Search for Dark Photon Trident Through Primordial Black Hole Signature

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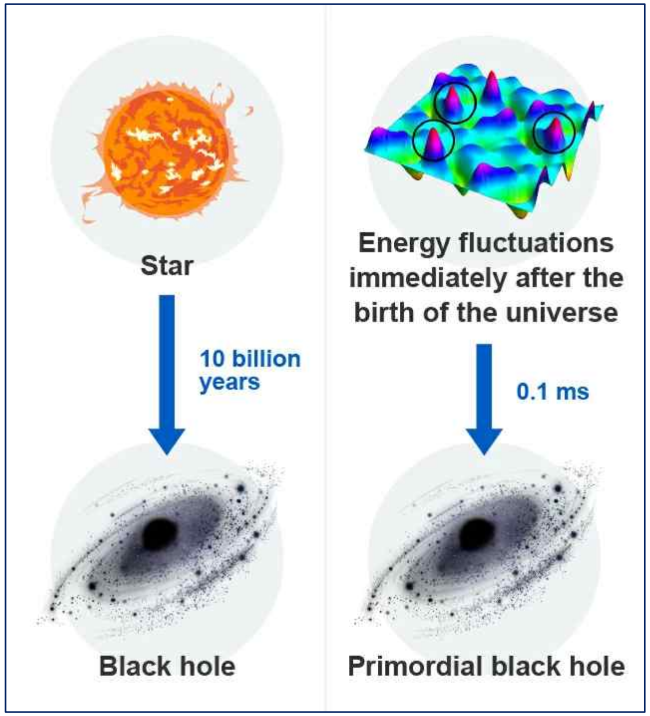
Outline

- Introduction : Primordial Black Hole (PBH) as DM
  - Hawking radiation & motivation for this study
- Dark photon as a probe of BSM physics via Hawking radiation from PBHs
  - dark photon theory & loop-induced trident decay of dark photon
- Gamma-ray signatures from PBH evaporation
  – trident-induced deformation of the gamma-ray spectrum
- Numerical Analysis & Results
  - methodology, expected sensitivities for PBH signal & dark-photon identification
- Conclusion

I. Introduction

PBH as a Dark Matter Candidate

- Primordial black holes (PBHs) are hypothetical black holes that may have formed in the early Universe, before stars and galaxies existed.



- PBHs can form through the gravitational collapse of sufficiently large primordial overdensities
- Possible formation scenarios include enhanced inflationary perturbations, bubble collisions from 1^{st} PT, and cosmic string collapse.
- These scenarios produce PBHs over a wide mass range, determining which PBHs survive today and may contribute to dark matter.

PBH as a Dark Matter Candidate

- PBHs formed in the early Universe can behave as cold dark matter because they are long-lived, non-relativistic & pressureless objects interacting via gravity
- PBHs with initial masses above ~10^{15} g can survive until today.
- Their allowed abundance is strongly constrained and depends on M_{PBH}.
- PBHs may still constitute a fraction of dark matter, so we treat

  $f_{PBH} = \frac{\rho_{PBH}}{\rho_{DM}}$ as free parameter.
- The PBH mass range we consider : $M_{PBH} \sim 10^{15} - 10^{18}$ g

  for which Hawking radiation can provide observable signatures.

Hawking Radiation

- PBHs lighter than 10^{15} g are expected to have completely evaporated by now, unless new physics alters their lifetime. → standard picture of Hawking radiation

  (CMP43(1975),PRD15(1977))

- The primary emission spectra depend on $T_{\mathrm{H}} \sim \frac{1}{M_{\mathrm{PBH}}}$, the masses and spins of the particles, regardless of their interaction strengths.
- Therefore, unlike in collider experiments, PBHs can emit feebly interacting particles through Hawking radiation.
- A particle is emitted efficiently when its mass is not much larger than T_H, while production becomes exponentially suppressed for $m_i \gg T_H$

Why light PBHs are special

- For sufficient light PBHs, Hawking radiation becomes important.
- Lighter PBHs have higher T_H
- We focus on PBHs with $M_{PBH} \sim 10^{15} - 10^{18}$ g, whose Hawking emission lies in the sub-MeV–MeV range.
- Existing observations require them to constitute only a fraction of DM,

$$f_{PBH} < 1$$

- Such MeV-scale photon emission can probe both the PBH abundance and BSM particles, and falls within the target energy range of future MeV gamma-ray telescopes.

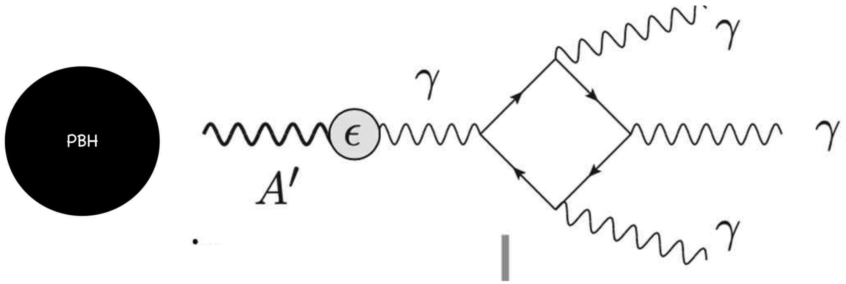
Motivation of this work

- Using Hawking radiation from PBHs as a probe of BSM physics, we investigate the signatures of sub-MeV dark photons emitted directly from PBHs.
- We focus on the loop-induced trident decay of dark photon, and assess whether future MeV gamma-ray telescopes can distinguish this signal from SM-only Hawking radiation.
- This approach opens a new window into dark-sector physics and the particle content of PBH evaporation.

II. Dark Photon & Its Trident Decay

Dark Photon and its Trident Decay

- Dark photon is the gauge boson of an extra U(1) symmetry, and kinetically mixes with the SM photon.
- If $m_{A'} < 2m_e$,
  - $A' \to e^+e^-$ is kinematically forbidden
  - $A' \to 2\gamma$ is forbidden by Landau-Yang theorem
  - the dominant visible decay mode is loop-induced trident decay : **A' → 3γ.**



Dark photon trident decay :
(2406.1944)

Dark Photon and its Trident Decay

- The three-body decay produces a broader, characteristic photon-energy distribution than a two-body decay.
- This signal is likely inaccessible in colliders due to extremely low detectability arising from small kinetic mixing, loop suppression, and limited resolution.
- However, PBH Hawking radiation provides an unsuppressed production channel for dark photons, independent of the small kinetic mixing.
- The resulting **$A' \to 3\gamma$** decays generate a characteristic additional component in the MeV gamma-ray spectrum, enhancing detectability with future missions.

Dark Photon and its Trident Decay

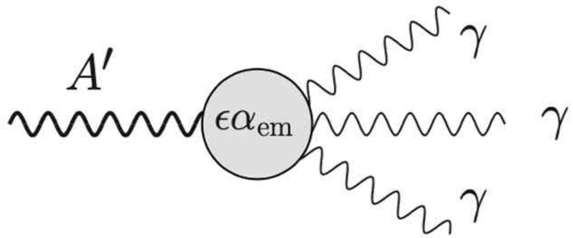
- The Lagrangian for the dark photon is given by

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2_{A'}A'_\mu A'^\mu - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}, \qquad F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu,$$

- The mass term for the dark photon can arise from a dark Higgs mechanism (Mondino et al PRD103(2021)) or the Stueckelberg model (Kingmna et al, JHEP03(2007))

- By integrating out fermions at one-loop, the resulting effective Lagrangian follows the Euler-Heisenberg form:

$$\mathcal{L}^{\rm EH}_{A'} = \frac{\epsilon\alpha_{\rm em}}{45m_e^4}\left(14F'_{\mu\nu}F^{\nu\lambda}F_{\lambda\rho}F^{\rho\mu} - 5F'_{\mu\nu}F^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}\right),$$



Dark Photon and its Trident Decay

- The decay width in the Euler-Heisenberg limit

$$\Gamma_{\rm EH} = \frac{17\epsilon^2\alpha_{\rm em}^4}{11664000\pi^3} \times \frac{m_{A'}^9}{m_e^8} \simeq 1{\rm s}^{-1} \times \left(\frac{\epsilon}{0.003}\right)^2 \times \left(\frac{m_{A'}}{m_e}\right)^9$$

- To account for corrections beyond the Euler-Heisenberg limit, the full decay width can be expressed as

$$\Gamma_{A'\to 3\gamma} = \Gamma_{\rm EH} \times f_{\rm loop}(m_{A'}) = \Gamma_{\rm EH}\left[1 + \sum_{n=1}^{\infty} c_k \left(\frac{m_{A'}^2}{m_e^2}\right)^n\right],$$

(T. Tait et al: 2406.1944)

- Coefficients in the expansion of the decay width for a dark photon mass below twice m_e up to the sixth order
- The series is expected to converge

	c_k	$c_k \times 4^k$
c_1	335 / 714	1.88
c_2	128,941 / 839,664	2.46
c_3	44,787 / 1,026,256	2.79
c_4	1,249,649,333 / 108,064,756,800	5.92
c_5	36,494,147 / 12,382,420,050	3.02
c_6	867,635,449 / 1,614,300,688,000	2.20

III. Signature from PBH

Photon Spectrum from Trident Decay

- The photon-energy spectrum in the dark-photon rest frame is

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} = \frac{2x^3}{17m_{A'}}(1715 - 3105x + \frac{2919}{2}x^2),$$

(T. Tait et al: 2402.01839)

$x = 2E_\gamma/m_{A'}$ varies between 0 and 1.

- The corresponding photon spectrum in the PBH frame is obtained by Lorentz-boosting the rest-frame distribution:

$$\frac{dN'_\gamma}{dE'_\gamma} = \frac{1}{2}\int dE_\gamma\, d\cos\theta\, \frac{dN_\gamma}{dE_\gamma}\delta\left(E'_\gamma - \gamma(E_\gamma + \beta p\cos\theta)\right)$$

$$= \frac{1}{2}\int_{E'_1}^{E'_2} dE_\gamma \frac{dN_\gamma}{dE_\gamma}\frac{1}{p\beta\gamma},$$

$$E'_2 = \gamma(E'_\gamma + p'\beta)$$

$$E'_1 = \gamma(E'_\gamma - p'\beta)$$

Photon Spectrum from PBH evaporation

- The total photon emission rate includes primary Hawking photons and secondary photons from particle decays and final-state radiation

$$\frac{\partial N_{\gamma,\mathrm{tot}}}{\partial E_\gamma \partial t} = \frac{\partial N_{\gamma,\mathrm{primary}}}{\partial E_\gamma \partial t} + \int dE_{A'} \frac{\partial N_{A',\mathrm{primary}}}{\partial E_{A'} \partial t} \frac{dN_{A',\mathrm{decay}}}{dE_\gamma} + \int dE_{\pi^0}\, 2\frac{\partial N_{\pi^0,\mathrm{primary}}}{\partial E_{\pi^0} \partial t} \frac{dN_{\pi^0,\mathrm{decay}}}{dE_\gamma} + \sum_{i=e^\pm,\mu^\pm,\pi^\pm} \int dE_i \frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} \frac{dN_{i,\mathrm{FSR}}}{dE_\gamma}.$$

$$\frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} = \frac{g_i}{2\pi} \frac{\Gamma_i(E_i, M, m_i)}{e^{E_i/T_H} \pm 1},$$

Γ_i : greybody factor

T_H : Hawking temperature ($1/8\pi GM$)

$$\frac{dN_{\pi^0,\mathrm{decay}}}{dE_\gamma} = \frac{\Theta(E_\gamma - E_{\pi^0}^-)\Theta(E_{\pi^0}^+ - E_\gamma)}{E_{\pi^0}^+ - E_{\pi^0}^-},$$

$$E_{\pi^0}^\pm = \frac{1}{2}\left(E_{\pi^0} \pm \sqrt{E_{\pi^0}^2 - m_{\pi^0}^2}\right),$$

$$\frac{dN_{i,\mathrm{FSR}}}{dE_\gamma} = \frac{\alpha}{\pi Q_i} P_{i\to i\gamma}(x) \left[\log\left(\frac{1-x}{\mu_i^2}\right) - 1\right],$$

$$P_{i\to i\gamma}(x) = \begin{cases} \frac{2(1-x)}{x}, & i = \pi^\pm \\ \frac{1+(1-x)^2}{x}, & i = \mu^\pm, e^\pm \end{cases}$$

$$x = \frac{2E_\gamma}{Q_i},\ \mu_i = \frac{m_i}{Q_i},\ \text{and } Q_i = 2E_i.$$

Exact greybody factors and finite-mass effects are included using BlackHawk v2.0.

Photon Spectrum from PBH evaporation

- The photon flux observed near Earth:

$$\frac{d\Phi_\gamma}{dE_\gamma} = \bar{J}_D \frac{\Delta\Omega}{4\pi} \int dM \frac{f_{\rm PBH}(M)}{M} \frac{\partial N_{\gamma,tot}}{\partial E_\gamma \partial t},$$

$$\bar{J}_D = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{\rm LOS} dl \rho_{\rm DM}.$$

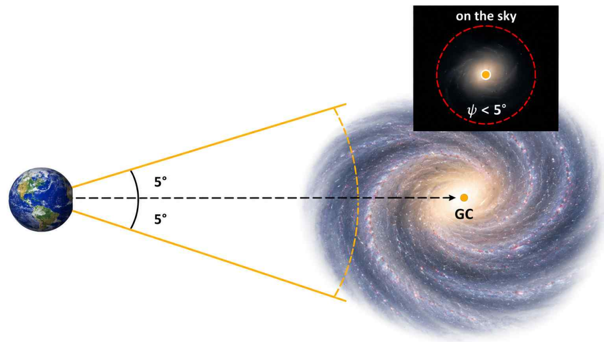
$f_{\rm PBH}$:fraction of the present DM density in PBHs

- The Galactic dark matter distribution is modeled with an NFW profile

$$\rho_{\rm DM}(r) = \frac{\rho_s}{\frac{r}{r_s}(1+\frac{r}{r_s})^2} \Theta(r_{200} - r),$$

$$r_s = 11 \text{ kpc}, \ \rho_s = 0.838 \text{ GeV/cm}^3, \ r_{200} = 193 \text{ kpc}$$

- We adopt a circular ROI of angular radius 5° centered on the Galactic Center.



$$\bar{J}_D = 1.597 \times 10^{26} \text{ MeVcm}^{-2}\text{sr}^{-1}, \qquad \Delta\Omega = 2.39 \times 10^{-2}\text{sr}.$$

Photon Spectrum from PBH evaporation

- We take into account the average probability of dark photon decaying during its propagation from the GC to Earth

$$\langle P_{A',\text{decay}}\rangle \equiv \frac{\Phi_{A',\text{dec}}}{\Phi_{A',\text{tot}}},$$

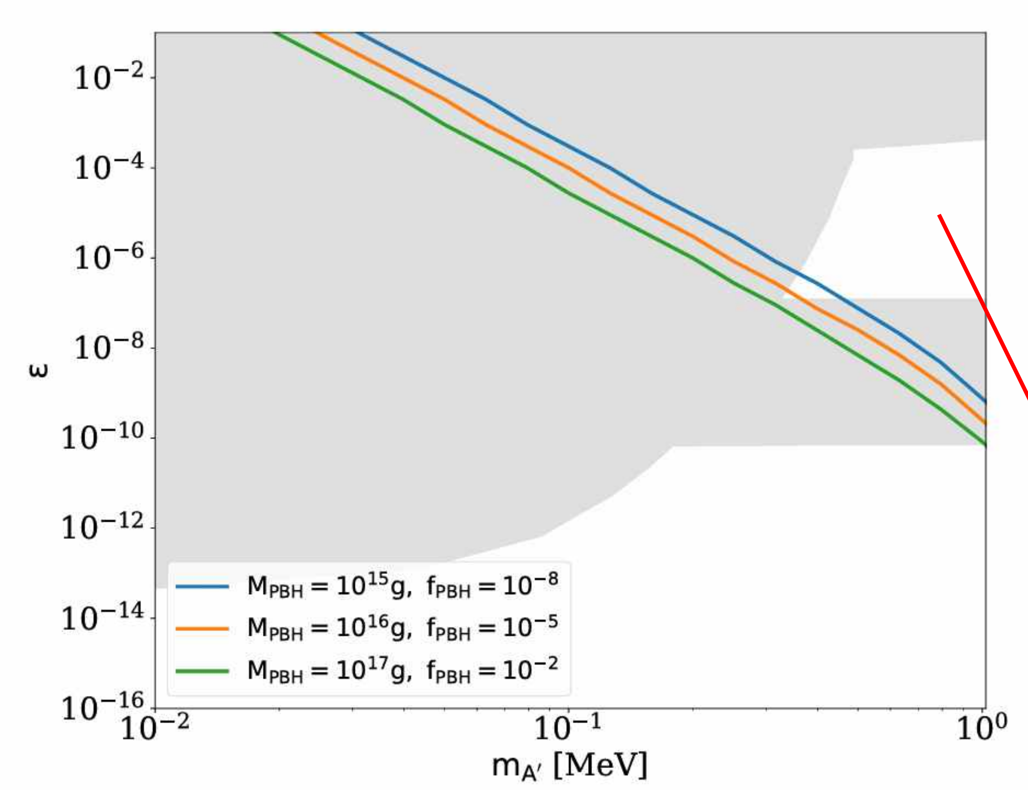
$$\Phi_{A',\text{tot}} = \int_{\Delta\Omega}\frac{d\Omega}{4\pi}\int_{\text{LOS}} d\ell \int dE_{A'}\frac{f_{\text{PBH}}\rho_{\text{DM}}}{M_{\text{PBH}}}\frac{\partial N_{A',\text{primary}}}{\partial E_{A'}\partial t} = \bar{J}_D\frac{\Delta\Omega}{4\pi}\frac{f_{\text{PBH}}}{M_{\text{PBH}}}\int dE_{A'}\frac{\partial N_{A',\text{primary}}}{\partial E_{A'}\partial t}$$

$$\Phi_{A',\text{dec}} = \int_{\Delta\Omega}\frac{d\Omega}{4\pi}\int_{\text{LOS}} d\ell \int dE_{A'}\frac{f_{\text{PBH}}\rho_{\text{DM}}}{M_{\text{PBH}}}\frac{\partial N_{A',\text{primary}}}{\partial E_{A'}\partial t} P_{A',\text{decay}}(E_{A'},\ell).$$

- A' decay probability over a distance D

$$P_{A',\text{decay}}(E_{A'},D) = 1-\exp\left(-D\,\Gamma_{A'\to 3\gamma}\frac{m_{A'}}{\sqrt{E_{A'}^2-m_{A'}^2}}\right),$$

- Since $\Gamma_{A'\to 3\gamma} \propto \epsilon^2$, for a fixed $m_{A'}$ we determine the min. value of ϵ required to satisfy a chosen value of $\langle P_{A',\text{decay}}\rangle$



The parameter space for dark photons that can be explored using PBHs

- The curves correspond to $\langle P \rangle$=99%
- In the numerical analysis, we require $\langle P \rangle \geq$ 99%
- The gray region is disallowed by experimental constraints (JCAP07 (2012) 026)
- So, this PBH dark-photon scenario can probe the unexplored parameter space

$$10^{-7} \leq \epsilon \leq 10^{-3} \text{ and } m_{A'} \geq 0.5 \text{ MeV}$$

IV. Numerical Analysis

Methodology

- For numerical results, we perform the likelihood analysis using a reference model that gives the expected gamma-ray signal (PRD105,123009, PRD108, 023014),
- In our analysis, this is regarded as the astrophysical background.
- Two PBH test models are (i) the SM scenario, (ii) the dark-photon scenario
- The probability that the Test model reproduces the gamma-ray signal predicted by the reference model follows the Poisson statistics represented as

$$\mathcal{L} = \exp\left(\sum_i n_i \ln \sigma_i - \sigma_i - \ln n_i!\right)$$

n_i: observed photon counts from reference
σ_i : expected photon counts from test model

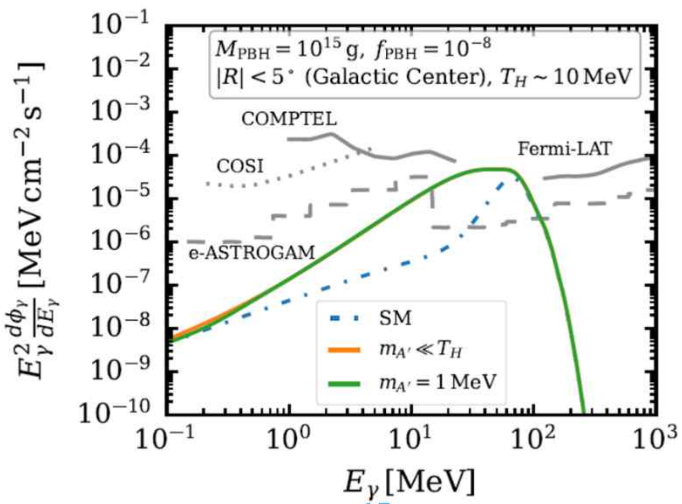
- To assess how distinguishable the test model is from reference, the test statistic (TS) is introduced

$$\mathrm{TS} = -2\ln\left(\frac{\mathcal{L}}{\mathcal{L}_{\mathrm{Ref}}}\right) = \Sigma^2,$$

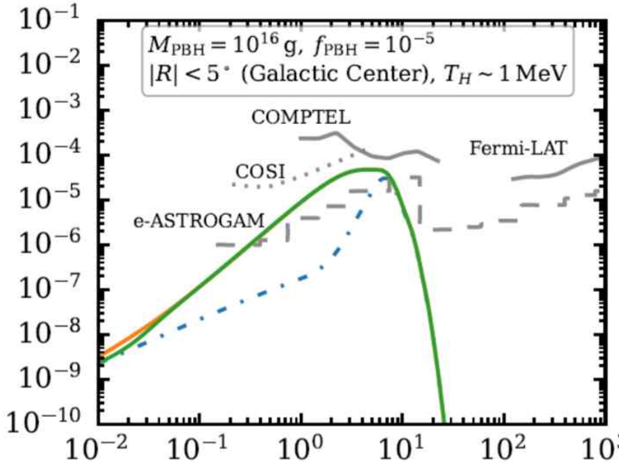
→ A significance threshold of $\Sigma = 3$ is adopted

Photon spectrum from PBH: SM vs Dark Photon

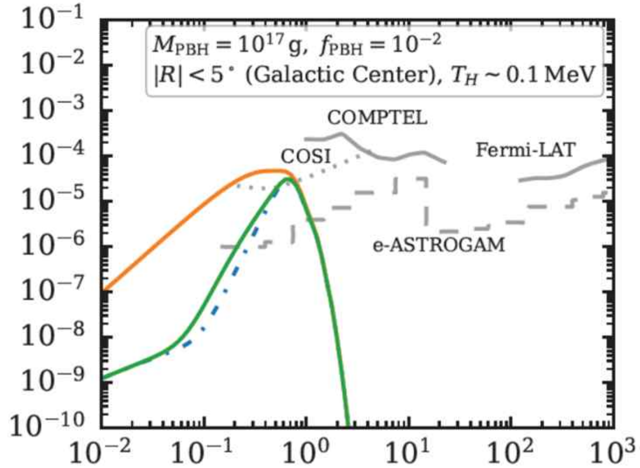
Three benchmark PBH masses: 10^{15}g, 10^{16} g, and 10^{17} g.



(a) $M_{PBH} = 10^{15}$ g, $T_H \sim 10$ MeV



(b) $M_{PBH} = 10^{16}$g, $T_H \sim 1$MeV



(c). $M_{PBH} = 10^{17}$g, $T_H \sim 0.1$ MeV

Light A' ($m_{A'} \leq T_H$) is efficiently emitted → the photons from trident decay lead to a broad enhancement.

The A' spectrum is strongest when m_A' is near or below T_H; the peak lies in the MeV window.

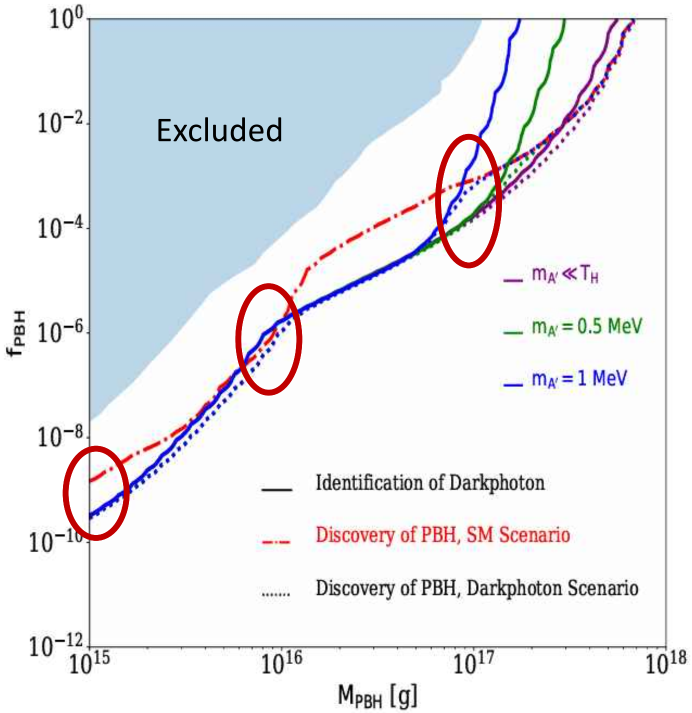
Heavier A'(($m_{A'} > T_H$) emission is Boltzmann-suppressed; the visible decay photons appear at lower E_γ.

- **Blue dot-dashed** : SM-only PBH spectrum
- **colored curves:** PBH + A' with different $m_{A'}$.

- Production of dark photon is suppressed after the primary photon peak.

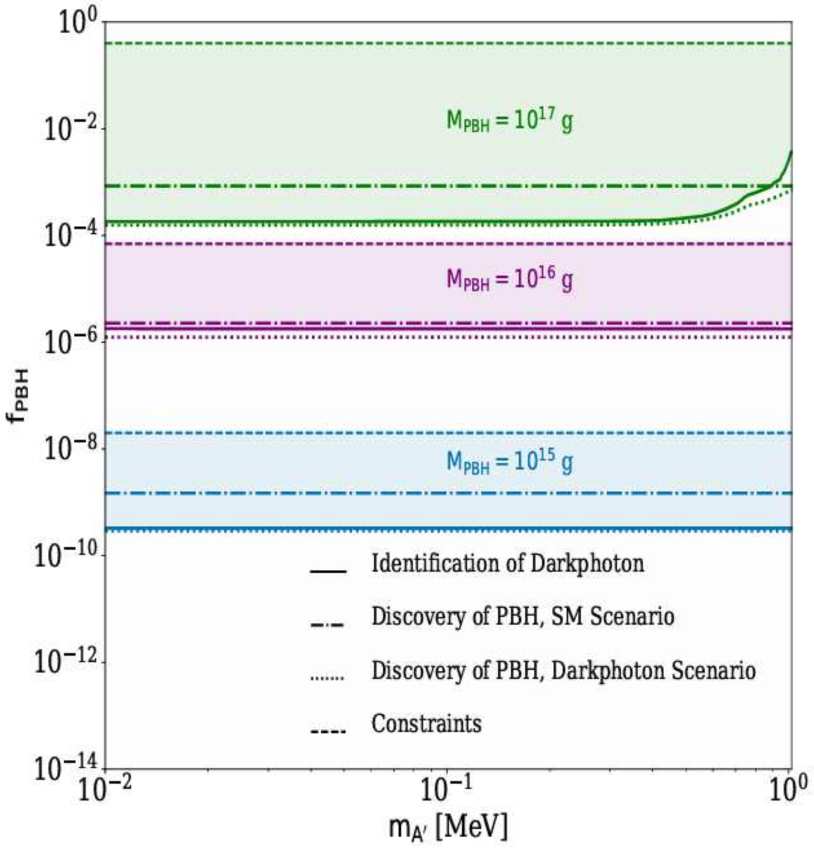
Expected Detection & Identification Sensitivities

- We scan the parameter space and select points satisfying $\Sigma > 3$.
- The resulting curves represent the minimum f_{PBH} required to reach the expected 3σ sensitivity at a given PBH mass.



- dot-dashed line : PBH detection thresholds for the SM-only scenario relative to the astrophysical bg.
- dotted lines : PBH detection thresholds for the A' -scenario relative to the astrophysical bg.
- **the solid curves** : A' identification thresholds, obtained by comparing the A' scenario with the SM-only PBH scenario.
- above the soild curves→ A' scenario can be distinguished from SM-only PBH

Expected Detection & Identification Sensitivities



- dot-dashed line : PBH detection thresholds for the SM-only scenario relative to the astrophysical bg.
- dotted lines : PBH detection thresholds for the A' -scenario relative to the astrophysical bg.
- **the solid curves** : A' identification thresholds
- Regions above the solid curves: A' scenario can be distinguished from SM-only PBH

- For small $m_{A'}$, these curves remain relatively flat, as A' is emitted efficiently and behaves approximately as a relativistic particle.
- For large $m_{A'}$, it becomes non-relativistic and its production is exponentially suppressed once $T_H < m_{A'}$

Conclusion

- PBH evaporation can generate dark photons through Hawking radiation even when their ordinary coupling is tiny
- For $m_{A'} < 2m_e$, the visible signature is $A' \to 3\gamma$, producing a distinct MeV gamma-ray spectrum.
- We show that the trident photons can modify both the peak location and spectral shape relative to the SM PBH spectrum.
- Likelihood scans at 3 σ sensitivity identify regions where PBHs can be probed and where the dark-photon scenario can be separated from SM-only evaporation.
- The result opens a complementary path to search for sub-MeV dark photons and light mass PBHs.