CAP, June 17th 2014

Echoes of the early Universe

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Work in collaboration with Mercedes Martin-Benito and Luis J. Garay

In preparation

Work in collaboration with Ana Blasco, Mercedes Martin-Benito and Luis J. Garay

Bourses postdoctorales Banting Postdoctoral Fellowships

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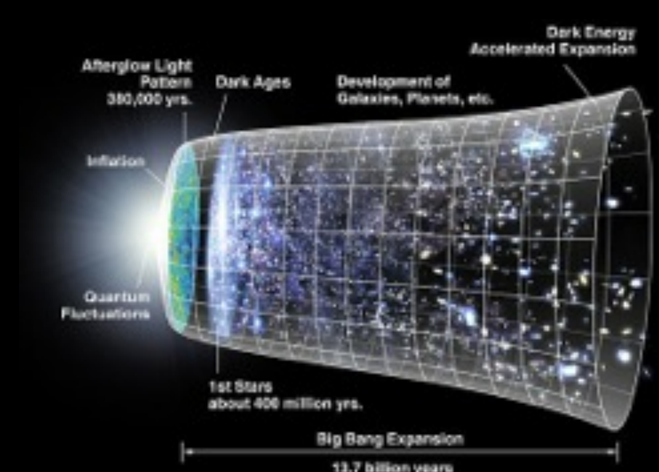
Looking for Signatures of QG today

- 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

- Most promising window: COSMOLOGY



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?

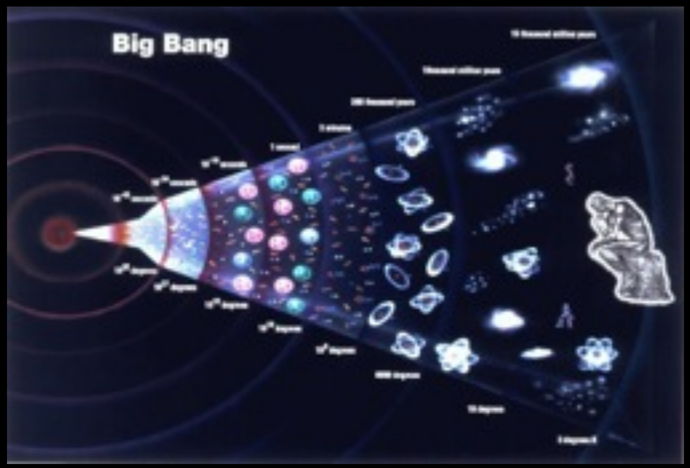
- Will it be possible to validate or falsify different QG proposals by looking at the data? Is the information RECOVERABLE?

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

- **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?

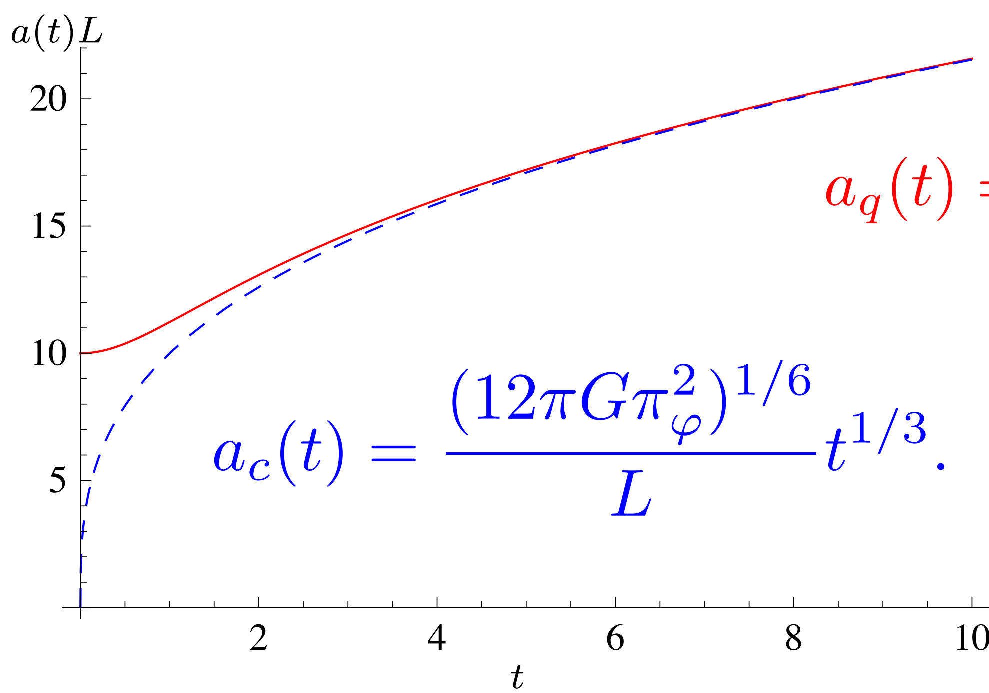


$$t_{Pl} \sim 10^{-44} s \quad ; \quad T \sim 10^{17} s$$

Early Universe dynamics

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_\star}\right), \quad \rho_\star := \frac{6\pi G}{l^6}.$$

GR vs Effective LQC



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

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

l ~ quantum of length

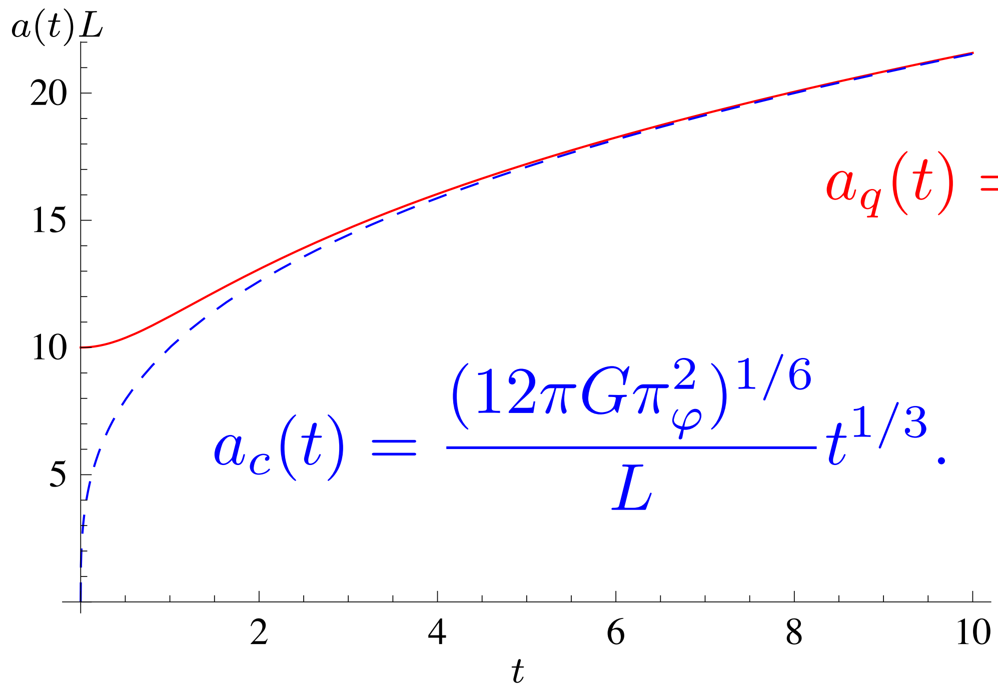
L ~ compactification scale

Early Universe dynamics

- Flat FRW with 3-Torus 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

GR vs Effective LQC



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Gibbons-Hawking effect

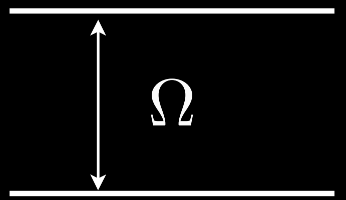
- We consider a massless scalar field ϕ in the conformal vacuum

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

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

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

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)

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

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

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

Do the effects wash out?

- **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**

$$I^c_{\vec{n}}(T_0,T) = I^c_{\vec{n}}(T_0,T_m) + I^c_{\vec{n}}(T_m,T)$$

$$\eta_q(T_m) \approx \eta_c(T_m) + \beta$$

$$I^q_{\vec{n}}(T_0,T) = I^q_{\vec{n}}(T_0,T_m) + e^{i\omega_{\vec{n}}\beta} I^c_{\vec{n}}(T_m,T)$$

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$$\Delta P_{\rm e}(T_0,T) = \lambda^2 \sum_{\vec{n}} \Big[\left|I^q_{\vec{n}}(T_0,T_m)\right|^2 - \left|I^c_{\vec{n}}(T_0,T_m)\right|^2 + 2\mathrm{Re}\Big(I^{c\,*}_{\vec{n}}(T_m,T) \left[e^{-i\beta\omega_{\vec{n}}} I^q_{\vec{n}}(T_0,T_m) - I^c_{\vec{n}}(T_0,T_m) \right] \Big) \Big]$$

Probabilities: GR vs effective LQC

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

- **We split the integrals**

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

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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 to the quantum parameters

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

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

- **Sub-Planckian detector** $\Omega \ll 12\pi G/l^3$

- **Estimator to study sensitivity with quantum of length**

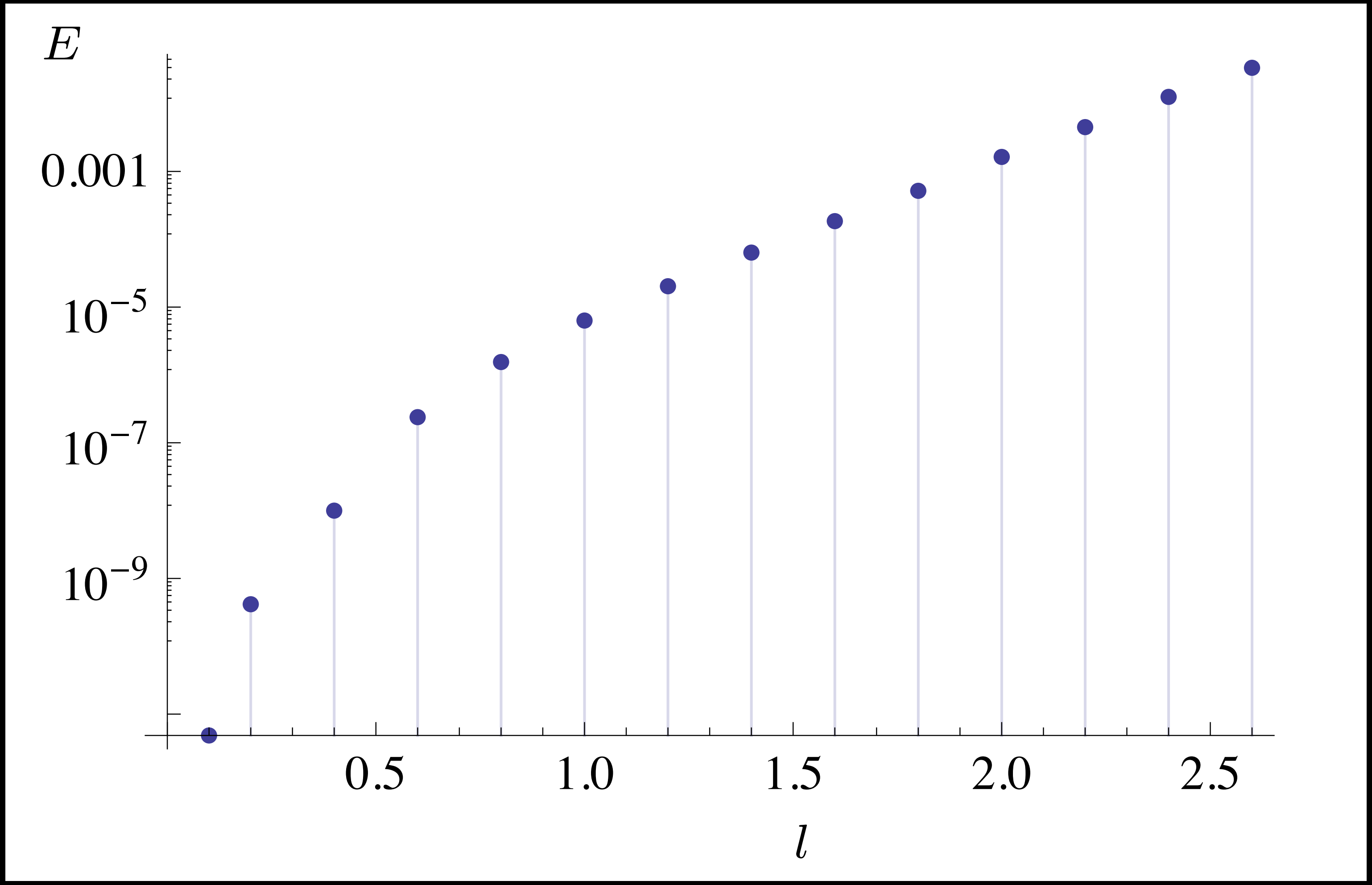
$$E = \left\langle \frac{\langle \Delta P_{\rm e}(T_0,T)\rangle_{\mathcal{T}}}{\langle P_{\rm e}^{\rm GR}(T_0,T)\rangle_{\mathcal{T}}} \right\rangle_{\Delta T}$$

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

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

Sensitivity to the quantum parameters

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

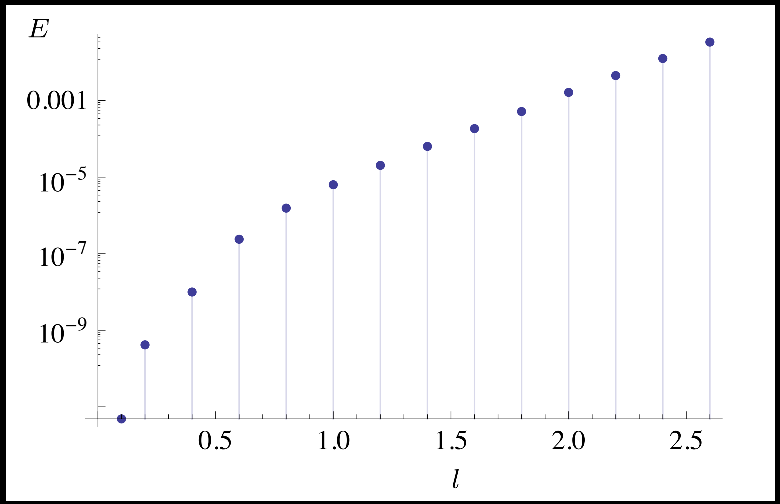


Exponential with the size of the spacetime quantum

- Cosmological observations could put stringent upper bounds to l

Sensitivity to the quantum parameters

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



Sub-Planckian detector:

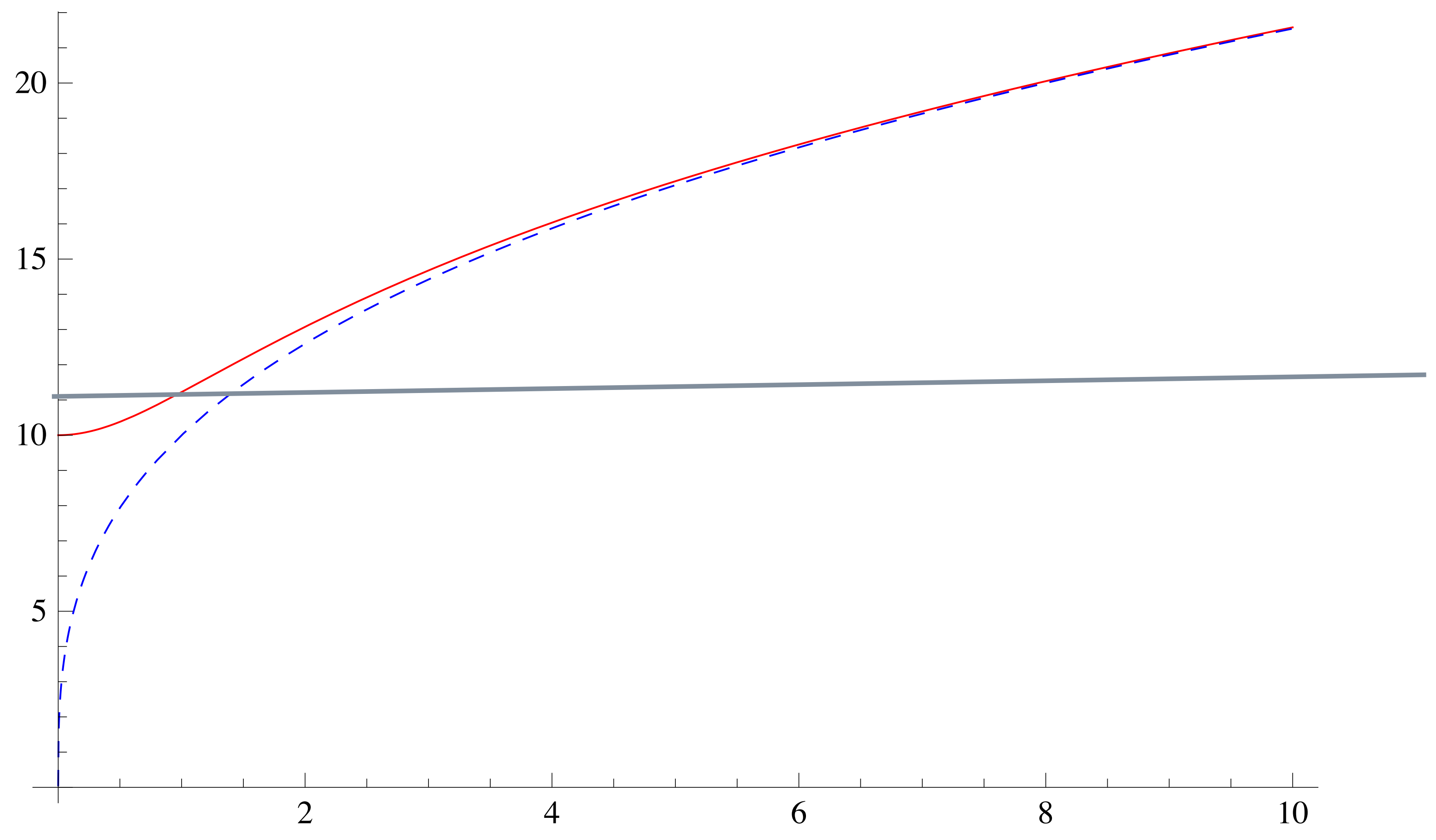
-Low Energy gap (as compared to the Planck scale)

-Observed nowadays (far from the Planck scale)

-Long Detection time (as compared to the Planck scale)

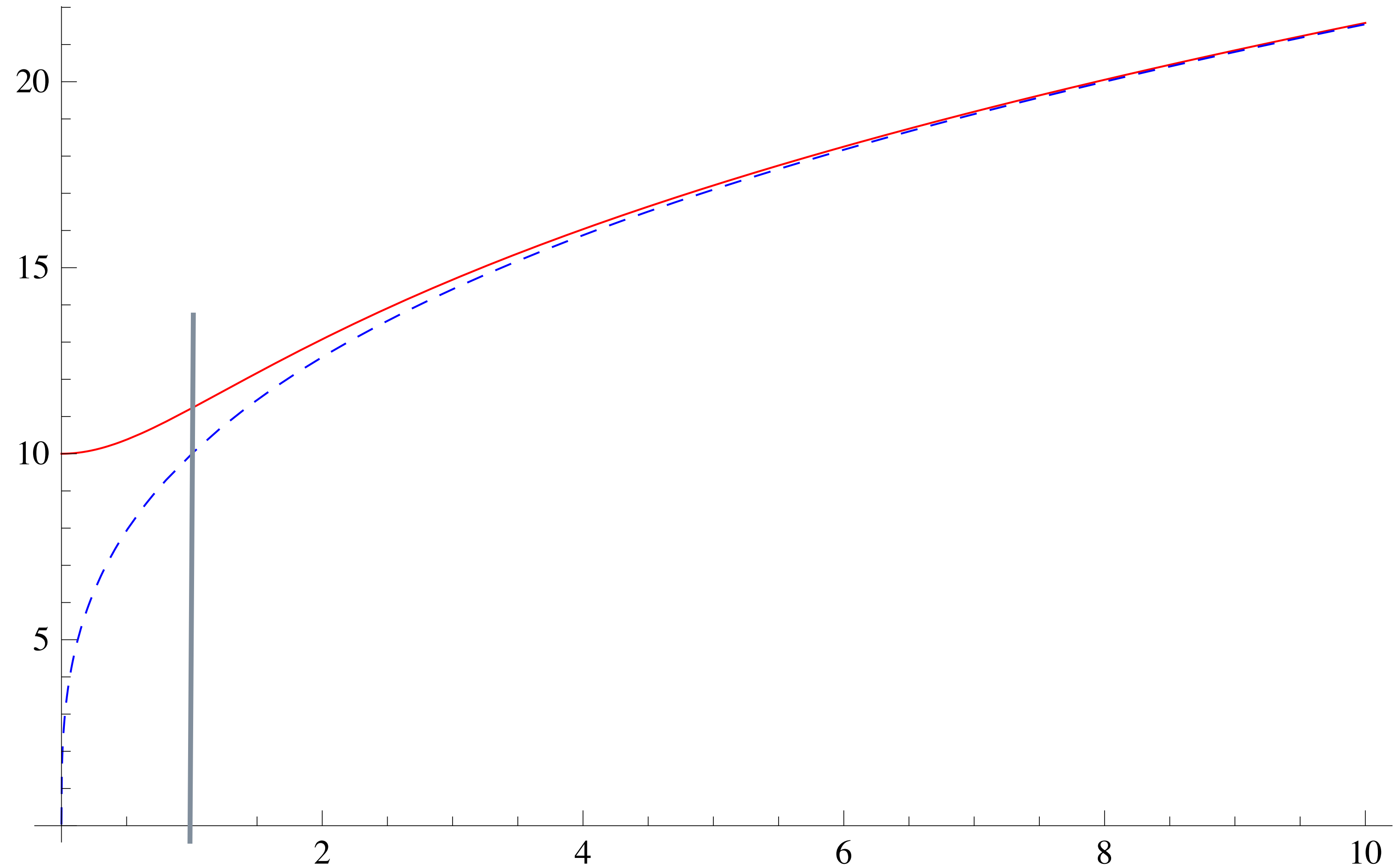
Stability of the results

Scenario 1: The detectors were switched on at a given total volume of the Universe



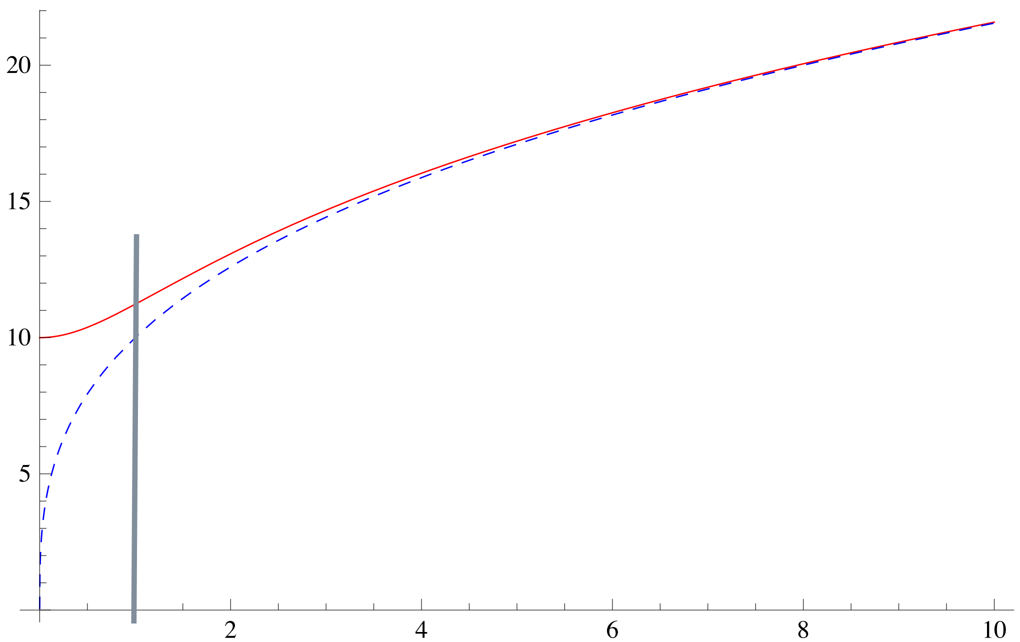
Stability of the results

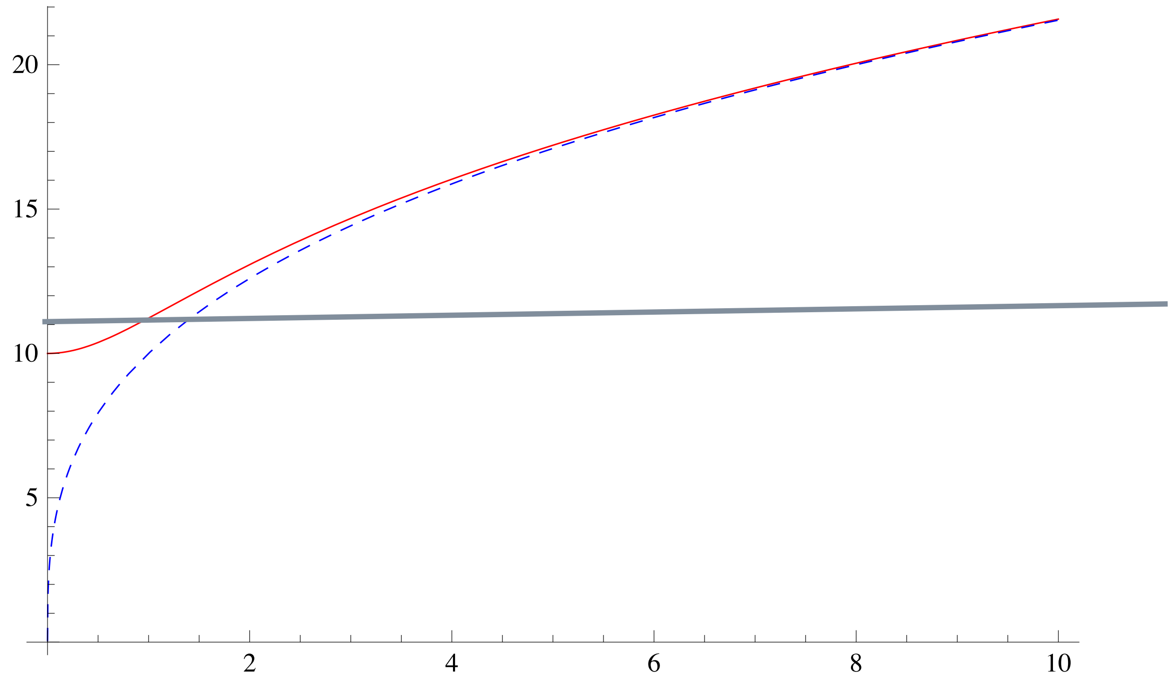
Scenario 2: The detectors have been switched on for the same amount of (proper) time

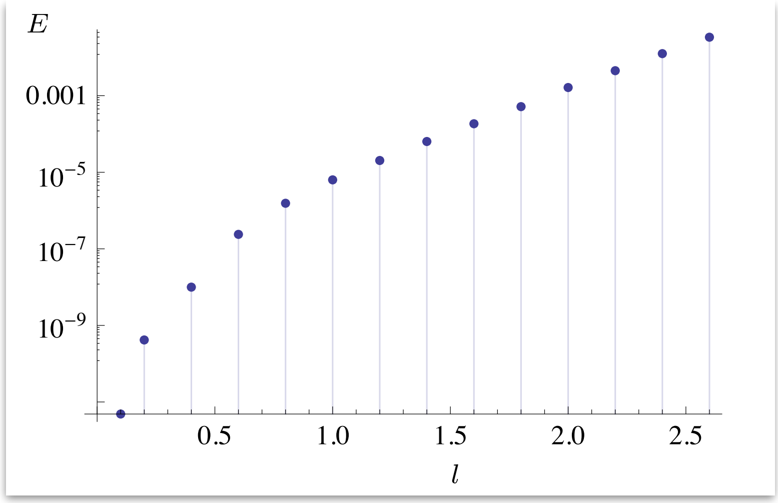


Stability of the results

Identical results in both scenarios







Early Universe dynamics

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_\star}\right), \quad \rho_\star := \frac{6\pi G}{l^6}.$$

GR vs Post-Einstenian gravity

- In the early universe there might not even be any notion of geometry

- There has to be an intermediate regime where we have effective (perturbed) Friedmann equations.

- Information about these corrections makes it all the way to nowadays in the noise spectrum of vacuum fluctuations and its recoverable at low energy.

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 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 would 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

The response of a particle detector today carries the imprint of the specific dynamics of the spacetime in the early Universe

Decoherence mechanisms?

MOSTLY UNKNOWN

Quantum information lost, how about classical information?

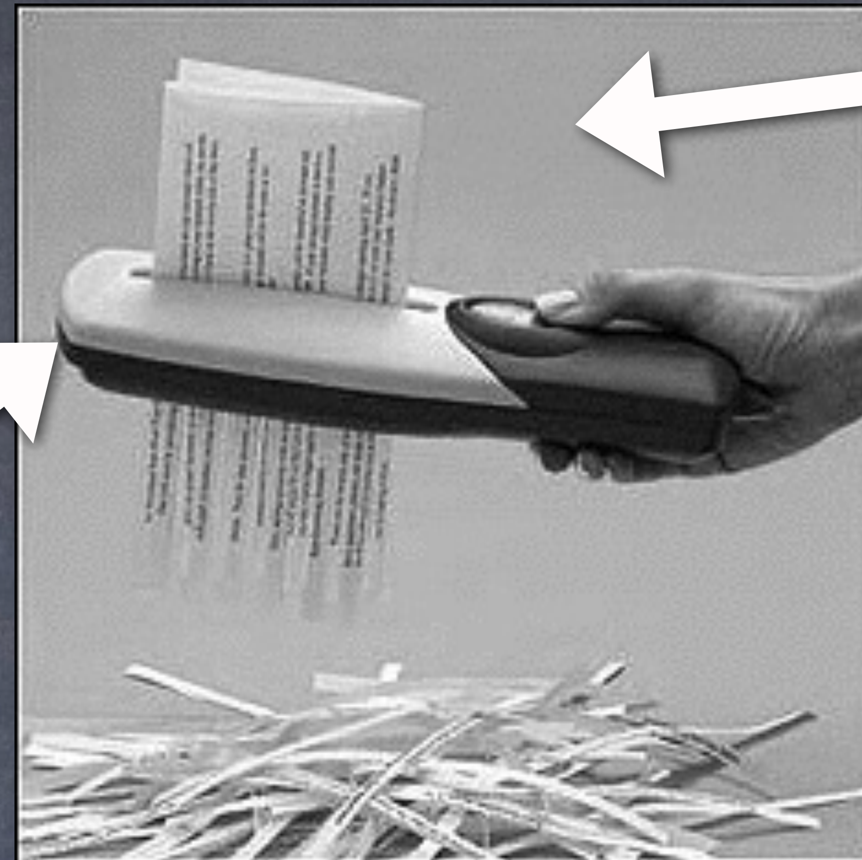
Ongoing Work:

Can quantum information survive a cosmological cataclysm?

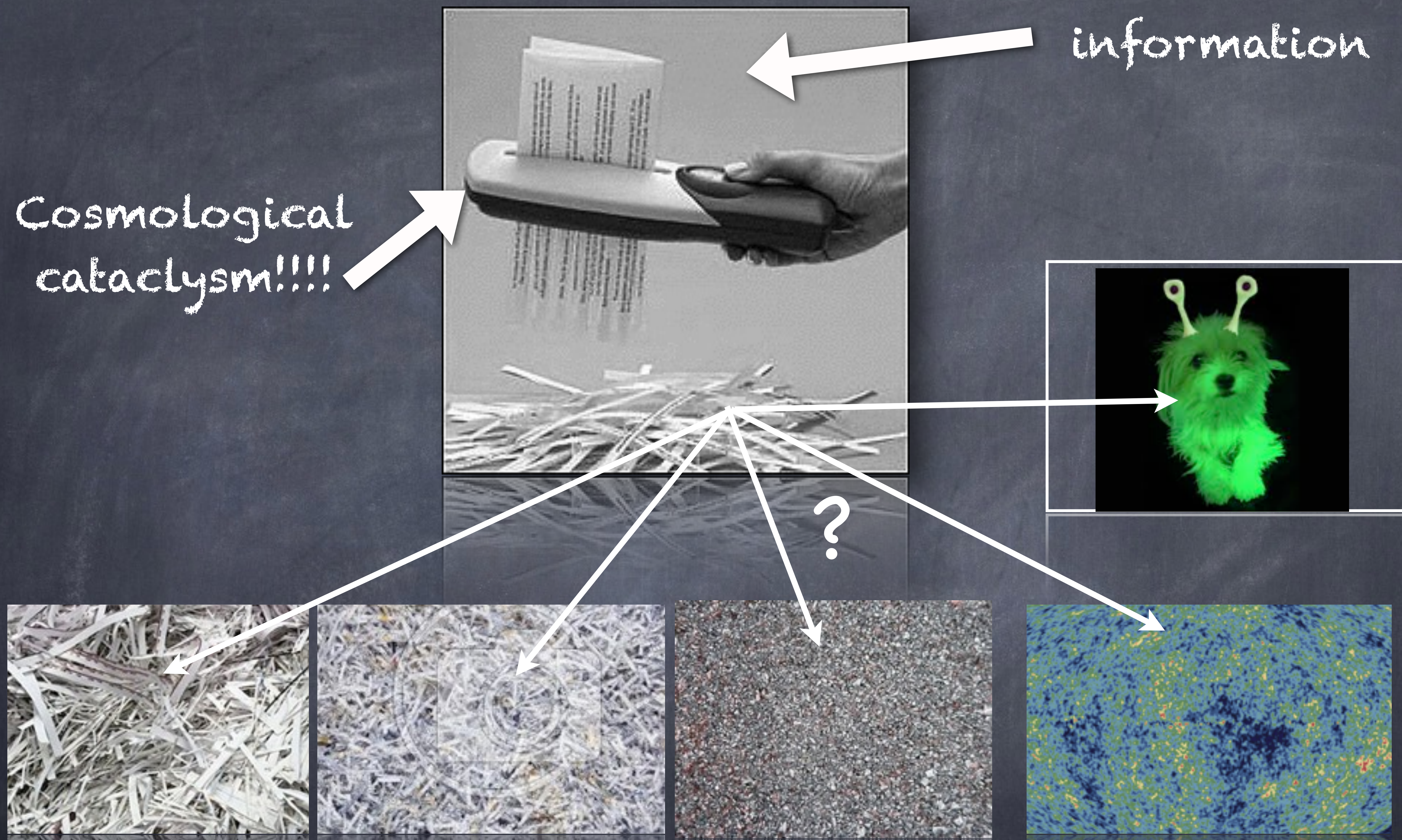
Work in collaboration with
Luis J. Garay, Mercedes Martin-Benito, Ana Blasco

How much information survives a Cosmological cataclysm!!!!

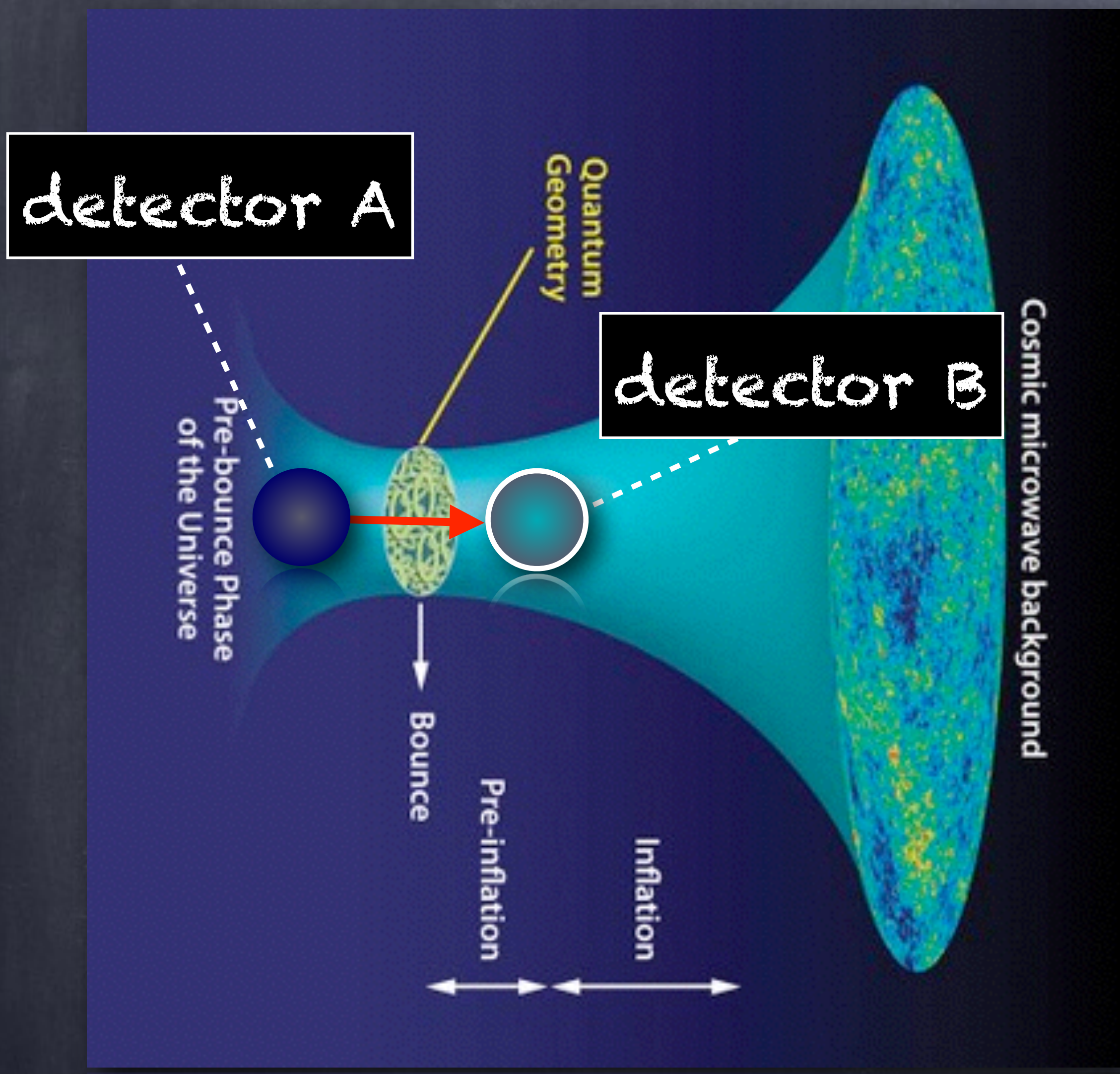
Cosmological cataclysm!!!!



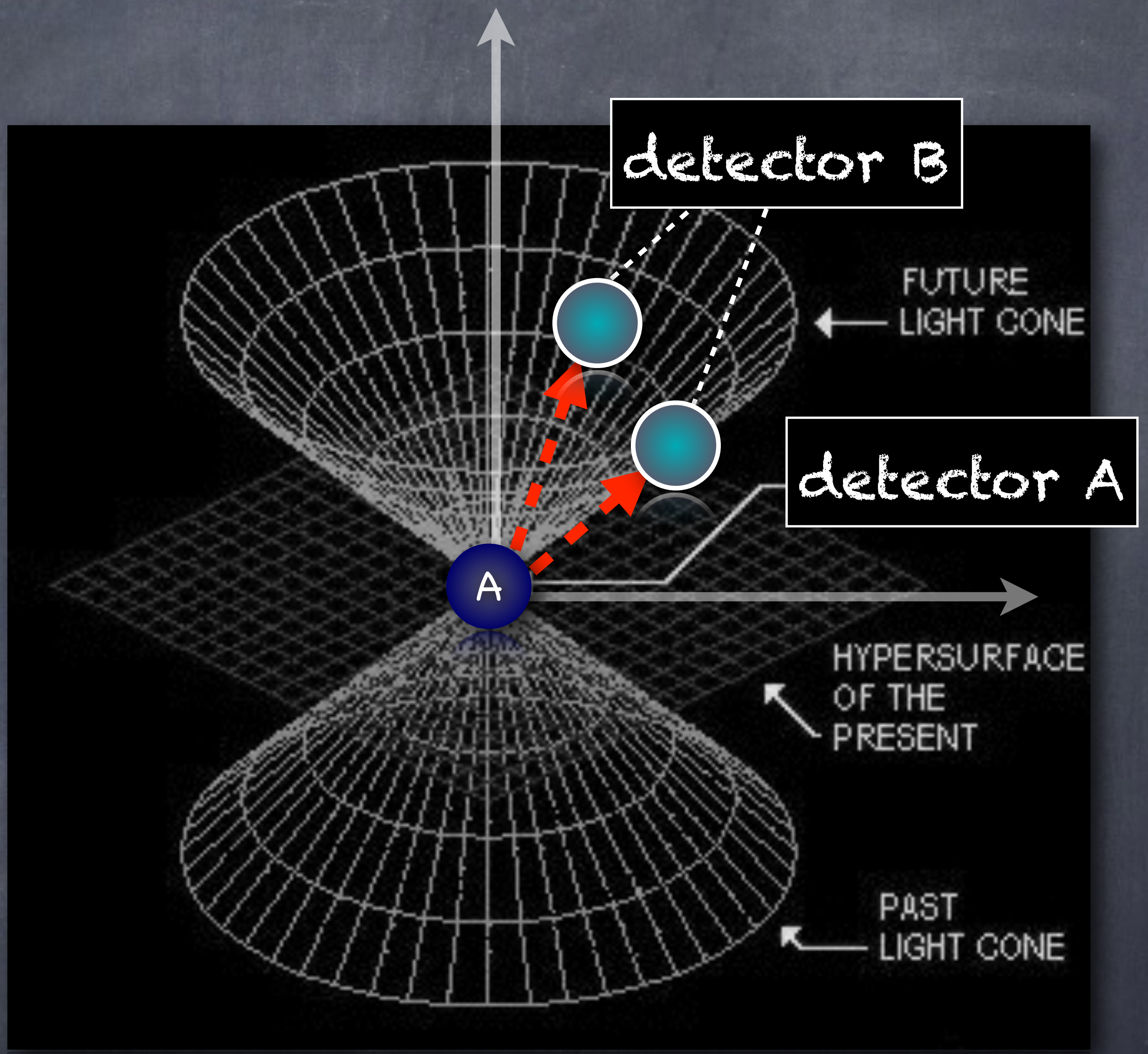
information


information
Cosmological cataclysm!!!!
?

Two detectors: setting



A before the bounce
B after the bounce



A and B timelike separated

$$H_I = \sum_{\nu=A,B} \lambda_\nu \chi_\nu(t)\sigma(\Omega_\nu, t) \sum_n \frac{1}{a(t)\sqrt{2L_c^3\omega_n}} \times \left(\hat{a}_n e^{-i\omega_n\eta(t)} e^{ik_n\cdot x_\nu} + \hat{a}_n^\dagger e^{i\omega_n\eta(t)} e^{-ik_n\cdot x_\nu}\right)$$

$$U = 1 + U^{(1)} + U^{(2)} + O(\lambda^3)$$

$$U^{(1)} = -i\int_0^t dt_1 H_I(t_1)$$

$$U^{(2)} = -\int_0^t dt_1 \int_0^{t_1} dt_2 H_I(t_1) H_I(t_2)$$

$$\rho_T = U\rho_0 U^\dagger = (1 + U^{(1)} + U^{(2)} + O(\lambda^3))\rho_0(1 + U^{(1)} + U^{(2)} + O(\lambda^3))^\dagger$$

$$\rho_T = \rho_0 + \rho_T^{(1)} + \rho_T^{(2)} + O(\lambda^3)$$

$$\rho_0 = \rho_{A0} \otimes \rho_{B0} \otimes |0><0|$$

$$\rho_T^{(1)} = U^{(1)}\rho_0 + \rho_0 U^{(1)\dagger}$$

$$\rho_T^{(2)} = U^{(2)}\rho_0 + \rho_0 U^{(2)\dagger} + U^{(1)}\rho_0 U^{(1)\dagger}$$

-How much information is RECOVERABLE?

Thanks!!