Title: Phenomenological Aspects of LQC

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Abstract:

Phenomenological Aspects of Loop Quantum Cosmology

QUANTUM GRAVITY IN THE AMERICAS WORKSHOP

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Parampreet Singh

IGPG

Outline

- Key issues for Loop Cosmology
- Modification of geometrical density at short scales
- Dynamical equations and effects in early Universe
- Observational signatures
- Open Issues & Summary

Key Issues for Loop Cosmology

- What are the modifications predicted by Loop Quantum Gravity for very early Universe ?
- Do we expect to observe any signature of modified dynamics in astronomical observations ?
- Are the modifications and effects immune to underlying quantization ambiguities ?
- What are the links with other approaches like string cosmology, braneworlds etc. ?
- Is the effective modified phase in loop cosmology guaranteed to exist ?
- Is modified dynamics unique or are there some differences which depend on factor ordering ?

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Inverse scale factor in Loop Cosmology

- Basic variables are c and p satisfying $\{c, p\} = \frac{8\pi}{3}\gamma G$.
- Triad p has a discrete spectrum. It is related to scale factor as $|p|^2 = a$.
- The inverse scale factor operator is defined using THIEMANN TRICK (1998)

$$a^{-1} = 6\gamma^{-1}\frac{1}{8\pi G}\{c, V^{1/3}\}\,.$$

- The inverse scale factor operator has bounded eigenvalues, even at $a = 0$. (Bojowald (2001)).
- Evolution through Big Bang ($a = 0$) is non-singular.

Geometrical density in Loop Cosmology

- The geometrical density is modified to

$$d_j(a) = a^{-3}\, D(q),\ q = a^2/a_*^2,\ a_*^2 = \gamma \ell_{\rm pl}^2\, j/3$$

with

$$\begin{aligned} D(q) \quad &= (8/77)^6 q^{3/2}\{7[(q+1)^{11/4} - |q-1|^{11/4}] \\ &- 11q[(q+1)^{7/4} - \mathrm{sgn}\,(q-1)|q-1|^{7/4}]\}^6. \end{aligned}$$

- At scales smaller than a_*

$$d_j \approx (12/7)^6 (a/a_*)^{15} a^{-3}\ .$$

- At classical scales ($a \gg a_*$), $d_j \approx a^{-3}$.

Dynamical equations for a massive scalar field

- Effective Friedmann Equation

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi\ell_{\rm pl}^2}{3}\left(\frac{1}{D}\frac{\dot{\phi}^2}{2} + V(\phi)\right)$$

- Klein-Gordon Equation

$$\ddot{\phi} = \left[-3\frac{\dot{a}}{a} + \frac{\dot{D}}{D}\right]\dot{\phi} - D\,V_{,\phi}$$

- For $a \ll a_*$ we have $D \ll 1$ and $\dot{D} \approx 15\frac{\dot{a}}{a}D$. For $a \gg a_*$, $D = 1$.
- Modifications are such that potential is suppressed and thus effects are expected to be generic.

Comparison with classical cosmology

- In classical cosmology Klein-Gordon equation is

$$\ddot{\phi} = -3\frac{\dot{a}}{a}\dot{\phi} - V_{,\phi}$$

- Loop cosmology predicts that for $a \ll a_*$ it shall be

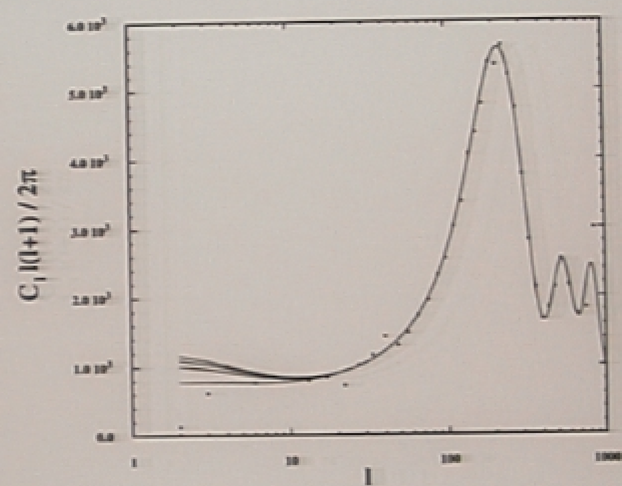
$$\ddot{\phi} = 12\frac{\dot{a}}{a}\dot{\phi} - D\,V_{,\phi}$$

- The roles of friction and anti-friction are reversed.
- The field ϕ encounters friction (anti-friction) at all scales in a classical expanding (contracting) Universe. An expanding (contracting) loop cosmos would have anti-friction (friction) for ϕ at scales smaller than a_*.
- This is the key element of all phenomenological applications.

Some Applications

- The anti-friction term in loop cosmology leads to super-inflation in very early universe (Bojowald (2002)).
- This phase can be coupled to standard conventional inflation (Bojowald, Vandersloot (2003)).
- Between super-inflation and conventional inflation lies a phase which is absent in classical cosmology and can provide signatures in CMB (Tsujikawa,PS,Maartens (2003)).
- The friction term in a contracting phase generically avoids problem of Big Crunch (PS,Toporensky (2003)).
- The friction term leads to a non-singular collision of branes in the Steinhardt-Turok's Cyclic Model (Bojowald,Maartens,PS (2004)).

Loop Cosmology signature in CMB



From top to bottom, the curves correspond to (i) no loop quantum era (standard slow-

chaotic inflation), (ii) $\bar{\alpha} = -0.04$ for $k \leq k_0 = 2 \times 10^{-3}\,\mathrm{Mpc}^{-1}$, (iii) $\bar{\alpha} = -0.1$ for $k \leq$

and (iv) $\bar{\alpha} = -0.3$ for $k \leq k_0$. $\mathcal{P} \propto k^{n-1}, \alpha = \left(\frac{dn}{d\ln k}\right)_{k=aH}$.

Some Open Issues

- How well does the effective description matches that from quantum difference equations ? Cosmological constant and dust match very well (Bojowald,PS,Skirzewski (2004)). Scalar field in progress.
- The Friedmann equation has further quantum corrections (Ashtekar,Bojowald,Willis (2004)). It may lead to new observable effects. These modifications match well with difference equations (Bojowald,PS,Skirzewski (2004)).
- There can be different effective descriptions which may arise due to factor ordering, like Perez-Noui-Vandersloot model based on Plebanski action. How different are its phenomenological effects from standard loop cosmology ?

Summary

- Loop cosmology predicts that at short enough scales the geometrical density becomes proportional to positive powers of scale factor.
- This flips the sign of $\dot{\phi}$ term in Klein-Gordon equation and leads to various interesting effects.
- An important effect is setting up of right conditions for conventional inflation which follows super-inflation and a phase which can leave signatures in CMB.
- The modified dynamics comes to use also for alternative to inflation. It can make brane collision non-singular in cyclic model.
- Effects are robust to quantization ambiguities and modified dynamics seems to match well with discrete evolution.