Title: PSI 2018/2019 - Explorations in Quantum Information - Lecture 12

Speakers: Eduardo Martin-Martinez

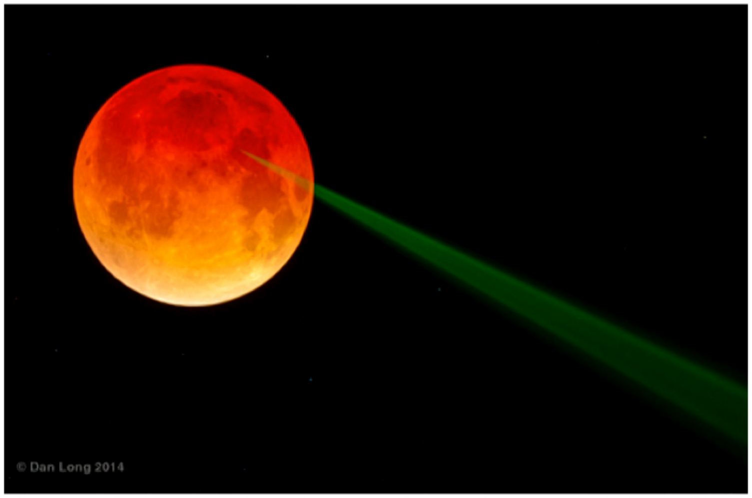
Collection: PSI 2018/2019 - Explorations in Quantum Information (Martin-Martinez)

Date: May 01, 2019 - 9:00 AM

URL: http://pirsa.org/19050002

Communication through the EM field

Communcation mediated by 'real' energy-carrying quanta



An emitter emits photons. A receiver captures photons.

Communication through the EM field

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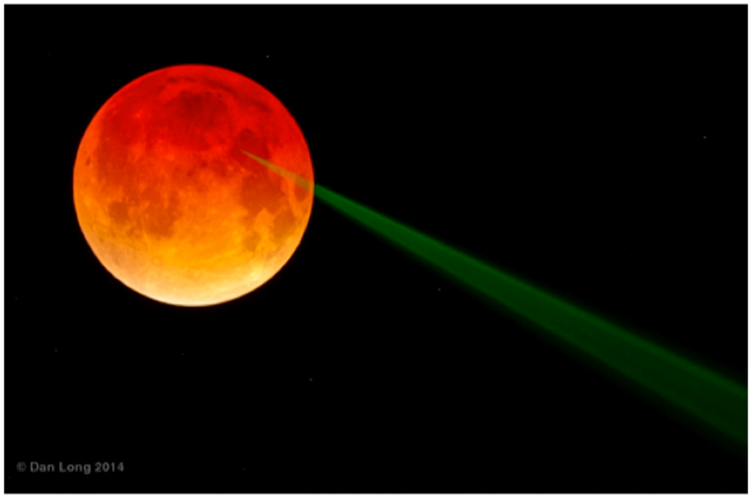


An emitter emits photons. A receiver captures photons.

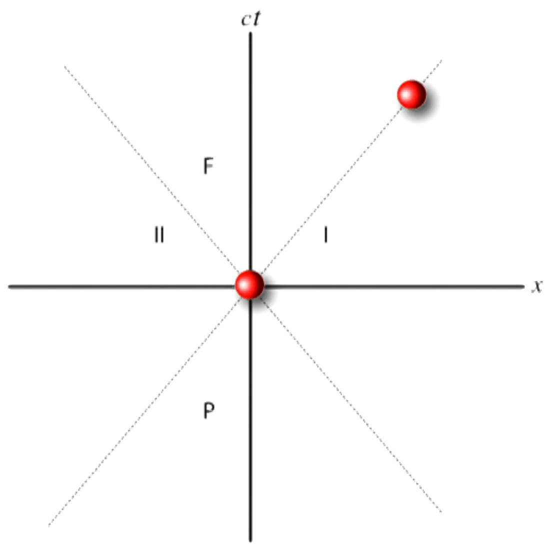
Communication through the EM field

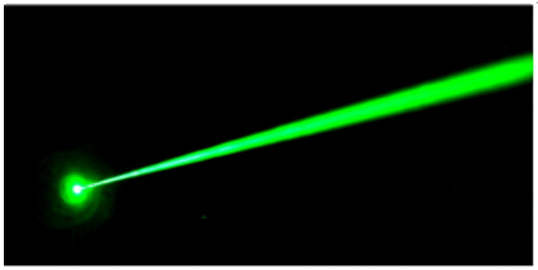
Information flow carried by (an average) energy flow

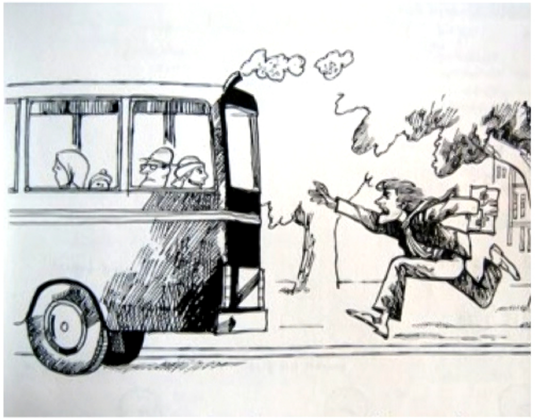
Information reaches you when energy reaches you

Communication through the EM field

Communication is only possible at the speed of light (in vacuum)





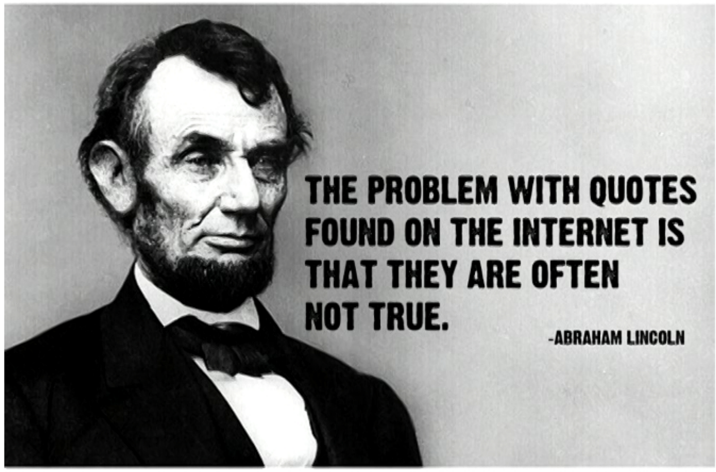


If you miss the beam, you miss the message

Communication through massless fields

Communication through a masses fields in the vacuum

- -Only At the speed of light. ✗
- -Through the exchange of real quanta ✗
- -Information flow carried by energy flow. ✗
- -Miss the beam, miss the message ✗



Communication through massless fields

Communication through a massless fields in vacuum

-Information propagates arbitrarily slow even for massless field.

-Recover the message even if the beam is missed.

-Information flow not supported by real quanta (photons) flow.

-Information flow in absence of energy flow.

PHYS.ORG Nanotechnology Physics Earth Astronomy & Space Technology Chemistry Biology Other Sciences

search

Home » Physics » Quantum Physics » March 31, 2015

Photon 'afterglow' could transmit information without transmitting energy

March 31, 2015 by Lisa Zyga feature

(Phys.org)—Physicists have theoretically shown that it is possible to transmit information from one location to another without transmitting energy. Instead of using real photons, which always carry energy, the technique uses a small, newly predicted quantum afterglow of virtual photons that do not need to carry energy. Although no energy is transmitted, the receiver must provide the energy needed to detect the incoming signal—similar to the

Mathematical Methods: Beyond the Strong Huygens Principle

Subtleties in the behaviour of the solutions of certain PDEs:
The strong Huygens principle

Mathematical Methods: Beyond the Strong Huygens Principle

Subtleties in the behaviour of the solutions of certain PDEs:
The strong Huygens principle

The Green's function of the (massless) wave equation in 3+1D Minkowski space has support only on the light cone. Hence, any disturbances propagate strictly along null geodesics (at the speed of light)

Exploitable when emitters are quantum!

TECHNICAL DETAILS

R. H. Jonsson, E. Martin-Martinez, A. Kempf, Phys. Rev. Lett. 114, 110505 (2015)

A. Blasco, L. J. Garay, M. Martin-Benito, E. Martin-Martinez, Phys. Rev. Lett. 114, 141103 (2015)

A. Blasco, L. J. Garay, M. Martin-Benito, E. Martin-Martinez, Phys. Rev. D 93, 024055 (2016)

P. Simidzija, E. Martin-Martinez, Phys. Rev. D 95, 025002 (2017)

See also:

R. H. Jonsson, J. of Phys. A, 44, 445402 (2016)

STRONG **HUYGENS PRINCIPLE**

The radiation Green's function (or equivalently the commutator) of a massless field has support only on the light-cone

$$\Box G(x,x') = -4\pi\delta_4(x,x') \qquad [\Phi(x),\Phi(x')] = \frac{\mathrm{i}}{4\pi}G(x,x')$$

⟶ **Communication** has support only on the **light-cone**

True in 3+1 Flat spacetime

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⟶ **Communication** has support only on the **light-cone**

True in 3+1 Flat spacetime

BEYOND THE STRONG **HUYGENS PRINCIPLE**

In general: if there is curvature (unless there is conformal invariance)

⟶ In curved spacetimes, **communication through massless fields** is not confined to the light-cone, but there can be a leakage of information towards the **inside of the light-cone decoupled from energy propagation**.

SPACETIME
GEOMETRY

SPATIALLY **FLAT**, **OPEN** **FRW** SPACETIME 3+1D:

$$ds^2 = a(\eta)^2(-d\eta^2 + dr^2 + r^2 d\Omega^2)$$

η : conformal time

$a(\eta)$: scale factor

t : cosmological time,

$\mathrm{d}t = a(\eta)\mathrm{d}\eta$

units: $\hbar = c = 1$

This geometry will be generated by:

a **perfect fluid** with a constant density-to-presure ratio $p = w\rho$

⟶ the **scale factor** evolves as $a \propto \eta^{\alpha+\frac{1}{2}} \propto t^{\frac{2\alpha+1}{2\alpha+3}}$ with $\alpha = \frac{3-3w}{6w+2}$

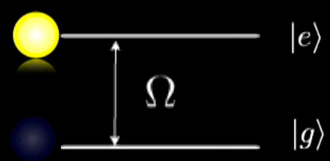
A TEST **SCALAR FIELD** QUANTIZED IN THE **BUNCH-DAVIS VACUUM** WILL BE COUPLED TO THE BACKGROUND GEOMETRY.

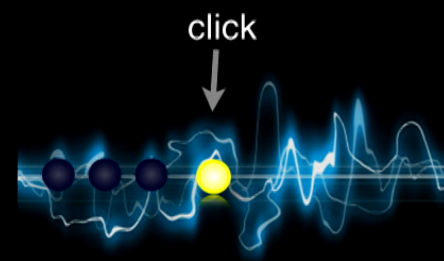
ALICE & BOB's

DETECTOR MODEL

Unruh-DeWitt DETECTOR

-Two-level system



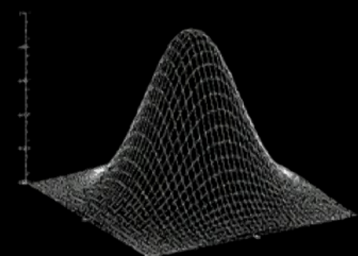


-Energy gap ground-excited states: Ω

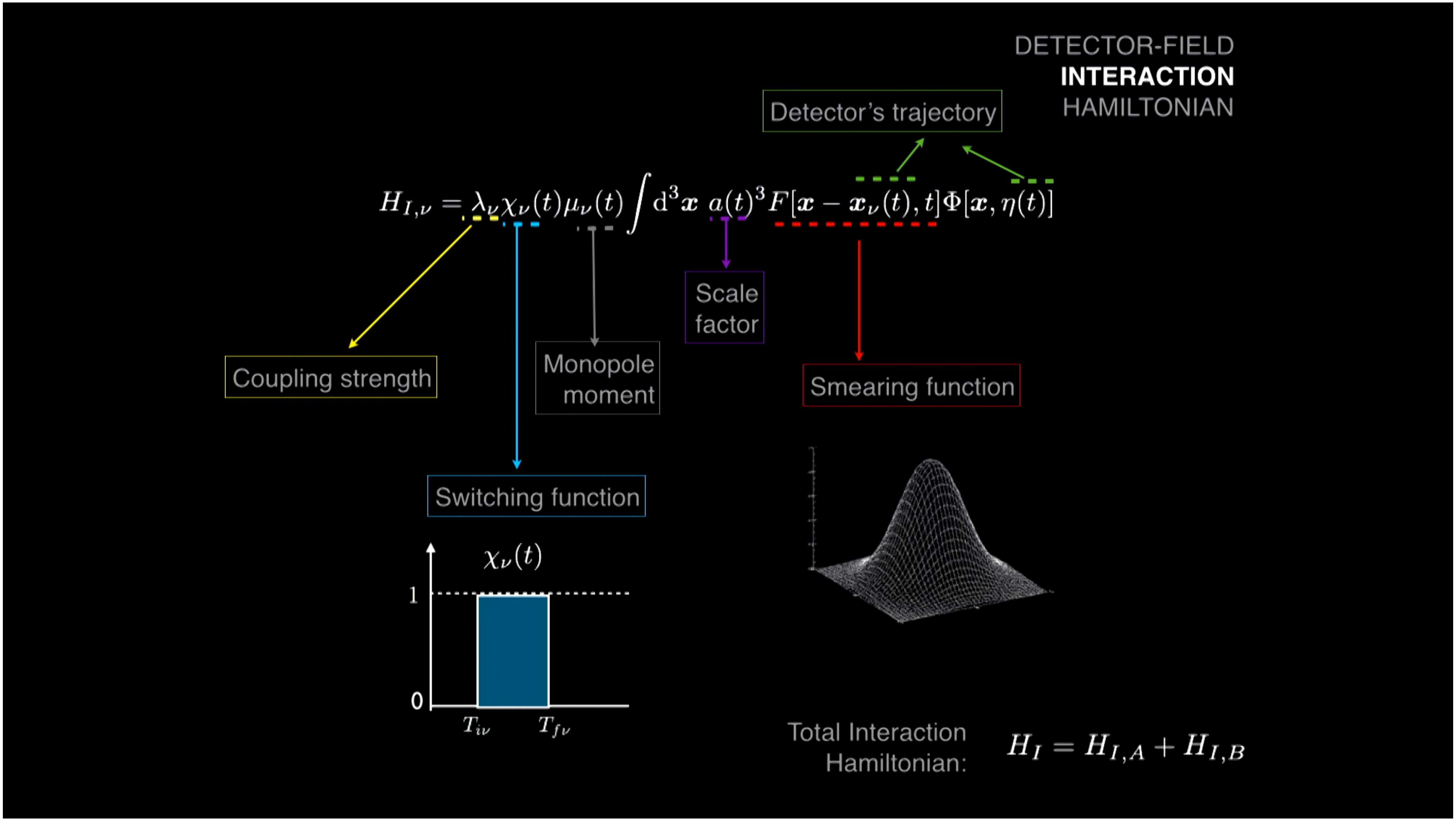
-Monopole moment operator: $\mu_\nu(t) = |e_\nu\rangle\langle g_\nu| e^{i\Omega_\nu t} + |g_\nu\rangle\langle e_\nu| e^{-i\Omega_\nu t}$

$\nu = \{A, B\}$

-Spatially smeared: $F(\vec{x}, t) = \dfrac{1}{\sigma^3\sqrt{\pi^3}} e^{-a(t)^2 \vec{x}^2/\sigma^2}$



Detectors: $|\psi_\nu\rangle = \alpha_\nu\, |e_\nu\rangle + \beta_\nu\, |g_\nu\rangle$


DETECTOR-FIELD
INTERACTION
HAMILTONIAN
Detector's trajectory
$H_{I,\nu} = \lambda_\nu \chi_\nu(t) \mu_\nu(t) \int \mathrm{d}^3\boldsymbol{x}\, a(t)^3 F[\boldsymbol{x} - \boldsymbol{x}_\nu(t), t] \Phi[\boldsymbol{x}, \eta(t)]$
Scale factor
Coupling strength
Monopole moment
Smearing function
Switching function
$\chi_\nu(t)$
1
0
$T_{i\nu}$
$T_{f\nu}$
Total Interaction Hamiltonian:
$H_I = H_{I,A} + H_{I,B}$

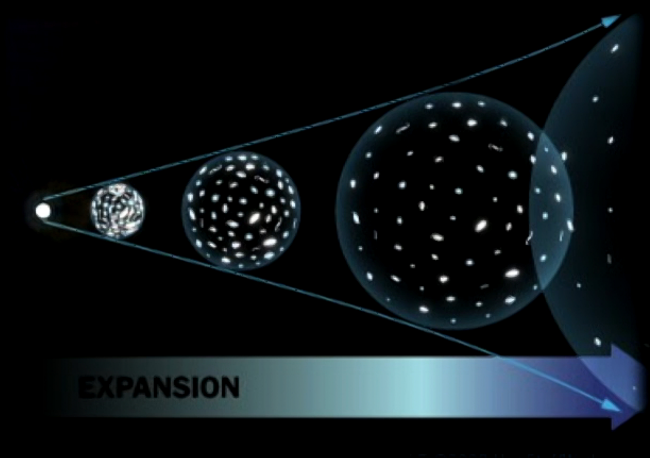
TRANSMISSION OF **INFORMATION**

Influence of the presence of A on B → **SIGNALING ESTIMATOR, S**

$$P_e(t) = |\alpha_B|^2 + P_{vac}(t) + S(t).$$

how much information can be sent? → **CHANNEL CAPACITY, C**

THE **BIG BANG** Setting



BIG BANG CASE, ST. COSMOLOGICAL MODEL: GENERAL RELATIVITY

SCALAR FIELD:
COUPLING TO GRAVITY

KLEIN-GORDON EQUATION

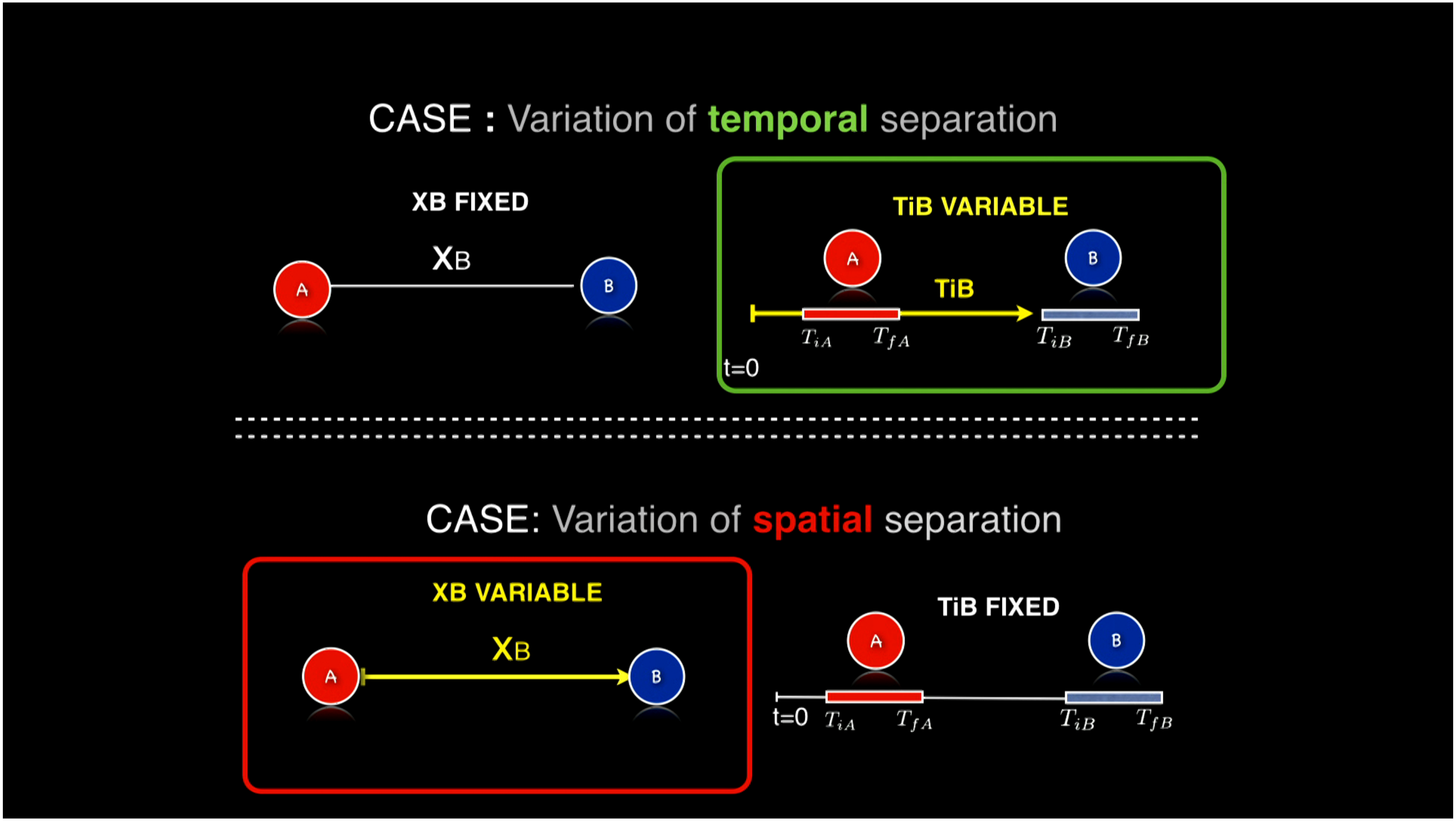
$$(\Box - m^2 + \xi R)\phi = 0 \qquad \Box = \frac{1}{\sqrt{|g|}}\partial_\mu\left(\sqrt{|g|}g^{\mu\nu}\partial_\nu\right)$$

CONFORMAL COUPLING

$\xi = \frac{1}{6}$ Yields Conformally Invariant Action

MINIMAL COUPLING

$\xi = 0$ Gives good predictions (Cosmology, etc..)


CASE : Variation of temporal separation
XB FIXED
XB
A
B
TiB VARIABLE
A
B
TiB
T_{iA} T_{fA} T_{iB} T_{fB}
t=0
CASE: Variation of spatial separation
XB VARIABLE
XB
A
B
TiB FIXED
A
B
t=0 T_{iA} T_{fA} T_{iB} T_{fB}

IS INFORMATION
TRANSMITED?

Influence of the presence of A on B →

SIGNALING ESTIMATOR, S

$$P_e(t) = |\alpha_B|^2 + P_{vac}(t) + S(t).$$

CONFORMAL COUPLING

SIGNALING
ESTIMATOR, S

$$S = \lambda_A \lambda_B S_2 + \mathcal{O}(\lambda_\nu^4)$$

$$S_2 = 4 \int a(t)^3 \, \mathrm{d}^3\boldsymbol{x} \, \mathrm{d}t \int a(t')^3 \, \mathrm{d}^3\boldsymbol{x}' \, \mathrm{d}t' \chi_A(t)\chi_B(t') \mathrm{Re}(\alpha_A^* \beta_A) F(\boldsymbol{x} - \boldsymbol{x}_A, t) \times F(\boldsymbol{x}' - \boldsymbol{x}_B, t) \mathrm{Re}\left(\alpha_B^* \beta_B [\phi(\boldsymbol{x}, t), \phi(\boldsymbol{x}', t')]\right)$$

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

$$\Delta\eta = \eta(t) - \eta(t')$$

$$|\psi_{0,\nu}\rangle = \alpha_\nu |e_\nu\rangle + \beta_\nu |g_\nu\rangle$$

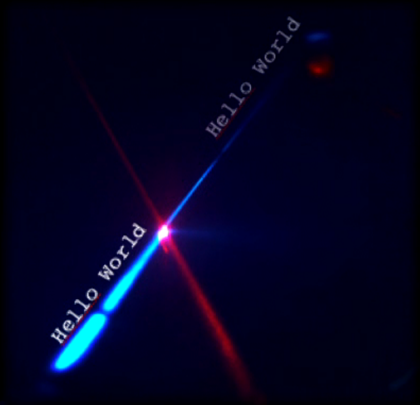
CHANNEL **CAPACITY**

To obtain a lower bound to the channel capacity, we use a simple **COMMUNICATION PROTOCOL:**

- **Alice** encodes "**1**" by coupling her detector A to the field, and "**0**" by not coupling it.
- Later **Bob** switches on B and measures its energy. If B is excited, Bob interprets a "**1**", and a "**0**" otherwise.

$$C \simeq \lambda_A^2 \lambda_B^2 \frac{2}{\ln 2}\left(\frac{S_2}{4|\alpha_B||\beta_B|}\right)^2 + \mathcal{O}(\lambda_\nu^6)$$

(noisy asymmetric binary channel)



Robert H. Jonsson, Eduardo Martín-Martinez, and Achim Kempf.
Quantum Collect Calling.
Phys. Rev. Lett. 114, 110505 (2015).

CONFORMAL COUPLING

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

support on the light cone

Decay with Spatial separation

SIGNALING
ESTIMATOR, S

MINIMAL COUPLING

$$S = \lambda_A \lambda_B S_2 + \mathcal{O}(\lambda_\nu^4)$$

$$S_2 = 4\int a(t)^3\,\mathrm{d}^3\boldsymbol{x}\,\mathrm{d}t \int a(t')^3\,\mathrm{d}^3\boldsymbol{x}'\,\mathrm{d}t' \chi_A(t)\chi_B(t')\mathrm{Re}(\alpha_A^*\beta_A)F(\boldsymbol{x}-\boldsymbol{x}_A,t)$$
$$\times F(\boldsymbol{x}'-\boldsymbol{x}_B,t)\mathrm{Re}\left(\alpha_B^*\beta_B\left[\phi(\boldsymbol{x},t),\phi(\boldsymbol{x}',t')\right]\right)$$

$$[\phi(\boldsymbol{x}_A,t_A),\phi(\boldsymbol{x}_B,t_B)] = \mathrm{i}\frac{\theta(\eta(t_B)-\eta(t_A)) - \theta(\eta(t_A)-\eta(t_B))}{(2\pi)^3|\boldsymbol{x}-\boldsymbol{x}'|a(\eta(t_A))a(\eta(t_B))}\int_0^\infty \mathrm{d}k\; k\; \sin(k|\boldsymbol{x}-\boldsymbol{x}'|)\hat{g}(\eta(t_A),\eta(t_B),k)$$

$$\Delta\eta = \eta(t) - \eta(t')$$

$$|\psi_{0,\nu}\rangle = \alpha_\nu|e_\nu\rangle + \beta_\nu|g_\nu\rangle$$

MINIMAL COUPLING

SIGNALING
ESTIMATOR, S

$$[\phi(\boldsymbol{x}_A, t_A), \phi(\boldsymbol{x}_B, t_B)] = \mathrm{i}\frac{\theta(\eta(t_B) - \eta(t_A)) - \theta(\eta(t_A) - \eta(t_B))}{(2\pi)^3|\boldsymbol{x} - \boldsymbol{x}'|a(\eta(t_A))a(\eta(t_B))} \int_0^\infty \mathrm{d}k\, k\, \sin(k|\boldsymbol{x} - \boldsymbol{x}'|)\hat{g}(\eta(t_A), \eta(t_B), k)$$

$$\hat{g}(\eta, \eta', k) = \frac{8\pi}{k}\sqrt{\left|\frac{\eta}{\eta'}\right|}\frac{\mathrm{sgn}(\eta')[J_{\alpha-1/2}(k|\eta|)Y_{\alpha-1/2}(k|\eta'|) - Y_{\alpha-1/2}(k|\eta|)J_{\alpha-1/2}(k|\eta'|)]}{Y_{\alpha-1/2}(k|\eta'|)\left[J_{\alpha-3/2}(k|\eta'|) - J_{\alpha+1/2}(k|\eta'|)\right] - J_{\alpha-1/2}(k|\eta'|)\left[Y_{\alpha-3/2}(k|\eta'|) - Y_{\alpha+1/2}(k|\eta\right.}$$

J_α , Y_α BESSEL FUNCTIONS

SIGNALING
ESTIMATOR, S

$$[\phi(\boldsymbol{x}_A, t_A), \phi(\boldsymbol{x}_B, t_B)] = \mathrm{i}\frac{\theta(\eta(t_B)-\eta(t_A)) - \theta(\eta(t_A)-\eta(t_B))}{(2\pi)^3|\boldsymbol{x}-\boldsymbol{x}'|a(\eta(t_A))a(\eta(t_B))}\int_0^\infty \mathrm{d}k\; k\; \sin(k|\boldsymbol{x}-\boldsymbol{x}'|)\hat{g}(\eta(t_A), \eta(t_B), k)$$

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J_α Y_α BESSEL FUNCTIONS

MATTER DOMINATED UNIVERSE $\longrightarrow$ $\alpha = 2$ $\longrightarrow$ $a \propto \eta^2 \propto t^{2/3}$

$$J_{2-1/2}(k|\eta|) = \sqrt{2/\pi}\frac{1}{\sqrt{k|\eta|}}\left[-\cos(k\eta) + \frac{\sin(k\eta)}{k\eta}\right]$$

$$Y_{2-1/2}(k|\eta|) = \sqrt{2/\pi}\frac{\mathrm{sgn}(\eta)}{\sqrt{k|\eta|}}\left[-\sin(k\eta) + \frac{\cos(k\eta)}{k\eta}\right]$$

SIGNALING ESTIMATOR, S

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

VIOLATION OF STRONG HUYGENS PRINCIPLE !!!!

MINIMAL COUPLING

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

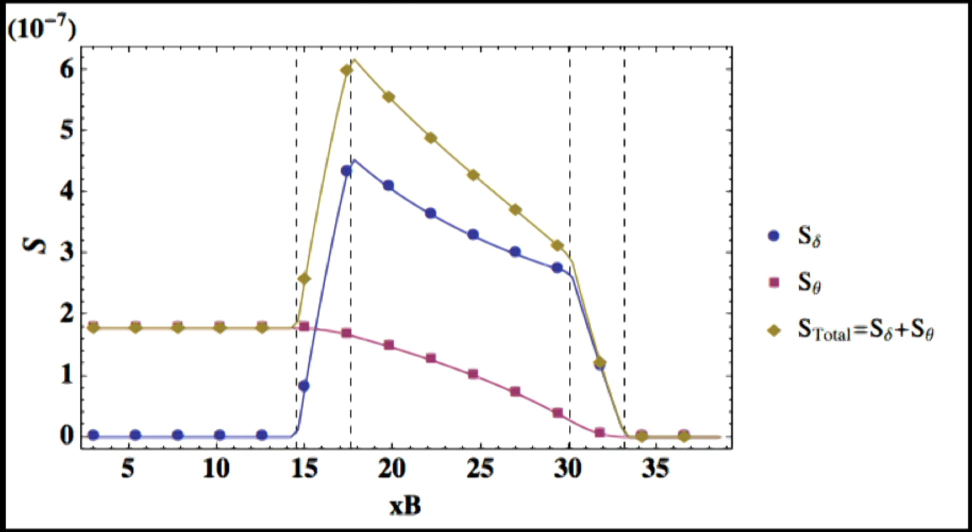
Does NOT decay with Spatial separation

Timelike-leakage

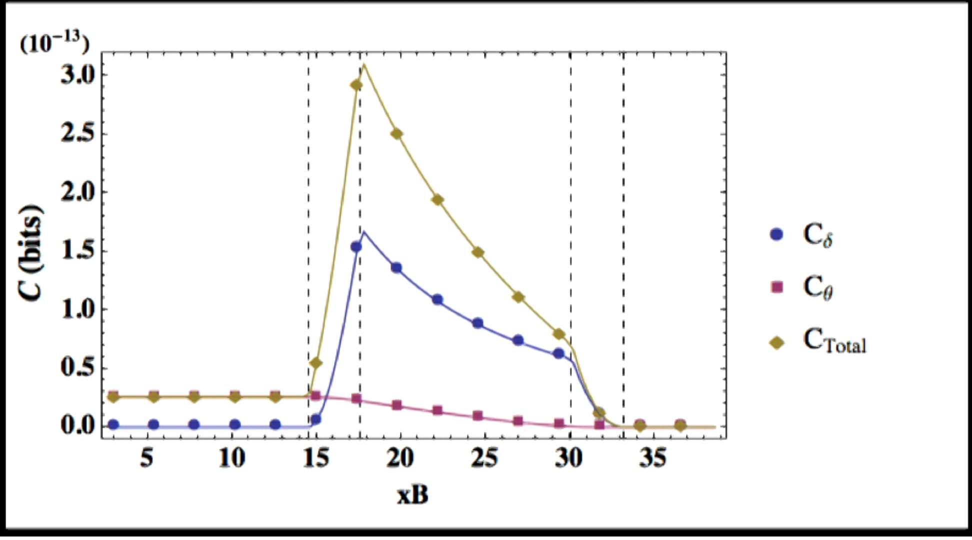
Case: **MINIMAL** COUPLING

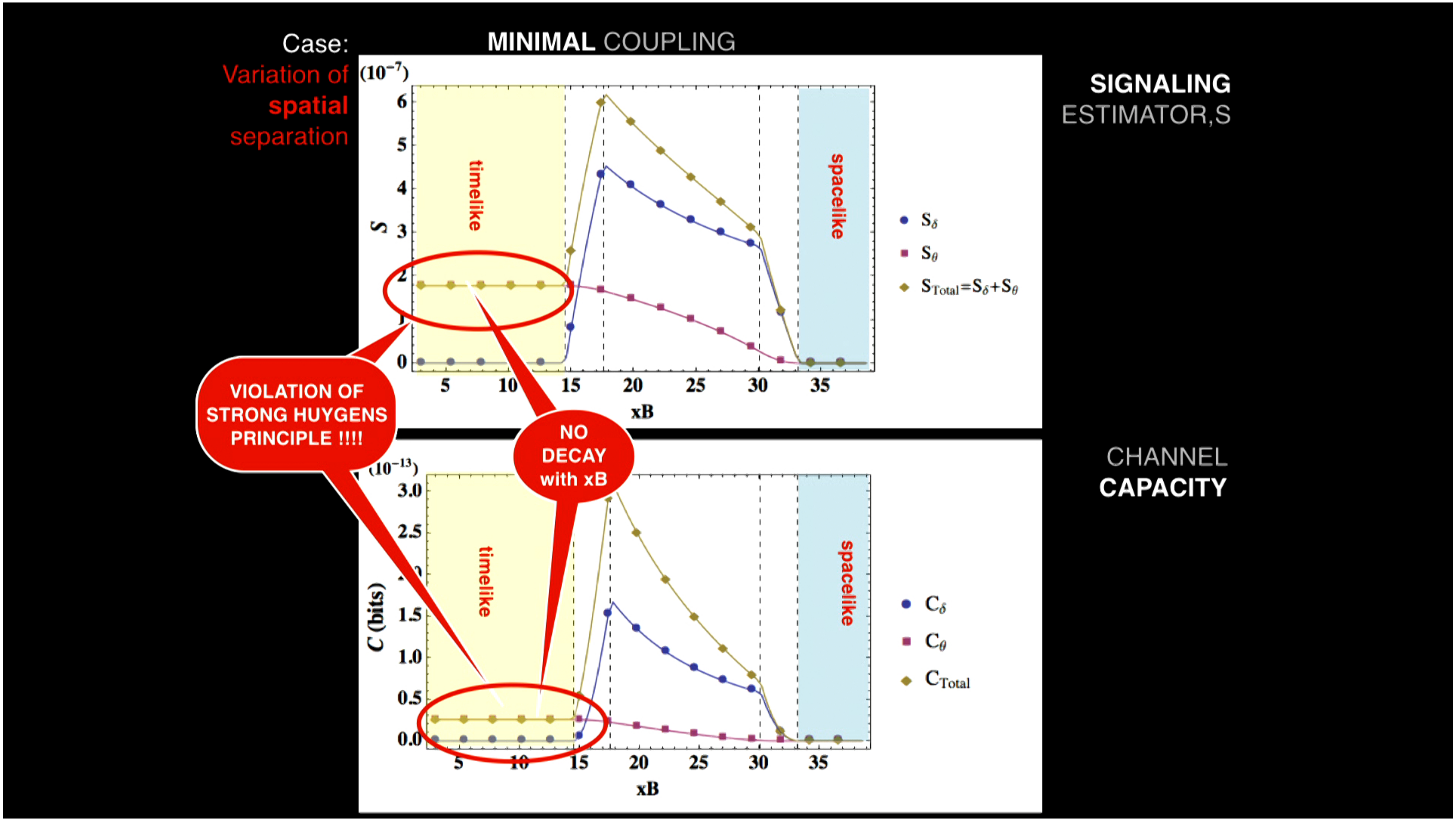
Variation of **spatial** separation

SIGNALING ESTIMATOR,S



CHANNEL **CAPACITY**



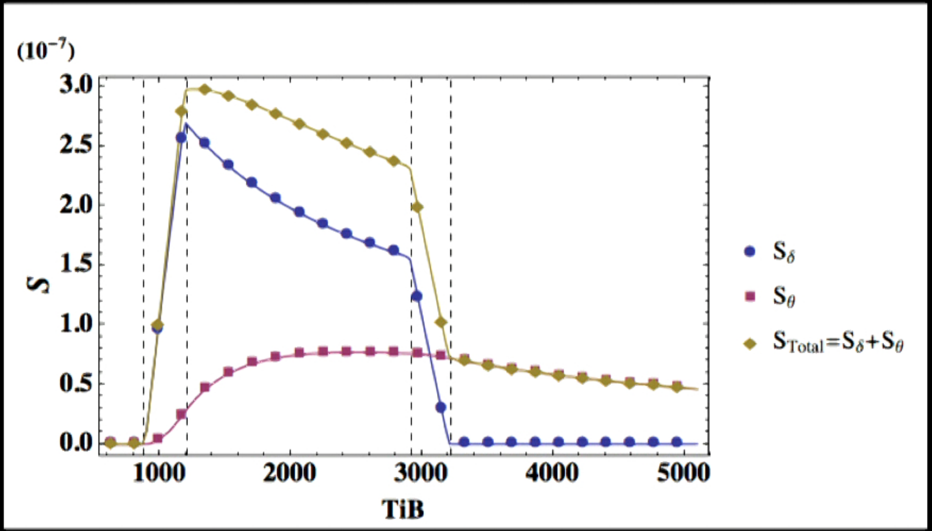


Case:
Variation of
spatial
separation
MINIMAL COUPLING
SIGNALING
ESTIMATOR,S
CHANNEL
CAPACITY
VIOLATION OF
STRONG HUYGENS
PRINCIPLE !!!!
NO
DECAY
with xB
timelike
spacelike
xB
C (bits)
S_δ
S_θ
S_Total=S_δ+S_θ
C_δ
C_θ
C_Total

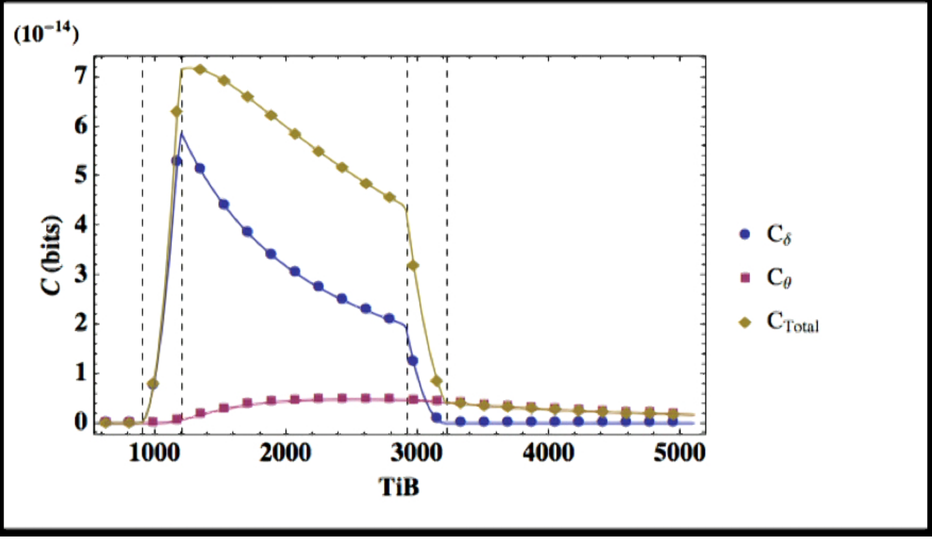
Case:
Variation of **temporal** separation

MINIMAL COUPLING

SIGNALING ESTIMATOR,S



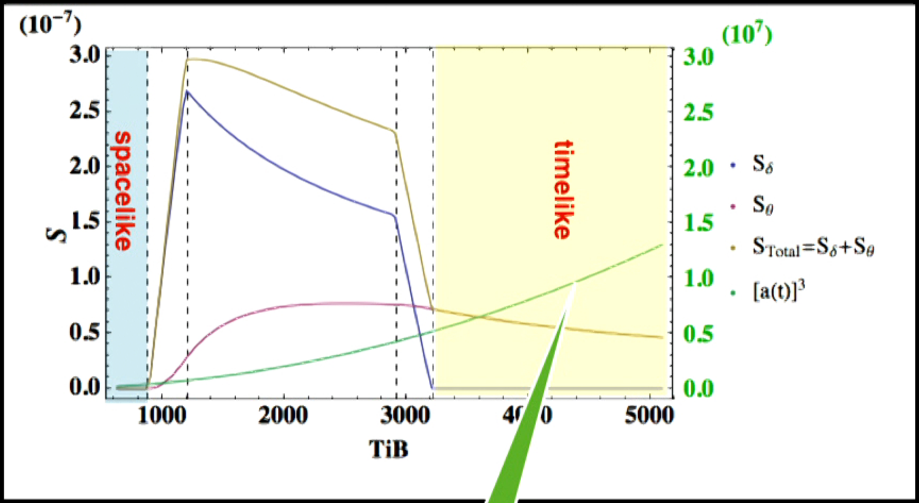
CHANNEL **CAPACITY**



Case:
Variation of **temporal** separation

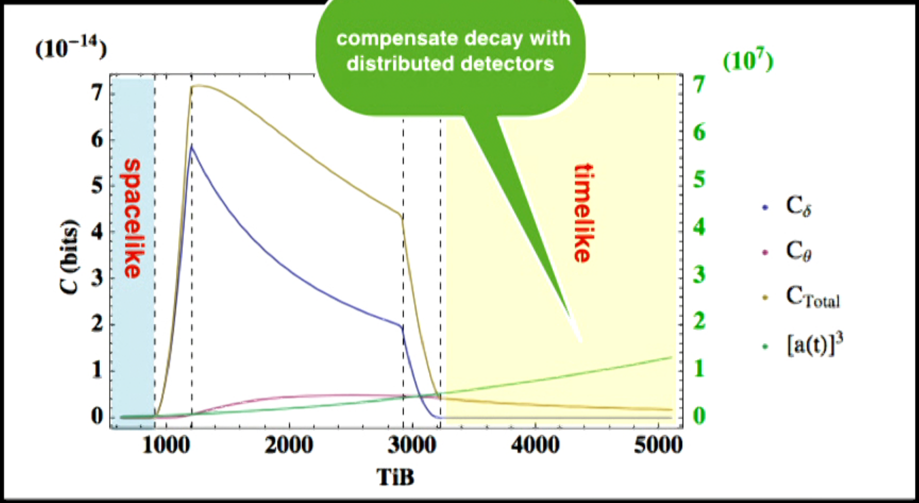
MINIMAL COUPLING

SIGNALING ESTIMATOR,S



compensate decay with distributed detectors

CHANNEL **CAPACITY**



Exponential Expansion (deSitter): No decay in time!

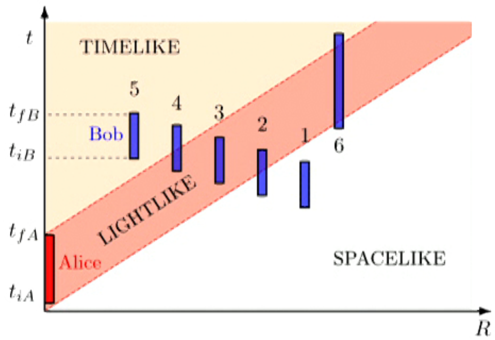
P. Simidzija, E. Martin-Martinez, Phys. Rev. D 95, 025002 (2017)

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:

Local Noise

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

Signalling terms

Communication Scenario

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

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

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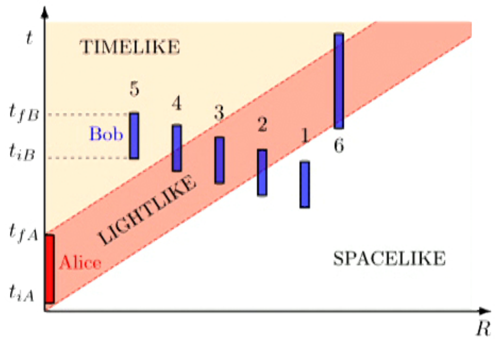


$$P_e = |\alpha_B|^2 + P_{\text{noise}} + S$$

Signalling terms

Probability of finding Bob excited:

Local Noise

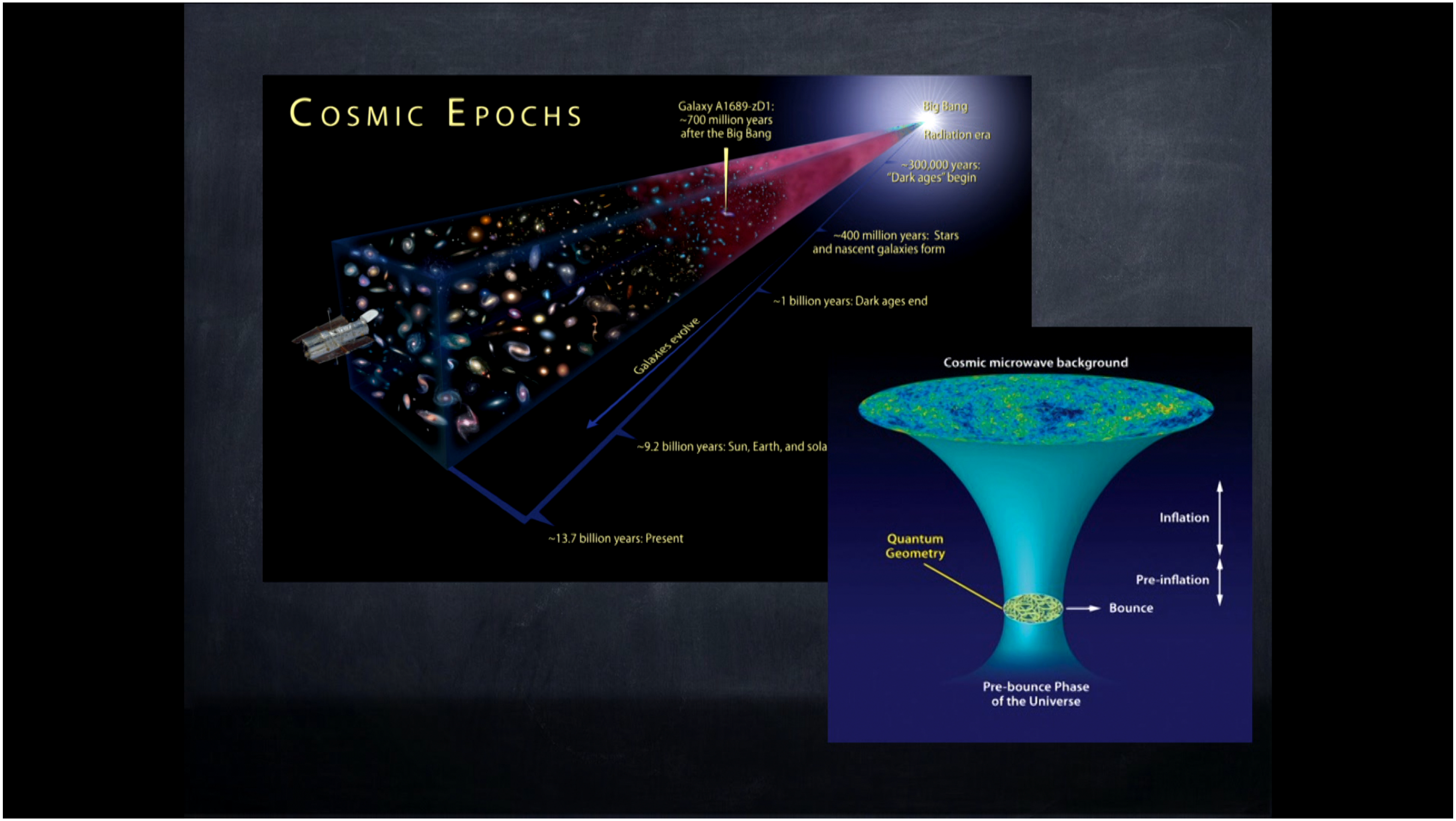
$$P_{|e_B\rangle} = |\alpha_B|^2 + \mathcal{O}(\lambda_B) + \mathcal{O}(\lambda_B^2) + \mathcal{O}(\lambda_A\lambda_B) + \mathcal{O}(\lambda_B^4) + \mathcal{O}(\lambda_A^2\lambda_B^2) + \cdots$$

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
Quantum
Geometry
Pre-inflation
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

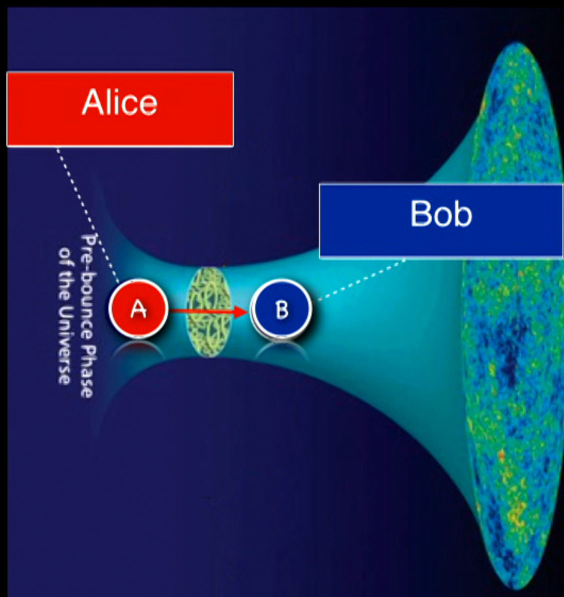
Imagine an ancient (pre-bounce) and very advanced civilization

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

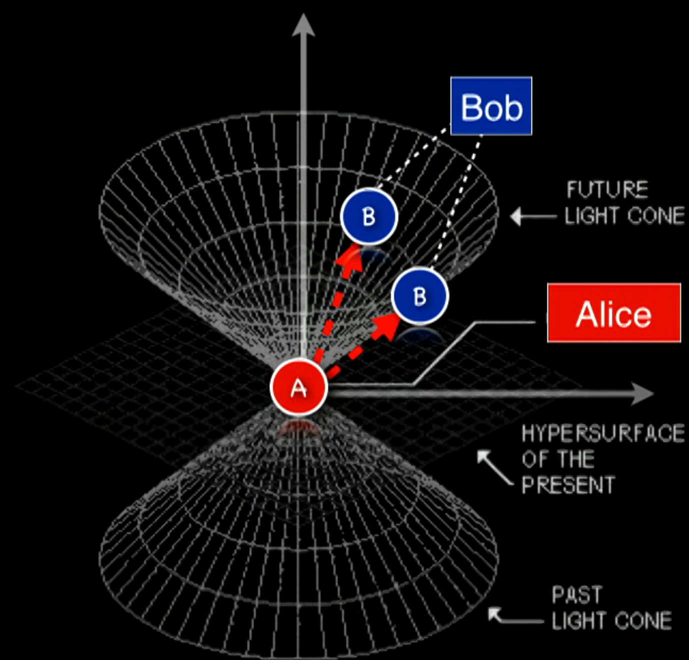
Encode the information in the quantum field: detectors and field get entangled.

Assuming optimality, how much information is recoverable nowadays?

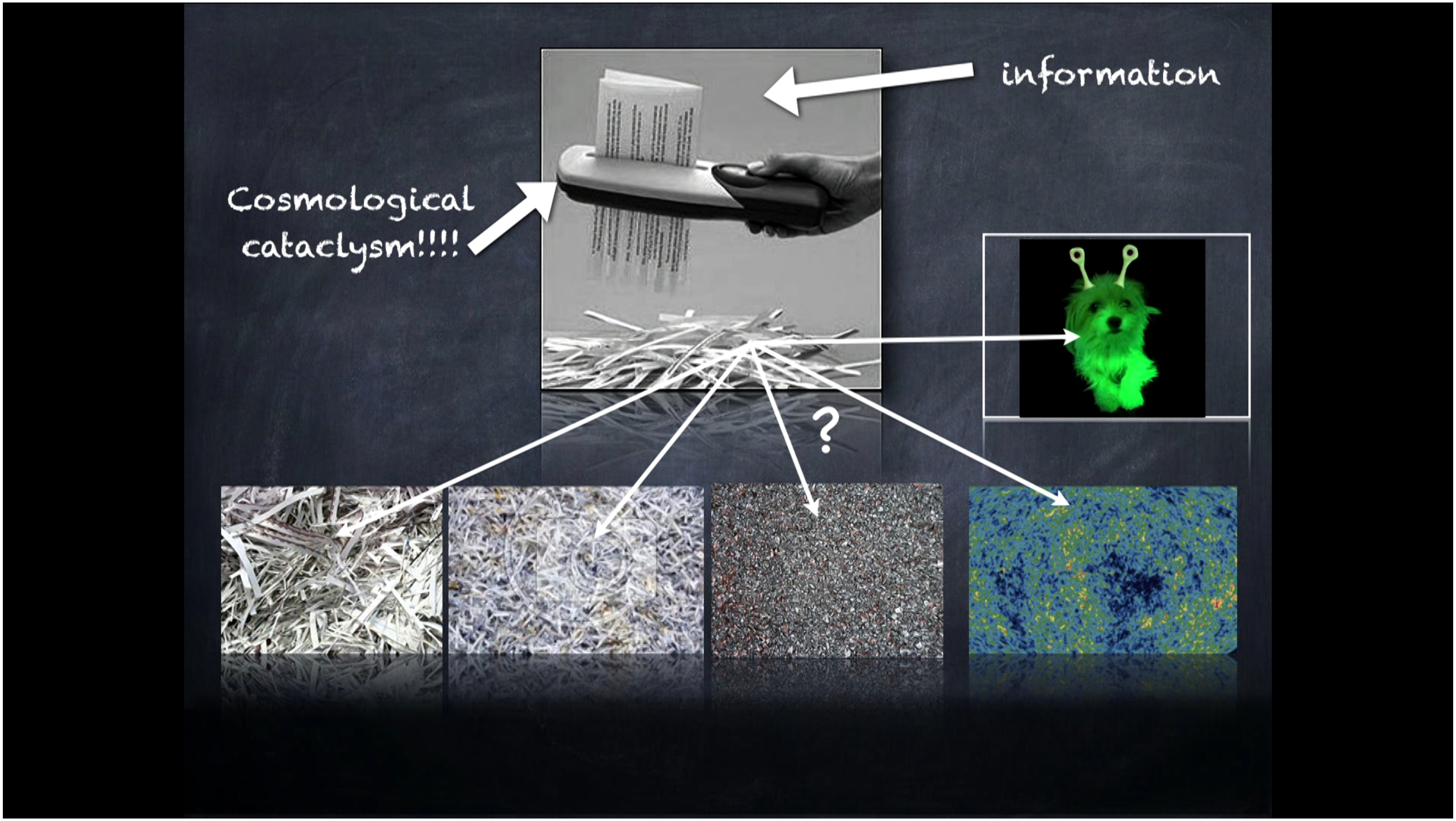
Setting
QUANTUM
BOUNCE

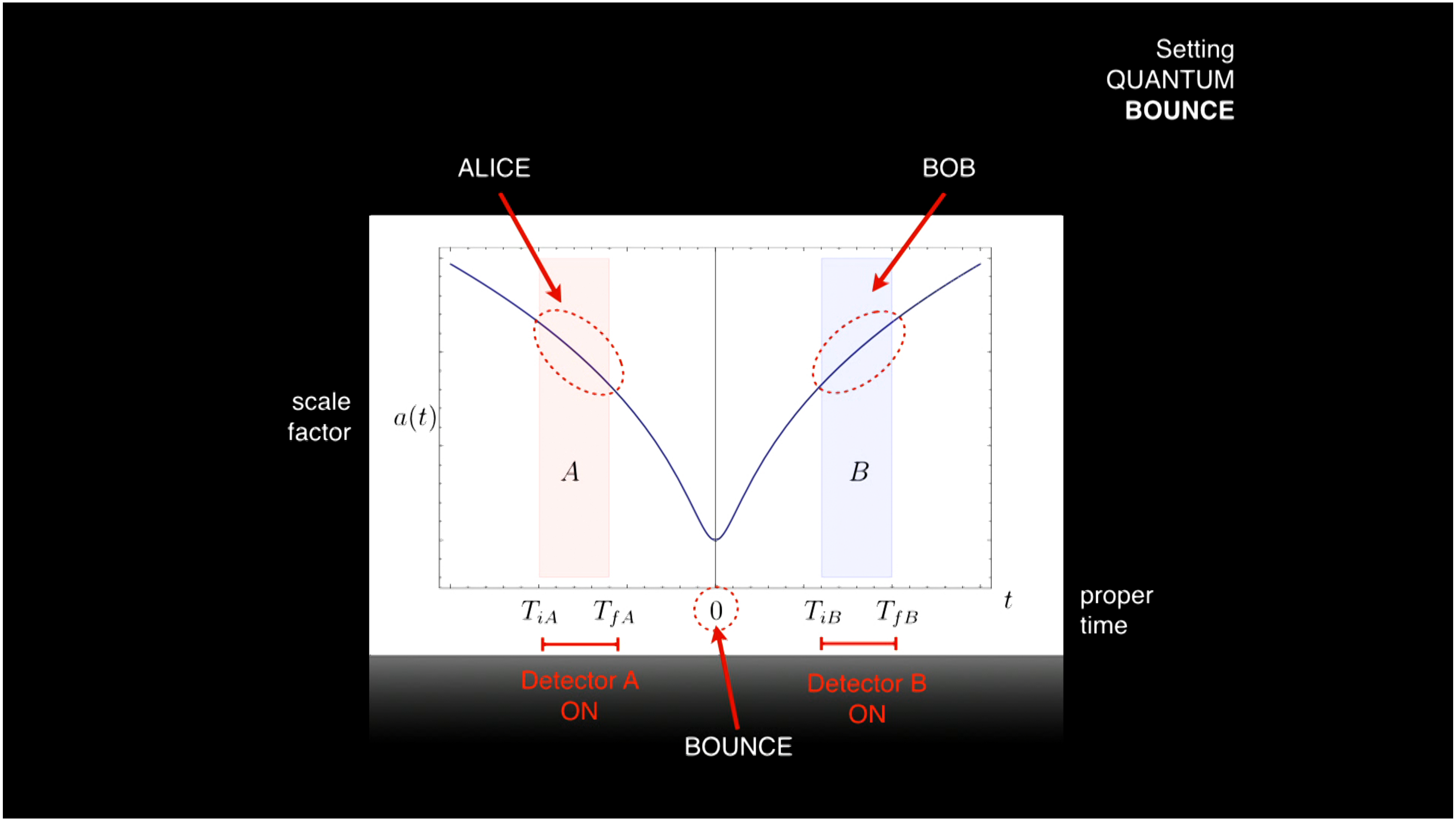


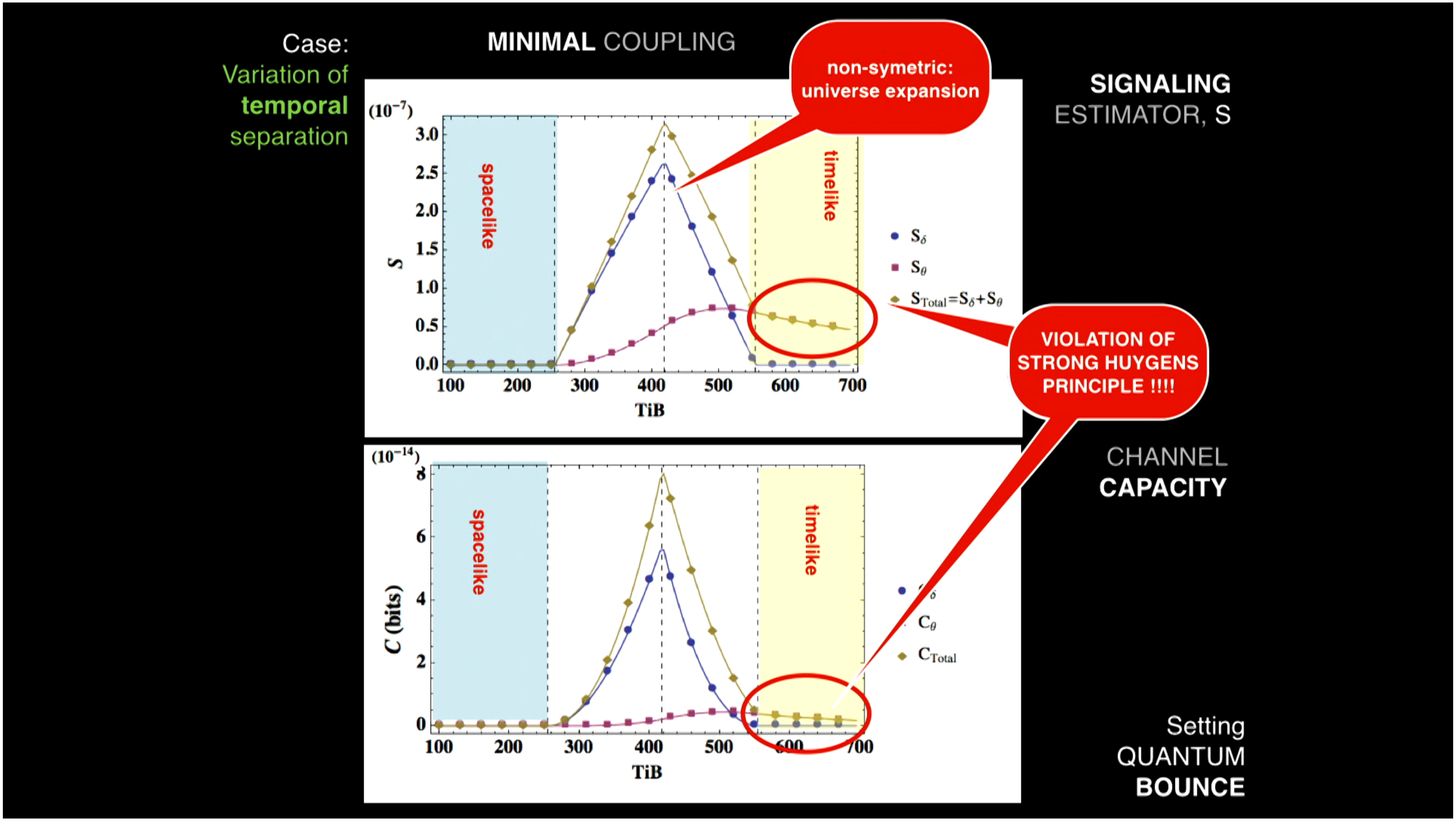
A: before the bounce
B: after the bounce



Lightcone of Alice


information
Cosmological
cataclysm!!!!
?


Setting
QUANTUM
BOUNCE
ALICE
BOB
scale factor
$a(t)$
A
B
T_{iA}
T_{fA}
0
T_{iB}
T_{fB}
t
proper time
Detector A ON
Detector B ON
BOUNCE



Case:
Variation of
temporal
separation
MINIMAL COUPLING
non-symetric:
universe expansion
SIGNALING
ESTIMATOR, S
(10⁻⁷)
S
spacelike
timelike
S_δ
S_θ
$S_{Total}=S_\delta+S_\theta$
TiB
VIOLATION OF
STRONG HUYGENS
PRINCIPLE !!!!
CHANNEL
CAPACITY
(10⁻¹⁴)
C (bits)
spacelike
timelike
C_θ
C_{Total}
TiB
Setting
QUANTUM
BOUNCE

Conclusions

The information can be, for example, Information about quantum gravity!

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Echo of the quantum bounce

Luis J. Garay,[1,2] Mercedes Martín-Benito,[3] and Eduardo Martín-Martínez[3,4,5]

We identify a signature of quantum gravitational effects that survives from the early Universe to the current era: Fluctuations of quantum fields as seen by comoving observers are significantly influenced by the history of the early Universe. In particular, we show 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. Furthermore, we estimate an upper bound for the typical energy and length scales where quantum effects are relevant. We discuss how this signature might be observed and therefore used to build falsifiability tests of quantum gravity theories.

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