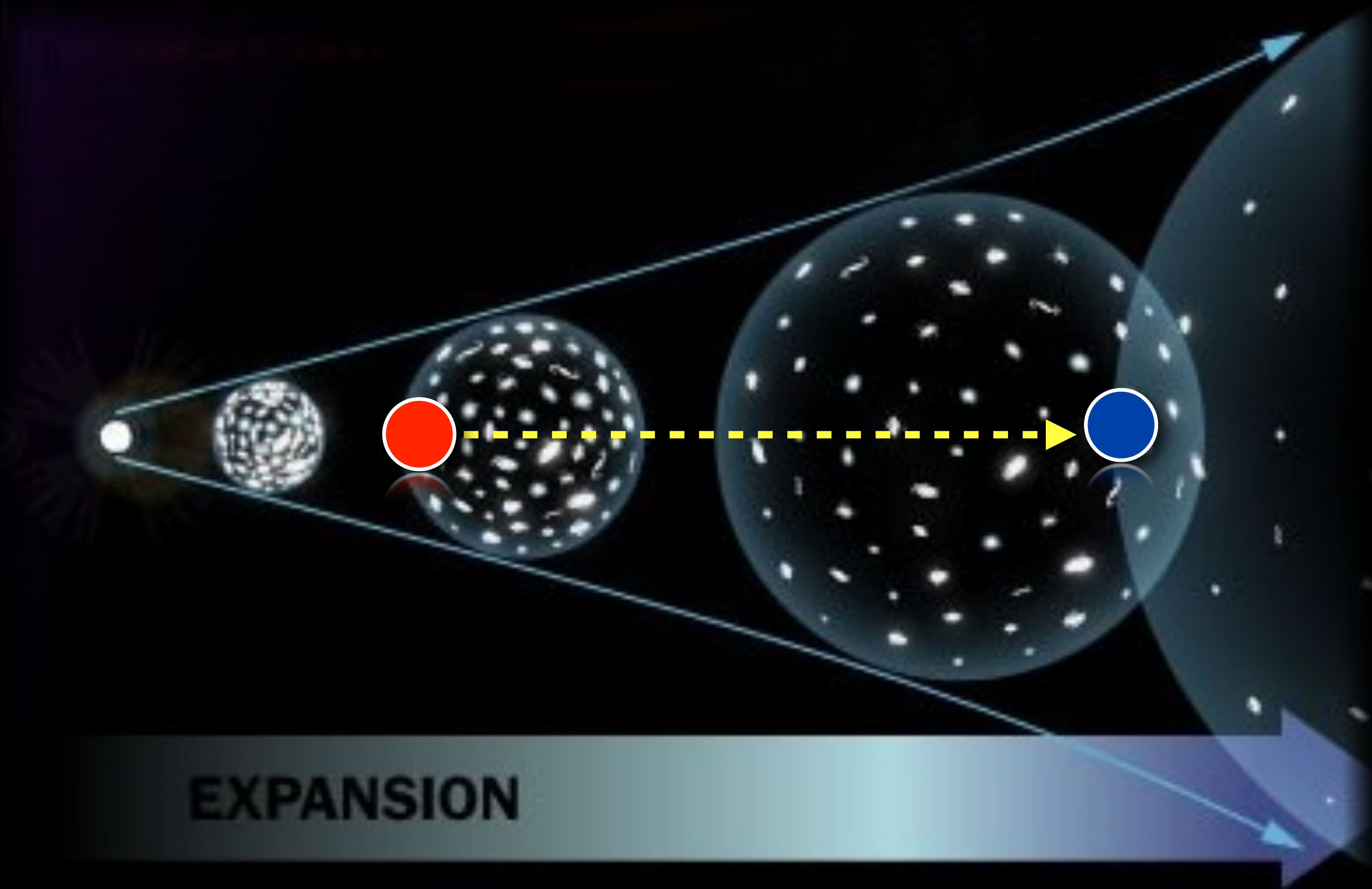
A GLIMPSE OF THE EARLY UNIVERSE WITHOUT REAL LIGHT

arXiv:1501.01650

ANA BLASCO
Universidad Complutense de Madrid

In collaboration with MERCEDES MARTÍN-BENITO LUIS J. GARAY, EDUARDO MARTÍN-MARTÍNEZ

Jarramplas 2015



Transmission of information from the early Universe to the current era

STRONG **HUYGENS PRINCIPLE**

THE **RADIATION GREEN'S FUNCTION** OF A MASSLESS SCALAR FIELD HAS SUPPORT ONLY ON THE LIGHT-CONE

⟶ THE **COMMUTATOR** HAS SUPPORT ONLY ON THE **LIGHT-CONE**

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

- True in 3+1 Flat spacetime

- **Violated** in general if there is **curvature** (unless there is conformal invariance)

[McLenaghan, Sonego, Faraoni, …]

VIOLATION OF THE STRONG **HUYGENS** PRINCIPLE: CONSEQUENCES ON **RELATIVISTIC QUANTUM COMMUNICATION in COSMOLOGY**

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**.

Robert H. Jonsson, Eduardo Martín-Martinez, and Achim Kempf.
Quantum Collect Calling. arXiv:1405.3988, 2014.

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,

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

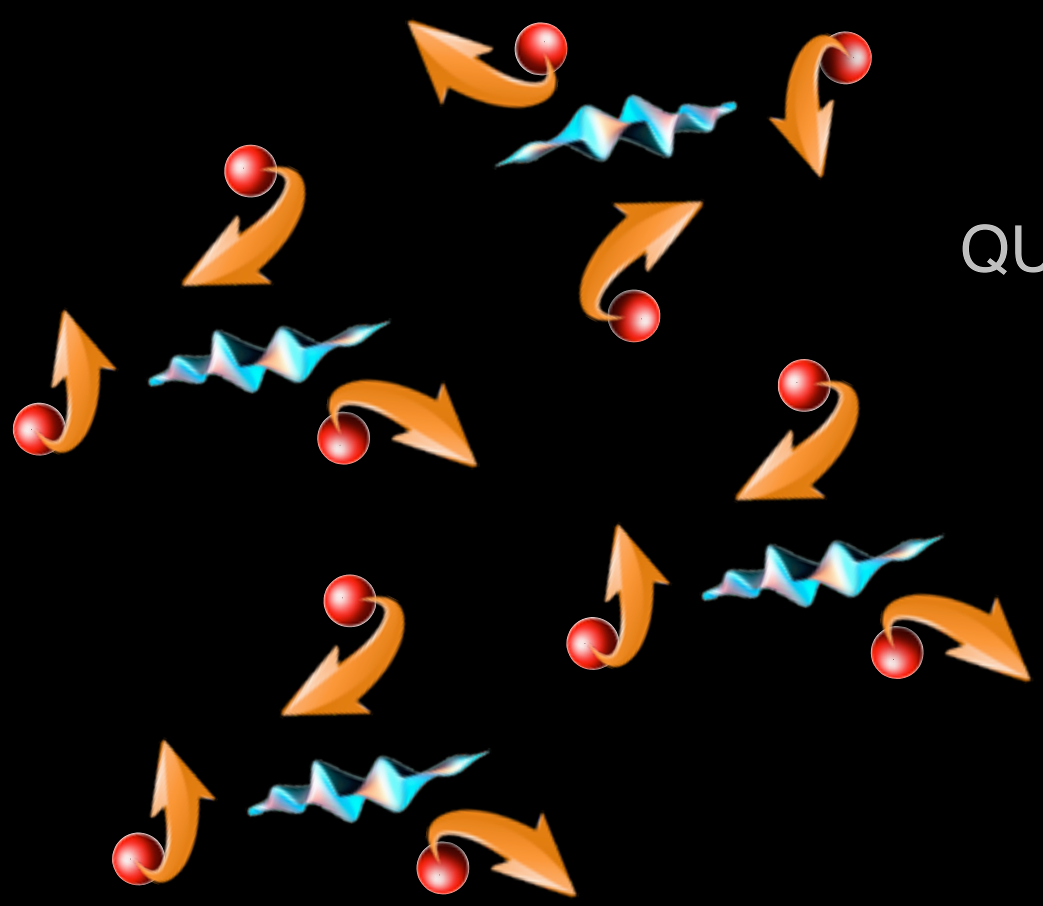
units: $\hbar = c = 1$

This geometry will be generated by:

a **perfect fluid** with a constant density-to-presure ratio $p = w\rho$ $\quad w > -1$

→ the **scale factor** evolves as $a \propto \eta^{\frac{2}{3w+1}} \propto t^{\frac{2}{3(w+1)}}$

COUPLED TO THIS BACKGROUND GEOMETRY:



A TEST **MASSLESS SCALAR FIELD**
QUANTIZED e.g. IN THE ADIABATIC VACUUM

KLEIN-GORDON EQUATION

$$(\Box - m^2 + \xi R)\phi = 0$$

$$\Box = \frac{1}{\sqrt{|g|}}\partial_\mu(\sqrt{|g|}g^{\mu\nu}\partial_\nu)$$

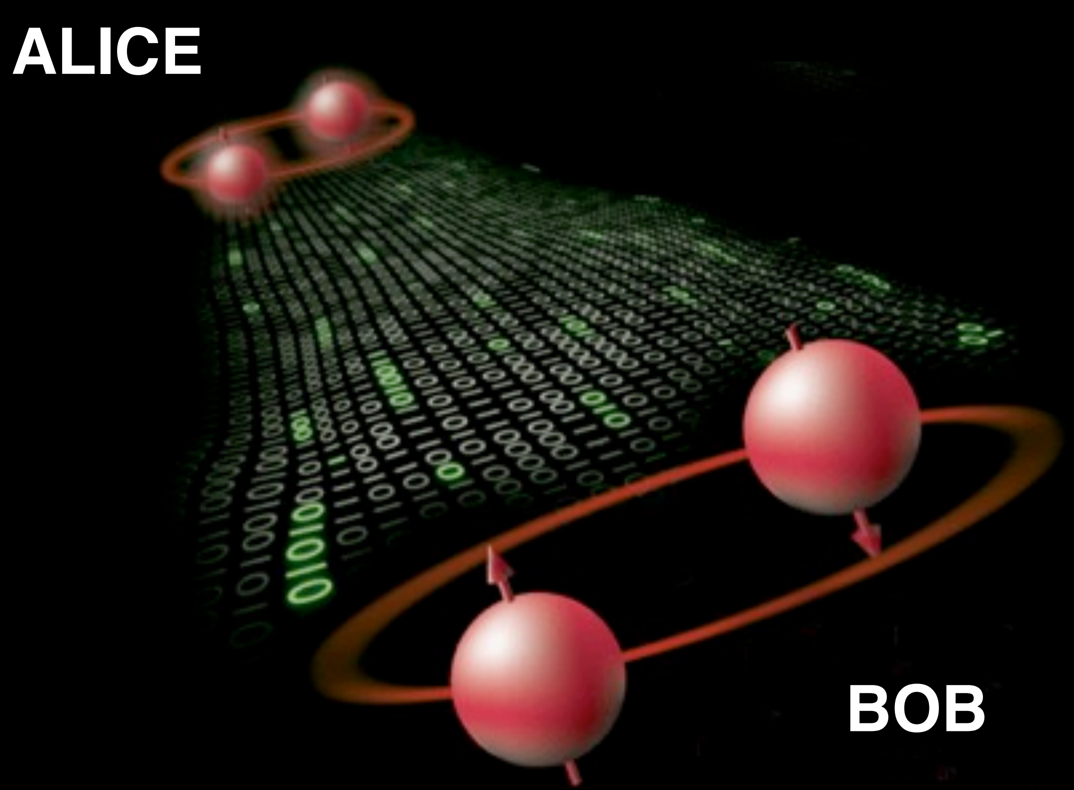
CONFORMAL COUPLING

$$\xi = \frac{1}{6}$$

vs

MINIMAL COUPLING

$$\xi = 0$$



Alice & Bob do not have direct access to the field.

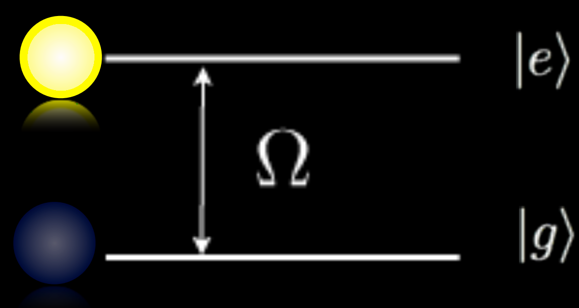
Alice makes a local perturbation of the field (let's model it with a particle detector)

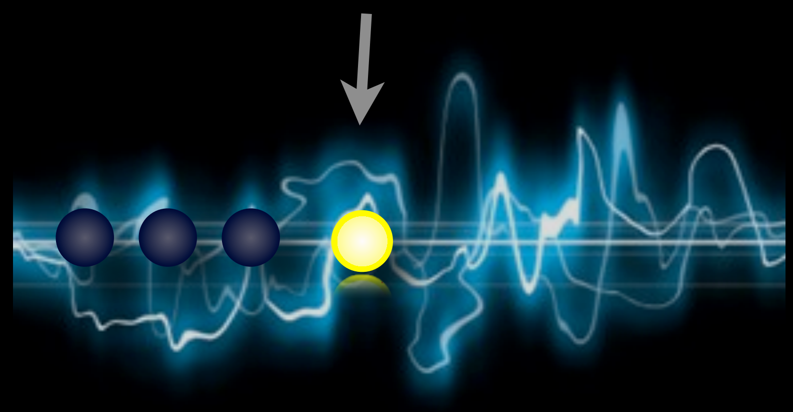
Bob can perform measurements on the fielf indirectly by **locally coupling 'particle detectors'**

Information is **encoded** in the **quantum state of the field**

ALICE & BOB's **DETECTOR** MODEL

Unruh-DeWitt DETECTOR





-Two-level system

-Energy gap ground-excited states: Ω

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

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

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

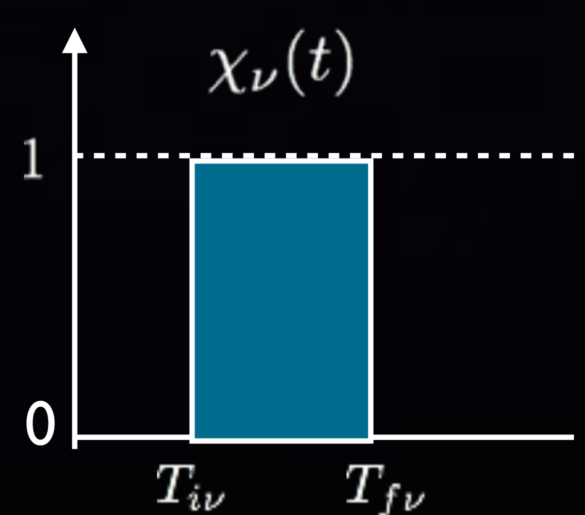
DETECTOR-FIELD **INTERACTION** HAMILTONIAN

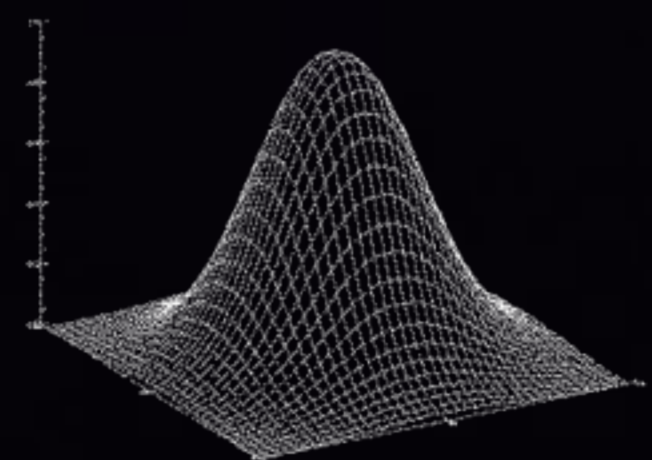
$$H_{I,\nu} = \lambda_\nu \chi_\nu(t) \mu_\nu(t) \int \mathrm{d}^3\boldsymbol{x}\ a(t)^3 F[\boldsymbol{x} - \boldsymbol{x}_\nu(t), t] \Phi[\boldsymbol{x}, \eta(t)]$$

DETECTOR-FIELD **INTERACTION** HAMILTONIAN

$$H_{I,\nu} = \lambda_\nu \chi_\nu(t) \mu_\nu(t) \int \mathrm{d}^3\boldsymbol{x}\; a(t)^3 F[\boldsymbol{x} - \boldsymbol{x}_\nu(t), t] \Phi[\boldsymbol{x}, \eta(t)]$$

- Coupling strength: λ_ν
- Switching function: $\chi_\nu(t)$
- Monopole moment: $\mu_\nu(t)$
- Scale factor: $a(t)^3$
- Smearing function: $F[\boldsymbol{x} - \boldsymbol{x}_\nu(t), t]$
- Detector's trajectory: $\boldsymbol{x}_\nu(t)$, $\eta(t)$





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***

How is **B's excitation probability** modulated by the interaction of A with the field?

-Initial state: $\rho_0 = \rho_{A0} \otimes \rho_{B0} \otimes |0\rangle\langle 0|$

$\rho_{\nu 0} = |\psi_{\nu 0}\rangle\langle\psi_{\nu 0}|$

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

-At time *T*: $\rho(T) = U_T \rho_0 U_T^\dagger$

Taking λ_ν small, perturbative expansion: $U_T = \mathbb{I} + U_T^{(1)} + U_T^{(2)}$

$$\rho_B(T) \simeq \mathrm{Tr}_{A,\Phi}\left[\rho_0 + U_T^{(1)}\rho_0 + \rho_0 {U_T^{(1)}}^\dagger + U_T^{(1)}\rho_0 {U_T^{(1)}}^\dagger + U_T^{(2)}\rho_0 + \rho_0 {U_T^{(2)}}^\dagger\right]$$

How is **B's excitation probability** modulated by the interaction of A with the field?

-Initial state: $\rho_0 = \rho_{A0} \otimes \rho_{B0} \otimes |0\rangle\langle 0|$

$$\rho_{\nu 0} = |\psi_{\nu 0}\rangle\langle\psi_{\nu 0}|$$

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

-At time *T*: $\rho(T) = U_T \rho_0 U_T^\dagger$

Taking λ_ν small, perturbative expansion: $U_T = \mathbb{I} + U_T^{(1)} + U_T^{(2)}$

$$\rho_B(T) \simeq \rho_{B0} + \lambda_B^2 \left(\cdots\cdots \right) + \lambda_A \lambda_B \left(\boxed{S_2} \cdots\cdots \right) + \mathcal{O}(\lambda_\nu^4)$$

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

SIGNALING
ESTIMATOR, *S*

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

$$S_2 = 4 \int \mathrm{d}t \int \mathrm{d}t' \chi_A(t) \chi_B(t') \mathrm{Re}(\alpha_A^* \beta_A e^{\mathrm{i}\Omega_A t}) \mathrm{Re}(\alpha_B^* \beta_B e^{\mathrm{i}\Omega_B t'} [\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t']))$$

SIGNALING ESTIMATOR, *S*

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

(INDEPENDENT OF STATE OF Φ)

$$S_2 = 4 \int \mathrm{d}t \int \mathrm{d}t' \chi_A(t) \chi_B(t') \mathrm{Re}(\alpha_A^* \beta_A e^{\mathrm{i}\Omega_A t}) \mathrm{Re}(\alpha_B^* \beta_B e^{\mathrm{i}\Omega_B t'} [\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')])$$

CONFORMAL COUPLING

$$[\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{\mathrm{i}}{4\pi} \frac{\delta(\Delta\eta + R) - \delta(\Delta\eta - R)}{a(t) a(t') R}$$

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

$$R = \| \vec{x}_A - \vec{x}_B \|$$

COMMUTATOR

CONFORMAL COUPLING

support on the light cone

$$[\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{\mathrm{i}}{4\pi} \frac{\delta(\Delta\eta + R) - \delta(\Delta\eta - R)}{a(t)a(t')R}$$

Decay with Spatial separation

CONFORMAL INVARIANCE
NO VIOLATION OF STRONG HUYGENS PRINCIPLE

COMMUTATOR

CONFORMAL COUPLING

support on the light cone

$$[\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{\mathrm{i}}{4\pi} \frac{\delta(\Delta\eta + R) - \delta(\Delta\eta - R)}{a(t)a(t')R}$$

Decay with Spatial separation

BUT...WHAT HAPPENS IF WE CONSIDER **MINIMAL** COUPLING?

COMMUTATOR

MINIMAL COUPLING

$$[\Phi(\vec{x}_A,t),\Phi(\vec{x}_B,t')] = \mathrm{i}\frac{\theta(-\Delta\eta)-\theta(\Delta\eta)}{\pi^2 a(t)a(t')R}\int_0^\infty dk\,\sin(kR)\,g_\alpha(\eta(t),\eta(t'),k)$$

$$g_\alpha(\eta,\eta',k) = \sqrt{\frac{\eta}{\eta'}}\frac{J_\alpha(k\eta)Y_\alpha(k\eta')-Y_\alpha(k\eta)J_\alpha(k\eta')}{Y_\alpha(k\eta')\left[J_{\alpha-1}(k\eta')-J_{\alpha+1}(k\eta')\right]-J_\alpha(k\eta')\left[Y_{\alpha-1}(k\eta')-Y_{\alpha+1}(k\eta')\right]}$$

J_α , Y_α BESSEL FUNCTIONS $\qquad \alpha = \frac{3-3w}{6w+2}$

COMMUTATOR

MINIMAL COUPLING

$$[\Phi(\vec{x}_A,t),\Phi(\vec{x}_B,t')] = \mathrm{i}\,\frac{\theta(-\Delta\eta)-\theta(\Delta\eta)}{\pi^2 a(t)a(t')R}\int_0^\infty dk\,\sin(kR)\,g_\alpha(\eta(t),\eta(t'),k)$$

$$g_\alpha(\eta,\eta',k) = \sqrt{\frac{\eta}{\eta'}}\,\frac{J_\alpha(k\eta)Y_\alpha(k\eta')-Y_\alpha(k\eta)J_\alpha(k\eta')}{Y_\alpha(k\eta')\left[J_{\alpha-1}(k\eta')-J_{\alpha+1}(k\eta')\right]-J_\alpha(k\eta')\left[Y_{\alpha-1}(k\eta')-Y_{\alpha+1}(k\eta')\right]}$$

$J_\alpha\,,Y_\alpha$ BESSEL FUNCTIONS $\qquad \alpha = \frac{3-3w}{6w+2}$

MATTER DOMINATED UNIVERSE $\longrightarrow$ $w=0$, $\alpha = 3/2$ $\longrightarrow$ $a \propto \eta^2 \propto t^{2/3}$

$$[\Phi(\vec{x}_A,t),\Phi(\vec{x}_B,t')] = \frac{\mathrm{i}}{4\pi}\left[\frac{\delta(\Delta\eta+R)-\delta(\Delta\eta-R)}{a(t)a(t')R} + \frac{\theta(-\Delta\eta-R)-\theta(\Delta\eta-R)}{a(t)a(t')\eta(t)\eta(t')}\right]$$

COMMUTATOR

CONFORMAL COUPLING

support on the light cone

$$[\Phi(\vec{x}_A,t),\Phi(\vec{x}_B,t')] = \frac{\mathrm{i}}{4\pi}\frac{\delta(\Delta\eta+R)-\delta(\Delta\eta-R)}{a(t)a(t')R}$$

Decay with Spatial separation

MINIMAL COUPLING

$$[\Phi(\vec{x}_A,t),\Phi(\vec{x}_B,t')] = \frac{\mathrm{i}}{4\pi}\left[\frac{\delta(\Delta\eta+R)-\delta(\Delta\eta-R)}{a(t)a(t')R}+\frac{\theta(-\Delta\eta-R)-\theta(\Delta\eta-R)}{a(t)a(t')\eta(t)\eta(t')}\right]$$

COMMUTATOR

CONFORMAL COUPLING

support on the light cone

$$[\Phi(\vec{x}_A,t),\Phi(\vec{x}_B,t')] = \frac{\mathrm{i}}{4\pi}\frac{\delta(\Delta\eta+R)-\delta(\Delta\eta-R)}{a(t)a(t')R}$$

Decay with Spatial separation

VIOLATION OF STRONG HUYGENS PRINCIPLE !!!!

MINIMAL COUPLING

$$[\Phi(\vec{x}_A,t),\Phi(\vec{x}_B,t')] = \frac{\mathrm{i}}{4\pi}\left[\frac{\delta(\Delta\eta+R)-\delta(\Delta\eta-R)}{a(t)a(t')R}+\frac{\theta(-\Delta\eta-R)-\theta(\Delta\eta-R)}{a(t)a(t')\eta(t)\eta(t')}\right]$$

Does NOT decay with Spatial separation

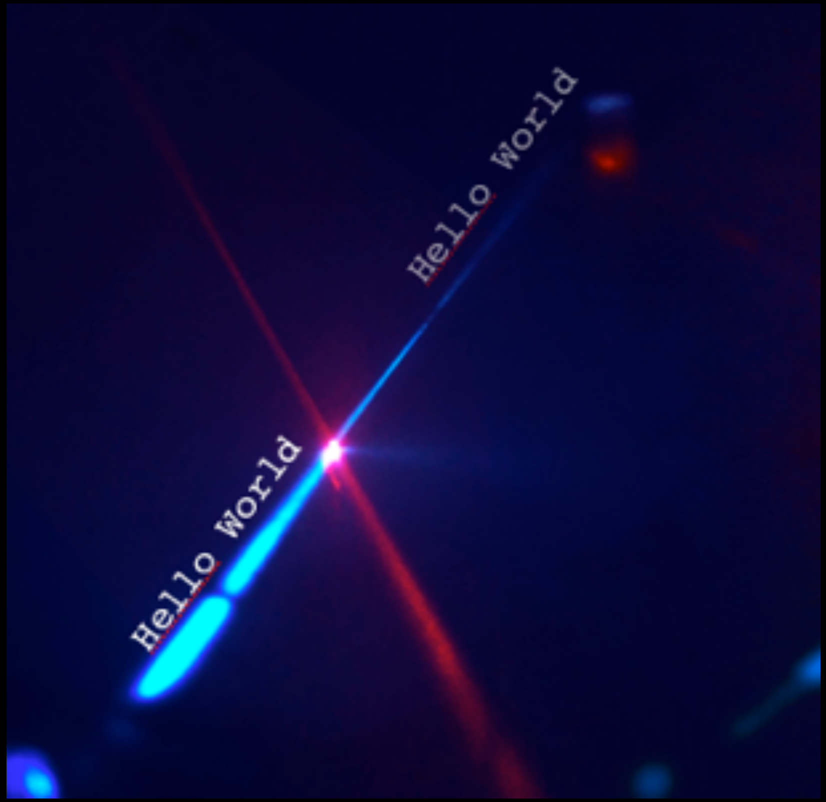
Timelike-leakage

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.

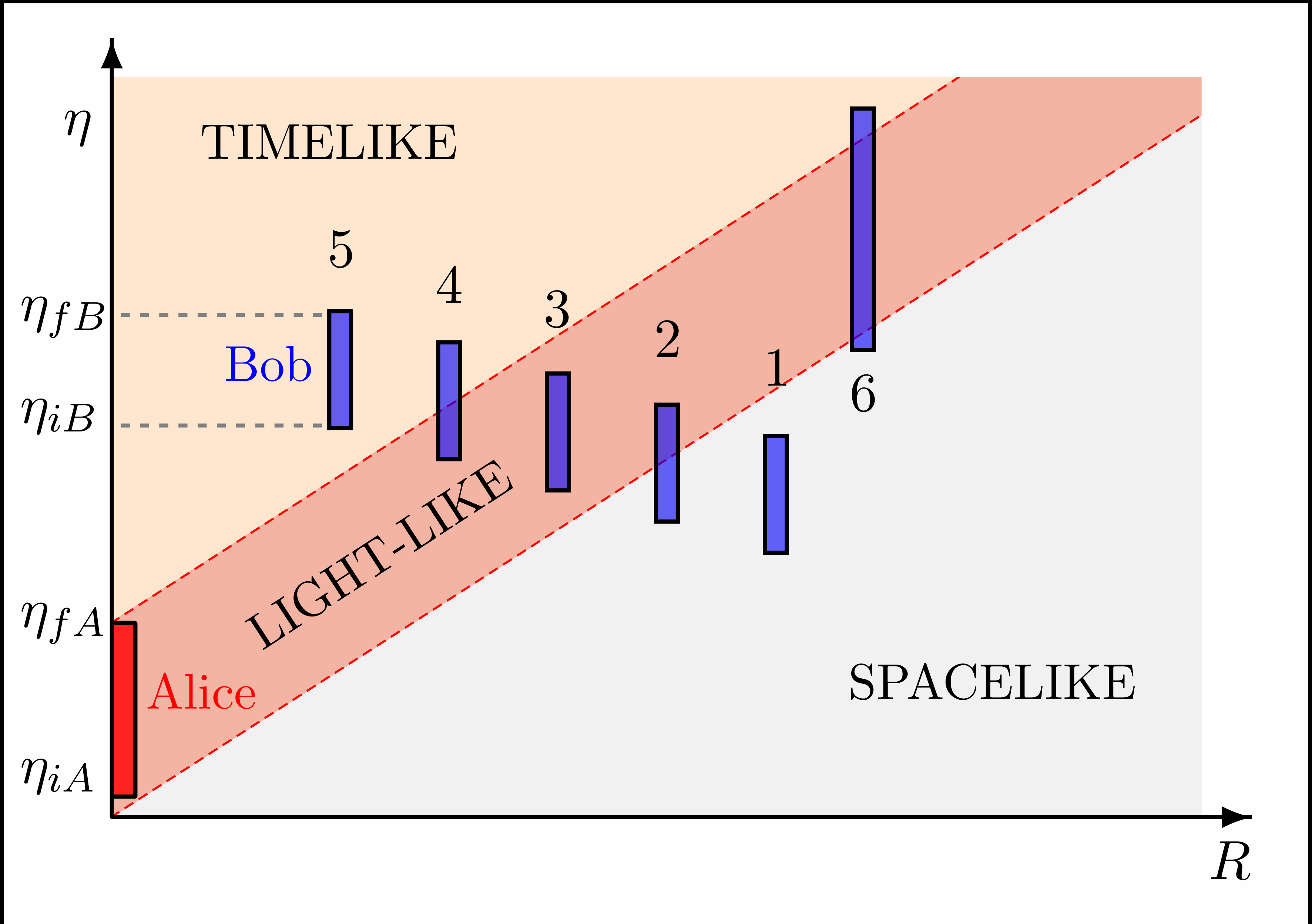
- Later **Bob** switches on B and measures its energy. If B is excited, Bob interprets a “**1**", and a “**0**" otherwise.

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



(noisy asymetric binary channel)

A&B **CAUSAL** RELATIONSHIPS

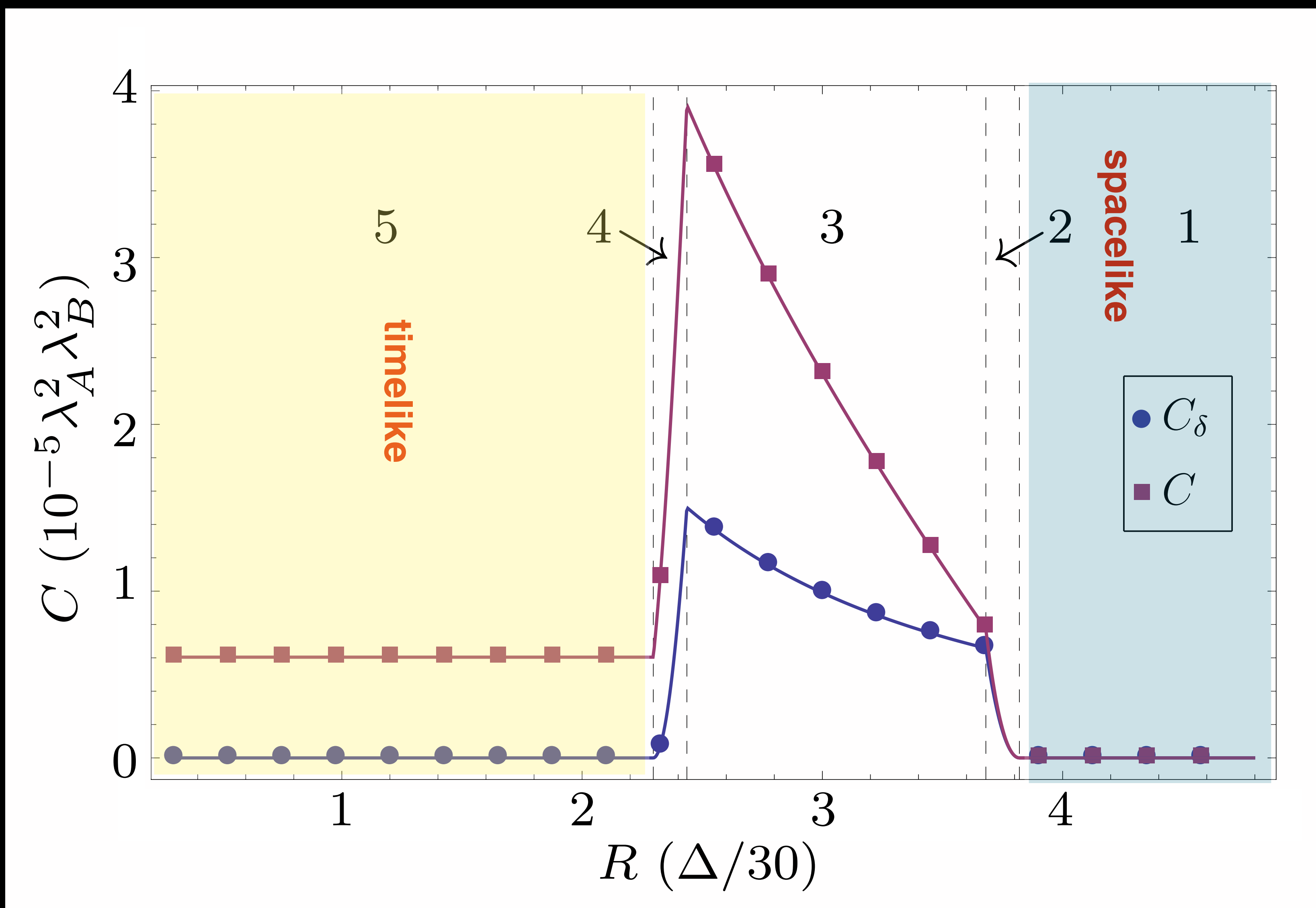


$$\eta_{i\nu} \equiv \eta(T_{i\nu})$$

$$\eta_{f\nu} \equiv \eta(T_{f\nu})$$

CHANNEL
CAPACITY

VARIATION WITH THE **SPATIAL SEPARATION** BETWEEN ALICE AND BOB



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

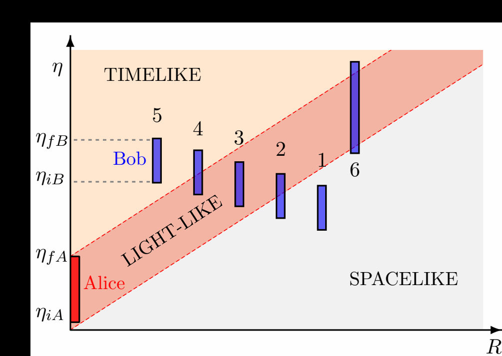
$$|\alpha_A| = |\beta_A| = 1/\sqrt{2}$$

$$\arg(\alpha_A) - \arg(\beta_A) = \pi$$

$$\arg(\alpha_B) - \arg(\beta_B) = \pi/2$$

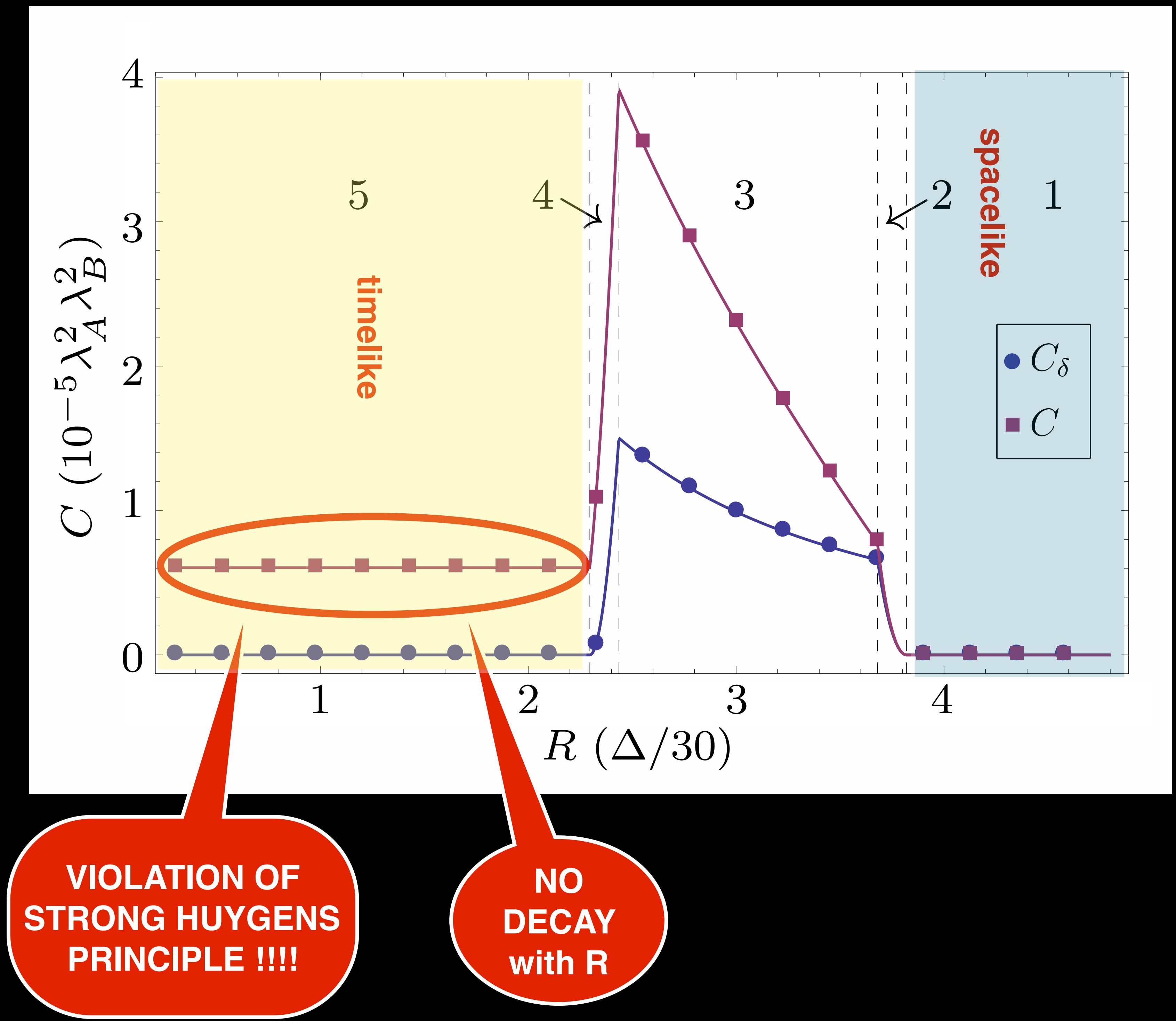
$$T_{fA} - T_{iA} = T_{fB} - T_{iB} = \Delta$$

$$T_{iA} = \Delta/30 \qquad T_{iB} = 10\Delta$$



CHANNEL
CAPACITY

VARIATION WITH THE **SPATIAL SEPARATION** BETWEEN ALICE AND BOB



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

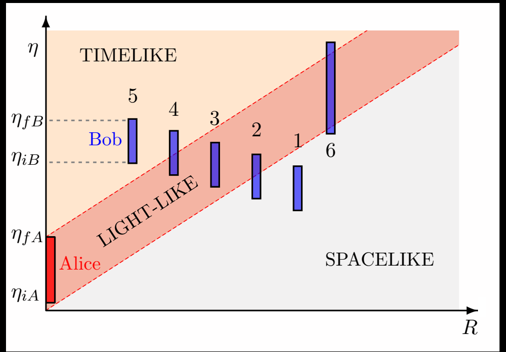
$$|\alpha_A| = |\beta_A| = 1/\sqrt{2}$$

$$\arg(\alpha_A) - \arg(\beta_A) = \pi$$

$$\arg(\alpha_B) - \arg(\beta_B) = \pi/2$$

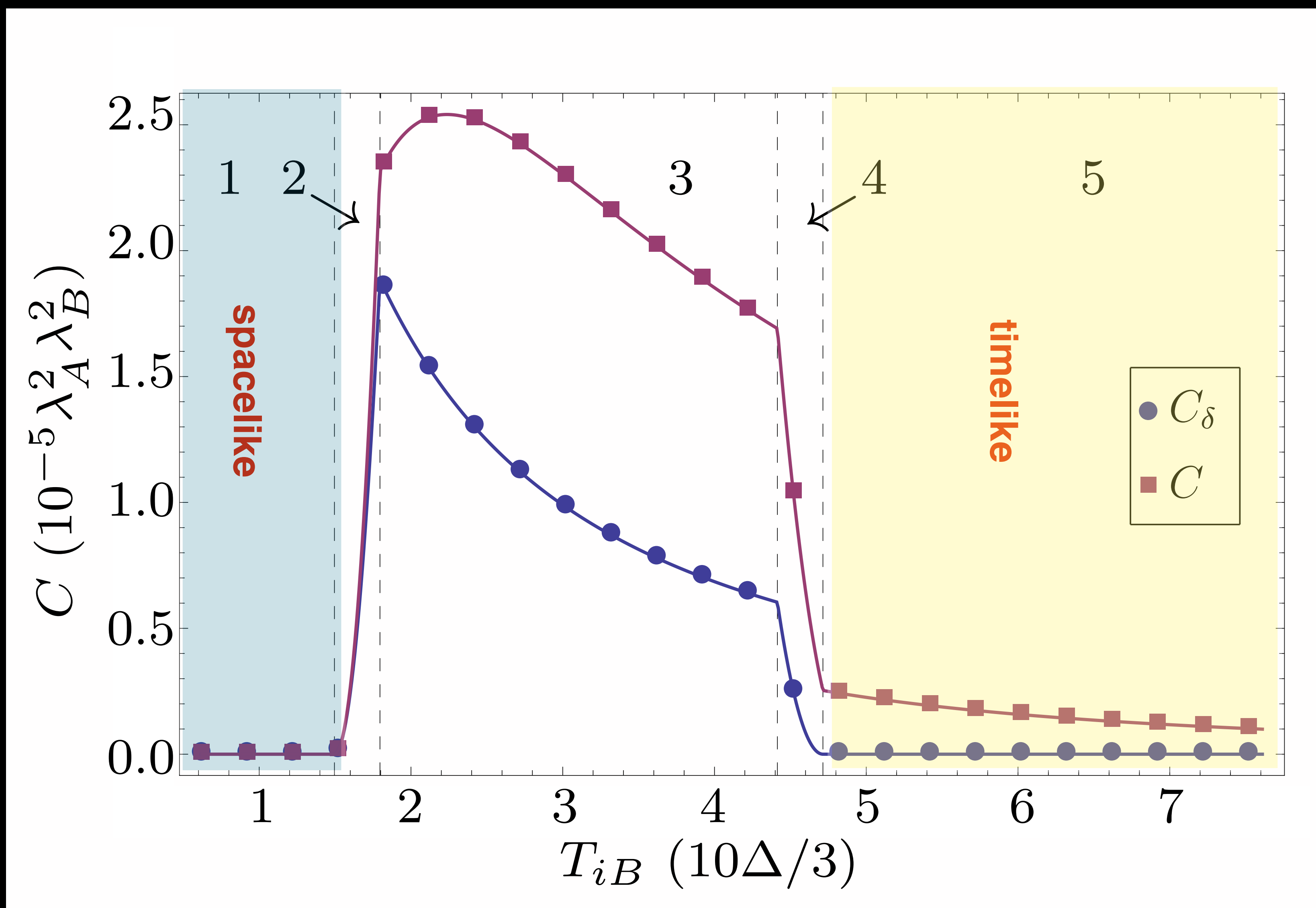
$$T_{fA} - T_{iA} = T_{fB} - T_{iB} = \Delta$$

$$T_{iA} = \Delta/30 \qquad T_{iB} = 10\Delta$$



CHANNEL
CAPACITY

VARIATION WITH THE **TEMPORAL SEPARATION** BETWEEN ALICE AND BOB



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

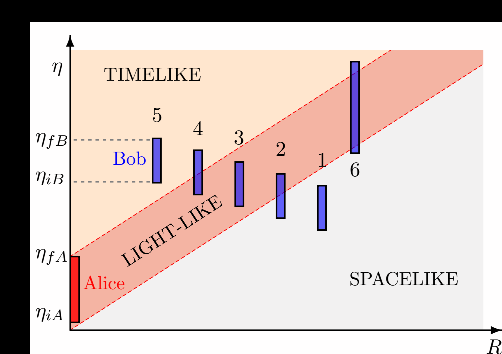
$$|\alpha_A| = |\beta_A| = 1/\sqrt{2}$$

$$\arg(\alpha_A) - \arg(\beta_A) = \pi$$

$$\arg(\alpha_B) - \arg(\beta_B) = \pi/2$$

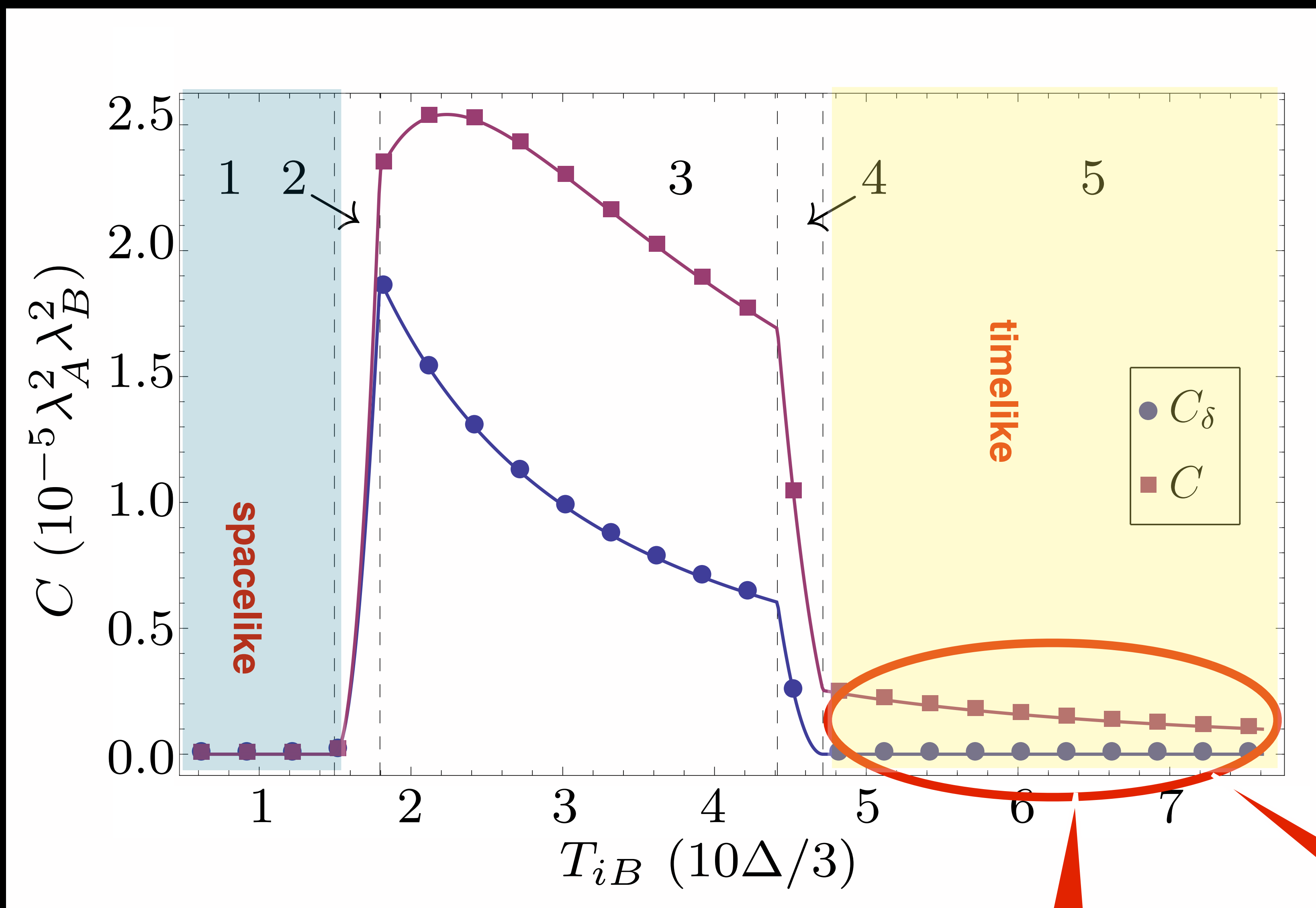
$$T_{fA} - T_{iA} = T_{fB} - T_{iB} = \Delta$$

$T_{iA} = \Delta/30$ $\qquad R = \Delta/10$



CHANNEL **CAPACITY**

VARIATION WITH THE **TEMPORAL SEPARATION** BETWEEN ALICE AND BOB



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

$$|\alpha_A| = |\beta_A| = 1/\sqrt{2}$$

$$\arg(\alpha_A) - \arg(\beta_A) = \pi$$

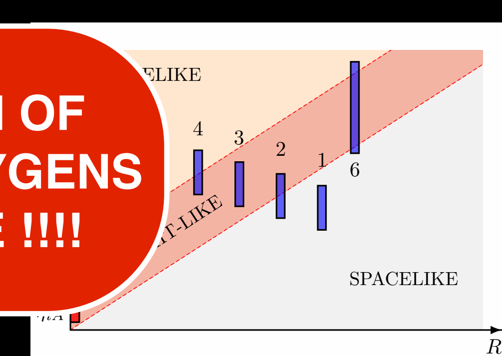
$$\arg(\alpha_B) - \arg(\beta_B) = \pi/2$$

$$T_{fA} - T_{iA} = T_{fB} - T_{iB} = \Delta$$

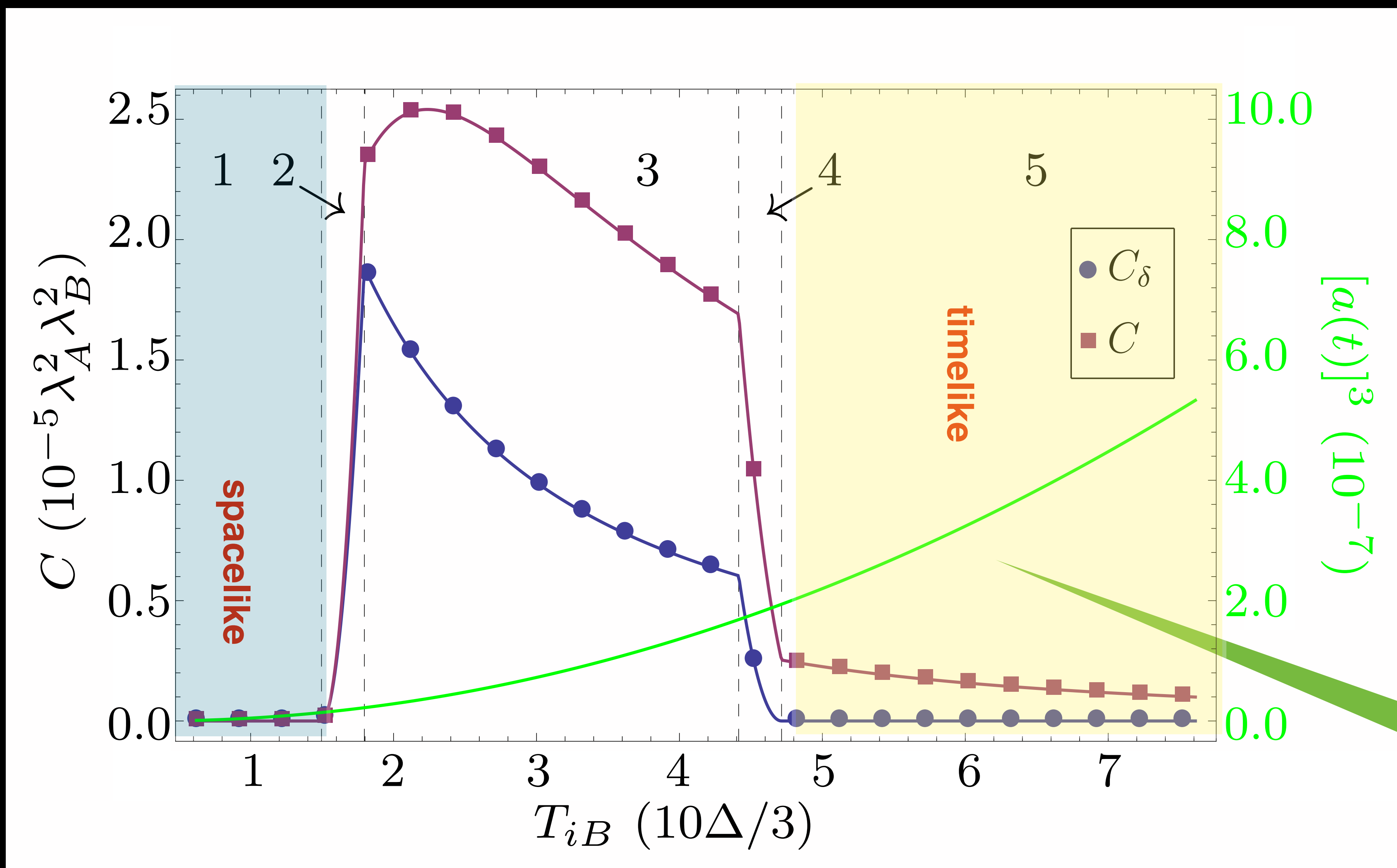
$$T_{iA} = \Delta/30 \qquad R = \Delta/10$$

DECAY, could we compensate it?

VIOLATION OF STRONG HUYGENS PRINCIPLE !!!!



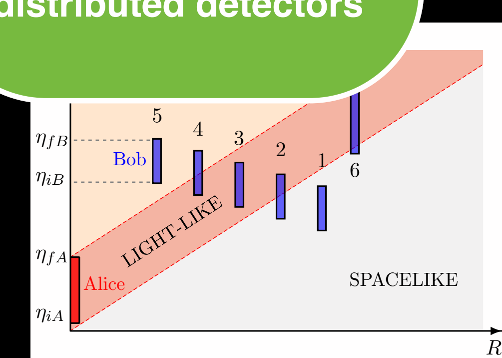
VARIATION WITH THE **TEMPORAL SEPARATION** BETWEEN ALICE AND BOB



$$S_2 \propto \ln\left(\frac{\eta_{fA}}{\eta_{iA}}\right)\ln\left(\frac{\eta_{fB}}{\eta_{iB}}\right)$$

$$\eta_{iB} = \eta(T_{iB})$$

compensate decay with distributed detectors



THE **ELECTROMAGNETIC TENSOR** $F_{\mu\nu}$ IS CONFORMALLY INVARIANT

⟶ IT **DOES NOT VIOLATE** STRONG HUYGENS PRINCIPLE

THE **ELECTROMAGNETIC TENSOR** $F_{\mu\nu}$

IS CONFORMALLY INVARIANT

→ IT **DOES NOT VIOLATE** STRONG HUYGENS PRINCIPLE

BUT

THE **ELECTROMAGNETIC POTENTIAL** A_μ **DOES** VIOLATE IT

Charged currents couple to A_μ. Electromagnetic **antennas will see** the strong Huygens principle **violation** (in the same fashion they see e.g. the Aharonov-Bohm effect or Casimir forces.)

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.

OUR RESULTS MAY PERHAPS INSPIRE NOVEL WAYS TO LOOK AT THE EARLY UNIVERSE VIA THE TIMELIKE SIGNALS

NAME THAT EXOPLANET
The rush to go down in astronomical history

NewScientist

WEEKLY January 24 - 30, 2015

Dig that reverb

Ancient echoes speak to us from the big bang


NAME THAT EXOPLANET
The rush to go down in astronomical history
NewScientist
WEEKLY January 24 - 30, 2015
Dig that reverb
Ancient echoes speak to us from the big bang

THANK YOU