Constraining ALPs via PBH

with time-varying decay process

Tae-Geun Kim

Yonsei University

with Yongsoo Jho, Jongchul Park, Seongchan Park, Yeji Park

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Primordial Black Hole

- Produced cosmologically (e.g. during inflation)

- The one of viable candidates for dark matter

- It can be evaporated through Hawking radiation

- **Hawking temperature of PBH**

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

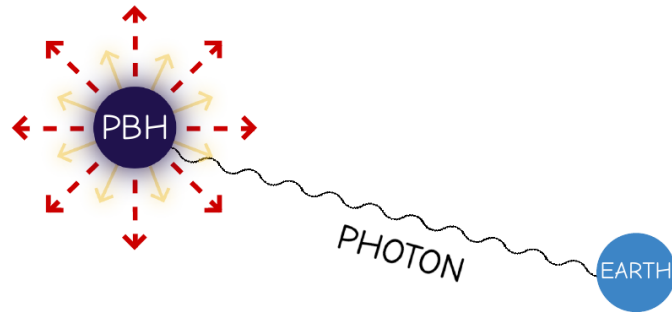- **Emission rates of i particle** - This can be computed by `BlackHawk`

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

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

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

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

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)]

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

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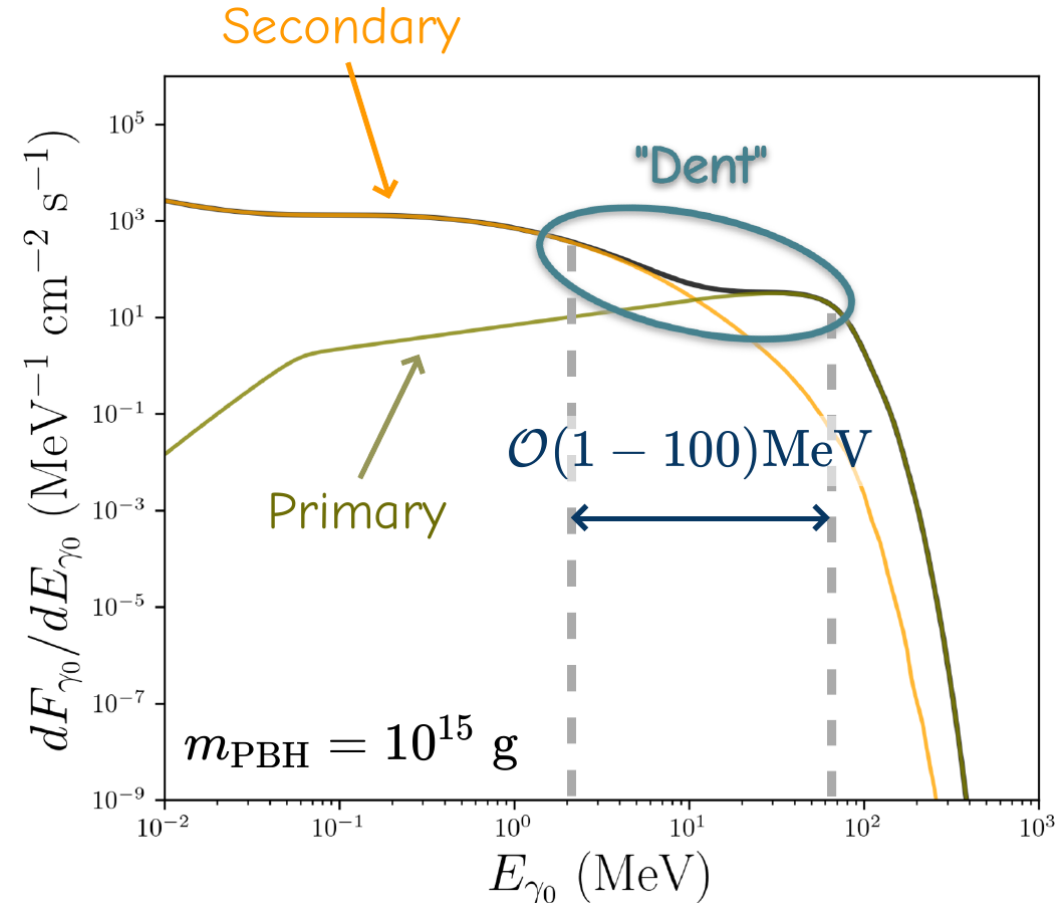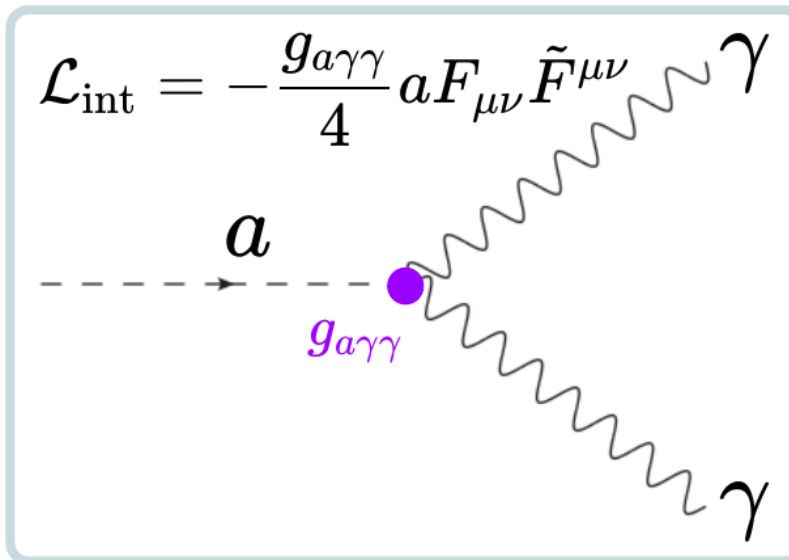
Flux of photons from PBH

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.

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

Properties

- Decays to 2 photons

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

Motivation for time-varying decay

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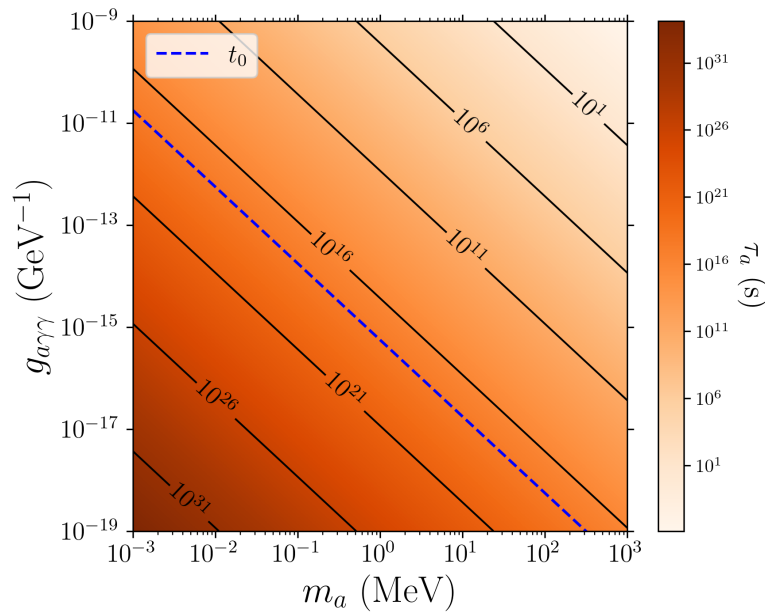

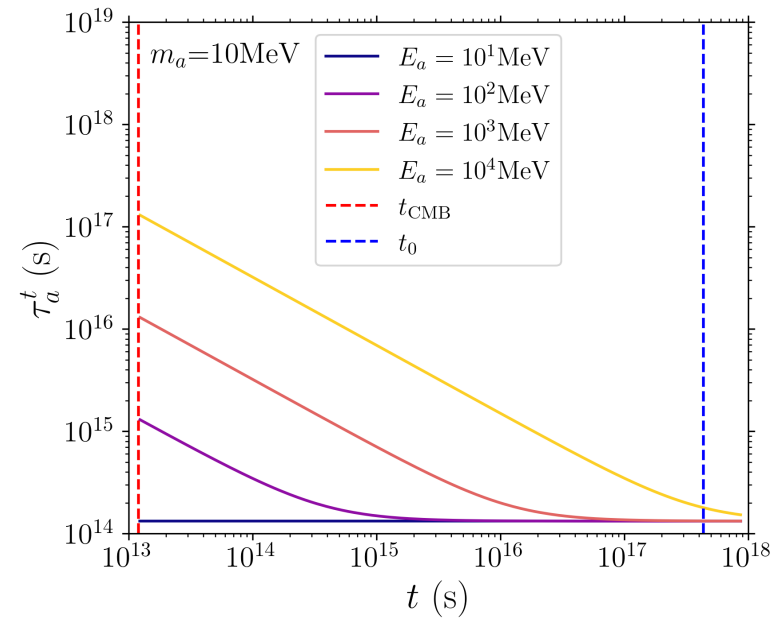**Fig.3** Mean lifetime of ALPs in the rest frame

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

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

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	$h(t) = -\dfrac{\mathrm{d}}{\mathrm{d}t}[\log S(t)]$	Decay rate	Γ_a^t
Failure density function	$\displaystyle\int_0^t f(u)\,du = 1 - S(t)$	Decay density function	$\mathcal{P}_{\mathrm{decay}}$

Decay number density

- **Survival probability & Decay density function**

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

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

- **Differential number density for decaying ALPs**

From (t_e, E_a) **to** t :

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

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

$$\phi_a(t, \widetilde{E}_a; t_e) = \phi(t; t_e, E_a)\Big|_{E_a = \mathcal{R}_{t \to t_e}^{-1}(\widetilde{E}_a)}$$
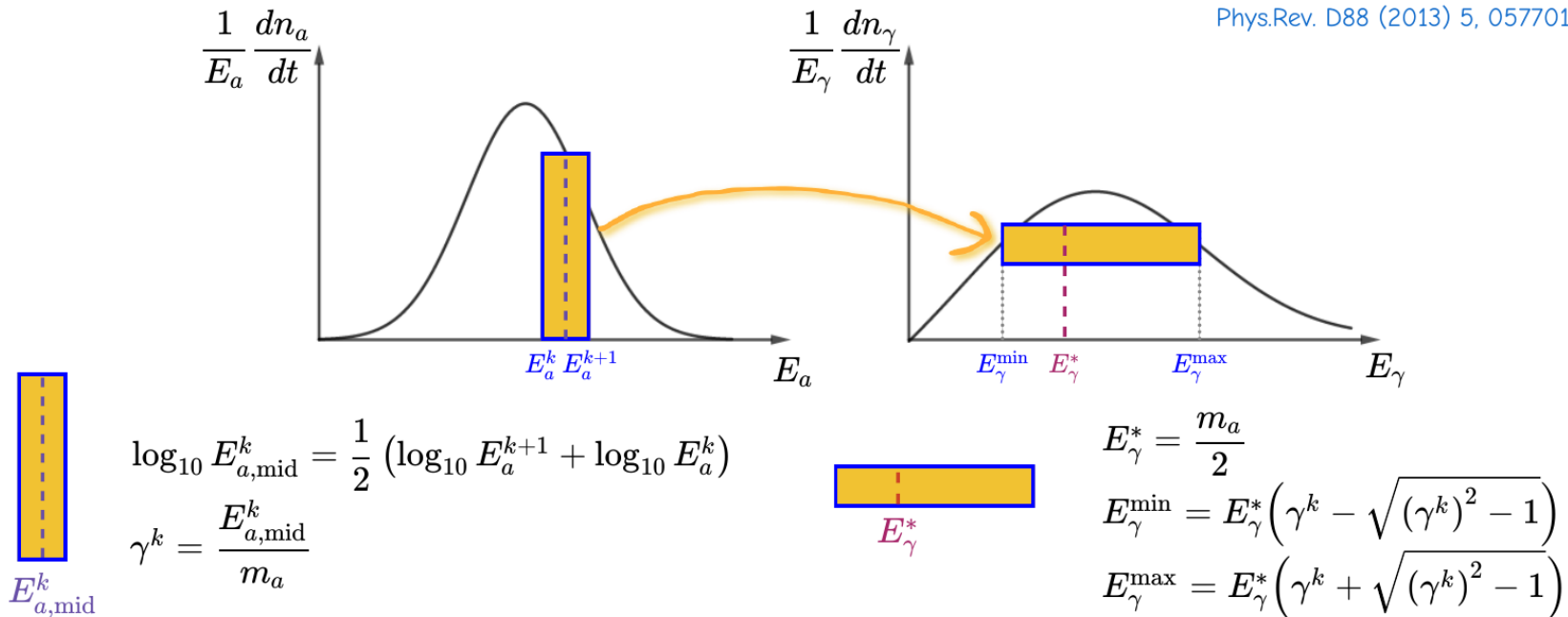
$$\therefore \text{ At } (t, E_a): \quad \frac{\mathrm{d}n_a^{\mathrm{dec}}}{\mathrm{d}t} = \int_{t_e^{\min}}^{t} \left(\frac{1 + z(t)}{1 + z(t_e)}\right)^3 \phi_a(t, E_a; t_e)\mathrm{d}t_e$$

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

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

$$\gamma^k = \frac{E_{a,\text{mid}}^k}{m_a}$$

$$E_\gamma^* = \frac{m_a}{2}$$

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

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

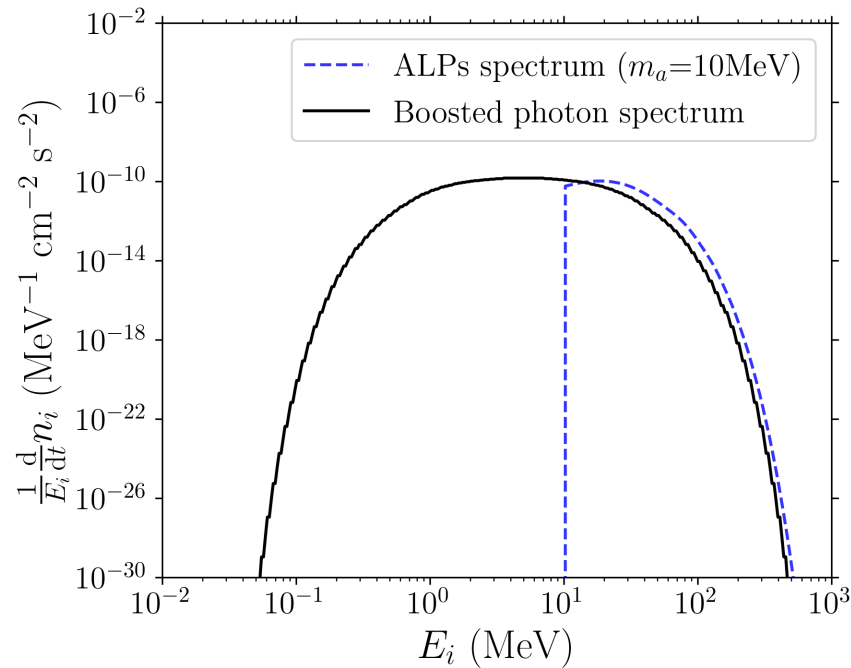# Boosted & Redshifted photon flux

Fig.5 Boosted photon spectrum

- **Boosted photon flux**
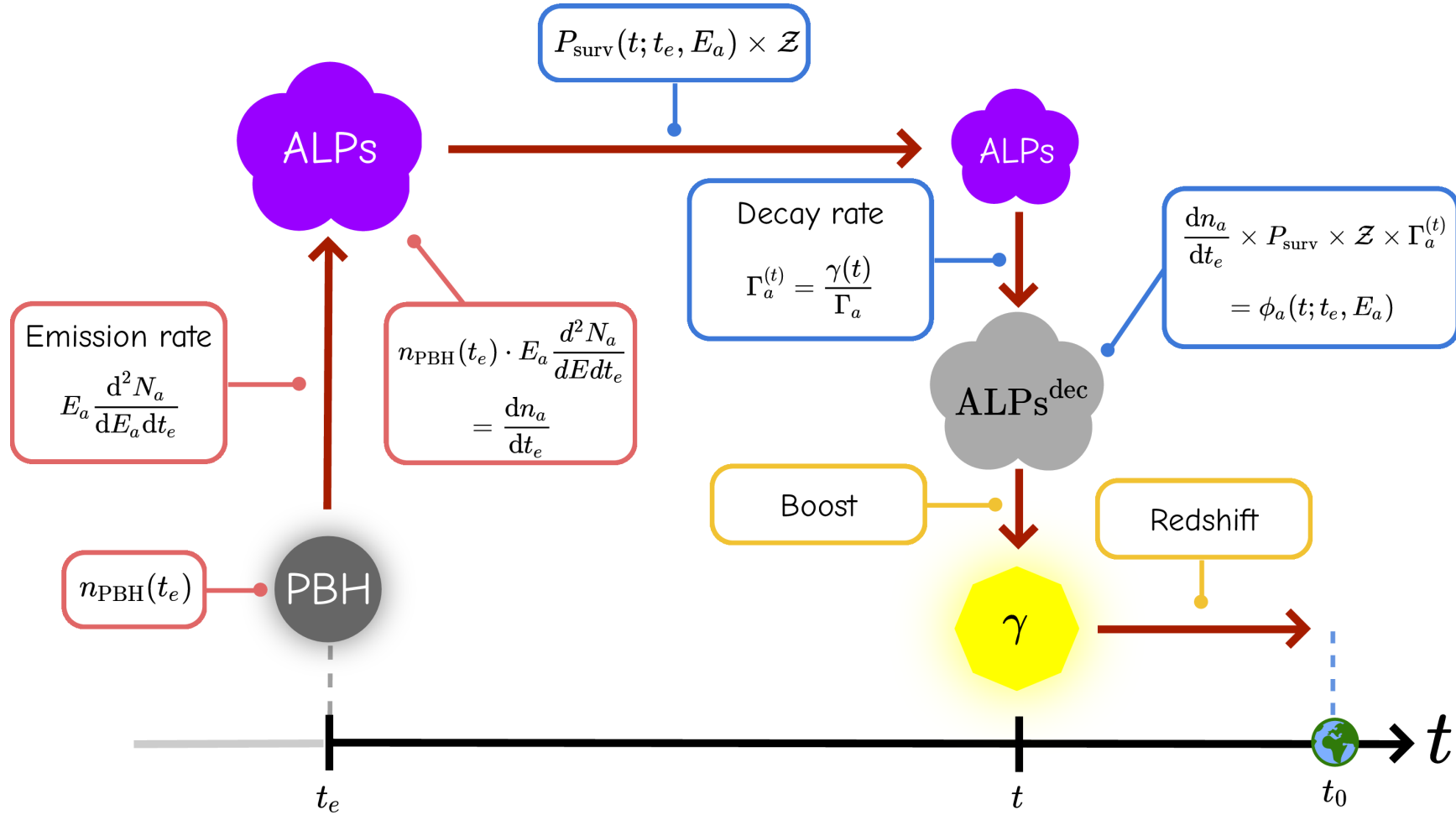 [K. Agashe, R. Franceschini, and D. Kim, Phys. Rev. D 88, 057701 (2013)]

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

- **Integration of redshifted photon flux**
  [B. J. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, Phys. Rev. D 81, 104019 (2010)]

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

Summary of time-varying decay

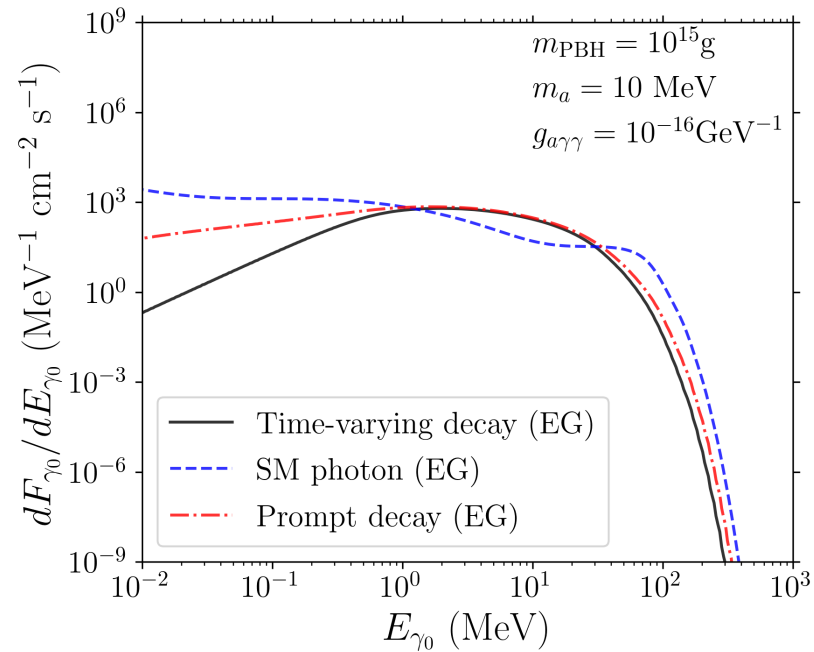# Differential flux of photons

Fig.6 Differential flux for $g_a = 10^{-16} \mathrm{GeV}^{-1}$
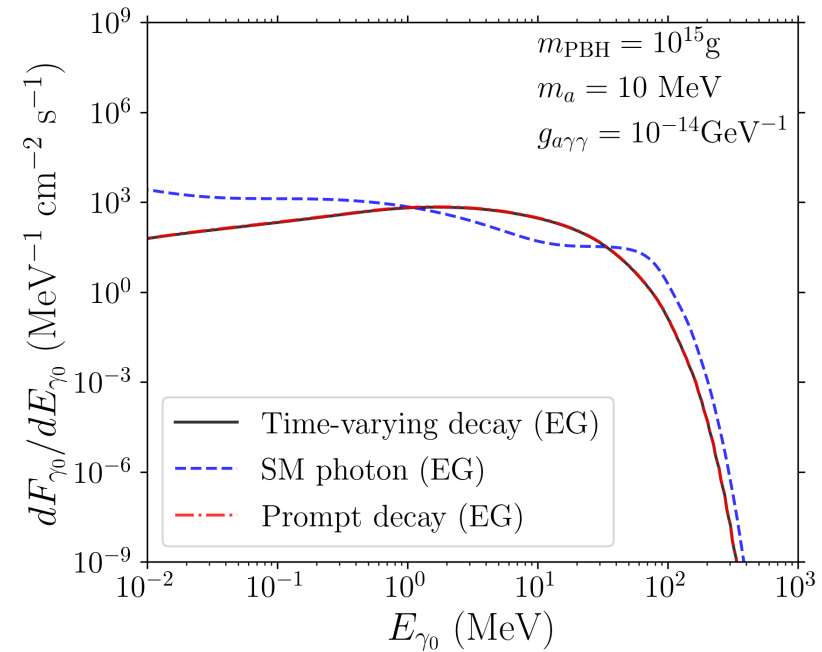
Fig.7 Differential flux for $g_a = 10^{-14} \mathrm{GeV}^{-1}$

ALPs : "The dent puller"

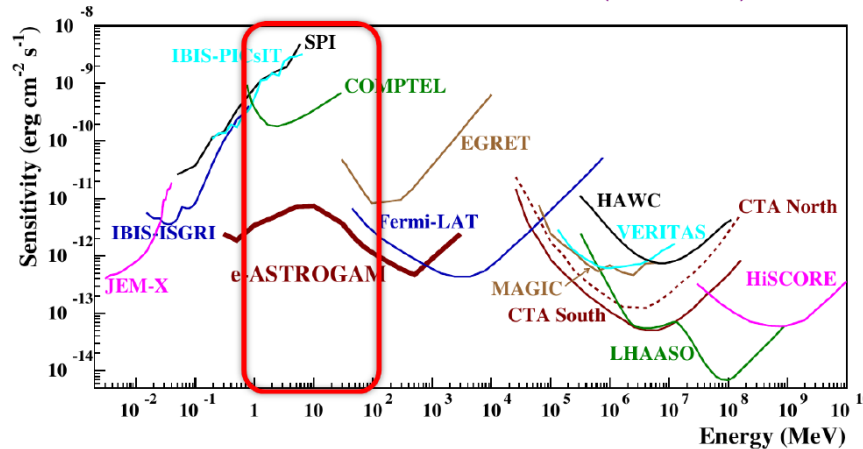Dent (without ALP)   Pull (with ALP)

Dent Puller = ALPs

e-ASTROGAM

- **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

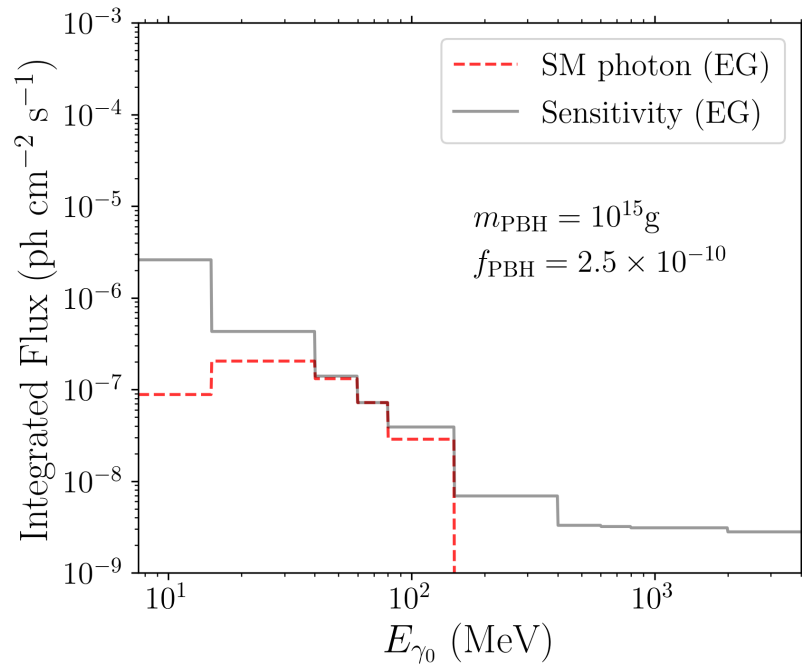| E (MeV)	Galactic center Sensitivity (ph cm^{-2} s^{-1})	Extragal. Sensitivity 3σ (ph cm^{-2} s^{-1})
7.5 - 15	1.3×10^{-5}	2.6×10^{-6}
15 - 40	2.4×10^{-6}	4.3×10^{-7}
40 - 60	8.0×10^{-7}	1.4×10^{-7}
60 - 80	4.5×10^{-7}	7.2×10^{-8}
80 - 150	2.7×10^{-7}	3.9×10^{-8}
150 - 400	7.8×10^{-8}	6.9×10^{-9}
400 - 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

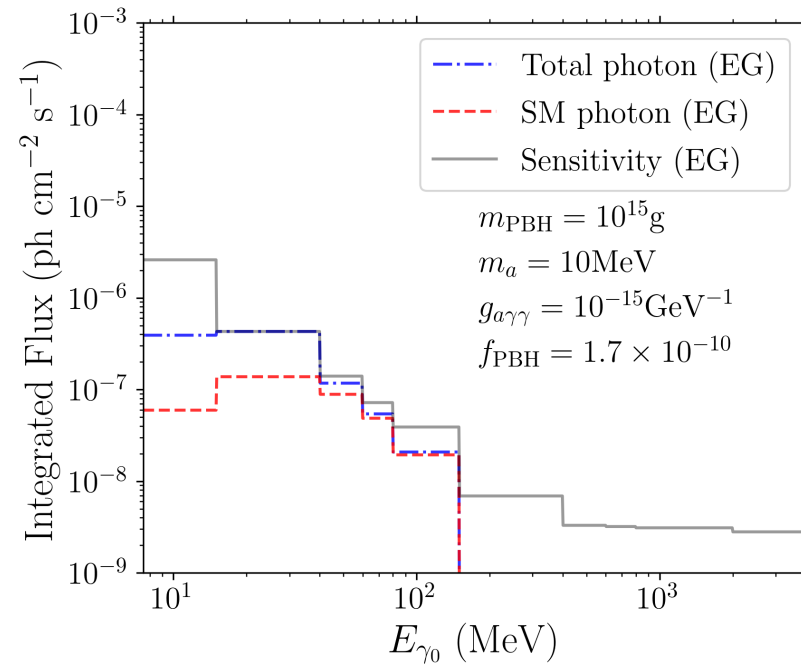**Fig.8** f_{PBH} **for SM photon only**

Fig.9 f_{PBH} **for total photon**

Results & Summary

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)
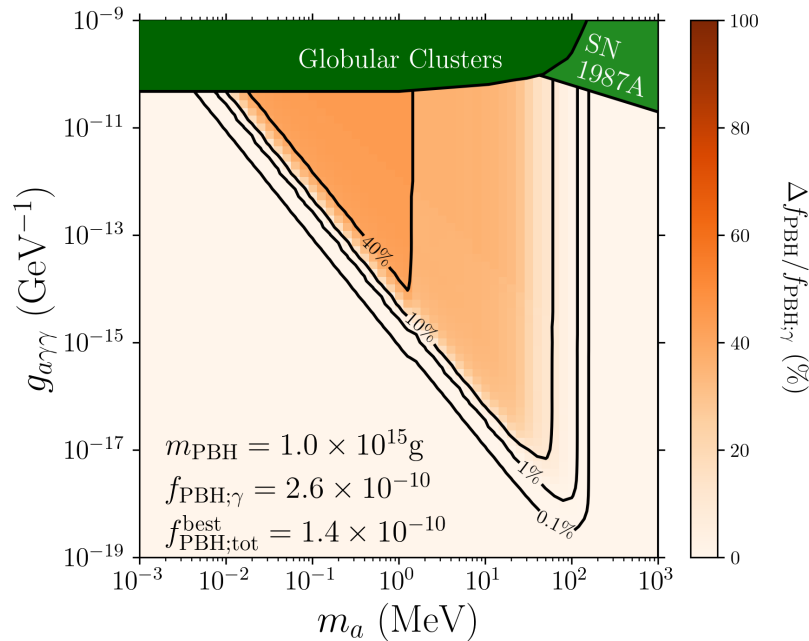

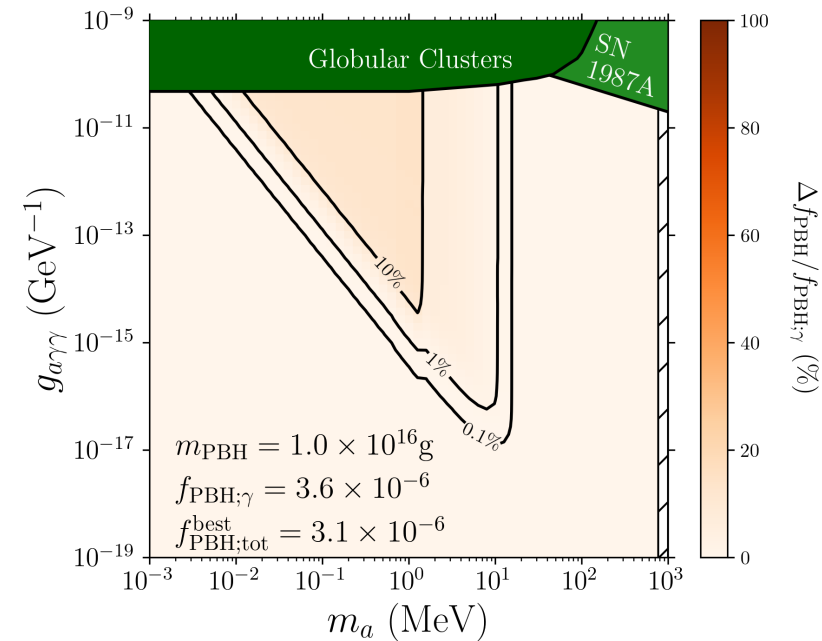**Fig.10 New constraint for ALPs ($m_{\mathrm{PBH}} = 10^{15}$g)**   **Fig.11 New constraint for ALPs ($m_{\mathrm{PBH}} = 10^{16}$g)**

1 If a particle has a very long lifetime, we should consider the **time-varying decay**.

2 When consider ALPs decay, we should consider the **boost effect** to photon.

✅ Using PBH as a source of ALPs, we can give a new constraint on ALPs.