18/02/2015
TUX - AUSTRIA

A GLIMPSE OF THE EARLY UNIVERSE WITHOUT REAL LIGHT

arXiv:1501.01650

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THIRD EFI WINTER CONFERENCE ON QUANTUM GRAVITY

GOAL

CONSEQUENCES IN RELATIVISTIC QUANTUM COMMUNICATION OF THE **VIOLATION** OF THE STRONG **HUYGENS** PRINCIPLE

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.

STRONG **HUYGENS PRINCIPLE**

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

$\longrightarrow$ 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, …]

CONSEQUENCES IN RELATIVISTIC QUANTUM COMMUNICATION IN **COSMOLOGY**

Propagation of information from the early Universe to the current era

SET UP:

SPACETIME GEOMETRY

SPATIALLY **FLAT**, **OPEN**, **FRW** SPACETIME:

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

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:

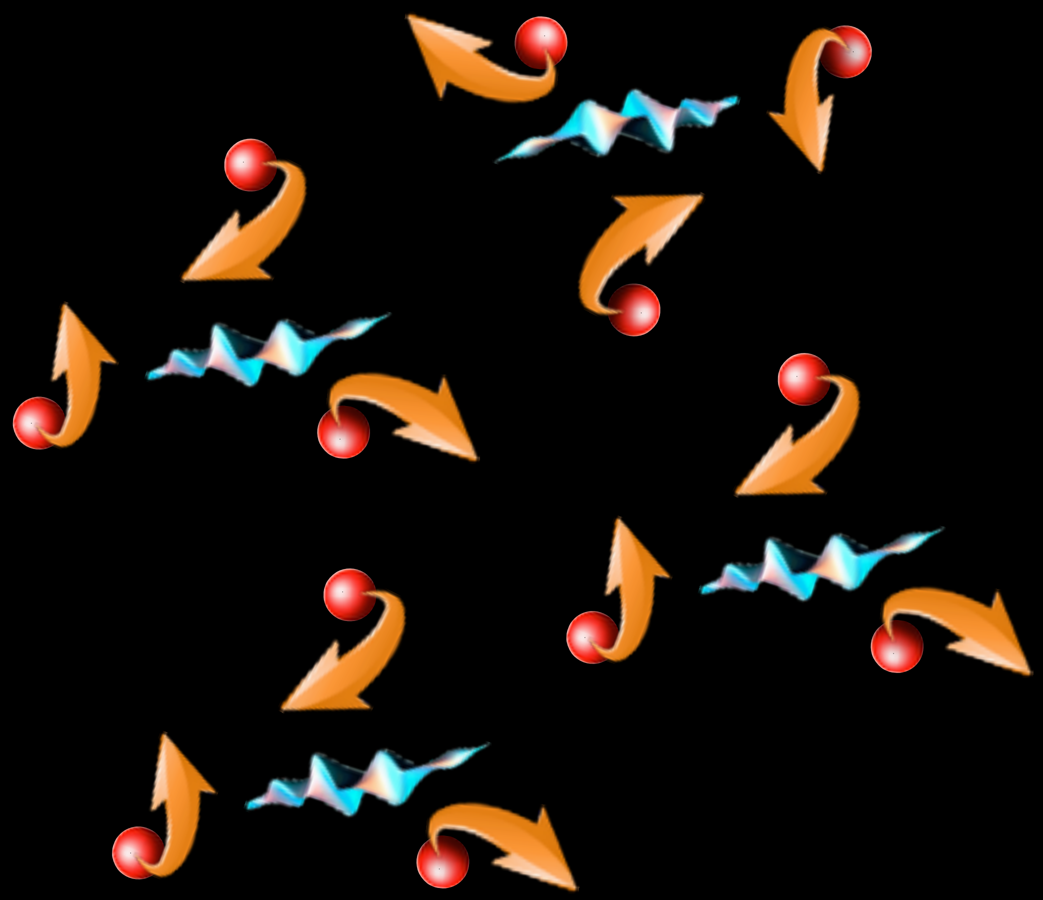
a **perfect fluid** with a constant pressure-to-density ratio $\boxed{p = w\rho}$ $w > -1$

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

SET UP:

TEST FIELD

A TEST **MASSLESS SCALAR FIELD** QUANTIZED e.g. IN THE ADIABATIC VACUUM WILL BE COUPLED TO THIS BACKGROUND GEOMETRY



Φ

CONFORMAL COUPLING

VS

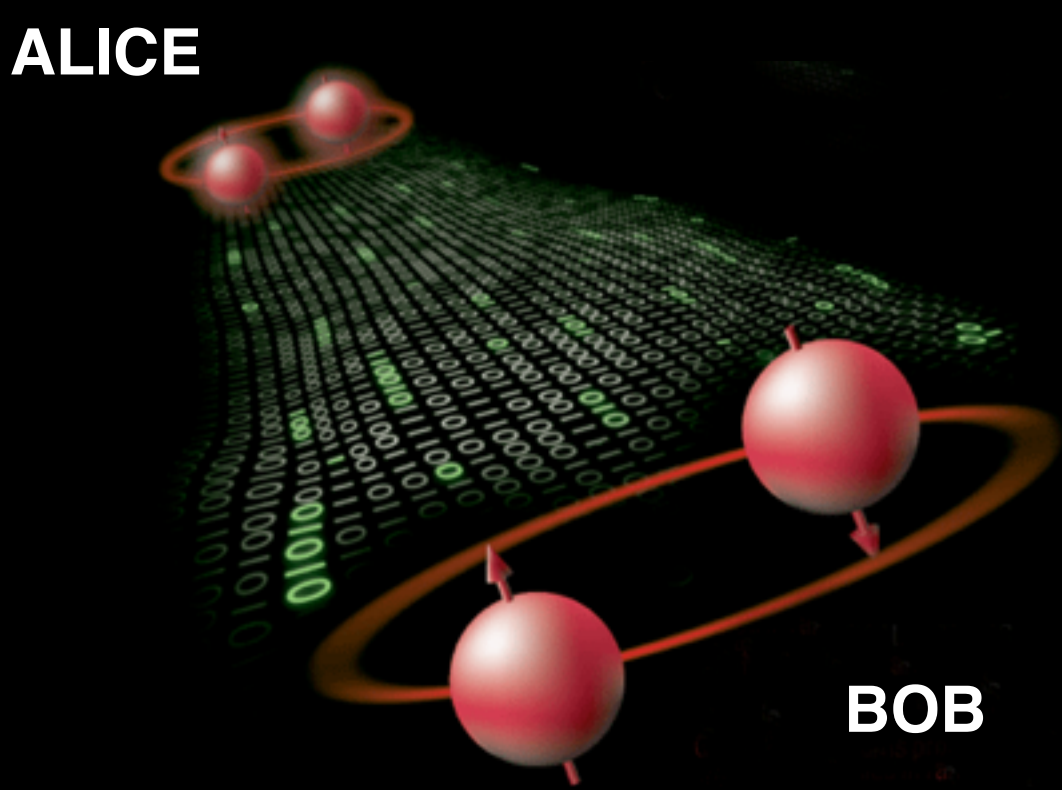
MINIMAL COUPLING

SET UP:

OBSERVERS: ALICE AND BOB

COMOVING OBSERVERS: GEODESIC OBSERVERS THAT SEE **ISOTROPY.**

ALICE (EARLY UNIVERSE OBSERVER) **& BOB** (LATE TIME OBSERVER)



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

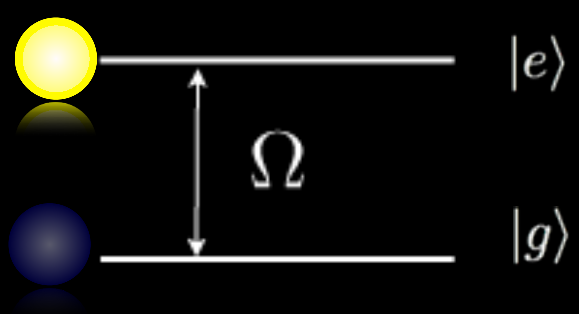
They can perform measurements on it indirectly by **locally coupling 'particle detectors'**

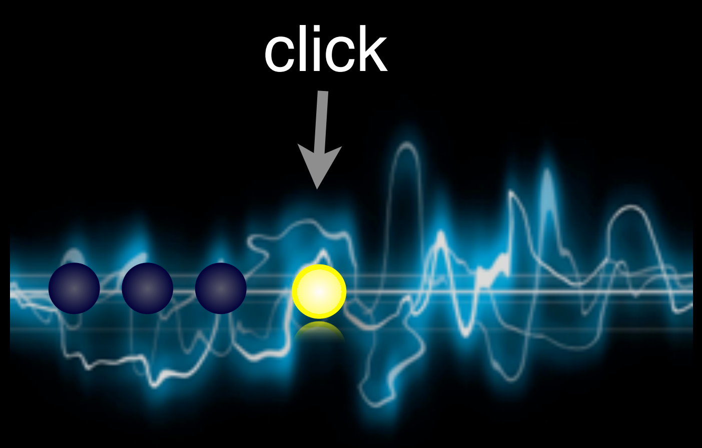
Information is **encoded** in the **quantum state of the field**

ALICE & BOB's
DETECTOR MODEL

Unruh-DeWitt DETECTOR

-Two-level system





Models **light-matter interaction** when there is no exchange of orbital angular momentum

-Interaction Hamiltonian (interaction picture):

$$H_{I,\nu} = \lambda_\nu \chi_\nu(t) \mu_\nu(t) \Phi[\vec{x}_\nu, \eta(t)]$$

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

DETECTOR-FIELD
INTERACTION HAMILTONIAN

$$H_{I,\nu} = \lambda_\nu \chi_\nu(t) \mu_\nu(t) \Phi[\vec{x}_\nu, \eta(t)]$$

Monopole moment

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

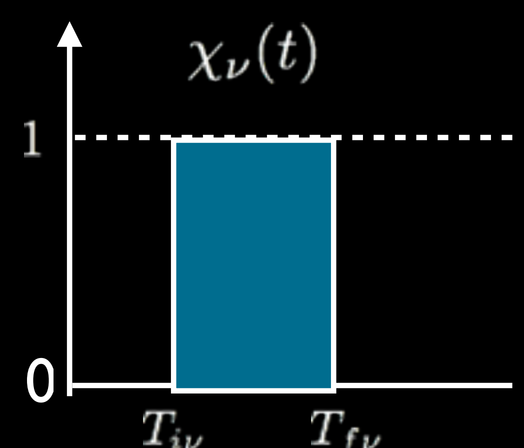
$$H_{I,\nu} = \lambda_\nu \chi_\nu(t) \mu_\nu(t) \Phi[\vec{x}_\nu, \eta(t)]$$

Coupling strength

Detector's world-line

Comoving detectors
$\vec{x}(t) = \vec{x}_\nu = \text{cte}$

Switching function



DETECTOR-FIELD
INTERACTION HAMILTONIAN

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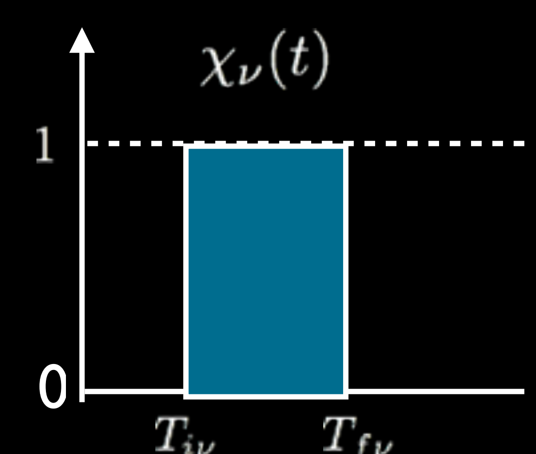

Total Interaction Hamiltonian:

$$H_I = H_{I,A} + H_{I,B}$$

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?

We need to look at the ([1,1] component of the) partial density matrix of B, $\rho_B(T)$

-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: $U_T = \mathbb{I} + U_T^{(1)} + U_T^{(2)}$

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

SIGNALING
ESTIMATOR, *S*

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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*

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

(INDEPENDENT OF STATE OF Φ)

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

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ESTIMATOR, *S*

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

COMMUTATOR

MINIMAL COUPLING

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

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

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

$$J_{3/2}(k\eta) = \sqrt{\frac{2}{\pi k\eta}}\left[-\cos(k\eta)+\frac{\sin(k\eta)}{k\eta}\right]$$

$$Y_{3/2}(k\eta) = \sqrt{\frac{2}{\pi k\eta}}\left[-\sin(k\eta)+\frac{\cos(k\eta)}{k\eta}\right]$$

COMMUTATOR

MINIMAL COUPLING

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

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

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

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

SIGNALING
ESTIMATOR, *S*

MINIMAL COUPLING & **MATTER** DOMINATED UNIVERSE

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

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

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

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

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

S_2 HAS ANALYTICAL EXPRESSION FOR $\Omega_\nu = 0$

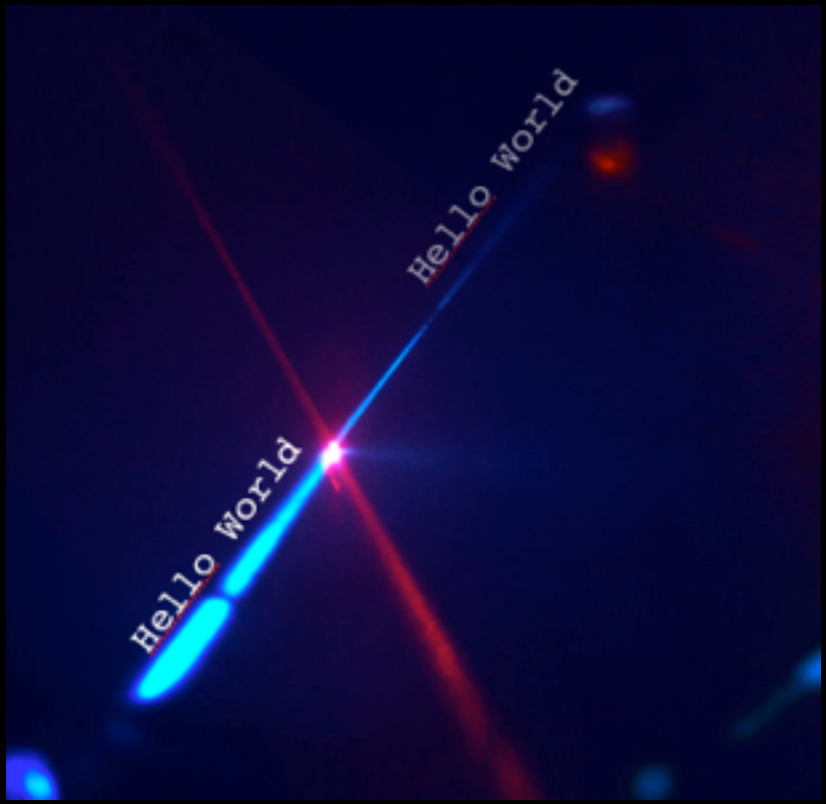
(e.g. electron-flip transitions)

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.

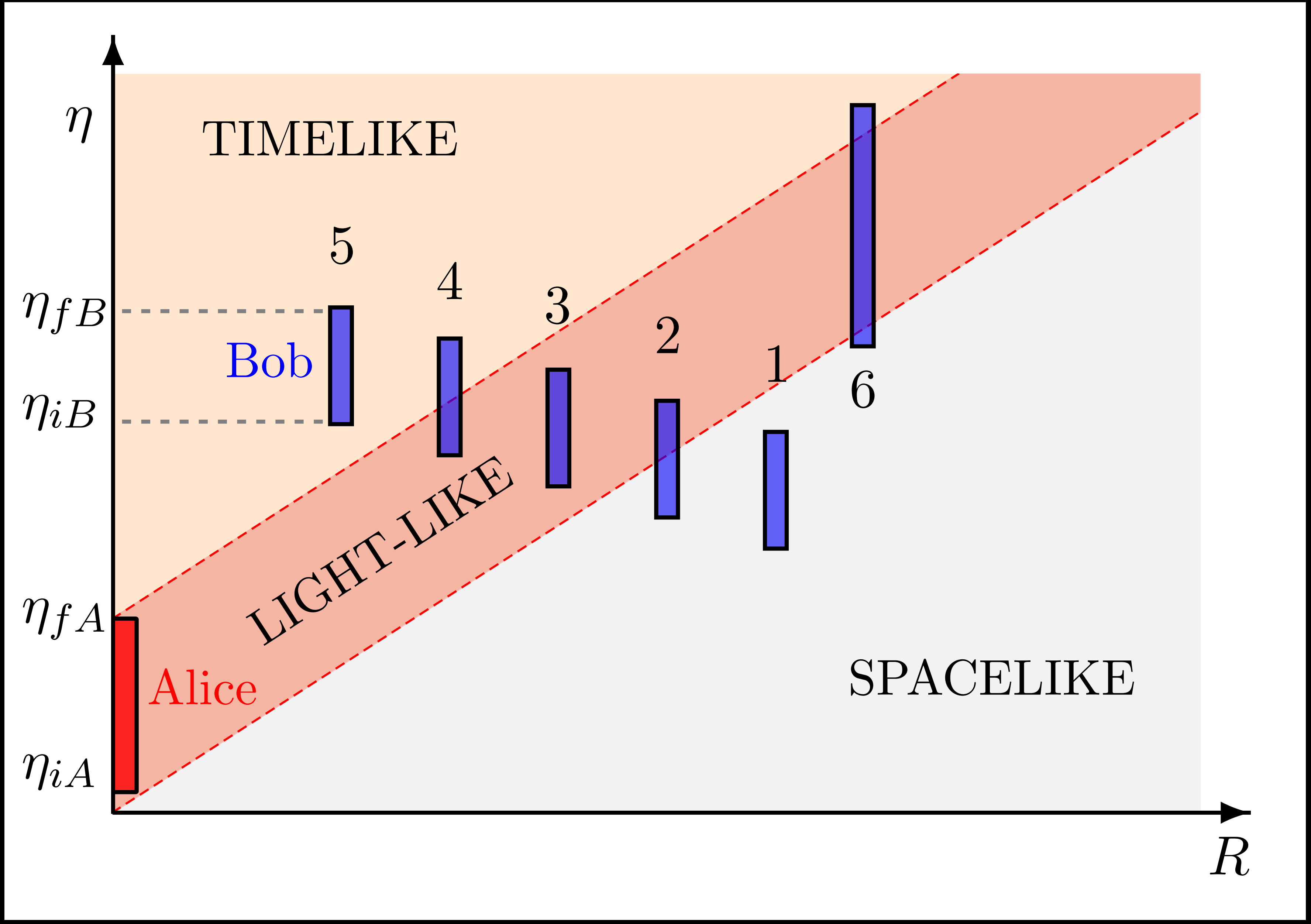
- Later **Bob** switches on B and measures its energy. If B is excited, Bob interprets a "**1**", and a "**0**" otherwise.

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



(noisy asymetric binary channel)

A&B **CAUSAL** RELATIONSHIPS

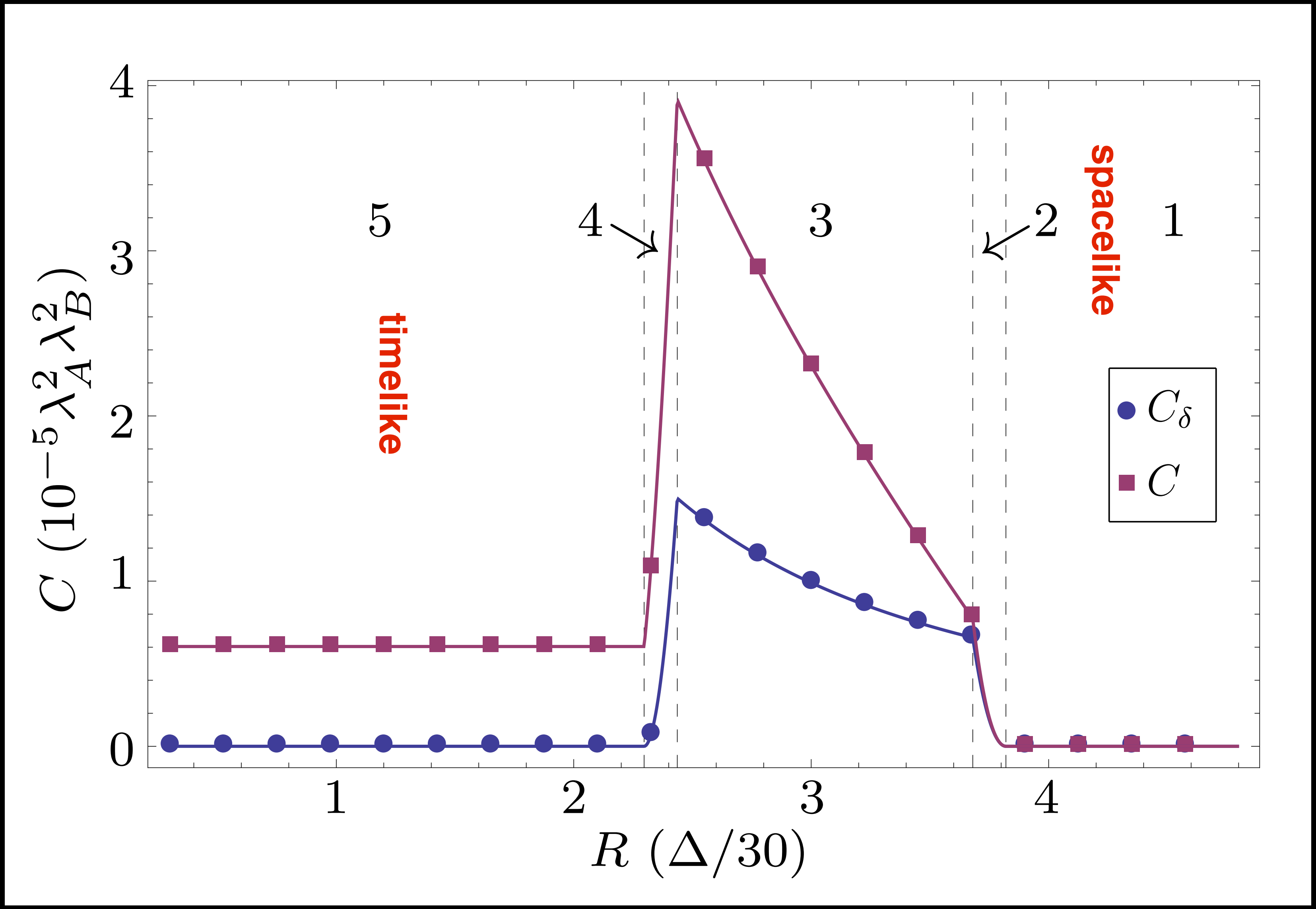


$$\eta_{i\nu} \equiv \eta(T_{i\nu})$$

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

CHANNEL
CAPACITY

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



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

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

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

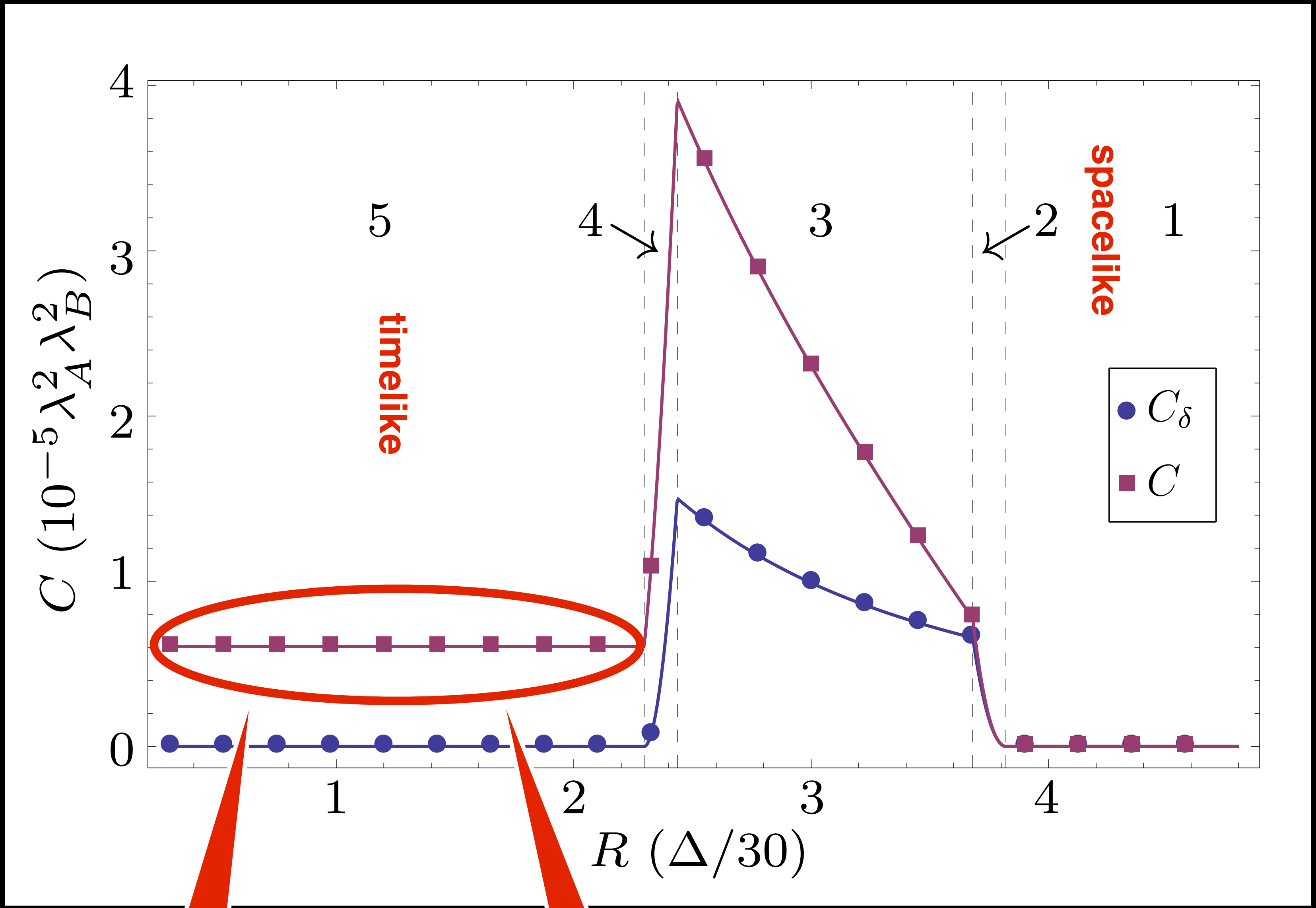
$$\arg(\alpha_B) - \arg(\beta_B) = \pi/2$$

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

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

CHANNEL
CAPACITY

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



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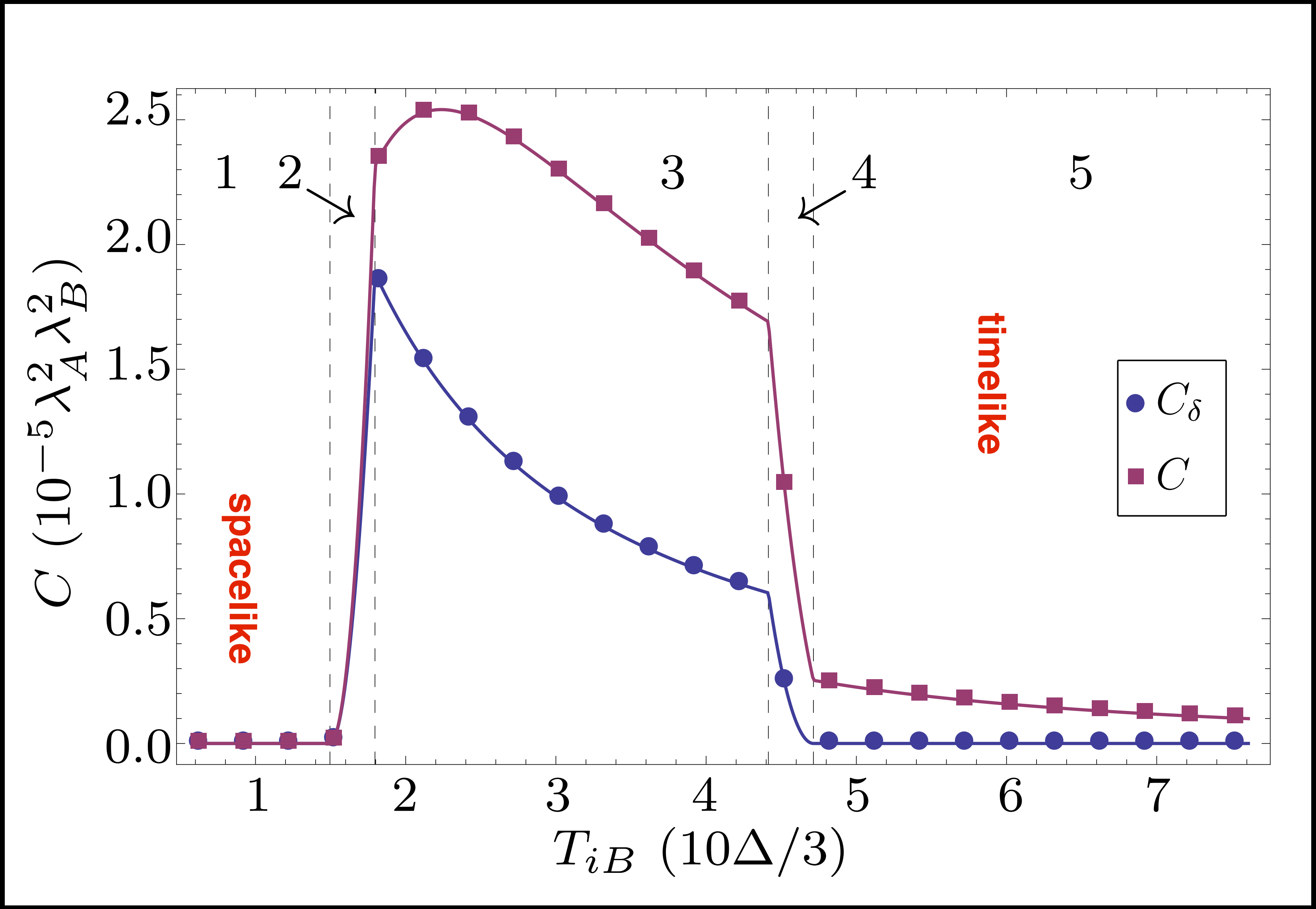
$$T_{iA} = \Delta/30 \qquad T_{iB} = 10\Delta$$

VIOLATION OF STRONG HUYGENS PRINCIPLE !!!!

NO DECAY with R

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



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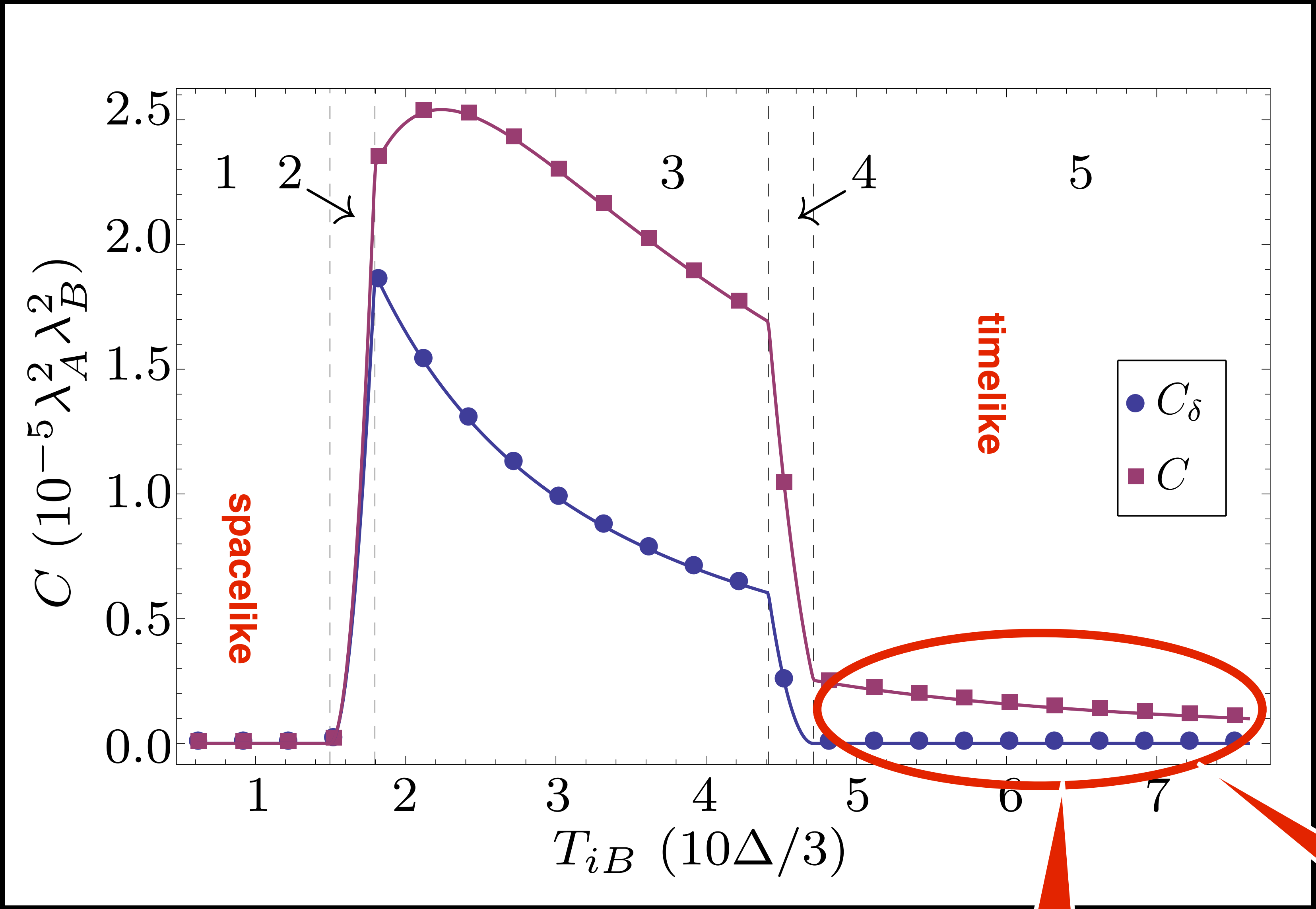
CHANNEL
CAPACITY

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



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

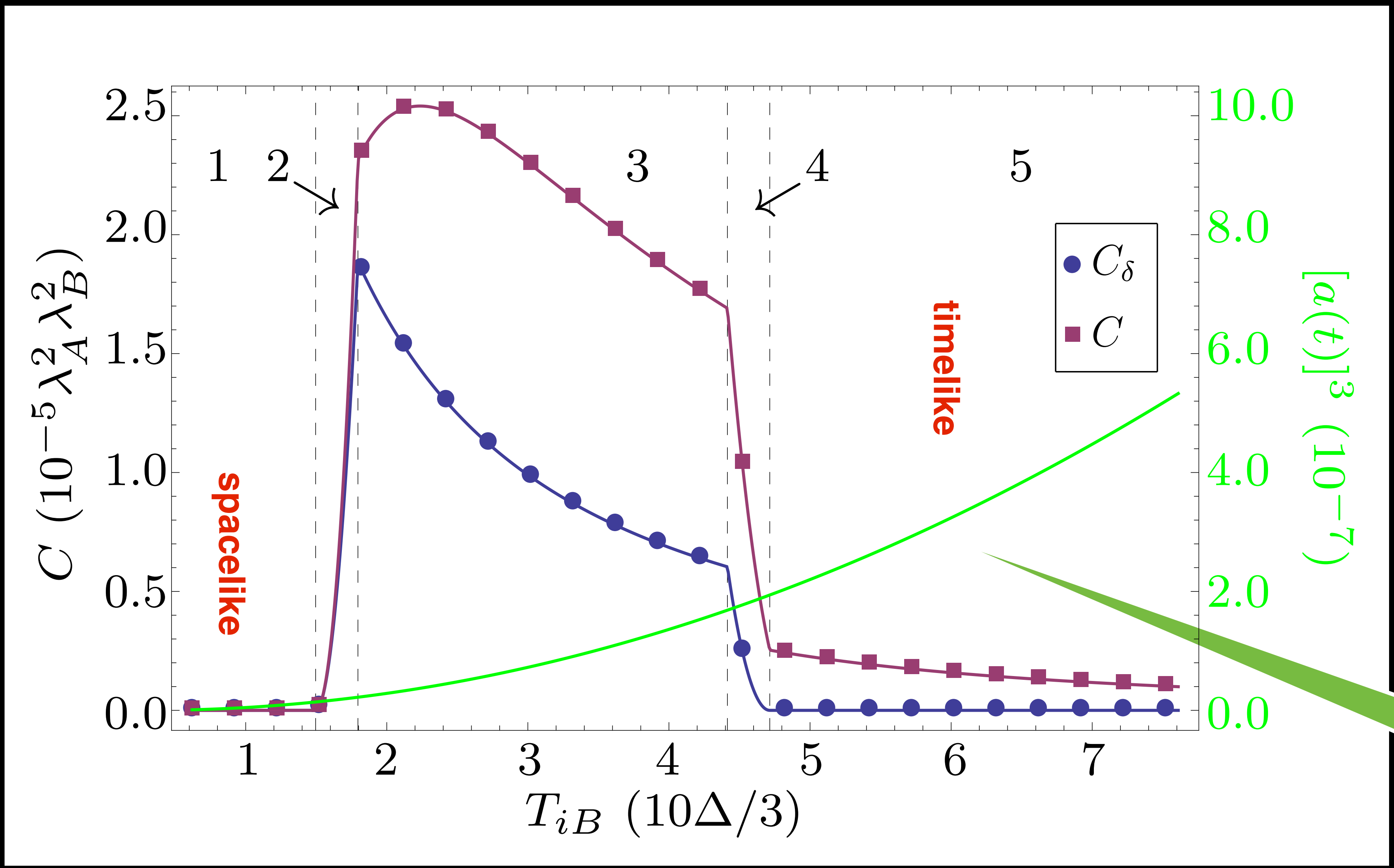
$$T_{iA} = \Delta/30 \qquad R = \Delta/10$$

DECAY, could we compensate it?

VIOLATION OF STRONG HUYGENS PRINCIPLE !!!!

CHANNEL
CAPACITY

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

$\longrightarrow$ IT **DOES NOT VIOLATE** STRONG HUYGENS PRINCIPLE

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

$\longrightarrow$ 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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THANK YOU