Detecting Axion-Like Particles with Primordial Black Holes

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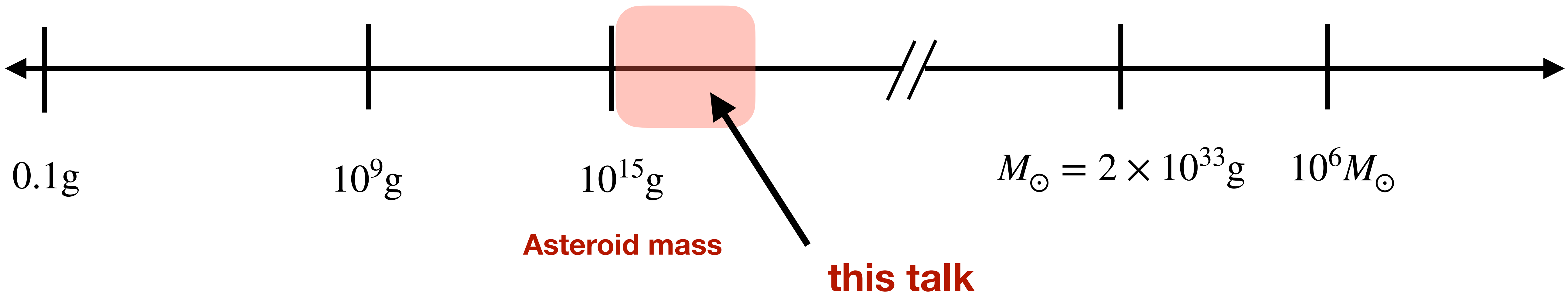
arXiv: 2212.11980

Mitchell Conference on Collider, Dark Matter, and Neutrino Physics
Texas A&M University
May 18, 2023

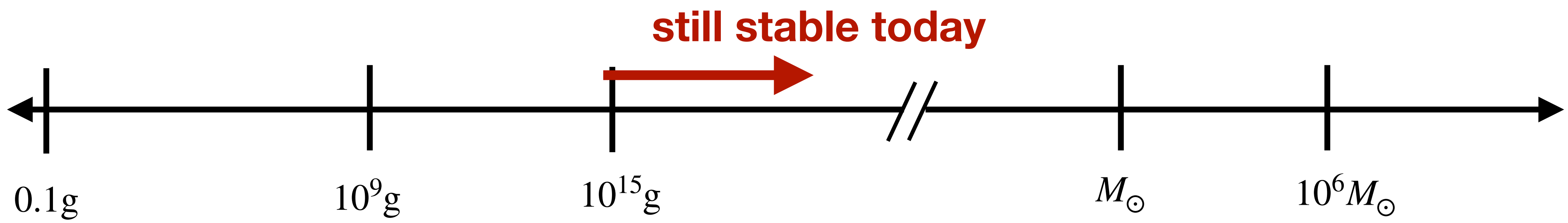
Black Holes can have different masses.

Primordial black holes can be produced in the early universe.



- **Origin of PBHs related to interesting cosmology models.**
- **PBHs can be macroscopic dark matter candidates.**
- **Hawking temperature is higher when PBH is light.**
- **Different observation channels including Hawking radiation and GWs.**

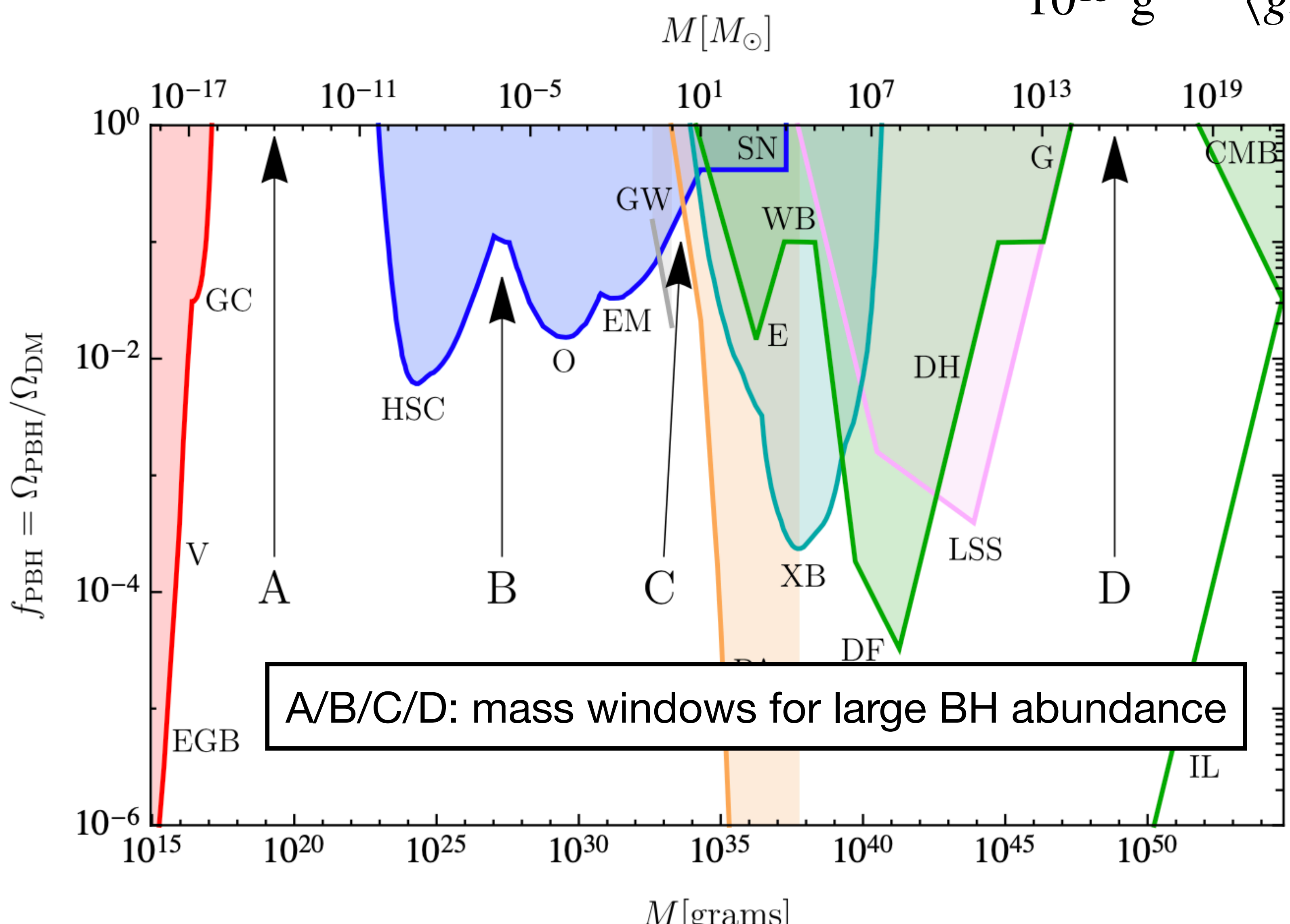
Primordial Black Holes



BH evaporation lifetime: $\tau_{BH} \simeq 12.7 \times 10^9 \text{ yr } \left(\frac{M_{PBH}}{10^{15}\text{ g}}\right)^3 \left(\frac{108}{\langle g_\star \rangle}\right)$

fraction of DM made of PBHs

$$f_{PBH} = \frac{\Omega_{PBH}}{\Omega_{DM}}$$



Carr, Kuhnel, 2006.02838

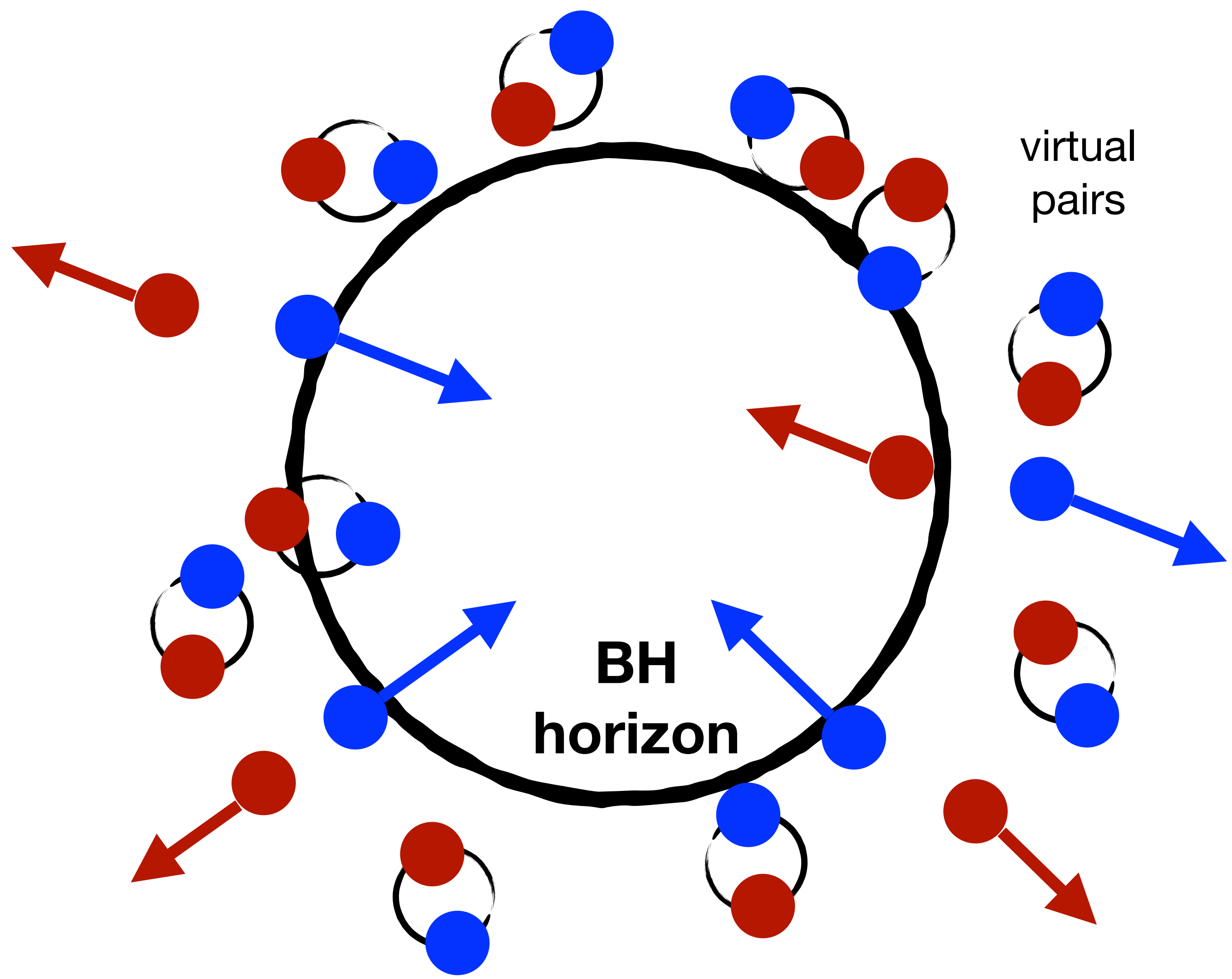
evaporation, lensing, gravitational waves, dynamical effects, accretion, CMB distortion, large scale structure

Hawking radiation

Particle production around horizon due to tidal force: $$\frac{\partial N_i}{\partial E_i \partial t} = \frac{g_i}{2\pi} \frac{\Gamma_i}{e^{E_i/T_{\rm PBH}} \pm 1}$$

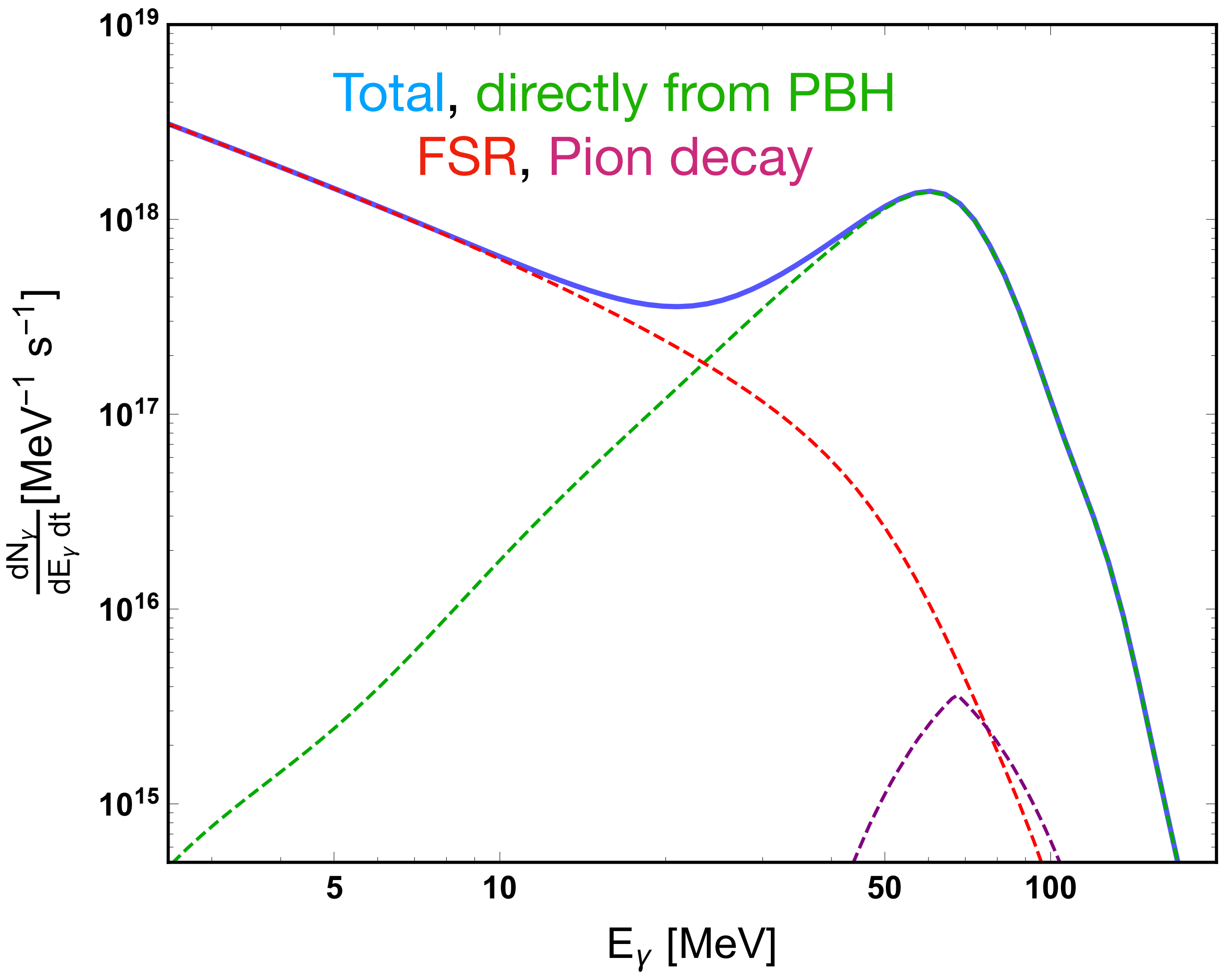
BH Hawking temperature: $$T_{\rm PBH} = \frac{1}{8\pi G M_{\rm PBH}} \simeq 10.5 \left(\frac{10^{15}\,{\rm g}}{M_{\rm PBH}}\right) {\rm MeV}$$

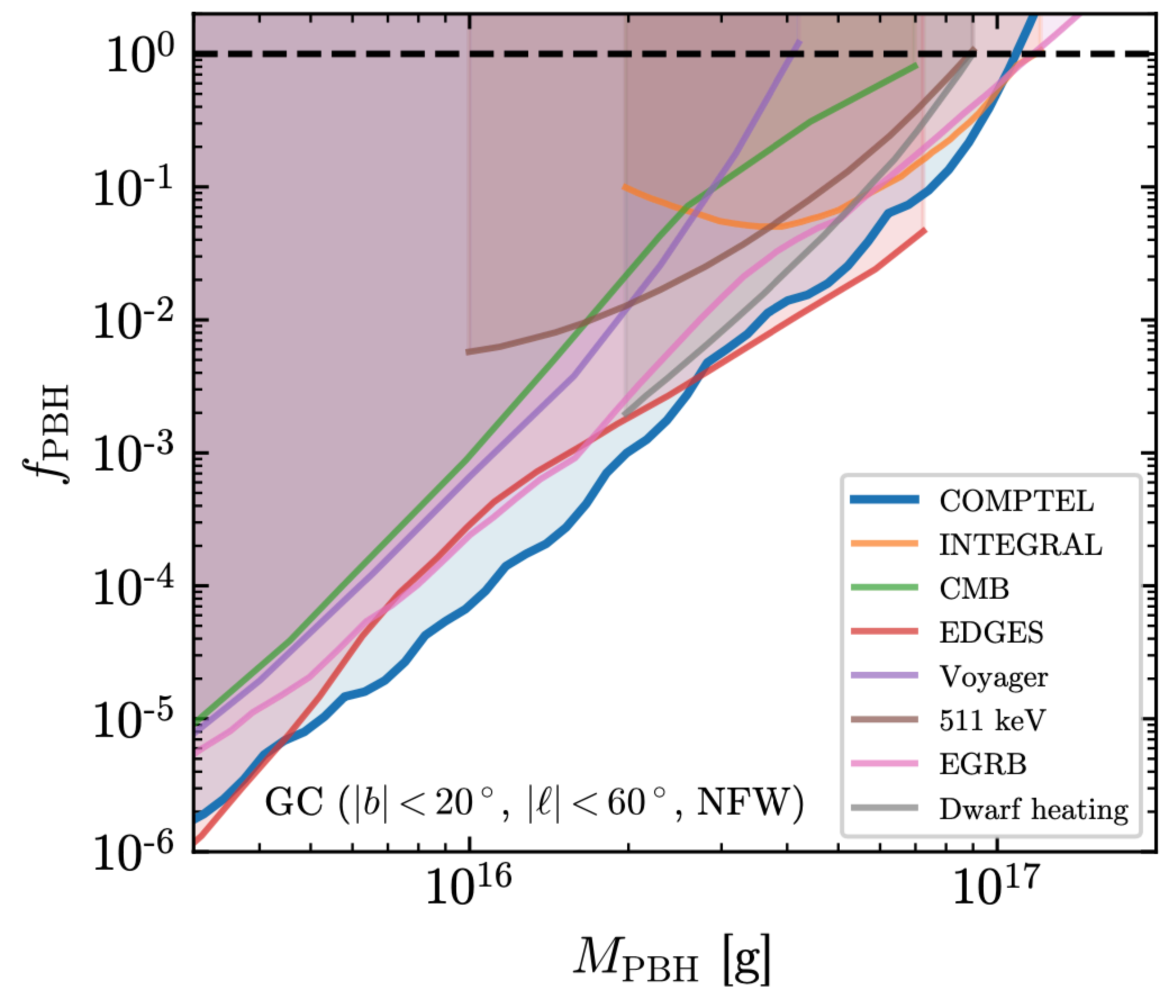
Asteroid-mass PBHs are Hawking evaporating at $\mathcal{O}(\mathrm{MeV})$ energy.



We can use gamma-ray to constrain PBHs as (fraction of) DM:

$$\underbrace{\frac{\partial N_{\gamma,\mathrm{tot}}}{\partial E_\gamma \partial t} = \frac{\partial N_{\gamma,\mathrm{primary}}}{\partial E_\gamma \partial t}}_{\text{primary photon}} + \sum_{i=e^\pm,\mu^\pm,\pi^\pm} \underbrace{\int dE_i \frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} \frac{dN_{i,\mathrm{FSR}}}{dE_\gamma}}_{\text{final-state radiation}} + \sum_{i=\pi^0} \underbrace{\int dE_i 2 \frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} \frac{dN_{i,\mathrm{decay}}}{dE_\gamma}}_{\text{pion decay}}$$





A. Coogan, L. Morrison, S. Profumo, 2010.04797

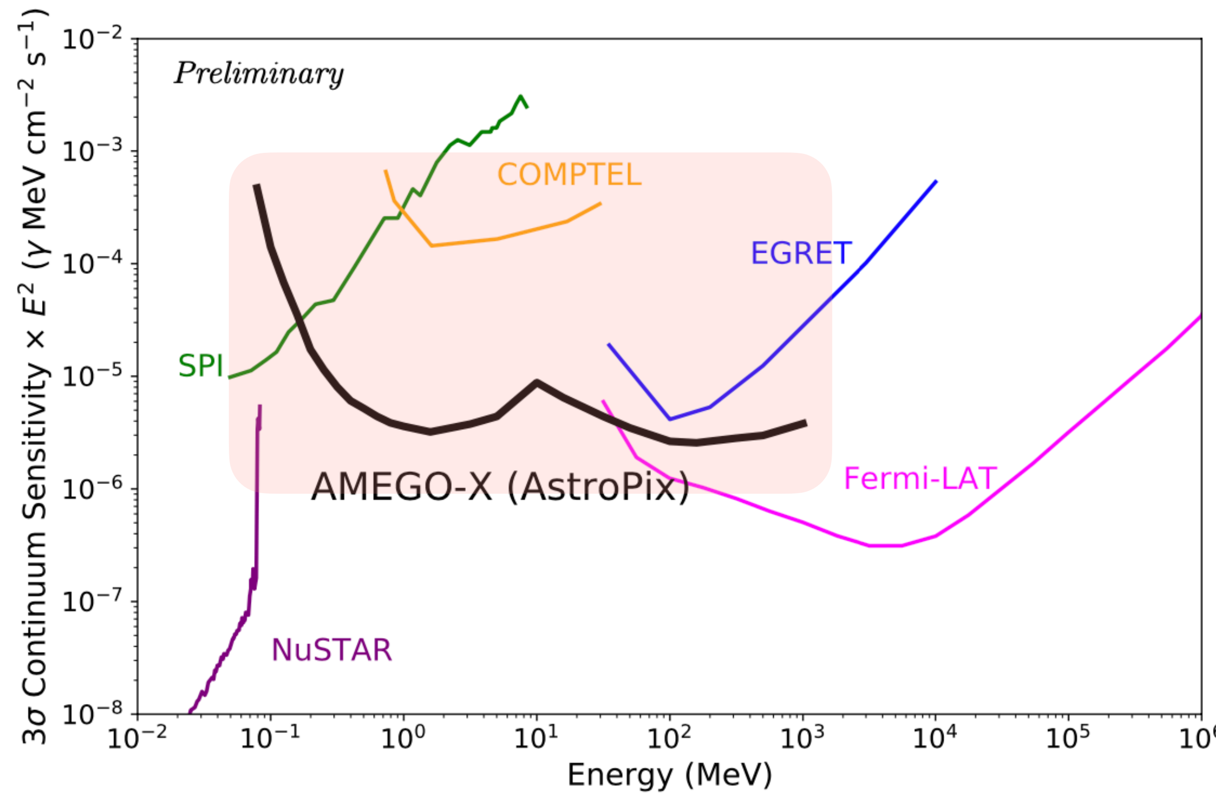
Future MeV gamma-ray searches including AMEGO, ASTROGAM, APT and more

- Covers gamma-ray energy

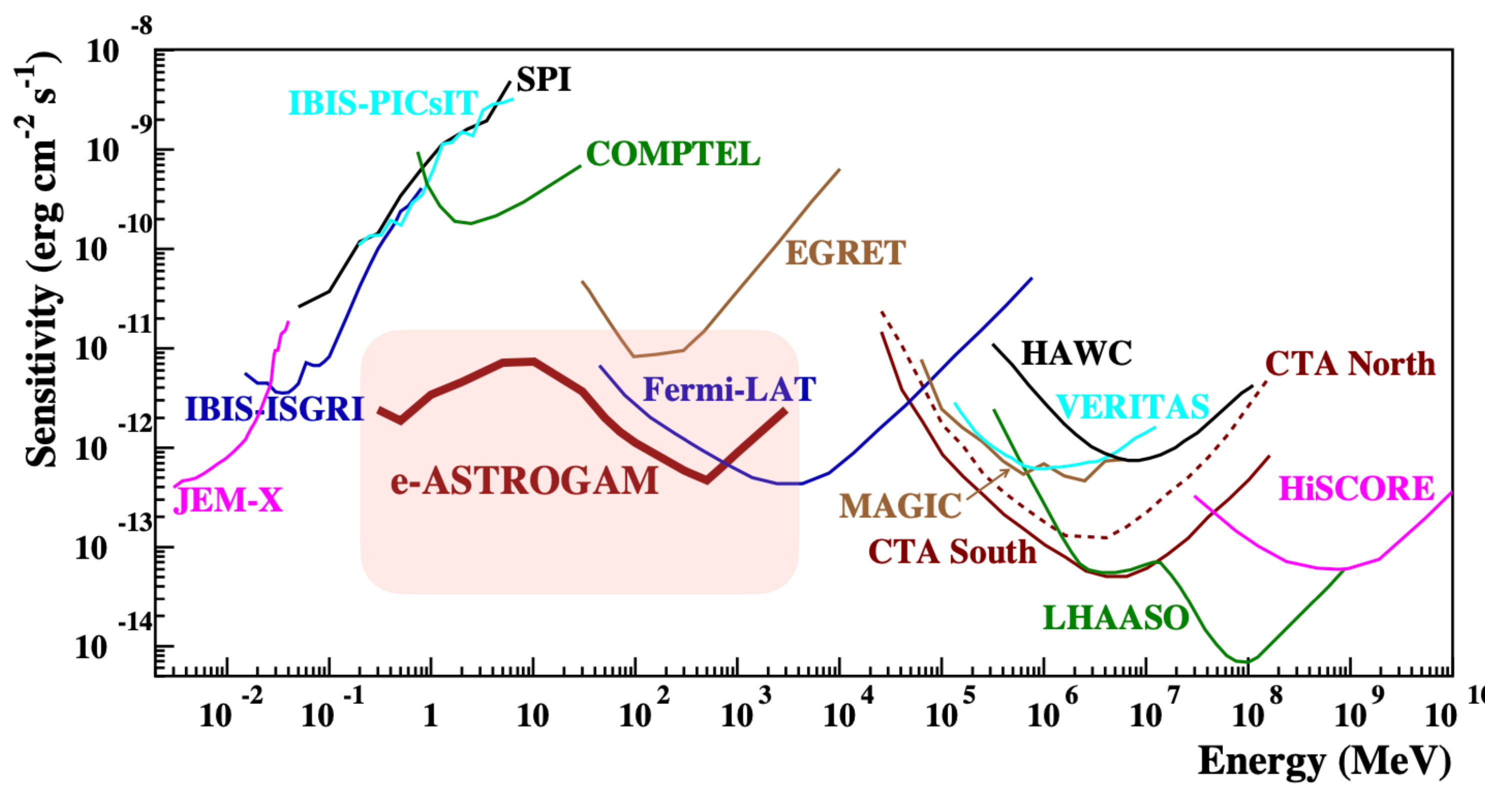
$$0.1\ \mathrm{MeV} \lesssim E_\gamma \lesssim 100\ \mathrm{MeV}$$

- Corresponds to the Hawking temperature of PBHs

$$10^{14}\ \mathrm{g} \lesssim M_{\mathrm{PBH}} \lesssim 10^{17}\ \mathrm{g}$$



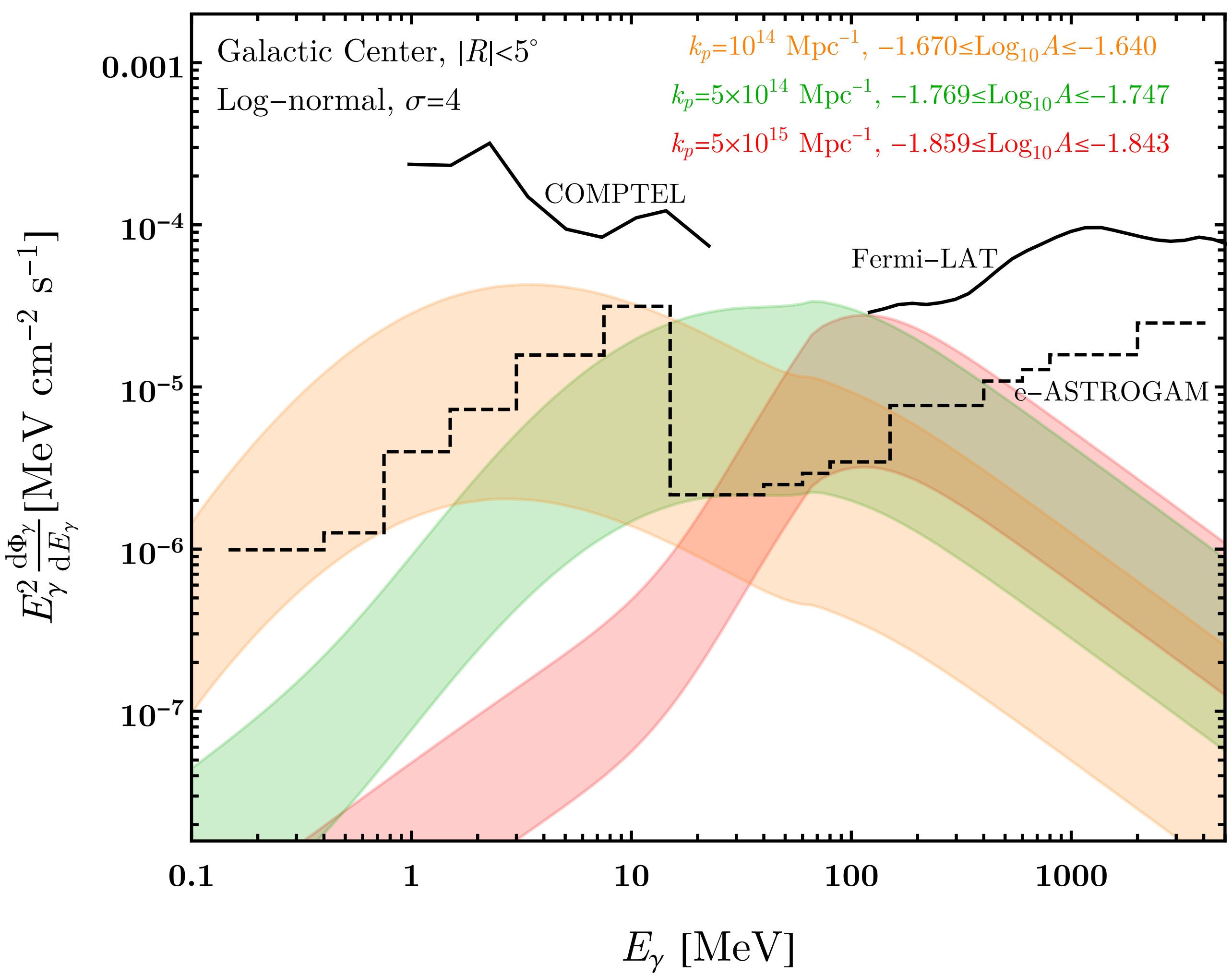
AMEGO-X 2108.02860

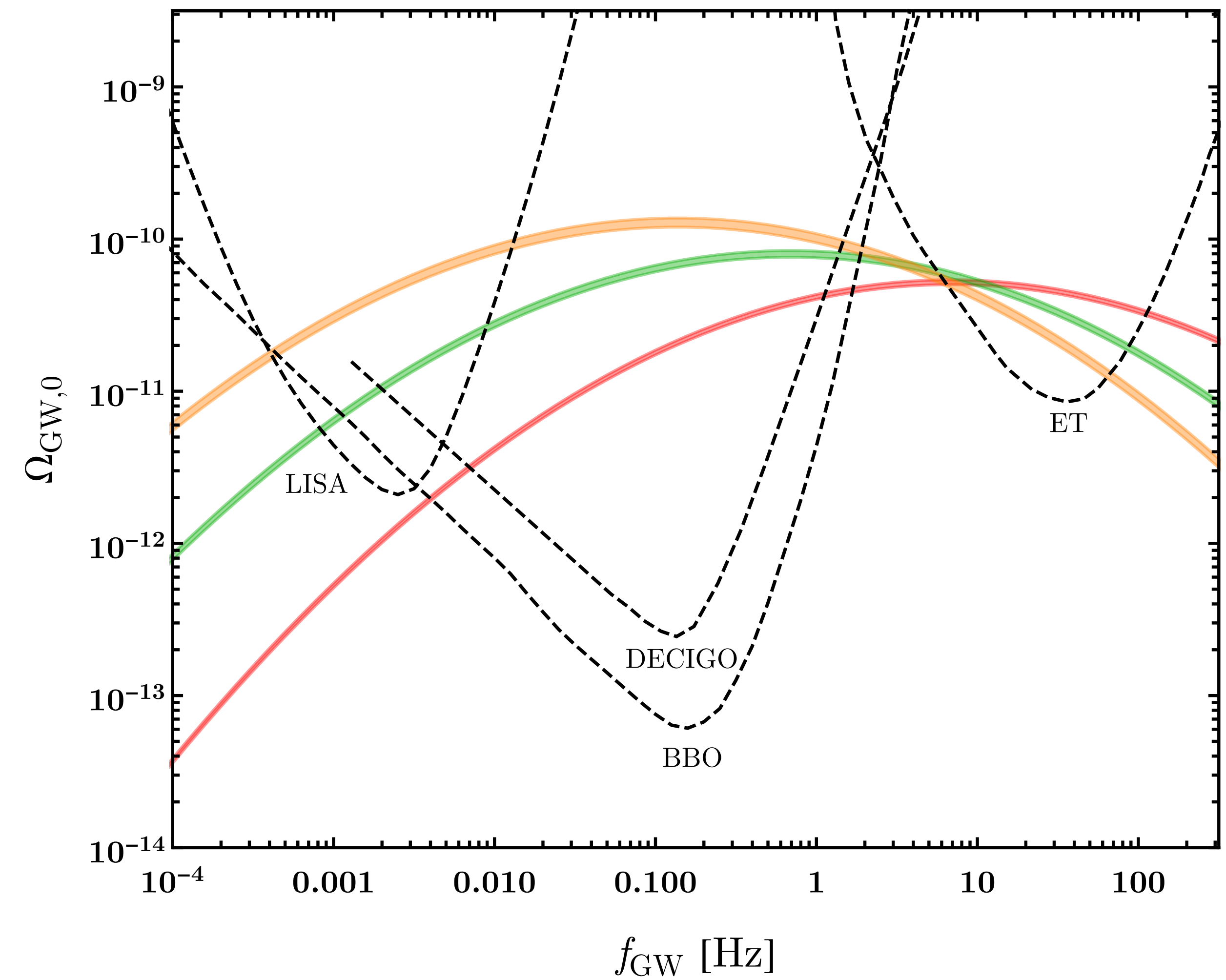


e-Astrogam, 1611.02232

GWs are generated by curvature perturbations at PBH formation.

Multi-messenger observations of **gamma-ray** and **GWs** to study asteroid-mass PBH DM.





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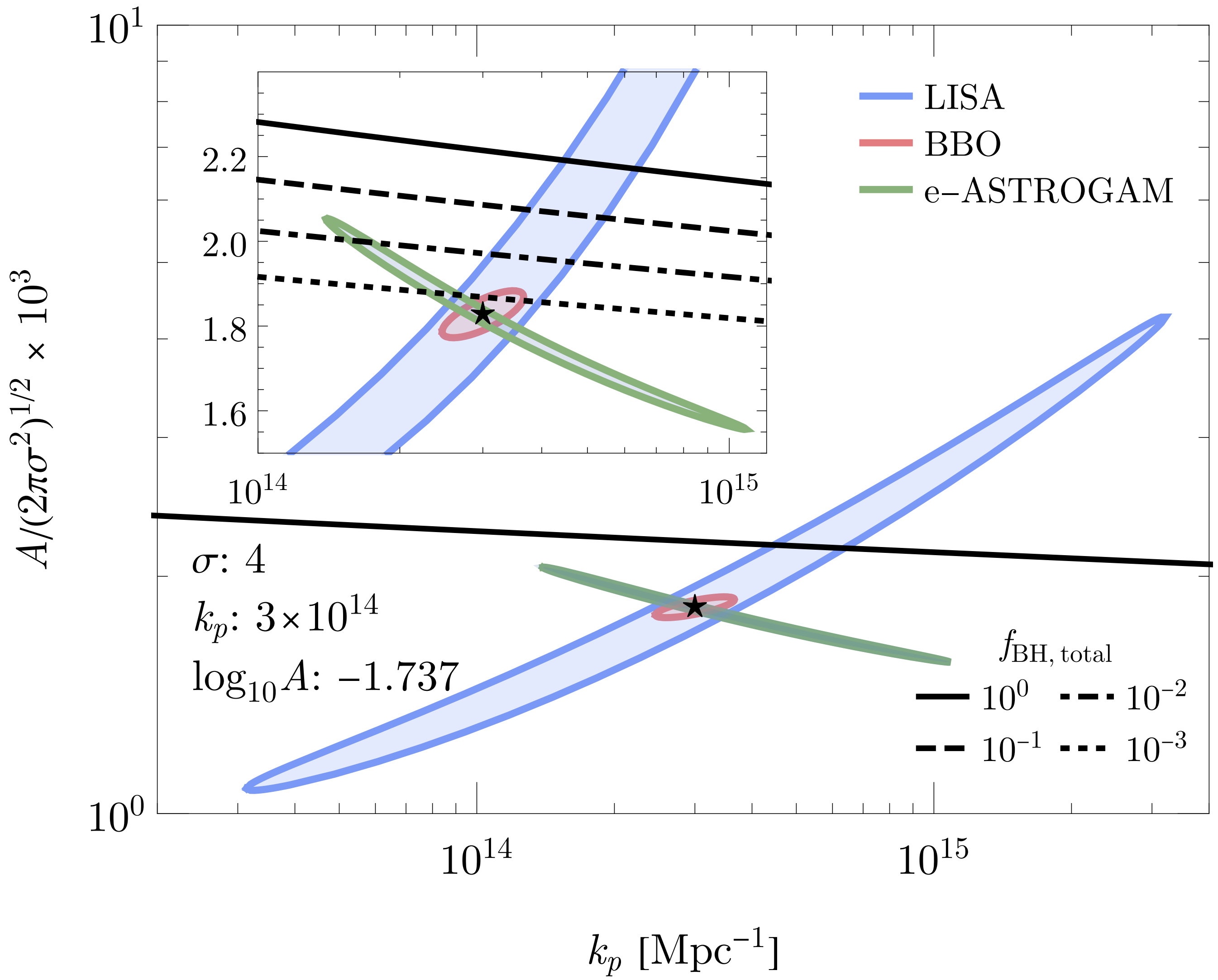
2202.04653, PRD 2022

parameter fit to the curvature perturbations responsible for PBH formation

$$P_\zeta(k) = \frac{A}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\log k - \log k_p)^2}{2\sigma^2}\right)$$



Multi-messenger observation can test PBH DM **abundance** and **cosmic origin**

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2202.04653, PRD 2022

Hawking radiation production rate:

$$\frac{\partial N_i}{\partial E_i \partial t} = \frac{g_i}{2\pi} \frac{\Gamma_i}{e^{E_i/T_{\rm PBH}} \pm 1}$$

- particle mass **kinematically allowed** $m_i \lesssim E_i \lesssim T_{\rm PBH}$

  Asteroid-mass PBHs can produce MeV or lighter BSM particles as well

- production via gravity only depends on **degree of freedom** g_i, not coupling

  BH Hawking radiation is another channel to produce new particles

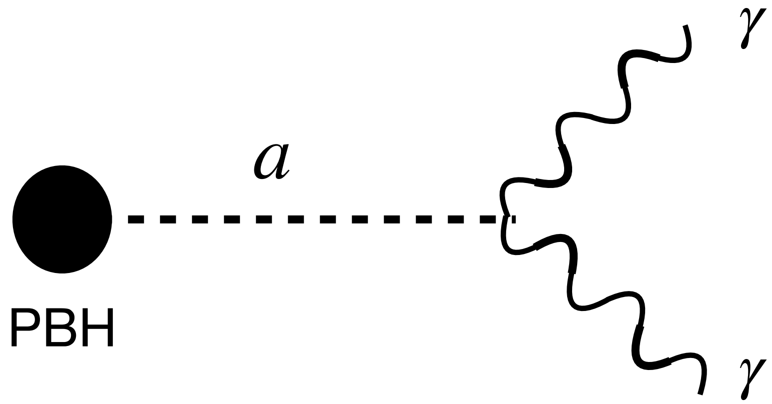
- Γ_i contains the graybody factor for the re-absorption of low energy particles

BSM with PBHs

- If exists an **Axion-Like-Particle** in the particle spectrum

$$\mathscr{L}_{a\gamma\gamma} \supset \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{1}{2} m_a^2 a_a^2 + \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

light pseudoscalar couples to photon



$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2\, m_a^3}{64\pi}$$

- Gamma-ray spectrum is modified by ALPs

$$\frac{\partial N_{\gamma,\mathrm{tot}}}{\partial E_\gamma \partial t} = \underbrace{\frac{\partial N_{\gamma,\mathrm{primary}}}{\partial E_\gamma \partial t}}_{\text{primary photon}} + \sum_{i=e^\pm,\mu^\pm,\pi^\pm} \underbrace{\int dE_i \frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} \frac{dN_{i,\mathrm{FSR}}}{dE_\gamma}}_{\text{final-state radiation}} + \sum_{i=\pi^0} \underbrace{\int dE_i 2 \frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} \frac{dN_{i,\mathrm{decay}}}{dE_\gamma}}_{\text{pion decay}}$$

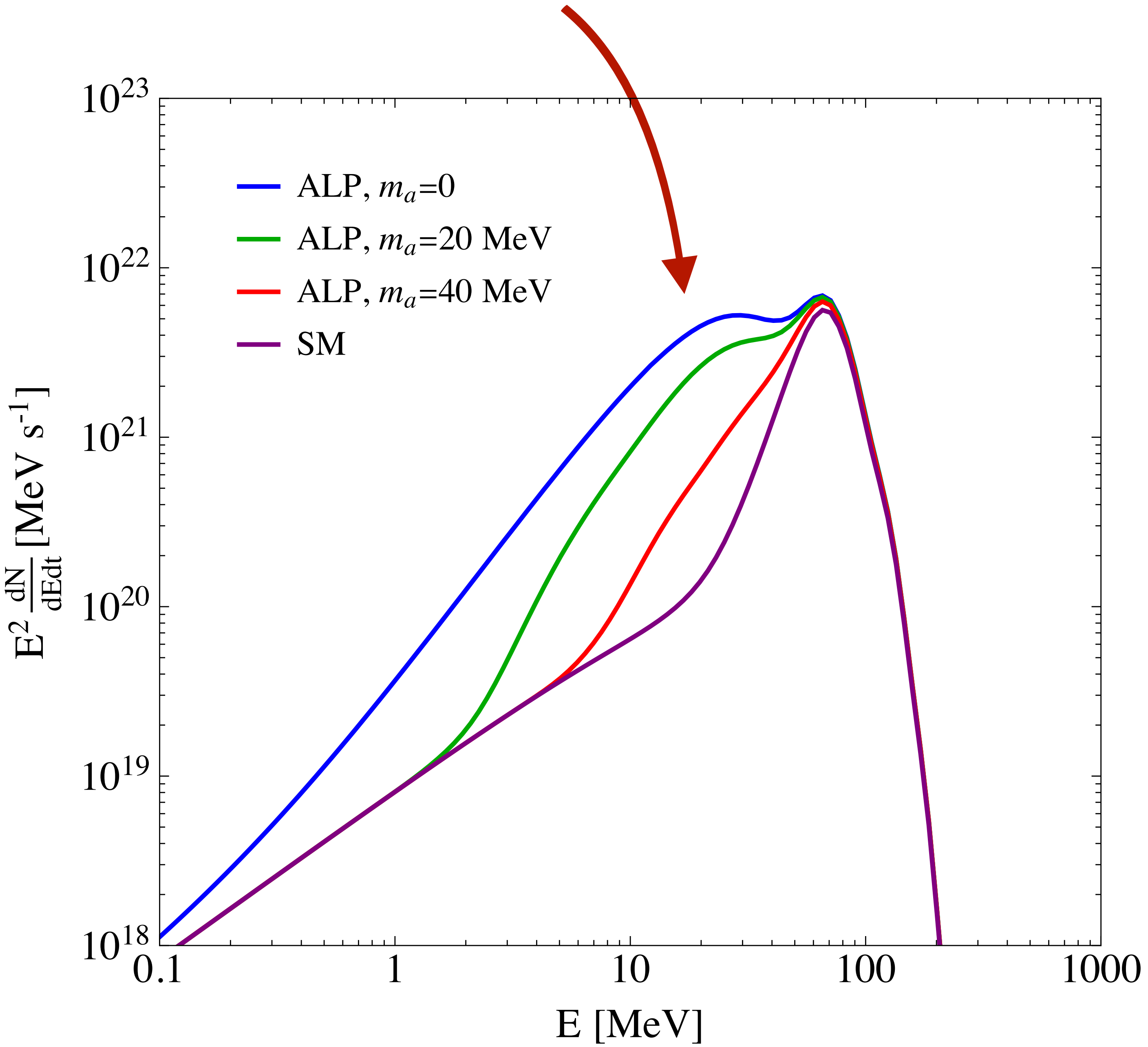
add new physics contributions

$$\boxed{+ \underbrace{\int dE_a 2 \frac{\partial N_{a,\mathrm{primary}}}{\partial E_a \partial t} \frac{dN_{a,\mathrm{decay}}}{dE_\gamma}}_{\text{ALP decay}}}$$

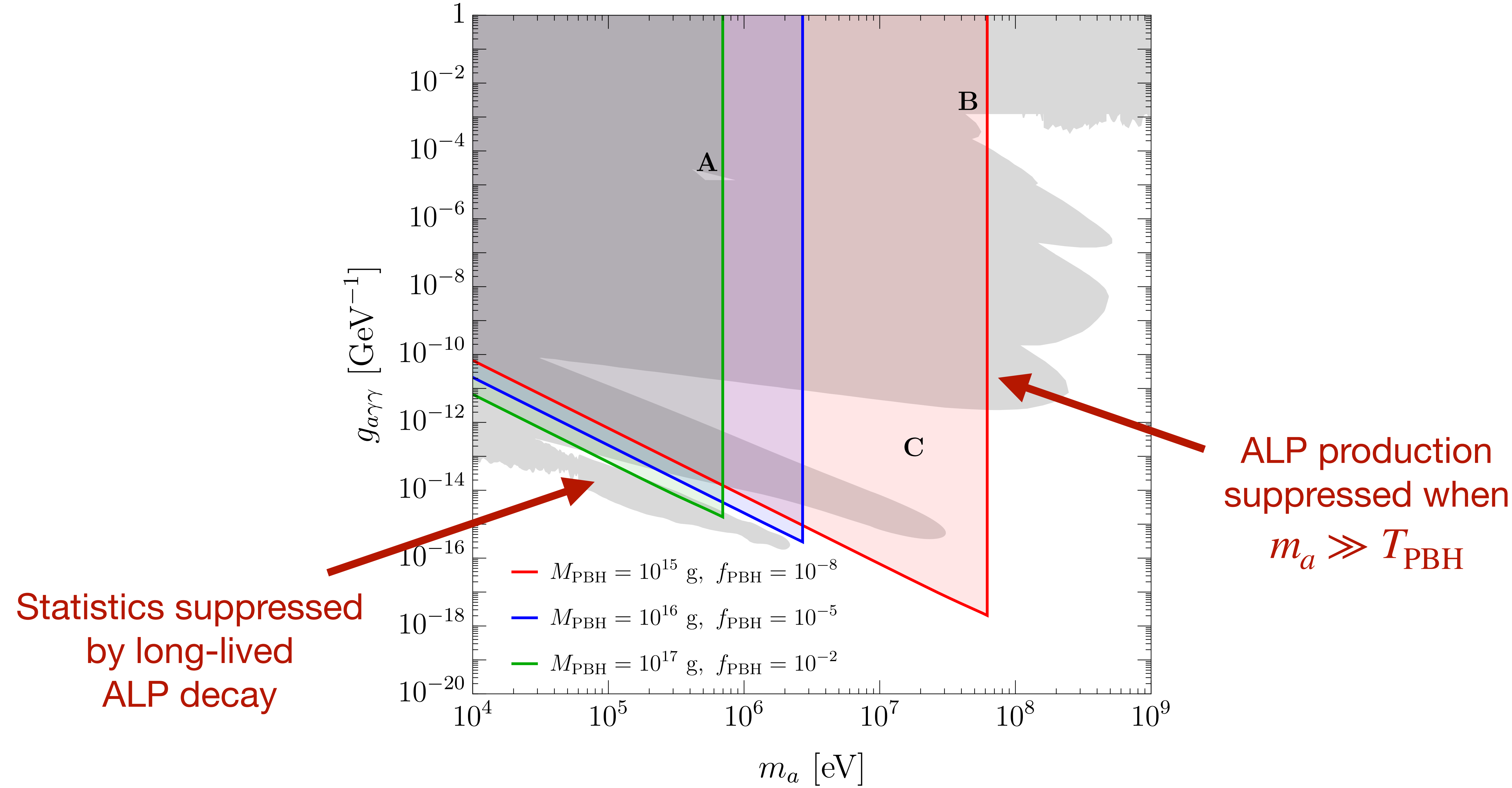
Gamma-ray spectrum (SM+ALP)

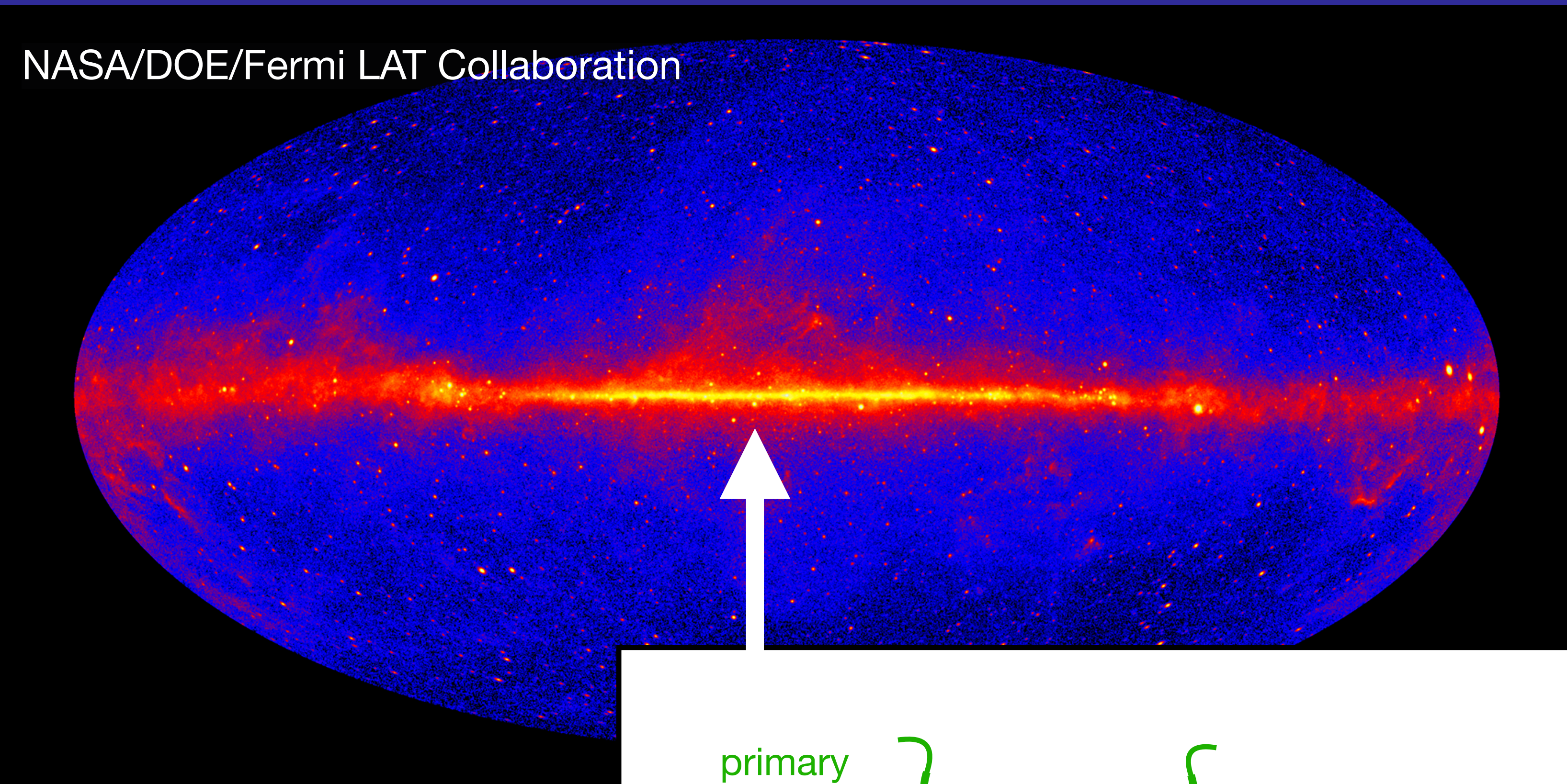
Gamma-ray spectrum, SM (purple) vs. SM+ALP (red, green, blue).

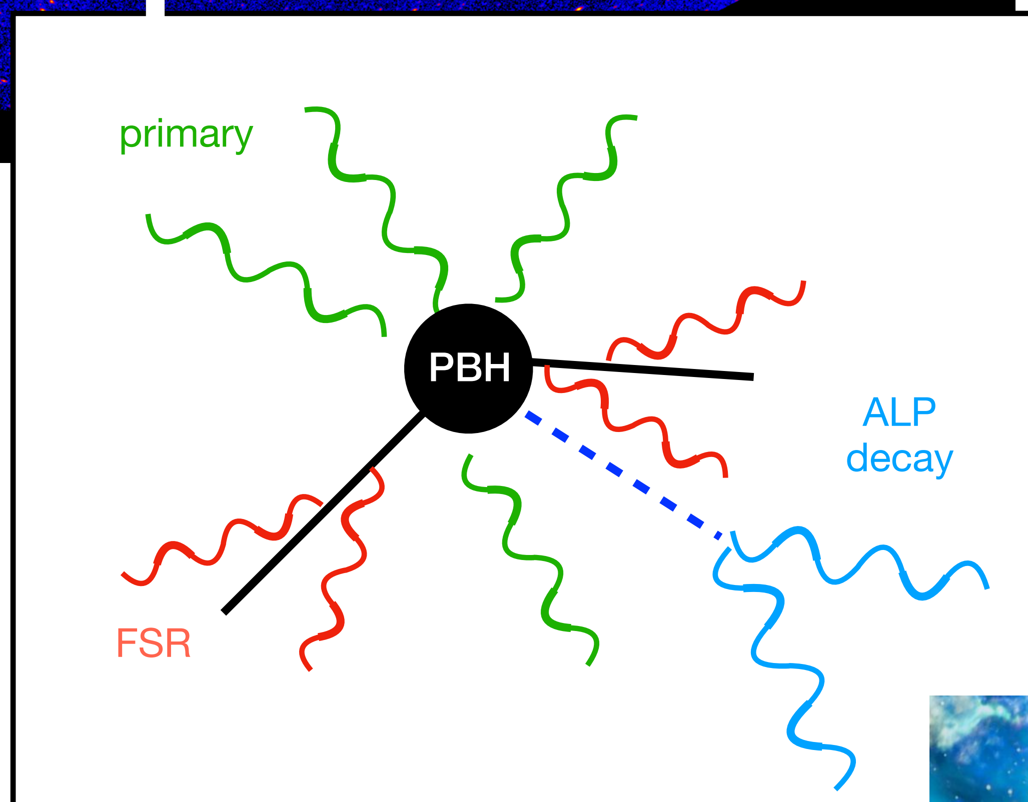
the $a \rightarrow \gamma\gamma$ decay generates a double-peak feature



ALP parameter space that can be probed with PBHs.







Gamma-ray source

Target: Galactic Center (GC)

Angular extent: $|R| < 5^\circ$

Background

forecasted by e-Astrogam

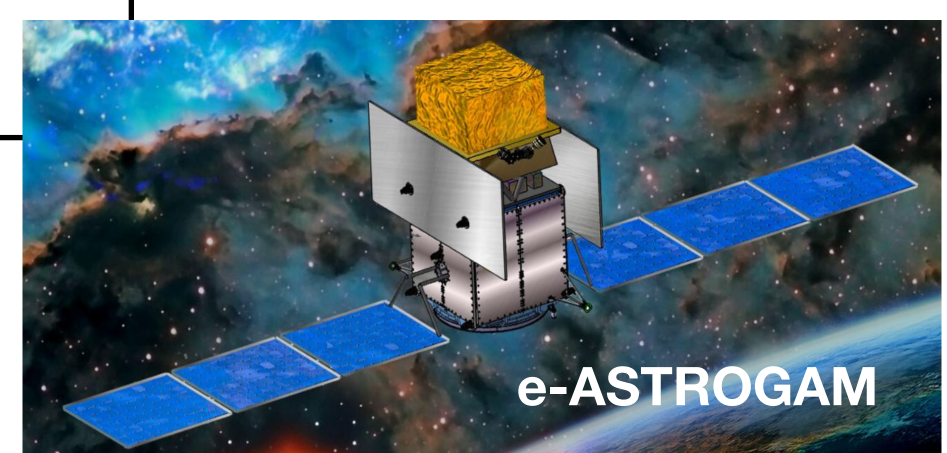
Model to test

SM: only SM particles

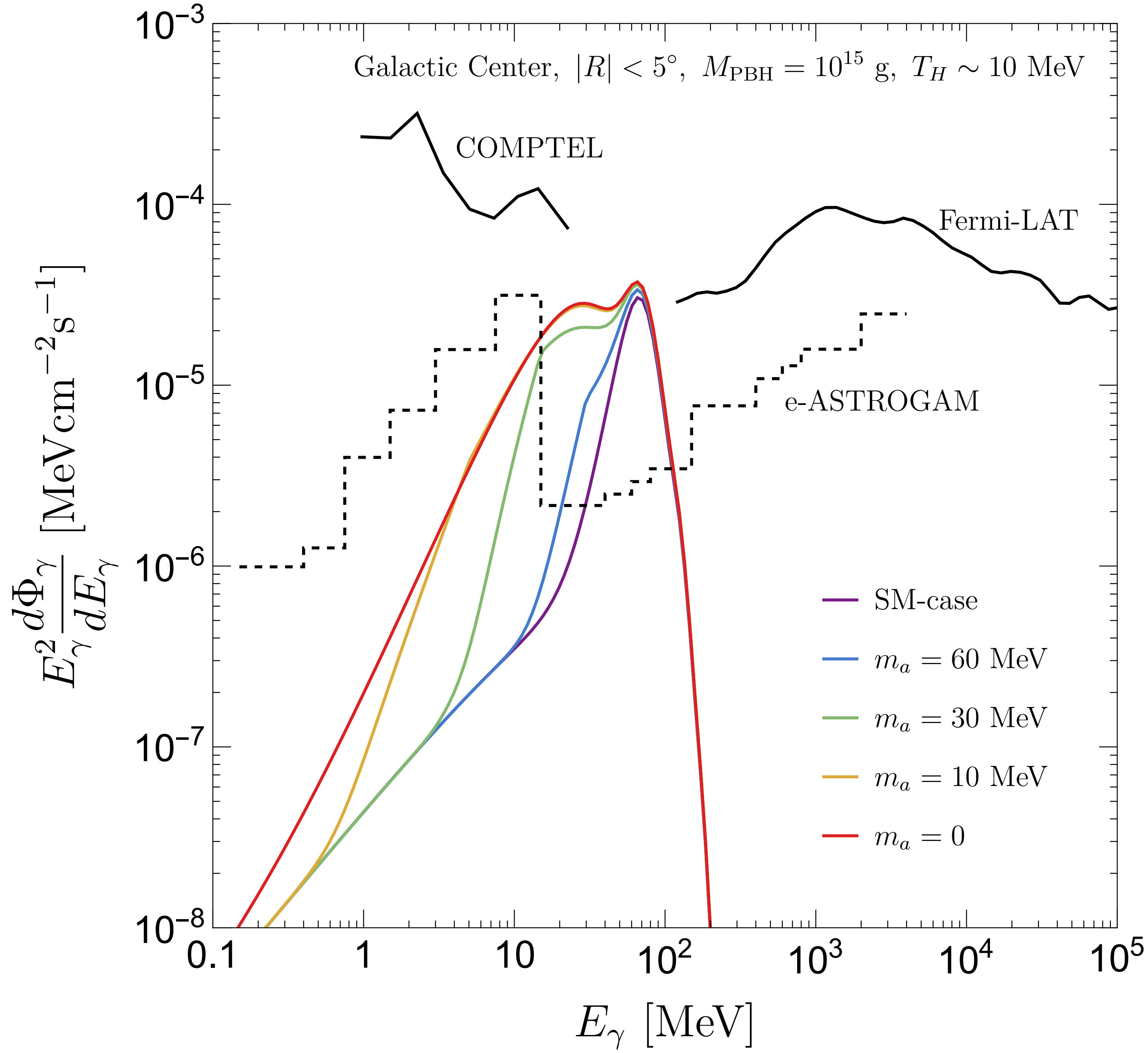
ALP: SM particles + ALP

Assume PBHs make up $f_{\rm PBH}$ of DM

$$\frac{d\Phi_\gamma}{dE_\gamma} = \bar{J}_D \frac{\Delta\Omega}{4\pi} \int dM \frac{f_{\rm PBH}(M)}{M} \frac{\partial N_{\gamma,tot}}{\partial E_\gamma \partial t}$$

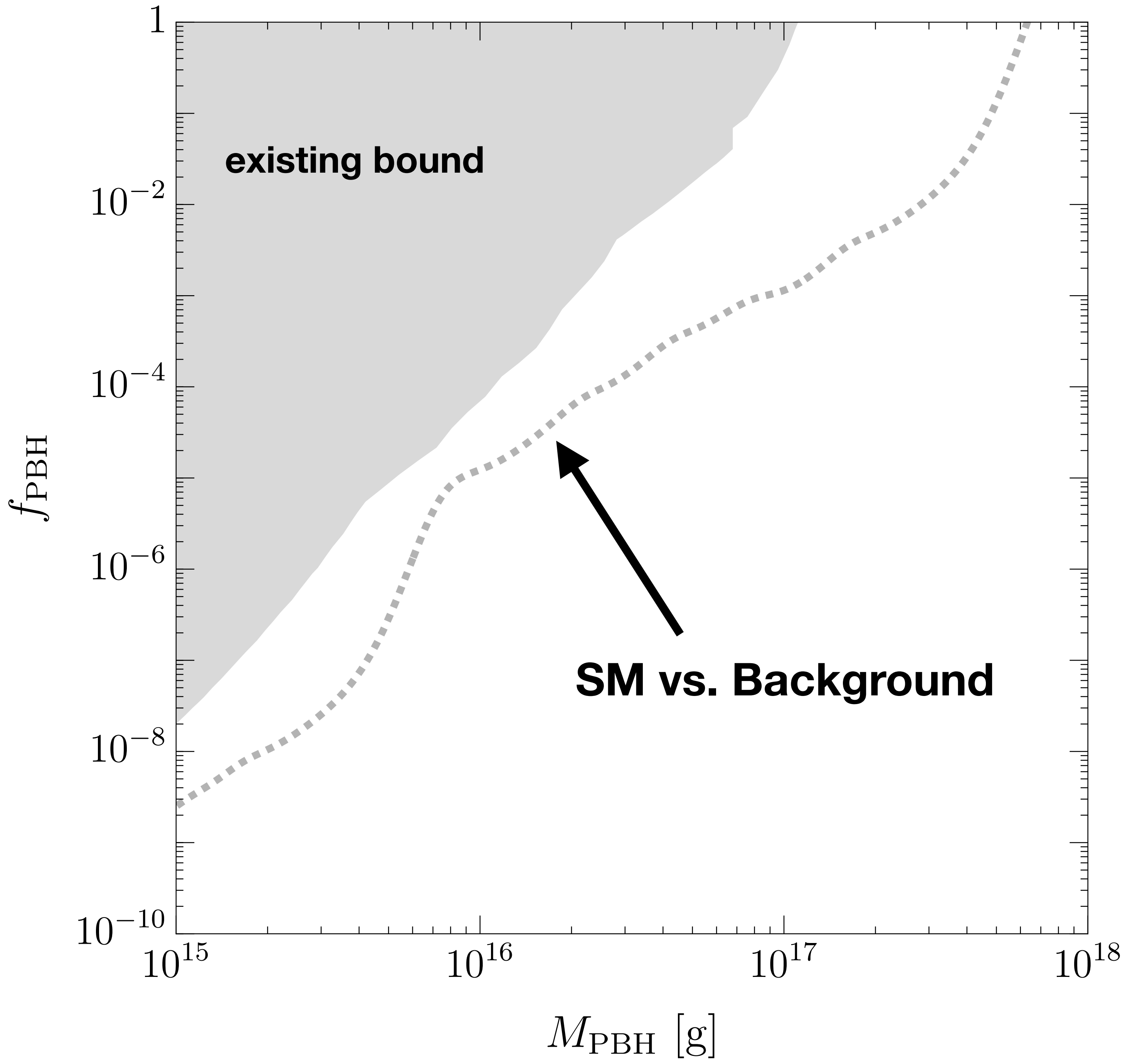


Gamma-ray spectrum from galactic center,
PBH mass and abundance $M_{\rm PBH} = 10^{15}$ g, $f_{\rm PBH} = 10^{-8}$.



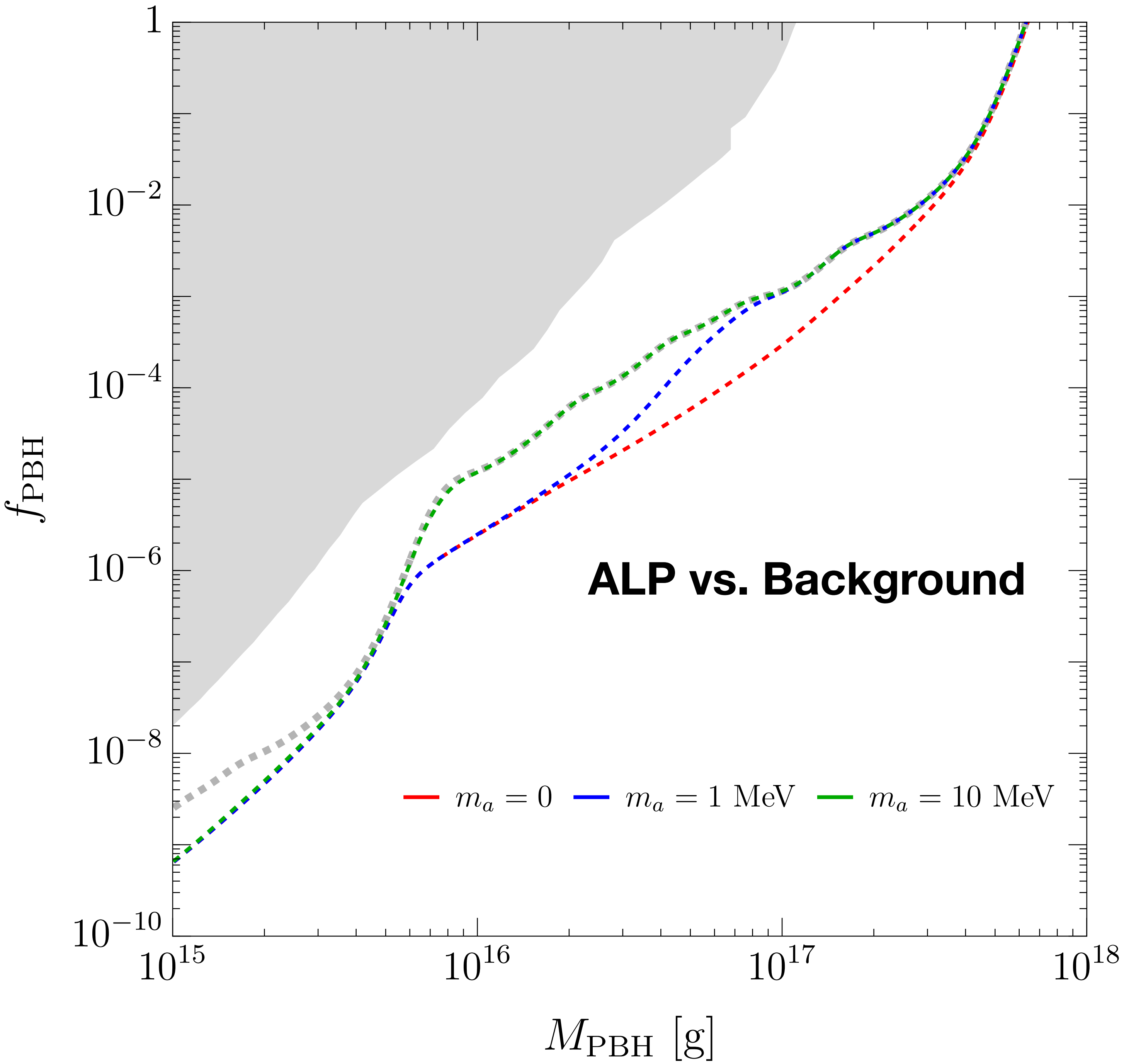
PBH constraint depends on theory assumptions of Hawking radiation spectrum.

Previous sensitivity is assuming only SM particles are produced by PBHs.



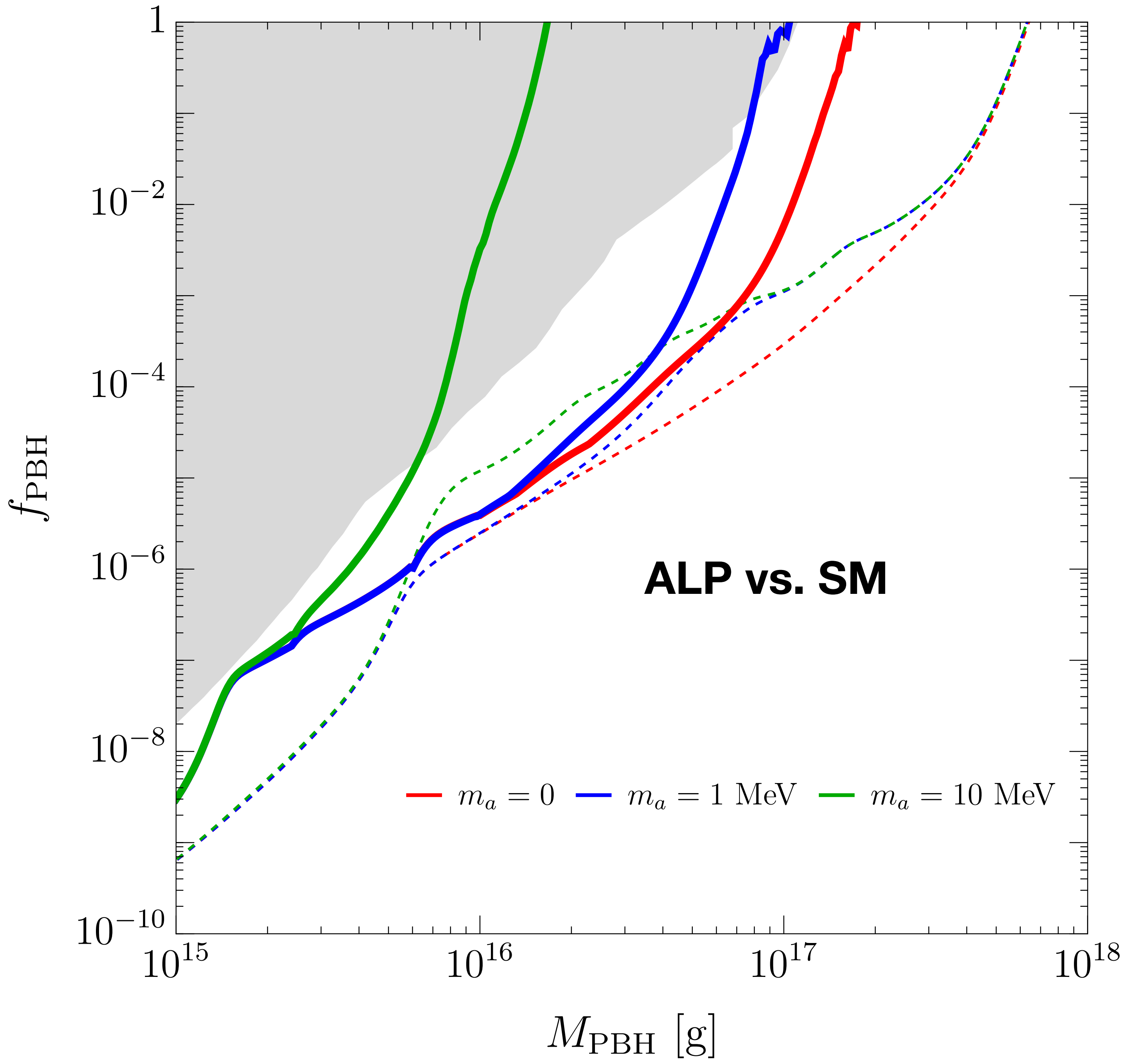
When ALPs are produced with the SM particles, the gamma-ray signal is enhanced.

PBH constraints are stronger if ALP exists.

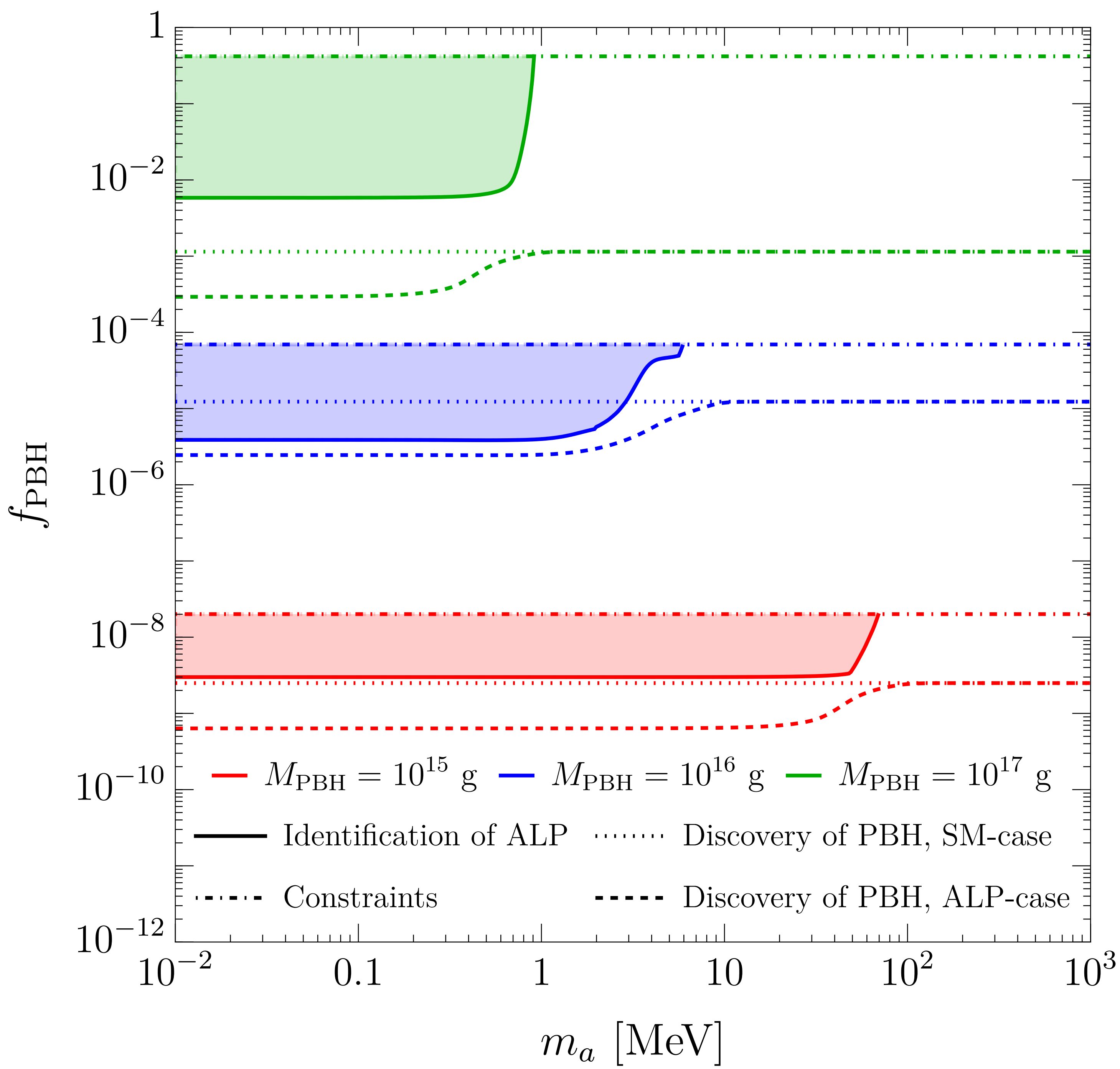


If $f_{\rm PBH}$ is larger than the detection limit, enough statistics to distinguish the ALP.

We will be able to know if ALP exists from the shape of gamma-ray spectrum.



On the f_{PBH} vs. m_a plane, the shaded regions show the range of ALP mass that can be probed with PBHs of different masses.



Light axions can be produced by Kerr BH via superradiance when $\omega_a < m\,\Omega$

Ω: BH angular velocity

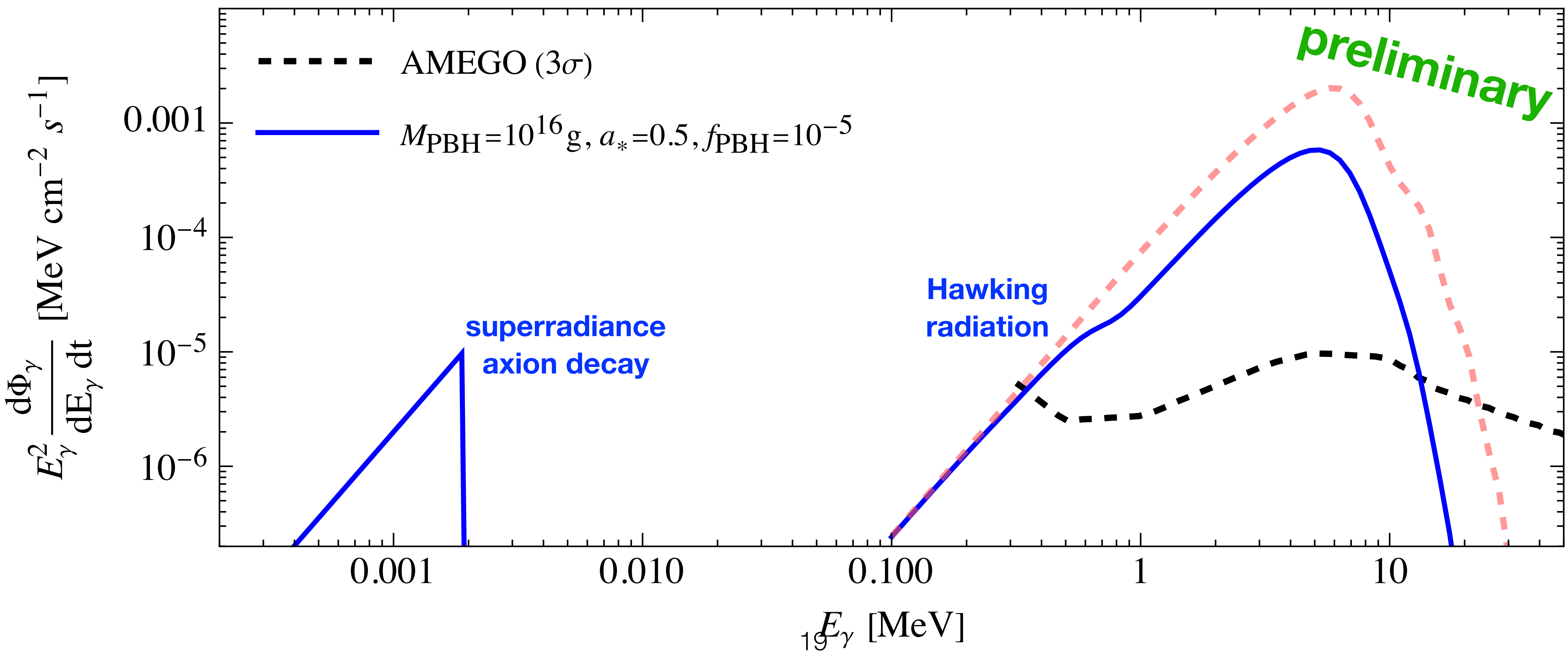
m: azimuthal quantum number

The rotational energy of a PBH is **depleted** into the axion cloud

rotating PBH $\xrightarrow{\text{superradiance}}$ non-rotating PBH

- Correlate extra-galactic gamma-rays at different redshift
- Correlate Hawking radiation with superradiance axion cloud decay

[James B. Dent, Bhaskar Dutta, TX, in progress]



Summary

- **Asteroid-mass PBHs can make up (fraction of) DM. The MeV gamma-ray signals from Hawking radiation process can be used to probe PBHs. Multi-messenger observation with GWs provides more information about PBHs.**

- **Hawking radiation is via gravity. PBHs can produce new particles efficiently as long as the new particles are not too heavier than the Hawking temperature.**

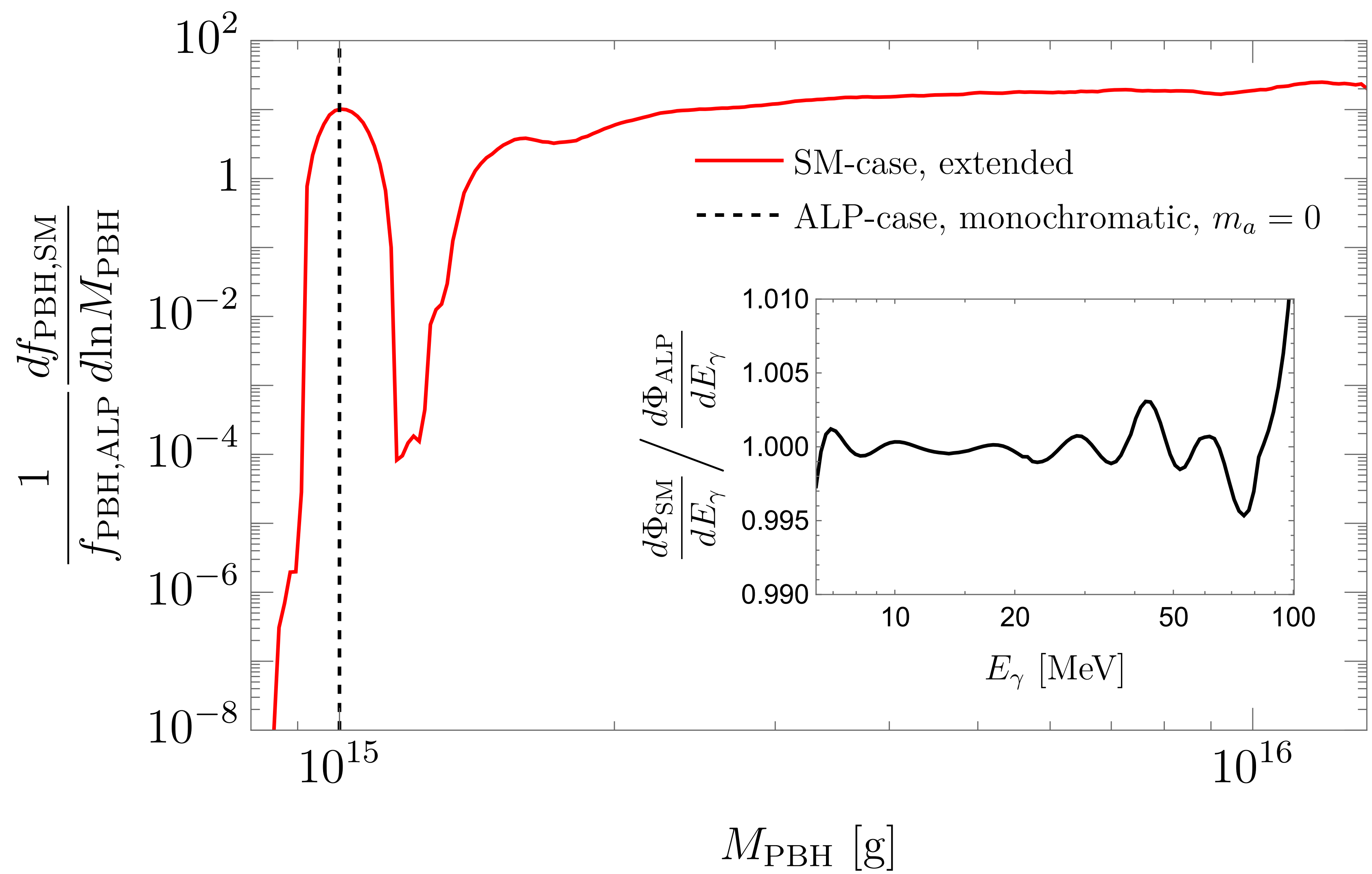
- **We show gamma-ray spectrum analysis can be used to detect ALPs produced by PBHs and decay into photons.**

If we do detect Hawking radiation in the future, we can use the radiation spectrum to probe both PBHs and BSM degrees of freedom that could have been produced via Hawking radiation.

Thank you!

back up slides

PBH mass function



The PBH mass functions are very different in order to mimic the gamma-ray spectrum with an extended mass function

can be tested with GWs

Fitting spectrum model

choose ALP case spectrum as true model ($\star$),
perform fitting (3σ) with ALP and SM model assumptions