Title: A Quantum Gravity Extension of the Infationary Scenario

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Abstract: Since the standard inflationary paradigm is based on quantum field theory on classical space-times, it excludes the Planck era. Using techniques from loop quantum gravity, the theory is extended to overcome this limitations. The new framework sharpens conceptual issues by distinguishing between the true and apparent trans-Planckian difficulties and provides sufficient conditions under which the true difficulties can be overcome within a quantum gravity theory, with interesting lessons for both theory and observations.

A Quantum Gravity extension of the inflationary scenario

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Work in collaboration with: A. Ashtekar and W. Nelson

Loops13, Perimeter Institute, July 2013

Motivation

LQG: Nice ideas and beautiful mathematical formulation

But important open issues remain

Lots of efforts (see talks in this conference): new ideas and mathematical techniques are being developed.

Important:

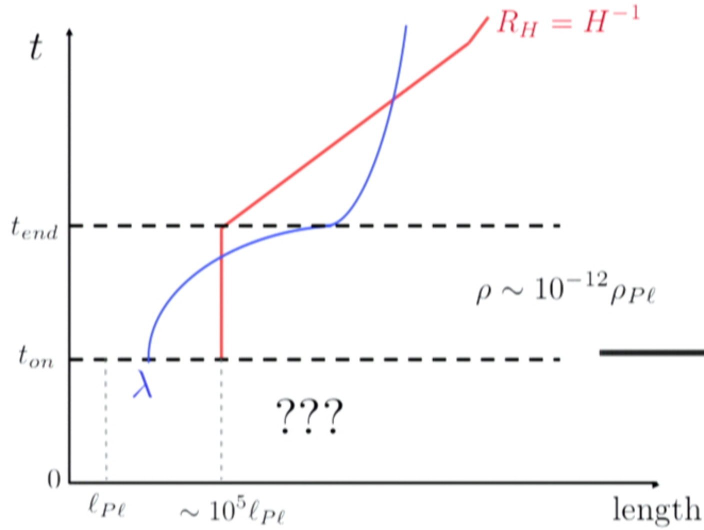
also develop approximate methods. Clearly state the approximations and, when possible, establish criteria to check if they are satisfied

They will make the theory closer, and useful to other communities

This talk: step in that direction in the context of cosmology. See also A. Barrau, M. Bojowald and E. Wilson-Ewing's talks.

In this talk, I consider the **inflationary scenario**. **Why?**

By far the most accepted framework to account for the origin of cosmic inhomogeneities



"Safe" to describe perturbations as quantum fields propagating in a classical FRW

QFT in curved space-times: the interaction of the quantized perturbations with the space-time curvature excites quanta out from the vacuum: **Primordial Spectrum of perturbations.**

Mukhanov, Chibisov, Hawking, Guth, Pi, Starobinsky, Bardeen, Steinhardt, Turner

1. Cosmological perturbation theory in quantum s-t

2. The pre-inflationary universe of Loop Quantum Cosmology

2. Truncated Classical Hamiltonian framework

Gravity + Scalar field (ADM variables for brevity): $\Gamma = \{q_{ij}(\vec{x}), \pi^{ij}(\vec{x}), \Phi(\vec{x}), \Pi(\vec{x}\})$

+ constraints: $\mathbb{S}[N] = \int d^3x\, N(\vec{x})\, S(\vec{x}) \approx 0 \qquad \mathbb{V}[\vec{N}] = \int d^3x\, N^i(\vec{x})\, V_i(\vec{x}) \approx 0$

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Consider $\gamma(\epsilon)$ in Γ such that $\gamma(0) \in \Gamma_{FRW}$

$$q_{ij}(\vec{x}) = a\ \mathring{q}_{ij} + \epsilon\ \delta q^{(1)}_{ij}(\vec{x}) + \ldots \qquad \Phi(\vec{x}) = \phi + \epsilon\, \delta\phi^{(1)}(\vec{x}) + \ldots$$

$$\pi^{ij}(\vec{x}) = \pi_a\ \mathring{q}^{ij} + \epsilon\ \delta\pi^{(1)\,ij}(\vec{x}) + \ldots \qquad \Pi(\vec{x}) = p_{(\phi)} + \epsilon\ \delta p^{(1)}_{(\phi)}(\vec{x}) + \ldots$$

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Fiducial flat metric $\equiv$ gauge fixing

TRUNCATION

Truncation:

$a\,,\, \pi_a\,,\, \phi\,,\, p_{(\phi)} \in \Gamma_{FRW}$

$\delta q^{(1)}_{ij}(\vec{x})\,,\, \delta\pi^{(1)\, ij}(\vec{x})\,,\, \delta\phi(\vec{x})\,,\, \delta p^{(1)}_{(\phi)}(\vec{x}) \in \Gamma_1$ Purely inhomogeneous: e.g. $\left(\int d^3x\, \delta\phi^{(1)}(\vec{x}) = 0 \right)$

$\Gamma_{\rm Trunc} = \Gamma_{FRW} \times \Gamma_1$ and $\Omega = \Omega_0 + \Omega_1$

Constraints

$$\mathbb{C} \approx 0 \xrightarrow{\text{Expand}} \mathbb{C}_0 := \mathbb{C}|_{\epsilon=0} \approx 0 \quad , \quad \mathbb{C}_1 := \frac{d\mathbb{C}}{d\epsilon}|_{\epsilon=0} \approx 0 \quad \ldots$$

0th order:

Vector: $\mathbb{V}_0[N^i] = 0$

Scalar: $\mathbb{S}_0[N_{hom}] = N_{hom}\left[\frac{p_{(\phi)}{}^2}{2\,a^3} - \frac{\kappa}{12\,a}\pi_{(a)}{}^2 + a^3 V(\phi)\right] \approx 0 \longrightarrow$ Evol. of the Background $a(t), \phi(t), \ldots$

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1st order:

$$\mathbb{S}_1[N_{inh}] = \int d^3x\, N_{inh}\,(\ldots \text{linear in 1st order pert.}) \approx 0$$

$$\mathbb{V}_1[N^i_{inh}] = \int d^3x\, N^i_{inh}\,(\ldots \text{linear in 1st order pert.}) \approx 0$$

➡ 4 constraints on 1st order variables

Solve constraints to find gauge invariant variables. Beautiful geometrical method Langlois'94 Goldberg, Newman, Rovelli, 91

$$\delta q^{(1)}_{ij}(\vec{x}) \quad \delta\phi(\vec{x}) \quad \in \Gamma_1 \longrightarrow \mathcal{Q}_{\vec{k}} \quad \mathcal{T}^{(1)}_{\vec{k}} \quad \mathcal{T}^{(2)}_{\vec{k}} \quad \in \tilde{\Gamma}_1$$

gauge inv. scalar and tensor perturbations:

$$\tilde{\Gamma}_{Trunc} = \Gamma_{FRW} \times \tilde{\Gamma}_1$$

truncated, reduced phase space

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2nd order:

$$\mathbb{S}_2[N_{hom}] = \int d^3x\, N_{hom}\,(\dots \text{quadratic in 1st order pert.} + \text{linear in 2nd order pert.}\ ) \approx 0$$

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$$\tilde{\mathbb{S}}_2[N_{hom}] = \int d^3x\, N_{hom}\,(\ldots \text{quadratic in 1st order pert.})$$ Not constrained to vanish

Hamiltonian evolution for first order pert: $\tilde{\mathbb{S}}_2^{(\mathcal{T})}[N_{hom}] = \frac{N_{hom}}{2(2\pi)^3} \int d^3k \left(\frac{4\kappa}{a^3} |\mathfrak{p}_{\vec{k}}^{(\mathcal{T})}|^2 + \frac{a\,k^2}{4\kappa} |\mathcal{T}_{\vec{k}}|^2 \right)$

Eg. $N_{hom} = a$ (conformal time) $\longrightarrow$ $\mathcal{T}_{\vec{k}}'' + 2\frac{a'}{a}\mathcal{T}_{\vec{k}}' + k^2 \mathcal{T}_{\vec{k}} = 0$ filed theory in a fixed FRW backg.

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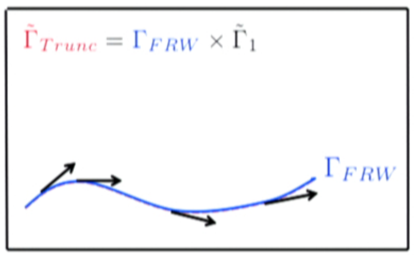

Dynamical vector field:

$$X^\alpha|_{\Gamma_{FRW}} = \Omega_0^{\alpha\beta}\, \partial_\beta \mathbb{S}_0$$ (indep. of perturb.)

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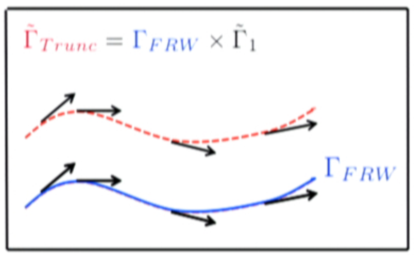

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$$X^\alpha = \Omega_0^{\alpha\beta}\,\partial_\beta \mathbb{S}_0 + \Omega_1^{\alpha\beta}\,\partial_\beta \tilde{\mathbb{S}}_2 \neq (\Omega_0^{\alpha\beta} + \Omega_1^{\alpha\beta})\,\partial_\beta(\mathbb{S}_0 + \tilde{\mathbb{S}}_2)$$

Evolution in this truncated theory is not hamiltonian: back-reaction is neglected

3. Quantum Theory

In standard cosmology: $$\tilde{\mathbb{S}}_2^{(\mathcal{T})}[N_{hom}] = \frac{N_{hom}}{2(2\pi)^3} \int d^3k \left(\frac{4\kappa}{a^3} |\mathfrak{p}_{\vec{k}}^{(\mathcal{T})}|^2 + \frac{a\, k^2}{4\kappa} |\mathcal{T}_{\vec{k}}|^2 \right)$$

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We want to quantize the whole system

$$\tilde{\Gamma}_{Trunc} = \Gamma_{FRW} \times \tilde{\Gamma}_1 \quad \text{suggests} \quad \mathcal{H} = \mathcal{H}_o \otimes \mathcal{H}_1 \longrightarrow \Psi = \Psi_0 \otimes \psi$$

Same strategy: solve for Ψ_0 and study the evolution of ψ on Ψ_0

Heisenberg equations for perturbations (using ϕ as a time: $N_\phi = a^3/p_{(\phi)}$)

$$\partial_\phi \hat{\mathcal{T}}_{\vec{k}}(\phi) = i\,[\hat{\mathcal{T}}_{\vec{k}}, \hat{\tilde{\mathbb{S}}}_2^{\mathcal{T}}] = 4\kappa\; \hat{p}_{(\phi)}^{-1} \otimes \hat{\mathfrak{p}}_{\vec{k}}^{(\mathcal{T})} \qquad \partial_\phi \hat{\mathfrak{p}}_{\vec{k}}^{(\mathcal{T})} = -\frac{k^2}{4\kappa}\, \hat{p}_{(\phi)}^{-1/2}\, \hat{a}^4(\phi)\, \hat{p}_{(\phi)}^{-1/2} \otimes \hat{\mathcal{T}}_{\vec{k}}$$

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This is a QFT in a quantum space time

I.A., Ashtekar, Dapor, Kaminski, Lewandowski, Nelson, Puchta, Tavakoli

Propagation only sensitive to two moments of the quantum geometry

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Theory mathematically equivalent to a QFT in smooth FRW metric:

$$\mathfrak{a}^4 = \langle \hat{p}_{(\phi)}^{-1/2}\, \hat{a}^4(\phi)\, \hat{p}_{(\phi)}^{-1/2} \rangle\, \langle \hat{p}_{(\phi)}^{-1} \rangle^{-1}$$

Moving to conformal time:

$$\mathfrak{g}_{ab} dx^a dx^b = \mathfrak{a}^2(\tilde{\eta})\,(-d\tilde{\eta}^2 - d\vec{x}^2)$$ effective, dressed background metric.

where $d\tilde{\eta} = \mathfrak{a}\, \langle \hat{p}_{(\phi)}^{-1} \rangle\, d\phi$

And the e.o.m.: $\hat{\mathcal{T}}_{\vec{k}}'' + 2\frac{\mathfrak{a}'}{\mathfrak{a}} \hat{\mathcal{T}}_{\vec{k}}' + k^2\, \hat{\mathcal{T}}_{\vec{k}} = 0$

But this construction has been formal so far. We need:

1. A quantum theory of gravity providing the quantization of the background: **LQC**
   Ashtekar, Bojowald, Brizuela, Campiglia, Corichi, Fernandez-Mendez, Garay, Gupt, Martin-Benito, Martin de Blas, Mena-Marugan, Montoya, Olmedo, Pawlowski, Singh, Willson-Ewing, ...

2. To make sense of the quantum theory of perturbations: import the machinery from QFT in CST. The adiabatic approach (Fulling & Parker):
   - $\mathcal{H}_{\rm pys}$ made of 4th adiabatic order states
   - Operators of interest, such as $\tilde{\mathbb{S}}_2$ and T_{ab} , can be renormalized in $\mathcal{H}_{\rm pys}$

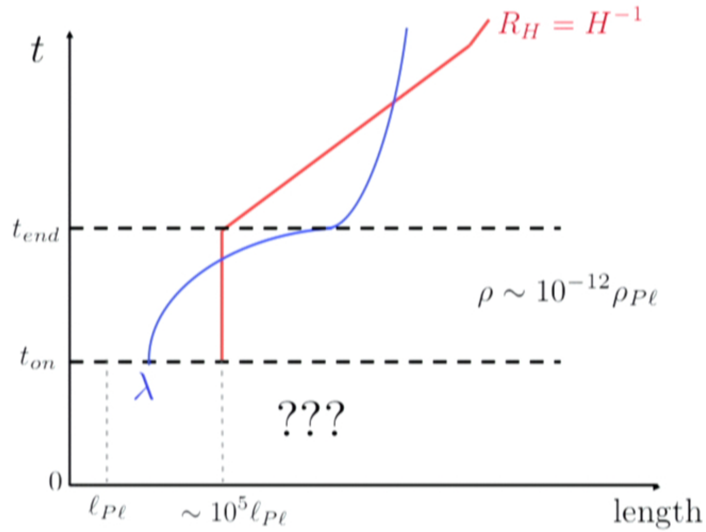
In summary...

The quantum theory of cosmological perturbations in classical space-times can be extended to a self-consistent QFT in quantum backgrounds.

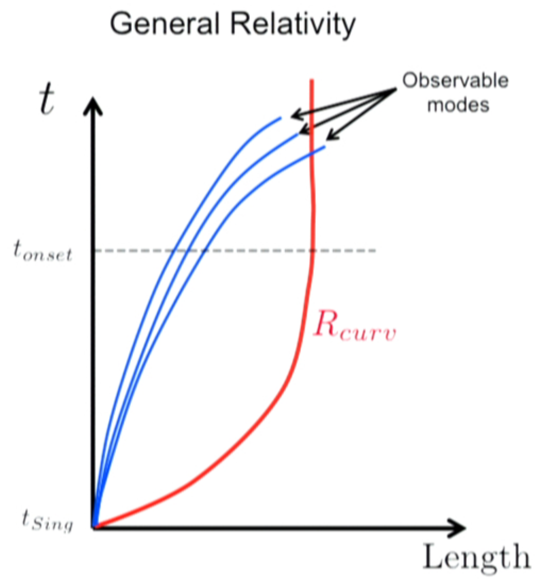
Quantum fields propagate as if they were in a space-time with smooth metric that encodes the information of the quantum geometry.

This theory provides a bridge between QG and standard theory QFT on cosmological s-t

Inflationary Scenario $V(\phi) = 1/2\, m^2\, \phi^2$



Why pre-inflationary dynamics should matter?



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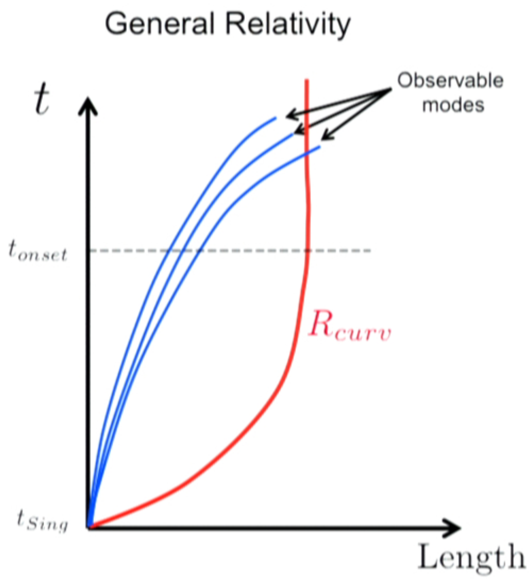

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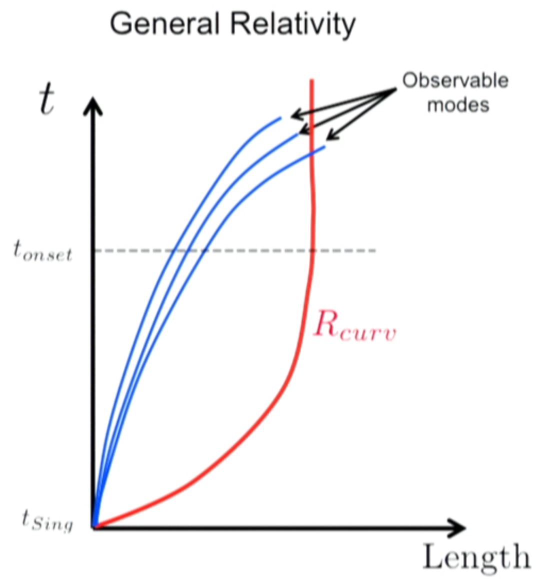

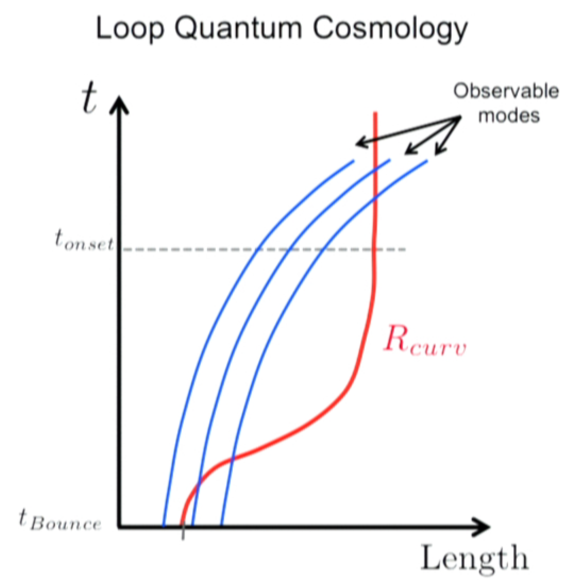

$k \propto a/\lambda$ comoving momentum

Initial conditions at the bounce

1) Background **Reminder:** (Ashtekar, Corichi, Pawlowski, Singh, Taveras, Vandersloot,...)

LQC: coherent states Ψ_o highly peaked at late times in a classical trajectory

They remain highly peaked at any time: small quantum fluctuations, effective trajectories

Effective trajectories uniquely characterized by the value of $\phi_B \in [0, 7.5 \times 10^5]$

Initial data for the background: Ψ_o peaked in a trajectory with $|\phi_B| \in [0, 7.5 \times 10^5]$

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2) Perturbations

In $\mathcal{H}_{pert}$ there is no preferred ground state.

Physical criteria: symmetry + regularity

Initial data for perturbations: 4th adiabatic order vacua

This is equivalent to impose quantum homogeneity at the bounce. Strong assumption.

Our motivation: at the bounce observable universe $\lesssim 10\ell_{Pl}$ + quantum repulsive force at the bounce

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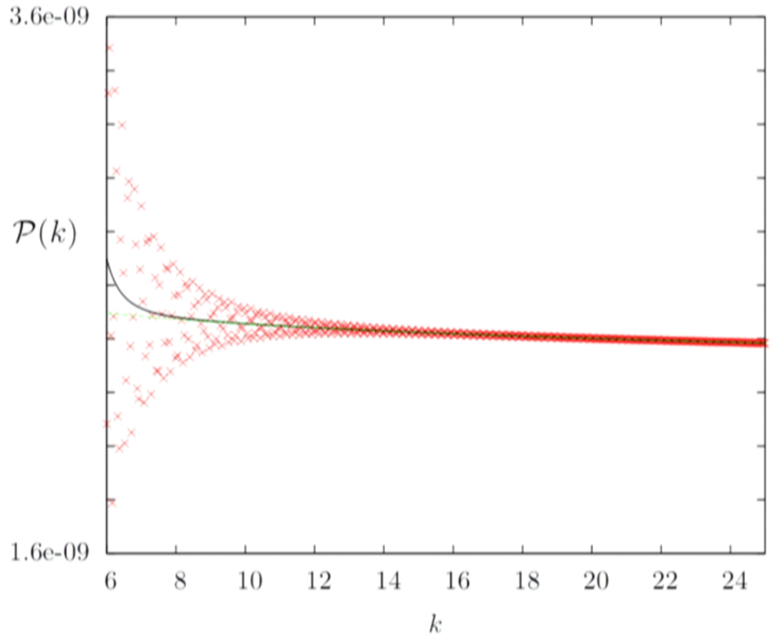
Observables:



Oscillations + enhancement for low k's

- **This plot is not very sensitive to the chosen 4th order adiabatic vacuum**
- **This plot is essentially insensitive to the chosen value of ϕ_B inside the range we've explored**
- **ϕ_B changes where the range of observable modes $\approx [k_{\rm min}, 2000k_{\rm min}]$ is located in the plot**

ϕ_B	1.1	1.2	1.3
$k_{\rm min}$	0.14	8.2	500

$\longrightarrow$ **For $\phi_B \gtrsim 1.2$** **LQC corrections become negligible**

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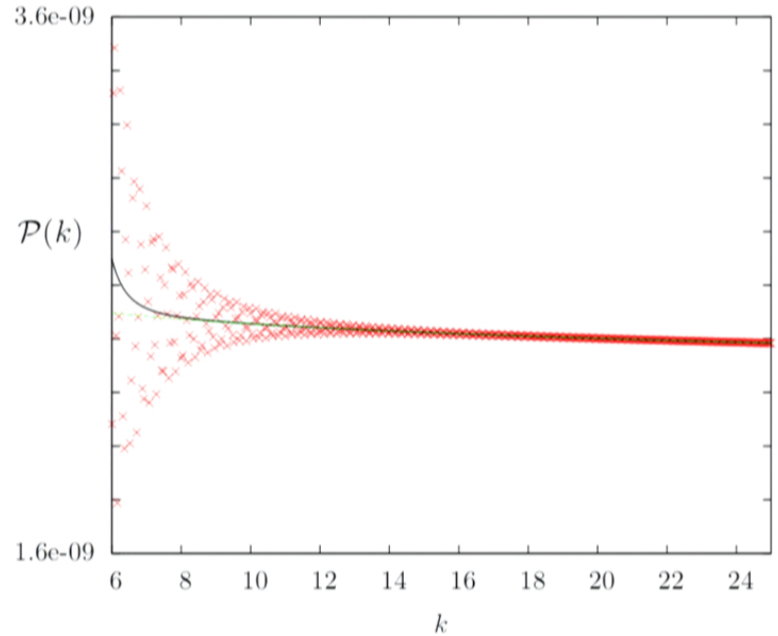

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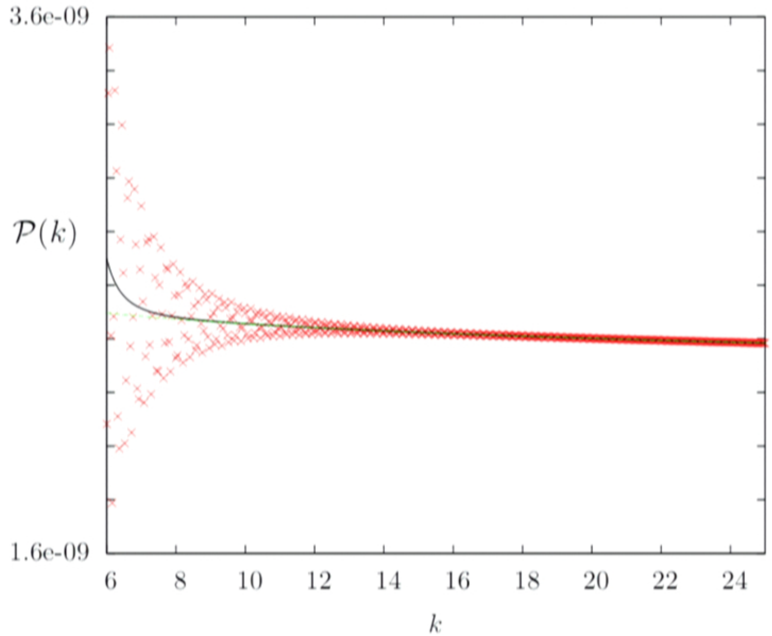

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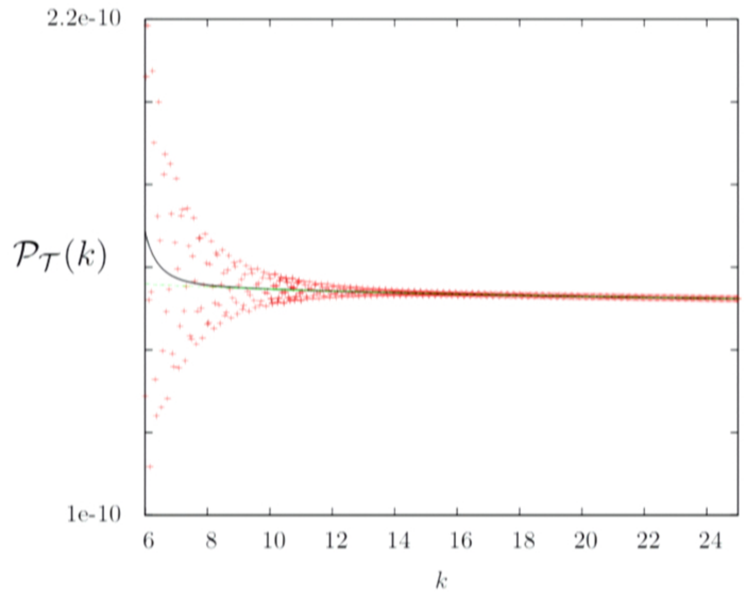

- **Similar plot for tensor perturbations:**
- Tensor-to-scalar ratio $r_{LQC} \approx r_{infl}$
- Inflationary consistency relation $r_{\rm LQC} = -8\left(n_t - \frac{d\ln(1+2\,n_k)}{d\ln k}\right) \leq -8n_t$

Summary:

RANGE OF BACKGROUND INITIAL CONDITIONS: $|\phi_B| \in [0, 7.5 \times 10^5]$

- For $|\phi_B| < 0.93$, **predictions incompatible with observations**: CMB constrains parameter space!

- For $\phi_B > 1.2$ **negligible effects from LQC**
  QG extension of the standard inflationary scenario

- $0.93 < \phi_B < 1.2$ **deviations from standard predictions:**

  1) Oscillations and Larger Power Spectra for scalar and tensor at low k

  2) Modification of inflationary consistency relation

Self-consistency:

Is back-reaction negligible during the entire evolution?

- We have numerically computed $\langle\hat{\rho}\rangle_{\rm ren}$ and compare it with ρ_o
- Non trivial, because it requires numerical cancellation of quantities that diverge. Numerical issues appear and we only have upper bounds for $\langle\hat{\rho}\rangle_{\rm ren}$
- So far we have been able to show that for $\phi_B > 1.2$ back-reaction is negligible at any time during evolution.

There exist a subset of $\mathcal{H}$ in which self-consistency is negligible