Is there an origin of the Universe?
Interplay between theory and observations

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Seven Pines Symposium XX, May 14th 2016

Preamble: $\sim$ 600BC

Is there an origin of the Universe?

One day a disciple by name Māluṅkyaputta put to the Buddha some well-known metaphysical questions and demanded answers. (Cūla-Māluṅkya-sutta, no.63 of Majjhima-nikāya (PTS edition).

After an afternoon meditation, he went to the Buddha, saluted him, sat on one side and said: " Sir, when I was all alone meditating, this thought occurred to me: There are these problems unexplained, put aside and rejected by the Blessed One. Namely,
(1) is the universe eternal or (2) is it not eternal, (3) is the universe finite or (4) is it infinite, ... These problems the Blessed One does not explain to me. ....

If the Blessed one knows that the universe is eternal, let him explain it to me so. If the Blessed one knows that the universe is not eternal, let him say so. If the Blessed one does not know if the universe is eternal or not, etc, then for a person who does not know it is straightforward to say "I do not know, I do not see".

(Homework: How did the Enlightened One reply?)

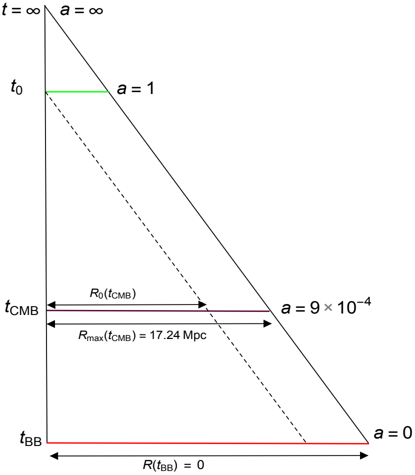
Preamble: 2016AD

• Continuing Māluṅkyaputta's tradition, we ask: Is there an Origin of the Universe? Now, the term 'Universe' refers to both, the underlying space-time, and the large scale structure of matter within it. So it is appropriate to divide the discussion into two parts.

• Jim Peebles emphasized observations and I will try to complement that discussion by focusing a bit more on theory. With paradigm shifts in physics, older questions often become ambiguous and sharper formulations can lead to very different answers. Examples: How much time has passed between the two meetings of twins one of whom stays on earth and the other makes a round trip to Mars on a very fast space-ship? Is the electron a wave or a particle?

• The same happens to the question "Is there an origin of the universe?" as we go from General Relativity (GR) to quantum gravity. To make the discussion concrete, I will often use Loop Quantum Cosmology to illustrate how the interplay between theory and observations is being used by the quantum gravity community to face/debate weighty philosophical questions.

1. Is there an origin of space-time?



Universe according to PLANK

- In general relativity (GR), the big bang provides an absolute beginning. Not just the matter, but spacetime itself is born at the big bang. So the question of 'what was there before' becomes meaningless.

- Brief history of the universe: Because of a positive Λ, there is a cosmological horizon. Using PLANCK data, one can fill in quantitative features to the future of the CMB epoch and account for the observed large scale structure using well established physics.

From GR to Quantum Gravity

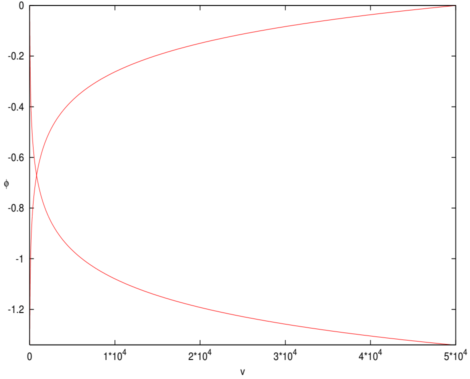
- But GR is incomplete because it ignores quantum physics. Quantum effects are not restricted just to microscopic systems. Neutron stars provide a spectacular example of how quantum mechanics can make qualitative difference even in astronomical systems. Density $\sim 10^{15}$ gm/cc. By contrast $\rho_{\rm Pl} \sim 10^{94}$ gm/cc ! Thus, Big Bang is a prediction of GR in a domain **outside** its validity! CMB is **not** a proof that the universe began with a Big Bang singularity.

- Loop Quantum Gravity: Based on a specific theory of quantum Riemannian geometry developed in detail in the mid-90s. Geometrical operators such as areas of physical surfaces and volumes of physical regions are quantized in a precise sense that their eigenvalues are discrete. But they crowd exponentially for large areas making the continuum an excellent approximation very quickly.

- Strong curvature singularities are naturally resolved in Loop Quantum Cosmology (LQC). The lowest non-zero eigenvalue of area $\Delta \ell_{\rm Pl}^2$ turns out to be the microscopic parameter that dictates new macroscopic upper bounds on matter density and curvature.

FLRW space-times

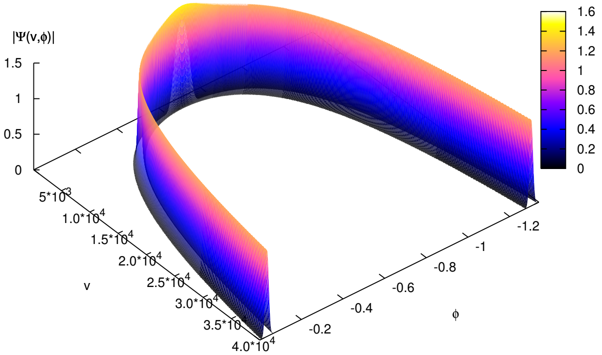
The Simplest Model: The k=0, $\Lambda = 0$ FRW Model coupled to a massless scalar field ϕ. Instructive because every classical solution is singular. Provides a foundation for more complicated models.



Classical trajectories

LQC Evolution

k=0 LQC with massless scalar field

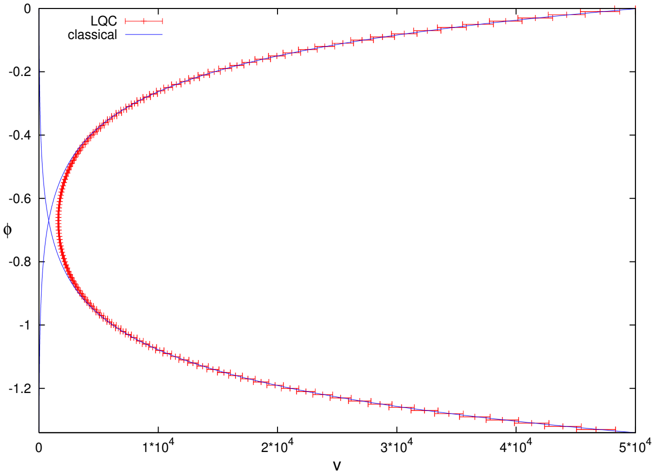


Absolute value of the physical state $\Psi(v, \phi)$

(AA, Pawlowski, Singh)

LQC Evolution

k=0 LQC with massless scalar field



Expectations values (and dispersions) of $\hat{V}|_\phi$ & classical trajectories.

(AA, Pawlowski, Singh)

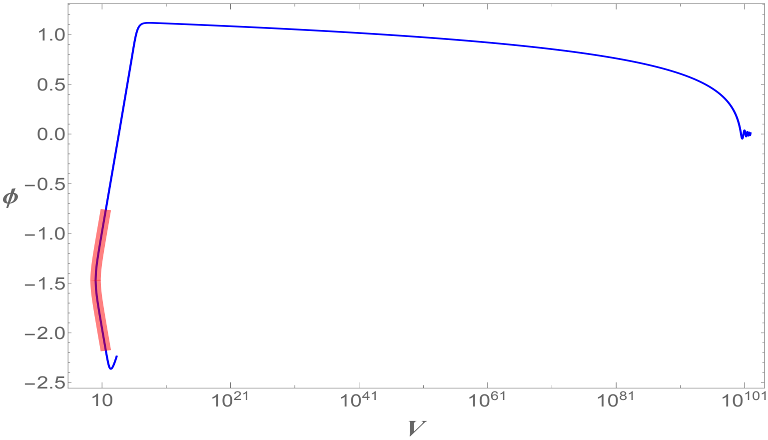
What is behind this singularity resolution?

• No unphysical matter or new boundary conditions. Rather, quantum geometry creates a brand new repulsive force in the Planck regime, overwhelming classical attraction. The Big Bang is replaced by a Big Bounce. Analyzed in detail using the Hamiltonian, Path integral and consistent histories frameworks.

• In FLRW models, quantum Einstein's equations dictate the (relational) evolution of $\Psi_o(a, \phi)$. Observables such as matter density and curvature remain bounded on *all* solutions $\Psi_o(a, \phi)$. The universal upper bounds are determined by inverse powers of the area gap Δ; e.g. $\rho_{\rm sup} = (const/\Delta^3)$. They diverge in the classical limit. Recall the hydrogen atom (Wheeler).

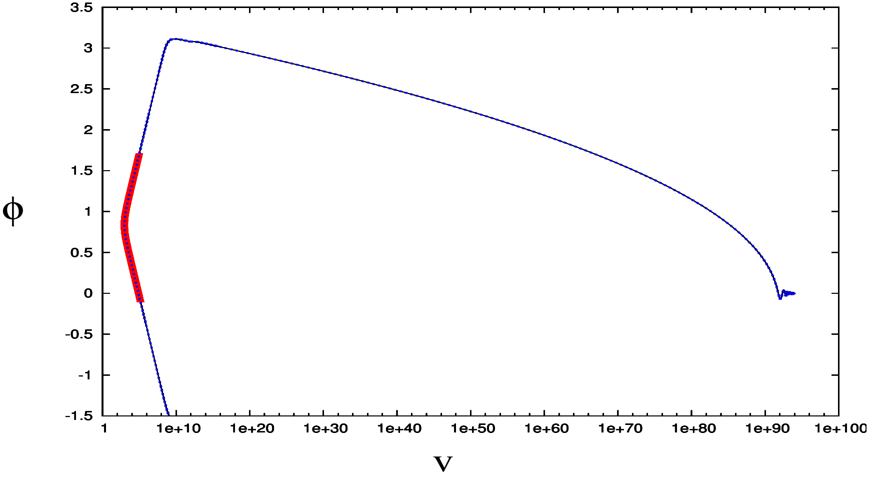
• Many generalizations (several thousand papers on LQC!): inclusion of spatial curvature, a cosmological constant Λ, inflaton potentials, anisotropies, simplest inhomogeneities (Gowdy models), . . . (Bojowald; AA, Pawlowski, Singh, Vandersloot; Lewandowski; Corichi; Wilson-Ewing; Brezuela, Martin-Benito, Mena, . . .). Qualitative summary: Every time a curvature scalar enters the Planck regime, the quantum geometry repulsive force dilutes it, preventing a blow up. The Big Bang is replaced by a Big Bounce and quantum space-time is vastly larger than in GR.

Singularity Resolution: Starobinsky inflaton Potential



Expectations values of volume $\hat{V}|_\phi$ for the Starobinsky potential (Bonga and Gupt)
$V(\phi) = (3M^2/32\pi)\,(1 - \exp - \sqrt{(16\pi/3)\phi})^2$. The Big Bang is replaced by a Big Bounce.

Singularity Resolution: $(1/2)m^2\phi^2$ inflaton Potential



Expectations values and dispersions of $\hat{V}|_\phi$ for a massive inflaton ϕ with phenomenologically preferred parameters (AA, Pawlowski, Singh). The Big Bang is replaced by a Big Bounce.

So, is there an origin of space-time?

• Recall that a more general theory often forces one to sharpen questions. Further qualifications are needed to obtain unambiguous answers.

• From quantum gravity perspective, the answer depends on what one means by 'space-time' and by 'origin'.

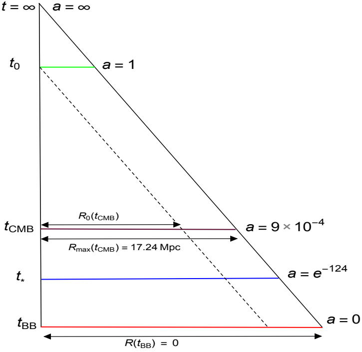
• If the question refers to Einstein's space-time continuum described by a smooth, single, Lorentzian metric satisfying Einstein's equation, then the answer is YES, space-time has a beginning. When the matter density falls below $\sim 10^{-3}\rho_{\rm Pl}$, general relativity becomes an excellent approximation in the sense that the GR trajectory lies within the spread of the sharply peaked $\Psi_o(a, \phi)$.

• If by 'origin' one means the end of space-time beyond which physics cannot be continued (as in GR), then the answer is NO!

• What we do have is a detailed, specific, self-consistent quantum extension of the Friedmann, Raychaudhuri and matter equations and quantum states $\Psi_o(a, \phi)$ satisfying these equations which reproduces the predictions of FLRW models when $\rho \ll \rho_{\rm Pl}$. The quantum space-time does not have an orign.

2. Origin of large scale structure

• Well-established physics implies that the inhomogeneity observed in the CMB serve as seeds for the formation of the observed large scale structure (LSS). But the universe was some 380,000 years young at the CMB epoch. Can we push the issue of origin of LSS back in time?



Inflation + PLANCK data

• We can, but we need quantum physics. Idea: Retain FLRW classical geometry and introduce first order perturbations thereon. But treat them as quantum fields on the FLRW background. The most successful framework so far is inflation. Pushes back the issue of 'origin' of LSS to astonishingly early times:

from $a \sim 10^{-3}$ at CMB time to $a \sim e^{-124}$ at the onset of inflation!, or,
from $R_{\rm max} = 17.24$ Mpc (at CMB time), to $R = 3.14 \times 10^{7} \ell_{\rm Pl}$!

Inflation: Caveats and successes

• Paradigm is based on 4 assumptions that have not been justified so far. Furthermore, as Penrose has argued clearly and forcefully, the original motivations were misplaced. (Unfortunately, they still continue to be repeated!)

• But there are outstanding examples in the history of science where the ideas turned out to be valuable even when the original motivation was faulty (e.g. the Dirac equation). Inflation correctly predicted the CMB spectrum, with 1 part in 10^5 anisotropy and a small red-tilt, starting from incredibly early times. Furthermore, it leads us to the conclusion that

All large scale structure emerged from vacuum fluctuations!

The issue of origin of LSS is reduced to the intrinsic Heisenberg uncertainties that cannot be removed even in principle.

In this paradigm, the early universe is astonishingly simple, much more so than what we had imagined! A priori we could have imagined that full, non-linear GR would open up an untold plethora of complications when space-time curvature is 10^{64} times that at the horizon of a solar mass black hole or matter density is 10^{80} times that of nuclear matter! Deep lesson here.

Limitation of Inflation

• Incompleteness: The paradigm continues to use GR with its big bang singularity. It just begins "in the middle" when space-time curvature is $\sim 10^{-11}\mathrm{curv}_{\mathrm{Pl}}$. Jim Peebles assessment in his reading material, *"general relativity is a theory, while inflation is a framework on which to hang a theory,"* provides an outstanding challenge and opportunity for quantum gravity theories.

• Particle Physics Issues: Where from the inflaton? A single inflaton or multi-inflatons? Interactions between them? How are particles/fields of the standard model created during 'reheating'? ... These are important issues for the question of 'origin'. There is a lot of ongoing work but in my view detailed, concrete scenarios are yet to emerge.

• Quantum Gravity Issues: (Brandenberger, Martin, Starobinsky, ..). A resolution of the big bang singularity from appropriate first principles? A systematic treatment of trans-Planckian issues? Corresponding replacement of QFT on classical FLRW space-times to appropriate FLRW quantum FLRW space-times to handle quantum perturbations in the Planck regime? In short, Can one consistently extend the inflationary scenario over 11 orders of magnitude in curvature and density all the way to the Planck regime? There are concrete and detailed scenarios, although they are still far from being definitive.

Why Planck scale dynamics matters

• Wide-spread belief until ~ 5 years ago: Pre-inflationary dynamics cannot possibly have any observational consequences. Whatever effects it produces would be just diluted away by the ~ 65 e-folds of inflation during which the size of a hydrogen atom expands to galactic scale!

• Quantum gravity community argued against this because:
(i) In GR, observable modes of cosmological perturbations do not experience any curvature prior to onset of inflation. But the ultraviolet modifications of GR dynamics makes it possible for the longest wavelength of observable modes to experience curvature in the Planck regime. These modes can get excited and will not be in the Bunch-Davies vacuum at the onset of inflation (Agullo, AA, Gupt, Morris, Nelson, ...).
(ii) These initial excitations do not get diluted away during inflation because of stimulated emission (Agullo, Parker, ...).
These considerations are now accepted by mainstream cosmologists (e.g., Komatsu, Holman & Tolley, Ganc, ...)

• Unforeseen interplay between the ultraviolet and the infrared!

Interplay between theory & observations?

• This analysis opens up the interesting possibility that pre-inflationary dynamics can leave observable imprints on the longest wavelength modes seen in CMB.

• Interestingly, PLANCK (and WMPAP) see certain anomalies –i.e. , departures from standard inflation based on the Bunch-Davies vacuum– precisely at the longest angular scales, i.e., for the longest wave-length modes. They could be statistical artifacts or have origin in late time physics (e.g., ISW effect). But they could also be a window into Planck scale physics. To quote Planck paper XII, "the anomalous features in the CMB .... could be the visible traces of fundamental physical processes occurring in the early universe."

• Thus, there is potential to see Planck scale physics in the sky! Researchers in LQC have worked very hard to exploit this opportunity to create a niche for inflation within a fundamental theory.

Developments in LQC

- Over the last 2-3 years, the community (AA, Kaminski, Lewandowski; Agullo, AA, Nelson, Gupt, Morris,...) has:

(i) Extended QFT on FLRW space-times to QFT on quantum FLRW space-times.

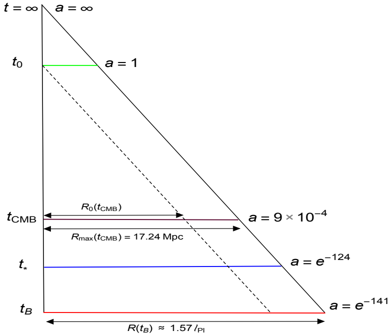
(ii) Used it to study in detail the evolution of quantum fields representing first order perturbations from the bounce to the onset of slow roll inflation (for the Starobinsky and $m^2\phi^2$ Potentials), spanning the 11 orders of magnitude in curvature and density.

(iii) Used observations to arrive at a candidate set of principles that severely narrow down the initial conditions at the bounce. (A quantum version of Penrose's Weyl curvature hypothesis is implemented in this process.)

(iv) Shown that this extension of inflationary scenario to the Planck regime is consistent with current observations and have predictions for the future observations (of E-E and T-E correlations). PLANCK team should release the data soon. If there is interest, I can show the plots during discussion.

- The analysis depends on basic LQC as well as the principles used to select initial conditions. May be ruled out by future observations. And there may be alternate explanations. But it is notable that quantum gravity has now begun to descend from its high, mathematical physics perch and making bridges to observations.

History of the universe from the bounce to infinite future



The domain of dependence of at any point in the entire universe within our cosmological horizon is contained in a an elementary ball of area $\sim 31 lp^2$!

Inflation + PLANCK data

Epoch	a	n_e	R_0	$R_{\max}$
t_0	1	0	0	2.58 Mpc
$t_{\rm CMB}$	9×10^{-4}	7	12.76 Mpc	17.24 Mpc
t_*	e^{-124}	124	$2.32 \times 10^7\ \ell_{\rm pl}$	$3.14 \times 10^7\ \ell_{\rm pl}$
$t_{\rm B}$	e^{-141}	141	$1.16\ \ell_{\rm pl}$	$1.57\ \ell_{\rm pl}$

3. Summary

- Because of the positive cosmological constant, we now encounter a new twist for our question "Is there an origin of the universe?" Should we restrict the question of 'origin' to the causal past of an eternal observer, or, should the question or 'origin' refer to all possible observers?

- In the first case, LQC, for example, provides a nice story. It suffices to trace back the origin of space-time and large scale structure to an elementary ball at the bounce (defined by the LQG quantum geometry).
There are reasons to believe that the initial conditions chosen in this ball arise dynamically (because of the repulsive force of quantum geometry that dilutes inhomogeneities). Dynamics would make the region outside the ball at the bounce irrelevant! One avenue for future work is to show this in detail.

- If on the other hand we want to consider all observers even though they cannot communicate with each (in distant future) other the issue of 'origins' would be much more complicated.

- Perhaps the most important lesson is that, with each major advance in cosmology and quantum physics, the issue of 'origin' has acquired new dimensions. To me, this is a good example of the 'back reaction' of physics on philosophy.

Main References for this talk

- For a summary, see:

Viewpoint article, P. Singh, Physics 5, 142 (2012);
AA, Barrau, CQG 32, 234001 (2015)
AA, arXiv 1605.02648

- More complete references:

AA, Agullo & Nelson, PRD 87, 043507 (2013); CQG 30, 085014 (2013)
AA & Sloan, GRG (2011), PLB (2009); Corichi & Karami, PRD
AA, Corichi & Singh, PRD (2008); AA, Pawlowski, Singh, PRL & PRD (2006).

Other Results Referred to in the Talk:

- Future Observations:

Agullo & Parker PRD & GRG (2011); Agullo & Shandera JCAP (2012); Ganc & Koamtzu PRD (2012).

- A recent detailed Review of Loop Quantum Cosmology

AA & Singh, CQG (2011).

Supplementary Material

The slides that follow contain supplementary material, providing some details that could not be covered in the talk.

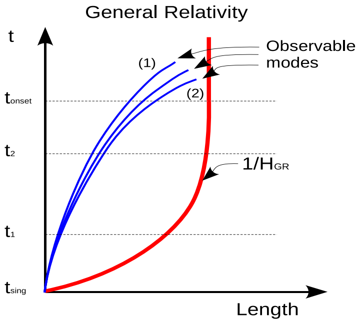
Buddha's response to Māluṅkyaputta

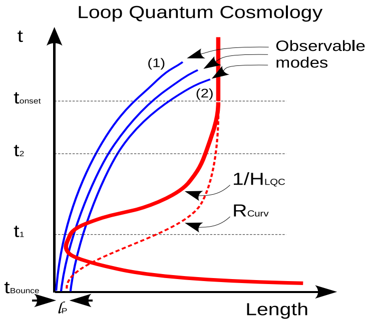
Buddha's response was that he never promised that he will explain these questions, nor did Māluṅkyaputta join the Order conditionally. ... Then he explained to Māluṅkyaputta that the holy life does not depend on theseviews. whatever the opinion one may have about these problems, there is birth, old age, decay, death, sorrow, lamentaion, pain, grief, distress, "the cessation of which (i.e. Nirvāṇa) I declare in this very life". "Therefore, Māluṅkyaputta, bear in mind what I have explained as explained, and what I have not explained as unexplained. What are the things that I have not explained? Whether the universe is eternal or not, etc., I have not explained. Why, Māluṅkyaputta, have I not explained them? Because it is not useful, it is not fundamentally connected with the spiritual holy life, is not conducive to aversion, detachment, cessation, tranquility, deep penetration, full realization, Nirvāṇa. That is why I have not told you about them.

Then, what Māluṅkyaputta, have I explained? I have explained dukkha, the arising of dukkha the cessation of dukkha, and the way leading to the cessation of dukkha. Why, Māluṅkyaputta, have I explained them? Because it is useful, fundamentally connected with the spiritual holy life, is conducive to aversion, detachment, cessation, tranquility, deep penetration, full realization, Nirvāṇa. Therefore, I have explained them.'

Why pre-inflationary dynamics matters

Contrary to a wide-spread belief, pre-inflationary dynamics does matter because modes with $\lambda_{\rm phys} > R_{\rm curv}$, the curvature radius, in the pre-inflationary era are excited and populated at the onset of inflation. They can leave imprints on CMB, naturally leading to 'anomalies' at low ℓs .





The UV LQG regularization tames the FLRW singularity. The new FLRW dynamics in turn affects the IR behavior of perturbations!

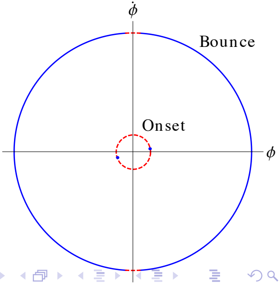
Background Quantum Geometry Ψ_o

- Let us begin with the effective theory, consider generic data at the bounce and evolve. Will the solution enter slow roll at curvature scale $\rho \approx 7.32 \times 10^{-12} m_{\rm Pl}^4$ determined from the CMB data ? Note: 11 orders of magnitude from the bounce to the onset of the desired slow roll!

- **Answer: YES.** In LQC, $|\phi_{\rm B}| \in (0, 7.47 \times 10^5)$. If $\phi_{\rm B} \geq 0.93$, the initial data evolves to a solution that encounters the slow roll compatible with the 7 year WMAP data sometime in the future. In this sense, 'almost every' initial data at the bounce evolves to a solution that encounters the desired slow roll sometime in the future. (AA & Sloan; Further results: Corichi & Karami; Barrau & Linsefors)

- For the background quantum geometry, we can choose a 'coherent' state Ψ_o sharply peaked at an effective trajectory with $\phi_{\rm B} > 0.93$ and evolve using LQC. It remains sharply peaked on that effective trajectory. Hence the desired slow roll automatically occurs in this quantum geometry!

- Choice of the background geometry Ψ_o is dictated by ϕ_B; Free parameter in LQC.



4. Perturbations ψ on the Quantum Geometry Ψ_o

- Strategy: Assume perturbations ψ can be regarded as test fields on the quantum geometry Ψ_o, find solutions $\Psi_o \otimes \psi_{\rm pert}$, and finally check self consistency. Then, the Planck regime is dealt with squarely provided $\rho_{\rm Pert} \ll \rho_{\rm BG}$ all the way from the bounce to the onset of slow roll.

- Unforeseen Simplification: dynamics of perturbations $\hat{T}^{(1)}, \hat{T}^{(2)}, \hat{\mathcal{R}}$ on the quantum geometry of Ψ_o is mathematically equivalent to that of $\hat{T}^{(1)}, \hat{T}^{(2)}$, $\hat{\mathcal{R}}$ as quantum fields on a smooth space-time with a 'dressed' effective, c-number metric $\bar{g}_{ab}$ (whose coefficients depend on $\hbar$):

$$\bar{g}_{ab} dx^a dx^b = \bar{a}^2(-d\bar{\eta}^2 + d\vec{x}^2)$$

with

$$d\bar{\eta} = \langle \hat{H}_o^{-1/2} \rangle \, [\langle \hat{H}_o^{-1/2} \hat{a}^4 \hat{H}_o^{-1/2} \rangle]^{1/2} \, d\phi; \qquad \bar{a}^4 = (\langle \hat{H}_o^{-1/2} \, \hat{a}^4 \hat{H}_o^{-1/2} \rangle)/\langle \hat{H}_o^{-1} \rangle$$

where H_o is the Hamiltonian governing dynamics of Ψ_o. For the $\hat{\mathcal{R}}$ there is also a quantum corrected effective potential, $\bar{\mathcal{U}}(\bar{a}, \phi)$. Analogy with light propagating in a medium. (AA, Lewandowski, Kaminski; AA, Agullo, Nelson)

- Because of this, the mathematical machinery of adiabatic states, regularization and renormalization can be lifted to the QFT on cosmological QSTs under consideration. Result: Full mathematical control on dynamics starting from the bounce.

Initial Conditions on Perturbations ψ

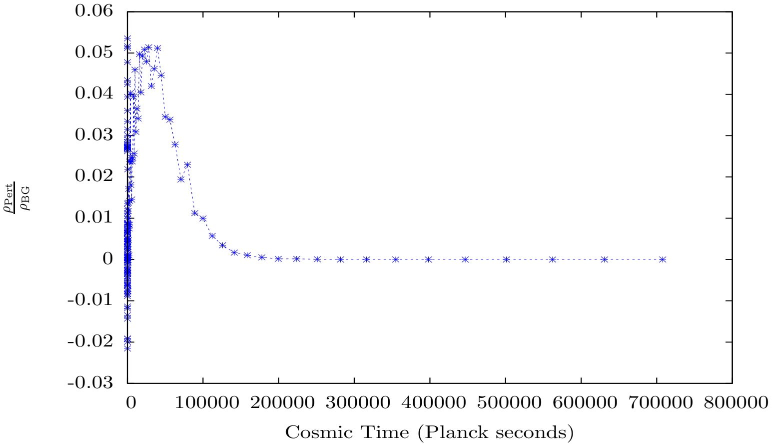
• The procedure is technically subtle and only a well-motivated proposal. (Analogy: the Bohr model of hydrogen atom).

• Ψ_o: Peaked at the effective trajectory in which interior of the 'elementary' ball of quantum area $\sim 30\ell_{\rm Pl}^2 \sim \pi^3 \ell_{\rm Pl}^2$ at the bounce determines the physics in the entire observable universe to infinite future. Selects a very narrow class of Heisenberg states Ψ_o.
(There are reasons to believe that due to the repulsive force of origin in quantum geometry, the state at the bounce would be 'as homogeneous and isotropic as the uncertainty principle allows'.)

• ψ: Cannot use the BD vacuum because the pre-inflationary phase is far from de Sitter! Demand (i) Appropriate symmetry and regularity; (ii) Quantum version of the Weyl curvature hypothesis This provides a ball of preferred states that mimic Minkowski vacua; and, (iii) Maximizing classicality at late times. This selects a *very* narrow class of Heisenberg states ψ.

5. Dynamics and Results

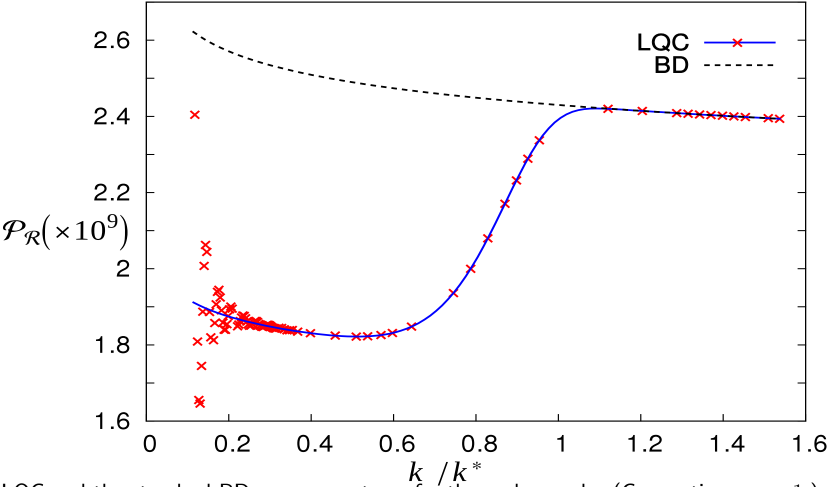
Facing trans-Planckian issues squarely: Is $\rho_{\rm Pert}/\rho_{\rm BG} \ll 1$ all the way from the bounce to the onset of slow roll? If so, self-consistency.



Yes!. Our initial conditions on ψ do ensure self-consistency of the test field approximation as hoped. Illustrative plot. (Agullo, AA, Nelson)

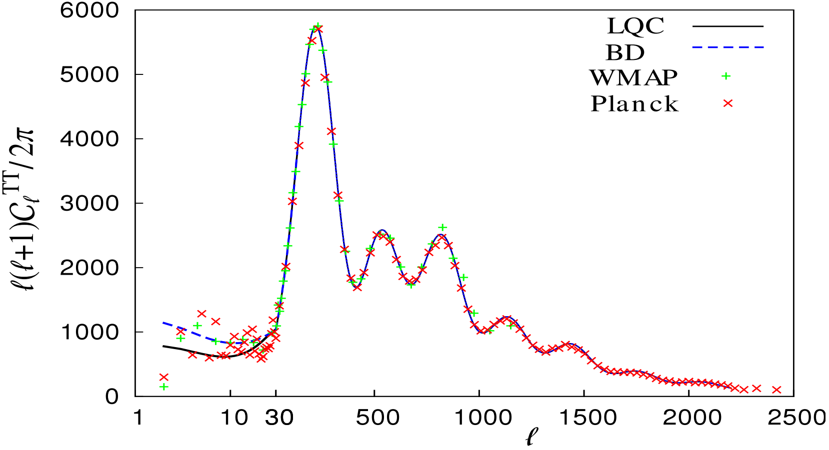
The Scalar Power spectrum

"Top-down approach"



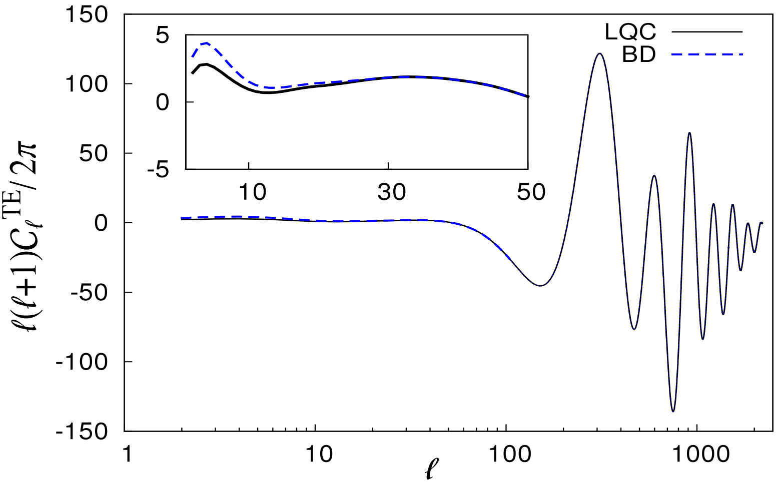
The LQC and the standard BD power spectrum for the scalar mode. (Convention $a_{\rm B} = 1$.) Red: Raw 'data' from LQC. blue: best fit curve. Here, the WMAP reference mode $k^{\star}_{\rm B}/a_{\rm B} = 54 m_{\rm Pl}$ and $k^{\rm min}_{\rm B}/a_{\rm B} = 6.3 m_{\rm Pl}$. (AA, Gupt)

LQC: Predicted TT-Power spectrum



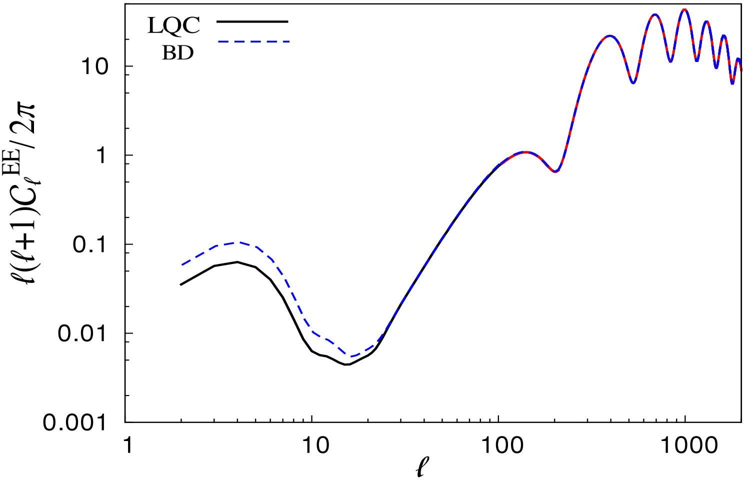
There exist permissible states $\Psi_o \otimes \psi$ such that the LQC power spectrum agrees with the standard BD power spectrum for $\ell \gtrsim 30$, but in LQC power is suppressed for $\ell \lesssim 30$. (AA, Gupt)

LQC: Predicted TE Correlations



The LQC prediction for the TE spectrum, for the initial state that gave the TT-spectrum in the last slide. Small suppression of power at small ℓ is a signature that the TT power suppression is of primordial origin. (AA, Gupt)

LQC: Predicted EE Correlations



The LQC prediction for the TE spectrum, for the initial state that gave the TT-spectrum in the last but one slide. The small suppression of power at small ℓ is a signature that the TT power suppression is of primordial origin. (AA, Gupt)

6. Summary

• The early universe provides an ideal setting to test quantum gravity ideas. Key questions: Can one obtain an extension of successful cosmological scenarios to include the Planck regime? Can the pre-inflationary, Planck scale dynamics leave observable imprints?

• No approach to quantum gravity is complete. Still in LQG progress could be made by truncating the classical theory to the physical problem under consideration and then passing to the quantum theory using LQG techniques. For inflation, the relevant sector: FLRW background with an inflation ϕ in a suitable potential as matter, together with first order perturbations.

Result: LQC provides a self-consistent extension of this sector.

Perturbations

- Since they propagate on quantum geometry, using QFT on cosmological quantum geometries, (AA, Lewandowski, Kaminski), trans-Planckian issues can be handled systematically provided the test field approximation holds. There exist natural states $\Psi_o \otimes \psi_{\rm pert}$ in which it does. (Agullo, AA, Nelson).

In this scenario, the observable universe was a ball of radius $\sim 10\ell_{\rm Pl}$ at the Big Bounce. Qualitatively, the quantum geometry repulsive force of LQG provides a mechanism to 'explain' the extraordinary initial homogeneity and isotropy in this ball, making the pre-big-bounce history largely irrelevant for foreseeable observations.

- There are natural restrictions on initial conditions on $\Psi_{o\otimes}\psi$ at the bounce. In this allowed class, there is agreement with standard (BD-based) inflation for $\ell > 30$ or so. In this sense, LQC provides a natural extension of the inflationary paradigm over 12 orders of magnitude in curvature from the bounce to the onset of inflation.

Theory and Observations

• But for low values of ℓ, there can be deviations (in a small window for the parameter $\phi_{\rm B}$. For these states, pre-inflationary dynamics leaves an imprint. A new mechanism for primordial power suppression. For these states, LQC differs from the standard, BD-based inflation also for E-E and E-T correlations for $\ell < 30$. Other 'standard' predictions, such as the consistency relation $r = -8n_t$, is also modified for a single inflaton. These results open an avenue to see fundamental Planck scale physics in cosmological observations.

• The issue of initial conditions. General physical considerations already constraint the state $\Psi_o \otimes \psi$ at the bounce. But it is not unique. Work in progress on uniqueness. Observations can potentially inform the theory! Possibility being pursued: A new physical principle (such as the quantum version of Penrose's Weyl curvature hypothesis) could lead to a preferred 'initial' state. Thus Loop quantum gravity has now sufficiently matured to create a 2-way bridge between the the Planck scale geometry and observations of the very early universe.

• But note that, so far, LQC does not take into account any of the particle physics issues. The analysis simply assumes an inflaton and a suitable potential. Therefore, it cannot imply that inflation must have occurred. On the other hand, the LQC framework can be, and is being, used to address quantum gravity issues also in non-inflationary scenarios.

Merits and Limitations of QC

One's first reaction to Quantum Cosmology is often: Symmetry reduction gives only toy models! Full theory much richer and much more complicated.

But examples can be powerful.

- Full QED versus Dirac's hydrogen atom.
- Singularity Theorems versus first discoveries in simple models.
- BKL behavior: homogeneous Bianchi models.

Do not imply that behavior found in examples is necessarily generic. Rather, they can reveal important aspects of the full theory and should not be dismissed a priori.

One can work one's way up by considering more and more complicated cases.
(e.g. the work of the Madrid group on Gowdy models which have infinite degrees of freedom).
At each step, models provide important physical checks well beyond formal mathematics. Can have strong lessons for the full theory.