Transitioning to Memory Burden: Detectable Small PBHs as Dark Matter

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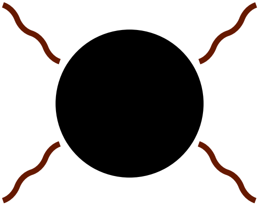
Work[1] with Gia Dvali, Marco Michel and Michael Zantedeschi

20^{th} May 2025

[1] *Transitioning to Memory Burden: Detectable Small Primordial Black Holes as Dark Matter*, `arXiv:2503.21740`.
The Timescales of Quantum Breaking, Fortschr. Phys. **71** (2023) 2300163, `arXiv:2306.09410`. [News article "Where is the boundary to the quantum world?"].

The fate of an old black hole



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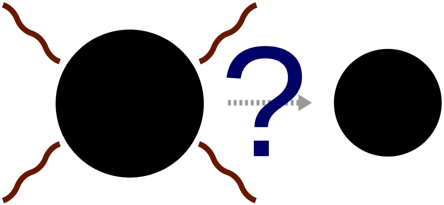

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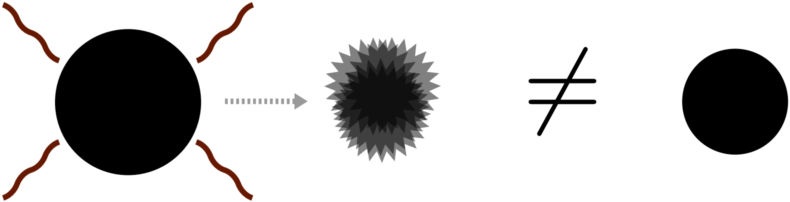

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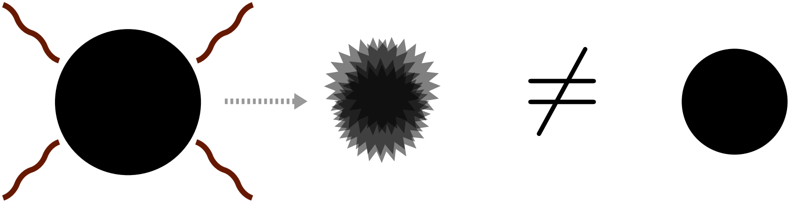

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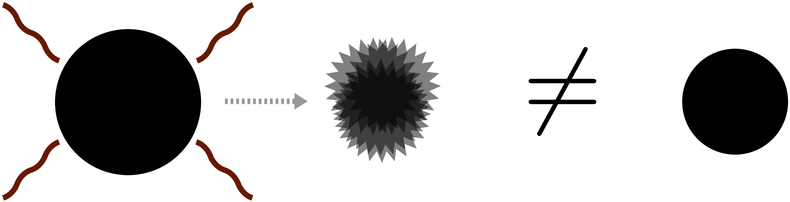

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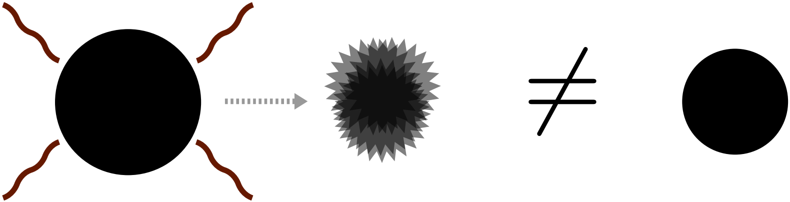

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- Inflationary production compatible with CMB [talk B. Gladwyn]

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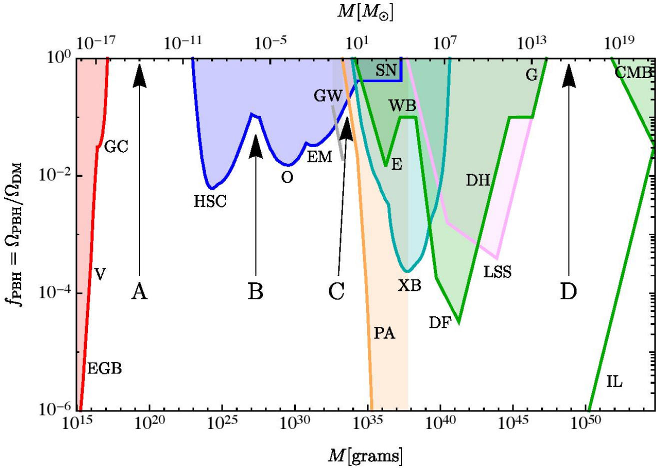

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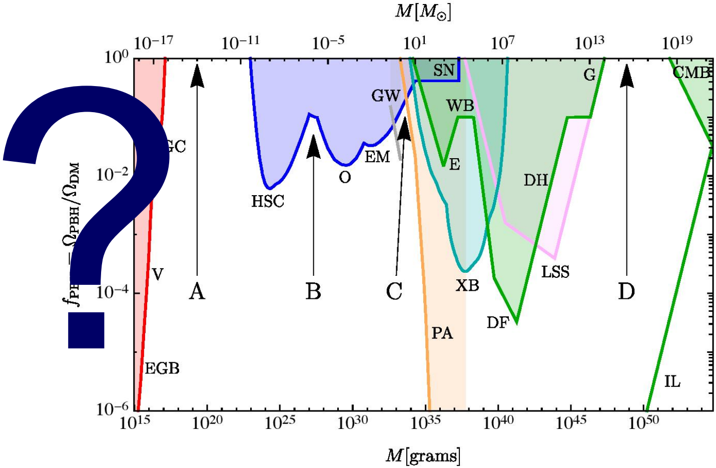

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A. Alexandre, G. Dvali, E. Koutsangelas, *New Mass Window for Primordial Black Holes as Dark Matter from Memory Burden Effect*, `arXiv:2402.14069`.
V. Thoss, A. Burkert, K. Kohri, *Breakdown of Hawking Evaporation opens new Mass Window for Primordial Black Holes as Dark Matter Candidate*, `arXiv:2402.17823`.

Outline

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$$r_g \sim GM$$

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[6] MB also in inflation: G. Dvali, L. Eisemann, M. Michel, S. Z., *Universe's Primordial Quantum Memories*, arXiv:1812.08749.

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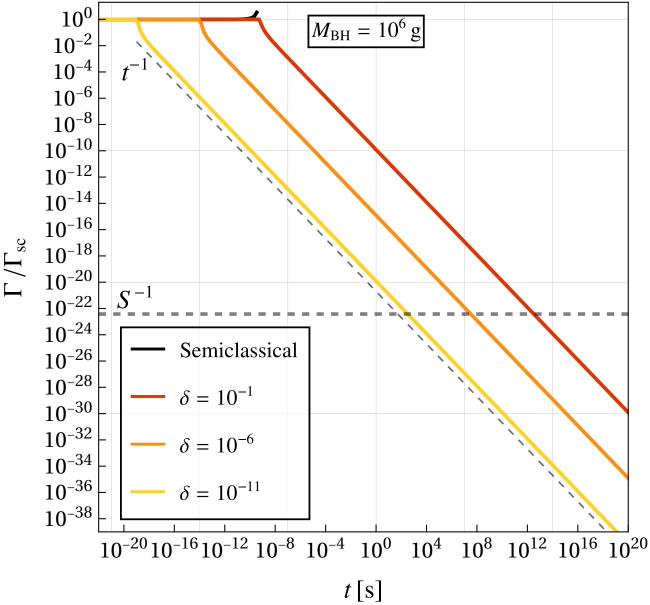

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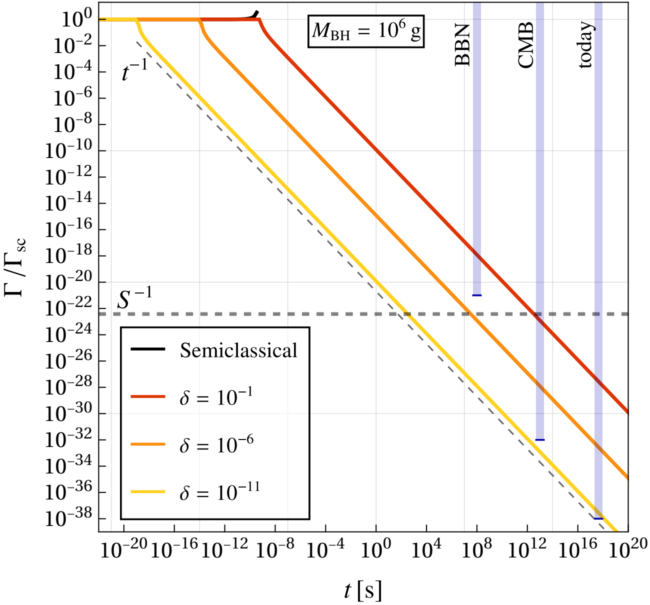

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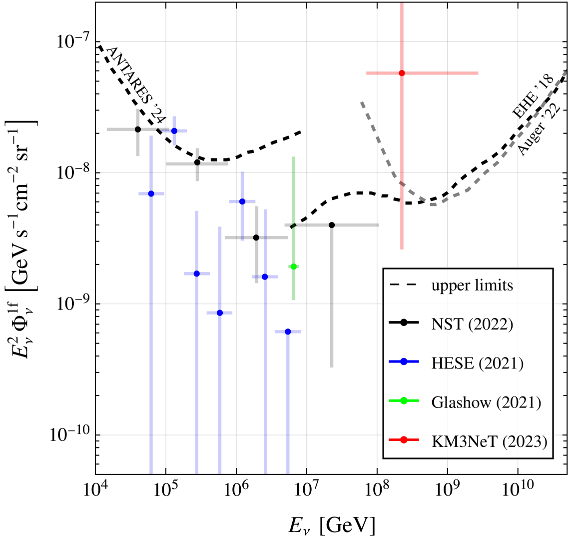

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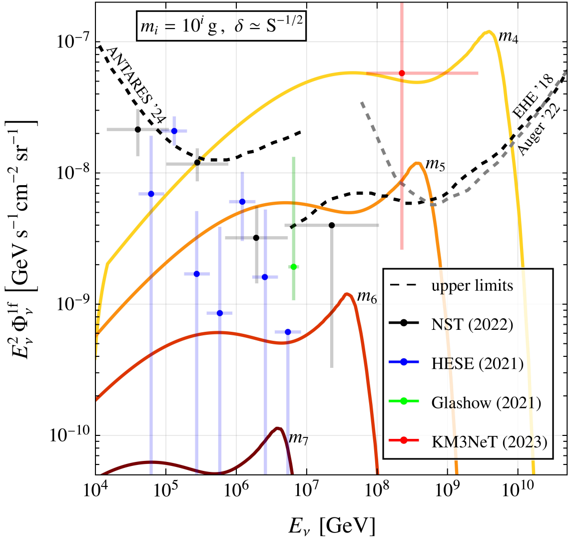

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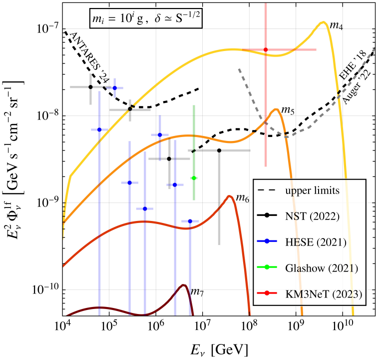

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- Crucial: all microstates must have similar energy

Enhanced memory storage[15]

- Hamiltonian

$$\frac{\hat{\mathcal{H}}_S}{r_g^{-1}} = \sqrt{S} \sum_{k=1}^{S} \underbrace{\hat{n}_k}_{\hat{a}_k^\dagger \hat{a}_k}$$

[15] G. Dvali, *Critically excited states with enhanced memory and pattern recognition capacities in quantum brain networks: Lesson from black holes*, arXiv:1711.09079.
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- Dictionary

$\hat{n}_0$: carries mass

$\langle \hat{n}_0 \rangle = S$: black hole state

$\hat{n}_k$: carry entropy

$\hat{n}_b$: Hawking quanta

[15] G. Dvali, *Critically excited states with enhanced memory and pattern recognition capacities in quantum brain networks: Lesson from black holes*, `arXiv:1711.09079`.
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Time evolution

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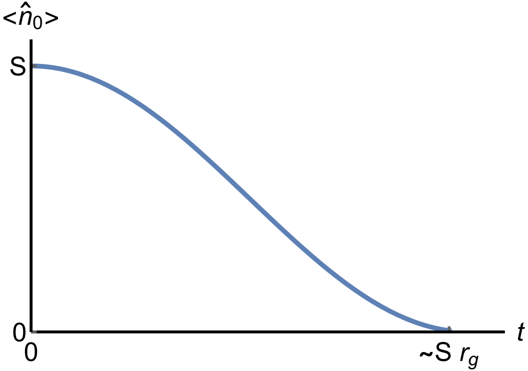

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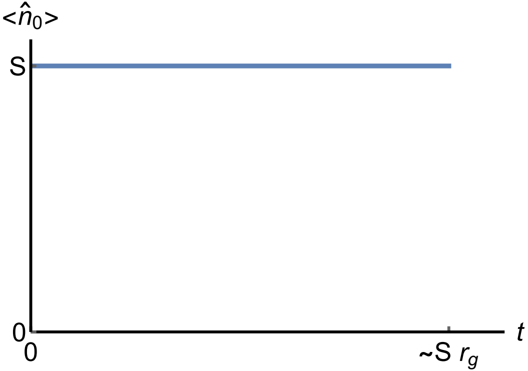

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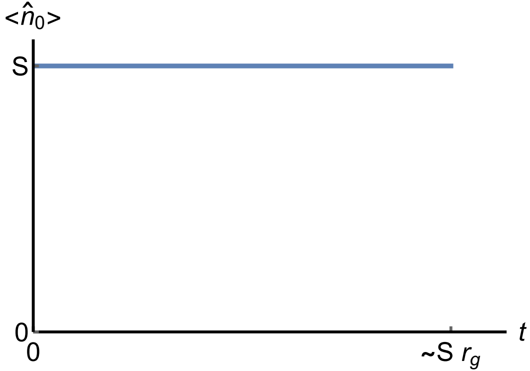

Memory burden:[16] entropy prevents evaporation

[16] G. Dvali, *A Microscopic Model of Holography: Survival by the Burden of Memory*, `arXiv:1810.02336`.

Full model[15]

$$\hat{\mathcal{H}} = \hat{\mathcal{H}}_{S_>} + \hat{n}_b + \frac{1}{S}\left(\hat{a}_0^\dagger \hat{b} + \text{h.c.}\right)$$

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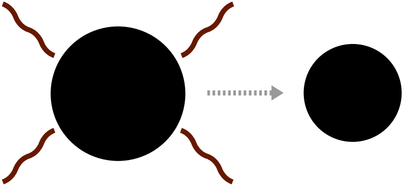

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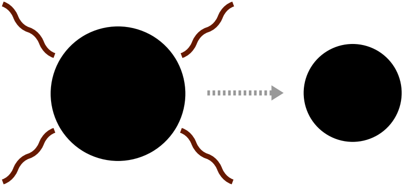

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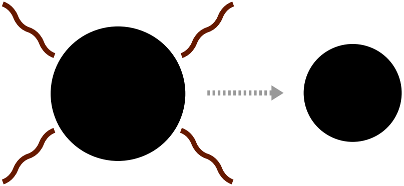

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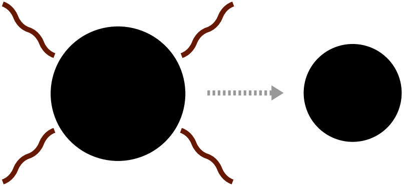

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- Exact time evolution:[16] transition suppressed dynamically
- Slowdown at the latest after half evaporation back

[15] G. Dvali, L. Eisemann, M. Michel, S. Z., *Black Hole Metamorphosis and Stabilization by Memory Burden*, arXiv:2006.00011.

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Black hole criticality

- Gravitational coupling

$$\alpha = \hbar G r_g^{-2}$$

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- Critical collective coupling[17]

$$\alpha N = 1$$

[17] G. Dvali, C. Gomez, *Black Holes as Critical Point of Quantum Phase Transition*, arXiv:1207.4059.

Imitate criticality

- Prototype model

$$\hat{\mathcal{H}} = \sum_{k=1}^{Q} \left(\hat{n}_k - \frac{\alpha}{4} \left(2\hat{n}_0 \hat{n}_k + \hat{a}_0^{\dagger\,2} \hat{a}_k^2 + \hat{a}_k^{\dagger\,2} \hat{a}_0^2 \right) \right) + \frac{C_m}{2} \sum_{k=1}^{Q} \sum_{l=k+1}^{Q} f(k,l) \left(\hat{a}_k^{\dagger\,2} \hat{a}_l^2 + \text{h.c.} \right) .$$

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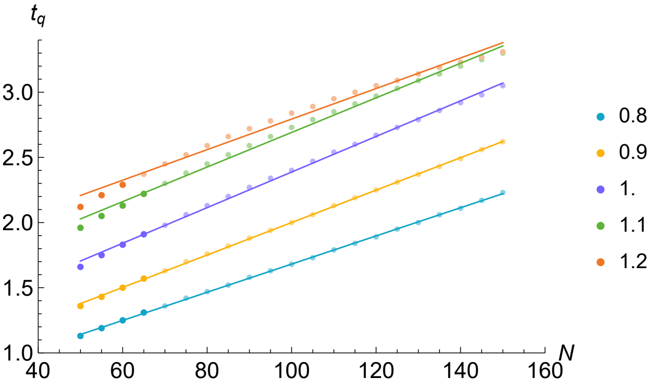
- Study quantum break-time:[18]
timescale of breakdown of semi-classical approximation

[18] G. Dvali, C. Gomez, D. Flassig, A. Pritzel, *Scrambling in the Black Hole Portrait*, arXiv:1307.3458.

Result[19]



[19] M. Michel, S. Z., *TimeEvolver: A Program for Time Evolution With Improved Error Bound*, `arXiv:2205.15346`.
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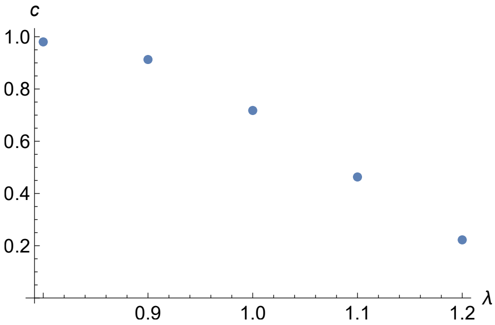
Result[19]

$$t_q = a \cdot N^c + b \, ,$$



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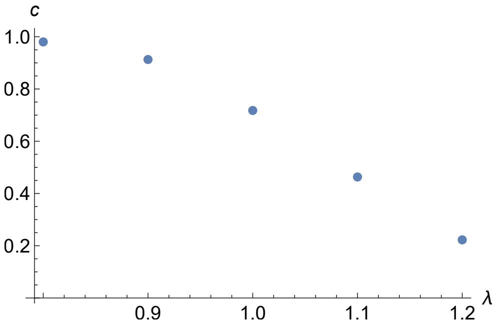

$$\lambda = \alpha N = 1 \quad \Rightarrow \quad c \approx 0.5$$

back

[19] M. Michel, S. Z., *TimeEvolver: A Program for Time Evolution With Improved Error Bound*, arXiv:2205.15346.
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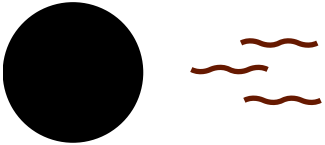
Page time[20]



[20] D. Page, *Information in black hole radiation*, arXiv:hep-th/9306083.

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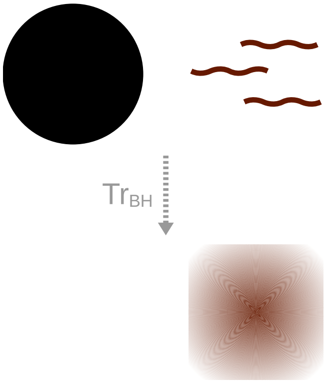

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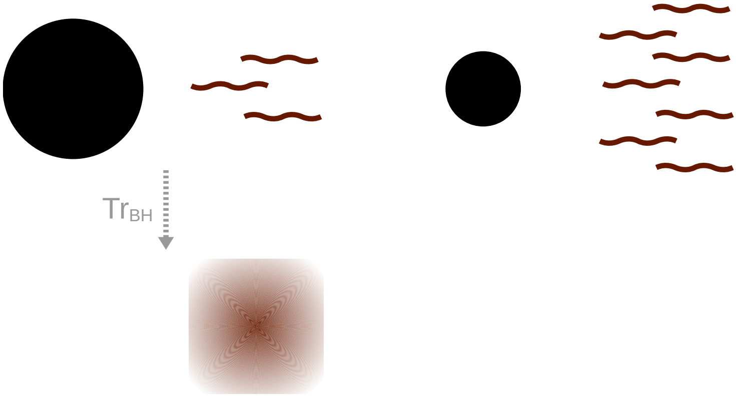

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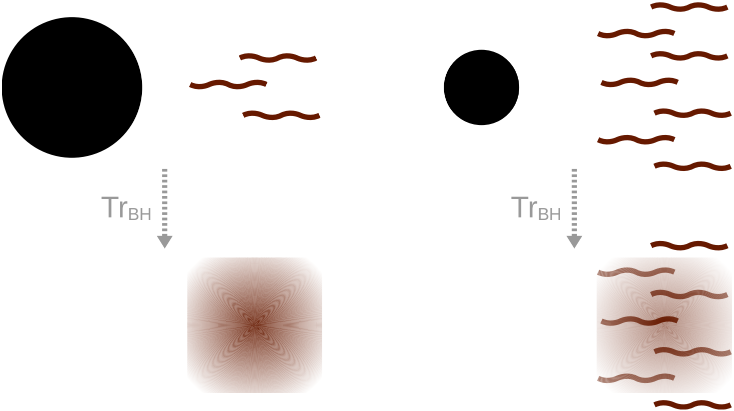

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Classical black hole: no hair

- Geometry fully determined by mass

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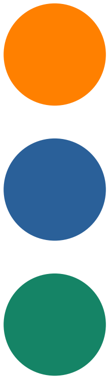

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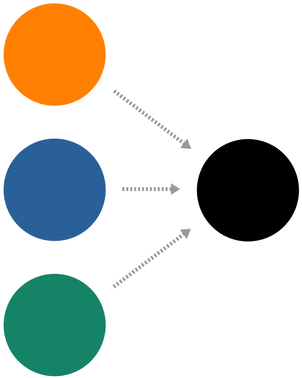

Classical black hole: no hair

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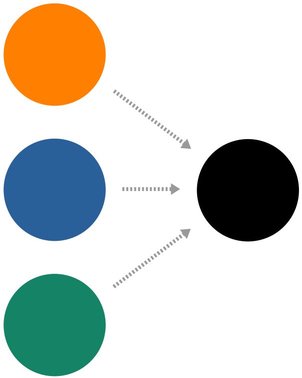
- No hair outside[21]



[21] See e.g., P. Chrusciel, J. Costa, M. Heusler, *Stationary Black Holes: Uniqueness and Beyond*, `arXiv:1205.6112`.

Quantum black hole: entropy[22]

- Entropy

$$S \sim \frac{r_g^2}{\hbar G}$$

[22] J. Bekenstein, *Black holes and entropy*, Phys. Rev. D **7** (1973).

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Quantum black hole: entropy[22]

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- $\exp(S)$ different versions of a black hole of mass M

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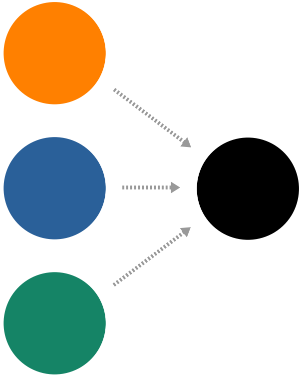
Add evaporation[17]



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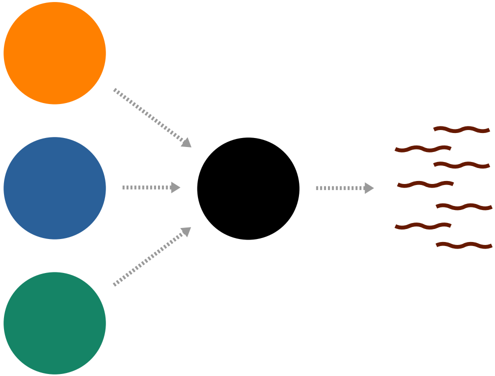

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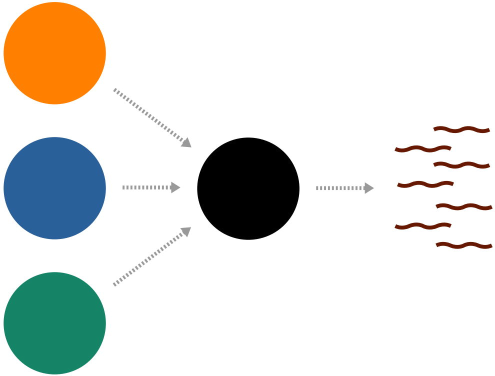

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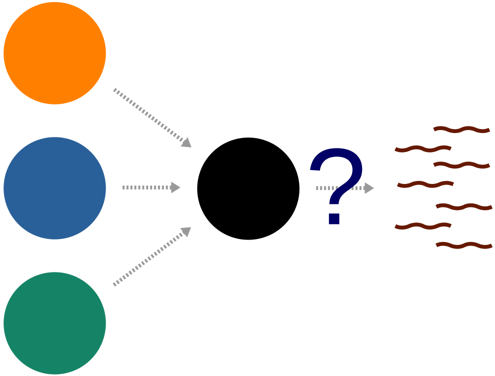

- Not unitary: information about initial state lost[18]
- Question: how long is Hawking evaporation valid?

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Breakdown of semi-classicality

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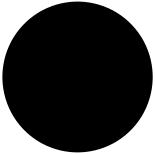

$|\mathrm{BH}; M\rangle$

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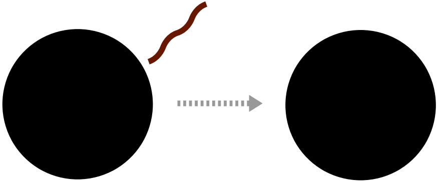

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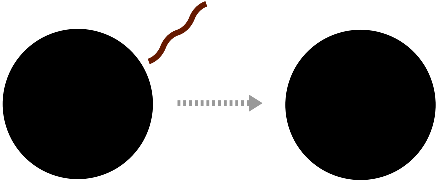

$|\mathrm{BH}; M\rangle$ $\qquad$ $\approx |\mathrm{BH}; M\rangle$

Breakdown of semi-classicality

- Semi-classical approximation: fixed mass
- Small correction after single emission

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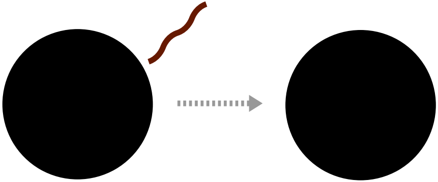

$|\text{BH}; M\rangle \quad \approx |\text{BH}; M\left(1 - \frac{1}{S}\right)\rangle$

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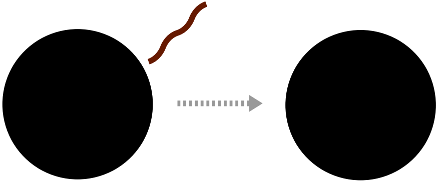

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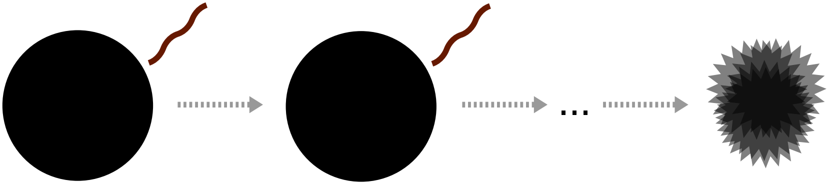

$$|\mathrm{BH}; M\rangle \qquad \approx |\mathrm{BH}\left(1-\frac{1}{S}\right); M\left(1-\frac{1}{S}\right)\rangle \qquad \approx |\mathbf{?}; \frac{M}{2}\rangle$$

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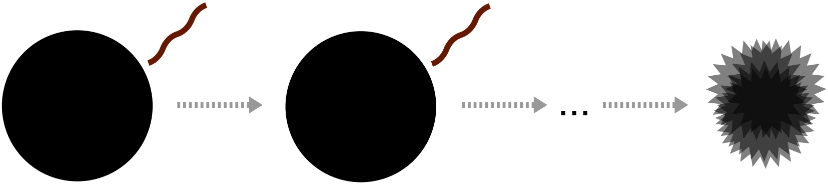

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- Full breakdown of semi-classical description back

Microscopic MB[19]

- Microscopic model

$$\frac{\hat{\mathcal{H}}}{r_g^{-1}} = \hat{n}_0 + \sqrt{S}\left(1 - \frac{\hat{n}_0}{S}\right)^p \sum_{k=1}^{S} \hat{n}_k$$

[19] G. Dvali, L. Eisemann, M. Michel, S. Z., *Black Hole Metamorphosis and Stabilization by Memory Burden*, arXiv:2006.00011.

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- Critical value

$$q \equiv \frac{(S - n_0)_{\text{crit}}}{S} = \left(p\sqrt{S}\right)^{-1/(p-1)}$$

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Transition to MB[20]

- Increased energy gap

$$\Delta N = \mu\, r_g = \frac{p\sqrt{S}}{2}\left(\frac{M_0 - M(t)}{M_0}\right)^{p-1}$$

[20] G. Dvali, M. Zantedeschi, S. Z., *Transitioning to Memory Burden: Detectable Small Primordial Black Holes as Dark Matter*, arXiv:2503.21740.

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$$\Gamma = \left(\frac{1}{S}\right)^{\Delta N}\, \Gamma_{\mathrm{sc}}$$

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- Approximate around onset of MB

$$\Gamma \simeq \exp\left(-\frac{(1-q)M_0 - M(t)}{\delta M_0}\right)\ \Gamma_{\rm sc}$$

with

$$\delta = \frac{q}{(p-1)\ln S}$$

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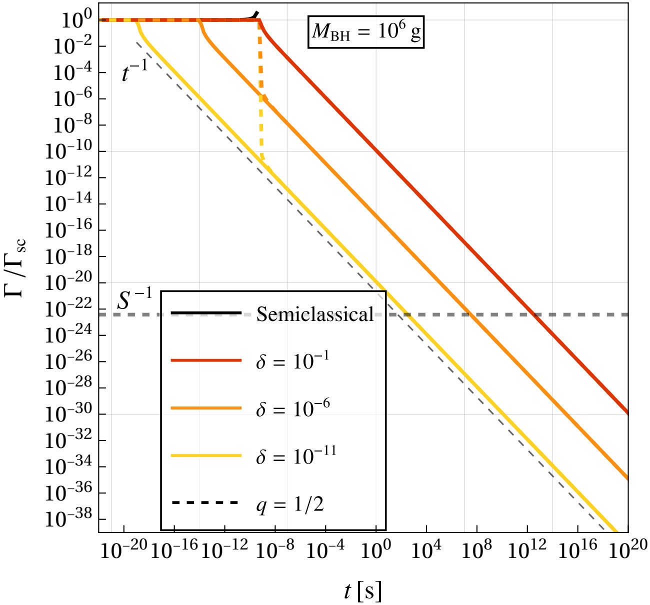
No dependence on q



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