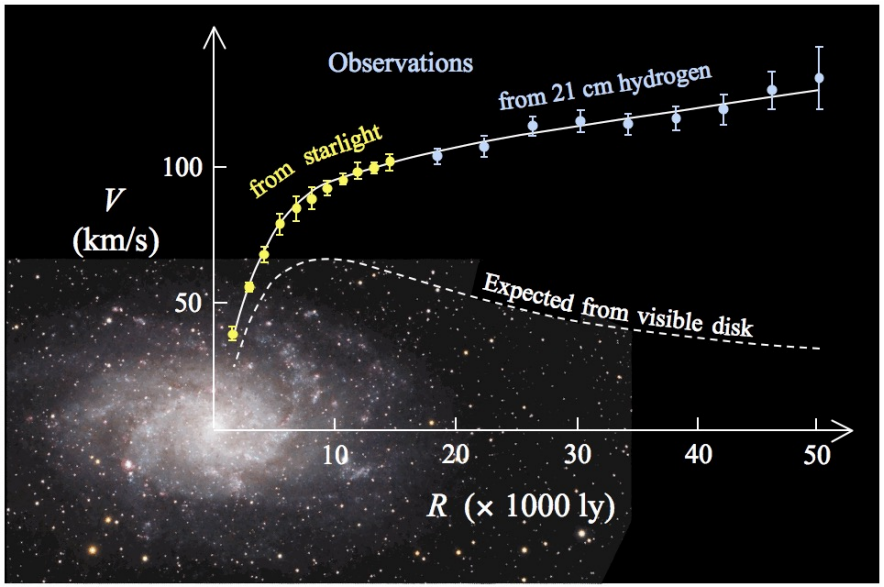
# PRIMORDIAL BLACK HOLES AS DARK SECTOR FACTORIES

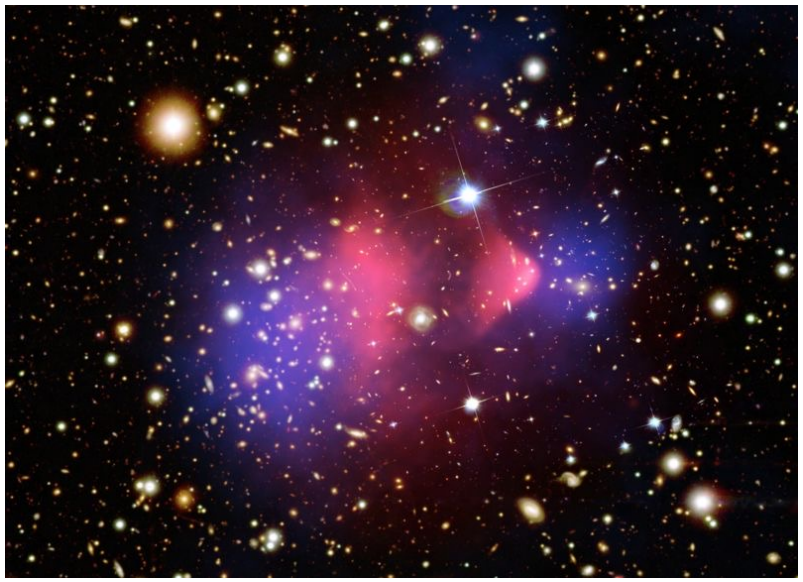
Based on arXiv:2212.11980, arXiv:2409.13811, and arXiv:260x.xxxxx
with Kaustubh Agashe, Manuel Buen-Abad, Steven J. Clark, Bhaskar Dutta, Yuhsin Tsai, and Tao Xu

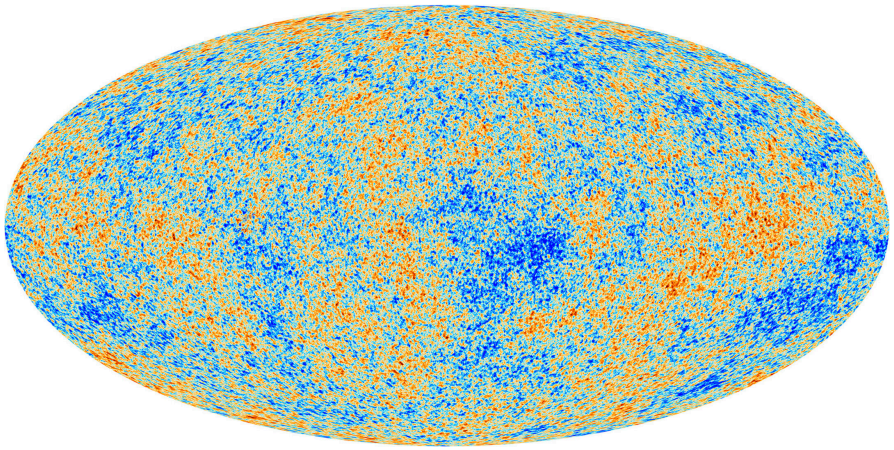
Jae Hyeok Chang
Seoul National University

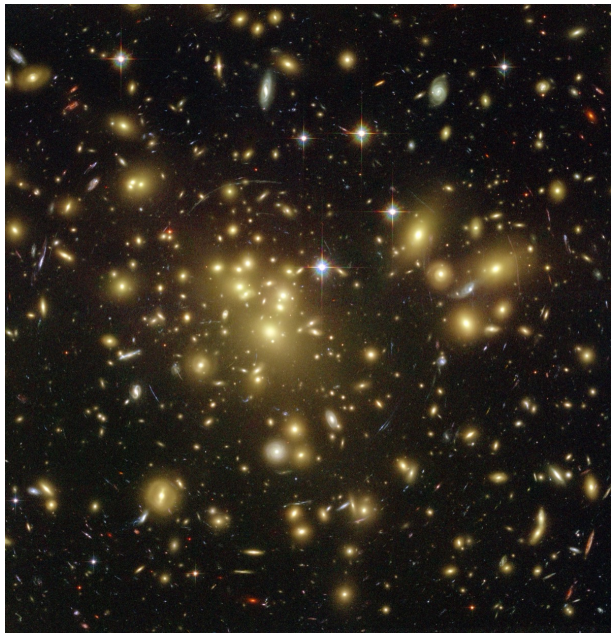
2025.04.25 CUBES 2026

# We all know Dark Matter exists



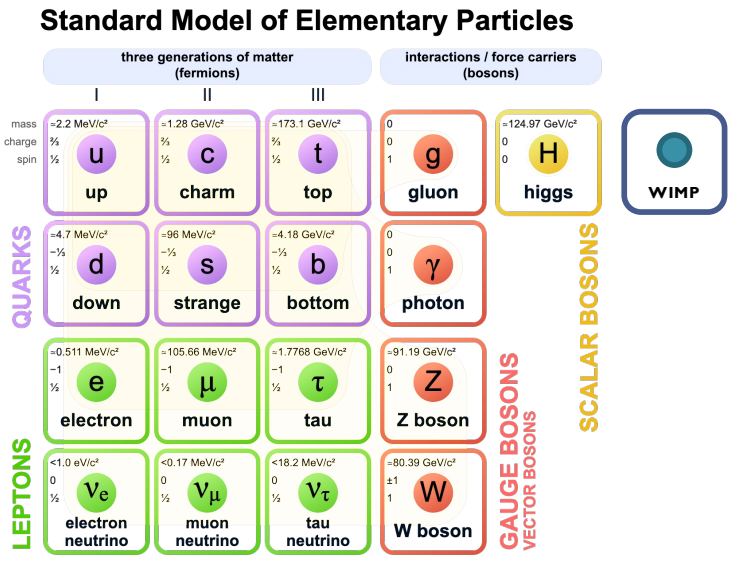





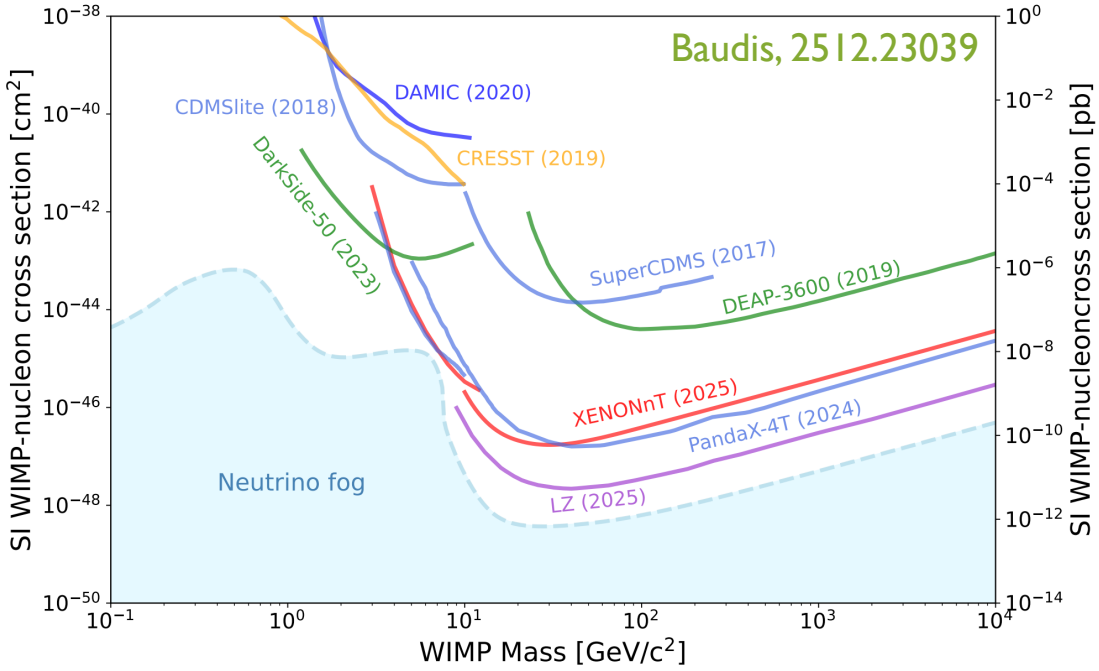


# Dark Matter Candidates : WIMP

- Weakly Interacting Massive Particle (WIMP)
- Predicts the observed dark matter energy density today "WIMP Miracle"
- No signal yet
- Need models beyond WIMP

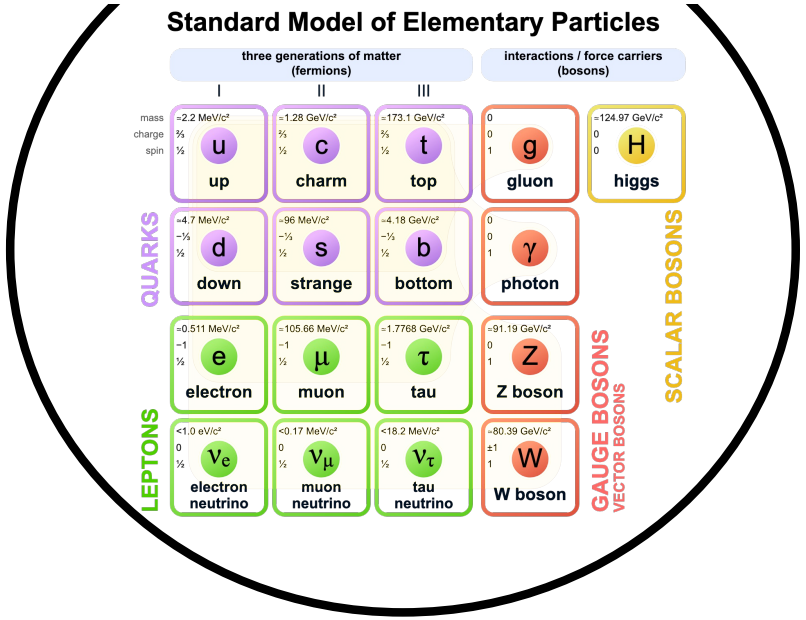



$$SU(3)_c \times SU(2)_L \times U(1)_Y$$



# Dark Matter Candidates : Dark Sector

## SM SECTOR




## DARK SECTOR

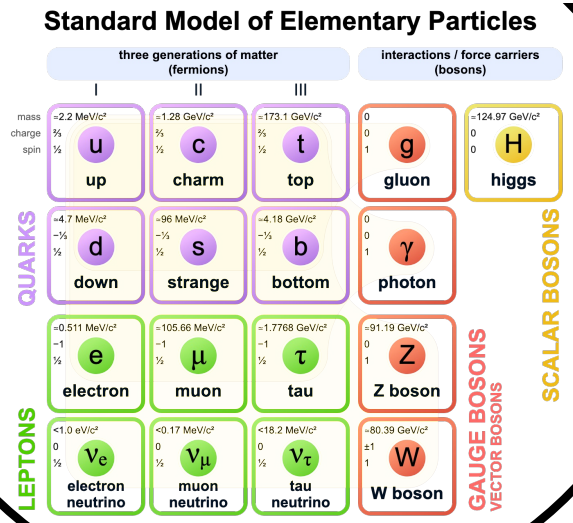
Dark forces

Dark Matter

Dark sector particles

# Dark Matter Candidates : Dark Sector

## SM SECTOR




## DARK SECTOR

Dark forces

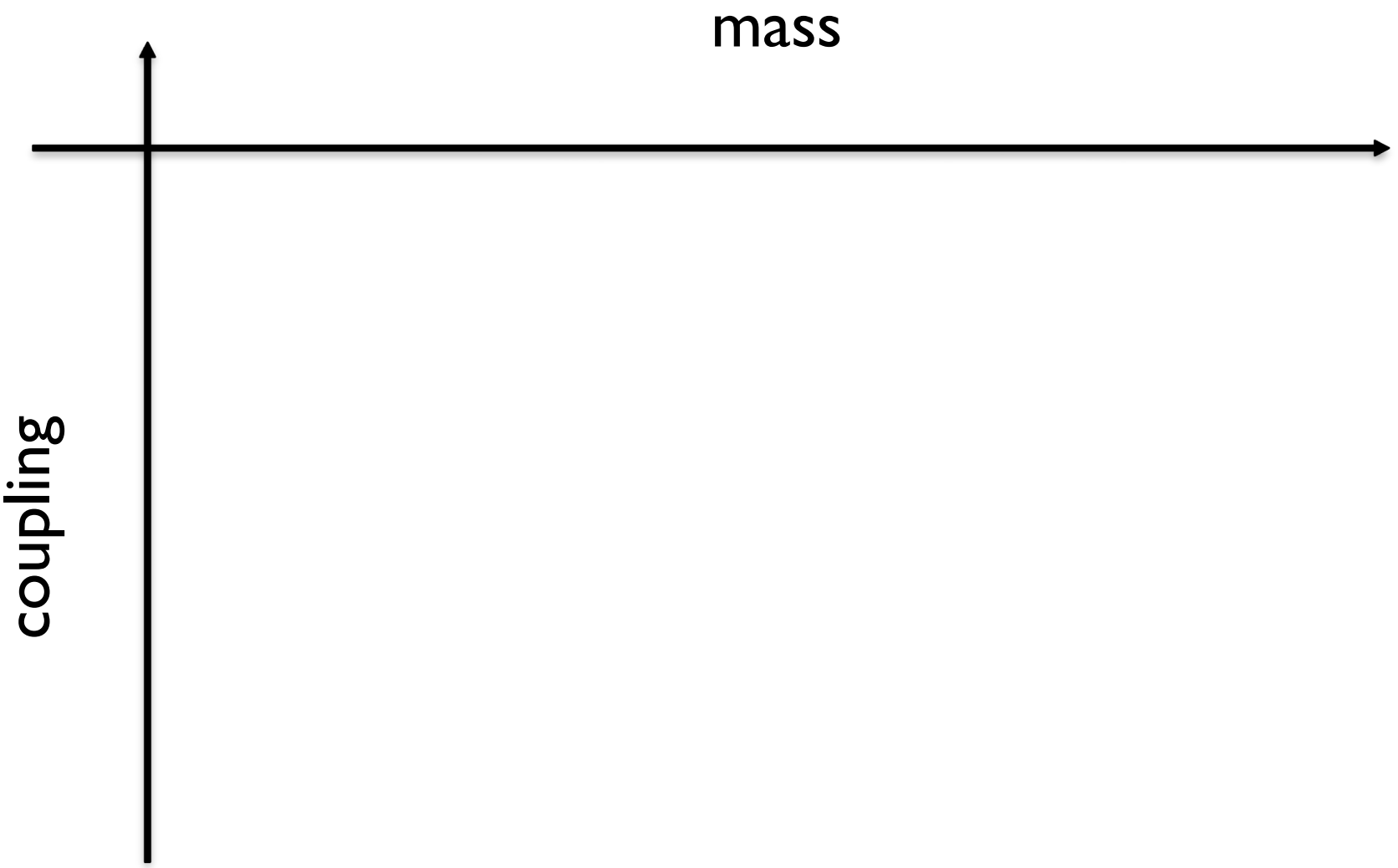
Dark Matter

Dark sector particles

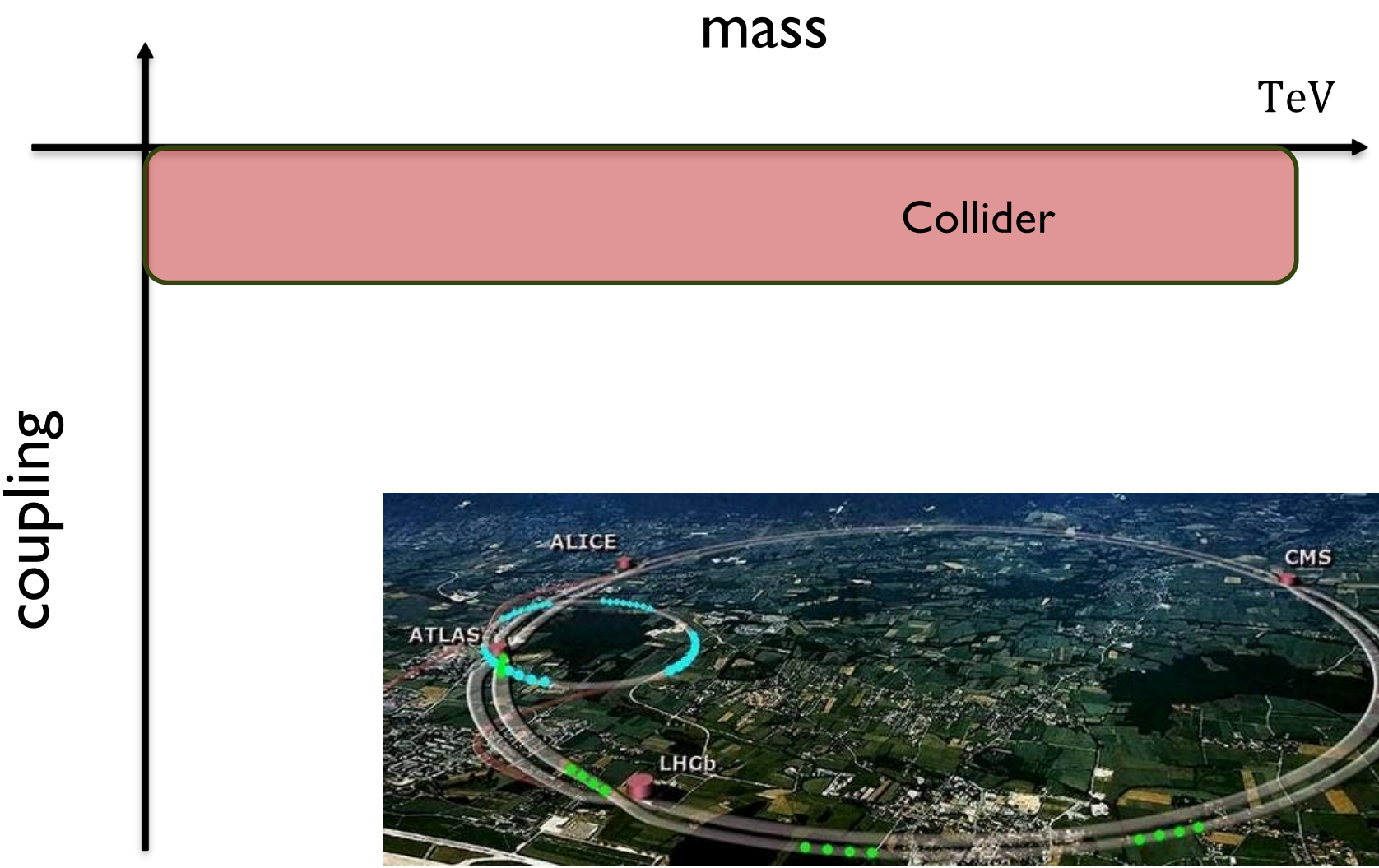
# Portal Interactions

- Scalar Portal : $\kappa|S|^2|H|^2 + \mu S|H|^2$
- Neutrino Portal : $\mathrm{y}LHN$
- Vector Portal : $\epsilon F^{\mu\nu} F'_{\mu\nu}$
- Axion Portal : $\mathrm{g}_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$

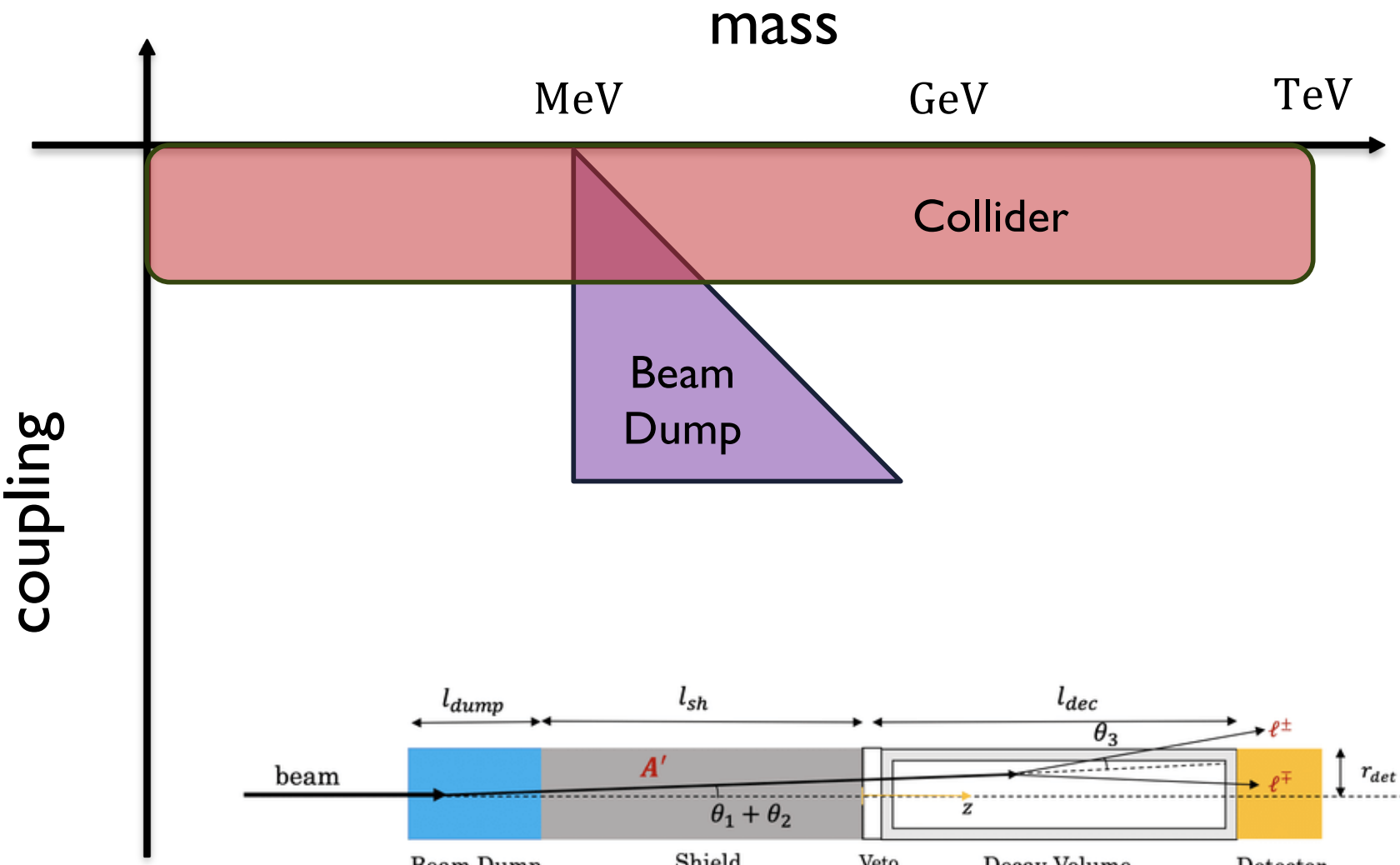
# Dark Sector Particle Parameterization



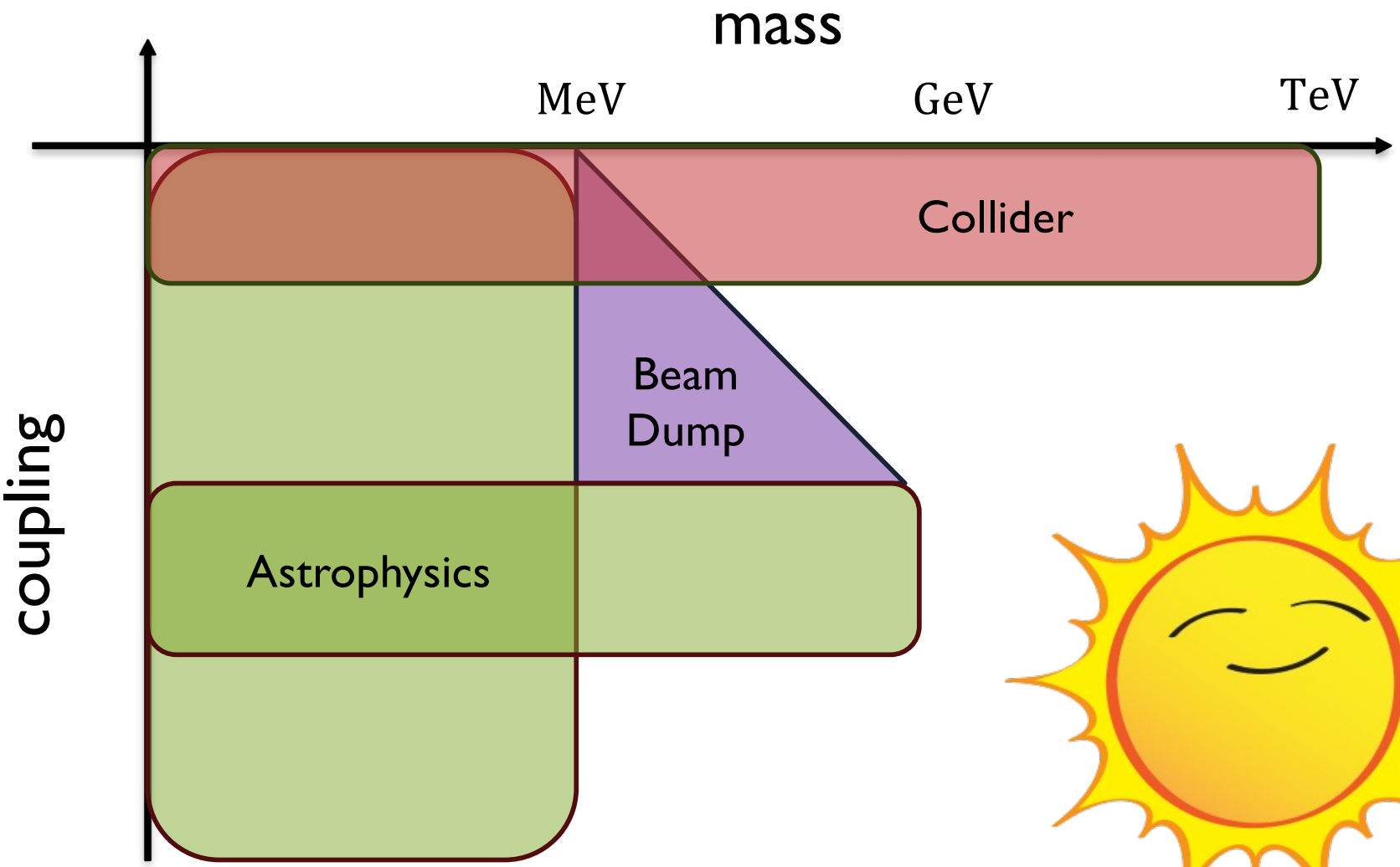
# Collider Searches



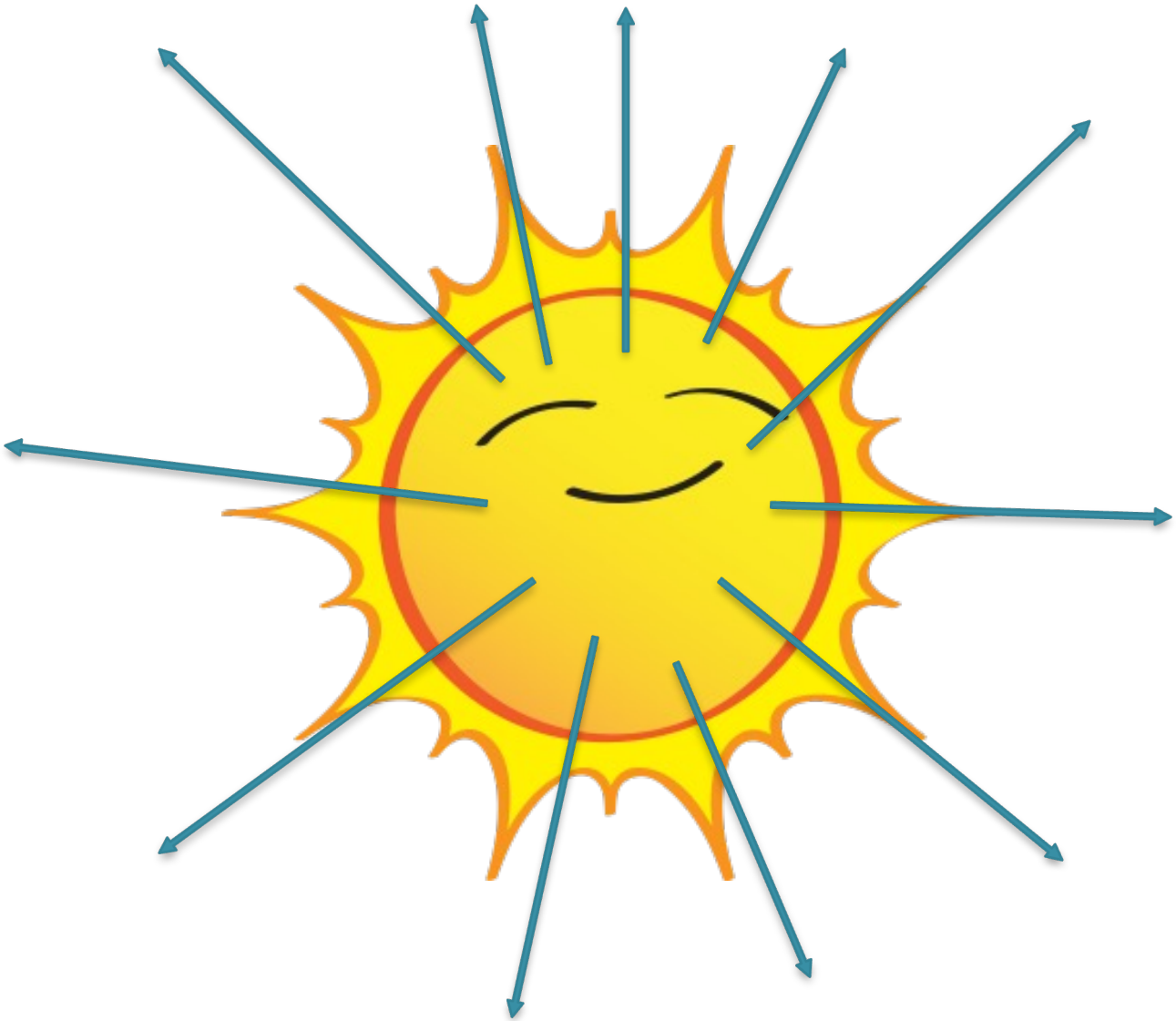
# Beam Dump Experiments



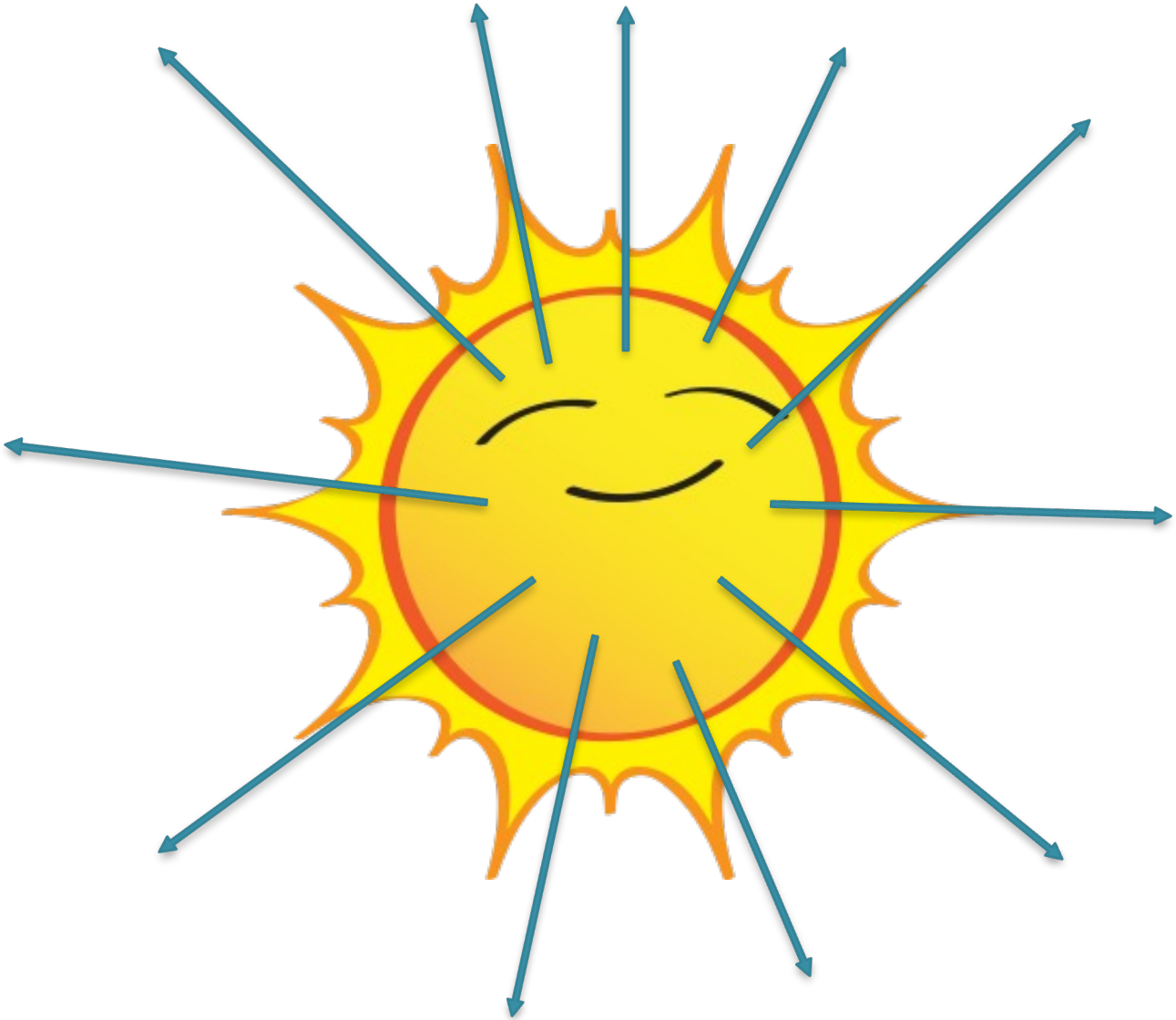
# Astrophysical Searches



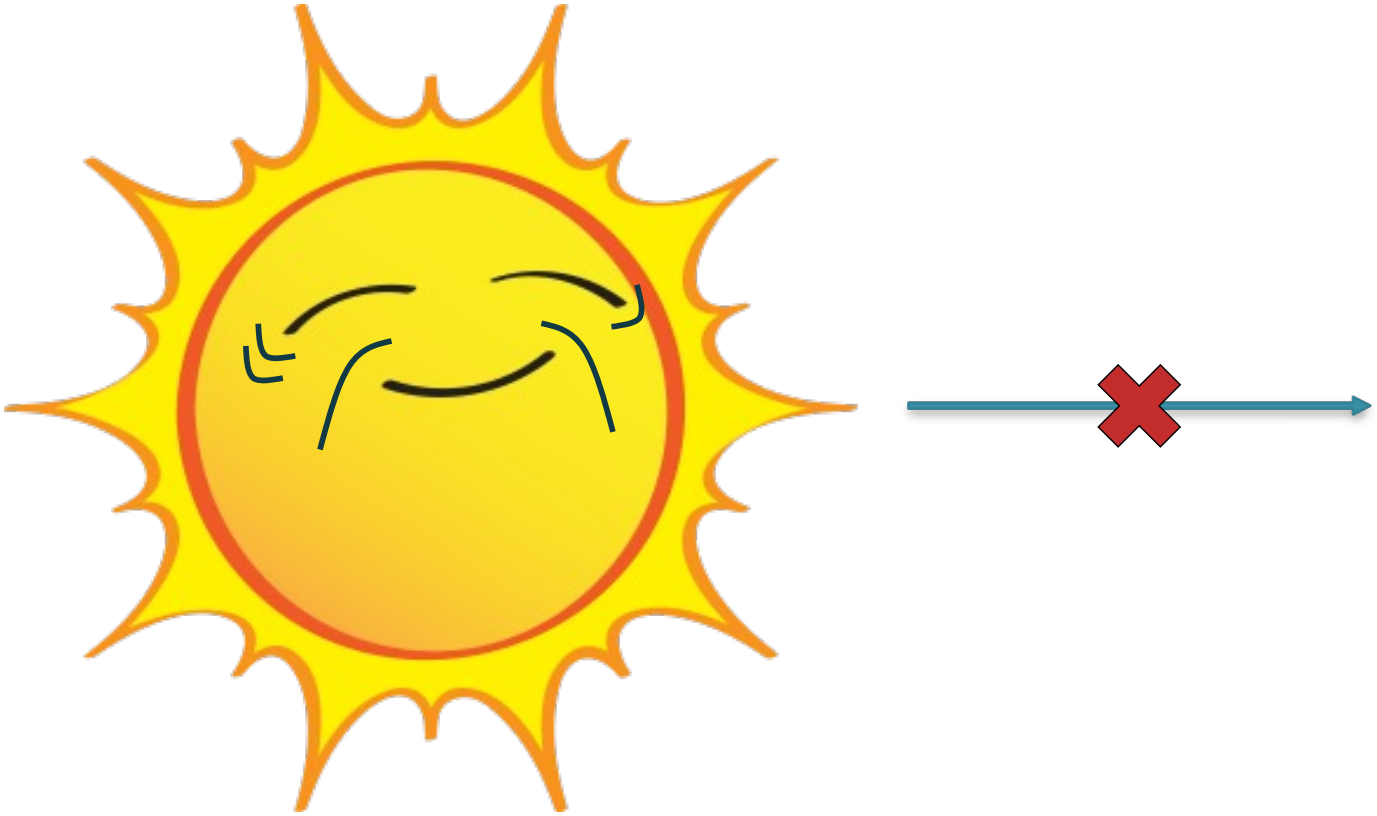
# Particle Production from Stellar Objects



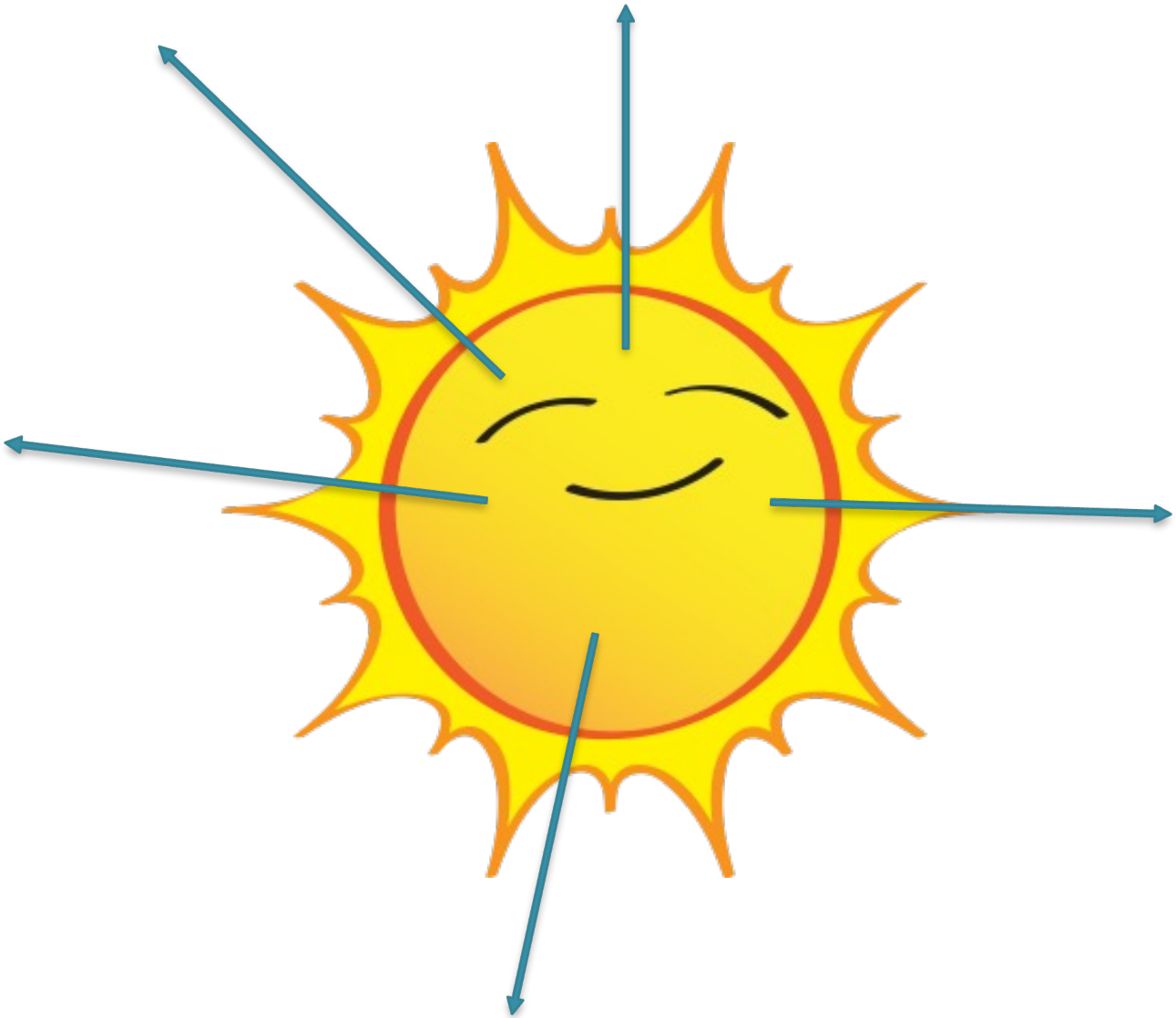
# Cooling of Stars



# Cooling of Stars



# Decay to EM energy



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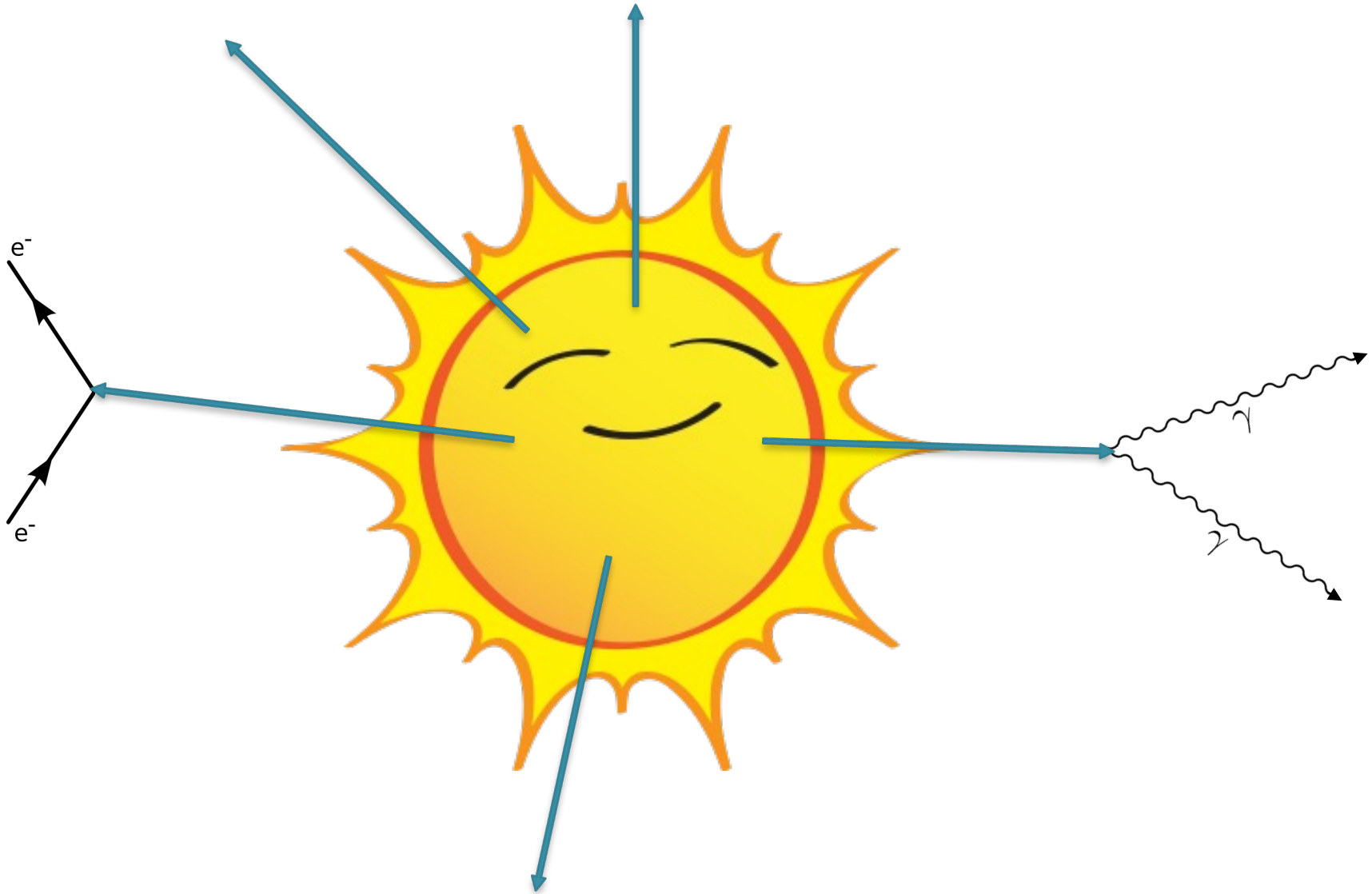
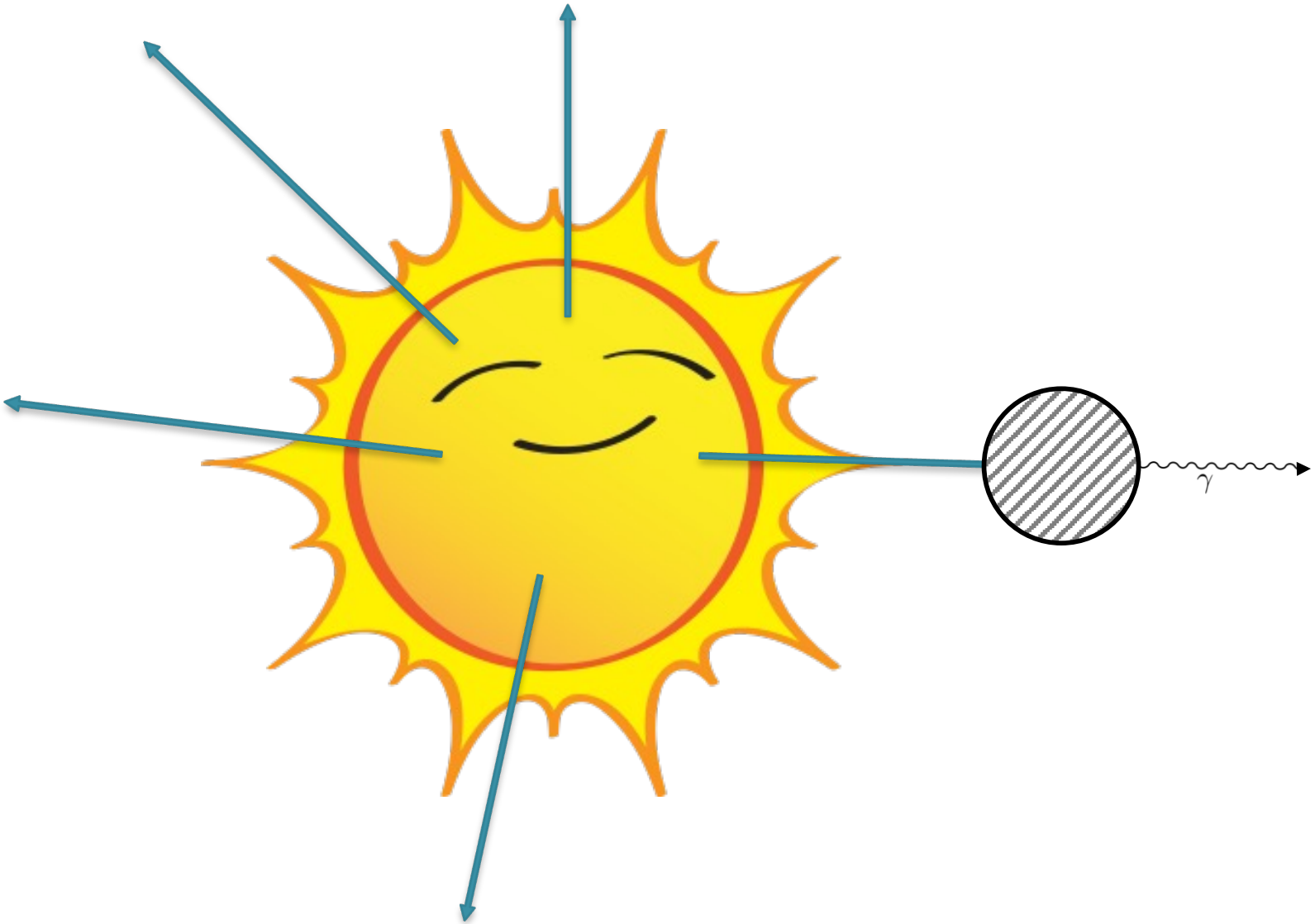


# Conversion to EM energy



# Axion Constraints

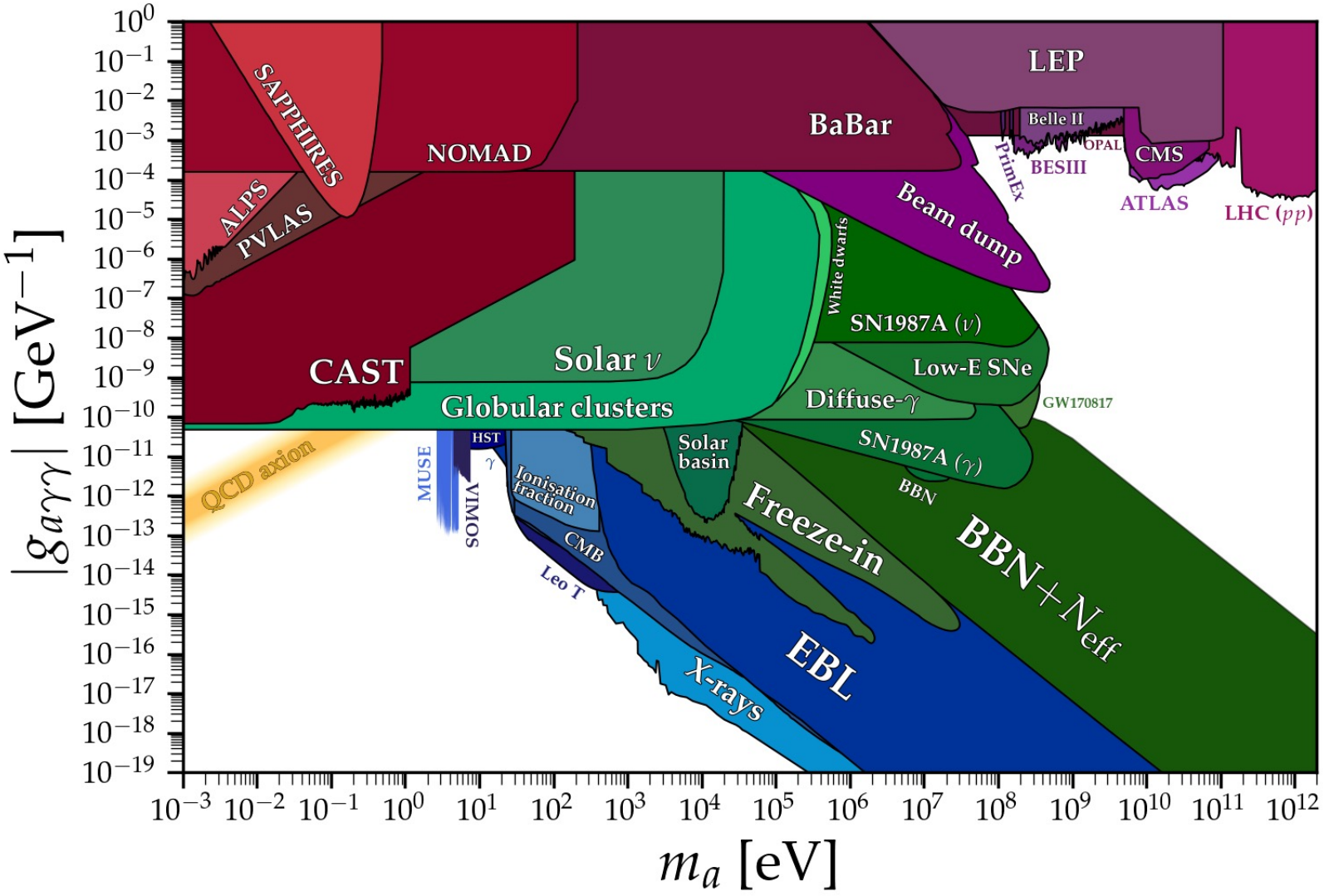
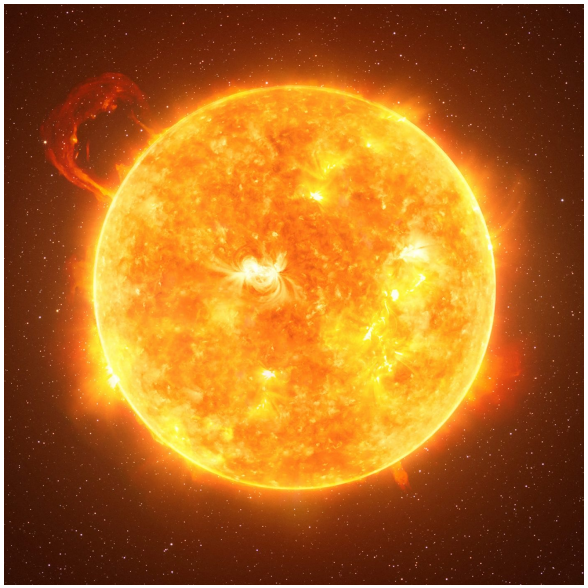



Image from https://cajohare.github.io/AxionLimits/docs/ap.html

# Astrophysical Sources



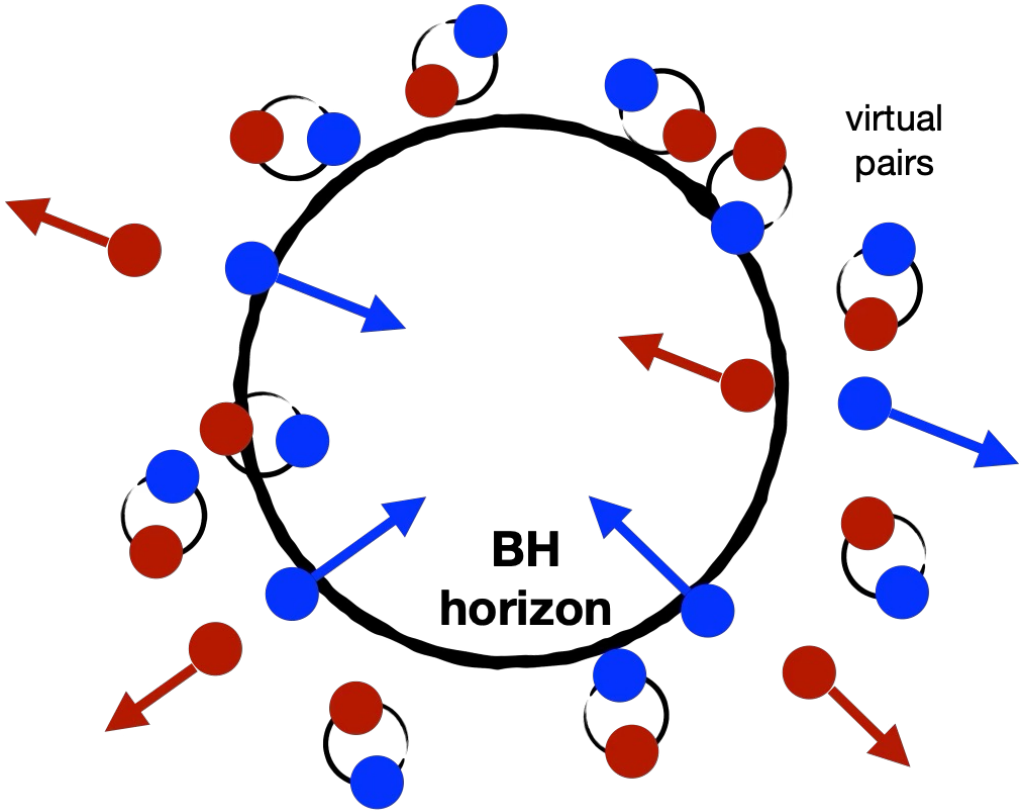
The Sun

Supernovae

White dwarfs

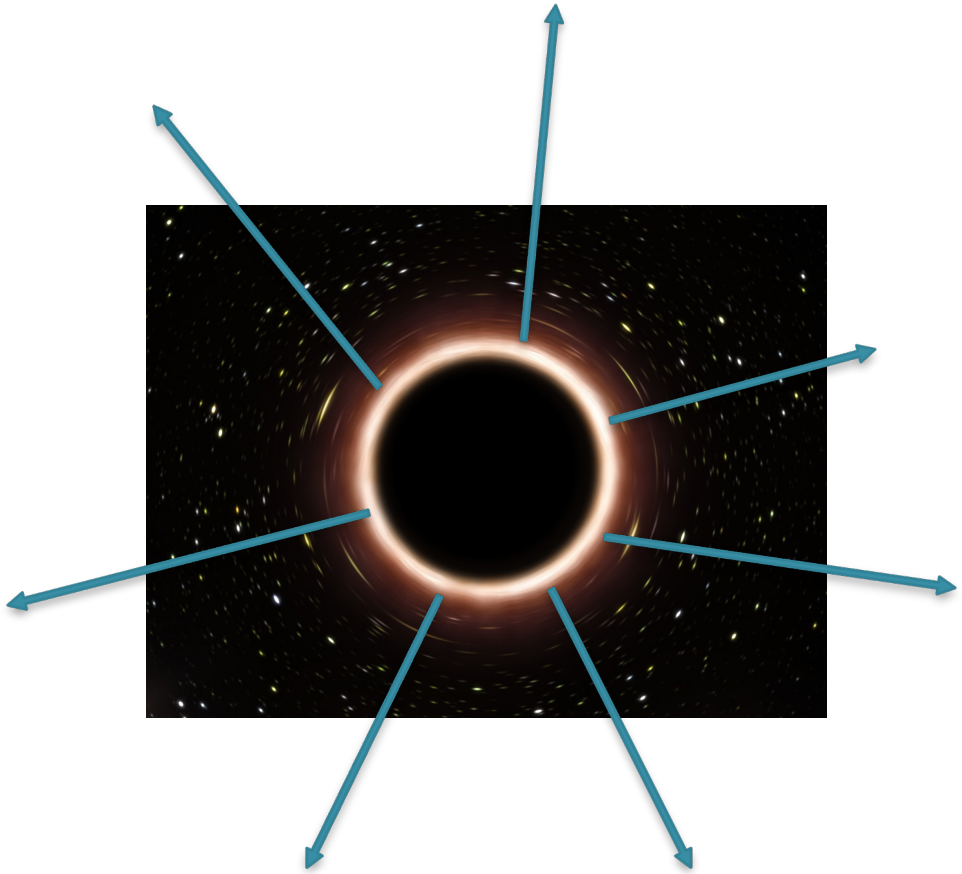
And many more…

# Another source: Black Holes




- BHs emit thermal radiation due to quantum effects near the horizon Hawking, 1974
- BHs can produce all existing particles
- PBHs are preferred: lighter BHs have higher Hawking temperature

# Dark Sector Particles from PBH



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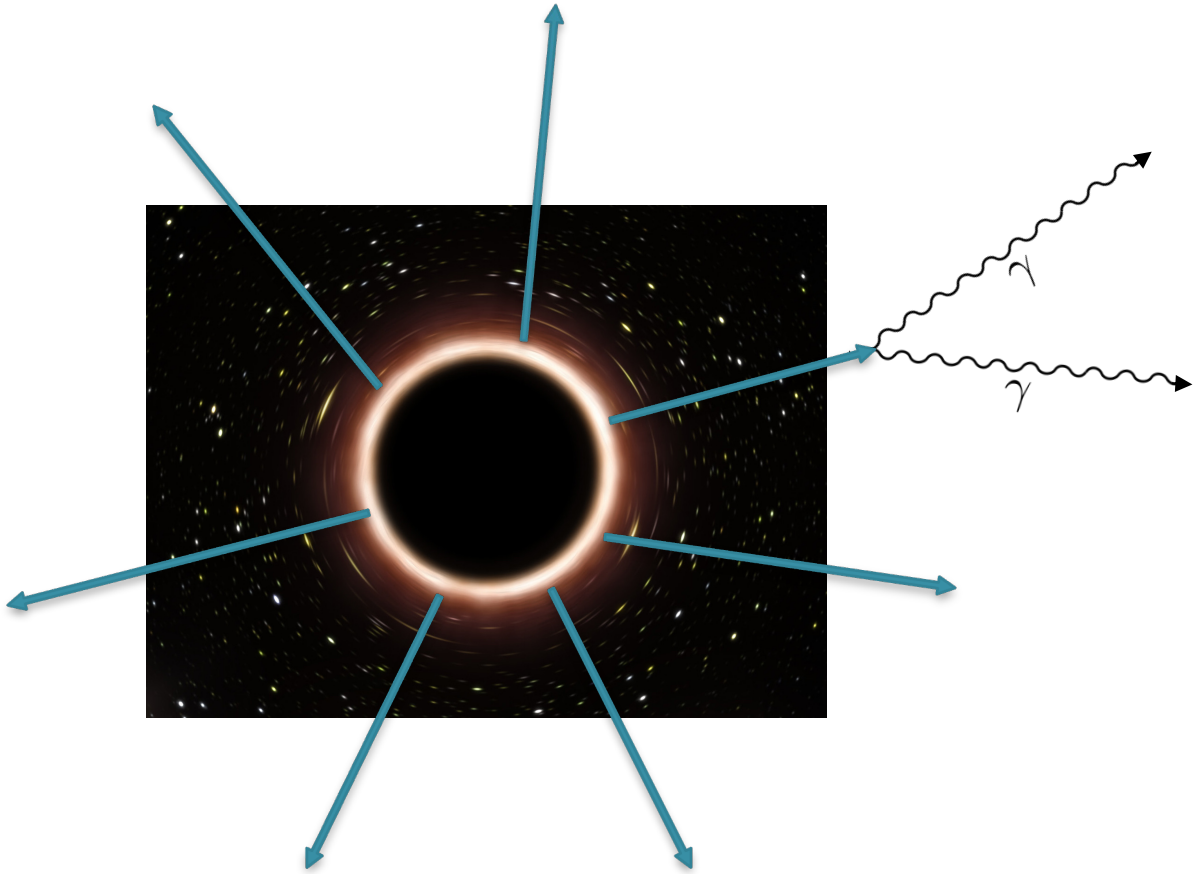
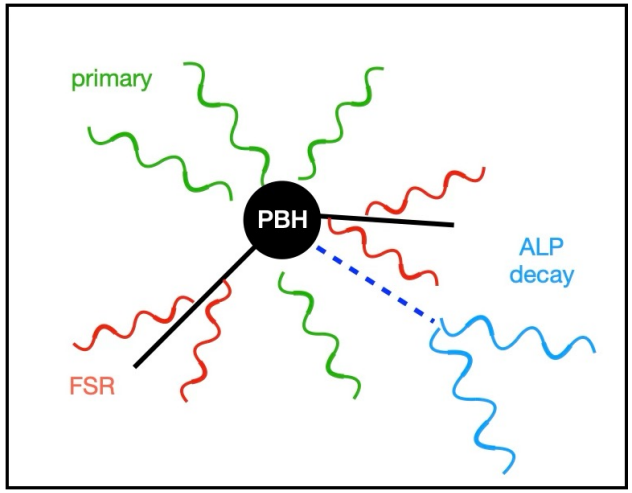
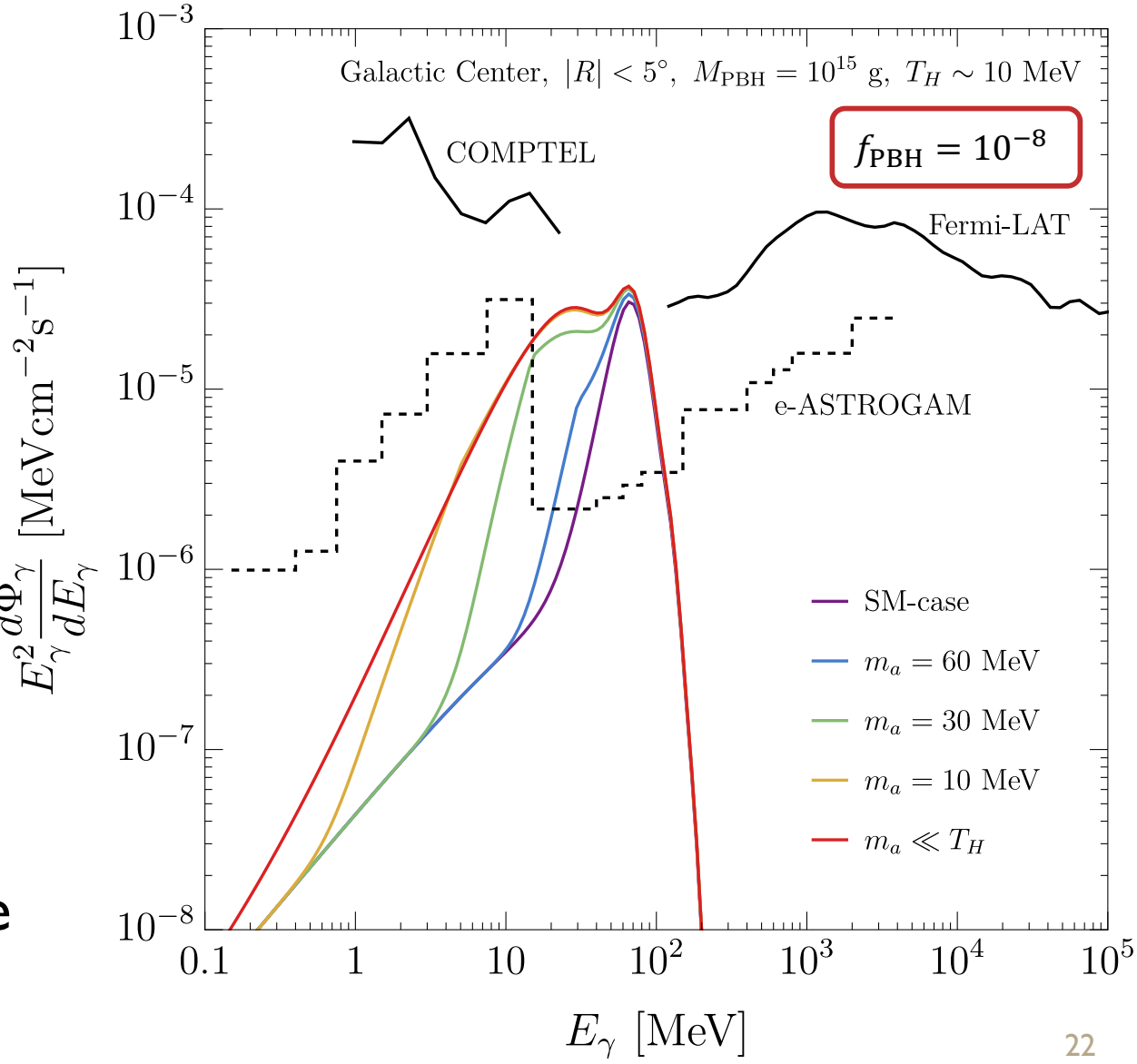



- Decay to EM energy

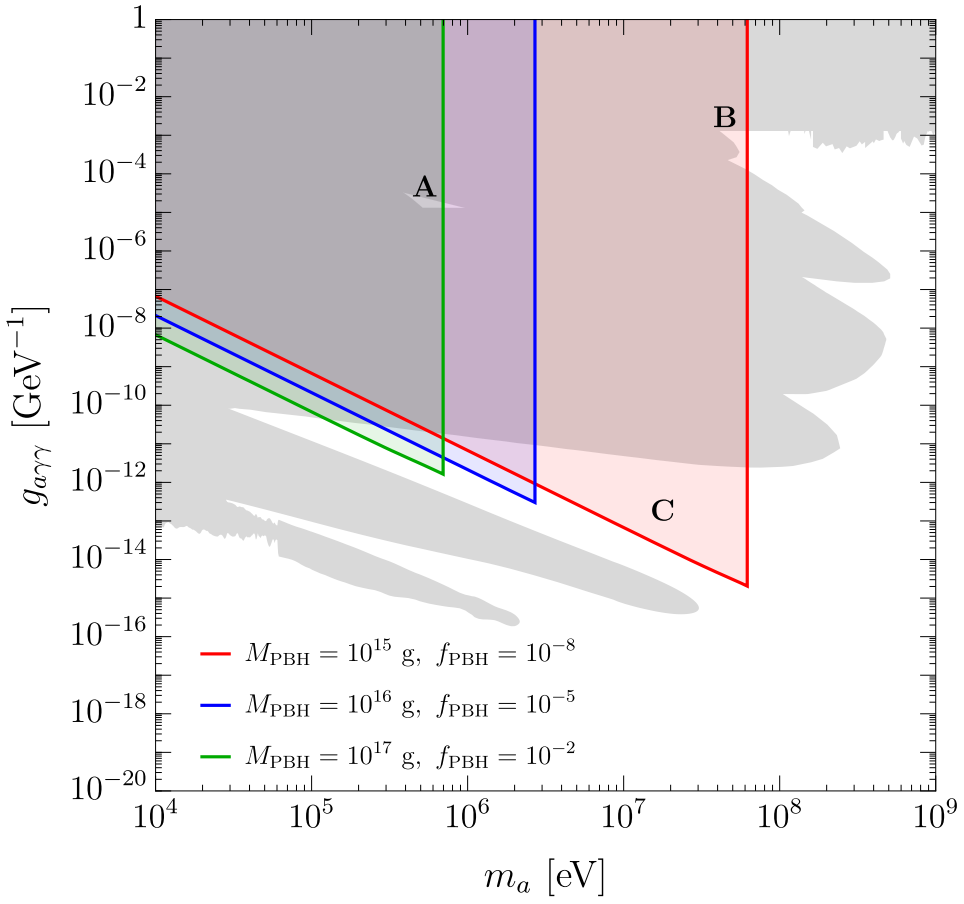
# PBH photon spectrum with axions



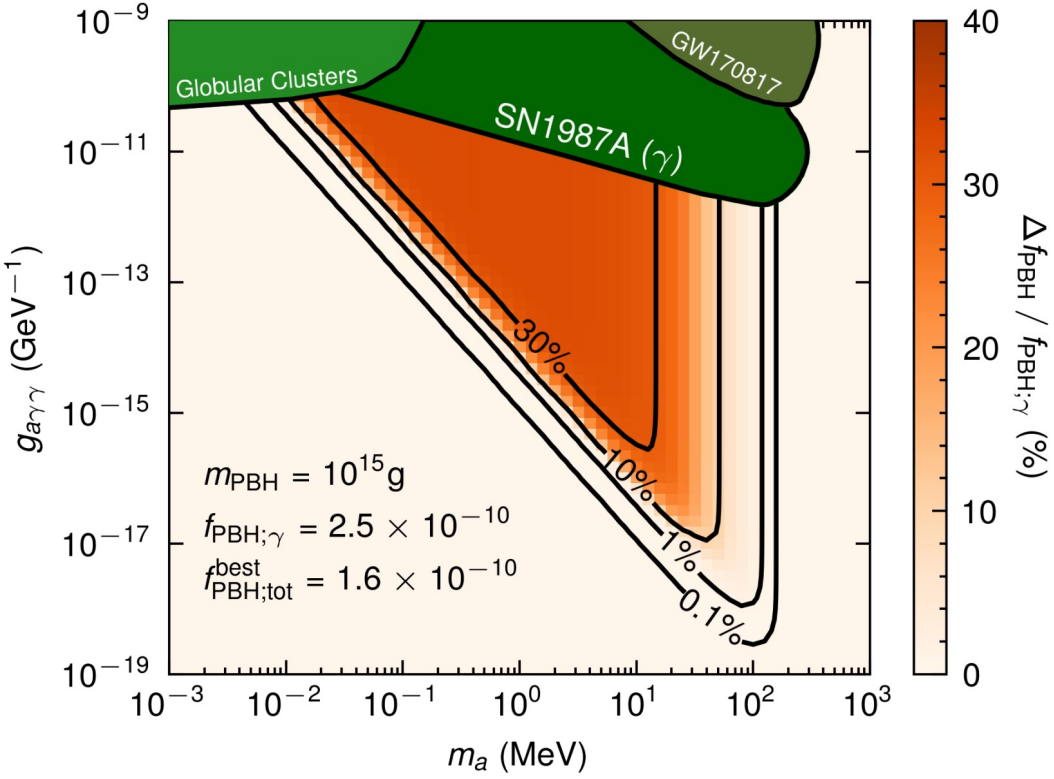

- Axion decay gives a double-peak feature
- Once the PBH photon spectrum is discovered, we can tell the existence of the axion



# Axion probes from PBH

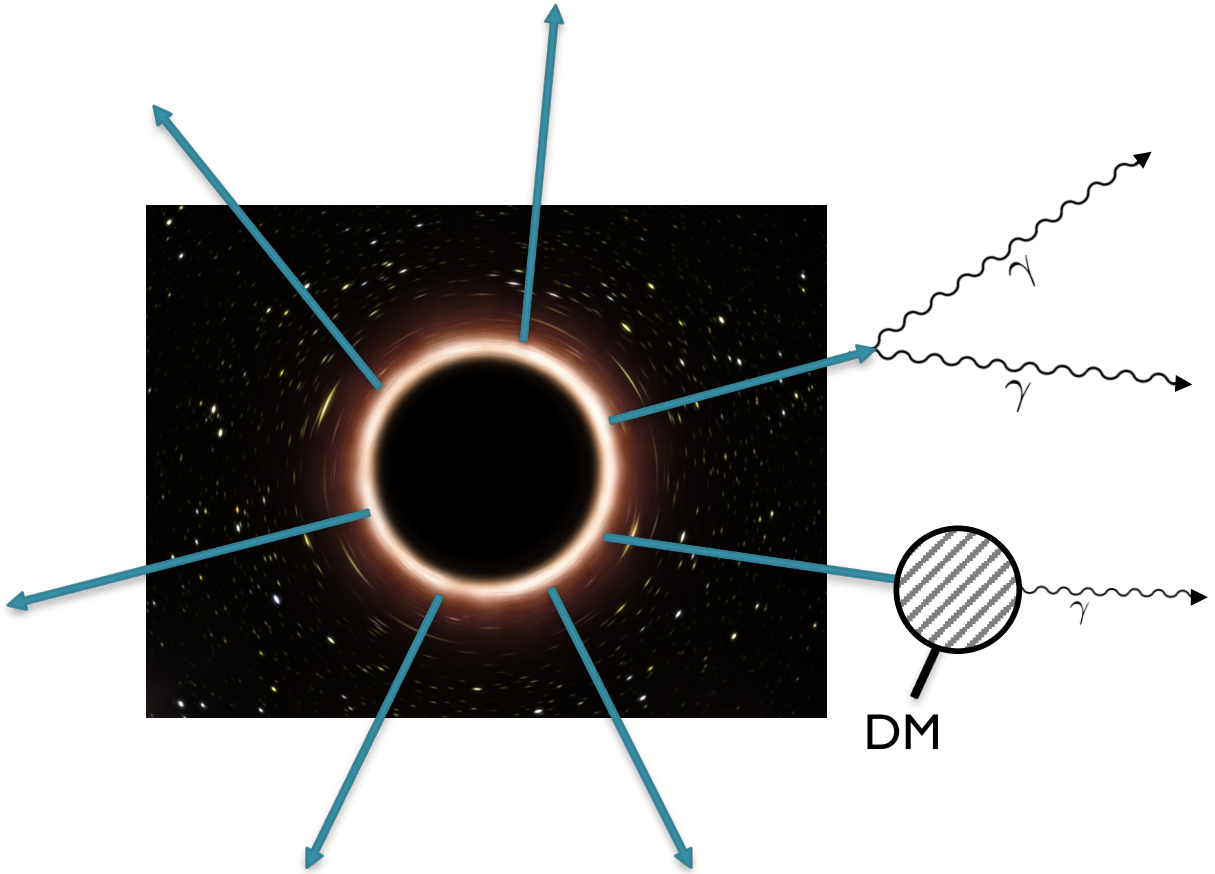



Agashe, **JHC**, Clark, Dutta, Tsai, and Xu, 2212.11980



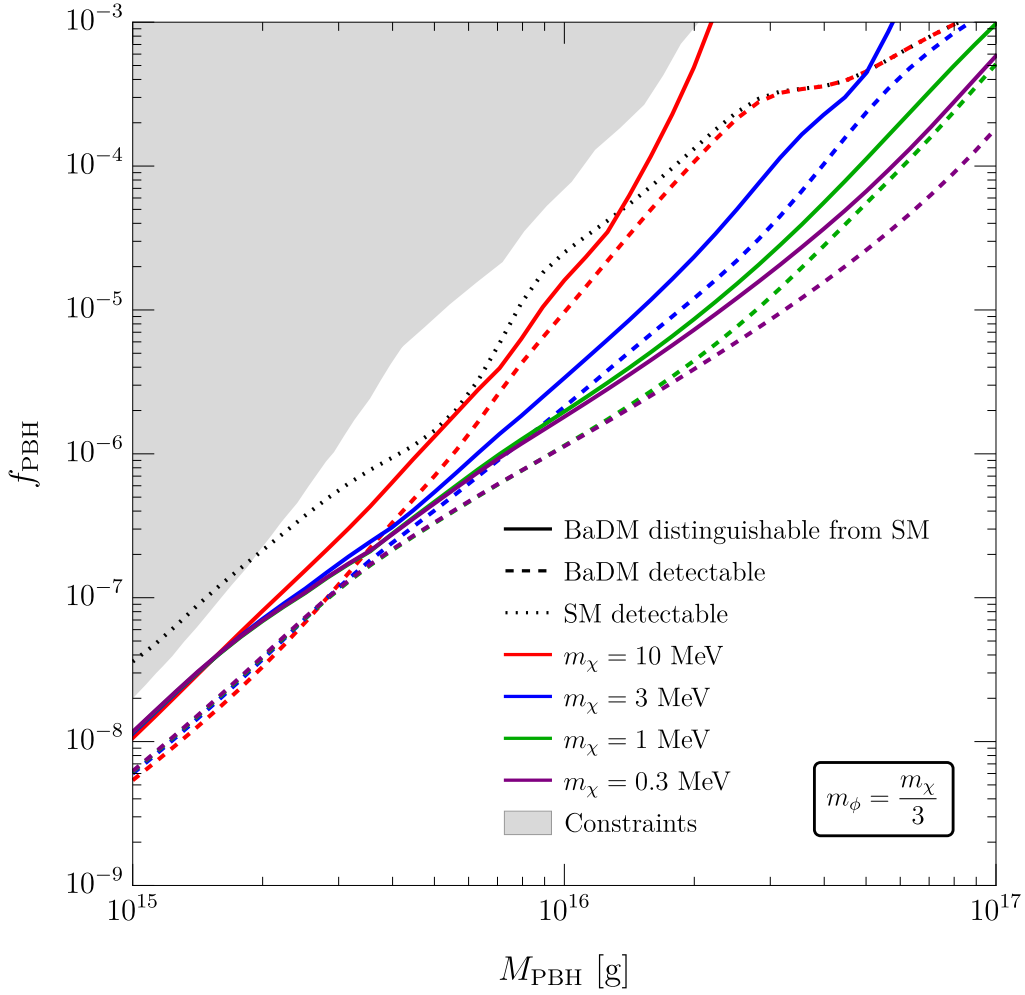

Y Jho, T-G Kim, J-C Park, SC Park, and Y Park, 2212.11977

# Dark Sector Particles from PBH

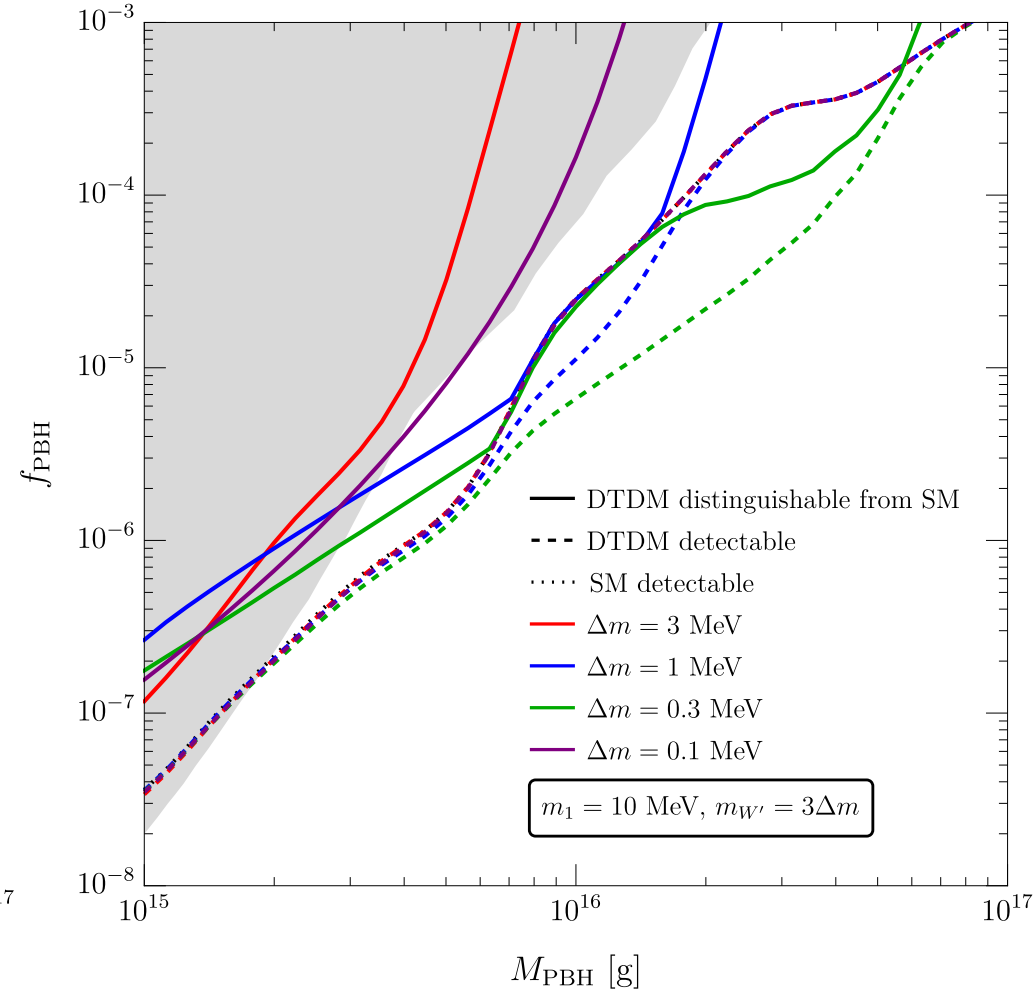



- Decay to EM energy
- Conversion to EM energy

# Models that excites DM



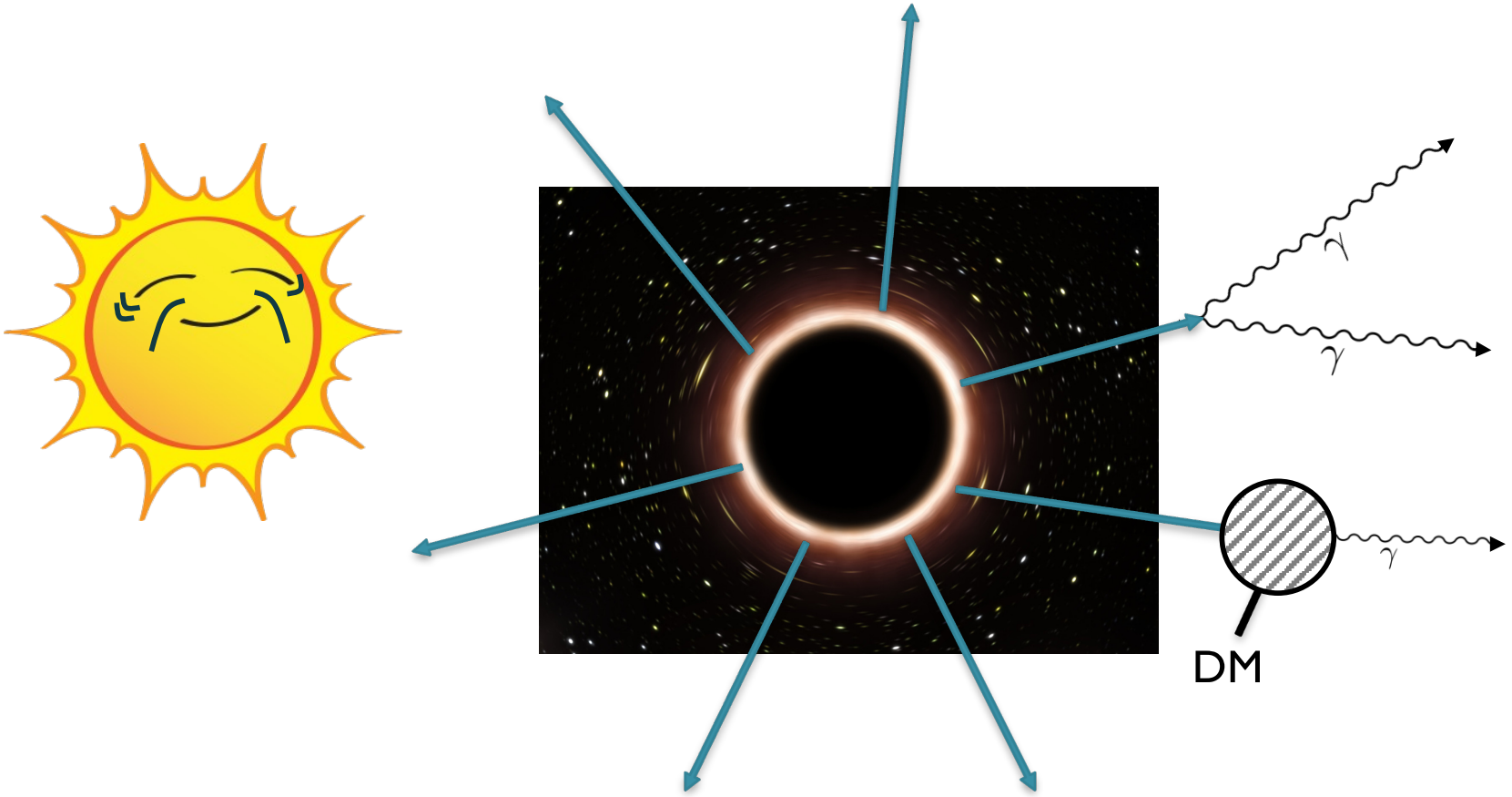

BaDM Model




DTDM Model

Agashe, Buen-Abad **JHC**, Clark, Dutta, Tsai, and Xu, 2409.13811

# Dark Sector Particles from PBH

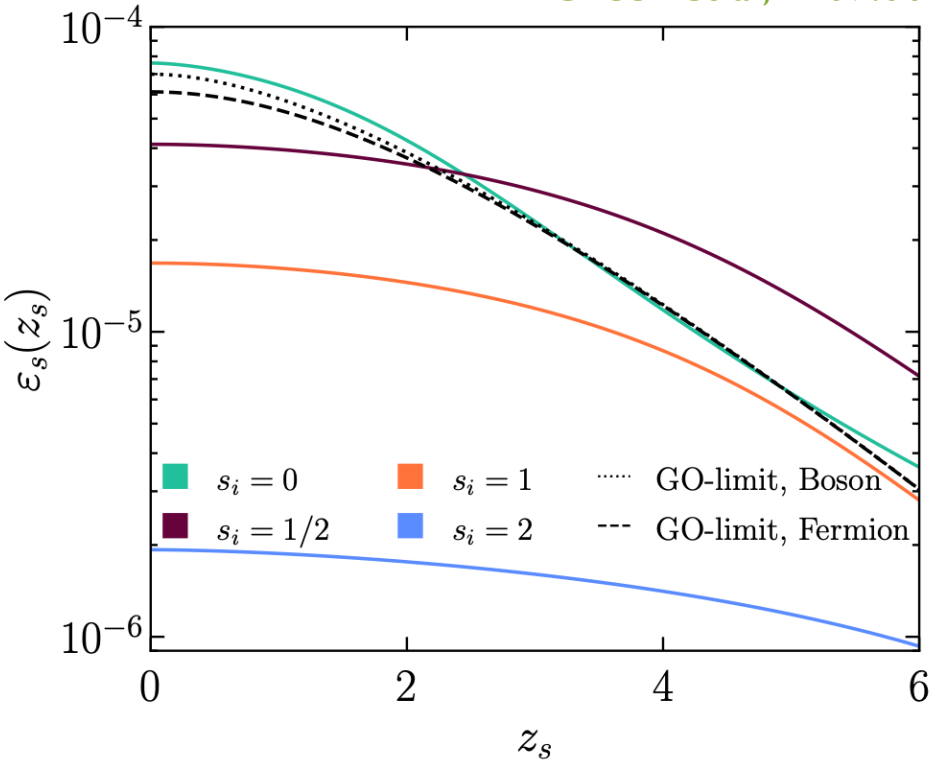



- Decay to EM energy
- Conversion to EM energy
- Evolution history

# PBH evaporation

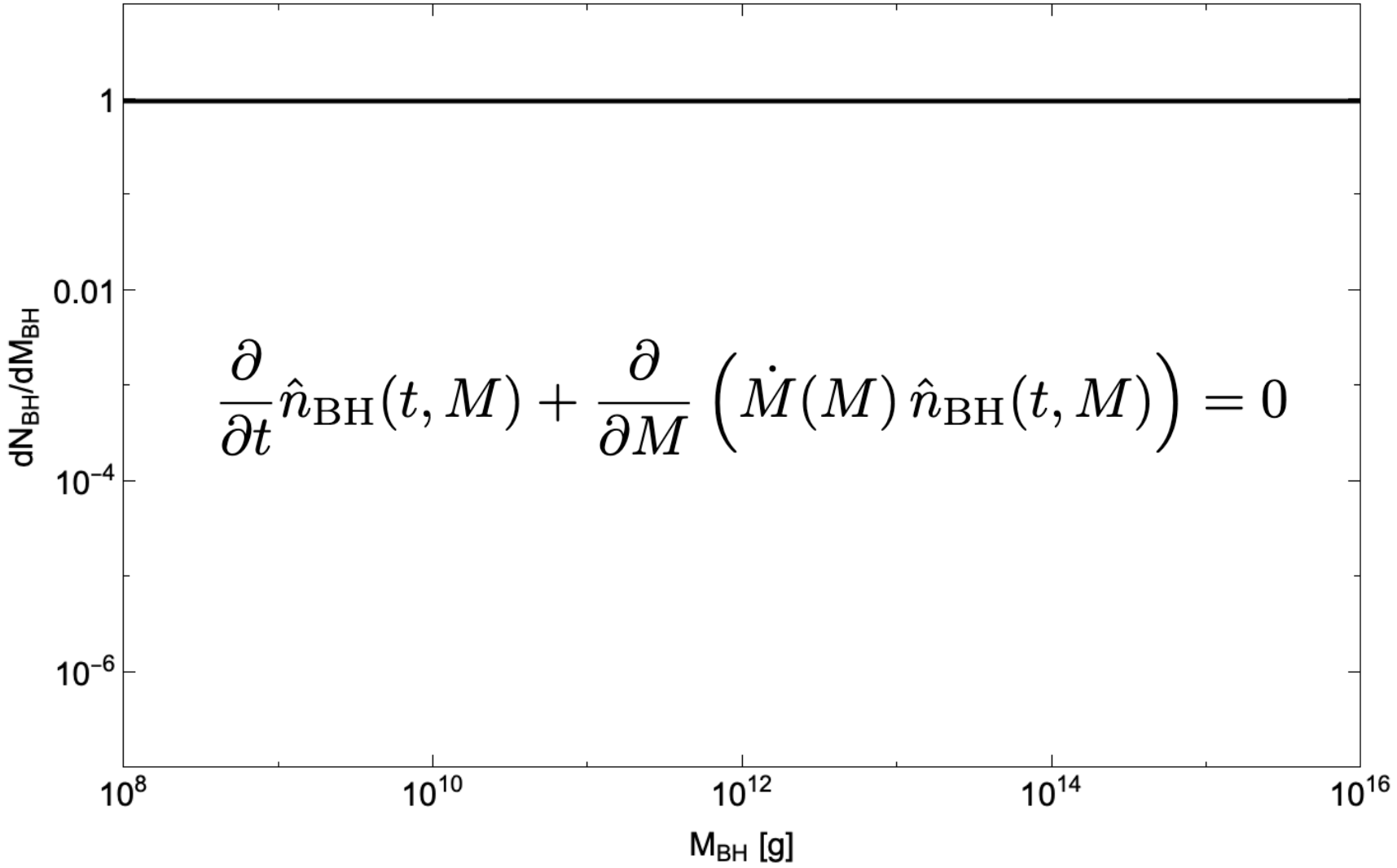
- $\dot{M}_{\rm BH} = -\varepsilon(M_{\rm BH})\,\frac{M_P^4}{M_{\rm BH}^2}$
- $\varepsilon(M_{BH}) = \sum_i g_i \varepsilon_i(z_i)$
- $z_i = m_i/T_{\rm BH}$

Cheek et al, 2107.00013




- If there are more d.o.f,
  $\dot{M}_{\rm BH}$ is larger and the PBH evaporates faster

# BH mass function evolution



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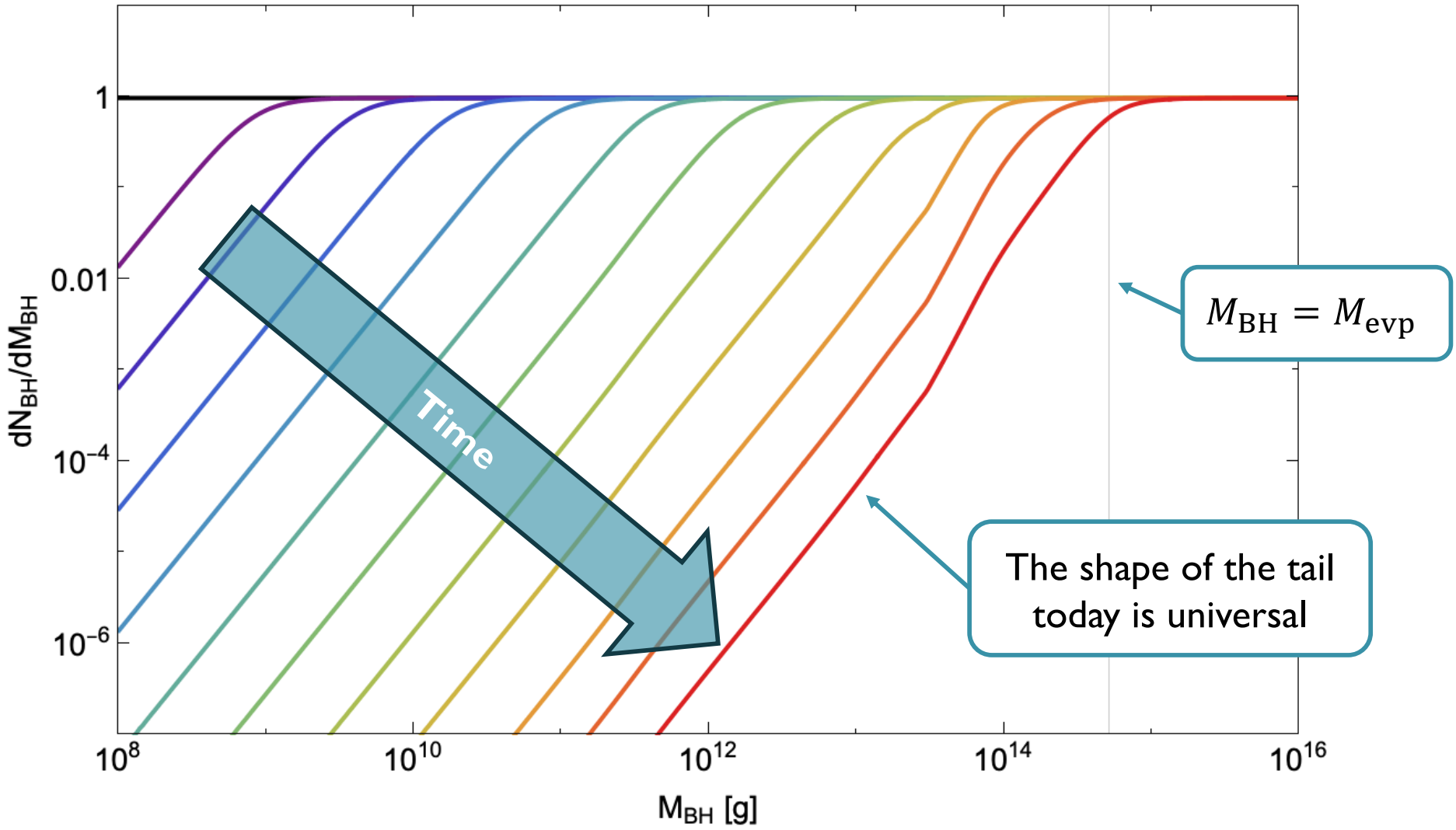
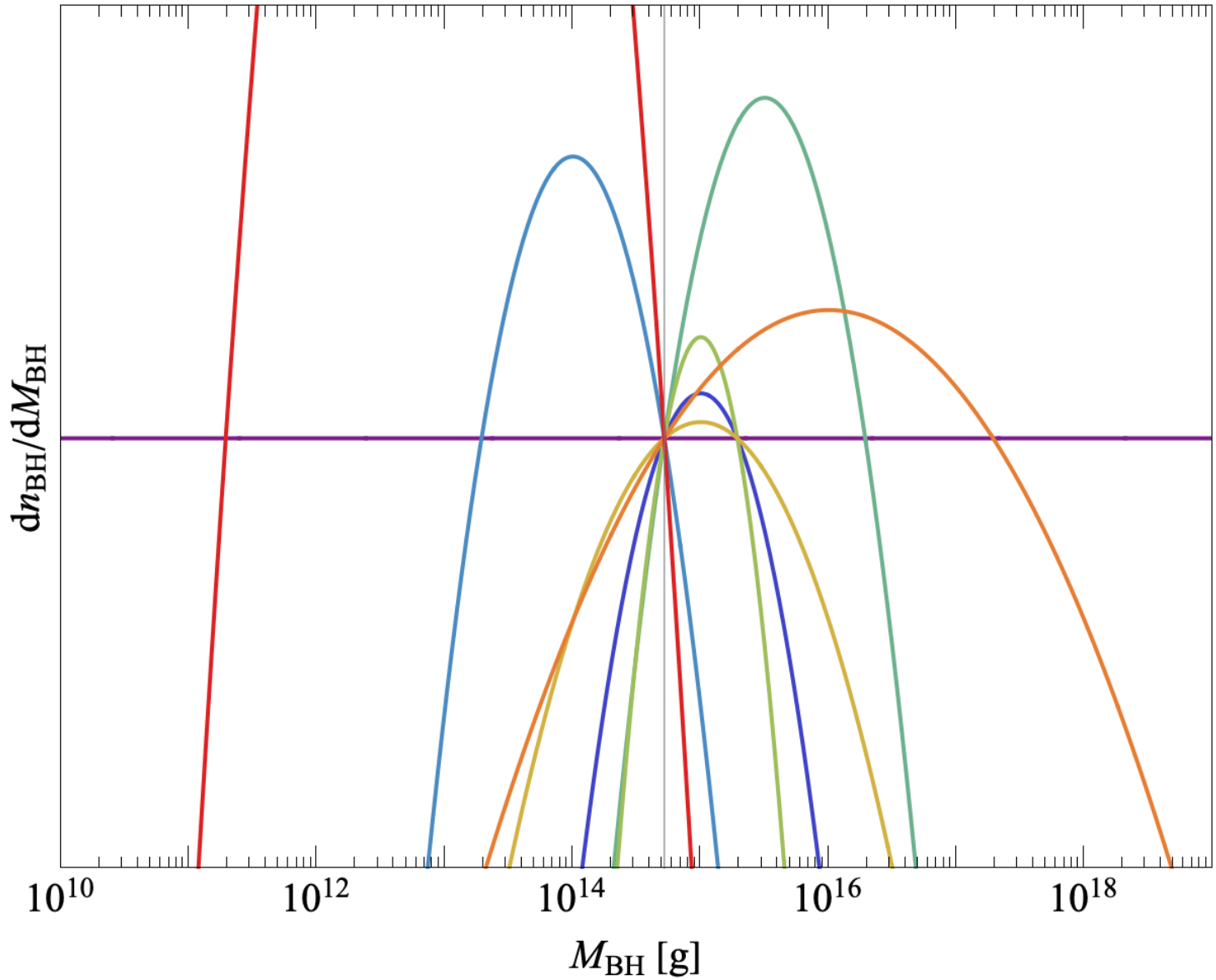
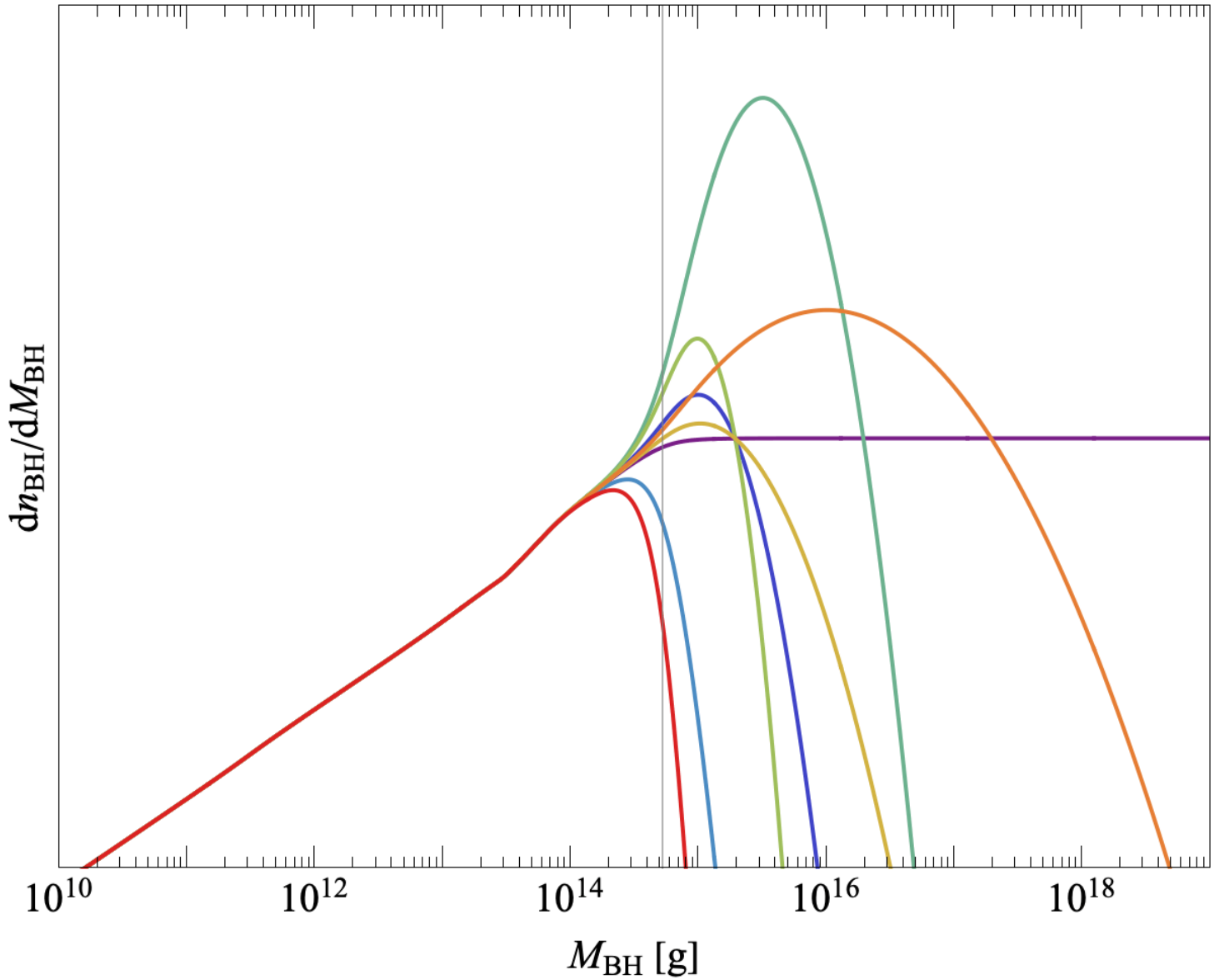


# Different BH mass functions



# Different BH mass functions today



# The tail of mass function

$$\hat{n}_{BH}(t_0, M) = \frac{\varepsilon(M_i)}{\varepsilon(M)} \frac{M^2}{M_i^2} \hat{n}_{BH}(t_0, M_i)$$

- $M_i$ is the initial mass of a PBH that has evaporated to a mass $M$ by today

- For $M \ll M_{\rm evp},\ M_i \approx M_{\rm evp}$

$$\hat{n}_{BH}\left(t_0, M \ll M_{\rm evp}\right) = \frac{\varepsilon\left(M_{\rm evp}\right)}{\varepsilon(M)} \frac{M^2}{M_{\rm evp}^2} \hat{n}_{BH}\left(t_0, M_{\rm evp}\right)$$

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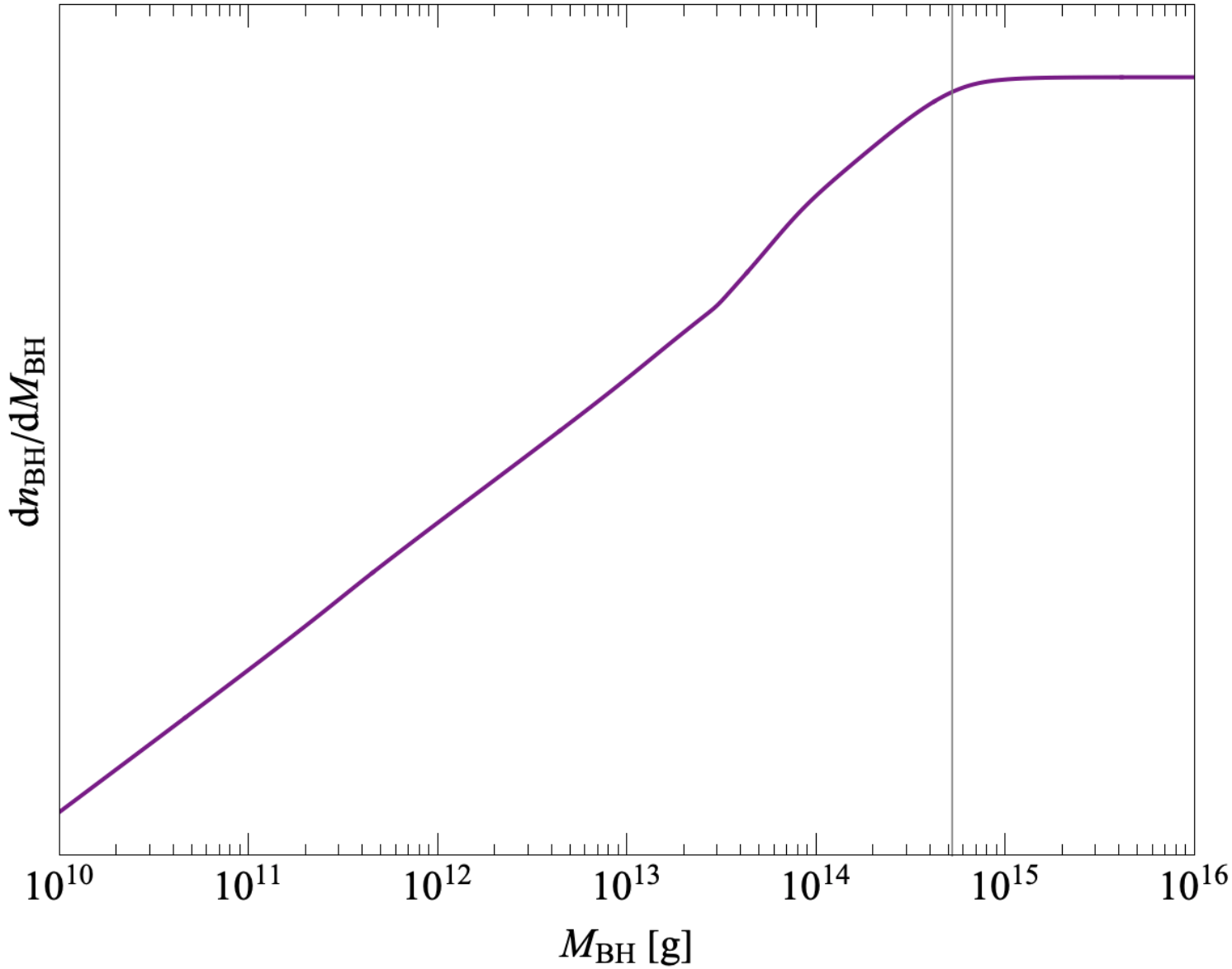
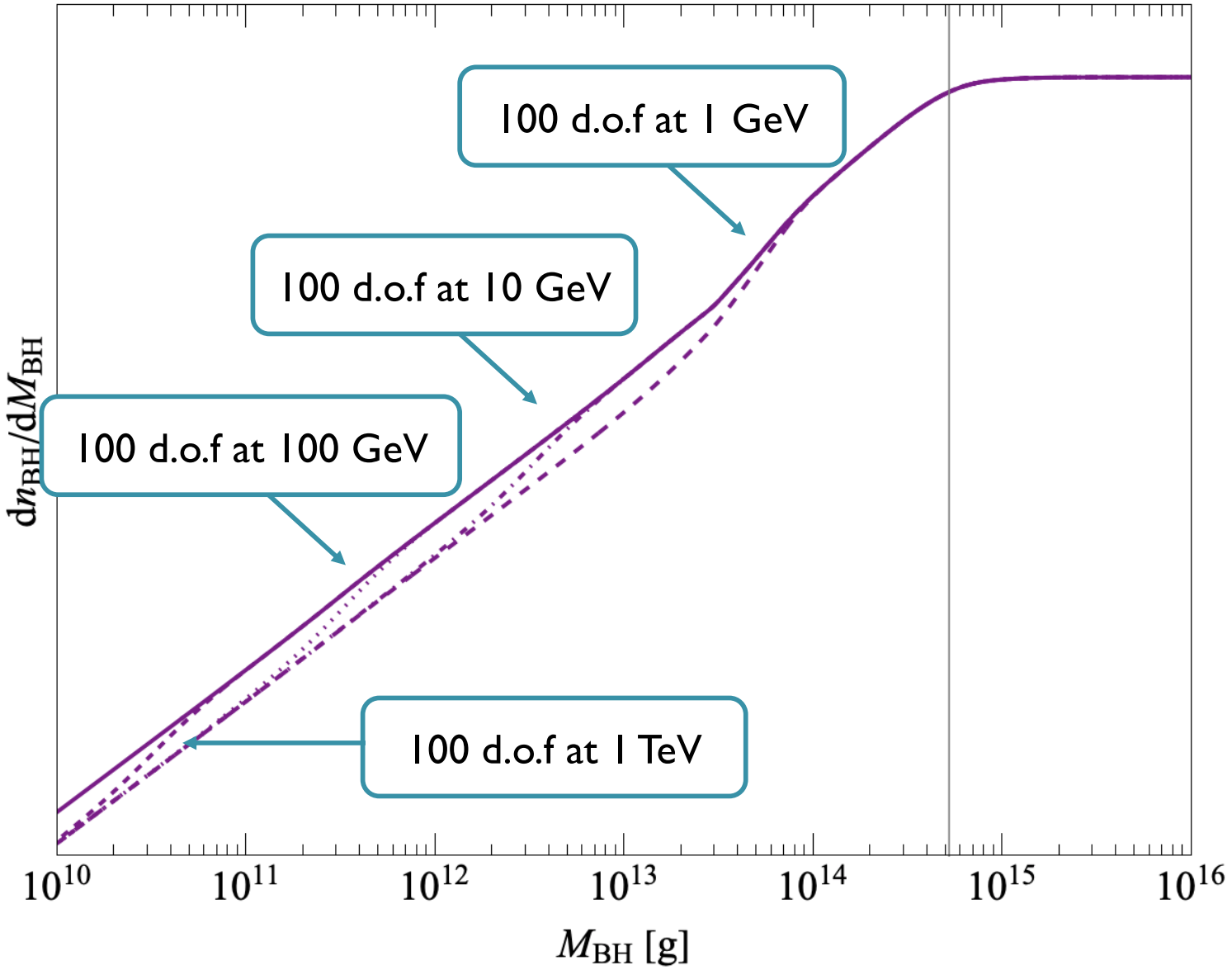
- For $M \ll M_{\rm evp}$, $M_i \approx M_{\rm evp}$

$$\hat{n}_{BH}\left(t_0, M \ll M_{\rm evp}\right) = \frac{\varepsilon\left(M_{\rm evp}\right)}{\varepsilon(M)} \frac{M^2}{M_{\rm evp}^2} \hat{n}_{BH}\left(t_0, M_{\rm evp}\right)$$

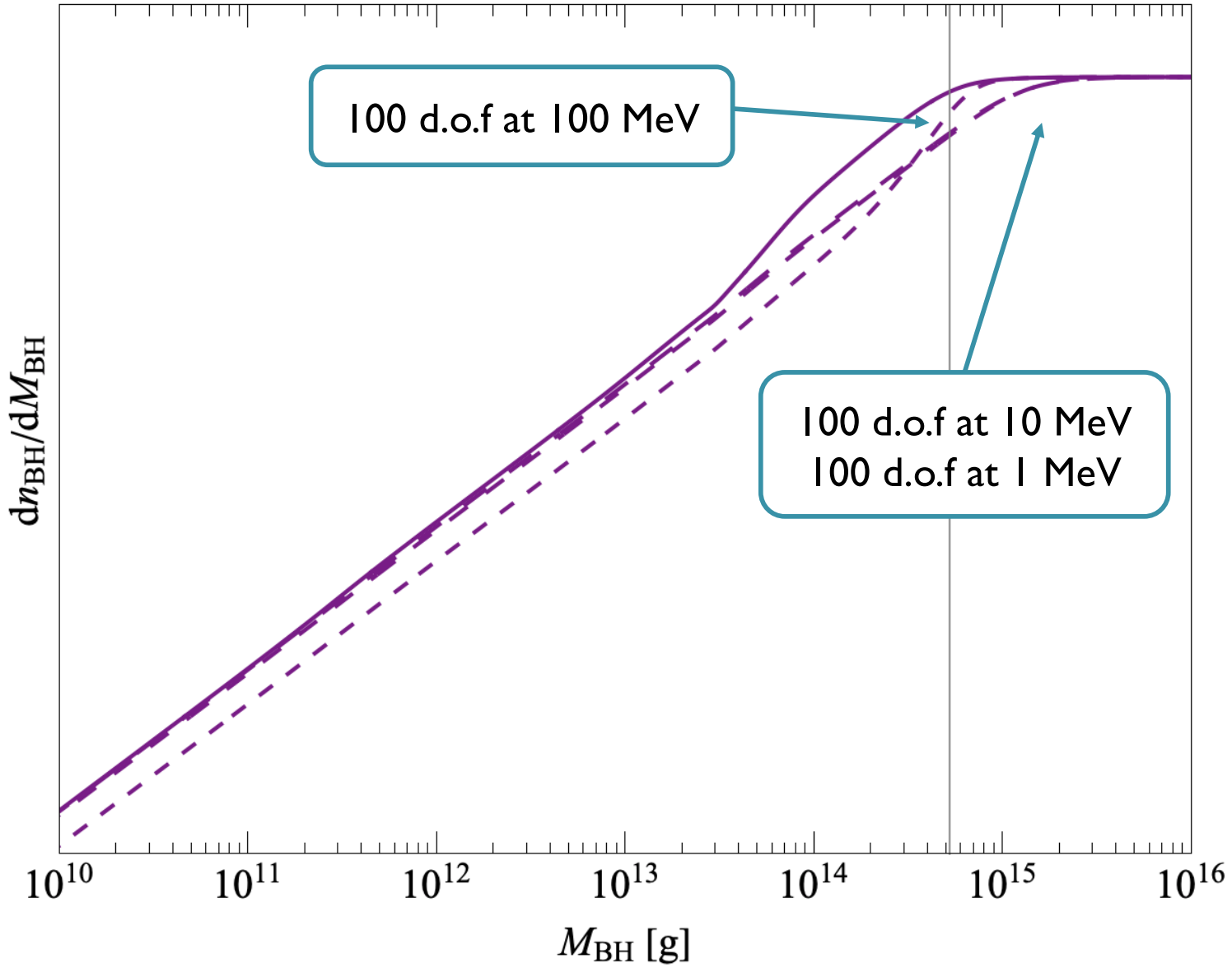
# Let's focus on the flat spectrum



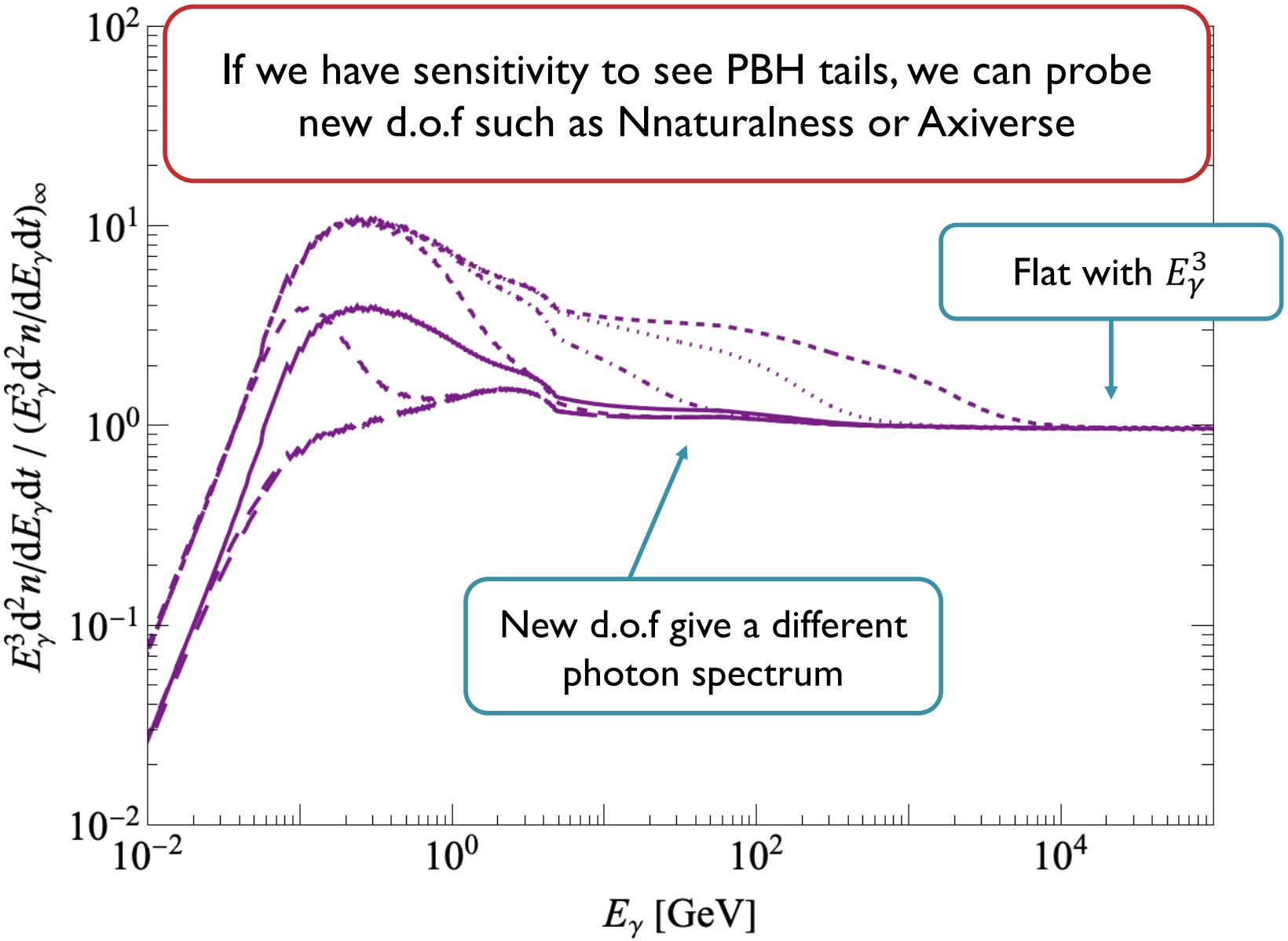
# The tail changes if we have new physics



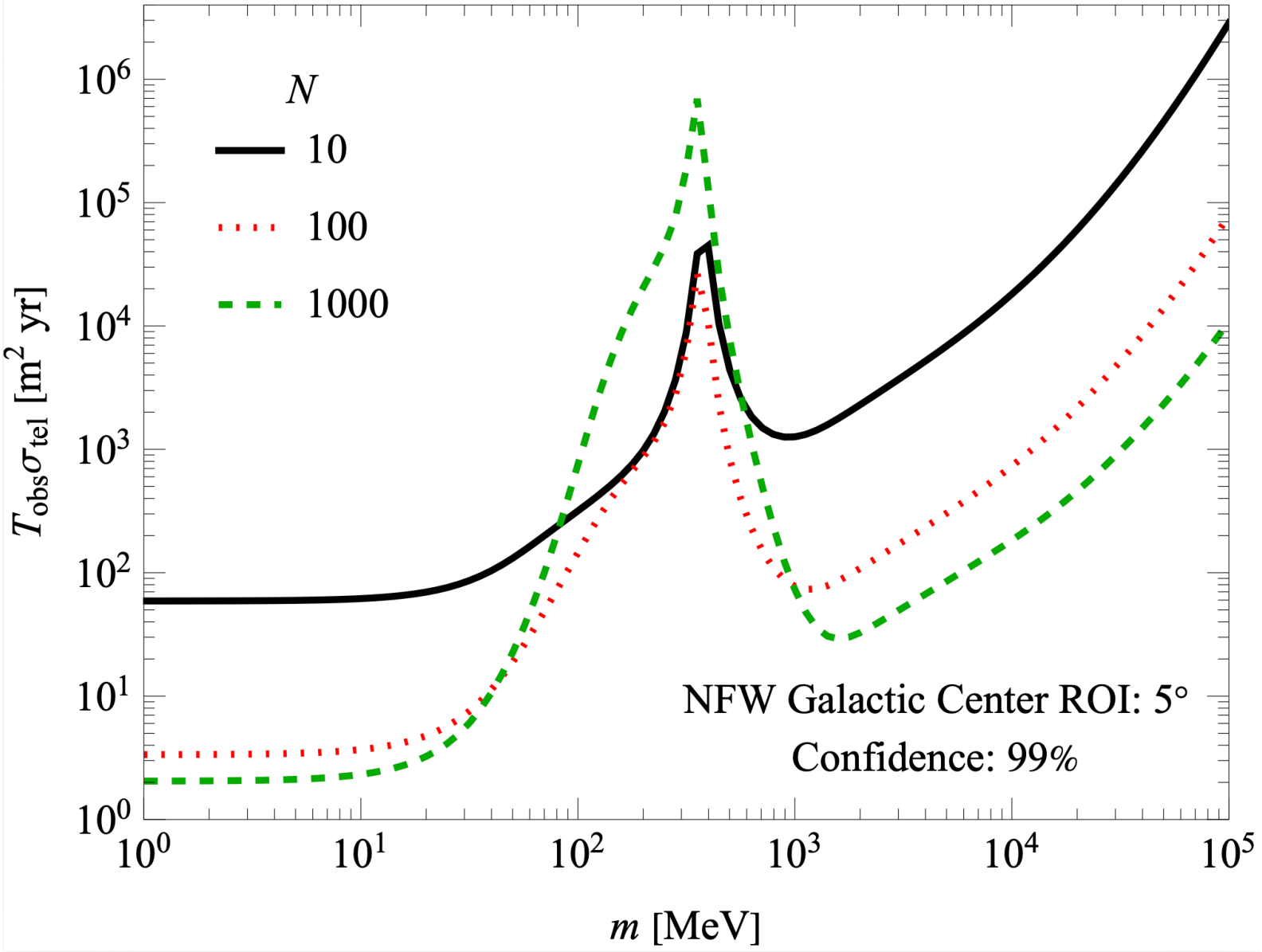
# Even $M_{\rm evp}$ is affected



# Photon Spectra



# Results


N
10
100
1000
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$T_{obs}\sigma_{tel}$ [m$^2$ yr]
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
$m$ [MeV]
NFW Galactic Center ROI: 5°
Confidence: 99%

# Summary

- PBHs can be good sources for dark sector particles
- Once the PBH spectrum is discovered, we can tell the existence of dark sector particles that
  - decay into photons
  - excite dark matter
- If we can see the tail of the PBH mass spectrum, we can tell the existence of additional d.o.f regardless of their interactions with the SM

# THANK YOU

# BACK UP

# Hawking Temperature

- Hawking radiation is a purely gravitational process
- Every particle can be emitted from BHs regardless of its interaction as long as $m \lesssim T_{\mathrm{BH}}$
- $T_{\mathrm{BH}} = \frac{1}{8\pi G M_{\mathrm{BH}}}$
- Intuition from the uncertainty principle:

$$\Delta x \sim r_s = 2GM \rightarrow T \sim \Delta p \sim \frac{1}{\Delta x} \sim \frac{1}{GM}$$

# Primordial Black Holes

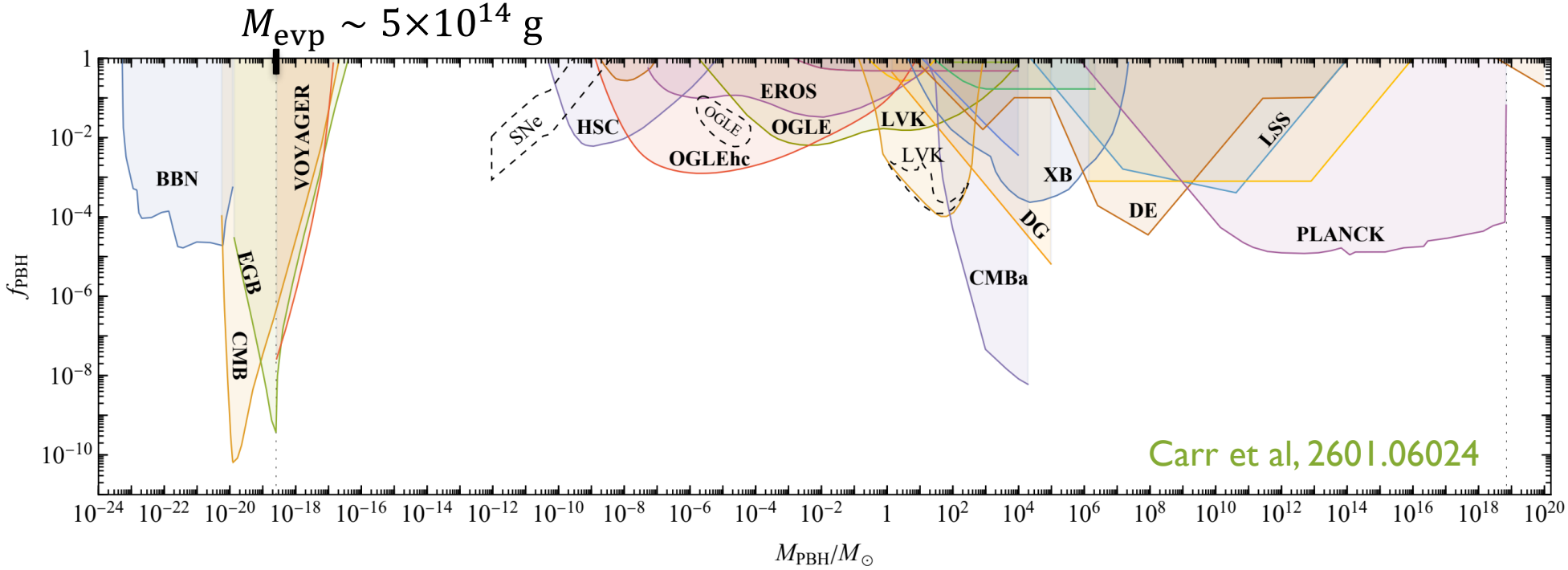
- We need a small BH mass for larger particle emission
- Astrophysical BHs are heavier than the Chandrasekhar limit

$$T_{\mathrm{BH}} \sim 10^{-11}\ \mathrm{eV} \left(\frac{M_\odot}{M_{\mathrm{BH}}}\right)$$

- PBHs form in the early Universe by collapse of Hubble patches, so they can have any mass

$$T_{\mathrm{BH}} \sim 10\ \mathrm{MeV} \left(\frac{10^{15}\ \mathrm{g}}{M_{\mathrm{BH}}}\right)$$

# Primordial Black Holes

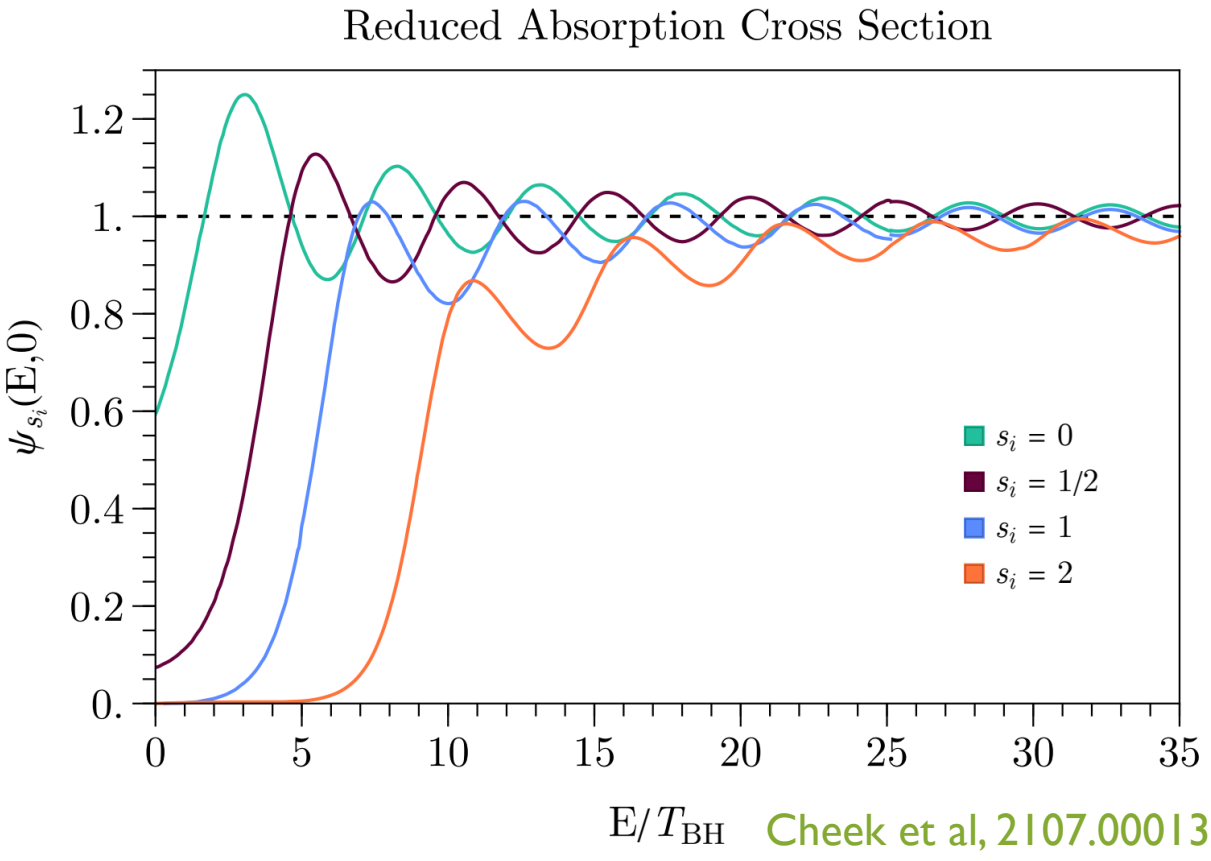



- PBHs form in the early Universe by collapse of Hubble patches, so they can have any mass

$$T_{\rm BH} \sim 10\ {\rm MeV}\left(\frac{10^{15}\ {\rm g}}{M_{\rm BH}}\right)$$

# Particle Emission Rate

- $\frac{\partial N_i}{\partial E_i \partial t} = \frac{g_i}{2\pi} \frac{\Gamma_i}{e^{E_i/T_{\rm BH}} \pm 1}$
- $\Gamma_i = \frac{\sigma_{s_i} p^2}{\pi}$
  is the greybody factor
- $\psi_{s_i} = \frac{\sigma_{s_i}}{\sigma_{GO}}$
- $\sigma_{GO} = 27\pi G^2 M_{BH}^2$
- The greybody factor depends on particle spins

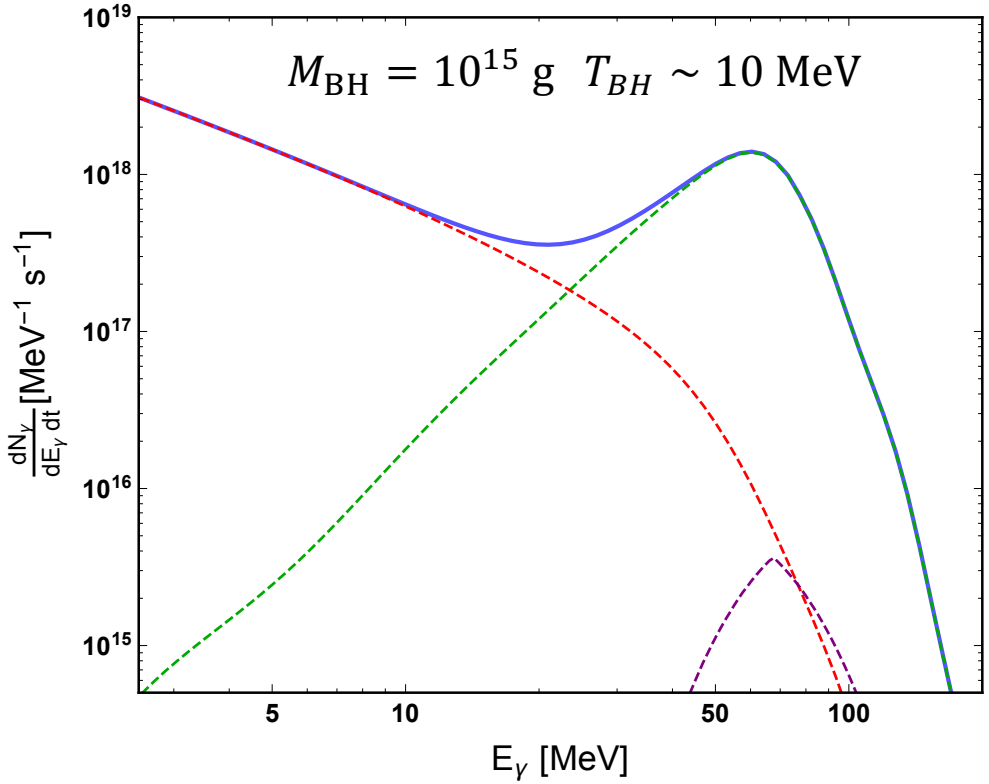


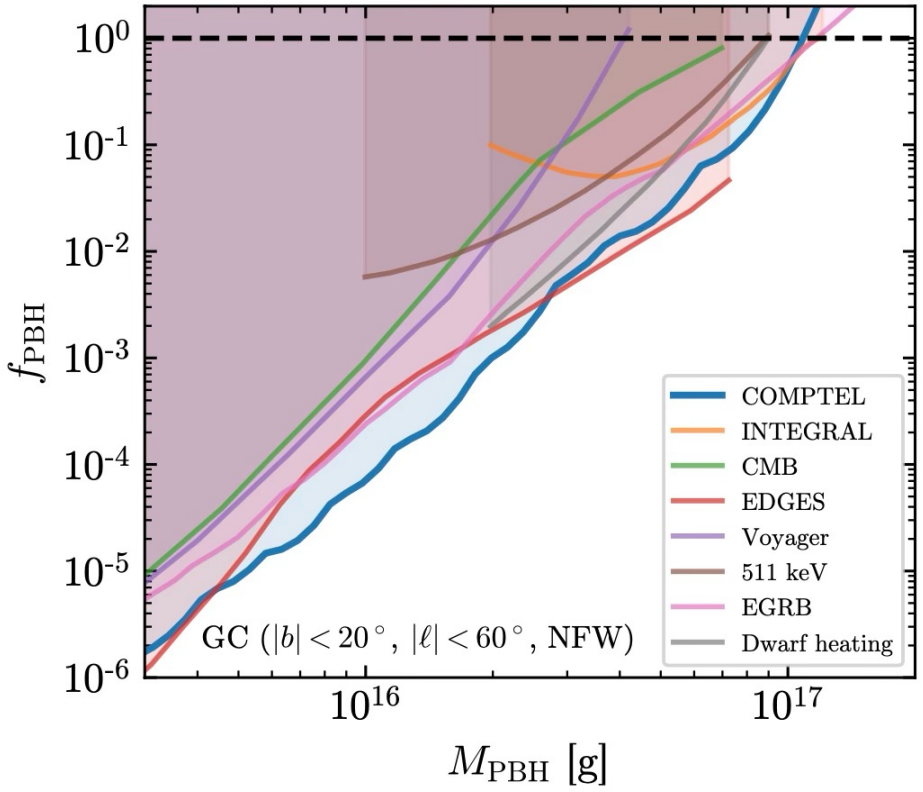

Cheek et al, 2107.00013

# Photon spectrum of Hawking radiation

$$\frac{\partial N_{\gamma,\mathrm{tot}}}{\partial E_\gamma \partial t} = \frac{\partial N_{\gamma,\mathrm{primary}}}{\partial E_\gamma \partial t} + \sum_{i=e^\pm,\mu^\pm,\pi^\pm} \int dE_i \frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} \frac{dN_{i,\mathrm{FSR}}}{dE_\gamma} + \sum_{i=\pi^0} \int dE_i 2 \frac{\partial N_{i,\mathrm{primary}}}{\partial E_i \partial t} \frac{dN_{i,\mathrm{decay}}}{dE_\gamma}$$

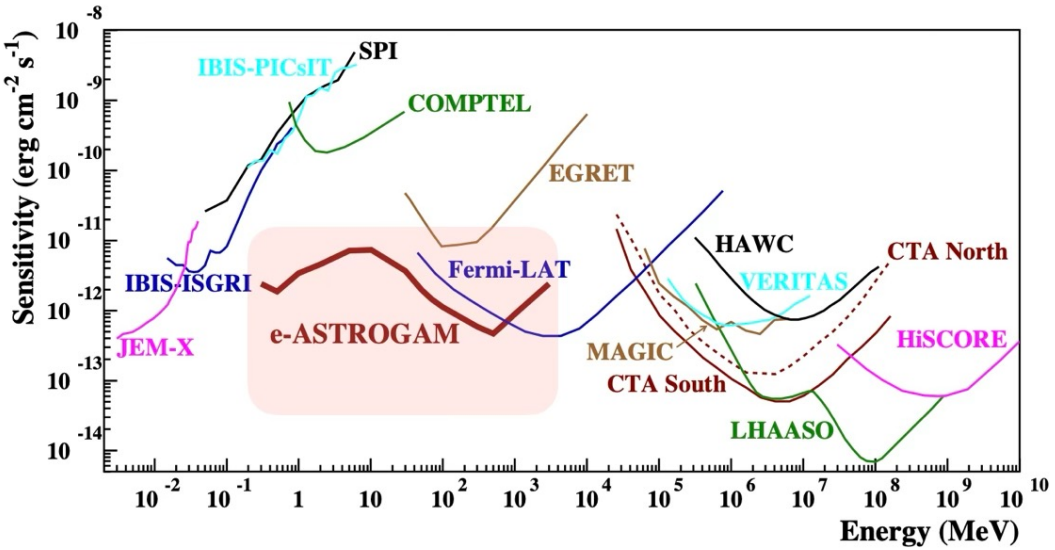
primary photon — final-state radiation — pion decay



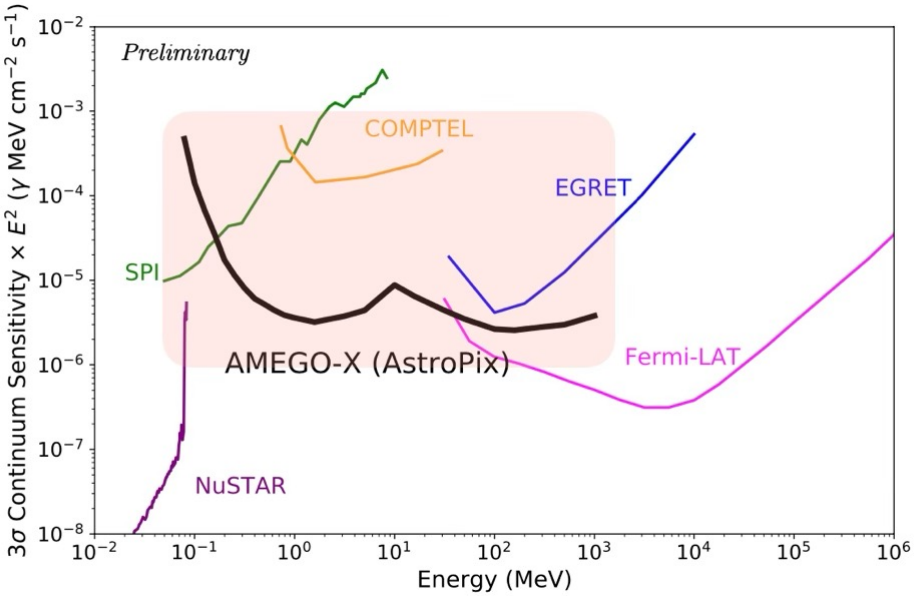




Coogan, Morrison, and Profumo, 2010.04797

# Future gamma-ray telescopes




e-Astrogam, 1611.02232

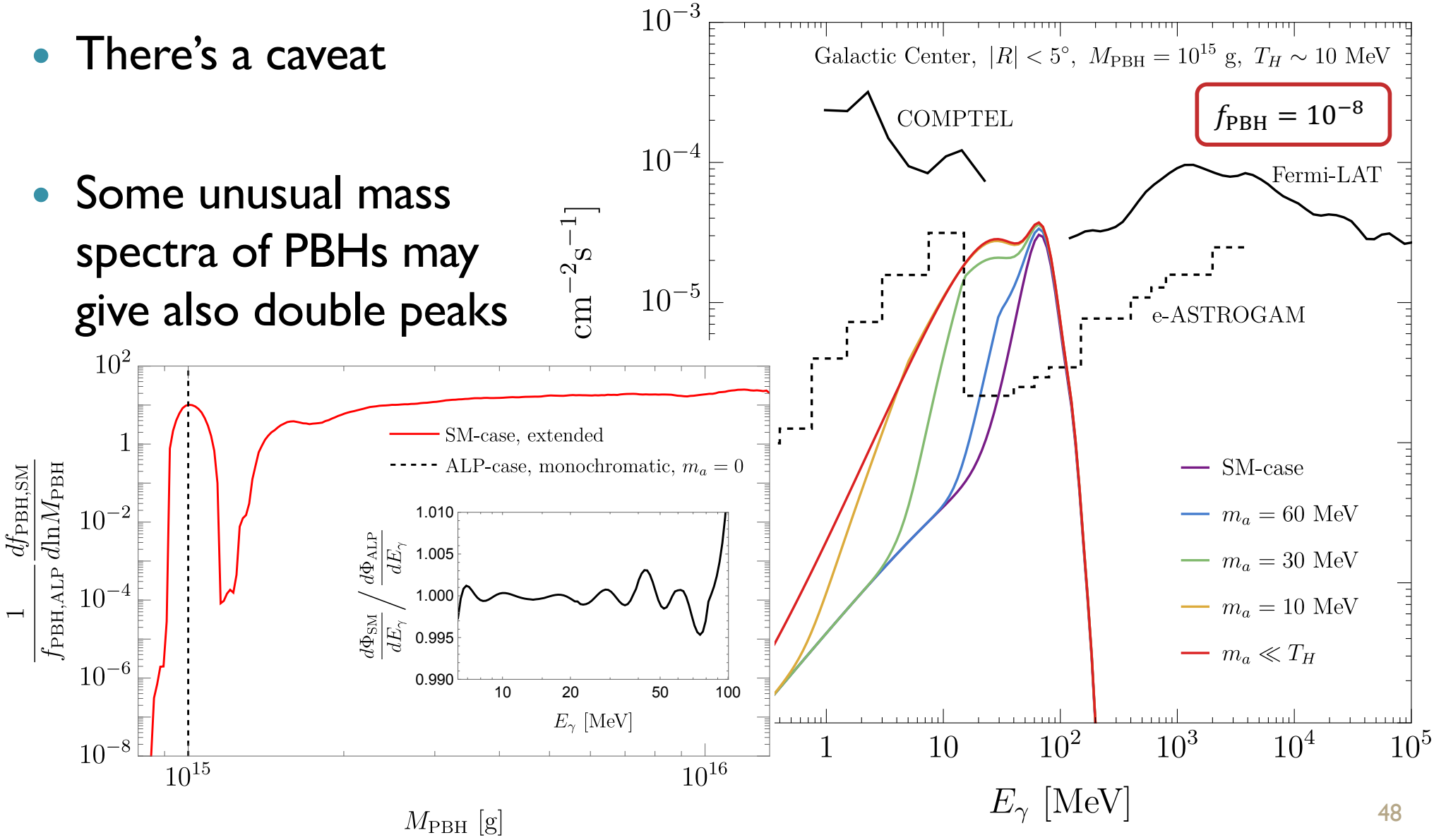



AMEGO-X 2108.02860

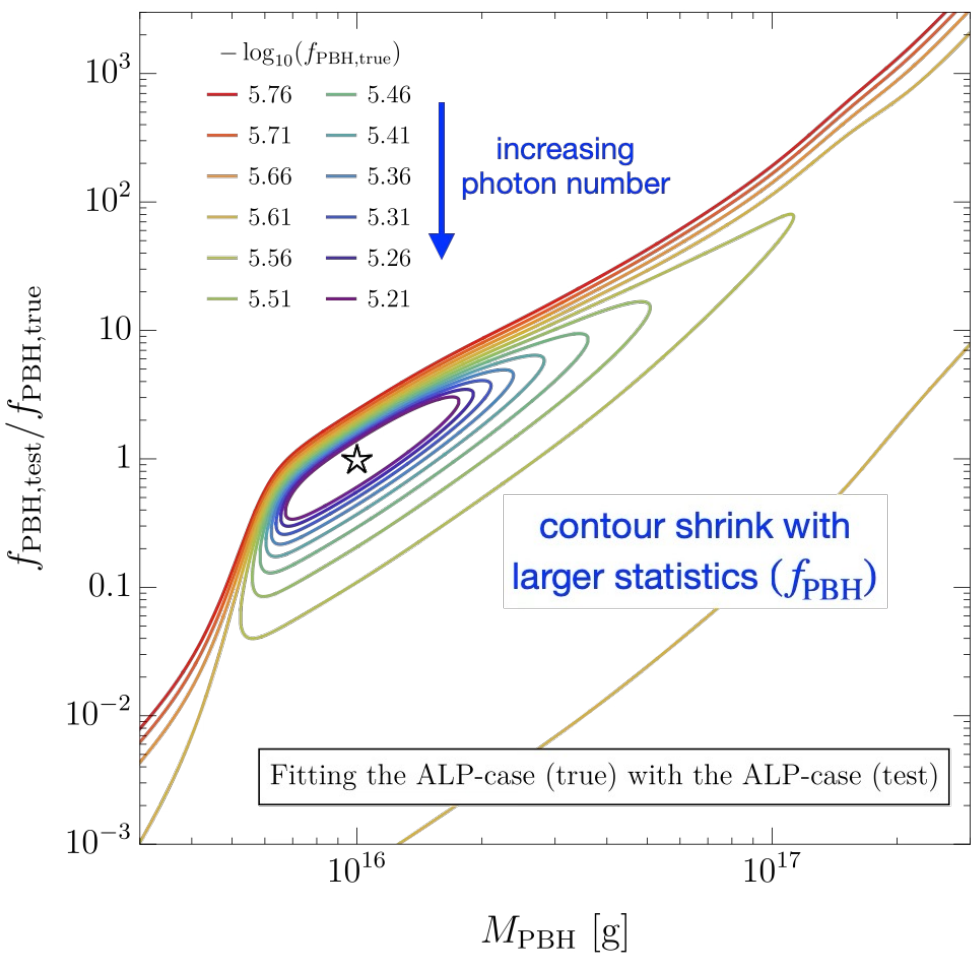
- Covers gamma-ray energy $0.1\ \mathrm{MeV} \lesssim E_\gamma \lesssim 100\ \mathrm{MeV}$
- Corresponds to $10^{14}\ \mathrm{g} \lesssim M_{\mathrm{BH}} \lesssim 10^{17}\mathrm{g}$

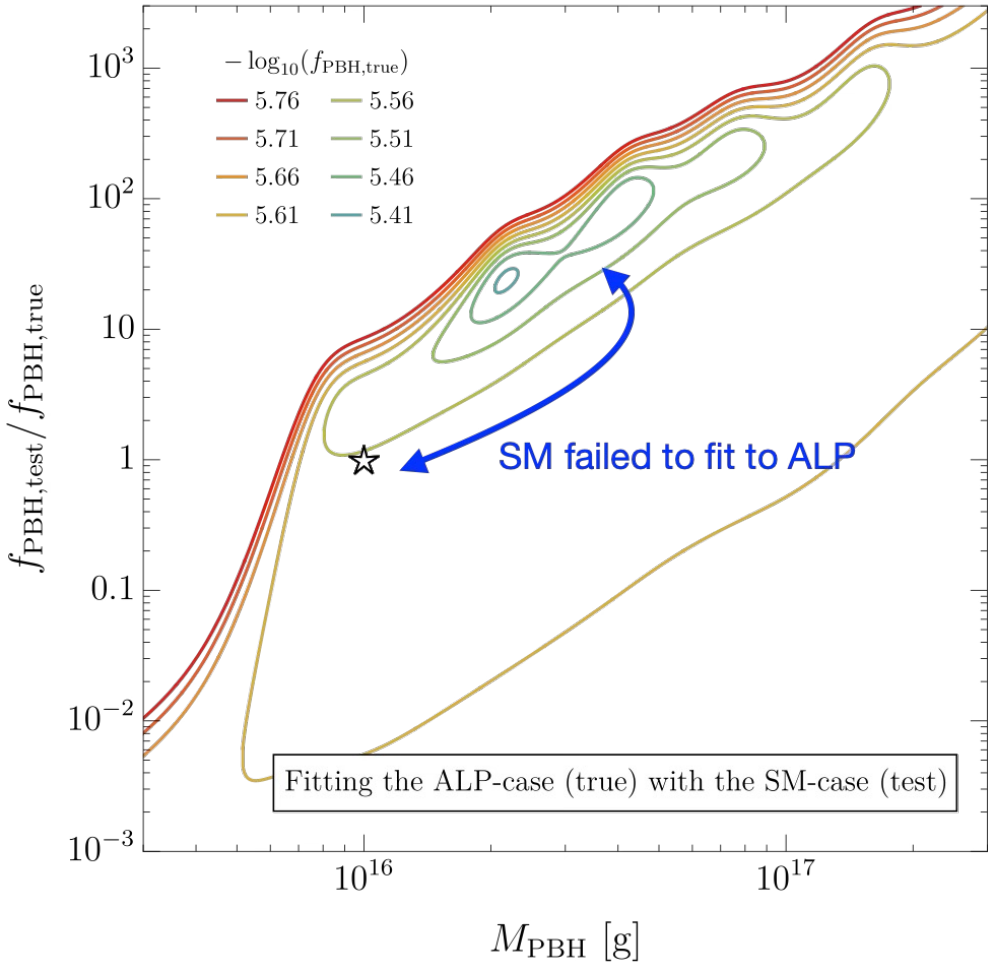
# PBH photon spectrum with axions

- There's a caveat
- Some unusual mass spectra of PBHs may give also double peaks

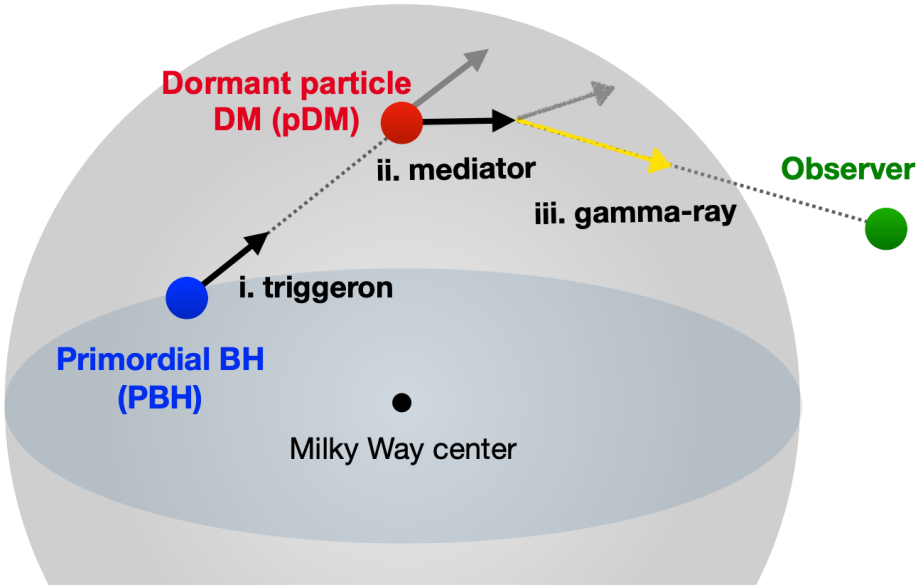


# How to distinguish between two cases



# Triggeron Mechanism

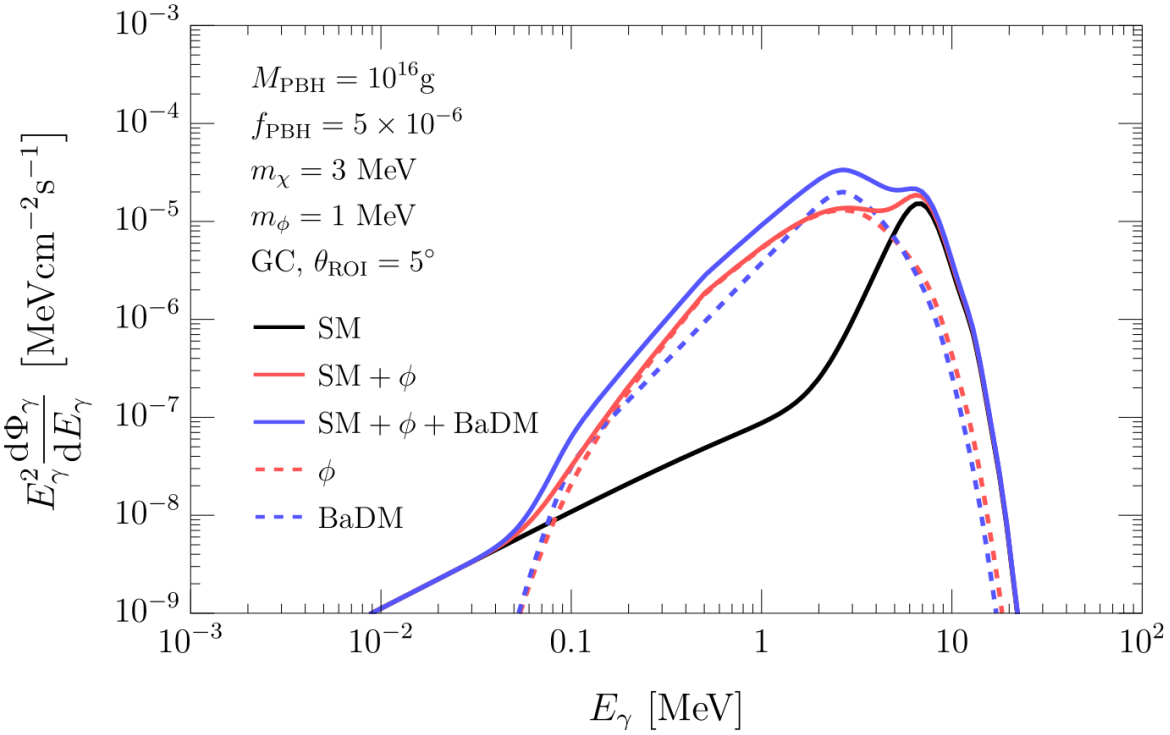



$$\begin{aligned}
\text{(i) emission:} \quad & \text{PBH} \rightarrow \text{triggeron} \quad \text{(via Hawking radiation)}; \\
\text{(ii) annihilations:} \quad & \text{triggeron} + \text{pDM} \rightarrow \text{mediator} + \text{other} \ ; \\
\text{(iii) decays:} \quad & \text{mediator} \rightarrow \text{SM} + \ldots \ .
\end{aligned}$$

# Boosted anti-DM (BaDM) model

BaDM model:
$$\begin{cases} \text{emission:} & \text{PBH} \to \overline{\chi} \\ \text{annihilations:} & \overline{\chi}\chi \to \phi\phi \\ \text{decays:} & \phi \to \gamma\gamma \end{cases}$$

Kinematics: $m_\phi < m_\chi \lesssim \mathcal{O}(\text{few}) \times T_{\rm PBH}$



# Dipole Transition DM (DTDM) model

DTDM model:

$$\begin{cases} \text{emission:} & \text{PBH} \to W^{a\prime} \\ \text{annihilations:} & W^{a\prime}\chi_1 \to W^{b\prime}\chi_2 \\ \text{decays:} & \chi_2 \to \chi_1\gamma \\ \text{(but not:} & \chi_2 \not\to \chi_1 W'\text{)} \end{cases}$$

Kinematics: $\Delta m < m_{W'} \lesssim \mathcal{O}(\text{few}) \times T_{\rm PBH} \ll m$