Multi-messenger Probes of Primordial Black Holes and Axion-like Particles

Tao Xu
University of Oklahoma

with James B. Dent (SHSU) and Bhaskar Dutta (TAMU)
arXiv: 2404.02956

DPF-Pheno 2024

May 16, 2024

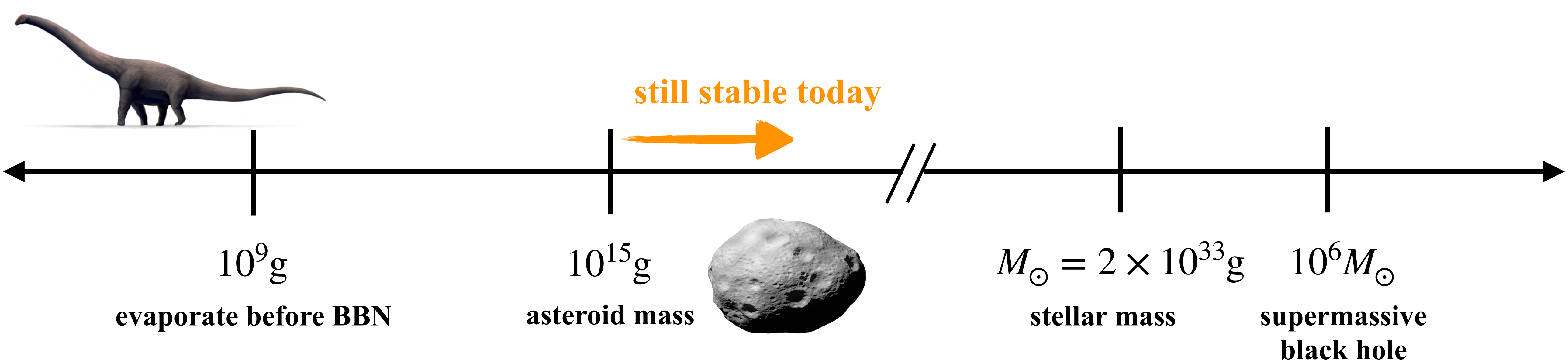
Primordial Black Hole

Black holes can have a wide mass range

Massive astrophysical BHs
from the collapse of stars,
heavier than solar mass

Hypothetical light BHs from
primordial epoch

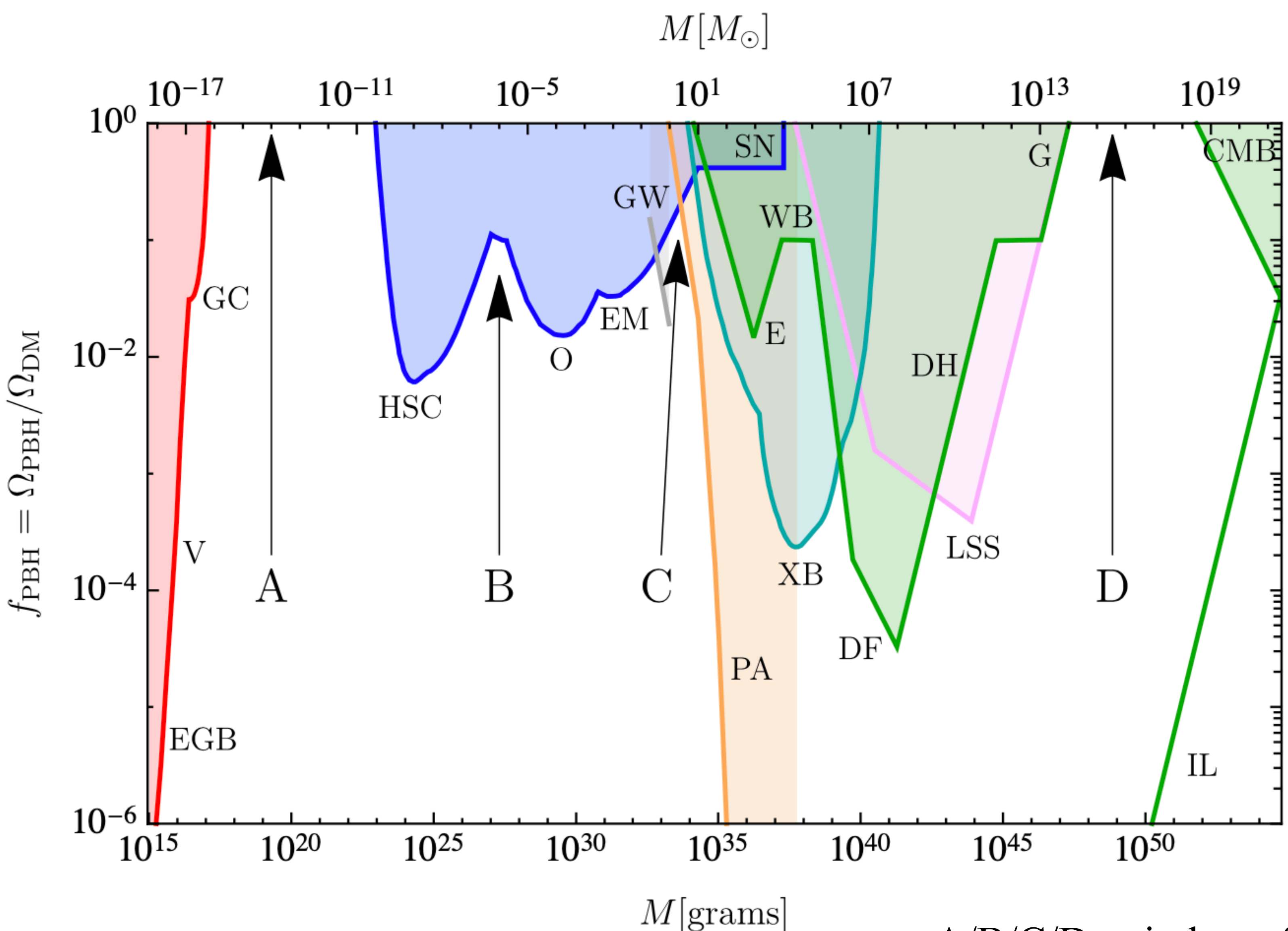
S.Hawking, Mon.Not.Roy.Astron.Soc. 152 (1971)
B.J.Carr and S.W.Hawking, Mon.Not.Roy.Soc. 168 (1974),
B.J.Carr, Astrophys.J. 201 (1975)



PBH mass range

fraction of DM made of PBHs

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



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

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

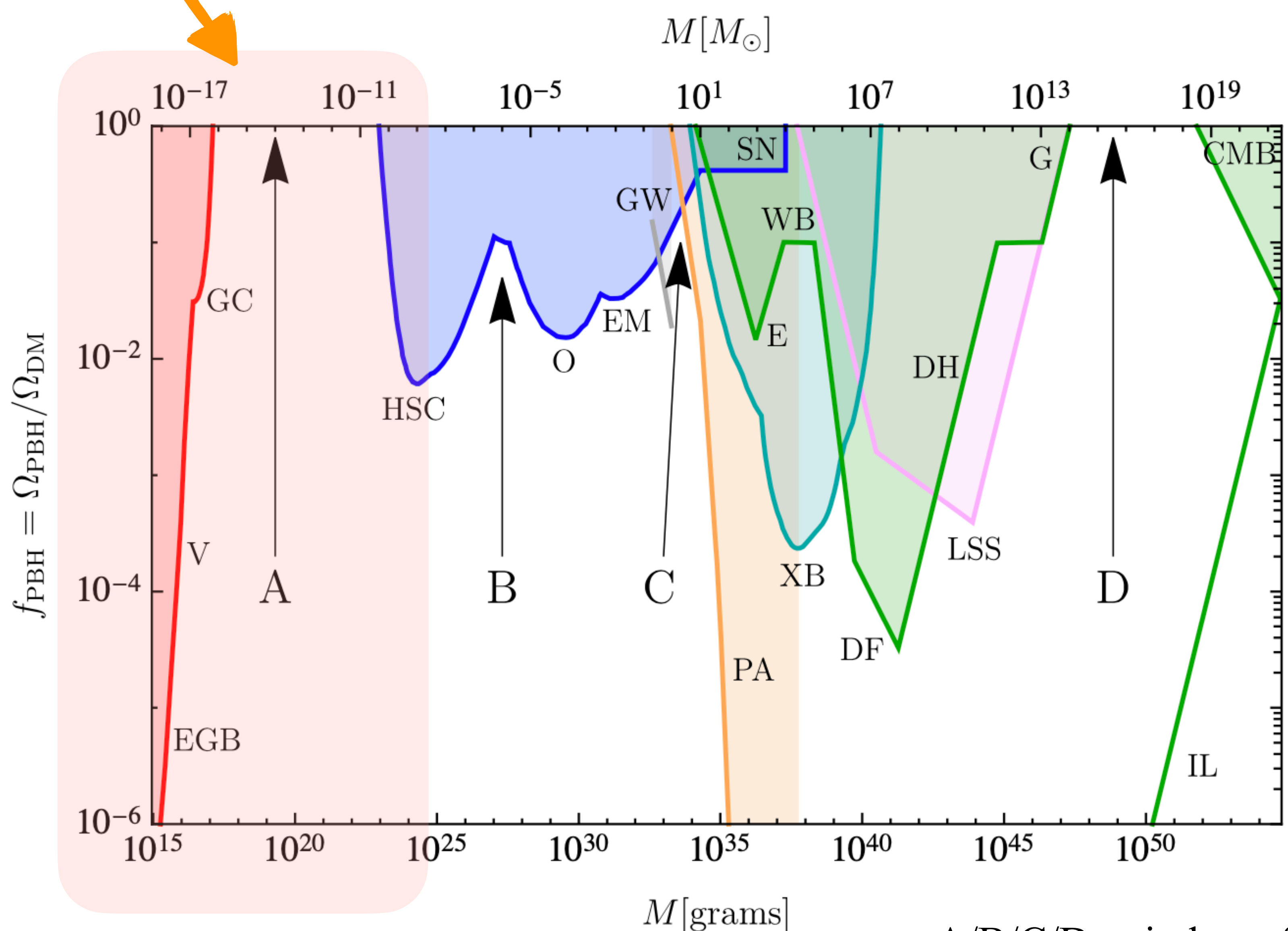
Carr, Kuhnel, 2006.02838

PBH mass range

this talk

fraction of DM made of PBHs

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



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

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

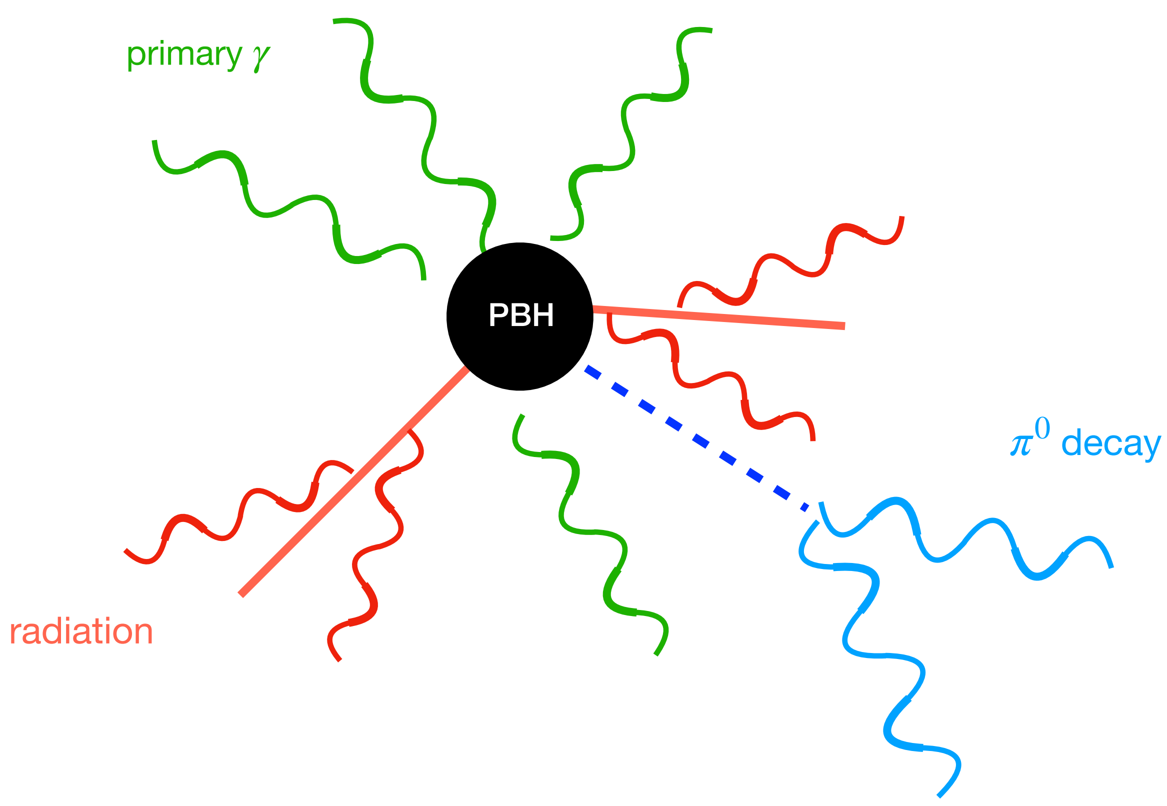
Carr, Kuhnel, 2006.02838

Hawking radiation

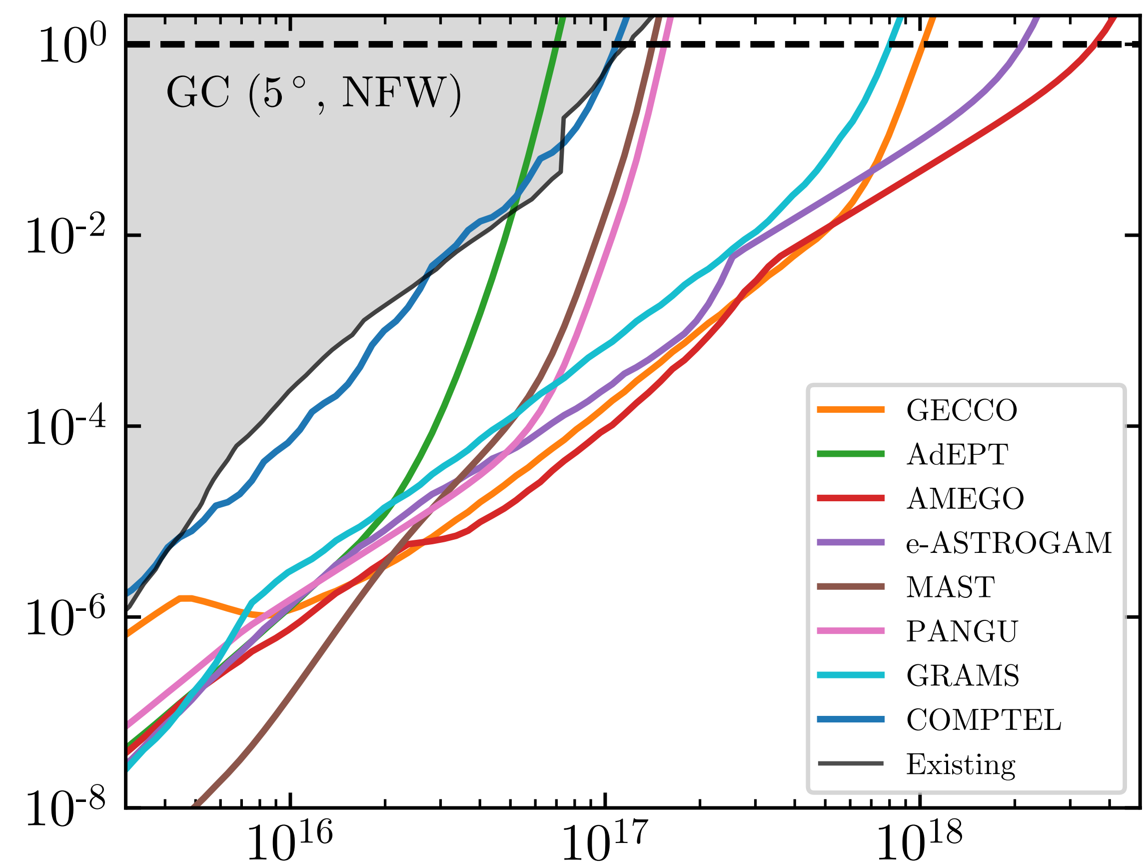
Asteroid-mass PBHs are evaporating at $\mathcal{O}$(MeV) energy

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

smaller BH mass, higher temperature, faster evaporation



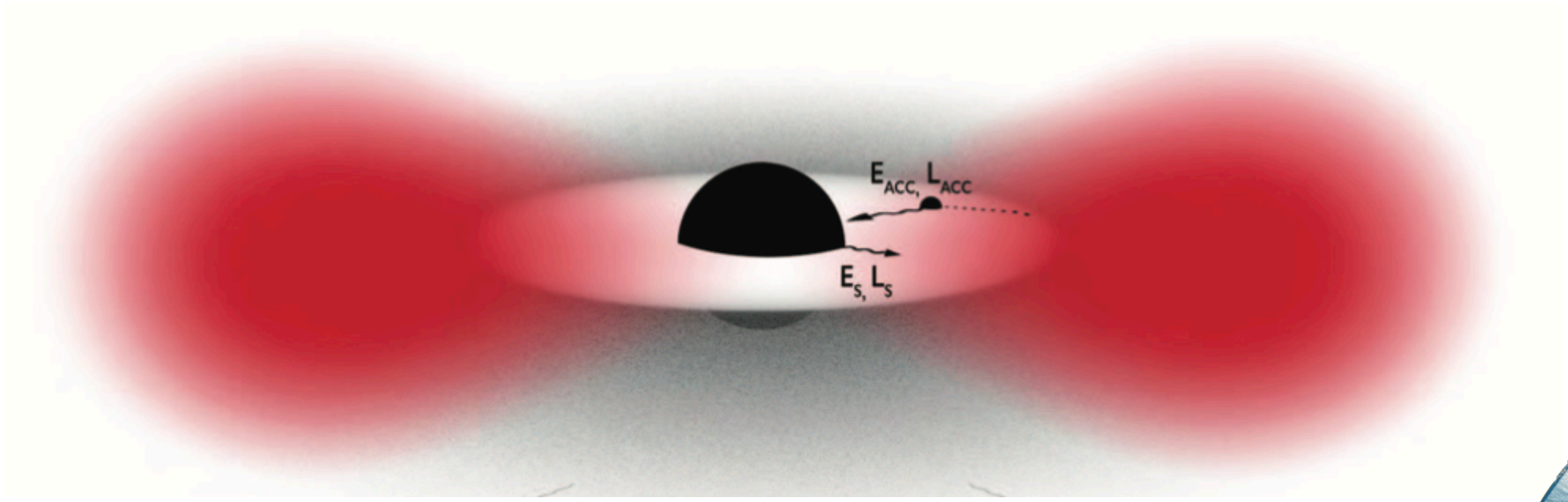
indirect detection constraints



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

Superradiance

So far we only talked about BH mass, BH spin is also involved for particle production



BH can produce **massive bosons** with BH angular momentum when

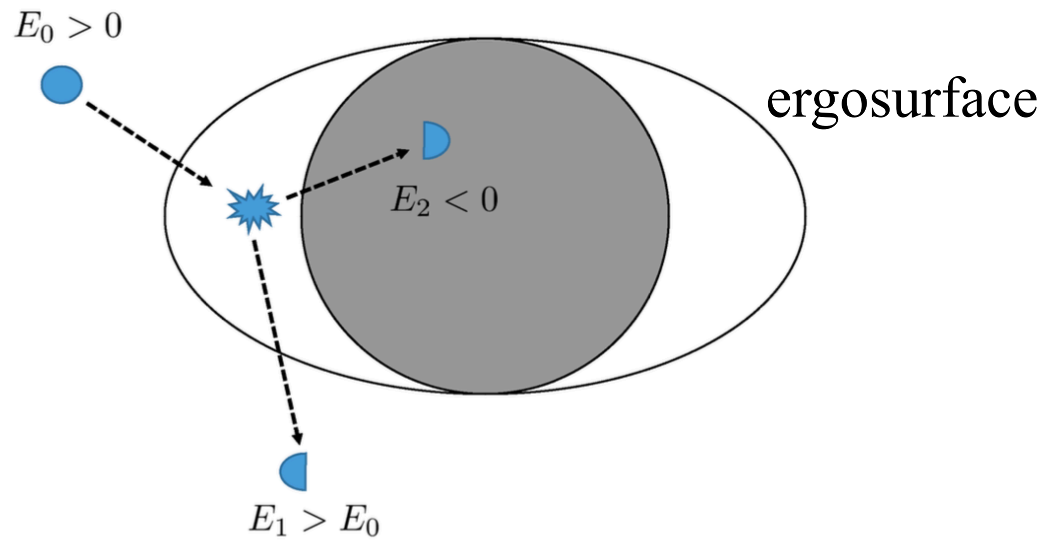
$$m_a \lesssim \Omega$$

particle mass (m_a)

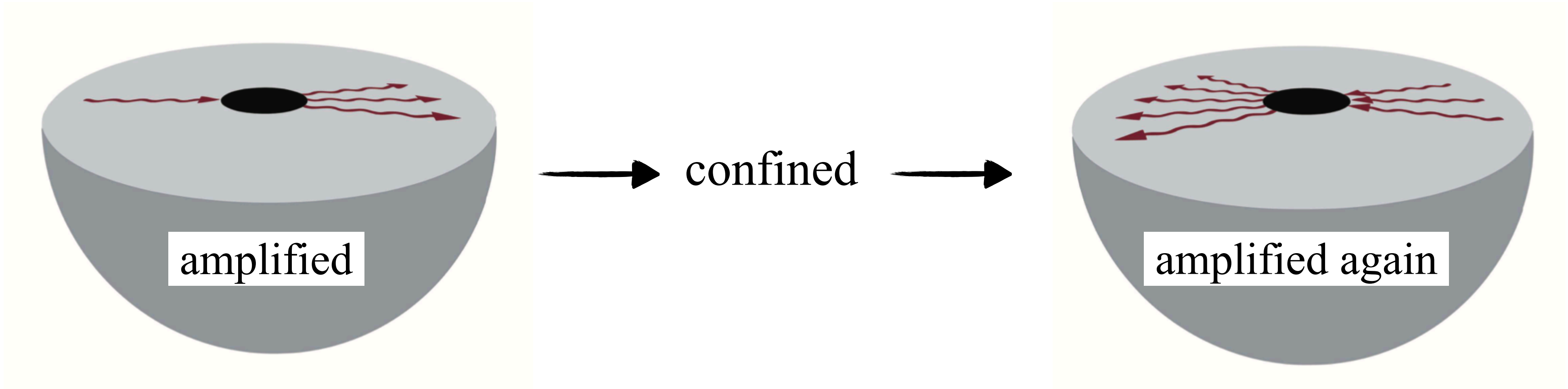
BH angular frequency (Ω)

Superradiance

Penrose process: energy extraction from rotating BHs



Growth of superradiance cloud:



massive
confined by gravitational
potential of the BH

boson
large occupation number
in the cloud

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

Superradiance rate

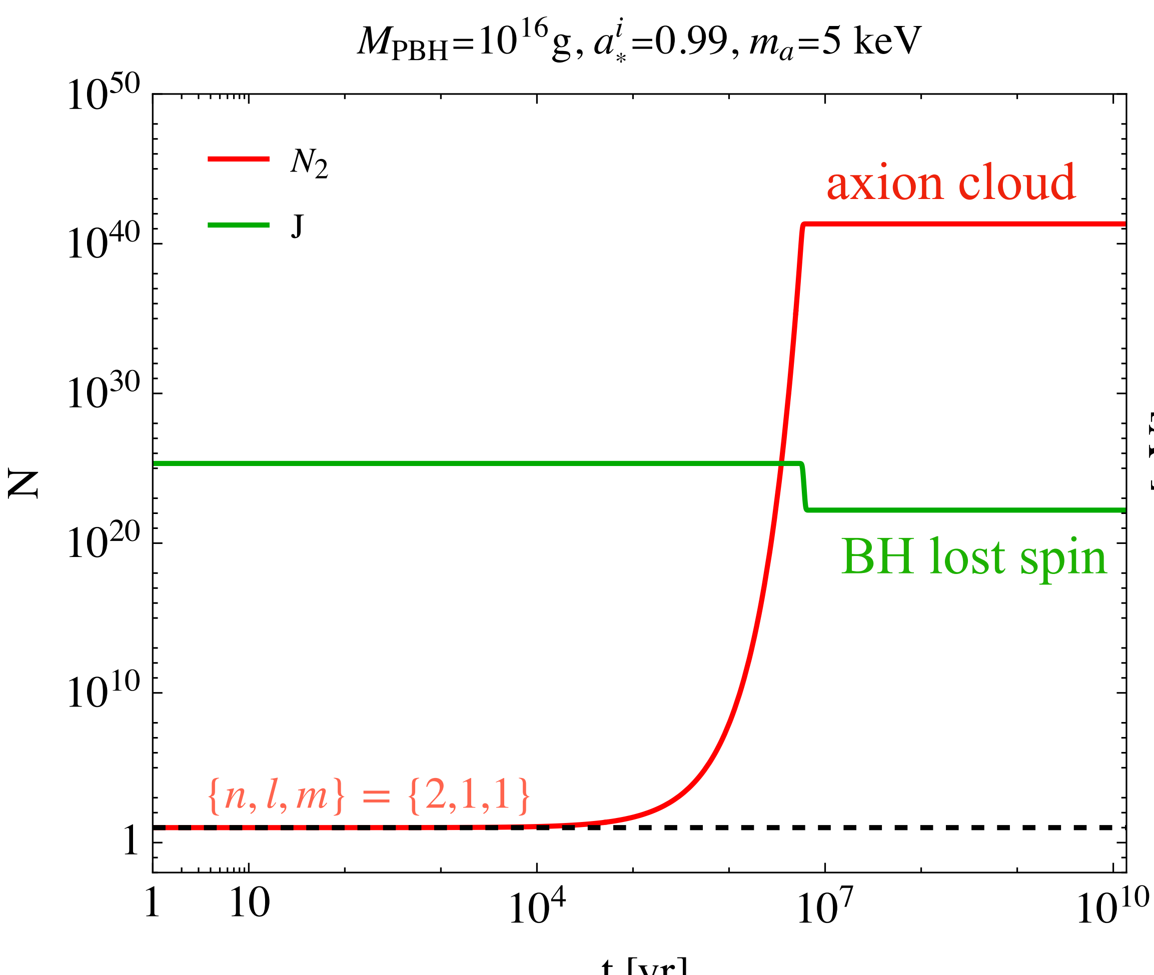
- Gravitational coupling between BH and axion: $\alpha = G_N M m_a$
- Frequency of axion mode bounded by BH: $\omega = \omega_R + i\omega_I$ — determines superradiance rate (ω_I); $\omega_R \simeq m_a$

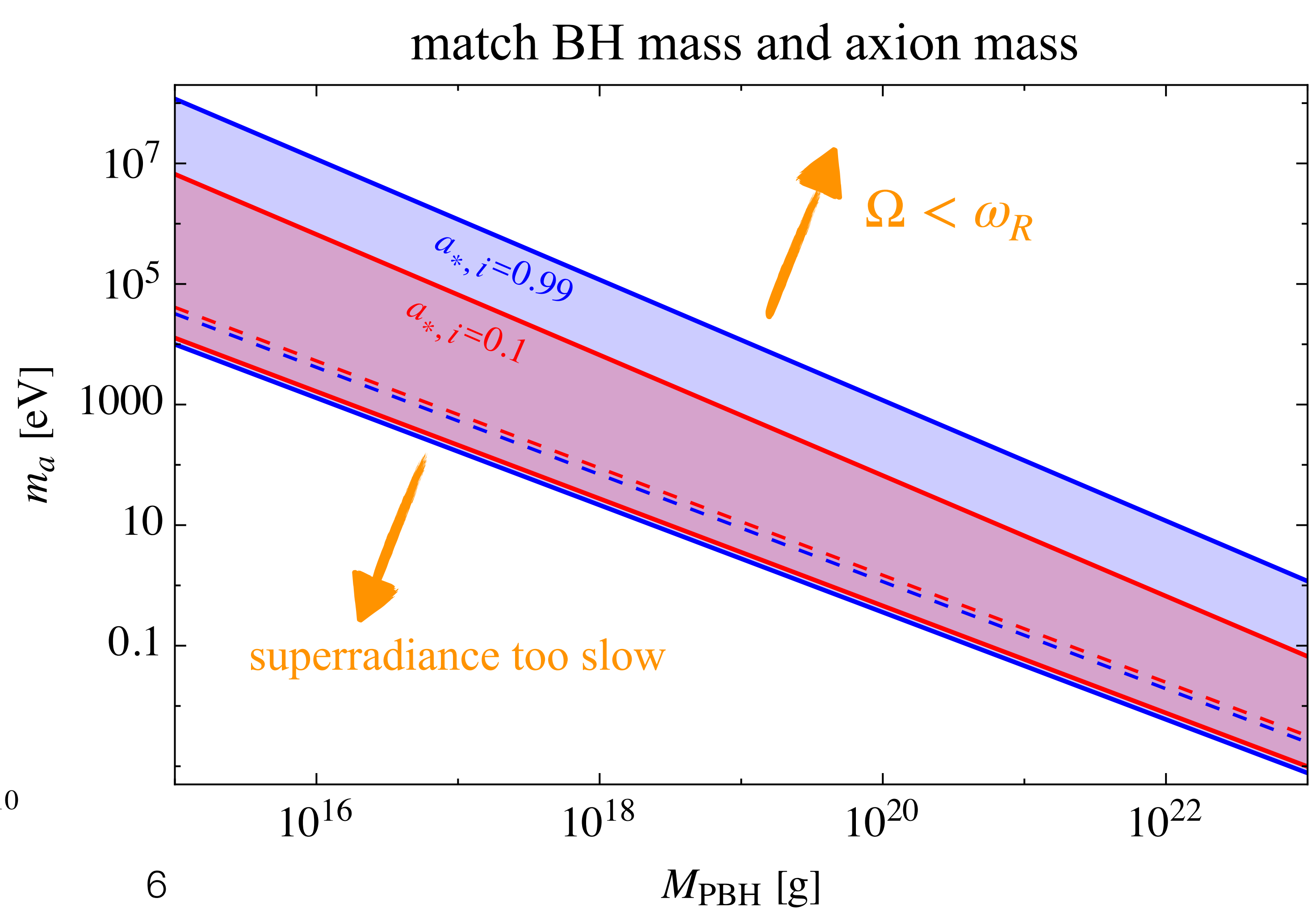
exponential cloud growth

$$N_a(t) \simeq N_0 e^{4\omega_I t}$$

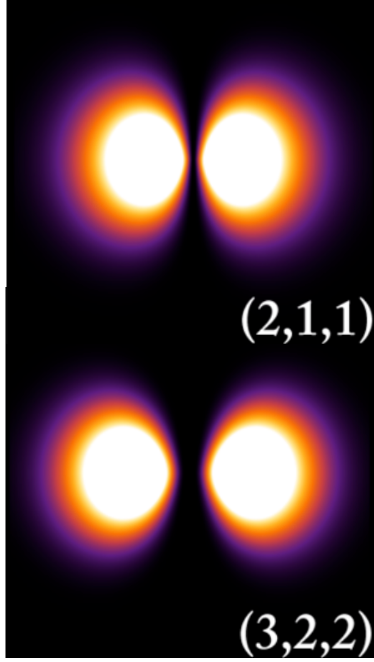
$$\frac{\omega_I}{m_a} \simeq \alpha^{4l+4} (m\Omega - \omega_R) 2 r_+ \mathscr{C}_{nlm}$$

superradiance condition ($m\Omega - \omega_R$)



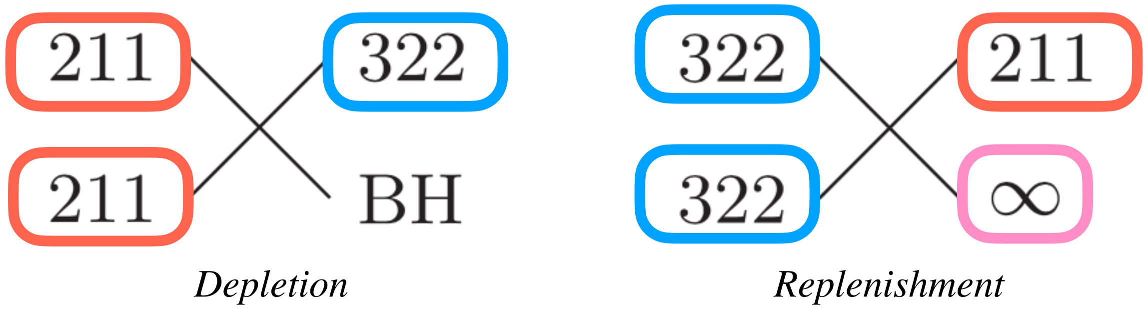


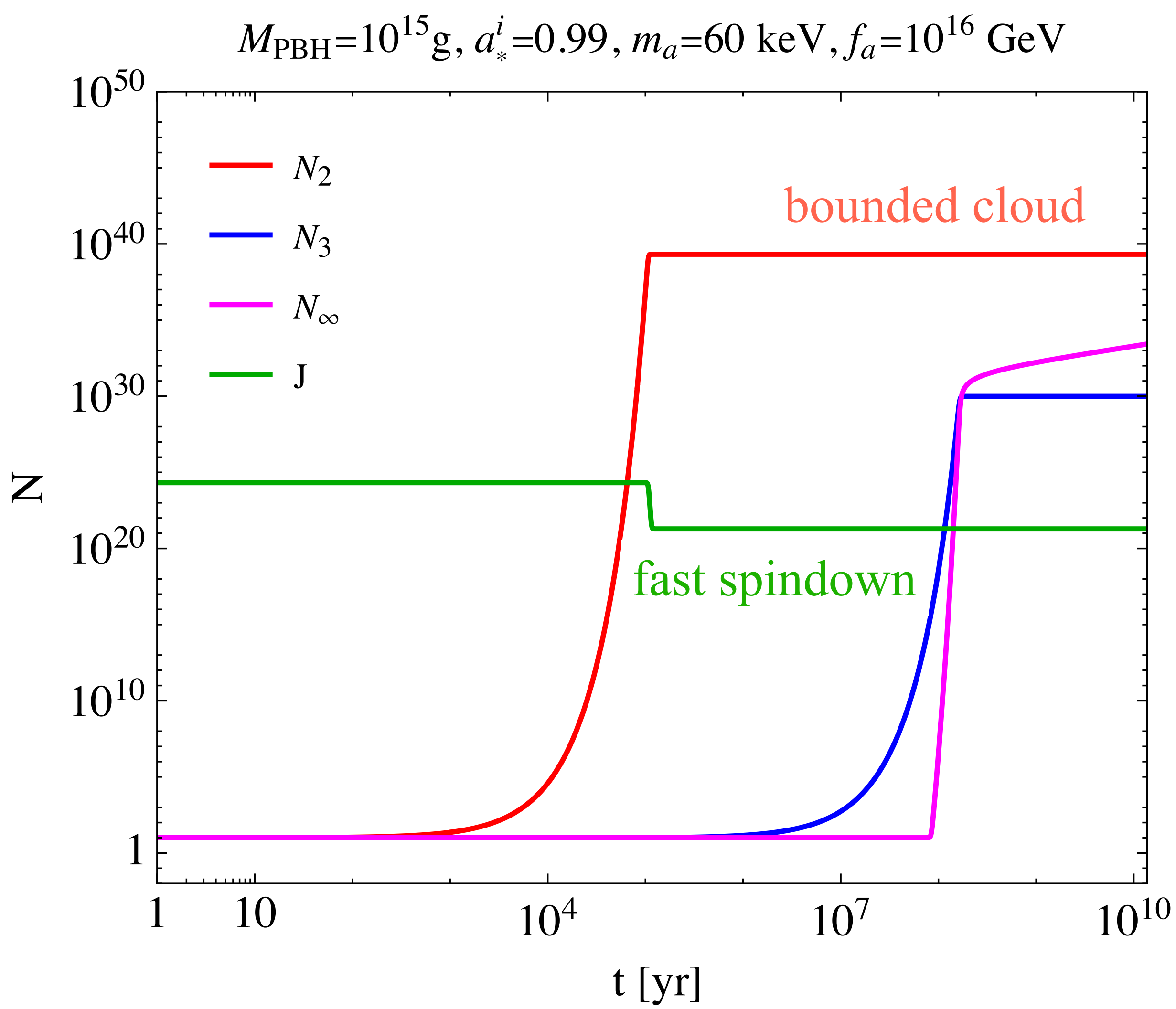
Self-interactions

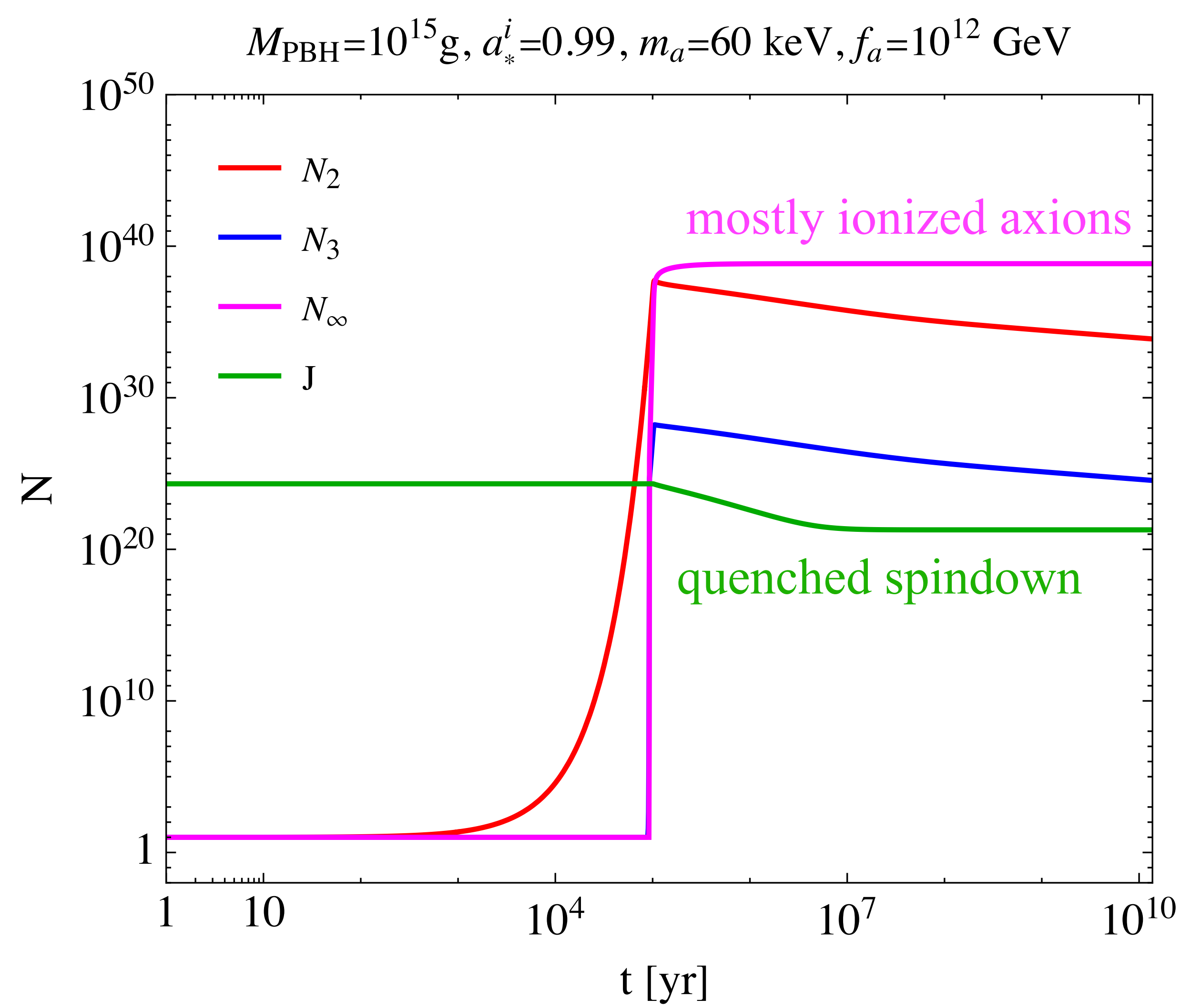


If there are axion self-interactions,

$$\mathscr{L}_{int} \supset \frac{m_a^2}{f_a^2}\frac{a^4}{4!} \equiv \frac{\lambda}{4!}a^4$$

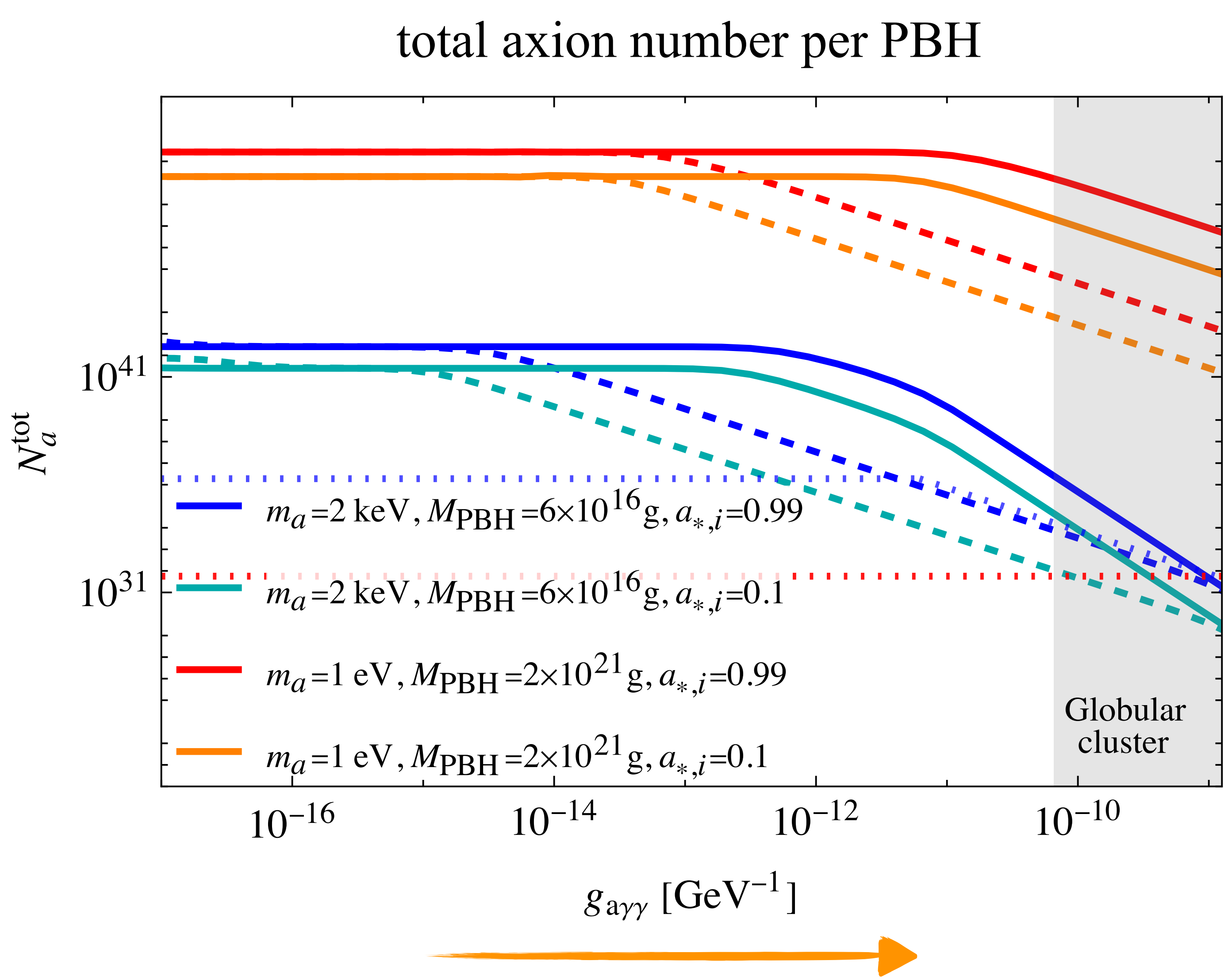






M. Baryakhtar, et al 2011.11646

axion population



larger axion decay signal :D

stronger axion self-interaction :(

- axion number suppressed in the existence of self-interactions. Ionized state dominates when coupling to photon is large.
- Heavier BHs produce more axions for the maximal available angular momentum

$$N_a^{max} = G_N M_{PBH}^2 \Delta a_* / m$$
$$\simeq 2 \times 10^{39} a_{\star,i} \frac{\Delta J}{J_i} \left(\frac{M_{PBH}}{10^{15}\ g} \right)^2$$

- Hawking radiation production (dotted) is smaller than superradiance in most regions.

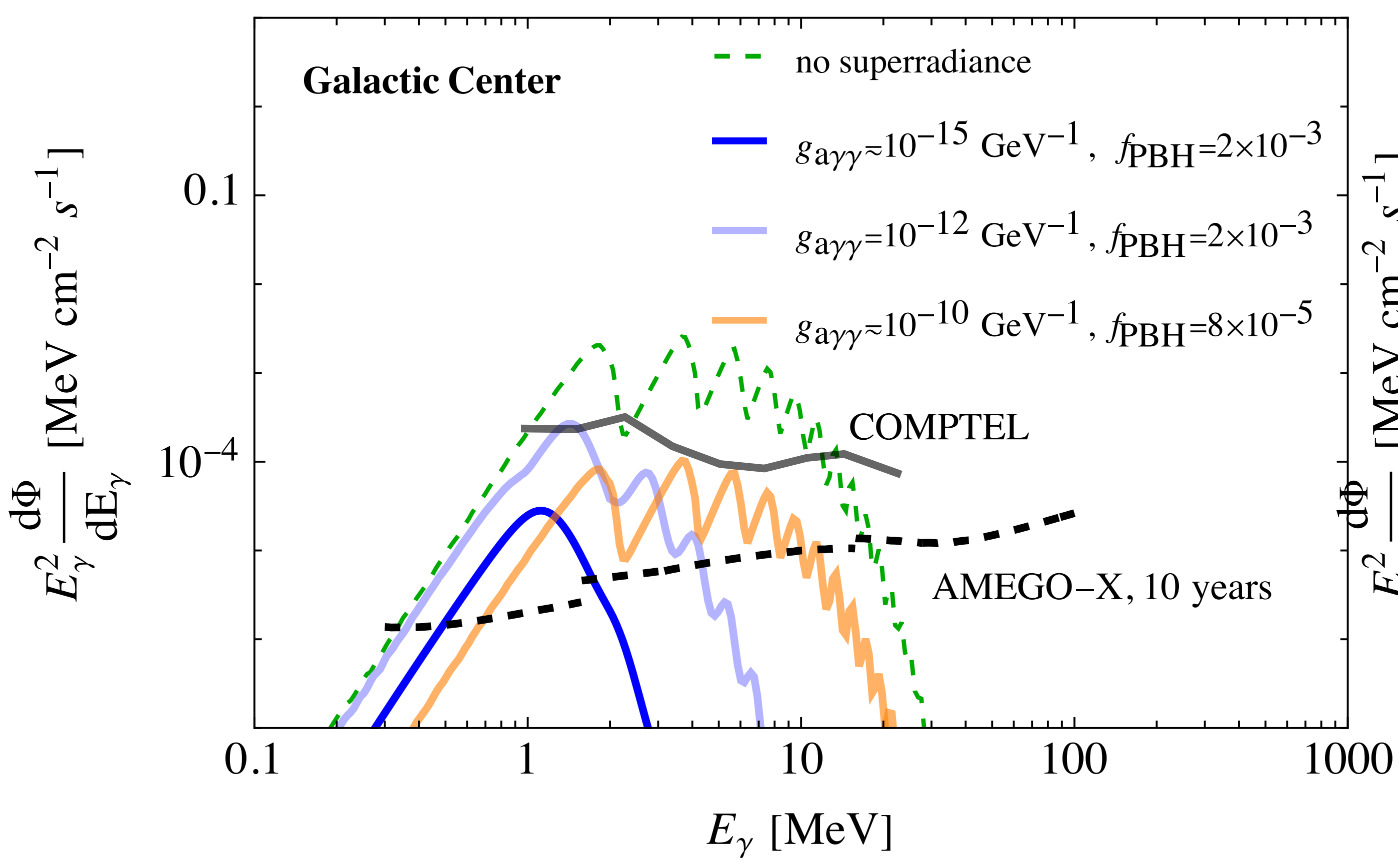
Signal: Hawking radiation

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

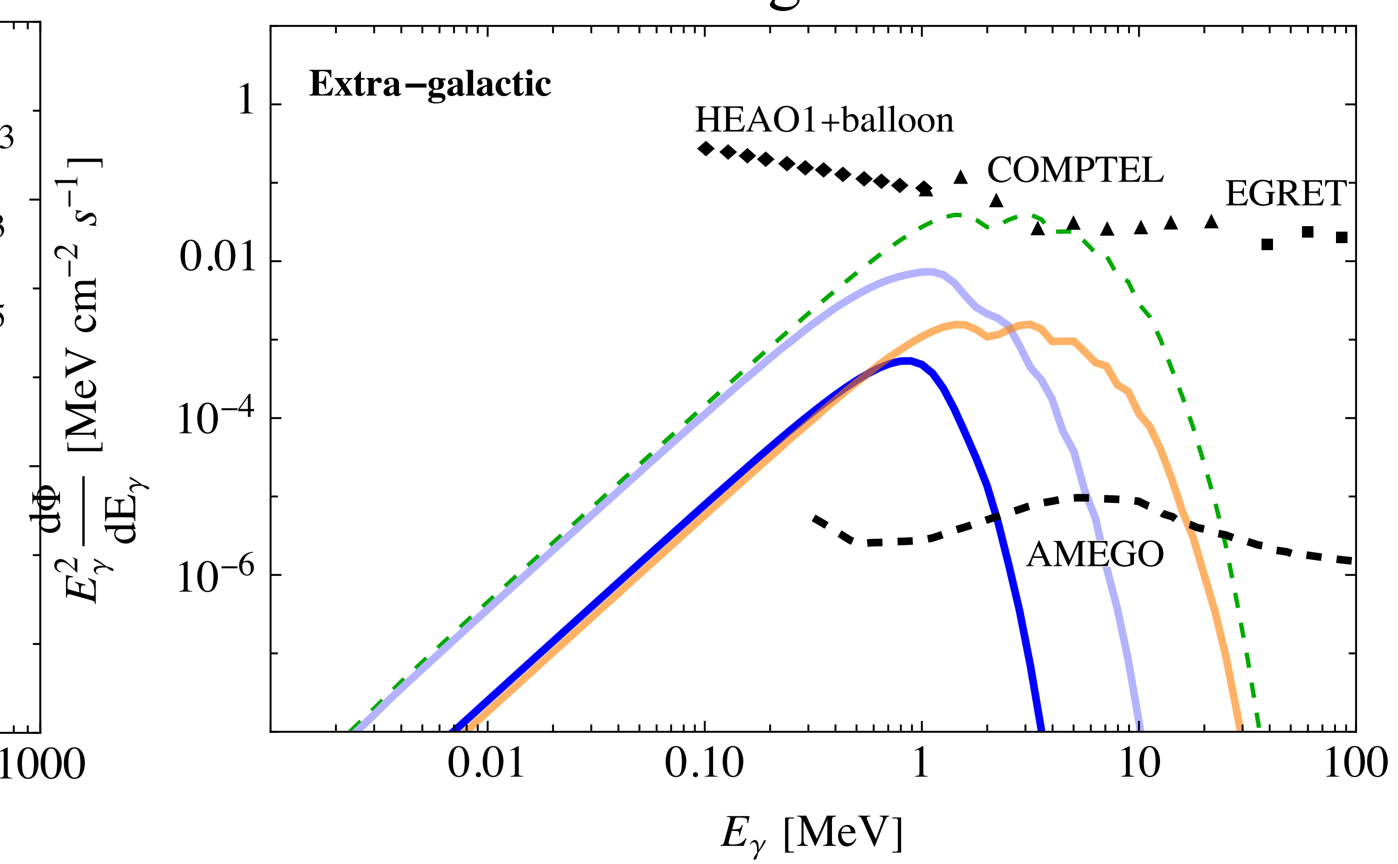
rotating PBH —superradiance→ non-rotating PBH

- Hawking radiation spectrum is a direct method to track BH spin.

Galactic Center



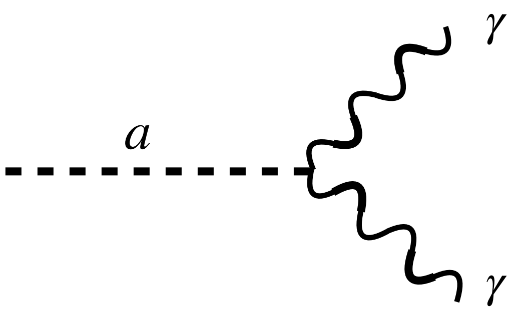
Extra-galactic



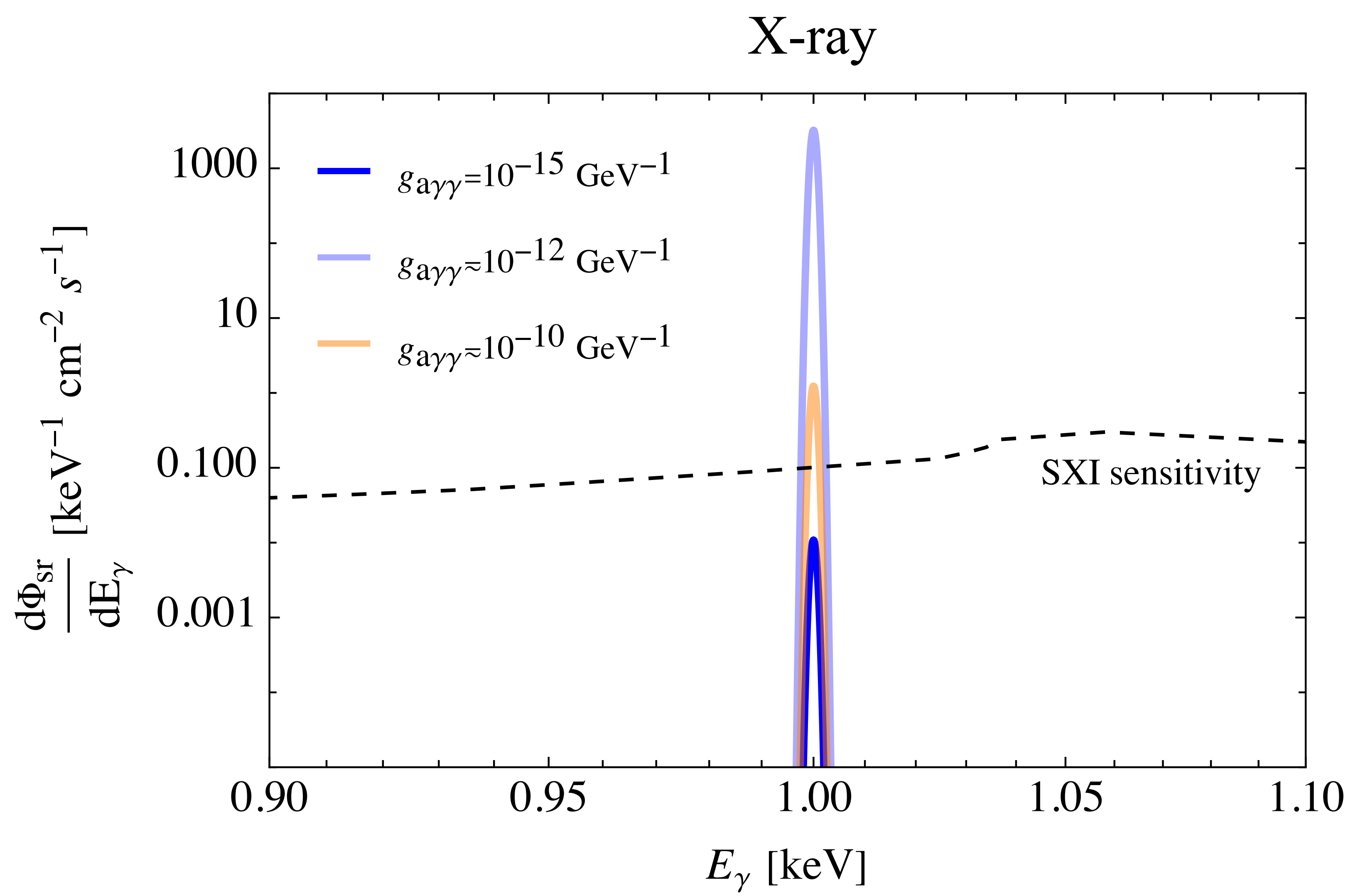
tail amplitude tells BH spin at high redshift

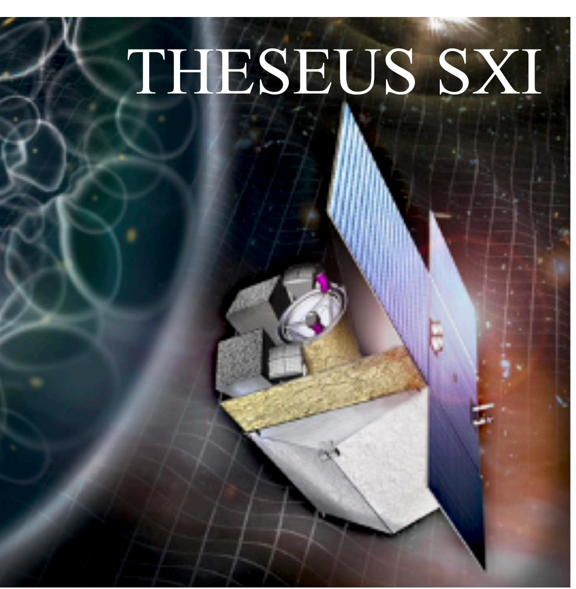
Signal: superradiance cloud decay

keV axions from superradiance cloud contribute to X-ray line signal at half axion mass

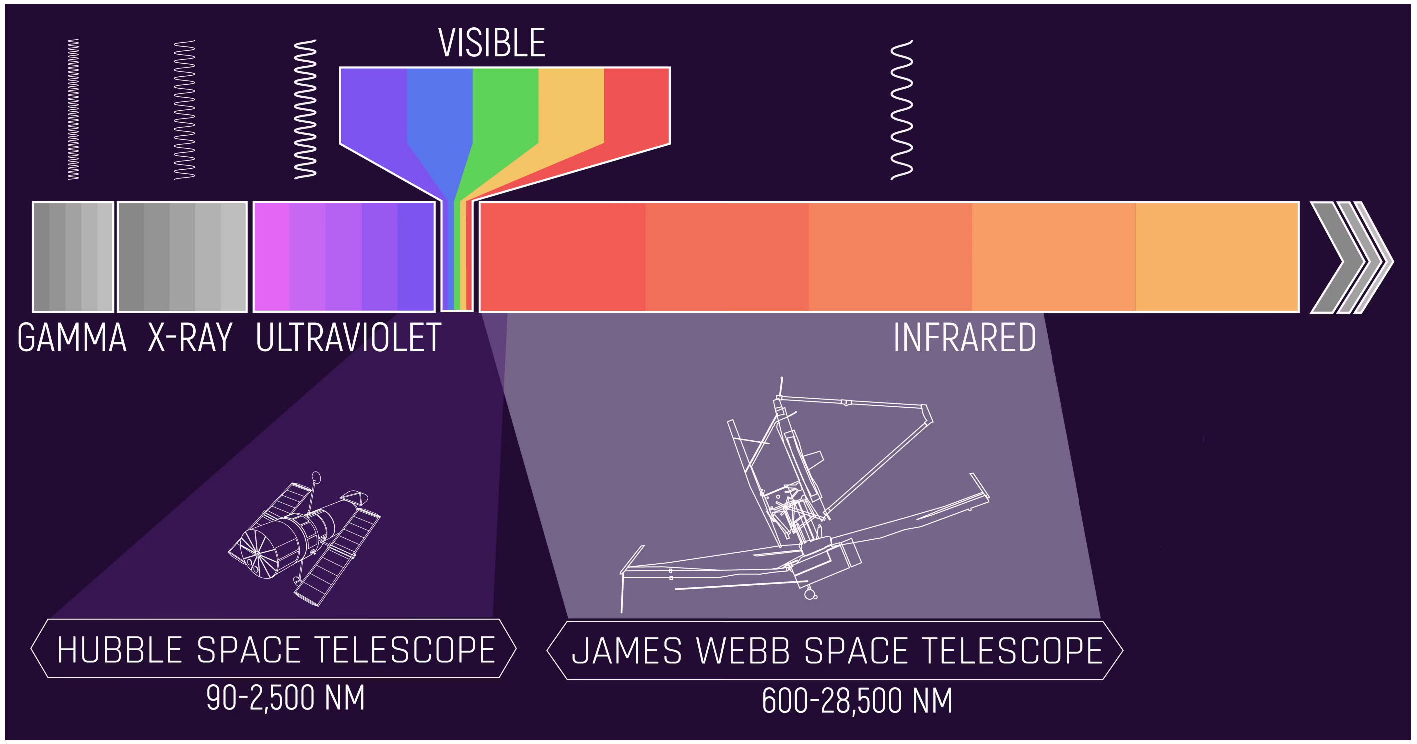


$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2\, m_a^3}{64\pi}$$

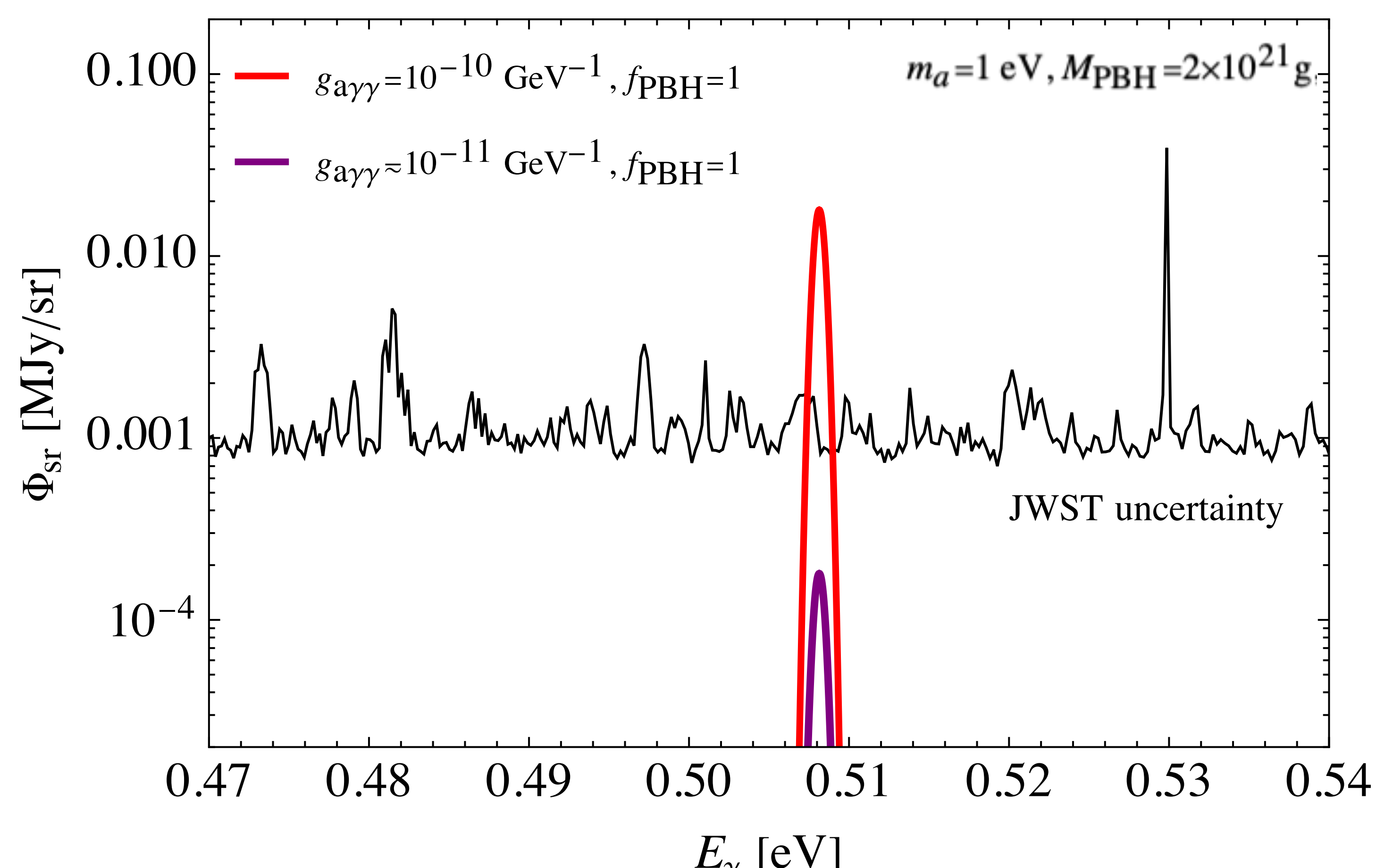


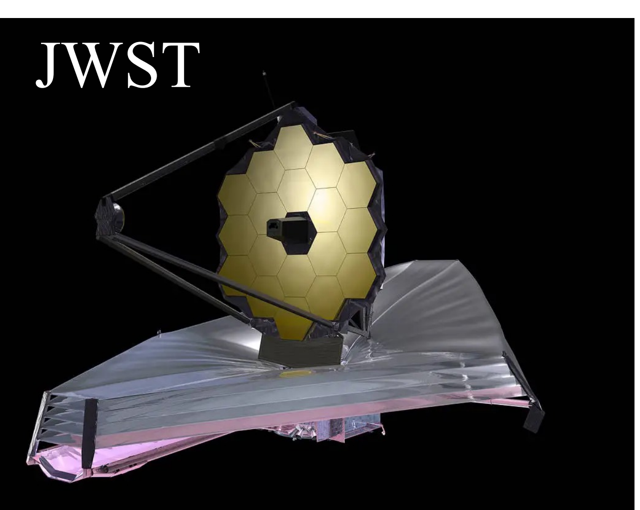


Signal: superradiance cloud decay



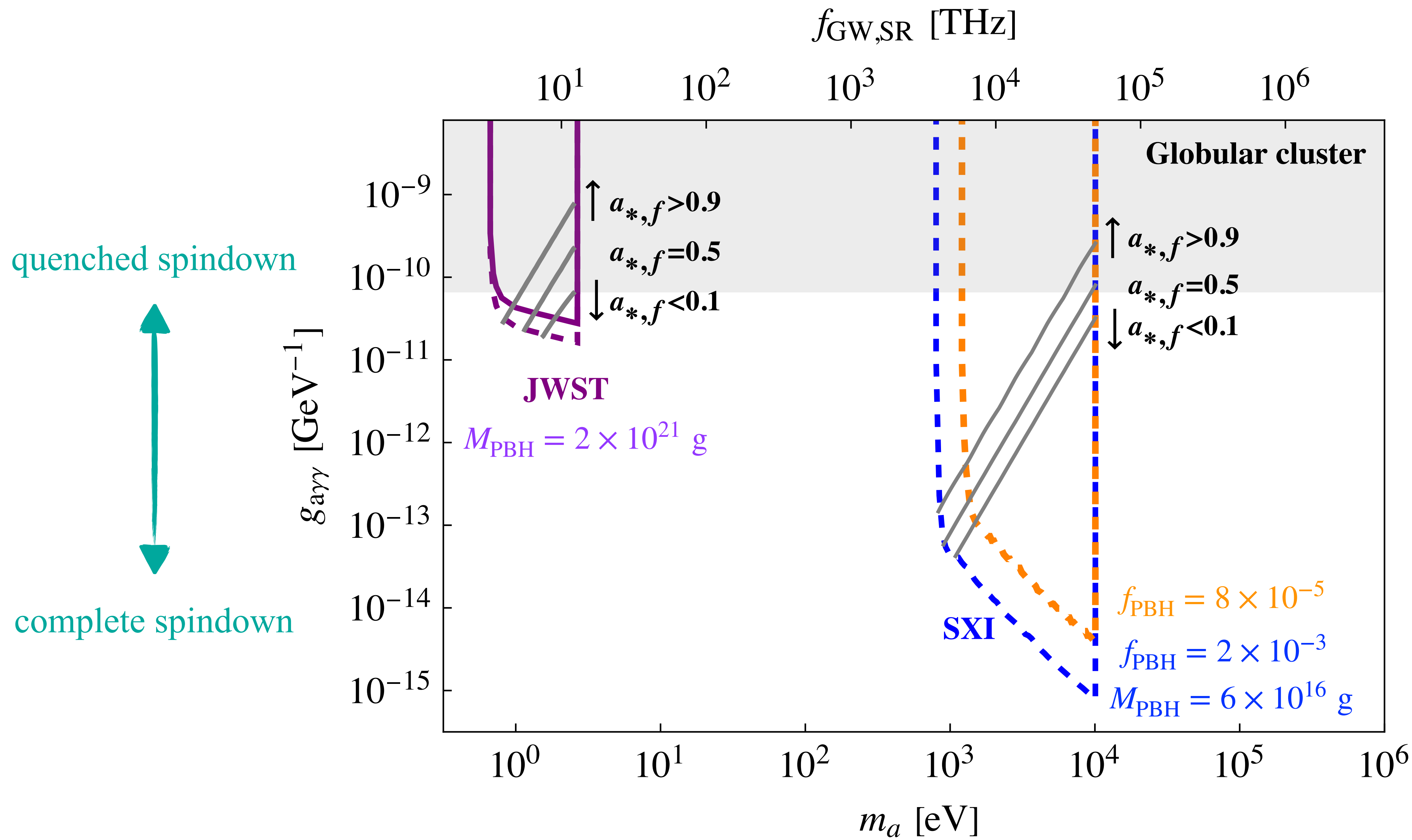
JWST's sensitivity at IR frequency allows for indirect detection searches with low energy photons





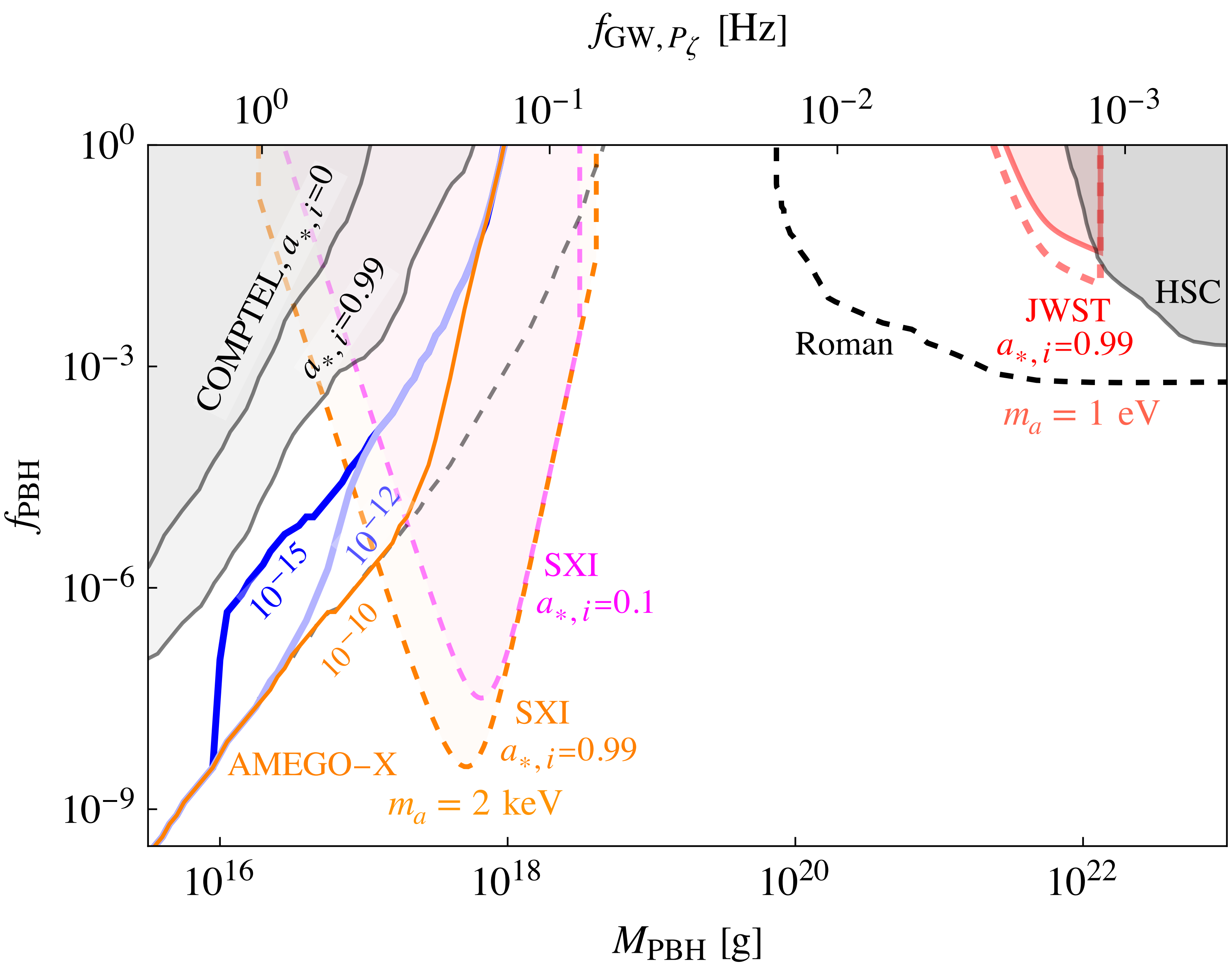
Result: axion parameters

The decay of axion cloud can probe open parameter space, with additional current spin $a_{\star,f}$ information of PBHs.



Result: PBH parameters

Multi-messenger probe of Hawking radiation, decay line and gravitational lensing sensitive to PBHs in the unexplored mass gap.



- *left:* Gamma-ray (AMEGO-X) constraints on Hawking radiation altered due to PBH spin loss.
- *middle:* X-ray line signal (SXI) sensitive to the decay of superradiance axion.
- *right:* eV photon searches (JWST) complementary to microlensing observations (HSC, Roman).

Summary

- PBHs can produce particles gravitationally via superradiance and Hawking radiation.

- For asteroid-mass PBHs, superradiance can be used to probe the eV-keV mass axions with the axion decay signal, while the PBH Hawking radiation also show features of the spin-down process.

- Future eV-MeV telescopes and microlensing observations will be used for multi-messenger probes of PBHs and axions.

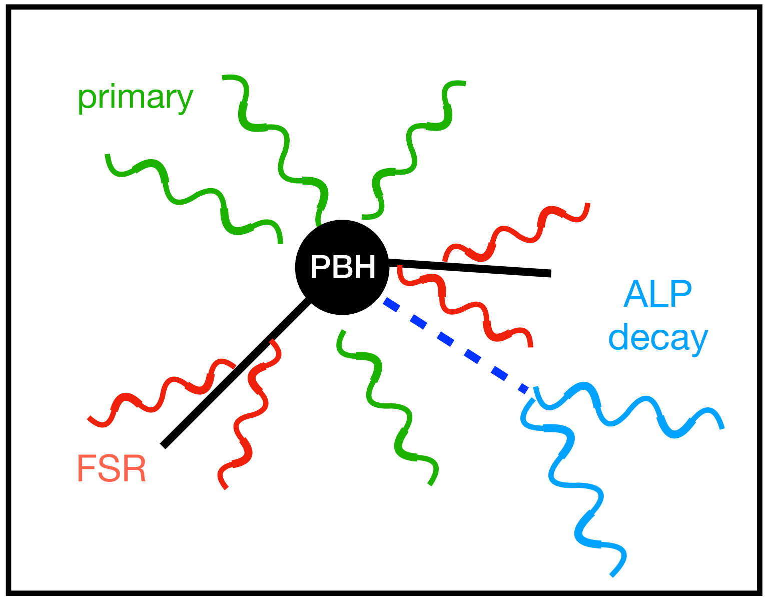
Thank you!

back up slides

ALP from Hawking radiation

arXiv: 2212.11980

- 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

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

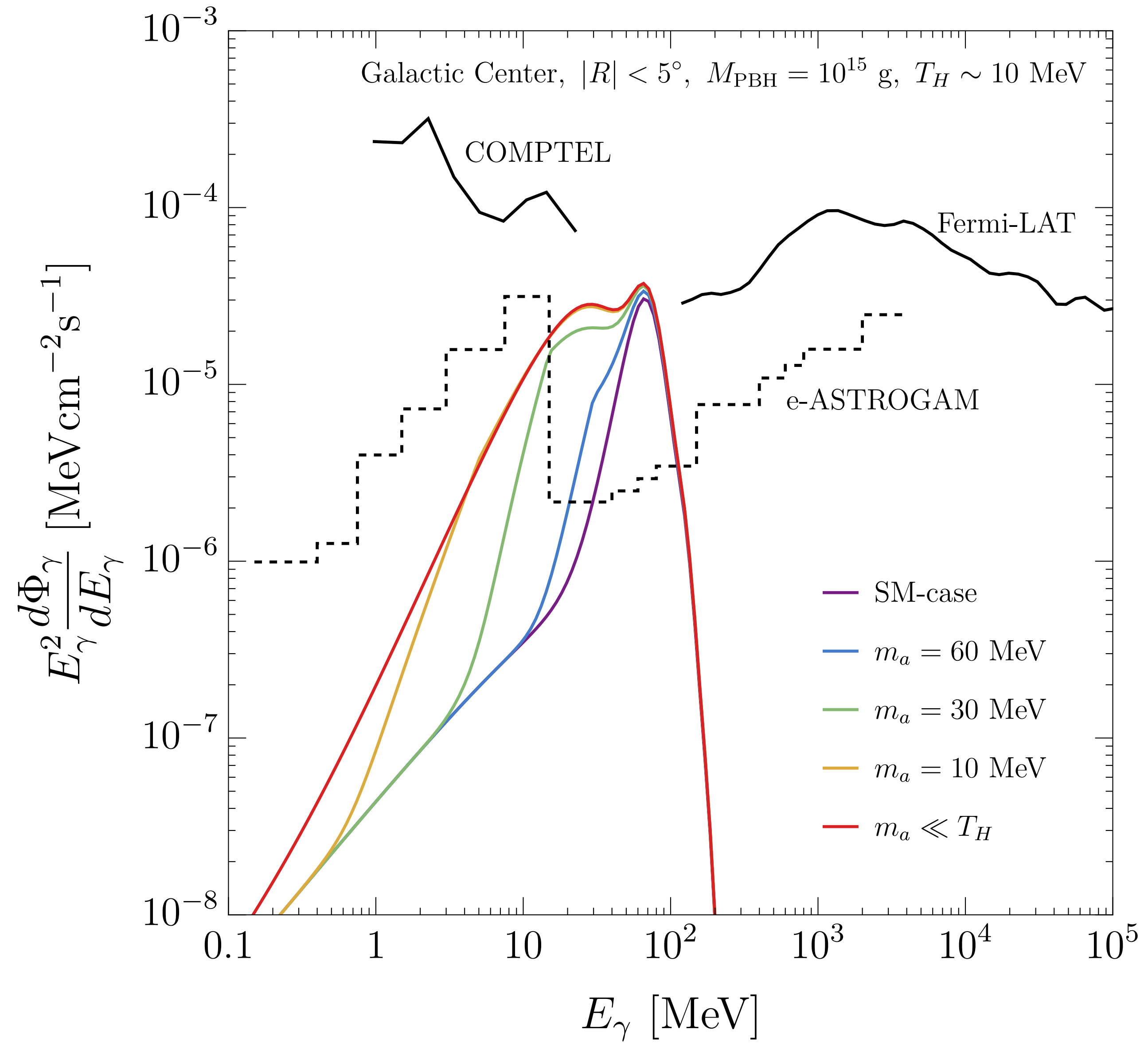
final-state radiation

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

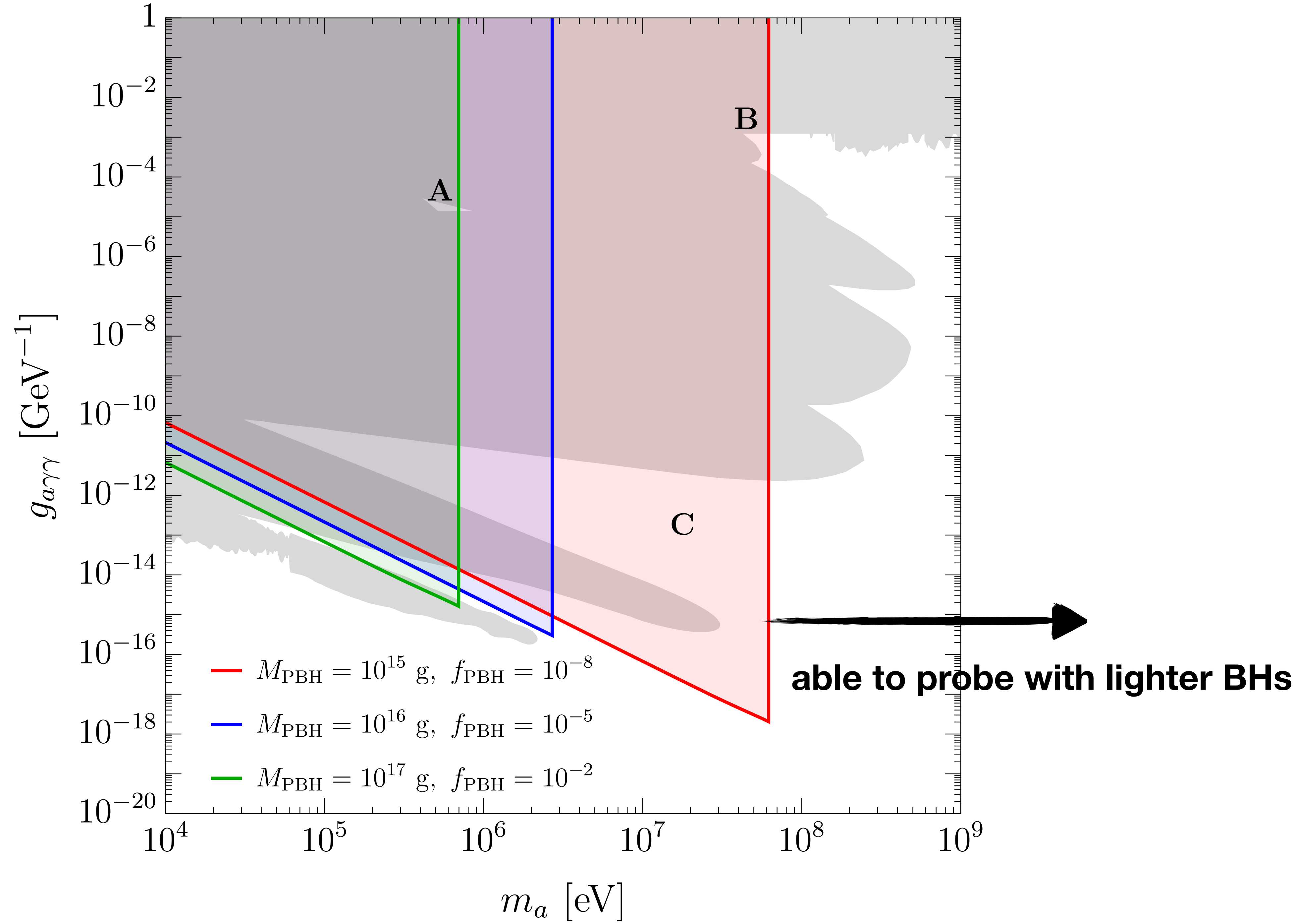
pion decay

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

add ALP decay



ALP parameter space that can be probed with BHs.



Hawking radiation