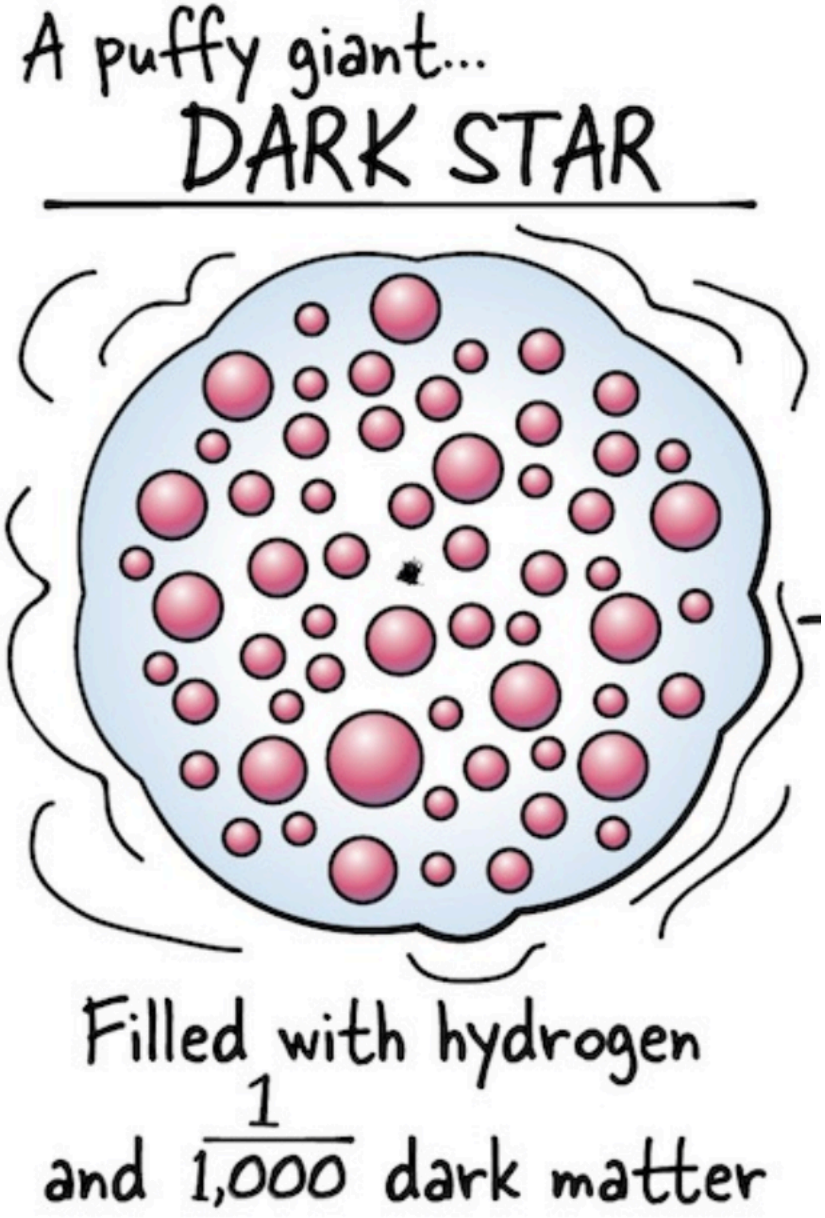


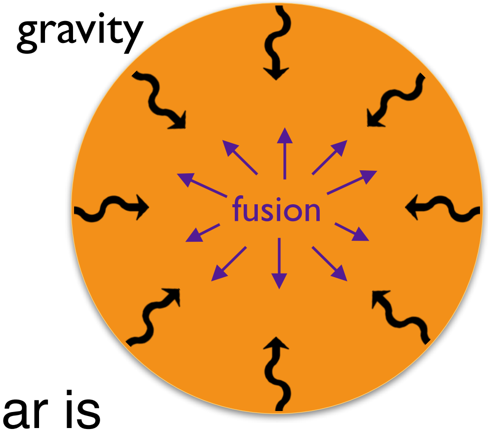
Dark Stars: A Dark Matter-Powered Phase of Stellar Evolution

Pearl Sandick
University of Utah

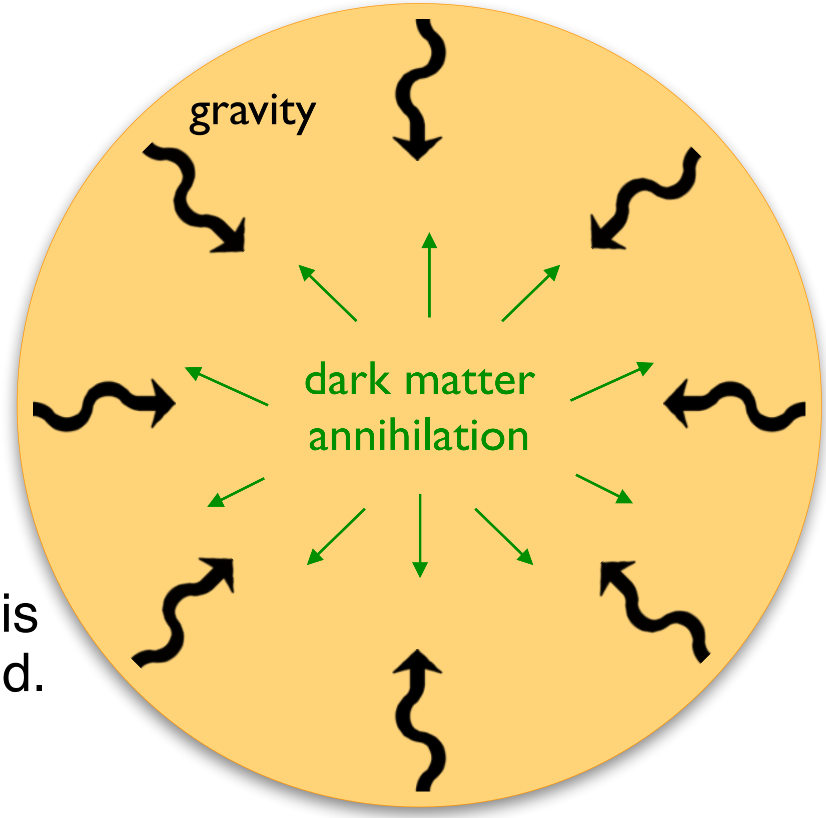
EDSU - November 2022

Dark Star Phase

Dark Star: a star powered by dark matter annihilation that formed with the first generation of stars



“Regular” star is fusion-powered.



“Dark” star is DM-powered.

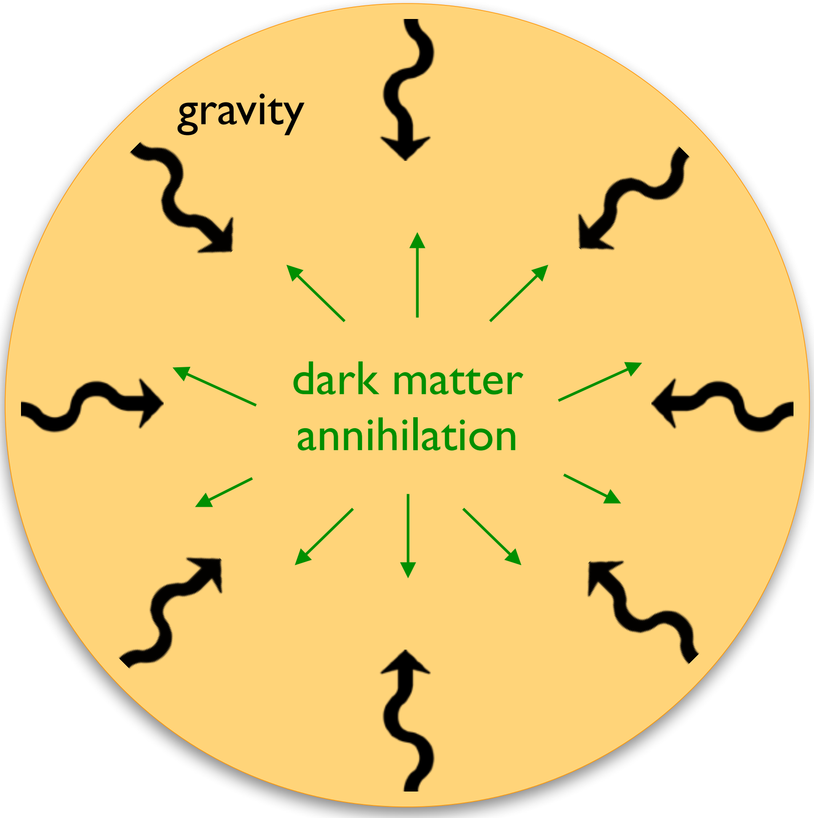
- Dark stars are **bigger**, **puffier**, **colder**, and **more luminous** than regular (fusion-powered) stars

Dark Star Phase

Dark Star: a star powered by dark matter annihilation that formed with the first generation of stars

- Dark stars are **bigger**, **puffier**, **colder**, and **more luminous** than regular (fusion-powered) stars

  - Could be seen directly by JWST!
  - Interesting cosmological and astrophysical signatures possible
  - Seeds for Super-Massive Black Holes (millions-billions time the mass of the Sun)?



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 - w/ 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

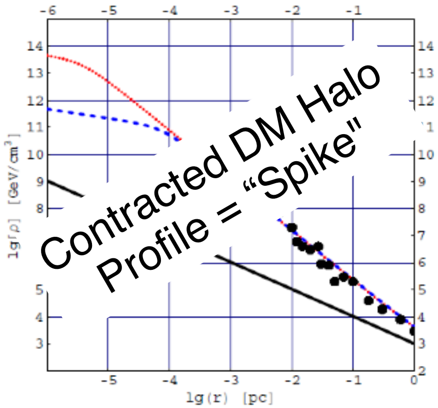
- Pop III.1 stars formed at ***high redshift*** ➔ *$\rho \sim (1+z)^3$*
- If dark matter particles annihilate ➔ ***annihilation rate*** *$\sim \rho^2$*
- Each Pop III.1 star formed at the ***center of a minihalo***

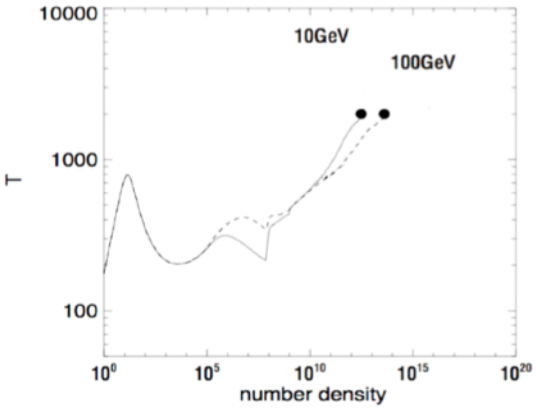
Could DM annihilation power a star? Spolyar, Freese & Gondolo (2008+)

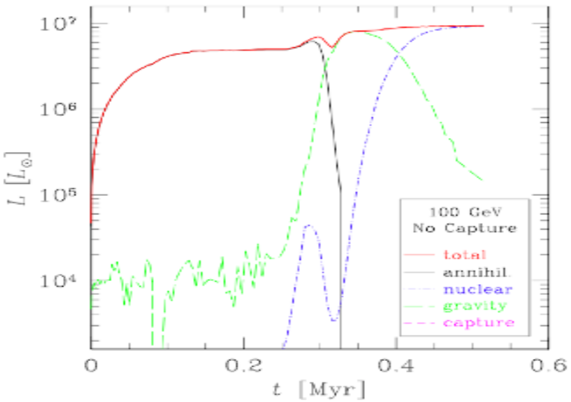
✔ 1. Sufficiently high DM density for large annihilation rate

✔ 2. Annihilation products get stuck in star $f_Q \approx 2/3$

✔ 3. Dark matter heating is dominant

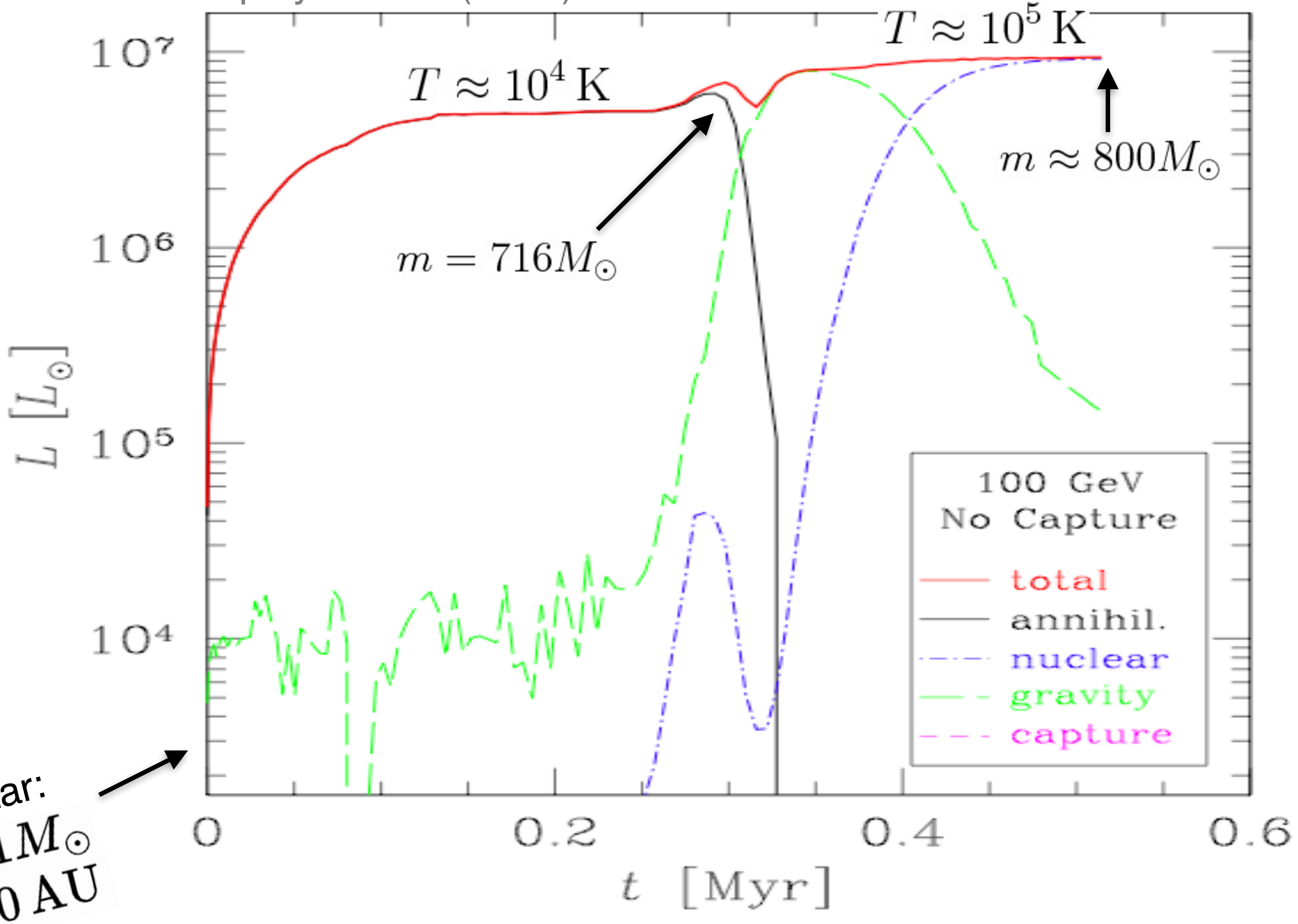

Contracted DM Halo Profile = "Spike"





Dark Star Evolution

Spolyar et al. (2009)



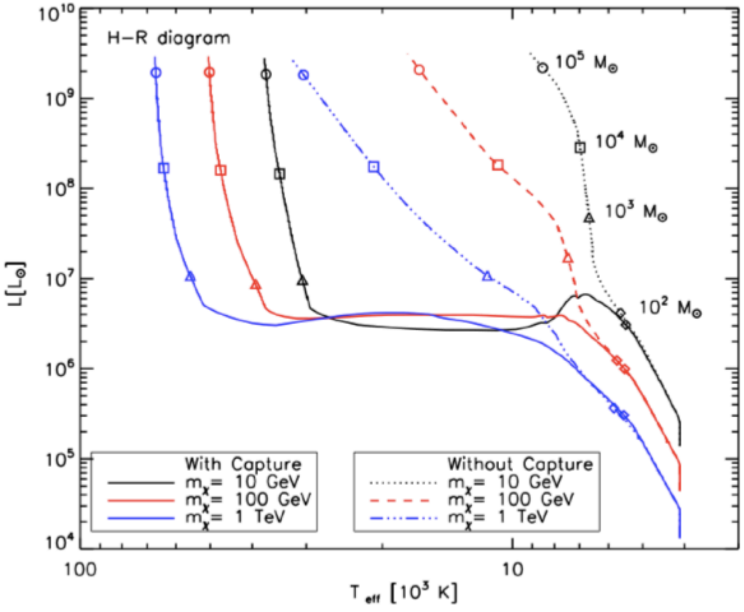
Protostar:
$m < 1 M_\odot$
$r > 10\,\mathrm{AU}$

Dark Star Mass and Lifetime

- 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.
  - (initially) triaxial halos, an O(1) fraction of DM particles remain on centrophilic orbits. See work by Valluri et al.
- **Dark Matter Capture:** DM particles scatter with nuclei in the star, becoming bound.
  - Dark Star continuously fed DM fuel.
- These different mechanisms that prolong the Dark Star phase lead to stars with different properties!

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

Freese et al. (2010)



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.

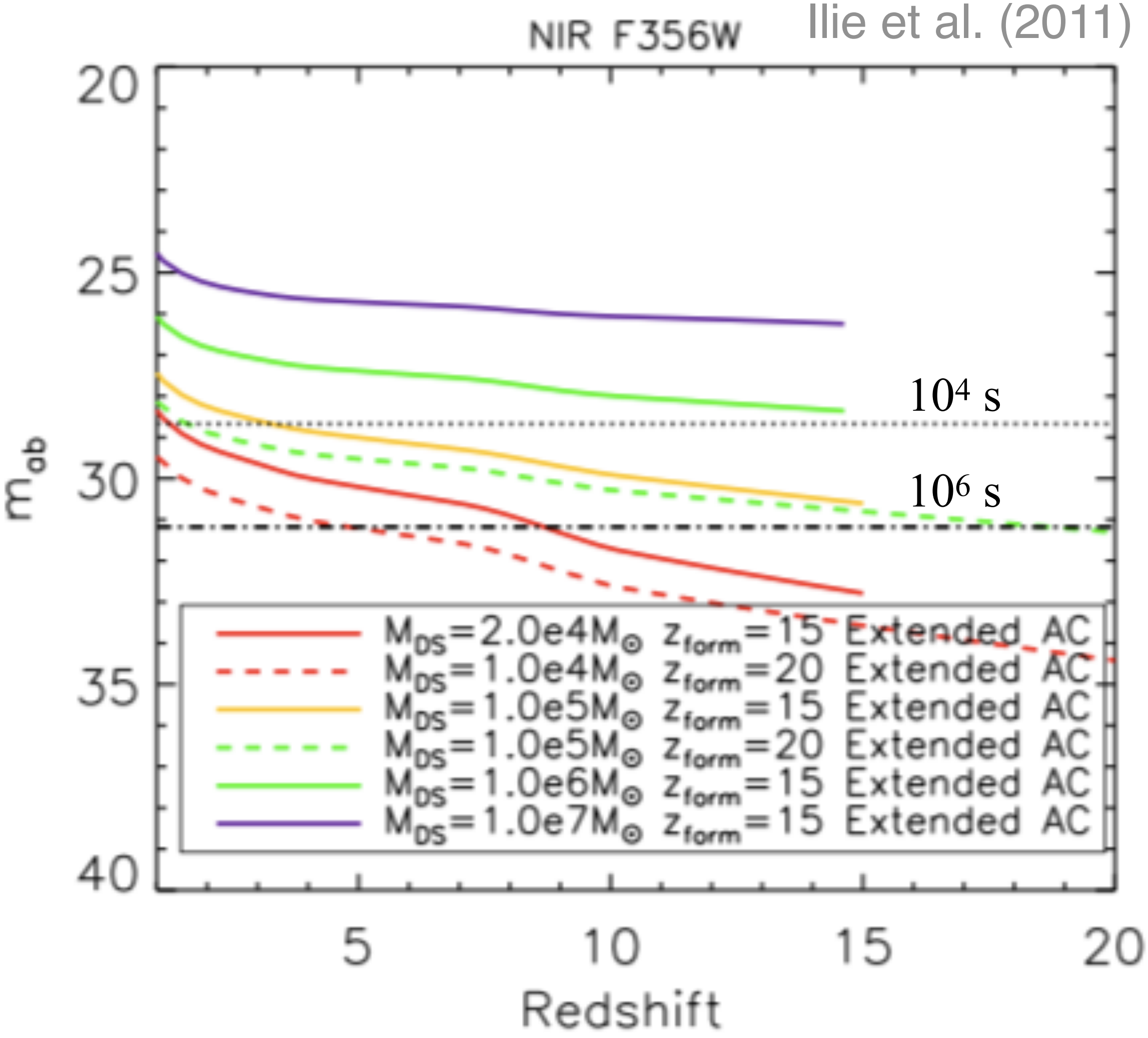
Dropout technique: detected in all frequencies down to where Lyman-α absorption becomes significant Ilie, Freese, Valluri, Iliev, & Shapiro (2011)

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

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

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

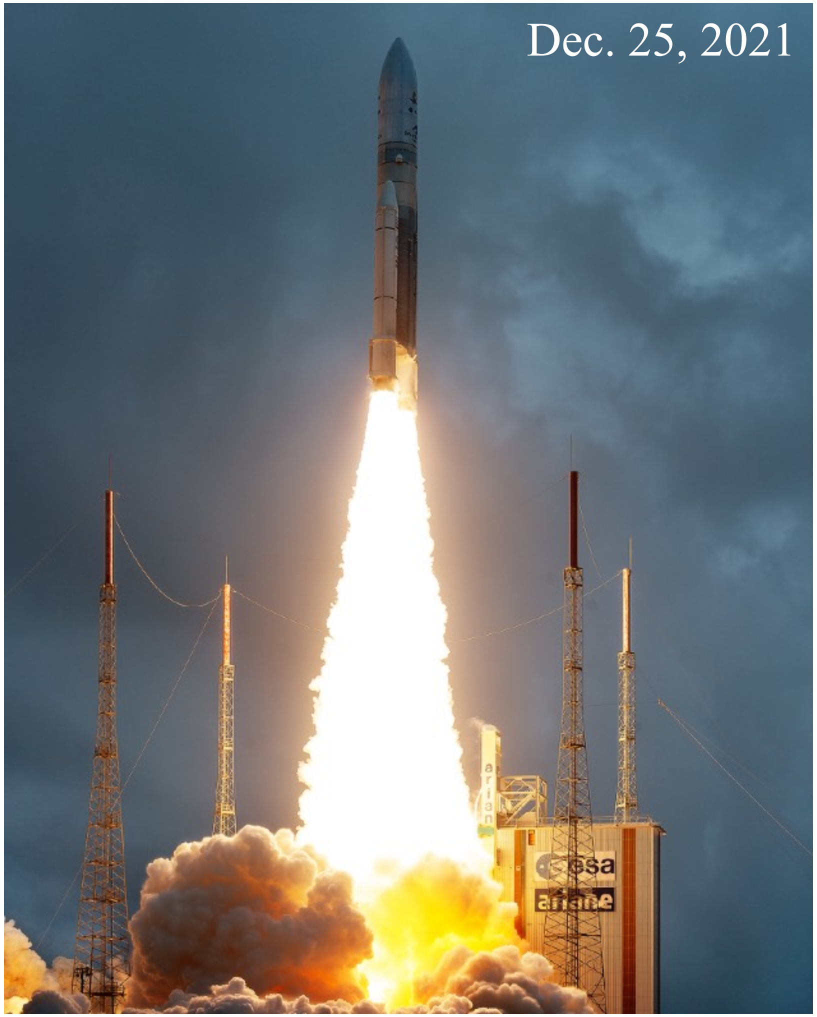
Also Freese, Ilie, Spolyar, Valluri, Bodenheimer (2010)



Ilie et al. (2011)

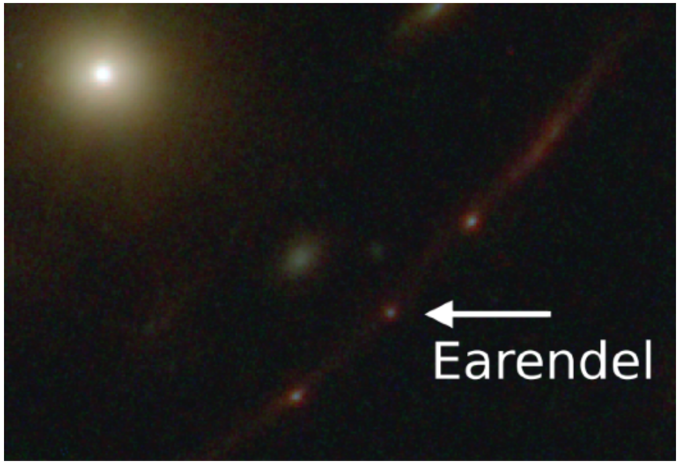
Detection

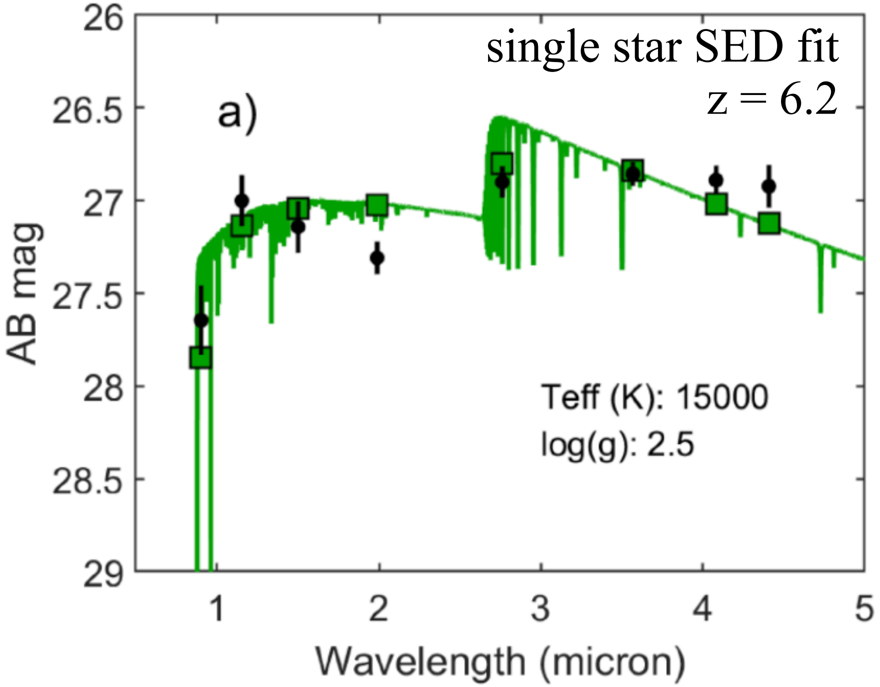
1. Direct observation with JWST


Dec. 25, 2021

NASA/Chris Gunn

Welch et al. (2022)




single star SED fit
z = 6.2

Detection

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

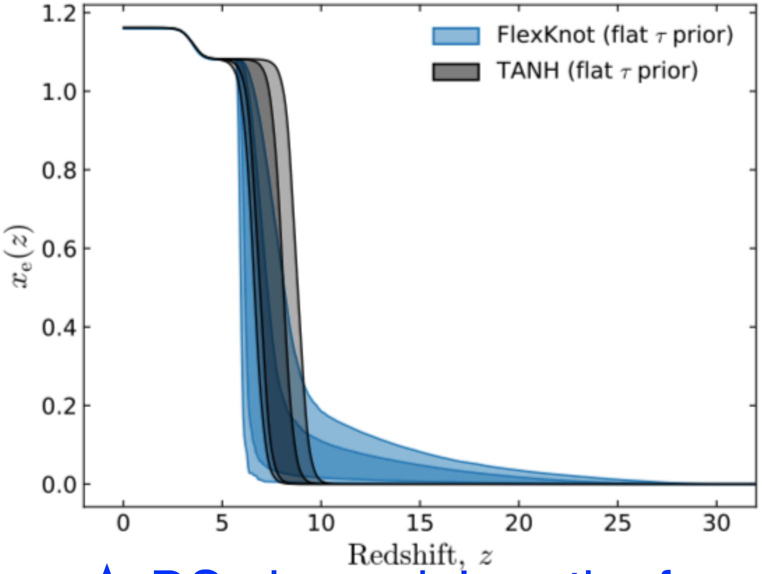
- ➔ extragalactic background light (EBL) contribution from DS phase
- ➔ accumulated flux from DMA around cosmological remnant BHs
  - ➔ photons
    - ➔ radio signal from synchrotron radiation of charged annihilation products around remnant BHs (w/ Matt Stephens)
  - ➔ neutrinos
- ➔ **optical depth** (w/ P. Gondolo & B. Shams Es Haghi, 2022)
- ➔ 21cm (w/ A. Perko, N. Tapia Arellano, & 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)

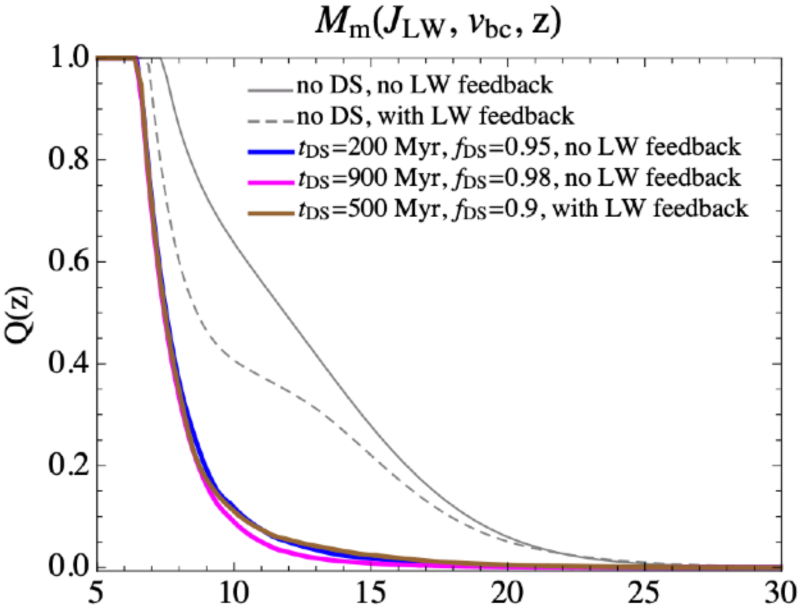
Optical Depth

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 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 (2022)

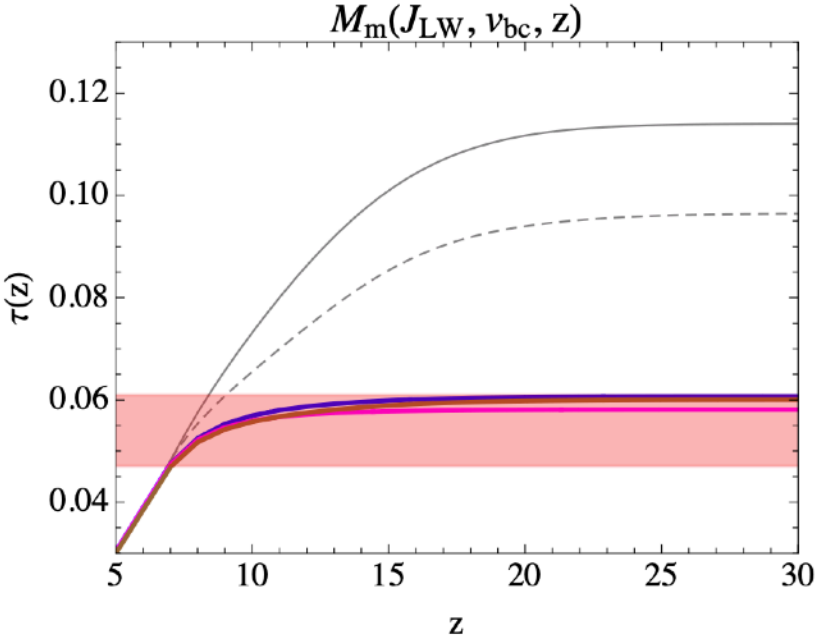
Optical Depth

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)

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 many stars had a dark star phase and it lasted for some time.



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

w/ Gondolo, Shams Es Haghi, & Visbal (2022)

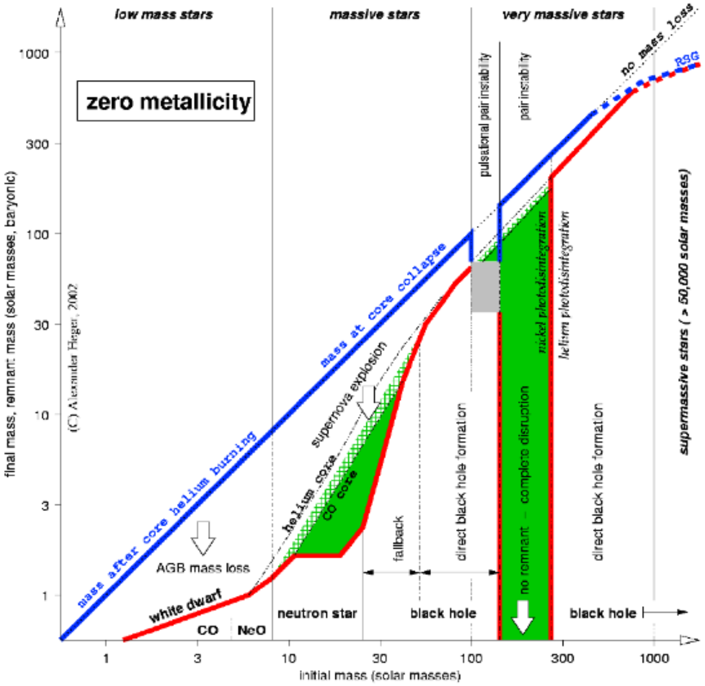
Detection

Dark Star PopIII Star Remnant BH

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

Dark Star → PopIII star → BH remnant

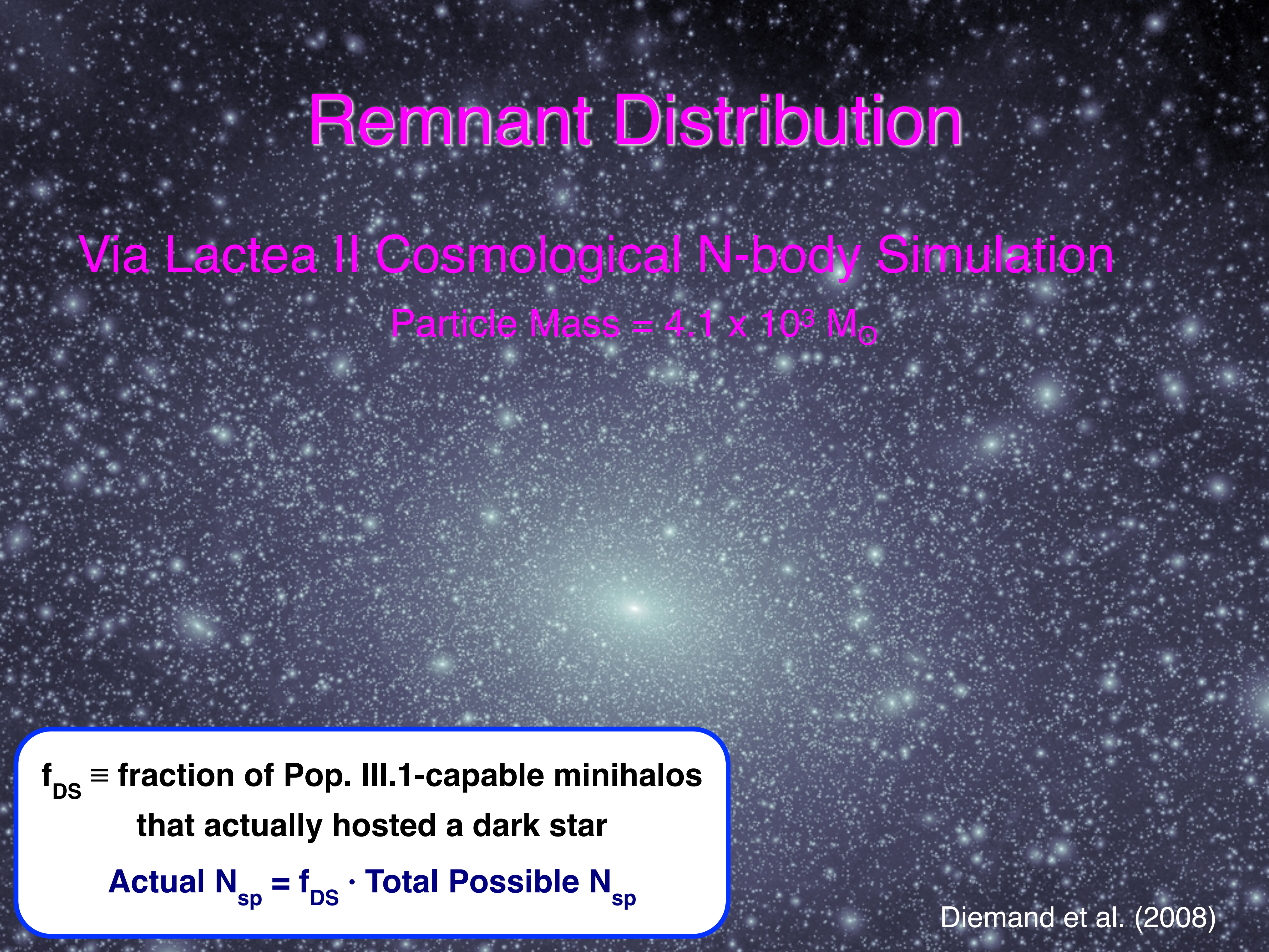
- ➔ point sources (if they are bright enough)
  - ➔ gamma rays
  - ➔ neutrinos
- ➔ contribution the diffuse flux (if they are faint)
  - ➔ gamma rays
  - ➔ neutrinos
  - ➔ charged leptons, (anti)protons, etc.


Heger and Woosley (2002)

- Sandick Diemand, Freese, Spolyar (2011)
- Sandick & Watson (2011)
- Sandick, Diemand, Freese, Spolyar (2012)
- Galstyan, Freese, Sandick, & Stengel (2022)

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

Remnant Distribution



Via Lactea II Cosmological N-body Simulation

Particle Mass = $4.1 \times 10^3\ M_\odot$

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

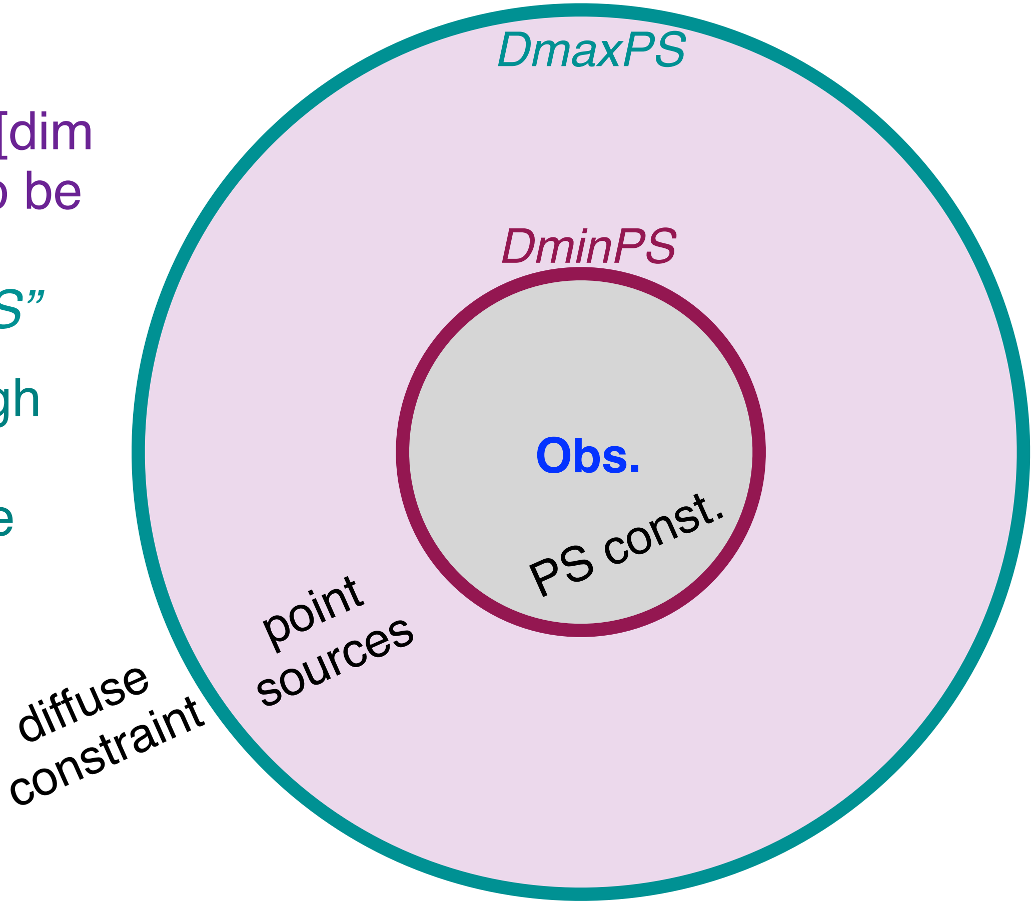
Actual $N_{sp} = f_{DS} \cdot$ Total Possible N_{sp}

Diemand et al. (2008)

Diffuse vs. Point Source Flux

Assuming some **characteristic DS model**, two ways they could show up:

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

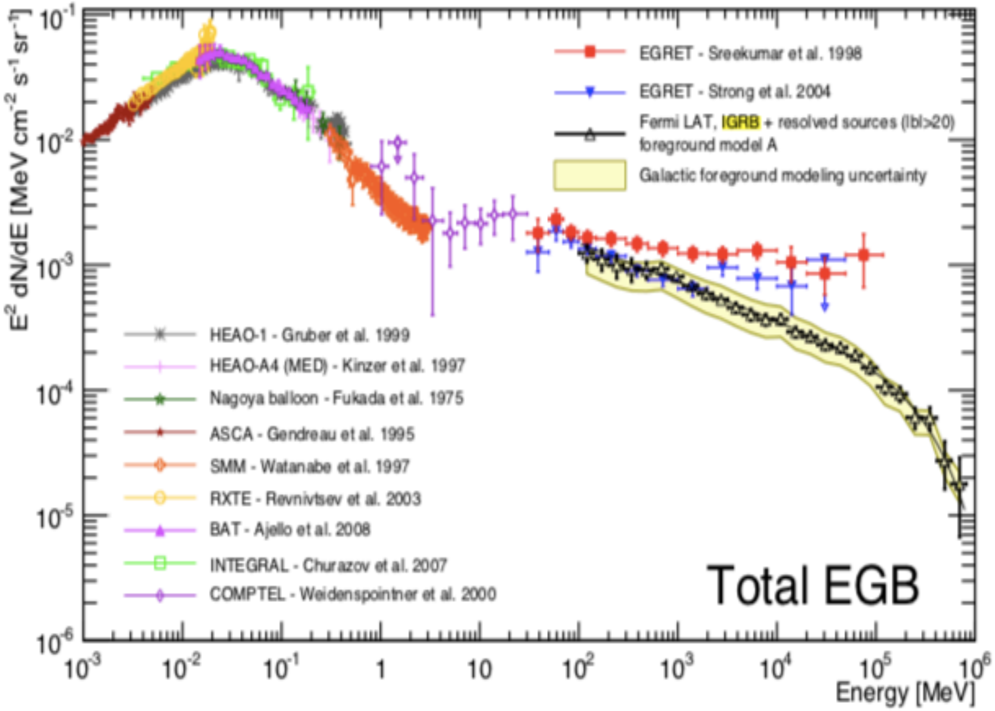


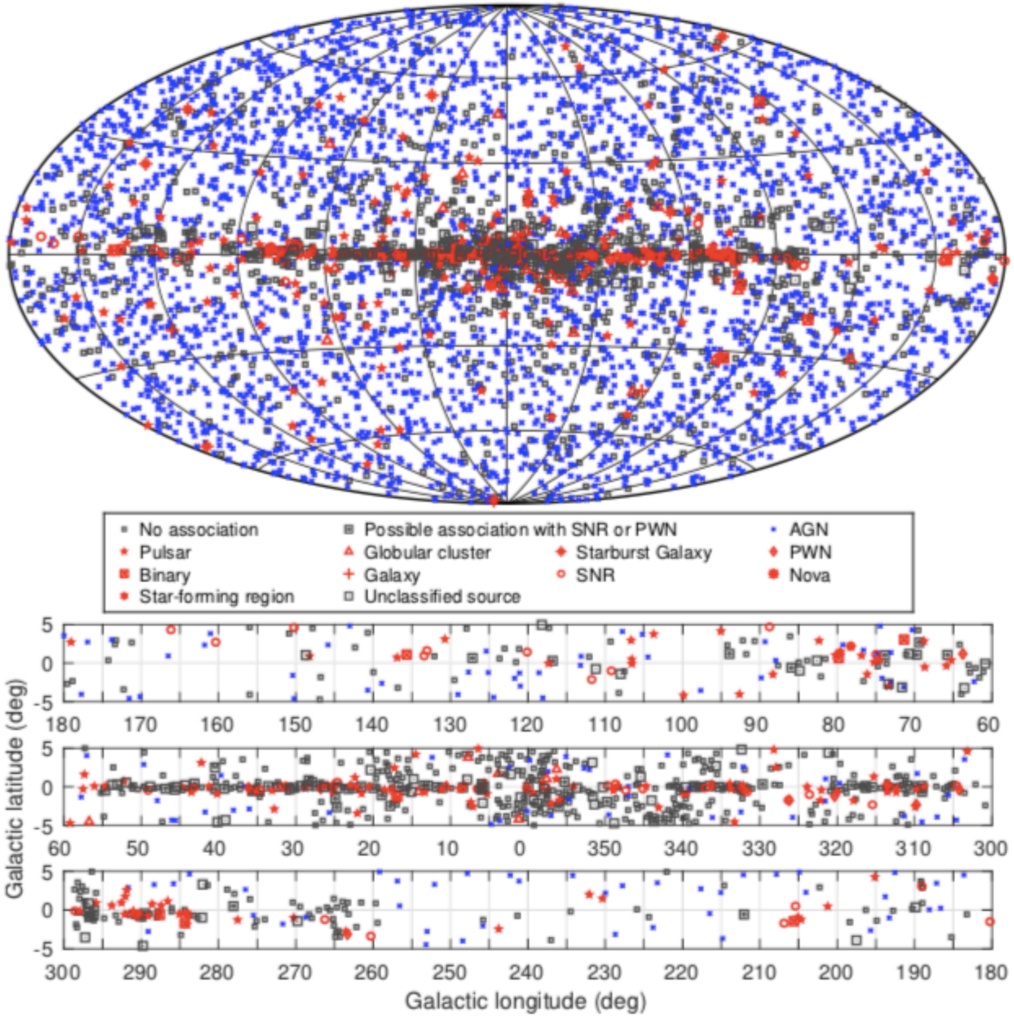
Sandick Diemand, Freese, Spolyar (2011)
Sandick & Watson (2011)
Sandick, Diemand, Freese, Spolyar (2012)

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)

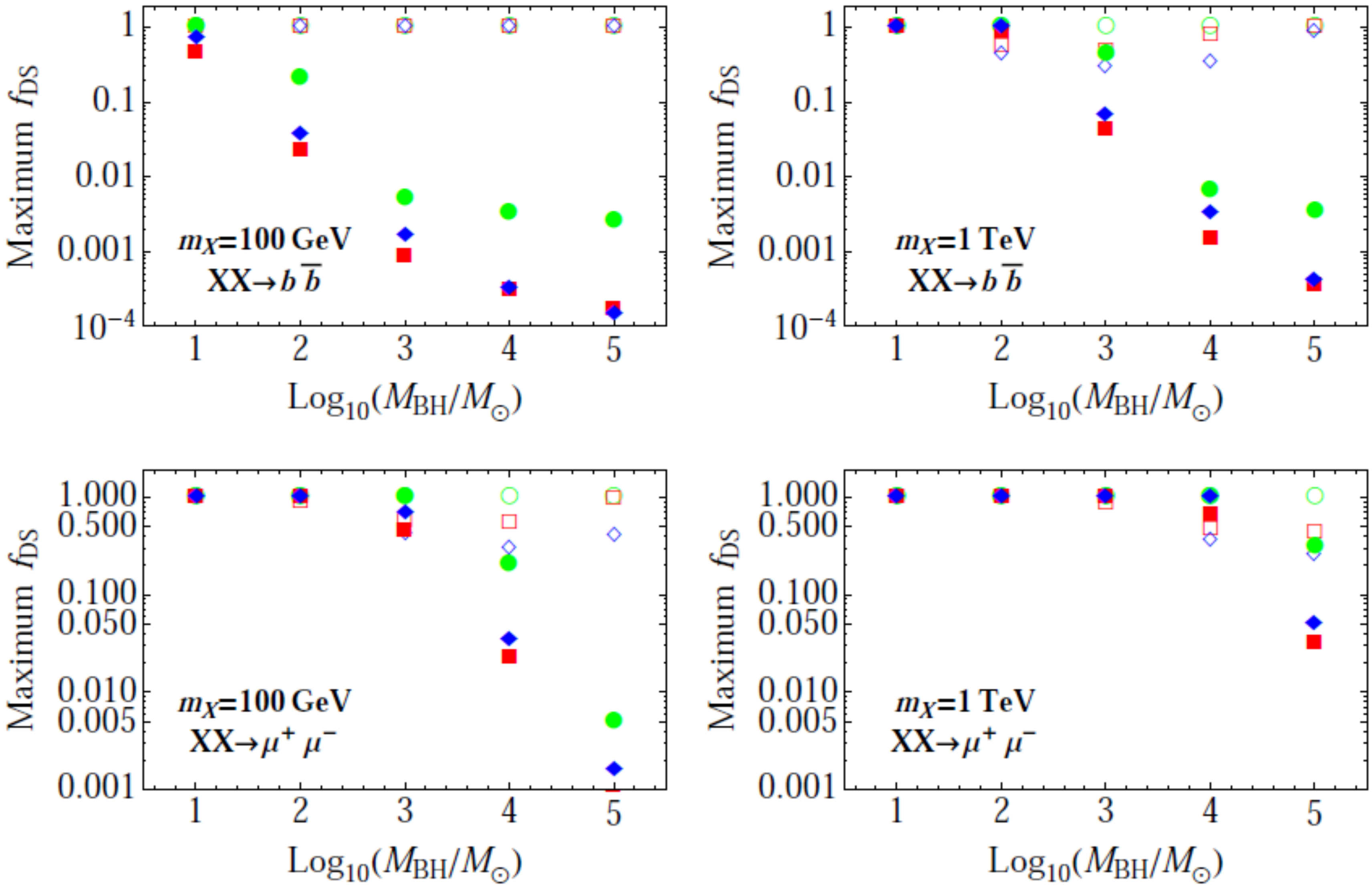
Unassociated FGST PSs

$z_f = 23$

$z_f = 15$

$z_f = 11$

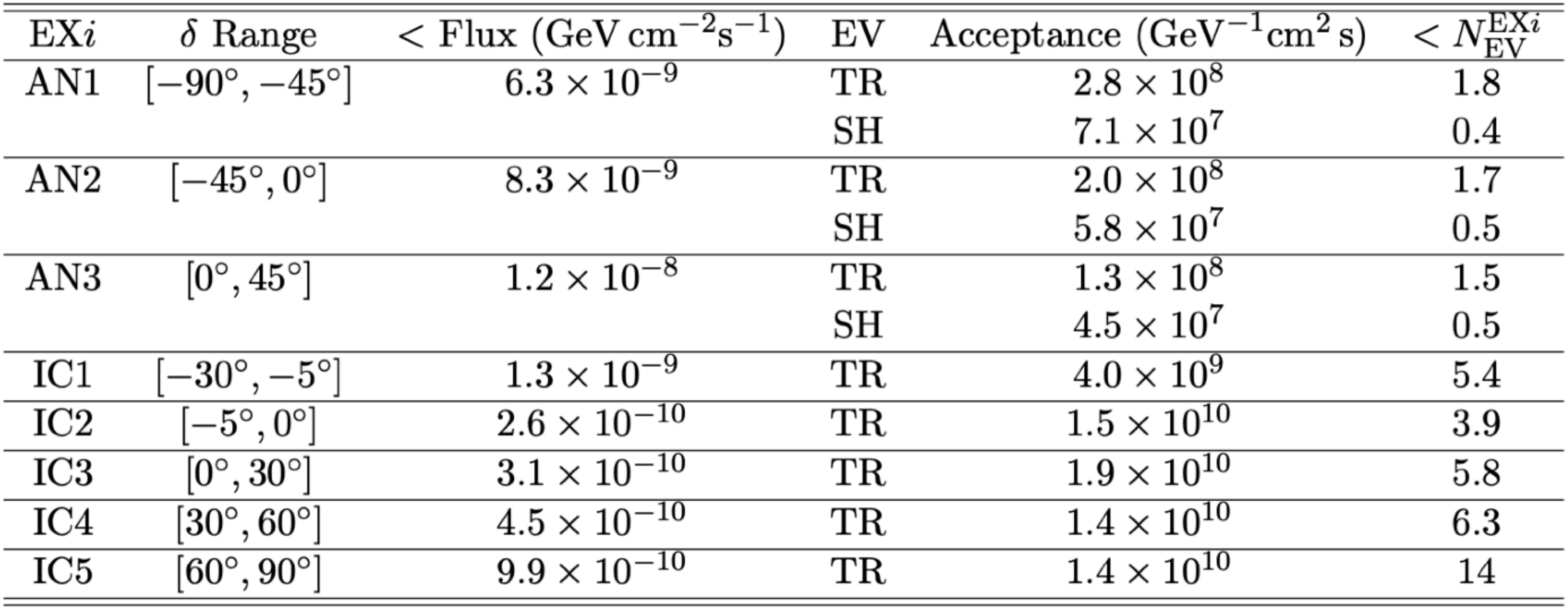
diffuse → open   point source → filled



Sandick Diemand, Freese, Spolyar (2011)

ANTARES and IceCube

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



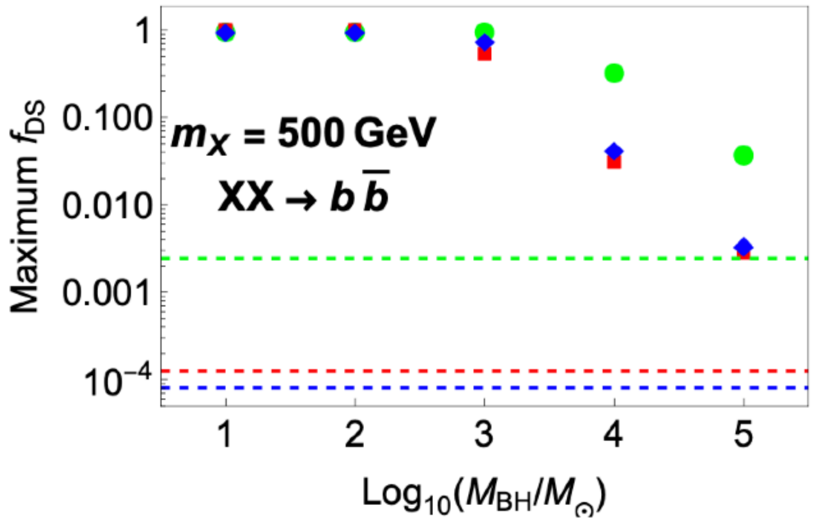
EXi	δ Range	$<$ Flux (GeV cm^{-2}s^{-1})	EV	Acceptance (GeV^{-1}cm^2 s)	$< N_{\rm EV}^{{\rm EX}i}$
AN1	$[-90°, -45°]$	6.3×10^{-9}	TR	2.8×10^8	1.8
			SH	7.1×10^7	0.4
AN2	$[-45°, 0°]$	8.3×10^{-9}	TR	2.0×10^8	1.7
			SH	5.8×10^7	0.5
AN3	$[0°, 45°]$	1.2×10^{-8}	TR	1.3×10^8	1.5
			SH	4.5×10^7	0.5
IC1	$[-30°, -5°]$	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 Galstyan et al. (2022)

Constraining f_{DS} w/ Neutrinos

$z_f = 23$
$z_f = 15$
$z_f = 11$

excluding inner 5 kpc → open   all nuPSs → filled



Constraints are stronger for larger DM masses and for leptonic final states (relative to gamma-ray constraints).

- **Examples of limits on f_{DS}, 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).**
  - Both gamma-ray and neutrino point source constraints are strong!
  - Could one be hiding in the Fermi catalog? >1300 unassociated sources in 4FGL. eg. Buckley & Hooper (2010) analysis

$\mathrm{Log}_{10}(M_{BH}/M_\odot)$

w/ Galstyan, Freese, & Stengel (2022)

Summary

- The fist stars may have experienced a phase where they were powered by DM annihilation (rather than nuclear fusion) → **Dark Stars**.
- A Dark Star phase could have led to a huge variety of astrophysical and cosmological effects that could be observable.
- These stars could have been very large (up to $\sim 10^7 M_\odot$) and very bright (up to $\sim 10^{11} L_\odot$), such that they **may be observable with JWST** out to redshifts of ~15.
- There are a number of possible diffuse signals and **cosmological effects** (eg. optical depth).
- Each probably left a **BH remnant** surrounded by a **DM spike**, which could be observable using various DM indirect detection techniques.

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

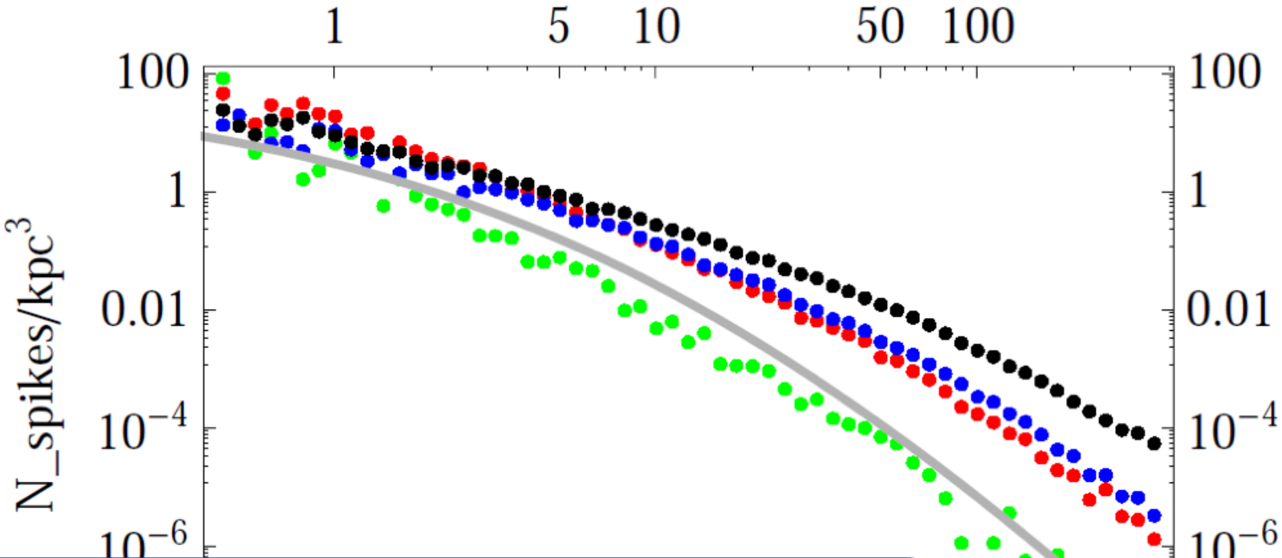
Evidence of these objects would help us understand the nature of dark matter.

Extra Slides

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}

Constraining f_{DS}

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

$$\boxed{\begin{gathered} N_{sp}(R, f_{DS}) = f_{DS} \times N_{sp}(R, f_{DS} = 1) \\ \int_0^{D_{min}^{PS}} r^2 dr \int_0^{4\pi} d\Omega \, N_{sp}(R, f_s) \leq 1 \end{gathered}}$$

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

- With diffuse flux ("Diffuse Constraint"):

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

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