Title: Future-past Correlations in Relativistic Quantum Information

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Abstract: In the Unruh effect, long-distance correlations in a pure quantum state cause accelerated observers to experience the state as a thermal bath. We discuss a similar phenomenon for quantum states that contain correlations between the distant future and the distant past. Examples include Minkowski half-space with a static mirror and an eternal black hole with an unusual global structure behind the horizon. The question of utilising the future-past correlations in quantum information tasks is raised.

Future-past correlations in relativistic quantum information

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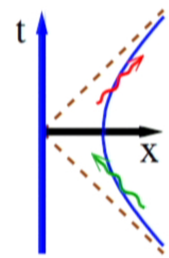
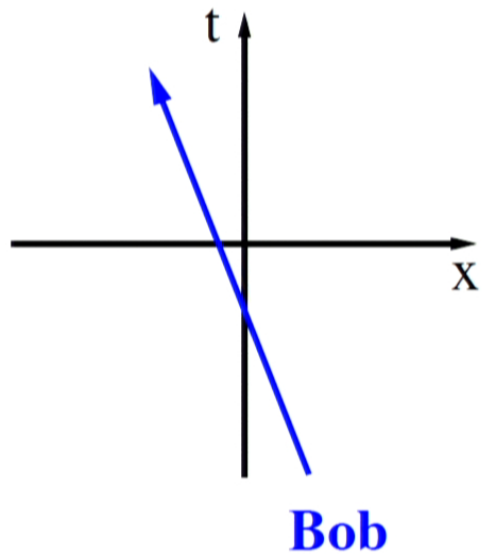
With D. E. Bruschi, G. T. Kottanattu, P. Langlois,
R. B. Mann, D. Marolf, S. F. Ross



Plan

1. Rindler space
   - Space correlations and thermality
   - **Time** correlations
2. Rindler half-space
   - **Time** correlations $\Rightarrow$ **thermality!**
3. Eternal black (half-)holes
   - Topological geon (Sorkin)
4. Summary

Minkowski vacuum $|0\rangle$ (1 + 1 scalar field)

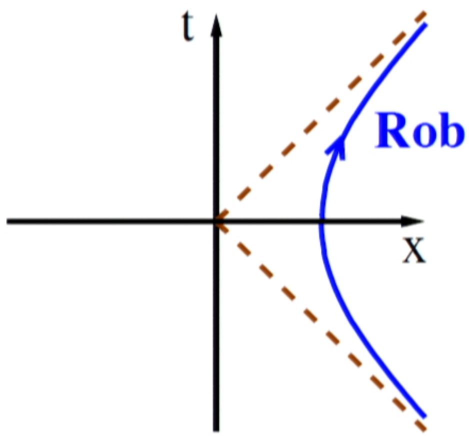


Minkowski particles:

- Defined with respect to **Minkowski** time t
- $|0\rangle$ is Poincaré invariant!

Inertial observer sees no particles in $|0\rangle$

$|0\rangle$ as seen by Rindler observer

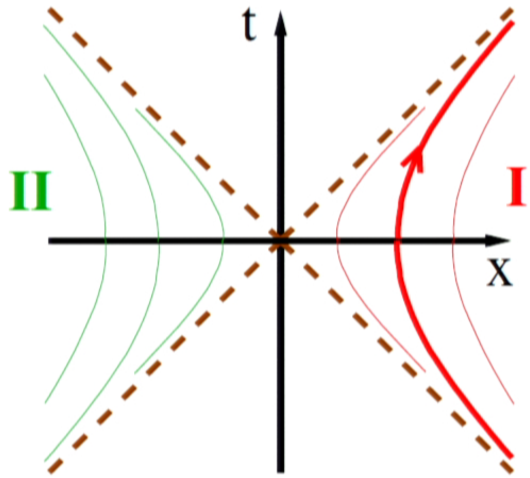


$x^2 - t^2 = \frac{1}{a^2}$, a acceleration

$\Rightarrow$ $\boxed{T = \frac{a}{2\pi}}$ **Thermal!**

- Uniformly linearly accelerated observer sees $|0\rangle$ as a **thermal** state Unruh (1976)
- Switching and back-reaction effects
  Lin and Hu (2007); Satz (2007)

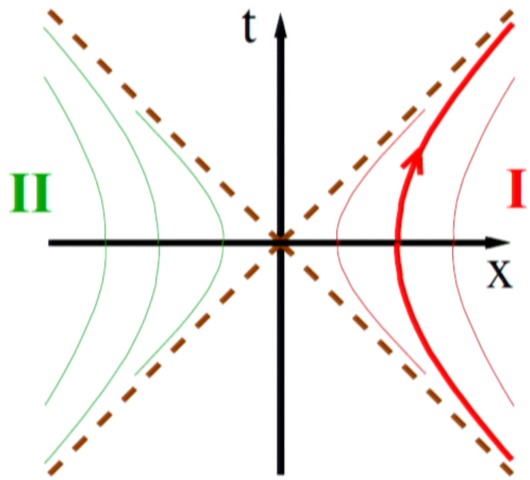
Rindler thermality: **spatial** correlations



Rindler particles:

- Defined with respect to **boost** time:
  Killing vector $x\partial_t + t\partial_x$
- Labelled by boost 'frequency' Ω

Rindler thermality: **spatial** correlations



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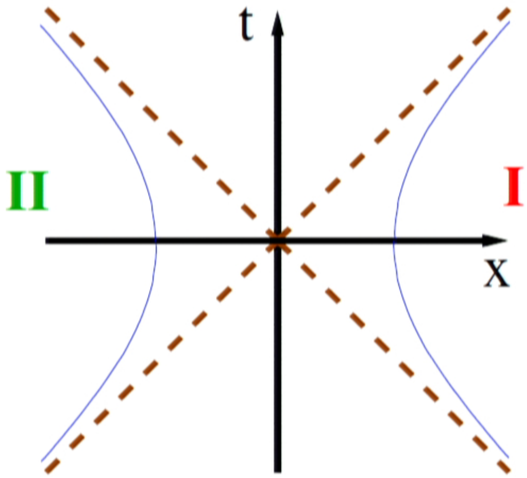
$$|0\rangle = \prod_{\Omega} |0\rangle_{\Omega}\,, \quad \boxed{|0\rangle_{\Omega} = N_{\Omega} \sum_{n=0}^{\infty} e^{-n\pi\Omega}\, |n\rangle\rangle^{\mathrm{I}}_{\Omega}\, |n\rangle\rangle^{\mathrm{II}}_{\Omega}} \quad N_{\Omega} = \sqrt{1 - e^{-2\pi\Omega}}$$

- Two-mode squeezed state
- Tracing out II $\Rightarrow$ thermal density matrix in I

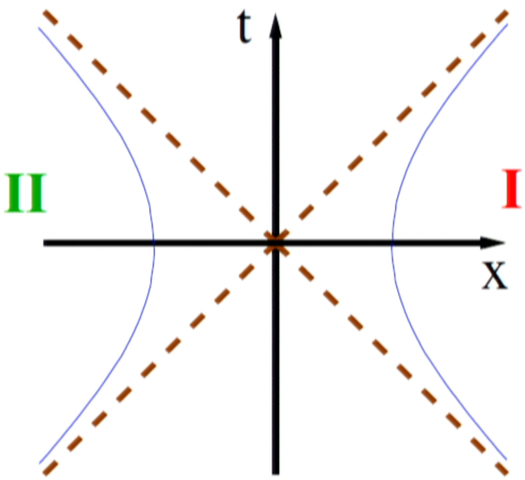
Rindler thermality: **time** correlations



Rindler wave packets:

- Localised in time and space
- Labelled by approximate frequency and location

Rindler thermality: **time** correlations



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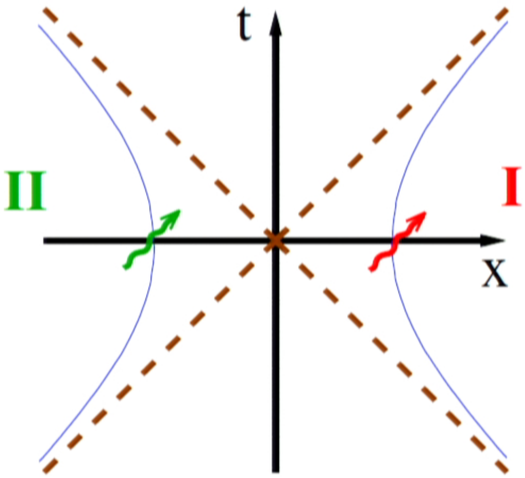
$$|0\rangle = \prod_j |0\rangle_j \,, \quad \boxed{|0\rangle_j = N_j \sum_{n=0}^{\infty} C_{j,n} \, |n\rangle\rangle_j^{\mathrm{I}} \, |n\rangle\rangle_j^{\mathrm{II}}} \quad C_{j,n} \approx e^{-n\pi\Omega_j}$$

- Boost invariance:

Rindler thermality: **time** correlations



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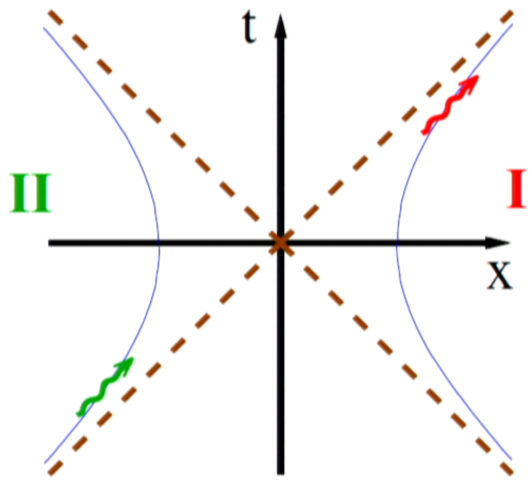

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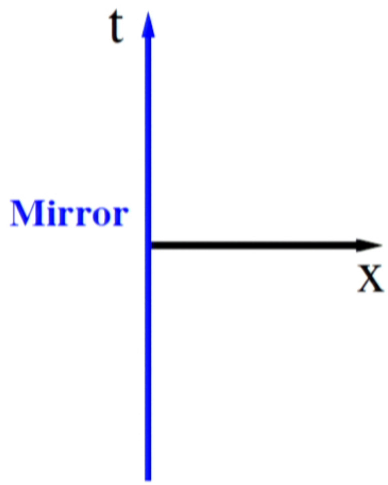
- Boost invariance: **late time** Rindler excitations **in I** correlated with **early time** Rindler excitations **in II** (and vice versa)
- Correlations still spacelike separated

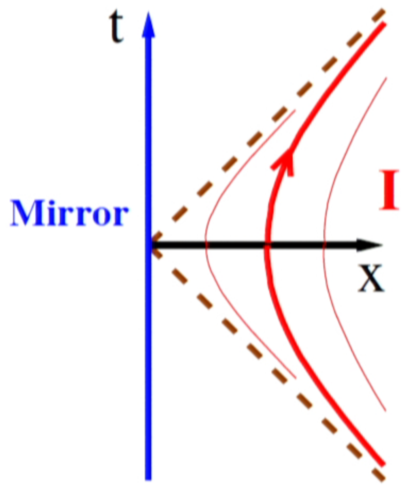
Minkowski half-space



Mirror at $x = 0$:

- Dirichlet or Neumann, method of images
- Minkowski-like vacuum $|0\rangle$, not Lorentz invariant

Minkowski half-space $\longrightarrow$ **Rindler** half-space



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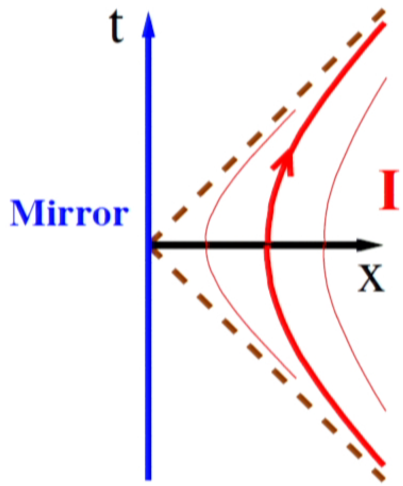

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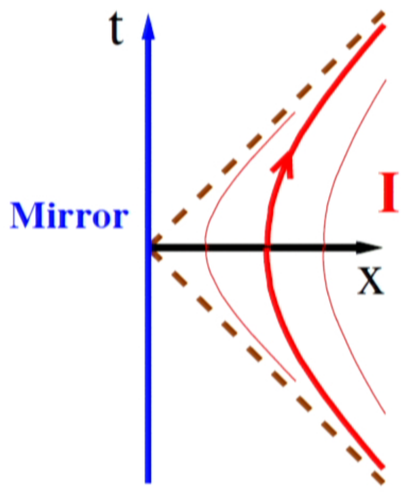

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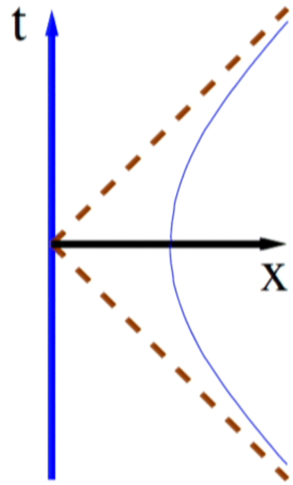
$$|0\rangle = \prod_{\Omega} |0\rangle_{\Omega} \; , \qquad \boxed{|0\rangle_{\Omega} = (N_{\Omega})^{1/2} \sum_{n=0}^{\infty} \frac{\sqrt{(2n)!}}{2^n \, n!} \, e^{-n\pi\Omega} \, |2n\rangle\rangle^{\mathrm{I}}_{\Omega}}$$

- Single-mode squeezed state   Louko and Marolf (1998)
- **Pure state in I**

Rindler half-space: **time** correlations



Rindler wave packets:

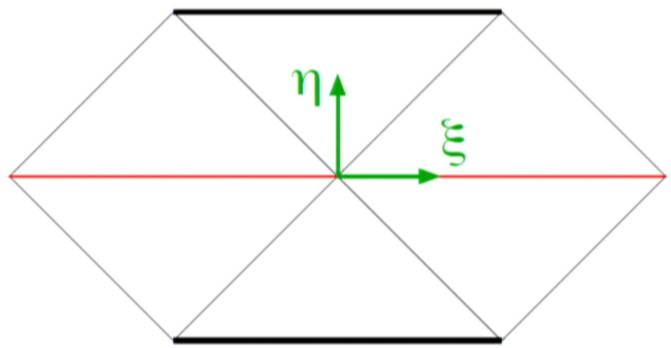
$$|0\rangle = \prod_j |0\rangle_j \ ,$$

$$|0\rangle_j \approx N_j \sum_{n=0}^{\infty} e^{-n\pi\Omega_j} \, |n\rangle\rangle^{!}_{j+} \, |n\rangle\rangle^{!}_{j-}$$

$\mathbb{RP}^3$ geon

Misner and Wheeler (1957); Giulini (1989); Friedman, Schleich and Witt (1993)

Kruskal



$$(\eta, \xi, \theta, \varphi) \mapsto (\eta, -\xi, P(\theta, \varphi))$$

involutive isometry, free action

$\mathbb{RP}^3$ geon

Misner and Wheeler (1957); Giulini (1989); Friedman, Schleich and Witt (1993)

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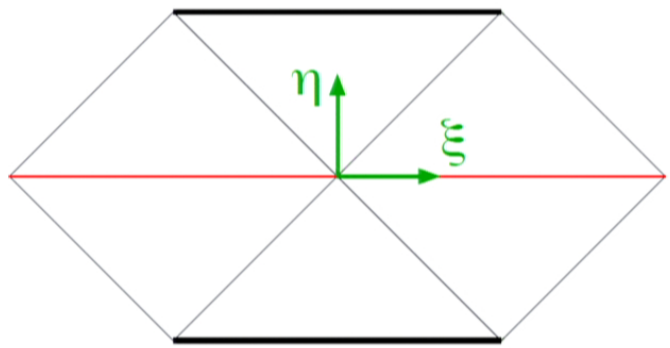
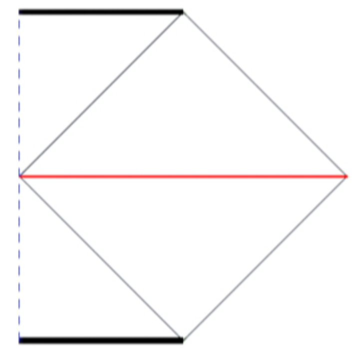


$\mathbb{RP}^3$ geon $=$ Kruskal$/\mathbb{Z}_2$



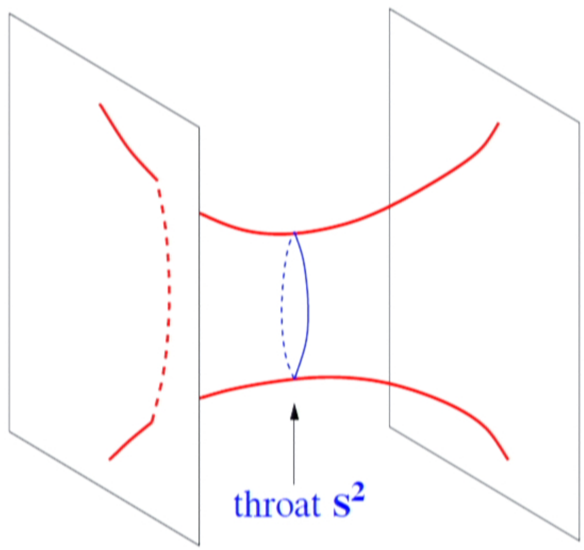
$$(\eta, \xi, \theta, \varphi) \mapsto (\eta, -\xi, P(\theta, \varphi))$$

involutive isometry, free action

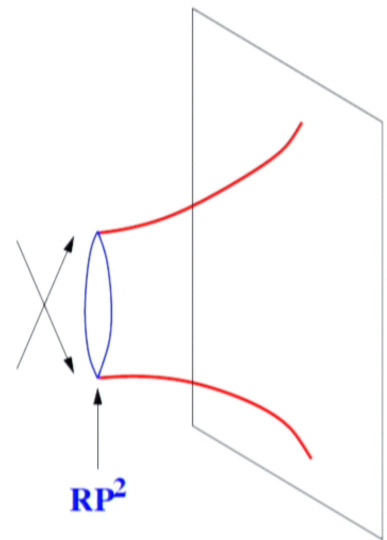
- black (and white) hole
- spherically symmetric
- time and space orientable
- spatially $\mathbb{RP}^3 \setminus \{\text{point}\}$

Snapshot: wormhole

Kruskal spacelike surface



Geon spacelike surface



Topological geon (Sorkin 1985)

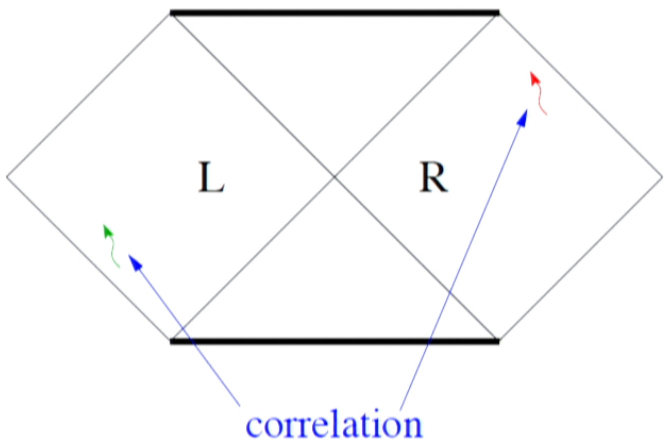
$\mathbb{RP}^3$ geon: Hawking-Unruh effect

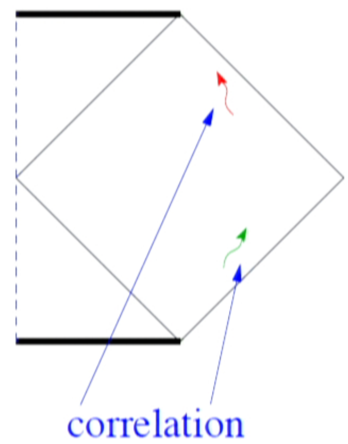
Kruskal vacuum $|0_{\rm K}\rangle$

Hartle and Hawking (1976), Israel (1976)

Induced geon vacuum $|0_{\rm G}\rangle$

Louko and Marolf (1998)





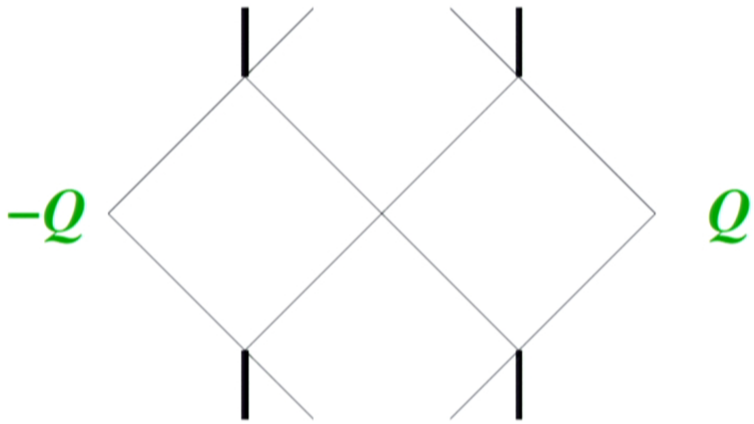
$$|0_{\rm K}\rangle = \sum f_{ij\ldots} \underbrace{a^\dagger_{R,i} a^\dagger_{L,i}}_{\text{corr}} \underbrace{a^\dagger_{R,j} a^\dagger_{L,j}}_{\text{corr}} \cdots |0_{\rm Mink}\rangle$$

In R: $\boxed{T = \frac{1}{8\pi M}}$

Reissner-Nordström geon

Louko, Mann and Marolf (2005)

Reissner-Nordström:



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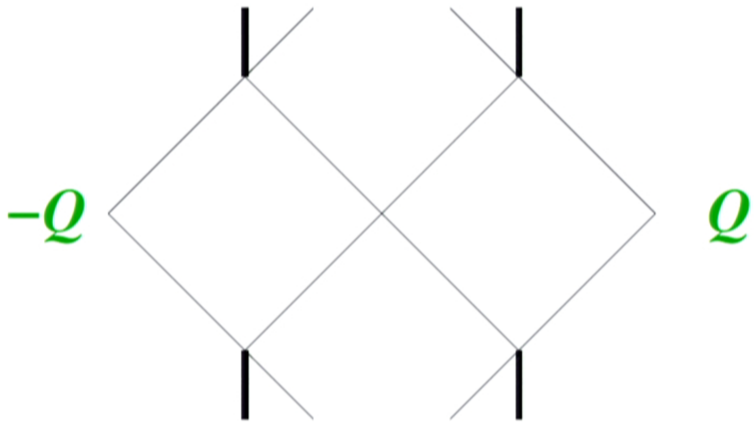

Summary

- **Unruh effect in half-space**
  - Exists: correlations between **early** and **late** times
  - Usual Unruh temperature for **early** and **late** observations
  - Thermality confirmed by particle detector response
- **Eternal black holes with special internal structure**
  - Similar story
  - **Interior** geometry encoded in **exterior** quantum correlations
  - Exist in a variety of spacetime dimensions with a variety of gauge charges, and generalise to string theory

    Louko and Marolf (1999); Louko, Marolf and Ross (2000); P. Langlois (2004); Louko, Mann and Marolf (2005); Kottanattu and Louko (2011)