# Primordial Black Holes Dark Matter in the Context of Extra Dimensions

Based on arxiv:2201.11761 (PRD 105, 103508)
August 8th, 2022
Work by: **Avi Friedlander**, Katherine Mack, Sarah Schon, Ningqiang Song, and Aaron Vincent


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

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- When r >> R

$$V(r) = \frac{m_1 m_2}{M_*^{2+n} R^n r}$$

$$M_*^{2+n} R^n = M_{pl}^2$$

# Extra Dimensional Black Holes

- Black holes with $r_h << R$ 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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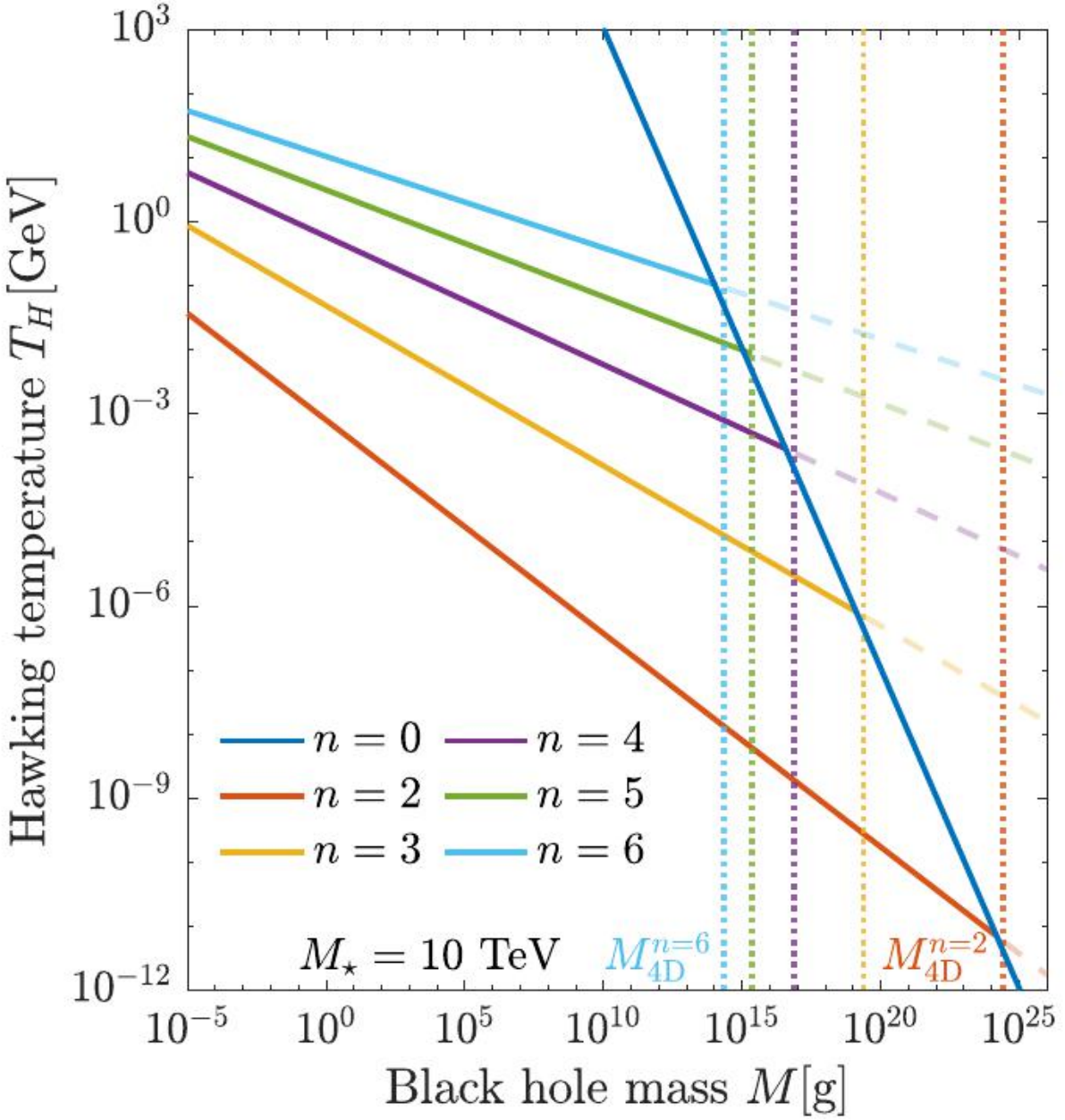


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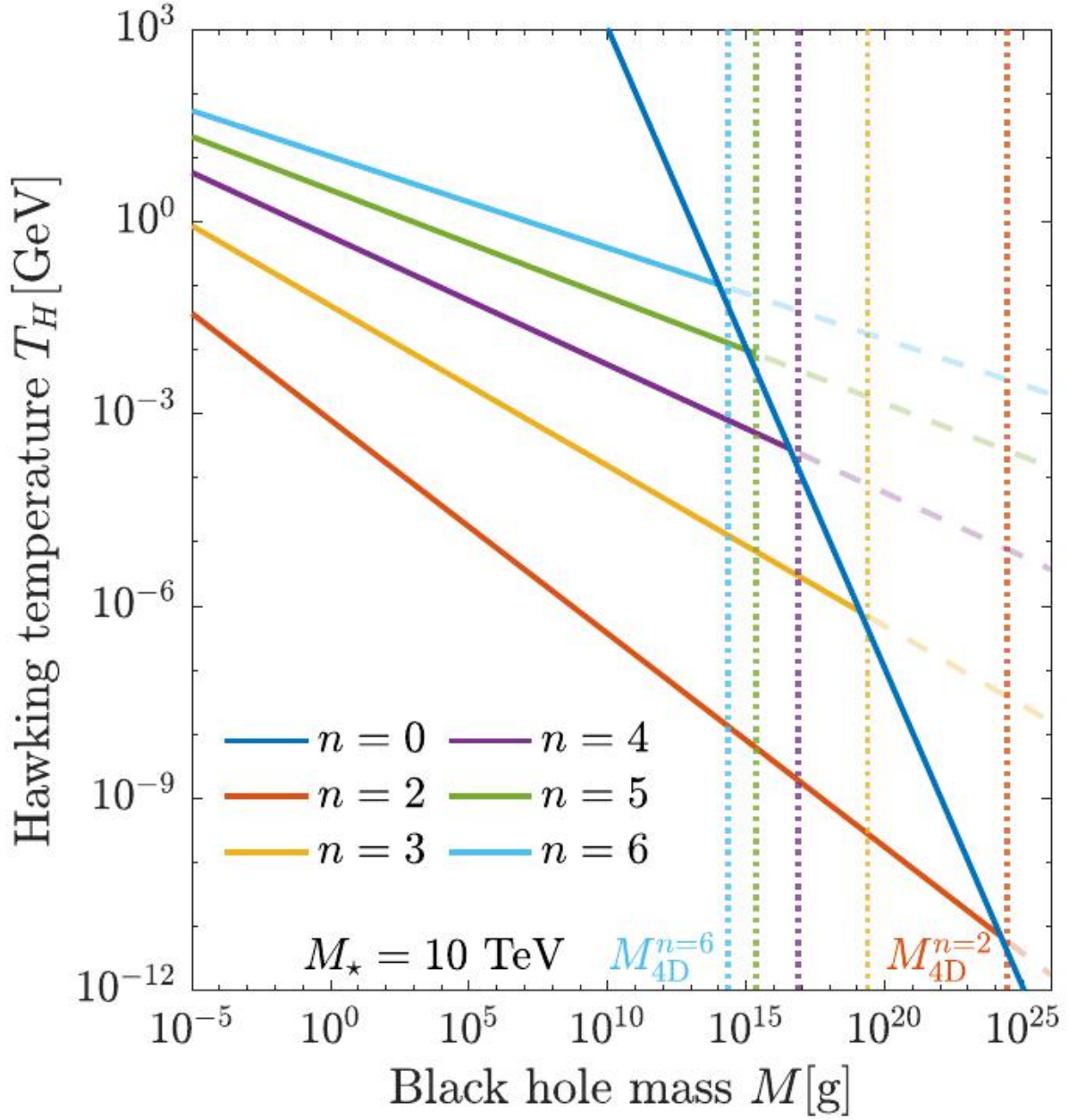
# Extra Dimensional Black Holes

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

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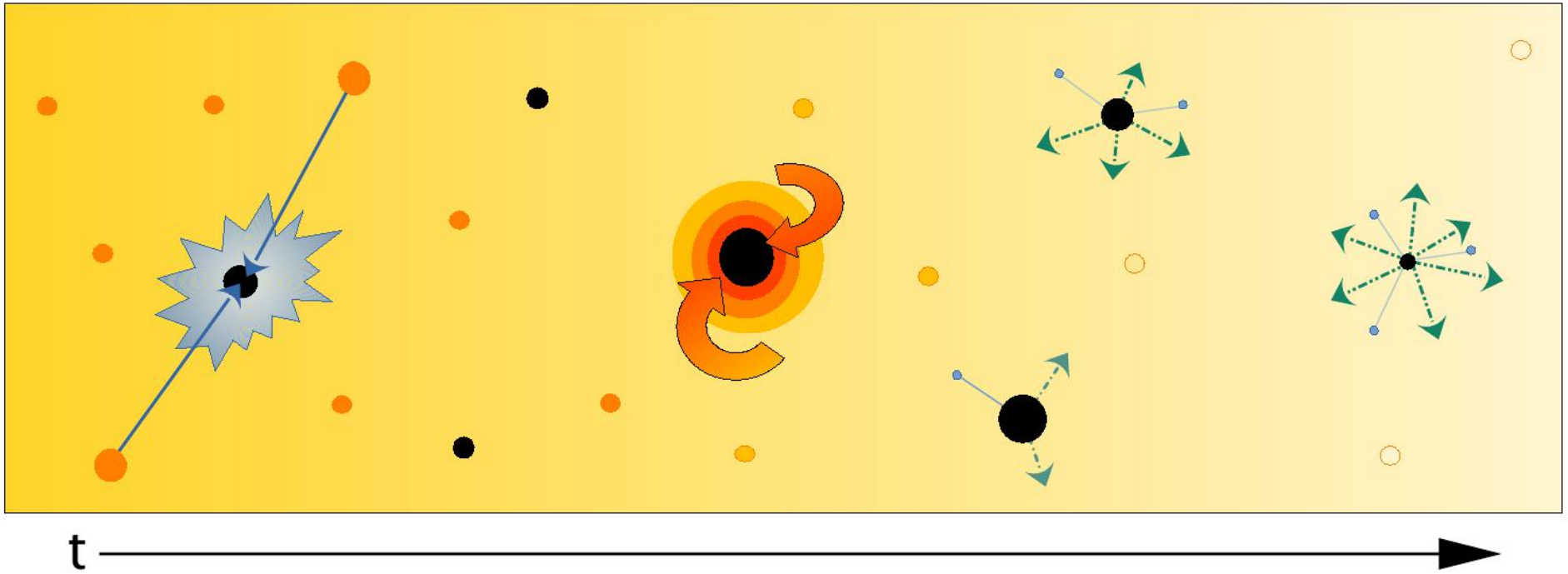
# Black Hole Evolution



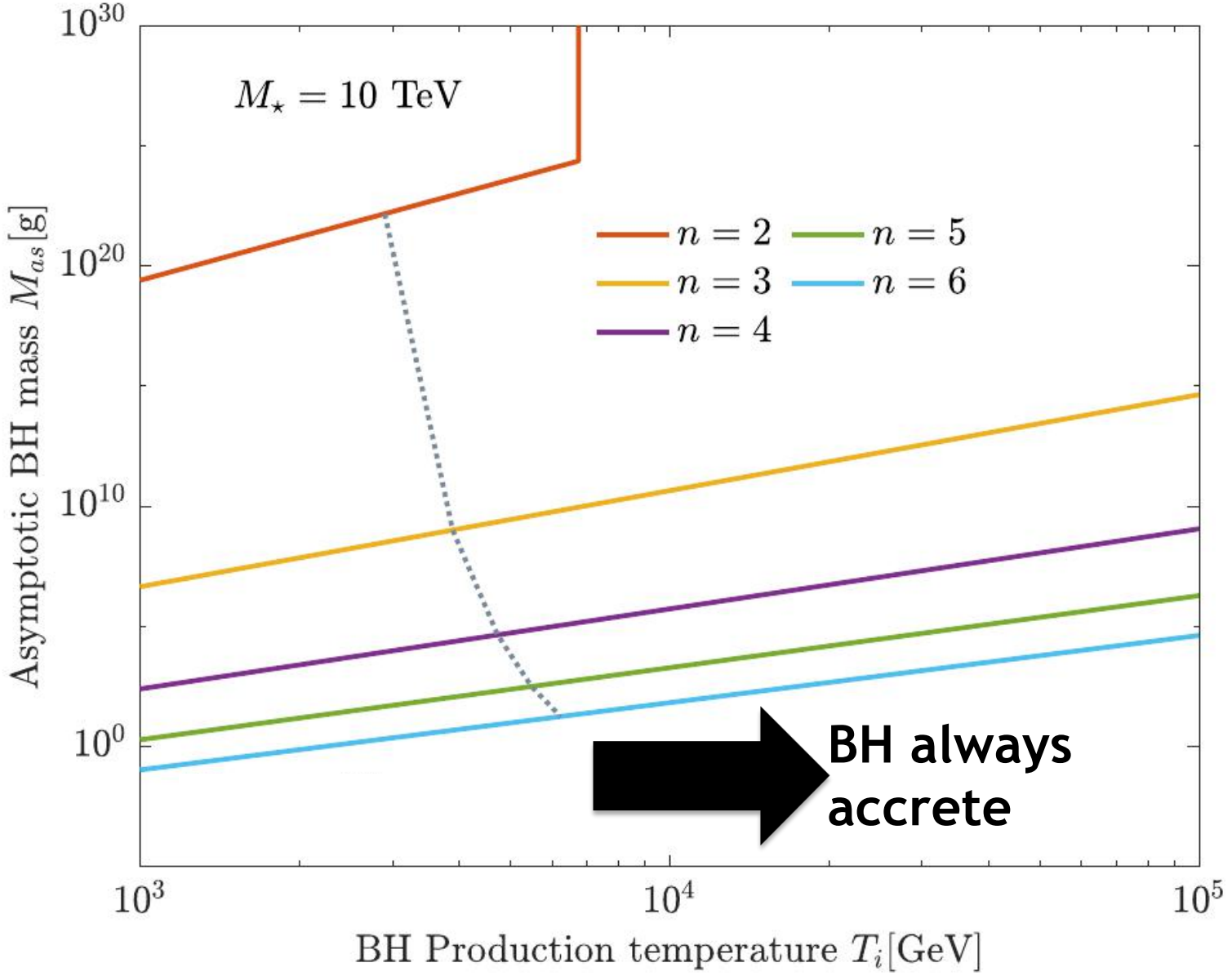

Black hole mass evolves due to **accretion** and **evaporation**

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

Evaporation Accretion

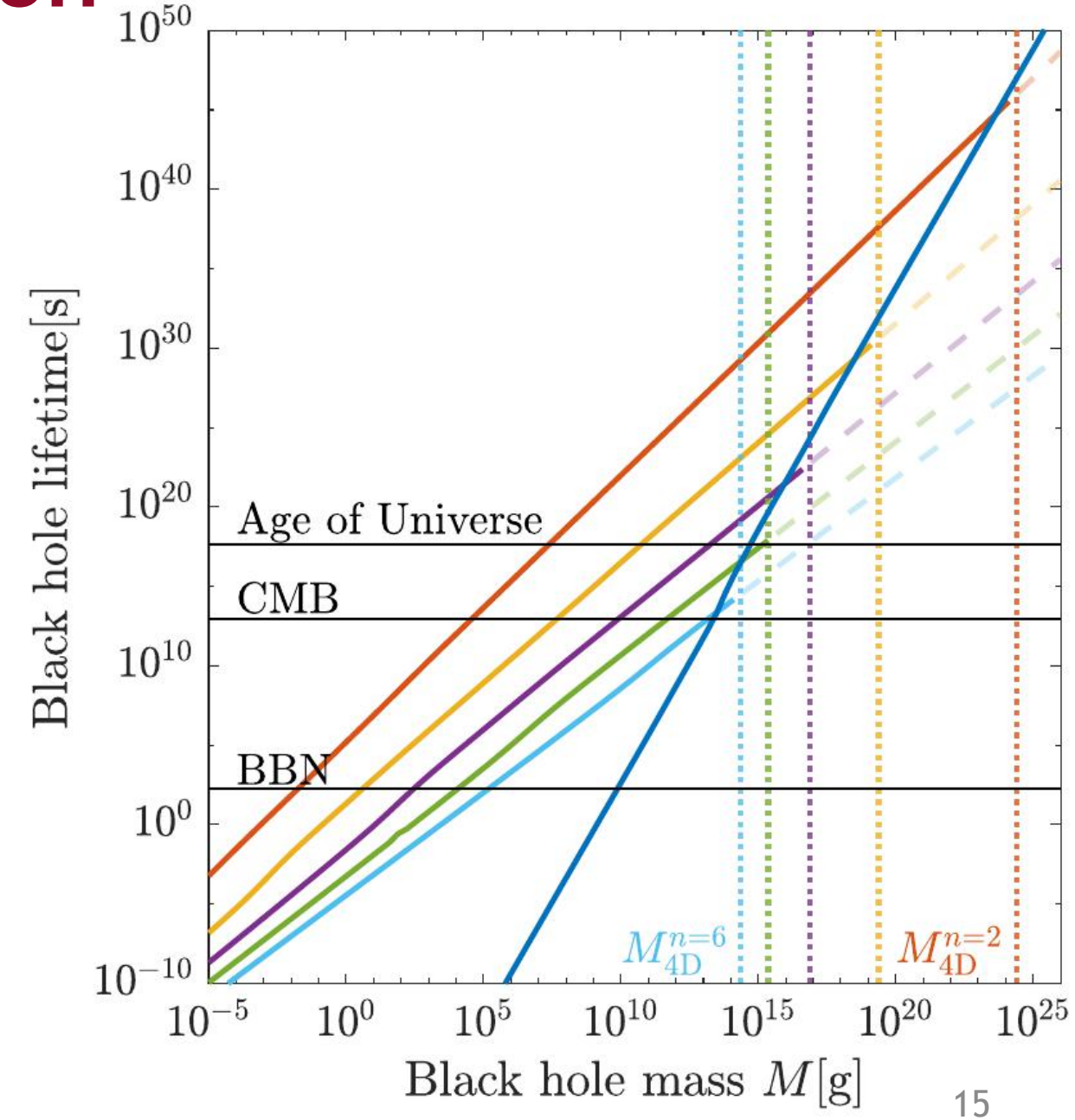
# Black Hole Growth

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**)
  - **CMB** angular power spectrum
  - **Galactic centre** photon flux
  - **Isotropic x-ray** and **gamma**-ray flux

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# Isotropic Light Constraints

- PBH evaporation post-recombination produces an isotropic X-ray and gamma ray background

- There are two seperate components:
  - Extragalactic evaporation
  - Isotropic galactic evaporation

# Extragalactic Evolution

- Extragalactic photon spectrum tracked from recombination to today

- Each redshift step updated using:

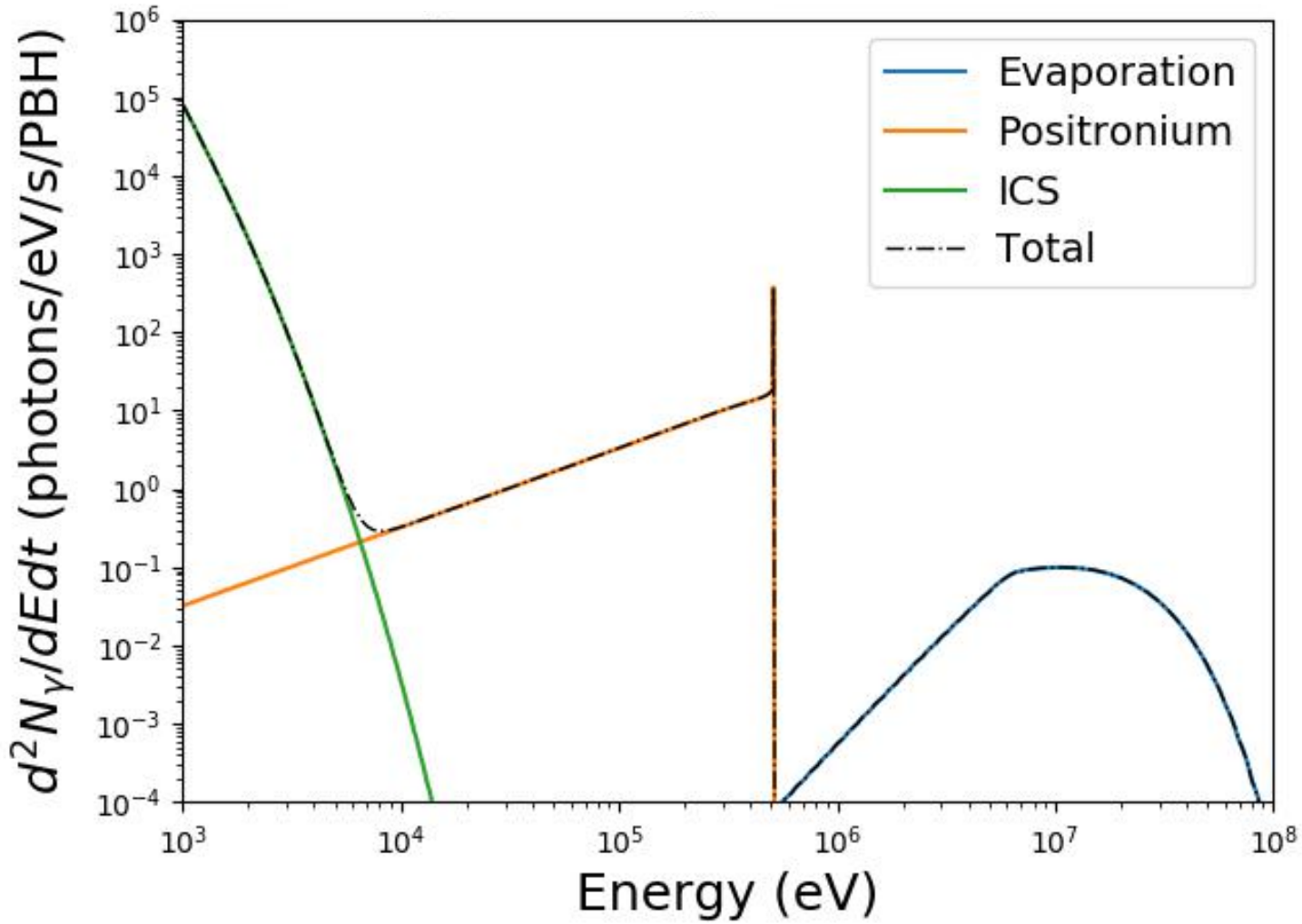
$$\frac{d\Phi_{\gamma,\mathrm{EBL}}}{dE_i} = \frac{V_{i-1}}{V_i}\frac{dE_{i-1}}{dE_i}\frac{d\Phi_{\gamma,\mathrm{EBL}}}{dE_{i-1}}e^{-\tau} + \frac{d\Phi_{\gamma,\mathrm{comp}}}{dE_i dz_i}\Delta z + \frac{d\Phi_{\gamma,\mathrm{inj}}}{dE_i dz_i}\Delta z$$

Universe Expansion | Attenuation | Scattering | Injected Photons

# Extragalactic Photon Production

Extragalactic Photons produced via 3 mechanisms:

- Evaporation



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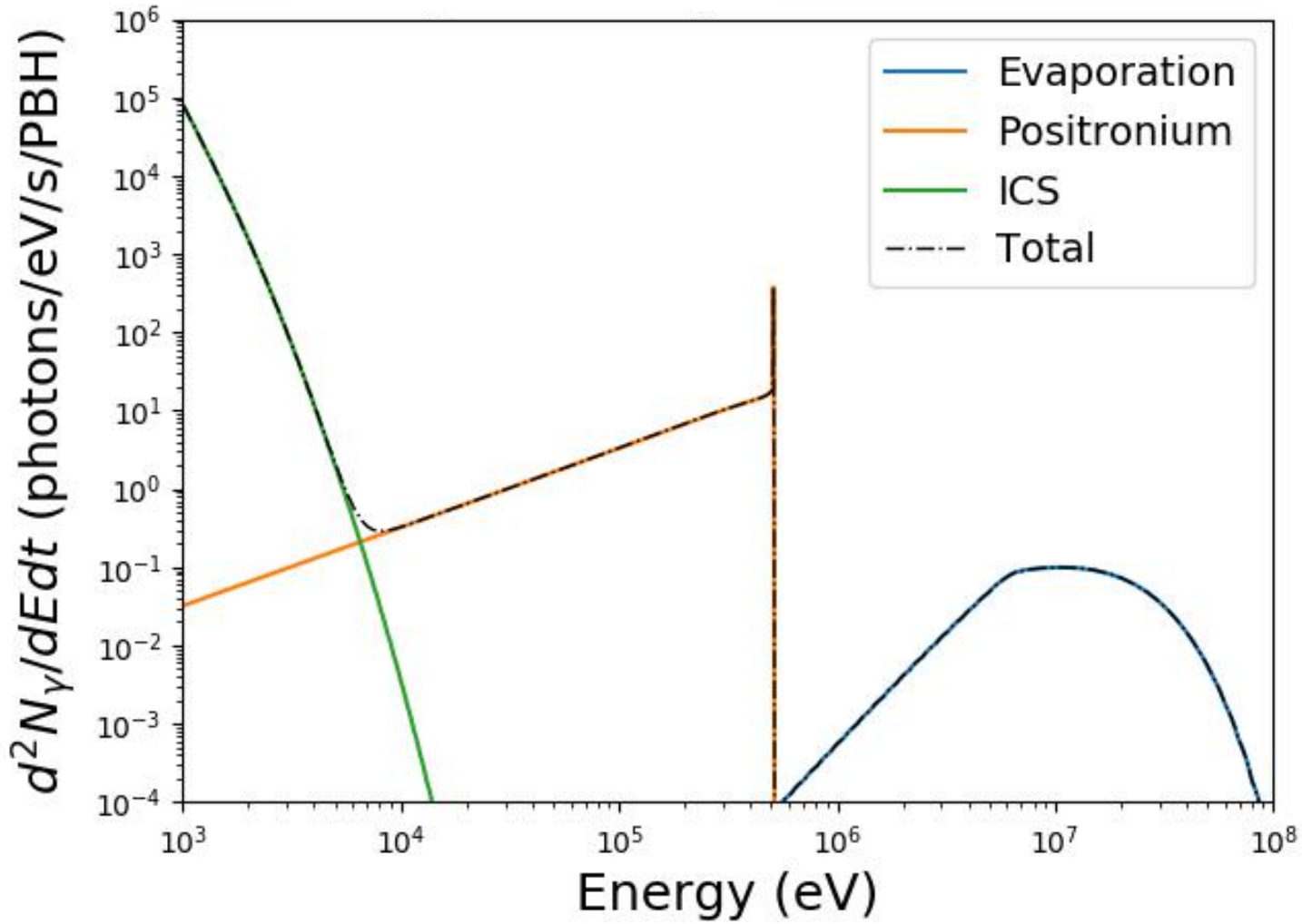

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Extragalactic Photons produced via 3 mechanisms:

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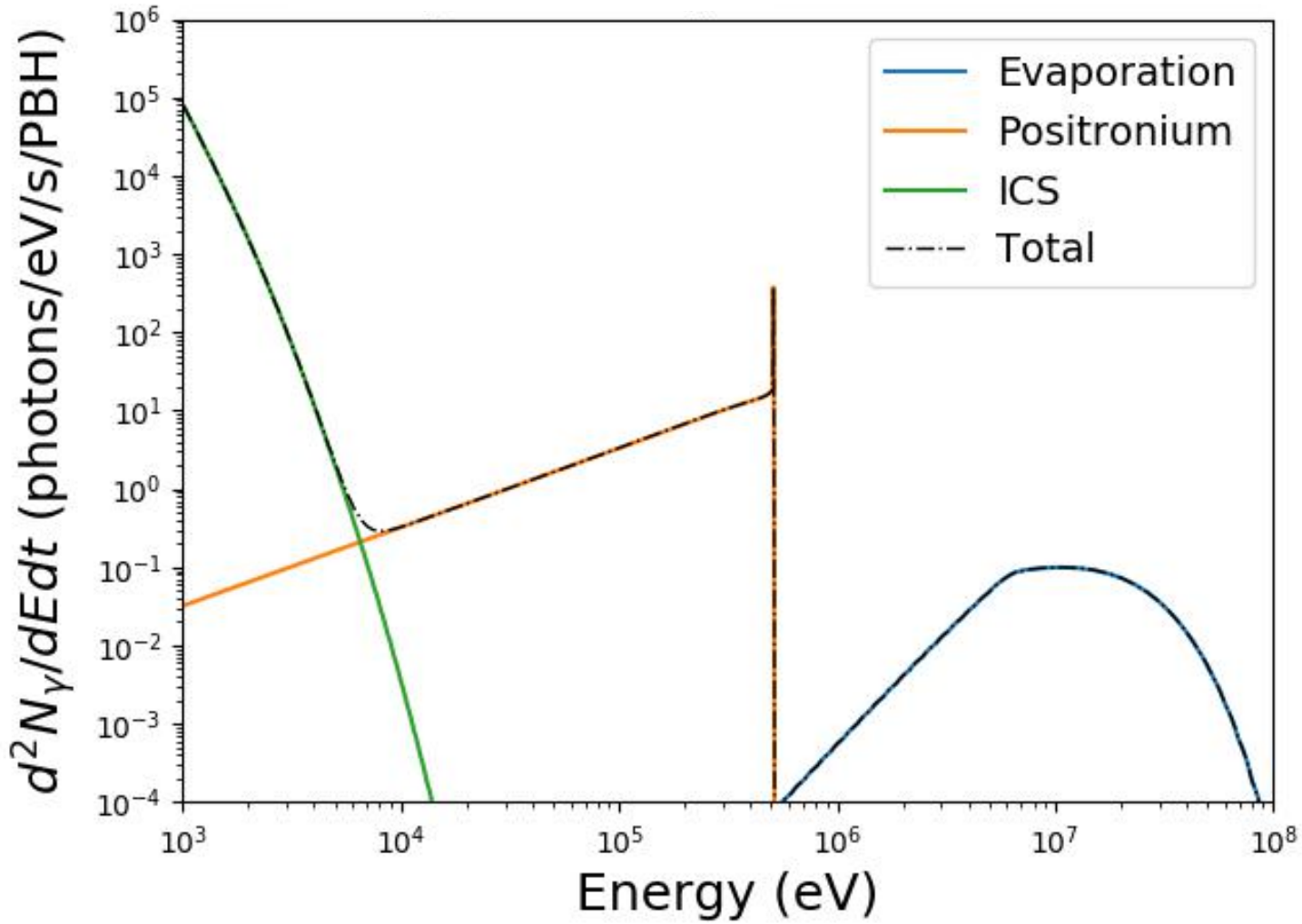
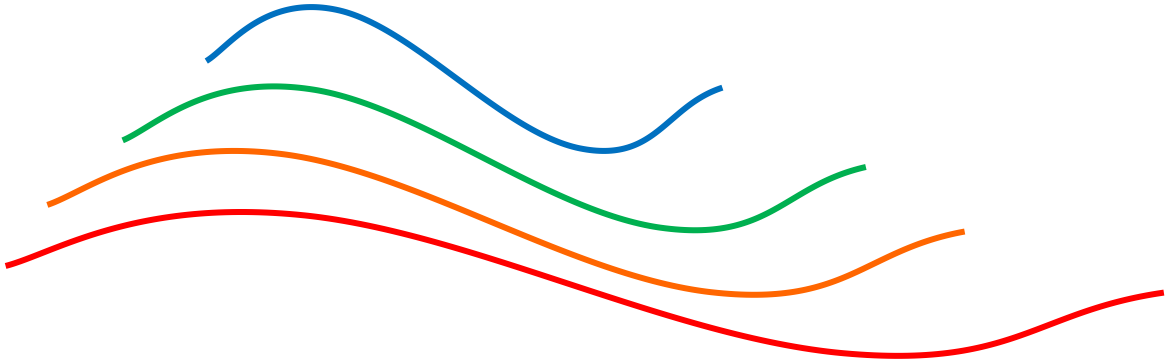
- Positronium annihilation
- Inverse Compton scattering (ICS)



# Photon Energy Loss

Redshifting



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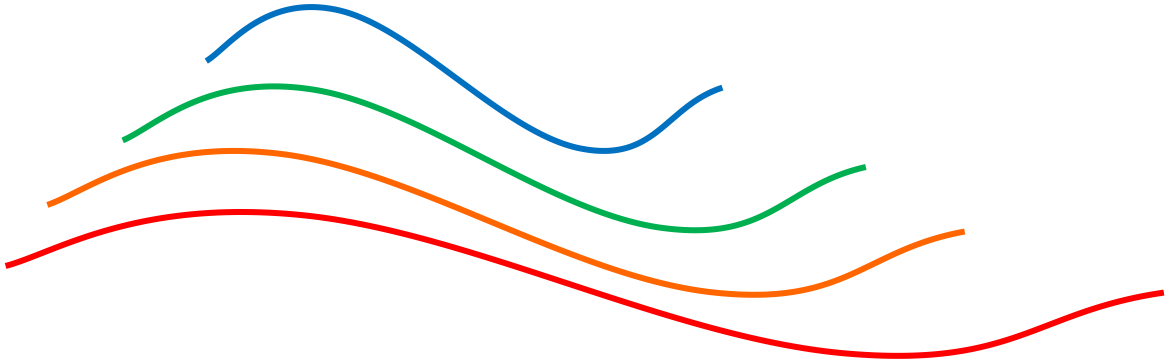
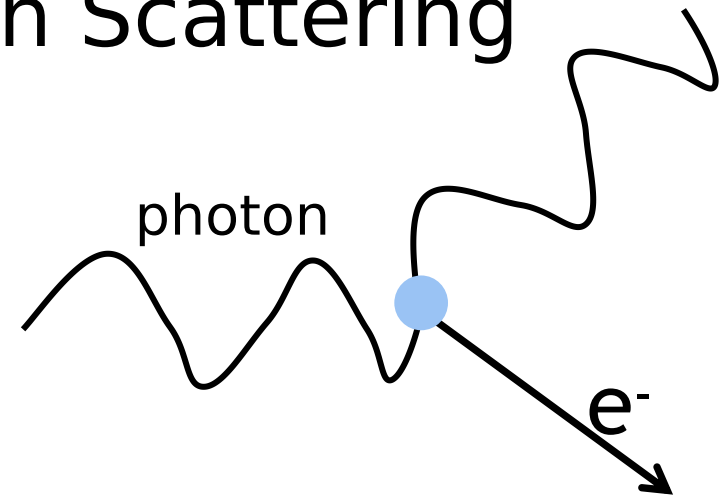


## Compton Scattering



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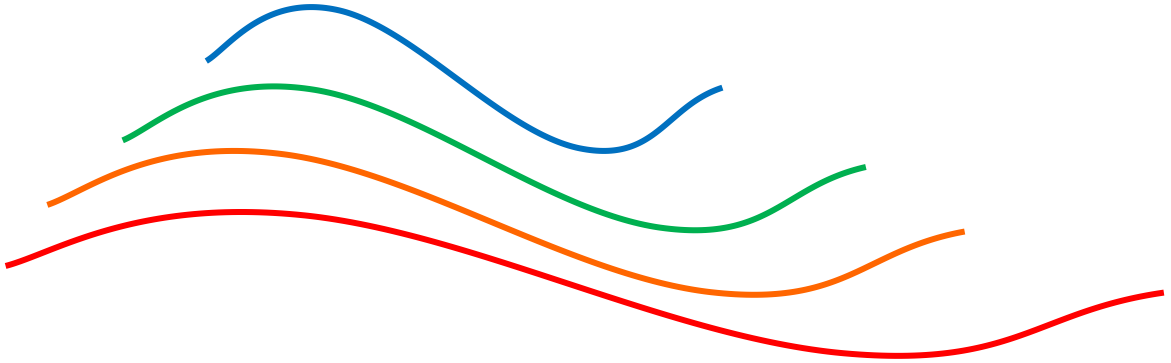

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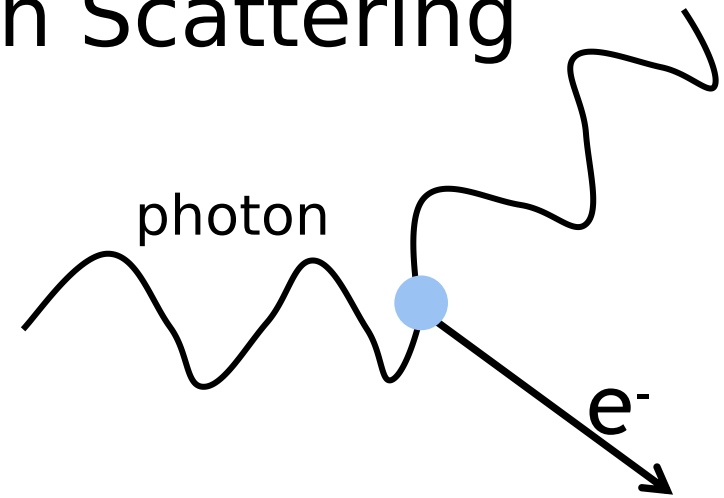
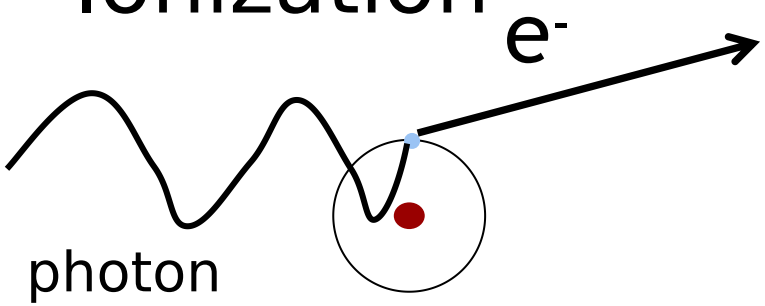



## Ionization



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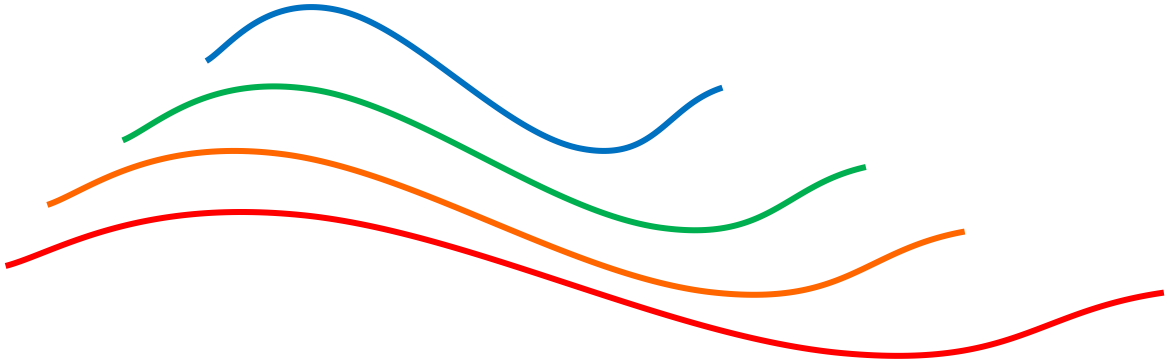

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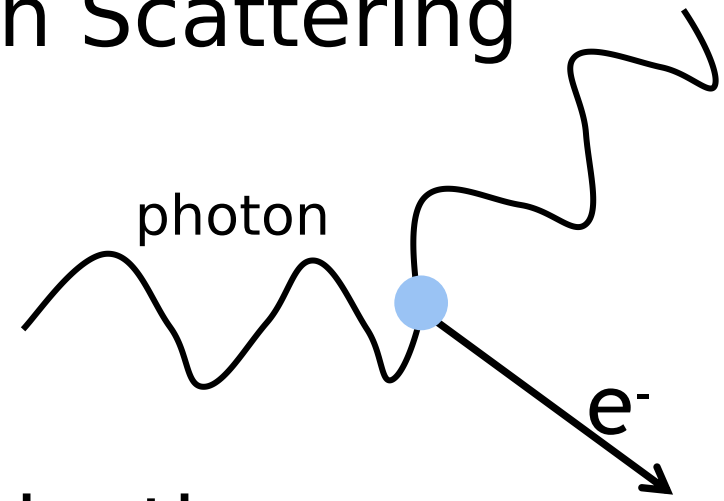


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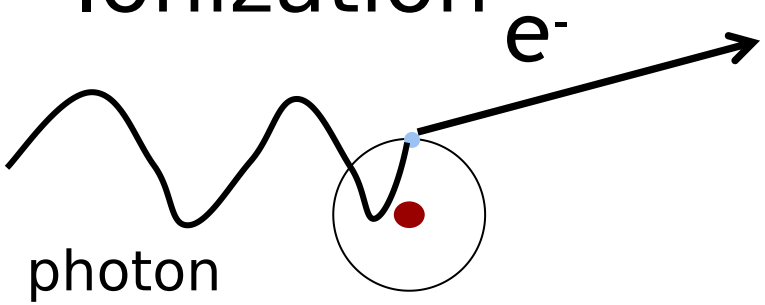
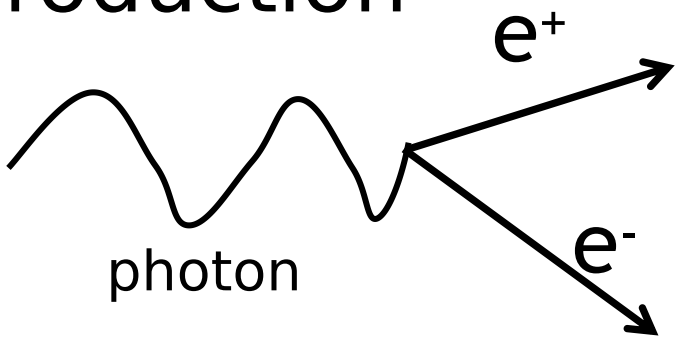



## Pair Production



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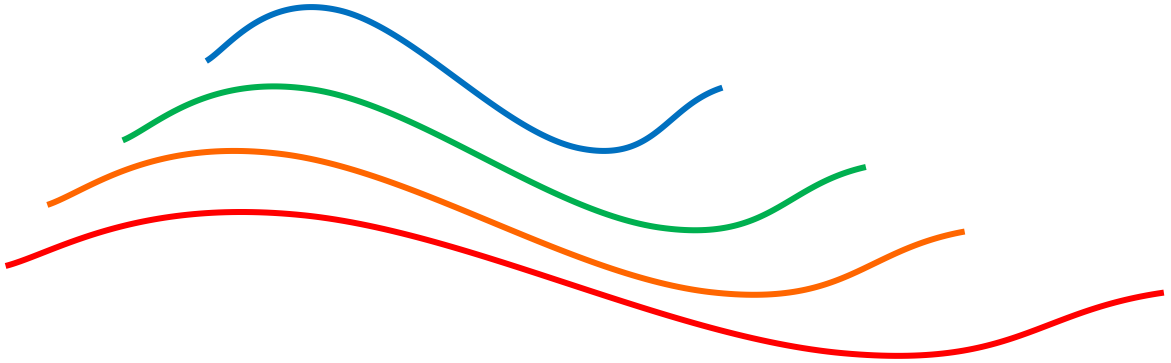

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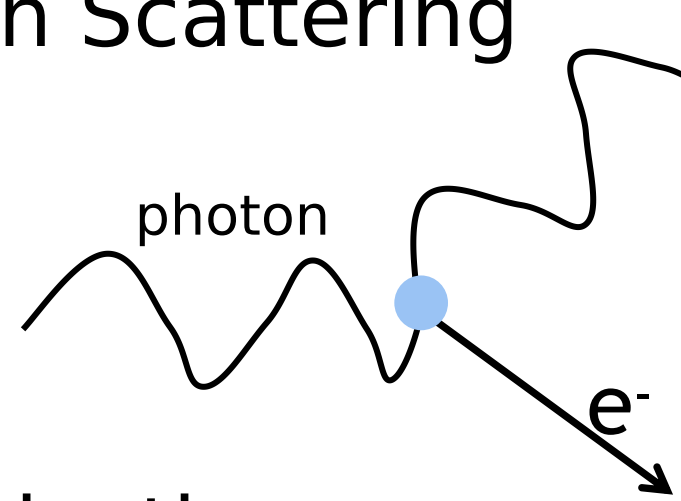


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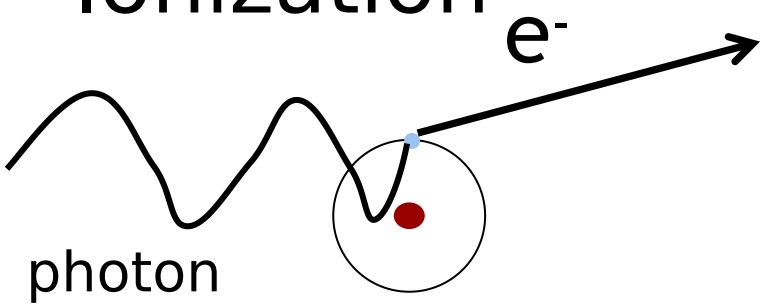


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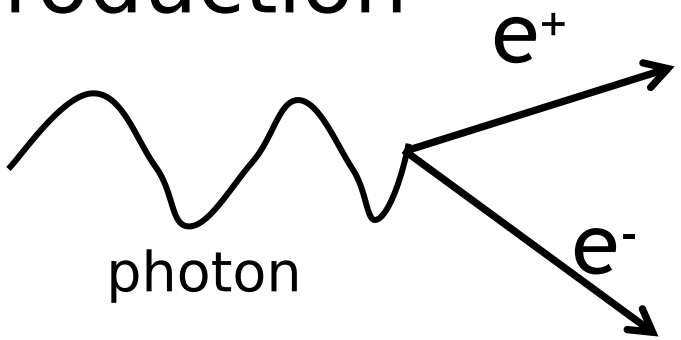



For the observed energy range (1 keV - 100 MeV) attenuation is important for high redshift (z > 100)

# Galactic Isotropic Signal

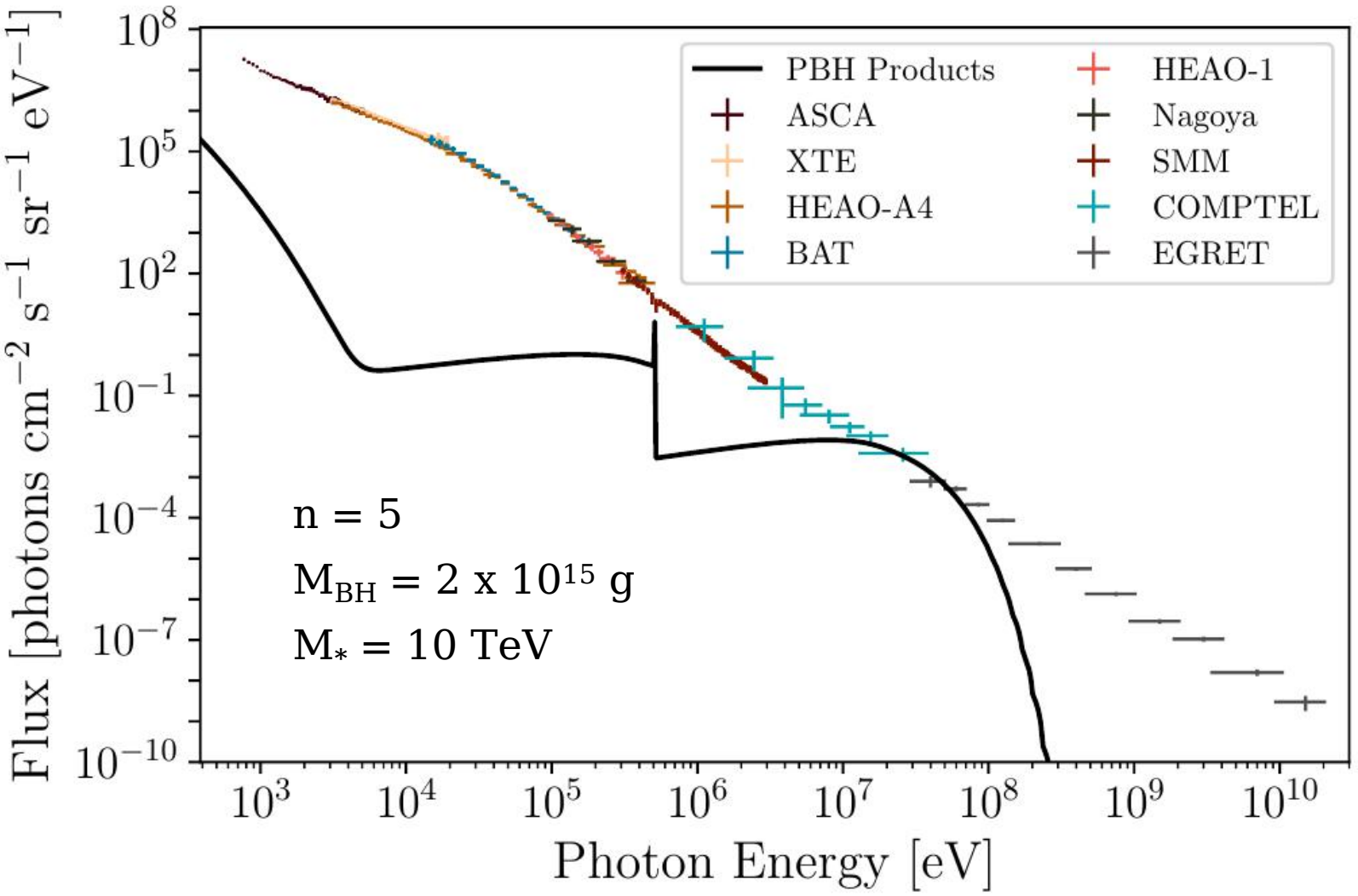
- Galactic photon flux is highly anisotropic but non-zero in all directions
- Isotropic component can be determined with

$$\frac{d\Phi_{\gamma,\mathrm{gal}}}{dE} = \frac{f_{\bullet,0}}{4\pi M}\frac{d^2N_\gamma}{dEdt}(E,M)\mathcal{D}_{\mathrm{min}}$$

$$\mathcal{D}_{\mathrm{min}} = \int_{R_0}^{\infty} dr\,\rho_{DM}(r)$$

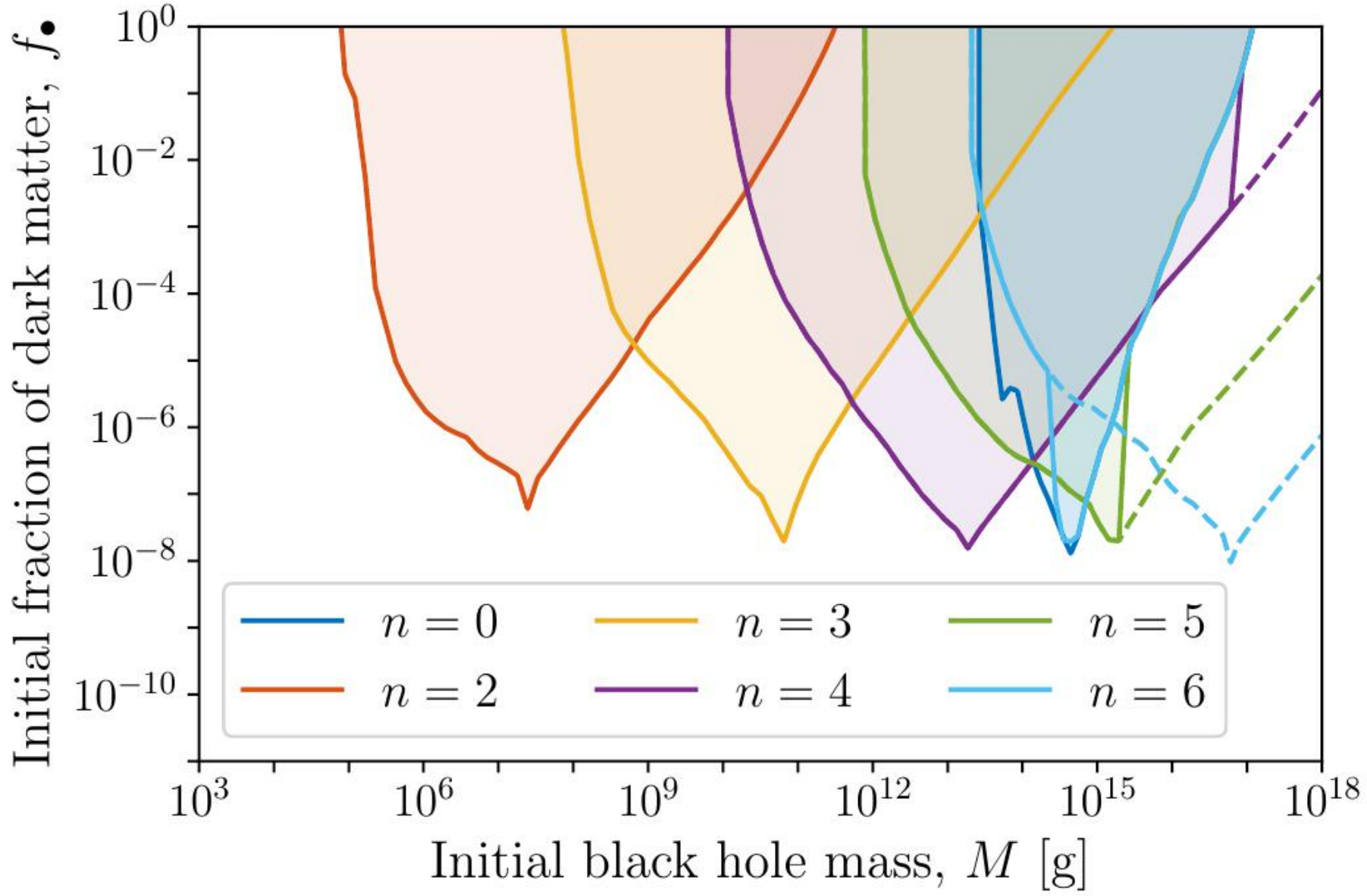
See: Iguaz et al. arxiv:2104.03145

# Observed Flux

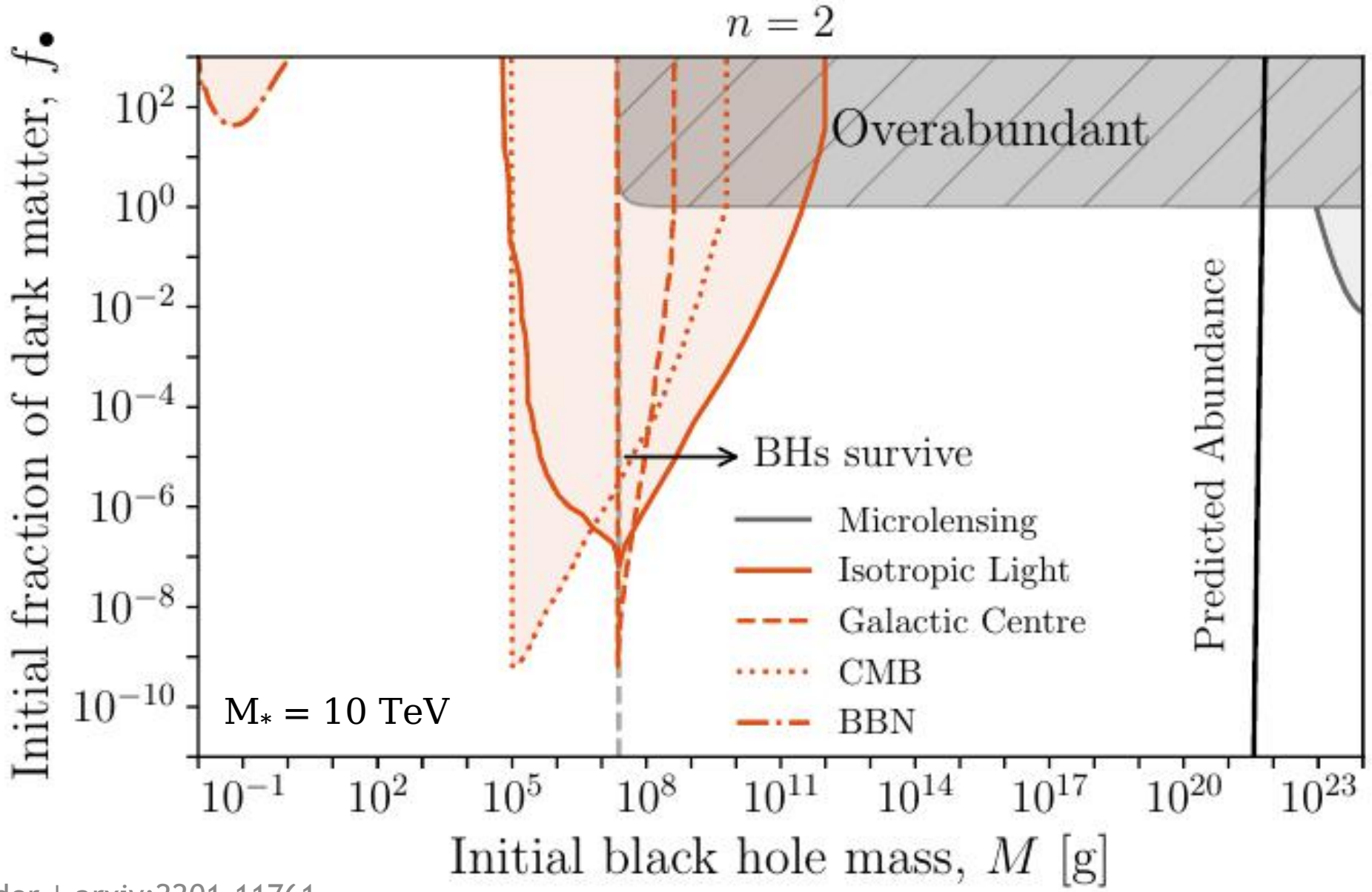


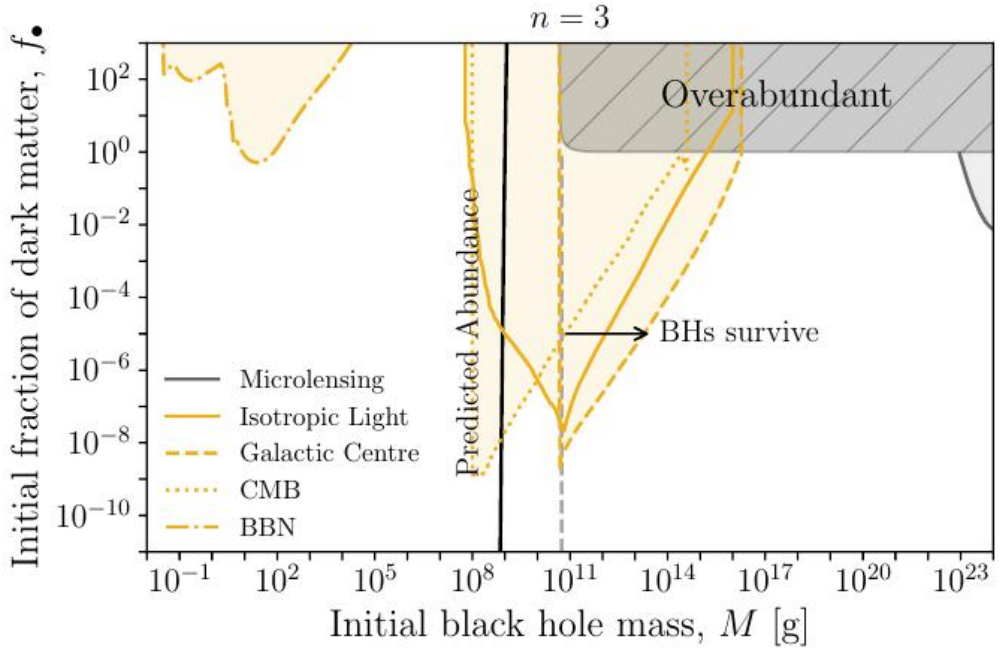

Calculated flux is compared to various **x-ray and gamma-ray telescopes** as compiled by Ajello et al. (arxiv:0808.3377)

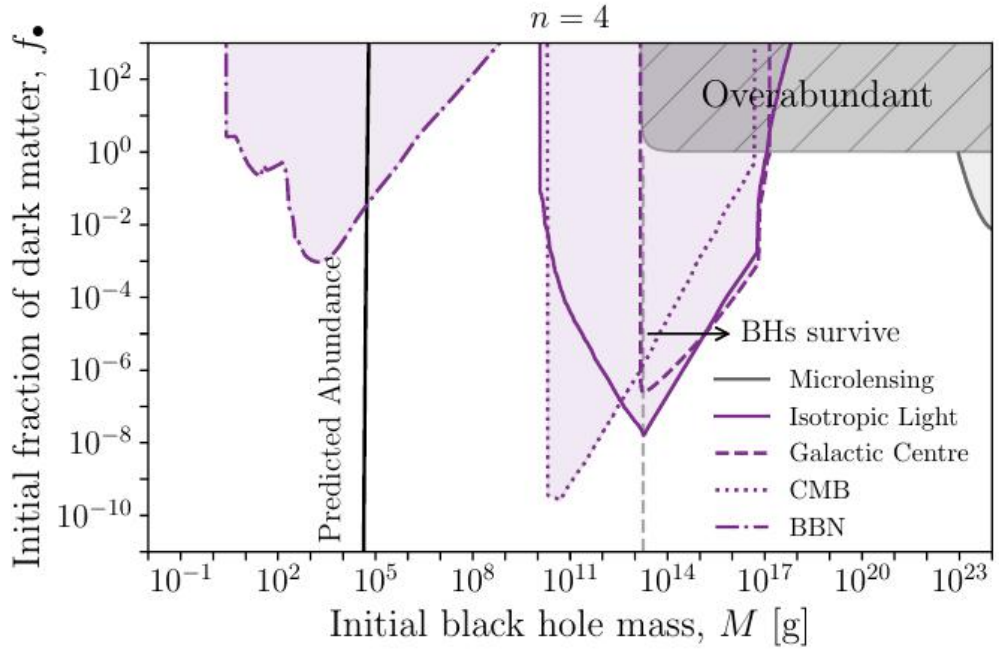
# Preliminary Isotropic Light Constraints

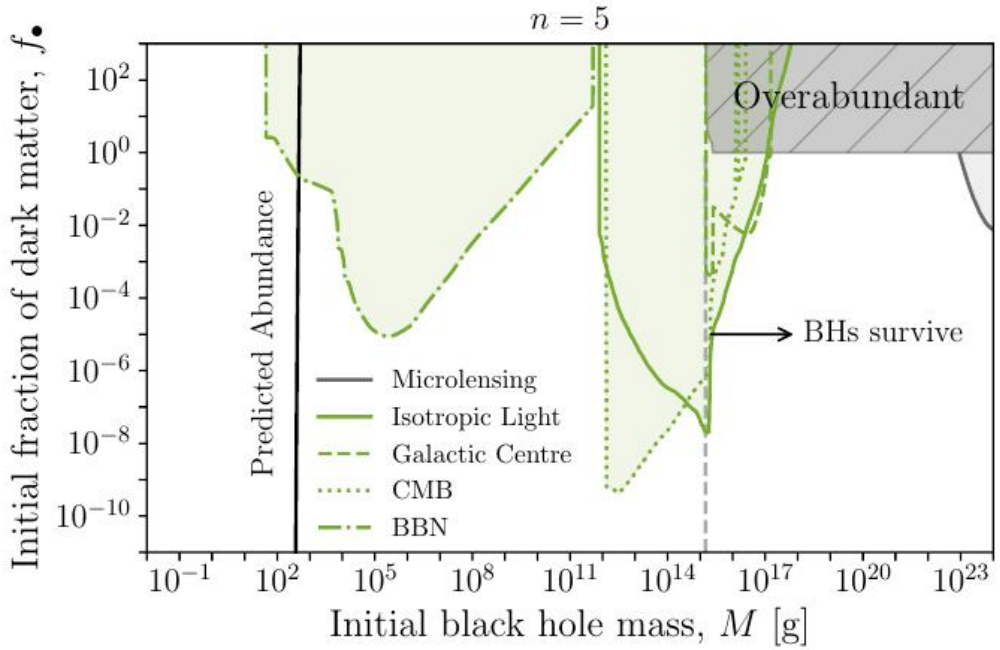


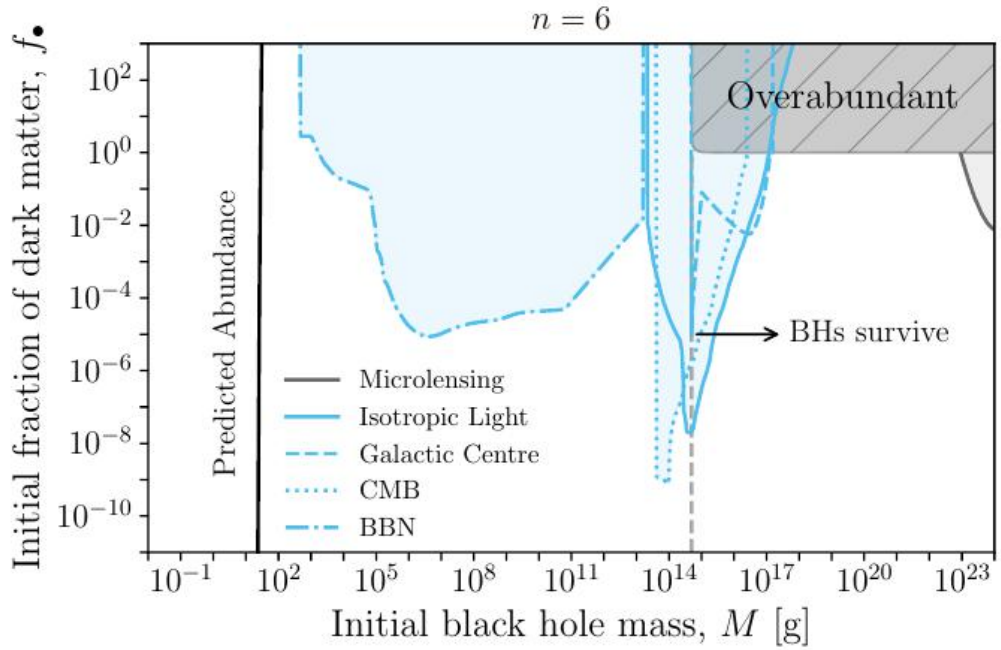
# Combined Constraints




$n = 3$
Overabundant
Predicted Abundance
BHs survive
Microlensing
Isotropic Light
Galactic Centre
CMB
BBN
Initial fraction of dark matter, $f_\bullet$
Initial black hole mass, $M$ [g]


$n = 4$
Overabundant
Predicted Abundance
BHs survive
Microlensing
Isotropic Light
Galactic Centre
CMB
BBN
Initial fraction of dark matter, $f_\bullet$
Initial black hole mass, $M$ [g]


$n = 5$
Overabundant
Predicted Abundance
BHs survive
Microlensing
Isotropic Light
Galactic Centre
CMB
BBN
Initial fraction of dark matter, $f_\bullet$
Initial black hole mass, $M$ [g]


$n = 6$
Overabundant
Predicted Abundance
BHs survive
Microlensing
Isotropic Light
Galactic Centre
CMB
BBN
Initial fraction of dark matter, $f_\bullet$
Initial black hole mass, $M$ [g]

# Conclusions

- Theories of Large Extra Dimensions predict the existence of Primordial Black Holes
- Astrophysical observables of LED PBHs is very different from regular PBHs
- Primordial Black Holes with two extra dimensions might comprise all of dark matter!
- Check out the paper for more! (arxiv:2201.11761)

# 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

# Extra Dimensional Black Holes

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

$$r_h = \frac{a_n}{M_\star}\left(\frac{M}{M_\star}\right)^{1/(n+1)}$$

$$T_H = \frac{n+1}{4\pi r_h}$$

See Conley and Wizanksy
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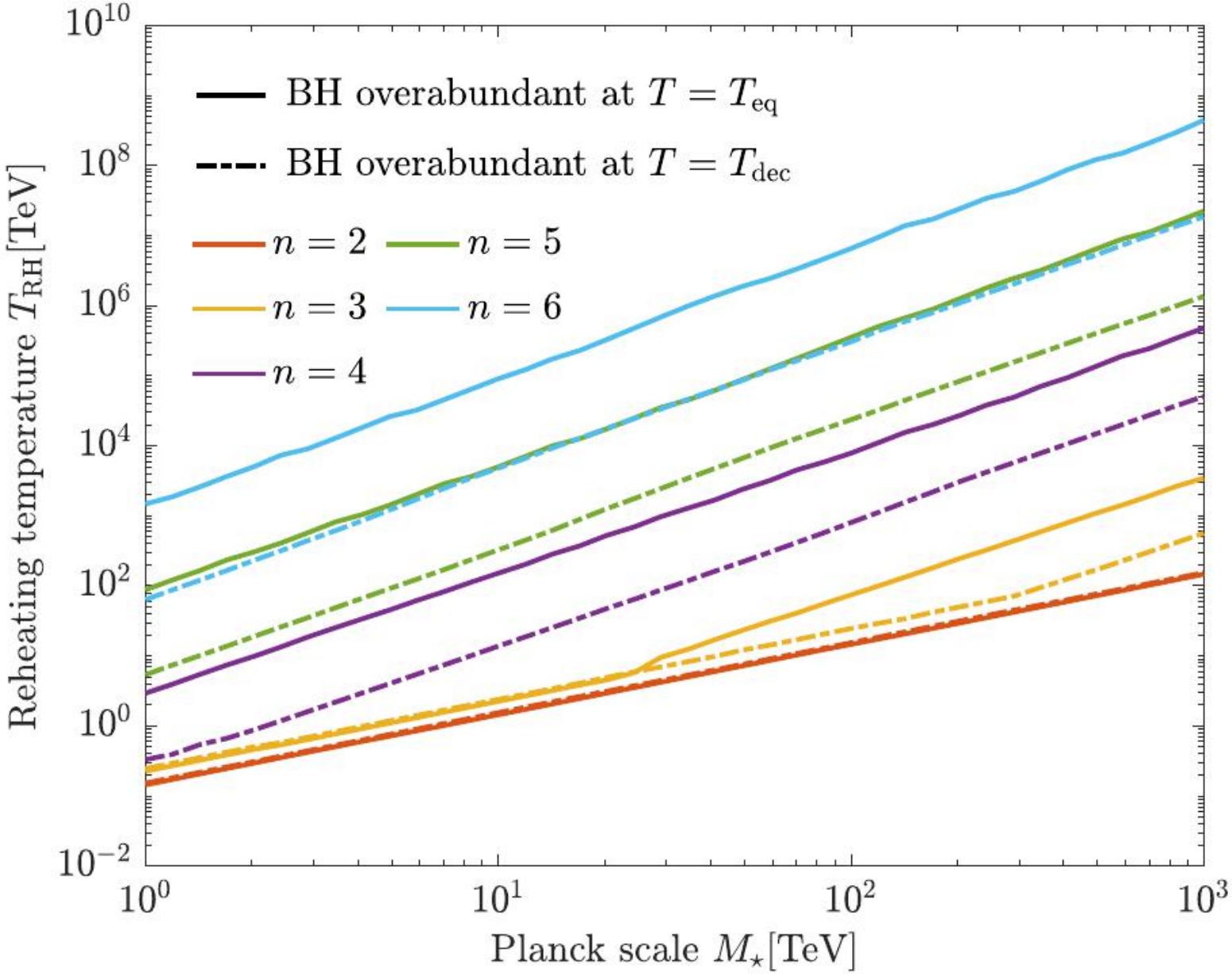
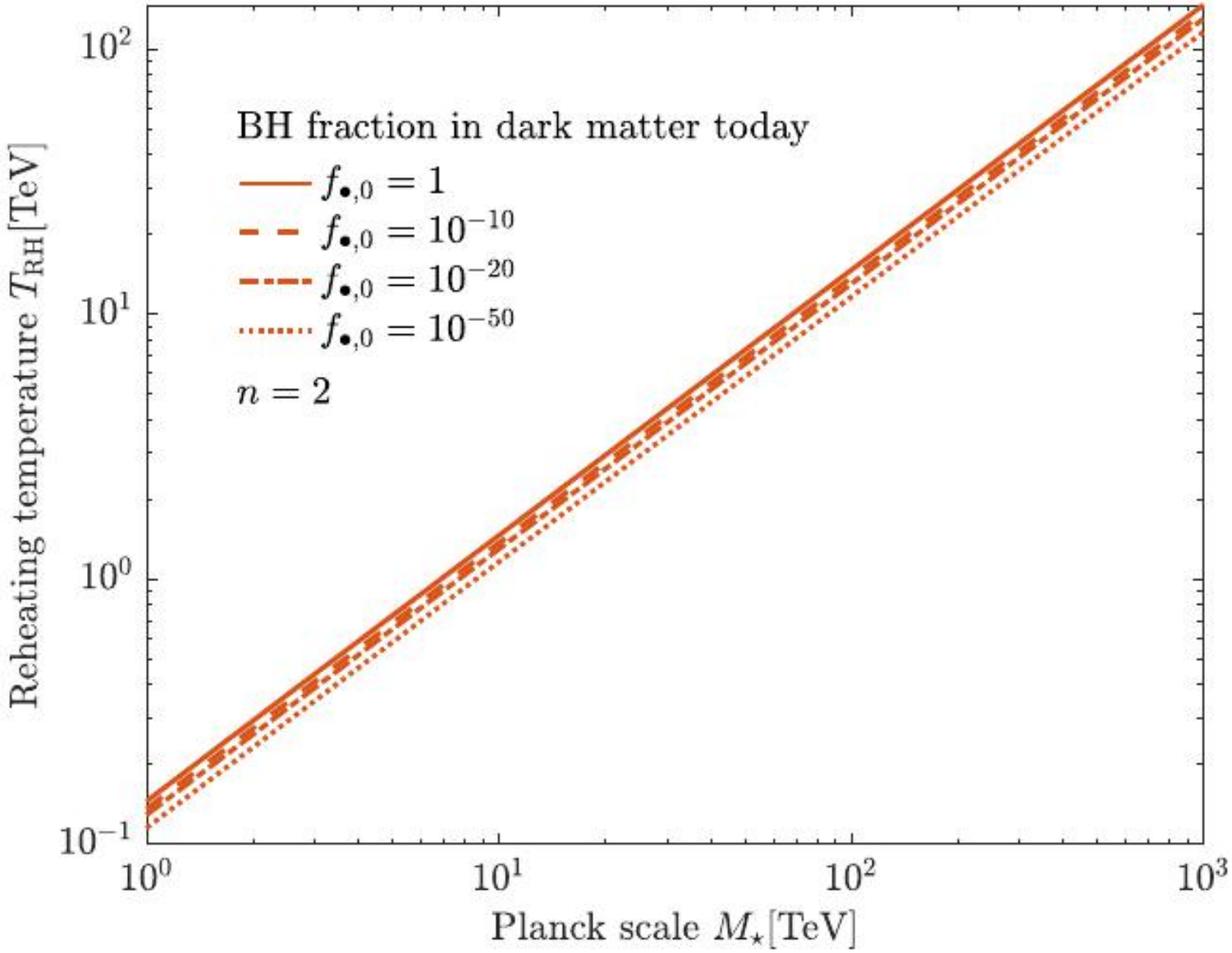
# Constraints on Extra Dimensions



# Predicted PBH Abundance



# 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

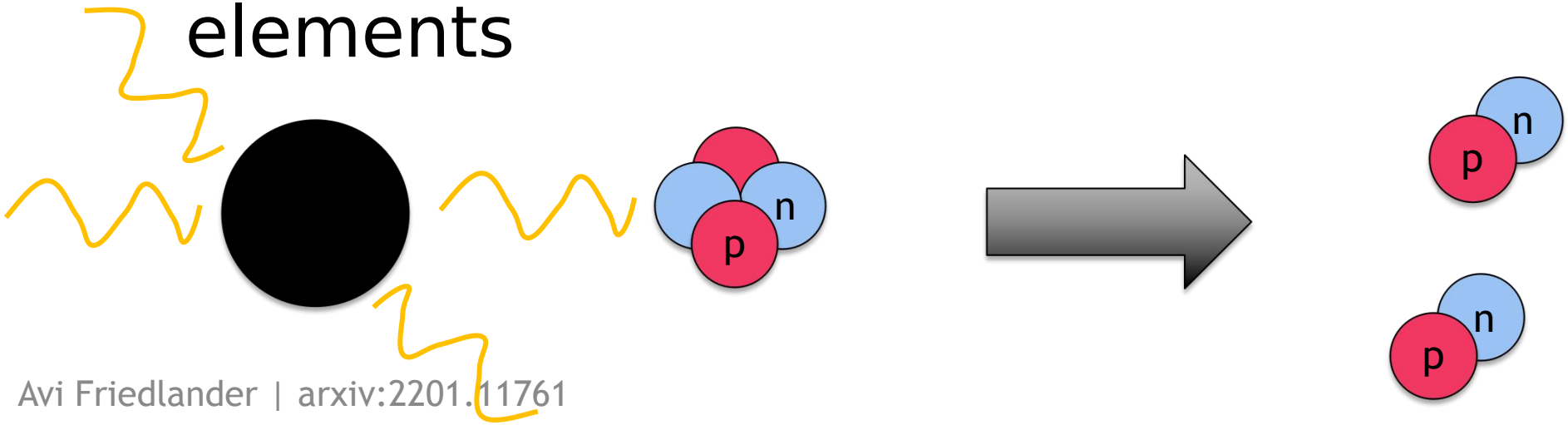
- The effect of decaying dark matter on BBN has been studied in detail (Kawasaki et al. arxiv:1709.01211)

- 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)

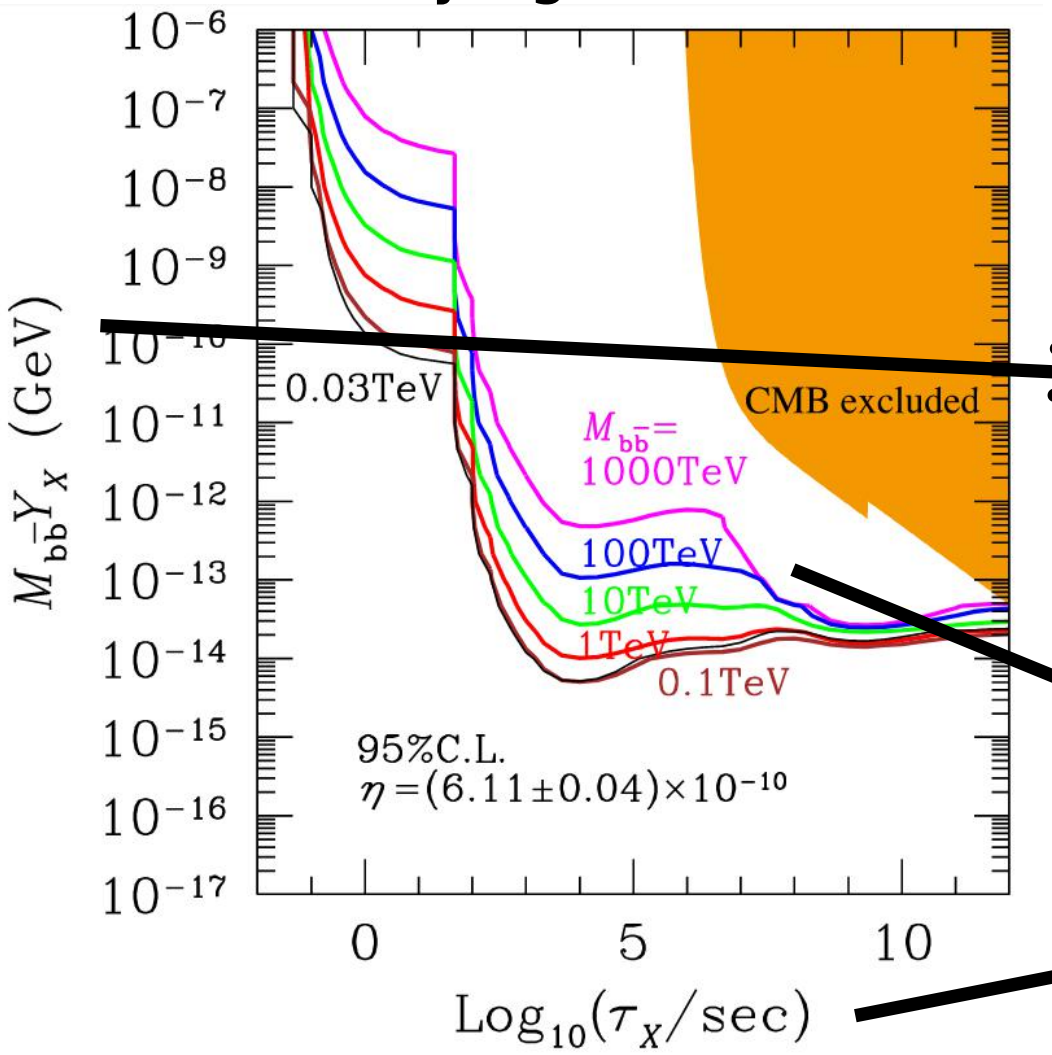
# PBH and Big Bang Nucleosynthesis

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



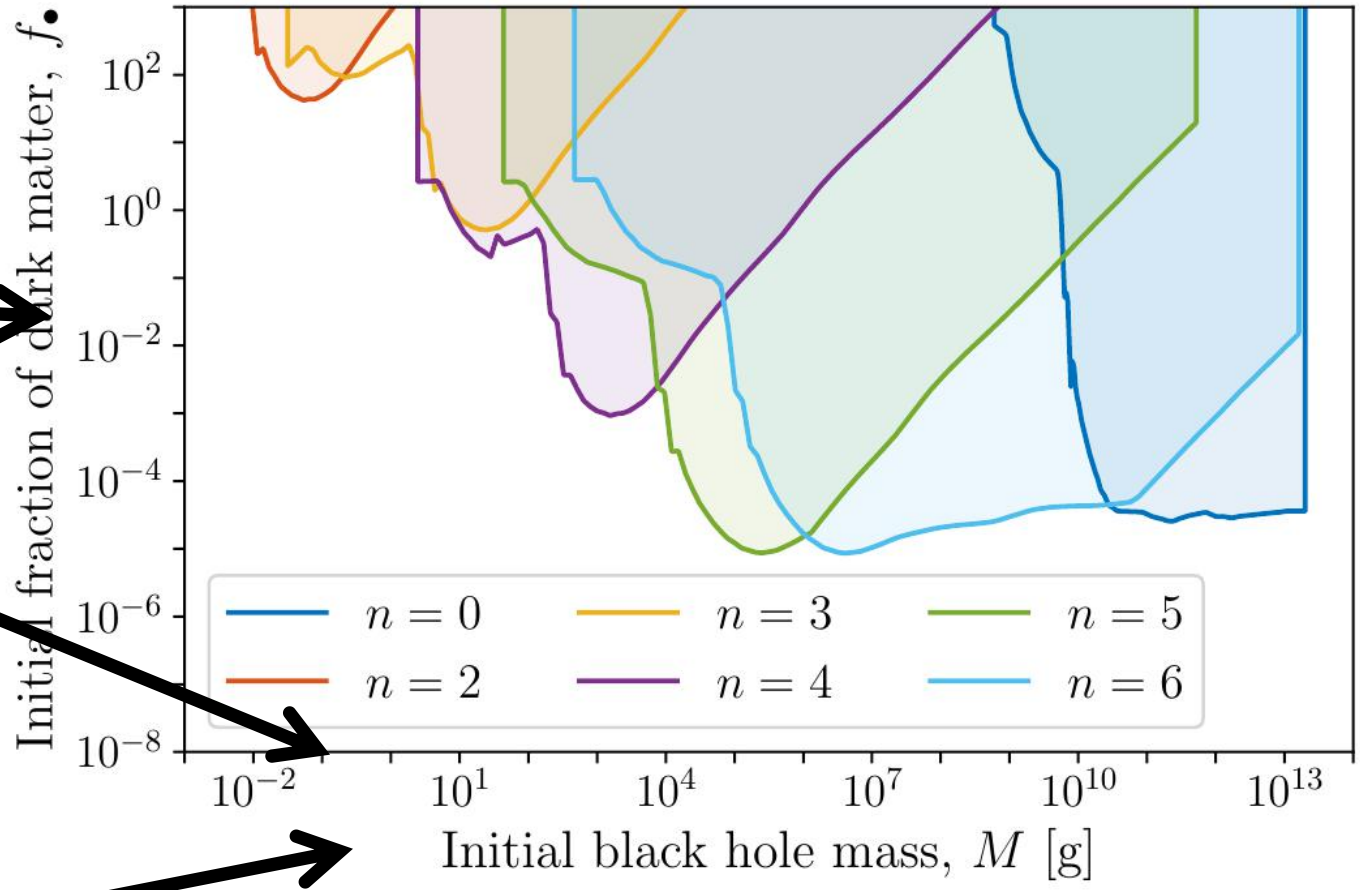
# Preliminary BBN Results

## Decaying Dark Matter




Kawasaki et al. arxiv:1709.01211

## Primordial Black Holes

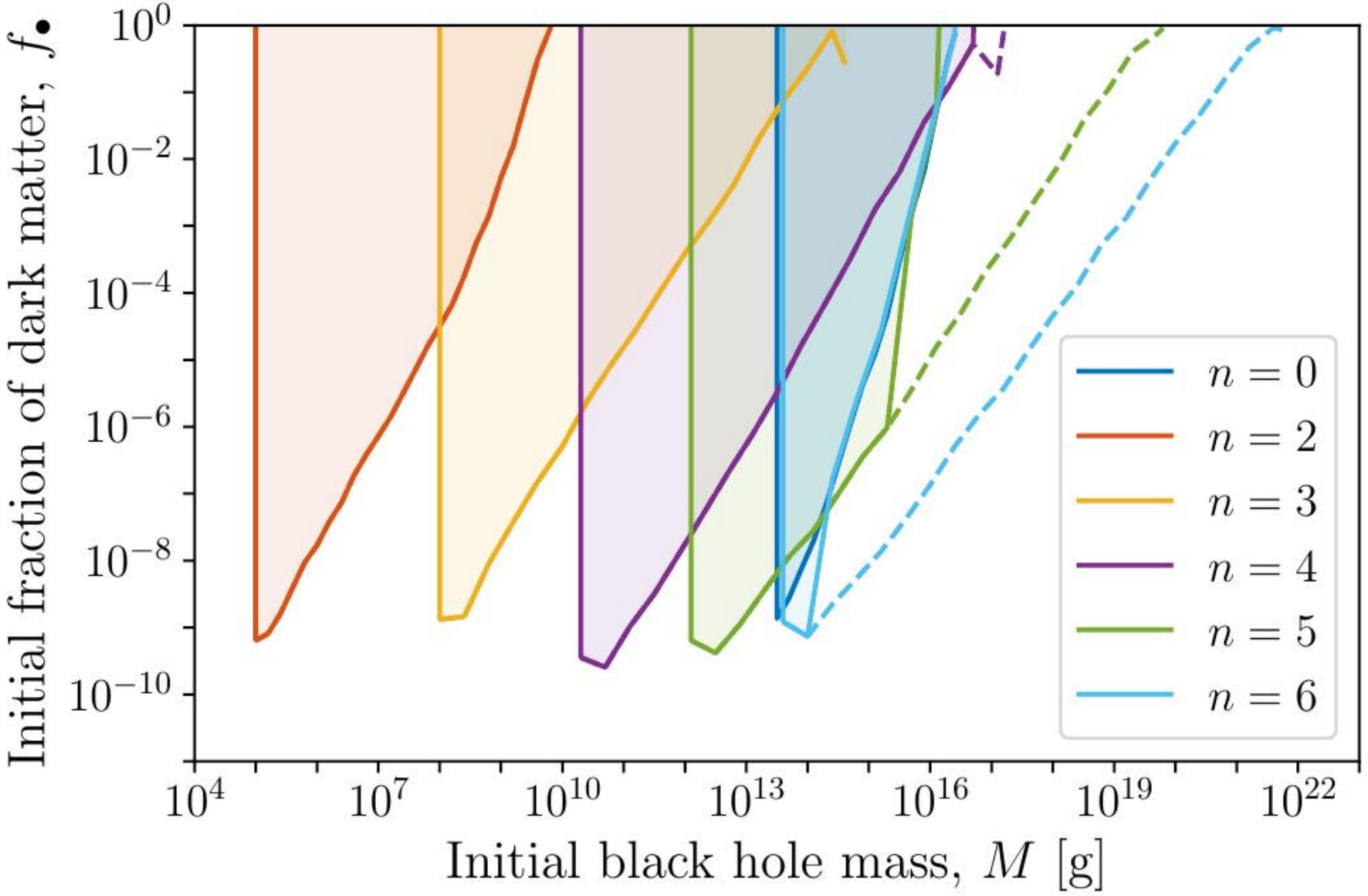



See Kieth et al. arxiv:2006.03608
for recasting details

# Effect on the CMB

- Evaporation products during and after recombination scatter CMB photons changing the observed power spectrum
- We modify ExoCLASS to determine the effect from LED PBHs
- Constraints are from performing a MCMC

# CMB Constraints



# Galactic Centre Photons

$$\frac{d\Phi_\gamma}{dEd\Omega} = \frac{1}{4\pi}\frac{dN}{dEdt}\frac{f_{\bullet,0}}{M}\frac{1}{\Delta\Omega}\mathcal{D}(\Omega)$$

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

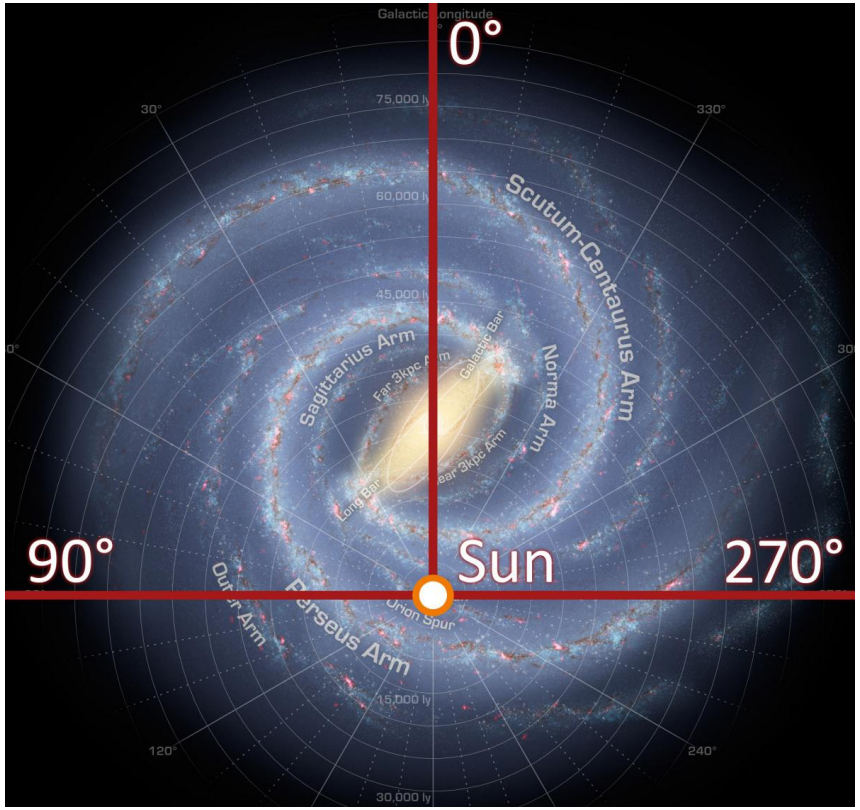



Image from NASA

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

# Galactic Centre Positrons

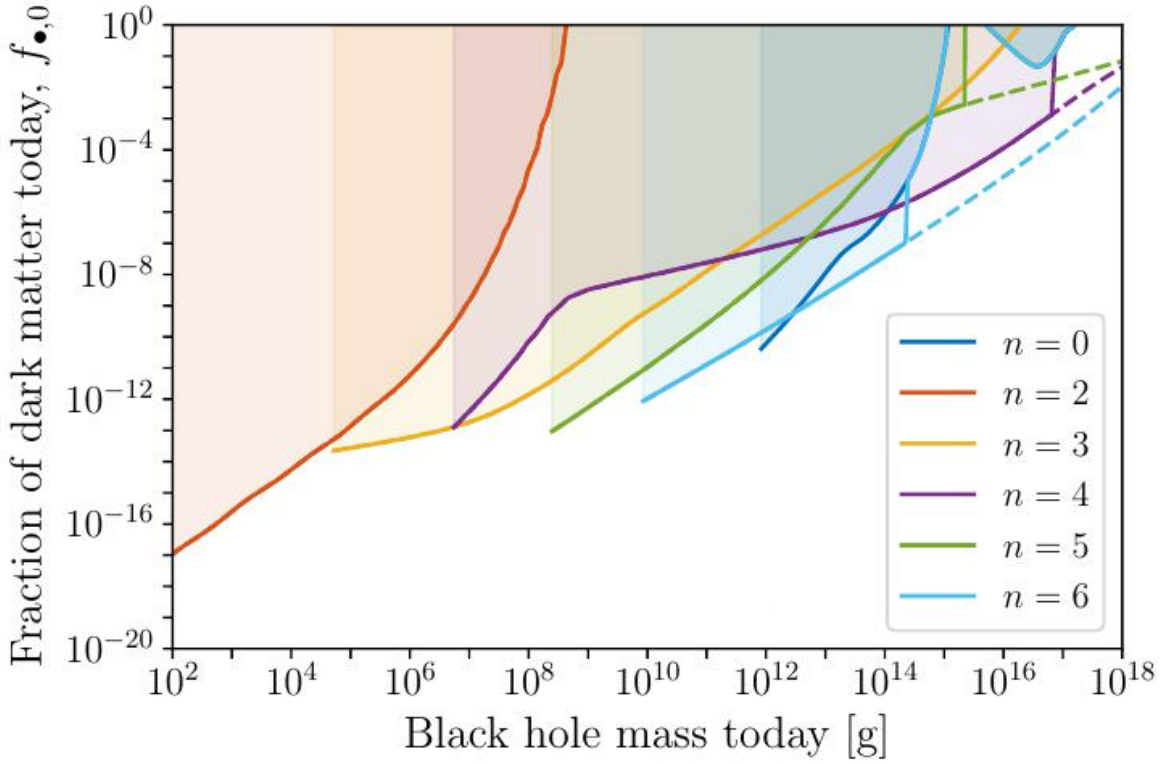
- If PBHs evaporate to positrons, they will annihilate to produce an additional 511 keV signal

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

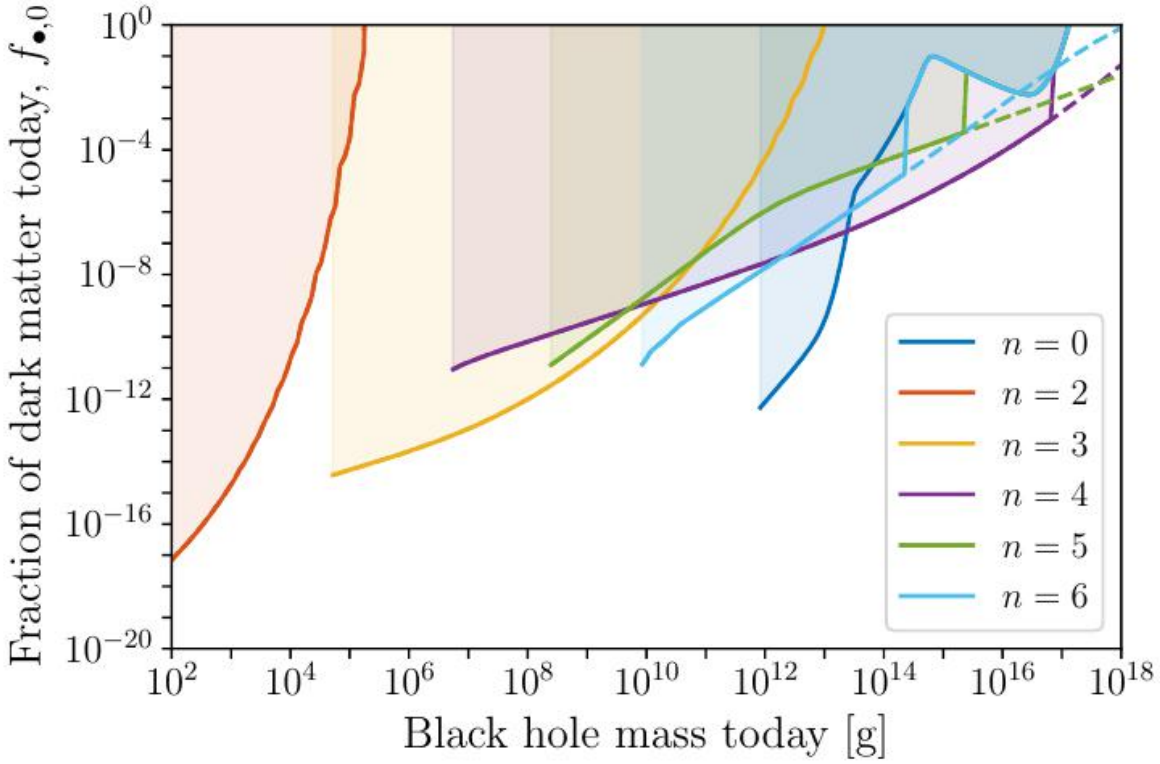
- Compared to INTEGRAL/SPI 511 keV line data (Siegert et al. arxiv:1906.00498)

# Galactic Centre Constraints

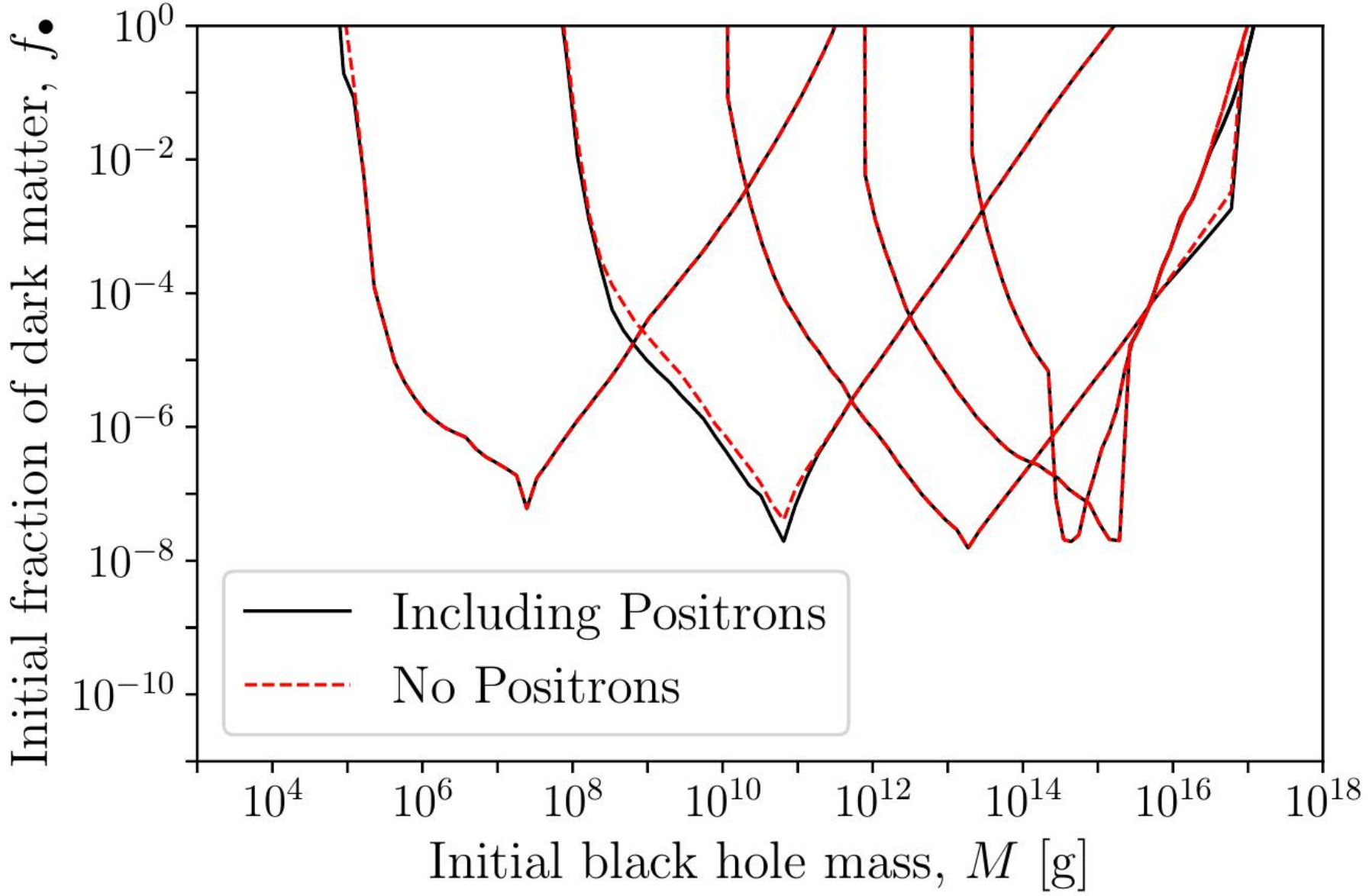
## Gamma ray continuum



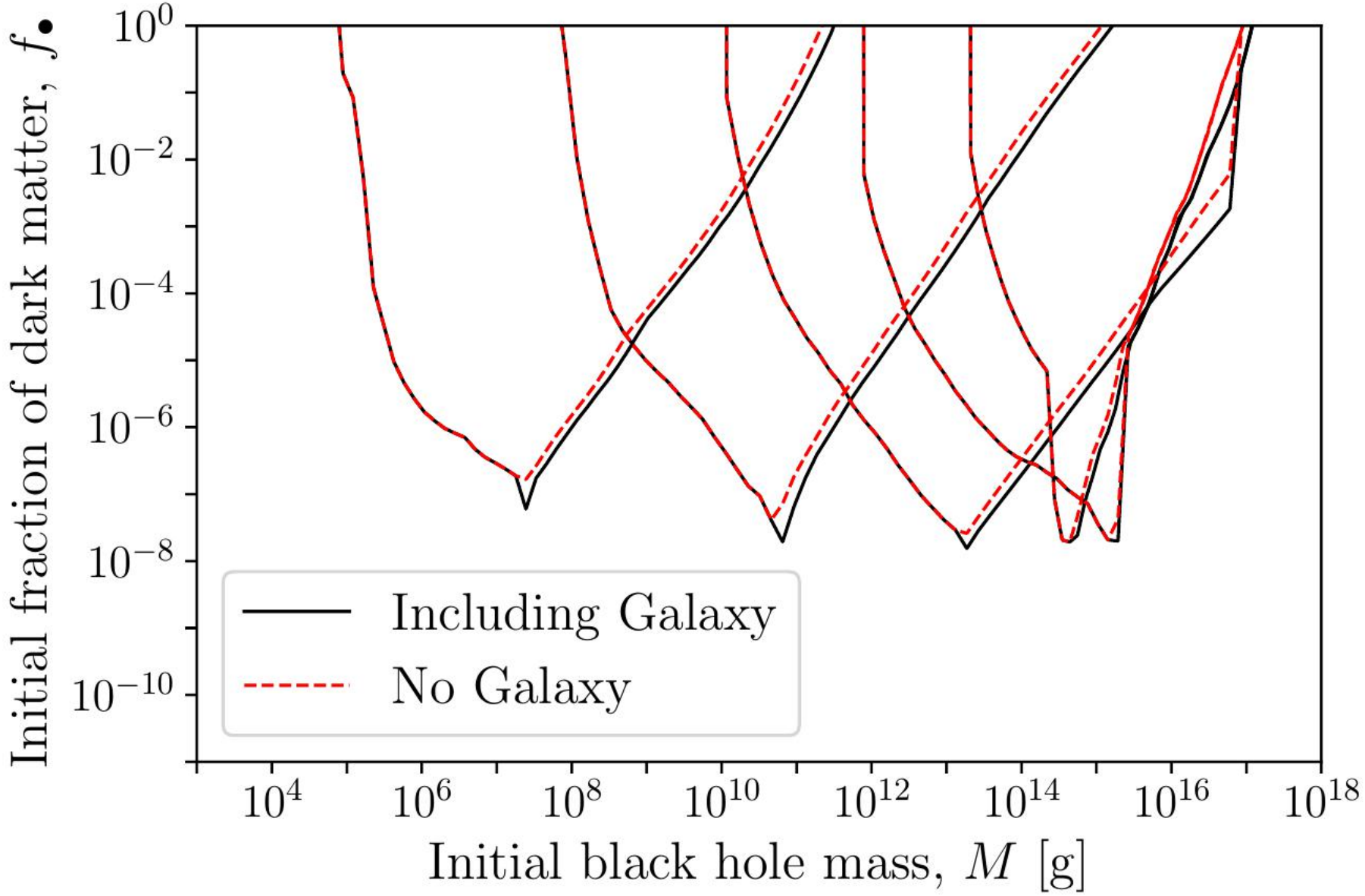

## Positron Annihilation



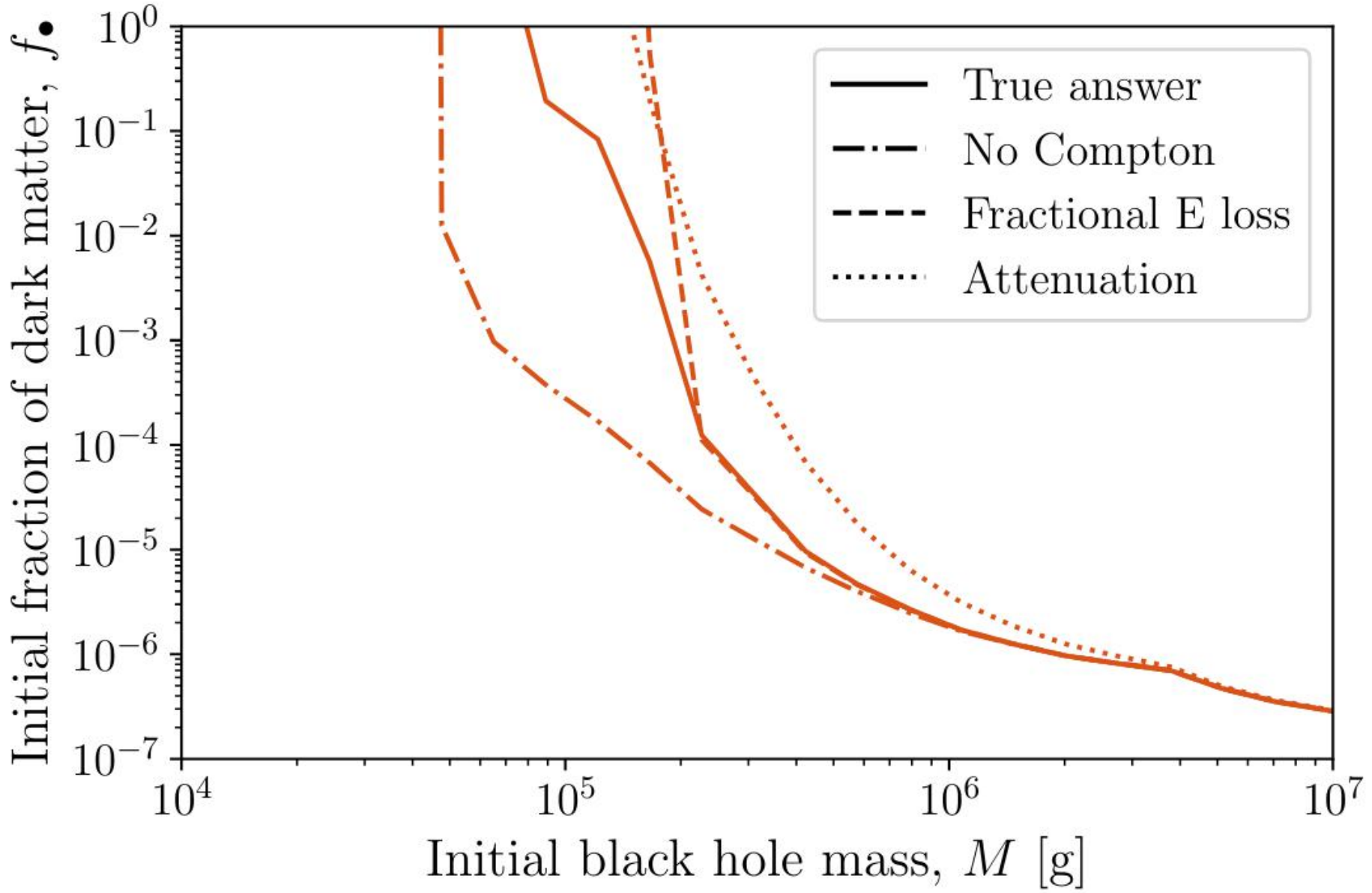
# Impact of Positronium on Isotropic Photon Limits



# Impact of Milky Way on Isotropic Photon Limits



# Compton Scattering Approximations



# 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

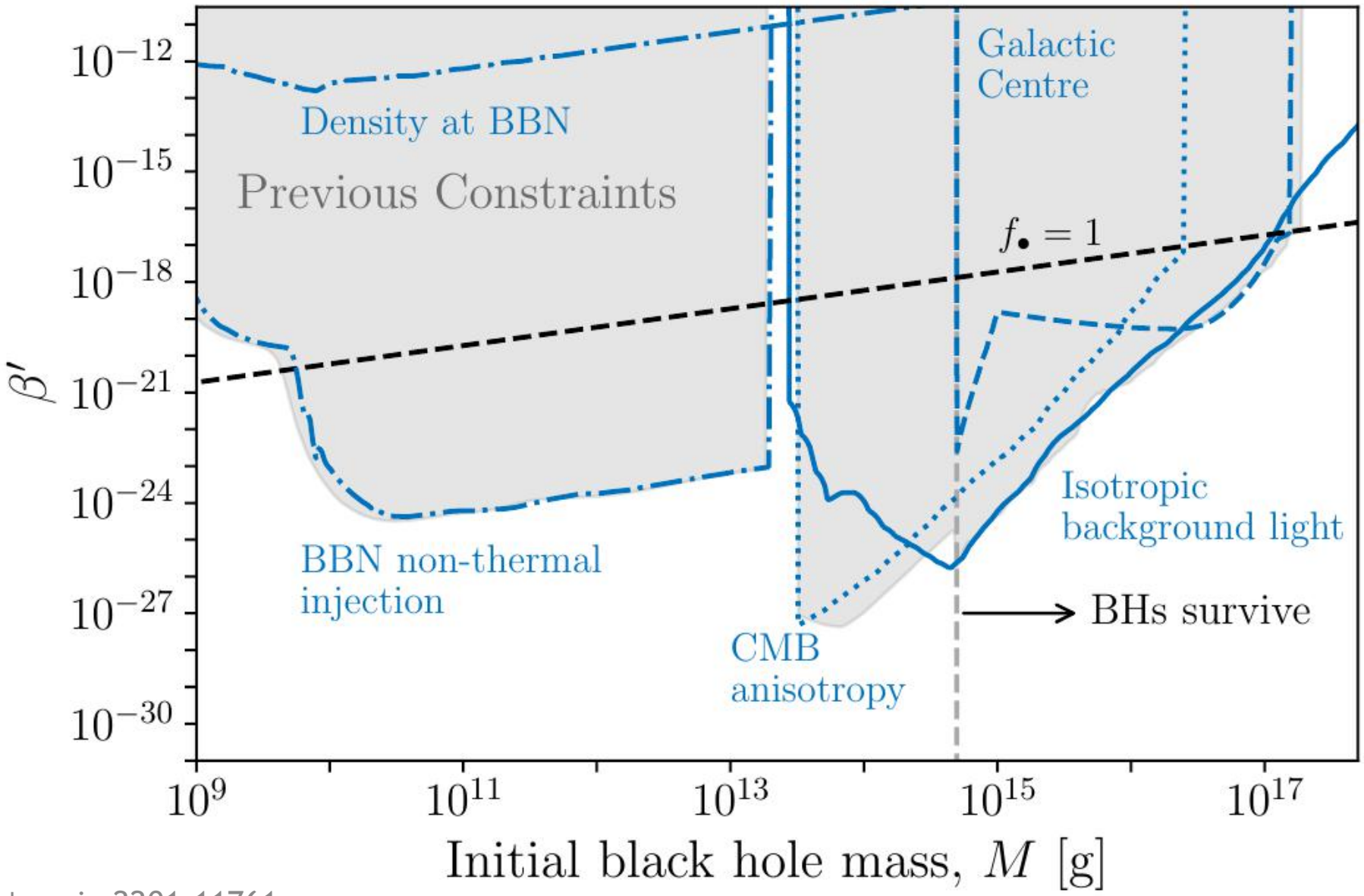
- Positrons annihilate into photons via formation of positronium
  - Each annihilation produces spectrum

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

  - All positrons assumed to immediately annihilate

See: Iguaz et al.
arxiv: 2104.03145

# 4D PBH Constraints



# 4D Galactic Constraints