Primordial black holes as axion factories

Seong Chan Park (Yonsei & KIAS)

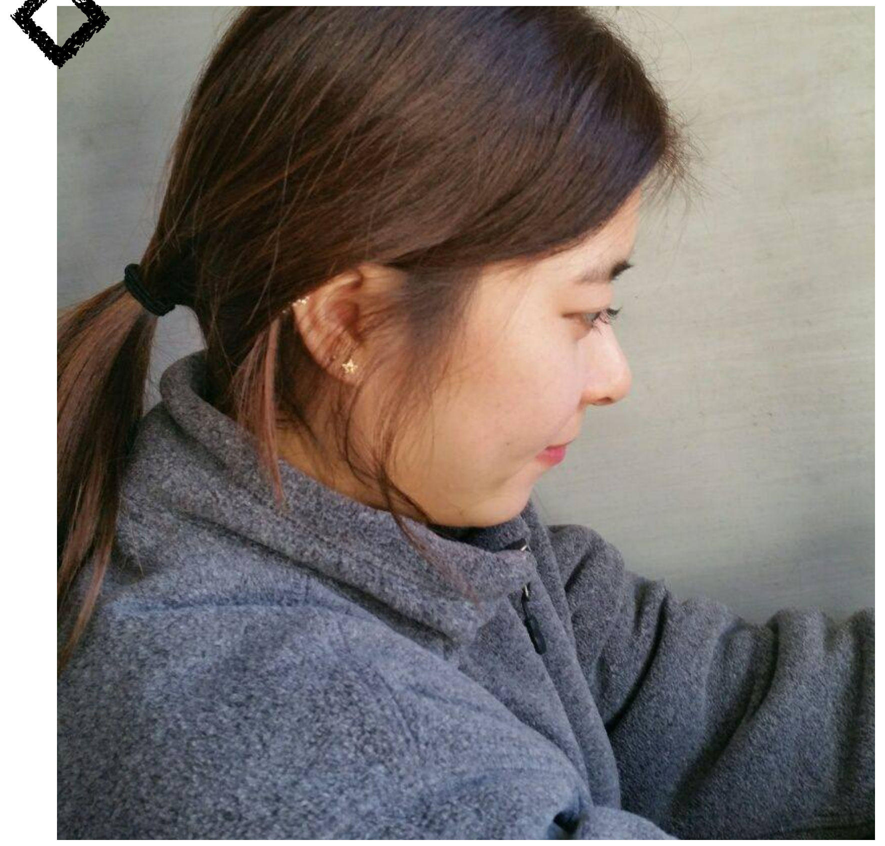
Chung-Ang University BSM workshop, Feb 20, 2023

3 Main players

Yonsei students

REF: [2212.11977]
with Yongsoo Jho, Tae-Geun Kim, Yeji Park and J-C Park

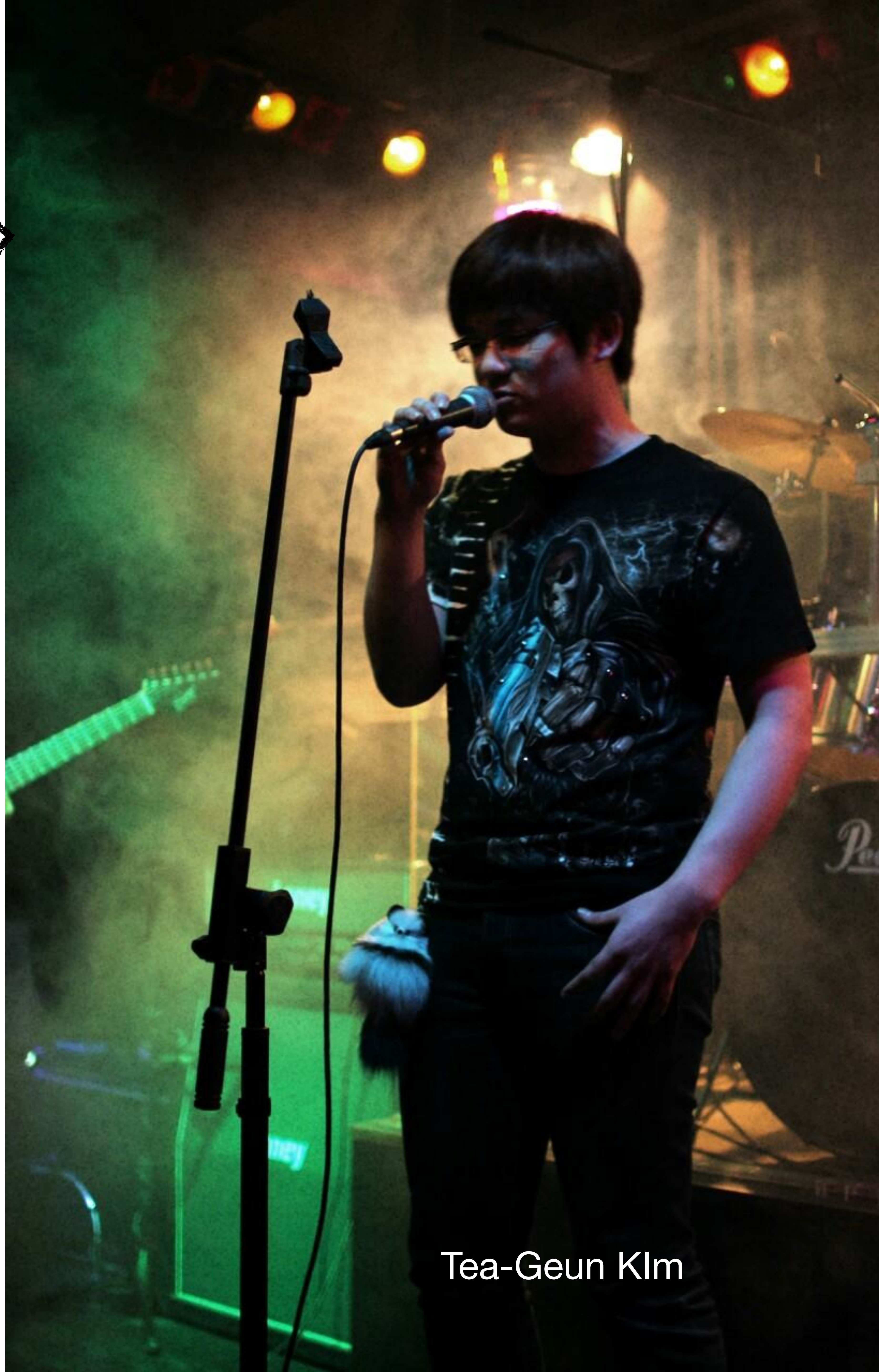
** Several slides are from TG, YJ & JC's talks



Yeji Park

Dr. Yongsoo Jho

now in Weizmann Institute



Tea-Geun KIm

2 more

History of PBH

- Y. Zel'dovic, I. Novikov, 1966 Soviet Astronomy: PBH, if existed, grows fast $dM/dt \sim R_{Sch}^2 \rho_r$, making the universe highly inhomogeneous

- B. Carr, S. Hawking, Feb.25, 1974 MNRAS, " …black holes will not in fact substantially increase their original mass by accretion (due to expansion). There could thus be primordial black holes around now with masses from 10^{-5} g upwards."

> "Stephen and I were able to show that such growth was impossible, thereby allowing the possibility that PBHs may have existed after all. We each made the discovery independently. I recall rushing excitedly to his office to give the good news and being rather dismayed to find that he had just come to the same conclusion by doing the calculation in his head!"
>
> B. Carr, interview with Physics Today, 2018

history

- S. Hawking, March 1, 1974 Nature: “Any such black hole of mass less than 10^{15} g would have evaporated by now. Near the end of its life the rate of emission would be very high and about 10^{30} erg would be released in the last 0.1 s. This is a fairly small explosion by astronomical standards but it is equivalent to about 1 million 1 Mton hydrogen bombs.”

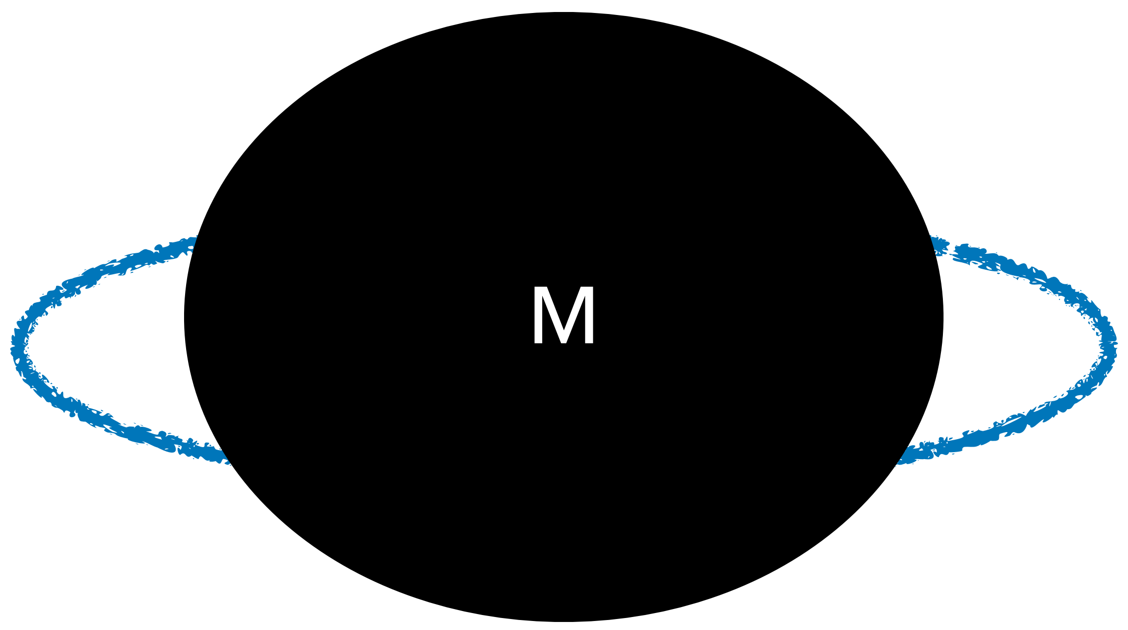
“I would bet you at least 50% that they exist, maybe even more.”

Bernard Carr, 2022 @ KIAS seminar

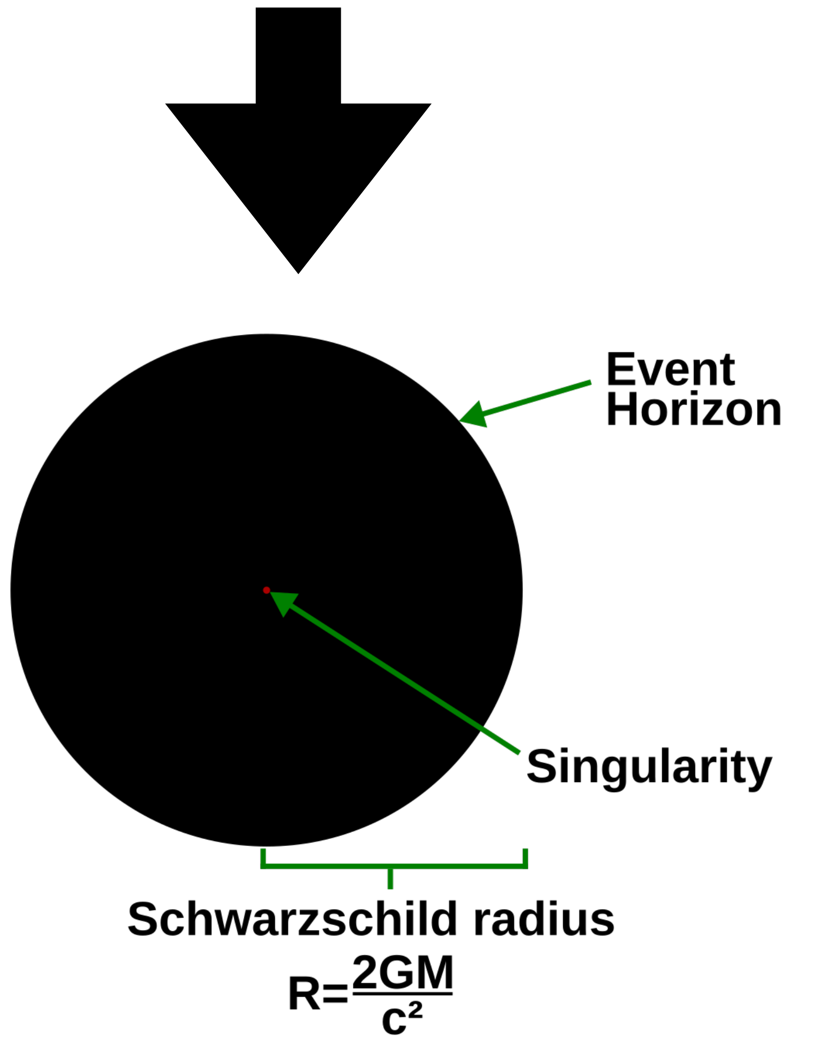
Our idea:

if PBHs are really around us, why don’t we use them as factories of BSM particles?

Production of PBH



$circ = 2\pi R_{Sch}(M)$



- Generally, a BH forms when enough large mass M is built inside of a hoop $circ = 2\pi R_{Sch}(M)$ (Hoop conjecture, Kip Thorne 1970s)

- A large density contrast $\delta\rho/\rho \sim 1$ can be induced in the early universe Carr, Hawking (1974), Bardeen et. al. (1986), Green, Liddle (1997), Motohashi, Hu (2017), Cheong, Lee, SCP, JCAP(2021), Cheong, SCP, Kohri, JCAP (2022), He, Jinno, Kamada, SCP, Starobinsky, Yokoyama, PLB(2019), C-M. Yoo, K. Kohri PRD (2013),….

  ✓ ultra-slow roll, inflection point, tachyonic instability during inflation (single field (X?), multi-fields (O))

  ✓ collapse of cosmic string loops, domain walls, scalar fields…

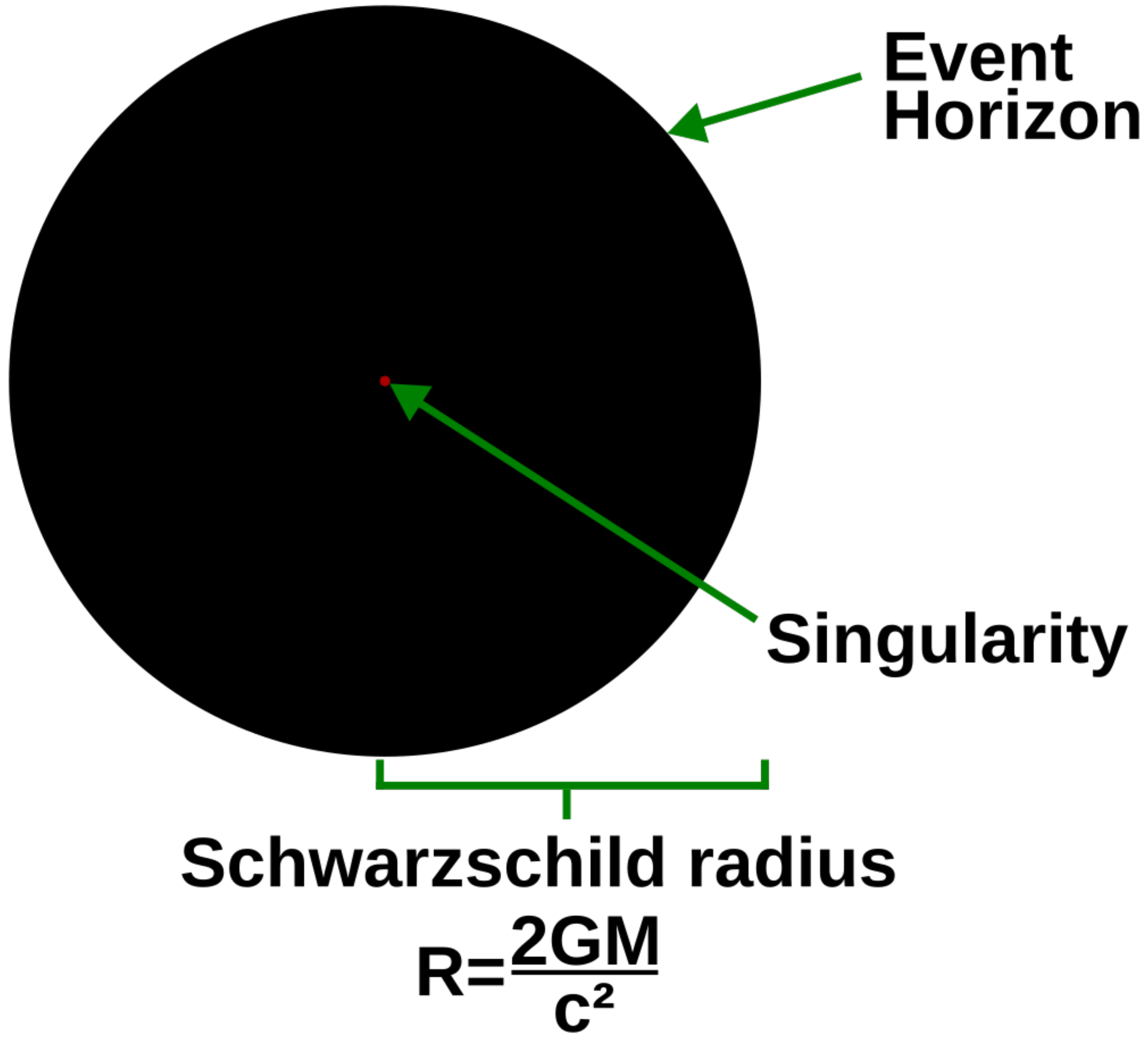
  ✓ collapse from bubble collision/phase transition

  ✓ Many many ideas …

- $M(t) \sim$ Hubble mass $\sim c^3 t/G \sim 10^{15} g(t/10^{-23} sec)$ @ time t

- Cosmological: Isotropic, mono-scale (?), Schwarzschild like

Hawking Radiation & Temperature



Ida, Oda, SCP [PRD(03), PRD(05), PRD(06)]

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

Γ_i : greybody factors

s_i : spin of i-particle

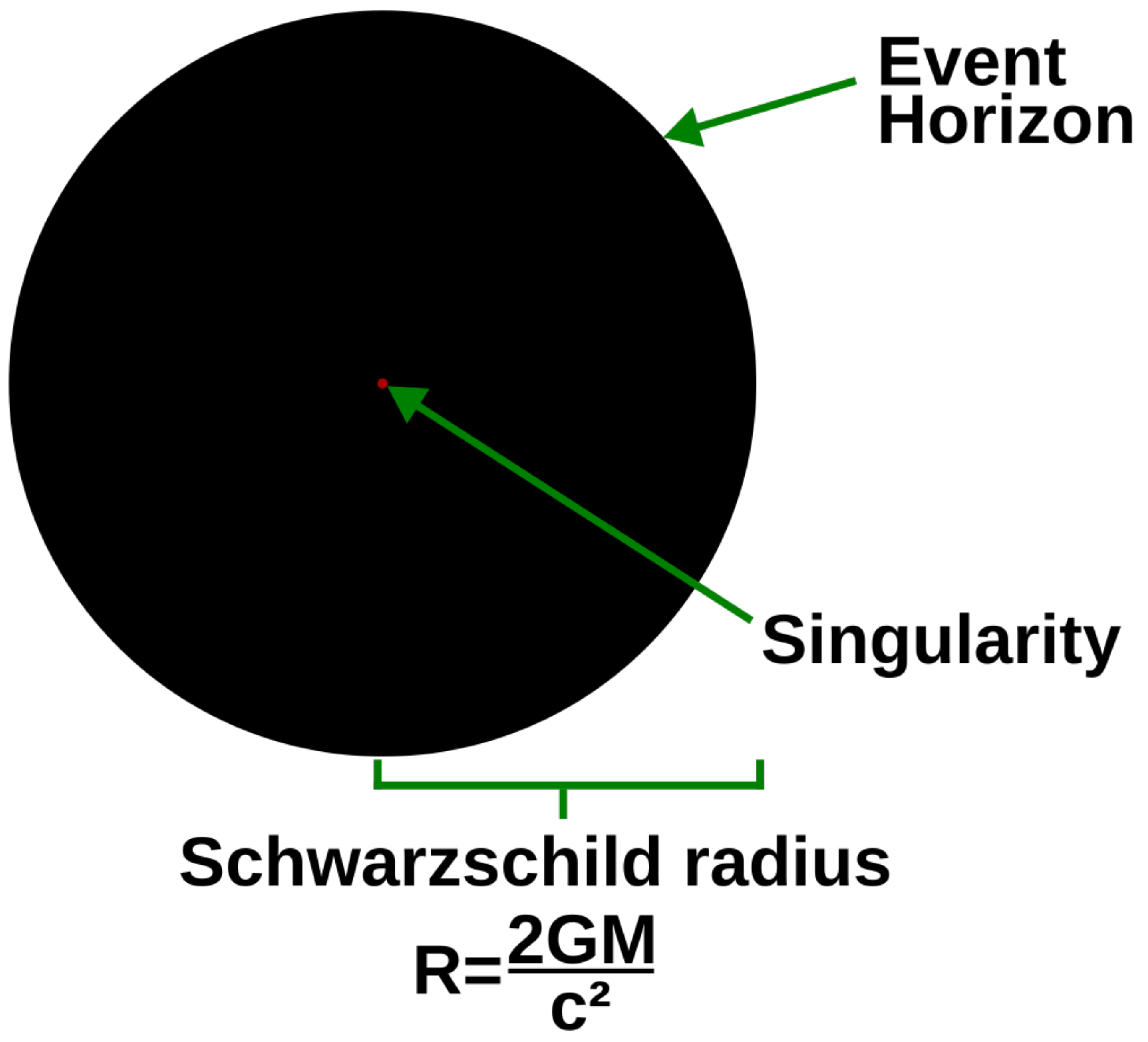
$$k_BT_H = \frac{1}{4\pi R_{Sch}} = \frac{1}{8\pi GM_{PBH}} = \frac{M_{Pl}^2}{M_{PBH}}$$

Therefore if a BSM particle is 'light',
they will be produced from the PBH via Hawking radiation:

$$m_{BSM} \lesssim k_BT_{PBH} = \frac{M_{Pl}^2}{M_{PBH}}$$

(note) For consistency, we request $R_{Sch} \sim \frac{M_{PBH}}{M_P^2} \gg \ell_{Pl}$

and we only consider $M_{PBH} \gg M_{Pl}$ or $m_{BSM} \lesssim \frac{M_{Pl}^2}{M_{PBH}} \ll M_{Pl}$



Therefore if a BSM particle is 'light', they will be produced from the PBH:

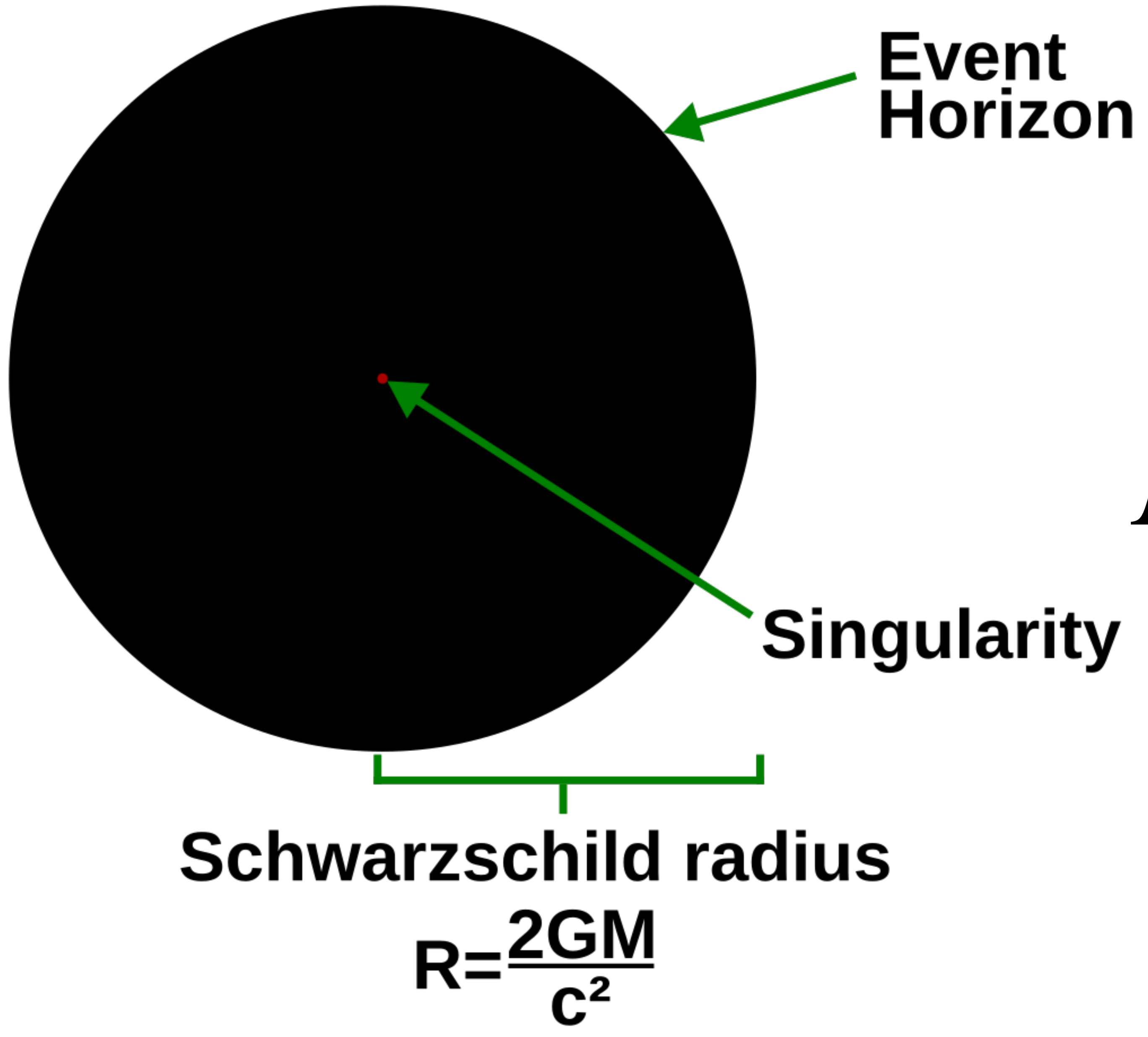
$$m_{BSM} \lesssim k_B T_{PBH} = \frac{M_P^2}{M_{PBH}}$$

In other words, for a BSM particle of mass m_{BSM}, will be produced by PBH

$$M_{PBH} \lesssim \frac{M_P^2}{m_{BSM}}$$

==> A light PBH is an excellent factory of BSM particles!

Some useful numbers



$$M_{PBH} \lesssim \frac{M_P^2}{m_{BSM}} \sim \left(\frac{\mathrm{MeV}}{m_{BSM}}\right) \times 10^{16}\ \mathrm{g}$$

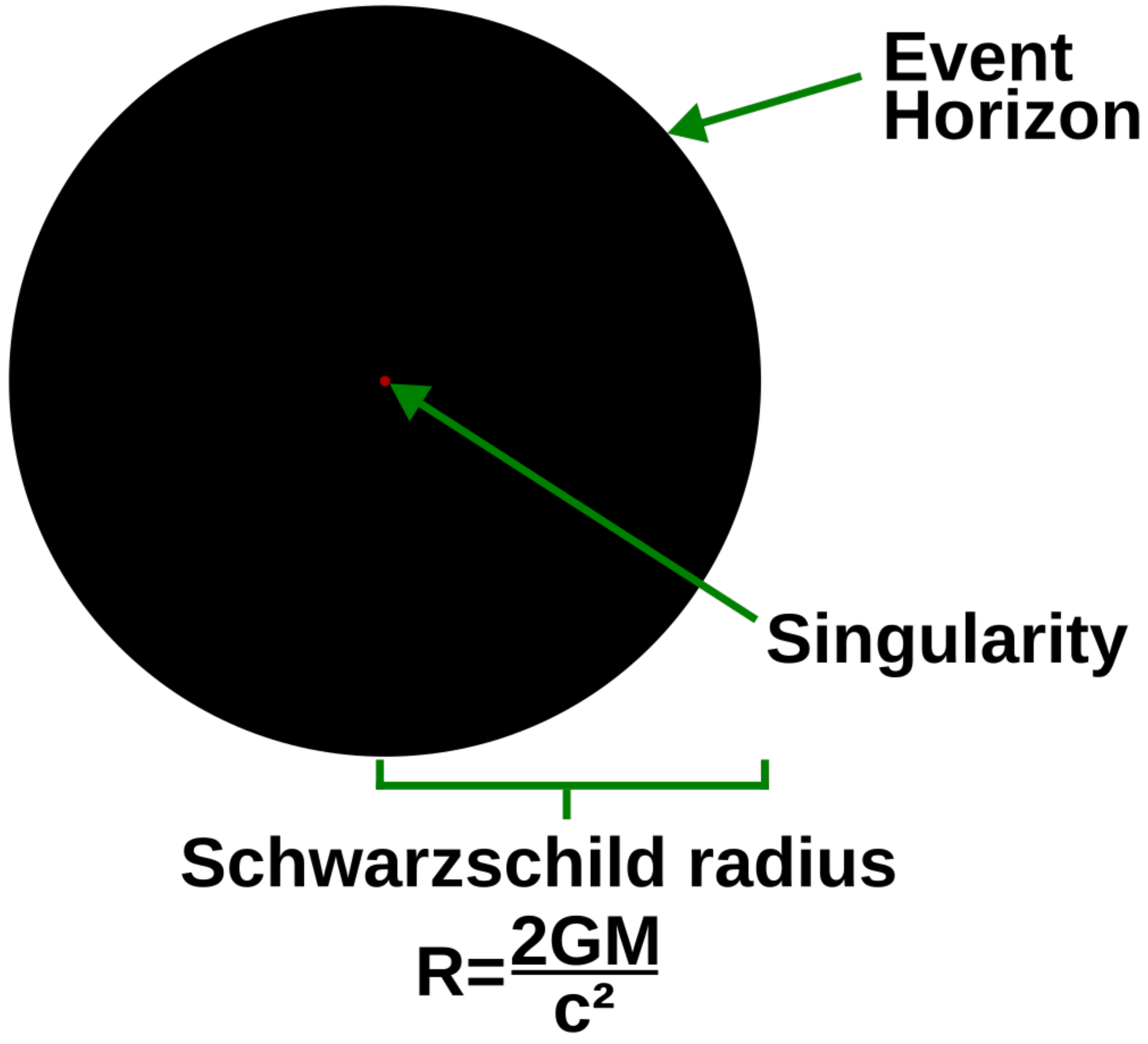
~current bound

The corresponding lifetime of PBH is

$$\tau_{PBH} \sim 10^4 t_{\mathrm{Univ}} \left(\frac{M_{PBH}}{10^{16}\ \mathrm{g}}\right)^3$$

Some useful numbers

$\ell_P \sim 1.6 \times 10^{-33}\mathrm{cm}$
$M_{Pl} \sim 2 \times 10^{-5}\mathrm{g}$



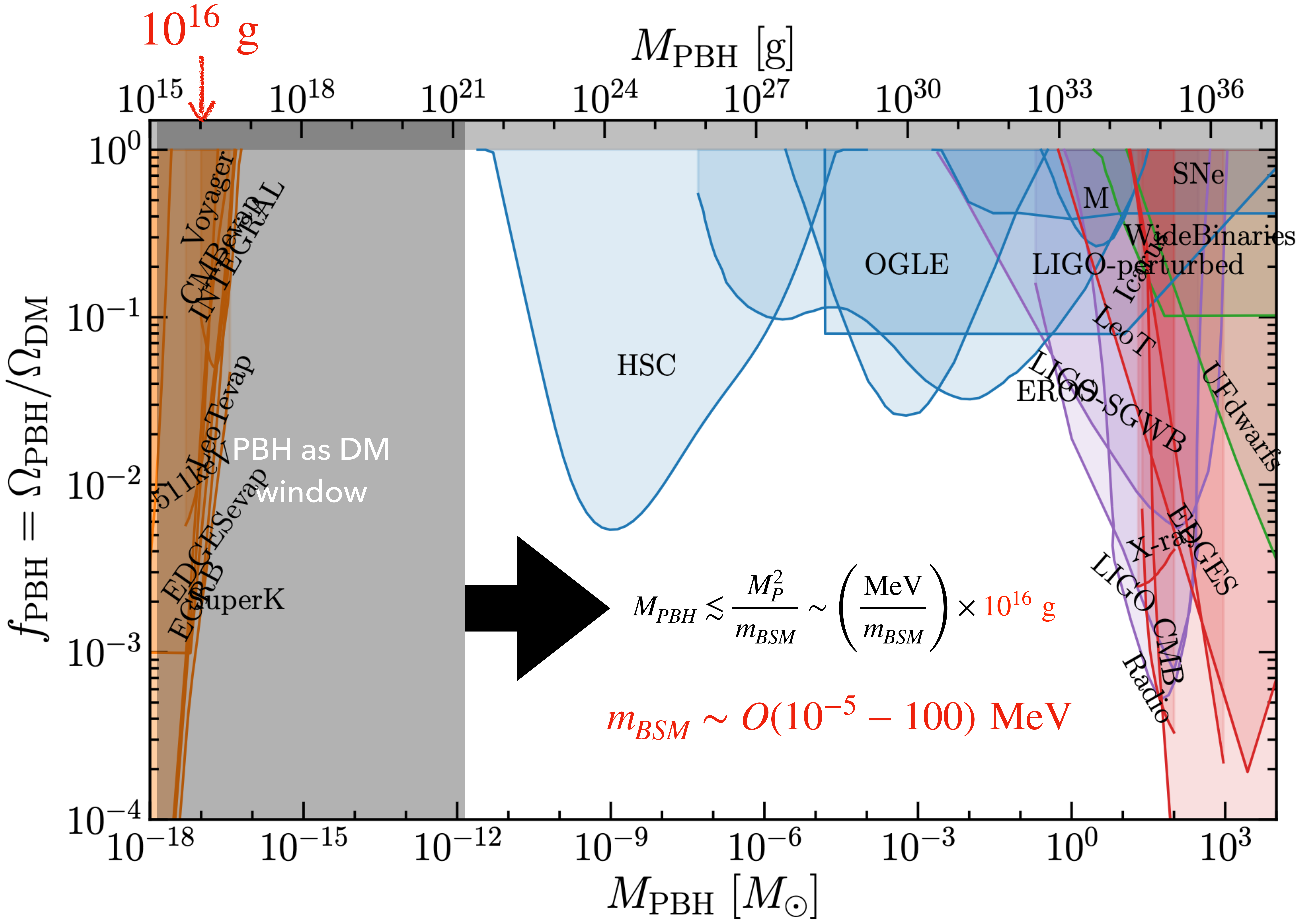
$$R_{Sch} = 2GM \sim \left(\frac{2M}{M_{Pl}}\right)\ell_P$$

$$\sim 1.6 \left(\frac{M}{10^{16}\mathrm{g}}\right) \times 10^{-12}\mathrm{cm}$$

sub-atomic size!

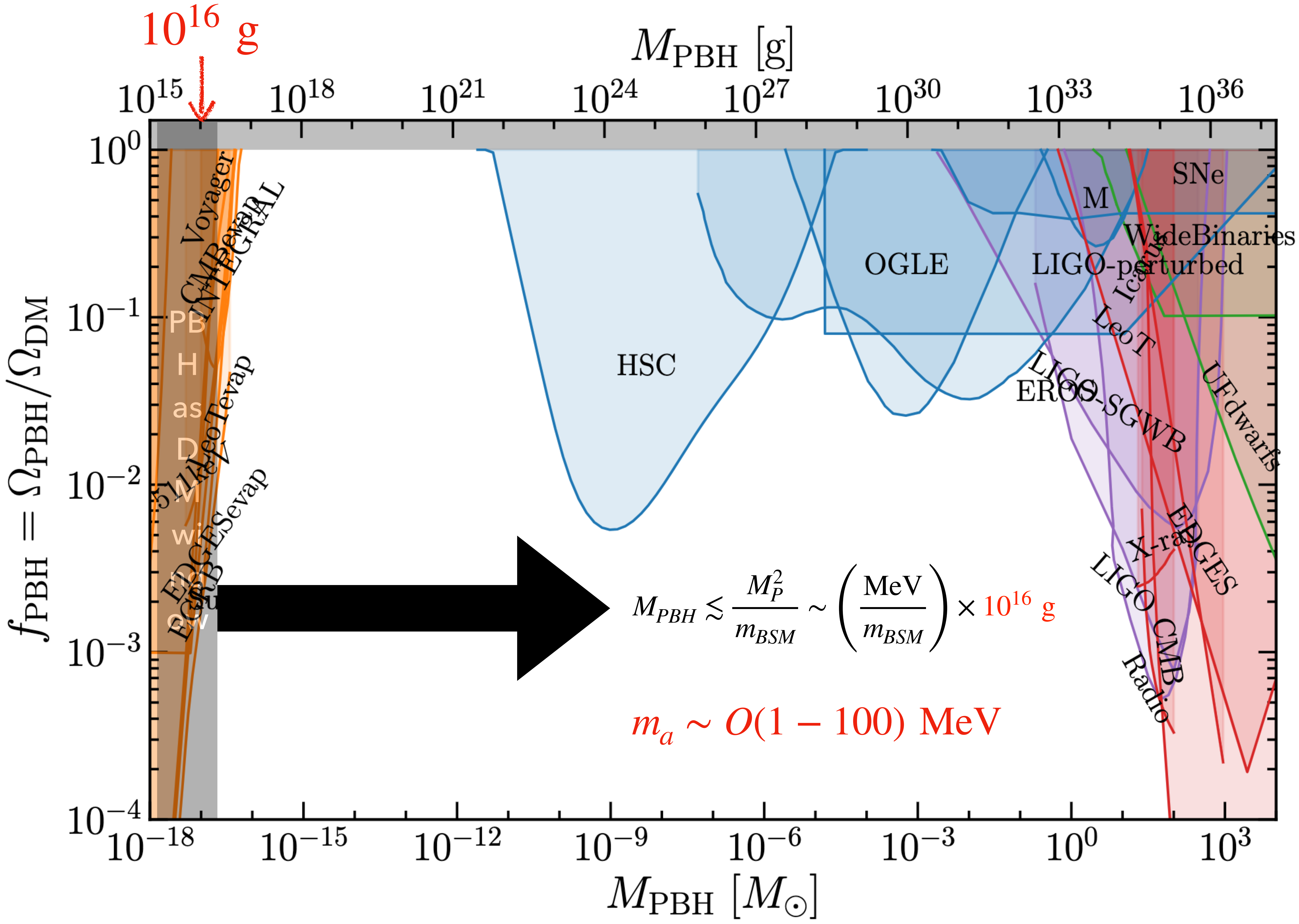
Therefore it is extremely hard to detect.

(cf) $M_\odot \sim 2 \times 10^{33}\mathrm{g}$ ==> 3 km



(collection of PBH bounds)

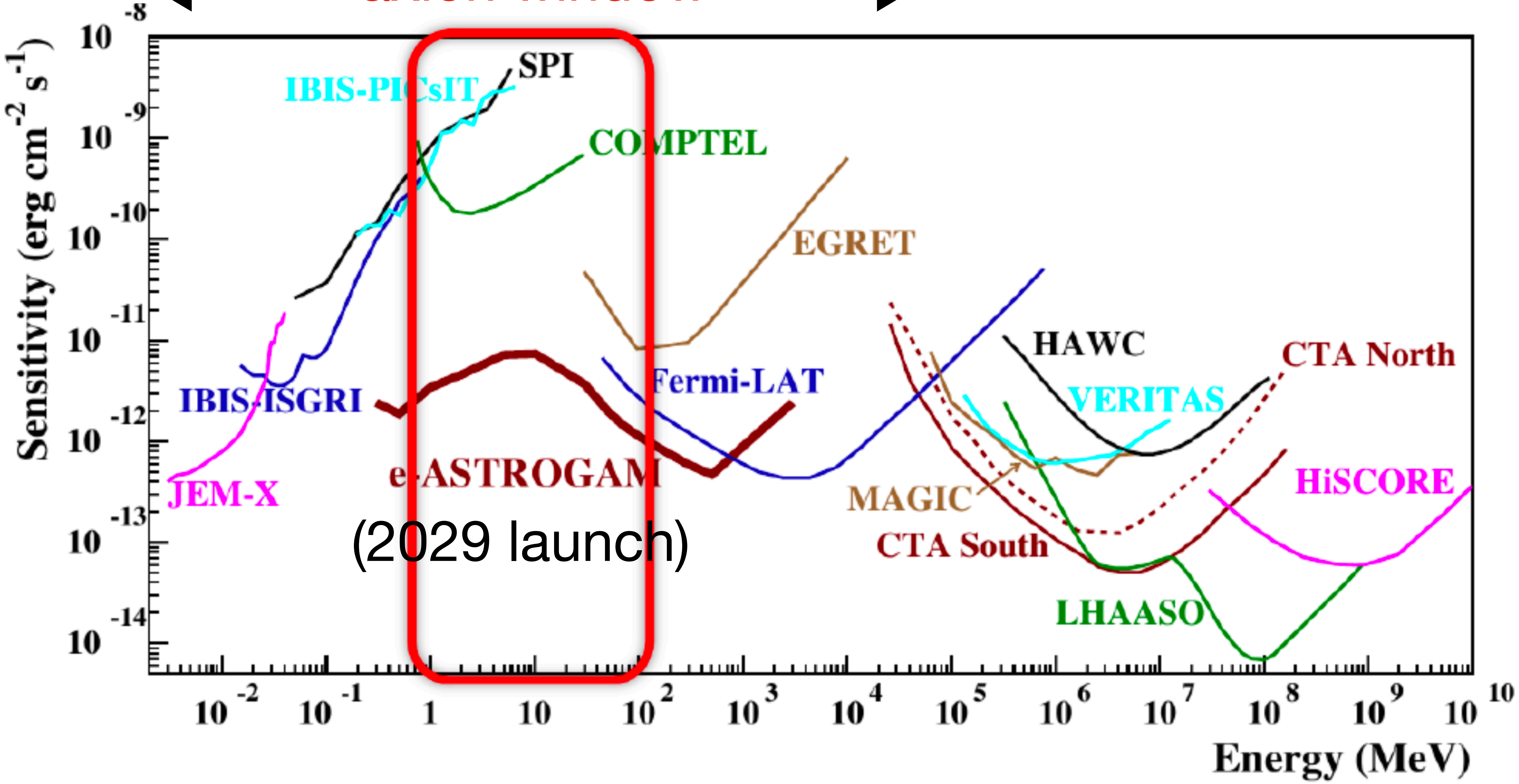
https://github.com/bradkav/PBHbounds



(collection of PBH bounds)

https://github.com/bradkav/PBHbounds

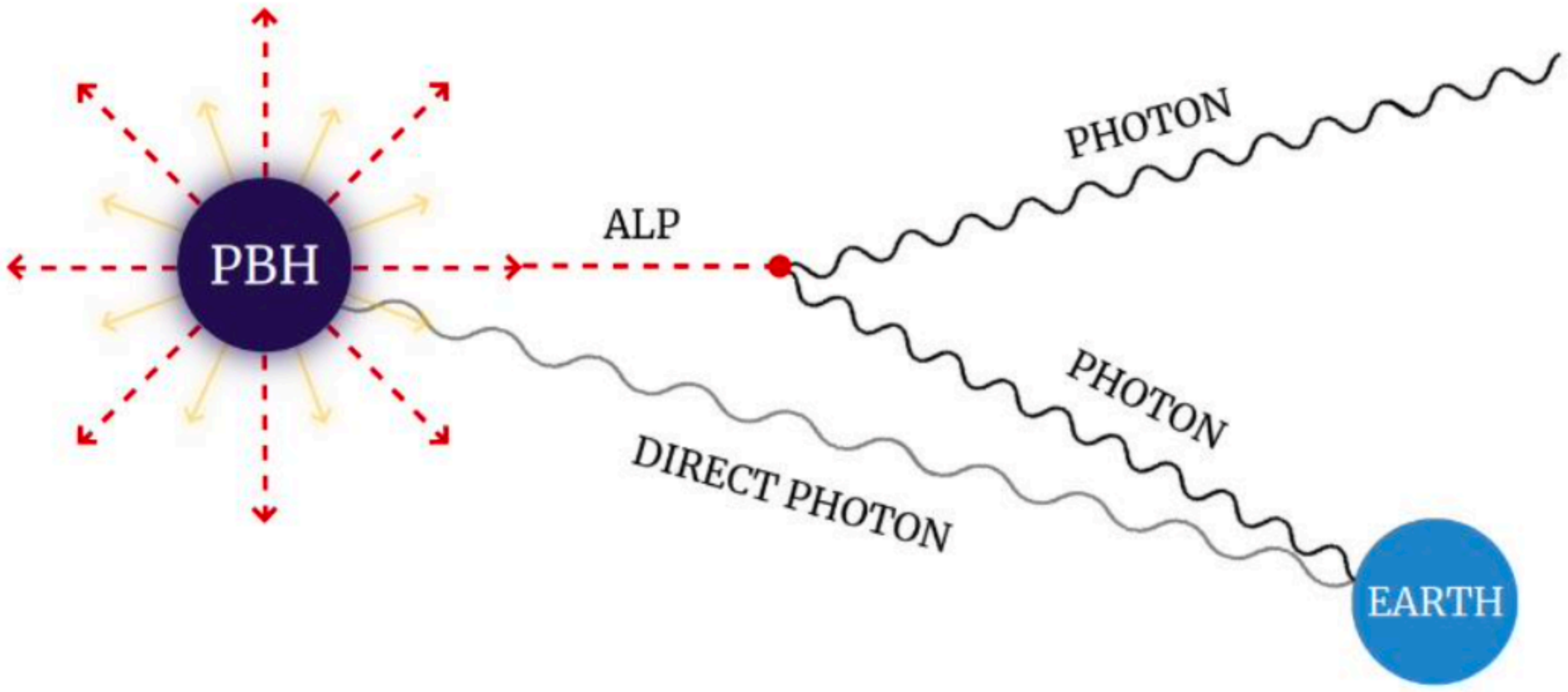
heavier ← **O(1-100) MeV axion window** → lighter regime



[e-ASTROGAM, Exper Astron (2017)]

NOTE) We don't have to limit ourselves in this window.
But, certainly this window is an interesting one!

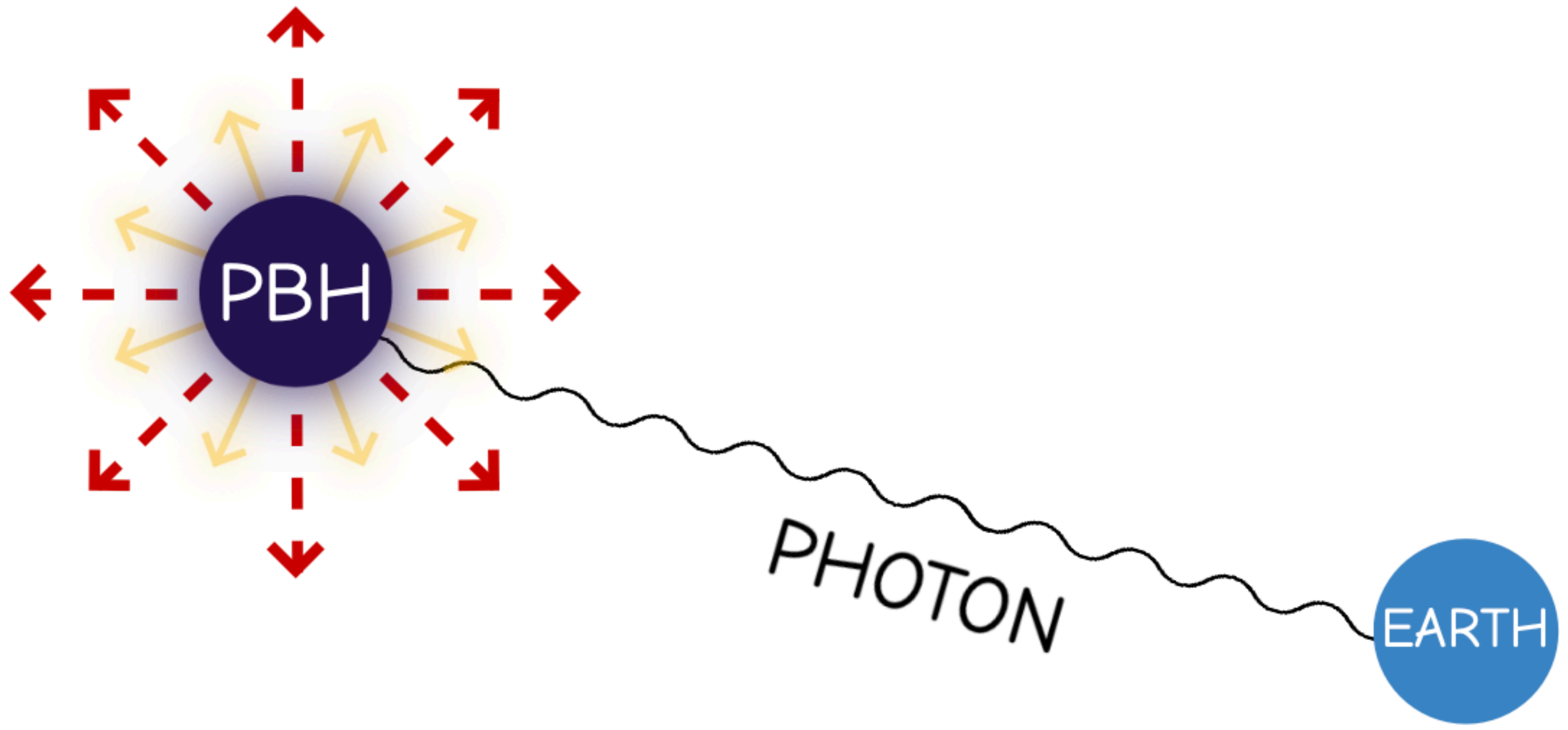
Axion Signal & SM contribution



-(if primordial) located everywhere, isotropic
-(for simplicity) monochromatic mass ~ $(10^{14}, 10^{16})\ g$ or $m_a \sim (1-100)\mathrm{MeV}$
-Schwarzschild (angular momentum, charge ~ rapid loss)
-Galactic + extra-Galactic contributions

Photons from PBH

: Photons are emitted directly from PBH + decay productions of SM from PBH



Assumption on PBH

- Monochromatic mass distribution
- Schwarzschild PBH
- Isotropically distributed

Redshfted effect

- Number density : $n(t_0) = \left(\frac{1}{1+z(t)}\right)^3 n(t)$
- Momentum : $p|_{t_0} = \frac{1}{1+z(t)} p|_t$

Photon flux expected to be observed

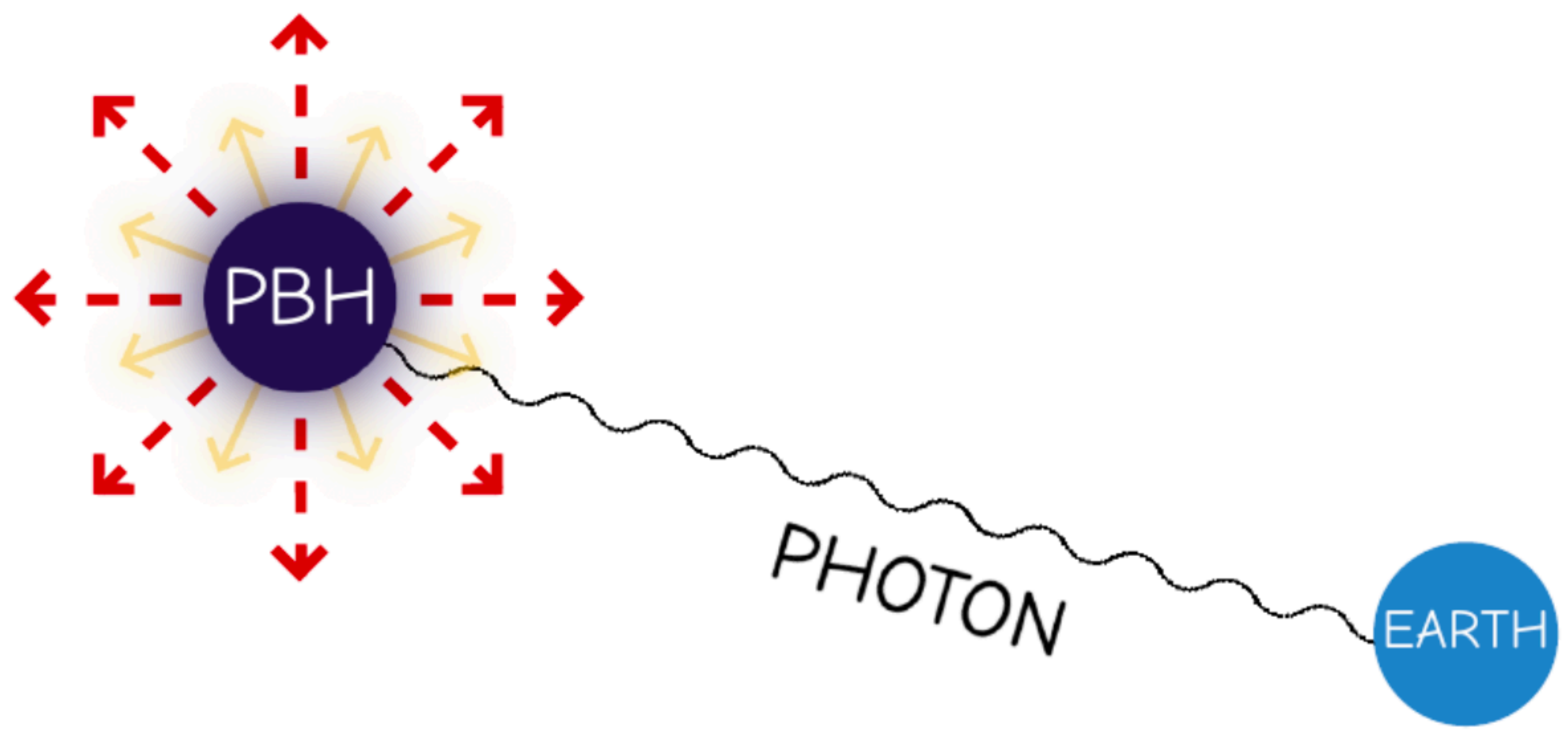
- B. J. Carr, Kazunori Kohri, Yuuiti Sendouda, and Jun'ichi Yokoyama Phys. Rev. D 81, 104019

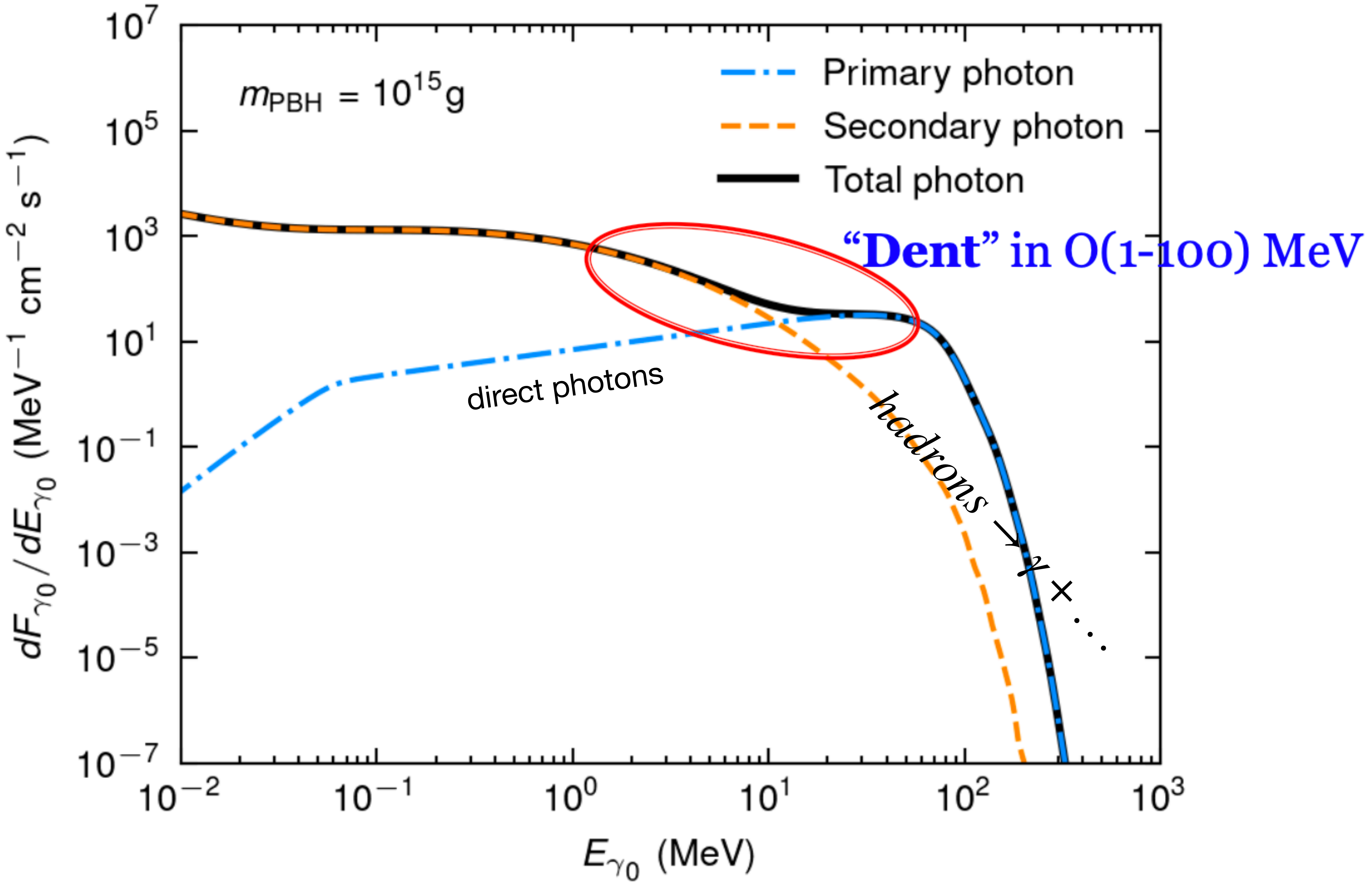
now

$$n_{\gamma 0}(E_{\gamma 0}, t_0) = \int_{t_{\mathrm{CMB}}}^{\min(\tau_{\mathrm{PBH}}, t_0)} dt \, (1+z(t))^{-3} \times \frac{dn_\gamma}{dt}(E'_\gamma, t)$$

$$E'_\gamma|_t = (1+z(t)) E_{\gamma 0}$$

SM contribution

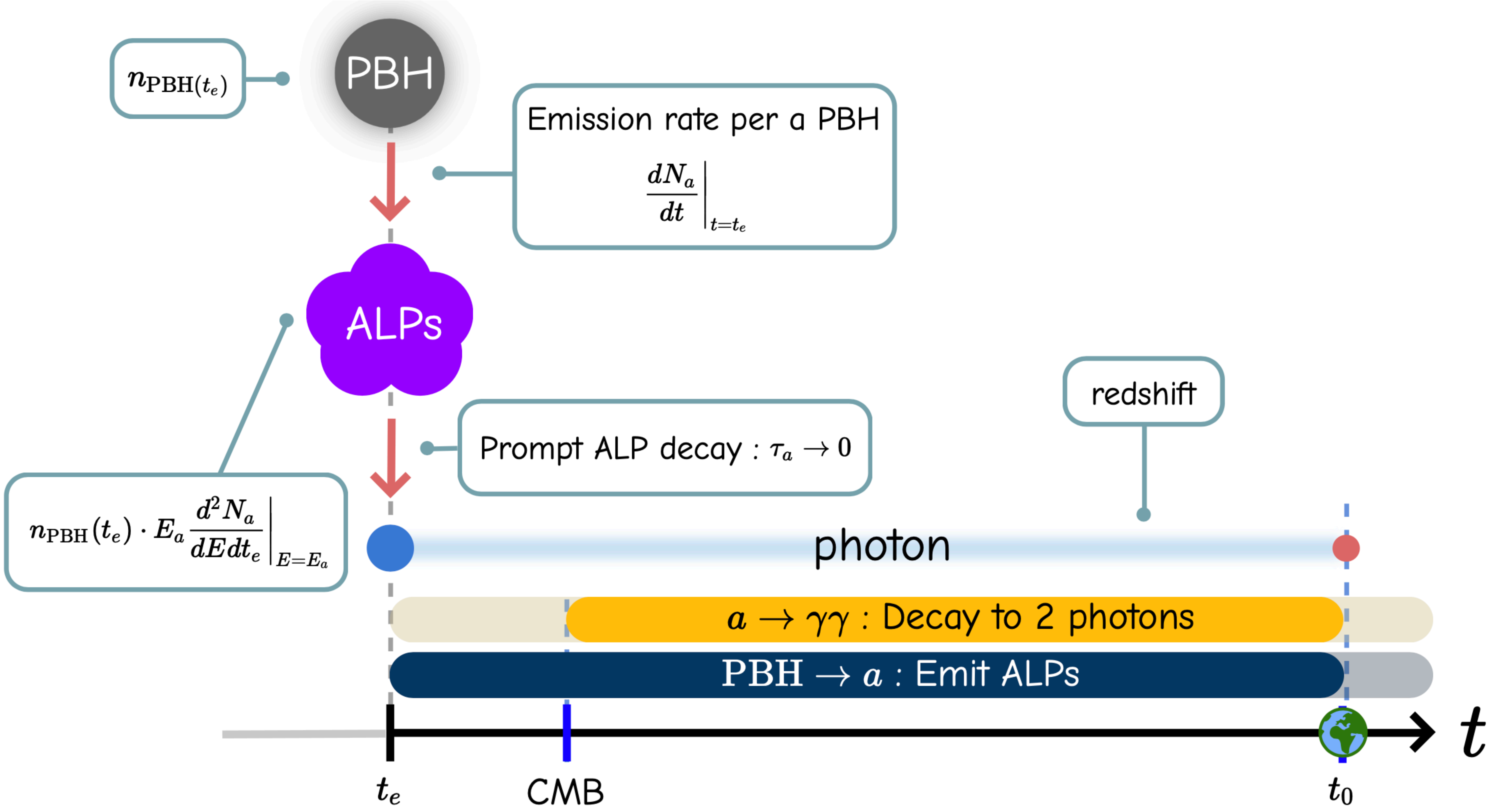




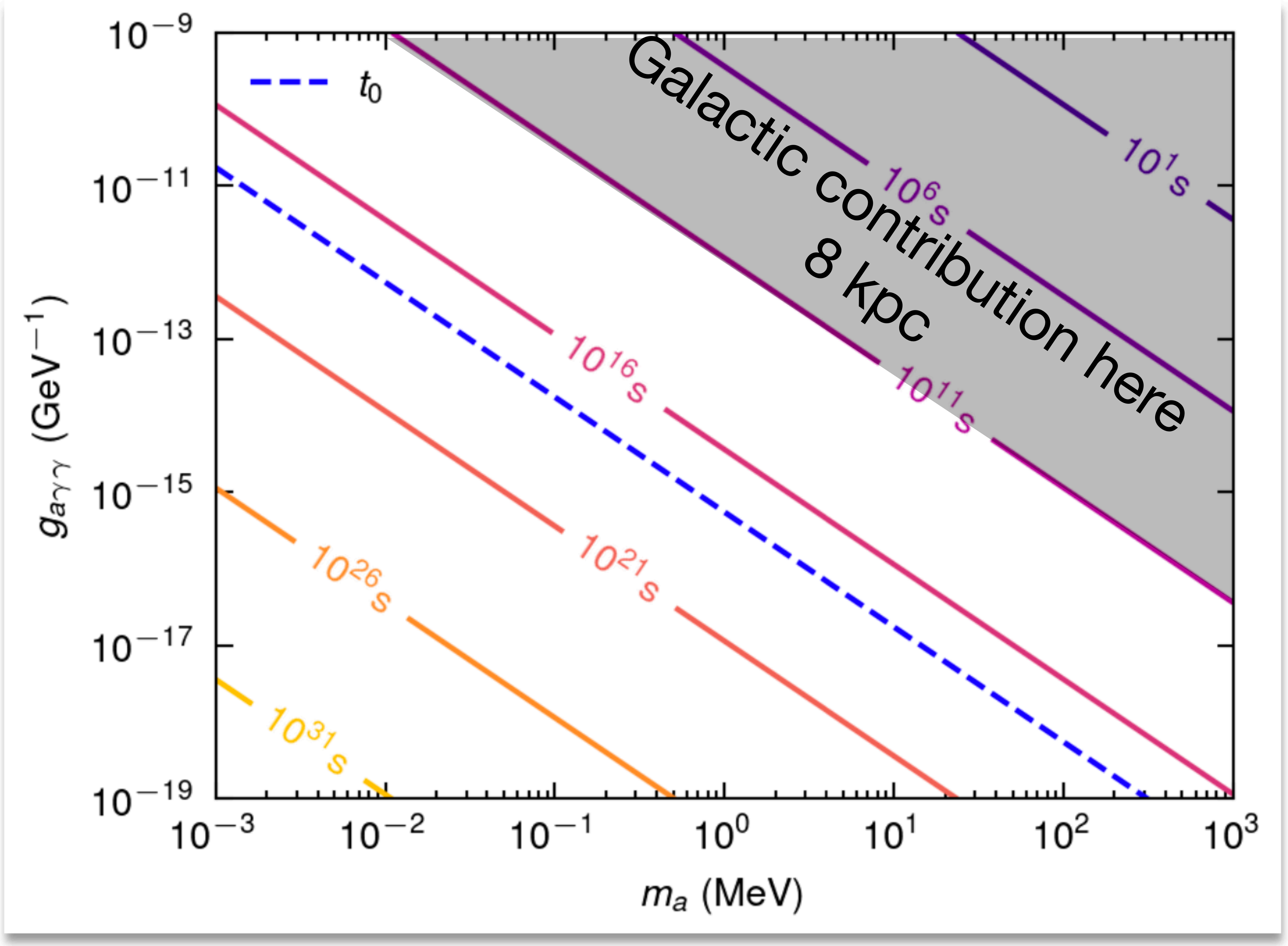
[Carr & Kohri et al., PRD (2010)]

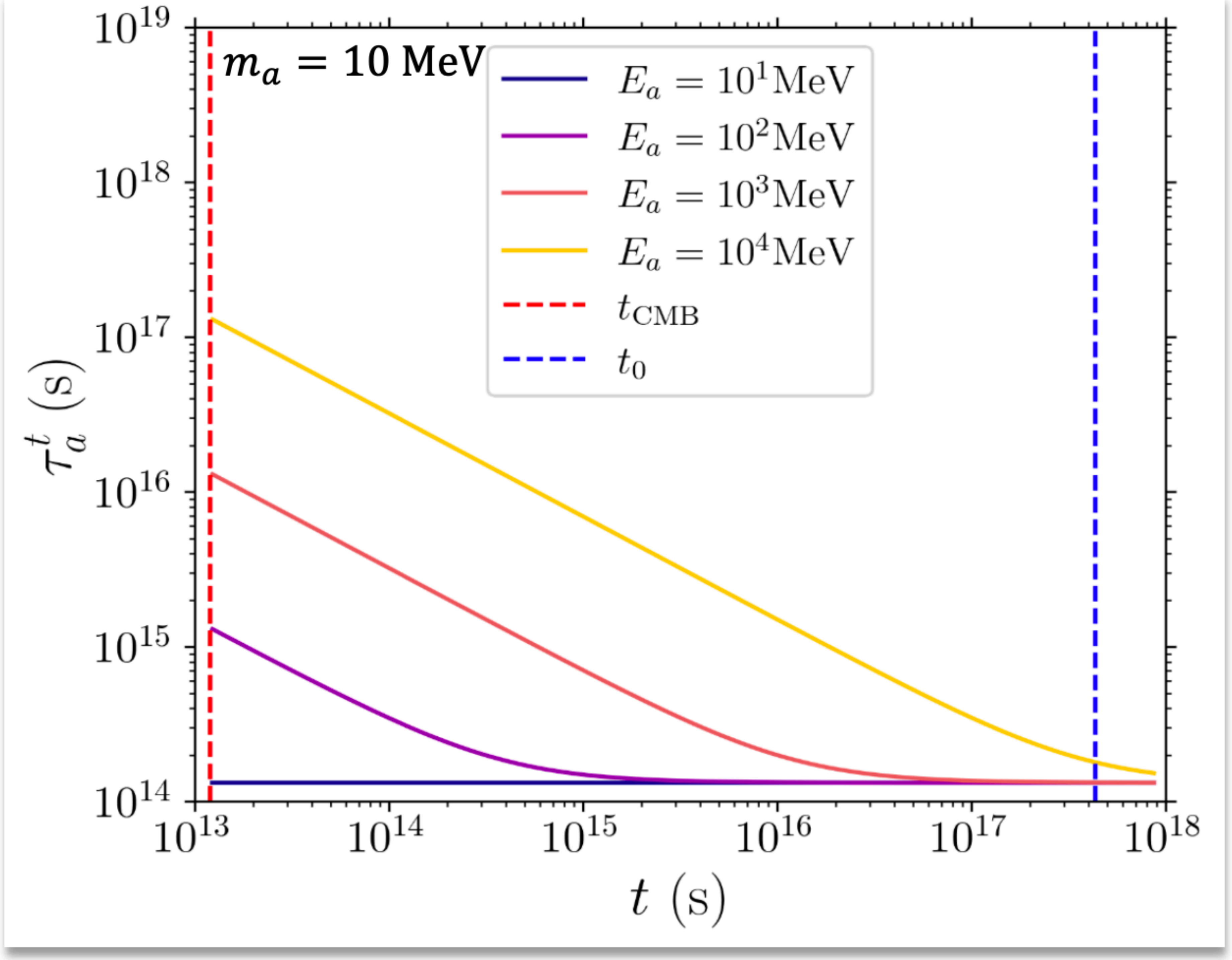
BlackHawk: [Arbey & Auffinger, EPJC (2019) & (2021)]

γ from Axion decay (prompt case)



❖ In our target parameter region, ALPs are very long-lived (i.e., cosmological scale lifetime) .

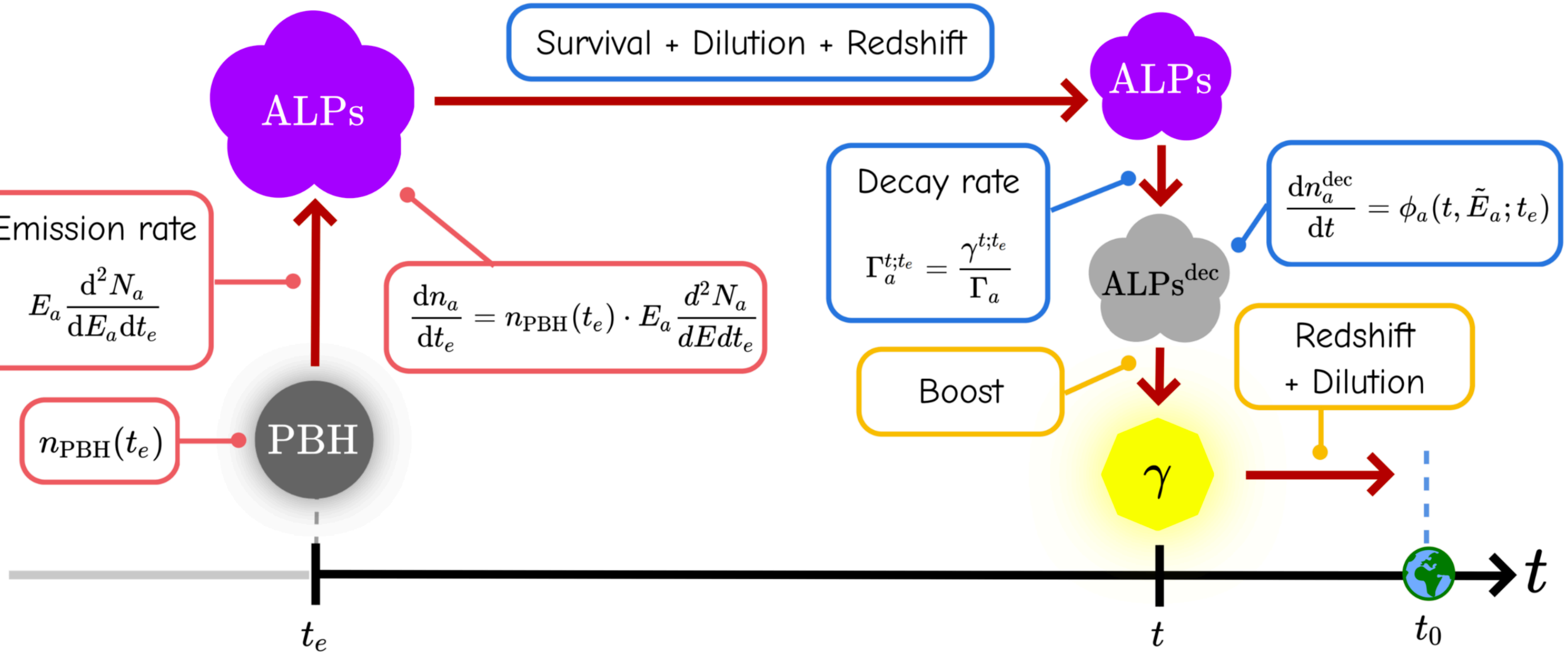




ALP's mean lifetime : $\tau_a^t \equiv \gamma(t)\tau_a = \frac{64\pi E_a(t)}{g_a^2 m_a^4} \equiv \frac{1}{\Gamma_a^t}$

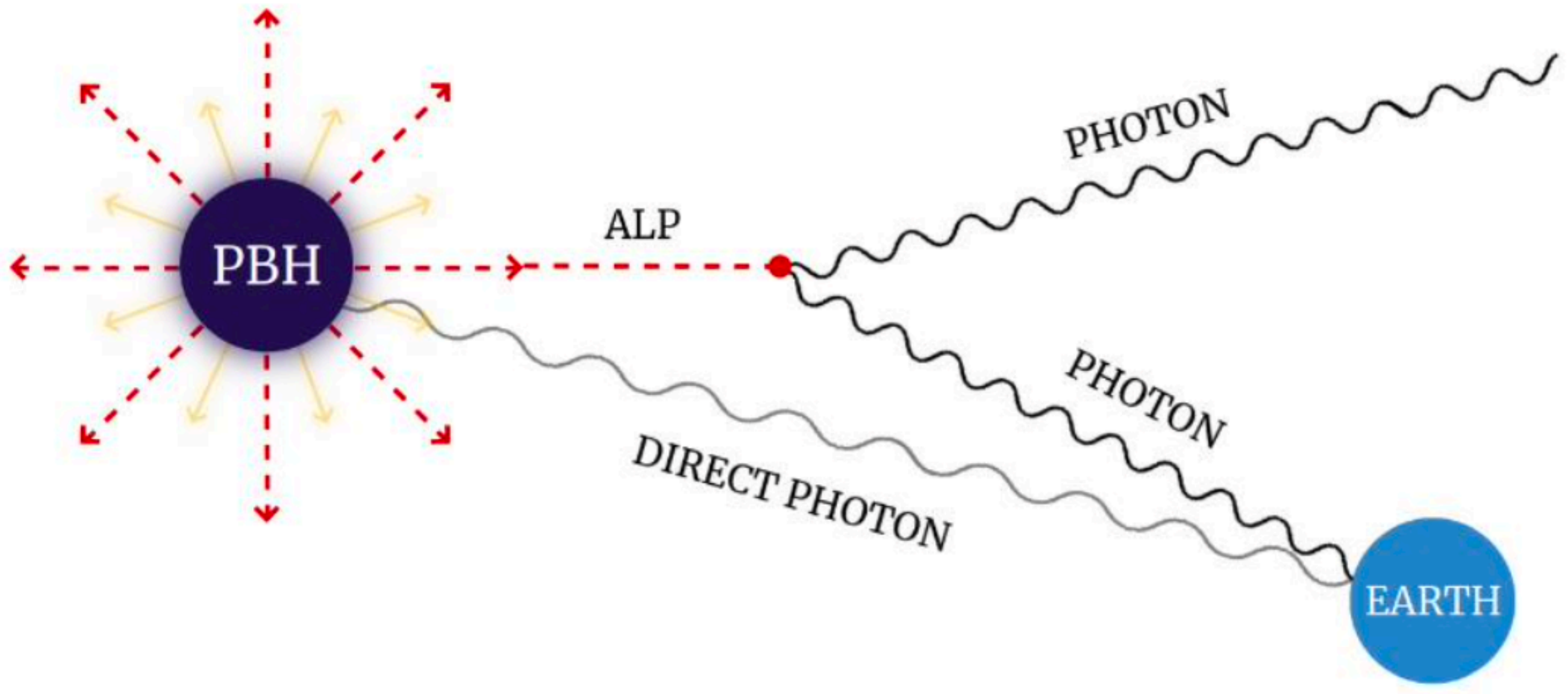
γ from Axion decay (non-prompt case)

The decay width also changes due to expansion!



$$dn/dt = P(prod) \times (Dilution) \times P(survival)$$

Boosted axion decay



$$k_B T_H = \frac{1}{4\pi R_{Sch}} = \frac{1}{8\pi G M_{PBH}} = \frac{M_{Pl}^2}{M_{PBH}}$$ “the smaller, the hotter”

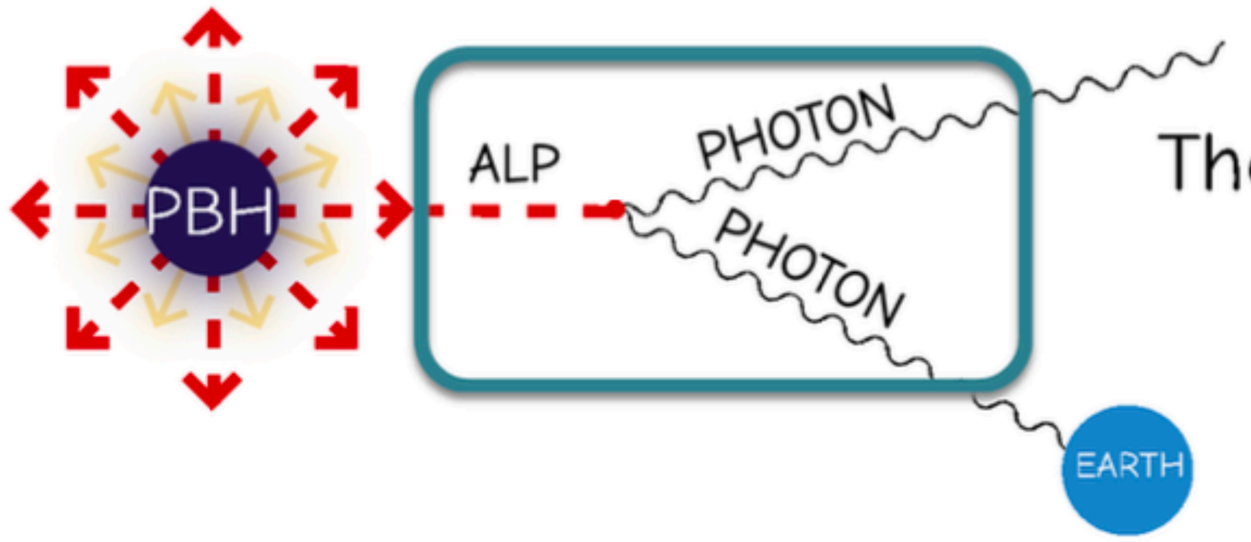
In the final stage of PBH,

$k_B T_H \gg m_a$, thus axions are boosted!

=> spectrum of decay product is also boosted

- Collider: K. Agashe, Franceschini & D. Kim, PRD (2013)
- Cosmic-ray: D. Kim & J-C Park, PLB (2015); PDU (2016)

Boosted ALP decay to Photon



The decay of a massive particle to 2 massless particles: $a \to \gamma\gamma$

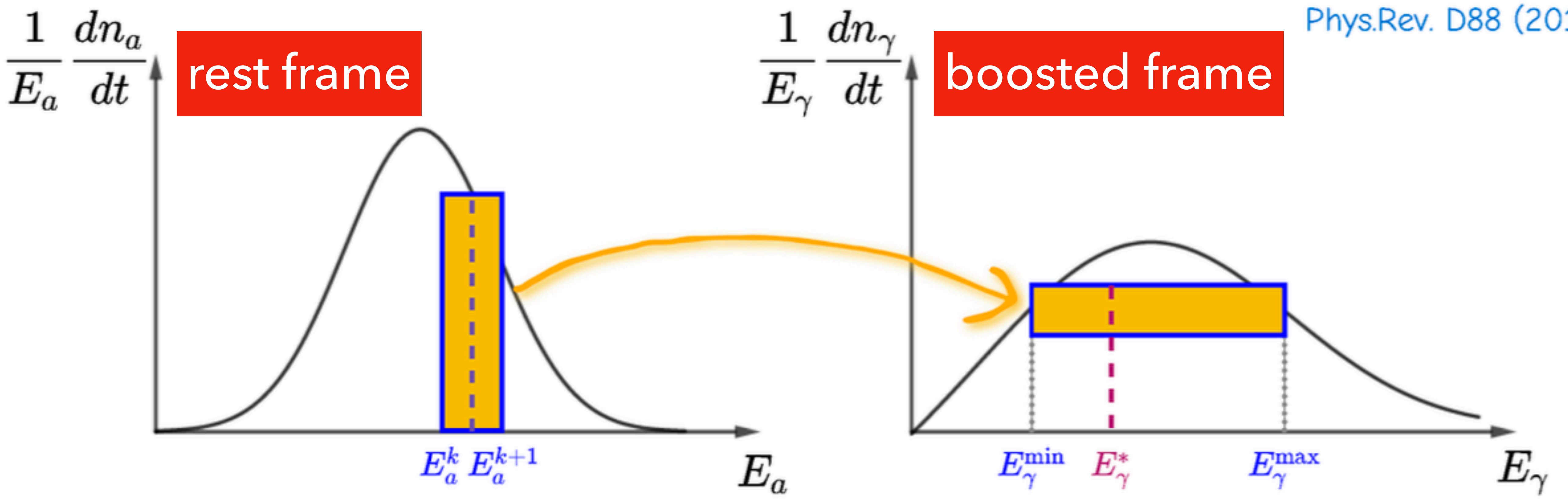
"Two body decay kinematics"

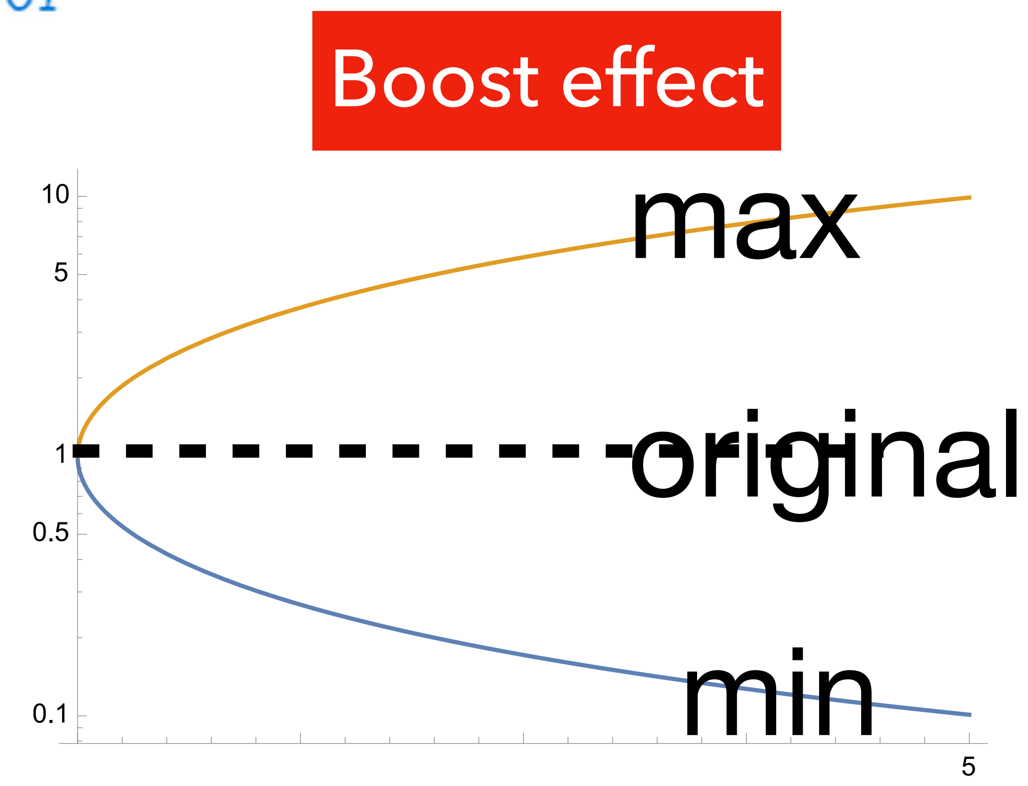
- Lorentz transformation : $E_\gamma = E_\gamma^*(\gamma \pm \sqrt{\gamma^2 - 1})$

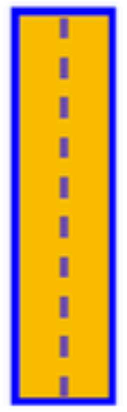
- $E_\gamma^* = \frac{m_a}{2}$: photon energy in the rest frame of the ALP
- $\gamma = \frac{E_a}{m_a}$: the Lorentz factor

[Schematic Figure For This Process]

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







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

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

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

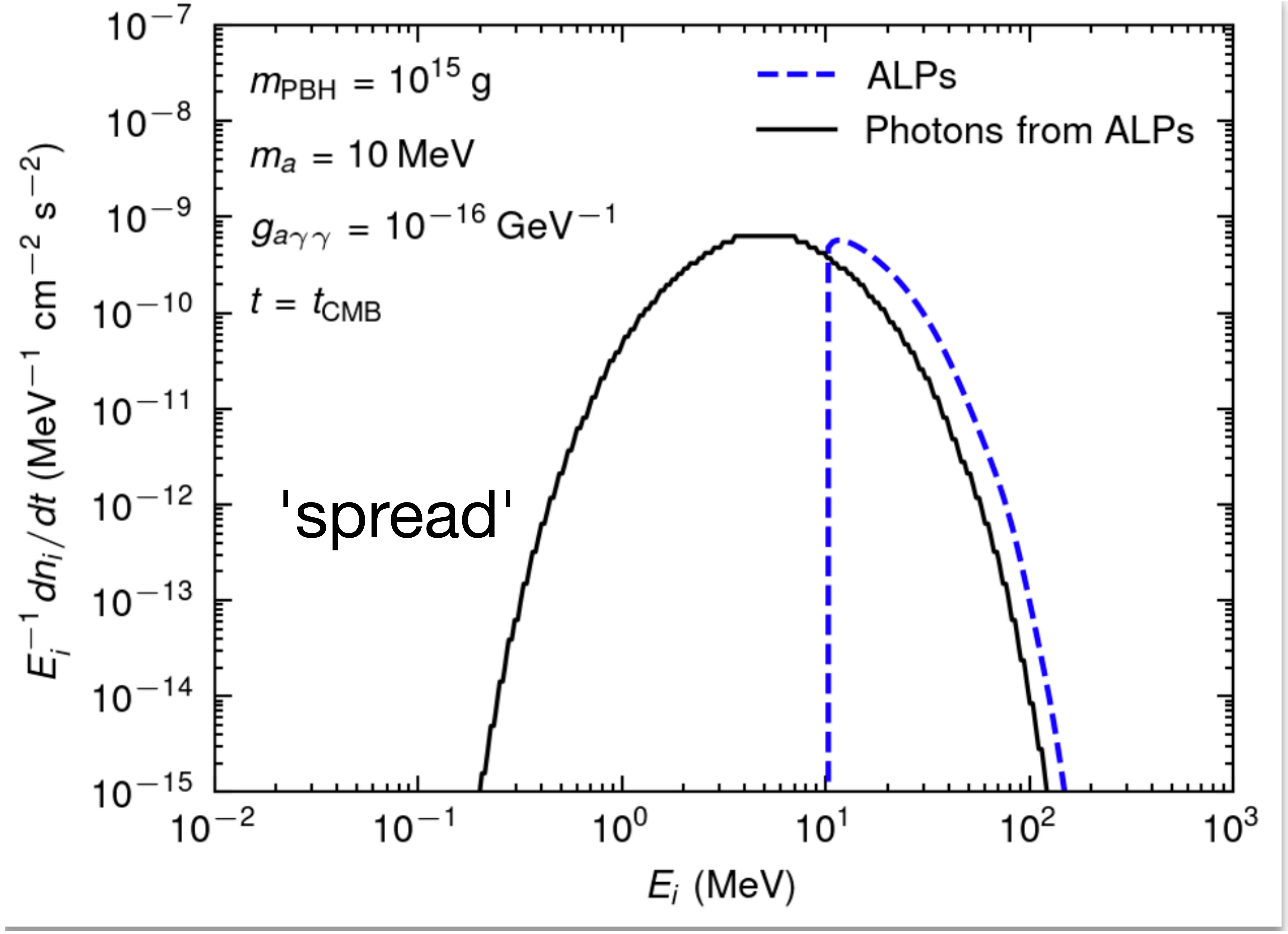
E_γ^*

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

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

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

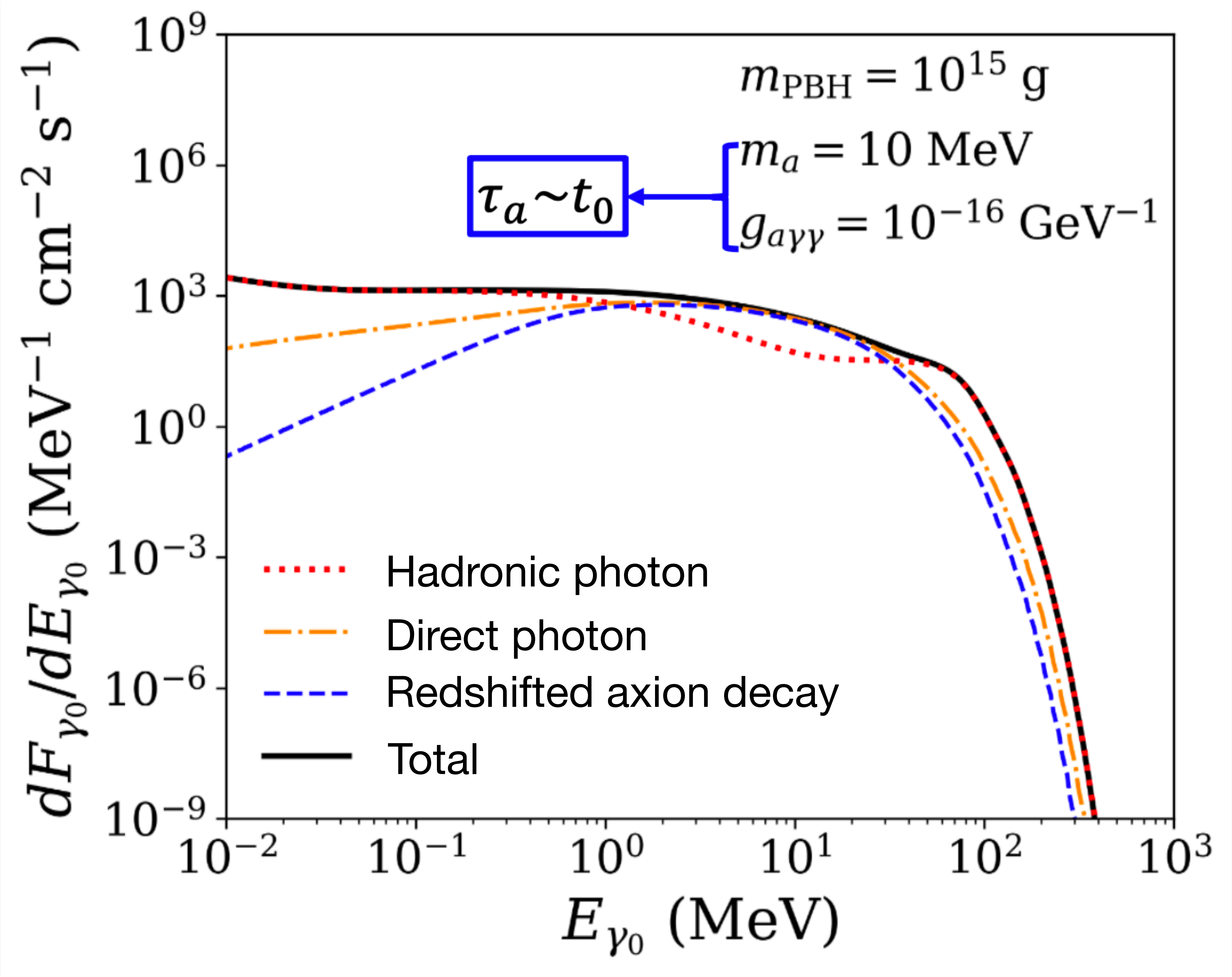
boosted spectrum



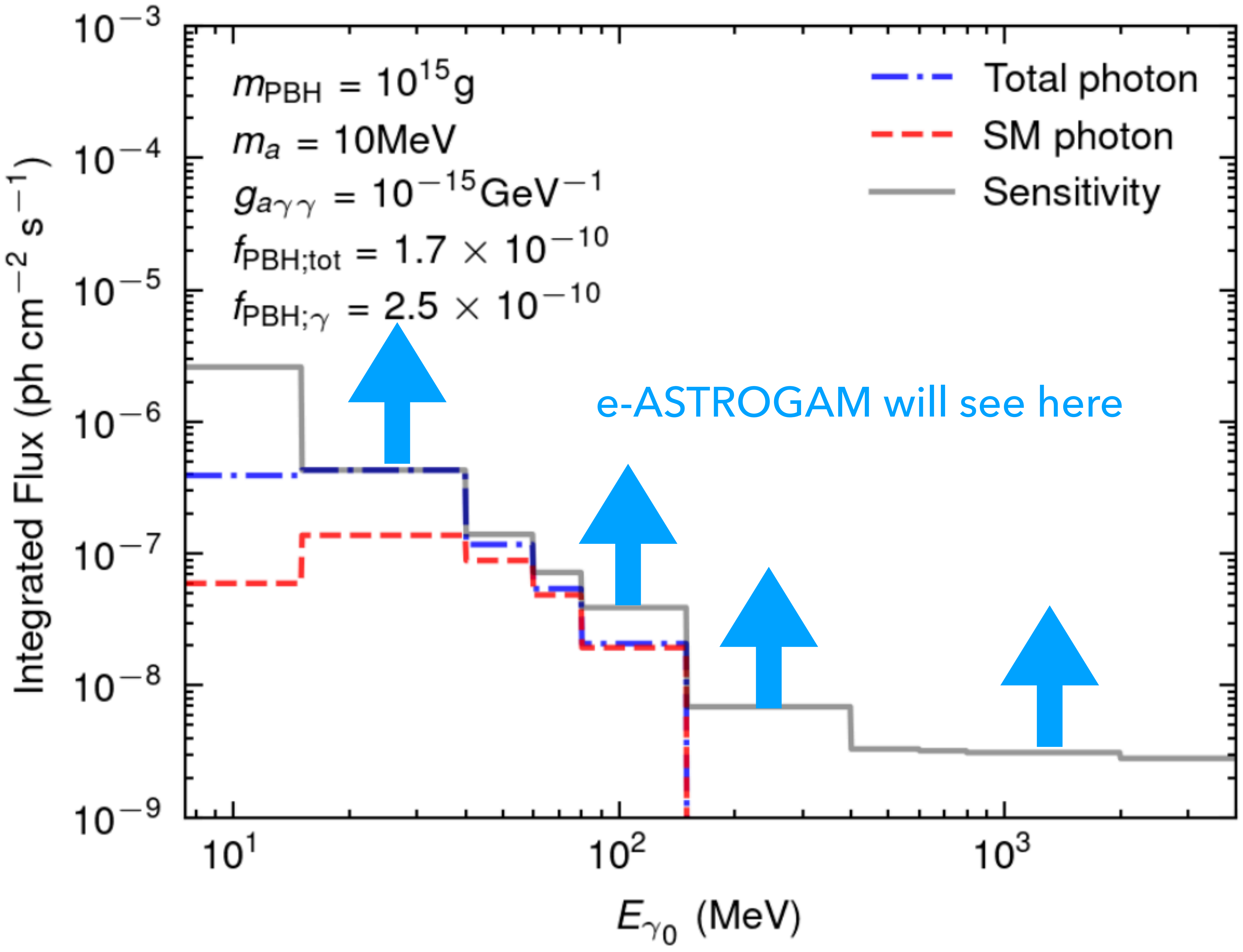
not much forward boost
because of direction

Final photon flux

= (SM) + (Axion : evaporation + expansion + redshift + redshifted decay + boosted decay)

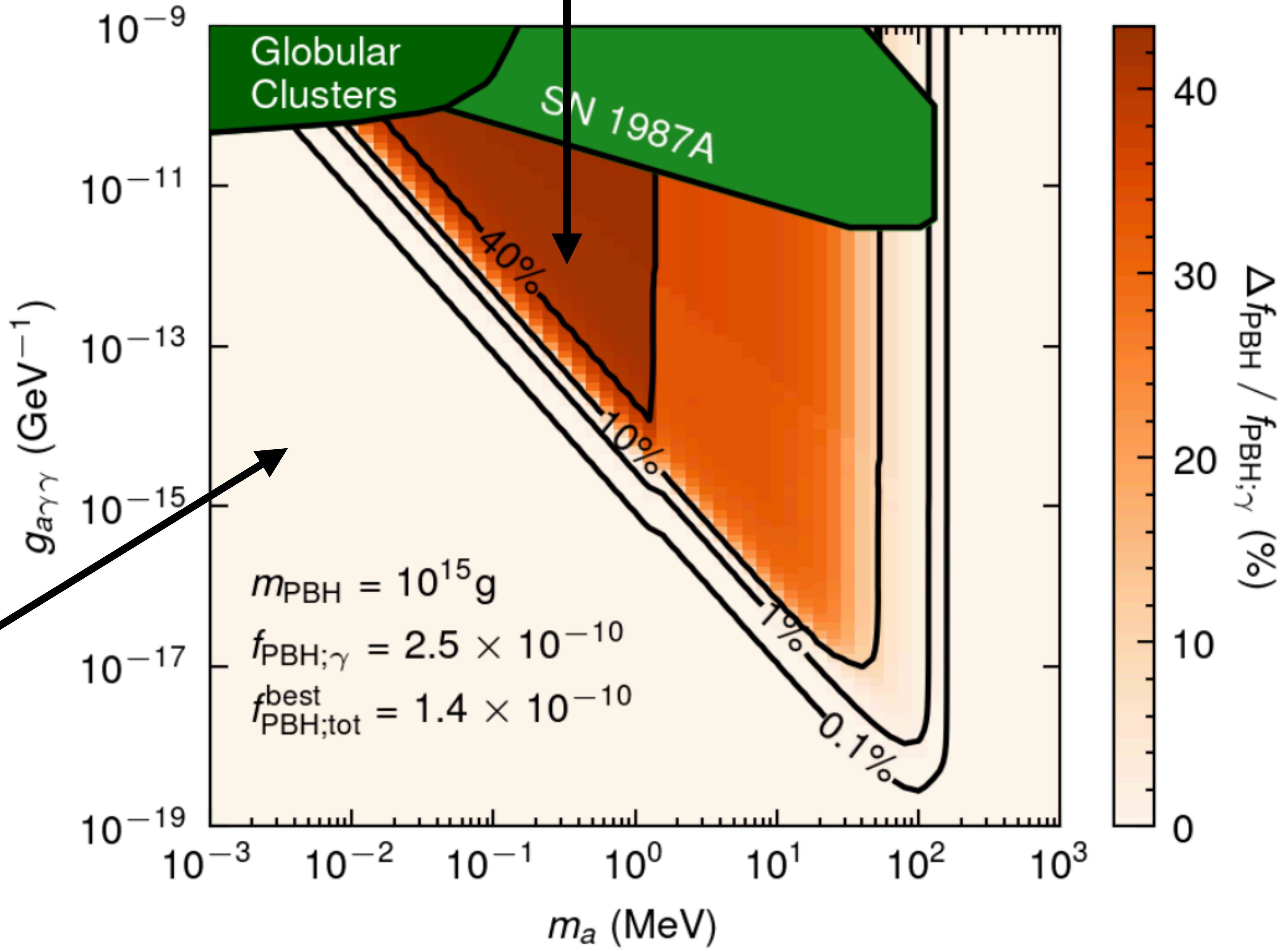


e-ASTROGAM vs PBH-a signal



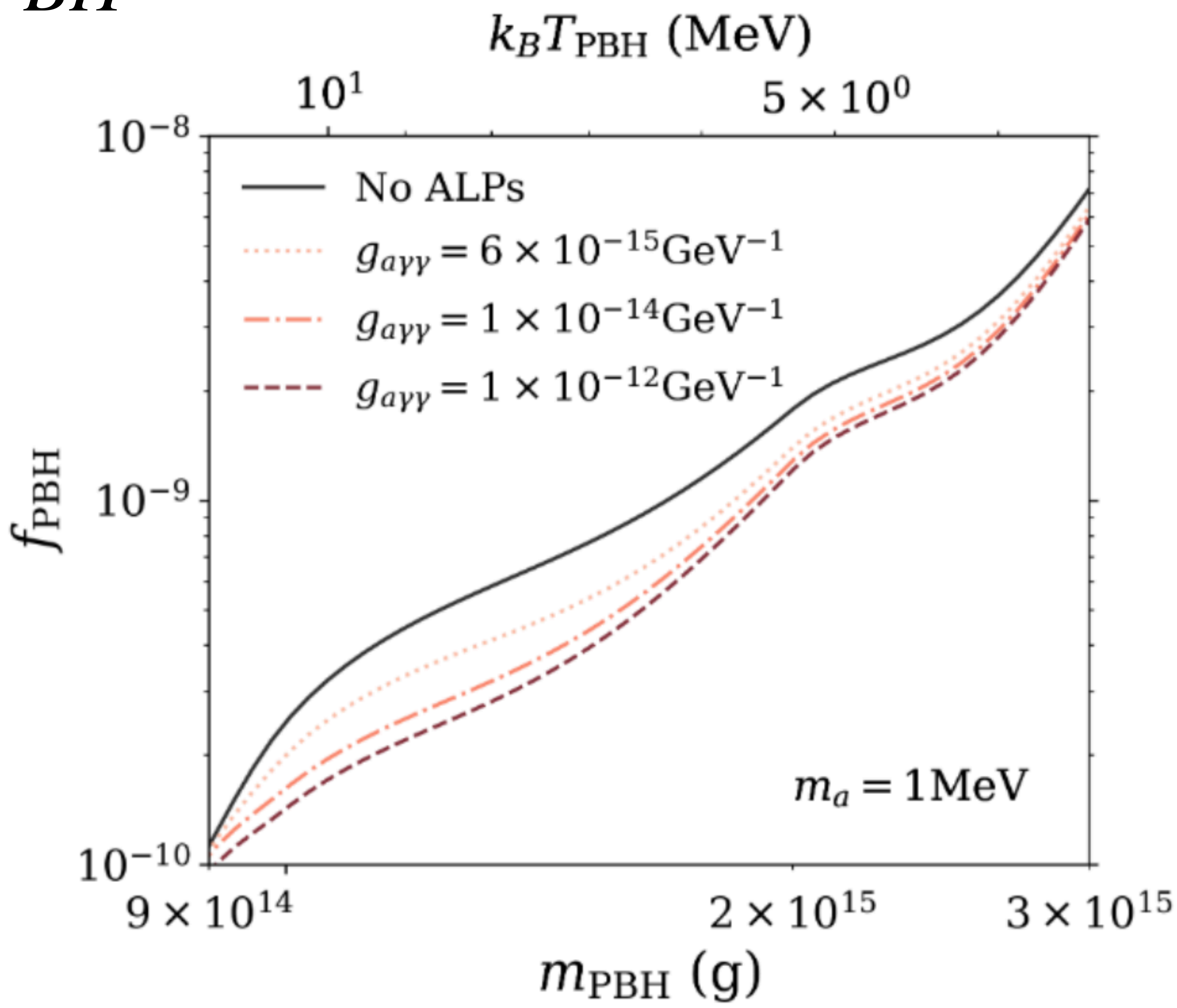
Axion effect over the SM γ

most apparent part



axion effect
is small here

Expected sensitivity on f_{PBH}



Summary & discussion

- PBH is an excellent BSM factory for $m_{BSM} \lesssim k_B T_{PBH} = \frac{M_{Pl}^2}{M_{PBH}}$
- We carefully study the effects of axions (1-100 MeV)

  ✓boost effect ($T \gg m_a$)

  ✓redshift effect on decay width & kinematics ($\Gamma(z)$ …)
- We find that future experiments e.g. e-ASTROGAM, will have a chance to detect photon signals (SM as well as axion-photon)
- Other BSM particles such as dark photon, additional neutrinos are also interesting. (under progress)