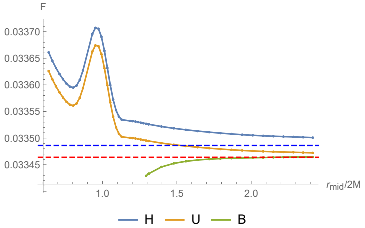
A little excitement across the black hole horizon

Jorma Louko
School of Mathematical Sciences, University of Nottingham

GR23, Beijing, 4-8 July 2022

K. K. Ng, C. Zhang, J. Louko and R. B. Mann, arXiv:2109.13260



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Plan

1. **Black hole infall**
   - Level of **quantum** input
2. **Schwarzschild infall**
   - **Quantum state** choice
3. **"Quantum dot"**
   - Infalling "atom"
4. **Results**
   - **Hartle-Hawking** and **Unruh** states
5. **Conclusions**

Black hole infall

1. Classical general relativity

2. General relativity with (some) Hawking radiation

3. Quantum gravity with (sustained) Hawking radiation

Black hole **infall**

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   - No worries across horizon
2. **General relativity with (some) Hawking radiation**
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   - Information loss: ongoing (teleological) debate!
     - Brick walls?
     - Fuzzballs?
     - Firewalls?
     - Energetic curtains?
     - ...

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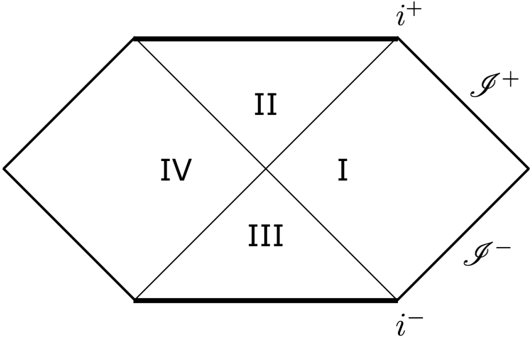
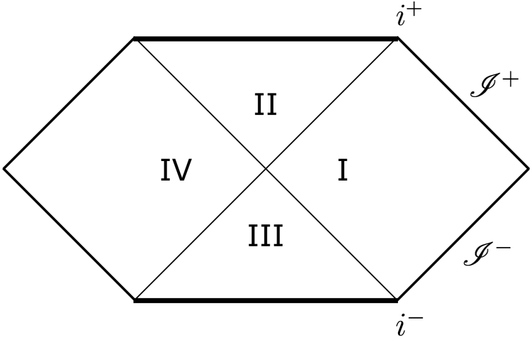
Today's setting: 2

No worries, but any phenomena?

3+1 Schwarzschild infall



3+1 Schwarzschild infall



Field: massless real scalar

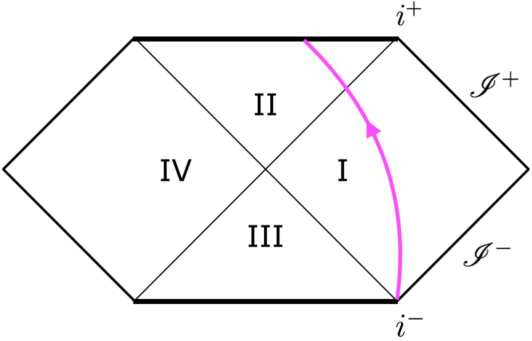
Hartle-Hawking(-Israel) state

- Regular throughout
- Thermal equilibrium at infinity

Unruh state

- Regular in I and II
- Mimics star collapse late time state

3+1 Schwarzschild infall



Radial infall

- Timelike geodesic
- No velocity at i^-

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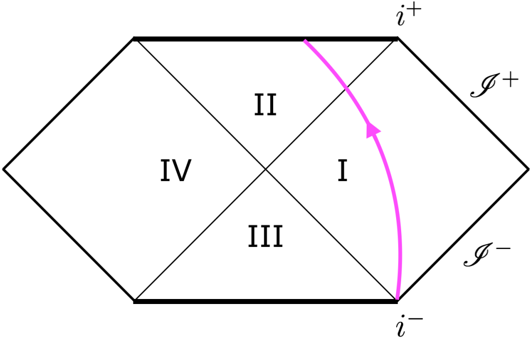

Radial infall

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Time dependent!

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Infalling "quantum dot"

Unruh(1976)-DeWitt(1979)

Quantum field

ϕ real scalar field

$|\Psi\rangle$ initial state ('vacuum')

Two-state detector (atom)

$\|0\rangle\rangle$ state with energy 0

$\|1\rangle\rangle$ state with energy Ω

$\mathsf{x}(\tau)$ detector worldline, τ proper time

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$\mathsf{x}(\tau)$	detector worldline, τ proper time

Interaction

$$H_{\mathrm{int}}(\tau) = c\chi(\tau)\mu(\tau)\phi\big(\mathsf{x}(\tau)\big)$$

c	coupling constant
χ	switching function, real-valued, sufficiently smooth
μ	detector's monopole moment operator

Probability of transition

$$\|0\rangle\rangle \otimes |\Psi\rangle \longrightarrow \|1\rangle\rangle \otimes |\text{anything}\rangle$$

in first-order perturbation theory:

$$P(\Omega) = c^2 \underbrace{\left|\langle\langle 0\|\mu(0)\|1\rangle\rangle\right|^2}_{\substack{\text{detector internals only:} \\ \text{drop!}}} \times \underbrace{F_\chi(\Omega)}_{\substack{\text{trajectory and } |\Psi\rangle\text{:} \\ \text{response function}}}$$

$$F_\chi(\Omega) = \int d\tau' d\tau'' \, e^{-i\Omega(\tau'-\tau'')} \, \chi(\tau')\chi(\tau'') \, W(\tau', \tau'')$$

$$W(\tau', \tau'') = \langle\Psi|\phi\big(x(\tau')\big)\phi\big(x(\tau'')\big)|\Psi\rangle \qquad \text{Wightman function}$$

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Wightman function (distribution)

Well defined for Hadamard $|\Psi\rangle$!

Switching

Δ: half the interaction duration

τ_{mid}: interaction interval midpoint

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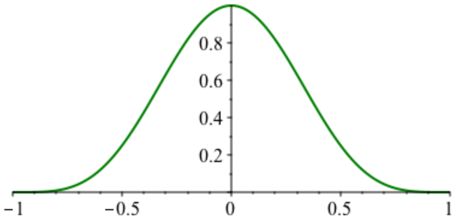
$$\chi(\tau) = \begin{cases} \cos^4\left(\frac{\pi(\tau - \tau_{\text{mid}})}{2\Delta}\right) & \text{for } |\tau - \tau_{\text{mid}}| < \Delta \\ 0 & \text{otherwise} \end{cases}$$



$\frac{\tau - \tau_{\text{mid}}}{\Delta}$

- Finite duration, C^3
- Close to Gaussian

Results

Parameters: $\Omega = 5/(2M)$, $\Delta = 0.3 \times 2M$

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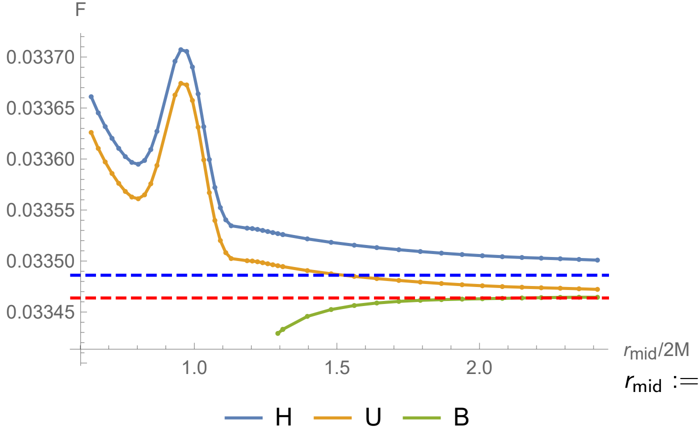

$r_{\text{mid}} := r(\tau_{\text{mid}})$

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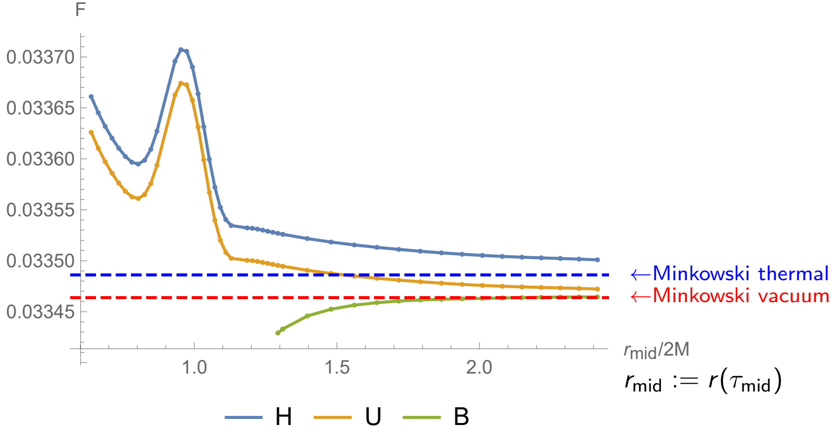

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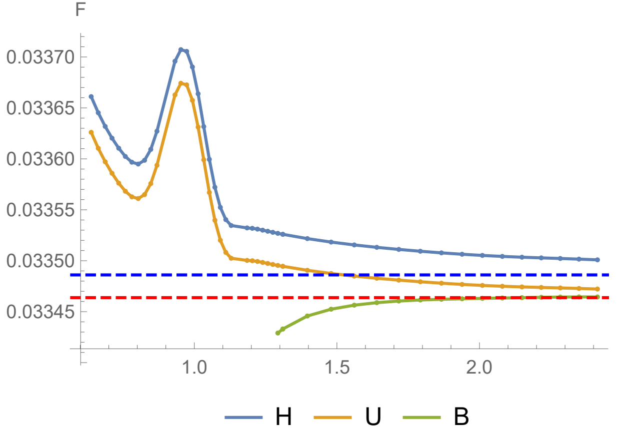

←Minkowski thermal
←Minkowski vacuum

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- **Small** bumps on reaching/crossing the horizon

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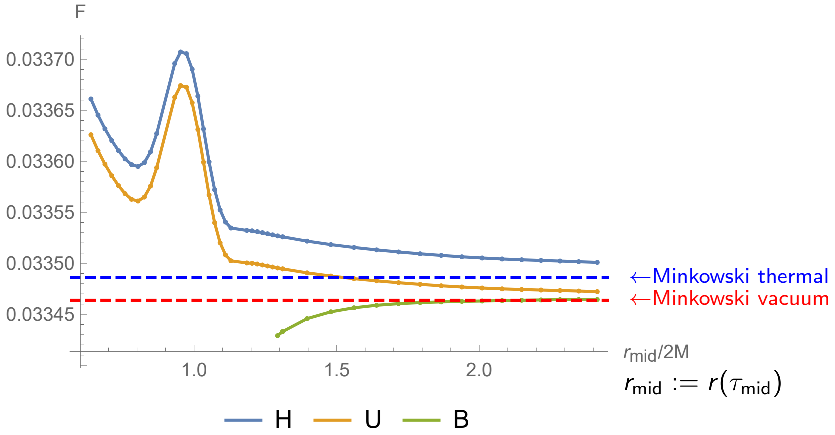

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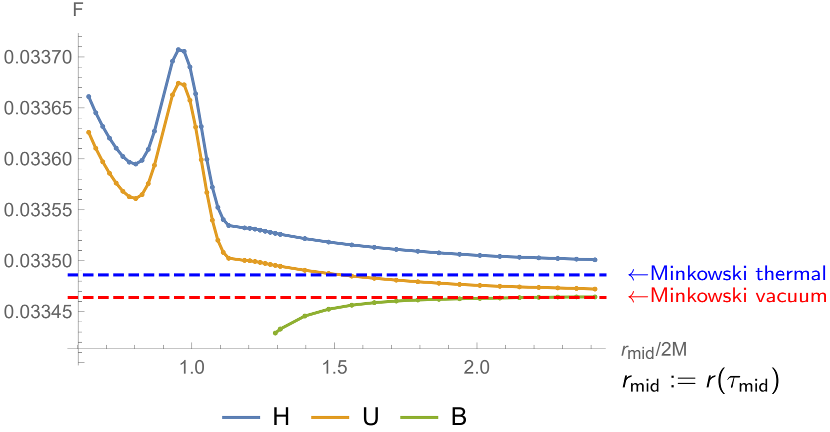

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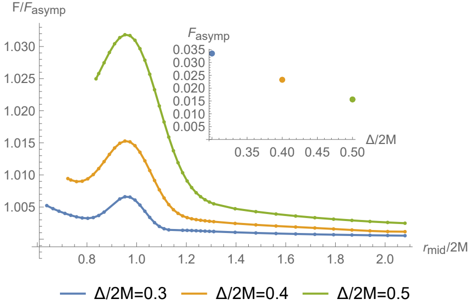
- **Analytic explanation?**

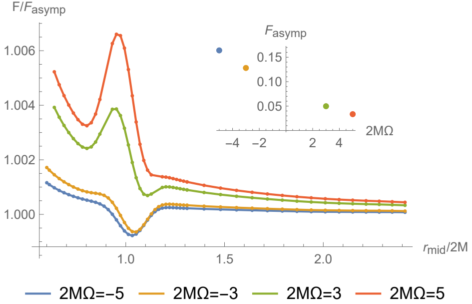
Results (cont'd): HH state

(normalised at $r_{mid} \to \infty$)



Δ varying

$\Omega = 5/(2M)$ as previous slide



Ω varying

$\Delta = 0.3 \times 2M$ as previous slide

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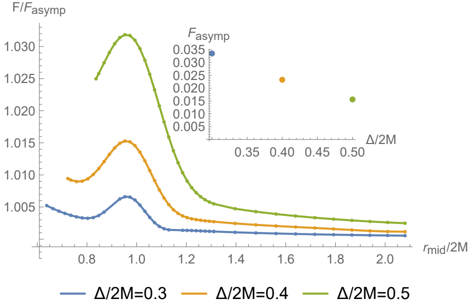

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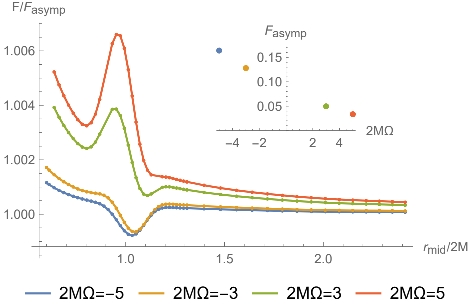

Ω varying, including sign

$\Delta = 0.3 \times 2M$ as previous slide

Conclusions

Setting

- 3+1 Schwarzschild: massless scalar
- Hartle-Hawking(-Israel) and Unruh states
- UDW detector ("quantum dot") infall

Outcomes

- **Small** but distinctive **structure** across the horizon
  - **Evidence numerical**
  - Appears numerically robust

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Outlook

- Analytic explanation of the across-the-horizon structure?

Angular momentum role?