The First Stars in the Universe as Dark Matter Laboratories

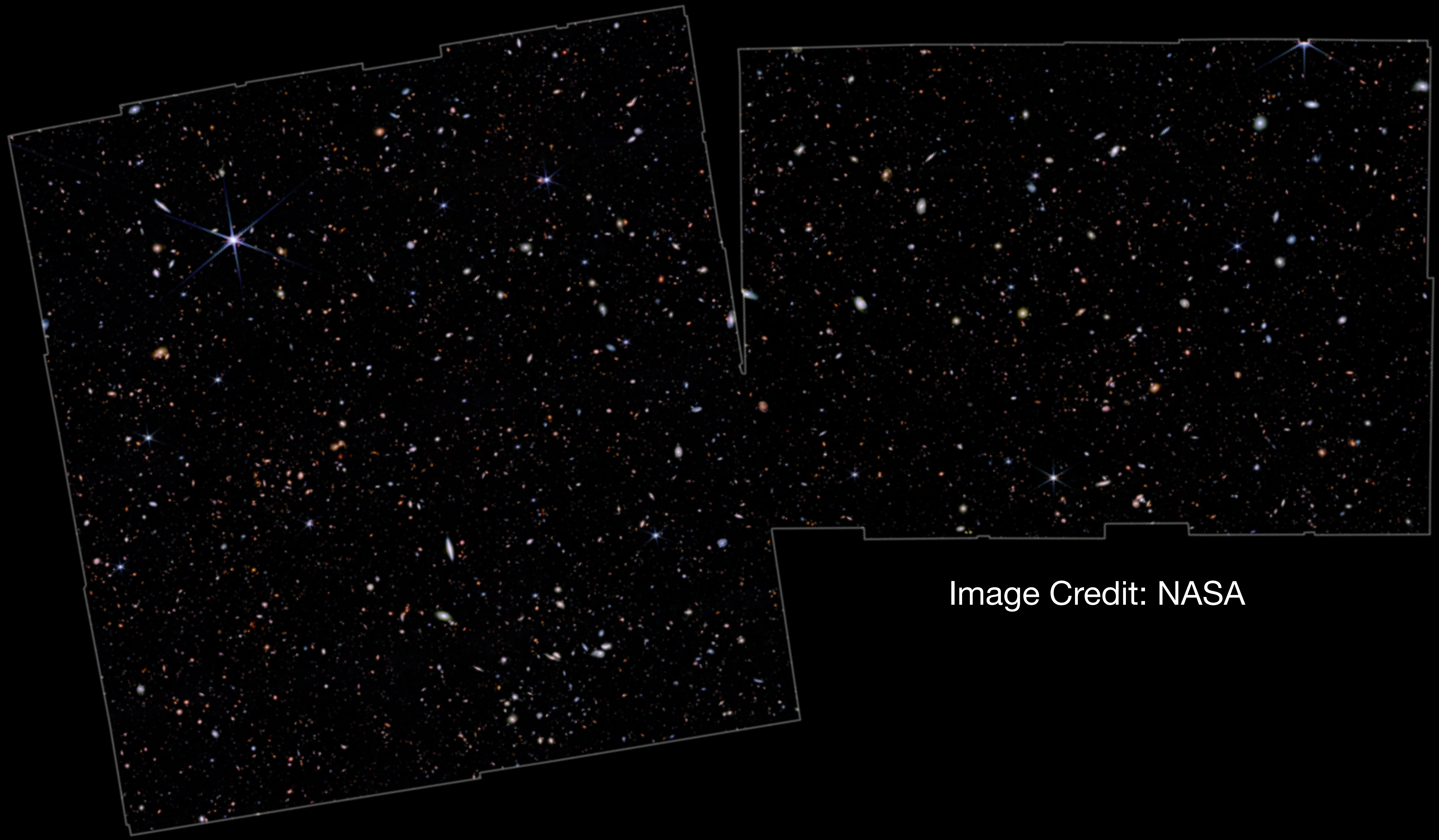
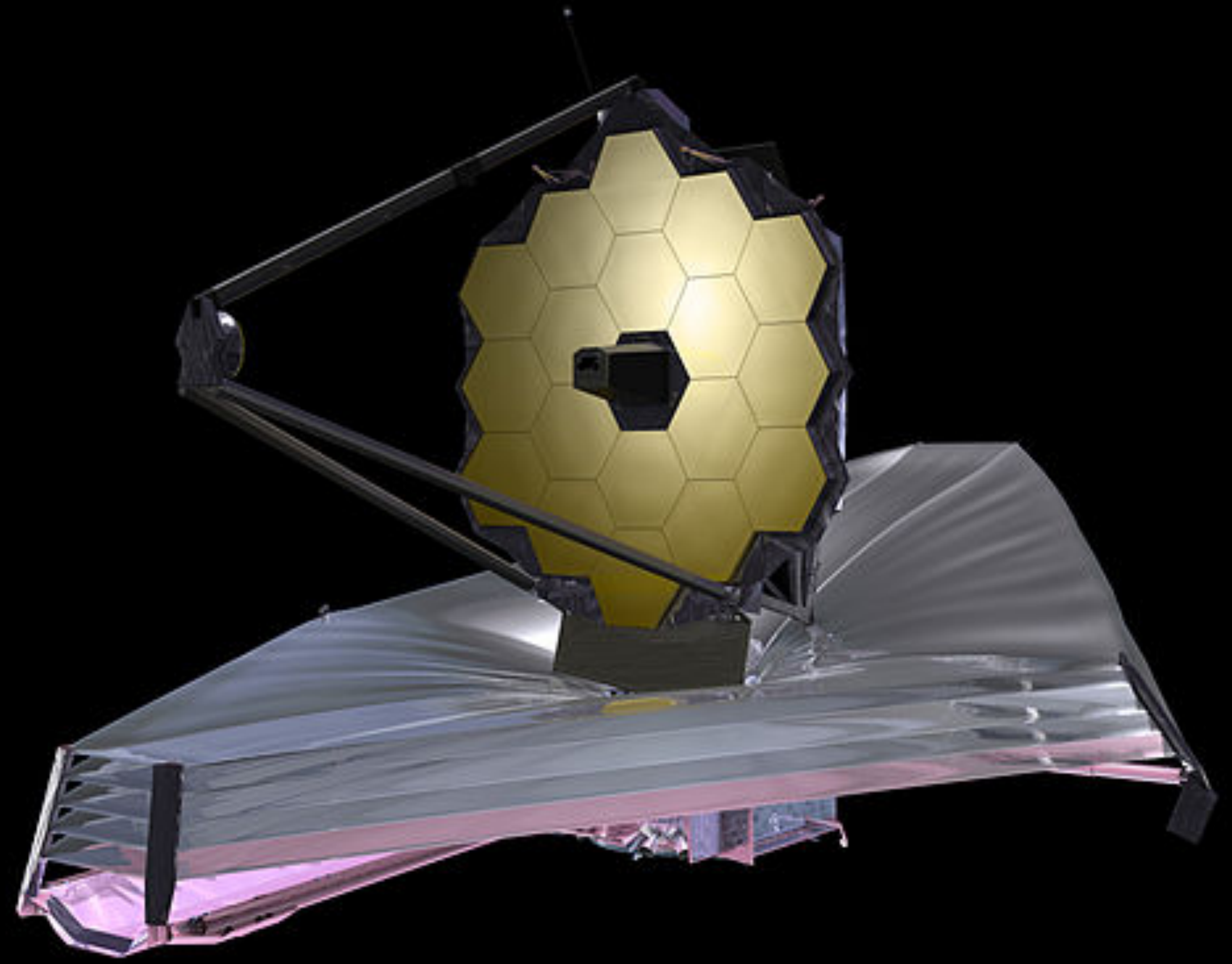


Image Credit: NASA



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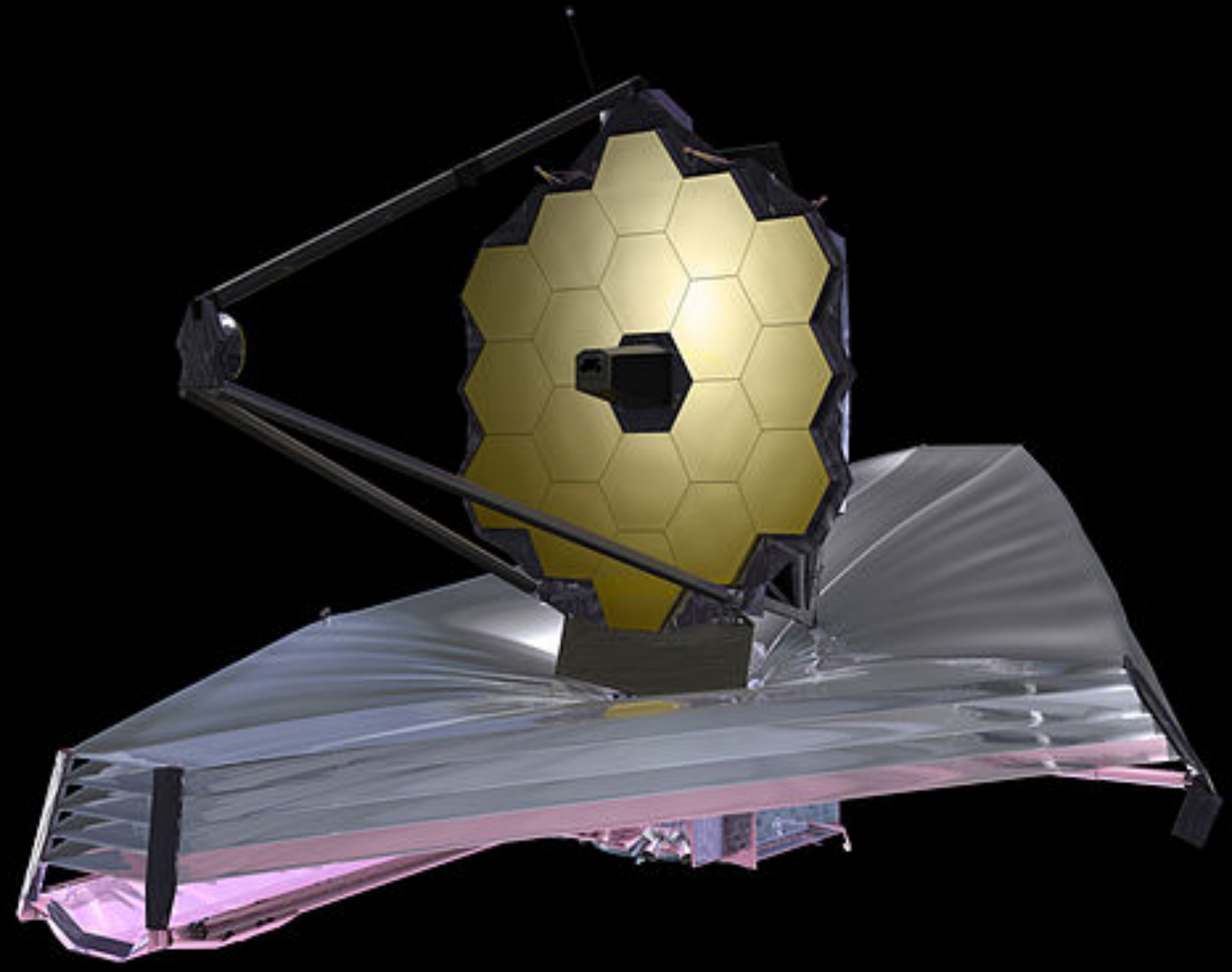
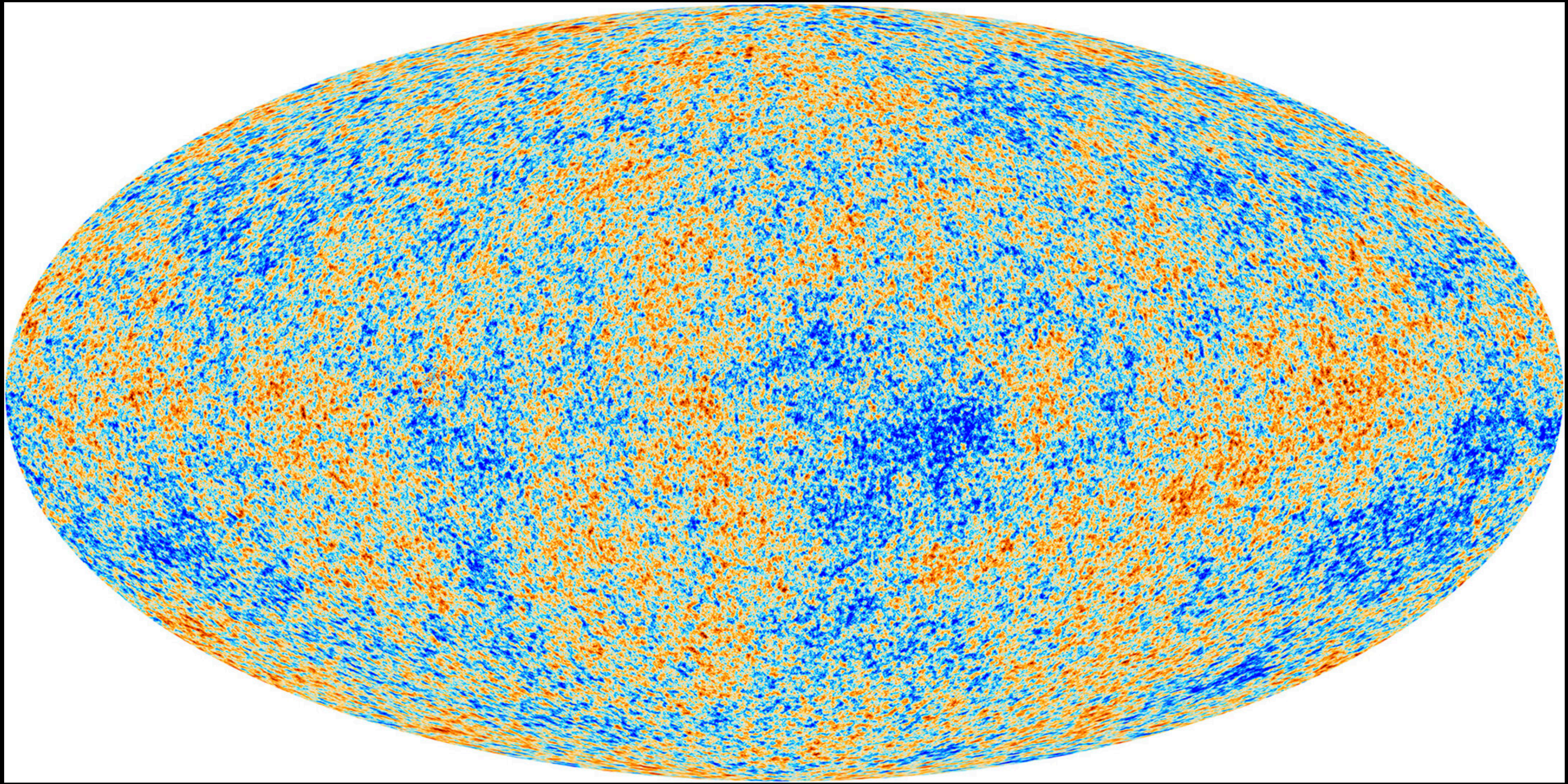
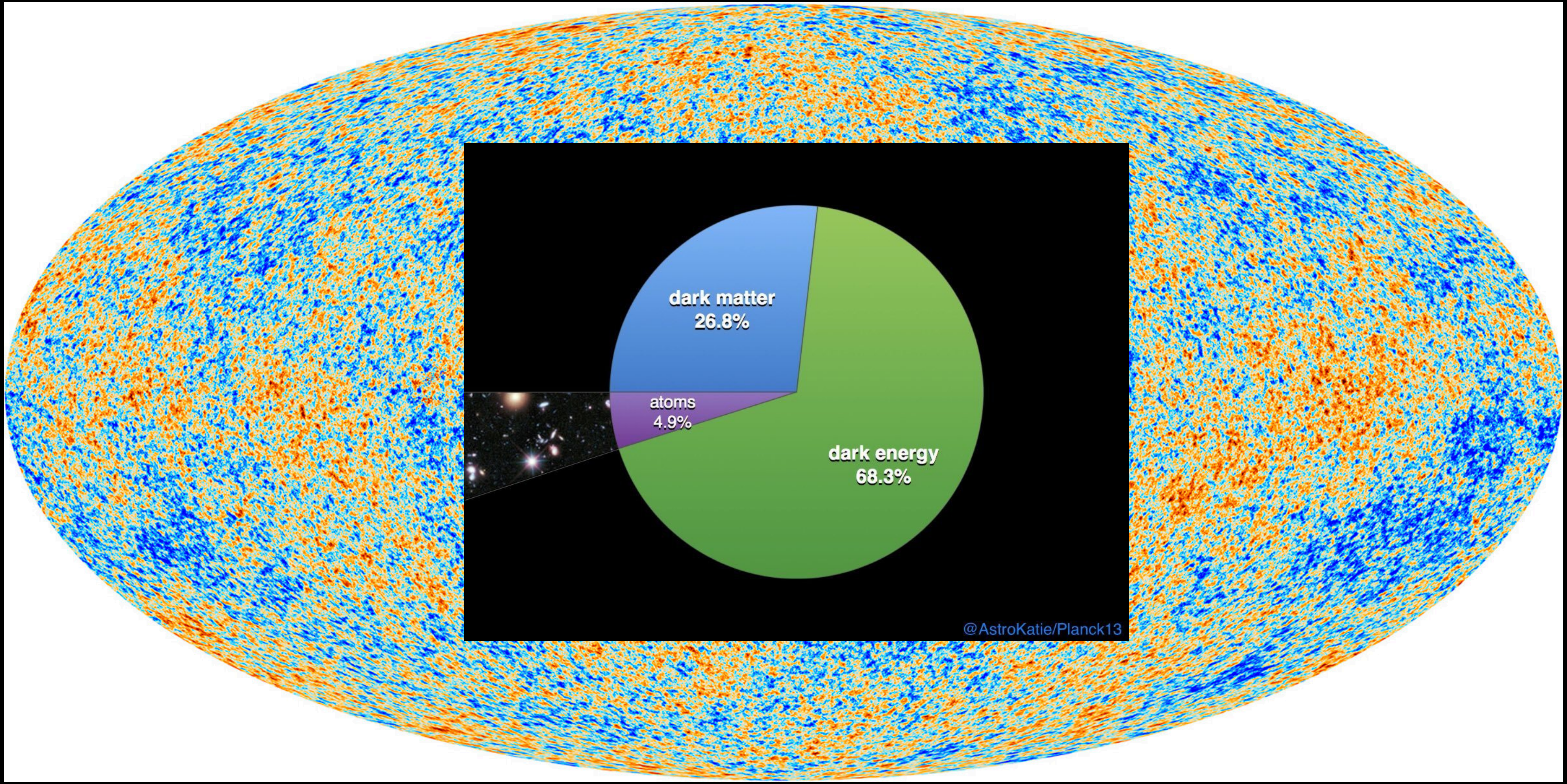


 Cosmin Ilie cilie@colgate.edu

Cosmic Microwave background as a DM probe



Cosmic Microwave background and contents of the Universe



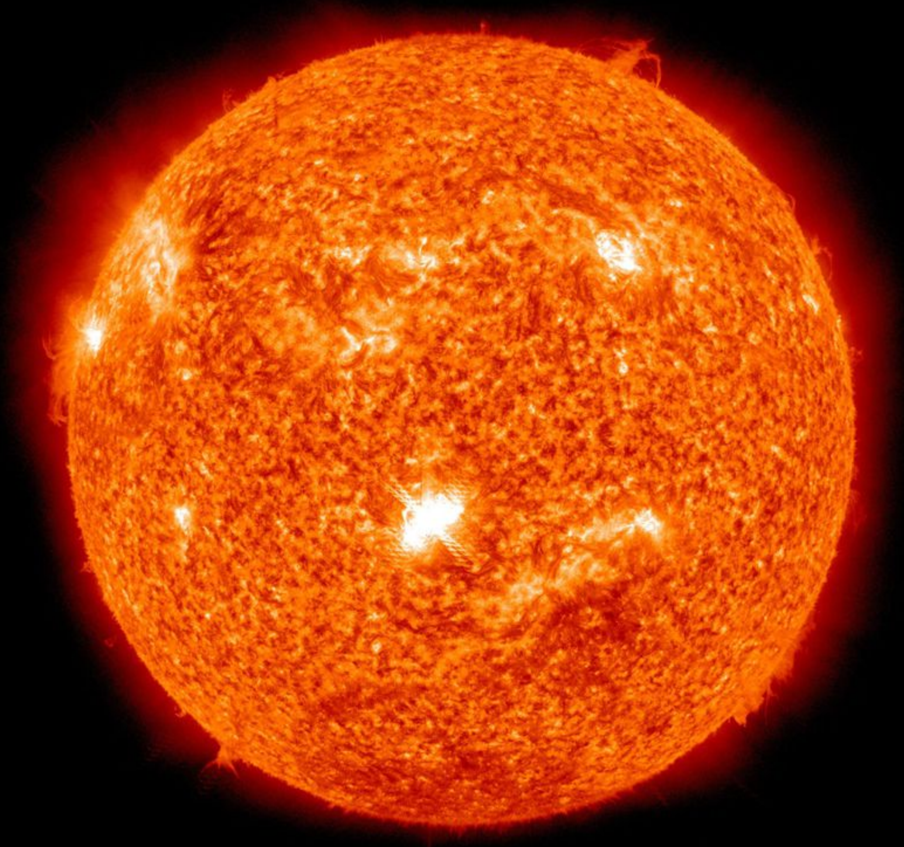
Searches to find DM via other effects rather than Gravity

- Direct Detection. Probes DM-Regular Matter interactions
    - Deep underground experiments (LUX, XENON, DAMMA, etc.)
- Indirect Detection. Probes DM-DM interactions
    - Detect signals of Dark Matter annihilations in high DM density environments
- Production of DM particles in accelerators (LHC).
    - Would be detected as missing energy

Astrophysical Objects as DM Probes

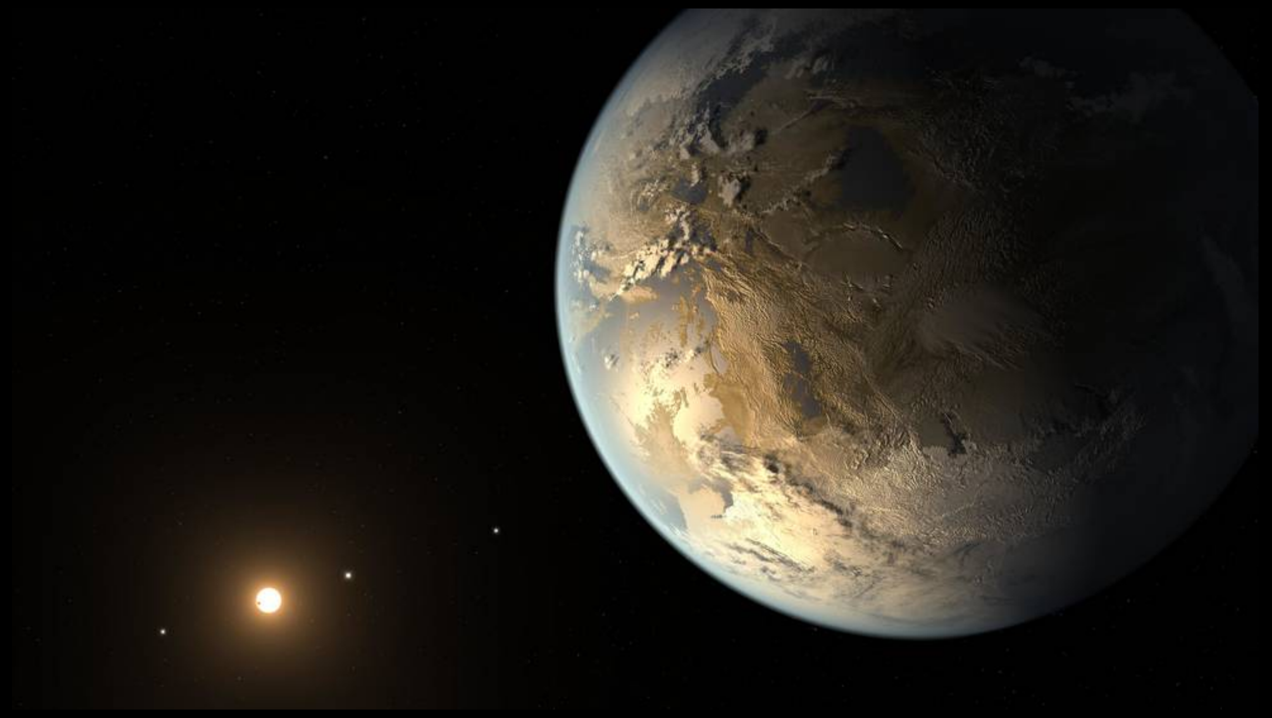
Earth

Moon



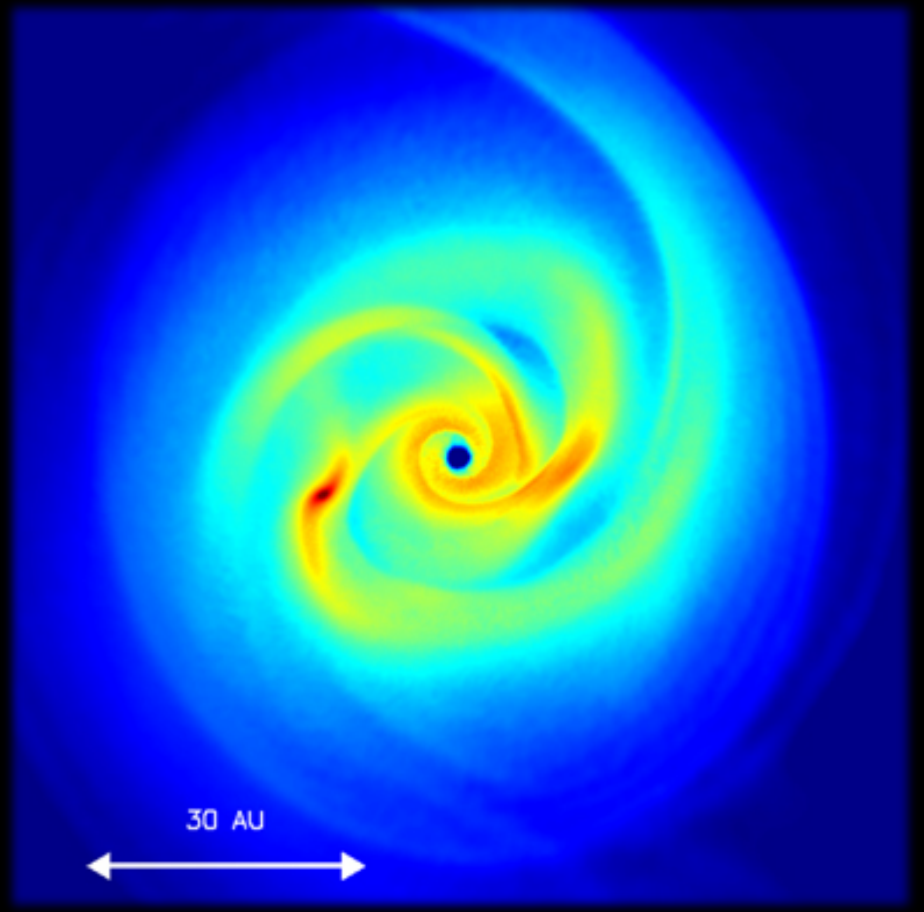
Sun

Neutron Stars



Exoplanets

White Dwarfs



The First Stars

Astrophysical Objects as DM Probes

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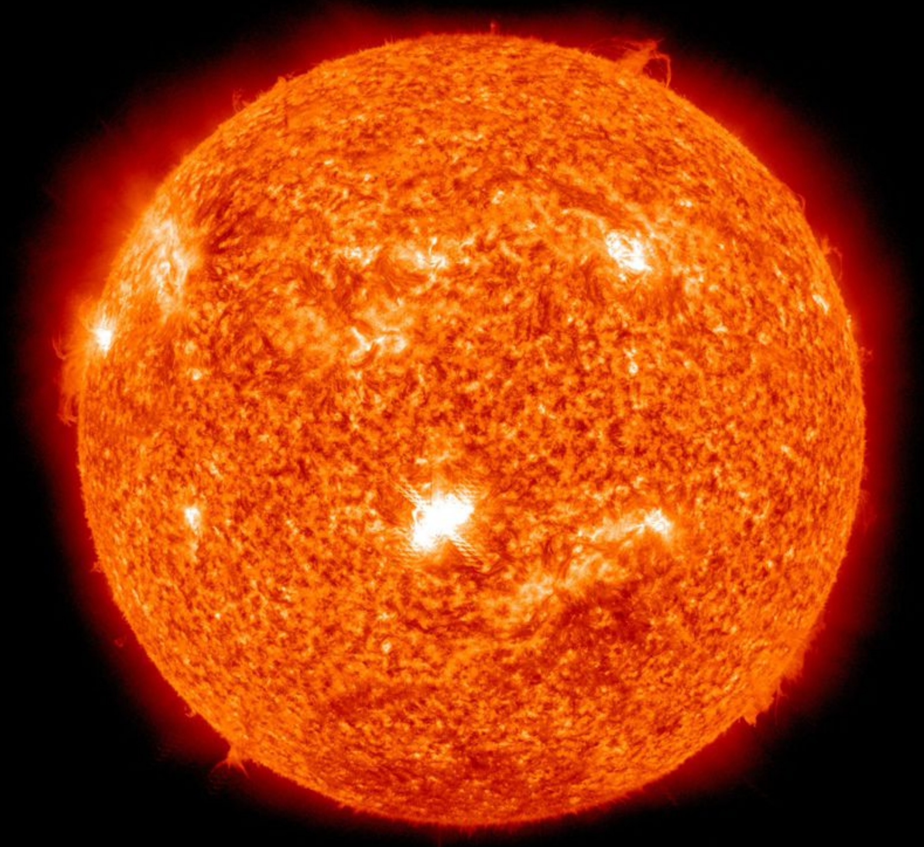

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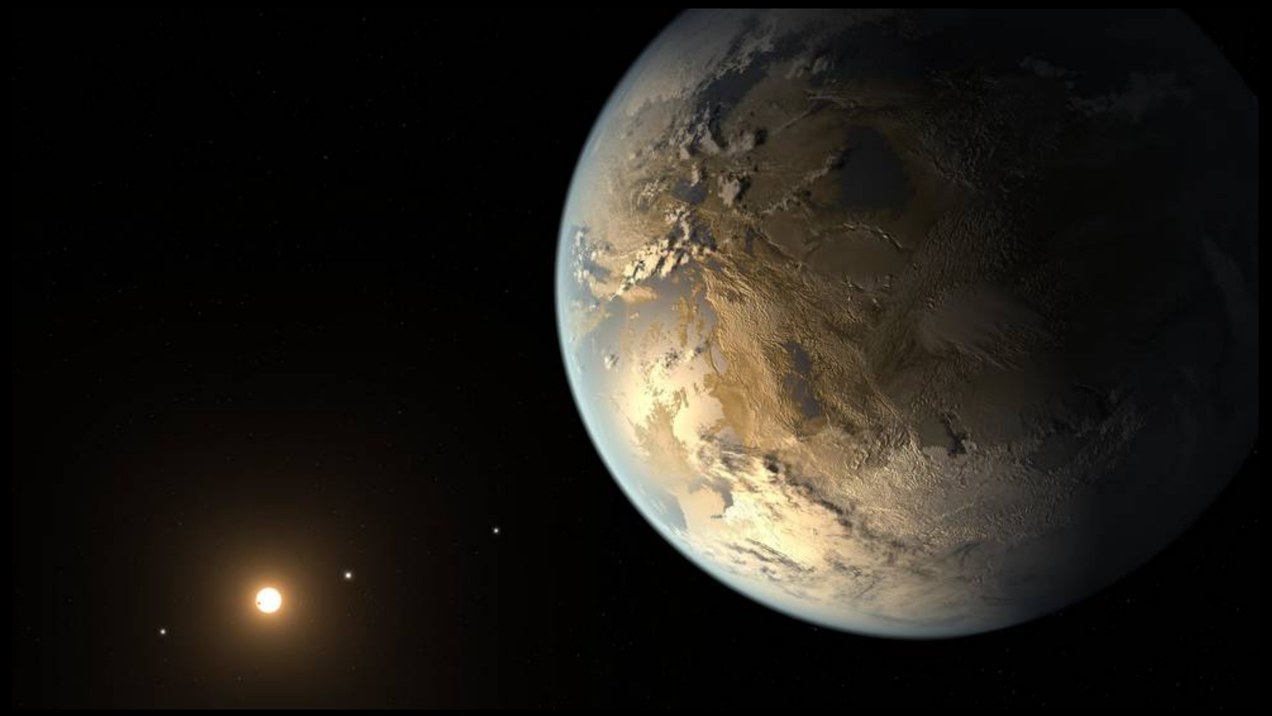

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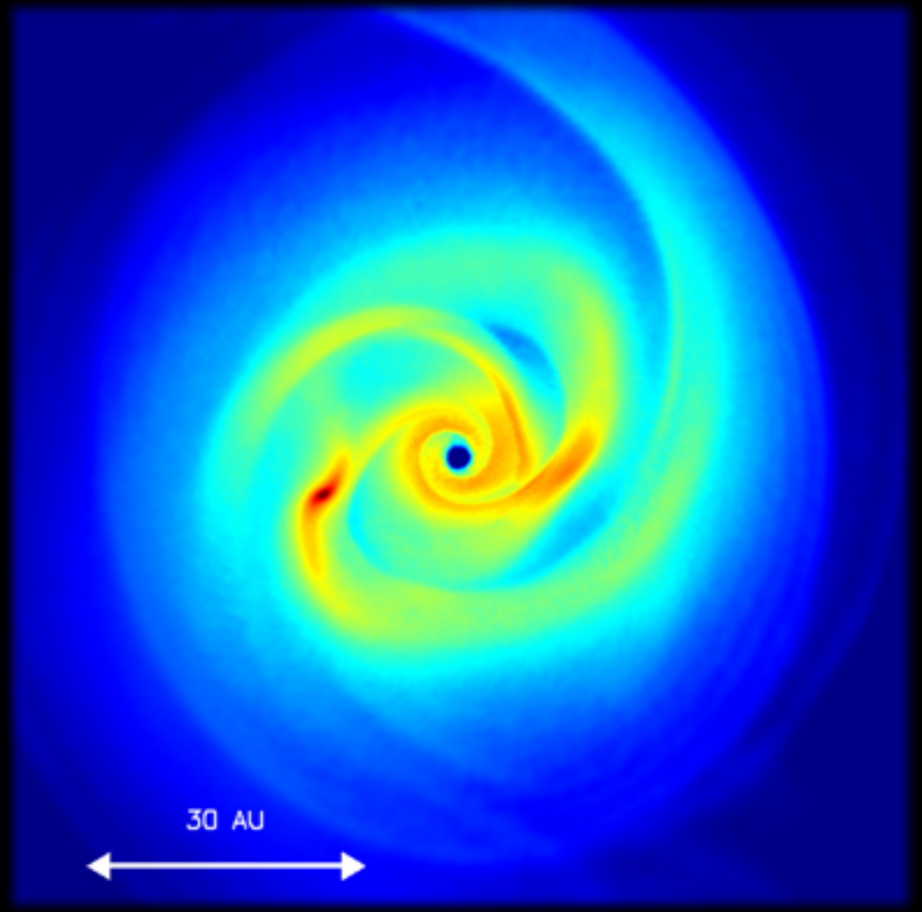
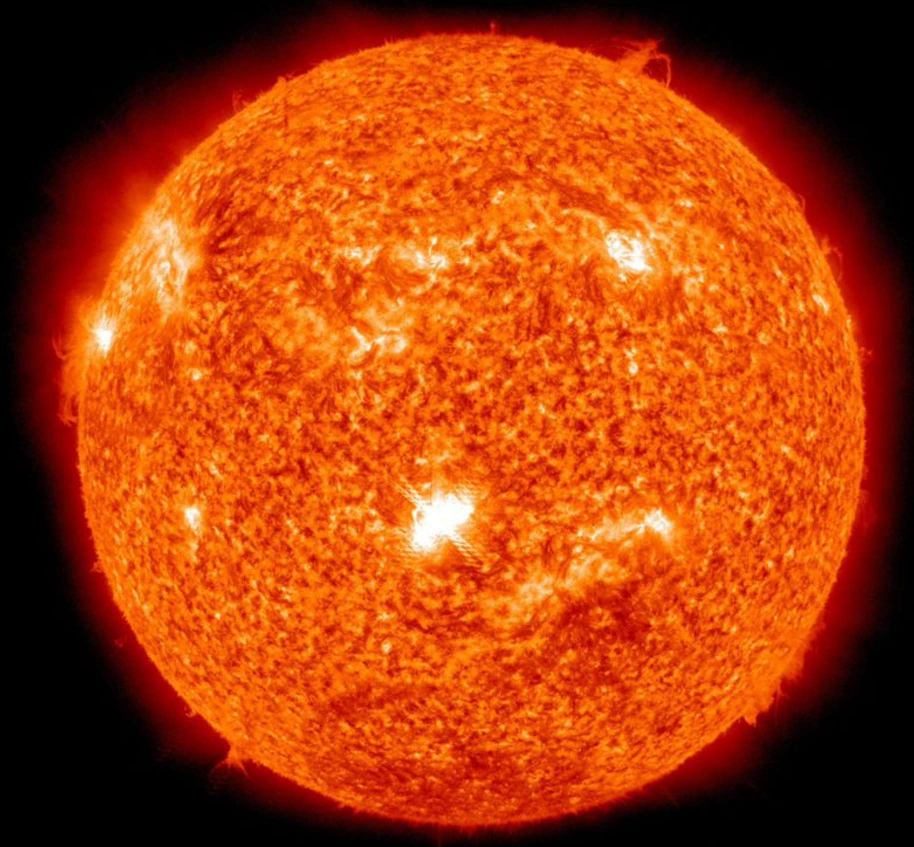


The First Stars

Astrophysical Objects as DM Probes


Earth


Moon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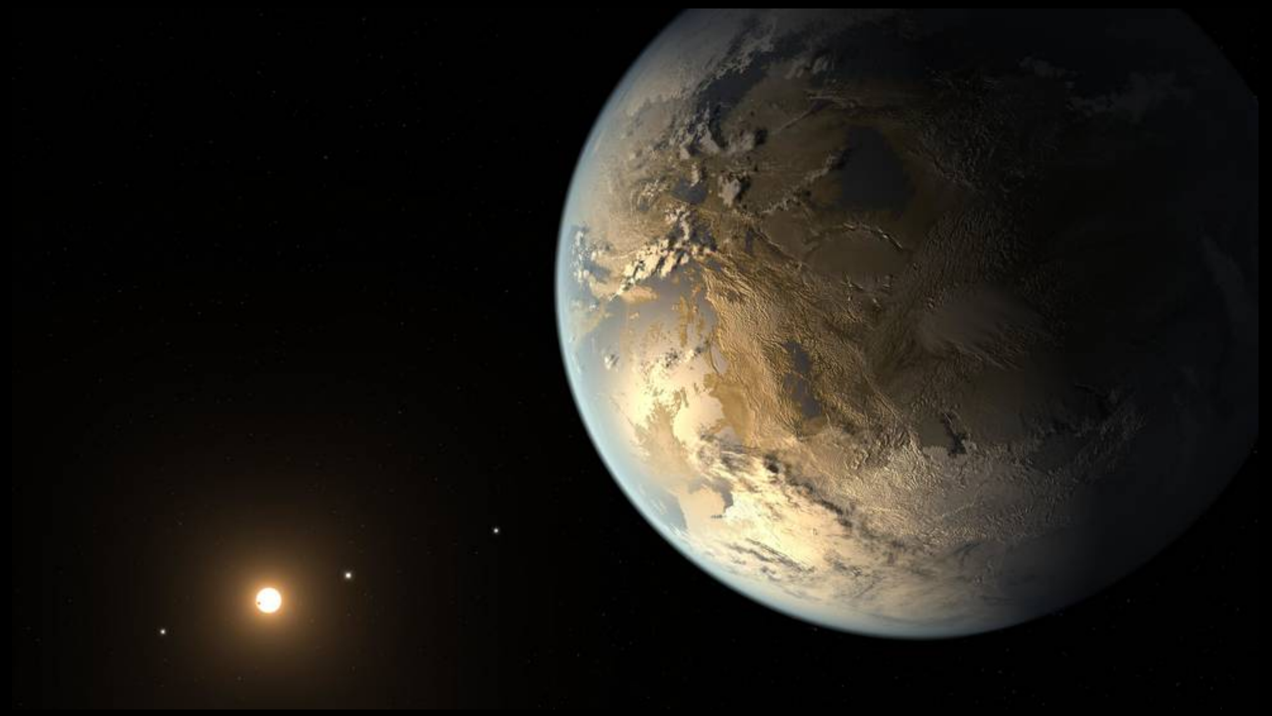
Exoplanets


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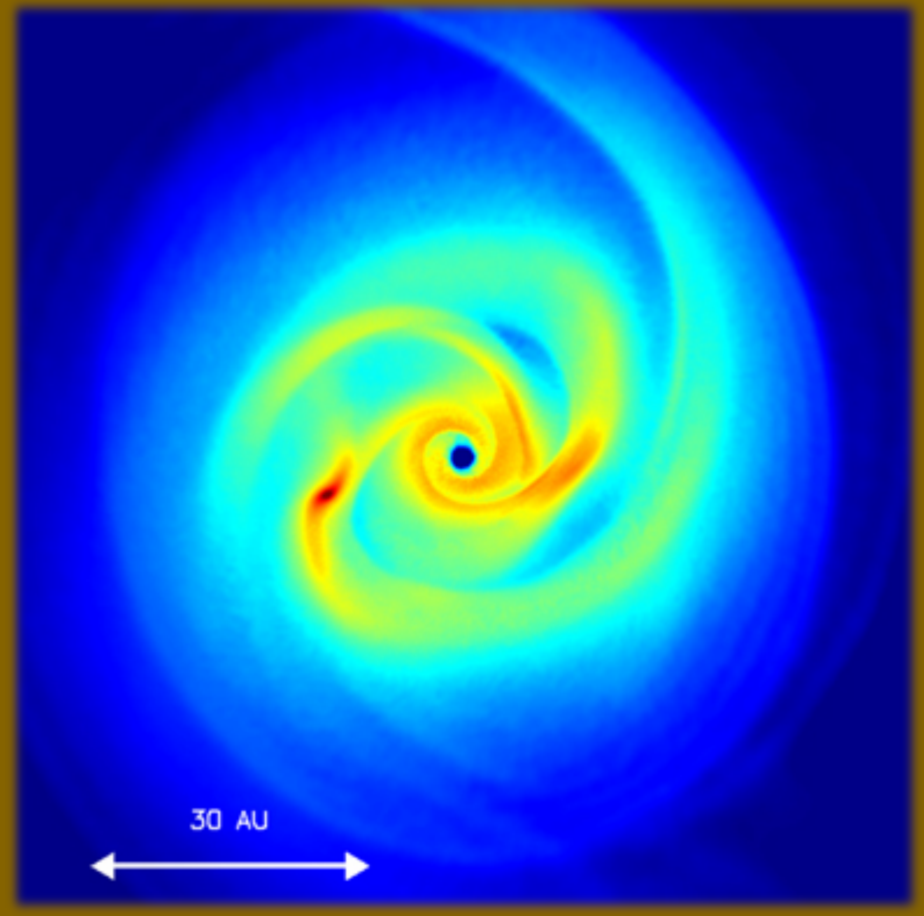

The First Stars

The first Stars, bird’s-eye view

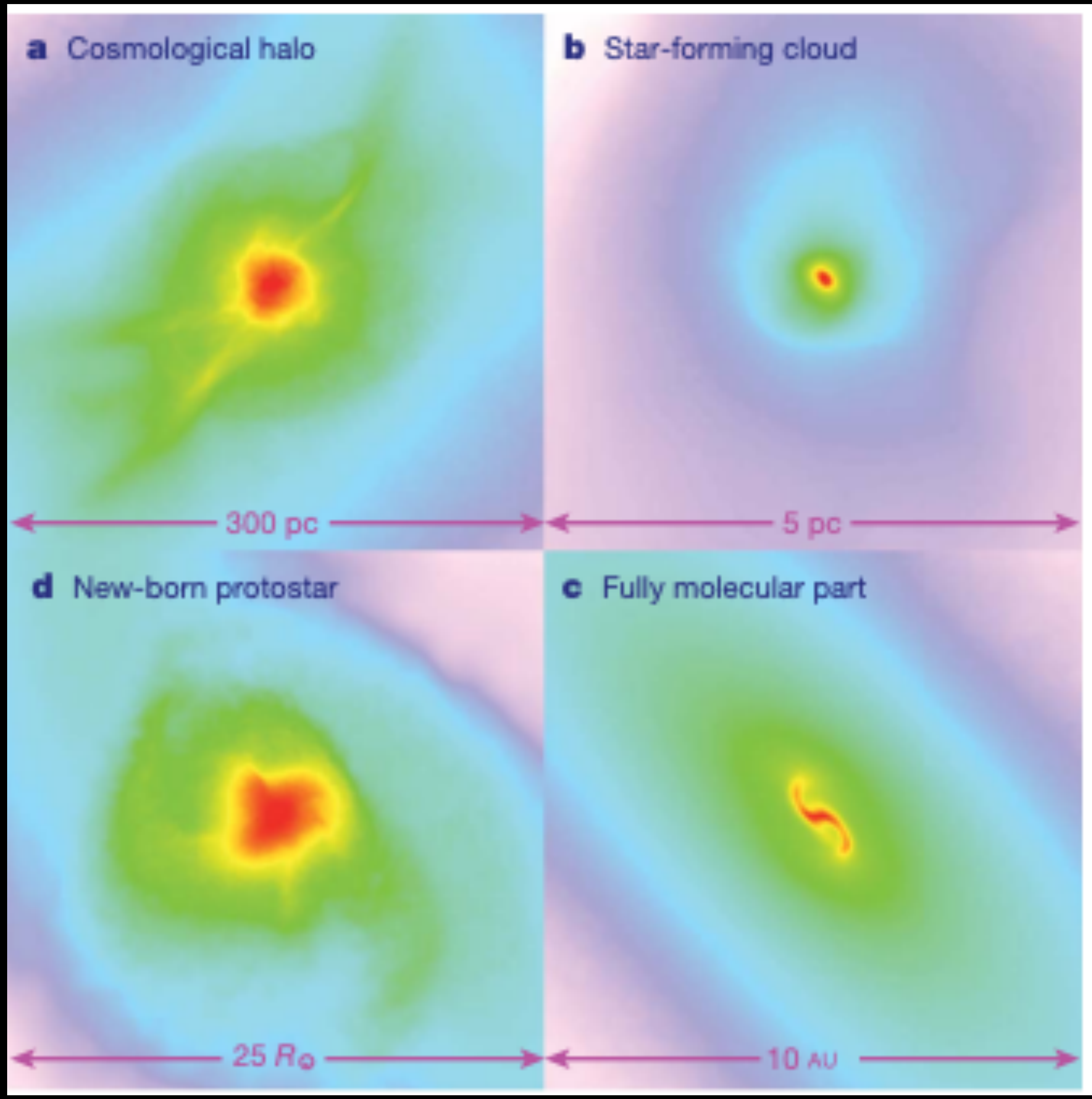

Figure From: Bromm et al. Nature 459 (2009)

- The form at high redshift (z~10-40) from pristine BBN H and He gas
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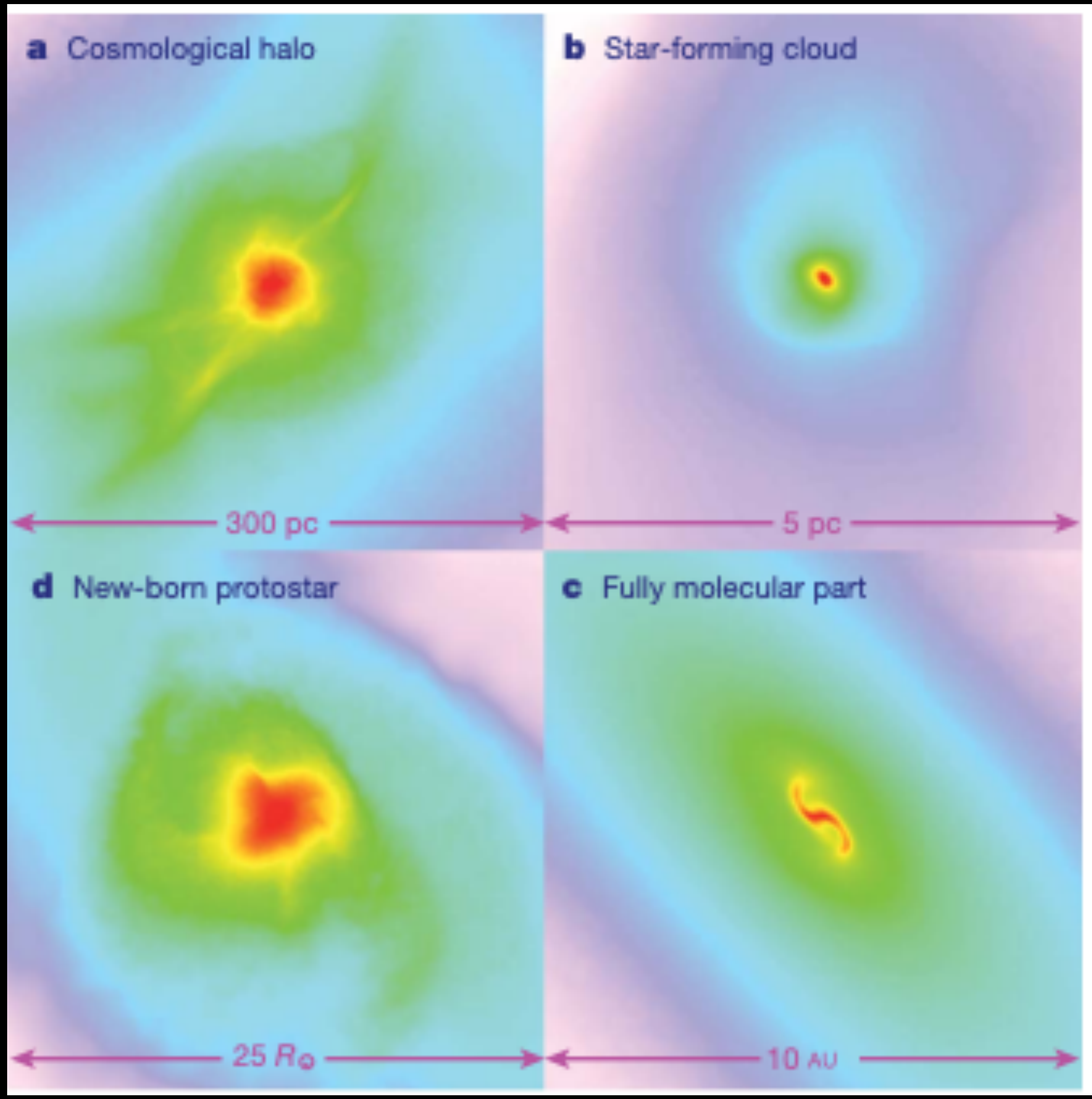


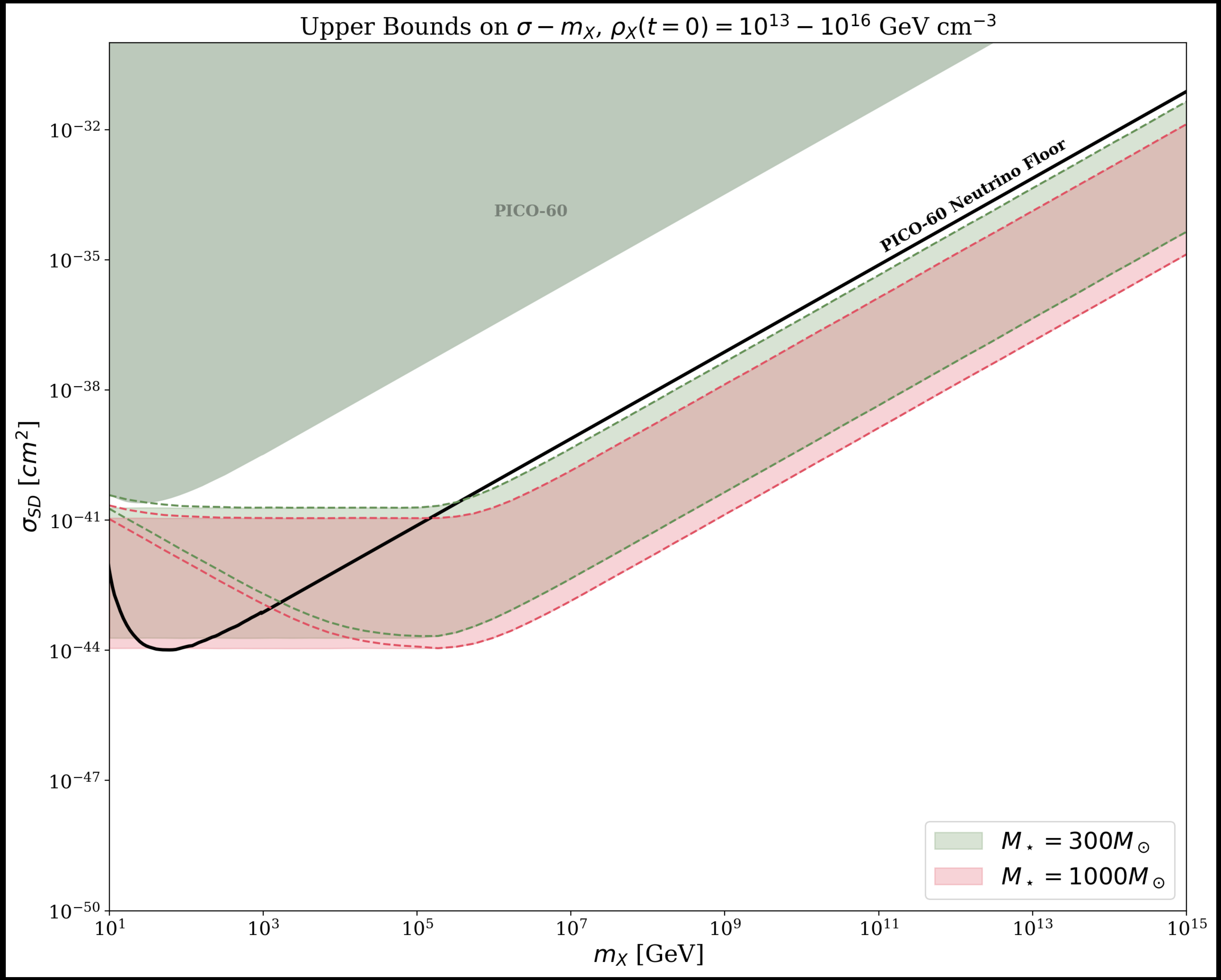
Figure From: Bromm et al. Nature 459 (2009)

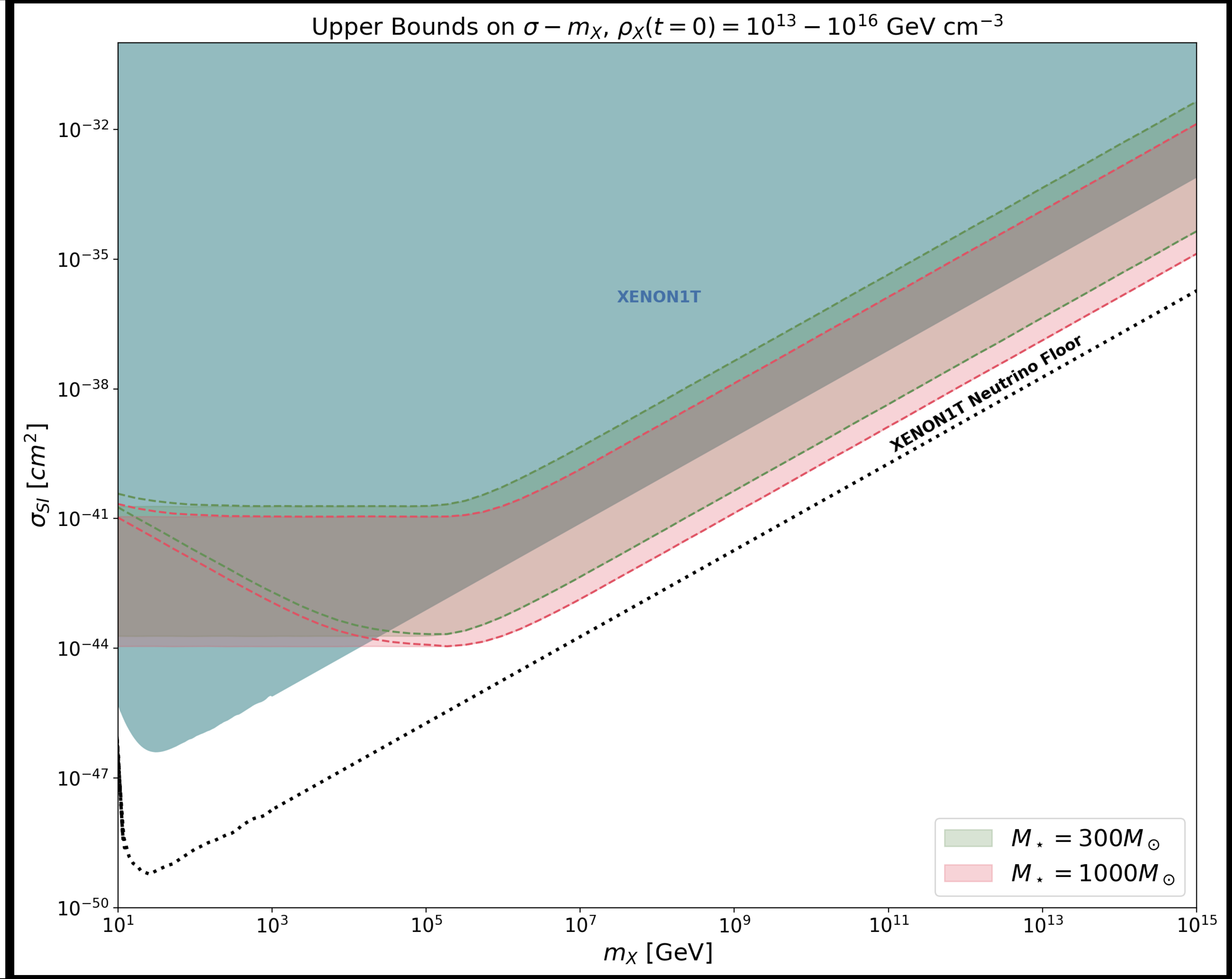
- The form at high redshift (z~10-40) from pristine BBN H and He gas
- In very DM rich environments, at the center of DM microhalos
- Usually in isolation, or with few companions
- They can grow as massive as $1000 M_\odot$ (Population III aka PopIII stars: zero metallicity stars powered by H fusion)

PopulationIII stars as DM probes

Bounds from imposing sub-Eddington Luminosity:

$$L_{DM}(M_\star, R_\star; DM\ params) \leq L_{Edd}(M_\star) - L_{nuc}(M_\star)$$



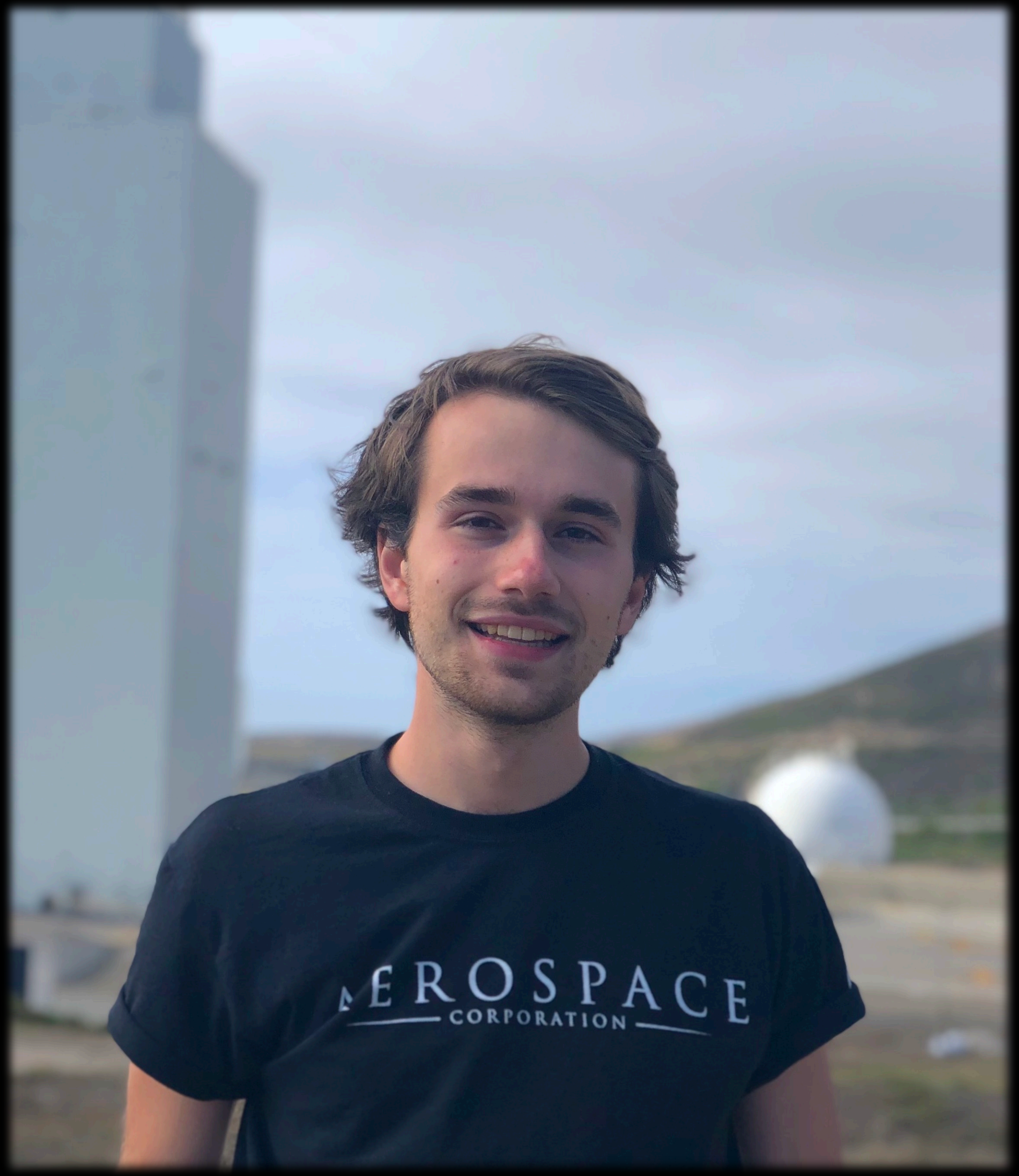


Ilie et al. PhysRevD.104.123031 (2021) (arXiv: 2009.11474)

PopulationIII stars as DM probes

The team:

Caleb Levy (Harvard U)



Jacob Pilawa (UC Berkeley)

Saiyang Zhang (UT Austin)

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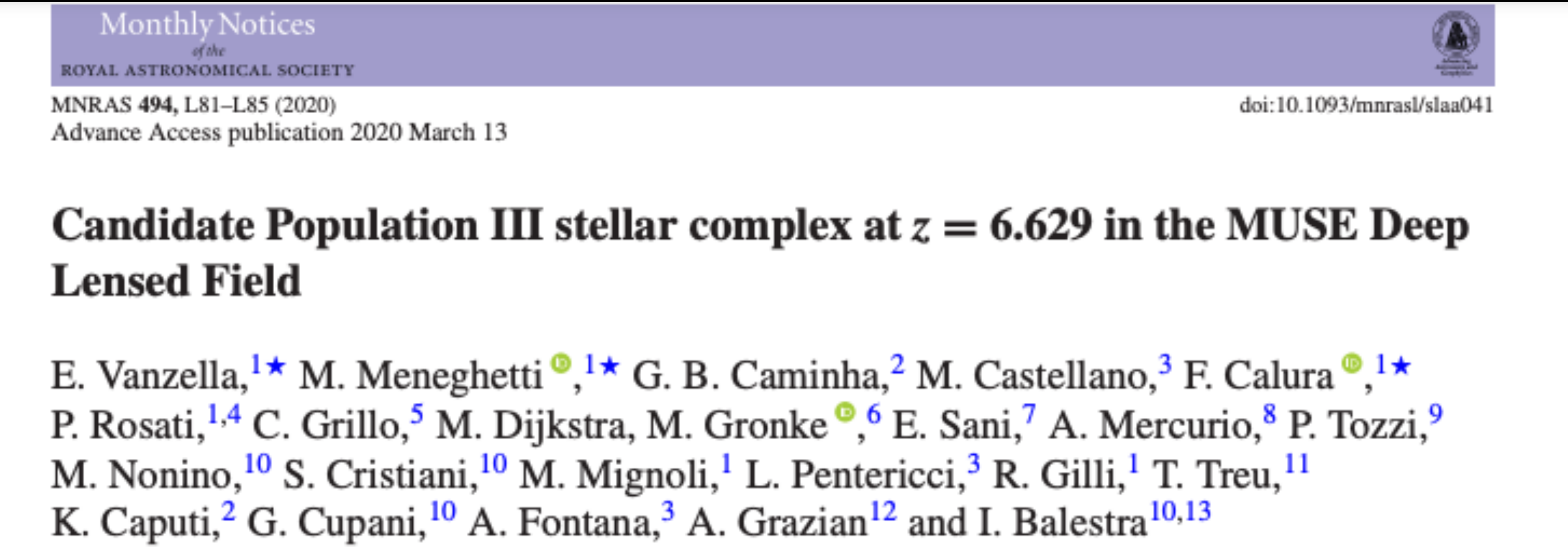
PopIII stars Observational Status


Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 494, L81–L85 (2020) doi:10.1093/mnrasl/slaa041
Advance Access publication 2020 March 13

Candidate Population III stellar complex at $z = 6.629$ in the MUSE Deep Lensed Field

E. Vanzella,[1★] M. Meneghetti,[1★] G. B. Caminha,[2] M. Castellano,[3] F. Calura,[1★] P. Rosati,[1,4] C. Grillo,[5] M. Dijkstra, M. Gronke,[6] E. Sani,[7] A. Mercurio,[8] P. Tozzi,[9] M. Nonino,[10] S. Cristiani,[10] M. Mignoli,[1] L. Pentericci,[3] R. Gilli,[1] T. Treu,[11] K. Caputi,[2] G. Cupani,[10] A. Fontana,[3] A. Grazian[12] and I. Balestra[10,13]

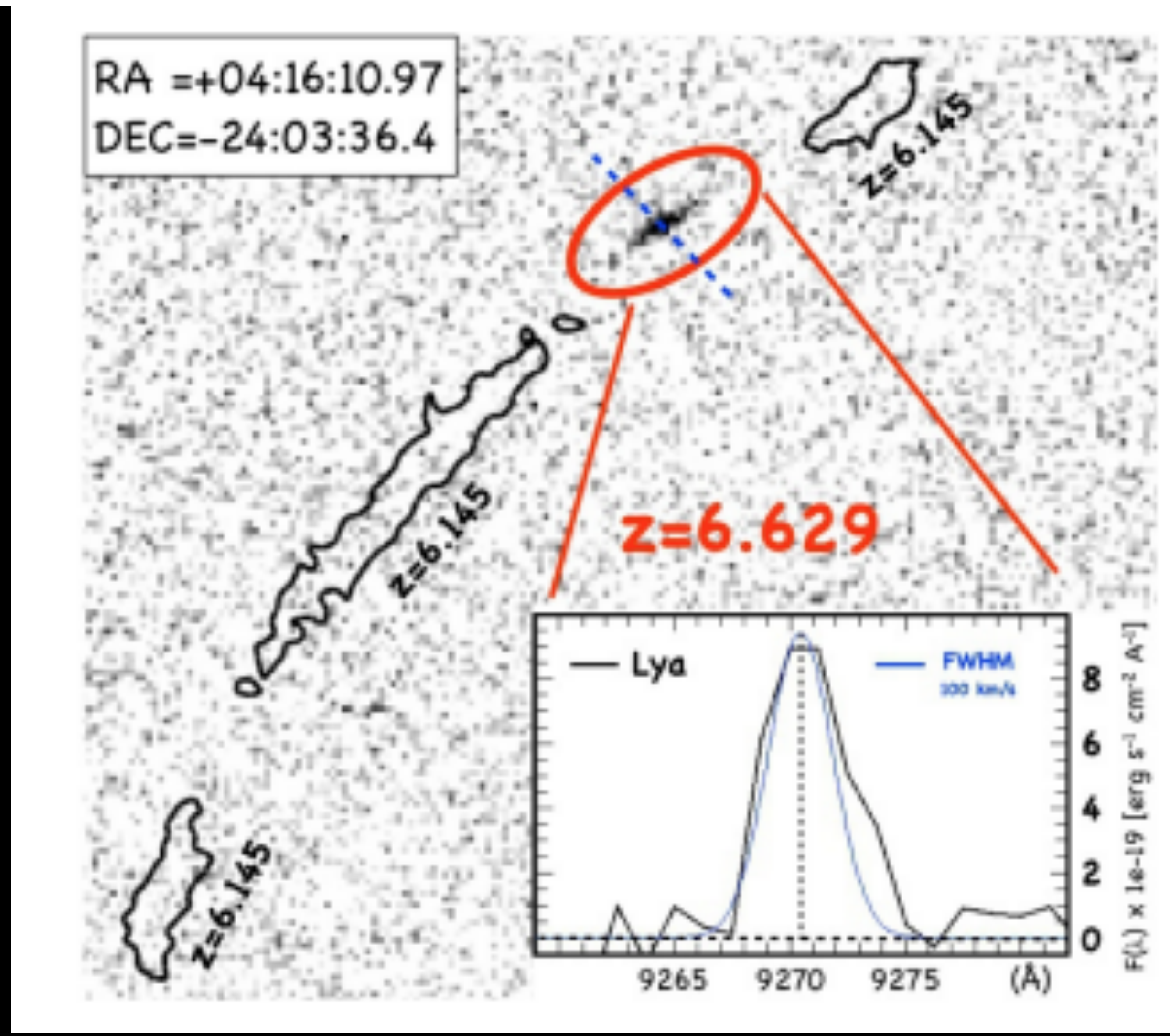
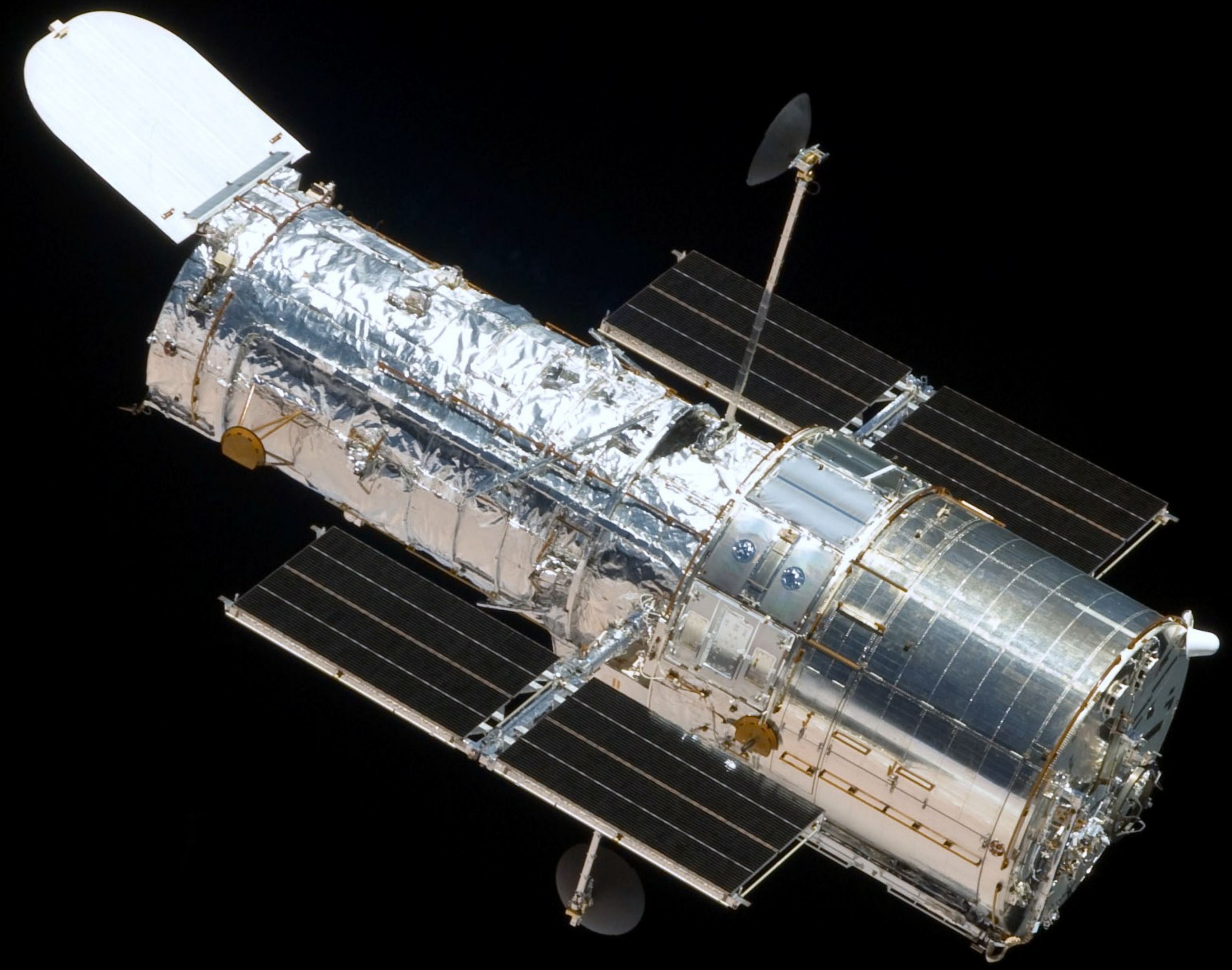
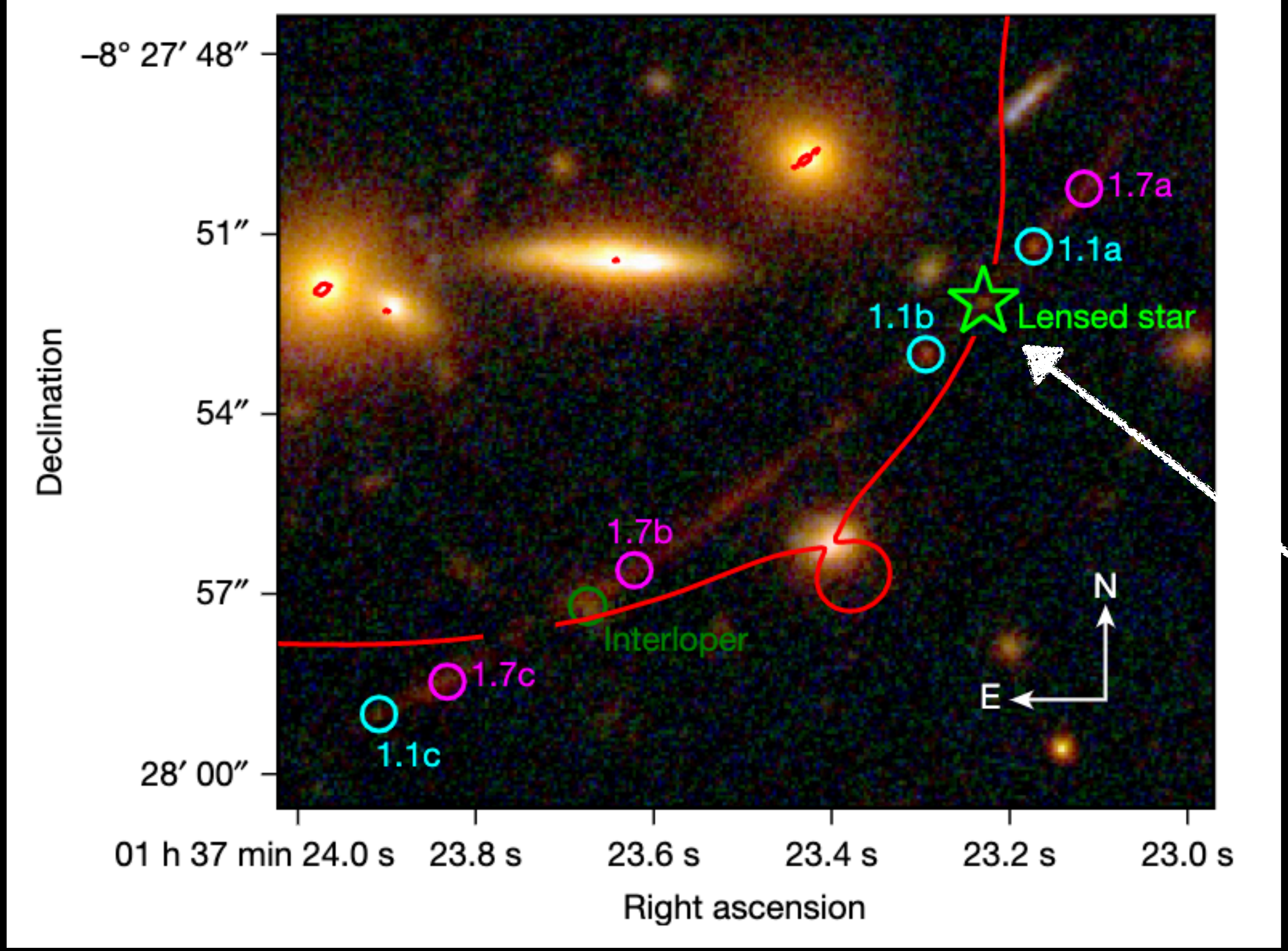


Fig. From Vanzella et al. MNRAS Lett. 294 (2020)



Hubble Space Telescope. Image credit: NASA

PopIII stars Observational Status


A highly magnified star at redshift 6.2

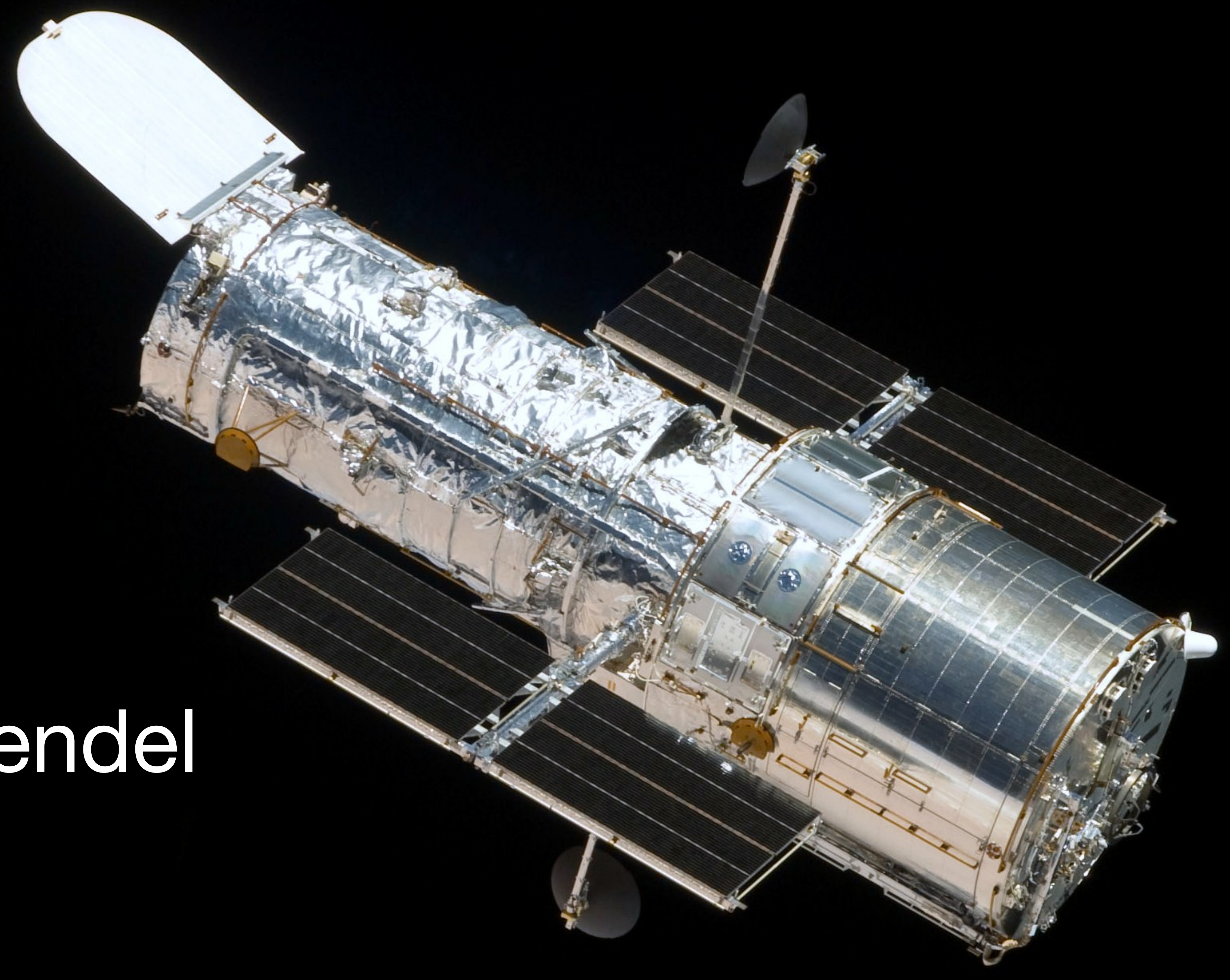
Brian Welch, Dan Coe, ... Tom Broadhurst + Show authors

Nature **603**, 815–818 (2022) | Cite this article

1940 Altmetric | Metrics

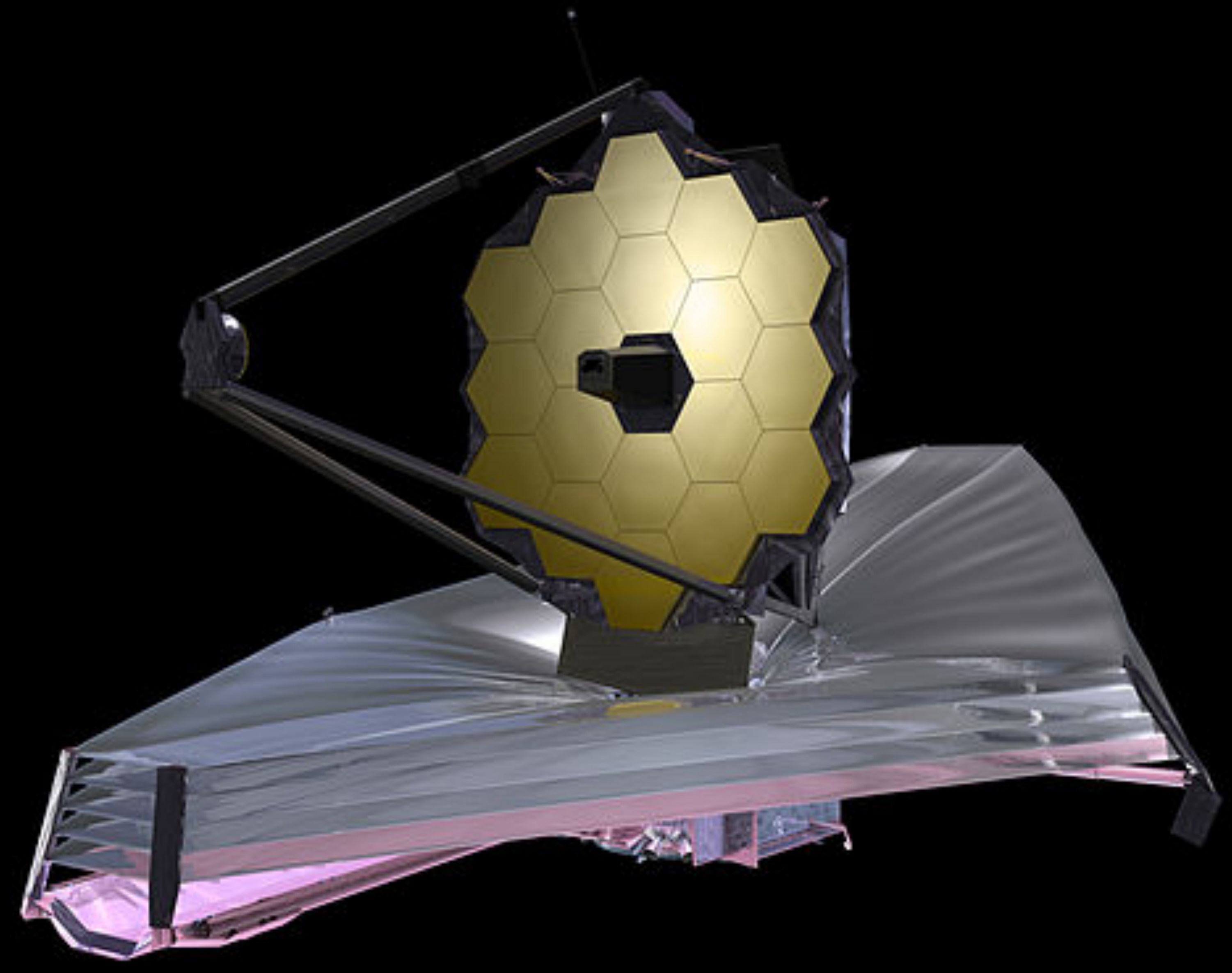
Fig. From Welch et al. Nature **603**, 815-818 (2022)

Earendel

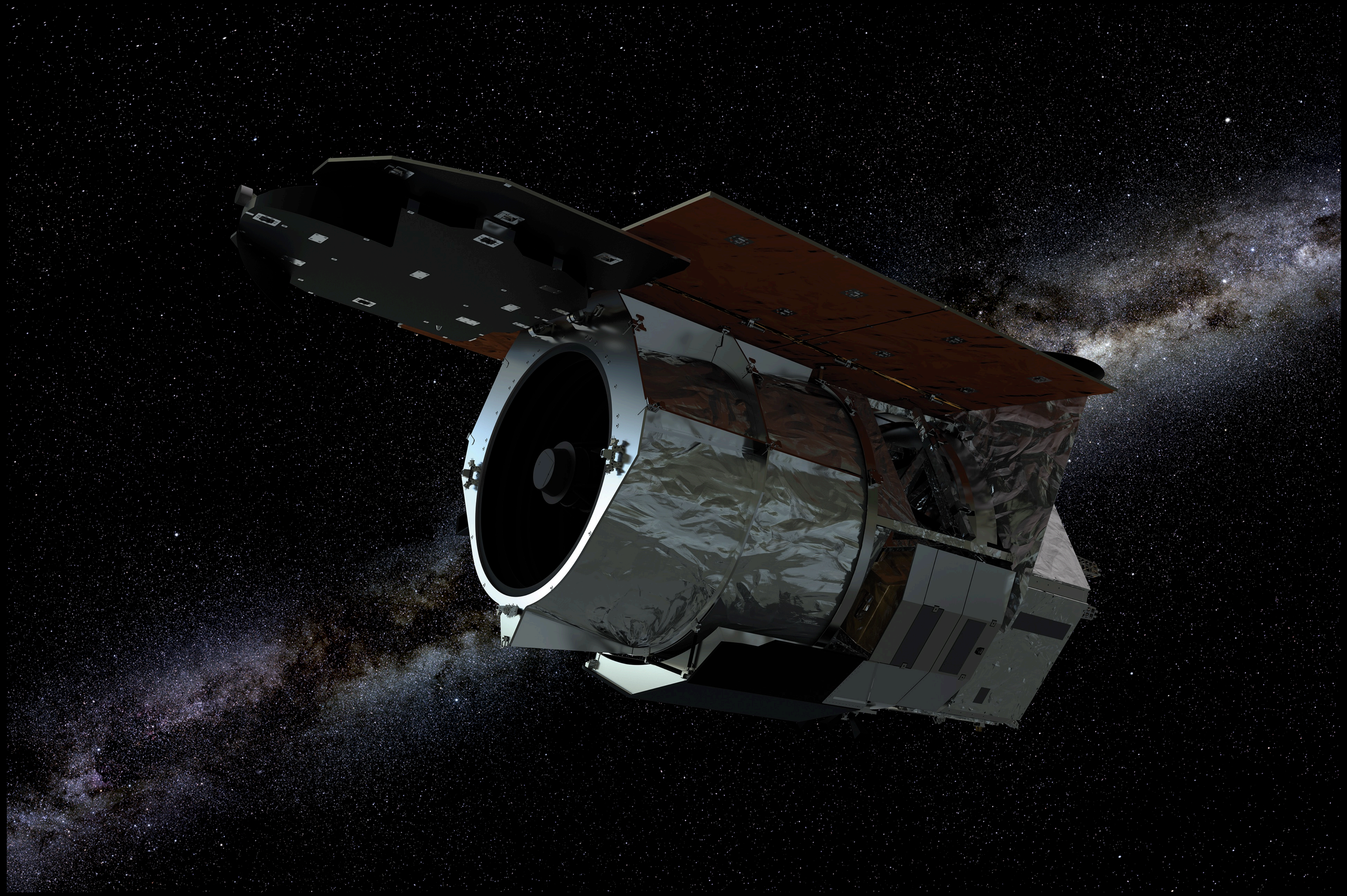


Hubble Space Telescope. Image credit: NASA

Observational Prospects

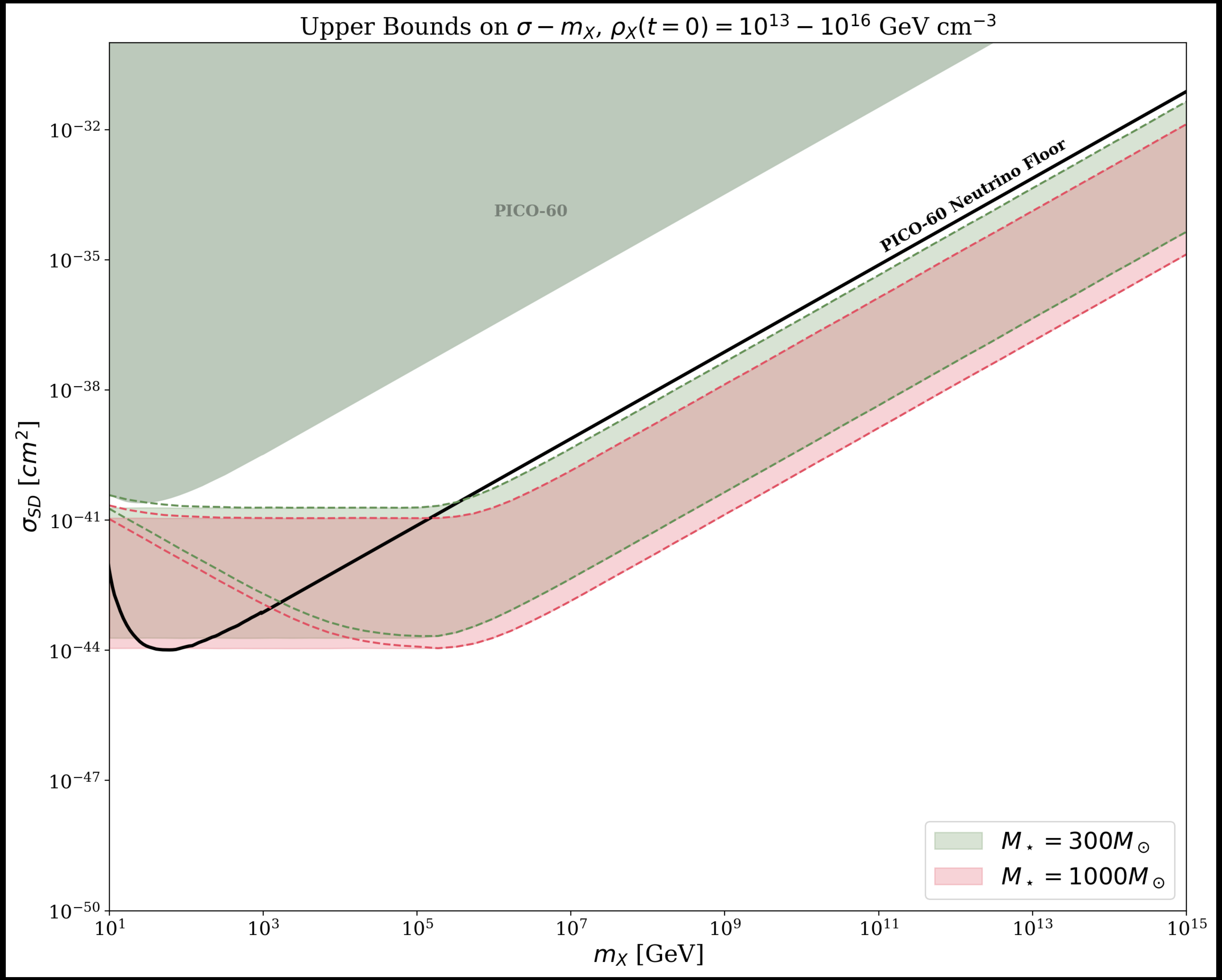


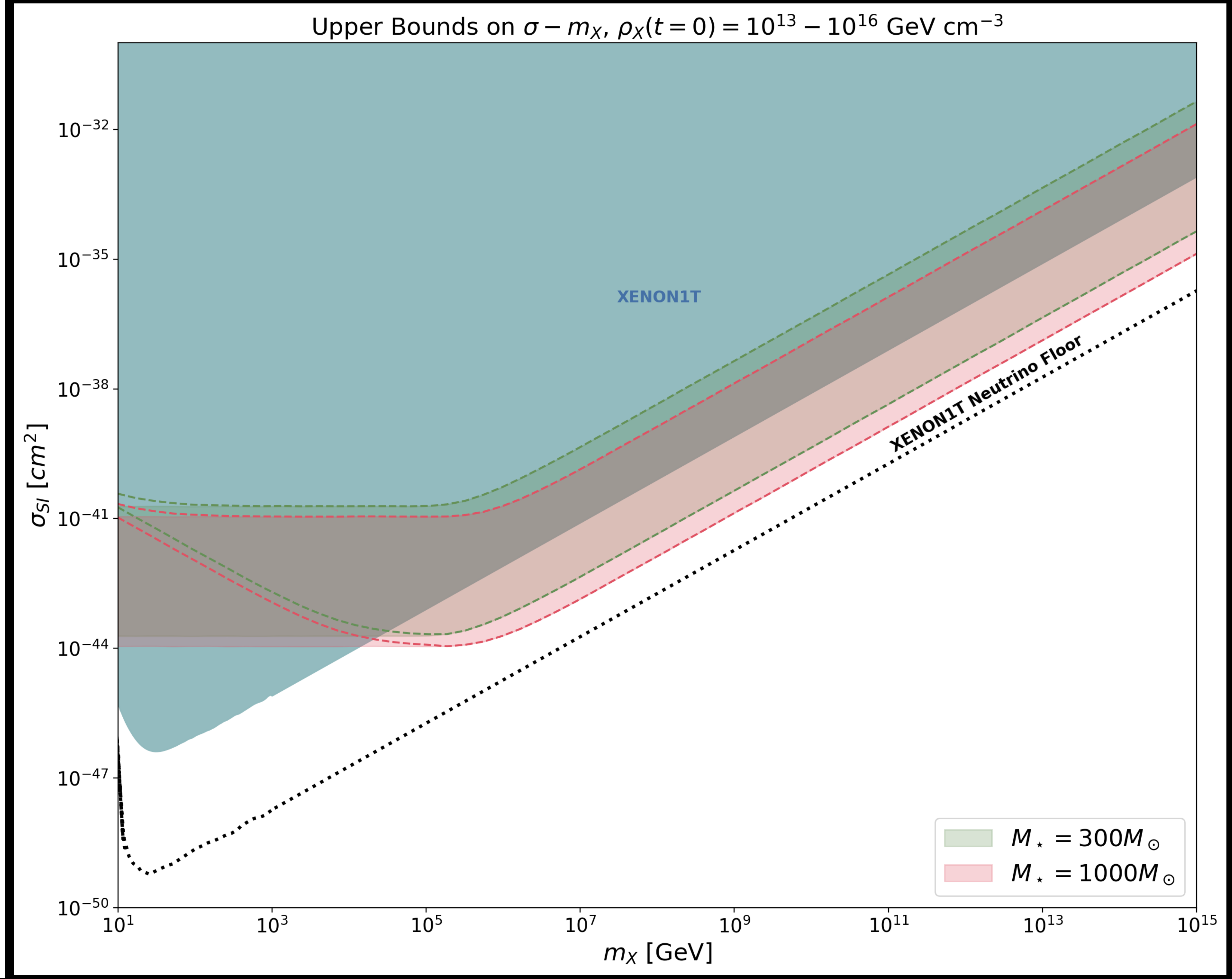
JWST



Roman (WFIRST)

Why are PopIII stars such powerful DM probes?



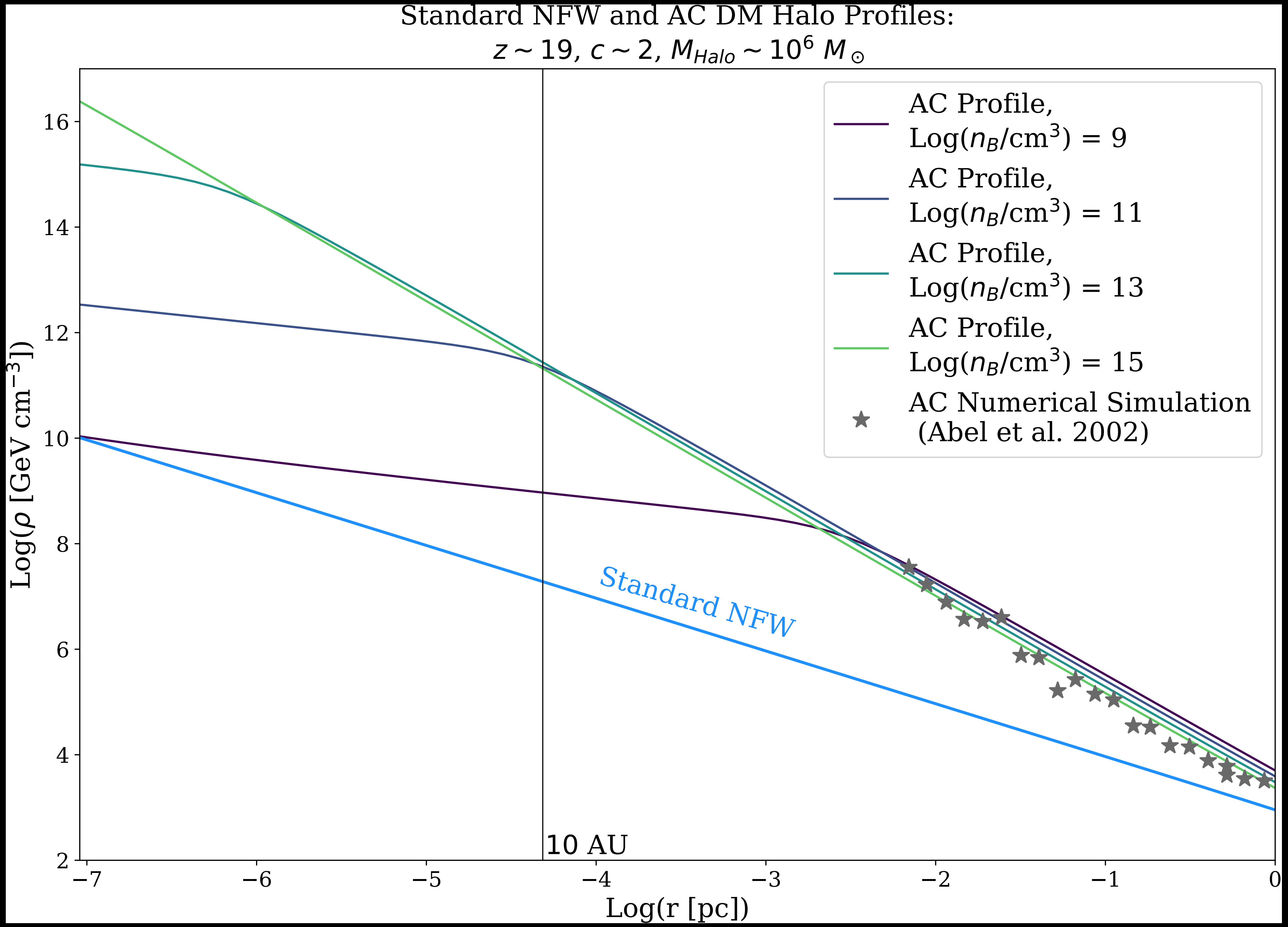


Ilie et al. PhysRevD.104.123031 (2021) (arXiv: 2009.11474)

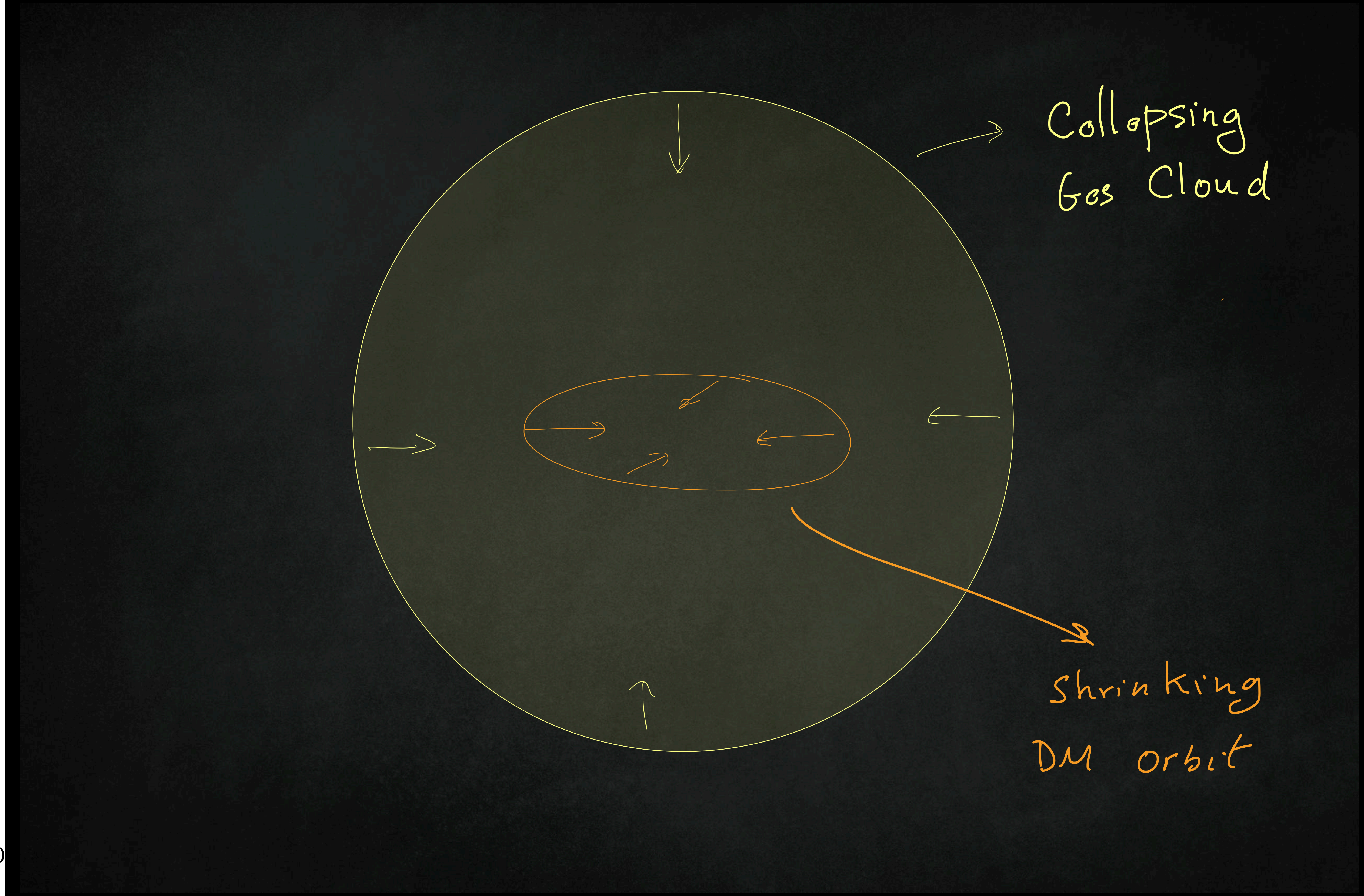
Why are PopIII stars such powerful DM probes?

- They form in very DM rich environments (at the center of high z DM halos)
- They are quite large, and, as such, great Dark Matter “captors”
- They shine close to the Eddington limit even if one includes only nuclear fusion power

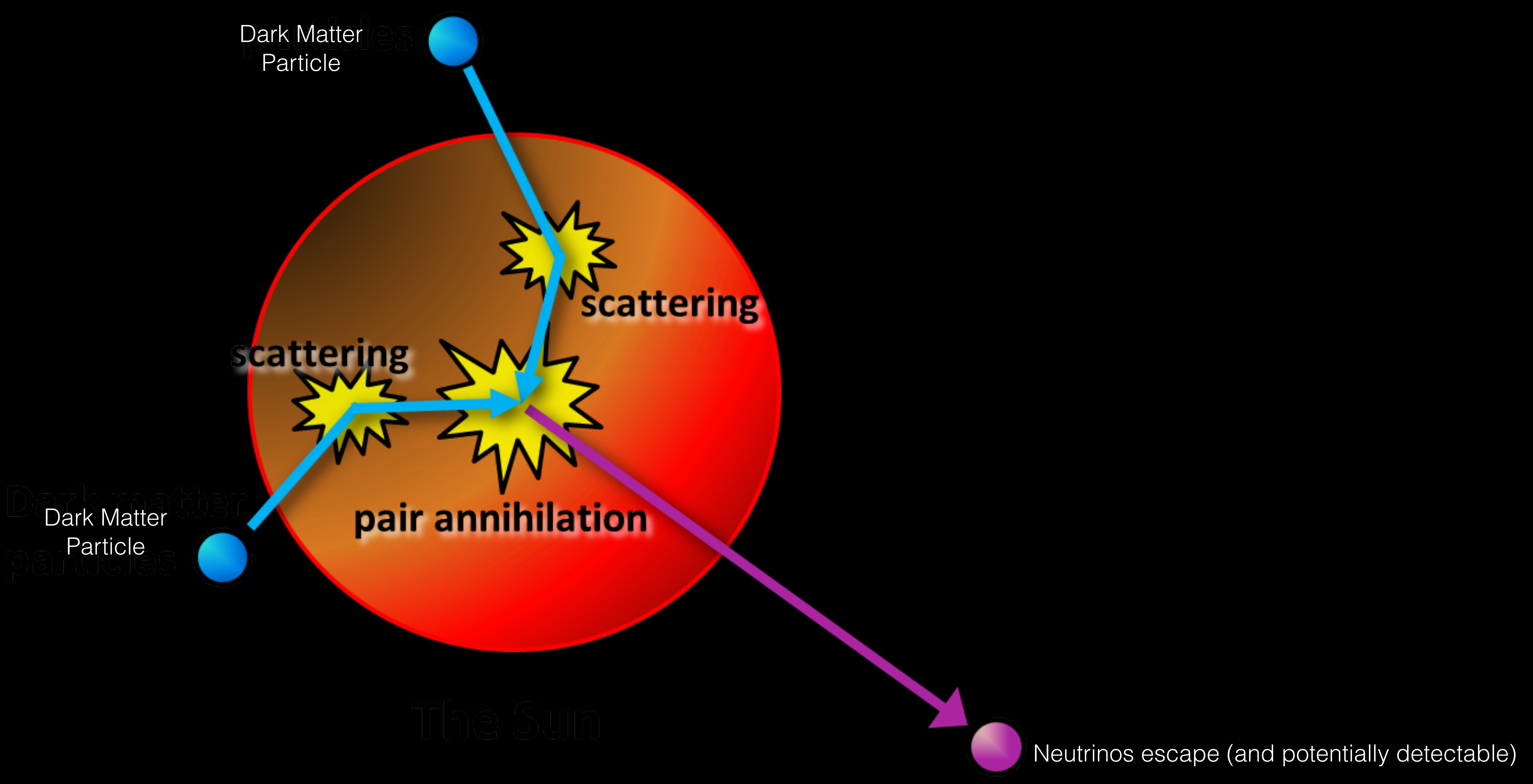
DM Densities enhancement: AdiabaticCompression



Blumenthal AC formalism vs Abel et al Science (2002) Simulation



A Star burning Captured Dark Matter



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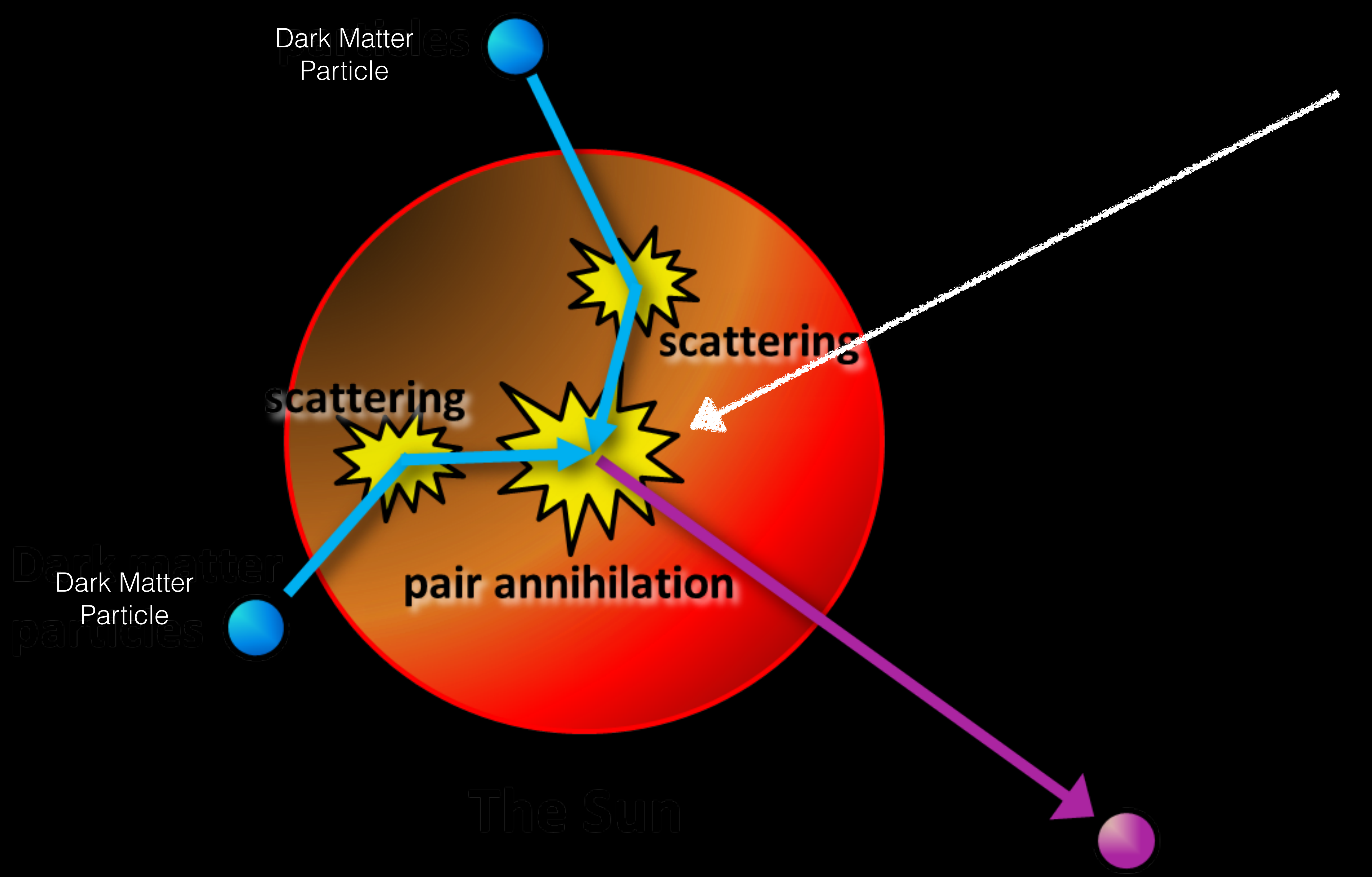

DM Luminosity can increase brightness

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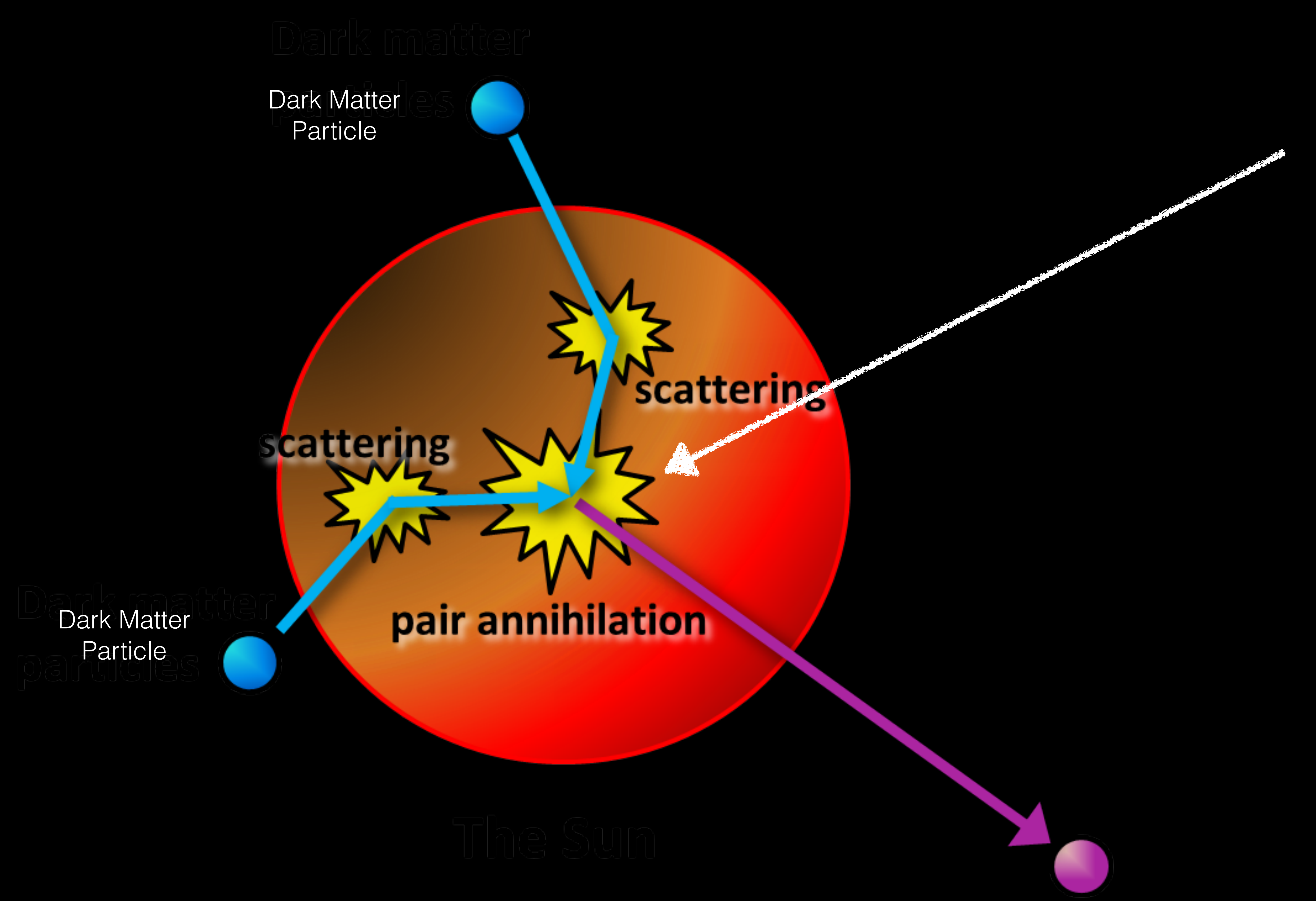
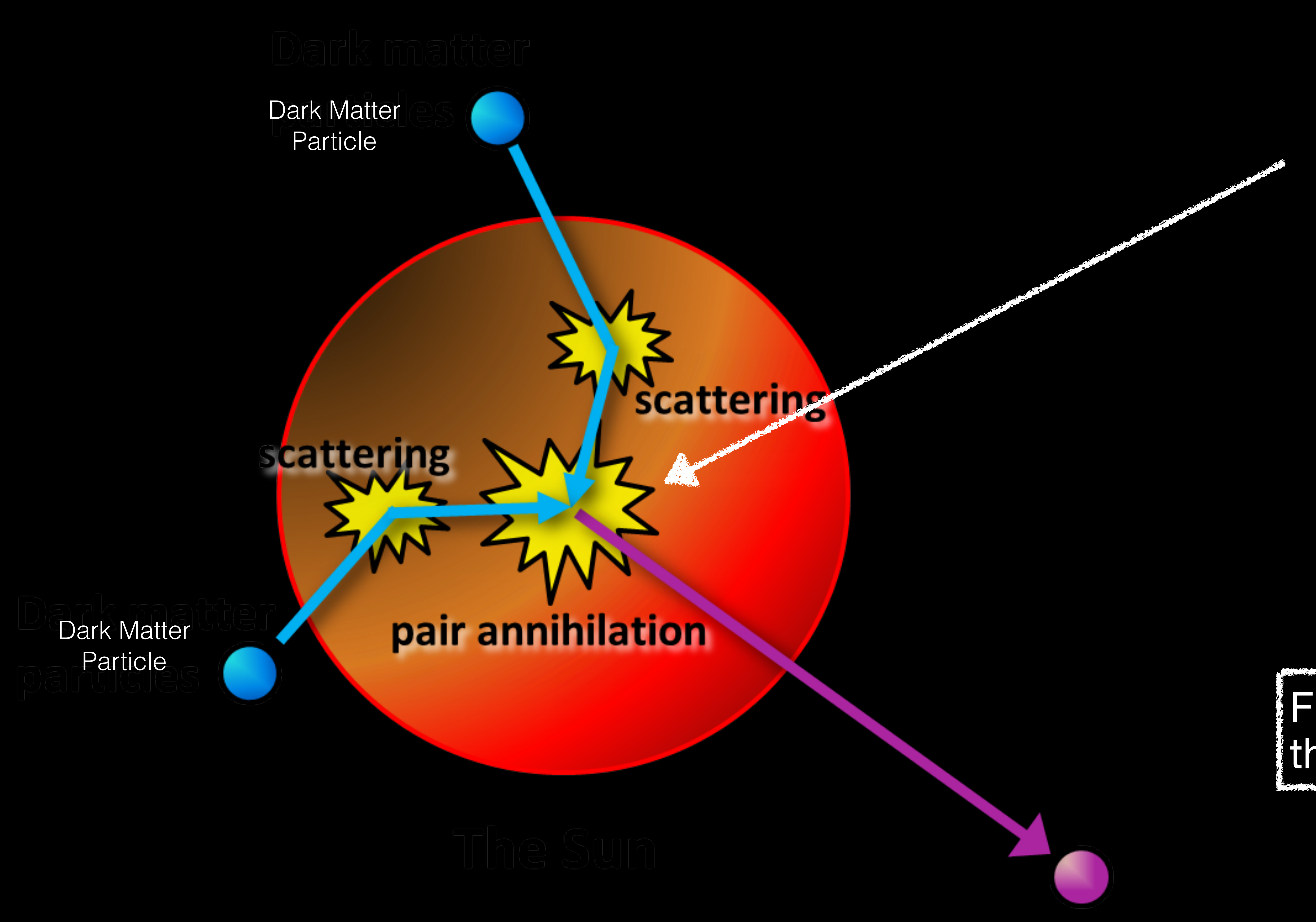


DM Luminosity can increase brightness

$$L_{DM} = f \cdot \Gamma_A \cdot m_X$$

A Star burning Captured Dark Matter



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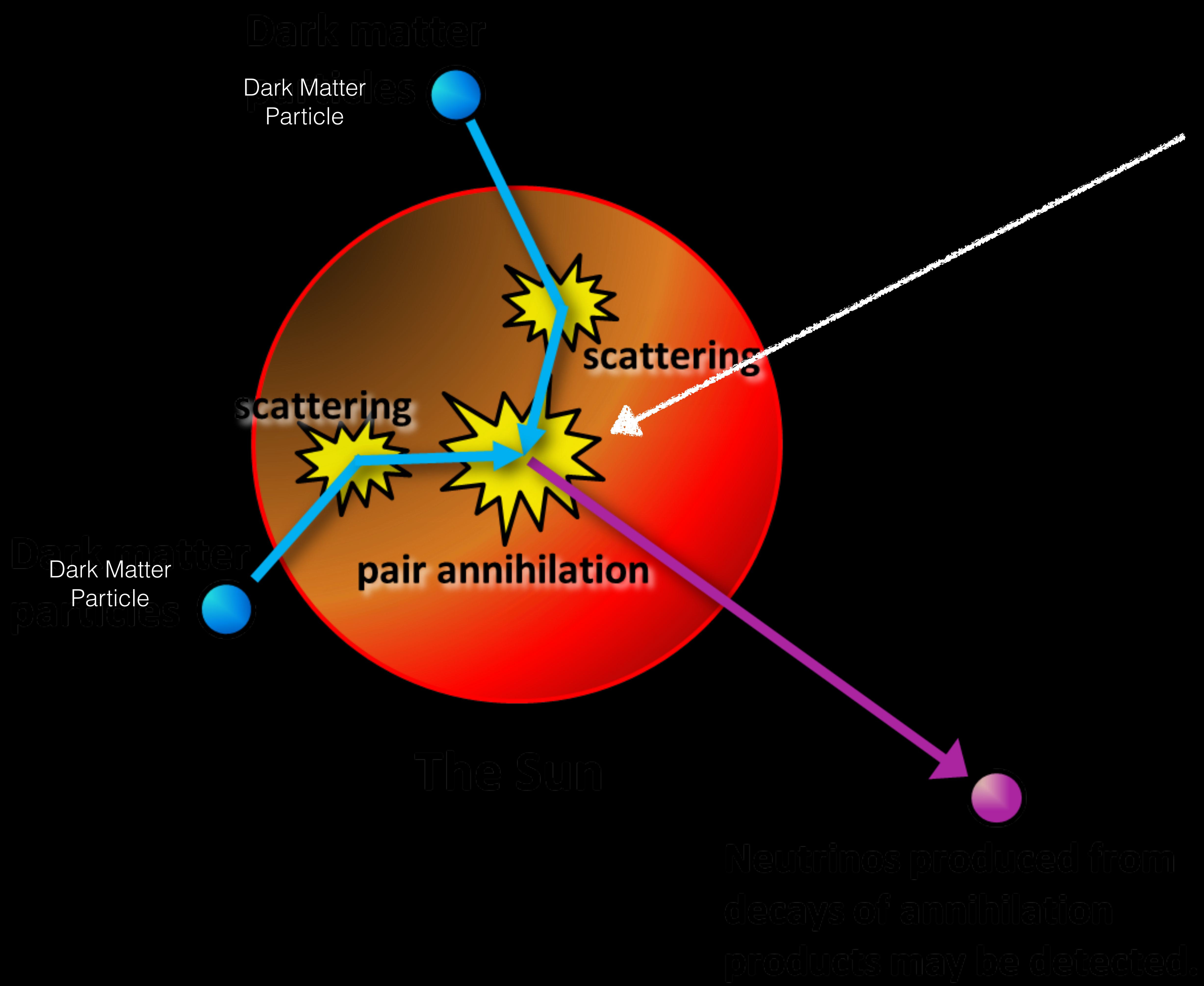
Fraction of annihilation energy deposited inside the star, i.e. not lost to neutrinos.

A Star burning Captured Dark Matter



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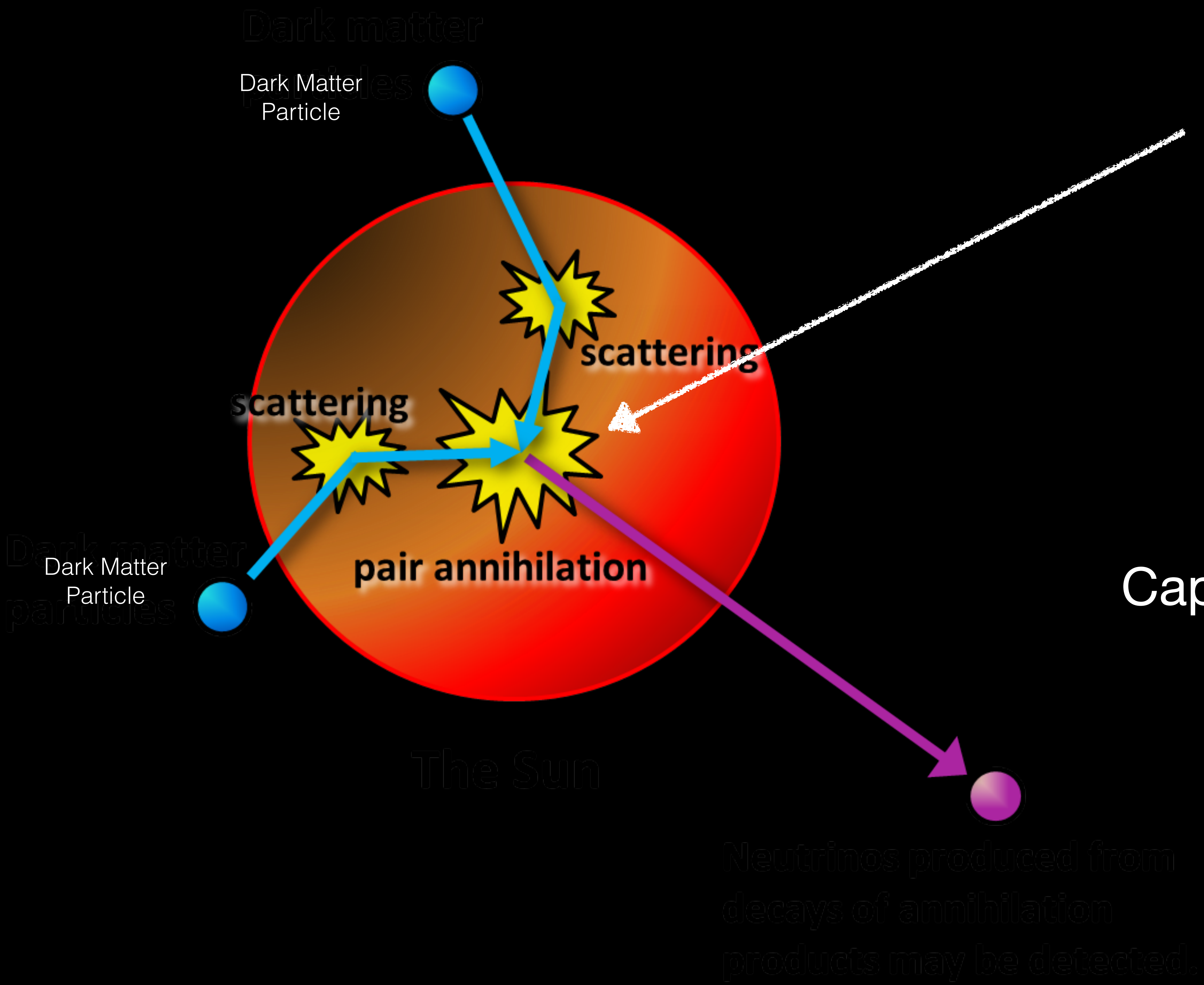
$$L_{DM} = f \cdot \Gamma_A \cdot m_X$$

$$\Gamma_A \xrightarrow[\text{Capture-Annihilation Equilibrium}]{\text{2 Captured DM annihilated each event}} \frac{C}{2}$$

A Star burning Captured Dark Matter



DM Luminosity can increase brightness

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Capture & Annihilation | Equilibrium

$$L_{DM} \propto C_{tot} \propto \sigma \times \rho_X$$

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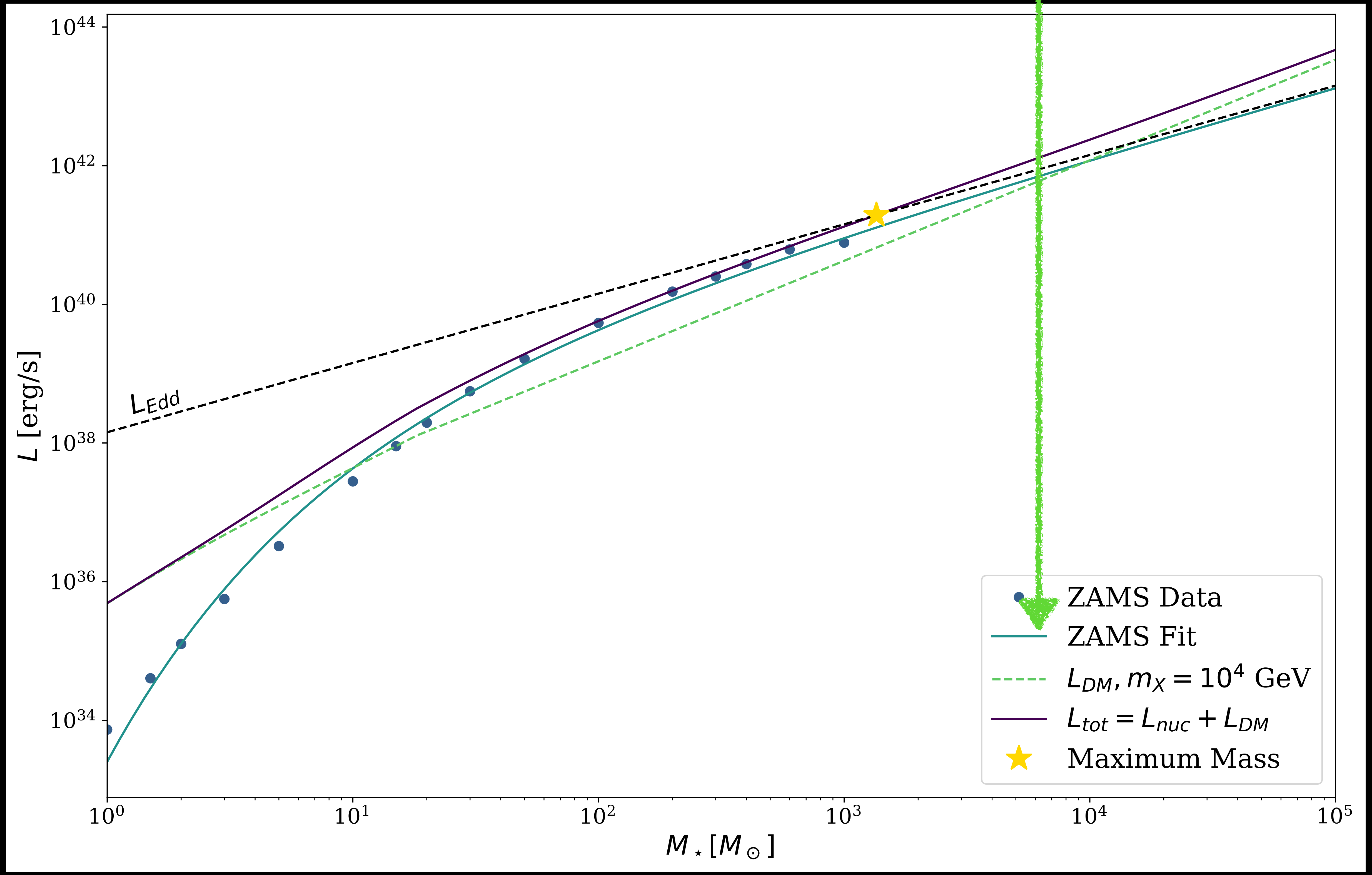

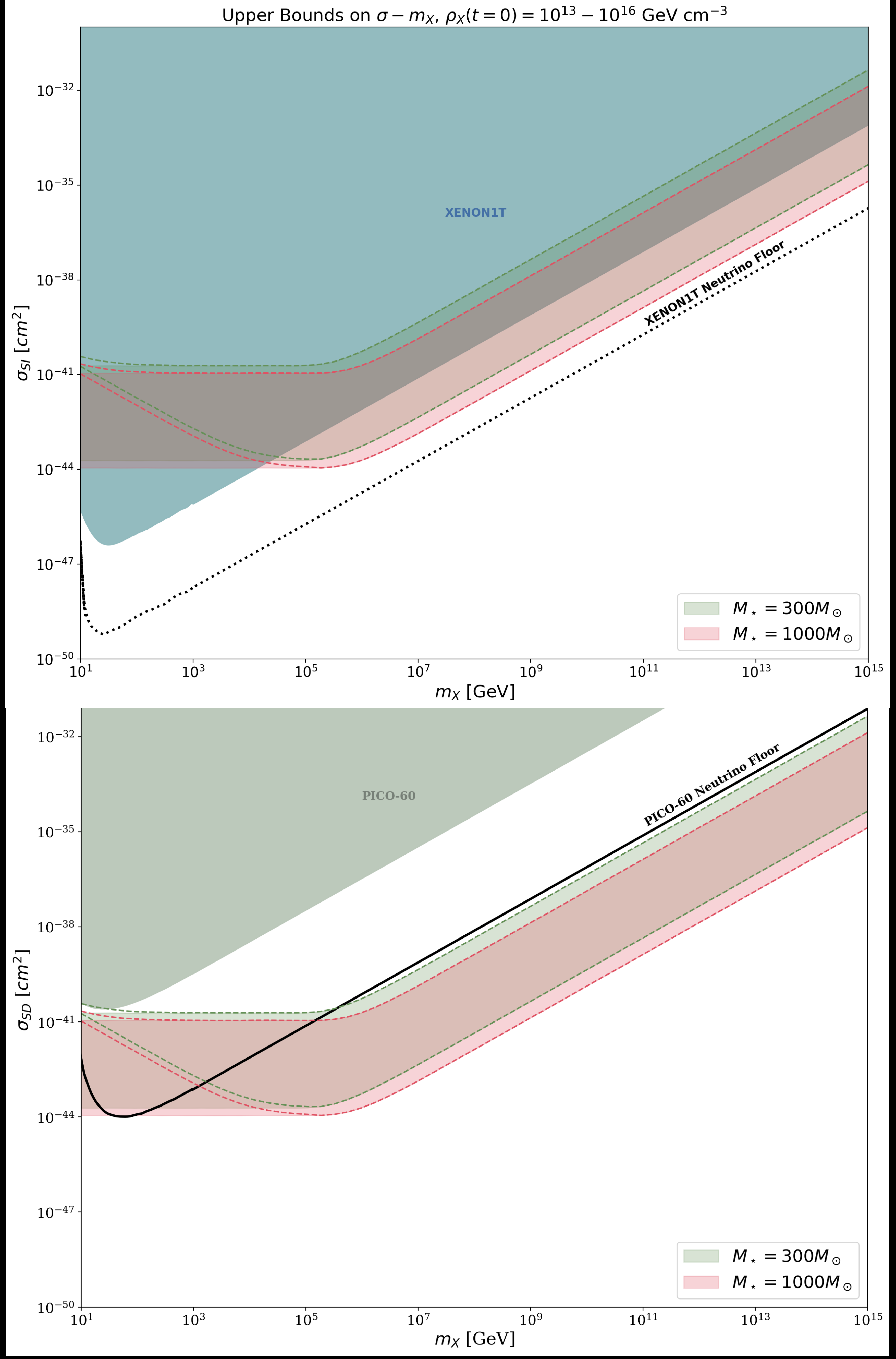

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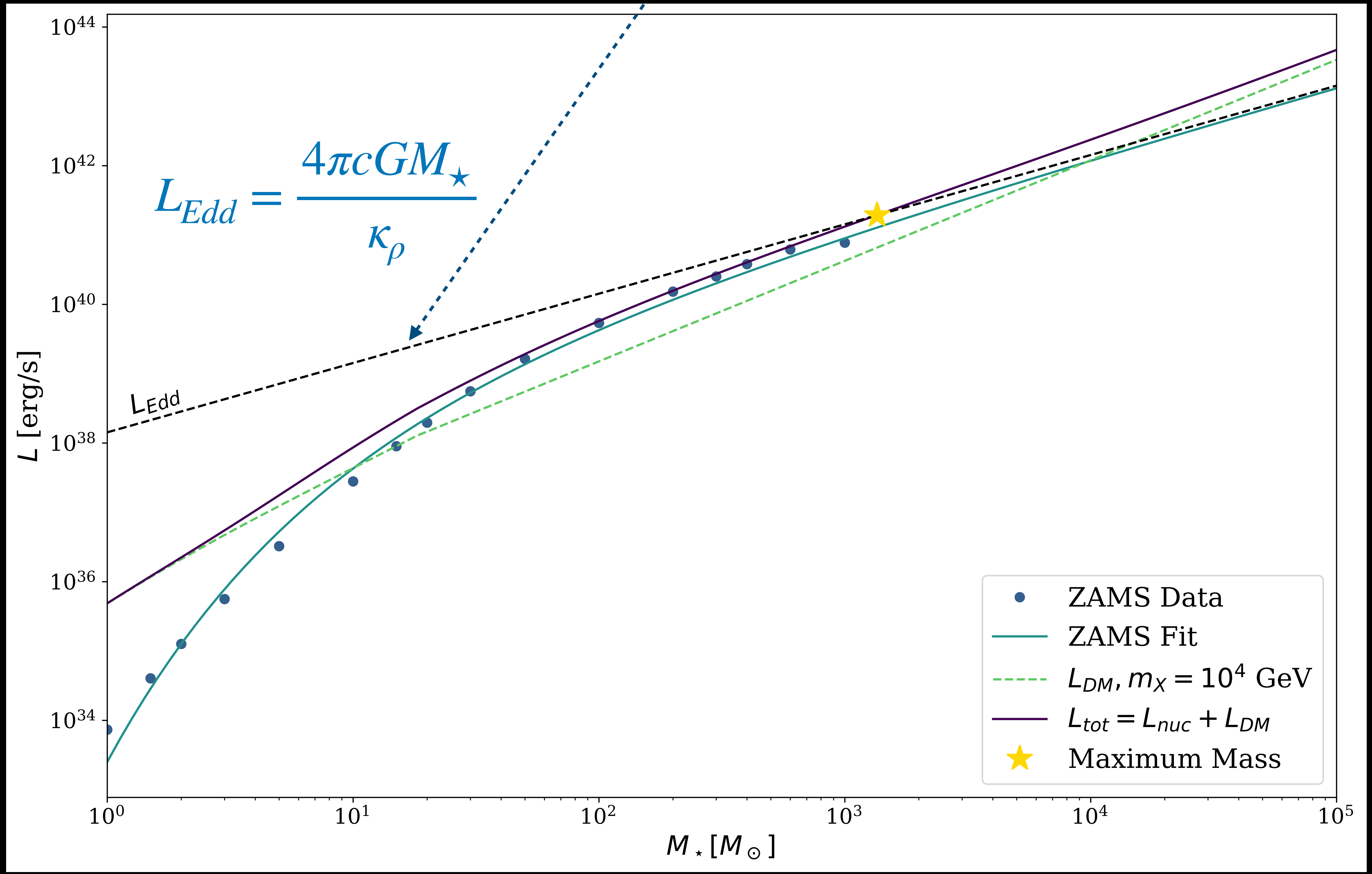

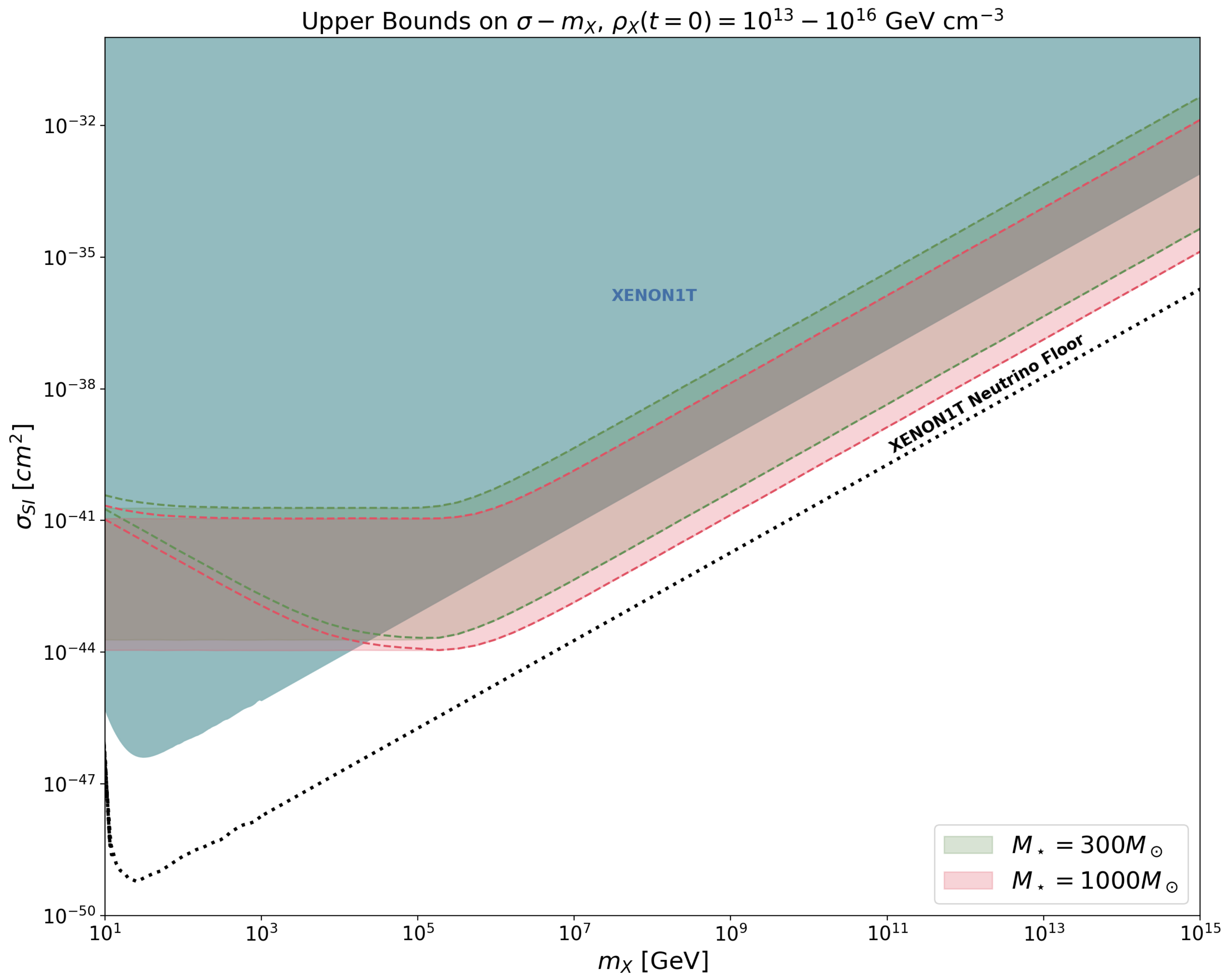

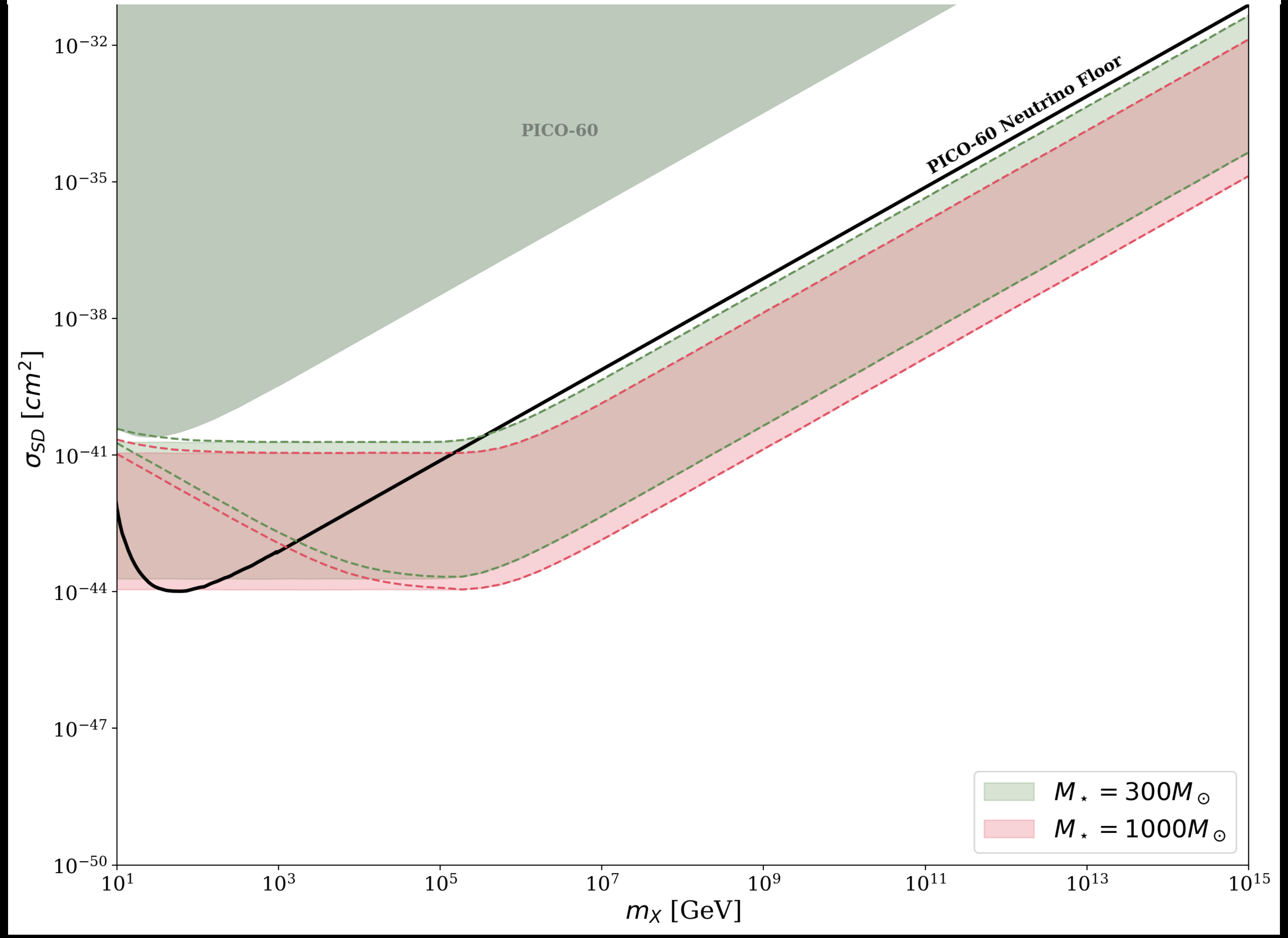

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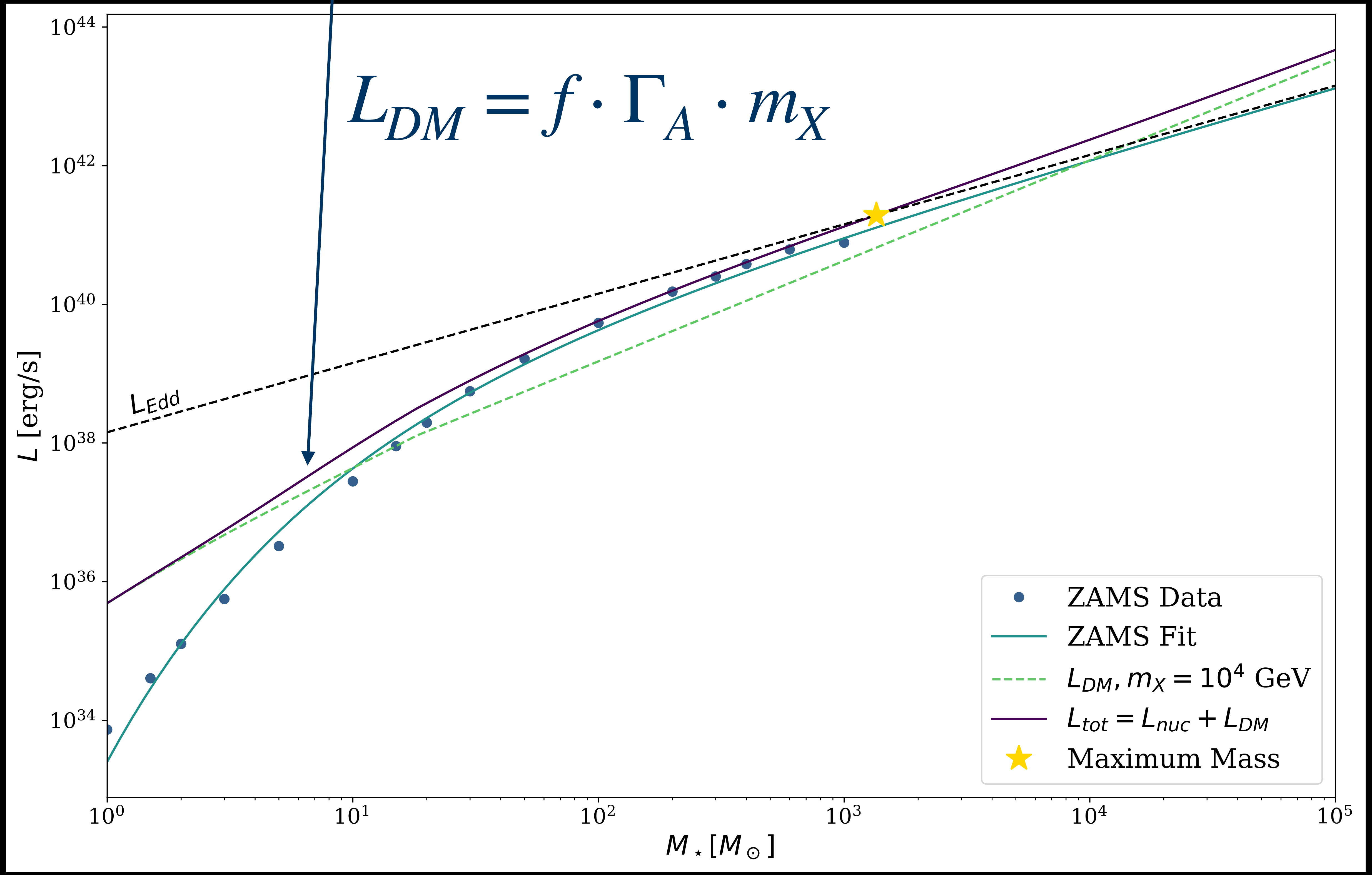

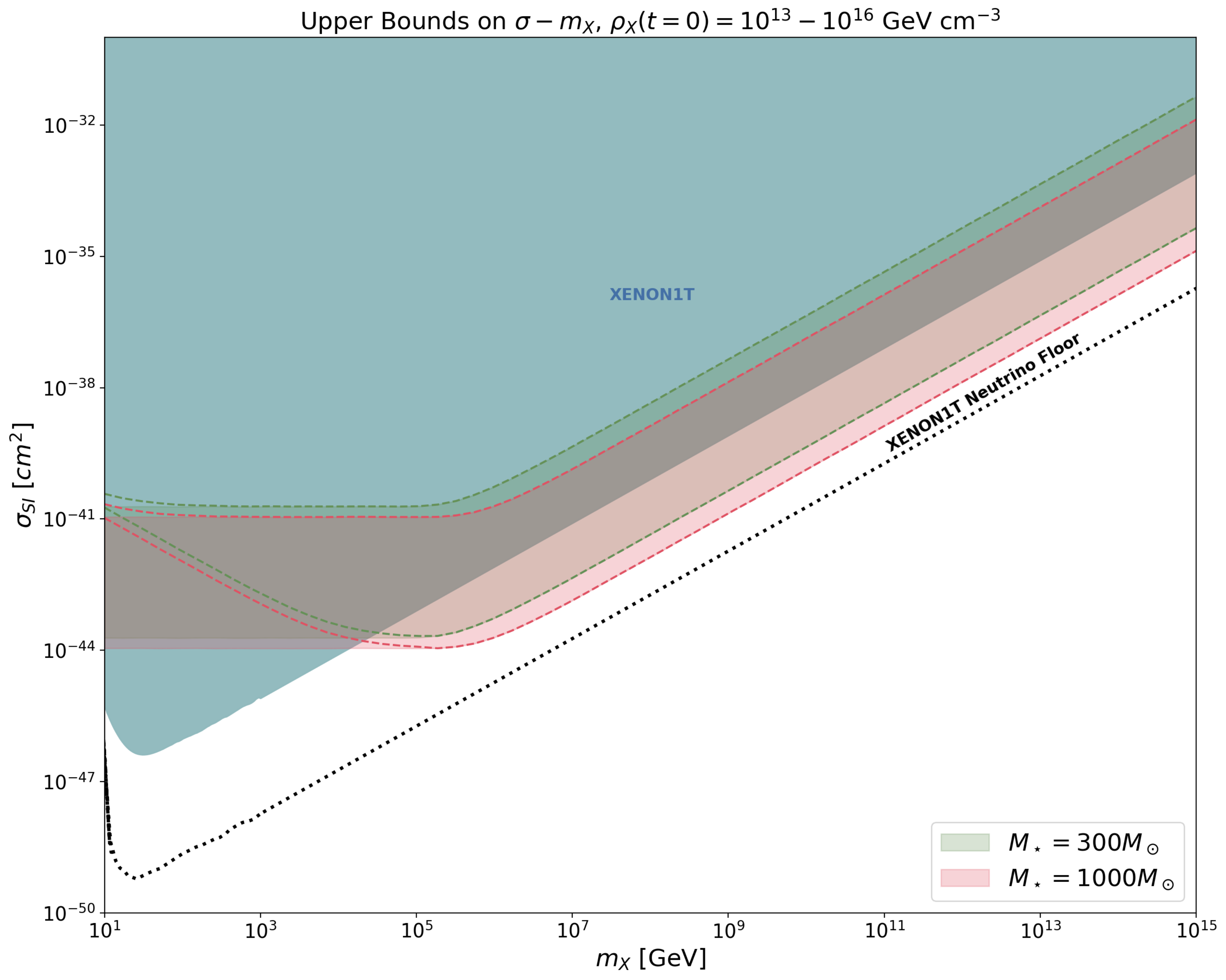

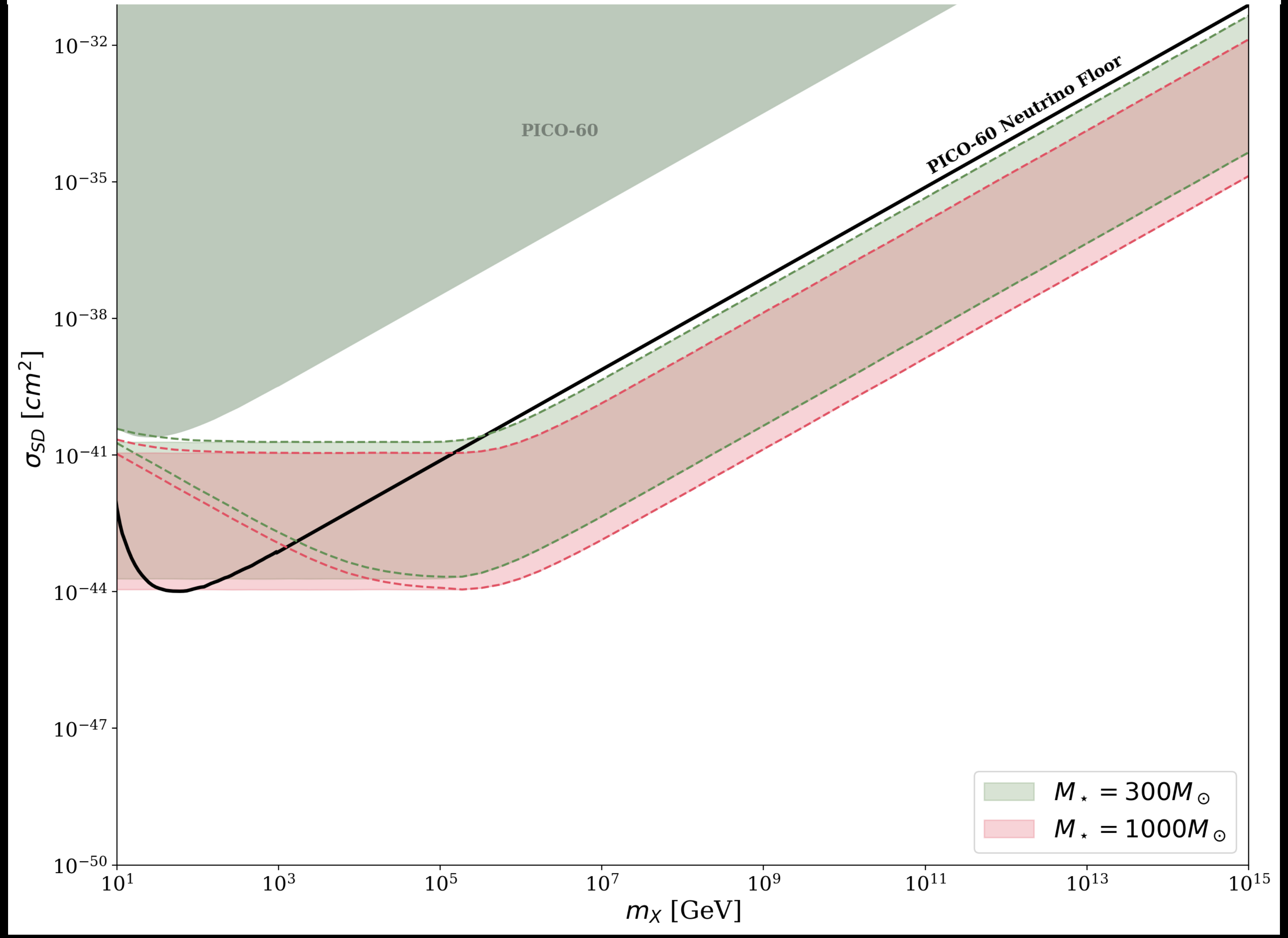

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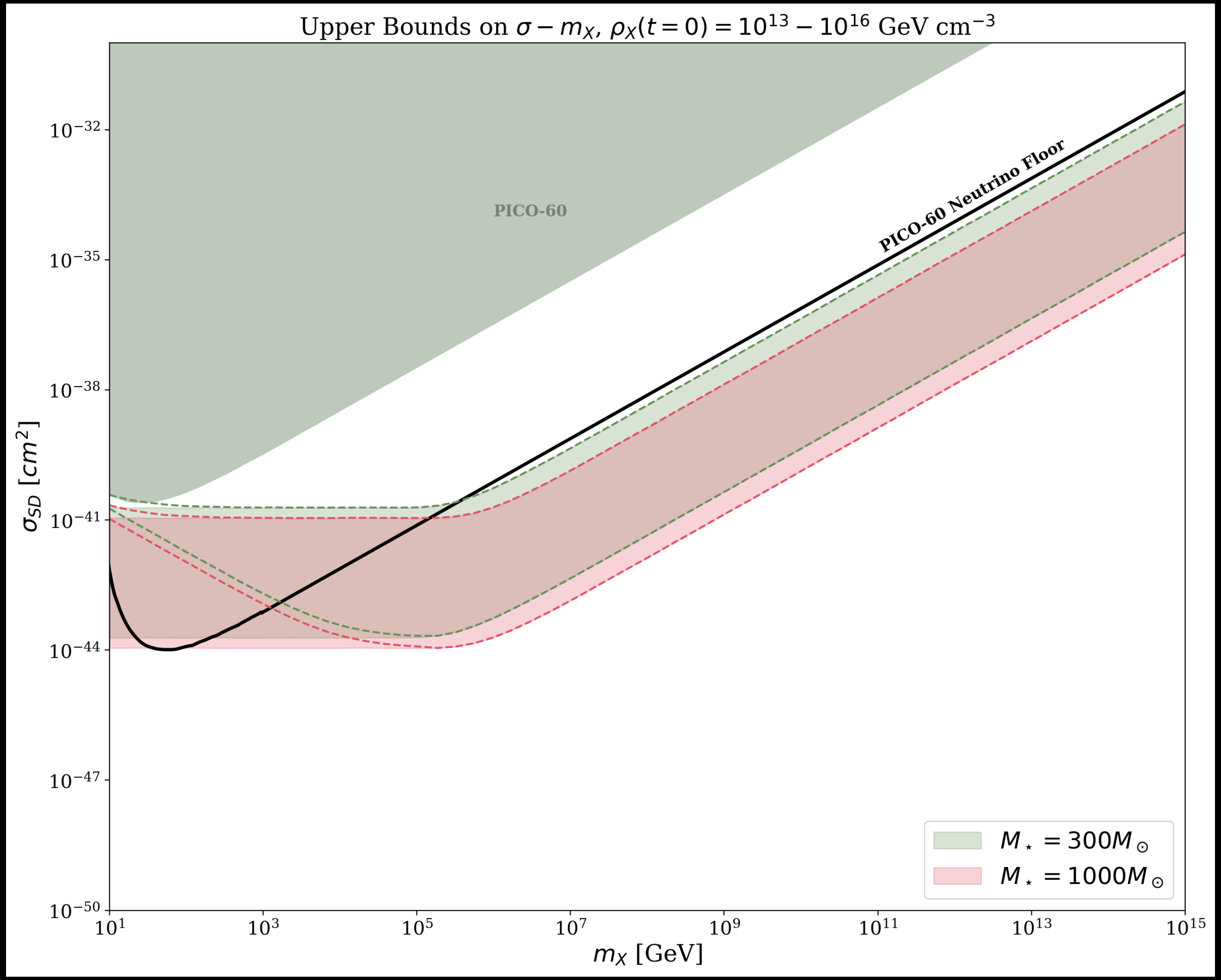
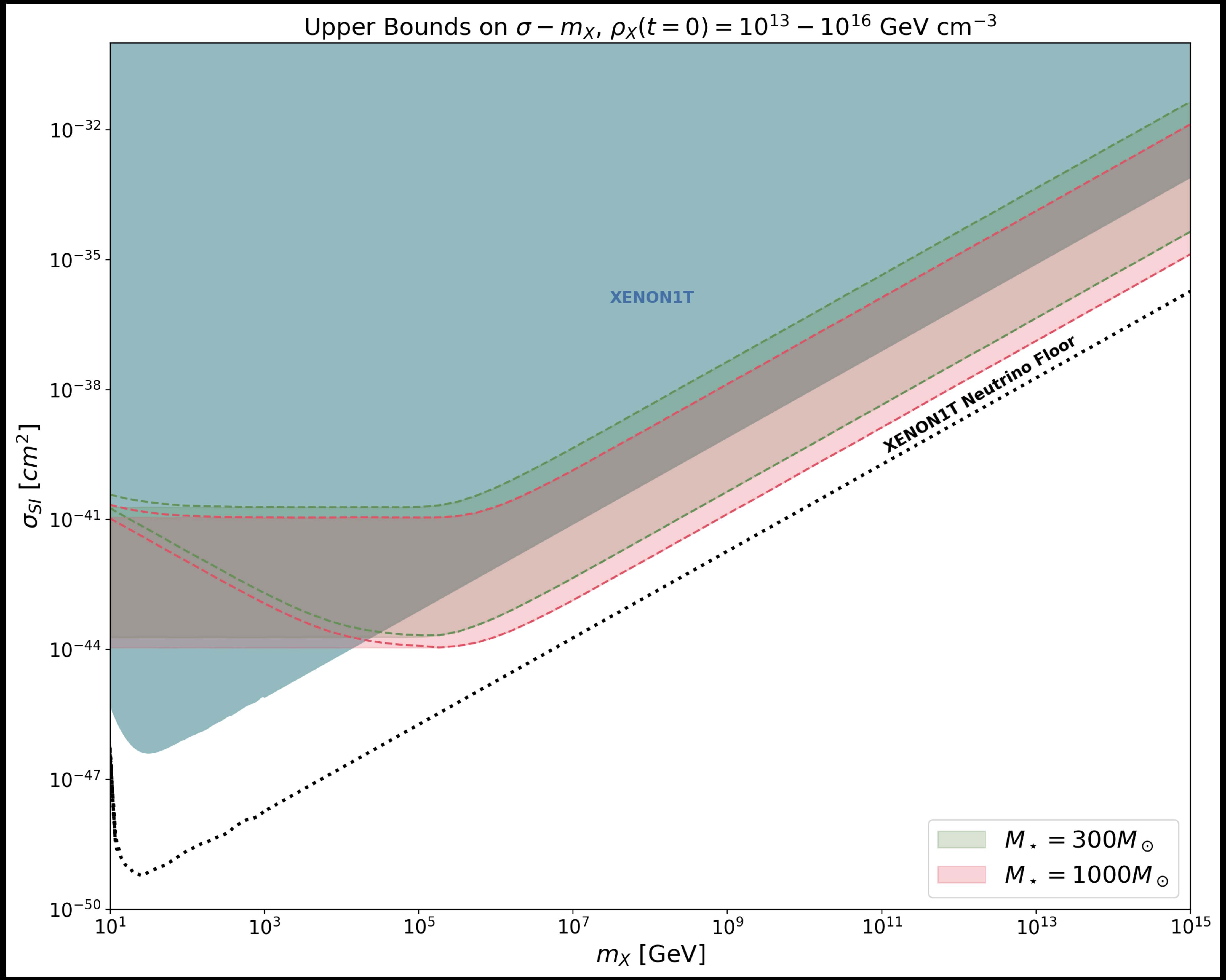
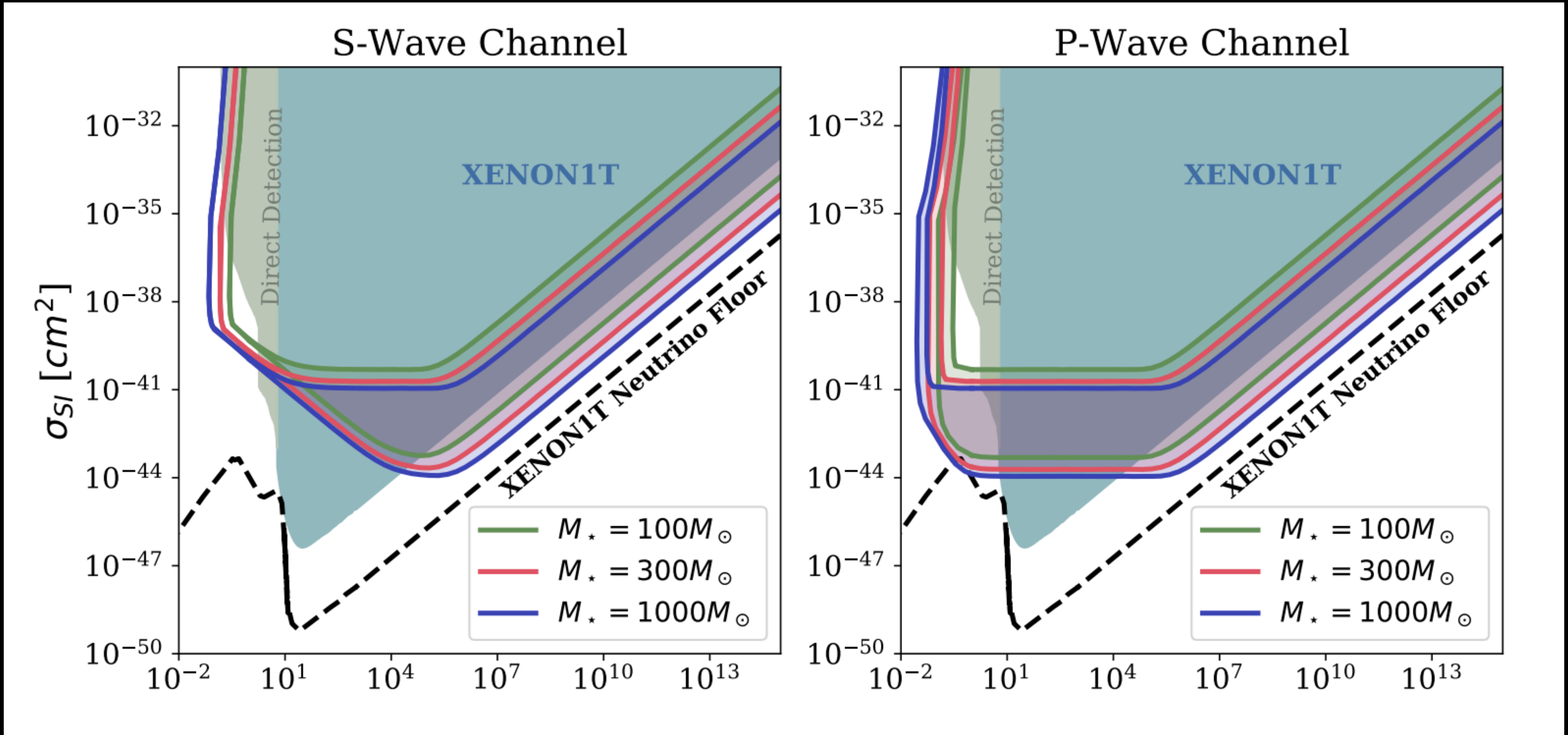




Sub GeV WIMP DM regime?



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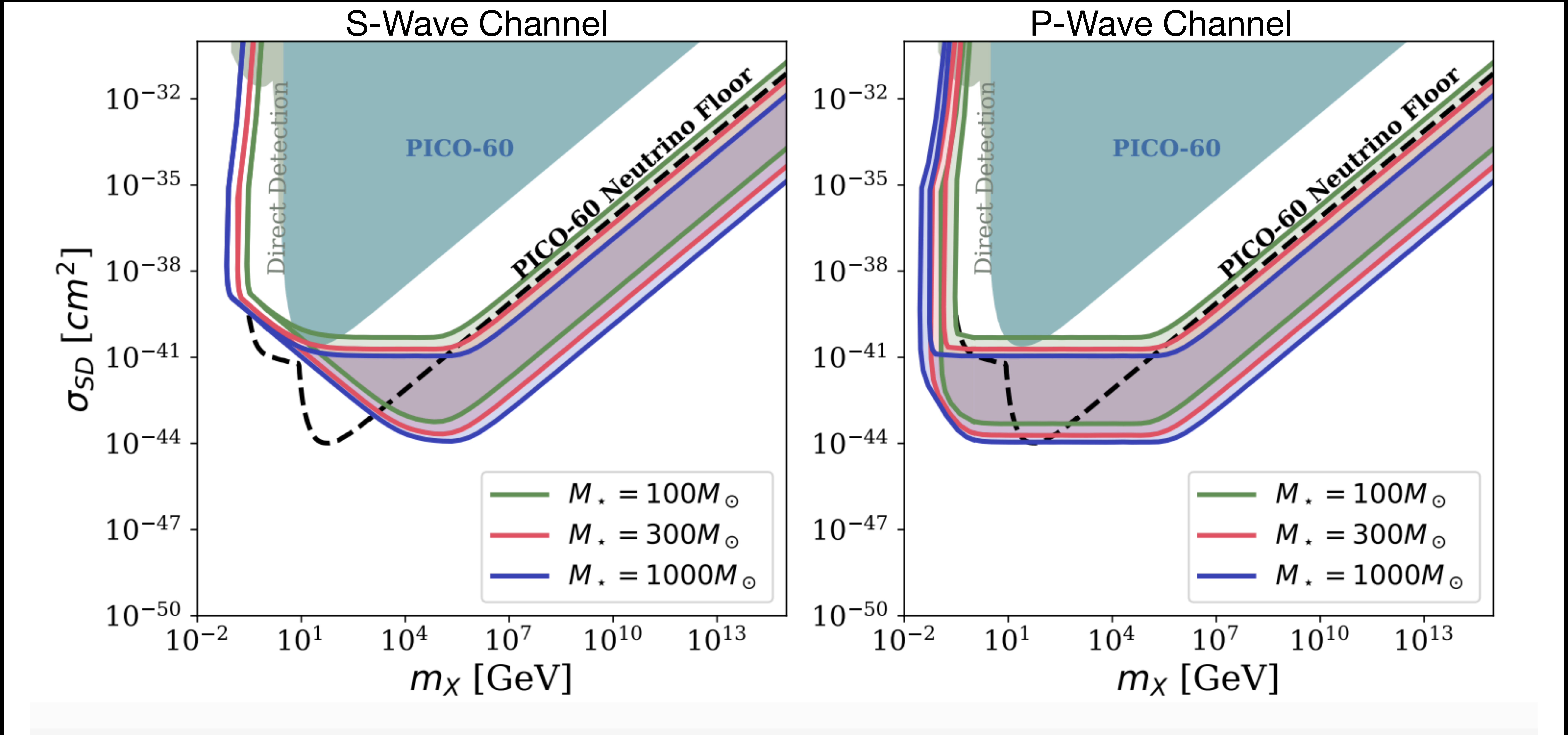
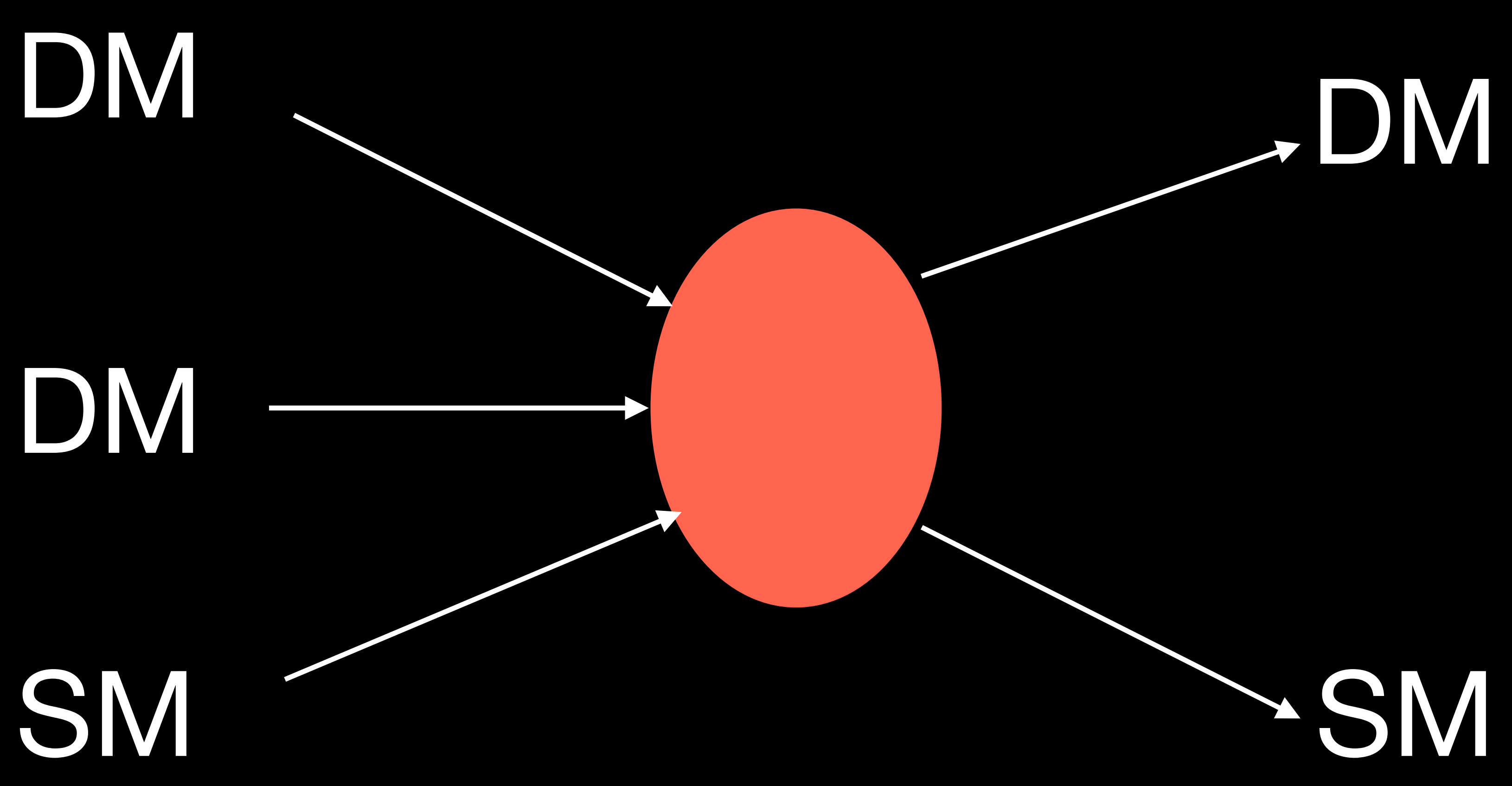


Other sub GeV DM Models

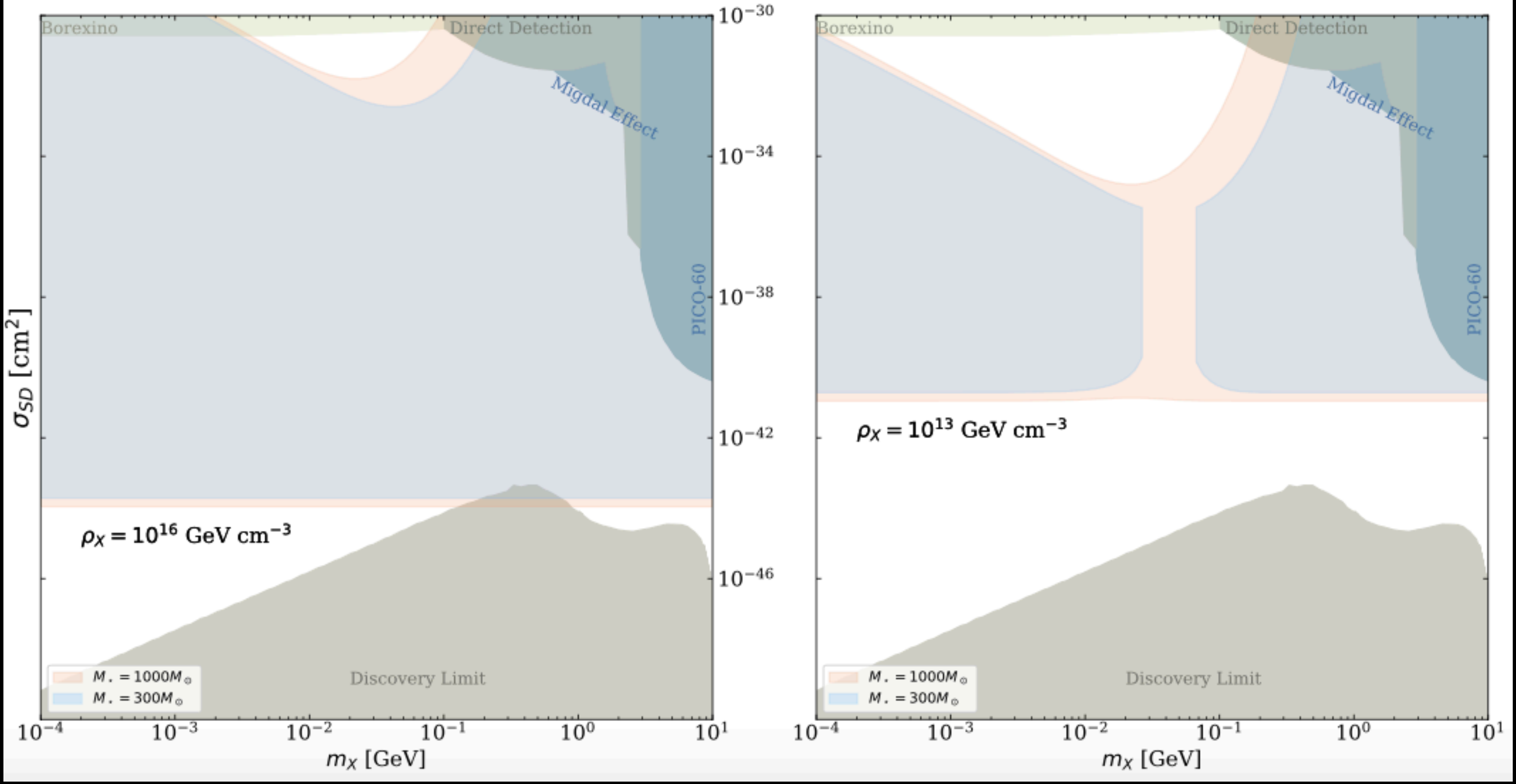


$$\langle \sigma_{CoSIMP} v^2 \rangle \sim 10^{12} \left(\frac{\text{MeV}}{m_X} \right)^3 \left(\frac{0.12}{\Omega_X h^2} \right)^2 \text{GeV}^{-5}$$

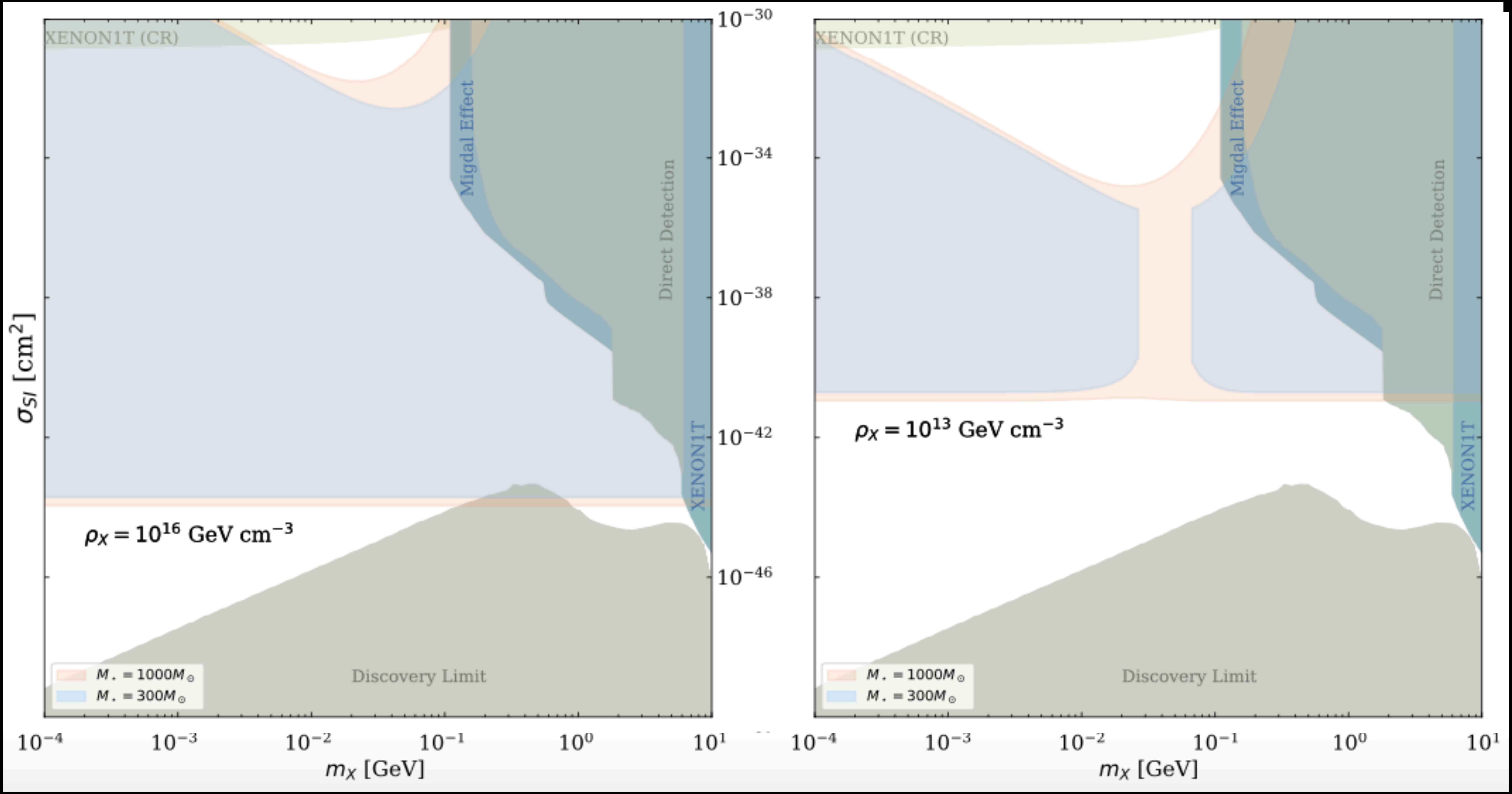
CoSIMP DM

J. Smirnov and J. Beacom PRL 125 (2020)

SD Bounds on Co-SIMP sub GeV DM



SI Bounds on Co-SIMP sub GeV DM



Summary for PopIII stars as DM probes

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- If/when direct detection finds σ our method can be used to constrain ρ_X (i.e. the DM density at the center of z>10 DM halos)

Summary for PopIII stars as DM probes

- If observed in isolation they immediately place a constraint on $\rho_X \cdot \sigma$
- We assume ρ_X is adiabatically contracted to obtain (forecast) bounds on σ
- If/when direct detection finds σ our method can be used to constrain ρ_X
- PopIII stars can probe below the neutrino floor of SD experiments
- PopIII stars are excellent sub-GeV DM probes

Conclusion for PopIII stars as DM probes

- PopIII stars could tell us about what DM cannot be

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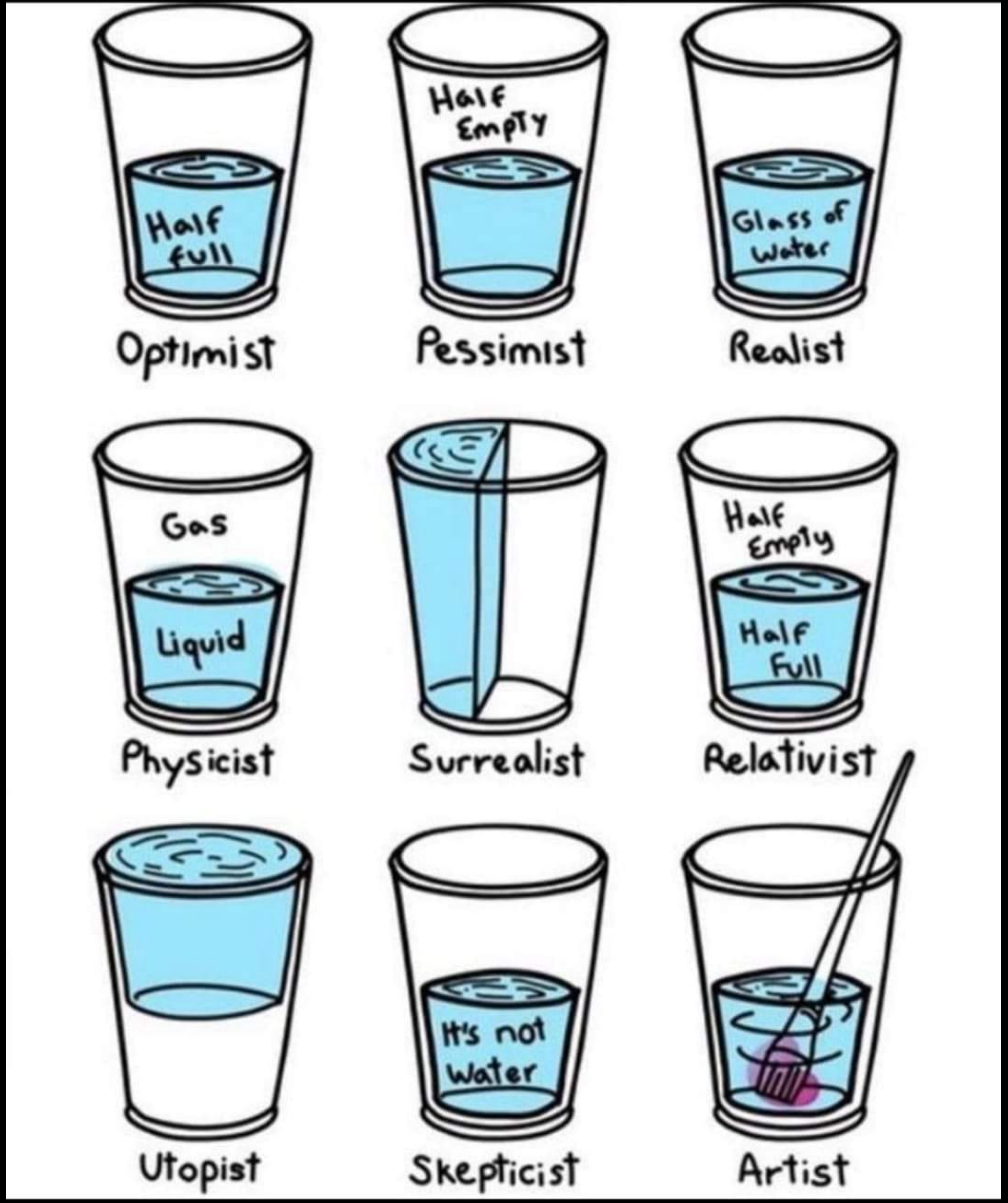

The first Stars, bird's-eye view

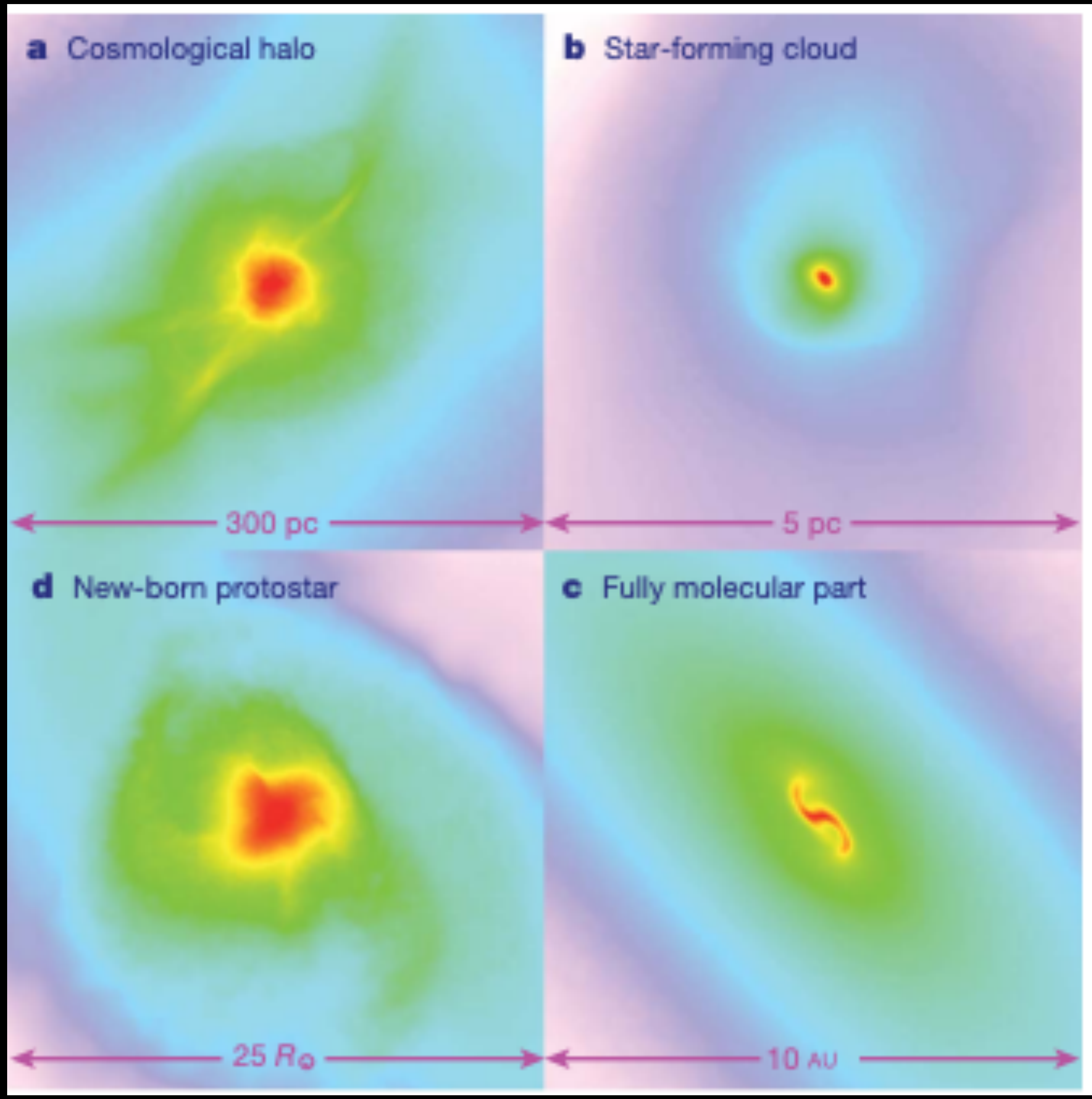

Figure From: Bromm et al. Nature 459 (2009)

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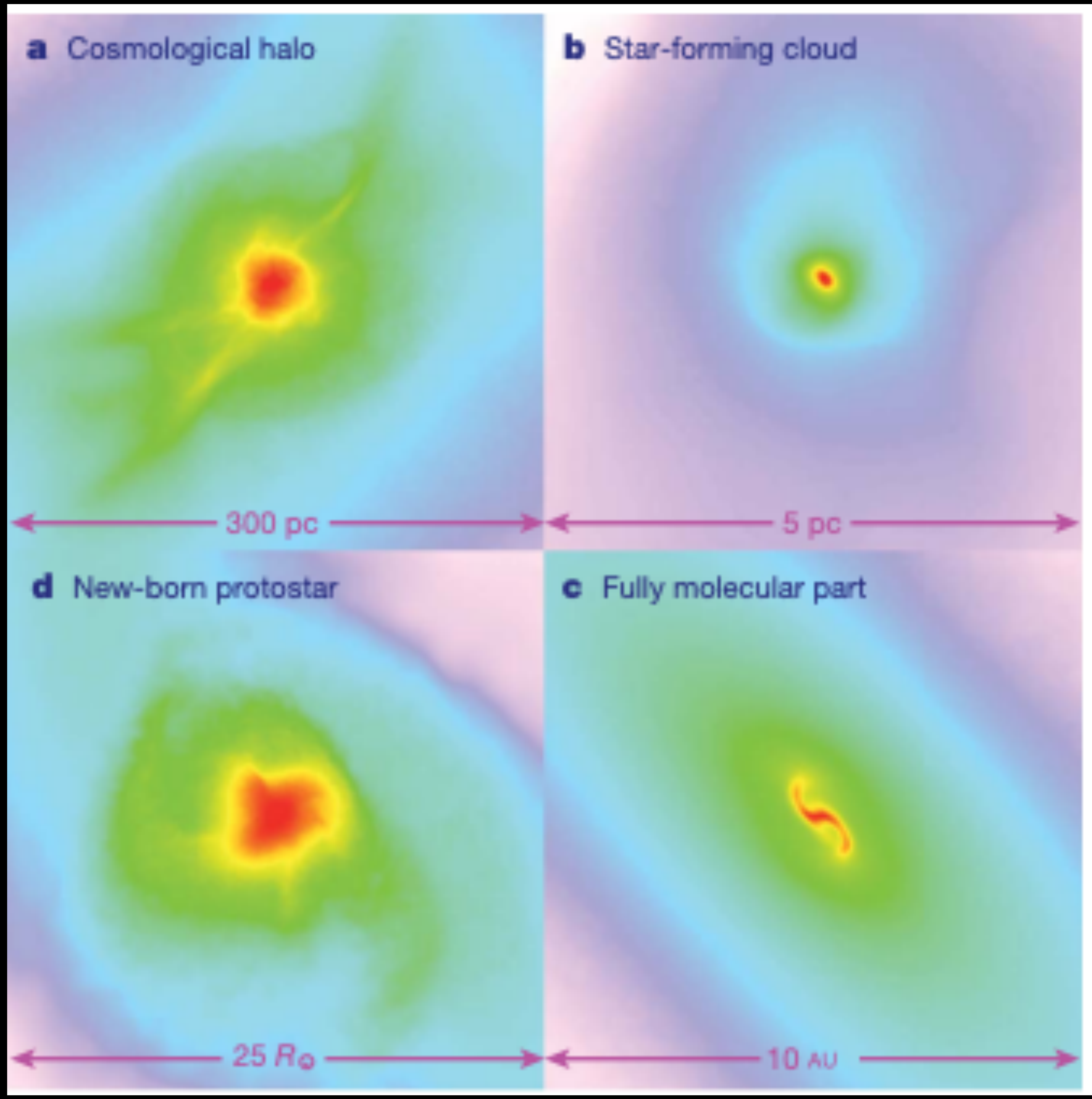

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- The form at high redshift (z~10-40) from pristine BBN H and He gas
- In very DM rich environments, at the center of DM microhalos
- Usually in isolation, or with few companions
- DM annihilations can lead to formation of Dark Stars (DS) powered solely by DM annihilations [Spolyar, Freese, Gondolo PRL 2007]

The three conditions for the formation of a Dark Star

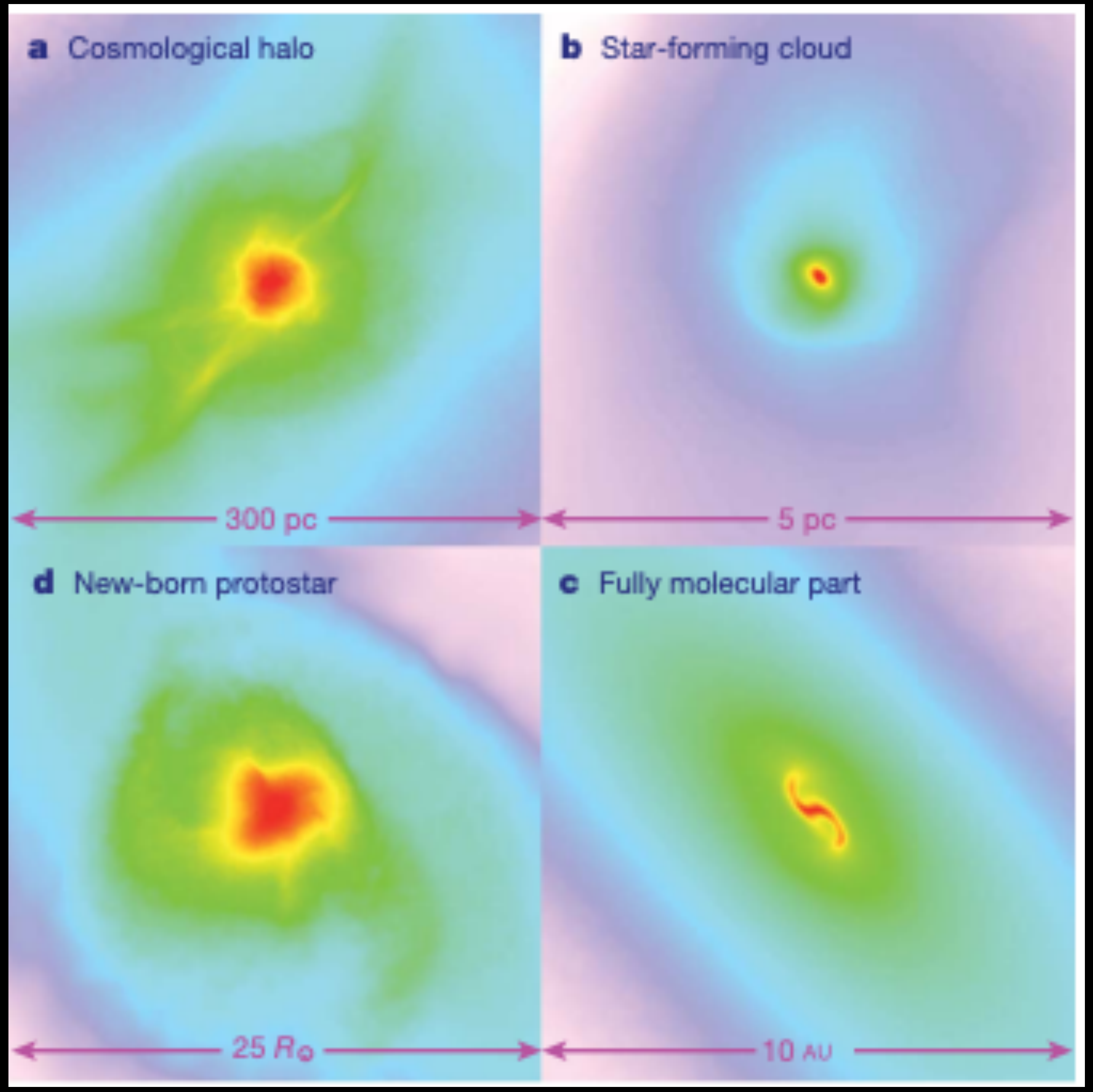
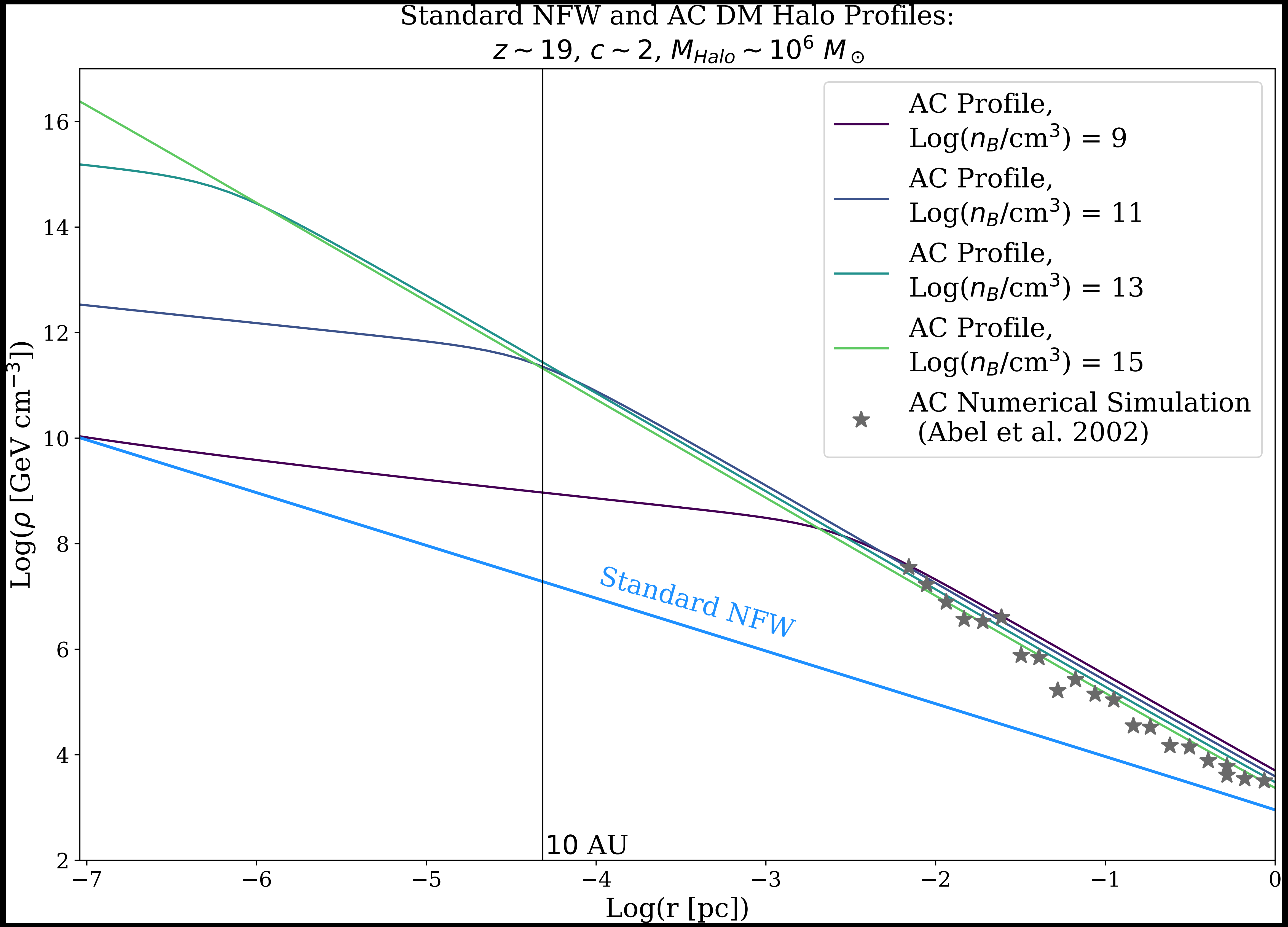
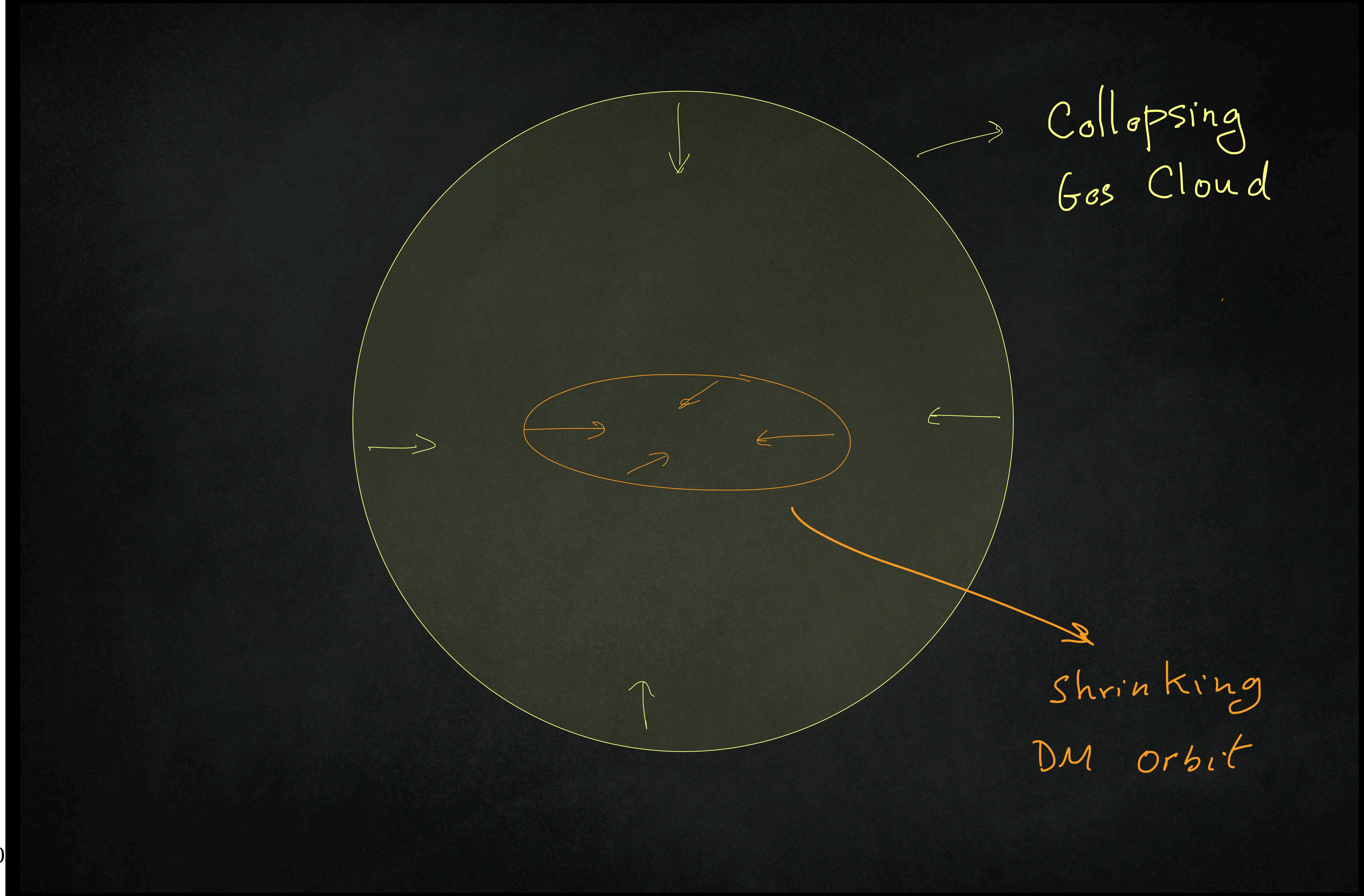


Figure From: Bromm et al. Nature 459 (2009)

- Sufficiently high DM densities
- Poor cooling mechanisms for the collapsing molecular cloud
- DM annihilation products can thermalize efficiently with the baryons in the cloud

DM Densities at the location of the first stars (Adiabatic Compression aka AC)

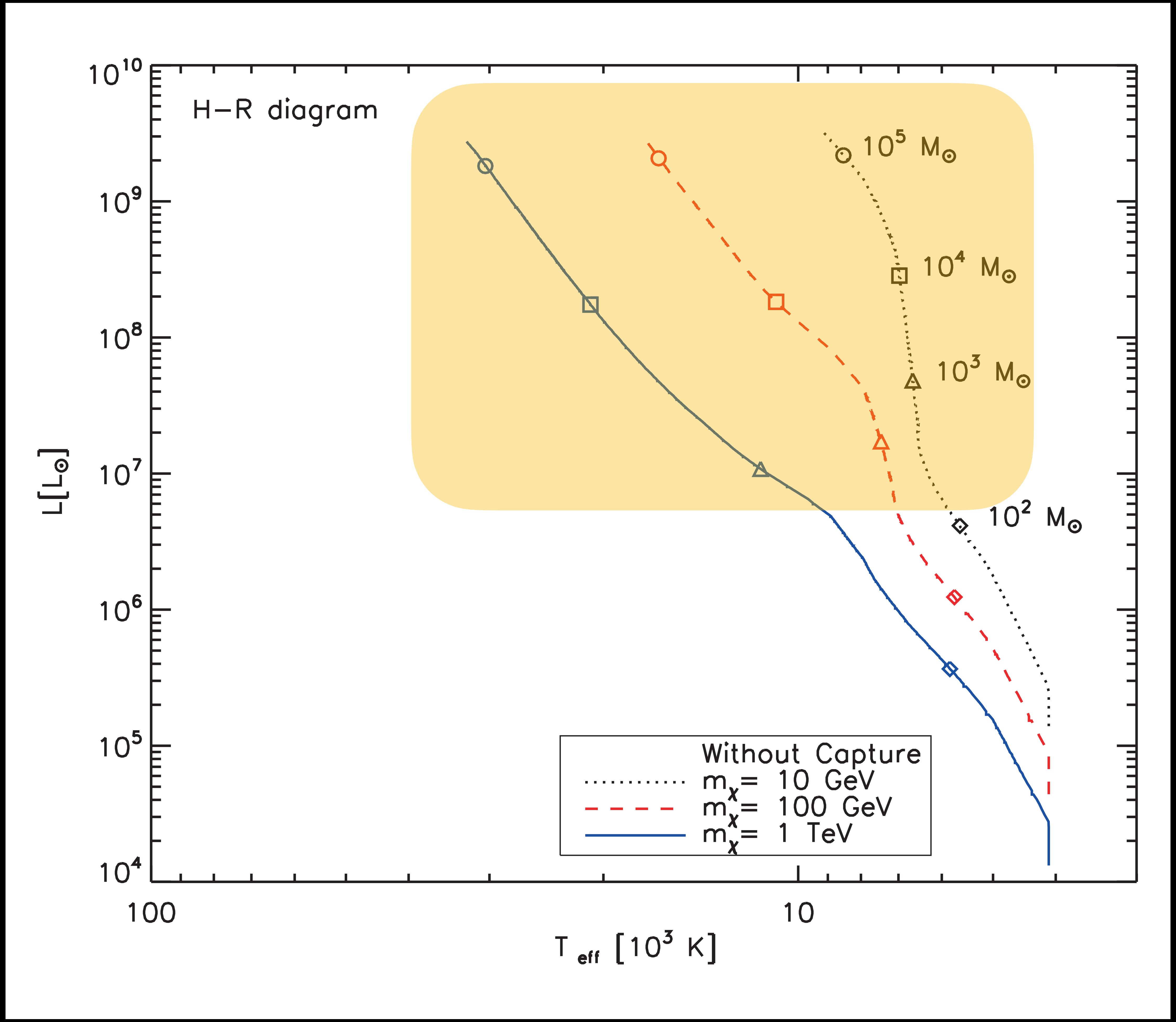




Blumenthal AC formalism vs Abel et al Science (2002) Simulation

Growth of DS to Supermassive Status: via Extended AC

- In triaxial DM halos (expected from simulations) a large population DM orbits are centrophilic (chaotic and box orbits)
- Those orbits can continue to supply DM to provide a heat source for the DS for a prologued time



Freese, CI, Spolyar, et al. 2010 ApJ

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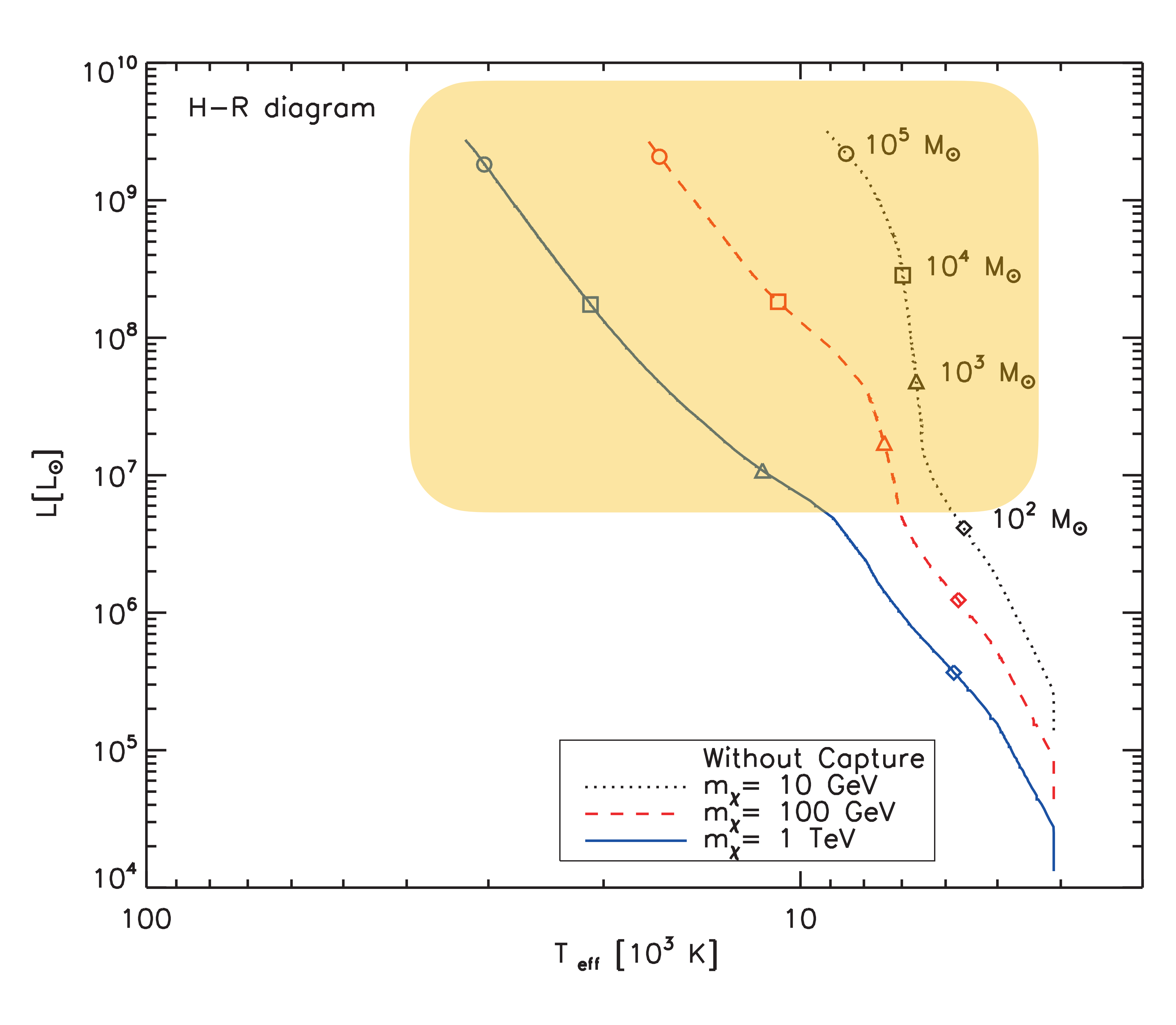
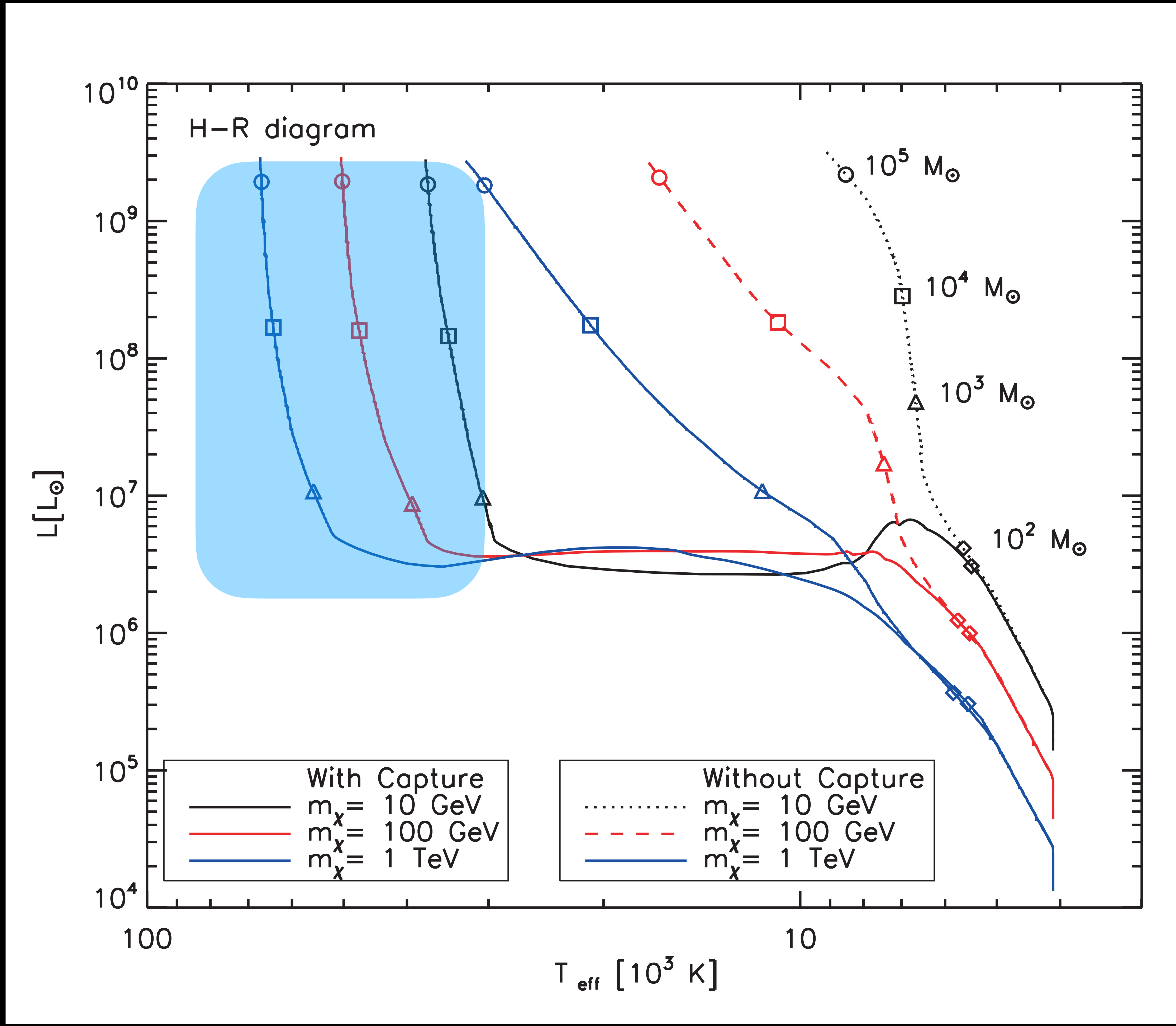
- DS growing via accretion inside a $10^6 M_\odot$ DM halo to reach $M_{SMDS} \sim 10^5 M_\odot$



Freese, CI, Spolyar, et al. 2010 ApJ

Growth of DS to Supermassive Status: via DM capture

- If DM interacts with baryons inside a star it can get trapped (Captured)
- Same basic physics as that exploited by Direct Detection experiments: elastic collisions of DM with nuclei
- Plot on Right for the assumes $\rho_\chi \sigma = 10^{14}$ GeVcm$^{-3} \times 10^{-40}$cm^2



Freese, CI, Spolyar, et al. 2010 ApJ

Observational puzzles SMDS can solve

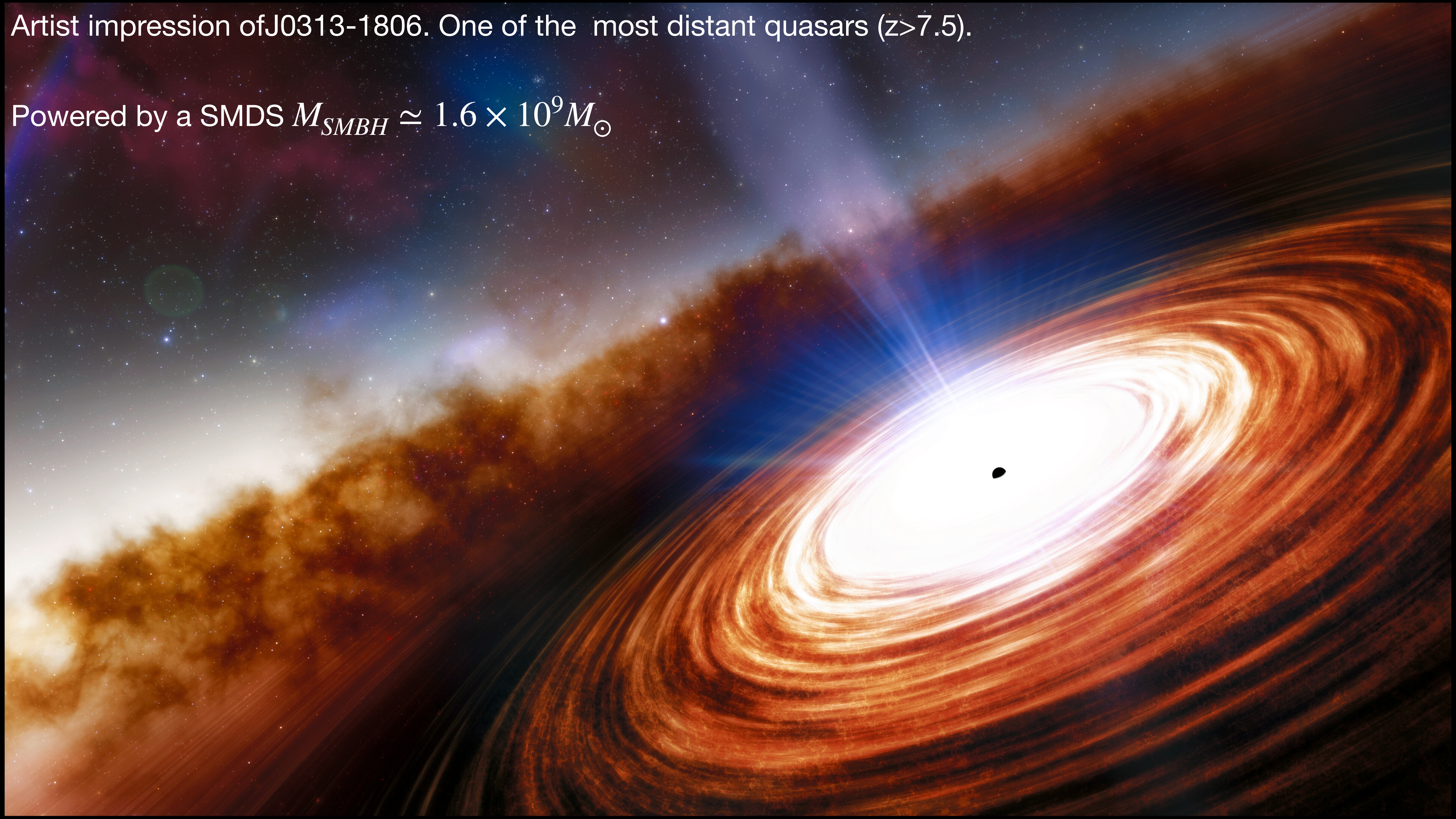
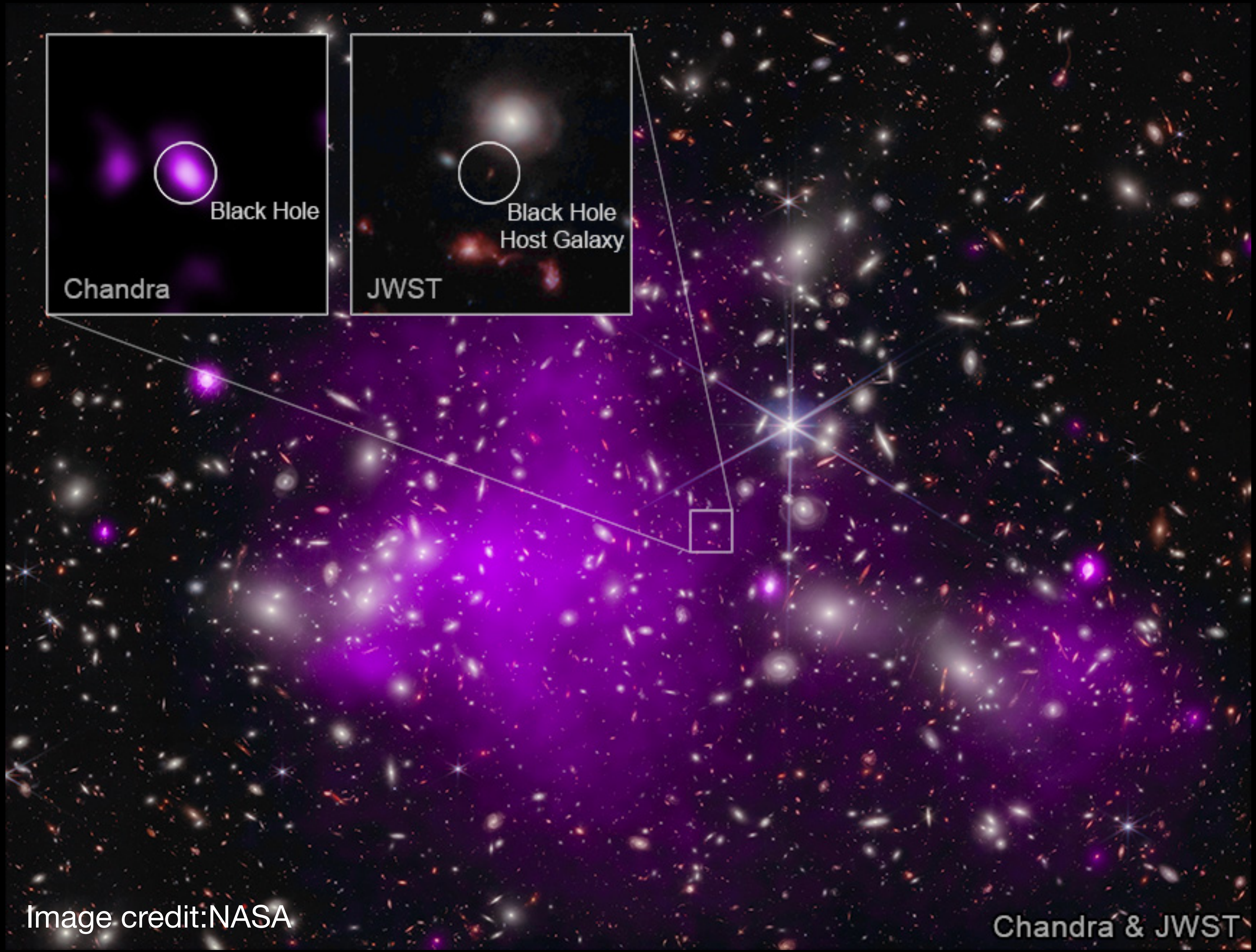


Image Credit: NOIRLab/NSF/AURA/J. da Silva

- The many Supermassive Black Holes powering observed quasars at z>6 for which either a heavy seed is necessary, or sustained Super Eddington Accretion.

SMDS solution to the UHZ1 puzzle



- UHZ1: a system at z~10
- Observed with JWST/ Chandra
- Contains a quasar of powered by a BH $\sim 10^7 M_\odot$
- Significant stellar population, $M_\star \sim 10^7 M_\odot$

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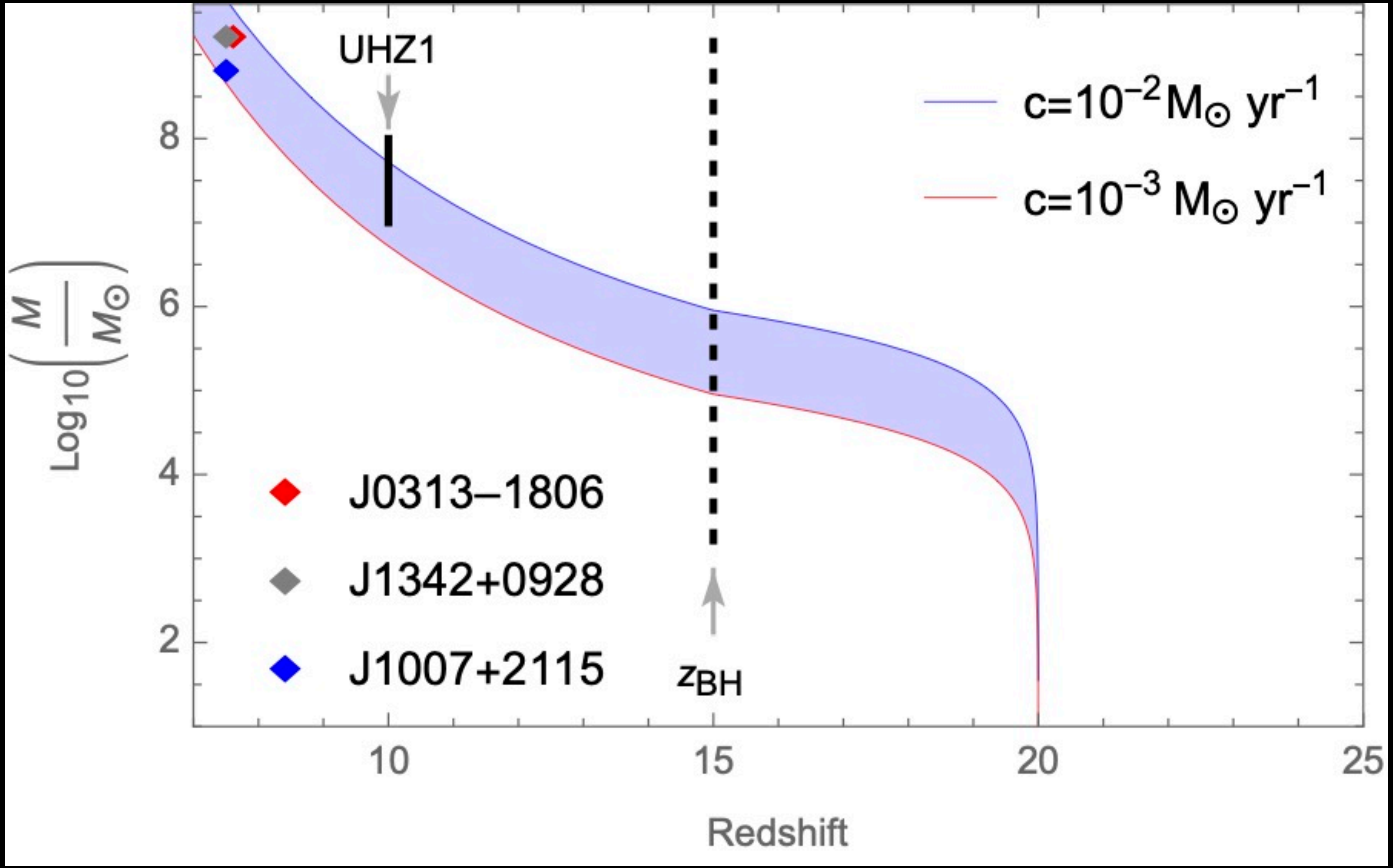

Figure from: CI et al. ArXiV: 2312.13837

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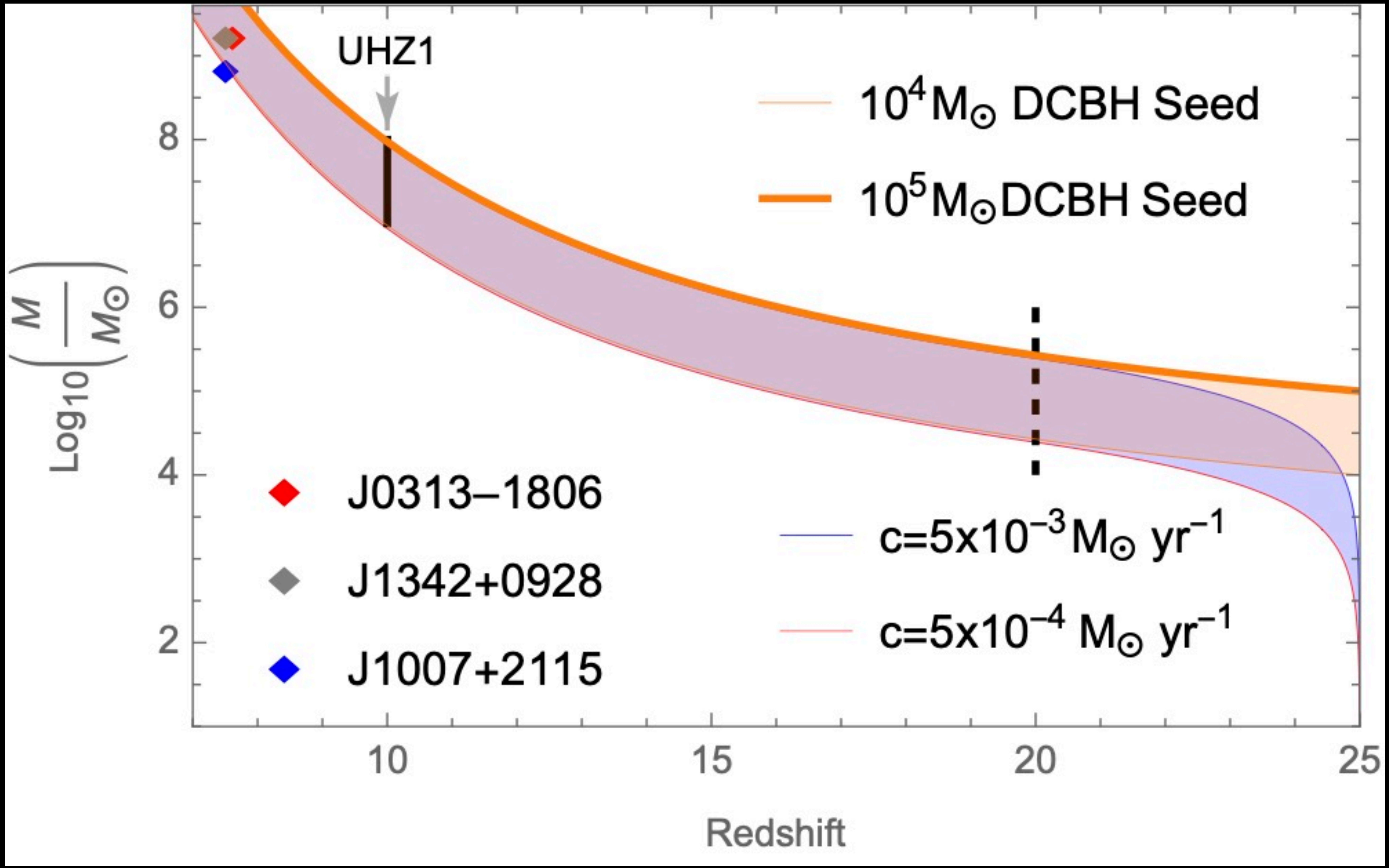
SMDS vs DCBH solution to the UHZ1 puzzle



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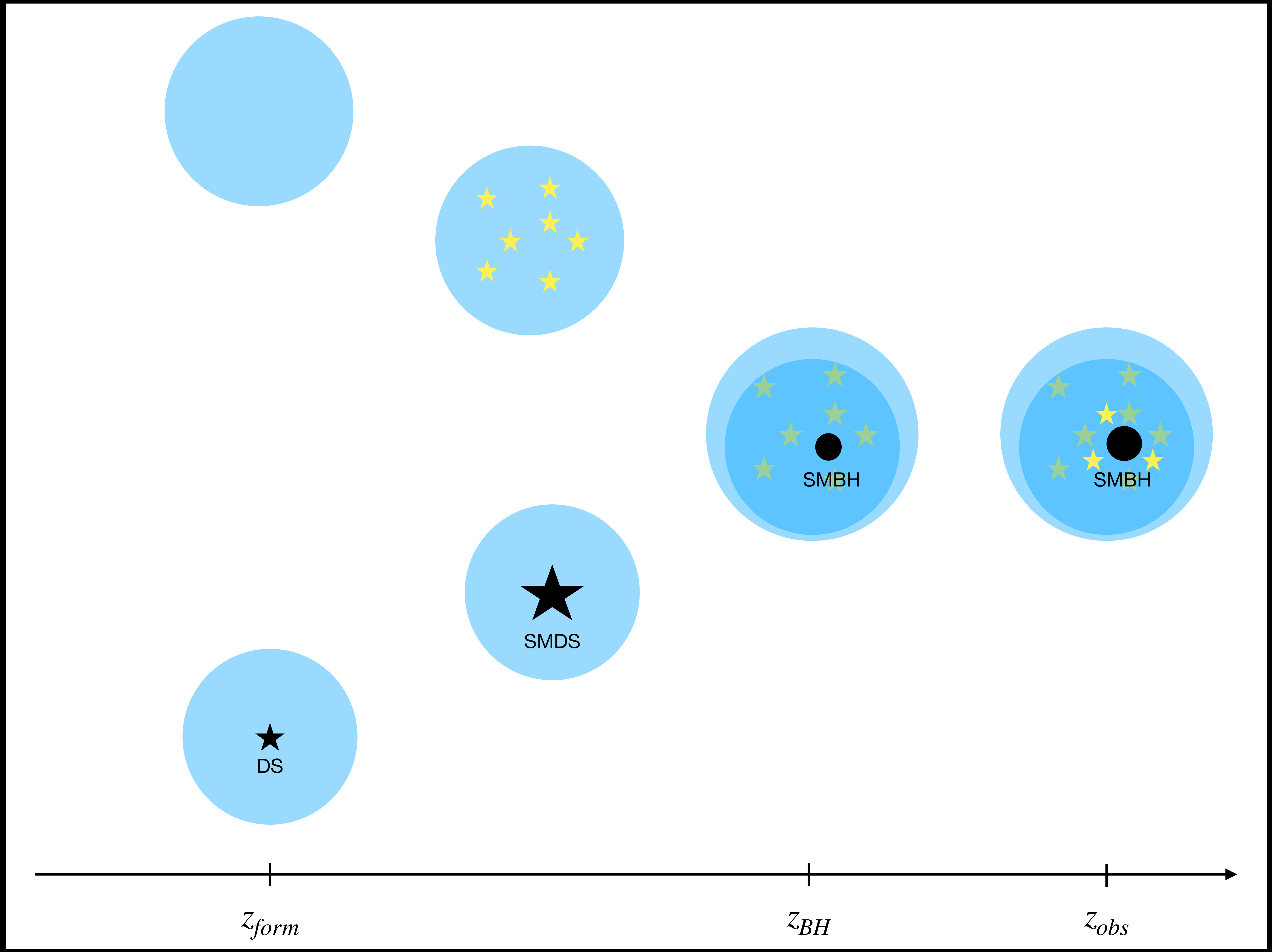

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JWST Observational motivations for SMDS

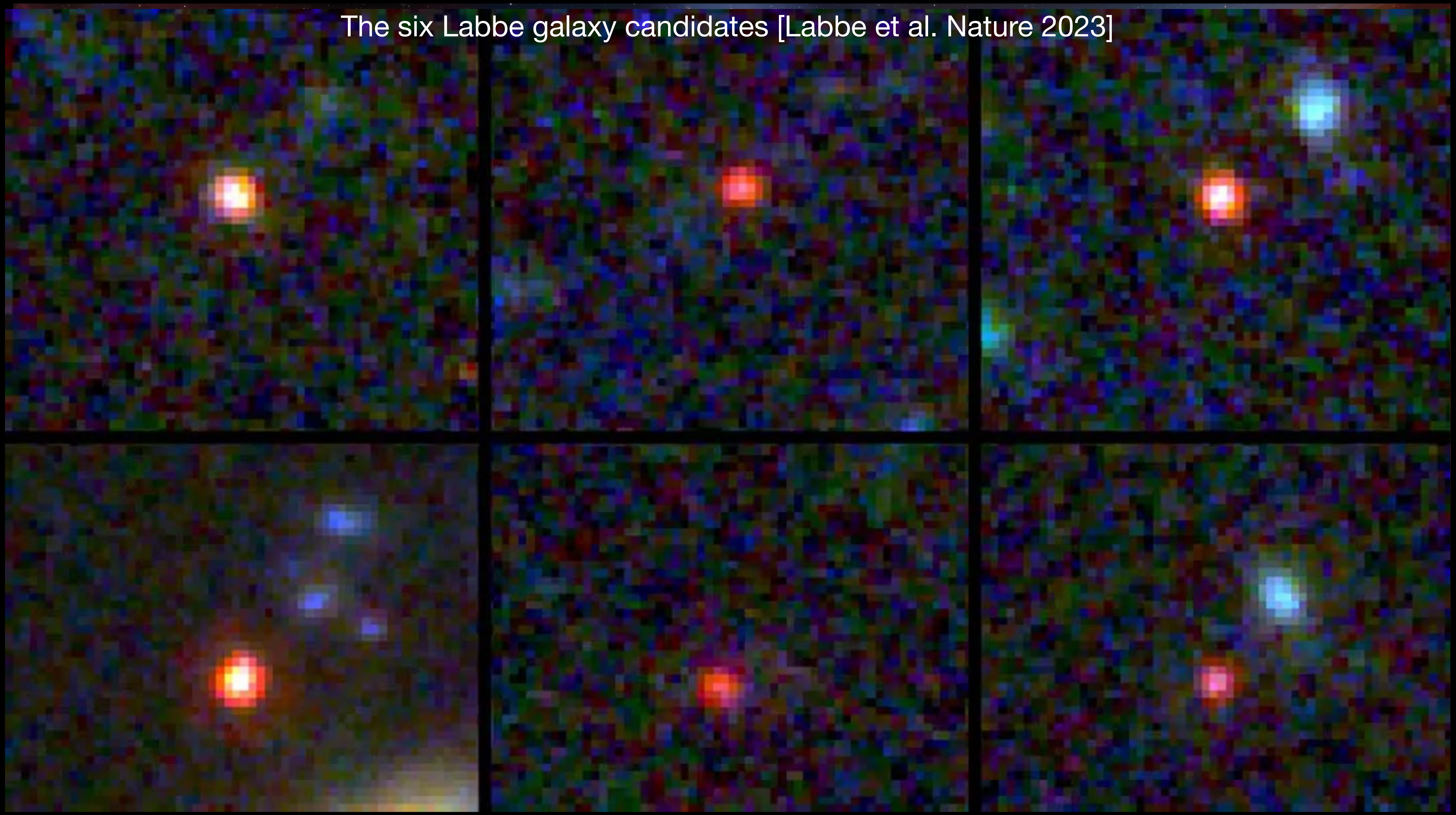


Image Credit: NASA/JWST/STSci

- Too many too massive too soon galaxies observed by JWST
- They would require almost 100% efficiency of gas to star conversion.

JWST Observational motivations for SMDS

Insights from HST into Ultramassive Galaxies and Early-Universe Cosmology

Nashwan Sabti, Julian B. Muñoz, and Marc Kamionkowski

Phys. Rev. Lett. **132**, 061002 – Published 9 February 2024

Physics See News Feature: JWST Sees More Galaxies than Expected

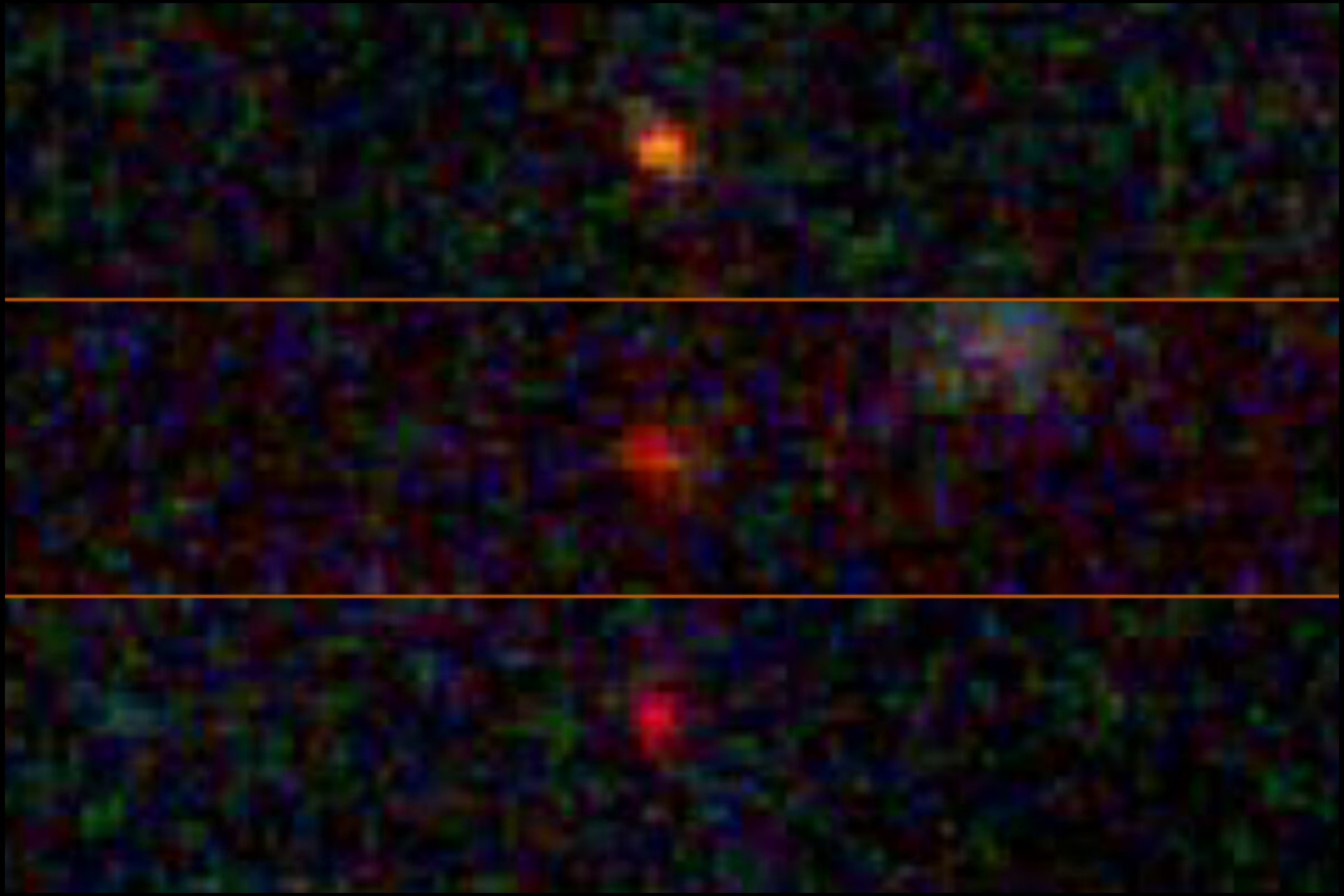
Article | References | No Citing Articles | Supplemental Material | PDF | HTML | Export Citation

ABSTRACT

The early-science observations made by the James Webb Space Telescope (JWST) have revealed an excess of ultramassive galaxy candidates that appear to challenge the standard cosmological model (ΛCDM). Here, we argue that any modifications to ΛCDM that can produce such ultramassive galaxies in the early Universe would also affect the UV galaxy luminosity function (UV LF) inferred from the Hubble Space Telescope (HST). The UV LF covers the same redshifts ($z \approx 7$–10) and host-halo masses ($M_h \approx 10^{10}$–$10^{12} M_\odot$) as the JWST candidates, but tracks star-formation rate rather than stellar mass. We consider beyond-ΛCDM power-spectrum enhancements and show that any departure large enough to reproduce the abundance of ultramassive JWST candidates is in conflict with the HST data. Our analysis, therefore, severely disfavors a cosmological explanation for the JWST abundance problem. Looking ahead, we determine the maximum allowable stellar-mass function and provide projections for the high-z UV LF given our constraints on cosmology from current HST data.

- "Universe breaker" type "galaxies:" too many too massive too soon
- They would require almost 100% efficiency of gas to star conversion.
- HST data highly disfavors LCDM modifications as a solution to this puzzle

Supermassive Dark Stars: Observational Status



First three SMDS Candidates identified:

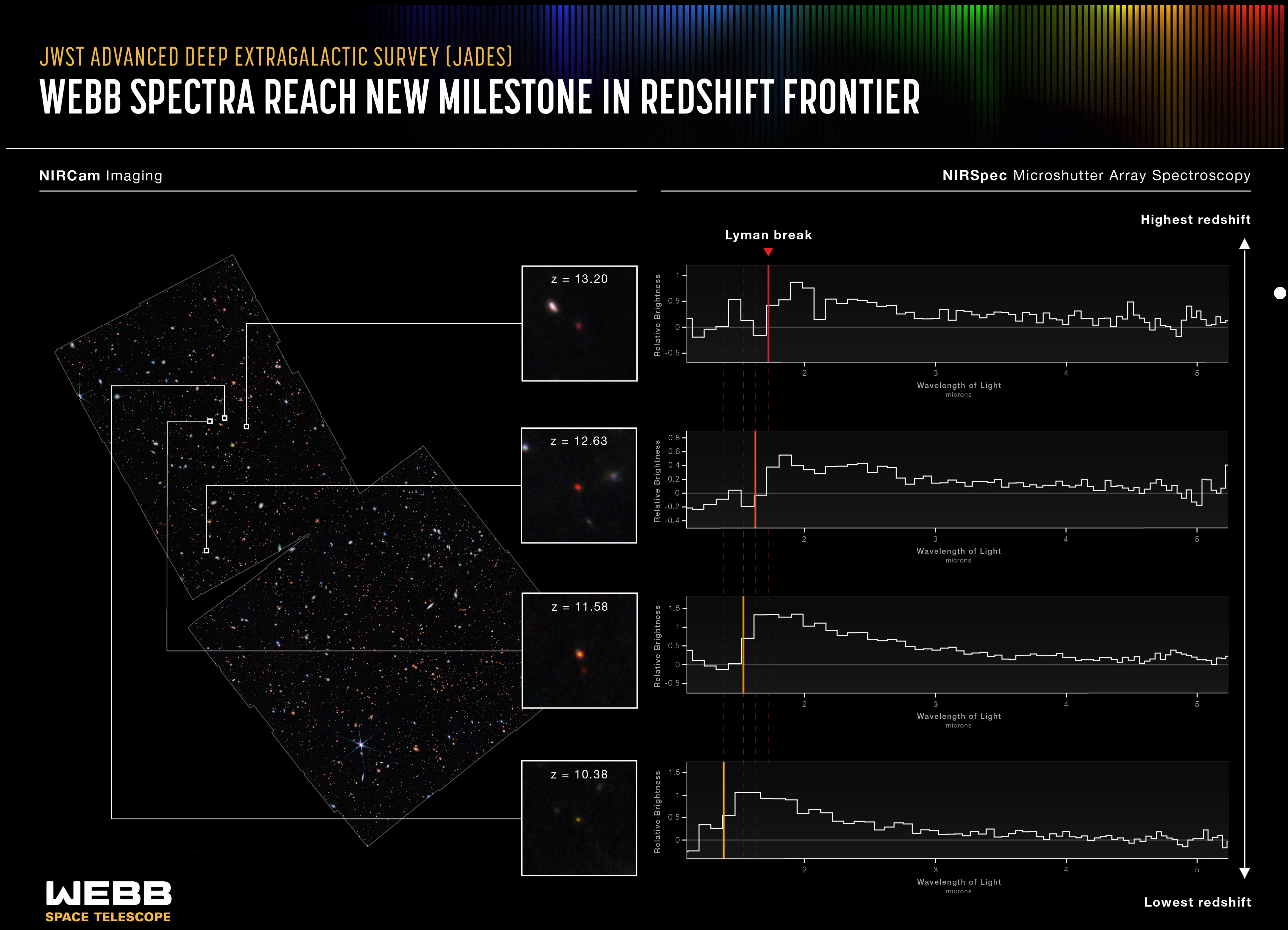
CI, Paulin and Freese PNAS 120 (30) 2023

Three criteria for selection of SMDS candidates

A. Spectroscopically confirmed as high redshift objects: $z_{spec} \gtrsim 10$

B. Consistent with a point source interpretation

C. Available photometric or spectra data is fit well by SMDS SEDs



- The four JADES objects identified by Robertson et al. 23 and spectroscopically confirmed by Curtis-Lake et. al 23 were selected based on criteria A and B.

Method to identify the best fit SMDS candidates to JWST data

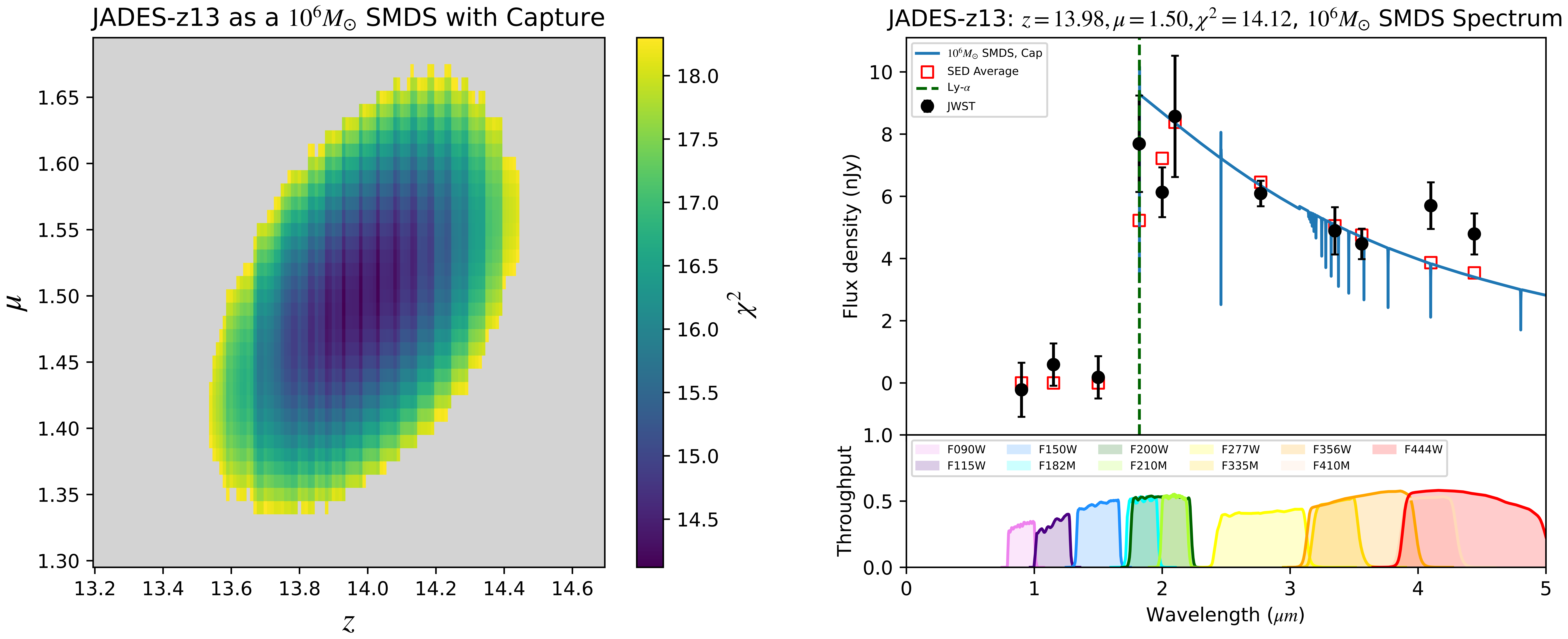
A. Spectroscopically confirmed as high redshift objects: $z_{spec} \gtrsim 10$

B. Consistent with a point source interpretation

C. Available photometric or spectra data is fit well by SMDS SEDs

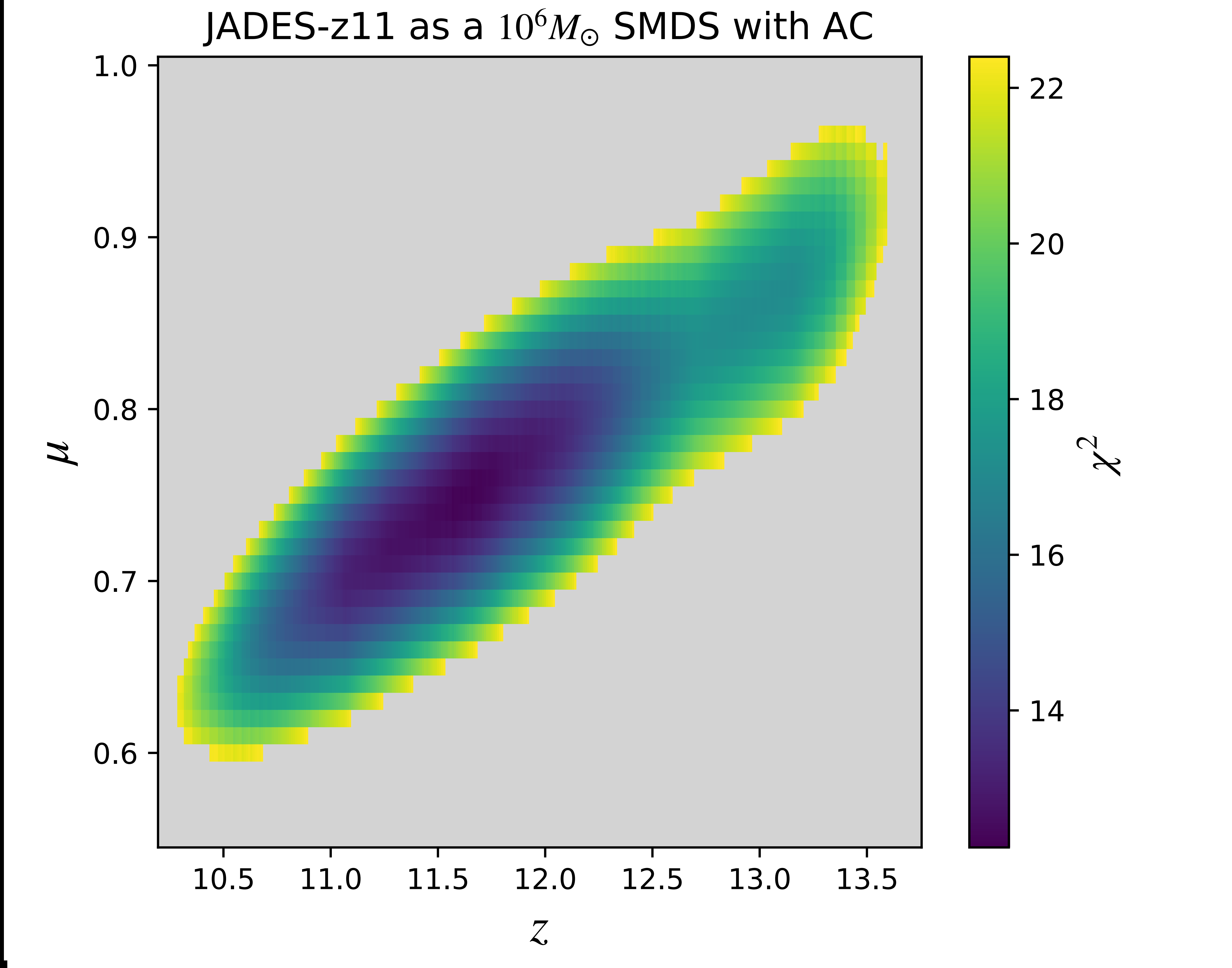
- We generated rest frame SMDS SEDs using TLUSTY on a coarse stellar mass grid for each formation mechanism and for a canonical WIMP 100 GeV DM.
- We perform a two parameter scan over z and μ to determine the best fit via the minimum χ^2 method

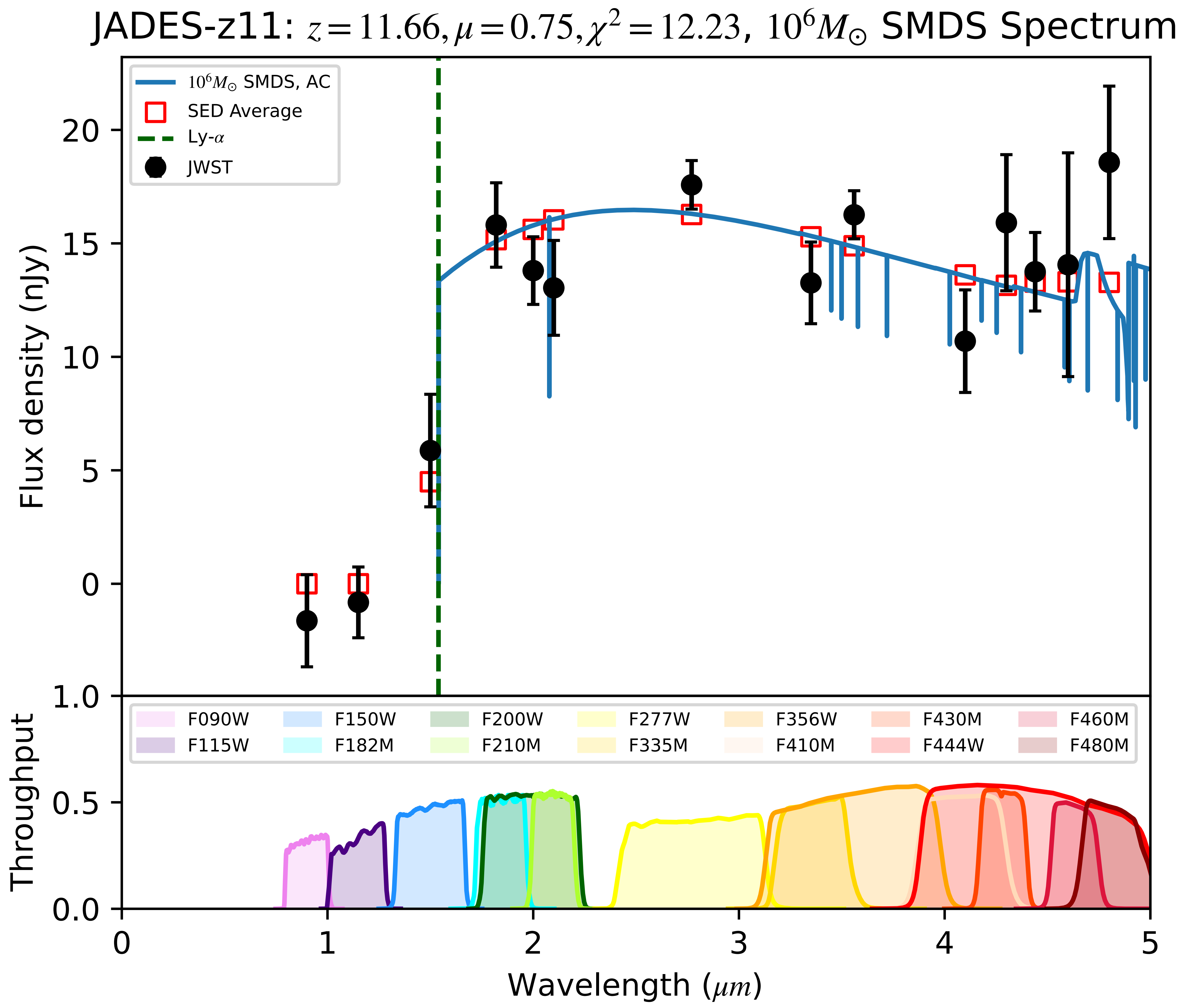
JADES-GS-z13-0 as a SMDS candidate



JADES-GS-z12-0 as a SMDS candidate

JADES-GS-z11-0 as a SMDS candidate





Three SMDSs candidates

Table S2. The best-fit parameters corresponding to each of the SMDS candidates.

Candidate	z_{phot}	z_{spec}	μ	χ^2	χ^2_{crit}	χ^2_{gal}	Formation Mechanism	SMDS Mass ($M_\odot$)
JADES-GS-z13-0	13.98	13.20	1.50	14.12	18.3	6.8	Capture	10^6
JADES-GS-z12-0	12.27	12.63	1.11	5.64	15.5	3.6	Extended AC	5×10^5
JADES-GS-z11-0	11.66	11.58	0.75	12.23	22.4	14.7	Extended AC	10^6

Table from: Ilie, Paulin and Freese PNAS 120 (30) 2023

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Notes:

- There is a strong degeneracy between the gravitational lensing factor (μ) and the SMDS Mass

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Notes:

- There is a strong degeneracy between the gravitational lensing factor (μ) and the SMDS Mass
- $\mu < 1$ is statistically preferred for sources at high z [Wang+,Astrophys.J. 572 (2002) L15-L18]

Conclusions and outlook

- We identified three SMDS candidates out of the four JADES objects selected
- SMDS are generically very good fits for photometric data for $z>10$ point sources in JWST data

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- Promising smoking gun signature of SMDSs is the HeII 1640 absorption line (JADES-GS-z13-0 already shows tentative signs of this feature)
- Once a statistically sufficient sample of SMDSs is identified we can infer particle DM parameter likelihood fits

Summary

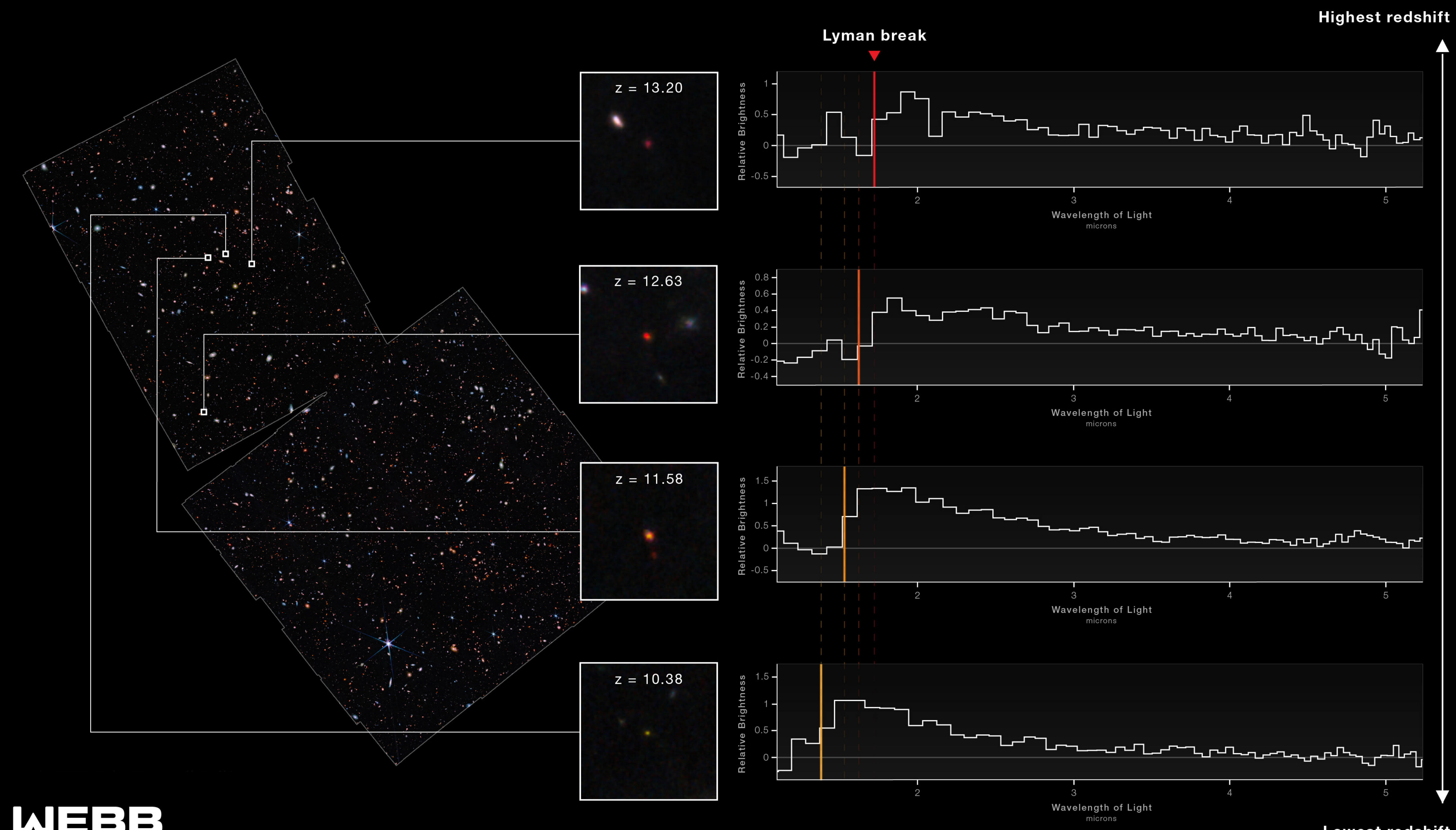
- JWST is poised to find observe the first stars
- Population III stars (i.e. zero metallicity H burners) can be used to constrain the Spin Dependent DM-proton interaction cross section (σ) below the neutrino floor
- Supermassive Dark Stars provide natural Heavy BH Seeds required by the most distant quasars data
- Supermassive Dark Stars can be part of the solution to the too many too massive early galaxies observed by JWST

JWST ADVANCED DEEP EXTRAGALACTIC SURVEY (JADES)

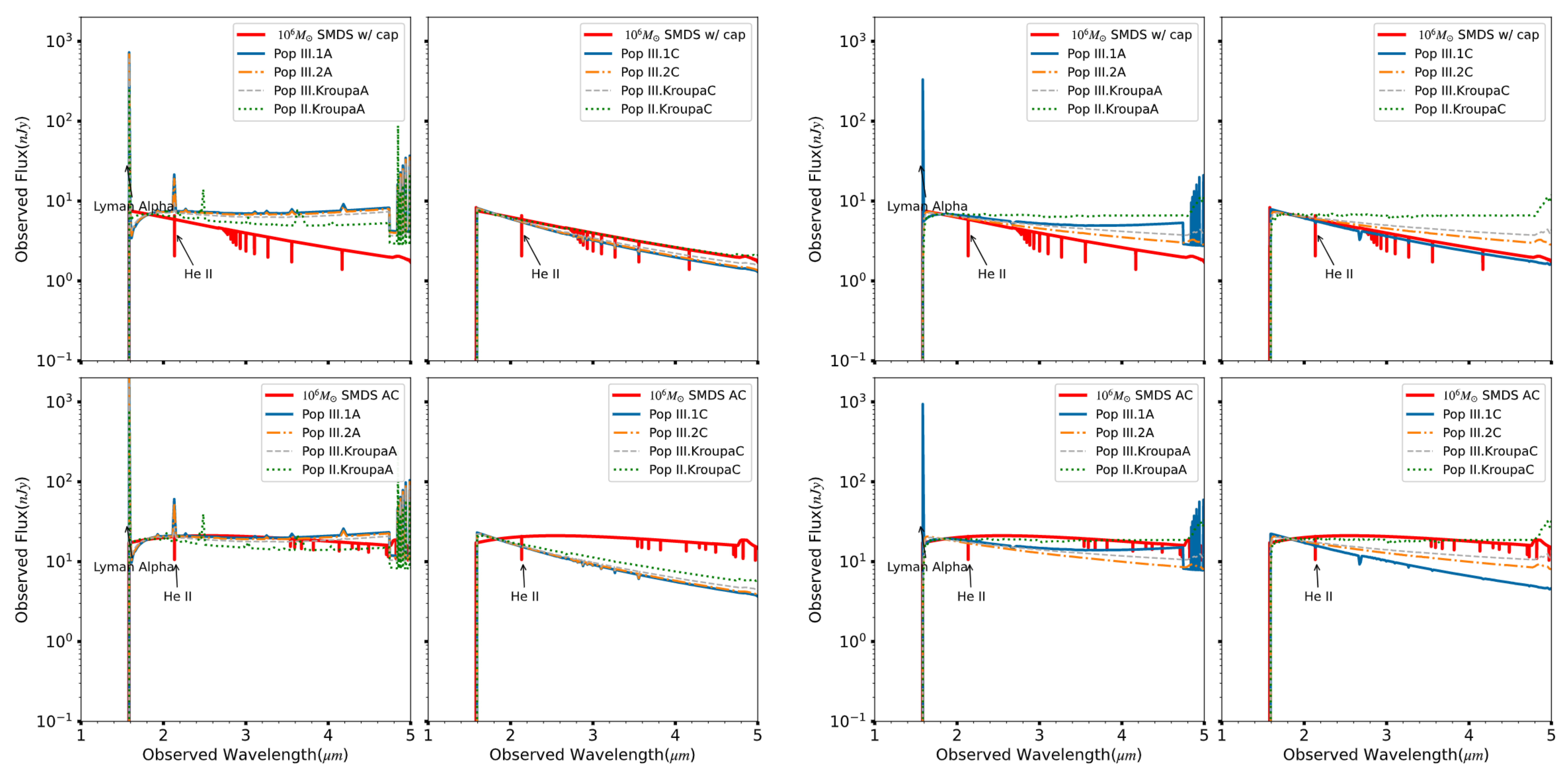
WEBB SPECTRA REACH NEW MILESTONE IN REDSHIFT FRONTIER

NIRCam Imaging

NIRSpec Microshutter Array Spectroscopy



WEBB
SPACE TELESCOPE



$10^6 M_\odot$ SMDS w/ cap
Pop III.1A
Pop III.2A
Pop III.KroupaA
Pop II.KroupaA
$10^6 M_\odot$ SMDS w/ cap
Pop III.1C
Pop III.2C
Pop III.KroupaC
Pop II.KroupaC
$10^6 M_\odot$ SMDS AC
Pop III.1A
Pop III.2A
Pop III.KroupaA
Pop II.KroupaA
$10^6 M_\odot$ SMDS AC
Pop III.1C
Pop III.2C
Pop III.KroupaC
Pop II.KroupaC
Lyman Alpha
He II
Observed Flux(nJy)
Observed Wavelength(μm)