Asteroid-mass Dark Matter

Tao Xu
University of Oklahoma

CETUP*2023 Workshop
June 19, 2023

Outline

- Asteroid-mass primordial black holes (PBHs) and their searches.

Kaustubh Agashe, Jae Hyeok Chang, Steven J. Clarks, Bhaskar Dutta, Yuhsin Tsai, TX
arXiv: 2202.04653

- Detecting BSM particles with Hawking radiation of PBHs.

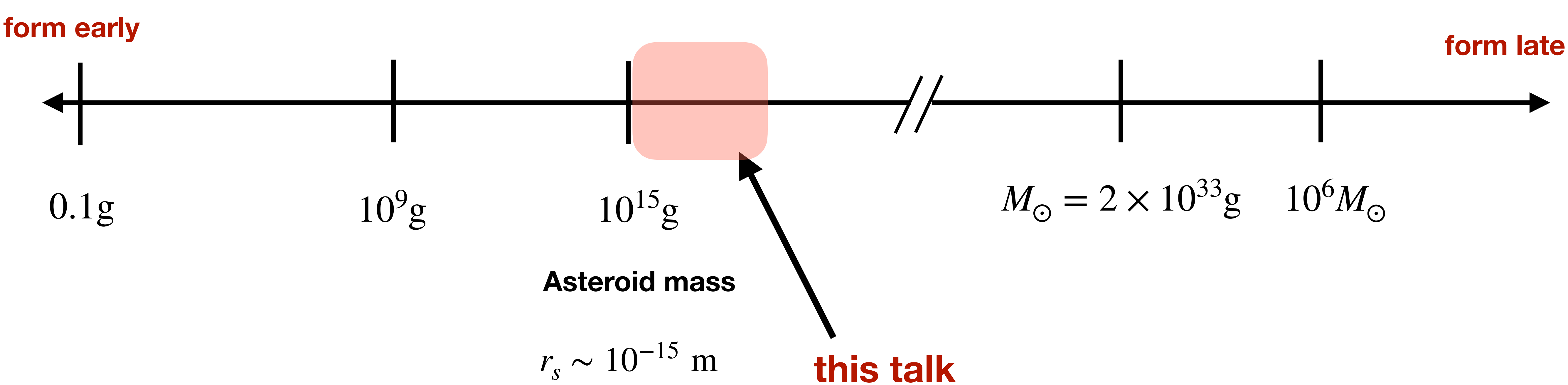
Kaustubh Agashe, Jae Hyeok Chang, Steven J. Clarks, Bhaskar Dutta, Yuhsin Tsai, TX
arXiv: 2212.11980

- Stellar binary hardening as a new method to probe light PBHs.

Badal Bhalla, Benjamin V. Lehmann, Kuver Sinha, TX
2307.XXXXX

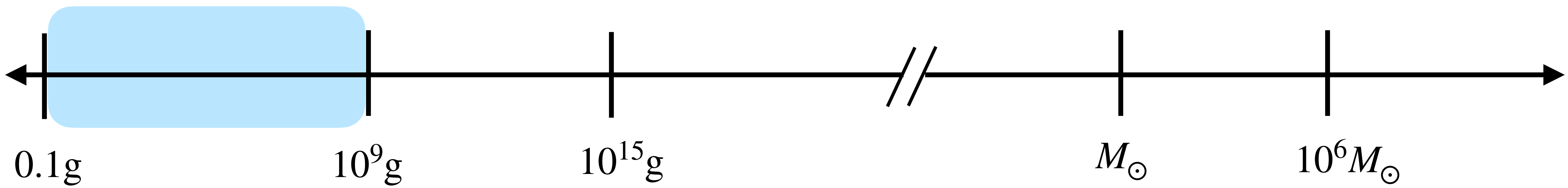
- Origin of PBHs related to interesting cosmology models.
- PBHs are heavy dark matter candidates.
- Hawking temperature is higher for light PBHs.
- Interesting phenomenology of particle production with Hawking radiation.

PBHs can exist in a wide mass range



Primordial Black Holes

Light PBHs **completely evaporated** in the early universe is difficult to probe



Big Bang Nucleosynthesis

Requiring PBH totally evaporate **before** BBN $\tau_{\mathrm{PBH}} < 1\mathrm{s}$, leads to $M_{\mathrm{PBH}} \lesssim 10^9\ \mathrm{g}$

Initial condition of the universe

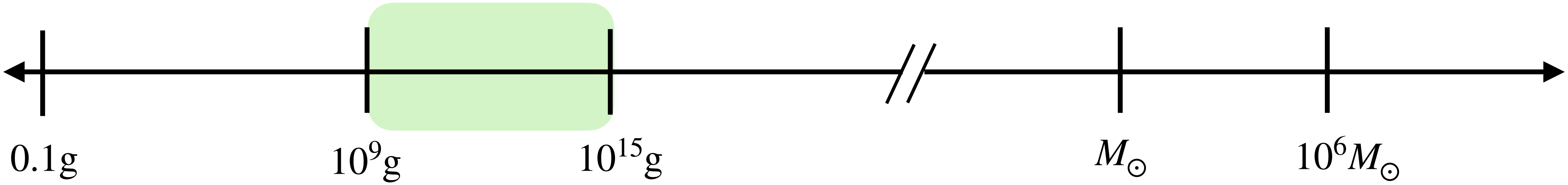
Largest inflationary Hubble parameter $H_I/M_{\mathrm{Pl}} < 2.5 \times 10^{-5}$ means $M_{\mathrm{PBH}} \gtrsim 0.1\mathrm{g}$

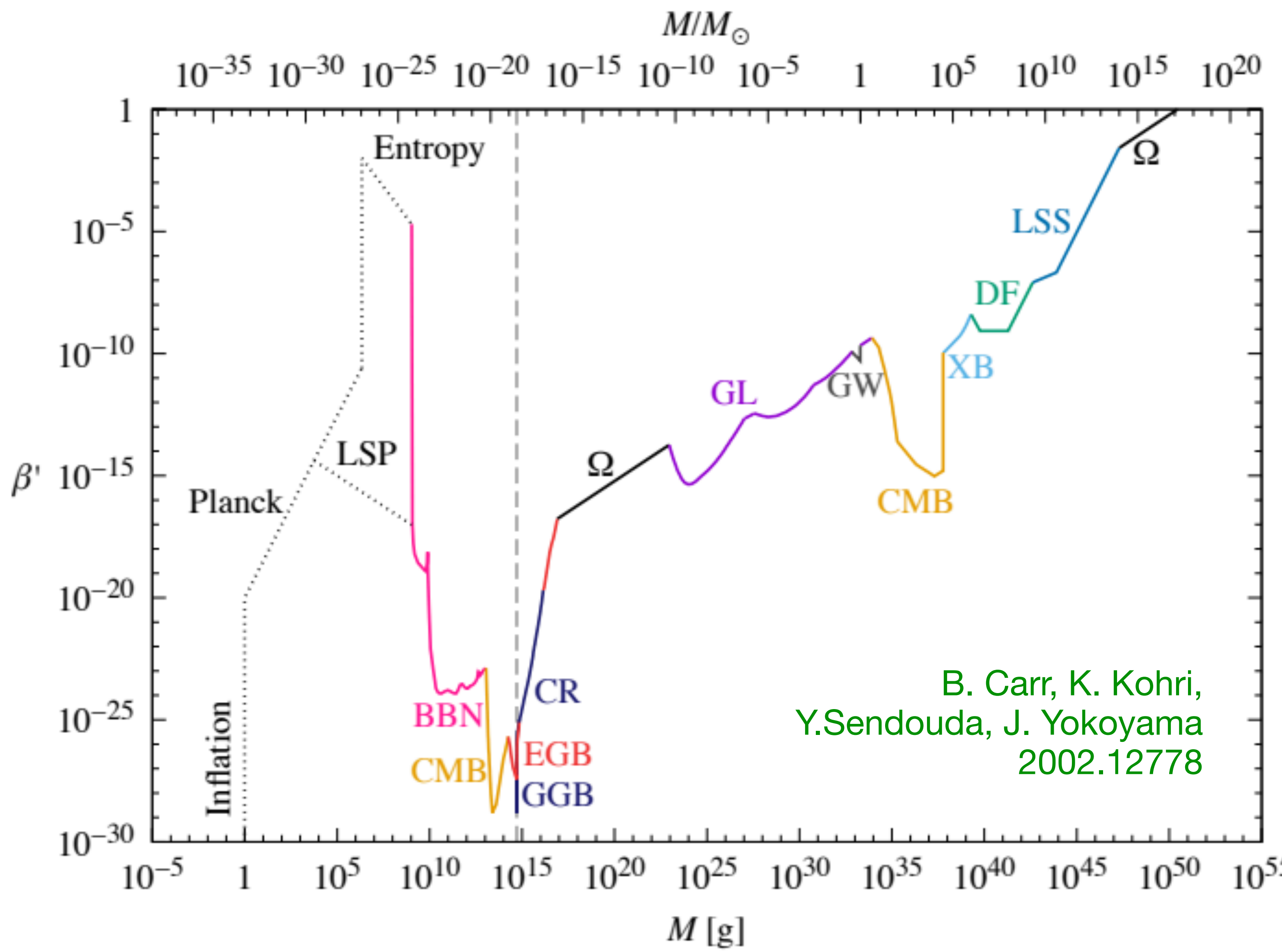
Planck 2018

$0.1\mathrm{g} \lesssim M_{\mathrm{PBH}} \lesssim 10^9\mathrm{g}$ still allowed

PBHs in this mass window can affect cosmology
with Hawking radiation.

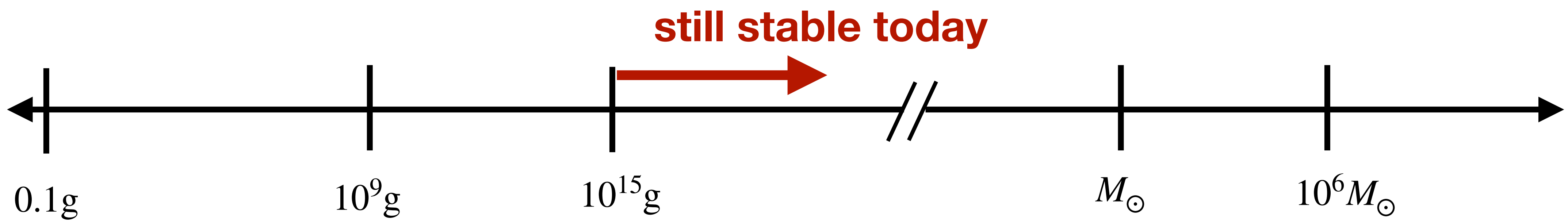
Primordial Black Holes





For lighter PBHs which have evaporated today, constraints can be set with BBN, CMB and gamma-ray observations.

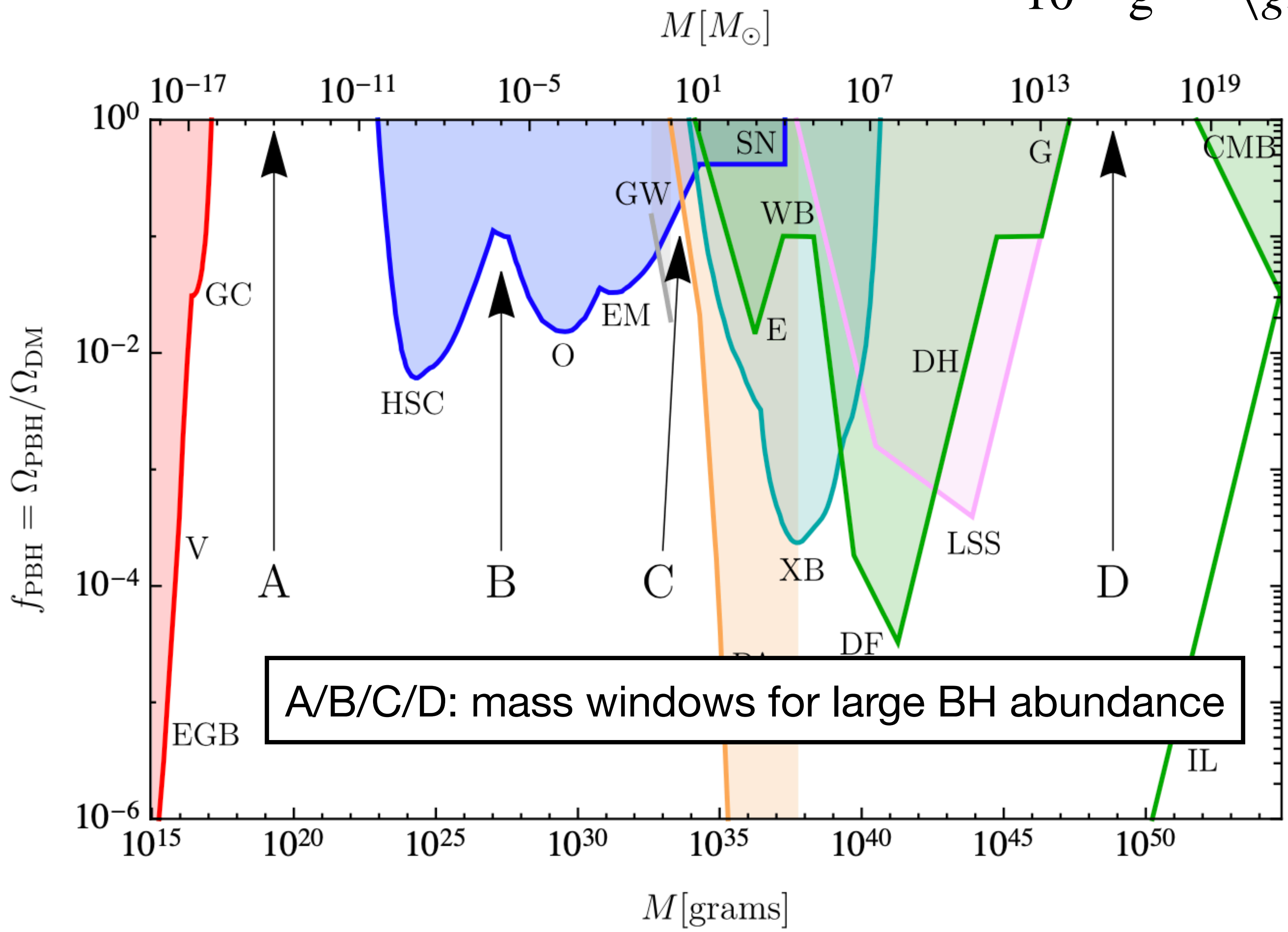
Primordial Black Holes



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

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



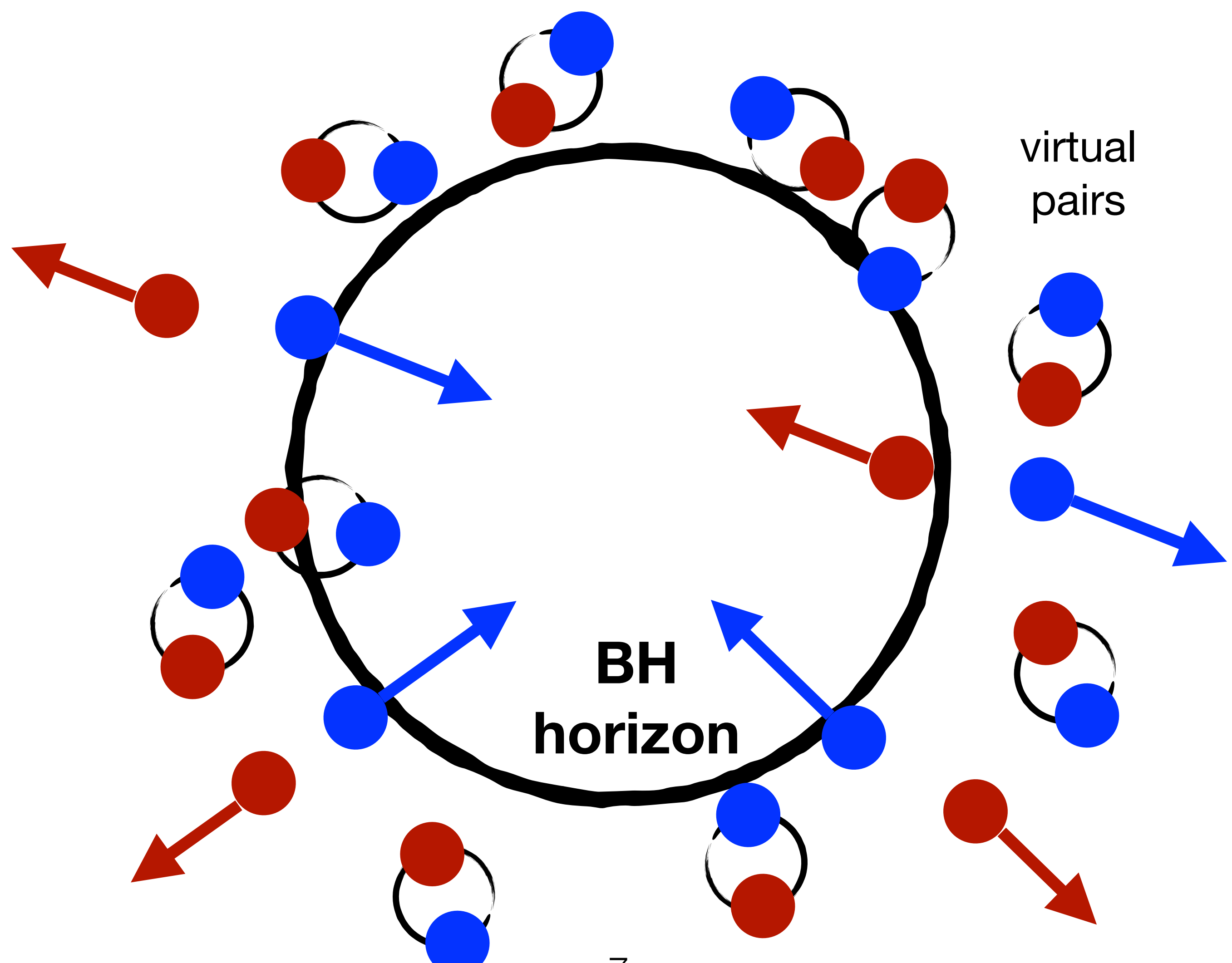
B. Carr, F. Kuhnel
2006.02838

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

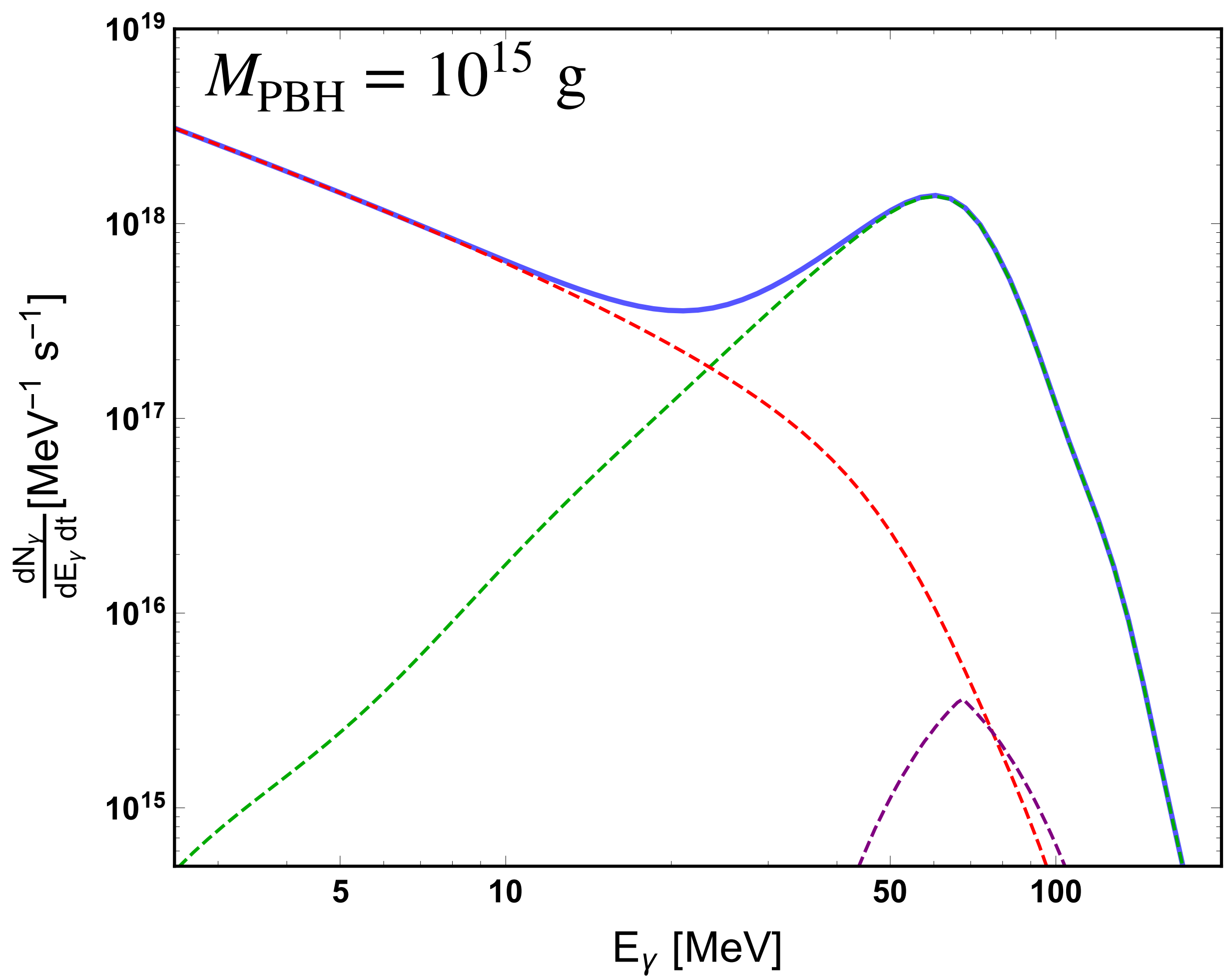
Asteroid-mass PBHs are Hawking evaporating at $\mathcal{O}(\mathrm{MeV})$ **energy.**



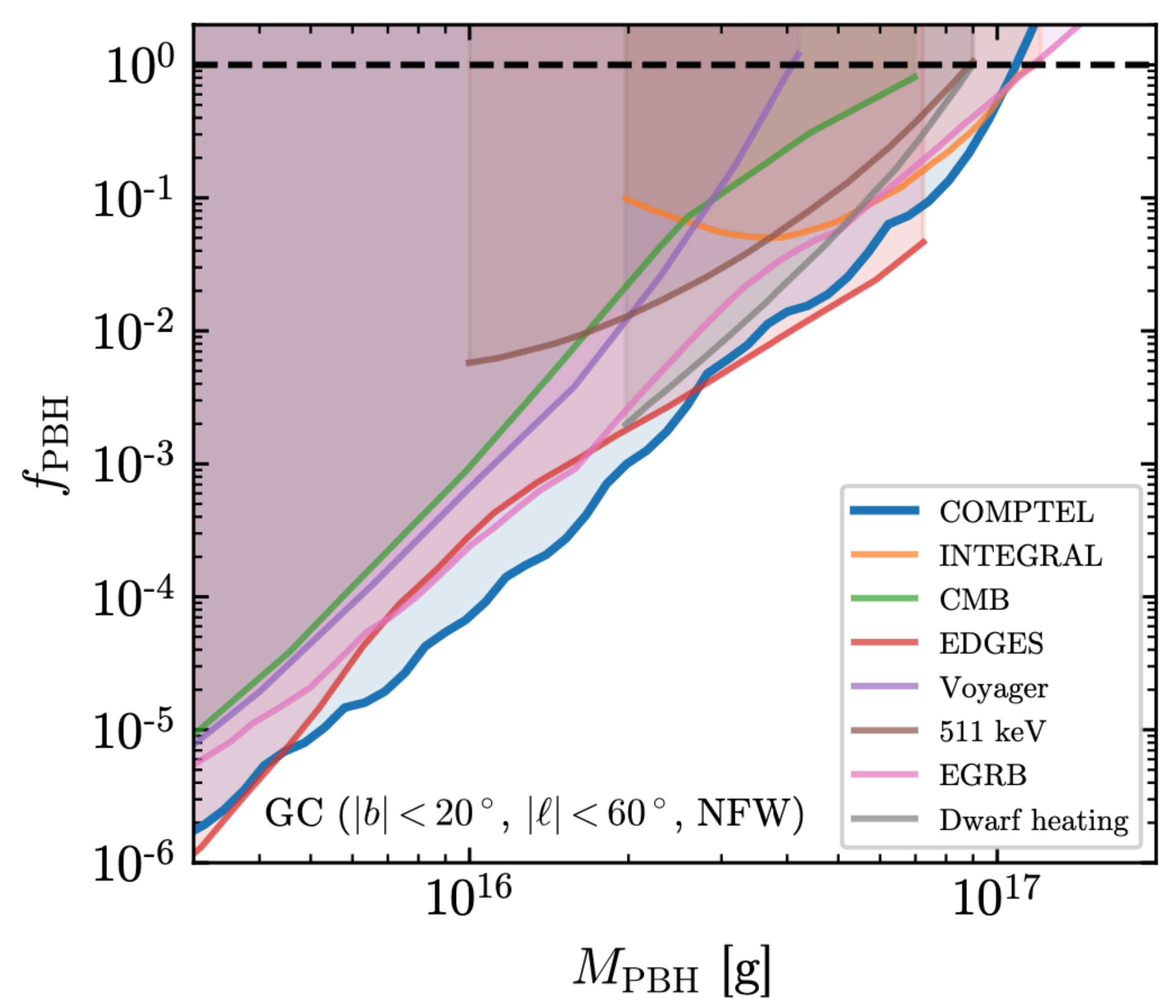
We can use gamma-ray to constrain PBHs as (fraction of) DM:

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

primary photon — final-state radiation — pion decay



Total, directly from PBH
FSR, Pion decay



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

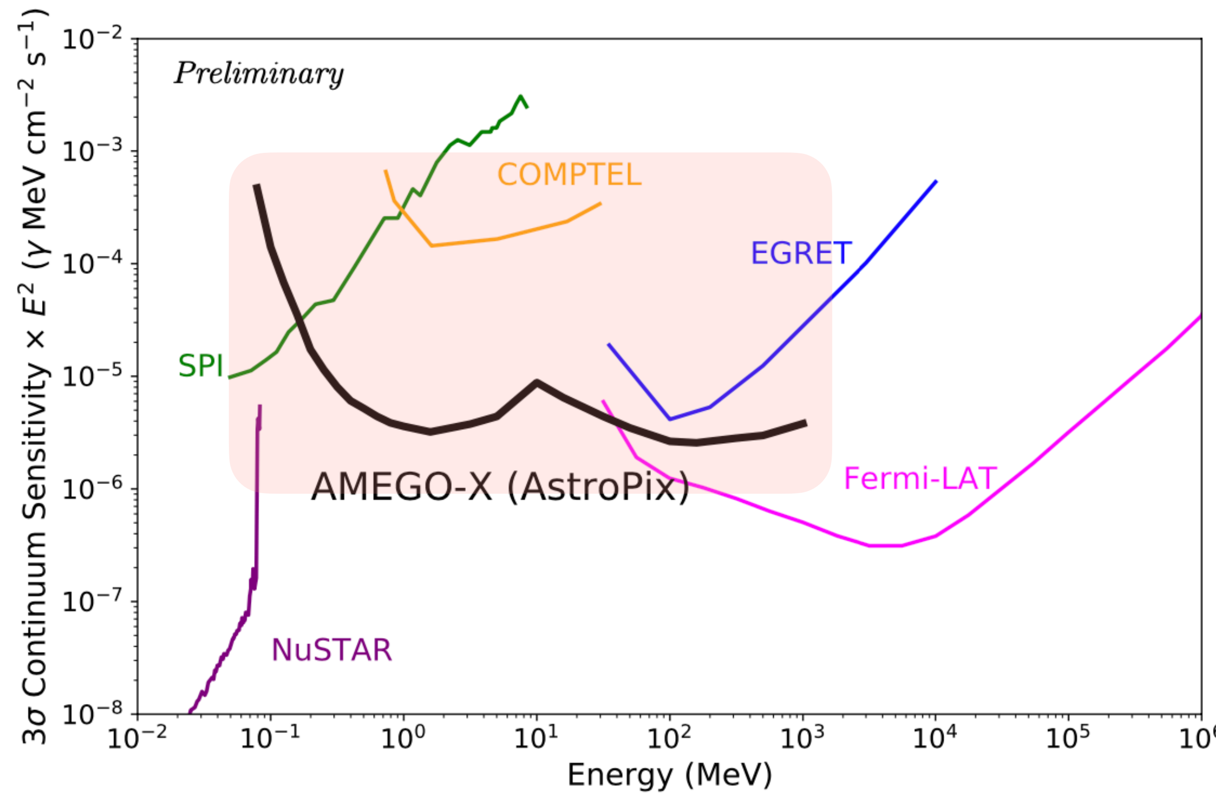
Future MeV gamma-ray searches including AMEGO, ASTROGAM, APT and more

- Covers gamma-ray energy

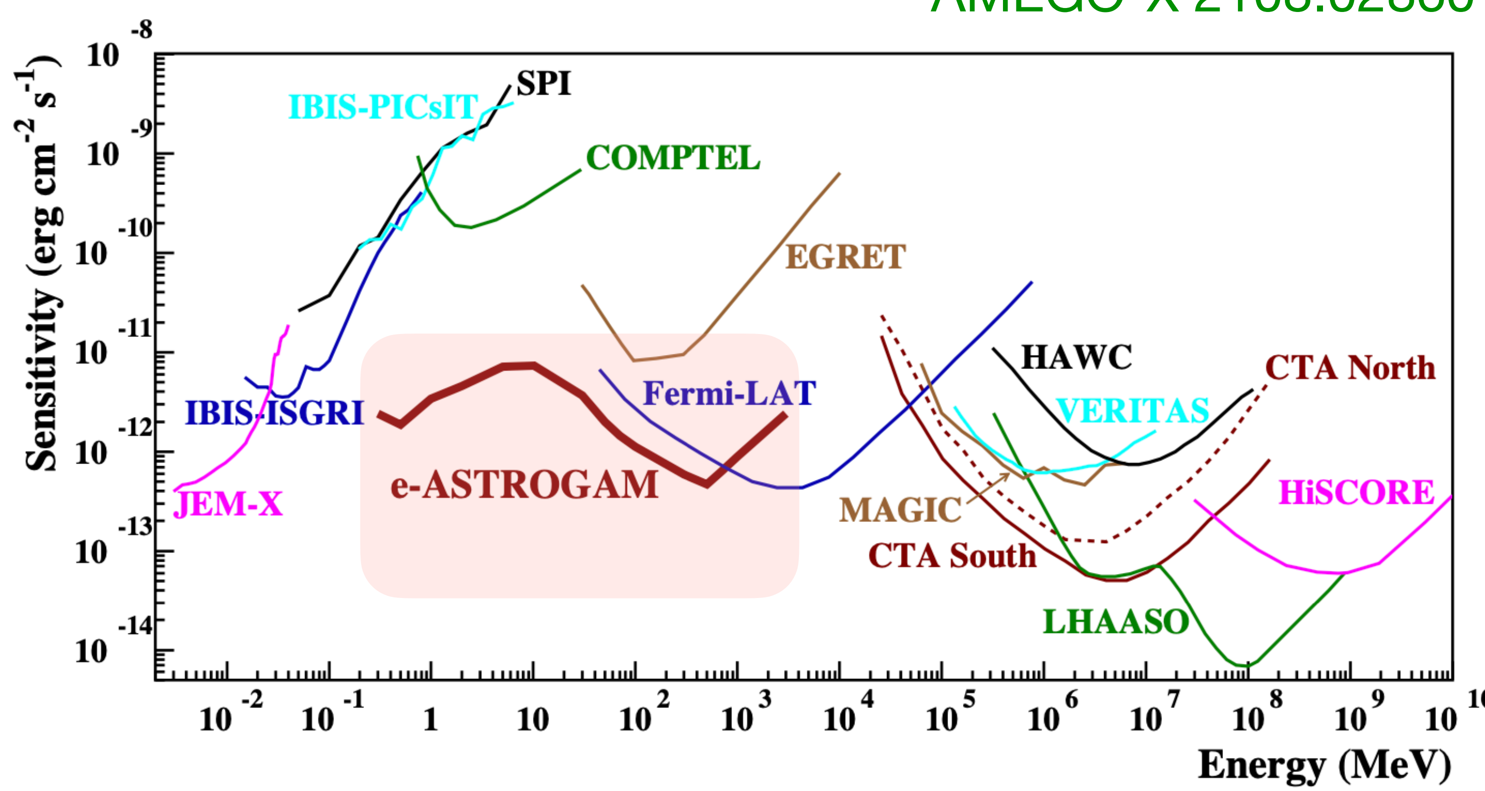
$$0.1\ \mathrm{MeV} \lesssim E_\gamma \lesssim 100\ \mathrm{MeV}$$

- Corresponds to the Hawking temperature of PBHs

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



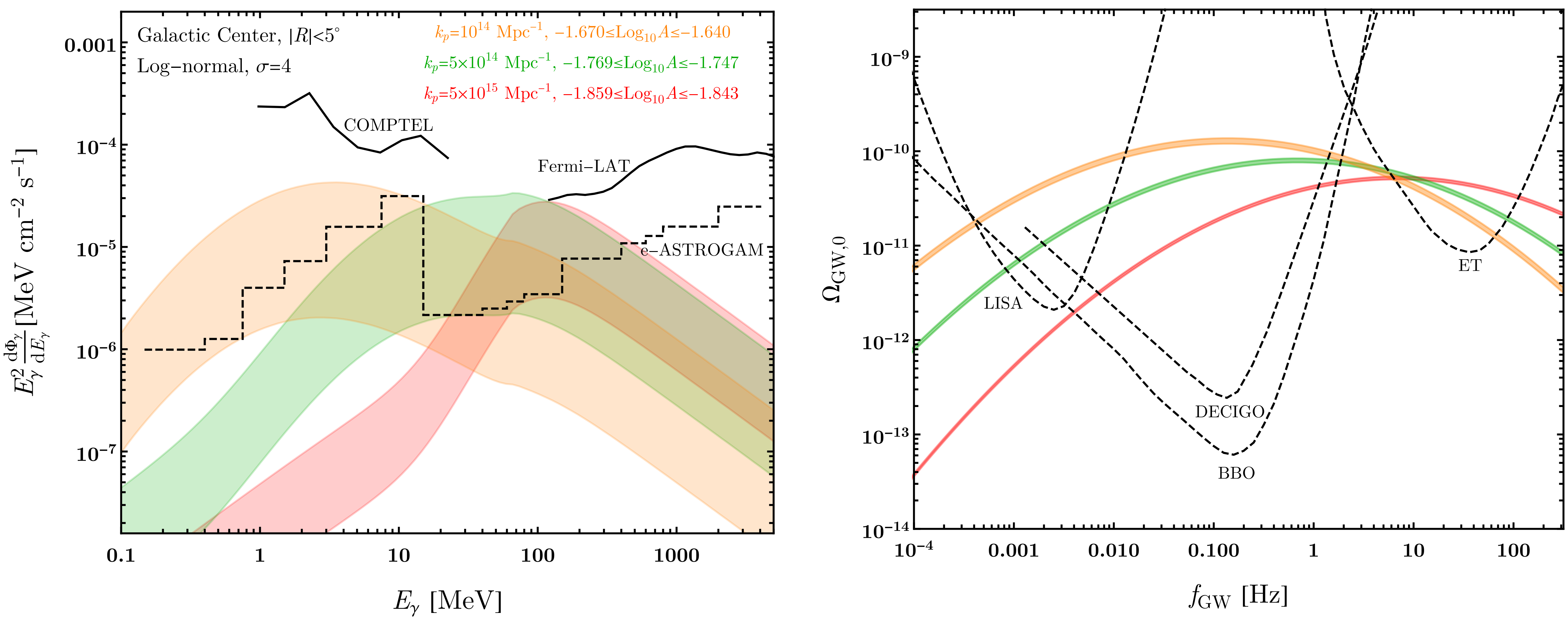
AMEGO-X 2108.02860



e-Astrogam, 1611.02232

Gravitational waves are generated by curvature perturbations at PBH formation.

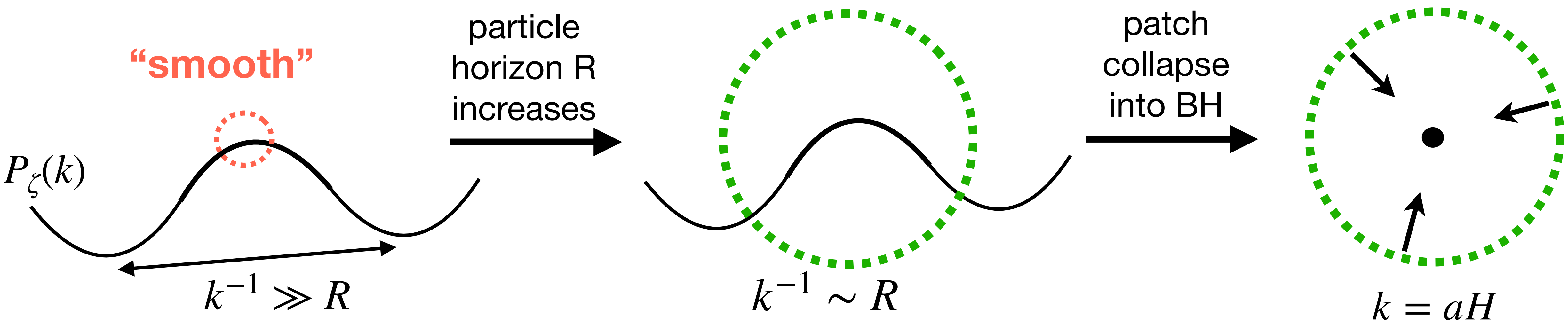
Multi-messenger observations of **gamma-ray** and **GWs** to study asteroid-mass PBH DM.



color band: signal for future searches

PBH formation from curvature perturbations

PBH form from the **collapse of large over-dense regions** in the early universe



PBH mass is fraction of horizon patch mass

$$M_{\rm PBH} \simeq 4 \times 10^{15}\ {\rm g}\ \left(\frac{k}{10^{15}\ {\rm Mpc}^{-1}}\right)^{-2}$$

For asteroid-mass PBHs, we need

$$10^{14}\ {\rm Mpc}^{-1} \lesssim k \lesssim 10^{15}\ {\rm Mpc}^{-1} \quad \text{or} \quad 10^{6}\ {\rm GeV} \lesssim T_i \lesssim 10^{7}\ {\rm GeV}$$

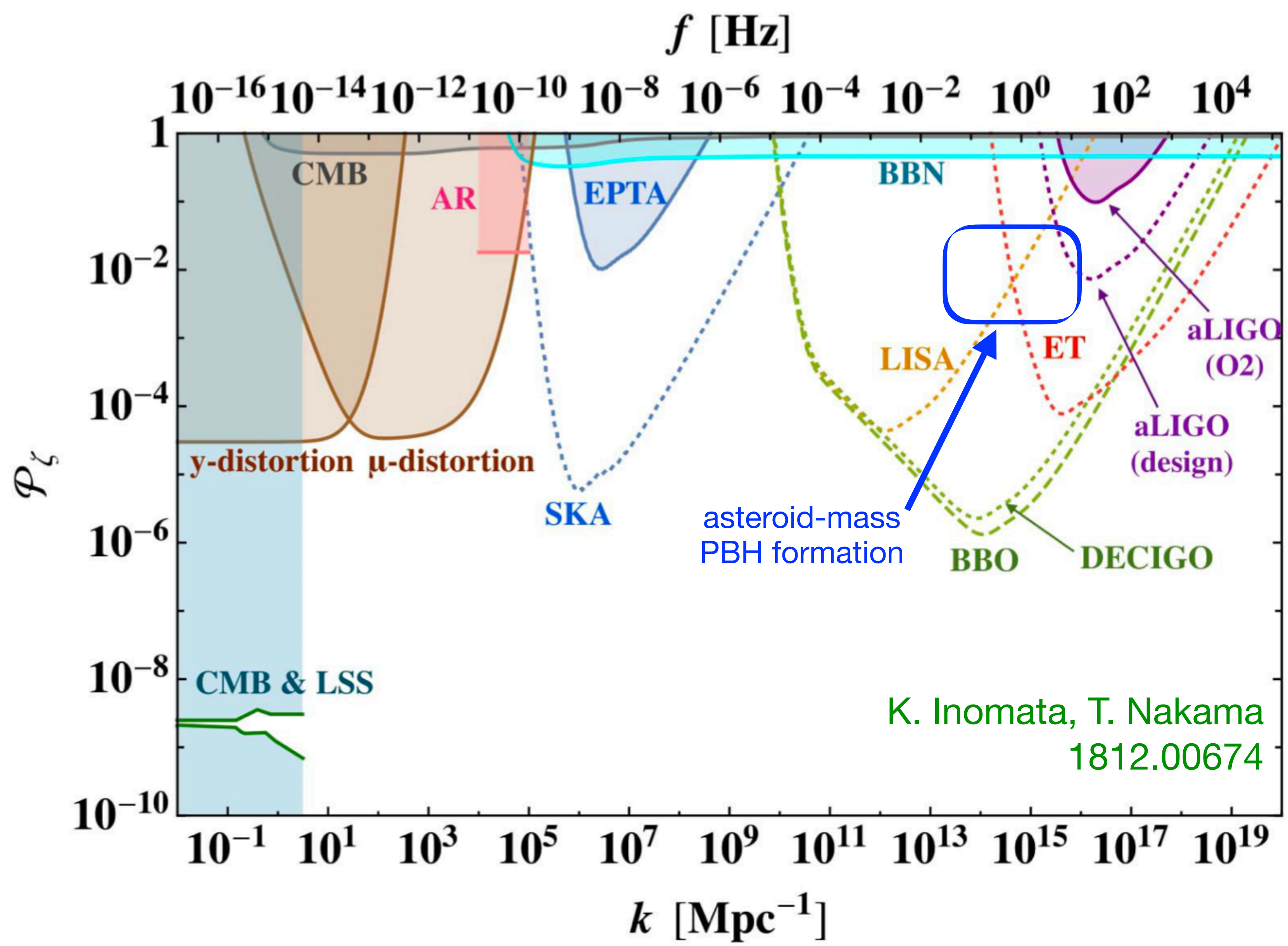
Formation **density contrast** $\delta \simeq \delta_c \simeq \mathcal{O}(0.1)$ and assuming Gaussian $\delta \sim \sqrt{P_\zeta}$

$P_\zeta \sim 10^{-2}$ needed for PBH formation is **less constrained on small scales**

The PBH formation mechanism can be tested with GWs sourced by P_ζ

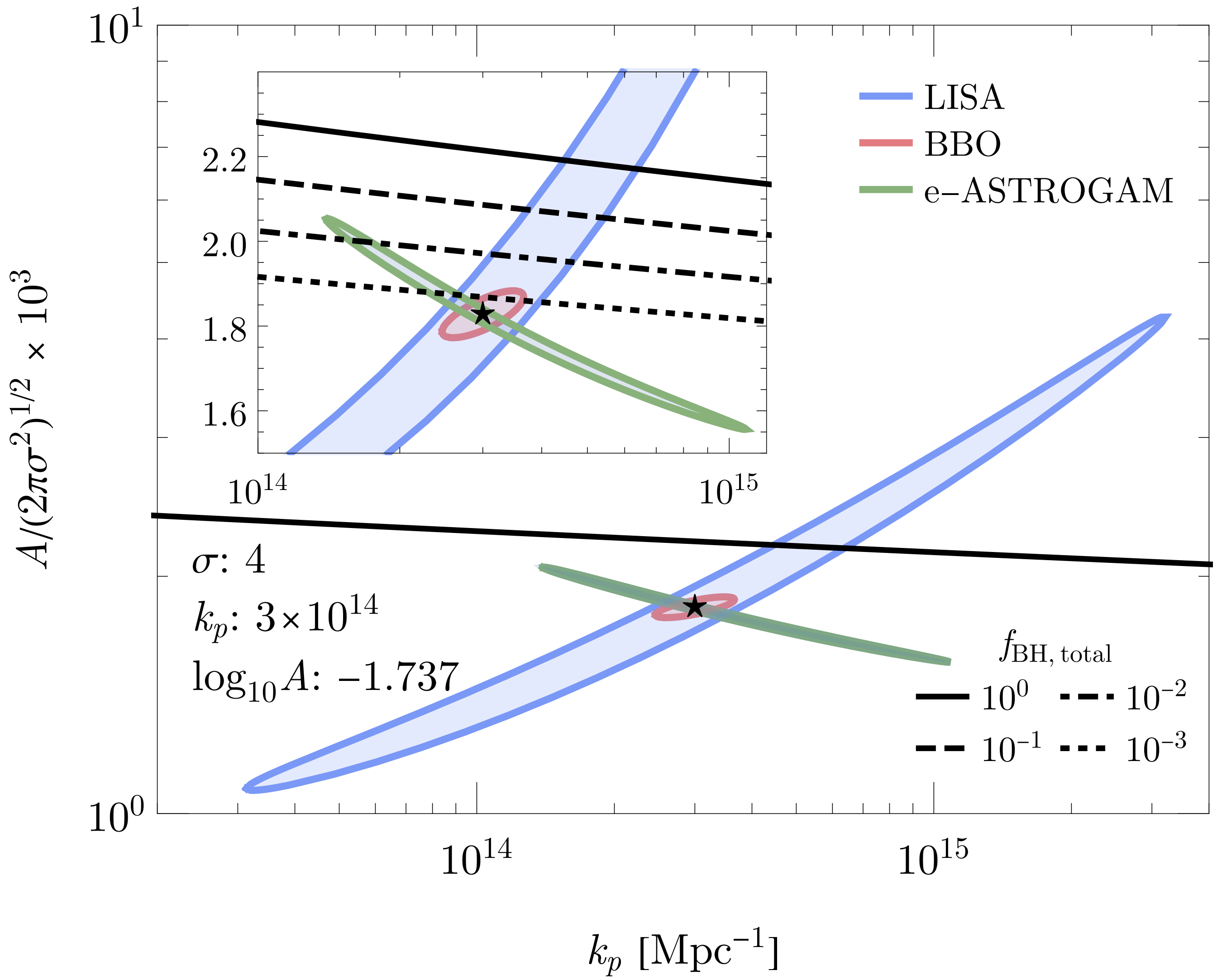
$$f^{\rm peak}_{{\rm GW},\zeta} = 1.546 \times \left(\frac{k_p}{10^{15}{\rm Mpc}^{-1}}\right) {\rm Hz} \qquad \Omega_{\rm GW,today} \simeq P_\zeta^2 \times \Omega_{\rm CMB,today} \sim 10^{-9}$$

large P_ζ for PBH formation predicts strong GWs at ~Hz frequency



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**

K. Agashe, J.H. Chang, S.J. Clarks, B. Dutta, Y. Tsai, TX
2202.04653

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

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

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

  Asteroid-mass PBHs can produce MeV or lighter BSM particles

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

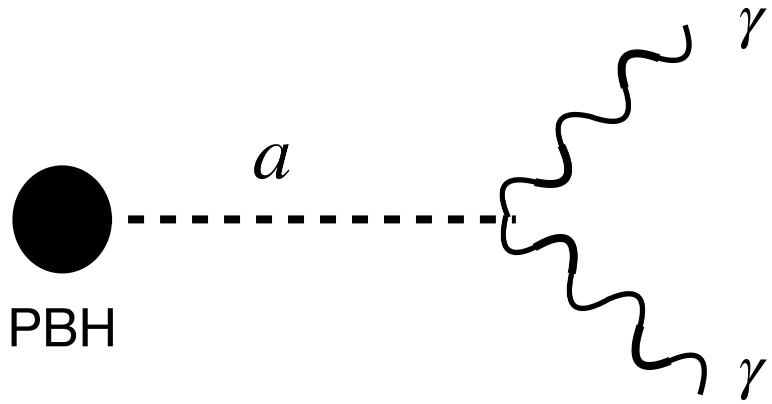
  Hawking radiation is another channel to produce new particles in the spectrum

- can we use PBH DM as a **BSM particle factory**?
  - "built" in the early Universe
  - energy scale determined by Hawking temperature
  - large BSM particle production rate, even if non-gravitational interaction is feeble
  - clear SM "background" spectrum from Hawking radiation calculation

- 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 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

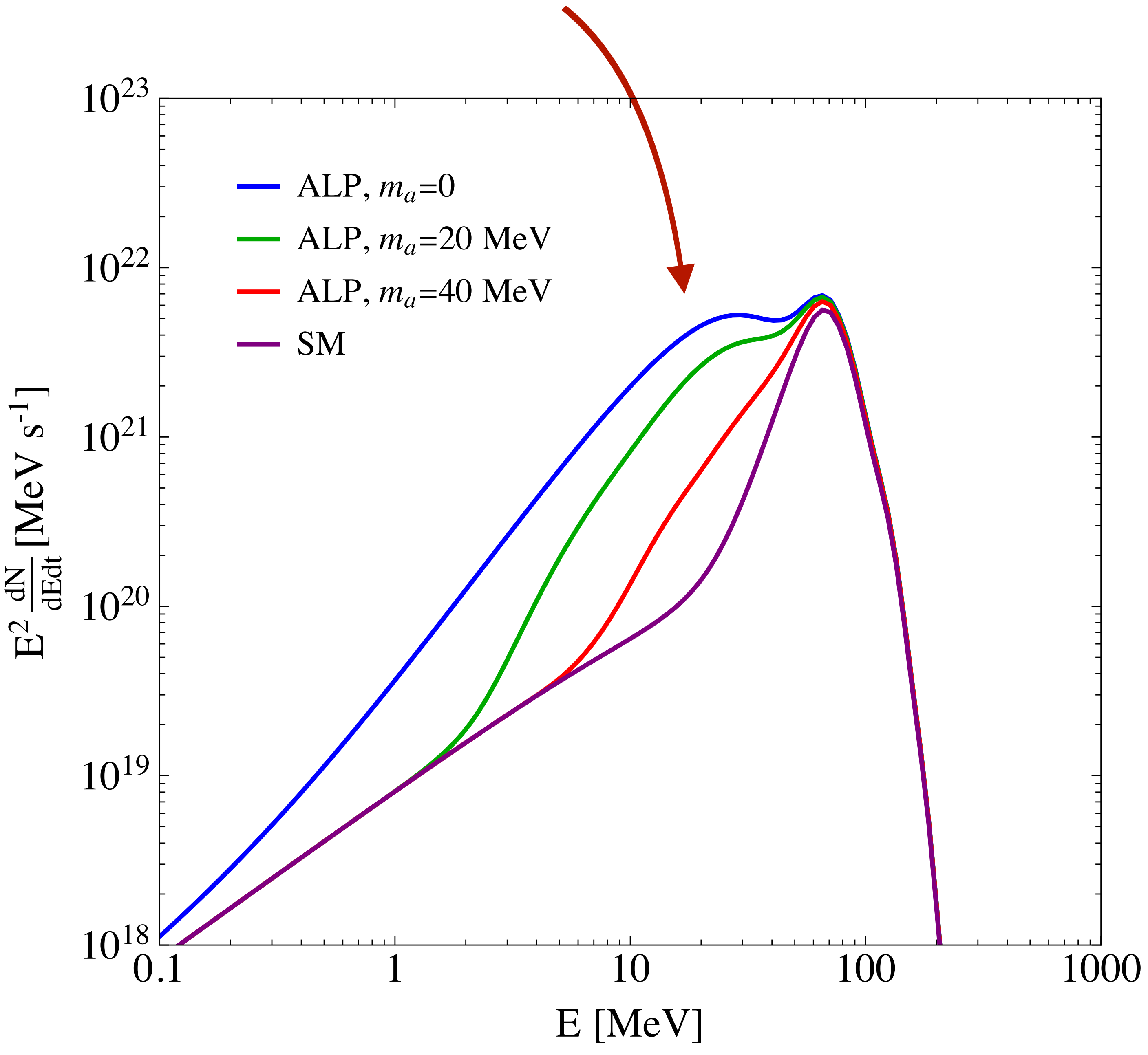
$$+ \int dE_a 2 \frac{\partial N_{a,\mathrm{primary}}}{\partial E_a \partial t} \frac{dN_{a,\mathrm{decay}}}{dE_\gamma}$$

ALP decay

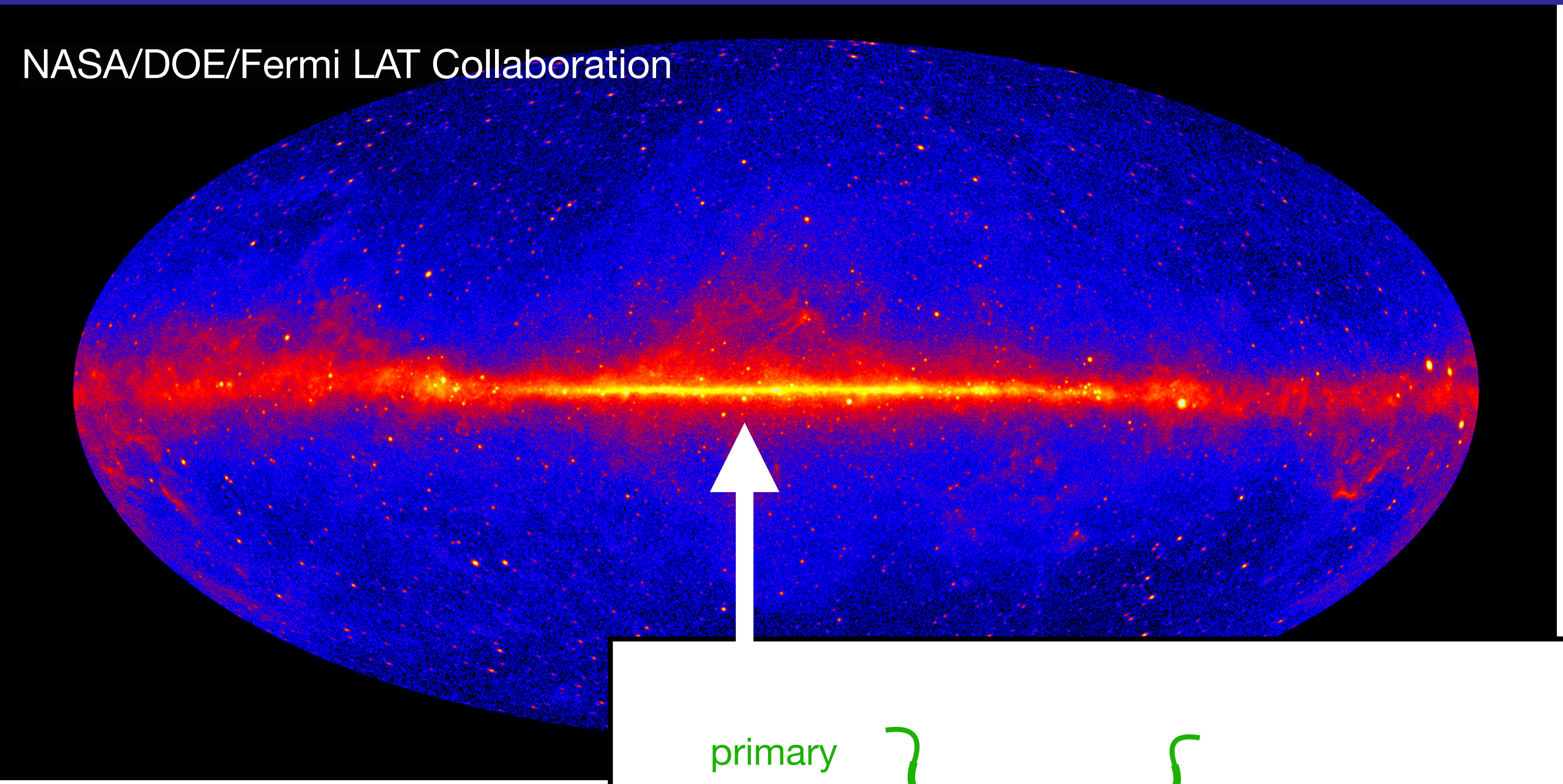
Gamma-ray spectrum (SM+ALP)

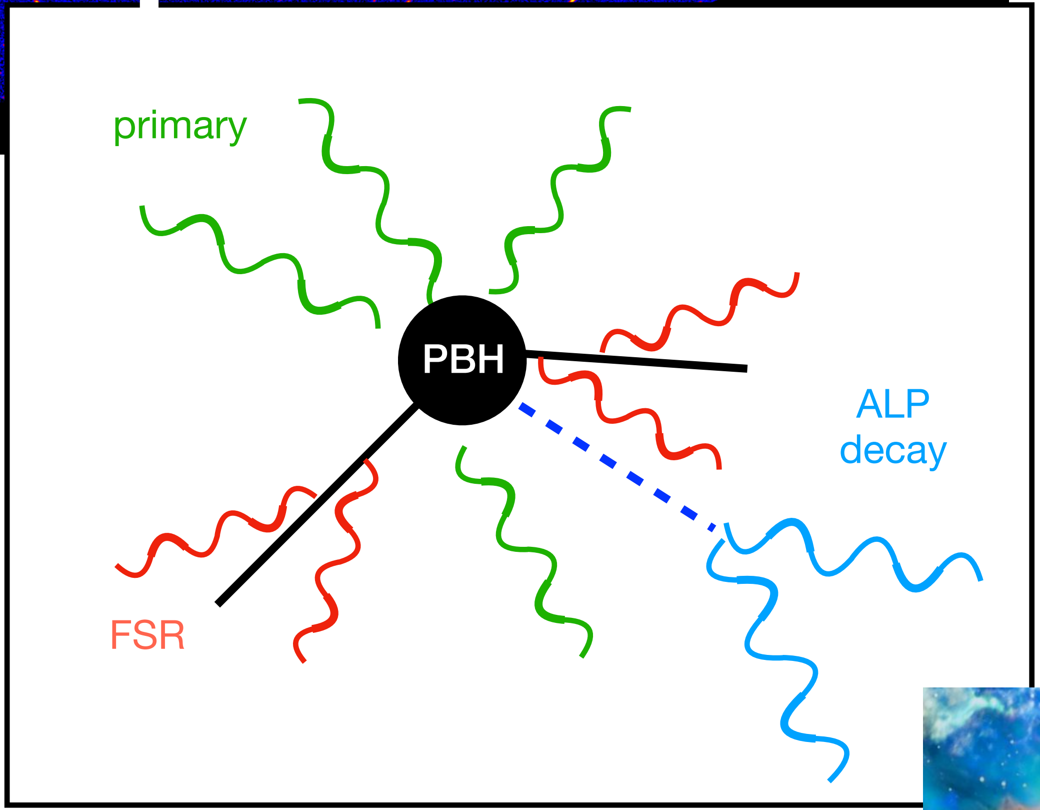
Gamma-ray spectrum, **SM** (purple) vs. **SM+ALP** (red, green, blue).

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



Galactic gamma-ray search

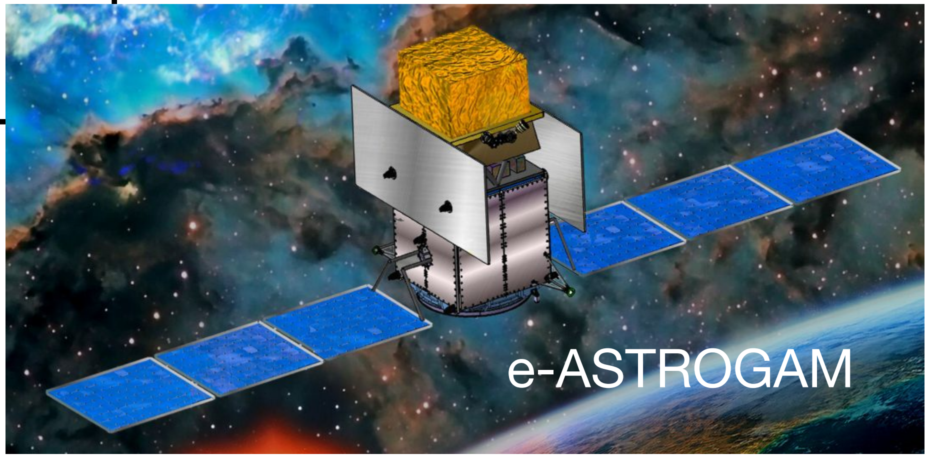




Gamma-ray source
Target: Galactic Center
Angular extent: $|R| < 5^\circ$

Background
forecasted by e-Astrogam

Model to test
SM: only SM particles
ALP: SM particles + ALP

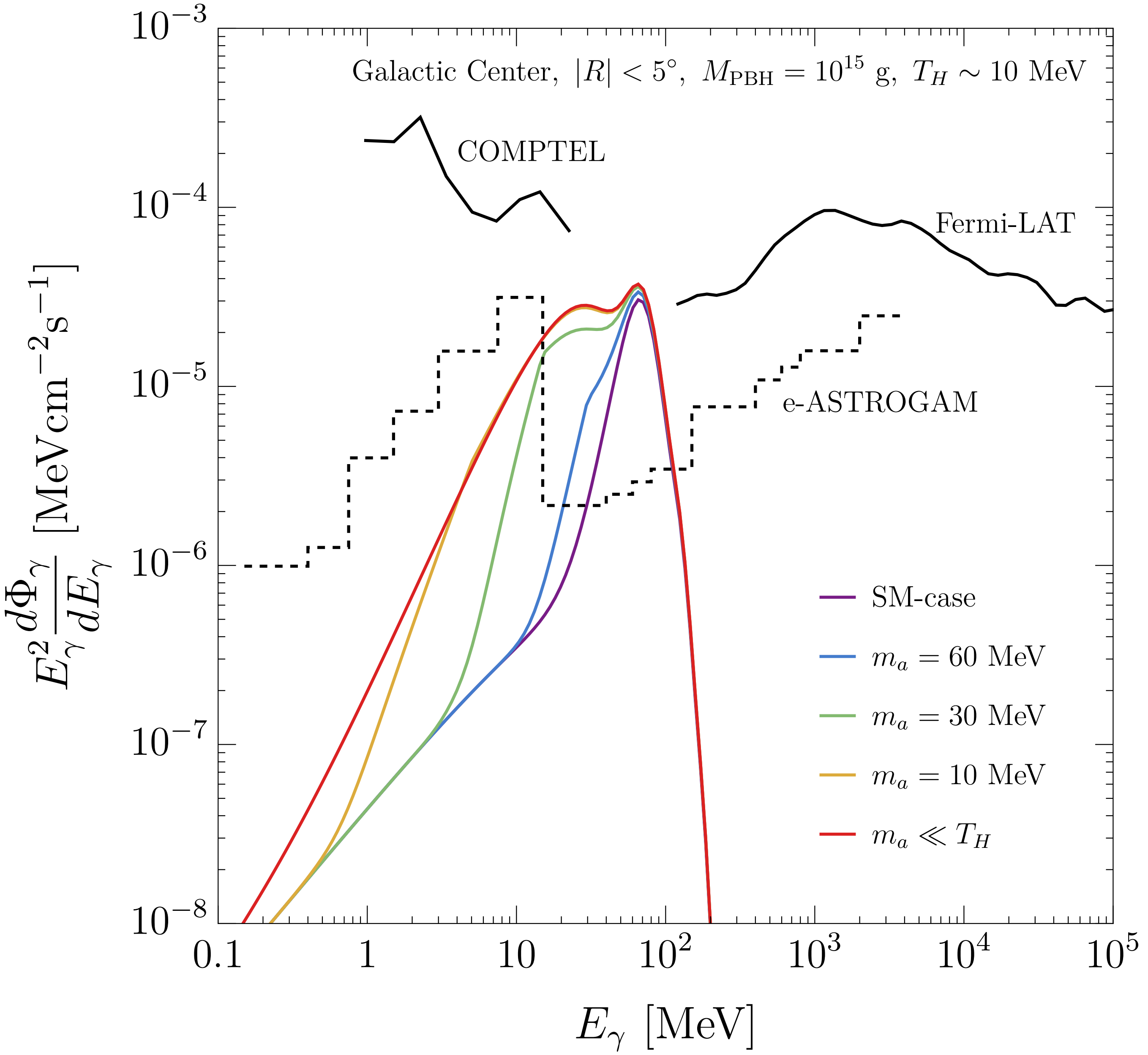


Assume PBHs make up $f_{\rm PBH}$ of DM

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

Galactic gamma-ray search

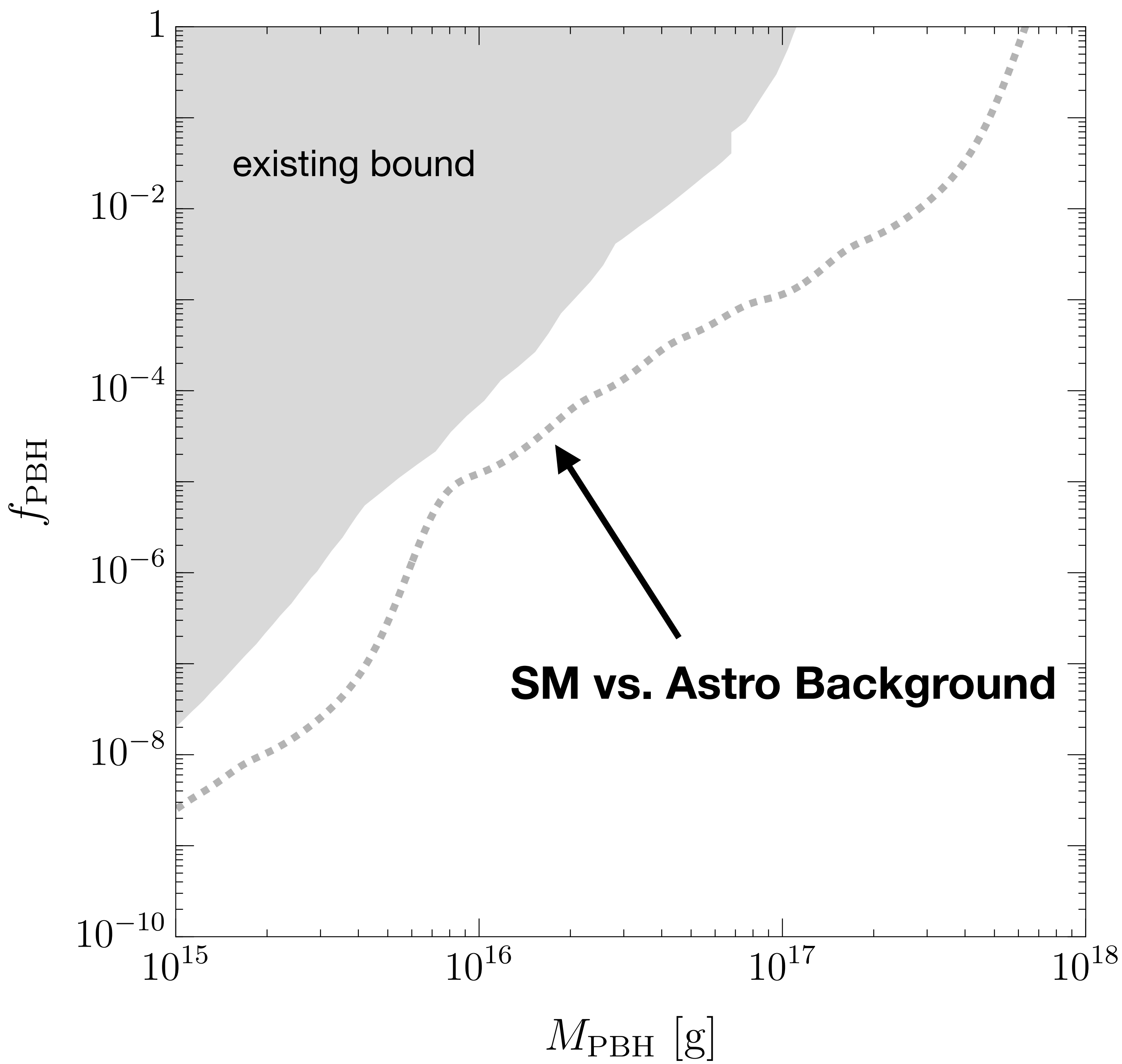
Example gamma-ray spectrum from galactic center,
PBH mass and abundance $M_{\rm PBH} = 10^{15}$ g, $f_{\rm PBH} = 10^{-8}$.



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

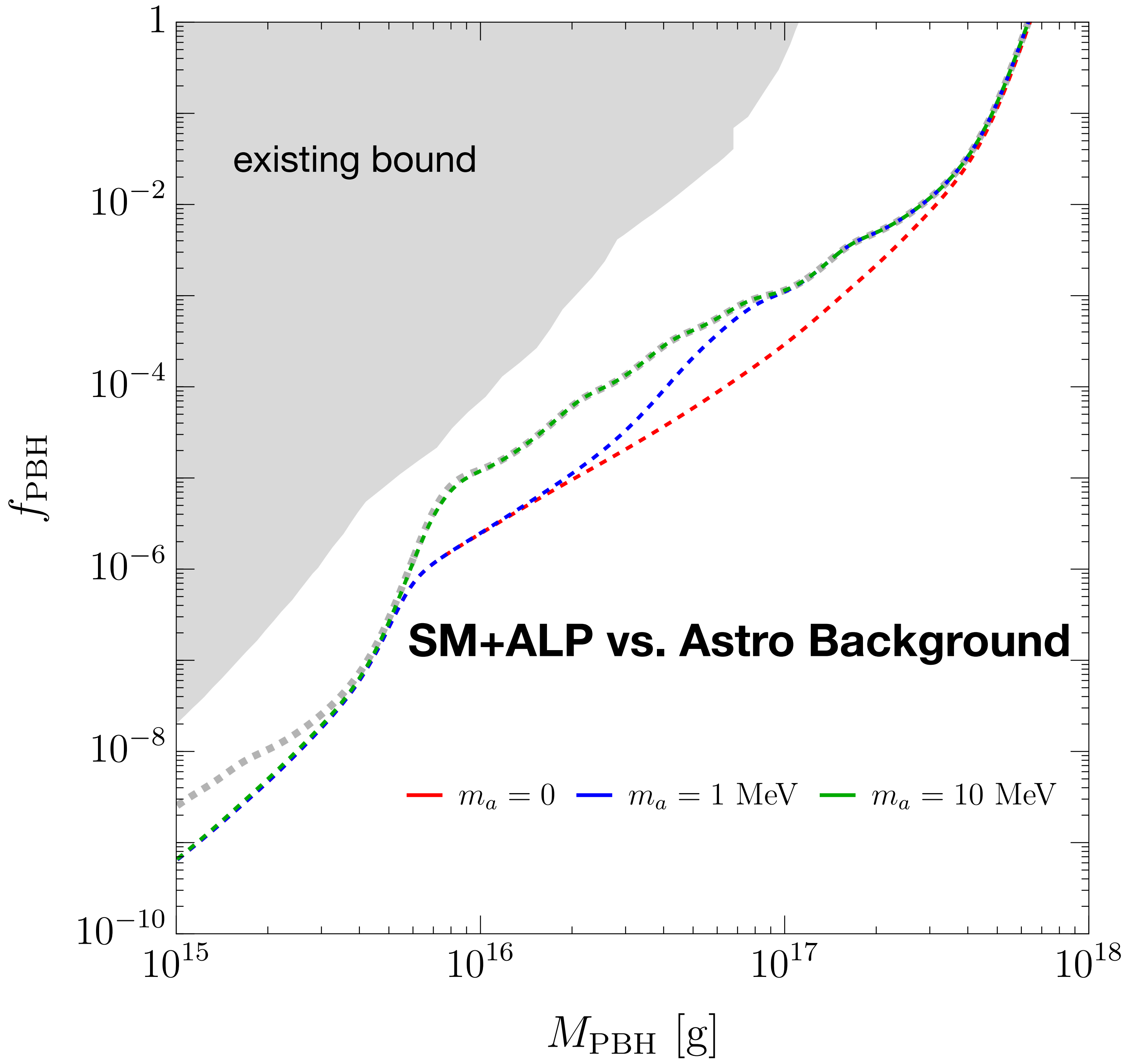
PBH constraint depends on **theory assumptions** of Hawking radiation spectrum.

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



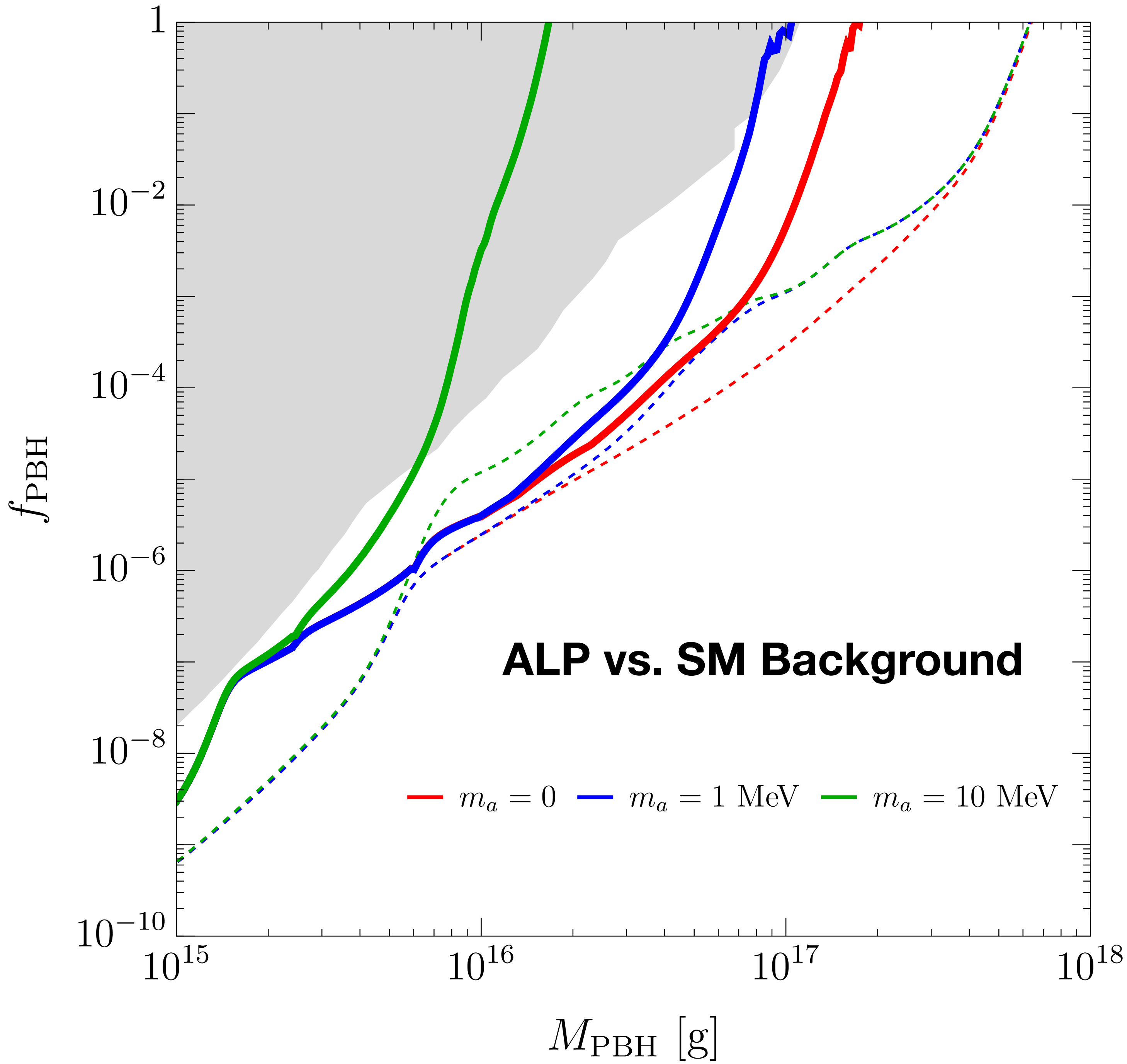
When ALPs are produced together with SM particles, the gamma-ray flux is enhanced.

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

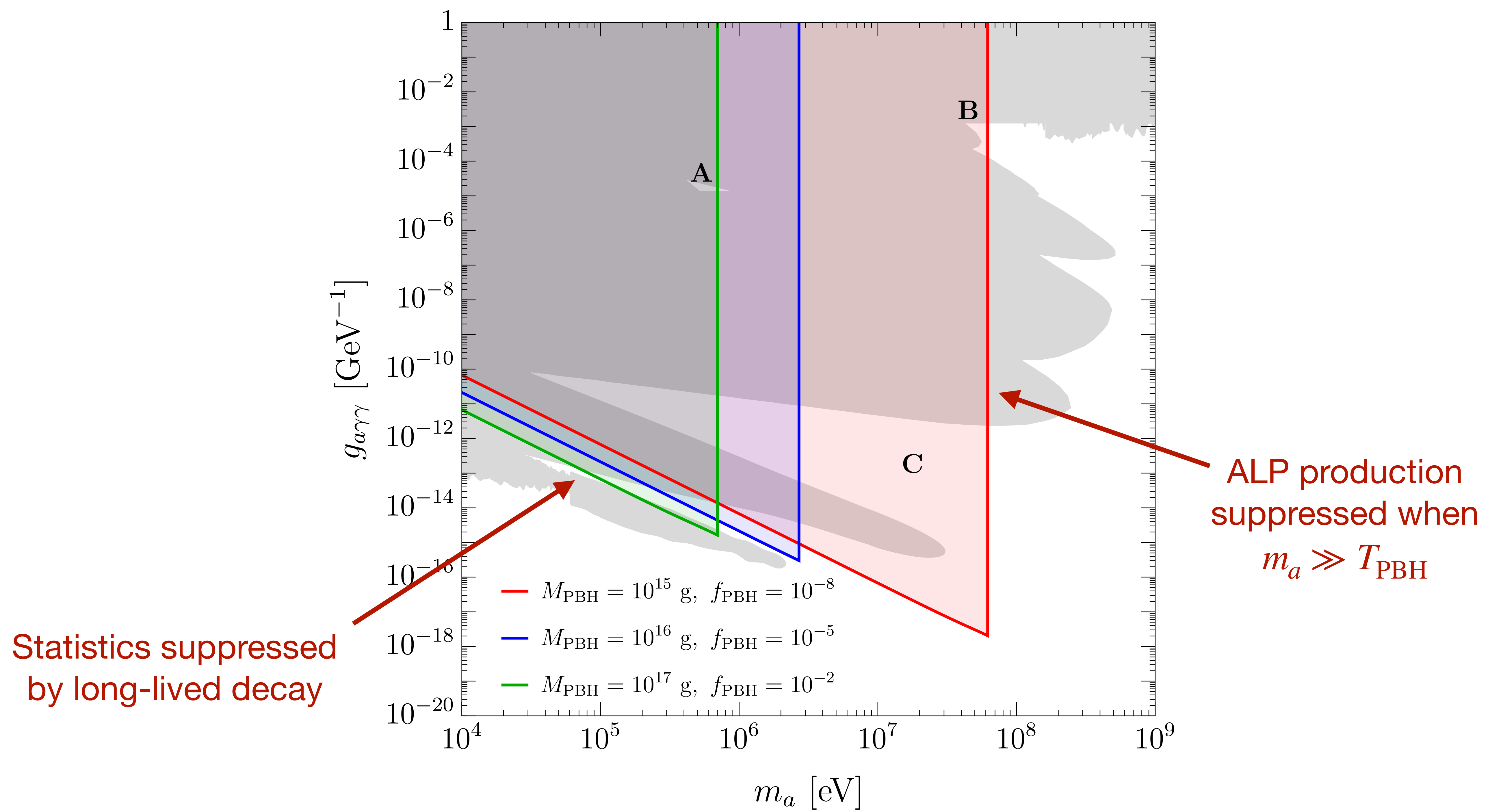


If f_{PBH} is larger than the detection limit, enough statistics to **distinguish** the ALP.

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.

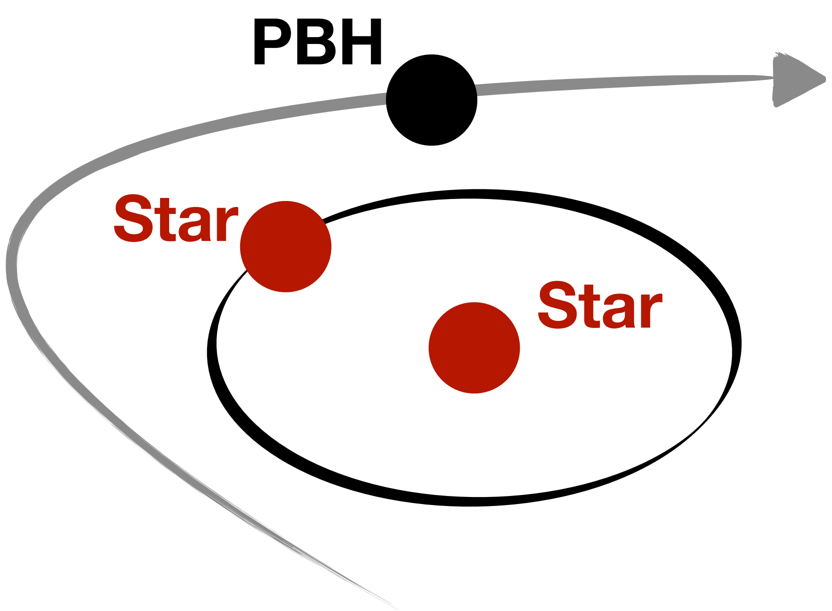


Dynamical constraint on heavy DM

- **Dynamical method** to probe PBHs is important complementary if Hawking radiation signal is not accessible, for example when PBHs are heavier or PBHs are extremal.

- Dynamical method that **depends only on gravitational effects** from the PBH mass can apply to other heavy DM model in the asteroid-mass range as well.

Three-body gravitational interaction between stellar binary and PBH encounter.

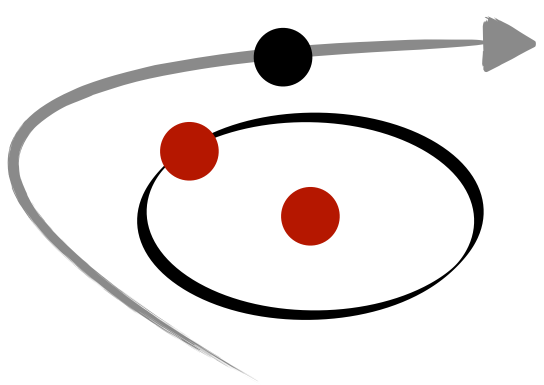


Badal Bhalla, Benjamin V. Lehmann, Kuver Sinha, TX

Heggie's law

- Binary of stars $m_{1,2}$ is described by the **binding energy** E_b and the **semi-major axis** a.

$$E_b = -\frac{G_N\, m_1\, m_2}{2\, a}$$



- Energy is transferred between the binary and the perturber during the three-body encounter process.

- **Heggie's law** in stellar dynamics:

Binary Evolution in Stellar Dynamics, D. Heggie

Hard binaries tend to become harder and **soft binaries tend to become softer**.

- Whether a binary is hard or soft depends on the kinetic energy of the perturber,

Hard binary: $\frac{G_N\, m_1\, m_2}{2\, a} > \frac{1}{2} m_p\, \sigma_p^2$

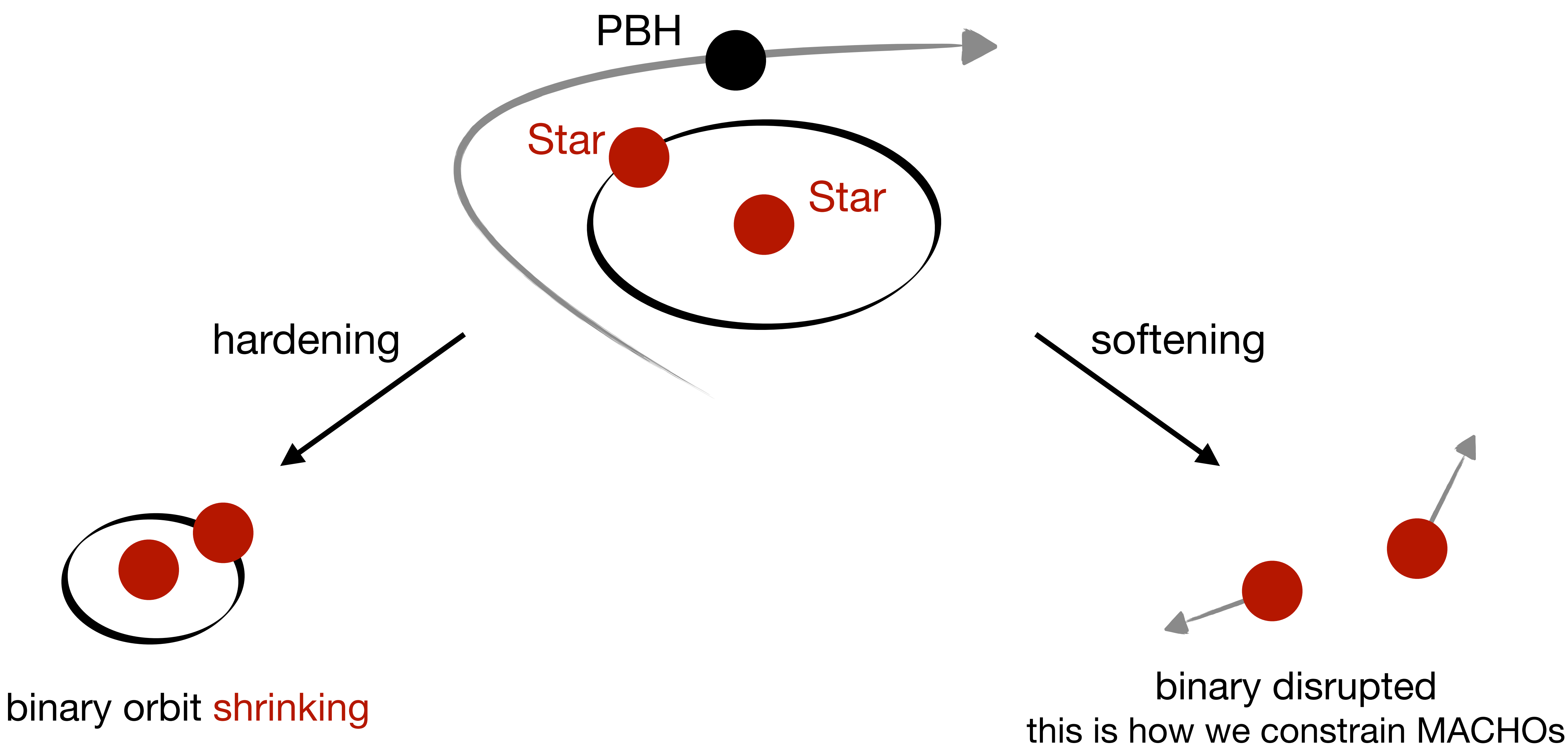
binary **lose energy** to perturber
E_b more negative
axis shrinks $a_f < a_i$

Soft binary: $\frac{G_N\, m_1\, m_2}{2\, a} < \frac{1}{2} m_p\, \sigma_p^2$

binary **gain energy** from perturber
E_b less negative
axis expands $a_f > a_i$

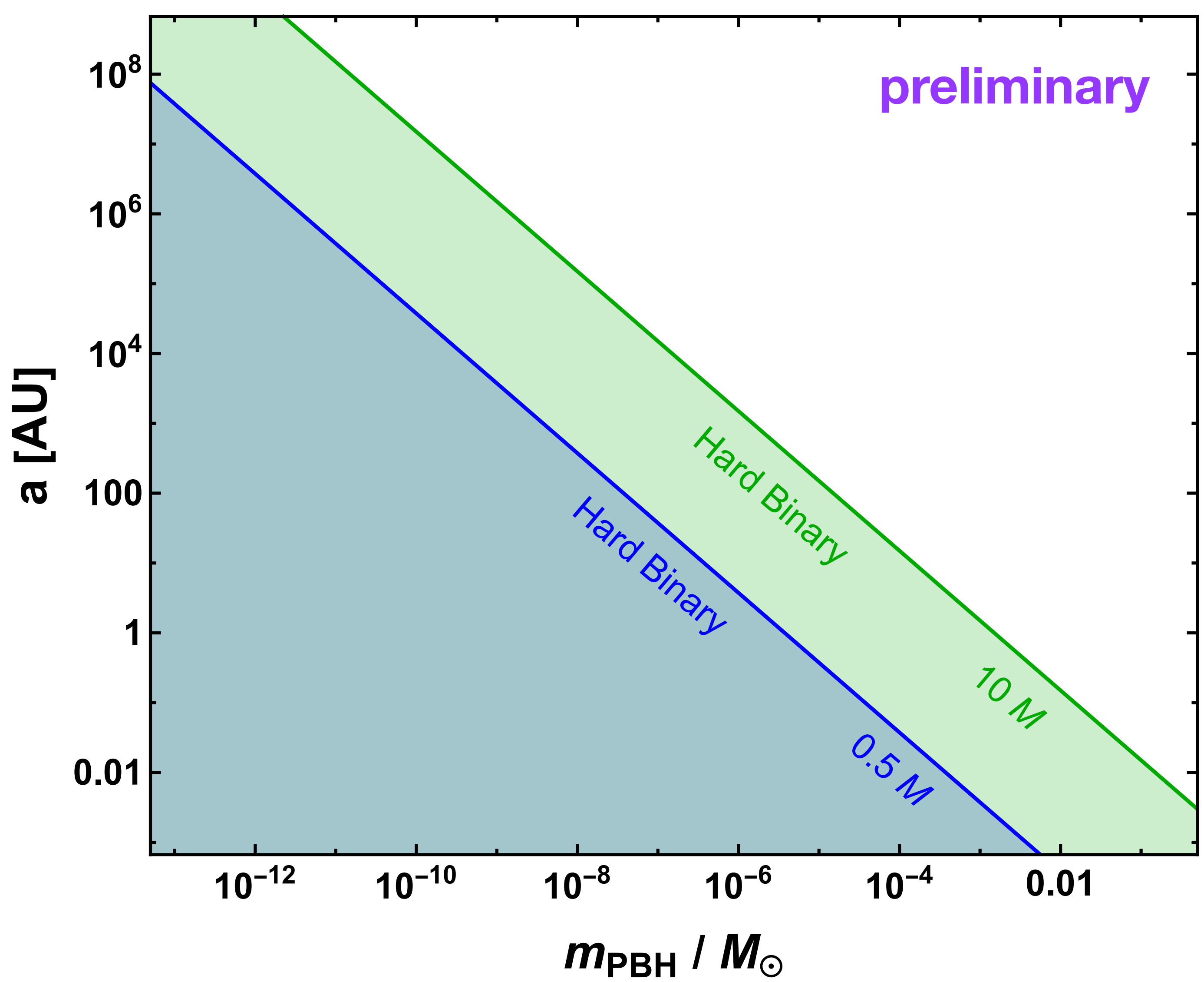
- If the perturber is PBH, the velocity is fixed by the DM velocity $\sigma_p \to \sigma_\chi \sim 10^{-3}$.
- The binary binding energy vs. PBH kinetic energy relation is determined by $M_{\rm PBH}$.

A stellar binary behaves as **hard binary for light PBHs** and as **soft binary for heavy PBHs**



Wide binary hardening

Asteroid-mass PBHs can lead to hardening of **wide binaries** $\frac{G_N m_1 m_2}{2a} > \frac{1}{2} m_{\rm PBH} \sigma_\chi^2$.



Wide binary hardening

$$\langle \Delta E \rangle = \xi \frac{m_{\rm PBH}}{2m_\star} |E_b|$$

$$\frac{dN}{dt} = \frac{4\pi G_N m_\star n_{\rm PBH}\, a}{\sigma_\chi}$$

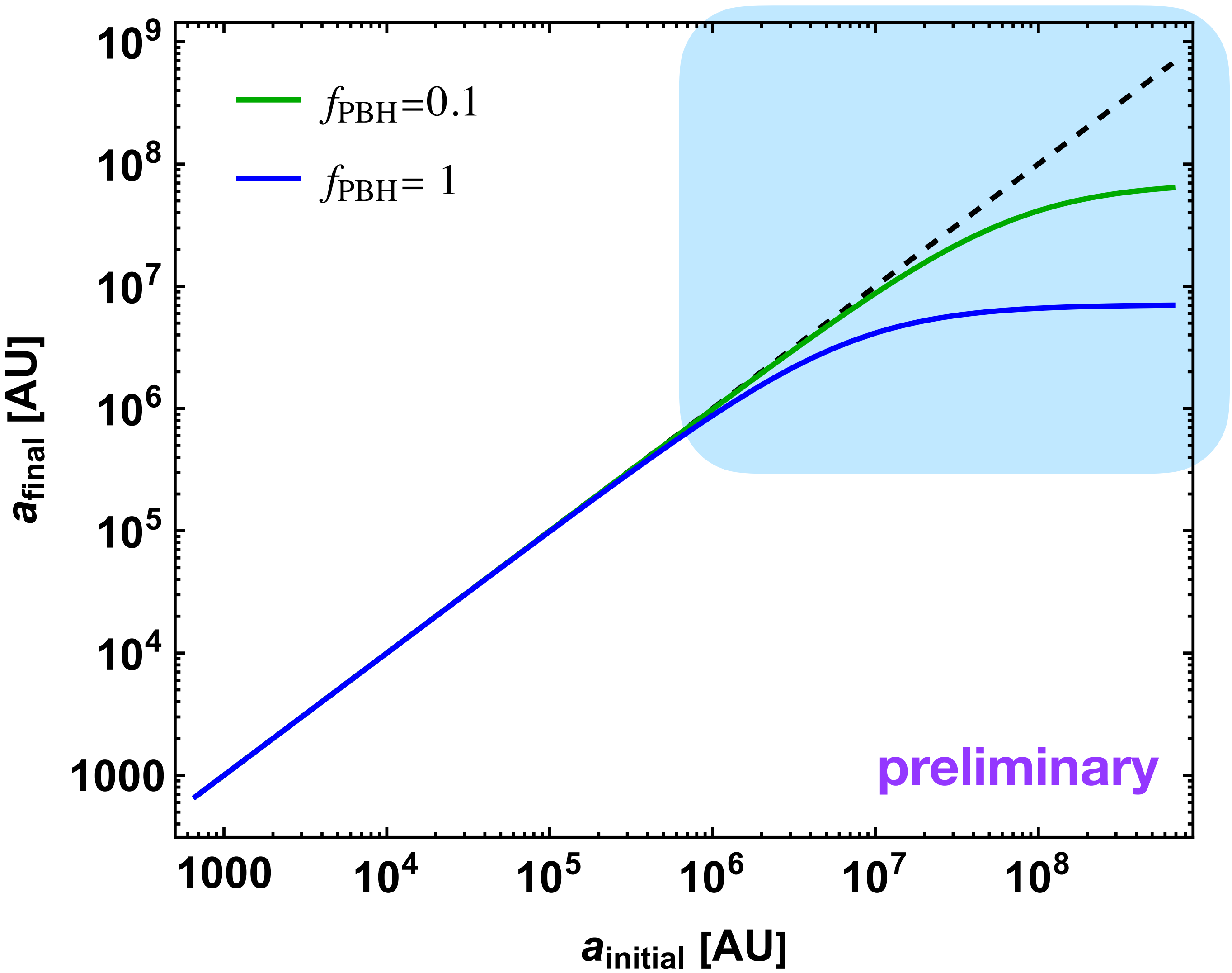
hardening effect accumulates

$$\frac{dE_b}{dt} = \langle \Delta E \rangle \frac{dN}{dt}$$

$$\frac{dE_b}{dt} = \pi \xi G_N^2 m_\star^2 \frac{\rho_{\rm PBH}}{\sigma_\chi}$$

$$\frac{da}{dt} = -2\pi G_N \xi \frac{\rho_{\rm PBH}}{\sigma_\chi} a^2$$

- Total hardening rate is proportional to **energy density**, not single PBH mass.
- Hardening effect is more efficient for wide binaries.



future binary data, e.g. **Gaia**

Summary

- Asteroid-mass PBH is an interesting example of heavy DM. MeV gamma-ray signals from the Hawking radiation process can be used to probe PBHs. Multi-messenger observation with GWs provides more information about the abundance and origin.
- Hawking radiation is via gravity. PBHs can produce new particles efficiently as long as the new particles are not much heavier than the Hawking temperature.
- We use ALP as an example to show that gamma-ray spectrum analysis can be used to probe both PBHs and the BSM degrees of freedom that could have been produced via Hawking radiation.
- We find three-body encounter between stellar binary and asteroid-mass DM can lead to a novel hardening effect. Future wide binary data will provide a new way to probe asteroid-mass DMs with their gravitational effects.

Thank you!