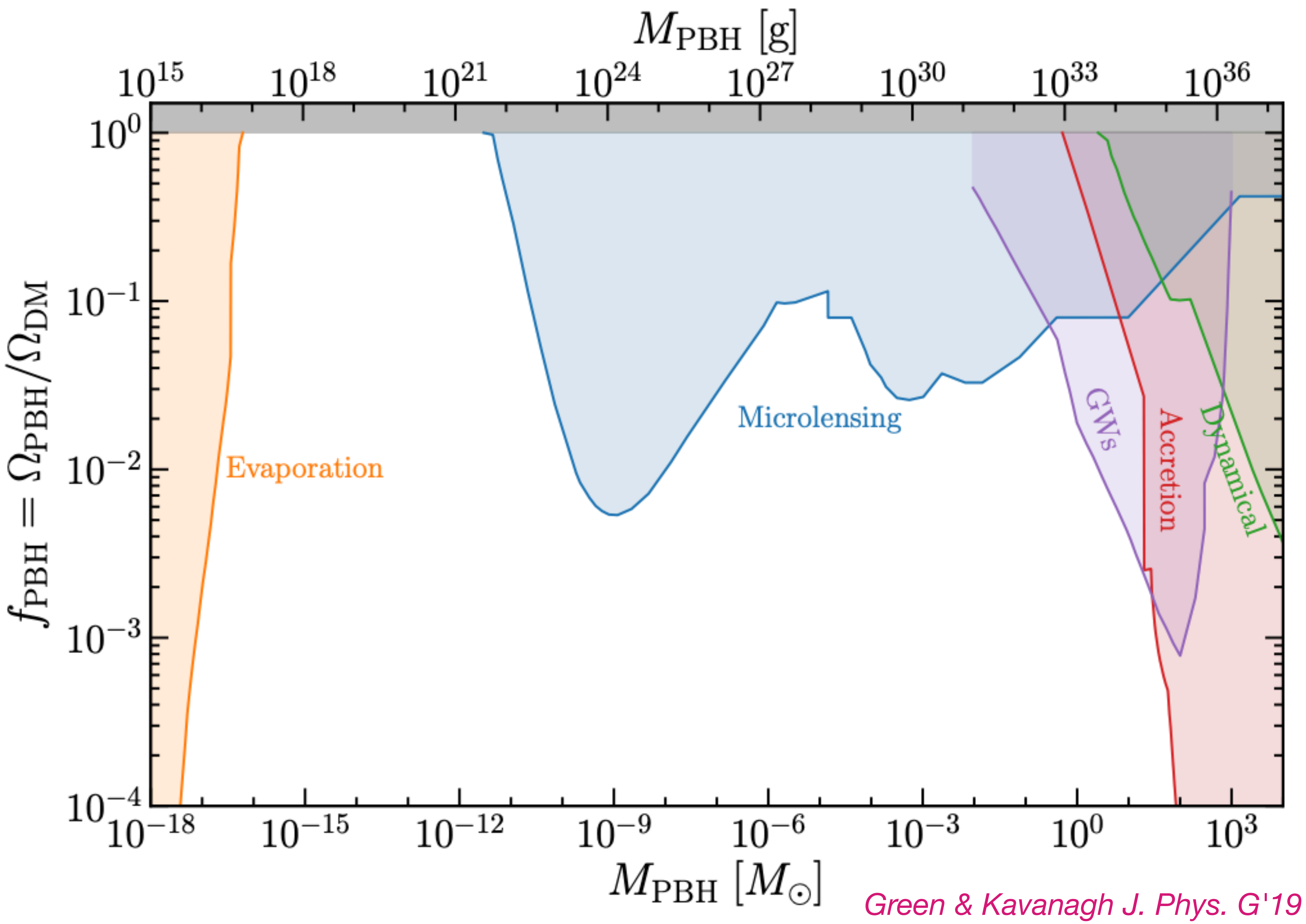
Probing PBHs with high-energy astrophysics

New Horizons in Primordial Black Holes Physics, NEHOP
Naples, 21.06.23

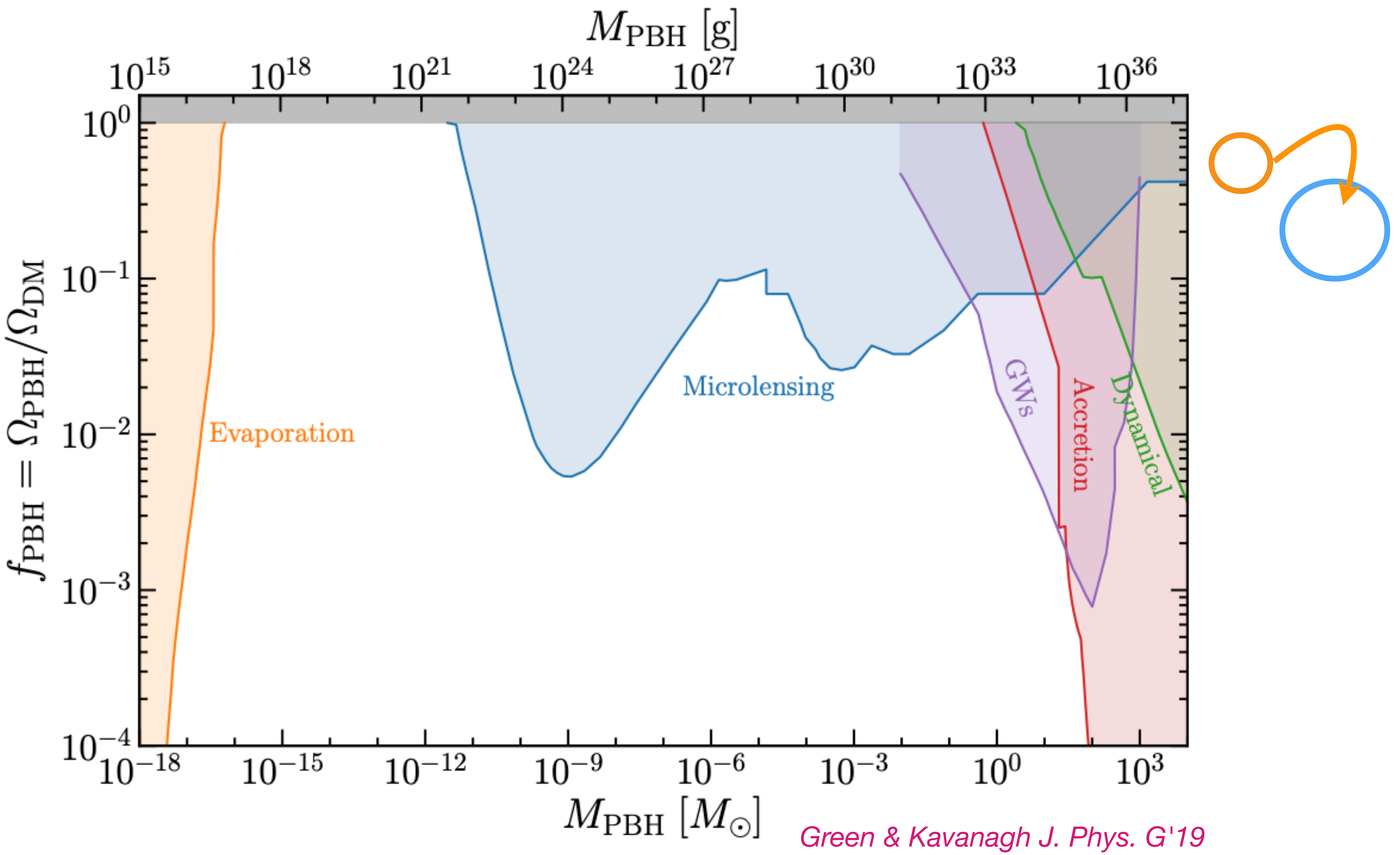
Francesca Calore
AstroCosmo Group @ LAPTh

Constraining primordial black holes (PBHs)



Green & Kavanagh J. Phys. G'19

Constraining primordial black holes (PBHs)



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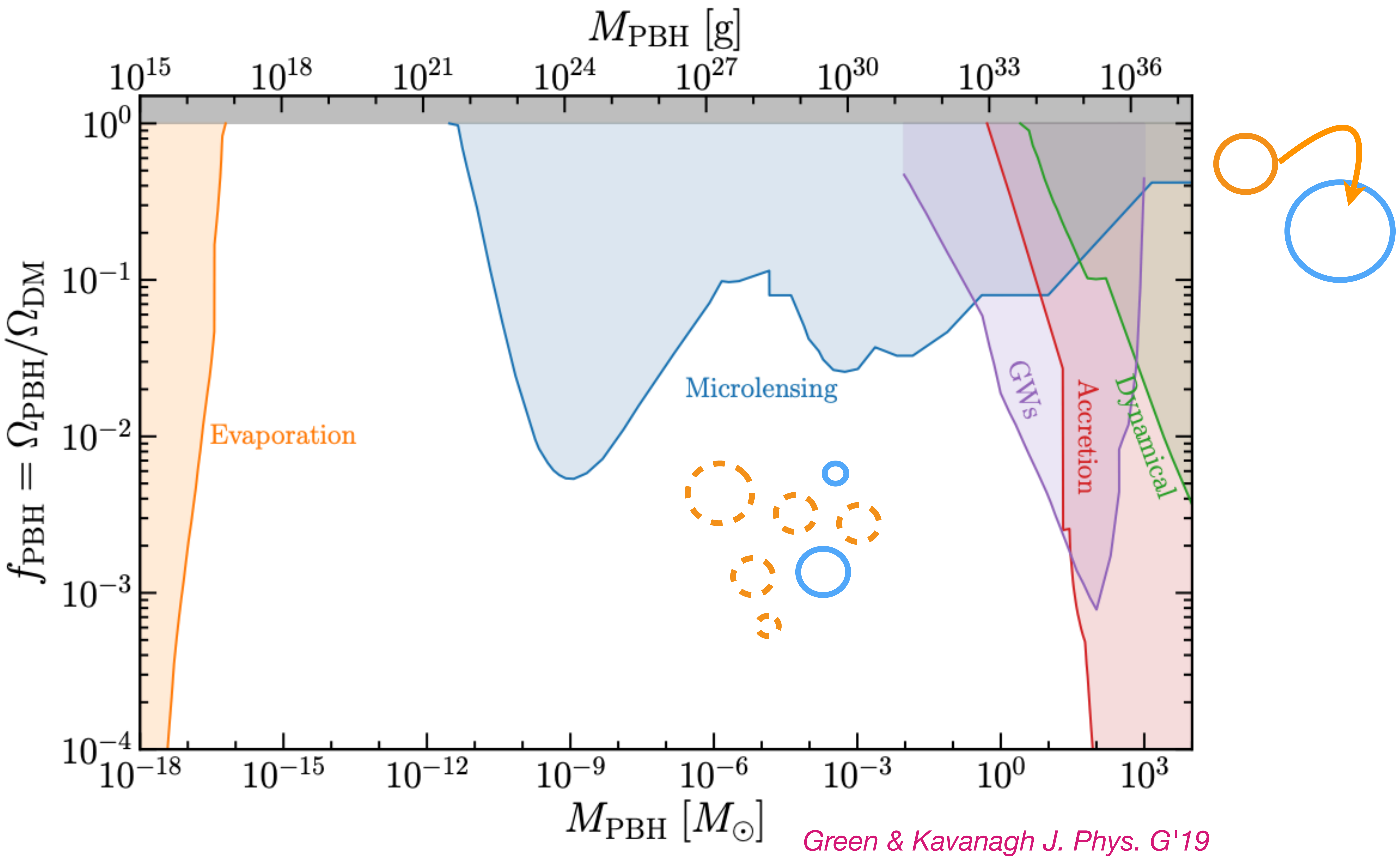

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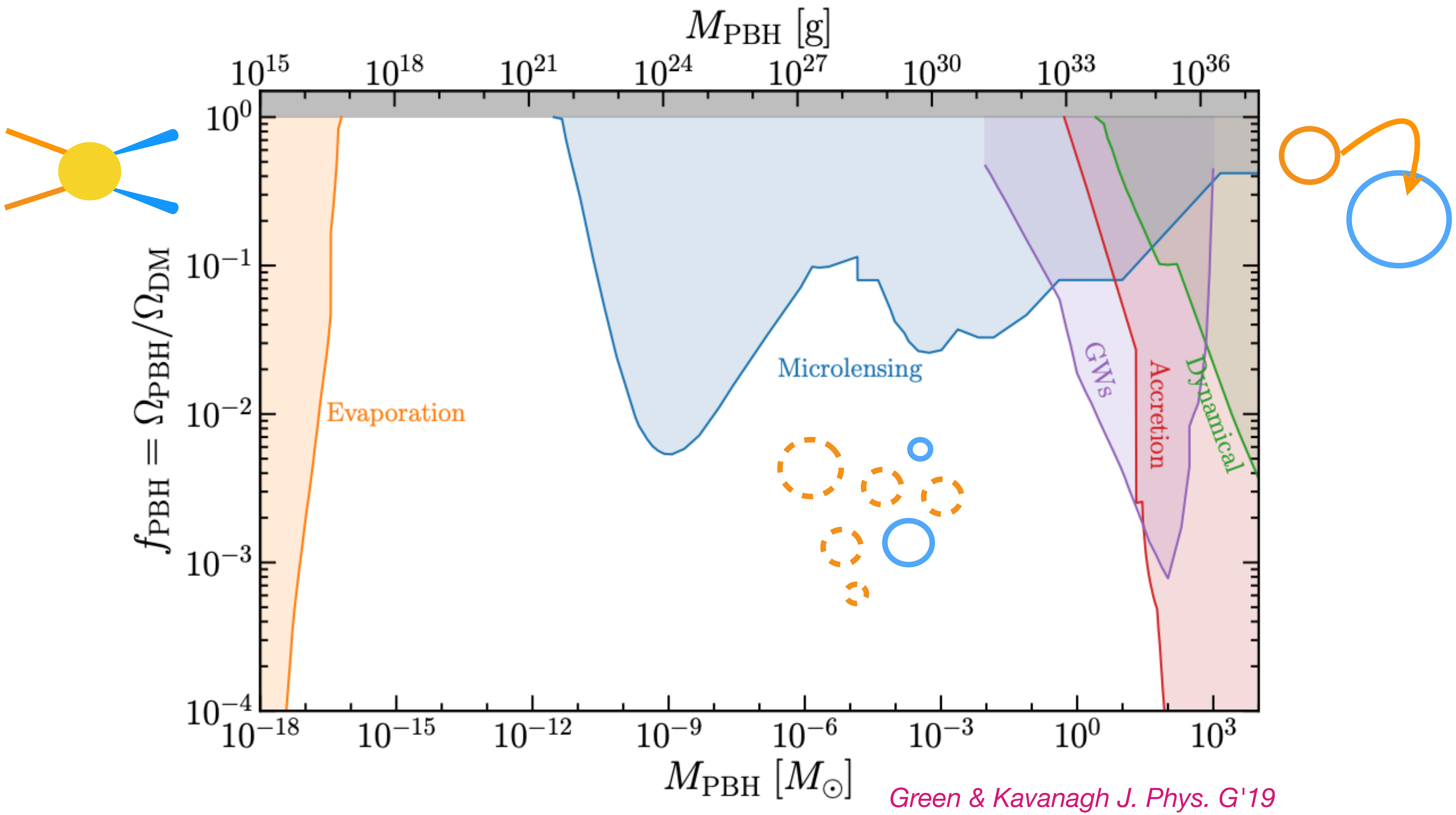

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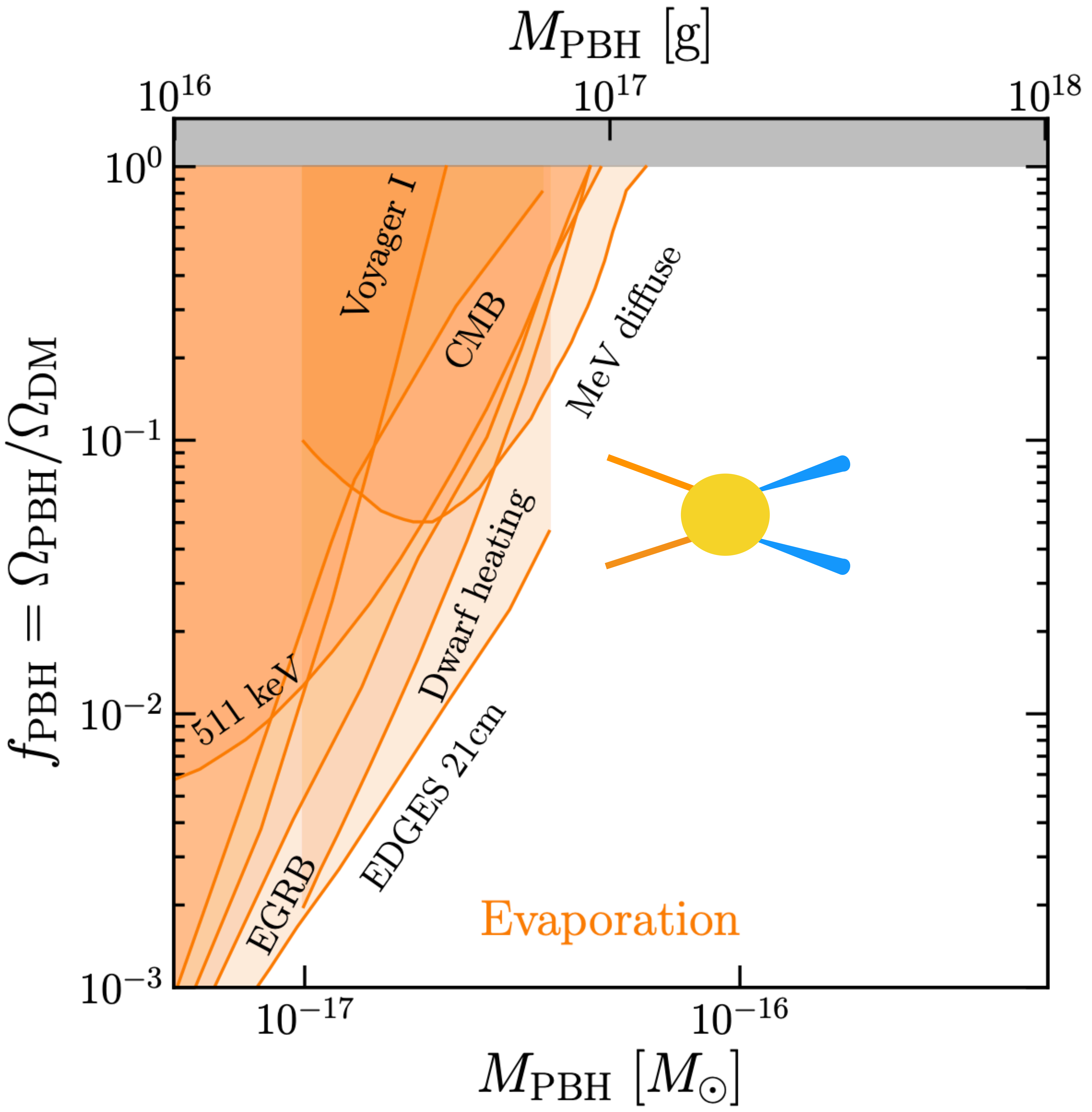
Limits from PBH evaporation



- PBH can emit **charged cosmic rays** and **photons** via Hawking radiation => Almost-black (grey) body emission

$$T_{\rm PBH} \simeq \frac{10^{13}{\rm g}}{M_{\rm PBH}}\,{\rm GeV}$$

Page & Hawking ApJ'76; Carr & MacGibbon Phys. Rep.'98

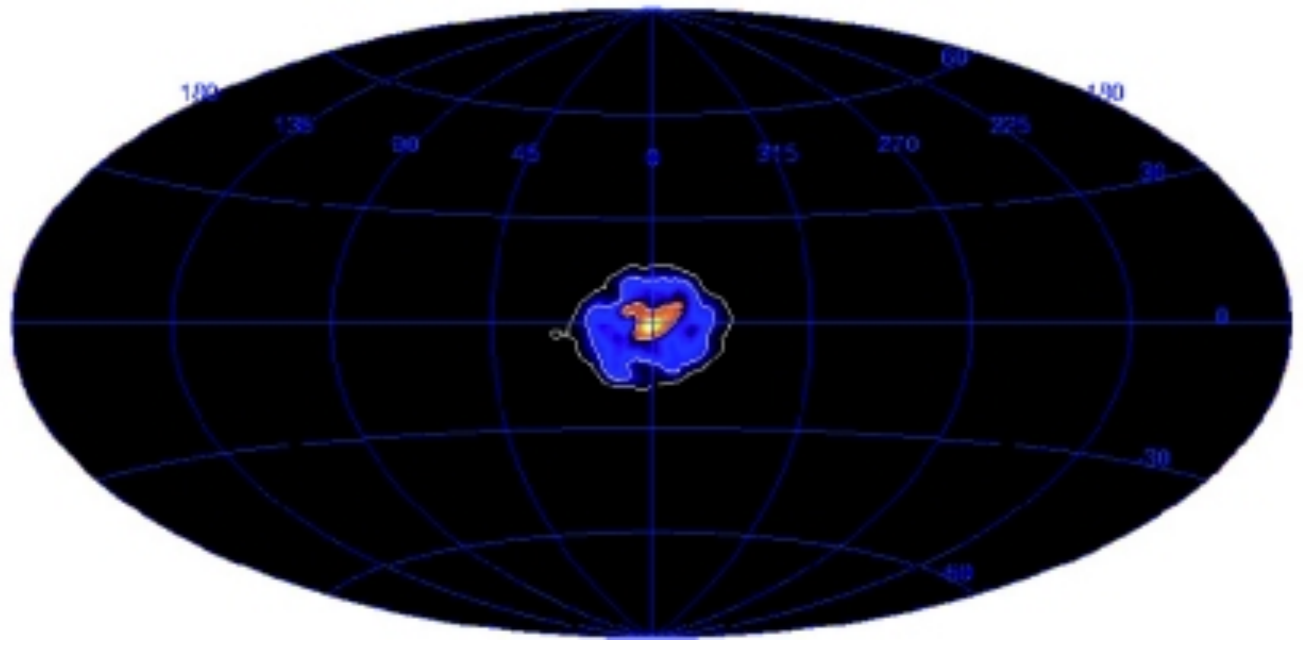
- Sufficient emission from $M_{\rm PBH} > 10^{14}$ g to set limits on their evaporation products today

- Unconstrained mass range ~10^{17} — 10^{22} g, the so-called *asteroid mass gap* where f_{PBH} can be 1

Green & Kavanagh J. Phys. G'19

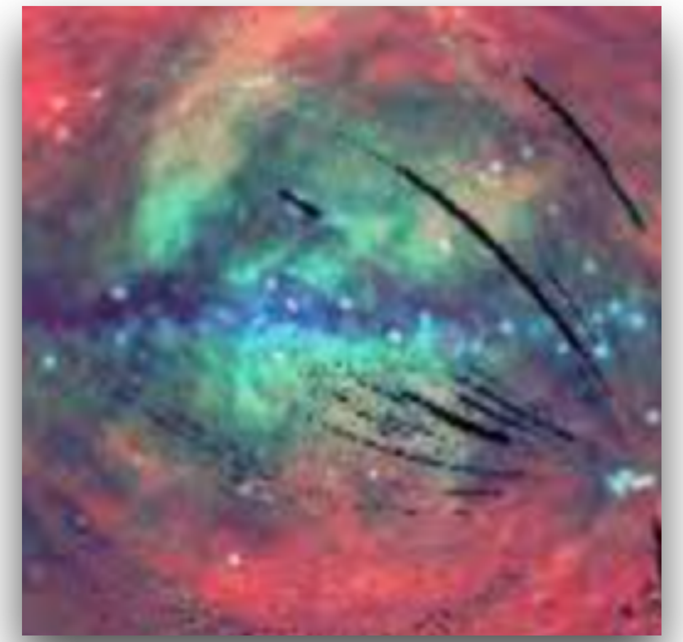
PBH evaporation observables

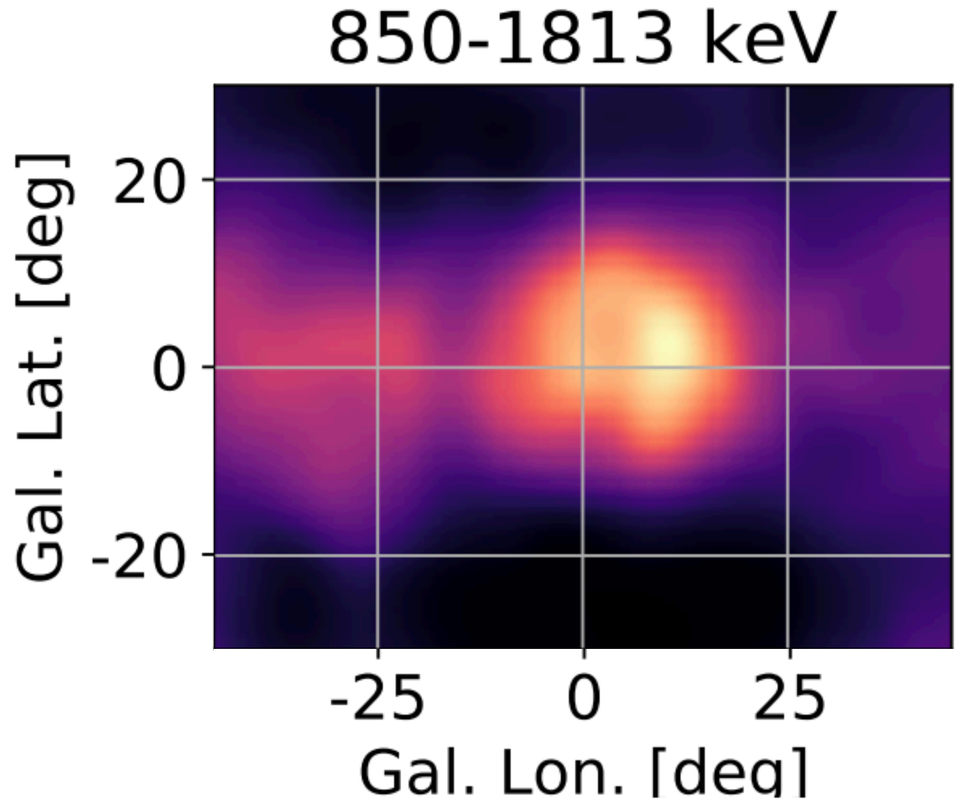
1. Cosmic-ray electron-positron fluxes



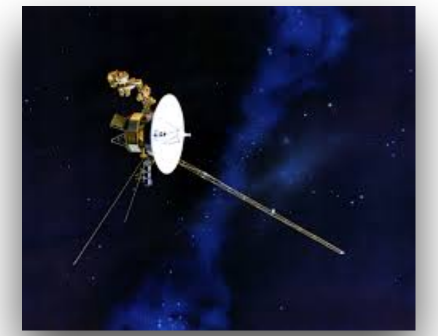
2. 511 keV electron-positron annihilation line

3. Continuum X- and gamma-ray emission

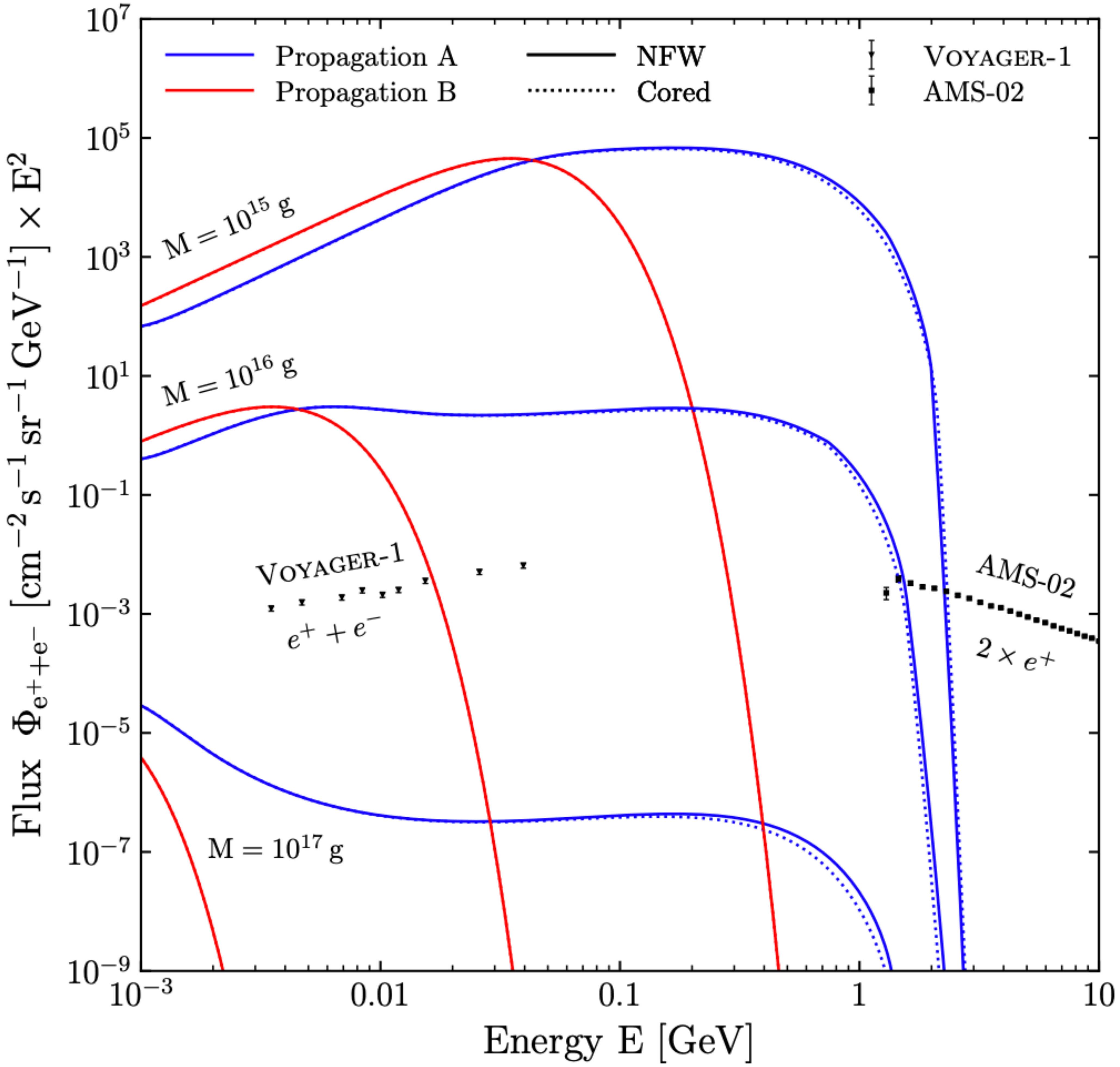


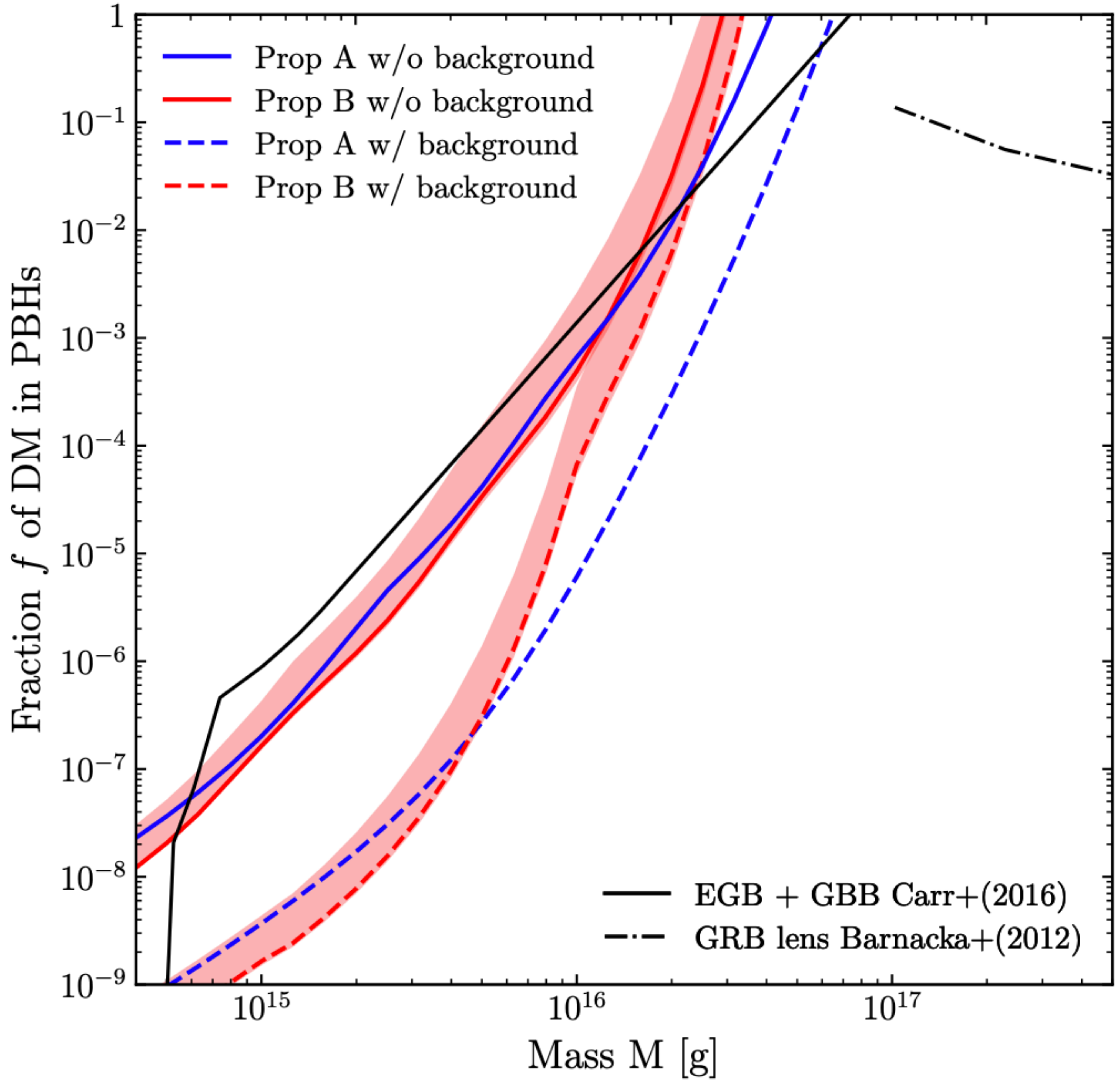


Cosmic-ray electron/positron flux



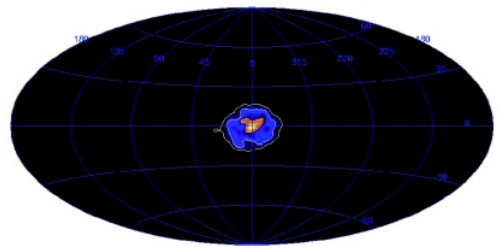
Cirelli & Boudaud PRL'19





$$Q(E,\vec{x}) = \frac{\rho(\vec{x})}{\rho_\odot} \int_{M_{\rm inf}} dM \, \frac{g(M)}{M} \frac{dN_e}{dtdE}, \qquad \Phi_{e^\pm}(E,\odot) \simeq \frac{c}{4\pi b(E)} \int_E dE_{\rm s} \, Q(E_{\rm s},\odot)$$

511 keV annihilation line



$$\Phi_{511} \sim 10^{-3}\mathrm{ph/cm2/s}$$

$$L_{e^+} \sim 2 \times 10^{43}\mathrm{e^+/s}$$

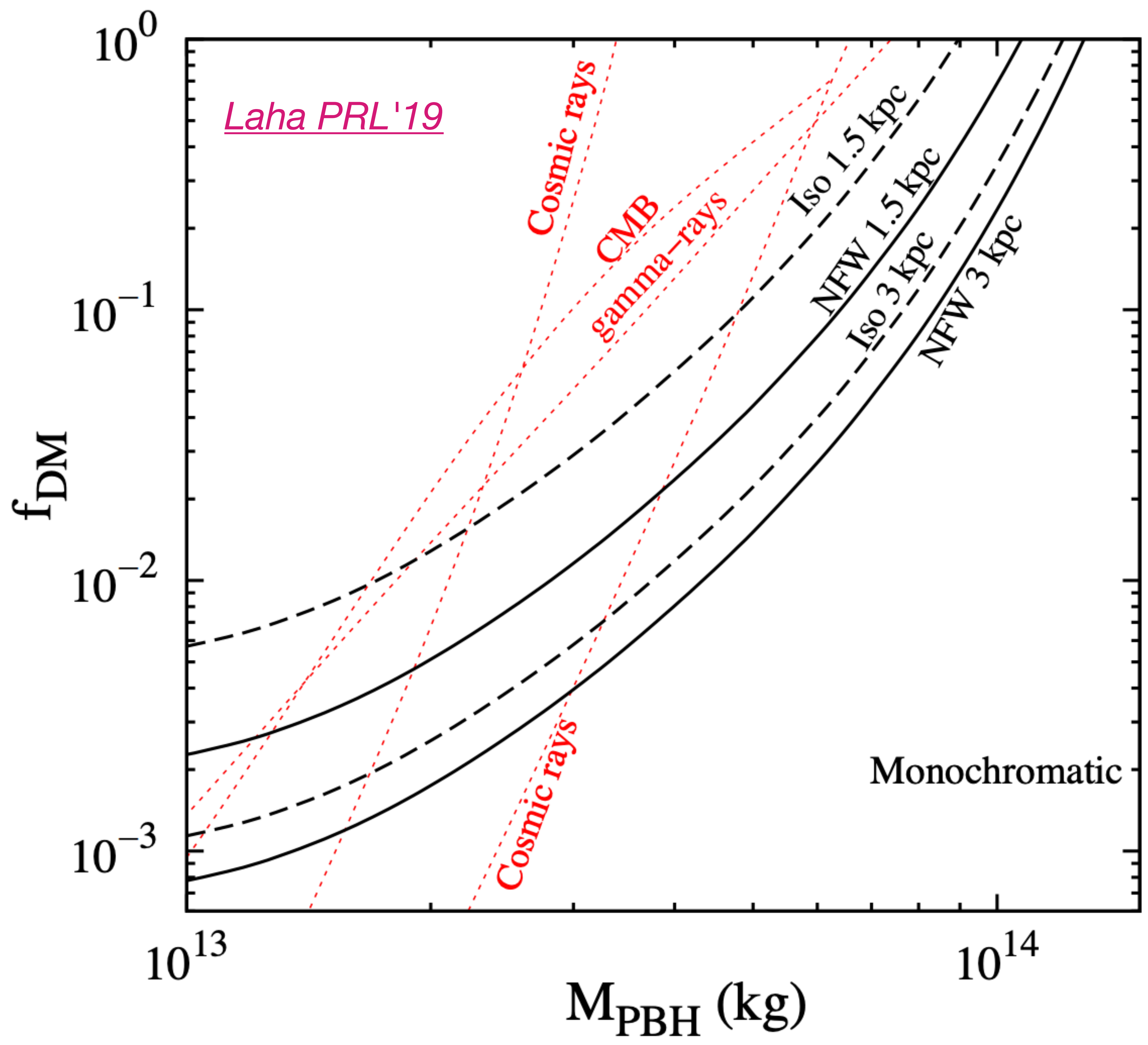
$$L_{e^+}^{\mathrm{PBH}} = \frac{f_{\mathrm{PBH}}}{M_{\mathrm{PBH}}} \int dV \rho(r) \int_{\mathrm{m_e}}^{\infty} d\omega \frac{dN_{e^+}}{d\omega dt}$$

Laha PRL'19
De Rocco & Graham PRL'19

Large uncertainty on low-energy **positron propagation** and ISM conditions

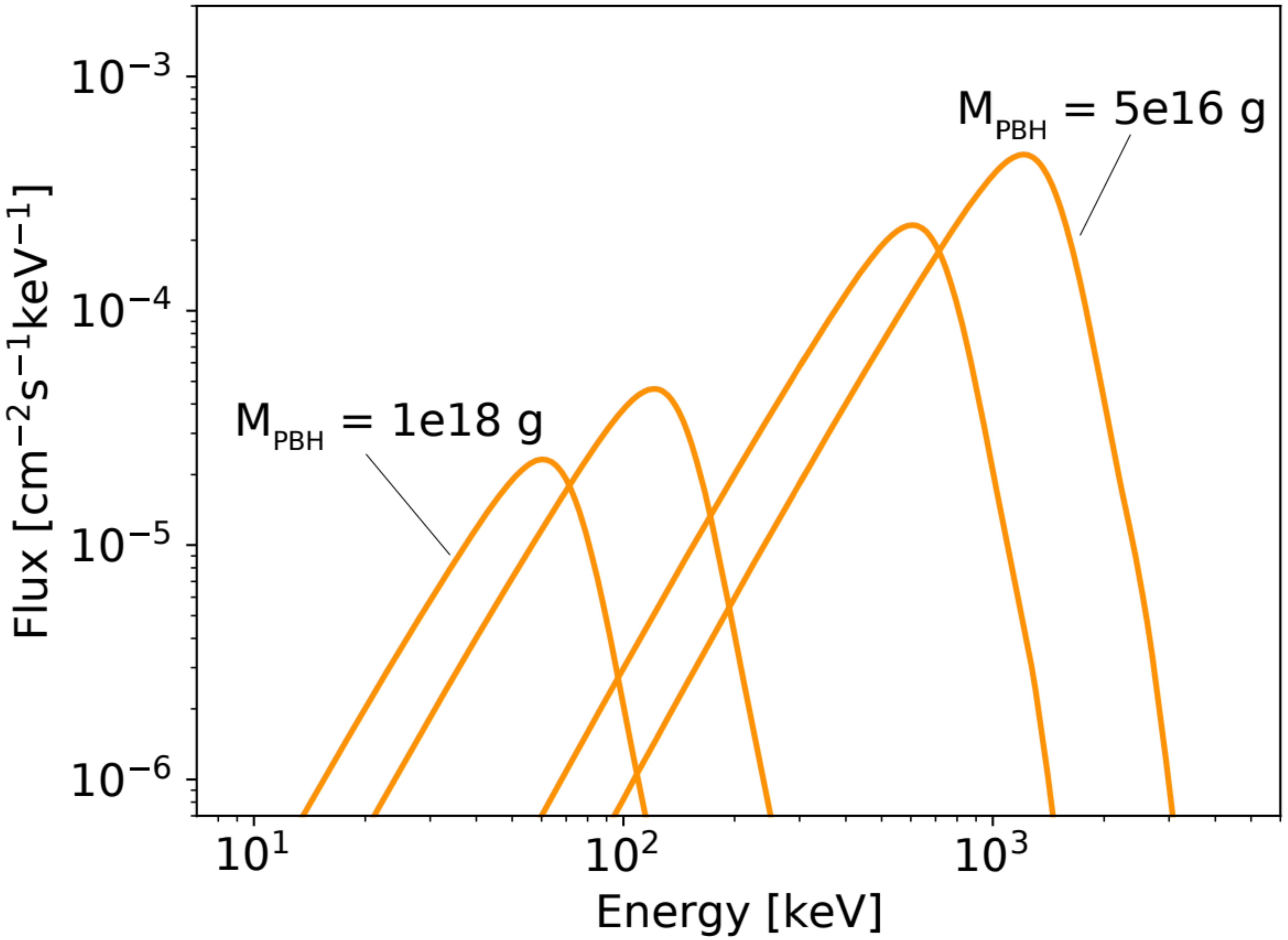
Electron-positron annihilation occurs at rest (Integral/SPI)

Siegert, FC+ MNRAS'21

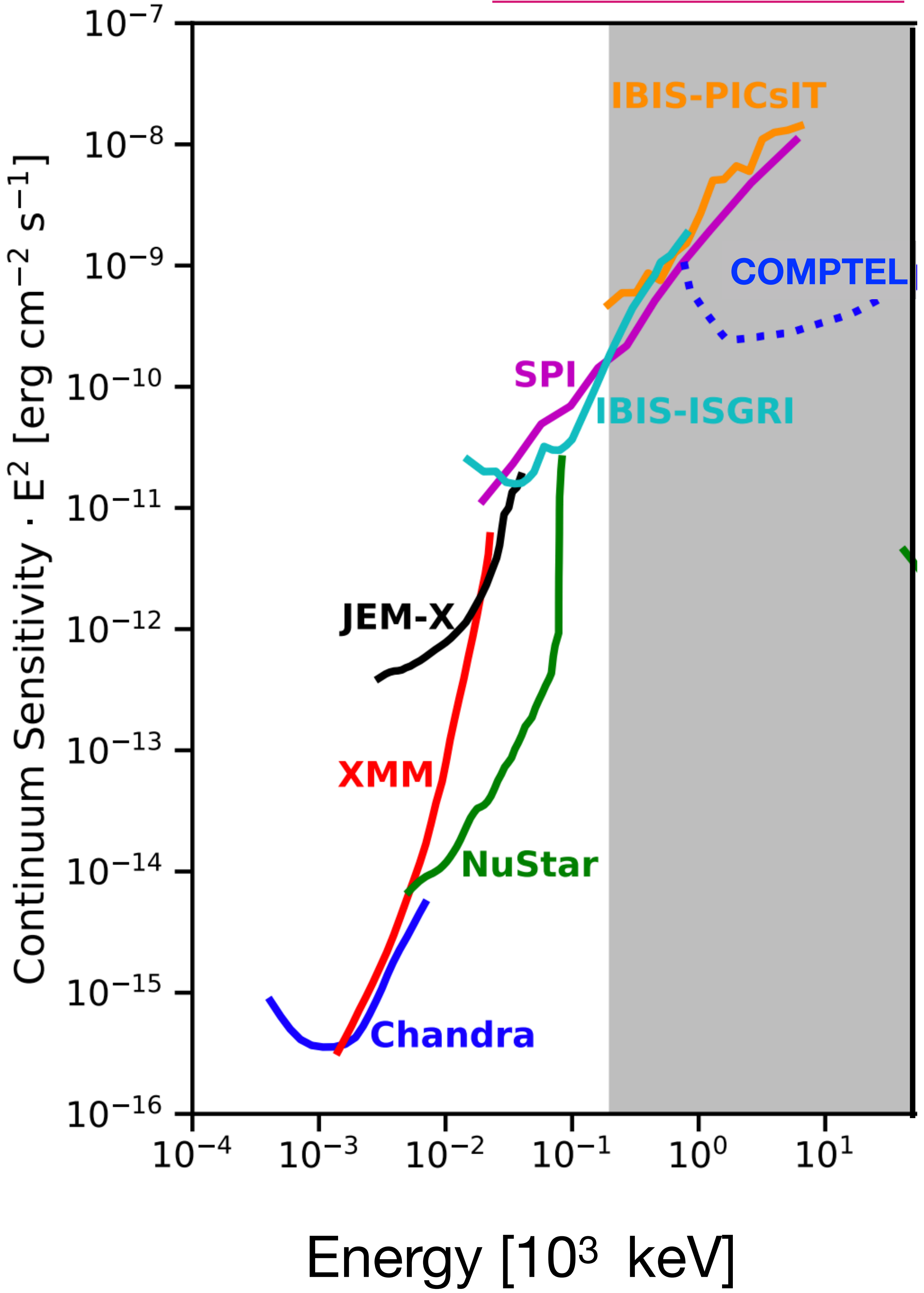


Continuum gamma-ray emission

Data coverage and PBH photon spectra

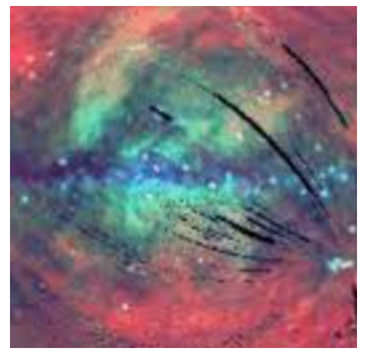


Lucchetta+ JCAP'22

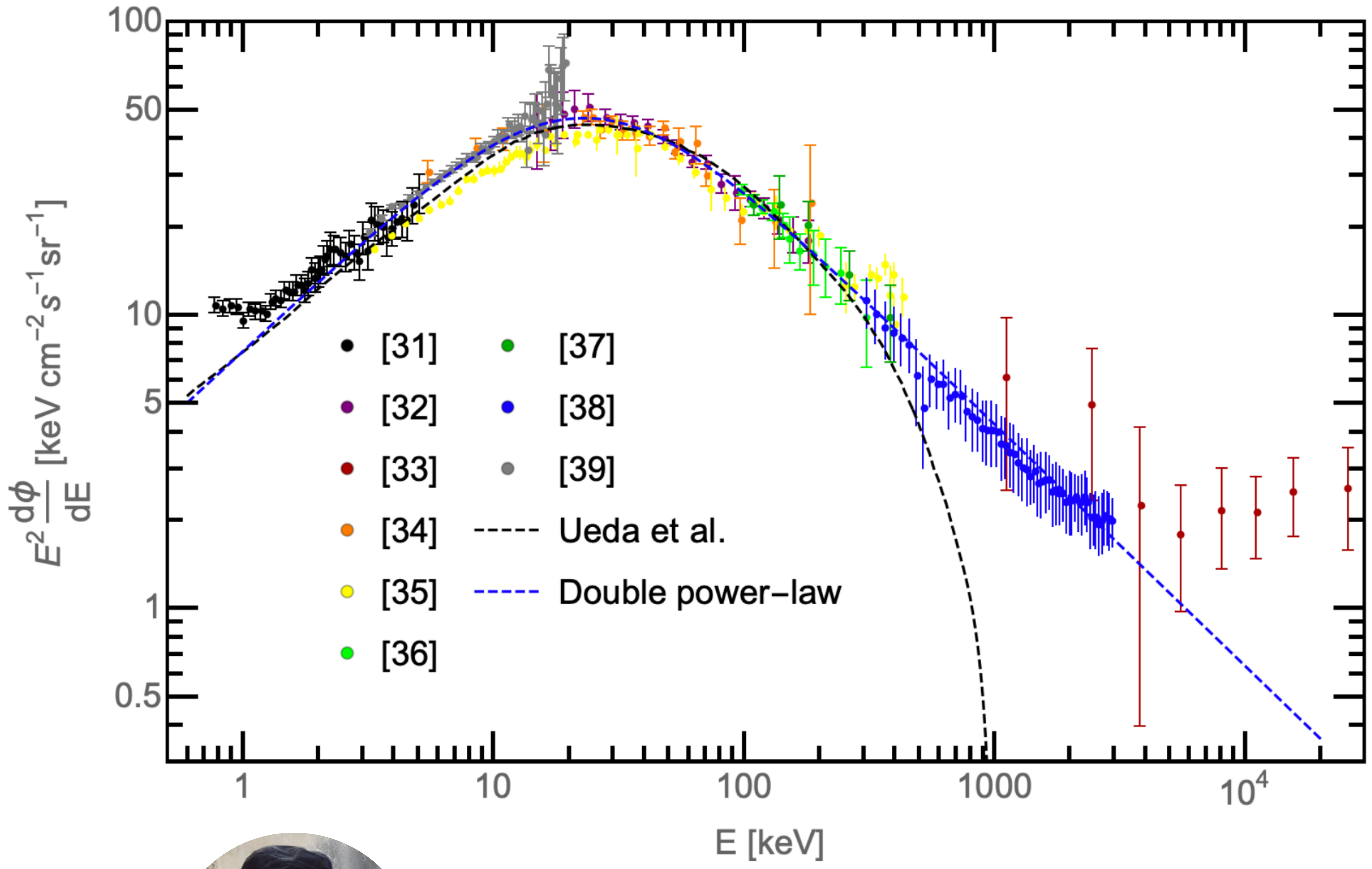


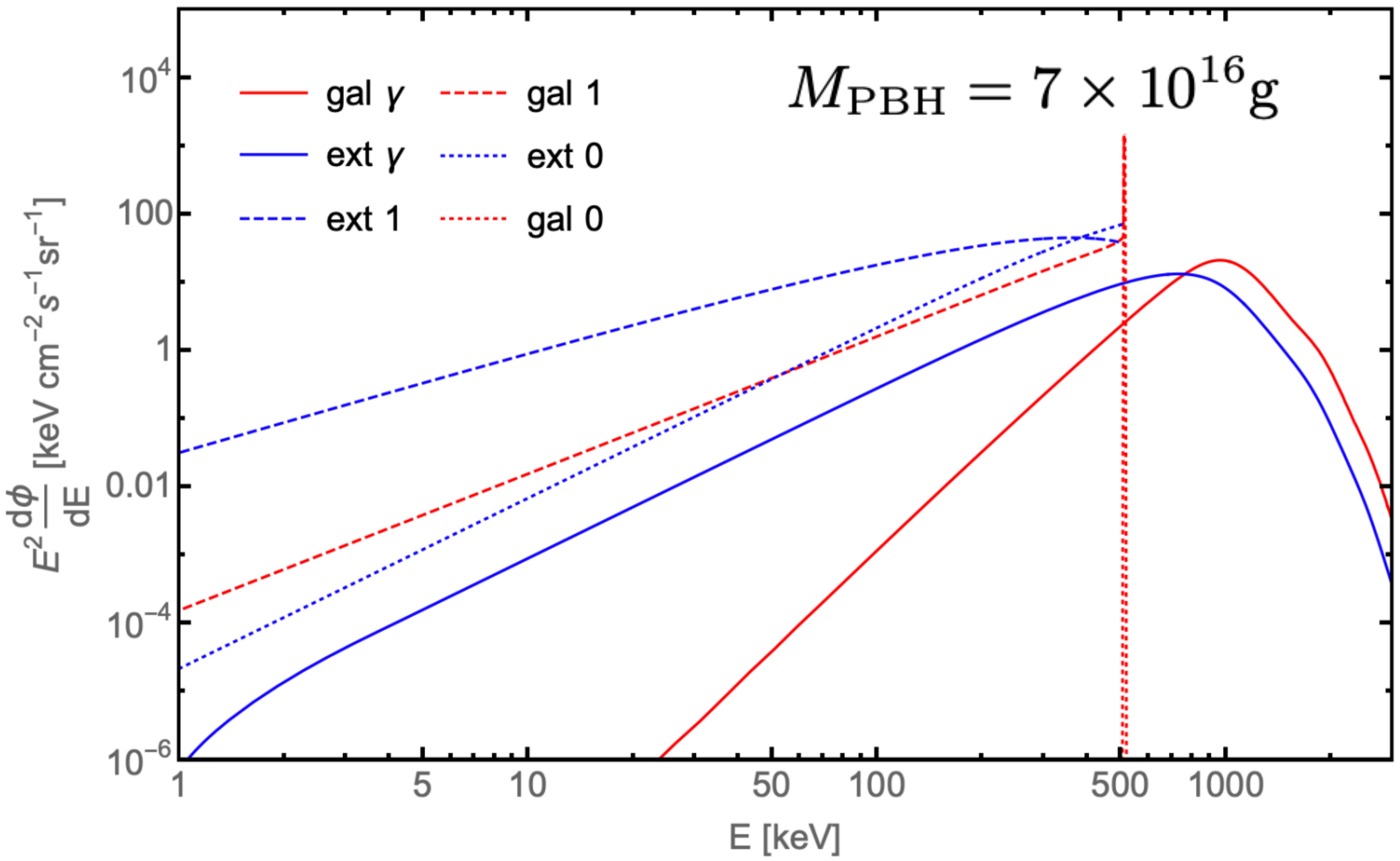
Continuum gamma-ray emission

Cosmic backgrounds



Iguaz+ PRD'21

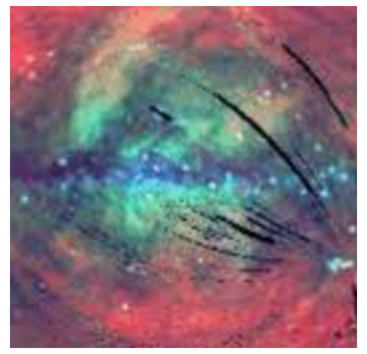




Total isotropic diffuse emission vs cosmic X-ray background

Continuum gamma-ray emission

Cosmic backgrounds



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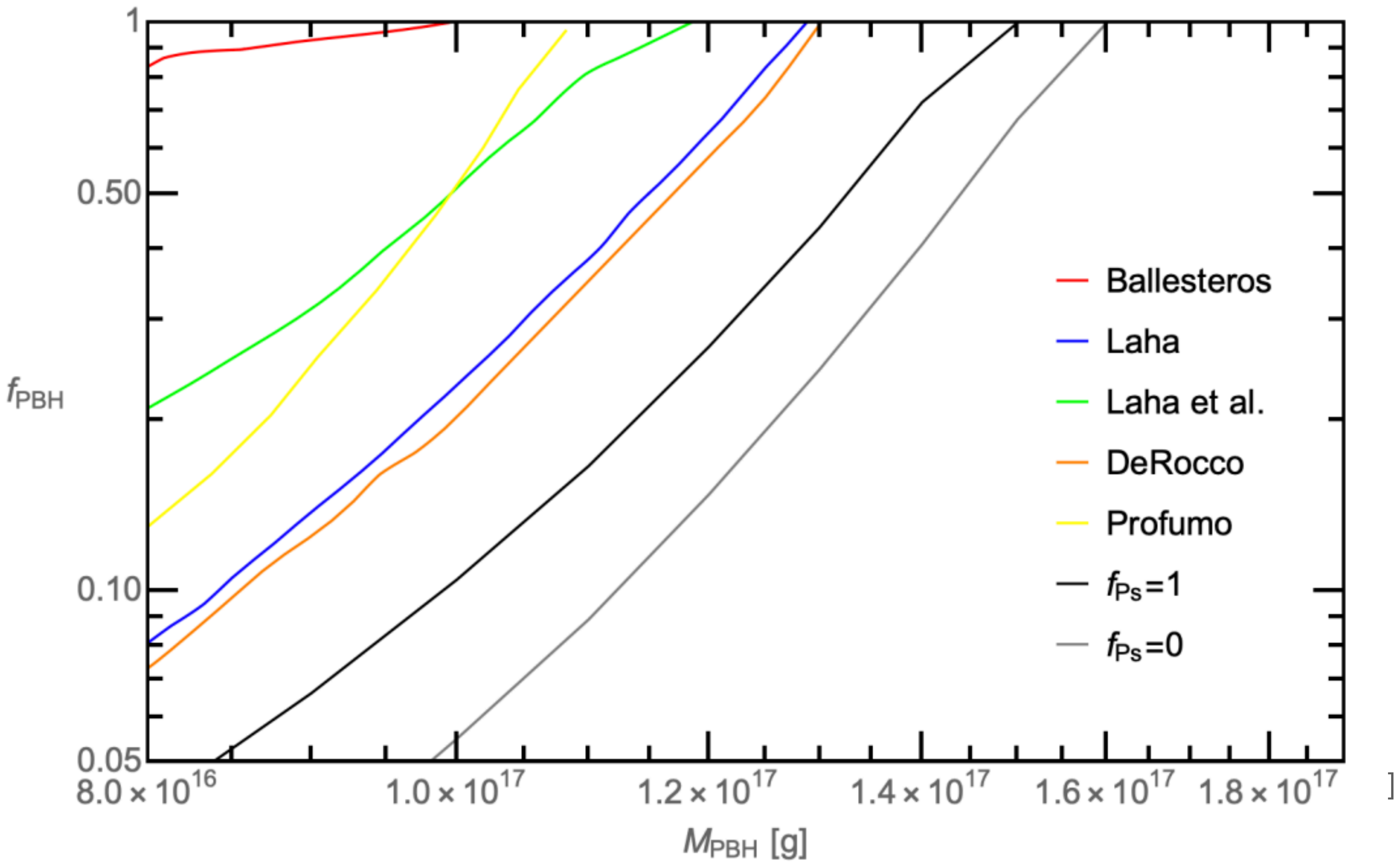
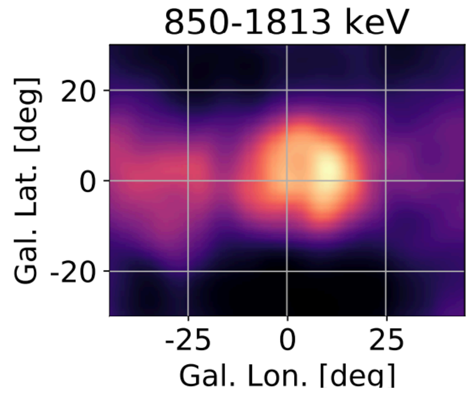
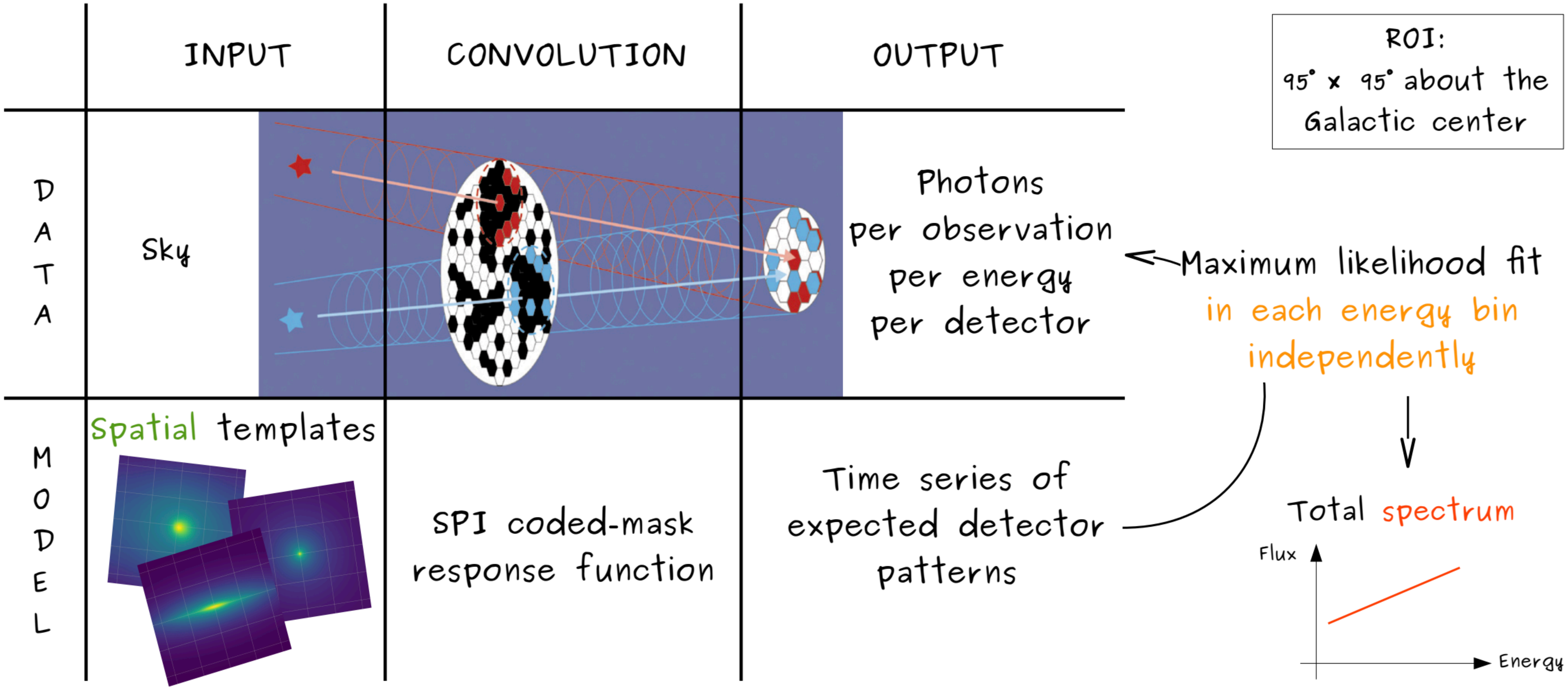


See also *Carr+ PRD'10; Ballesteros+ PLB'20*

Continuum gamma-ray emission

How do we measure the Milky Way diffuse emission?



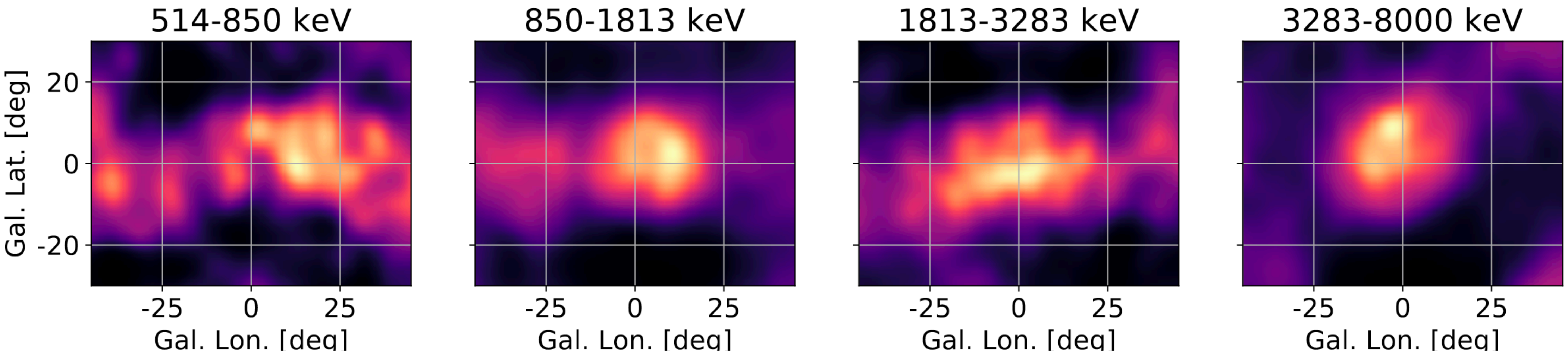


Credit: J. Berteaud, RICAPP'22

Continuum gamma-ray emission

Siegert, FC+ A&A'22

Residual emission after bkg-only model fit



Instrumental CR-induced background dominates by far the SPI detected counts

Residuals from bkg-only fit reveal the presence of correlated large-scale emission, around the Galactic plane

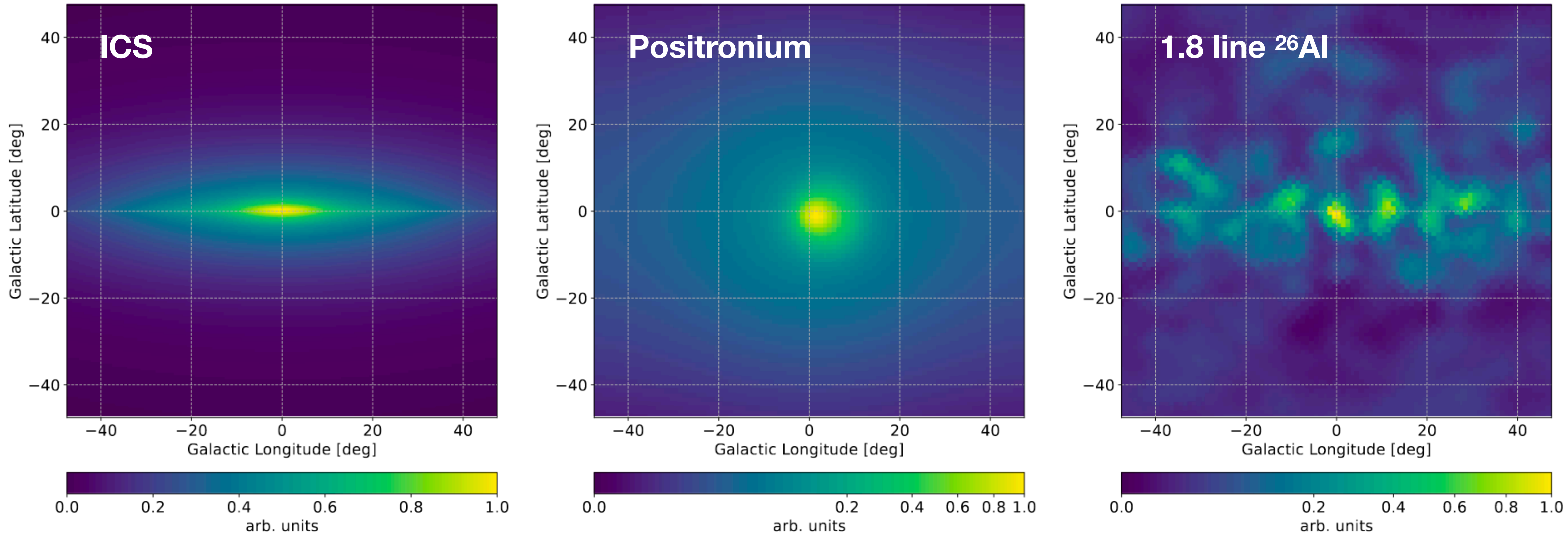
MeV Galactic diffuse emission

Astrophysical contributions

Berteaud, FC+ PRD'22

Modelled **spatial templates** (30 keV — 8 MeV)

- **Inverse Compton scattering** of electrons off the interstellar radiation field $\mathrm{e}^{\pm}_{\mathrm{CR}} + \gamma \longrightarrow \mathrm{e}^{\pm} + \gamma_{\mathrm{MeV}}$
- Unresolved sources (<100 keV)
- Nuclear lines
- Positronium annihilation line+continuum



MeV Galactic diffuse emission

Is there evidence for an additional PBH component?

[Berteaud, FC+ PRD'22]

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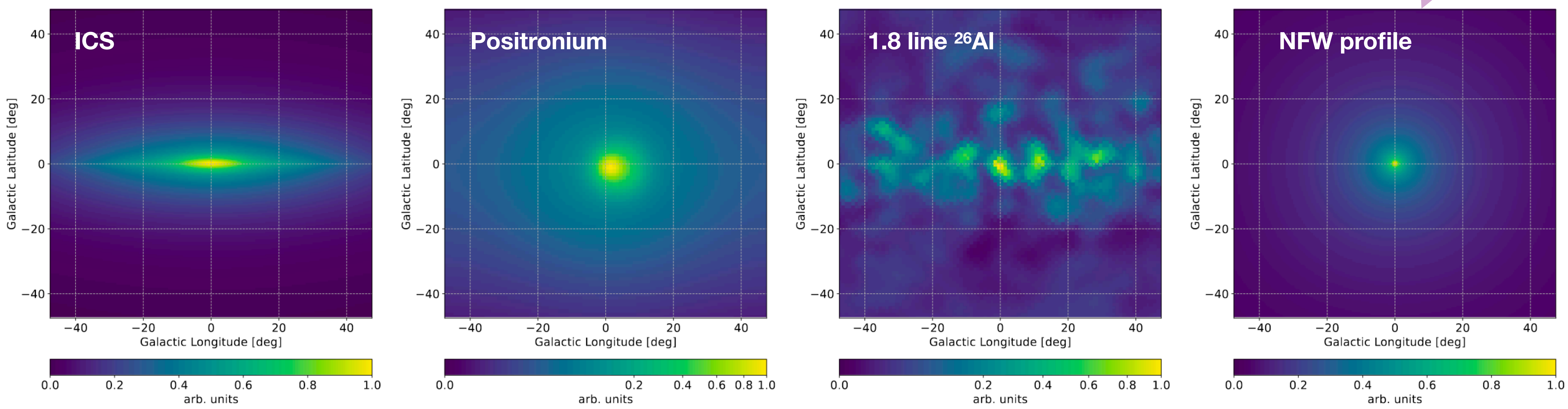
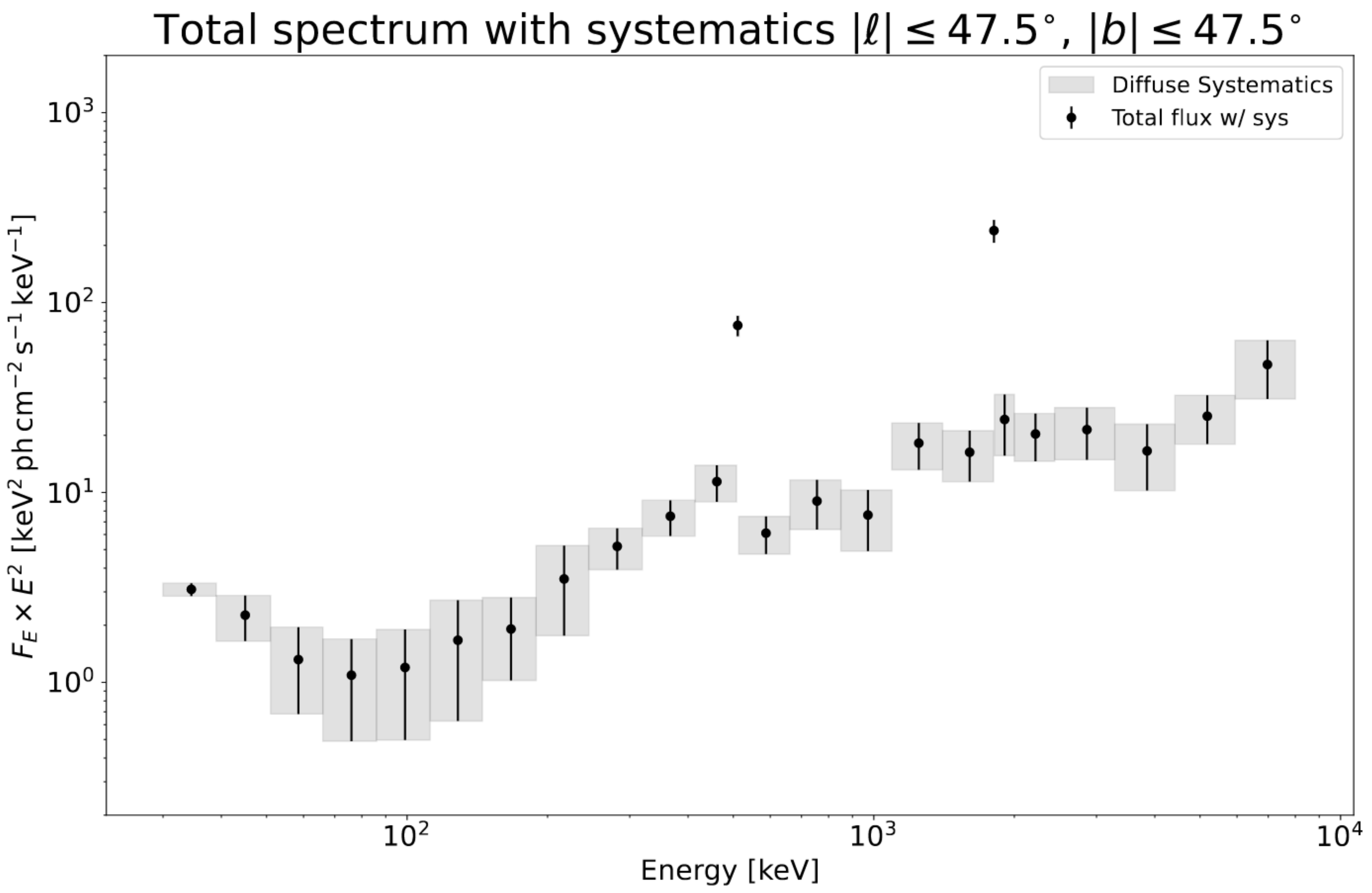
- **PBH evaporation?**

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E}(l,b) = \frac{f_{\mathrm{PBH}}}{4\pi M_{\mathrm{PBH}}} \frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}E\mathrm{d}t} \boxed{\int_{\mathrm{l.o.s.}} \mathrm{d}s\, \rho(r(s,l,b))}$$



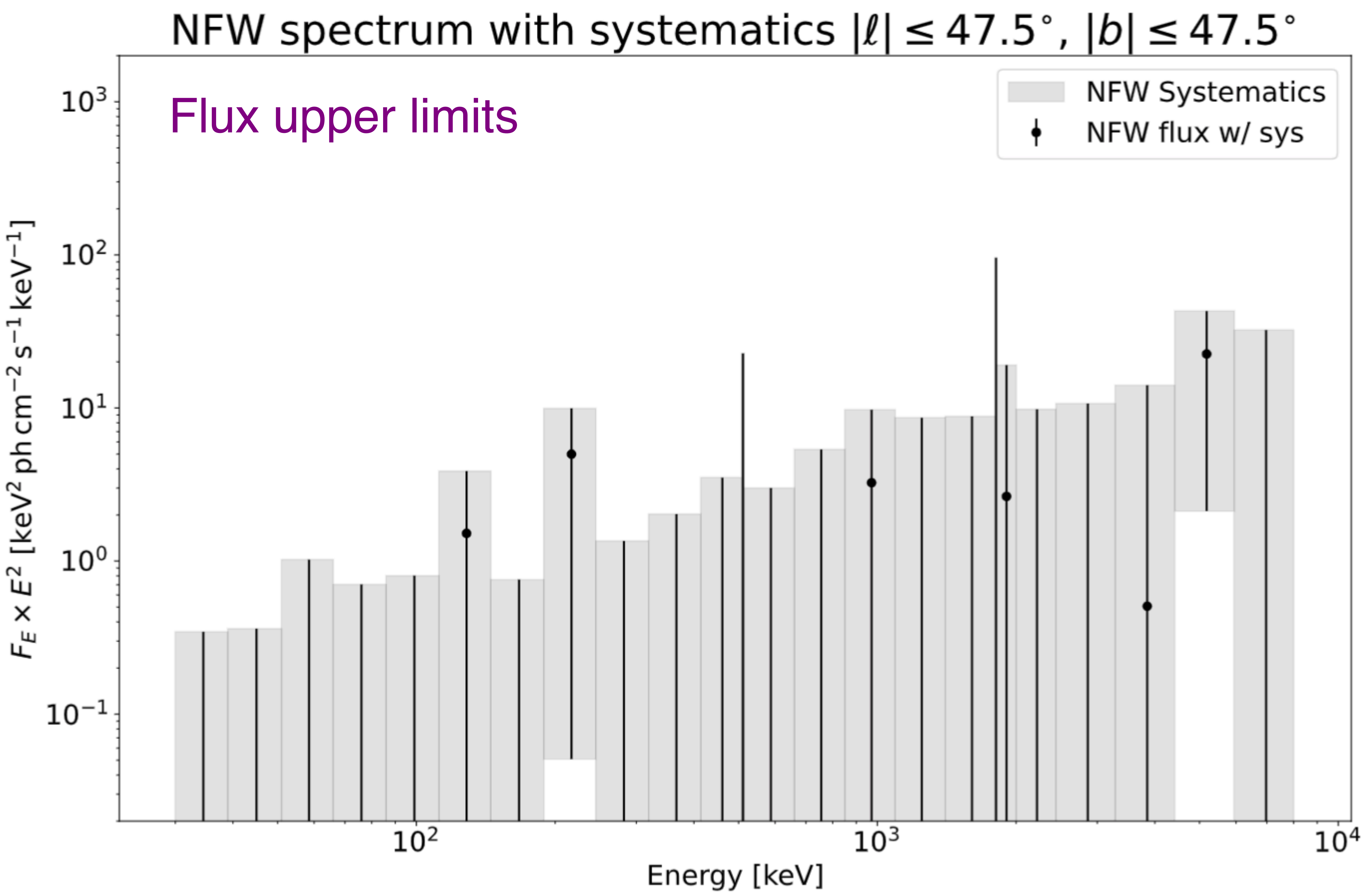
MeV Galactic diffuse total spectrum

Berteaud, FC+ PRD'22



Flux upper limits on PBH distribution

Berteaud, FC+ PRD'22



No signal detected

=> Upper limits on **PBH evaporating flux**

Limits on PBH DM fraction

Berteaud, FC+ PRD'22

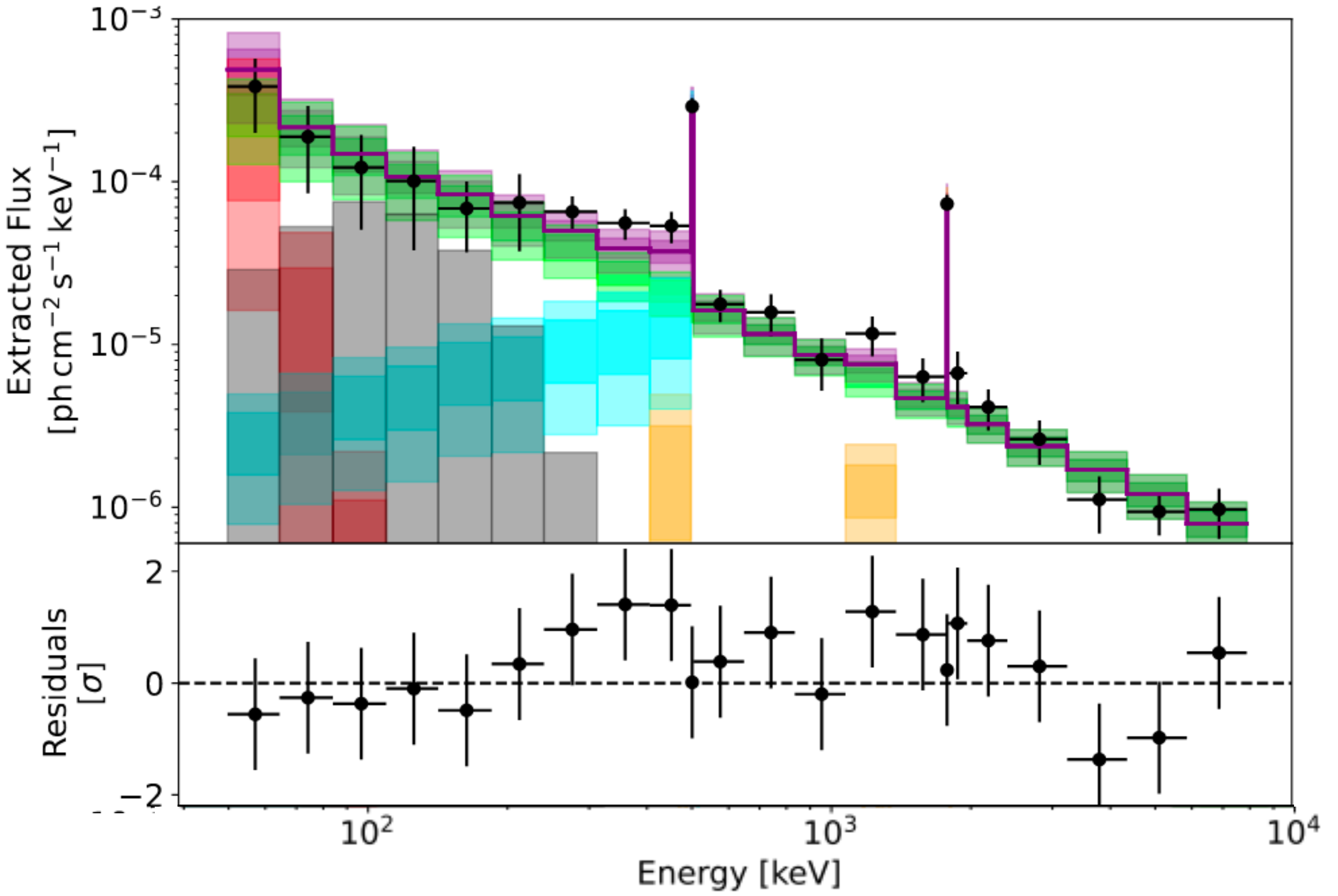
Multi-component spectral fit

Modelled **spectral components** to extracted SPI data

- **Inverse Compton** power-law
- Unresolved sources power-law with cutoff
- Nuclear lines
- Positronium annihilation line + continuum
- **PBH evaporating** signal

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E}(l,b) = \frac{f_{\mathrm{PBH}}}{4\pi M_{\mathrm{PBH}}} \boxed{\frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}E\mathrm{d}t}} \int_{\mathrm{l.o.s.}} \mathrm{d}s\, \rho(r(s,l,b))$$

$$\frac{\mathrm{d}^2 N_i}{\mathrm{d}E\mathrm{d}t} = \frac{1}{2\pi} \frac{\Gamma_i(E, M_{\mathrm{PBH}})}{e^{E/T_{\mathrm{PBH}}} - (-1)^{2s}}$$



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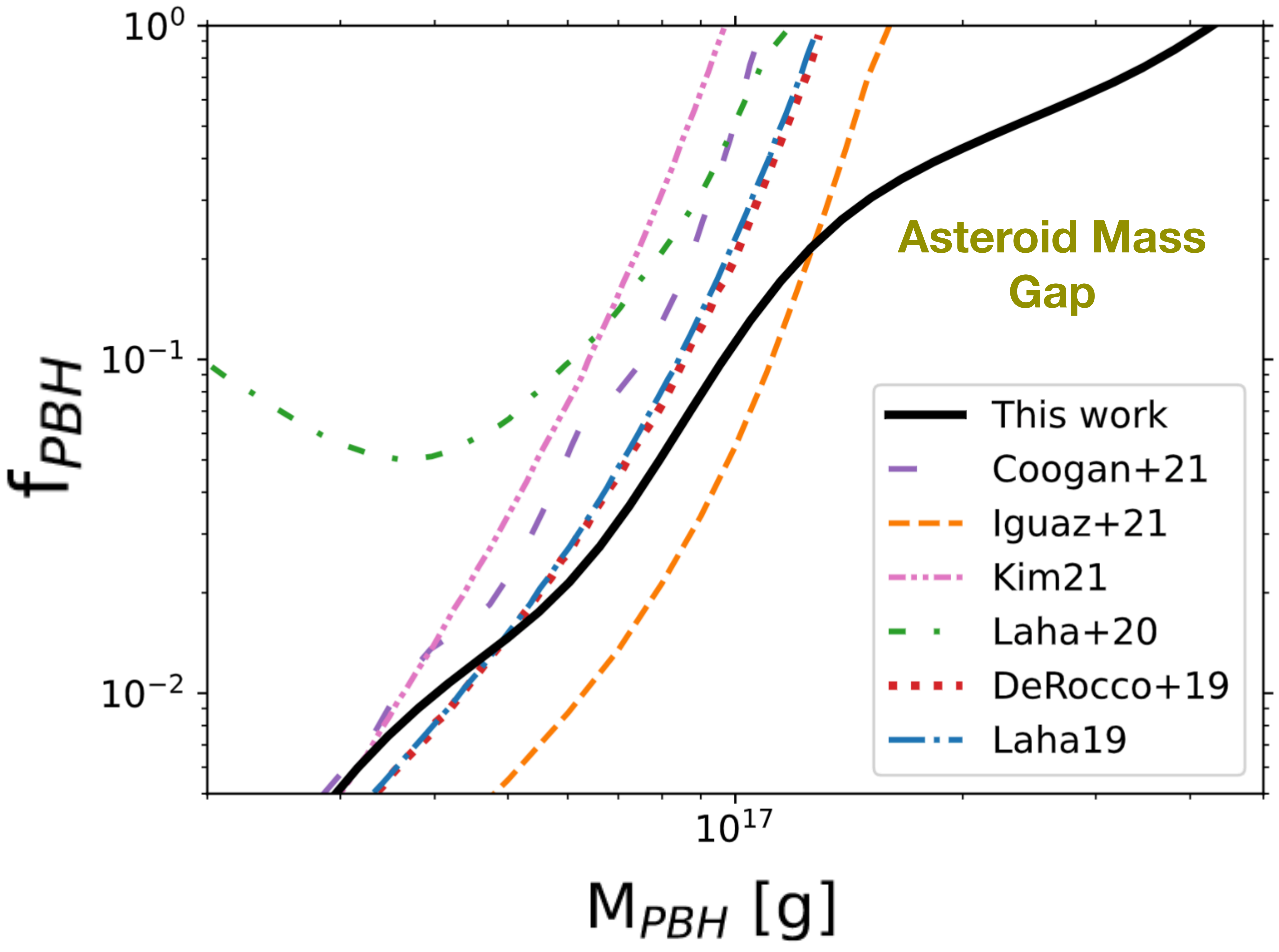
=> Upper limits on **PBH DM fraction**

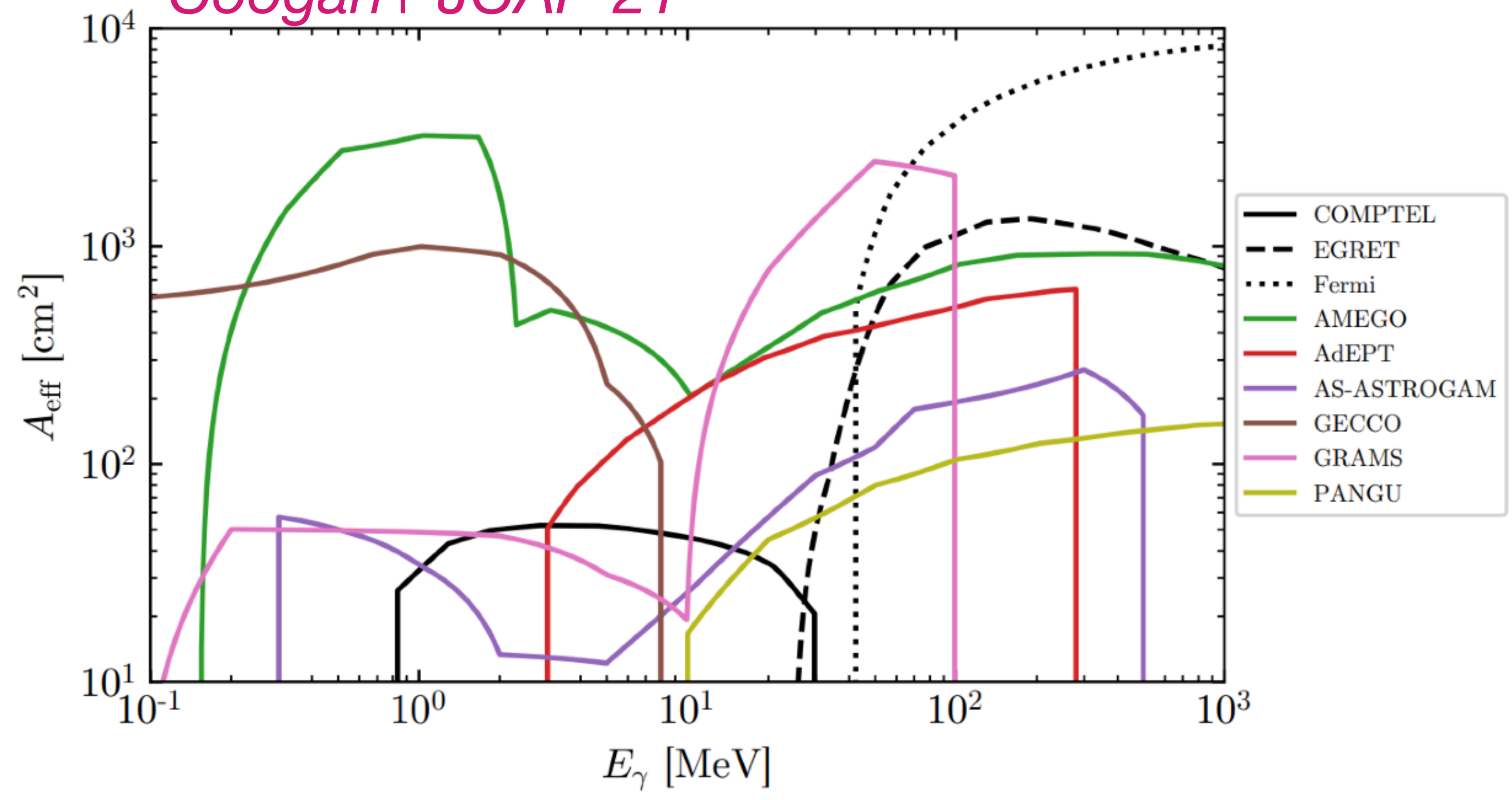


https://zenodo.org/record/6505275

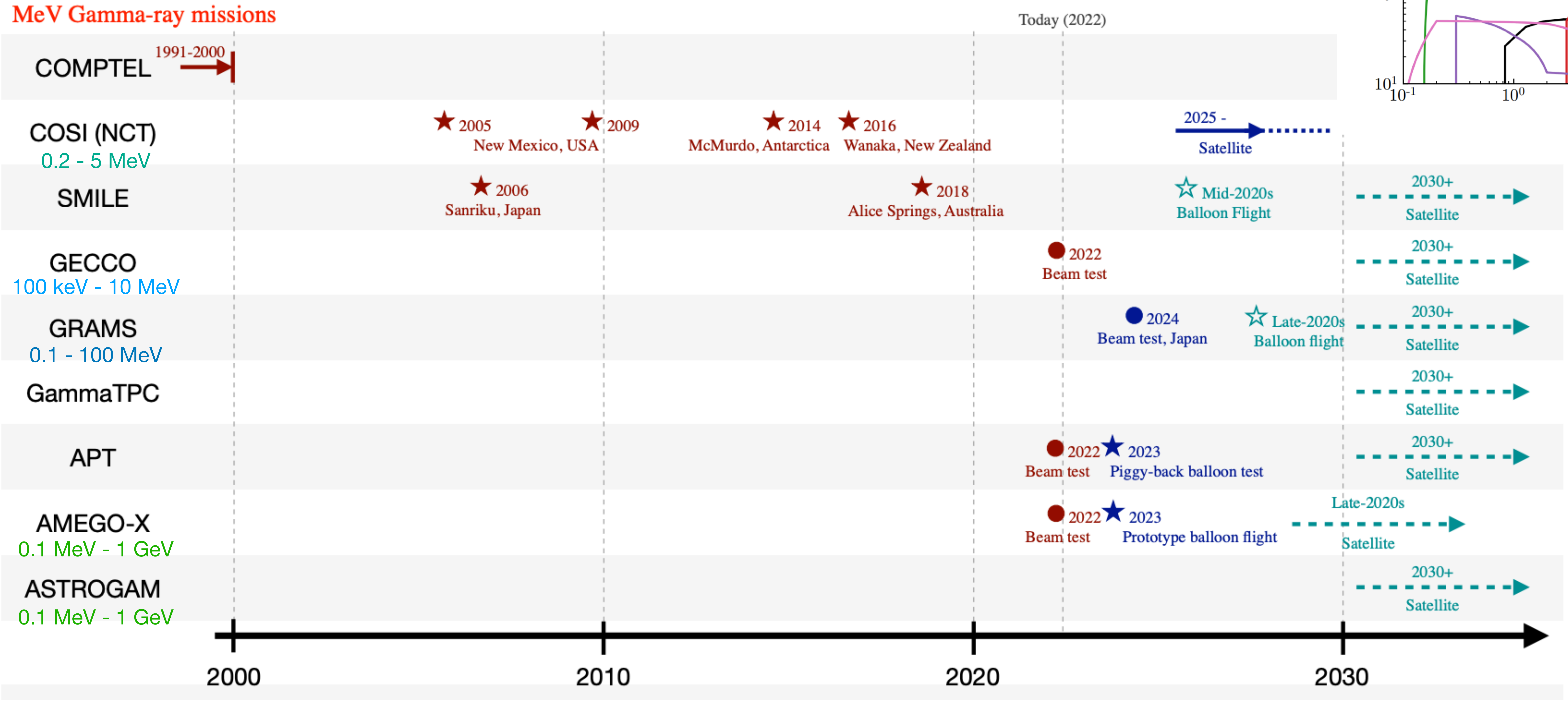
Future: MeV Galactic diffuse emission

Covering the MeV sensitivity gap

Coogan+ JCAP'21



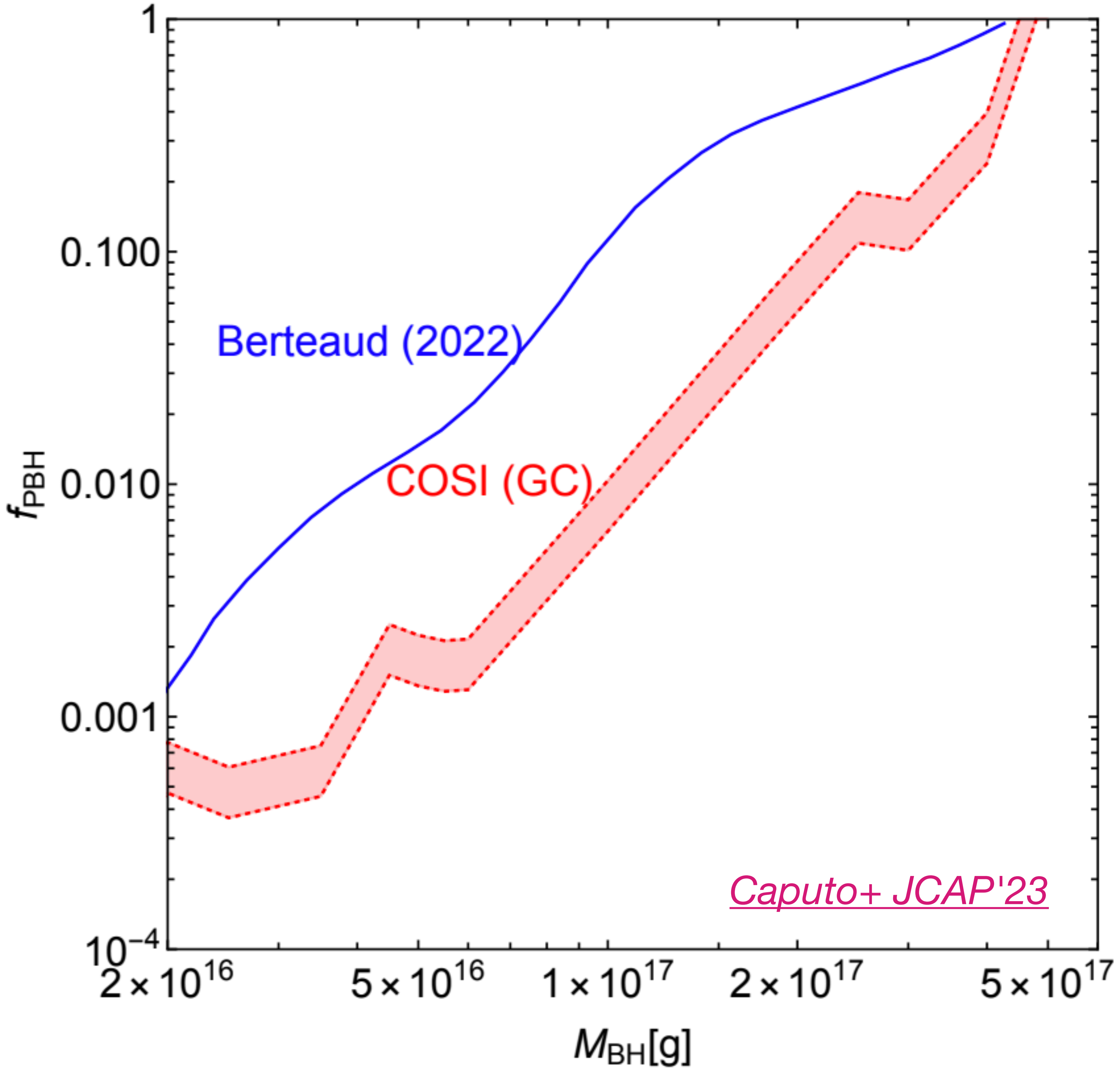
$$N_\gamma = T_{\rm obs} \int_{E_{\rm min}}^{E_{\rm max}} {\rm d}E\, A_{\rm eff} \frac{{\rm d}\Phi}{{\rm d}E_\gamma}$$

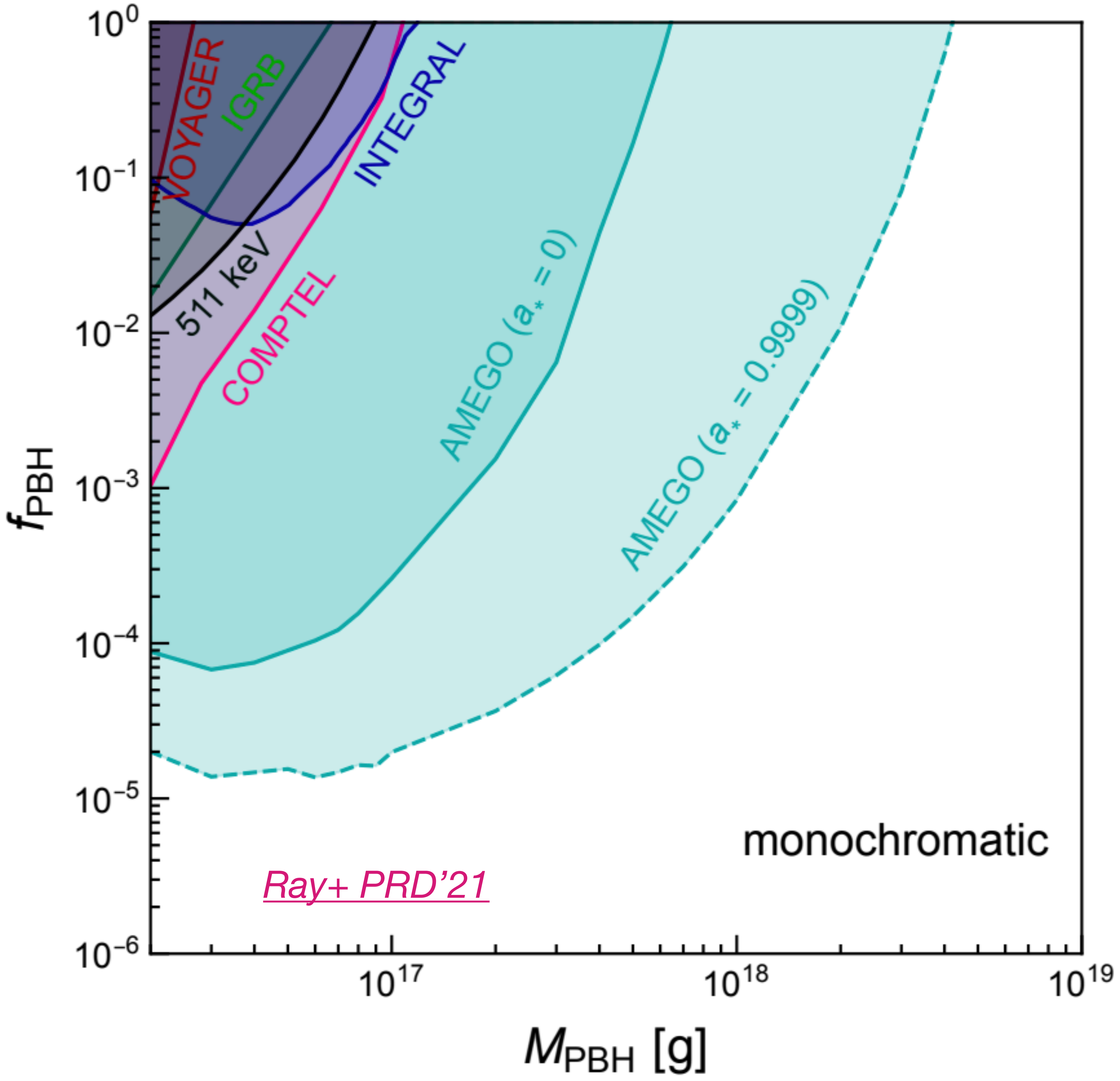


Aramaki+ Snowmass'21 CF

Future: MeV Galactic diffuse emission

Prospects on PBH





Future instruments will allow a more precise measurement of the isotropic gamma-ray and X-ray backgrounds => Improved constraints in the **10^{17}–10^{18} g mass window**

Conclusions & Outlook

- ✓ **PBHs** of different masses can be constrained by high-energy astrophysics
- ✓ **Low-mass PBH evaporation** leverages on diverse observables, from cosmic rays to high-energy photons
- ✓ One can still do quite a bit with current probes, e.g. Integral/SPI Galactic diffuse emission measurement
- ✓ But to **cut further into the asteroid mass gap** we really need a new dedicated, large FoV, telescope in hard X rays

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Thank you for the attention

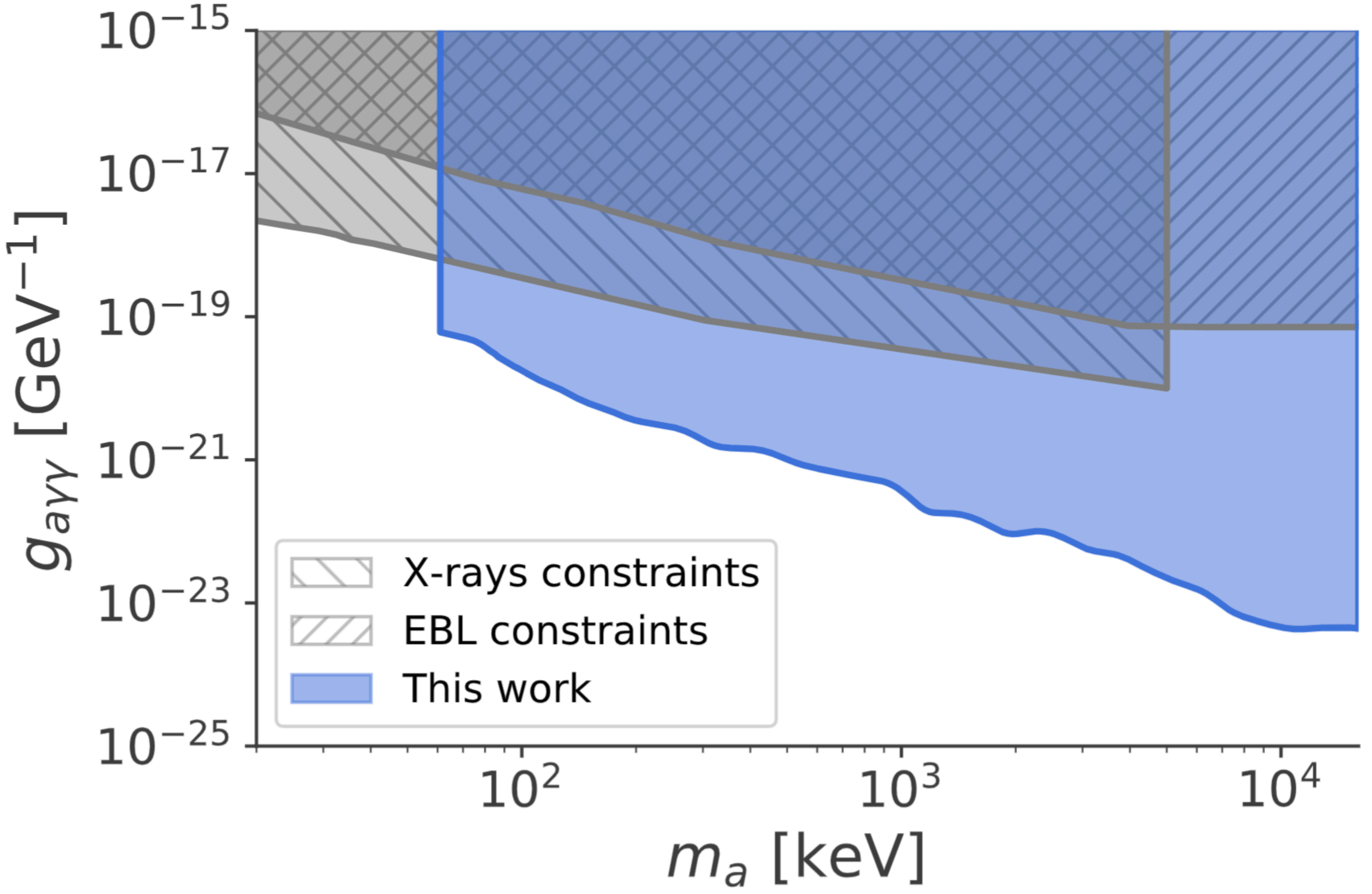
Backup

Limits on feebly interacting particles

FC+MNRAS'22

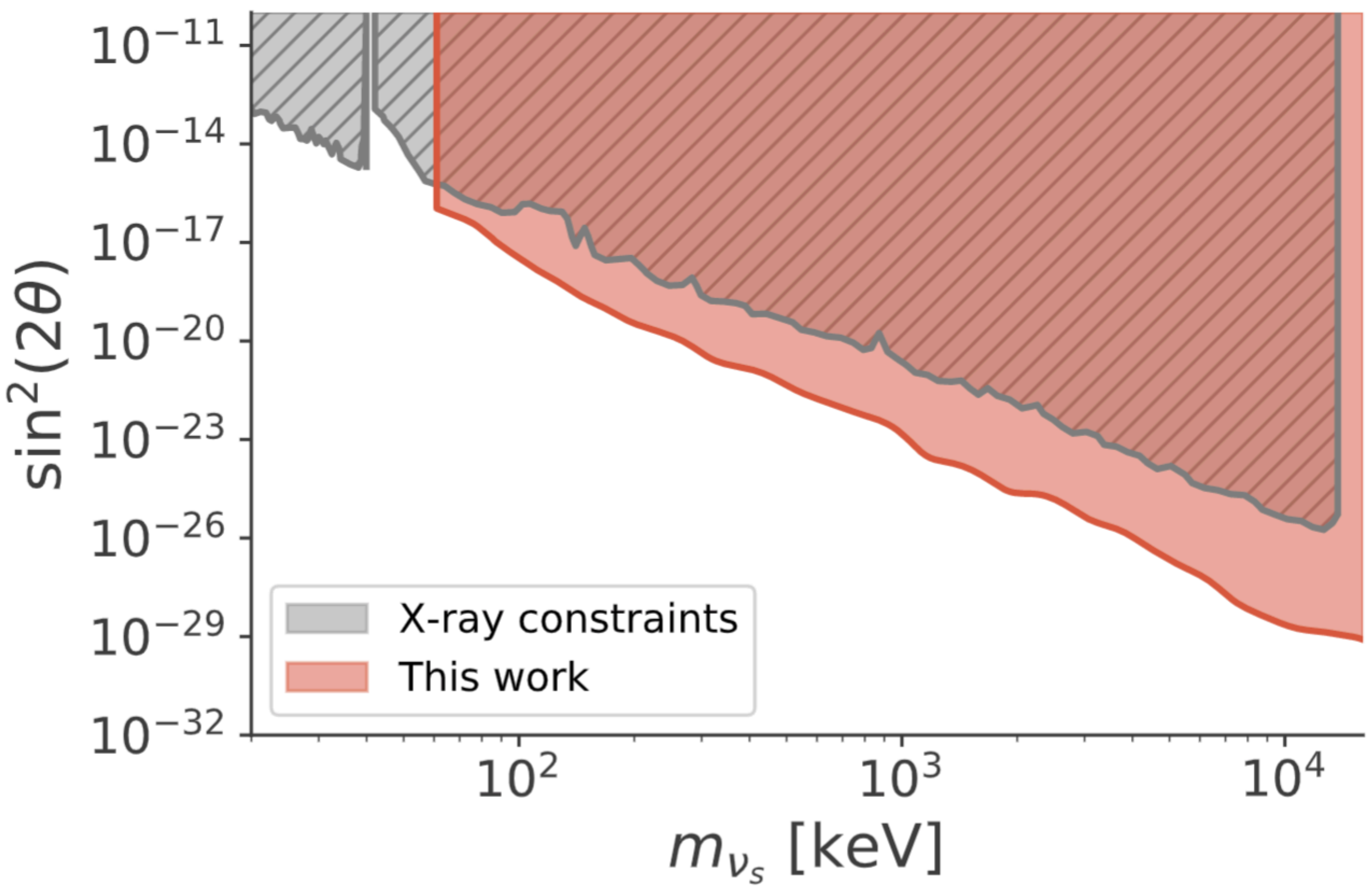
Axion-like particles

$$\Gamma_{2\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 0.755 \times 10^{-30} \left(\frac{g_{a\gamma\gamma}}{10^{-20}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{m_a}{100\,\mathrm{keV}}\right)^3 \mathrm{s}^{-1}$$



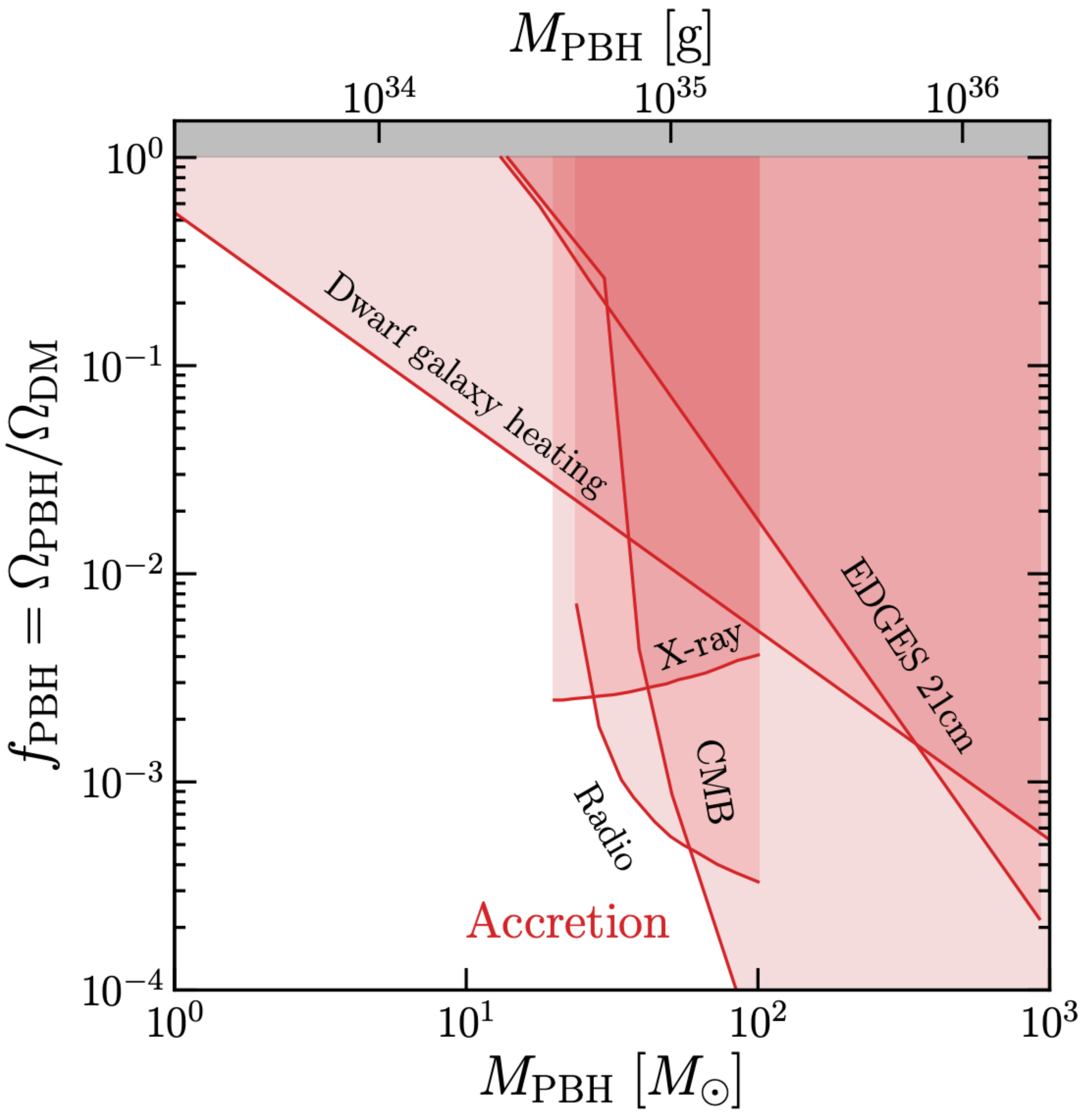
Sterile neutrinos

$$\Gamma_{\nu\gamma} \simeq \frac{9\alpha G_F^2 m_s^5 \sin^2(2\theta)}{1024\pi^4} \simeq 1.36 \times 10^{-29}\ \mathrm{s}^{-1} \left[\frac{\sin^2(2\theta)}{10^{-7}}\right] \left(\frac{m_{\nu_s}}{1\ \mathrm{keV}}\right)^5$$



TAKE AWAY: Re-analysis of INTEGRAL data provides the strongest constraints on particle DM ~100 keV

Limits on accreting PBH



- **10-100 solar mass** PBH can accrete interstellar gas and produce observable **X-ray** and **radio emission** today

  Gaggero, FC+ PRL'17; Inoue & Kusenko JCAP'17; Lu+ ApJL'21

- Same mechanism can also modify the recombination history of the Universe => constraints set by anisotropies and spectrum of the **CMB**

  Carr MNRAS 1981; Ricotti+ ApJ'08; Poulin, FC+ PRD'17

- Significant **theoretical uncertainties**: e.g. accretion rate and the ionizing effects of the radiation; impact of more realistic/complex mass functions

  Manshanden+ JCAP'19

➡ **Future** radio facilities (**SKA**, **ngVLA**) have the potential to either set very strong constraints on PBH abundance or to detect a population of PBHs at the GC

Weltman+ PASA'20