Advances in General Relativity and Gravitation: A Bird's Eye View

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Berlin 2015 Centenary Conference: 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.'' It has also led to unforeseen insights into mathematics particularly at the interface of geometry and analysis.

Organization

GR3: Warsaw 1962

1st Texas Symposium: Dallas 1963

- Goal of This Talk: To Provide a broad overview of this transformation through illustrative examples.
- 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, … 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, … Wald …).

- 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.

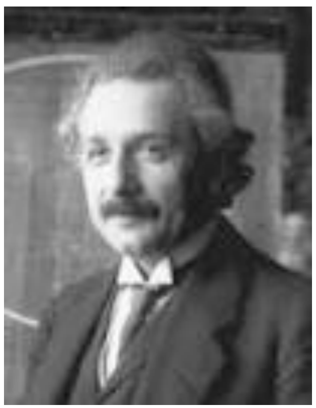
(i) Positive energy theorems. (Schoen & Yau; Witten; …) Transformative event sparked by a conference in California during which Geroch explained the issues to the mathematics community. Created an influx of `pure mathematicians' to GR especially in the US. Brought out another dimension of the depth of 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 nonlinear 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.

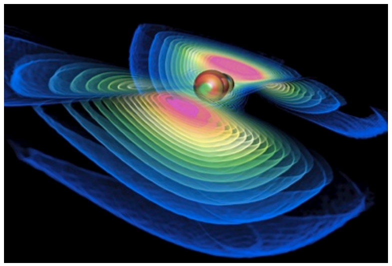
- But the `ho hair theorems' fail in more general theories (e.g. Einstein-Yang Mills) in 4-d and even vacuum GR in higher dimensions.

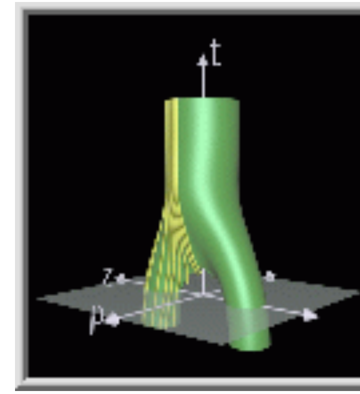
- A fascinating surprise: Laws of Black hole mechanics have an uncanny resemblance to laws of thermodynamics! (Bekenstein; Bardeen, Carter, Hawking, …) A driving force for a large body of research over the last 40+ years.

- Quasi-local horizons: Overcoming the limitations of event horizons. (Hayward, AA, Krishnan, …) both in classical and quantum gravity.

Numerical Relativity

- The field was born only in the 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 neutron star collisions). Binary BH problem under full control.





- The thriving subfields of GR I described did not even exist a few years before Warsaw and Dallas conferences!

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.'' It has also led to unforeseen insights into mathematics particularly at the interface of geometry and analysis.

- Goal of This Talk: To Provide a broad-brush-stroke picture of this renaissance from a contemporary perspective, bringing together the diverse areas.

- 1. Structure/Foundations of GR $\surd$
- 2. Applications of GR
- 3. Beyond GR

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!

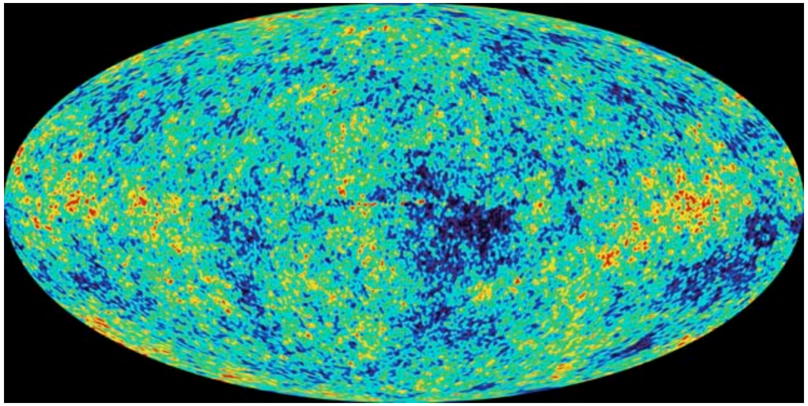
- We know that the temperature of the CMB is 2.7255 within 0.02% error! We know that the power spectrum is not exactly scale invariant because n_s is 0.968 within less than 0.62% error. All this with an excellent fit to a 6 parameter model. By 1962, Hubble parameter was estimated to be 75 < H < 130 (km/s Mpc); in the 70s, lively debate between values 100 and 55. Now the discrepancy between the Planck value 67.8 and the distance ladder value 73.2 is causing stir.

- 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

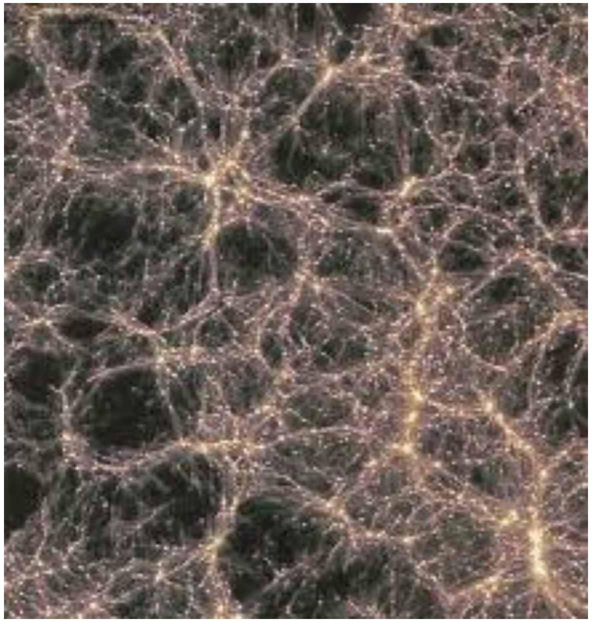
- Cosmology and the issue of the Big bang remained outside mainstream physics until
- Nucleosynthesis was understood: Gamow, Alpher, Herman (1948-65: Early universe essential as an oven for cooking light elements)
- Cosmic Micro-wave Background: CMB Dicke, Peebles, Roll, Wilkinson (1965 onwards: Relic 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



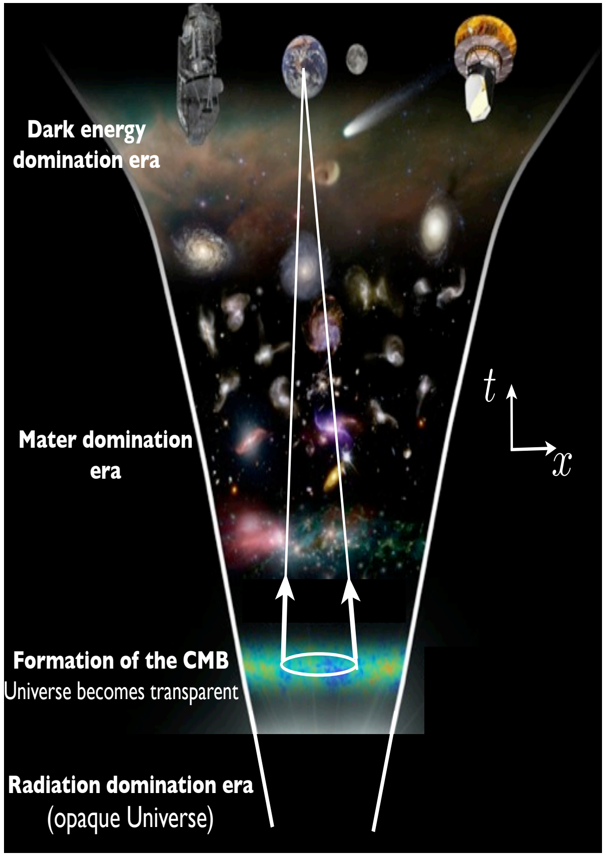
…Into the complex large scale structure of the universe seen now, 13.8 billion years later.

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

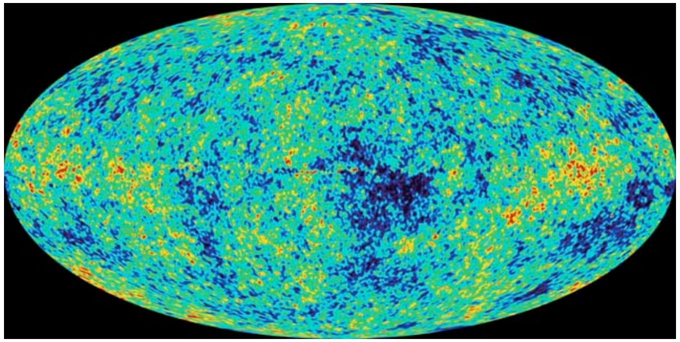


Triumph of General Relativity & Astrophysics! In human terms: from the Snapshot of a baby 1 day after birth, providing an accurate profile at age 100!

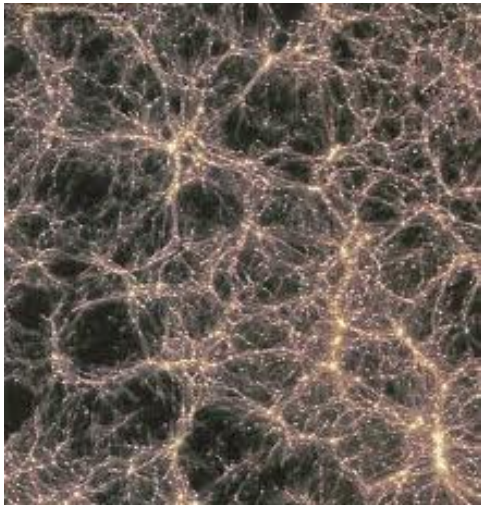
Origin of Inhomogeneities in the CMB?



QFT on a classical FLRW space-time

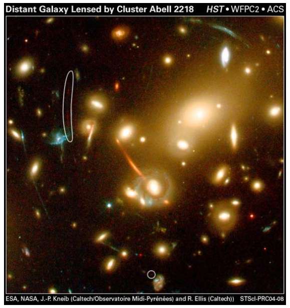


Classical gravity

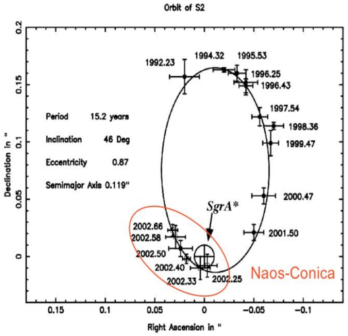


The origin of the Cosmic Structure:
Quantum Nothingness!

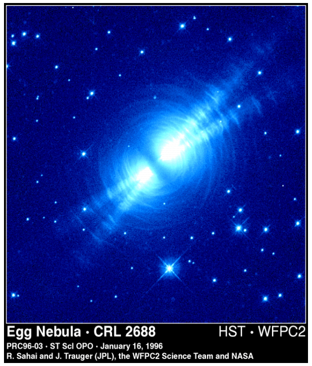
Very interesting paradigm shift.
Idea not restricted to inflation.

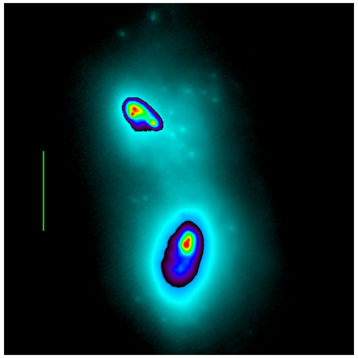


Relativistic Astrophysics



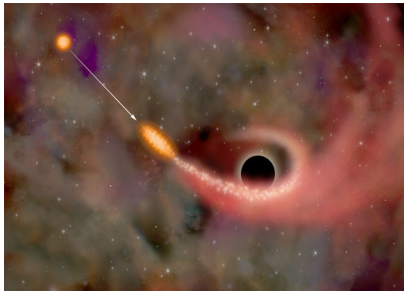
Not a single talk on this subject in the Warsaw conference. Field essentially born at the Dallas conference with the discovery of quasars. Since then the field has evolved considerably in several directions!



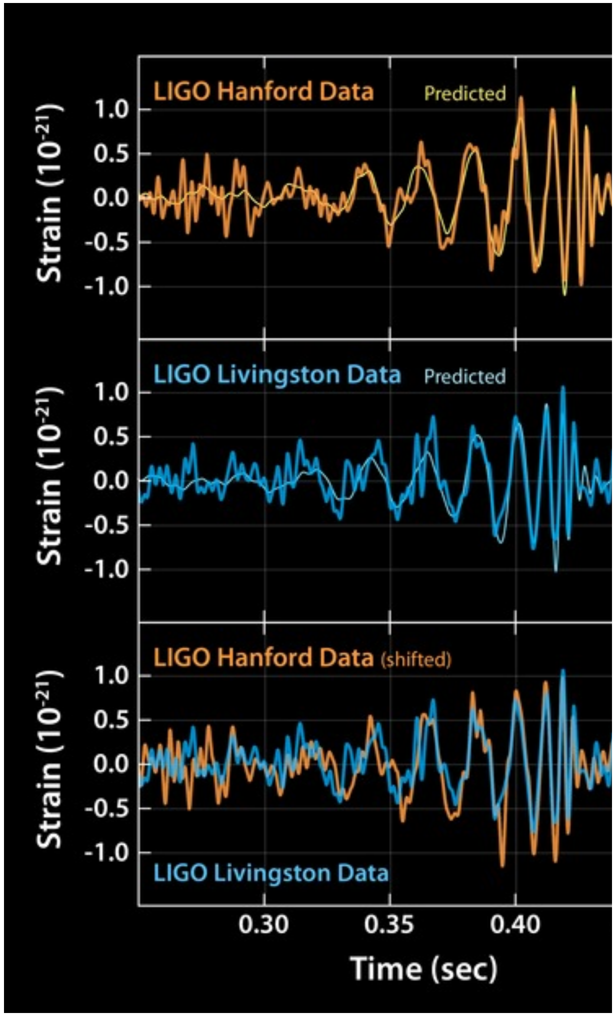


Striking Examples:

- Gravitational Lensing
- Neutron Stars & Double pulsars
- Black holes.



Dawn of a new era



LIGO Discoveries: So far 3 black hole mergers have been discovered. Complete agreement with GR numerical simulations. They provide:

(i) Test of GR dynamics in the strong field limit

(ii) Strongest evidence for black holes to date

(iii) A surprise: Black holes with 20-30 solar masses seem to be abundant!

Rumors of more events, including a binary neutron star merger. Would not be surprising: long considered the most promising events. VIRGO is now operational and with 3 detectors, localization to 100 deg^2. (With LIGO India expectation 10 deg^2.) Optical follow ups for subsequent radiation feasible. Will very significantly enrich our understanding of neutron stars (compactness, tidal deformability,…) & kilonovas (definitive detection and nuclear processes)

Opportunities

- In addition to greatly improving our knowledge of astrophysics, stringent tests of general relativity in the strong field regime:

1) Quasi-normal ringing. But Challenges remain (even for the first loud event with final 60 M_o: i) Too few cycles in the LIGO band; need even larger M; ii) Quasi-normal damping; need larger s/n)

2) Prior phase, before the quasi-normal ringing sets in? (highly non-linear phase when the common dynamical horizon is highly distorted and shedding invariantly defined multipole moments as it transits to the Kerr horizon. Evidence in numerical simulations that this evolution is reflected in the radiation (Jaramillo, Rezolloa, ….)

3) Global network of ground based detectors (2 LIGO + VIRGO + KAGRA + LIGO-India); LISA; 3rd Generation being planned (e.g., Einstein Telescope). Will significantly improve: source localization; reach in terms of distances; frequencies and hence black hole masses; interface of astrophysics with cosmology.

Opportunities: Conceptual side

- Warsaw ’62 conference: Gravitational waves were first discussed. There was an interesting exchange.

Weber: Why Asymptotically Minkowski (AM) boundary conditions rather than Friedmann type expanding universe boundary conditions?

Bergmann: Field is less than 2 years old … mathematically simplest …purely psychological-historical …

Bondi: … I regret as much as you do that we haven't got to the point of doing Friedmann universe.

- 5 years later, Penrose introduced conformal completion. Friedmann with positive CC is asymptotically de Sitter. So we have a good arena. But we still do not have a good generalization of the AM framework (Bicak, Penrose…). Einstein’s quadrupole formula was extended only last year!

- Important conceptual Challenge and Opportunity. The extension Weber wanted will become important in another decade.

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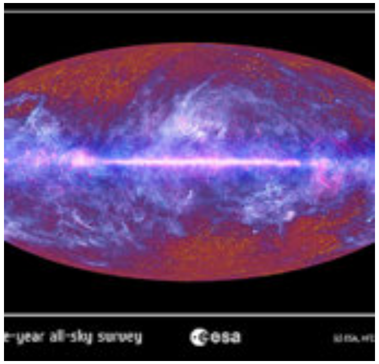
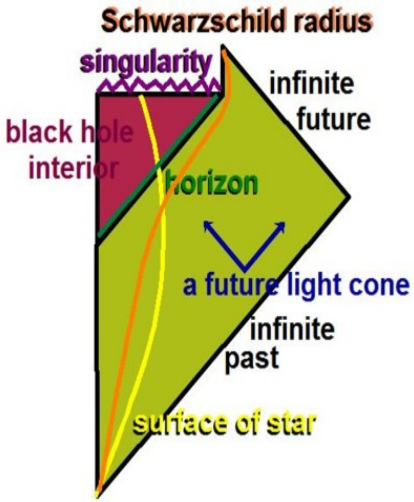
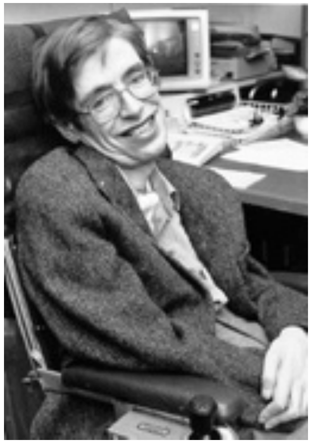
Quantum Aspects: Landmarks

- 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. In addition, interface of cosmology and quantum principles has become an exciting area.



- 

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?



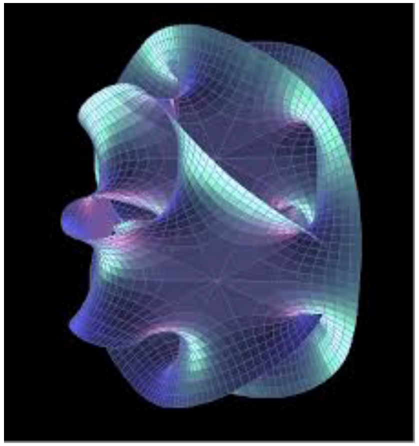
Quantum Aspects: Assessment

- Interestingly, in the Warsaw conference, there were 4 main talks (DeWitt, Feynman, Lichnerowicz, Madelstam), seminars and lively discussions on the canonical approach, non-local `path-dependendent' variables, as well as the perturbative, field theoretic one, which was first introduced there!

- 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!

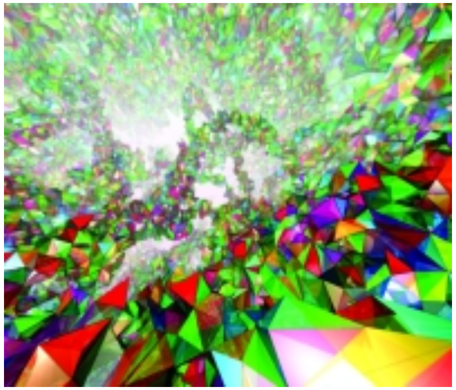
- Reason: Since Einstein taught us that gravity is encoded in geometry, we have to learn to live with quantum geometry; quantum space-times. It is relatively recently that we embarked on this voyage.

String Theory and Loop Quantum Gravity

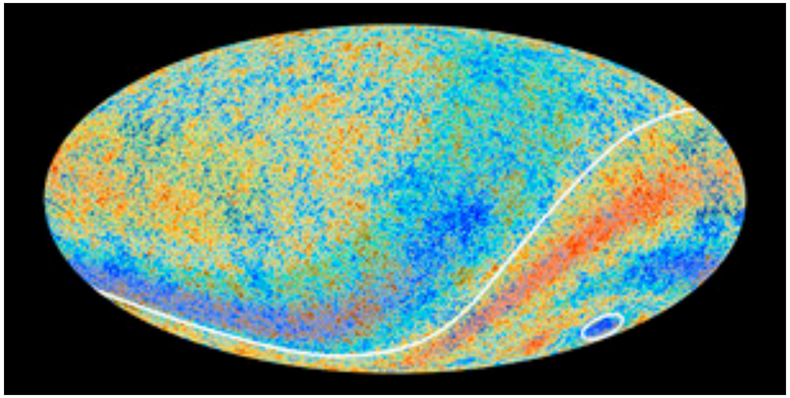


ST started out as continuation of perturbative QG. Original goal: unification of all interactions by replacing point particles with strings. Accelerated research in higher dimensional GR and super-symmetry. Last 2 decades: Because of the AdS/CFT conjecture, focus has shifted to extending the reach of GR techniques to othe areas of physics: Quark-gluon plasma; high TC superconductivity; …

LQG started out from non-perturbative approa-ches and emphasized quantum nature of geometry. Last two decades: emphasis on original problems of quantum gravity: The issue of time; resolution of the big-bang singularity in Loop Quantum Cosmology; n-point functions in a background independent theory; ….



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.

Assessing Einstein's Legacy in Post WWII Physics

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."