Constraining memory-burdened PBHs with graviton-photon conversion and binary merger

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References: arXiv 2511.01848

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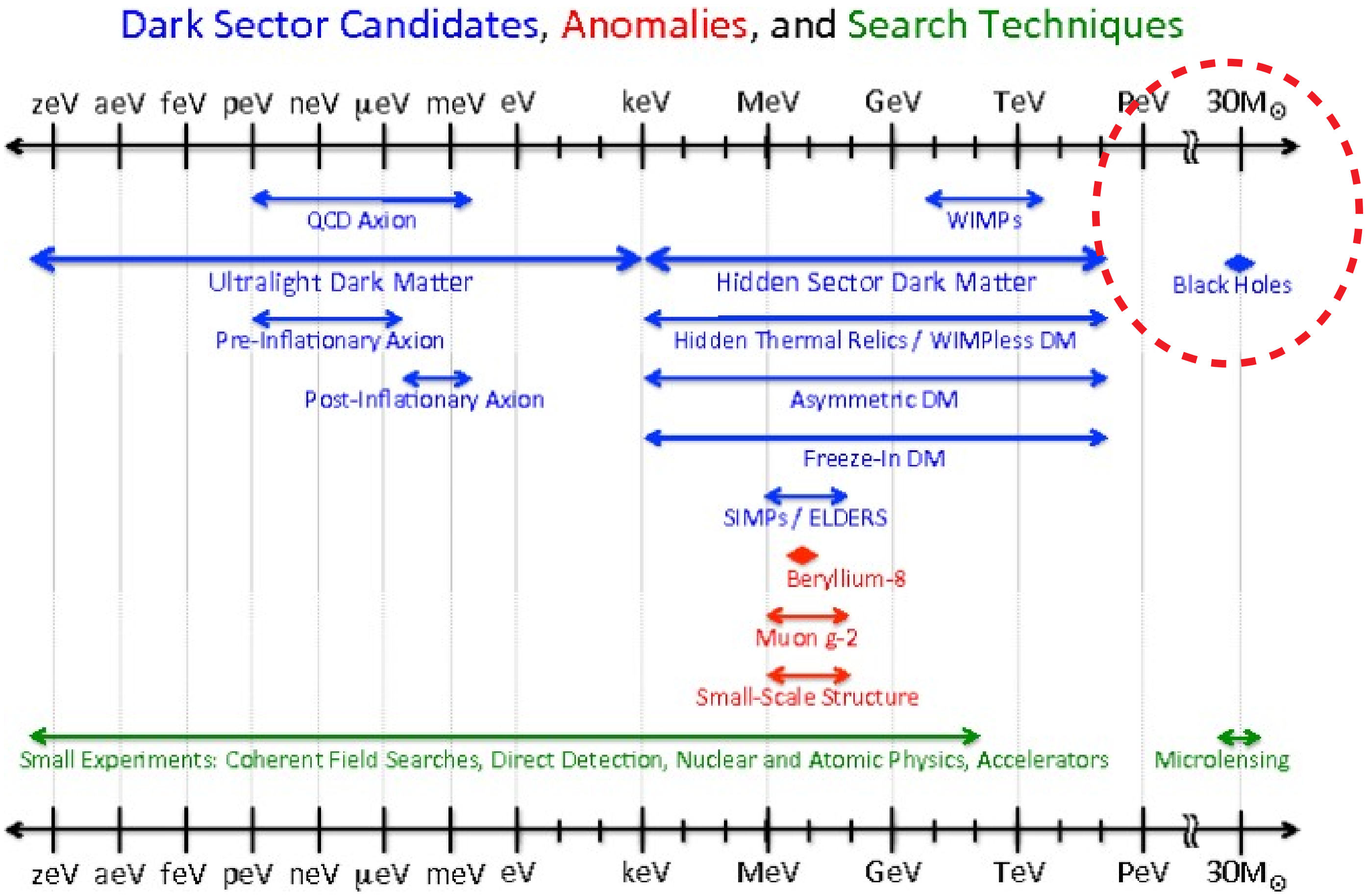
DM candidate

- Range of DM mass:



CERN document Server: US:Cosmic Visions: New ideas in dark matter 2017

PBH: Hawking evaporation

- Stability is one of the criteria to be DM candidate.
- A PBH, 1E14 g, has lifetime comparable with age of the Universe.
- A PBH lighter than 1E17 g leads to significant Hawking evaporation (*semiclassical phase*).
- In [1E17 g,1E23 g] range, PBH can constitute the entirety of DM abundance.

B.Carr, K.Kohri, Y.Sendouda, and J.Yokoyama, arXiv:2002.12778

PBH: Hawking evaporation

- Hawking temperature characterizes black-body spectrum from PBH evaporation:

BlackHawk v2.1, A.Aarbey, J.Auffinger: 2108.02737

$$T_{\rm PBH} \simeq 5.3~\text{MeV} \times \left(\frac{10^{-18} M_\odot}{M_{\rm PBH}}\right)$$

$$\frac{\mathrm{d}^2 N_s}{\mathrm{d}t\mathrm{d}E} = \frac{\Gamma_s}{e^{E/T_{\rm BH}} - (-1)^{2s}}$$

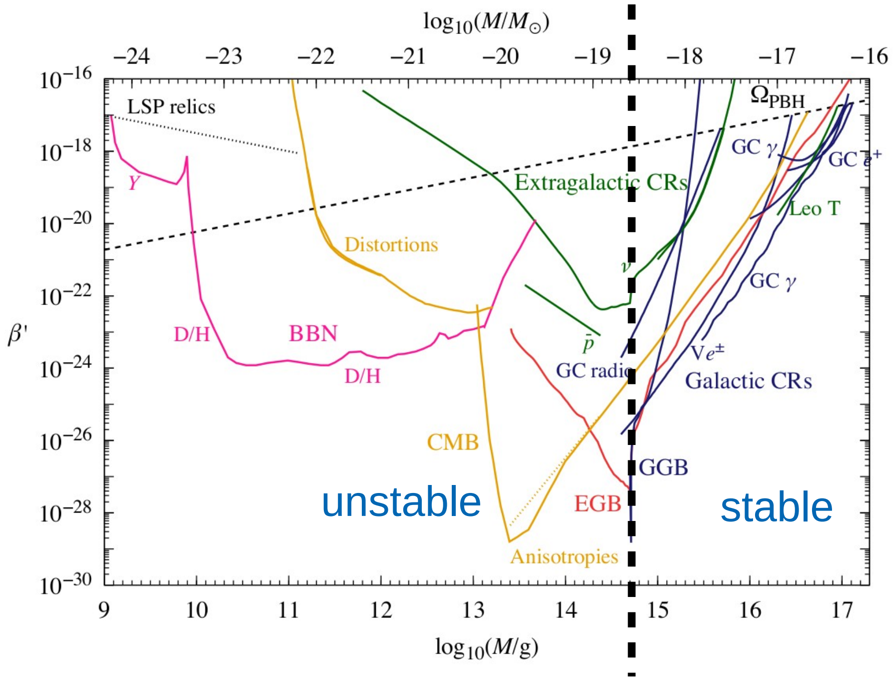
- PBH evaporation contribution of the extragalactic cosmic ray can be obtained by:

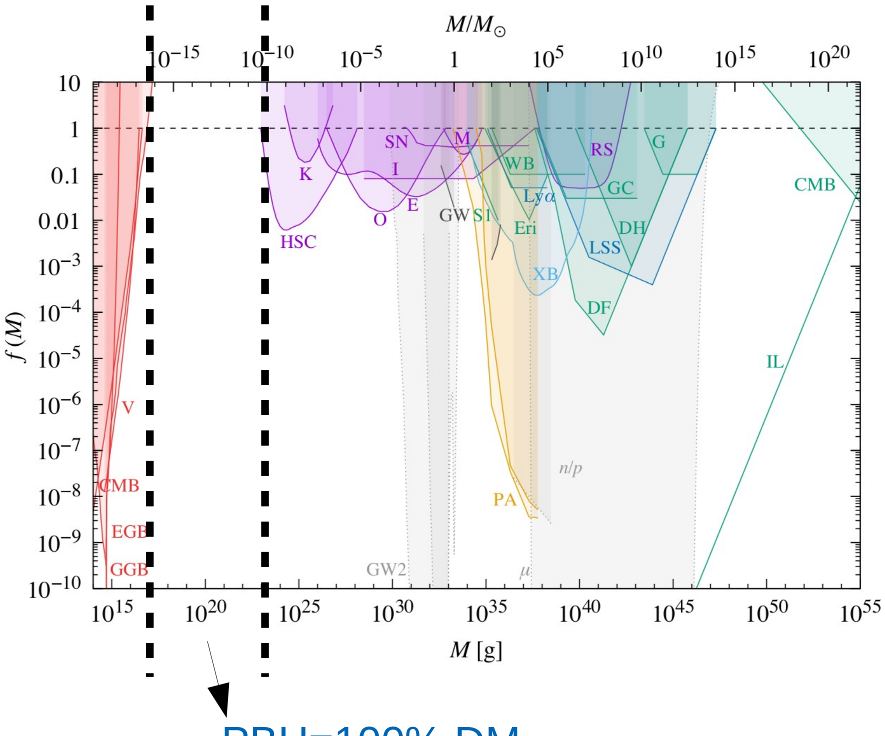
$$\frac{d\Phi}{d\mathcal{T}} = \int_{t_\phi}^{\min(t_{\rm eva},t_0)} c\,dt[1+z(t)]\,\frac{f_{\rm PBH}\rho_{\rm DM}}{M_{\rm PBH}}\,\frac{d^2 N_\chi}{d\mathcal{T}\,dt}\bigg|_{\tilde{E}=\sqrt{(E^2-m_\chi^2)(1+z(t))^2+m_\chi^2}}$$

R.Calabrese et. al: 2203.17093

PBH constraints

- Mass range of PBH (Primordial Black Holes):





B.Carr, K.Kohri, Y.Sendouda, and J.Yokoyama, 2002.12778

PBH: memory burden effect

- It pointed out that semiclassical approximation will break down when BH lost half of its initial mass (*burden phase*).

  G.Dvali, et.al: 1810.02336, 2006.00011.

- The backreaction of the emission on quantum state significantly suppressed the BH evaporation by k-th power of BH entropy S.

- It prolongs the lifetime of low-mass PBH and modifies their upper limits of abundance, thus opening up the light-mass window for PBH DM.

  V.Thoss, A.Burkert, K.Kohri: 2402.17823

PBH: spectra of particle

- PBH in burden phase, the mass loss rate, as well as the primary emission rate, are suppressed by the entropy factor:

$$\frac{dN_i}{dtdE}(t > t_q) = \frac{1}{S(M_{\rm PBH})^k}\frac{dN_i}{dtdE}$$

$$S(M_{\rm PBH}) = 4\pi G_N M_{\rm PBH}^2, \quad t_q = t_{\rm PBH}(1-q^3)$$

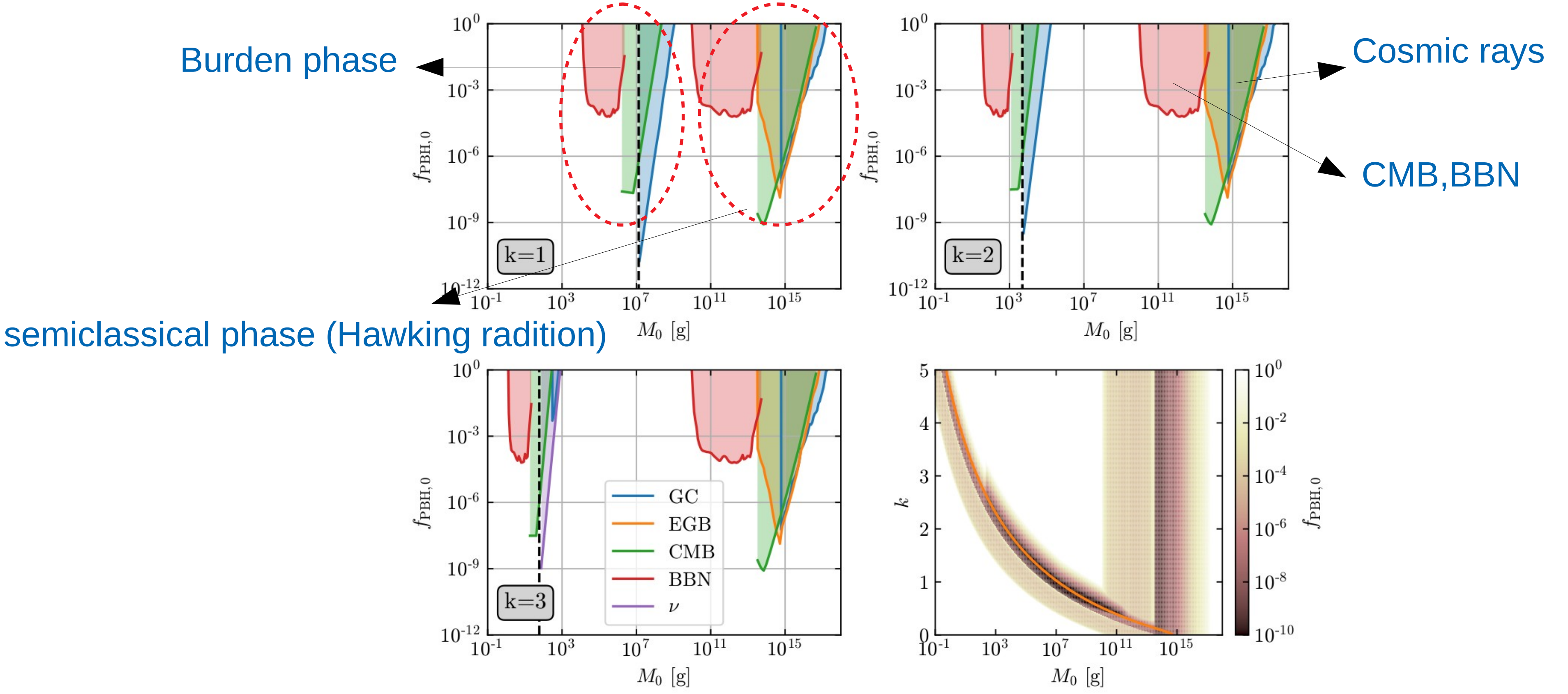
V.Thoss, A.Burkert, K.Kohri: 2402.17823

- *S* is the BH entropy. *k* governs the degree of entropy suppression. *q* indicate the mass ratio (w.r.t initial mass), when memory burden effect becomes relevant. We used *q=0.5*.

PBH: memory burden effect

- The mass window for PBH DM candidate with various k:

V.Thoss, A.Burkert, K.Kohri: 2402.17823



PBH: extragalactic gamma ray

- PBH DM contributes to the cosmic gamma ray:

$$\Phi_{\mathrm{PBH}} = \frac{c n_{\mathrm{t}}}{4\pi} \int_{t_{\mathrm{rec}}}^{t_0} \mathrm{d}t\, (1+z) \frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}E\,\mathrm{d}t} \Big((1+z)E, M(t) \Big)$$

V.Thoss, A.Burkert, K.Kohri: 2402.17823

where n_{t} is the PBH number density today, t_{rec} is the cosmic recombination time.

- A PBH, lighter than 1E-20 solar mass, entered burden phase before recombination, so we are unable to detect photons emitted from semiclassical phase.

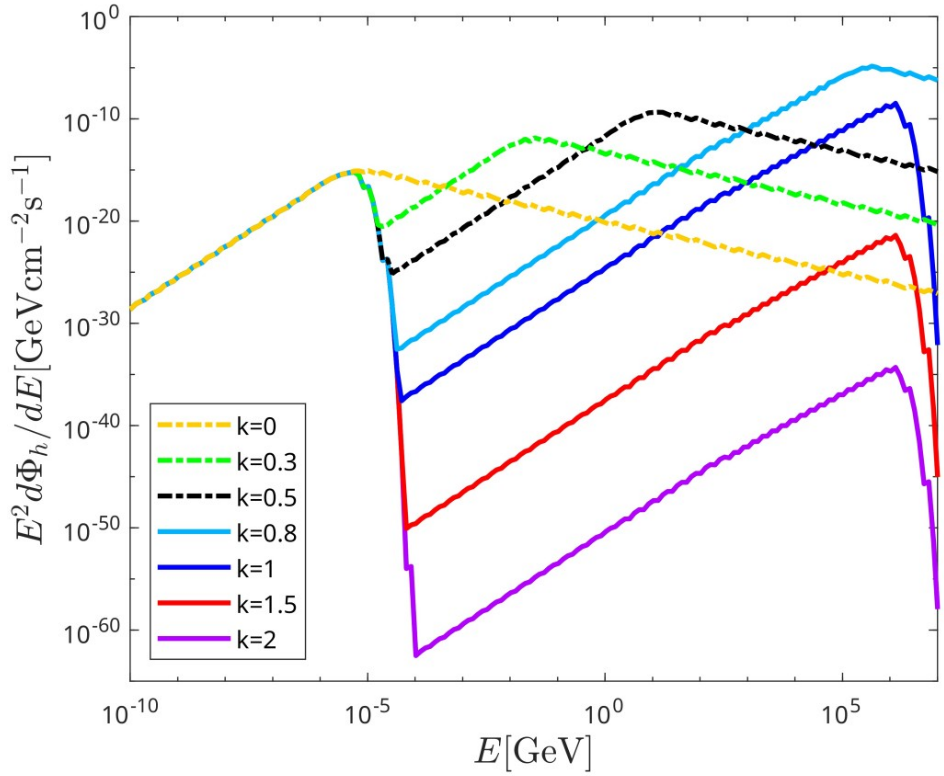
$$n_{\mathrm{t}} \approx 2.2 \times 10^{-30}\ \mathrm{cm}^{-3}\ f_{\mathrm{PBH},0} \left(\frac{M_0}{1\mathrm{g}} \right)^{-1}$$

PBH: extragalactic graviton

- Since gravitons are free streaming before recombination, their extragalactic spectra from PBH DM today is:

M_PBH=1E8 g ~ 1E-25 solar mass

P.Y.Tseng, Y.M.Yeh: 2511.01848



PBH: extragalactic graviton

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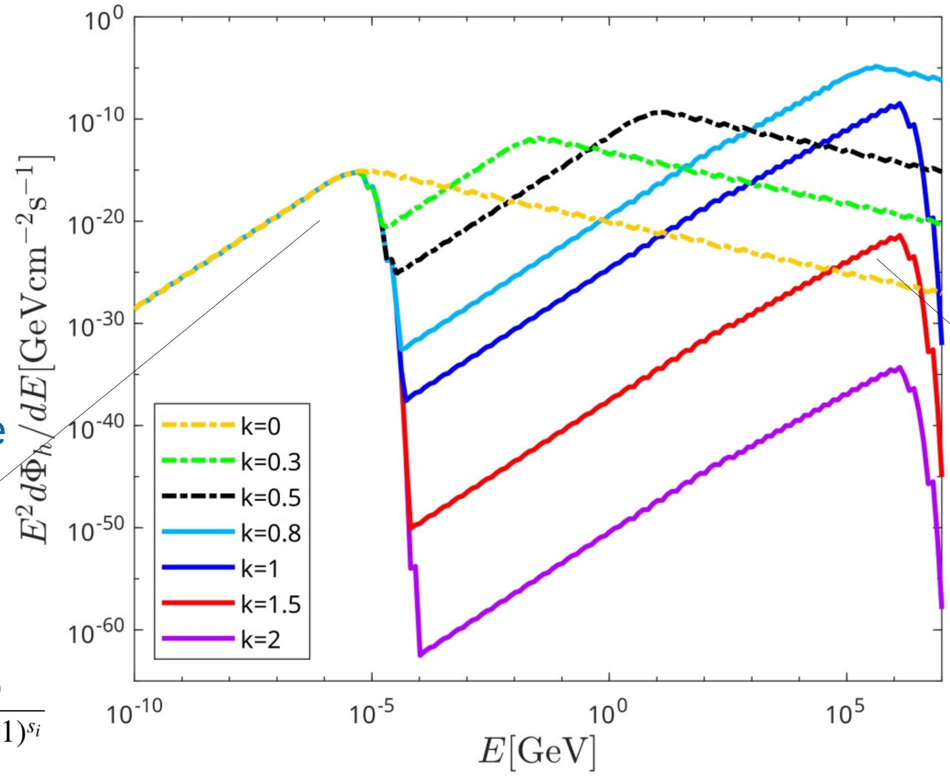
Double-peak spectrum

P.Y.Tseng, Y.M.Yeh: 2511.01848



2^{nd} peak: burden phase

$$\frac{dN_i}{dtdE}(t > t_q) = \frac{1}{S(M_{\rm PBH})^k} \frac{dN_i}{dtdE}$$

1^{st} peak: semiclassical phase (Hawking radiation)

$$\frac{\mathrm{d}^2 N_{i,\mathrm{SC}}}{\mathrm{d}E\mathrm{d}t}(E, M, s_i) = \frac{g_i}{2\pi\hbar} \frac{\Gamma(E, M, s_i)}{e^{E/k_B T(M)} - (-1)^{s_i}}$$

Graviton-photon convertion

- Gertsenshtein effect: a graviton converts to a photon in the presence of a uniform magnetic field.

M.Gertsenchtein: Sov.Phys.JETP 14(1962) 84.
V.Domcke, C.Garcia-Cely: PRL 126 (2021), no.2, 021104.

- The probability of graviton-photon conversion:

$$P_{h\to\gamma} = |K_{\rm osc}|^2 \ell_{\rm osc}^2 \sin^2\left(\frac{\ell}{\ell_{\rm osc}}\right)$$

$$|K_{\rm osc}| = \frac{\sqrt{\mu}\kappa B}{1+\mu}\,, \quad \ell_{\rm osc} = \frac{2}{\sqrt{\omega^2(1-\mu)^2+\kappa^2 B^2}}$$

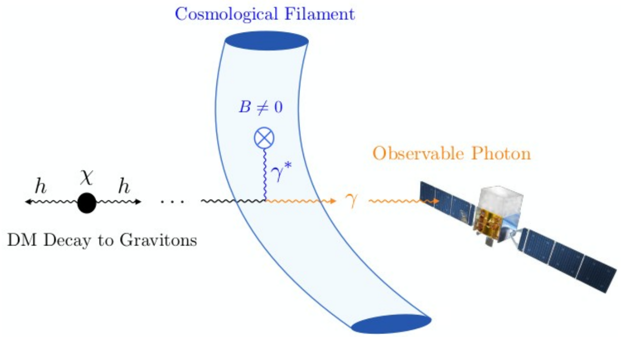
where $\kappa^2 = 16\pi G_N$ and μ is the refractive index in the plasma.

Graviton-photon convertion

- Cosmological Filaments:

  the magnetic file is red-shift dependent

$$B(z) = B_0(1+z)^2$$



D.I.Dunsky, G.Krnjaic, E.Pinetti: 2503.19019.

- The observed constraint on B_0 is 1nG-600nG. In our calculation, we take 100 nG.

- For single filament, the leading-order to the conversion probability

$$P^{(1)}(z) \approx 4\pi G_N [B(z) l_f(z)]^2$$

$$l_f = \frac{4}{1+z}\,\mathrm{Mpc}$$

Graviton-photon convertion

- Cosmological Filaments:

- Including the number density of filament, the differential conversion probability are

$$\frac{dP}{dz} = \frac{f_{\text{vol}}(z)}{l_f(z)} \frac{P(z)}{H(z)(1+z)} \qquad P(z) = \int dN_f P^{(1)}(z)$$

- Convolute it with graviton flux from PBH evaporation at redshift z_c:

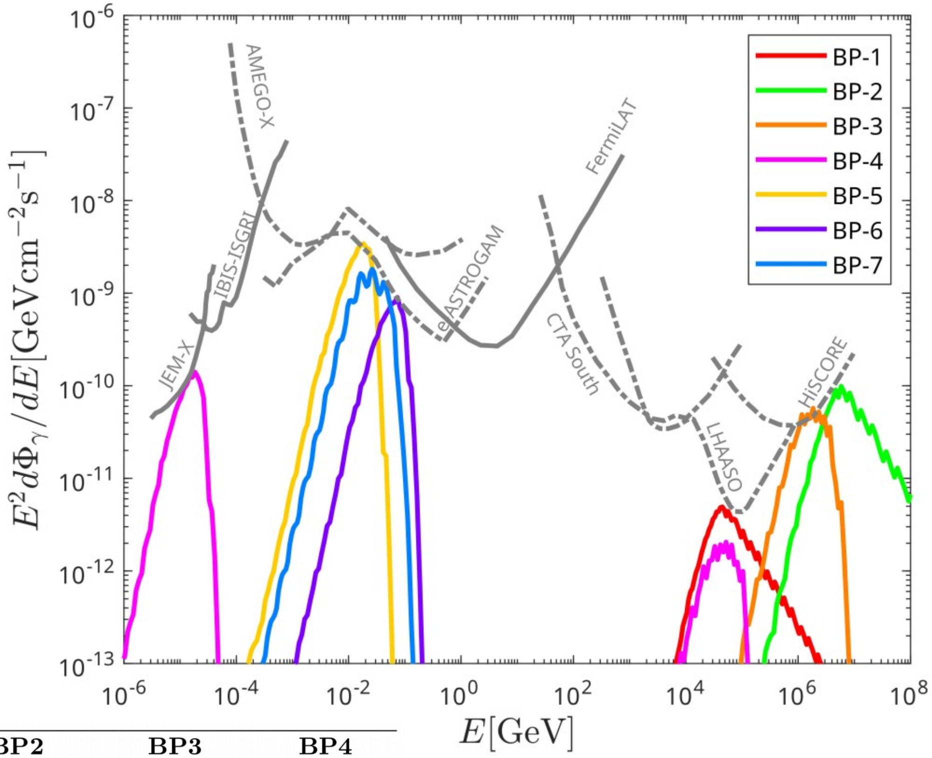
$$\frac{d\Phi_h}{dE}(z_c) = \frac{f_{\text{PBH}}|_{T_\phi} \Omega_{\text{DM}} \rho_c(t_0)}{M_{\text{PBH}}|_{T_\phi}} \int_{z_c}^{\infty} \frac{dz}{H(z)} \frac{dN_h}{d\tilde{E} dt} \bigg|_{\tilde{E}=E[1+z(t)]}$$

- We obtain the converted photon spectrum at present:

$$\boxed{\frac{d\Phi_\gamma}{dE}(z) = \int_z^\infty dz_c \frac{dP(z_c)}{dz_c} \frac{d\Phi_h}{dE}(z_c)}$$

Graviton-photon convertion

- Converted photon spectra from benchmark points with k=1:



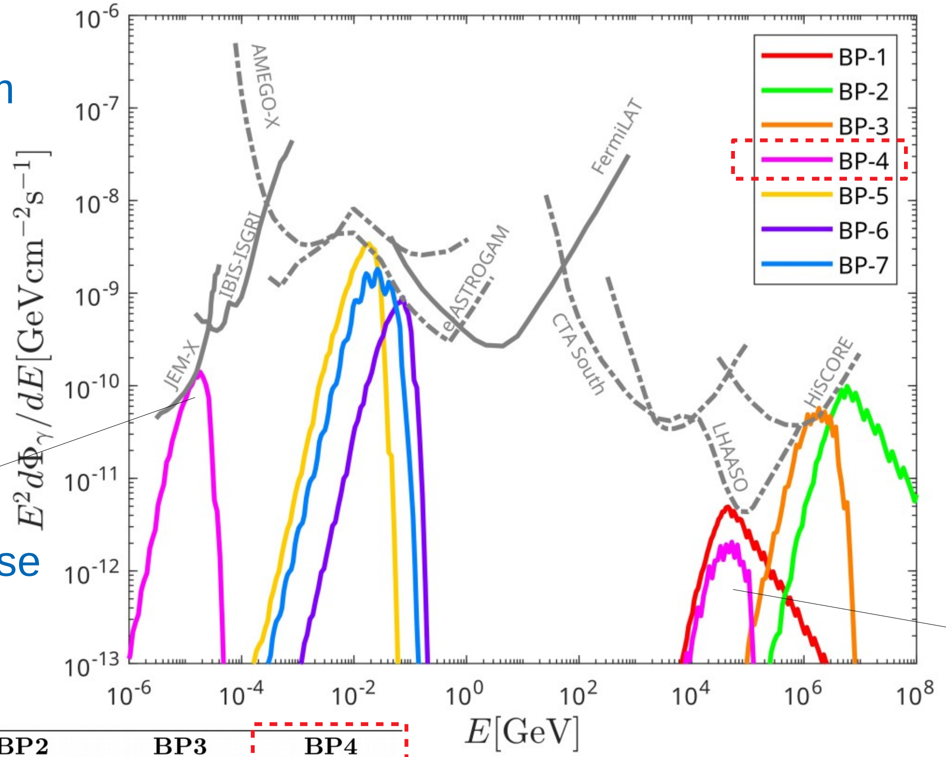
	BP1	BP2	BP3	BP4
$M_{\rm PBH}\vert_{T_\phi}/{\rm g}$	1.35×10^6	1.11×10^7	3.32×10^7	1.35×10^9
$f_{\rm PBH}\vert_{T_\phi}$	1.02×10^{-1}	2.06×10^{-3}	4.45×10^{-1}	1.73×10^6
	BP5	**BP6**	**BP7**	
$M_{\rm PBH}\vert_{T_\phi}/{\rm g}$	1.00×10^{14}	3.67×10^{14}	1.22×10^{15}	
$f_{\rm PBH}\vert_{T_\phi}$	4.94×10^{-1}	8.12×10^{-3}	4.45×10^{-1}	

P.Y.Tseng, Y.M.Yeh: 2511.01848

Graviton-photon convertion

- Converted photon spectra from benchmark points with k=1:

BP4: Double-peak spectrum



1st peak: semiclassical phase (Hawking radiation)

2nd peak: burden phase

	BP1	BP2	BP3	BP4
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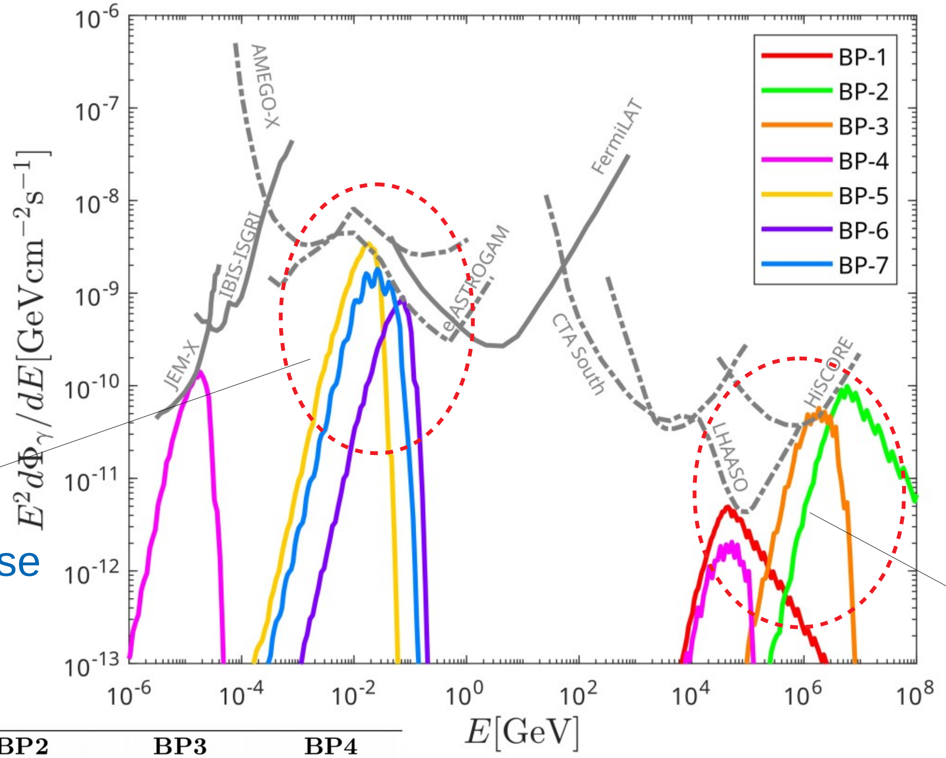

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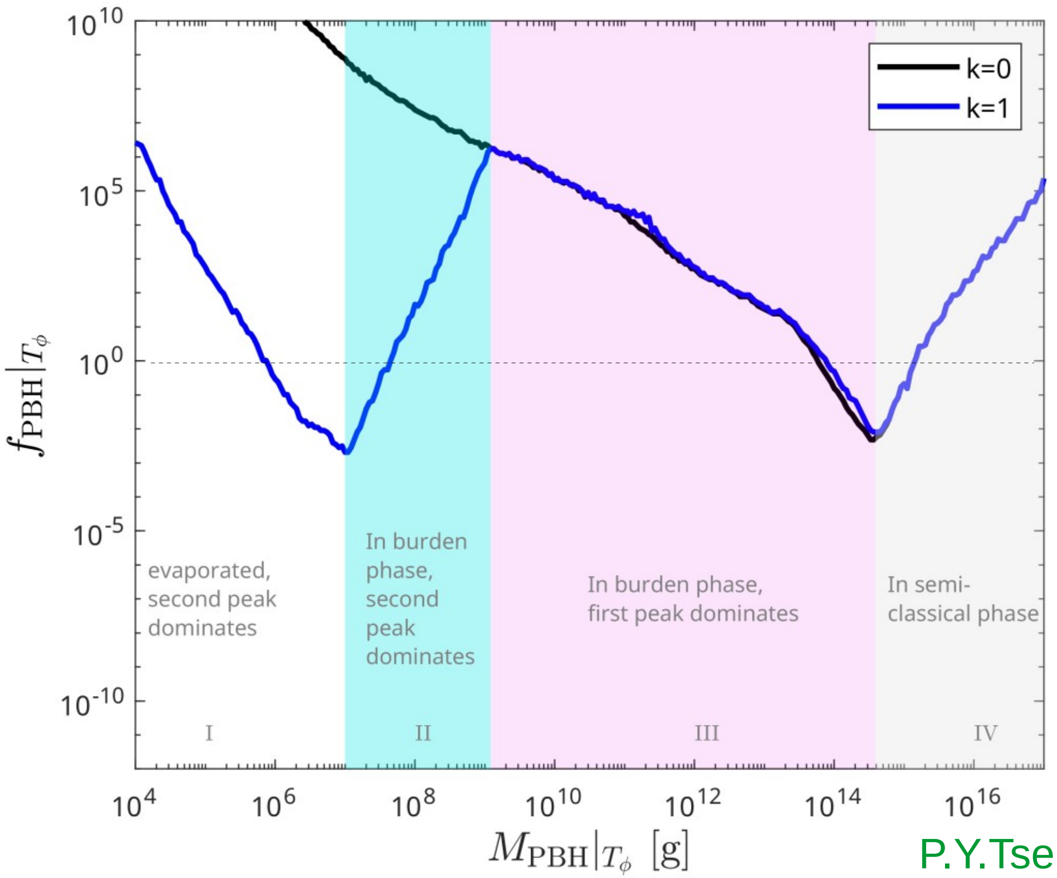
Graviton-photon convertion

- Upper limits on PBHs from extragalactic gamma-ray observations:



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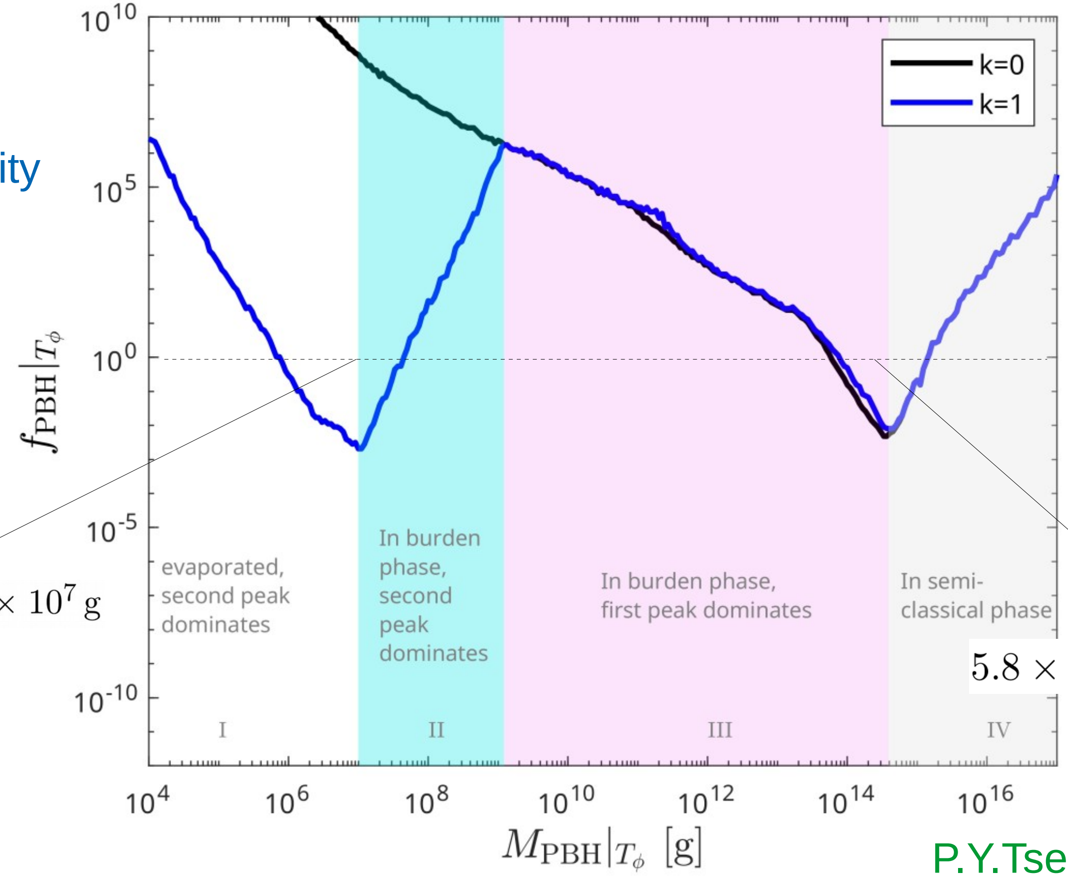
Graviton-photon convertion

- Upper limits on PBHs from extragalactic gamma-ray observations:

PBH as entire DM entity is disfavored



$7.5 \times 10^5\,\mathrm{g} \le M_{\rm PBH} \le 4.4 \times 10^7\,\mathrm{g}$

$5.8 \times 10^{13}\,\mathrm{g} < M_{\rm PBH}|_{T_\phi} < 1.4 \times 10^{15}\,\mathrm{g}$

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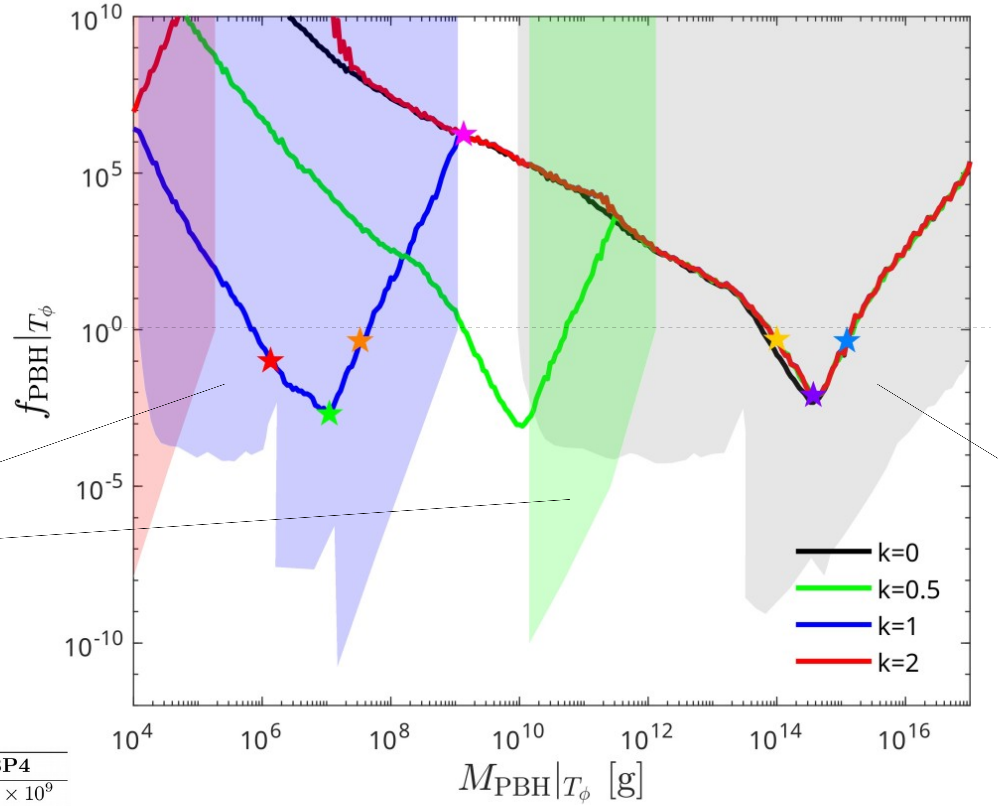
Graviton-photon convertion

- Comparing with other analysis:



Color shaded areas: constraints from burden phase

Grey area: constraints from semiclassical phase

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Graviton-photon convertion

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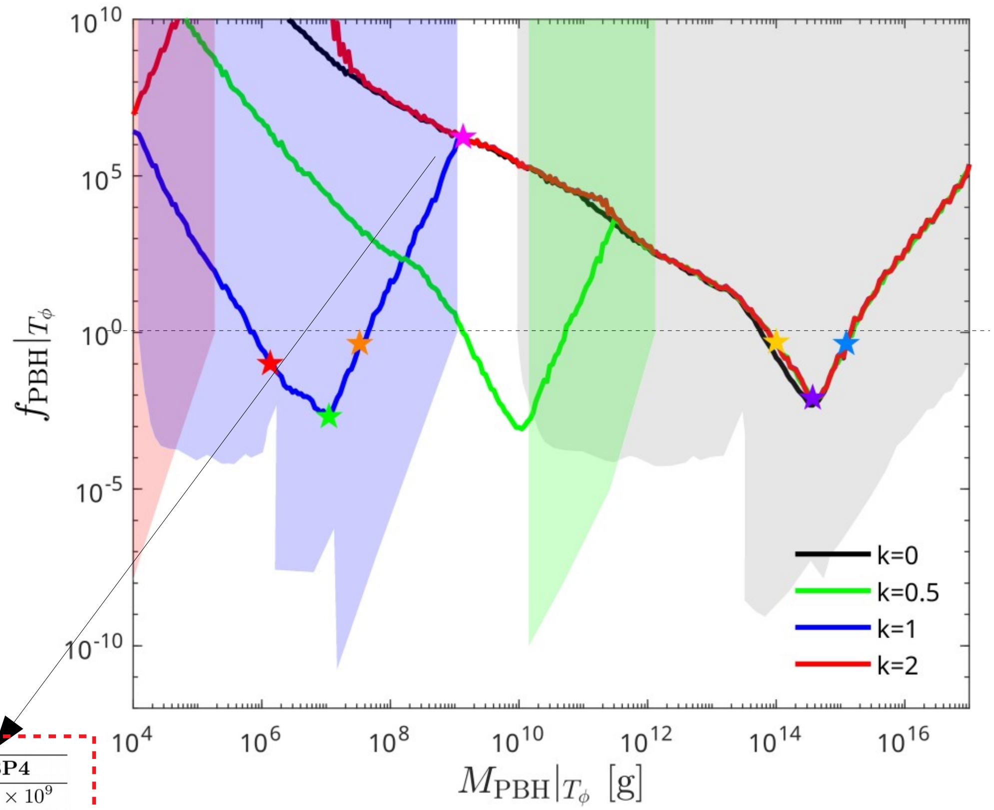

BP4 locates at
boundary of Region-II and III

	BP1	BP2	BP3	BP4
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P.Y.Tseng, Y.M.Yeh: 2511.01848

PBH merger

- For two burdened PBHs in a binary, they merge and reproduce a *new* PBH. …

M.Zantedeschi, L.Visinelli: 2410.07037

- The new PBH emits semiclassically until it reaches half of its mass.

- This provides another opportunity to detect particles emitted from PBH in semiclassical phase.

PBH merger

- The differential merger rate

M.Zantedeschi, L.Visinelli: 2410.07037

$$R_{\rm PBH} = \frac{5.7\times 10^{-66}}{\rm cm^3\ s} f_{\rm PBH0}^{\frac{53}{37}} \left(\frac{t_0}{t}\right)^{\frac{34}{37}} \left(\frac{2M_{\rm PBH0}}{10^{10}\ \rm g}\right)^{-\frac{32}{37}} S_1 S_2$$

$$S_1 \approx 0.24,\ S_2(x) \approx \min[1, 9.6\times 10^{-3} x^{-0.65} \exp\left(0.03 \ln^2 x\right)]$$

$$x \equiv (t/t_0)^{0.44} f_{\rm PBH0}$$

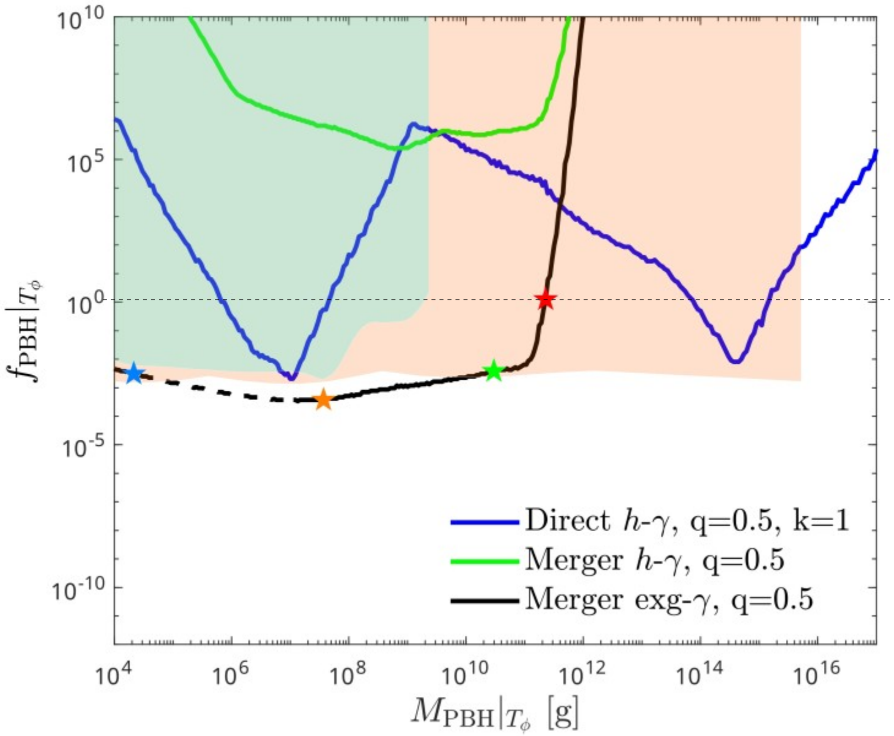
- The extragalactic flux from the mergered PBHs is

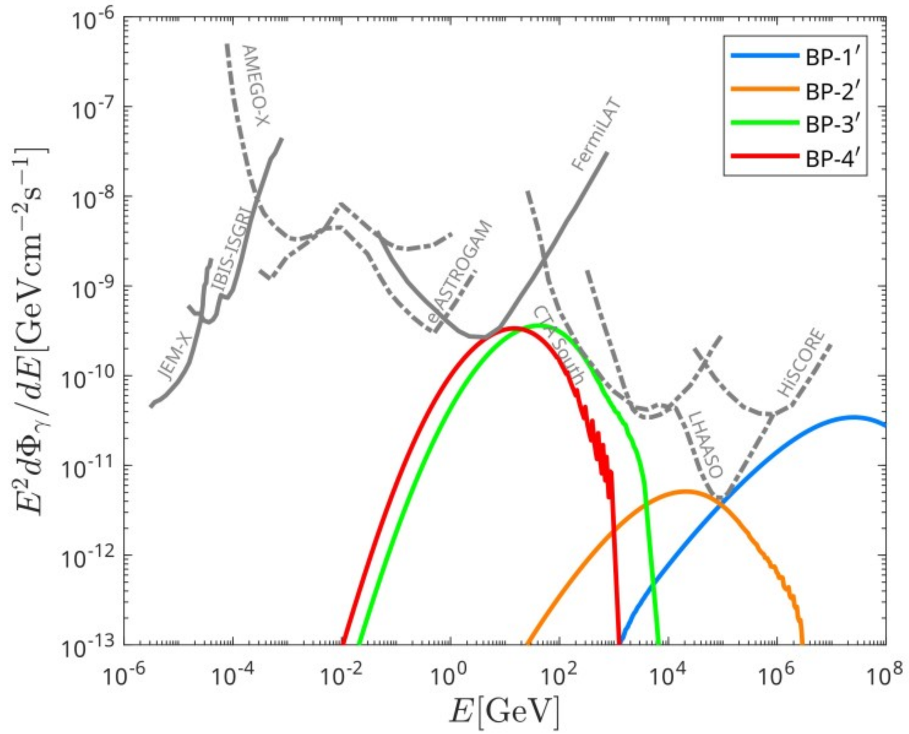
$$\frac{d\Phi_i}{dE} = t_q \int_0^{z_{\max}} \frac{dz}{H(z)} R_{\rm PBH}(t(z)) \left(\left.\frac{dN_i}{d\tilde{E}dt}\right|_{\tilde{E}=E[1+z(t)]} \right)_{\rm avg}$$

where we averaged the emission rate of PBH over the semiclassical phase.

PBH merger

- Upper limit from PBH merger (black curve):





	BP-1′	BP-2′	BP-3′	BP-4′
$M_{\rm PBH}\|_{T_\phi}$/g	2.14×10^4	3.70×10^7	2.98×10^{10}	2.28×10^{11}
$f_{\rm PBH}\|_{T_\phi}$	3.08×10^{-3}	3.74×10^{-4}	3.81×10^{-3}	1.25

Summary

- PBH lighter than 1E14 g has entered the memory burden phase at present, and thus the BH evaporation is suppressed.
- We study two scenarios: I) *graviton-photon conversion*, ii) *merger of PBHs*, where we can detect the particles emitted from PBHs in semiclassical phase.
- The graviton spectrum and thus converted photon spectrum are characterized by *double-peak* structure.
- PBH as entire DM entity is disfavored in light PBH mass:

for k=0.5(1.0), $1.3 \times 10^{9}\ \mathrm{g} < M_{\rm PBH}|_{T_\phi} < 5.2 \times 10^{10}\ \mathrm{g}$

$$\left(7.5 \times 10^{5}\,\mathrm{g} \leq M_{\rm PBH} \leq 4.4 \times 10^{7}\,\mathrm{g} \right)$$

Summary

- For the merging scenario, which is insensitive on k, restricts PBH DM lighter than 1.1E11 g.

Thank you for your attention!

Back up