Probing New Physics with Primordial Black Holes

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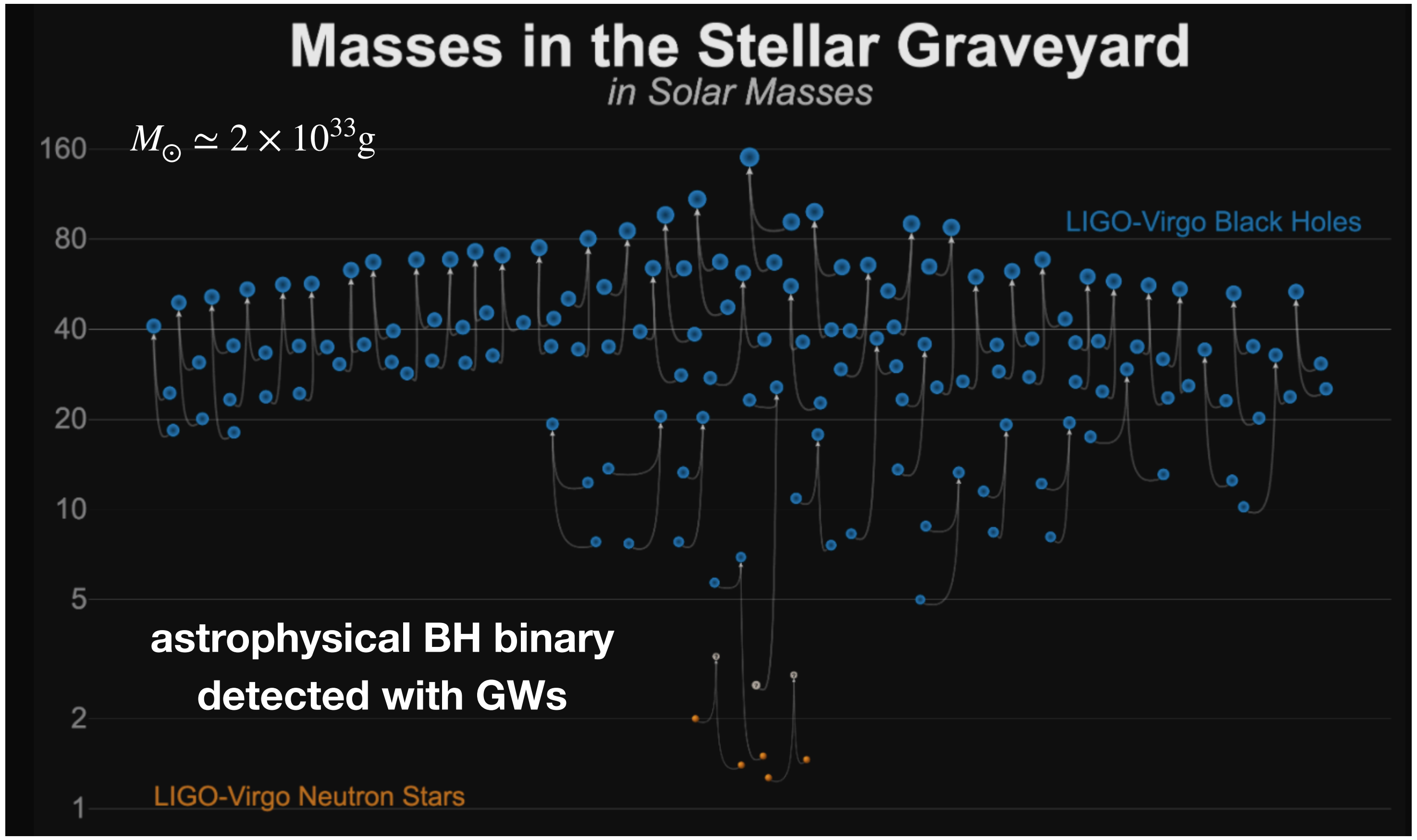
Primordial Black Holes

Black Holes are simple but fascinating objects that **intertwine theories of gravity** and **elementary particles.**

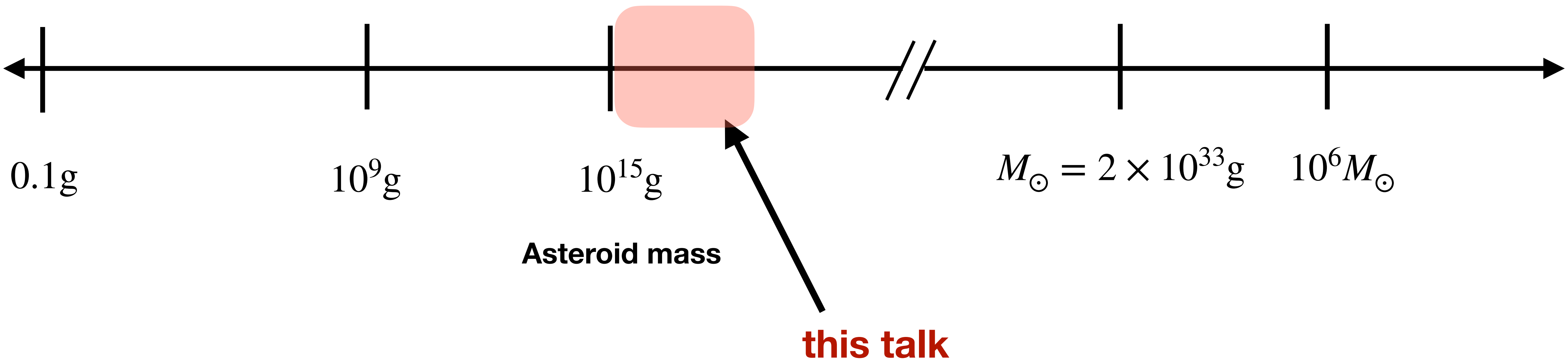
There are heavy BHs formed from the collapse of stars. These astrophysical BHs are studied with various observations of electromagnetic signals and GW signals.



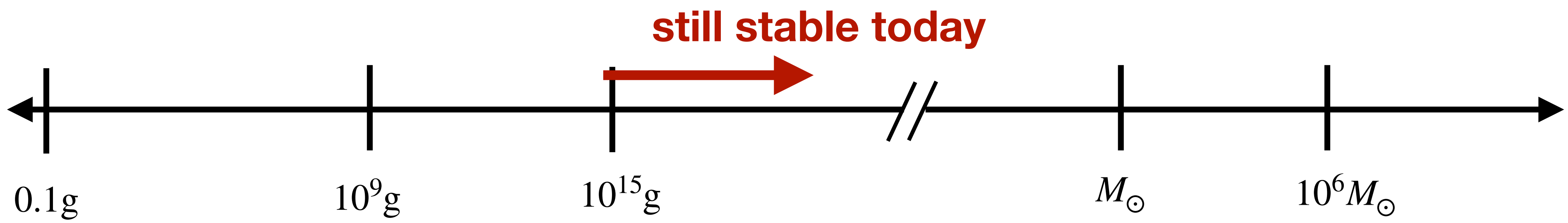
BHs can also form in the **early universe** where the environment is very dense,

→ **Primordial Black Holes (PBHs)**

PBHs can exist in a wide mass range



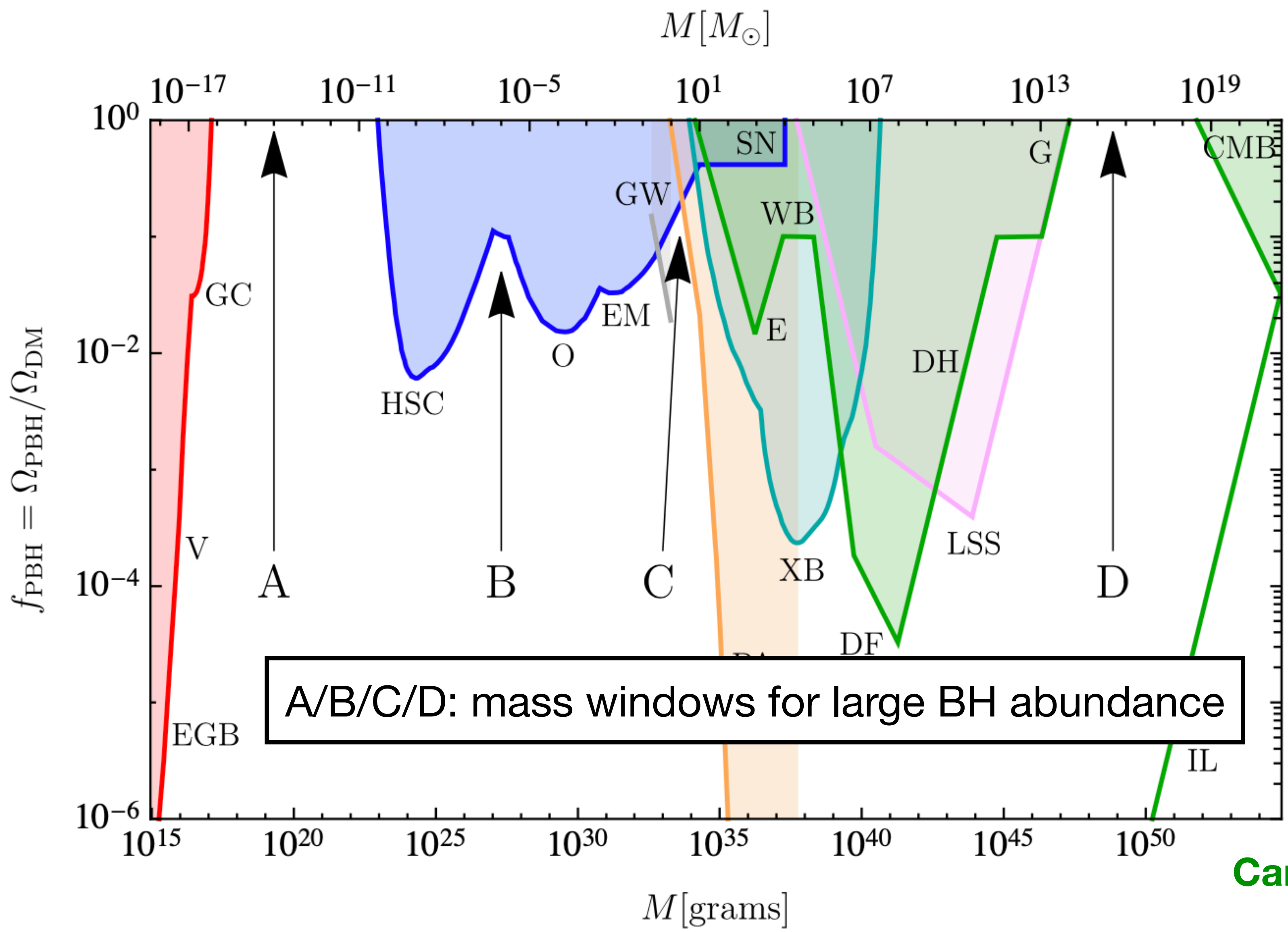
- Origin of PBHs related to interesting cosmology models.
- PBHs are heavy dark matter candidates.
- Hawking temperature is higher for light PBHs.
- Interesting phenomenology of particle production with Hawking radiation.



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

fraction of DM made of PBHs

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



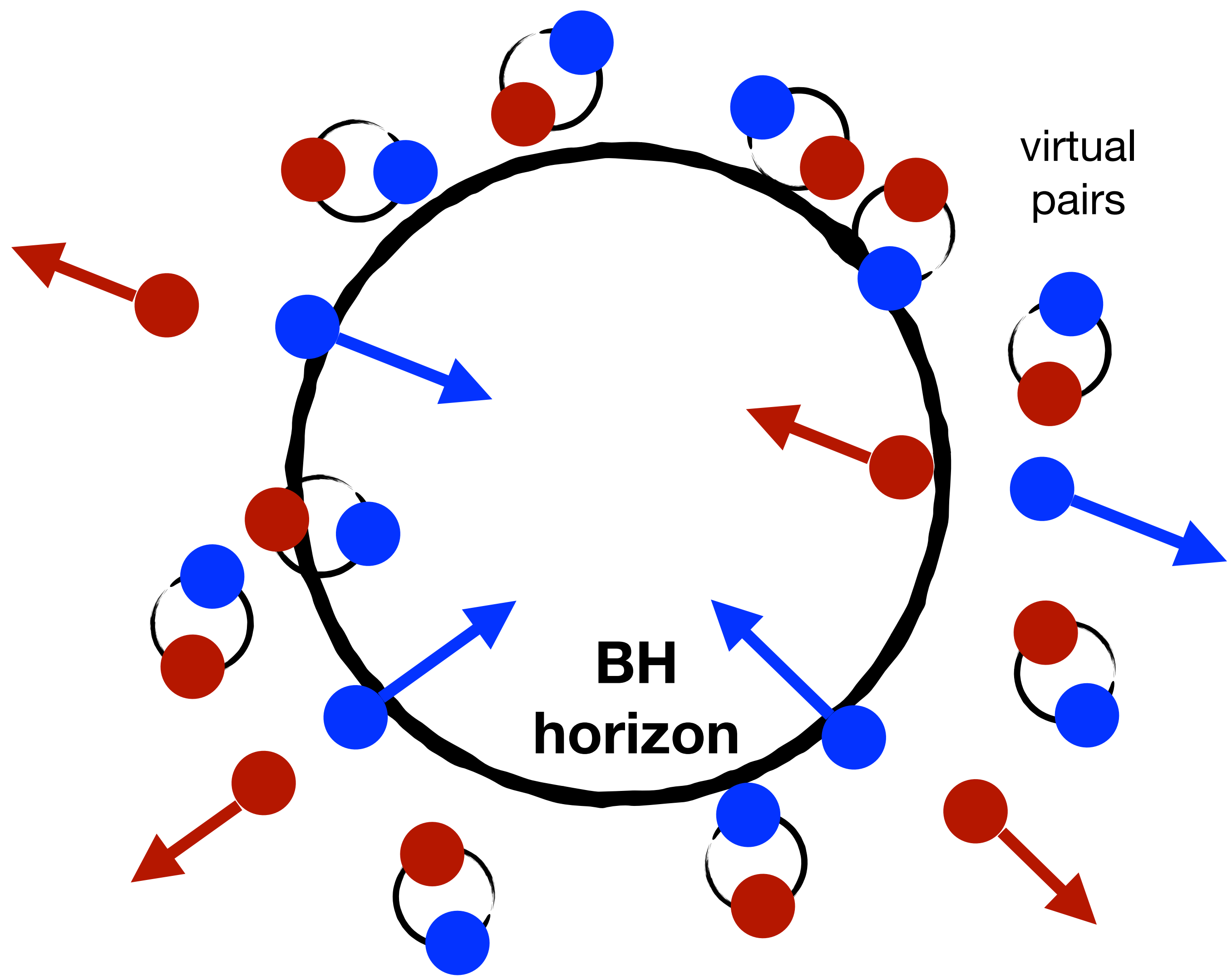
Carr, Kuhnel, 2006.02838

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

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

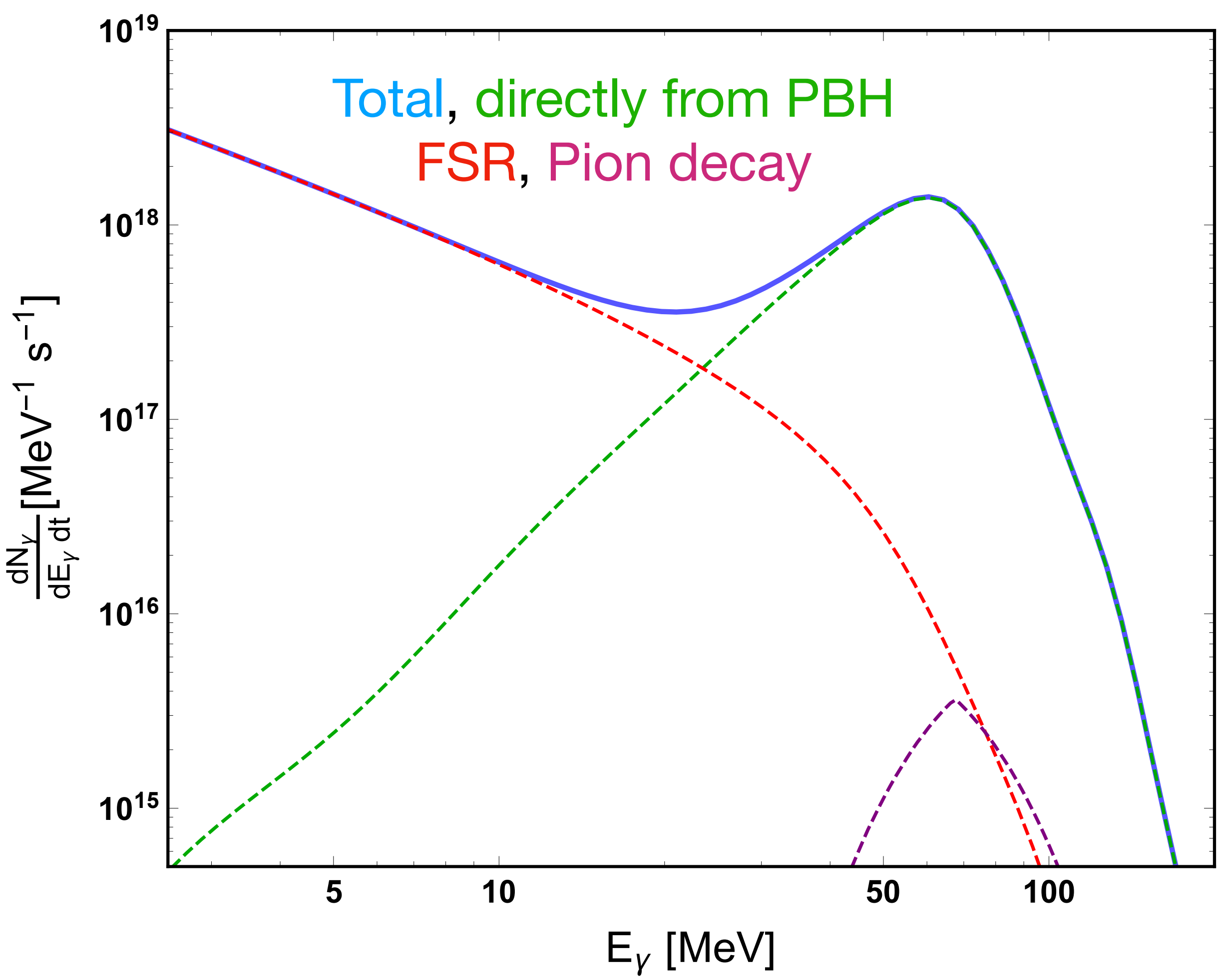
BH Hawking temperature: $T_{\rm PBH} = \frac{1}{8\pi G M_{\rm PBH}} \simeq 10.5 \left(\frac{10^{15}\,{\rm g}}{M_{\rm PBH}} \right) {\rm MeV}$

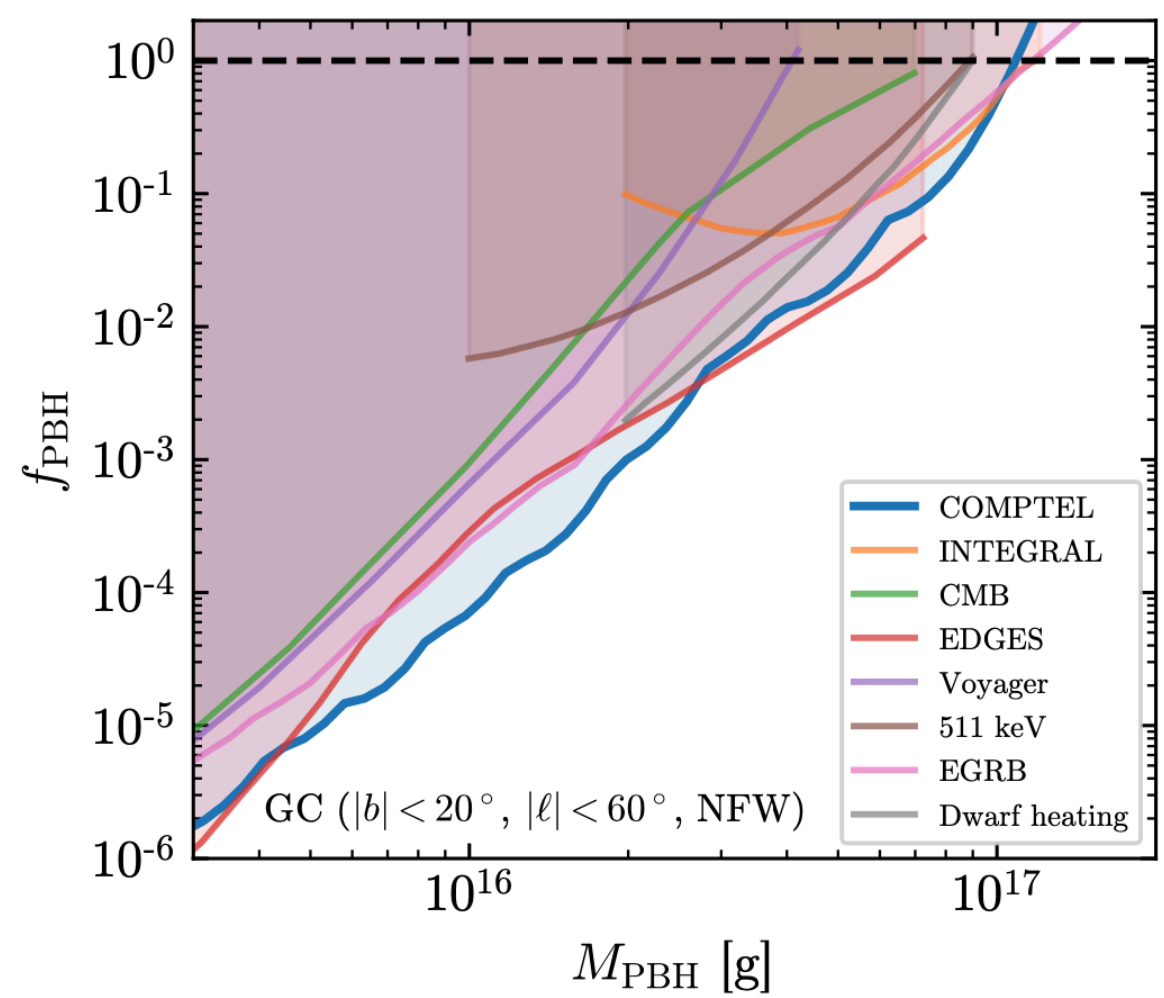
Asteroid-mass PBHs are Hawking evaporating at $\mathcal{O}({\rm MeV})$ energy.



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

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





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

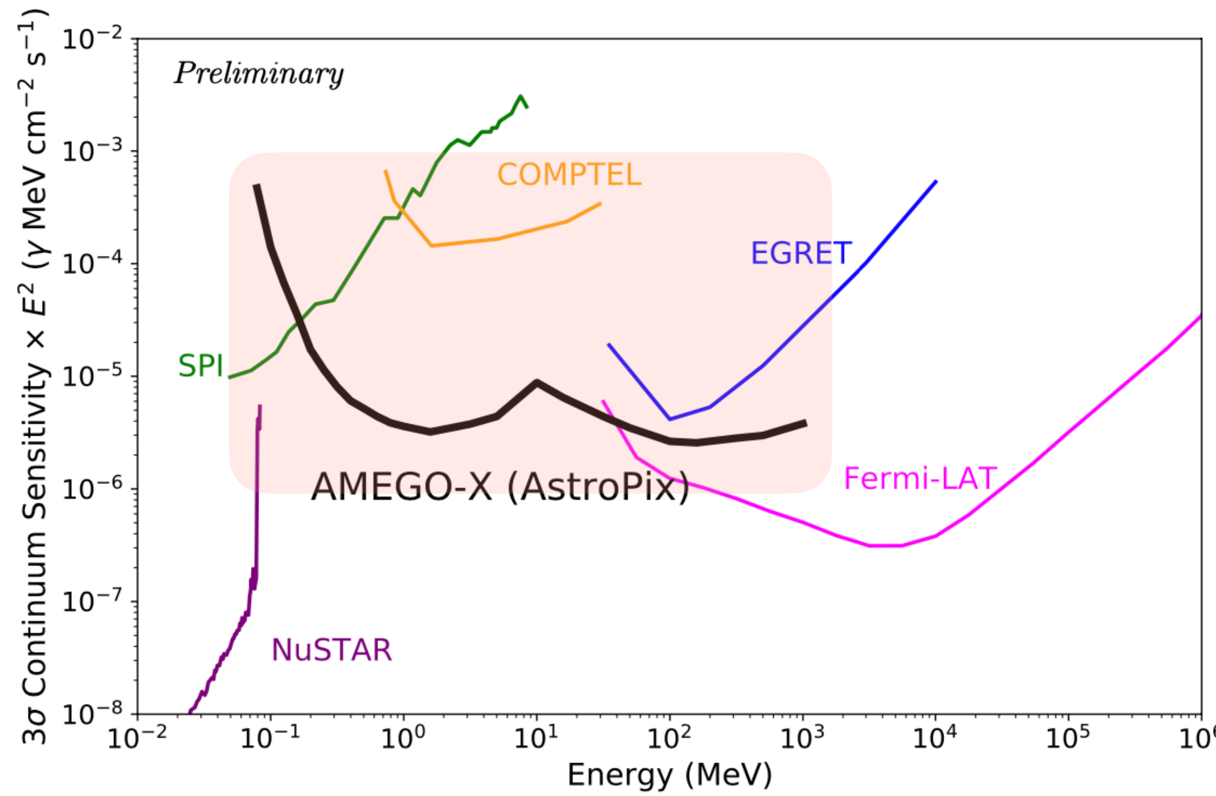
Future MeV gamma-ray searches including AMEGO, ASTROGAM, APT and more

- Covers gamma-ray energy

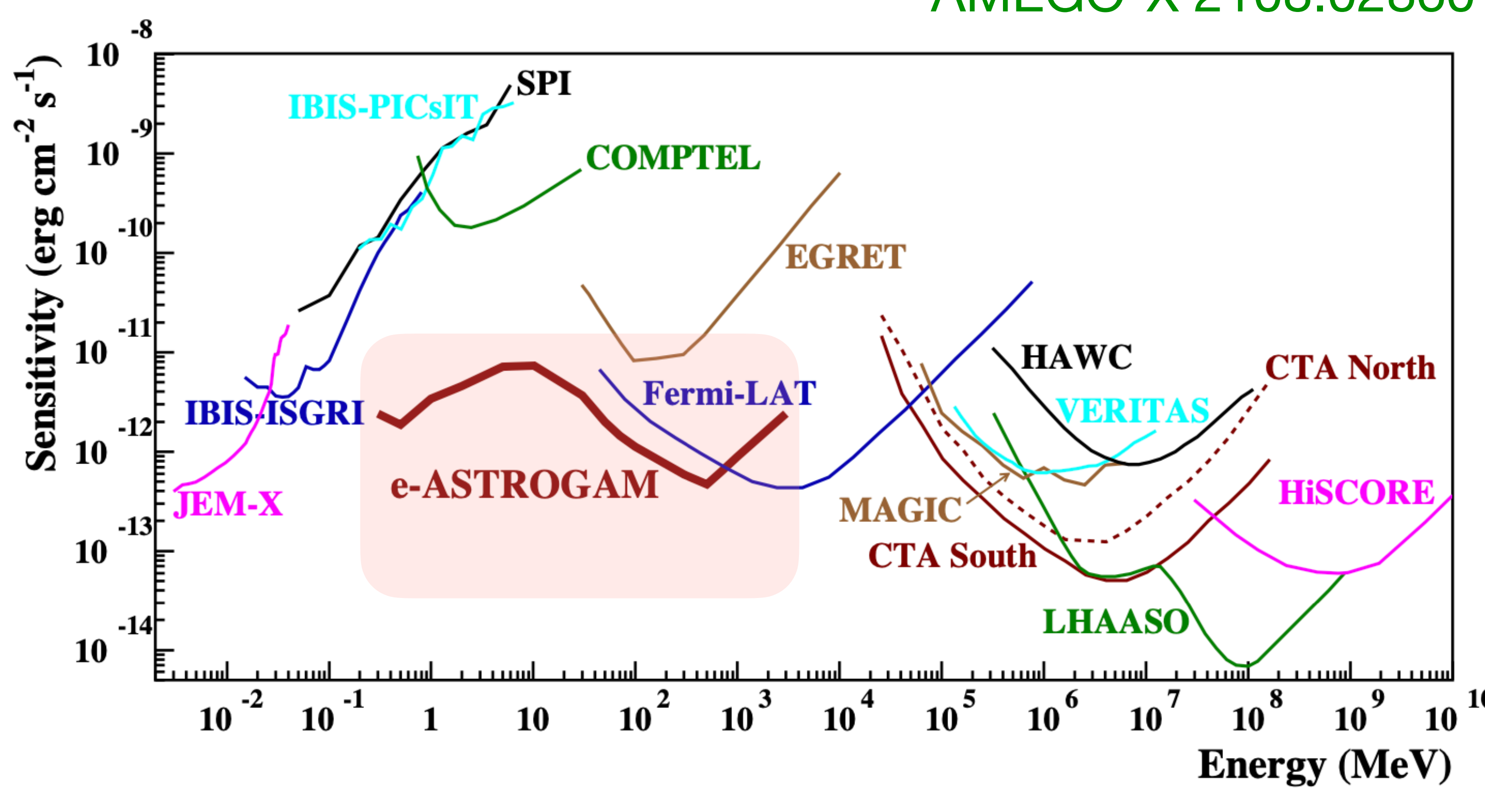
$$0.1\ \mathrm{MeV} \lesssim E_\gamma \lesssim 100\ \mathrm{MeV}$$

- Corresponds to the Hawking temperature of PBHs

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

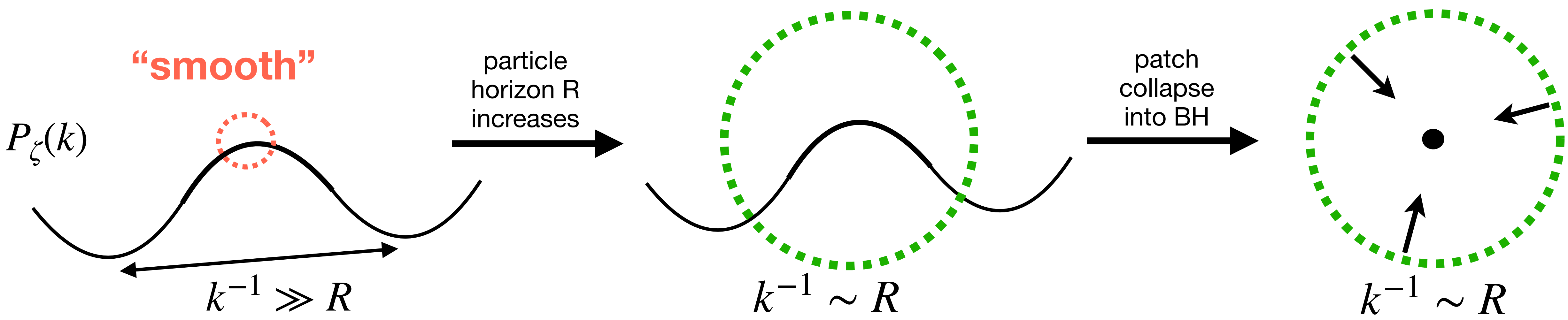


AMEGO-X 2108.02860

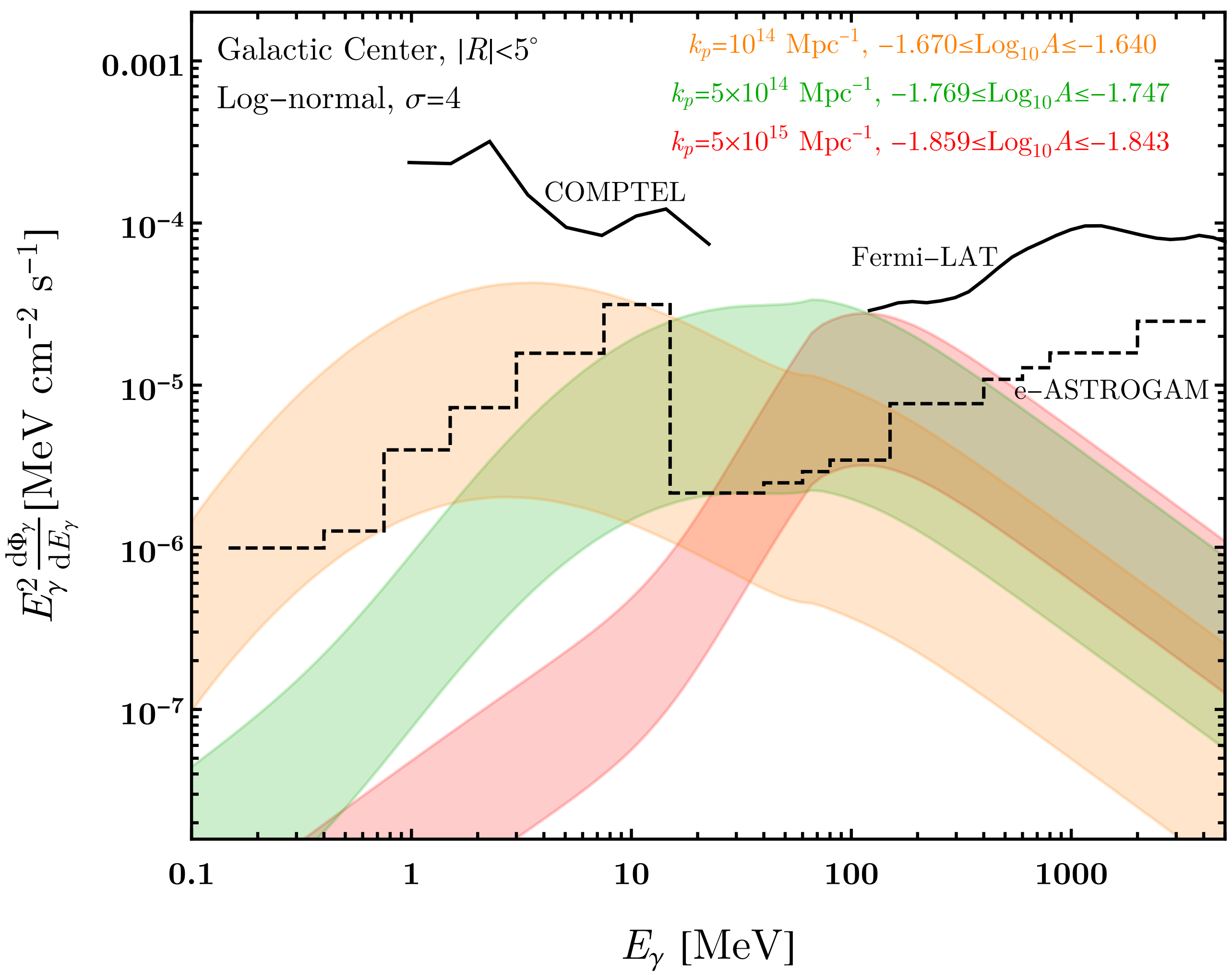


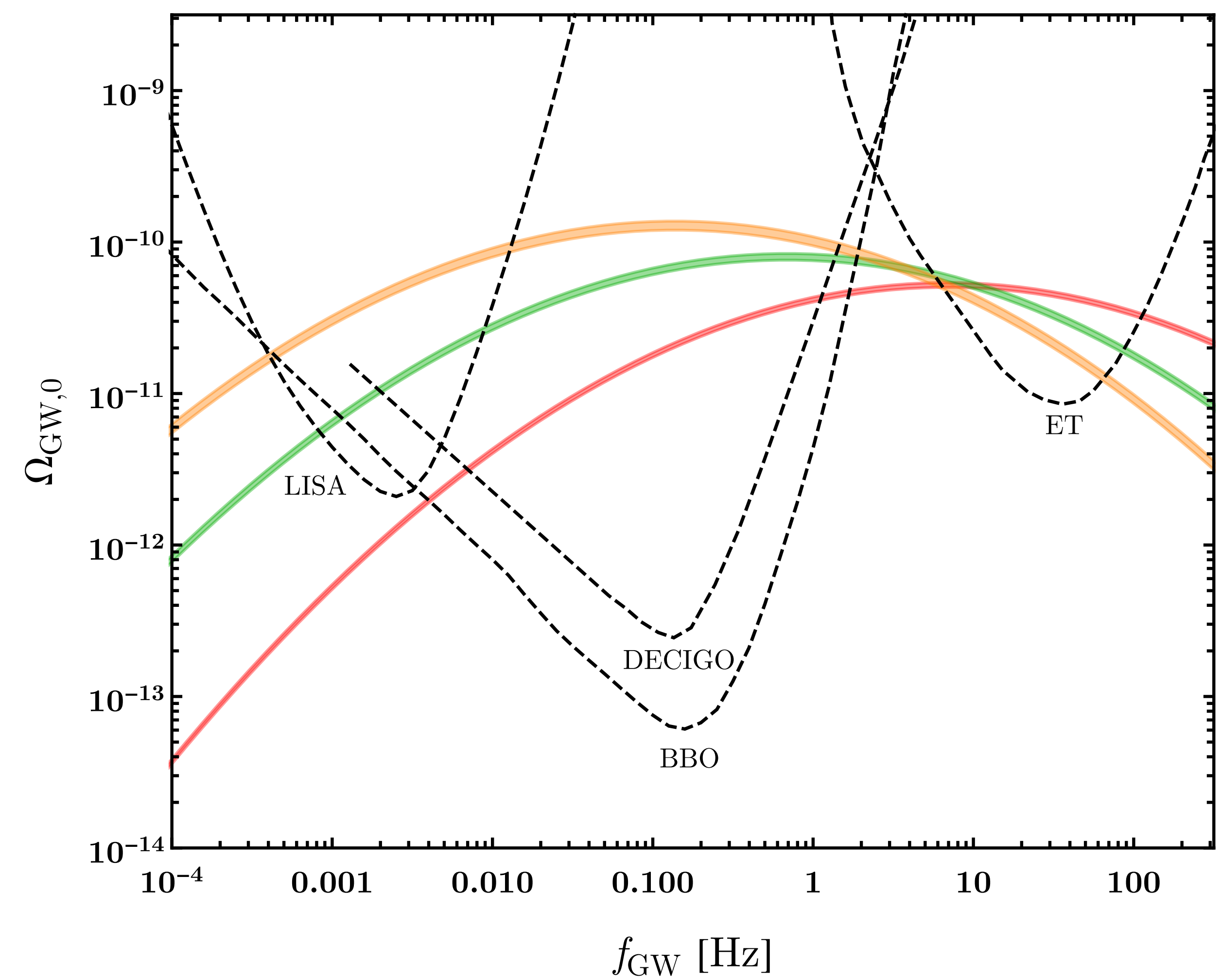
e-Astrogam, 1611.02232

Gamma-ray and GWs



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



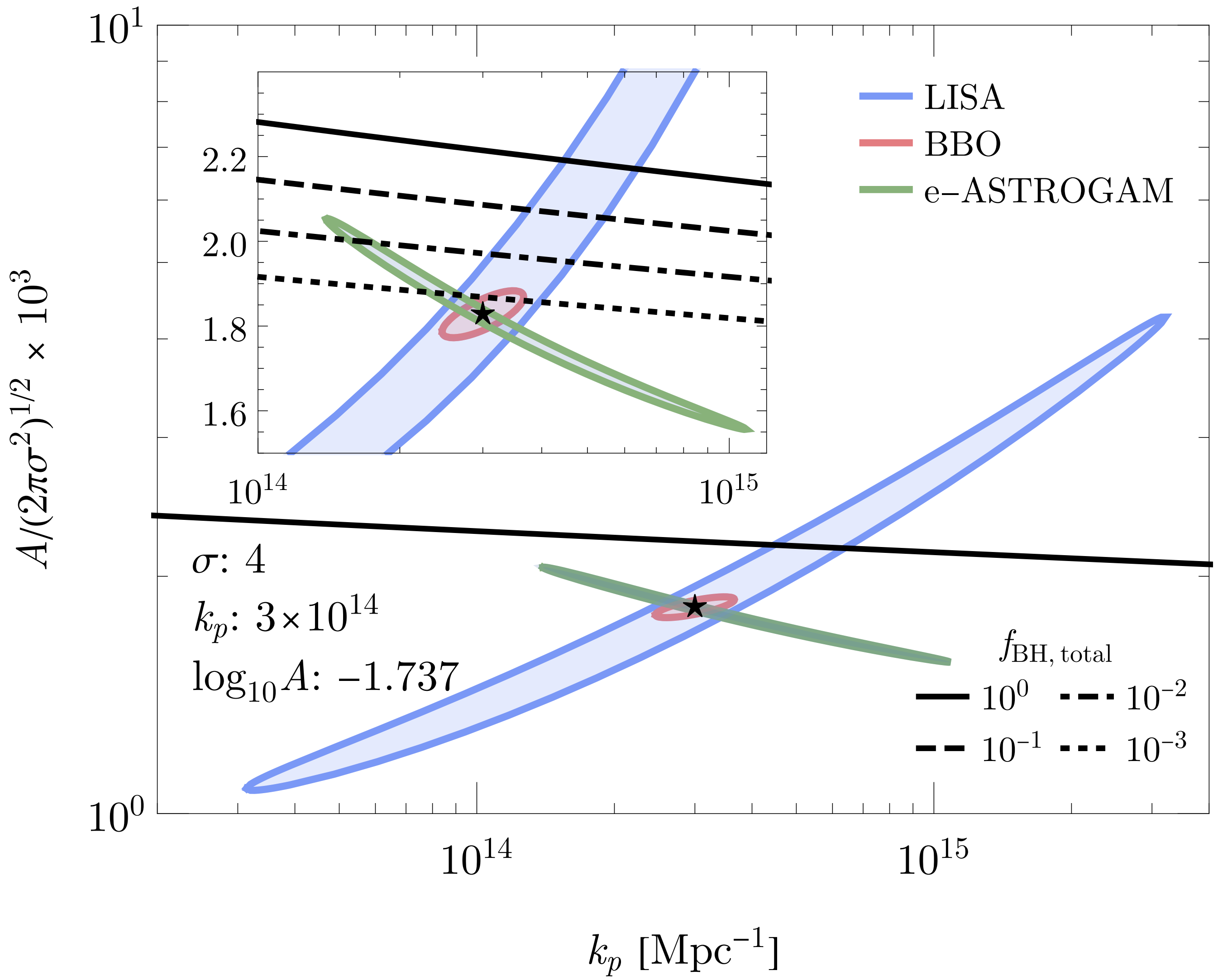


2202.04653

Gamma-ray and GWs

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**

2202.04653

Hawking radiation rate of particle i from a non-rotating BH:

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

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

Hawking radiation is another channel to produce new particles in the spectrum

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

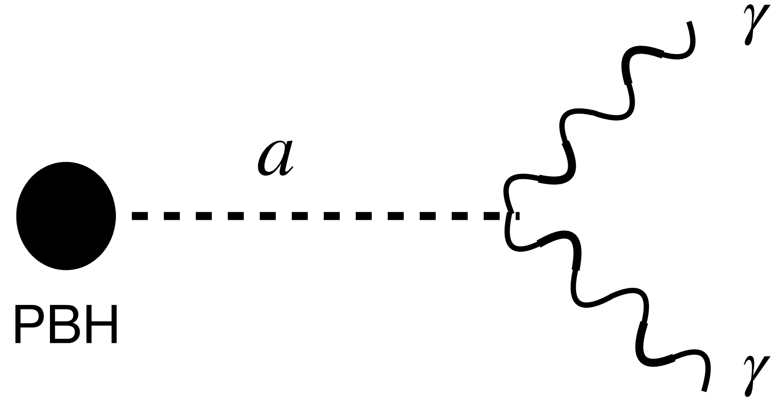
Asteroid-mass PBHs can produce MeV or lighter BSM particles

- can we use PBH as a **BSM particle factory**?

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

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

a new pseudoscalar particle couples to photons



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

- Gamma-ray spectrum is modified by ALPs

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

primary photon — final-state radiation — pion decay

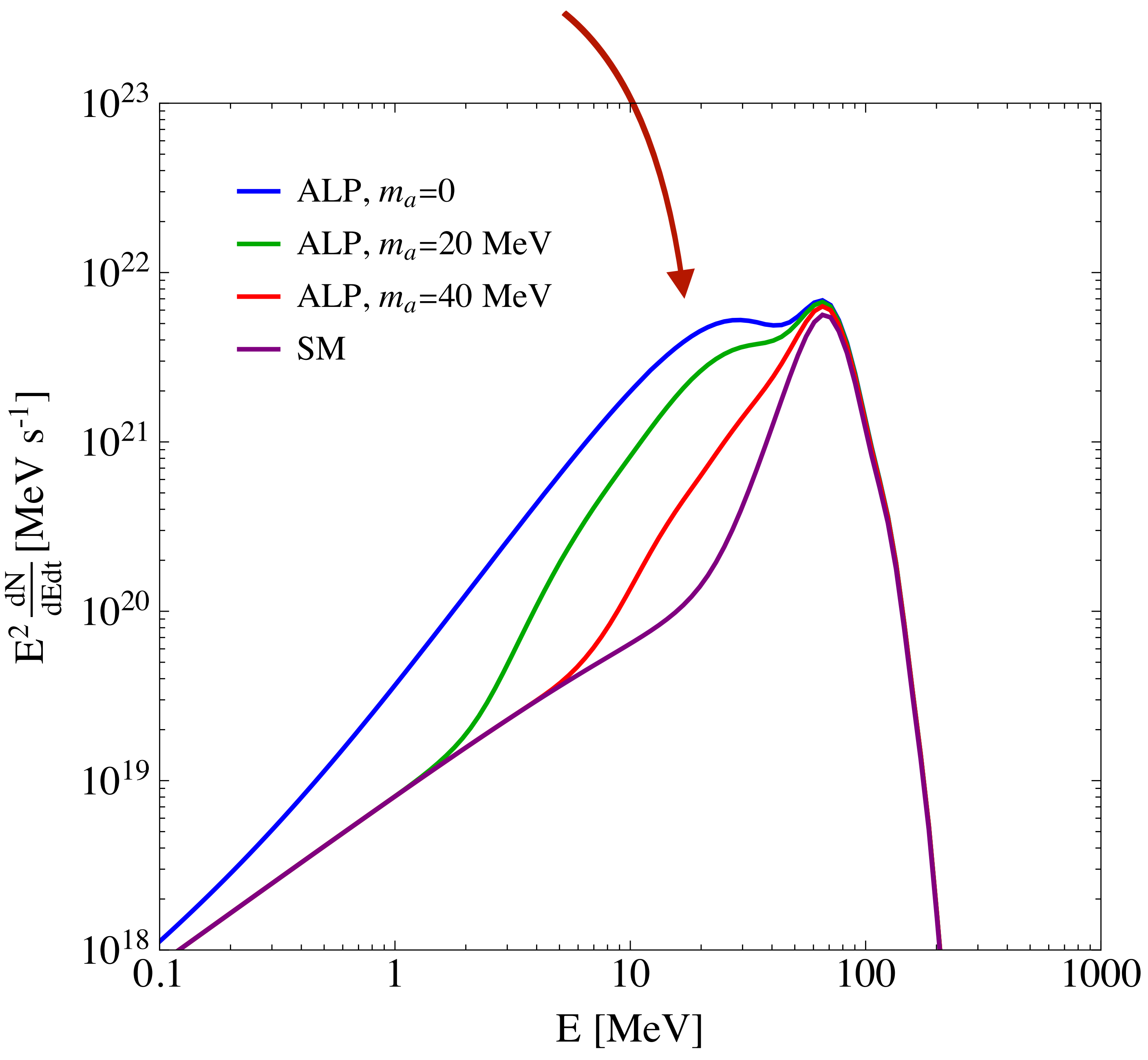
add new physics contributions

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

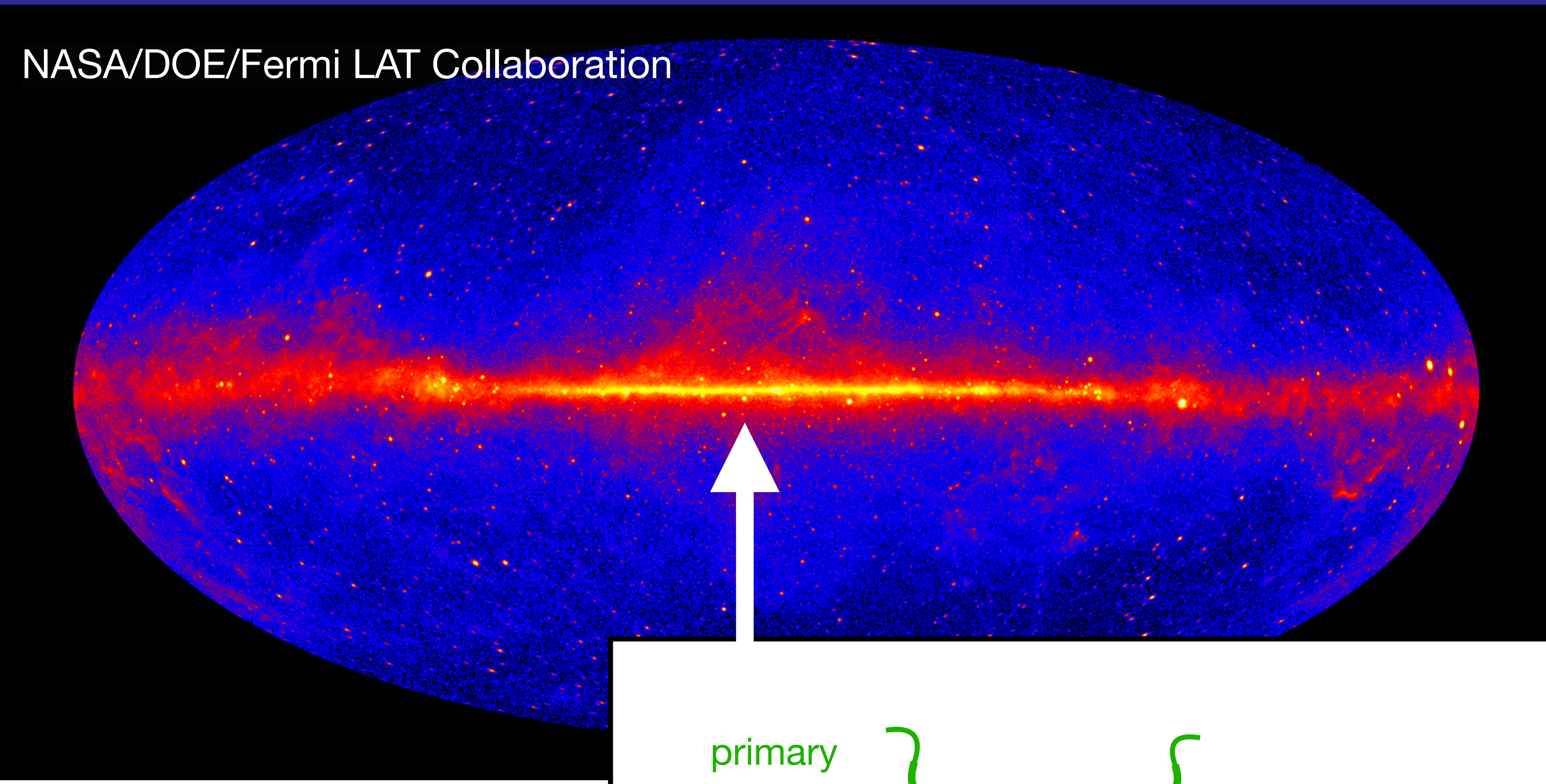
ALP decay

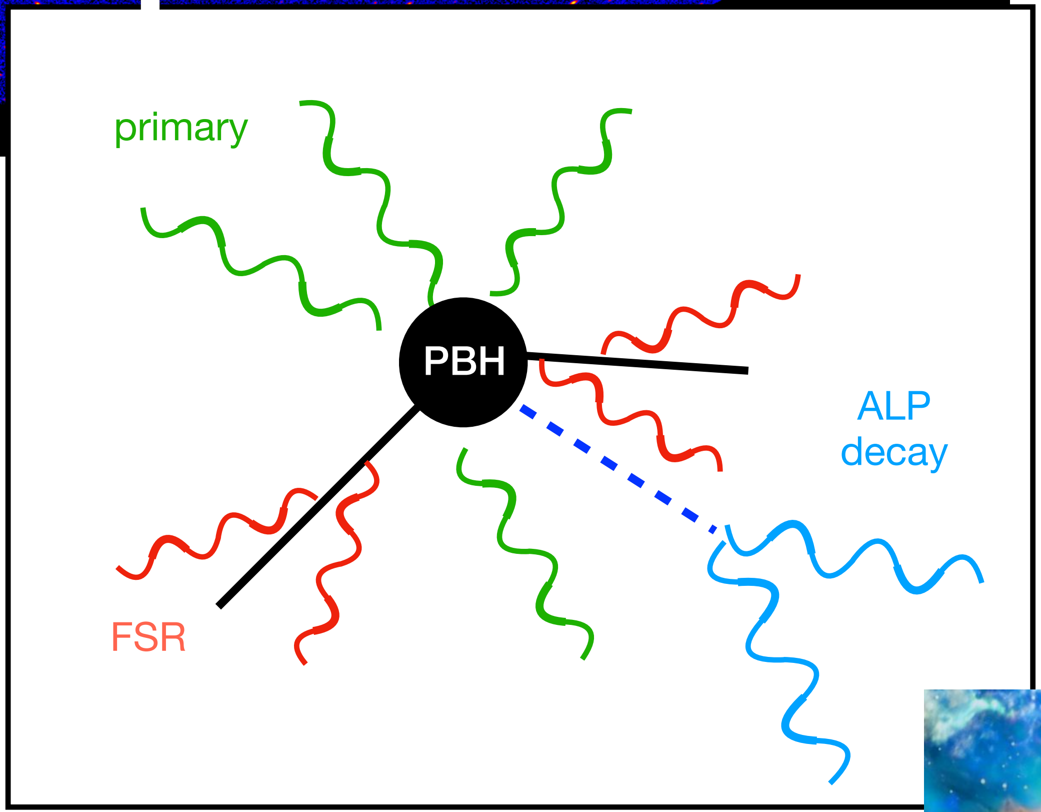
Gamma-ray spectrum, **SM** (purple) vs. **SM+ALP** (red, green, blue).

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



GC Gamma-ray search





Gamma-ray source

Target: Galactic Center (GC)

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

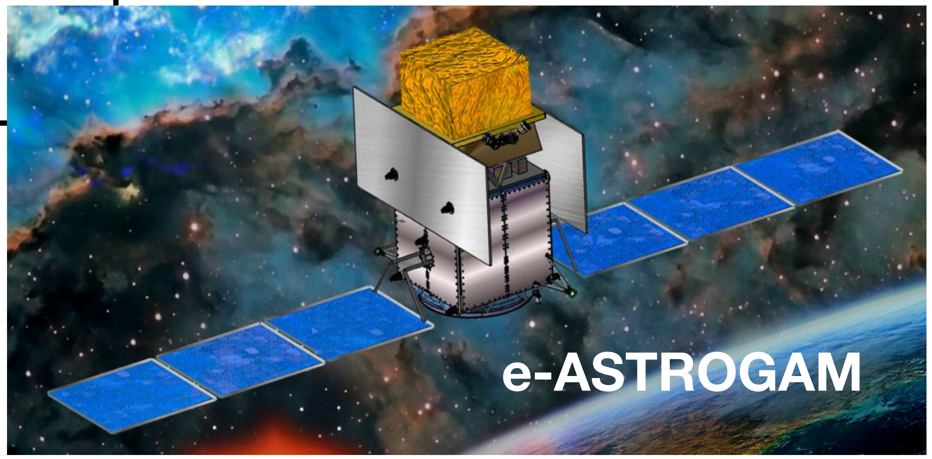
Background

forecasted by e-Astrogam

Model to test

SM: only SM particles

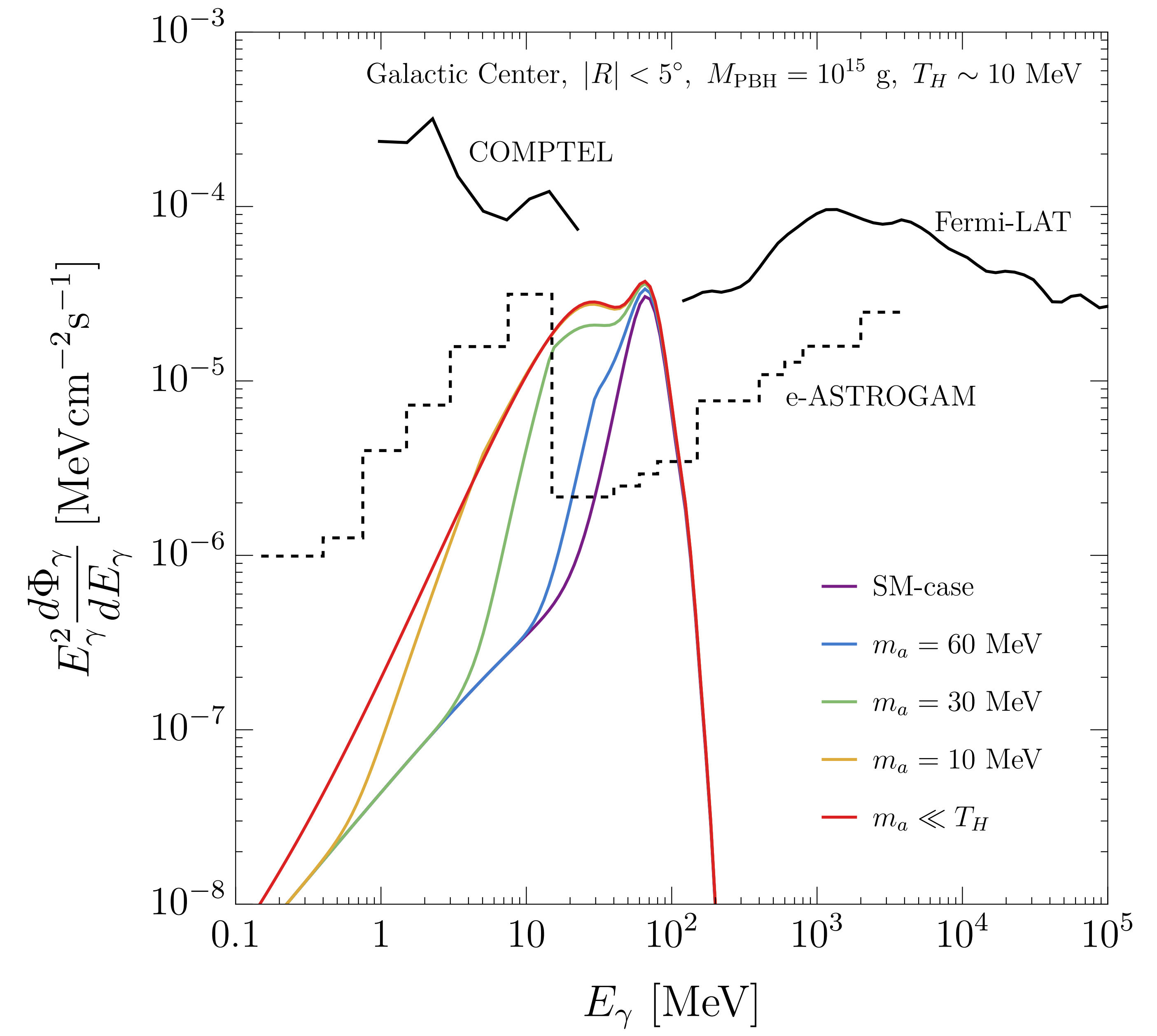
ALP: SM particles + ALP



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

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

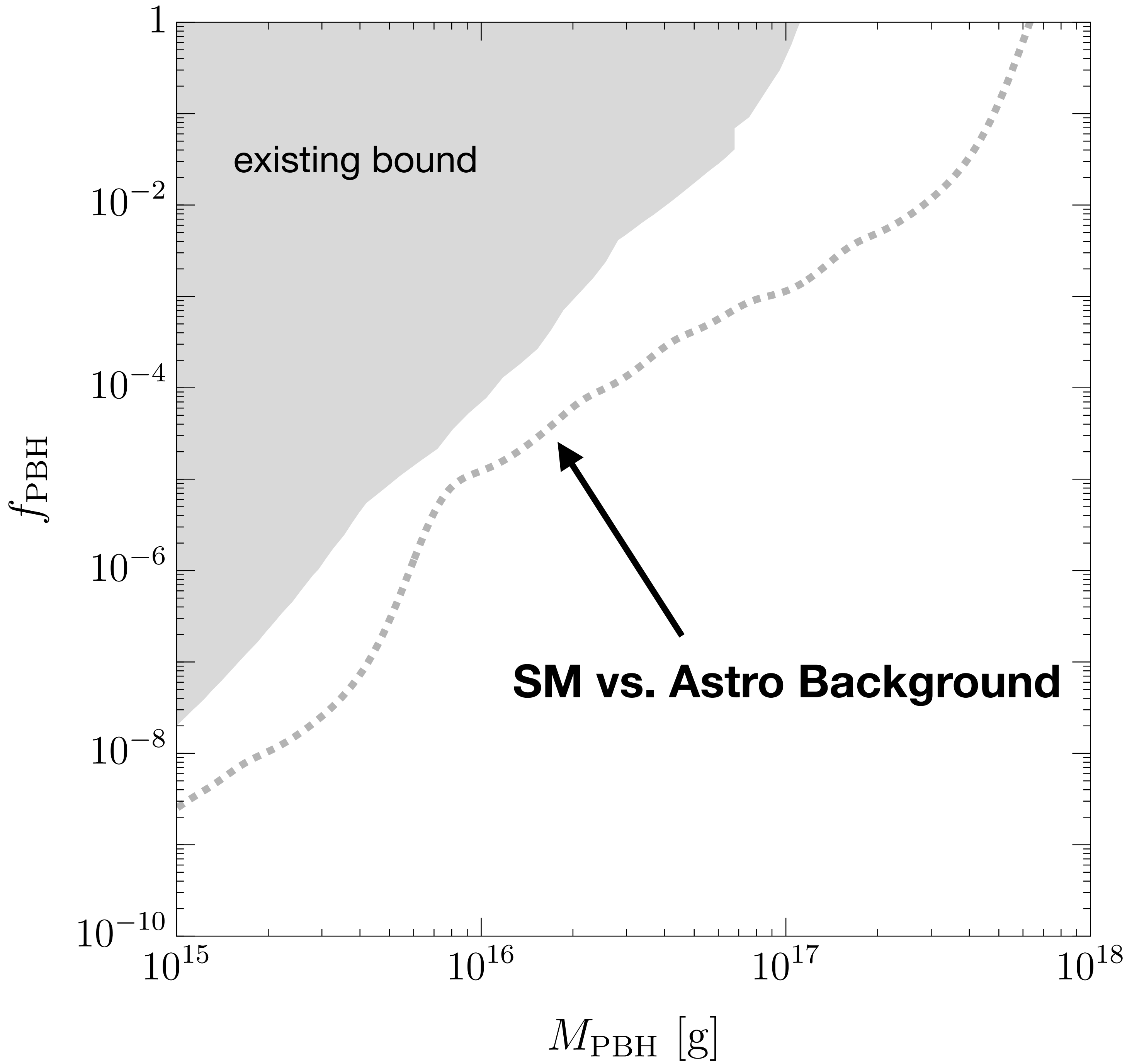
Example gamma-ray spectrum from galactic center,
PBH mass and abundance $M_{\rm PBH} = 10^{15}$ g, $f_{\rm PBH} = 10^{-8}$.



We can perform spectrum analysis with number of photons in the energy bins.

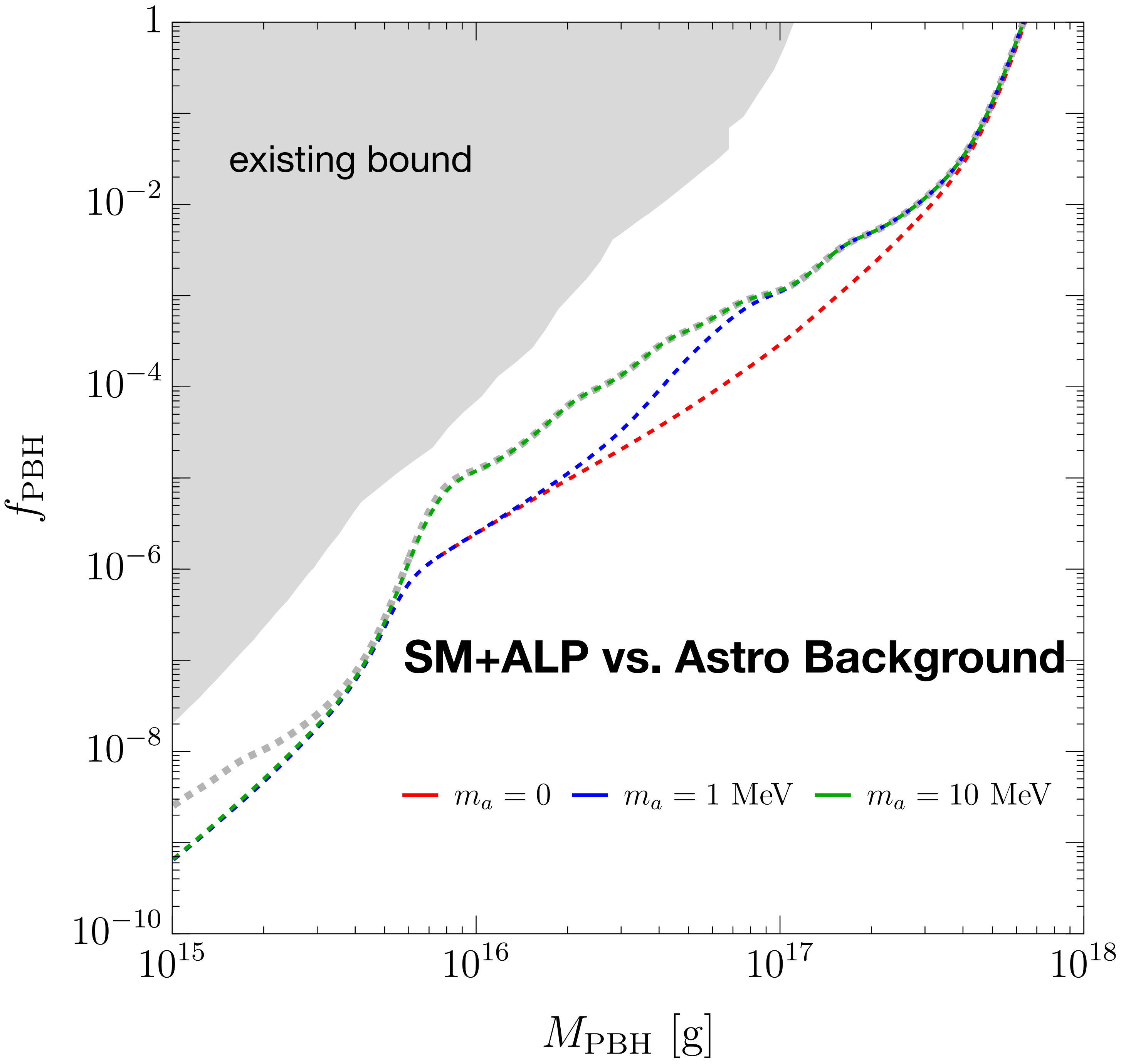
PBH constraint depends on **theory assumptions** of Hawking radiation spectrum.

Previous sensitivity assumes **only SM particles** are produced and contribute to photons.



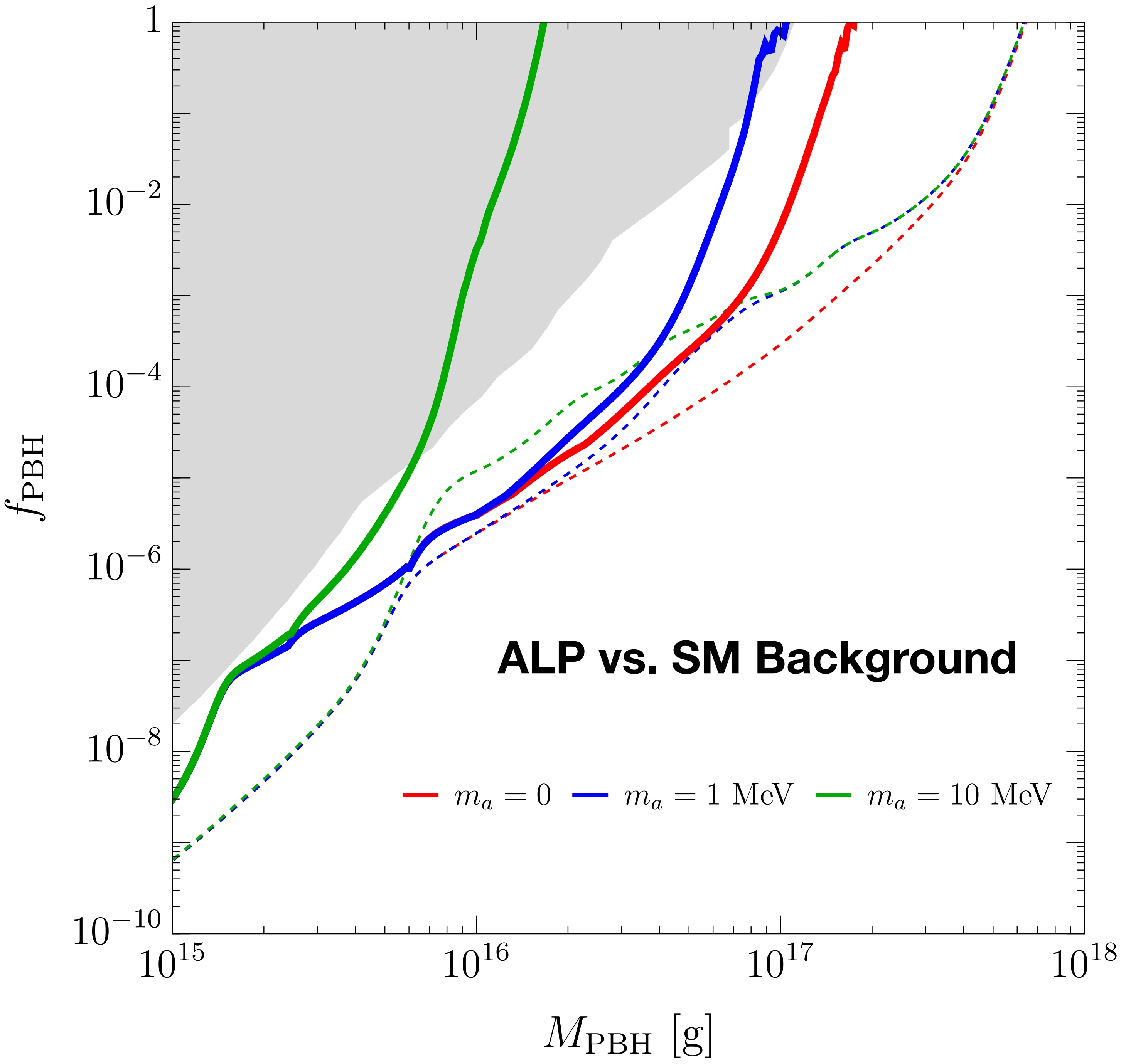
When ALPs are produced together with SM particles, the gamma-ray flux is enhanced.

PBH constraints are **stronger if ALP exists.**

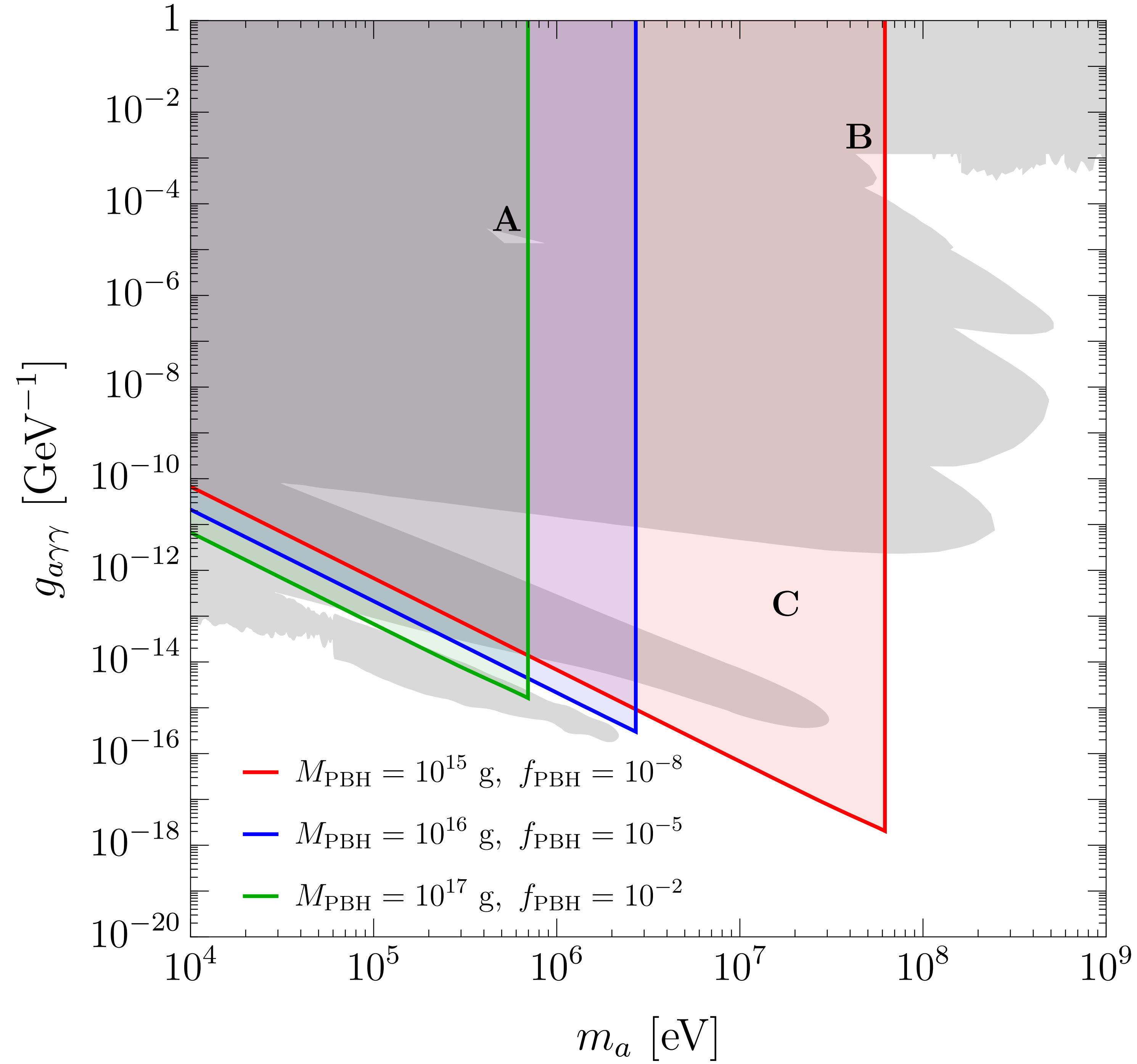


If $f_{\rm PBH}$ is larger than the detection limit, enough statistics to **distinguish** the ALP.

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



ALP parameter space that can be probed with PBHs.



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.**

arXiv: 2202.04653

- **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 use ALP to show that Hawking radiation spectrum analysis can be used to detect new particles produced by PBHs.**

arXiv: 2212.11980

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!