Echoes of the Early Universe

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Experimental Search for Quantum Gravity
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Looking for Signatures of QG today

- To test proposals for Quantum Gravity we need
  i) predictions
  ii) experimental data encoding QG effects

- QG scales out of reach of experiments on earth

- One of most promising windows: COSMOLOGY
Looking for Signatures of QG today

- Evidence of early Universe physics imprinted onto the CMB

  WMAP, Planck, …

- Primordial gravitational waves may carry information of the quantum fluctuations of the geometry of the early Universe

  BICEP2
Looking for Signatures of QG today

- Have QG signatures really survived from the early Universe all the way to our current era?

- If so, how strong are they?

- Will it be possible to validate or falsify different QG proposals by looking at the data?

We explore a simple way, based on a toy model, to assess the strength of the quantum signatures of the early Universe that might be observed nowadays.
Setting

- We will analyze Gibbons-Hawking effect:
  Creation of particles measured by a particle detector due to cosmological expansion when the surrounding matter fields are in vacuum.

- Particle detector coupled to matter fields from the early stages of the Universe until today:

Would the detector conserve any information from the time when it witnessed the very early Universe dynamics?

\[ t_{Pl} \sim 10^{-44} \text{s} \quad ; \quad T \sim 10^{17} \text{s} \]
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**YES**

\[ t_{Pl} \sim 10^{-44} \text{s} \quad ; \quad T \sim 10^{17} \text{s} \]
Early Universe dynamics

- Flat FRW with T3 topology and matter source a massless scalar $\varphi$

- We will compare the response of the detector evolving under two different Universe dynamics which disagree only during the short time when matter-energy densities are of the order the Planck scale
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GR vs Effective LQC

$$a_q(t) = l \left( \frac{\pi^2 \varphi}{12\pi G} \right)^{1/6} \left[ 1 + \left( \frac{12\pi G}{l^3} \right)^2 t^2 \right]^{1/6}$$

$$a_c(t) = (12\pi G \pi^2 \varphi)^{1/6} t^{1/3}$$

$l \sim$ quantum of length
Gibbons-Hawking effect

- We consider a massless scalar field $\phi$ in the conformal vacuum

- The proper time of comoving observers (who see an isotropic expansion) does not coincide with the conformal time

\[
\eta_c(t) = \frac{3t^{2/3}}{2(12\pi G \pi_\varphi^2)^{1/6}}
\]

\[
\eta_q(t) = \frac{1}{l} \left( \frac{12\pi G}{\pi_\varphi^2} \right)^{1/6} \left[ t \cdot 2F_1 \left[ \frac{1}{6}, \frac{1}{2}, \frac{3}{2}, - \left( \frac{12\pi G}{l^3} t \right)^2 \right] \right] \quad \rightarrow \quad \eta_c(t) + \beta
\]

$t \gg t^3/(12\pi G)$
The Unruh-De Witt model

\[ |e\rangle = \sigma^+ |0\rangle \]

\[ |0\rangle = \sigma^- |e\rangle \]

\[ \hat{H}_I(t) = \lambda \chi(t) (\sigma^+ e^{i\Omega t} + \sigma^- e^{-i\Omega t}) \hat{\phi}[\vec{x}_0, \eta(t)] \]

- \( t \) proper time of the detector (comoving)
- \( \lambda \) coupling strength
- \( \chi(t) \) switching function
- \([\vec{x}_0, \eta(t)]\) world-line of the detector (stationary)
Probability of excitation

- $T_0$: field in the conformal vacuum and detector in its ground state

- Transition probability for the detector to be excited at time $T$:
  
  At leading order ($\lambda$ small enough)

  \[ P_e(T_0, T) = \lambda^2 \sum_{\vec{n}} |I_{\vec{n}}(T_0, T)|^2 + O(\lambda^4) \]

  \[ I_{\vec{n}}(T_0, T) = \int_{T_0}^{T} dt \frac{\chi(t)}{a(t)\sqrt{2\omega_{\vec{n}}L^3}} e^{-\frac{2\pi i \vec{n} \cdot \vec{x}_0}{L}} e^{i[\Omega t + \omega_{\vec{n}} \eta(t)]} \]

  \[ \vec{n} = (n_x, n_y, n_z) \in \mathbb{Z}^3 - \vec{0} \]

  \[ \omega_{\vec{n}} = \frac{2\pi}{L} |\vec{n}| \]
Probabilities: GR vs effective LQC

- Difference of probabilities
  \[ \Delta P_e(T_0, T) \equiv P^q_e(T_0, T) - P^c_e(T_0, T) \]

- We split the integrals
  \[
  I^c_n(T_0, T) = I^c_n(T_0, T_m) + I^c_n(T_m, T) \quad \quad \eta_q(T_m) \approx \eta_c(T_m) + \beta
  \]
  \[
  I^q_n(T_0, T) = I^q_n(T_0, T_m) + e^{i\omega_n \beta} I^c_n(T_m, T)
  \]

\[
\Delta P_e(T_0, T) = \lambda^2 \sum_{\vec{n}} \left[ |I^q_n(T_0, T_m)|^2 - |I^c_n(T_0, T_m)|^2 \right] + 2 \text{Re} \left( I^c_n(T_m, T) \left[ e^{-i\beta \omega_n} I^q_n(T_0, T_m) - I^c_n(T_0, T_m) \right] \right)
\]
Probabilities: GR vs effective LQC

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- We split the integrals
  \[ I^c_n(T_0, T) = I^c_n(T_0, T_m) + I^c_n(T_m, T) \]
  \[ I^q_n(T_0, T) = I^q_n(T_0, T_m) + e^{i\omega \beta} I^c_n(T_m, T) \]
  \[ \eta_q(T_m) \approx \eta_c(T_m) + \beta \]

\[ \Delta P_e(T_0, T) = \lambda^2 \sum \left[ |I^q_n(T_0, T_m)|^2 - |I^c_n(T_0, T_m)|^2 \right. \]
\[ + 2 \text{Re} \left( I^c_n(T_m, T) \left[ e^{-i\beta \omega \bar{n}} I^q_n(T_0, T_m) - I^c_n(T_0, T_m) \right] \right) \]

The relative difference on the detector's particle counting in both scenarios will be appreciably different even for long \( T \)
Sensitivity with the quantum parameter

- Any observations we may make on particle detectors will be averaged in time over many Planck times

\[ \langle P_e(T_0, T) \rangle_T = \frac{1}{T} \int_{T-T}^{T} P_e(T_0, T') \, dT' \quad \mathcal{T} \gg l^3/(12\pi G) \]

- Sub-Planckian detector \( \Omega \ll 12\pi G/l^3 \)

- Estimator to study sensitivity with quantum of length:
  Mean relative difference between probabilities of excitation averaged over a long interval in the late time regime

\[ E = \left( \frac{\langle \Delta P_e(T_0, T) \rangle_T}{\langle P_e^{GR}(T_0, T) \rangle_T} \right)_{\Delta T} \quad \Delta T = T - T_{\text{late}} \]
\[ \Delta T, \ T_{\text{late}} \gg l^3/(12\pi G) \]
Sensitivity with the quantum parameter

\[ E = \left\langle \frac{\Delta P_e(T_0, T)}{P_e^{GR}(T_0, T)} \right\rangle_{\Delta T} \]

Exponential with the size of the spacetime quantum

- Cosmological observations could put stringent upper bounds to \( l \)
Transmission of information

- Combination of cosmology and quantum information

- Transmission and recovery of information propagated through cosmological catastrophes (big-bang, inflation, quantum bounce, …)

- Setting: two detectors A and B on LQC dynamics, before and after the bounce
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- Transmission and recovery of information propagated through cosmological catastrophes (big-bang, inflation, quantum bounce, ...)

- Setting: two detectors A and B on LQC dynamics, before and after the bounce

  • Mutual information
    (it measures the information that A and B share)

  • Signalling
    (it measures whether B knows about the existence of A)

  • Channel capacity
    (upper bound on the rate of reliable transmitted information)

— WORK IN PROGRESS —
Conclusions

- Although this is a toy model, it captures the essence of a key phenomenon: Quantum field fluctuations are extremely sensitive to the physics of the early Universe.

- The signatures of these fluctuations survive in the current era with a possible significant strength.

- We showed how the existence (or not) of a quantum bounce leaves a trace in the background quantum noise that is not damped and that may be non-negligible even nowadays.

- The use of LQC in this derivation is anecdotal, and we believe that our main result is general:

  The response of a particle detector today carries the imprint of the specific dynamics of the spacetime in the early Universe.
Thanks for your attention!