Title: Quantum Information Science and Quantum Optics as Tools to Probe the Spacetime Structure

Date: Oct 31, 2011 04:00 PM

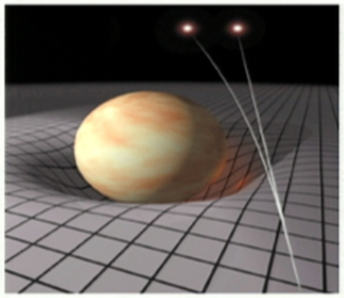
URL: http://pirsa.org/11100109

Abstract: Relativistic quantum information theory uses well-known tools coming from quantum information and quantum optics to study quantum effects provoked by gravity and to learn information about the spacetime. One can take advantage of our knowledge about quantum optics and quantum information theory to analyse from a new perspective the effects produced by the gravitational interaction. I will present some results and new ideas in this topic: from experimental proposals for detection of the Unruh and Hawking effects and cosmological implications of gravitationally generated entanglement to quantum simulation of general relativistic settings.

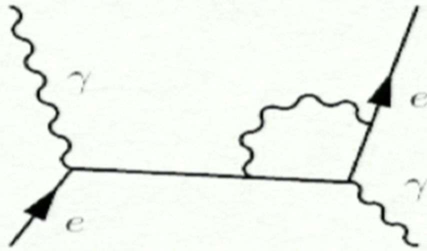
Quantum Information and Quantum Optics as tools to probe the Spacetime Structure

Eduardo Martín Martínez, QUINFOG (CSIC)
31st October, Perimeter Institute

Relativistic Quantum Information



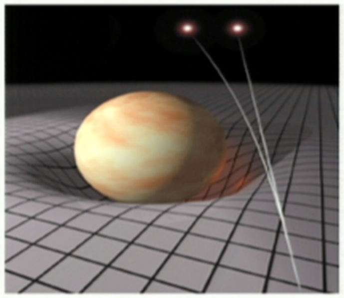
General relativity



Quantum field theory

Quantum information

Relativistic Quantum Information



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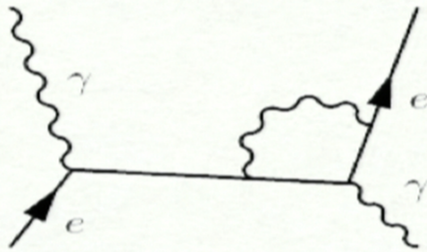
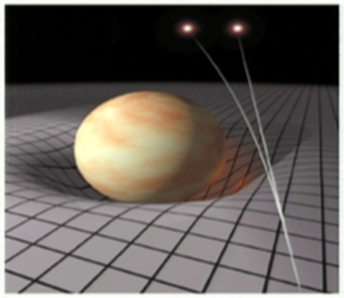


Quantum field theory

Quantum information

- Understanding quantum correlations behaviour and quantum information tasks in non-inertial settings

Relativistic Quantum Information



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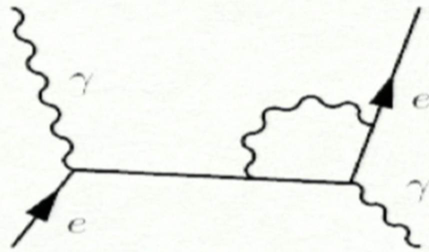


Quantum field theory

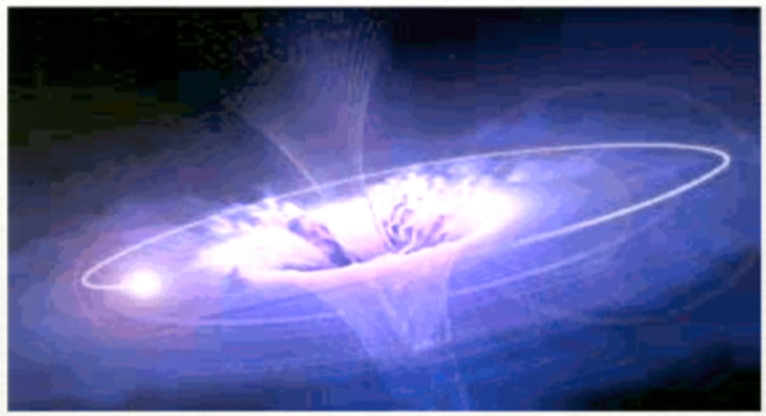
Quantum information

- Understanding quantum correlations behaviour and quantum information tasks in non-inertial settings
- Take advantage of gravity and acceleration as a feature to perform quantum information tasks

Outline

- Entanglement in a stellar collapse
- Entanglement generated by the expansion of the Universe
- Quantum optical tools to detect the Unruh effect (for real)
- Quantum simulation of general relativistic effects

Quantum Entanglement Created in a Gravitational Collapse



Entanglement generated in quantum fields due to the collapse

E. Martín-Martínez, L. J. Garay and J. León. Phys. Rev. D, 82, 064028 (2010)

Entanglement in a Stellar Collapse

Analyse quantum fields in this background is not easy:

- Non-stationary spacetime: Problems with the field quantization.
- No unique notion of vacuum.
- Problems with the construction of a Fock space.

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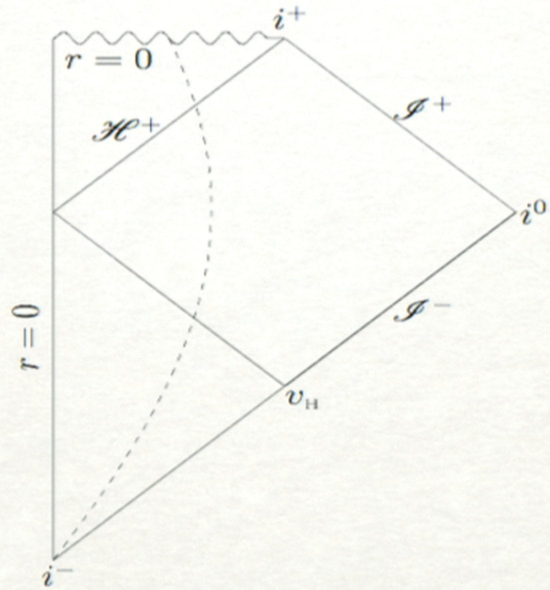
Entanglement in a Stellar Collapse

Forunately, there are asymptotically stationary regions



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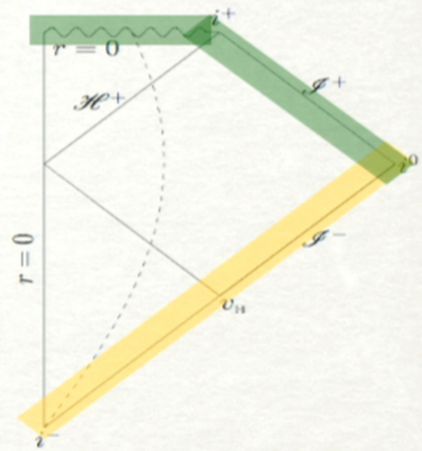


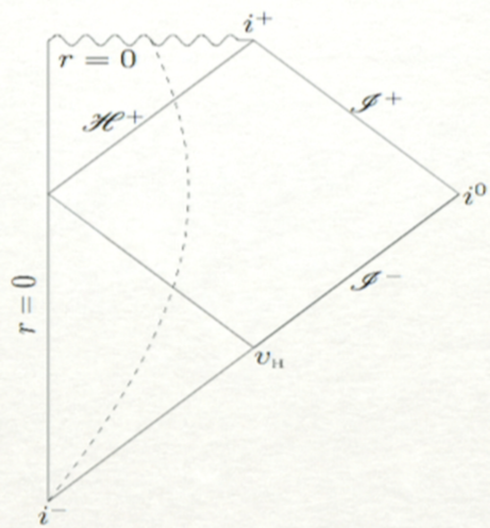
Forunately, there are asymptotically stationary regions

QFTs can be constructed in the asymptotic past and the asymptotic future

E. Martín-Martínez, L. J. Garay and J. León. Phys. Rev. D, 82, 064028 (2010)

Entanglement in a Stellar Collapse

We need to write the annihilation operators of field modes in the asymptotic past in terms of the corresponding creation and annihilation operators defined in terms of modes in the future:



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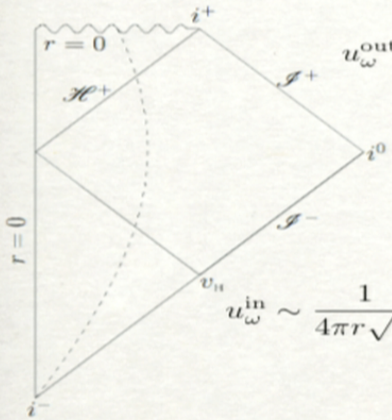

$$u_\omega^{\text{out}} \approx \frac{1}{4\pi r\sqrt{\omega}} e^{-i\omega\left(v_H - 4m \ln \frac{|v_H - v|}{4m}\right)} \theta(v_H - v)$$

$$u_\omega^{\text{in}} \sim \frac{1}{4\pi r\sqrt{\omega}} e^{-i\omega v}$$

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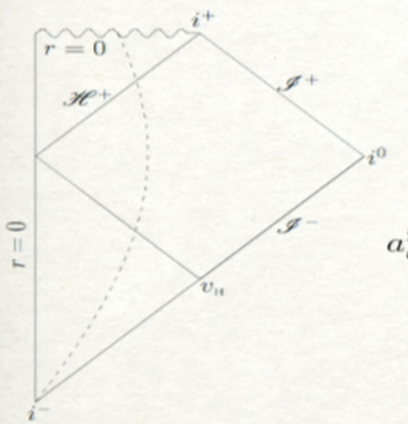

$$u_\omega^{\text{in}} \sim \frac{1}{4\pi r\sqrt{\omega}} e^{-i\omega v} \qquad u_\omega^{\text{out}} \approx \frac{1}{4\pi r\sqrt{\omega}} e^{-i\omega\left(v_{\text{H}} - 4m \ln \frac{|v_{\text{H}} - v|}{4m}\right)} \theta(v_{\text{H}} - v)$$

$$u_\omega^{\text{hor}} \sim \frac{1}{4\pi r\sqrt{\omega}} e^{i\omega\left(v_{\text{H}} - 4m \ln \frac{|v_{\text{H}} - v|}{4m}\right)} \theta(v - v_{\text{H}})$$

$$a_{\omega'}^{\text{in}} = \int d\omega \left[\alpha^*_{\omega\omega'}\left(a_\omega^{\text{out}} - \tanh r_\omega \, a_\omega^{\text{hor}\dagger}\right) + \alpha_{\omega\omega'} e^{i\varphi}\left(a_\omega^{\text{hor}} - \tanh r_\omega \, a_\omega^{\text{out}\dagger}\right)\right]$$

$$|0\rangle_{\text{in}} = \prod_\omega \frac{1}{\cosh r_\omega} \sum_{n=0}^{\infty} (\tanh r_\omega)^n \, |n_\omega\rangle_{\text{hor}} |n_\omega\rangle_{\text{out}}$$

$$\begin{aligned} |0\rangle_{\text{in}} \;=\; & \prod_\omega \Big[(\cos\tilde{r}_\omega)^2 \, |00\rangle_{\text{hor}} |00\rangle_{\text{out}} - \frac{\sin 2\tilde{r}_\omega}{2} \left(|01_\omega\rangle_{\text{hor}} |1_\omega 0\rangle_{\text{out}} - |1_\omega 0\rangle_{\text{hor}} |01_\omega\rangle_{\text{out}} \right) \\ & - (\sin\tilde{r}_\omega)^2 \, |1_\omega 1_\omega\rangle_{\text{hor}} |1_\omega 1_\omega\rangle_{\text{out}} \Big], \end{aligned}$$

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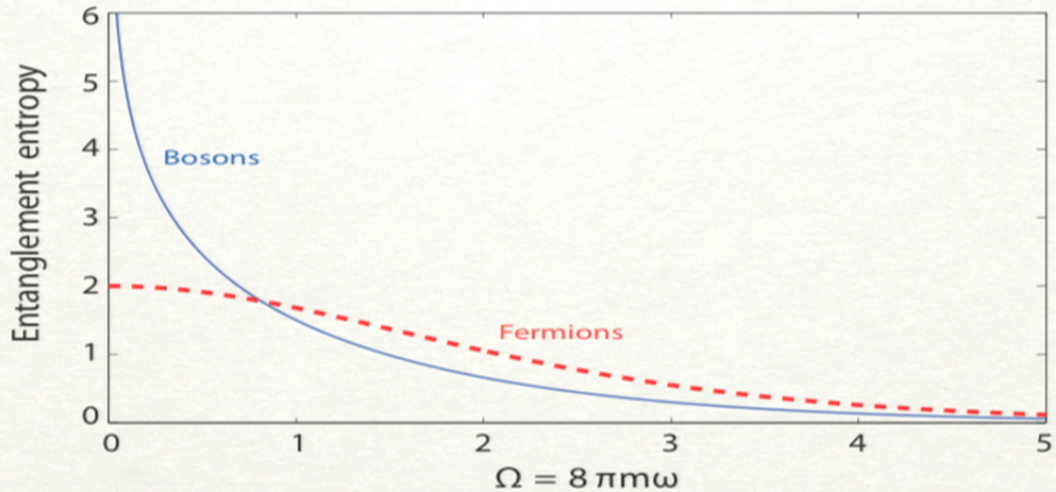
Entanglement in a Stellar Collapse

Vacuum evolves to an entangled state of infalling and outgoing modes

Scalar $S_{\text{E},\omega} = (\cosh r_\omega)^2 \log_2 (\cosh r_\omega)^2 - (\sinh r_\omega)^2 \log_2 (\sinh r_\omega)^2$

Grassman $S_{\text{E},\omega} = 2\left[(\cos \tilde{r}_\omega)^2 \log_2 (\cos \tilde{r}_\omega)^2 + (\sin \tilde{r}_\omega)^2 \log_2 (\sin \tilde{r}_\omega)^2\right]$



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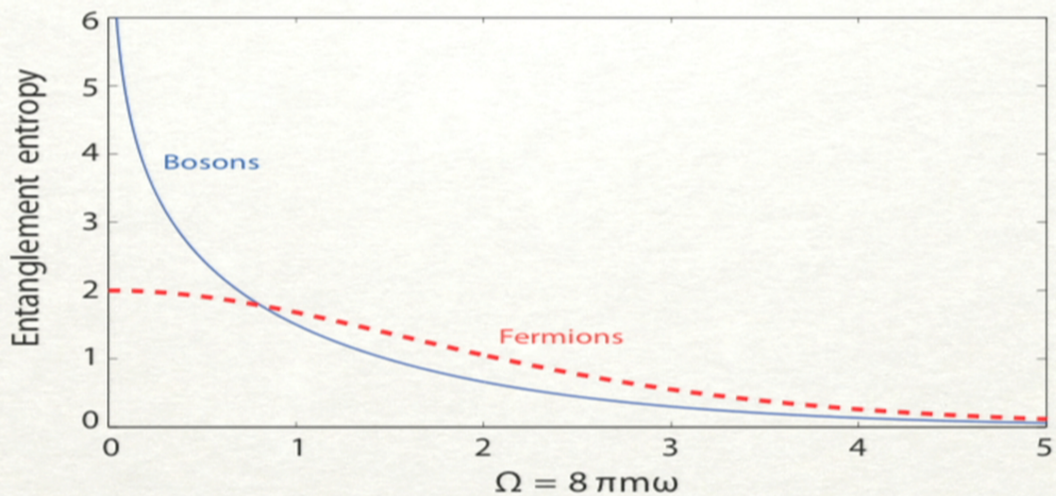

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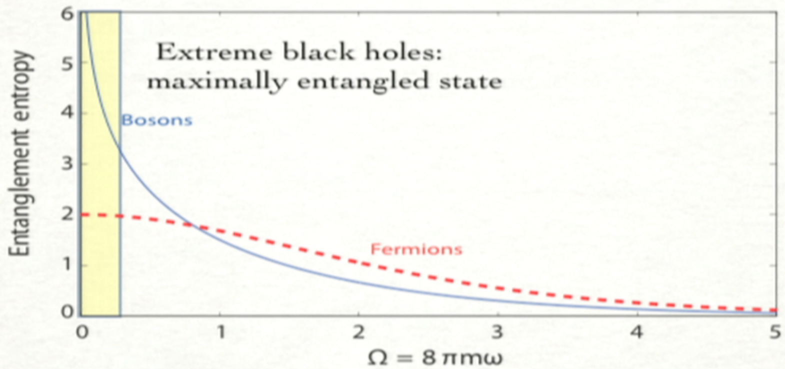

Analysing results I: Sci-Fi

- Micro-black holes, Final state of a black hole

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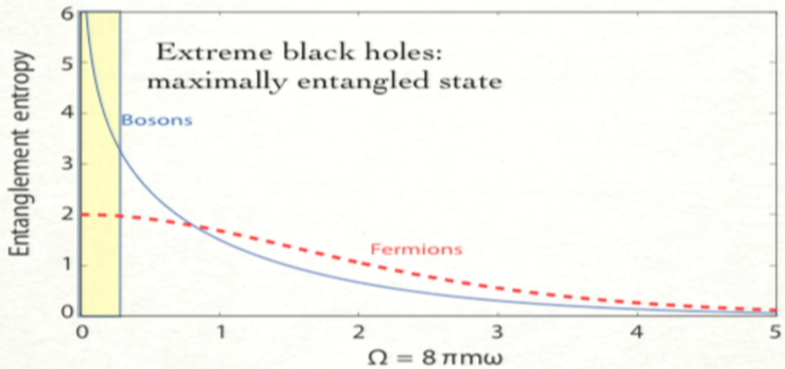

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- Micro-black holes, Final state of a black hole
- Hawking radiation maximally correlated with infalling radiation!

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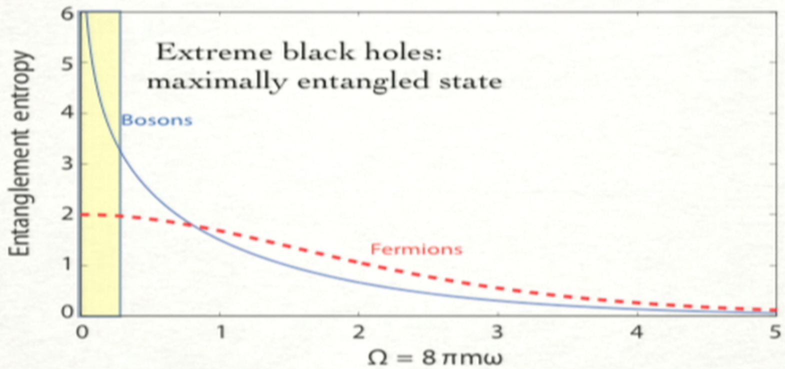

Analysing results I: Sci-Fi

- Micro-black holes, Final state of a black hole
- Hawking radiation maximally correlated with infalling radiation!
- e.g. high fidelity teleportation from the horizon to the asymptotic future

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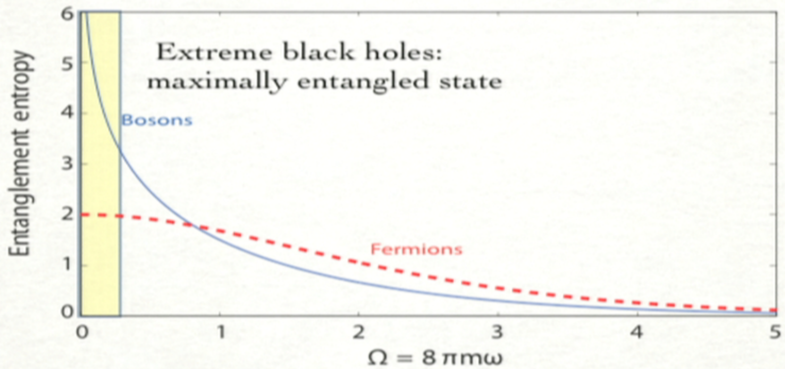
Entanglement in a Stellar Collapse



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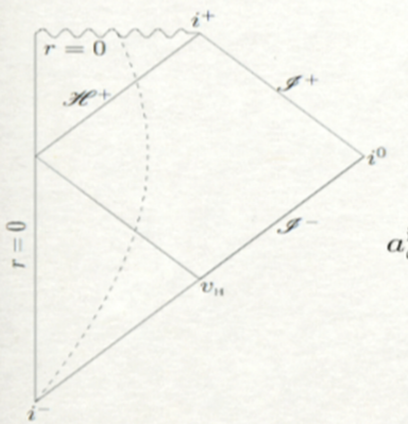

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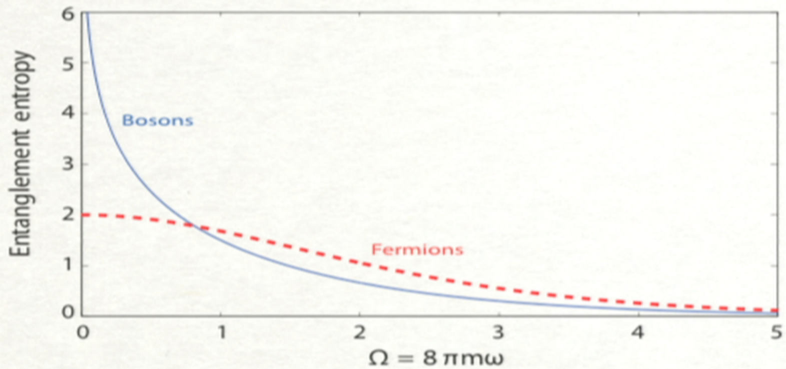

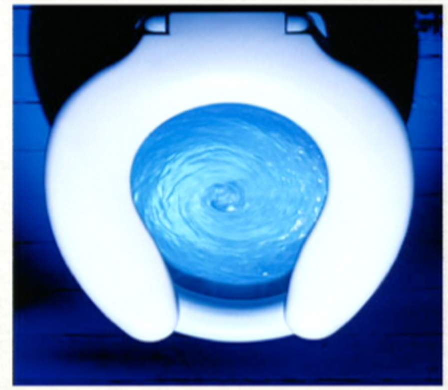

Analysing results II: non-Sci-Fi

- Analog-gravity experiments utility

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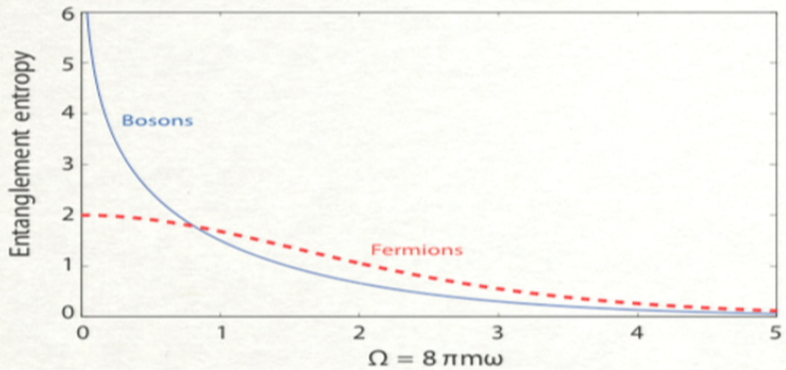

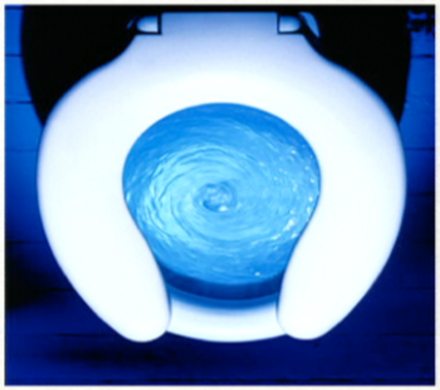

Analysing results II: non-Sci-Fi

- Analog-gravity experiments utility
  - Difference between classical induced thermal emission and Hawking effect
  - Entanglement has no classical analog: Use of entanglement to check the quantum nature of the Hawking radiation generation process
  - Fermions are more reliable for these experiments

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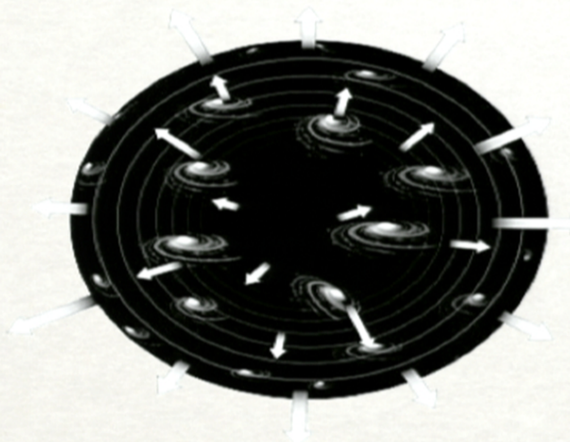
The expansion of the Universe as a source of quantum entanglement



I. Fuentes, R.B. Mann, E. Martín-Martínez and S. Moradi, Phys. Rev. D, 82, 045030 (2010)

The Setting

FRW spacetime $\quad ds^2 = C(\eta)(-d\eta^2 + dx_i dx^i)$

Where $C(\eta)$ controls the expansion of the spacetime and η is the conformal time.

Regimes where there are asymptotically stationary regions, e.g.

$$C(+\infty) \to \text{const.} \quad C(-\infty) \to \text{const.}$$

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Positive & negative freq. modes can be identified in the far past and future where the spacetime admits the timelike Killing vector ∂_η

We can express the vacuum state in the past as a function of modes in the future

I. Fuentes, R.B. Mann, E. Martín-Martínez and S. Moradi, Phys. Rev. D, 82, 045030 (2010)

Cosmological Entanglement

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$$|0\rangle_{\rm in} = \prod_k \frac{|0\rangle_{\rm out} - \xi^{-*}(k)\chi(\bar{k})|1_k 1_{-k}\rangle_{\rm out}}{\sqrt{1+|\xi^{-}(k)\chi(\bar{k})|^2}}$$

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$$S_F = \log\left(\frac{1+|\gamma_F^-|^2}{|\gamma_F^-|^{\frac{2|\gamma_F^-|^2}{|\gamma_F^-|^2+1}}}\right)$$

Massive fields get entangled by the expansion of the Universe

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Massive fields get entangled by the expansion of the Universe

Let us analyse as a toy model: the analytically solvable Duncan model

$$C(\eta) = (1+\epsilon(1+\tanh\rho\eta))^2$$

Where $\epsilon, \rho \in \mathbb{R}$ controls the total volume and rapidity of the expansion.

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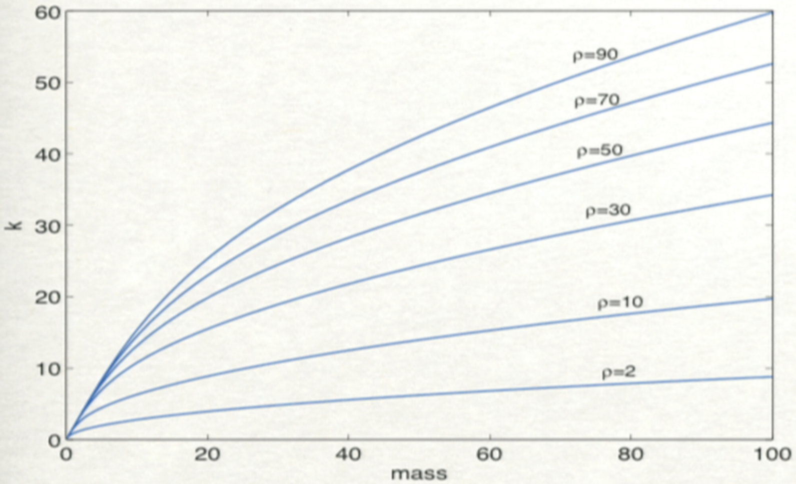
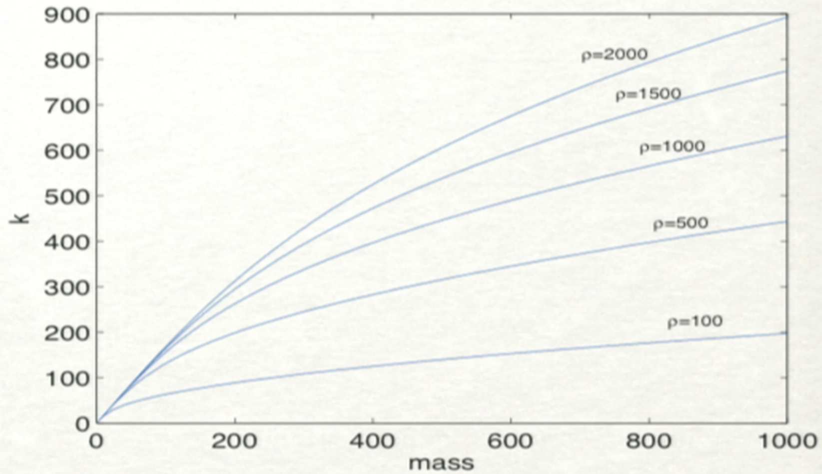
Optimal Entanglement Curve

Mode of maximal entanglement creation for a given mass





It 'sees' the rapidity but it is almost insensitive to ε

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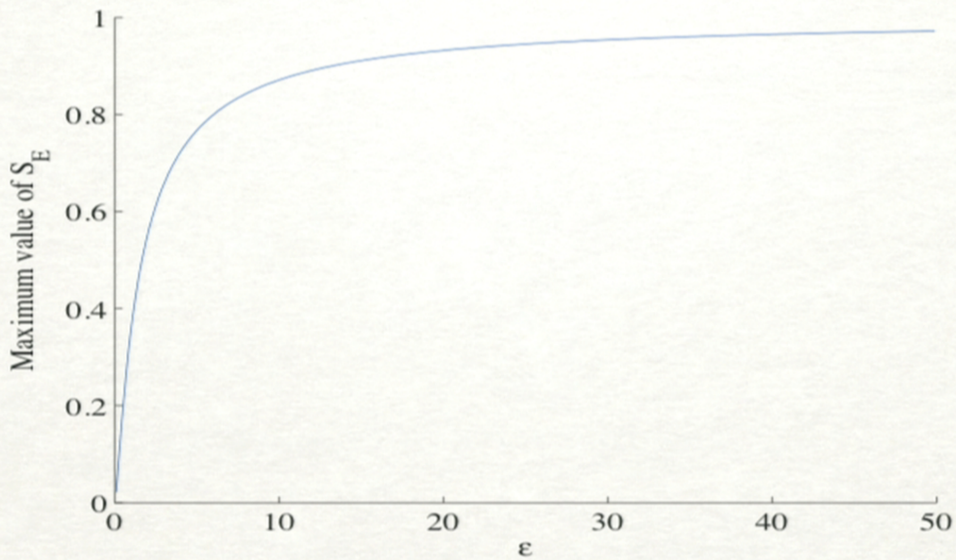
Maximum Achievable Entanglement

Amount of entanglement in the optimal curve $S_E(m, k_{opt}(m))$



It 'sees' ε but it is insensitive to the rapidity

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Entanglement in Expanding Universes

Analysing results

- Estimation of expansion parameters:
  - Maximally entangled mode gives the rapidity of the expansion
  - Amount of entanglement in this mode gives the total volume of expansion
- The expansion of the spacetime generates entanglement.
- Radical differences between fermionic and bosonic fields
- Being fermion is important: Information is better codified in fermionic fields.

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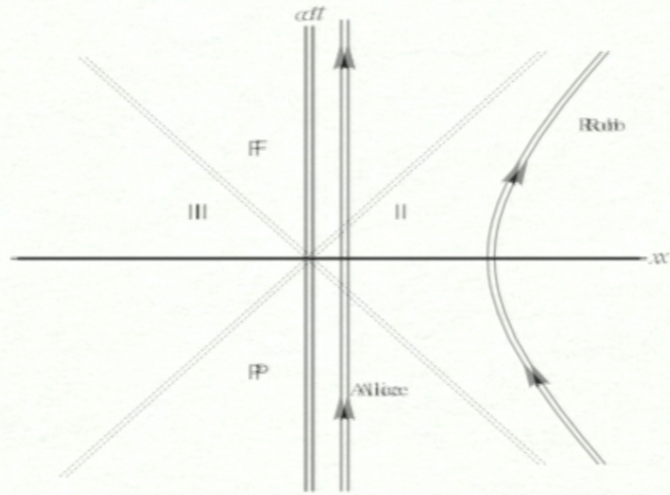
Field Quantization: Observer dependence

- Example: different observers of flat spacetime



Positive freq. solutions $\nabla^\mu \nabla_\mu u = 0$

Basis$\{ \ (x,t) \to u^{\mathrm{M}}_{\hat{\omega}} \propto e^{-i\hat{\omega} t}$

Field Quantization: Observer dependence

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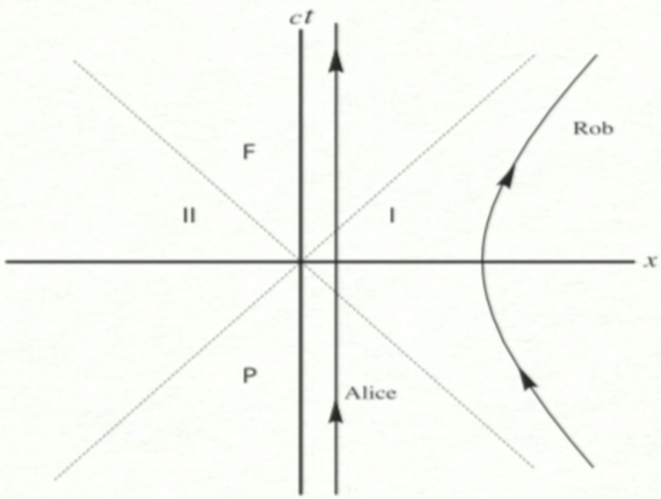

$$ct = \xi \sinh\left(\frac{a\tau}{c}\right), \qquad x = \xi \cosh\left(\frac{a\tau}{c}\right)$$

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$$(\xi, \tau) \to u^{\mathrm{I}}_{\omega} \propto e^{-i\omega\tau}$$

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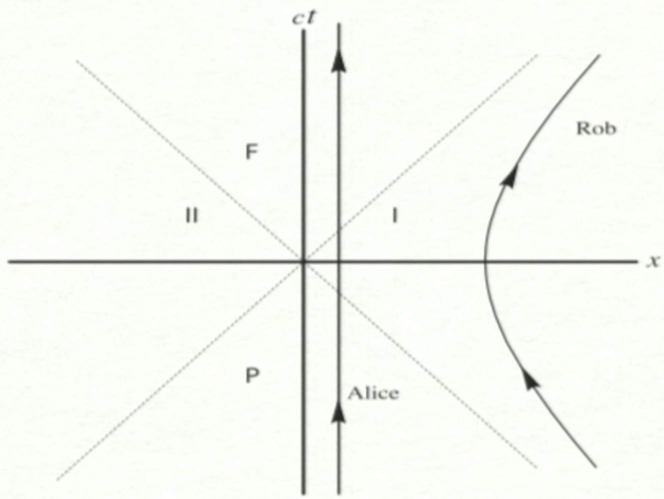

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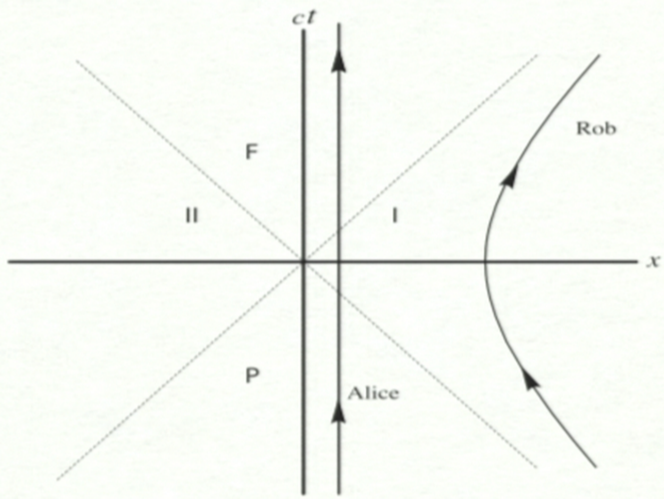

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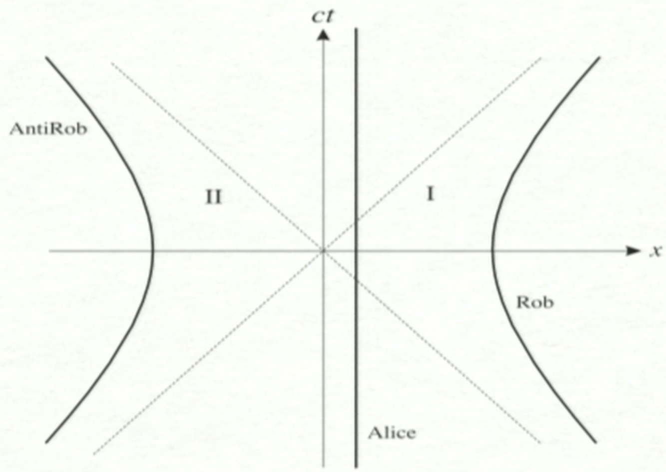
Field Quantization: Observer dependence

- Example: different observers of flat spacetime



The field

Basis$\{$ $(x,t) \to u^{\mathrm{M}}_{\hat{\omega}} \propto e^{-i\hat{\omega}t}$

Basis$\begin{cases} (\xi,\tau) \to u^{\mathrm{I}}_{\omega} \propto e^{-i\omega\tau} \\ (\xi,\tau) \to u^{\mathrm{II}}_{\omega} \propto e^{i\omega\tau'} \end{cases}$

Positive freq. solutions $\nabla^{\mu}\nabla_{\mu}u = 0$

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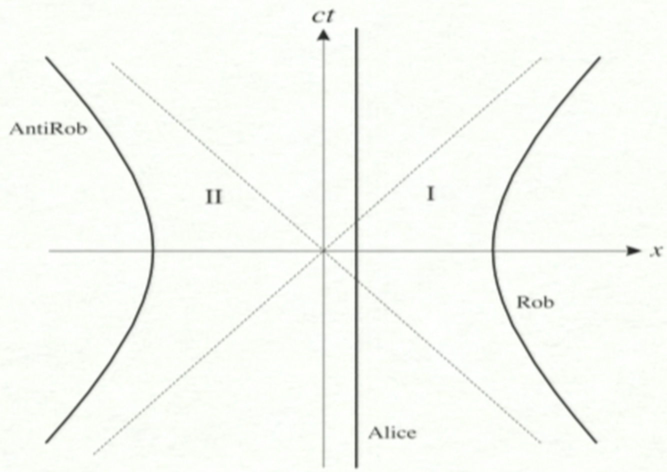

The field can be spanned in either basis

$$\phi = \sum_i \left(a_{\hat{\omega}_i,\mathrm{M}} u^{\mathrm{M}}_{\hat{\omega}_i} + a^{\dagger}_{\hat{\omega}_i,\mathrm{M}} u^{\mathrm{M}*}_{\hat{\omega}_i} \right)$$

or equi

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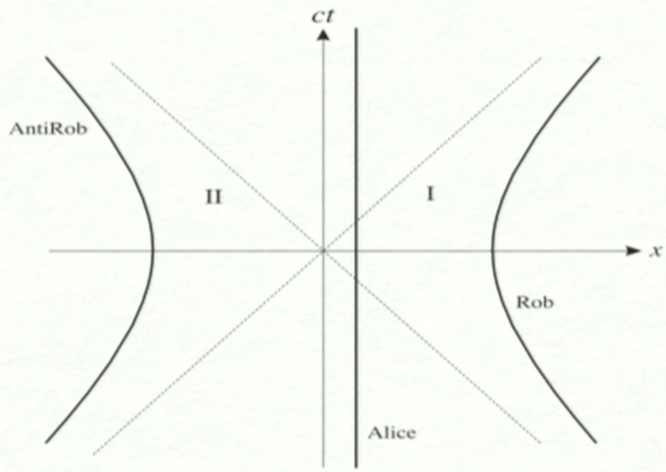

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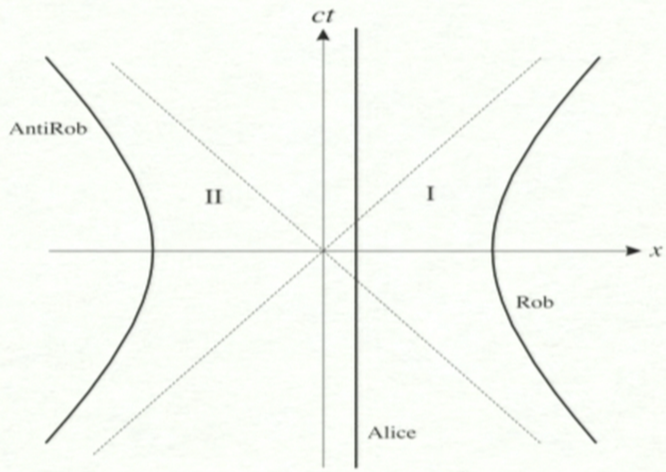

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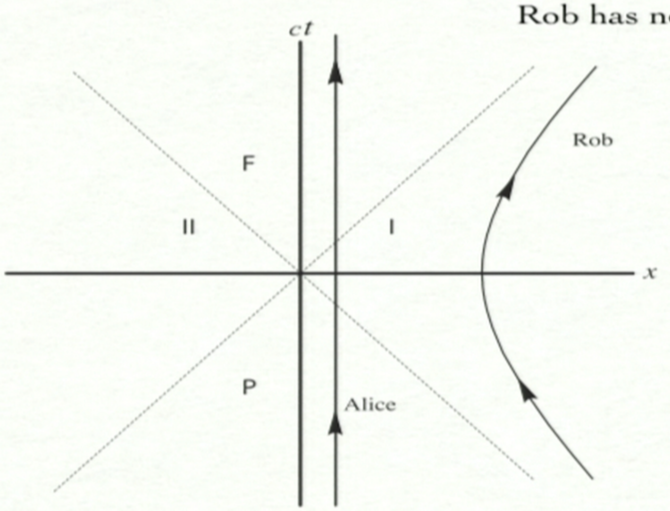
The Importance of the Horizon



$$\tanh r_\omega = \exp\left(-\frac{\pi c\,\omega}{a}\right)$$

Rob has no access to region II

Example: Minkowskian vacuum. Rob's perspective

$$|0\rangle_\mathrm{M}$$

First: change of Fock basis

$$|0\rangle_\mathrm{M} = \bigotimes_\omega \frac{1}{\cosh r_\omega} \sum_{n=0}^{\infty} \tanh^n r_\omega |n\rangle_\mathrm{I} |n\rangle_\mathrm{II}$$

Second: Trace out the disconnected region

$$\rho_{\mathrm{R},\omega} = \mathrm{Tr}_\mathrm{II}\left(|0_\omega\rangle\langle 0_\omega|\right) = \frac{1}{\cosh^2 r_\omega} \sum_n \tanh^{2n} r_\omega |n_\omega\rangle_\mathrm{I} \langle n_\omega|_\mathrm{I}$$

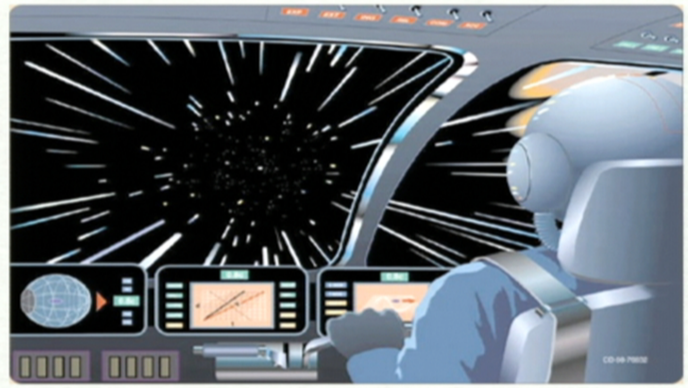
Result: thermal state

$$\langle N_{\omega,\mathrm{R}}\rangle = \frac{1}{e^{2\pi c/\omega a} - 1} \qquad T_\mathrm{U} = \frac{\hbar a}{2\pi K_\mathrm{B}}$$

The Unruh Effect

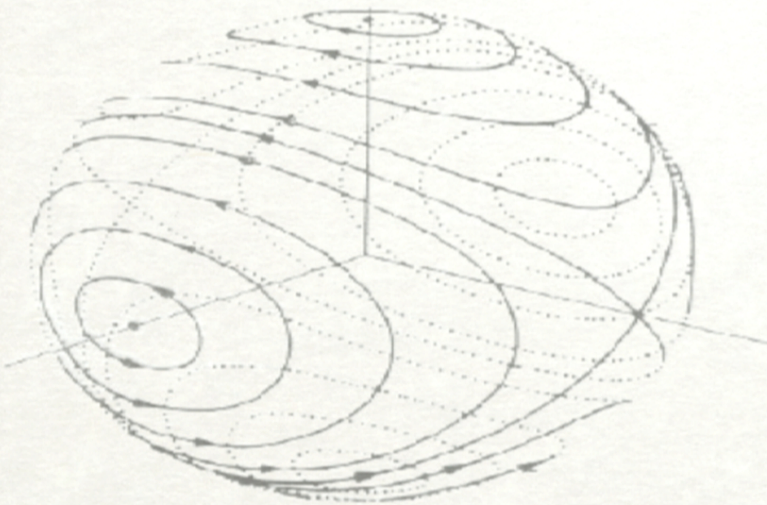
Inertial frame

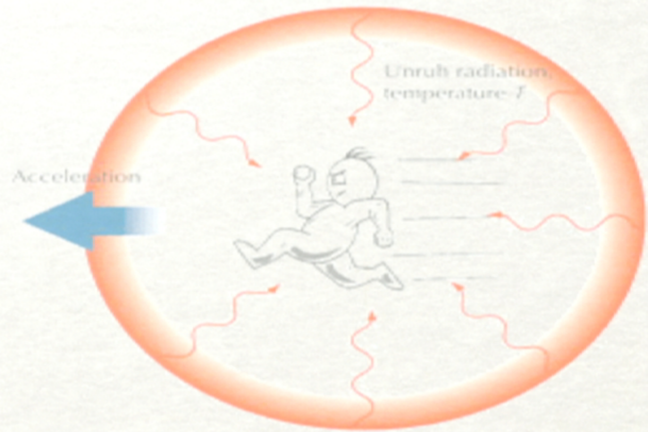
Accelerated frame



- Alice Observes the field vacuum.
- Rob observes a thermal bath of temperature $T_{\mathrm{U}} \propto a$

Berry's Phase and the Detection of the Unruh Effect





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Geometrical Phases and adiabatic evolution

$$H(t) = H(R_1(t), \dots, R_k(t))$$

$R_1(t), \dots, R_k(t)$ Cyclicly and adiabatically varying parameters

$$|\psi\rangle \to e^{i\gamma} e^{i\phi} |\psi\rangle$$

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$$i\gamma = \oint_R \boldsymbol{A} \cdot \mathrm{d}\boldsymbol{R} \qquad \boldsymbol{A} = \begin{pmatrix} \langle\psi(t)|\,\partial_{R_1}|\psi(t)\rangle \\ \langle\psi(t)|\,\partial_{R_2}|\psi(t)\rangle \\ \vdots \\ \langle\psi(t)|\,\partial_{R_k}|\psi(t)\rangle \end{pmatrix}$$

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The Hamiltonian (Inertial)

Consider a single mode Unruh-Dewitt Hamiltonian

$$H_T = \Omega_a\, a^\dagger a + \Omega_b\, b^\dagger b + \lambda(b + b^\dagger)(a^\dagger e^{i\varphi} + a\, e^{-i\varphi})$$

For an inertial observer $\varphi = |\Omega_a| x/c - \Omega_a t$ Where (x, t) are Minkowskian coordinates

The movement of the detector in spacetime generates a change in the interaction Hamiltonian between the field and the atom.

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The Hamiltonian (Accelerated)

The Hamiltonian for the accelerated detector from the accelerated observer frame

$$\hat{H}_T = \Omega_a\,\hat{a}^\dagger\hat{a} + \Omega_b\,b^\dagger b + \lambda(b + b^\dagger)(\hat{a}^\dagger e^{i\varphi} + \hat{a}\,e^{-i\varphi})$$

On its own right, for an accelerated observer $\varphi = |\Omega_a|\xi - \Omega_a\tau$

Where (τ, ξ) are Rindler coordinates and $\hat{a}, \hat{a}^\dagger$ are field operators in the Rindler basis

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Starting The Experiment

Inertial scenario

We consider the field and the detector initially in the bare ground state $|0_f 0_d\rangle$

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From the accelerated perspective, the initial state is $\rho_f \otimes |0_d\rangle\langle 0_d|$

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The interaction is suddenly switched on: small (but not negligible) excitation probability

Projective Measurement: the detector must be in the ground state

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Adiabatic Evolution

We require that if the detector starts in the ground state at time t_0
it evolves to the ground state at time t

$$|0_d\rangle \longrightarrow e^{i\gamma}e^{i\phi}\,|0_d\rangle$$

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With realistic coupling regimes and the accelerations required this holds extremely well

$$P_{\text{excitation}} < 10^{-10}$$

We can use Berry's formalism to compute the phase acquired after a cycle of adiabatic evolution

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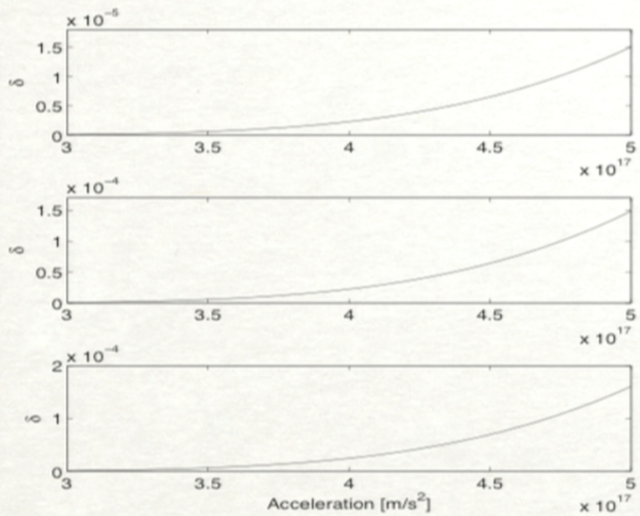
Phase Difference



- $\Omega_a \simeq 2.0$ GHz $\Omega_b \simeq 2.0$ GHz $\lambda \simeq 34$ Hz.
- $\Omega_a \simeq 2.0$ GHz $\Omega_b \simeq 2.0$ GHz $\lambda \simeq 0.10$ KHz.
- $\Omega_a \simeq 2.0$ GHz $\Omega_b \simeq 2.0$ GHz $\lambda \simeq 0.25$ KHz.

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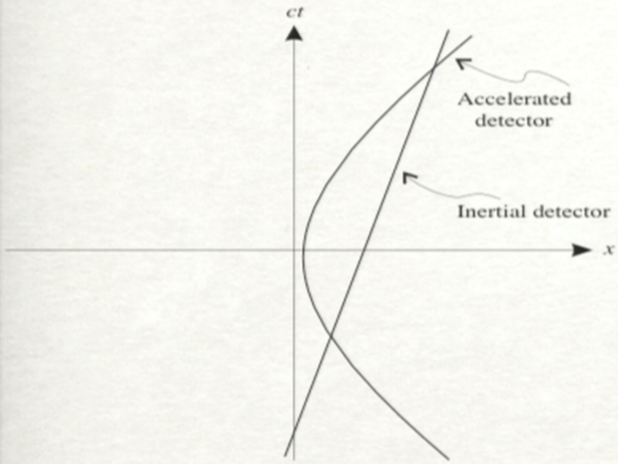

Example: Atomic interferometry

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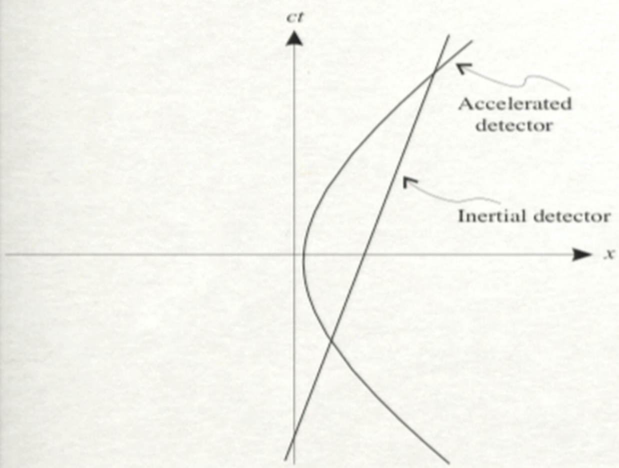

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- Sustaining accelerations of $10^{16}g$ for times of nanoseconds
- Previous best result: $10^{25}g$ Phys. Rev. Lett. 83, 256 (1999)

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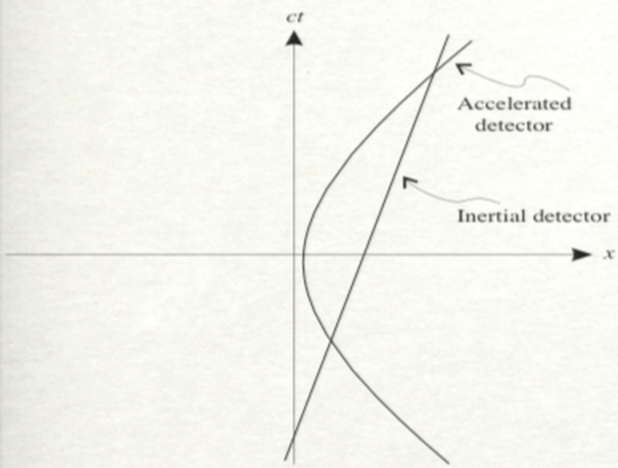

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- If MHz only $10^{13}g$ needed
- The difference of phase accumulates
  - We can wait! (microseconds for π dephase)
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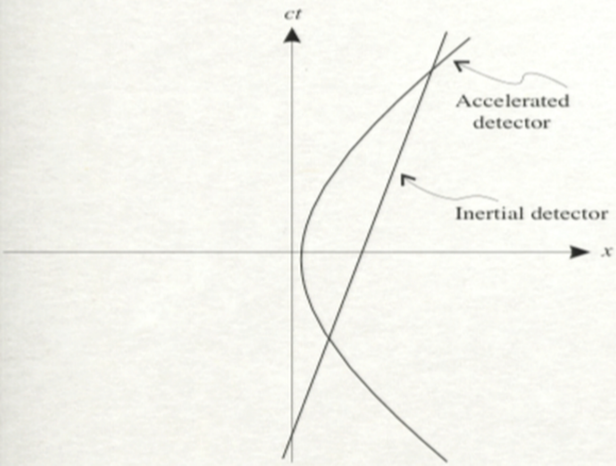

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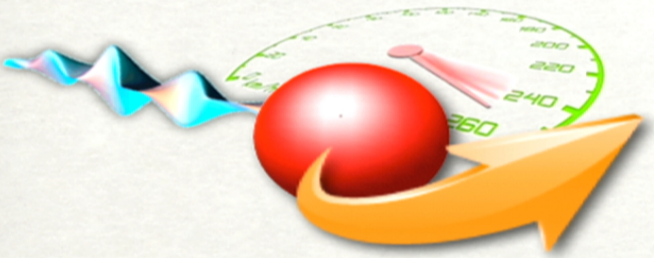
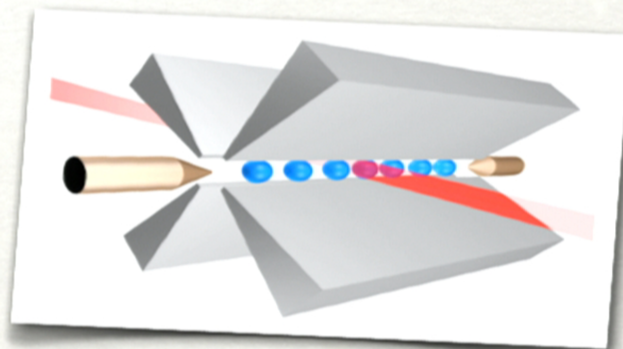
Simulating accelerated atoms in quantum optical setups





M. del Rey, D. Porras and E. Martín-Martínez, ArXiv:1109.0209

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The movement of the detector in spacetime generates a change in the interaction Hamiltonian between the field and the atom.

The change is cyclic: After $\Delta t \sim \Omega_a^{-1}$ the parameter φ completes a 2π cycle.

Completing a closed trajectory in the parameter space

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