

Primordial Black Hole as Dark matter with γ -ray emissions

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Based on *Xiu-Hui Tan et al 2022 ApJL 939 L15*



Revisiting Primordial Black hole

Why a better DM candidate:

- Offer over-densities in early Universe
© Zel'dovich and Novikov; Hawking
- $M > 10^{15}$ g: non-baryonic and still exist
- Not rival against particle DM
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- Candidate of DM within the Standard Model
- More observable signals:
Gravitational waves , lensing

Mechanisms of Generation:

1. Primordial inhomogeneities
2. Collapse from scale-invariant fluctuations
3. Collapse in a matter-dominated era
4. Collapse from inflationary fluctuations
5. Collapse at QCD phase transition
6. ...

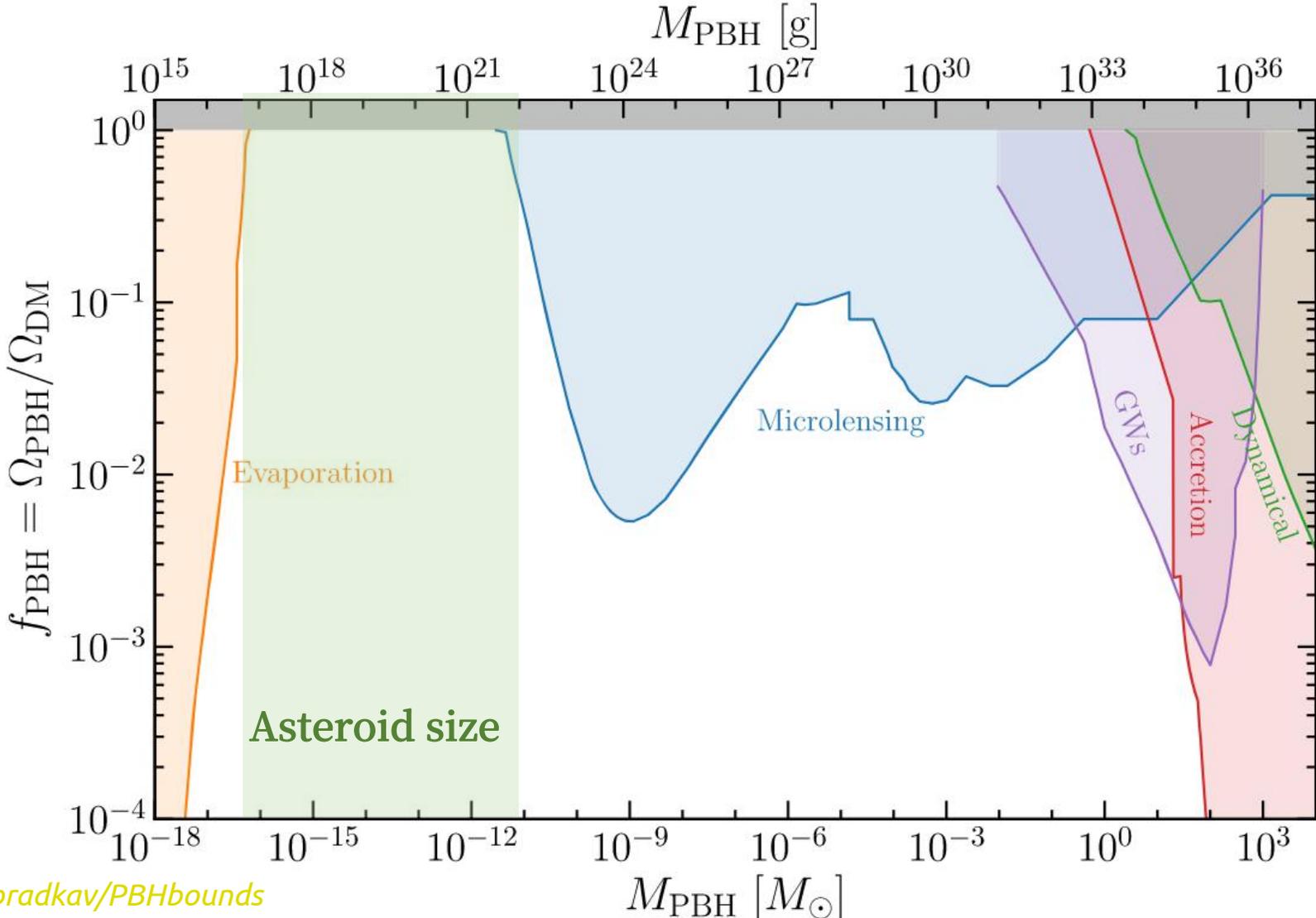
- **Astrophysical black holes:**
Stars much heavier than Sun may collapse

$$> M_{\odot} \approx 2 \times 10^{30} \text{kg}$$

- **Primordial black holes:**
Formed very early of the Universe
Asteroid size to $10^5 M_{\odot}$

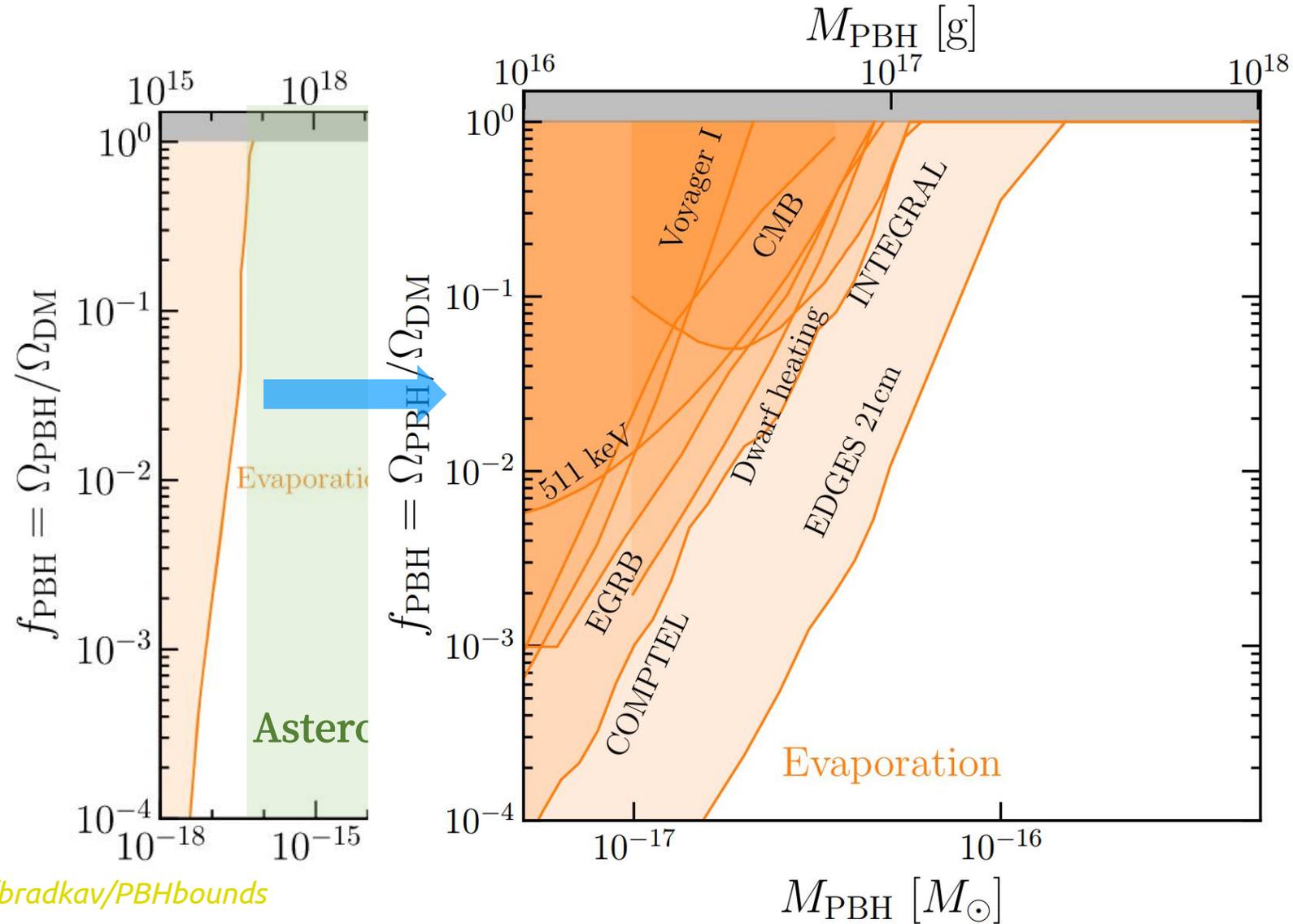
$$10^{15} \text{kg} \sim 10^{35} \text{kg}$$

State-of-the-art for PBHs



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

State-of-the-art for PBHs

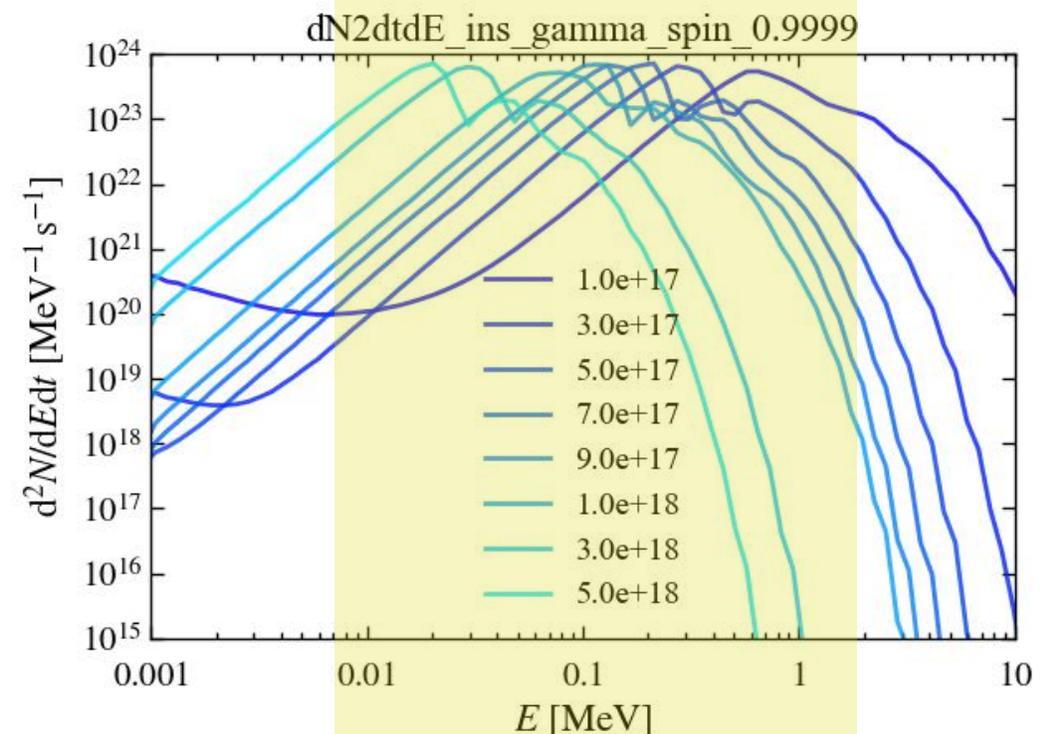
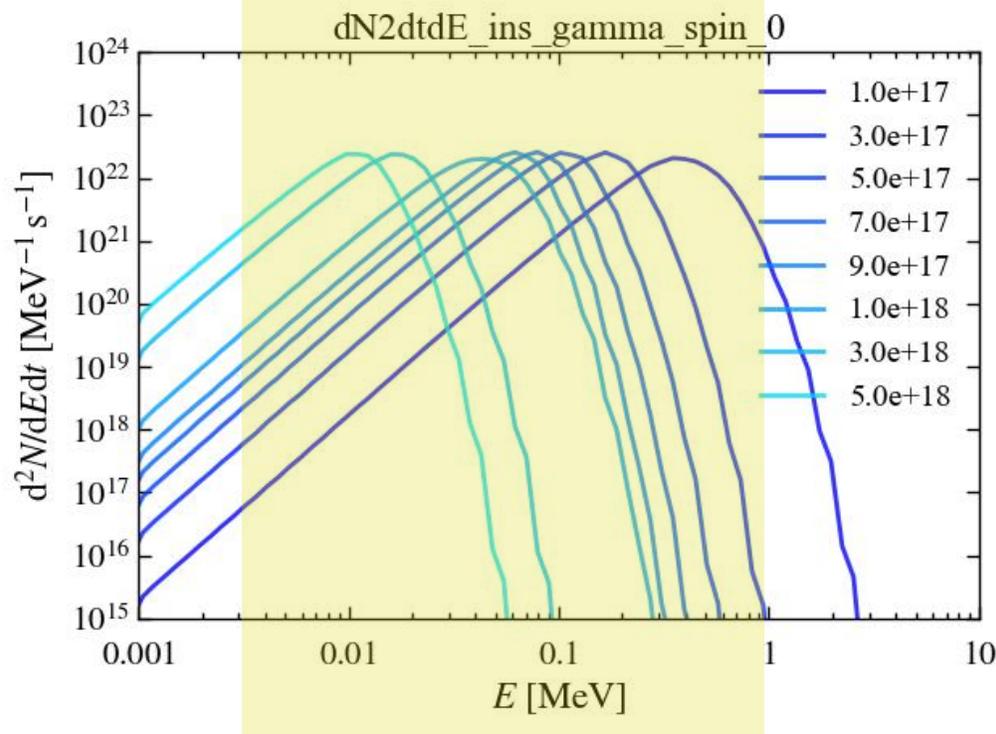
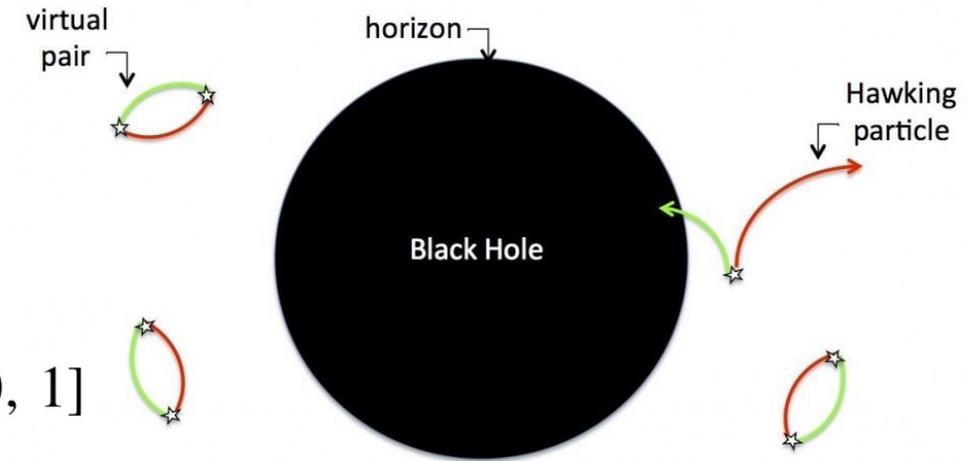


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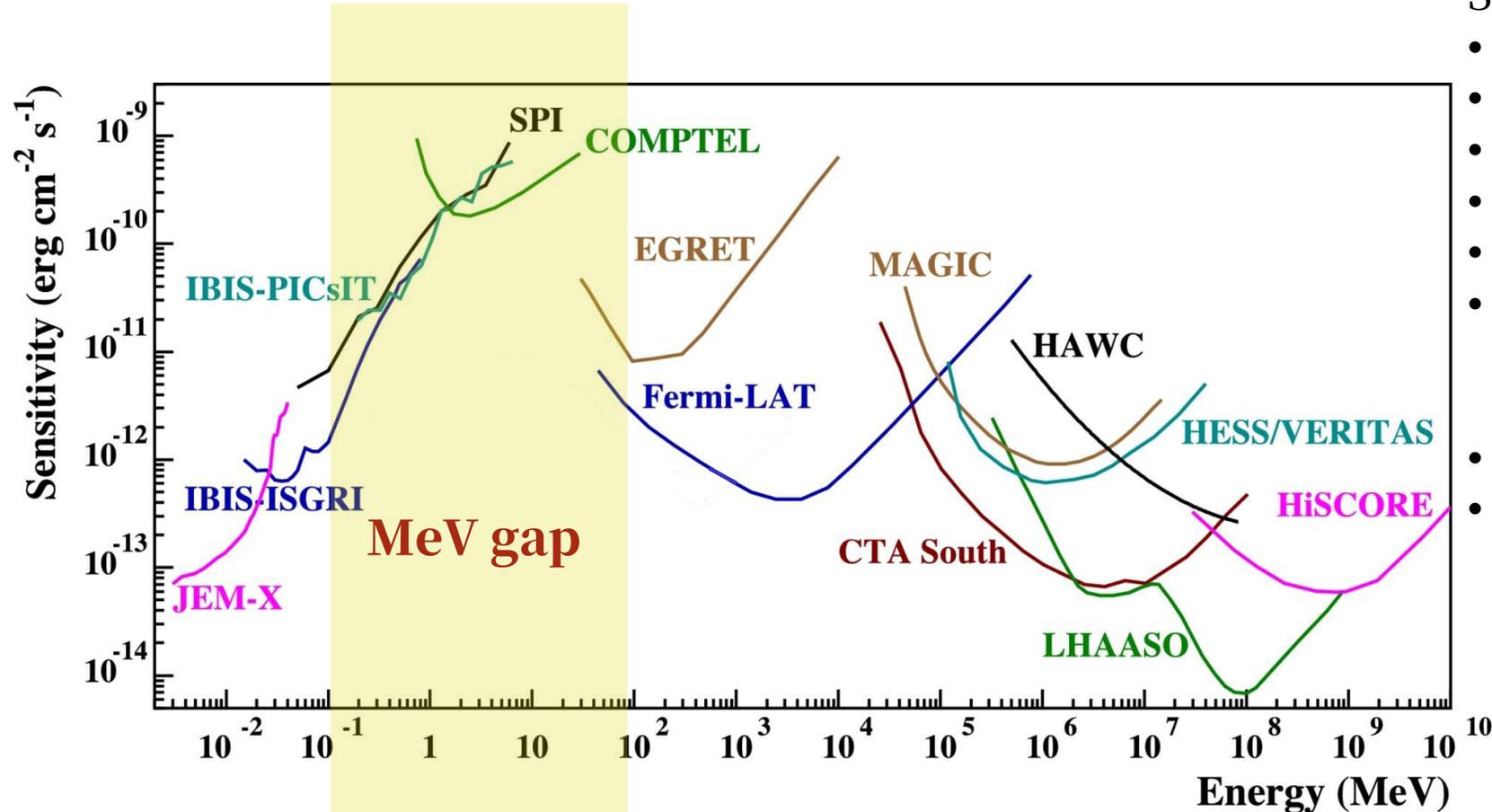
Gamma-ray from PBH

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

$$T_{\text{BH}} = \frac{1}{8\pi G_N M} \approx 1.06 \text{ MeV} \left(\frac{10^{16} \text{ gm}}{M} \right), \quad a_* \equiv J/GM_{\text{PBH}}^2 \in [0, 1]$$



Gamma-ray Observatory



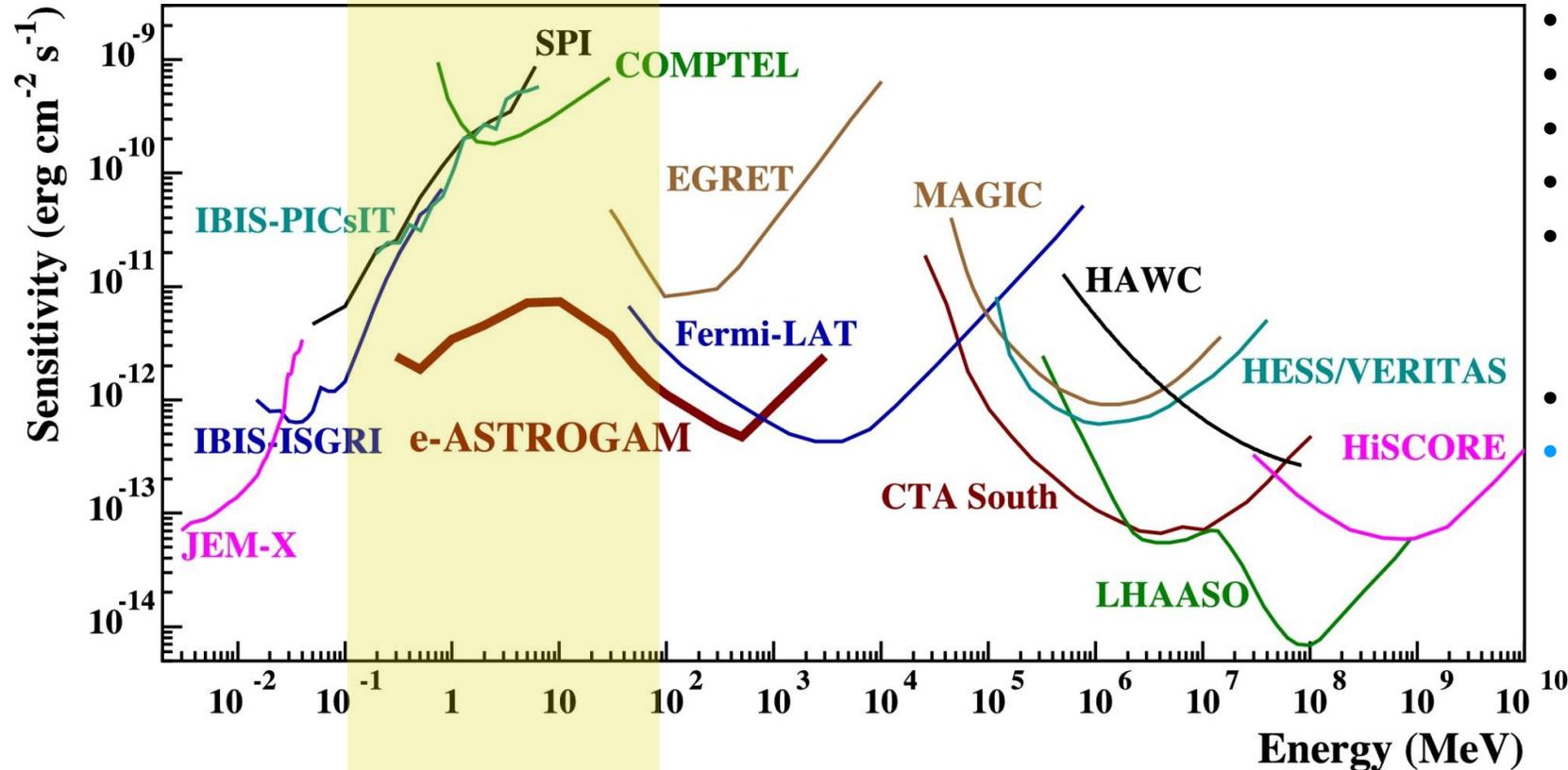
Some future MeV detectors!

- COSI: 0.2-5 MeV
- AMEGO: 25 keV - 1 GeV
- GECOO: 100 keV - 10 MeV
- NuSTAR: 2-79 keV
- MeVCube: 100 keV - 1 MeV
- Advanced particle astrophysics telescope: 300 keV - 10 MeV, 20 MeV - 1 TeV
- ...
- e-ASTROGAM: 150 keV - 3 GeV

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Gamma-ray Observatory

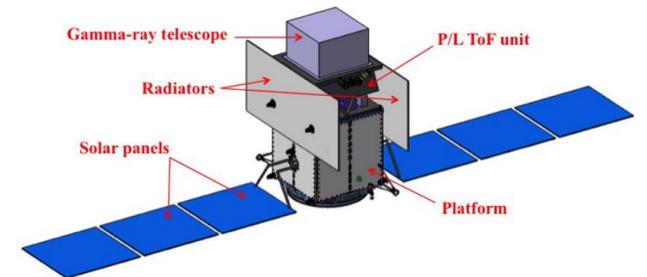
Seems a lot!? But if we consider Asteroid size...



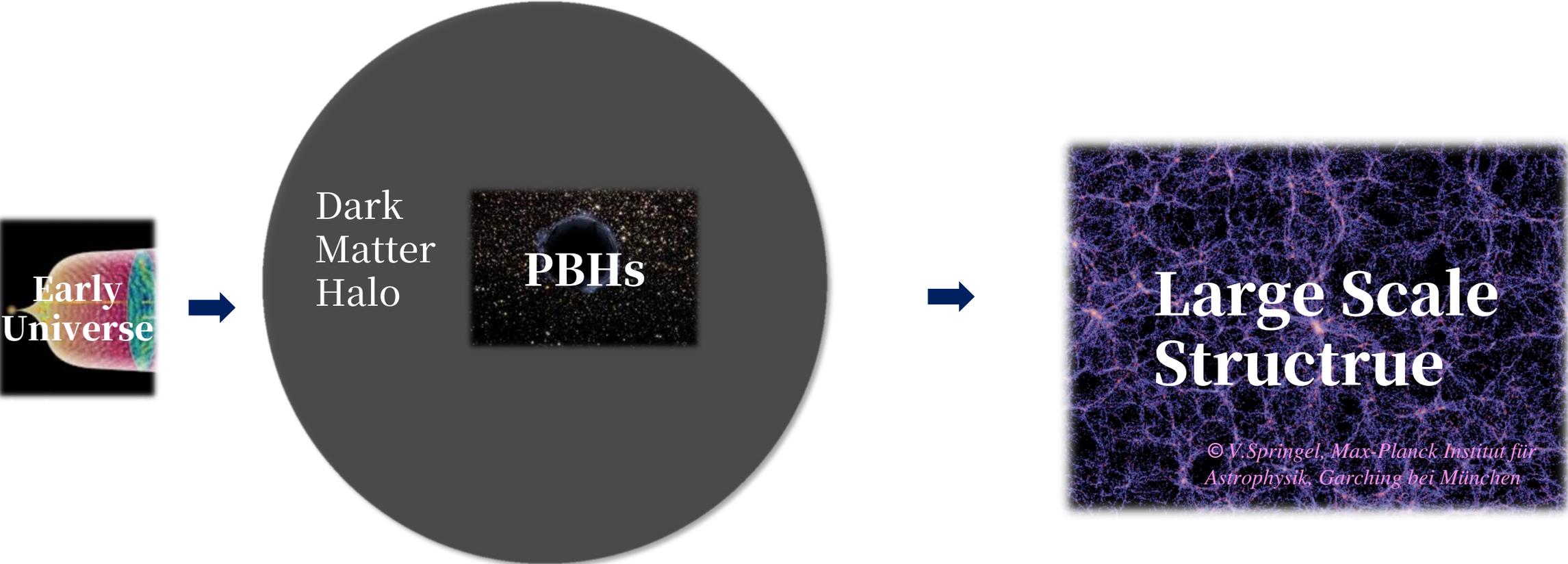
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- **e-ASTROGAM: 150 keV - 3 GeV**

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How to cross-correlate the signal?



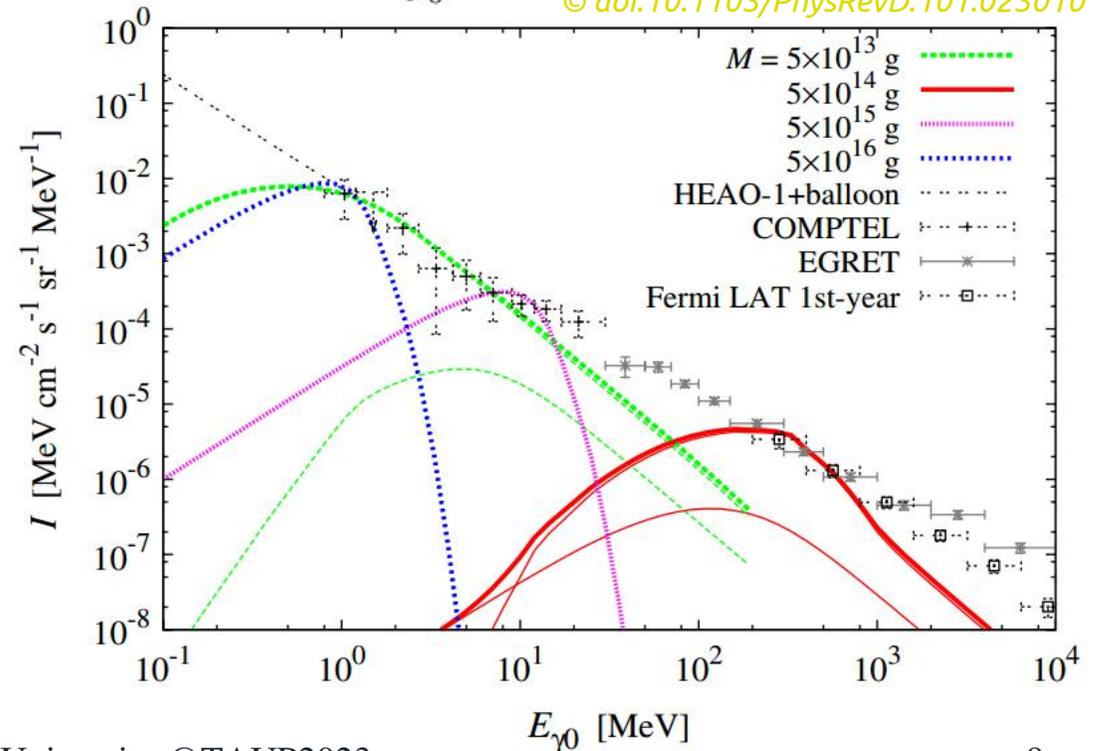
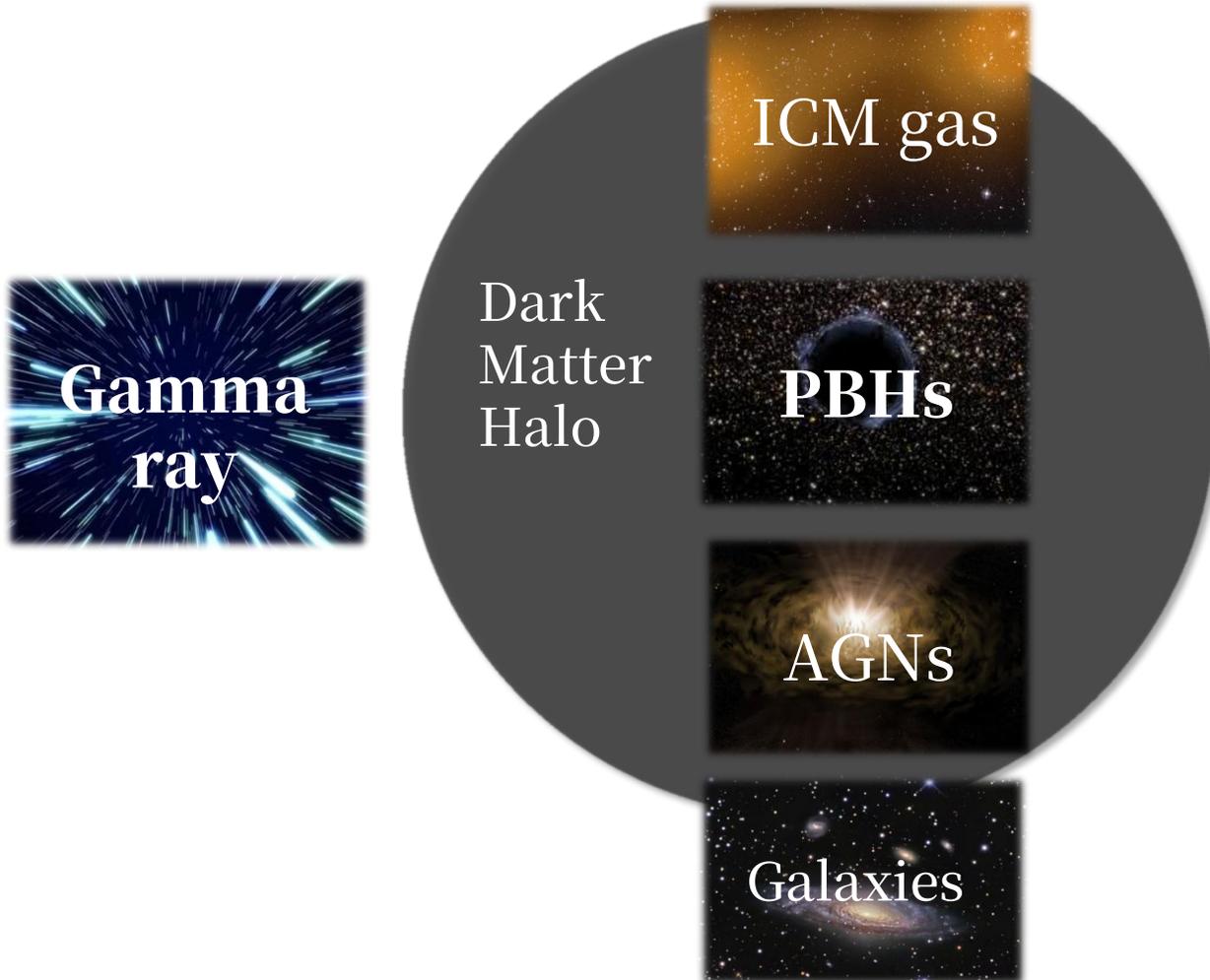
How to cross-correlate the signal?

$$W_{\text{PBH}}(\chi) = \frac{f_{\text{PBH}} \Omega_{\text{DM}} \rho_c}{4\pi M_{\text{PBH}}} \times \int_{\delta E} \int_{t_{\text{min}}}^{t_{\text{max}}} \left[\frac{d^2 N}{dt dE_\gamma} \right]_{\text{tot}} E_\gamma(\chi) e^{-\tau[\chi, E_\gamma(\chi)]} dE_\gamma dt$$

$$W_X(E, z) = \int_{L_{X,\text{min}}}^{L_{X,\text{max}}(F_{\text{sens}}, z)} \frac{dL_X}{L_X} \Phi_X(L_X, z) \mathcal{L}_X(E, z)$$

$$I_X(E) = \int_0^\infty d\chi W_X(E, z)$$

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How to cross-correlate the signal?

$$t_{\min} = 380,000 \text{ yr}$$

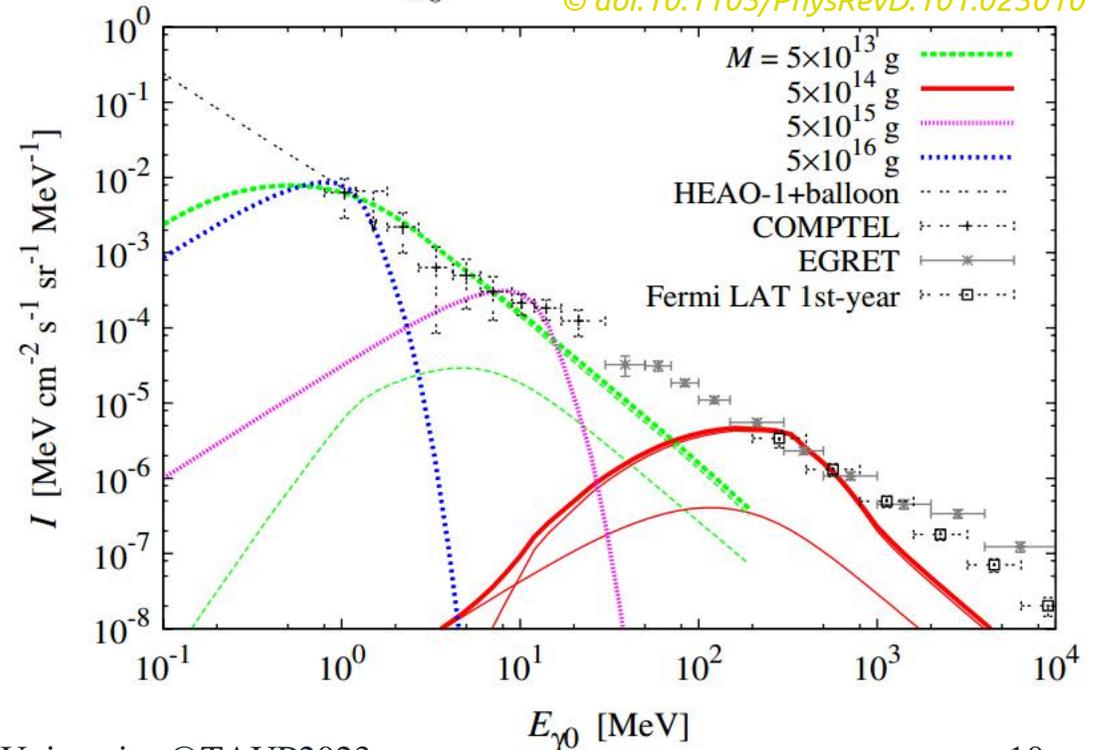
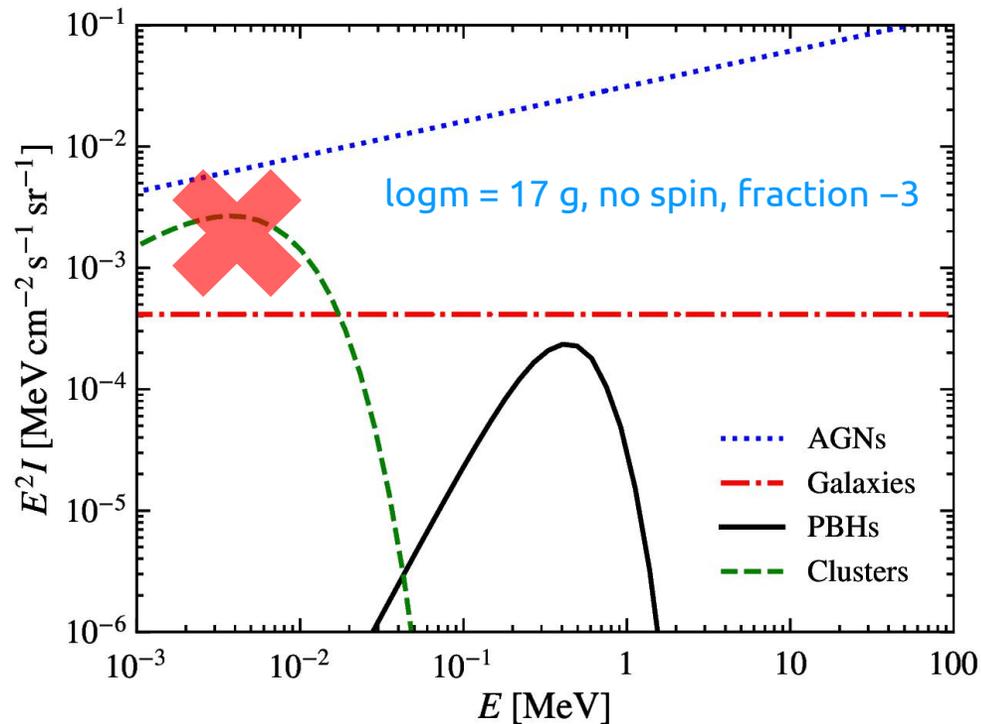
$$t_{\max} = \min(t(M), t_0)$$

$$W_{\text{PBH}}(\chi) = \frac{f_{\text{PBH}} \Omega_{\text{DM}} \rho_c}{4\pi M_{\text{PBH}}} \times \int_{\delta E} \int_{t_{\min}}^{t_{\max}} \left[\frac{d^2 N}{dt dE_\gamma} \right]_{\text{tot}} E_\gamma(\chi) e^{-\tau[\chi, E_\gamma(\chi)]} dE_\gamma dt$$

$$W_X(E, z) = \int_{L_{X, \min}}^{L_{X, \max}(F_{\text{sens}}, z)} \frac{dL_X}{L_X} \Phi_X(L_X, z) \mathcal{L}_X(E, z)$$

$$I_X(E) = \int_0^\infty d\chi W_X(E, z)$$

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How to cross-correlate the signal?

Other Tracers: with Same Physical origin!

CMB
Shear

Galaxy
Counts

Cosmic
Shear

21cm
HI

$$W_\kappa(z) = \frac{3}{2} \Omega_m H_0^2 \frac{1+z}{H(z)} \frac{\chi(z)}{c} \left[\frac{\chi_{\text{cmb}} - \chi(z)}{\chi_{\text{cmb}}} \right]$$

$$C_\ell^{\kappa, \text{PBH}} = \int \frac{dz}{c} \frac{H(z)}{\chi^2(z)} W_\kappa(z) W_{\text{PBH}}(z) P_{\kappa, \text{PBH}}(k = \ell/\chi, z)$$

$$P_{ij}(k) = P_{ij}^{1\text{h}}(k) + P_{ij}^{2\text{h}}(k)$$

where

$$P_{ij}^{1\text{h}}(k) = \int dM' \frac{dn}{dM'} \tilde{f}_i(k|M') \tilde{f}_j(k|M')$$

$$P_{ij}^{2\text{h}}(k) = \left[\int dM'_1 \frac{dn}{dM'_1} b_i(M'_1) \tilde{f}_i(k|M') \right] \times \left[\int dM'_2 \frac{dn}{dM'_2} b_i(M'_2) \tilde{f}_i(k|M') \right] P^{\text{lin}}(k)$$

- **b: Bias**

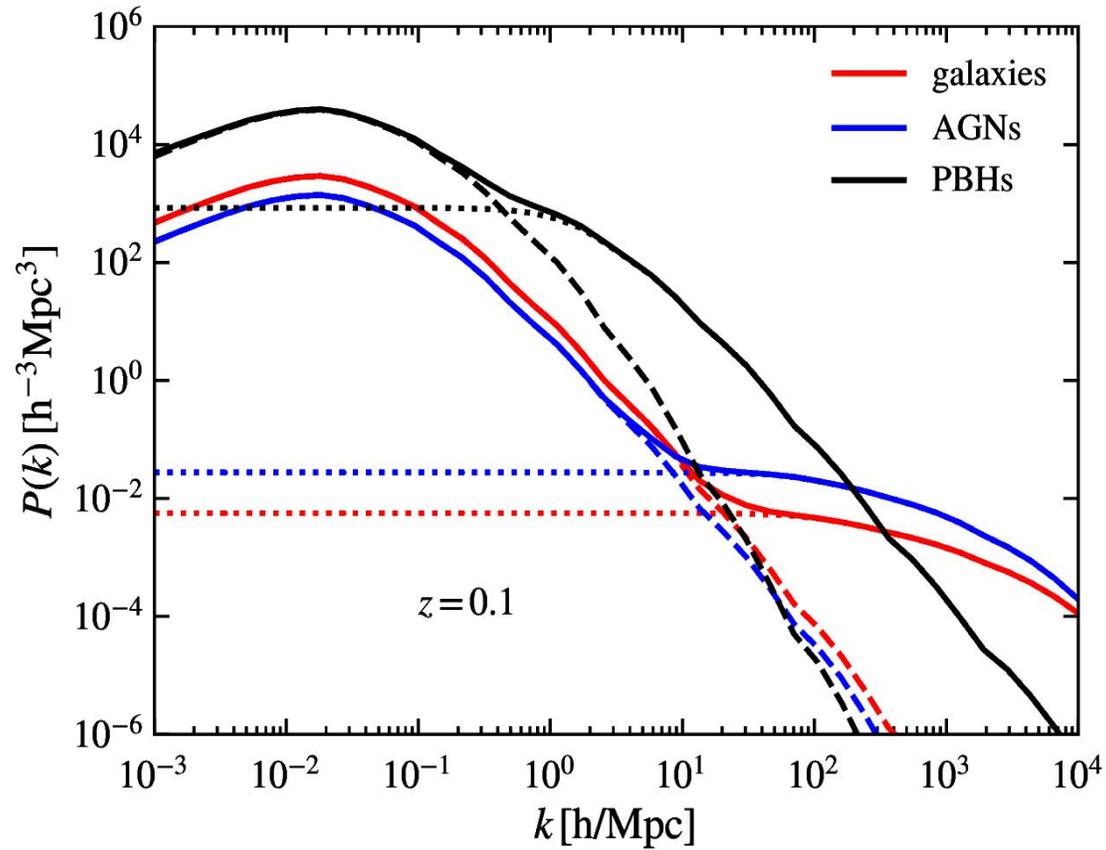
© Sheth, R. K., & Tormen, G. 1999, MNRAS, 308, 119

- **dn/dM (mass function): variance of the smoothed density contrast: adiabatic + isocurvature**

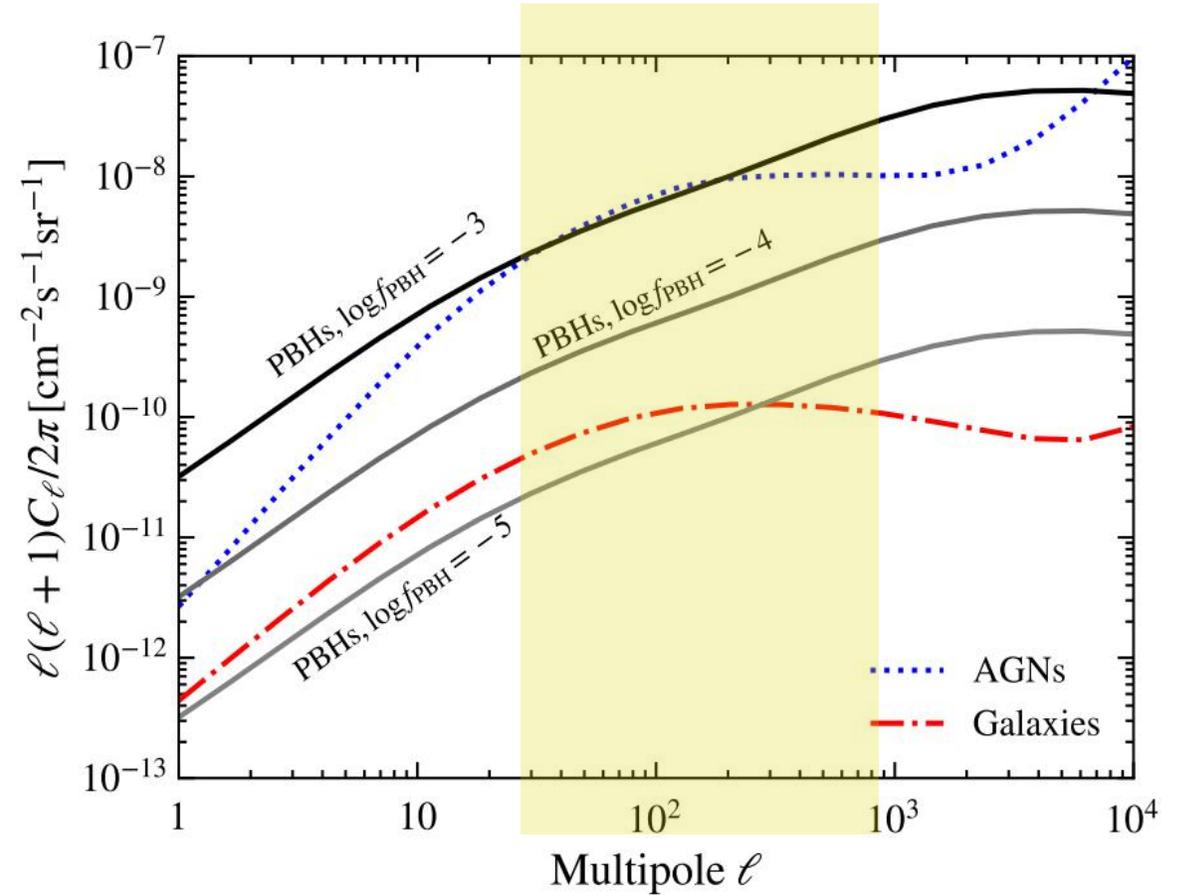
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- **Monochromatic number density distribution**
- **NFW halo profile**

Theoretical Cross-Correlation Results



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$\log m = 17 \text{ g, no spin}$

Forecast by e-ASTROGAM

$$\chi^2 = \sum_{\ell} (C_{\ell}^{\gamma, \kappa} \Gamma_{\ell \ell'}^{-1} C_{\ell'}^{\gamma, \kappa})$$

$$\Gamma_{\ell, \ell'}^{\gamma, \kappa} = \frac{\delta_{\ell \ell'}}{(2\ell + 1) f_{\text{sky}} \Delta \ell}$$

$$\times [C_{\ell}^{\gamma \kappa} C_{\ell'}^{\gamma \kappa} + (C_{\mathcal{N}}^{\gamma} + \sqrt{C_{\ell}^{\gamma} C_{\ell'}^{\gamma}})(C_{\mathcal{N}}^{\kappa} + C_{\ell}^{\kappa})]$$

$$C_{\mathcal{N}}^{\gamma} = 4\pi f_{\text{sky}} \langle I_{\text{X}} \rangle^2 N_{\text{X}}^{-1} W_{\ell}^{-2}$$

$$N_{\text{X}} = \langle I_{\text{X}} A_{\text{eff}} \rangle t_{\text{obs}} \Omega_{\text{FoV}}$$

$$W_{\ell} = \exp(-\sigma_b^2 \ell^2 / 2)$$

e-ASTROGAM: 2030s & CMB-S4

150 keV to 3 GeV

f_{sky} (Sky coverage): 23%

Field of view: 2.9 sr

Flux sensitivity: $1.1 \times 10^{-12} \text{ erg cm}^{-1} \text{ s}^{-1}$

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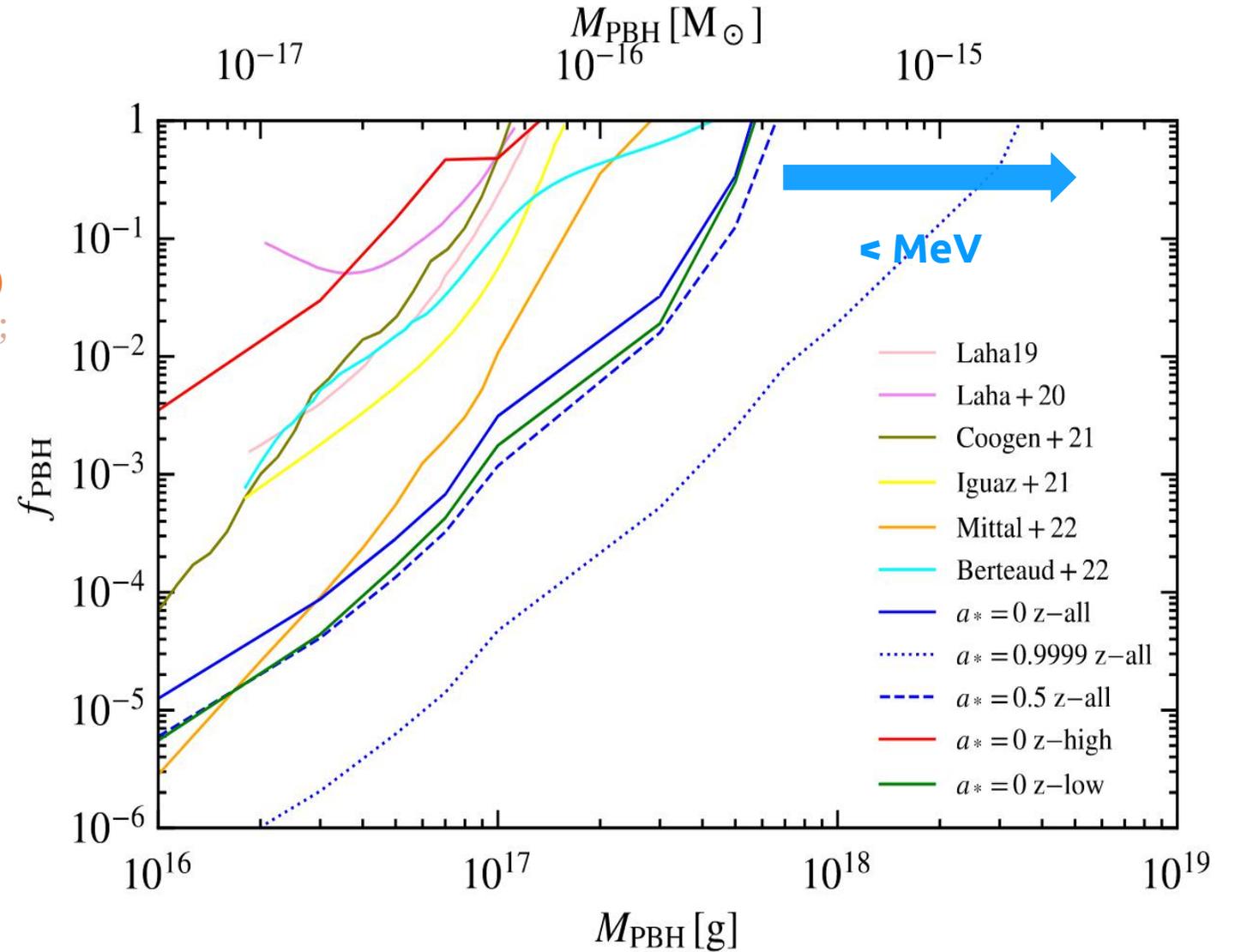
The Best Energy Performance E_{peak} (keV) and Angular Resolution σ_b Selection Used for Different Masses of PBHs

M_{PBH} (g)	1×10^{16}	3×10^{16}	5×10^{16}	7×10^{16}	1×10^{17}	3×10^{17}	5×10^{17}	7×10^{17}	1×10^{18}	3×10^{18}	5×10^{18}
$a_* = 0$	4690	2234	1204	831	448	213	150	102	50	23	12
$a_* = 0.5$	4690	2234	1362	940	507	213	150	102	50	23	12
$a_* = 0.9999$	7690	3662	2234	1541	831	350	213	167	79	38	20
σ_b	0°.8	0°.8	1°.1	1°.5	1°.5	2°.5	4°.3	4°.3	4°.3	4°.3	4°.3

Constraint Results

- the central region of the galaxy (Coogan et al. 2021; olive line)
- the 21 cm absorption signal of the EDGES experiment (Mittal et al. 2022; orange line)
- the Galactic center 511 keV line (Laha 2019; pink line)
- the INTEGRAL satellite (SPI) results (Laha et al. 2020; purple line)
- the cosmic X-ray background (Iguaz et al. 2021; yellow line)
- diffuse soft gamma-ray emission toward the inner galaxy by the SPI data (Berteaud et al. 2022; cyan line)

z-all: [0, 10]
 z-low: [0, 1]
 z-high: [1, 10]



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Take home messengers

- PBHs as a Dark Matter candidates mass window: **asteroid mass $10^{17}\sim 10^{23}$ gram**
- Redshift 1-10 dominated by **Astrophysical sources**
- **Less or Around 1 MeV** of Gamma ray data more related to asteroid mass of PBHs
- **More data for Gamma-ray:** Cluster, Galactic Centre, dwarf spheroidal galaxies
- **More tracers for cross-correlation: Galaxy counts, Cosmic Shear, Stochastic Gravitational Wave Background, 21cm HI**
- Way to avoid other signal original sources are challenges
- More perspectives: other radiation process, Scalar induced gravitational waves



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Thank you!

