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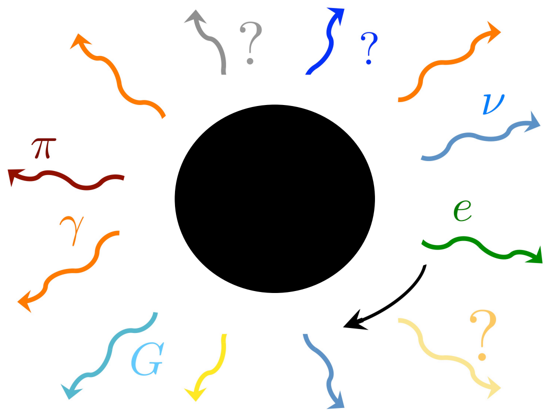
CFisUC

Primordial Black Holes in the String Axiverse



João G. Rosa
University of Coimbra, Portugal
with Marco Calzà & John March-Russell

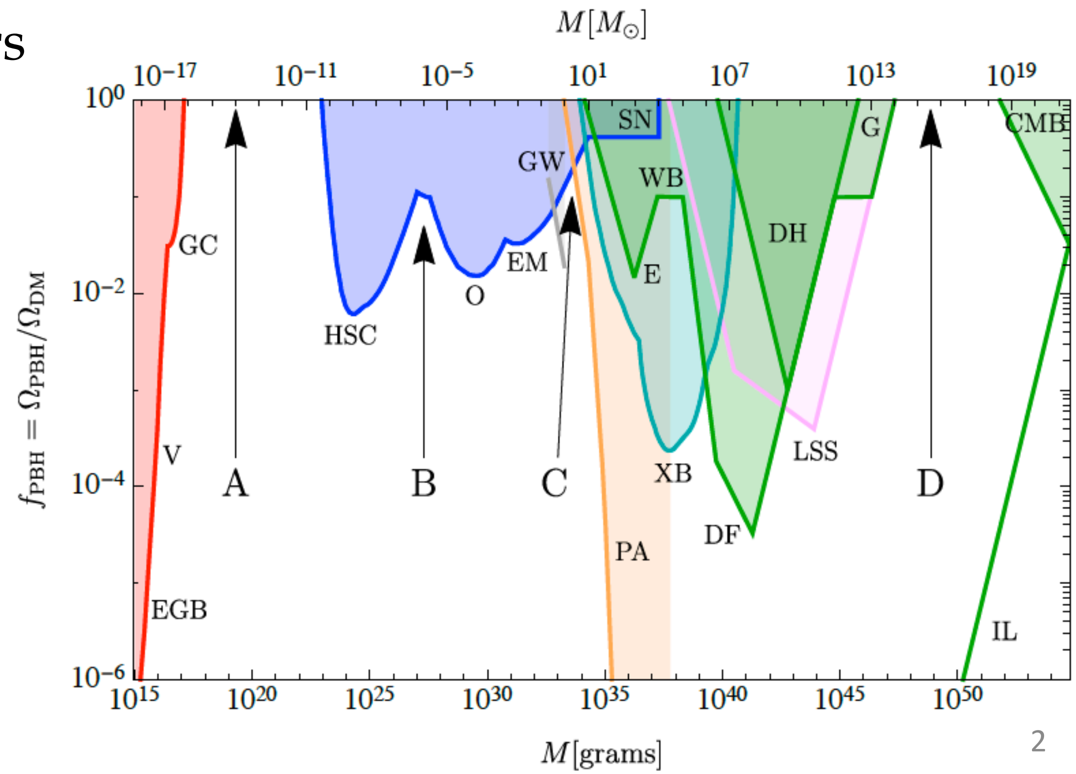
"WISPs in String Cosmology" Workshop
23 October 2024

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 mergers



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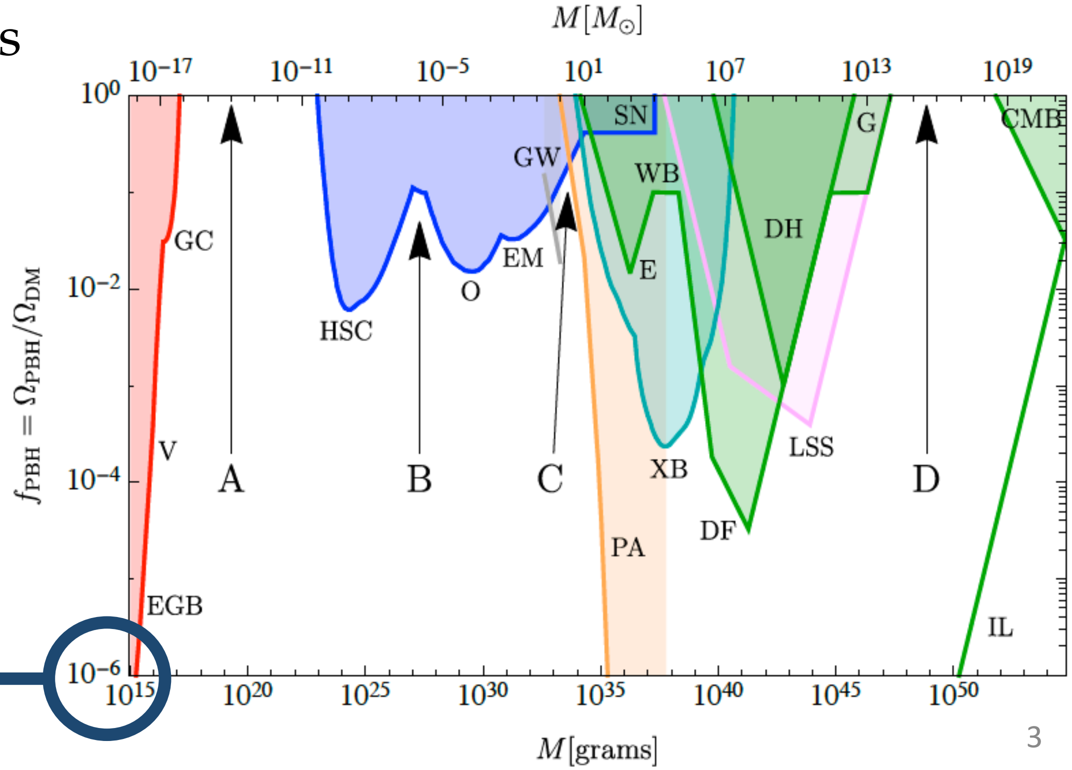


Evaporating PBHs:
$\lesssim 1\ \mathrm{PBH\,mpc^{-2}yr^{-1}}$

Hawking evaporation

Hawking effect [Hawking (1974-75)] (semi-classical):

Quantum fields in vacuum state @ past infinity (collapsing matter) are in nearly-thermal state @ future infinity (after BH horizon forms)

Hawking temperature:

$$T_H = \frac{\kappa}{2\pi} \simeq \frac{1}{8\pi G M} \simeq 10\ \mathrm{MeV} \left(\frac{10^{12}\ \mathrm{kg}}{M} \right)$$

Particle emission spectrum:

$$\frac{d^2 N_s}{dt d\omega} = \frac{1}{2\pi} \sum_{l,m} \frac{\Gamma_{s,l,m}(\omega)}{e^{2\pi(\omega - m\Omega)/\kappa} \pm 1}$$

Hawking evaporation

Particle emission extracts mass and spin from the BH:

$$\frac{dM}{dt} = -\mathcal{F}\frac{M_P^4}{M^2} \qquad \frac{dJ}{dt} = -\mathcal{G}\frac{M_P^4}{M^3}J$$

$$\begin{pmatrix} \mathcal{F} \\ \mathcal{G} \end{pmatrix} = \sum_{i,l,m} \frac{1}{2\pi}\int_0^\infty dx \frac{\Gamma_{i,l,m}}{e^{2\pi(\omega - m\Omega)/\kappa} \pm 1} \begin{pmatrix} x \\ m\tilde{a}^{-1} \end{pmatrix}$$

$$x = \frac{\omega M}{M_P^2} \qquad \tilde{a} = \frac{J M_P^2}{M^2}$$

Finite BH lifetime: $t_{ev} = \frac{M^3}{3\mathcal{F}M_P^4} \simeq 14\left(\frac{M}{5\times 10^{11}\ \text{kg}}\right)^3$ Gyrs

Standard lore: BHs spin down as they evaporate ➡ **not in string theory!**

Particles emitted when Hawking temperature exceeds their mass

String axiverse

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

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

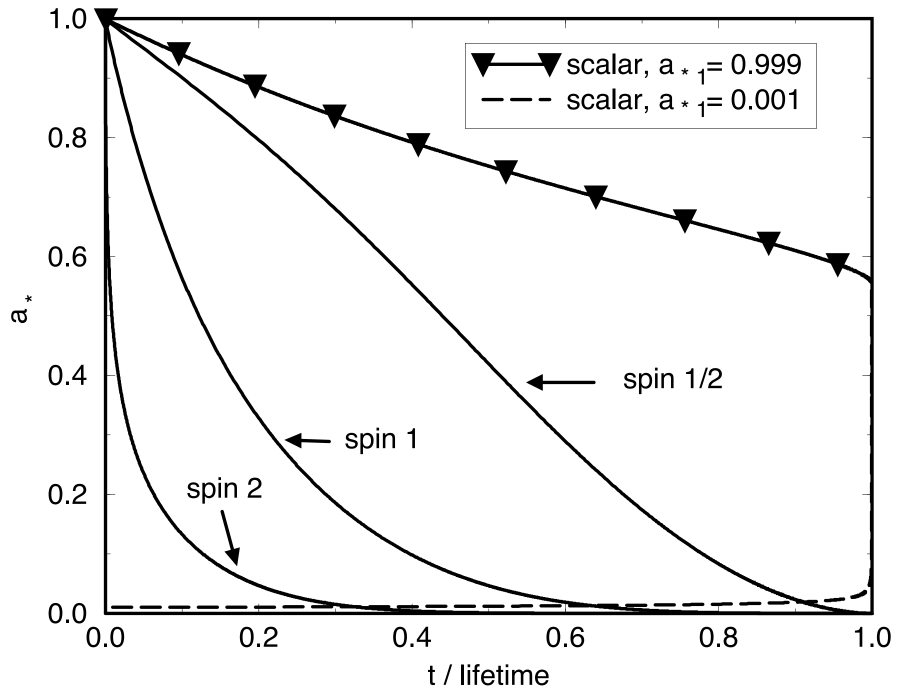
- # axions = # compact cycles in the 6 extra-dimensions
- perturbative shift symmetries inherited from p-form gauge fields
- exponentially small masses from non-perturbative effects (assuming one QCD axion)

Expect O(100 - 1000) light axions in realistic string compactifications

PBH evaporation in string axiverse

[Calzà, March-Russell & JGR, arXiv:2110.13602]

Scalar particles can be emitted without carrying angular momentum from the BH (*l=0* mode) [Taylor, Chambers & Hiscock (1997-98)]

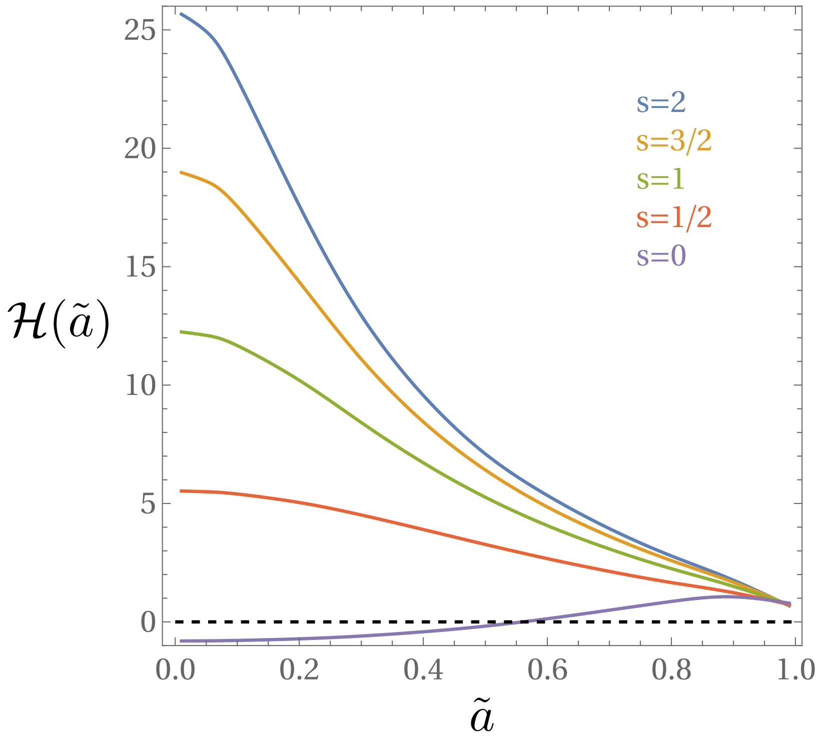


For pure scalar emission, PBHs spin up for ã<0.555

PBH evaporation in string axiverse

[Calzà, March-Russell & JGR, arXiv:2110.13602]

Regge trajectories: $$\frac{d \log \tilde{a}}{d \log M} = \frac{\mathcal{G}}{\mathcal{F}} - 2 \equiv \mathcal{H}(\tilde{a})$$



[c.f. Page (1976)]

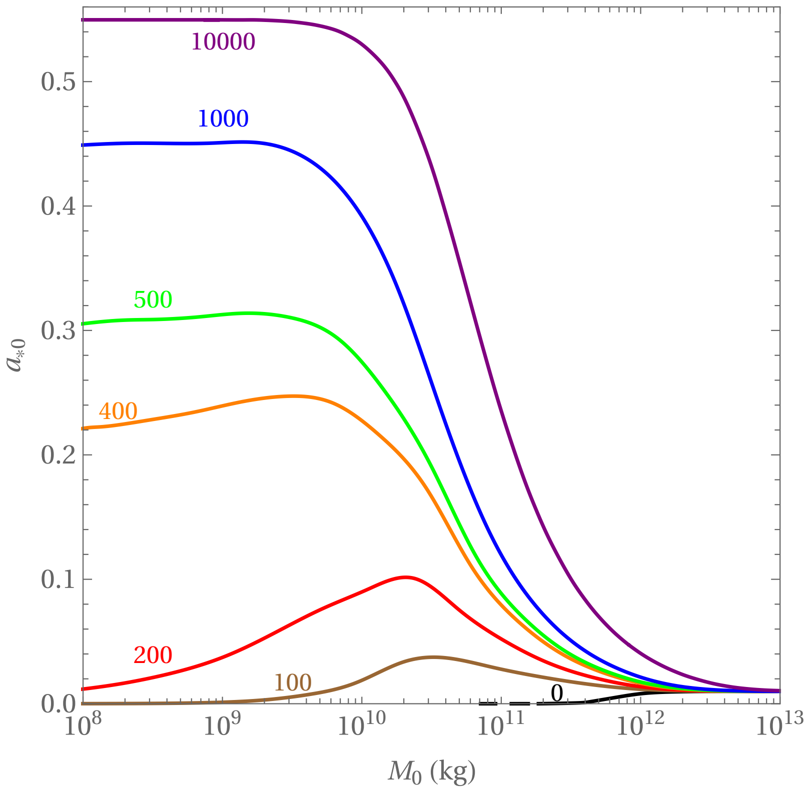
PBH evaporation in string axiverse

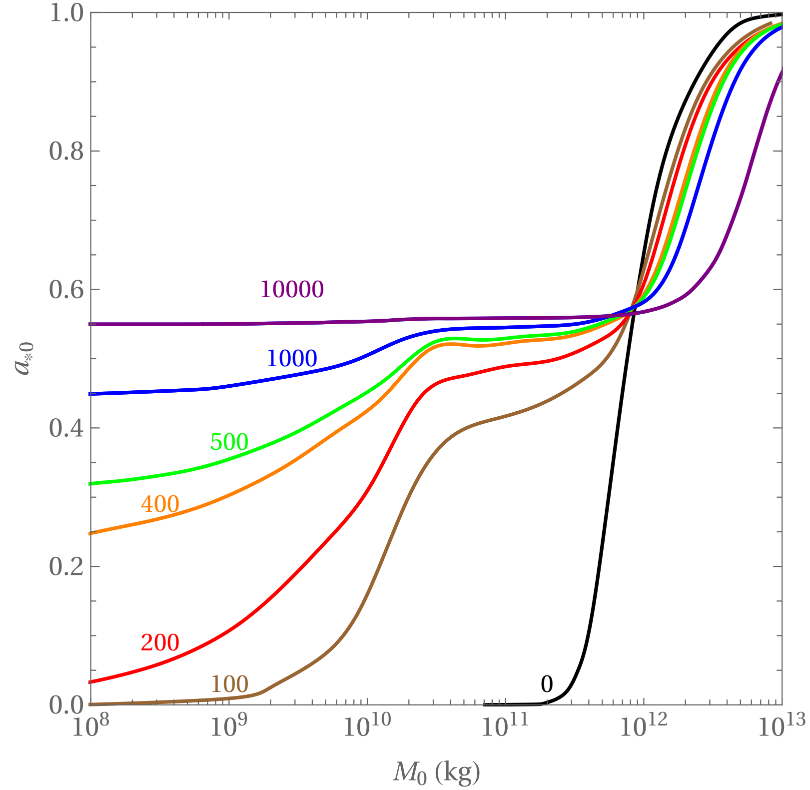
[Calzà, March-Russell & JGR, arXiv:2110.13602]

Study dynamics of PBH evaporation with:

SM particles + graviton + N_a light axions (sub-MeV)

Note: Particles included as T_H increases above mass thresholds





PBH evaporation in string axiverse

[Calzà, March-Russell & JGR, arXiv:2110.13602]

- PBH mass-spin distribution probes the whole string axiverse

- Finding only a few spinning PBHs with 10^9-10^{11} kg would be a smoking-gun for $N_a>100$

- PBH mergers have negligible effect on mass-spin distribution

- Relaxed limits on PBH abundance

- New astrophysical population of hot axions:

$$\Phi_{ALP} \sim 3 \times 10^{22} N_a (10^{10}\mathrm{kg}/M)\ \mathrm{s}^{-1}$$ ➡ can exceed $\rho_{\mathrm{CMB},0}$

New BSM physics

[Calzà & JGR, arXiv:2312.09261]

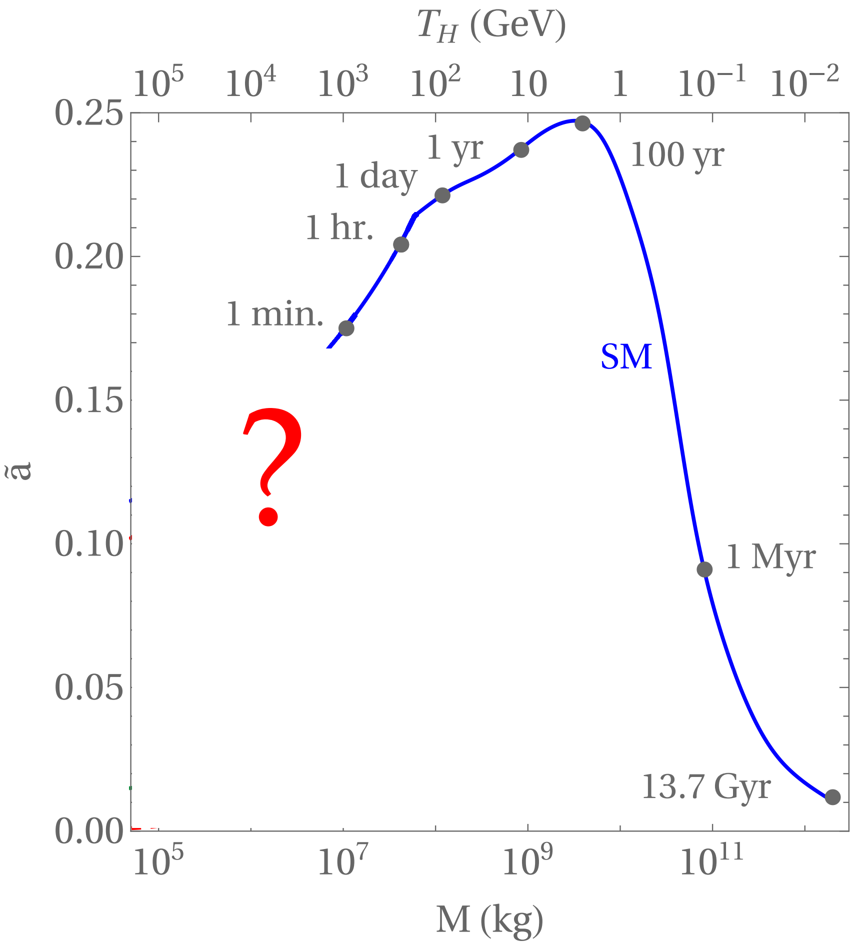
PBHs born with masses $M_i \sim 10^{12}$ kg evaporate through Hawking emission completely in 14 Gyrs, so we could hope to observe their final "explosion":

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

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

Lots of new information about new physics from PBH spin

New BSM physics

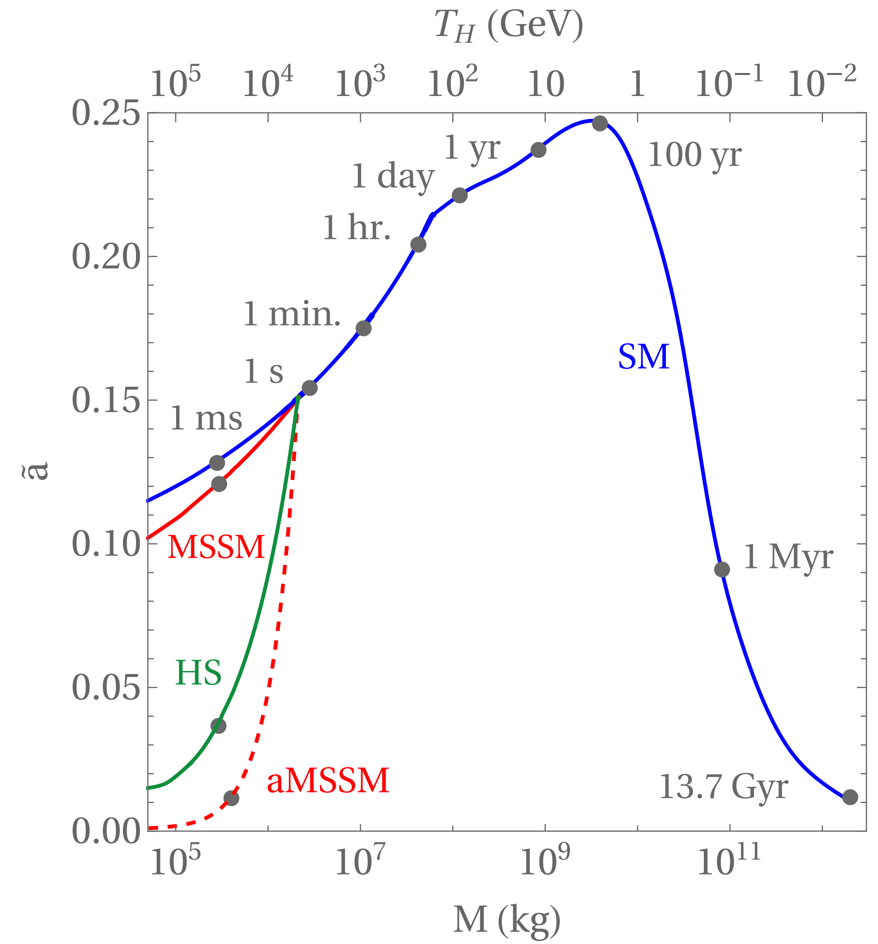


[Calzà & JGR, arXiv:2312.09261]

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



[Calzà & JGR, arXiv:2312.09261]

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.)

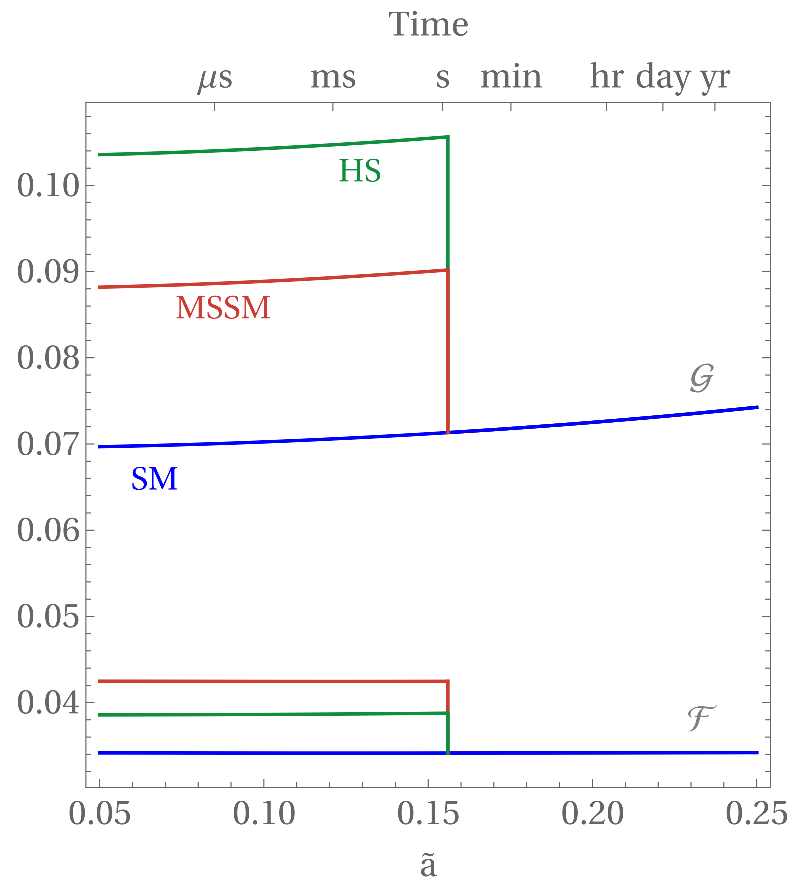
Tracking the PBH evolution

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!



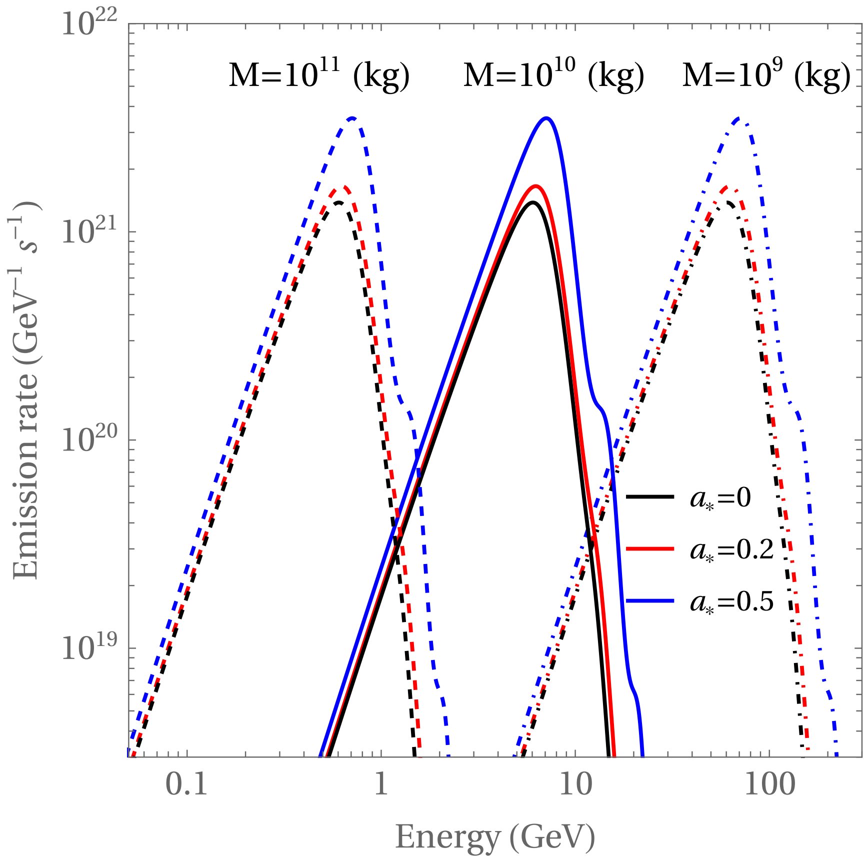
Potential problem:

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

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

PBH mass and spin from Hawking spectrum

- Primary photon peak (d_{PBH} from parallax)
  [Calzà, March-Russell & JGR, 2110.13602]



Measuring the PBH mass and spin from Hawking spectrum

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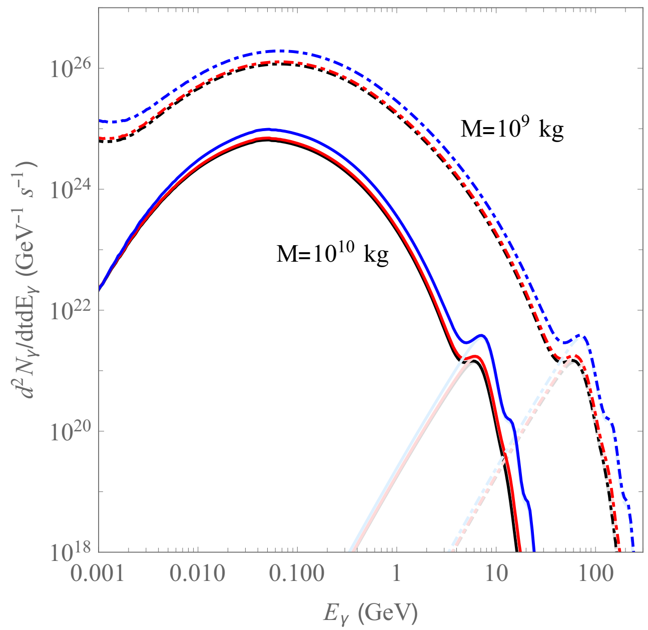
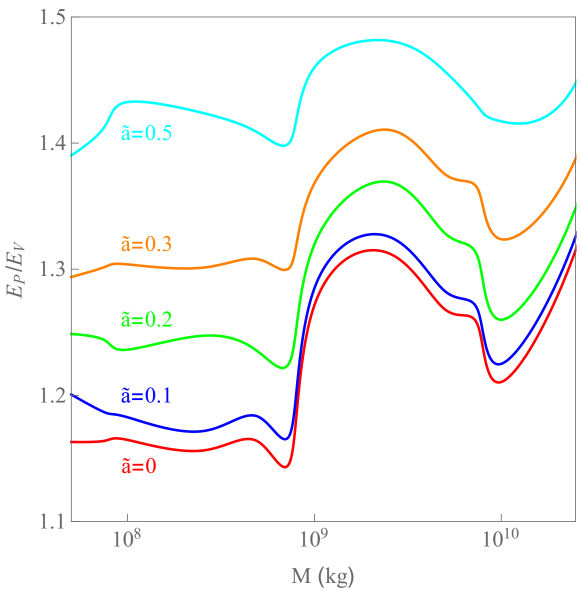
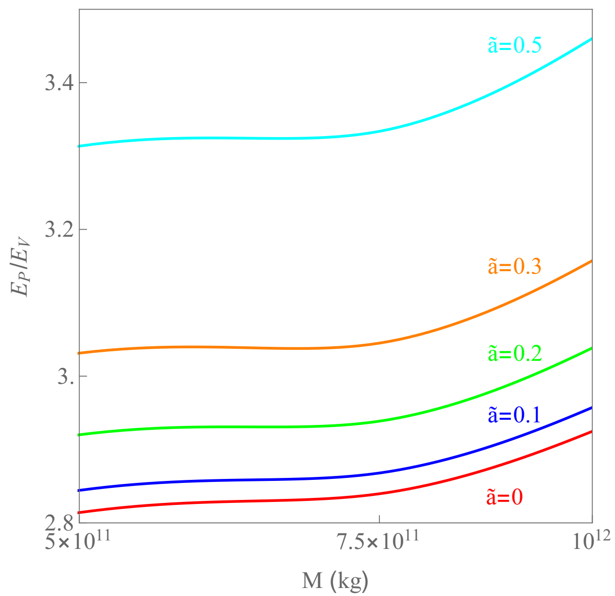
- "Peak-valley" of primary + secondary photon spectra [Calzà & JGR, 2210.06500]







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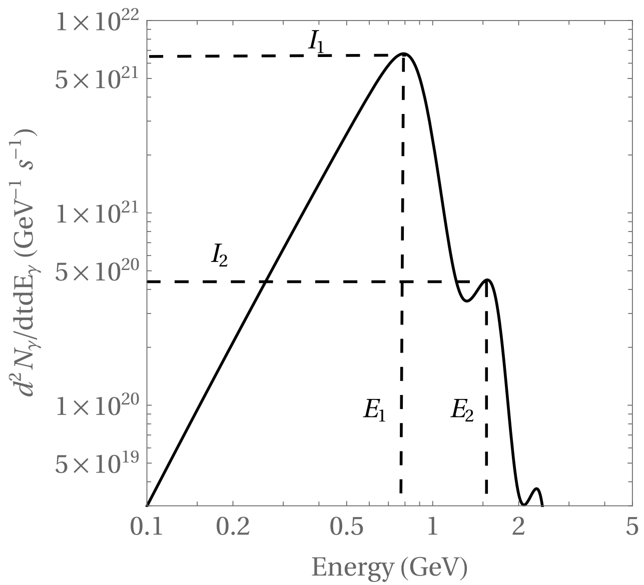
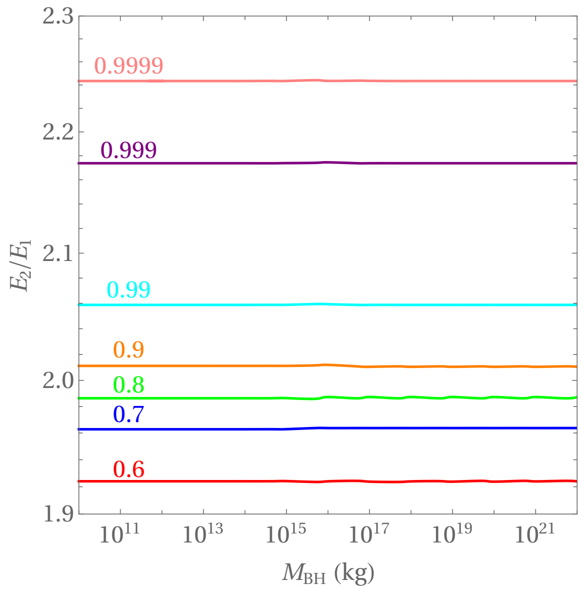
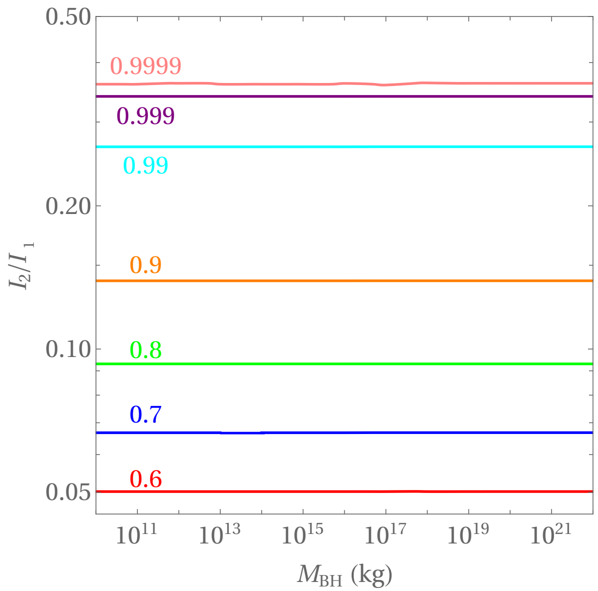
- Multipolar peaks in photon spectrum ($\tilde{a} > 0.6$) [Calzà & JGR, 2311.12930]

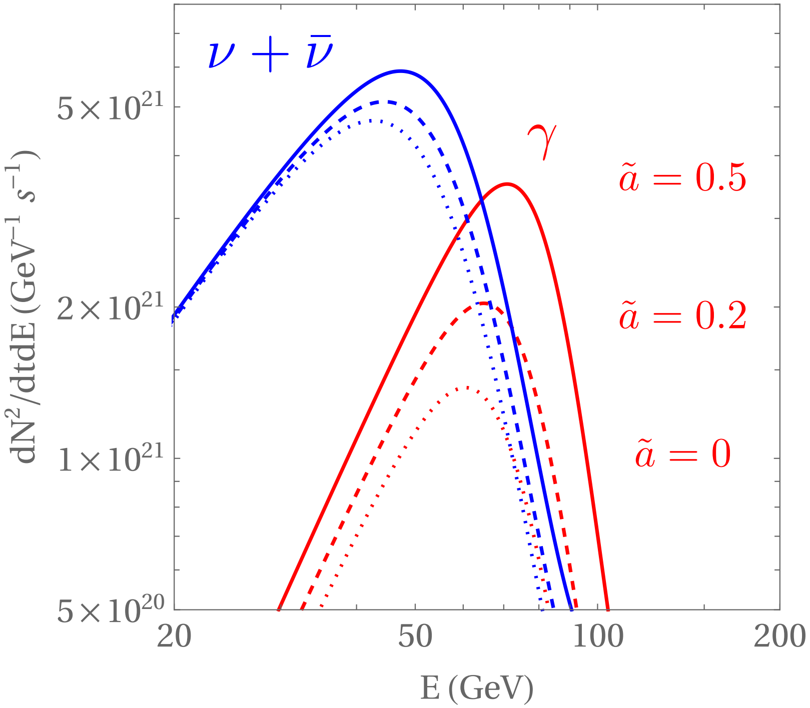






Measuring the PBH mass and spin from Hawking spectrum

- Primary photon peak (d_{PBH} from parallax) [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, 2311.12930]
- Photon + neutrino primary emission [Calzà & JGR, 2312.09261]



But emission is not isotropic so need to:

(i) Measure $\nu - \bar{\nu}$ (& γ polarization) asymmetry [Perez-Gonzalez (2023)]

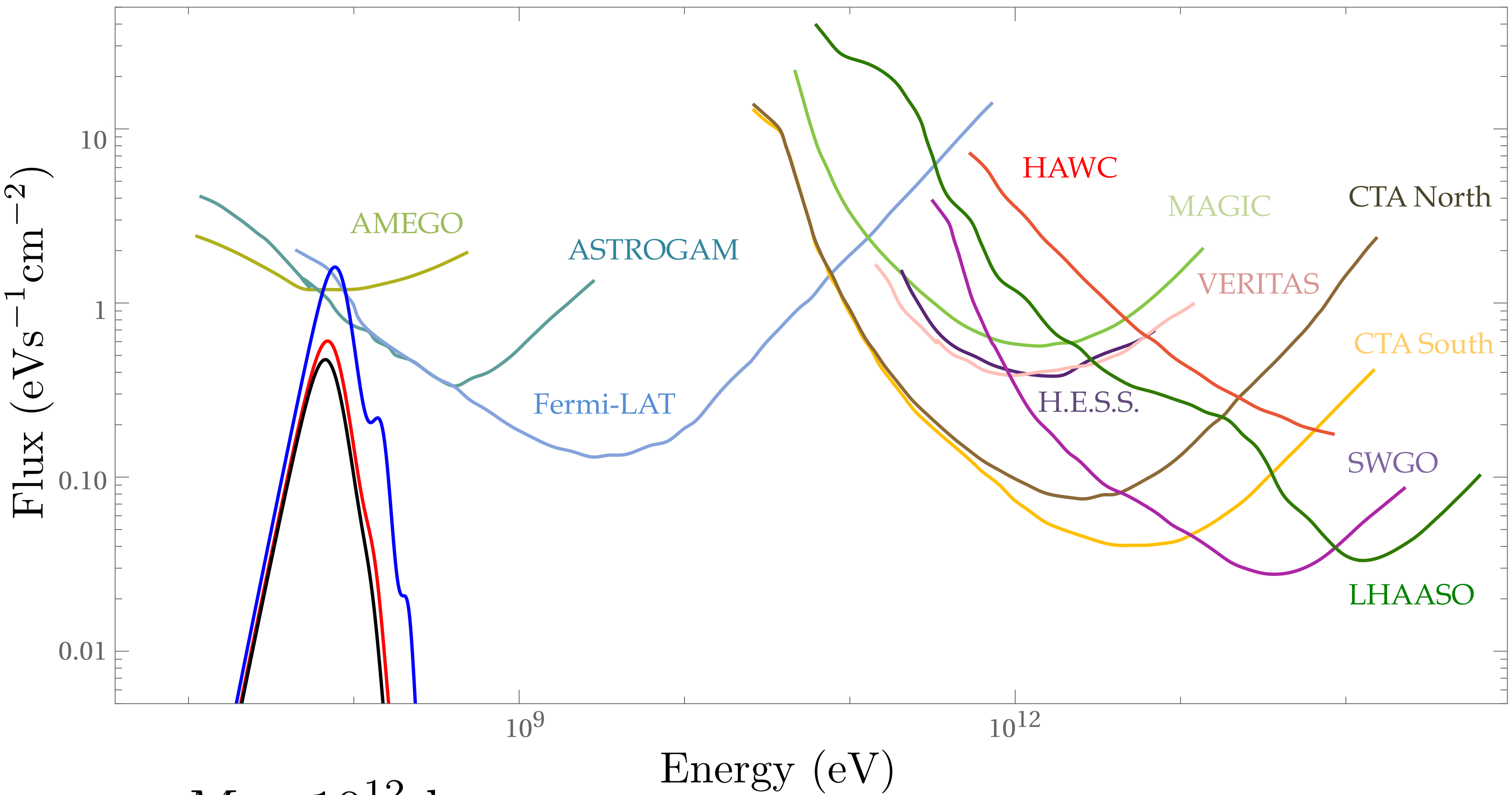
(ii) Measure intensity modulation from PBH proper motion (~50 AU/yr)

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

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

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

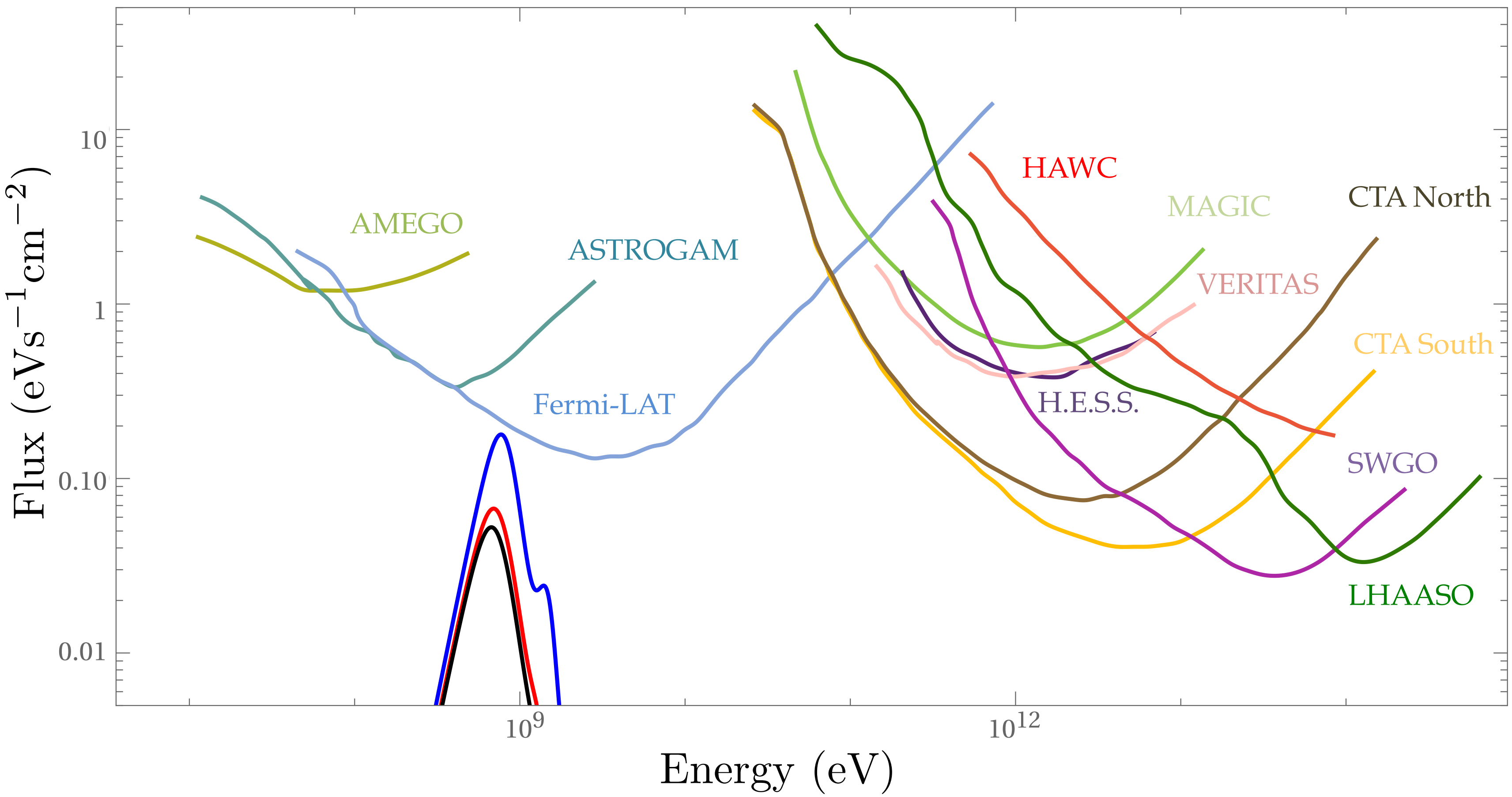
Detecting Kerr PBHs (primary γ)



$M = 10^{12}$ kg

$d = 10^{-5}$ pc

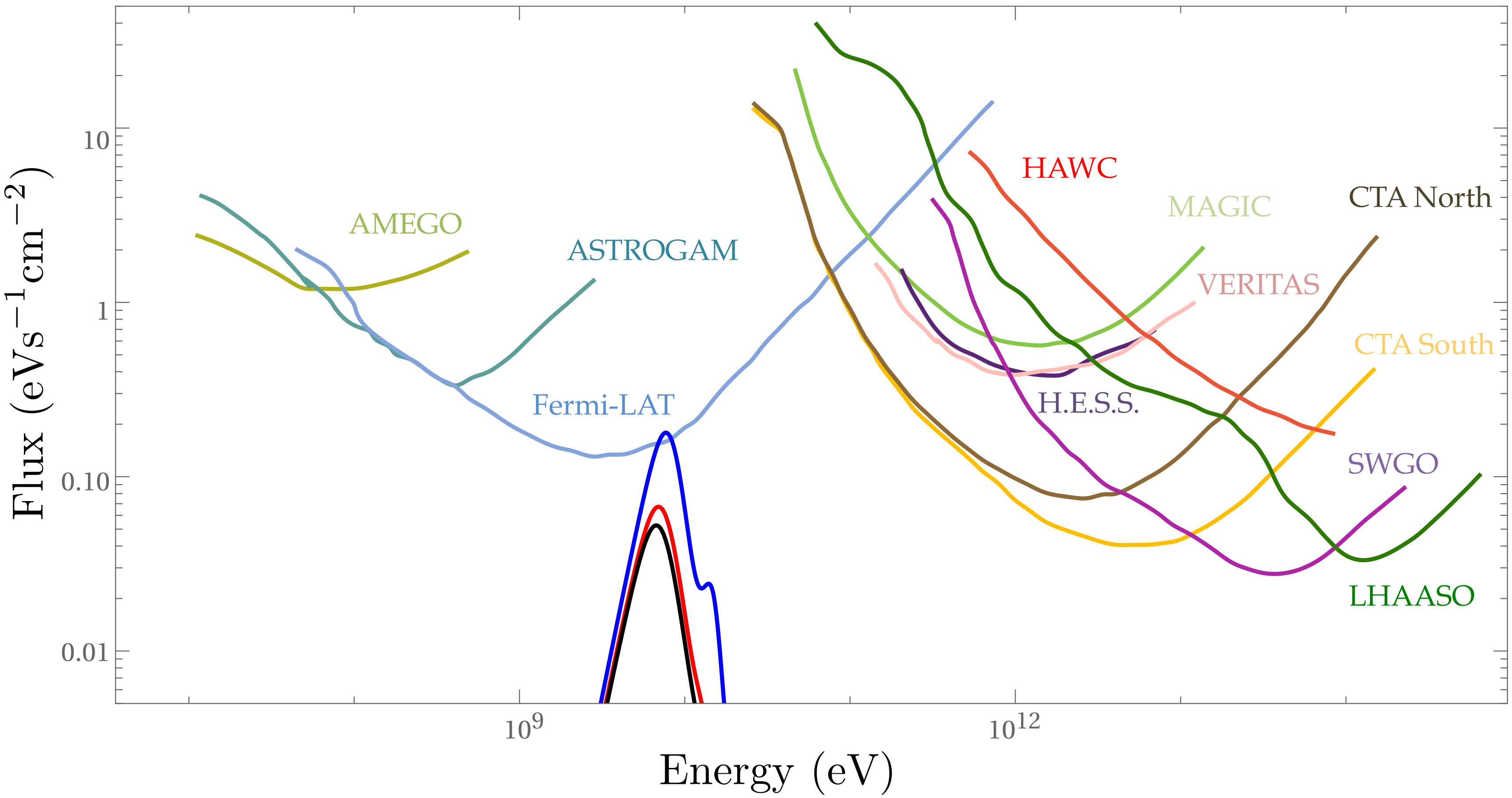
Detecting Kerr PBHs (primary γ)



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

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

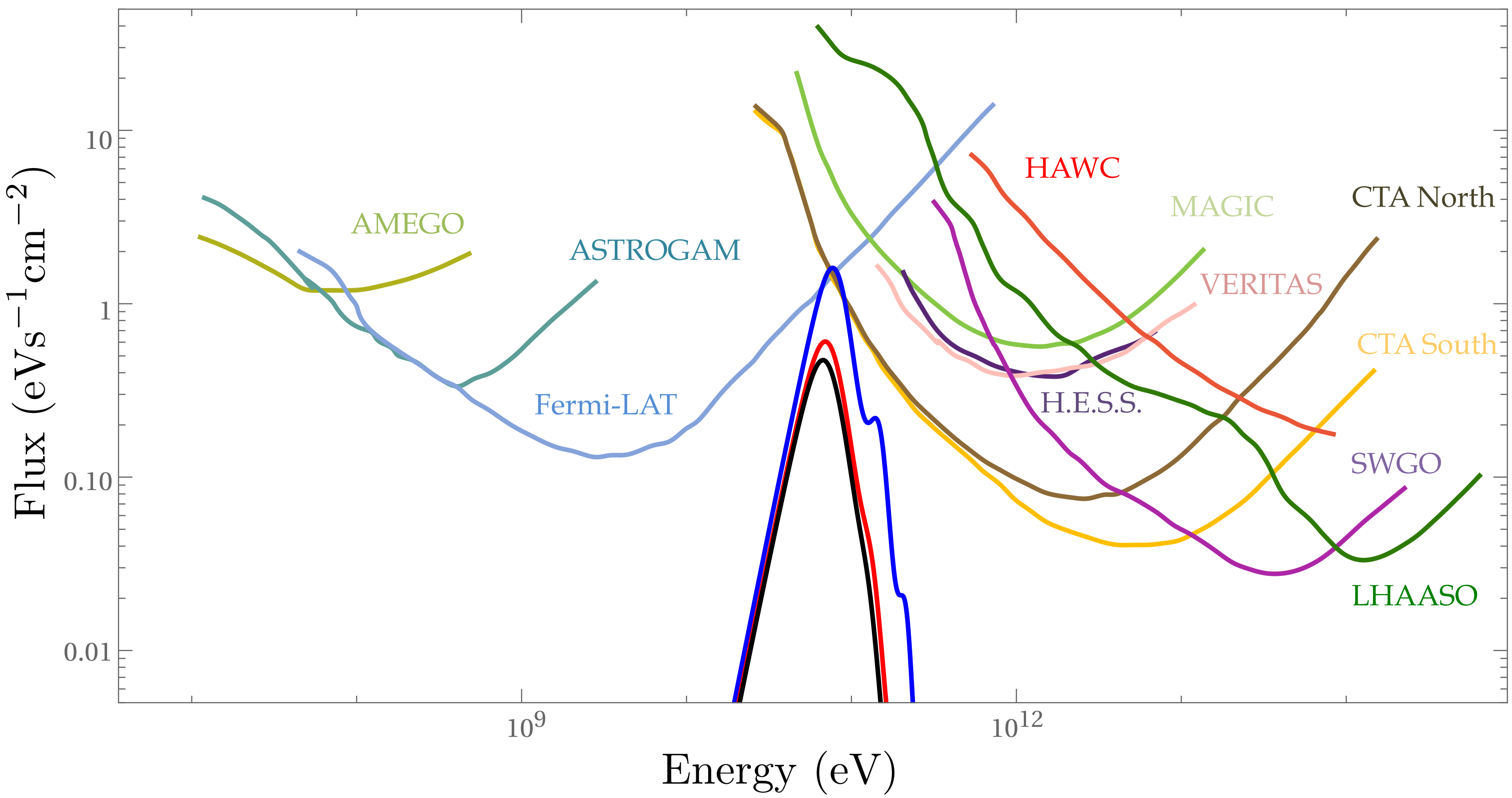
Detecting Kerr PBHs (primary γ)



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

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

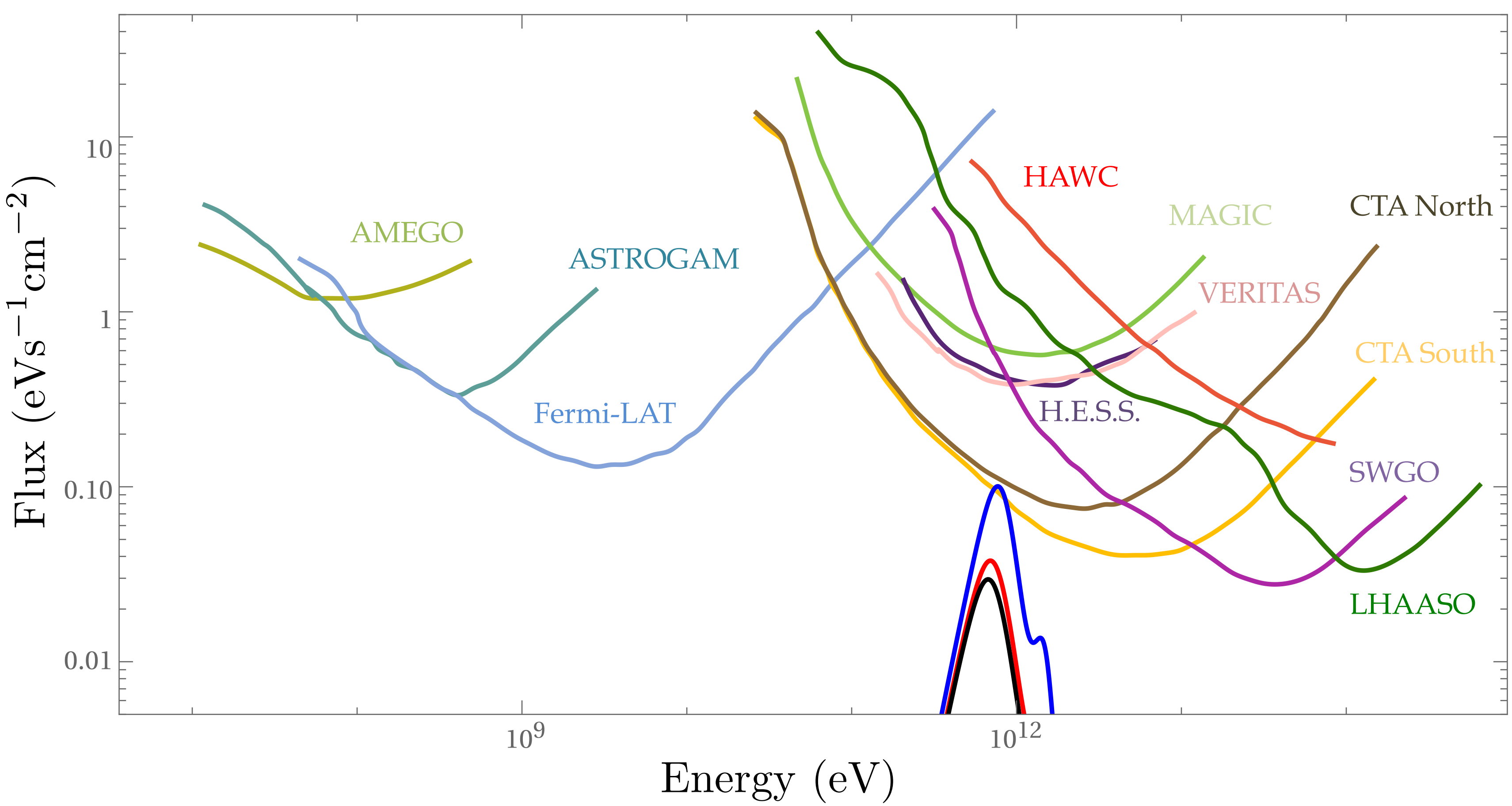
Detecting Kerr PBHs (primary γ)



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

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

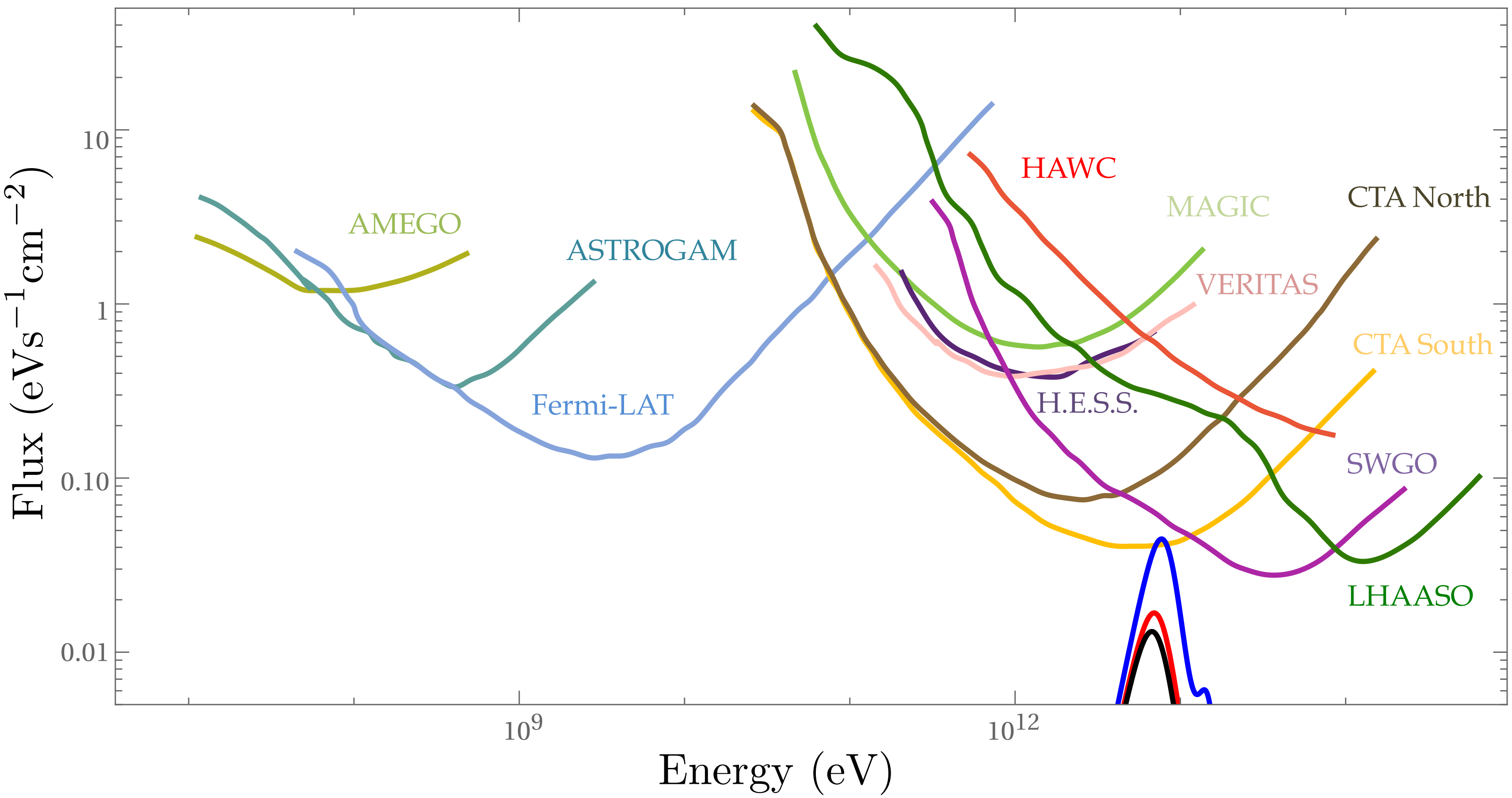
Detecting Kerr PBHs (primary γ)



$$M = 10^8 \text{ kg}$$

$$d = 0.4 \text{ pc}$$

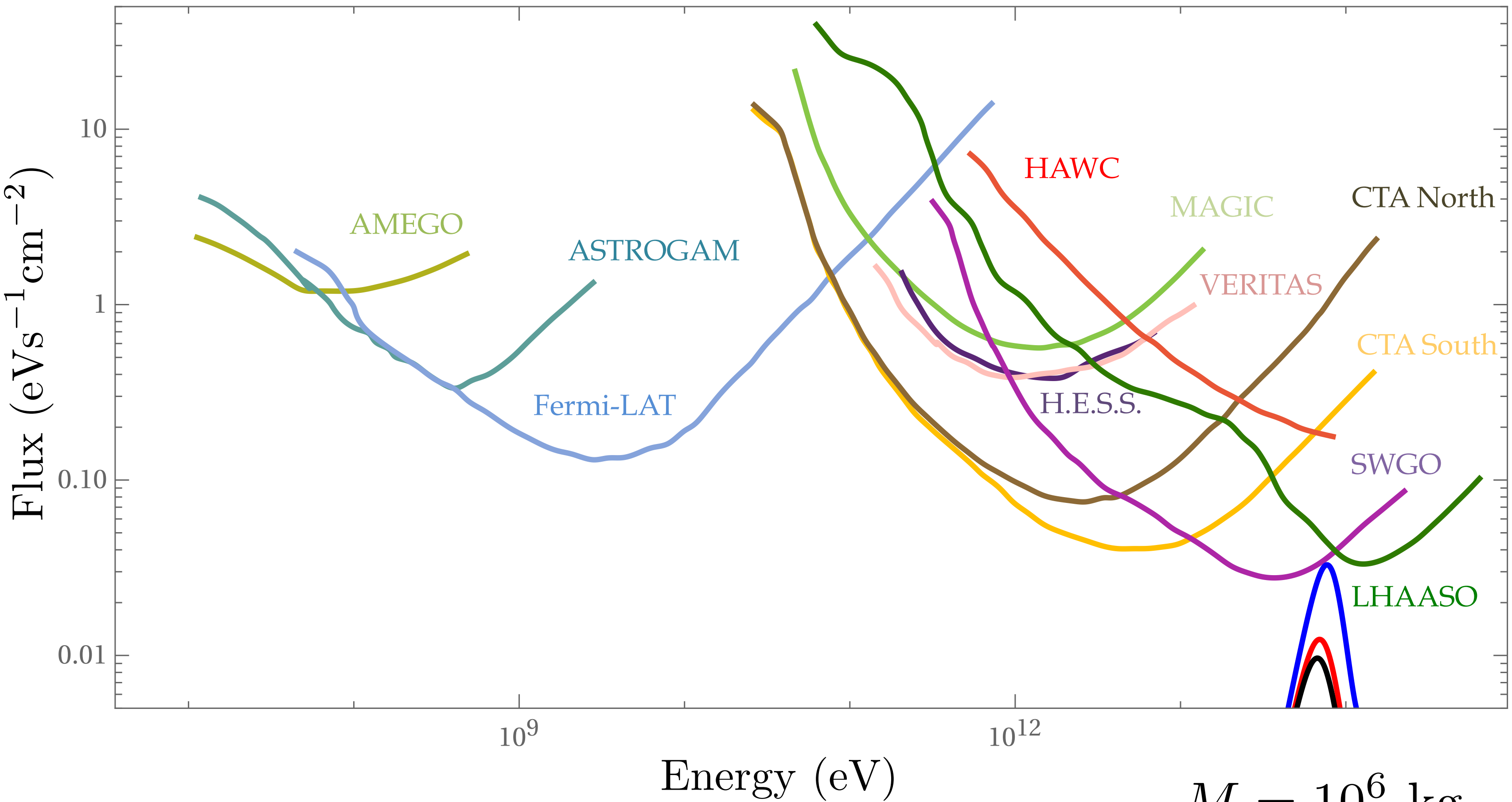
Detecting Kerr PBHs (primary γ)



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

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

Detecting Kerr PBHs (primary γ)



$M = 10^6$ kg

$d = 70$ pc

Take home messages

- Evaporating PBHs are fantastic particle physics laboratories
- PBHs with non-negligible spin = smoking-gun for string axiverse
- PBH Regge plot = total # light axions (<MeV)
- Tracking PBH mass and spin = new BSM physics (>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

Thank you!