Diffuse Multimessenger Signals of Dark Matter Powered Stars Seeding Supermassive Black Holes
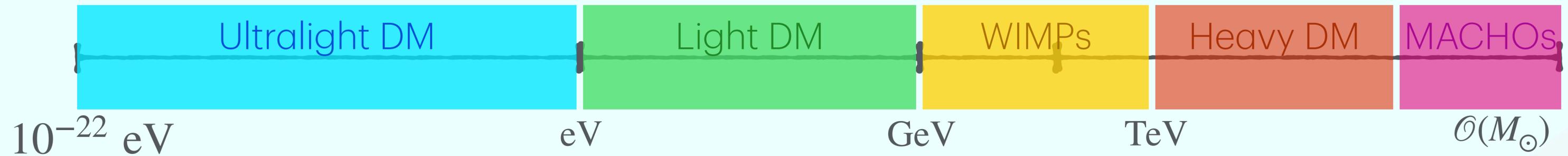
KEK Theory Meeting on Particle Physics Phenomenology

- *Astrophys.J.Lett.* 989 (2025) 2, L44 **T.S.**, V. Takhistov
- ArXiv 2512.04061 M. Manno, **T.S.**, V. Takhistov

Tom Schwemberger

Dark Matter Mass Range

| Ultralight DM | Light DM | WIMPs | Heavy DM | MACHOs |

10^{-22} eV　　　　　　　　　eV　　　　　　GeV　　　　TeV　　　　　$\mathcal{O}(M_\odot)$

Thermal Relic Production:

$$\psi\ \psi \leftrightarrow \chi\ \chi$$

- In thermal equilibrium in early universe due to balanced production/annihilation

- T falls until $T < M_{DM}$ forbids production and the population decays exponentially

- When the annihilation rate is less than Hubble ($\Gamma < H$) annotation stops and we have a thermal relic dark matter population
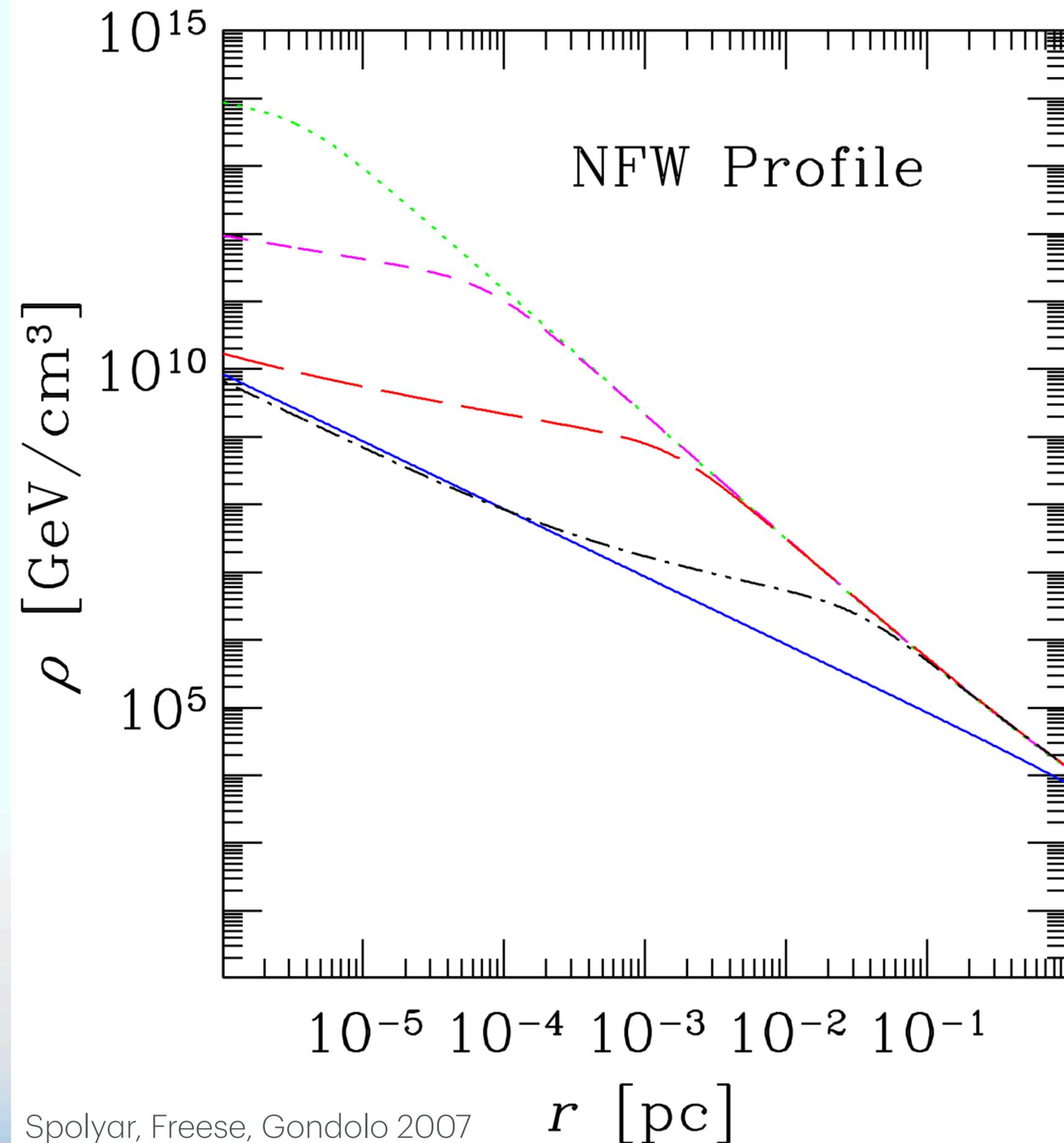

Kolb and Turner
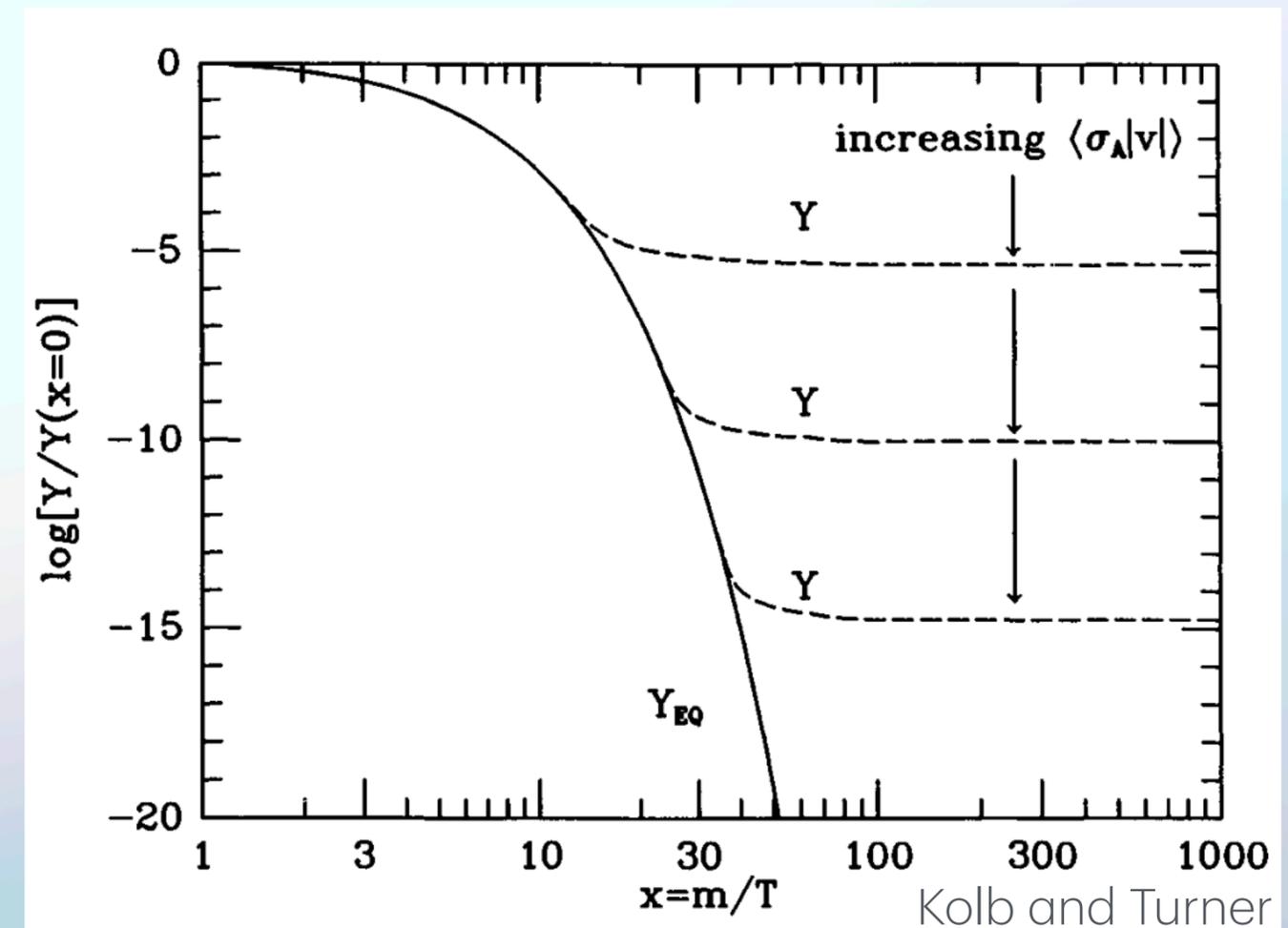
Star Formation

- Formed from $z \sim 20 - 30$ or a few hundred million years after the Big Bang

- Gravitational collapse and molecular cooling (H_2) allowed high (baryon) density environments

  - DM cannot drive this collapse despite its gravitational influence (no cooling)

  - It does contract with the baryons to an extent due to adiabatic contraction
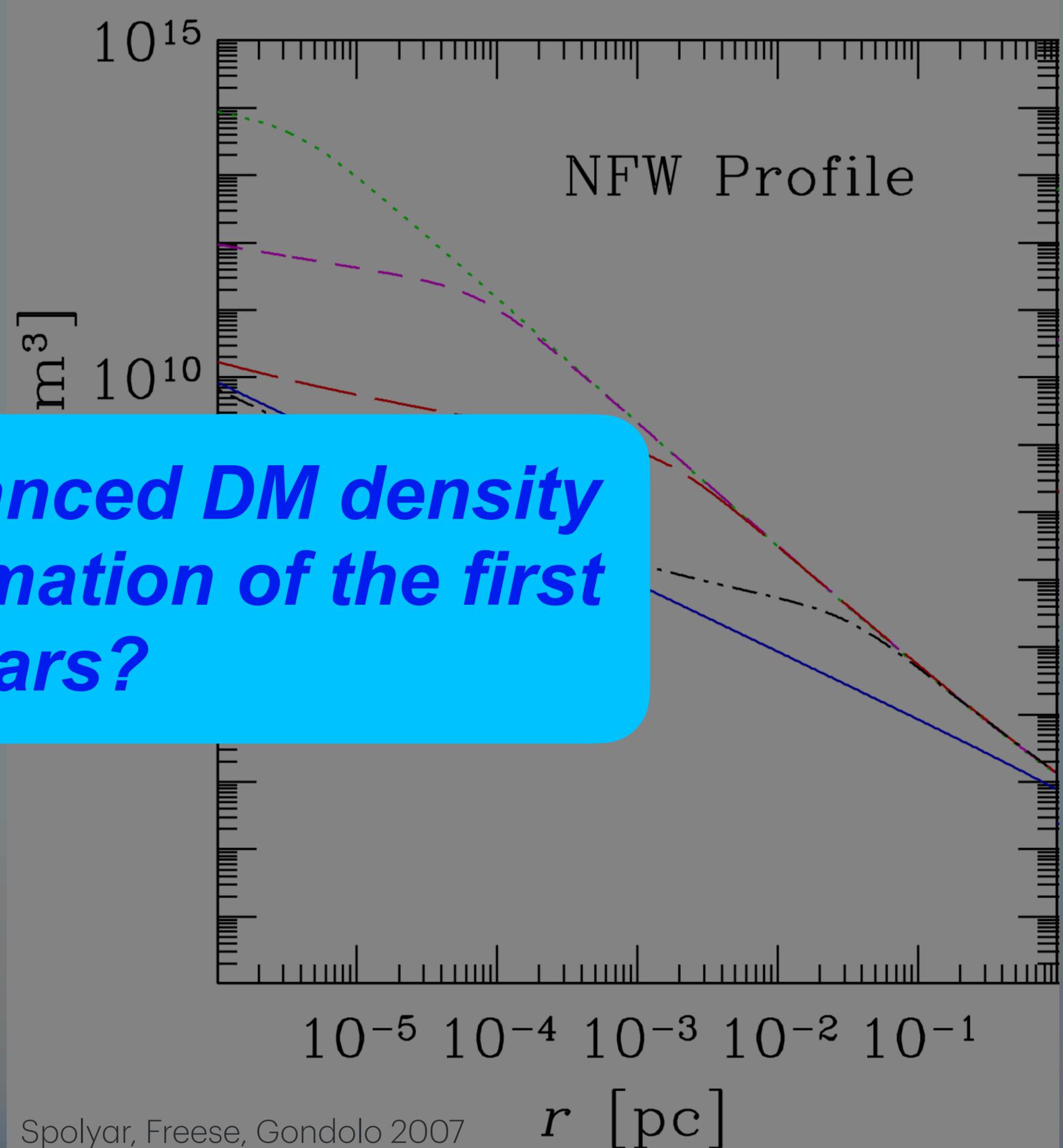
Contraction of the first DM halos

- As the first halos collapse, there are no compact objects to disperse the contracting halo

  - Conventional heating/relaxation is suppressed

  - Higher and more persistent central density than modern halos

- Thermal relic dark matter annihilates in regions of high densities

Spolyar, Freese, Gondolo 2007

Contraction of the first DM halos

- As the first halos collapse, there are no compact objec... contracting hal...

  - Conventional ... suppressed

  - Higher and more persistent central density than modern halos

- Thermal relic dark matter annihilates in regions of high densities

NFW Profile

10^{15}

10^{10}

m^3]

10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}

r [pc]

Spolyar, Freese, Gondolo 2007

**Does this enhanced DM density modify the formation of the first stars?**

Dark Stars

- *Include DM annihilation* and model stars as polytropes and balance hydrostatic equilibrium with gravitational force

- Large, low density, low temperature stars

- Low temperature, weak solar wind, large surface area means sustained accretion

Supermassive dark stars would collapse directly to $\sim 10^6 \ M_\odot$ black holes which would seed SMBH *(Freese et. al. 2025)*
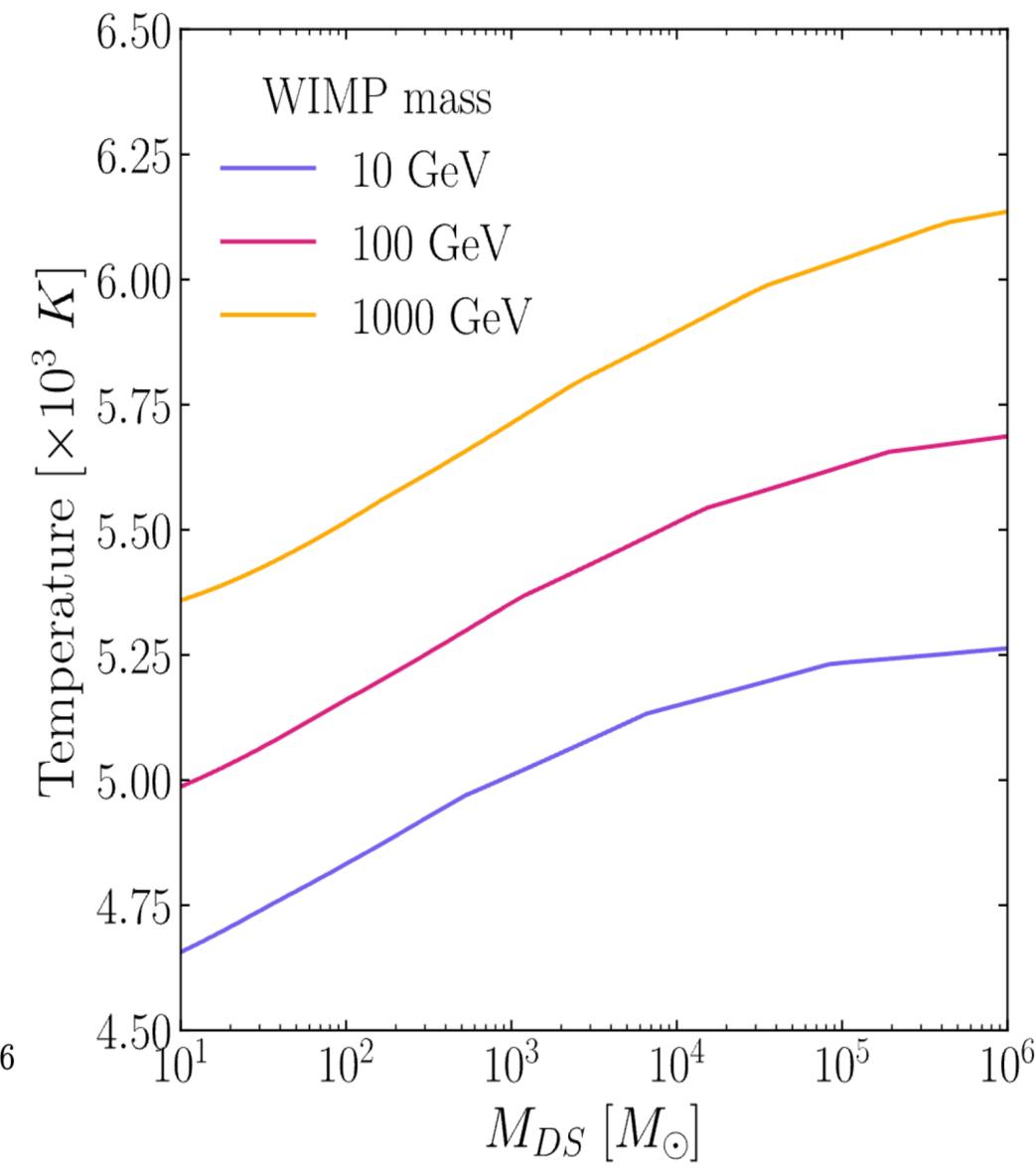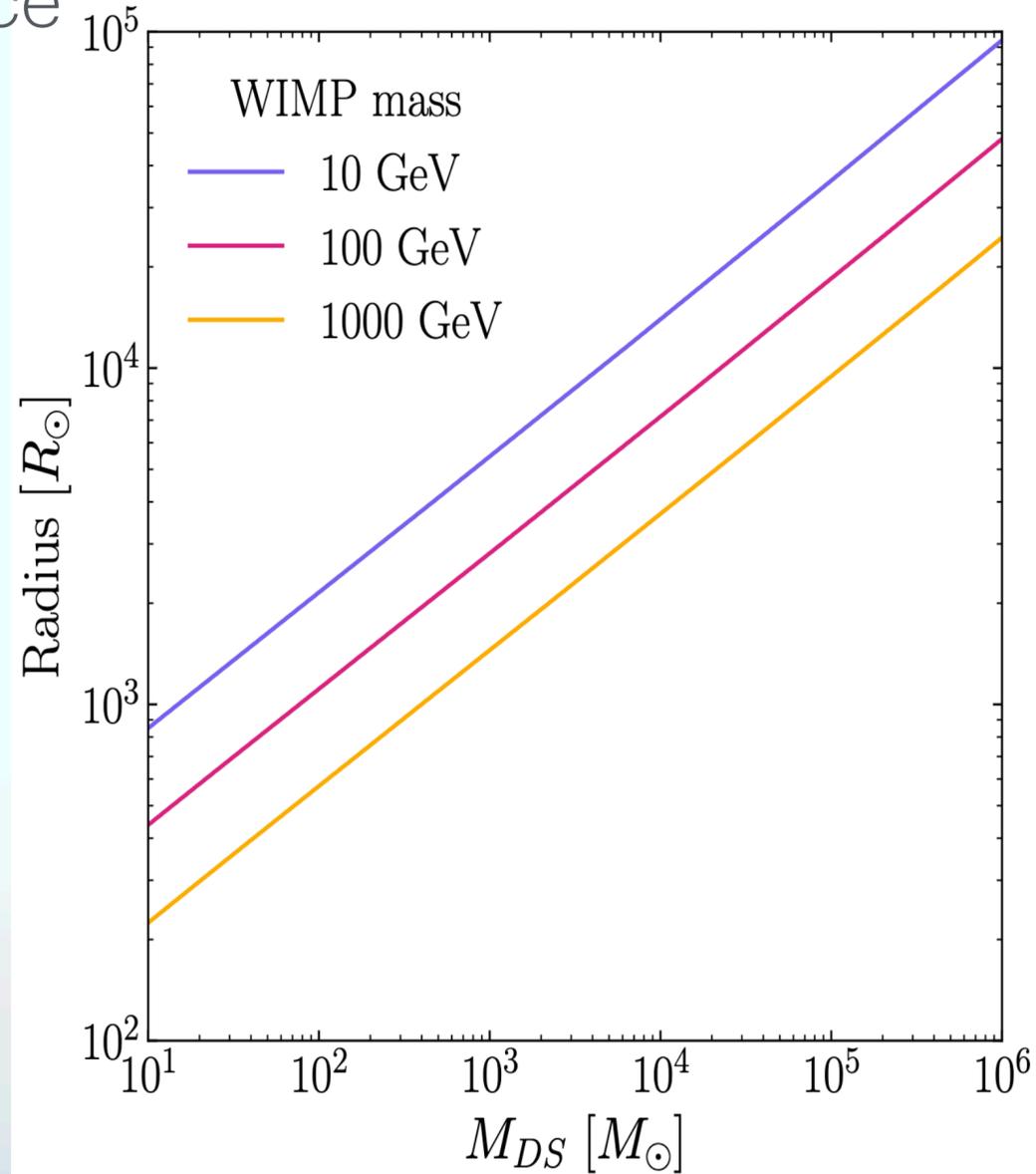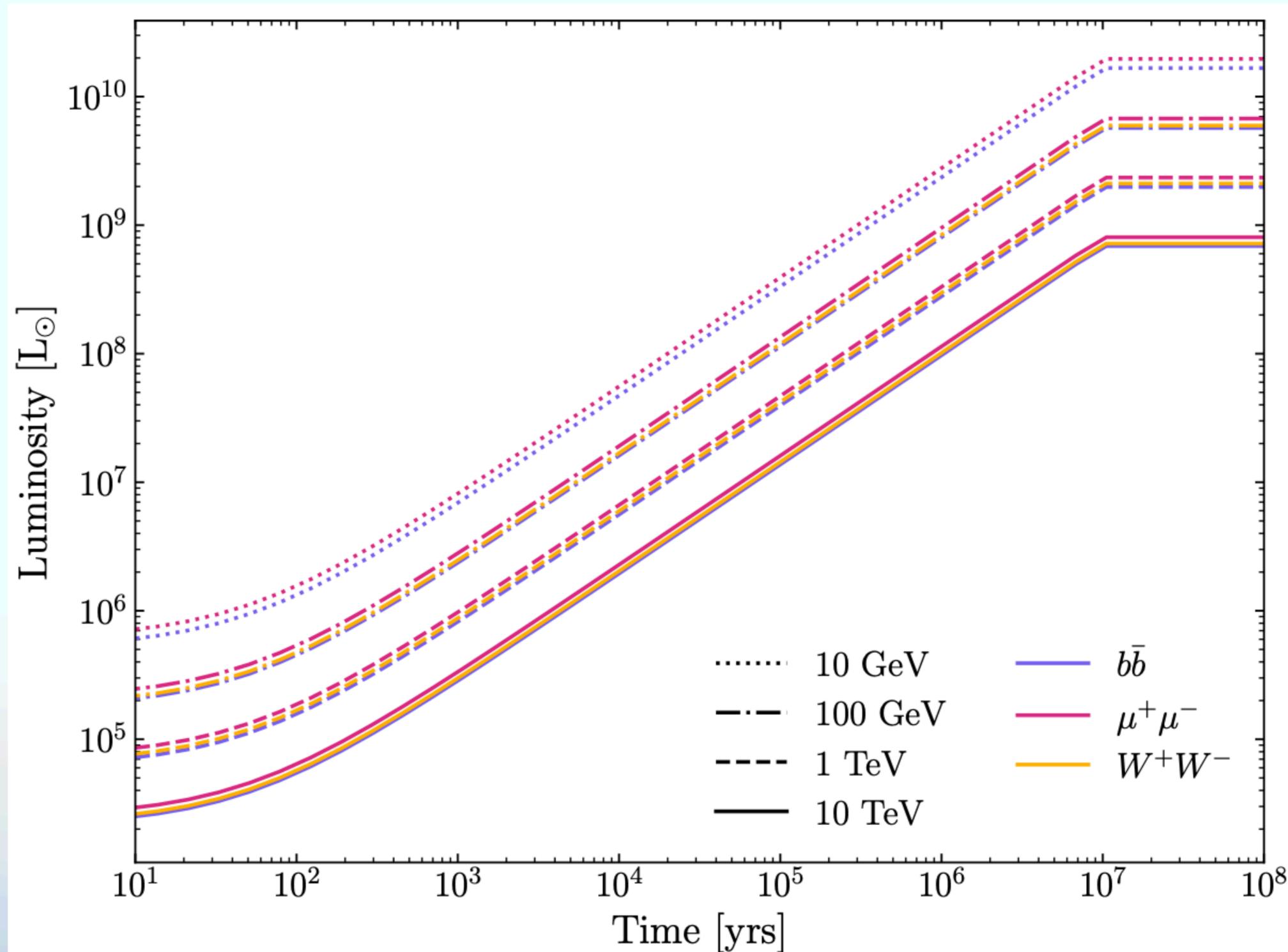
Dark Star Luminosity

- Weak dependence on the DM annihilation channel

- Very large integrated luminosity $\sim 10^{59}$ergs

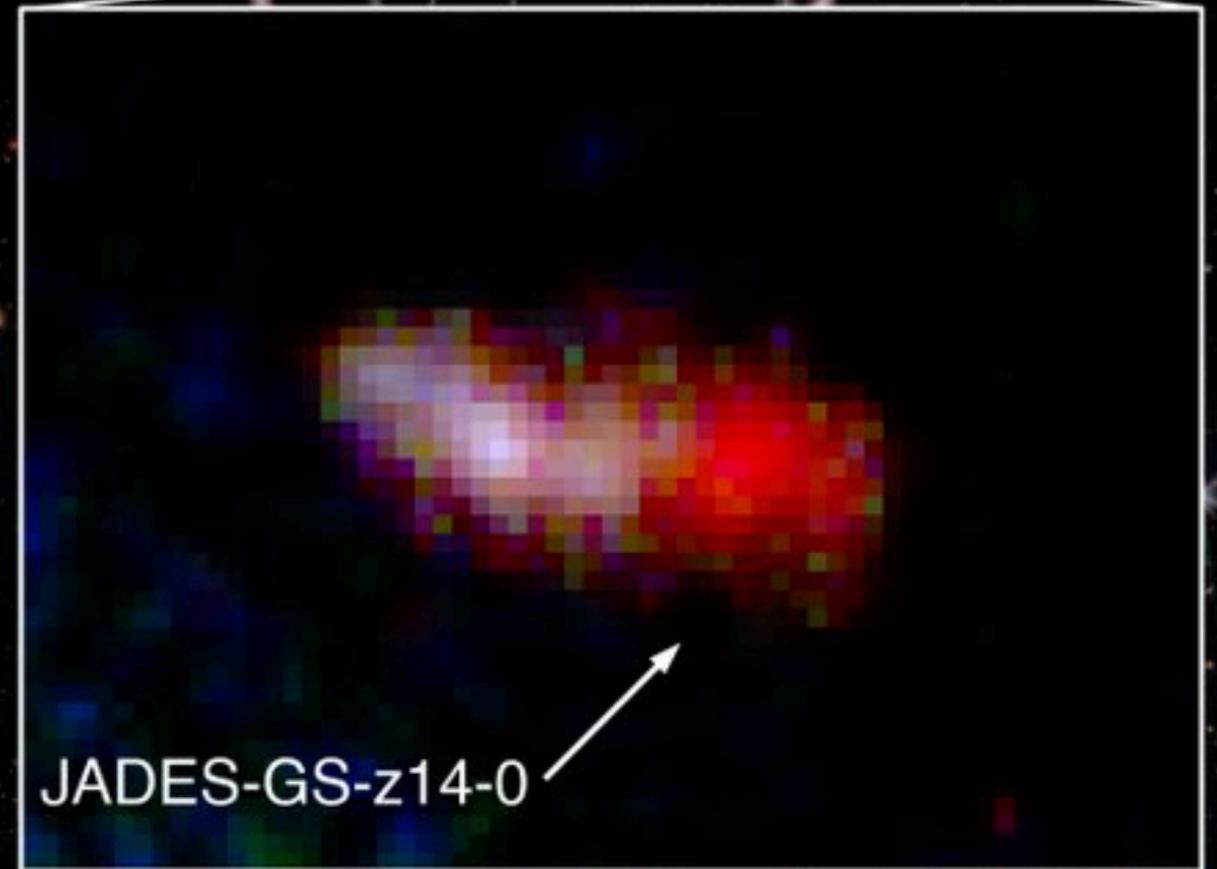 - Such a large luminosity motivates the consideration of multi-messenger probes

Assumptions:

- $\dot{M} \propto M_h$ (constant)
- $M_{DS} \leq M_h/100$

JWST Observation

The James Webb Space Telescope (JWST) has seen several objects consistent with supermassive dark stars at redshifts $z \sim 10 - 15$

JADES-GS-z14-0

JADES-GS-z14-0 (NASA)

The Mystery of Supermassive Black Holes

The formation of such objects is not well understood

- Stellar black holes cannot grow fast enough

- Many alternative cosmologies have been suggested

- JWST has seen SMBH at earlier times than expected

Event Horizon Telescope
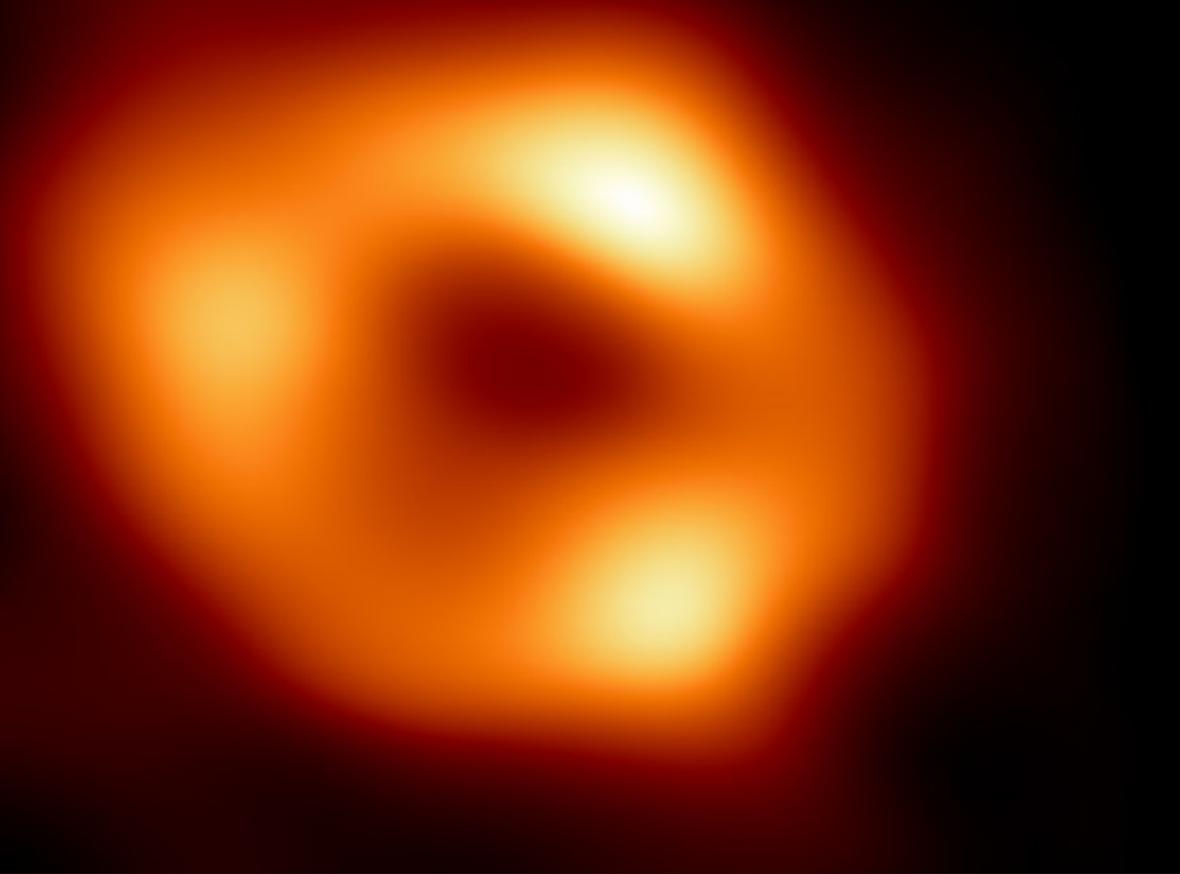
Objectives:

- Allow a population of dark stars to seed supermassive black holes

- Ensure such a population is consistent with JWST observations

- Predict the multi-messenger signals from a population of supermassive dark stars

- Develop a new method to search for dark stars

- Identify which dark matter parameters are consistent with this story
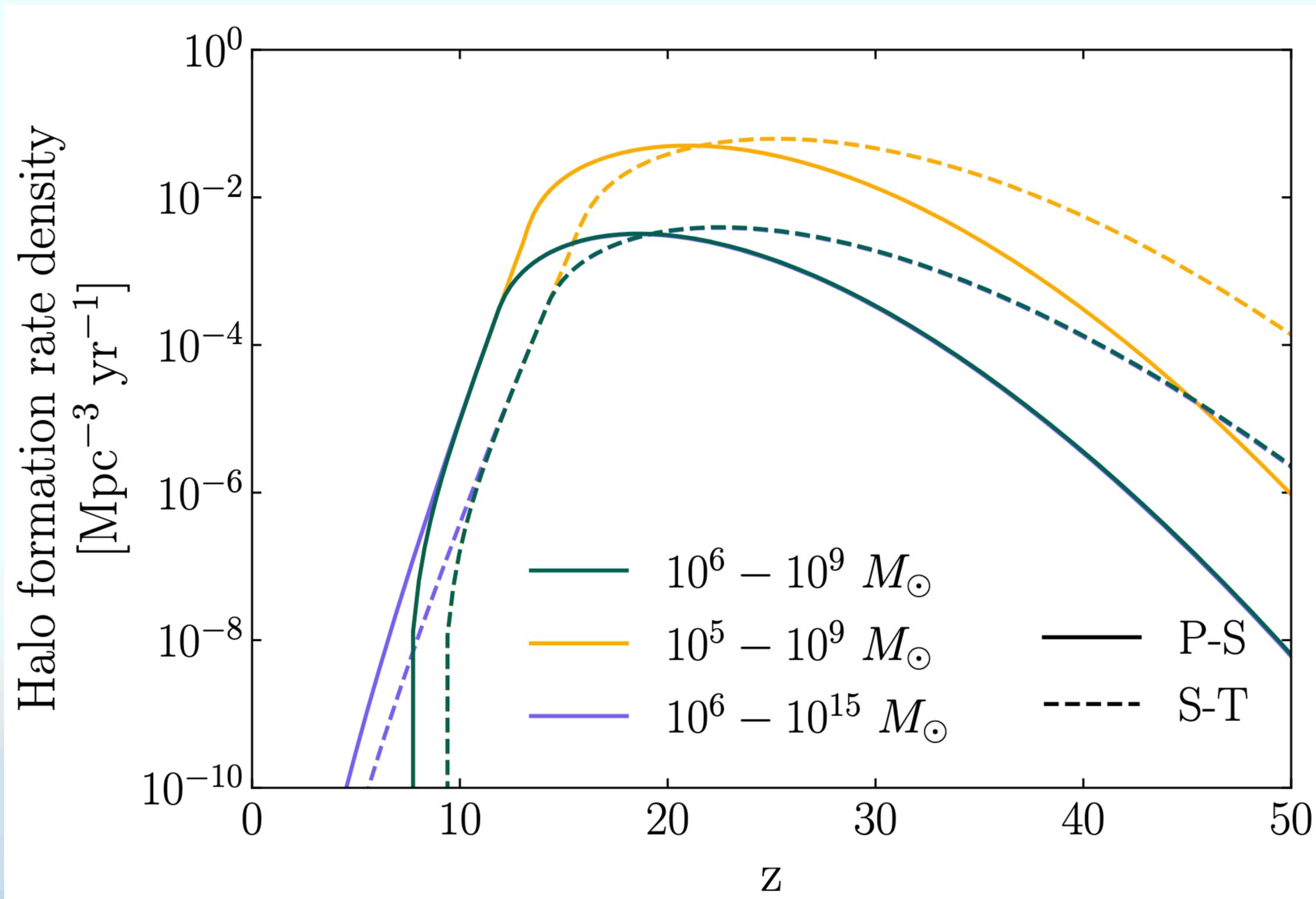
Dark Star Evolution
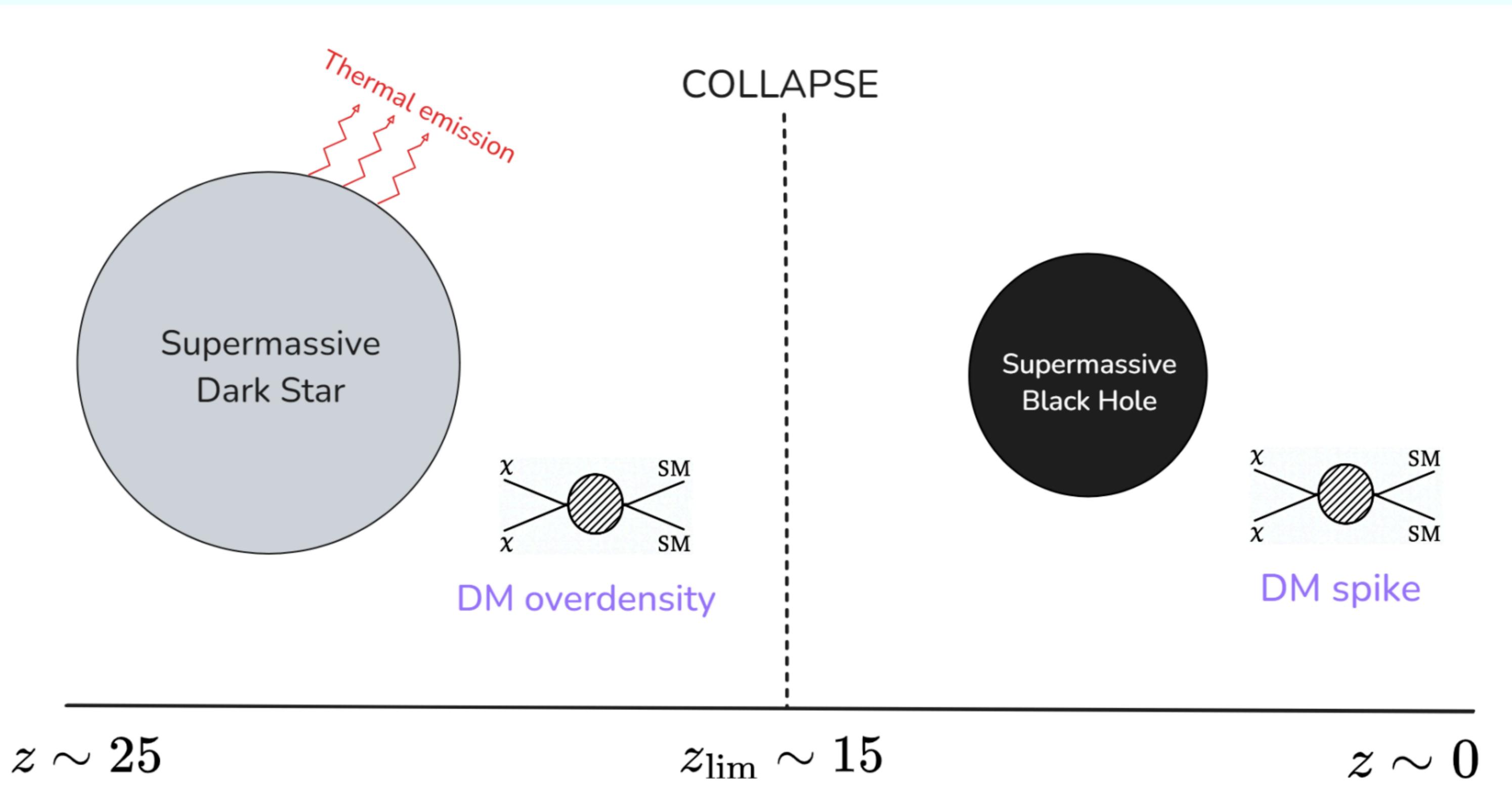
The Dark Star Population

Re-scale halo population to that of SMBHs

JWST has "only" seen a few candidates in 26.4 arcmin² with sensitivity out to $z \sim 15$
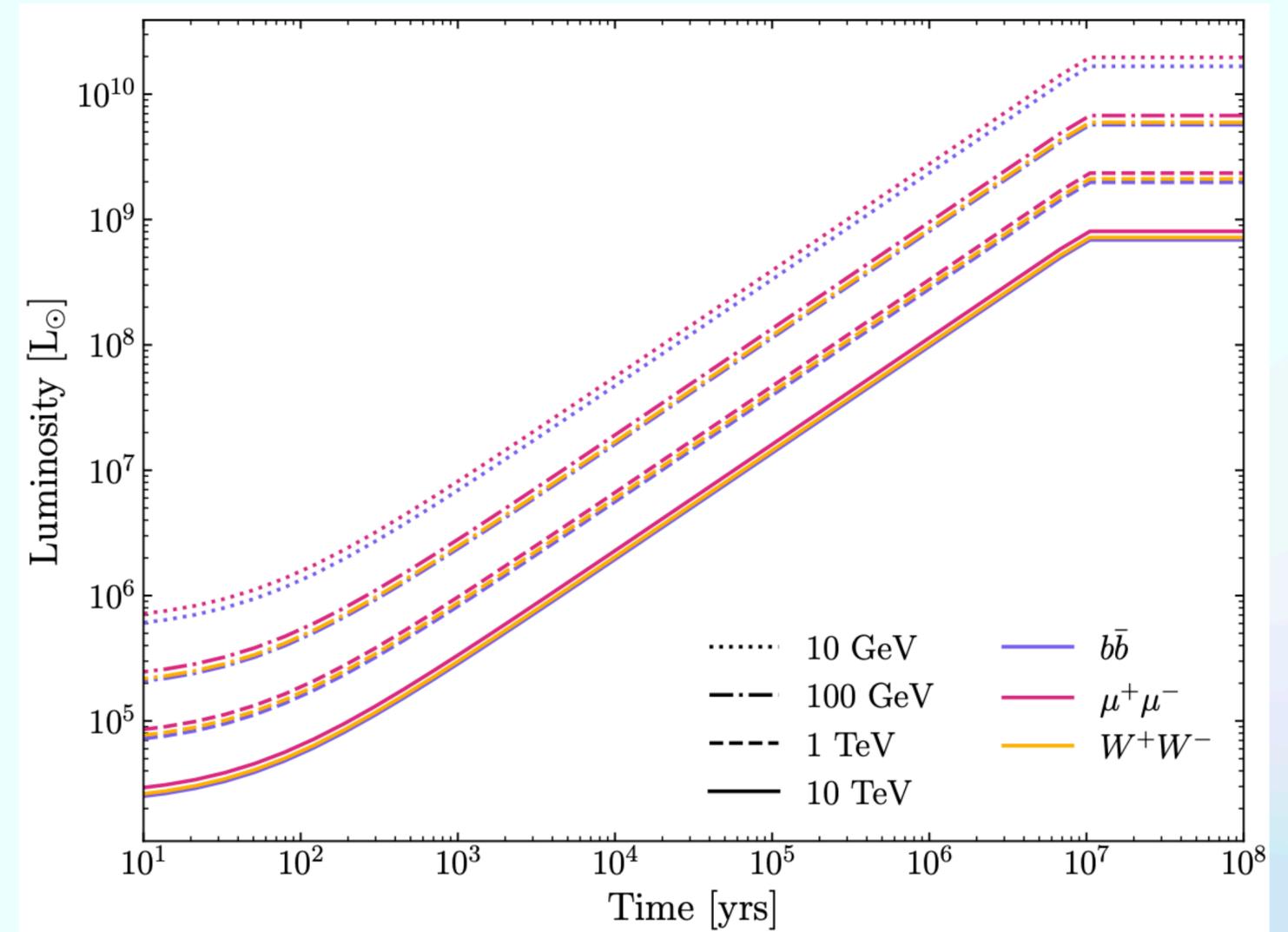
Assumptions:
- All DS collapse at $z = 15$
- Uniform fraction of halos host dark stars $\rightarrow 1\%$
- No mergers

Dark Star Population Luminosity

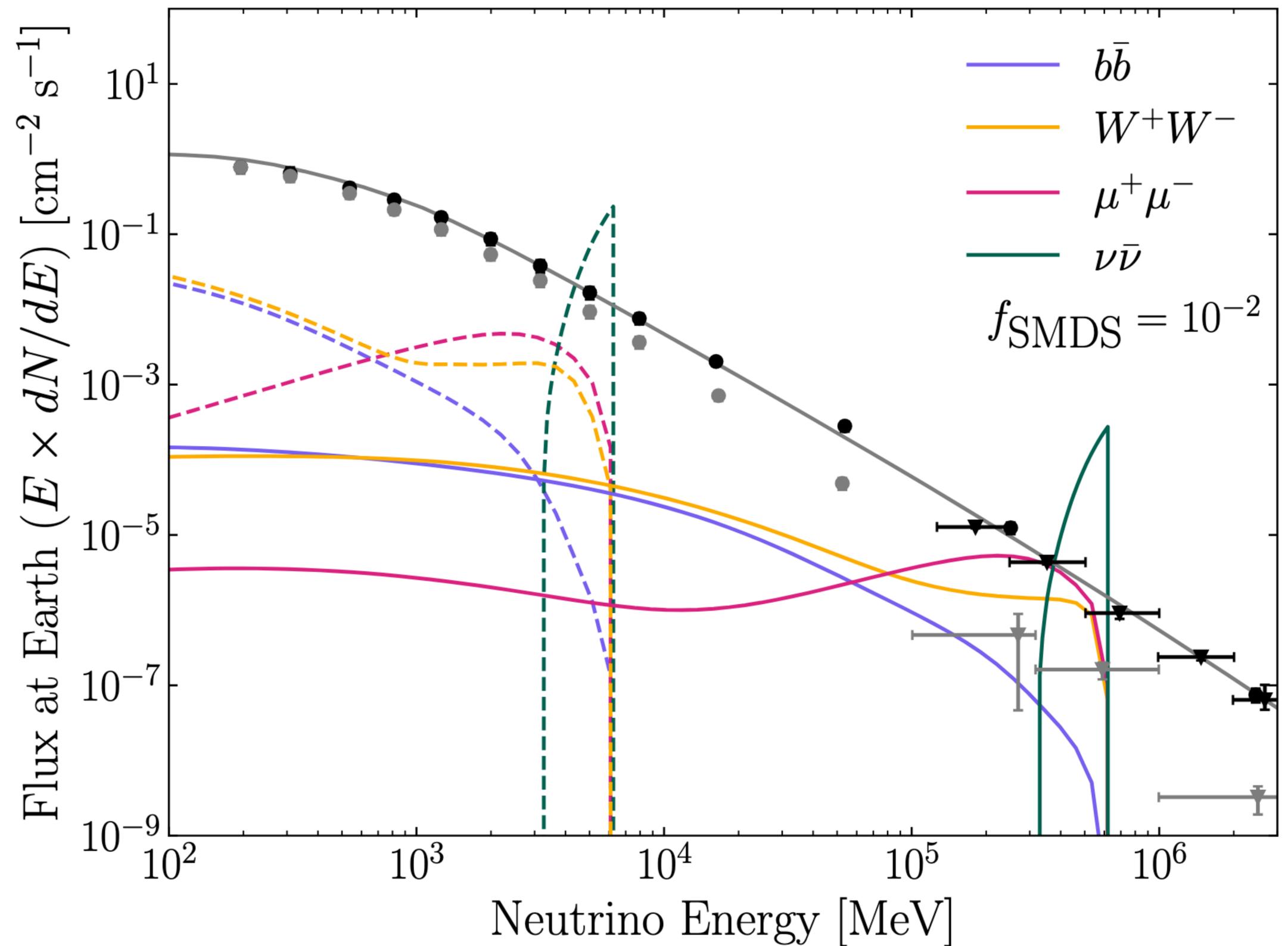Want luminosity of all surviving dark stars at a given redshift

$$L_{\mathrm{EM}}(z) = \int_0^{t(z)} d\tau \int_{M_{h,\mathrm{min}}}^{M_{h,\mathrm{max}}} dM_h \left[f_{\mathrm{sur}}(z) \frac{d^2 n_{\mathrm{DS}}}{dM_h dt}(M_h, z(t-\tau)) \right] \times L_{\mathrm{DS}}(M_h, \tau)$$
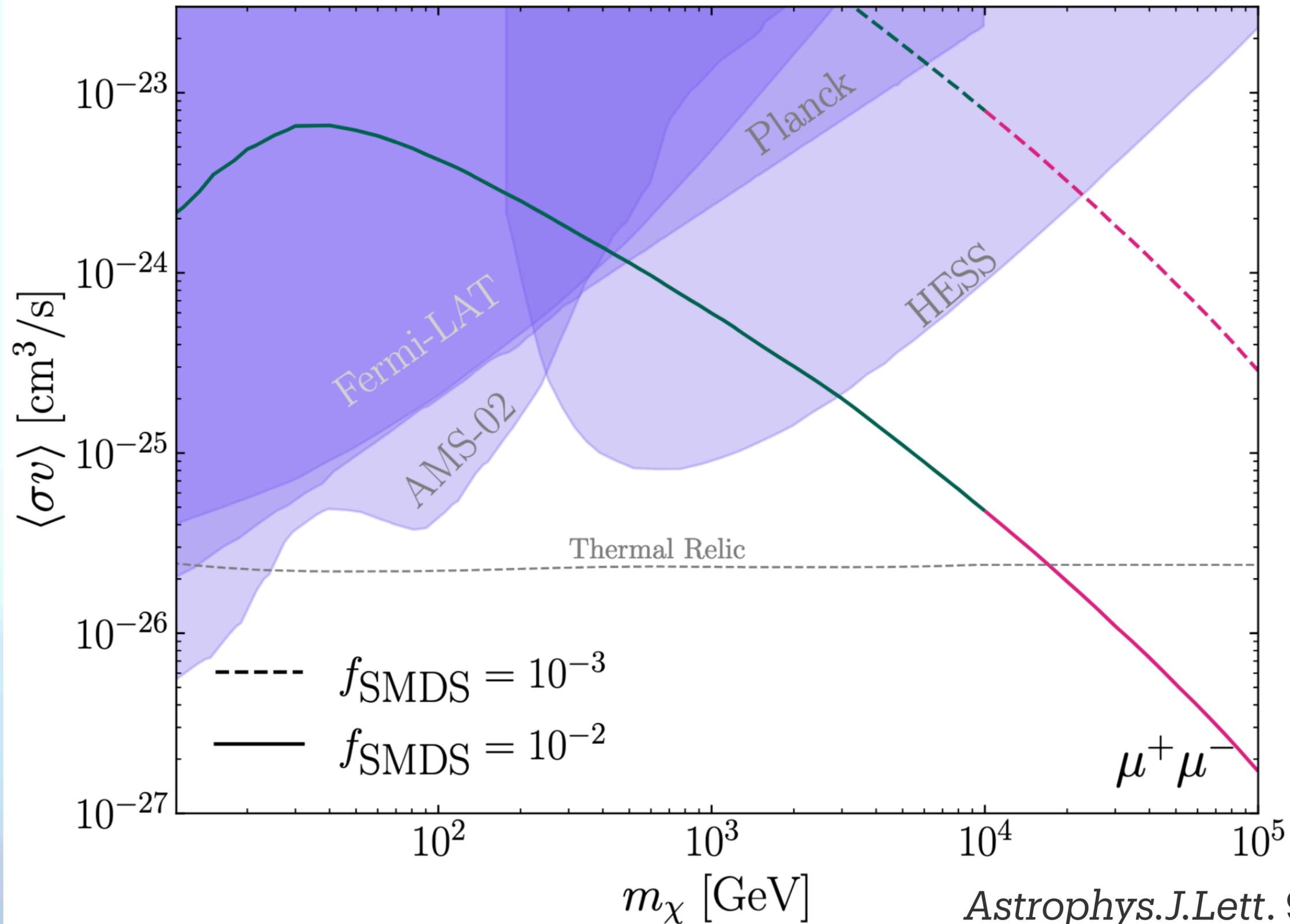
Dark Star Neutrino Flux

$$\frac{d\phi}{dE_\nu} = \int_{z_{\text{lim}}}^{\infty} dz \left[\frac{dN}{dE_\nu} \times \left(\frac{f_\nu}{(1 - f_\nu)\langle E_\nu \rangle} L_{\text{EM}}(z) \right) \times (1 + z) \left| c \frac{dt}{dz} \right| \right]$$

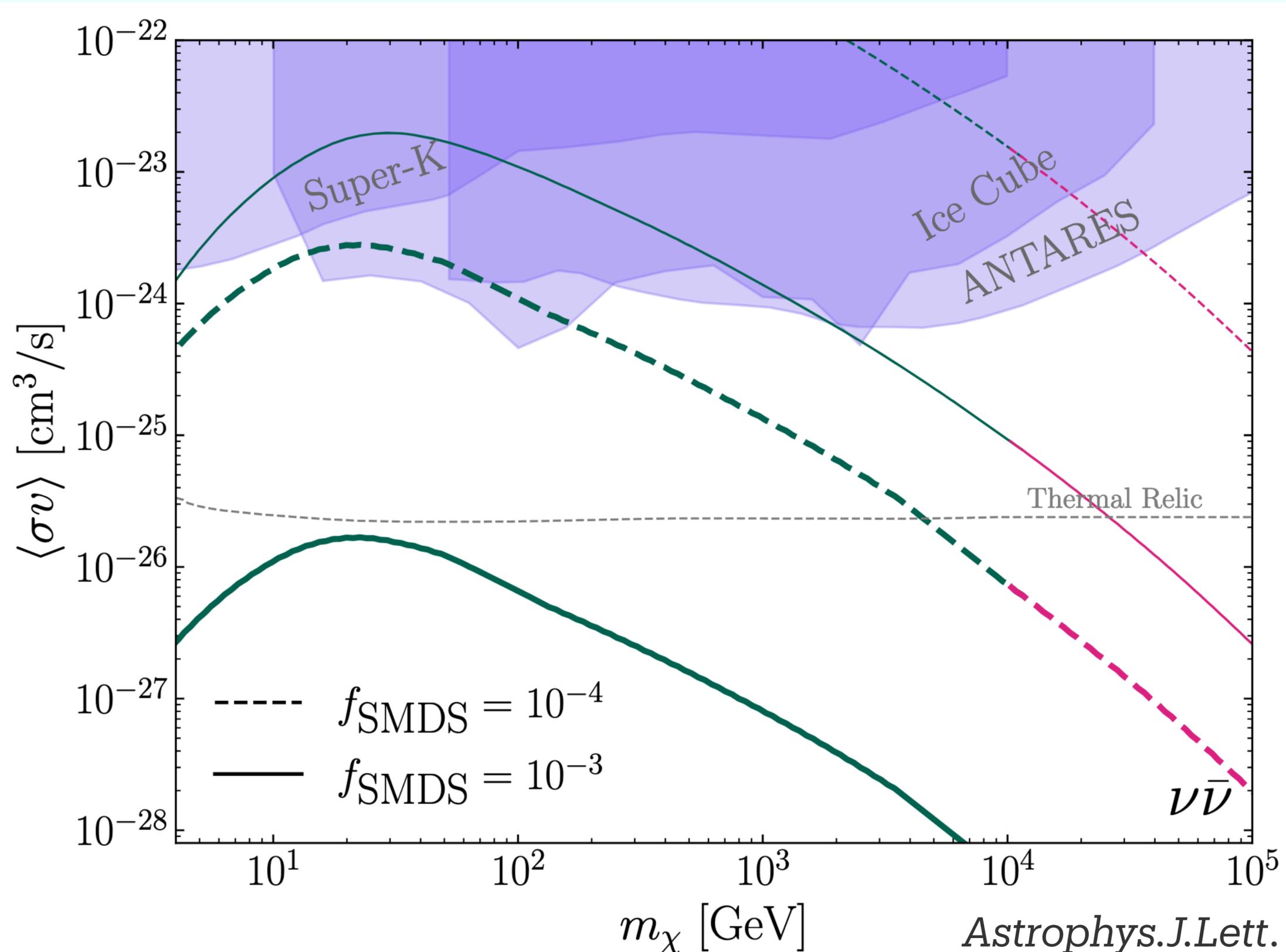# The Dark Star Neutrino Background

- Dominant background is atmospheric neutrinos

- Energy scale set by DM mass and z

- Spectral shape set by the annihilation channel

The Dark Star Neutrino Measurements

The Dark Star Neutrino Measurements

Dark Stars photon emission

M. Manno, TS, V. Takhistov: 2512.04061

- For neutrino emission, we studied the neutrino counterpart to the annihilation which powers the star

- There is also significant annihilation from the halo outside the baryonic surface

- Such a large over density is required to support the continued annihilation powering the star

NFW Profile

Spolyar et. al. 2007
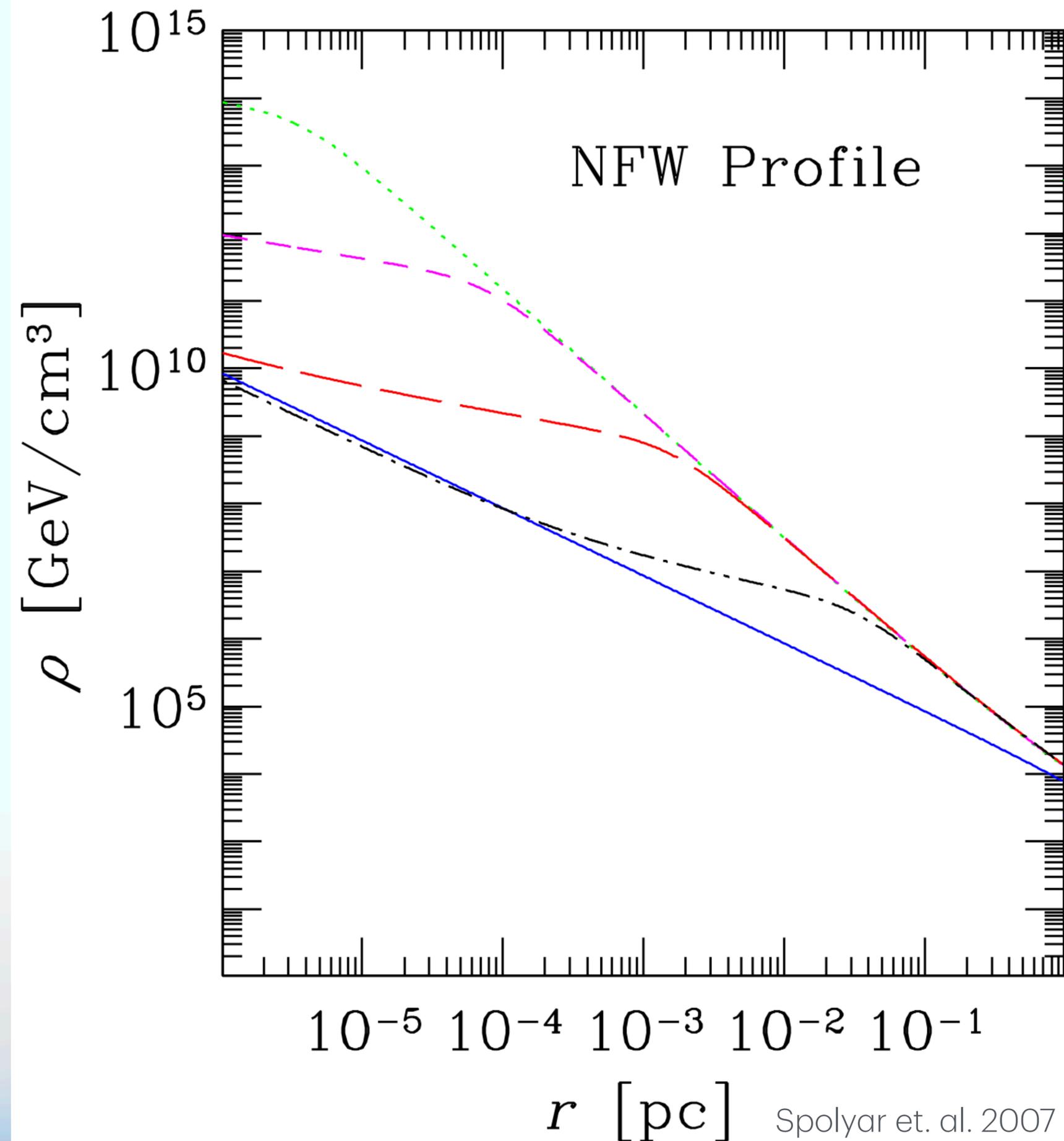
Dark Star Electromagnetic Flux

DM annihilation outside the star:

$$L_{\text{out}} = f_\gamma \int_{R_s}^{r_h} dr \, 4\pi r^2 \frac{\langle \sigma v \rangle}{m_\chi} \rho_\chi(r)^2$$

$$\frac{d\phi_\gamma^{\text{out}}}{dE_\gamma}(E_\gamma) = \int_{z_{\text{lim}}}^{25} dz \left| \frac{dt}{dz} \right| \boxed{\frac{(1+z)}{\langle E_\gamma \rangle} L_{\text{out}}^{\text{pop}}(z) \boxed{\frac{dN_\gamma}{dE}}} \bigg|_{E'=(1+z)E_\gamma} \boxed{e^{-\tau(E_\gamma, z)}}$$

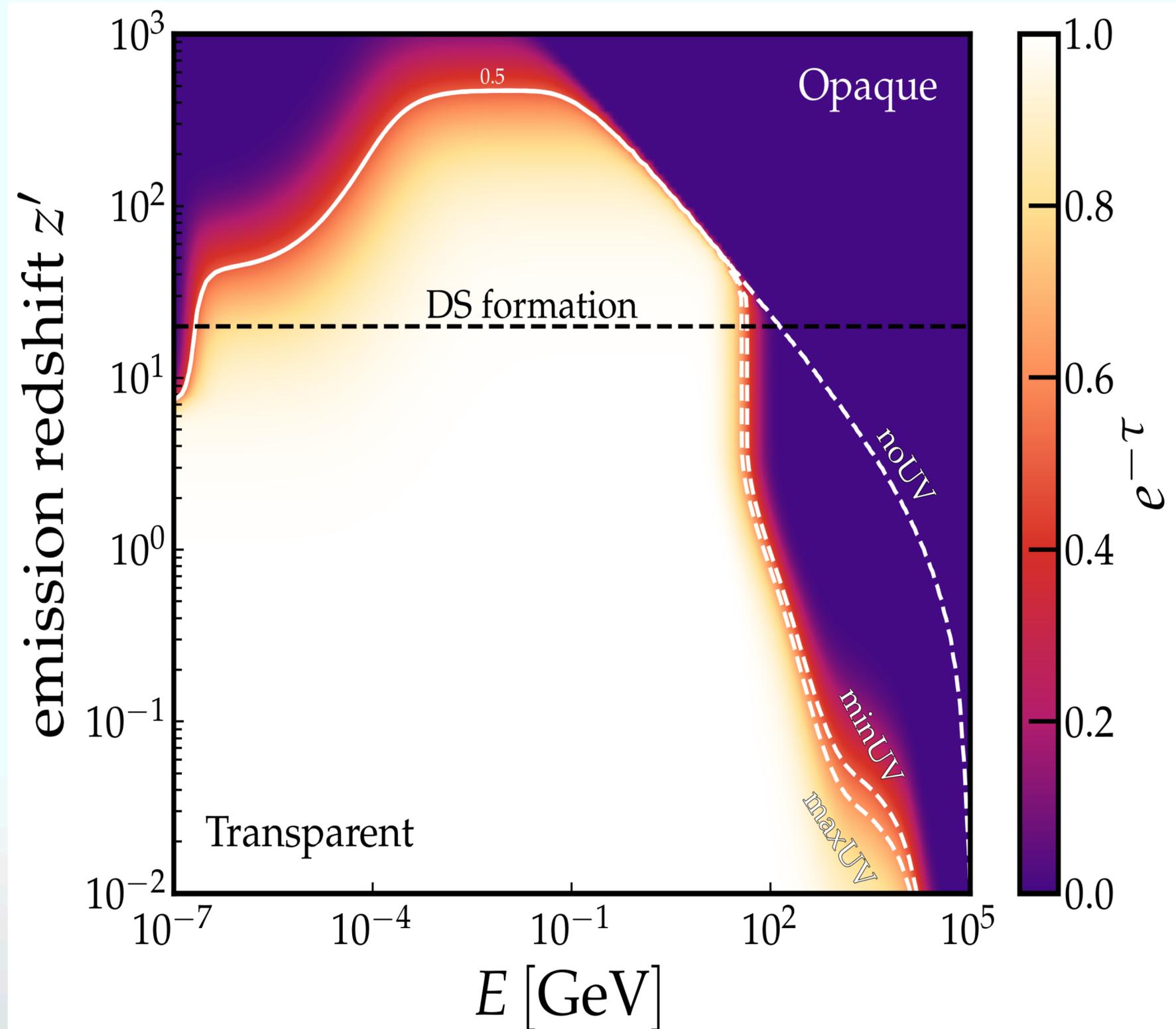Photon luminosity
(in number of
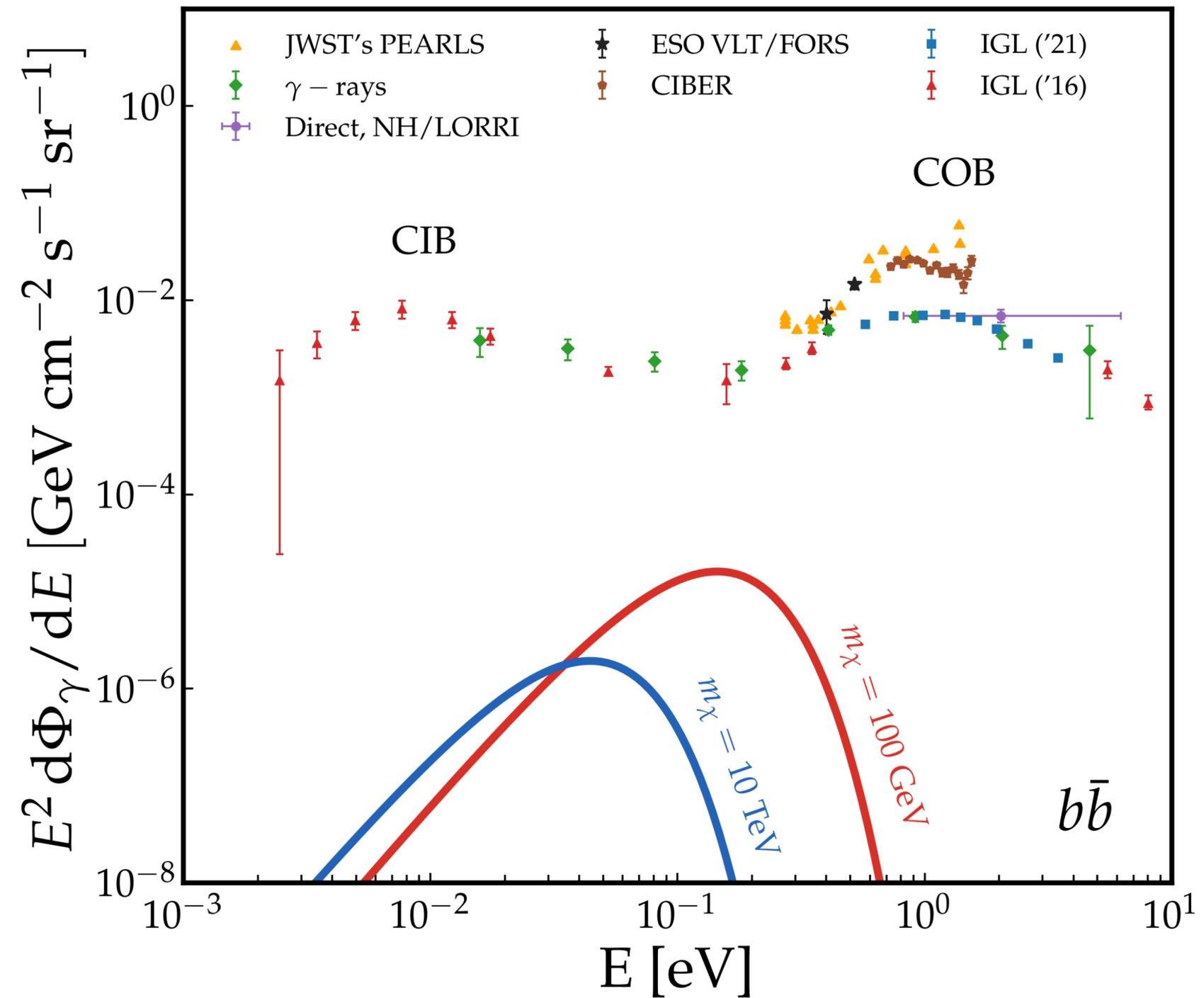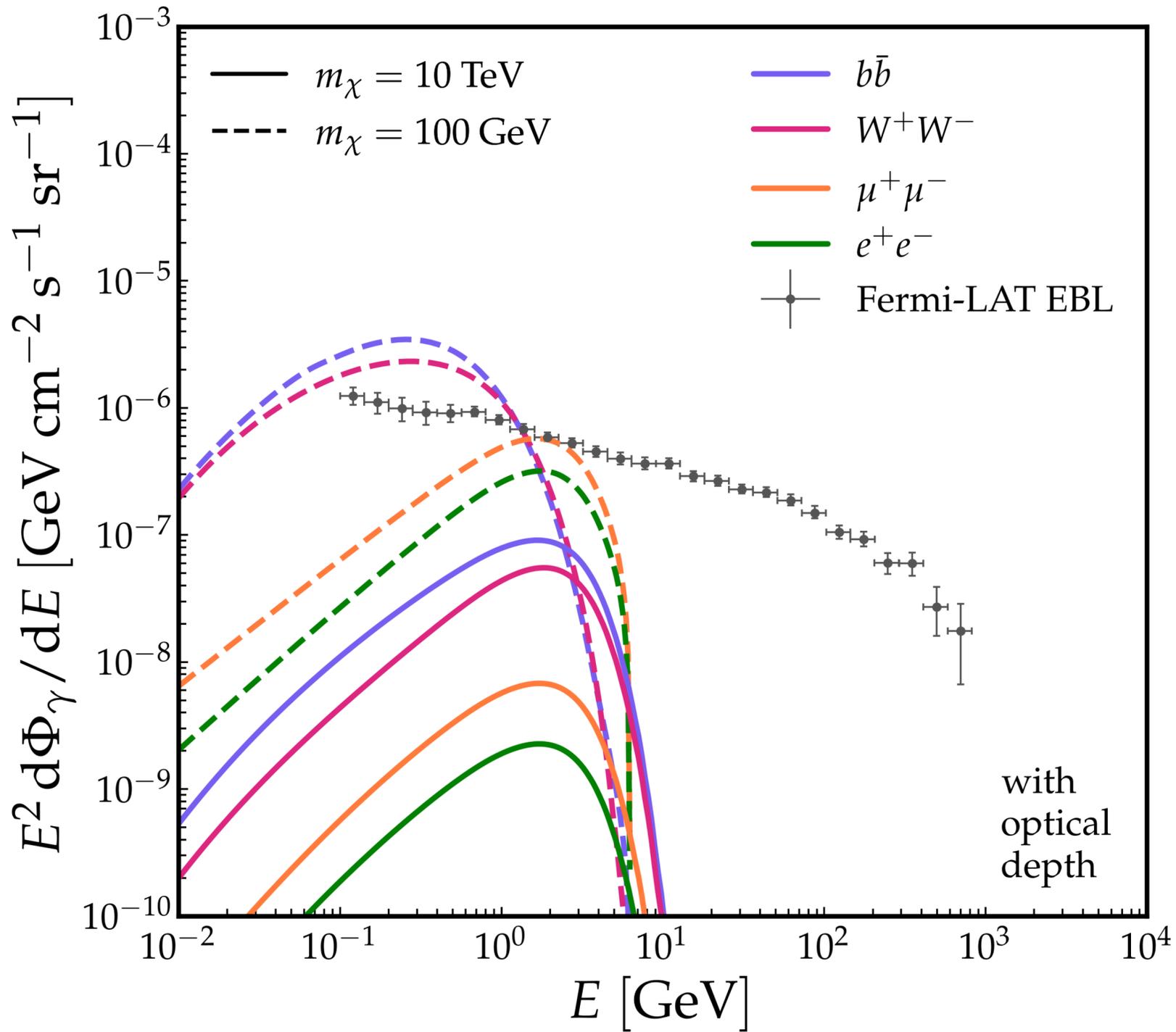photons / s)

Photon Spectrum
(per photon)

Optical Depth

Optical Depth

- Photons are absorbed by the IGM

- Above ~ 100 GeV pair production of electrons from CMB scattering is allowed

  - High energy photons are easily absorbed

- Less important for low energy and lower redshift photons

Dark Star Electromagnetic Flux

DM Distribution Around SMBH

- Dark Stars collapse when the DM fueling them becomes less abundant

- The rest of the nearby DM halo is still enhanced relative to NFW

- Further adiabatic contraction following DS collapse

- Various sources of depletion and repopulation over cosmic time
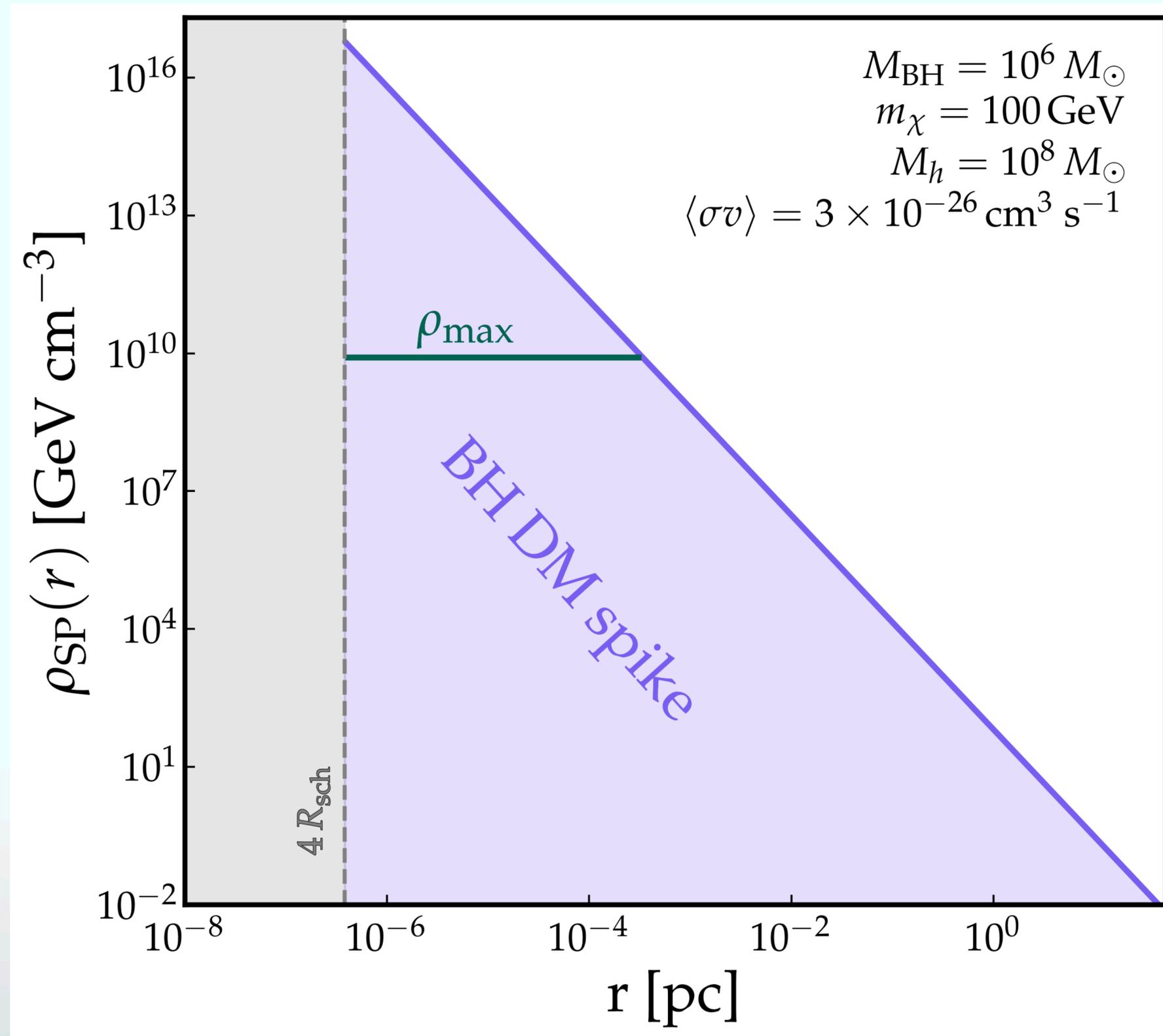
Subsequent BH Spike

- DM continues to annihilate efficiently in this spike

- Consider two extreme cases to bracket the physical case of an evolving DM spike

We have again neglected the evolution of the system due to mergers
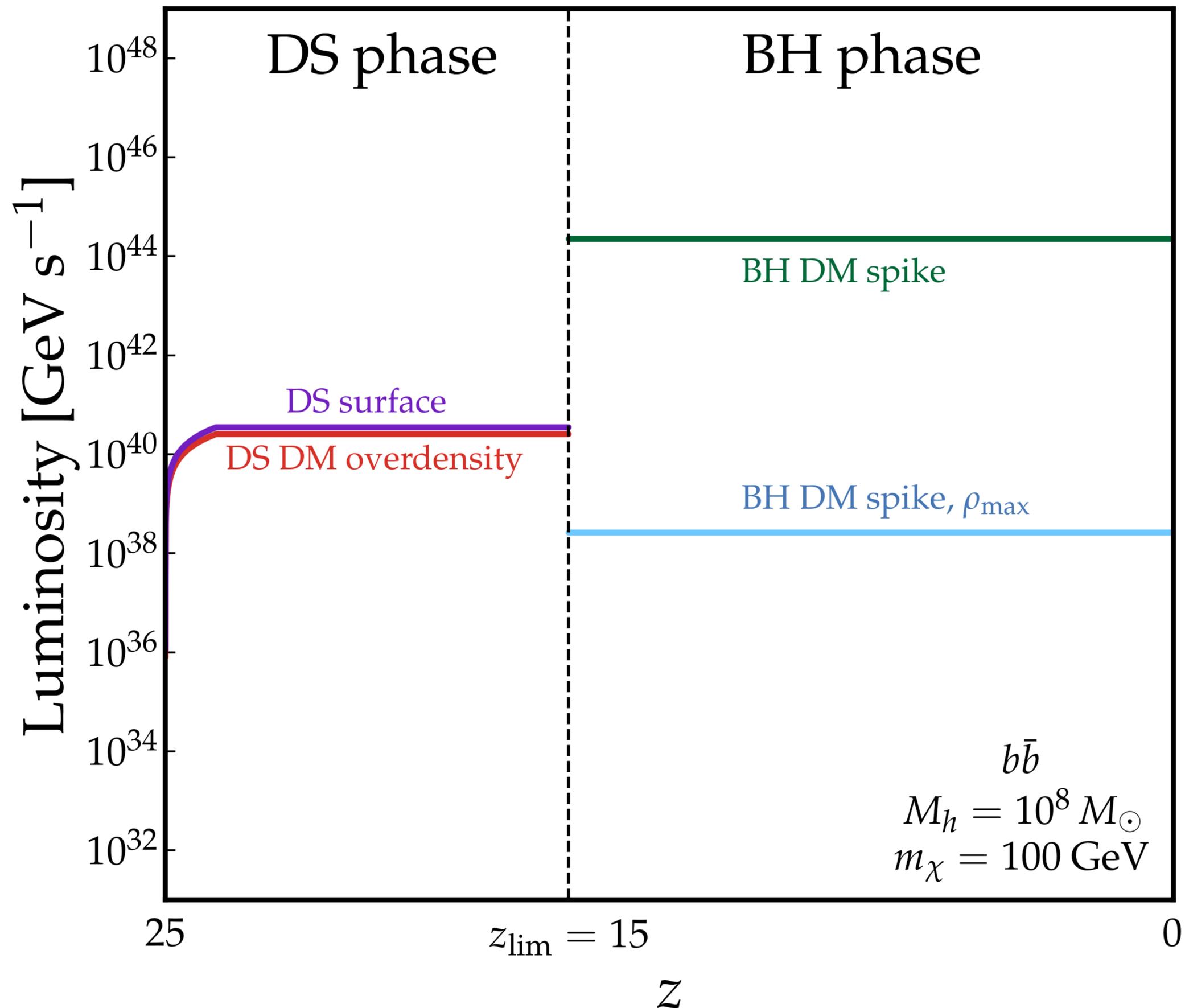
Subsequent BH Spike

- DM continues to annihilate efficiently in this spike

- Consider two extreme cases to bracket the physical case of an evolving DM spike
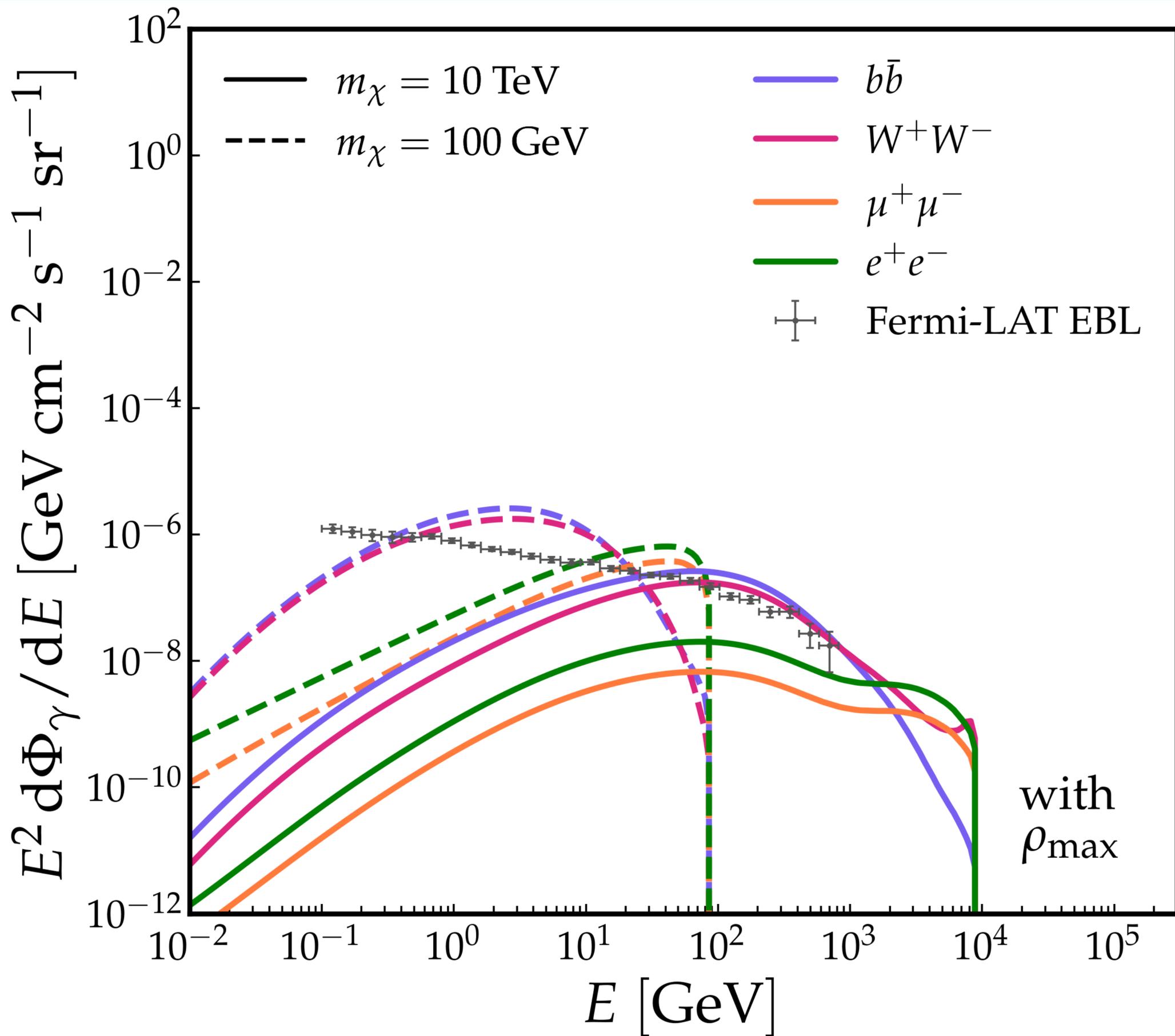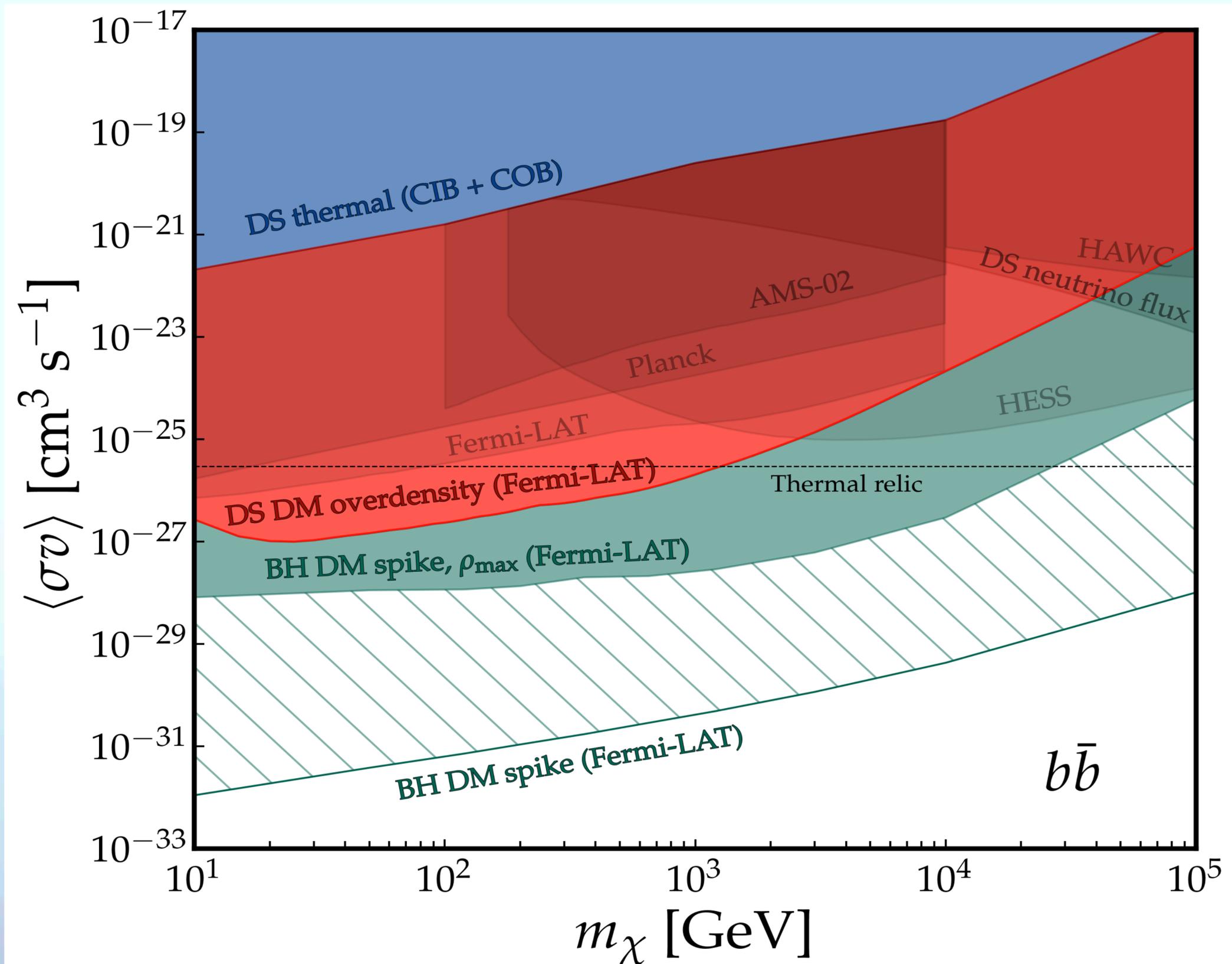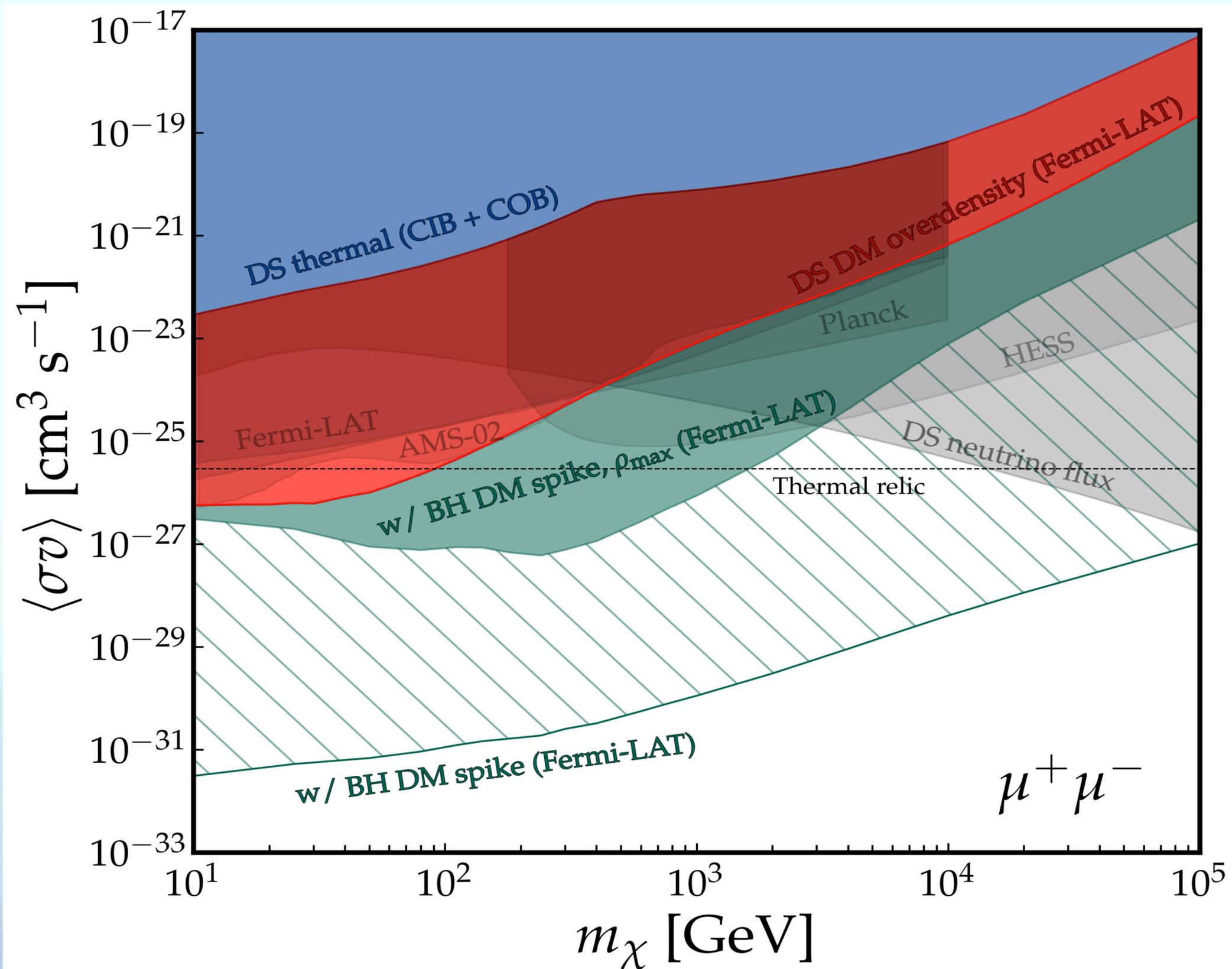
We have again neglected the evolution of the system due to mergers

The Dark Star Photon Measurements

ArXiv: 2512.04061

The Dark Star Photon Measurements

Summary

- We consider Supermassive Dark Stars as the progenitors of Supermassive Black Holes and study their emission of neutrinos as well as high and low energy photons

- We find that neutrino emission is most constraining for heavy dark matter while high energy photon emission is most constraining for lighter dark matter

- Using this multi-messenger probe, we find that much of the DM parameter space at the thermal relic cross-section is ruled out in this scenario
  - Smaller DSs, collapse at $z > 15$, or a stronger disruption of the DM over density may still be viable