Title: PSI 2017/2018 - Relativistic Quantum Information - Lecture 11

Date: Apr 03, 2018 09:00 AM

URL: http://pirsa.org/18040004

Abstract:

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.

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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

Antenna states

$$|\psi_A\rangle = \alpha_A |e_A\rangle + \beta_A |g_A\rangle$$

$$|\psi_B\rangle = \alpha_B |e_B\rangle + \beta_B |g_B\rangle$$

$$\rho^{\text{sig}}_{\text{signal}} \quad \tilde{\lambda} \int dt \int dt' \int dx \int dx' \, \chi_A(t)\, \chi_B(t')\, F_A(\vec{x}-\vec{x}_A)\, F_B(\vec{x}'-\vec{x}_B) \underbrace{\left\langle [\phi(t,\vec{x}), \phi(t',\vec{x}')] \right\rangle_{\rho_\phi}}_{\text{state independent}}$$

ONLY NON-ZERO if
THERE ARE COHERENCES IN INITIAL STATE

Mathematical Methods: Beyond the Strong Huygens Principle

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

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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)

Mathematical Methods: Beyond the Strong Huygens Principle

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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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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 $\alpha = \dfrac{3-3w}{6w+2}$

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

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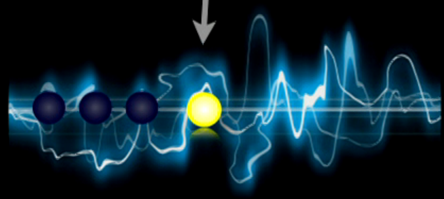
TRANSMISSION OF **INFORMATION**

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

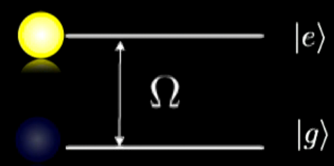
how much information can be sent? → **CHANNEL CAPACITY, C**

ALICE & BOB's **DETECTOR** MODEL



Unruh-DeWitt DETECTOR

-Two-level system

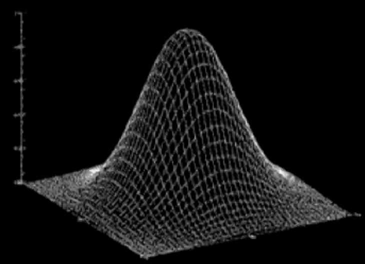


-Energy gap ground-excited states: Ω

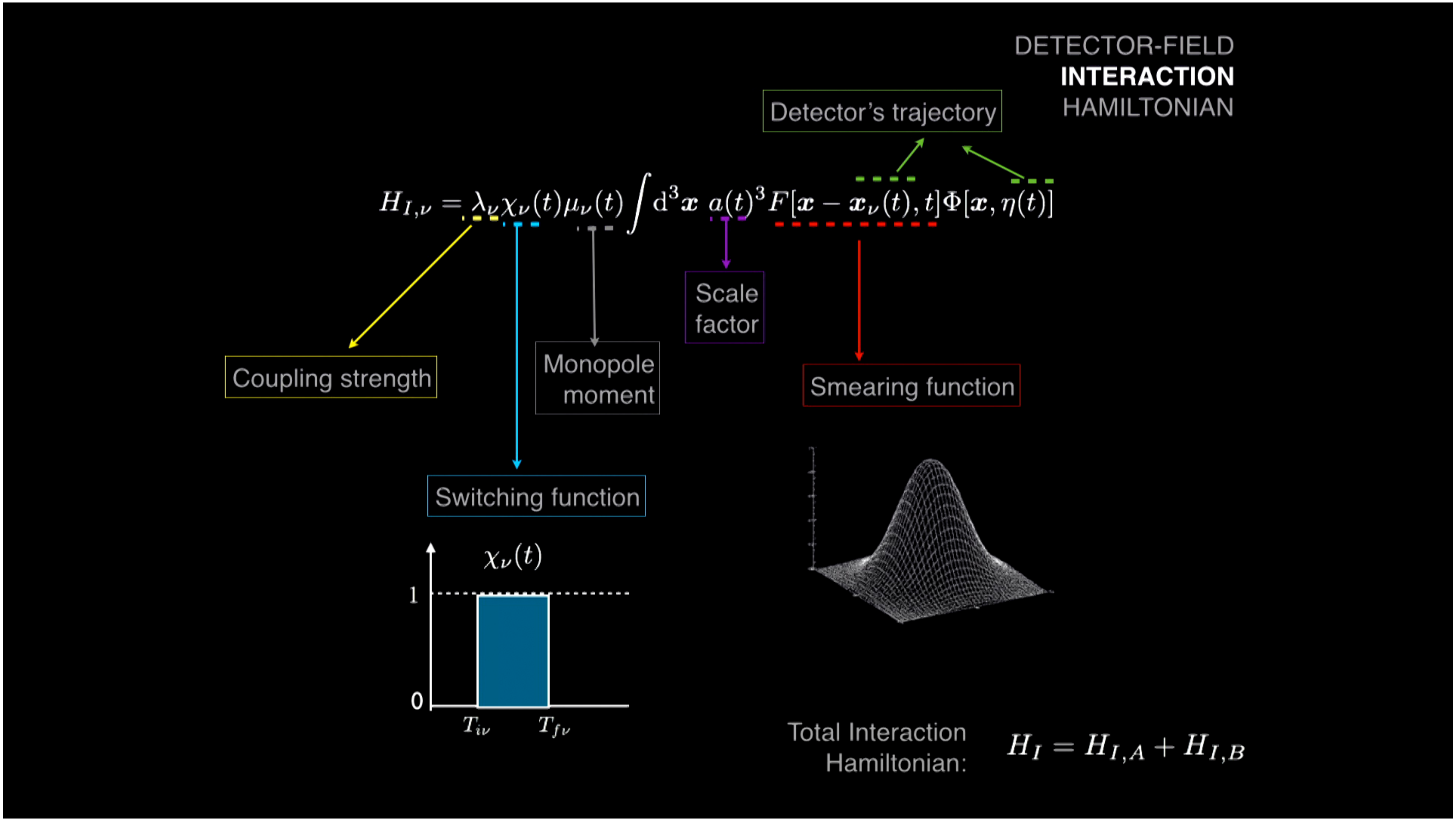
-Monopole moment operator: $\mu_\nu(t) = |e_\nu\rangle\langle g_\nu| e^{i\Omega_\nu t} + |g_\nu\rangle\langle e_\nu| e^{-i\Omega_\nu t}$

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

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



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**

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

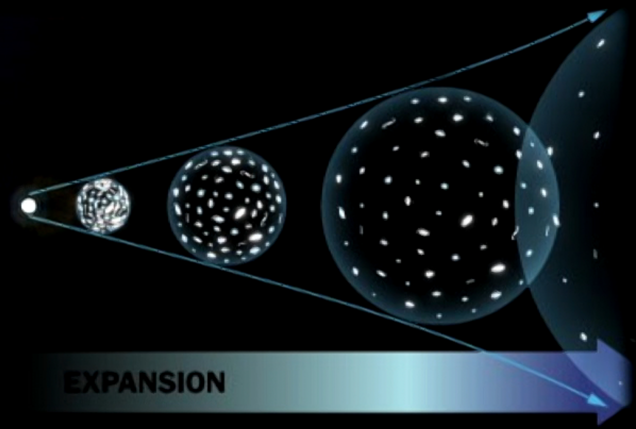
TRANSMISSION OF **INFORMATION**

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

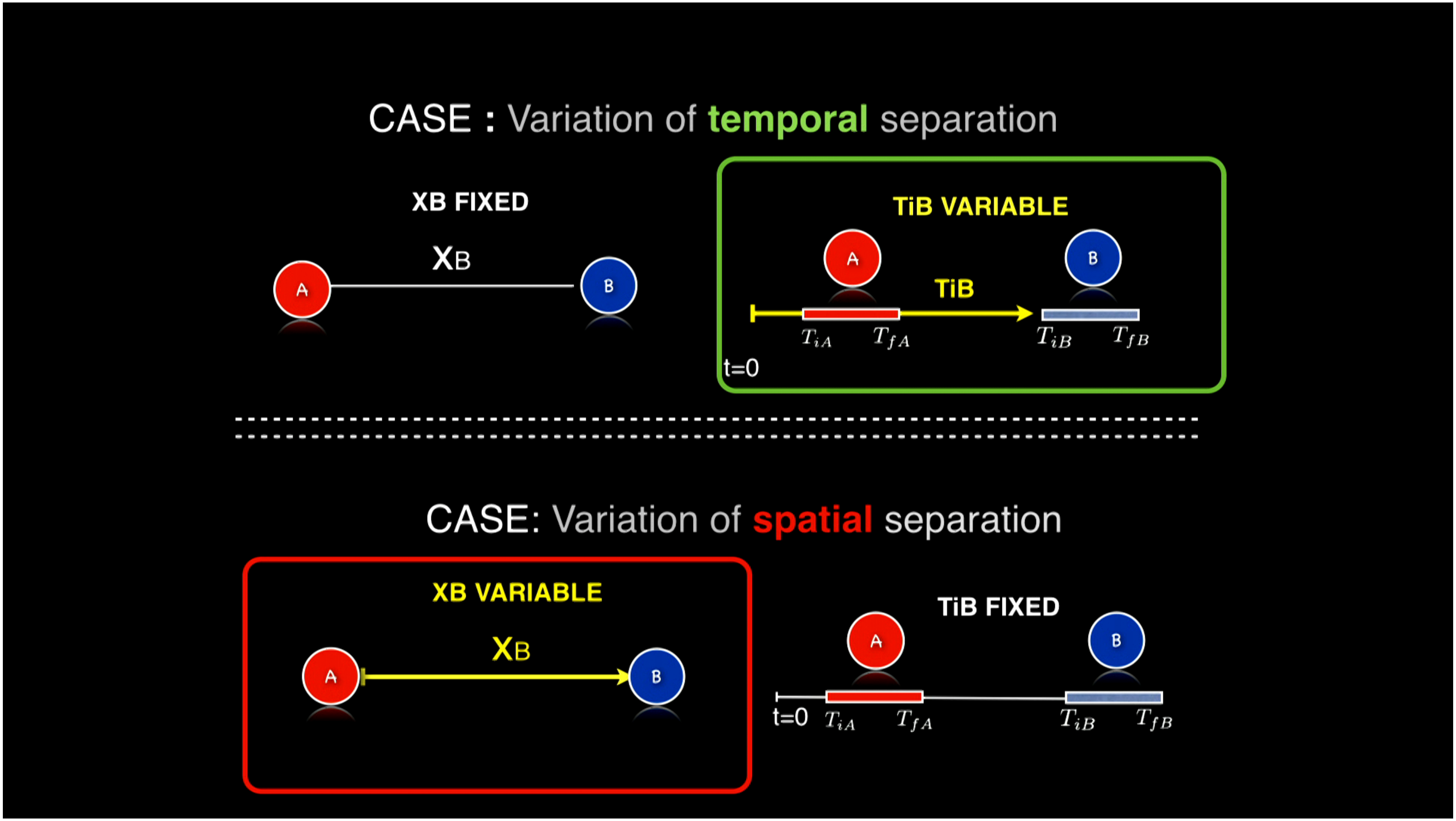
$$(\Box - m^2 + \xi R)\phi = 0 \qquad \Box = \frac{1}{\sqrt{|g|}}\partial_\mu\left(\sqrt{|g|}g^{\mu\nu}\partial_\nu\right)$$

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

IS INFORMATION **TRANSMITED**?

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

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

SIGNALING
ESTIMATOR, S

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

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

SIGNALING ESTIMATOR, S

CONFORMAL COUPLING

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

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$$\times F(\boldsymbol{x}' - \boldsymbol{x}_B, t)\mathrm{Re}\left(\alpha_B^* \beta_B [\phi(\boldsymbol{x}, t), \phi(\boldsymbol{x}', t')]\right)$$

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

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

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

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

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

SIGNALING ESTIMATOR, S

MINIMAL COUPLING

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

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

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

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

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

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

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

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

MINIMAL COUPLING

SIGNALING
ESTIMATOR, S

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

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

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

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

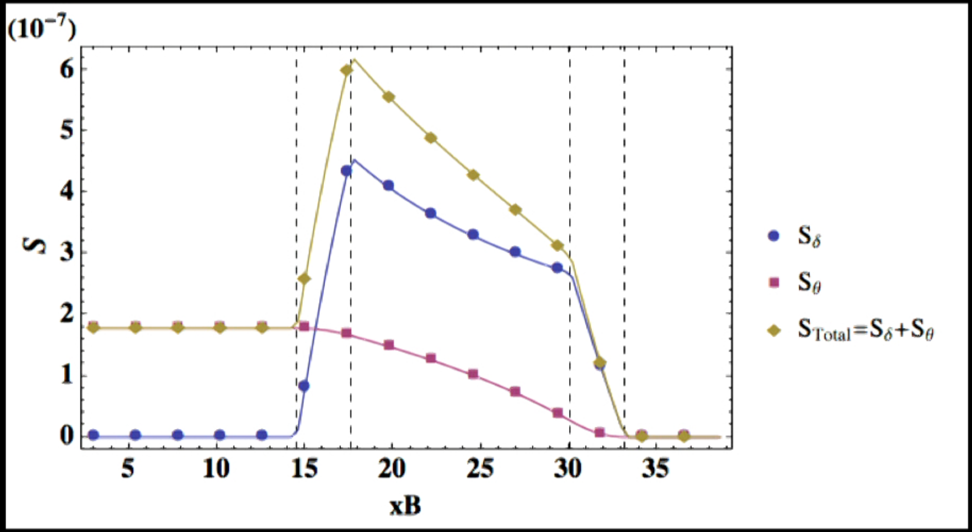
Does NOT decay with Spatial separation

Timelike-leakage

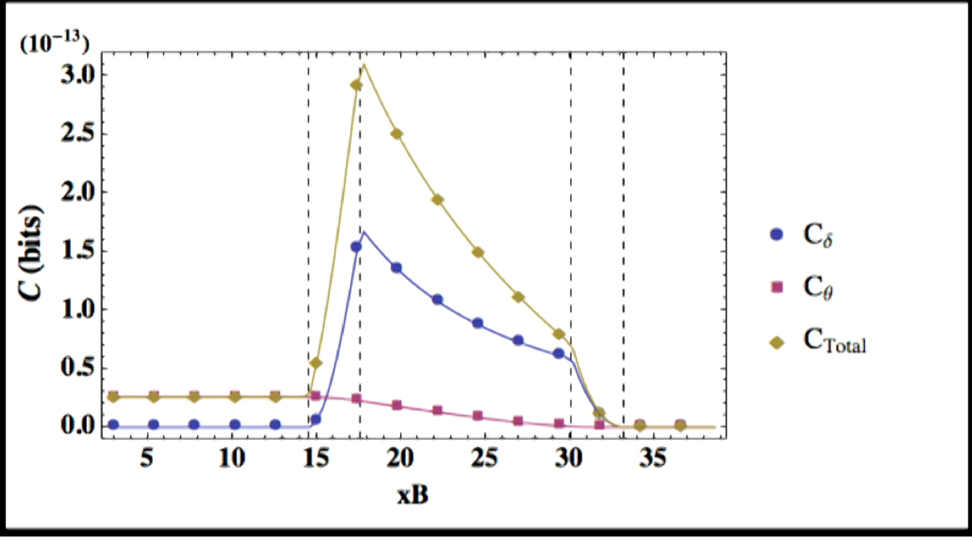
Case: Variation of **spatial** separation

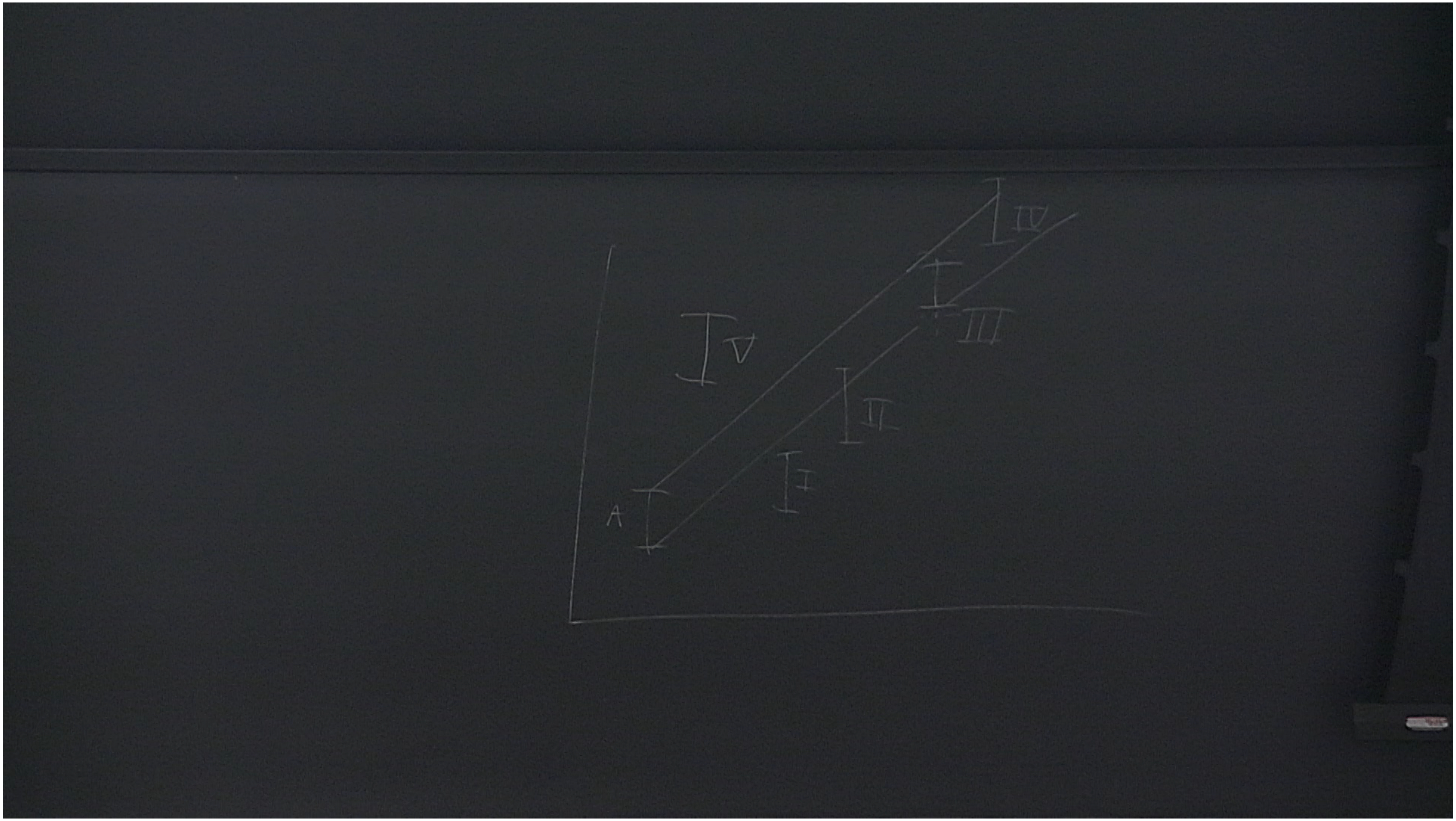
MINIMAL COUPLING

SIGNALING ESTIMATOR,S

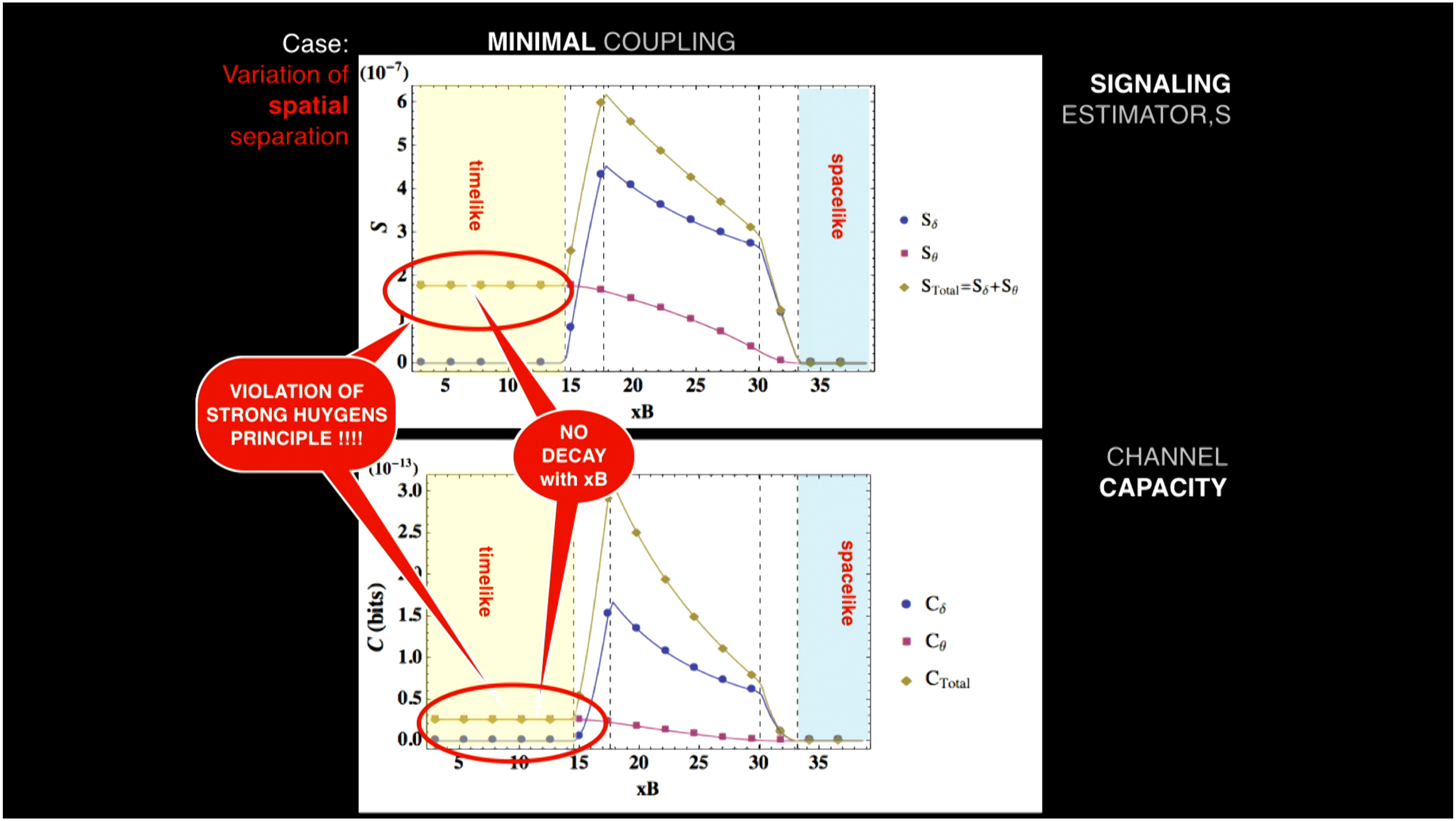


CHANNEL **CAPACITY**



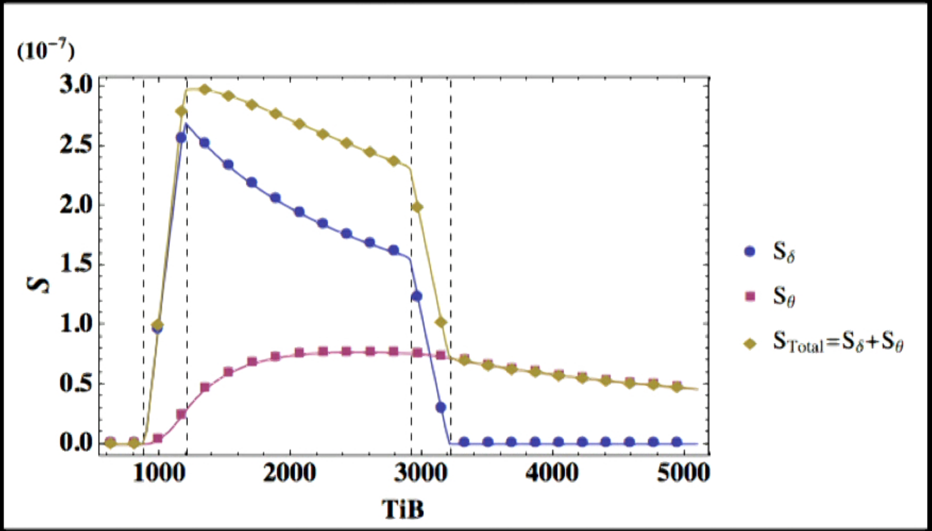


IV
III
II
I
V
A

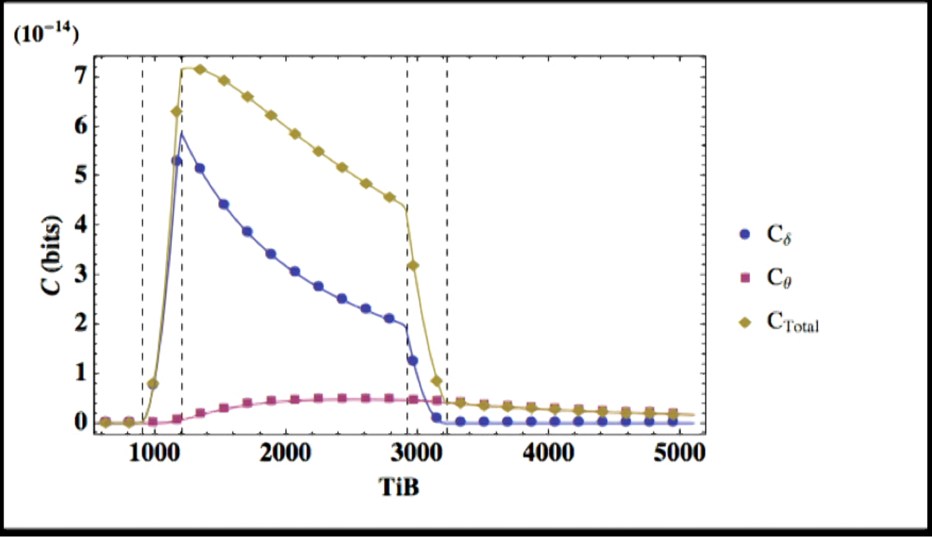

Case:
Variation of spatial separation
MINIMAL COUPLING
SIGNALING ESTIMATOR,S
CHANNEL CAPACITY
VIOLATION OF STRONG HUYGENS PRINCIPLE !!!!
NO DECAY with xB
timelike
spacelike
xB
(10^{-7})
S
S_δ
S_θ
$S_{Total}=S_\delta+S_\theta$
(10^{-13})
C (bits)
C_δ
C_θ
C_{Total}

Case:
Variation of **temporal** separation

MINIMAL COUPLING



SIGNALING ESTIMATOR,S



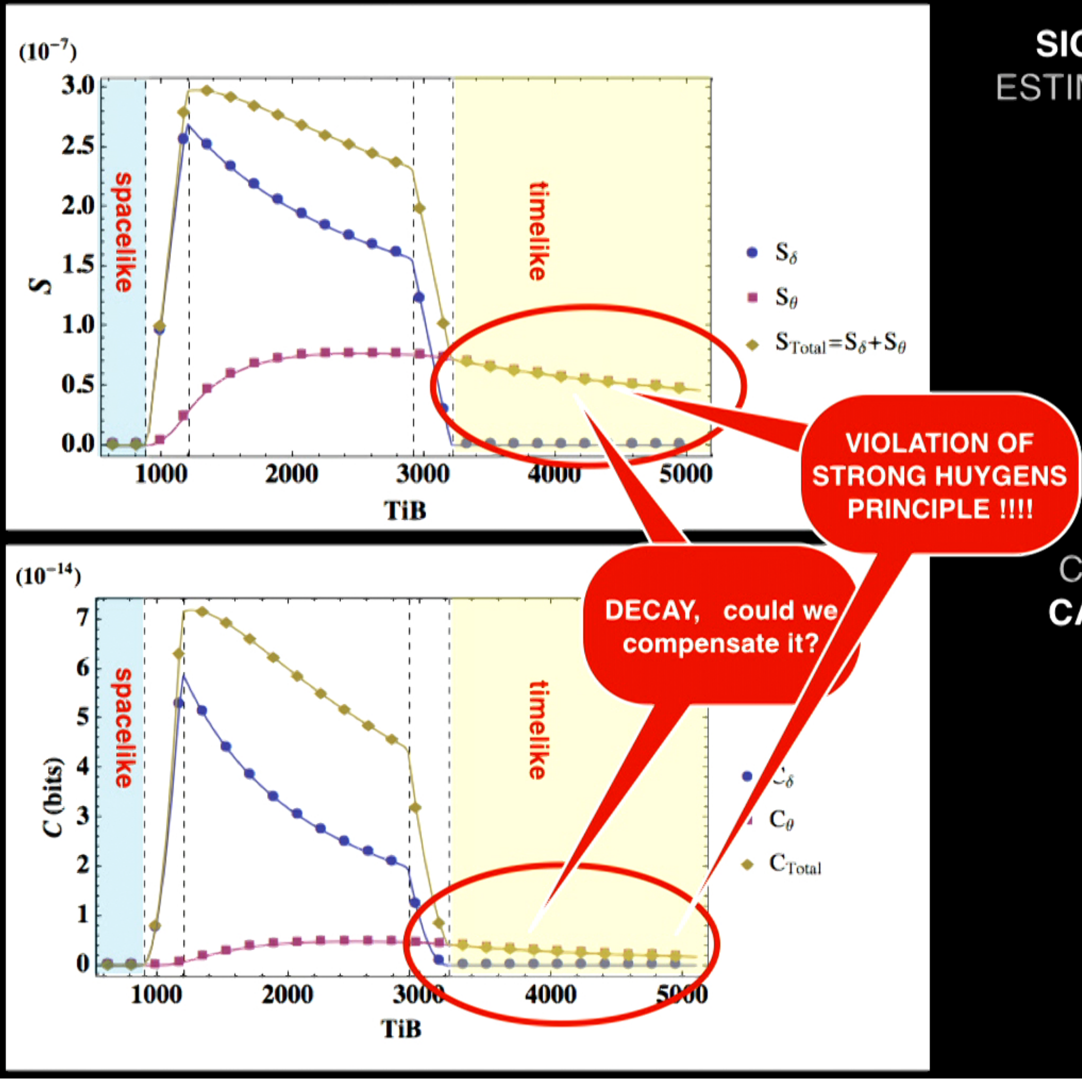
CHANNEL **CAPACITY**

Case:
Variation of **temporal** separation

MINIMAL COUPLING

SIGNALING ESTIMATOR,S

CHANNEL **CAPACITY**

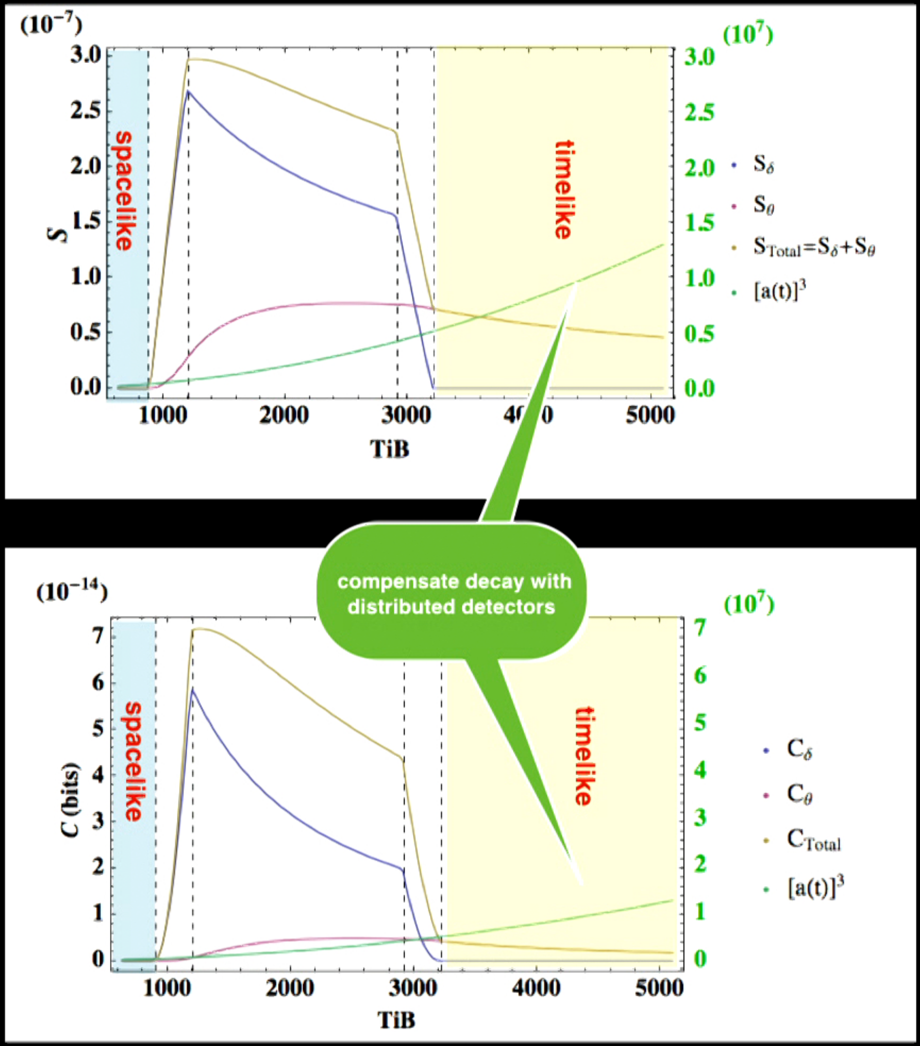


Case:
Variation of **temporal** separation

MINIMAL COUPLING

SIGNALING ESTIMATOR,S

CHANNEL **CAPACITY**

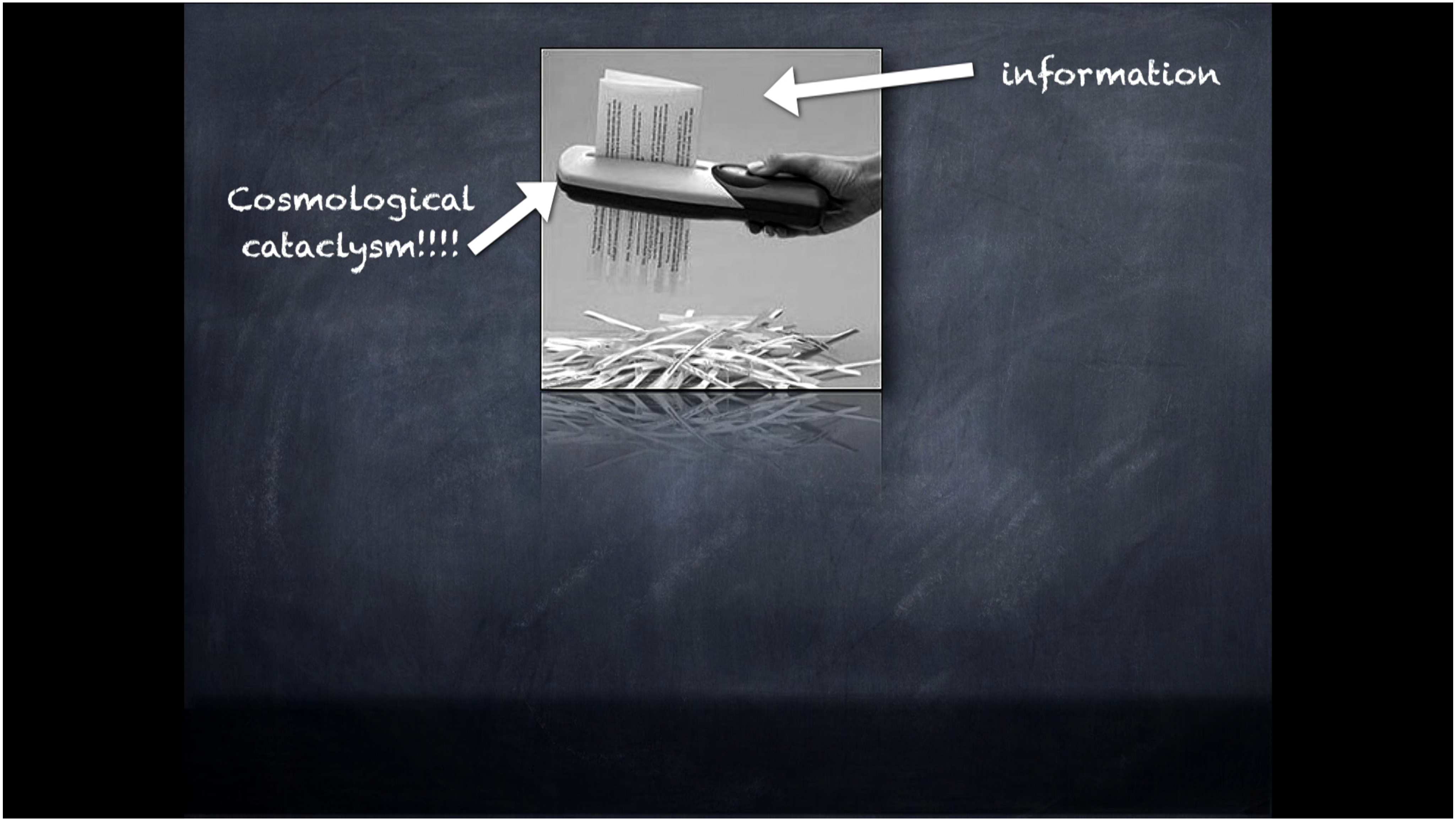


Exponential Expansion (deSitter): No decay in time!

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

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

How much information survives a Cosmological cataclysm!!!!


information
Cosmological cataclysm!!!!