Loop Quantum Gravity:
Recent Advances

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Will summarize the work of many researchers; especially:
Agullo, Barbero, Barrau, Bianchi, Bojowald, Corichi, Dittrich, Freidel, Gambini, Gupt, Lewandowski, Mena, Nelson, Oriti, Pawlowski, Pullin, Rovelli, Singh, Thiemann, ...

14th Marcel Grossmann Conference; 14th July 2015

1. Historical and 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?

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• 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. How do you do physics without a space-time continuum in the background? Need new concepts and new mathematical tools. We learned how to lift the anchor that tied us to a background space-time and sail the open seas relatively recently.

• Several voyages in progress:
Causal sets, twistors, Regge Calculus, Euclidean quantum gravity, Asymptotic safety, AdS/CFT conjecture of string theory, Loop Quantum Gravity.

Evolution: 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.

From Particle Physics side: ‘Unification’ Central:
Extend Perturbative, flat space QFTs; Gravity just another force.

- Higher derivative theories; • Supergravity
- String theory incarnations:

⋆ Perturbative strings; ⋆ Matrix Models;
⋆ F theory & M theory ⋆ AdS/CFT Correspondence.

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From General Relativity side: 'Background independence' Central.

- Canonical quantum gravity (Dirac, Bergmann, Wheeler, DeWitt, ...)
- Path Integral Approach (Misner, Hawking, Hartle, ...)
- Loop Quantum Gravity:

⋆ Hamiltonian Theory (used for cosmology & BHs),
⋆ Spin-foams (Path integrals, bridge to low energy physics.)

A. Ashtekar: LQG: Four Recent Advances and a dozen FAQs; arXiv:0705.2222

Contrasting String theory & LQG

• String Theory: 'Unification' Central; Supersymmetry, higher dimensions, holography; built-in ultraviolet cut-off

• LQG: 'Background independence' Central; based on quantum Riemannian geometry; leads to an in-built UV cut-off.

• **Current** Mainstream Thrusts:

$\star$ String theory: AdS/CFT use (mostly classical) gravity to solve open problems in other areas of physics: Quark Gluon Plasma, Superconductivity, Black hole evaporation; ...

$\star$ LQG: Focus 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 in a theory without a background space-time; ...

Riemannian Quantum Geometry

- GR is formulated using Riemannian geometry. LQG is formulated using a specific quantum version thereof. Idea: Gravity **is** geometry.

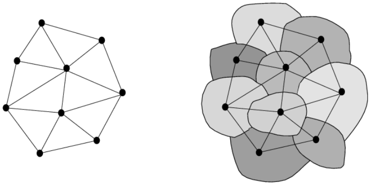
- No background geometry (Diff invariance) $\Rightarrow$ Unique Quantum Kinematics

(AA, Lewandowski, Okolow, Sahlmann, Thiemann, Fleischhack)

Geometric Operators, e.g., $\hat{A}_S$, $\hat{V}_R$ have purely discrete eigenvalues. Riemannian geometry quantized in a fundamental but rather subtle sense.

Area gap Δ : Fundamental microscopic parameter of LQG that sets scales for new macroscopic phenomena. Analogy with superconductivity:

- energy gap $\Delta_E \leftrightarrow \Delta$; $[T_C = (\text{const})\ \Delta_E] \leftrightarrow [\text{curv}_{\text{sup}} \sim \rho_{\text{sup}} = \text{const}/\Delta^3]$



- Fundamental excitations of geometry are polymer-like; 1-dimensional. Continuum arises only on coarse graining.

Spin Networks: Convenient basis of states that diagonalizes the geometric operators.

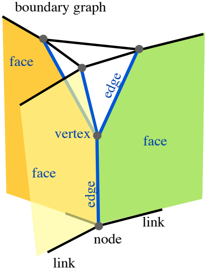
node $\sim$ quantum chunk of space;

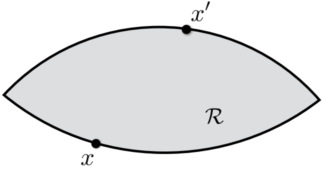
link $\sim$ deposits a quantum of area on any surface it intersects.

Quantum Dynamics: Current Status

- Hamiltonian methods well tailored to cosmology. The Area gap Δ sets upper bound on, e.g., energy density ρ, taming the singularity.

- In full LQG, recent advances on dynamics have mostly been in the path integral framework. Spinfoams: Sum over histories of quantum geometries represented by spin networks. A promising spin foam model has emerged (Engle, Perini, Rovelli, Livine; Freidel, Krasnov). Ultraviolet finiteness is built-in. Infrared finiteness assured if $\Lambda > 0$.





- Application: n-point function in a background independent context. If the boundary spin network chosen to be sharply peaked on Minkowski geometry, one recovers the the standard graviton propagator to leading order.(Bianchi, Ding, Magliaro, Perini, ...)

Important open issues still remain but partial results to date have been promising and currently improvements are being pursued vigorously. (Engle, Han, Wieland, ...)

2. Application: UV Completion of standard inflation

- In LQC, the Big Bang singularity is naturally resolved in LQC; replaced by a Big Bounce. Goals laid out by Wheeler, Misner and others were achieved. The Area gap Δ plays a key role in taming the singularity.

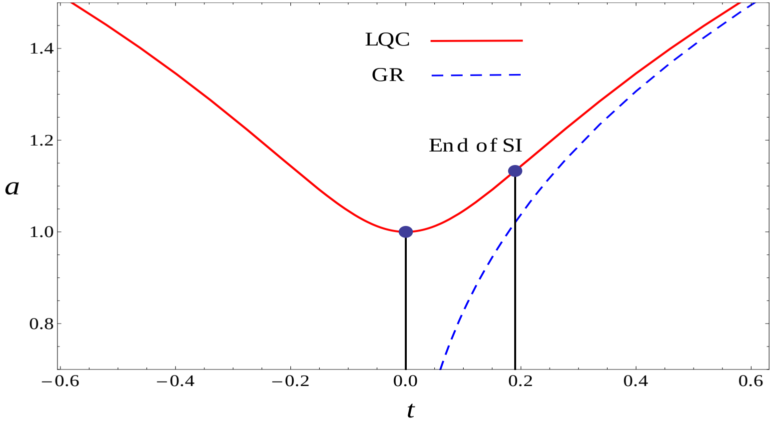
  In FLRW Models: $a(t), \phi(t) \quad \rightarrow \quad \Psi_o(a, \phi)$.

- Quantum states $\psi_{\rm pert}(T^{(1)}, T^{(2)}, \mathcal{R})$ of perturbations propagate on the quantum FLRW geometry $\Psi_o(a, \phi)$. Planck scale issues faced squarely. (Evolution over 11 orders of magnitude in curvature)

- Agreement with standard inflation for $\ell \gtrsim 30$. But the pre-inflationary dynamics can leave imprints on large wave length modes. e.g., Power spectrum can be suppressed for $\ell \lesssim 30$. (Seems counter-intuitive at first. Will explain.)

Thus, LQG opens a window to complete the inflationary scenario in a direction that is complementary to those based in particle physics. I will now explain these points in a little more detail. Summary: (AA & Barrau arXiv:1504.07559)

Singularity Resolution in LQC: Starobinsky Potential



GR and LQC dynamics for Starobinsky potential with phenomenologically determined parameters (Bonga & Gupt). The Big Bang is replaced by a Big Bounce. Similar resolution in other cosmological models.

What is behind this singularity resolution?

- The key modification of Einstein dynamics is well-captured in effective equations. For example, the effective Friedmann equation is (AA, Pawlowski, Singh):

$$(\dot{a}/a)^2 = (8\pi G\rho/3)[1 - \rho/\rho_{\rm sup}] \quad \text{where} \quad \rho_{\rm sup} = (18\pi)/(G^2\hbar\,\Delta^3) \sim 0.41\rho_{\rm Pl}.$$

Big Bang replaced by a quantum bounce. Separation of scales: effects become negligible for $\rho << \rho_{\rm Pl}$. Eigenvalues of physical observables, such as matter density and curvature have an absolute upper bound on the physical Hilbert space.(AA, Corichi, Singh)

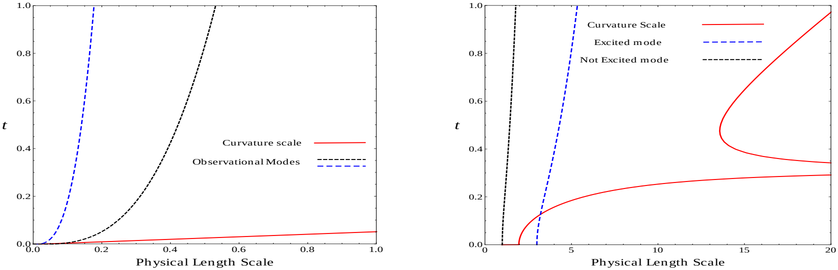
- Mechanism: No unphysical matter or new boundary conditions. Quantum geometry creates a brand new repulsive force in the Planck regime, overwhelming classical attraction. Understood in the Hamiltonian, Path integral and consistent histories frameworks. (AA, Campiglia, Henderson; Craig & Singh)

- Many generalizations: inclusion of spatial curvature, a cosmological constant Λ, anisotropies, ... (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.

Details of singularity resolution will be discussed in the session EU2 on Thursday.

Why pre-inflationary dynamics matters

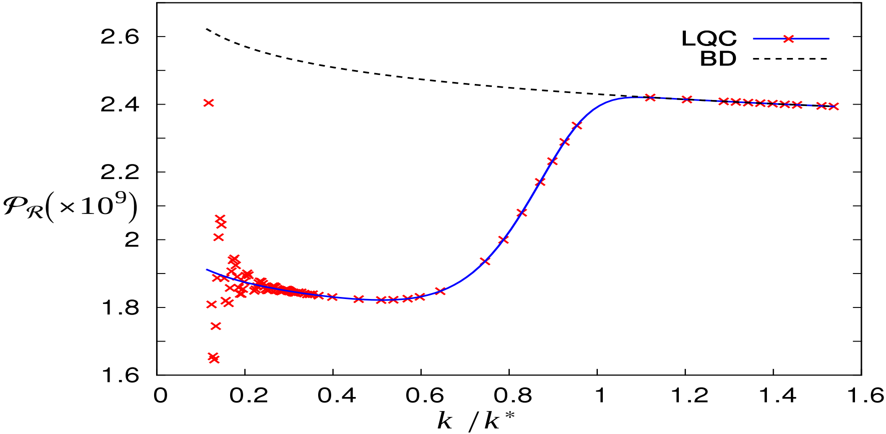
Contrary to a wide-spread belief, pre-inflationary dynamics does matter because modes which at the bounce have $\lambda_{\rm phys} > R_{\rm curv} \propto \Delta^{3/2}$, in the pre-inflationary era are excited and populated at the onset of inflation. They can leave imprints on CMB, naturally leading to 'anomalies' at $\ell \lesssim 30$: Signature of the area gap Δ imprinted on CMB!



LQG quantum geometry effects in the UV tame the FLRW singularity.
The new FLRW dynamics in turn affects the IR behavior of perturbations!
(Details: discussed in session QG3.)

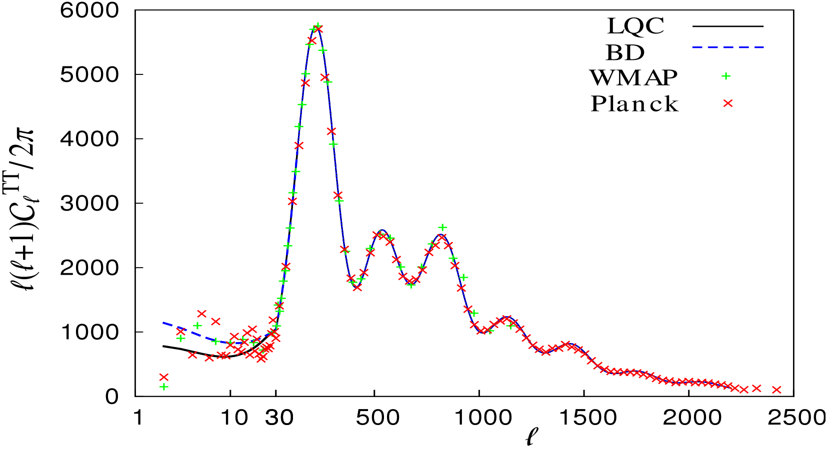
LQC: Dynamics and Results

The Scalar Power spectrum ("Top-down approach")



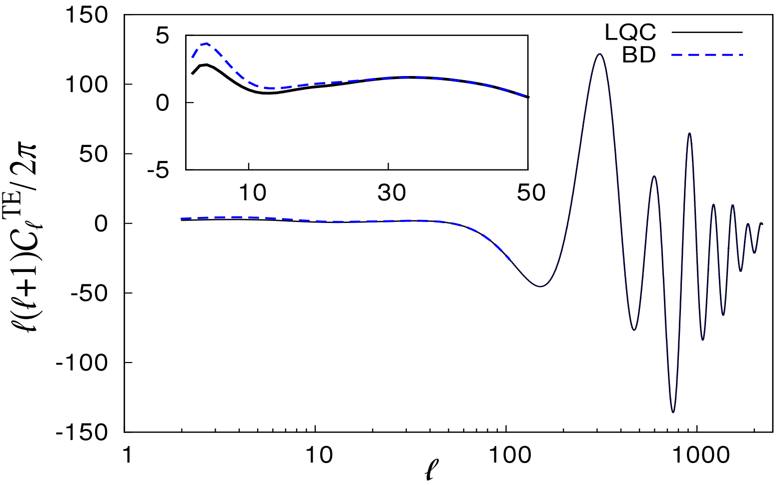
The LQC and the standard BD power spectrum for the scalar mode. (Convention $a_{\rm B} = 1.$)
Red: Raw 'data' from LQC for the $m^2\phi^2$ potential. blue: best fit curve. For $\phi_{\rm B} = 1.19 m_{\rm Pl}$.
Here, the WMAP reference mode $k^{\star}_{\rm B}/a_{\rm B} = 54 m_{\rm Pl}$ and $k^{\rm min}_{\rm B}/a_{\rm B} = 6.3 m_{\rm Pl}$. (AA, Gupt)

LQC: Predicted TT-Power spectrum



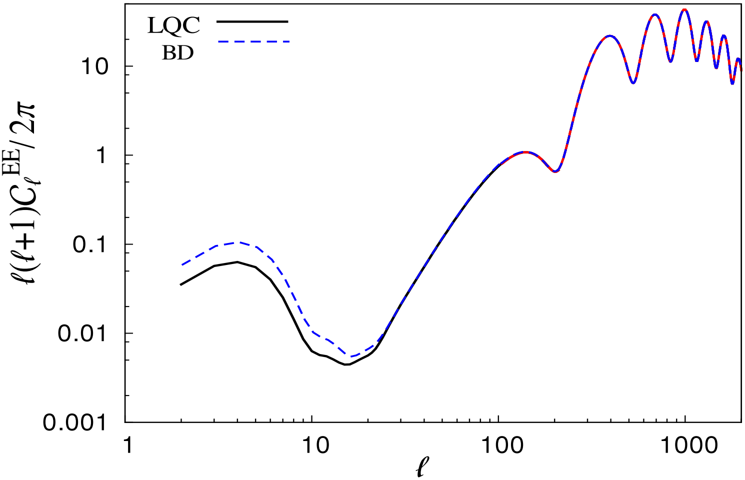
There exist permissible states $\Psi_o \otimes \psi$ such that the LQC power spectrum agrees with the standard BD power spectrum for $\ell \gtrsim 30$, but in LQC power is suppressed for $\ell \lesssim 30$. (AA, Gupt)

LQC: Predicted TE Correlations



New prediction: The LQC TE spectrum, for the initial state that gave the TT-spectrum in the last slide. (AA, Gupt)

LQC: Predicted EE Correlations



New Prediction: The LQC EE 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)

3. Summary

- Background independence of LQG is directly responsible for the fundamental discreteness of the underlying Riemannian quantum geometry which is rather subtle. An in-built UV cut off because of quantum geometry.

- No approach to quantum gravity is complete. 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. In these truncations, ultraviolet finiteness is manifest.

- I had time to discuss one such truncation tailored to cosmology: FLRW background with an inflation ϕ in a suitable potential as matter, together with first order perturbations. Unforeseen interplay between the taming of the FLRW background by UV modifications of Einstein dynamics and IR properties of perturbations $(\hat{\mathcal{R}}, \hat{\mathcal{T}}^I)$. 'Consistency relations' such as $r = -8n_t$ are transcended.

Result: LQC provides a self-consistent extension of standard inflation to the Planck regime. It opens a new avenue –complementary to particle physics– to account for the 3σ anomalies seen by Planck at large scales. LQG has matured sufficiently to lead to new predictions for future missions.

- Other applications and recent advances in LQG: sessions EU2 and QG3.