Exploration of PBHs and ALPs through a novel decay model on cosmological scale

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arXiv: 2212.11977

Primordial Black Hole

- Cosmologically produced (e.g., during the inflationary epoch)
- Considered as one of the viable candidates for dark matter
- Possess the ability to evaporate through a process known as *Hawking radiation*
- **Hawking temperature of PBH**

$$k_B T_{\text{PBH}} = \frac{\hbar c^3}{8\pi G M_{\text{PBH}}} \sim 10.6 \left(\frac{10^{15}\text{g}}{M_{\text{PBH}}}\right) \text{MeV} \sim 10^{11}\ \text{K}$$

- **The lifetime of PBH** [Don N. Page, Phys. Rev. D 13, 198 (1976)]

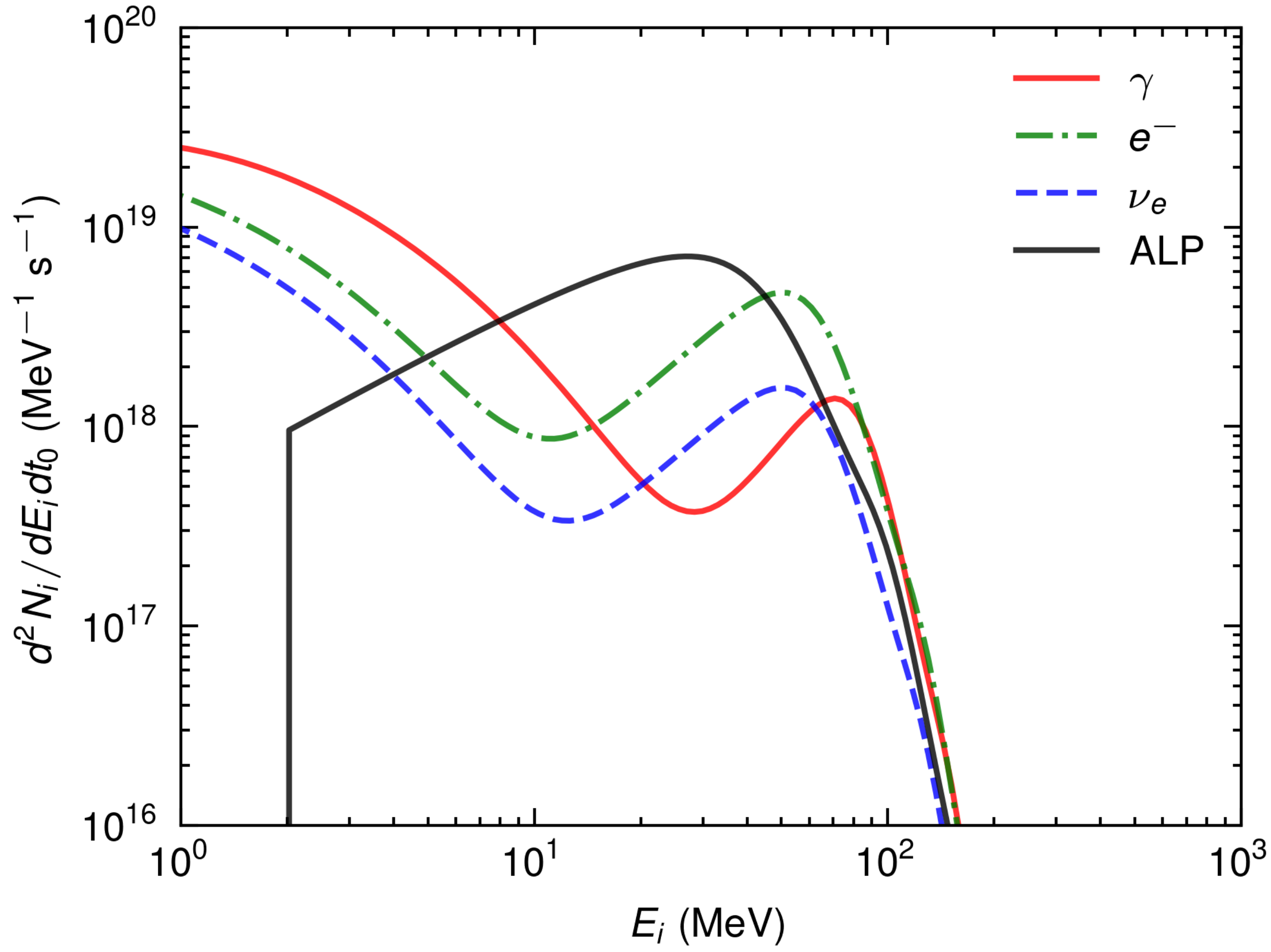
$$\tau_{\text{PBH}} \sim 13.8 \times 10^9 \text{yr} \left(\frac{M_{\text{PBH}}}{5 \times 10^{14}\text{g}}\right)^3$$

- **Emission rates of particle i** - This can be computed by `BlackHawk`

[Alexandre Arbey, Jérémy Auffinger, Eur. Phys. J. C 81 10, 910 (2010)]

$$\frac{d^2 N_i}{dEdt} = \frac{g_i}{2\pi} \frac{\Gamma(E, M_{\text{PBH}})}{e^{E/k_B T_{\text{PBH}}} - (-1)^{2s_i}}$$

PBH as a Particle Factory



Photons from PBH

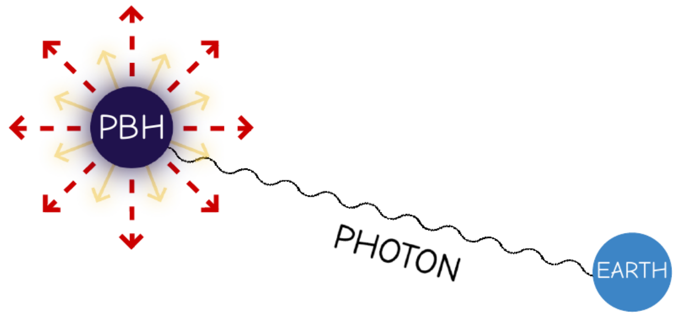


Fig.1 Photon from PBH

Our assumptions on PBH

- Monochromatic mass distribution
- Schwarzschild PBH
- Isotropically distributed

Differential photon flux from Extragalaxy

[B. J. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, Phys. Rev. D 81, 104019 (2010)]

$$\frac{\mathrm{d}F_{\gamma_0}}{\mathrm{d}E_{\gamma_0}} = n_{\mathrm{PBH}}(t_0) \int_{t_{\mathrm{CMB}}}^{\min(\tau_{\mathrm{PBH}}, t_0)} \mathrm{d}t\ (1+z(t))\ \frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}E\mathrm{d}t}\bigg|_{E=(1+z(t))E_{\gamma_0}}$$

$$n_{\mathrm{PBH}}(t_0) = \frac{f_{\mathrm{PBH}}\rho_{\mathrm{DM}}}{M_{\mathrm{PBH}}},\ \rho_{\mathrm{DM}} = 2.35 \times 10^{-30}\mathrm{g\ cm}^{-3},\ f_{\mathrm{PBH}} = \Omega_{\mathrm{PBH}}/\Omega_{\mathrm{DM}}$$

Flux of photons from PBH

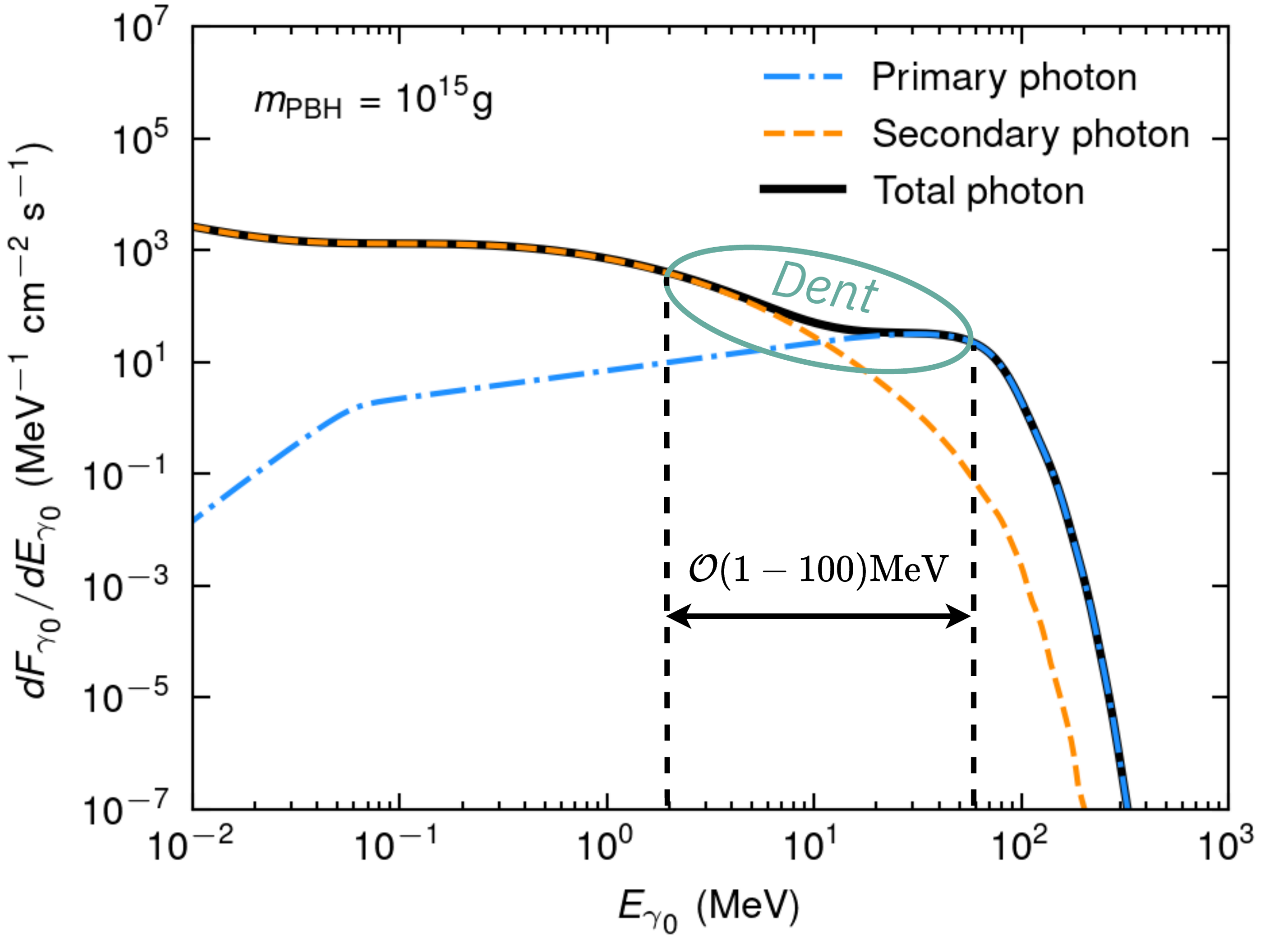
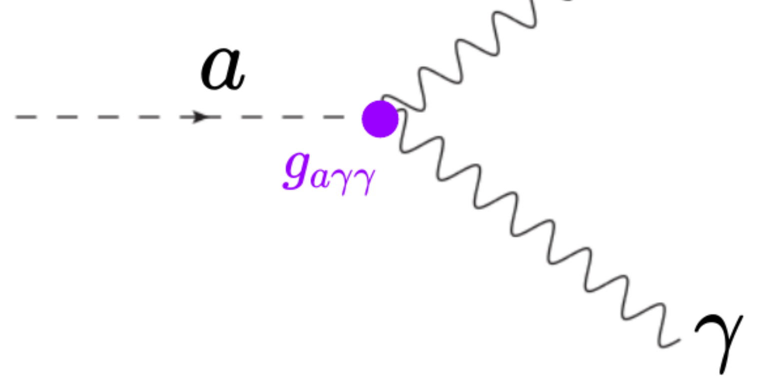


Fig.2 Redshifted differential flux of (primary + secondary) photon

Axion-Like Particles (ALPs)

- ALPs : Pseudo NG bosons of the spontaneously broken global $U(1)$ symmetry
- ALPs studies in cosmology : inflation, dark matter, relaxion and etc.
  - [Katherine Freese, Joshua A. Frieman, and Angela V. Olinto-Phys. Rev. Lett. 65, 3233 (1990)]
  - [P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald-JCAP06013 (2012)]
  - [P. W. Graham, D. E. Kaplan, and S. Rajendran-Phys. Rev. Lett. 115 no. 22, 221801 (2015)]
- Astrophysical sources of ALPs : SN, Sun, NS, **PBH**, and etc.

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



Properties

- Decays to 2 photons
- Its mass and the coupling to photons are *independent* in general

Motivation for time-varying decay

$$\text{ALP's mean lifetime} : \gamma\tau_a = \frac{64\pi E_a}{g_a^2 m_a^4} \equiv \frac{\gamma}{\Gamma_a}$$

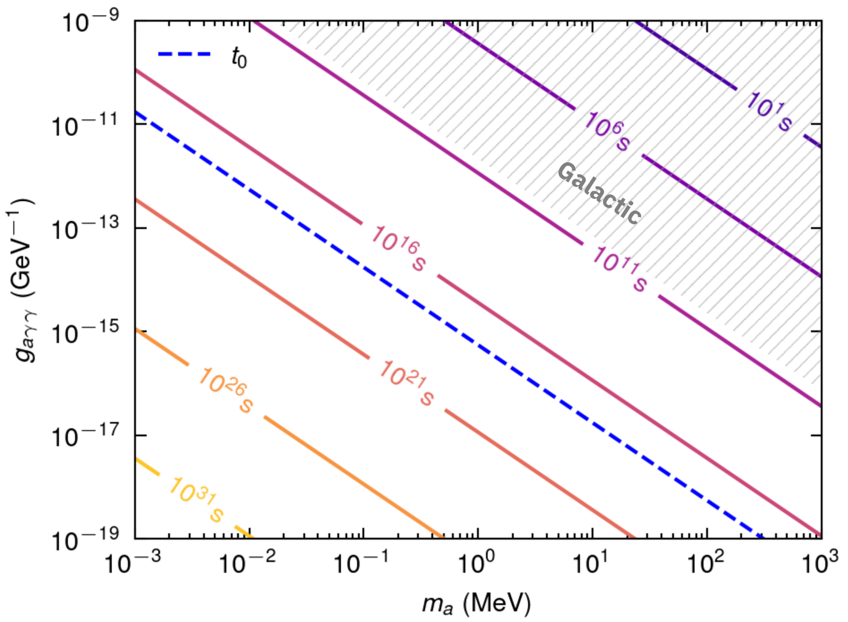


Fig.3 Mean lifetime of ALPs in the rest frame

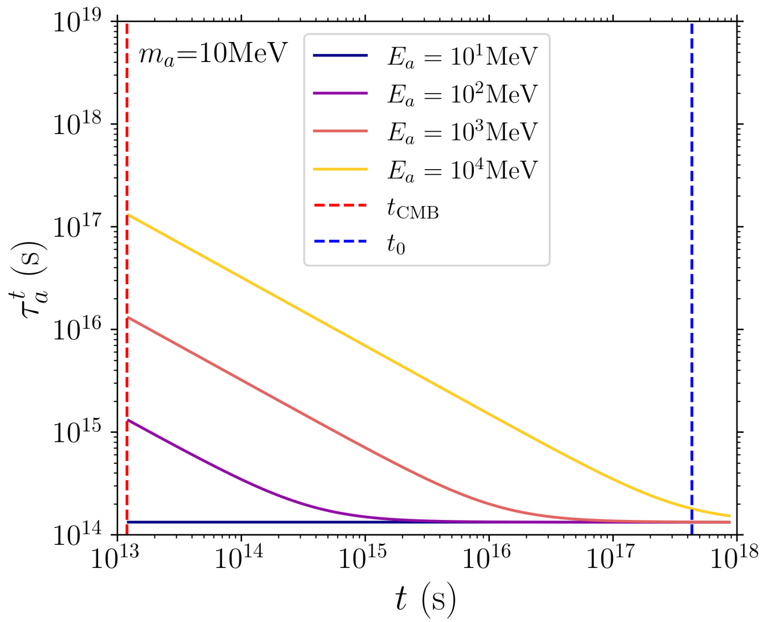


Fig.4 Mean lifetime of ALPs from CMB (Boosted + Redshifted)

$$\therefore \ \text{ALP's mean lifetime} : \tau_a^t \equiv \gamma(t)\tau_a = \frac{64\pi E_a(t)}{g_a^2 m_a^4} \equiv \frac{1}{\Gamma_a^t}$$

Decay equation

- **Time-varying decay equation**

$$\frac{\mathrm{d}N_a}{dt} = -\Gamma_a^t N_a \;\Rightarrow\; N_a(t) = N_a(t_e)\exp\left(-\int_{t_e}^{t} \Gamma_a^{t';t_e}\,\mathrm{d}t'\right)$$

- **Time-varying decay in terms of Survival analysis**

[D. G. Kleinbaum (1996) Survival analysis: A self learning text. New York: Springer]

Survival analysis	Expression	Time-varying decay	Notation
Survival function	$S(t) = \mathbb{P}[X > t]$	Survival probability	P_{surv}
Hazard function	$h(t) = -\frac{\mathrm{d}}{\mathrm{d}t}[\log S(t)]$	Decay rate	Γ_a^t
Failure density function	$\int_0^t f(u)du = 1 - S(t)$	Decay density function	$\mathcal{P}_{\text{decay}}$

Decay number density

- **Survival probability & Decay density function**

$$P_{\rm surv}(t; t_e, E_a) = \exp\left(- \int_{t_e}^{t} \Gamma_a^{t';t_e} \, \mathrm{d}t' \right)$$

$$\mathcal{P}_{\rm decay}(t; t_e, E_a) = P_{\rm surv}(t; t_e, E_a) \times \Gamma_a^{t;t_e}$$

- **Differential number density for decaying ALPs**

From (t_e, E_a) to t :

$$\phi_a(t; t_e, E_a) = \frac{\mathrm{d}n_a}{\mathrm{d}t_e} \times \mathcal{P}_{\rm decay}(t; t_e, E_a)$$

From t_e to $(t, \widetilde{E}_a)$:

$$\phi_a(t, \widetilde{E}_a; t_e) = \phi(t; t_e, E_a)\Big|_{E_a = \mathcal{R}^{-1}_{t \to t_e}(\widetilde{E}_a)}$$

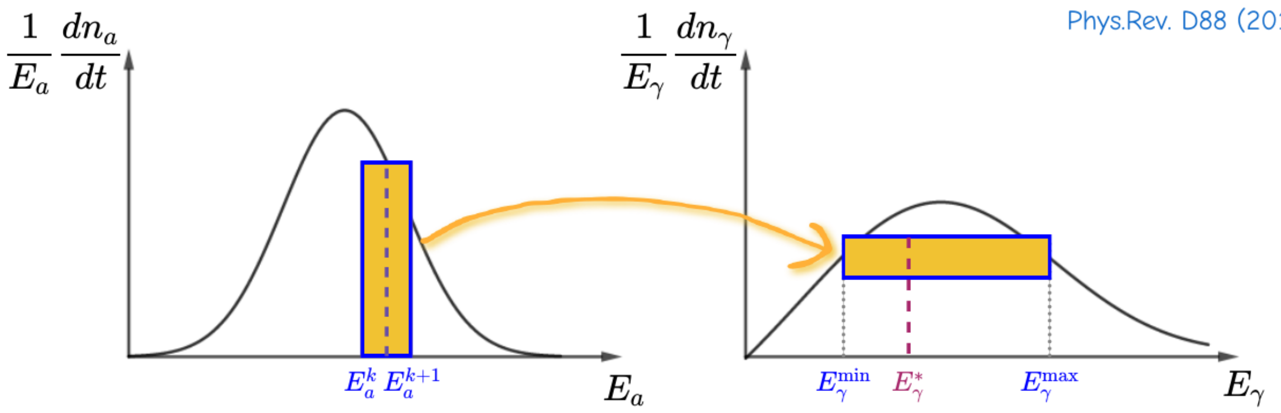
$$\therefore \text{ At } (t, E_a) : \quad \frac{\mathrm{d}n_a^{\rm dec}}{\mathrm{d}t} = \int_{t_e^{\rm min}}^{t} \left(\frac{1+z(t)}{1+z(t_e)} \right)^3 \phi_a(t, E_a; t_e) \mathrm{d}t_e$$

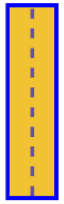
Boosted ALP decay to photons

- Using *Two body decay kinematics* to describe the decay of ALP to photon: $a \to \gamma\gamma$
- Lorentz boost : $E_\gamma = E^*_\gamma(\gamma \pm \sqrt{\gamma^2 - 1})$ where $E^*_\gamma = m_a/2$

[Schematic Figure For This Process]

- Kaustubh Agashe, Roberto Franceschini, and Doojin Kim Phys.Rev. D88 (2013) 5, 057701





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

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

$$E^*_\gamma = \frac{m_a}{2}$$

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

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

Boosted & Redshifted photon flux

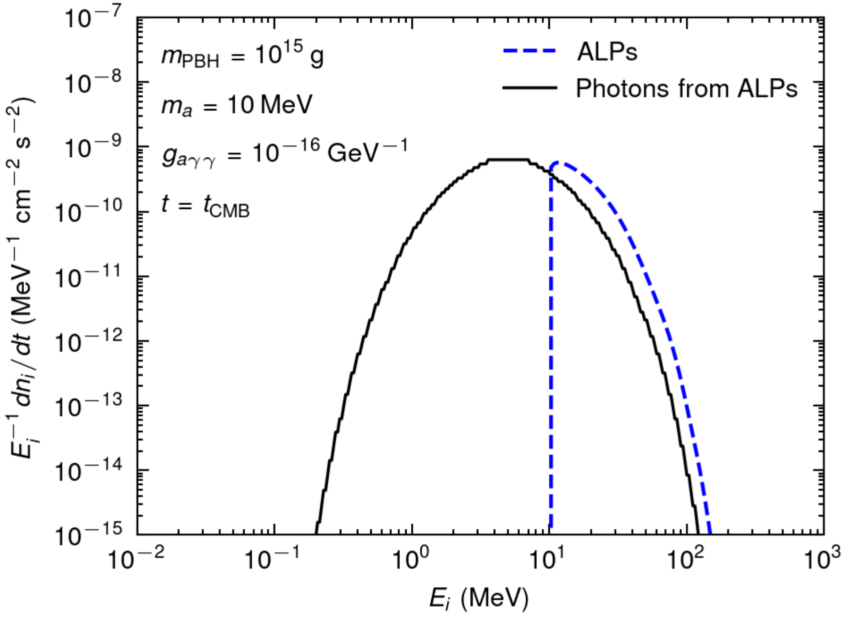


Fig.5 Boosted photon spectrum

- **Boosted photon flux**

[K. Agashe, R. Franceschini, and D. Kim, Phys. Rev. D 88, 057701 (2013)]

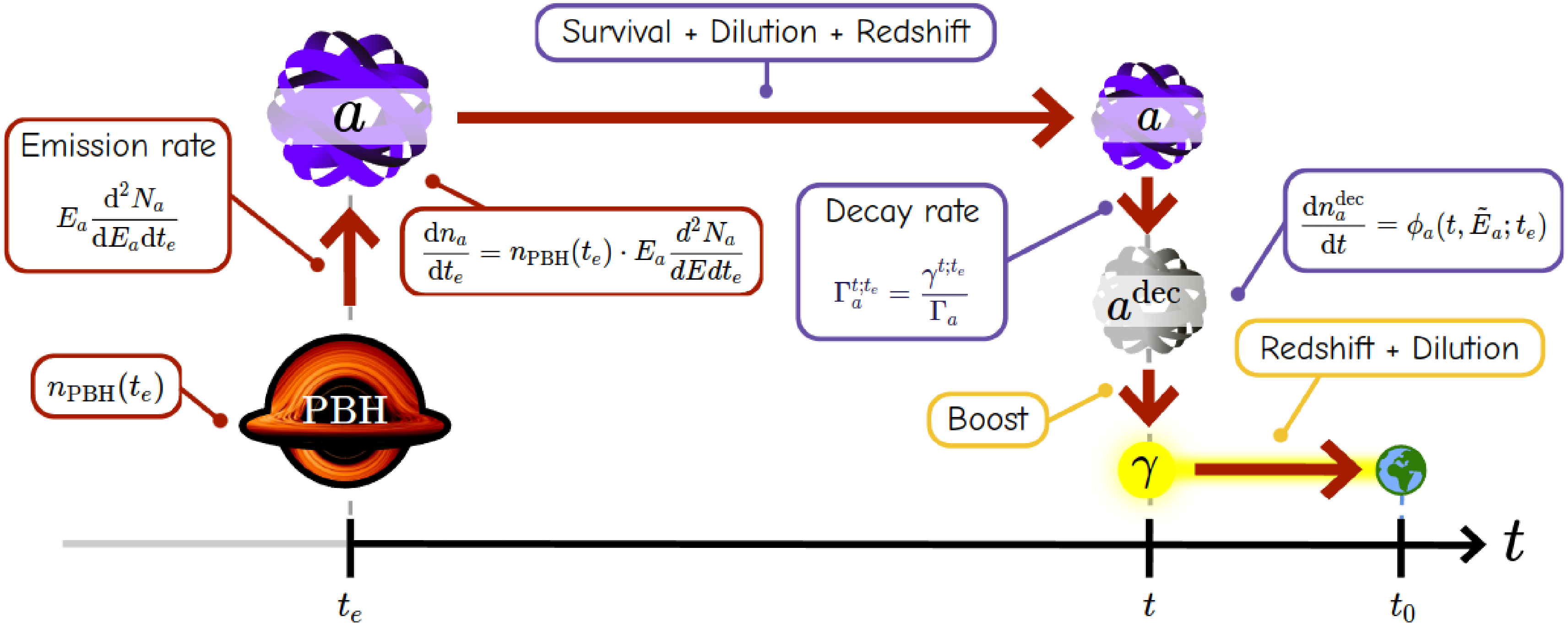
$$\left\{\left(E_a, \frac{1}{E_a}\frac{\mathrm{d}n_a^{\rm dec}}{\mathrm{d}t}\right)\right\} \xrightarrow{\text{Boost}} \left\{\left(E_\gamma, \frac{1}{E_\gamma}\frac{\mathrm{d}n_\gamma}{\mathrm{d}t}\right)\right\}$$

- **Integration of redshifted photon flux**

[B. J. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, Phys. Rev. D 81, 104019 (2010)]

$$\frac{\mathrm{d}F_{\gamma_0}}{\mathrm{d}E_{\gamma_0}} = \int_{t_{\rm CMB}}^{t_0} \frac{\mathrm{d}t}{(1+z(t))^3 E_{\gamma_0}} \frac{\mathrm{d}n_\gamma}{\mathrm{d}t}\bigg|_{E_\gamma=(1+z(t))E_{\gamma_0}}$$

Summary of time-varying decay



Differential flux of photons

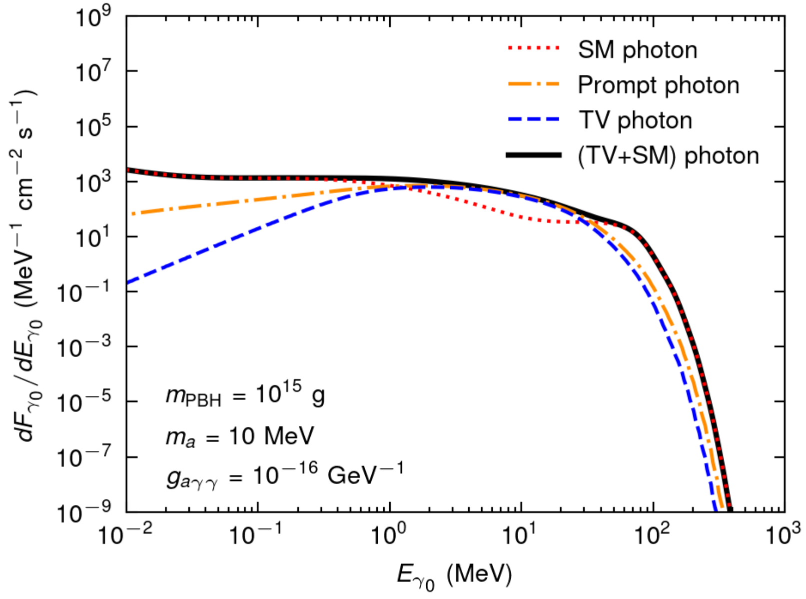


Fig.6 Differential flux for $g_a = 10^{-16}\mathrm{GeV}^{-1}$

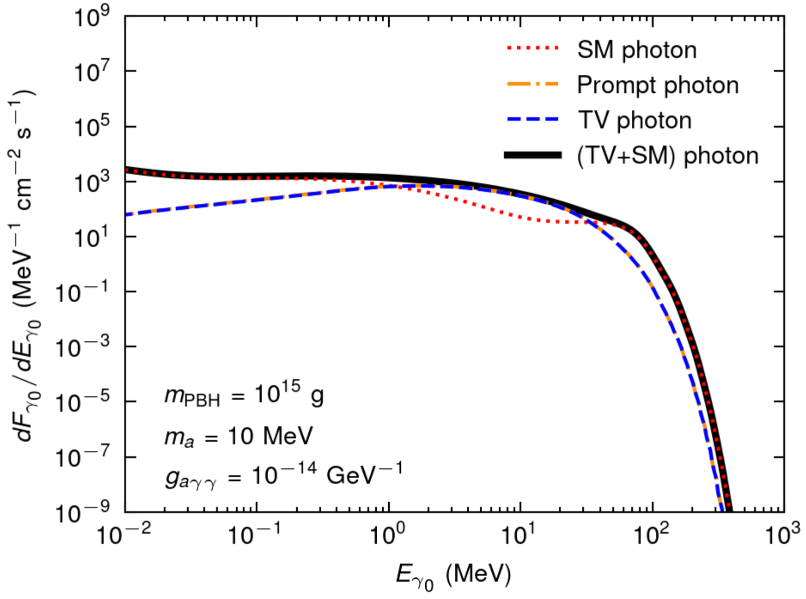
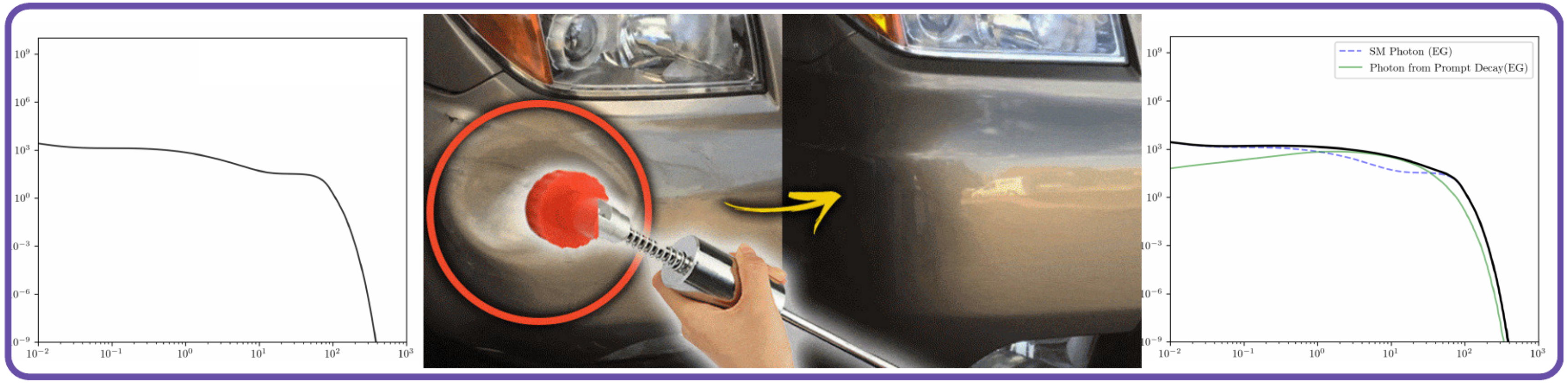


Fig.7 Differential flux for $g_a = 10^{-14}\mathrm{GeV}^{-1}$

ALPs : "The dent puller"

Dent (without ALP) Pull (with ALP)



Dent Puller = ALPs

e-ASTROGAM

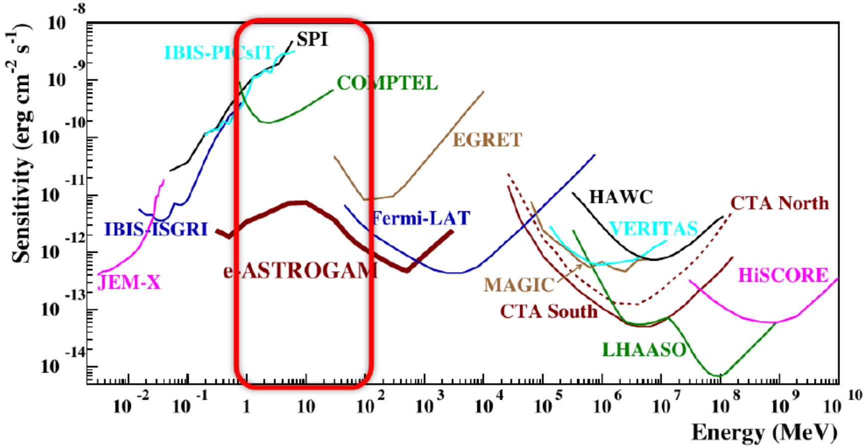
[Experimental Astronomy 44 (2017) 25-82]

- **A gamma-ray mission** and the planned launch date is 2029 by ESA

- Sensitive in **1 ~ 1000 MeV** range

- 1-2 orders of magnitude improvement in sensitivity comparing to COMPTEL experiment

The exceed area is occurred in $\mathcal{O}(1 - 100)\mathrm{MeV}$



Gamma rays in the MeV – GeV range

E (MeV)	Galactic center Sensitivity (ph cm^{-2} s^{-1})	Extragal. Sensitivity 3σ (ph cm^{-2} s^{-1})
7.5 - 15	1.3×10^{-5}	2.6×10^{-6}
15 - 40	2.4×10^{-6}	4.3×10^{-7}
40 - 60	8.0×10^{-7}	1.4×10^{-7}
60 - 80	4.5×10^{-7}	7.2×10^{-8}
80 - 150	2.7×10^{-7}	3.9×10^{-8}
150 - 400	7.8×10^{-8}	6.9×10^{-9}
400 - 600	3.8×10^{-8}	3.3×10^{-9}
600 - 800	2.5×10^{-8}	3.2×10^{-9}
800 - 2000	1.4×10^{-8}	3.1×10^{-9}
2000 - 4000	5.0×10^{-9}	2.8×10^{-9}

e-ASTROGAM for PBH

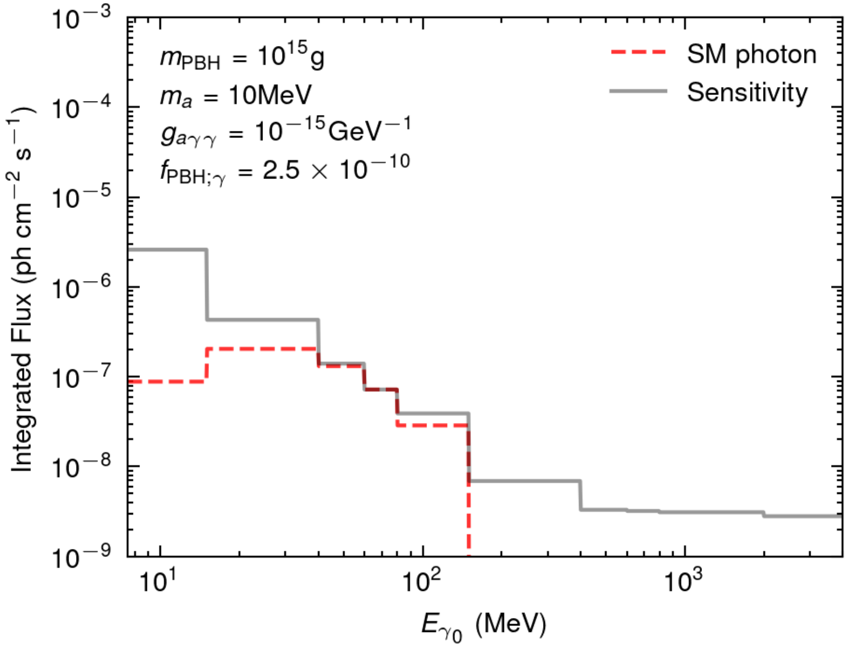


Fig.8 $f_{\rm PBH}$ for SM photon only

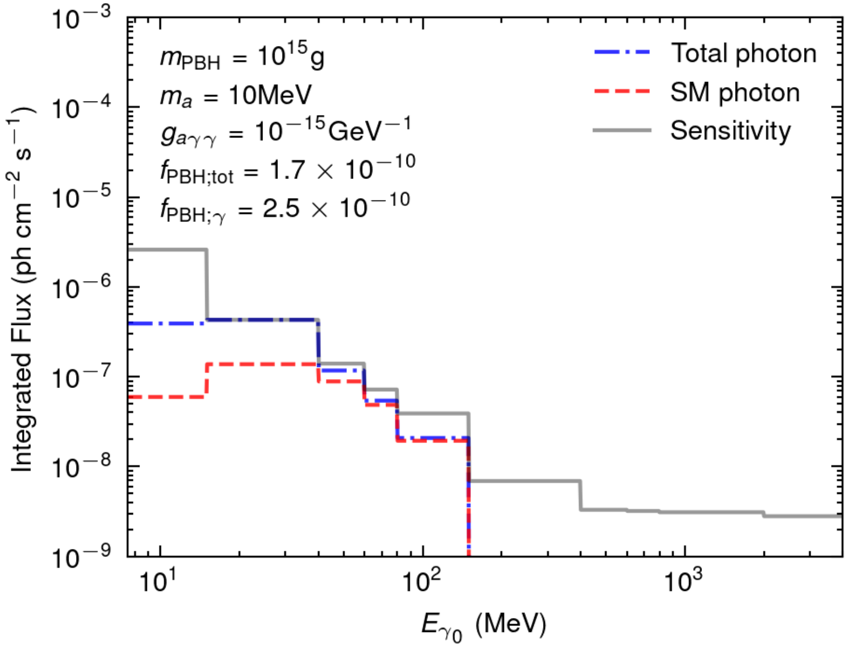


Fig.9 $f_{\rm PBH}$ for total photon

e-ASTROGAM for PBH

GC: M. J. Dolan, F. J. Hiskens, and R. R. Volkas, [arXiv:2207.03102] (2022)
SN1987A: J. Jaeckel, P. C. Malta, and J. Redondo, Phys. Rev. D 98, 055032 (2018)

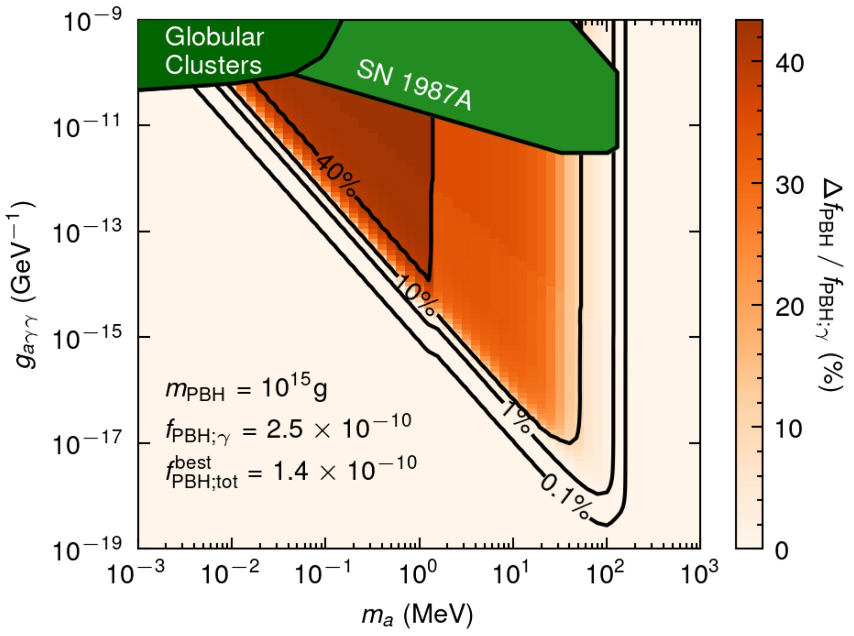


Fig.10 $\Delta f_{\rm PBH}/f_{\rm PBH;\gamma}$ $(m_{\rm PBH} = 10^{15}{\rm g})$

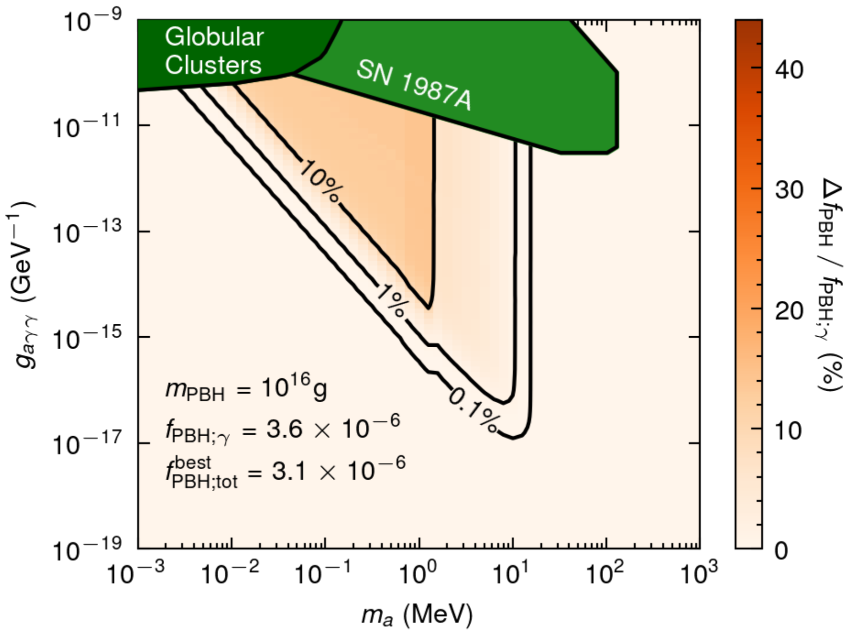


Fig.11 $\Delta f_{\rm PBH}/f_{\rm PBH;\gamma}$ $(m_{\rm PBH} = 10^{16}{\rm g})$

$$\Delta f_{\rm PBH} \equiv |f_{\rm PBH;tot} - f_{\rm PBH;\gamma}|$$

Results & Summary

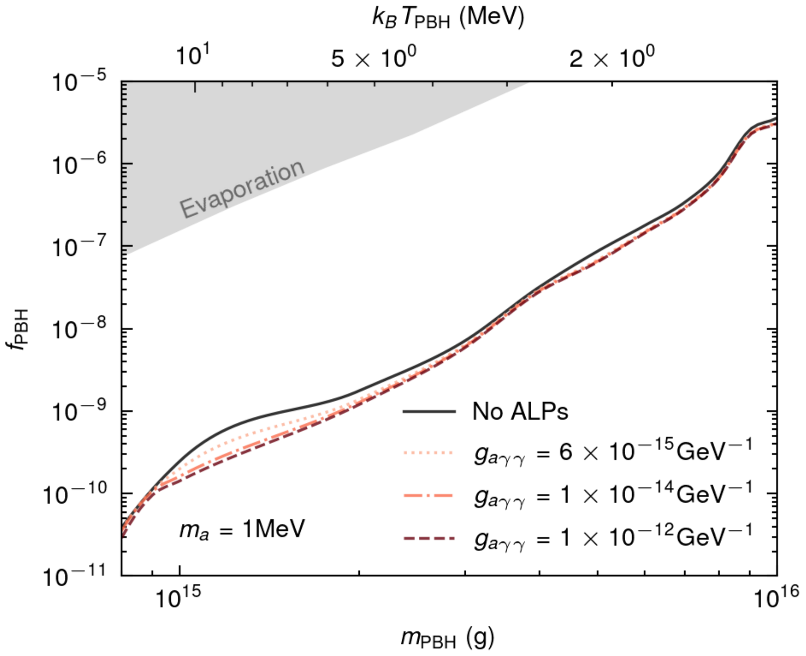


Fig.12 New constraint for PBHs ($m_a = 1\text{MeV}$)

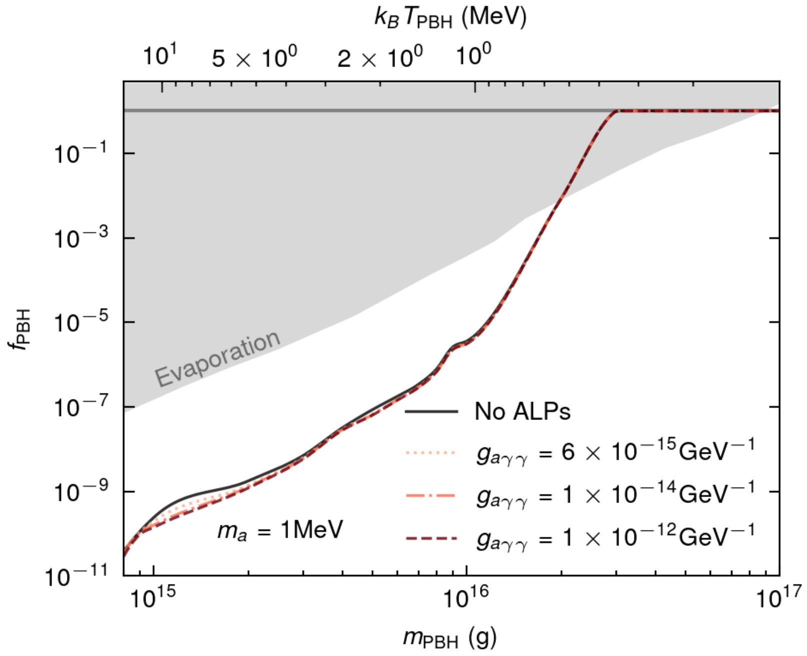


Fig.13 New constraint for PBHs ($m_a = 1\text{MeV}$) (extend)

1️⃣ For particles with a very long lifetime, time-varying decay must be considered.

2️⃣ When examining ALPs decay, the boost effect on photons should be taken into account.

☑️ By using PBHs as a source of ALPs, we can establish new constraints on PBHs.