Title: PSI 2017/2018 - Relativistic Quantum Information - Lecture 12

Date: Apr 04, 2018 09:00 AM

URL: http://pirsa.org/18040005

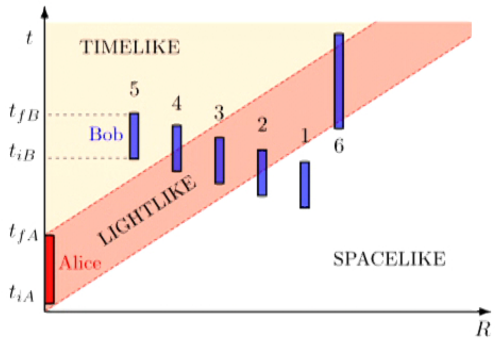
Abstract:

Communication Scenario

Initial state: $\rho_0 = |\psi_0\rangle\langle\psi_0| \otimes \rho_\phi$

$$|\psi_0\rangle = (\alpha_A |e_A\rangle + \beta_A |g_A\rangle) \otimes (\alpha_B |e_B\rangle + \beta_B |g_B\rangle)$$

Bob's evolved state: $\rho_{Bf} = \mathrm{Tr}_A \mathrm{Tr}_\phi \left[U \rho_0 U^\dagger\right]$



$$P_e = |\alpha_B|^2 + P_{\text{noise}} + S$$

Signalling terms

Probability of finding Bob excited:

$$P_{|e_B\rangle} = |\alpha_B|^2 + \mathcal{O}(\lambda_B) + \mathcal{O}(\lambda_B^2) + \mathcal{O}(\lambda_A\lambda_B) + \mathcal{O}(\lambda_B^4) + \mathcal{O}(\lambda_A^2\lambda_B^2) + \cdots$$

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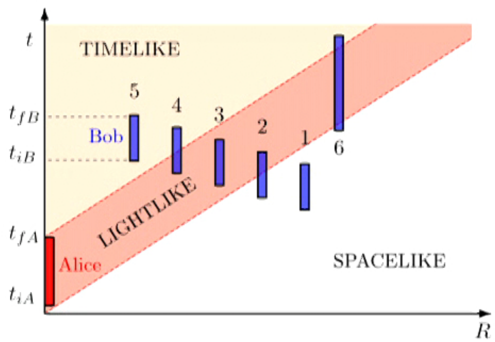

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Signalling terms

Probability of finding Bob excited:

Local Noise

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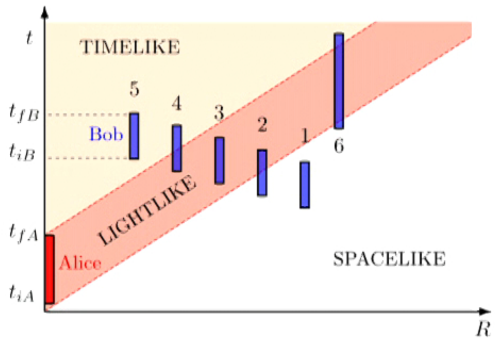

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Casimir-Like interactions

Real photon exchange

Communication Scenario

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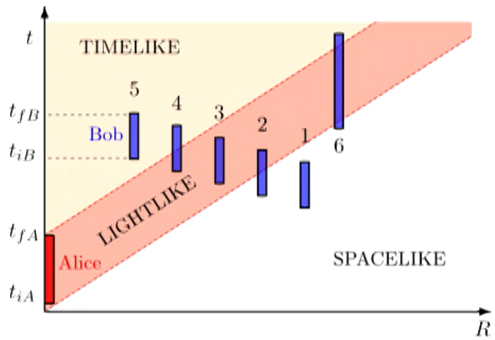

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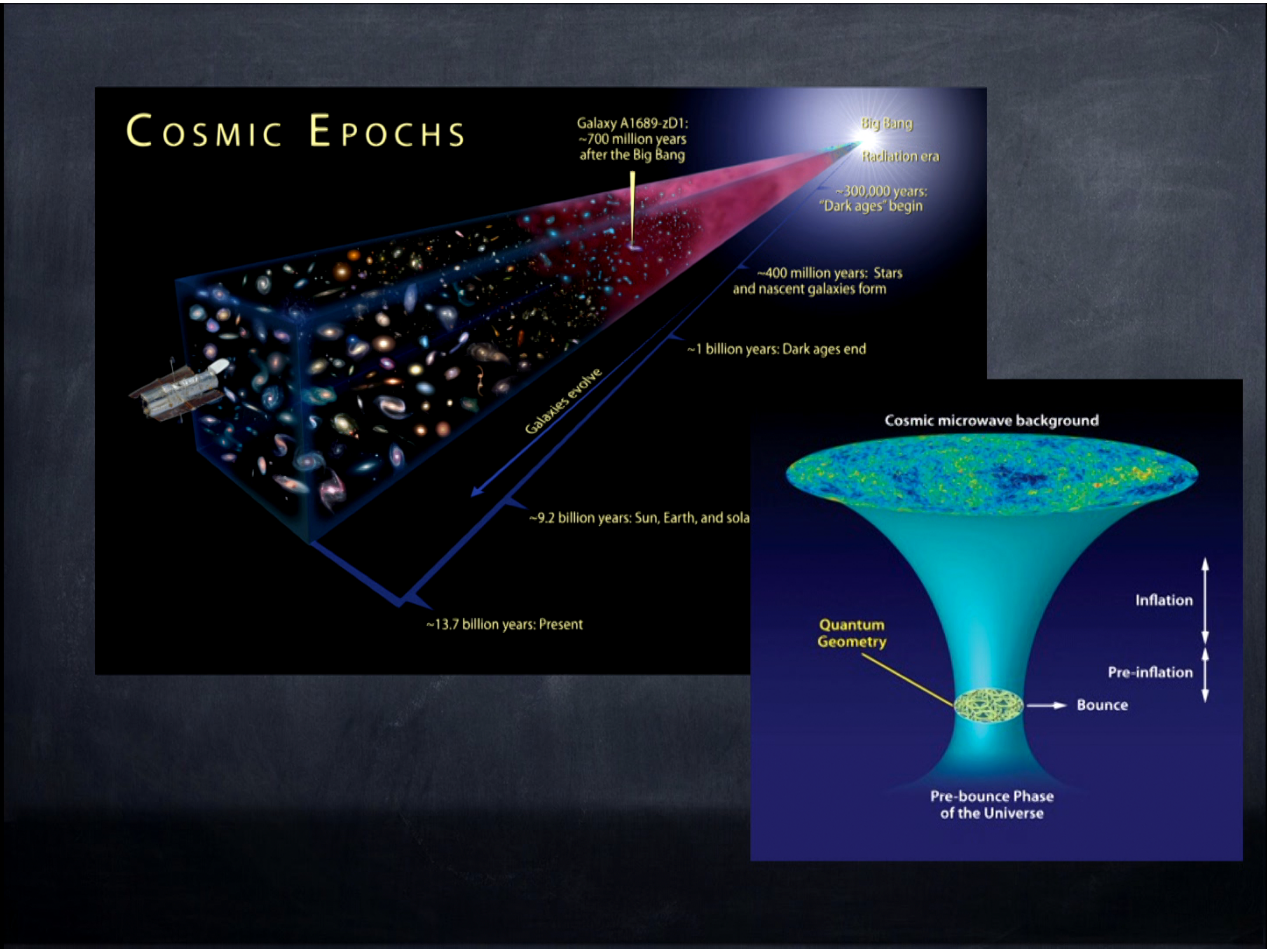
Not present if $\alpha_A = 1$ $\beta_A = 1$ ← Casimir-Like interactions

Real photon exchange

AND...WHAT HAPPENS in the case of **QUANTUM BOUNCE** Setting ?

How much information survives a Cosmological cataclysm!!!!


COSMIC EPOCHS
Galaxy A1689-zD1:
~700 million years
after the Big Bang
Big Bang
Radiation era
~300,000 years:
"Dark ages" begin
~400 million years: Stars
and nascent galaxies form
~1 billion years: Dark ages end
Galaxies evolve
~9.2 billion years: Sun, Earth, and sola
~13.7 billion years: Present
Cosmic microwave background
Inflation
Pre-inflation
Quantum
Geometry
Bounce
Pre-bounce Phase
of the Universe

Outlook: The RQI echo of an ancient civilization

Atoms (or any complex system) will not survive a quantum bounce

Imagine an ancient (pre-bounce) and very advanced civilization

Outlook: The RQI echo of an ancient civilization

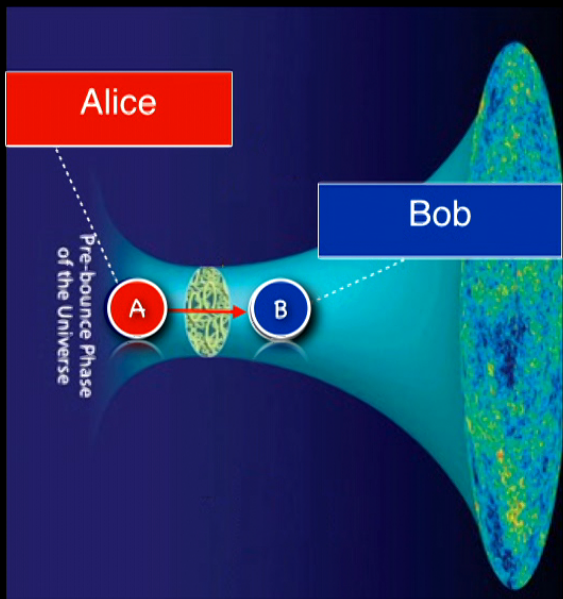
Atoms (or any complex system) will not survive a quantum bounce

Imagine an ancient (pre-bounce) and very advanced civilization

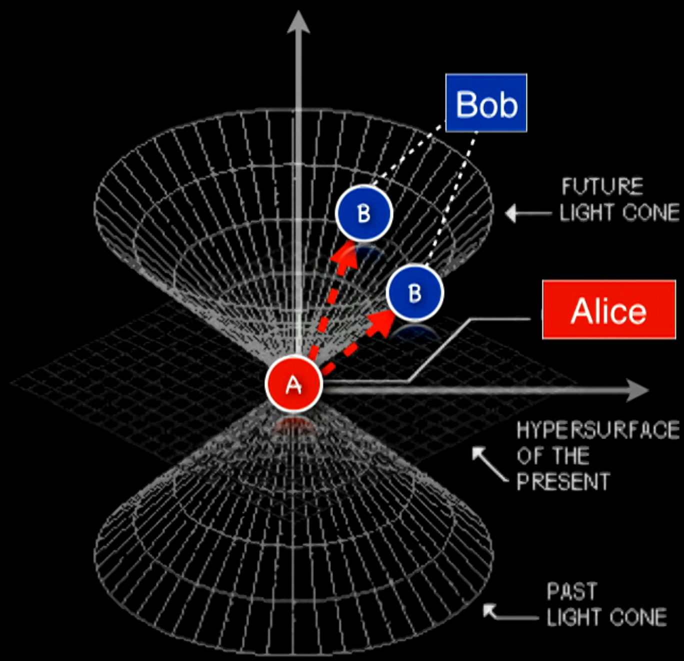
What would you do if you wanted your legacy to survive?

Encode the information in the quantum field: detectors and field get entangled.

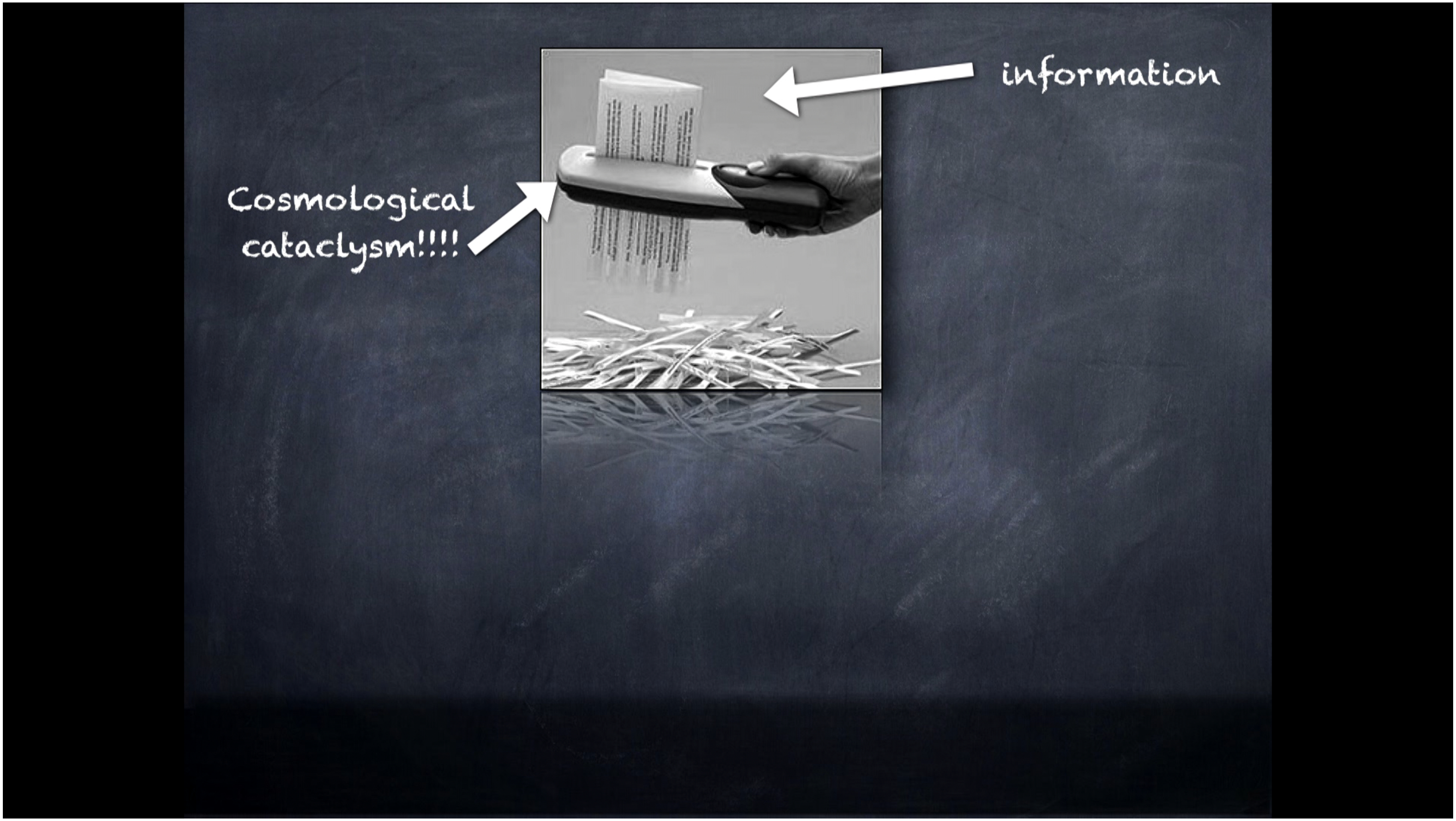
Setting
QUANTUM
BOUNCE

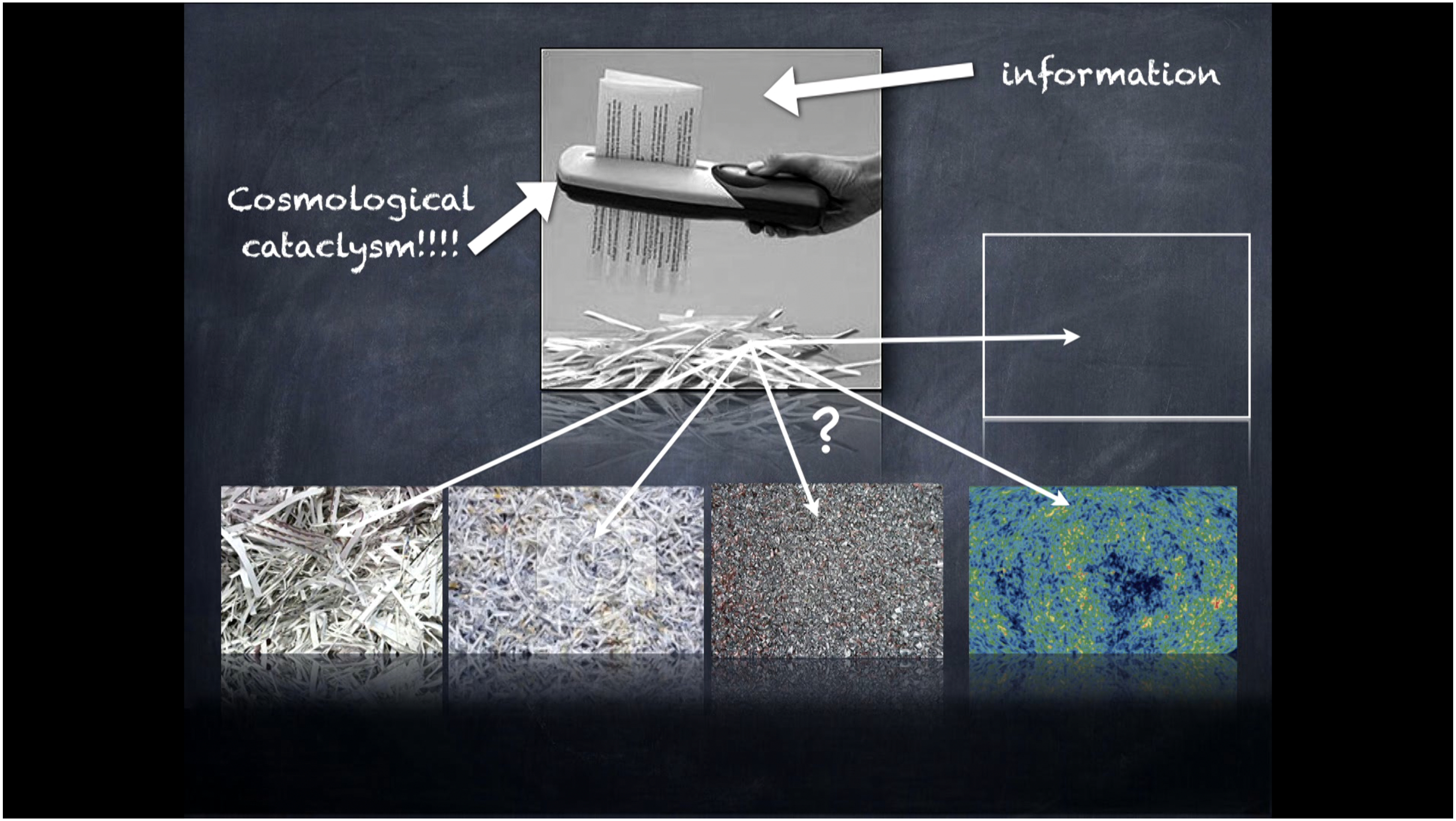


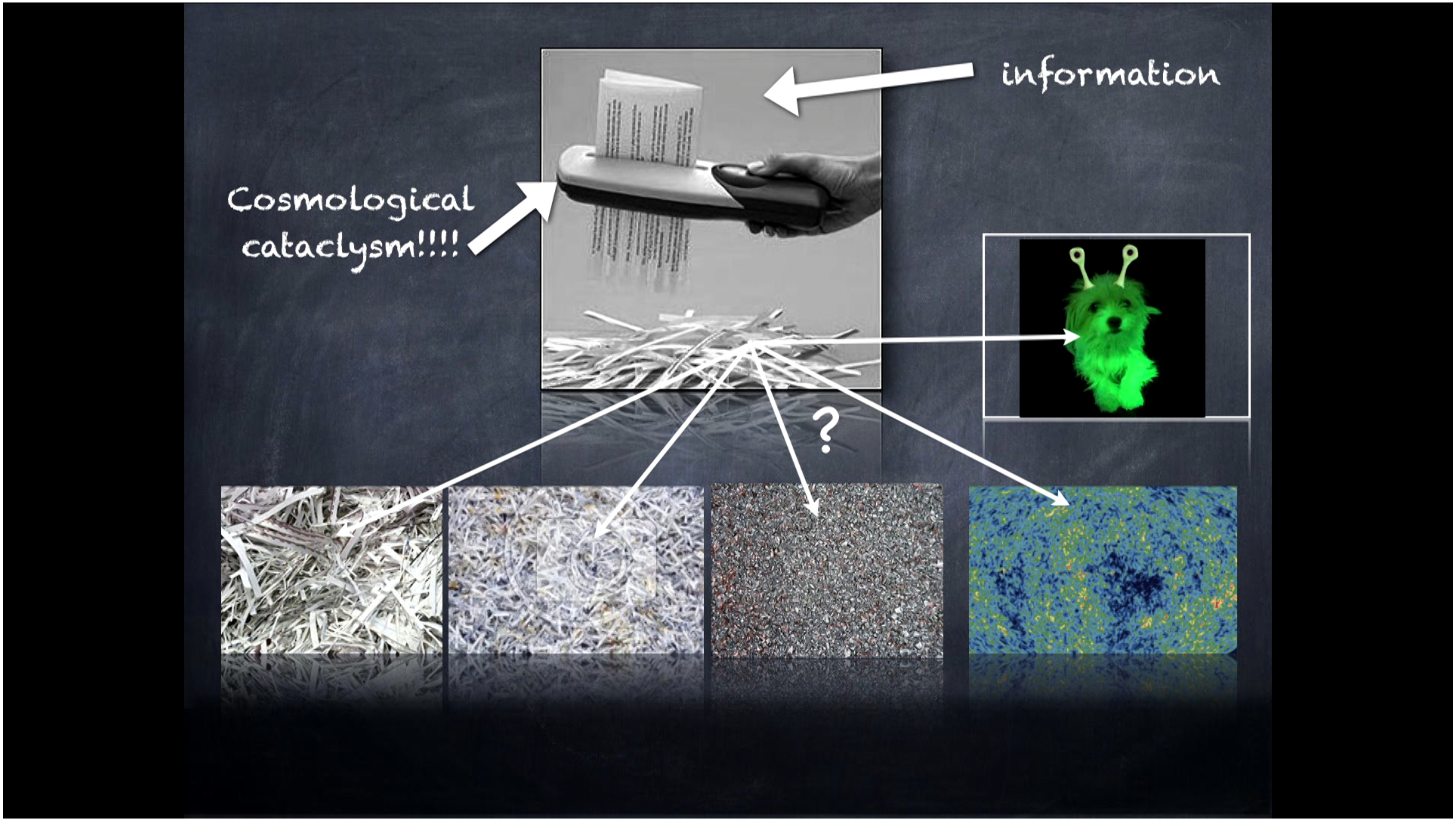
A: before the bounce
B: after the bounce



Lightcone of Alice


information
Cosmological
cataclysm!!!!


information
Cosmological
cataclysm!!!!
?


information
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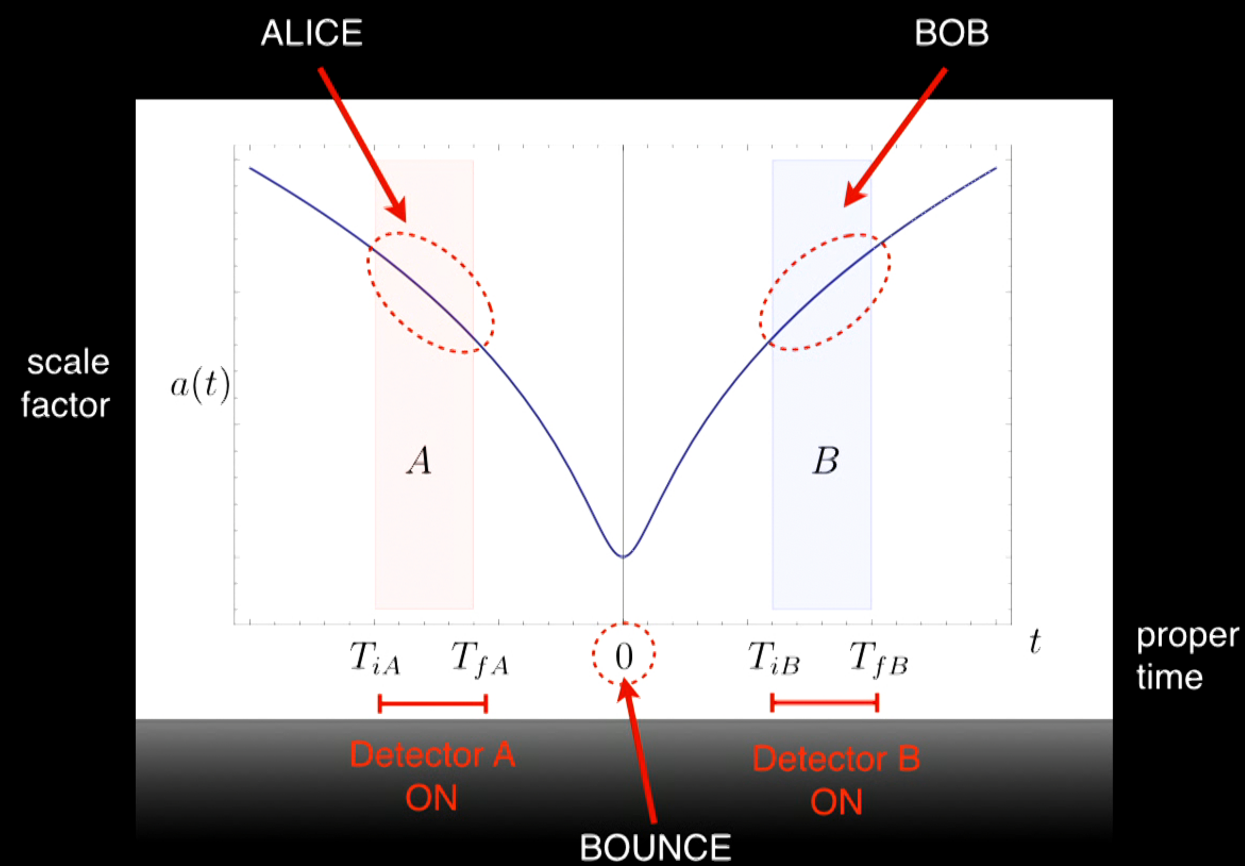
cataclysm!!!!
?

Setting
QUANTUM
BOUNCE

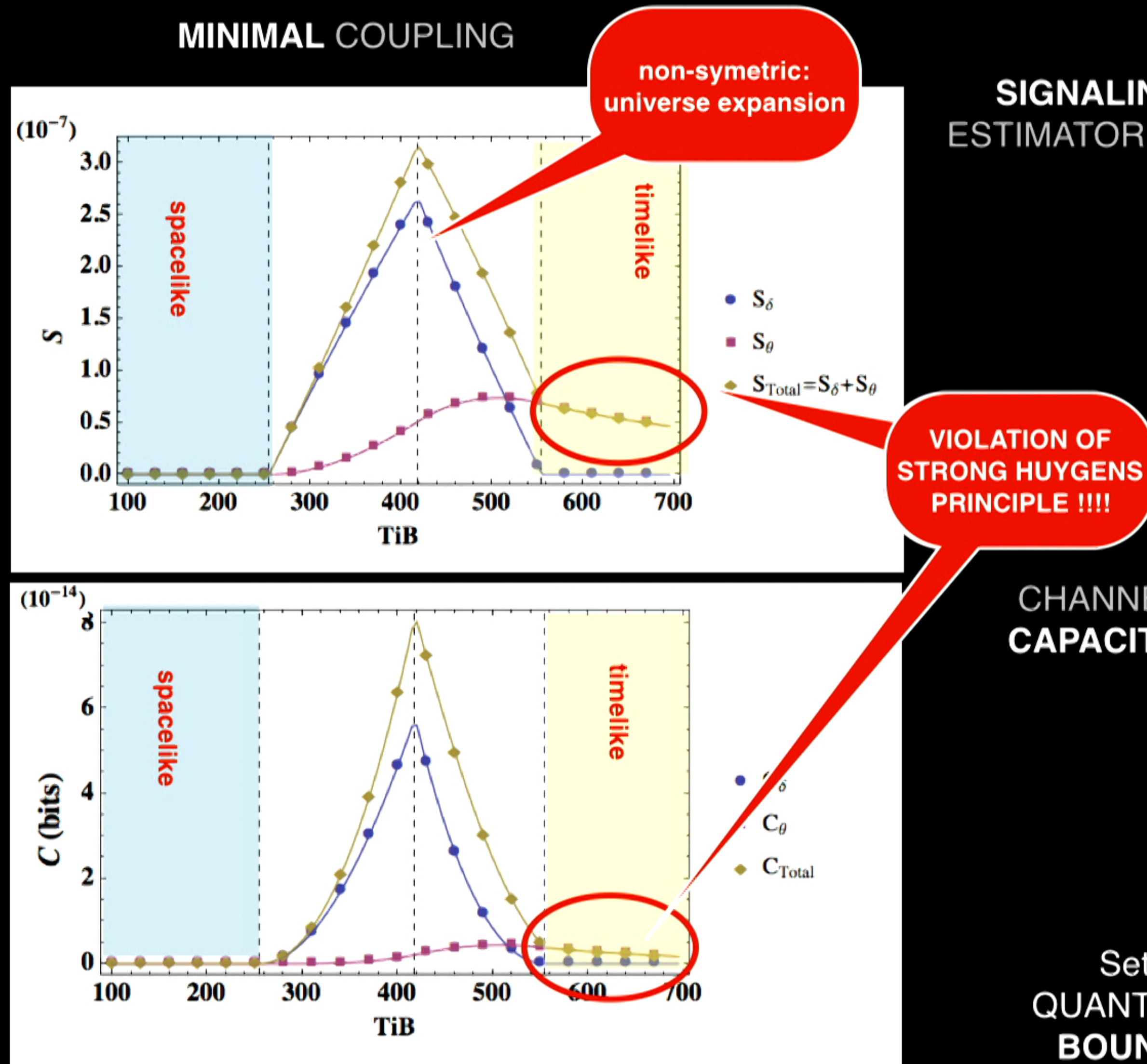


Atoms (or any complex system) will not survive a quantum bounce

Imagine an ancient (pre-bounce) and very advanced civilization

Case:
Variation of **temporal** separation

MINIMAL COUPLING



SIGNALING ESTIMATOR, S

CHANNEL **CAPACITY**

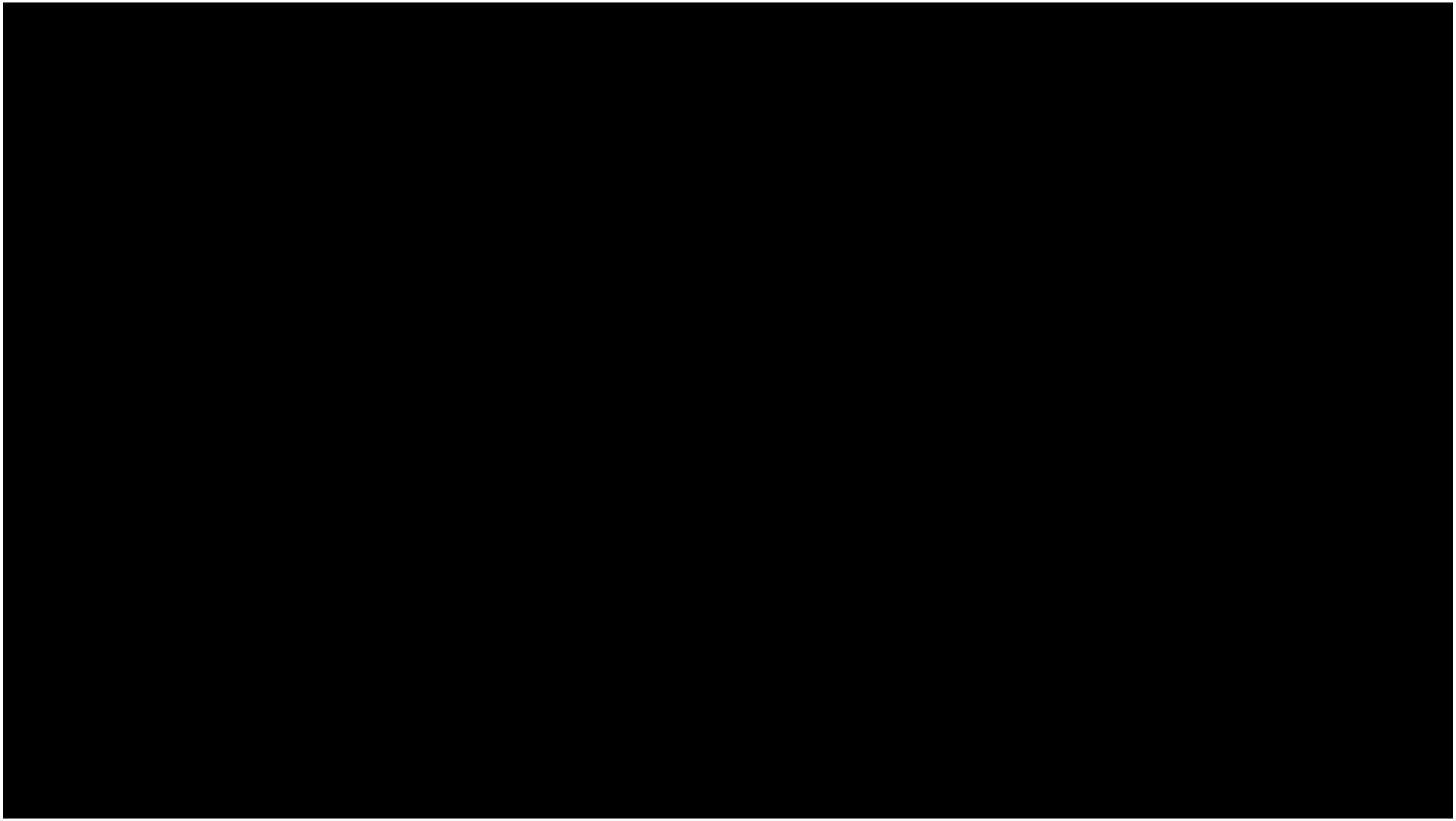
Setting QUANTUM **BOUNCE**

CONFORMAL COUPLING

support on the light cone

$$[\phi(\boldsymbol{x},t),\phi(\boldsymbol{x}',t')] = \frac{\mathrm{i}}{4\pi}\left[\frac{\delta(\Delta\eta+|\boldsymbol{x}-\boldsymbol{x}'|)-\delta(\Delta\eta-|\boldsymbol{x}-\boldsymbol{x}'|)}{a(t)a(t')|\boldsymbol{x}-\boldsymbol{x}'|}\right]$$

Decay with Spatial separation

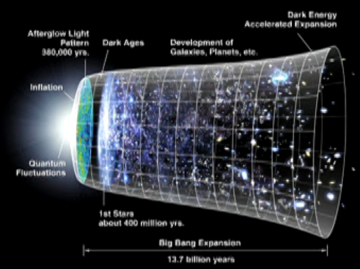


Looking for Signatures of QG today

- 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?

-Fact: Decoherence
(time does no good to information)

Looking for Signatures of QG today

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

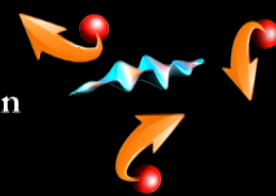
- If so, how strong are they?

- 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

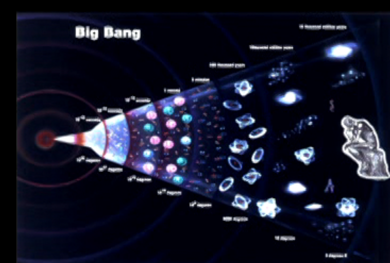
Setting

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

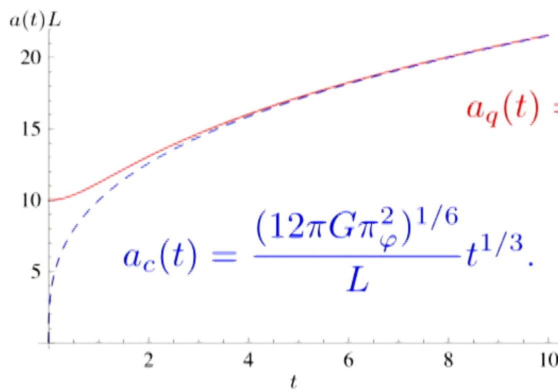


$$t_{Pl} \sim 10^{-44} s \quad ; \quad T \sim 10^{17} s$$

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

Gibbons-Hawking effect

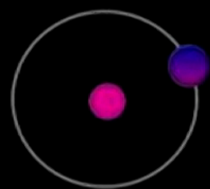
- We consider a massless scalar field ϕ in the conformal vacuum

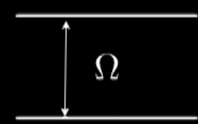
- The proper time of comoving observers (who see an isotropic expansion) does not coincide with conformal time

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

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

The Unruh -DeWitt 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)

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

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

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

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

Sensitivity to the quantum parameters

- 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 dependence on the quantum of length

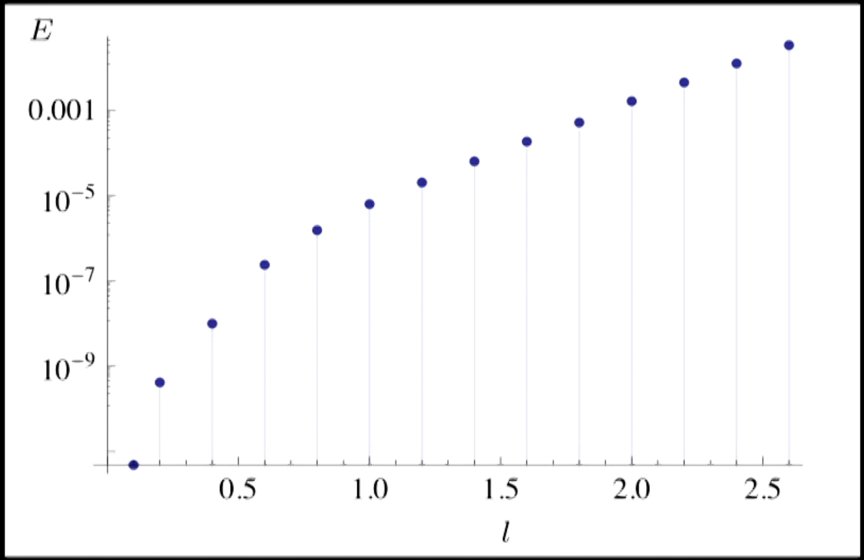
$$E = \left\langle \frac{\langle \Delta P_{\mathrm{e}}(T_0,T)\rangle_{\mathcal{T}}}{\langle P_{\mathrm{e}}^{\mathrm{GR}}(T_0,T)\rangle_{\mathcal{T}}} \right\rangle_{\Delta T}$$

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

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

Sensitivity to the quantum parameters

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

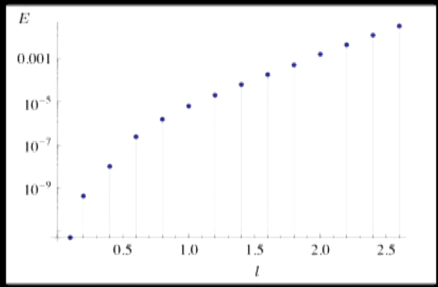


Exponential with the size of the spacetime quantum

- Cosmological observations could put stringent upper bounds to l

Sensitivity to the quantum parameters

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



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)

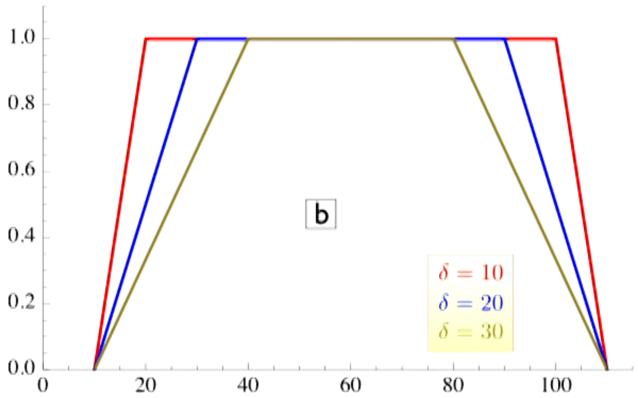
Stability of the results

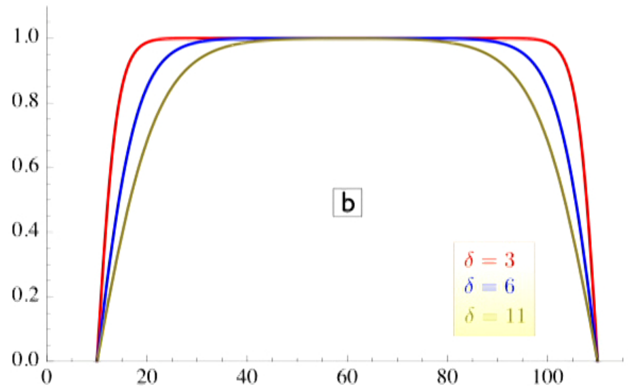
Switching effects?

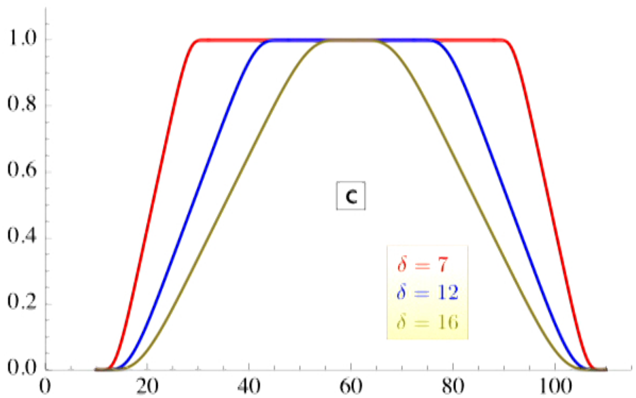
Suddenly switching a detector excites it!!

Stability of the results

Switching effects?

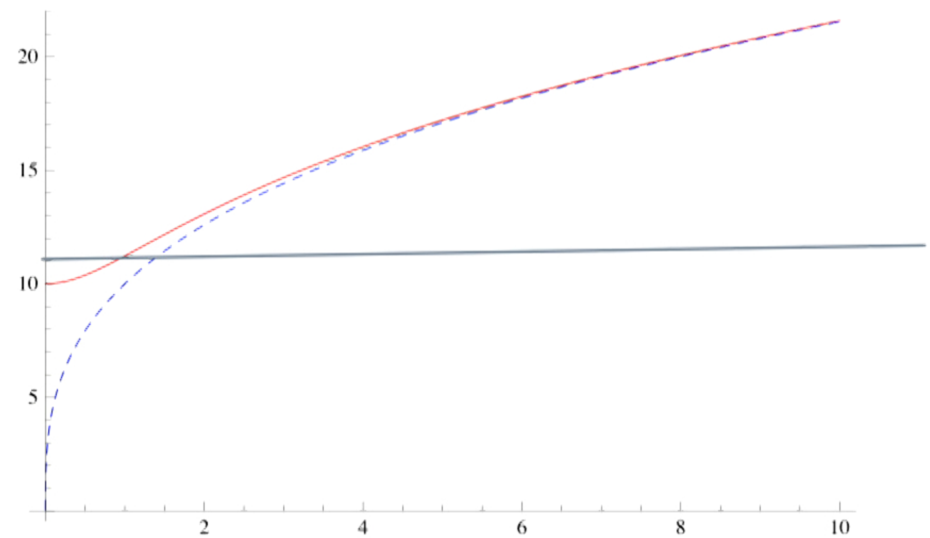






Stability of the results

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



Early Universe dynamics

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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.

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

What is a particle detector

-Multilevel system that couples to the field and breaks conformal symmetry.

-Massive quantum field.

-Minimally coupled quantum field.

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 impacted, not classical information!

IOP PUBLISHING   Highlights of the Year 2012: CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **29** (2012) 224003 (30pp)   doi:10.1088/0264-9381/29/22/224003

Cosmological quantum entanglement

Eduardo Martín-Martínez[1] and Nicolas C Menicucci[2]

Conclusions

- ✓ All events that generate light signals also generate timelike signals (not mediated by massless quanta exchange), that decay slower.
- ✓ For a matter dominated universe we find that these signals do not decay with the spatial separation to the source. Temporal decay can be compensated by deploying a network of receivers inside the light-cone.
- ✓ We particularize the discussion to a concrete channel as a mere example to illustrate the non-decaying behaviour of the information capacity.
- ✓ Inflationary phenomena, early universe physics, primordial decouplings, etc, will also leave a timeline echo on top of the light signals that we receive from them.

is restored polynomially in
ıcreasing the cutoff does not
the strict limit $\Lambda \to \infty$.

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strict limit $\Lambda \to \infty$. This
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; as $\sim \Lambda^{-\alpha}$, with $\alpha > 1$ for
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result for 1+1-dimensional
19] where the causal influ-
ır decayed with the square
; considered in the model.

The rotating-wave approximation (RWA) is yet another very common approximation made in the modelling of quantum optical settings. In fact, it is arguably the most common approximation in quantum optics, and it can be ubiquitously found anywhere from basic textbooks to research works [12]. To better understand this approximation, let us first expand the field in plane-wave modes in the Hamiltonian (1):

$$\hat{H}_I = \sum_\nu \lambda_\nu \chi_\nu(t) \int \mathrm{d}^n \boldsymbol{k}\, \frac{\tilde{F}(\boldsymbol{k})}{\sqrt{|\boldsymbol{k}|}} \times \Big(\hat{a}_{\boldsymbol{k}} \hat{\sigma}_\nu^+ e^{-\mathrm{i}[(|\boldsymbol{k}|-\Omega_\nu)t - \boldsymbol{k}\cdot\boldsymbol{x}_\nu]} + \hat{a}^\dagger_{\boldsymbol{k}} \hat{\sigma}_\nu^- e^{\mathrm{i}[(|\boldsymbol{k}|-\Omega_\nu)t - \boldsymbol{k}\cdot\boldsymbol{x}_\nu]} + \hat{a}^\dagger_{\boldsymbol{k}} \hat{\sigma}_\nu^+ e^{\mathrm{i}[(|\boldsymbol{k}|+\Omega_\nu)t - \boldsymbol{k}\cdot\boldsymbol{x}_\nu]} + \hat{a}_{\boldsymbol{k}} \hat{\sigma}_\nu^- e^{-\mathrm{i}[(|\boldsymbol{k}|+\Omega_\nu)t - \boldsymbol{k}\cdot\boldsymbol{x}_\nu]} \Big) \tag{67}$$

where the integral over $\mathrm{d}^n\boldsymbol{x}$ has already been performed and where we have defined the Fourier transform of the

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where the integral over $\mathrm{d}^n\boldsymbol{x}$ has already been performed and where we have defined the Fourier transform of the

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$$\mathrm{d}^n \boldsymbol{x}\, F(\boldsymbol{x}) e^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}. \tag{68}$$

ing the terms proportional conjugates in the Hamil- he so-called rotating-wave ıcing the Hamiltonian (67)

$$+ \hat{a}^\dagger_{\boldsymbol{k}} \hat{\sigma}^-_\nu e^{\mathrm{i}[(|\boldsymbol{k}|-\Omega_\nu)t-\boldsymbol{k}\cdot\boldsymbol{x}_\nu]}\Big). \tag{69}$$

roximation is that the ne- stationary phase for the Ω, and as such, those ıs when integrated in time. hese bounded oscillations

and the fact that the detectors are considered pointlike, that is $\tilde{F}(\boldsymbol{k}) = 1$.

We can quickly evaluate the integral over $\mathrm{d}^3\boldsymbol{k}$ that we will denote as

$$\begin{aligned} \mathcal{C}(t,t',\boldsymbol{x}_\nu,\boldsymbol{x}_\eta) &= \int \frac{\mathrm{d}^3\boldsymbol{k}}{|\boldsymbol{k}|} e^{\mathrm{i}[(|\boldsymbol{k}|-\Omega)(t-t')-\boldsymbol{k}\cdot(\boldsymbol{x}_\nu-\boldsymbol{x}_\eta)]} \\ &= \frac{4\pi\, e^{-\mathrm{i}\Omega(t-t')}}{|\boldsymbol{x}_\nu-\boldsymbol{x}_\eta|} \int_0^\infty \mathrm{d}|\boldsymbol{k}|\, e^{\mathrm{i}|\boldsymbol{k}|(t-t')} \sin\left(|\boldsymbol{k}||\boldsymbol{x}_\nu-\boldsymbol{x}_\eta|\right) \\ &= \frac{4\pi\, e^{-\mathrm{i}\Omega(t-t')}}{|\boldsymbol{x}_\nu-\boldsymbol{x}_\eta|} \Bigg(\frac{|\boldsymbol{x}_\nu-\boldsymbol{x}_\eta|}{|\boldsymbol{x}_\nu-\boldsymbol{x}_\eta|^2-(t-t')^2} + \frac{\mathrm{i}\pi}{2} \\ &\times \Big[\delta(t-t'-|\boldsymbol{x}_\nu-\boldsymbol{x}_\eta|) - \delta(t-t'-|\boldsymbol{x}_\nu+\boldsymbol{x}_\eta|)\Big]\Bigg). \end{aligned} \tag{72}$$

Here we see explicitly how for the signalling terms (proportional to $\lambda_\text{A}\lambda_\text{B}$), the rotating-wave approximation breaks causality: if we compare this expression with the commutator (29), we see that the result under the

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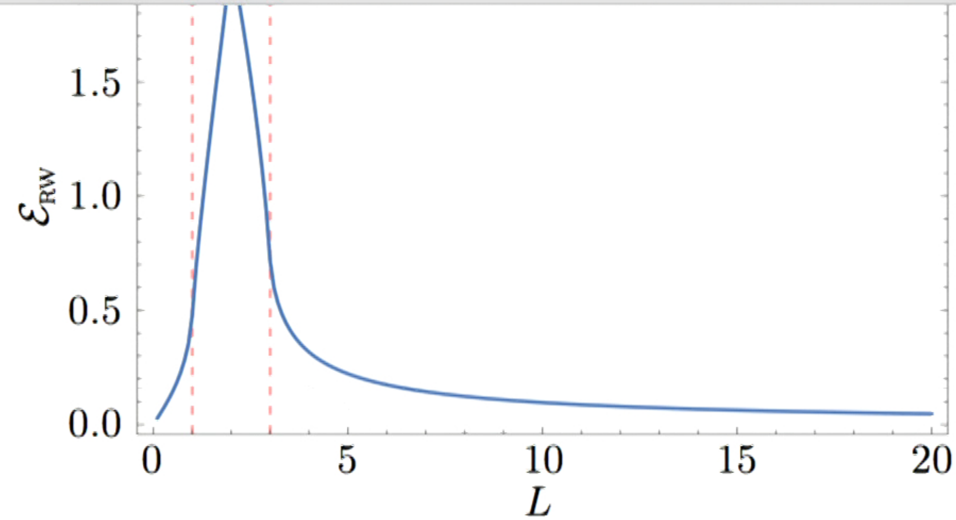

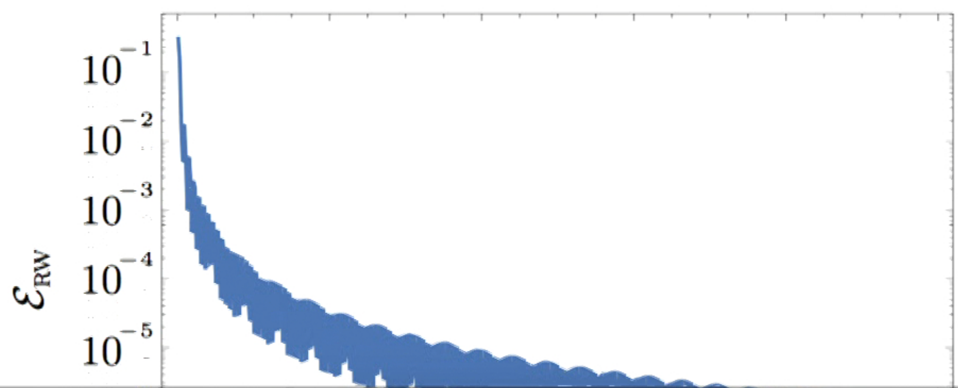

$$\mathcal{E}_{\text{RW}} = \frac{1}{2}\Big| \int_{T+\Delta}^{2T+\Delta} \mathrm{d}u \int_{-u}^{u-2\ldots}$$
$$+ \int_{2T+\Delta}^{3T+\Delta} \mathrm{d}u \int_{u-4T\ldots}^{-u-\ldots}$$

The closed expression is le
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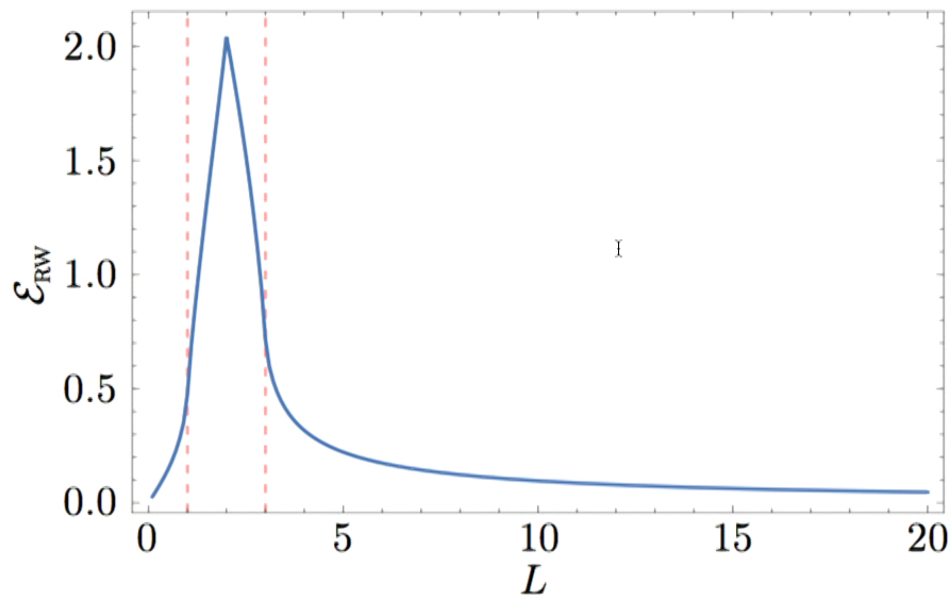

which maps the integral t

$$\mathcal{E}_{\rm RW} = \frac{1}{2}\Bigg| \int_{T+\Delta}^{2T+\Delta} \mathrm{d}u \int_{-u}^{u-2} \ldots$$
$$+ \int_{2T+\Delta}^{3T+\Delta} \mathrm{d}u \int_{u-4T}^{-u-} \ldots$$

The closed expression is le gral and cosine integral fu

The two pointlike dete separated for values of L see how the violation of approximation behaves wi of the interaction, we are g

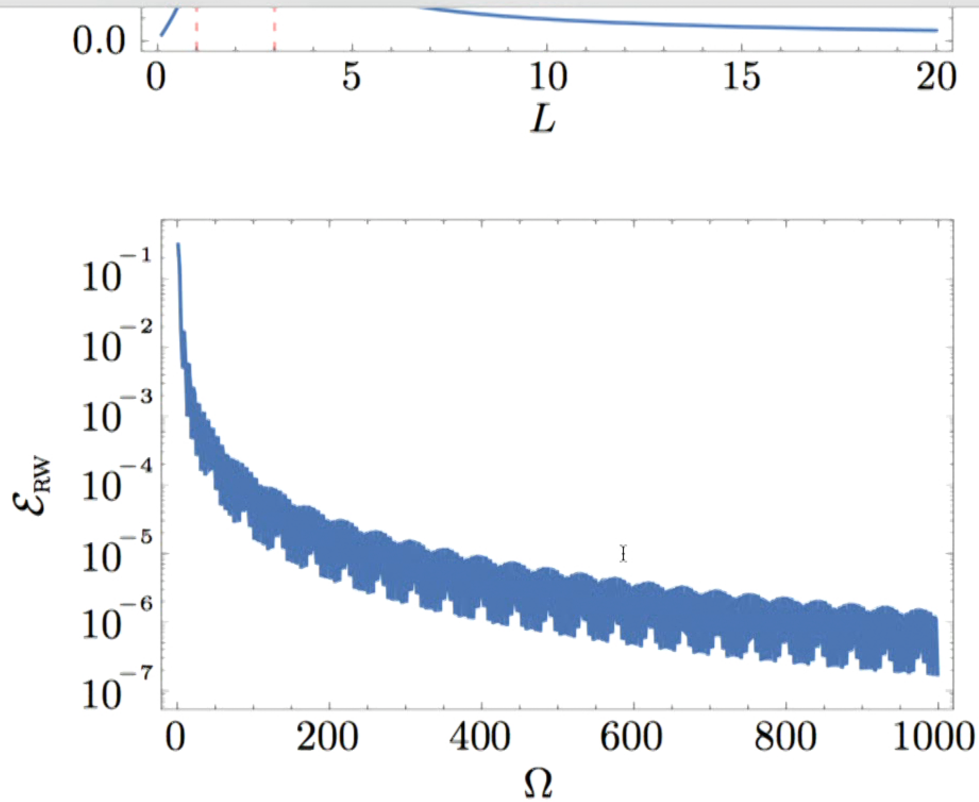

Figure 6. **(Top)** Estimator $\mathcal{E}_{RW}$ of the signalling contribution from detector A to the state of B under the RWA for

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We see also that as we
RWA violation of causalit
However, importantly, as
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of the RWA-approximate