Hawking Radiation, Superradiance, and Dark Sector

in collaboration with

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arXiv: 2212.11980

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in preparation

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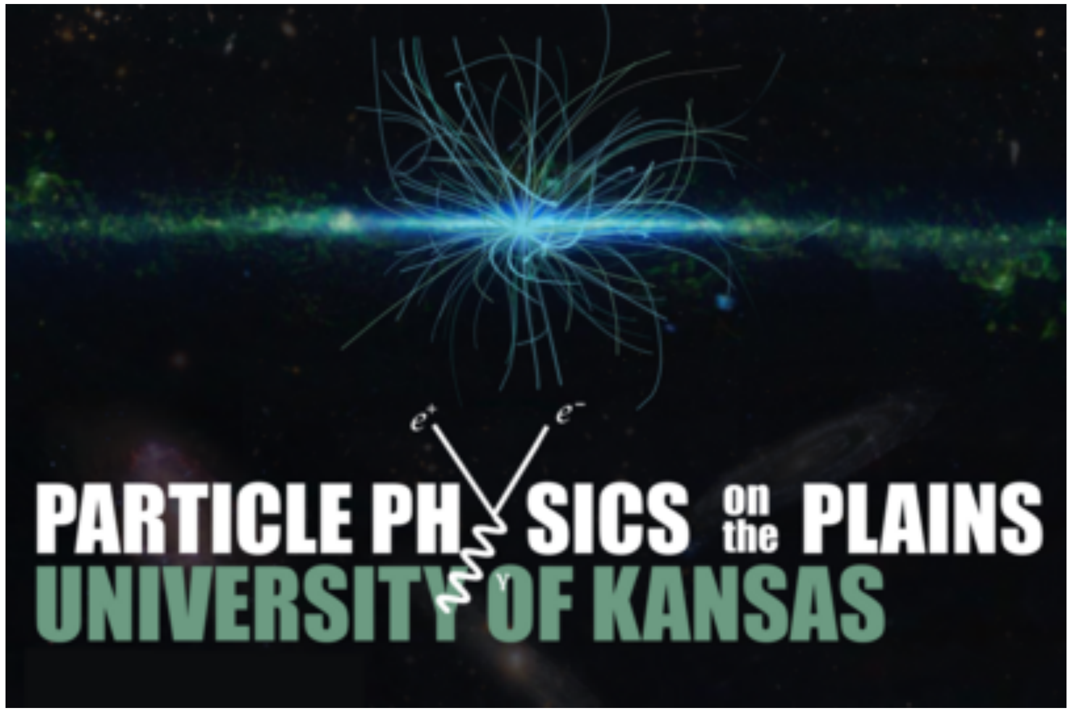
October 15, 2023



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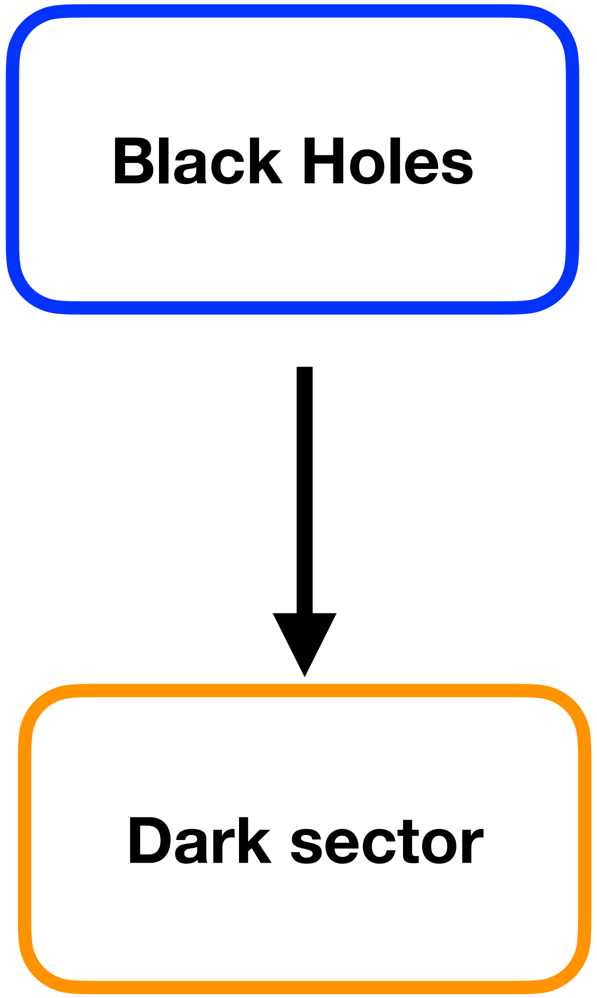
Motivations

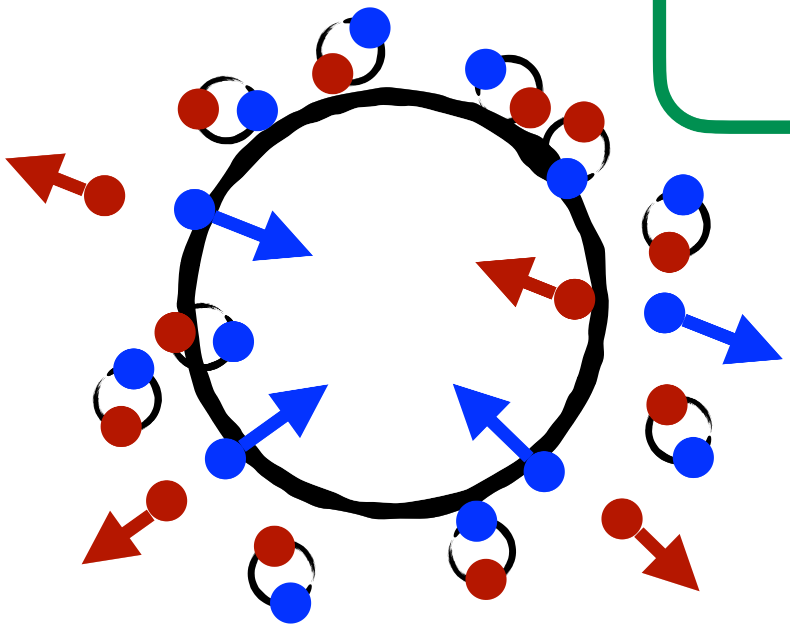


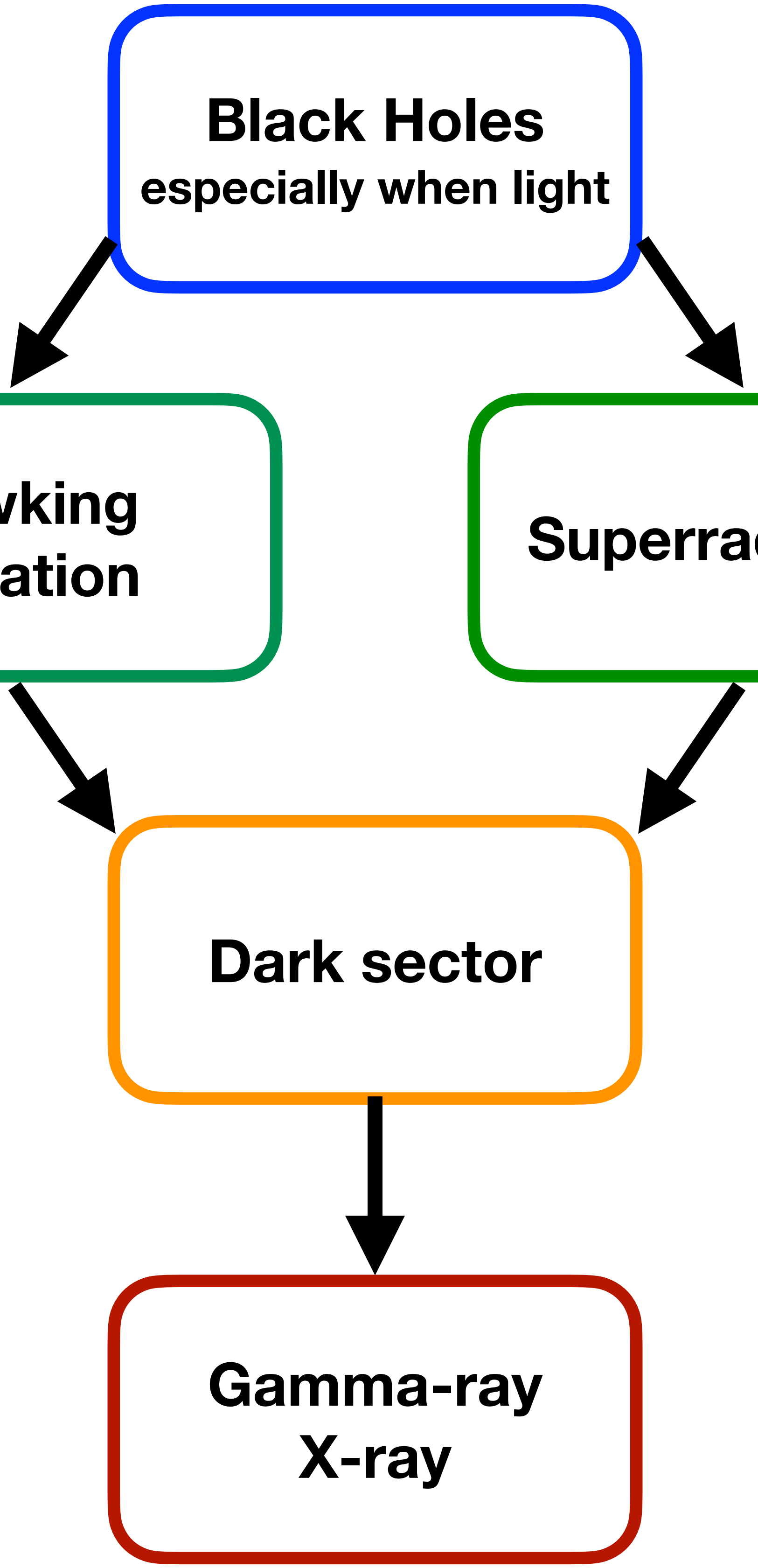
Black Holes

Dark sector

Can we use black holes to probe dark sector?

Outline





Black Holes
especially when light

Hawking radiation

Superradiance

Dark sector

Gamma-ray
X-ray

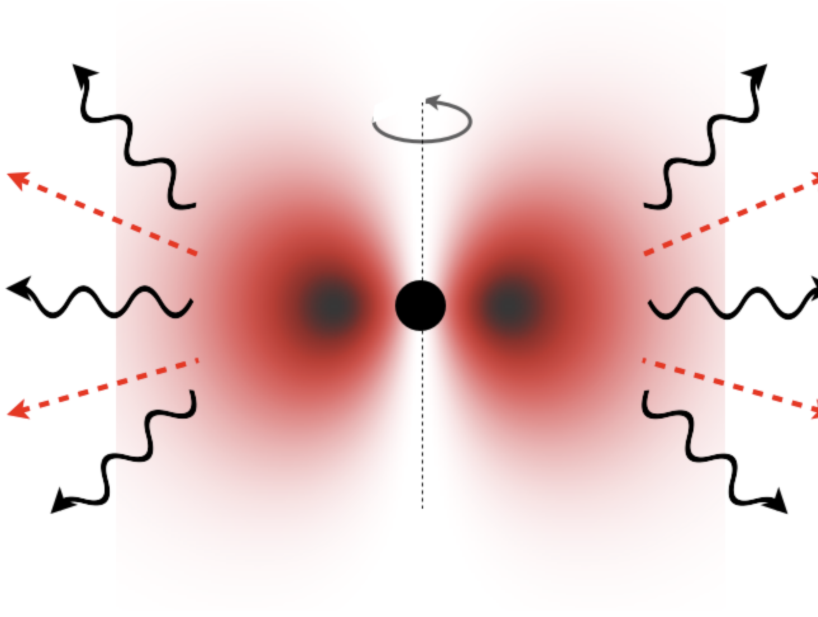
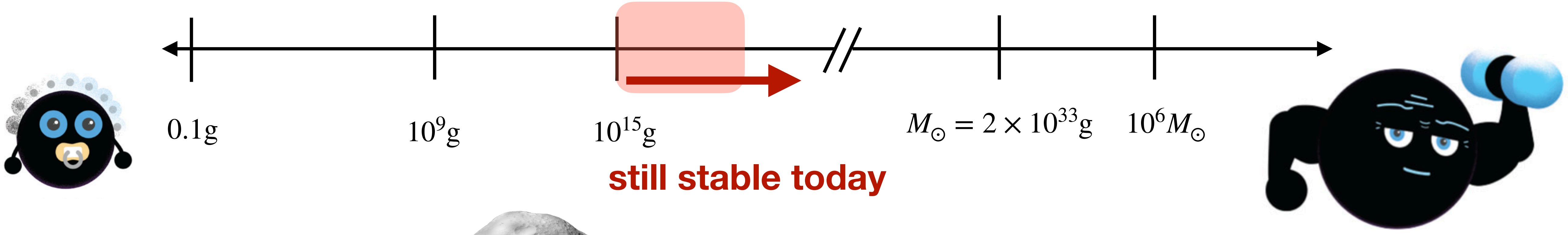
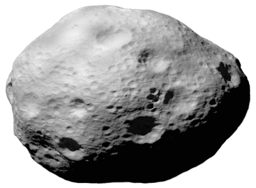


figure from 1004.3558

Black Holes



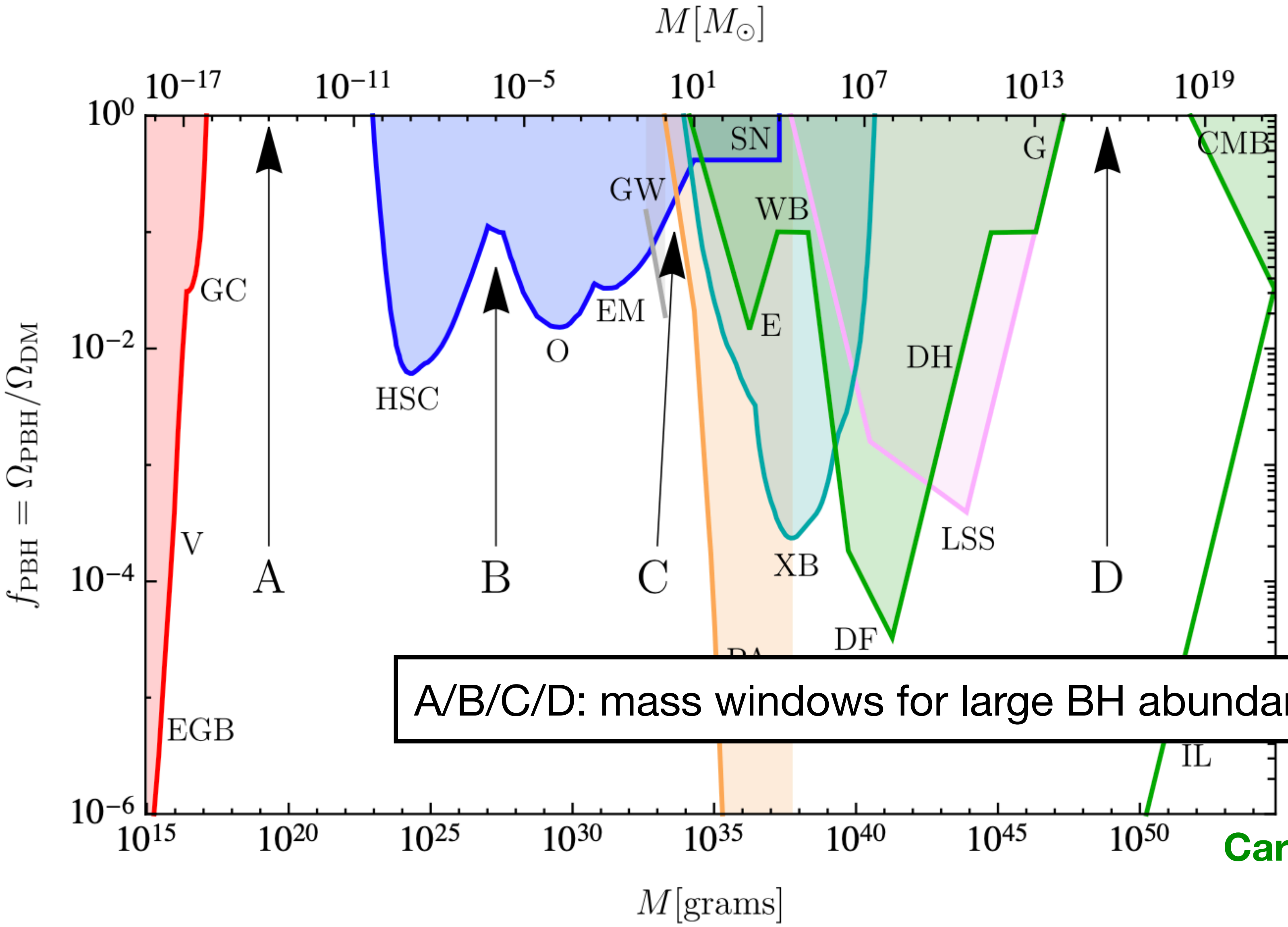
still stable today



Asteroid mass

fraction of DM made of PBHs

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



A/B/C/D: mass windows for large BH abundance

Carr, Kuhnel, 2006.02838

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

figure credit: NASA

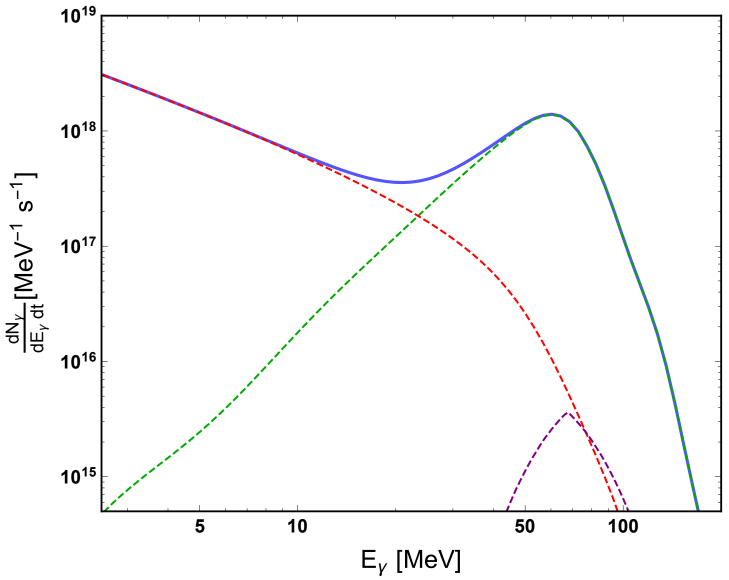
Detect BHs via Hawking Radiation

- Hawking temperature:

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

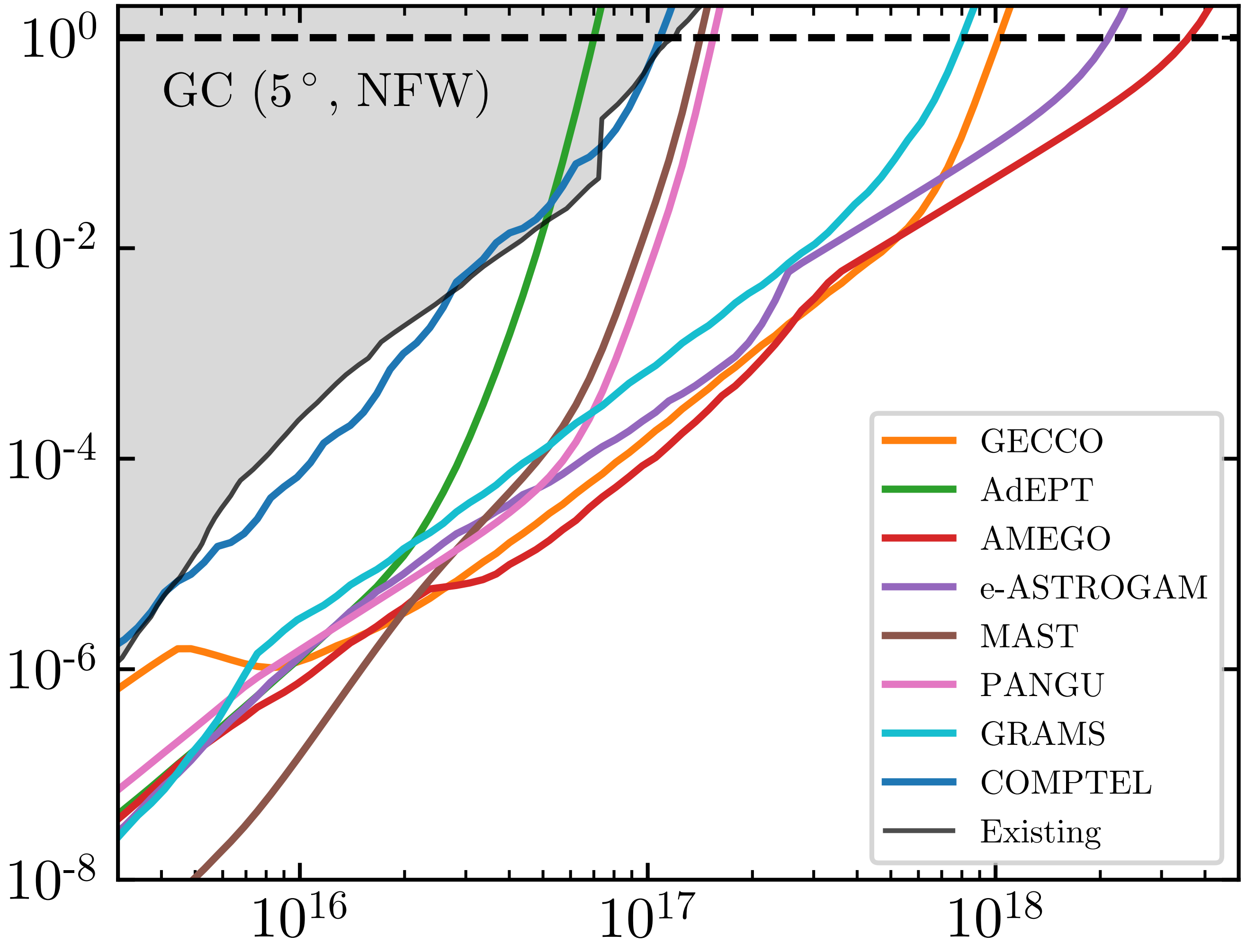
- Particle emission nearly **blackbody**

$$\frac{dN_i}{dE_i dt} = \frac{g_i}{2\pi} \frac{\Gamma_i(E_i, m, m_i)}{e^{E_i/T_{\mathrm{PBH}}} \pm 1}$$



- We test light BHs with particles produded at **MeV-GeV** energy for example, gamma-rays

Future constraint
or
Opportunity of observation?



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

Dark Sector from Hawking Radiation

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 BHs can produce MeV or lighter particles

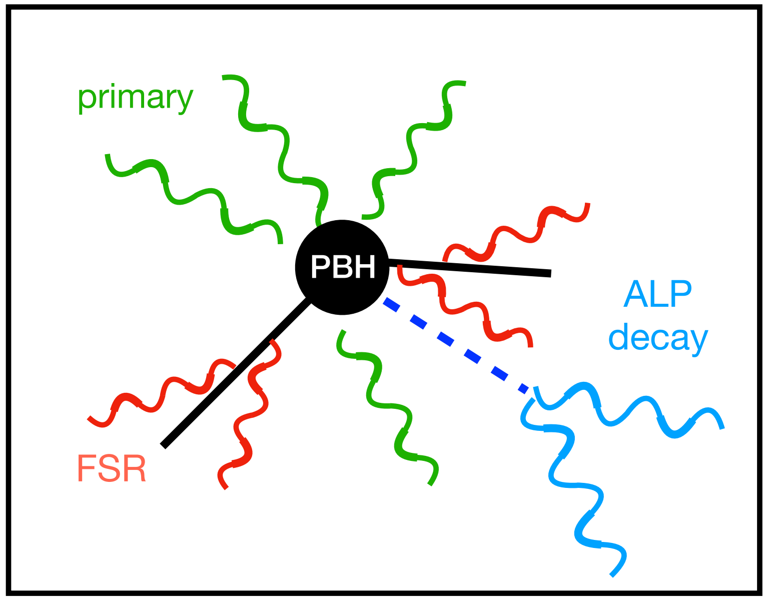
- production via gravity, only depends on **degree of freedom** g_i**, not coupling**

  Hawking radiation is good at producing weakly coupled particles in the spectrum

- how to detect the effect?
  - energy scale determined by Hawking temperature
  - large BSM particle production rate, modify the radiation spectrum
  - clear SM “background” spectrum from Hawking radiation calculation

ALP from BHs

- If exists an **Axion-Like-Particle** in the particle spectrum
- Gamma-ray spectrum is modified by ALPs: double peak



$$\frac{\partial N_{\gamma,\mathrm{tot}}}{\partial E_\gamma \partial t} = \frac{\partial N_{\gamma,\mathrm{primary}}}{\partial E_\gamma \partial t}$$

primary photon

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

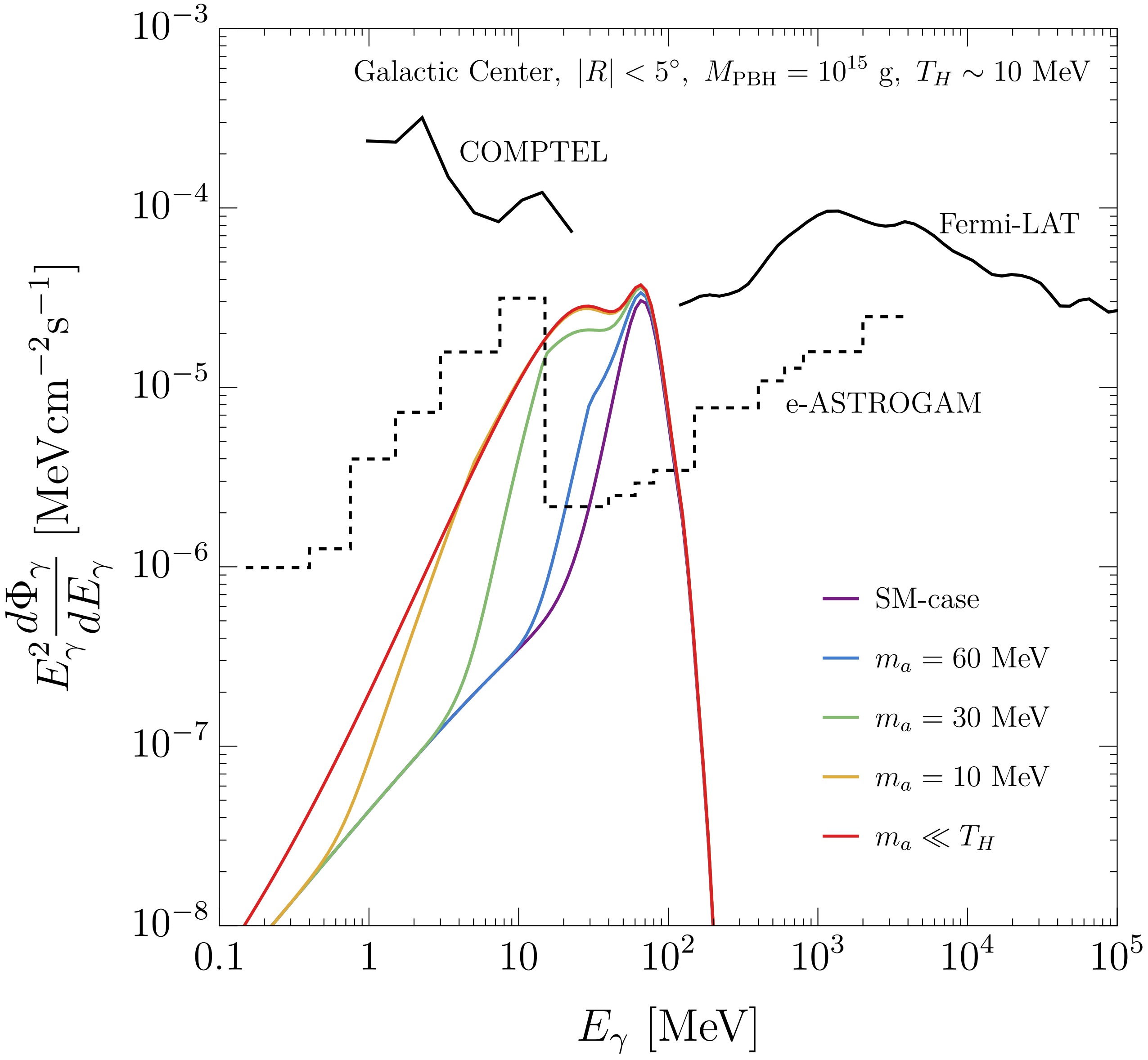
final-state radiation

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

pion decay

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

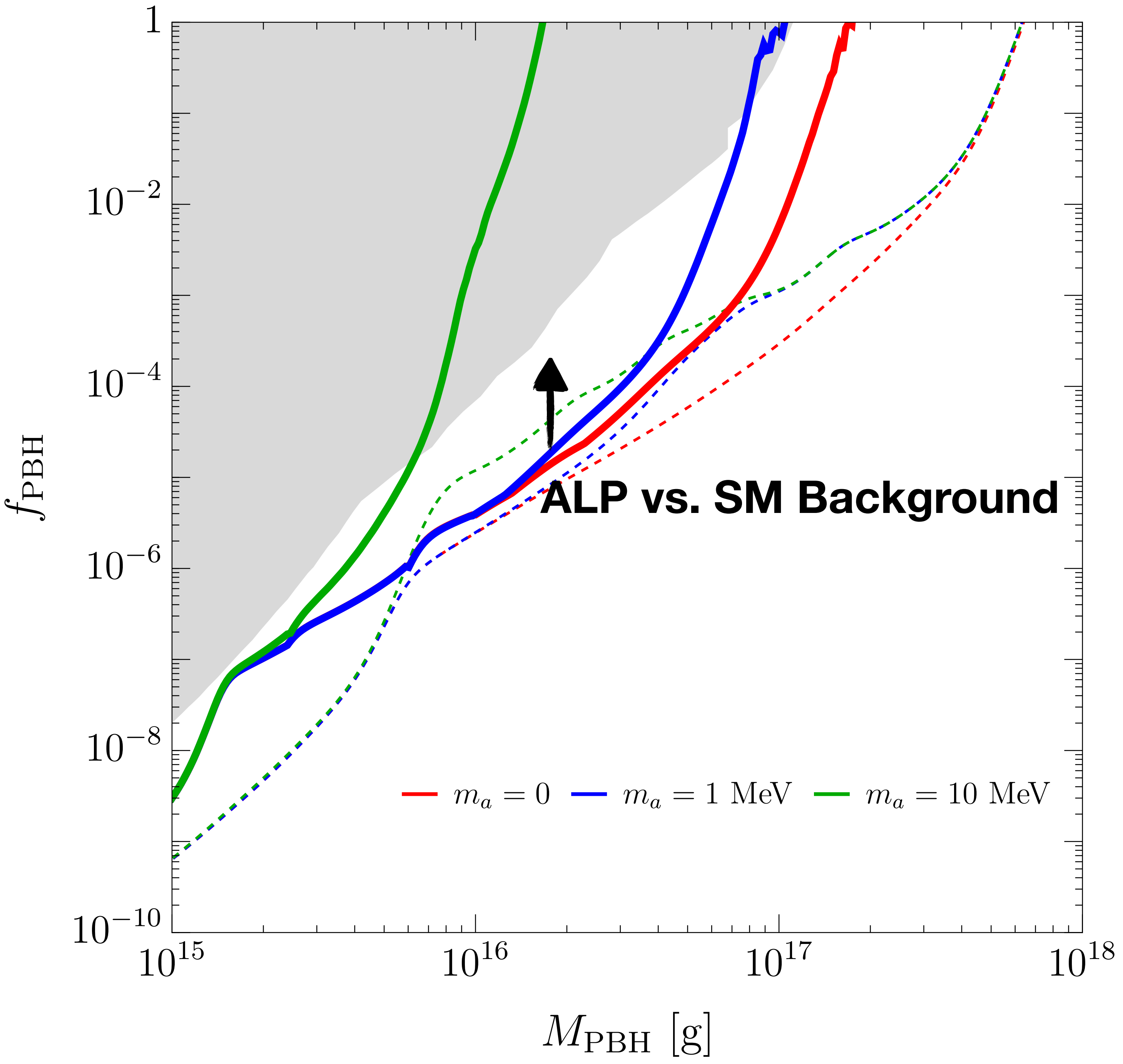
add ALP decay



Identification of ALPs

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.



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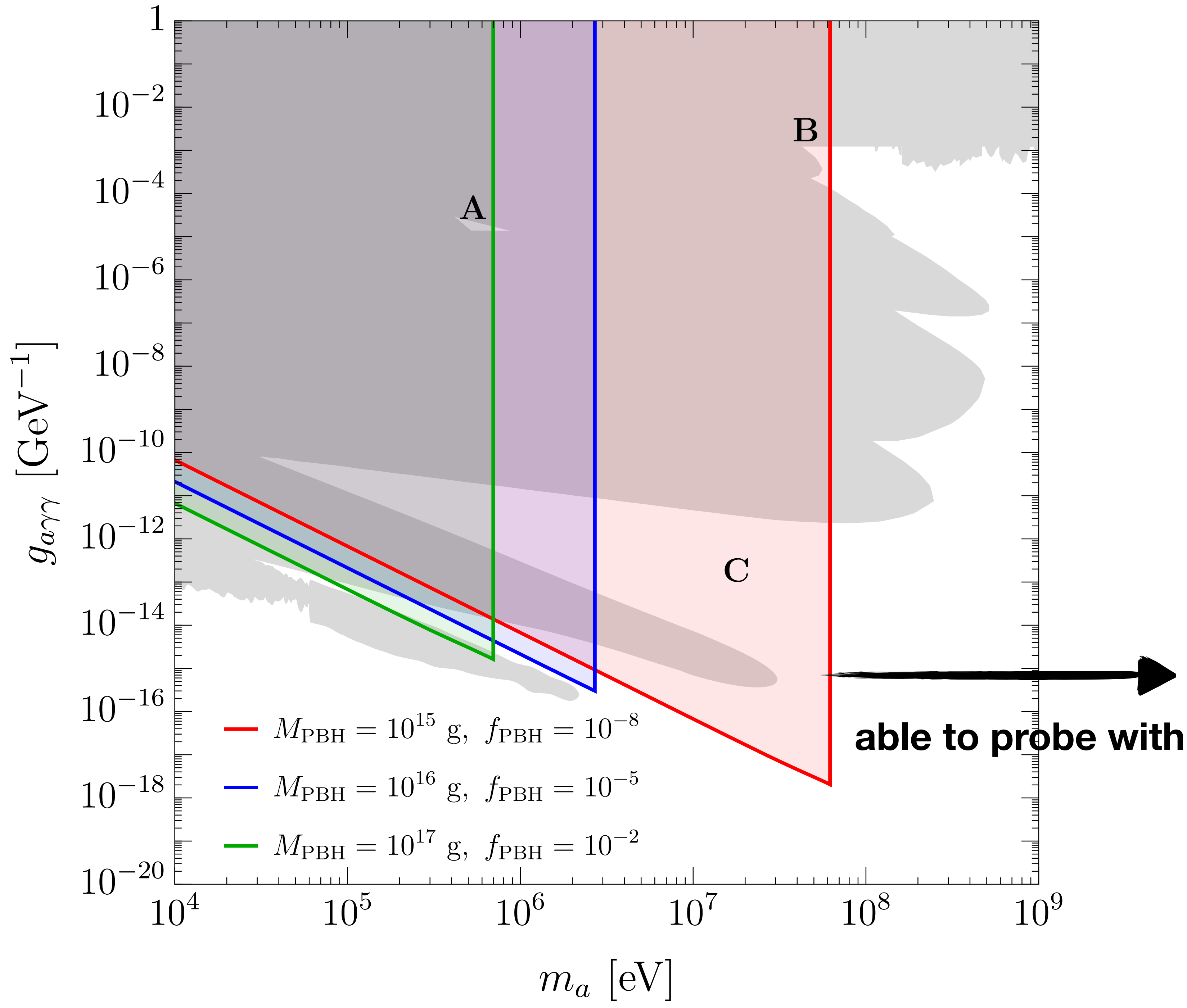
2212.11980

Identification of ALPs

ALP parameter space that can be probed with BHs.



able to probe with lighter BHs

ALP decay width

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

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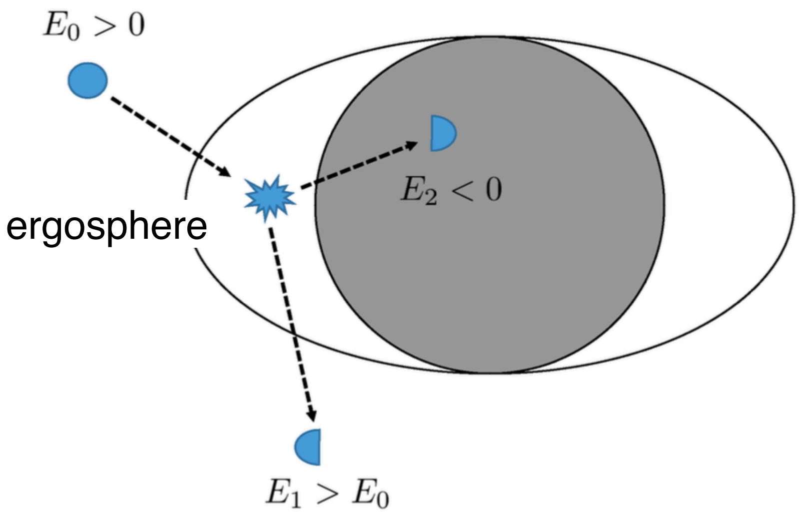
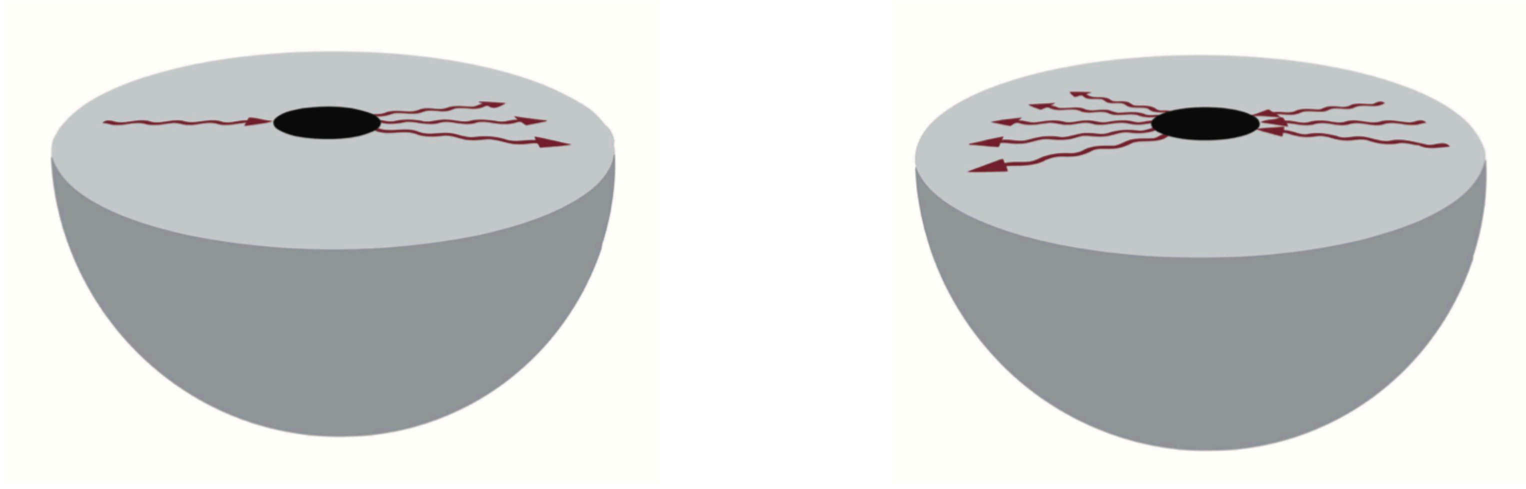
2212.11980

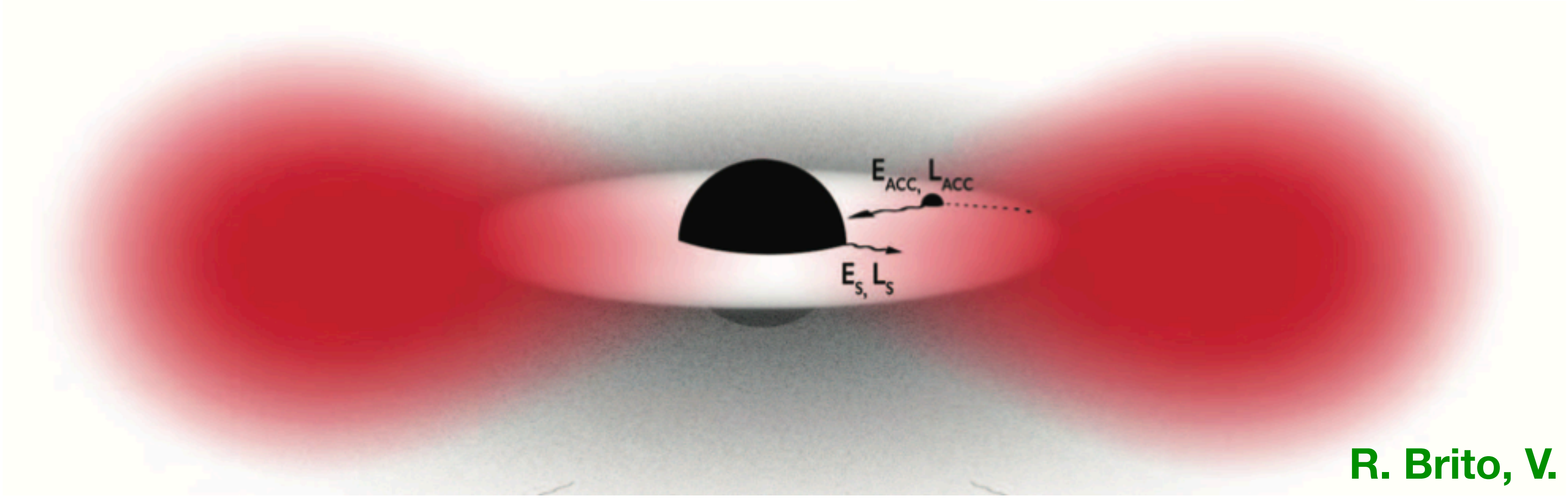
Superradiance

So far we only talked about BH mass, how about BH spin?





amplified → confined → amplified again



R. Brito, V. Cardoso, P. Pani
1501.06570

BH can produce **massive bosons** with BH angular momentum when $\omega_a < m\,\Omega$

Ω: BH angular velocity
m: azimuthal quantum number

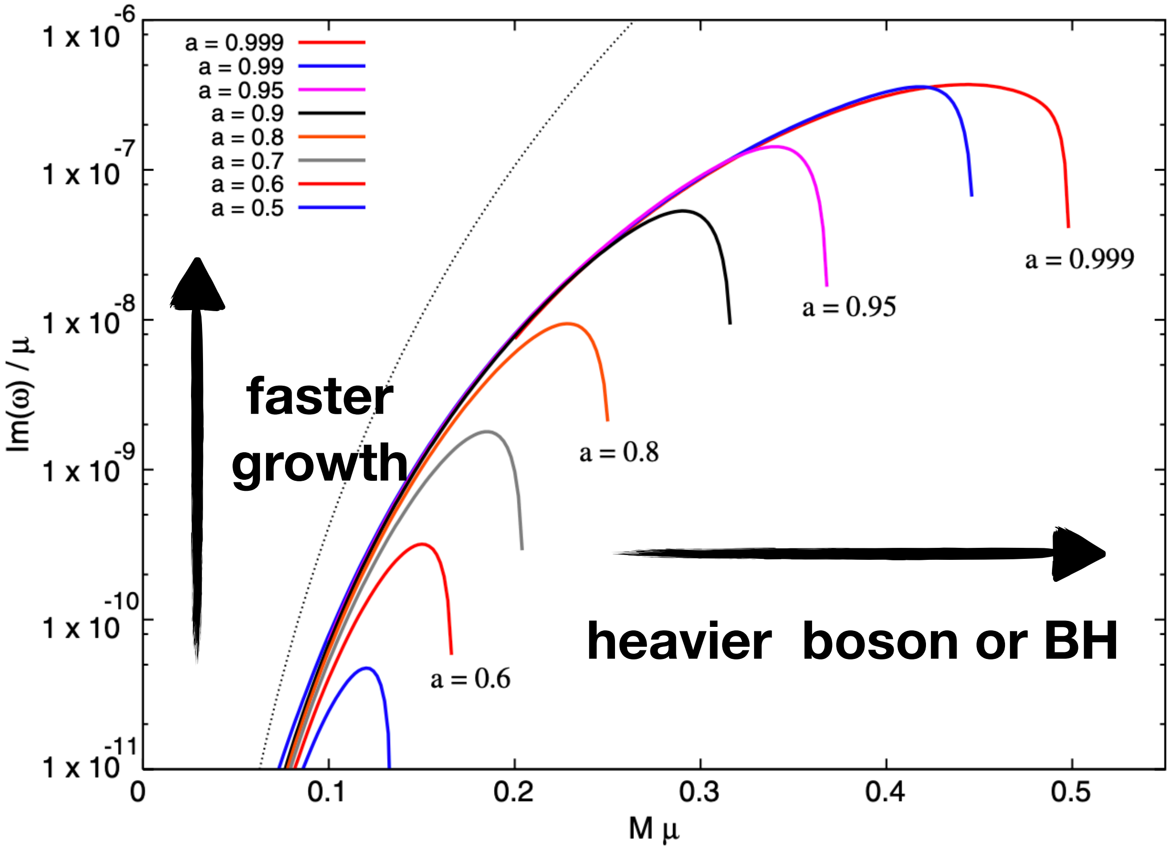
Superradiance Condition and Rate

- Gravitational coupling between BH and axion: $\alpha = G_N M m_a$
- Frequency of axion mode bounded by BH: $\omega = \omega_R + i\omega_I$

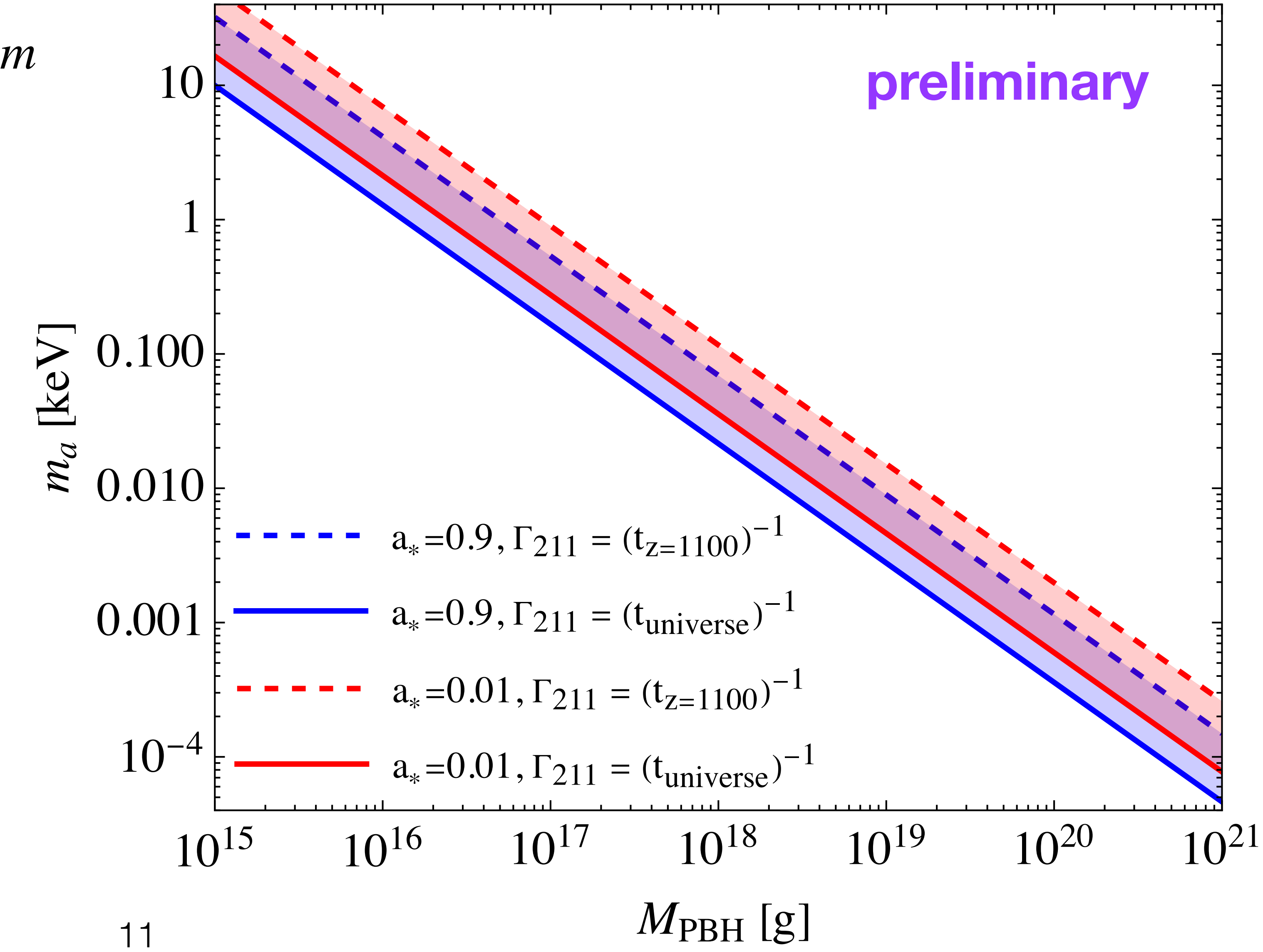
$$\omega_R = m_a\left(1 - \frac{\alpha^2}{2n^2}\right) \qquad N_a(t) \simeq N_0\, e^{2\Gamma_{nlm} t} \qquad \Gamma_{nlm} = 2\,\omega_I$$

$$\frac{\omega_I}{m_a} \simeq \alpha^{4l+4}\,\underline{(m\Omega - \omega_R)}\, 2\, r_+ \mathscr{C}_{nlm}$$

superradiance condition



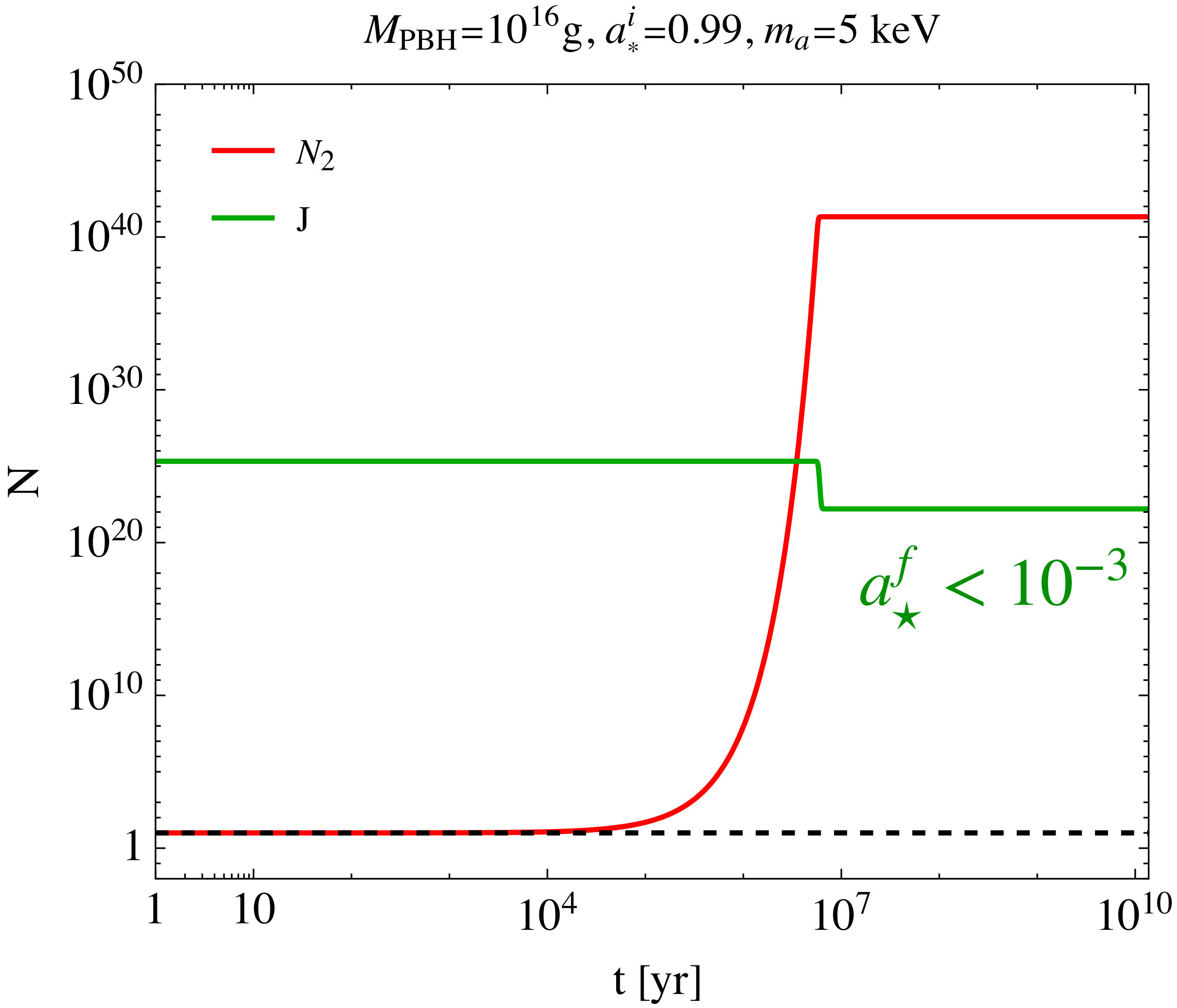
S. Dolan, 0705.2880 here μ is m_a

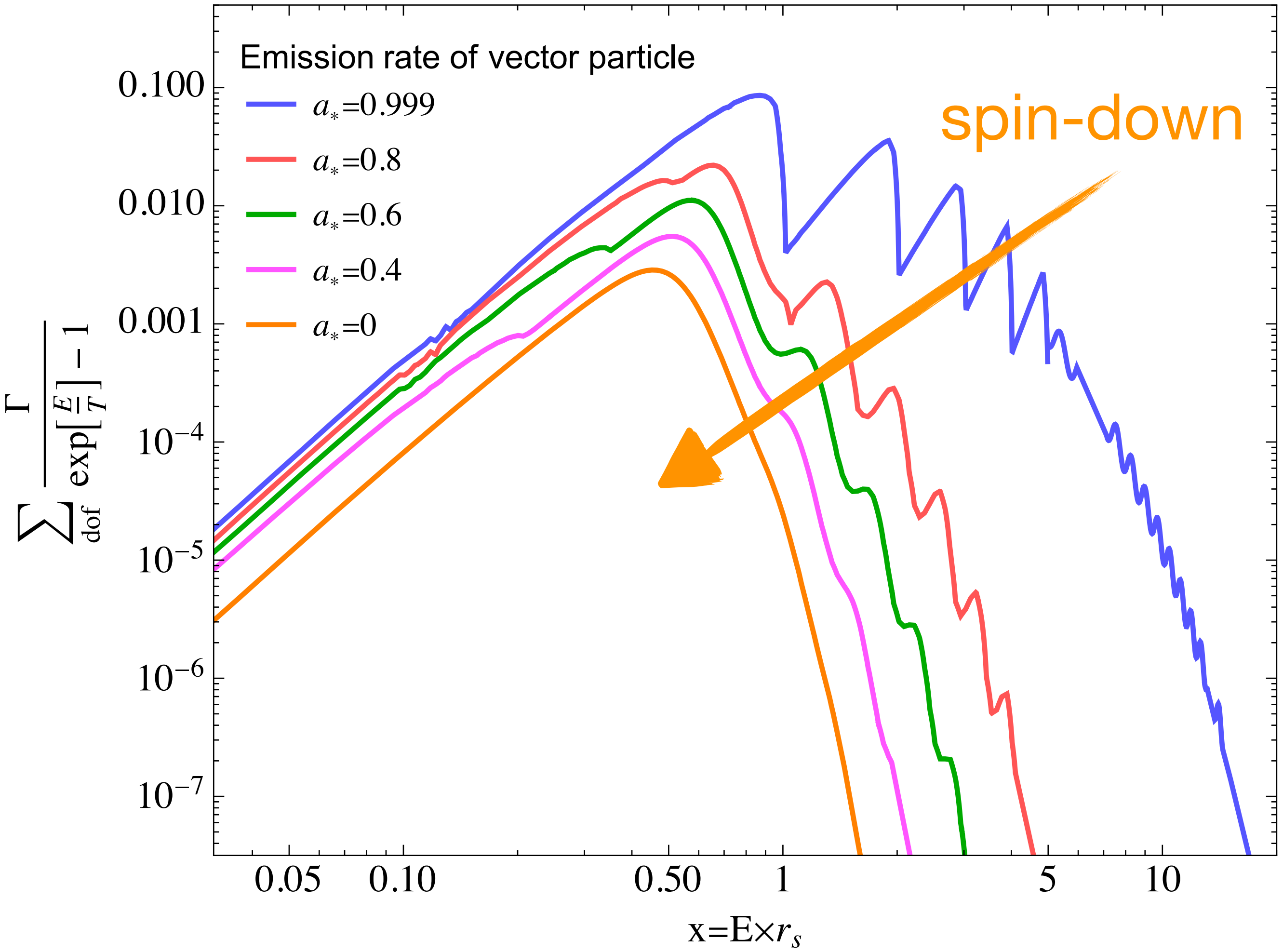


Spin-down of BH

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

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





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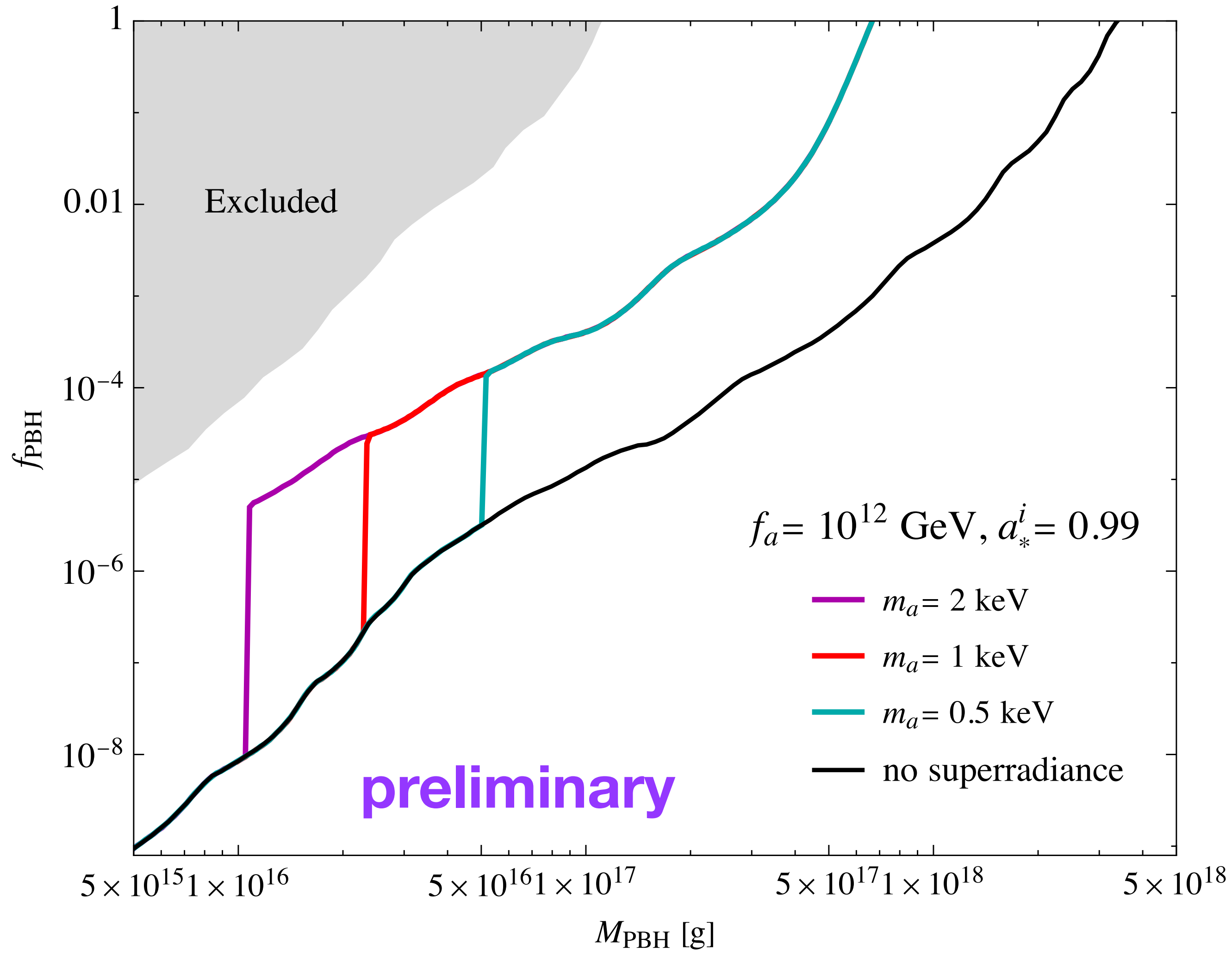
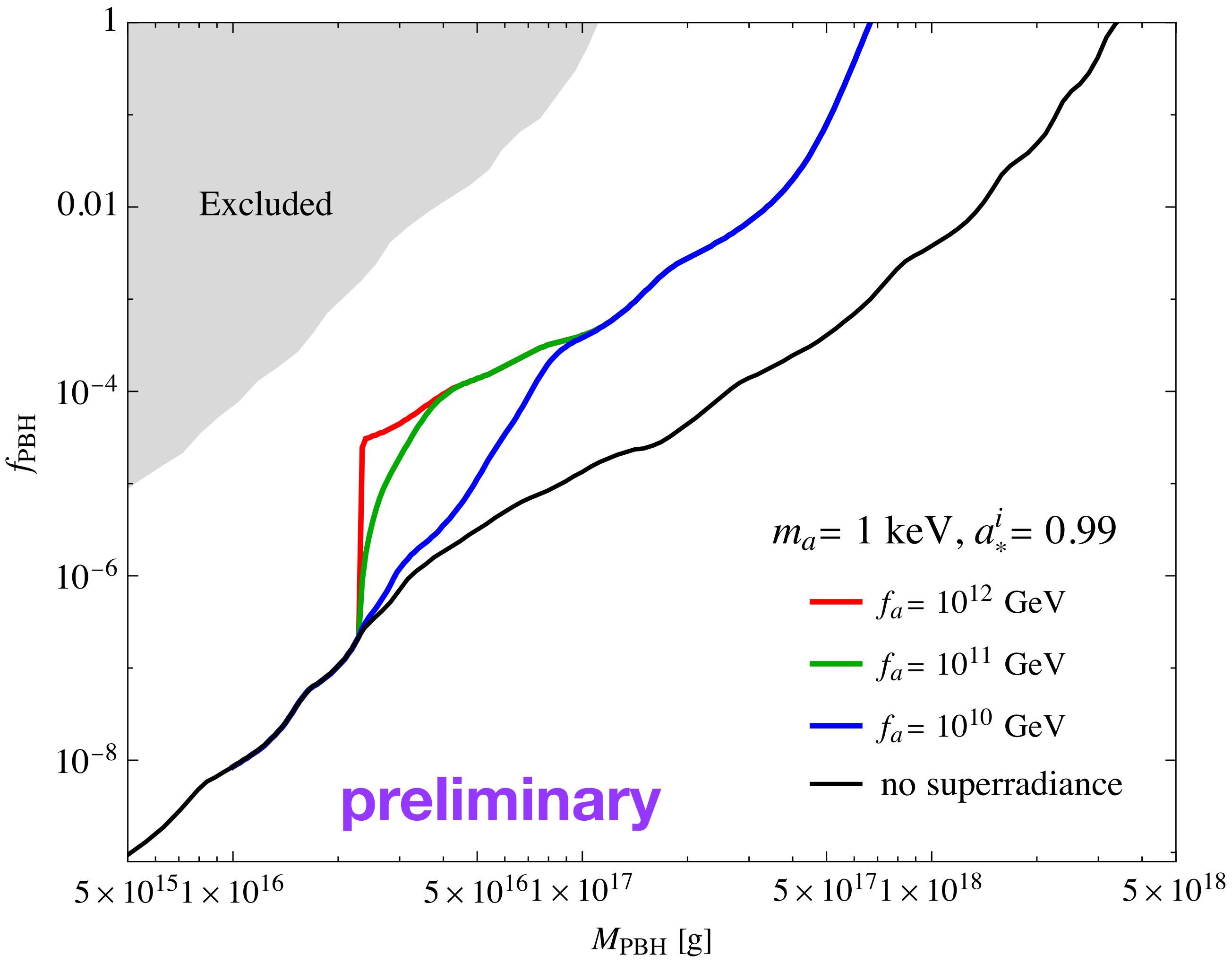
Spin-down of BH

Galactic Center searches for BHs are only sensitive to the **final spin** of the Kerr BH.

Constraints becomes weaker with superradiance.



different axion mass



different axion self-interaction

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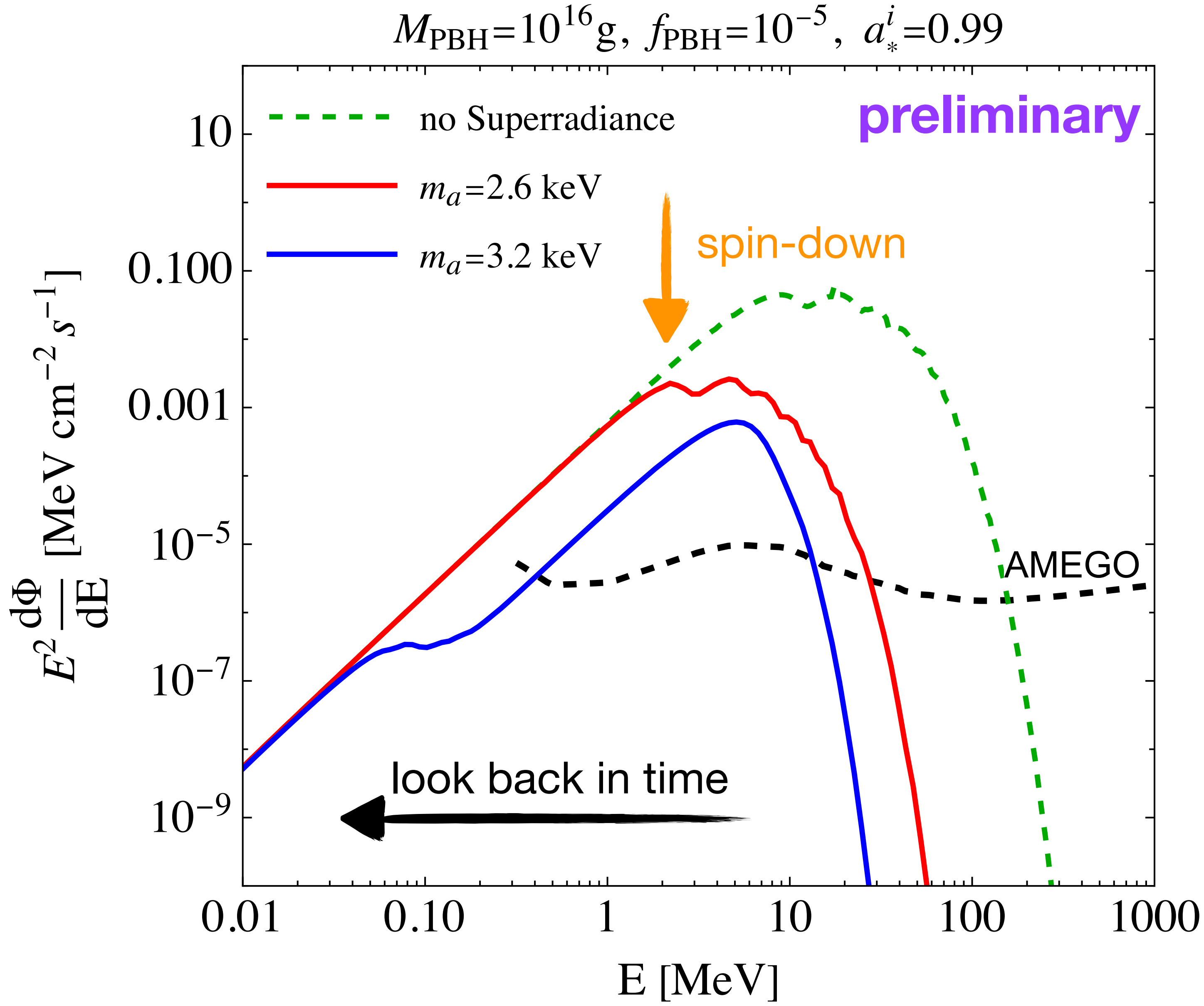
Extra-galactic Gamma-ray

Extra-galactic flux can be correlated to test BH spin evolution at higher redshift.

- Reduction in gamma-ray flux happens as BHs lose spin due to superradiance process

- Heavier axion spin down sooner, $\Gamma \propto \alpha^{4l+4}$, flux drops earlier at low energies



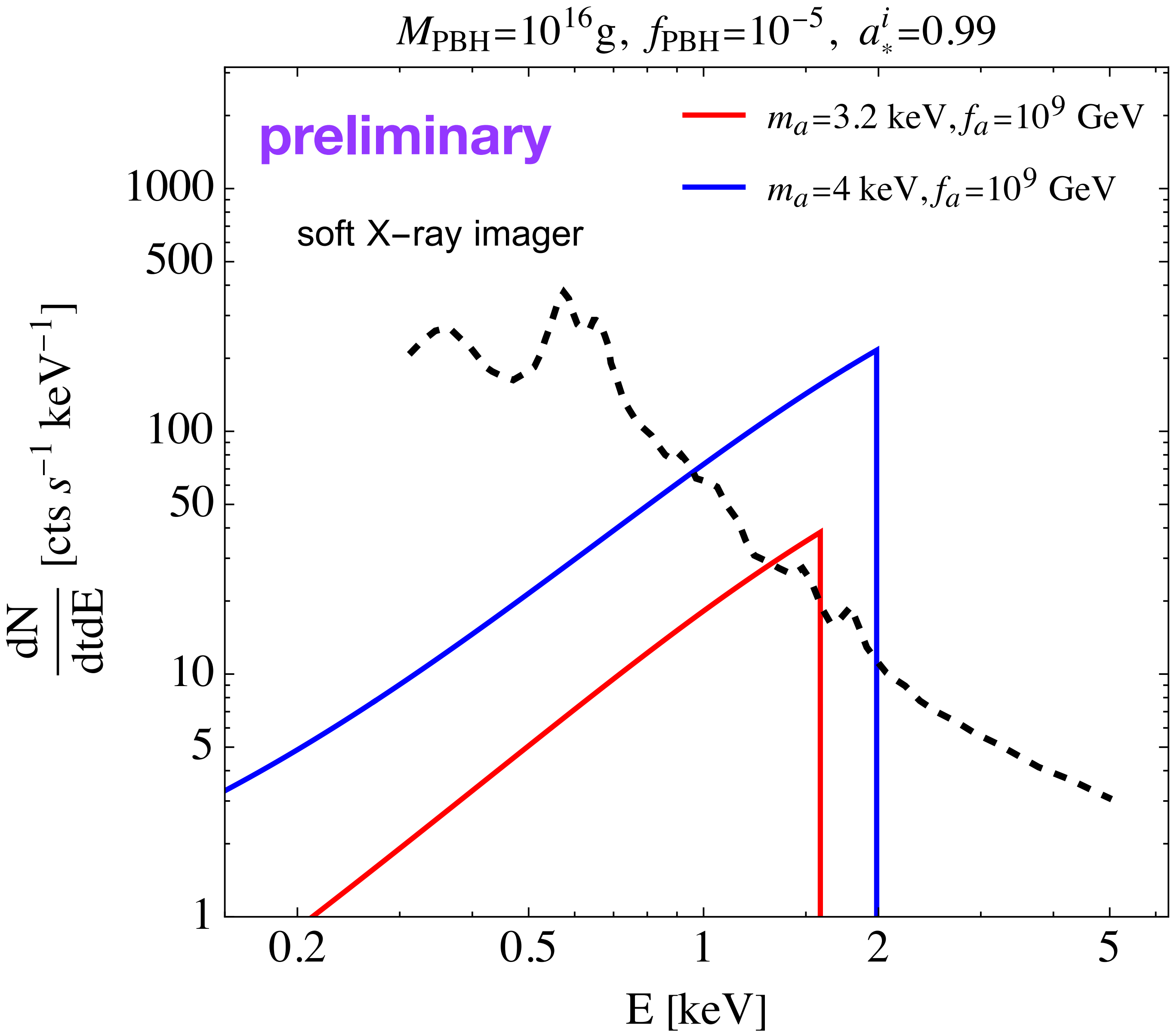
keV Line Search

Axions produced with BH superradiance can contribute to keV lines with decay.

$$g_{a\gamma\gamma} = \frac{\alpha_{\rm EM}}{2\pi f_a}$$

- Direct axion production signal within reach of future X-ray observations

- Signal strength depends on f_a for both axion decay width and superradiance dynamics



Summary

- Black holes can be particle factories with gravitational production. Hawking radiation and superradiance combined create interesting searches for new physics.

- To correlate a particle physics energy scale to BH physics
  - Hawking radiation: Particle mass comparable to Hawking temperature or below.
  - Superradiance: Particle wavelength matches BH radius.
    Timescale of superradiance in the observation window.

- To test the idea with asteroid-mass BHs, we use ALP as an example
  - Modification of Hawking radiation spectrum from galactic center
  - Spin evolution of BHs from galactic and extra-galactic signals
  - Decay signal from the superradiance cloud
  - Outlook: a variety of possible correlative channels to probe dark sector.

Thank you!