On the fate of evaporating black holes: how the burden of their memory stabilizes them

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Motivation

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

- Phenomenological consequence → new ultralight-mass window for dark matter $M_{\mathrm{BH}} \lesssim 10^{15}$ g Dvali '18, + Eisemann, Michel, Zell '20 and more recently Dvali, Valbuena, **MZ** '24

- 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*. Black holes are a prominent example. But it can be found also in renormalizable field theory, e.g., in solitons Dvali, Valbuena, **MZ** '24

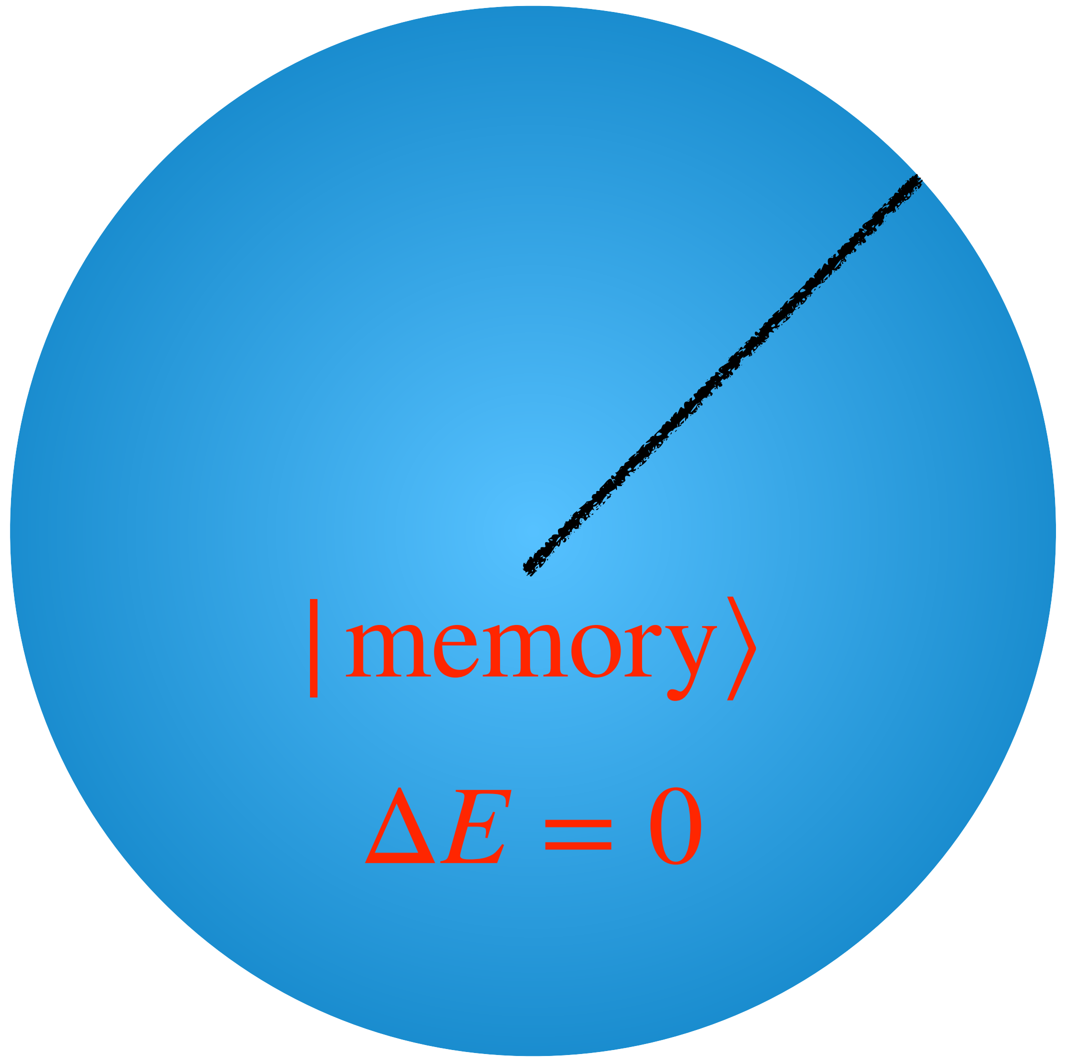
- Production of high-energy astrophysical particles Visinelli, **MZ** '24, Dvali, **MZ**, Zell '25

Evaporating black holes

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

$R_{\rm BH} = 2G_{\rm N}M_{\rm BH}$

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



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

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

These degrees of freedom have no cost in energy on the black holes support

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

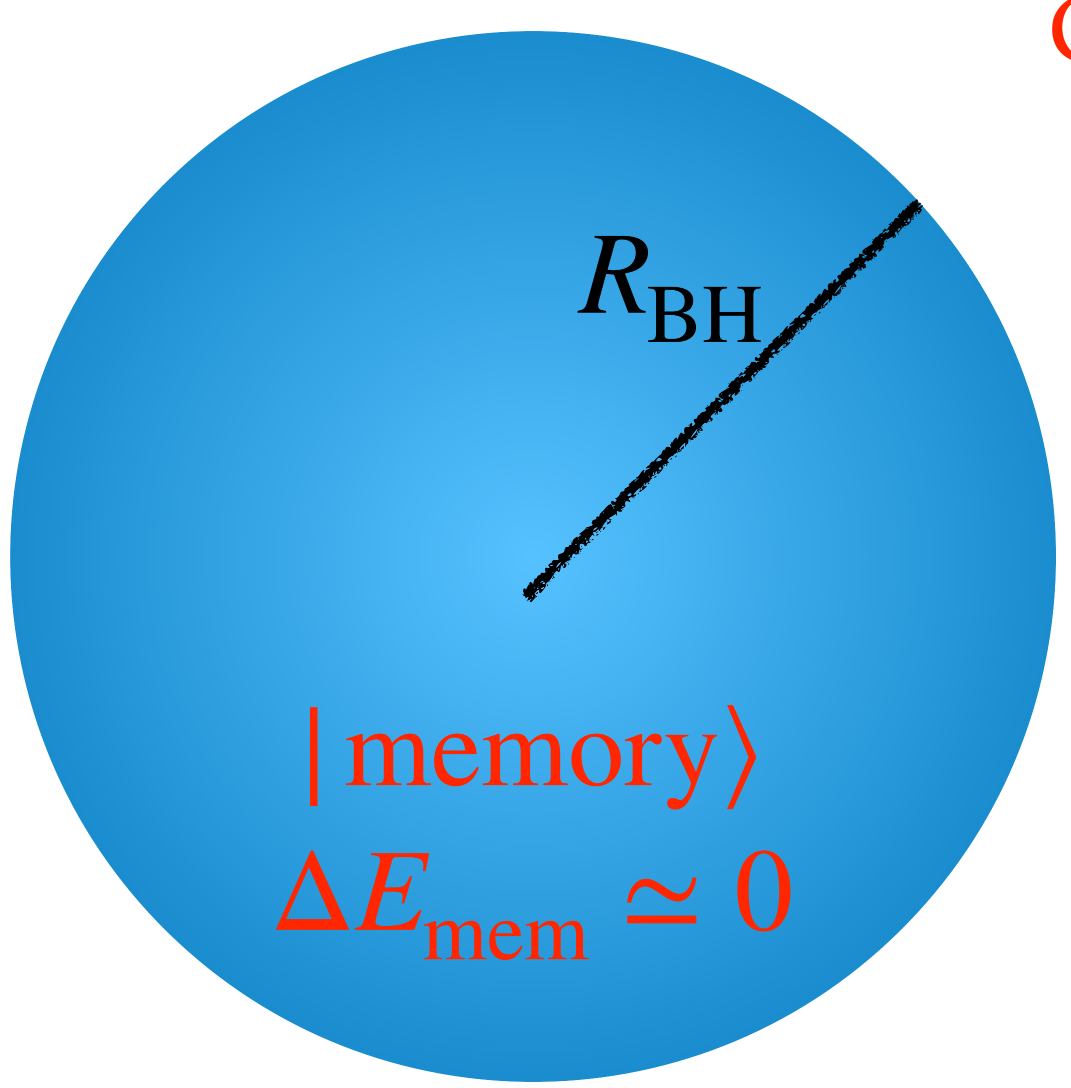
$S = \log n_{\rm st} \simeq N$

What is origin of this S-dimensional “flavor” space?

Entropy and memory

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

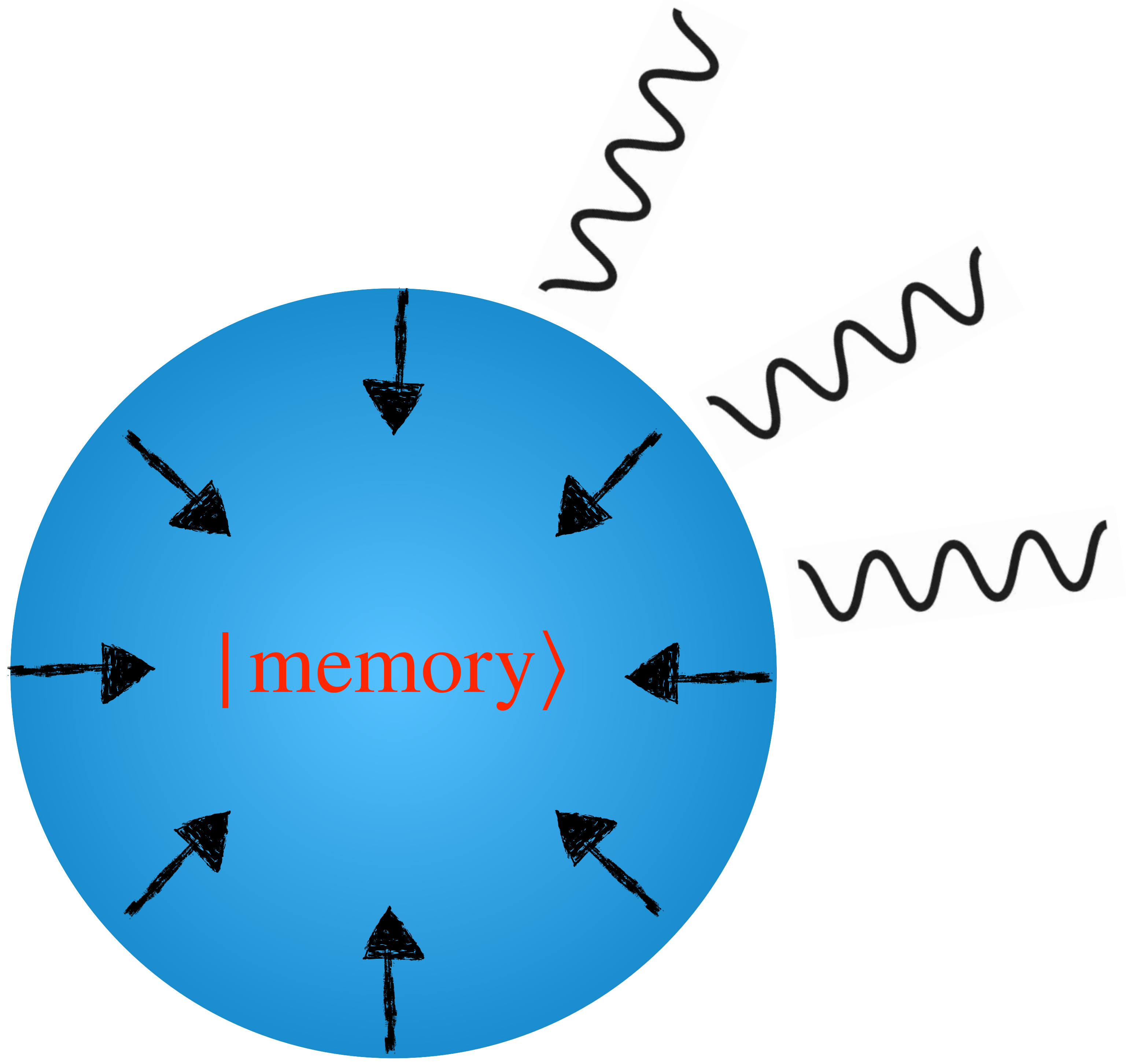
Gapless memory modes (Goldstones) localized inside



The modes outside are highly gapped. $\Delta E_{\mathrm{mem}} \neq 0$
Due to this, information stored in memory modes cannot escape for a long time.

- ''Flavour'' space of Goldstones $|\,n_1, \ldots, n_{\mathrm{N}}\rangle$ can give large entropy
- Maximal entropy is bounded by **unitarity** $S \leq \mathrm{Area}\, f^2$, with f being the Goldstone decay constant Dvali '21
- The localization of gapless modes can be characterized by a critical exponent p

Evaporating black holes



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

Full evaporation requires
$\tau_{\rm SC} \simeq R_{\rm BH}\, S$

$M_{\rm BH} \lesssim 10^{15}\,\mathrm{g} \implies \tau \lesssim \mathrm{t}_0$
Not a viable dark matter?

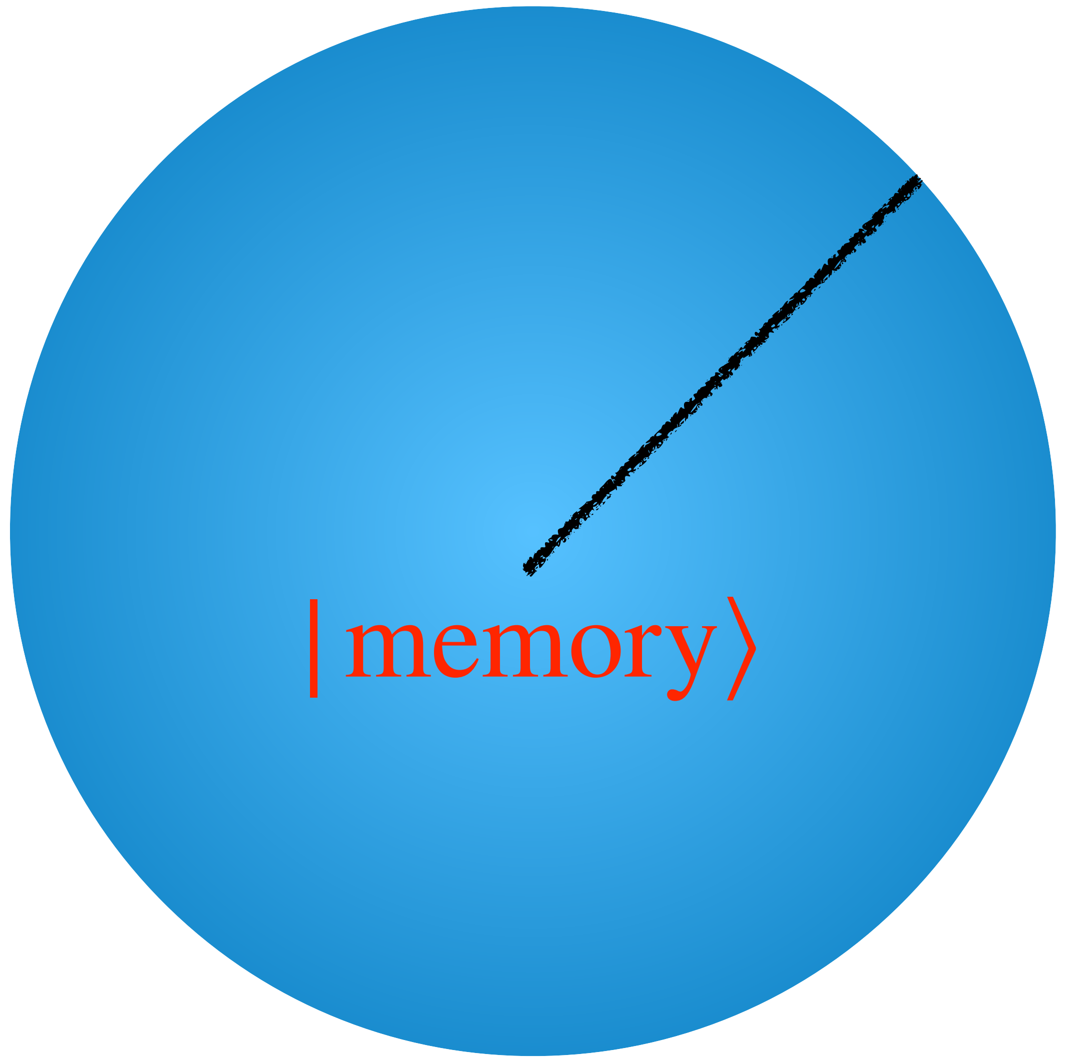
Thermal emission is not sensible to $|\,\mathrm{memory}\rangle$
Hawking rate is computed in semiclassical limit, ignoring backreaction on geometry

Prototype Hamiltonian

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

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

$R_{\text{BH}} = 2G_{\text{N}}M_{\text{BH}}$



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

Consider the state $|\,\text{memory}\rangle = |\,m\rangle = |\,n_1, \ldots, n_S\rangle$

Without background master mode: $\langle \text{m}\,|\,\hat{H}\,|\,\text{m}\rangle_{|n_\phi=0} = \sum_j^S m_j n_j \simeq M_{\text{Pl}}\, S/2\,,$

With background master mode: $\langle \text{m}\,|\,\hat{H}\,|\,\text{m}\rangle_{|n_\phi=S} = m_\phi\, S = \dfrac{1}{R_{\text{BH}}} S = M_{\text{BH}}$

Prototype Hamiltonian

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

$$\hat{H} = \underbrace{m_\phi \hat{n}_\phi}_{E_{\mathrm{ms}}} + \underbrace{\left(1 - \frac{\hat{n}_\phi}{S}\right)^p \sum_{j=1}^{S} m_j \hat{n}_j}_{E_{\mathrm{memory}}} + \ldots$$

Initial state for black hole requires no energy from memory $\rightarrow \langle n_\phi \rangle = S$:

As n_ϕ decreases (Hawking emission), memory modes become energetic.

Dynamical stabilization at $E_{\mathrm{ms}} \simeq \frac{1}{p} E_{\mathrm{memory}}$: $q = \frac{\Delta M_{\mathrm{BH}}}{M_{\mathrm{BH}}} \simeq \left(\frac{2}{p\sqrt{S}}\right)^{\frac{1}{p-1}}$

$$\longrightarrow q = \frac{\Delta M_{\mathrm{BH}}}{M_{\mathrm{BH}}} \overset{(p \gg 1)}{\lesssim} 1/2 \text{ gives } \tau_{\mathrm{MB}} \lesssim \tau_{\mathrm{SC}} = S\, R_{\mathrm{BH}}$$

$$\longrightarrow q = \frac{\Delta M_{\mathrm{BH}}}{M_{\mathrm{BH}}} \overset{(p=2)}{\simeq} S^{-1/2} \text{ gives } \tau_{\mathrm{MB}} = \sqrt{S}\, R_{\mathrm{BH}} \ll \tau_{\mathrm{SC}}$$

Memory burden: towards pheno

1) Backreaction stabilizes the BH, the latest, around half-mass semiclassical evaporation time i.e.

$$\frac{1}{\sqrt{S}} \lesssim q \doteq \frac{\Delta M_{\mathrm{BH}}}{M_{\mathrm{BH}}} \lesssim \frac{1}{2}\,, \qquad \tau_{\mathrm{MB}} = q\,\tau_{\mathrm{SC}}$$

2) In the memory burden phase, there is still (suppressed) emission with release of memory modes leading to lifetime

$$\tau = S^{1+k} R_{\mathrm{BH}} \quad (\alpha_{\mathrm{gr}} = S^{-1})$$

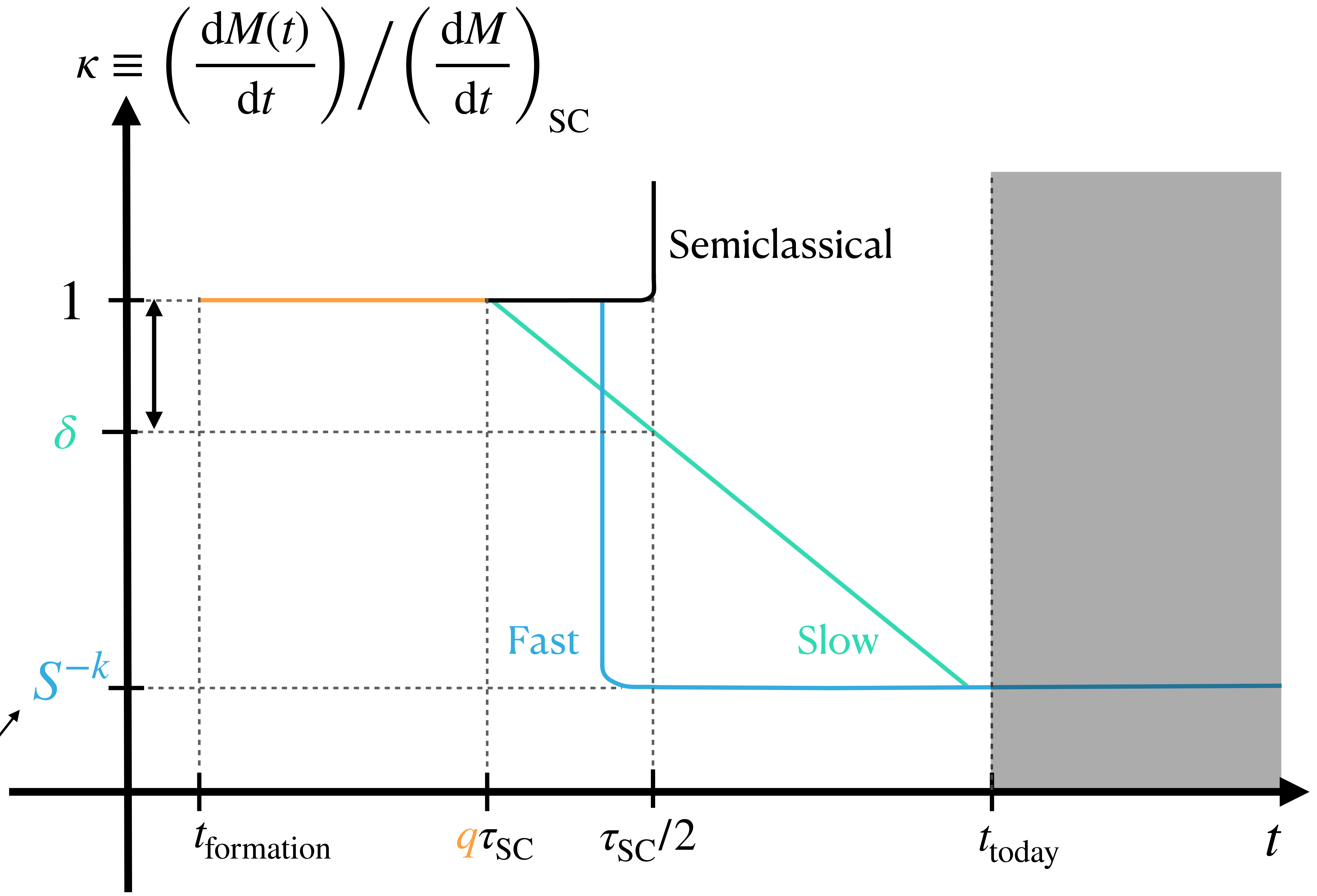
Correspondingly, PBHs heavier than 10^4 g are sufficiently long lived to be dark matter ($k = 2$)

There is a large parameter space in q and k, some of which is constrained

3) The transition of memory burden is not instantaneous, it is characterized by width δ Dvali, **MZ**, Zell, '25

On the width of the transition

[Dvali, **MZ**, Zell, '25]

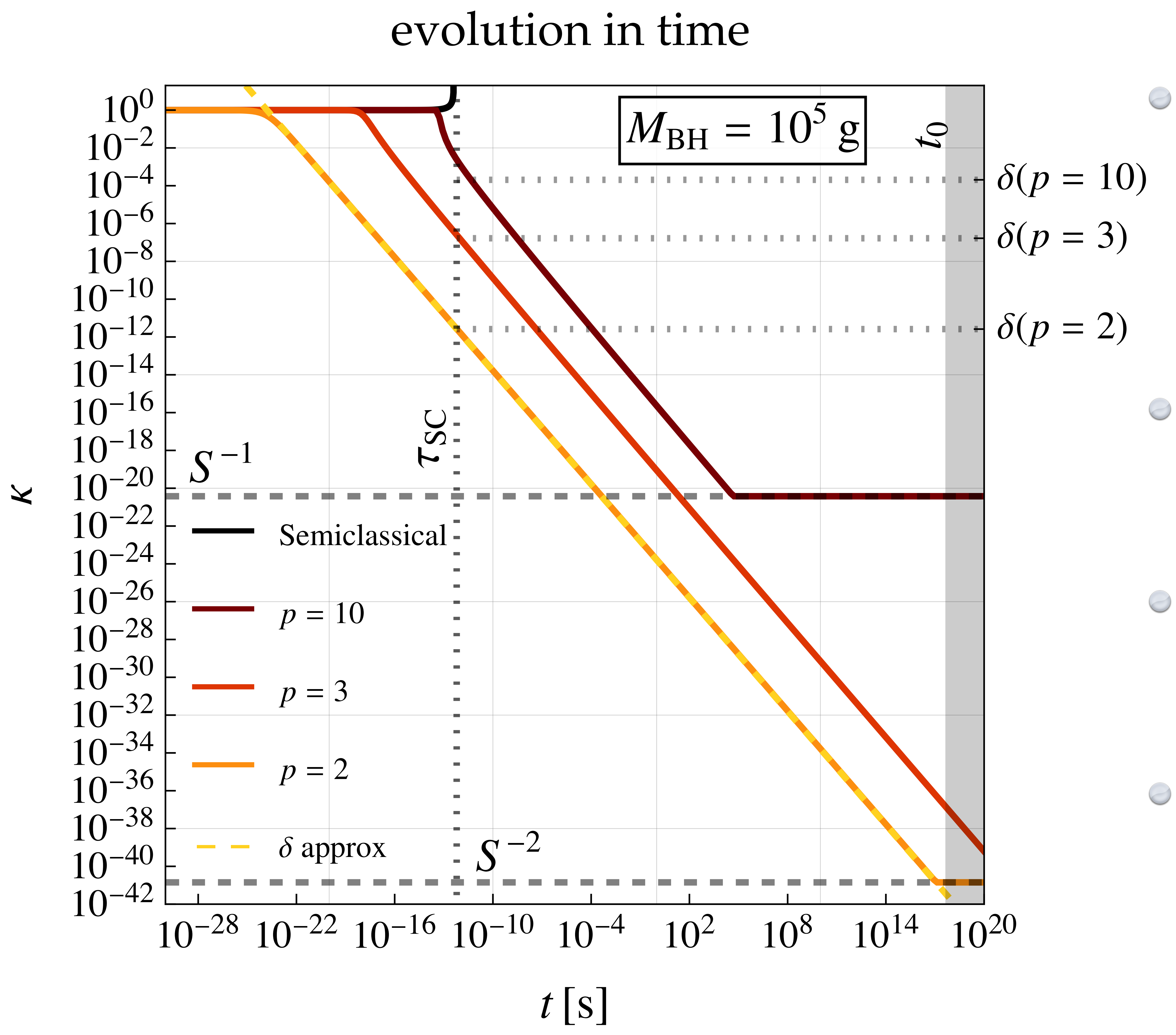


Phase that is constrained in the literature

[Thoss et al '24, Alexandre et al '24, Boccia et al '24, Chianese et al '25,Liu et al '25, Than, Zhou '25,…]

Consequences for black holes as dark matter

Dvali, **MZ**, Zell '25



- $\kappa \doteq \frac{dM}{dt} \Big/ \left(\frac{dM}{dt}\right)_{SC} \simeq -\frac{\delta\, \tau_{SC}}{2t}, \qquad t \gtrsim \tau_{SC},$ where

  $\delta \simeq \frac{2}{(p-1)\ln(S)} S^{\frac{1}{2-2p}}$

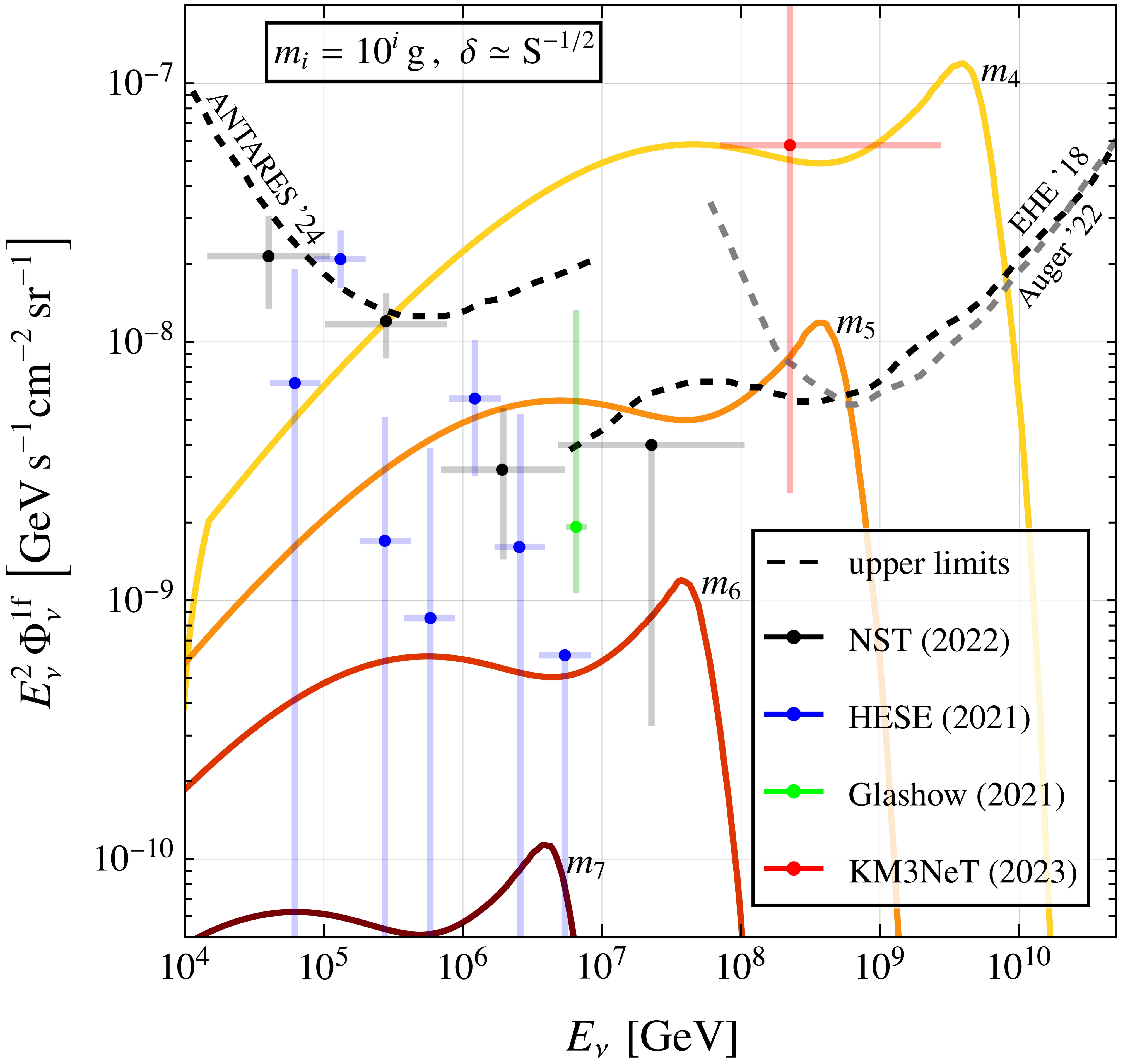
- The energy injected by evaporating PBHs is proportional to dM/dt and therefore to κ

- The full memory burden phase is realized when $\kappa \simeq S^{-k}$

- PBHs are still transitioning today, leading to astrophysical fluxes of high energy neutrinos and photons

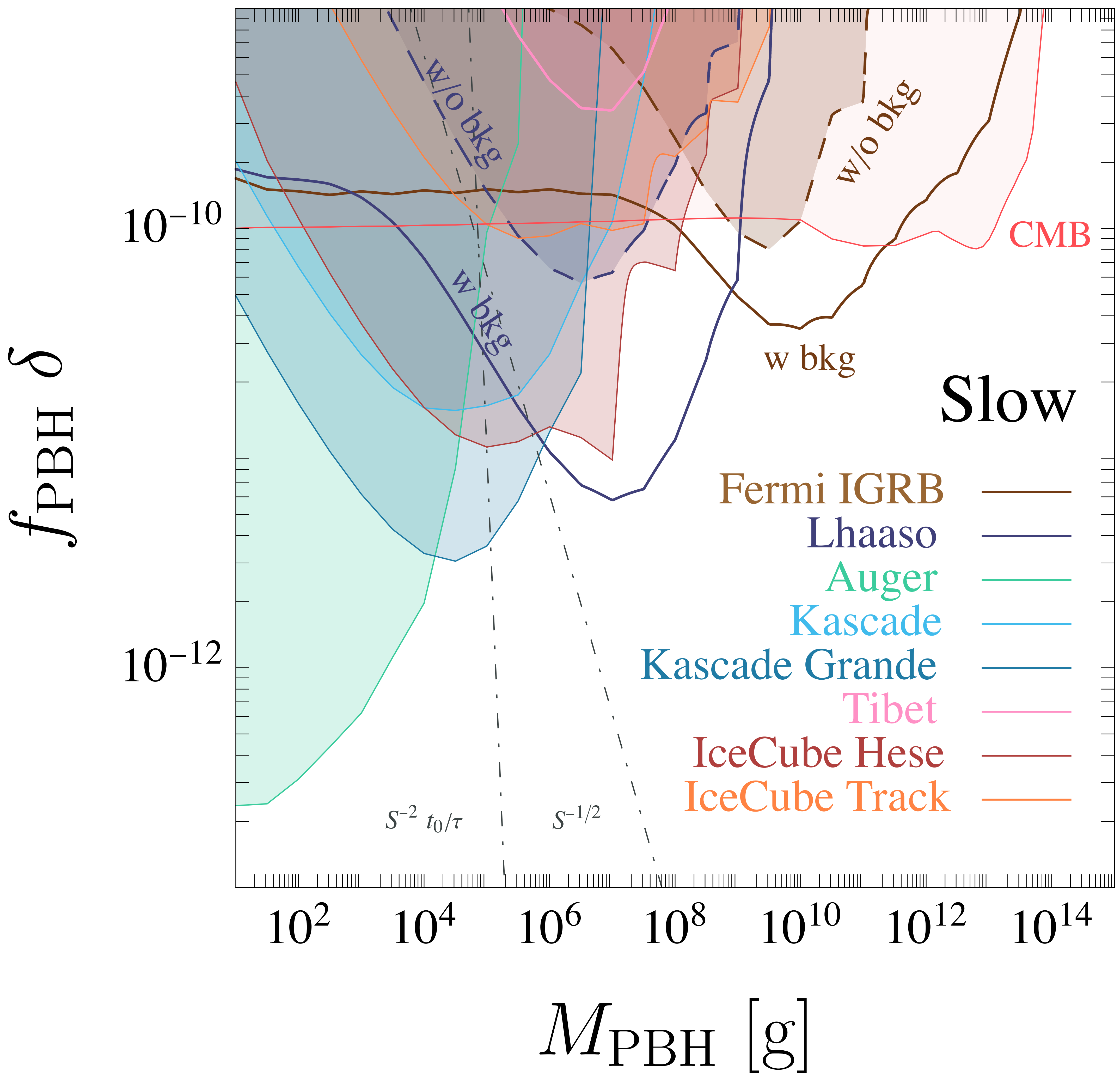
Consequences for black holes as dark matter

All flavour neutrino flux from PBHs transitioning to the memory burden phase [Dvali, **MZ**, Zell, ’25]



Consequences for black holes as dark matter

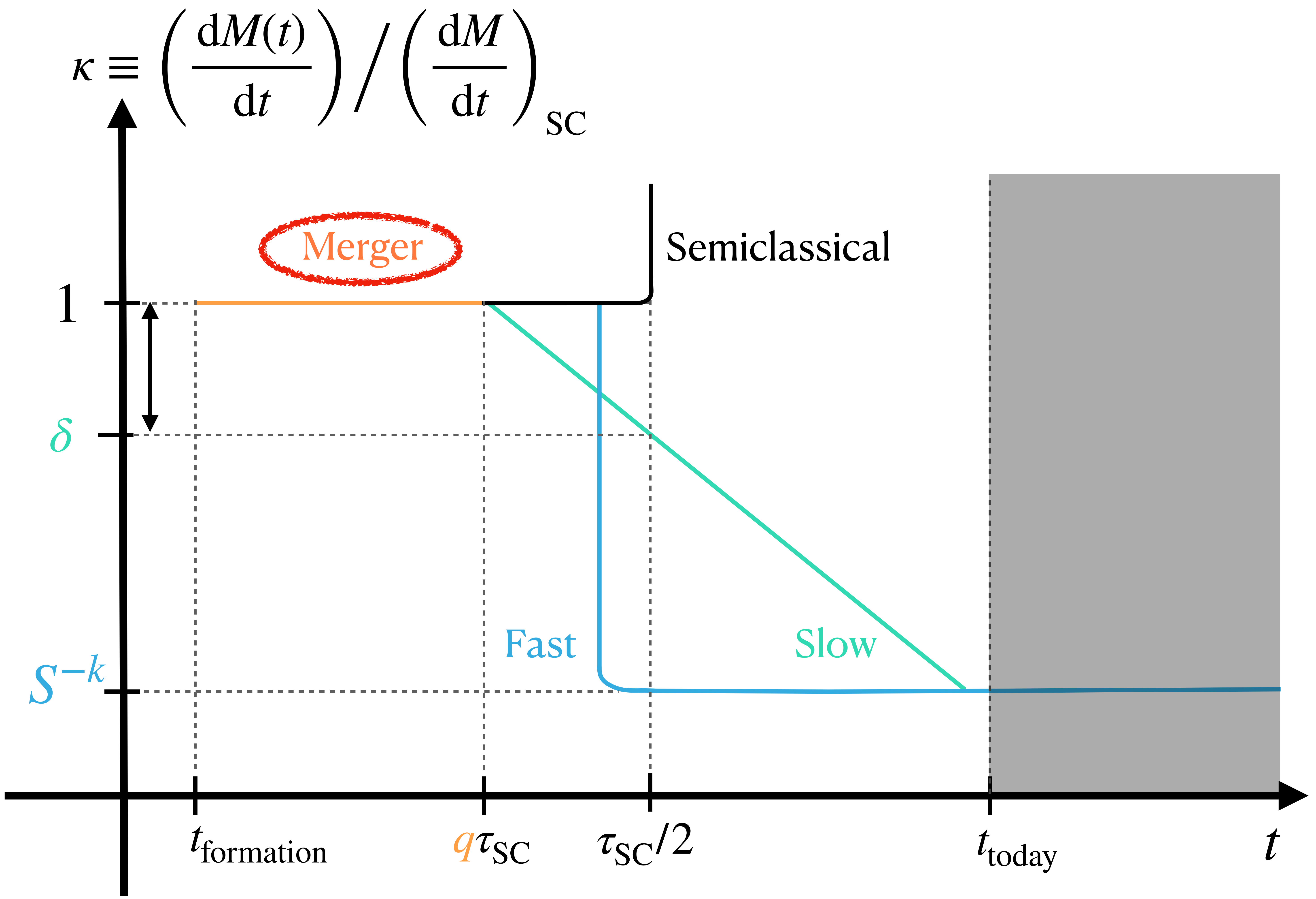
Bounds are derived for the combination $f_{\rm PBH}\,\delta$ [to appear Dondarini, Marino, Panci, **MZ**]



- Bound gives $f_{\rm PBH}\,\delta \lesssim 10^{-11}$ below 10^{10} g
- CMB leads to flat constraints on δ (compatible with Montefalcone et al '25)
- For $\delta \lesssim S^{-1/2}$ ($p = 2$), PBHs heavier than 10^6 g can be the dark matter

Signal independent of the quantum phase? the case of merging memory-burdened PBHs

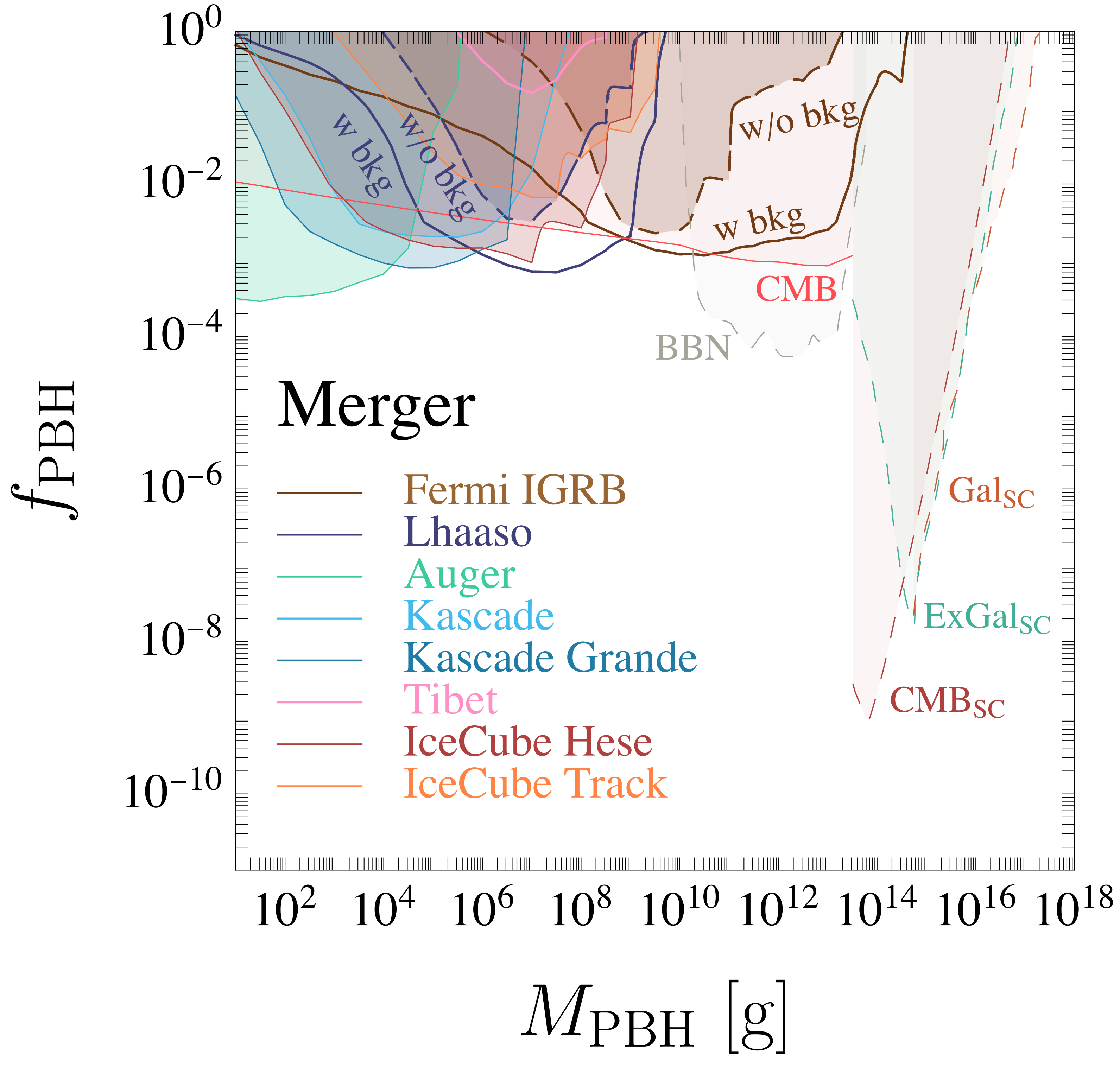
Visinelli, **MZ** '24

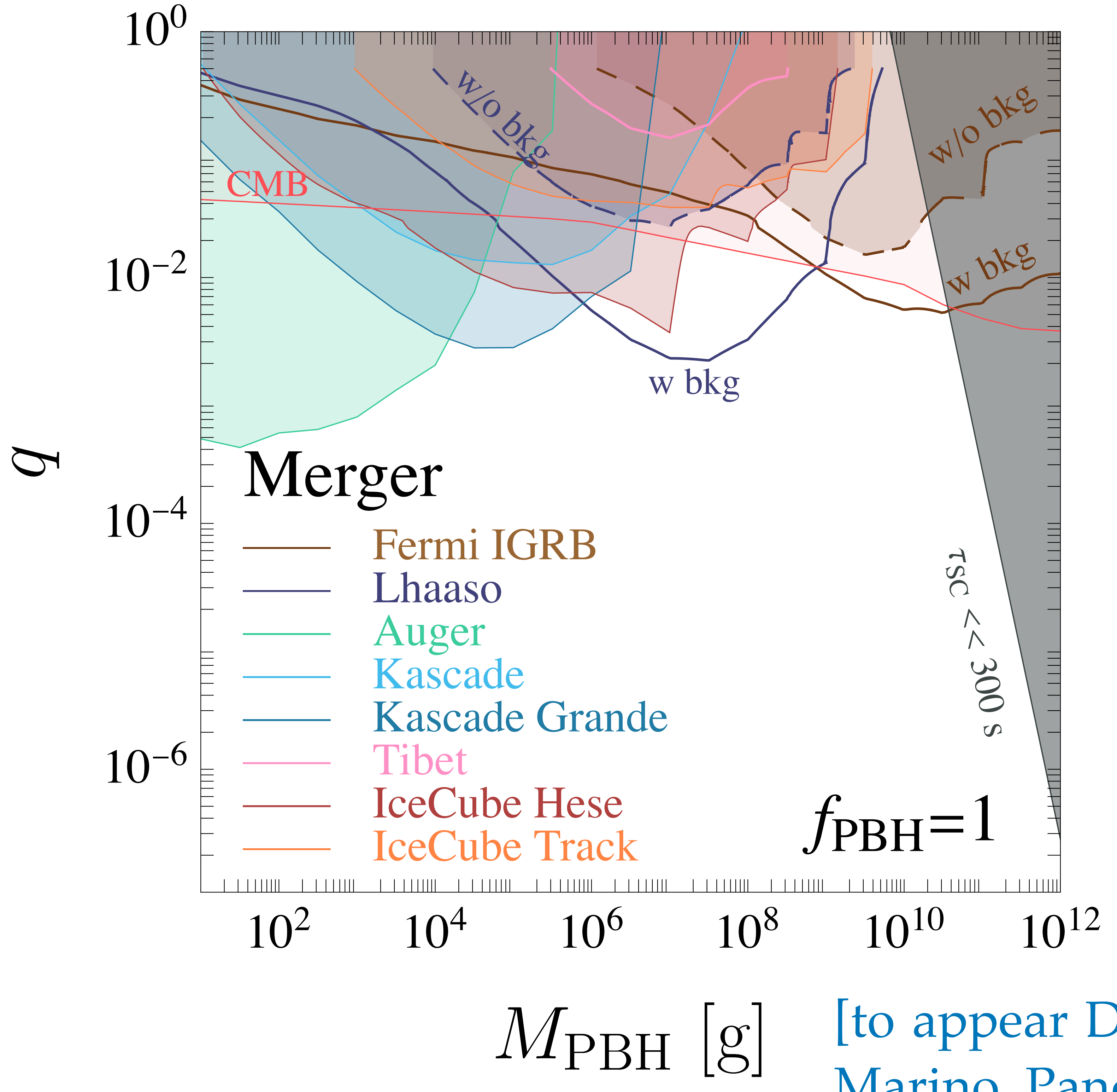


Consequences for black holes as dark matter

$$\frac{\mathrm{d}E}{\mathrm{dVol}\,\mathrm{d}t} \propto R_{\rm PBH}(f_{\rm PBH}, M_{\rm BH})\, q$$ [Visinelli, **MZ** '24]

$$q \equiv \frac{\Delta M_{\rm BH}}{M_{\rm BH}} = \frac{1}{2}$$





[to appear Dondarini, Marino, Panci, **MZ**]

- $q \lesssim 10^{-2}$ allows for dark matter for masses below 10^{11} g
- Constraints do not rely on the quantum evaporation phase

Conclusion

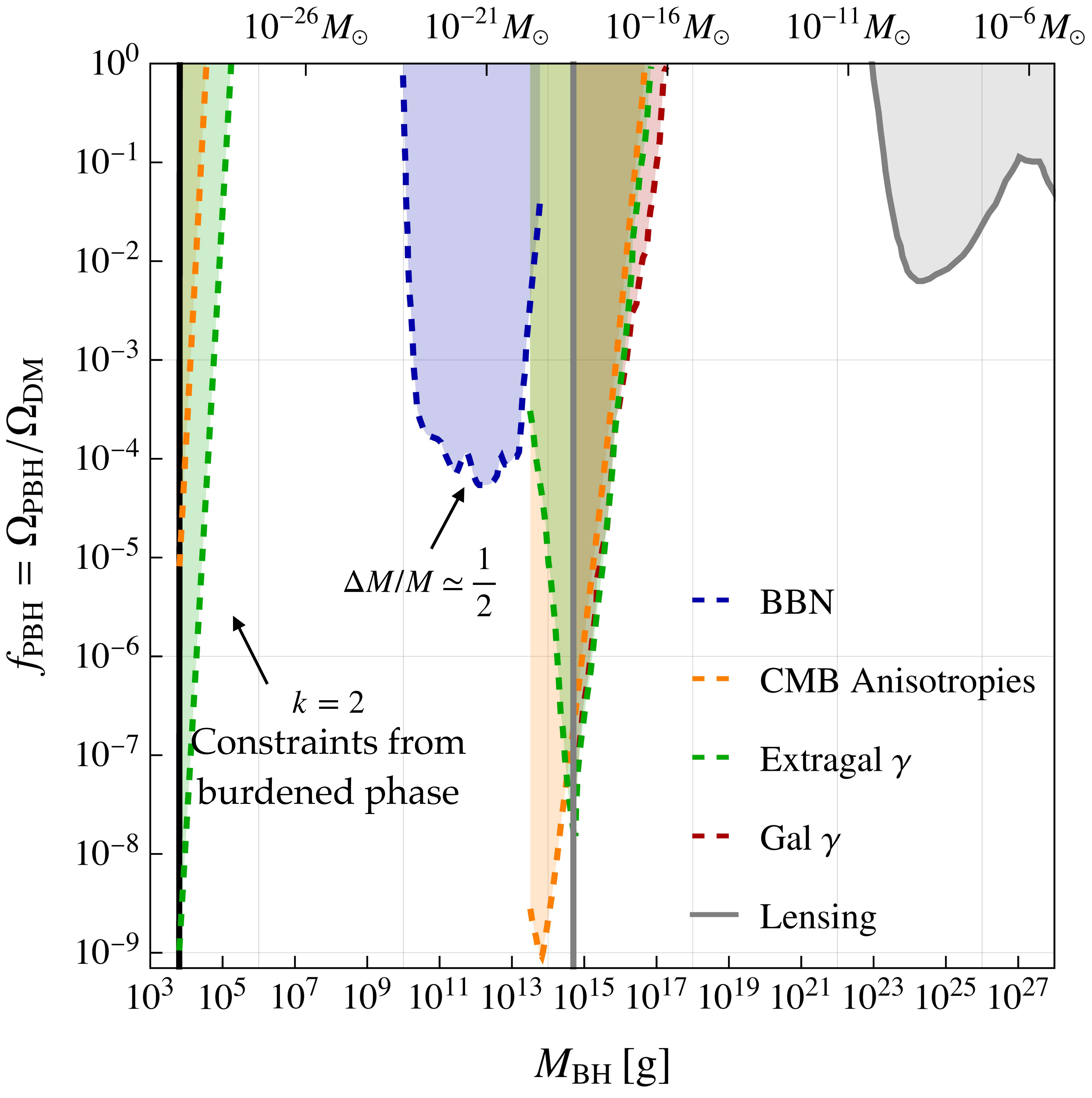
- Memory burden indicates that evaporating BHs are stabilized by quantum backreaction
- This has the consequence of opening a new mass-window for ultralight PBHs as viable dark matter candidates
- These objects - as the memory burden kicks in - keep ''leaking'' quanta with a suppressed rate. Therefore, high-energetic particles whose fluxes are comparable to present-day observations are possible - either in the fully stabilized phase or while transitioning to it
- A possibility is that they undergo mergers in today's Universe, leading to ''young'' black holes re-emitting with semiclassical, unsuppressed rate.
- The prompt emission is known → multi-messenger analysis, cosmological tracking of the signal…

Thank you

Backup

Existing constraints

Primordial black hole as a dark matter candidate Zel'dovich, Novikov '67; Hawking '71; Carr, Hawking '74



Resulting constraints from Thoss, Burkert, Kohri '24

Already for large values of $\Delta M/M$, and $k = 2$ there is a large viable dark matter window between $10^5 - 10^{10}$ g

For large enough $k \gtrsim 3$, no constraints follow from the quantum evaporation phase

If $\Delta M/M \ll 1$ also the bounds starting at 10^{10} g are lifted

All existing works assumed, so far, a sharp transition to the memory burden phase

Consequences for black holes as dark matter

The transition to memory burden phase is not sharp. It might lead to PBHs that are still transitioning from the memory burden to the semiclassical phase today (Dvali, **MZ**, Zell, '25)

Semiclassically, a PBH looses mass due to Hawking radiation as

$$\left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{\mathrm{SC}} \simeq -\left(\frac{1}{R_{\mathrm{BH}}}\right)^2$$

Consider the following parametrization as the system approaches the memory burden phase

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{\mathrm{SC}} \left(\frac{1}{S}\right)^{\Delta N(p,M)} \xrightarrow{t \gtrsim \tau_{\mathrm{SC}}} \kappa \doteq \frac{\mathrm{d}M}{\mathrm{d}t} \Big/ \left(\frac{\mathrm{d}M}{\mathrm{d}t}\right)_{\mathrm{SC}} \simeq -\frac{\delta\, \tau_{\mathrm{SC}}}{2t},$$

where $\delta \simeq \frac{2}{(p-1)\ln(S)} S^{\frac{1}{2-2p}}$ characterizes the width of the transition phase. It's roughly the mass fraction emitted through it.

Consequences for black holes as dark matter

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

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

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

K. Kohri, T.Terada, T. Yanagida '25 computed GWs from merger of memory burden PBHs adopting a similar (but less conservative) rate M. Sasaki, T. Suyama, T. Tanaka, and S. Yokoyama '18

Consequences for black holes as dark matter

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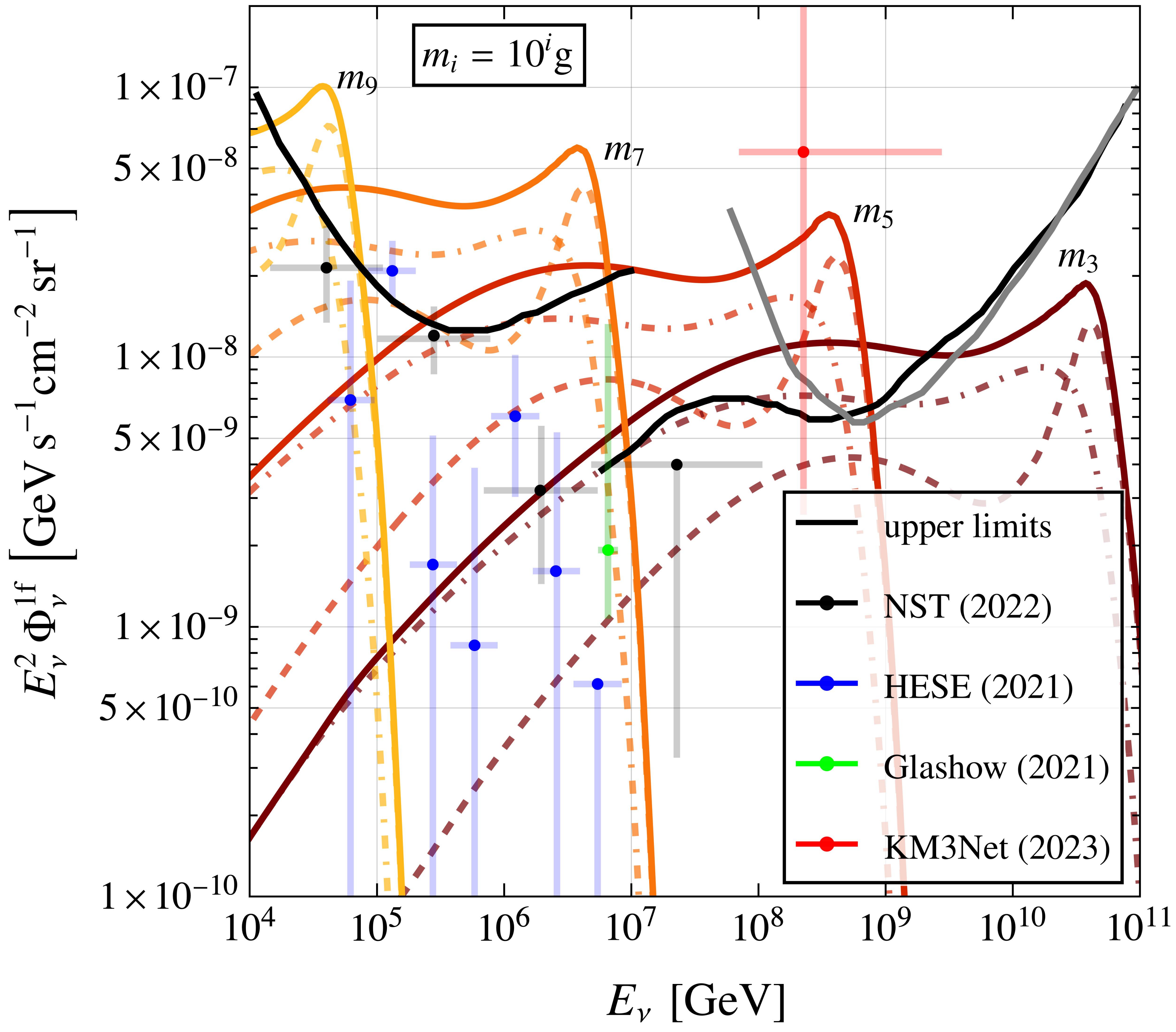
From this, we can compute the galactic and extragalactic flux, respectively as

$$\frac{{\rm d}\Phi_i^{\rm gal}}{{\rm d}E\,{\rm d}\Omega} = \frac{1}{4\pi} R_{\rm PBH}(M_{\rm PBH}; f_{\rm PBH}) \frac{q\,\tau_{\rm SC}}{\rho_{\rm DM}} \bar{J}(\Delta\Omega) \frac{{\rm d}^2 N_i}{{\rm d}E\,{\rm d}t}$$

$$\frac{{\rm d}\Phi_i^{\rm Ex.gal.}}{{\rm d}E\,{\rm d}\Omega} = \frac{1}{4\pi} \int_0^{z_{\rm MReq}} \frac{dz}{H(z)} R_{\rm PBH}(M_{\rm PBH}; f_{\rm PBH}; z)\, q\,\tau_{\rm SC}\, \frac{{\rm d}^2 N_i(E_i(1+z))}{{\rm d}E\,{\rm d}t}$$

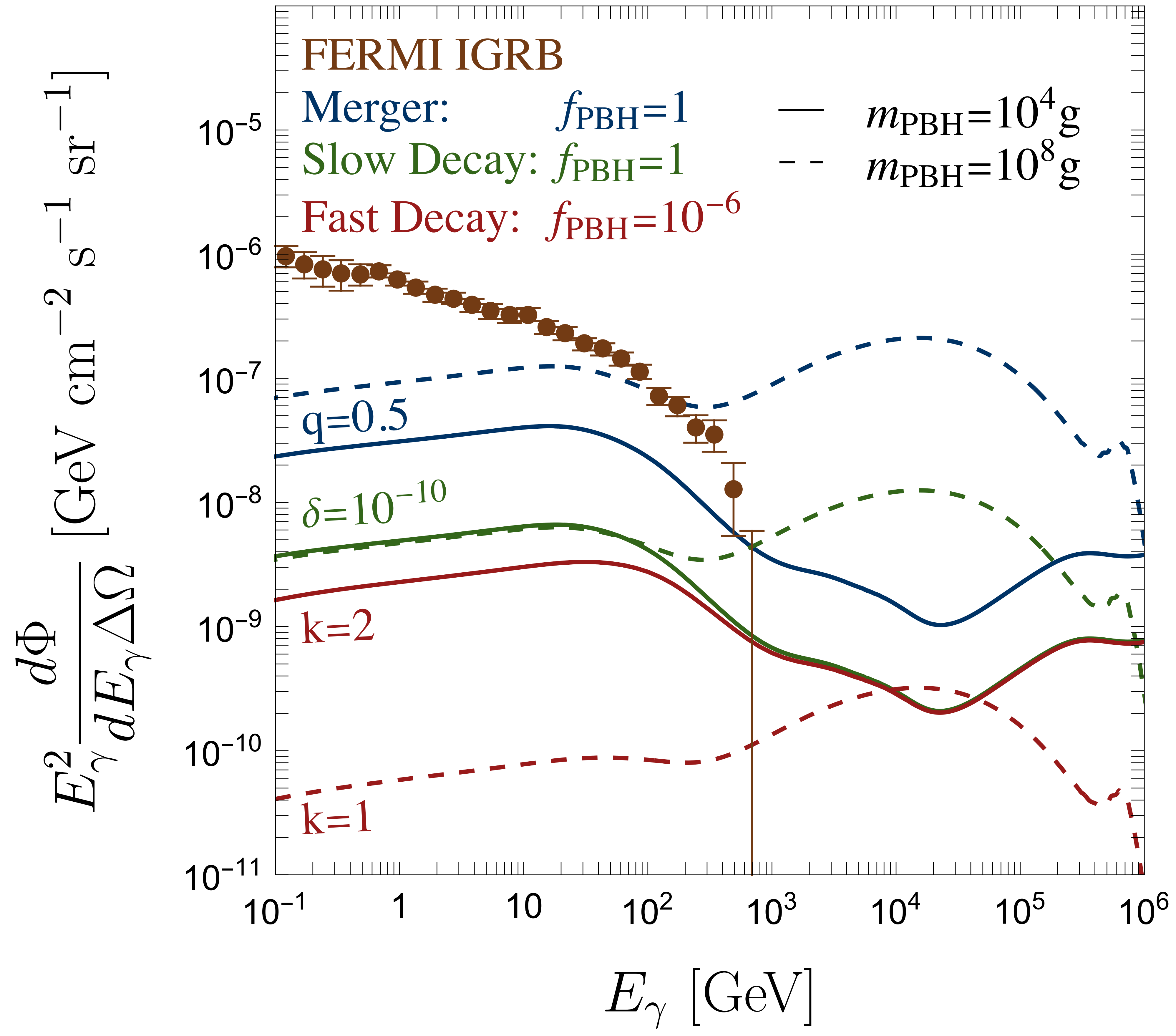
Consequences for black holes as dark matter

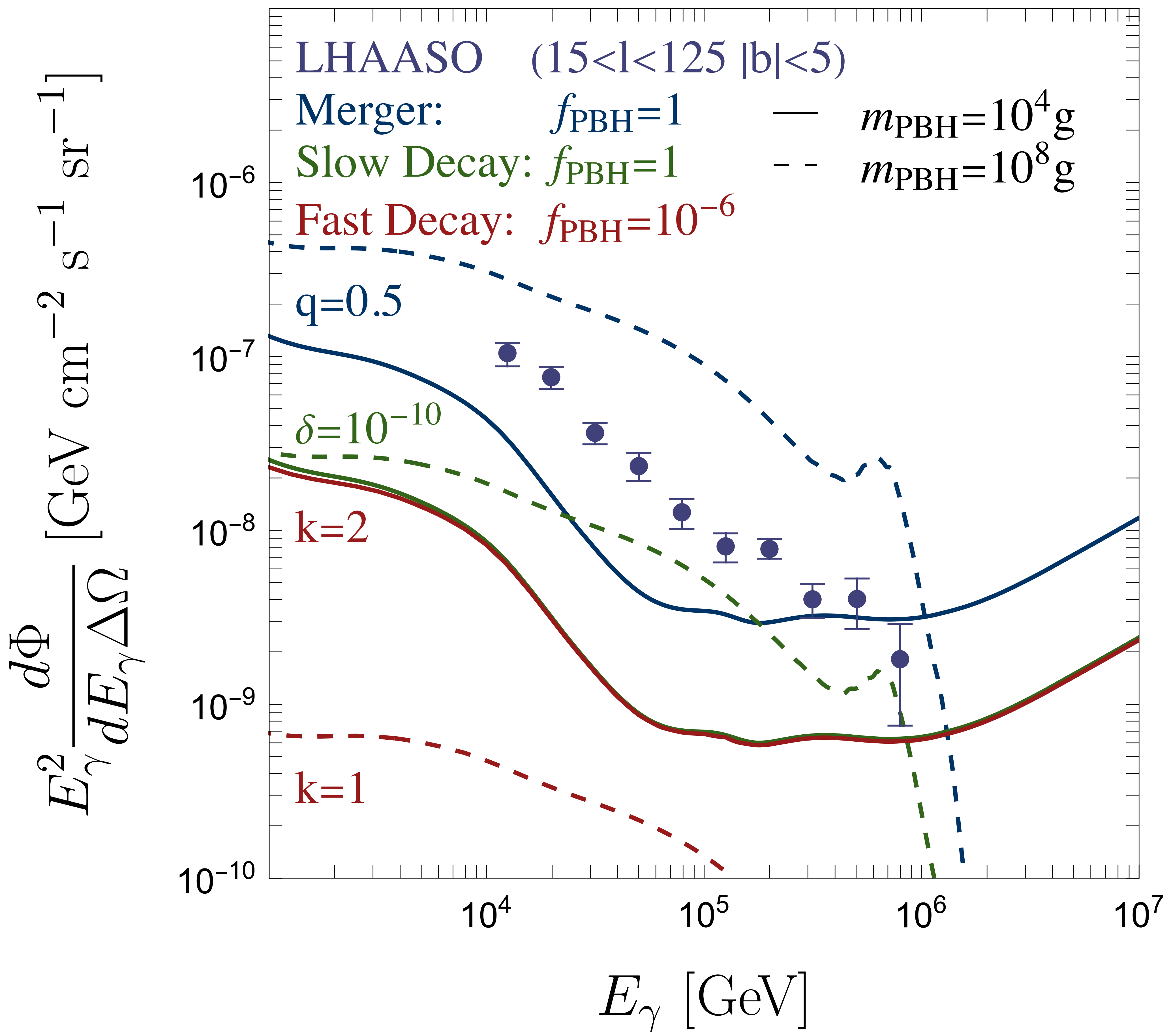
Averaged sky per-flavor neutrino flux assuming monochromatic PBH mass distribution and $f_{\mathrm{PBH}} = 1$



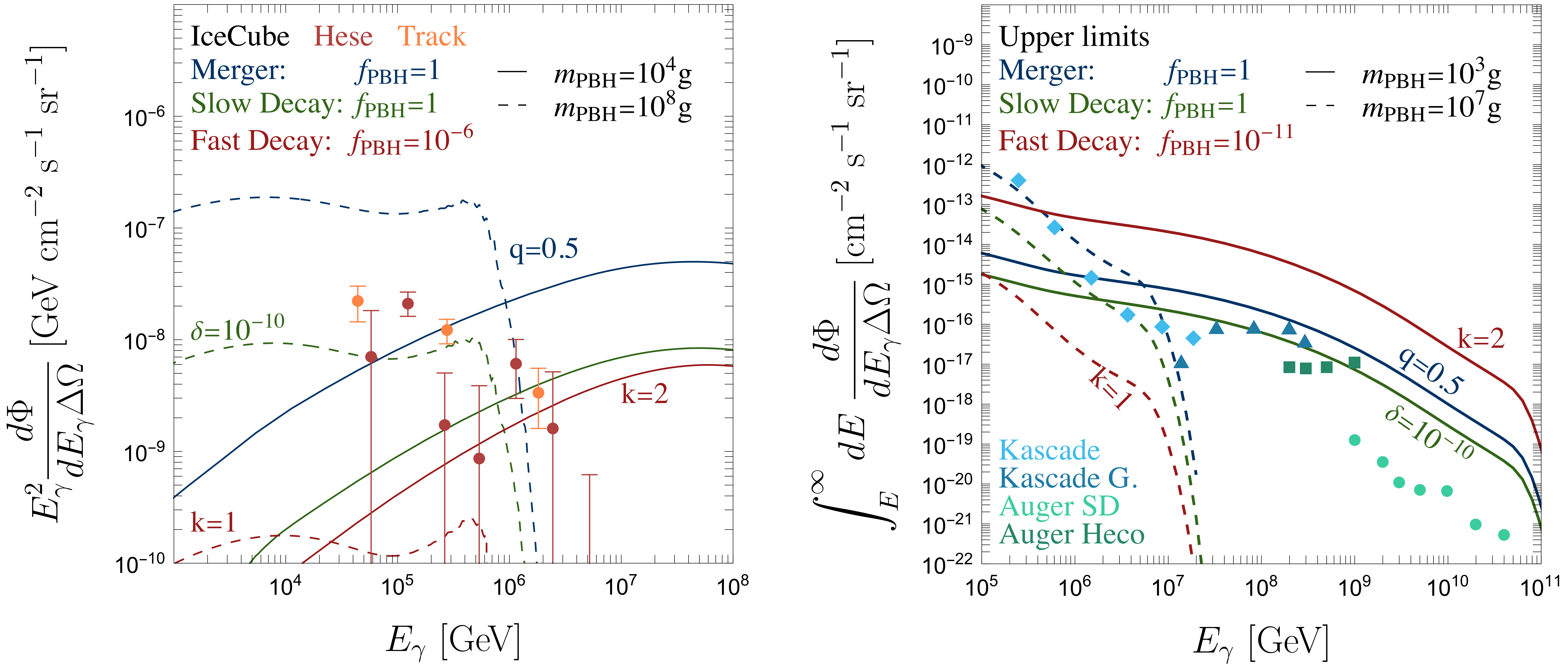
- The amount of mass released through the semiclassical phase post merger is assumed to be $q \doteq \Delta M/M = 25\,\%$. Notice this rescales $\tau_{\mathrm{SC}} \to \tau_{\mathrm{SC}}\,q$
- Galactic (Egal) fluxes are shown by dashed (dashedotted) lines. The total flux is given by the continuous line
- Effectively closes the window between $10^3\,\mathrm{g} \lesssim \mathrm{M_{BH}} \lesssim 10^9\,\mathrm{g}$ unless $q \ll 1$

Consequences for black holes as dark matter





Consequences for black holes as dark matter



Entropy and memory

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

- BHs are an example of saturon $f \leftrightarrow M_{\mathrm{pl}}$
- 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

Vacuum bubble with high information-storage capacity

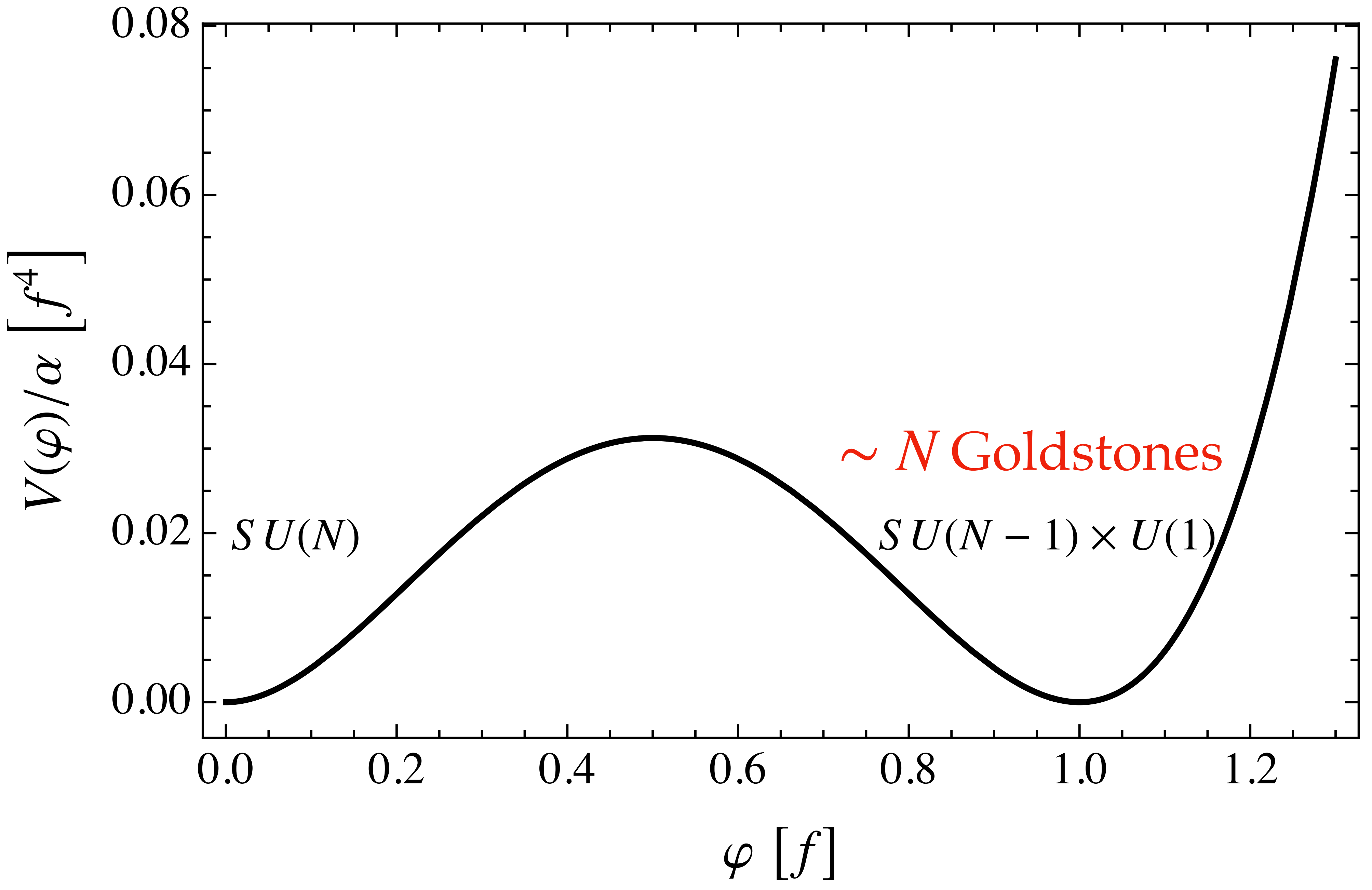
- $d = 3 + 1$
- ϕ in the adjoint representation of $SU(N)$ global symmetry
- $N \gg 1$
- Theory is renormalizable

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

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

Unitarity requires: $\alpha N \leqslant 1$

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:

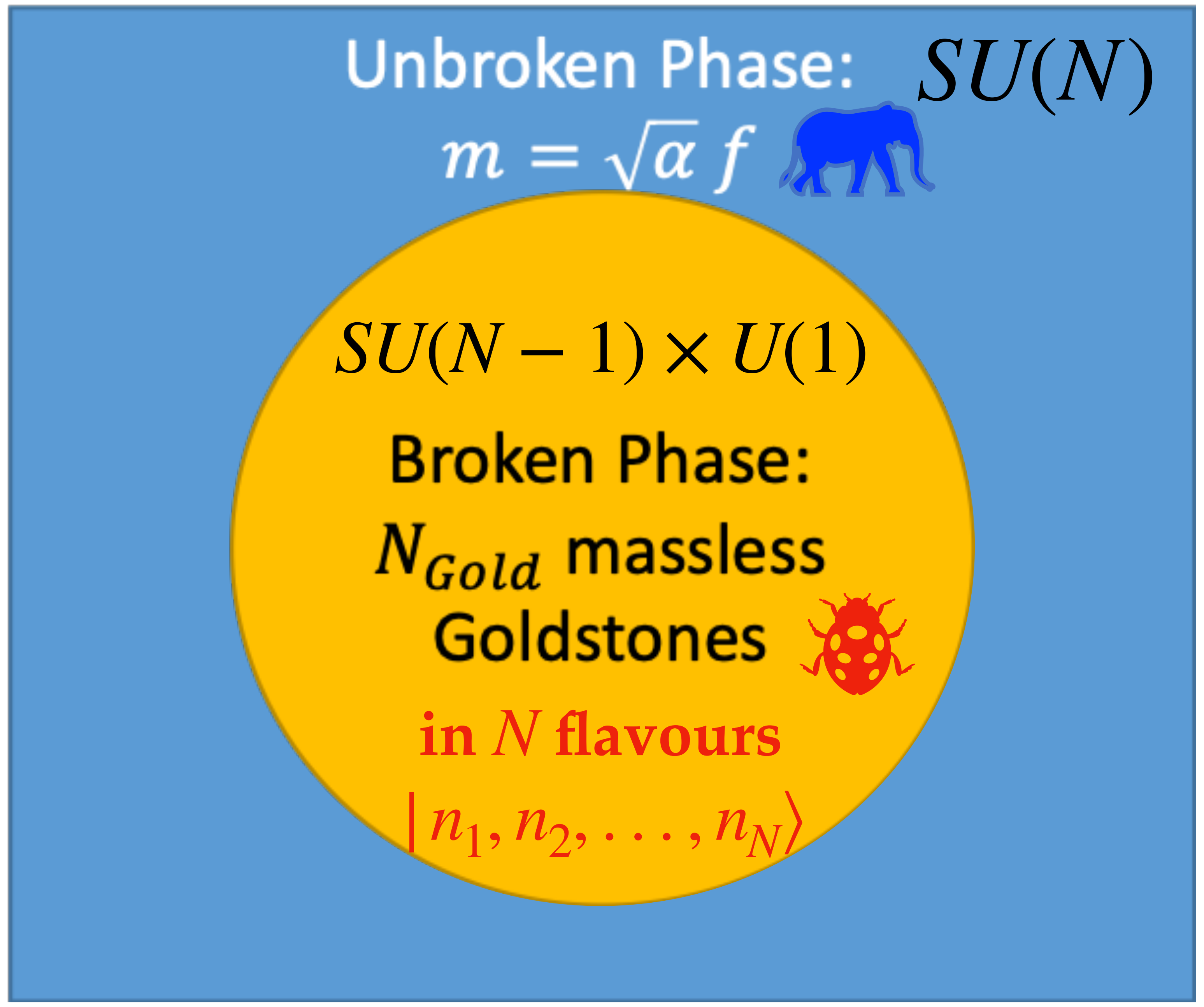
$$\phi = U^{\dagger}\Phi_D U$$

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

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

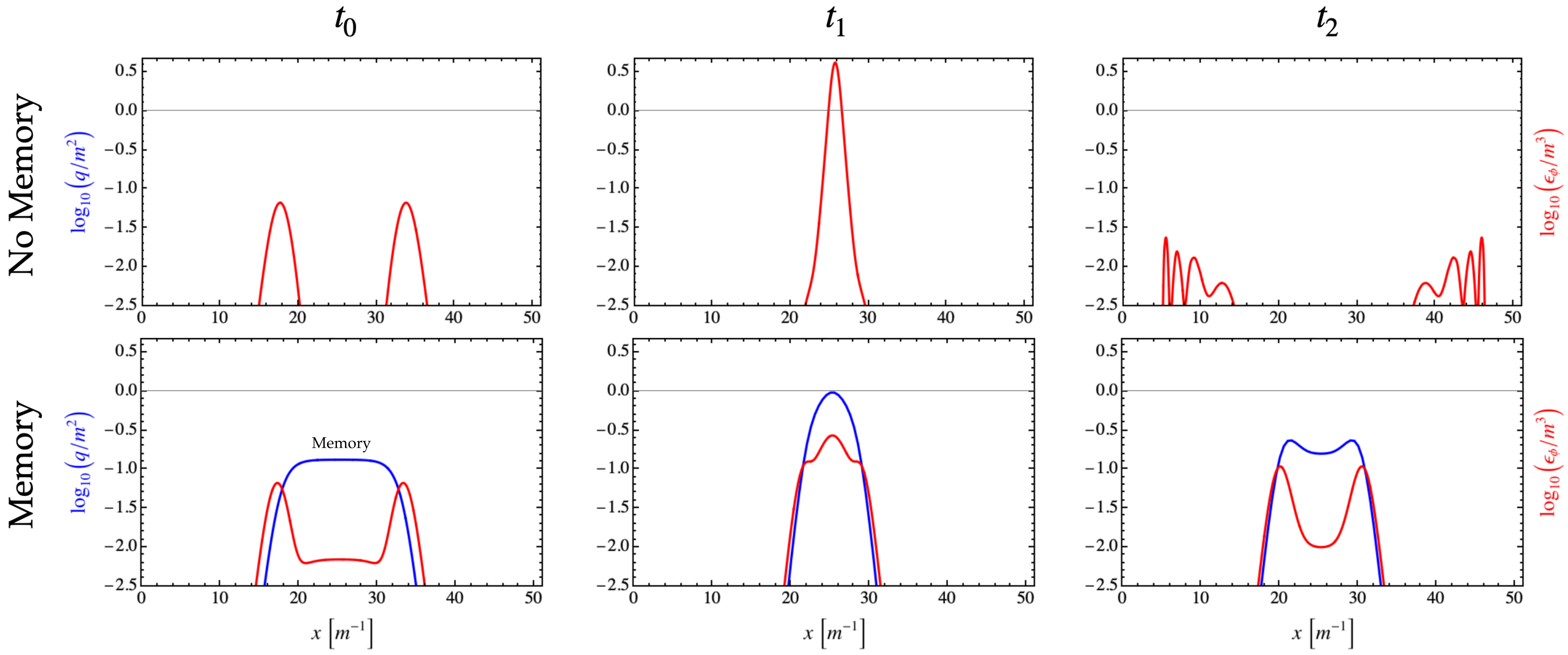
- Bubble endowed with charge $Q = N_G$

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



Stabilization via memory burden

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



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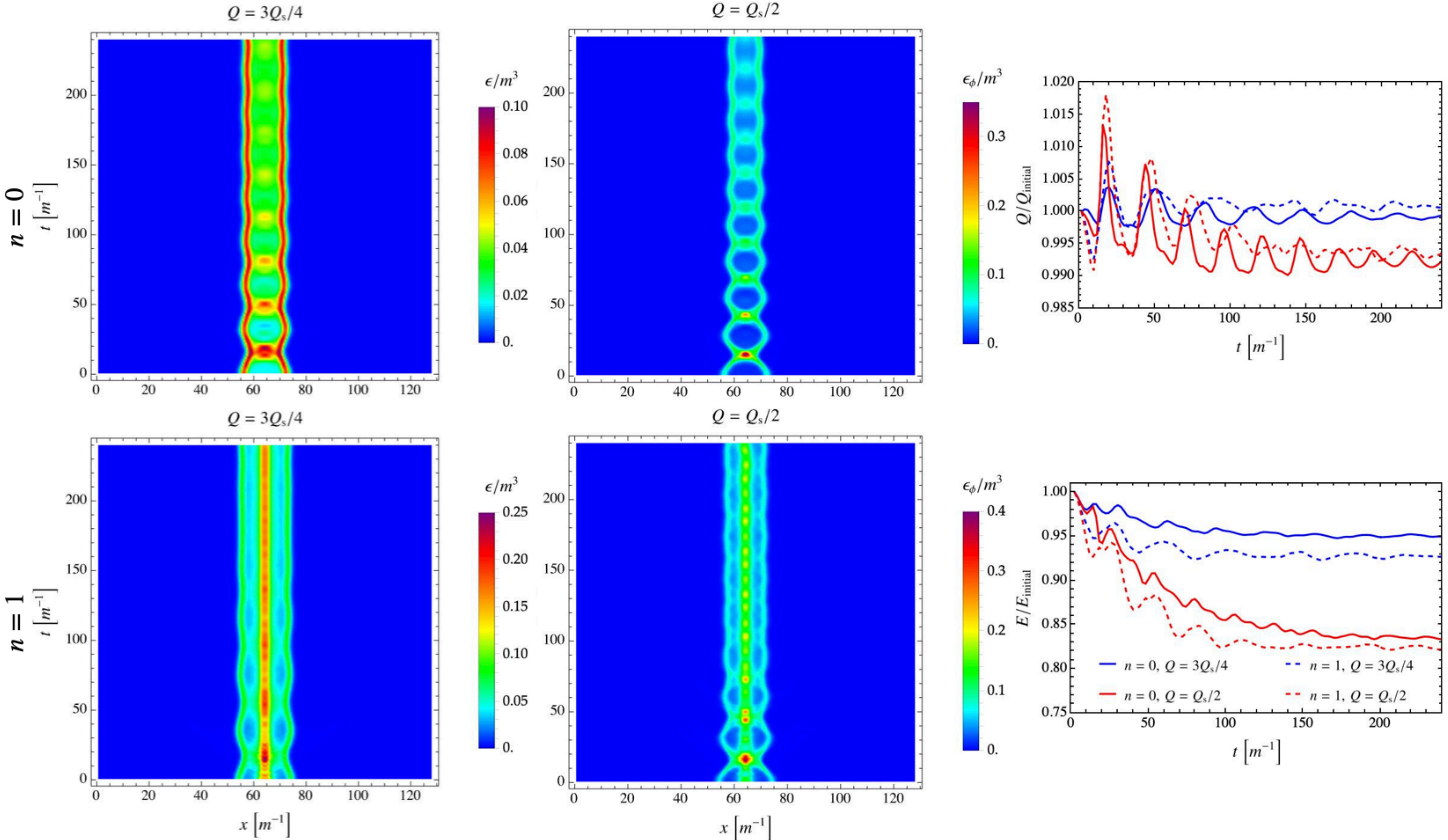

Implications for black holes

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

	Prototype $\hat{H}$	Saturon bubble	BH
Master mode	$\hat{a}_\phi$	Radial mode $\varphi(r)$	$g_{\mu\nu}$
Goldstone modes	$\hat{a}_j$	Goldstones $N_G \sim S$	?

- 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

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

These modes have a gap of order M_{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 mode) has rate

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

The emission of memory takes place when quanta of similar spherical harmonics interact - but these have $\mathcal{O}(1)$ occupation number (“leakage”):

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

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

$$\tau \simeq \tau_{\rm SC}\, S^k$$

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