Title: Alice falls into a black hole: Entanglement in non-inertial frames

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Abstract:

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

Alice falls into a black hole:
Entanglement in non-inertial frames

quant-ph/0410172
and work in preparation…

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$$ds = \left(1-\frac{2m}{R}\right)dT^2 - \left(\frac{1}{1-2m/R}\right)dR^2$$

Change of coordinates

$$R-2m = x^2/8m$$

$$1-2m/R = (kx^2)/(1+(kx)^2) \approx (kx)^2$$

near $x = 0$ with $k = 1/4m$

$$R \approx 2m$$

$$a = k^{-1}$$

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near $x = 0$ with $k = 1/4m$

$$R \approx 2m$$

Schwarzschild space-time can be approximated by Rindler space

$$ds^2 = -(kx)^2 dT^2 + dx^2$$

$$T = a^{-1} e^{a\xi} \sinh a\eta, \quad x = a^{-1} e^{a\xi} \cosh a\eta \qquad a = k^{-1}$$

$$ds^2 = e^{2a\xi}(d\eta^2 - d\xi^2)$$

Outline

- Entanglement
- Relativity and entanglement
- Entanglement in non-inertial frames
- Proper entanglement

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- Current work

    Can one prepare states robust to acceleration?

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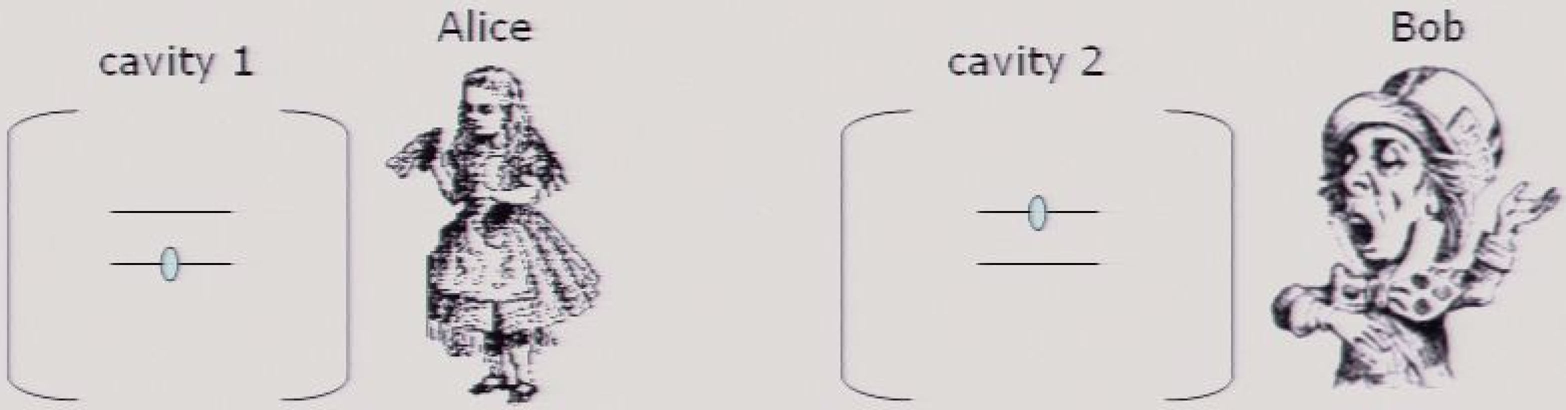
- Proper entanglement
- Alice falls into a black hole
- Current work
    - Can one prepare states robust to acceleration?
    - Signaling from a black hole?

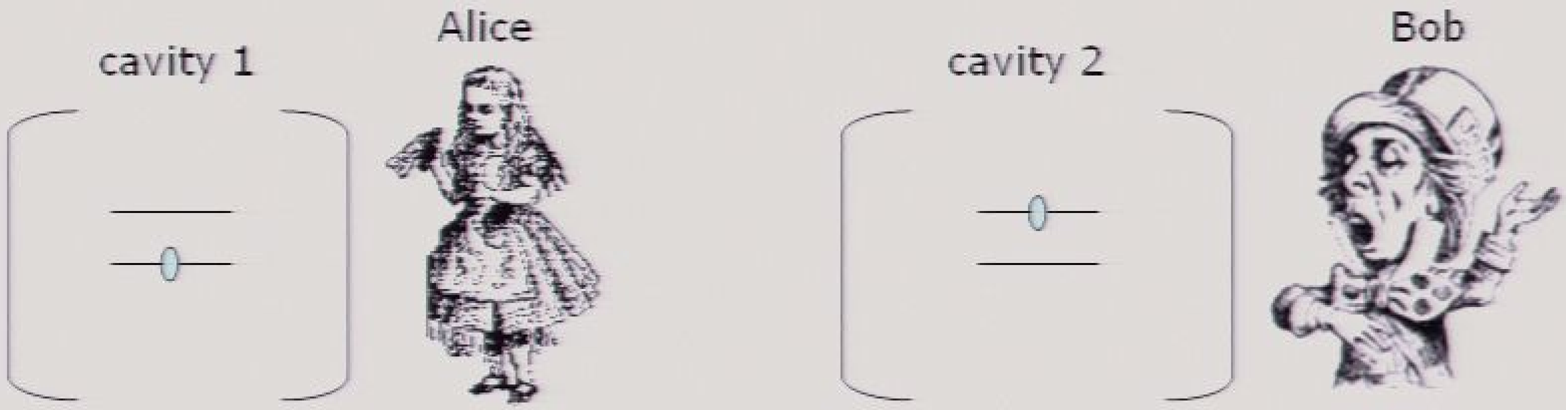
Entanglement



cavities: one-mode scalar field (for simplicity)

single photon excitation

Entanglement



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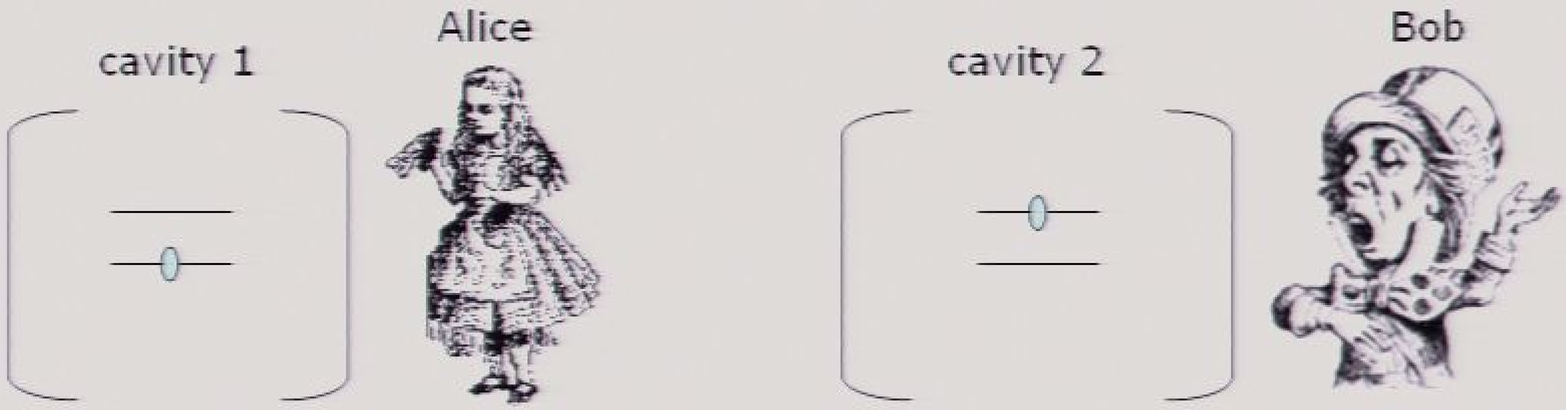
Separable state:

$$|\Phi\rangle_{AB} = |\phi\rangle_1^A \otimes |\psi\rangle_2^B$$

Local Operations and Classical Communication

Entanglement



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⇒ Local Operations and Classical Communication

Entangled state: Defined as non-separable

$$|\phi\rangle_{AB} = \frac{1}{\sqrt{2}}(|0\rangle_1^A|0\rangle_2^B + |1\rangle_1^A|1\rangle_2^B)$$

⇒ Cannot be prepared by LOCC

Maximal correlations when measured in any basis

Resource for information tasks: teleportation

Quantifying entanglement

For pure states:

$$|\Phi\rangle_{AB} = \sum_{ij} \omega_{ij} |i\rangle_1^A \otimes |j\rangle_2^B \quad \Longrightarrow \quad |\Phi\rangle_{AB} = \sum_{n} \omega_n |n\rangle_1^A \otimes |n\rangle_2^B$$

Schmidt decomposition

Quantifying entanglement

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Schmidt decomposition

Measure of entanglement: von-Neumann entropy $S(\rho) = -\mathrm{Tr}(\rho \log_2(\rho))$

$$S(\rho_{AB}) = 0 \qquad S(\rho_A) = S(\rho_B)$$

$$\rho_{AB} = |\Phi\rangle\langle\Phi| \qquad \rho_A = \mathrm{Tr}_B(\rho_{AB})$$

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For mixed states:

$$\rho_{AB} = \sum_{ijlm} p_{ijlm} |i\rangle|j\rangle\langle l|\langle m| \quad \Longrightarrow$$

No analogous Schmidt decomposition

Indeed entropy no longer quantifies entanglement....

Entanglement for mixed states

Separable state: $\rho_{AB} = \sum_i \alpha_{ij} \rho_A^i \otimes \rho_B^j$

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Decide if a state is separable or not: easy

Necessary separability condition:

The partial transpose of the density matrix has positive eigenvalues if the state is separable.

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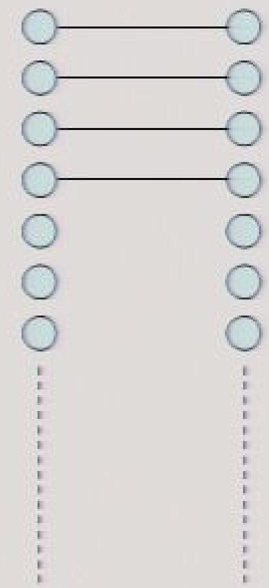

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Entanglement measures: hard

Entanglement cost

Relative entropy of entanglement

Entanglement of distillation

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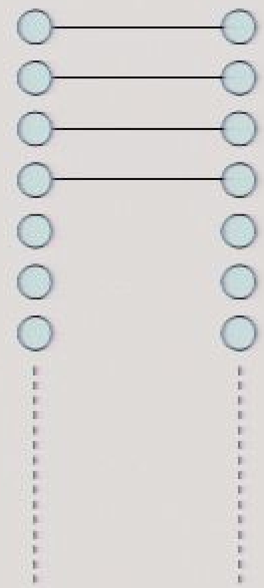

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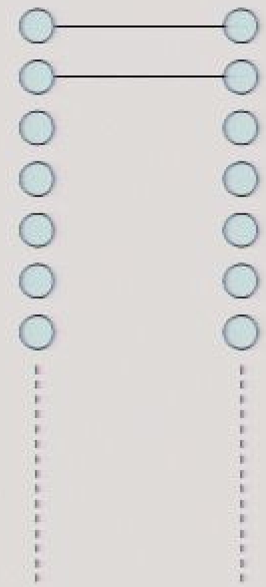

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Logarithmic negativity easy!

$$N(\rho) = \log_2 ||\rho^T||_1$$

$$E_D \leq E_R \leq E_C \leq N$$

Relativistic entanglement

What happens if Bob moves with respect to Alice?

Relativistic entanglement

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Inertial frames:

Entanglement between inertially moving parties remains constant although the entanglement between some degrees of freedom can be transferred to others.

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Non-inertial frames: Teleportation with a uniformly accelerated partner

Alsing and Milburn, PRL (91): 180404, (2003).

- Teleportation protocol with one uniformly accelerated party
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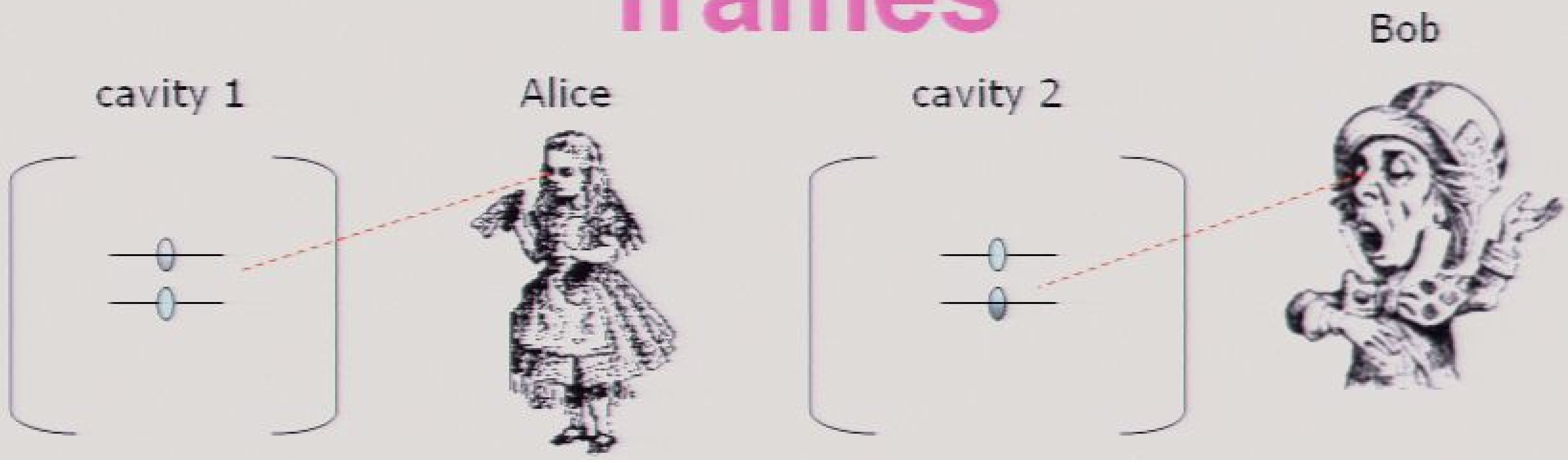
- Entanglement between moving observers
- Space time in quantum mechanics and quantum information

Entanglement in non-inertial frames



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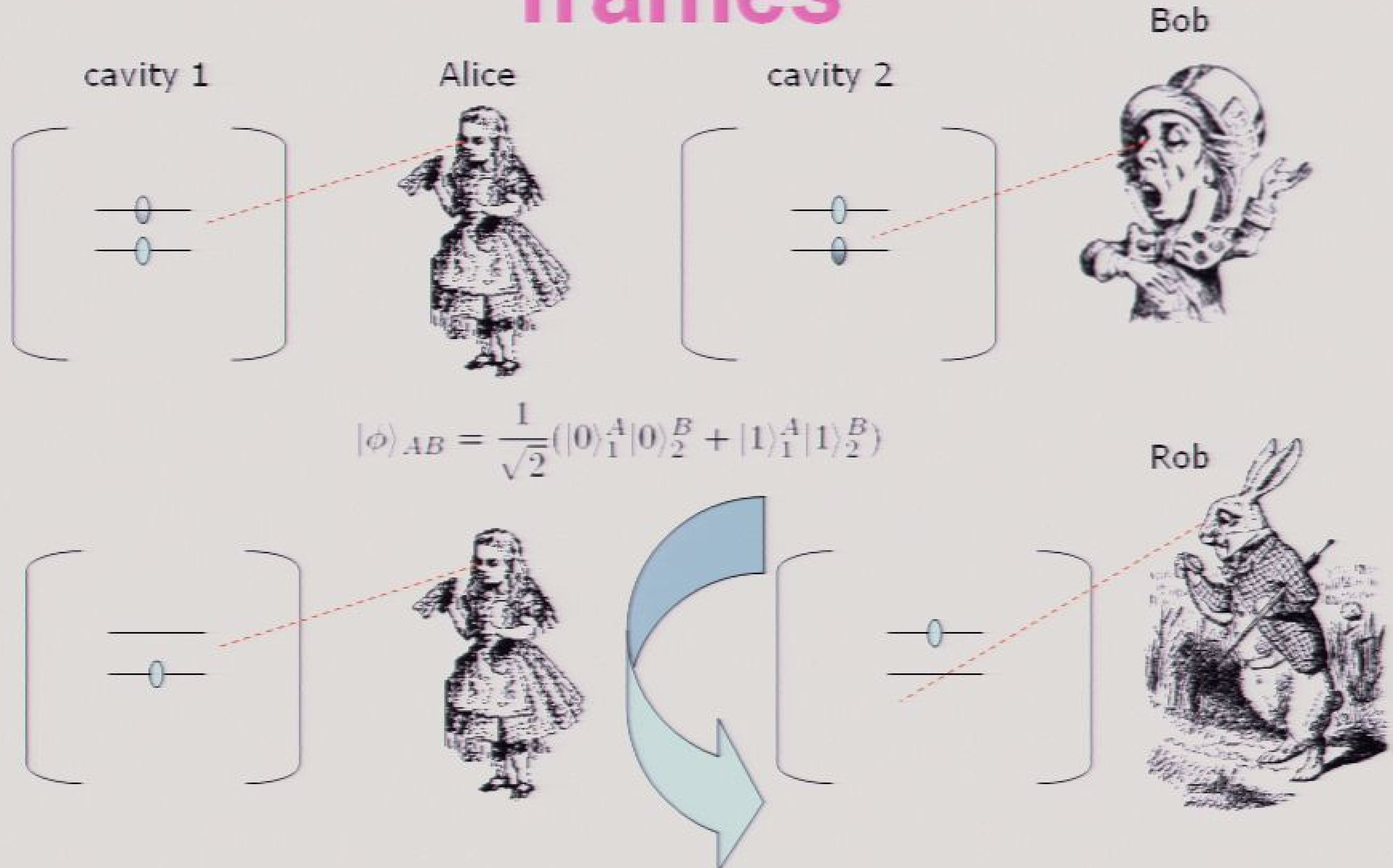

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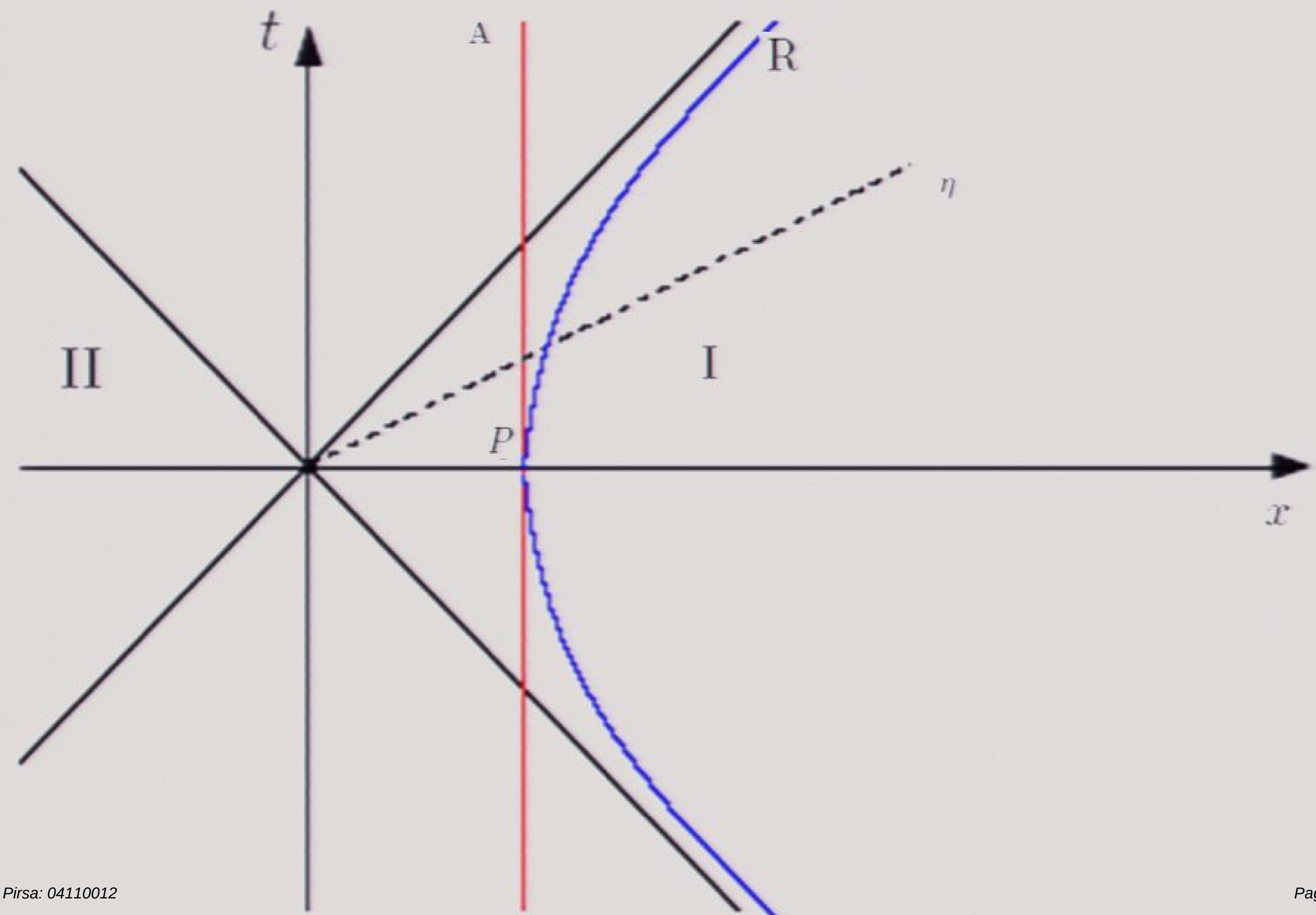
$$|\phi\rangle_{AR} = ?$$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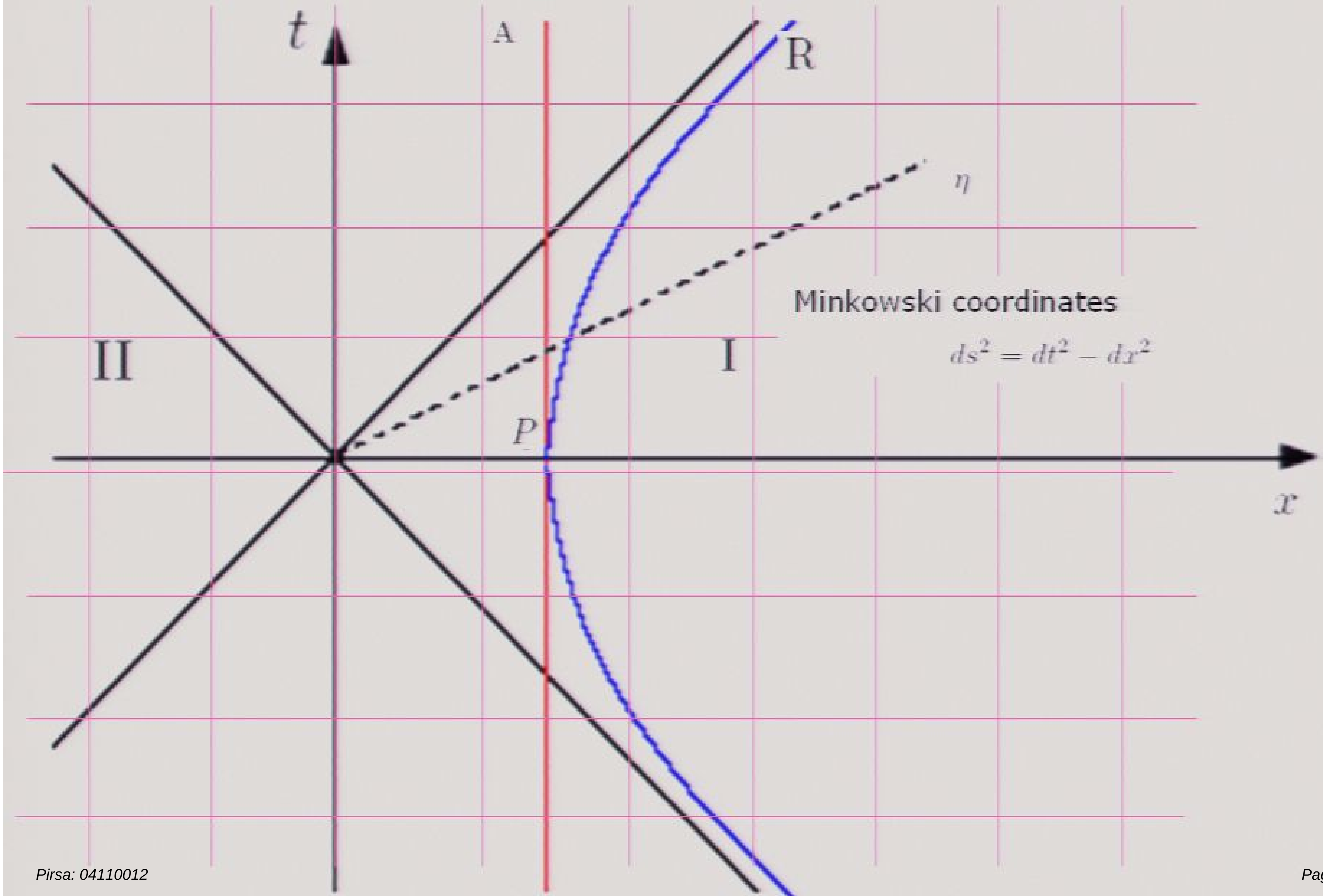
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Minkowski coordinates
$ds^2 = dt^2 - dx^2$
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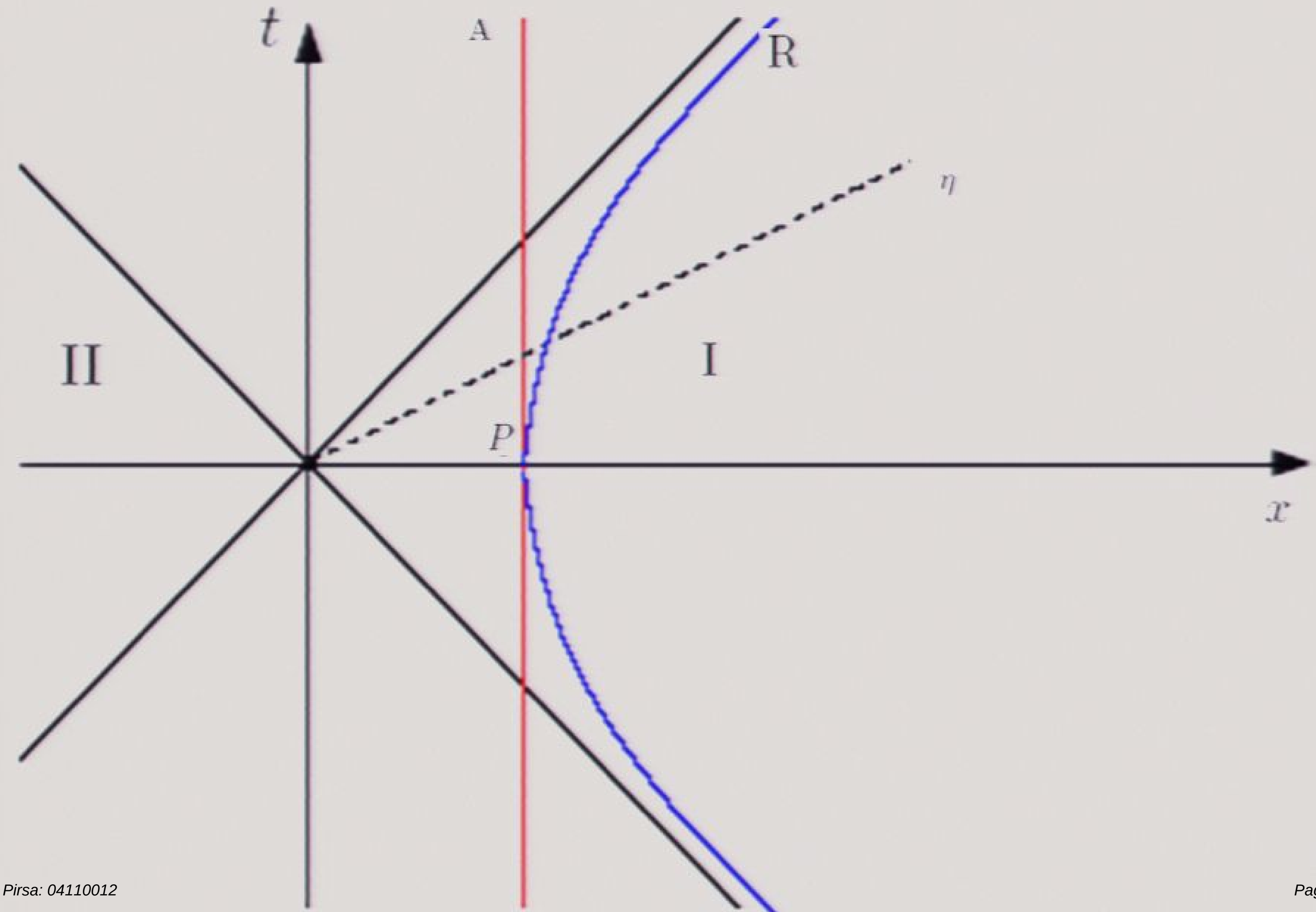
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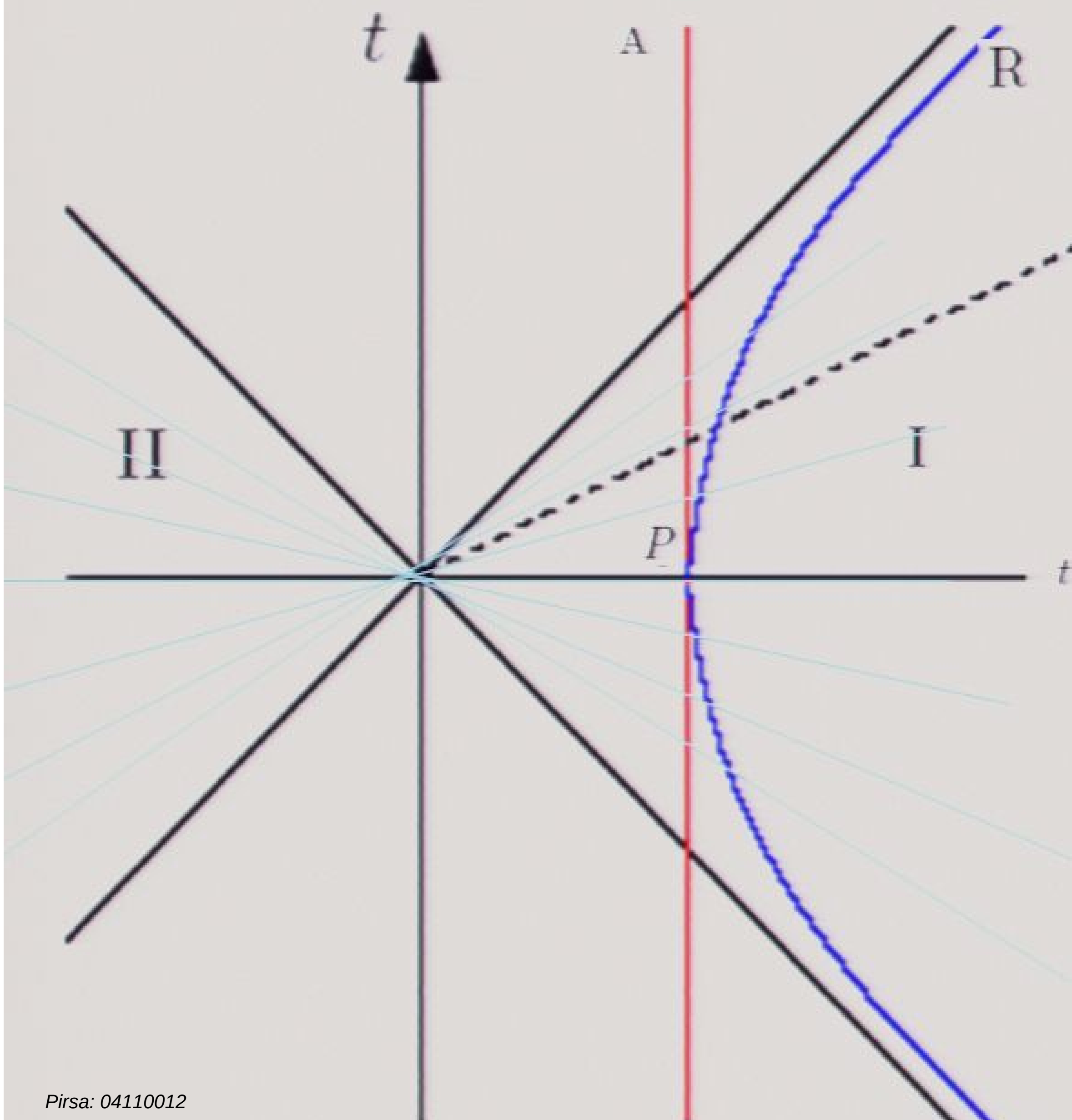
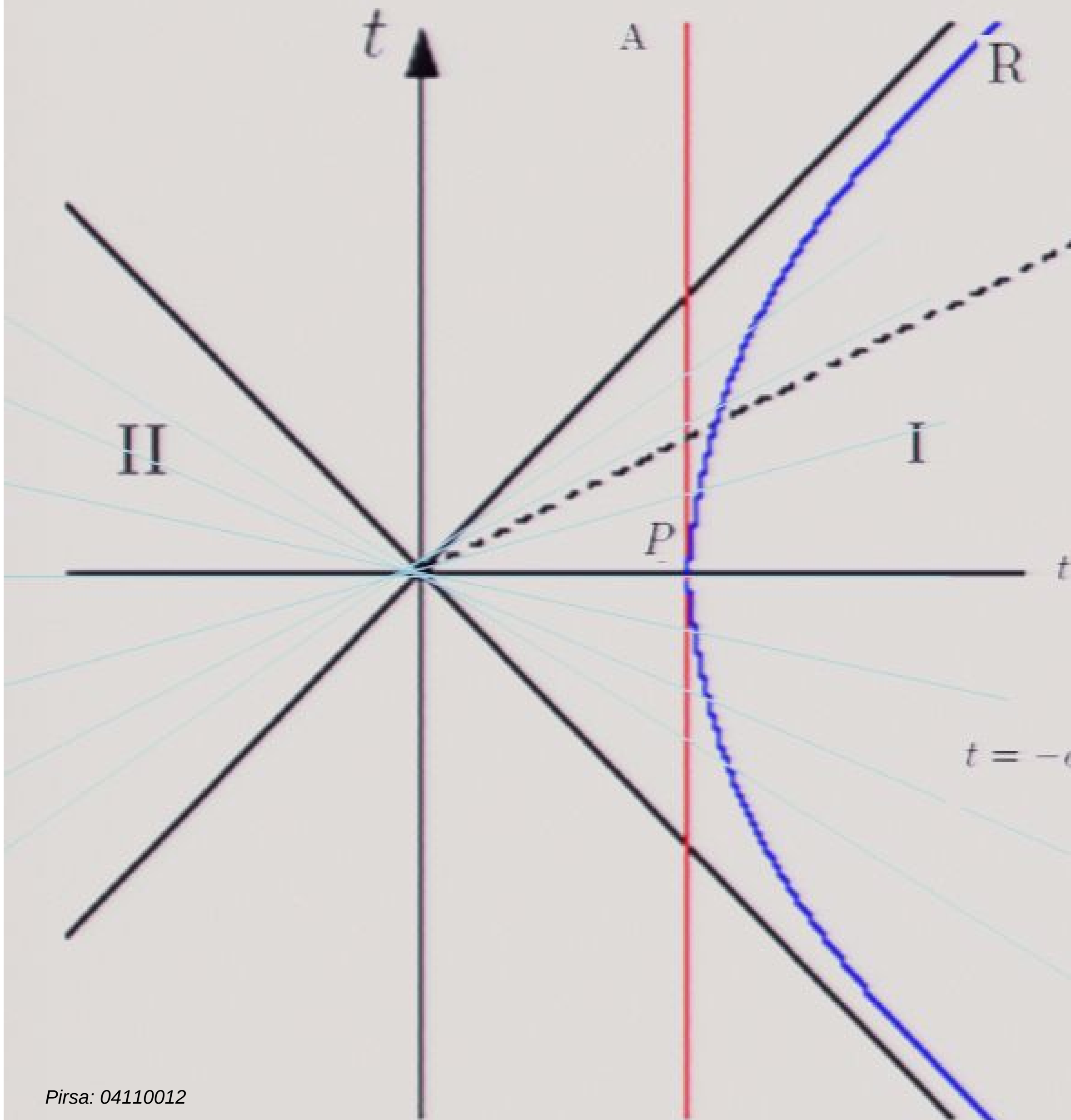


Rindler coordinates

$$t = a^{-1} e^{a\zeta} \sinh a\eta, \quad x = a^{-1} e^{a\zeta} \cosh a\eta$$

$$x > |t|$$



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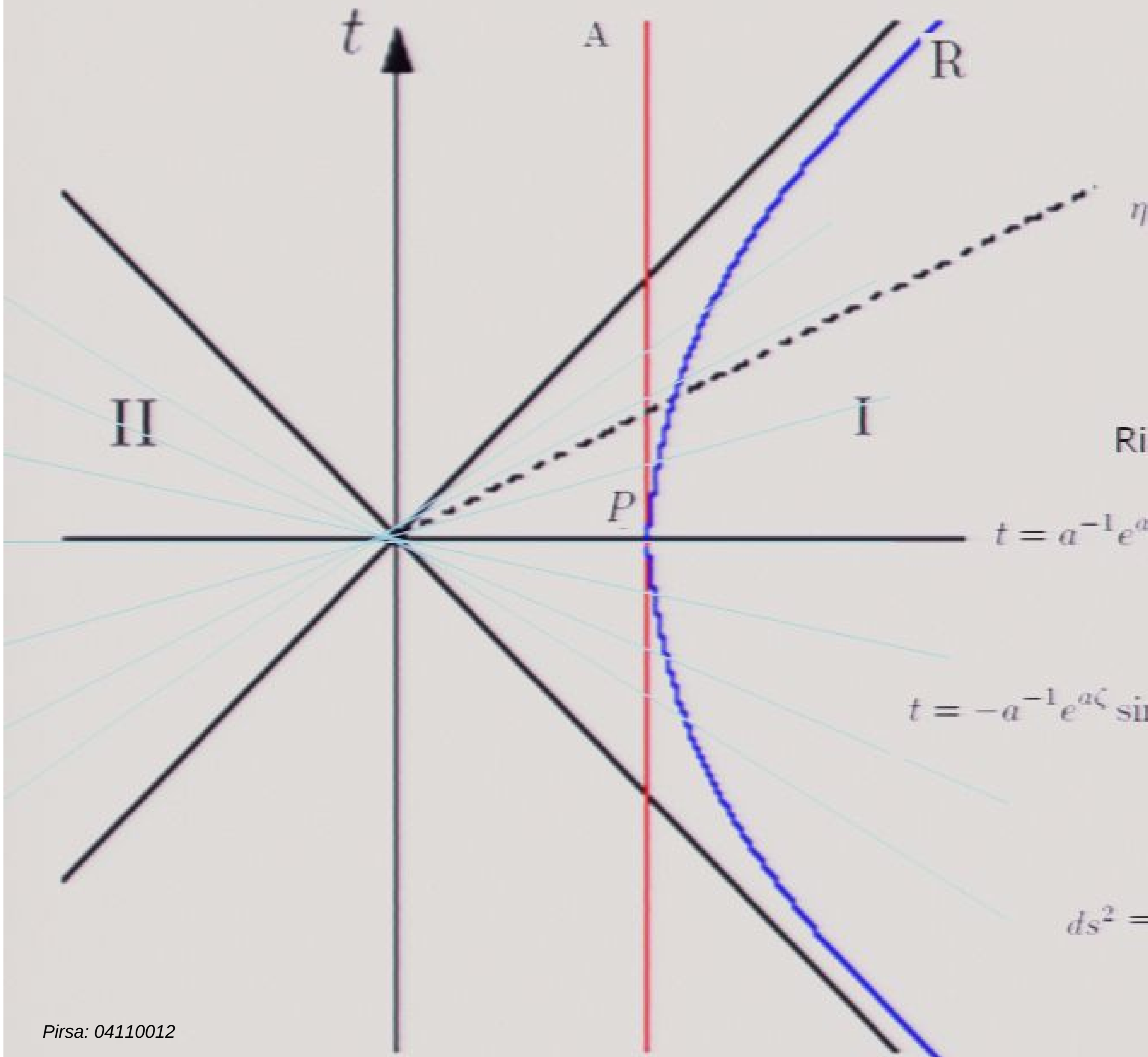

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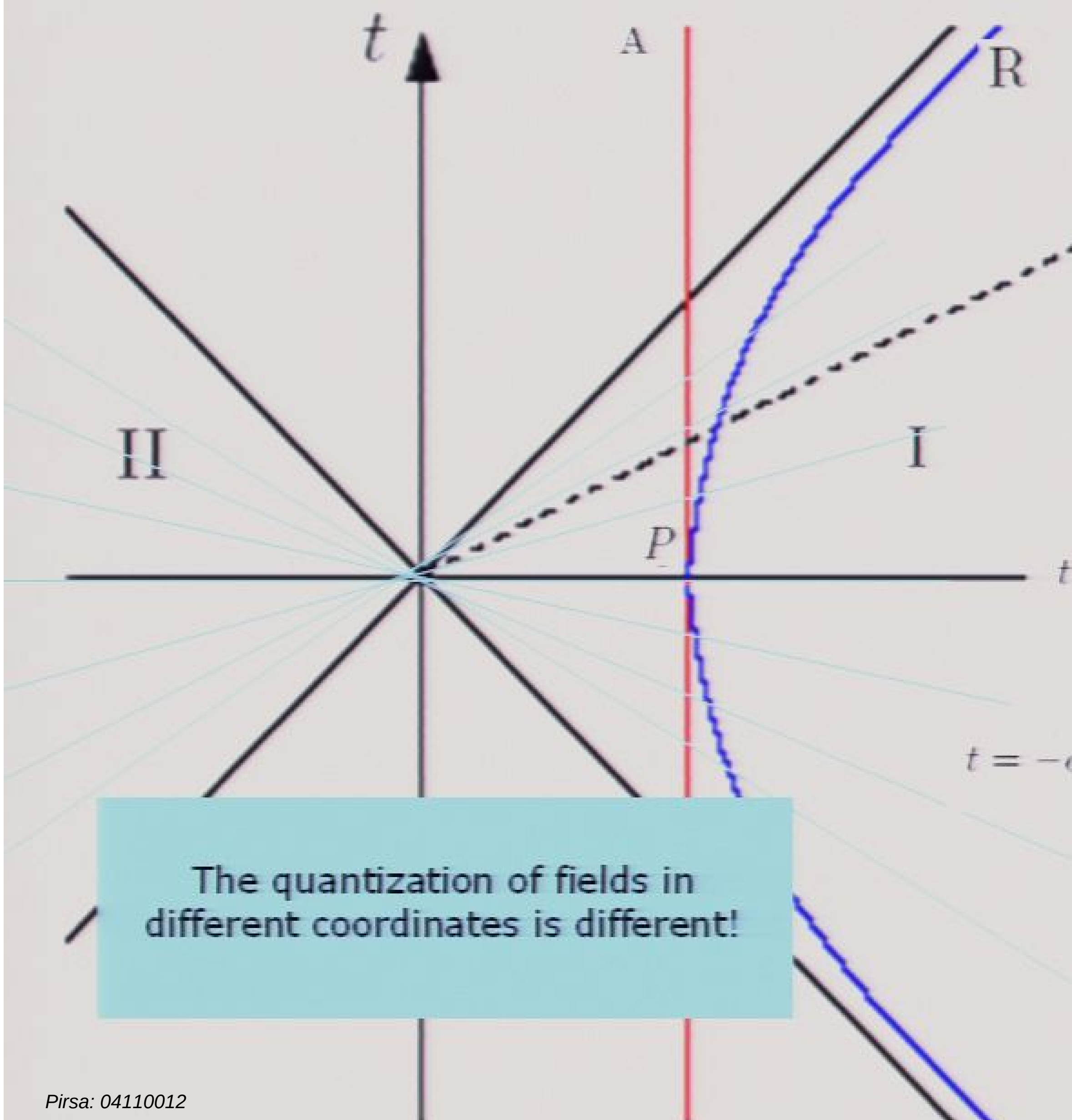
$$ds^2 = e^{2a\xi}(d\eta^2 - d\xi^2)$$



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The quantization of fields in different coordinates is different!

What a Rindler observer sees in a Minkowski vacuum

linkowski coordinates $ds^2 = dt^2 - dx^2$

Rindler coordinates $ds^2 = e^{2a\xi}(d\eta^2 - d\xi^2)$

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Klein-Gordon scalar field

$$\Box\phi \equiv \left(\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)\phi = 0$$

$$\Box\phi = e^{-2a\xi}\left(\frac{\partial^2}{\partial \eta^2} - \frac{\partial^2}{\partial \xi^2}\right)\phi = 0$$

Mode solution

$$\bar{u}_k = (4\pi\omega)^{-1/2} e^{ikx - i\omega t}$$

$$u_k = (4\pi\omega)^{-1/2} e^{ik\xi \pm i\omega\eta}$$

$$^{\mathrm{I}}u_k = \begin{cases} (4\pi\omega)^{-1/2} e^{ik\xi - i\omega\eta}, & \text{in I}; \\ 0, & \text{in II} \end{cases}$$

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where $\omega = |k| > 0$ and $-\infty < k < \infty$

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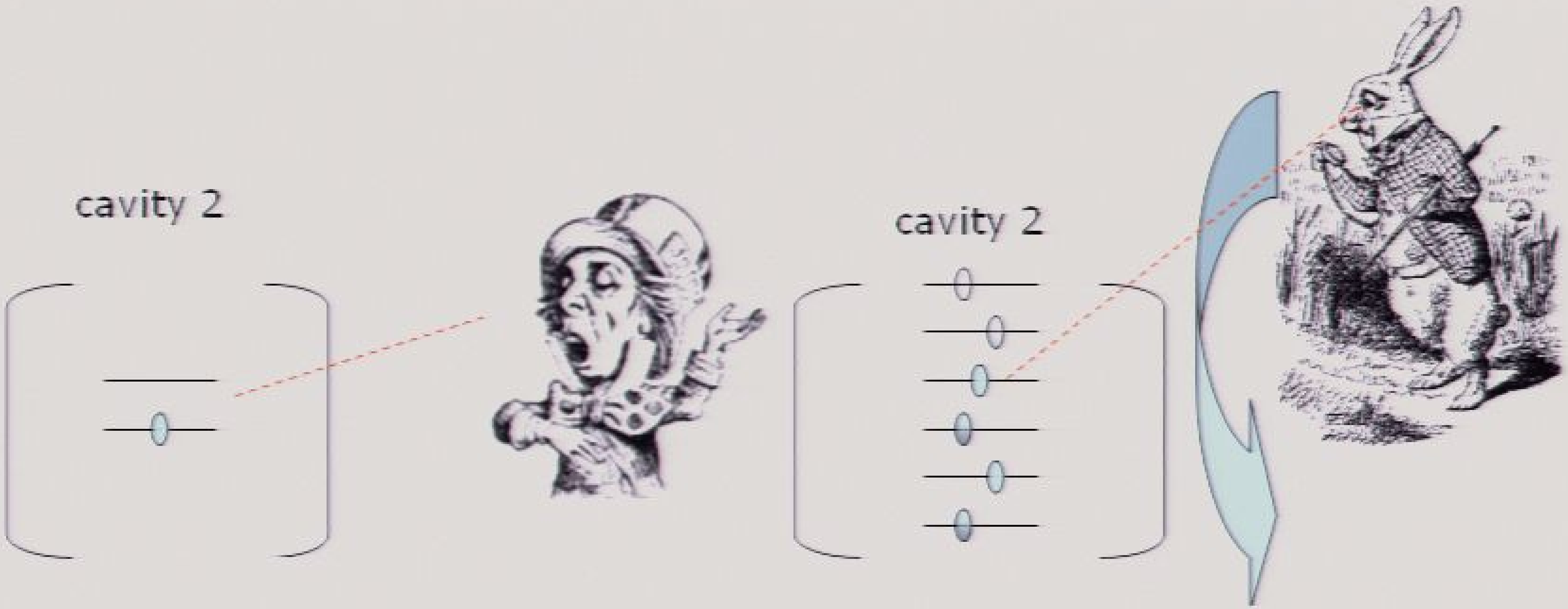
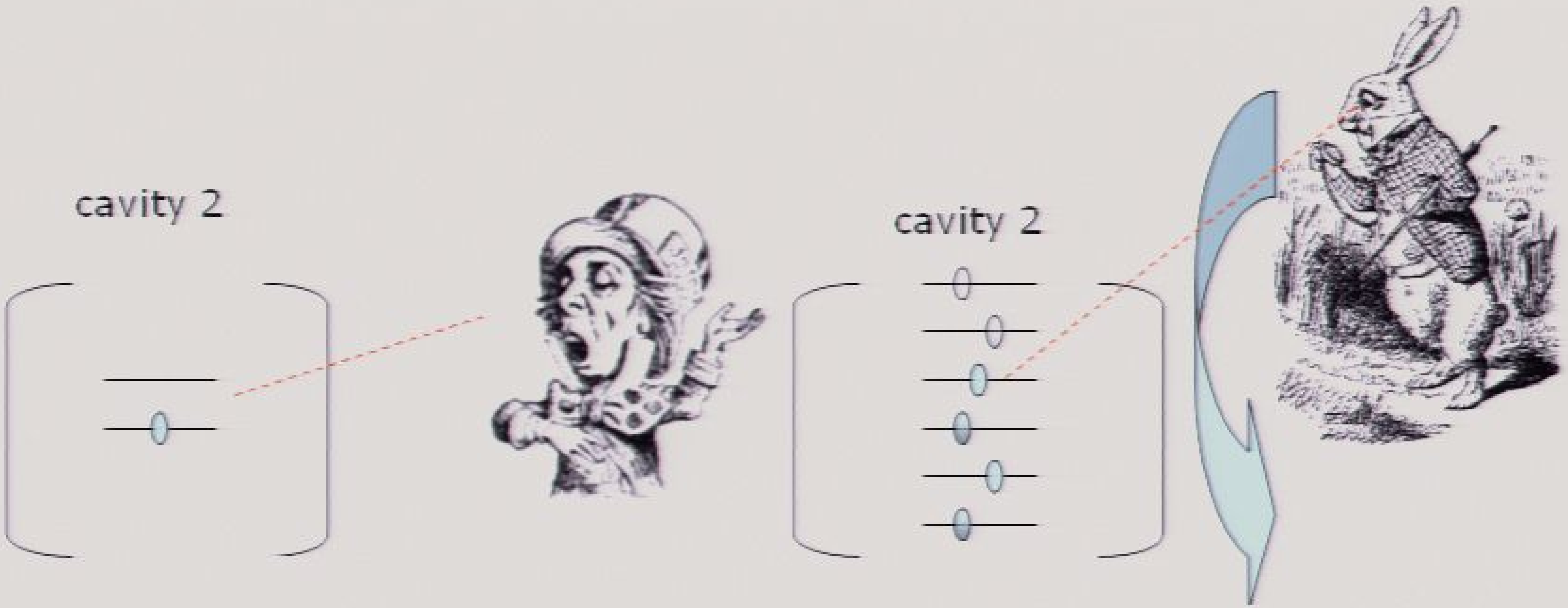


$|0\rangle_2^B$

$$|0\rangle_2^R = \frac{1}{\cosh r}\sum_{n=0}^{\infty}\tanh^n r\,|n\rangle_I|n\rangle_{II}$$

Rindler modes

$$\cosh r = (1-e^{-2\pi\Omega})^{-1/2}, \quad \Omega = \omega_R/(a/c)$$



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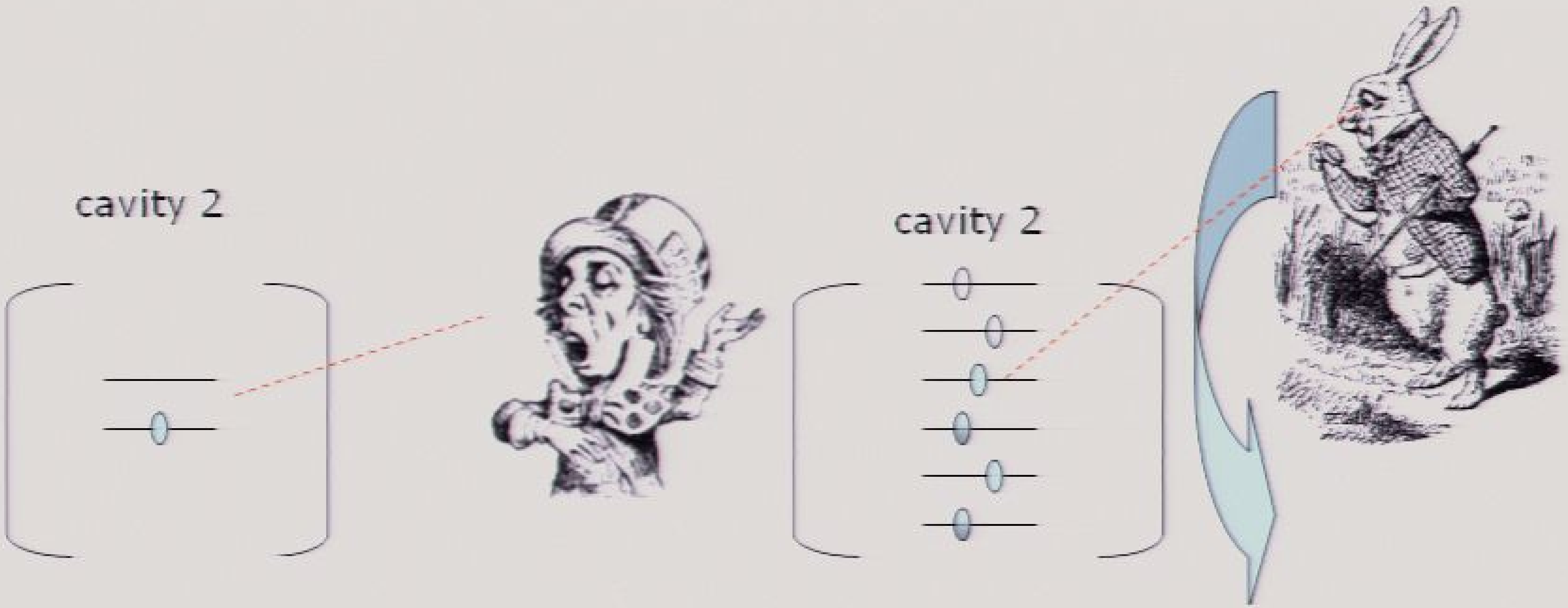

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Rob is causally disconnected form region II

Unruh effect!

$$|\phi\rangle_{AR} = \frac{1}{\sqrt{2}}(|0\rangle_1^A|0\rangle_2^R + |1\rangle_1^A|1\rangle_2^R)$$

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Tracing over region II

$$\rho_{AR} = \frac{1}{2\cosh^2 r}\sum_n (\tanh r)^{2n}\rho_n$$

$$\rho_n = |0n\rangle\langle 0n| + \frac{\sqrt{n+1}}{\cosh r}|0n\rangle\langle 1n+1| + \frac{\sqrt{n+1}}{\cosh r}|1n+1\rangle\langle 0n| + \frac{(n+1)}{\cosh^2 r}|1n+1\rangle\langle 1n+1|$$

Separability condition:

$$\lambda_{\pm}^{n} = \frac{\tanh^{2n} r}{(4\cosh^2 r)}\left[\left(\frac{n}{\sinh^2 r} + \tanh^2 r\right) \pm \sqrt{Z_n}\right]$$

$$Z_n = \left(\frac{n}{\sinh^2 r} + \tanh^2 r\right)^2 + \frac{4}{\cosh^2 r}$$

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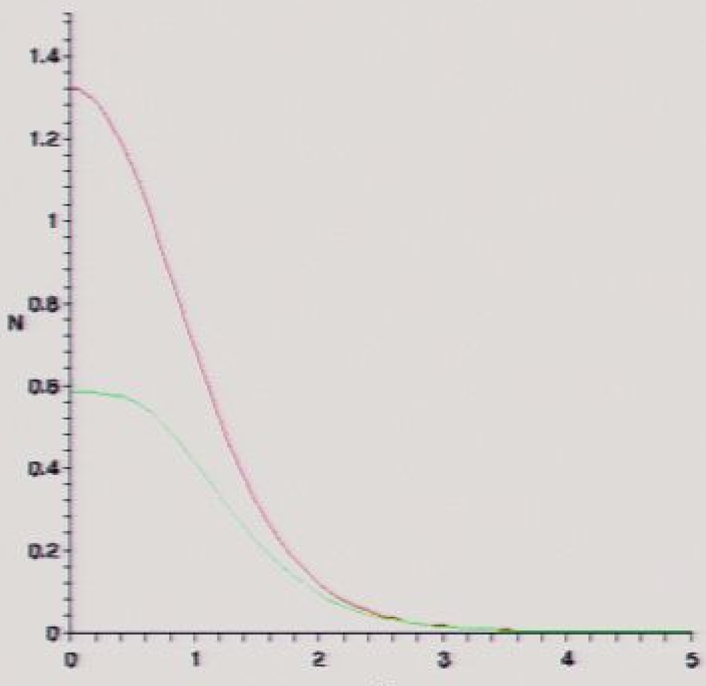
finite r: always entangled

Entangled:

$$N(\rho_{AR}) = \log_2(1 + \Sigma_n) \qquad \Sigma_n = \sum_{n=0}^{\infty} \frac{\tanh^{2n} r}{2\cosh^4 r}\sqrt{\left(\frac{n}{\sinh^2 r} + \tanh^2 r\right)^2 + \frac{4}{\cosh^2 r}}$$



Lower and upper bounds to the negativity as a function of r

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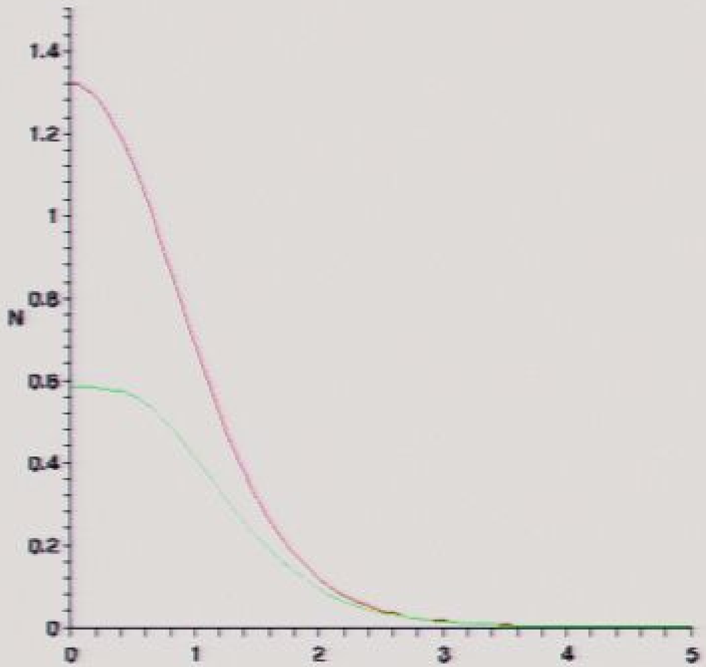

Lower and upper bounds to the negativity as a function of r

Mutual information:

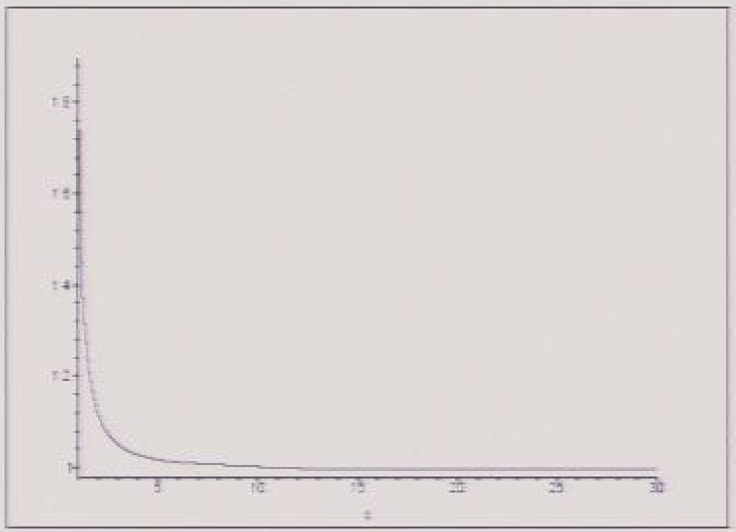

FIG. 3: Mutual information as a function of cosh(r

Where did the entanglement go?

Pure state: $S(\rho_{ARI,II}) = 0$ → $S(\rho_{ARI}) = S(\rho_{RII})$

Entanglement between Alice+Rob in region I
With modes in region II

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For finite acceleration: the entanglement between Alice+Rob is degraded
and entanglement with region II grows

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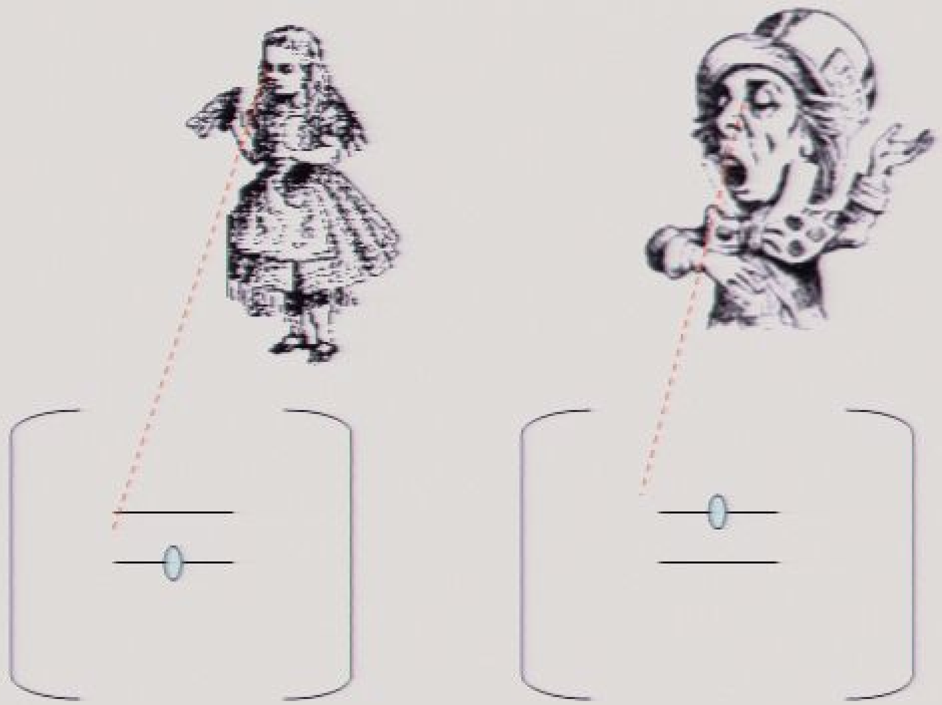

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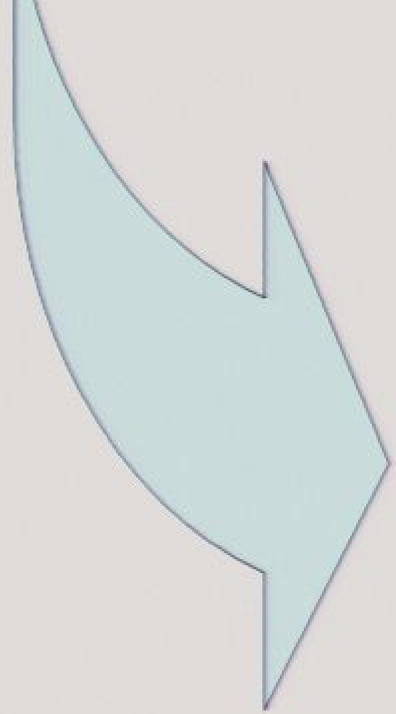
$$\rho_{AR} = \frac{1}{2\cosh^2 r}\sum_n (\tanh r)^{2n}\rho_n$$

$$\rho_n = |0n\rangle\langle 0n| + \frac{\sqrt{n+1}}{\cosh r}|0n\rangle\langle 1n+1| + \frac{\sqrt{n+1}}{\cosh r}|1n+1\rangle\langle 0n| + \frac{(n+1)}{\cosh^2 r}|1n+1\rangle\langle 1n+1|$$



$$\rho_{QR} = \frac{1}{2\cosh^2 r}\sum_{nm}(\tanh r)^{2(n+m)}\rho_{nm}$$

$$\rho_{nm} = |n,m\rangle\langle n,m| + \frac{(n+1)(m+1)}{\cosh^2 r}|n+1,m+1\rangle\langle n+1,m+1|$$

$$+ \frac{\sqrt{(n+1)(m+1)}}{\cosh r}(|n,m\rangle\langle n+1,m+1| + |n+1,m+1\rangle\langle n,m|)$$

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Well defined notion of entanglement in non-inertial frames:

Proper entanglement:

Observer in the same reference frame as the system

Alice falls into a black hole

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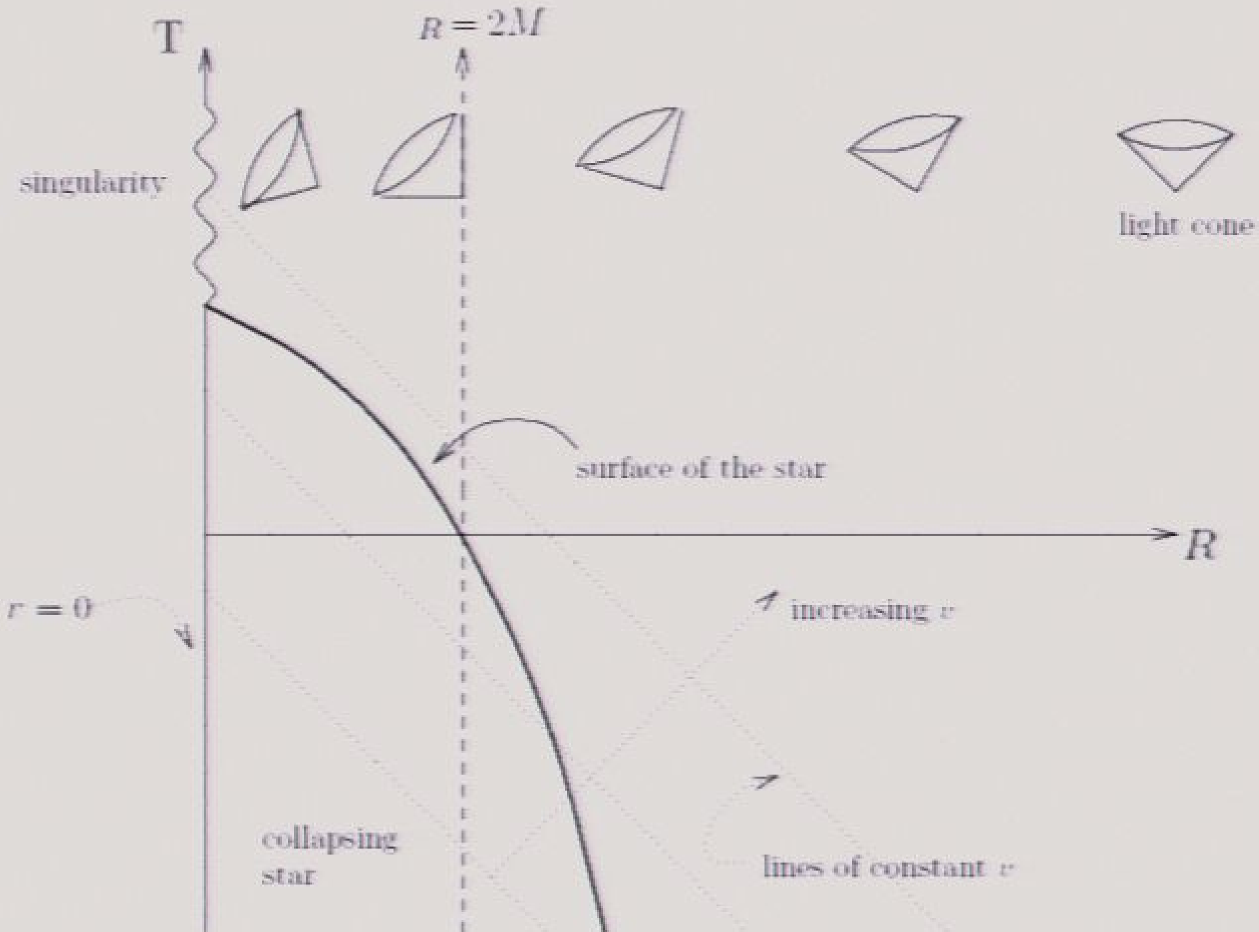
Schwarzschild space-time: geometry of a spherical non-rotating mass m.

$$ds^2 = \left(1 - \frac{2m}{R}\right) dT^2 - \left(\frac{1}{1 - 2m/R}\right) dR^2$$



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Change of coordinates

$$R - 2m = x^2/8m$$

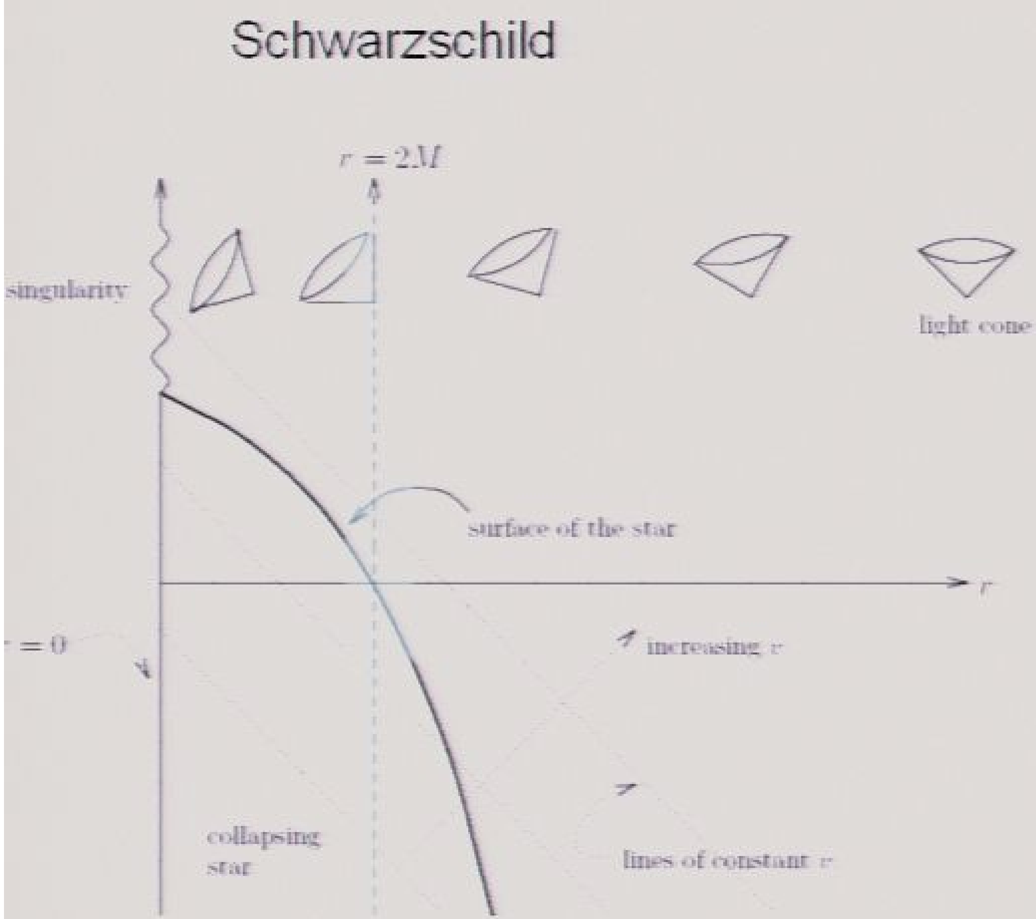
$$1 - 2m/R = (kx^2)/(1 + (kx)^2) \approx (kx)^2$$

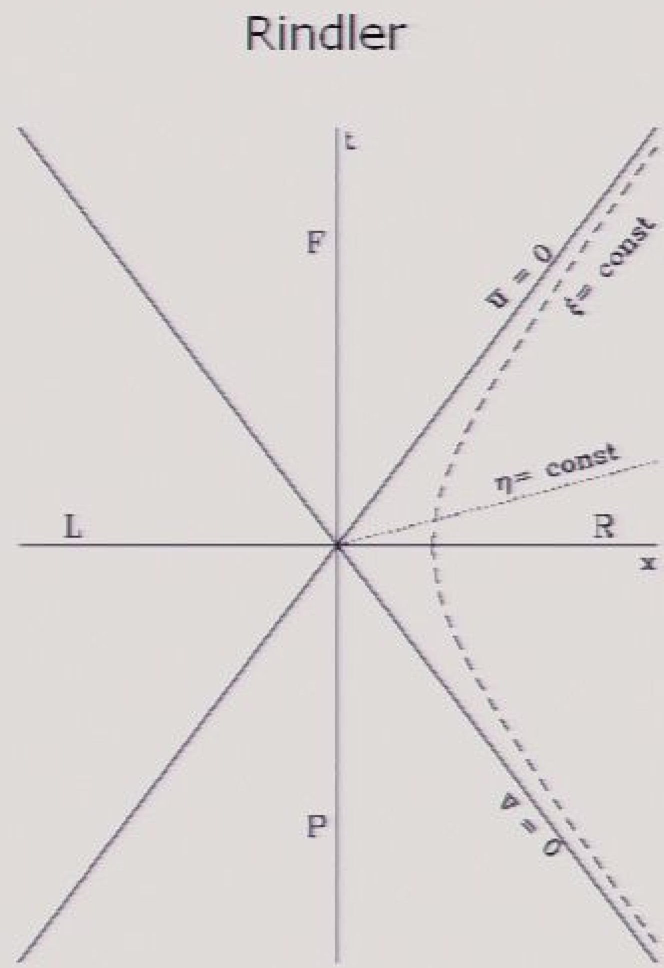
near $x = 0 \text{ with } k = 1/4m$

$$R \approx 2m$$

Schwarzschild space-time can be approximated by Rindler space

$$ds^2 = -(kx)^2 dT^2 + dx^2$$


Schwarzschild
r = 2M
singularity
light cone
surface of the star
r
increasing r
collapsing star
lines of constant r


Rindler
t
F
u = 0
ξ= const
η= const
L
R
x
P
v = 0

Can a maximally entangled state robust to acceleration be prepared?

$$|\phi\rangle_{AR} = \frac{1}{\sqrt{2}}(|0\rangle_1^A|0\rangle_2^R + |1\rangle_1^A|1\rangle_2^R)$$

$$|0\rangle_2^R = |0\rangle_I|0\rangle_{II}, \quad |1\rangle_2^R = |1\rangle_I|0\rangle_{II}$$

The only restriction on its use for quantum information tasks is given by the possibility of exchanging classical communication. For example, in the case one observer falls into a black hole classical communication can only be exchanged in one direction.

Signaling from a black hole?

Protocol: Alice and Rob prepare an entangled state

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If Rob detects this entropy change he obtained one bit of information from Alice:

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