SSM Scuola Superiore Meridionale

PhD SPACE
Cosmology, Space Science & Space Technology

Based on arXiv 2502.19245 (PRD 112) and arXiv:2410.07604 (PRD 111)

PRIMORDIAL BLACK HOLES AND THE "MEMORY BURDEN" EFFECT: OBSERVABLES IN THE LOCAL UNIVERSE

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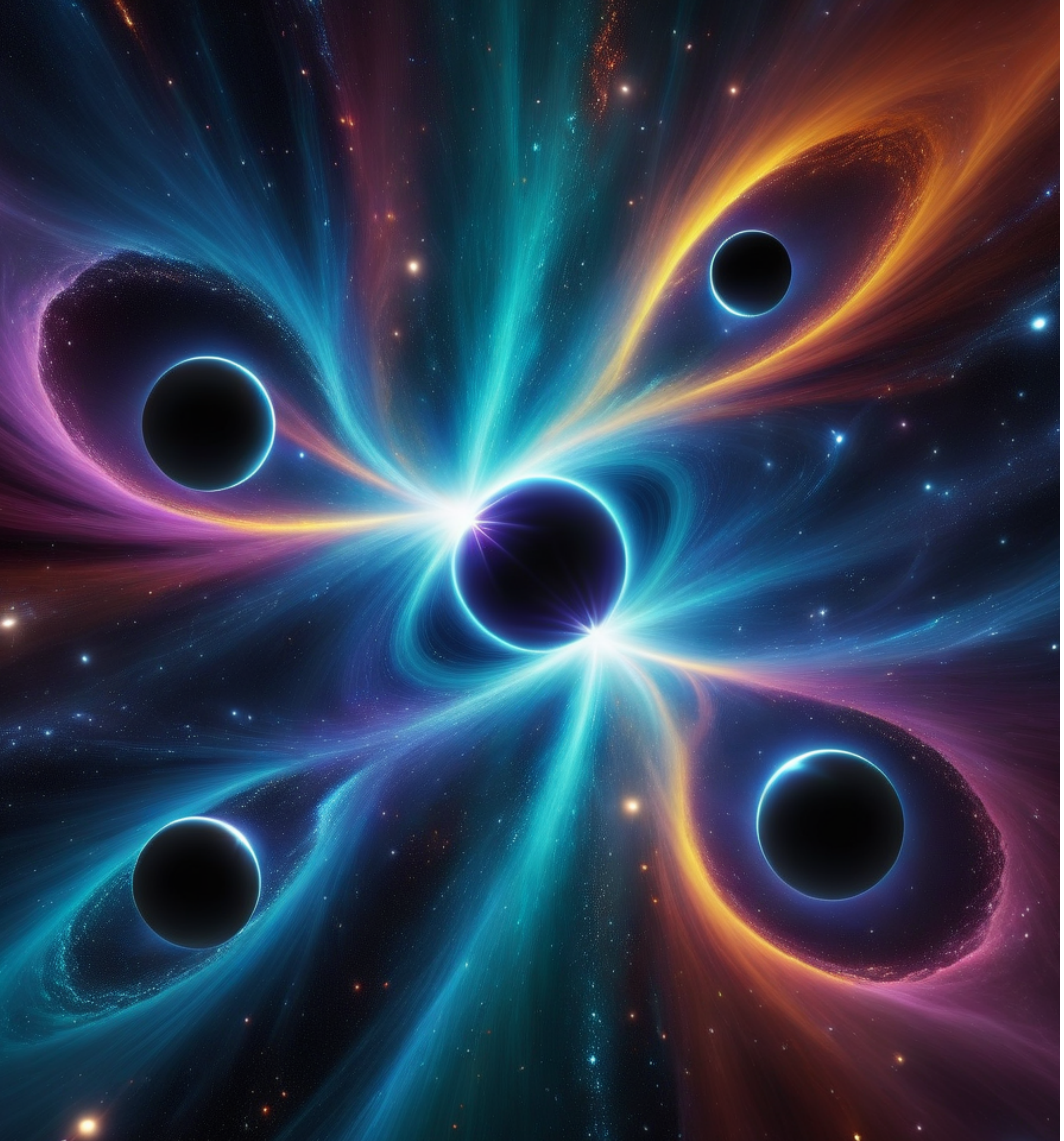


OUTLINE

- Black Hole evaporation;
- Memory Burden effect;
- Memory Burden in PBHs;
- New mass window for PBHs as DM;
- UHE particles from burdened PBHs;
- The KM3-230213A event.

BLACK HOLE EVAPORATION

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

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

Hawking Temperature

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

BH Life-Time

$$\frac{d^2 N_i}{dt dE} = \frac{g_i}{2\pi} \frac{\mathcal{G}(E, M_{\rm BH})}{e^{E/T_{\rm H}} \pm 1}$$

Emitted Spectra

$$T_{\rm H}\left(10^{18}{\rm g}\right) \lesssim 10\,{\rm keV}$$

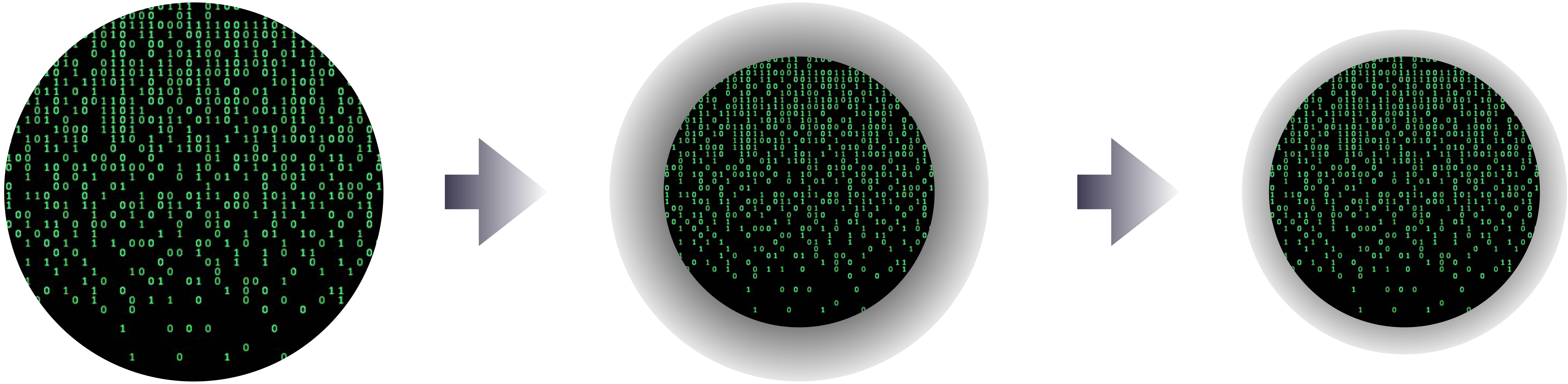
MEMORY BURDEN EFFECT

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

High capacity information storage (black hole)

Thermal decay

Stabilized system (suppressed flux)



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

Thermal radiation doesn't carry information from BH.

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.

$$S(M_{\rm PBH}) = 4\pi G M_{\rm PBH}^2$$

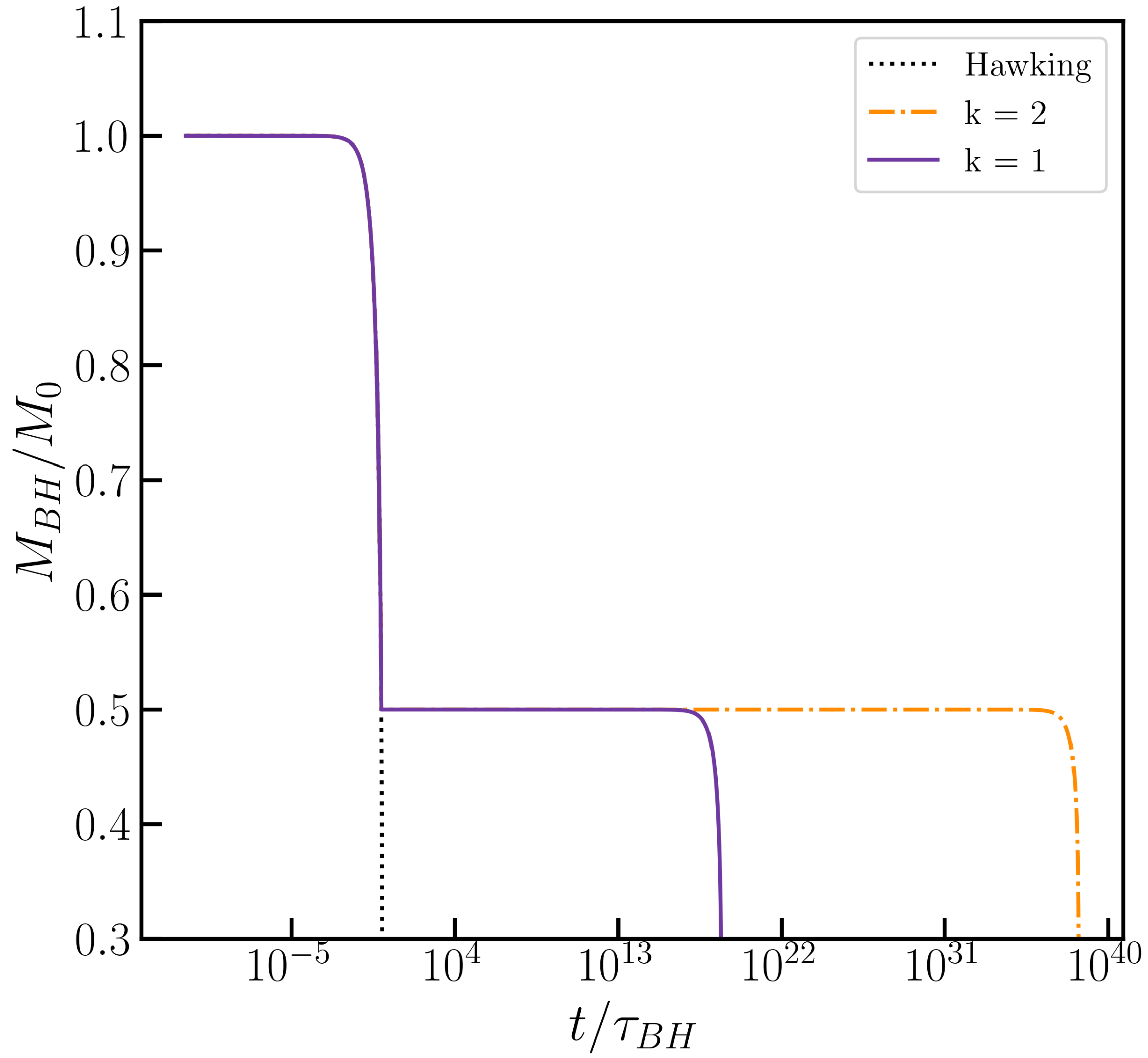
PBH Entropy

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

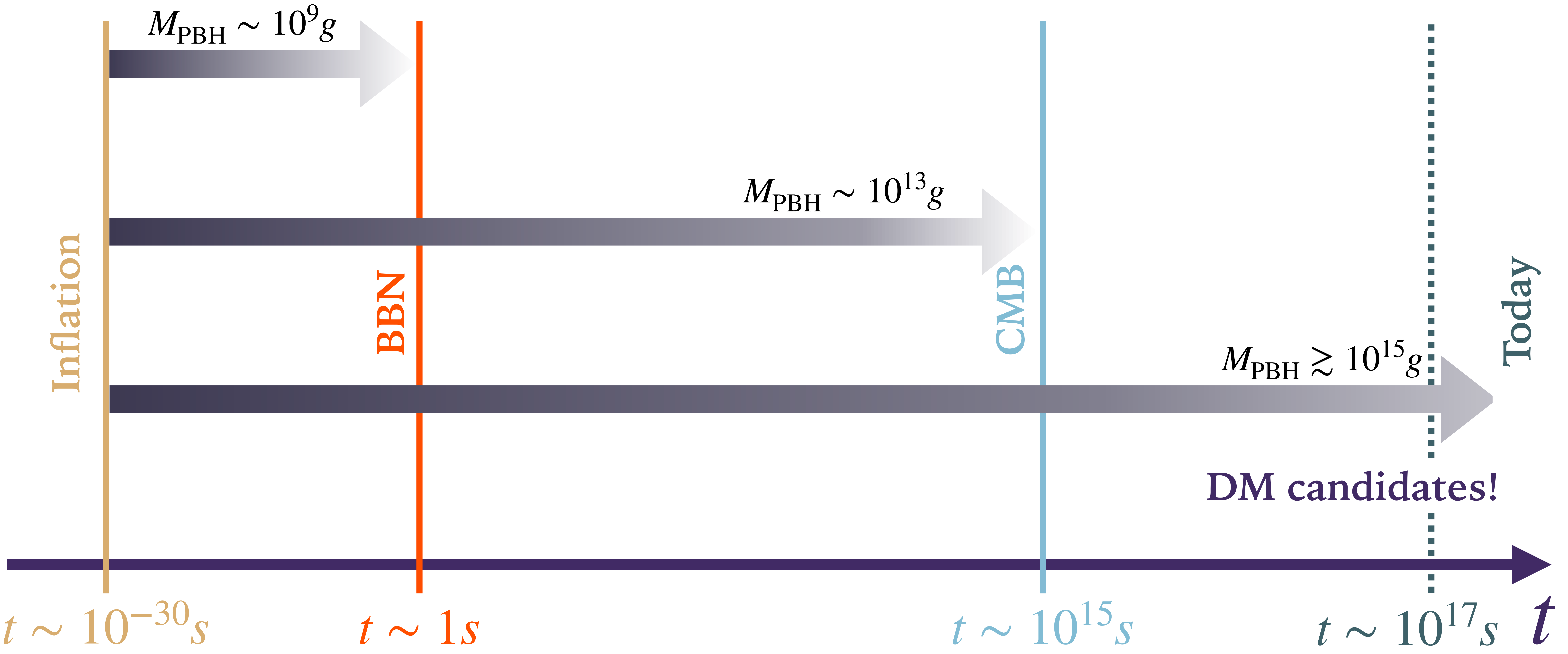
Suppressed mass loss rate

k = memory burden “strength”

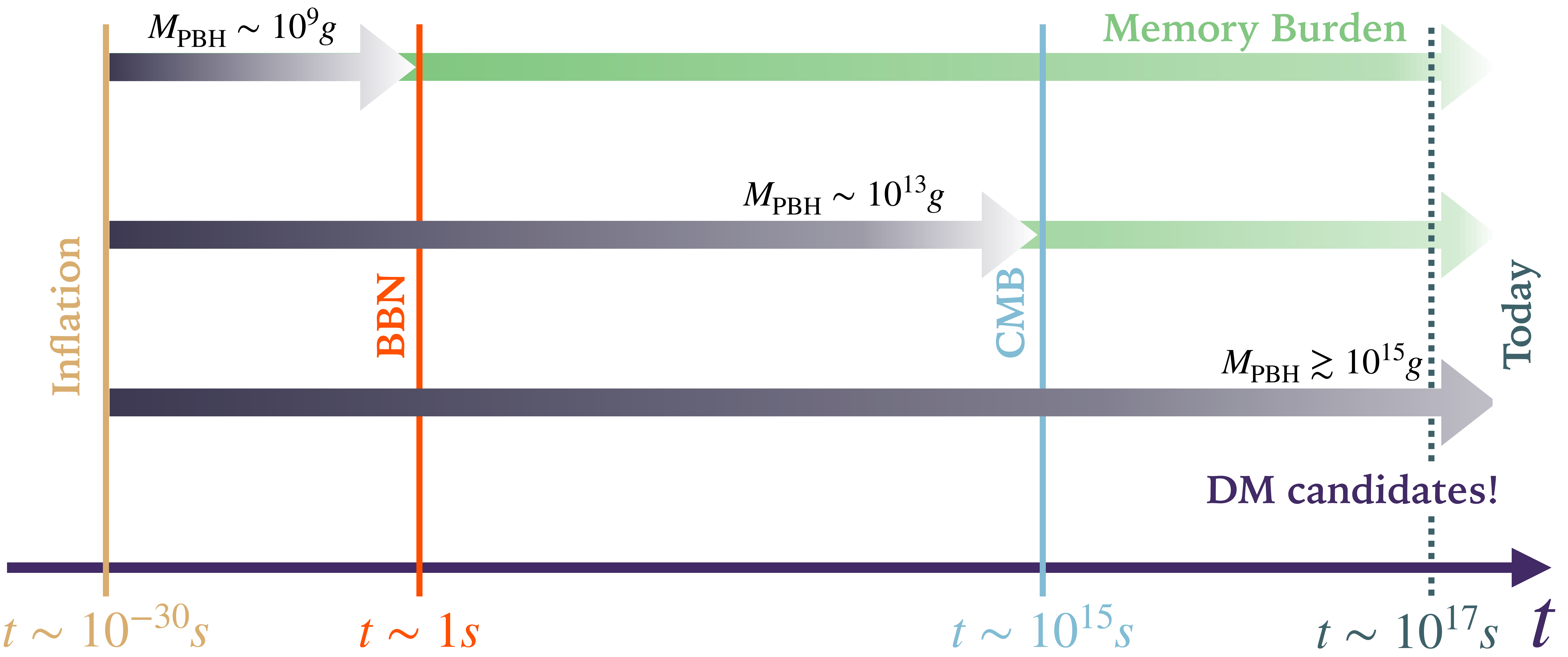
Details of transitioning debated in:
arXiv:2503.21740 and arXiv:2503.21005



MEMORY BURDEN IN BLACK HOLES



MEMORY BURDEN IN BLACK HOLES



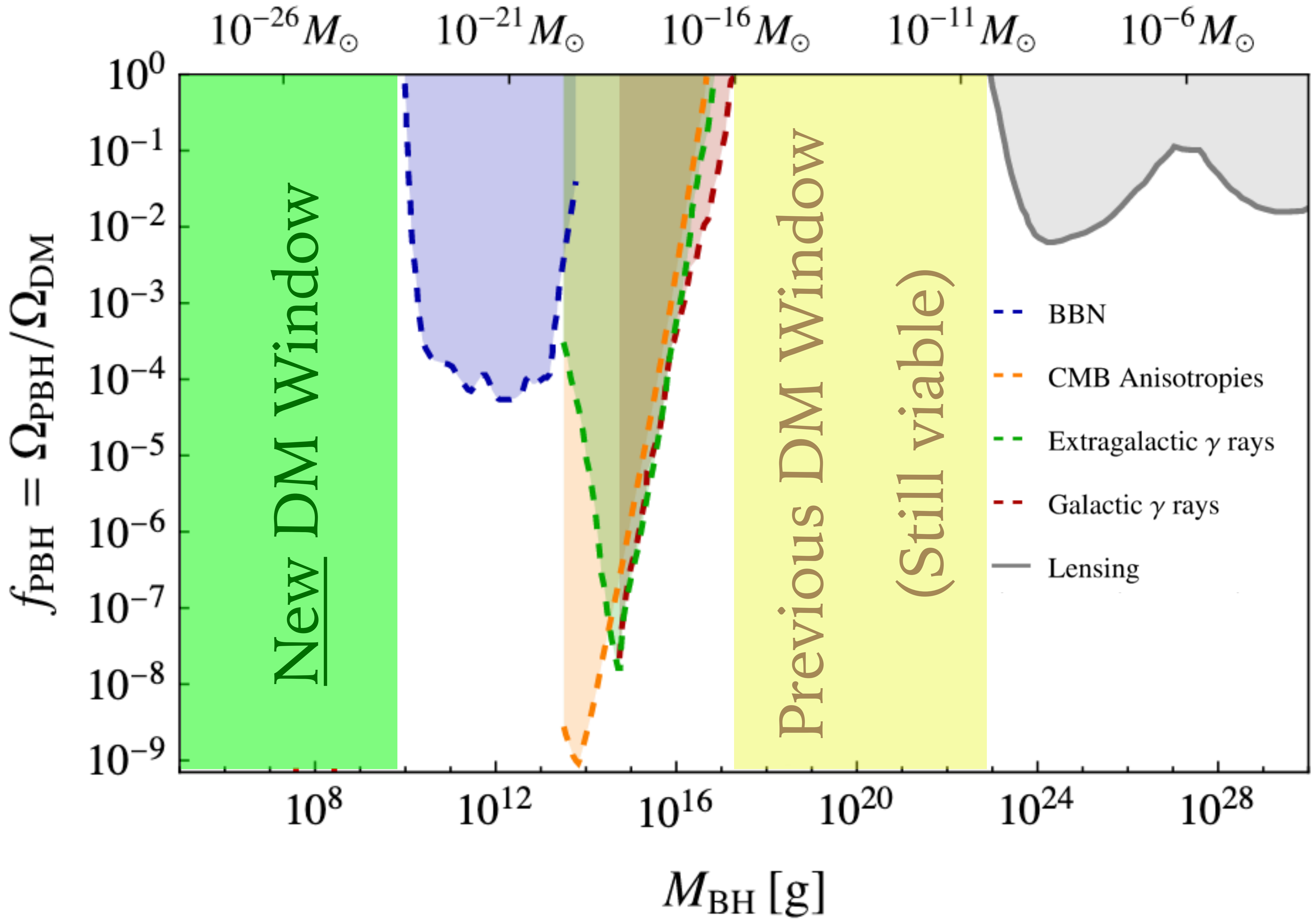
NEW MASS WINDOW FOR PBHS AS DM

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

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

New mass window for DM!

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



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

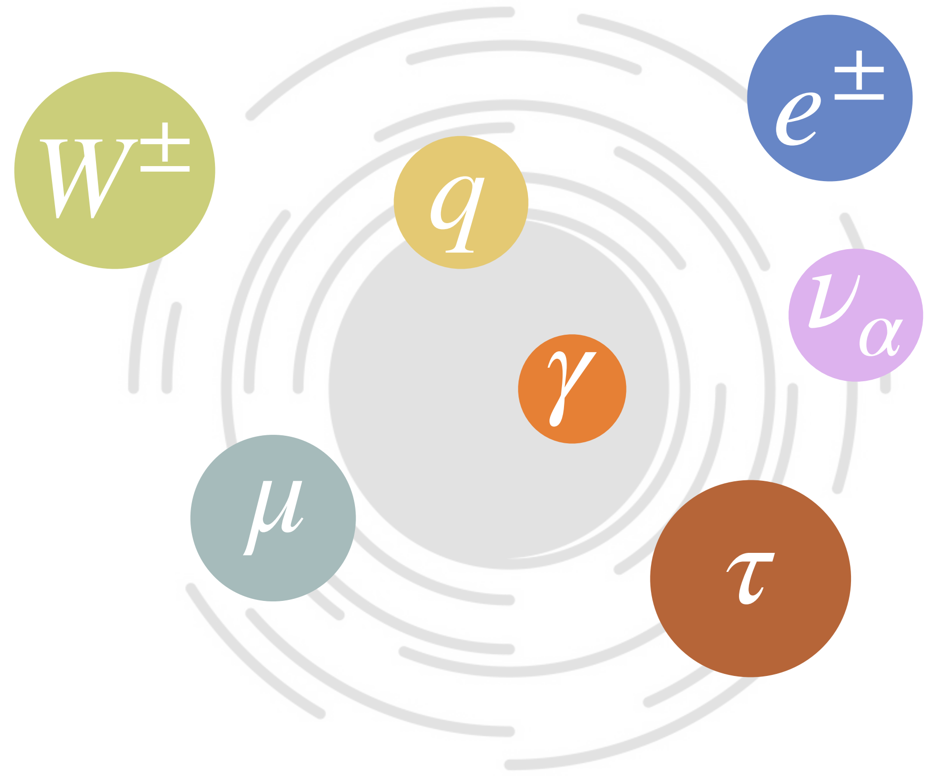
UHE NEUTRINOS FROM BURDENED PBHS

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.

$$M_{\rm PBH} \leq 10^9 {\rm g} \quad \Rightarrow \quad T_{\rm H} \geq 10^4\,{\rm GeV}$$

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 ?

Galactic:

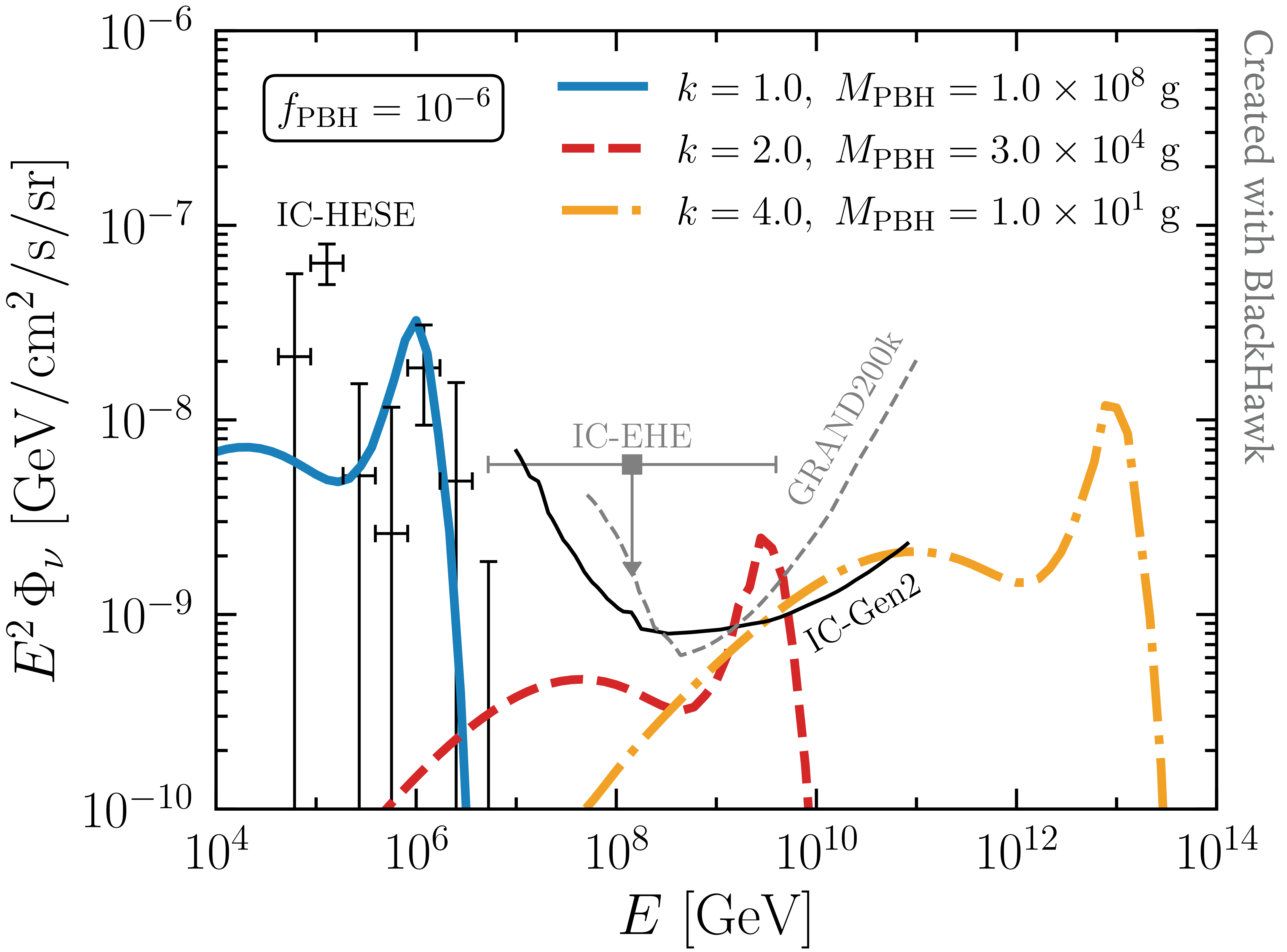
$$\frac{d^2\phi^{gal}_{\nu_\alpha}}{dE d\Omega} = \frac{f_{PBH}\,\mathcal{J}}{4\pi M^{mb}_{PBH}} \frac{d^2N^{mb}_{\nu_\alpha}}{dEdt}$$

Extra-galactic: (subleading)

$$\frac{d^2\phi^{egal}_{\nu_\alpha}}{dE d\Omega} = \frac{f_{PBH}\,\rho_{DM}}{4\pi M^{mb}_{PBH}} \int_{t_{min}}^{t_{max}} dt\,\left[1+z(t)\right] \frac{d^2N^{mb}_{\nu_\alpha}}{dEdt}$$

All-flavour sum:

$$\Phi_\nu = \sum_\alpha \left(\frac{d^2\Phi^{gal}_{\nu_\alpha}}{dEd\Omega} + \frac{d^2\Phi^{egal}_{\nu_\alpha}}{dEd\Omega} \right)$$



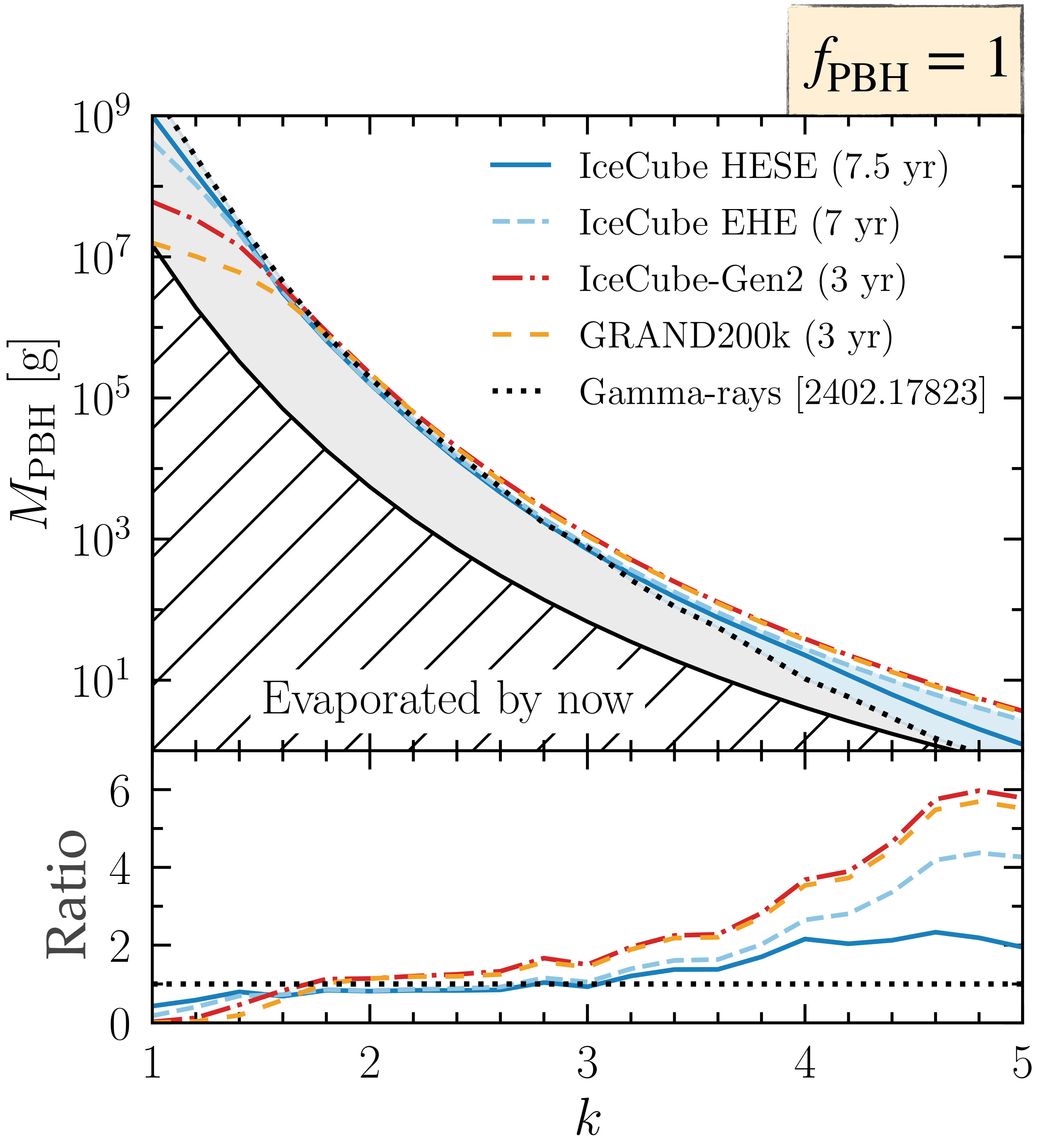
Chianese, M., **Boccia, A.,** Iocco, F., Miele, G., & Saviano, N. (2025). Light burden of memory: Constraining primordial black holes with high-energy neutrinos. Phys. Rev. D, 111(6), 063036. https://doi.org/10.1103/PhysRevD.111.063036

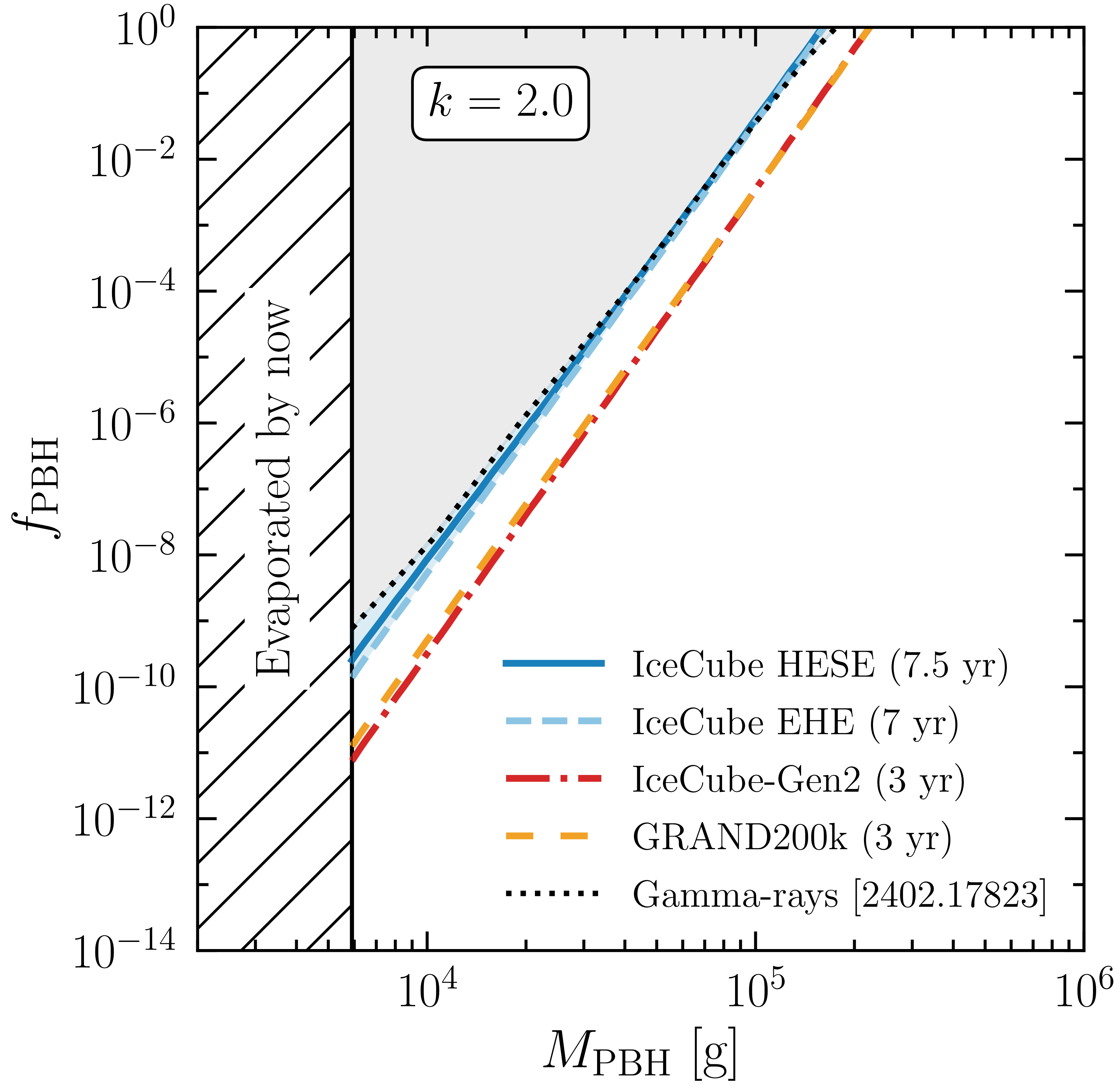
UHE NEUTRINOS FROM BURDENED PBHS

We can compare our results with current and future observations from neutrino observatories.

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

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





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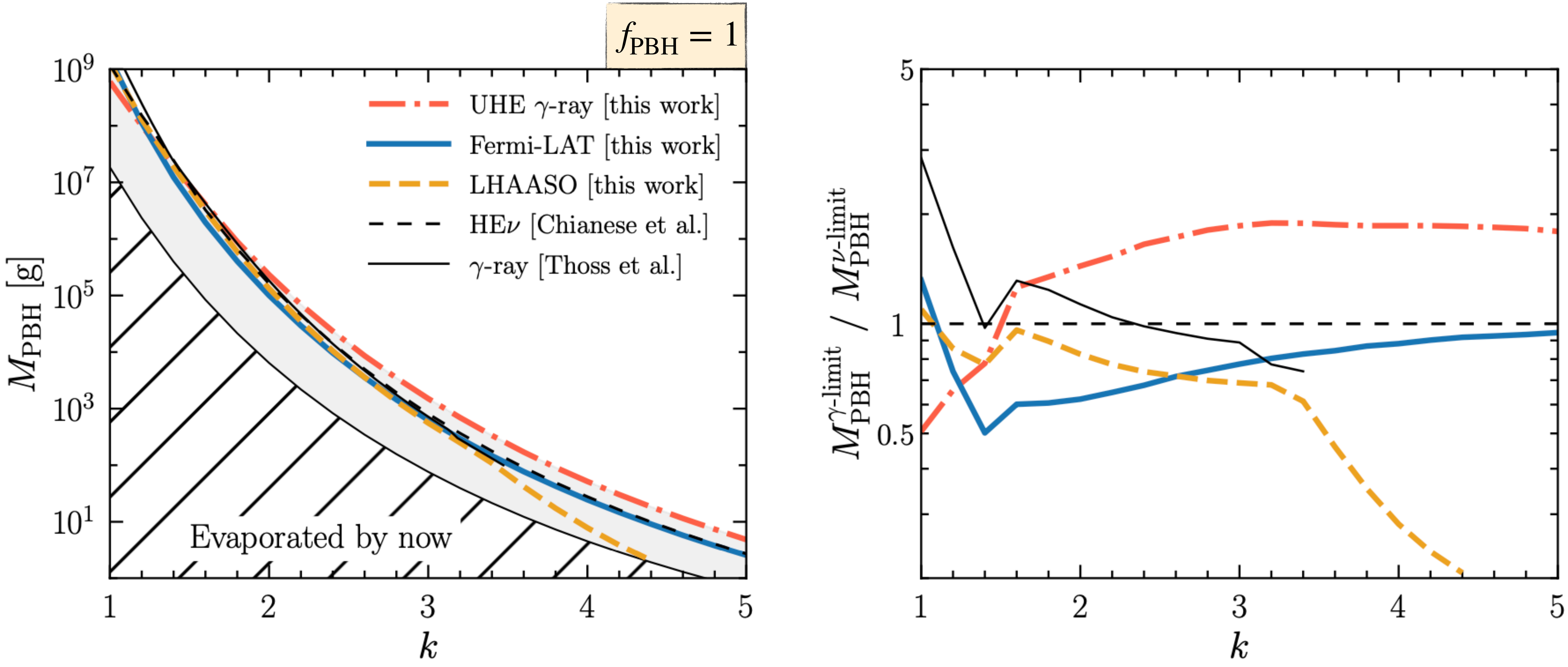
UHE PARTICLES FROM BURDENED PBHS

The same analysis can be performed with gamma-rays.



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

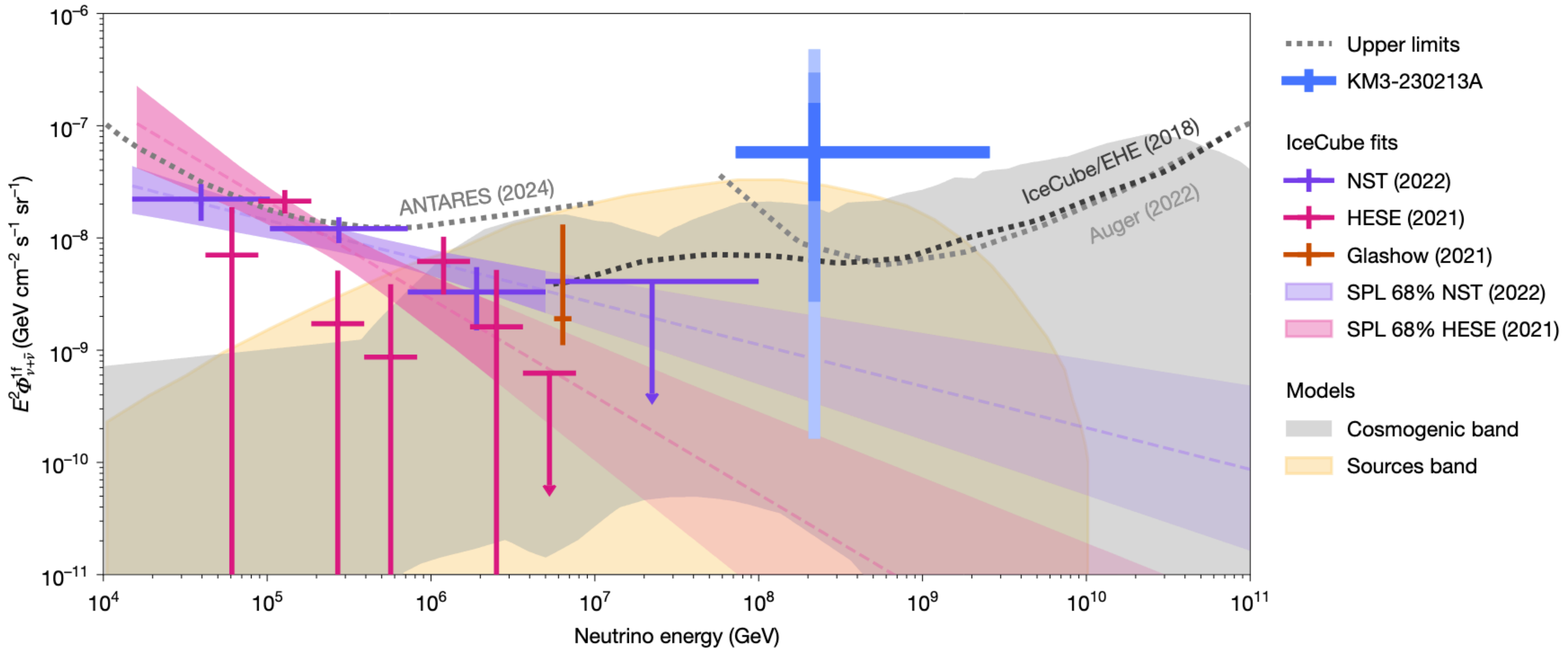
THE KM3–230213A EVENT

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

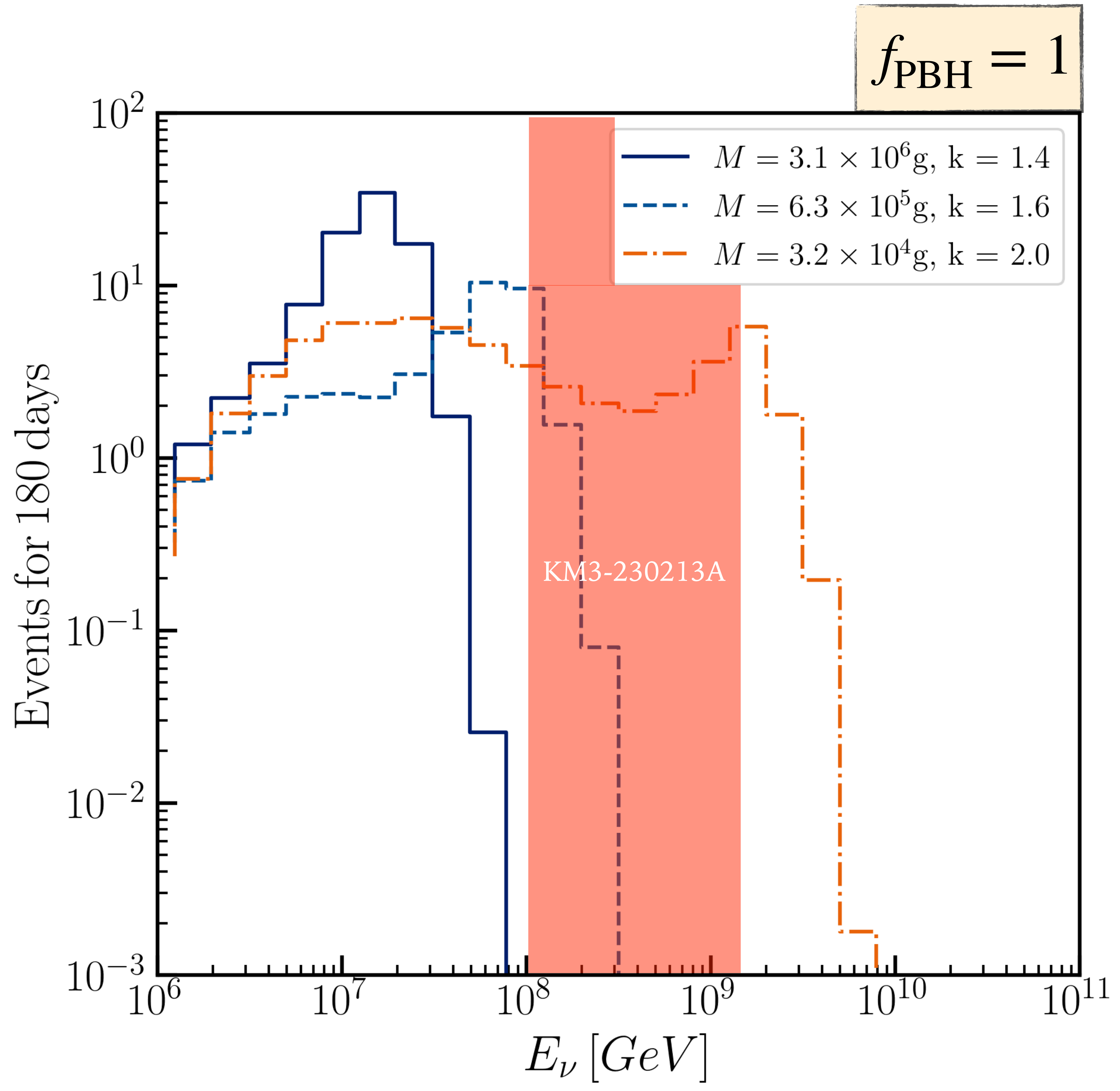
THE KM3–230213A EVENT

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

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

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

$$\phi_\nu(E) \simeq \frac{d^2\phi_\nu^{\rm gal}}{dE d\Omega} = \frac{f_{\rm PBH}\,\mathcal{J}}{4\pi M_{\rm PBH}^{\rm mb}} \frac{d^2 N_\nu^{\rm mb}}{dE dt}$$

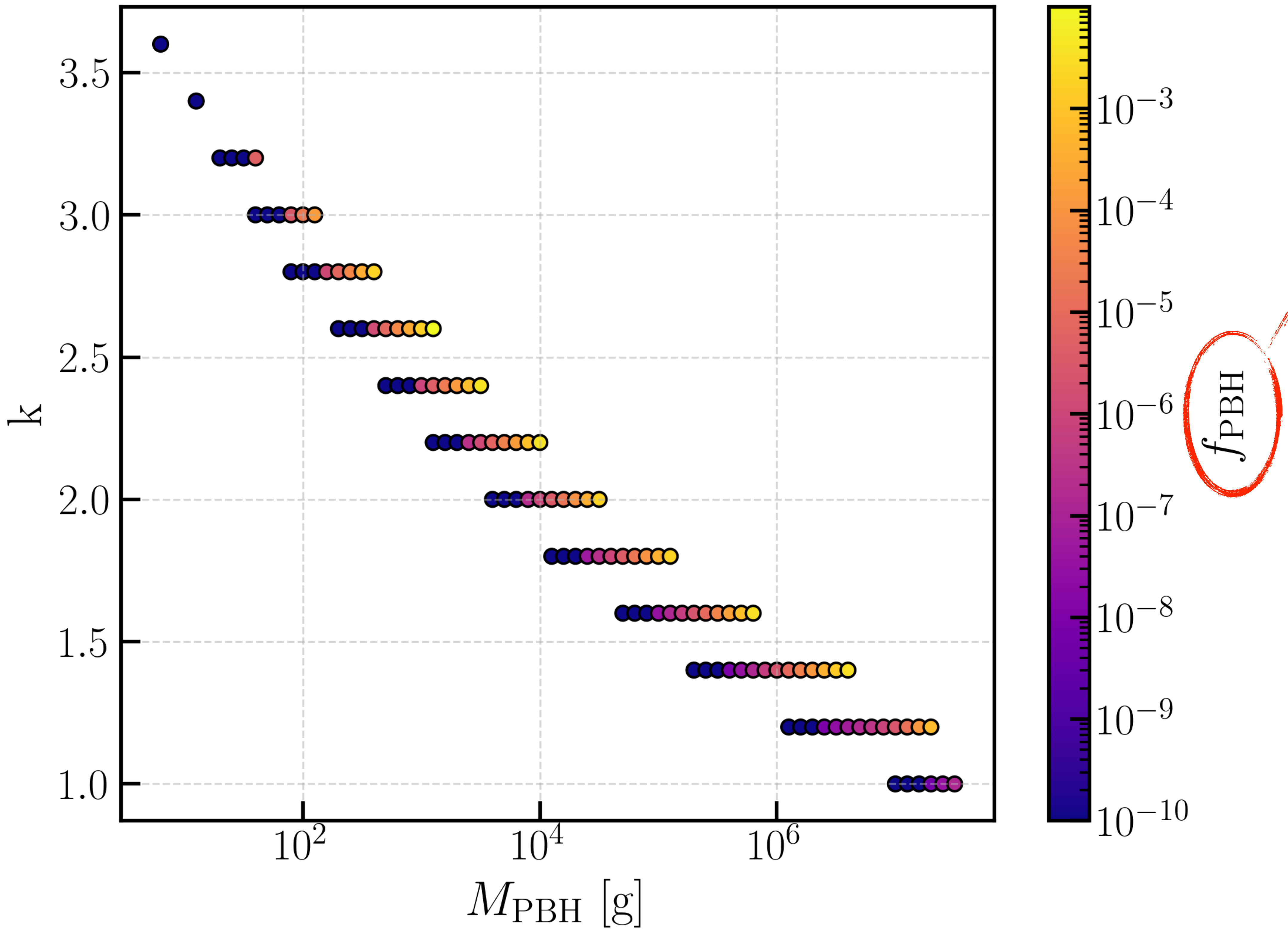


Boccia, A., & Iocco, F. (2025). Could the KM3–230213A event be caused by an evaporating primordial black hole?. *Phys. Rev. D, 112(6), 063045*.

THE KM3–230213A EVENT

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

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



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

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

Full multi-messenger analysis in order.

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!

SUMMARY

- 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 $\left(E_{\gamma/\nu} = \mathcal{O}(10\,\mathrm{PeV})\right)$;
- 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

*See next talk by Sebastian Zell

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?

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

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- **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 EFFECT

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

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

Energy gaps: $\omega_j = \left(1 - \dfrac{n_\phi}{N_\phi}\right)^q m_j$ → ***"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

$$S \equiv ln(n_{st}) \leq 1/\alpha = \pi R^2 f^2$$

→ **QFT limit on microstate degeneracy**

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

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

What implications for PBHs?

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

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

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

$$S(M_{\rm PBH}) = 4\pi G M_{\rm PBH}^2$$

PBH Entropy

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

Suppressed mass loss rate

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

Suppressed emission rate

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

Decay rate with MB

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

Lifetime with MB

MEMORY BURDEN IN BLACK HOLES

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k = memory burden “strength”

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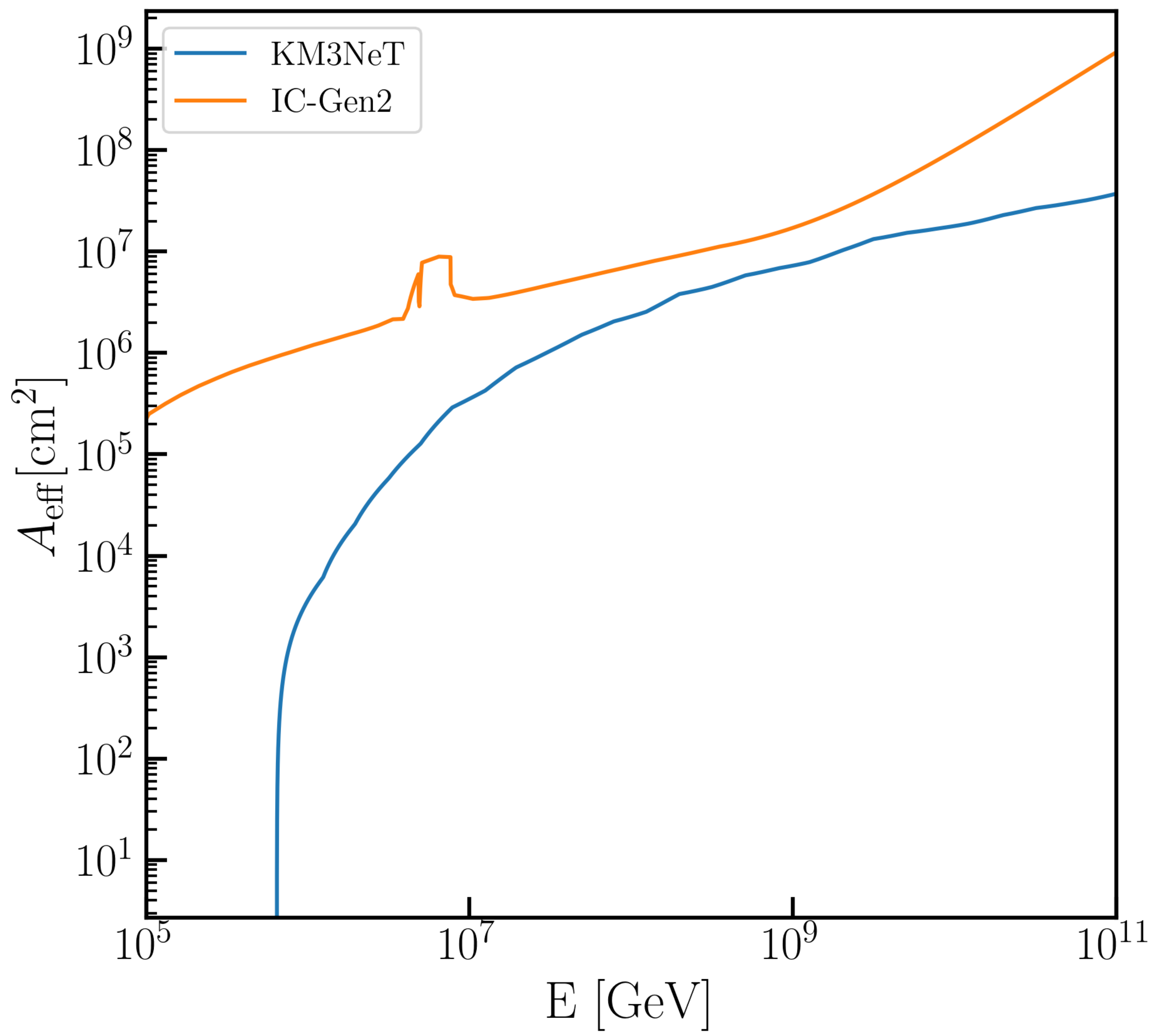
7.9×10^5	1.6	2.2×10^{-3}	22	0.39
1.0×10^6	1.4	3.3×10^{-7}	22	0.35
1.0×10^6	1.6	1.0×10^{-2}	22	0.35
1.3×10^6	1.2	4.0×10^{-11}	22	0.32
1.3×10^6	1.4	1.4×10^{-6}	22	0.32
1.3×10^6	1.6	4.5×10^{-2}	22	0.32
1.6×10^6	1.2	1.5×10^{-10}	22	0.30



THE KM3-230213A EVENT

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

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[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 3.5σ 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 $3.1 - 3.6\sigma$. The least disfavored scenario is a steady or transient point source, though still leading to 2.9σ and 2.0σ 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.