Dark Stars: A Dark Matter-Powered Phase of Stellar Evolution

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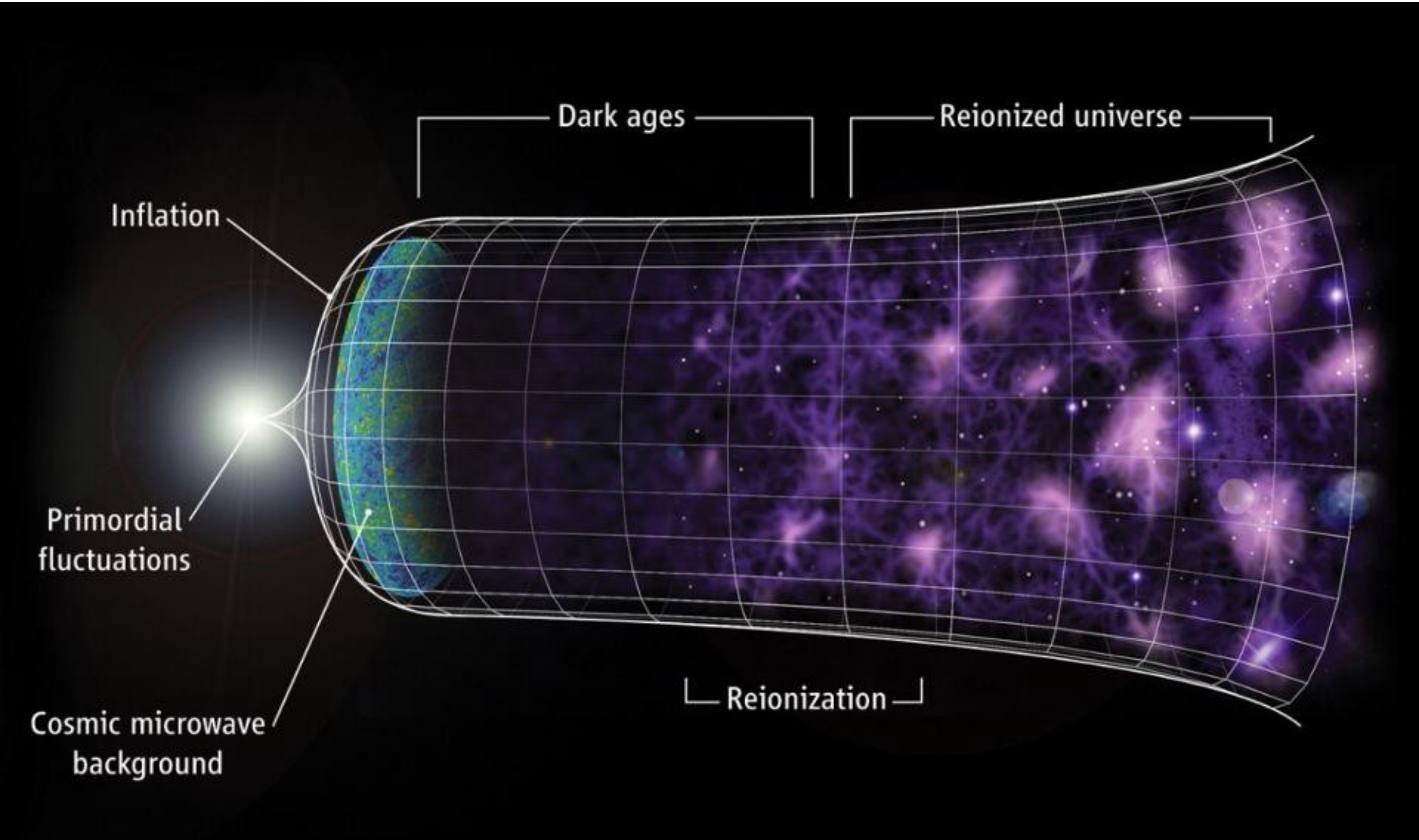
The First Stars



C. Faucher-Giguère, A. Lidz, and L. Hernquist, Science 319, 5859 (47).

The First Stars - Standard Picture

- **Population III.1**: BBN abundances, unaffected by other astrophysical sources
  - Formed in dark matter minihalos at $z \gtrsim 20$
  - Gas collapses to protostar when molecular hydrogen cooling is possible

- Minimum halo mass for star formation
  - Protostar forms, then fusion powered star

- Predicted to be quite massive
  - Theory: insufficient cooling allowed them to grow large Larson (1999)
  - Simulations: also show typical masses $\gtrsim 100\ M_\odot$ Bromm, Coppi & Larson (1999, 2002); Abel, Bryan & Norman (2000, 2002); Nakamura & Umemura (2001); O'Shea & Norman (2007); Yoshida *et al.* (2006, 2008); McKee & Tan (2008); etc.

The First Stars - with Dark Matter

- **Population III.1**: BBN abundances, unaffected by other astrophysical sources
  - Formed in dark matter minihalos at $z \gtrsim 20$
  - Gas collapses to protostar when molecular hydrogen cooling is possible
  - **DM rich environment**
- Minimum halo mass for star formation
  - Protostar forms, then fusion powered star
  - **DM falls into deepening potential well**
  - **DM heating dominates prior to fusion power (Dark Star phase)**
- Predicted to be quite massive
  - Theory: insufficient cooling allowed them to grow large Larson (1999)
  - Simulations: also show typical masses $\gtrsim 100\ M_\odot$ Bromm, Coppi & Larson (1999, 2002); Abel, Bryan & Norman (2000, 2002); Nakamura & Umemura (2001); O'Shea & Norman (2007); Yoshida *et al.* (2006, 2008); McKee & Tan (2008); etc.
  - **Baryons continue to accrete during DS phase → very massive stars!** Spolyar, Freese, & Gondolo (2008)++

Dark Star Phase

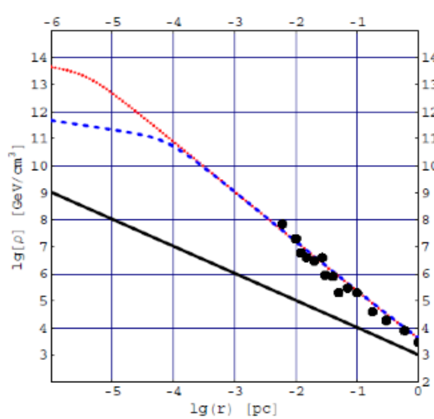
- If dark matter particles annihilate the ***annihilation rate*** *~ρ²*
- Pop III.1 stars formed at ***high redshift*** *and ρ ~ (1+z)³*
- Each Pop III.1 star formed at the ***center of a minihalo***:

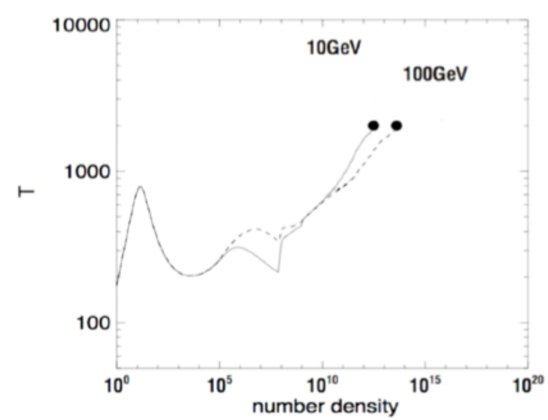
Could DM annihilation power a star? Spolyar, Freese & Gondolo (2008+)

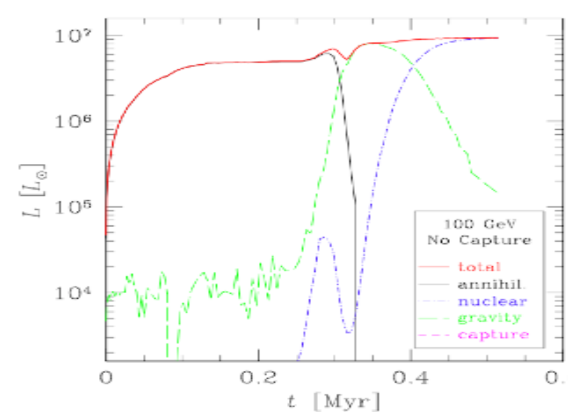
✔ 1. Sufficiently high DM density for large annihilation rate

✔ 2. Annihilation products get stuck in star

✔ 3. Dark matter heating is dominant

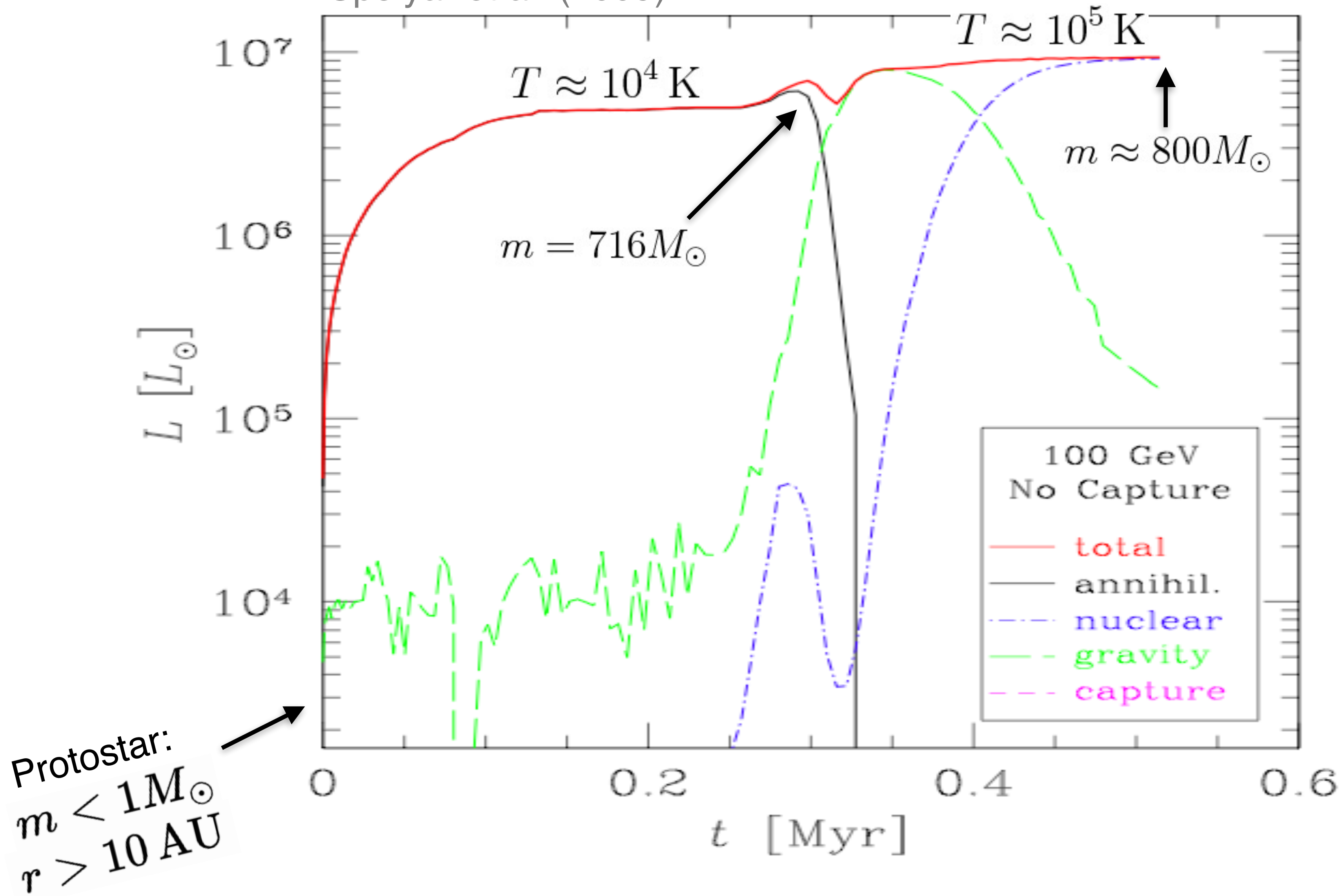






Dark Star Evolution

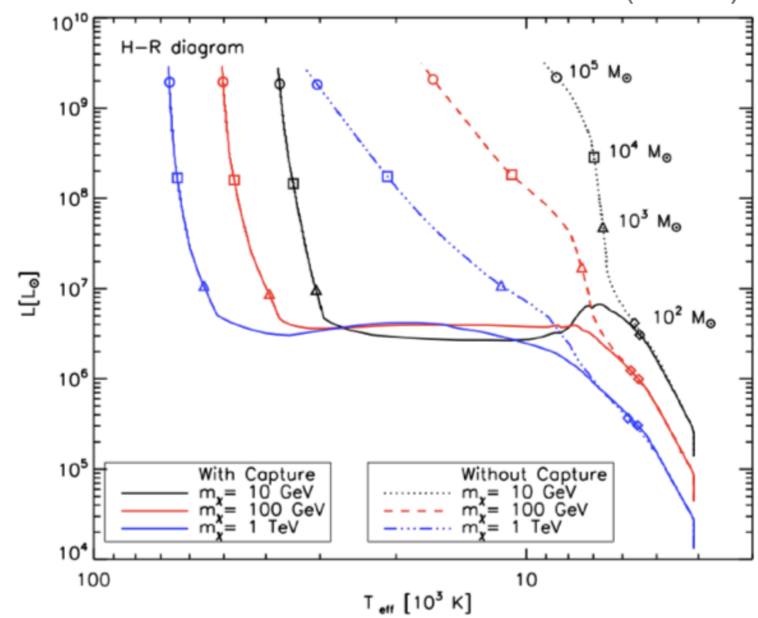
Spolyar et al. (2009)



Dark Star Growth

- Most simplistic case: DM in the center of Dark Star annihilates away.
- **Centrophilic Particle Orbits:** Continuous gravitational infall of particles that pass near the core of the Dark Star. For (initially) triaxial halos, an O(1) fraction of DM particles would remain on centrophilic orbits. See work by Valluri et al.
- **Dark Matter Capture:** DM particles elastically scatter with nuclei in the star, reducing their velocity to below the escape velocity. Continuously feeds the Dark Star with new DM fuel.
- These different mechanisms that prolong the Dark Star phase lead to stars with different properties!

Freese et al. (2010)



The Dark Star phase may be very long-lived, resulting in super massive stars and black hole remnants.

Detection

How can we **observe** these objects or **find evidence** of their existence?

1. **Direct observation with JWST**
2. **Diffuse or cosmological signals from all DS's in the Universe**
3. **Signatures of remnants in our Galaxy**

Detection

1. Direct observation with JWST

Individual DS's could be seen by JWST out to high redshift.

Dropout technique
- Ilie, Freese, Valluri, Iliev, & Shapiro (2011):

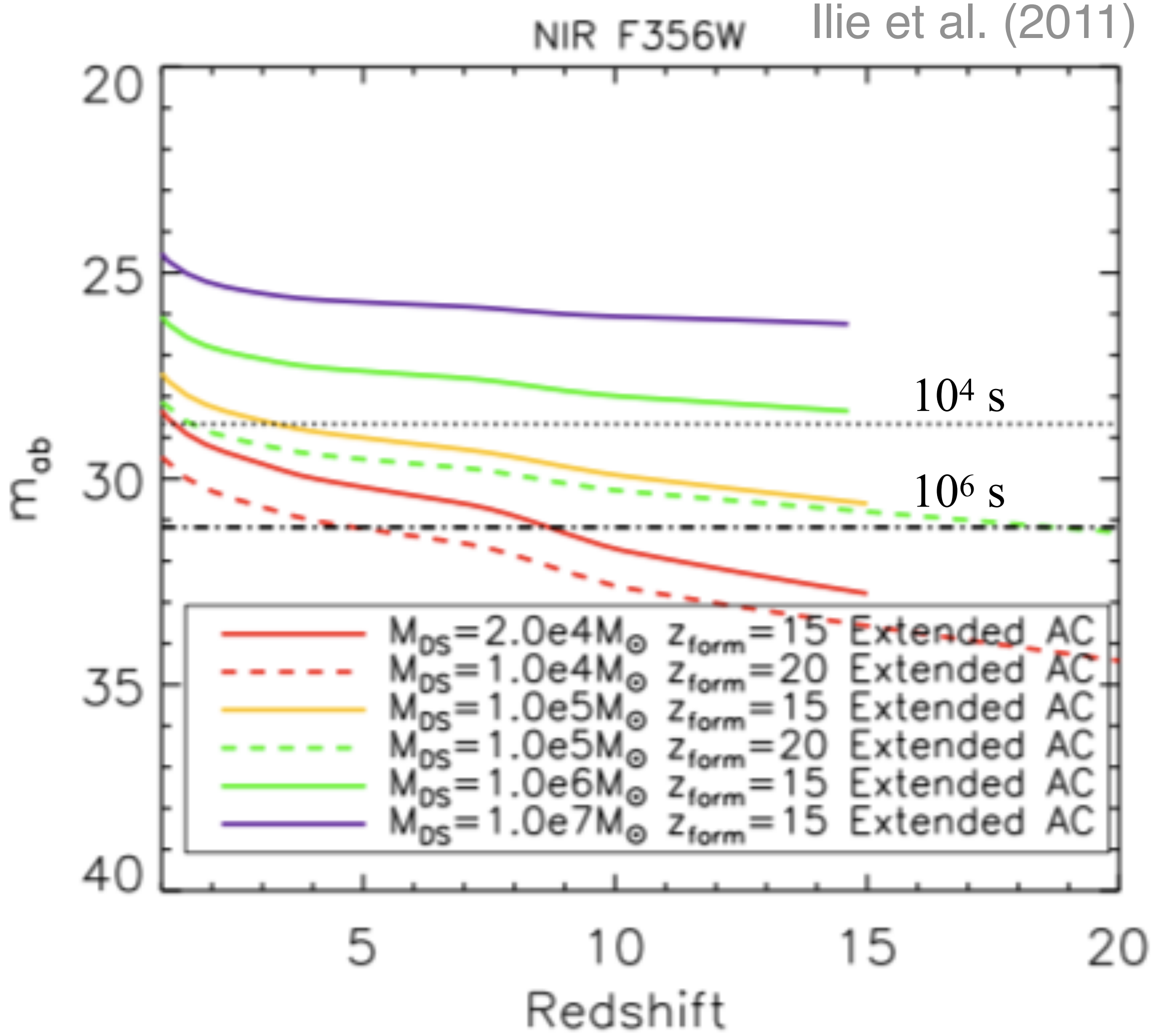
$$m \geq 10^4 M_\odot$$

Magnification by a foreground cluster
- Zackrisson et al. (2010a,b)

$$m \approx 10^3 M_\odot$$

Also Freese, Ilie, Spolyar, Valluri, Bodenheimer (2010)

Ilie et al. (2011)



Detection

1. **Direct observation with JWST**
2. **Diffuse or cosmological signals from all DS's in the Universe**

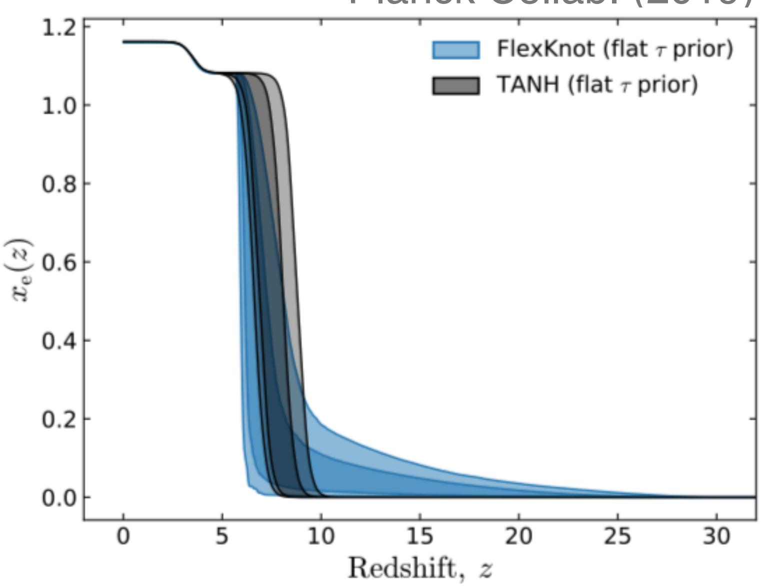
- ➔ extragalactic background light (EBL) contribution from DS phase
- ➔ accumulated flux from DMA around cosmological remnant BHs
  - ➔ photons
    - ➔ radio signal from synchrotron radiation of charged annihilation products around remnant BHs (w/ Matt Stephens, *in progress*)
  - ➔ neutrinos
- ➔ **optical depth** (w/ P. Gondolo & B. Shams Es Haghi, 2112.04525)
- ➔ 21cm (w/ A. Perko and J. Covington, *in progress*)
- ➔ BH mass function, affect on PISNe (see Freese & Ziegler, 2021)
- ➔ gravitational waves from DS collapse or remnant mergers (eg. Coogan et al., 2022)

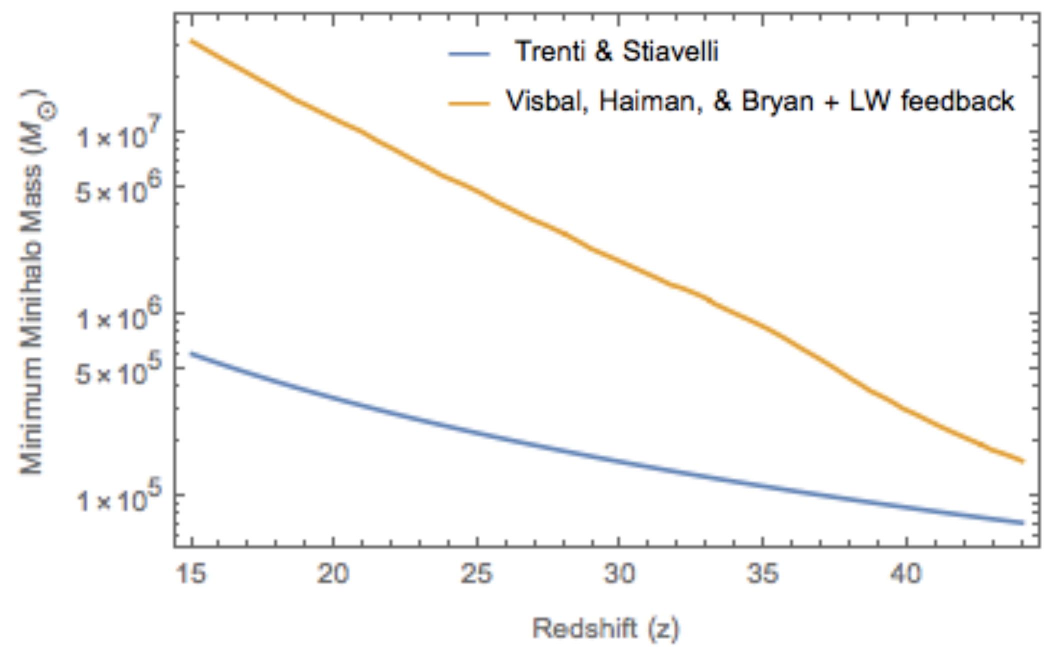
Optical Depth

The optical depth to reionization is $\tau \sim \int n_e \sigma_T d\ell$, and is measured by Planck to be $\tau \approx 0.05$. Planck Collab. (2019)

Smaller optical depth means hydrogen wasn't ionized (by fusion-powered stars) until later - delayed/limited formation of Pop III.1 stars? eg. Visbal, Haiman, & Bryan (2015)

Planck Collab. (2019)





★ DS phase delays the formation of fusion-powered stars, decreasing the optical depth.

w/ Gondolo, Shams Es Haghi, & Visbal (arXiv:2112.04525)

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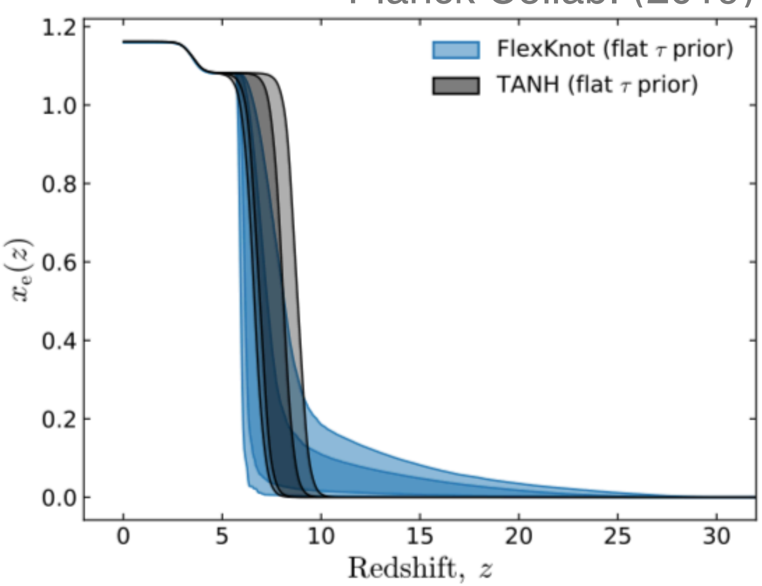

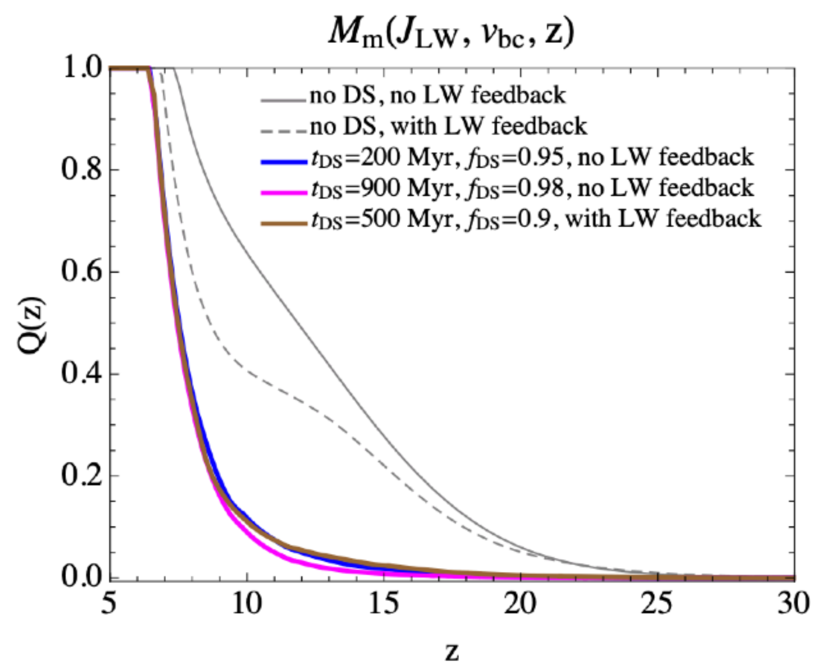

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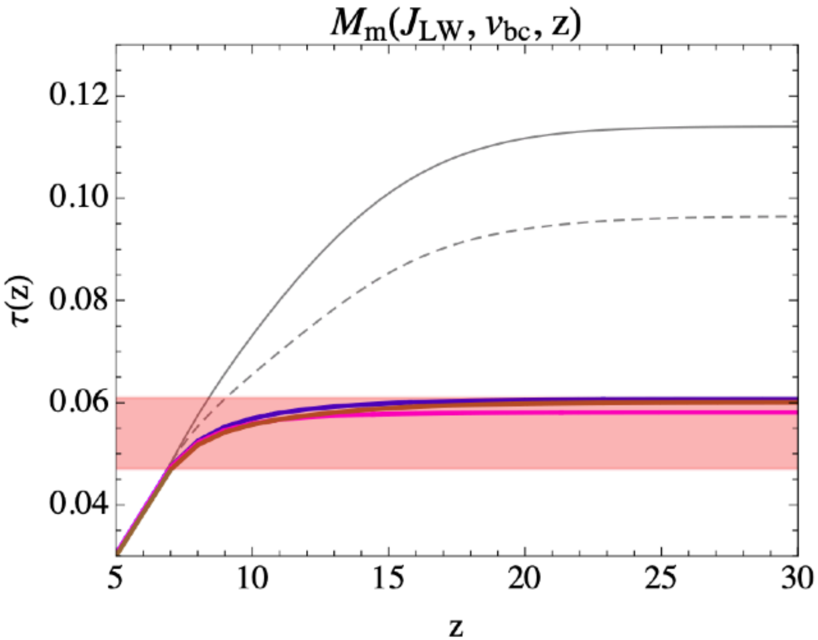
With Dark Stars, an optical depth in the observed range is easily achieved, whether or not LW feedback is significant.

Results are robust to the details of the DM model, so long as dark stars existed for some time.



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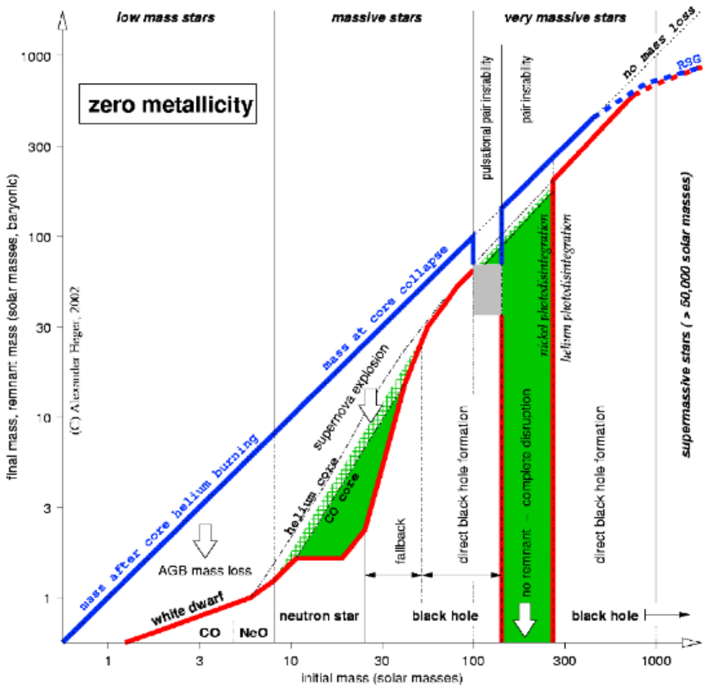
Detection

1. **Direct observation with JWST**
2. **Diffuse or cosmological signals from all DS's in the Universe**
3. **Signatures of remnants in our Galaxy**

→ point sources (if they are bright enough)
  → gamma rays
  → neutrinos
→ contribution the diffuse flux (if they are faint)
  → gamma rays
  → neutrinos
  → charged leptons, (anti)protons, etc.

Heger and Woosley (2002)



- Sandick Diemand, Freese, Spolyar (2011)
- Sandick & Watson (2011)
- Sandick, Diemand, Freese, Spolyar (2012)
- Galstyan, Freese, Sandick, & Stengel (2202.01126)

[Also work by J. Silk. P. Gondolo, G. Bertone, A. Zentner, H. Zhao, M. Fornasa, M. Taoso, and others]

DM Annihilation in a DM Spike

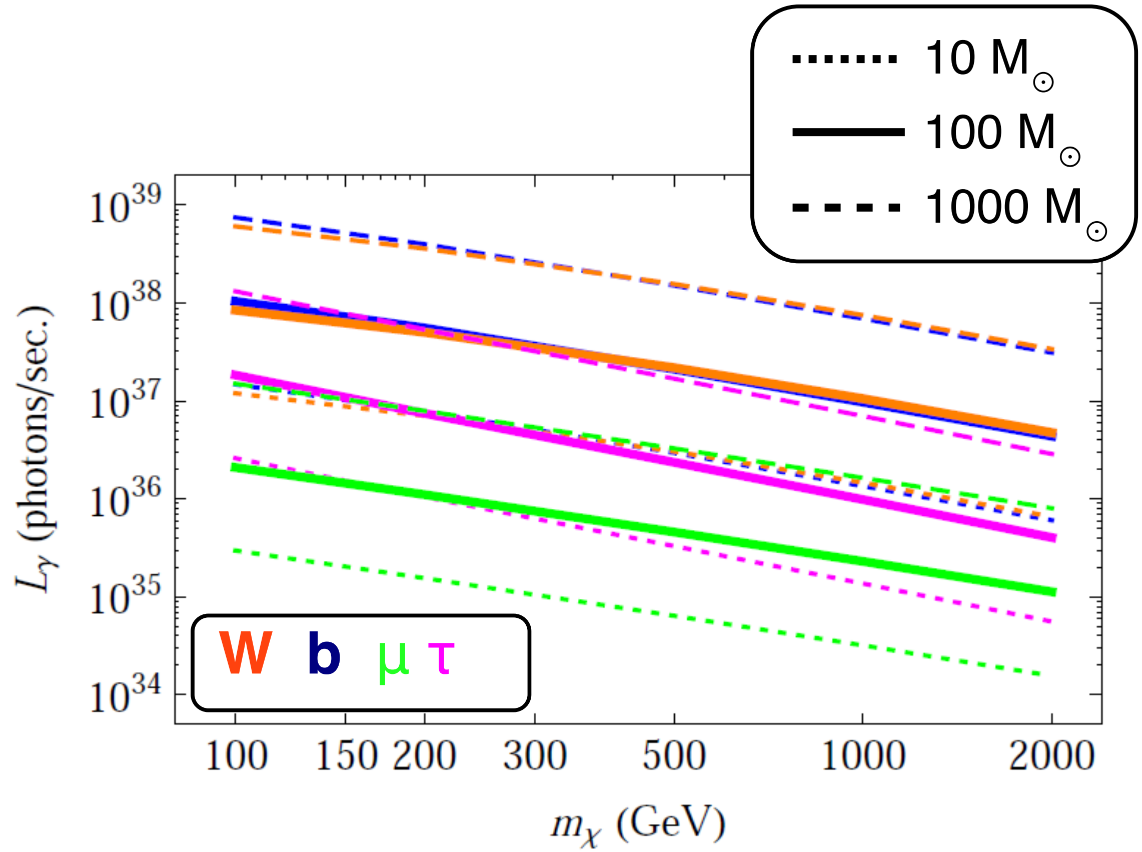
Annihilation Rate

$$\Gamma = \frac{\langle \sigma v \rangle}{2m_\chi^2} \int_{r_{min}}^{r_{max}} dr\, 4\pi r^2\, \rho_{DM}^2$$

$$\langle \sigma v \rangle = 3 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$$

Intrinsic Luminosity

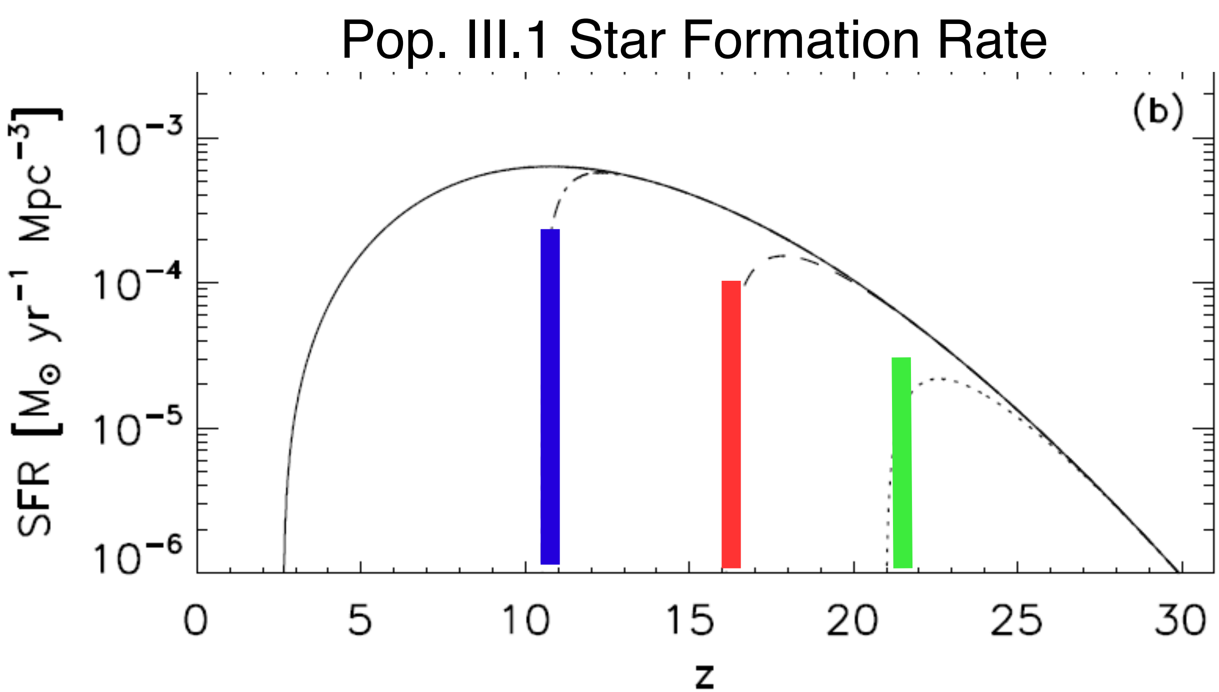
$$\mathcal{L} = \int dE \sum_f \frac{dN_f}{dE} \Gamma_f$$



- Increasing black hole mass means bigger spike, so higher luminosity.
- Increasing WIMP mass means fewer in each spike, so lower luminosity.
- Leptonic final states less luminous (especially muons – FSR only)

End of Population III.1

The number of BH remnants (and spikes) in our Galaxy *depends on the duration of the epoch of Pop. III star formation* during which DS's could have formed.



Parametrize end of Population III.1 star formation:

Greif & Bromm (2006)

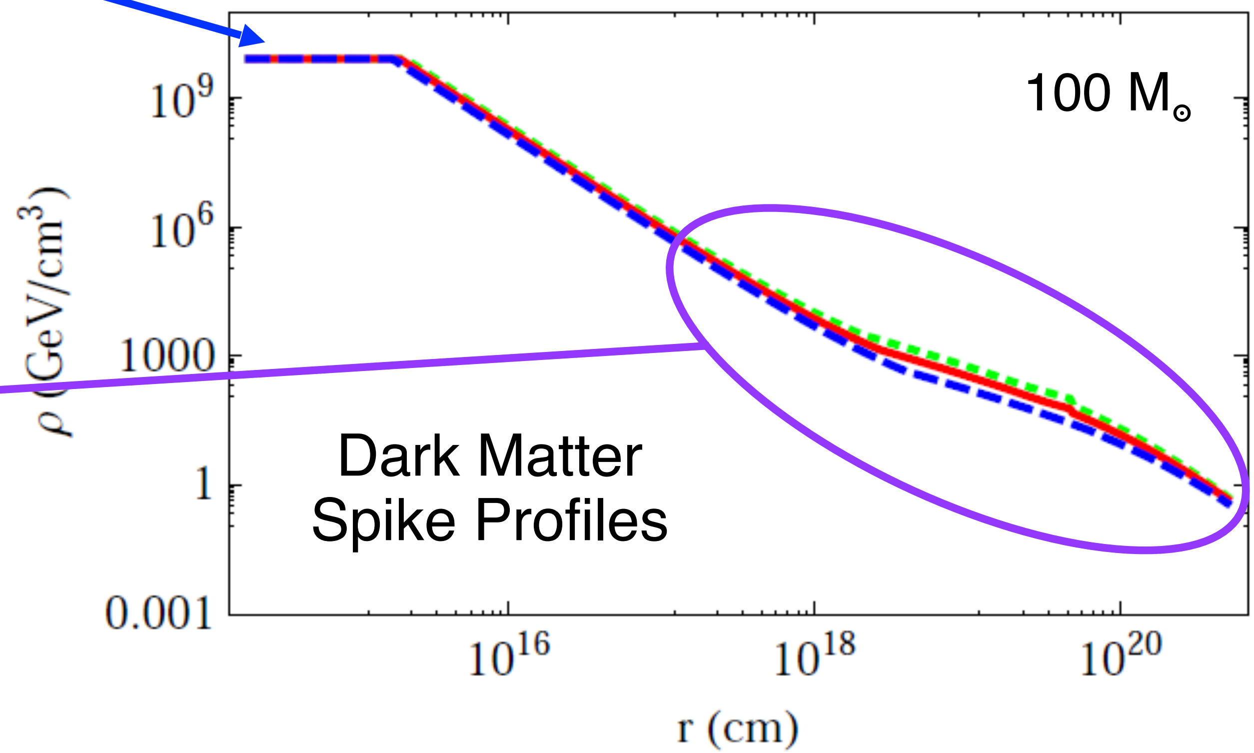
Early	$z_f = 23$
Intermediate	$z_f = 15$
Late	$z_f = 11$

End of Population III.1

$$\rho_{max} = \frac{m_\chi}{\langle \sigma v \rangle \tau}$$

(circular orbits)

profile depends
on redshift of formation
$\rho \sim (1+z)^3$



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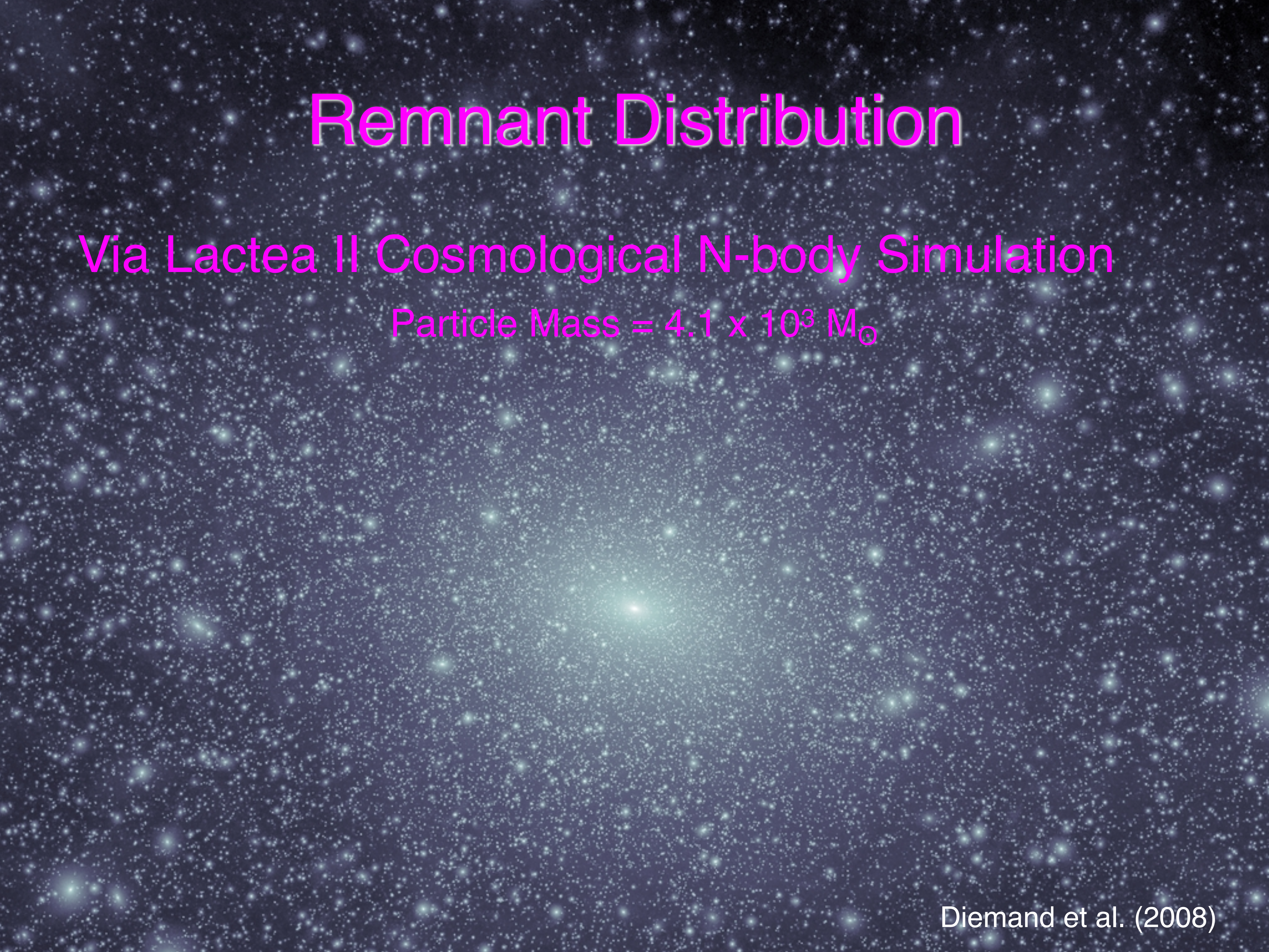
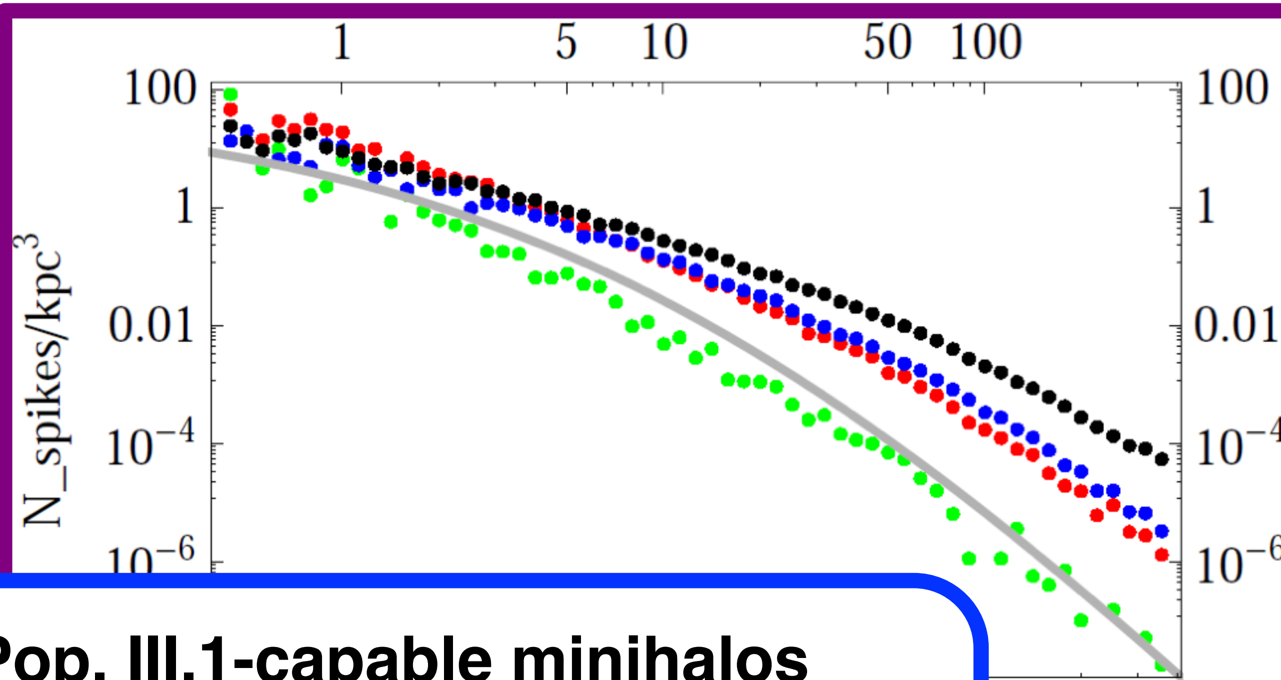

Remnant Distribution
Via Lactea II Cosmological N-body Simulation
Particle Mass = 4.1 x 10^3 M$_\odot$
Diemand et al. (2008)

Remnant Distribution

- Given ranges for redshift and minihalo mass, use VL2 simulation to find the distribution today of DM spikes (assuming each hosted a star)

Early	**409**
Intermediate	**7983**
Late	**12416**
Bertone, Zentner & Silk (2005)	1027 ± 84



f_{DS} ≡ **fraction of Pop. III.1-capable minihalos that actually hosted a dark star**

Actual $N_{sp} = f_{DS} \cdot$ Total Possible N_{sp}

Diffuse vs. Point Source Flux

Two ways they could show up: FSC and EGB both Abdo et al. (2010)

- DM spikes may appear as gamma-ray or neutrino **point sources**
  - Brightest one can't be brighter than the brightest observed source → minimal distance, "D*minPS*"
  - If a source is far enough away [dim enough], it would be too faint to be detected as a point source → maximal distance, *"DmaxPS"*

  ★ How many point sources are there? Is the number predicted by simulations consistent with observed unassociated FGST sources? Consistent with photon and neutrino point source flux limits? What can we learn about the number of these objects that formed in the early universe?

- If spikes are dim enough [far enough away], they won't be identifiable as point sources, and would contribute to the **diffuse gamma-ray and neutrino flux**.

  ★ Is the expected diffuse flux from all non-PS spikes consistent with the measured diffuse flux?

Constraining f_{DS}

- With point source population ("Point Source Constraint"):

$$N_{sp}(R, f_{DS}) = f_{DS} \times N_{sp}(R, f_{DS} = 1)$$

$$\int_0^{D_{min}^{PS}} r^2 dr \int_0^{4\pi} d\Omega \, N_{sp}(R, f_s) \leq 1$$

Require an expectation of <1 spike within *DminPS* of our Solar System.

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Require an expectation of <1 spike within *DminPS* of our Solar System.

- With diffuse flux ("Diffuse Constraint"):

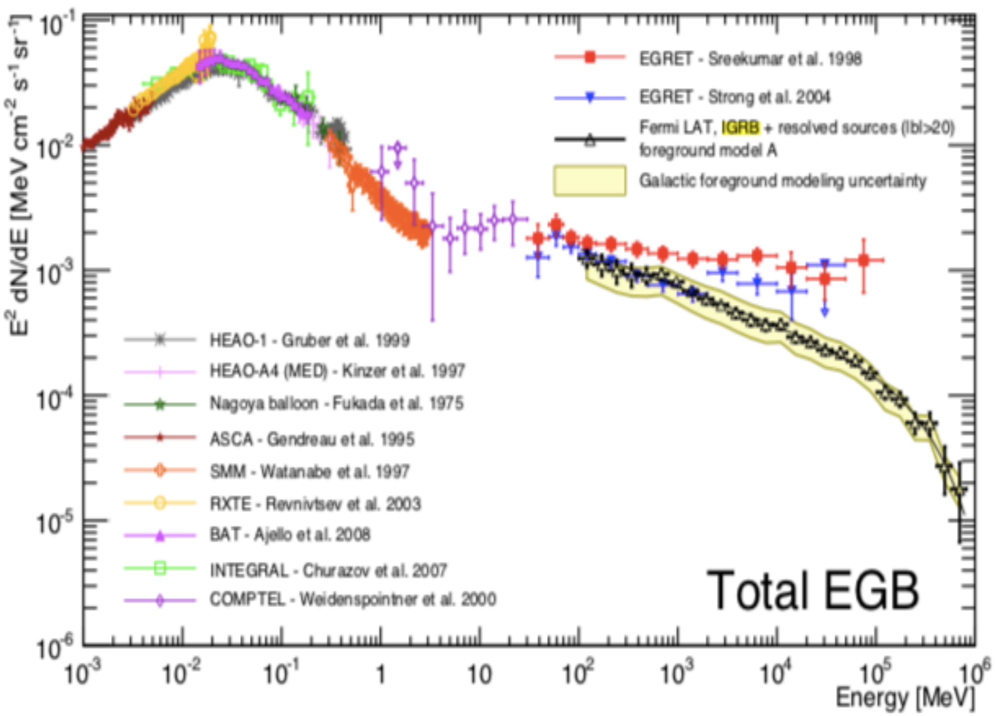
$$\Phi_i(f_{DS}) = f_{DS} \times \Phi_i(f_{DS} = 1)$$

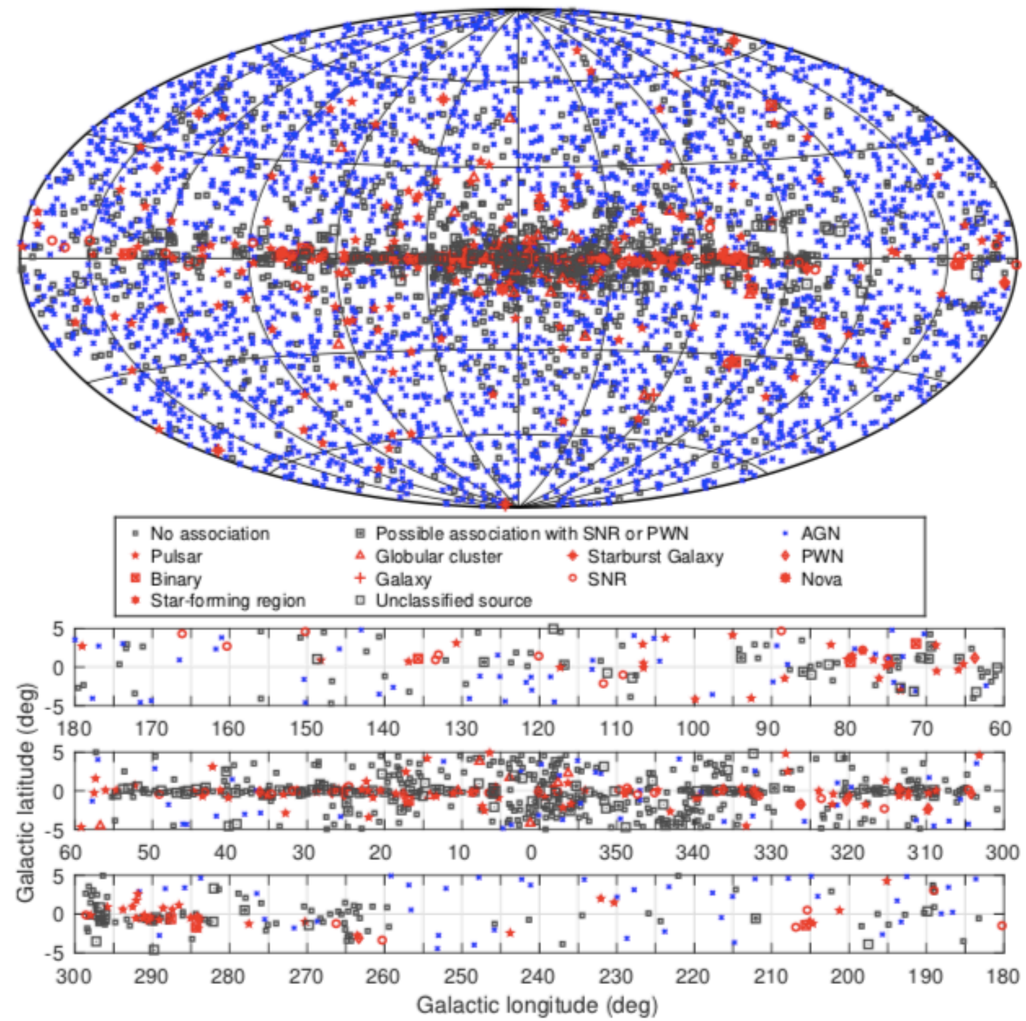
Require that the diffuse flux not exceed the measured flux by more than 3σ.

Fermi Gamma-Ray Space Telescope

Using Fermi-LAT data to constrain early star formation and/or models of dark matter annihilation

Diffuse Gamma-Ray Flux



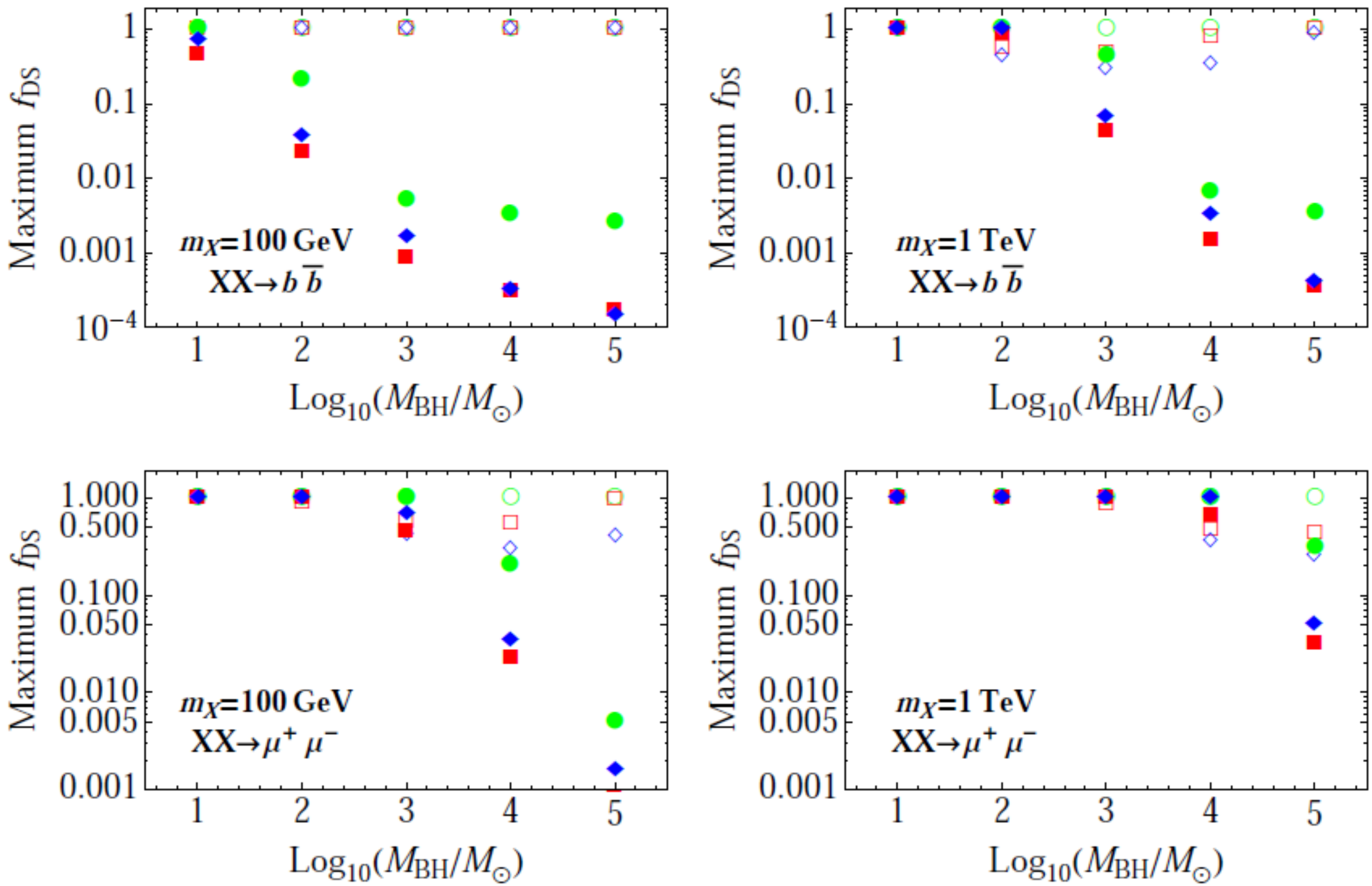


Acero et al. (2015); Abdollahi et al. (2020); Abdo et al. (2010)

Unassociated FGST PSs

z_f = 23
z_f = 15
z_f = 11

diffuse → open   point source → filled



ANTARES and IceCube

Using neutrino point source constraints to constrain early star formation and/or models of dark matter annihilation

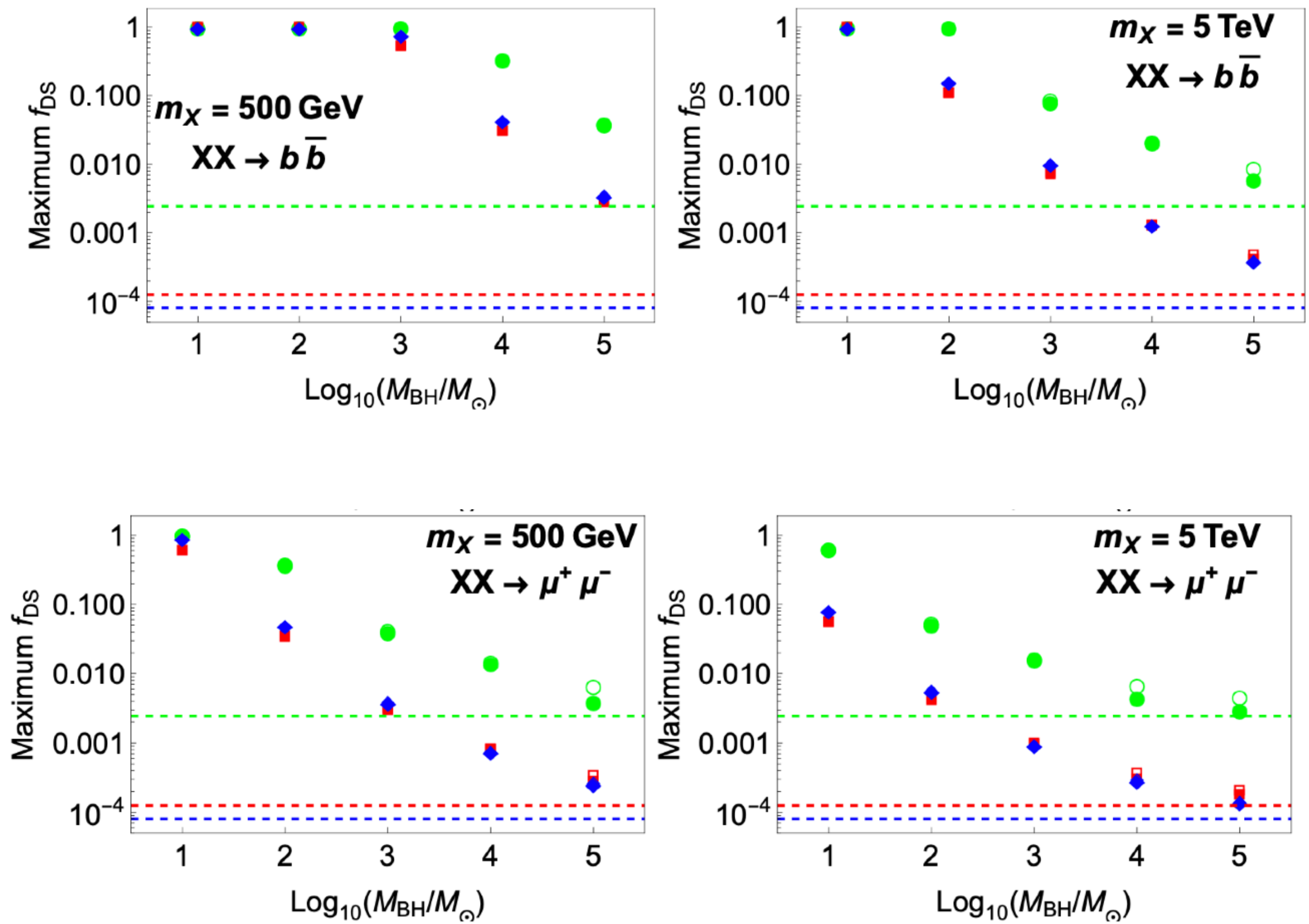
EXi	δ Range	$<$ Flux (GeV cm^{-2}s^{-1})	EV	Acceptance (GeV^{-1}cm^2 s)	$< N_{\rm EV}^{{\rm EX}i}$
AN1	$[-90°, -45°]$	6.3×10^{-9}	TR	2.8×10^8	1.8
			SH	7.1×10^7	0.4
AN2	$[-45°, 0°]$	8.3×10^{-9}	TR	2.0×10^8	1.7
			SH	5.8×10^7	0.5
AN3	$[0°, 45°]$	1.2×10^{-8}	TR	1.3×10^8	1.5
			SH	4.5×10^7	0.5
IC1	$[-30°, -5°]$	1.3×10^{-9}	TR	4.0×10^9	5.4
IC2	$[-5°, 0°]$	2.6×10^{-10}	TR	1.5×10^{10}	3.9
IC3	$[0°, 30°]$	3.1×10^{-10}	TR	1.9×10^{10}	5.8
IC4	$[30°, 60°]$	4.5×10^{-10}	TR	1.4×10^{10}	6.3
IC5	$[60°, 90°]$	9.9×10^{-10}	TR	1.4×10^{10}	14

Albert et al. (2017); Aartsen et al. (2020); Table from 2202.01126

Constraining f_{DS} w/ Neutrinos

excluding inner 5 kpc → open　　　all nuPSs → filled

z_f = 23
z_f = 15
z_f = 11



Constraints on the First Stars from DM Spikes

- **Examples of how to place limits on the fraction of minihalos in the early universe that could have hosted formation of dark stars (robust w.r.t. uncertainties about inner halo dynamics).**
    - If remnant black holes are very massive, the fraction of early minihalos that hosted one is small.
    - If DM annihilates to quarks or gauge bosons, and if the typical remnant is ~100 $M_\odot$, there are some constraints on the fraction of early minihalos that hosted such an object.
    - The smallest black holes considered are largely unconstrained (Population III.1 remnants?).
- Could one be hiding in the Fermi catalog? >1300 unassociated sources in 4FGL. eg. Buckley & Hooper (2010) analysis
- Neutrino point source analysis is even more powerful! w/ Galstyan, Freese, & Stengel (2202.01126)

Summary

★ The fist stars may have experienced a phase where they were powered by DM annihilation (rather than nuclear fusion) → **Dark Stars**.

★ In some cases, the Dark Star phase could have lasted a very long time, potentially until today!

★ These stars could have been very large (up to ~10^7 $M_\odot$) and very bright (up to ~10^{11} $L_\odot$), such that they **may be observable with JWST** out to redshifts of ~15.

★ Each would leave a **BH remnant** surrounded by a **DM spike**, which could be observable using various DM indirect detection techniques.

★ Cosmological measurements will provide insight about the Dark Star phase.

Dark matter may have played a critical role in the lives of the very first stars in the Universe.

Evidence of these objects would help us understand the nature of dark matter.