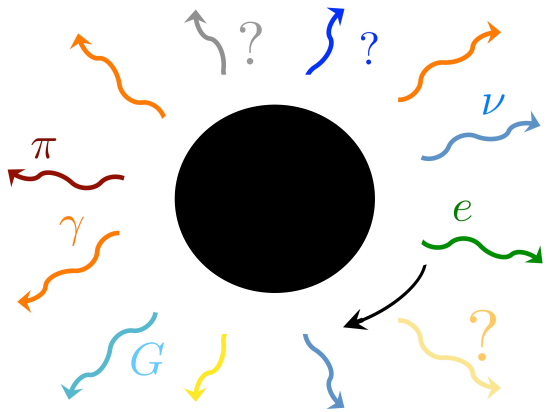
Evaporating Kerr black holes as probes of new physics

(in the string axiverse)



João G. Rosa

University of Coimbra, Portugal

arXiv:2312.09261 (with Marco Calzà)

New Horizons in Primordial Black Holes, Edinburgh

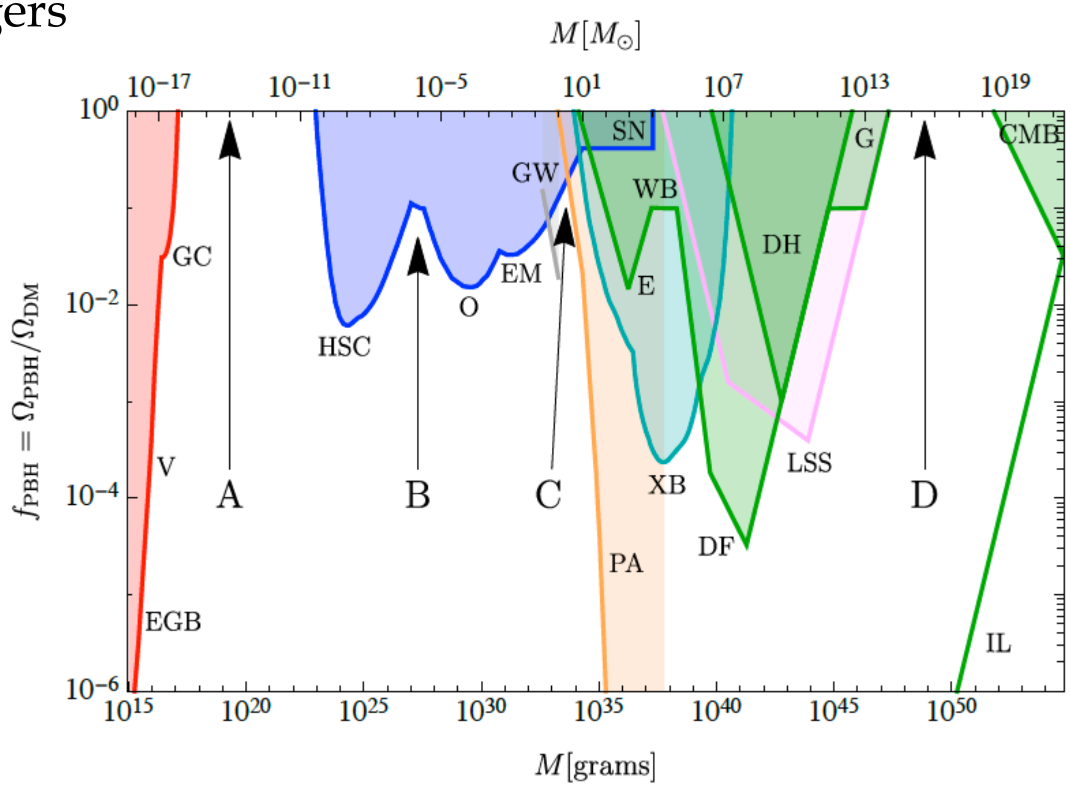
18 June 2024

Primordial black holes

Several cosmological scenarios predict formation of primordial BHs (non-standard inflation, phase transitions, etc) [c.f. Escrivá & Kuhnel (2022)]

Typical scenarios predict broad PBH mass spectrum that could explain:

- Dark matter
- OGLE ultrashort microlensing events
- LIGO-Virgo-Kagra BBH mergers



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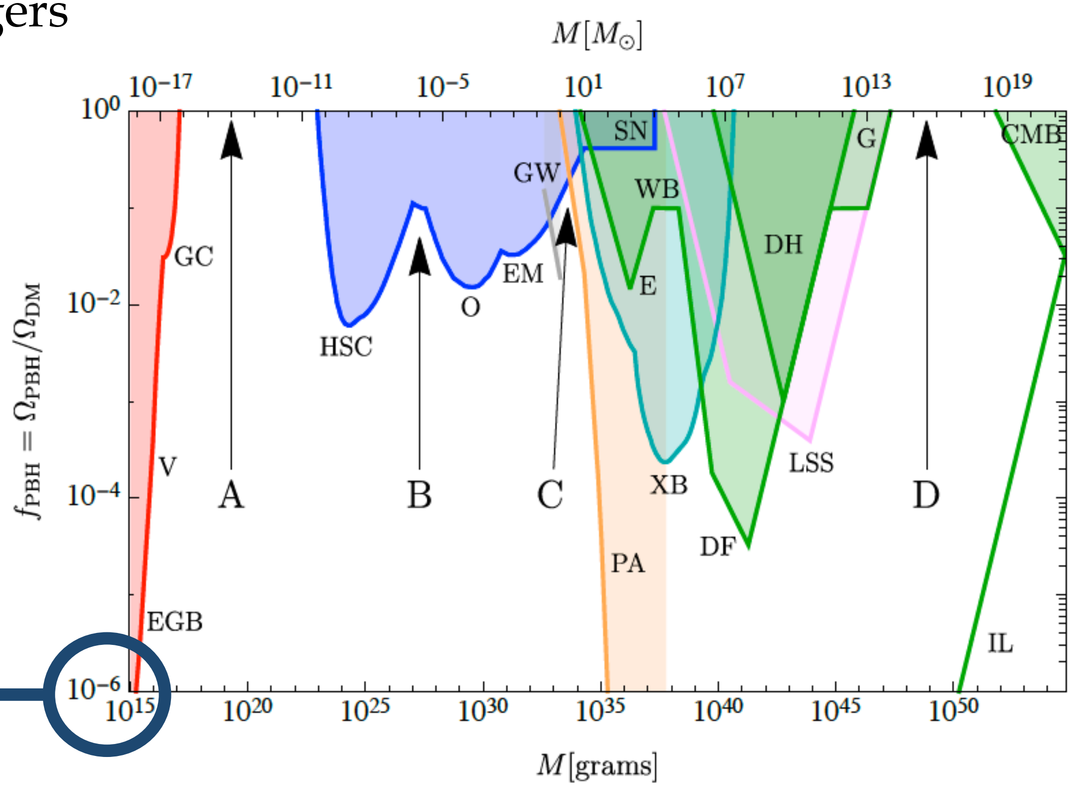
Evaporating PBHs:
$\lesssim 1$ PBH $\mathrm{mpc}^{-2}\mathrm{yr}^{-1}$



Evaporating primordial black holes

PBHs born with masses $M_i \sim 10^{12}$ kg evaporate through Hawing emission completely in 14 Gyrs, so we could hope to observe their final "explosion"

$$T_H = \frac{M_P^2}{8\pi M} \simeq \left(\frac{10^7 \text{ kg}}{M}\right) \text{ TeV}$$

PBHs could emit new particle species in their final seconds, and this speeds up evaporation [Baker & Thamm (2022-23)]

Standard lore:
PBHs quickly lose their spin as they evaporate ⇒ not in string theory!

Lots of new information about new physics from PBH spin

String axiverse

Dimensional reduction of NS & RR p-form fields leads to 4D axions:
[Arvanitaki et al. (2010)]

$$B_{\mu\nu} = \frac{1}{2\pi} \sum_i a_i(x) \omega^i_{\mu\nu}(y) \qquad\qquad \int_{C_j} \omega^i = \delta^i_j$$

- # axions = # compact cycles in the 6 extra-dimensions
- perturbative shift symmetries inherited from p-form gauge fields
- exponentially small masses from non-perturbative effects
  (assuming one QCD axion)

Expect $O(10^2 - 10^3)$ light axions in realistic string compactifications!

Evaporation of Kerr black holes

Mass and angular momentum loss functions:

$$\mathcal{F}(\tilde{a}) = -\left(\frac{M^3}{M_P^4}\right)\frac{\dot{M}}{M}\,, \qquad \mathcal{G}(\tilde{a}) = -\left(\frac{M^3}{M_P^4}\right)\frac{\dot{J}}{J}$$

$$\begin{pmatrix}\mathcal{F}\\ \mathcal{G}\end{pmatrix} = \sum_{i,l,m}\frac{1}{2\pi}\int_0^\infty d\bar{\omega}\,\frac{\Gamma^s_{lm}}{e^{(\omega-m\Omega_H)/T_H}\pm 1}\begin{pmatrix}\bar{\omega}\\ m\tilde{a}^{-1}\end{pmatrix}$$

Regge trajectory:

$$\frac{d\log\tilde{a}}{d\log M} = \frac{\mathcal{G}}{\mathcal{F}} - 2 \equiv \mathcal{H}(\tilde{a}) \qquad\qquad J = \tilde{a}\frac{M^2}{M_P^2}$$

Approximation:
only include each particle for $T_H > m$ and neglect their mass

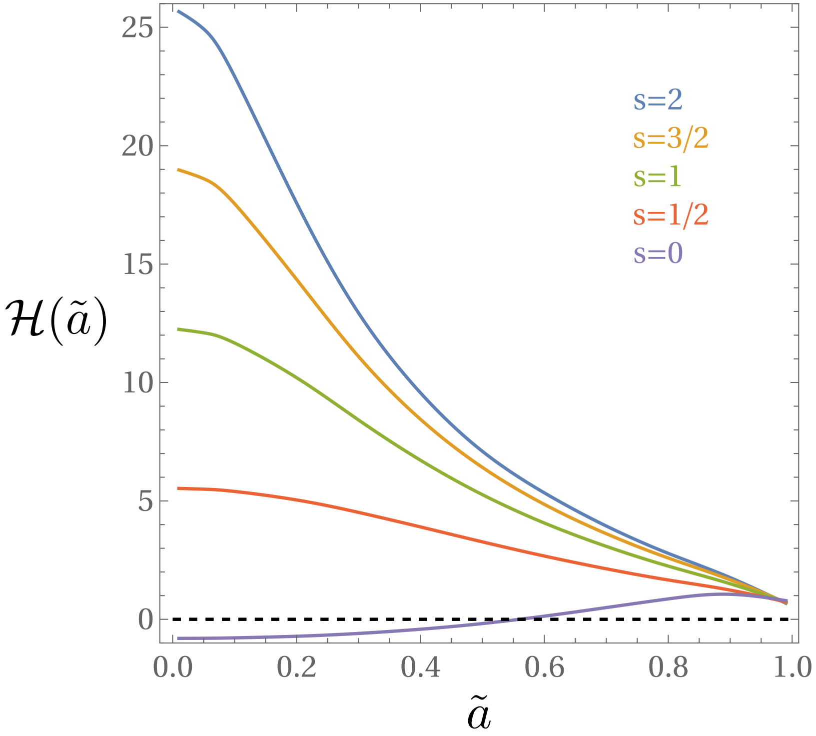
Evaporation of Kerr black holes

Scalar emission can spin up a PBH for $\tilde{a} < 0.555$, since $l=m=0$ mode is dominant.
[Chambers, Hiscock & Taylor (1997)]

In the SM the only scalars are pions and Higgs doublet…

… but in string theory there should $O(10^2\text{-}10^3)$ light axions!
[Arvanitaki et al. (2010)]

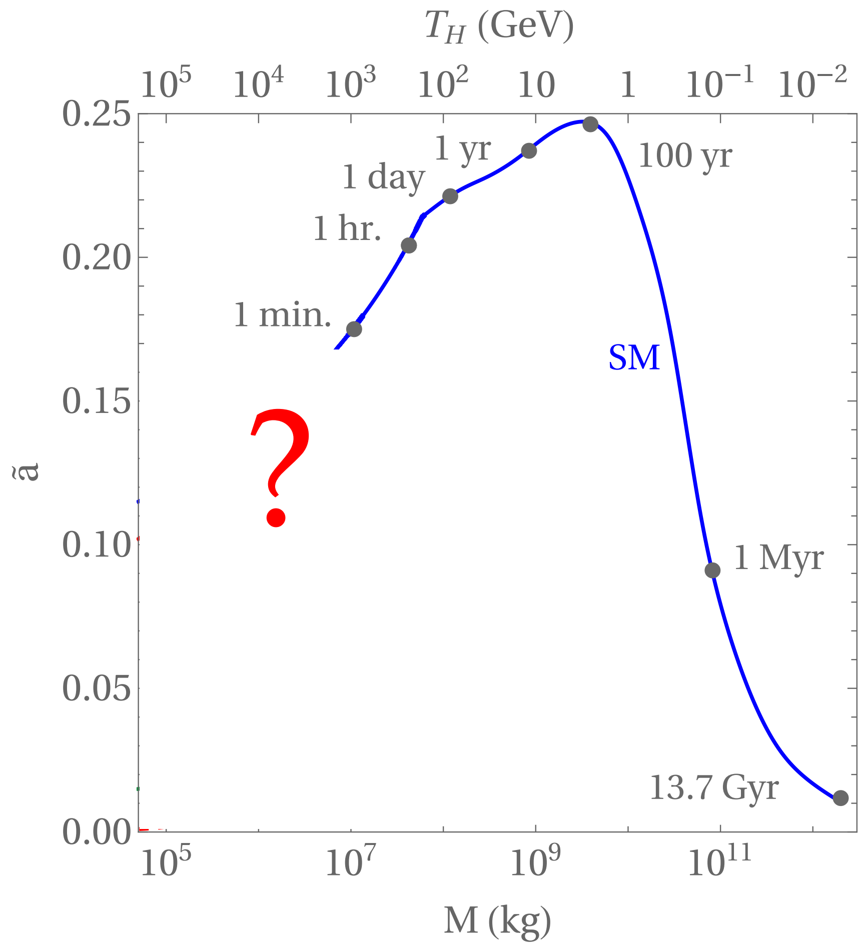
$$\frac{d\log\tilde{a}}{d\log M} = \mathcal{H}(\tilde{a})$$



[c.f. Page (1976)]

PBHs can spin up in the string axiverse!
[Calzà, March-Russell & JGR, 2110.13602]

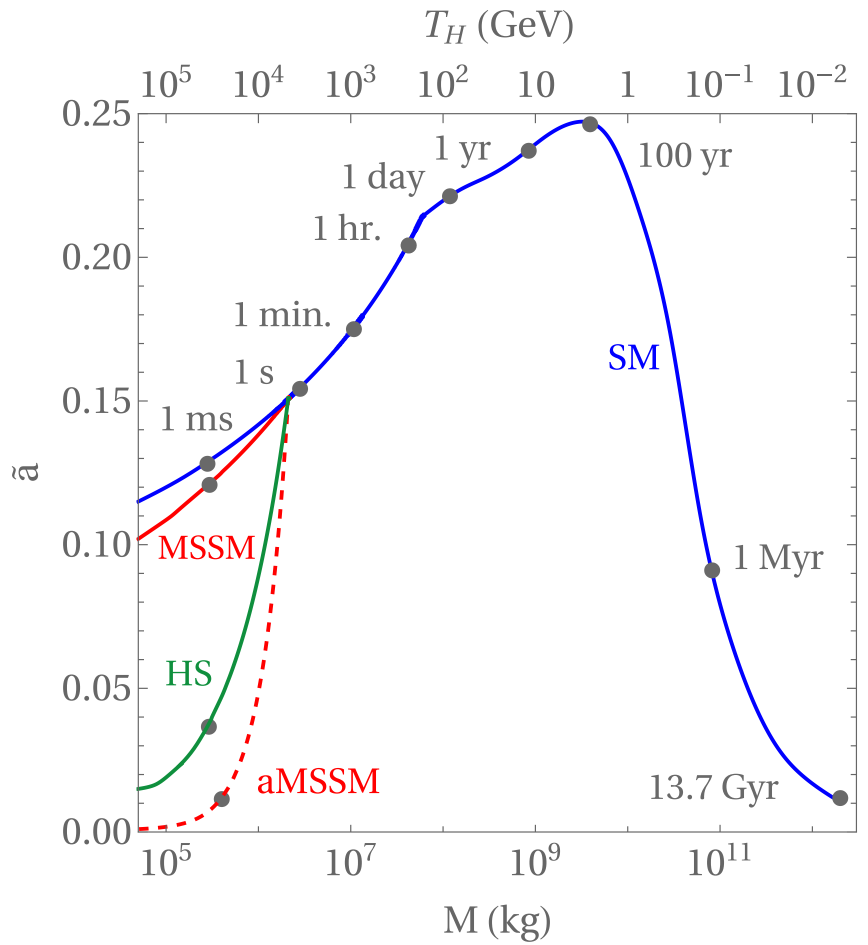
Kerr PBHs in the string axiverse



SM = Standard Model + graviton + 400 axions

$(n_0, n_{1/2}, n_1, n_{3/2})=(400+4, 45, 12, 0)$

Adding new physics @ 5 TeV



MSSM: $(n_0, n_{1/2}, n_1, n_{3/2})=(400+4+4+90, 45+12+4, 12, 1)$ (+128 d.o.f.)

aMSSM: $(n_0, n_{1/2}, n_1, n_{3/2})=(400+4+4+90+400, 45+12+8+400, 12, 1)$ (+1336 d.o.f.)

HS: $(n_0, n_{1/2}, n_1, n_{3/2})=(400+4+4, 45+45, 12+12, 0)$ (+118 d.o.f.)

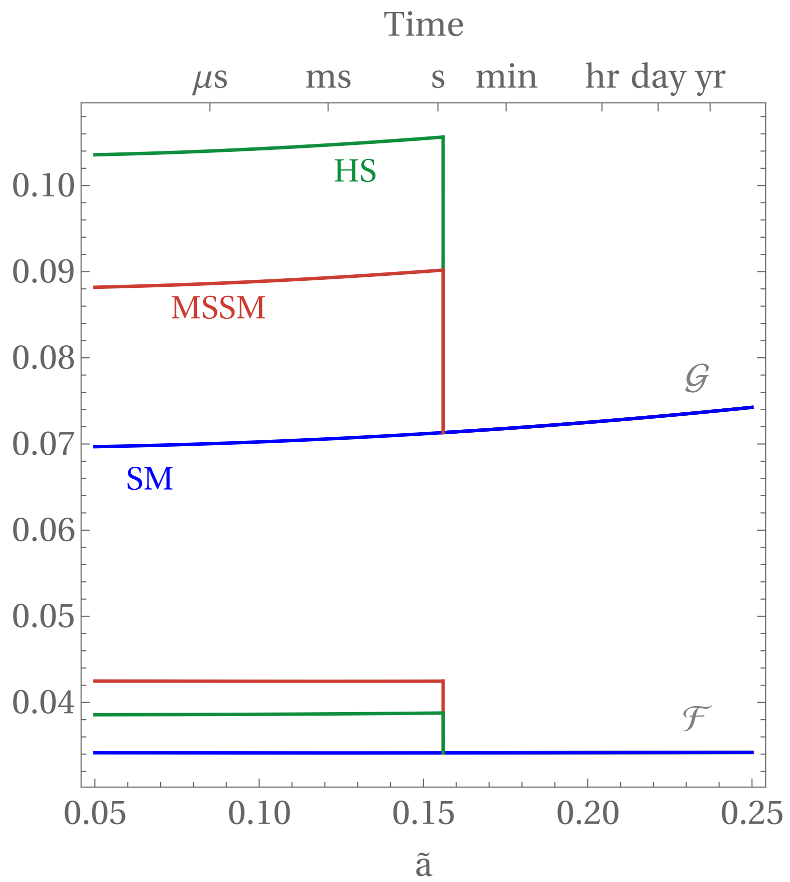
Tracking the PBH evolution

If we detect a PBH and track *M(t)* and *ã(t)*, we can determine the loss rates:

$$\begin{pmatrix} \mathcal{F} \\ \mathcal{F}' \\ \mathcal{G} \\ \mathcal{G}' \end{pmatrix} = \begin{pmatrix} \mathcal{F}_0 & \mathcal{F}_{1/2} & \mathcal{F}_1 & \mathcal{F}_{3/2} \\ \mathcal{F}'_0 & \mathcal{F}'_{1/2} & \mathcal{F}'_1 & \mathcal{F}'_{3/2} \\ \mathcal{G}_0 & \mathcal{G}_{1/2} & \mathcal{G}_1 & \mathcal{G}_{3/2} \\ \mathcal{G}'_0 & \mathcal{G}'_{1/2} & \mathcal{G}'_1 & \mathcal{G}'_{3/2} \end{pmatrix} \begin{pmatrix} n_0 \\ n_{1/2} \\ n_1 \\ n_{3/2} \end{pmatrix}$$

for each value of ã.

We could fully determine the particle content!



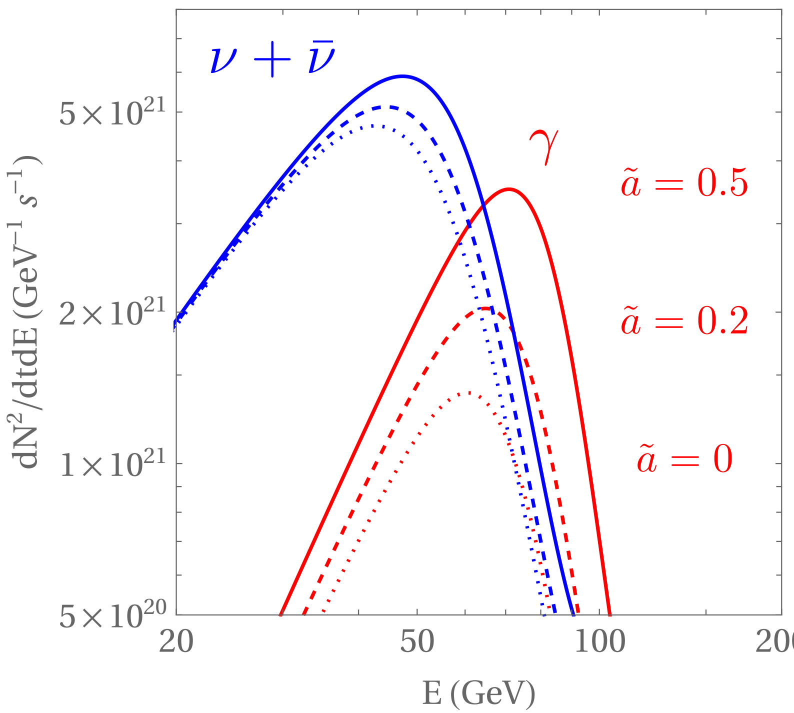
Potential problem:

hard to measure $\mathcal{F}'$ due to cancellation between scalar (<0) and non-scalar (>0) contributions.

Solution: measure $\mathcal{G}''$!

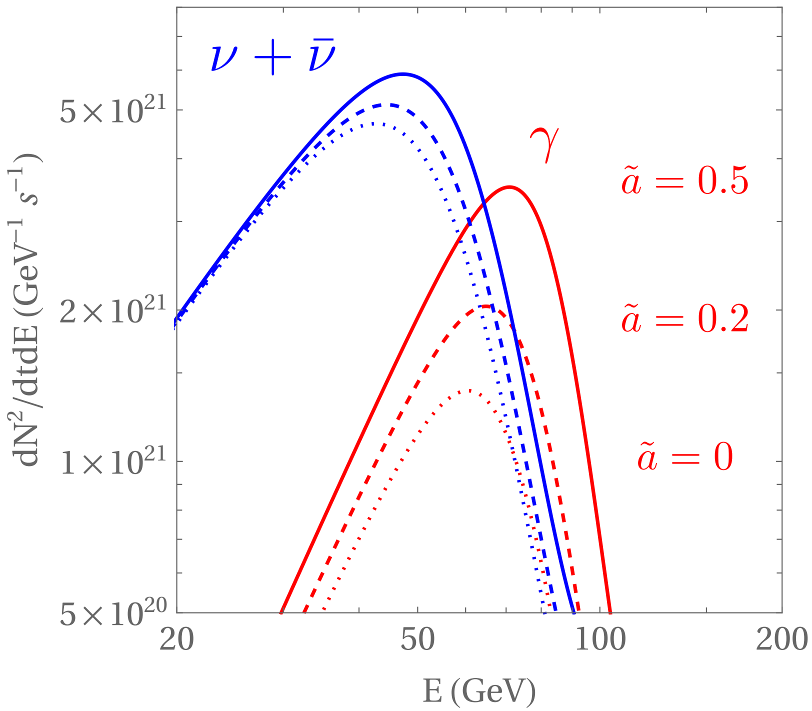
Measuring the PBH mass and spin from Hawking spectrum

- Primary photon peak (known distance)
  [Calzà, March-Russell & JGR, 2110.13602]
- "Peak-valley" of primary + secondary photon spectra [Calzà & JGR, 2210.06500]
- Multipolar peaks in photon spectrum ($\tilde{a}$ > 0.6) [Calzà & JGR, 2312.11930]
- Multi-messenger approach:
  photon + neutrino primary emission



$$\frac{d^3 N_s}{dE dt d\Omega} = \frac{1}{4\pi} \sum_{l,m} \frac{\Gamma^s_{l,m}(\omega)}{e^{(\omega - m\Omega_H)/T_H} \pm 1} \left(|_s S_{lm}(\theta)|^2 + |_{-s} S_{lm}(\theta)|^2 \right)$$

Measuring the PBH mass and spin from Hawking spectrum



$$E_{\gamma,\nu} \propto T_H \propto M^{-1}$$

$$\frac{E_\nu}{E_\gamma} = 0.705 - \frac{0.559\tilde{a}^2}{1 + 5.18\tilde{a}}$$

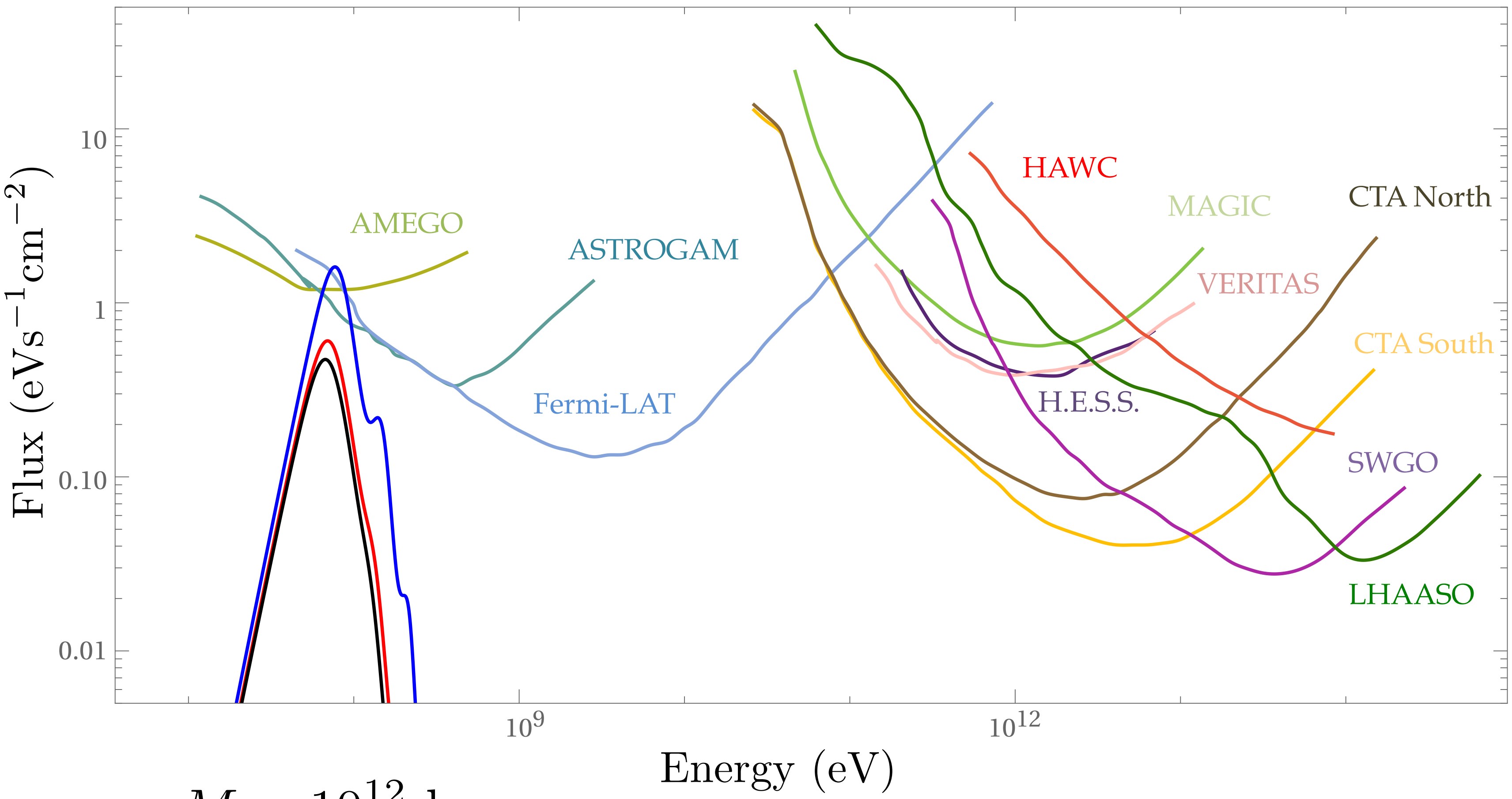
$$\frac{I_\nu}{I_\gamma} = 3.423 - \frac{31.05\tilde{a}^2}{1 + 7.05\tilde{a}}$$

Problem:
Emission is anisotropic and depends on unknown inclination of PBH axis

Solutions:
(i) Measure $\nu - \bar{\nu}$ (& photon polarization) asymmetry [Perez-Gonzalez (2023)]
(ii) Measure intensity modulation from PBH proper motion:

$$v_{PBH} \sim 50\ \text{AU/yr}$$

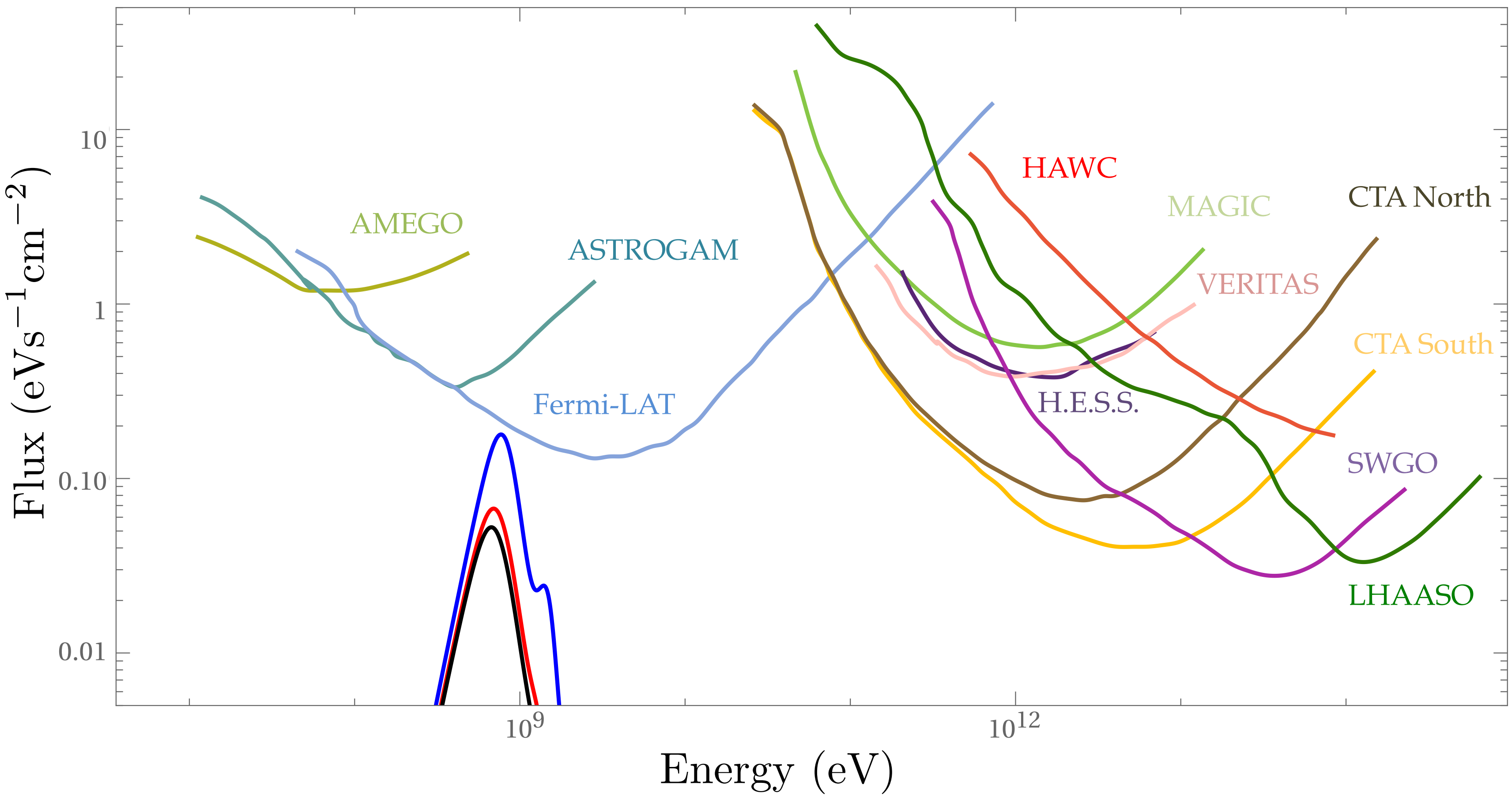
Detecting Kerr PBHs (primary γ)



$M = 10^{12}$ kg

$d = 10^{-5}$ pc

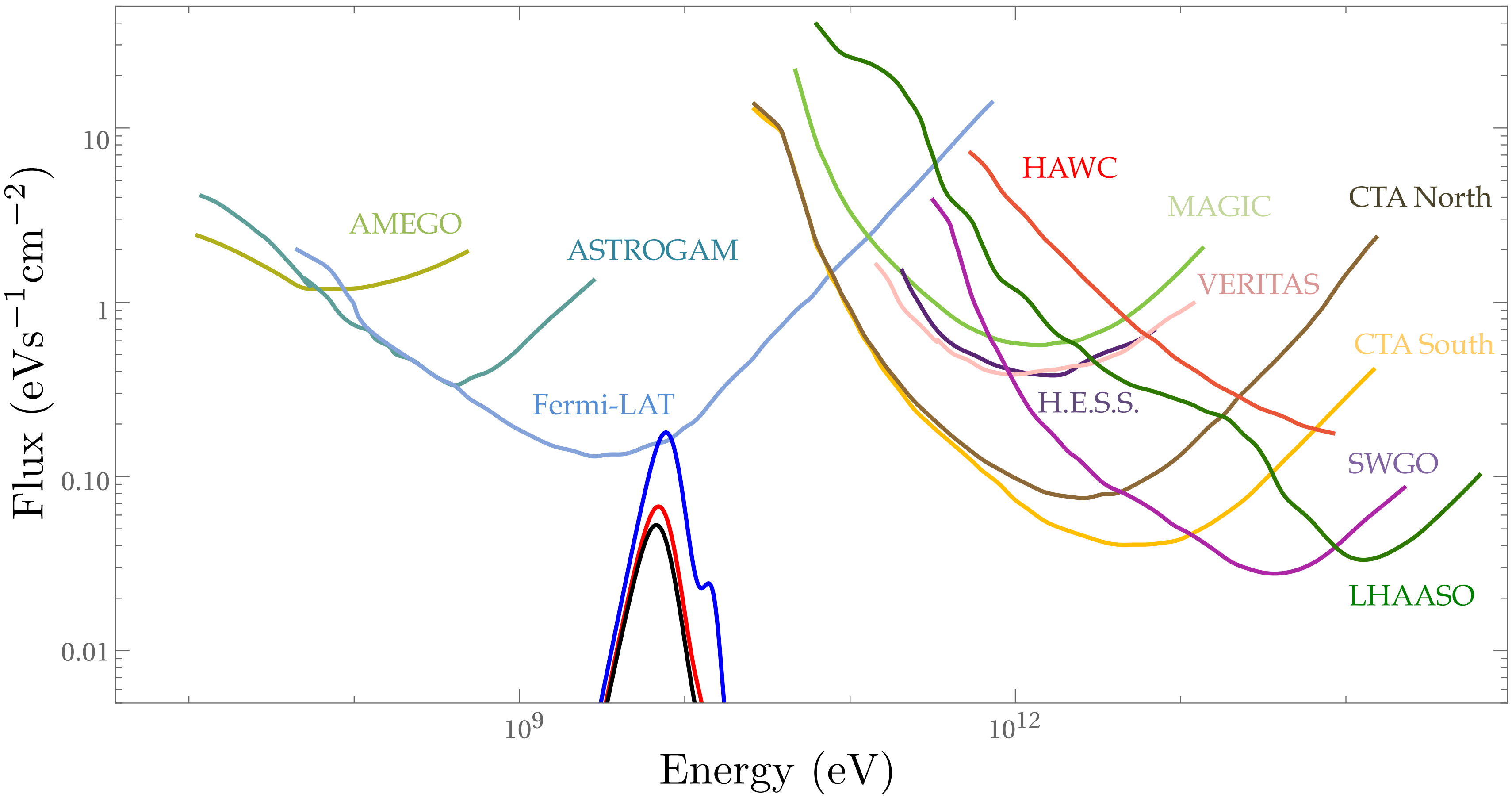
Detecting Kerr PBHs (primary γ)



$$M = 10^{11}\ \mathrm{kg}$$

$$d = 3 \times 10^{-4}\ \mathrm{pc}$$

Detecting Kerr PBHs (primary γ)



$$M = 10^{10} \text{ kg}$$

$$d = 3 \times 10^{-3} \text{ pc}$$

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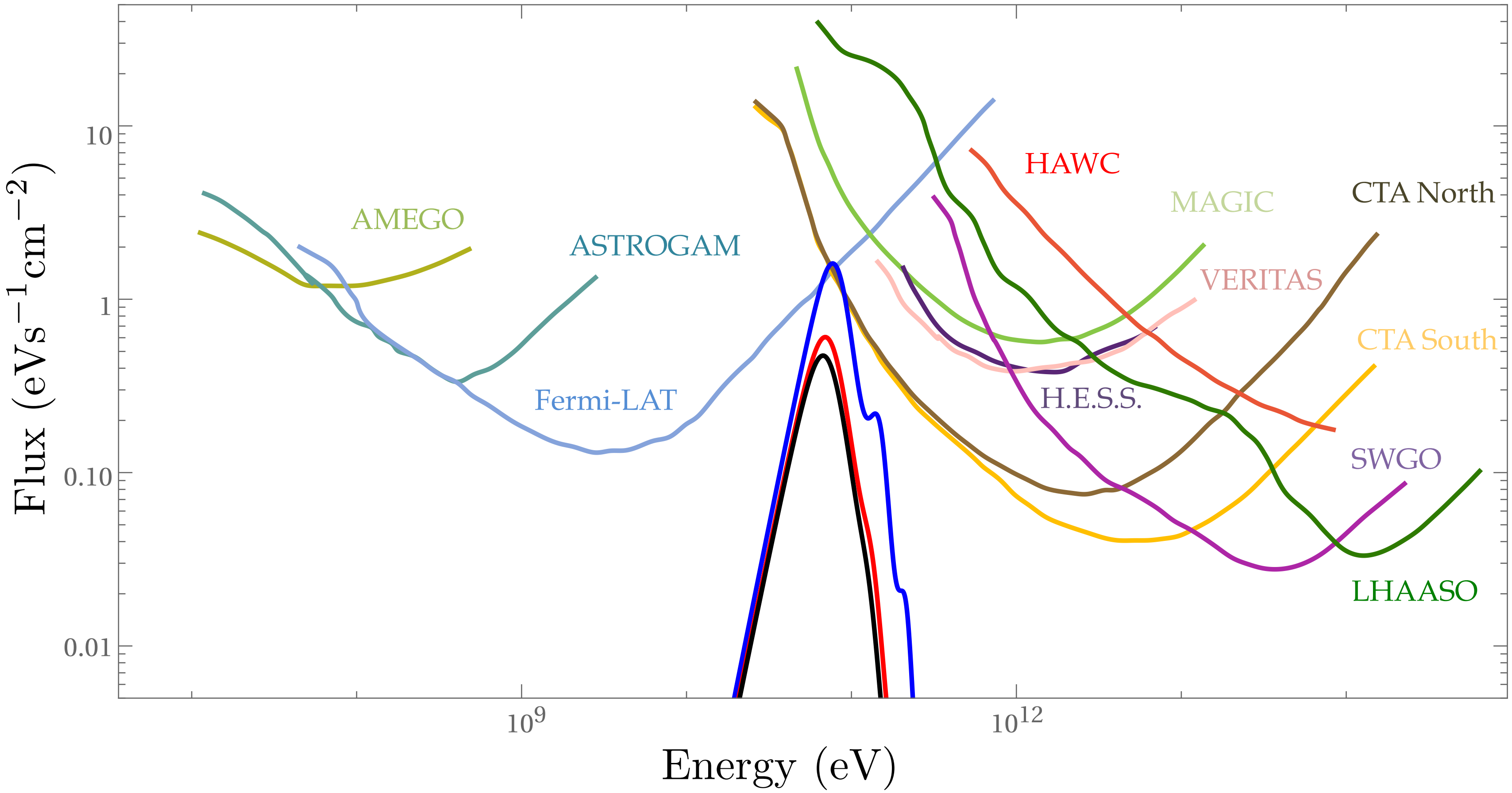
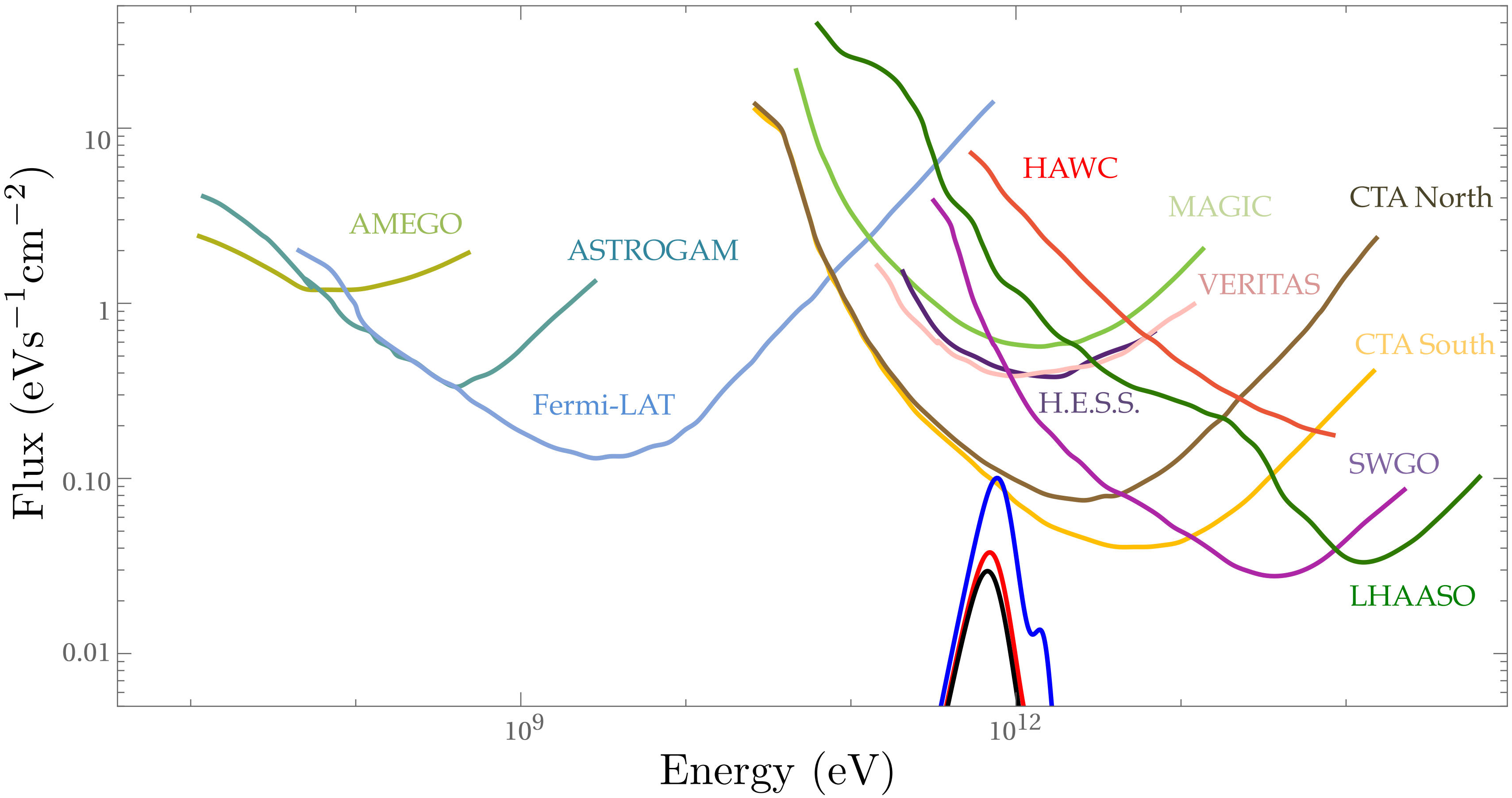


$$M = 10^9 \text{ kg}$$

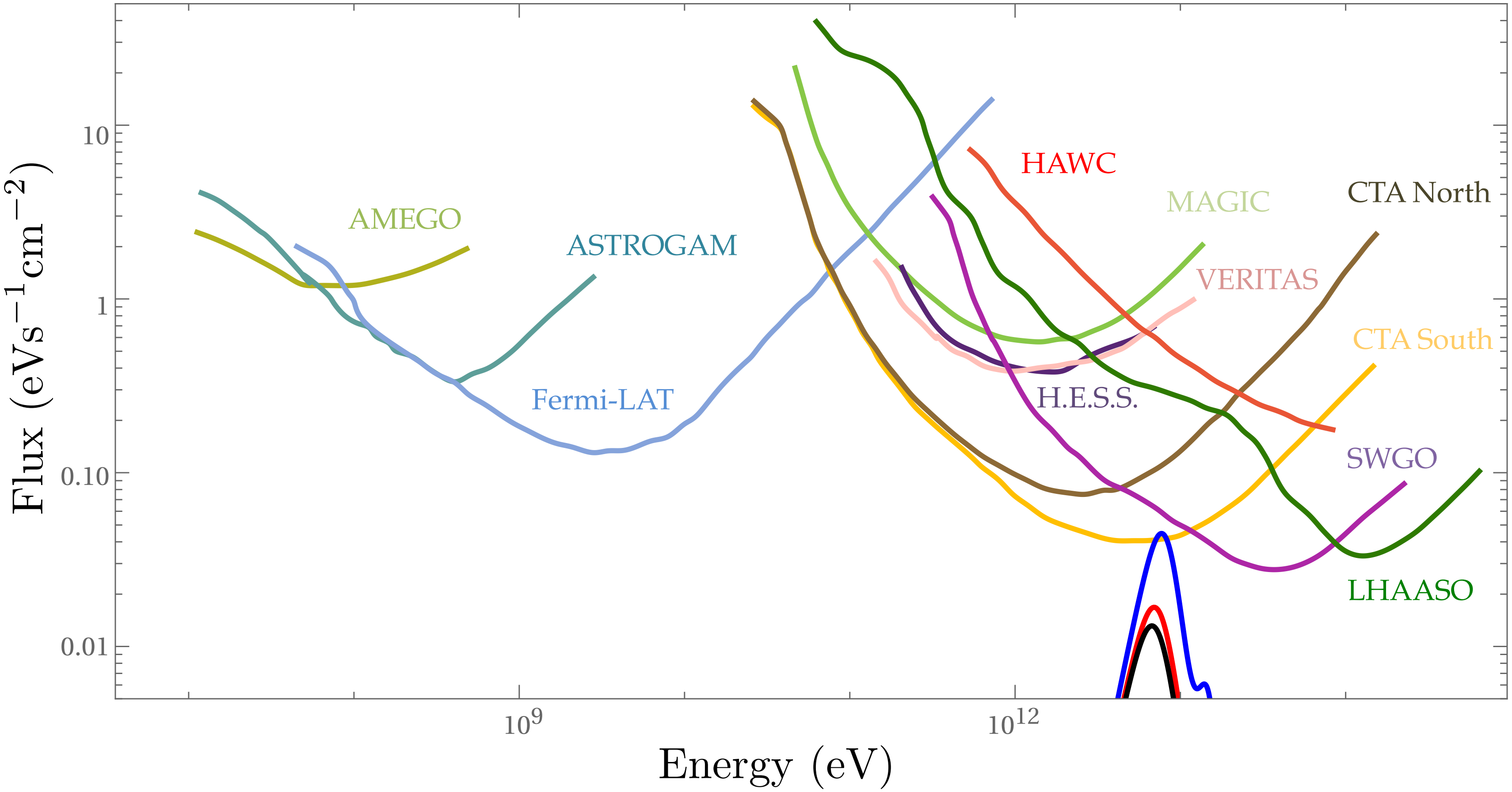
$$d = 10^{-2} \text{ pc}$$

Detecting Kerr PBHs (primary γ)



$$M = 10^8 \text{ kg}$$
$$d = 0.4 \text{ pc}$$

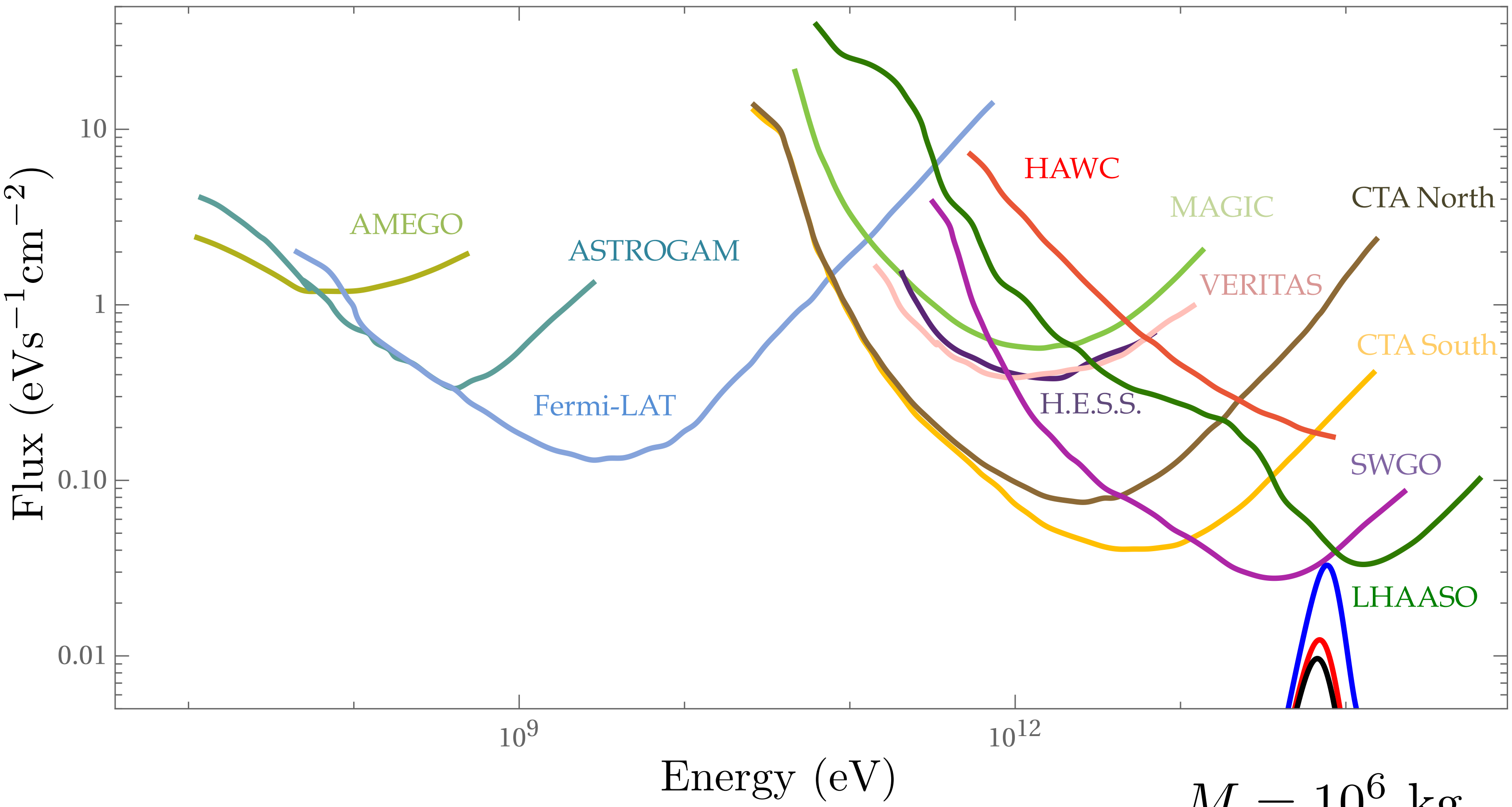
Detecting Kerr PBHs (primary γ)



$$M = 10^7 \text{ kg}$$

$$d = 6 \text{ pc}$$

Detecting Kerr PBHs (primary γ)



$M = 10^6$ kg

$d = 70$ pc

Take home messages

- Evaporating PBHs are fantastic particle physics laboratories
- Finding a single PBH with non-negligible spin in its last stages would be evidence for a string axiverse
- Tracking the PBH mass and spin in its last second can reveal new physics and distinguish SM extensions (>TeV scale)
- Multi-messenger astronomy to detect and track PBH Hawking emission:

γ-rays: H.E.S.S., Milagro, VERITAS, HAWC, Fermi-LAT, LHAASO
CTA, SWGO, AMEGO, ASTROGAM

neutrinos: IceCube,
KM3Net, P-ONE, Trident, Baikal-GVD

Further details: arXiv:2312.09261 [hep-ph]