LQC and the early Universe

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LQG: nice mathematical foundations, but not simple to work out physical consequences

Cosmology: Interesting. Symmetries + observations!! (COBE, WMAP, PLANCK, BICEP2, more coming...) ➡ Opportunity

We don't have full LQG. Need physical assumptions and approximations. Important they are clearly identified: motivation, regime of validity and check they are satisfied in solutions.

1. Quantization of the background **LQC**

2. Inclusion of perturbations

3. Phenomenology

1. Quantization of the background: LQC

Ashtekar, Bojowald, Brizuela, Campiglia, Corichi, Diener, Fernandez-Mendez, Garay, Gupt, Martin-Benito, Martin de Blas, Megavan, Mena-Marugan, Montoya, Lewandoswki, Olmedo, Pawlowski, Singh, Sloan, Taveras, Willson-Ewing, ...

We do not have full LQG. Take advantage of symmetries: Mini-superspace quantization + deparametrization for ready physical interpretation

Drastic approx: solve diffeo. constrains and keep scalar constr. to generate dynamics

From ∞-many to a few d.o.f. $a\,,\phi$

But do it paying attention to LQG and compatibility with the observed universe

(compare with approxs. made in early universe cosmology, e.g. inflation)

- Results:

  Bounce, detailed numerical simulations with highly peaked states at late times, effective eqns., compatibility with late time inflation, etc

- Lot of work to do. Examples:

  Numerical simulations with more general states (Pawlowski; Singh, Diener, Gupt, Megavan)

  More precise connexion LQG-LQC: (different groups: US, Germany, France, ...)

  ...

2. Inclusion of perturbations

Difficulty: how do we study quantum fields (matter+metric grav. perturbations) propagating on a quantum space-time?

Different approaches: see e.g. Barrau, Mena-Marugán talk.

AAN'12-13: follow same approach as in cosmology: propagation of gauge invariant scalar $\mathcal{Q}$ and tensor perturbations $\mathcal{T}^{(+,\times)}$ on the quantum background Ψ_{FRW}.

Fock quantization (Cf. Hybrid approach, Madrid group) of gauge invariant perturbations on the quantum LQC background. Neglect back-reaction and check for consistency.

(again, compare with approxs. made in early universe cosmology, e.g. inflation)

At the math level, we extend work initiated by Ashtekar, Kaminski and Lewandowski on QFT in QST, by adapting it to gauge invariant perturbations and to ∞-many do.f.

Reults:

For arbitrary background states Ψ_{FRW} (not necessarily highly peaked), evolution of perturbations (scalar and tensor) mathematically equivalent to propagation in a FRW smooth metric $\tilde{g}_{ab}$.

$\tilde{g}_{ab}$ is constructed from expectation values of background operators. Of course, it does not satisfy Einstein eqns, and coefficients prop. to $\hbar$

$$\tilde{g}_{ab}dx^a dx^b = \tilde{a}(\tilde{\eta})[-d\tilde{\eta}^2 + d\vec{x}^2] \quad \text{with} \quad \tilde{a}^4 = \frac{\langle \hat{H}_0^{-1/2} \hat{a}^4 \hat{H}_0^{-1/2} \rangle_{\Psi_{FRW}}}{\langle H_0^{-1} \rangle_{\Psi_{FRW}}}\,, \quad d\tilde{\eta} = \tilde{a}\, \langle \hat{H}_0^{-1} \rangle_{\Psi_{FRW}}\, d\phi$$

Ψ_{FRW} encodes lot of info, but perturbations only “feel” a couple of quantum moments. Interestingly, the way they appear allows to encode them in a smooth metric tensor

$\boxed{\tilde{g}_{ab} \quad \text{effective, dressed metric}}$

Formally, QFT in curved space-time: import well known techniques: Adiabatic Renormalization

L. Parker & S. Fulling’74

- Construct explicitly Hilbert space $\mathcal{H}_{adb}$ of adiabatic states (unique equivalent class of quantum representations)
- In $\mathcal{H}_{adb}$ there is well defined prescription to renormalize composite operators, e.g. $\hat{T}_{ab}$

Important : we can check back-reaction is negligible in physically interesting solutions

3. Phenomenology

AAN: Quantum Gravity completion of the inflationary scenario

Matter content: $\phi \; , \; V = \frac{1}{2} m^2 \phi^2$

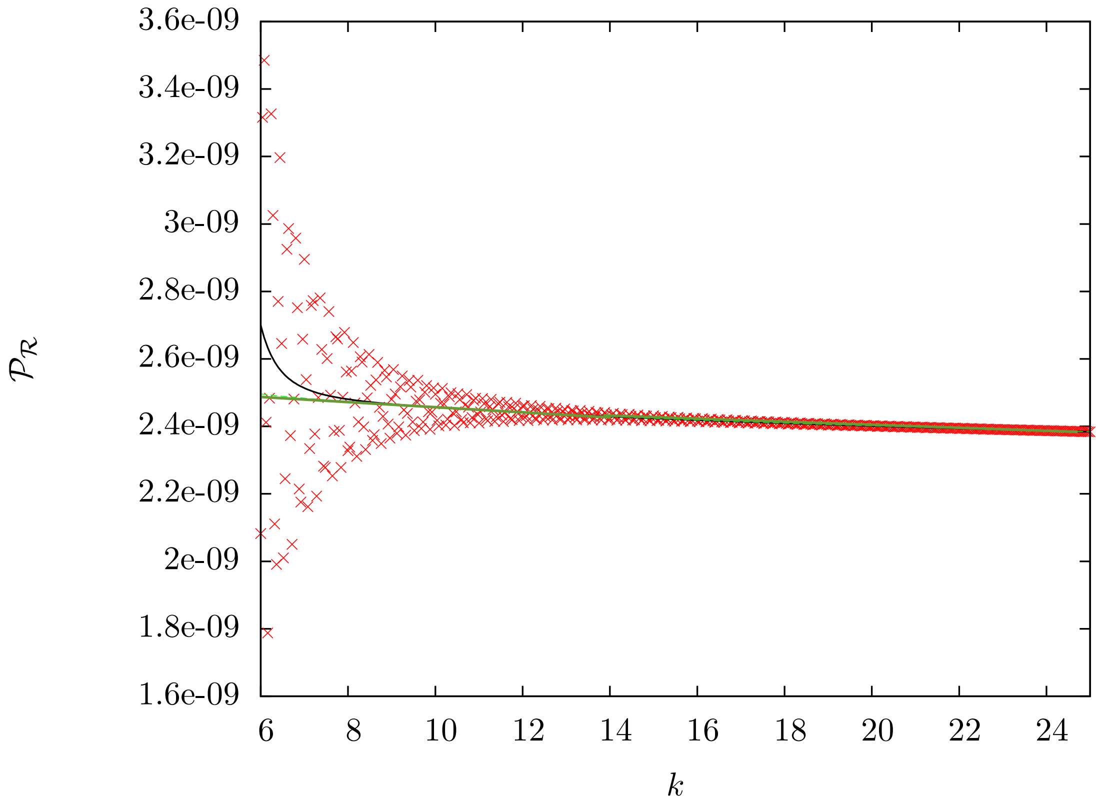
$\Longrightarrow$ LQC bounce + late time phase of inflation

Initial conditions:

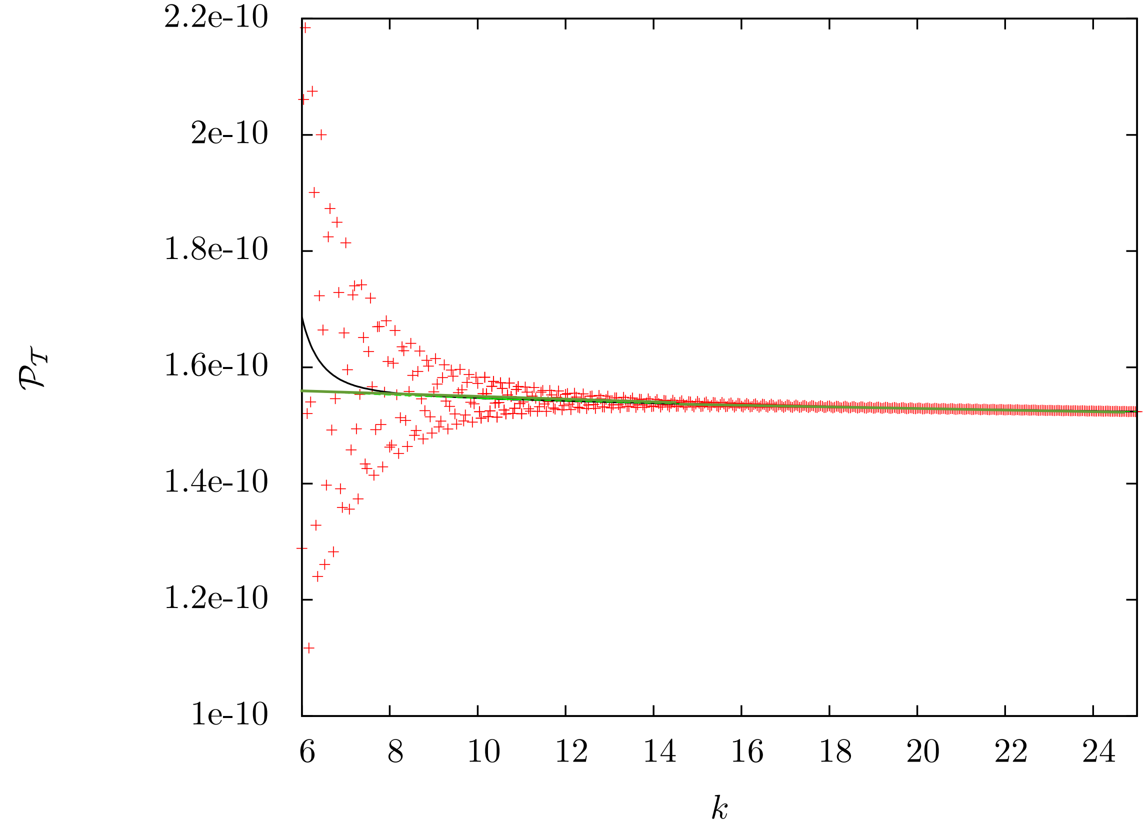
Standard Inflation: quantum homogeneity @ onset of inflation

LQC: quantum homogeneity @ the bounce.

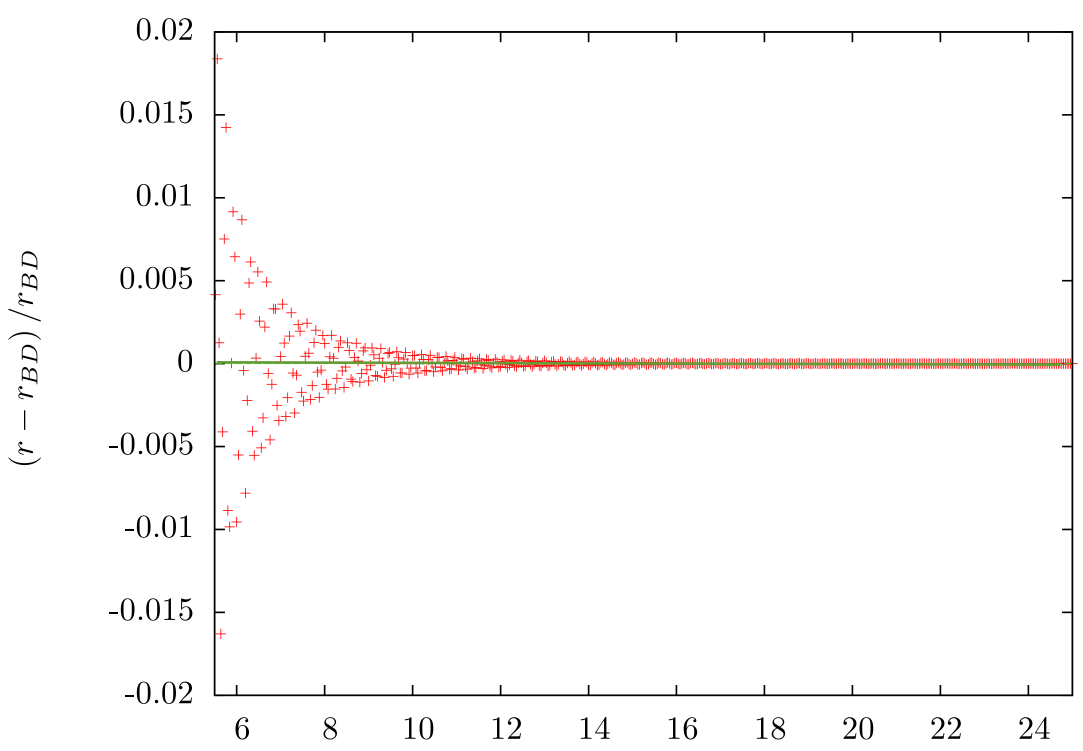
Semi-heuristic justification: radius observable universe is $10\ell_{Pl}$ @ the bounce time. At those scales quantum repulsive force is able to “iron” inhomogeneities. Also: compatible with observations



Scalar Power Spectrum



Tensor Power Spectrum



Tensor to scalar ratio

Comparing with standard inflation:

LQC-Power spectra oscillatory at low multipoles

LQC-running of spectral indices non-zero

Same tensor to scalar ratio (average)

Consistency relation

Inflation $$r = -8n_t$$

LQC $$r_{LQC} = -8\left(n_t - \frac{d\ln[1+2|\beta_k^{(\mathcal{T})}|^2]}{d\ln k}\right)$$