Ultralight black holes burdened by their memory: a new window for dark matter

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Motivation

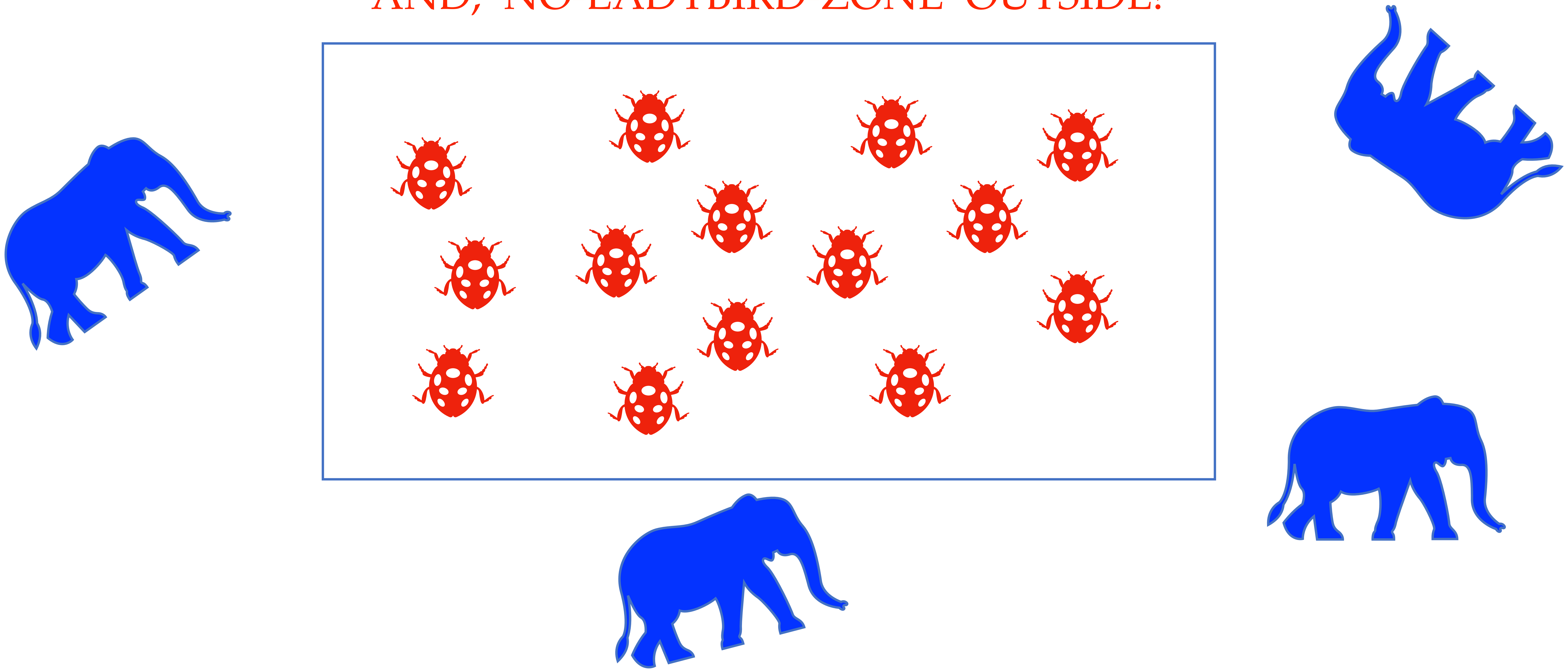
"The memory carried by an object resists its decay." Dvali '18

- Universality of the phenomenon: memory burden is prominent in localized configurations possessing large capacity to store information. It is inevitable for configurations with an *entropy area-law*, so-called *saturons* Dvali '21. Black holes belong to this class.
- Explicit example: soliton in renormalizable field theory. Its Hamiltonian is in correspondence with holography models of BHs Dvali, Valbuena, **MZ** '24
- Leads to the potential stabilization of evaporating black holes Dvali '18 ; Dvali, Eisemann, Michel, Zell '20 opening a new mass window for ultra-light primordial black holes (PBHs) as dark matter. Zel'dovich, Novikov '67; Hawking '71; Carr, Hawking '74
- Predicts spread of the mass function distribution of primordial black holes. Dvali, Valbuena, **MZ** '24
- Unique effect: Stabilized BHs as a source of astrophysical highly energetic particles **MZ,** Visinelli '24

Memory burden effect

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

AND, NO-LADYBIRD-ZONE OUTSIDE!

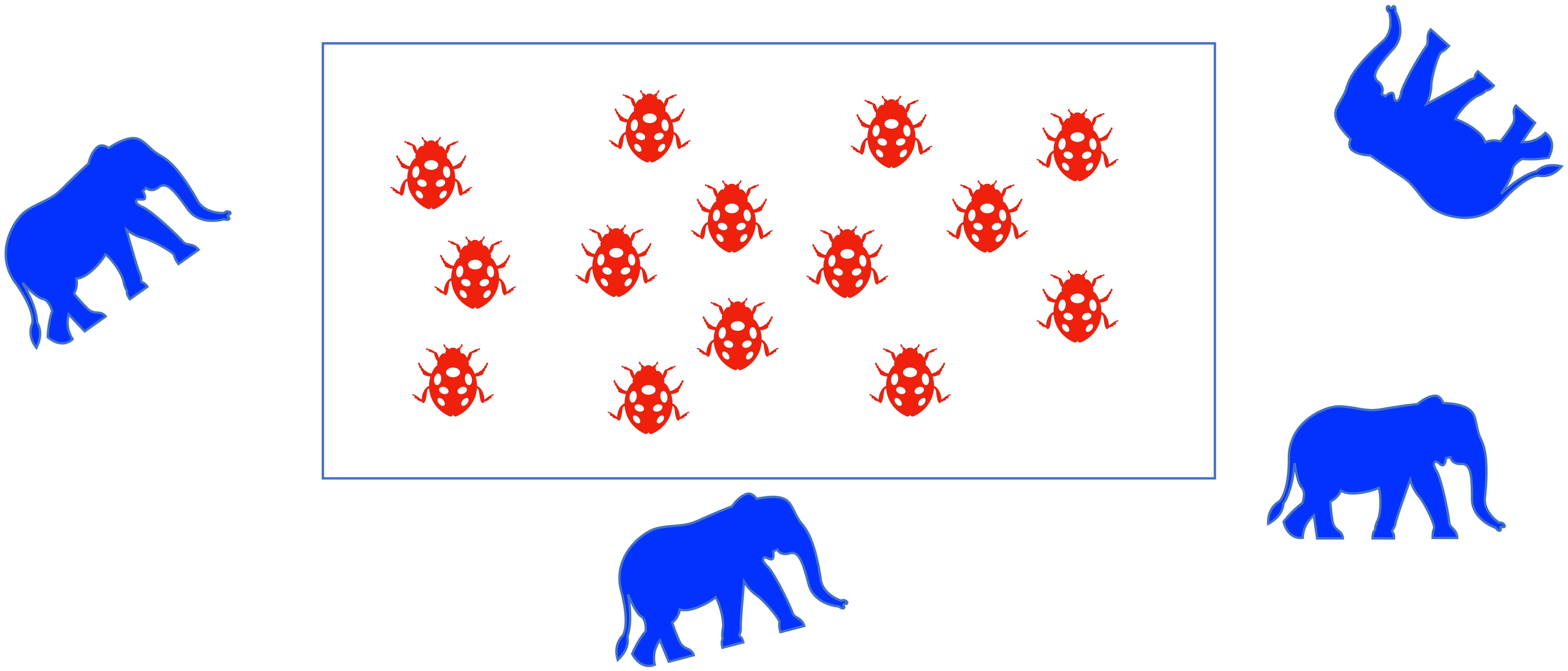


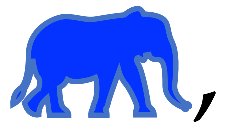
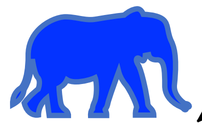
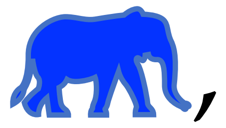
State (0,🐞,🐞, 0,0,🐞, ...) is much less costly in energy than (0,🐘,🐘,0,0,🐘,...)

Memory burden effect

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

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

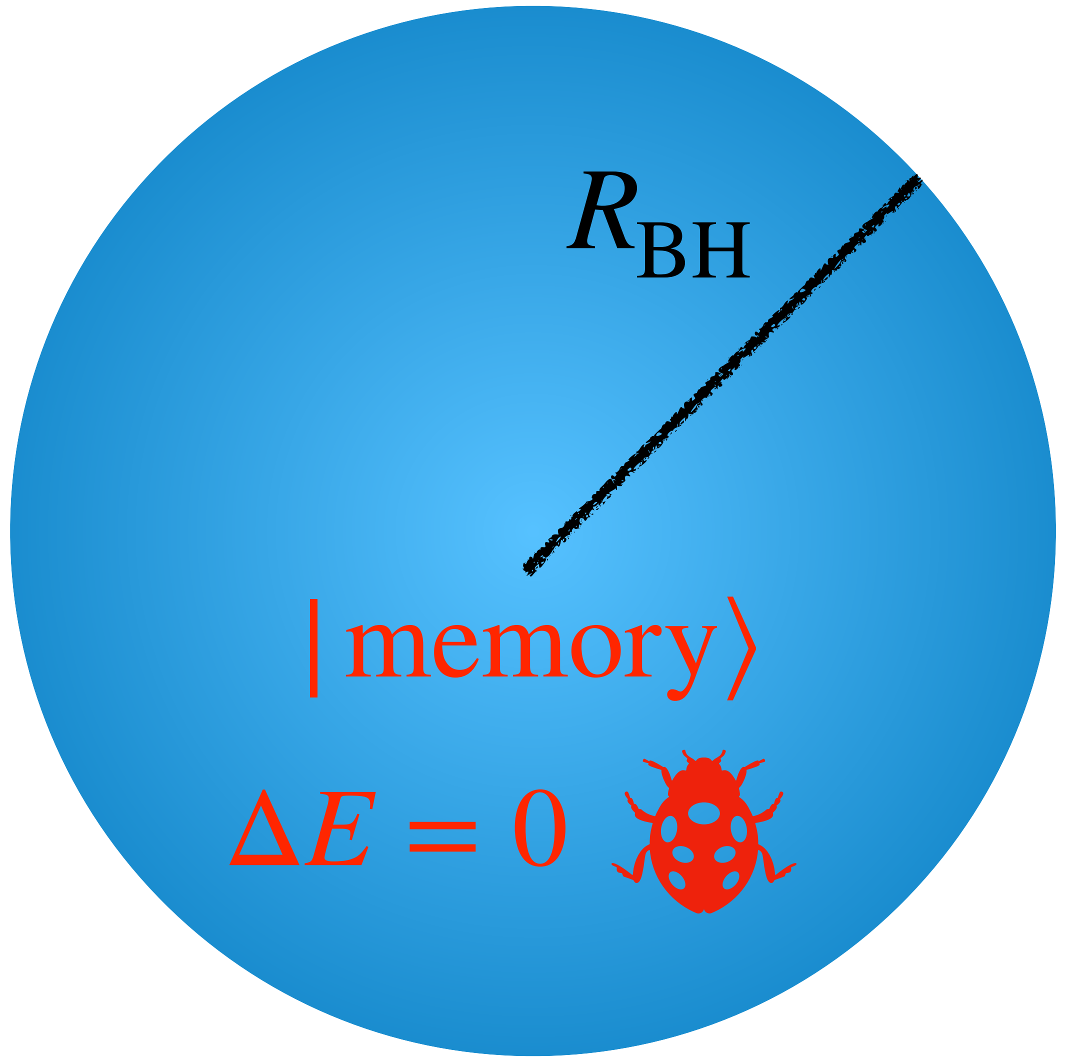


State (0,,, 0,0,, ...) is much less costly in energy than (0,,,0,0,,...)

Evaporating black holes

Entropy Area - Law (Bekenstein): $S = \frac{(R_{BH})^2}{\hbar\, G_N} = \left(\frac{R_{BH}}{L_{Pl}}\right)^2 = \frac{1}{\alpha_{\rm gr}}$

$\alpha_{\rm gr} = (q/M_{\rm pl})^2$



Information stored in a memory pattern (in terms of N qubits)

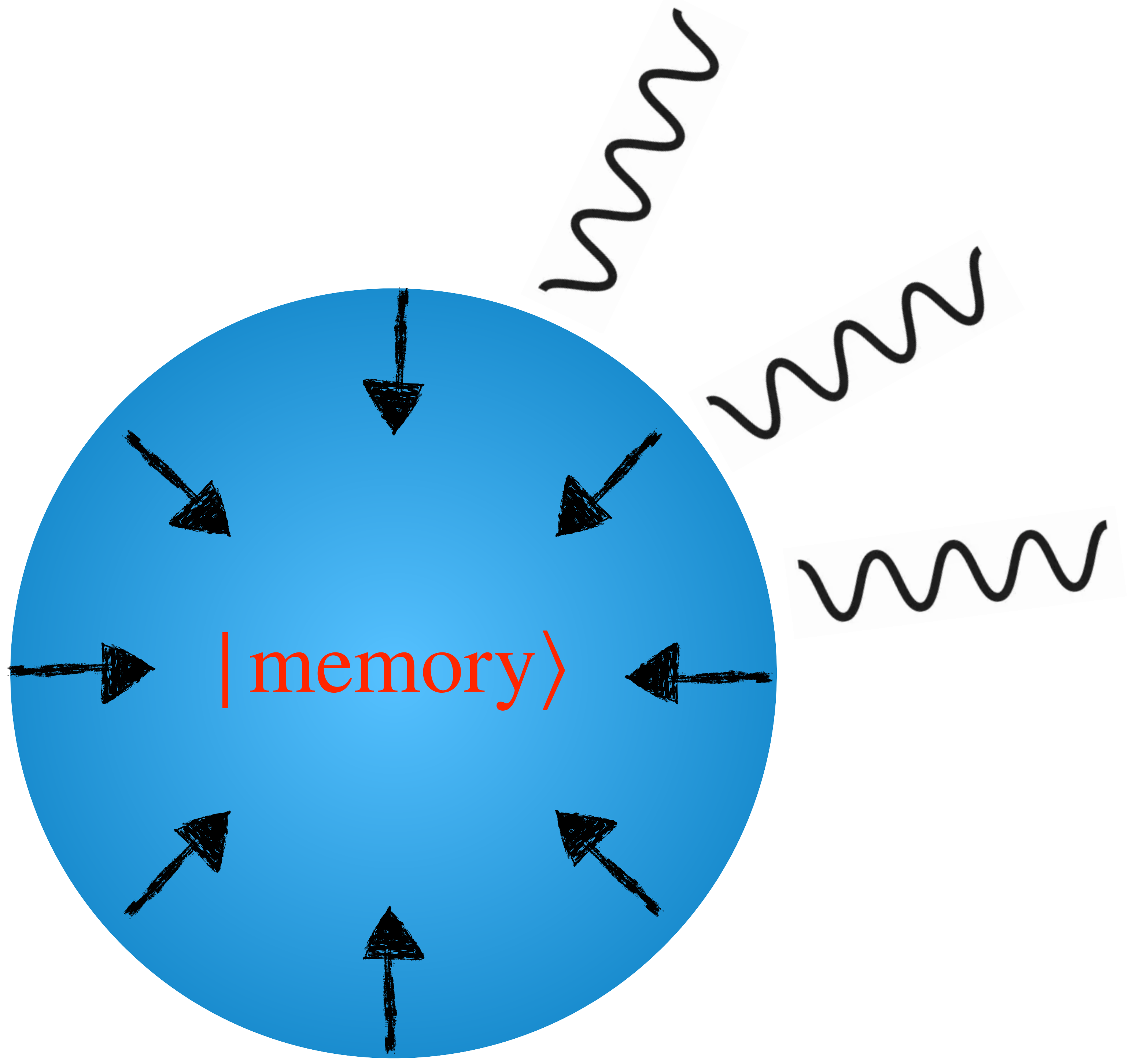
$|\,\text{memory}\rangle = |\,n_1, n_2, \ldots, n_N\rangle ='' \,|\,0{,}1{,}1{,}...{,}0{,}0{,}1\rangle''$

These our lady-birds - classically, no cost in energy.

The number of degenerate states is $n_{\rm st} = 2^N$ implying

$S = \log n_{\rm st} \simeq N$

Evaporating black holes



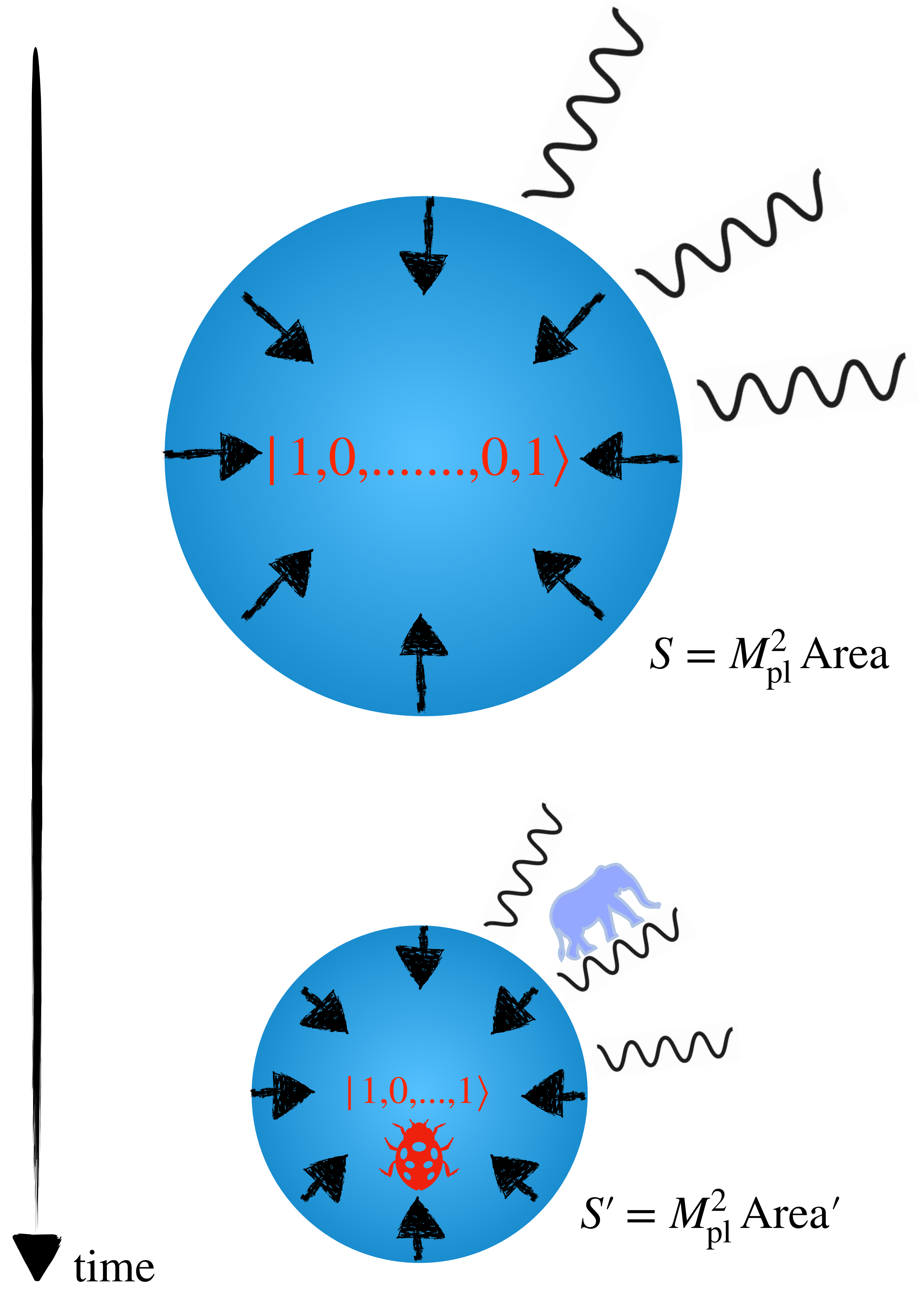
Black holes emit thermally (Hawking): $T = \dfrac{1}{R_{\mathrm{BH}}}$

Full evaporation requires
$\tau_{\mathrm{Page}} \simeq R_{\mathrm{BH}}\, S$

$M_{\mathrm{BH}} \lesssim 10^{15}\,\mathrm{g} \implies \tau \lesssim t_0$
Not a viable dark matter?

!! Thermal emission is not sensible to $|\text{memory}\rangle$

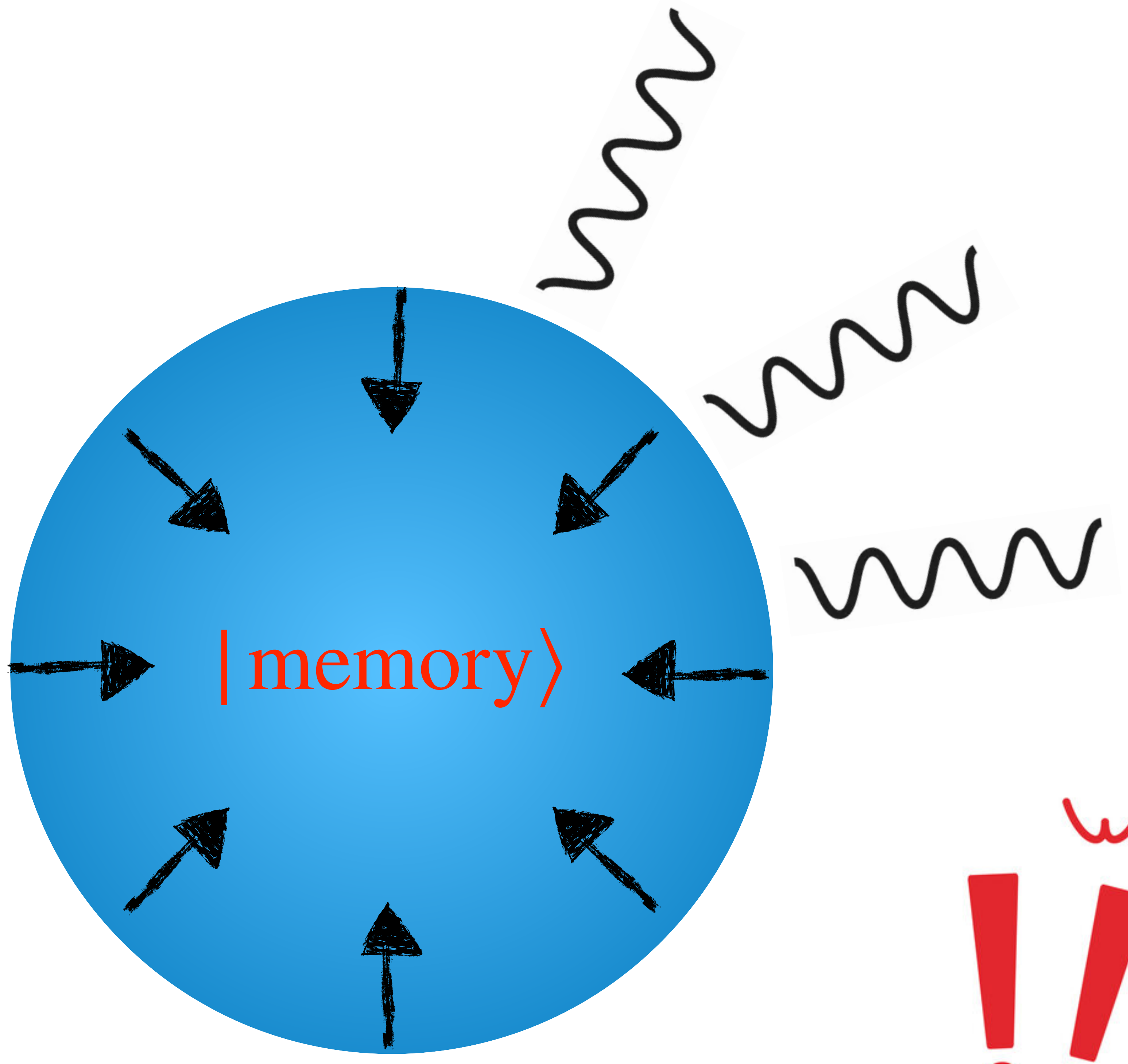
Evaporating black holes



The area of the BH becomes insufficient to store the initial information

This cannot be released due to the high cost in energy. It backreats halting the evaporation, the latest, at half-mass evaporation time.

Evaporating black holes



Hawking calculation is performed in semiclassical limit of fixed geometry:

$$\hbar \to 0: \qquad S = \frac{R_{\rm BH}^2}{\hbar G_{\rm N}} = \frac{1}{\alpha_{\rm gr}} \to \infty$$

$$R_{\rm BH}\ \text{finite}, \quad M_{\rm pl} \to 0, \quad M_{\rm BH} \to \infty$$

After $\tau_{\rm Page}$, $\Delta M_{\rm BH} \sim M_{\rm BH}$: Semiclassical description is broken

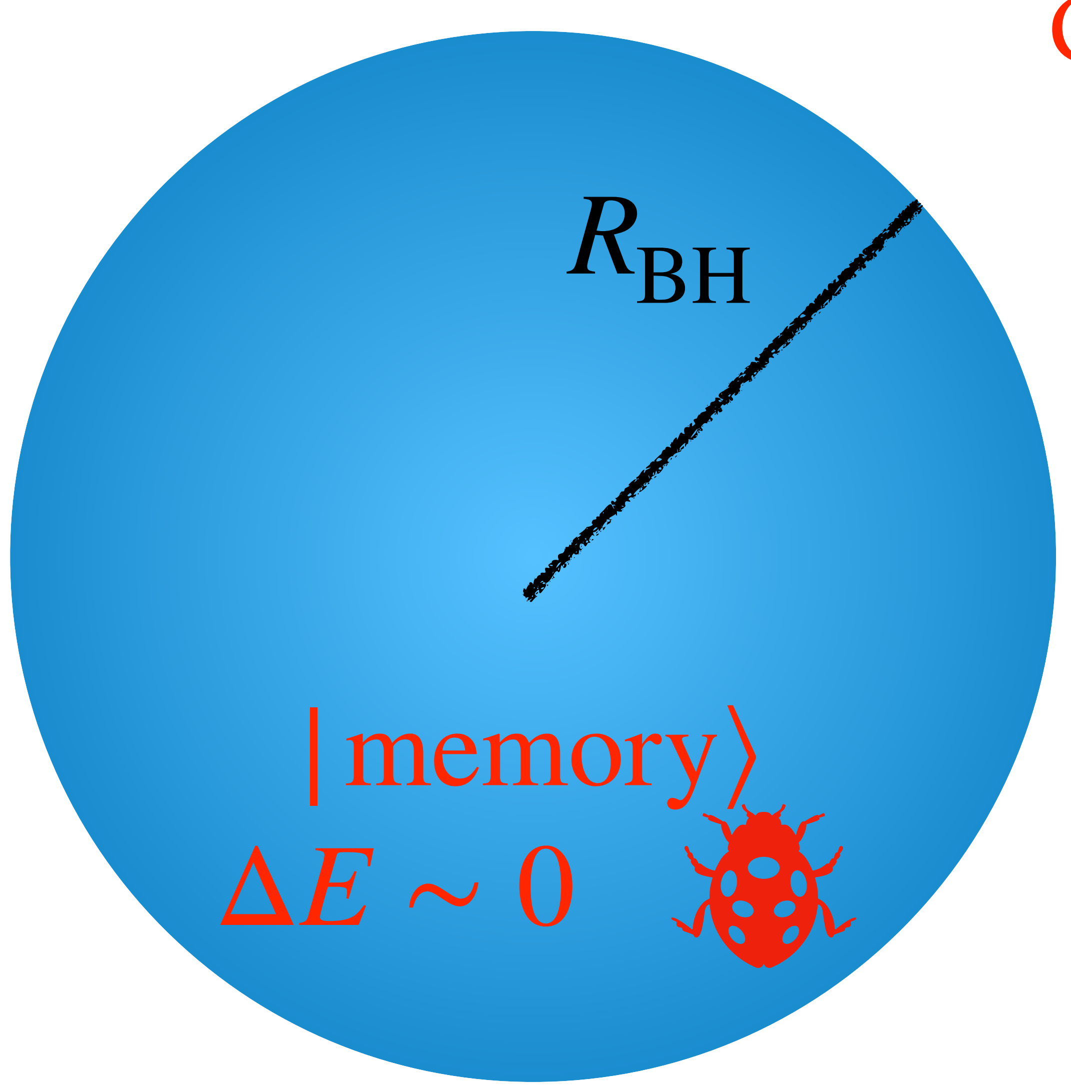
Is a young BH the same as an old BH with the same mass?

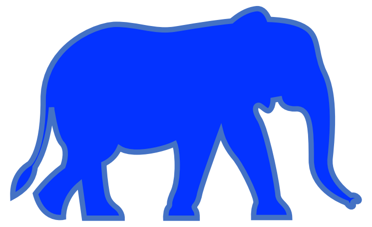
$|\,\text{memory}\rangle$ backseats on the evaporation, halting it.

Entropy and memory

Any localized self-sustained configuration spontaneously breaks a set of symmetries - internal or external

Gapless memory modes (Goldstones) live only inside



The modes outside are highly gapped. 
Due to this, information stored in memory modes cannot escape for a long time.

- Flavour of Goldstones $|n_1, \ldots, n_{\mathrm{N}}\rangle$ can give large entropy
- Maximal entropy is bounded by **unitarity** $S \leq \text{Area} f^2$, with f being the Goldstone decay constant

Dvali '21

Entropy and memory

$$S = \text{Area} \times f^2 = \text{"Saturon"}$$ Dvali '21

- BHs are an example of saturon $f \leftrightarrow M_{\rm pl}$
- Saturons can be built in renormalizable field theories, also in different dimensions
- Saturons in the Standard Model → Color Glass Condensate G. Dvali, Venugopalan '21
- Universal emergence of properties akin to the ones of BHs: Thermal rate, presence of information horizon, **extremality**, Page's time

G. Dvali, Sakhelashvili '21, + Venugopalan '21 …
G.Dvali, O. Kaikov, J. Bermudez, '21,G. Dvali, F. Kühnel, **MZ,** '22, G. Dvali, O. Kaikov, J. Bermudez, F. Kühnel, **MZ,** '24, G. Dvali, J. Bermudez, **MZ,** '24,…

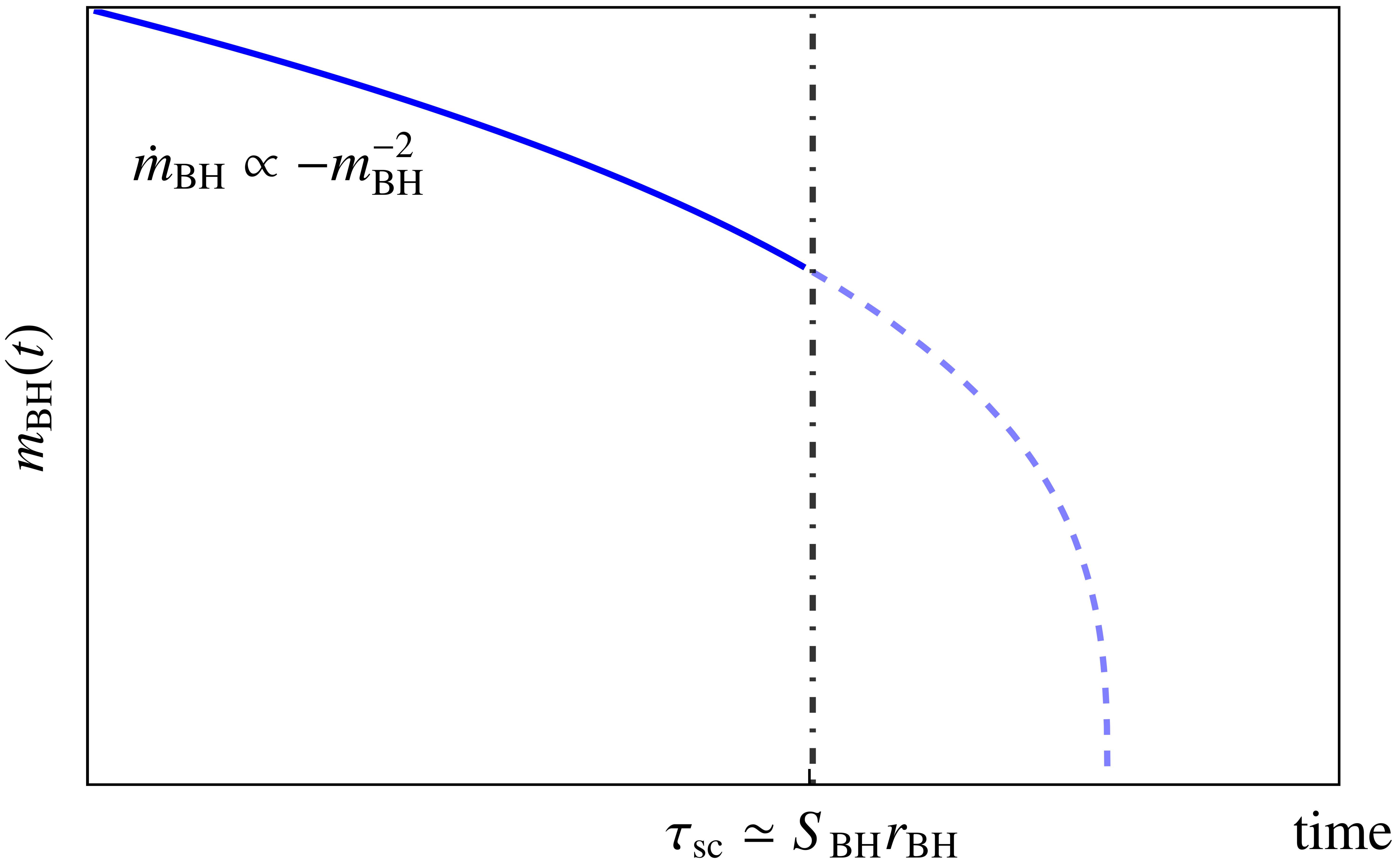
→ BHs properties are not unique to gravity

→ Useful theoretical laboratories to understand BHs

→ Predict new features

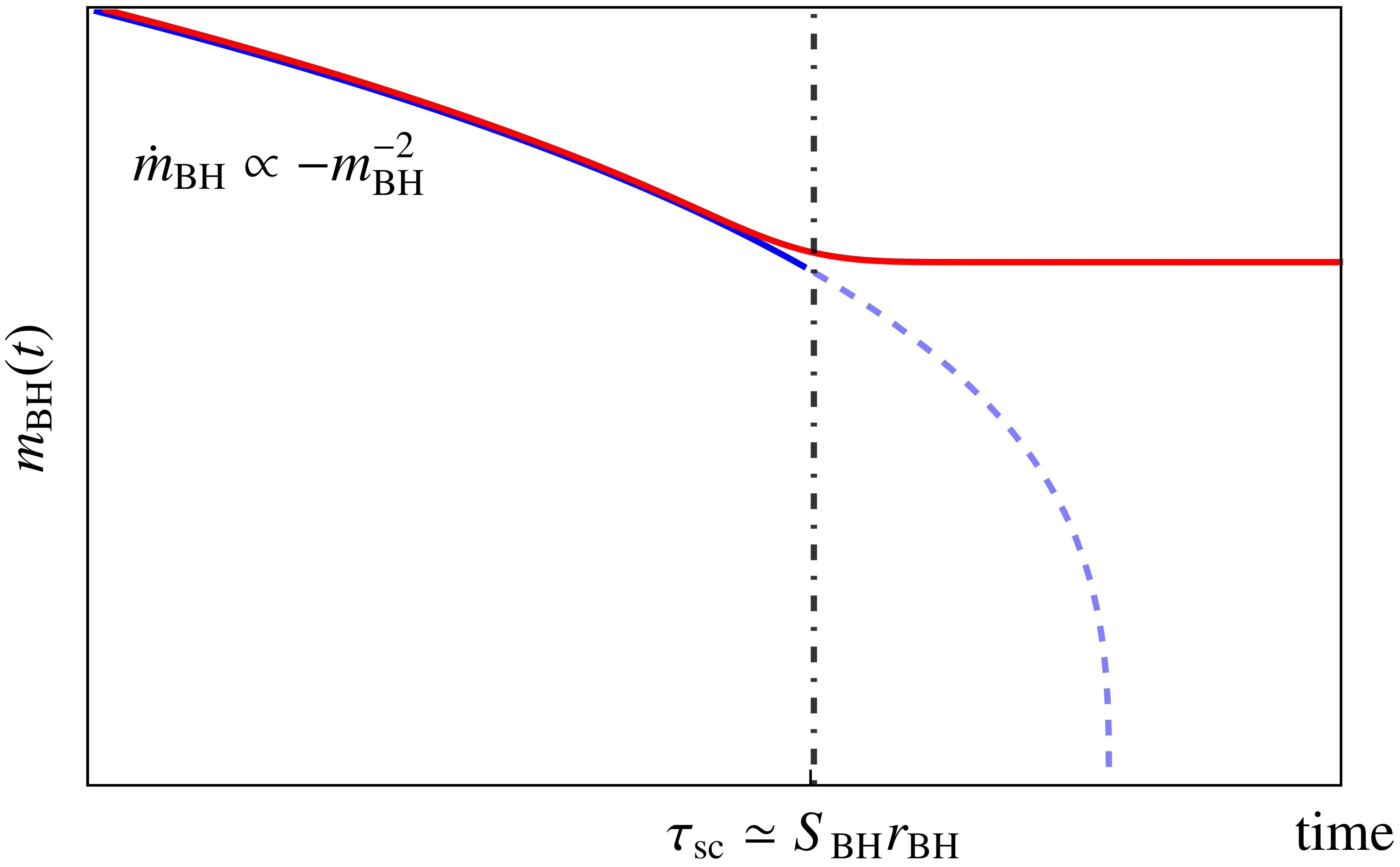
Memory burden

Adopting Hawking rate throughout all of the evolution



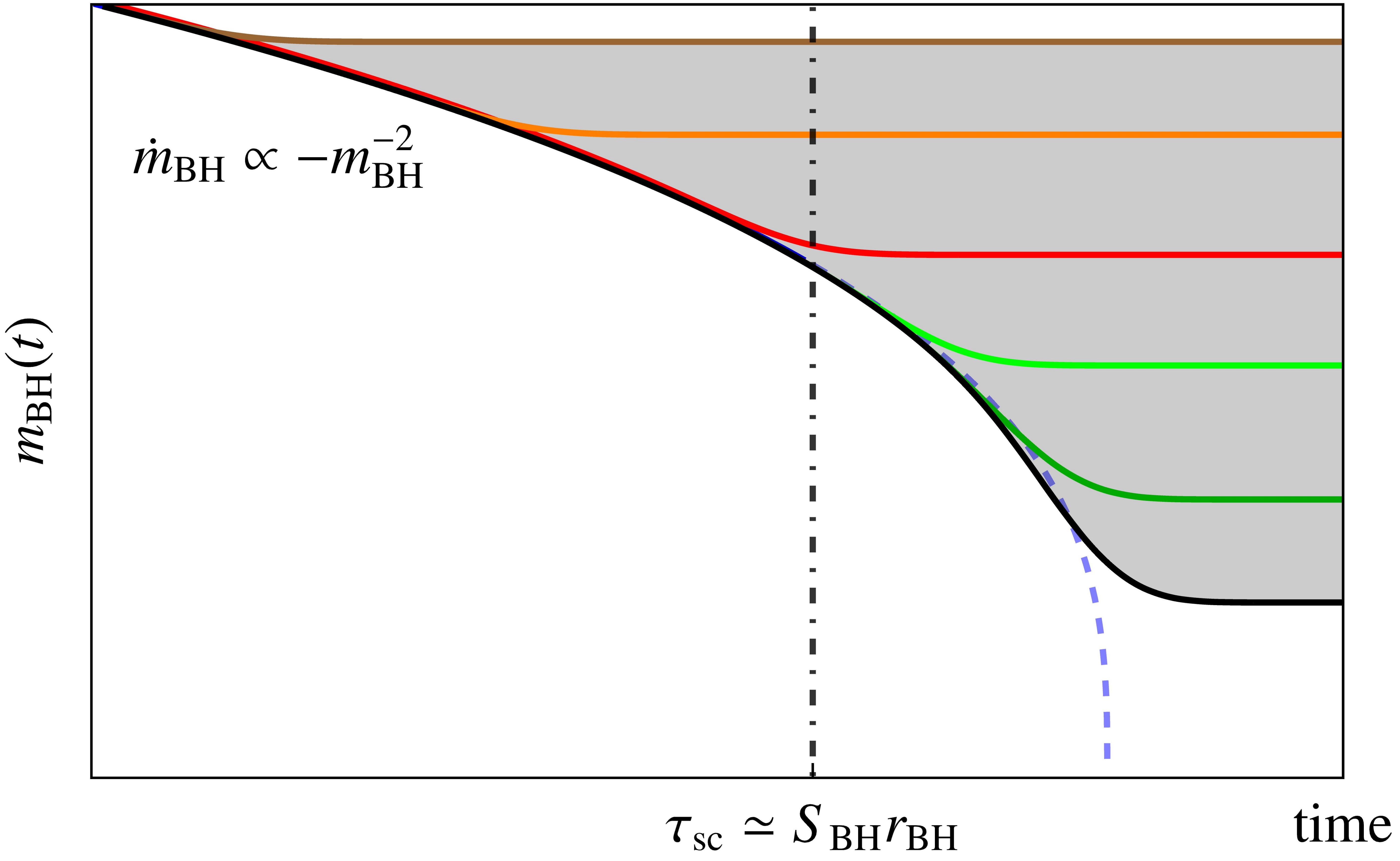
Memory burden

Memory burden stabilizes the BH at late times



Memory burden

BHs with different initial memories (but same initial mass) asymptotes to different masses due to memory burden.



Example of a burdened soliton

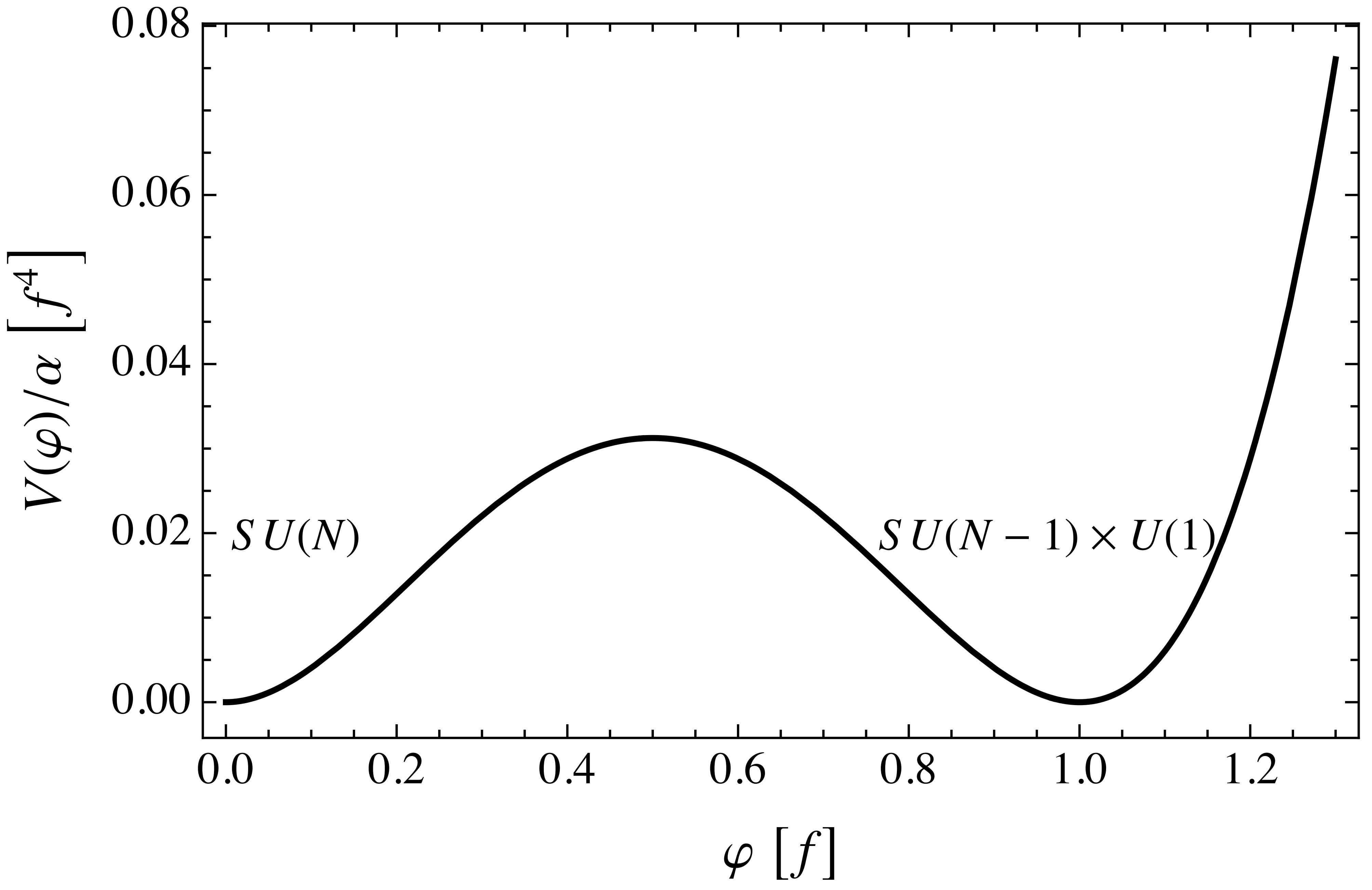
Vacuum bubble

G.Dvali, J.S. Valbuena-Bermudez, **MZ** '24.

- $d = 3+1$
- ϕ in the adjoint representation of $SU(N)$ ($N \times N$ hermitian, traceless matrix)
- We work in the $N \gg 1$ limit.

$$\mathcal{L} = \frac{1}{2}\mathrm{Tr}\left[(\partial_\mu\phi)(\partial^\mu\phi)\right] - V[\phi]$$

$$V[\phi] = \frac{\alpha}{2}\mathrm{Tr}\left[\left(f\phi - \phi^2 + \frac{I}{N}\mathrm{Tr}[\phi^2]\right)\right]$$



Unitarity requires: 't Hooft coupling $\alpha N \leqslant 1$

↑

Validity domain of QFT description in terms of ϕ

$$\varphi^2 = \mathrm{Tr}\left[\phi^2\right]$$

$$V(\varphi) \sim \frac{\alpha}{2}\varphi^2(f-\varphi)^2$$

Vacuum bubble

G.Dvali, J.S. Valbuena-Bermudez, **MZ** '24.

Vacuum bubbles:

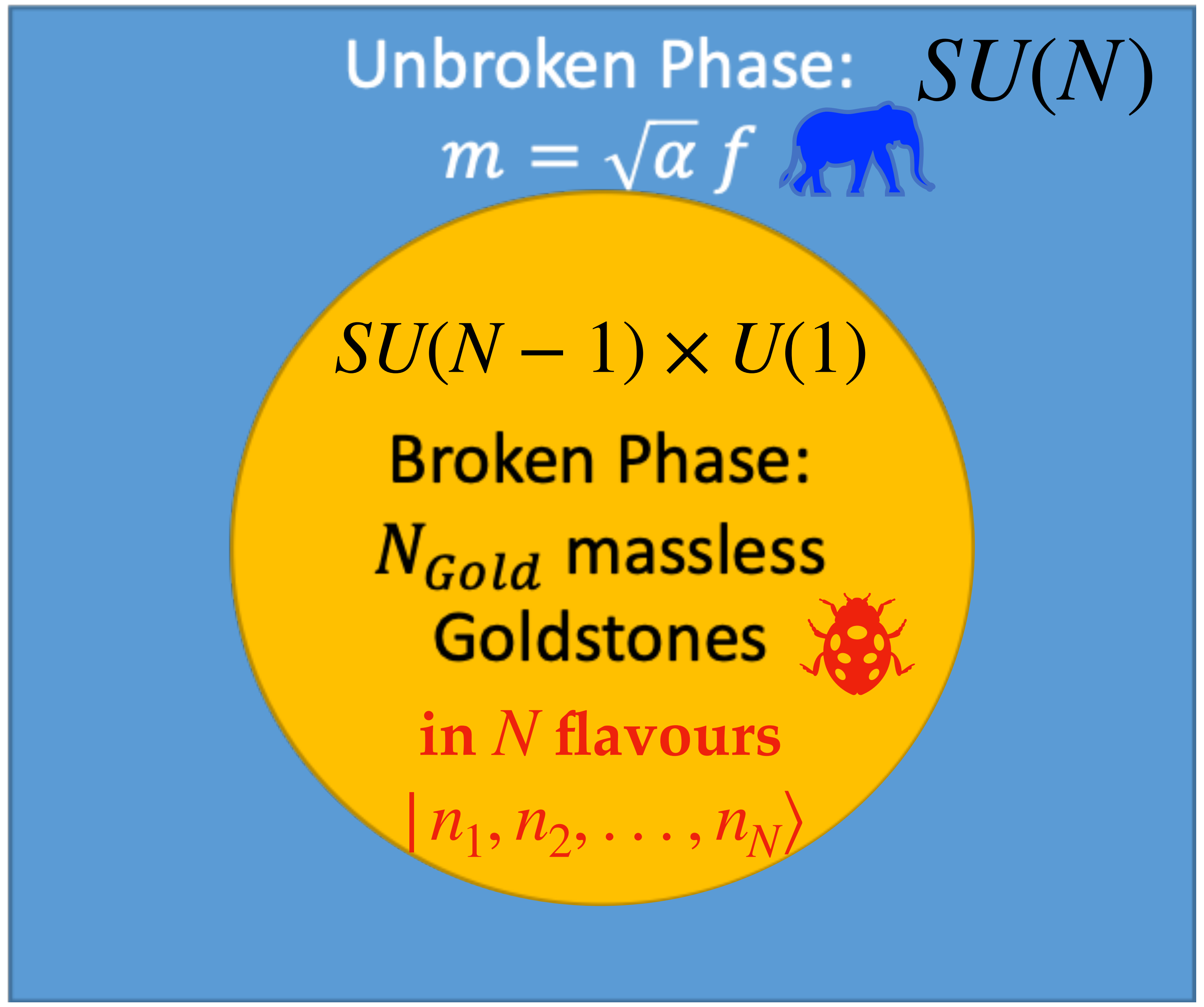
$$\phi = U^\dagger \Phi_D U$$

- $U = \exp\left[-i\,\theta\, T\right]$
- T corresponds to broken generator

$$\theta = \omega\, t$$

- Bubble endowed with charge $Q = N_G$

$$\Phi_D = \frac{\varphi(r)}{\sqrt{N(N-1)}} \text{diag}\,(N-1, -1, -1, \ldots, -1)$$

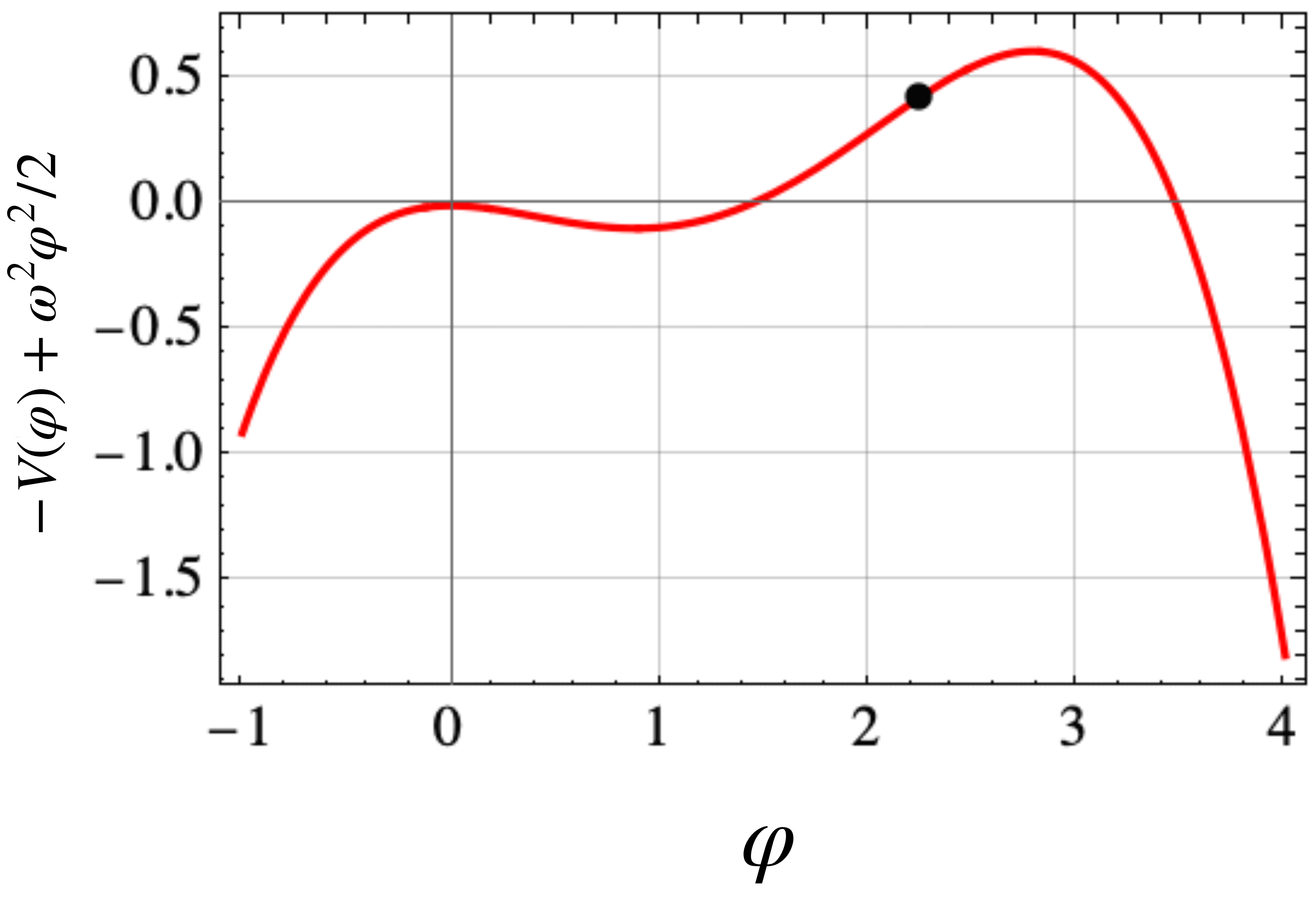


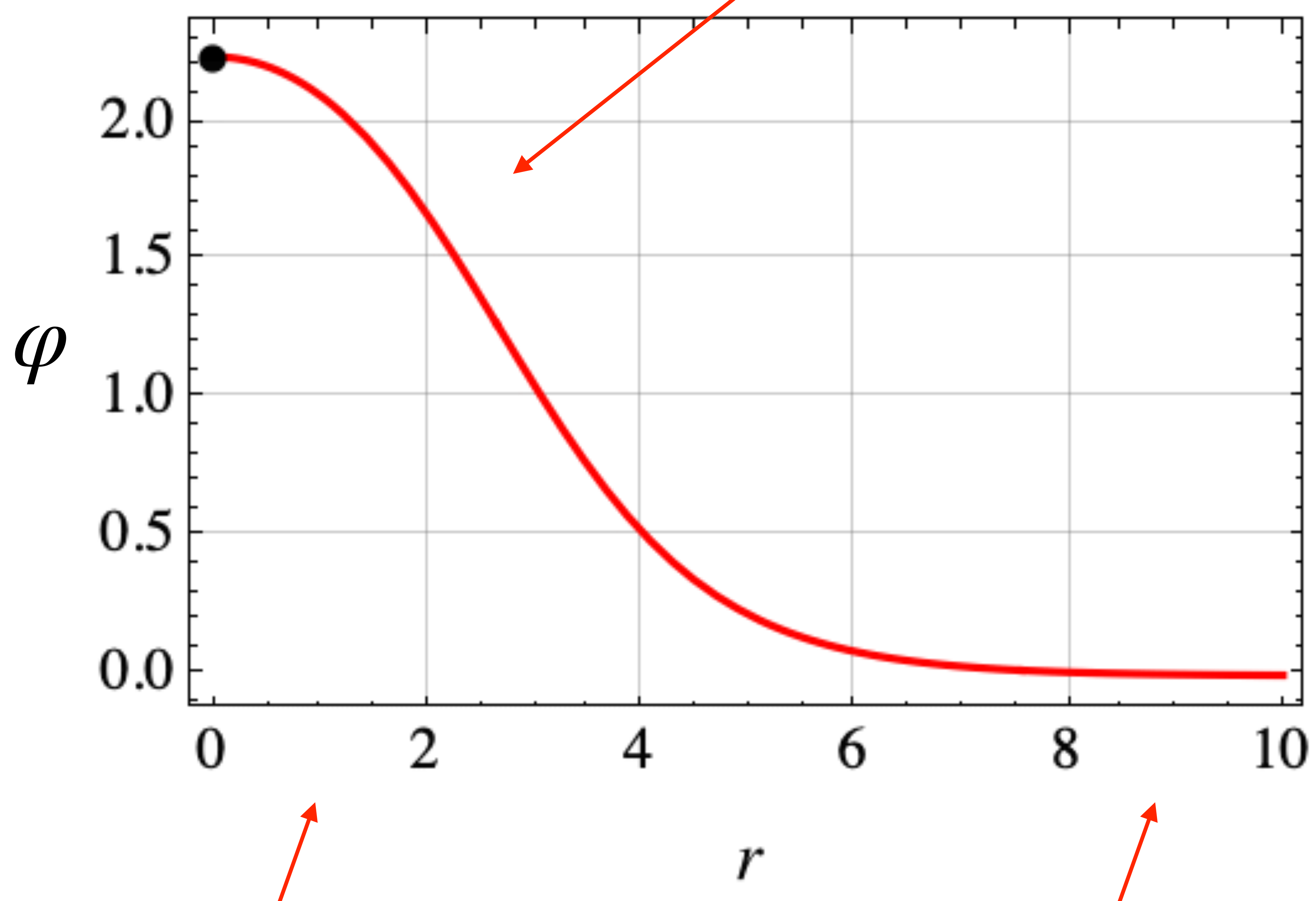
Vacuum bubble

Solution example with charge N_G:

$$\partial_r^2\varphi(r) + \frac{2}{r}\partial_r\varphi(r) + \omega^2\varphi(r) - \frac{\partial V[\varphi]}{\partial\varphi} = 0$$

Wall-Thickness $\sim 1/m$





$\Phi_{\mathrm{D}} \propto \varphi(r)\,\mathrm{diag}\,(N-1, -1, -1, \ldots, -1)$

$SU(N-1)\times U(1)$ vacuum

$SU(N)$ vacuum

$\varphi(r)$ is the order parameter localising the Goldstone modes (memory) - "**master mode**"

Vacuum bubble

G.Dvali, J.S. Valbuena-Bermudez, **MZ** '24.

$$E = \frac{2\pi}{3\alpha} m^3 R^2 (1 - \dot{R}^2)^{-1/2} + \frac{2\pi}{3\alpha} m^2 \omega^2 R^3 = E_{\rm ms} + E_{\rm memory}$$

Where

$E_{\rm ms}$ = energy of bubble radial "**master**" mode: spontaneously breaks the symmetry, localizing the Goldstones

$E_{\rm memory}$ = energy of Goldstones responsible for the stabilization

$$E_{\rm memory} = \frac{2}{3} E_{\rm ms}$$

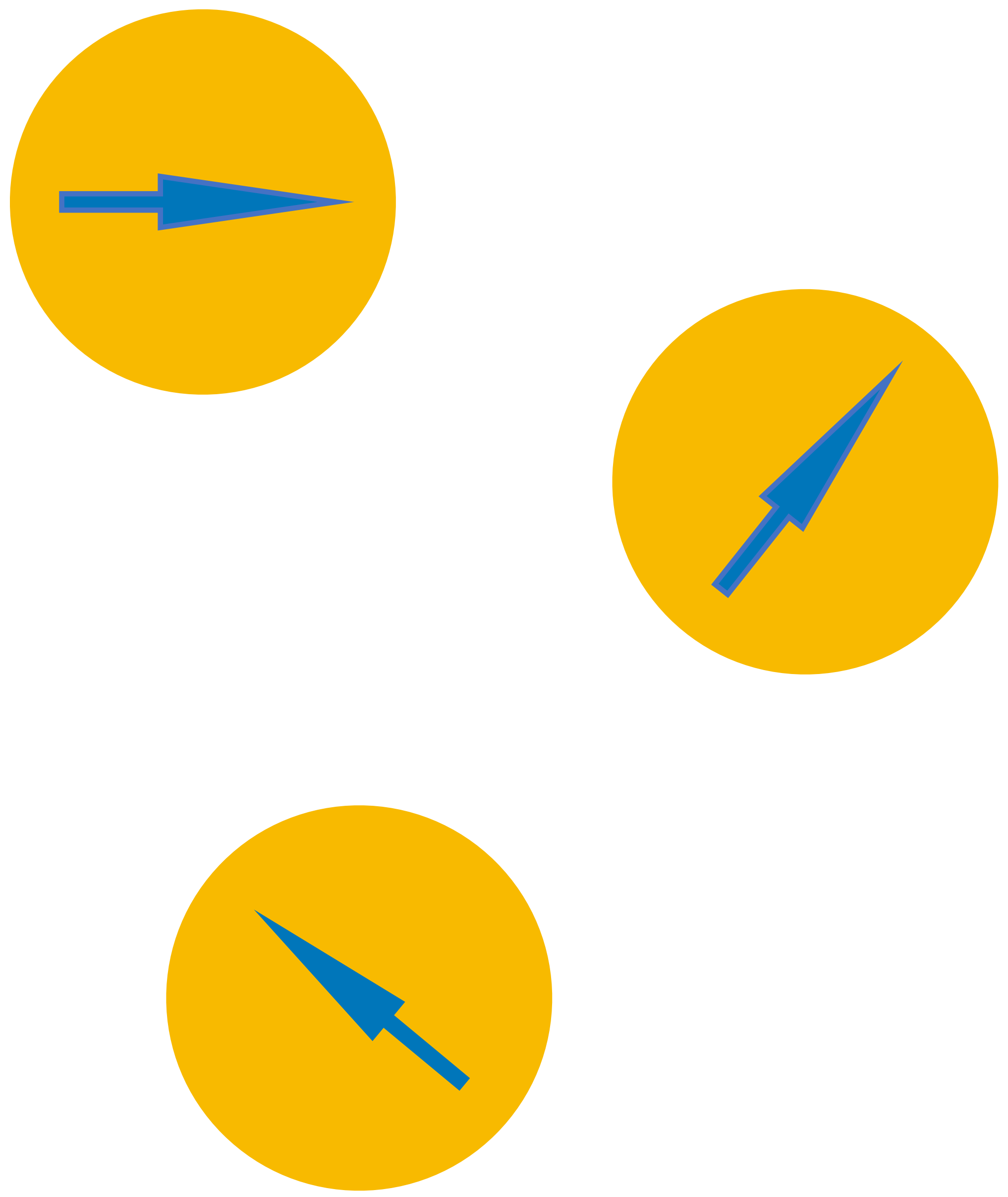
$$\langle {\rm memory} \,|\, \dot{\theta}^2 \,|\, {\rm memory} \rangle = \omega^2$$

$\longrightarrow$ This stabilizes the bubble.

Vacuum bubble as a black hole prototype

Bubbles rotated by relative $SU(N)$ transformations: $\Phi \rightarrow U^{\dagger}\Phi U$

Using different broken generators leads to same classical bubble. Therefore, there is an exponential micro state degeneracy.



$$U = \exp\{i\theta_a \hat{T}^a\} \xrightarrow{"\theta_a = \omega t"} \mathscr{L}_{\text{eff}} \supset \varphi(r)^2 (\partial_\mu \theta^a)(\partial^\mu \theta^a)$$

$$|\,\text{memory}\rangle = |\,n_1, n_2, \ldots, n_N\rangle \qquad \text{With: } \sum_a^N n_a = N_{\text{G}} = Q_{\text{s}}$$

$$n_{\text{states}} = \binom{N_G}{2N} \simeq \left(1 + \frac{2N}{N_{\text{Gold}}}\right)^{N_{\text{Gold}}} \left(1 + \frac{N_{\text{Gold}}}{2N}\right)^{N} \qquad S = \log n_{\text{states}}$$

Vacuum bubble as a black hole prototype

These stationary objects display properties analogous to black holes in certain parameter space region

In particular, for $\omega \simeq m \simeq 1/R \quad \text{and} \quad N_{\text{G}} \simeq N \simeq 1/\alpha$

↓

$$S = R^2 f^2 = MR = \frac{1}{\alpha} = N = N_G$$

- Identifying $f \leftrightarrow M_{\text{Planck}}$ entropy area-law for black hole is reproduced
- $\alpha N \simeq \alpha N_G \simeq 1 \longrightarrow$ Unitarity saturation

Example of property analogous to BH: Extremality

Saturons as laboratory: vorticity meets extremality

Spinning BHs are characterized by quantity: $a = \frac{J}{M^2}$

Event horion at: $r_+ = M + M\left(1 - a^2\right)^{1/2}$

- $a \leq 1 \quad (J \leq S)$: to avoid "naked singularity"

- $a = 1$: Extremal BH: Hawking emission is absent

$\longrightarrow$ For the saturated bubble this is understood by the emergence of vorticity

Saturons as laboratory: vorticity meets extremality

G. Dvali, F. Kühnel, **MZ,** PRL 129 (2022) 6, 061302

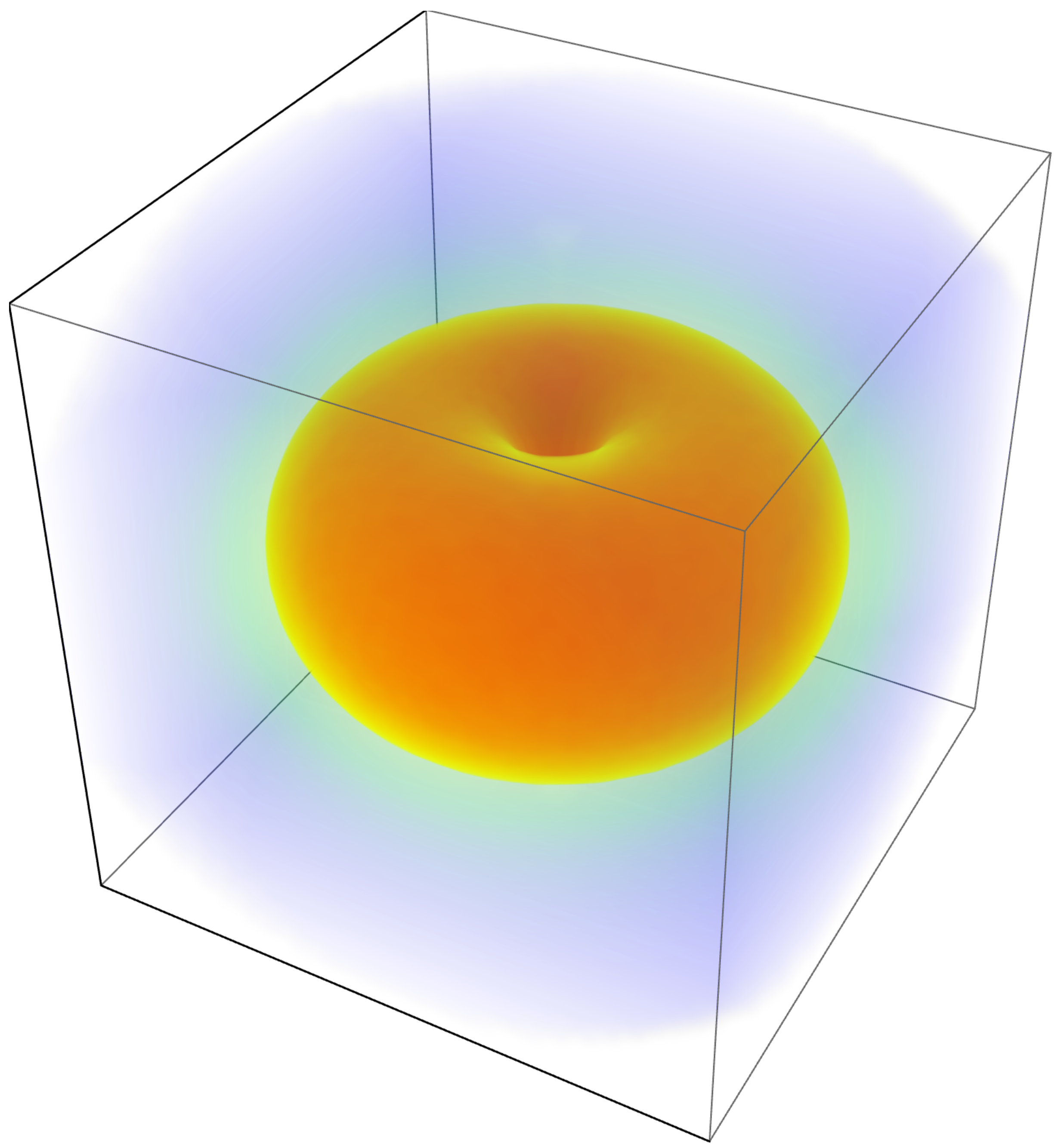
There is a way to spin a saturon bubble in an axial-symmetric way: Vorticity

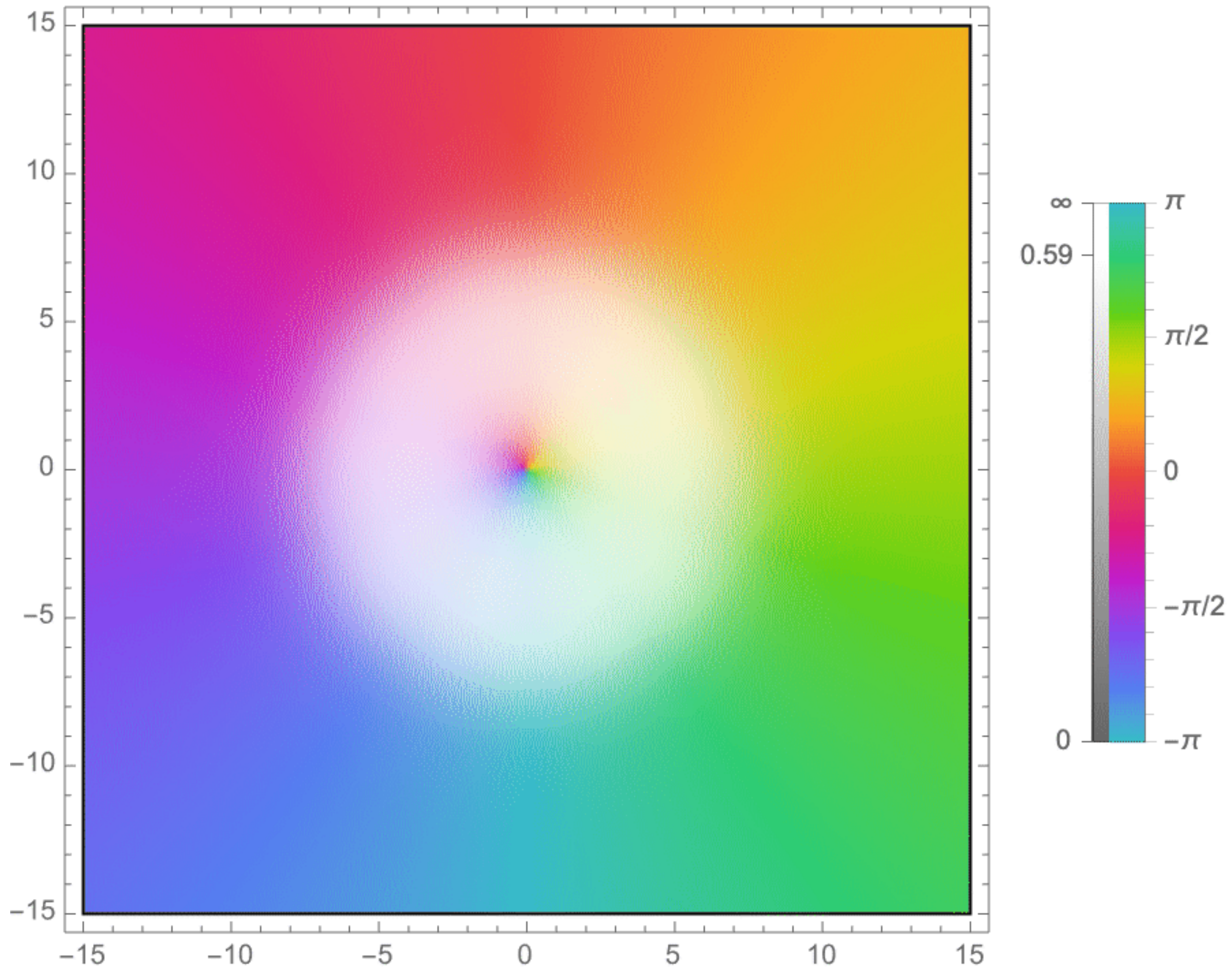
$$\Phi = \frac{\rho(r)}{f} e^{i(\omega t + n\varphi)\hat{T}} \langle \Phi \rangle e^{-i(\omega t + n\varphi)\hat{T}}$$

winding number $= n = 0, \pm 1, \pm 2, \ldots$

Angular momentum $J = n\, N_{\text{Gold}}$

Profile for $n = 1$





Construction has similarities with spinning U(1) Q-ball see Volkov, Wohnert '02

Saturons as laboratory: vorticity meets extremality

G. Dvali, F. Kühnel, **MZ,** PRL 129 (2022) 6, 061302

Angular momentum $J \simeq n\,N_{\text{Gold}} \simeq n\,S$ @ saturation

Requiring that bubble maintains an entropy area law leads to

$$E_{\text{spin}} \lesssim M_{\text{bubble}} \Rightarrow n \sim \mathcal{O}(1)$$

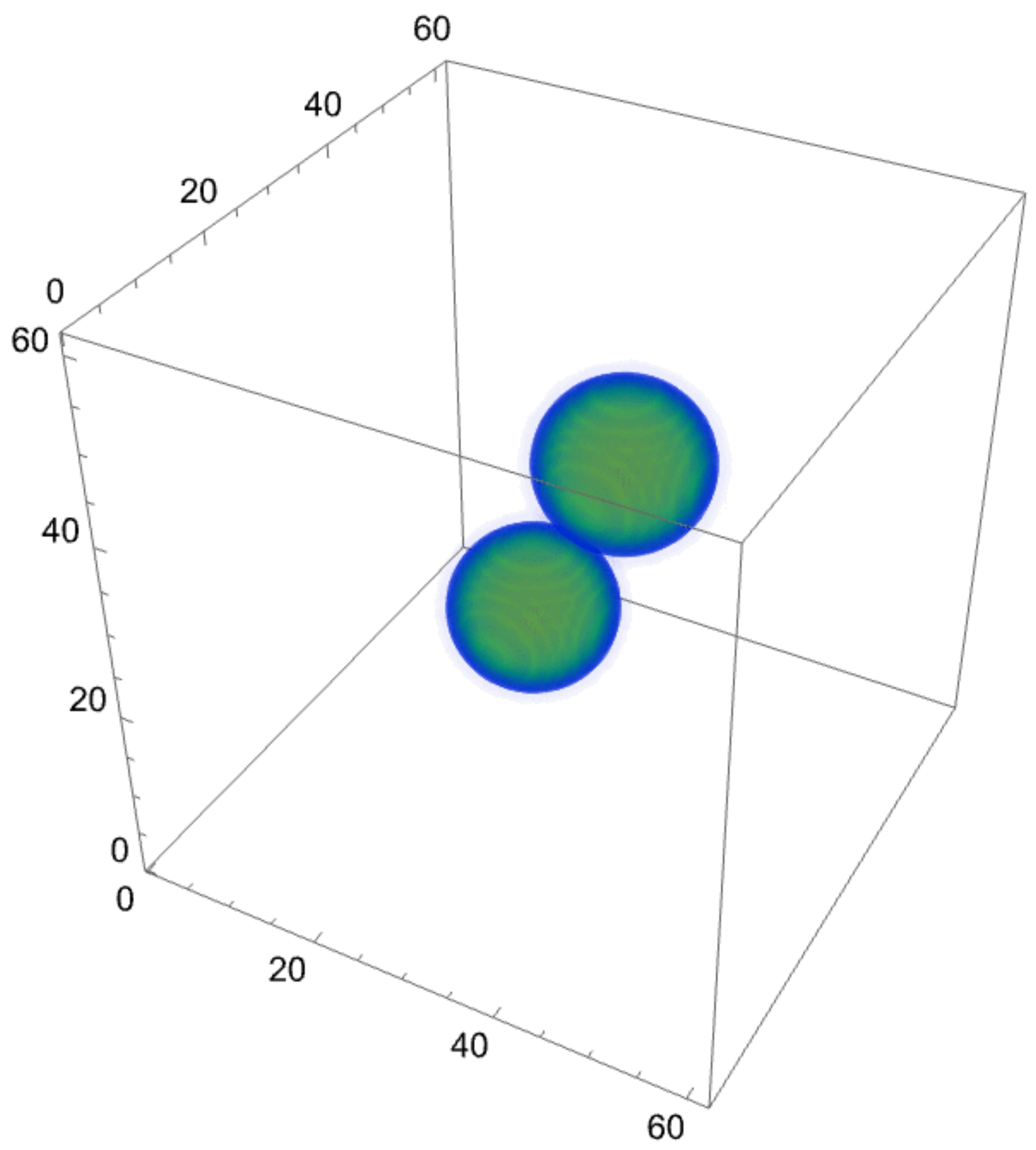
	Saturon bubble	Black hole
Maximal spin	$\underset{n\sim\mathcal{O}(1)}{S}$	S_{BH}

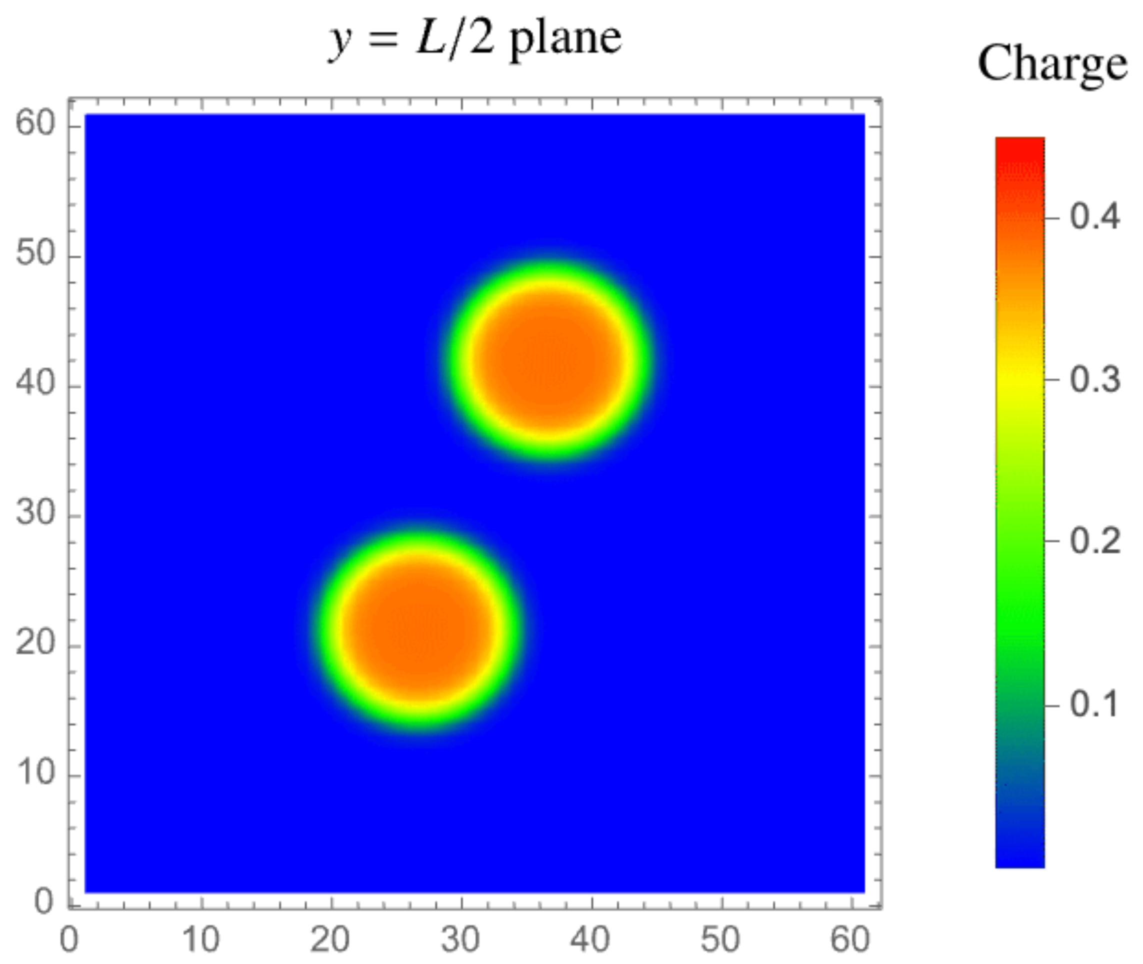
- For higher J, the bubble would no longer possess an entropy-area law
- Topological explanation of the absence of Hawking (soft) radiation due to macroscopic integer nature of the vortex
- Can vorticity be a property manifesting in highly spinning black holes? If so, pheno consequences?

Saturons as laboratory: vorticity meets extremality

G. Dvali, F. Kühnel, **MZ,** PRL 129 (2022) 6, 061302 + G. Dvali, O. Kaikov, J. Bermudez, F. Kühnel, **MZ,** PRL 132 (2024) 15, 151402

Example: Study the impact of vorticity in saturated configurations. Could similar features emerge in black hole mergers?





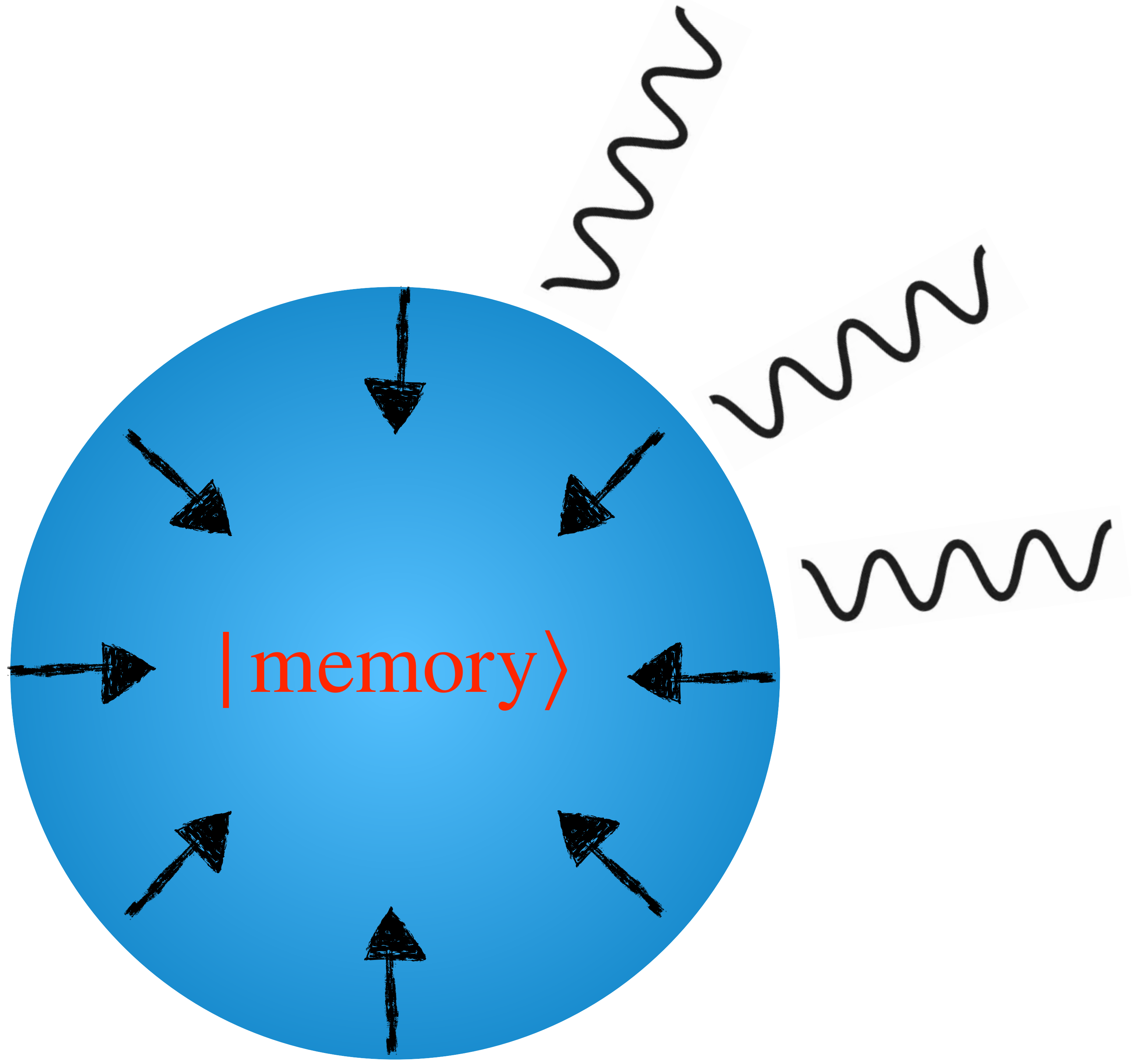
- Due to the integer nature of the vortex, its emergence leads to macroscopic deviations in the emitted radiation.
- Potential for time-delayed vortex ejection, resulting in a radiation burst.

- Similar behaviours are expected in black hole mergers if vorticity localizes in the intermediate configuration.
- Precise characterization of the gravitational signal in progress Dvali, MZ.

Dynamics of a soliton stabilized by its memory

Dynamics

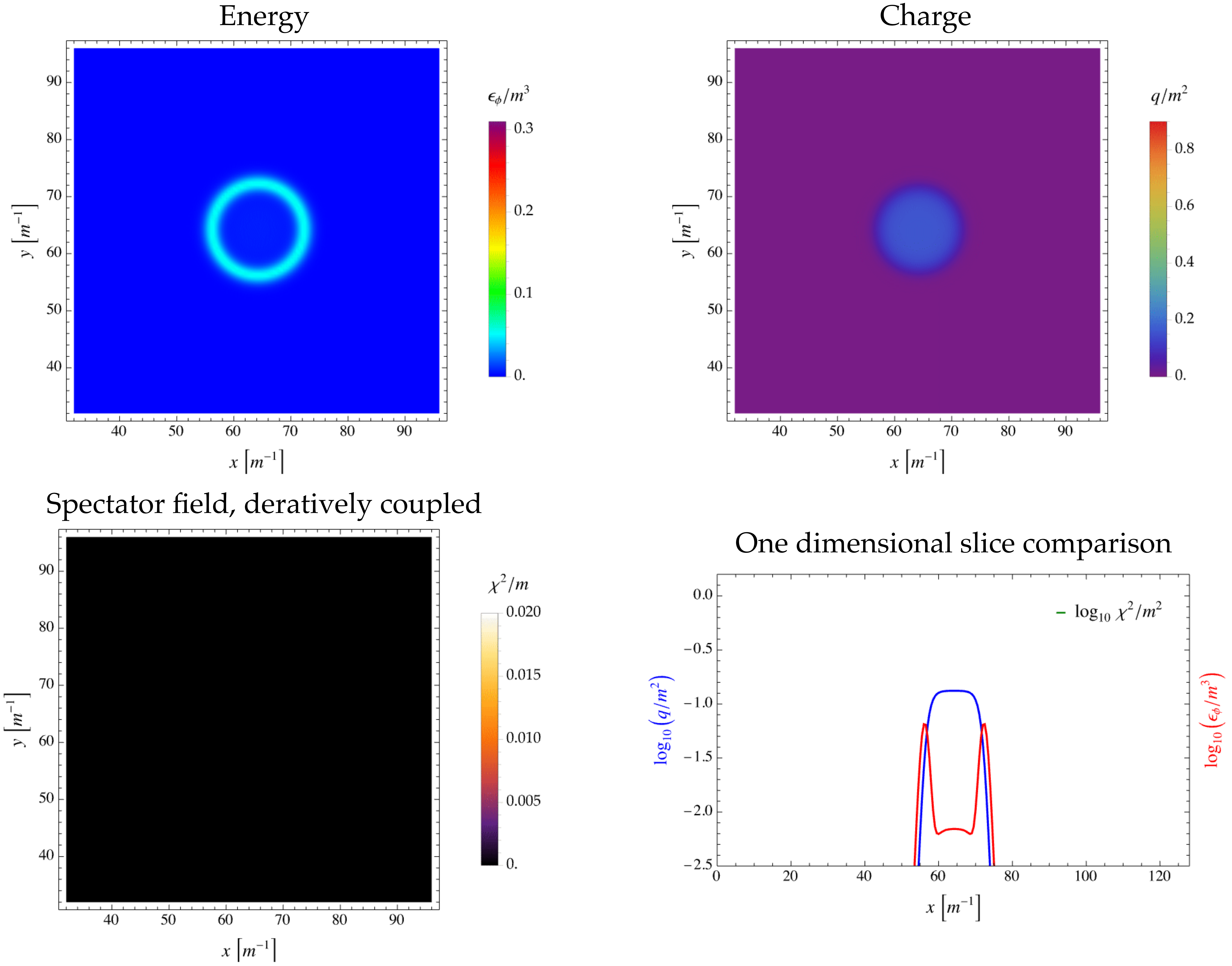
Example of bubble dynamically stabilized by memory.



In the limit $E_{\text{memory}} \ll E_{\text{ms}}$, the memory is initially insufficient to stabilize the bubble profile

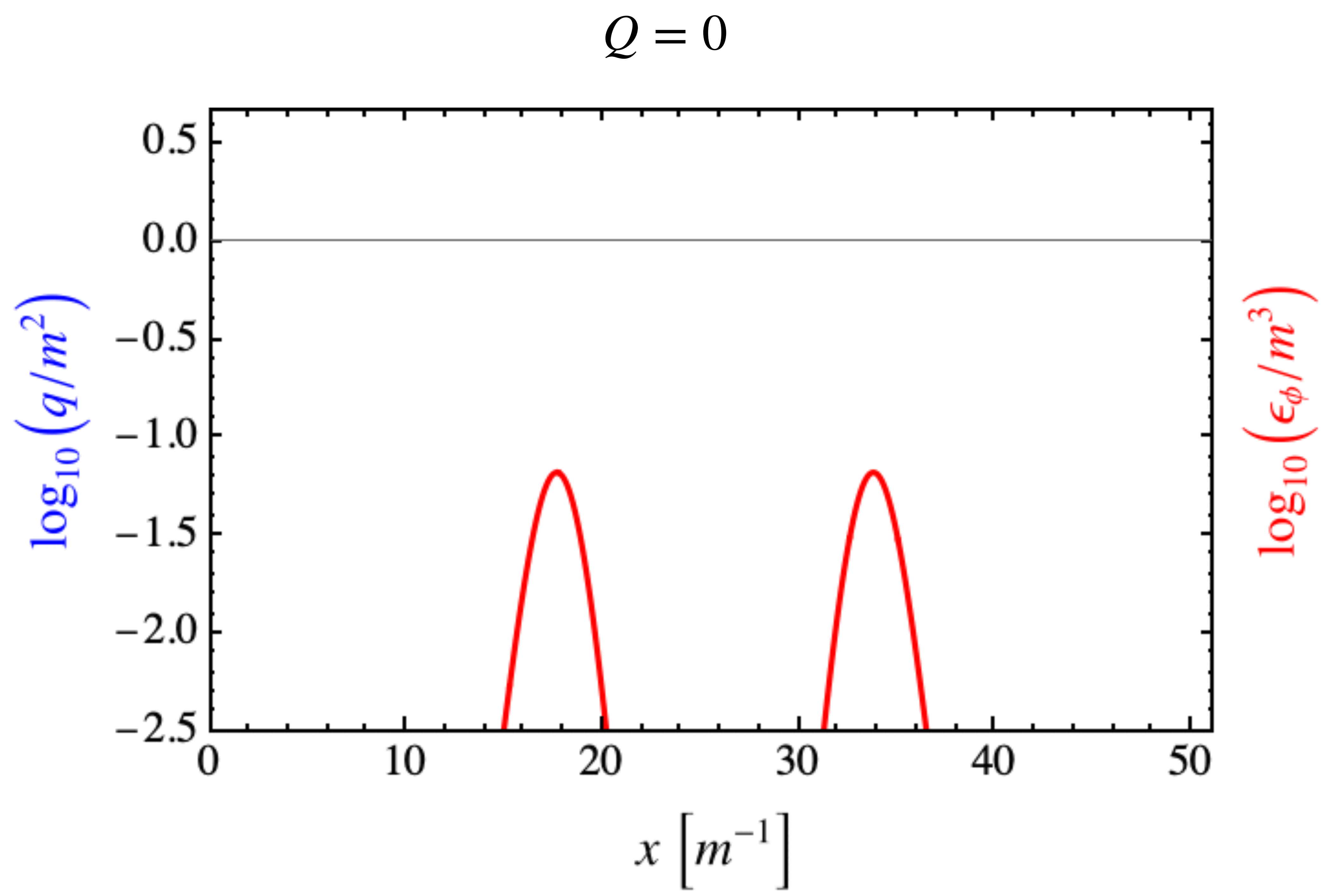
↓

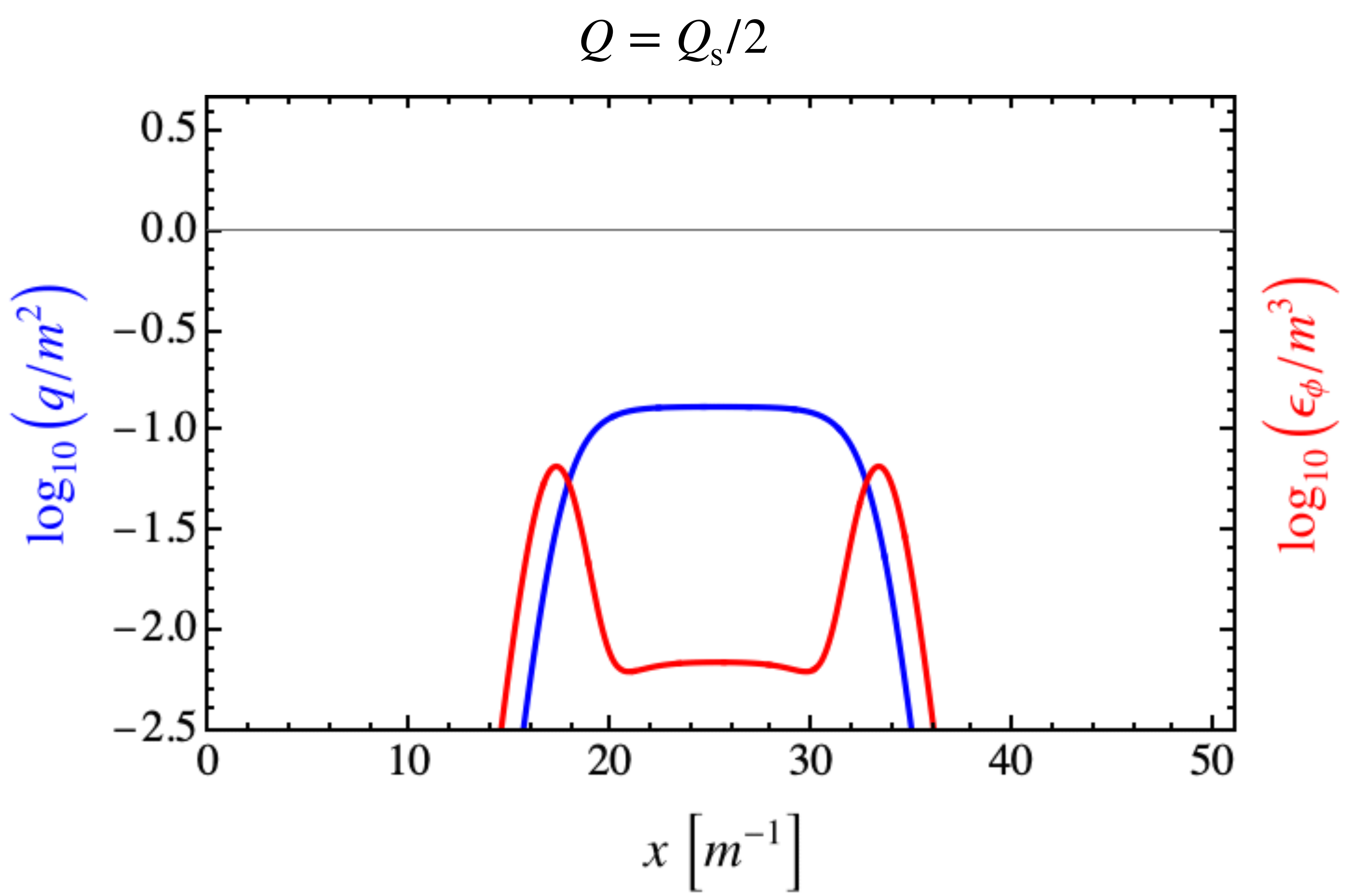
The bubble will evolve towards a stabilized remnant $E_{\text{memory}} \simeq \frac{2}{3} E_{\text{ms}}$


Energy
ϵ_ϕ/m^3
0.3
0.2
0.1
0.
90
80
70
60
50
40
$y\ [m^{-1}]$
$x\ [m^{-1}]$
Charge
q/m^2
0.8
0.6
0.4
0.2
0.
Spectator field, deratively coupled
χ^2/m
0.020
0.015
0.010
0.005
0.
One dimensional slice comparison
$\log_{10} \chi^2/m^2$
$\log_{10}(q/m^2)$
$\log_{10}(\epsilon_\phi/m^3)$
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
0
20
40
60
80
100
120

Dynamics

G. Dvali, J. Bermudez, **MZ,** '24

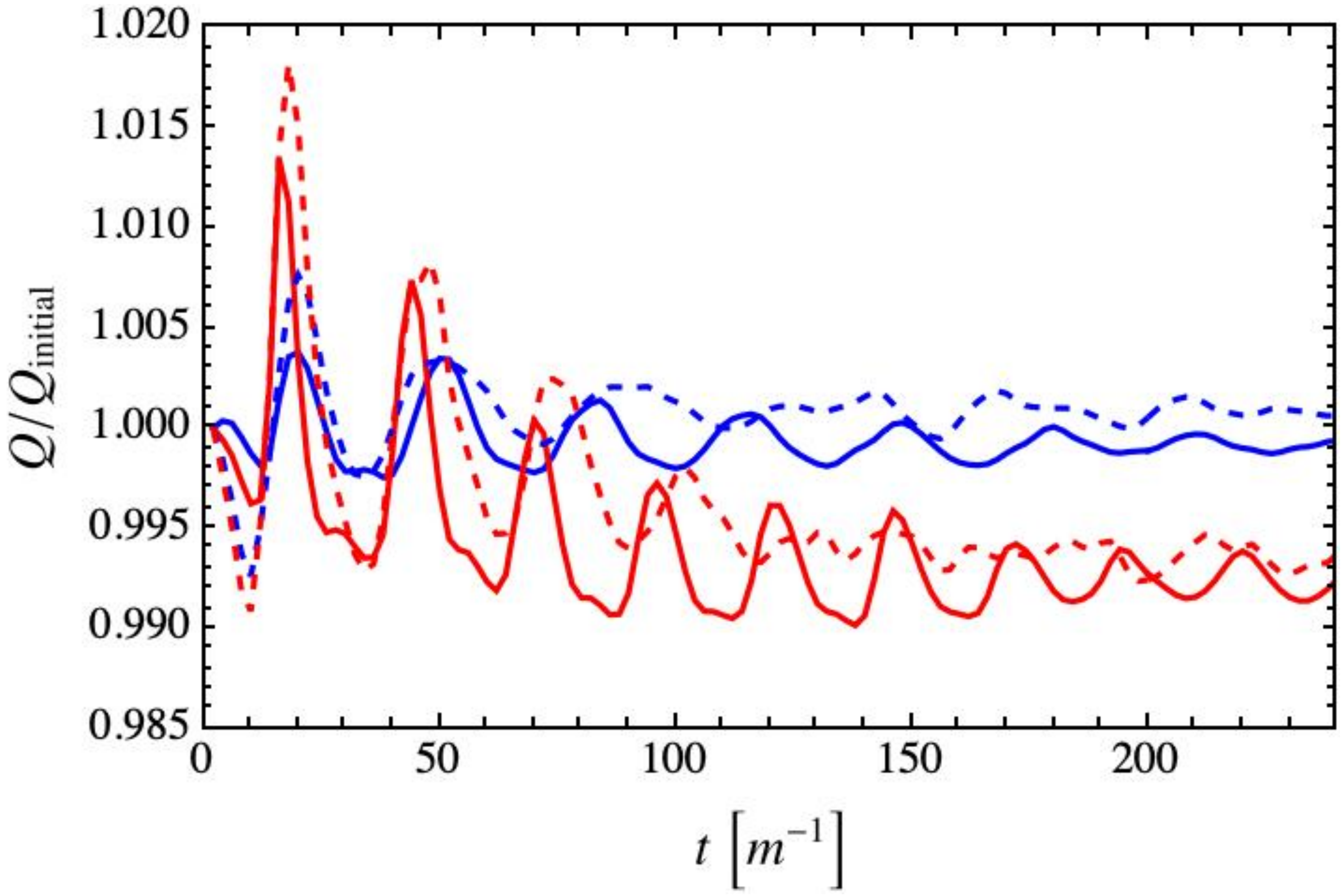


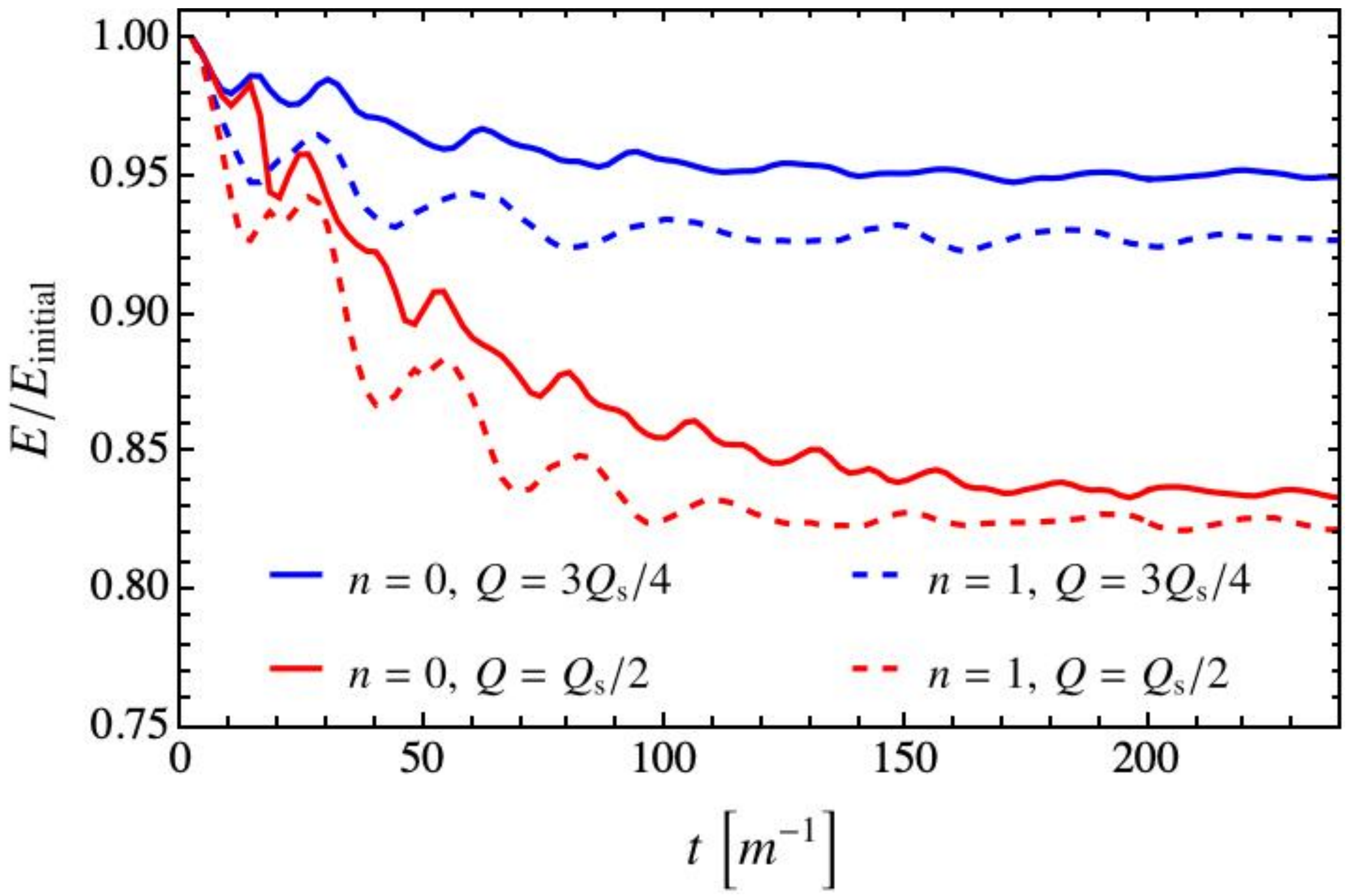


- The bubble without memory (left panel) simply annihilates.
- The bubble with charge (blue) is stabilized (right panel).
- Charge and energy are well-preserved within the bubble - presence of information horizon in the Goldstone flavour space.
- The stabilisation is independent on other details such as vorticity, width of the bubble wall or coupling to new degrees of freedom.

Dynamics

G. Dvali, J. Bermudez, **MZ,** ‘24





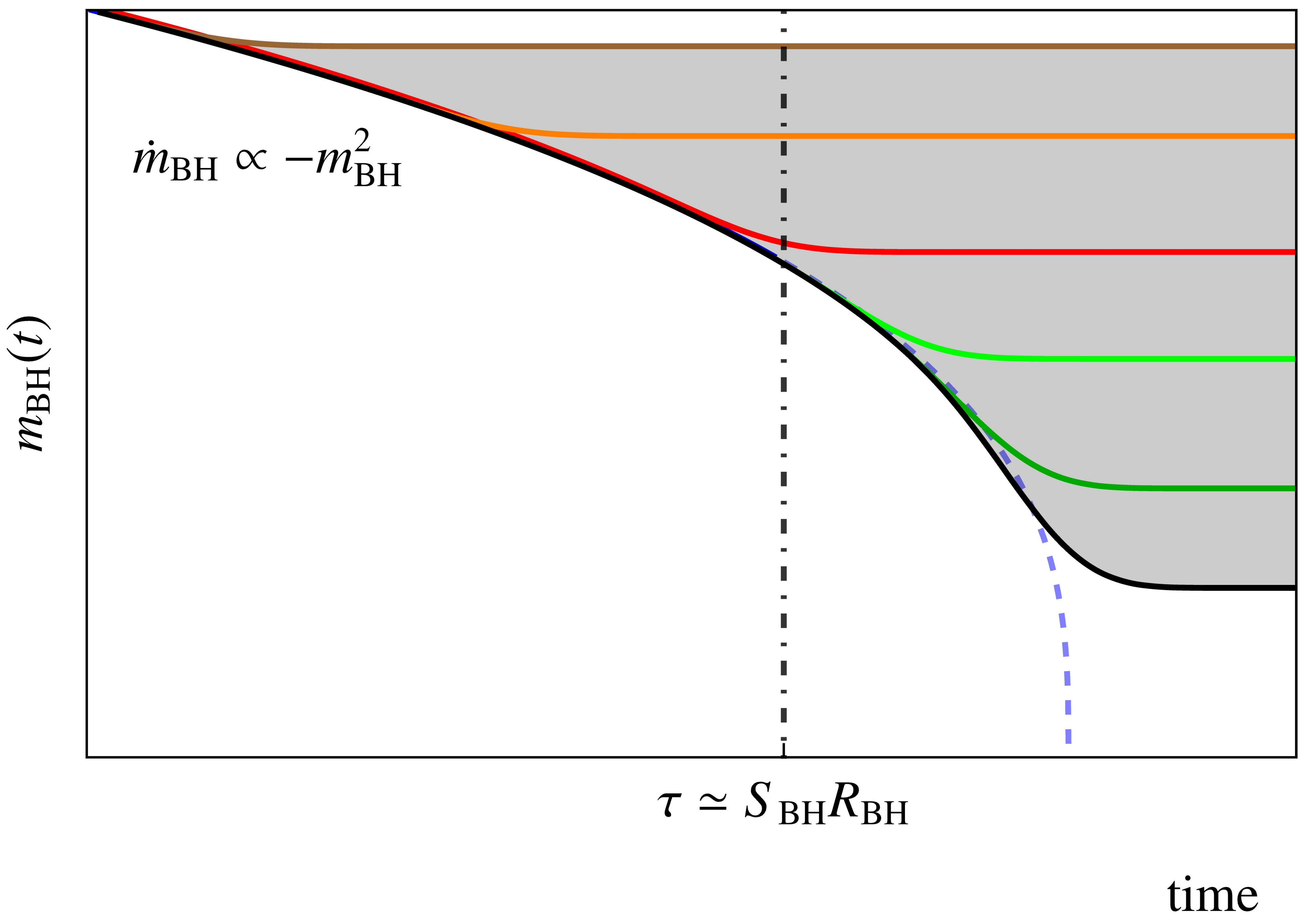
- Charge is conserved within 1%. These configurations are, in fact, highly efficient at storing information
- Presence of information horizon in Goldstone flavour space
- Energy emission, on the other hand, is macroscopic
- Different initial $N_G = Q$ lead to different final energies $\rightarrow$ N_G is order parameter determining asymptotic mass
- Winding $n = 1$ case is more efficient at releasing energy due to the extra gradient energy of the vortex

Implications for black holes

G. Dvali, J. Bermudez, **MZ**, '24

$$|\text{memory}\rangle = |n_1, n_2, \ldots, n_S\rangle \quad \text{With: } \sum_a^S n_a = N_G$$

The asymptotic BH mass is estimated as $$\frac{\Delta M_{BH}}{M_{BH}} \sim \left(\frac{\sqrt{S_{BH}}}{q\, N_G}\right)^{\frac{1}{q-1}}$$



The spread in masses of stabilized remnants is determined statistically

$$\mathscr{P}_{N_G} = 2^{-S} \frac{S!}{(S - N_G)!\, N_G!}$$

Average: $N_G \simeq S/2$
Width: $\sqrt{S}/2$
For $N_G \ll S$, the probability is exponentially suppressed.

Implications for black holes

G. Dvali, J. Bermudez, **MZ,** '24

	Saturon bubble	BH
Master mode	Radial mode $\varphi(r)$	$g_{\mu\nu}$
Memory modes	Charge N_G	?

- The Hamiltonian of the system can be mapped Dvali, Valbuena, **MZ** '24 to the one firstly adopted in Dvali '18 and further studied in Dvali, Eisemann, Michel, Zell '20

- The Hamiltonian also represents an holography model Dvali '18 in which the role of the memory modes is taken upon by the spherical harmonics $Y_{l,m}$ of the graviton field.

Their multiplicity is therefore the needed one

$$N_G \sim l^2 \sim (RM_{\rm Pl})^2 \simeq S_{\rm BH}$$

These modes have a gap of order $M_{\rm Pl}$. However, they are rendered gapless by the black hole background.

Implications for black holes

G. Dvali, J. Bermudez, **MZ,** ‘24

The emission of the coherent state quanta (master) has rate

$$\Gamma = (\alpha_{gr})^2 (N)^2 \omega \simeq \frac{1}{R} \rightarrow \text{recovers Hawking rate}$$

The emission of memory takes place when quanta of similar spherical harmonics interact - but these have $\mathcal{O}(1)$ occupation number (no enhancement!):

$$\Gamma = \alpha_{gr}^2 \omega = \frac{1}{S^2 R} \rightarrow \text{rate suppressed}$$

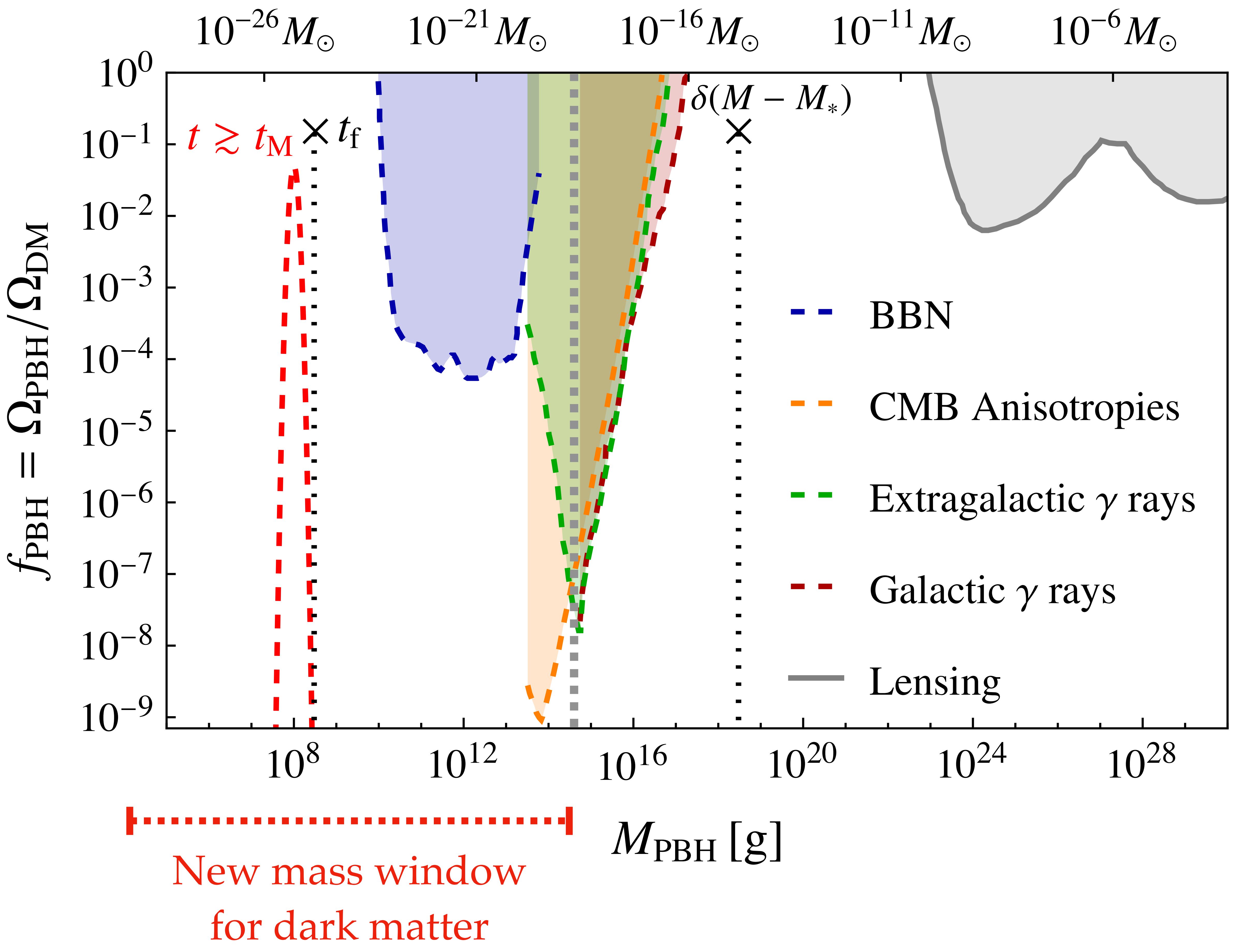
Single emission over timescales of order $t \sim S^{1+k} R$ with $k \geq 1$. Lifetime of black holes is prolonged as

$$\tau \rightarrow \tau_{Page} S^{1+k}$$

New window for PBHs DM opens up for masses $10^3 \text{g} \lesssim M_{PBH} \lesssim 10^{14} \text{g}$ Dvali, Eisemann, Michel, Zell, ’20

Implications for black holes

G. Dvali, J. Bermudez, **MZ**, ‘24



- Any initial distribution in such region will observe a natural spread on timescales longer than the memory burden back reaction time t_M. A cartoon version is showed in the figure.

- Constraints exist below 10^5 g Alexandre, Dvali, Koutsangelas, '24; Thoss, Burkert, Kohri ’24; Chianese, Boccia, Iocco, Miele, Saviano ’24 which depend on the modeling of the evaporation during quantum phase - relaxed for $k > 1$.

- Constraints between 10^{9-17} grams are similar to the ones derived assuming a fully evaporating scenario Carr, Kohri, Sendouda, Yokoyama ’20. These are also relaxed if the memory burden sets in at earlier time than half-mass evaporation.

Burdened black holes as dark matter are high-energy astrophysical particle factories

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Consequences for black holes as dark matter

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- Burdened black holes in the form of dark matter undergo mergers
- These new objects are young black holes, with a new memory statistically obeying the probability

$$\mathscr{P}_{N_G} = 2^{-S}\frac{S!}{(S-N_G)!N_G!}$$

- This statement is further supported by studies of mergers of saturated solitons
  G. Dvali, J. Bermudez, **MZ,** '24 + Dvali, **MZ** in progress

Therefore, they will emit again for a period of time τ_{sc}, to then be stabilised once more by the burden effect

Consequences for black holes as dark matter

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For a Poisson distribution at formation, the leading merger rate is given by PBH binaries that decouple from the Hubble flow before matter-radiation equality - see Y. Ali-Haïmoud, E. D. Kovetz, and M. Kamionkowski '17; M. Raidal, C. Spethmann, V. Vaskonen, and H. Veermäe '19

$$R_{\mathrm{PBH}}(t) = \frac{0.03}{\mathrm{kpc}^3\,\mathrm{yr}}\, f_{\mathrm{PBH}}^{\frac{53}{37}} \left(\frac{t_0}{t}\right)^{\frac{34}{37}} \left(\frac{m_{\mathrm{PBH}}}{10^{-12} M_\odot}\right)^{-\frac{32}{37}} S$$

where S is a suppression factor $S = S_1 \times S_2$

S_1 includes interactions with DM inhomogeneities and neighboring PBHs near the formation epoch G. Hütsi, M. Raidal, V. Vaskonen, and H. Veermäe '21.

S_2 includes the effect of successive disruption of binaries that populate PBH clusters formed from the initial Poisson inhomogeneities V. Vaskonen, and H. Veermäe '19 + numerical D. Inman and Y. Ali-Haïmoud '19. See also remarks on applicability in G. Franciolini, A. Maharana, F. Muia '19

Consequences for black holes as dark matter

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Local galactic DM enhancement boost the merger rate as O. Pujolas, V. Vaskonen, and H. Veermäe '21

$$R_{\rm local} = R_{\rm PBH}\,\delta(r) \qquad \text{where } \delta(r) = \rho(r)/\bar{\rho}_{\rm DM}$$

From this, we can compute the galactic and extragalactic flux, respectively as

$$\left.\frac{\mathrm{d}\Phi_i}{\mathrm{d}E}\right|_{\rm gal} \simeq \frac{\tau_{\rm sc}}{4\pi}\int_{s,\theta} R_{\rm PBH}\,\delta(r(s,\theta))\,\frac{\mathrm{d}^2N_i(E)}{\mathrm{d}E\,\mathrm{d}t}\,, \qquad \left.\frac{\mathrm{d}\Phi_i}{\mathrm{d}E}\right|_{\rm eg} \simeq \frac{\tau_{\rm sc}}{4\pi}\int_0^{z_f}\mathrm{d}z\left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| R_{\rm PBH}(t(z))\frac{\mathrm{d}^2N_i(E(z))}{\mathrm{d}E\,\mathrm{d}t}\,.$$

Notice that for masses between 10^{3-10} g, the emission temperature is given by $T \sim \dfrac{1}{R_{\rm PBH}} \sim 10^{4-11}$ GeV

$\dfrac{\mathrm{d}^2N_i(E)}{\mathrm{d}E\,\mathrm{d}t}$ is computed with BlackHawk code 2.2 Arbey and J. Auffinger '19 which provides the secondary spectrum with HDM option Bauer, Rodd, Webber '20. For energies too far from the primary peak ($E \ll 10^{-3}\,T$), the spectrum is not reliable and we therefore drop its contribution.

Consequences for black holes as dark matter

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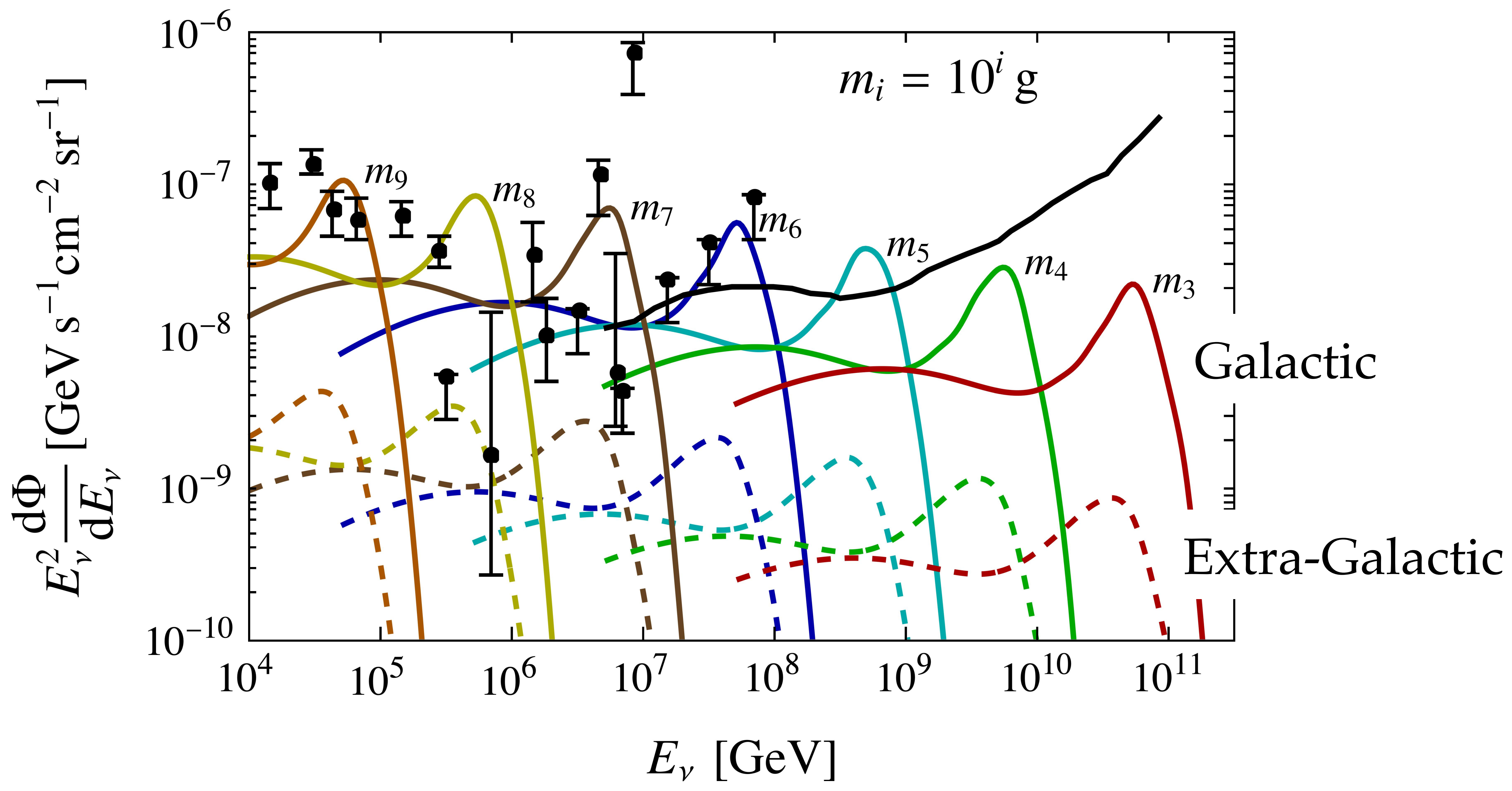
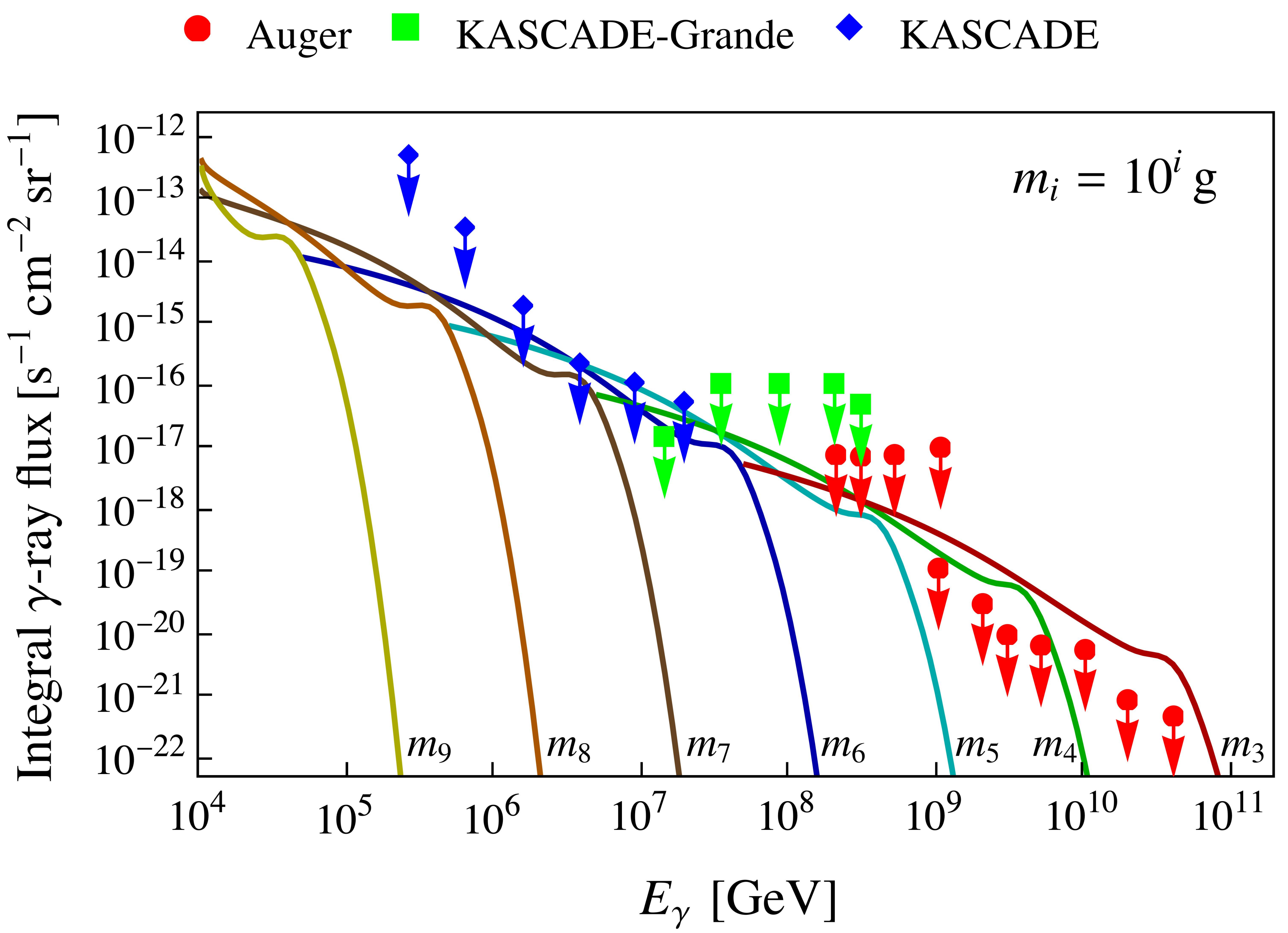
Assumption: Memory burden sets in the latest, i.e., at half-mass evaporation time $\tau_{sc} = \tau_{Page}$.

Spectrum assuming monochromatic distribution of dark matter

Comparison with IceCube neutrino data and bounds



Galactic gamma-ray



Consequences for black holes as dark matter

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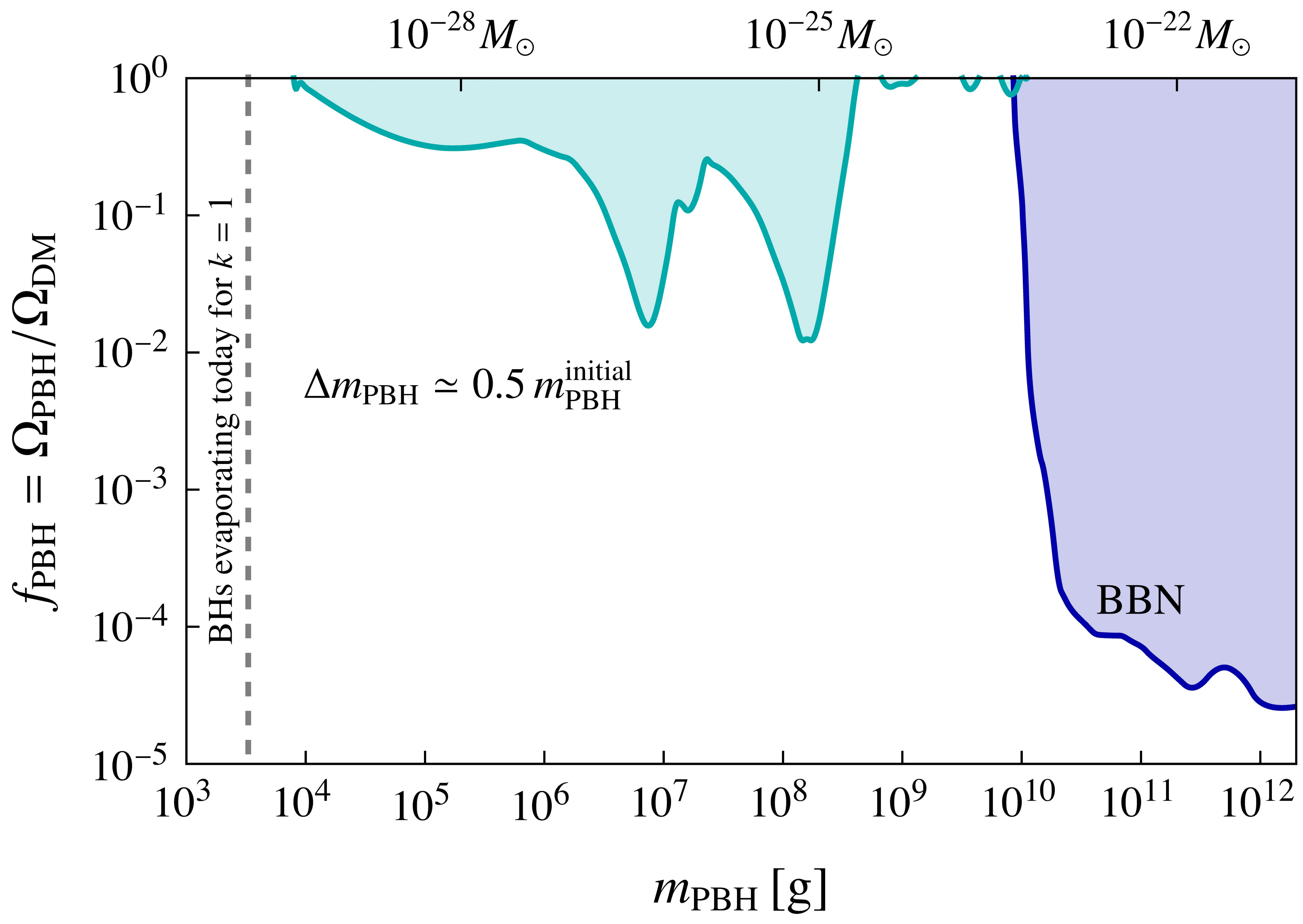

There is a tension (Cyan area) between IceCube data and the scenario of burdened black holes as dark matter.

These results are independent of the modeling of the memory burdened phase. It relies on the semiclassical picture applied in the realm of its validity.

Summary

- The memory stored in a configuration stops its decay
- This is especially relevant for localized configuration with a large capacity to store information, such as objects with an entropy area-law
- I constructed such an object within a renormalizable field theory. The soliton has properties akin to the essential ones of a BH.
- It is further stabilized the the memory burden effect, suggesting the universality of the properties of this class of objects
- The stabilization takes place, the latest, around half-mass decay, implying that ultralight BHs could be viable dark matter candidates
- I discussed some of the phenomenological consequences of this scenario: these objects undergo mergers in today's Universe resuming their evaporation and leading to peculiar signatures

Thank you