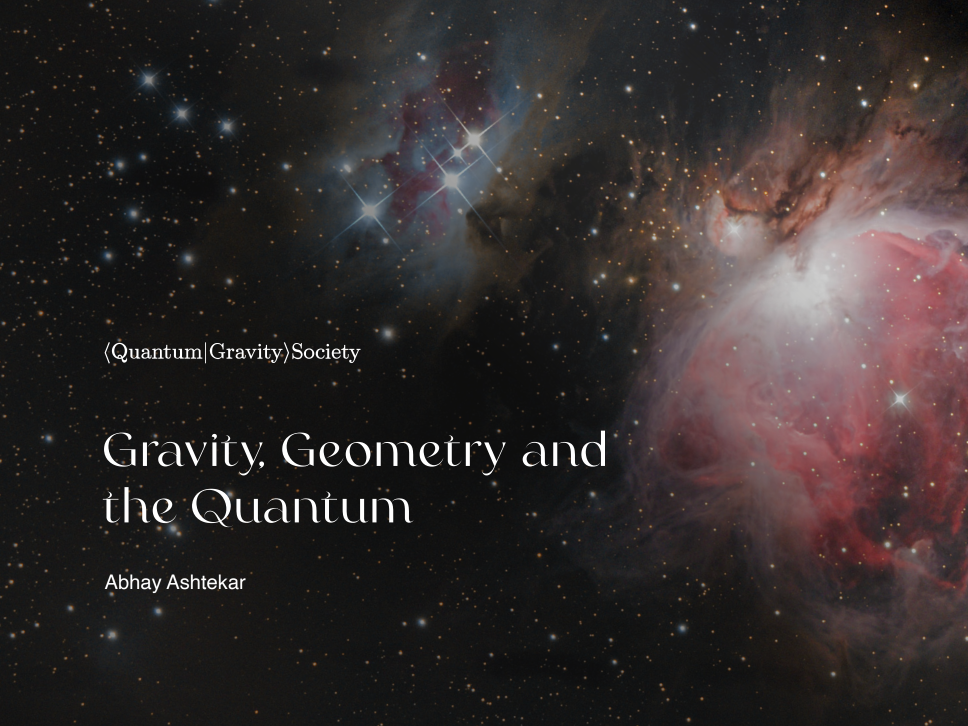


⟨Quantum|Gravity⟩Society

Gravity, Geometry and the Quantum

Abhay Ashtekar

Gravity, Geometry and the Quantum

Abhay Ashtekar
Institute for Gravitation and the Cosmos,
& Physics Department, Penn State

QM and Gravity: Marrying Theory and Experiment
Vancouver, 15-19 Aug 2022

Organization

1. Quantum Gravity: Conceptual Setting
2. A brief introduction to Loop Quantum Gravity (LQG) as a whole;
3. An illustrative example of recent advances:

   A bridge between theory and observations of the early universe;
4. Summary & a broad perspective on quantum gravity.

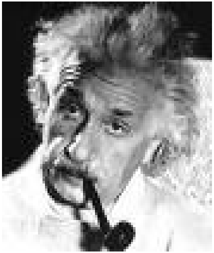
This is a broad overview: I will summarize the work of MANY researchers.
Recent Short Review: AA & Bianchi, 2021.

1. Historical and Conceptual Setting

Quantum Mechanics is arguably the most successful area of fundamental science. General relativity is the best theory of gravity we have and it has surpassed many stringent tests. Quantum gravity is the theory that will unify the principles underlying the two. Thus unification has been widely regarded as the most outstanding conceptual issue in fundamental physics. Einstein raised it already in 1916!

“Nevertheless, due to the inner-atomic movement of electrons, atoms would have to radiate not only electro-magnetic but also gravitational energy, if only in tiny amounts. As this is hardly true in Nature, it appears that quantum theory would have to modify not only Maxwellian electrodynamics, but also the new theory of gravitation.”

Albert Einstein,
Preussische Akademie Sitzungsberichte, 1916



Why is the problem still open?

- Physics has advanced tremendously over the last century but the the problem of unification of general relativity and quantum physics still open. Why?

$\star$ No experimental data with direct ramifications on the quantum nature of Gravity.

Why is the problem still open?

- Physics has advanced tremendously over the last century but the the problem of unification of general relativity and quantum physics still open. Why?

⋆ No experimental data with direct ramifications on the quantum nature of Gravity.

⋆ But then this should be a theorist's haven!

Why isn't there a plethora of theories?

Why is the problem still open?

- In general relativity, gravity is encoded in space-time geometry. Most spectacular predictions –e.g., the Big-Bang, Black Holes & Gravitational Waves– emerge from this encoding. Suggests: Geometry itself must become quantum mechanical –therefore fuzzy and probabilistic. How do you do physics if you do not have a sharp space-time continuum? We need new concepts as well as novel new mathematical tools. We have to lift the anchor that tied us to a background space-time and sail the open seas. It has taken us a while to learn how to do this.

- Several voyages in progress:
String Theory; Loop Quantum Gravity; Asymptotic Safety; Dynamical Triangulations; Regge Calculus, Causal Sets, Euclidean Quantum Gravity, Twistor Theory, . . . Because there are no direct experimental checks, approaches are driven by intellectual prejudices about what the core issues are and what will "take care of itself" once the core issues are resolved.

Evolution of Ideas: Parallel Developments

Because there are no direct experimental checks, approaches are driven by intellectual prejudices about what the blue core issues are and what will “take care of itself” once the core issues are resolved. This assertion must seem shocking to non-experts. Isn’t science meant to be objective?

> That taste and style have so much to do with physics may sound strange at first, since physics is supposed to deal objectively with the physical universe. But the physical universe has structure, and one’s perception of this structure, one’s partiality to some of its characteristics and aversion to others, are precisely the elements that make up one’s taste. Thus it is not surprising that taste and style are so important in scientific research.

Chen Ning Yang
Selected papers with Commentary 1945-1980

Two Illustrations of "Taste and Style"

⋆ String Theory: Developed by HE theorists. 'Unification' Central; led to the introduction of supersymmetry, higher dimensions, & -ve cosmological constant at the foundation of the theory. Point particles replaced by extended objects –UV cutoff.

⋆ LQG: Developed by Relativists. Non-perturbative methods and 'background independence' Central; led to the introduction of a quantum Riemannian geometry; hence an in-built UV cutoff.

- Current Mainstream Thrusts:

⋆ String theory: "The Strange Second Life of String Theory" by K.C. Cole (IAS website): "String theory has so far failed to live up to its promise as a way to unite gravity and quantum mechanics. At the same time, it has blossomed into one of the most useful sets of tools in science."

⋆ LQG: Focus continues on the long-standing problems of quantum gravity itself: Problem of time; Taming the big bang; Pre-inflationary dynamics and large scale anomalies in CMB; Graviton propagator and n-point functions in a theory without a background space-time; ...

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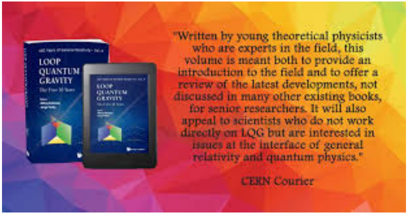
2. LQG: Underlying Viewpoint

- General Relativity is founded on Einstein's outrageous idea: Gravity is a not a force but a manifestation of curved space-time. Therefore GR needed a new syntax for all of classical physics: Riemannian Geometry.

- LQG Viewpoint: Geometry has 'atomic structure' like matter: Quantum gravity needs a yet new syntax, now for all known physics: Quantum Riemannian Geometry. Systematically developed by a very large number of researchers over last 3 decades.

- Main ideas and thrusts are summarized in Pedagogical Chapters written by leading younger researchers in LQG that appeared in a monograph 2 years ago in the series "100 Years of General Relativity".



"Written by young theoretical physicists who are experts in the field, this volume is meant both to provide an introduction to the field and to offer a review of the latest developments, not discussed in many other existing books, for senior researchers. It will also appeal to scientists who do not work directly on LQG but are interested in issues at the interface of general relativity and quantum physics."

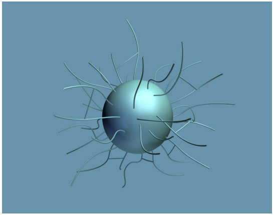
CERN Courier

Introductory, outreach YouTube Video (75 minute long):
The Story of Loop Quantum Gravity - From the Big Bounce to Black Holes.

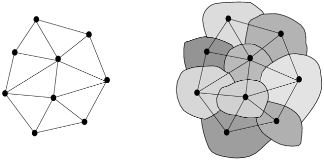
Quantum Geometry

- In LQG there is a precise & detailed mathematical framework that captures the nature of quantum geometry. It provides the syntax to describe how General Relativity is modified at the Planck scale.

Fundamental excitations of spatial geometry are polymer-like; 1-dimensional. Einstein's continuum arises only on coarse graining. Literally, the fabric of space is woven by 1 dimensional treads, in a precise manner.



Credits: Alex Corichi

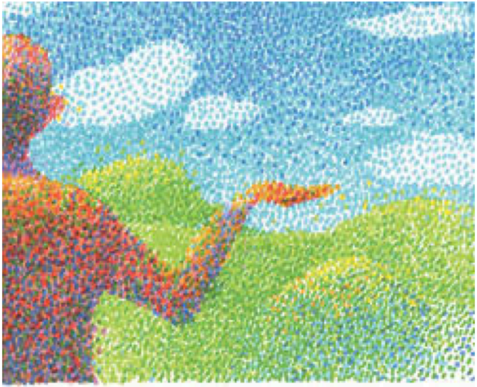


- Geometrical observables such as areas of physical surfaces and volumes of physical regions are represented by well-defined operators as is standard in quantum mechanics. Their values are quantized like the discrete energy levels of atoms! The minimum non-zero value $\mathring{\Delta} \sim 5.17\ell_{\rm Pl}^2 \approx 8.3 \times 10^{-66}\,{\rm cms}.$ $\mathring{\Delta}$ turns out to play a key role in the definition of quantum curvature and quantum Einstein equations.

But discreteness is sophisticated. Area-levels crowd exponentially, so the continuum limit is approached rapidly!

Space-time Continuum?

From the LQG perspective, Space-time Continuum of General Relativity is an approximation: Emerges only on "coarse graining", i.e., probing physics at scales $L \gg L_{\mathrm{Pl}}$. Then we can ignore the atomic structure of geometry. Like what we do when we look at a wall, or an impressionist painting.



Some Long Standing Issues of Quantum Gravity

Quantum Mechanics and General Relativity led to profound paradigm shifts in our understanding of the physical world, each in its own way. We had to learn to formulate meaningful questions before we could answer them. Quantum Gravity is expected to lead to an even more profound paradigm shift! We face deep conceptual quandaries. Examples:

1. How do you do physics if there is no space-time metric to anchor it?

2. What is ‘time’ and how do you speak of ‘dynamics’ or ‘happenings’?

3. Are (strong) curvature singularities of GR naturally resolved by quantum gravity? What really happened at the Big Bang and what really happens deep inside black holes?

Answers in Loop Quantum Gravity

1. How do you do physics if there is no space-time metric to anchor it? Matter fields and geometry are both quantum mechanical at birth. Matter propagates not on a fixed space-time geometry à la Einstein, but on a wave function $\Psi(\mathrm{geo})$ representing a probability distribution of such geometries.
(Analogy: electrons in a laser beam)

2. What is 'time' and how do you speak of 'dynamics' or 'happenings'? Relational time à la Leibnitz: A matter field or an attribute of space-time geometry can serve as a relational clock with respect to which other fields 'evolve' (e.g., in cosmology). There is no grandfather clock in the background. (There was no concept of a 'year' before earth started orbiting around the sun!) Example of 'happening': Creation or annihilation of new nodes –chunks/quata of volume.

3. Are strong curvature singularities of GR naturally resolved by quantum gravity? In all cosmological and black hole models considered so far, strong curvature singularities are tamed in LQG. So physics does not stop abruptly as in general relativity. LQG equations continue to be well defined and have definite predictions.

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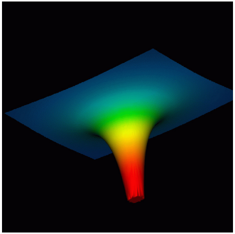
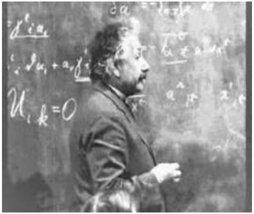
3. LQG and the Very Early Universe

- The Friedmann-Le Maitre-Robertson-Walker solution to Einstein's equations that captures the large scale structure of our expanding universe. However, if evolved back in time, all physical quantities diverge at a finite time. Space-time fabric is violently torn apart and physics just comes to an abrupt halt. This is the Big-Bang at which everything, including space-time is born in General Relativity.



Credits: Pablo Laguna

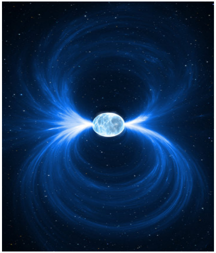


- However, already in the 1945 edition of *Meaning of Relativity*, Einstein cautioned against attributing fundamental significance to the Big Bang: *"One may not assume the validity of field equations at very high density of field and matter and one may not conclude that the beginning of the expansion should be a singularity in the mathematical sense."*

New Forces of Quantum Origin

- By now Einstein's conclusion is widely accepted: the prediction of Big Bang requires one to use general relativity beyond the domain of applicability. In the backward time evolution, matter density and space-time curvature become enormous and quantum physics become crucially important. These quantum effects are ignored in general relativity. Singularities like the Big Bang are gates to Physics Beyond Einstein.

- Genuinely quantum forces: Example Neutron stars would not even exist in a classical world: They are like gigantic nuclei. So dense that a teaspoon of their matter weighs $\sim 5 \times 10^6$ tons! If the world were classical such dense stars would collapse into a black hole under gravitational attraction. But quantum mechanics intervenes, creates a repulsive force that balances gravitational attraction. Quantum mechanics stabilizes neutron stars if their mass is less than $\sim 2\mathrm{M}_\odot$.



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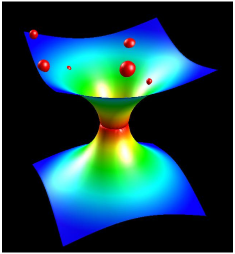
The Big Bounce of LQC

- Quantum geometry of LQG corrects Einstein's equations. As we go back in time, these corrections create a brand new repulsive force in the 'Planck regime' where matter densities are $\rho_{\rm Pl} \sim 10^{90} \times \rho_{\rm Nucl}$ and space-time curvature is $\sim 10^{76}$ times the curvature at the horizon of a solar mass black hole!! This force is negligible until we reach the Planck regime but then rises extremely rapidly and overwhelms the classical gravitational attraction and causes the universe to bounce. The big bang is replaced by a big bounce!

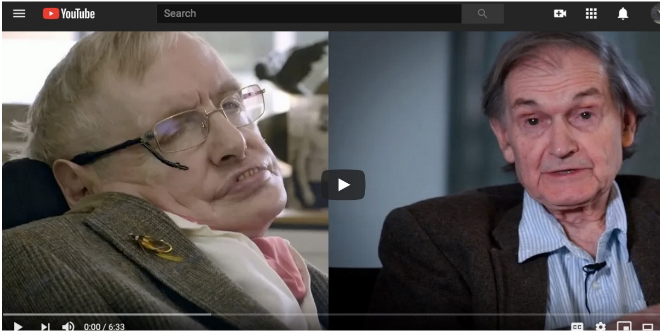


Credits: Cliff Pickover

- All physical quantities remain finite at the bounce. Space-time curvature is large $\sim 62 \times \ell_{\rm Pl}^{-2}$ but finite; matter density has an absolute upper bound; $\rho_{\rm sup} = 18\pi/(G^2\hbar\mathring{\Delta}^3) \approx 0.41\rho_{\rm Pl}$!. As area gap $\mathring{\Delta} \to 0$, $\rho_{\rm sup} \to \infty$ as in GR. Away from the Planck regime, when $\rho \lesssim 10^{-4}\rho_{\rm Pl}$, GR becomes a good approximation. At the 'onset' of inflation, $\rho \sim 10^{-11}\rho_{\rm Pl}$. So we can safely use a classical, continuum space-time during inflation, but not before!

- The area gap Δ of LQG serves as the microscopic parameter that sets the scale for macroscopic observables, e.g., $\rho_{\rm sup} = {\rm const}/\Delta^3$.

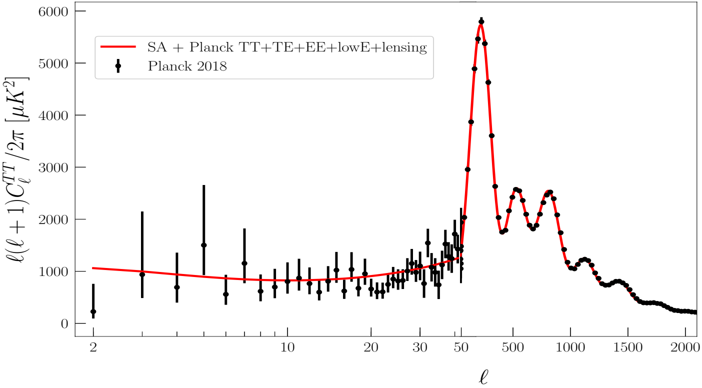
NEW Meaning of the Big Bang



- Now in mainstream cosmology, `Big Bang' refers not to an initial singularity but to a hot phase of the early universe (say at the end of inflation)! Short YouTube Video: The New Meaning of Big-Bang
- https://www.youtube.com/watch?v=U7kvjTRWtw\&feature=youtu.be

CMB Observations

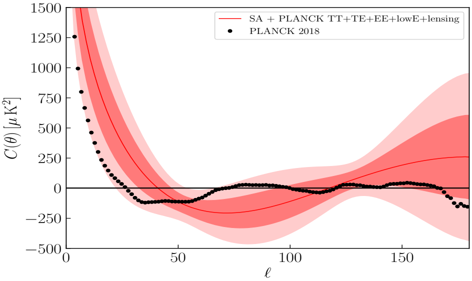
The Cosmic Microwave Background (CMB) provides a snapshot of the young universe. The 6 parameter ΛCDM universe selected by the PLANCK satelite data has had tremendous success in explaining all major features in the CMB temperature anisotropies and polarizations.



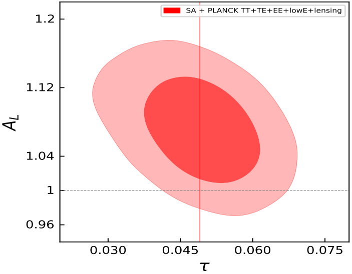
Furthermore, for this universe, one has theoretical predictions for other observables such as the lensing amplitude and the (odd-parity) BB power spectrum that can be tested by independent, future observations.

Observational signatures of the Big Bounce?

- By and large, predictions of both, the standard theory with Big Bang and LQC with Big Bounce, agree with with observations. But there are some anomalous features that cannot be accounted for by the standard theory. Examples:



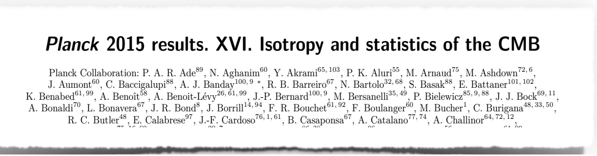
Lensing amplitude-optical depth anomaly



Left plot: Observed Power (black) is lower at large angular scale than the theoretical prediction (red) of the standard theory (Copi, Schawarz, Spergel, Starkman, PLANCK, . . .).

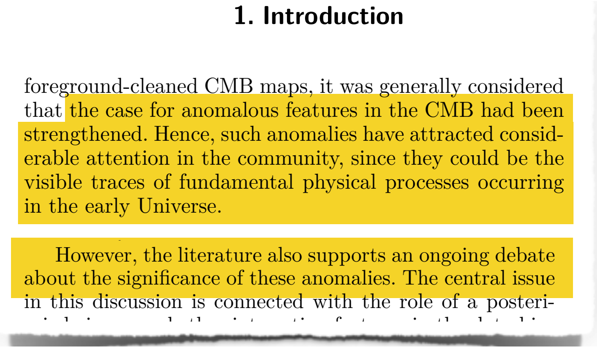
Right Plot: $A_L = 1$ lies outside 1σ of the PDF (Motloch, Hu, PLANCK . . .). Led to a suggestion (Di Valentino, Melchiorri, Silk) of a "a possible crisis in cosmology."

The Planck collaboration Perspective on Anomalies



Planck 2015 results. XVI. Isotropy and statistics of the CMB

Planck Collaboration: P. A. R. Ade[89], N. Aghanim[60], Y. Akrami[65, 103], P. K. Aluri[55], M. Arnaud[75], M. Ashdown[72, 6], J. Aumont[60], C. Baccigalupi[88], A. J. Banday[100, 9 *], R. B. Barreiro[67], N. Bartolo[32, 68], S. Basak[88], E. Battaner[101, 102], K. Benabed[61, 99], A. Benoît[58], A. Benoit-Lévy[26, 61, 99], J.-P. Bernard[100, 9], M. Bersanelli[35, 49], P. Bielewicz[85, 9, 88], J. J. Bock[69, 11], A. Bonaldi[70], L. Bonavera[67], J. R. Bond[8], J. Borrill[14, 94], F. R. Bouchet[61, 92], F. Boulanger[60], M. Bucher[1], C. Burigana[48, 33, 50], R. C. Butler[48], E. Calabrese[97], J.-F. Cardoso[76, 1, 61], B. Casaponsa[67], A. Catalano[77, 74], A. Challinor[64, 72, 12],



1. Introduction

foreground-cleaned CMB maps, it was generally considered that the case for anomalous features in the CMB had been strengthened. Hence, such anomalies have attracted considerable attention in the community, since they could be the visible traces of fundamental physical processes occurring in the early Universe.

However, the literature also supports an ongoing debate about the significance of these anomalies. The central issue in this discussion is connected with the role of a posteri-

2018 Planck 2018 Results. I. Overview and the cosmological legacy of Planck

...if any anomalies have primordial origin, then their large scale nature would suggest an explanation rooted in fundamental physics. Thus it is worth exploring any models that might explain an anomaly (even better, multiple anomalies) naturally, or with very few parameters.

Anomalies alleviated by LQC corrections!

Curvature is finite at the bounce and the curvature radius R_{B} provides a new quantum length scale. Modes with wave lengths $\lambda_{\mathrm{phy}} < R_{\mathrm{B}}$ don't experience the curvature while those with $\lambda_{\mathrm{phy}} > R_{\mathrm{B}}$ do! Thus, longer wave-length modes of cosmological perturbations receive LQC corrections. These turn out to be just right to alleviate several anomalies: Power suppression, $A_L - \tau$, that I mentioned, as well as dipolar modulation, and preference for odd parity.
(AA, Gupt, Jeong, Sreenath; Agullo, Kranas, Sreenath).

Cosmic Tango: Science Sections of Forbes; Novelle du Monde;...

The Big Bang singularity is resolved because of the Planck-scale corrections to Einstein's equations induced by quantum geometry. The new scale R_{B} they create affects the longest wave length modes we observe in the CMB. Thus, there is a cosmic tango between the very small (ultraviolet) and the very large (infrared) near the big bounce that makes it possible for the quantum gravity effects to leave an observable imprint on the large-scale features of CMB without compromising successes of standard inflation.

(AA, Gupt, Jeong, Sreenath, PRL 2020)

Standard ΛCDM versus ΛCDM with LQC

Parameter	Standard	LQC corrected
$\Omega_b h^2$	0.02238 ± 0.00014	0.02239 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012	0.1200 ± 0.0012
$100\theta_{MC}$	1.04091 ± 0.00031	1.04093 ± 0.00031
τ	0.0542 ± 0.0074	0.0595 ± 0.0079
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.054 ± 0.015
n_s	0.9651 ± 0.0041	0.9643 ± 0.0042

Comparison: The mean values of marginalized PDF for the six cosmological parameters of the standard ΛCDM model and ΛCDM + LQC. While 5 of the cosmological parameters changed by less than 0.4%, the optical depth increased by 9.8%! It will be measured more directly in the upcoming missions. Thus, there is a concrete bridge between theory and observations.

(AA, Gupt, Jeong, Sreenath, PRL 2020)

4. A Broad Perspective on Quantum Gravity

Because the problem of quantum gravity has been with us so long and until recently there was no obvious observational window to test the ideas, leaders have often made appeals to aesthetics. For example, one finds quotes from eminent and thoughtful people like:

“It would have been a cruel god to have laid down such a pretty scheme (H-space/ Haven) and not have it mean something deep”.

“I just think too many nice things have happened in string theory for it to be all wrong. Humans do not understand it very well, but I just don’t believe there is a big cosmic conspiracy that created this incredible thing that has nothing to do with the real world.”

Reminder from Feynman

“It would have been a cruel god to have laid down such a pretty scheme (H-space/ Haven) and not have it mean something deep”.

“I just think too many nice things have happened in string theory for it to be all wrong. Humans do not understand it very well, but I just don’t believe there is a big cosmic conspiracy that created this incredible thing that has nothing to do with the real world.”

“It doesn’t matter how beautiful your theory is, it doesn’t matter how smart you are, or what your name is. If it doesn’t agree with experiment, it is wrong.”
Richard Feynman.

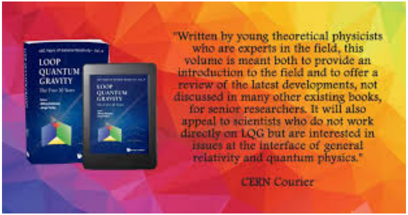
Examples from history:
Steady state Cosmology (Hoyle, Gold, Bondi, Sciama).
Elementary particles as Chemistry of Geometry (Wheeler)
Replacement of local QFT by analytic properties of the S-matrix (Chew)
Atoms as knotted vortices in space (Kelvin, Maxwell)

SUPPLEMENTARY MATERIAL

A few References

Recent reviews:
AA & Bianchi (RoPP, 2021);

Chapters by: Giesel, Laddha & Varadarajan, Bianchi, Dittrich, Agullo & Singh, Barbero & Perez; ... in *Loop Quantum Gravity: The first thirty years.*



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CERN Courier

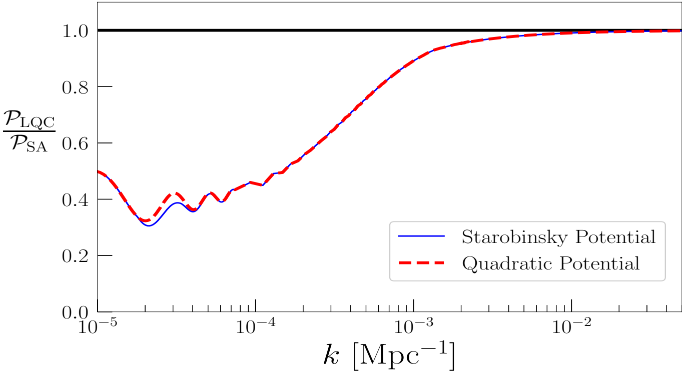
For beginning researchers:

75 minute long YouTube Video:
The Story of Loop Quantum Gravity - From the Big Bounce to Black Holes.
https://www.youtube.com/watch?v=x9jYH5VIF9Eto

Cover Story in the 'New Scientist': From Big Bang to the Big Bounce.
https://sites.psu.edu/institutegravitationandcosmos/files/2020/09/bigbounce.pdf

Primordial Spectrum of scalar modes

Standard Inflation predicts a nearly scale invariant primordial power spectrum a la Standard Ansatz (SA): $\mathcal{P}_{\mathcal{R}}(k) = A_s(\frac{k}{k_\star})^{n_s-1}$. LQC predicts that the primordial spectrum is nearly scale invariant only on small angular scales (large k). On large angular scales, there is power suppression: $\mathcal{P}_{\mathcal{R}}(k) = f(k)\ A_s(\frac{k}{k_\star})^{n_s-1}$ where $f(k) = 1$ for large k and $f(k) < 1$ for small k. (AA,Gupt,Jeong & Sreenath, PRL (2020))



Natural Questions

- What sets the scale at which power suppression occurs?

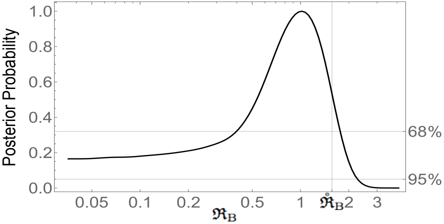
At the Big-bang, curvature diverges. In LQC, it is always finite. R reaches its universal maximum at the bounce $R_{\max} \simeq 62$ (Planck units). Dynamical equations obeyed by the modes imply that if the physical wavelength of a mode is much smaller than the curvature radius, the mode does not affected by curvature but otherwise curvature excites it. This sets the scale: Modes with comoving $k \lesssim 4 \times 10^{-3}\mathrm{Mpc}^{-1}$ get excited in their evolution from the bounce to the slow roll phase and are not in the Bunch Davies vacuum at the onset of the relevant slow roll. The primordial spectrum of these modes then fails to be approximately scale invariant.

- Why is there power suppression rather than enhancement at large scales?

This is because of the choice quantum state of perturbations. In inflation one cannot choose it at the Big-Bang because of the singularity. One chooses it, by positing that the state be the Bunch-Davies vacuum few e-folds before the modes of interest exit the Hubble horizon (or curvature radius) –in the middle of the evolution, so to say. In LQC one can specify it using a new principle that enforces maximum ‘quantum homogeneity and isotropy’ in the Planck regime and ‘maximum classicality’ at the end of inflation allowed by Heisenberg uncertainty (AA & Gupt). This initial state then automatically leads to power suppression.

Results I reported offer encouragement pursue other consequences of the LQC dynamics + these initial conditions.

From Observations to Fundamental Theory



- Check on the area gap $\mathring{\Delta}$: Make the area gap variable and find its best fit value. In the plot, $\mathfrak{R}_{\rm B} = (6\,\Delta/4\pi)^{\frac{1}{2}}$. The line, $\mathfrak{R}_{\rm B} = \mathring{\mathfrak{R}}_{\rm B} \equiv 1.57\ell_{\rm Pl}$ corresponding to $\Delta = \mathring{\Delta} \sim 5.17\ell_{\rm Pl}^2$. It is within the 68% confidence level of PLANCK results.

- An increase of area gap by a factor of 10 is observationally ruled out at 95% confidence level & decrease by a factor of 10 is ruled out at 68% confidence level. Totally unforeseen synergy! (AA,Gupt & Sreenath, (2021))

Two way bridge between observations and theory.

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