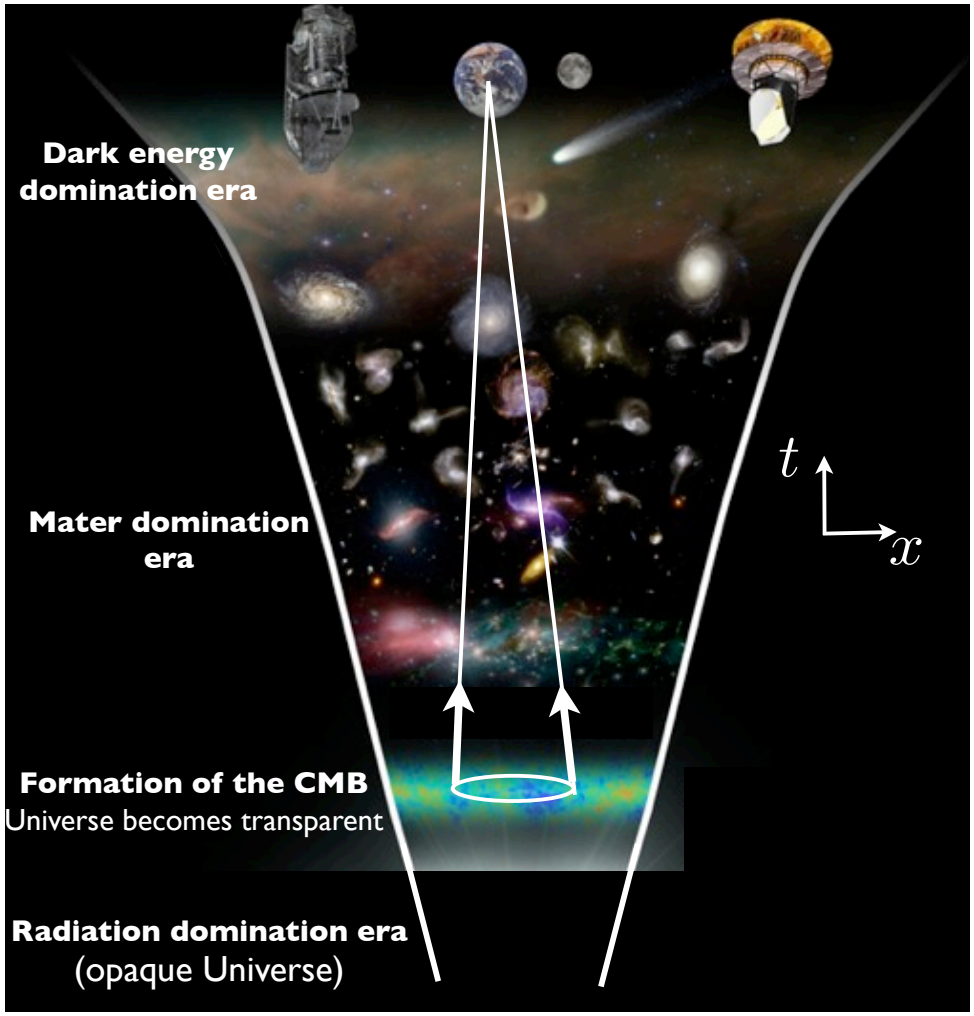
From Mathematics & Aesthetics to Physics

- Cosmology and the issue of the Big bang remained outside mainstream physics until

- 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



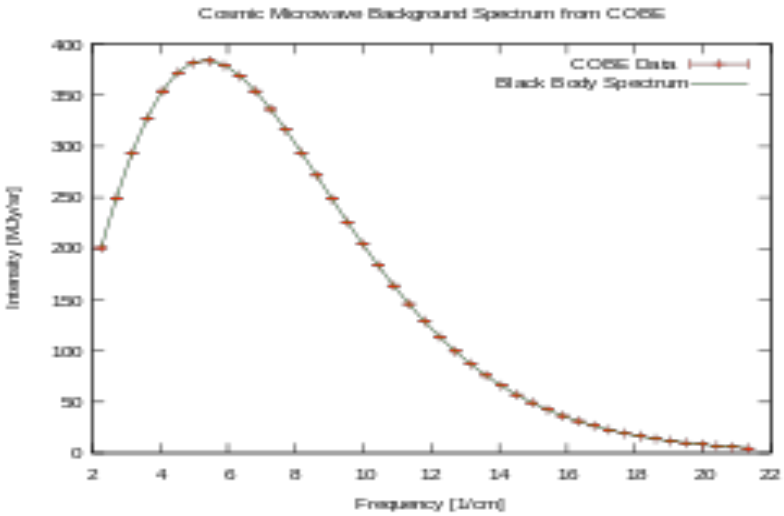
Snapshot of the universe when it was 380,000 years young!

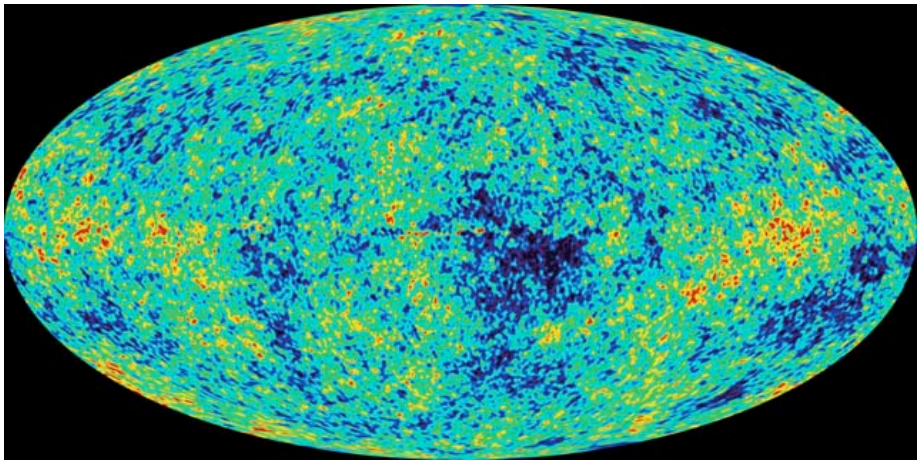
Spectacular success over the last two decades: Powerful interplay between theory and high precision observations especially through space missions,

COBE; WMAP & PLANCK

Cosmic Microwave Background

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

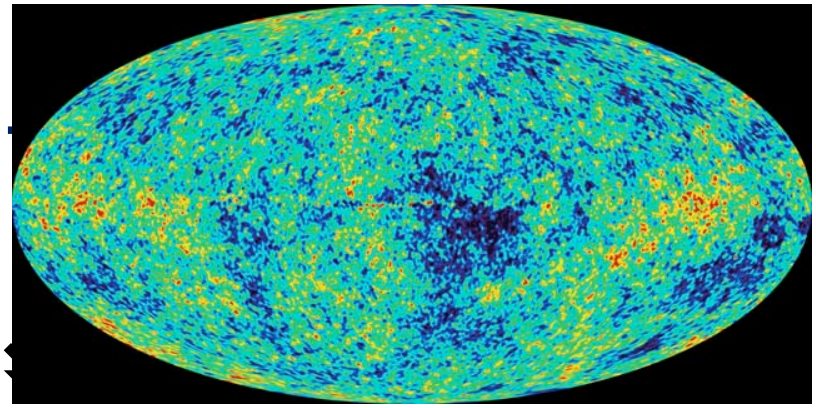




(Image credits: NASA)

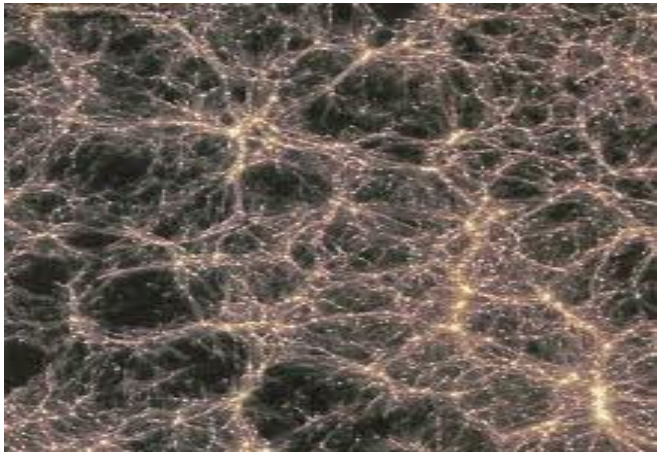
But tiny inhomogeneities of 1 part in 100,000.

Cosmic Microwave Background



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

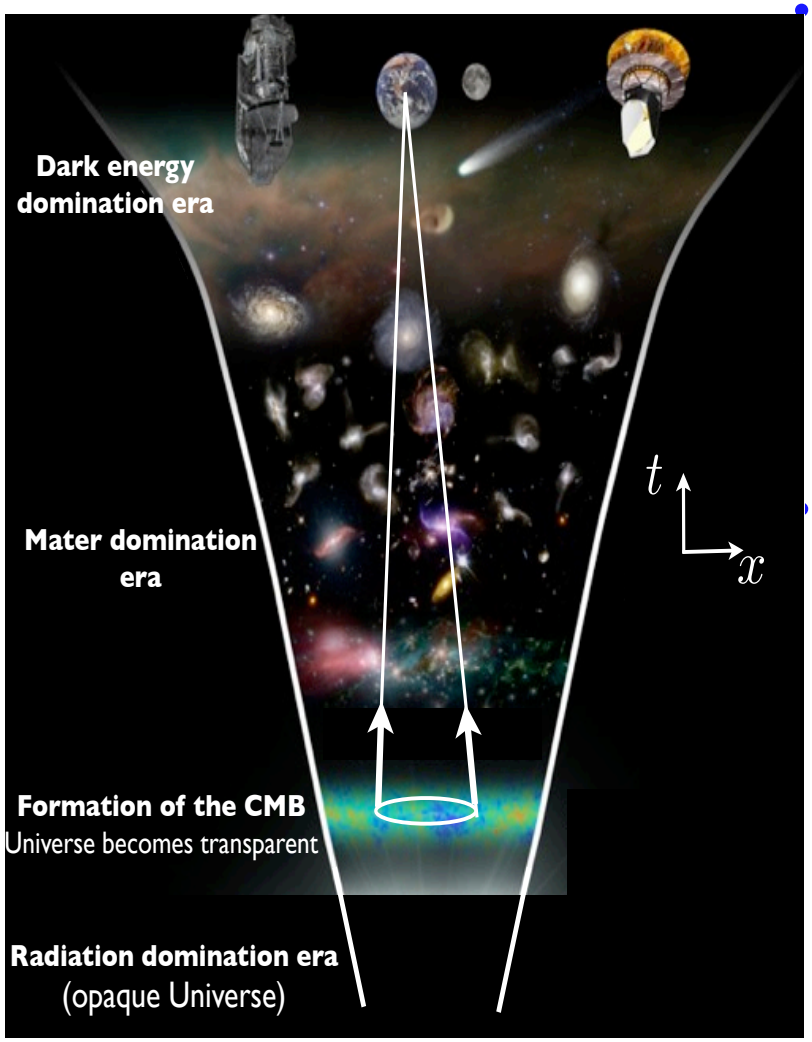
TINY inhomogeneities seen in CMB when the universe was 380,000 years young grow obeying general relativity…



Triumph of General Relativity!

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

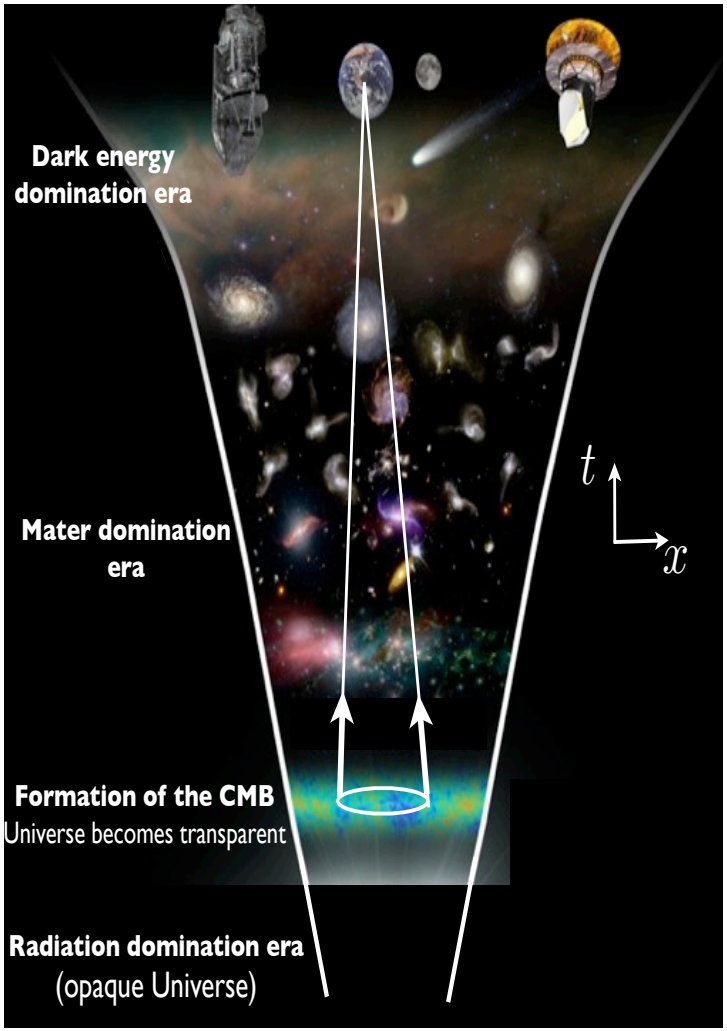
Origin of Inhomogeneities in the CMB?



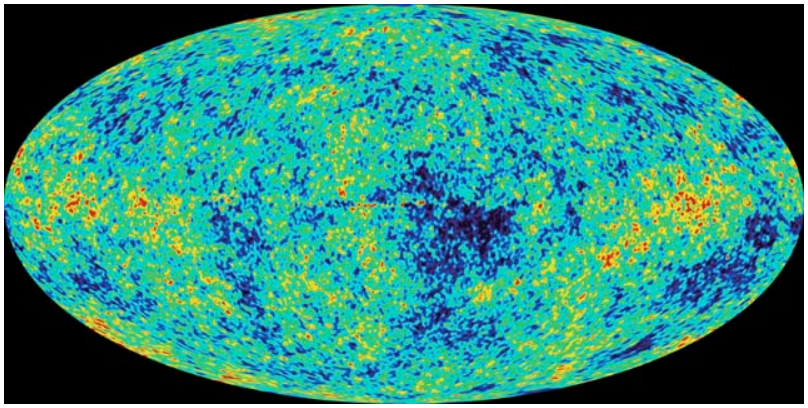
- **Inflation:** Soon after the Big Bang the universe underwent a phase of rapid expansion. At the onset of this phase universe was completely homogeneous EXCEPT for the ever present vacuum fluctuations which cannot be gotten rid of even in principle! (Mukhanov & Chibisov; Guth;...)

- The vacuum fluctuations are shown to grow in time to produce exactly the inhomogenities seen in the CMB.

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



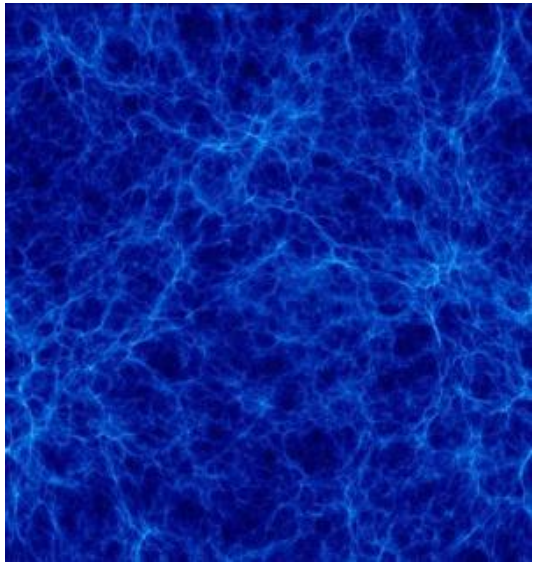
QFT on a classical FLRW space-time



Classical gravity

The origin of the Cosmic Structure:

Quantum Nothingness!



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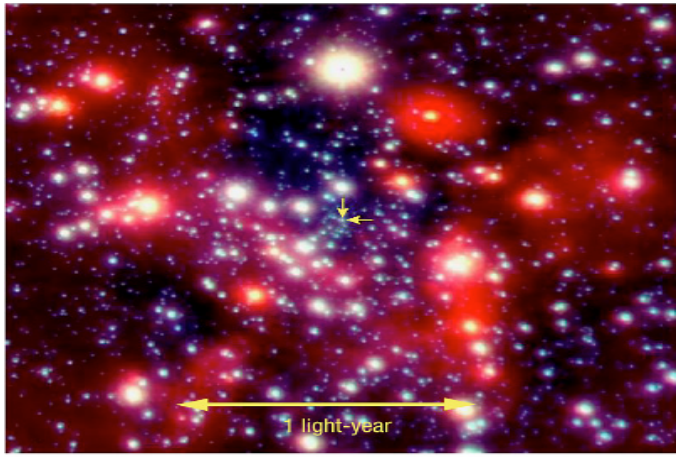
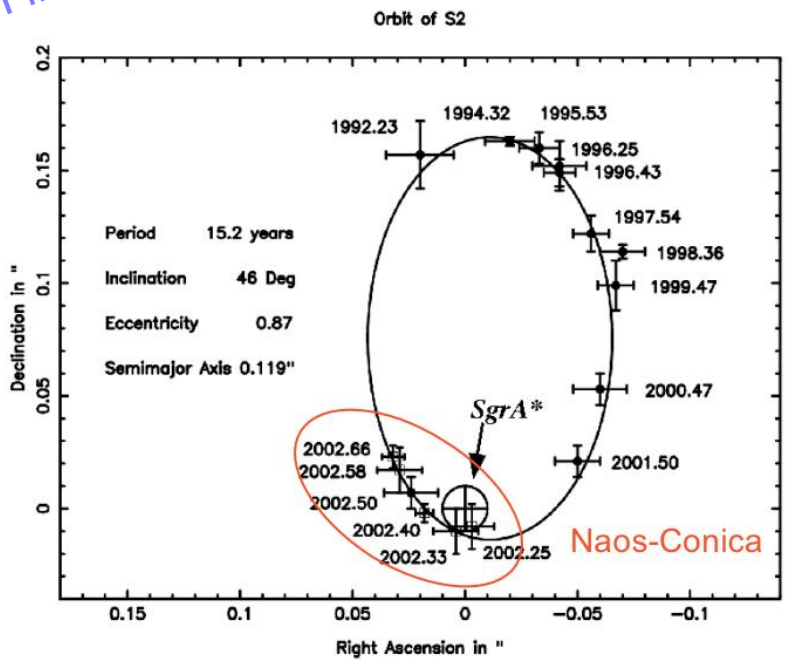
Our Own Black Hole: sgr A*



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_0 BH in the Center of the Milky Way



Amazingly, predictions appeared 232 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.''

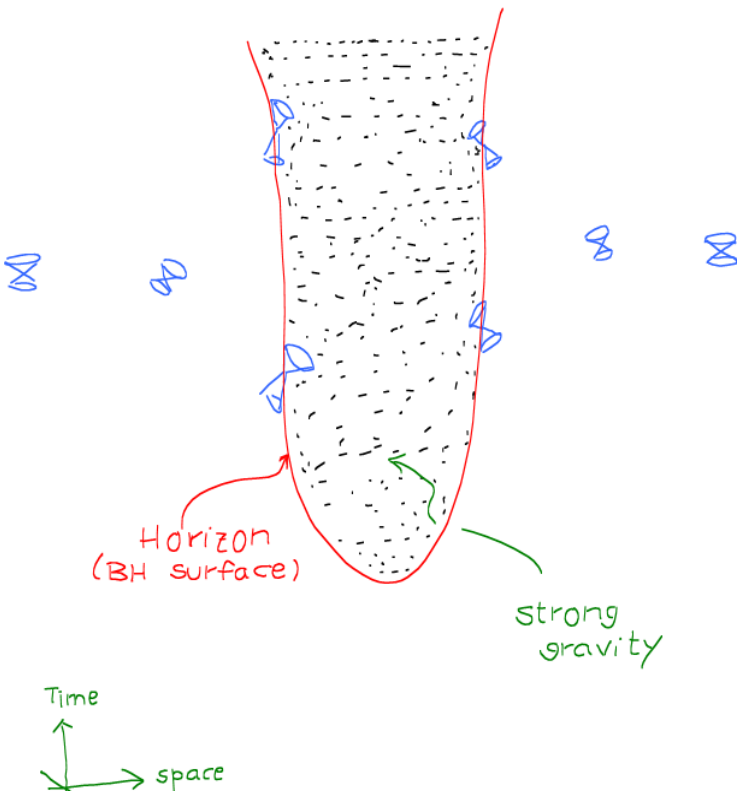
John Mitchell Phil. Trans. R. Soc. (Lon) (1784)

"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

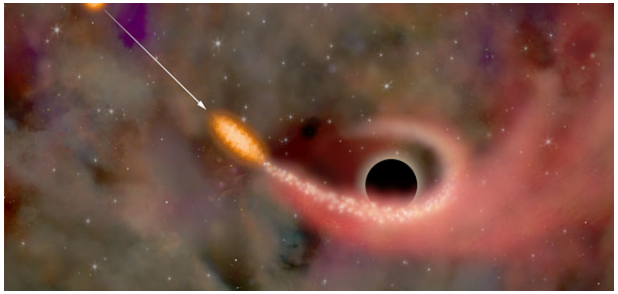
- The simplest black hole solution discovered by Schwarzschild while serving on the front during WWI. But a clear black hole interpretation had to await several decades!
- The Chandrasekhar-Eddington episode:

"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

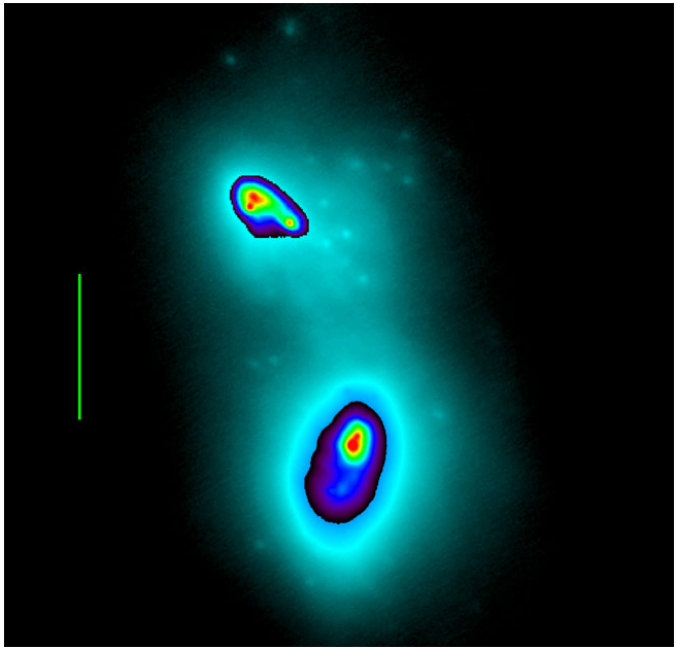
- Einstein: Ann. Math. XI, 922–936 (1939): Impossibility of formation of a black hole through gravitational collapse! Oppenheimer-Volkoff paper just a few months later! Bergmann: No mention of BHS in the influential 1942 book.

- Late seventies: Widespread belief that black holes were mathematical solutions with no physical significance.

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



Black hole accretion: X ray image



A Black hole merger

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

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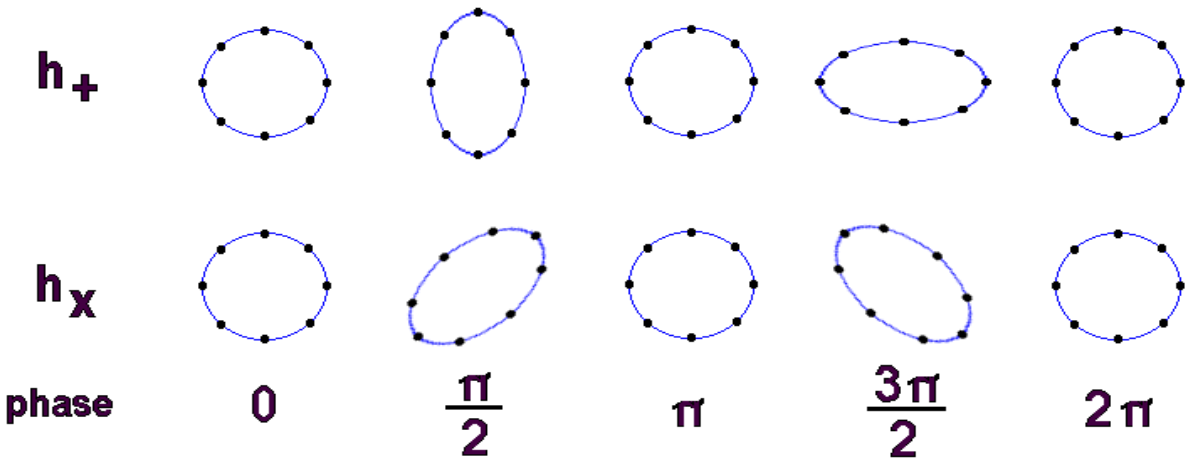
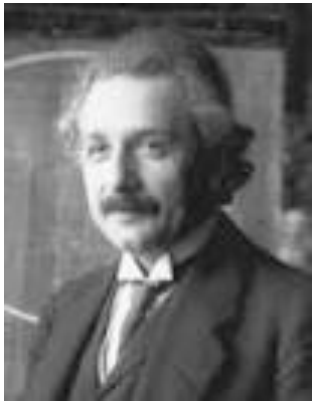
Ripples on space-time: Gravitational Waves

- Einstein: 1916: Just as moving electric charges produce electromagnetic waves (x rays, visible light, infrared, radio waves…), in general relativity, moving masses produce gravitational waves (technically, time changing quadrupole (rather than dipole) moment) .



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

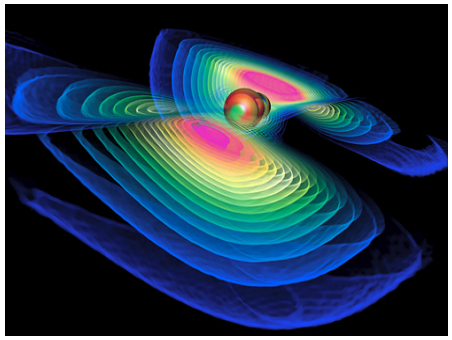
On the observational side, it was established by the careful observations by Russell Hulse and Joseph Taylor of a binary pulsar system in the 1970s-1990s period (1993 Nobel Prize).

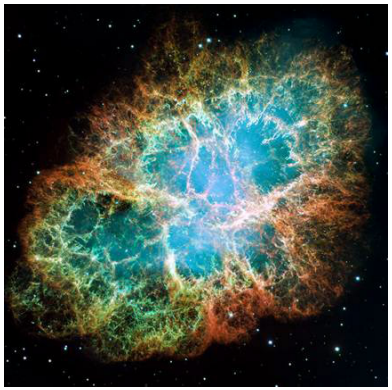
Russell Hulse

Joe Taylor

Novel Cosmic Messengers

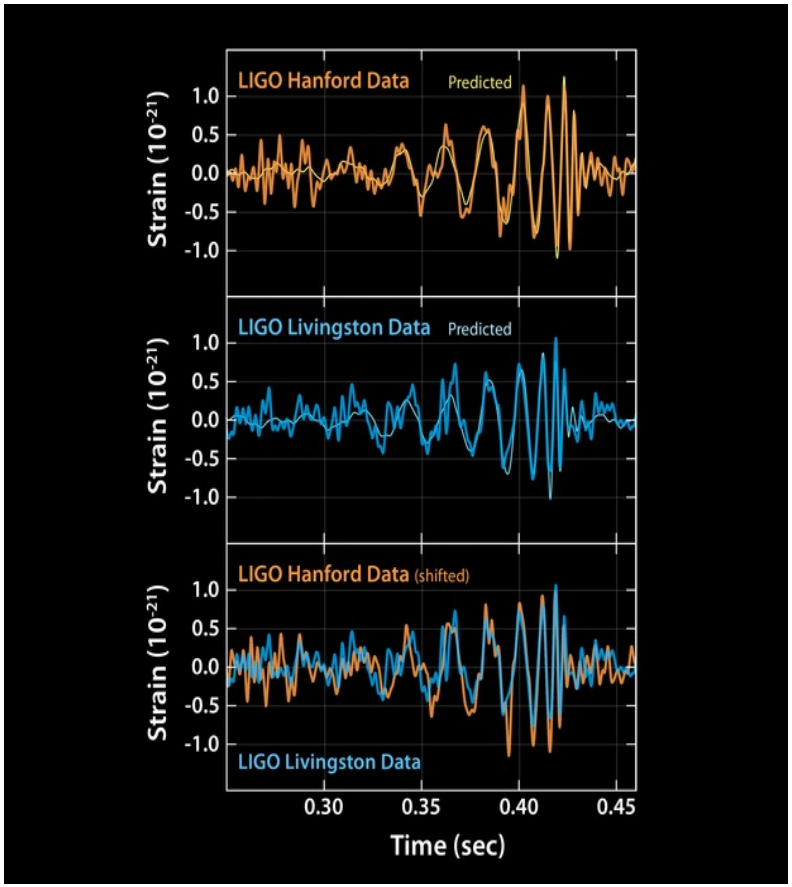
- A brand new tool to probe the most violent/ energetic events in the universe such as black hole collisions, supernovae explosions, gamma ray bursts. Gravitational waves will provide detailed 'images' we cannot obtain from conventional astronomy: A deep potential to unravel deep secrets of our cosmos.





Examples: We already knew that there are no mountains on the crab pulsar that is higher than a meter! We can already constrain equation of state of nuclear matter.

The cosmic messengers arrive on earth!



The Event of September 14th 2015: Livingston and Hanford observatories. Spectacular merger of two BHs ~30 M_o that took place when earth was spawning first multi-cellular life.

Sheer audacity of the human race!

Auspicious Beginning for the Second Century of GR

- Real reason for excitement: A brand new window on the universe has opened! Following footsteps of Galileo, radio astronomy, cosmic rays, neutrinos ⋯ and now ripples in the very fabric of space-time.

- We already had a second event on December 26th, 2015. Again a black hole collision ~20 M_o and ~6M_o. Over the next year, it is widely expected that there will be many more, including neutron star mergers that will enrich our understanding also astrophysics & nuclear physics.

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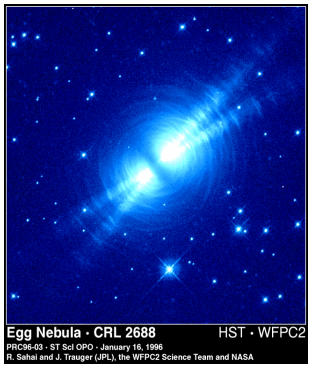
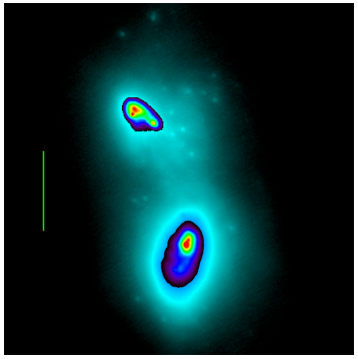
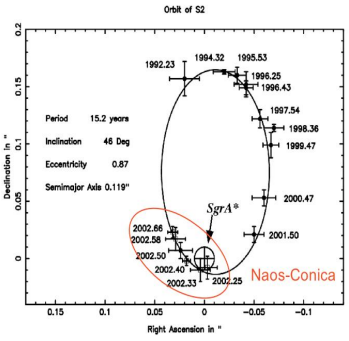
- The discovery of general relativity by Albert Einstein 100 years ago was quickly recognized as a supreme triumph of the human intellect. Dirac Called it “probably the greatest scientific discovery ever made”. For eight years, 1907-1915, Einstein had been consumed by the tension at the foundation of physics. He discovered a theory that represents an unprecedented combination of mathematical elegance, conceptual depth and observational success. **The process carries many lessons for young researchers.**
- As decades passed, new aspects of this revolutionary paradigm continued to emerge: The Big Bang, the black holes and the gravitational waves, …
- A century has now passed since Einstein’s discovery and yet every researcher who studies general relativity in a serious manner continues to be enchanted by its magic.

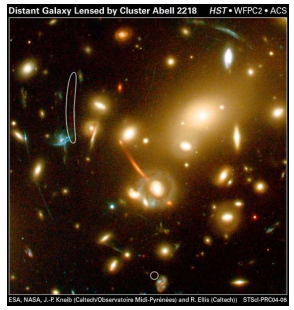


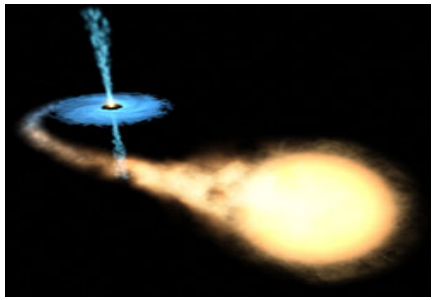
Triumphs of General Relativity

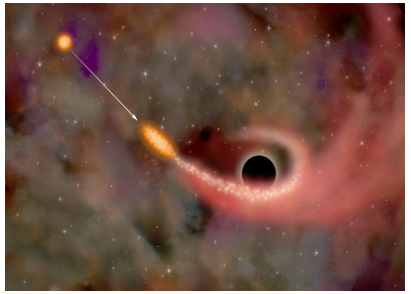


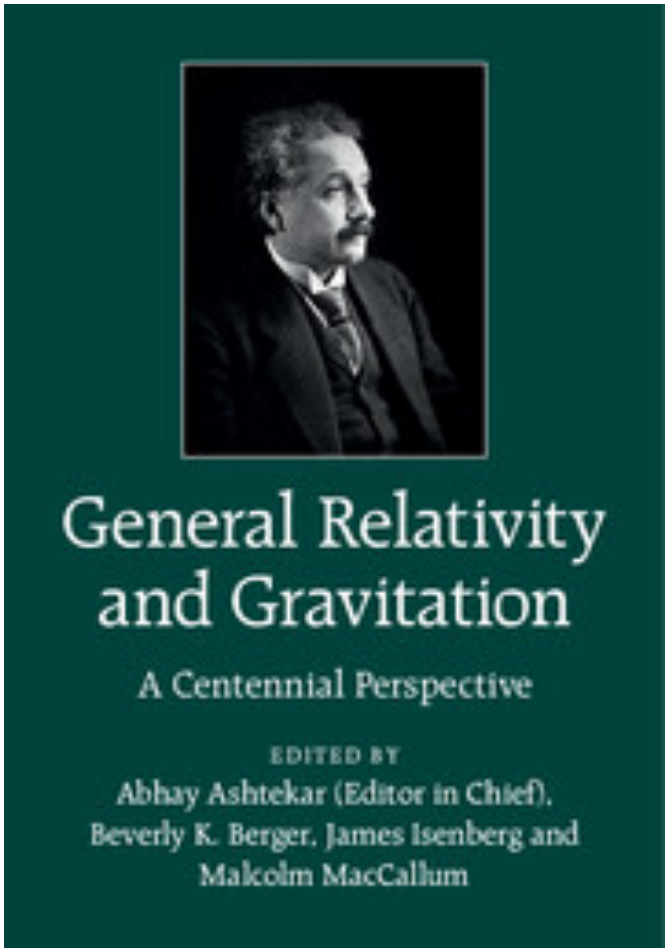
Thanks to the steady advances over the past 50 years, general relativity has matured. It has led to unforeseen developments in mathematics (geometric analysis) and computational-physics (numerical simulations and data analysis) and quantum physics in addition to cosmology and astrophysics I focused on.











Centennial Volume Commissioned by the International Society on General Relativity and Gravitation, published by Cambridge UP. Released during the Penn State Conference in June 2015. Provides a thorough perspective on all these areas.

Four PARTS

1. Einstein's Triumph
2. Gravitational Waves: A New Window on the Universe
3. Gravity is Geometry, Afterall
4. Beyond Einstein

First Century of General Relativity

Einstein to Sommerfeld
February 8, 1916

"of general theory of relativity, you will be convinced, once you have studied it. Therefore, I am not going to defend it with a single word."