TAUP 2025
19TH INTERNATIONAL CONFERRENCE ON
TOPICS IN ASTROPARTICLE AND
UNDERGROUND PHYSISCS

TAUP XICHANG

Multi-Wavelength Probing of Primordial Black Holes as Dark Matter

谭秀慧
Xiu-hui Tan
理论物理研究所
Institute of Theoretical Physics

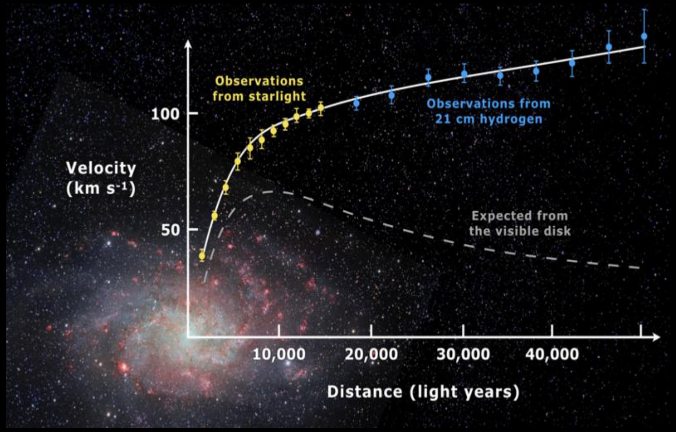
2025.08.25

based on
arXiv:2404.17119 (JCAP09(2024)022)
arXiv:2505.19857

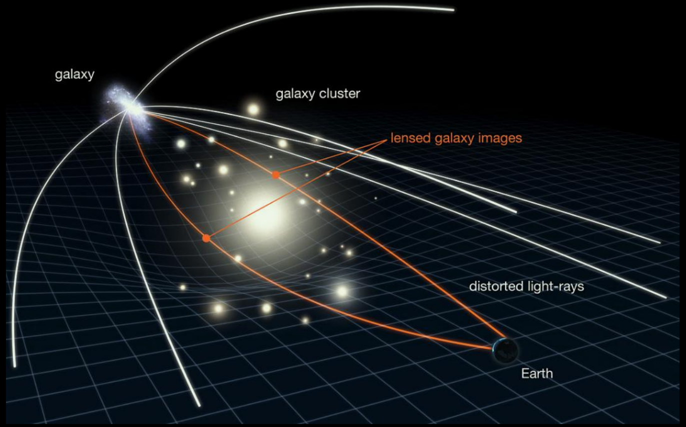
Dark Matter introduced

Evidences in different scales

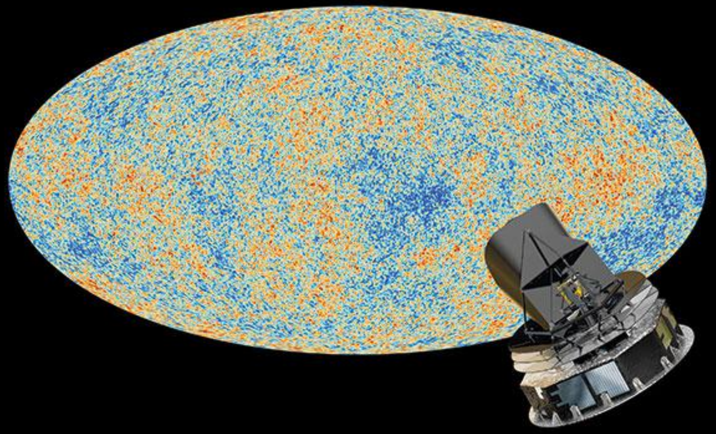
Galaxies: ~kpc
Rotation Curve: The relation between velocity and distance in galaxies (particular spiral galaxies).



Galaxy clusters: ~Mpc
Gravitational lensing: distant galaxies behind a galaxy cluster,visible mass represents only 10-20% of the total mass.



Large Scale Structure: >10Mpc
Power spectrum derived from the standard cosmological model LCDM agree with CMB from Planck Collaboration.



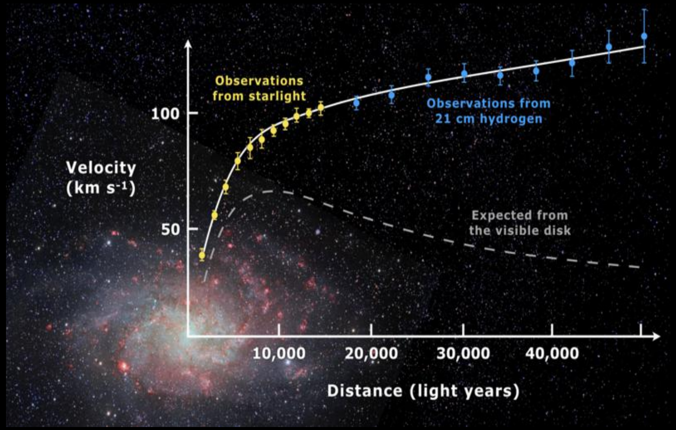
Dark Matter introduced

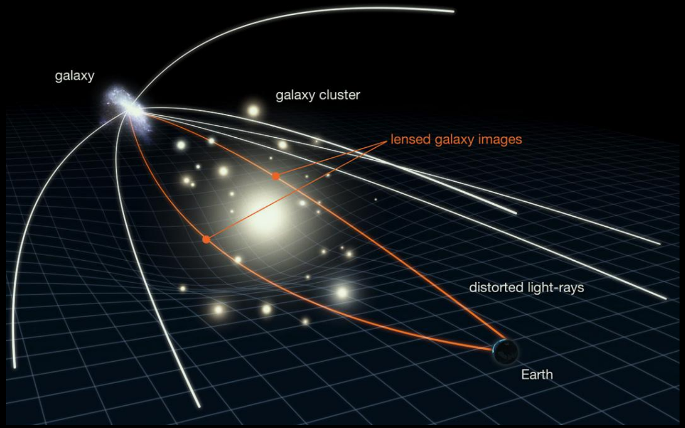
Evidences in different scales

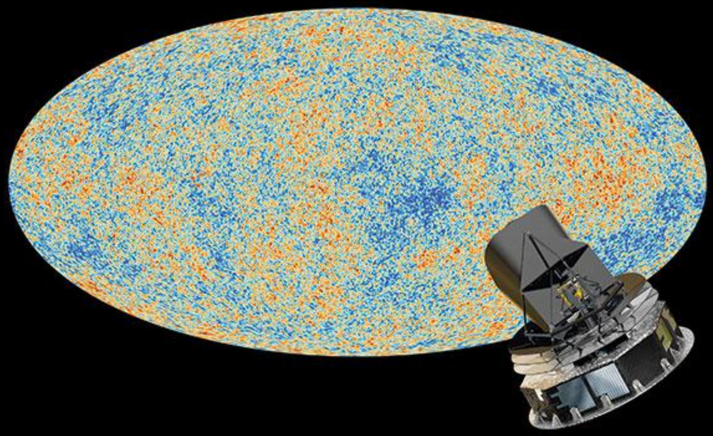
Galaxies: ~kpc
Rotation Curve: The relation between velocity and distance in galaxies (particular spiral galaxies).

Galaxy clusters: ~Mpc
Gravitational lensing: distant galaxies behind a galaxy cluster,visible mass represents only 10-20% of the total mass.

Large Scale Structure: >10Mpc
Power spectrum derived from the standard cosmological model LCDM agree with CMB from Planck Collaboration.







Long-lived

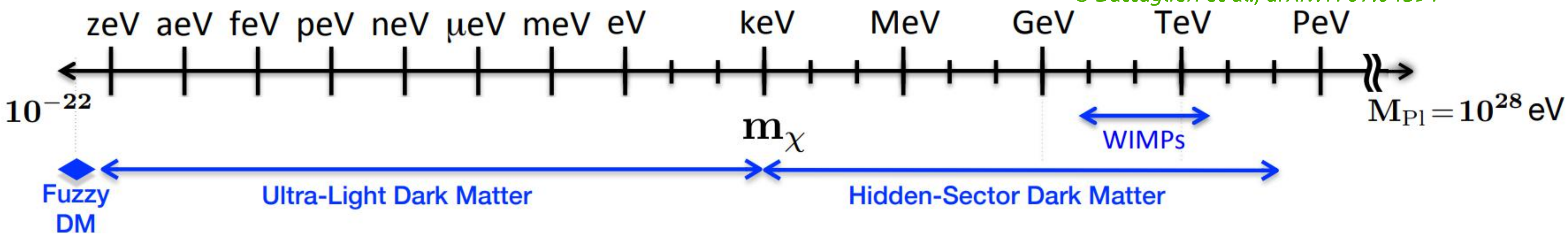
Mainly Cold

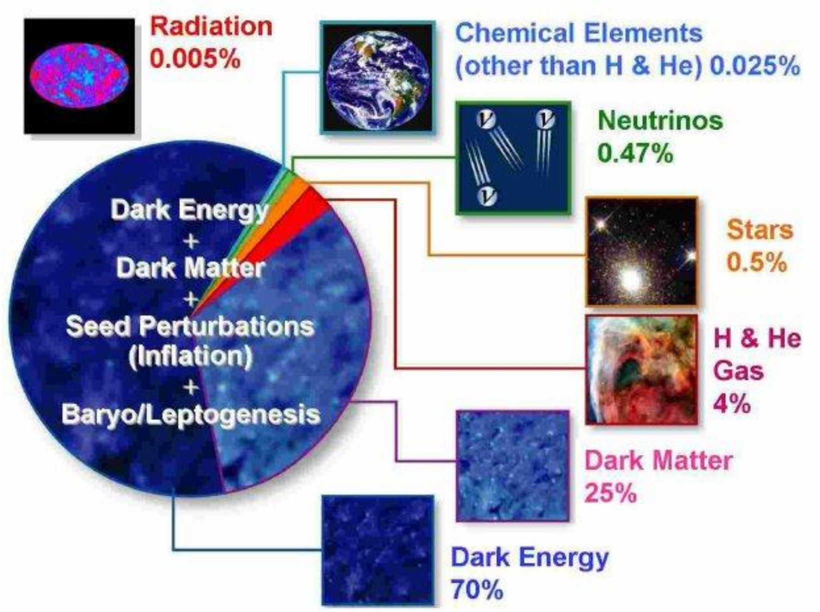
No EW charge

No Colour charge

Motivations of PBHs

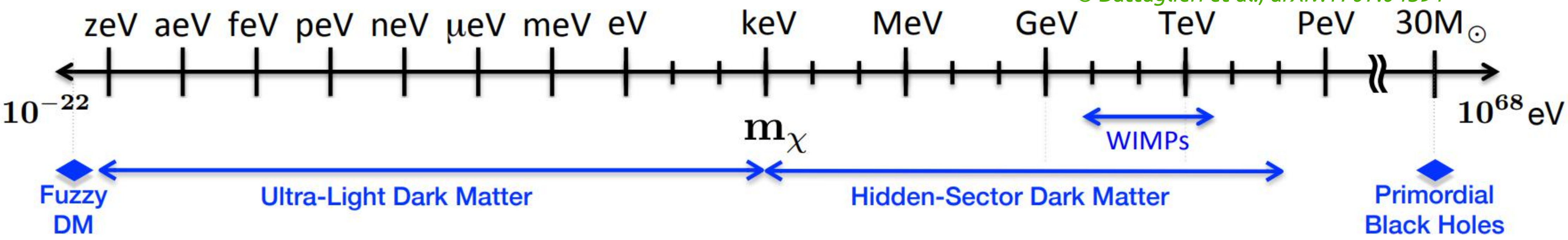
© Battaglieri et al., arXiv:1707.04591

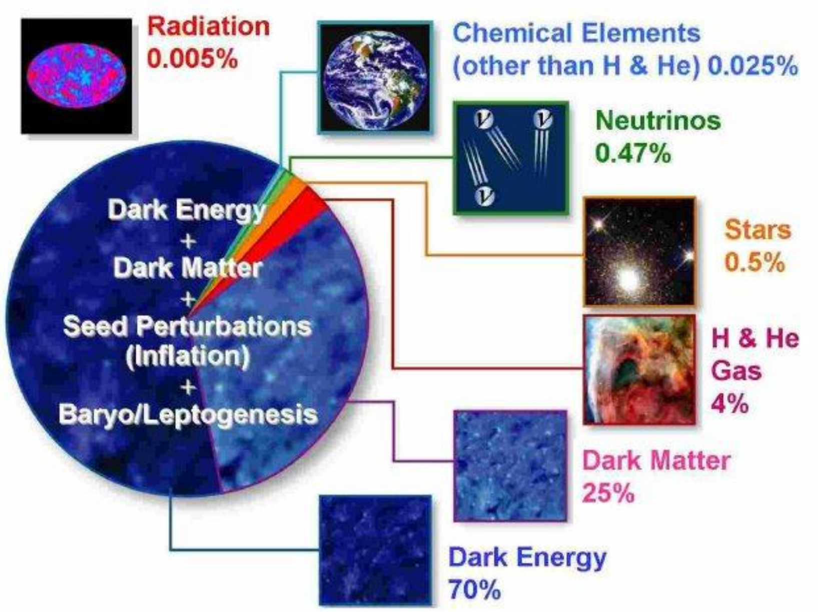




Motivations of PBHs

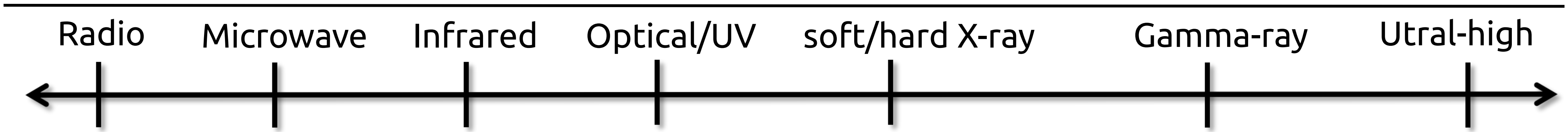
© Battaglieri et al., arXiv:1707.04591





- Not rival against particle DM
- M>10^{15} g: non-baryonic and still exist
- Memory burden indicate new windows below M<10^{15} g
- non-relativistic and nearly collision-less
- **No new physics required**!?
- More available signals to observe: © Carr&Silk, 1801.00672
  - electromagnetic signals
  - neutrinos
  - gravitational waves

Multi-Wavelength detect PBHs



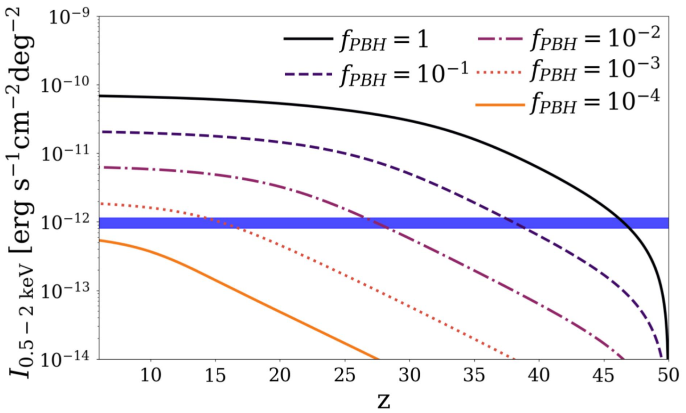
Hawking Radiation, Accretion

CRB, Radio Excess

synchrotron radiation

Magnetic Field,

Accretion in space



© F Ziparo, et.al. MNRAS,Volume 517, Issue 1, 2022

Multi-Wavelength detect PBHs

Radio | Microwave | Infrared | Optical/UV | soft/hard X-ray | Gamma-ray | Utral-high

Hawking Radiation, Accretion

Affect LSS evolution

CRB, Radio Excess

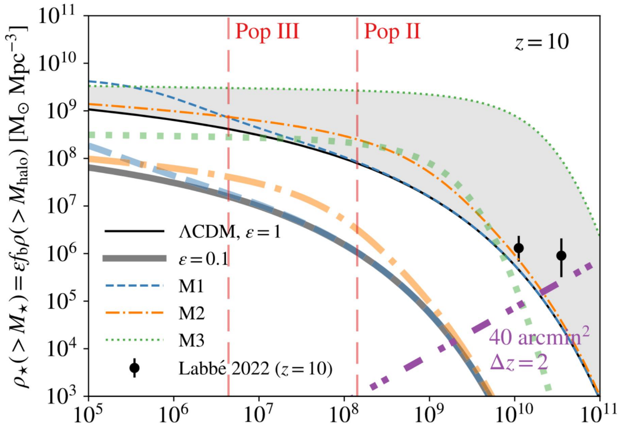
synchrotron radiation

Magnetic Field,

Accretion in space

High-redshift data Stellar Mass Density via LSS evolution:

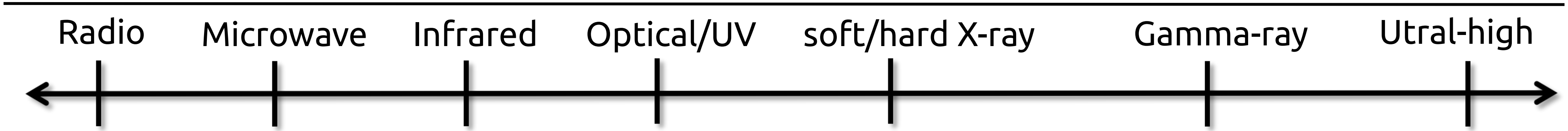
JWST



Massive galaxy candidates can be explained with lower star formation efficiency than required in LCDM if structure formation is accelerated/seeded by $\geq 10^9$ *solar mass PBHs that make up a small fraction* 10^{-6}-10^{-3} *of dark matter.*

© Boyuan Liu & Volker Bromm, ApjL, 937:L30 (7pp), 2022

Multi-Wavelength detect PBHs



Hawking Radiation, Accretion

CRB, Radio Excess
synchrotron radiation
Magnetic Field,
Accretion in space

Affect LSS evolution

High-redshift data SMD
via LSS evolution:
JWST

Hawking Radiation

CXB

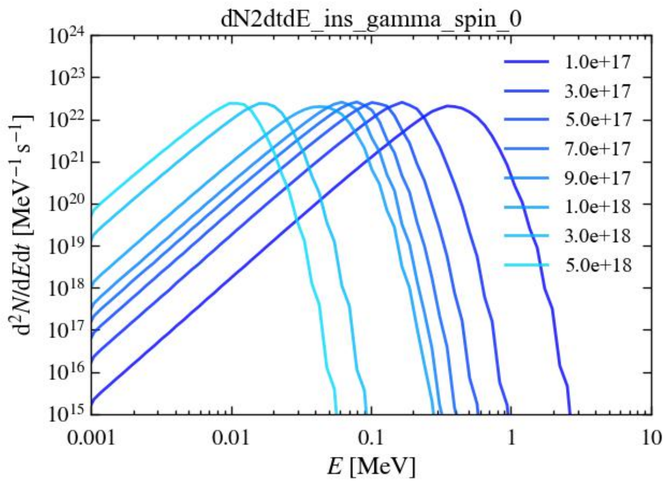
Temperature of a schwarzschild PBH:

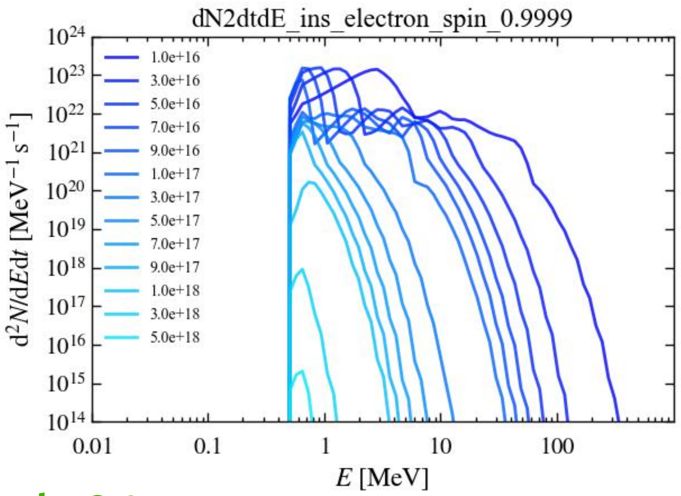
$$T_{\rm PBH} = \frac{M_P^2}{8\pi M_{\rm PBH}} \approx \frac{(1.22\times 10^{19}\ {\rm GeV})^2}{8\pi M_{\rm PBH}}$$

Particle species emissions from PBH:

$$\frac{d^2N}{dt\,dE} = \sum_{\rm dof.} \frac{\Gamma_s(E, M, a^*)/2\pi}{e^{E'/T} \pm 1}$$

$$a_* \equiv J/GM_{\rm PBH}^2 \in [0,\ 1]$$

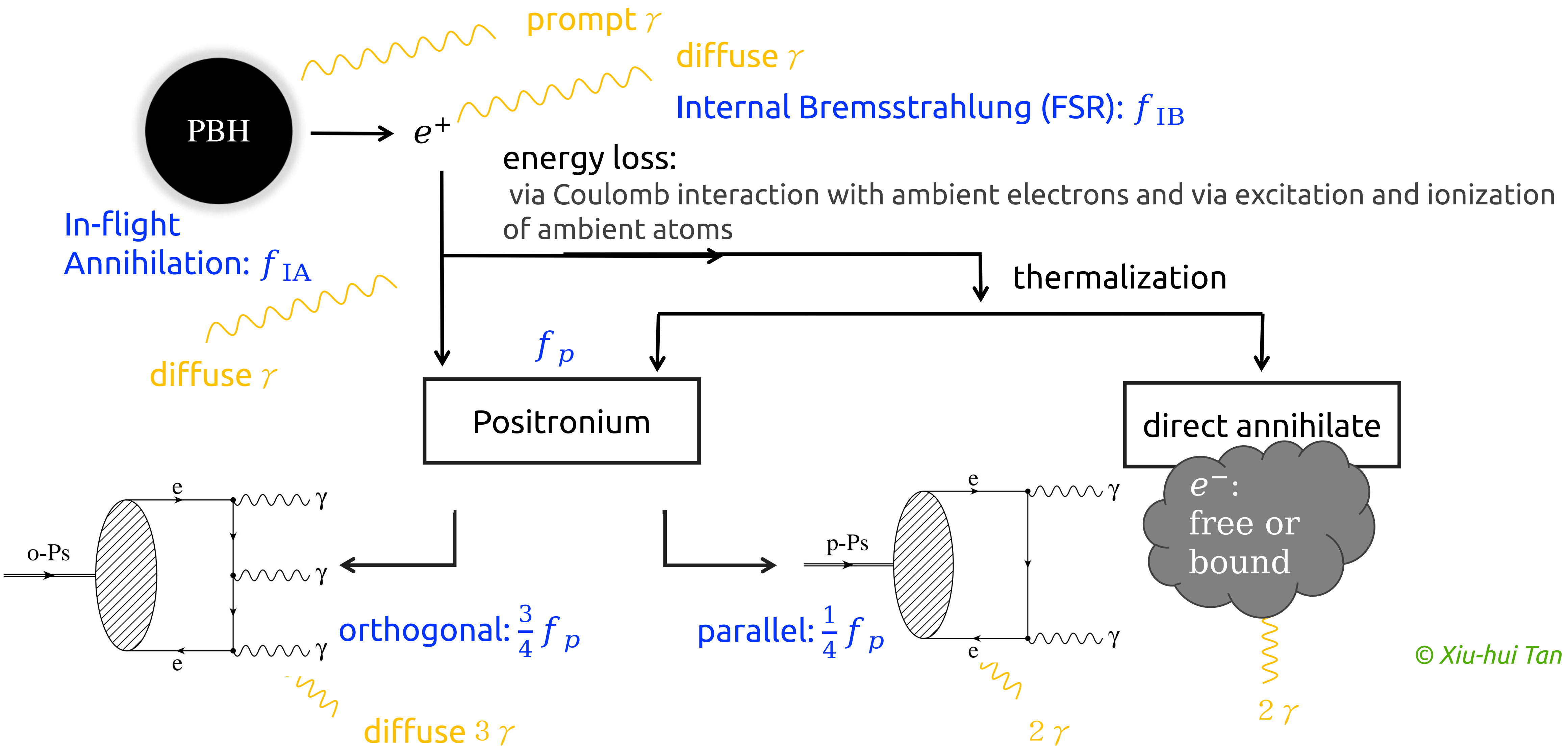




© BlackHawk v2.1

Probing with X/gamma rays

Photons from PBH:



Probing with X/gamma rays

Photons from direct radiation:

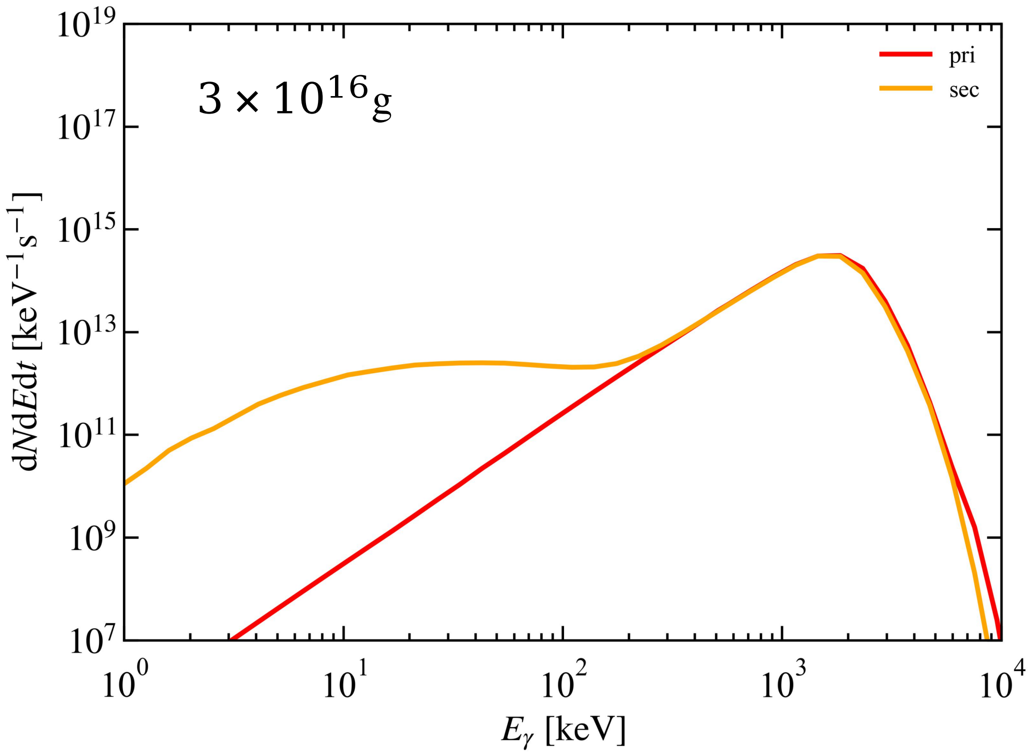
$$\frac{dN_\gamma^{\rm dir}}{dEdt} = \frac{dN_\gamma^{\rm prompt}}{dEdt} + \frac{dN_\gamma^{\rm FSR}}{dEdt} + \frac{dN_\gamma^{\rm dec}}{dEdt}$$

primary + secondary

Prompt radiation, comprising both primary and secondary emissions:
Secondary component arises from the disintegration of hadrons resulting from the fragmentation of primary quarks and gluons.

Under assumptions:

- Monochromatic mass distribution
- Schwarzschild PBH



© Xiu-hui Tan and Jun-qing Xia JCAP09(2024)022

Probing with X/gamma rays

Photons from direct radiation:

$$\frac{\mathrm{d}N_\gamma^{\mathrm{dir}}}{\mathrm{d}E\mathrm{d}t} = \frac{\mathrm{d}N_\gamma^{\mathrm{prompt}}}{\mathrm{d}E\mathrm{d}t} + \frac{\mathrm{d}N_\gamma^{\mathrm{FSR}}}{\mathrm{d}E\mathrm{d}t} + \frac{\mathrm{d}N_\gamma^{\mathrm{dec}}}{\mathrm{d}E\mathrm{d}t}$$

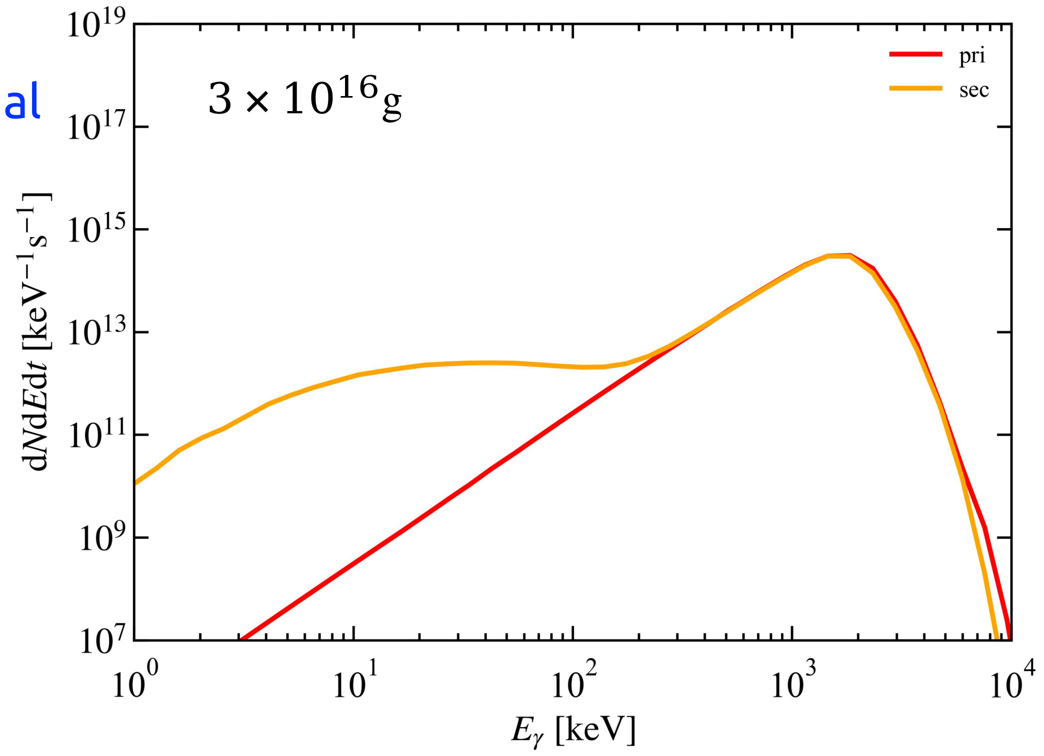
primary + secondary

final state radiation

radiative decay of final state particles

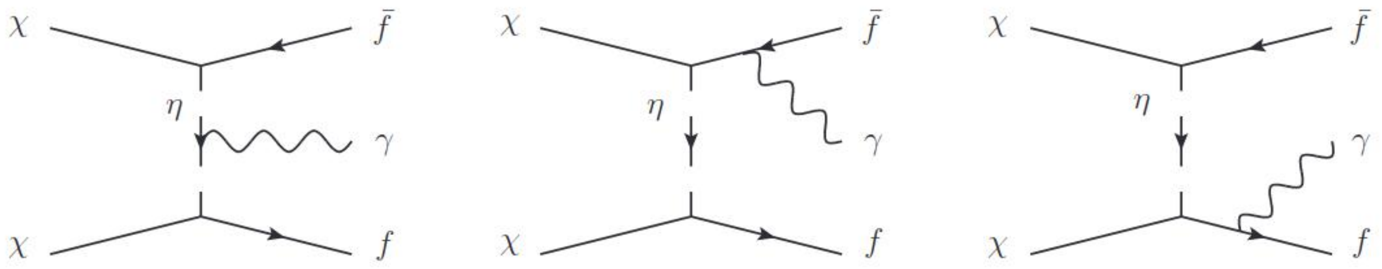
Under assumptions:

- ◯ Monochromatic mass distribution
- ◯ Schwarzschild PBH



© Xiu-hui Tan and Jun-qing Xia JCAP09(2024)022

positron:
internal bremsstrahlung (IB) spectrum =
virtual internal bremsstrahlung (VIB)+ final state radiation (FSR)



© Bringmann T, Huang X, Ibarra A, Vogl S and Weniger C 2012 J. Cosmol. Astropart. Phys. 2012 054–054

Probing with X/gamma rays

Photons from direct radiation:

$$\frac{\mathrm{d}N_\gamma^{\mathrm{dir}}}{\mathrm{d}E\mathrm{d}t} = \frac{\mathrm{d}N_\gamma^{\mathrm{prompt}}}{\mathrm{d}E\mathrm{d}t} + \frac{\mathrm{d}N_\gamma^{\mathrm{FSR}}}{\mathrm{d}E\mathrm{d}t} + \frac{\mathrm{d}N_\gamma^{\mathrm{dec}}}{\mathrm{d}E\mathrm{d}t}$$

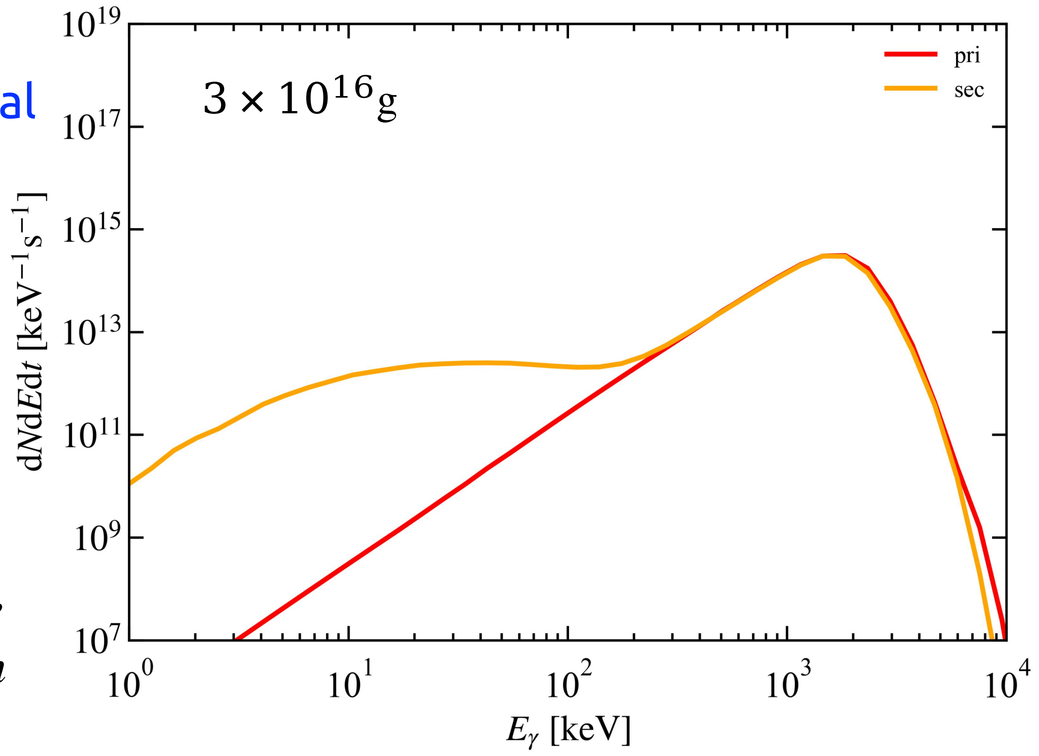
primary + secondary

final state radiation

radiative decay of final state particles

Under assumptions:

- Monochromatic mass distribution
- Schwarzschild PBH



*BSM particle interactions could also be implemented in the hadronization tables, and **low-energy processes such as inner Bremsstrahlung should be added**. Indeed, at MeV energies demonstrated that the **final state radiation of charged particles**, as implemented inside Hazma, is not relevant for HR as BHs emit independent particles and not pairs of charged particles. Hence, the single vortex effect of inner Bremsstrahlung should dominate, which would be of particular interest for future MeV constraints on PBHs*

© Jérémy, A., Primordial black holes as dark matter and Hawking radiation constraints with BlackHawk

© Xiu-hui Tan and Jun-qing Xia JCAP09(2024)022

Probing with X/gamma rays

Photons from direct radiation:

$$\frac{dN_\gamma^{\rm dir}}{dEdt} = \frac{dN_\gamma^{\rm prompt}}{dEdt} + \frac{dN_\gamma^{\rm FSR}}{dEdt} + \frac{dN_\gamma^{\rm dec}}{dEdt}$$

primary + secondary

final state radiation

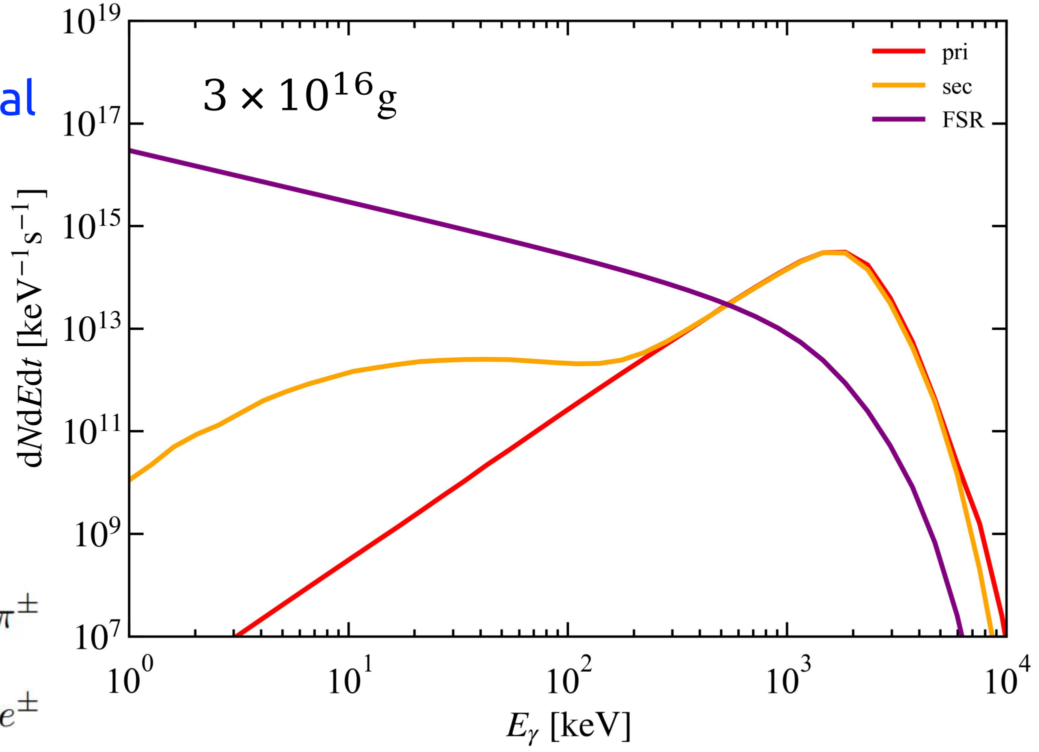
radiative decay of final state particles

$$\frac{dN_\gamma^{\rm FSR}}{dEdt} + \frac{dN_\gamma^{\rm dec}}{dEdt} = \sum_{i=e^\pm,\mu^\pm,\pi^\pm} \int dE_i \frac{dN_i^{\rm pri}}{dEdt}\frac{dN_i^{\rm FSR}}{dE} + \sum_{i=e^\pm,\pi^0,\pi^\pm} \int dE_i \frac{dN_i^{\rm pri}}{dEdt}\frac{dN_i^{\rm dec}}{dE},$$

$$\frac{dN_i^{\rm FSR}}{dE_\gamma} = \frac{\alpha}{\pi Q_i} P_{i\to i\gamma}(x)\left[\log\left(\frac{1-x}{\mu_i^2}\right) - 1\right], \quad P_{i\to i\gamma}(x) = \begin{cases} \frac{2(1-x)}{x}, & i = \pi^\pm \\ \frac{1+(1-x)^2}{x}, & i = \mu^\pm, e^\pm \end{cases}$$

Hazma © *A. Coogan, L. Morrison, and S. Profumo, JCAP 01, 056 (2020).*

Under assumptions:
- ◯ Monochromatic mass distribution
- ◯ Schwarzschild PBH



© Xiu-hui Tan and Jun-qing Xia JCAP09(2024)022

Probing with X/gamma rays

Photons from In-flight Annihilation:

$$\frac{dN_\gamma^{\rm IA}}{dE_\gamma {\rm d}t} = \frac{\pi\alpha^2 n_H}{m_e}\int_{m_e}^{\infty} dE_{e^+}\frac{dN_{e^+}}{dE_{e^+}{\rm d}t}\times\int_{E_{\rm min}}^{E_{e^+}}\frac{dE}{dE/dx}\frac{P_{E_{e^+}\to E}}{(E^2-m_e^2)}$$

$$\times\left(-2-\frac{(E+m_e)(m_e^2(E+m_e)+E_\gamma^2(E+3m_e)-E_\gamma(E+m_e)(E+3m_e))}{E_\gamma^2(E-E_\gamma+m_e)^2}\right)$$

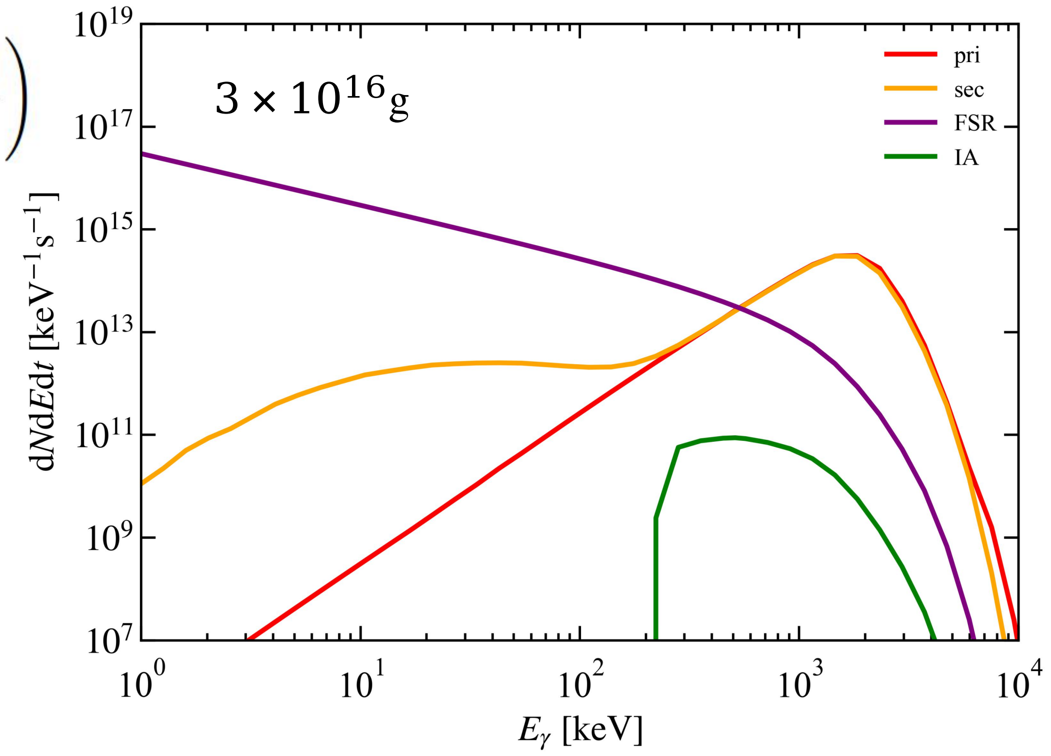
Relativistic positrons from PBH evaporation undergo in-flight annihilation with interstellar media, producing diffuse photon signals.

$$P_{E_{e^+}\to E} = \exp\left(-n_H\int_E^{E_{e^+}}{\rm d}E'\frac{\sigma_{\rm ann}(E')}{|{\rm d}E'/{\rm d}x|}\right)$$ → Bethe-Block

***Only a small percentage** of these positrons annihilate before becoming non-relativistic, then demonstrates the IA only contributes small X-ray emission.*

Under assumptions:

- ◯ Monochromatic mass distribution
- ◯ Schwarzschild PBH



© Xiu-hui Tan and Jun-qing Xia JCAP09(2024)022

Probing with X/gamma rays

Photons from Positrionium:

With Singlet state (25% probability) decays into ***two 511 keV photons****.*
Triplet state (orthopositronium, 75% probability) produces three-photon ***continuum with total energy 1022 keV****.*

Ortho-parallel Positronium: Via Ore-Powell result for one-loop QED correction:

$$\frac{d\Gamma}{dx} = \frac{4m\alpha^6}{9\pi}\left[\frac{2-x}{x} + \frac{(1-x)x}{(2-x)^2} - \frac{2(1-x)^2\log(1-x)}{(2-x)^3} + \frac{2(1-x)\log(1-x)}{x^2}\right]$$

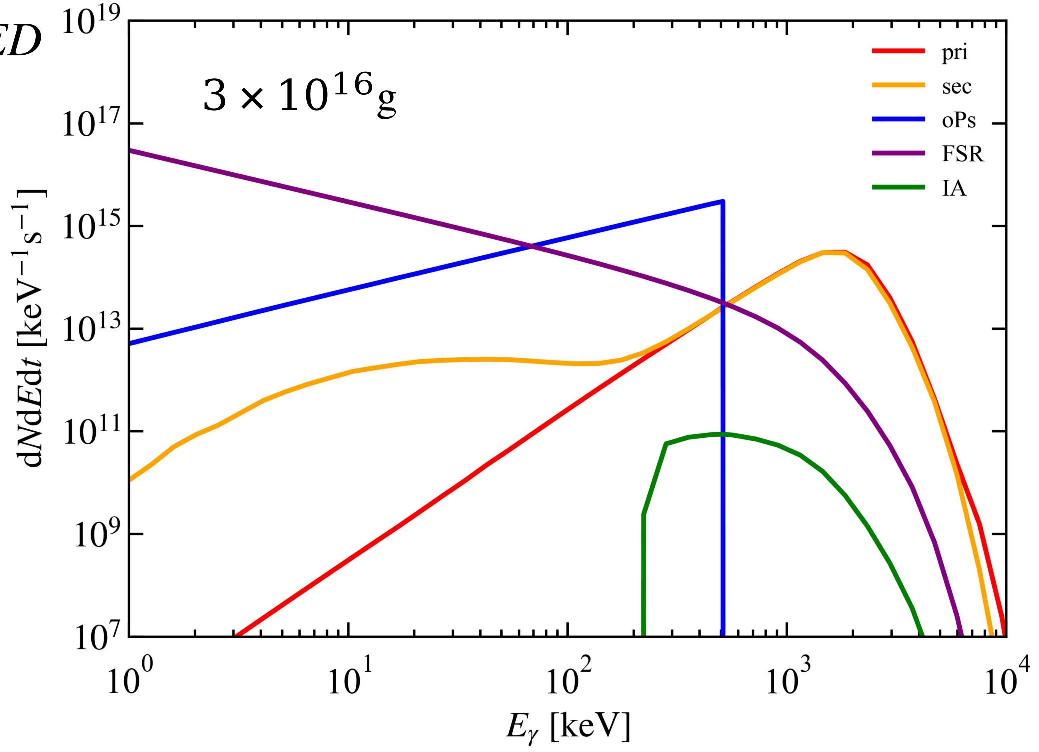
$$\frac{dN_\gamma^{oPs}}{dE_\gamma dt} = \frac{d\Gamma}{dx}\int_{m_e}^{\infty} dE \frac{dN_e}{dEdt}$$

Parallel positronium: Generate line spectrum, which together with photons from electron/positron pair:

$$\frac{dN_\gamma^{511}}{dE_\gamma dt} = \frac{dN_e}{dE_e dt}\delta(E_e - m_e)$$

Under assumptions:

- Monochromatic mass distribution
- Schwarzschild PBH



© Xiu-hui Tan and Jun-qing Xia JCAP09(2024)022

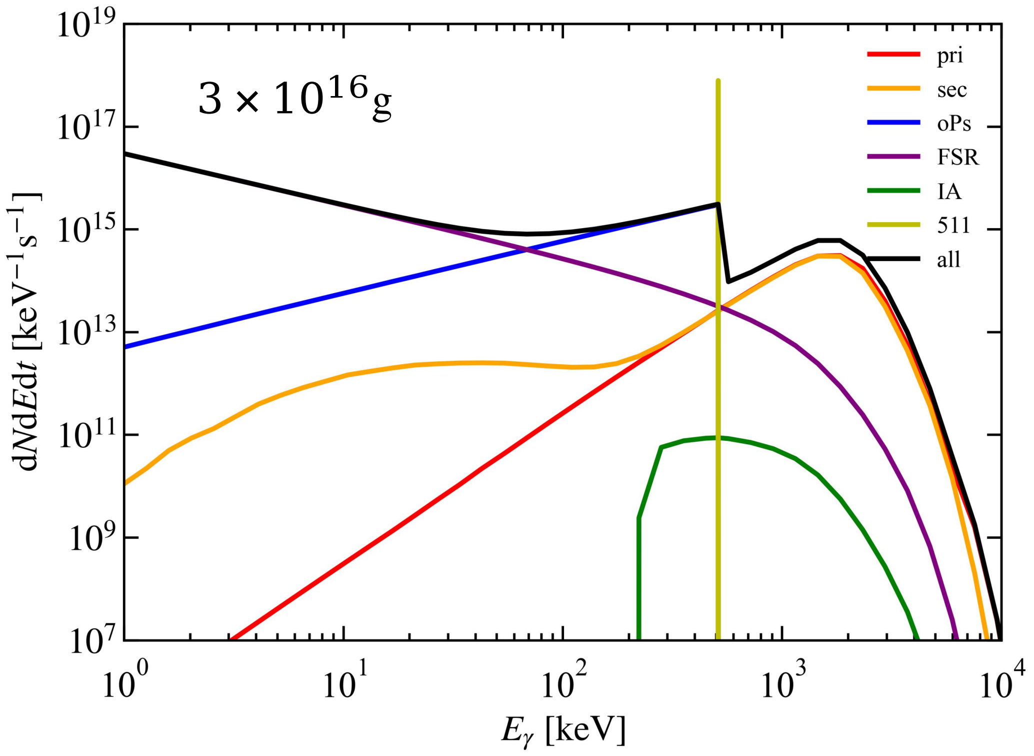
Probing with X/gamma rays

Total photons from PBHs:

$$\frac{dN_\gamma^{\rm tot}}{dEdt} = \frac{dN_\gamma^{\rm dir}}{dEdt} + \frac{dN_\gamma^{\rm Ann}}{dEdt}$$
$$= f_{\rm prompt}\frac{dN_\gamma^{\rm prompt}}{dEdt} + f_{\rm FSR}\frac{dN_\gamma^{\rm FSR}}{dEdt}$$
$$+ f_{511/{\rm line}}\frac{dN_\gamma^{511}}{dEdt} + f_{\rm IA}\frac{dN_\gamma^{\rm IA}}{dEdt} + f_{\rm oPs}\frac{dN_\gamma^{\rm oPs}}{dEdt}$$

Under assumptions:

- Monochromatic mass distribution
- Schwarzschild PBH



© Xiu-hui Tan and Jun-qing Xia JCAP09(2024)022

Fraction for every emission:

$$f_{\rm IA} = 1 - P,$$
$$f_{\rm oPs} = 3\times\frac{3}{4}P f_{\rm Ps},$$
$$f_{\rm IB/FSR} = \frac{1}{2}\left(1-\frac{3}{4}f_{\rm Ps}\right)^{-1},$$
$$f_{511/{\rm line}} = 2\times\left[P(1-f_{\rm Ps}) + \frac{1}{4}P f_{\rm Ps}\right].$$

Probing with X/gamma rays

Total theoretical diffuse emissions from PBHs:

$$\frac{d^2\phi^{PBH}}{dtdEd\Omega} = \frac{d^2\phi^{GC}}{dtdEd\Omega} + \frac{d^2\phi^{EG}}{dtdEd\Omega}$$

$$\frac{d^2\phi_\gamma^{GC}}{dtdEd\Omega} = \frac{f_{PBH}}{4\pi M_{PBH}}\left(\frac{d^2N_\gamma^{dir}}{dEdt}\mathcal{D}(b,\ell) + \frac{d^2N_\gamma^{Ann}}{dEdt}\mathcal{G}(b,\ell)\right)$$

$$\rho_{NFW}(r) = \rho_s\frac{r_s}{r}(1+\frac{r}{r_s})^{-2} \text{ with}$$

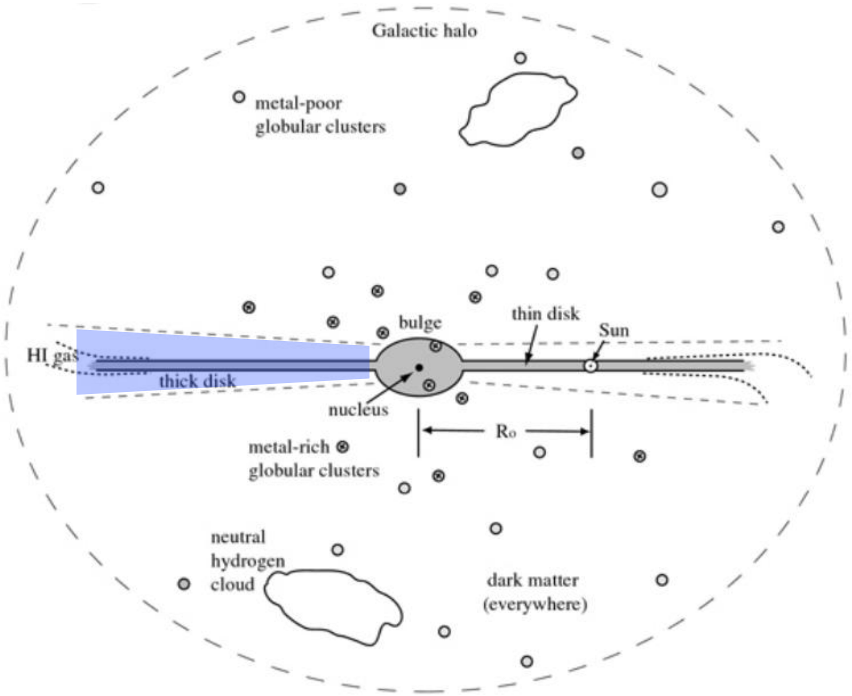
$$r_s = 9.98 \text{ kpc}, \ \rho_s = 2.2\times10^{-24} \text{ g cm}^{-3}$$

$$\rho_\odot = 0.3 \text{ GeV cm}^{-3}$$

$$r_\odot = 8.5\text{kpc}$$

$$\mathcal{D}(b,\ell) = \int_{l.o.s} ds\rho_{NFW}(s,r,\ell)$$

anti-Galactic Center



D factor for photon part; G factor for electron part. Integral for line of sight along anti-Galactic Center with NFW profile to get diffuse emissions that can compare with data.

Probing with X/gamma rays

Total theoretical diffuse emissions from PBHs:

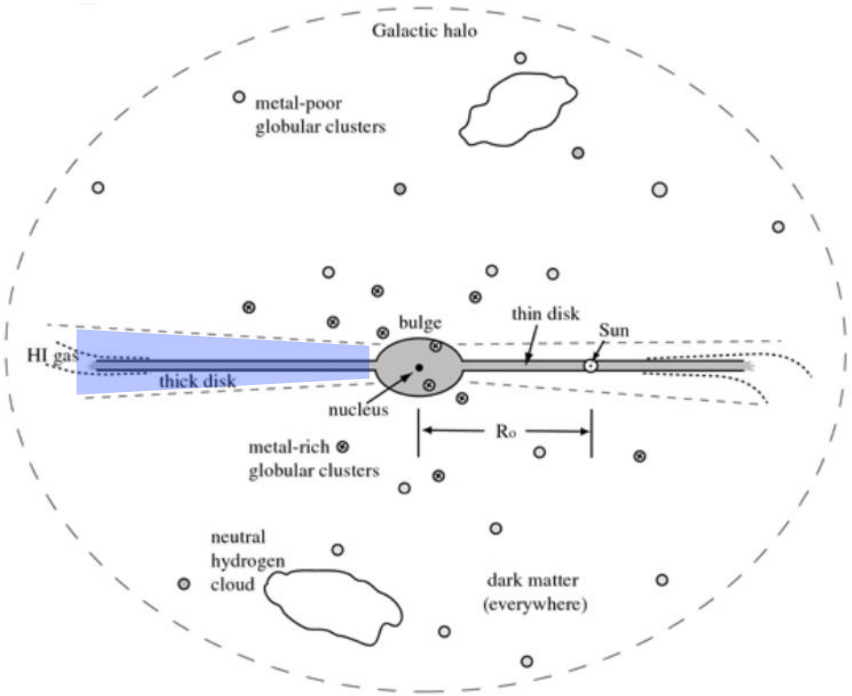
$$\frac{d^2\phi^{PBH}}{dt dE d\Omega} = \frac{d^2\phi^{GC}}{dt dE d\Omega} + \frac{d^2\phi^{EG}}{dt dE d\Omega}$$

$$\frac{d^2\phi_\gamma^{EG}}{dt dE d\Omega} = \frac{f_{PBH}\rho_c\Omega_{DM}}{4\pi M_{PBH}}\int_0^{z_{max}}\frac{dz}{H(z)} \times \left(\frac{d^2N_\gamma^{dir}}{dEdt} + \mathcal{F}(z)\frac{d^2N_\gamma^{Ann}}{dEdt}\right)\Big|_{E\to(1+z)E},$$

$$\mathcal{F}(z) = \frac{1}{\rho_m(z)}\int_{M_{min}(z)}^{\infty} dM\, M\frac{dn(M,z)}{dM}$$

$$\frac{dN_\gamma^{tot}}{dEdt} = \frac{dN_\gamma^{dir}}{dEdt} + \frac{dN_\gamma^{Ann}}{dEdt} = f_{prompt}\frac{dN_\gamma^{prompt}}{dEdt} + f_{FSR}\frac{dN_\gamma^{FSR}}{dEdt} + f_{511/line}\frac{dN_\gamma^{511}}{dEdt} + f_{IA}\frac{dN_\gamma^{IA}}{dEdt} + f_{oPs}\frac{dN_\gamma^{oPs}}{dEdt}$$

$e^{\pm}$



In low-z environments with electron density $n_e \approx 10^{-6}$ cm^{-3}, the annihilation timescale exceeds the age of the universe.

Within DM halos where PBH-released positrons encounter much denser media, the process becomes efficient. Cosmological simulations indicate only halos above ***M_min ≈ 10^7-10^{11} solar mass*** *can sustain baryonic collapse and galaxy formation.*

Probing with X/gamma rays

Total theoretical diffuse emissions from PBHs:

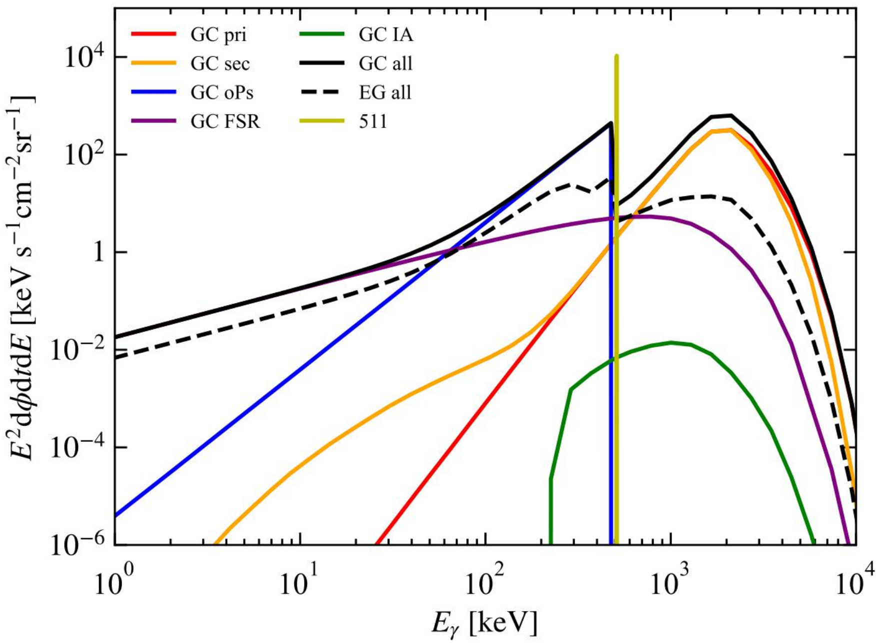
$$\frac{d^2\phi^{PBH}}{dt dE d\Omega} = \frac{d^2\phi^{GC}}{dt dE d\Omega} + \frac{d^2\phi^{EG}}{dt dE d\Omega}$$

$$\frac{d^2\phi_\gamma^{EG}}{dt dE d\Omega} = \frac{f_{PBH}\rho_c\Omega_{DM}}{4\pi M_{PBH}} \int_0^{z_{max}} \frac{dz}{H(z)} \times \left(\frac{d^2N_\gamma^{dir}}{dEdt} + \mathcal{F}(z)\frac{d^2N_\gamma^{Ann}}{dEdt}\right)\bigg|_{E\to(1+z)E},$$

$$\mathcal{F}(z) = \frac{1}{\rho_m(z)} \int_{M_{min}(z)}^{\infty} dM\, M \frac{dn(M,z)}{dM}$$

$$\frac{dN_\gamma^{tot}}{dEdt} = \frac{dN_\gamma^{dir}}{dEdt} + \frac{dN_\gamma^{Ann}}{dEdt} = f_{prompt}\frac{dN_\gamma^{prompt}}{dEdt} + f_{FSR}\frac{dN_\gamma^{FSR}}{dEdt} + f_{511/line}\frac{dN_\gamma^{511}}{dEdt} + f_{IA}\frac{dN_\gamma^{IA}}{dEdt} + f_{oPs}\frac{dN_\gamma^{oPs}}{dEdt}$$

$e^{\pm}$



The positron fraction f_p = 0.967 ± 0.022 in Galactic ISM translates to f_line ≈ 0.55 for the 511 keV line, with general bounds of 0.5 ≤ f_line ≤ 2.

Probing with X/gamma rays

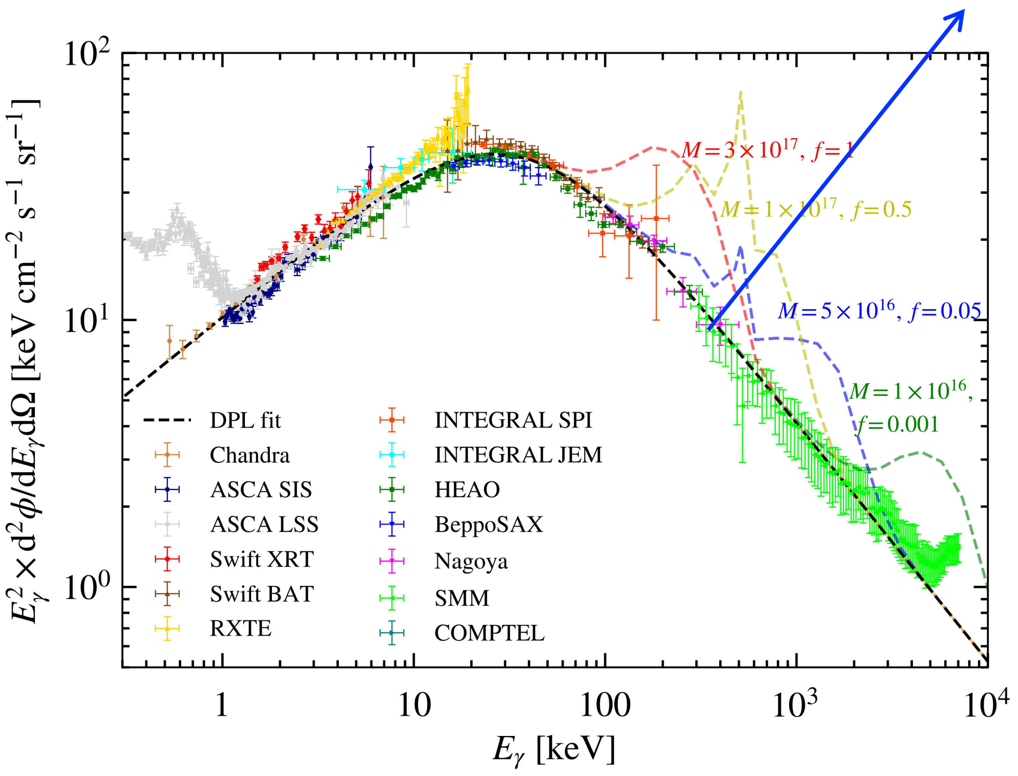
If DPL (double power-law) exists:

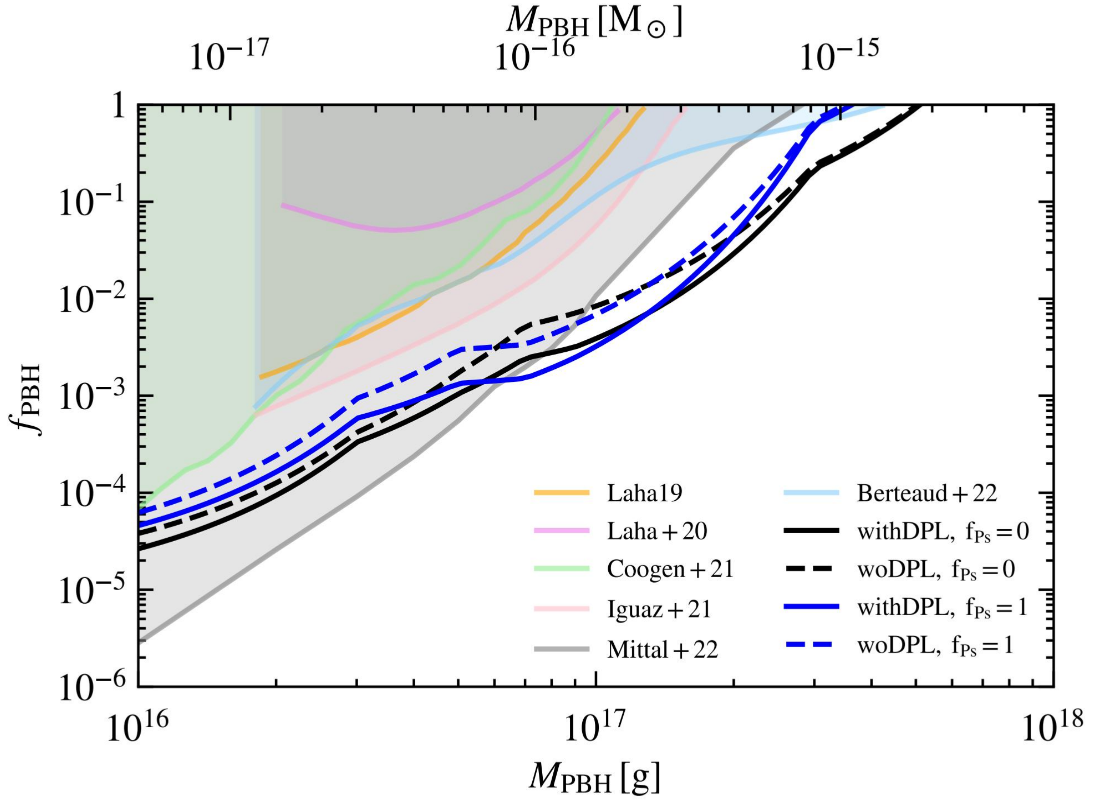
$$\chi^2 = \sum \left[\frac{\phi_\gamma^{\rm data} - \phi_\gamma^{\rm PBH}(\theta) - \phi_\gamma^{\rm AGN}}{\sigma^{\rm data}} \right]^2$$

$$\frac{\phi^{\rm AGN}}{{\rm d}E{\rm d}t} = \frac{A}{(E/E_b)^{n_1} + (E/E_b)^{n_2}}$$

$$\begin{aligned} E_b &= 35.6966 \ \ {\rm keV} \\ n_1 &= 1.4199 \\ n_2 &= 2.8956 \\ A &= 0.0642 \ {\rm keV}^{-1}{\rm s}^{-1}{\rm cm}^{-2}{\rm sr}^{-1} \end{aligned}$$

from the SMM, Nagoya, and HEAO





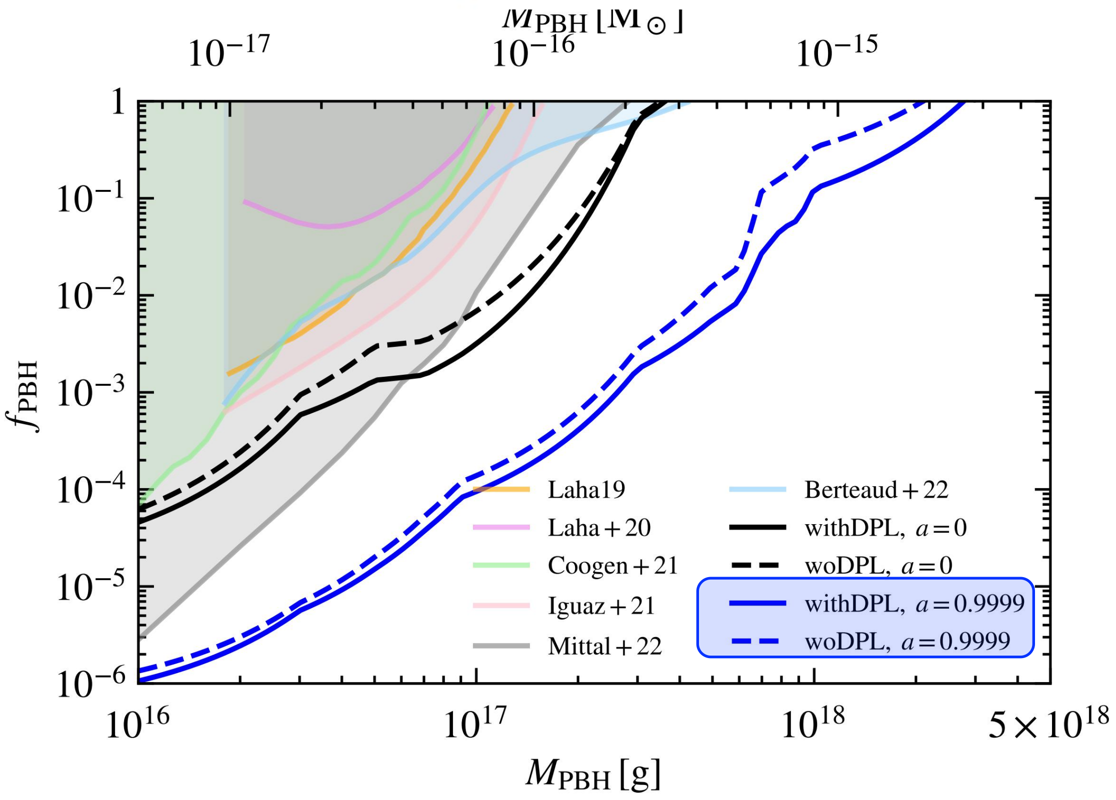
© Xiu-hui Tan and Jun-qing Xia JCAP09(2024)022

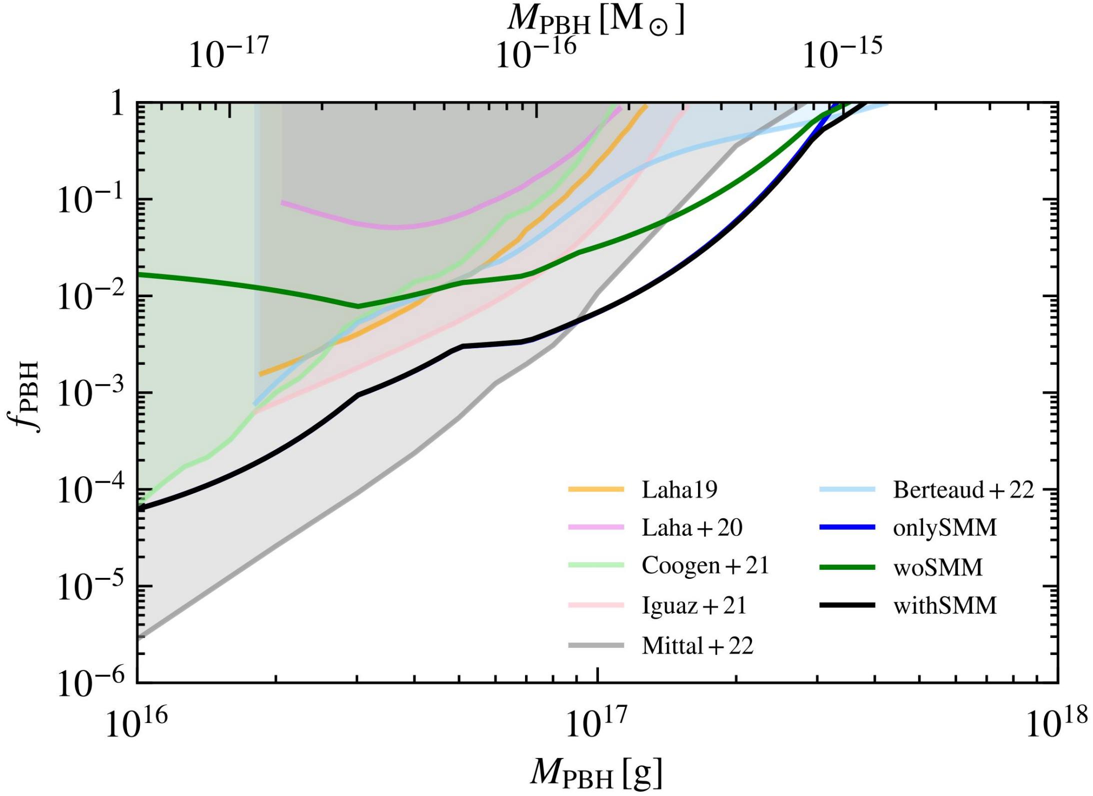
Probing with X/gamma rays

If PBH spins:

$$\chi^2 = \sum \left[\frac{\phi_\gamma^{\rm data} - \phi_\gamma^{\rm PBH}(\theta)}{\sigma^{\rm data}} \right]^2$$

Additionally, as mentioned in Korwar & Profumo (2023), the error bars from the SMM measurement of the isotropic X-ray flux are suspected to be unreliable. Hence, high energy could effect the bounds at low masses.





© Xiu-hui Tan and Jun-qing Xia. 2024 (submitted to ApJ)

Multi-Wavelength detect PBHs

Radio | Microwave | Infrared | Optical/UV | soft/hard X-ray | Gamma-ray | Utral-high

Hawking Radiation, Accretion

CRB, Radio Excess

Magnetic Field,
Accretion in space

Affect LSS evolution

High-redshift data SMD via LSS evolution:

JWST

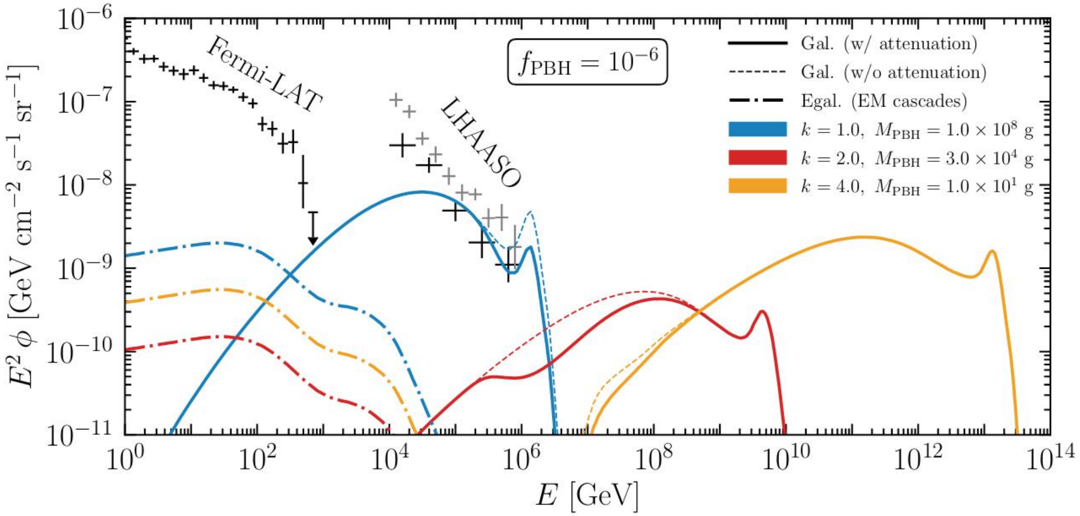
Hawking Radiation

CXB

PBH burst, memory berdened PBH

- H.E.S.S
- HAWC
- VERITAS
- Fermi-LAT
- LHAASO
- …….

Diffuse gamma-ray flux. The different colors correspond to different combinations of the initial PBH mass and the memory-burden parameter k (non-negative integer decay rate entropy), taking fraction is 10^{-6}.



© M. Chianese, arXiv:2504.03838(2025).

Probing PBHs with galaxy clusters

Memory burdend PBHs: *Information loaded in a system resists its decay.*

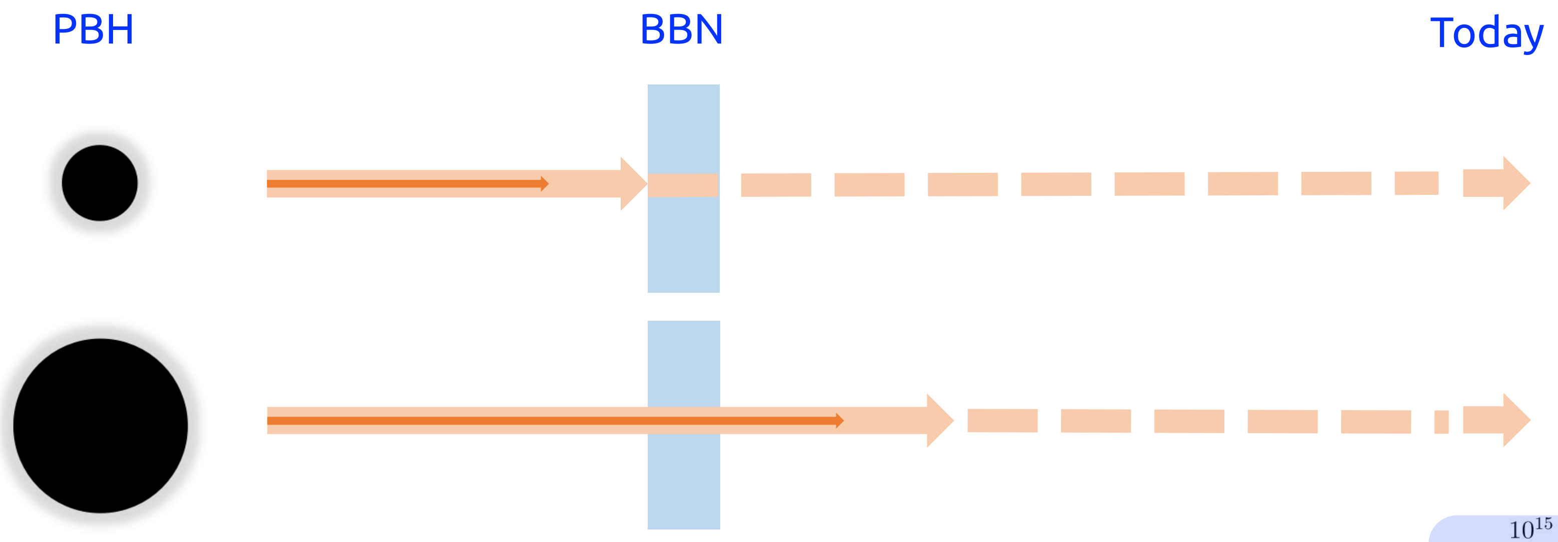
Inside the object, the information is stored in the excitations of gapless modes. At the same time, the asymptotic modes are highly gapped. Due to this, information is maintained internally. This create a back-reaction which resists against the decay of the object.

This gives us a concrete microscopic explanation for why black holes can't just release all their information early in the Hawking evaporation process.

© G. Dvali, etc. arXiv:2405.13117v1

Probing PBHs with galaxy clusters

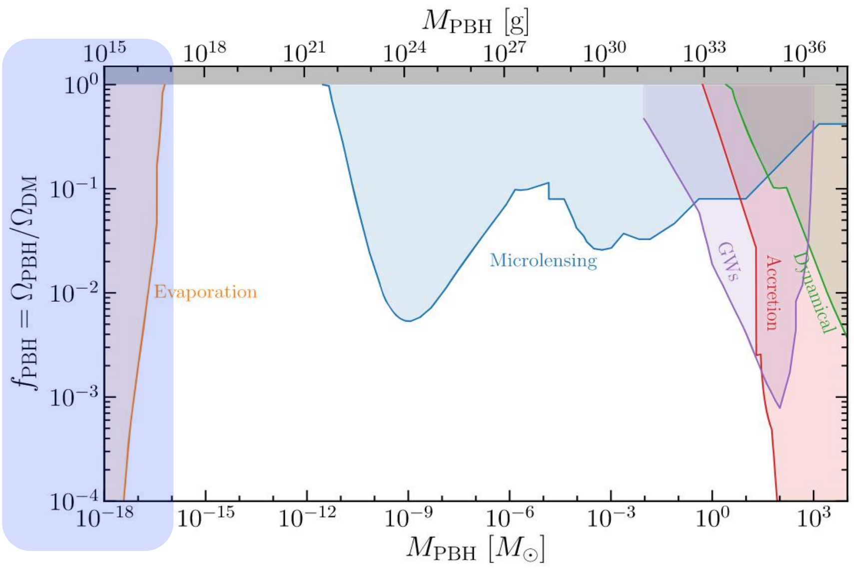
Memory burdend PBHs: *Information loaded in a system resists its decay.*



Semiclassical
Memory Burden

$$\} \; M^{(n=1)} \in [10^6, 10^9]\mathrm{g}$$

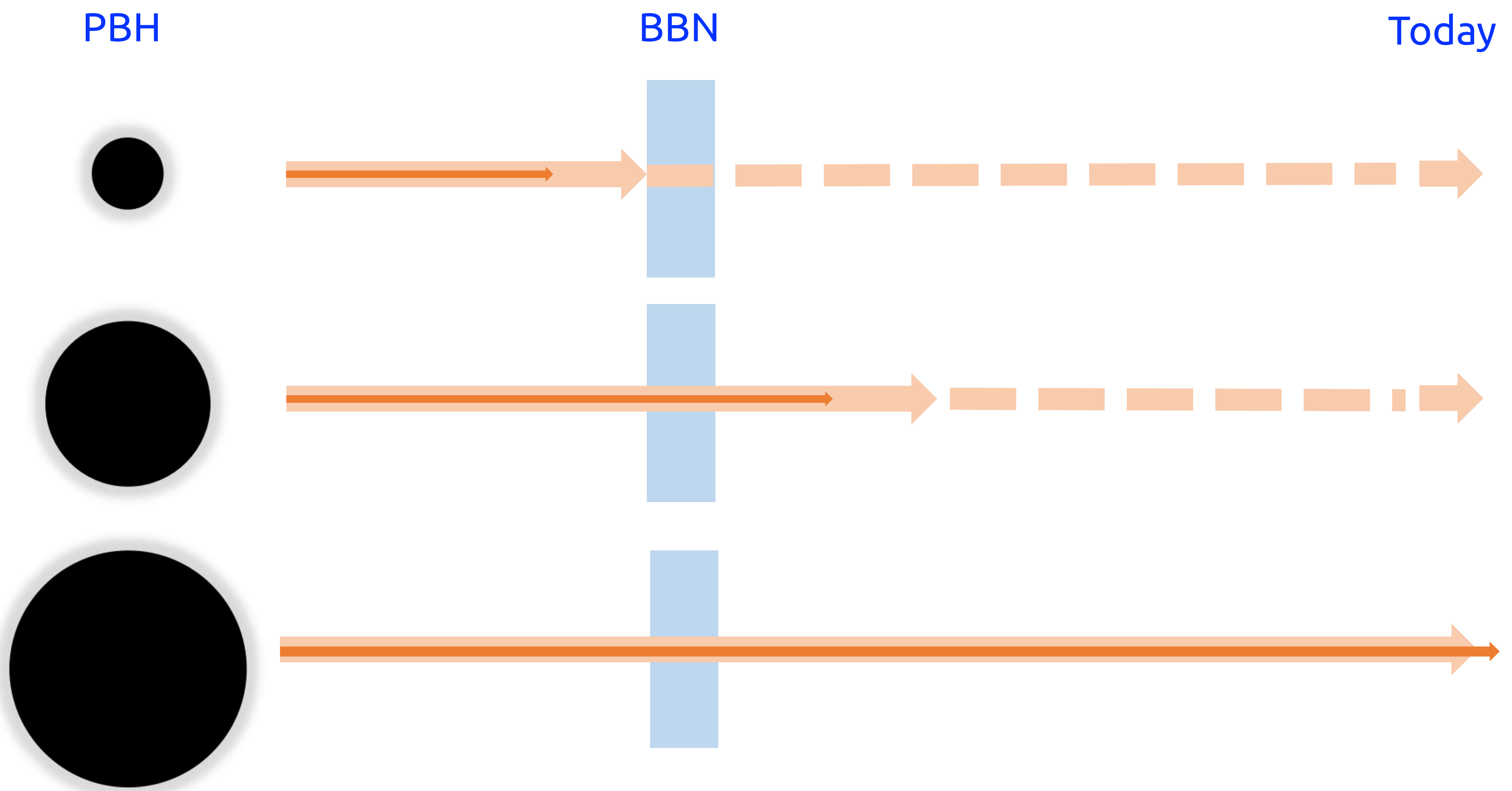
For PBHs in certain mass ranges that don't mess with big bang nucleosynthesis, this memory burden effect means they might not fully evaporate. They could survive as remnants until today, while heavier PBHs keep on evaporating.



© https://github.com/bradkav/PBHbounds

Probing PBHs with galaxy clusters

Memory burdend PBHs: *Information loaded in a system resists its decay.*



Semiclassical
Memory Burden

$\} \; M^{(n=1)} \in [10^6, 10^9]\mathrm{g}$

$M_{\mathrm{PBH}}^{\mathrm{mb}} = qM_{\mathrm{PBH}}$

The effect kicks in when the PBH has lost about half its original mass.

$$t_q = \tau_{\mathrm{PBH}}(1 - q^3) \simeq 4.4 \times 10^{17} \left(\frac{M_{\mathrm{PBH}}}{10^{15}\ \mathrm{g}} \right)^3 \ \mathrm{s}$$

Probing PBHs with galaxy clusters

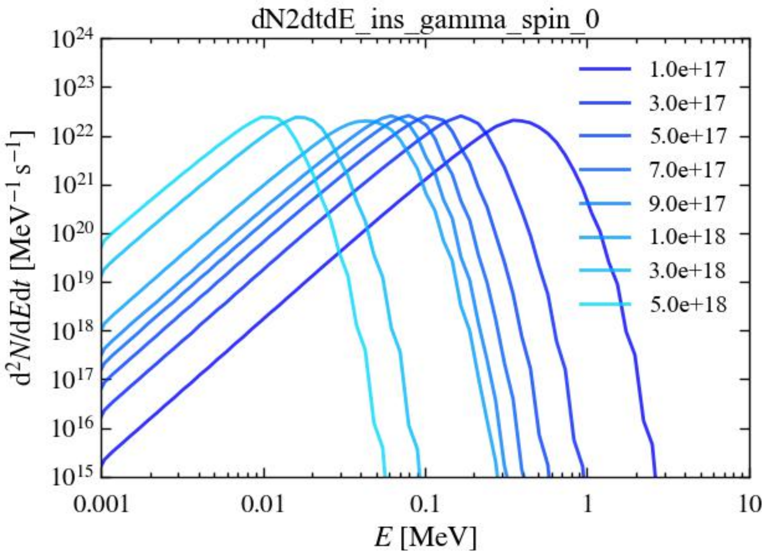
Memory burdend PBHs:

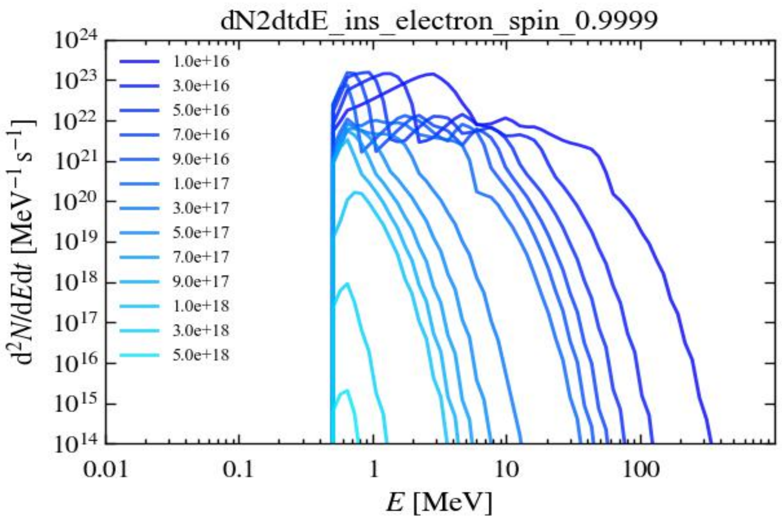
$$S(M_{\rm PBH}) = \frac{4\pi M_{\rm PBH}^2 G k_B}{\hbar c} \approx 2.6\times 10^{10} k_B \left(\frac{M_{\rm PBH}}{1\ {\rm g}}\right)^2$$

$$M_{\rm PBH}^{\rm mb} = q M_{\rm PBH}$$

$$\frac{{\rm d}M_{\rm PBH}^{\rm mb}}{{\rm d}t} = \frac{1}{S(M_{\rm PBH})^k}\frac{{\rm d}M_{\rm PBH}}{{\rm d}t}, k>0$$

$$\frac{{\rm d}^2 N_\gamma^{\rm mb}}{{\rm d}E{\rm d}t} = S(M_{\rm PBH})^{-k}\frac{{\rm d}^2 N_\gamma}{{\rm d}E{\rm d}t}$$





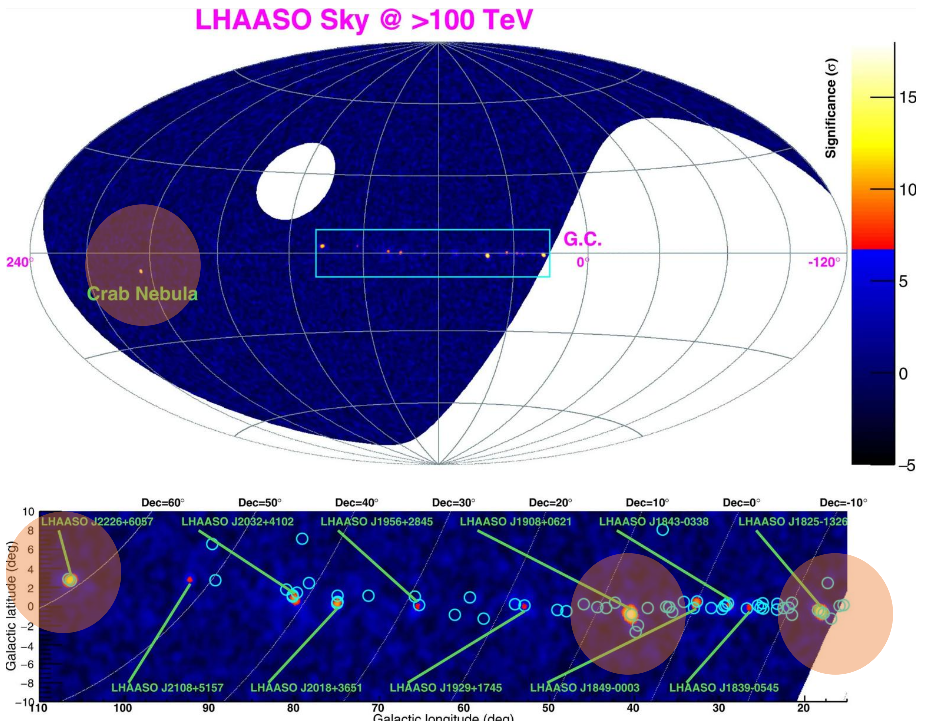
The memory burden suppresses particle production by a factor of S^{-k}, where S is the entropy. This actually helps us detect high-energy photons from even very light PBHs.

Probing PBHs with galaxy clusters

The emissions from memory burdend PBHs for GS:

$$\frac{\mathrm{d}^2\phi_\gamma^{\mathrm{GS}}}{\mathrm{d}E_\gamma \mathrm{d}t} = \frac{f_{\mathrm{PBH}}}{4\pi M_{\mathrm{PBH}}^{\mathrm{mb}}} \frac{\mathrm{d}^2 N_\gamma^{\mathrm{mb}}}{\mathrm{d}E \mathrm{d}t} \mathcal{D}(E_\gamma, \Delta\Omega)$$

$$\mathcal{D}(E_\gamma, \Delta\Omega) = \frac{1}{\Delta\Omega}\int_{\mathrm{ROI}} \mathrm{d}\Omega \int_{\mathrm{l.o.s}} \mathrm{d}s \rho_{\mathrm{DM}}(r) e^{-\tau_{\gamma\gamma}(E_\gamma, s, b, \ell)}$$



GS (Galactic Sources):
Crab Nebula
LHAASO J226+6057
LHAASO J1908+0621
LHAASO J1825-1326

Galactic Center where DM is concentrated. If PBHs are the DM, lots of small PBHs would be along our line of sight. PBH contributes when integrate along this direction.

Probing PBHs with galaxy clusters

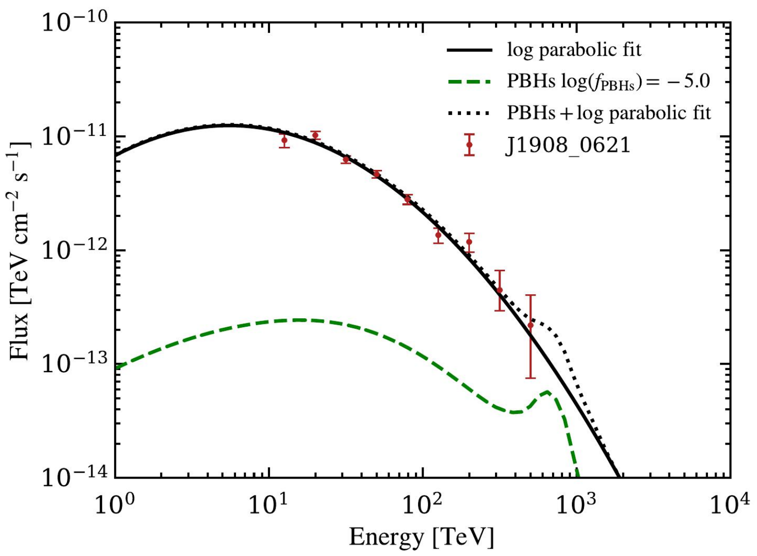
With IC spectrum:

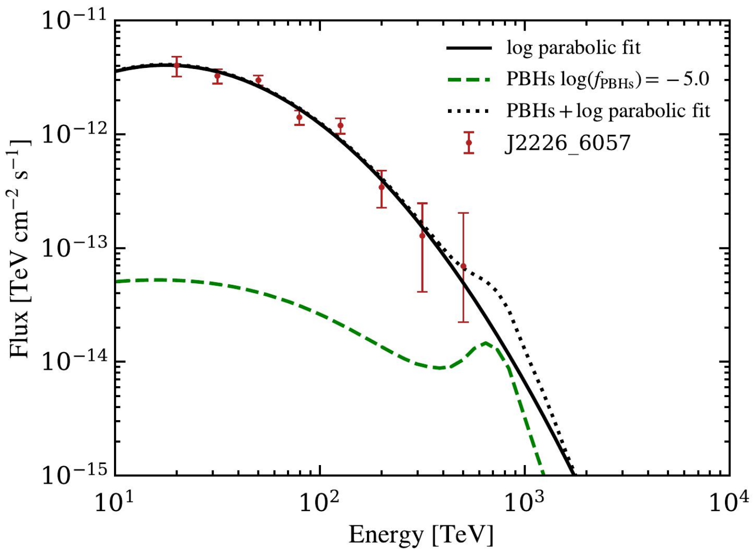
Expected Inverse-Compton (IC) emission spectrum from accelerated electrons within a magnetized nebula. This spectrum is described by a log-parabolic function.

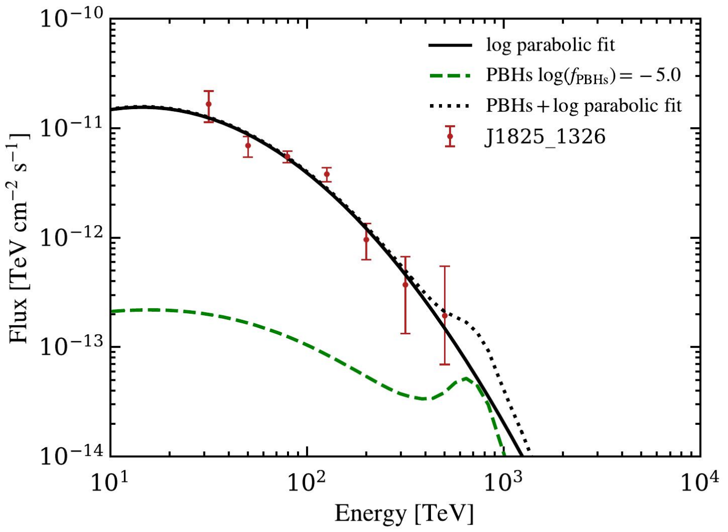
$$\frac{d\phi_\gamma^{IC}}{dE_\gamma} = F_0 \left(\frac{E}{E_0}\right)^{-a-b\log(E/E_0)}$$

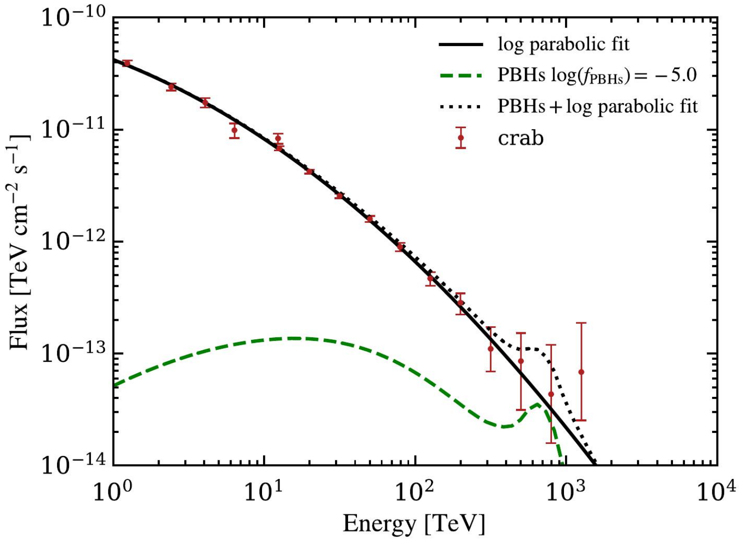
$$\chi^2 = \sum_{i,j} \left[\frac{\phi_{i,j}^{predict}(\theta) - \phi_{i,j}^{data}}{\sigma_{i,j}^{data}}\right]^2$$

© Xiu-hui Tan and Yu-feng Zhou, arXiv:2505.19857







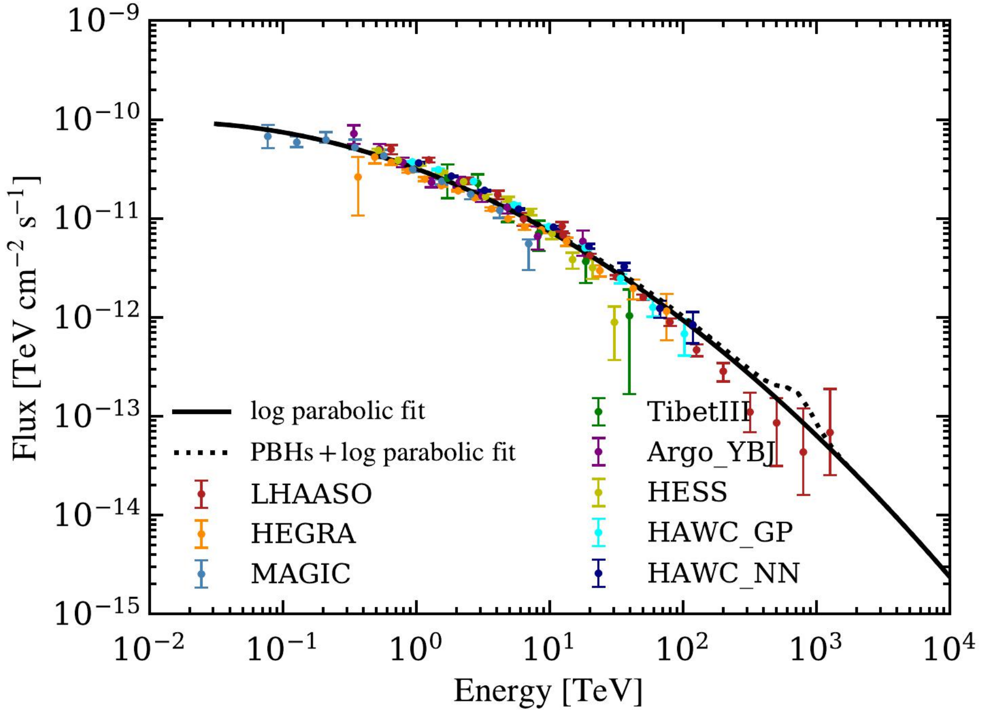


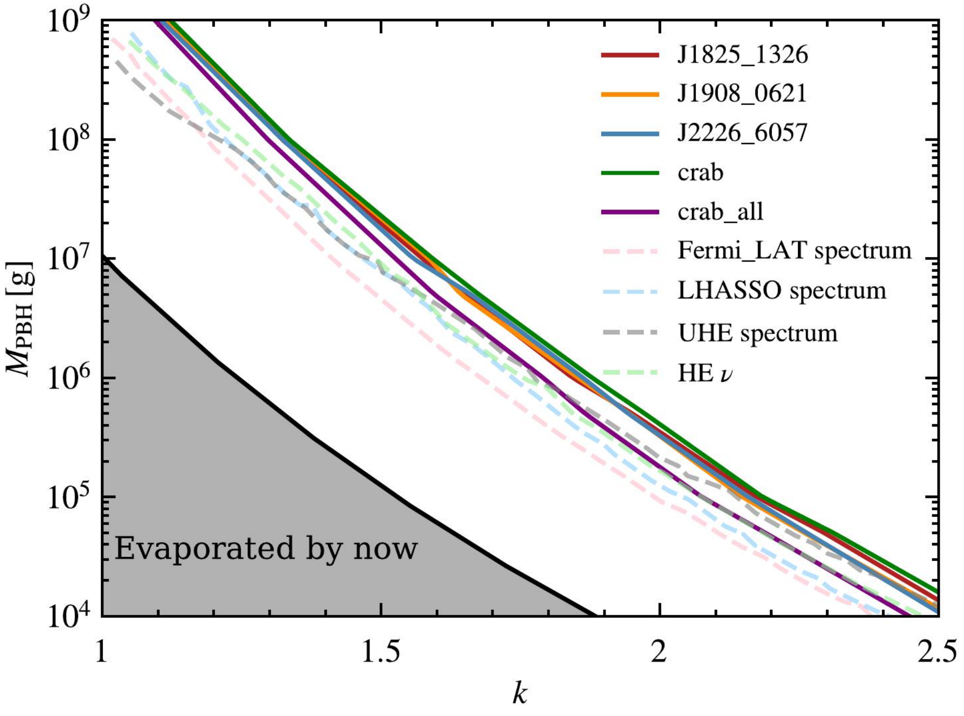
Probing PBHs with galaxy clusters

With more crab data:

$$\chi^2 = \sum_{i,j} \left[\frac{\phi_{i,j}^{\text{predict}}(\theta) - f_j^{n-1} \phi_{i,j}^{\text{data}}}{f_j^{n-1} \sigma_{i,j}^{\text{data}}} \right]^2 + \sum_j \left[\frac{(f_j - 1)}{\delta f_j} \right]^2$$

When fix fraction 1 for the entropy index k, implying that the region above the lines corresponds to PBHs that can fully constitute the DM component of the Universe and have not yet evaporated.



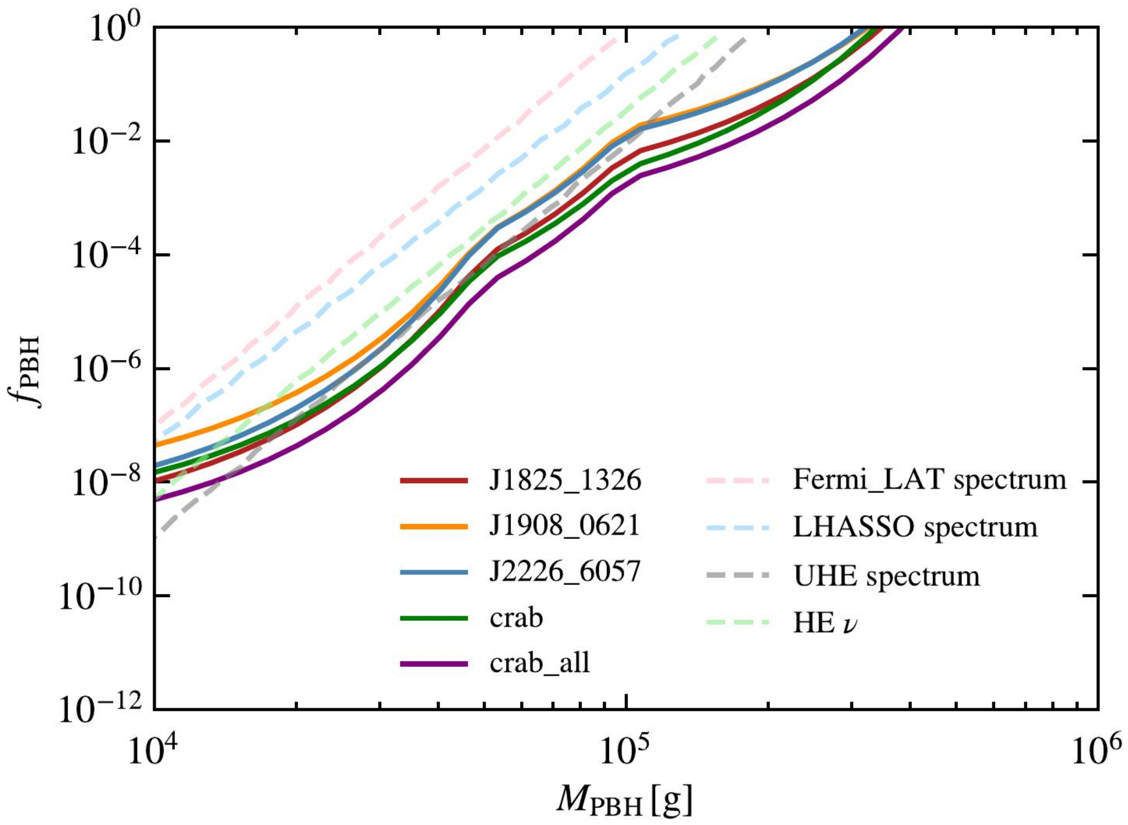


© Xiu-hui Tan and Yu-feng Zhou, arXiv:2505.19857

Probing PBHs with galaxy clusters

The bounds at the 95% C.L:

In the farcion and mass of PBHs plane of light PBHs resulting from the LHAASO observations of the Crab Nebula, LHAASO J2226+6057, LHAASO J1908+0621, and LHAASO J1825-1326.



© Xiu-hui Tan and Yu-feng Zhou, arXiv:2505.19857

Conclusions & Coulooks

- ○PBHs can be DM in some mass window.
- ○Memory burdened effect are particularly important for lighter PBHs.
- ○Tighter constraints derived in these two works.
- ○Multi-wavelength analysis might help constraint PBHs.
- ○Mass function model, astrophycial processes, DM profiles, etc, need to be comfirmed.
- ○Multi-messenger analysis may break degeneracy from non-DM components in the future.

Thank you!