The Renaissance of General Relativity

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Century of GR MPIWG Conference; Nov 2015; Berlin

GR3: Warsaw 1962

1st Texas Symposium: Dallas 1963

Organization

- Assessing Einstein's Legacy in Post WWII Physics: ``During this century, GR evolved from a revolutionary mathematical theory with limited contact with the empirical world to an observationally and experimentally based cornerstone of modern physics and cosmology."

- Goal of This Talk: To Provide a broad overview of this renaissance through illustrative examples that could serve as focal points of future studies for historians and philosophers.

- 1. Structure/Foundations of GR
- 2. Applications of GR
- 3. Beyond GR: Quantum Aspects

1. Structure & Foundations of GR

- Singularities of GR: Great debate on whether the singularities are artifacts of high degree of symmetry (e.g., the Soviet program of late 1950s). Singularity theorems of Penrose, Hawking, Geroch,… caused a paradigm shift. Singularities came to be recognized as common occurrences in GR. Global methods were introduced, transforming the `standard' GR monographs (from Eddington, …. Bergmann … to Hawking & Ellis, … Hartle …).

- Penrose's Cosmic censorship hypothesis has been a driving force behind many investigations in geometric analysis as well as numerical GR for decades.

- On the other hand, `classification of singularities' which drew a lot of attention in the 70s has not proved to be fertile field.

Geometric Analysis

- Complementary development: emphasis on hard analysis.

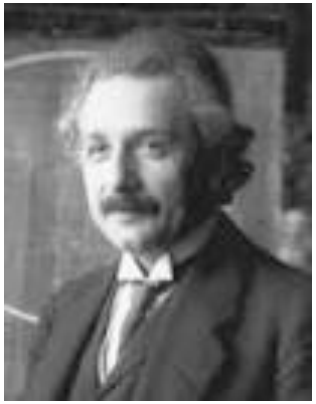
(i) Positive energy theorems. (Schoen & Yau; Witten; …) Transformative event sparked by a conference in California during which Geroch explained the issues to the mathematics community. Created an influx of `pure mathematicians' to GR especially in the US. Brought out another dimension of the depth of GR! The total (Arnowitt-Deser-Misner) energy provides a brand new invariant for Riemannian manifold with applications to mathematics.

(ii) Global existence and uniqueness. Non-linear stability of de Sitter space (Friedrich), Minkowski space (Christodoulou, Klainermann, …) and the surprising instability of the anti-de Sitter space (Bizon, …).

- This transformation has had significant impact: classical GR has steadily moved from physics to (pure) mathematics departments.

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 1917.



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 of the binary pulsar PSR 1913+16 by Russell Hulse and Joseph Taylor in the 1970s-1990s period.

Russell Hulse

Joe Taylor

Black Holes

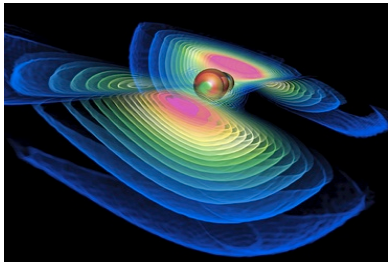
- Uniqueness theorems for Einstein-Maxwell theory in 4-space-time dimensions (Israel, Hawking, Robinson, Bunting, Mazur, …). Very surprising contrast with stationary stars.

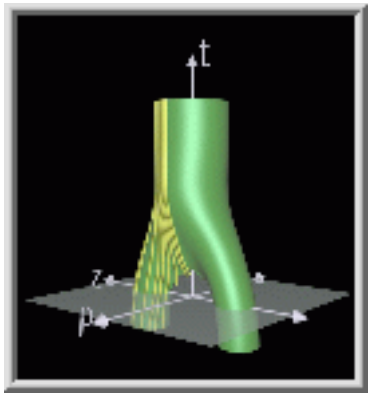
- But the `ho hair theorems' fail in more general theories (e.g. Einstein-Yang Mills) in 4-d and even vacuum GR in higher dimensions.

- A fascinating surprise: Laws of Black hole mechanics have an uncanny resemblance to laws of thermodynamics! (Bekenstein; Bardeen, Carter, Hawking, …) A driving force for a large body of research over the last 40+ years.

- Quasi-local horizons: Overcoming the limitations of event horizons. (Hayward, AA, Krishnan, …..).

Numerical Relativity





- The field was born only in the 1970s and therefore offers another interesting "case study". Brand new insights; discovery of critical phenomena; correction of intuition in important ways (e.g. for coalescence of binary black holes, simulations showed that the consequences of the non-linearities of GR, while important, are nowhere as wild as people had expected). Discovery of new physics that would not have been found analytically for decades if ever (e.g., new mechanisms for distribution of heavy elements from simulations of binary neutron star collisions).

- All the advances I discussed occurred during the Renaissance of GR. These thriving subfields of GR did not even exist a few years before Warsaw and Dallas conferences!

Organization

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- 1. Structure/Foundations of GR √
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2. Applications of GR: Cosmology

- Advances in cosmology have been spectacular. For example, the 1963 Warsaw conference had no plenary talk and only two seminars on cosmology proper. One on Steady state (Bondi), and one on anisotropy & inhomogenity (Zelmanov). We have come a very long way!

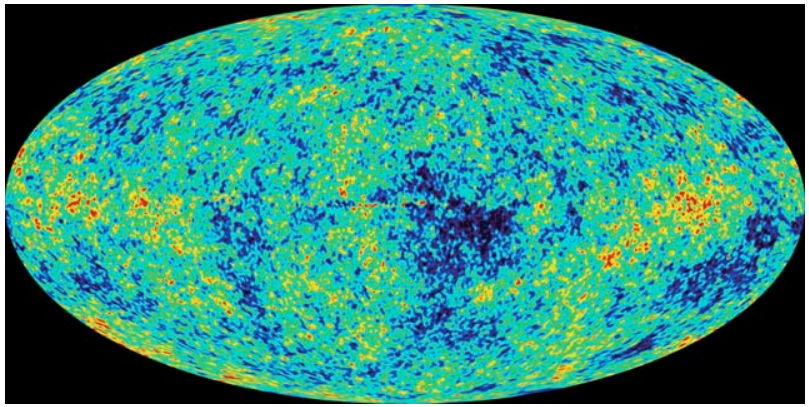
- In 1964, Hubble parameter was estimated to be 125km/(s Mpc); in the 70s, lively debate between values 100 and 55. Now we know it is 67.8 within 1.33% error! We know that the temperature of the CMB is 2.7255 within 0.02% error! We know that the power spectrum is not exactly scale invariant because n_s is 0.968 within less than 0.62% error. All this with an excellent fit to a 6 parameter model. Cosmology has evolved to `precision science'.

- Major input from the theoretical High energy community & huge advances on the observational front. Healthy confrontations between theory & observations reflecting maturity of the field.

From Mathematics & Aesthetics to Physics

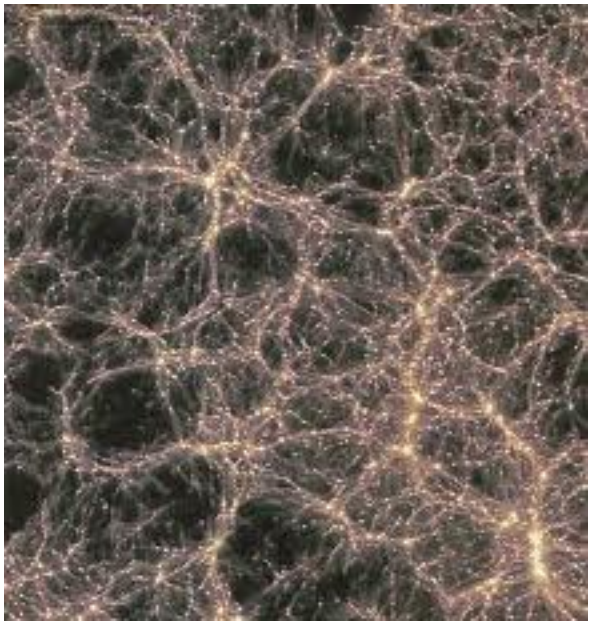
- Cosmology and the issue of the Big bang remained outside mainstream physics until
- Nucleosynthesis was understood: Gamow, Alpher, Herman (1948-65: Early universe essential as an oven for cooking light elements)
- Cosmic Micro-wave Background: CMB Dicke, Peebles, Roll, Wilkonson (1965 onwards: Relic or primordial radiation left over from when radiation decoupled from matter.)
- COBE (launched in 1989); WMAP (2001); and Planck (2009) have truly revolutionized our understanding of the cosmos. Parameter space vastly reduced.

Cosmic Microwave Background



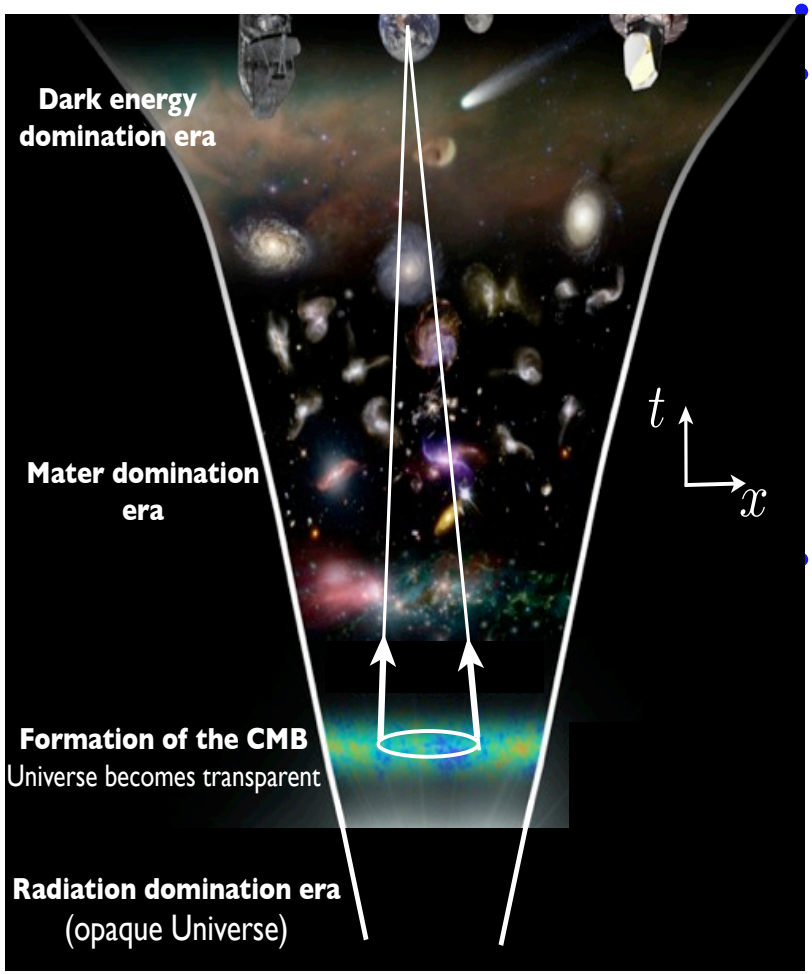
…Into the complex large scale structure of the universe seen now, 13.8 billion years later.

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



Triumph of General Relativity & Astrophysics! In human terms: from the Snapshot of a baby 1 day after birth, providing an accurate profile at age 100!

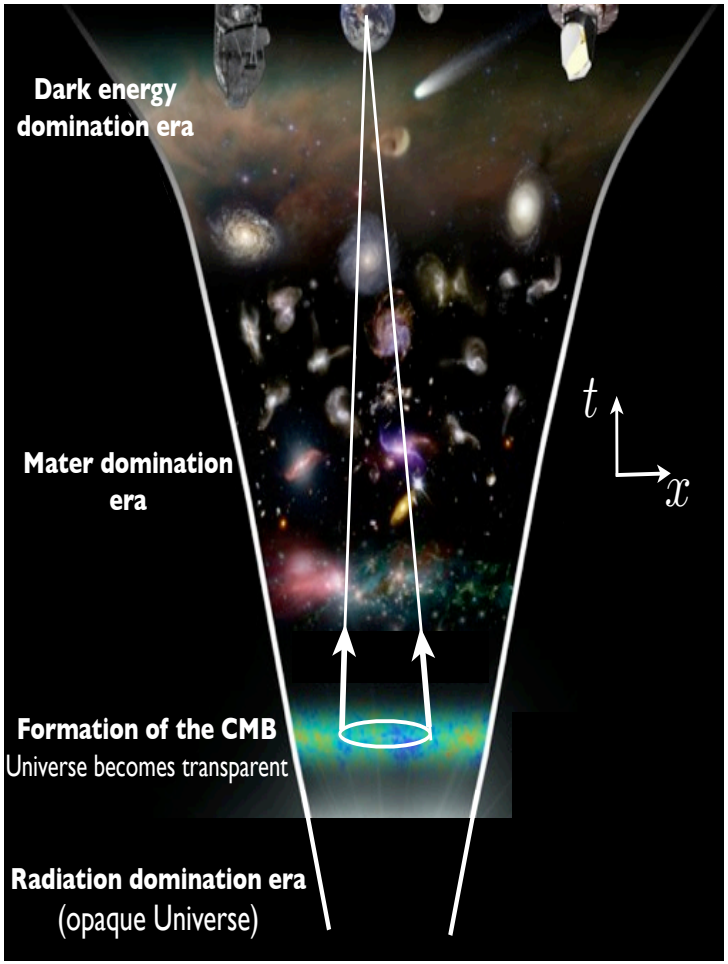
Origin of Inhomogeneities in the CMB?



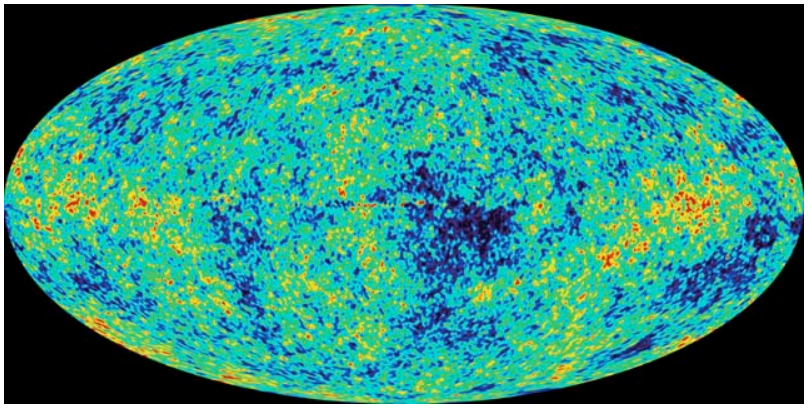
- **Current leading Scenario: Inflation.** Soon after the Big Bang the universe underwent a phase of rapid expansion. At the onset of this phase universe was completely homogeneous EXCEPT for the ever present vacuum fluctuations which cannot be gotten rid of even in principle! (Mukhanov & Chibisov; Guth;...)

- 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!**



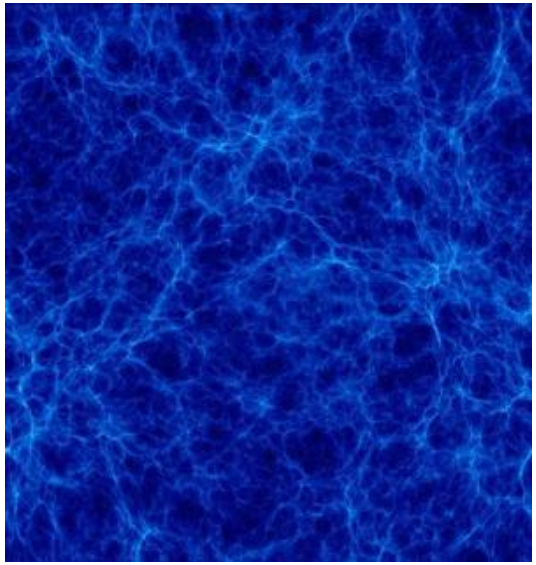
QFT on a classical FLRW space-time



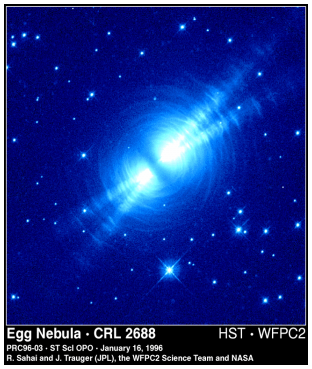
Classical gravity

The origin of the Cosmic Structure:

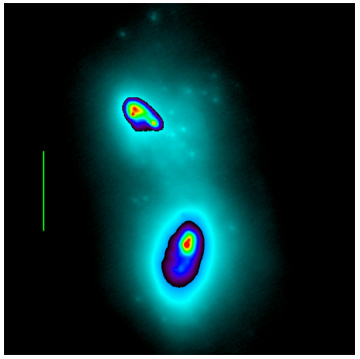
Quantum Nothingness!



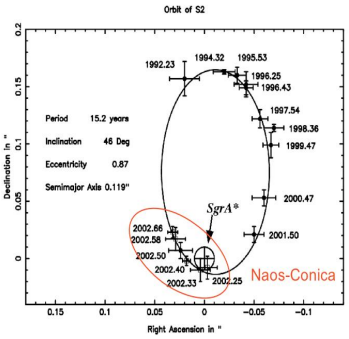
Very interesting paradigm shift for philosophy of science. Idea not restricted to inflation.

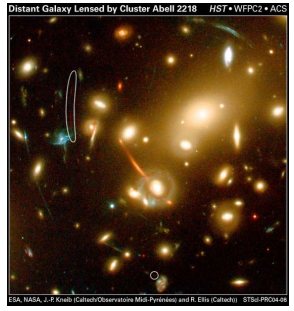


Relativistic Astrophysics



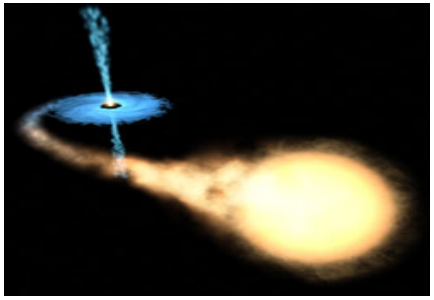
Not a single talk on this subject in the Warsaw conference. Field essentially born at the Dallas conference with the discovery of quasars. Since then the field has evolved considerably in several directions!

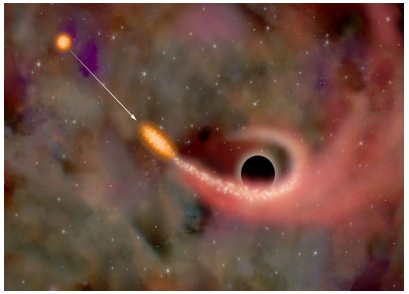




Some striking Examples:

- Gravitational Lensing
- Neutron Stars
- Black holes.



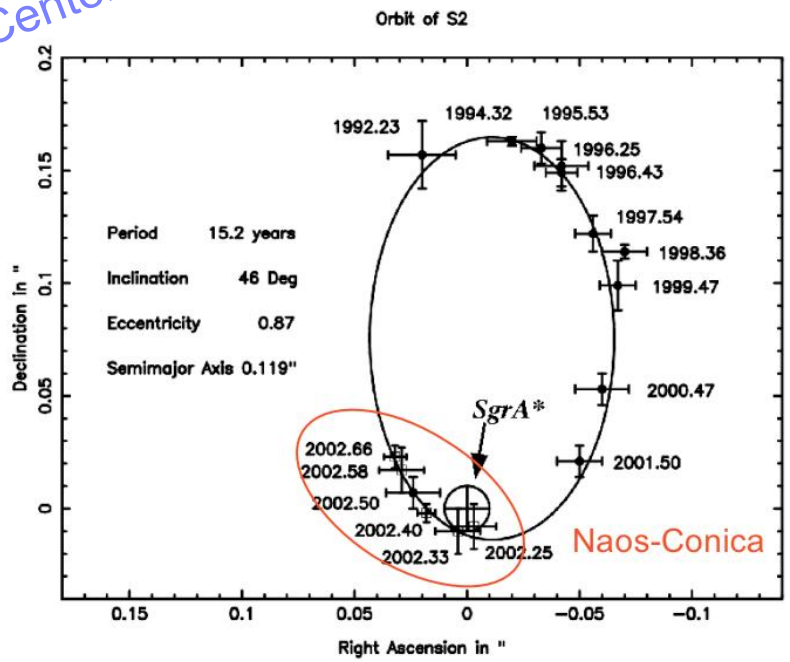


Our Own Black Hole: sgr A*

Interesting that the methods first used to study this BH were discussed by John Michell in Phil. Trans. R. Soc. (Lon) (1784)!

Sagittarius A*, ~ 4 Million M_0 BH in the Center of the Milky Way

Event Horizon Telescope has been studying this BH closely.



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.

Dawn of a new era

- The binary & especially double pulsars!
  (Einstein @ Home discoveries!!)

2.5 years after the discovery of the binary PSR J0737-3039 A/B
Keplerian parameter s same as in GR to 0.05% accuracy!
Masses: $m_A = 1.3381 M_o$; $m_B = 1.2489\ M_o$ to 0.05% accuracy.

- Revolution waiting in the wings: Gravitational Wave Astronomy. Global network of detectors: LIGO, VIRGO, GEO, (Kagra; LIGO-India). Mind-Boggling sensitivity; displacements

10^{-18} m measured using 4 km-arm interferometer. No detection has interesting consequences: No mountain on crab higher than a meter!

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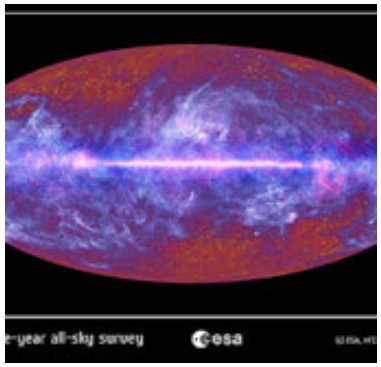
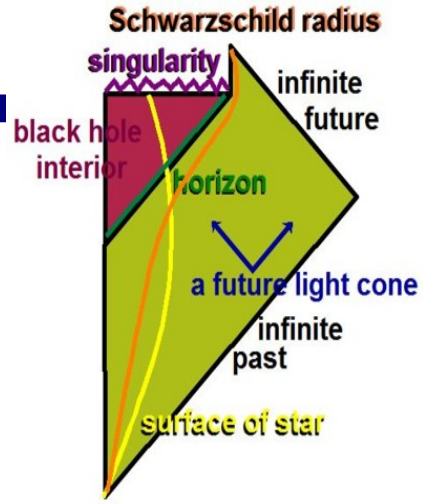
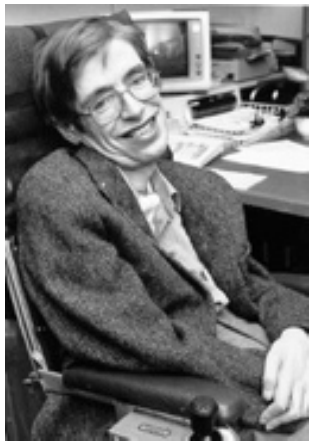
Quantum Aspects: Landmarks

- QFT in curved space-times now well established via algebraic approach. Spectacular application: very early universe. One can argue that we have observations supporting quantum nature of gravity, albeit at a perturbative level.





- Black hole evaporation by quantum processes. GR, QT and Stat Mechanics all brought together naturally. Spectacular conceptual advance we are still trying to grasp fully. What really happens to the singularity? Is the process unitary?



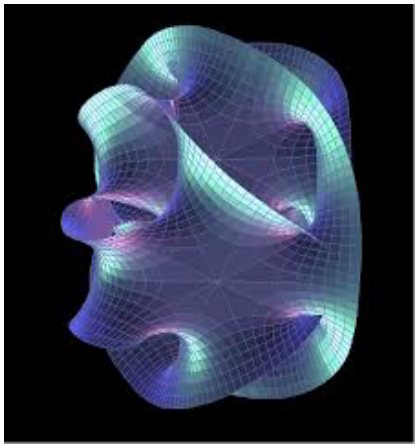
Quantum Aspects: Assessment

- Interestingly, in the Warsaw conference, there were 4 main talks (Bergmann, DeWitt, Feynman, Lichnerowicz, Madelstam, Misner) & lively discussions on the canonical approach, as well as the perturbative, field theoretic one, which was first introduced there! Lichnerowicz: Foundations for Linear QFT in globally hyperbolic space-times.

- But we are still far from a complete quantum theory of gravity. Why? Lack of observations? Cannot be the whole story. If it were, there should be a plethora of theories, not paucity!

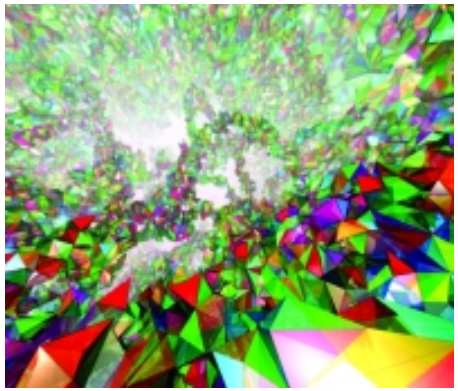
- Reason: Since Einstein taught us that gravity is encoded in geometry, we have to learn to live with quantum geometry; quantum space-times. It is relatively recently that we embarked on this voyage.

String Theory and Loop Quantum Gravity

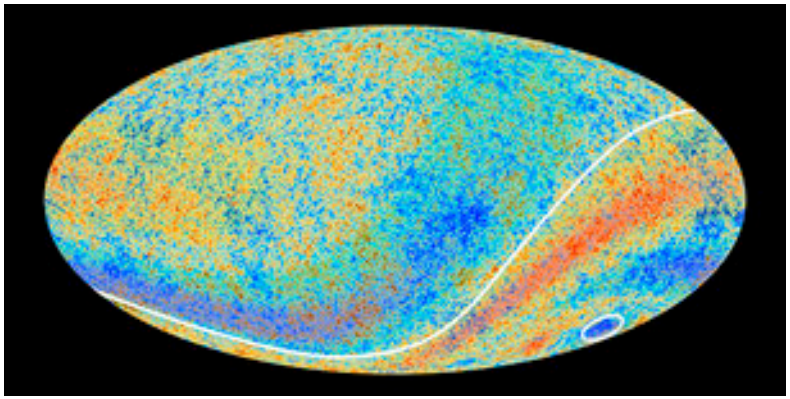


Original goal: unification of all interactions by replacing point particles with strings. Accelerated research in higher dimensional GR and super-symmetry. Last 2 decades: (super)Gravity related to QFT via AdS/CFT, extending the reach of GR techniques to other areas of physics; …

Concrete progress on long standing issues: The Problem of time; & resolution of the big-bang singularity in Loop Quantum Cosmology; n-point functions in a background independent theory using spin-foams ; ….

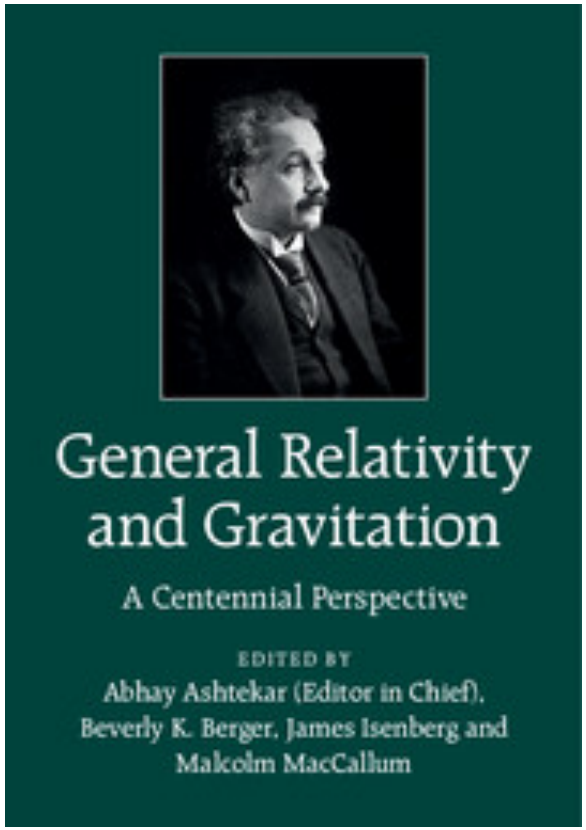


Quantum Gravity and Observations?



Interestingly, detailed calculations are now being performed to confront theory with observations in the very early universe. For example:

In LQC, the big bang singularity is naturally resolved and one explores the pre-inflationary dynamics of quantum fields representing cosmological perturbations which, in this era, propagate on quantum FLRW geometries. There is a surprising interplay between the Ultraviolet and the Infrared, leading to a possible explanation of the anomalies found by the Planck mission at the largest scales (Agullo, AA, Gupt, Nelson). Predictions of quantum gravity effects for future missions have also begun. The field is entering an exciting new phase, providing yet another opportunity of a `case study' .



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."