

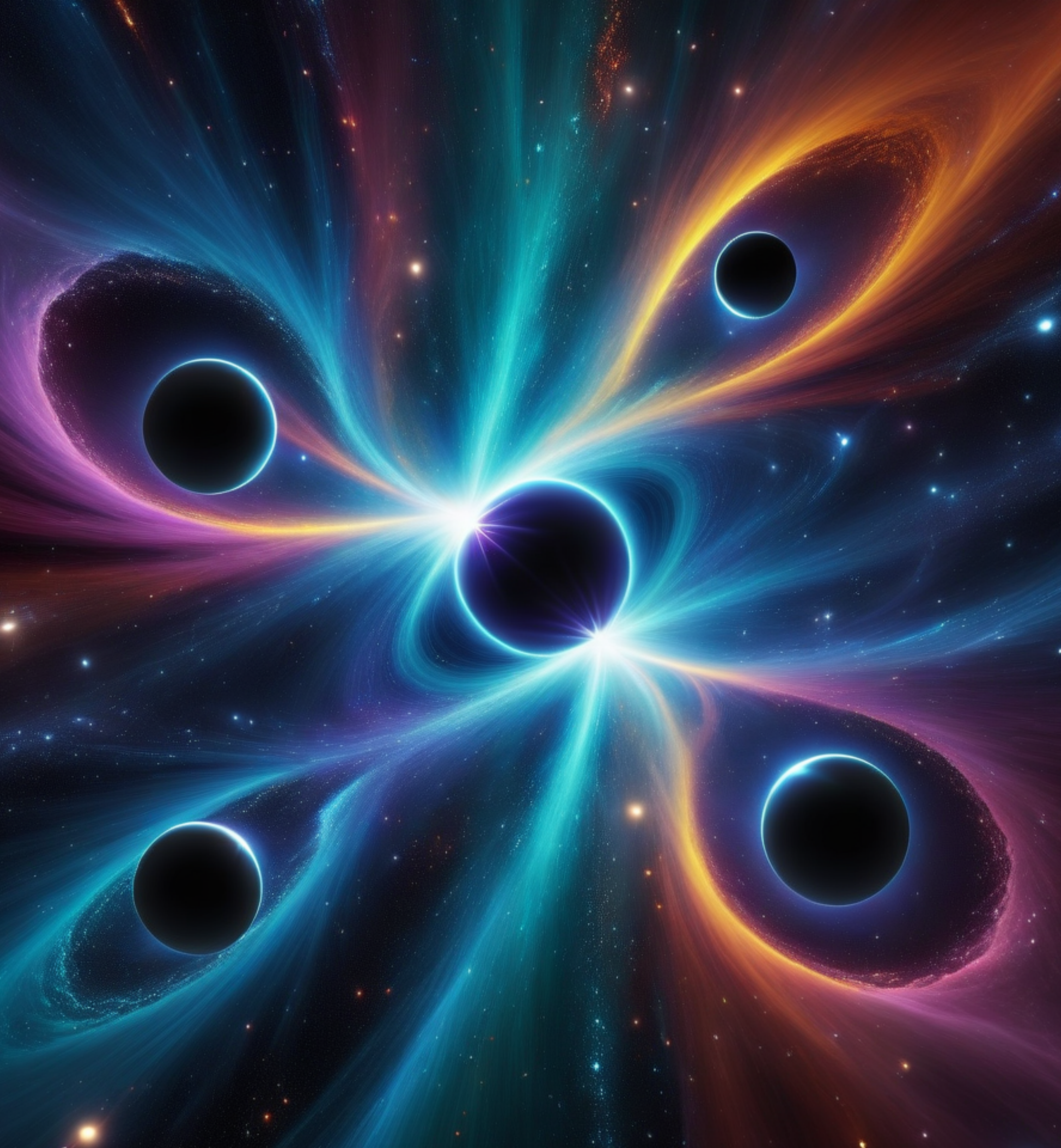


Based on [arXiv 2502.19245](https://arxiv.org/abs/2502.19245) (PRD 112) and [arXiv:2410.07604](https://arxiv.org/abs/2410.07604) (PRD 111)

A STRIKE OF LUCK: THE KM3NET NEUTRINO PRODUCED BY EVAPORATING BURDENED PBHS

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TaSP26 - Andrea Boccia - F. Iocco - M. Chianese



OUTLINE

- Black Hole evaporation;
- Primordial Black Holes;
- Memory Burden effect;
- Memory Burden in PBHs;
- UHE neutrinos from burdened PBHs;
- The KM3-230213A event.



BLACK HOLE EVAPORATION

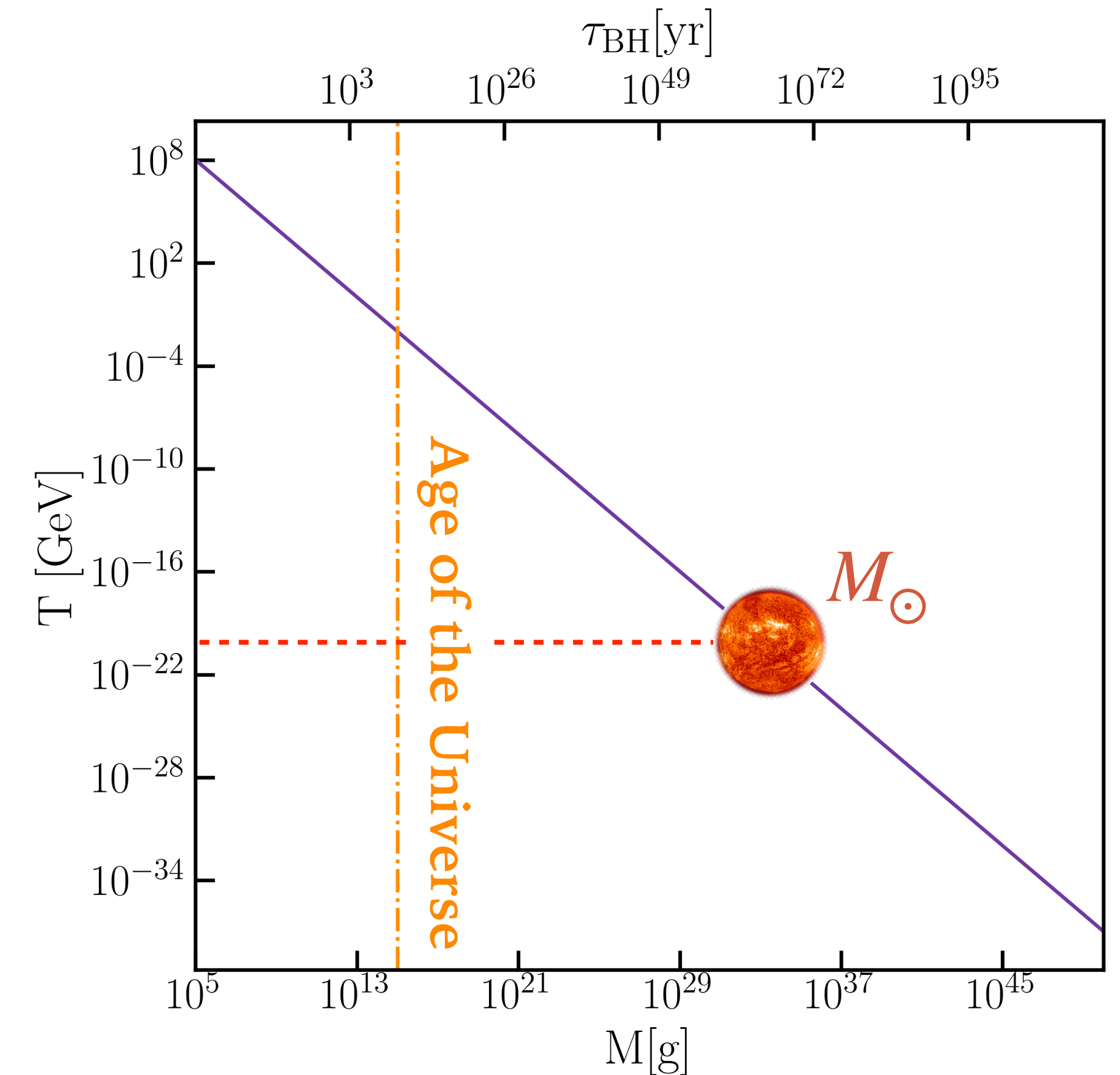
BHs evaporate due to quantum effects, emitting all SM particles.
Standard Hawking's picture:

$$T_{\text{H}} = \frac{1}{8\pi GM_{\text{BH}}} \simeq 10^4 \left(\frac{10^9 \text{g}}{M_{\text{BH}}} \right) \text{GeV}$$

Hawking Temperature

$$\tau_{\text{BH}} \simeq 0.4 \left(\frac{M_{\text{BH}}}{10^9 \text{g}} \right)^3 \text{s}$$

BH Life-Time



BLACK HOLE EVAPORATION

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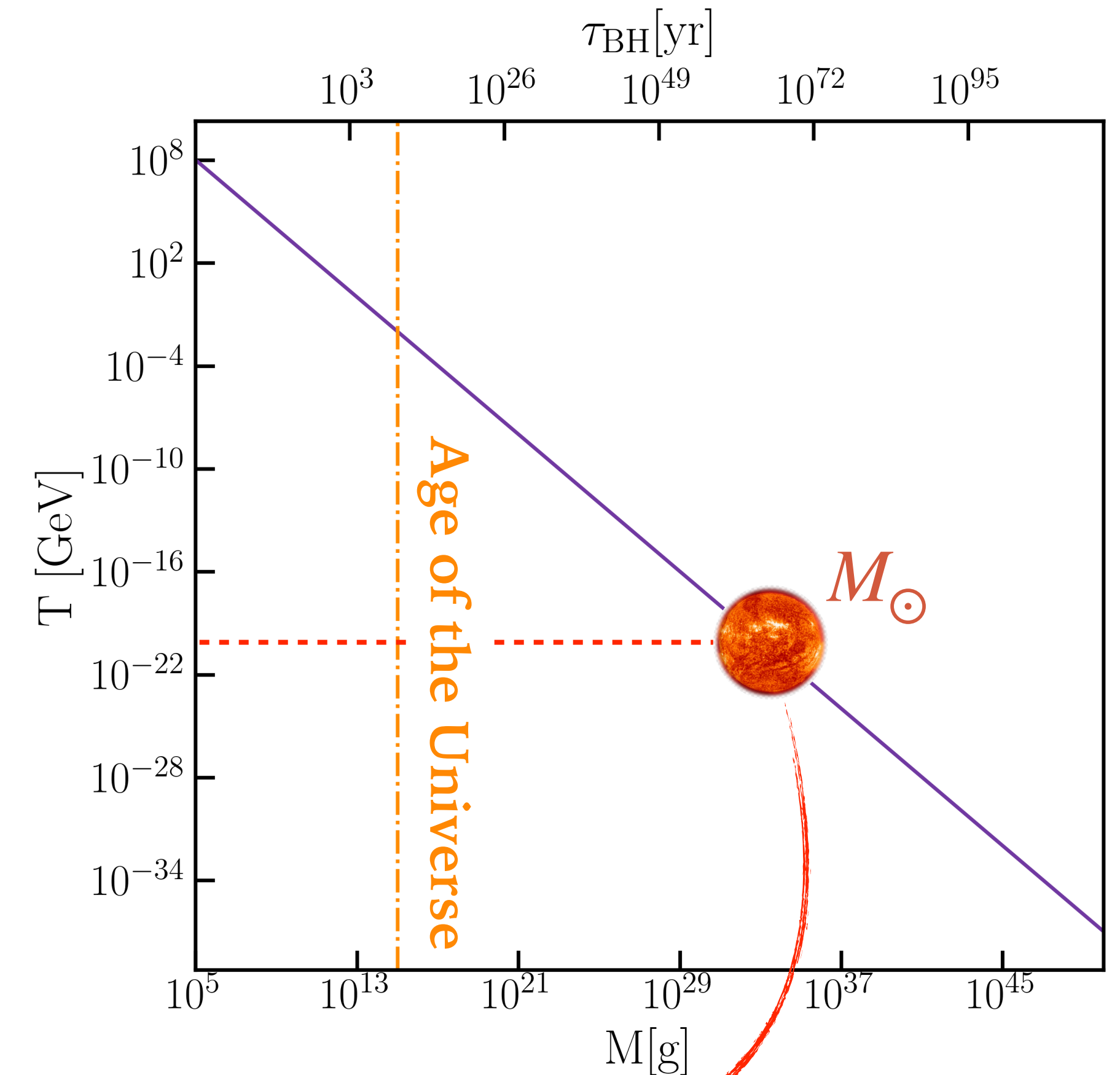
Hawking Temperature

BH Life-Time

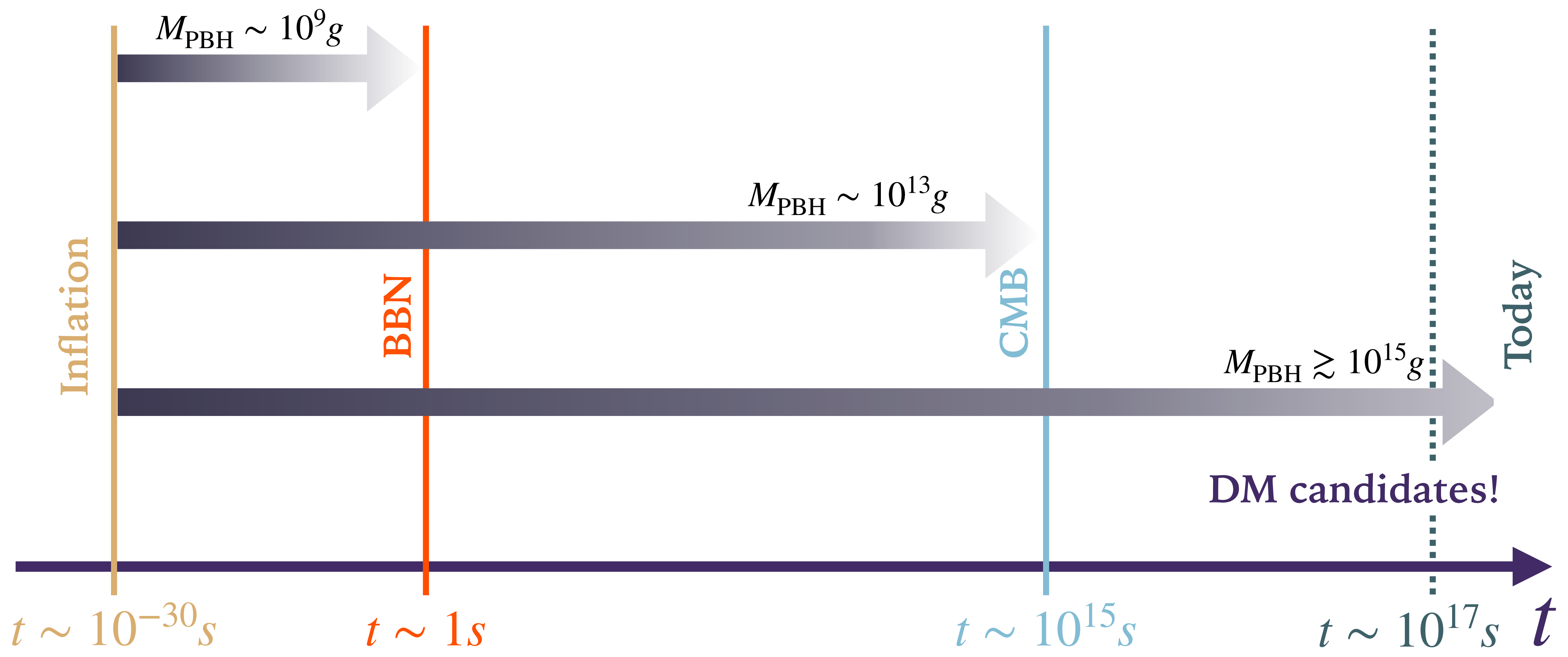
$$T_H (1.4M_{\odot}) \sim 10^{-12} \text{eV}$$

$$\tau_{\text{BH}} (1.4M_{\odot}) \sim 10^{57} \text{Gyr}$$

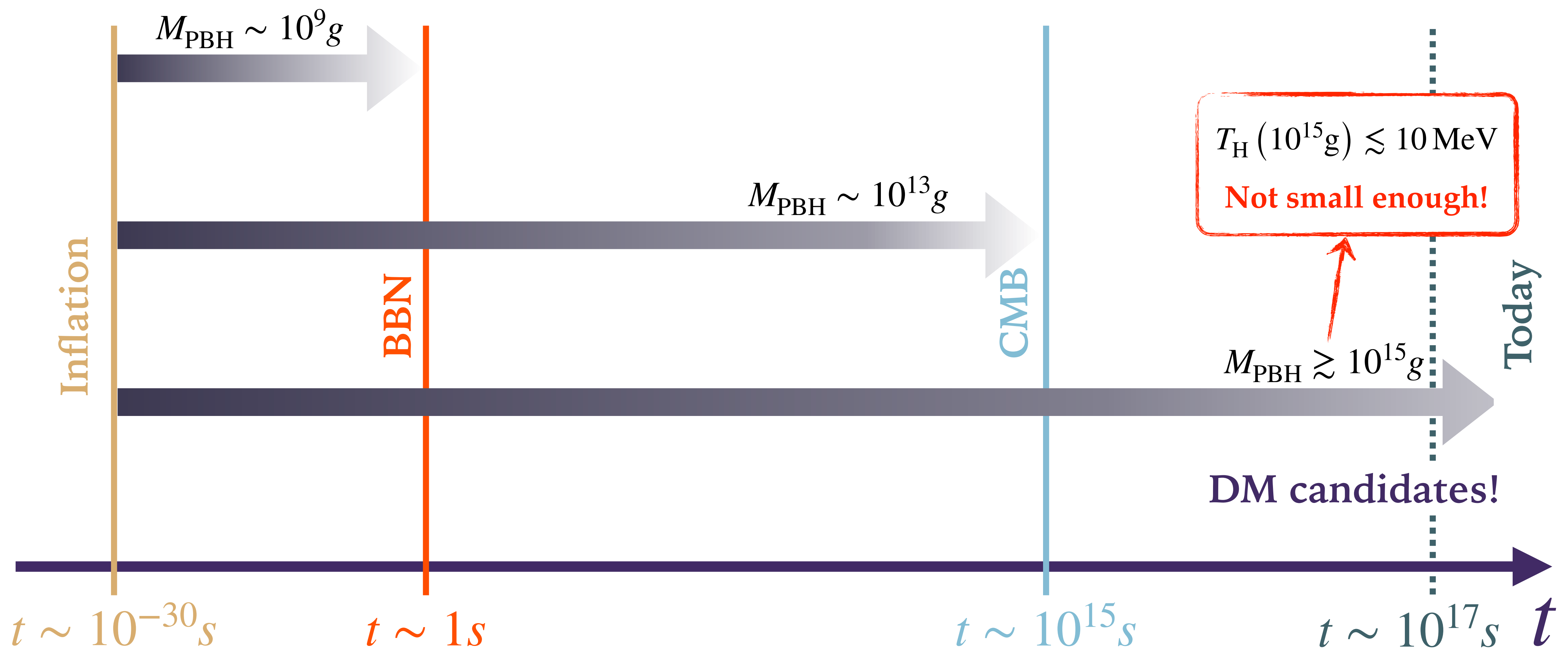
Can we have smaller black holes?



PRIMORDIAL BLACK HOLES (NON-STELLAR NATURE)



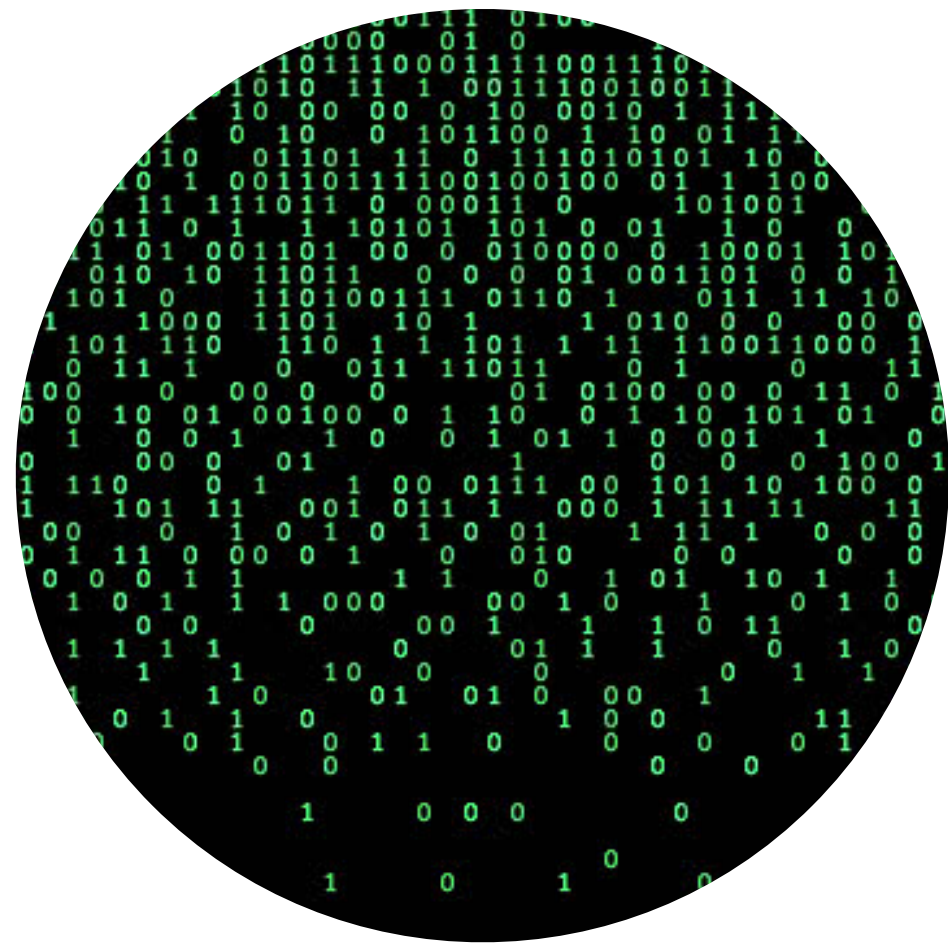
PRIMORDIAL BLACK HOLES (NON-STELLAR NATURE)



MEMORY BURDEN EFFECT

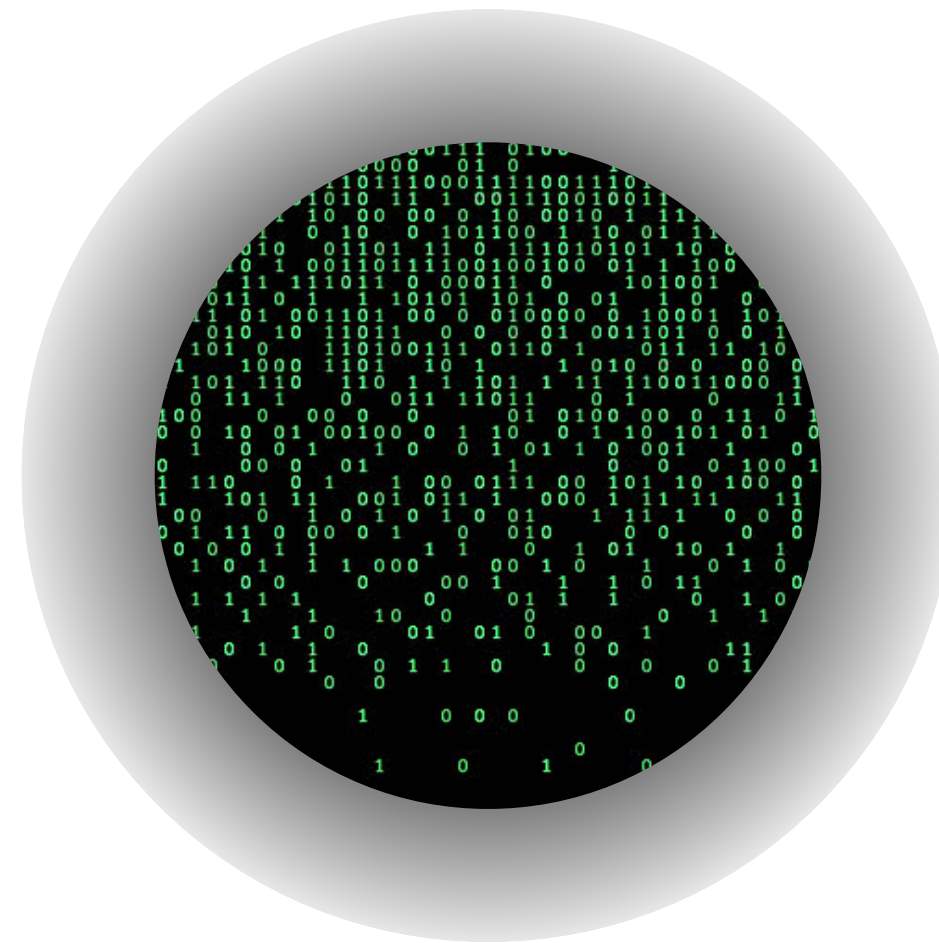
Memory Burden: *The information stored in a system resists its decay.*

High capacity information storage (black hole)



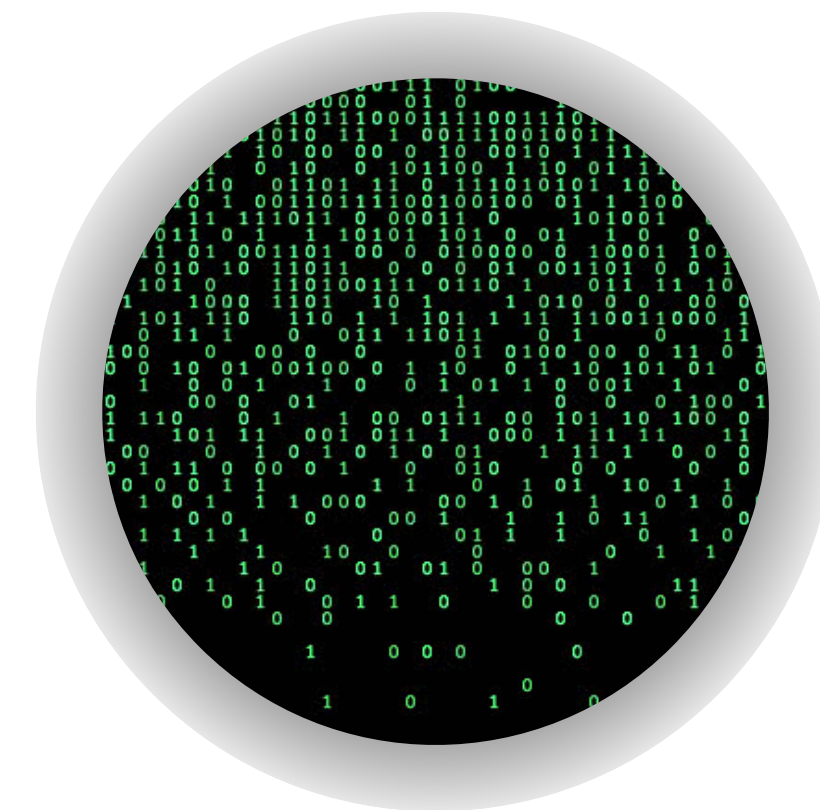
BHs are the most efficient information storages in physics (area-law entropy).

Thermal decay



Thermal radiation doesn't carry information from BH.

Stabilized system (suppressed flux)



Quantum back reaction of stored information stabilizes the system.

Dvali, G. (2018). A Microscopic Model of Holography: Survival by the Burden of Memory.

Dvali, G., Valbuena-Bermúdez, J. S., & Zantedeschi, M. (2024). Memory burden effect in black holes and solitons: Implications for PBH. Physical Review D, 110(5), 056029.

MEMORY BURDEN IN BLACK HOLES

What implications for PBHs?

Back-reaction of quantum modes stored in the object stabilizes the system, allowing light primordial black holes (PBHs) to survive until today.

$$S(M_{\text{PBH}}) = 4\pi GM_{\text{PBH}}^2$$

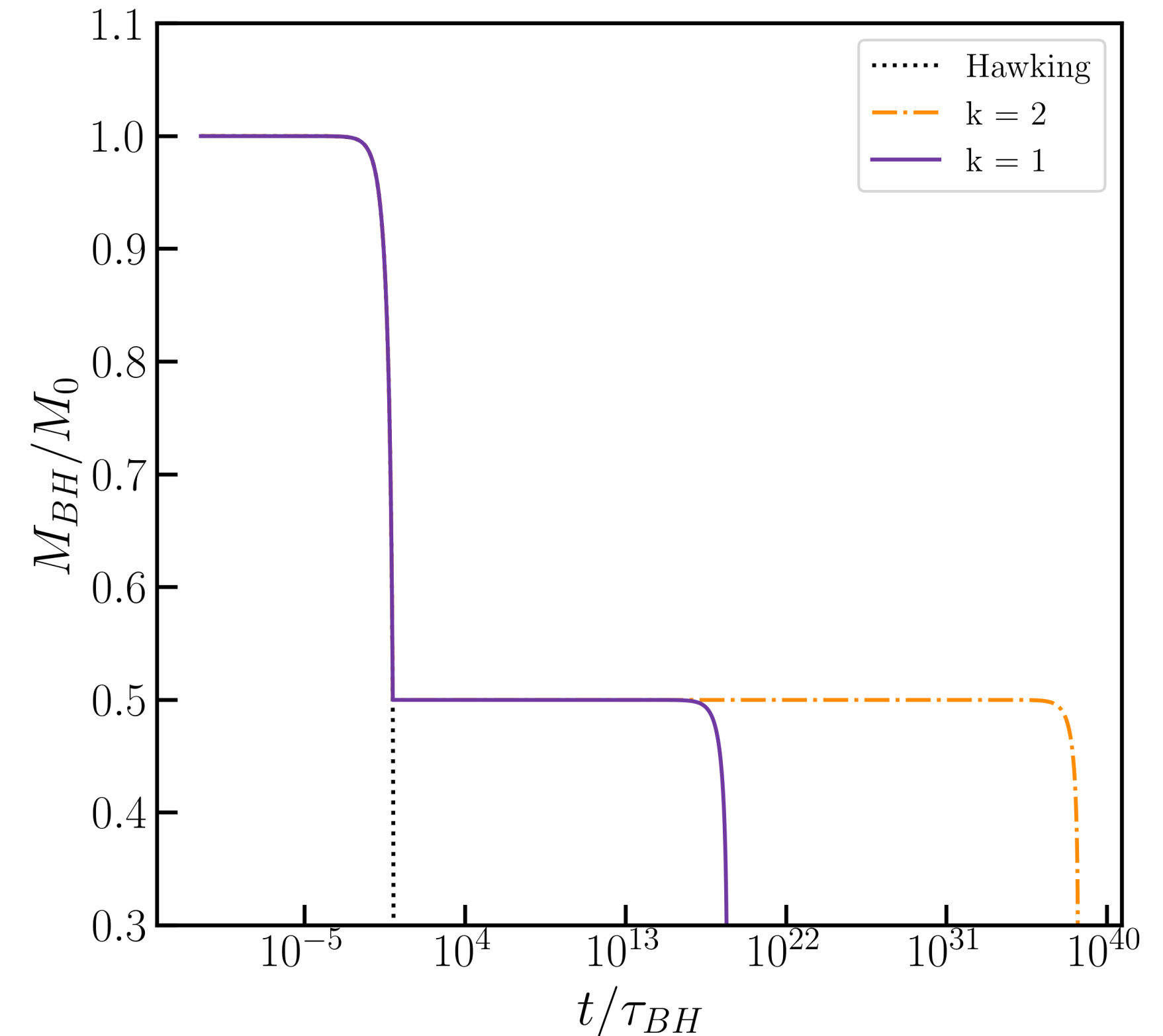
PBH Entropy

$$\frac{dM_{\text{PBH}}^{\text{mb}}}{dt} = S(M_{\text{PBH}})^{-k} \frac{dM_{\text{PBH}}}{dt}$$

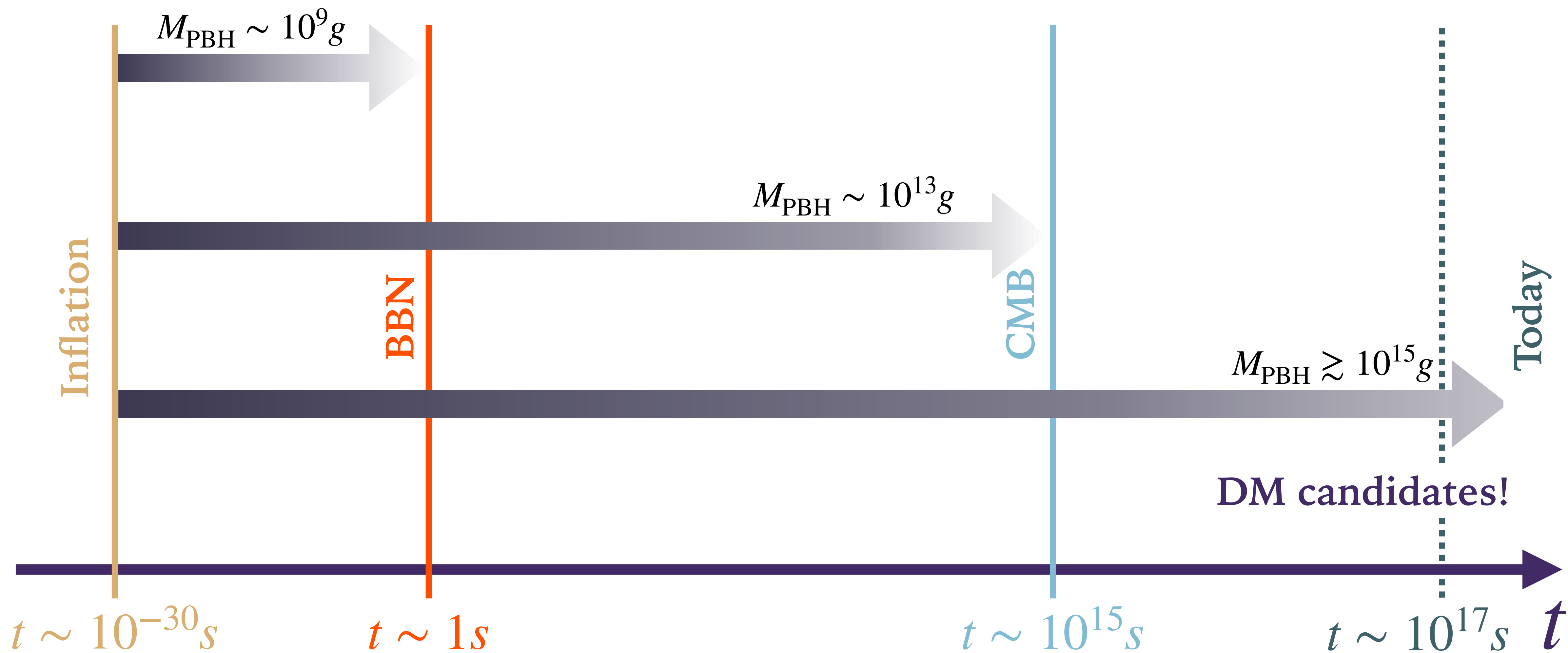
Suppressed mass loss rate

k = memory burden “strength”

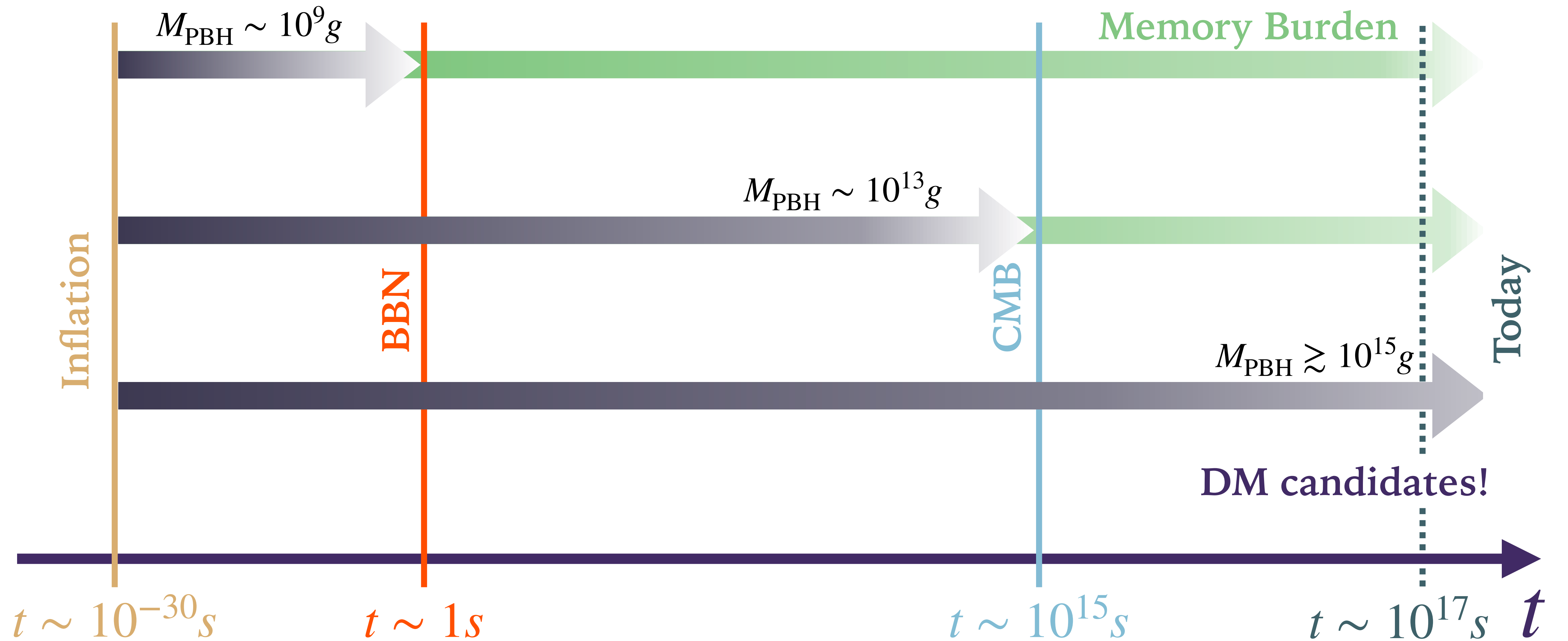
Details of transitioning debated in:
[arXiv:2503.21740](https://arxiv.org/abs/2503.21740) and [arXiv:2503.21005](https://arxiv.org/abs/2503.21005)



MEMORY BURDEN IN BLACK HOLES



MEMORY BURDEN IN BLACK HOLES

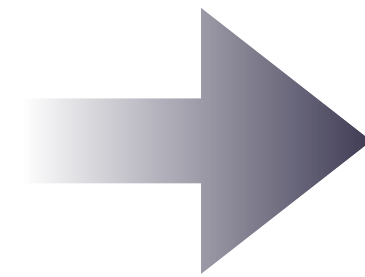


UHE NEUTRINOS FROM BURDENED PBHS

If burdened light PBHs make a fraction (or the totality) of DM can we detect them today?

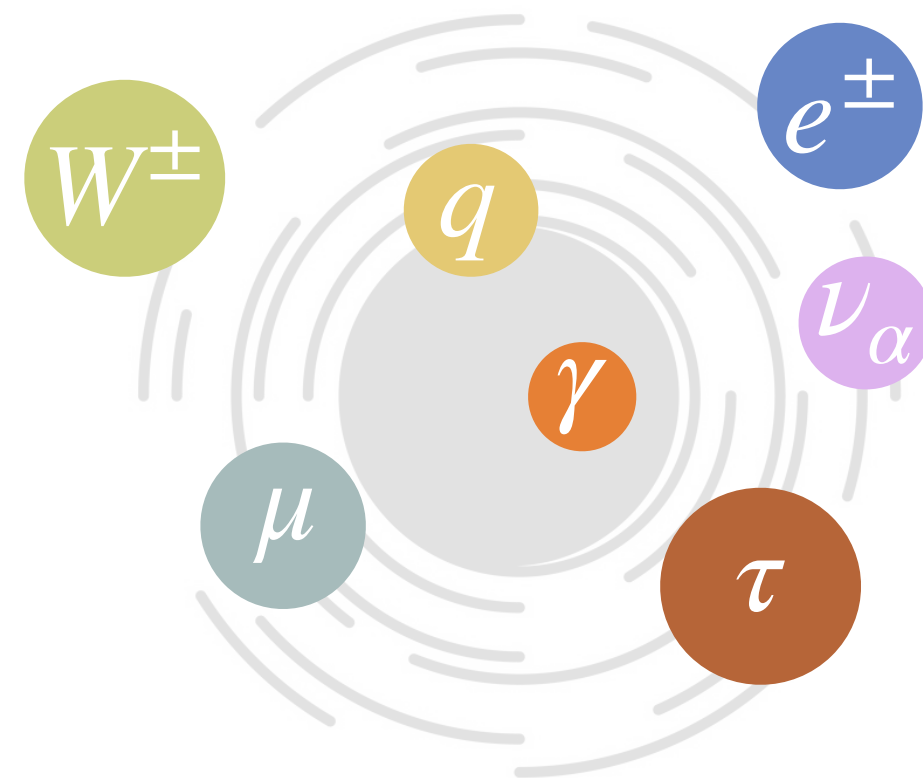
We should expect a **steady flux** of ultra-high-energy particles coming from every direction.

$$M_{\text{PBH}} \leq 10^9 \text{g}$$



$$T_{\text{H}} \geq 10^4 \text{ GeV}$$

For such energies the entire SM spectrum is available!



UHE NEUTRINOS FROM BURDENED PBHs

If PBHs are distributed like DM we should expect both a galactic and extra-galactic component of neutrinos flux.

Can any instrument see a flux Φ_ν of neutrinos from DM PBHs ?

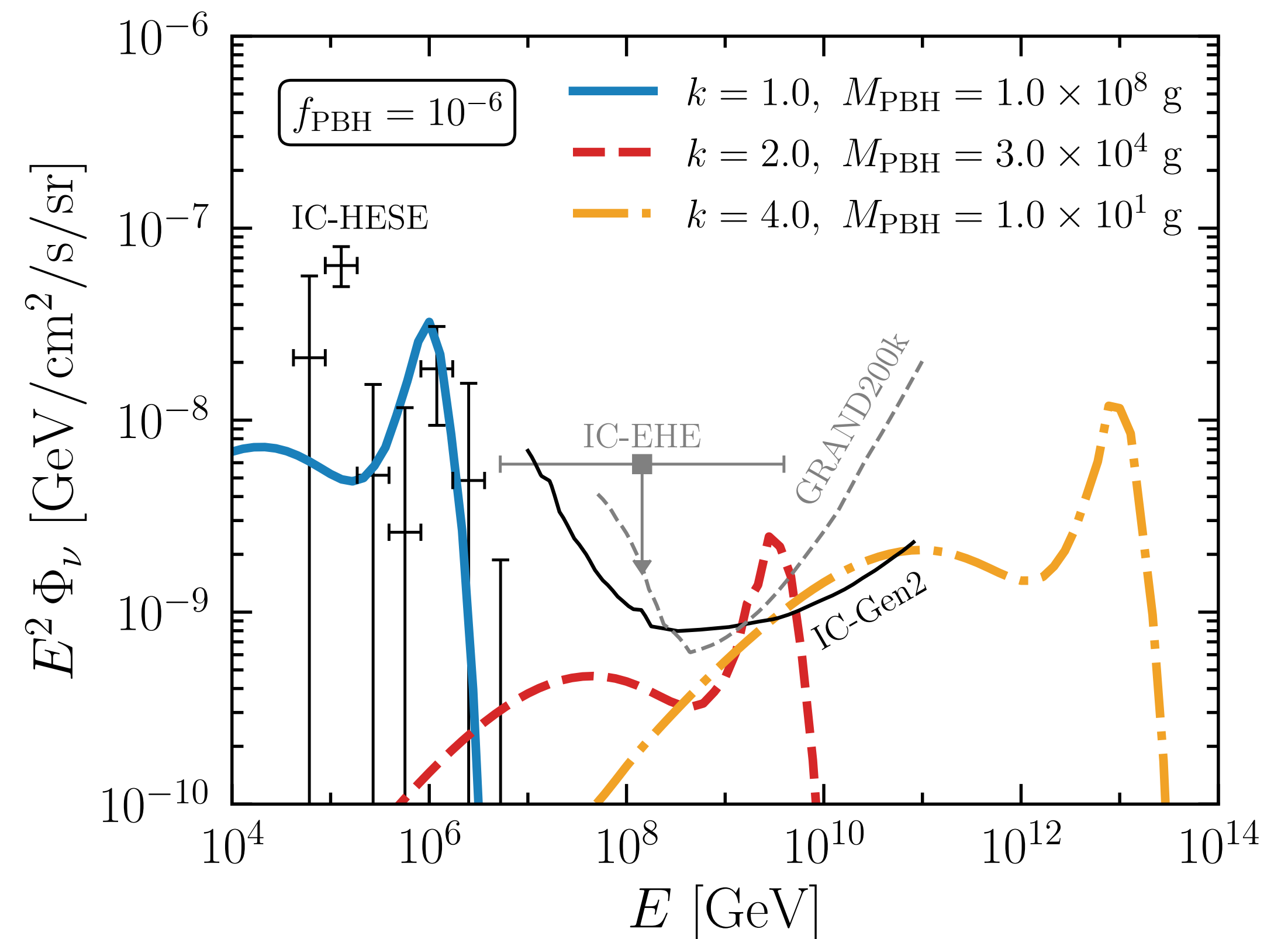
Suppressed
emission rate

$$\frac{d^2 N_i^{\text{mb}}}{dt dE} = S(M_{\text{PBH}})^{-k} \frac{d^2 N_i}{dt dE}$$

Galactic
flux

$$\frac{d^2 \phi_{\nu_\alpha}^{\text{gal}}}{dE d\Omega} = \frac{f_{\text{PBH}} \mathcal{J}}{4\pi M_{\text{PBH}}^{\text{mb}}} \frac{d^2 N_{\nu_\alpha}^{\text{mb}}}{dE dt}$$

(Extra-galactic is negligible)



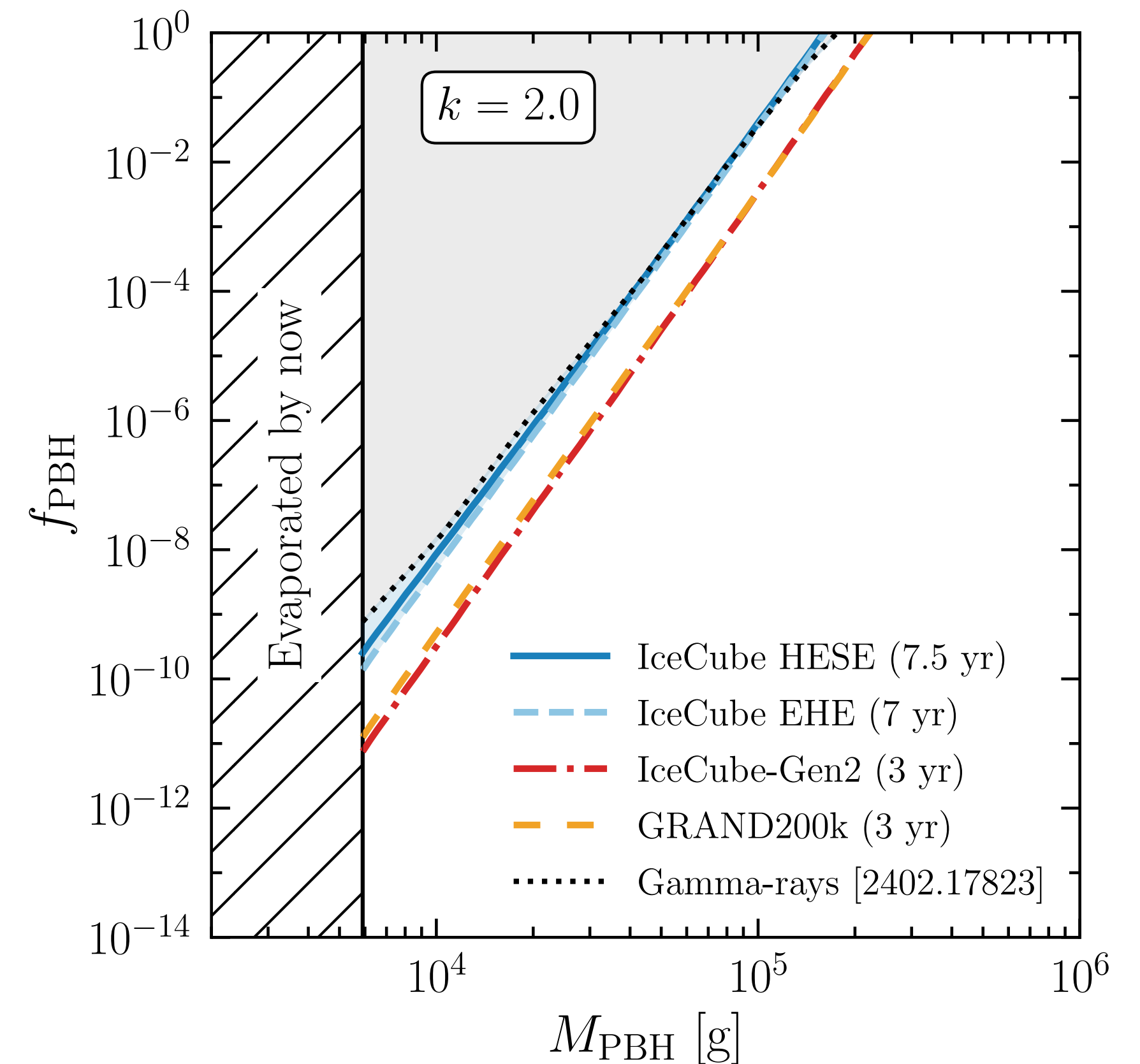
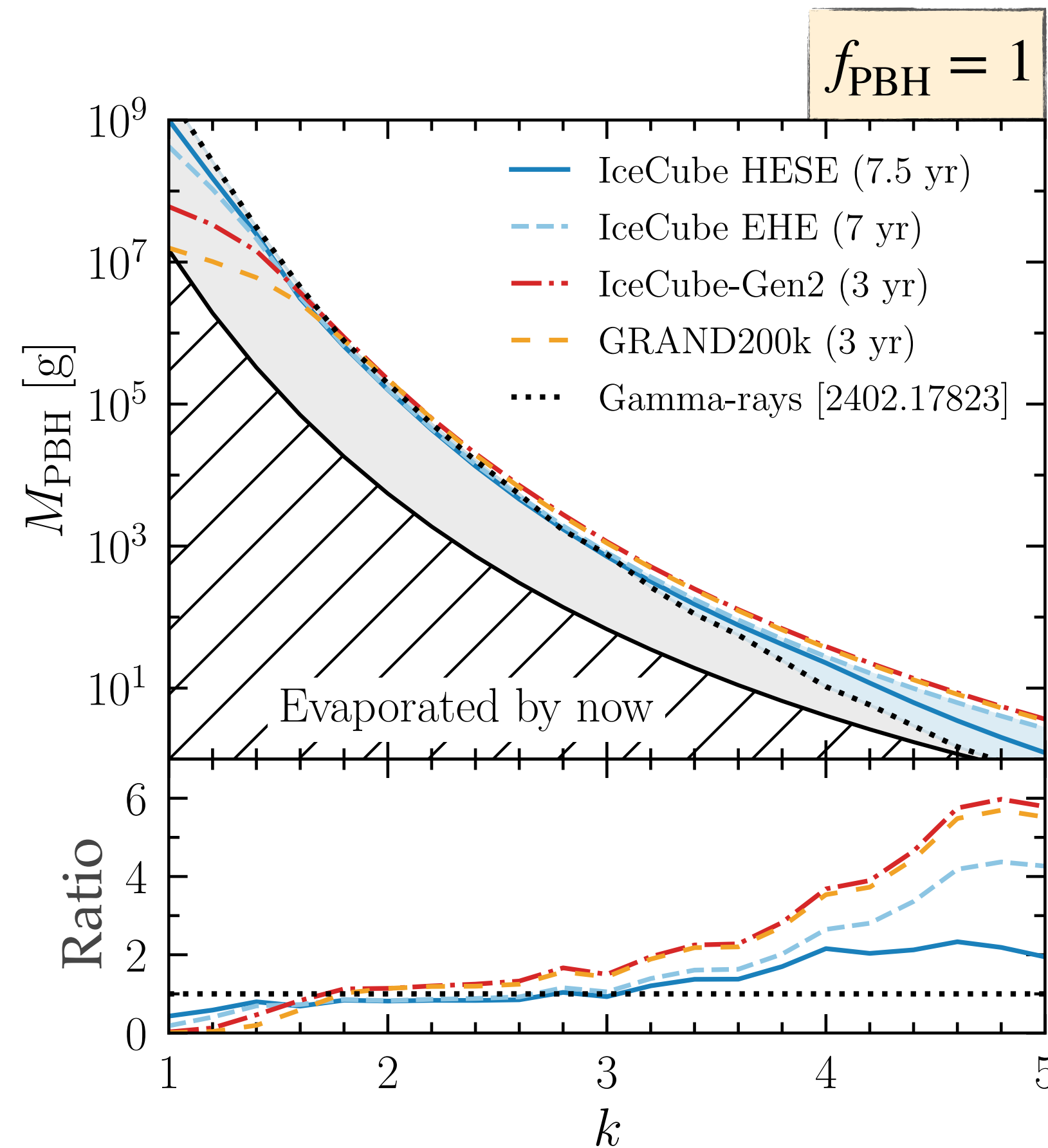
Chianese, M., Boccia, A., Iocco, F., Miele, G., & Saviano, N. (2025). Light burden of memory: Constraining primordial black holes with high-energy neutrinos. Phys. Rev. D, 111(6), 063036. <https://doi.org/10.1103/PhysRevD.111.063036>

UHE NEUTRINOS FROM BURDENED PBHs

We do use existing data to constrain memory burdened PBHs parameter space.

$$\frac{d^2 N_i^{\text{mb}}}{dt dE} = S(M_{\text{PBH}})^{-k} \frac{d^2 N_i}{dt dE}$$

$$\frac{dM_{\text{PBH}}^{\text{mb}}}{dt} = S(M_{\text{PBH}})^{-k} \frac{dM_{\text{PBH}}}{dt}$$



Chianese, M., **Boccia, A.**, Iocco, F., Miele, G., & Saviano, N. (2025). Light burden of memory: Constraining primordial black holes with high-energy neutrinos. *Phys. Rev. D*, 111(6), 063036. <https://doi.org/10.1103/PhysRevD.111.063036>

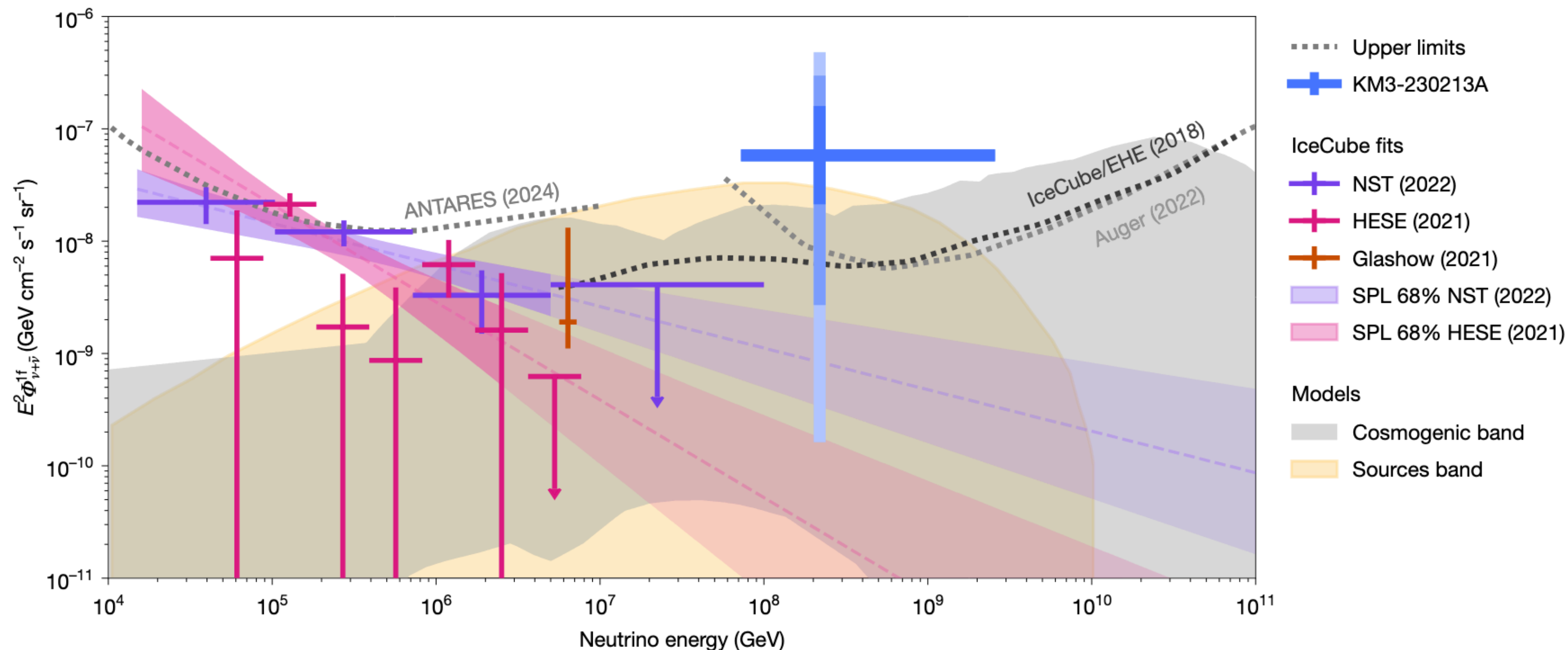
THE KM3-230213A EVENT

The KM3NeT collaboration has recently claimed the observation of one muon event with an energy of 120_{-60}^{+110} PeV probably originated from a neutrino of energy $\sim 110 - 790$ PeV.

The most energetic neutrino ever detected!

Where did it come from?

- Galactic source?
- Extragalactic?
- Cosmogenic?
- Transient?



Aiello, S., & others. (2025). Observation of an ultra-high-energy cosmic neutrino with KM3NeT. *Nature*, 638(8050), 376–382. <https://doi.org/10.1038/s41586-024-08543-1>

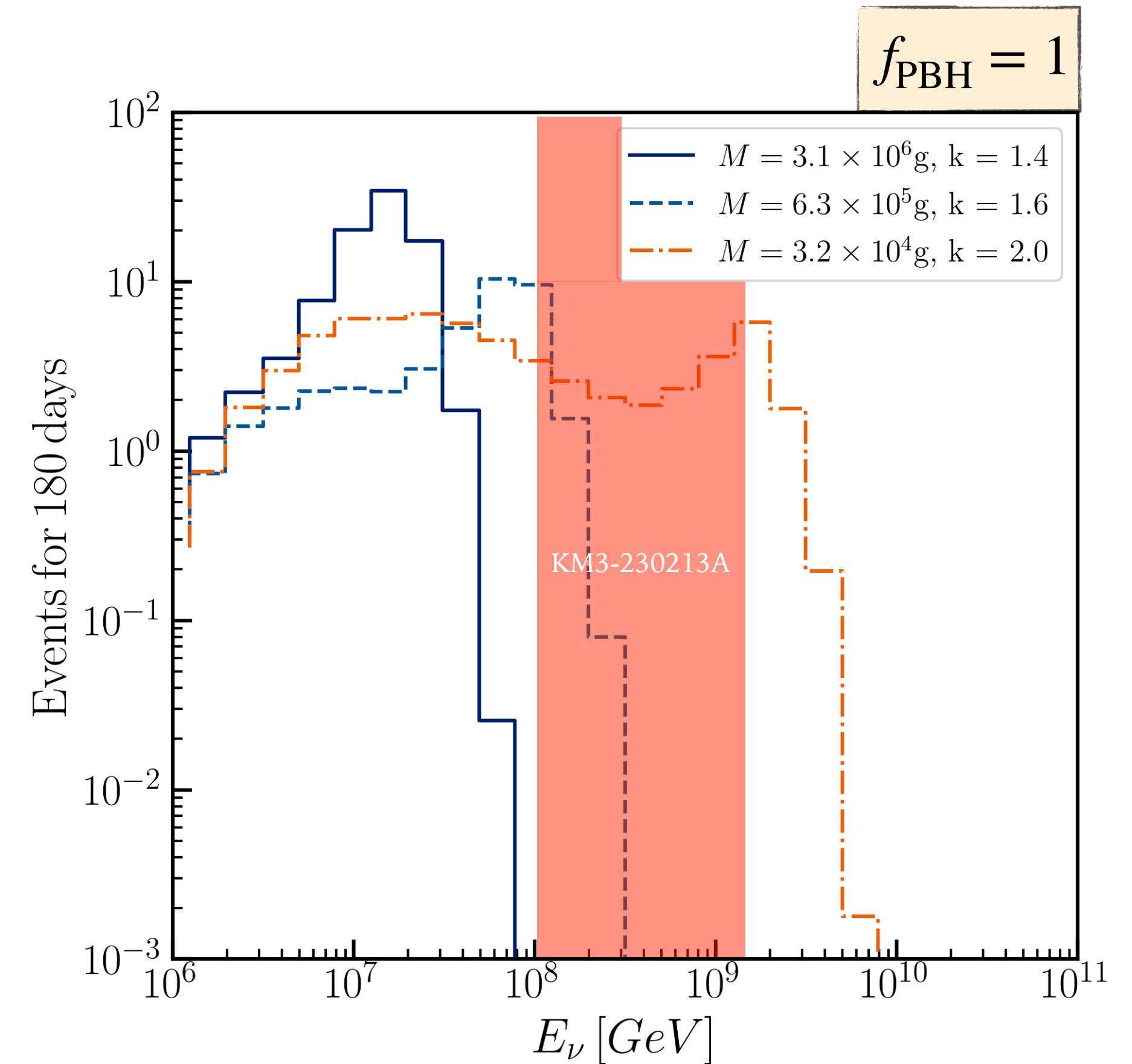
THE KM3-230213A EVENT

Could the KM3-230213A event be caused by an evaporating PBH?

$$n^{\text{exp}}(T) = 4\pi T \int_{E_{\text{min}}}^{E_{\text{max}}} dE A_{\text{eff}}(E) \phi_{\nu}(E)$$

$A_{\text{eff}}(E)$: all-flavour, sky-averaged effective area for KM3NeT.

$$\phi_{\nu}(E) \simeq \frac{d^2\phi_{\nu}^{\text{gal}}}{dEd\Omega} = \frac{f_{\text{PBH}} \mathcal{J}}{4\pi M_{\text{PBH}}^{\text{mb}}} \frac{d^2N_{\nu}^{\text{mb}}}{dEdt}$$

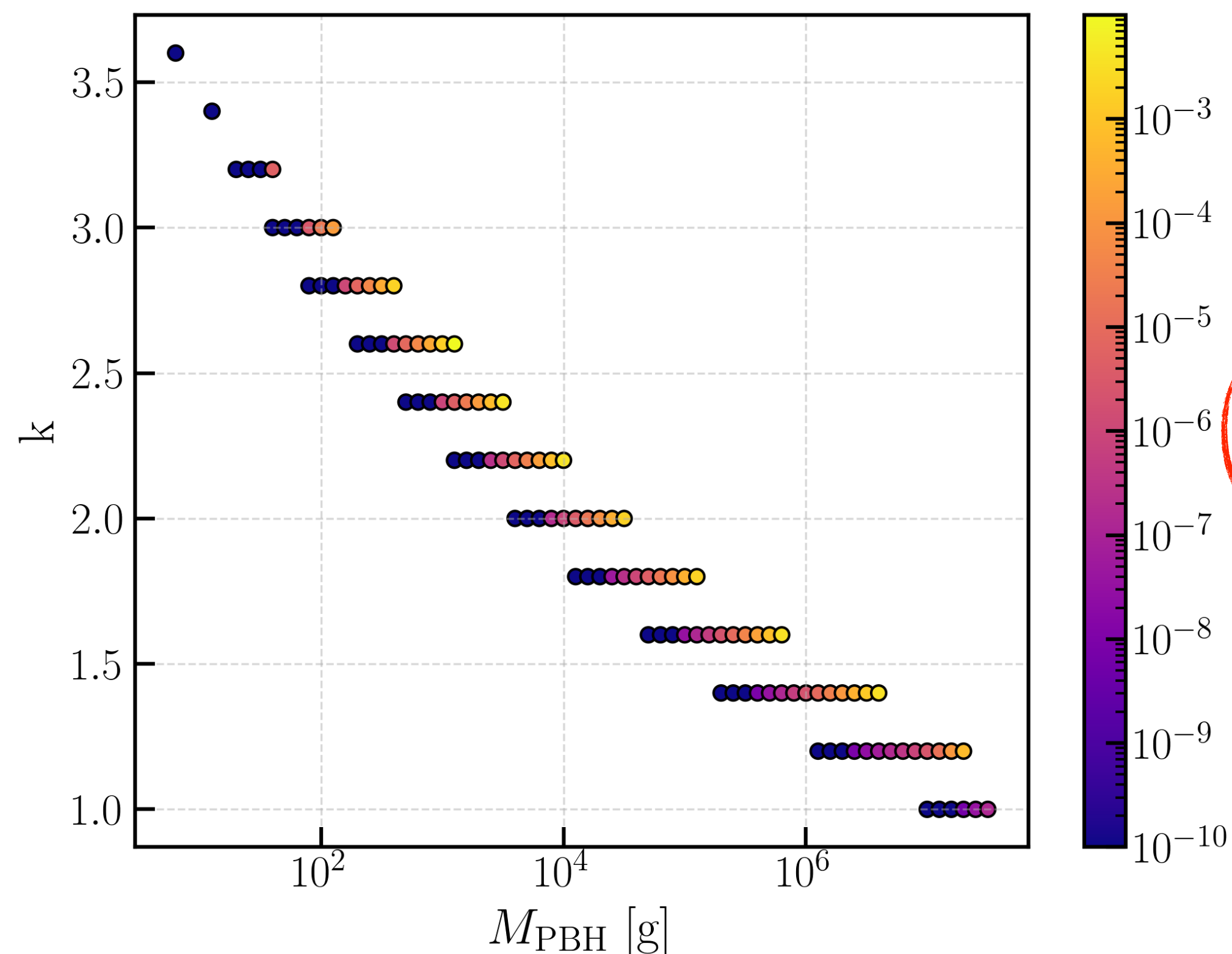


Boccia, A., & Iocco, F. (2025). Could the KM3-230213A event be caused by an evaporating primordial black hole?. *Phys. Rev. D*, 112(6), 063045.

THE KM3-230213A EVENT

Could the KM3-230213A event be caused by an evaporating PBH?

We scanned the $(M_{\text{PBH}} - k)$ parameter space to select the most promising candidates able to produce at least one event within 6 months.



f_{PBH}

$$\frac{d^2 \phi_\nu^{\text{gal}}}{dE d\Omega} = \frac{f_{\text{PBH}} \mathcal{J}}{4\pi M_{\text{PBH}}^{\text{mb}}} \frac{d^2 N_\nu^{\text{mb}}}{dE dt}$$

Boccia, A., & Iocco, F. (2025). Could the KM3-230213A event be caused by an evaporating primordial black hole?. *Phys. Rev. D*, 112(6), 063045.

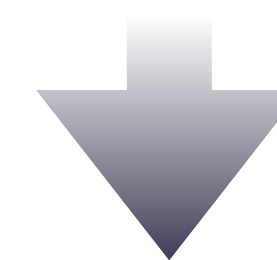
THE KM3-230213A EVENT

Could the KM3-230213A event be caused by an evaporating PBH?

We then accounted for the existing constraints on f_{PBH} and the actual exposure time of the observed event (335 days).

M_{PBH} [g]	k	f_{PBH}	t_{KM} [yr]
7.9×10^5	1.4	7.9×10^{-8}	22
7.9×10^5	1.6	2.2×10^{-3}	22
1.0×10^6	1.4	3.3×10^{-7}	22
1.0×10^6	1.6	1.0×10^{-2}	22
1.3×10^6	1.2	4.0×10^{-11}	22
1.3×10^6	1.4	1.4×10^{-6}	22
1.3×10^6	1.6	4.5×10^{-2}	22
1.6×10^6	1.2	1.5×10^{-10}	22

For all the candidates and for the **335 days** exposure time, the probability that the KM3-230213A event was produced by a burdened evaporating PBH is $\ll 1$.



A strike of luck!

Full multi-messenger analysis in order.

CONCLUSIONS

- PBHs are viable DM candidates and exhibit a rich phenomenology (falsifiability);
- Memory Burden (MB) extends mass range for PBHs as DM;
- Evaporating MB PBHs have observables in the local Universe;
- MB PBHs evaporating today: UHE gamma rays and neutrinos $\left(E_{\gamma/\nu} = \mathcal{O}(10 \text{ PeV})\right)$;
- Burdened PBHs can in principle explain the KM3-230213A event;
- Future neutrino (and gamma) observations provide test of MB PBH scenario.

BACKUP SLIDES

MEMORY BURDEN EFFECT

Memory Burden*: *The information stored in a system resists its decay.*

- **Mechanism**: information is prevented to leave the system due to suppressed energy gaps between internal *memory modes*.
- **Universality**: any system with efficient information storage inevitably experiences memory burden.

MEMORY BURDEN EFFECT

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Why do we expect memory burden to apply to black holes?

MEMORY BURDEN EFFECT

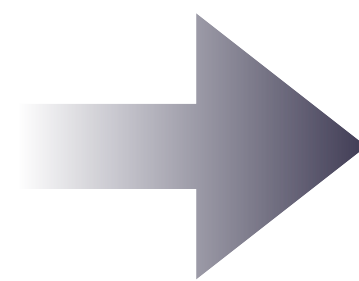
Memory Burden*: *The information stored in a system resists its decay.*

- **Mechanism**: information is prevented to leave the system due to suppressed energy gaps between internal *memory modes*.
- **Universality**: any system with efficient information storage inevitably experiences memory burden.

Why do we expect memory burden to apply to black holes?

The most efficient information storages in QFT are the **saturons**. They share properties with BHs:

- **Information horizon.**
- **Area-law entropy.**
- **Thermal decay.**
- **Page-like time for information retrieval.**



**For a direct analogy see
BH's Quantum N-Portrait:**

Gia Dvali and Cesar Gomez, "Black Hole's Quantum N-Portrait," Fortsch. Phys. 61, 742–767 (2013), arXiv:1112.3359 [hep-th].

MEMORY BURDEN IN BLACK HOLES

What implications for PBHs?

Evaporation begins semi-classically until the PBH has reached a fraction q of its initial mass.

$$M_{\text{PBH}}^{\text{mb}} = qM_{\text{PBH}} \quad t_q = (1 - q^3)\tau_{\text{PBH}}$$

Back-reaction of quantum modes stored on the event horizon stabilizes the system, allowing light primordial black holes (PBHs) to survive until today.

$$S(M_{\text{PBH}}) = 4\pi GM_{\text{PBH}}^2$$

PBH Entropy

$$\frac{dM_{\text{PBH}}^{\text{mb}}}{dt} = S(M_{\text{PBH}})^{-k} \frac{dM_{\text{PBH}}}{dt}$$

Suppressed mass loss rate

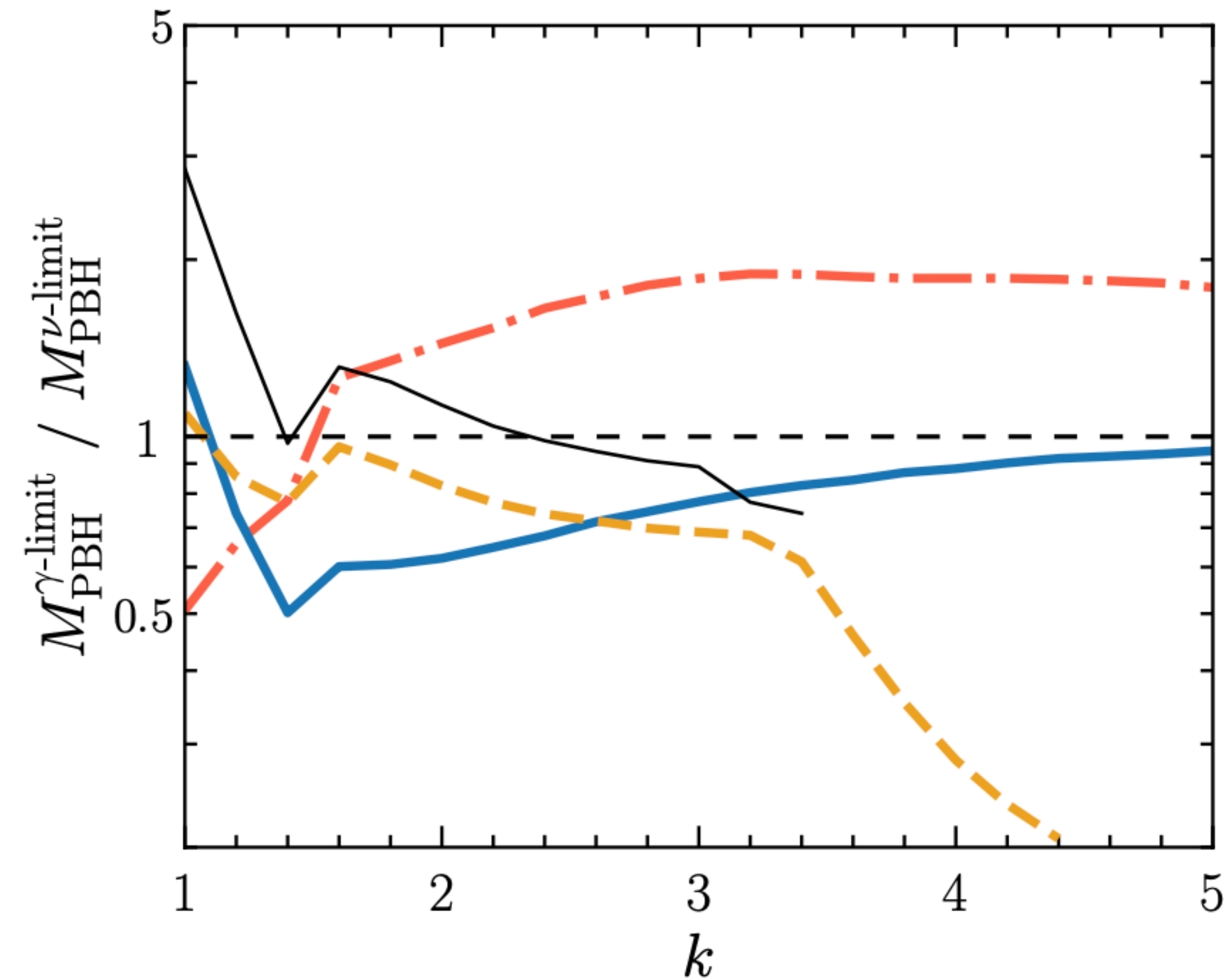
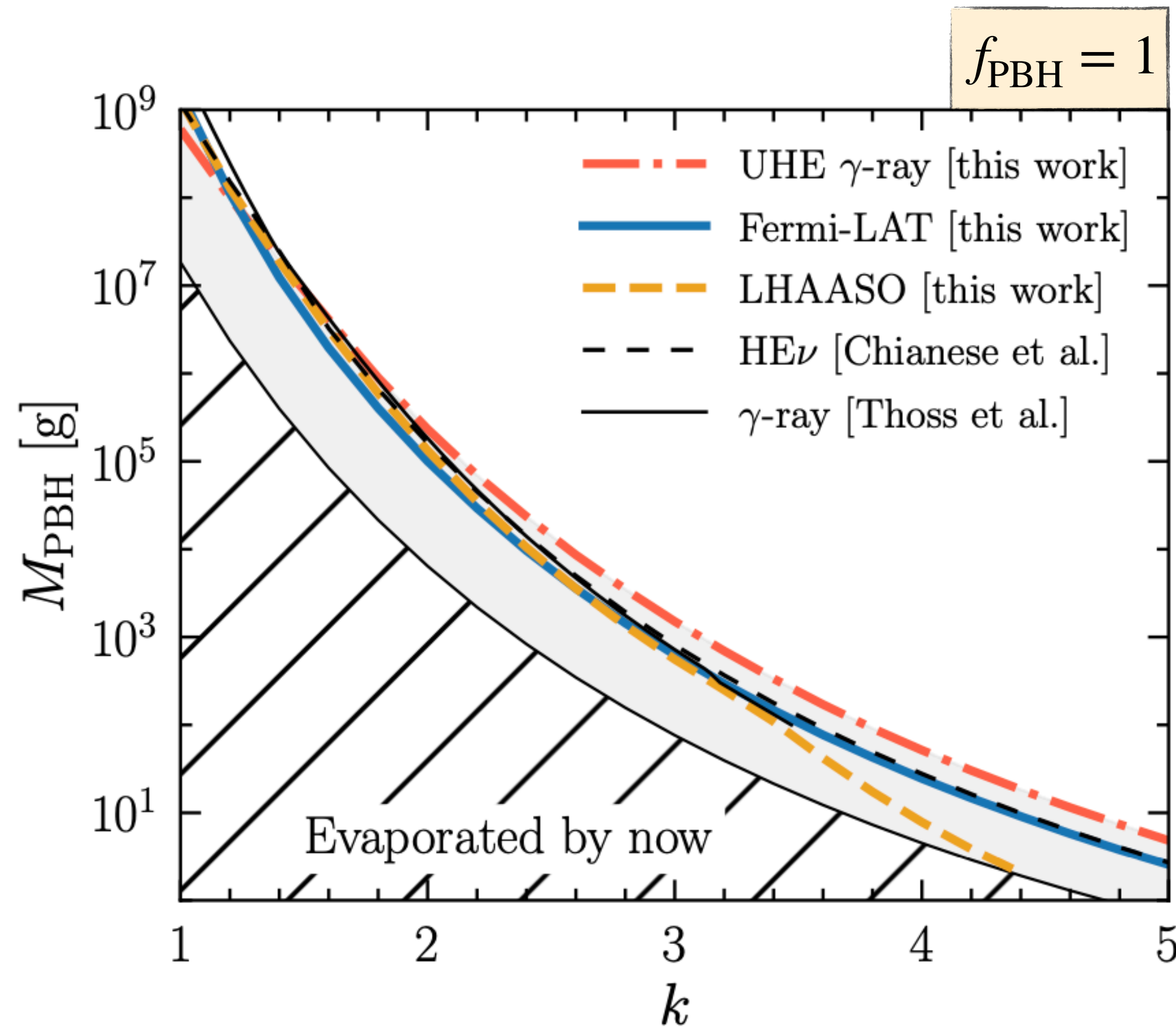
$$\frac{d^2 N_i^{\text{mb}}}{dtdE} = S(M_{\text{PBH}})^{-k} \frac{d^2 N_i}{dtdE}$$

Suppressed emission rate

k = memory burden “strength”

UHE PARTICLES FROM BURDENED PBHs

The same analysis can be performed with gamma-rays.



Chianese, M. (2025). High-energy gamma-ray emission from memory-burdened primordial black holes.

MEMORY BURDEN EFFECT

Memory Burden: *The information stored in a system resists its decay.*

$$\hat{H} = \hat{H}_{\text{ms}} + \hat{H}_{\text{mem}} \quad \left\{ \begin{array}{l} \hat{H}_{\text{ms}} = m_{\phi} \hat{n}_{\phi} \quad \text{Master Modes} \\ \hat{H}_{\text{mem}} = \left(1 - \frac{\hat{n}_{\phi}}{N_{\phi}}\right)^q \sum_j m_j \hat{n}_j \quad \text{Memory Modes} \end{array} \right.$$

Energy gaps: $\omega_j = \left(1 - \frac{n_{\phi}}{N_{\phi}}\right)^q m_j \rightarrow$ *“Assisted gaplessness”*: the master modes help the memory modes to become gapless.

Energy gaps between internal memory modes are significantly smaller than those between memory modes and external asymptotic modes, effectively preventing information from escaping the system.

Dvali, G., Valbuena-Bermúdez, J. S., & Zantedeschi, M. (2024). Memory burden effect in black holes and solitons: Implications for PBH. *Physical Review D*, 110(5), 056029.

MEMORY BURDEN IN BLACK HOLES

Why do we expect memory burden to apply to black holes?

Universality: it is impossible to construct a hermitian Hamiltonian with efficient information storage that avoids the memory burden phenomenon.

Information storage capacity = Microstate degeneracy

$$S \equiv \ln(n_{st}) \leq 1/\alpha = \pi R^2 f^2 \quad \longrightarrow \quad \text{QFT limit on microstate degeneracy}$$

An object that saturates this limit is called a *saturon*.

MEMORY BURDEN IN BLACK HOLES

Why do we expect memory burden to apply to black holes?

Similarity with saturons: BHs share with saturons many key-features.

- Information horizon;
- Area-law entropy;
- Thermal decay;
- Page-like time of information retrieval.

For a direct analogy we need a microscopic theory of a BH such as “BH quantum N-portrait”, which depicts a BH as a coherent condensate state of gravitons.

Gia Dvali and Cesar Gomez, “Black Hole’s Quantum N-Portrait,”
Fortsch. Phys. 61, 742–767 (2013), arXiv:1112.3359 [hep-th].

MEMORY BURDEN IN BLACK HOLES

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PBH Entropy

$$\frac{dM_{\text{PBH}}^{\text{mb}}}{dt} = S(M_{\text{PBH}})^{-k} \frac{dM_{\text{PBH}}}{dt}$$

Suppressed mass loss rate

$$\frac{d^2 N_i^{\text{mb}}}{dtdE} = S(M_{\text{PBH}})^{-k} \frac{d^2 N_i}{dtdE}$$

Suppressed emission rate

$$\Gamma_{\text{PBH}}^{(k)} = \frac{\mathcal{G} g_{\text{SM}}}{7680\pi} 2^k (3 + 2k) M_P \left(\frac{M_P}{M_{\text{PBH}}^{\text{mb}}} \right)^{3+2k}$$

Decay rate with MB

$$\tau_{\text{PBH}}^{(k)} = t_q + (\Gamma_{\text{PBH}}^{(k)})^{-1} \simeq (\Gamma_{\text{PBH}}^{(k)})^{-1}$$

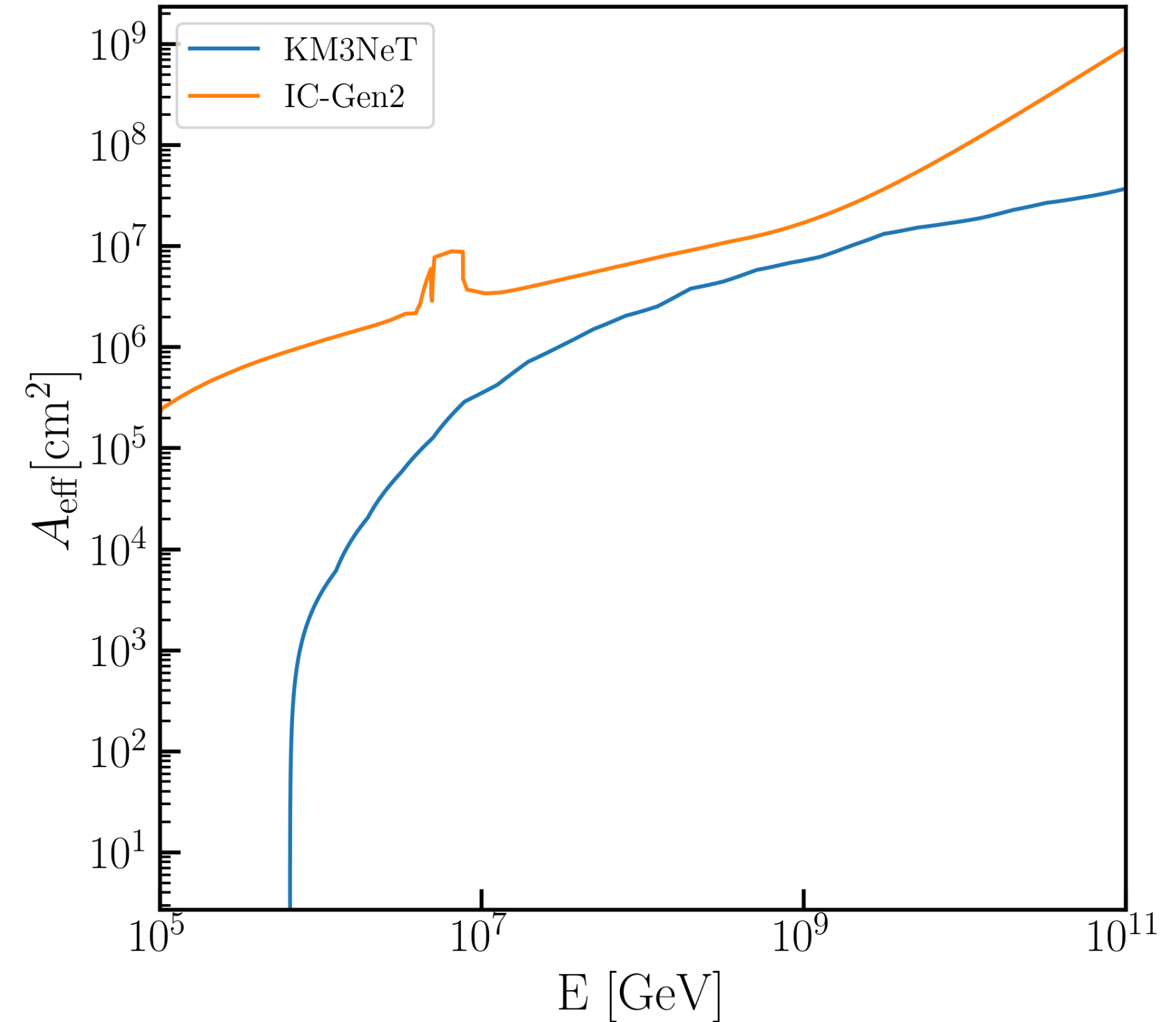
Lifetime with MB

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We then accounted for the existing constraints on f_{PBH} and the actual exposure time of the observed event (335 days).

M_{PBH} [g]	k	f_{PBH}	t_{KM} [yr]	t_{IC2} [yr]
7.9×10^5	1.4	7.9×10^{-8}	22	0.39
7.9×10^5	1.6	2.2×10^{-3}	22	0.39
1.0×10^6	1.4	3.3×10^{-7}	22	0.35
1.0×10^6	1.6	1.0×10^{-2}	22	0.35
1.3×10^6	1.2	4.0×10^{-11}	22	0.32
1.3×10^6	1.4	1.4×10^{-6}	22	0.32
1.3×10^6	1.6	4.5×10^{-2}	22	0.32
1.6×10^6	1.2	1.5×10^{-10}	22	0.30



THE KM3-230213A EVENT

Clash of the Titans: ultra-high energy KM3NeT event versus IceCube data

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²*Theoretical Physics Department, Fermilab, P.O. Box 500, Batavia, IL 60510, USA*

³*Departamento de Física Teórica and Instituto de Física Teórica UAM/CSIC,
Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain*

⁴*Department of Physics and Institute for Fundamental Science, University of Oregon
Eugene, Oregon 97403, USA*

(Dated: February 28, 2025)

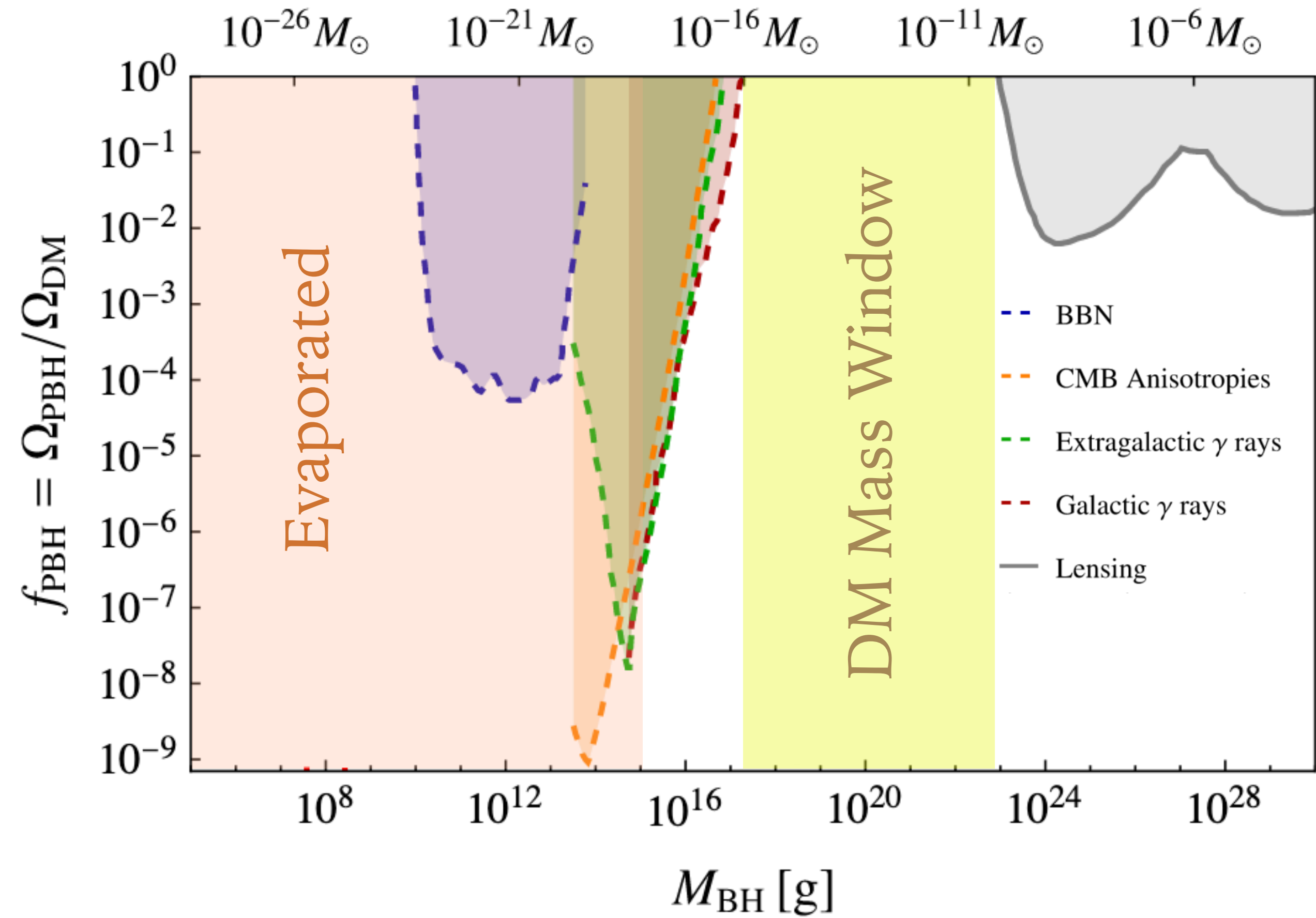
KM3NeT has reported the detection of a remarkably high-energy through-going muon. Lighting up about a third of the detector, this muon likely originated from a neutrino exceeding 10 PeV in energy. The crucial question we need to answer is where this event comes from and what its source is. Intriguingly, IceCube has been operating with a much larger effective area for a considerably longer time, yet it has not reported neutrinos above 10 PeV. We quantify the tension between the KM3NeT event and the absence of similar high-energy events in IceCube. Through a detailed analysis, we determine the most likely neutrino energy to be in the range of 23 – 2400 PeV. We find a 3.5 σ tension between the two experiments, assuming the neutrino is from the diffuse isotropic neutrino flux. Alternatively, assuming the event is of cosmogenic origin and considering three representative models, this tension still falls within 3.1 – 3.6 σ . The least disfavored scenario is a steady or transient point source, though still leading to 2.9 σ and 2.0 σ tensions, respectively. The lack of observation of high-energy events in IceCube seriously challenges the explanation of this event coming from any known diffuse fluxes. Our results indicate the KM3NeT event is likely the first observation of a new astrophysical source.

MASS WINDOW FOR PBHS AS DM

Asteroidal/planetary mass

$$10^{18} \text{g} \lesssim M_{\text{PBH}} \lesssim 10^{24} \text{g}$$

$$T_{\text{H}} \lesssim 1 \text{keV}$$



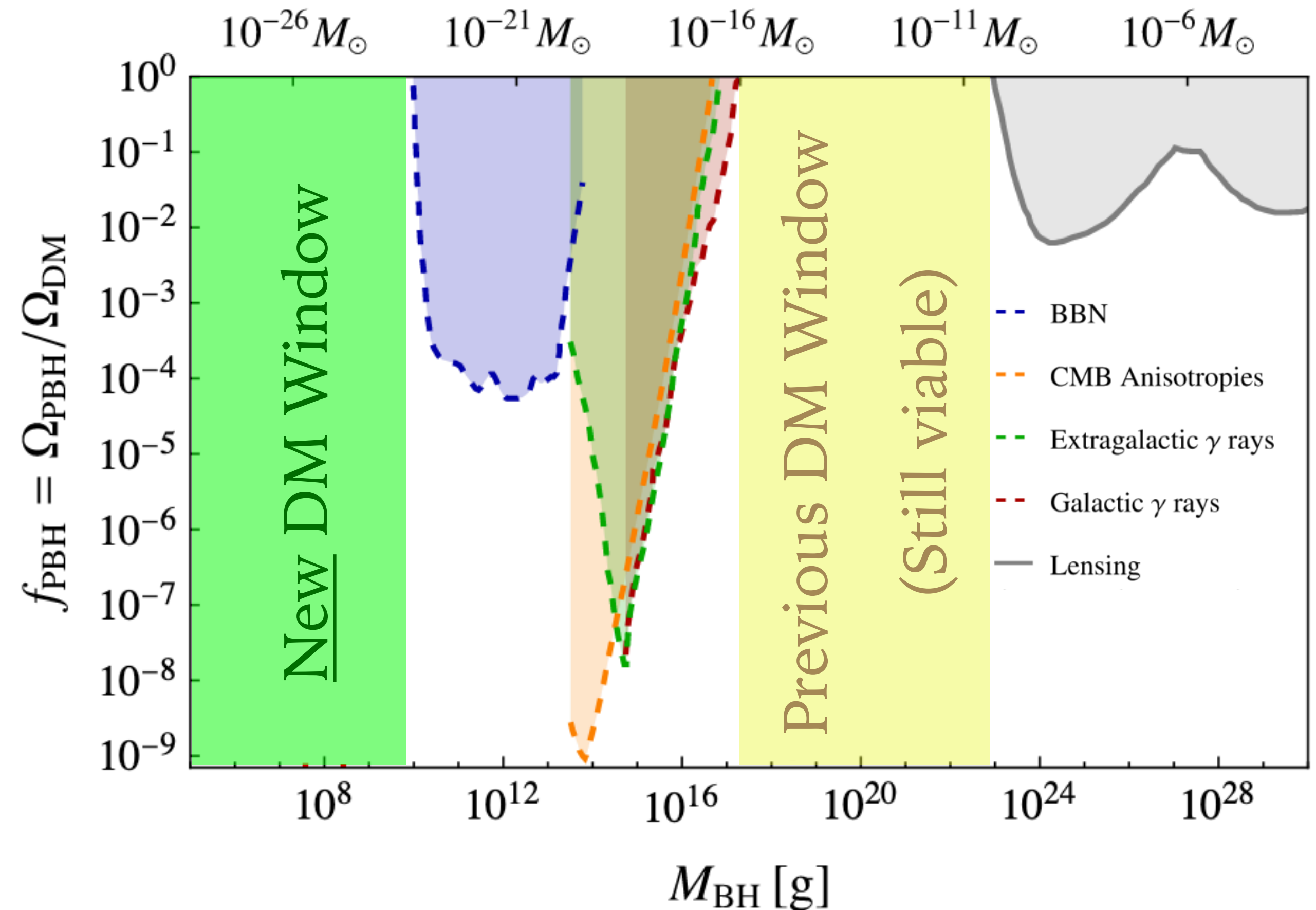
NEW MASS WINDOW FOR PBHS AS DM

Memory burden allows PBHs with mass $M_{\text{PBH}} < 10^{15}\text{g}$ to survive until today.

PBHs that enter the “burdened” phase before BBN are mostly unconstrained.

New mass window for DM!

$$M_{\text{PBH}} \lesssim 10^9\text{g}$$



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PBHs

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Memory Burden

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Gia Dvali and Cesar Gomez, "Black Hole's Quantum N-Portrait," *Fortsch. Phys.* 61, 742–767 (2013), arXiv:1112.3359 [hep-th].

Alexandre, A., Dvali, G., & Koutsangelas, E. (2024). New mass window for primordial black holes as dark matter from the memory burden effect. *Phys. Rev. D*, 110(3), 036004. <https://doi.org/10.1103/PhysRevD.110.036004>

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Phenomenology

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