Detecting Axion-Like Particles with Primordial Black Holes

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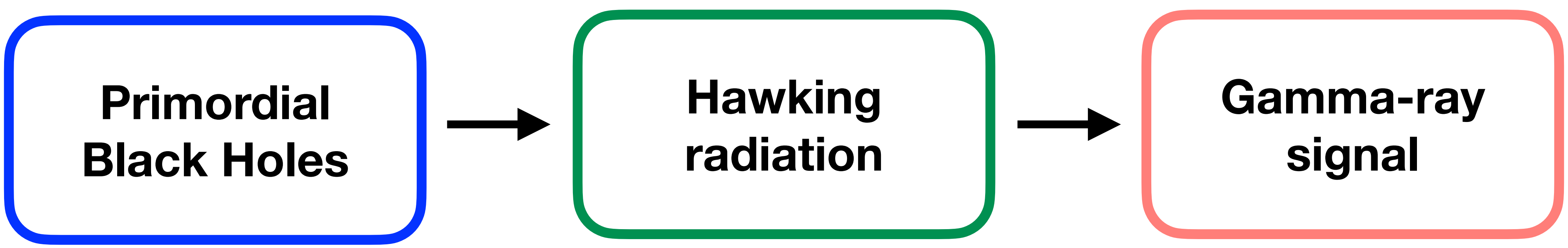
Motivations

- Primordial Black Holds can make up a fraction or all DM.

- PBH produce particles with Hawking radiation.

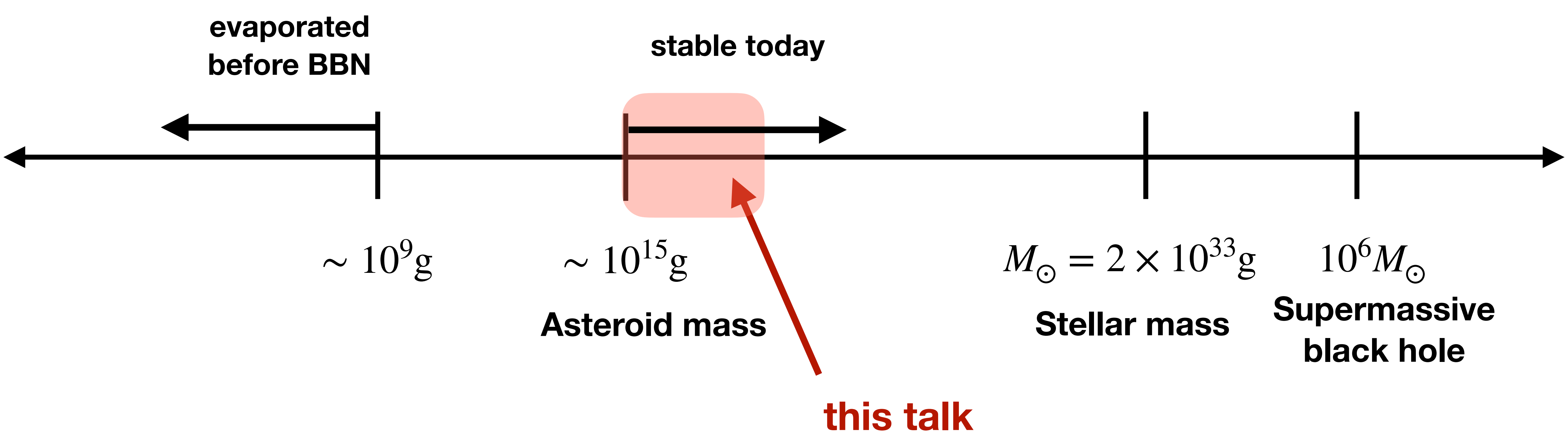
- We are interested in using gamma-ray searches for BSM particles produced by PBHs.



Primordial black holes are formed in the early universe.

- Origin of PBHs related to many cosmology models.
- PBHs are macroscopic dark matter candidates.
- GW signals from PBH formation and merger events.
- Hawking temperature is higher, Hawking radiation more active.

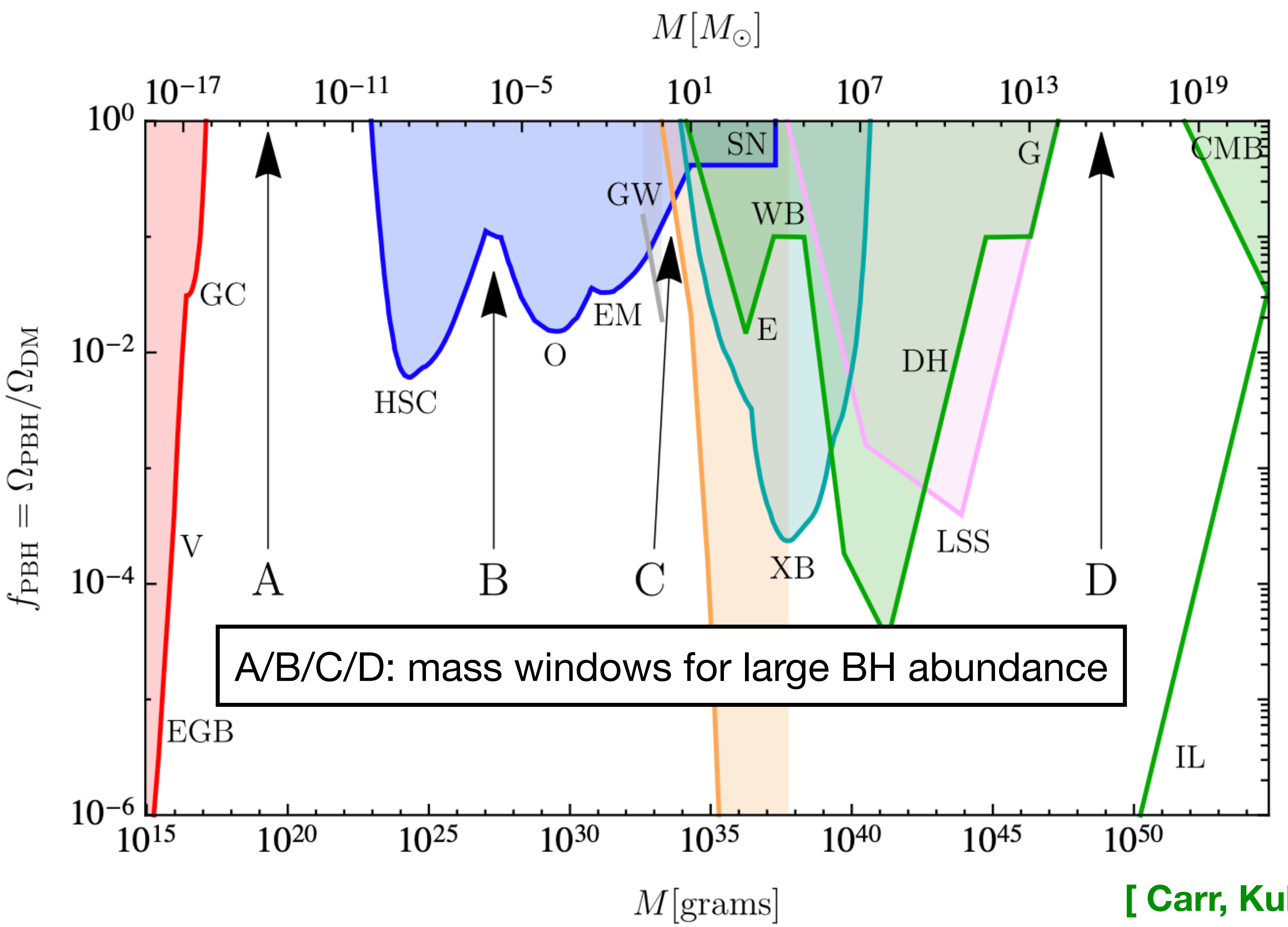
PBHs can exist in a wide mass window



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

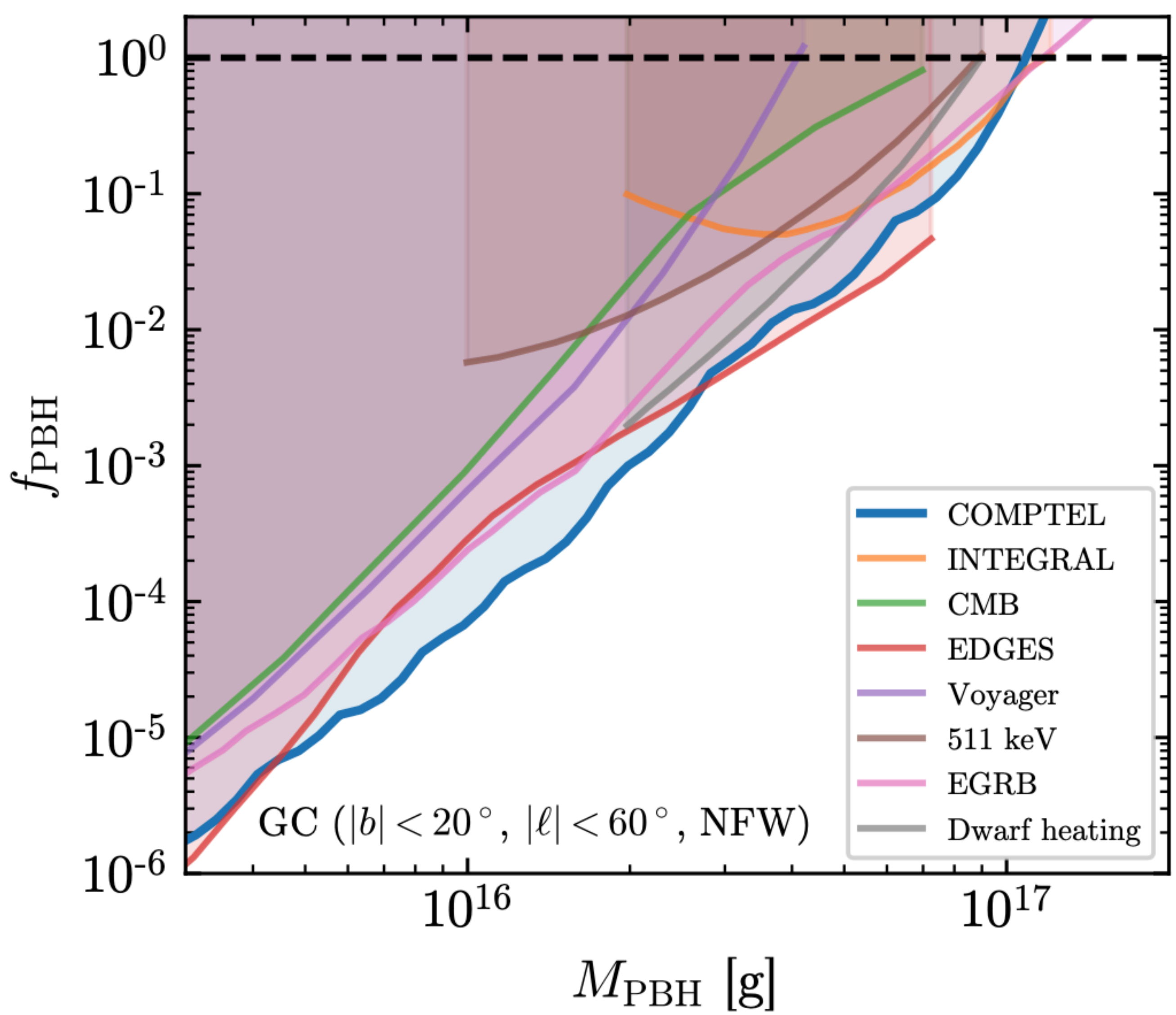
$f_{PBH} = \frac{\Omega_{PBH}}{\Omega_{DM}}$



[Carr, Kuhnel, 2006.02838]

Asteroid-mass PBHs are Hawking evaporating at MeV-GeV energy

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



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

Future MeV Sky

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

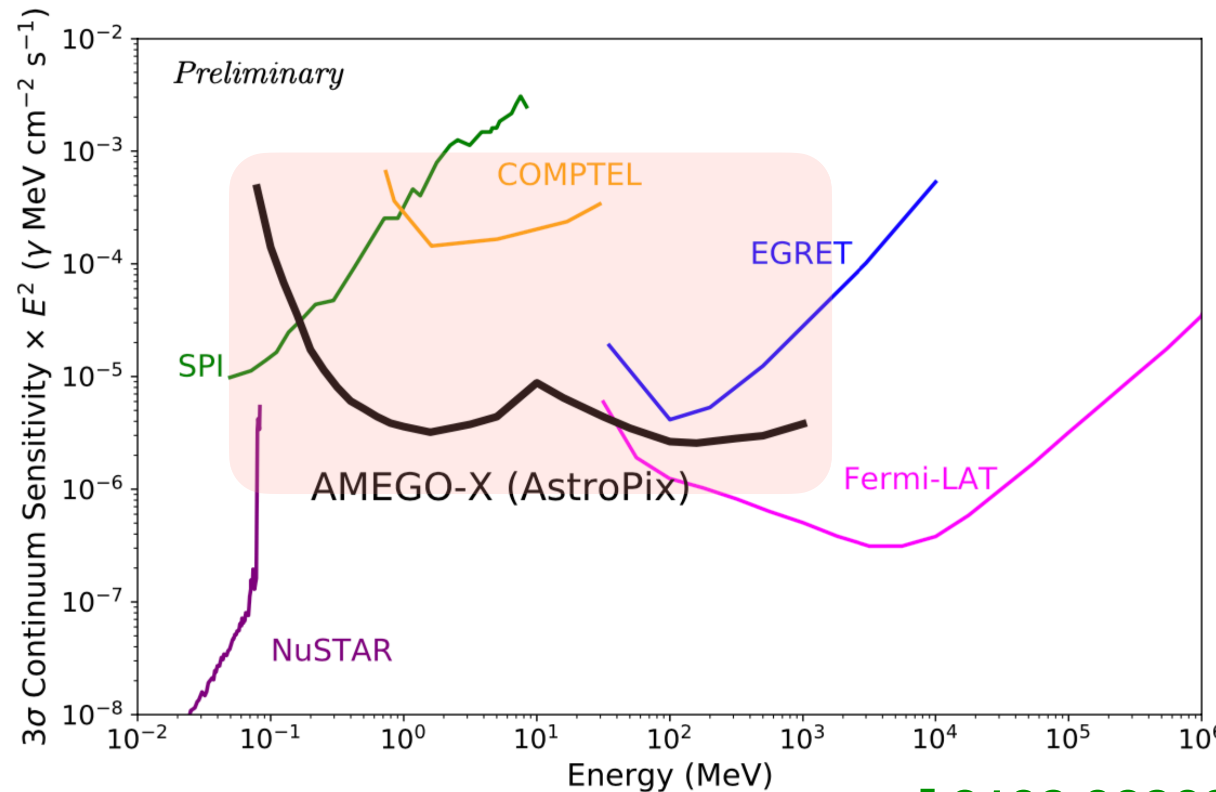
- **Covers gamma-ray energy**

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

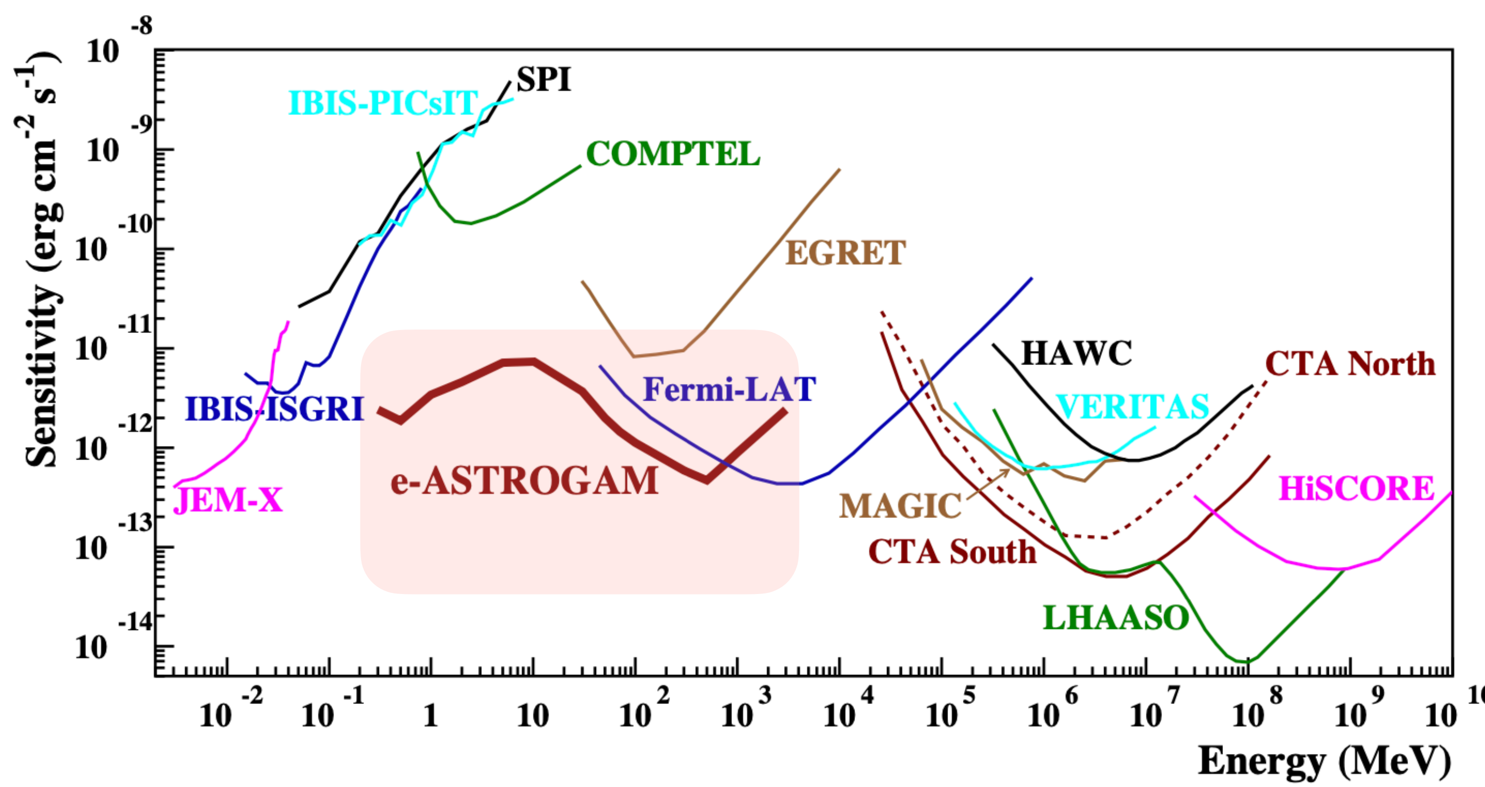
- **Corresponds to the Hawking temperature of PBHs**

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

potential to measure gamma-ray spectrum precisely

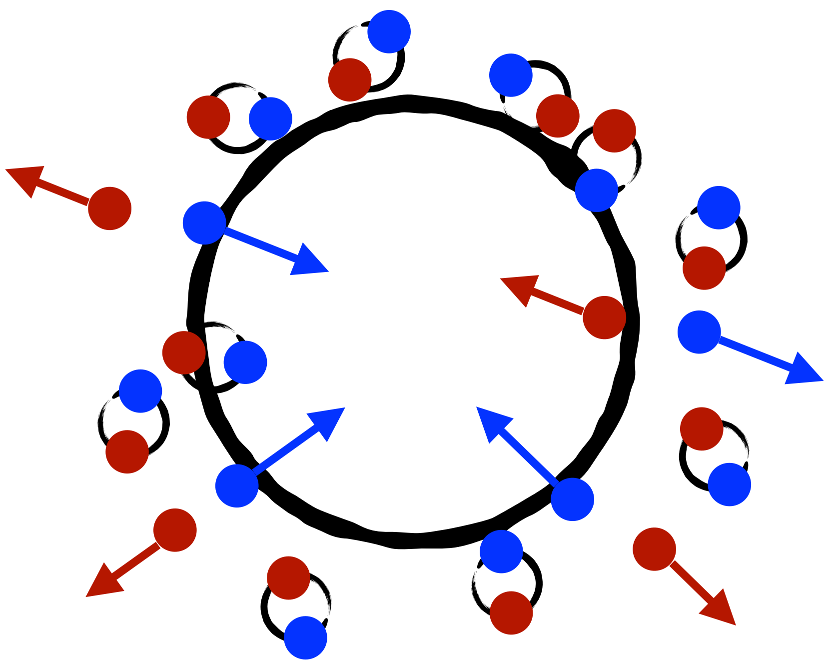


[2108.02860]



[1611.02232]

- **Particle emission is "blackbody + re-absorption"**



$$\frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} = \frac{g_i}{2\pi} \frac{\Gamma_i}{e^{E_i/T_{\mathrm{PBH}}} \pm 1}$$

- **Total gamma-ray flux is from primary photon directly from PBH and also photons from particle interactions.**

$$\frac{\partial N_{\gamma,\mathrm{tot}}}{\partial E_\gamma \partial t} = \frac{\partial N_{\gamma,\mathrm{primary}}}{\partial E_\gamma \partial t} + \sum_{i=e^\pm,\mu^\pm,\pi^\pm} \int dE_i \frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} \frac{dN_{\gamma,\mathrm{FSR}}}{dE_\gamma}$$

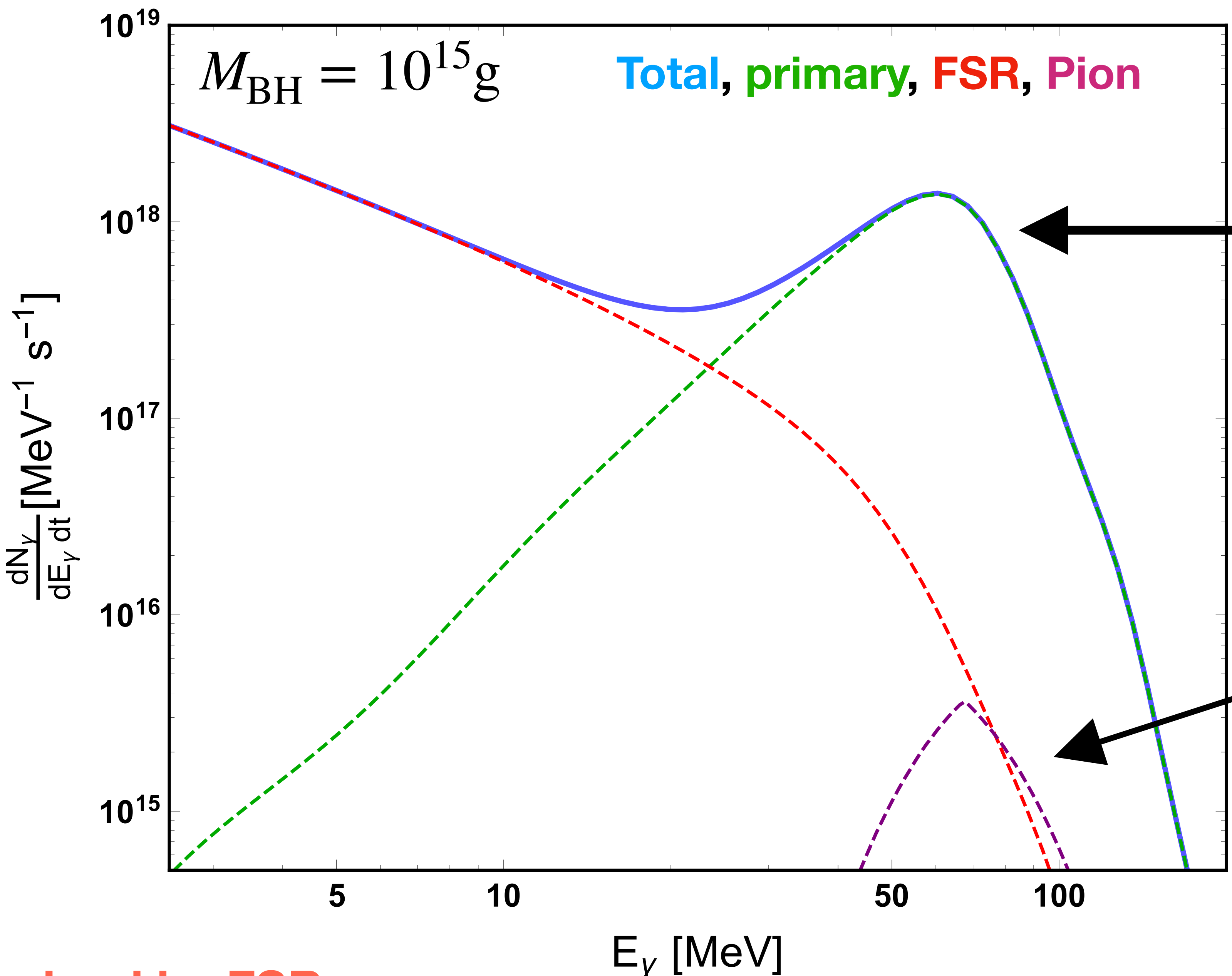
final-state radiation off charged particles

primary photon directly from PBHs

$$+ \sum_{i=\pi^0} \int dE_i 2 \frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} \frac{dN_{\gamma,\mathrm{decay}}}{dE_\gamma}$$

photons from pion decay

Instantaneous photon spectrum with $\mathcal{O}(\mathrm{MeV})$ energy



Spectrum peak determined by primary photon emission

Gamma-ray from decay is small since pion is heavy

Tail determined by FSR, fixed slope at low energies

BSM particle production

- **Hawking radiation rate:** $$\frac{\partial N_{i,\text{primary}}}{\partial E_i \partial t} = \frac{g_i}{2\pi} \frac{\Gamma_i}{e^{E_i/T_{\text{PBH}}} \pm 1}$$

    - **particle mass kinematically allowed** $m_i \lesssim E_i \lesssim T_{\text{PBH}}$
    - **only depends on degree of freedom** g_i **, not coupling**

- **PBHs produce all particles (SM and BSM) via gravity**

→ **a natural portal to new physics**

- **Axion is originally proposed to solve the strong CP problem in QCD.**
- **ALP is a generalization of the phenomenology of axion,**

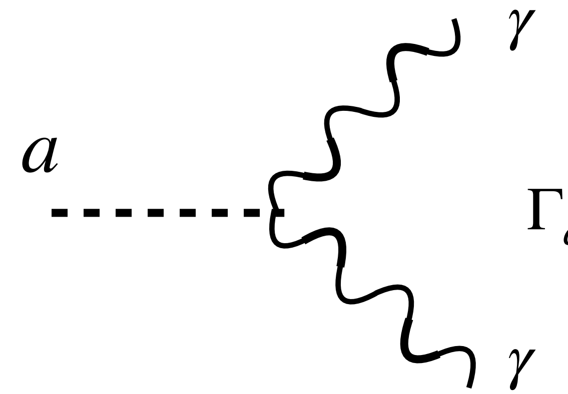
→ **light pseudoscalar BSM particle**

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

- **for ALP couples to photons, we use two parameters for phenomenology,**

  ALP mass m_a and ALP-photon coupling strength $g_{a\gamma\gamma}$

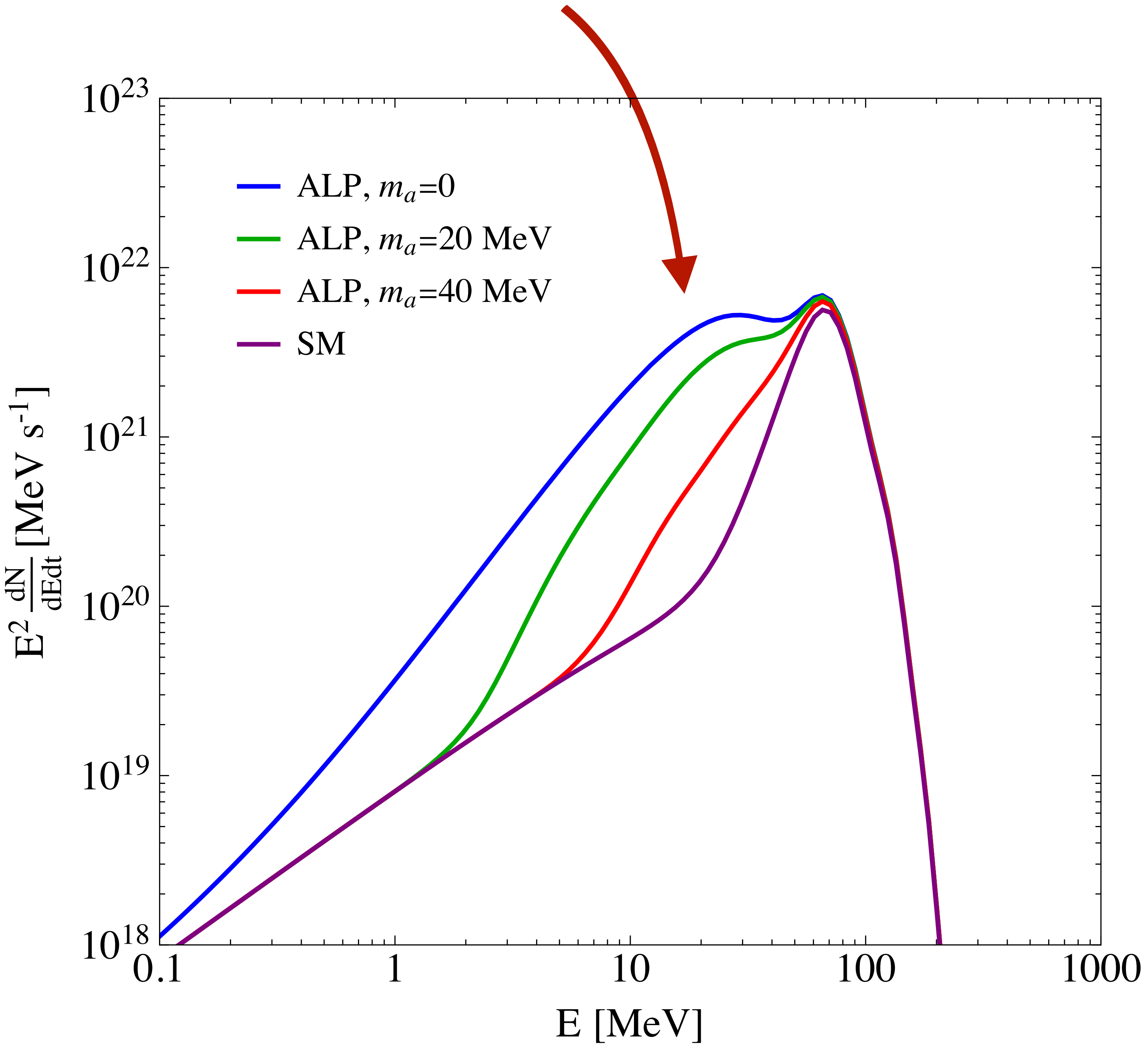
ALP decay



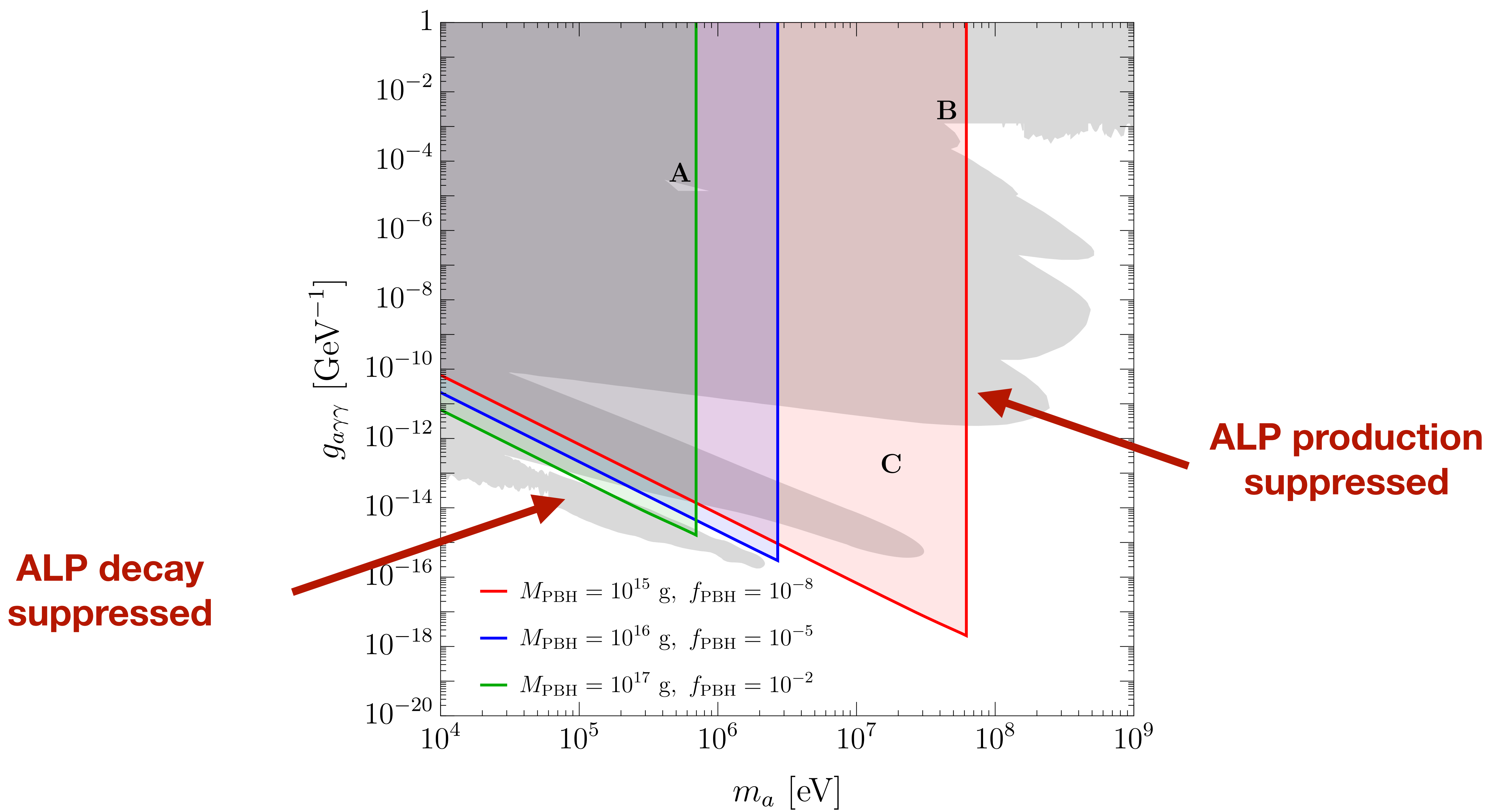
$$\Gamma_a = \frac{g_{a\gamma\gamma}^2\, m_a^3}{64\pi}$$

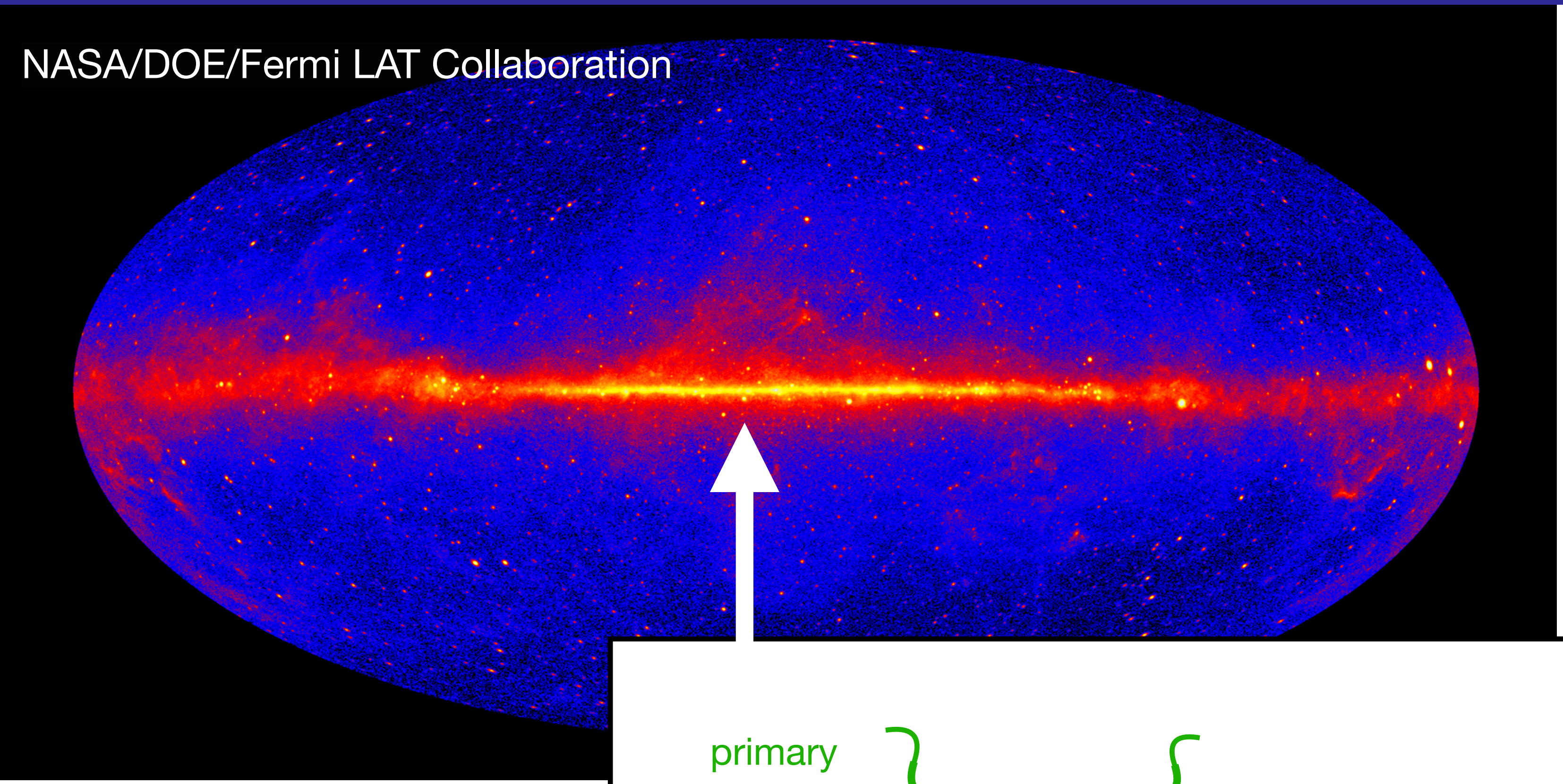
Gamma-ray spectrum, SM vs. SM+ALP.

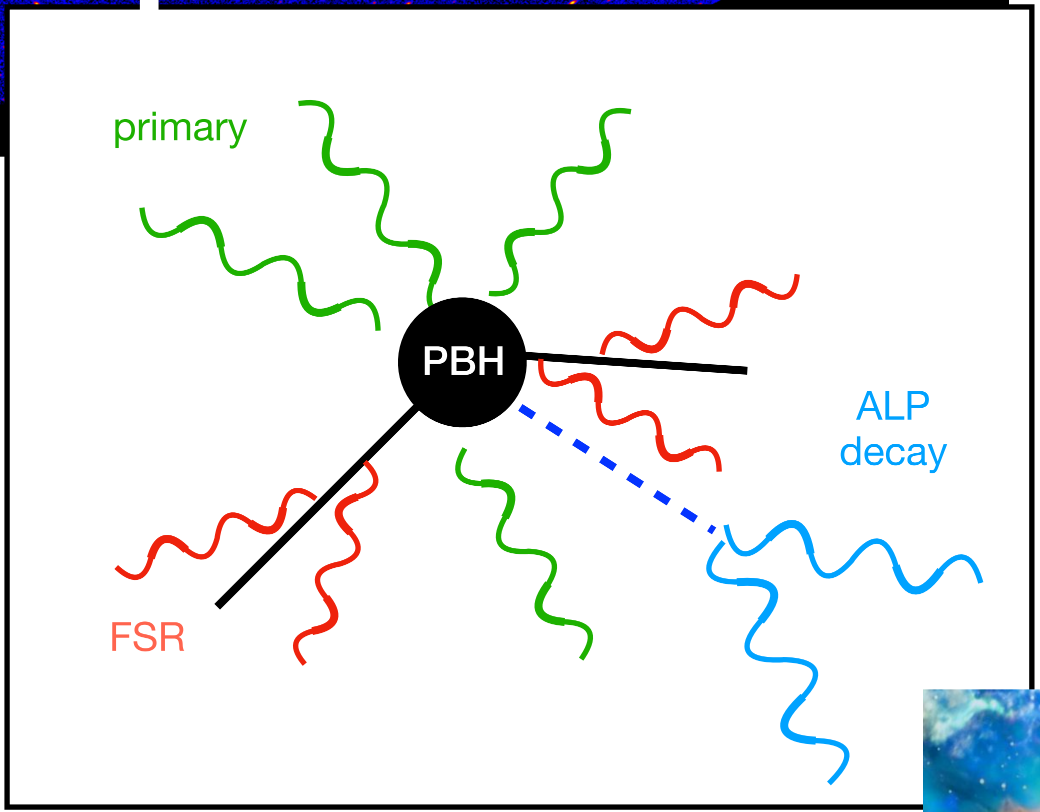
the $a \to \gamma\gamma$ decay generates a double-peak feature



ALP parameter space that can be probed with PBHs.







Signal

Target: Galactic Center (GC)

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

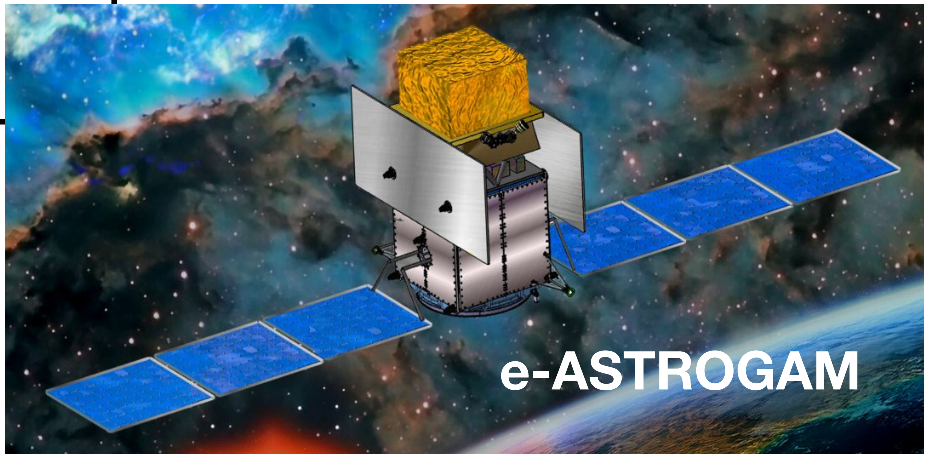
Background

forecasted by e-Astrogam

Model

SM: only SM particles

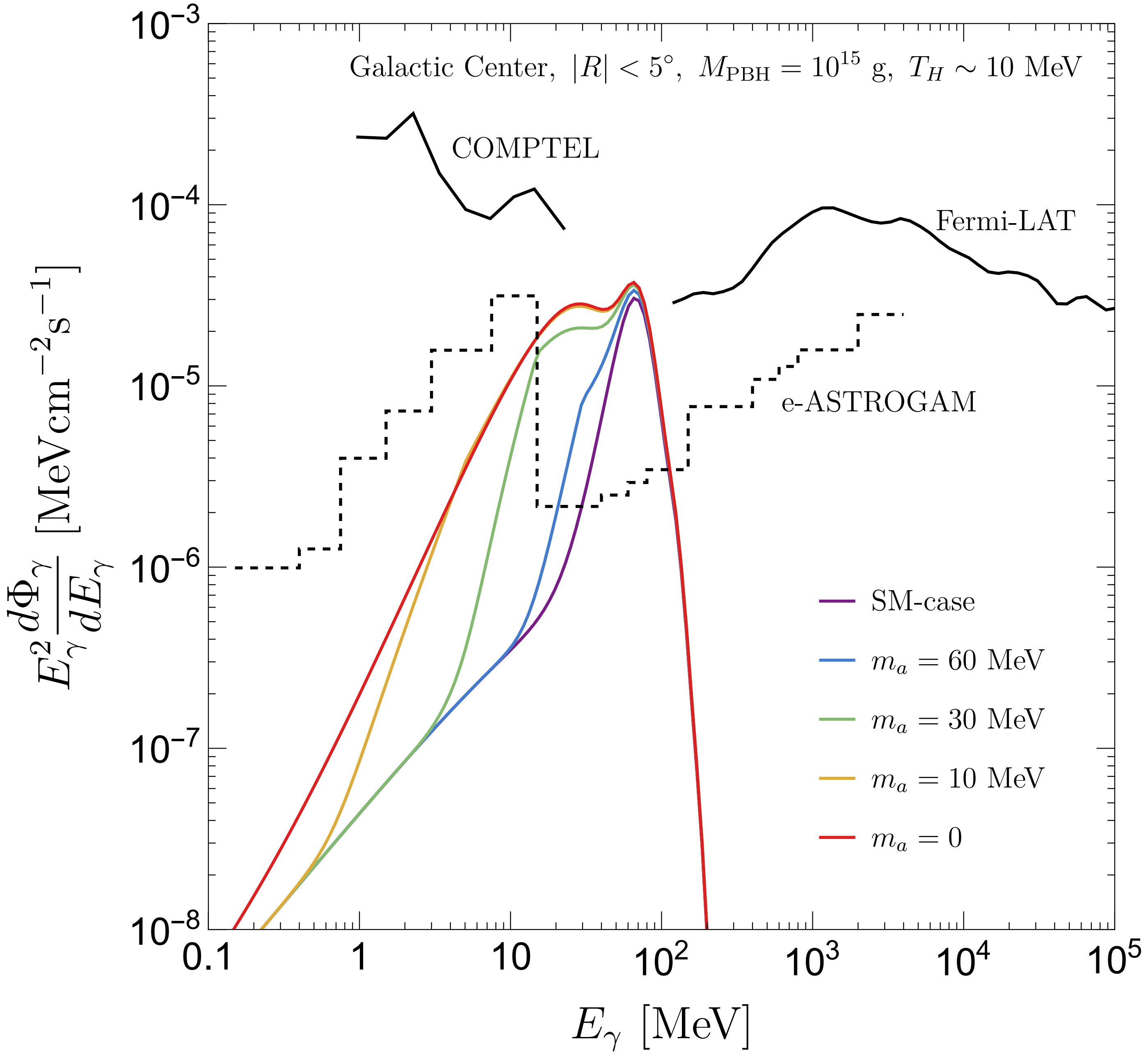
ALP: SM particles + ALP



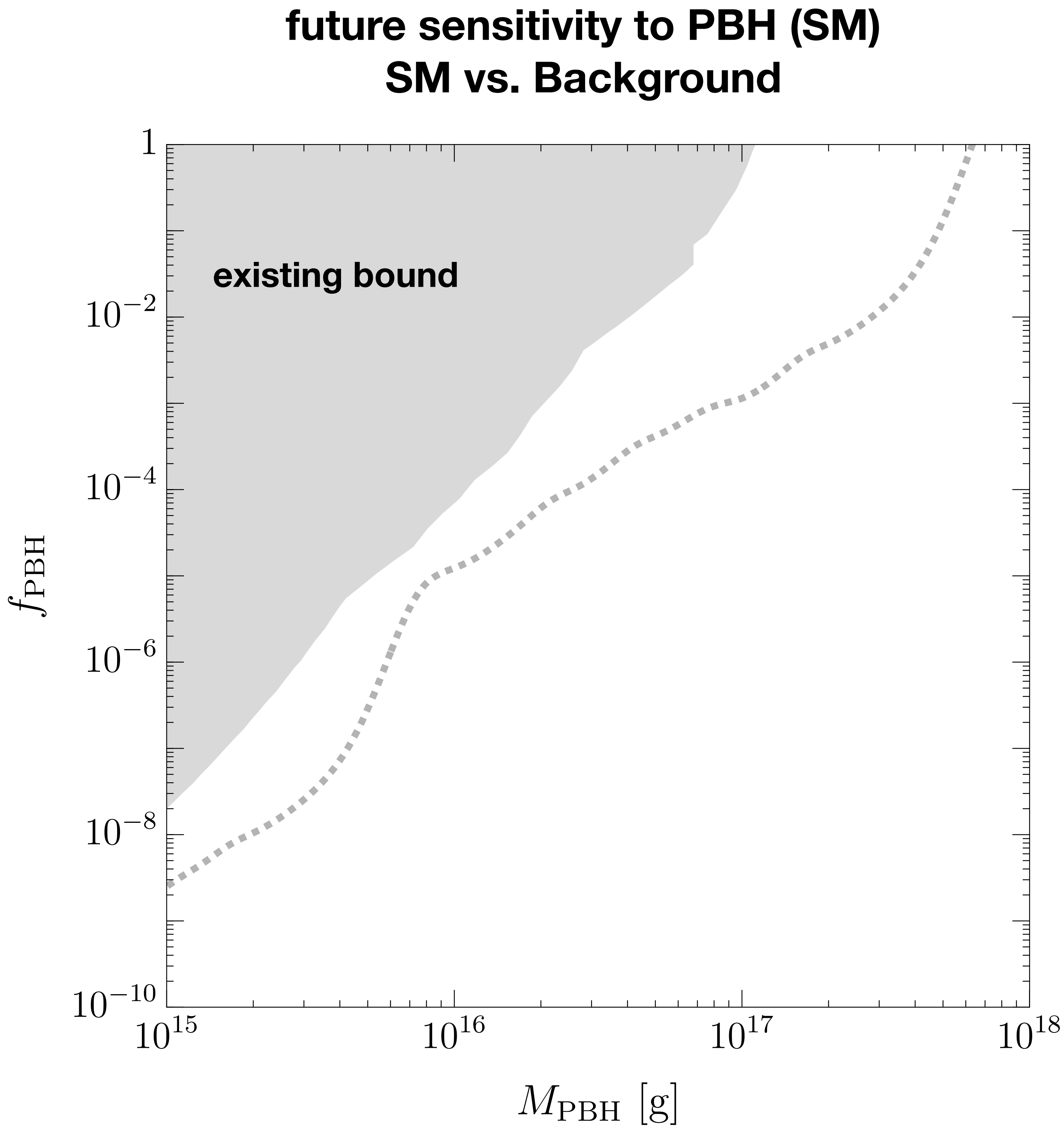
Assume PBHs make up $f_{\rm PBH}$ of DM

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

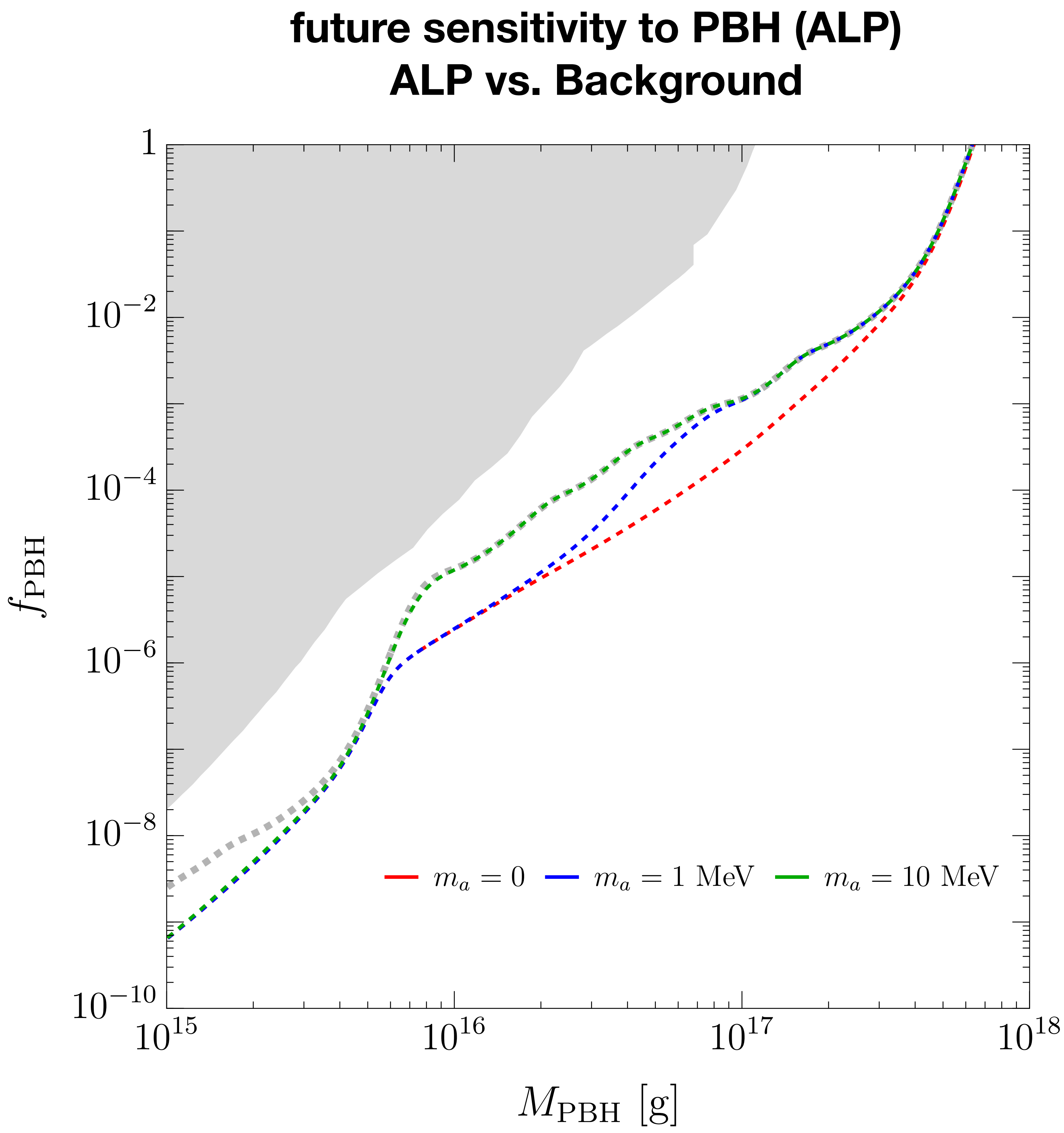
Gamma-ray spectrum from GC, $M_{\rm PBH} = 10^{15}$ g, $f_{\rm PBH} = 10^{-8}$.



PBH constraint is based on theory assumptions of Hawking radiation spectrum.

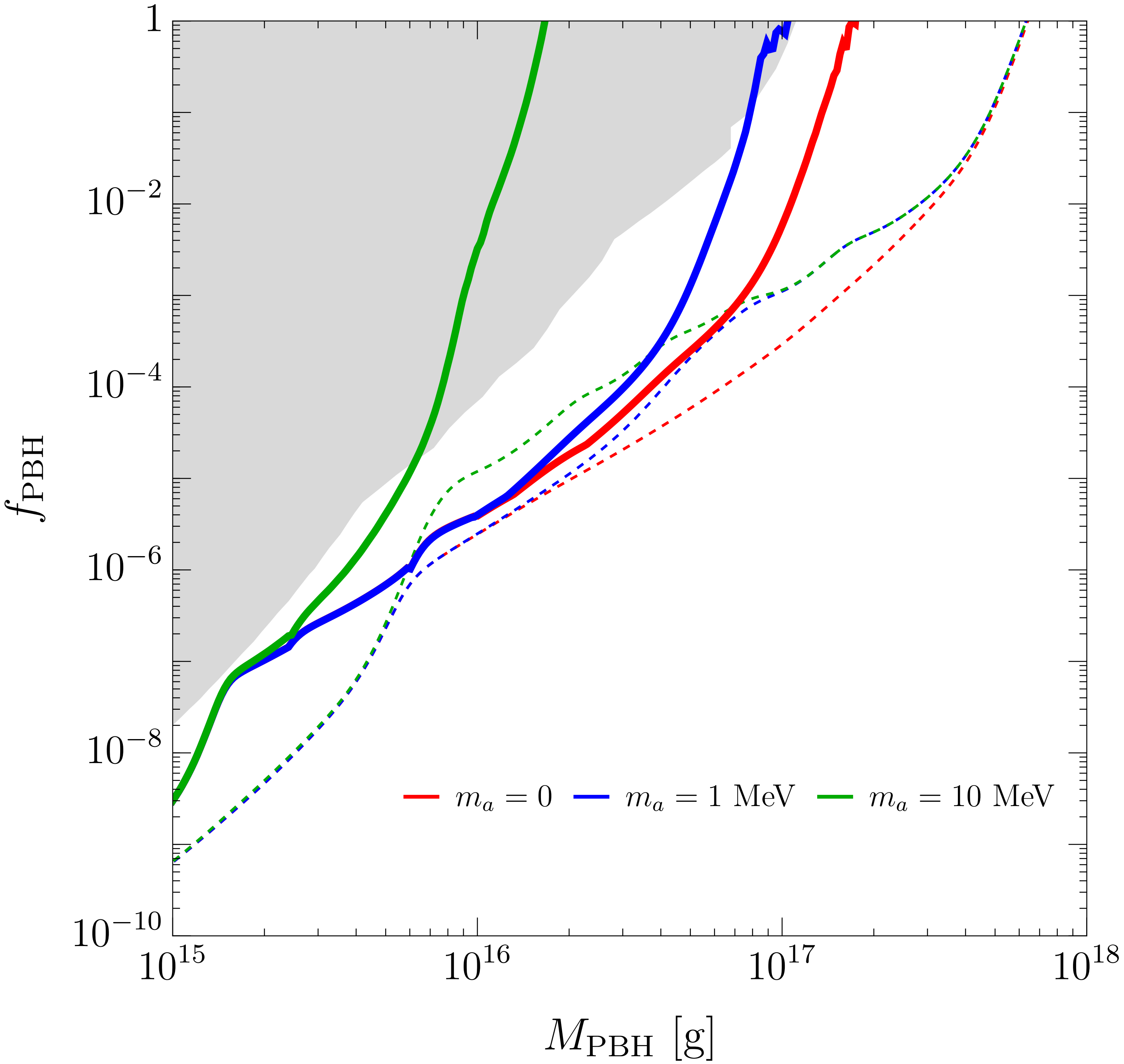


Constraints are stronger in the ALP case, because of extra photons from ALP decay.



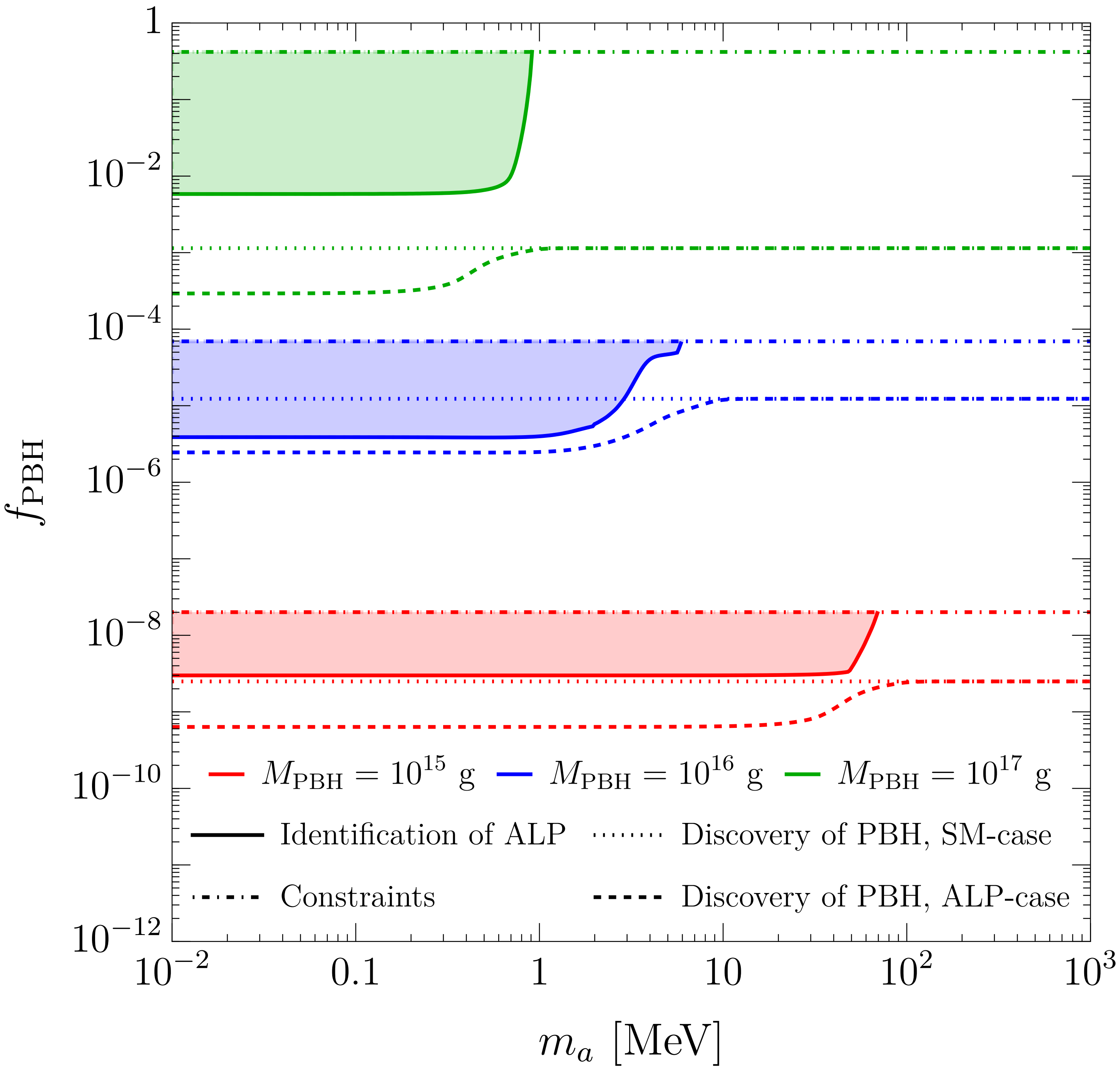
If $f_{\rm PBH}$ is larger than the detection limit, good statistics to distinguish the ALP.

future sensitivity to ALP
ALP vs. SM



Identification of ALPs

on the f_{PBH} vs. m_a plane



Summary

- Asteroid-mass PBHs can make up (fraction of) DM and produce gamma-ray via Hawking radiation.

- Hawking radiation is gravitational, new particles are produced efficiently by PBHs.

- We show gamma-ray spectrum analysis can be used to detect ALPs produced by PBHs within a large ALP parameter space.

If we do detect Hawking radiation in the future, we can uncover both PBH and BSM degrees of freedom with the signal spectrum.

Thank you!