Echoes of the Early Universe

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in collaboration with
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Experimental Search for Quantum Gravity

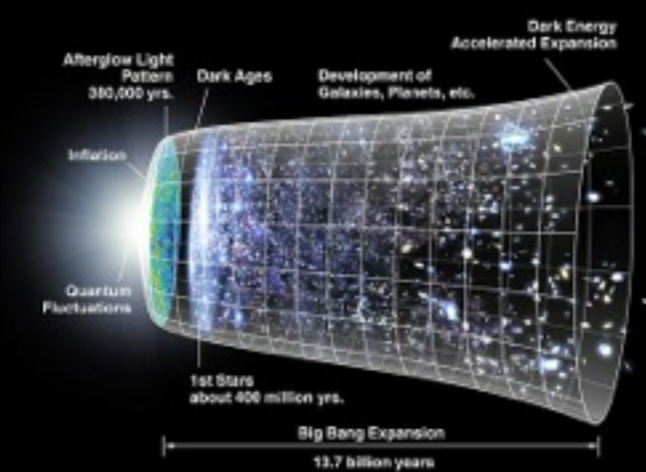
SISSA, Trieste — September 2014

Looking for Signatures of QG today

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

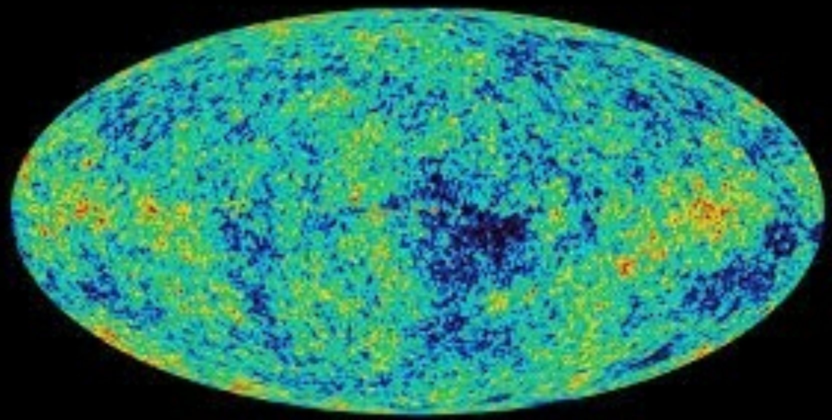
- QG scales out of reach of experiments on earth

- One of most promising windows: COSMOLOGY

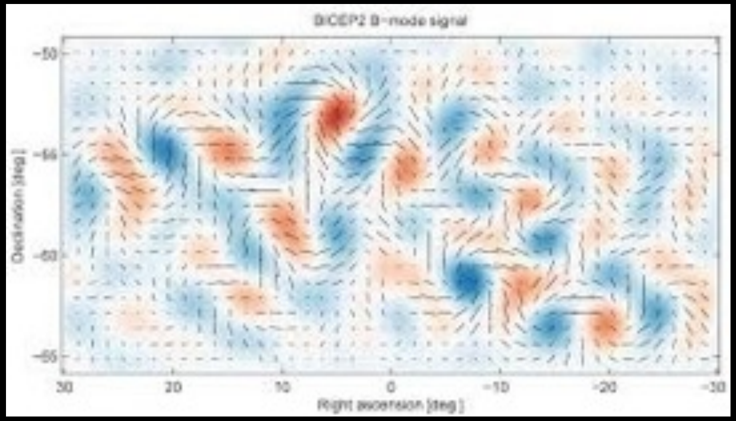


Looking for Signatures of QG today

- Evidence of early Universe physics imprinted onto the CMB

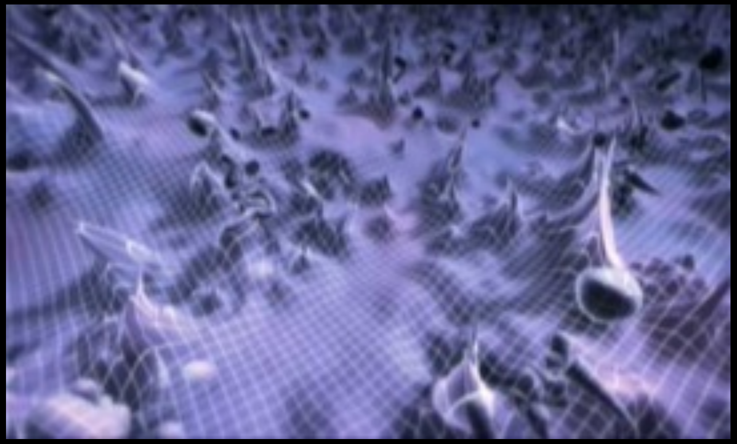


WMAP, Planck, …



BICEP2

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



Looking for Signatures of QG today

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

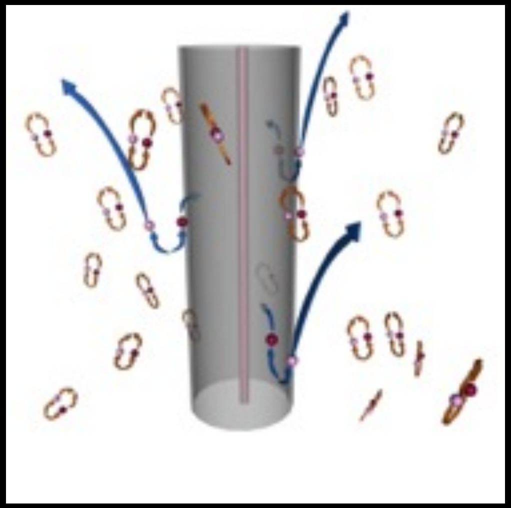
- If so, how strong are they?

- 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

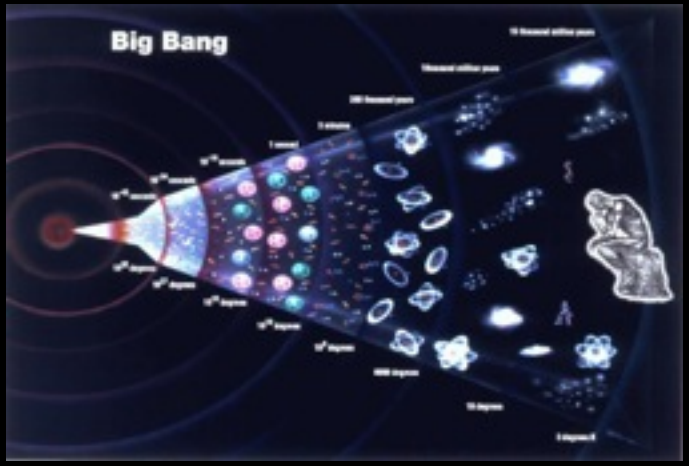
Setting

- 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?



$$t_{Pl} \sim 10^{-44} s \quad ; \quad T \sim 10^{17} s$$

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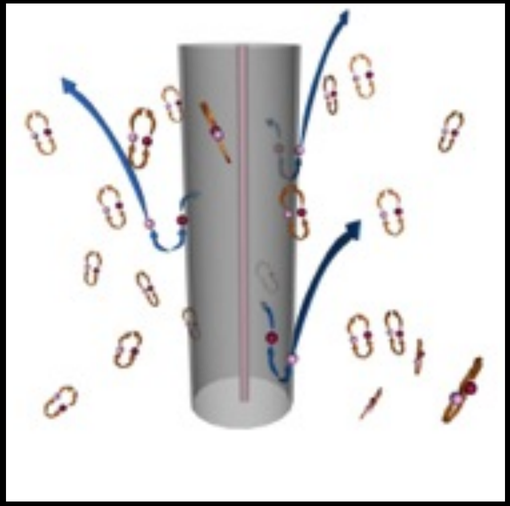

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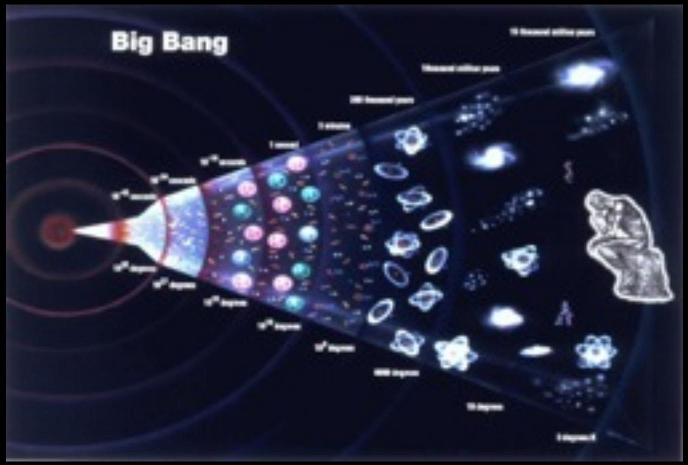
Would the detector conserve any information from the time when it witnessed the very early Universe dynamics?

YES



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Early Universe dynamics

- Flat FRW with T3 topology and matter source a massless scalar φ

- 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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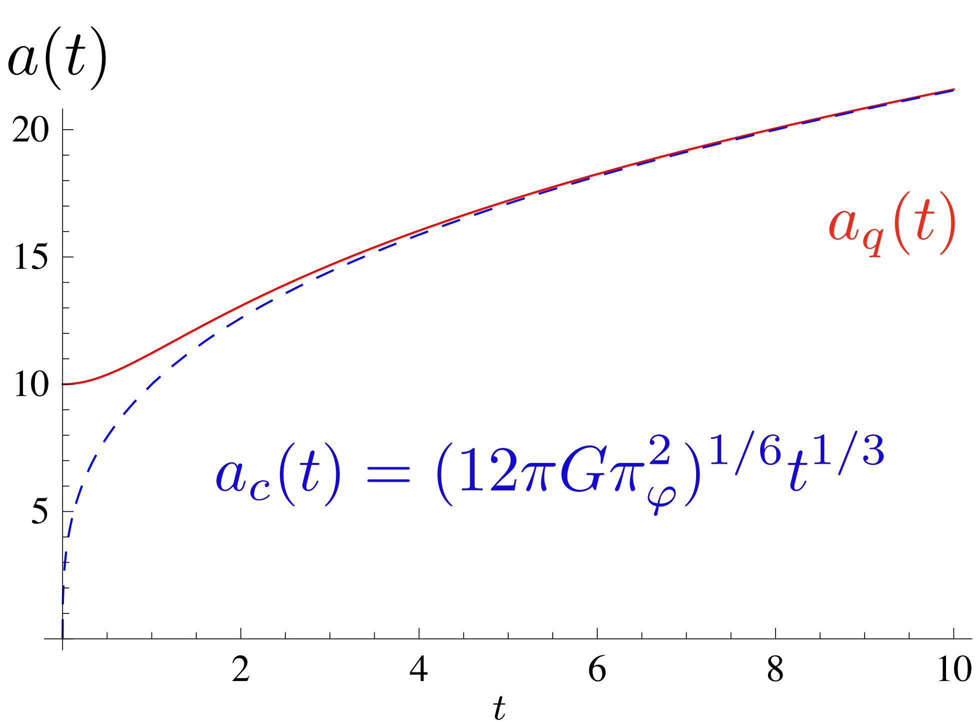
GR vs Effective LQC



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

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

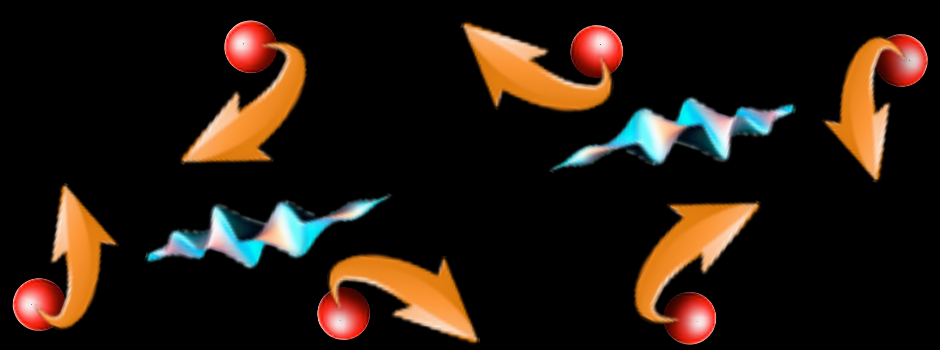
l ~ quantum of length

Gibbons-Hawking effect

- We consider a massless scalar field ϕ in the conformal vacuum

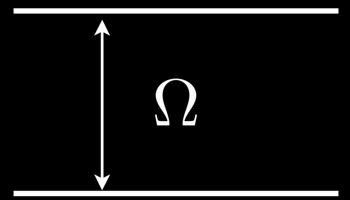
- The proper time of comoving observers (who see an isotropic expansion) does not coincide with the conformal time

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



$$\eta_q(t) = \frac{1}{l}\left(\frac{12\pi G}{\pi_\varphi^2}\right)^{1/6} t \cdot {}_2F_1\left[\frac{1}{6}, \frac{1}{2}, \frac{3}{2}, -\left(\frac{12\pi G}{l^3} t\right)^2\right] \xrightarrow[t \gg l^3/(12\pi G)]{} \eta_c(t) + \beta$$

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)**
λ	**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 (λ small enough)

$$P_{\mathrm{e}}(T_0, T) = \lambda^2 \sum_{\vec{n}} |I_{\vec{n}}(T_0, T)|^2 + \mathcal{O}(\lambda^4)$$

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

$$\vec{n} = (n_x, n_y, n_z) \in \mathbb{Z}^3 - \vec{0} \qquad \omega_{\vec{n}} = \frac{2\pi}{L} |\vec{n}|$$

Probabilities: GR vs effective LQC

- **Difference of probabilities** $\Delta P_{\mathrm{e}}(T_0, T) \equiv P_{\mathrm{e}}^{q}(T_0, T) - P_{\mathrm{e}}^{c}(T_0, T)$

- **We split the integrals**

$$I_{\vec{n}}^{c}(T_0, T) = I_{\vec{n}}^{c}(T_0, T_m) + I_{\vec{n}}^{c}(T_m, T) \qquad \eta_q(T_m) \approx \eta_c(T_m) + \beta$$

$$I_{\vec{n}}^{q}(T_0, T) = I_{\vec{n}}^{q}(T_0, T_m) + e^{i\omega_{\vec{n}}\beta} I_{\vec{n}}^{c}(T_m, T)$$

$$\boxed{\begin{aligned}\Delta P_{\mathrm{e}}(T_0, T) = \lambda^2 \sum_{\vec{n}} \Big[& \left|I_{\vec{n}}^{q}(T_0, T_m)\right|^2 - \left|I_{\vec{n}}^{c}(T_0, T_m)\right|^2 \\ & + 2\mathrm{Re}\Big(I_{\vec{n}}^{c\,*}(T_m, T) \left[e^{-i\beta\omega_{\vec{n}}} I_{\vec{n}}^{q}(T_0, T_m) - I_{\vec{n}}^{c}(T_0, T_m) \right] \Big) \Big]\end{aligned}}$$

Probabilities: GR vs effective LQC

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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

$$\langle P_{\mathrm{e}}(T_0,T)\rangle_{\mathcal{T}} = \frac{1}{\mathcal{T}}\int_{T-\mathcal{T}}^{T} P_{\mathrm{e}}(T_0,T')\,\mathrm{d}T' \qquad \mathcal{T} \gg l^3/(12\pi G)$$

- 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

$$E = \left\langle \frac{\langle \Delta P_{\mathrm{e}}(T_0,T)\rangle_{\mathcal{T}}}{\langle P_{\mathrm{e}}^{\mathrm{GR}}(T_0,T)\rangle_{\mathcal{T}}} \right\rangle_{\Delta T}$$

$$\Delta T = T - T_{\mathrm{late}}$$

$$\Delta T,\ T_{\mathrm{late}} \gg l^3/(12\pi G)$$

Sensitivity with the quantum parameter

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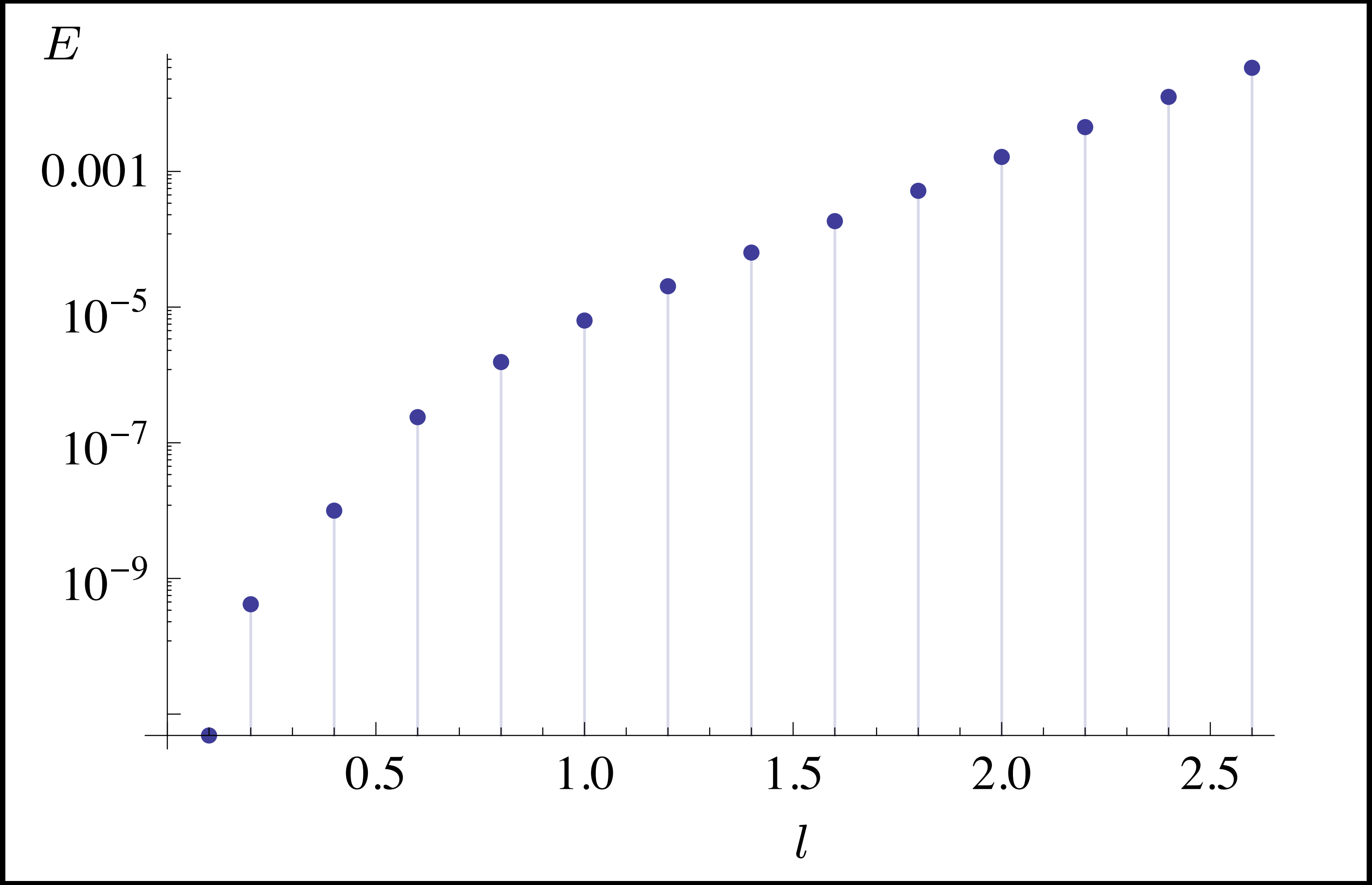


Exponential with the size of the spacetime quantum

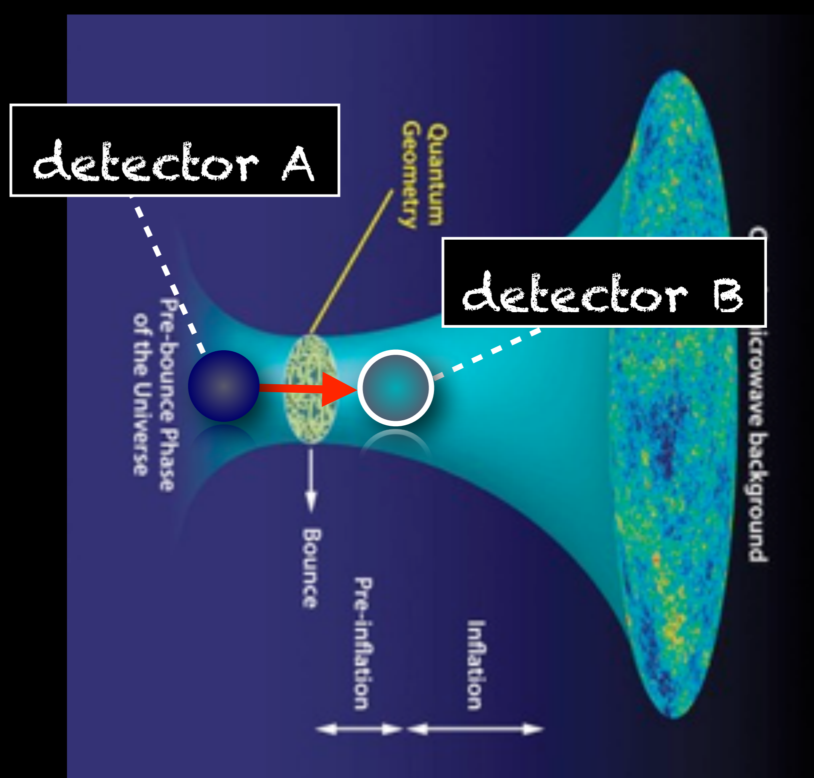
- Cosmological observations could put stringent upper bounds to l

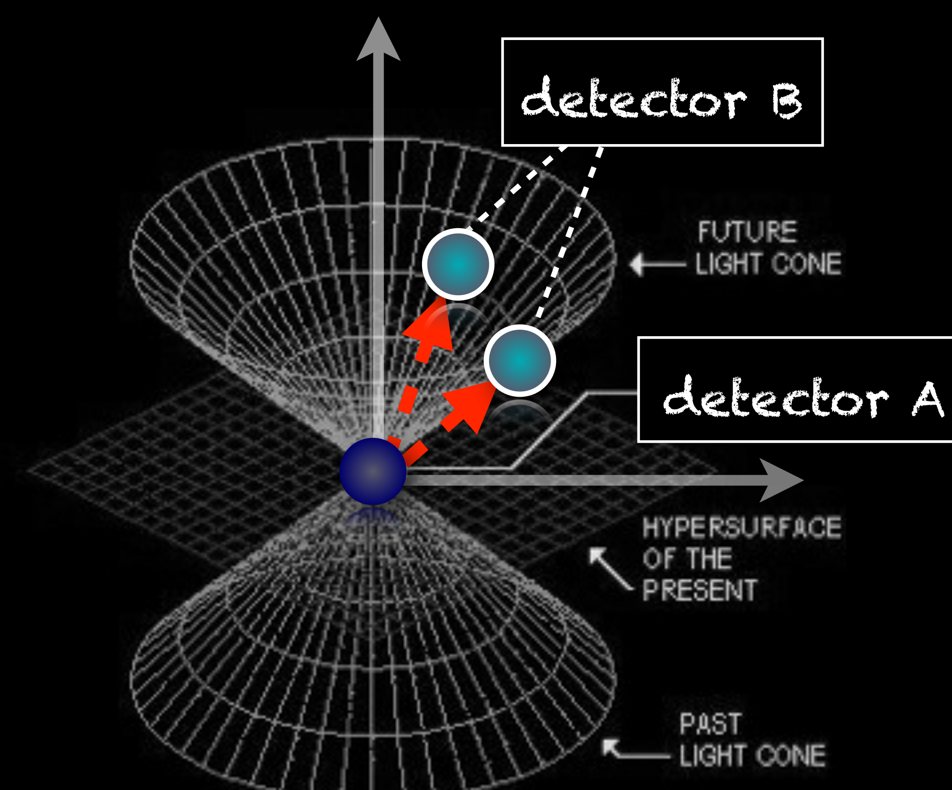
Transmission of information

- 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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  - 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 —

Conclussions

- 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 anecdotical, 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!