Constraining PBH with Photon Flux from ALPs

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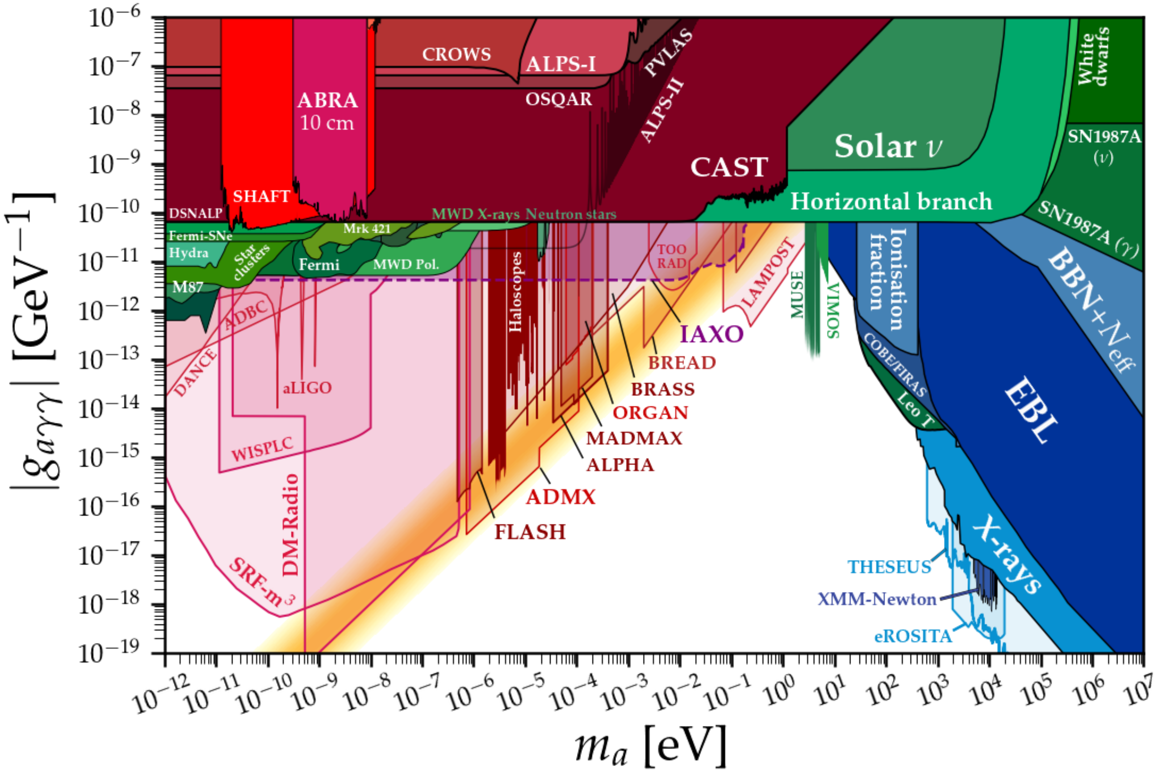
Introduction

- PBH generated in the very early universe is the one of candidates for dark matter.
  - *Nature* volume 253, pages 251–252 (1975)
- It releases the particles through evaporation.
  - Phys. Rev. D 13, 198 (1976)
- Through this predicted flux, we estimate the sensitivity to the primordial black hole abundance of experiments.
- Measurement of the photons in the range of $\mathrm{MeV} - \mathrm{GeV}$ (currently COMPTEL, e-ASTROGAM in future) are providing the most stringent upper limit on PBH abundance.
- Photon travels in straight line, transparent after CMB, and there are many observable devices in a wide energy range.
- It is a topic that is being actively studied.
  - *Phys.Lett.B* 808 (2020) 135624
  - Phys. Rev. D 101, 123514 (2020)
- We figured out how to produce this photon flux more effective.

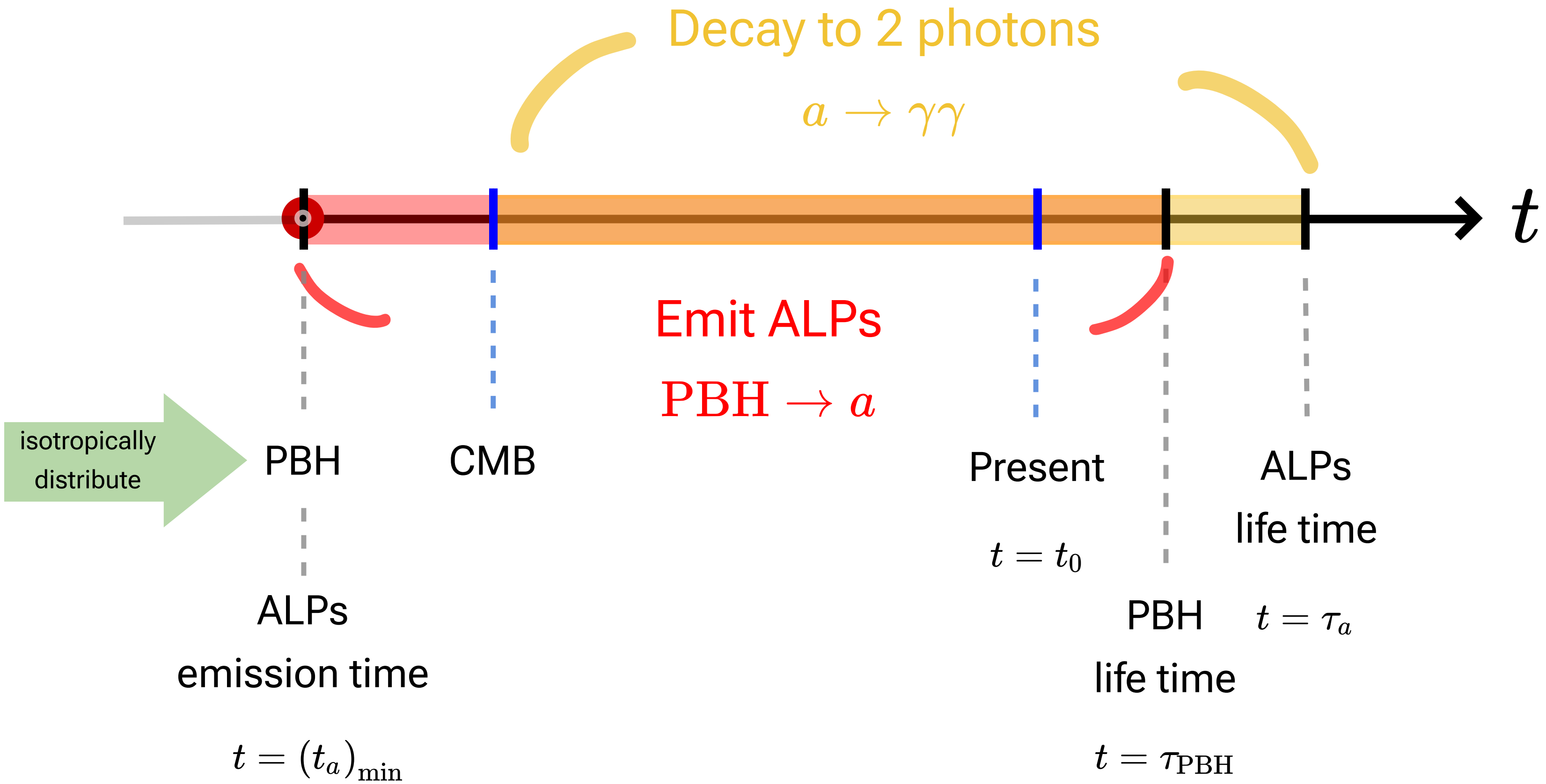
Introduction

$(g_{a\gamma\gamma} - m_a)$ parameter space



Areas that covered by future detections are colored with a bit transparency, while areas that are not are we already have.

A bird-eye view



Hawking Radiation from PBHs

Hawking radiation is an approximately thermal particle emission with temperature

An uncharged, non-rotating Schwarzschild PBH

- the temperature of PBH

$$k_B T_{\rm PBH} = \frac{\hbar c^3}{8\pi G M_{\rm PBH}} \sim 10.6 \left(\frac{10^{15}{\rm g}}{M_{\rm PBH}}\right) {\rm MeV}$$

- Emission rates of i particle

$$\frac{d^2 N_i}{dEdt} = \frac{g_i}{2\pi} \frac{\Gamma(T, M_{\rm PBH})}{e^{(E+m_i)/k_B T_{\rm PBH}} + 1}$$

$\Gamma(T, M_{\rm PBH})$: the graybody factor

- the lifetime of PBH
  - *Eur.Phys.J.C* 82 (2022) 4, 384

$$\tau_{\rm PBH} \sim 13.8 \times 10^9 {\rm yr} \left(\frac{M_{\rm PBH}}{5 \times 10^{14}{\rm g}}\right)^3$$

- Phys. Rev. D 13, 198 (1976)

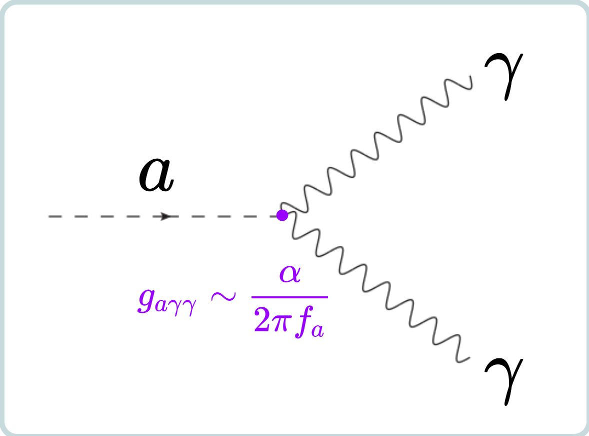
For the massless particles,

$$\tau_{\rm PBH} = \frac{5120\pi G^2}{\hbar c^4} M_{\rm PBH}^3$$

ALP decays to a photon pair

- ALP (Axion-Like Particle) :

    1. SOLELY interact with 2 photons
    2. mass and coupling are INDEPENDENT



$$\mathcal{L}_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- The ALP decay rate

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

- The lifetime of ALP observed at lab frame

$$\tau_a' \equiv \gamma \tau_a = \frac{\gamma}{\Gamma_{a\gamma\gamma}} = \frac{64\pi E_a}{g_{a\gamma\gamma}^2 m_a^4}$$

Extragalactic Contribution

We considered only the extragalactic contribution

- From detections, the fraction of PBH is a very small.

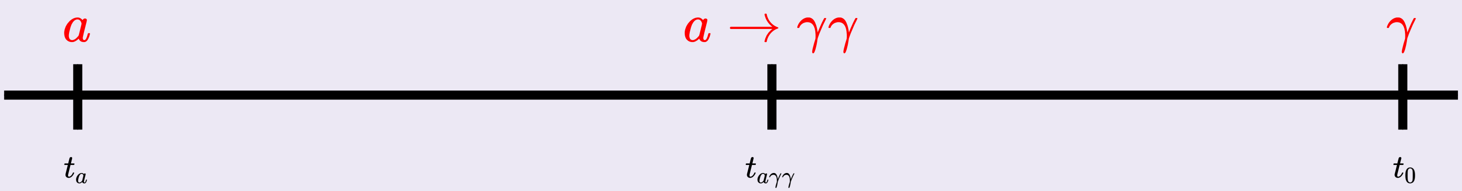
$\Rightarrow$ we focused on extragalactic contribution to accumulate a sufficient amount of signal

- Sensitivity in e-ASTROGAM is better for extragalactic contribution

E (MeV)	ΔE spectrum[(a)] (MeV)	PSF[(b)]	Effective area[(c)] (cm^2)	Inner Galaxy Backgr. rate (count s^{-1})	Inner Galaxy Sensitivity (ph cm^{-2} s^{-1})	Galactic Center[(d)] Sensitivity (ph cm^{-2} s^{-1})	Extragal. Backgr. rate (count s^{-1})	Extragal. Sensitivity 3σ (ph cm^{-2} s^{-1})
10	7.5 - 15	9.5°	215	3.4×10^{-2}	7.7×10^{-6}	1.3×10^{-5}	3.8×10^{-3}	2.6×10^{-6}
30	15 - 40	5.4°	846	1.6×10^{-2}	1.4×10^{-6}	2.4×10^{-6}	1.6×10^{-3}	4.3×10^{-7}
50	40 - 60	2.7°	1220	4.0×10^{-3}	4.6×10^{-7}	8.0×10^{-7}	3.4×10^{-4}	1.4×10^{-7}
70	60 - 80	1.8°	1245	1.3×10^{-3}	2.6×10^{-7}	4.5×10^{-7}	1.0×10^{-4}	7.2×10^{-8}
100	80 - 150	1.3°	1310	5.1×10^{-4}	1.6×10^{-7}	2.7×10^{-7}	3.2×10^{-5}	3.9×10^{-8}
300	150 – 400	0.51°	1379	4.8×10^{-5}	4.5×10^{-8}	7.8×10^{-8}	1.1×10^{-6}	6.9×10^{-9}
500	400 – 600	0.30°	1493	1.4×10^{-5}	2.2×10^{-8}	3.8×10^{-8}	1.8×10^{-7}	3.3×10^{-9}
700	600 – 800	0.23°	1552	6.3×10^{-6}	1.5×10^{-8}	2.5×10^{-8}	7.6×10^{-8}	3.2×10^{-9}
1000	800 – 2000	0.15°	1590	2.1×10^{-6}	8.3×10^{-9}	1.4×10^{-8}	2.1×10^{-8}	3.1×10^{-9}
3000	2000 - 4000	0.10°	1810	3.3×10^{-7}	2.9×10^{-9}	5.0×10^{-9}	2.9×10^{-9}	2.8×10^{-9}

- Experimental Astronomy 44 (2017) 25-82

Calculation Set Up



$$E_a(t_a) \xrightarrow{\text{redshift}} \left(\tilde{E}_a(t_{a\gamma\gamma}) \xrightarrow[\text{decay}]{\text{boost}} E'_\gamma(t_{a\gamma\gamma})\right) \xrightarrow{\text{redshift}} E_{\gamma 0}$$

$\tilde{E}$: redshifted energy

E' : Boosted energy

- $E_a(t_a)$: The energy of the ALP emitted by the evaporation of PBH at time t_a
- $\tilde{E}_a(t_{a\gamma\gamma})$: The redshift energy of $E_a(t_a)$ observed at time $t_{a\gamma\gamma}$
- $E'_\gamma(t_{a\gamma\gamma})$: The boosted energy of decay photon from ALP at time $t_{a\gamma\gamma}$
- E_{γ_0} : The energy of photon observed from Earth at t_0, which is redshifted energy of E'_γ

Redshift Effect

Redshift effect for particles propagating in an expanding universe

$$V(t) \propto (1+z(t))^{-3}, \; p|_t \propto (1+z(t))$$

- $\frac{n(t_1)}{n(t_2)} = \frac{V(t_2)}{V(t_1)} = \frac{(1+z(t_1))^3}{(1+z(t_2))^3} \Rightarrow n(t_1) = \left(\frac{1+z(t_1)}{1+z(t_2)}\right)^3 n(t_2)$
- $\frac{p|_{t_1}}{p|_{t_2}} = \frac{(1+z(t_1))}{(1+z(t_2))} \Rightarrow p|_{t_1} = \frac{1+z(t_1)}{1+z(t_2)} p|_{t_2}$

$$E|_{t_1} = \frac{1+z(t_1)}{1+z(t_2)} E|_{t_2}$$: for massless particles

$$E|_{t_1} = \sqrt{m^2 + \frac{1+z(t_1)}{1+z(t_2)} p|_{t_2}} = \sqrt{m^2 + \frac{1+z(t_1)}{1+z(t_2)} (E|_{t_2}^2 - m^2)}$$: for massive particles

Calculation Steps

STEP 1 The number density of ALPs with time

The number density of ALPs with energy $\tilde{E}_a$ at time $t_{a\gamma\gamma}$

$$n_a(\tilde{E}_a, t_{a\gamma\gamma}) = \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \left(\frac{1+z(t_{a\gamma\gamma})}{1+z(T)}\right)^3 \times \widetilde{\frac{dn_a}{dT}}(\tilde{E}_a, t_{a\gamma\gamma}; T)$$

- $\widetilde{\frac{dn_a}{dT}}(\tilde{E}_a, t_{a\gamma\gamma}; T) = \frac{dn_a}{dT}(E_a, T) \times P_{\rm surv}(t_{a\gamma\gamma} - T)$ $\quad \left| P_{\rm surv}(\Delta t) = e^{-\frac{\Delta t}{\tau'_a(E)}} \right.$

  : The number density of ALPs with $\tilde{E}_a$ at $t_{a\gamma\gamma}$ emitted from PBH at T

- $\frac{dn_a}{dT}(E_a, t_a)$

  : The emitted number density of ALPs with E_a at t_a

Calculation Steps

STEP 2 The change of number density with respect to time

- During the ALPs emission period, $T = [(t_a)_{\min}, t_{a\gamma\gamma}]$
- By using the logarithmic energy bin $\Delta E \simeq E$: $\frac{dn_a}{dT}(E_a, T) \simeq n_{\text{PBH}}(T) \cdot E_a \frac{d^2 N_a}{dEdT}\Big|_{E=E_a}$

$$\frac{d}{dt_{a\gamma\gamma}} n_a(\tilde{E}_a, t_{a\gamma\gamma})$$

- Change of n_{PBH} by redshift

$$= n_{\text{PBH}}(t_0) \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ (1 + z(t_{a\gamma\gamma}))^3 \right\} \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \; E_a \frac{d^2 N_a}{dEdT}\Big|_{E=E_a} \times e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}}$$

$$+ n_{\text{PBH}}(t_0)(1 + z(t_{a\gamma\gamma}))^3 \cdot \tilde{E}_a \frac{d^2 N_a}{dEdt_{a\gamma\gamma}}\Big|_{E=\tilde{E}_a}$$

$$+ n_{\text{PBH}}(t_0)(1 + z(t_{a\gamma\gamma}))^3 \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \; \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ E_a \frac{d^2 N_a}{dEdT}\Big|_{E=E_a} \right\} \times e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}}$$

$$+ n_{\text{PBH}}(t_0)(1 + z(t_{a\gamma\gamma}))^3 \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \; E_a \frac{d^2 N_a}{dEdT}\Big|_{E=E_a} \times \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}} \right\}$$

Calculation Steps

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$$\frac{d}{dt_{a\gamma\gamma}} n_a(\tilde{E}_a, t_{a\gamma\gamma})$$

$$= n_{\rm PBH}(t_0) \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ (1 + z(t_{a\gamma\gamma}))^3 \right\} \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \; E_a \frac{d^2 N_a}{dE dT}\Big|_{E=E_a} \times e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}}$$

$$+ n_{\rm PBH}(t_0)(1 + z(t_{a\gamma\gamma}))^3 \cdot \tilde{E}_a \frac{d^2 N_a}{dE dt_{a\gamma\gamma}}\Big|_{E=\tilde{E}_a}$$

- ALPs emission at $t_{a\gamma\gamma}$

$$+ n_{\rm PBH}(t_0)(1 + z(t_{a\gamma\gamma}))^3 \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ E_a \frac{d^2 N_a}{dE dT}\Big|_{E=E_a} \right\} \times e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}}$$

$$+ n_{\rm PBH}(t_0)(1 + z(t_{a\gamma\gamma}))^3 \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \; E_a \frac{d^2 N_a}{dE dT}\Big|_{E=E_a} \times \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}} \right\}$$

Calculation Steps

STEP 2 The change of number density with respect to time

- During the ALPs emission period, $T = [(t_a)_{\min}, t_{a\gamma\gamma}]$
- By using the logarithmic energy bin $\Delta E \simeq E$: $\frac{dn_a}{dT}(E_a, T) \simeq n_{\rm PBH}(T) \cdot E_a \frac{d^2 N_a}{dE dT}\Big|_{E=E_a}$

$$\frac{d}{dt_{a\gamma\gamma}} n_a(\tilde{E}_a, t_{a\gamma\gamma})$$

$$= n_{\rm PBH}(t_0) \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ (1+z(t_{a\gamma\gamma}))^3 \right\} \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT\, E_a \frac{d^2 N_a}{dE dT}\Big|_{E=E_a} \times e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}}$$

$$+ n_{\rm PBH}(t_0)(1+z(t_{a\gamma\gamma}))^3 \cdot \tilde{E}_a \frac{d^2 N_a}{dE dt_{a\gamma\gamma}}\Big|_{E=\tilde{E}_a}$$

- Change in the number of ALPs emitted from one PBH by redshift

$$+ n_{\rm PBH}(t_0)(1+z(t_{a\gamma\gamma}))^3 \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ E_a \frac{d^2 N_a}{dE dT}\Big|_{E=E_a} \right\} \times e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}}$$

$$+ n_{\rm PBH}(t_0)(1+z(t_{a\gamma\gamma}))^3 \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT\, E_a \frac{d^2 N_a}{dE dT}\Big|_{E=E_a} \times \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}} \right\}$$

Calculation Steps

STEP 2 | The change of number density with respect to time

- During the ALPs emission period, $T = [(t_a)_{\min}, t_{a\gamma\gamma}]$
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$$\frac{d}{dt_{a\gamma\gamma}} n_a(\tilde{E}_a, t_{a\gamma\gamma})$$

$$= n_{\rm PBH}(t_0) \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ (1+z(t_{a\gamma\gamma}))^3 \right\} \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \; E_a \frac{d^2 N_a}{dEdT}\Big|_{E=E_a} \times e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}}$$

$$+ n_{\rm PBH}(t_0)(1+z(t_{a\gamma\gamma}))^3 \cdot \tilde{E}_a \frac{d^2 N_a}{dEdt_{a\gamma\gamma}}\Big|_{E=\tilde{E}_a}$$

$$+ n_{\rm PBH}(t_0)(1+z(t_{a\gamma\gamma}))^3 \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \; \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ E_a \frac{d^2 N_a}{dEdT}\Big|_{E=E_a} \right\} \times e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}}$$

$$\frac{dn_a^{\rm dec}}{dt_{a\gamma\gamma}}(\tilde{E}_a, t_{a\gamma\gamma}) \equiv + n_{\rm PBH}(t_0)(1+z(t_{a\gamma\gamma}))^3 \int_{(t_a)_{\min}}^{t_{a\gamma\gamma}} dT \; E_a \frac{d^2 N_a}{dEdT}\Big|_{E=E_a} \times \frac{\partial}{\partial t_{a\gamma\gamma}} \left\{ e^{-\frac{t_{a\gamma\gamma}-T}{\tau_a'(E_a)}} \right\}$$

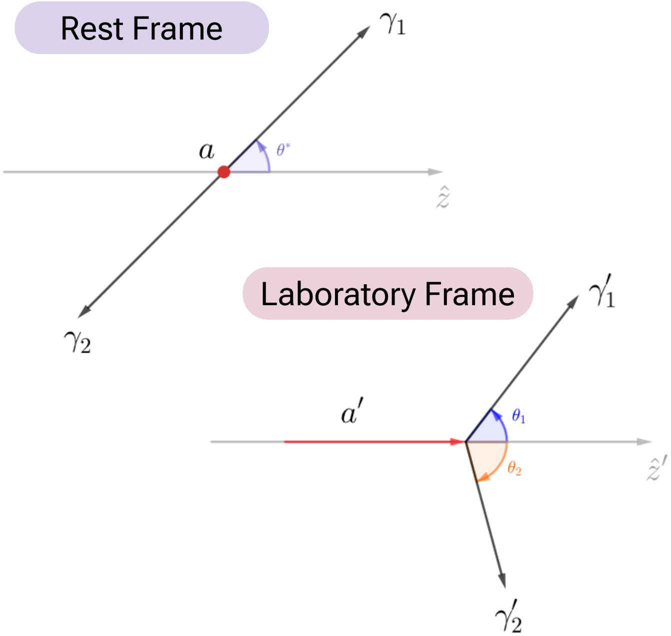
- Decay ALPs = Photon Production

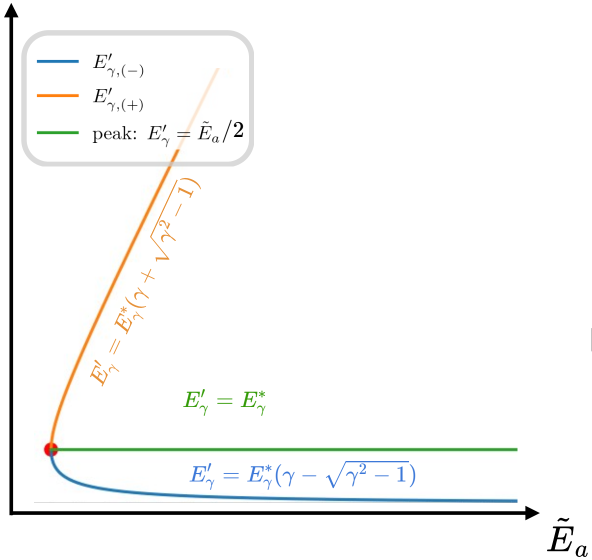
Boost Effect

Lorentz transformation

$$E'_\gamma = E^*_\gamma(\gamma \pm \sqrt{\gamma^2 - 1})$$

- $E^*_\gamma = \frac{\tilde{E}_a}{2}$: photon energy in the rest frame of the ALP
- $\gamma = \frac{\tilde{E}_a}{m_a}$: the Lorentz factor





monochromatic energy

↓

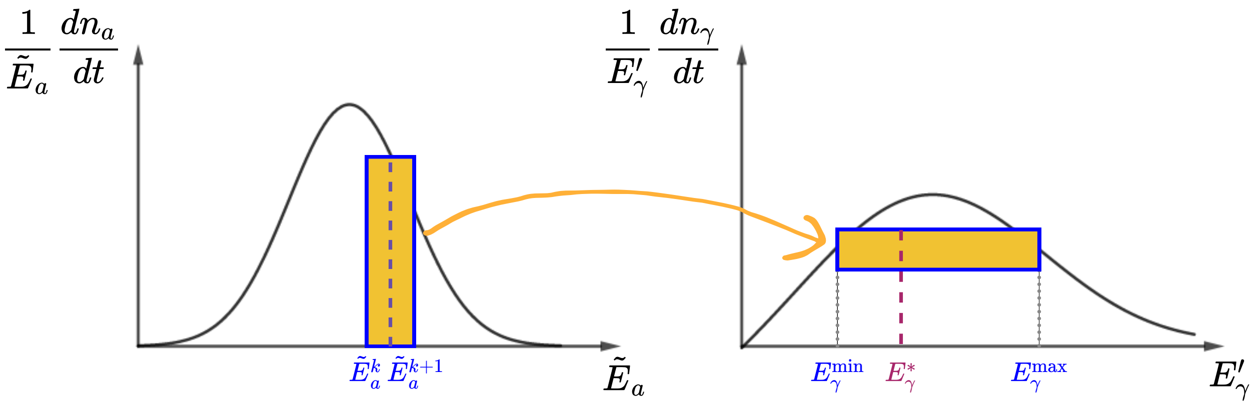
Energy has upper and lower bounds

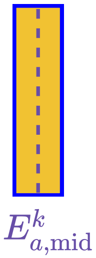
Calculation Steps

STEP 3 Boosted photon number density after decay

$$\tilde{E}_a \rightarrow E'_\gamma \Longrightarrow \frac{dn_a^{\rm dec}(\tilde{E}_a)}{dt} \rightarrow \frac{dn_\gamma}{dt}$$

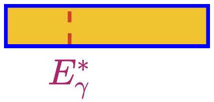
- Phys.Rev. D88 (2013) 5, 057701





$$\log_{10}\tilde{E}^k_{a,\rm mid} = \frac{1}{2}\left(\log_{10}\tilde{E}^{k+1}_a + \log_{10}\tilde{E}^k_a\right)$$

$$\gamma^k = \frac{\tilde{E}^k_{a,\rm mid}}{m_a}$$



$E_\gamma^* = \frac{m_a}{2}$: Rest energy of ALP

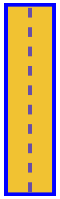
$$E_\gamma^{\rm min} = E_\gamma^*\left(\gamma^k - \sqrt{(\gamma^k)^2 - 1}\right)$$

$$E_\gamma^{\rm max} = E_\gamma^*\left(\gamma^k + \sqrt{(\gamma^k)^2 - 1}\right)$$

Calculation Steps

STEP 3 — Boosted photon number density after decay

- Phys.Rev. D88 (2013) 5, 057701



$E^k_{a,\mathrm{mid}}$

$$\log_{10} \tilde{E}^k_{a,\mathrm{mid}} = \frac{1}{2}\left(\log_{10} \tilde{E}^{k+1}_a + \log_{10} \tilde{E}^k_a\right)$$

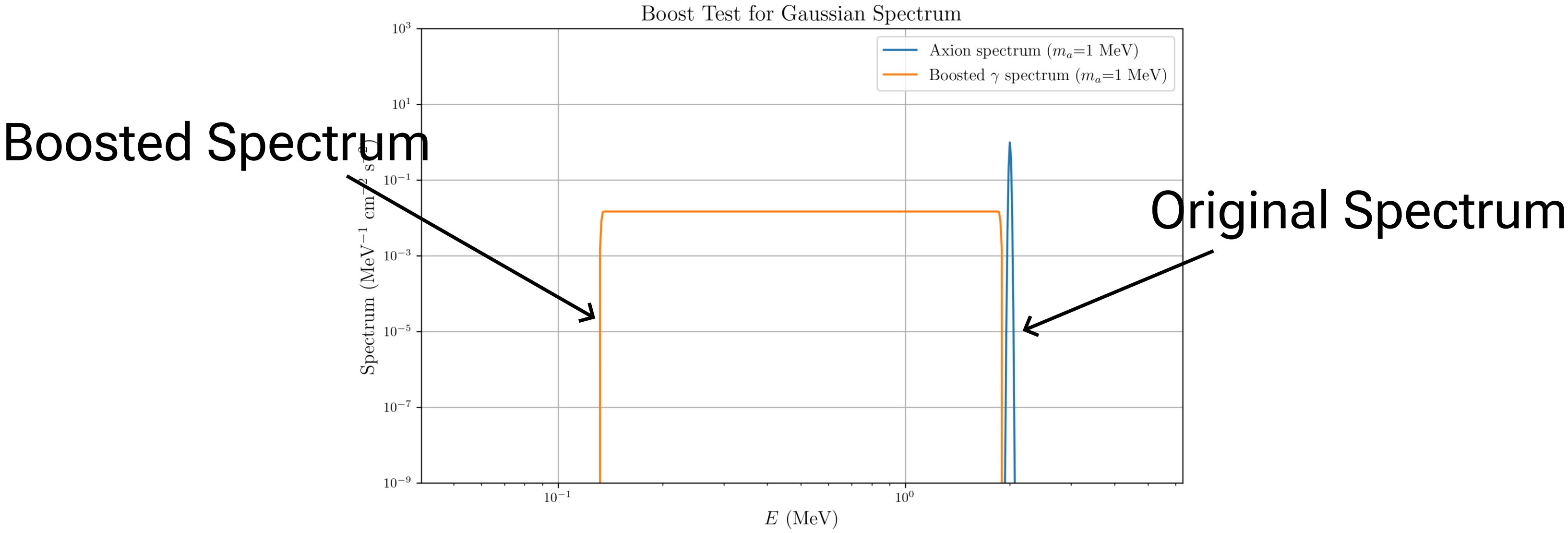
$$\gamma^k = \frac{\tilde{E}^k_{a,\mathrm{mid}}}{m_a}$$

E^*_γ

$$E^*_\gamma = \frac{m_a}{2} \text{ : Rest energy}$$

$$E^{\mathrm{min}}_\gamma = E^*_\gamma\left(\gamma^k - \sqrt{(\gamma^k)^2 - 1}\right)$$

$$E^{\mathrm{max}}_\gamma = E^*_\gamma\left(\gamma^k + \sqrt{(\gamma^k)^2 - 1}\right)$$



Calculation Steps

STEP 4 The expected differential photon flux with respect to energy

$$n_{\gamma_0}(E_{\gamma_0}, t_0) = \int_{(t_{a\gamma\gamma})_{\min}}^{\min(\tau_{\rm PBH}, t_0)} dt_{a\gamma\gamma}\ (1 + z(t_{a\gamma\gamma}))^{-3} \times \frac{dn_\gamma}{dt_{a\gamma\gamma}}(E'_\gamma, t_{a\gamma\gamma})$$

$$E'_\gamma|_t = (1 + z(t))E_{\gamma_0}$$

The expected photon spectral flux

$$\frac{dF_{\gamma_0}}{dE_{\gamma_0}} = \frac{n_{\gamma_0}}{E_{\gamma_0}}$$

in the natural units

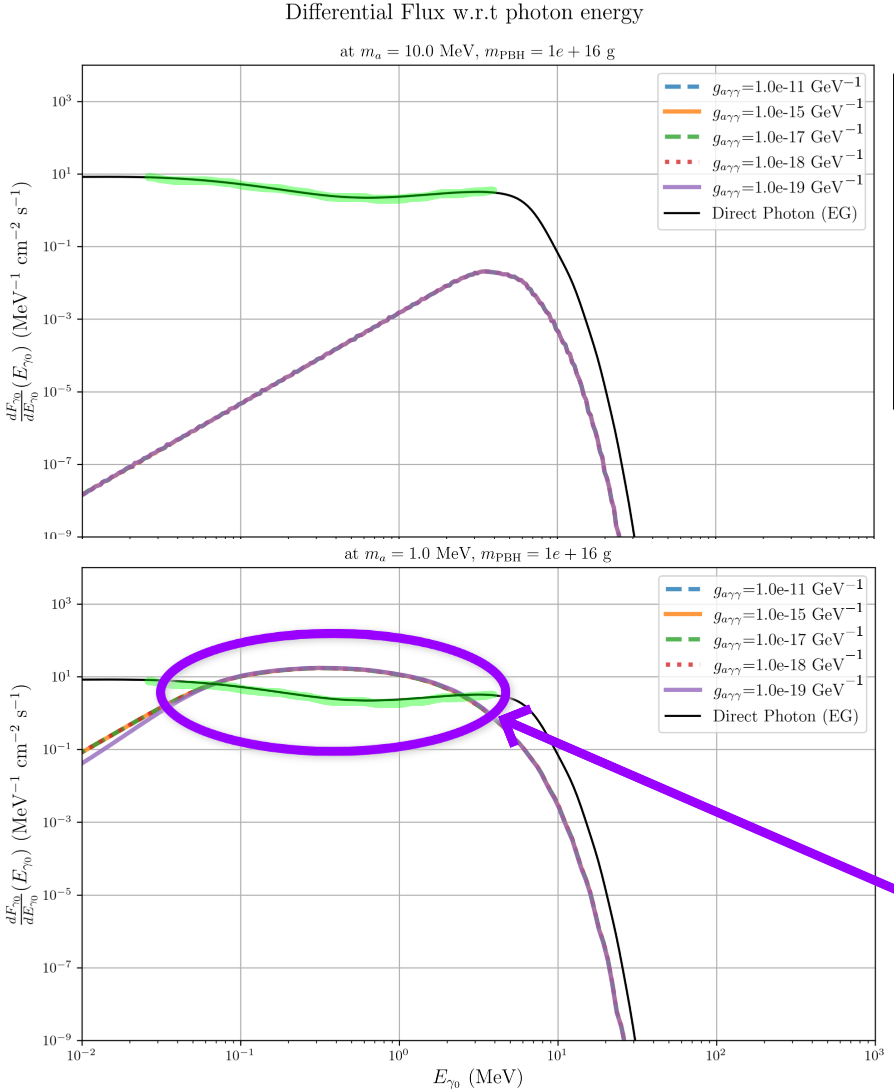
The Spectral Photon Flux

$$\frac{dF_{\gamma_0}}{dE_{\gamma_0}} = n_{{\rm PBH}(t_0)} \int_{(t_{a\gamma\gamma})_{\min}}^{\min(\tau_{\rm PBH}, t_0)} dt_{a\gamma\gamma}\ (1 + z(t_{a\gamma\gamma}))\frac{d^2 N_\gamma}{dE dt_{a\gamma\gamma}}(E'_\gamma, t_{a\gamma\gamma})\bigg|_{E=E'_\gamma}$$

$$n_{{\rm PBH}(t_0)} = \frac{f_{\rm PBH}\rho_{\rm DM}}{M_{\rm PBH}}$$

- $\rho_{\rm DM} = 2.35 \times 10^{-30} {\rm g\ cm}^{-3}$
  : The average energy density of dark matter in the present Universe
- $f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$: The fraction of PBH

The Spectral Photon Flux



- $m_{\rm PBH} = 1 \times 10^{16}$ g
- $g_{a\gamma\gamma} = [10^{-11}, 10^{-15}, 10^{-17}, 10^{-18}, 10^{-19}]$ GeV^{-1}
- The black line : Direct photon (EG) from PBH
- The green line over the Direct photon: the concave region

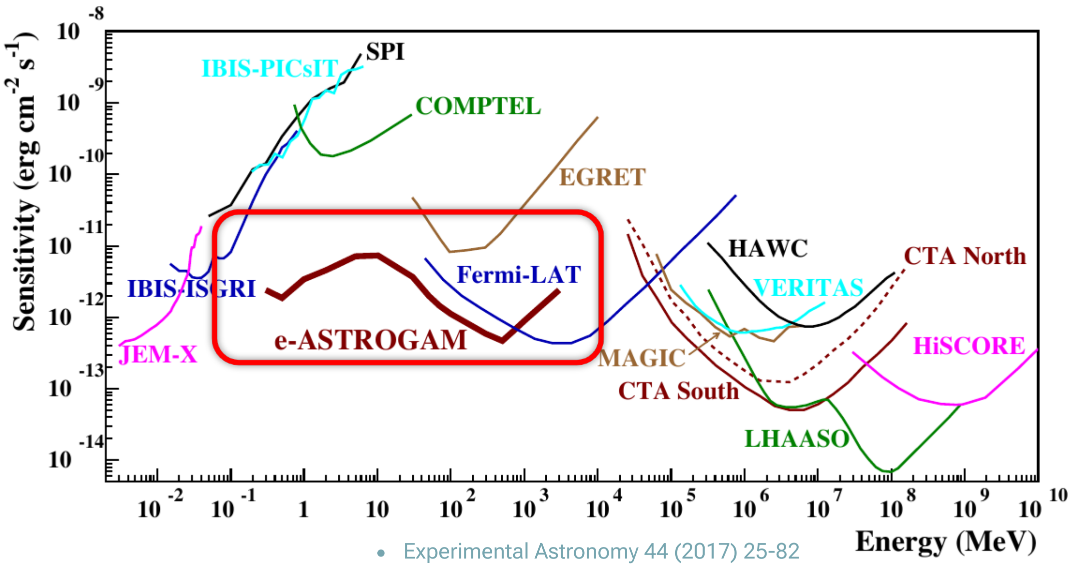
Comparision of examples

m_a	1.0 MeV	10 MeV
Peak Energy ($\mathrm{PBH} \to a \to \gamma\gamma$)	Lower	Higher
D. Flux ($\mathrm{PBH} \to a \to \gamma\gamma$)	Higher	Lower

There is a region where the generated photon in our model exceed the direct photon.

e-ASTROGAM Sensitivity

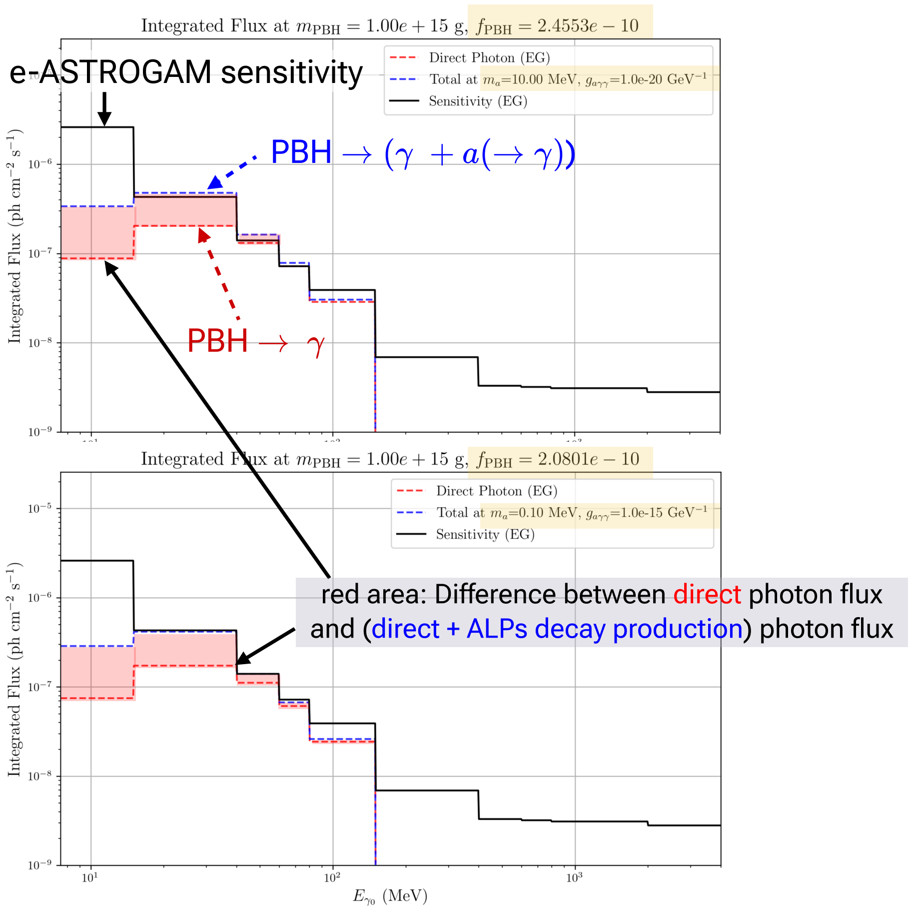
The exceed area seen earlier exists on the scale by MeV



- Experimental Astronomy 44 (2017) 25-82

- e-ASTROGAM open the window of MeV range
- One-two orders of magnitude improvement in sensitivity comparing to COMPEL experiment

e-ASTROGAM Sensitivity



e-ASTROGAM sensitivity

Gamma rays in the $\mathrm{MeV} - \mathrm{GeV}$ range

E (MeV)	ΔE (MeV)	Extragal. Sensitivity 3σ (ph cm^{-2} s^{-1})
10	7.5 - 15	2.6e-6
30	15 - 40	4.3e-7
50	40 - 60	1.4e-7
70	60 - 80	7.2e-8
100	80 - 150	3.9e-8
300	150 - 400	6.9e-9
500	400 - 600	3.3e-9
700	600 - 800	3.2e-9
1000	800 - 2000	3.1e-9
3000	2000 - 4000	2.8e-9

- Experimental Astronomy 44 (2017) 25-82

$\mathrm{PBH} \to \ \gamma$

$$f_{\rm PBH} \leq C(m_{\rm PBH})$$

VS

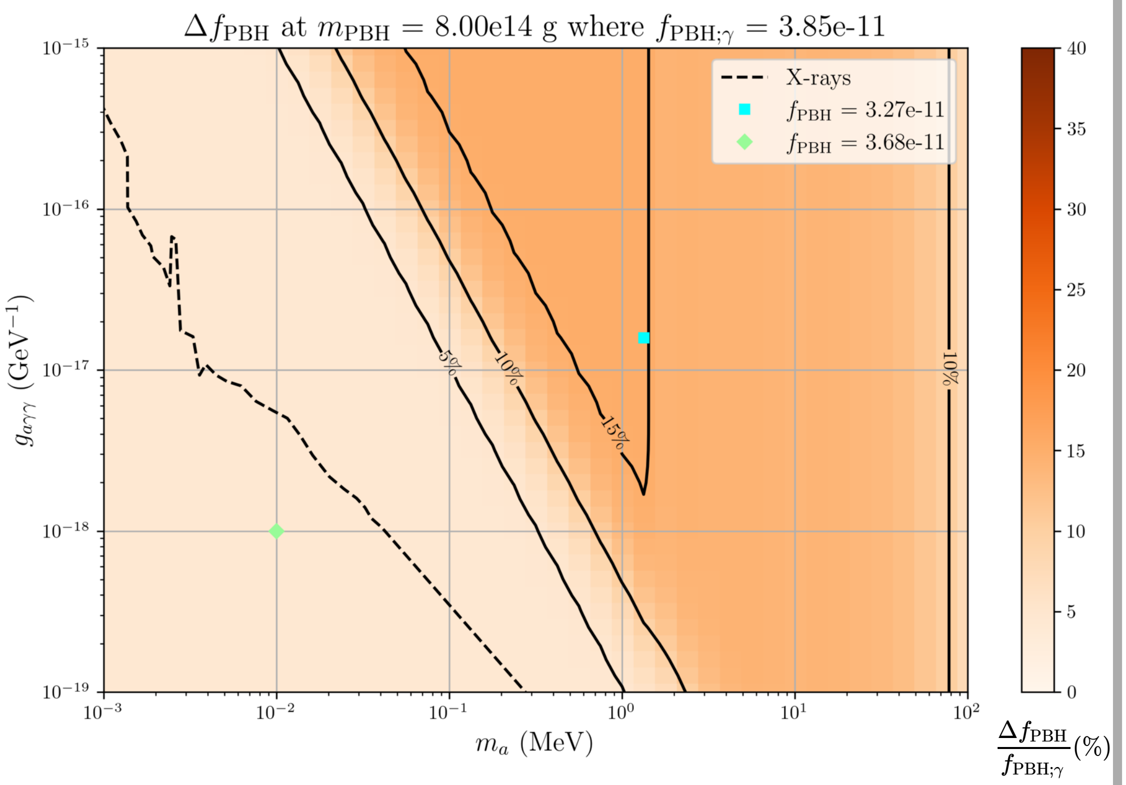
$\mathrm{PBH} \to (\gamma\ + a(\to \gamma))$

$$f_{\rm PBH} \leq C'(m_{\rm PBH}, m_a, g_{a\gamma\gamma})$$

If $C' < C$ effectively

$\Rightarrow$ **Enhanced!**

Result



$$\Delta f_{\mathrm{PBH}} = f_{\mathrm{PBH};\gamma} - f_{\mathrm{PBH;\,tot}}$$

$$\Delta f_{\mathrm{PBH}} / f_{\mathrm{PBH};\gamma} = \left(f_{\mathrm{PBH};\gamma} - f_{\mathrm{PBH;\,tot}}\right) / f_{\mathrm{PBH};\gamma}$$

- $f_{\mathrm{PBH};\gamma}$
  : PBH fraction by Direct photon
- f_{PBH}
  : PBH fraction by our model
- ■
  : Minimum value of f_{PBH}
- ◆
  : A reference point of f_{PBH}
- Contour
  : 5%, 10%, and 15% improvement over f_PBH from direct photon
- X-rays
  : From other experiment (axion decay), independent on f_{PBH}

Summary

- PBH is a good source for emitting both SM / BSM particles through hawking radiation.
- For numerical calculations, the emission rate of particles containing a complex graybody factor was calculated using the program BlackHawk.
- Considering the redshift and boost effects of particles flying across the expanding universe, we formulate the amount of photon flux observed from the Earth.
- The process (PBH $\to a \to \gamma\gamma$) can significantly increase the amount of photon flux some parameter space.
- Through the sensitivity of e-ASTROGAM, which is 1-2 orders of magnitude better than the previous observation, Our model imposes the stringent constraint of $f_{\rm PBH}$ in the $(g_{a\gamma\gamma} - m_a)$ parameter space.