Detectors and moving boundaries

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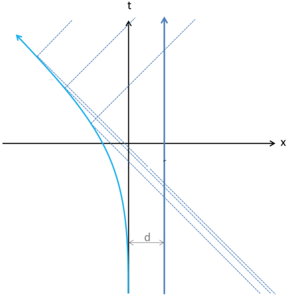
Vietri sul mare, 18 February 2025



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Plan

Part A

- Historical remarks
- Localised quantum system interacting with a non-localised quantum field: detector!
- Time dependent systems: switching interaction on and off
- Six examples 1977–2025

Part B

At most one of:

- Vacua in locally de Sitter cosmologies, and how to distinguish them
- Temperature of acceleration, in spacetime and in the laboratory

Pre-history: four lessons in quantum theory

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   Observation: 1958, 1997,. . .

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   Observation:
   Wilson et al 2011
   Lähteenmäki et al 2013
   (electrical simulation of motion)

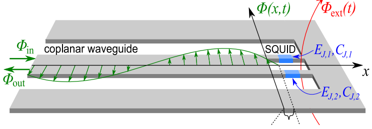


Image: Johansson et al 2009

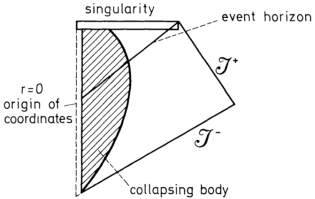
History

Cosmological ‘particle creation’ Parker 1968...

Gravitational collapse Hawking 1974, 1975

Late time outgoing thermal flux

$$T_H = \frac{1}{8\pi M}$$



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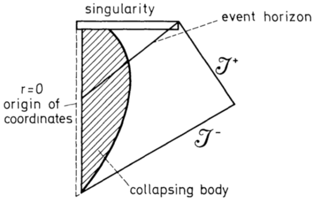
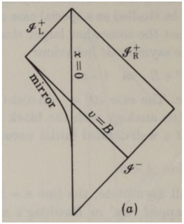


Receding mirror in Minkowski Davies and Fulling 1977

Tailored late time trajectory
⇒ Hawking-type radiation
from the mirror



Arena: Fock space

Input

- "vacuum plus excitations" (old school)
- relies on notion of "positive frequency"
  - ⇒ different positive frequency choices related by Bogoliubov transformations
- typically employs spread-out Fourier modes
  - ⇒ localising a "particle"?

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$\langle T_{\mu\nu} \rangle, \ldots$ (renormalisation)

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Pointlike two-state detector

Unruh(1976)-DeWitt(1979)

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Quantum field

D	spacetime dimension
ϕ	real scalar field
$\vert\Psi\rangle$	field initial state

Two-state detector (atom)

$\Vert 0\rangle\rangle$	state with energy 0
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$\mathsf{x}(\tau)$	detector worldline, τ proper time

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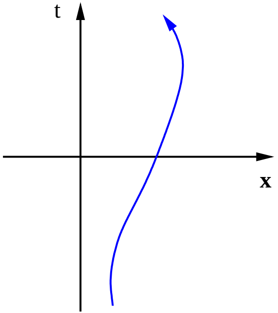

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Interaction

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

c	coupling constant
χ	switching function, C_0^∞, real-valued
μ	detector's monopole moment operator

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Linear!

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Probability of transition

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

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

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

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Wightman function
(distribution)

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W: field initial state $|\Psi\rangle$ and detector motion

χ: detector switching

E: detector energy gap

- $E > 0$: excitation
- $E < 0$: de-excitation

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Theorem (Hörmander 1971)

If $|\Psi\rangle$ is Hadamard and $\mathsf{x}(\tau)$ is smooth, then $W(\tau', \tau'')$ is a well-defined distribution on $\mathbb{R} \times \mathbb{R}$

Corollary

If χ is C_0^∞ and $\mathsf{x}(\tau)$ is smooth, $F_\chi(E)$ is **well defined**!

Switching?

$$F_\chi(E) = \int \mathrm{d}\tau' \mathrm{d}\tau''\, \mathrm{e}^{-iE(\tau'-\tau'')}\, \chi(\tau')\chi(\tau'')\, W(\tau',\tau'')$$

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Switching effects (artefacts?) intertwine with effects due to $|\Psi\rangle$, motion, energy gap

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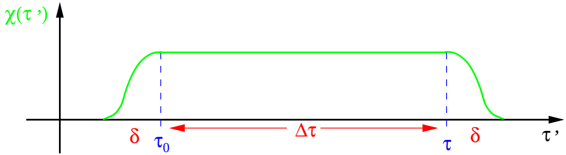
Stationary motion: $W(\tau', \tau'') = W(\tau' - \tau'', 0)$

- uniform linear acceleration in Minkowski vacuum (Unruh effect)
- static observer outside Schwarzschild black hole,...

Long time limit $\rightarrow$ **transition rate**:



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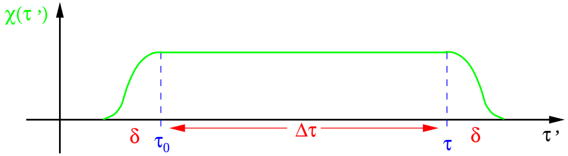

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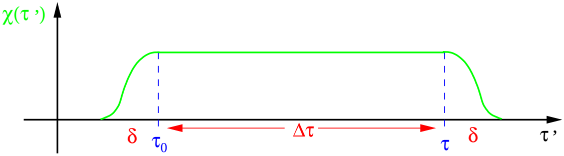
Long time limit → **transition rate**: yet within linear perturbation theory!



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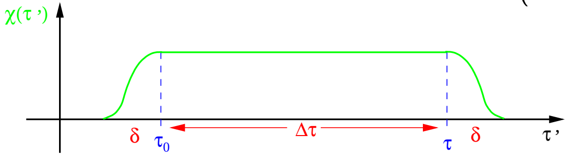

$\delta \to 0$? Switching effects grow...

Hodgkinson and JL 2012

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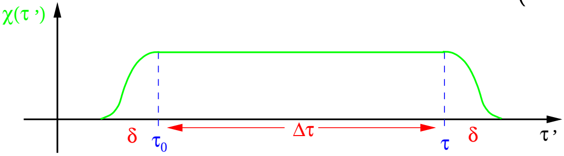

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$D = 2, 3$: $F_\chi(E)$ finite as $\delta \to 0$

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$D = 6$:

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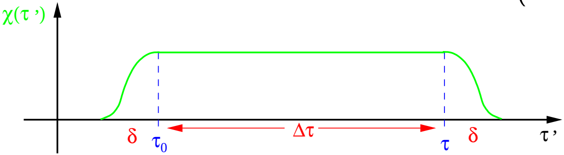

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Instantaneous transition rate still well defined

(measurable in an ensemble of ensembles)

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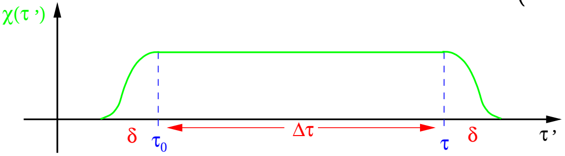

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Instantaneous transition rate divergent

(for generic states/trajectories)

Remarks

- $W(\tau', \tau'')$ sometimes infrared divergent (eg $D = 2$ massless)
  Cure: $H_{\mathrm{int}}(\tau) \propto \frac{d}{d\tau}\phi(\mathsf{x}(\tau))$ (but more singular at sharp switching)
- Fermions: $H_{\mathrm{int}}(\tau) \propto \overline{\psi(\mathsf{x}(\tau))}\psi(\mathsf{x}(\tau))$ quadratic Takagi 1986
  $\Rightarrow$ more singular JL and Toussaint 2016
- Higher-order perturbation theory? More singular!
  Needed in entanglement harvesting by multiple detectors
- Spatially smeared detectors? Less singular!
  ... but acausality appears Sorkin 1991, Bostelmann et al 2021

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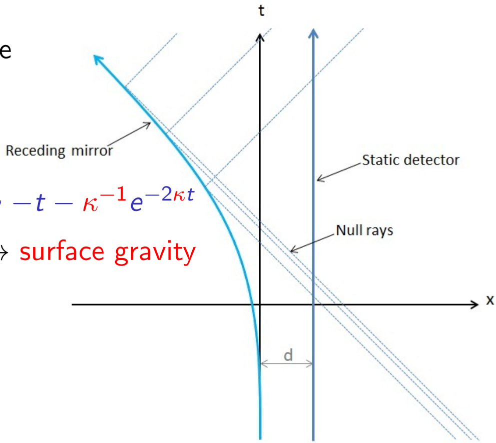
- Moving cavities Bruschi et al 2012, Lorek et al 2015,. . .
- Complementary track: open quantum systems approach
  Long time, weak coupling, Markovian approximation
  $\Rightarrow$ Sharp switch-off well defined (after renormalisation)
  Benatti and Floreanini 2004,. . .
- Pointlike two-state detector $\rightarrow$ pointlike SHO
  $\Rightarrow$ Gaussian nonperturbative methods Lin and Hu 2007,. . .

Example: 1+1 receding mirror

Juárez-Aubry and JL 2015

Closely similar to
collapsing star spacetime



$$x \sim -t - \kappa^{-1} e^{-2\kappa t}$$

$\kappa \leftrightarrow$ surface gravity

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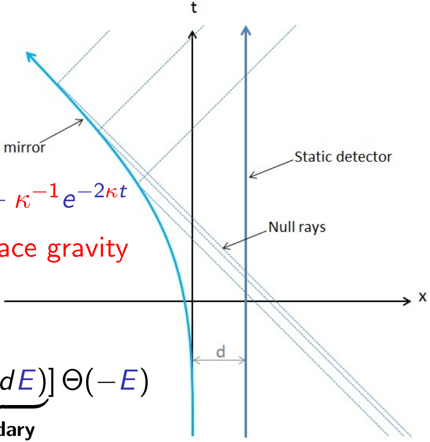

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Past:

- $\dot{F}_\tau(E) \sim -E\,[1 - \underbrace{\cos(2dE)]}_{\textbf{boundary}}\,\Theta(-E)$

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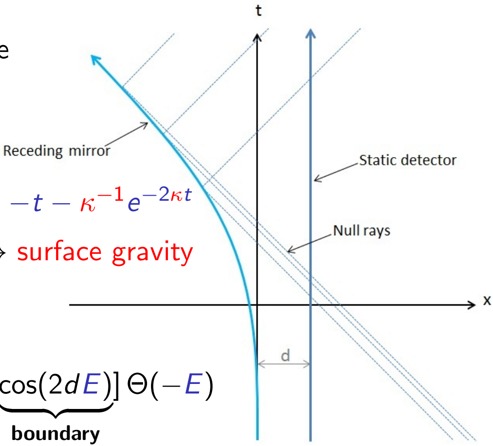

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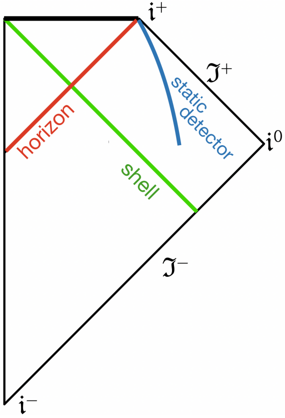
Onset of thermal flux

Example: 1+1 null shell collapse

Juárez-Aubry and JL 2018



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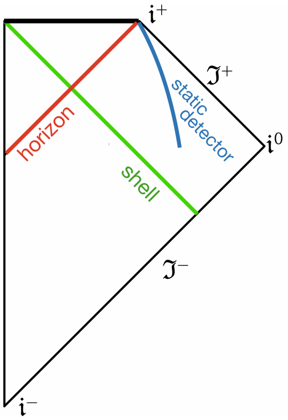

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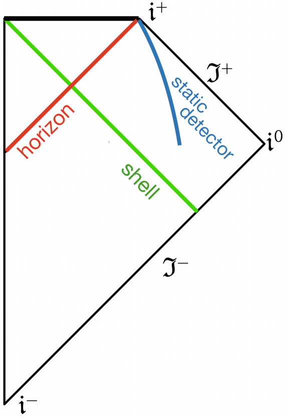

Late time state approaches the Unruh state on Kruskal (stationary outgoing flux)

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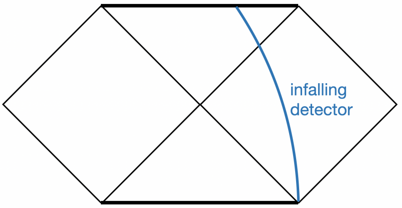

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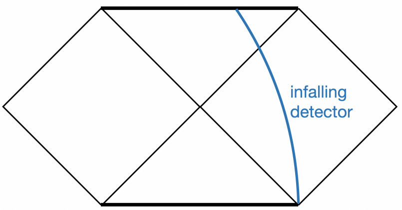

Vacua (stationary wrt Killing time)

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- Hartle-Hawking-Israel: thermal **equilibrium** $T_\infty = 1/(8\pi M)$
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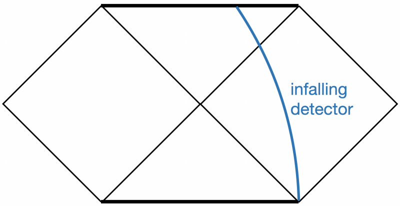

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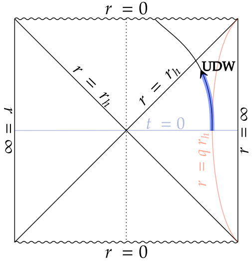
Outcomes (massless field)

- At infinity Boulware empty, HHI thermal, Unruh half-thermal
- HHI and Unruh:
  - (half-)thermality gradually lost during the fall
  - Horizon-crossing non-drastic
  - $\dot{F}_\tau \sim r^{-3/2}$ near the singularity

Example: 2+1 BTZ infall

Conformal field, HHI state

Spinless Hodgkinson and JL 2012, Preciado-Rivas et al 2024



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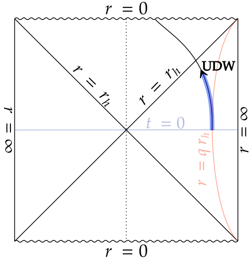
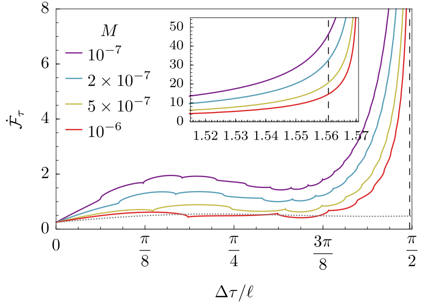
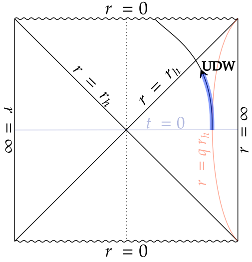


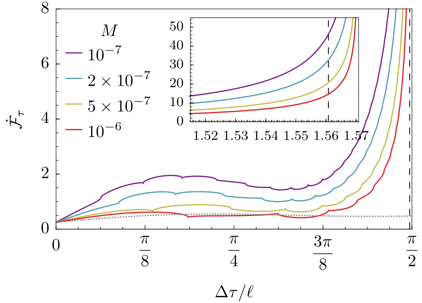


Example: 2+1 BTZ infall

Conformal field, HHI state

Spinless Hodgkinson and JL 2012, Preciado-Rivas et al 2024





- $\dot{F}_\tau$ has discontinuous derivative ("glitch") when switch-off moment is on the lightcone of the switch-on moment
- Happens already outside the horizon!

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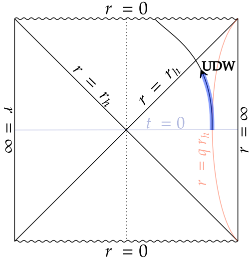

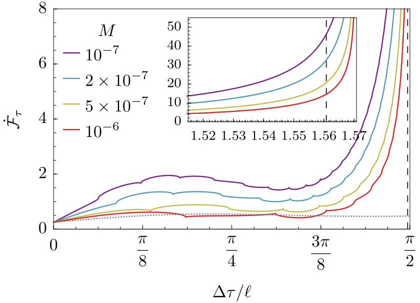

- $\dot{F}_\tau$ has discontinuous derivative ("glitch") when switch-off moment is on the lightcone of the switch-on moment
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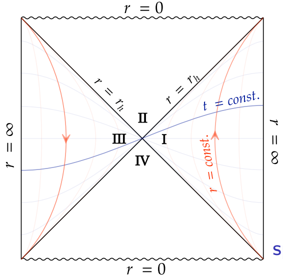
Spinning Wang et al 2024

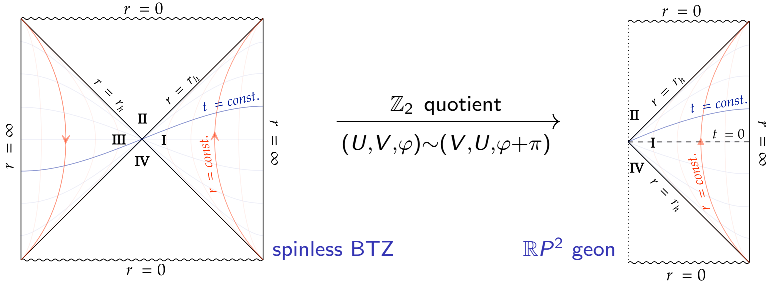
- HHI state has singularities beyond the inner horizon Steif 1994
  $\Rightarrow$ severe glitches there

Example: infall in a single-exterior BTZ hole Spadafora et al 2024



spinless BTZ

Example: infall in a single-exterior BTZ hole Spadafora et al 2024



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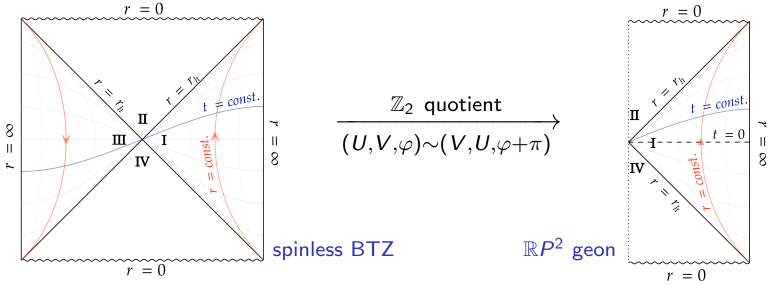
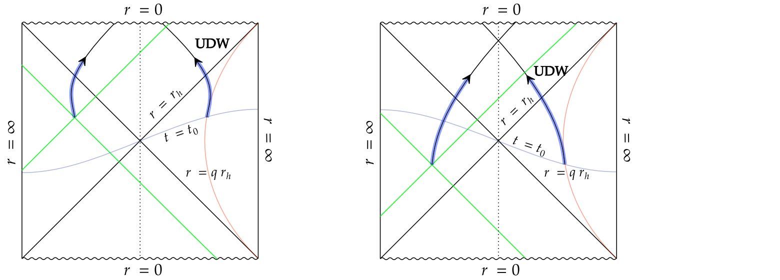
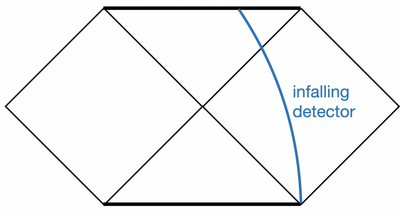


Infalling detector configurations on the geon:



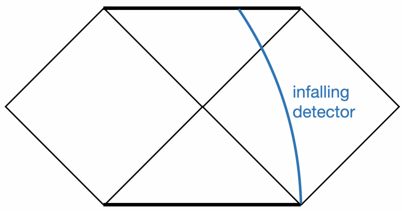
- New glitches after horizon-crossing

Example: 3+1 Schwarzschild infall Ng et al 2022; Shallue and Carroll 2025



Example: 3+1 Schwarzschild infall Ng et al 2022; Shallue and Carroll 2025

$\dot{F}_\tau$ numerically difficult!



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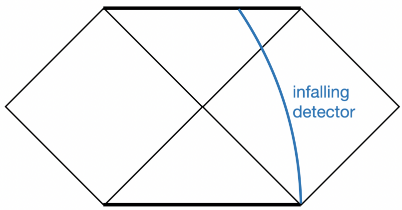


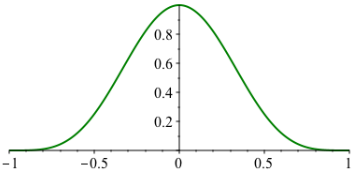
$\dot{F}_\tau$ numerically difficult!

Consider F_χ with

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

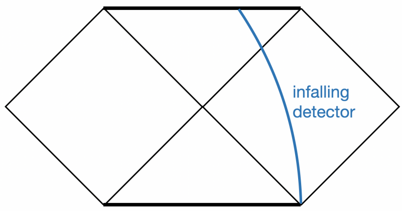
Δ: half the interaction duration

τ_{mid}: interaction interval midpoint



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

Example: 3+1 Schwarzschild infall Ng et al 2022; Shallue and Carroll 2025



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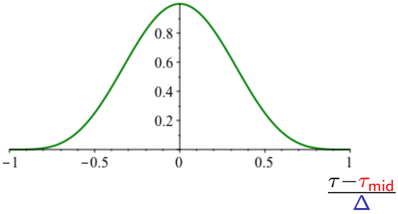
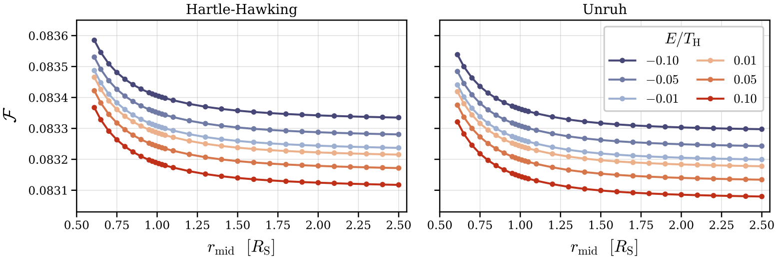


- Finite duration, C^3
- Close to Gaussian

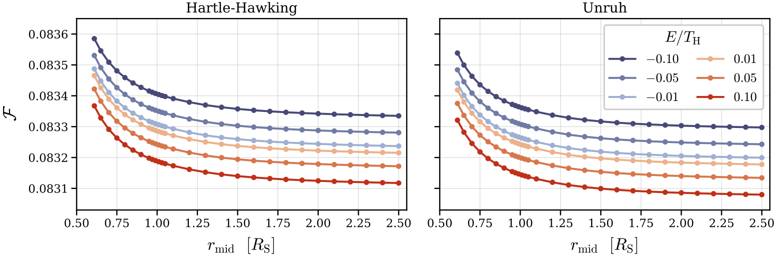
3+1 Schwarzschild infall (cont'd) Shallue and Carroll [arXiv:2501.06609]

F_χ



3+1 Schwarzschild infall (cont'd) Shallue and Carroll [arXiv:2501.06609]

F_χ

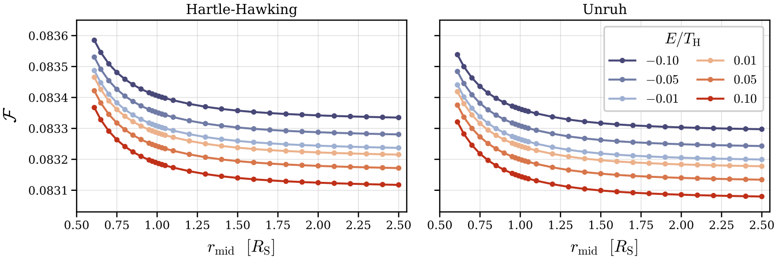


$\Delta \lesssim M$ needed to resolve timescales near and beyond the horizon

$\Rightarrow F_\chi$ dominated by switching effects

3+1 Schwarzschild infall (cont'd) Shallue and Carroll [arXiv:2501.06609]

F_χ



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Notion of 'effective temperature' during the infall continues to be under debate!