Evaporating black holes: how the burden of their memory stabilizes them

Michael Zantedeschi
INFN, Pisa
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Istituto Nazionale di Fisica Nucleare
Sezione di PISA

Motivation: when does black-hole memory become dynamical?

The memory carried by an object resists departures from the state that stores it efficiently

- Can black-hole entropy backreact on macroscopic evolution?
  $\Longrightarrow$ **Memory burden** as an effective framework

- Stabilization against Hawking **evaporation**

  $\Longrightarrow$ new primordial black hole (PBH) dark-matter window with distinct astro and cosmo signatures

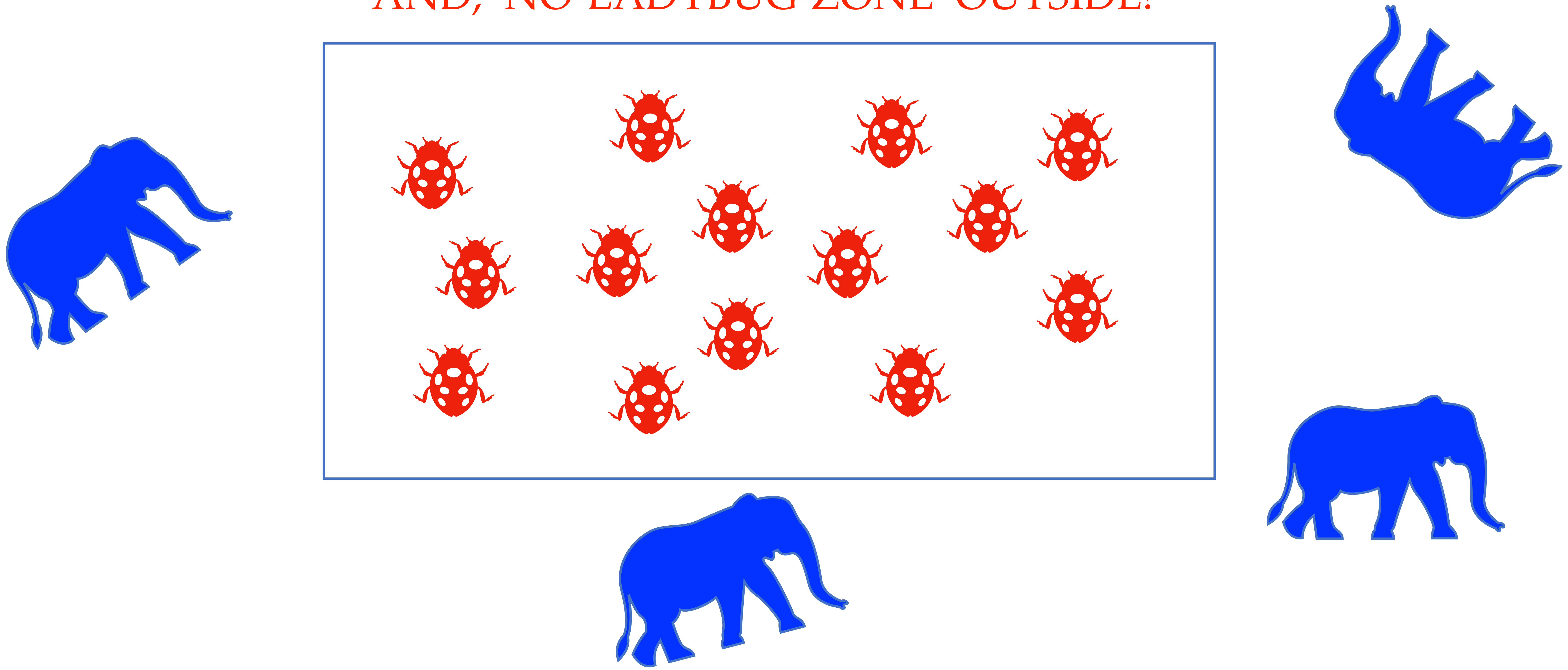
- Beyond evaporation: **mergers**

Dvali '18, + Eisemann, Michel, Zell '20, Dvali, Valbuena, **MZ** '24, Thoss, Buckert, Kohri '24,
Visinelli, **MZ** '24, Dvali, **MZ**, Zell '25, Dondarini, Marino, Panci, **MZ**, '25, Dvali '25,…

Memory burden effect

Imagine a room. Inside the room information is written in ladybugs, outside - in elephants.

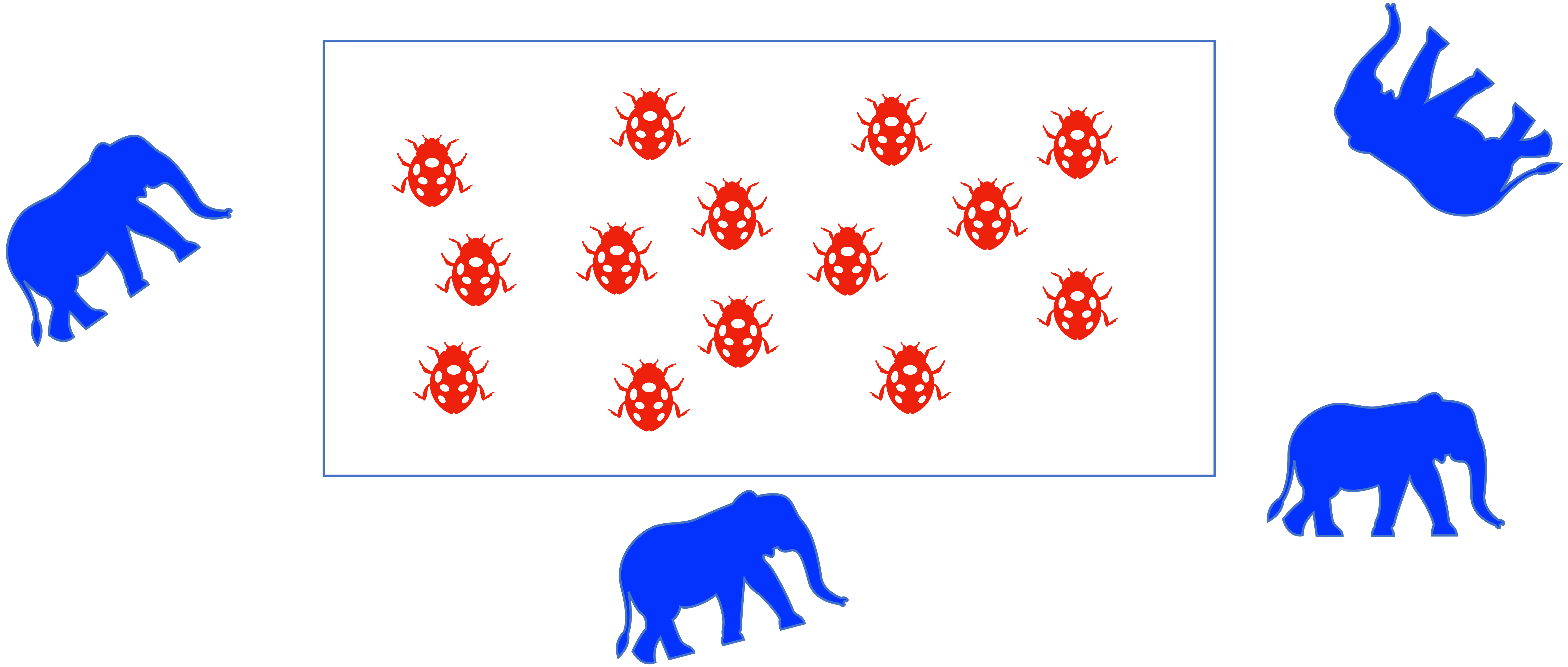
AND, NO-LADYBUG-ZONE OUTSIDE!



State $|0, \ , \ , 0, 0, \ , \ldots\rangle$ is much less costly in energy than $|0, \ , \ , 0, 0, \ , \ldots\rangle$

Memory burden effect

If the room decays, information cannot escape, because ladybirds cannot live outside and elephants cost very high energy!



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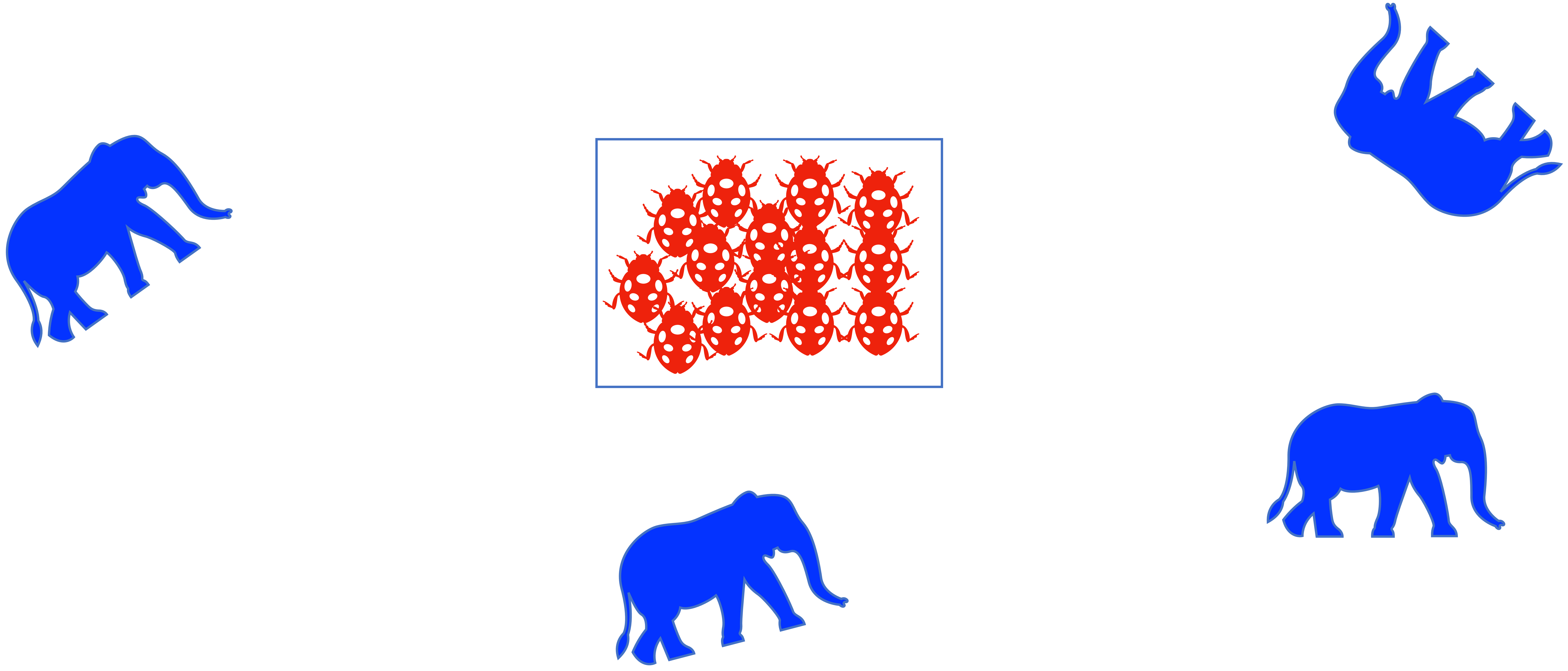
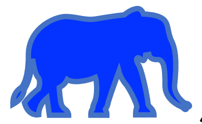
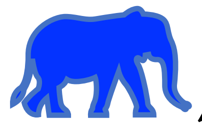
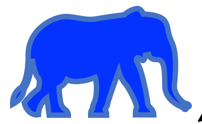
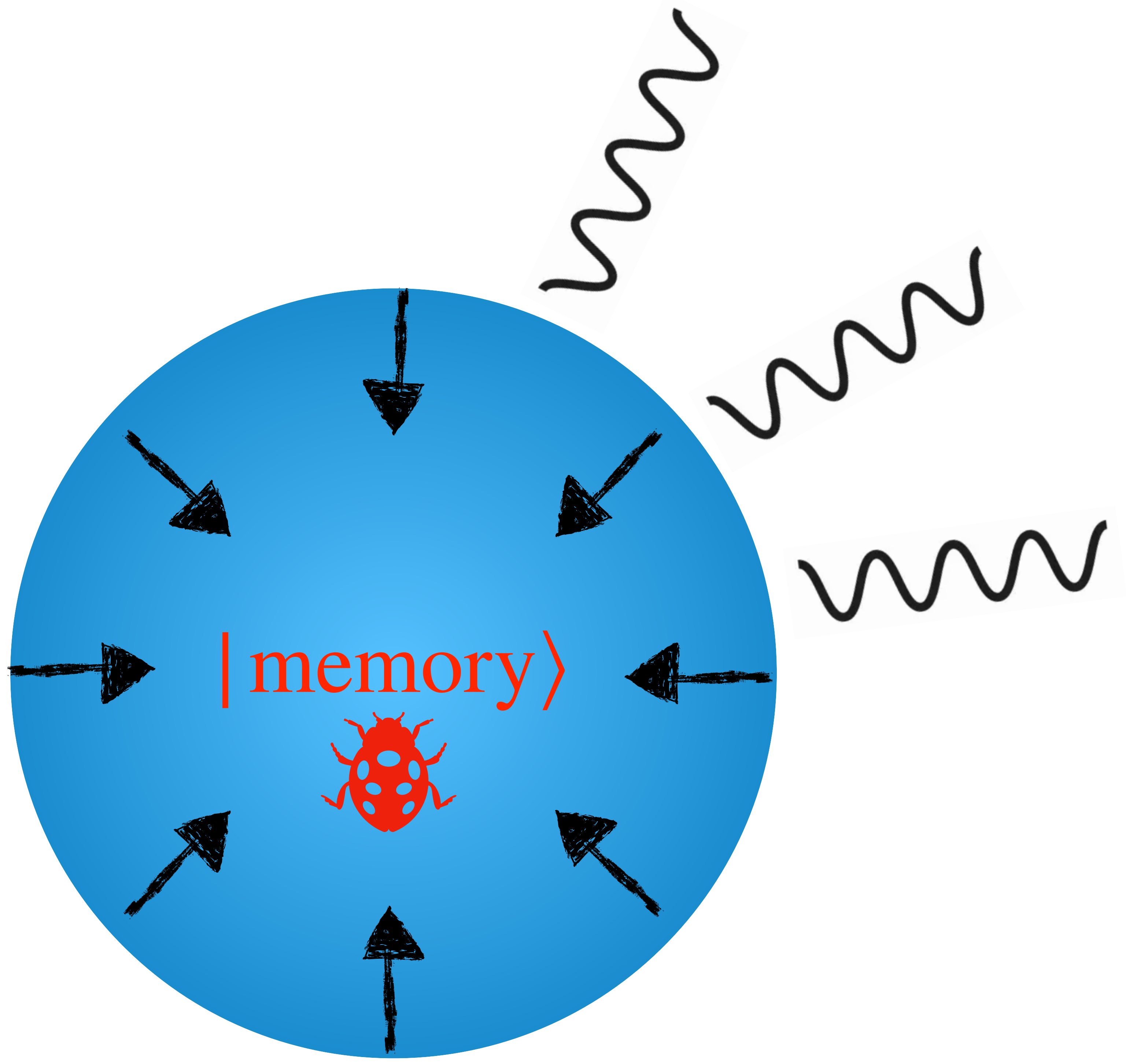
Due to this, the room gets stabilized by the burden of memory stored in ladybugs.



State $|0,$$,$$, 0,0,$$, \ldots \rangle$ is much less costly in energy than $|0,$$,$$,0,0,$$,\ldots\rangle$

Evaporating black holes



$R_{\text{BH}} = G_{\text{N}}\, M_{\text{BH}}$

Black holes emit thermally (Hawking): $T = \dfrac{\hbar}{R_{\text{BH}}}$ ( are not released)

Thermodynamically: $S = \dfrac{\text{Area}}{\hbar G_{\text{N}}}$

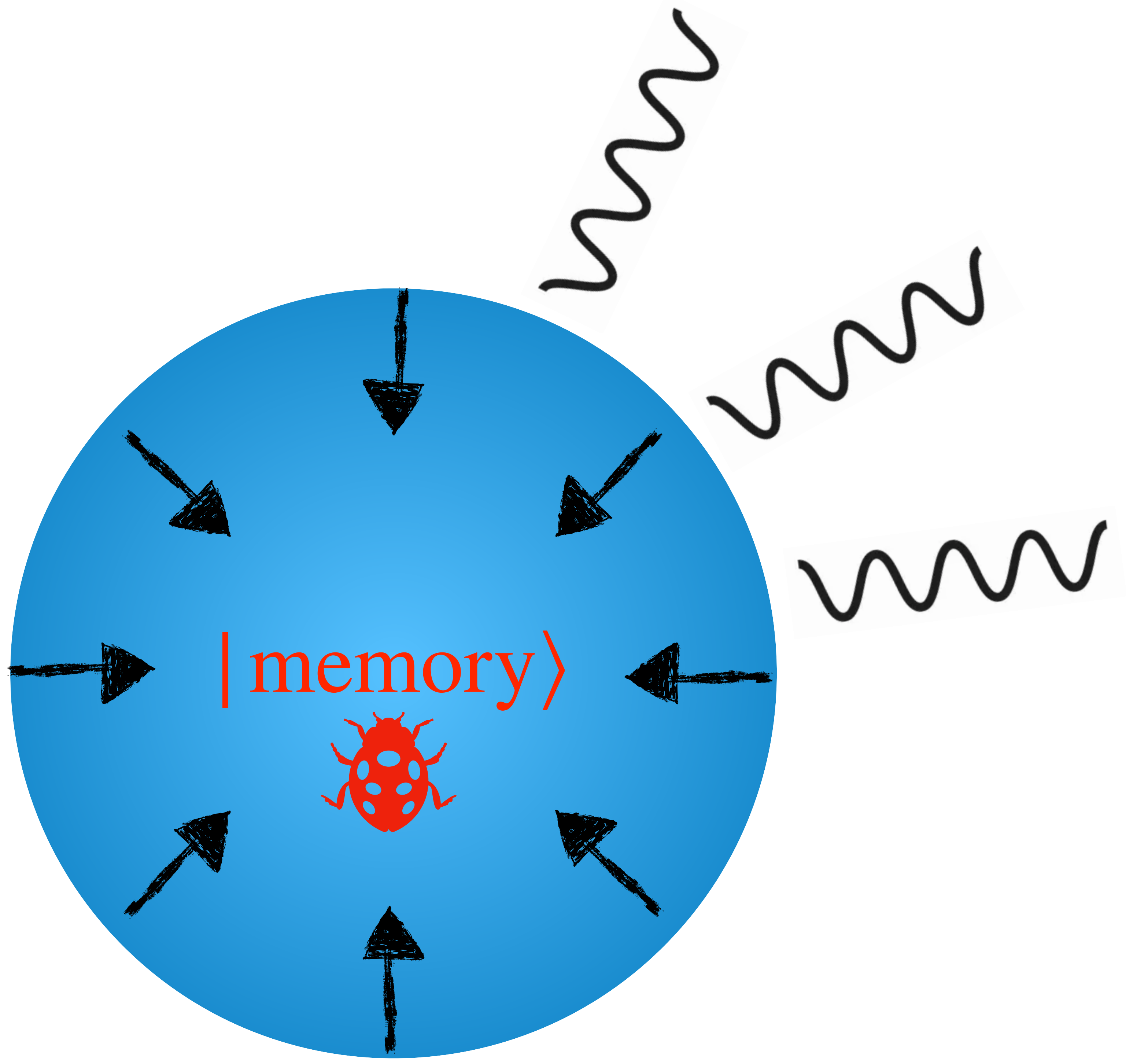
Full semiclassical evaporation requires

$\tau_{\text{SC}} \simeq S\, R_{\text{BH}}$

$M_{\text{BH}} \lesssim 10^{15}\,\text{g} \implies \tau_{\text{SC}} \lesssim \text{t}_0$

Not a viable dark matter semiclassically?

Evaporating black holes



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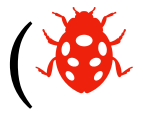
Black holes emit thermally (Hawking): $T = \dfrac{\hbar}{R_{\rm BH}}$ ( are not released)

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Not a viable dark matter semiclassically?

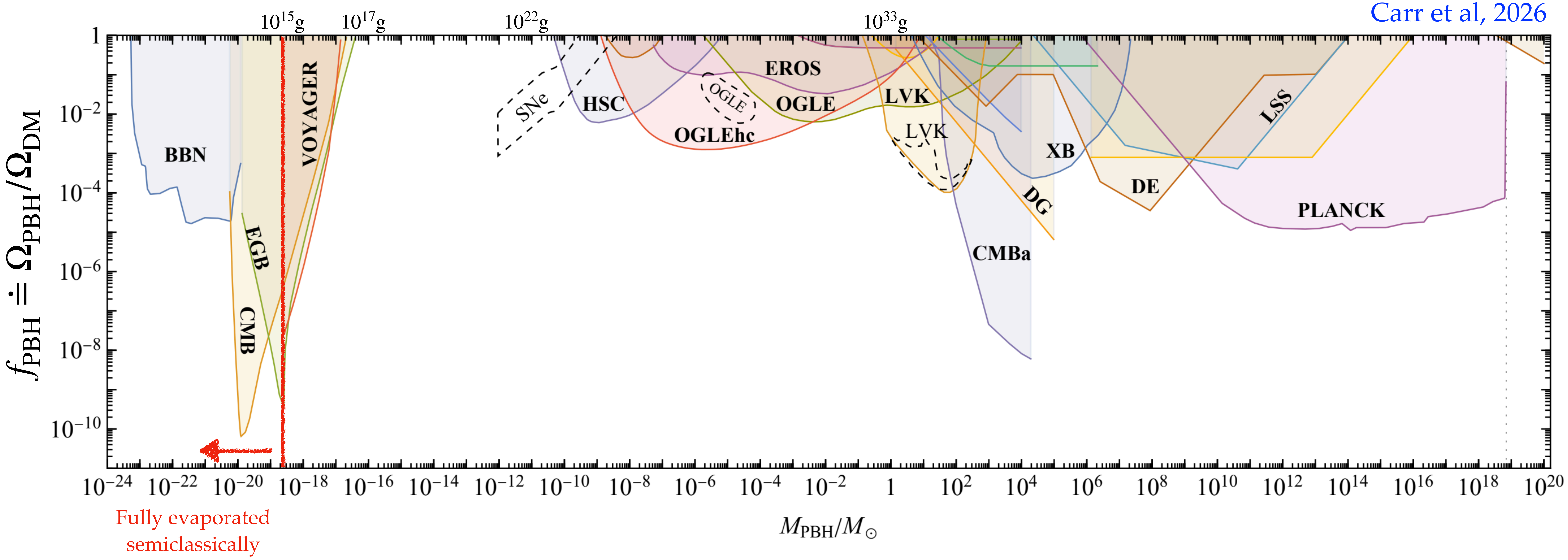
Hawking rate is computed in semiclassical limit, ignoring changing geometry.

Extrapolating this self-similar evolution through the full lifetime violates unitarity

Page '80

PBHs as dark matter

Carr et al, 2026



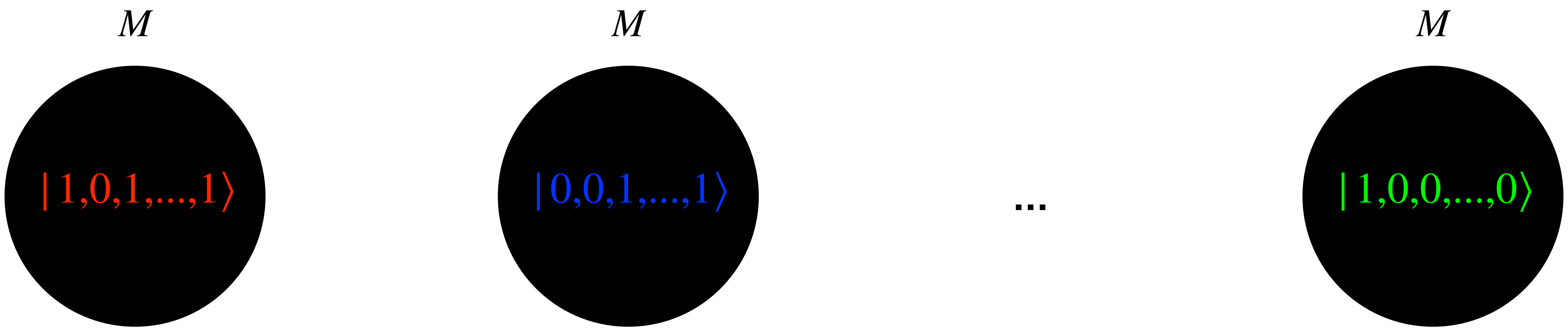
- PBHs have long been considered dark-matter candidates Zel'dovich & Novikov '67; Hawking '71; Carr & Hawking '74
- **Can memory burden reopen the window below asteroid mass $M_{\rm PBH} \lesssim 10^{17}$ g? (Yes!)**

Entropy as information storage capacity

Entropy Area - Law (Bekenstein): $S = \frac{R_{\rm BH}^2}{l_{\rm pl}^2} = \frac{M_{\rm BH}^2}{M_{\rm Pl}^2}$

What is its microscopic origin?

Black holes of the same mass M can contain different memories encoded in N qubits, $|\text{memory}\rangle = |n_1, \ldots, n_N\rangle$.



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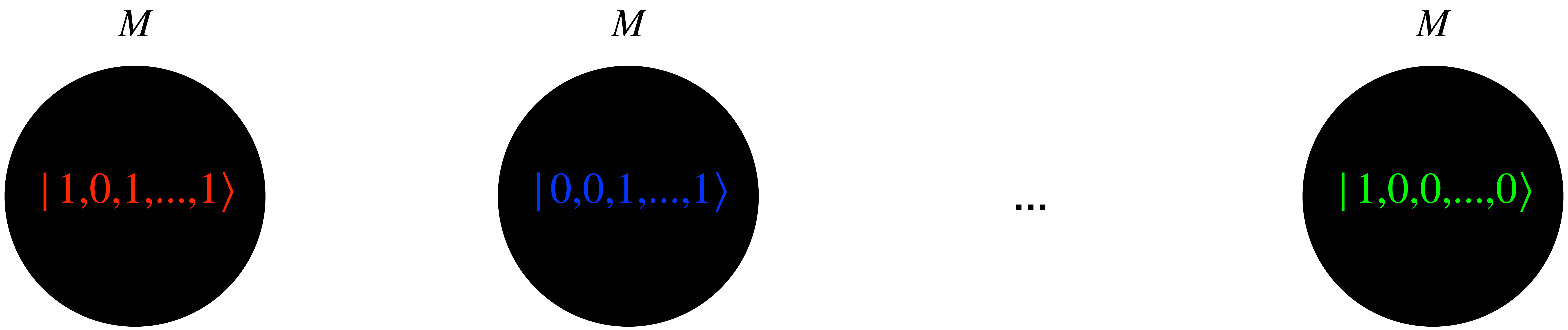

Gaplessness of memory modes: $\Delta E_{\mathrm{memory}} \sim 0$, so all memory configurations are macroscopically identical.

Entropy Counting: $n_{\mathrm{microstates}} = 2^N \longrightarrow S = \log n_{\mathrm{microstates}} \simeq N$

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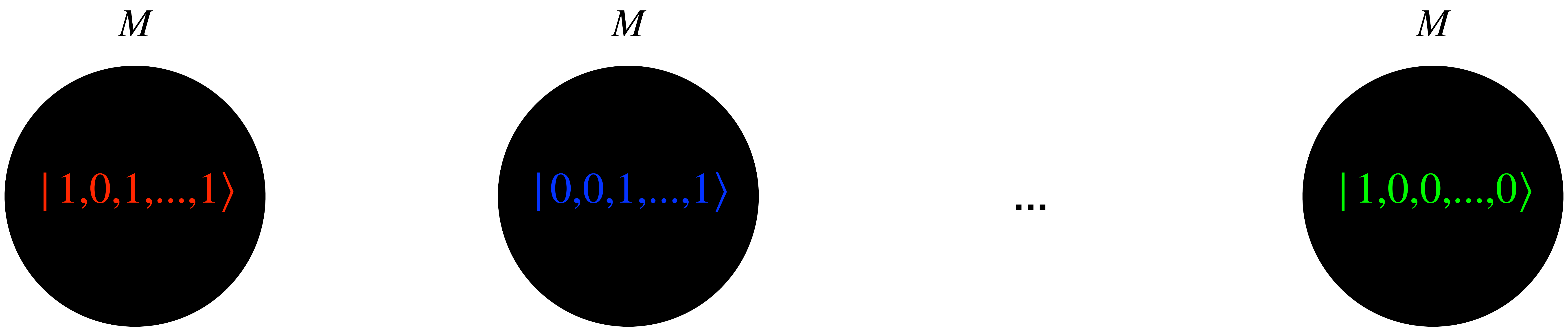

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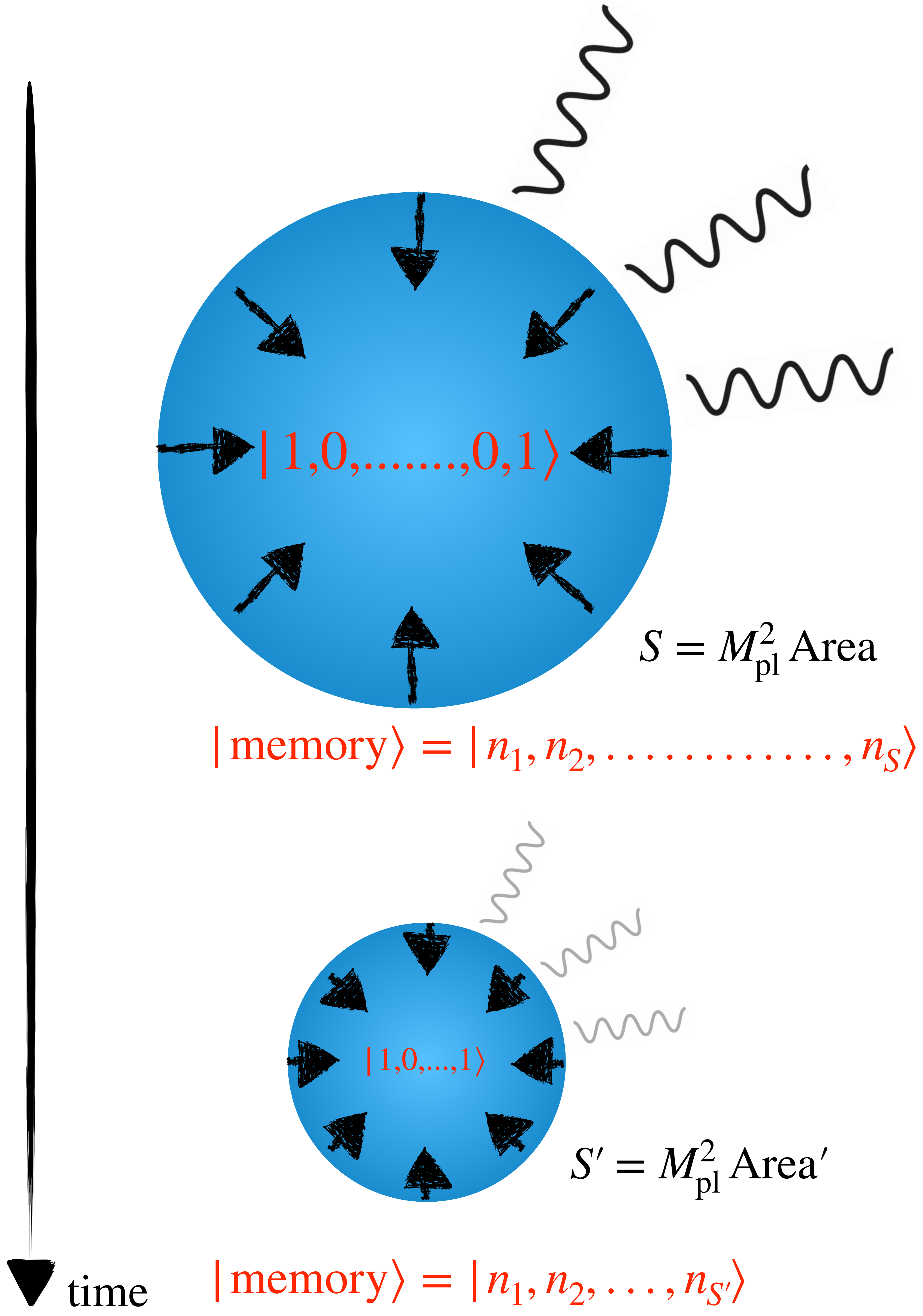
Thermal evaporation lowers the storage capacity, but not the stored memory

$\Delta E_{\mathrm{memory}} \neq 0 \implies$ memory burden

Evaporating black holes

[Dvali '18, + Eisemann, Michel, Zell '20, + Valbuena, **MZ** '24]



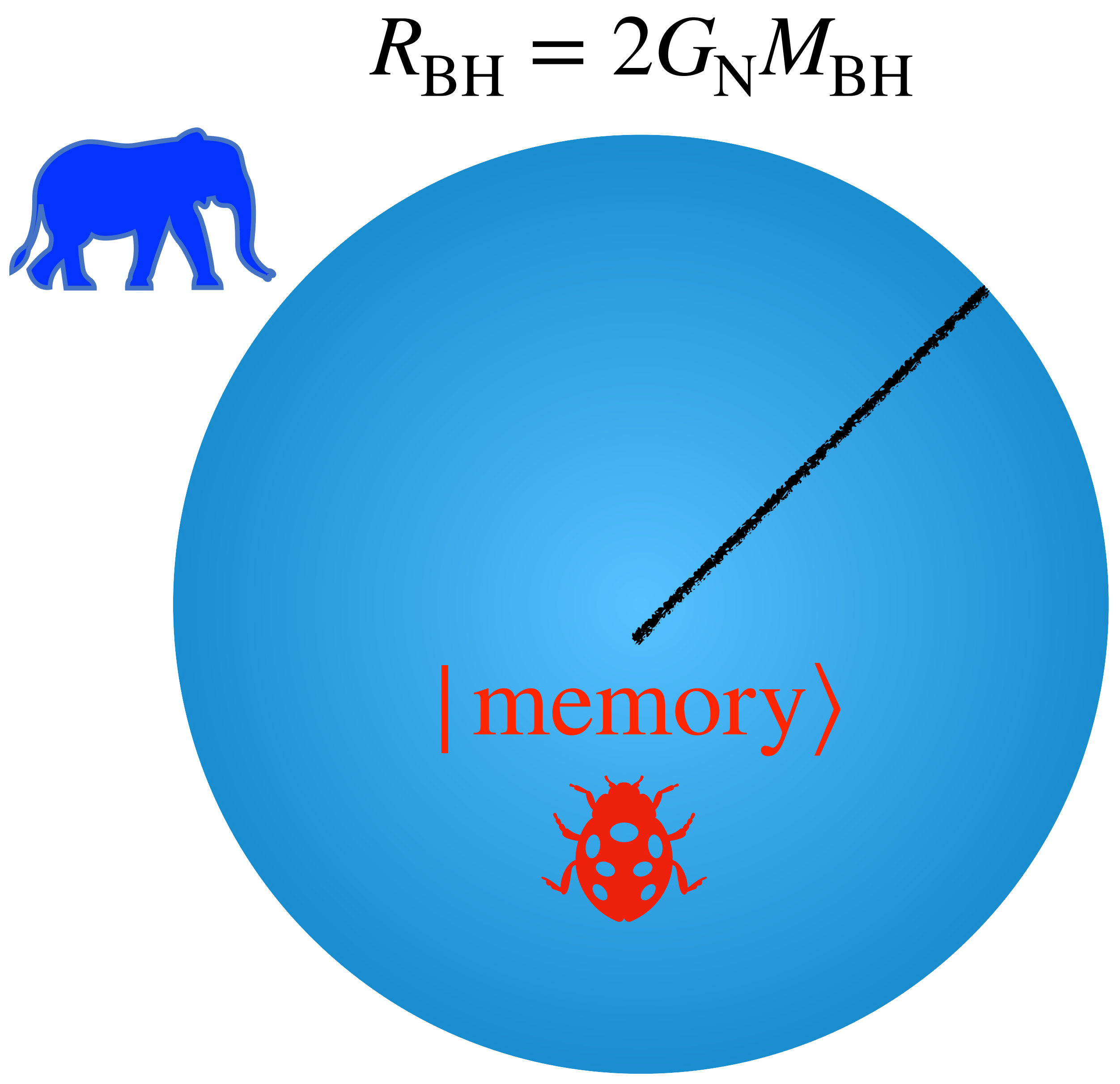
Hawking radiation leads to a decrease of the area of the black hole, $S \to S' \ll S$

However memory remains inside. It cannot be emitted by thermal emission. Memory space is exhausted due to evaporation

Prototype Hamiltonian

Dvali '18, + Eisemann, Michel, Zell '20, …

Consider two sets of modes satisfying CCR: $\hat{a}_\phi, \hat{a}^\dagger_\phi$, master modes (Order parameter) $\hat{a}_j, \hat{a}^\dagger_j\,, j = 1,\ldots,S$ memory modes (Goldstones localized)



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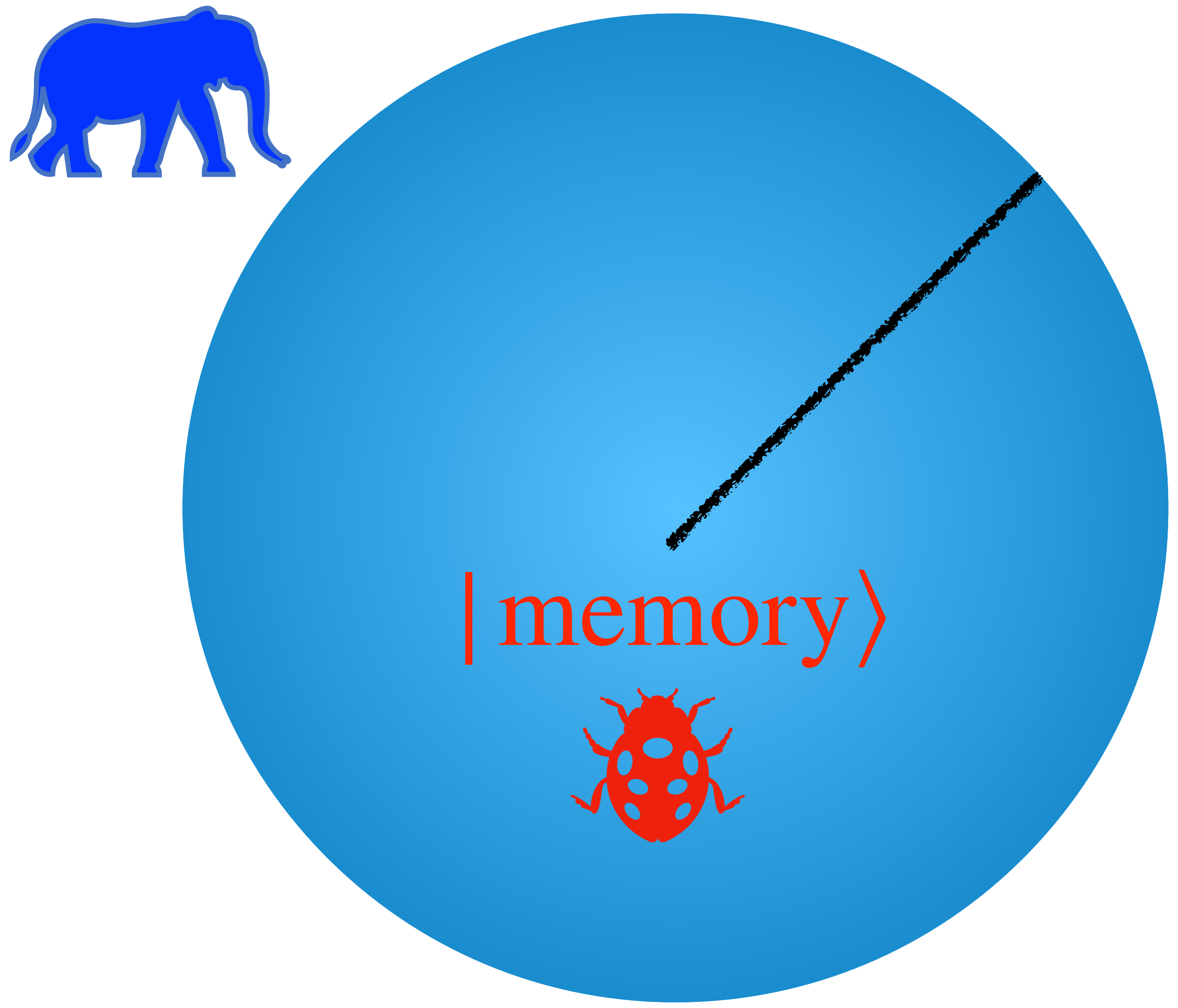

$$\hat{H} = \underbrace{m_\phi \hat{n}_\phi}_{\text{Background (room)}} + \left(1 - \frac{\hat{n}_\phi}{S}\right)^p \underbrace{\sum_{j=1}^{S} m_j \hat{n}_j}_{|\text{memory}\rangle} + \ldots$$

$\mathbf{n}_\phi = \mathbf{S}$:

- Memory modes are **gapless** $\longrightarrow$ storing information costs zero energy
- This is the semiclassical black hole

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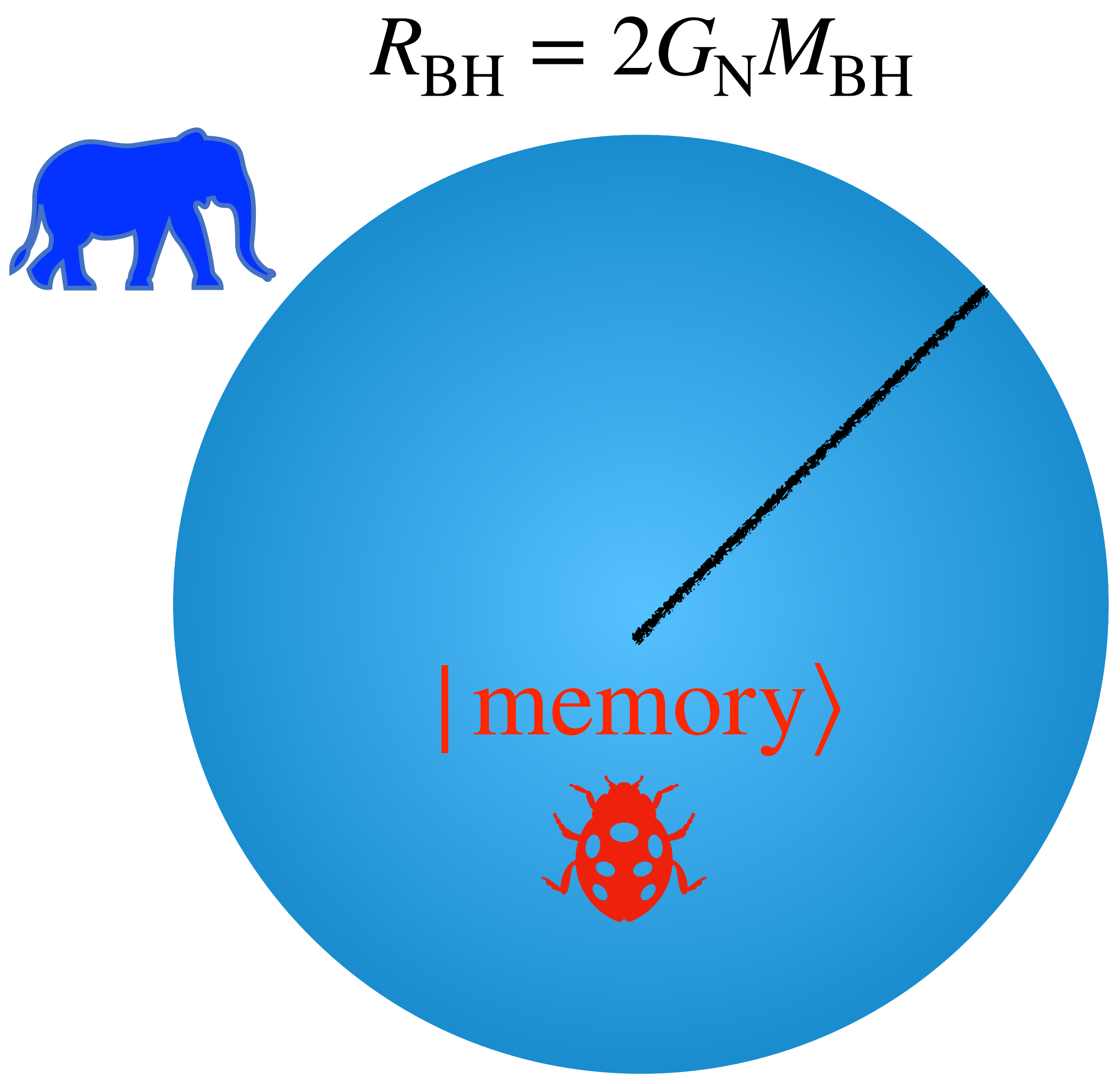

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When evaporation reduces $\mathbf{n}_\phi$:

- The factor $\left(1 - \frac{\hat{n}_\phi}{S}\right)^p$ turns on
- Memory modes become **gapped**
- Evaporation must overcome a <u>collective energy barrier</u> (origin of memory burden)

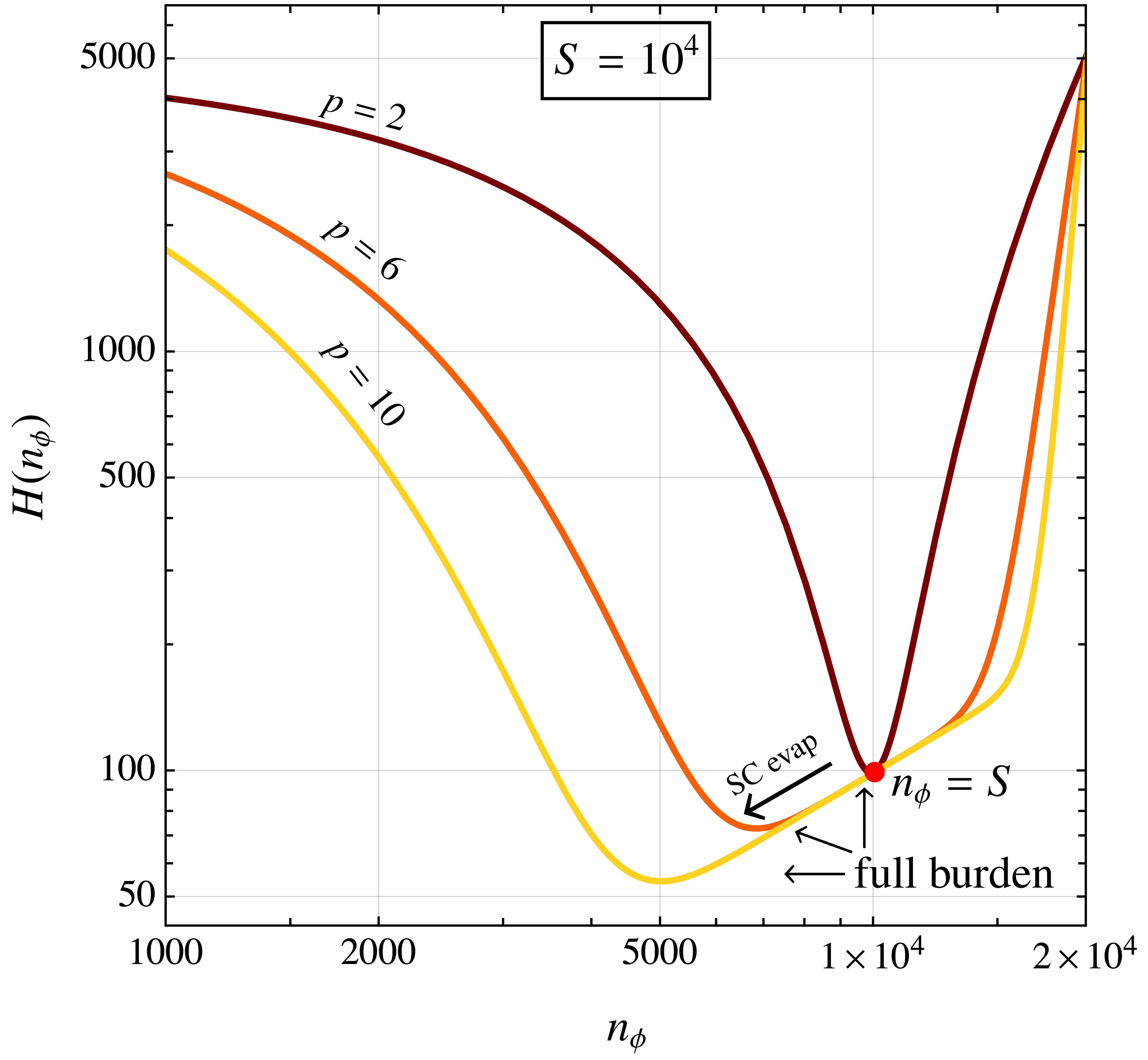
Prototype Hamiltonian

Dvali '18, + Eisemann, Michel, Zell '20, …

Microstate realizations are energetically identical → distributed with uniform probability Dvali, Valbuena, **MZ** '24

$$\sum_{j=1}^{S} m_j \langle \hat{n}_j \rangle \simeq M_{\rm Pl} \frac{S}{2} = \text{"memory load"}$$

$$H \simeq m_\phi n_\phi + \left(1 - \frac{n_\phi}{S}\right)^p M_{\rm Pl} \frac{S}{2}$$



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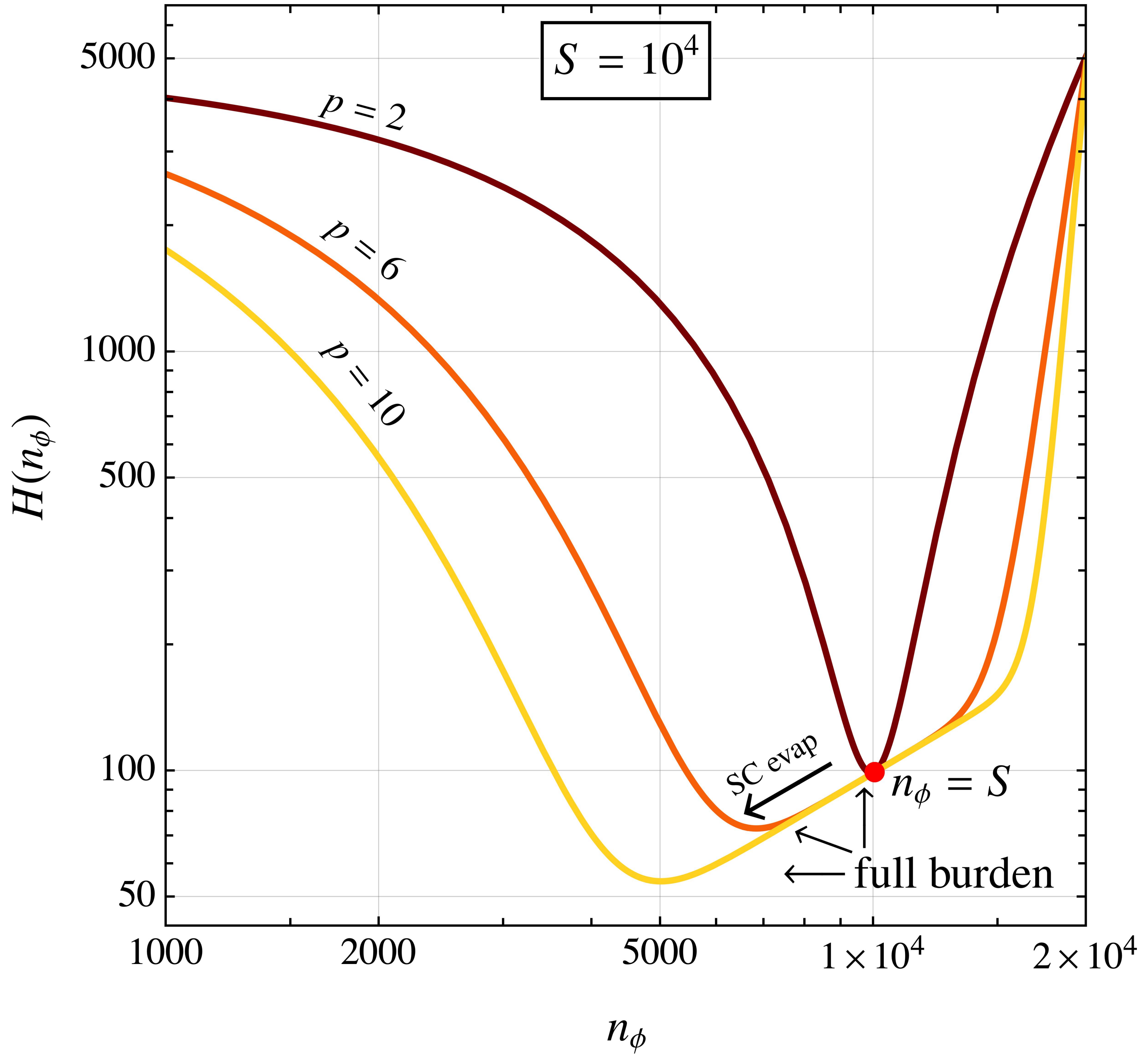


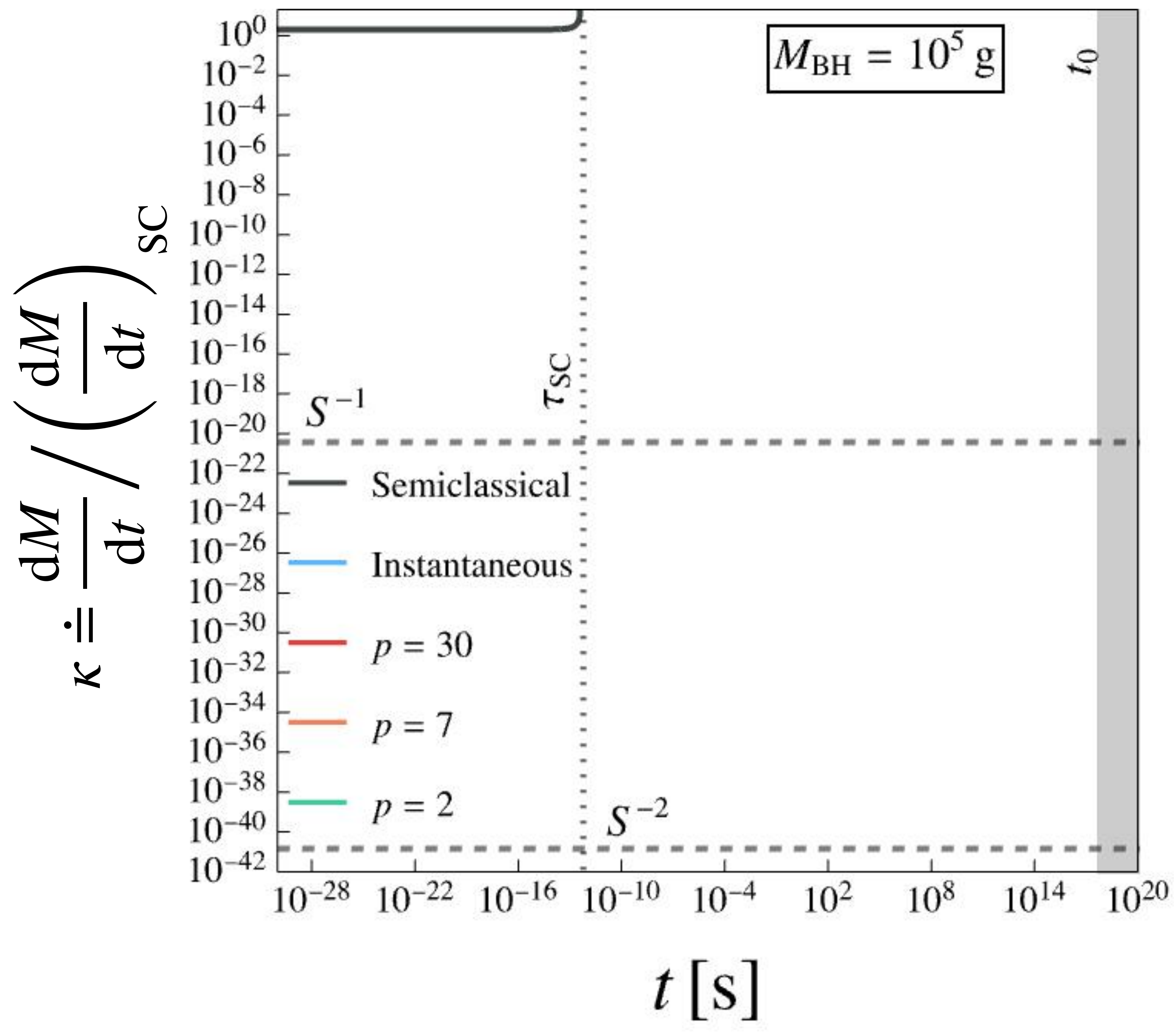
Prototype provides stabilization time and mass fraction emitted

p determines shape of the potential

On the evolution

Dvali, **MZ**, Zell, ’25

Semiclassically, $\left(\mathrm{d}M/\mathrm{d}t\right)_{\mathrm{SC}} \simeq 1/R_{\mathrm{BH}}^2$, a BH fully evaporates



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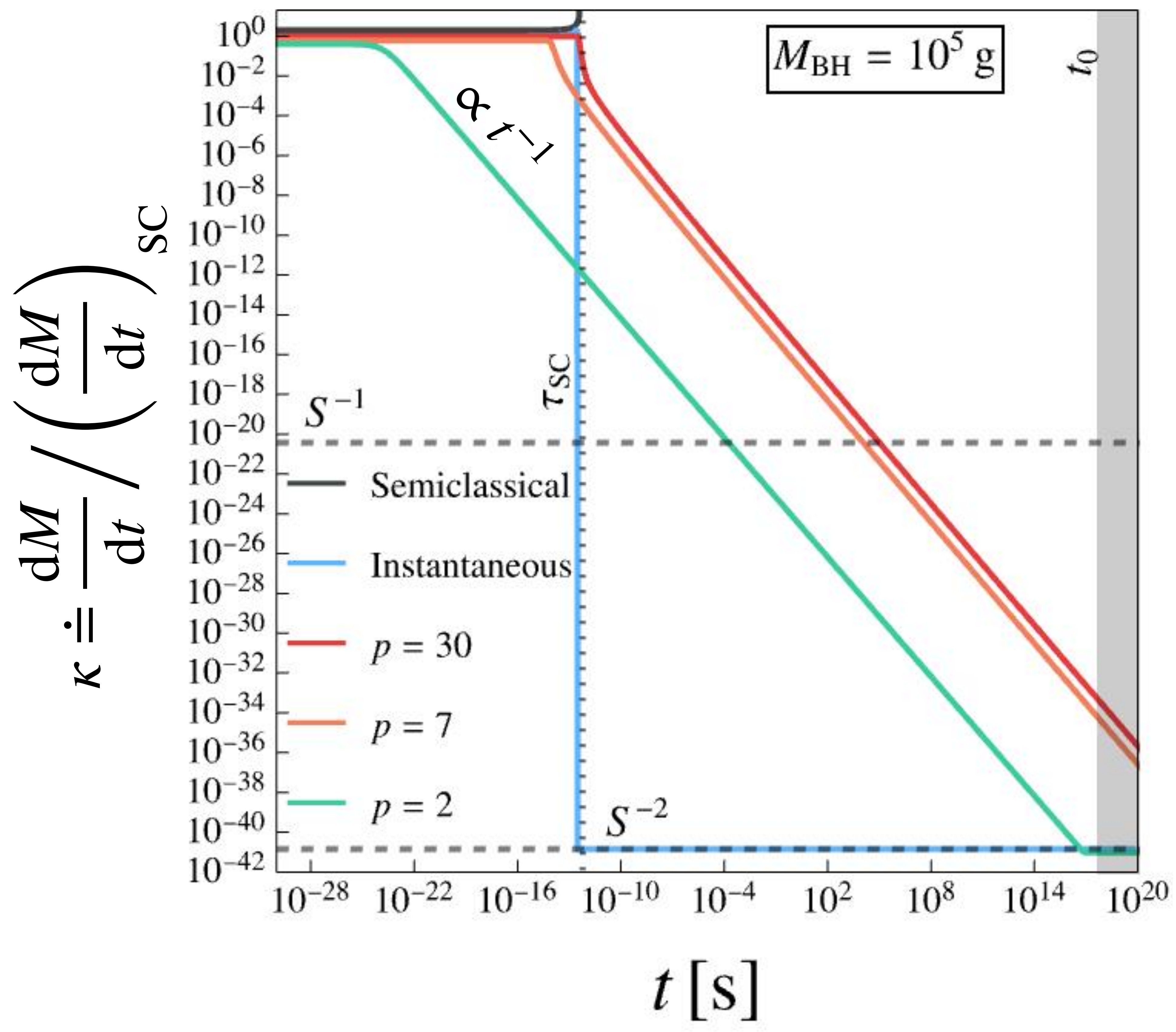
Memory burden leads to different fate

There are three different phases:



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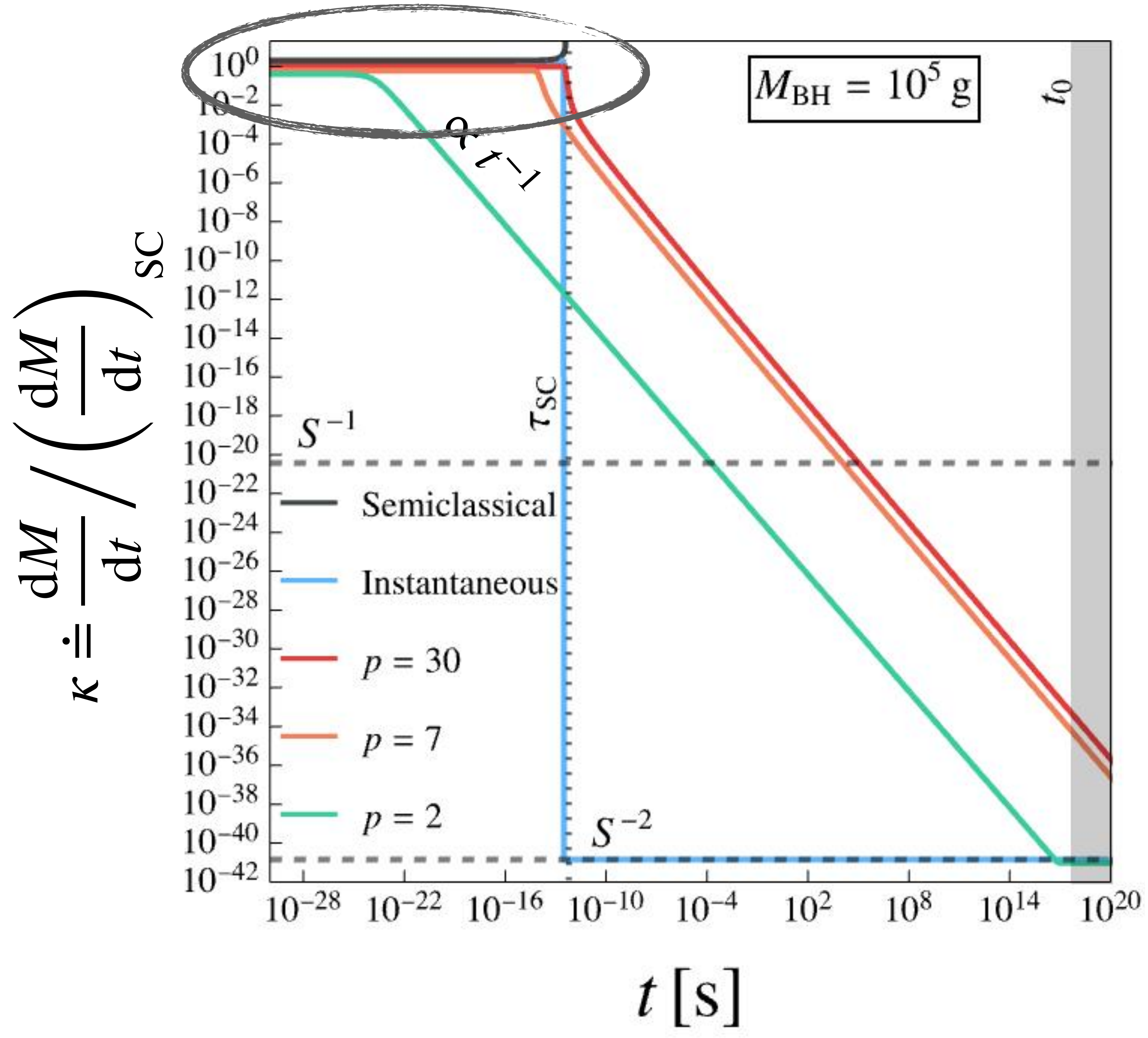

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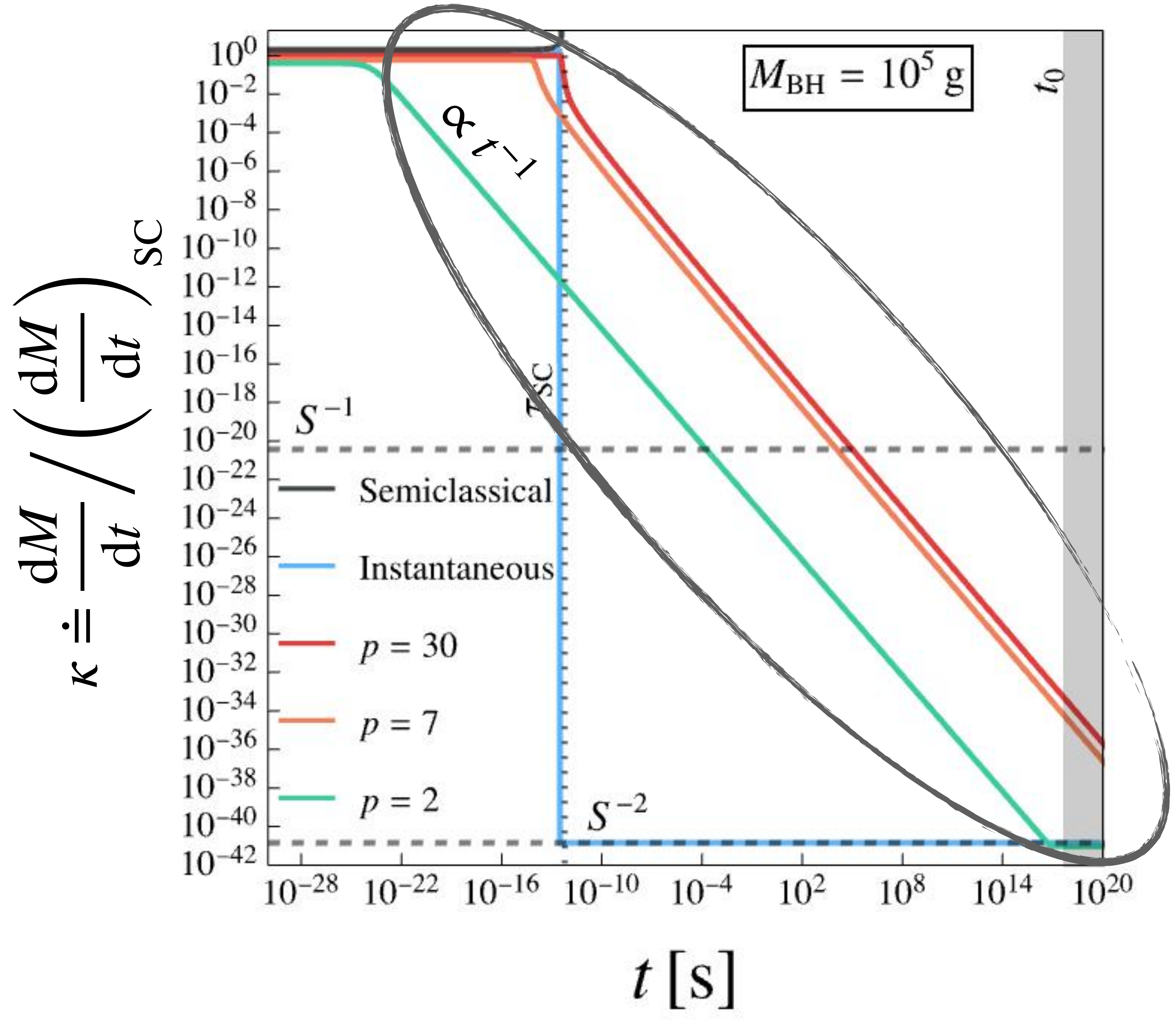

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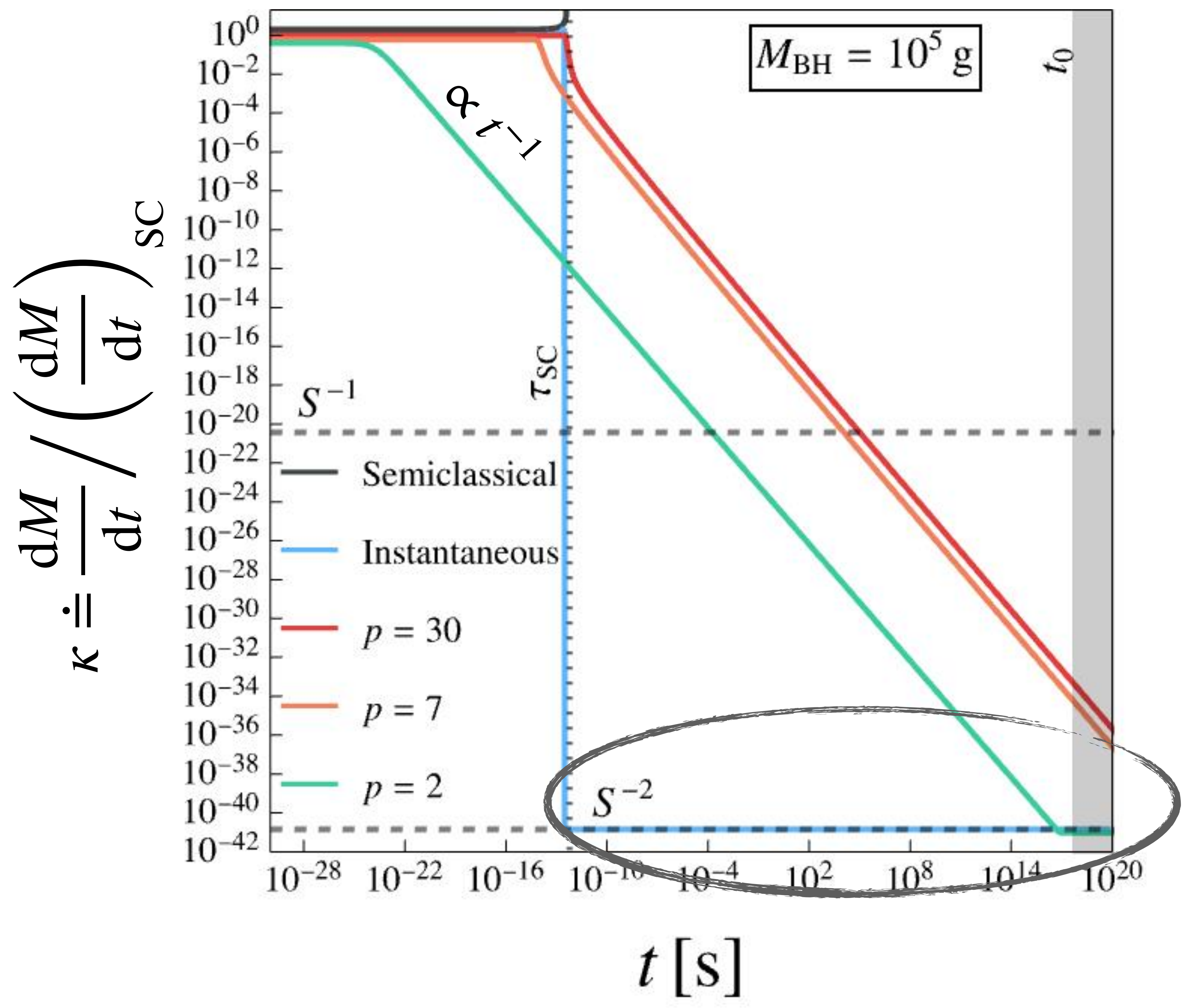
3. MB floor: $\kappa = \frac{1}{S^k}$, k an integer



Memory burden in solitons

Dvali, Valbuena, **MZ** '24

The prototype Hamiltonian can be mapped to solitons → they also display the memory burden phenomenon

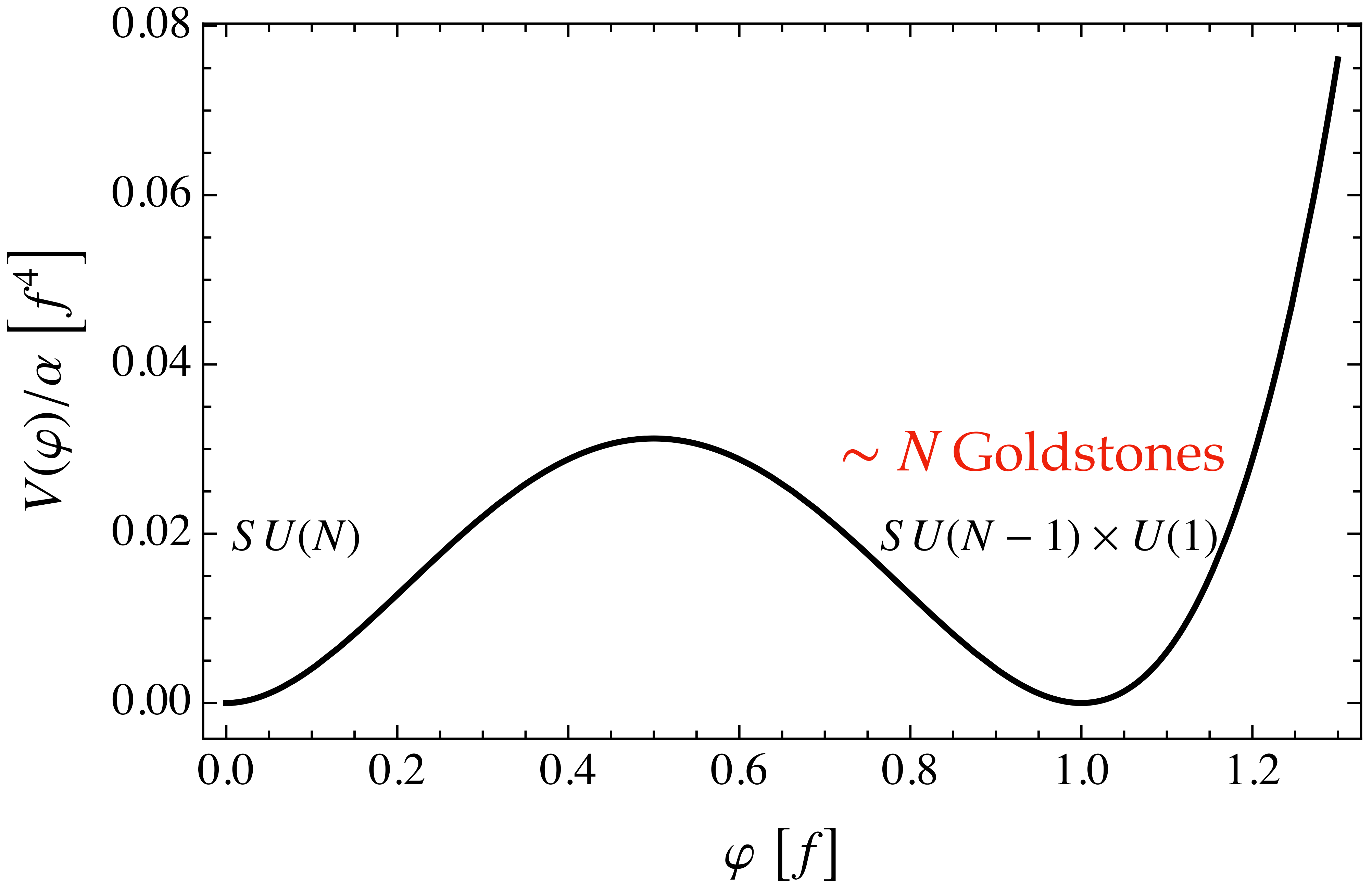
Memory burden in solitons

Dvali, Valbuena, **MZ** '24

Consider a renormalizable field theory with global $SU(N)$ symmetry, spontaneously broken by a scalar adjoint field Φ (no gravity)

$$SU(N) \xrightarrow{\langle\Phi\rangle} SU(N-1) \times U(1)$$

The breaking leads to $2(N-1)$ massless Goldstone modes



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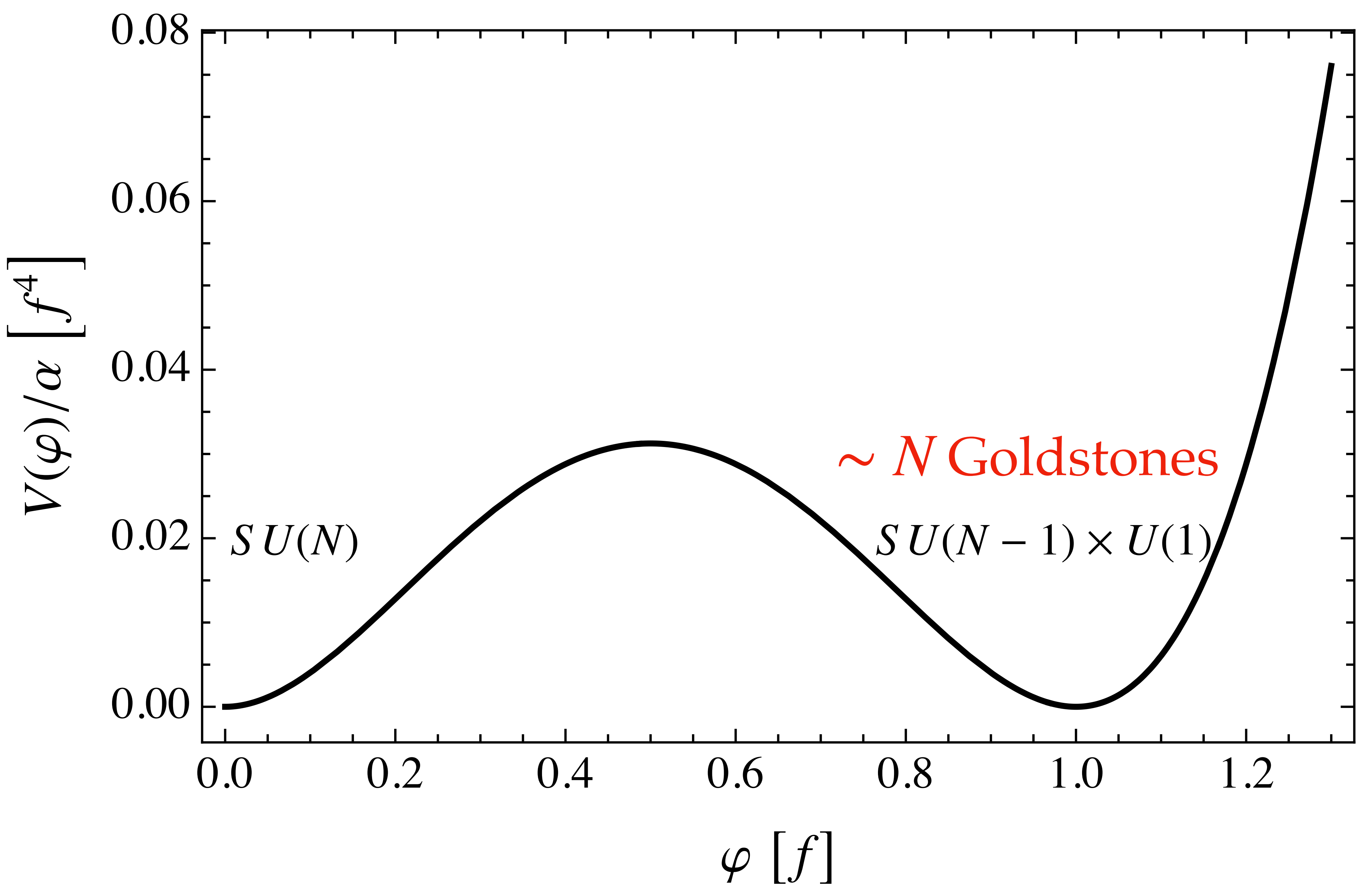
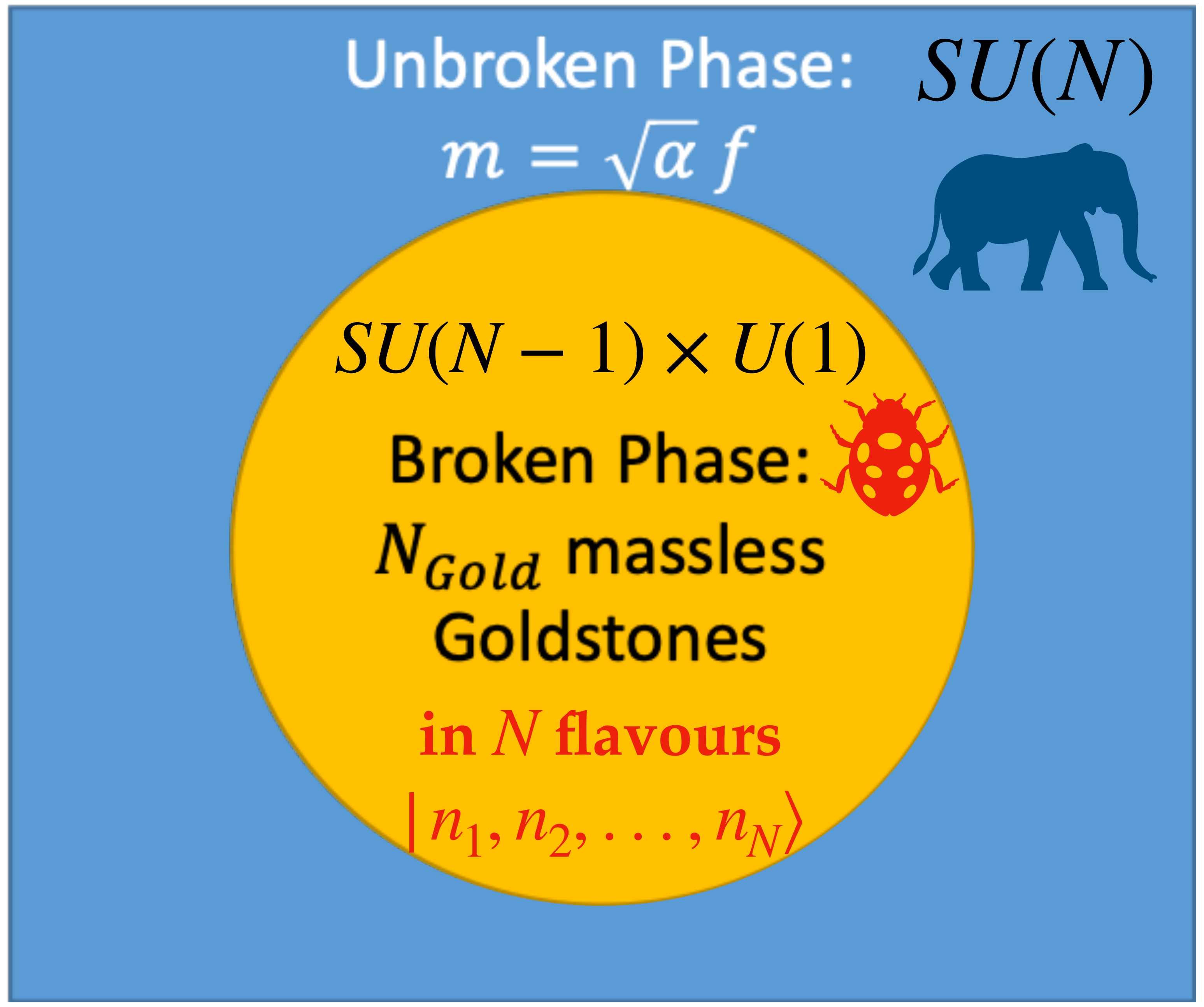
The potential allows for bubble solutions (solitons)





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The amount of Goldstone (memory) stored inside the bubble is

$$|\text{memory}\rangle = |n_1, n_2, \ldots, n_N\rangle \qquad N_{\text{Gold}} = Q = \sum_{j=1}^{N} n_j$$

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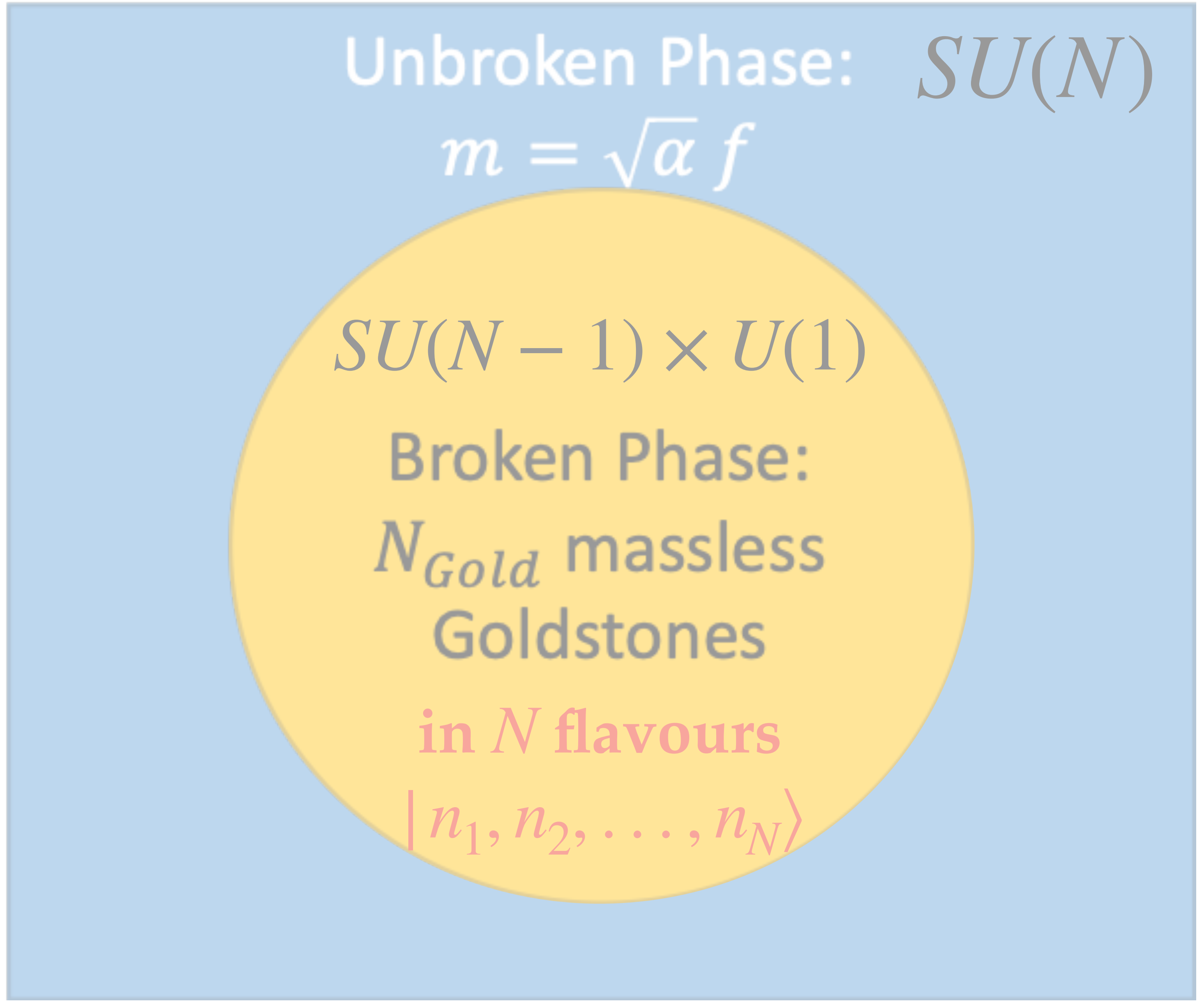

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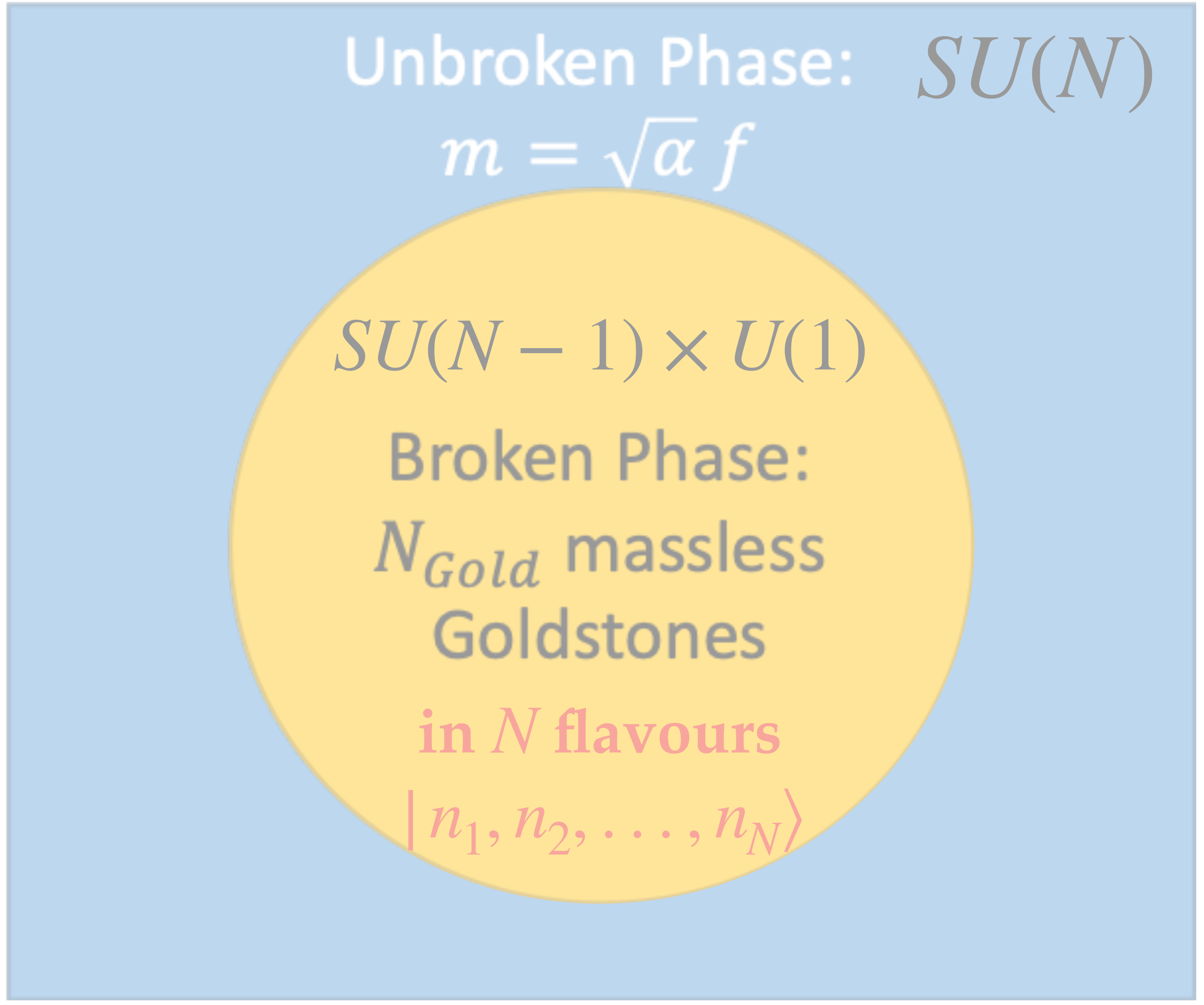

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$$|\,\text{memory}\rangle = |\,n_1, n_2, \ldots, n_N\rangle \qquad\qquad N_{\text{Gold}} = Q = \sum_{j=1}^{N} n_j$$

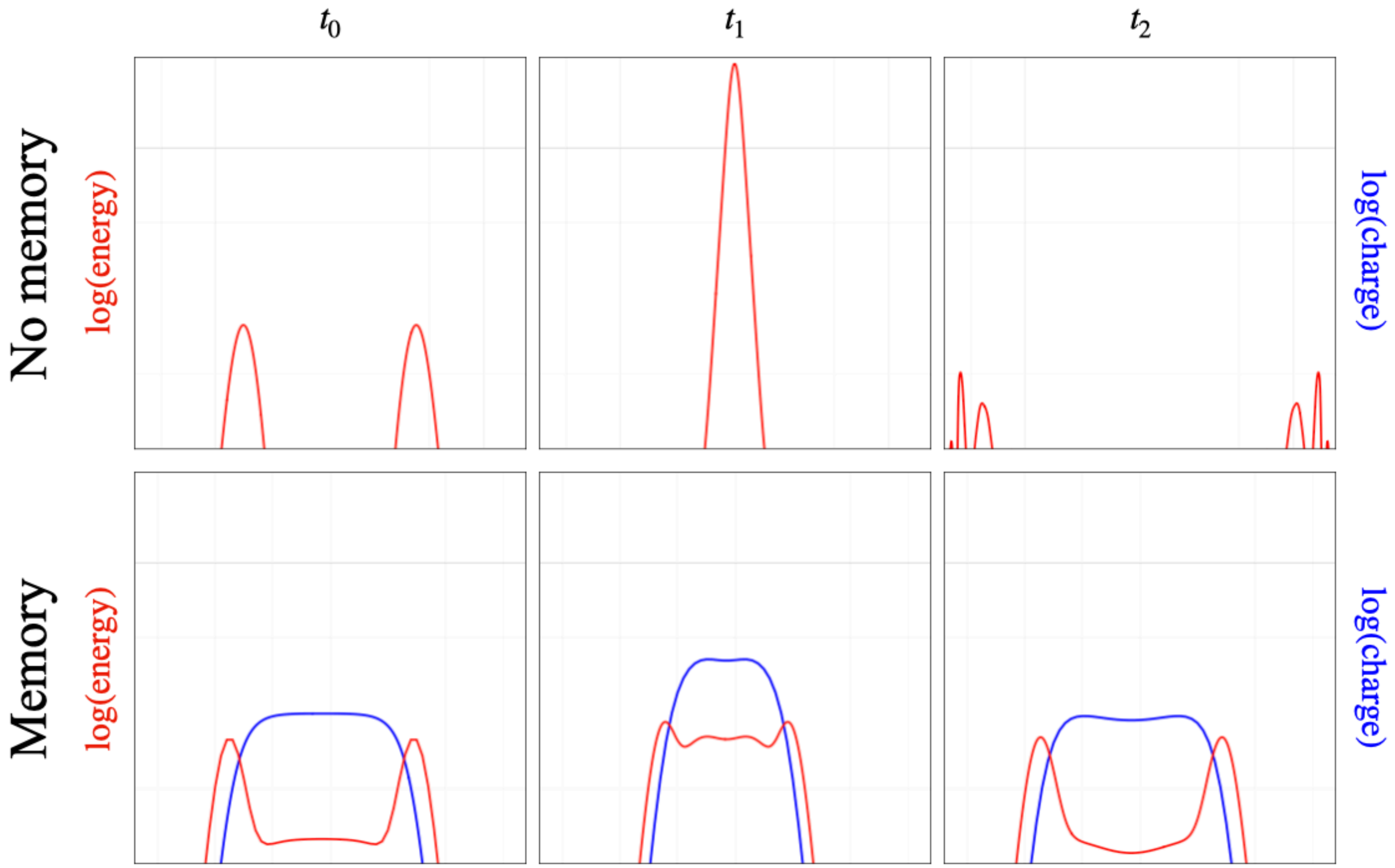
$$n_{\text{states}} = \binom{N_G}{N} \simeq \left(1 + \frac{N}{N_{\text{Gold}}}\right)^{N_{\text{Gold}}} \left(1 + \frac{N_{\text{Gold}}}{N}\right)^{N}$$

$$S = \log n_{\text{states}} \simeq N_{\text{Gold}} = N = \text{Area}\, f^2$$

- Large memory storage capacity
- Several properties analogous to BHs manifest
- Memory burden?

Dynamics

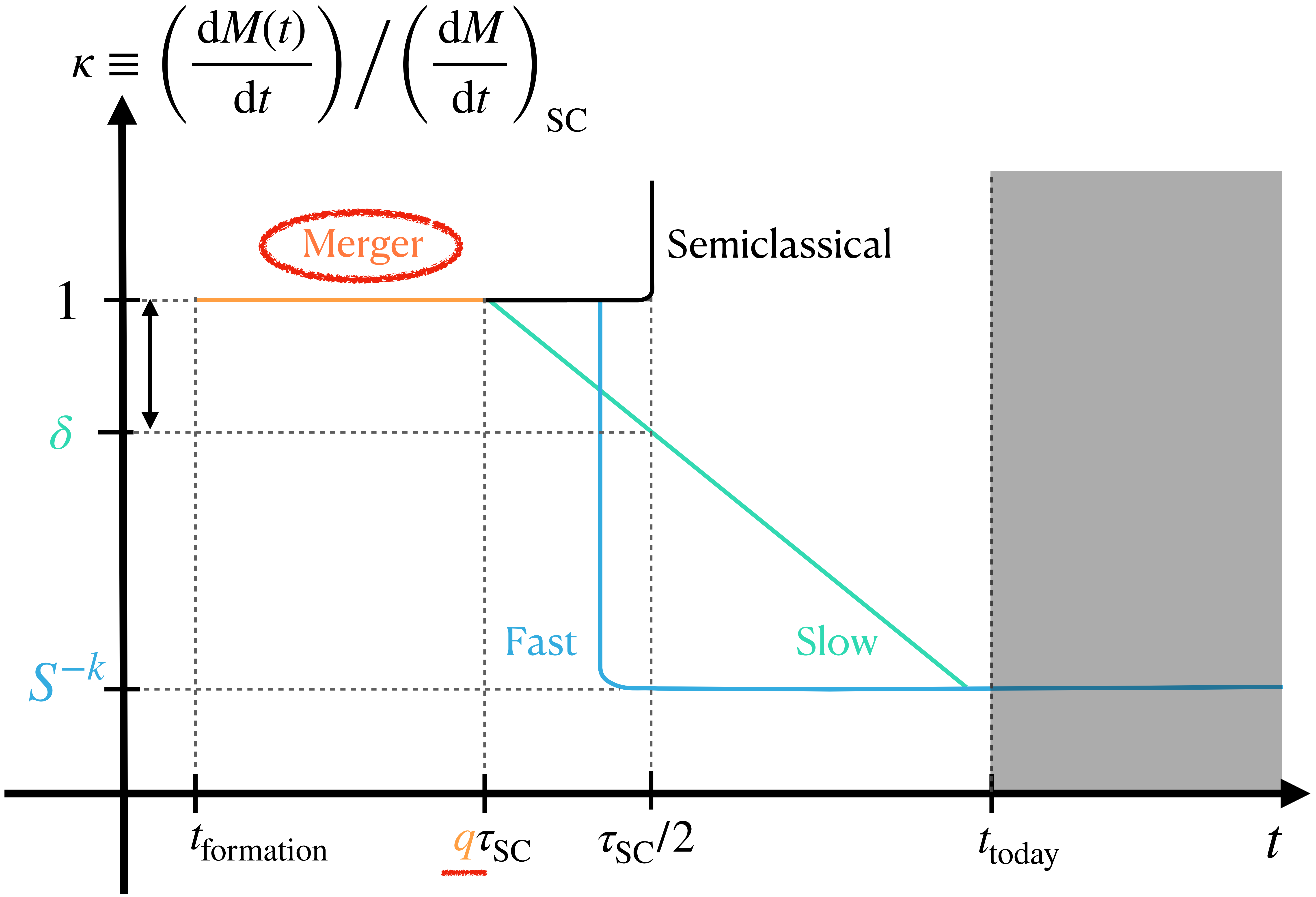
G. Dvali, J. Bermudez, **MZ,** ‘24



- Presence of information horizon
- Stabilisation happens in most parameter space

Direct probe of the semiclassical phase? the case of merging memory-burdened PBHs

Visinelli, **MZ** '24



$$\frac{\mathrm{d}E}{\mathrm{dVol}\,\mathrm{d}t} \propto R_{\mathrm{PBH}}(f_{\mathrm{PBH}}, M_{\mathrm{BH}})\, q \quad \longrightarrow$$ we can constrain the duration of semiclassical evaporation phase, q

Signal can sit near present-day sensitivities

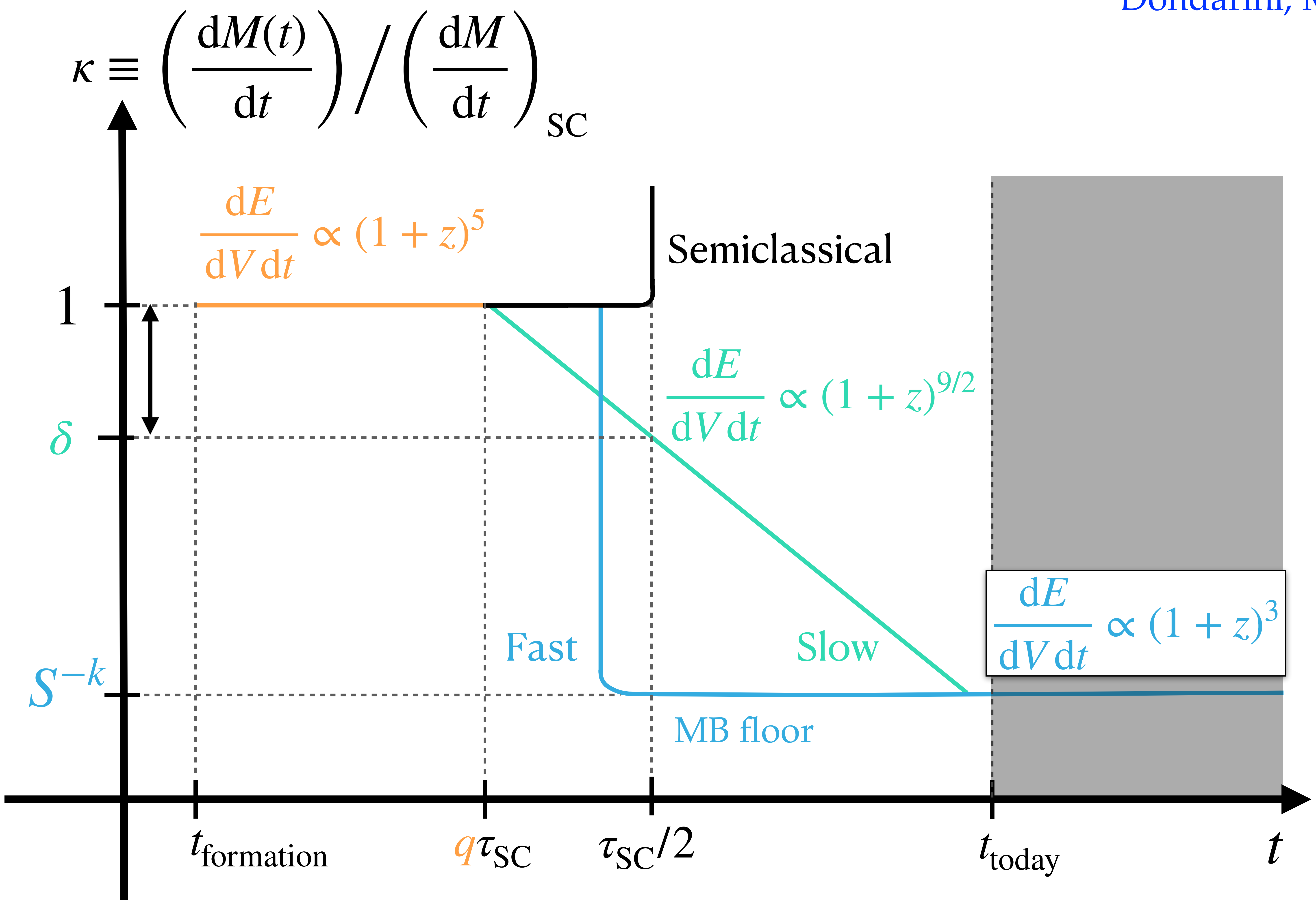
[Dondarini, Marino, Panci, **MZ,** ‘25]

- Signal is largely within reach of present day observations
- Neutrinos and γ-rays lead to similar constraints

Redshift can distinguish the signal origin

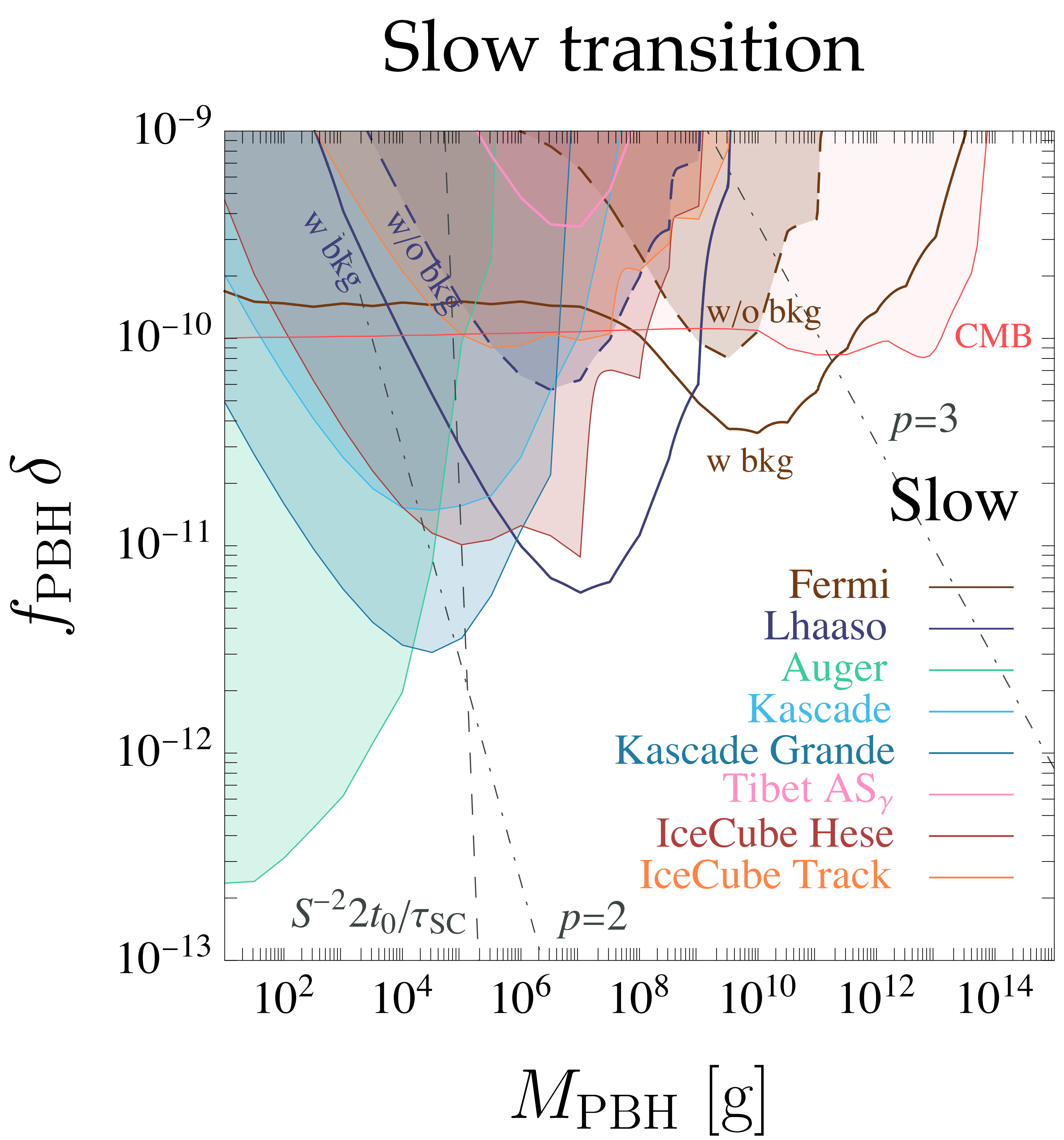
Possibility to track the signal cosmologically.

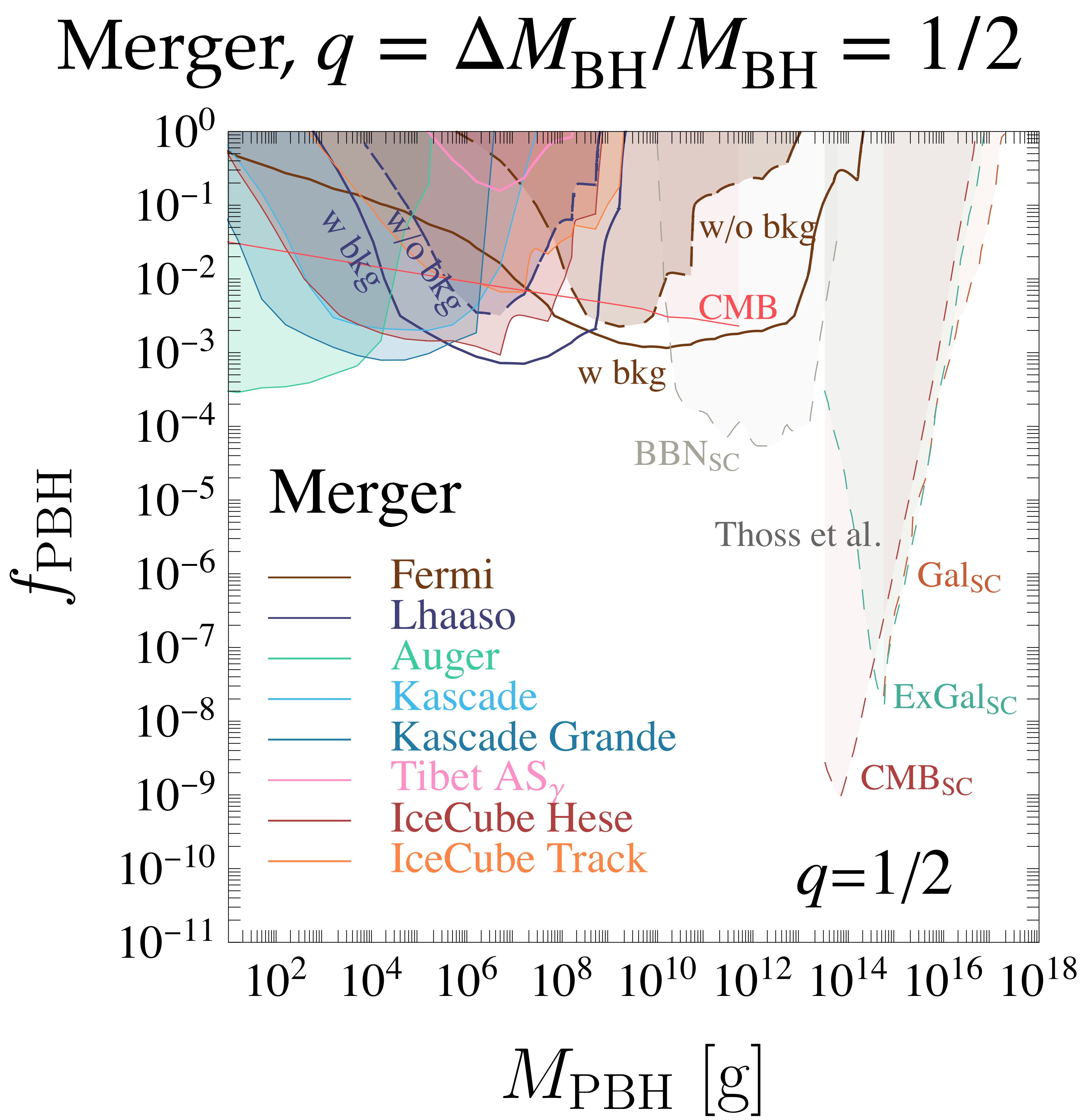
Dondarini, Marino, Panci, **MZ**, '25



Consequences for black holes as dark matter

[Dondarini, Marino, Panci, **MZ,** '25]

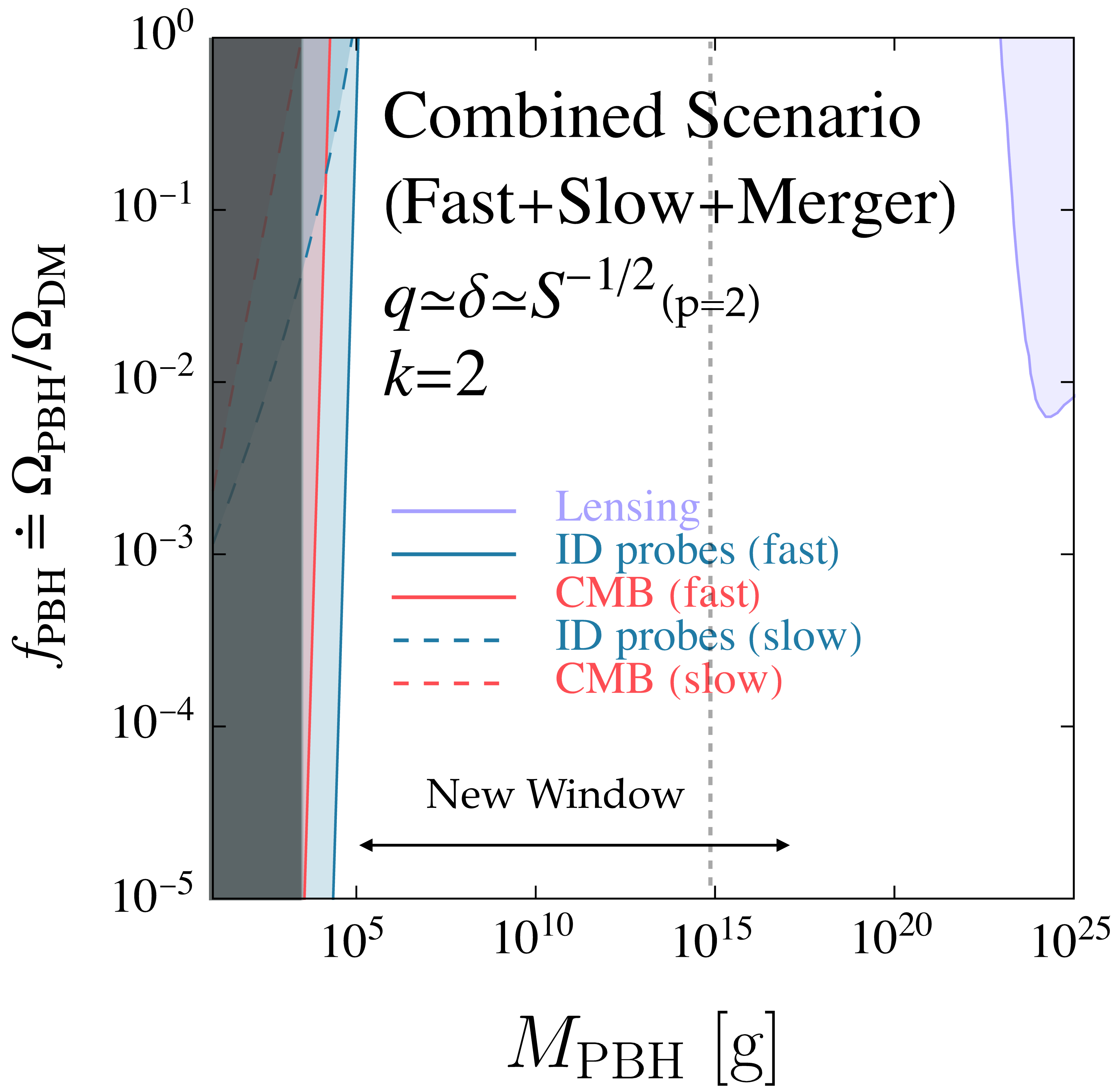




- For BBN and CMB, see also the analysis of Montefalcone et al '25
- See Thoss et al (Kohri) '24 for constraints in instantaneous transition case and Boccia et al '24 for KM3NeT event discussion

Resulting window - $M_{\rm PBH} \gtrsim 10^5$ g is viable

Theoretical viable scenario for PBHs as dark matter:



- **Theoretical bias:** $2 \leq p \lesssim 3$ to have the window for the entirety of dark matter

- **Phenomenologically:**

$q \lesssim 10^{-3}, \quad \delta \lesssim 10^{-11}, \quad k \gtrsim 1$

[Dondarini, Marino, Panci, **MZ**, '25]

Swift memory burden: deviations in black-hole ringdown

Dvali ’25; Yuan & Brito ’25; Dvali, **MZ**, Zell to appear

A direct and testable merger observable

- A merger perturbation can trigger a **swift memory-burden response**
- Ringdown QNMs may acquire: frequency shift and change of damping time
- Schematically:

$$f_{\mathrm{QNM}} = f_{\mathrm{rd}} \left[1 - \mu^{-1} \left(- |\delta g|^2 \right)^{p-1} \right], \quad |\delta g| = \text{amplitude of the ringdown metric perturbation}$$

- **Sensitivity controlled by** memory-burden exponent p and memory load μ

Phenomenological message

Strong swift-MB effects could macroscopically distort the ringdown

Dvali, **MZ**, Zell to appear

Take home

- **Memory burden:** quantum backreaction can stabilize evaporating black holes against complete decay.

- **Universality:** the same mechanism appears in generic highly entropic systems, such as memory-bearing solitons.

- **PBH dark matter:** memory burden opens a new ultralight mass window, with correlated cosmological and high-energy astroparticle signatures.

- **Beyond evaporation:** mergers may probe the information sector directly through **rejuvenated particle emission** and **modified merger/ringdown dynamics**.

Black-hole memory may be hidden in equilibrium, but visible when the system is forced to evolve.

Thank you