Einstein's Cosmos and the Quantum

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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. Brief Summary.

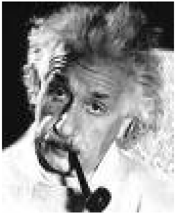
This is a broad overview: I will summarize the work of MANY researchers.

1. Quantum Gravity: Conceptual Setting

Einstein's resistance to accept quantum mechanics as a fundamental theory is well known. However, he had a deep respect for quantum mechanics and was the first to raise the problem of unifying general relativity with quantum theory.

"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?

- No experimental data with direct ramifications on the quantum nature of Gravity. (Recall: The first tests of full nonlinear general relativity came in 2015 through gravitational waves, $\sim$ 100 years after Einstein's discovery of the theory!)

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- But then this should be a theorist's haven! Why isn't there a plethora of theories?

Why is the problem still open?

- From the LQG standpoint, the real reason is the following:

In general relativity, gravity is encoded in spacetime geometry. Most spectacular predictions –e.g., the Big-Bang, Black Holes & Gravitational Waves– emerge from this encoding. Suggests: Geometry itself must become quantum mechanical. How do you do physics without a spacetime continuum in the background? Need new concepts and new mathematical tools. We learned how to lift the anchor that tied us to a background spacetime and sail the open seas relatively recently.

- Several voyages in progress:

Non-commutative geometry, twistors, Regge Calculus, Euclidean quantum gravity, Causal sets, Asymptotic safety and Causal Dynamical triangulations, AdS/CFT conjecture of String Theory, Loop Quantum Gravity, ...

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 core issues are and what will "take care of itself" once the core issues are resolved. This sounds strange at first. 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

Illustrations of "Taste and Style"

⋆ String Theory: Developed by HE theorists. 'Unification' Central; Supersymmetry, higher dimensions, & -ve cosmological constant at its foundation; Extended objects, rather than point particles; a natural UV cut-off

⋆ LQG: Developed by Relativists. Non-perturbative methods and 'background independence' Central; based on quantum Riemannian geometry; hence an in-built UV cut-off.

- 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 has continued to be on the long-standing issues in quantum gravity itself. Ongoing concrete results on: 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 spacetime; ...

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Short Review: AA & Bianchi, Rep. Prog. Phys. 84, 042001 (2021).

Introductory YouTube Video (75 minute long):

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2. LQG: A New Syntax for all of Physics

• At the core of General Relativity (GR) is Einstein's outrageous idea: Gravity is a not a force but a manifestation of curved spacetime. As a result GR needed a new syntax for all of classical physics: Riemannian Geometry.

• LQG Viewpoint: Geometry is a physical entity like matter. Therefore, it too has 'atomic structure': Quantum gravity needs an even deeper syntax, now for all of known physics: Quantum Riemannian Geometry. It was systematically developed by a very large number of researchers in the 1990s.

Creation of this syntax was guided by two observations:

(1) A central lesson of GR is that there are no background fields: Everything, including spacetime geometry is dynamical. No spectators in the cosmic dance!

(2) In all non-gravitational fundamental interactions the fundamental 'mediating field' is a connection – a derivative operator rather than a metric– that serves as the vehicle to parallel transport fundamental matter fields of the theory (electrons in QED and quarks in QCD). Can we express GR as a theory of connections rather than of metrics? (Fascinating episode involving Einstein and Schrödinger!) If so, we can use the powerful non-perturbative techniques of gauge theories at the quantum level.

When combined, these guiding principles turn out to be surprisingly powerful.

Emergent space-time

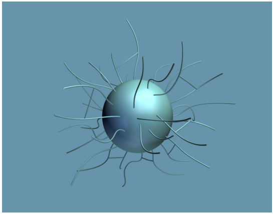
Classical theory: The 'obvious' Hamiltonian theory of connections (with two local degrees of freedom as in GR) based on these two principles is remarkably simple: all equations are low order polynomials in the connection and its conjugate momentum. Therefore, the theory is very well suited for 'quantization' using non-perturbative techniques of gauge theories. But its physics is very different from QED or QCD because there is no background metric. In fact it is GR in disguise!! The metric emerges as a 'composite field' in terms of the 'fundamental' variables of gauge theory, just as nuclei are composite objects in QCD.

LQG perspective: Spacetime Continuum of GR is an approximation. It emerges only on "coarse graining", i.e., probing physics at scales $L \gg \ell_{\rm Pl}$. Then we can ignore the atomic structure of geometry. Analogous to looking an impressionist painting from afar. Note that $R_{\rm proton} \approx 10^{20} \ell_{\rm Pl}$!! Therefore we can feely use Einstein's continuum approximation even in the highest energy experiments at CERN.

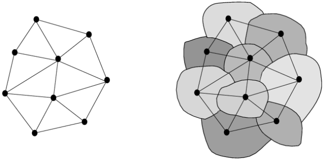
But at a fundamental level, quantum geometry has an inbuilt discreteness, and it dominates the physics of the extreme universe near singularities of GR.

Flavor of Quantum Geometry

- In LQG there is a precise & detailed mathematical framework for quantum geometry. It provides the syntax to describe how GR 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 quantum 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 in standard 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 & in quantum Einstein equations.

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

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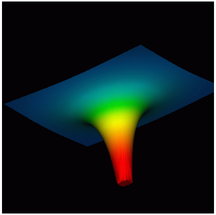
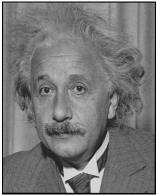
3. LQG and The Big Bang

• In General Relativity, we have the (Friedmann-Lemaître) solution to Einstein's equations that correctly captures the large scale structure of our expanding universe. However, if evolved back in time, all physical quantities diverge at a finite time, and physics just comes to an abrupt halt. Fabric of space-time is violently torn apart at this Big Bang singularity!



Credits: Pablo Laguna

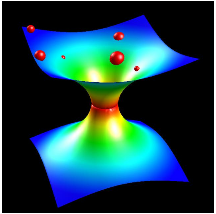


• However, already in the 1945 edition of *Meaning of Relativity*, Einstein cautioned against attributing fundamental significance to the Big Bang:
"One may not assume the validity of field equations at very high density of field and matter and one may not conclude that the beginning of the expansion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

• It is now widely believed that Big Bang is a prediction of General Relativity but beyond its domain of validity; it ignores quantum physics which becomes crucially important in the very early universe. In LQG, therefore, singularities like the Big Bang regarded as gates to Physics Beyond Einstein.

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!

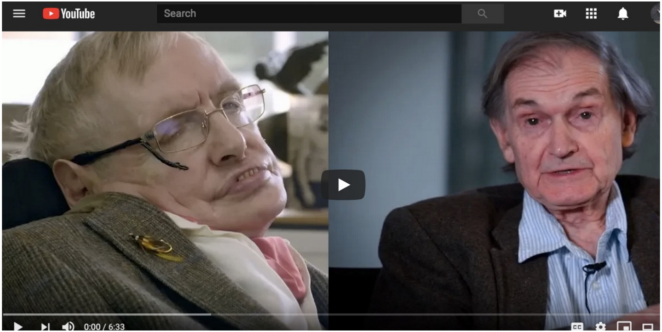


Credits: Cliff Pickover

• 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 $\mathring{\Delta}$ of LQG serves as the microscopic parameter that sets the scale for macroscopic observables, e.g., $\rho_{\rm crit} = {\rm const}/\mathring{\Delta}^3$.

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

From fundamental theory to observations

• Natural question: Conceptually, the LQG bounce is attractive. But how would ever know that there was a big bounce rather than a big bang? Our information about the early universe comes from observations of the Cosmic Microwave Background (CMB). Currently, the most commonly used model to account for these observations assumes that the universe underwent an early phase of exponential expansion, called inflation. During this phase, inevitable quantum fluctuations at the Planck scale are stretched enormously and become observable in the CMB.

• Since the curvature at the big-bang is infinite, the curvature radius is zero. At the bounce it is non-zero and has a universal value $L_{\mathrm{LQC}} \approx 7.9\ell_{\mathrm{Pl}}$. So the CMB modes which have a wavelength $\lambda < L_{\mathrm{LQC}}$ are not affected by the pre-inflationary curvature but those with $\lambda > L_{\mathrm{LQC}}$ do. (Just as I don't feel earth's curvature when I am walking, but it played an important role in my flight from the US to Germany!) These turn out to be the modes with longest wavelength in CMB.

• Interestingly predictions from the standard inflationary model fits very well with observations for most observable modes, but for the longest observable modes, there are some anomalies. Statistical significance of any one anomaly is low but two or more anomalies, taken together, imply that if the standard inflationary scenario is correct then we live in a very exceptional universe. Therefore the anomalies and mechanisms to alleviate them have drawn significant attention.

But are these effects relevant for observations?

***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.

LQG in the sky!

- Since the longest wave length modes associated with anomalies are just the modes that experienced curvature in the pre-inflationary dynamics of LQC, several anomalies were analyzed using LQC. Detailed analysis by the Penn State and Louisiana State Universities has shown that they cease to be anomalous in LQC!

- The Penn State group has shown that while 5 of the 6 parameters used in the current standard cosmological models remain essentially unchanged by these LQC effects, but the 6th (called the optical depth) increases by $\sim 9.8\%$!

Parameter	Std. Inflation	LQC
$\Omega_b h^2$	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

Currently all parameters but τ have been measured to $\leq 1\%$ accuracy while τ has $\sim 13\%$ error bars. Forthcoming missions will measure it to $\sim 1\%$ accuracy. It is exciting that a quantum gravity prediction is within observational reach!

3. Summary

• LQG starts with a new syntax –Quantum Riemannian Geometry– and uses it to address the longstanding conceptual issues of QG related to the absence of a sharp spacetime geometry, as well as mathematical problems stemming from infinite number of degrees of freedom of GR. By now the basic framework has matured sufficiently to seek physically interesting applications. Jurek Lewandowski played a major role in all these developments.

• In GR the most dramatic effects are associated with the physical, dynamical nature of spacetime in cosmology and black holes. At the onset of inflation, curvature is about 10^{66} times that at the horizon of a solar mass BH! That's why I used the early universe to illustrate the LQG implications.

• Interesting interplay between the UV and the IR. Singularity resolution because of UV corrections to GR. A new scale: curvature radius $R_{\rm curv}$ at the bounce. Then perturbations with $\lambda_{\rm Phy} \gtrsim R_{\rm curv}$ at the bounce receive LQC corrections $\Rightarrow$ corrections to CMB at the largest angular scales!

These effects alleviate two anomalies and also lead to predictions for future missions (measurements of τ, and the BB spectrum) without compromising successes of the standard paradigm. Quantum gravity in the sky!

SUPPLEMENTARY MATERIAL

A final thought

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".

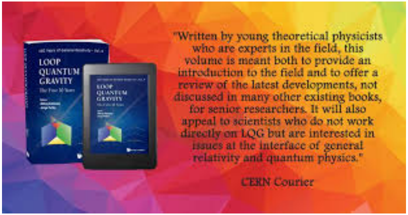
"I just think too many nice things have happened in string theory for it to be all wrong. Humans do not understand it very well, but I just don't believe there is a big cosmic conspiracy that created this incredible thing that has nothing to do with the real world."

"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)
Atoms as knotted vortices in space (Kelvin, Maxwell)

A few References

Recent reviews: AA & Bianchi (RoPP, 2021);
Chapters by Bianchi, Dittrich, Giesel, Laddha & Varadarajan, Agullo & Singh, Barbero & Perez; ... in *Loop Quantum Gravity: The first thirty years.*



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

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 spacetime 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?

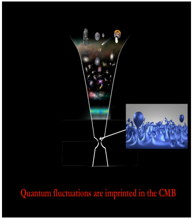
Answers in Loop Quantum Gravity

1. How do you do physics if there is no spacetime metric to anchor it? Matter fields and geometry are both quantum mechanical at birth. Matter propagates not on a fixed spacetime 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'? Happening is relational concept (à la Leibniz!) A matter field or an attribute of spacetime 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.

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 GR. LQG equations continue to be well defined and have definite predictions.

Inflationary Scenario



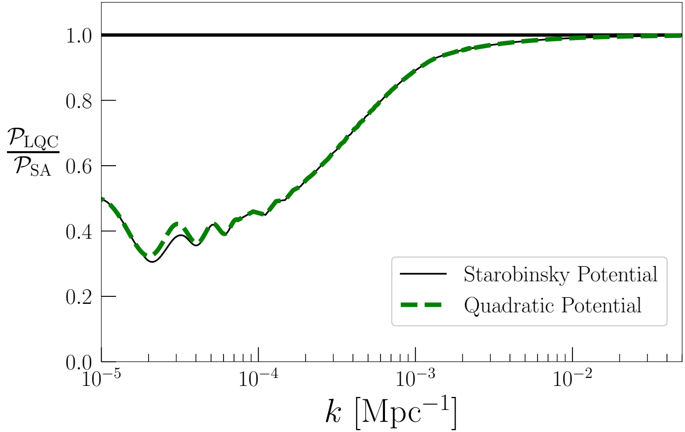
• Current understanding of the early universe: The large scale structure we see in the universe can be traced back to the tiny, 1 part in 10,000 fluctuations that have been observed in the cosmic microwave background (CMB) that was emitted when the universe was only 380,000 years young. Today, the leading scenario to account for the CMB fluctuations posits that there was a short inflationary phase in the very early universe.

• During this nearly exponential expansion, the early 'vacuum fluctuations' –inevitable consequence of the Heisenberg uncertainty principle– in cosmological perturbations are converted to the seeds of large scale structure.

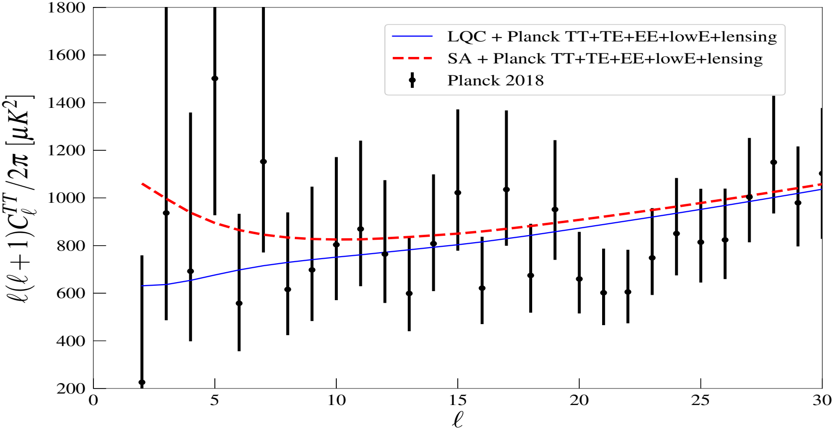
• Natural question: Conceptually, the LQG bounce is attractive. But how would ever know that there was a big bounce rather than a big bang? Would the effects of the bounce not be just washed away?

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))



The three TT-Power spectra: $\ell < 30$



Starobinsky potential: $V(\phi) = \frac{3m^2}{32\pi G}\left(1 - e^{-\frac{16\pi G}{3}\phi^2}\right)$

Natural Questions

- What sets the scale at which power suppression occurs?

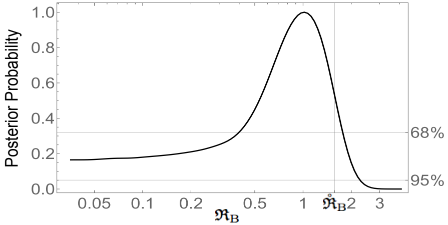
At the Big-bang, curvature diverges. In LQC, it is always finite. R reaches its universal maximum at the bounce $R_{\max} \simeq 62$ (Planck units). Dynamical equations obeyed by the modes imply that if the physical wavelength of a mode is much smaller than the curvature radius, the mode does not affected 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



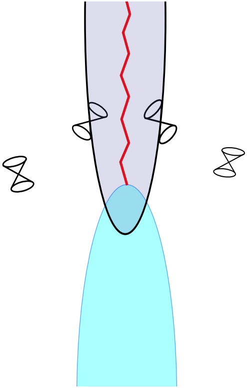
- Check on the area gap $\mathring{\Delta}$: Make the area gap variable and find its best fit value. In the plot, $\mathfrak{R}_{\rm B} = (6\,\Delta/4\pi)^{\frac{1}{2}}$. The line, $\mathfrak{R}_{\rm B} = \mathring{\mathfrak{R}}_{\rm B} \equiv 1.57\ell_{\rm Pl}$ corresponding to $\Delta = \mathring{\Delta}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

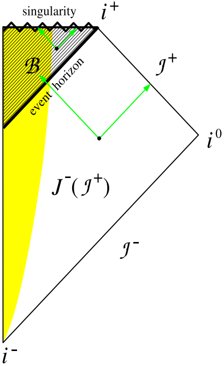
Two way bridge between observations and theory.

BHs: The issue of information loss

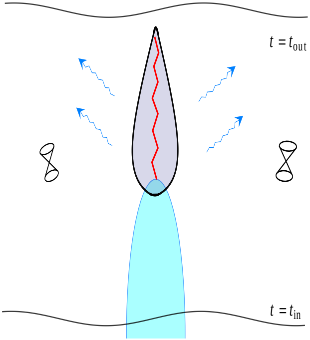
• Information is lost in the classical gravitational collapse: What falls across event horizon is invisible to outside observers. While $\mathcal{I}^-$ is a good 'initial data surface', $\mathcal{I}^+$ is not.



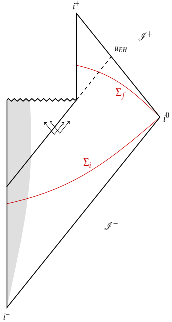
A collapsing star creates an event horizon, the boundary of a trapped region from where even light cannot escape however long you wait.



Black hole evaporation

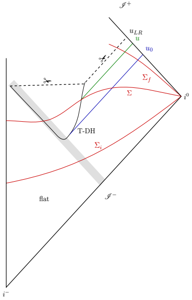


Consider a quantum fields in state $|0_{\rm in}\rangle$. The curved geometry creates pairs of modes, one falls across the horizon and the other escapes to infinity. Energy flux at infinity $\Rightarrow$ black hole shrinks and expected to eventually disappear.



If the a singularity persists, then again there is sink of information. Pure states in the past appear to evolve to mixed states in the future. Most relativists think that if the singularity persists, information would be lost in our asymptotic region. But if one insists on unitarity in this spacetime, as one often does in string theory, then one is led to invoke novel ideas: first we had quantum xerox machines, then firewalls along the horizon, then fast scramblers, ... Firewalls, for example, would imply a surprising failure of semi-classical physics! (Impetus for such considerations is diminished because of LIGO-Virgo discoveries.)

A puzzle already in the semi-classical regime

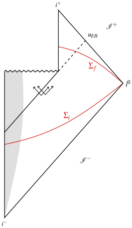


- Heuristics: Evaporation of a solar mass BH to lunar mass takes $\sim 10^{63}$ years. $\sim 10^{75}$ modes are emitted to infinity and are correlated with the modes that fell into the BH. How could these modes 'fit in' the ball of radius only 0.1mm, the Schwarzschild radius of a lunar mass BH? Even if they had the 'largest' $\lambda \sim 0.1$mm, their energy would be some 10^{22} times the lunar mass! Quandry: Too little available energy to pack so much 'information'. This has been the key reason to seek 'mechanisms for purification' already in the semi-classical regime irrespective of what happens in the full Planck regime.

- Resolution: Semi-classical considerations show that as the area of the dynamical horizon (DH) shrinks, the (e.g. $\mathrm{Tr}K = \mathrm{const}$) 3-surfaces develop extremely long necks; Wheeler's 'bags of gold'. As a solar mass BH shrinks to a lunar mass the neck grows from $\sim$ kms, to some $\sim 10^{55}$ light years in length! So the modes that have fallen in the DH get enormously stretched –become infrared. They can easily hold a lot of correlations with outside modes even though they have very little total energy. (AA & Ori; Christodoulou & De Lorenzo)

Beyond semi-classical theory: paradigm 2

Singularity resolution can change the whole picture. (Alesci, AA, Bianchi, Bahrami, Bojowald, Christodoulou, De Lorenzo, Gambini, Haggard, Martin-Dussaud, Olmedo, Perez, Rovelli, Singh, Smerlak, Ori, Pullin, Vidotto, . . .)



Suppose the singularity is resolved in a consistent theory, as in many current proposals (including Hawking's Take 2, (Hawking, Pope, Strominger)). Then there is no EH. Correlations between modes that escaped early on to $\mathcal{I}^+$ and those that were trapped 'inside the DH' in the semi-classical regime could be restored at $\mathcal{I}^+$, because the 'trapped modes' could pass through the quantum region and reach $\mathcal{I}^+$.

But how exactly this happens for the modes that are infrared in the semi-classical regime is still very much under debate. There are proposals and some detailed calculations are being pursued. Much work remains but one point is clear: If the singularity is resolved, obstruction to information recovery is removed.

(A concrete recent result that may help: $\langle \hat{T}_{ab} \rangle$ continues to be a well-defined distribution across space-like singularities (AA, De Lorenzo, Schneider).)