Quantum Gravity in the Sky ?

Interplay between Fundamental Theory and Observations

Abhay Ashtekar
Institute for Gravitation and the Cosmos & Physics Department,
The Pennsylvania State University

Will summarize the work of many researchers; especially
Agullo, Barrau, Bojowald, Corichi, Gupt, Kaminski,
Lewandowski, Mena, Nelson, Olmedo, Pawlowski, Singh, Sloan, ...

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Preamble

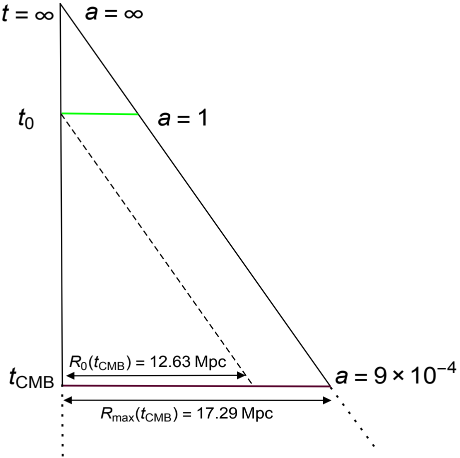
• Over the past 2-3 decades there have been spectacular advances in our understanding of the very early universe, both in terms of the nature of space-time geometry and and the large scale structure.

• Interestingly, these advances have opened an unforeseen window to see quantum gravity effects in the sky! There is a fascinating interplay between fundamental aspects of quantum gravity such as the quantum nature of geometry and observations of the early universe.

Organization of the talk

1. PLANCK data and inflation.
2. Quantum gravity and the early universe.
3. Loop quantum cosmology and observations.
4. Summary and Outlook.

1. PLANCK Mission data and space-time structure



Universe according to PLANCK

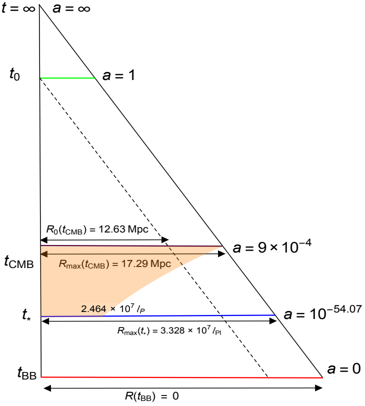
- Given the data provided by the PLANCK mission on H_0, Ω_m, Ω_r, and Ω_Λ, general relativity determines space-time geometry to the future of the CMB surface if we make the conservative assumption that the 'dark energy' is due to a cosmological constant. A key feature is that there are cosmological horizons.

- Any eternal cosmic observer will be able to see only a finite patch of the universe no matter how long she waits.

- CMB is extraordinarily homogeneous with tiny, 1 part in 10^5 fluctuations.

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. Arguably 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 $a \sim 10^{-54}$ at the onset of inflation!, or,
from $R_{\rm max} = 17.29$ Mpc (at CMB time), to $R_{\rm Max} = 3.3 \times 10^7 \ell_{\rm Pl}$!

Inflation: Caveats and successes

• Paradigm is based on 4 assumptions that have not been justified so far. Furthermore, as Penrose & others have 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!

(Bunch-Davies vacuum). 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 $\sim 10^{-11}\text{curv}_{\text{Pl}}$.

• 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'? ... There is a lot of ongoing work but 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? **Focus of this talk**

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2. From GR to Quantum Gravity

• 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 !

• Neither CMB nor the success of inflation implies there was a Big Bang. Big Bang is a prediction of GR in a domain where is it not applicable!!

"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."
A. Einstein, 1945

Loop Quantum Gravity

• 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.

• Indeed, quantum gravity effects change the story qualitatively. I will focus on Loop Quantum Cosmology (LQC), the cosmological sector of Loop Quantum Gravity. In FLRW models all strong curvature singularities are naturally resolved. The underlying reason is quantum geometry. Physical quantities such as density, curvature, anisotropies,. . . have an absolute upper bound on all physical states.

• The lowest non-zero eigenvalue $\Delta\, \ell_{\rm Pl}^2$ of the area operator turns out to be the fundamental microscopic parameter that dictates the new macroscopic parameters such as $\rho_{\rm sup}$.

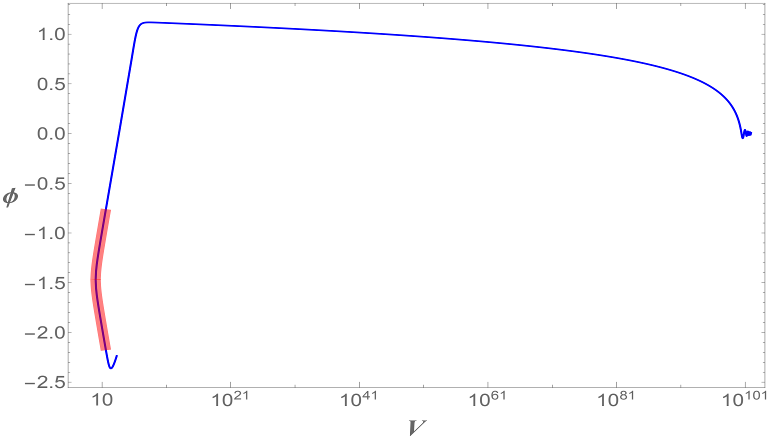
What is behind this singularity resolution?

• 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. $\rho_{\rm sup} = ({\rm const}/\Delta^3)$. They diverge in the classical limit. Recall the hydrogen atom (Wheeler).

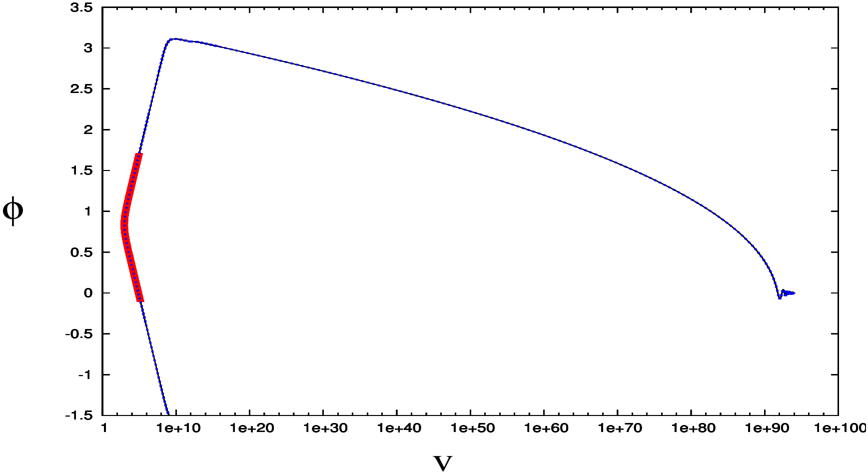
• Many generalizations (several thousand papers on LQC!): inclusion of spatial curvature, a cosmological constant Λ, inflaton potentials, anisotropies, simplest inhomogeneities (Gowdy models), ... (Bojowald; AA, Pawlowski, Singh, Vandersloot; Lewandowski; Corichi; Wilson-Ewing; Brezuela, Martin-Benito, 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. The Starobinsky potential is phenomenologically favored and naturally arises in the $R + R^2$ gravity theories.

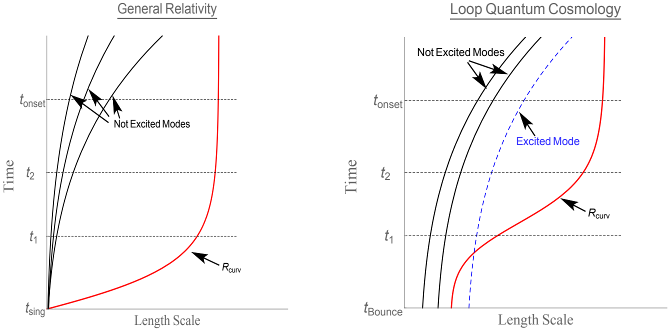
Singularity Resolution: $(1/2)m^2\phi^2$ inflaton Potential



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.

Why Planck scale 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 LQC regularization tames the FLRW singularity. The new FLRW dynamics in turn affects the IR behavior of perturbations! (Agullo, AA, Gupt)
Deep interplay between UV and IR!

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3. 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 XVI,

> *"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: Examples

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

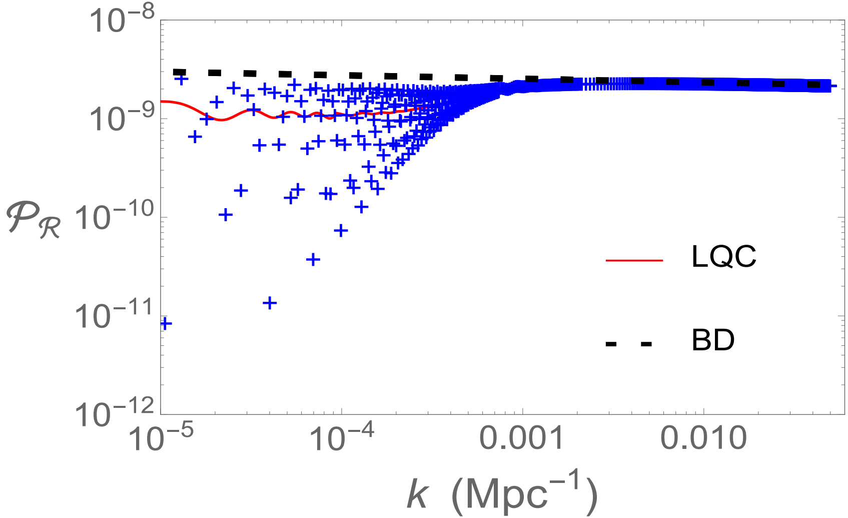
(iii) Proposed a candidate set of principles to greatly narrow down the initial conditions at the bounce.

(iv) Shown that this extension of inflationary scenario to the Planck regime is consistent with current observations and provides a better fit to the PLANCK data at large angular scales than standard inflation. Furthermore, there are predictions for the future observations (of T-E and E-E correlations). PLANCK team should release within a year!

- 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.

The Scalar Power spectrum

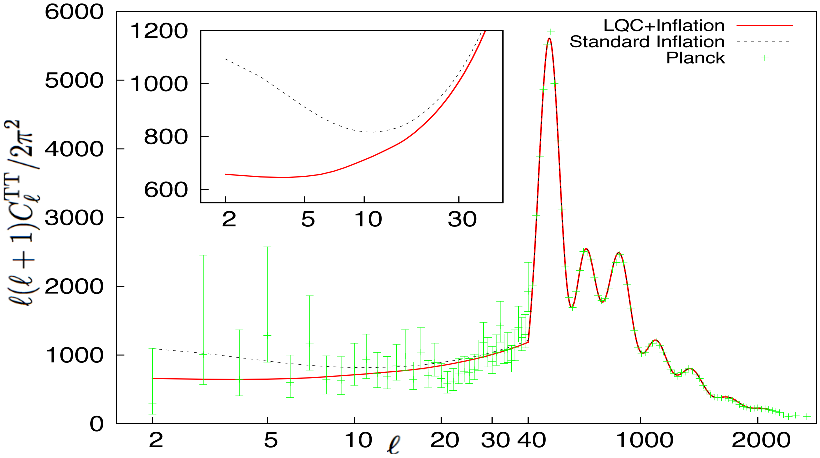
Starobinsky potential: $V(\phi) = \frac{3m^2}{32\pi}\left(1 - \exp(\sqrt{\frac{16\pi G}{3}}\phi)^2\right)$



The LQC and the standard BD power spectrum for the scalar mode.

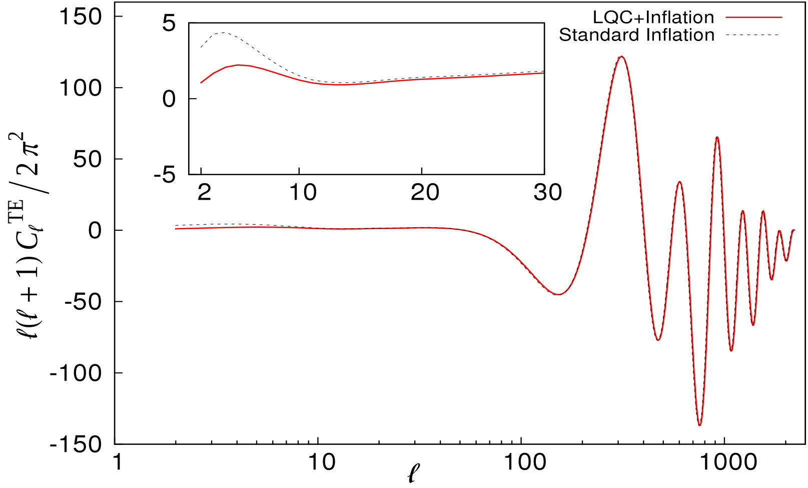
Red: Raw 'data' from LQC. blue: best fit curve. (AA, Gupt)

LQC: Predicted TT-Power spectrum



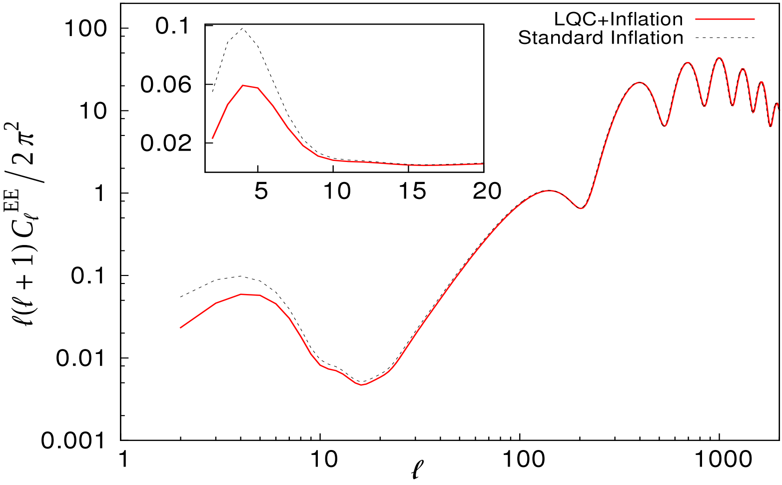
With our initial conditions for $\Psi_o \otimes \psi$, the LQC power spectrum agrees with the standard BD power spectrum for $\ell \gtrsim 30$, but in LQC power is suppressed for $\ell \lesssim 30$. Thus, the LQC curve provides a better χ^2-fit to the data for $\ell \lesssim 30$. Note: There are no new free parameters. Situation is the same for the quadratic potential. (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. Situation is the same for the quadratic potential. (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. Situation is the same for the quadratic potential. (AA, Gupt)

3. Summary

• Thanks to the spectacular progress on both observational and theoretical fronts, our understanding of the very early universe has deepened very significantly over the last 2-3 decades.

• Inflationary paradigm has had great success in accounting for the tiny inhomogeneity in the CMB which serve as the seeds of the large scale structure we observe. However the paradigm is incomplete. We need to expend it to the Planck regime.

• This is a great challenge as well as a great opportunity for quantum gravity theory. The PLANCK team question can be rephrased as: Can one trace back the origin of the anomalies seen in the CMB at $\sim 3\sigma$-level to Planck scale processes?

• In loop quantum cosmology, several groups have seized on this opportunity. I presented one 'main-stream' approach. Fundamental properties of quantum geometry underlying Loop Quantum Gravity not only resolve the big bang singularity but create an unforeseen interplay between the ultraviolet properties of quantum geometry and the infrared properties of quantum perturbations thereon.

Quantum Gravity in the Sky

• We have made a first stab at fixing the initial conditions by linking properties of the Planck scale quantum geometry with the late-time universe. These initial conditions determine the power spectra and n-point functions, where the evolution starts in a self-consistent fashion in the deep Planck regime, rather than 'in the middle' as in standard inflation.

• We find that for TT power spectrum there is agreement with standard inflation at small wave lengths but a difference at the largest wave lengths: Power is suppressed. Hence, on the full observable range, there is better agreement with the PLACNK data than standard inflation.

• The difference can be traced back to the LQC dynamics during just 2-3 e-folds near the bounce, in the Planck regime. Thus in a very concrete, detailed sense, within this LQC approach, the power suppression at $\ell \lesssim 30$ can be traced directly to quantum gravity effects!

• There are predictions of power suppression for the TE and EE correlation functions. The PLANCK data for these will be released within a year. There are other investigations along very similar lines that account for the 'hemispherical anisotropies' (Agullo) without violating any observational bounds.

• At long last we are reaching the stage in which there is an active interplay between quantum gravity theory and observations.

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;
I. Agullo and P. Singh, arXiv:1612.01236.

- More complete references:

AA and Gupt, arXiv arXiv:1610.09424,
AA, Agullo and Gupt arXiv:1611.09810, arXiv:1608.04228
Agullo, arXiv:1507.04703

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 this Lecture:

- Future Observations:

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

- A detailed Review of the first decade of Loop Quantum Cosmology

AA & Singh, CQG (2011).

Initial Conditions

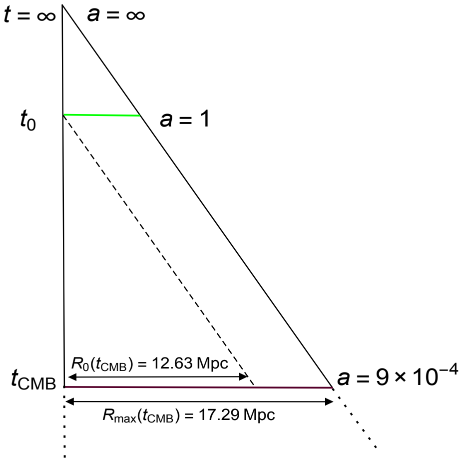
• We have a well motivated proposal but represents only a working hypothesis at this stage –analogous to the Bohr atom. The idea is again to test if we are moving in the right direction by comparing the predictions with observations. (AA, Gupt)

• To fix the background quantum FLRW geometry one considers the past evolution of the largest 2-sphere on the CMB surface that is accessible to an eternal observer. How large is it at the bounce? Idea: should be an 'elementary 2-sphere' of quantum geometry which has area $\sim 30\ell_{\rm Pl}^2 \sim 6\Delta\,\ell_{\rm Pl}^2$. This fixes the number of e-folds from the bounce to the onset of slow roll, i.e. the essential aspect of pre-inflationary dynamics.

• To pick the quantum state ψ of perturbations, we cannot use the BD vacuum because the pre-inflationary phase is far from de Sitter! Demand instead: (i) Appropriate symmetry and regularity; (ii) Quantum refinement of Penrose's Weyl curvature hypothesis. This provides a ball of preferred states in the Planck regime. Then demand that the state be maximally classical in a precise sense (of squeezing) at the end of inflation. This selects a *very* narrow class of Heisenberg states ψ.

• With these initial conditions, we obtain unique predictions, e.g. for the CMB power spectrum for any given inflationary potential.

1. PLANCK data and space-time structure



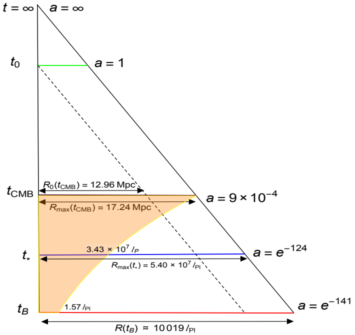
Universe according to PLANCK

- Given the data provided by the PLANCK mission on H_0, Ω_m and Ω_r, general relativity determines space-time geometry to the future of the LSS if we make the conservative assumption that the 'dark energy' is due to a cosmological constant. A key feature is that there are cosmological horizons.

- Any eternal cosmic observer will be able to see only a finite patch of the universe no matter how long she waits.

- CMB is extraordinarily homogeneous with tiny, 1 part in 10^5 fluctuations.

History of the universe from the bounce to infinite future



LQC + PLANCK data

There is a maximum size $R_{\rm max}(t_{\rm CMB})$ to the observable universe at the CMB time even if one waits for an infinite time. An elementary ball of area $\sim 31\ell_{\rm Pl}^2$ at the bounce time expands out to fill this entire region!

Epoch	a	n_e	R_0	$R_{\rm max}$
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	$2.32 \times 10^7\ \ell_{\rm pl}$	$5.4 \times 10^7\ \ell_{\rm pl}$
$t_{\rm B}$	e^{-141}	141	$1.16\ \ell_{\rm pl}$	$10^4\ \ell_{\rm pl}$

Supplementary Material

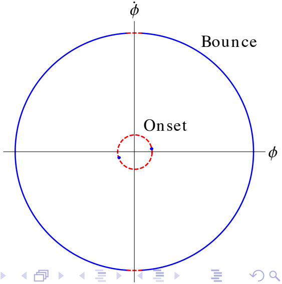
The slides that follow contain supplementary material, providing some details that could not be covered in the talk.

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)

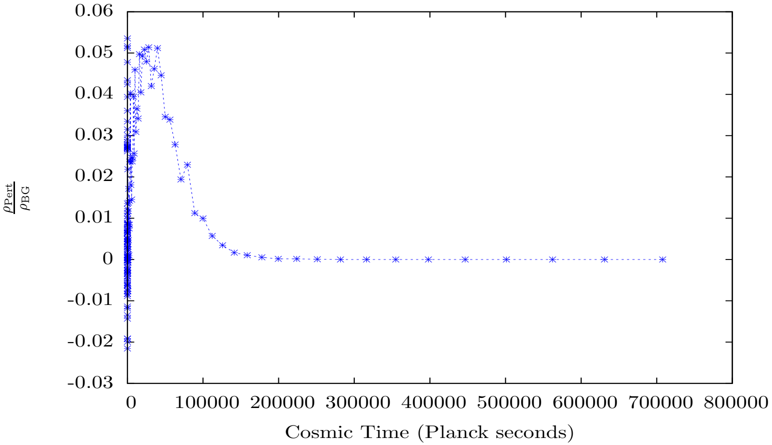
- For the background quantum geometry, we can choose a 'coherent' state Ψ_o sharply peaked at an effective trajectory with $\phi_{\rm B} > 0.93$ and evolve using LQC. It remains sharply peaked on that effective trajectory. Hence the desired slow roll automatically occurs in this quantum geometry!



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

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)

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.

Advances over last 2 years on bridging LQC and LQG (Engle, Fleishhack, Hanusch, Alesci & Cianfani, ...)