DM Contributions to the Galactic Center 511keV Gamma-ray Line: **from PBHs and BSM Particles.**

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In collaboration with

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arXiv:2306.XXXXX

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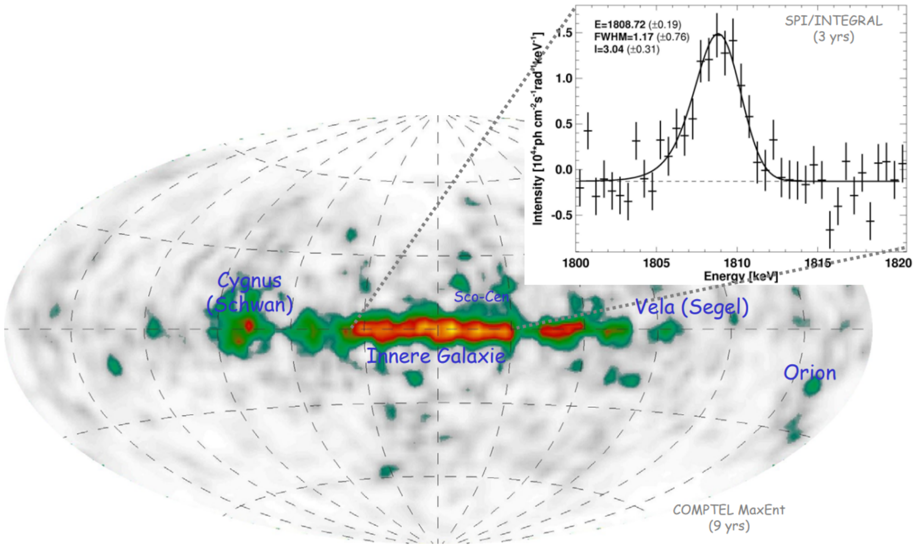
2023. June. 12th

Anomalous 511 keV gamma ray from GC



[Image is derived from COMPTEL and a spectrum is measured from SPI/INTEGRAL]

[Johnson, W. N., F. R. Harnden, and R. C. Haymes-Astrophysical Journal, vol. 172, p.L1]

- In the early 1970's, the 511 keV emission was first detected from GC by balloon-borne instruments
- At low energy case (non-relativistic positron), photons are produced by e^-e^+ annihilation, and each with equal to the rest energy of e^- or e^+ $(\mathbf{511keV})$
- PBH might be a source of positrons in Galaxy (By the Hawking radiation) : positrons produced from PBH propagate and annihilate within Galaxy and subsequently it can contribute to $\mathbf{511\ keV}$ γ-ray in Galaxy Center

Primordial Black Hole (PBH)

- Produced cosmologically *e.g.* during inflation
- The one of well-known candidates for dark matter
- It can be evaporated through Hawking radiation
- **Factory of both SM and BSM particles**

Thermal Properties

- Hawking temperature of PBH

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

$$T_{\rm PBH} \overset{M_{\rm PBH}=10^{15}{\rm g}}{\sim} 10^{11}\ {\rm K}$$

$$i.e.\quad T_{\odot} \sim 6\times 10^{-8}\ {\rm K}$$

- Emission rates of i particle : It can be calculated By **BlackHawk**

- Alexandre Arbey, Jérémy Auffinger
  Eur. Phys. J. C 81 (2021) 10, 910

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

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

- The lifetime of PBH

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

For the massless particles

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

- Don N. Page
  Phys. Rev. D 13, 198 (1976)

Primordial Black Hole (PBH)

[D. N. Page-Phys. Rev. D 14, 3260 (1976)]

- Hawking temperature of PBH

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$$T_{\rm PBH} \overset{M_{\rm PBH}=10^{15}\,{\rm g}}{\sim} 10^{11}\ {\rm K} \qquad i.e. \quad T_{\odot} \sim 6\times 10^{-8}\ {\rm K}$$

- the peaks in the flux per particle mode

$$E_{s=0} \approx 2.81 T_{\rm PBH}, \quad E_{s=1/2} = 4.02 T_{\rm PBH}, \quad E_{s=1} = 5.77 T_{\rm PBH}$$

i.e. $M_{\rm PBH} = 10^{17}$ g,

Hawking temperature		peak energy of emitted particles
$T_{\rm PBH} \sim 100$ keV	→	$E_e \sim 400$ keV $E_\gamma \sim 577$ keV

Primordial Black Hole (PBH)

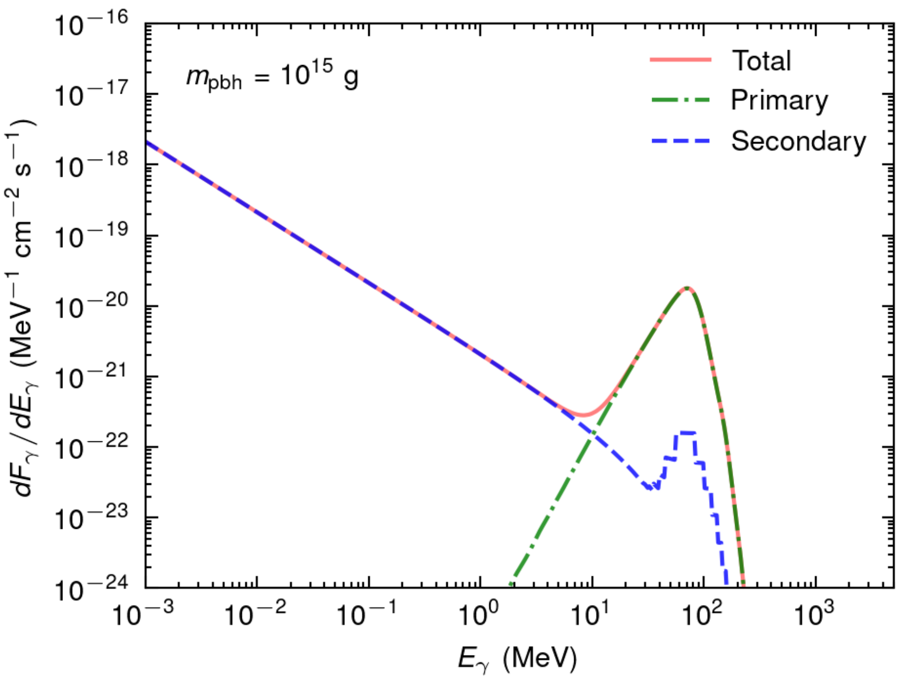
- **Emission rates** of i particle

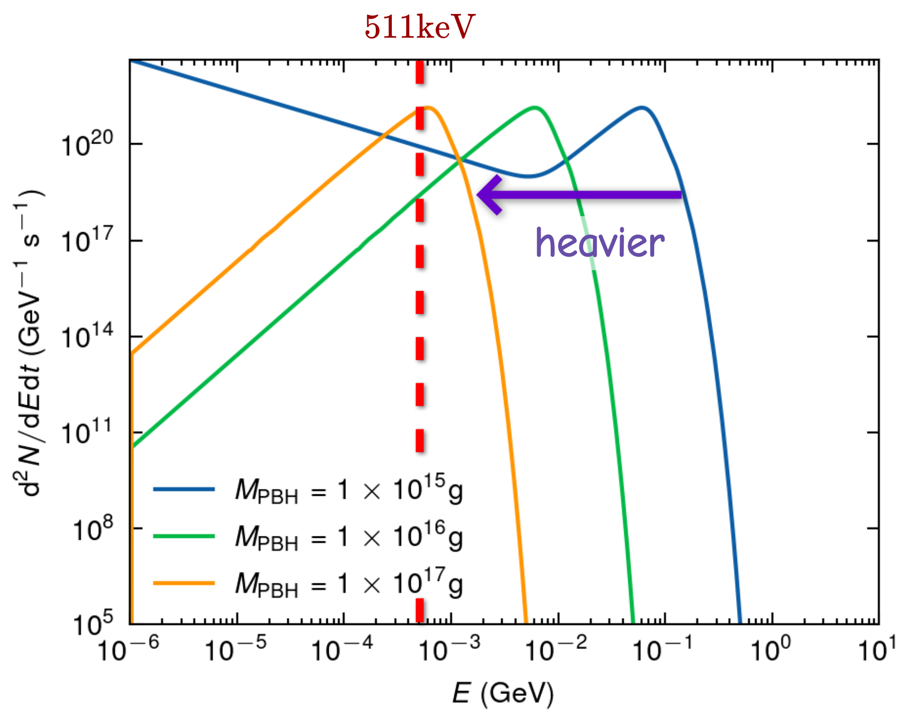
$$\frac{\mathrm{d}^2 N_i}{\mathrm{d}E\mathrm{d}t} = \frac{g_i}{2\pi}\frac{\Gamma_i(E, M_{\mathrm{PBH}})}{e^{E/k_B T_{\mathrm{PBH}}} - (-1)^{2s_i}}$$

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

[Characterization of particle emitted from a single PBH] By **BlackHawk v2.1**

- For photon





- Continuous spectrum
- Emitted particle spectrum: primary + secondary

- The **heavier PBH**, the **lower** energy of **peak** position of particles

Primordial Black Hole (PBH)

- The lifetime of PBH

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

i.e. for the massless particles

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

- Don N. Page
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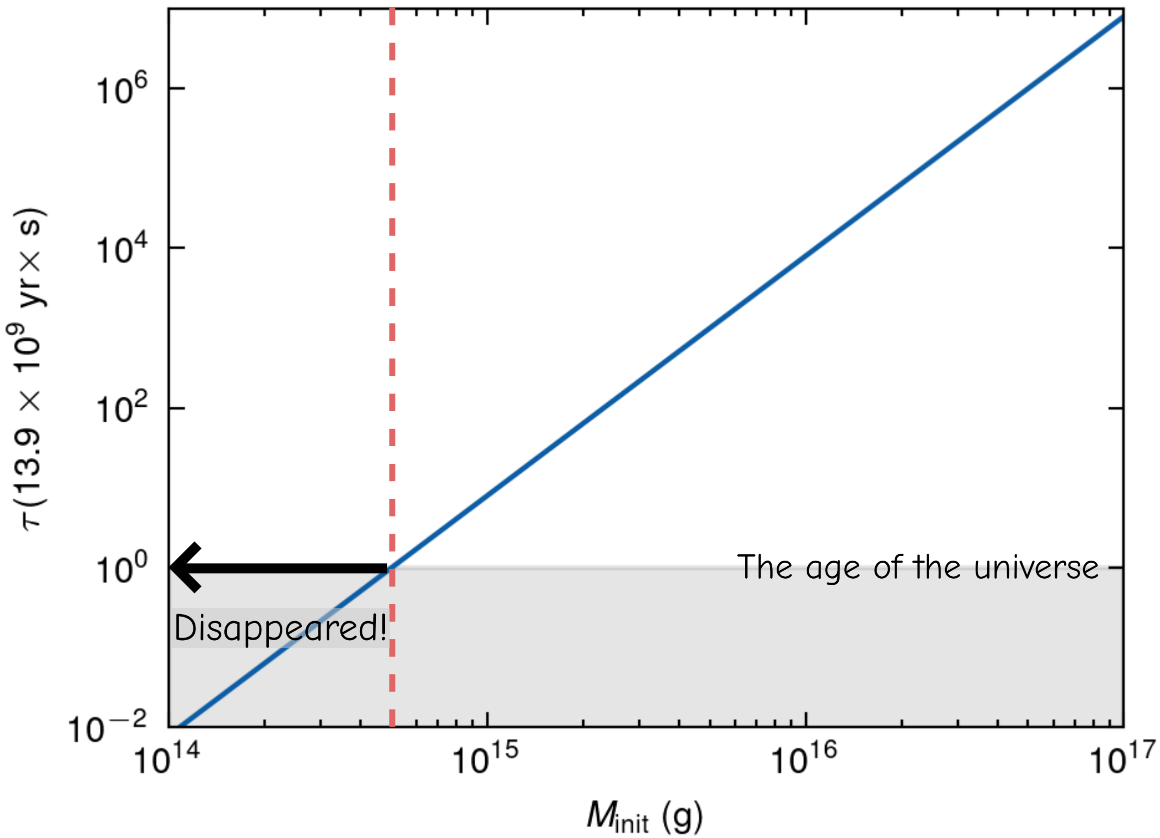
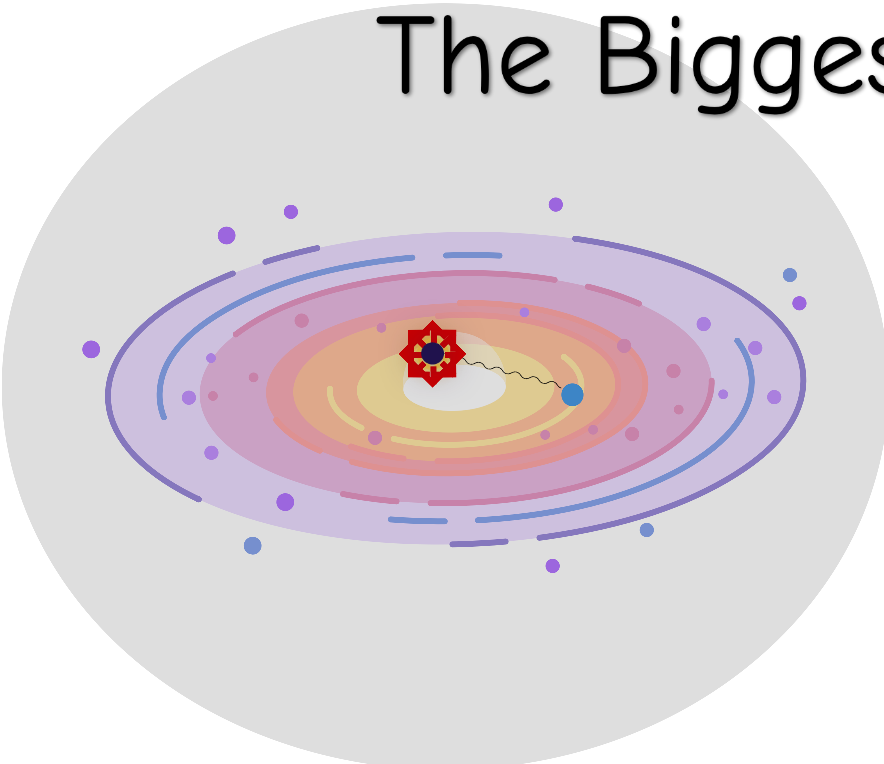
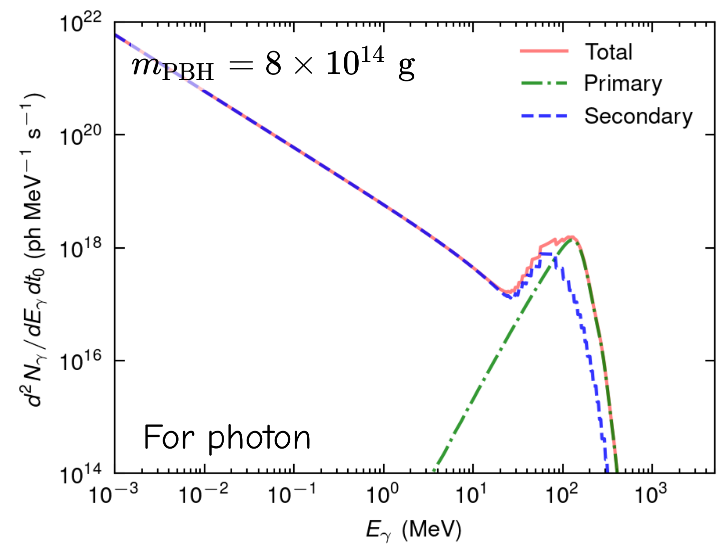
5×10^{14} g

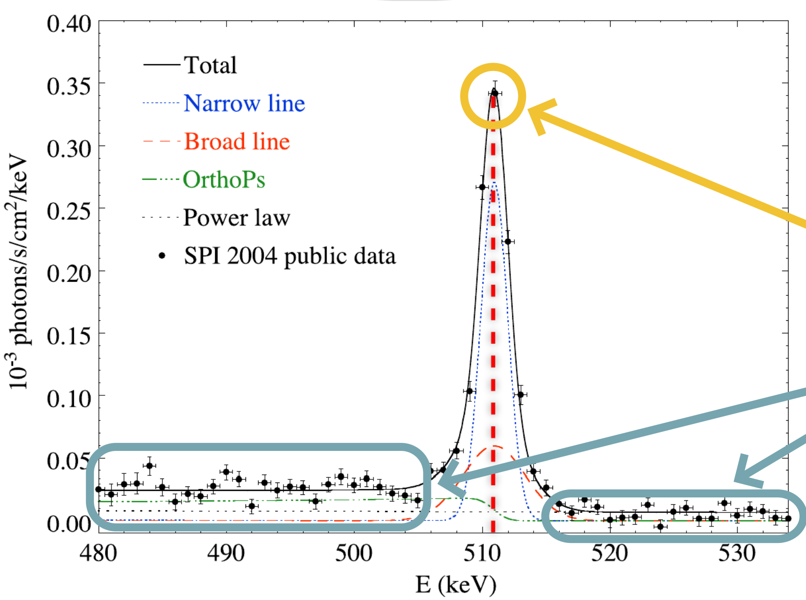


The Biggest Takeaways



1. PBHs emit particles in the energy distribution



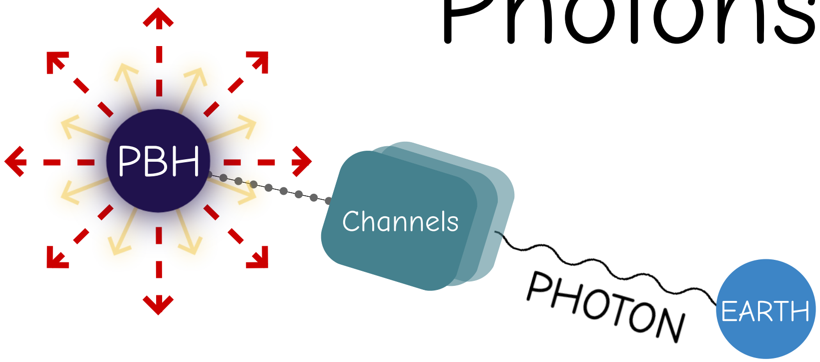


2. The photons derived from PBHs contribute

- **sufficient amount at 511 keV**
- **small amount in the continuum spectrum**

to not violate the observational data constraints.

Photons from PBH

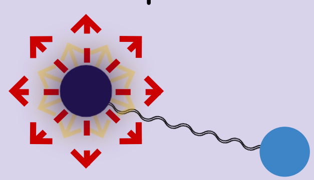


Assumption on PBH

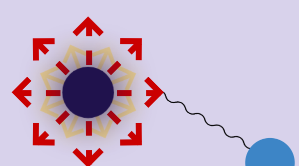
- Monochromatic mass distribution
- Schwarzschild PBH
- Isotropically distributed

possible channels

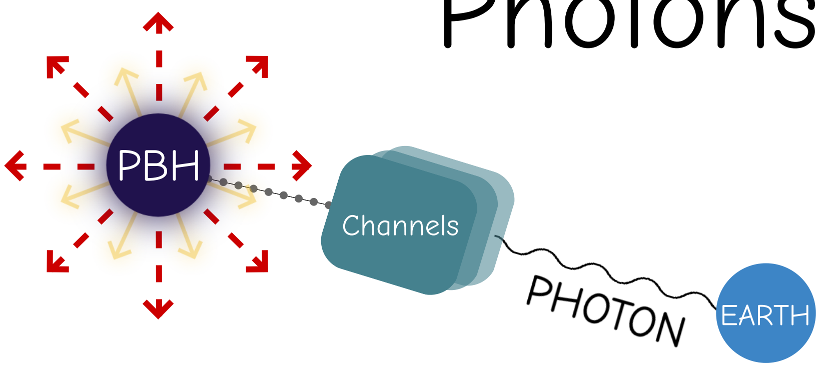
1. $\text{PBH} \xrightarrow{\text{Hawking radiation}} \text{(primary+secondary) } \gamma\text{-rays}$



2. $\text{PBH} \xrightarrow[\text{radiation}]{\text{Hawking}} e^{+} \xrightarrow[\text{annihilation}]{\text{pair}} \gamma\text{-rays}$



Photons from PBH



Assumption on PBH

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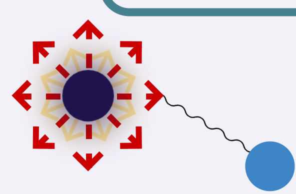
- Isotropically distributed

possible channels

1. PBH $\xrightarrow{\text{Hawking radiation}}$ (primary+secondary) γ-rays

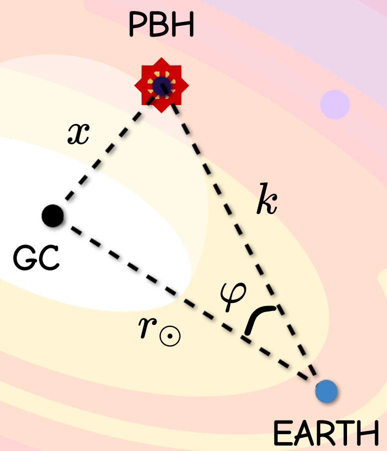
Note that secondary modes of Blackhawk does **not** contain the pair annihilation
we should calculate it by ourself

2. PBH $\xrightarrow[\text{radiation}]{\text{Hawking}}$ $\boxed{e^+ \xrightarrow[\text{annihilation}]{\text{pair}} \gamma\text{-rays}}$



Galactic Contribution on Photon from PBH

1. PBH $\xrightarrow{\text{Hawking radiation}}$ γ-ray



Differential photon flux from PBHs following NFW profile

$$\frac{dF_\gamma}{dE_\gamma} = \int^{k_{\max}} k^2 dk d\Omega_{\varphi,\theta} \frac{1}{4\pi k^2} \frac{f_{\mathrm{PBH}} \rho_{\mathrm{NFW}}(x[k,\varphi])}{M_{\mathrm{PBH}}} \boxed{\frac{d^2 N_\gamma}{dE_\gamma dt_0}}$$

For an evaporating PBH, the number of photons with an energy and at the time

$$x[k,\varphi] = \sqrt{k^2 + r_\odot^2 - 2kr_\odot \cos\varphi}$$

$$k_{\max} = \sqrt{r_h^2 - r_\odot^2 \sin^2\varphi} + r_\odot \cos\varphi$$

Assumption on PBH

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Galactic Contribution on Photon from PBH

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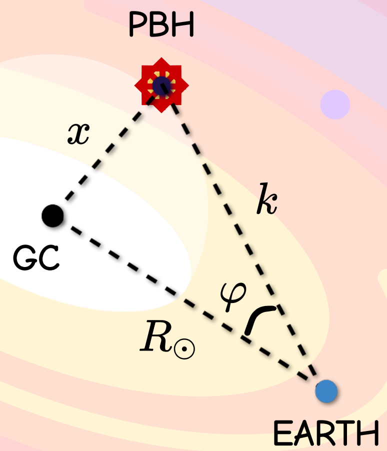

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$$\frac{f_{\mathrm{PBH}}\rho_{\mathrm{NFW}}}{M_{\mathrm{PBH}}} = n_{\mathrm{PBH}}$$

: PBH number density

$$x[k,\varphi] = \sqrt{k^2 + r_\odot^2 - 2kr_\odot \cos\varphi}$$

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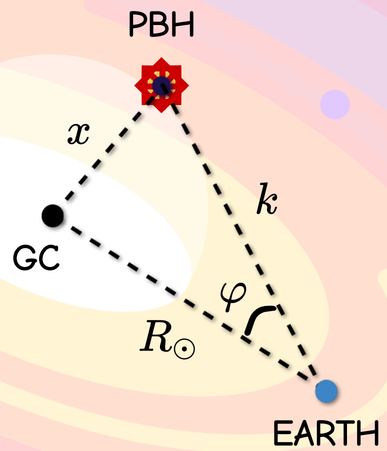
Assumption on PBH

- Monochromatic mass distribution
- Schwarzschild PBH
- Isotropically distributed

- $\frac{d^2 N_\gamma}{dE_\gamma dt_0}$: For an evaporating PBH, the number of photons with an energy and at the time

Galactic Contribution on Photon from PBH

1. PBH $\xrightarrow{\text{Hawking radiation}}$ γ-ray



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isotropically emitted photon flux with an energy at the time from PBHs **at a point** in the Milky way galaxy

$$x[k,\varphi] = \sqrt{k^2 + r_\odot^2 - 2kr_\odot \cos\varphi}$$

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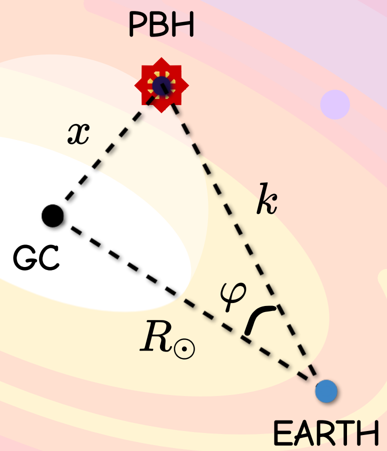
- $\frac{d^2 N_\gamma}{dE_\gamma dt_0}$: For an evaporating PBH, the number of photons with an energy and at the time
- $\frac{f_{\rm PBH}\rho_{\rm DM}}{M_{\rm PBH}} = n_{\rm PBH}$: PBH number density

Galactic Contribution on Photon from PBH

1. PBH $\xrightarrow{\text{Hawking radiation}}$ γ-ray



Differential photon flux from PBHs following NFW profile

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Spectral photon flux emitted from PBH in the dark halo of the Milky Way

$$x[k,\varphi] = \sqrt{k^2 + r_\odot^2 - 2kr_\odot \cos\varphi}$$

$$k_{\max} = \sqrt{r_h^2 - r_\odot^2 \sin^2\varphi} + r_\odot \cos\varphi$$

Assumption on PBH

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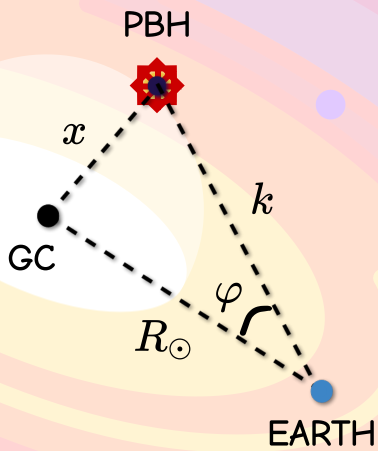

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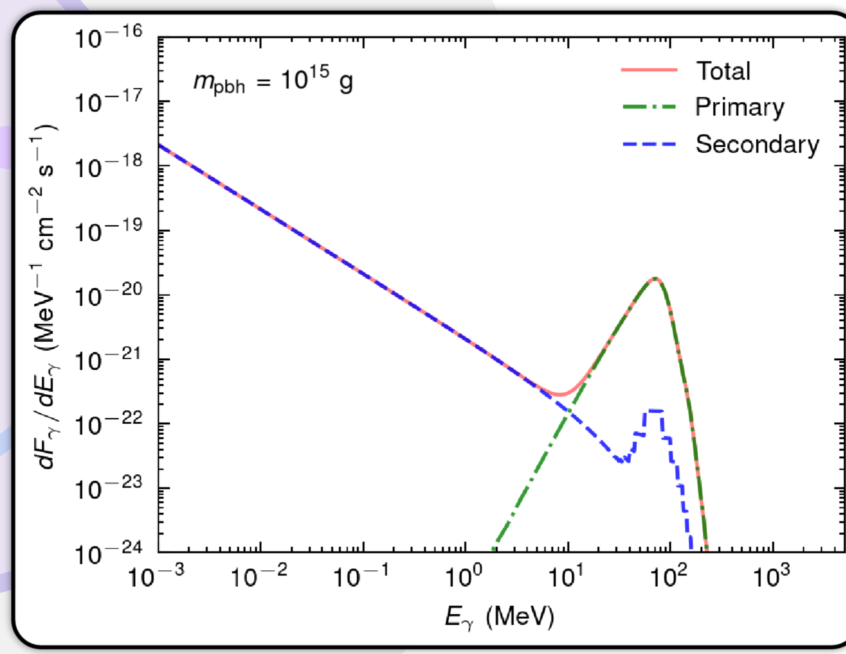

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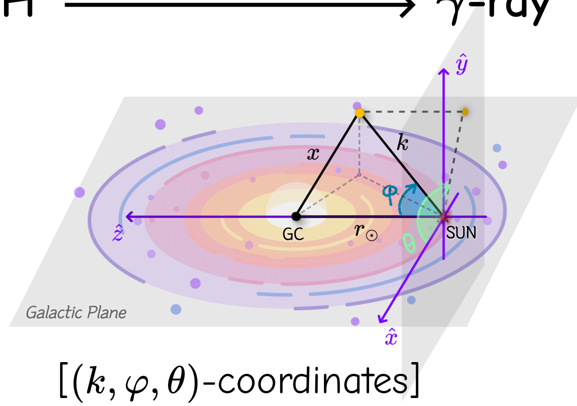
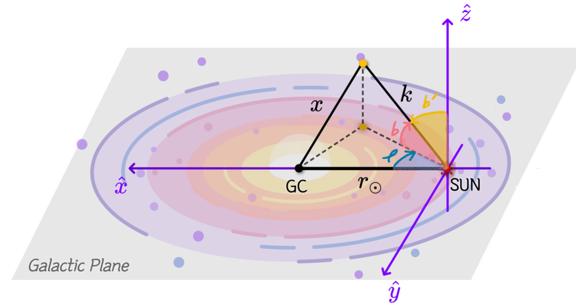
Galactic Contribution on Photon from PBH

1. PBH $\xrightarrow{\text{Hawking radiation}}$ γ-ray



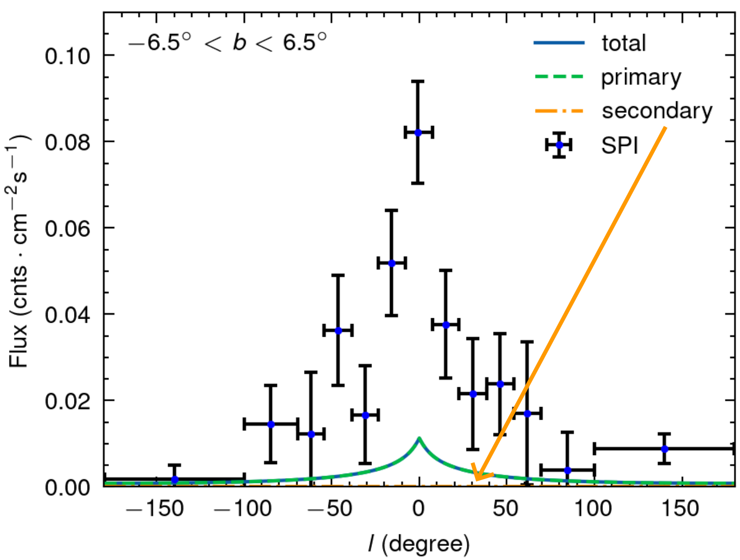
[(k,φ,θ)-coordinates]

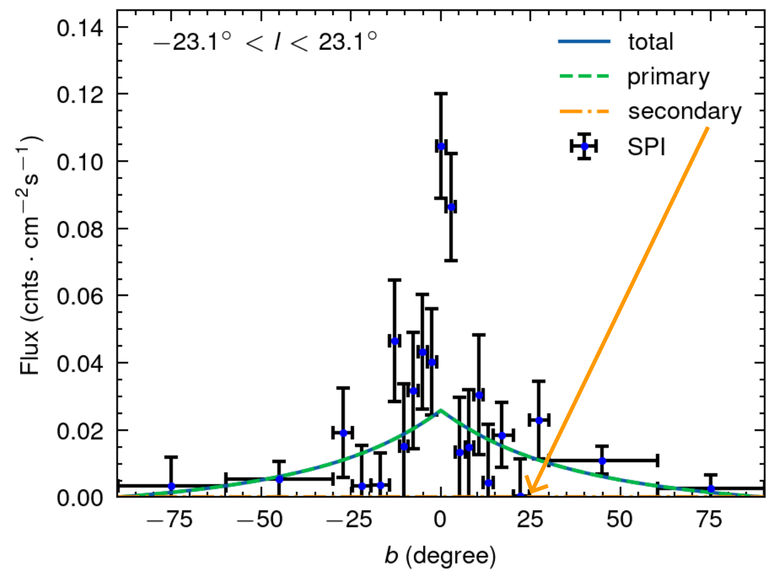


[(k,b',l)-coordinates]

$$I_\gamma^l\left(b_1,b_2\right)=\frac{1}{4\pi}\int_{\frac{\pi}{2}-b_2}^{\frac{\pi}{2}-b_1}db'\sin b'\int_0^{k_{\max}}dk\;n_{\rm PBH}\left(x\right)\int_{E_1}^{E_2}dE\,\frac{d^2N_\gamma}{dE_\gamma dt_0}$$

$$I_\gamma^b\left(l_1,l_2\right)=\frac{\cos b}{4\pi}\int_{l_1}^{l_2}dl\int_0^{k_{\max}}dk\;n_{\rm PBH}\left(x\right)\int_{E_1}^{E_2}dE\,\frac{d^2N_\gamma}{dE_\gamma dt_0}$$





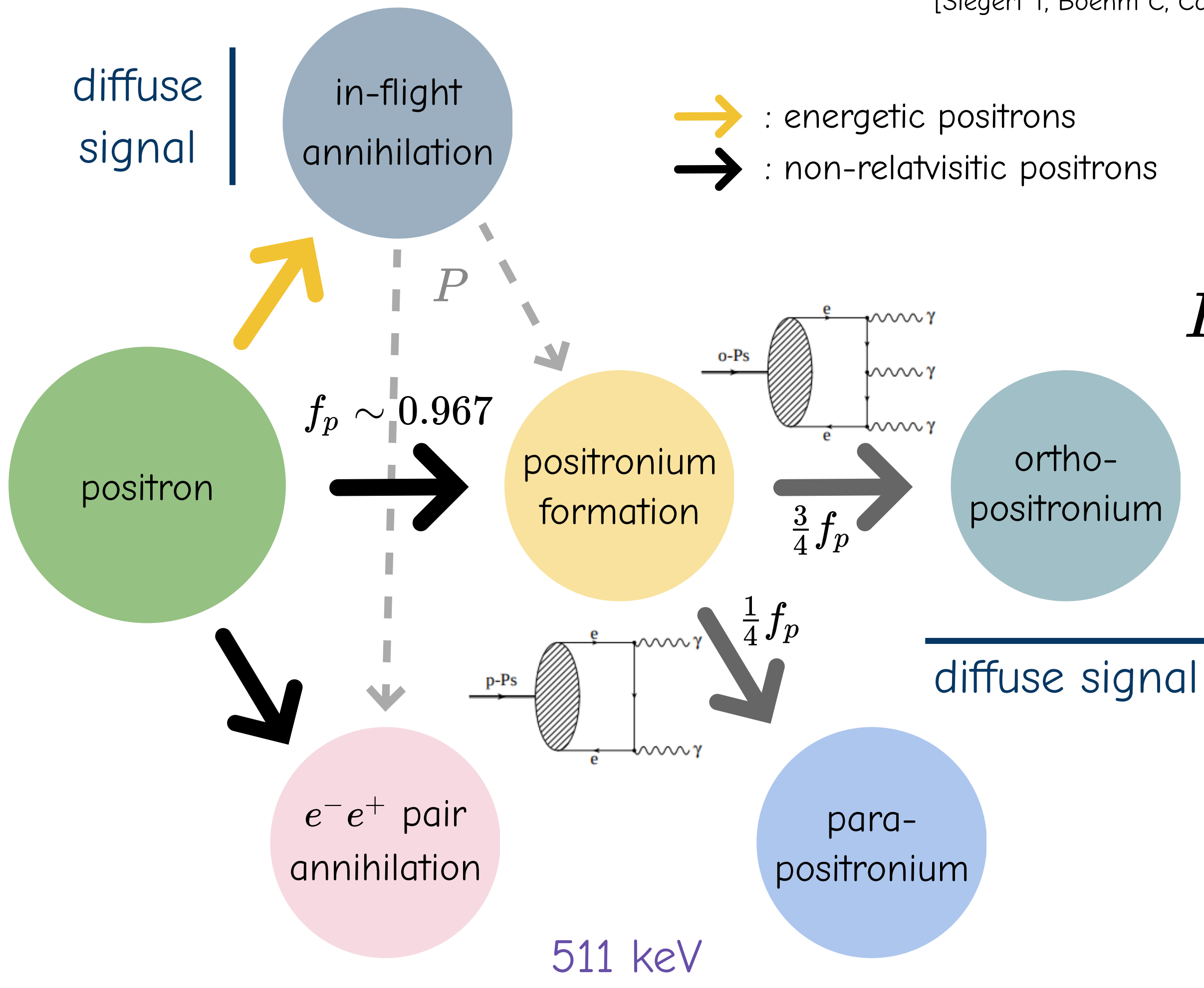
This photon spectrum affects both of **511 keV** and **the background diffuse γ-ray signal**

Galactic Contribution on Photon from PBH

2. PBH $\xrightarrow[\text{radiation}]{\text{Hawking}}$ e^+ $\xrightarrow[\text{annihilation}]{\text{pair}}$ γ-rays

This process can affect both **511 keV and diffuse γ-ray signal**

[John F. Beacom and Hasan Yüksel-PhysRevLett.97.071102]
[Siegert T, Boehm C, Calore F, et al-*Mon.Not.Roy.Astron.Soc.* 511 (2022) 1, 914-924]



The total annihilation flux

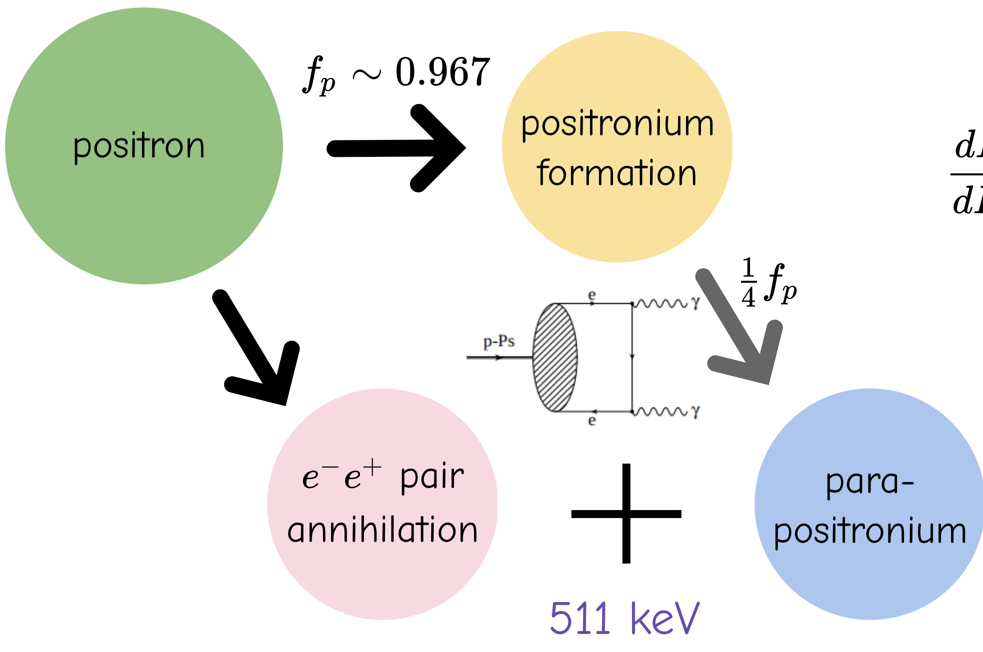
$$F_{\rm Ann} = F_{511} + F_{\rm oPs} + F_{\rm IA}$$

- F_{511}
  : The flux in the 511 keV due to direct and para-positronium annihilation
- $F_{\rm oPs}$
  : 3 photon decay flux of ortho-positronium
- $F_{\rm IA}$
  : The flux of e^+s annihilating in flight

Galactic Contribution on Photon from PBH

2. PBH $\xrightarrow[\text{radiation}]{\text{Hawking}}$ e^+ $\xrightarrow[\text{annihilation}]{\text{pair}}$ γ-rays

511 keV γ-ray signal



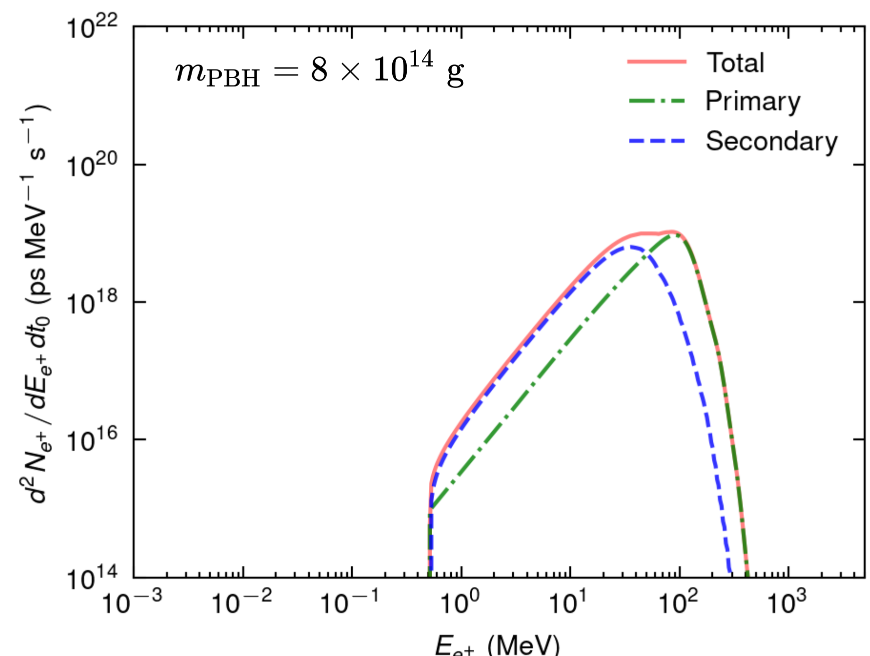
511 keV flux from non-relativistic positrons

$$F_{511} = \int dE_\gamma \int dE_{e^+} \boxed{\frac{dF_{e^+}}{dE_{e^+}}} \Big[2\delta(E_\gamma - 511\text{keV}) \Big]$$

The spectrum of positrons from PBH

$$\frac{dF_{e^+}}{dE_{e^+}} = \frac{1}{4\pi} \int dl \int db' \sin b' \int_0^{k_{\max}} dk \; n_{\rm PBH} \frac{d^2 N_{e^+}}{dE_{e^+} dt_0}$$

- $n_{\rm PBH} = \frac{f_{\rm PBH} \rho_{\rm NFW}\left(x\left[k,l,b'\right]\right)}{M_{\rm PBH}}$



Galactic Contribution on Photon from PBH

2. PBH $\xrightarrow[\text{radiation}]{\text{Hawking}}$ e^+ $\xrightarrow[\text{annihilation}]{\text{pair}}$ γ-rays

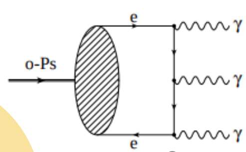
Diffuse γ-ray signal

diffuse signal | in-flight annihilation

: energetic positrons

: non-relatvisitic positrons

positron $\xrightarrow{f_p \sim 0.967}$ positronium formation $\xrightarrow{\frac{3}{4} f_p}$ ortho-positronium



diffuse signal

The ratio of the flux of oPs to 511 keV gamma rays

$$\frac{F_{\mathrm{oPs}}}{F_{511}} = \frac{9 f_{\mathrm{p}}}{8-6 f_{\mathrm{p}}}$$

f_p: The positronium fraction

The ratio of the total flux of IA to 511 keV gamma rays

$$\frac{F_{\mathrm{IA}}}{F_{511}} = \frac{2(1-\mathrm{P})}{2(1-3f/4)\mathrm{P}}$$

P: The survival probability of positrons

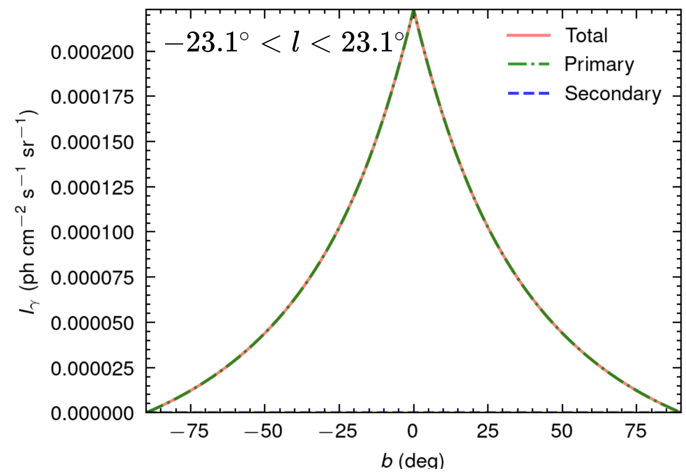
Galactic Contribution on Photon from PBH

2. PBH $\xrightarrow[\text{radiation}]{\text{Hawking}}$ e^+ $\xrightarrow[\text{annihilation}]{\text{pair}}$ γ-rays

Diffuse γ-ray signal

[The flux for Inflight Annihilating positrons]

$m_{\rm PBH} = 1.5 \times 10^{17}$ g



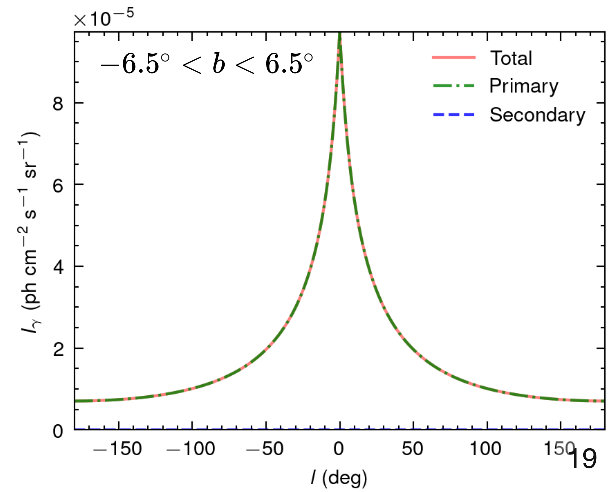
- For the **mono-energetic injection energy**, the best fit of positron injection energy is 3 MeV.
  "$\mathbf{3\ MeV}$ cut method"
- But, in our study we have the **continuous energy spectrum** of positrons from PBH.
  here, we additionally use "weighted energy distribution"

The total IA spectrum for distributive injection of e^+s

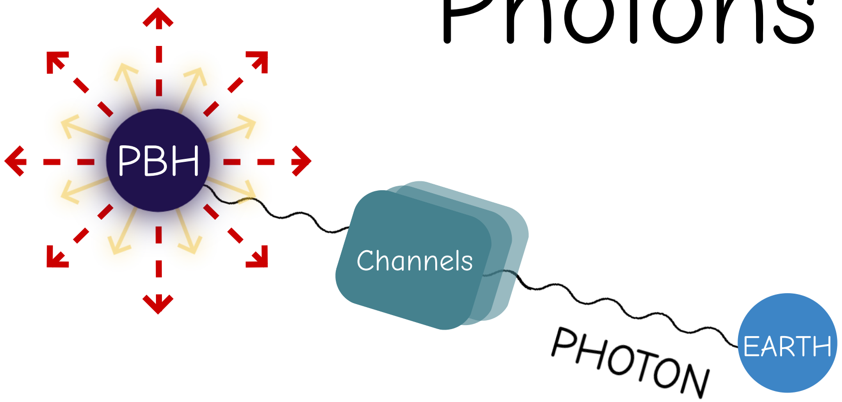
$$\frac{dF_{\rm IA}}{dk} = \left\langle \left(\frac{d\tilde{F}_{\rm IA}}{dk} \right) \right\rangle_{E_0} = \left(\int_{m_e}^{E_{e^+}^{\max}} dE_0 \frac{d^2N}{dE_0 dt_0} \frac{d\tilde{F}_{\rm IA}}{dk} \right) \Big/ \left(\int_{m_e}^{E_{e^+}^{\max}} dE_0 \frac{d^2N}{dE_0 dt_0} \right)$$

where $$\frac{d\tilde{F}_{\rm IA}}{dk} = \frac{F_{511}}{1-3f_p/4} \frac{n_H}{P} \int_{G(k)}^{E_0} P_{E_0 \to E} \frac{1}{2} \frac{d\sigma}{dk} \frac{dE}{|dE/dx|}$$

$$k = \frac{E_\gamma}{m_e}, \quad G(k) = \max\left(\frac{2k^2-2k+1}{2k-1}, k \right), \quad P = P_{E_0 \to m_e}$$



Photons from PBH



Assumption on PBH

- Monochromatic mass distribution
- Schwarzschild PBH
- Isotropically distributed

possible channels

1. PBH $\rightarrow$ γ-rays
2. PBH $\rightarrow$ e^+ $\rightarrow$ γ-rays

SM mode

3. PBH $\rightarrow$ BSM $\rightarrow$ γ-rays
4. PBH $\rightarrow$ BSM $\rightarrow$ e^+ $\rightarrow$ γ-rays

Improved way

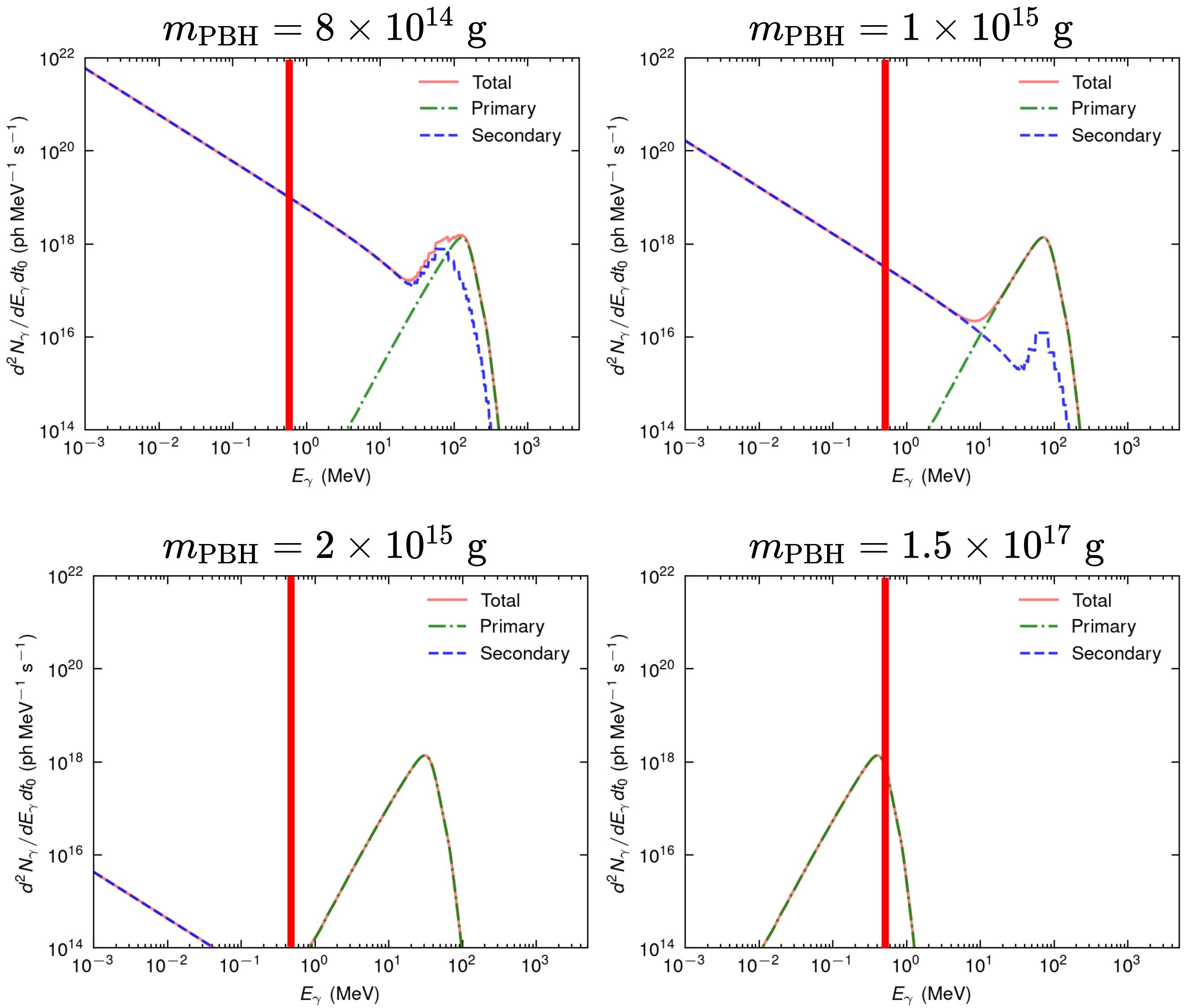
Summary

- PBH is a good source for emitting both SM / BSM particles through hawking radiation.
- Assuming that Primordial Black Holes (PBH) form part of the dark matter composition, the particles that are radiated from them and the ensuing decay or annihilation processes could potentially account for the peculiar 511 keV γ-ray detected at the center of the Milky Way.
- Using the Spectrometer on INTEGRAL (SPI) observation data for gamma rays at the Galactic Center - particularly for the 511 keV emissions as well as for the background diffuse gamma rays - it is possible to establish a limit on the abundance of Primordial Black Holes (PBHs).

further

- Considering Beyond Standard Model (BSM) particles
  : Incorporating their influence, BSM particles will amplify the intensity of γ-rays, resulting in giving a stronger bound of PBHs abundance and furthermore properties of BSM.

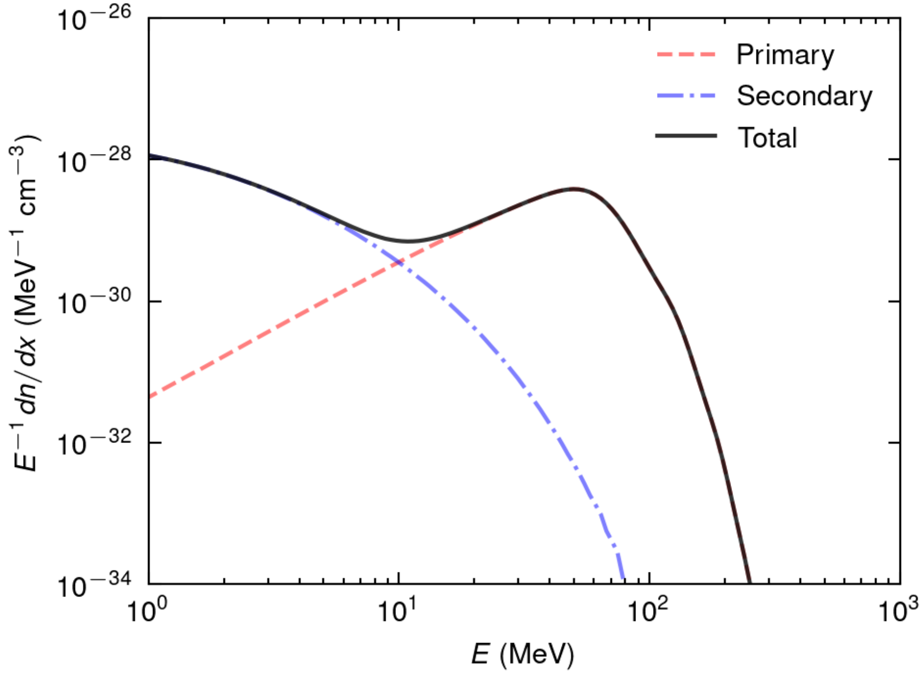
Back-Up


$m_{\rm PBH} = 8 \times 10^{14}$ g
$m_{\rm PBH} = 1 \times 10^{15}$ g
$m_{\rm PBH} = 2 \times 10^{15}$ g
$m_{\rm PBH} = 1.5 \times 10^{17}$ g
Total
Primary
Secondary
$d^2N_\gamma/dE_\gamma dt_0$ (ph MeV^{-1} s^{-1})
E_γ (MeV)
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Back-Up

$$4.\ \boxed{\text{PBH} \xrightarrow{\text{evaporation}} a/\gamma'} \xrightarrow[\text{Boost}]{\text{decay}} e^{\pm} \xrightarrow[\text{annihilation}]{\text{pair}} \textbf{511 keV } \gamma\textbf{-ray}$$

step 1: The number density of BSMs from PBH calculated by Blackhawk



Back-Up

$$\text{PBH} \xrightarrow{\text{evaporation}} \boxed{a/\gamma' \xrightarrow[\text{Boost}]{\text{decay}} e^{\pm}} \xrightarrow[\text{annihilation}]{\text{pair}} 511\ \text{keV}\ \gamma\text{-ray}$$

step 2: ALP or DP decays to e^+