Signatures of Primordial Black Holes in Theories of Large Extra Dimensions

Work by: **Avi Friedlander**, Katherine Mack, Sarah Schon, Ningqiang Song, and Aaron Vincent

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Overview

- Primordial Black Holes
- Large Extra Dimensions
- Ways To Observe Primordial Black Holes
- Conclusions

Primordial Black Holes

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- If PBHs survive they act as **Cold Dark Matter**
- PBHs have been studied extensively in 4D
  - But in **extra-dimensions** black holes behave differently!

Large Extra-Dimensions

- ADD model proposes M_* is true scale of Quantum Gravity (Arkani-Hamed et al. arxiv:hep-ph/9803315)

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$$V(r) = \frac{m_1 m_2}{M_*^{2+N_{\mathrm{ED}}} r^{1+N_{\mathrm{ED}}}}$$

- When r >> R

$$V(r) \approx \frac{m_1 m_2}{M_*^{2+N_{\mathrm{ED}}} R^{N_{\mathrm{ED}}} r} \quad \Rightarrow \quad M_*^{2+N_{\mathrm{ED}}} R^{N_{\mathrm{ED}}} = M_{\mathrm{pl}}^2$$

Extra Dimensional Black Holes

- Black holes with $r_s << R$ have **modified size and temperature**

$$r_s = \frac{a(N_{\mathrm{ED}})}{M_*}\left(\frac{M}{M_*}\right)^{\frac{1}{N_{\mathrm{ED}}+1}}$$

$$T_{BH} = \frac{N_{\mathrm{ED}}+1}{4\pi r_s}$$

See Conley and Wizanksy
arxiv:hep-ph/0611091

Extra Dimensional Black Holes

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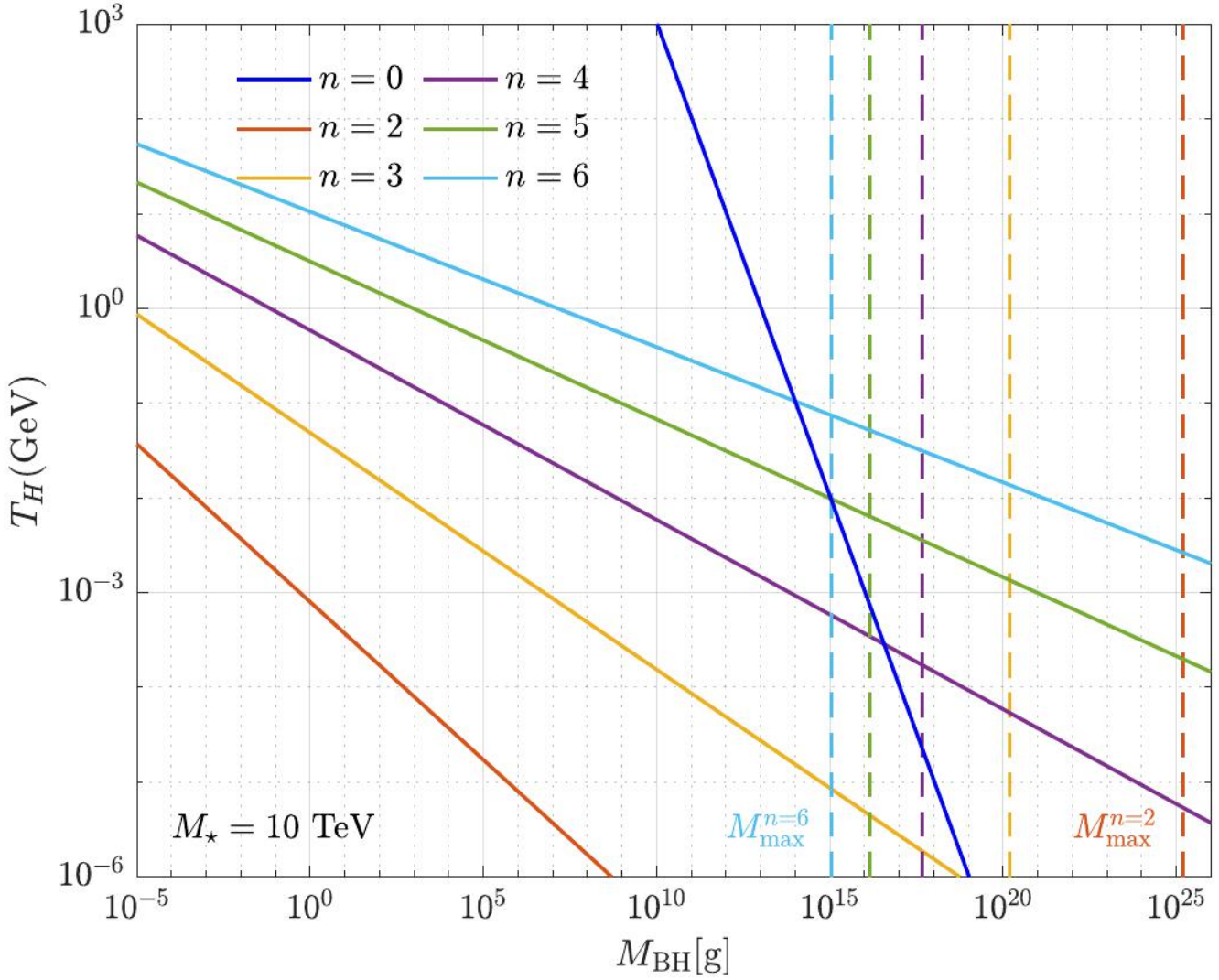

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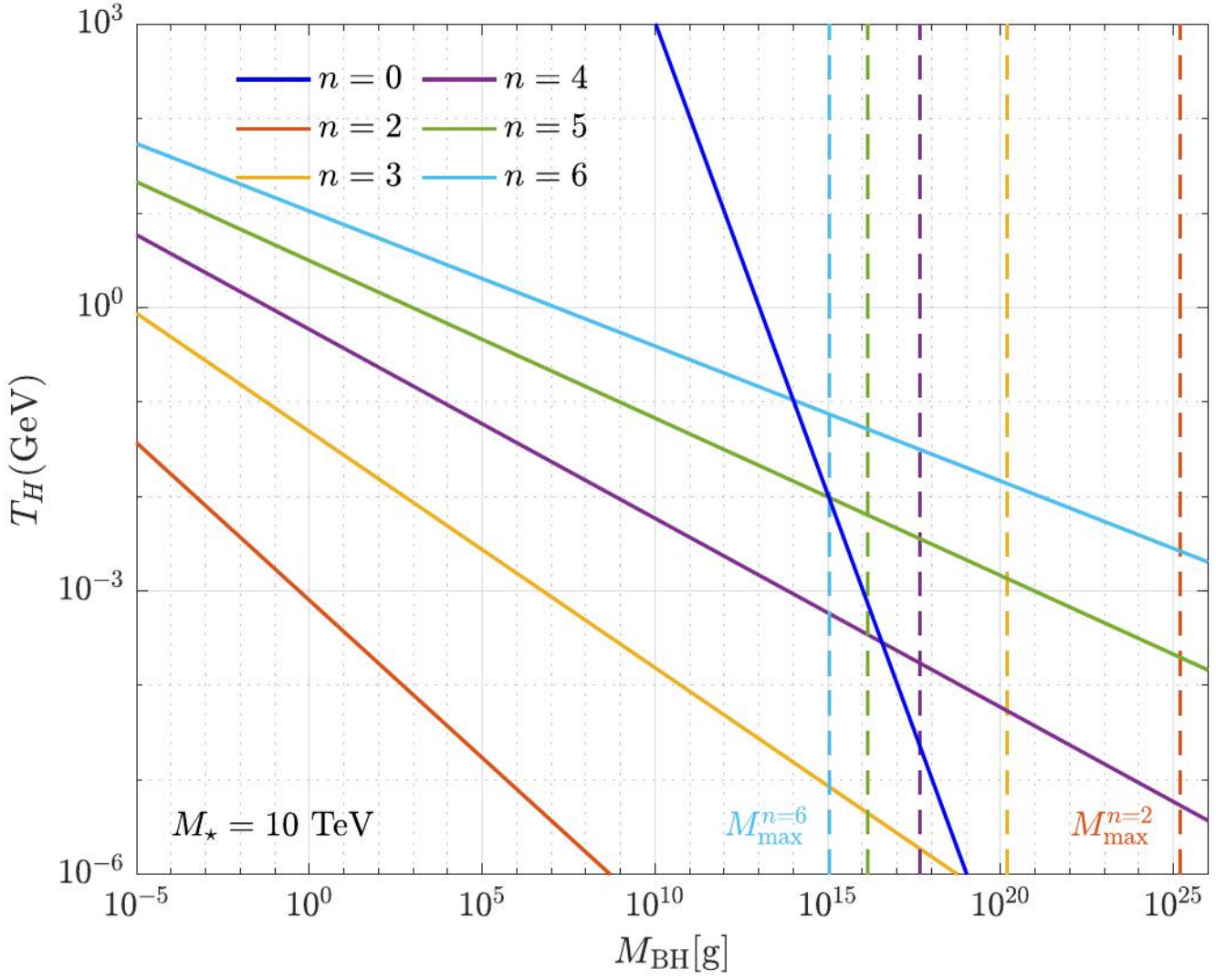
Extra Dimensional Black Holes

- Black holes with $r_s << R$ have **modified size and temperature**
- Particle collisions at $E > M_*$ can **produce microscopic black holes**



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Black Hole Evolution

- Black hole mass evolves due to **accretion** and **evaporation**

$$\frac{dM}{dt} = \left(-\alpha + \beta \frac{T^4}{T_H^4} \right) T_H^2$$

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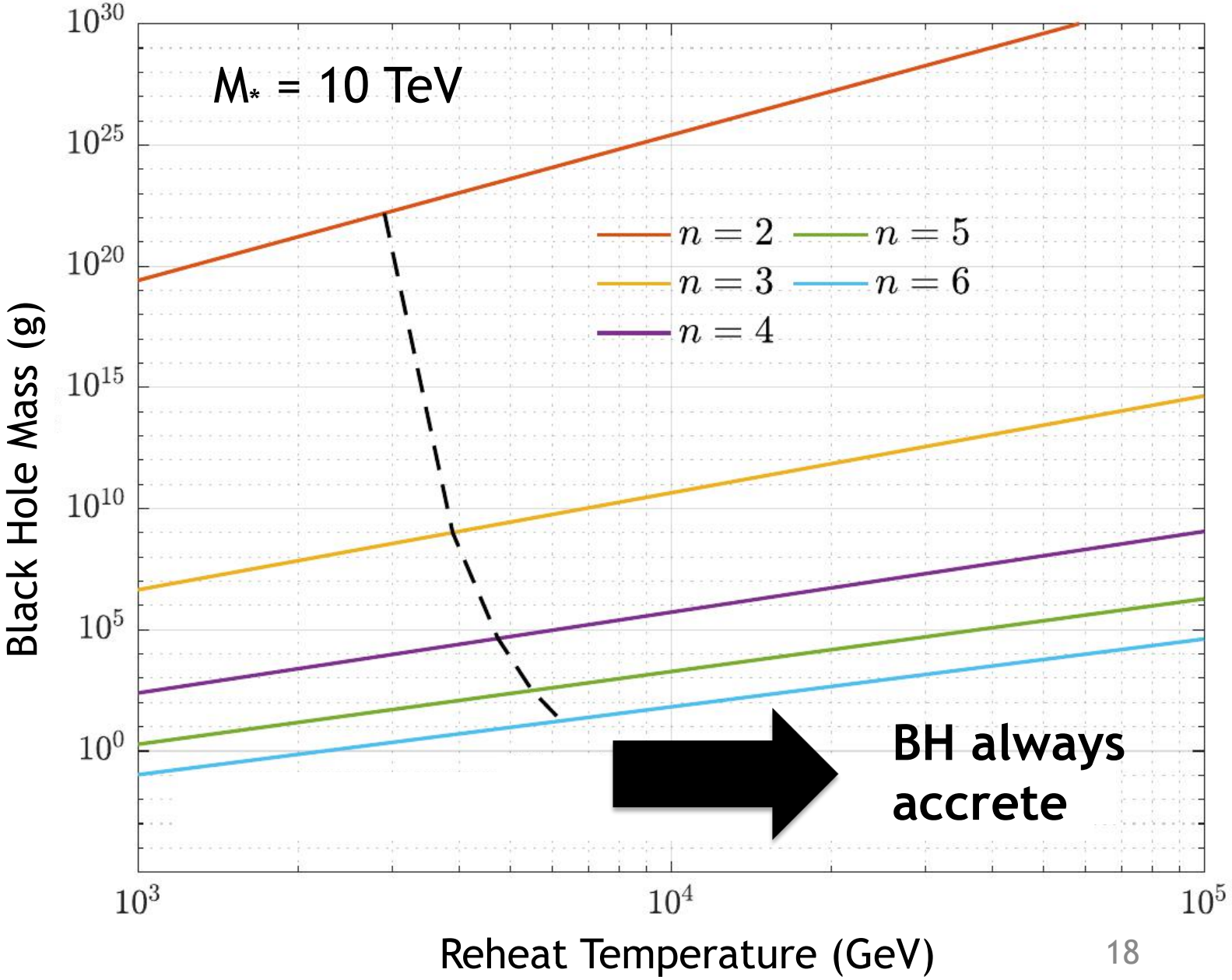
- Typically either accretion or evaporation dominate

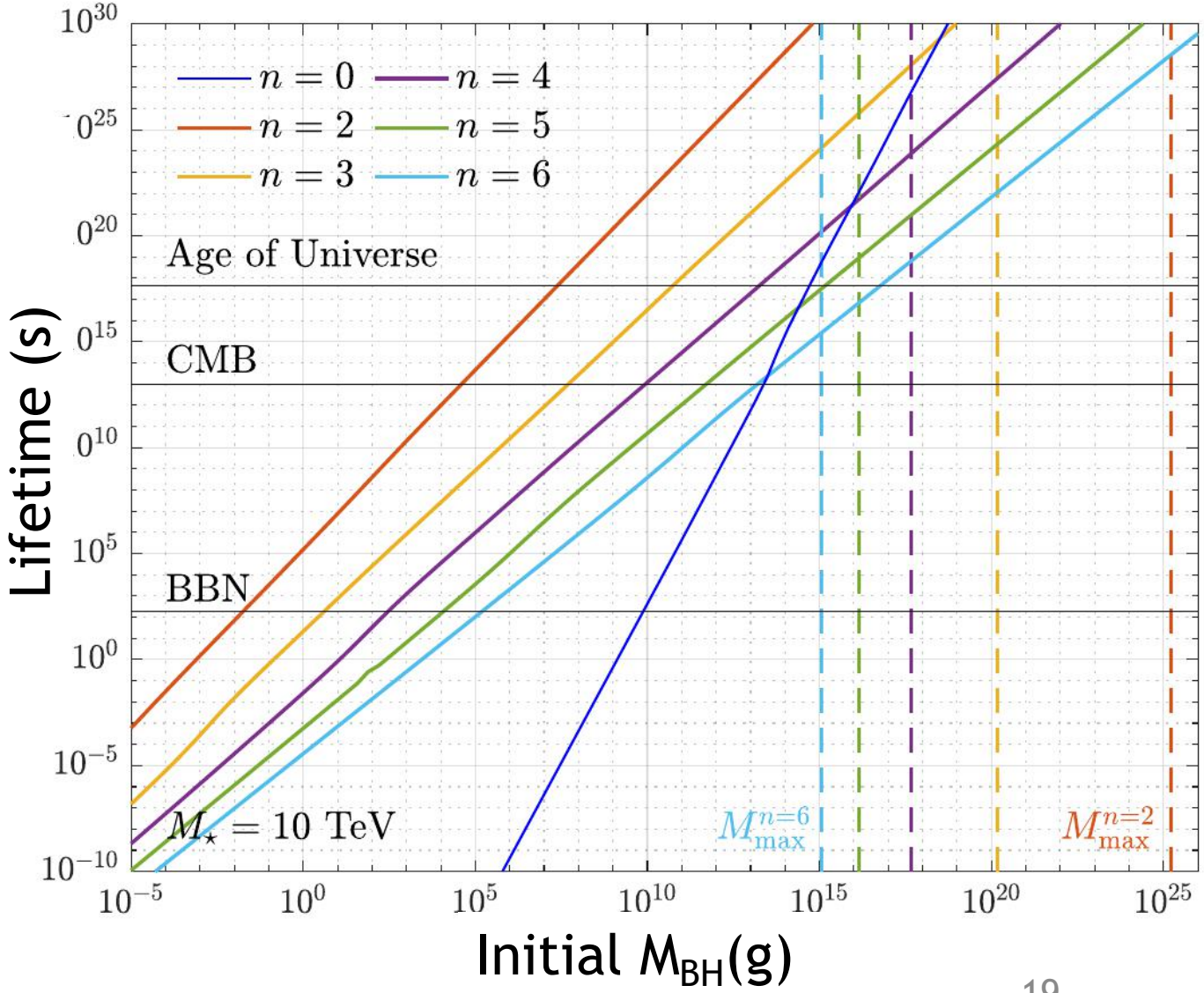
Black Hole Growth

Black holes in extra-dimensions initially **grow via accretion** depending if they are created when the universe is sufficiently hot



Black Hole Evaporation

- After accretion stops due to the universe cooling, black holes evaporate via Hawking radation
- Lifetime depends on initial mass and number of dimensions



Evaporation Spectrum

- Black holes evaporate to **all sufficiently light particles** with a grey-body spectrum

$$dP = \sigma_i \frac{\omega}{\exp(\omega/T_H) \mp 1} \frac{d^3p}{(2\pi)^3}$$

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- **Secondary photons** and **electrons** produced from **cascades** of unstable evaporation products
  - PPPC4DMID used for secondary spectrum

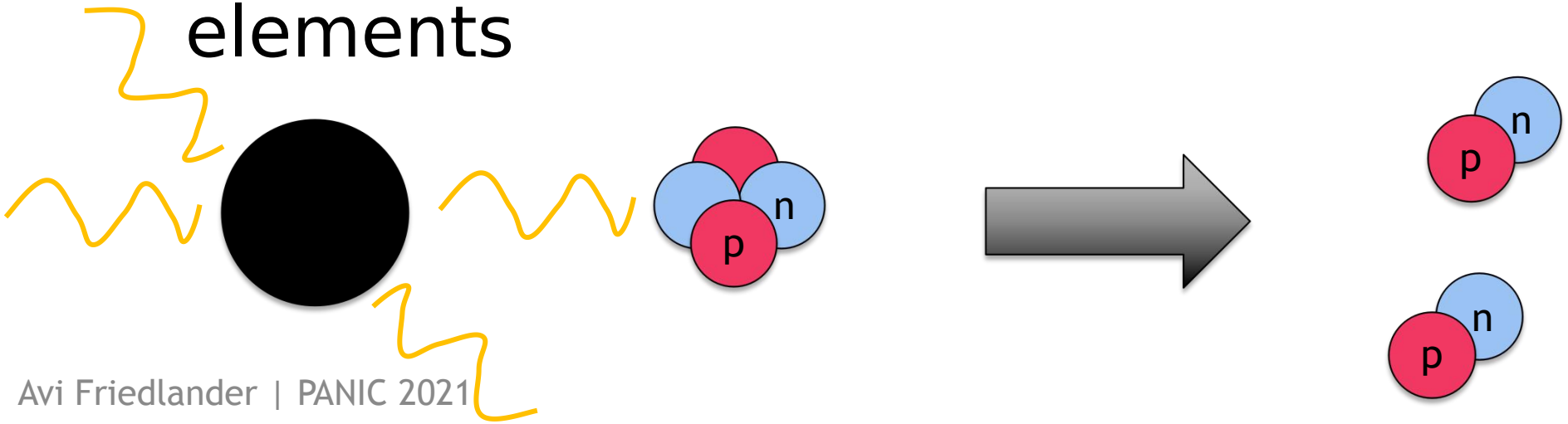
    Cirelli et al. arxiv:1012.4515

Constraining Large Extra-Dimensions

- Astrophysical constraints on PBHs come from a variety of sources:
  - Big Bang Nucleosynthesis (**BBN**)
  - **Galactic centre** photon flux
  - **Isotropic x-ray** and **gamma**-ray flux
  - **CMB** angular power spectrum
  - **21cm** Cosmology

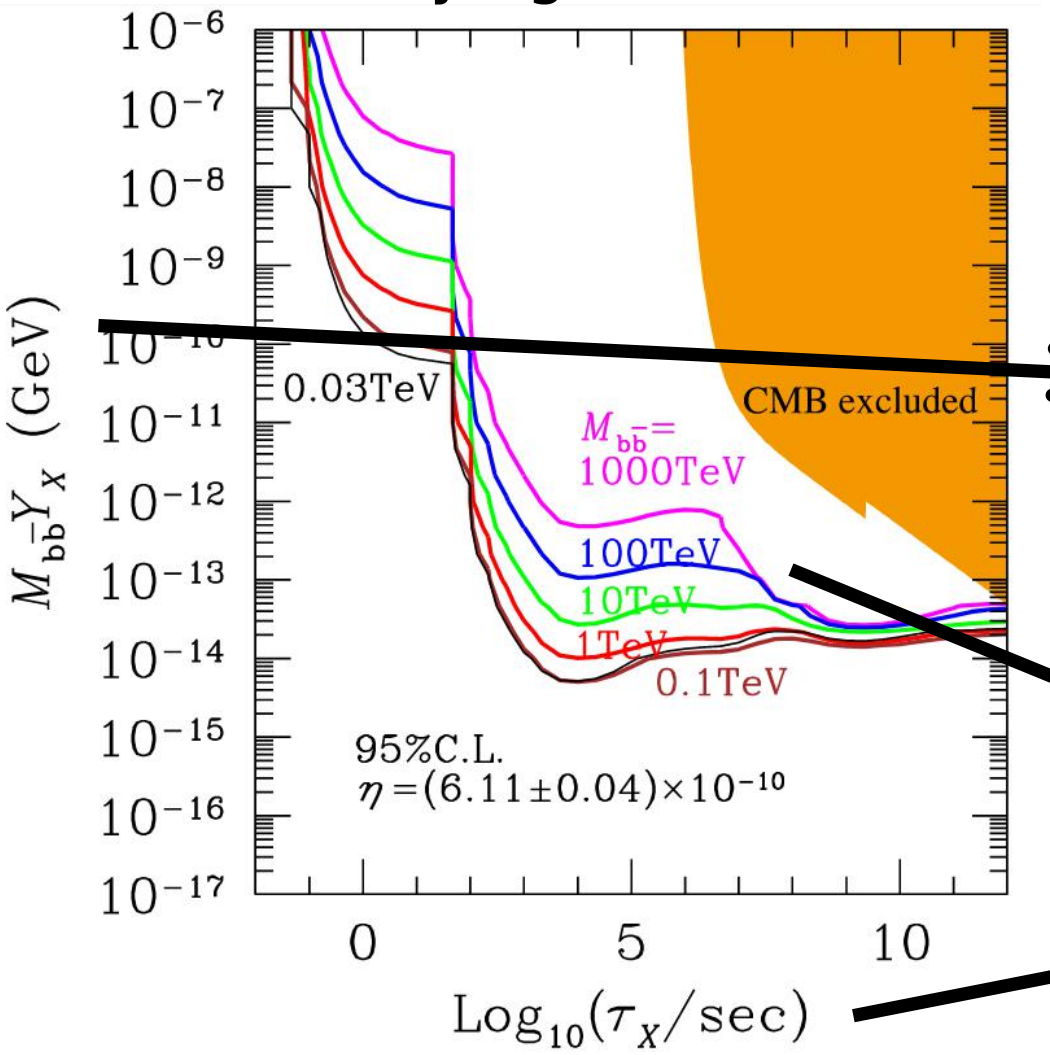
PBH and Big Bang Nucleosynthesis

- When the universe cools to ~1 MeV light **nuclei form**
- PBHs can change the **expansion rate** during BBN
- Evaporation products can **dissociate** primordial elements



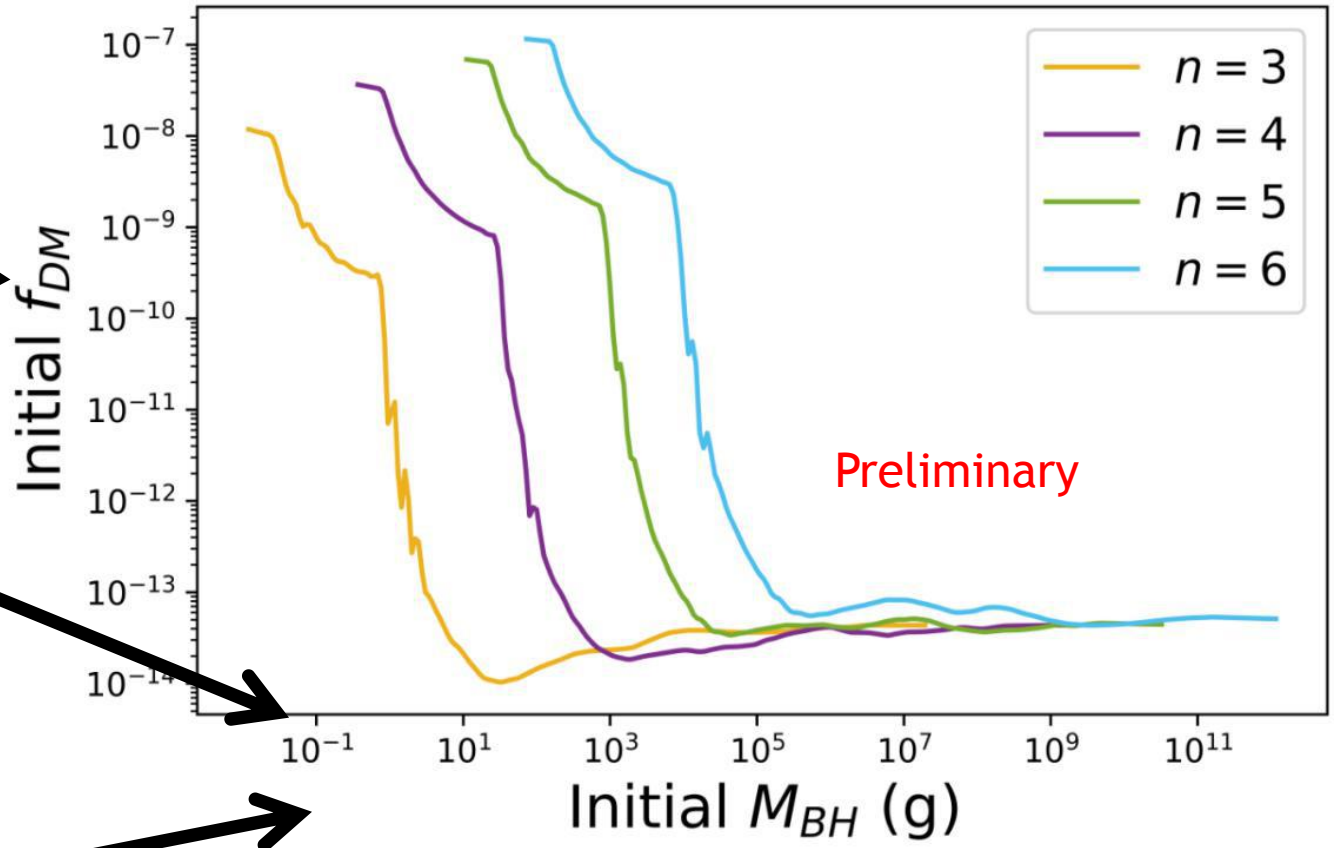
Preliminary BBN Results

Decaying Dark Matter



Kawasaki et al. arxiv:1709.01211

Primordial Black Holes



See Kieth et al. arxiv:2006.03608
for recasting details

Galactic Centre Photons

$$\frac{d\Phi_\gamma}{dEd\Omega} = \frac{f_{PBH}}{4\pi M_{BH}} \frac{dN}{dEdt} \frac{\mathcal{D}(\Omega)}{\Delta\Omega}$$

$$\mathcal{D}(\Omega) \equiv \int_{l.o.s.\Delta\Omega} \rho_{DM}(\vec{x}) d\Omega dx$$

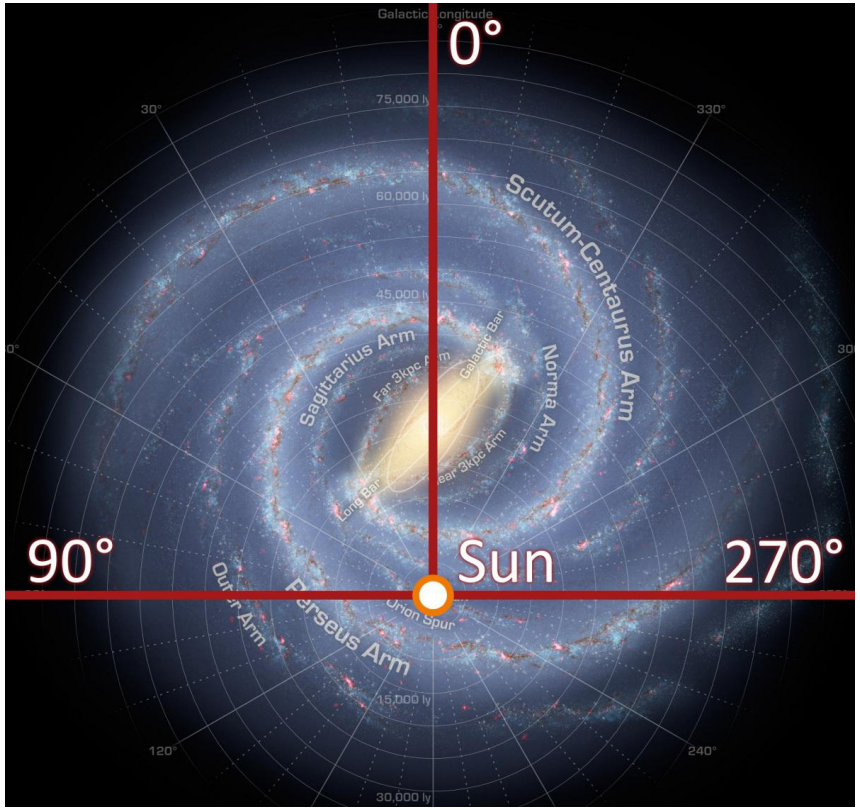


Image from NASA

- Compared to previously processed 6-years of INTEGRAL/SPI data (Bouchet et al. arxiv:1107.0200)

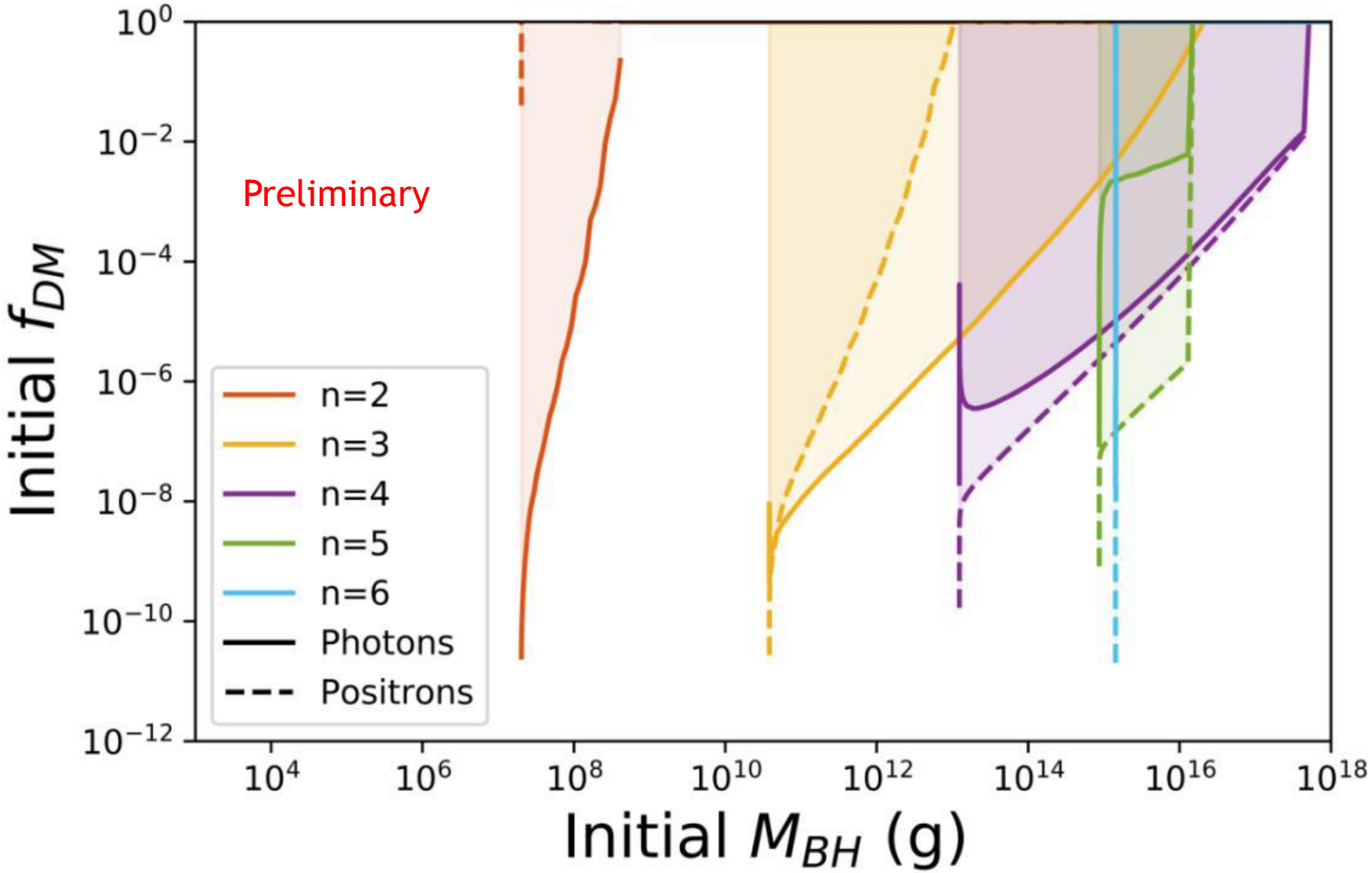
Galactic Centre Positrons

- If PBHs evaporate to positrons, they will annihilate to produce an additional 511 keV signal

$$\frac{d\Phi_{511}}{d\Omega} = 2(1 - 0.75 f_P) \frac{dN_{e^+}}{dt} \frac{1}{4\pi} \frac{1}{M_{BH}} \frac{1}{\Delta\Omega} \mathcal{D}(\Omega)$$

- Compared to INTEGRAL/SPI 511 keV line data (Siegert et al. arxiv:1906.00498)

Preliminary Galactic Centre Results



Extragalactic Background Light

- Photon spectrum tracked from recombination to today

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- Each redshift step updated using:

$$\frac{d\Phi_{\gamma,\mathrm{EBL}}}{dE}(E, z_i) = \frac{dE'}{dE}\frac{d\Phi_{\gamma,\mathrm{EBL}}}{dE'}(E', z_{i-1})e^{-\tau} + n_{BH}(z_i)\frac{d^2N_\gamma}{dEdt}\frac{z_{i-1} - z_i}{H(z_i)(1+z_i)}$$

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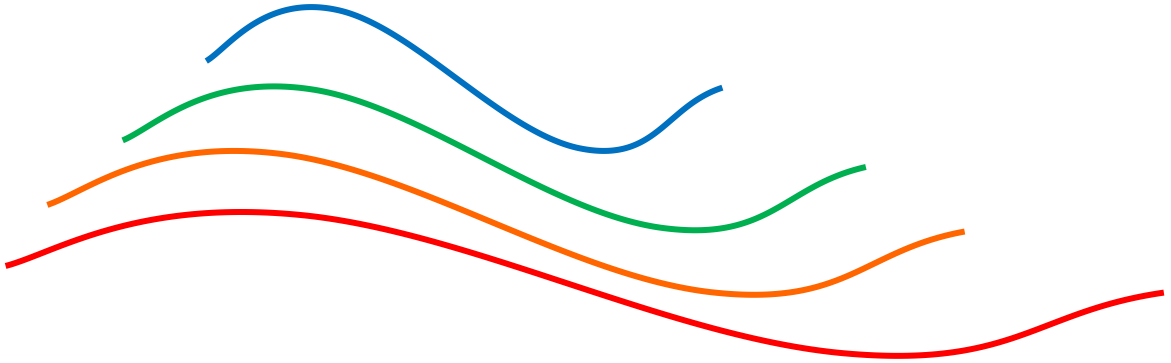
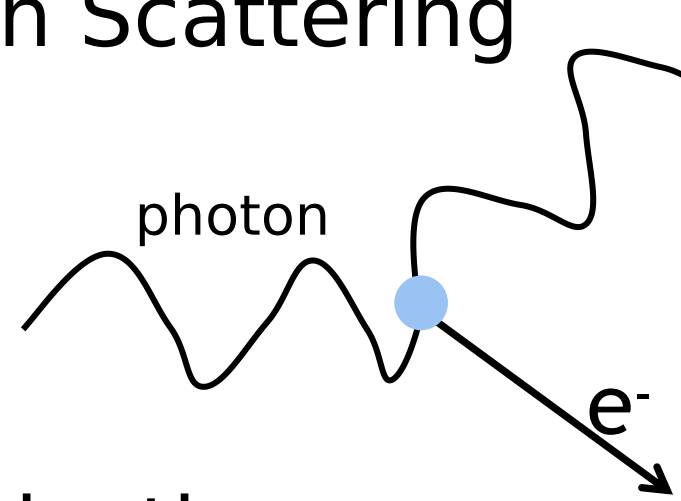
Photon Energy Loss

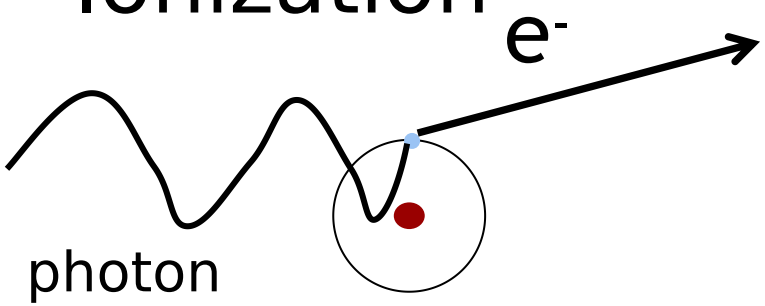
Redshifting



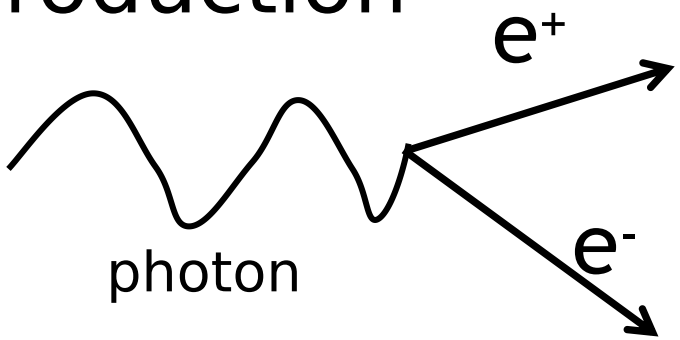
Compton Scattering



Ionization



Pair Production

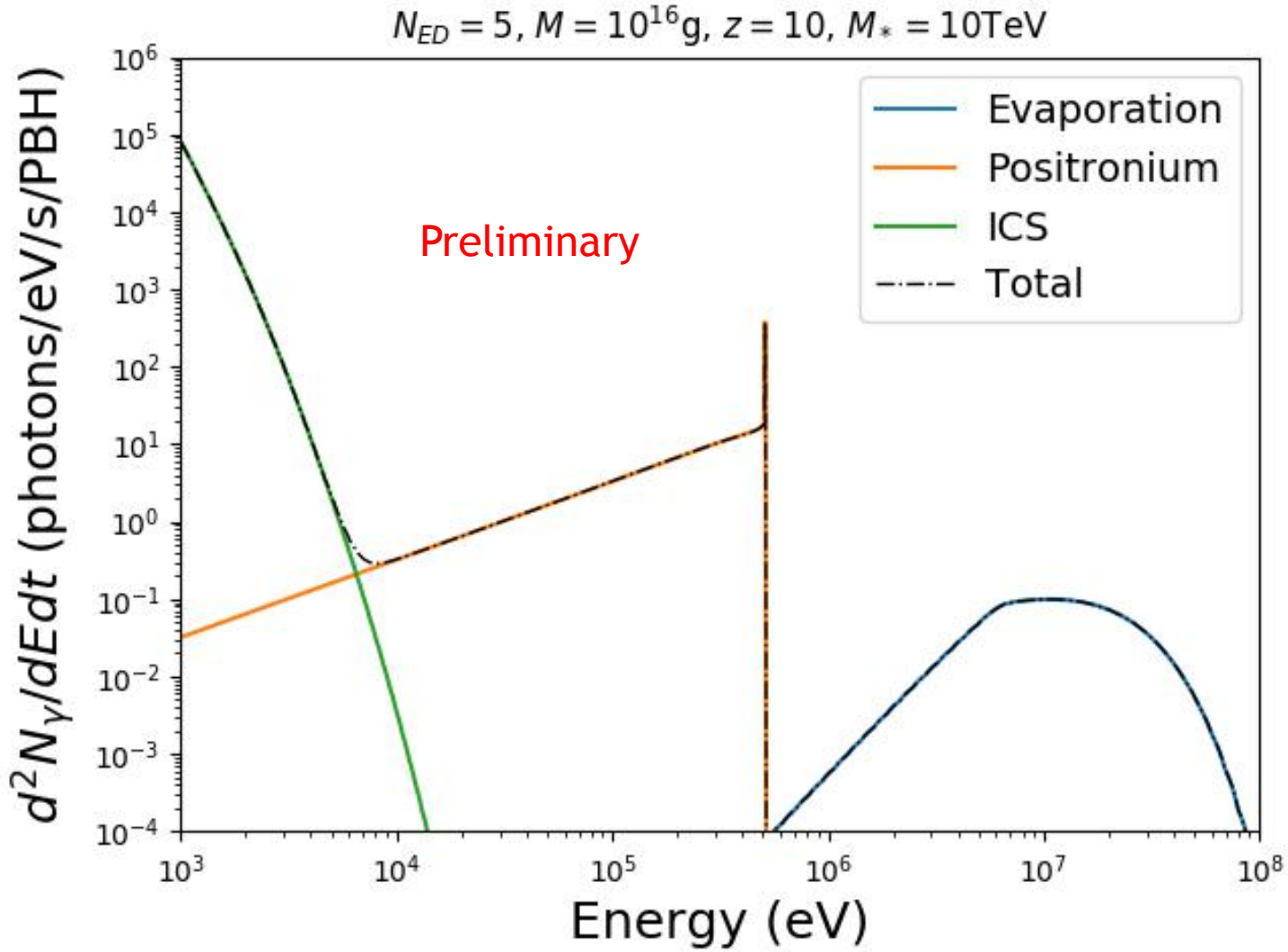


For the observed energy range (1 keV - 100 MeV) attenuation is important for high redshift (z > 100)

Extragalactic Photon Production

Extragalactic Photons produced via 3 mechanisms:

- Evaporation
- Positronium annihilation
- Inverse Compton scattering (ICS)



Galactic Isotropic Signal

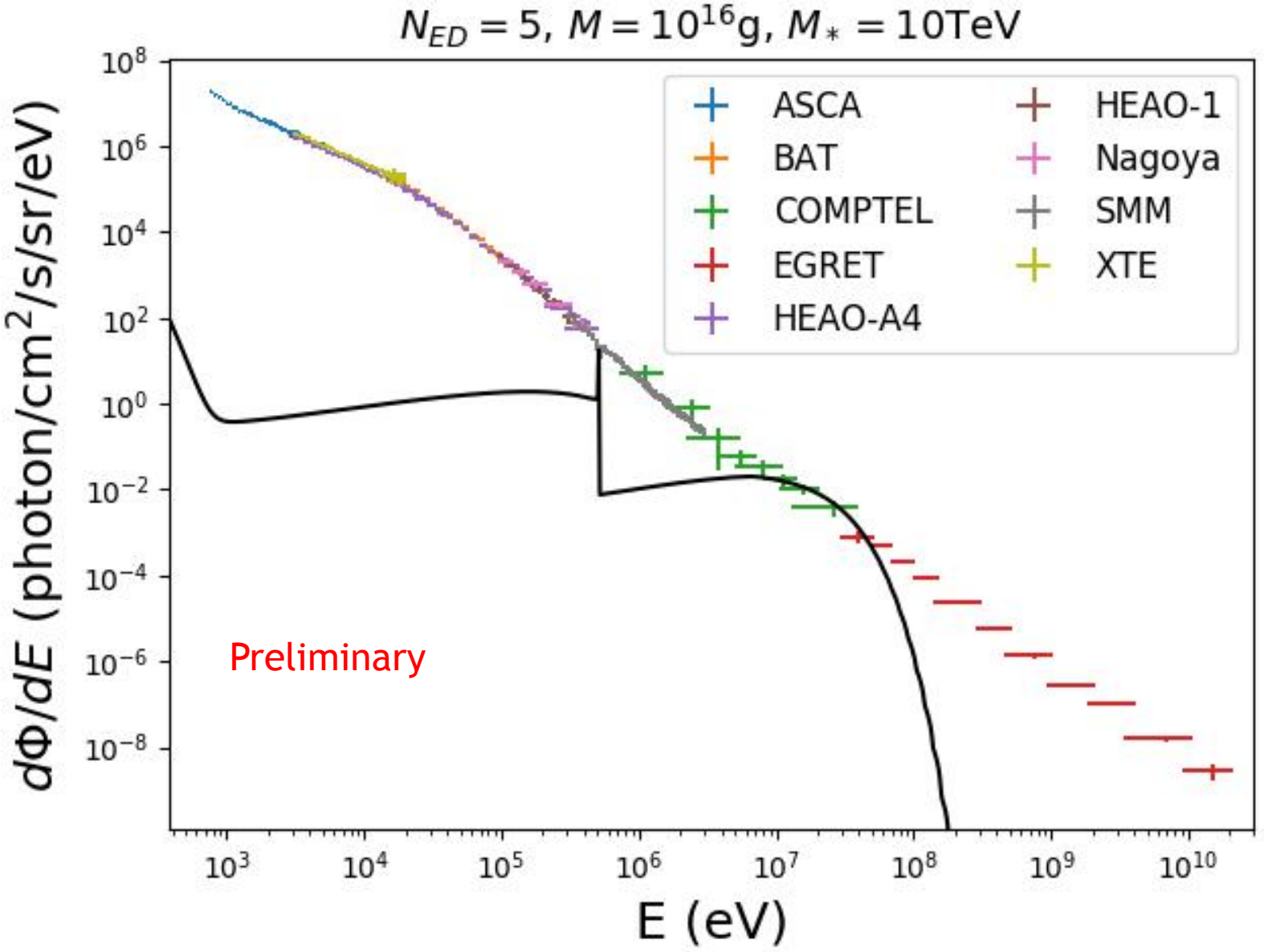
- Galactic photon flux is highly anisotropic but non-zero in all directions
- Isotropic component can be determined with

$$\frac{d\Phi_{\gamma,\mathrm{gal}}}{dE} = \frac{f_{PBH}}{4\pi M_{BH}} \frac{d^2 N_\gamma}{dEdt}(E, M_{BH})\mathcal{D}_{\mathrm{min}}$$

$$\mathcal{D}_{\mathrm{min}} = \int_{r_{\mathrm{earth}}}^{\infty} dr \rho_{NFW}(r)$$

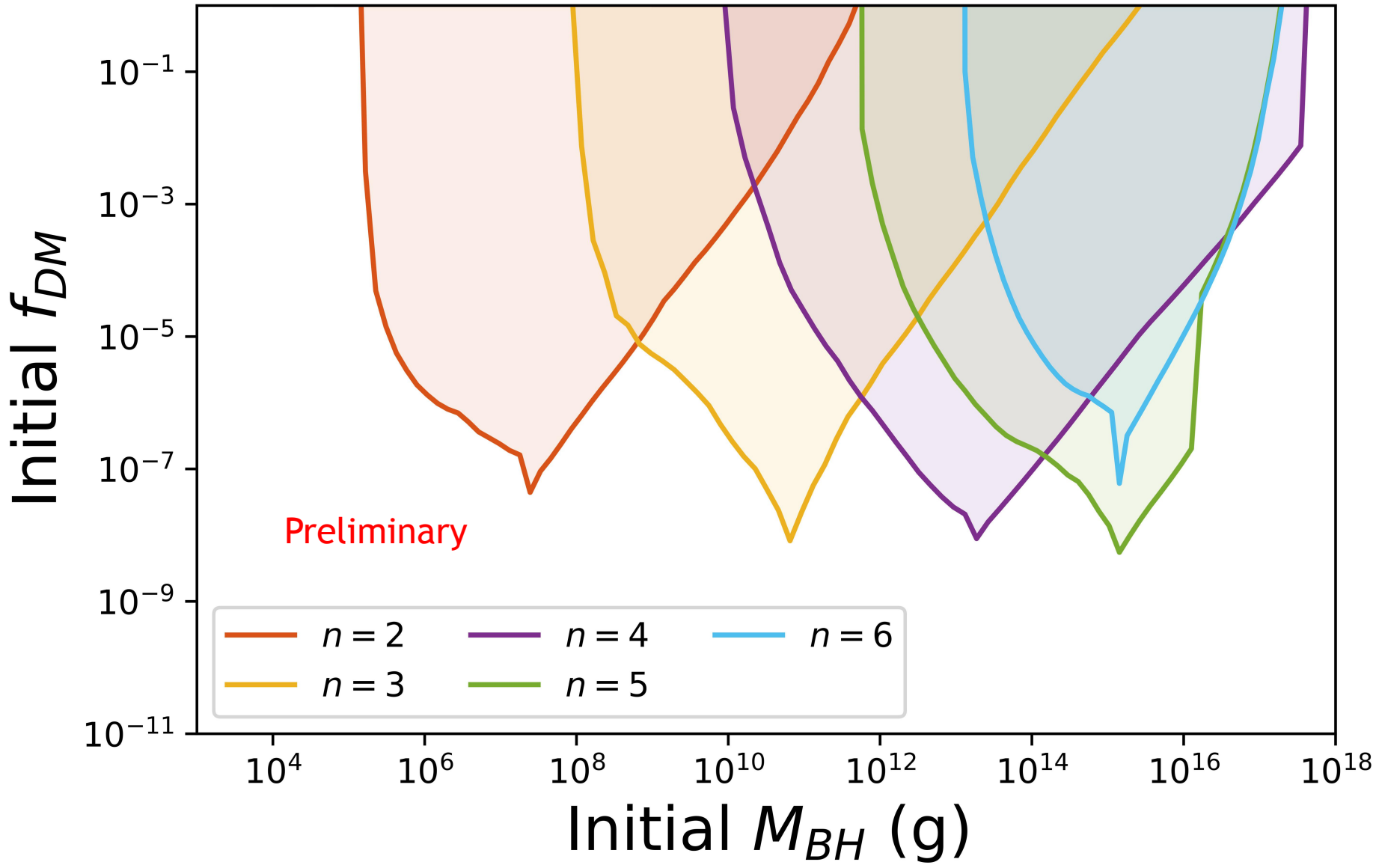
See: Iguaz et al.
arxiv:2104.03145

Observed Flux



Calculated flux is compared to various **x-ray and gamma-ray telescopes** as compiled by Ajello et al. (arxiv:0808.3377)

Preliminary Isotropic Light Constraints



Conclusions

- Theories of Large Extra Dimensions predict the existence of Primordial Black Holes
- Astrophysical observables of LED PBHs is very different from regular PBHs
- Constraints from BBN, galactic centre, and isotropic background light change significantly with additional large dimensions

Questions?

Extra Slides

The Hierarchy Problem

- Two scales exist in the Standard Model
  - Electroweak scale ($\sim 10^3$ GeV)
  - Planck/Quantum Gravity scale ($\sim 10^{18}$ GeV)

- Higgs boson mass is set by the electroweak scale but without fine tuning, quantum corrections would be expected to increase Higgs mass to the Planck

Detailed BBN Effects

- There are four main mechanism for PBHs to affect BBN
  - Increased universe expansion rate causing earlier neutron freeze-out
  - Hadrons and mesons converting protons to neutrons after freeze-out
  - Energetic mesons dissociating Helium nuclei
  - Energetic photons dissociating Helium nuclei

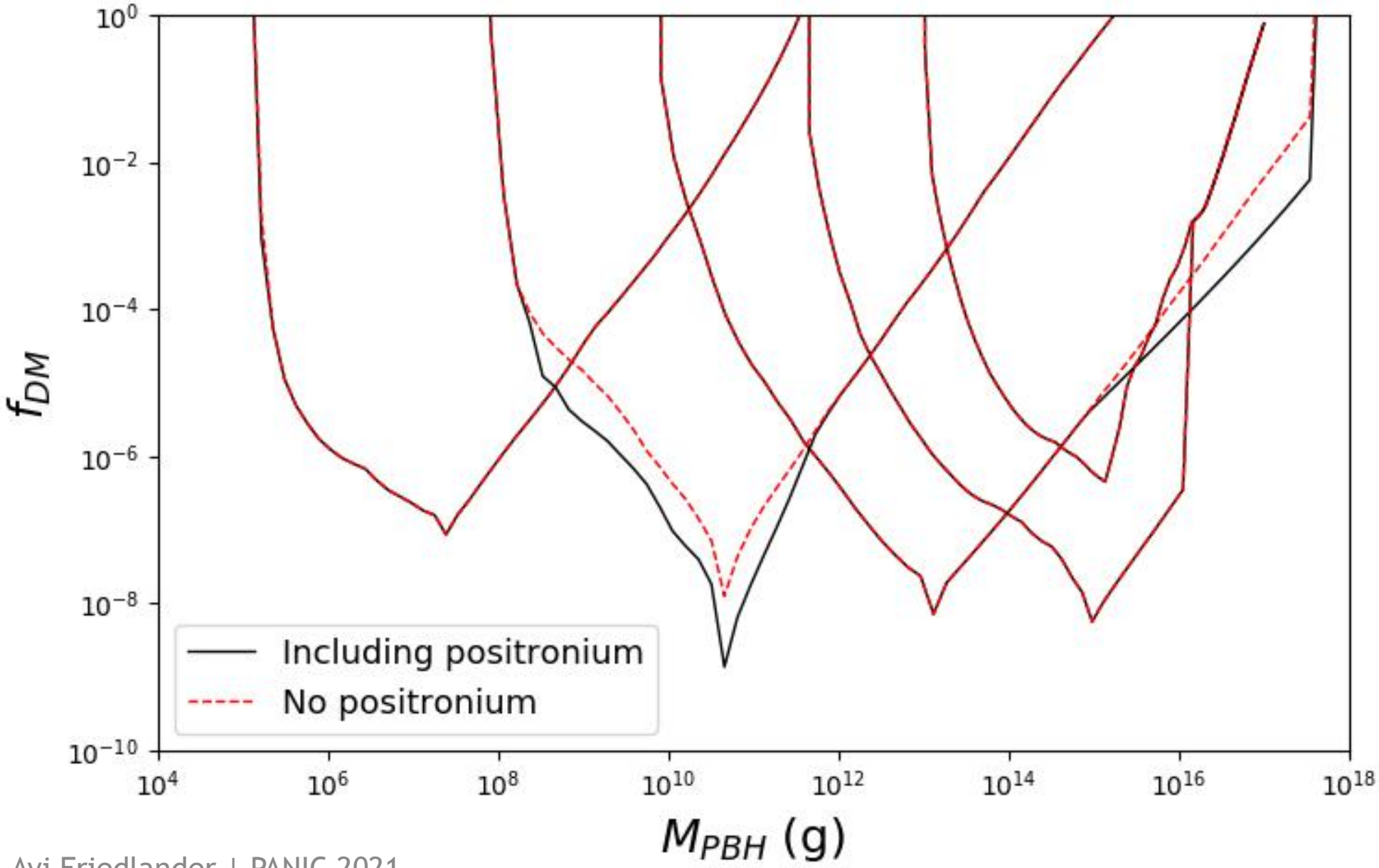
Calculating BBN Constraints

- The effect of decaying dark matter on BBN has been studied in detail (Kawasaki et al. arxiv:1709.01211)

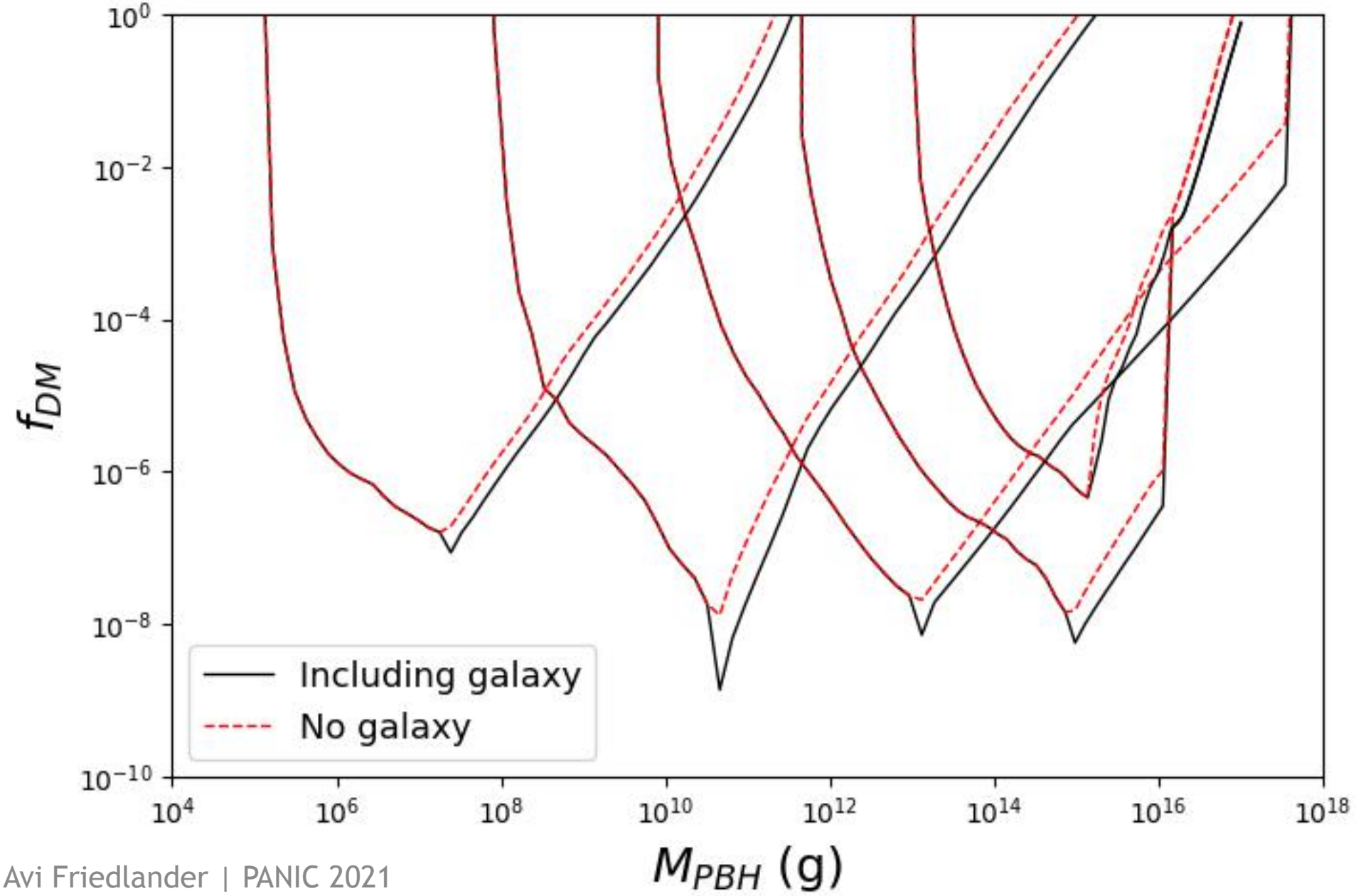
- PBHs can be mapped onto decaying dark matter models ensuring key properties match
  - Dark matter/PBH density
  - Average injected fermion energy
  - Average time of injected energy

  (Kieth et al. arxiv:2006.03608)

Impact of Positronium



Impact of Milky Way



Inverse Compton Scattering

- High energy electrons and positrons upscatter CMB photons

$$\frac{d^2 N_{\gamma,\mathrm{ics}}}{dEdt}(E, M_{BH}) = 2\int_0^\infty dE_e \frac{d^2 N_{e^-}}{dEdt}(E_e, M_{BH}) \frac{d\tilde{N}_{\gamma,\mathrm{ics}}}{dE}(E, E_e, T_{CMB})$$

Photons produced by ICS

Electron spectrum from evaporating PBH

ICS photon spectrum per electron calculated by DarkHistory (arxiv:1904.09296)

Positronium

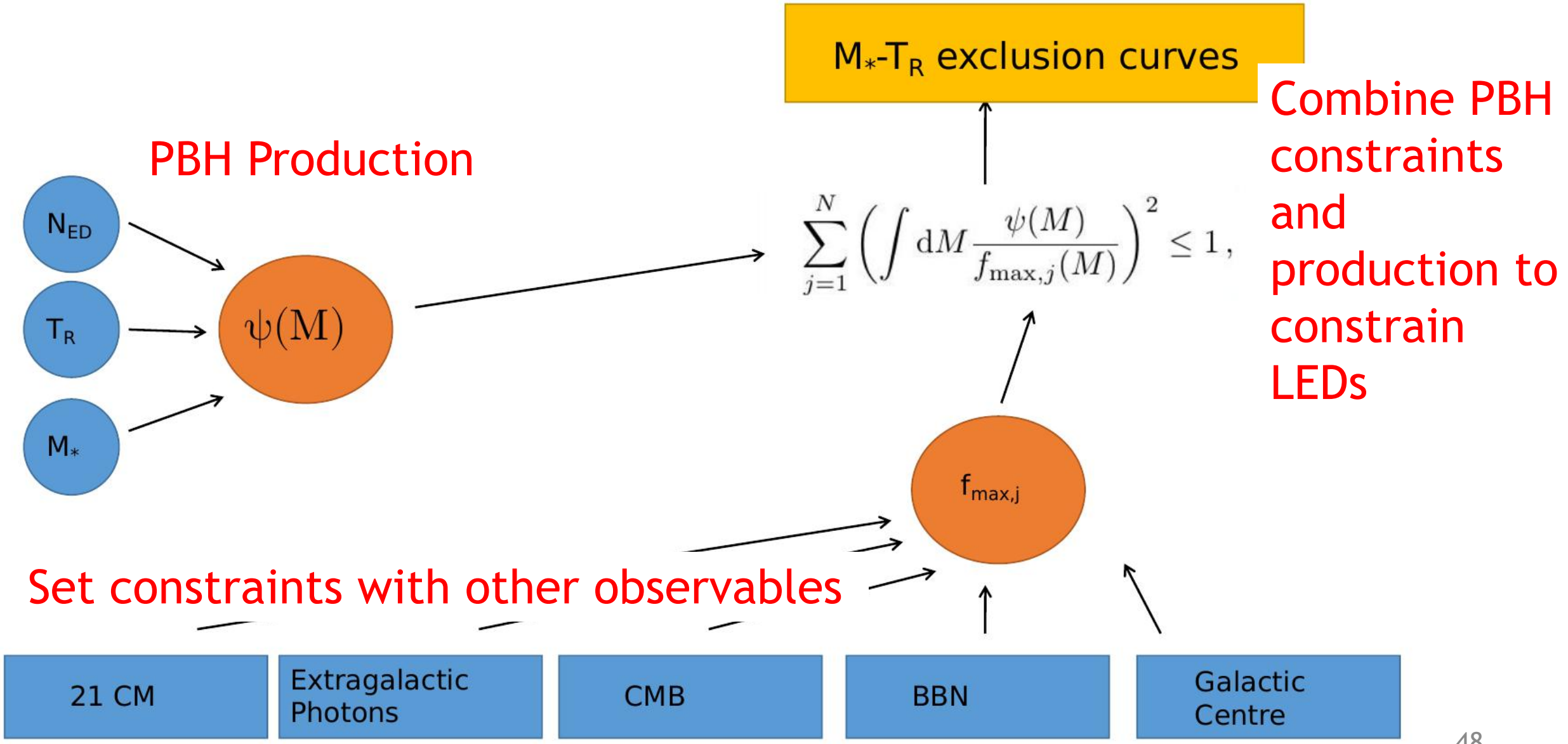
- Positrons annihilate into photons via formation of positronium
  - Each annihilation produces spectrum

$$\frac{d\tilde{N}_\gamma^{\rm ann}}{dE}(E) = \frac{1}{2}\delta(E - m_e) + \frac{3}{4}\frac{dN_\gamma^{\rm ann}}{dE}\bigg|_{\rm triplet}$$

  - All positrons assumed to immediately annihilate

See: Iguaz et al.
arxiv: 2104.03145

Next Steps


M*-TR exclusion curves
PBH Production
NED
TR
M*
ψ(M)
$\sum_{j=1}^{N}\left(\int \mathrm{d}M \frac{\psi(M)}{f_{\mathrm{max},j}(M)}\right)^2 \leq 1,$
fmax,j
Combine PBH constraints and production to constrain LEDs
Set constraints with other observables
21 CM
Extragalactic Photons
CMB
BBN
Galactic Centre