Constraining memory-burdened primordial black holes with graviton-photon conversion

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Contents

Introduction of PBH

PBH Introduction

PBH is the hypothetical black hole formed in the early universe.

Collapse of overdense regions
Cosmology first-order phase transtions
…

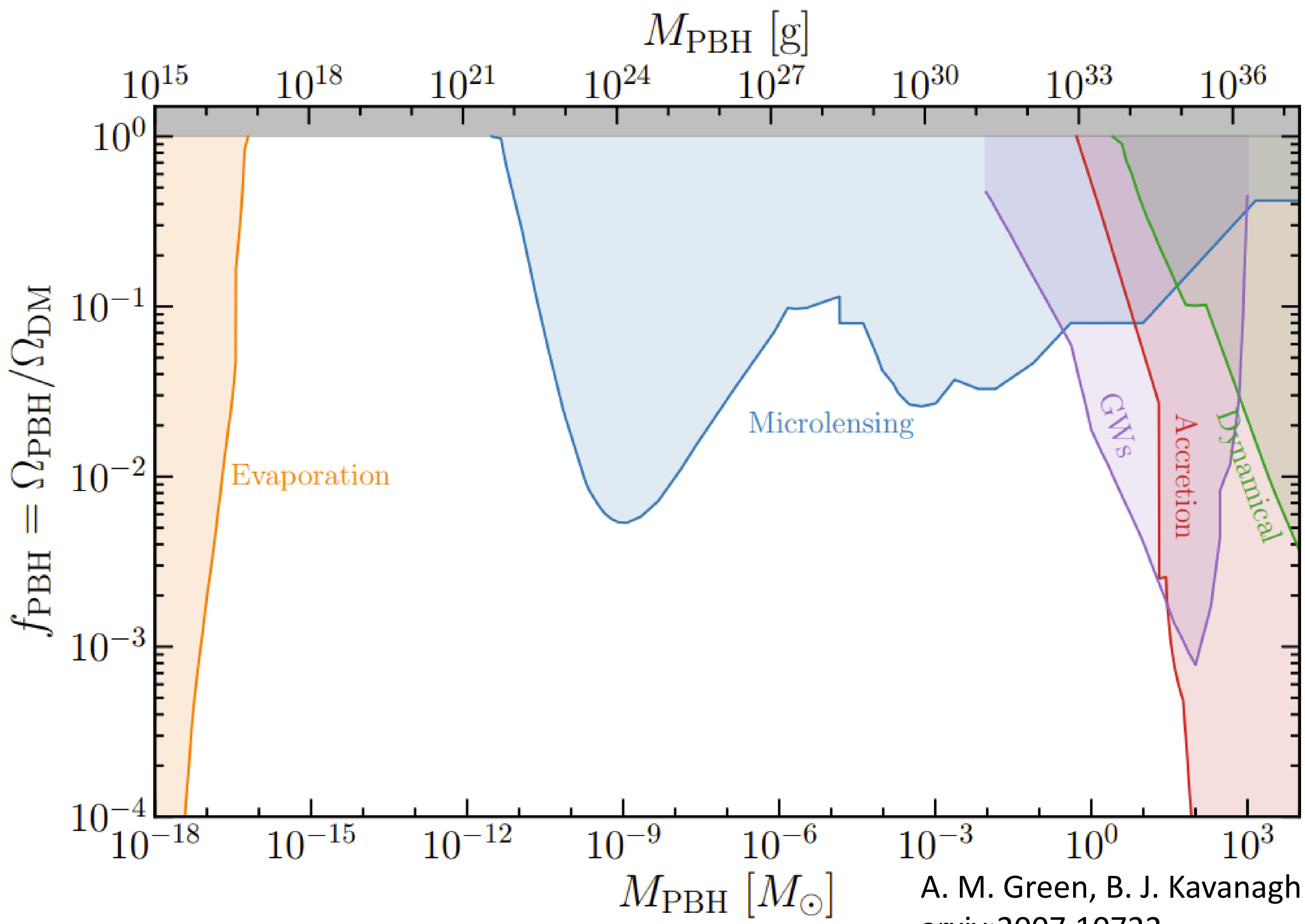
$M_{\rm PBH}$ can range from $10^{-20} M_\odot \sim 10^{20} M_\odot$

PBH

PBH

ly

univ



A. M. Green, B. J. Kavanagh
arxiv:2007.10722

PBH

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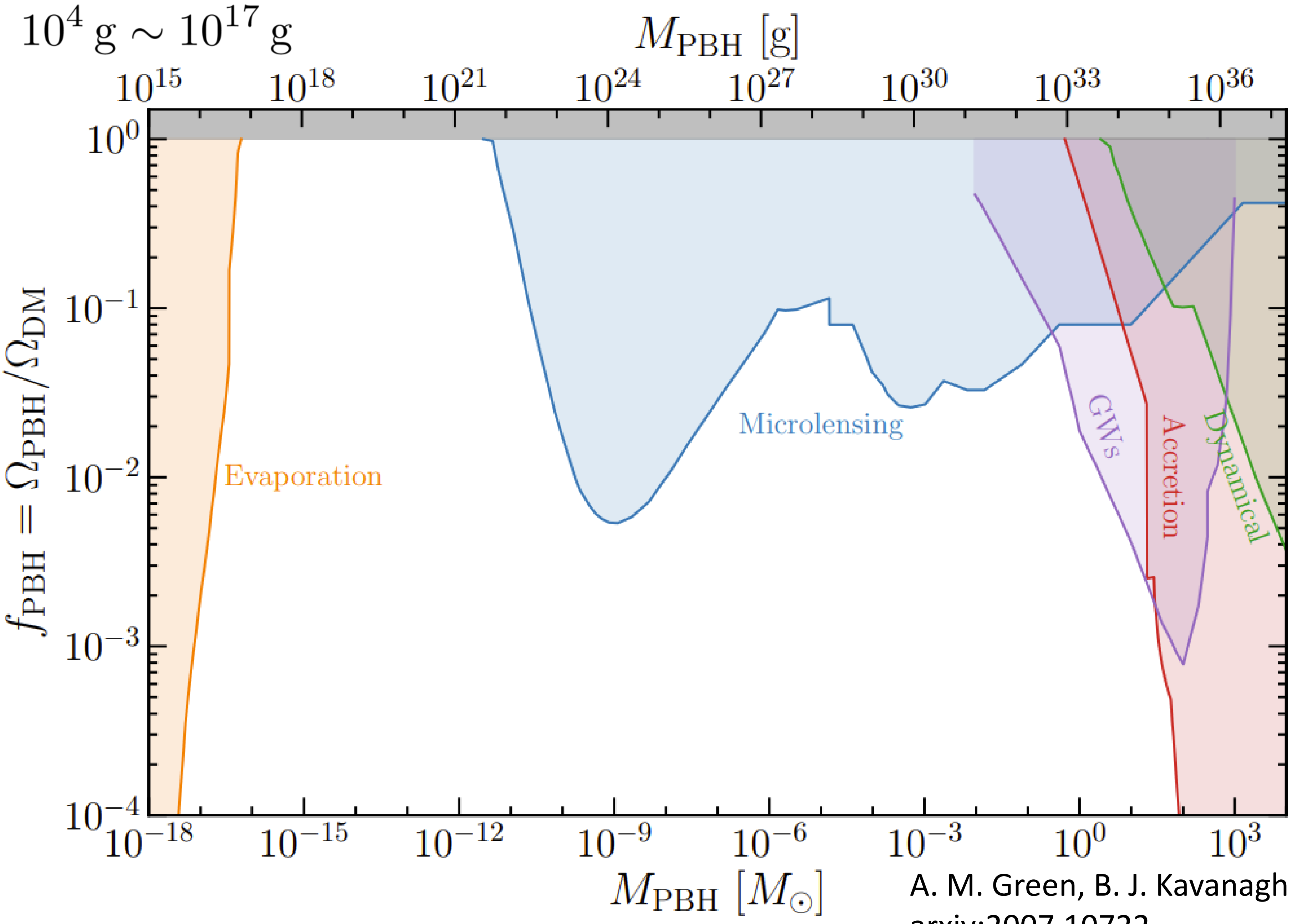

10^4 g $\sim 10^{17}$ g

A. M. Green, B. J. Kavanagh
arxiv:2007.10722

Hawking Radiation

PBH emits particles due to the Hawking evaporation. It emits particles with masses lighter than its temperature

B. Carr et al.
arxiv: 2002.12778

$$T_{\mathrm{PBH}} = \frac{\hbar c^3}{8\pi G_N M_{\mathrm{PBH}} k_B} \simeq 5.3\,\mathrm{MeV} \times \left(\frac{10^{-18} M_\odot}{M_{\mathrm{PBH}}}\right)$$

$M_{\mathrm{PBH}}/M_\odot \lesssim 10^{-16} \longrightarrow T_{\mathrm{PBH}} \gtrsim 53\,\mathrm{keV} \longrightarrow$ emits $\gamma, \nu, h, e^\pm, \mu^\pm, \ldots$

$(\sim 10^{17}\,\mathrm{g})$

Memory Burden Effect

Master mode and memory modes

The information of a system is proposed to be stored in the quantum state, which is composed by K "memory mode"

Gia Dvali
arxiv: 1810.02336

$$|n_1, n_2, ..., n_K\rangle = |n_1\rangle \otimes |n_2\rangle \otimes \cdots |n_K\rangle$$

$$N_i = a_i^\dagger a_i$$

$$N_i|n_i\rangle = n_i|n_i\rangle$$

Master mode and memory modes

The Hamiltonian is

$$H = \sum_{k=1}^{K} \underbrace{\epsilon_k}_{\downarrow} N_k$$

Energy gap for each memory mode

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Energy difference between different occupation number (or “memory pattern”) is

$$\Delta E = \sum_{k=1}^{K} \epsilon_k (n_k - n'_k)$$

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Energy gap for each memory mode

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$$\Delta E = \sum_{k=1}^{K} \epsilon_k (n_k - n_k')$$

If $\epsilon_k = 0$ or negligible , we can have a lot of degenerate states contributing to entropy

Master mode and memory modes

Instead, we introduce the “master mode” by adding attractive interaction

$$H = \epsilon_0 \underset{\underset{a_0^\dagger a_0 \leftarrow}{\lrcorner}}{N_0} + \left(1 - \underset{\downarrow}{\frac{N_0}{N_c}}\right)^p \sum_{k=1}^{K} \epsilon_k N_k$$

Interaction strength

Master mode and memory modes

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$a_0^\dagger a_0$

Interaction strength

$$n_0 \neq 0, \quad \epsilon_k^{\text{eff}} = \left(1 - \frac{n_0}{N_c}\right)^p \epsilon_k$$

$$n_0 = N_c, \quad \epsilon_k^{\text{eff}} = 0$$

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$|n_0 = N_c, n_1, ..., n_K\rangle$

with various value of n_i are degenerate. The entropy

$$S = \ln(\text{microstate number})$$

$$\sim K$$

Master mode and memory modes

The energy of $n_0 = N_c$ pattern is the local minimum. Changes in n_0 requires a climb uphill the energy barrier and creates the resistance against the loss of the master mode.

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$$S = 4\pi G_N M_{\rm PBH}^2 \qquad (S \sim 10^{26} \text{ for } M_{\rm PBH} = 10^8\,\text{g})$$

We assume PBH is initially at $n_0 = N_c$ pattern,
as PBH evaporate, $M_{\rm PBH} \downarrow$, $S \downarrow (n_0 \downarrow)$

Memory burden of PBH

When free parameter p is large, the memory burden can be delayed until half-decay.

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$$M_{\rm PBH}(t) > qM_{\rm PBH}|_{T_\phi} \longrightarrow \text{Semi-classical phase}$$

$$M_{\rm PBH}(t) < qM_{\rm PBH}|_{T_\phi} \longrightarrow \text{Memory burden phase}$$

$$q = 0.5$$

Memory burden of PBH

The mass loss rate and the emission rate are suppressed by entropy factor $S(M_{\rm PBH})^{-k}$

$$\frac{dM_{\rm PBH}}{dt}(t > t_q) = S^{-k}(M_{\rm PBH})\underline{\frac{dM_{\rm PBH}}{dt}}$$

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

unsuppressed rate

duration of semi-classical phase

Mem

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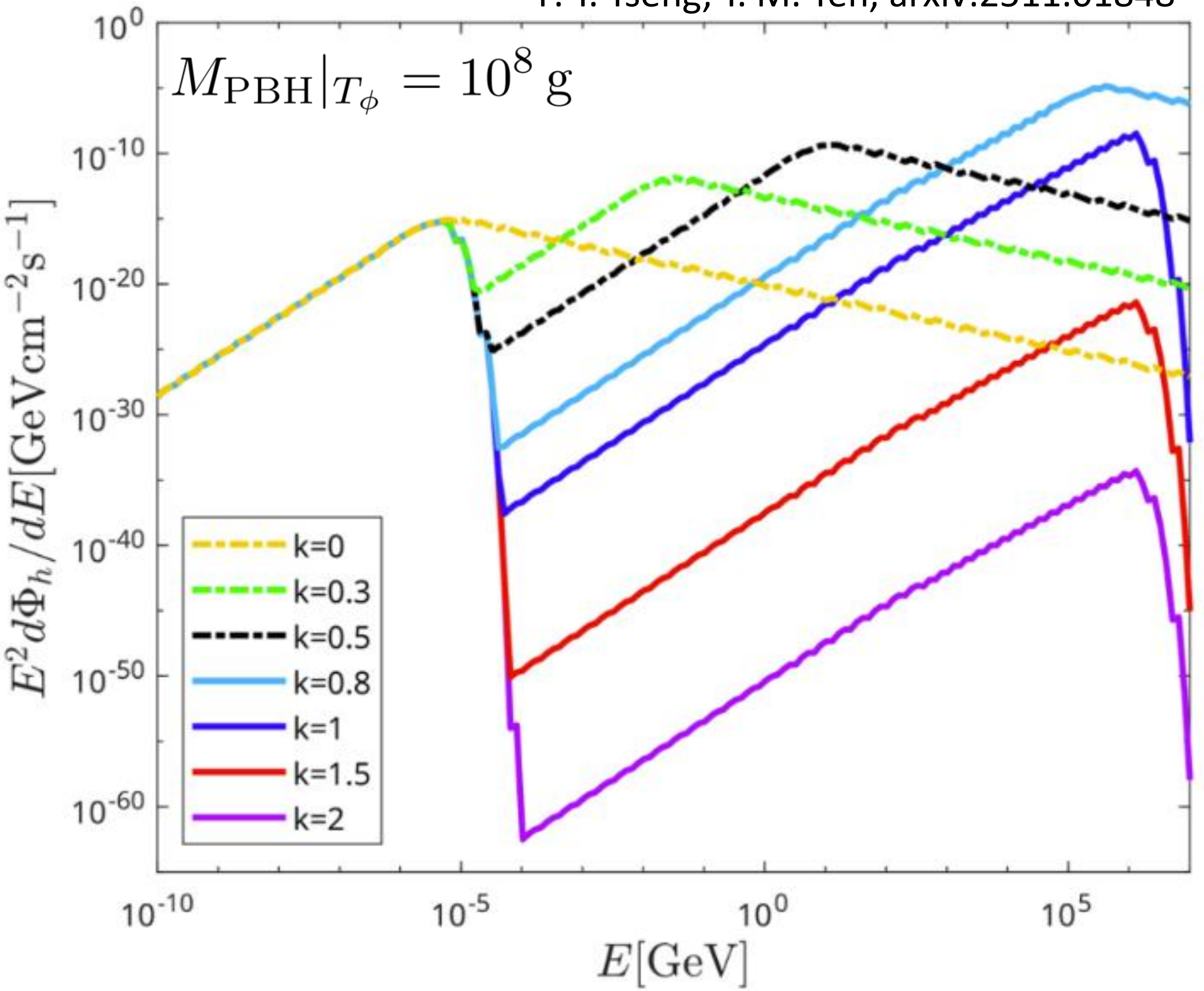
pressed

by entr



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

pressed rate

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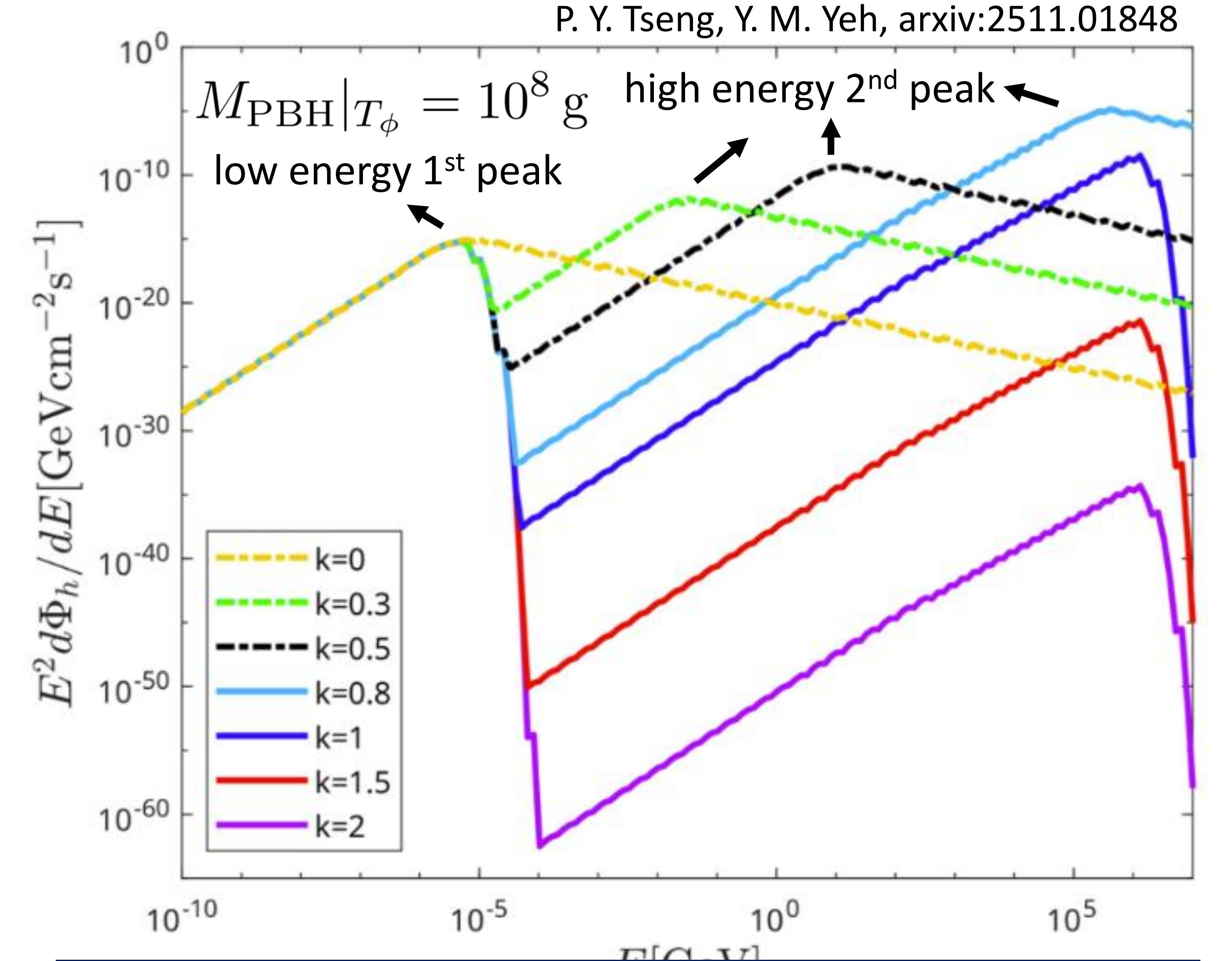

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pressed rate

The double peak spectrum is a feature due to burden effect

Graviton-Photon conversion (Gertsenshtein effect)

Instead of studying the gamma-ray directly from PBH, we consider the photon converted from graviton.

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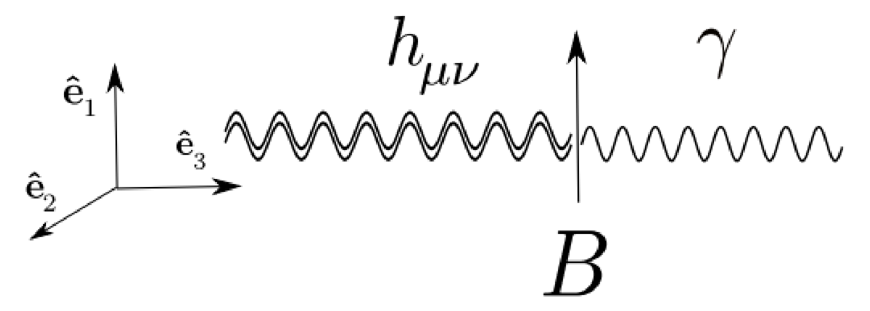
$$\Box h_{\mu\nu} = -16\pi T_{\mu\nu} \longrightarrow \text{energy-momentum tensor of EM field}$$



V. Domcke,
C. Garcia-Cely
arxiv: 2006.01161

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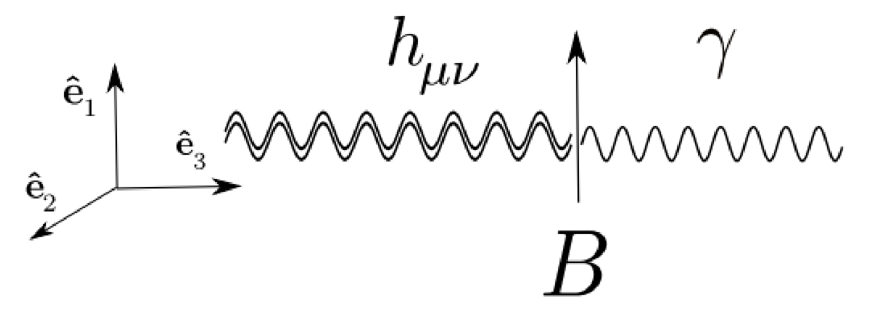

V. Domcke,
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Cosmic filament magnetic field

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

Graviton-Photon conversion

The photon flux at red shift z is given by

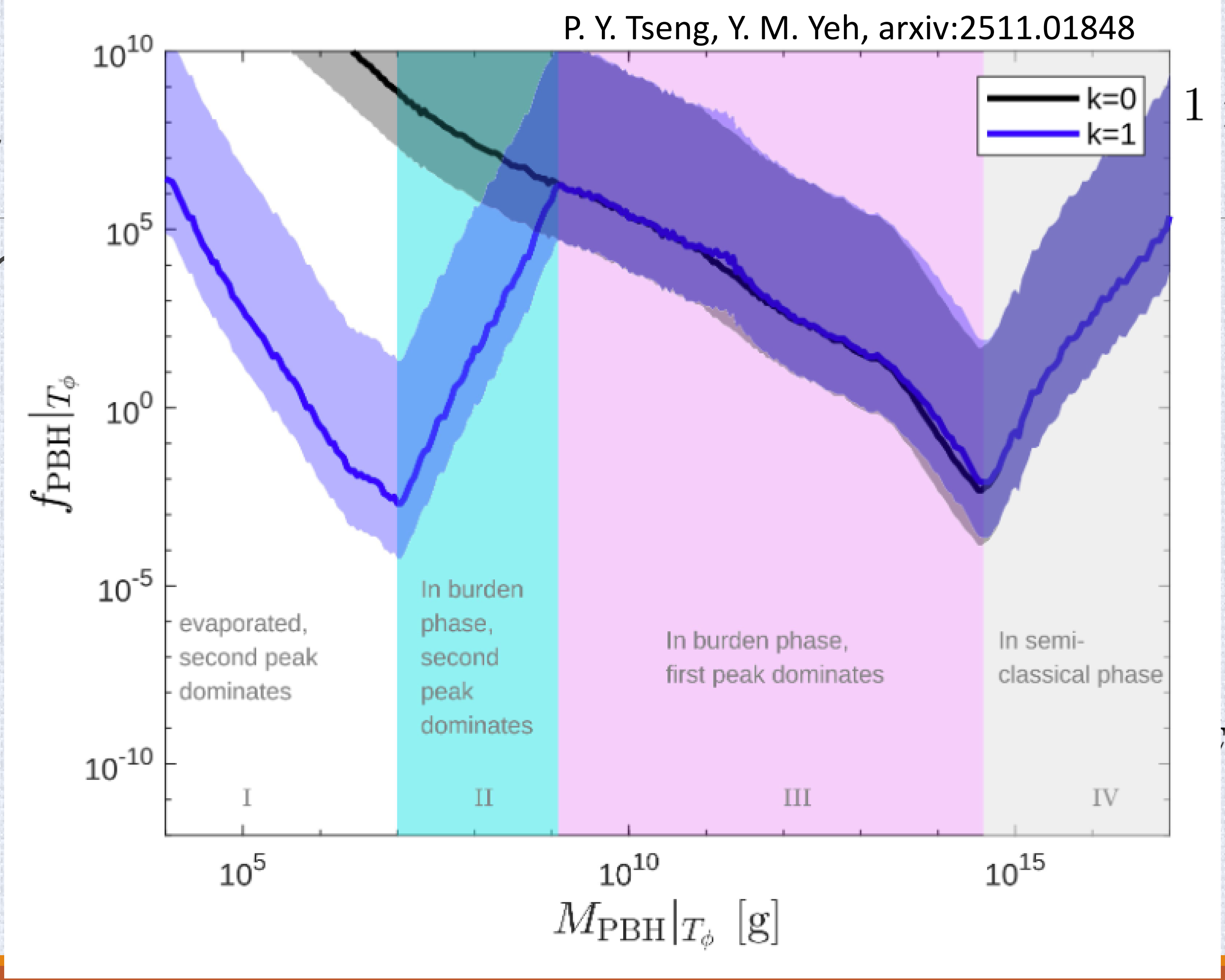
$$\propto B^2(z)$$

$$\frac{d\Phi_\gamma}{dE}(z) = \int_z^\infty dz' \frac{dP(z')}{dz'} \frac{d\Phi_h}{dE}(z')$$

$$\frac{d\Phi_h}{dE}(z') = \frac{f_{\rm PBH}|_{T_\phi} \Omega_{\rm DM} \rho_c(t_0)}{M_{\rm PBH}|_{T_\phi}} \int_{z'}^\infty \frac{dz}{H(z)} \frac{dN_h}{d\tilde{E}dt}\bigg|_{\tilde{E}=E[1+z(t)]}$$

Grav

The ph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$B_0 = 100\,\mathrm{nG}$

$1 \leq B_0/\mathrm{nG} \leq 600$

$=E[1+z(t)]$

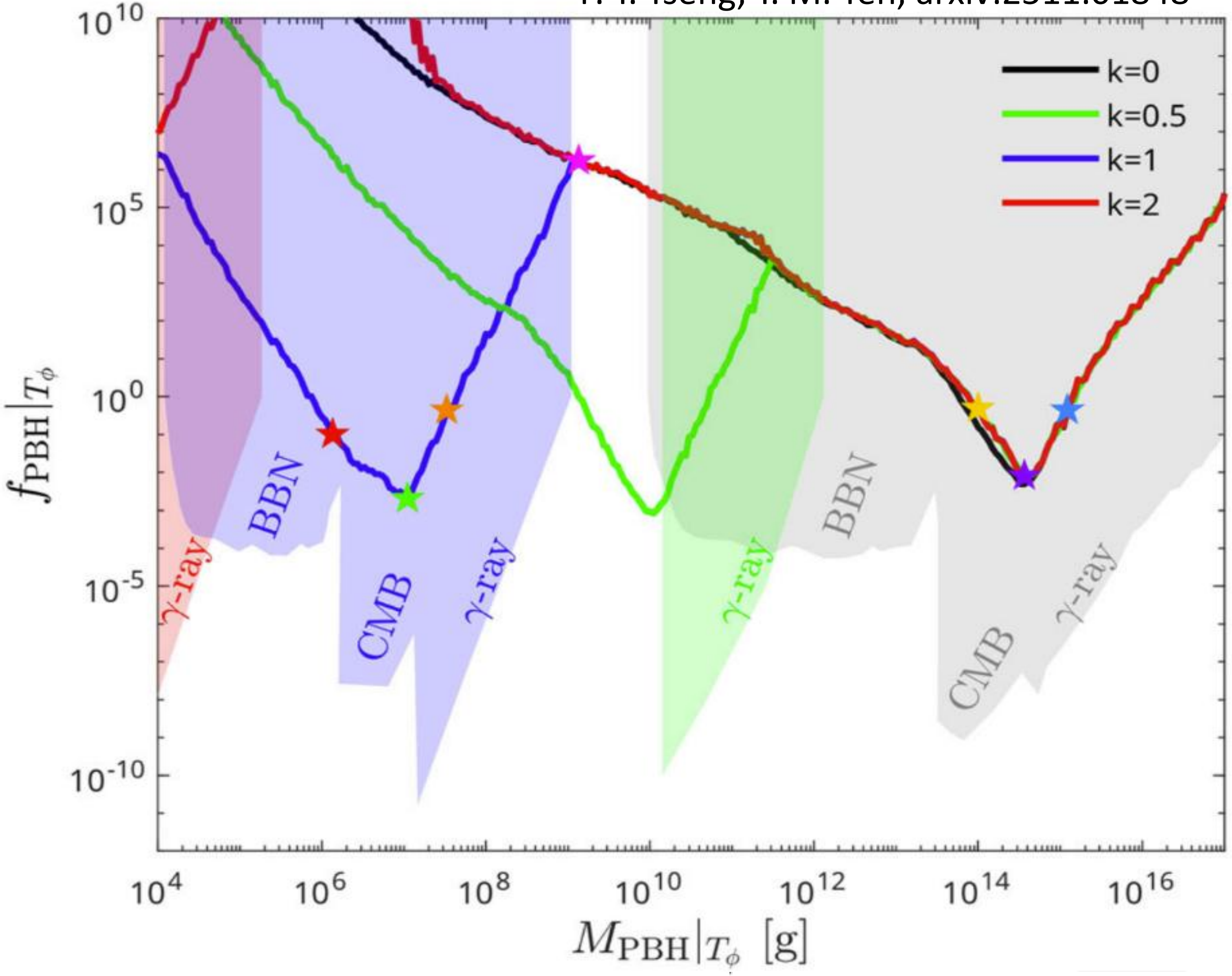
Grav

The ph

$B_0 = 100\,\mathrm{nG}$

$\leq B_0/\mathrm{nG} \leq 600$

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



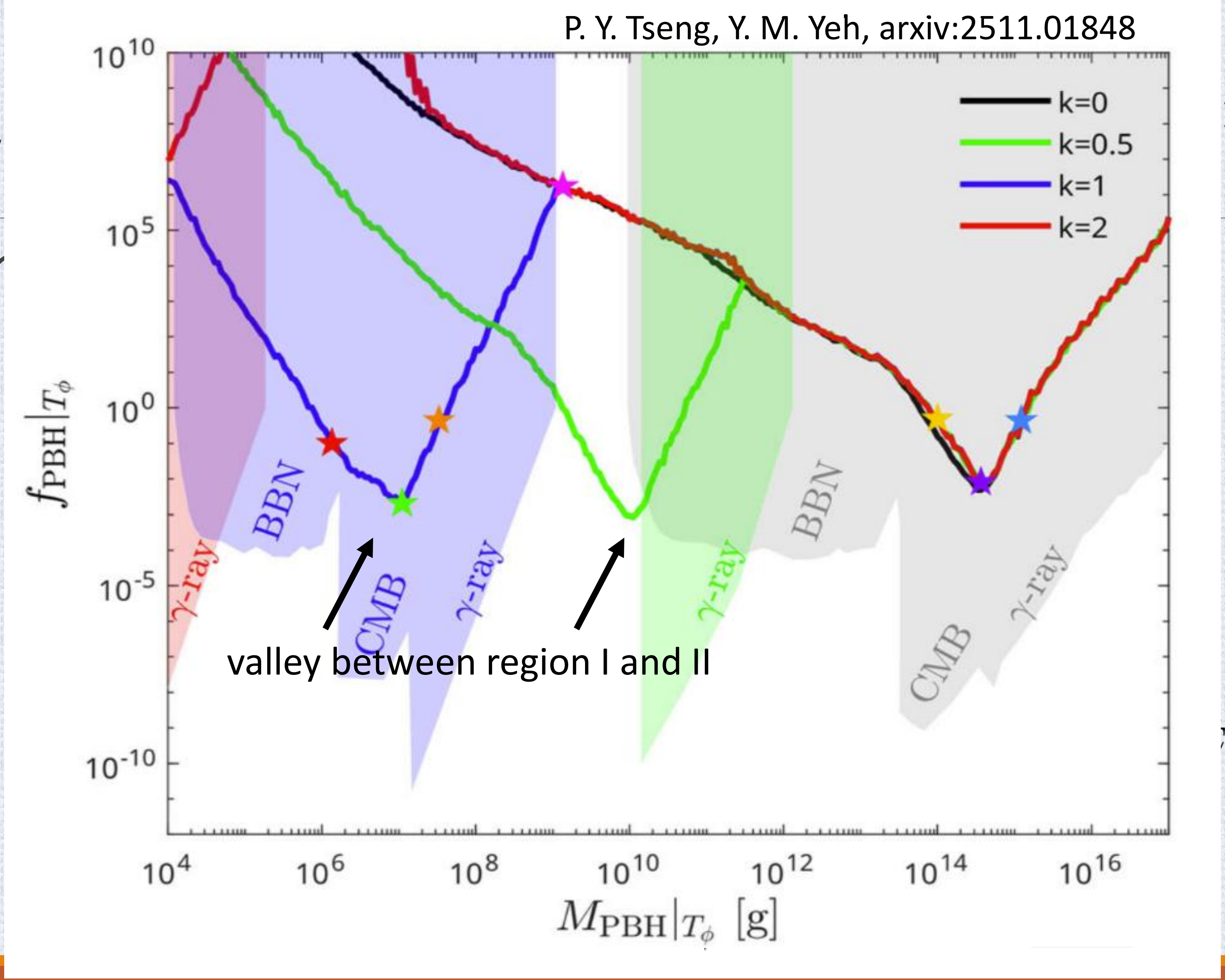
$=E[1+z(t)]$

Grav

The ph

$B_0 = 100\,\mathrm{nG}$

$\leq B_0/\mathrm{nG} \leq 600$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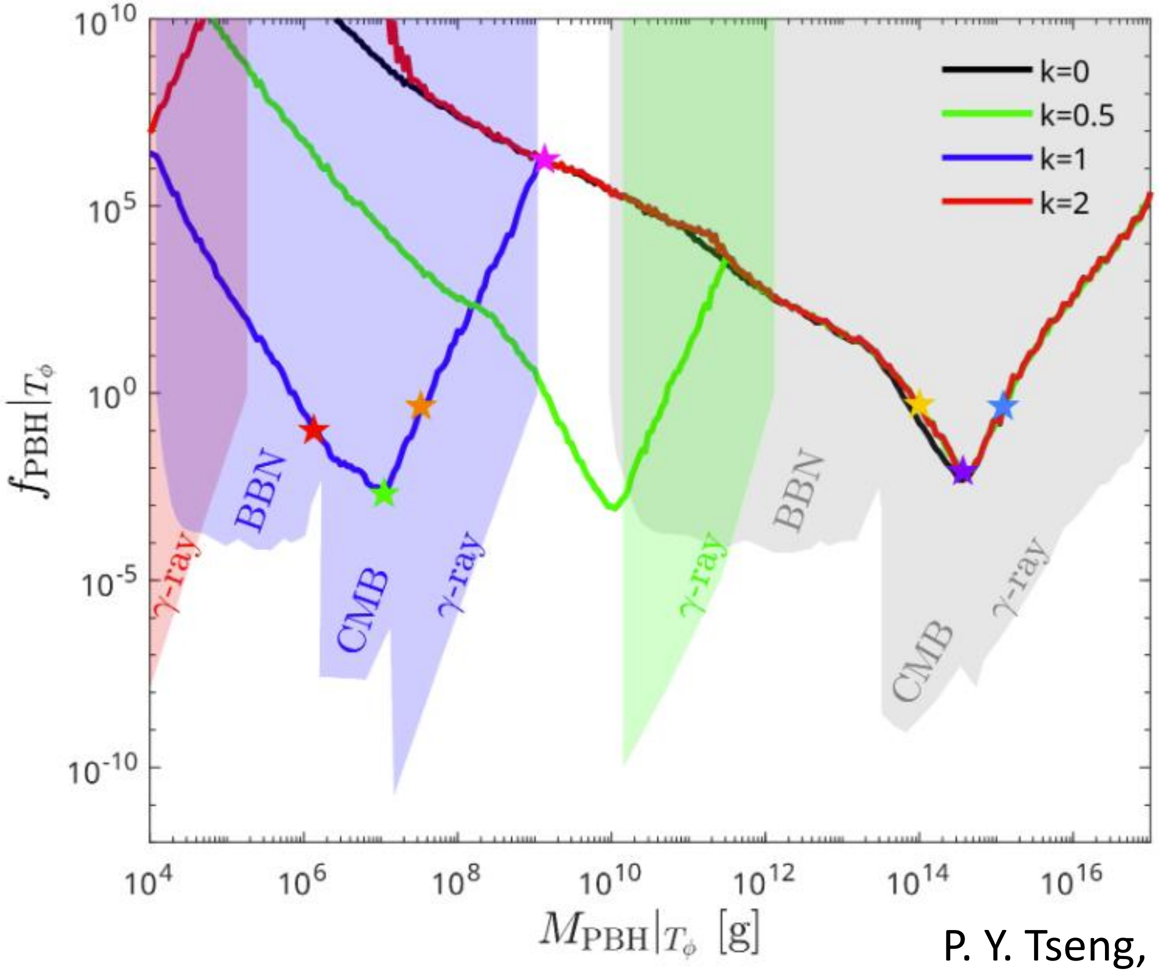
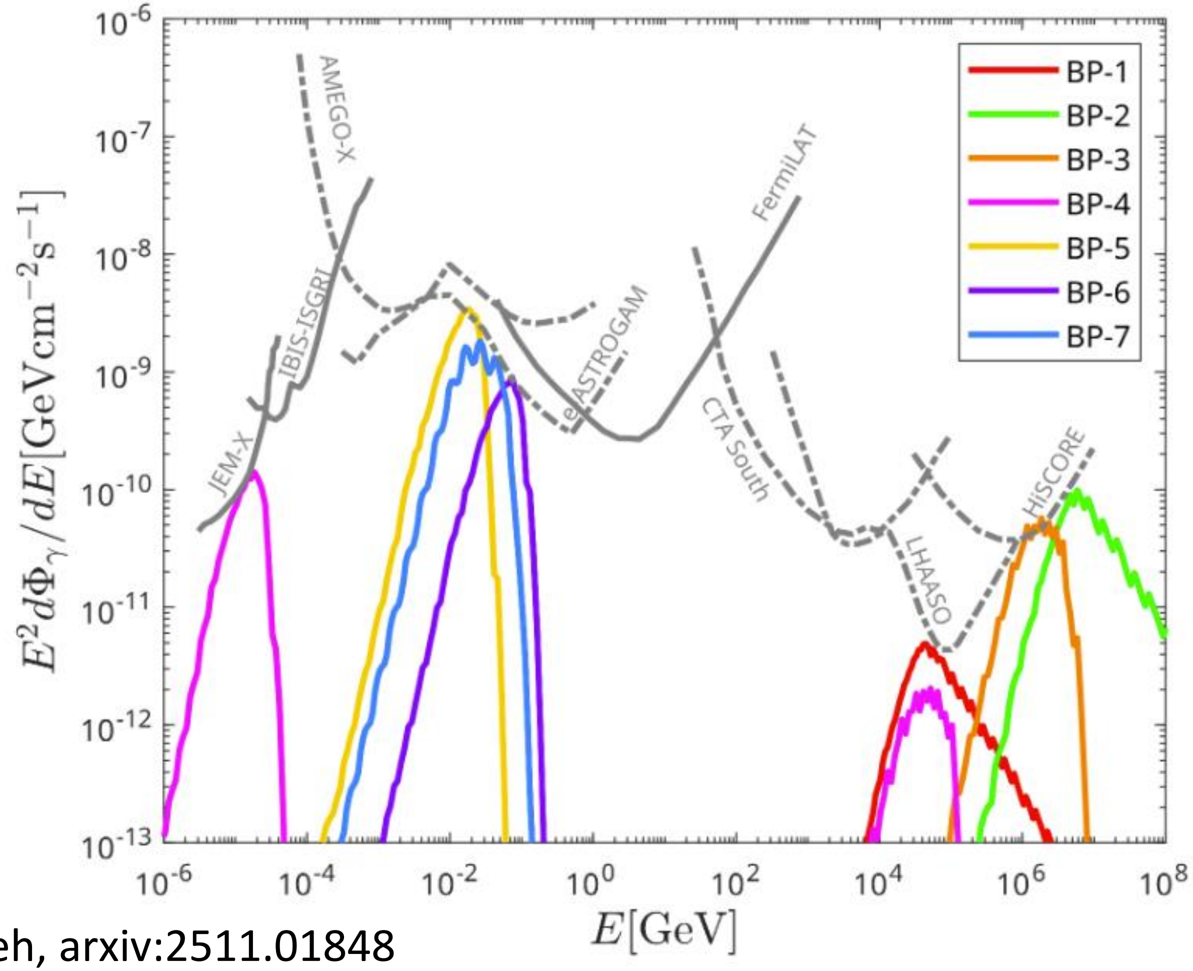
valley between region I and II

$=E[1+z(t)]$

Graviton-Photon conversion





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Summary

- The MB opens a new mass window for PBH DM lighter than $10^{15}\,\mathrm{g}$.
- The MB spectrum exhibit double peak feature.
- The MB photon spectra from h-γ conversion provide a complimentary constraint on f_{PBH} for photon spectra directly from PBH.

End

Backup

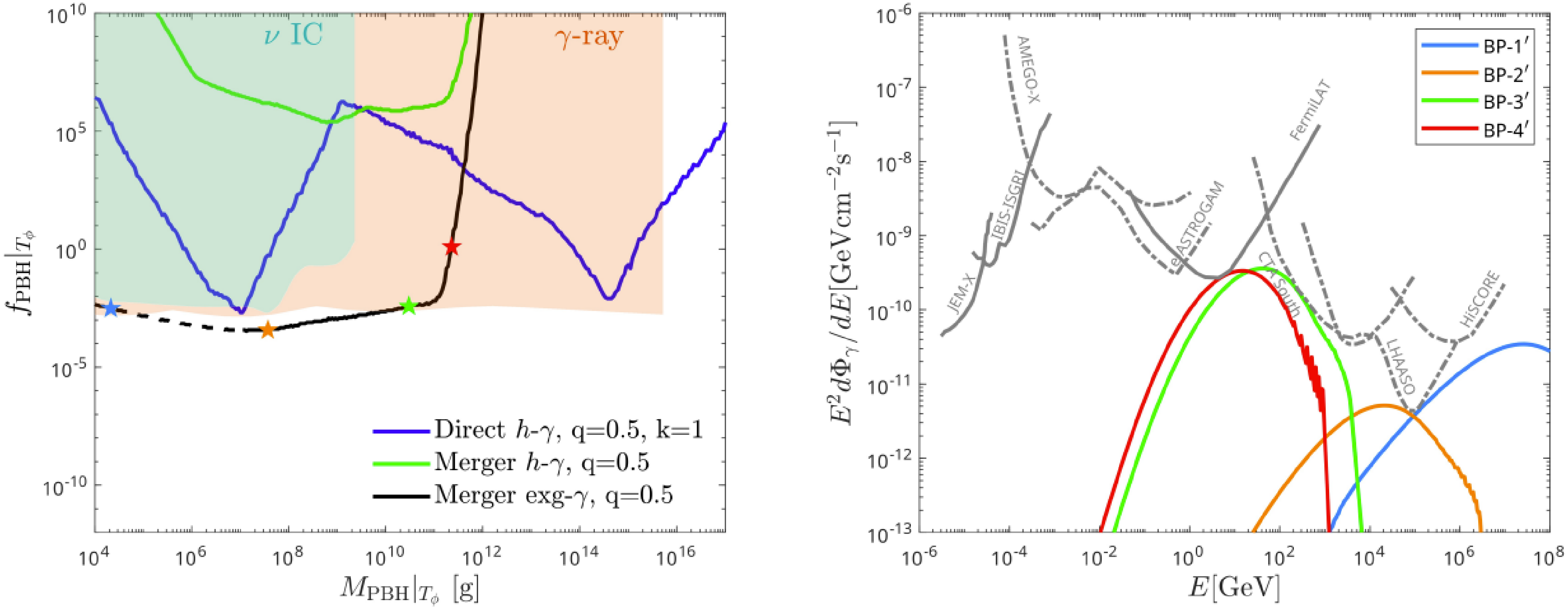


Figure 3: Left panel: The comparison of $f_{\rm PBH}|_{T_\phi}$ constraints via photon flux from graviton-photon conversion (blue curve), PBH merger (black curve), and combination of the two (green curve). Compared with other analysis, the cyan-shaded region is the merger neutrino constraint derived from IceCube Collaboration [36], and the orange-shaded region is the combined gamma-ray constraint (galactic and extragalactic) from [39]. The dashed part of the "Merger exg-γ" indicates the evaporated mass before present epoch for $k = 1$, and the "$\star$" label the benchmark points (**BP′**s) with corresponding values in Table 1. Right panel: The corresponding photon spectra of **BP′**s from left panel, and their values are listed in Table 1

Backup

$$\frac{dN_i}{dEdt} = \frac{n^{\mathrm{d.o.f}}\Gamma_i(E, M_{\mathrm{PBH}})}{2\pi(e^{E/\boxed{T_{\mathrm{PBH}}}} \pm 1)}$$

lower mass, higher temperature, higher energy peak

$$\rho(r) = \frac{\rho_0}{(r/R_s)^{\gamma}[1 + (r/R_s)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

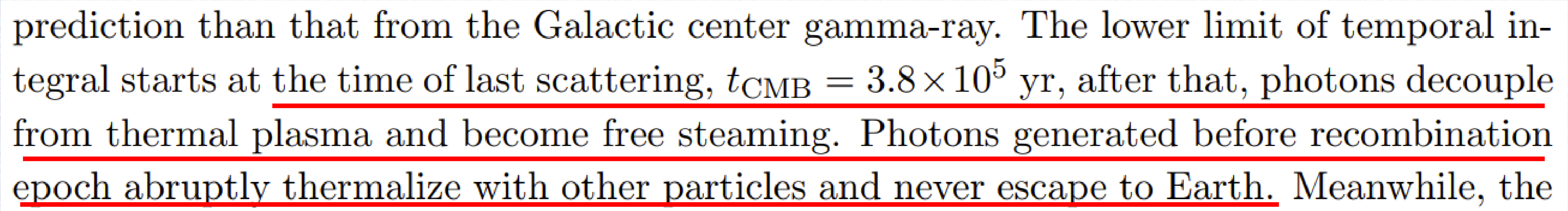
NFW $(\alpha, \beta, \gamma, R_s) = (1.0, 3.0, 1.6, 20\,\mathrm{kpc})$

Isothermal $(\alpha, \beta, \gamma, R_s) = (2.0, 2.0, 0, 3.5\,\mathrm{kpc})$

By scanning over the coefficients of the effective potential B, C ,D, λ, the asymmetry parameter, η_{DM}, the Yukawa coupling g_{χ}, and the mass of dark fermion M_i, we select six benchmark points that lie on the best fit band of 511 keV line and calculate their gamma-ray spectra.

Backup

$$\frac{d\Phi^{\rm EG}}{dE} = \frac{1}{4\pi}\int_{t_{\rm CMB}}^{\min(t_{\rm eva},t_0)} c[1+z(t)]\frac{f_{\rm PBH}\rho_{\rm DM}}{M_{\rm PBH}}\frac{d^2N_\gamma}{d\tilde{E}dt}\bigg|_{\tilde{E}=[1+z(t)]E} dt$$



prediction than that from the Galactic center gamma-ray. The lower limit of temporal integral starts at the time of last scattering, $t_{\rm CMB} = 3.8\times10^5$ yr, after that, photons decouple from thermal plasma and become free steaming. Photons generated before recombination epoch abruptly thermalize with other particles and never escape to Earth. Meanwhile, the

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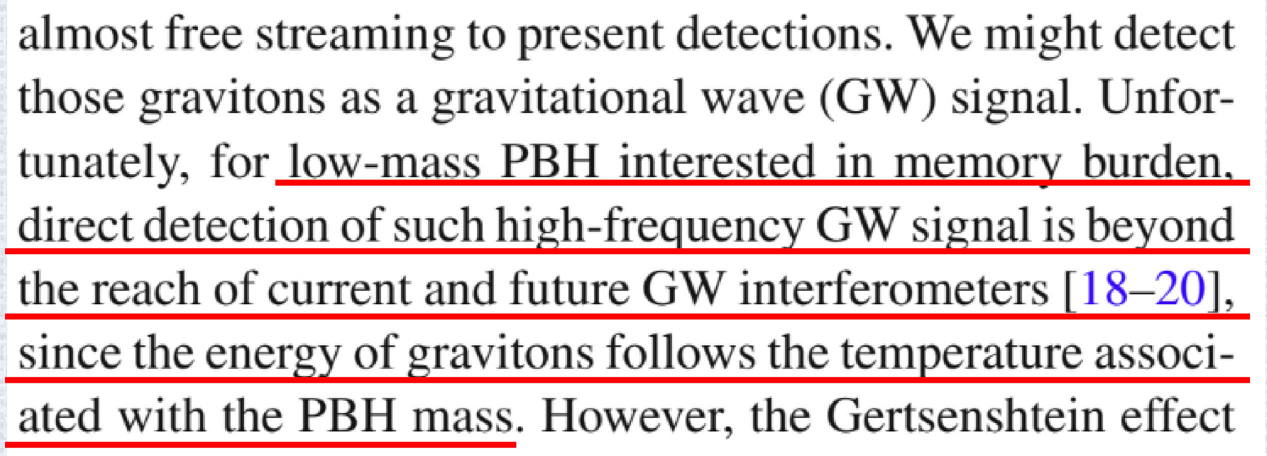
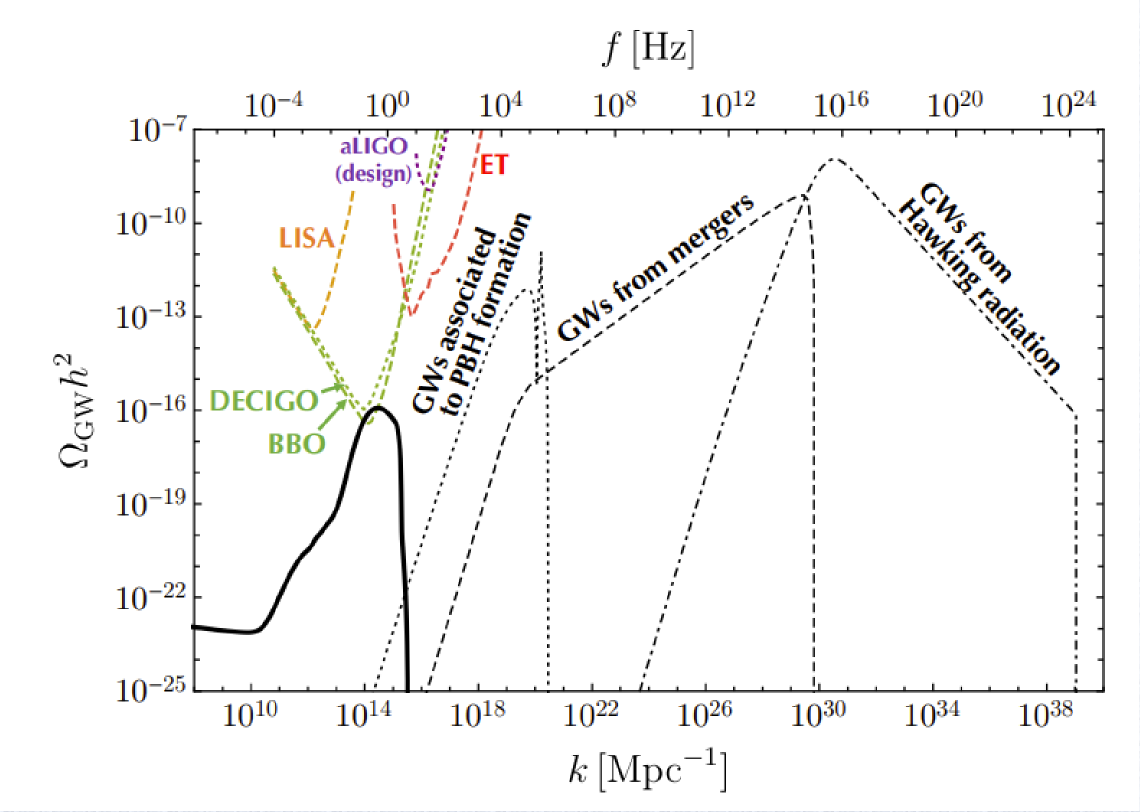


almost free streaming to present detections. We might detect those gravitons as a gravitational wave (GW) signal. Unfortunately, for low-mass PBH interested in memory burden, direct detection of such high-frequency GW signal is beyond the reach of current and future GW interferometers [18–20], since the energy of gravitons follows the temperature associated with the PBH mass. However, the Gertsenshtein effect

2003.10455



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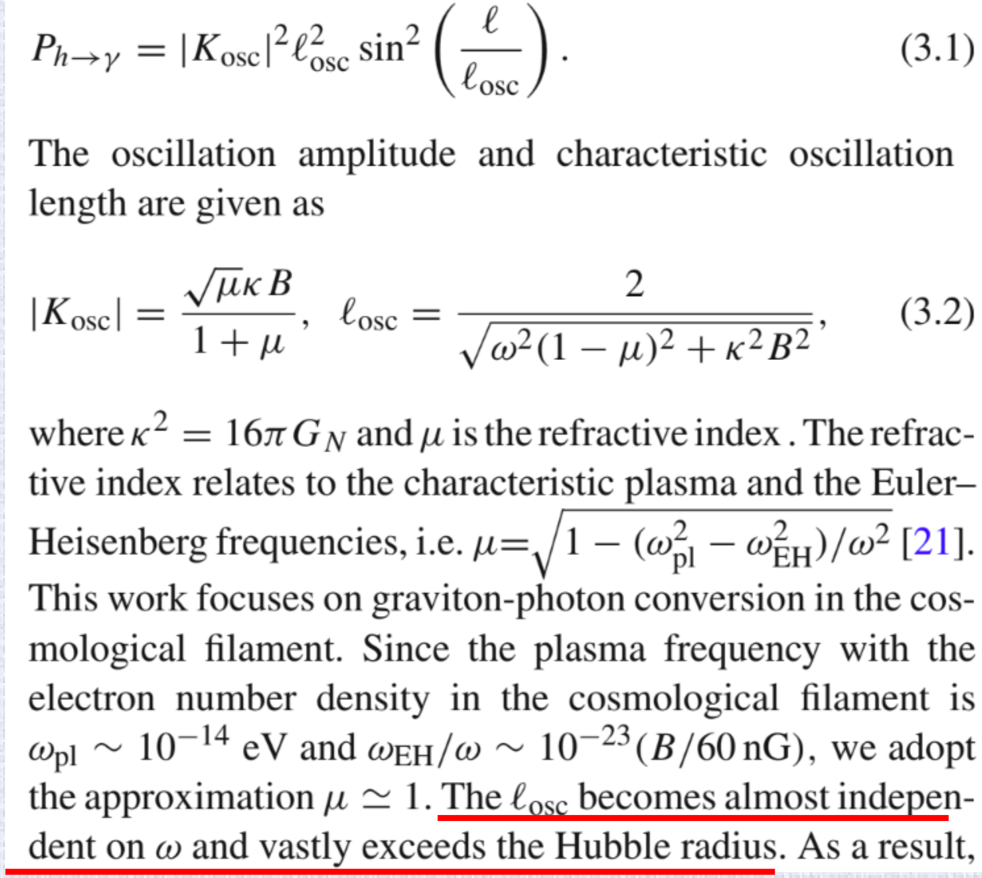
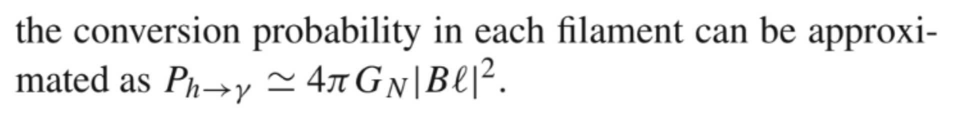


$$P_{h\to\gamma} = |K_{\rm osc}|^2 \ell_{\rm osc}^2 \sin^2\left(\frac{\ell}{\ell_{\rm osc}}\right). \qquad (3.1)$$

The oscillation amplitude and characteristic oscillation length are given as

$$|K_{\rm osc}| = \frac{\sqrt{\mu}\kappa B}{1+\mu}, \quad \ell_{\rm osc} = \frac{2}{\sqrt{\omega^2(1-\mu)^2+\kappa^2 B^2}}, \qquad (3.2)$$

where $\kappa^2 = 16\pi G_N$ and μ is the refractive index . The refractive index relates to the characteristic plasma and the Euler–Heisenberg frequencies, i.e. $\mu = \sqrt{1-(\omega_{\rm pl}^2-\omega_{\rm EH}^2)/\omega^2}$ [21]. This work focuses on graviton-photon conversion in the cosmological filament. Since the plasma frequency with the electron number density in the cosmological filament is $\omega_{\rm pl} \sim 10^{-14}$ eV and $\omega_{\rm EH}/\omega \sim 10^{-23}(B/60\,{\rm nG})$, we adopt the approximation $\mu \simeq 1$. The $\ell_{\rm osc}$ becomes almost independent on ω and vastly exceeds the Hubble radius. As a result,



the conversion probability in each filament can be approximated as $P_{h\to\gamma} \simeq 4\pi G_N |B\ell|^2$.

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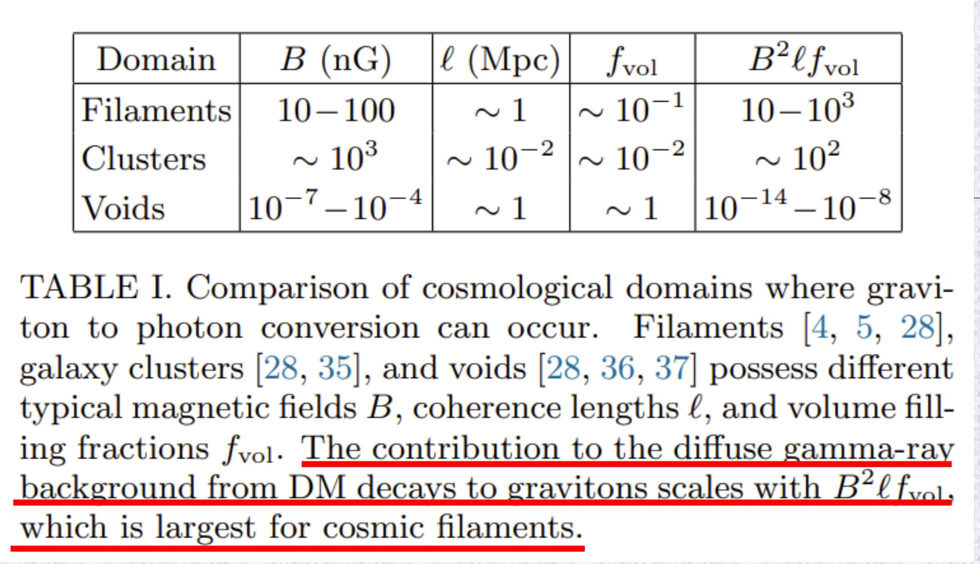

Domain	B (nG)	ℓ (Mpc)	$f_{\rm vol}$	$B^2\ell f_{\rm vol}$
Filaments	$10-100$	~ 1	$\sim 10^{-1}$	$10-10^3$
Clusters	$\sim 10^3$	$\sim 10^{-2}$	$\sim 10^{-2}$	$\sim 10^2$
Voids	$10^{-7}-10^{-4}$	~ 1	~ 1	$10^{-14}-10^{-8}$

TABLE I. Comparison of cosmological domains where graviton to photon conversion can occur. Filaments [4, 5, 28], galaxy clusters [28, 35], and voids [28, 36, 37] possess different typical magnetic fields B, coherence lengths ℓ, and volume filling fractions $f_{\rm vol}$. The contribution to the diffuse gamma-ray background from DM decays to gravitons scales with $B^2\ell f_{\rm vol}$, which is largest for cosmic filaments.

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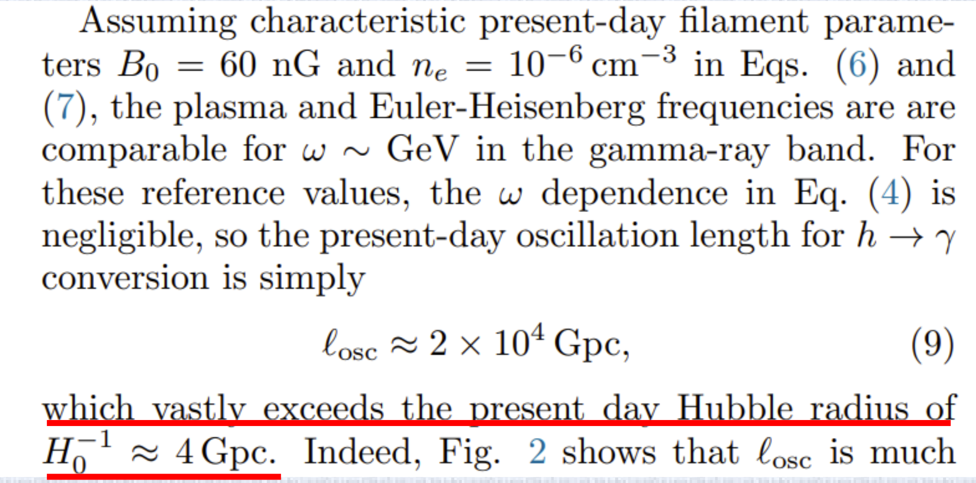

Assuming characteristic present-day filament parameters $B_0 = 60$ nG and $n_e = 10^{-6}\,{\rm cm}^{-3}$ in Eqs. (6) and (7), the plasma and Euler-Heisenberg frequencies are are comparable for $\omega \sim$ GeV in the gamma-ray band. For these reference values, the ω dependence in Eq. (4) is negligible, so the present-day oscillation length for $h \to \gamma$ conversion is simply

$$\ell_{\rm osc} \approx 2 \times 10^4\,{\rm Gpc}, \qquad (9)$$

which vastly exceeds the present day Hubble radius of $H_0^{-1} \approx 4\,{\rm Gpc}$. Indeed, Fig. 2 shows that $\ell_{\rm osc}$ is much

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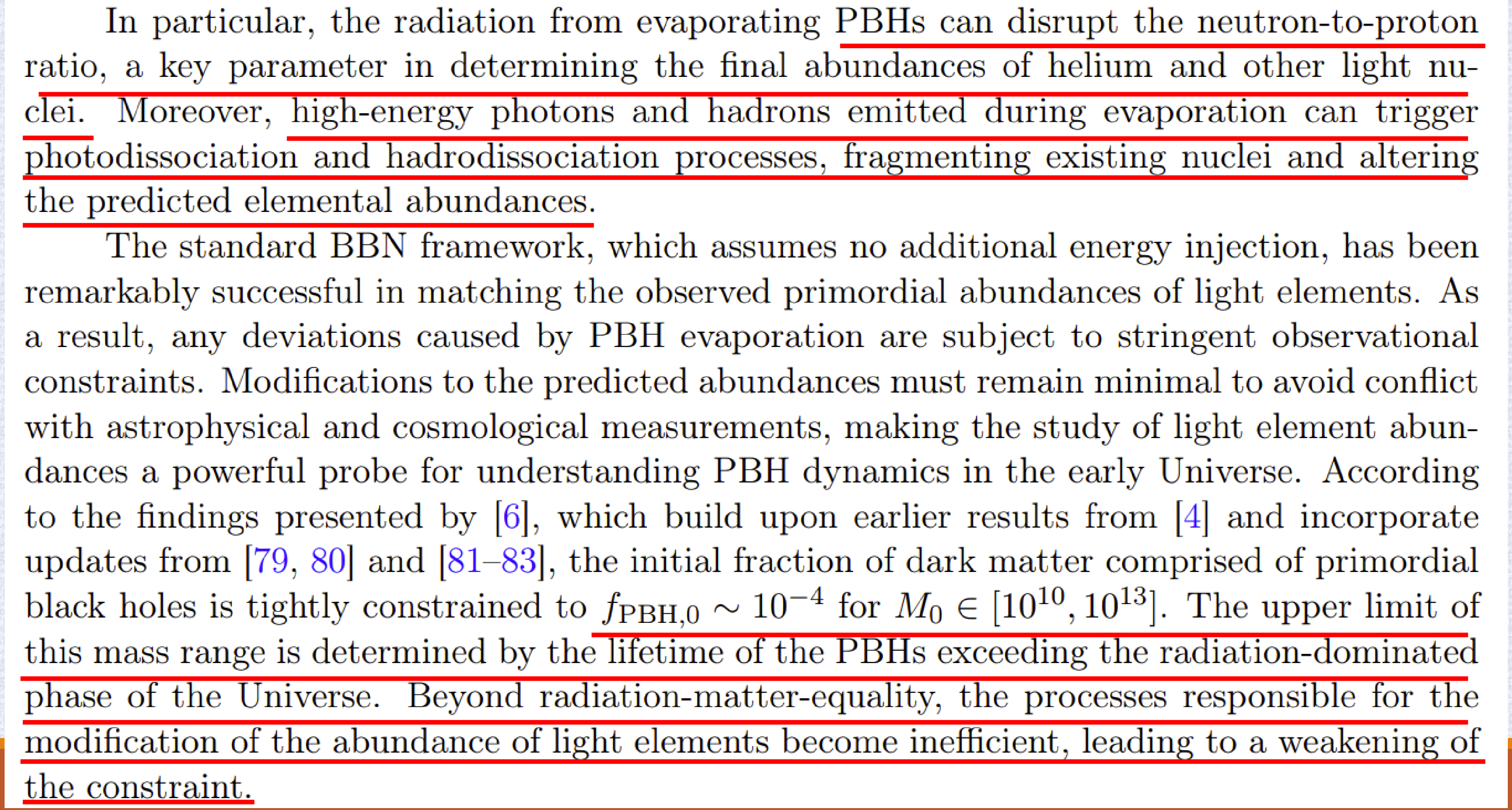

In particular, the radiation from evaporating PBHs can disrupt the neutron-to-proton ratio, a key parameter in determining the final abundances of helium and other light nuclei. Moreover, high-energy photons and hadrons emitted during evaporation can trigger photodissociation and hadrodissociation processes, fragmenting existing nuclei and altering the predicted elemental abundances.

The standard BBN framework, which assumes no additional energy injection, has been remarkably successful in matching the observed primordial abundances of light elements. As a result, any deviations caused by PBH evaporation are subject to stringent observational constraints. Modifications to the predicted abundances must remain minimal to avoid conflict with astrophysical and cosmological measurements, making the study of light element abundances a powerful probe for understanding PBH dynamics in the early Universe. According to the findings presented by [6], which build upon earlier results from [4] and incorporate updates from [79, 80] and [81–83], the initial fraction of dark matter comprised of primordial black holes is tightly constrained to $f_{\mathrm{PBH},0} \sim 10^{-4}$ for $M_0 \in [10^{10}, 10^{13}]$. The upper limit of this mass range is determined by the lifetime of the PBHs exceeding the radiation-dominated phase of the Universe. Beyond radiation-matter-equality, the processes responsible for the modification of the abundance of light elements become inefficient, leading to a weakening of the constraint.

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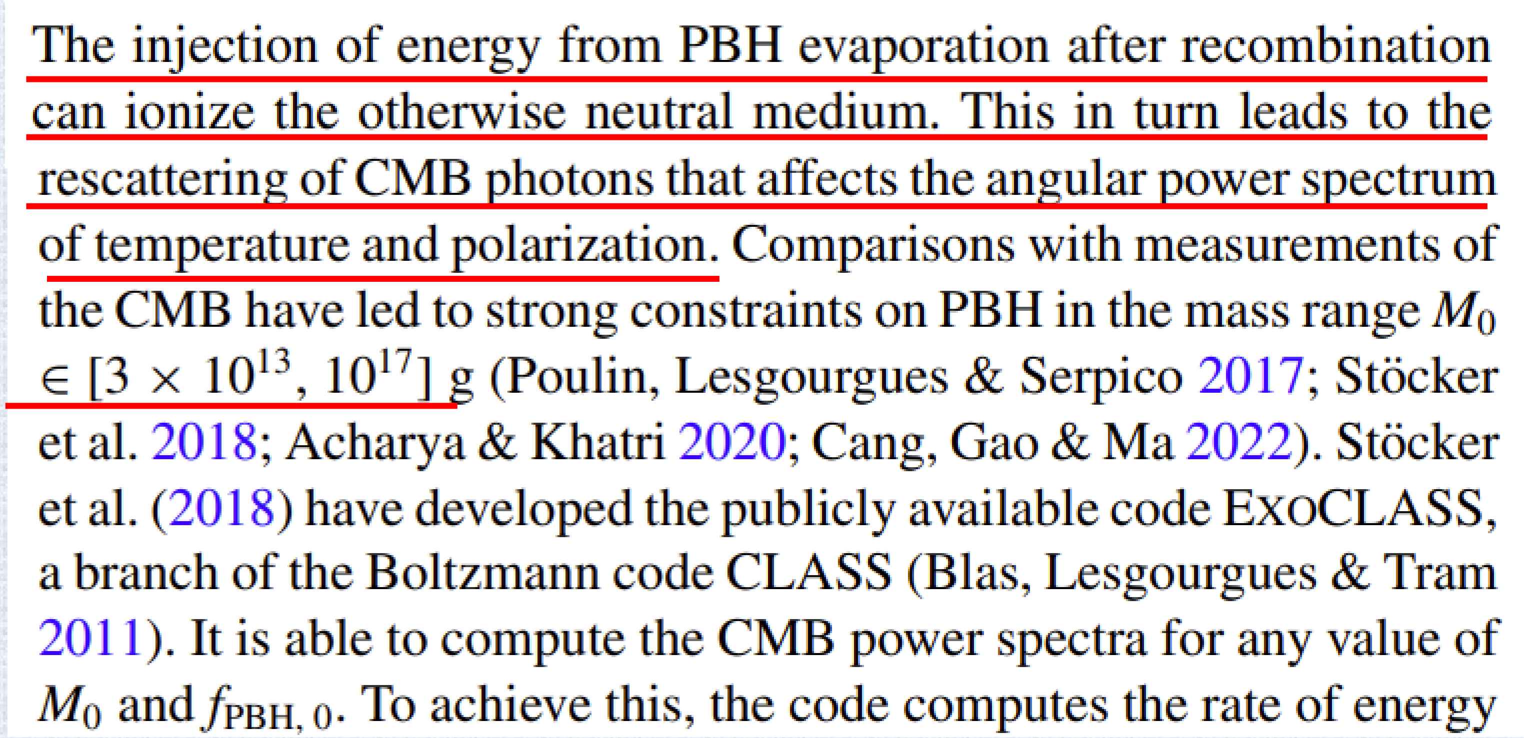

The injection of energy from PBH evaporation after recombination can ionize the otherwise neutral medium. This in turn leads to the rescattering of CMB photons that affects the angular power spectrum of temperature and polarization. Comparisons with measurements of the CMB have led to strong constraints on PBH in the mass range $M_0 \in [3 \times 10^{13}, 10^{17}]$ g (Poulin, Lesgourgues & Serpico 2017; Stöcker et al. 2018; Acharya & Khatri 2020; Cang, Gao & Ma 2022). Stöcker et al. (2018) have developed the publicly available code ExoCLASS, a branch of the Boltzmann code CLASS (Blas, Lesgourgues & Tram 2011). It is able to compute the CMB power spectra for any value of M_0 and $f_{\mathrm{PBH,\,0}}$. To achieve this, the code computes the rate of energy