

# Has JWST discovered Dark Stars?

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Proceedings of National Academy of Sciences, in proof

DAVID GRANT presents  
A JOHN CARPENTER film

From  
ALAN DEAN FOSTER  
FIRST  
2001: A SPACE ODYSSEY

THEN  
THE POSEIDON ADVENTURE

NOW

# DARK STAR<sup>A</sup>



bombed out in space  
with a spaced out bomb!

# Collaborators



Doug Spolyar



Paolo Gondolo



Pearl Sandick



Tanja Rindler-Daller



Peter Bodenheimer

# This work



Cosmin Ilie  
Colgate University



Jillian Paulin

# Dark Stars

The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion. Dark stars are made almost entirely of hydrogen and helium, with dark matter constituting 0.1% of the mass of the star).

- This new phase of stellar evolution may last millions to billions of years
- Dark Stars can grow to be very large: up to ten million times the mass of the Sun. Supermassive DS are very bright, up to ten billion times as bright as the Sun. **We have found candidates in James Webb Space Telescope**
- Once the Dark Matter runs out, the DS has a fusion phase before collapsing to a big black hole: **IS THIS THE ORIGIN OF SUPERMASSIVE BLACK HOLES?**

# Basic Picture

- The first stars form at  $z=10-20$  in  $10^6$   $M_{\text{sun}}$  minihaloes, right in the DM rich center.
- Made of hydrogen and helium only from the Big Bang.
- As a gas cloud cools and collapses en route to star formation, the cloud pulls in more DM gravitationally.
- DM annihilation products typically include  $e^+/e^-$  and photons. These collide with hydrogen, are trapped inside the cloud, and heat it up.
- At a high enough DM density, the DM heating overwhelms any cooling mechanisms; the cloud can no longer continue to cool and collapse. A Dark Star is born, powered by DM.

# The Bottom Line

- JWST has found ~ 700 high redshift objects with  $z > 10$ . They assume these are “galaxy candidates”
- Too many galaxies for Lambda CDM
- Are some of them Dark Stars?
- NIRSPEC on JWST has spectra for 9 of these; so far 5 are on the arxiv or published..

(W/out spectra, can't be sure of redshift; some are low redshift)

- Specifically, JADES has four. So far, these are the ones we have studied. (JWST Advanced Extragalactic Survey)
- **OUR RESULTS: Three of the four hi-z JWST objects we studied are consistent with Dark Stars.**



0.3 Mpc

Back to Formation  
of the First Stars



# Self-gravitating cloud

Eventually exceed  
Jeans Mass  
of 1000  $M_{\text{sun}}$

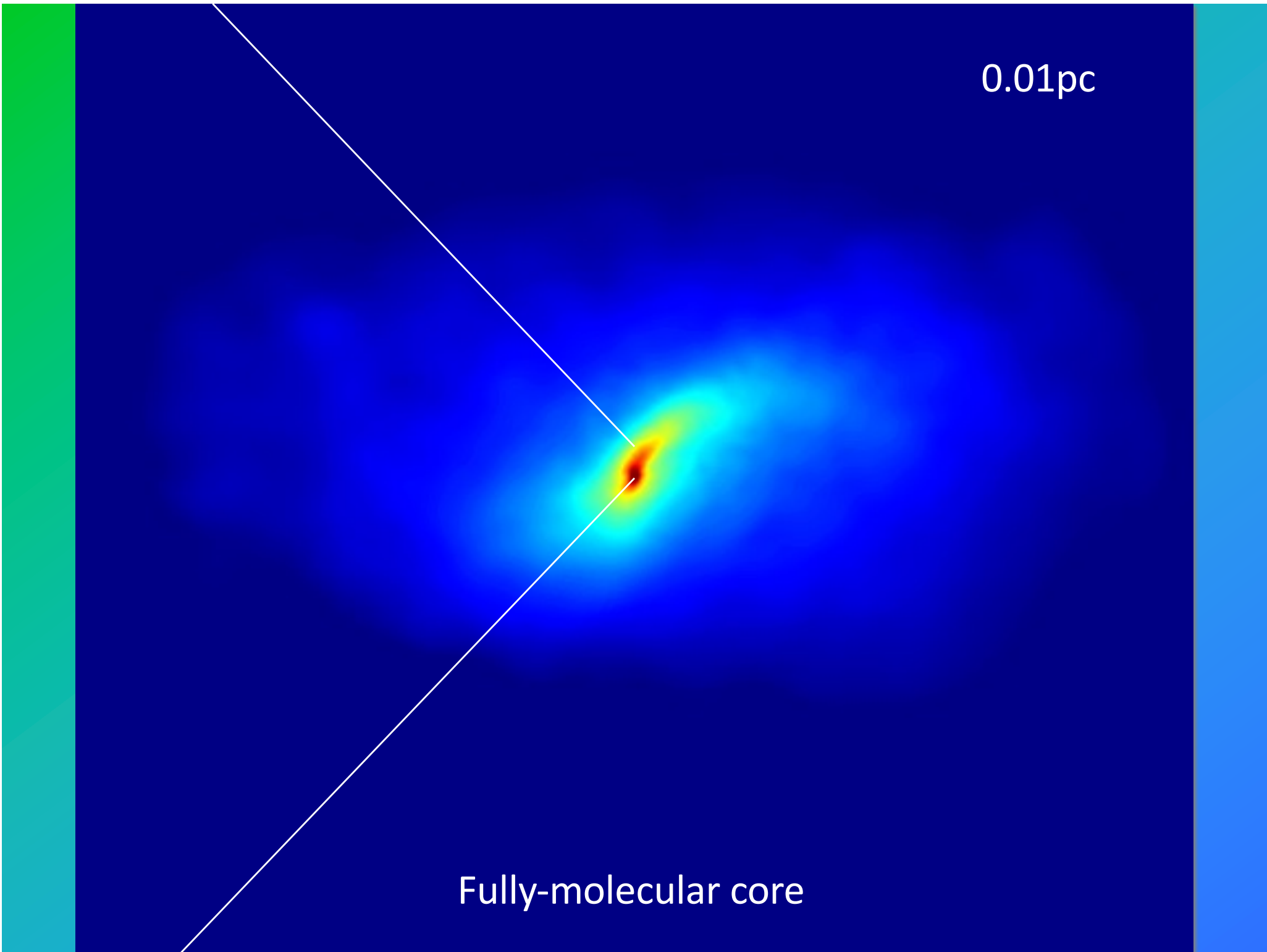


5pc

Yoshida

0.01pc

Fully-molecular core



# The role of WIMPs

Mass **1Gev-10TeV** (canonical **100GeV**)  
Annihilation cross section (WIMPS):

$$\langle\sigma v\rangle_{ann} = 3 \times 10^{-26} \text{ cm}^3 / \text{sec}$$

Same annihilation that leads to correct WIMP abundance in today's universe

Same annihilation that gives potentially observable signal in FERMI, PAMELA, AMS

# Dark Matter Heating

Heating rate:

$$Q_{ann} = n_{\chi}^2 \langle \sigma v \rangle \times m_{\chi}$$

$$= \frac{\rho_{\chi}^2 \langle \sigma v \rangle}{m_{\chi}}$$

Fraction of annihilation energy  
deposited in the gas:

$$\Gamma_{DMHeating} = f_Q Q_{ann}$$

$f_Q$ :

1/3 electrons

1/3 photons

1/3 neutrinos

# Dark Matter Power vs. Fusion

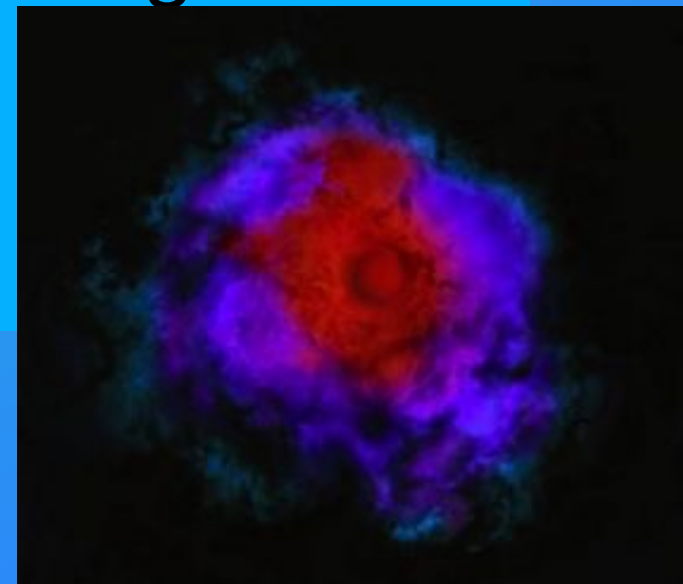
- DM annihilation is (roughly) 100% efficient in the sense that all of the particle mass is converted to heat energy for the star
- Fusion, on the other hand, is only 1% efficient (only a fraction of the nuclear mass is released as energy)
- Fusion only takes place at the center of the star where the temperature is high enough; vs. DM annihilation takes place throughout the star.

# Three Conditions for Dark Stars

(Spolyar, Freese, Gondolo 2007 aka Paper 1)

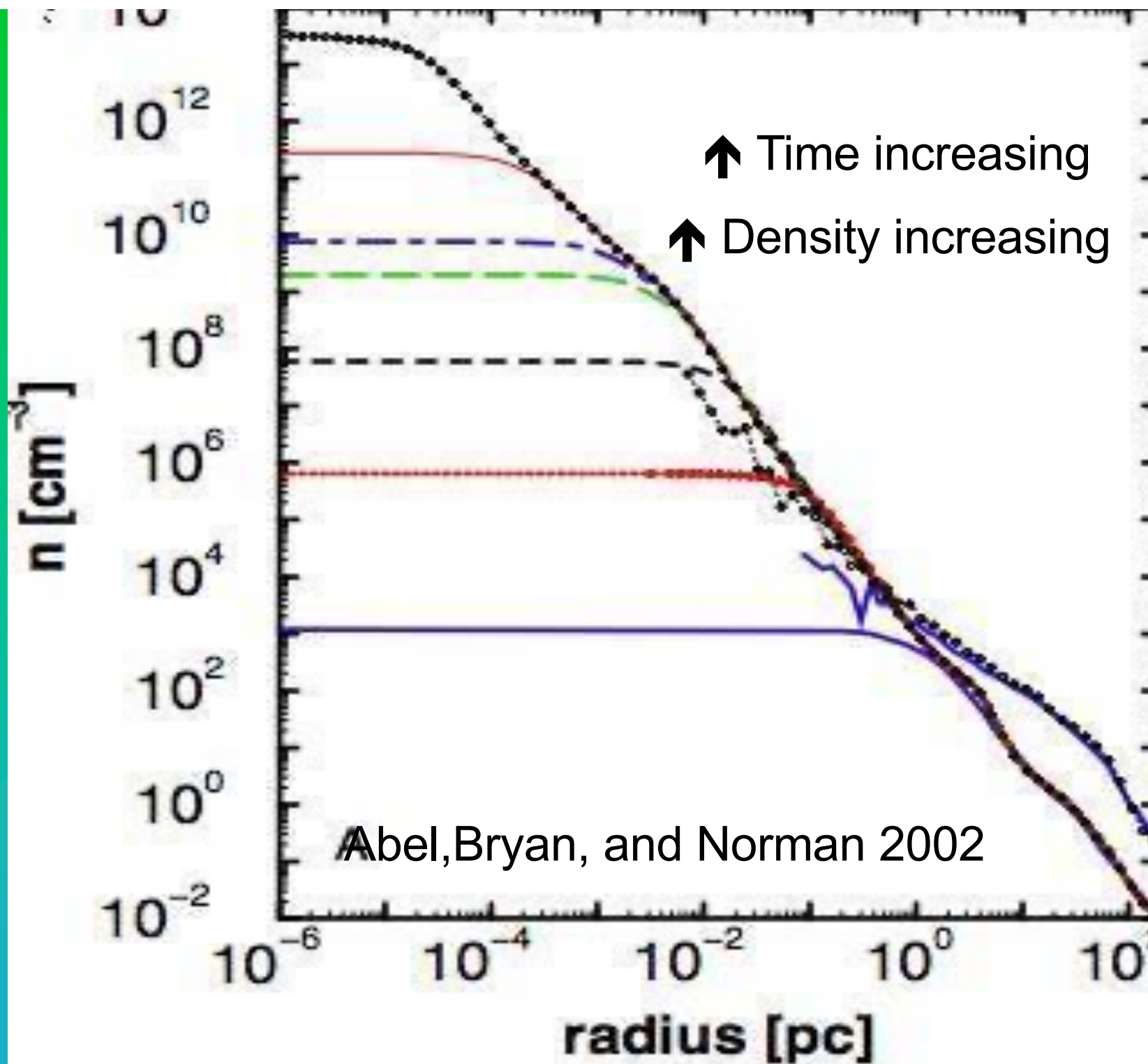
- 1) Sufficiently High Dark Matter Density ?
- 2) Annihilation Products get stuck in star ?
- 3) DM Heating beats H<sub>2</sub> Cooling ?

New Phase



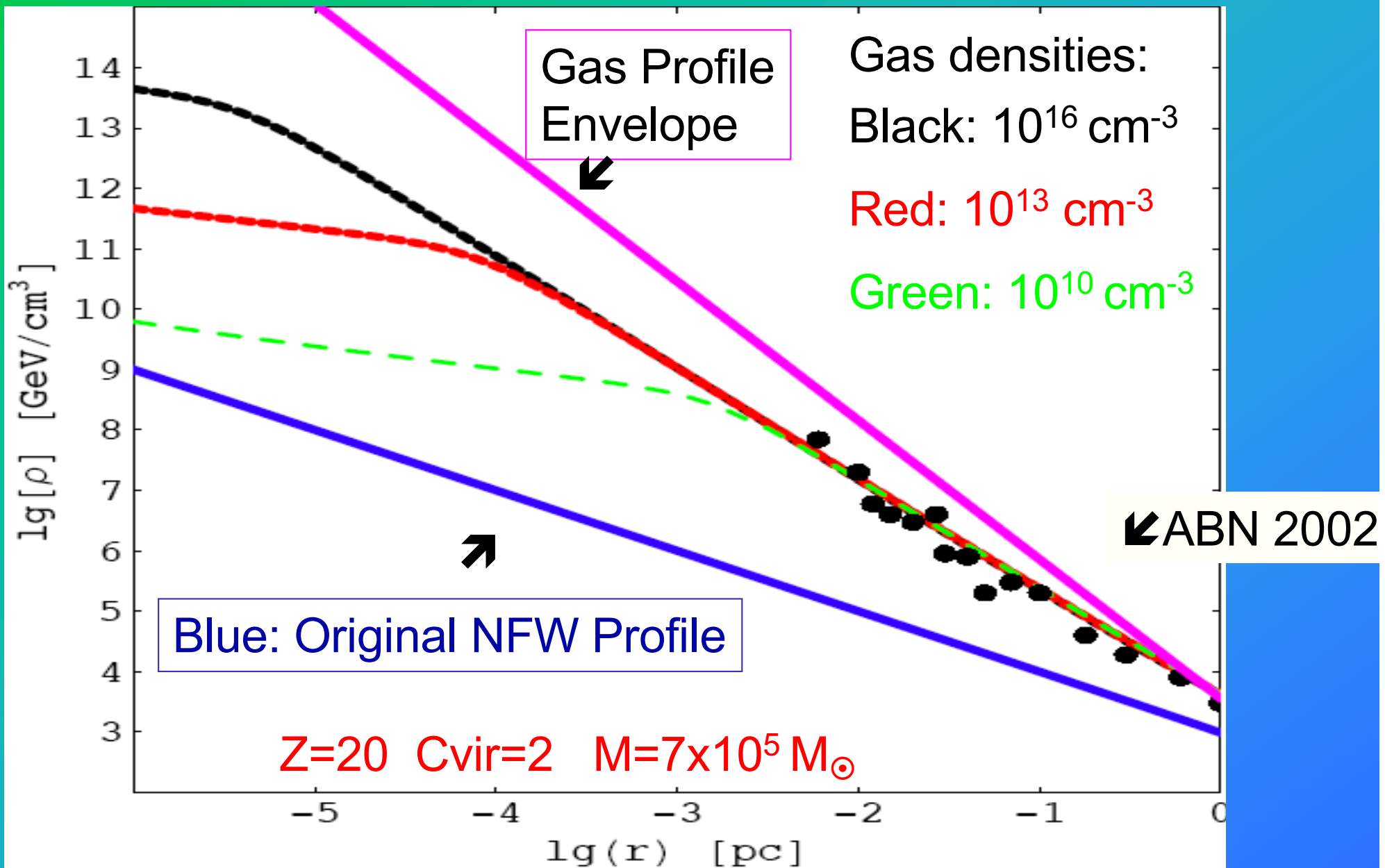
# First Condition: Large DM density

- DM annihilation rate scales as DM density squared, and happens wherever DM density is high. The first stars are good candidates: good timing since density scales as  $(1+z)^3$  and good location at the center of DM halo
- Start from standard NFW profile in million solar mass DM halo.
- As star forms in the center of the halo, it gravitationally pulls in more DM. Treat via **adiabatic contraction**.
- If the scattering cross section is large, even more gets **captured** (treat this possibility later).





# DM profile and Gas

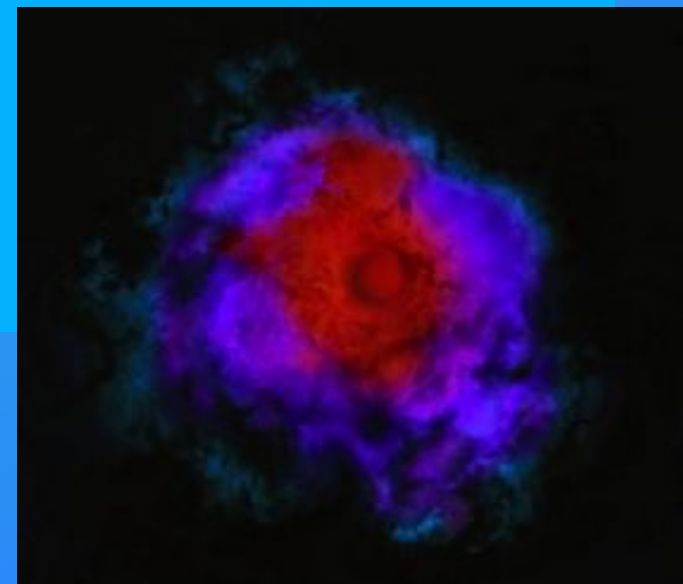


# Three Conditions for Dark Stars

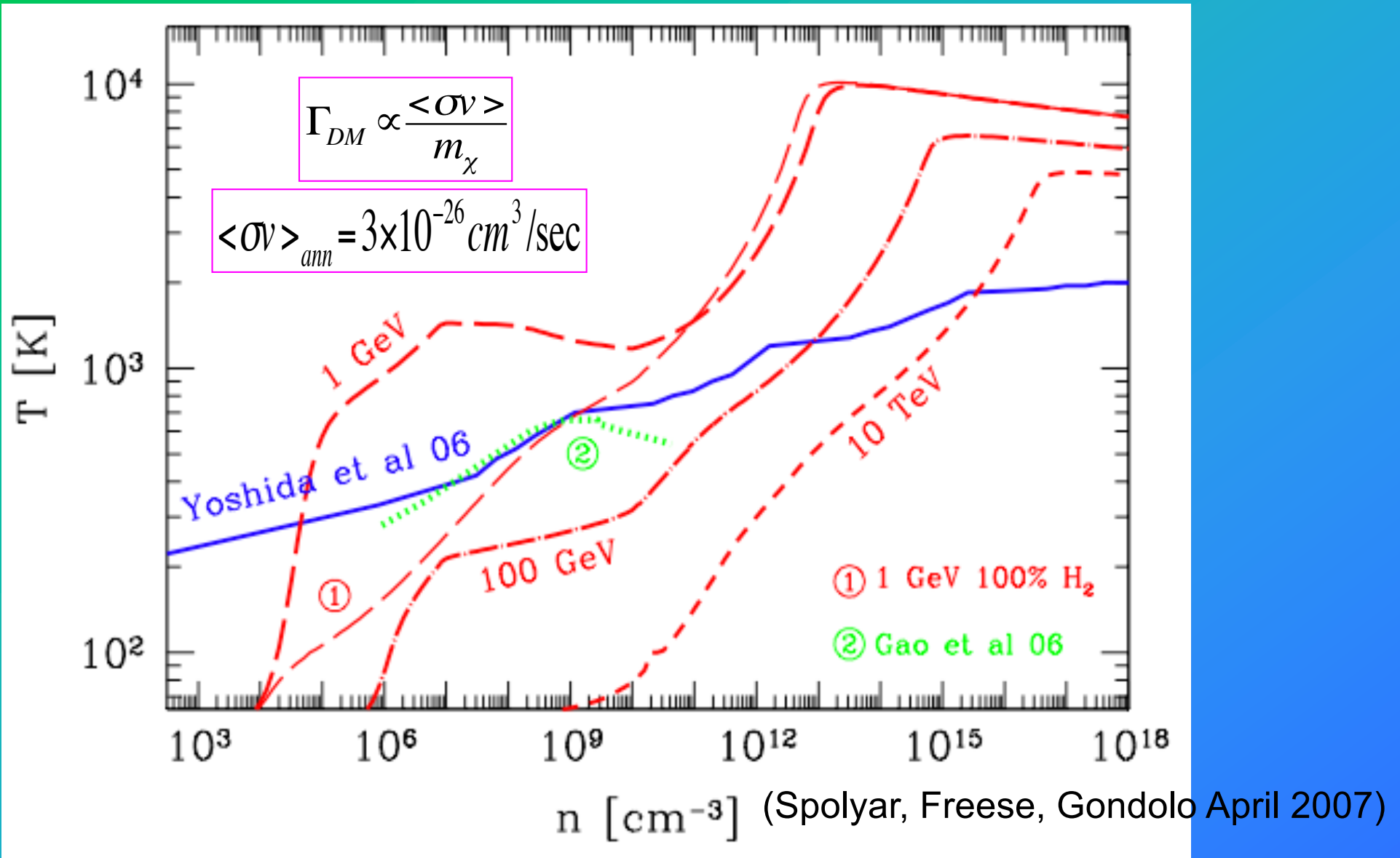
(Spolyar, Freese, Gondolo 2007 aka Paper 1)

- 1) Sufficiently High Dark Matter Density  
YES
- 2) Annihilation Products get stuck in star ?  
YES: we used Pythia and Demanded 80 radiation lengths
- 3) DM Heating beats  
H2 Cooling ? YES

New Phase



DM Heating dominates over cooling when the **red lines** cross the **blue/green lines** (standard evolutionary tracks from simulations). Then heating impedes further collapse.



# DS Basic Properties

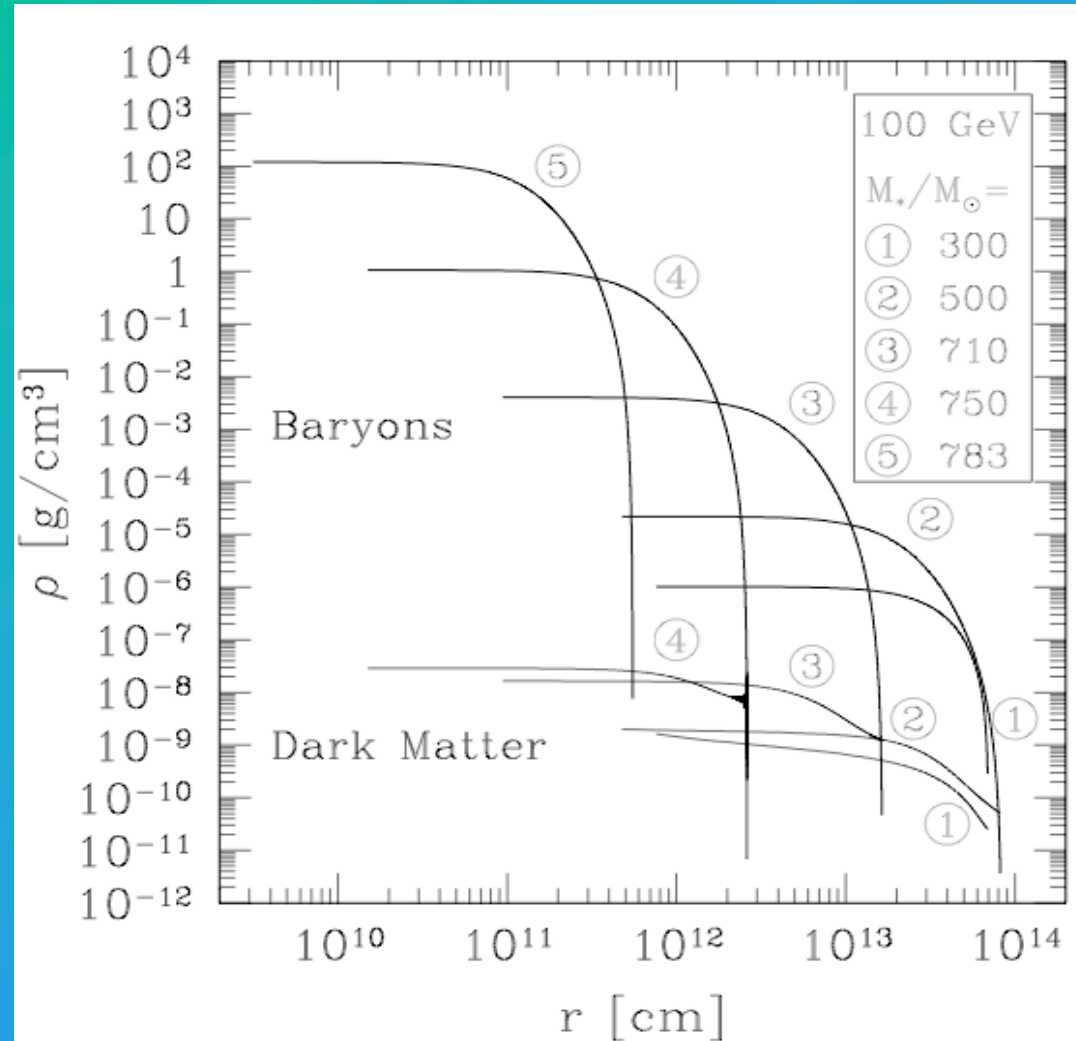
- We find that DS are big puffy objects:
  - Massive: can grow to  $10^7 M_{\odot}$
  - Large- 10 a.u. (radius of Earth's orbit around Sun)
  - Luminous: up to  $10^{10} L_{\odot}$
  - Cool: 10,000 K vs. 100,000 K plus
    - Will not reionize the universe.
  - Long lived: more than  $10^6$  years, even till today?.
  - With Capture or nonCircular orbits, get even more massive, brighter, and longer lived

# Building up the mass

- Start with a few  $M_{\odot}$  Dark Star, find equilibrium solution
- Accrete mass, one  $M_{\odot}$  at a time, always finding equilibrium solutions
- N.b. as accrete baryons, pull in more DM, which then annihilates
- Continue until you run out of DM fuel
- **VERY LARGE FIRST STARS.** Then, star contracts further, temperature increases, fusion will turn on, eventually make giant black hole

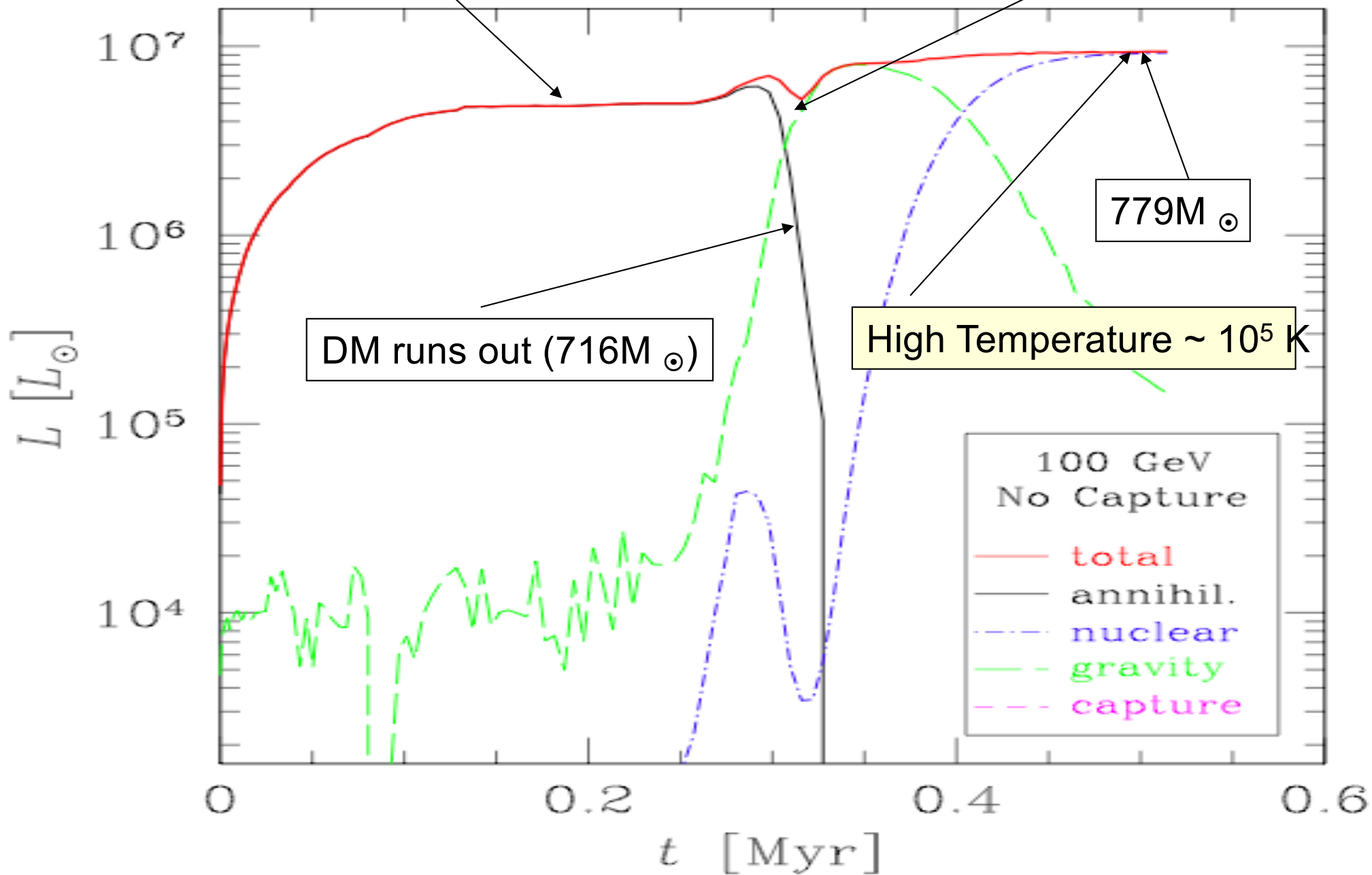
# Following DS Evolution

- Gas Accretes onto molecular hydrogen Core, the system eventually forms a star.
- We then solve for stellar Structure by:
  - Self consistently solve for the DM density and Stellar structure
  - (Overly Conservative) DM in spherical halo. We later relax this condition



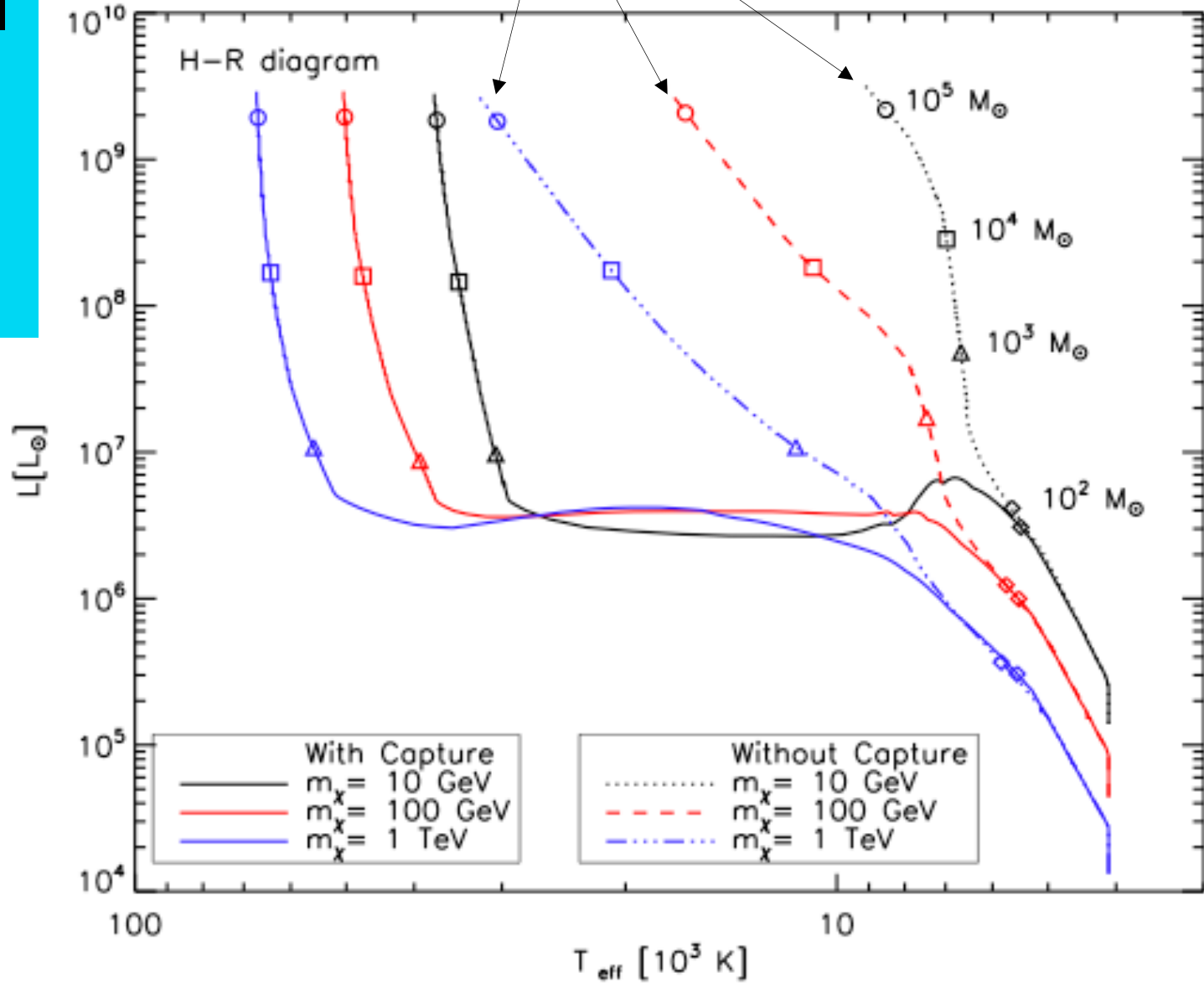
Low Temperature  $10^4$  K

Gravity turns on



Super Massive DS due to extended adiabatic contraction since reservoir has been replenished due to orbital structure

Assuming all of the baryons can accrete in a  $10^6 M_{\odot}$  halo





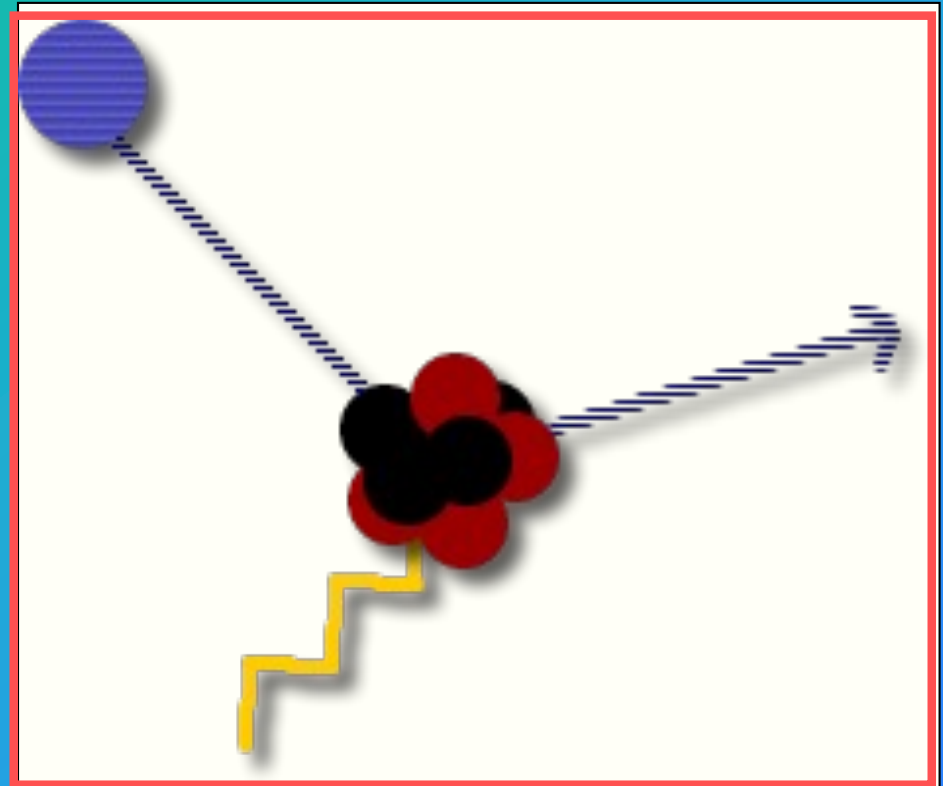
# Additional possible source of DM fuel: capture

- Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured. (This is the origin of the indirect detection effect in the Earth and Sun).
- Two uncertainties:
  - (i) ambient DM density (ii) scattering cross section must be high enough.
- Whereas the annihilation cross section is fixed by the relic density, the scattering cross section is a free parameter, set only by bounds from direct detection experiments.

# WIMP scattering off nuclei leads to capture of more DM fuel

Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured.

This is the same scattering that direct detection experiments are looking for

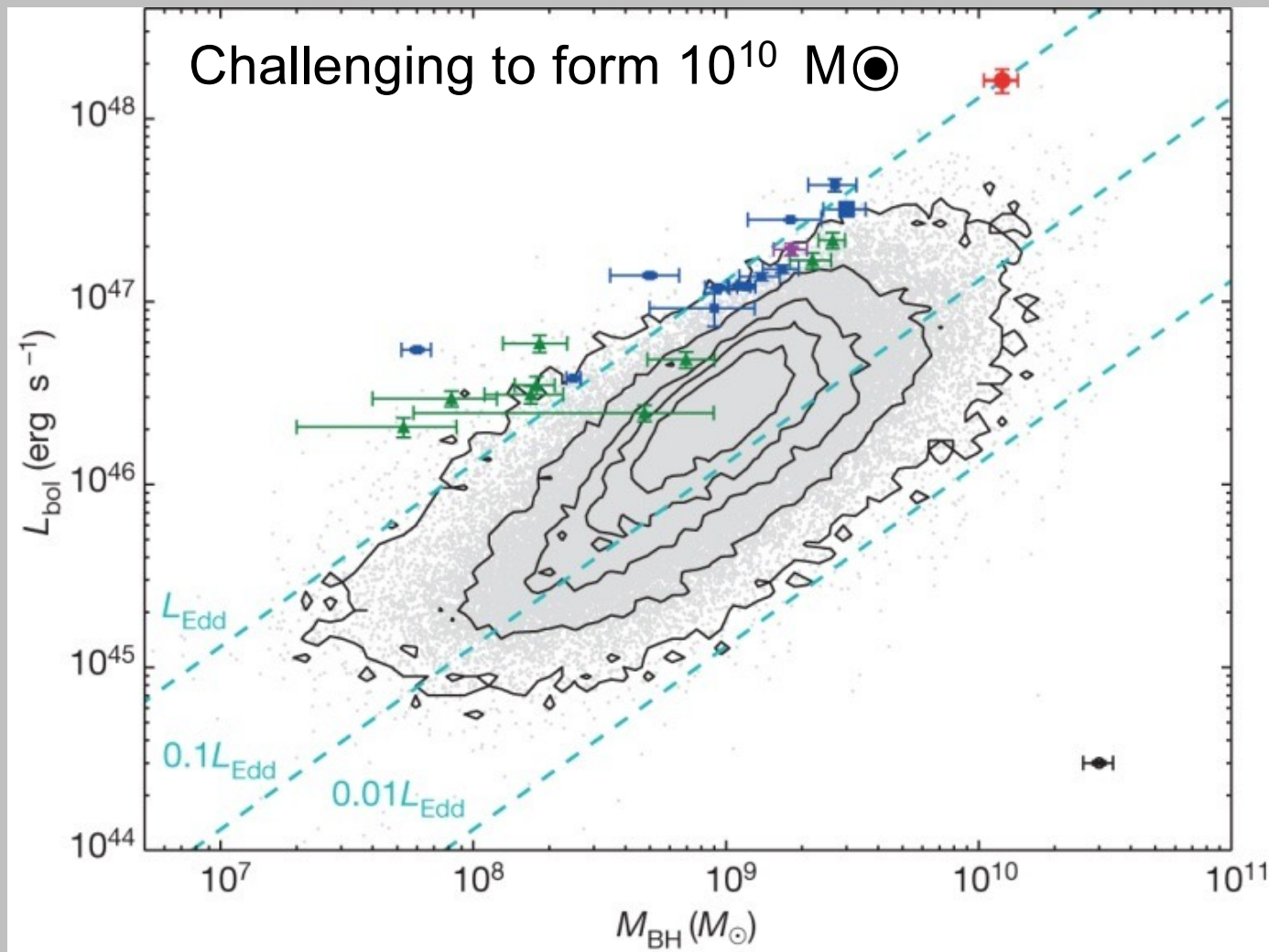


# *What happens next?*

## ***BIG BLACK HOLES***

- Star reaches  $T=10^7\text{K}$ , fusion sets in.
- A. Heger finds that fusion powered stars heavier than 153,000 solar masses are unstable and collapse to BH
- Less massive Pop III star lives a million years, then becomes a Black Hole
- Helps explain observed black holes:
  - (i) in centers of galaxies
  - (ii) billion solar mass BH at  $z=6$  (Fan, Jiang)
  - (iii) intermediate mass BH

SupperMassive Black holes from Dark Stars  
Very Massive progenitor Million Solar Masses  
No other way to form supermassive BH this early z=6



# An 800 million solar mass black hole in a significantly neutral universe at redshift 7.5

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<sup>2</sup>Max Planck Institut für Astronomie, Königstuhl 17, D-69117, Heidelberg, Germany

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<sup>5</sup>INAF – Osservatorio Astronomico di Bologna, via Gobetti 93/3, 40129, Bologna, Italy

<sup>6</sup>Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

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<sup>11</sup>Institut de Radioastronomie Millimétrique (IRAM), 300 rue de la Piscine, 38406 Saint Martin d'Hères, France

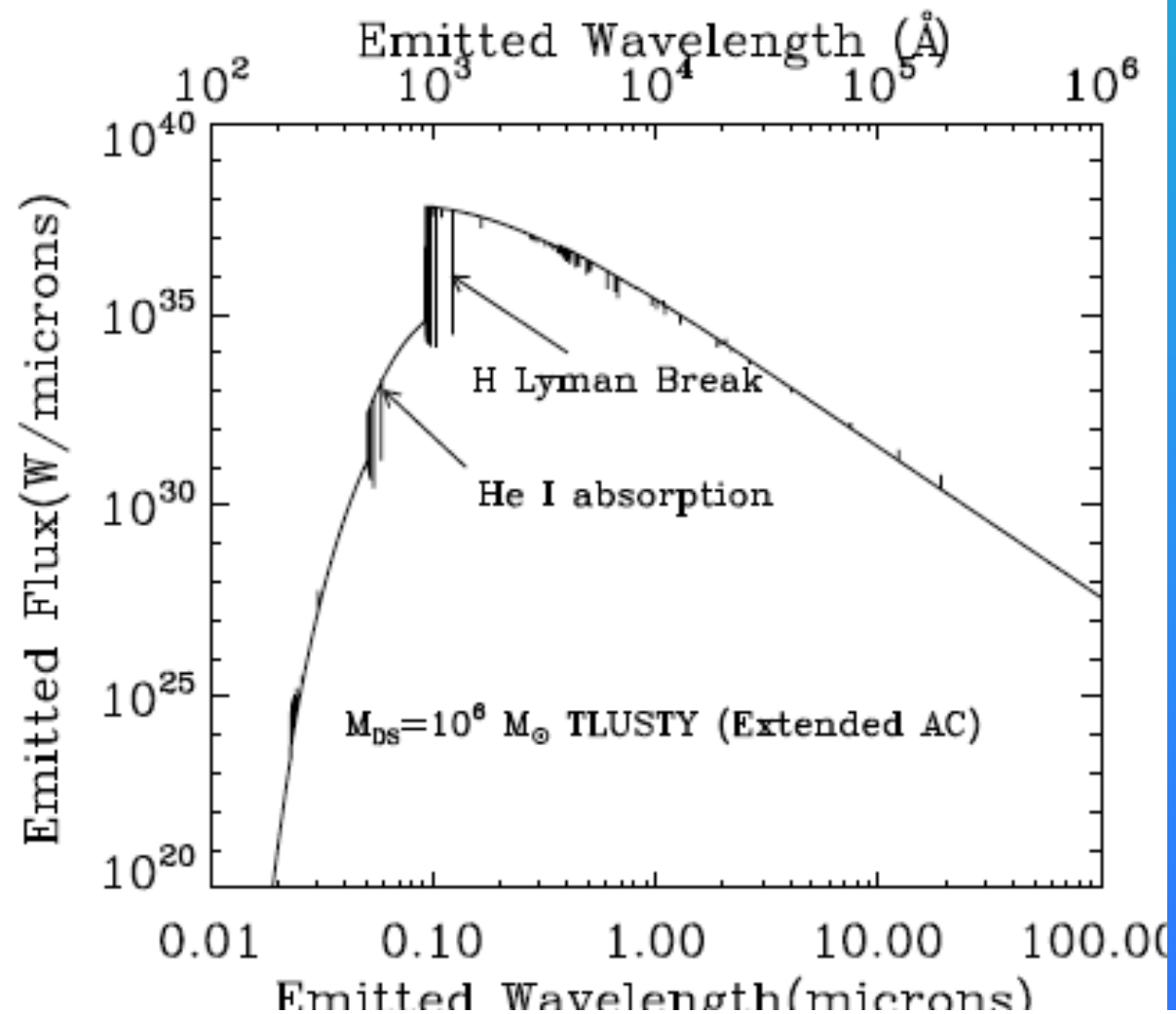
\*ebanados@carnegiescience.edu

## ABSTRACT

Quasars are the most luminous non-transient objects known, and as such, they enable unparalleled studies of the universe at the earliest cosmic epochs. However, despite extensive efforts from the astronomical community, the quasar ULAS J1120+0641 at  $z = 7.09$  (hereafter J1120+0641) has remained as the only one known at  $z > 7$  for more than half a decade<sup>1</sup>. Here we report observations of the quasar ULAS J134208.10+092838.61 (hereafter J1342+0928) at a redshift of  $z = 7.54$ . This quasar has a bolometric luminosity of  $4 \times 10^{13} L_{\odot}$  and a black hole mass of  $8 \times 10^8 M_{\odot}$ . The existence of this supermassive black hole when the universe was only 690 Myr old, i.e., just 5% its current age, reinforces early black hole growth models that allow black holes with initial masses  $\gtrsim 10^4 M_{\odot}$ <sup>2,3</sup> or episodic hyper-Eddington accretion<sup>4,5</sup>. We see strong evidence of the quasar's Ly $\alpha$  emission line being absorbed by a Gunn-Peterson damping wing from the intergalactic medium, as would be expected if the intergalactic hydrogen surrounding J1342+0928 is significantly neutral. We derive a significant neutral fraction, although the exact value depends on the modeling. However, even in our most conservative analysis we find  $\bar{x}_{\text{HI}} > 0.33$  ( $\bar{x}_{\text{HI}} > 0.11$ ) at 68% (95%) probability, indicating that we are probing well within the reionization epoch.

# OBSERVING DARK STARS

DS Spectrum from TLUSTY (stellar atmospheres code)



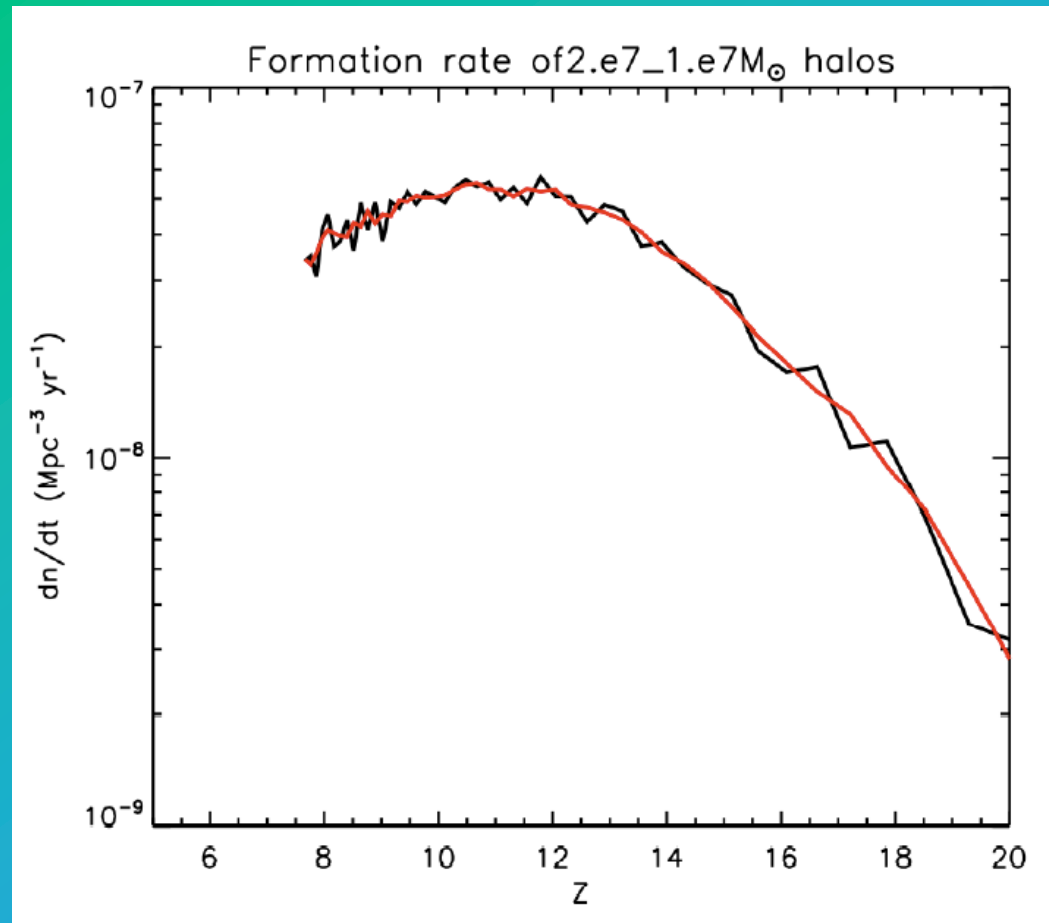
n.b. DS are made of hydrogen and helium only

# How many Dark Stars?

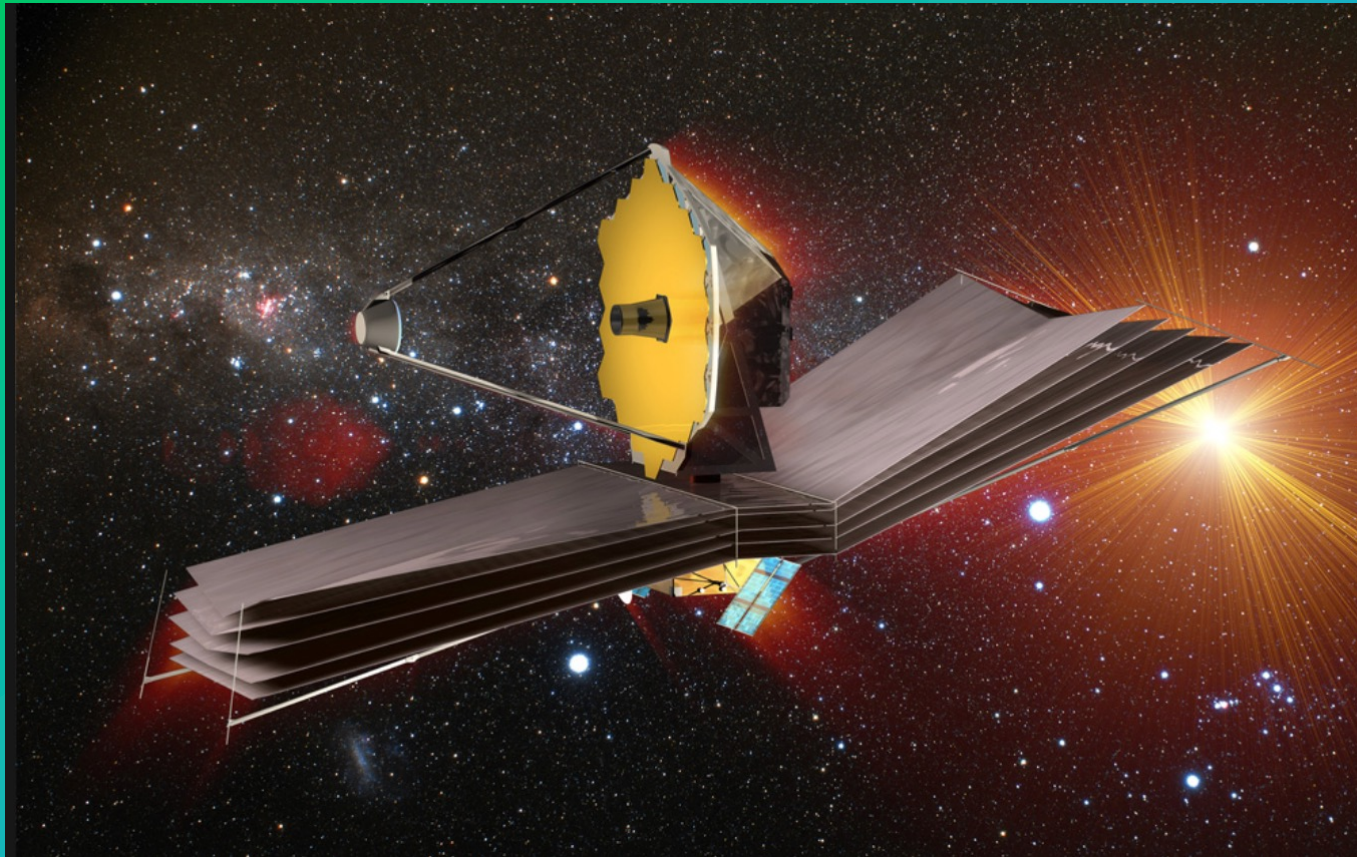
## Start with Minihalo formation rate



Paul Shapiro



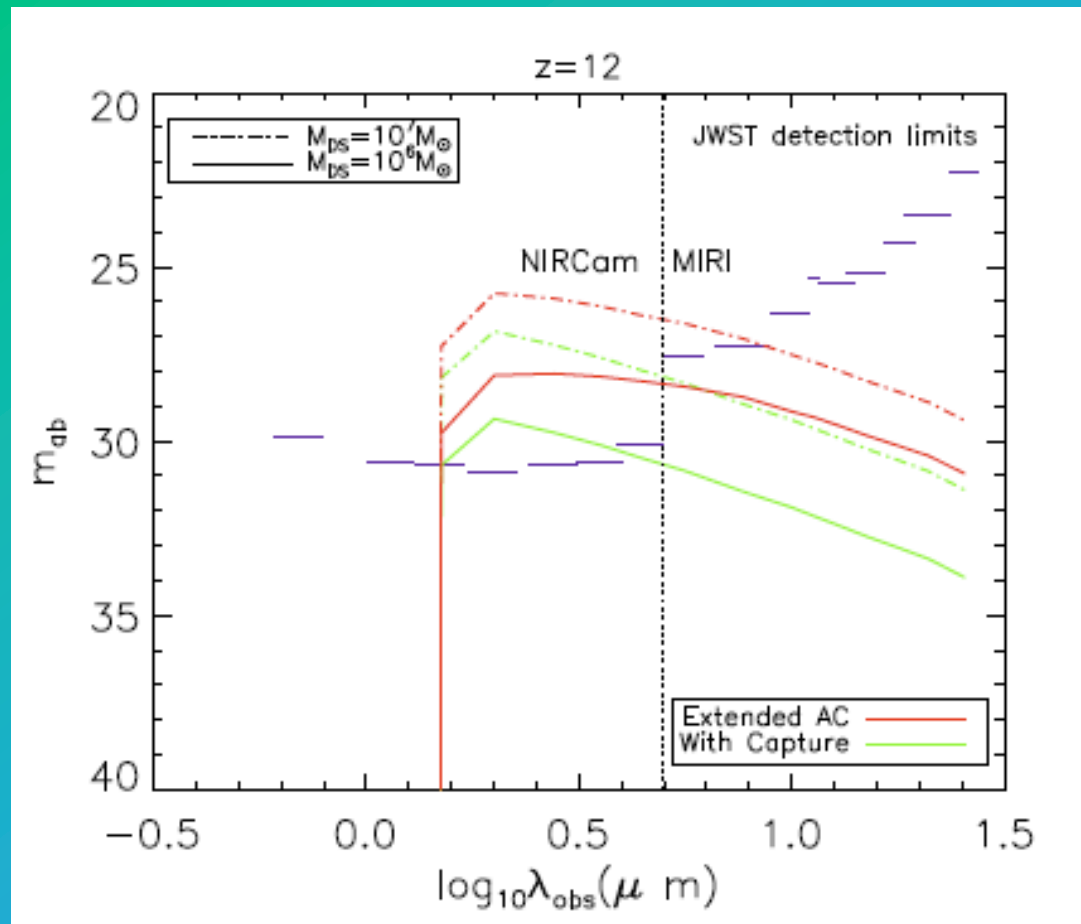
# James Webb Space Telescope



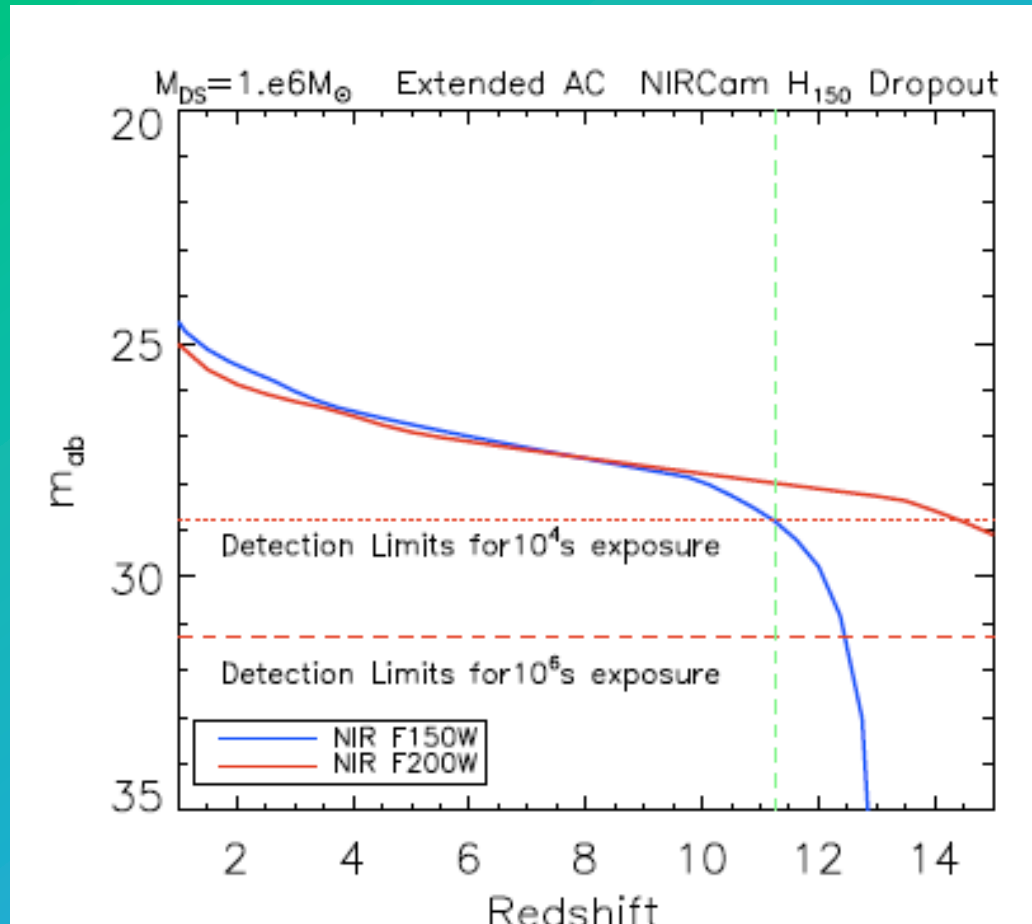
Supermassive Dark Stars:  
They would be a billion times brighter than the Sun  
But the same temperature as the Sun.



# Dark Stars in JWST



# Million solar mass SMDS as H-band dropout



(see in 2.0 micron but not 1.5 micron filter,  
implying it's a  $z=12$  object)

# Numbers of SMDS detectable with JWST as H-band dropouts

(see in 2.0 micron but not 1.5 micron filter, implying it's  $z=12$  object)

Upper limits on numbers of SMDS detectable with JWST as  $H_{150}$  dropout

$M_{DS}(M_{\odot})$	Formation Scenario	Bounds from HST	$N_{obs}^{FOV}$	$N_{obs}^{multi}$
$10^6$	Extended AC	Maximal Bounds	$\lesssim 1$	10
$10^6$	With Capture	Maximal Bounds	2	32
$10^7$	Any	Maximal Bounds	$\lesssim 1$	$\sim 1$
$10^6$	Extended AC	Intermediate	45	709
$10^6$	With Capture	Intermediate	137	2128
$10^7$	Any	Intermediate	4	64
$10^6$	Extended AC	Number of DM halos	28700	444750
$10^6$	With Capture	Number of DM halos	28700	444750
$10^7$	Any	Number of DM halos	155	2400

**Table 3.** Upper limits on the number of SMDS detections as  $H_{150}$  dropouts with JWST. In first three rows (labeled "Maximal Bounds") we assume that all the DS live to below  $z=10$  where they would be observable by HST, and we apply the bounds on the numbers of DS  $f_{SMDS}$  from HST data in Section 4.2. The middle three rows (labeled "Intermediate") relax those bounds by assuming that only  $\sim 10^{-2}$  of the possible DS forming in  $z=12$  haloes make it through the HST observability window. For comparison we also tabulate in the last three rows the total number of potential DM host halos in each case. We also split the number of observations in two categories,  $N_{obs}^{FOV}$  and  $N_{obs}^{multi}$ . The first assumes a sliver with the area equal to the FOV of the instrument (9.68 arcmin<sup>2</sup>), whereas in the second we assume multiple surveys with a total area of 150 arcmin<sup>2</sup>. Note that for the case of the  $10^7 M_{\odot}$  SMDS the predictions are insensitive to the formation mechanism.

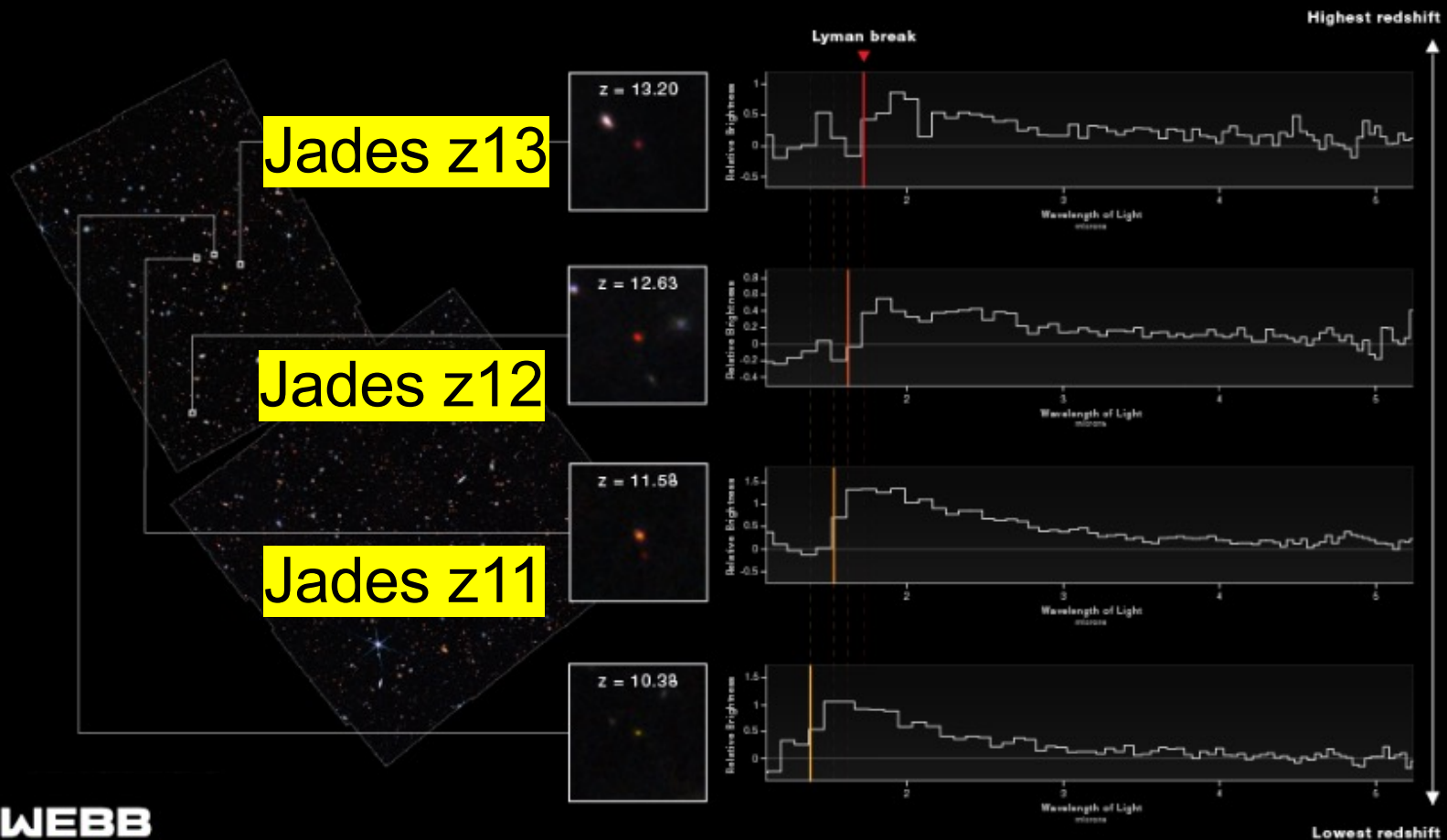
# Of 5 objects in JWST data with spectra: 3 could be Dark Stars!

JWST ADVANCED DEEP EXTRAGALACTIC SURVEY (JADES)

## WEBB SPECTRA REACH NEW MILESTONE IN REDSHIFT FRONTIER

NIRCam Imaging

NIRSpec Microshutter Array Spectroscopy



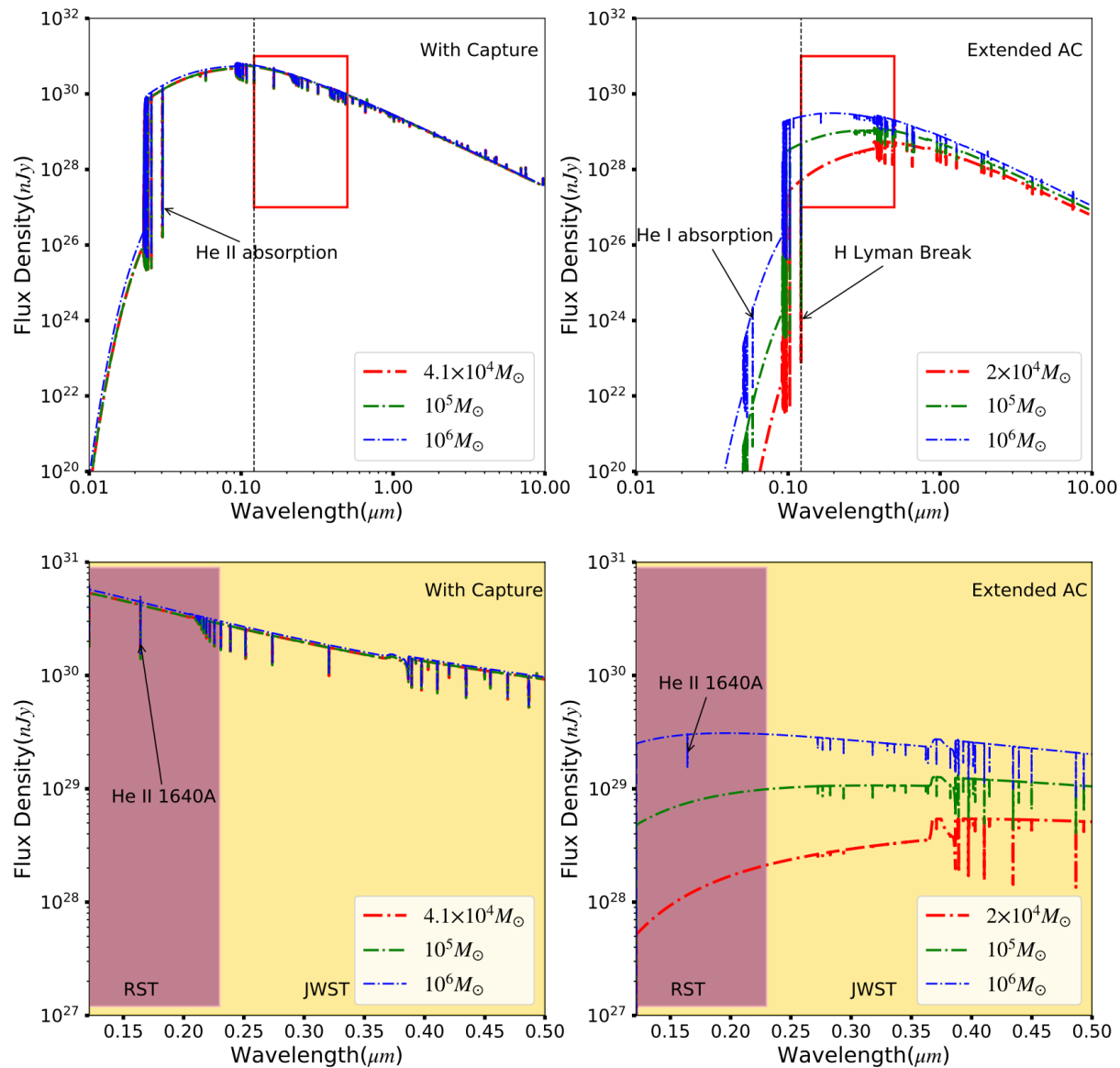
# Criteria for hi-z objects to be Supermassive Dark Star candidates

- 1) Point object (SMDS) vs. resolved (galaxy)
- 2) DS spectra match data. We used photometric data (not noisy spectra for which data are not public).
- 3) Dark stars predict HeII1640 absorption line vs. galaxies predict emission line and a lot of other lines too. Spectra are too noisy so far but will get better with longer exposure.

# All four JADES objects could be point objects

- Authors fit to spectral SEDs plus to galaxy profile (Sersic) and claimed best fit sizes of  $0.04''$  and  $0.02''$ ,  $\sim$  the size of one NIRCcam pixel, and one order of magnitude below the resolution limit  $\sim 0.1''$

# Dark Star spectra



Assumes  
 $z = 10$   
object

# TLUSTY simulated spectra

SEDs of supermassive dark stars of three different masses, as labeled. We assume a 100 GeV WIMP DM particle, following [24]. Left panels: SMDS formed via capture with  $M_* = 4.1 \times 10^4, 10^5, 10^6 M_\odot$ , effective temperatures  $T_{eff} = 4.9, 5.1, 5.1 \times 10^4 \text{K}$ , and radii of  $R_* = 1.8, 2.7, 8.5 \text{AU}$  respectively. Right panels: SMDS formed via Extended AC with  $M_* = 2 \times 10^4, 10^5, 10^6 M_\odot$ , effective temperatures  $T_{eff} = 1.0, 1.4, 1.9 \times 10^4 \text{K}$ , and radii of  $R_* = 31, 39, 61 \text{AU}$  respectively. Top panels are fluxes for rest frame wavelengths up to  $10 \mu\text{m}$ , whereas in the lower panels we zoom in the red boxed regions of the spectra. Those correspond to rest frame wavelengths that can be probed with the Grism on RST (shaded with clay color) and JWST NIRSpec (shaded with yellow) respectively, assuming  $z_{emi} \simeq 10$ . Note that the JWST region extends over all the wavelengths shown in the plot (the yellow JWST region merely looks obscured by the darker clay color of RST). The vertical line in the top panels represents the wavelength of the Lyman-alpha line, which is relevant since for objects at redshifts higher than  $z \sim 6$  the flux at shorter wavelengths than the Ly- $\alpha$  line is highly suppressed via the Gunn-Peterson trough effect due to the neutral H gas abundant in the Intergalactic Medium at  $z \gtrsim 6$ . The most significant spectral features from SMDSs are the He II absorption lines at  $0.1640 \mu\text{m}$ , marked in the standard notation as He II 1640Å in the lower two panels.

TO DO: include effects of nebula surrounding the DS with CLOUDY simulations, especially for hotter ones. V. large DS will have accreted a lot of that material.



# SMDS fits to JWST photometric data (brightness in 9 wavelength bands)

- Jillian Paulin did MCMC to optimize  $\chi^2$  for Dark Matter mass  $m = 100\text{GeV}$  with three parameters:
- Mass of SMDS ( $10^4, 10^5, 10^6$ )  $M_{\odot}$
- Redshift of object
- Magnification due to lensing  
n.b. could be  $\mu = 10$ ,  
or, most lines of light have  $\mu < 1$

(Wang, Holz, Wald)

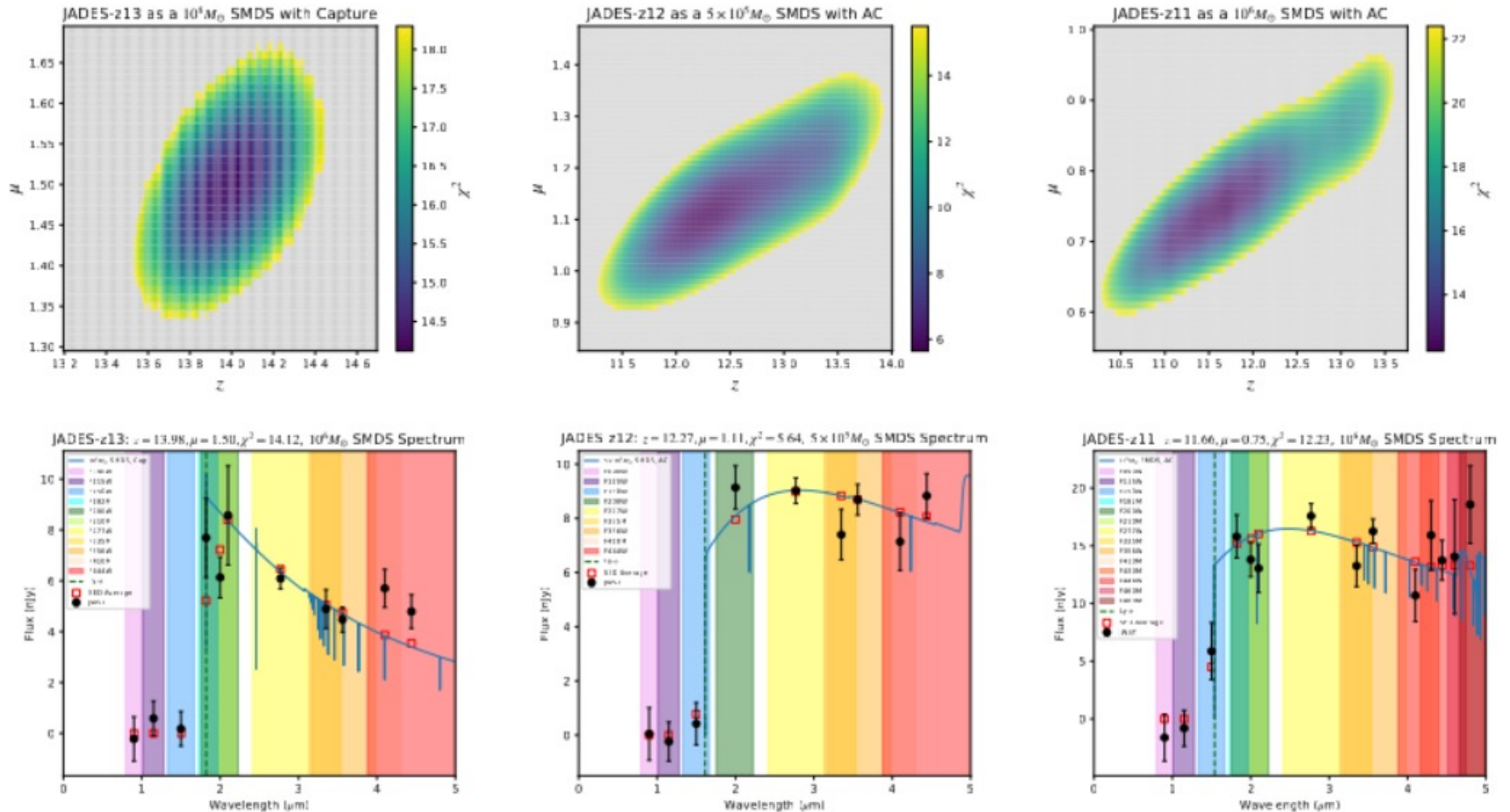
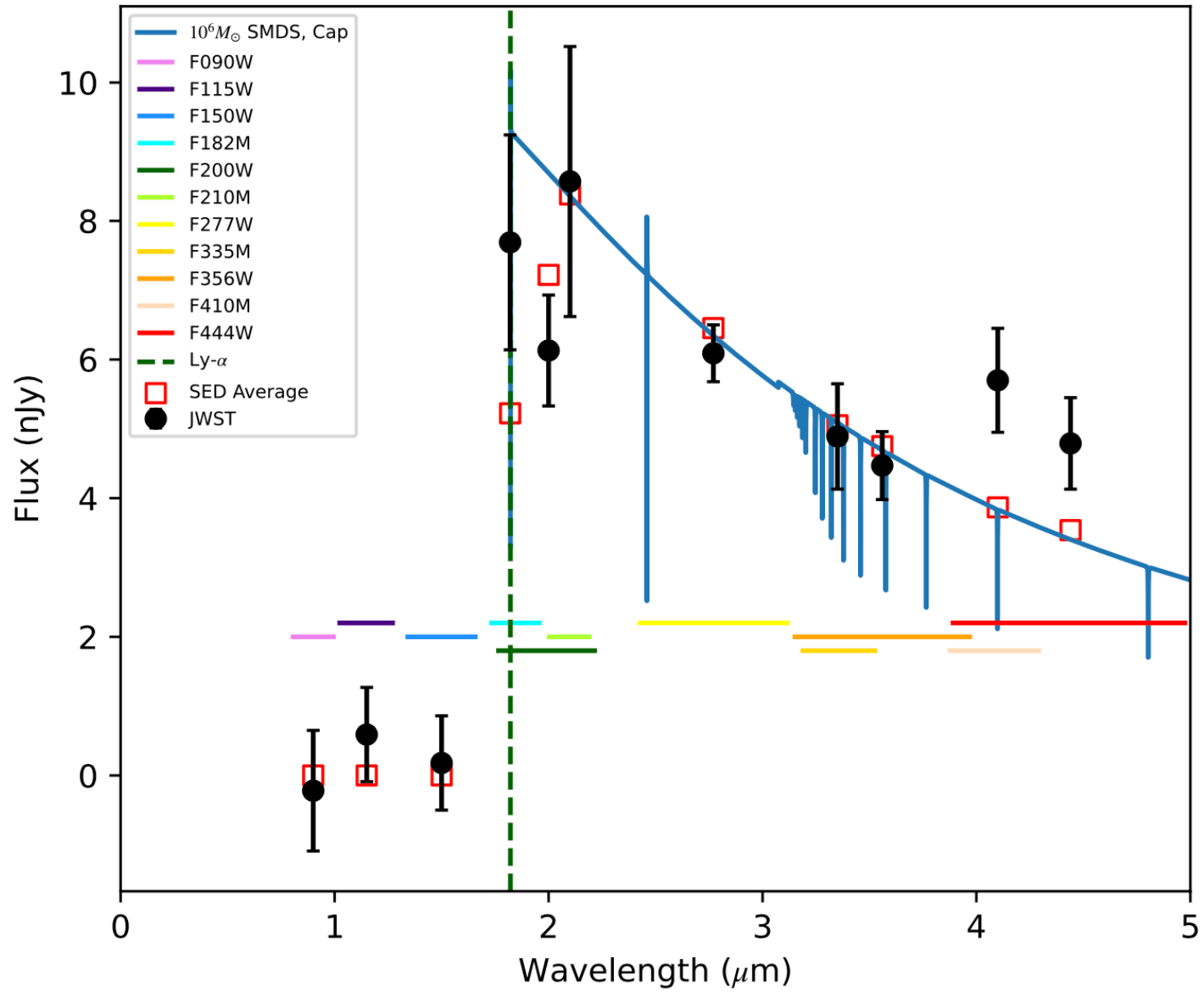


FIG. 1. (Top Row) Optimal fit regions in the  $z$  vs  $\mu$  (magnification) parameter space for Supermassive Dark Star fits to JADES-GS-z11-0, JADES-GS-z12-0, and JADES-GS-z13-0 photometric data. The heatmap is color coded according to the value of the  $\chi^2$ , and is cut off (grayed out) at the critical value corresponding to 95% CL. In addition to labeling the object, the title in each panel includes the the mass and formation mechanism for the SMDSs model considered. (Bottom Row) For each case we plot our best fit SEDs against the photometric data of [25] in each band (color coded and labeled in legend).

JADES-z13:  $z = 13.98, \mu = 1.50, \chi^2 = 14.12, 10^6 M_{\odot}$  SMDS Spectrum

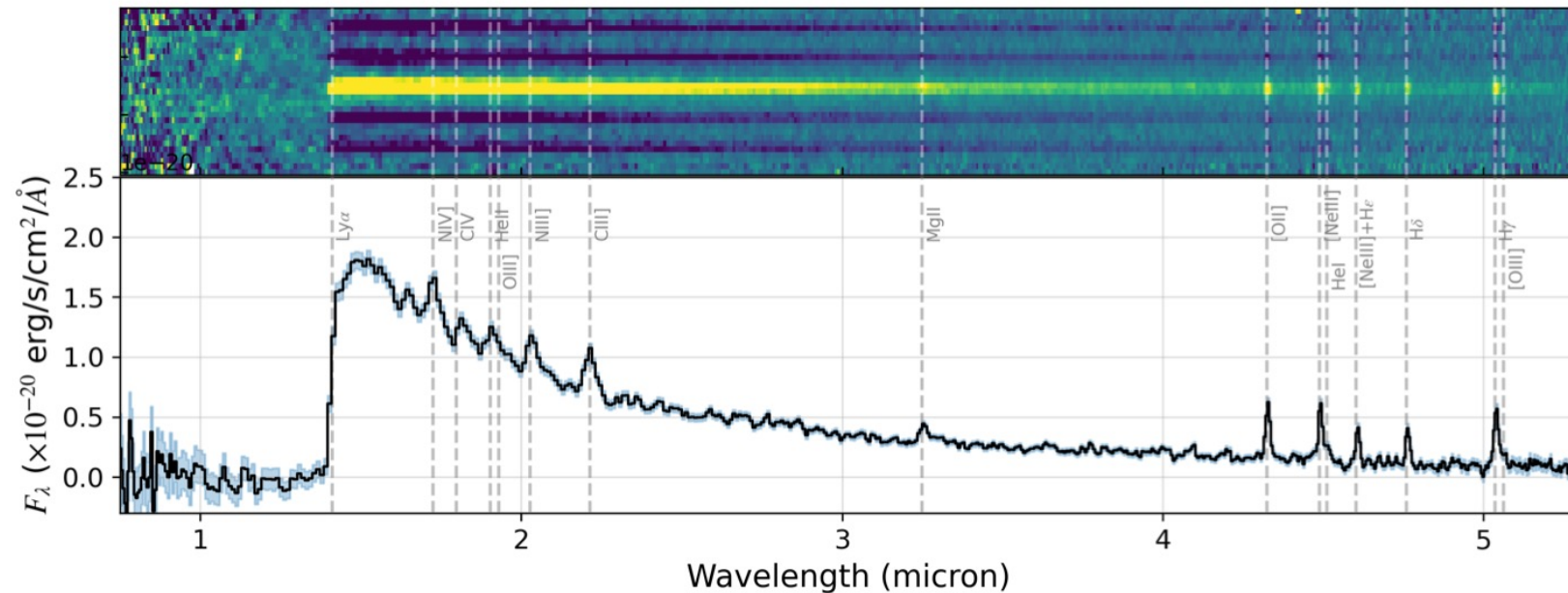


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# GNz11: An object with beautiful spectrum: a galaxy

A. J. Bunker et al.: JADES Spectroscopy of GN-z11



**Fig. 1.** 2D (top) and 1D (bottom) spectra of GN-z11 using PRISM/CLEAR configuration of NIRSspec. Prominent emission lines present in the spectra are marked. The signal to noise ratio (SNR) of the continuum is high and the emission lines are clearly seen in both the 1D and 2D spectra.

# Best bet to distinguish SMDS vs. early galaxies

- Hell 1640 absorption line is smoking gun for SMDS.
- Need to get better spectra: take data for a longer time, find a highly magnified object
- Also: Since SMDS are point object, maybe find Airy (diffraction) pattern if it's a strong signal (magnified bright object)
- Also: at  $\lambda > 5$  micron, spectra differ!

# Exposure time of JADES objects

- JADES-GS-z10-0: 67225.6 s ~ 18 hrs
- JADES-GS-z11-0: 100838.0 s ~ 28 hrs
- JADES-GS-z12-0: 67225.6 s ~ 18 hrs
- JADES-GS-z13-0: 33612.8 s ~ 9 hrs

# The Bottom Line

- JWST has found  $\sim 700$  high redshift objects with  $z > 10$ . They assume these are “galaxy candidates”
- Too many galaxies for Lambda CDM
- Are some of them Dark Stars?
- NIRSPEC on JWST has spectra for 9 of these; so far 5 are on the arxiv or published. One is a galaxy.

(W/out spectra, can't be sure of redshift; some are low redshift)

- Specifically, JADES has four. So far, these are the ones we have studied. (JWST Advanced Extragalactic Survey)
- **OUR RESULTS: Three of the five hi-z JWST objects w published spectra are consistent with Dark Stars.**



# Roman Space Telescope

- SMDS are also visible in RST which has MUCH larger field of view, making them easier to find.
- Find them with RST, then go study them with JWST which has much better angular resolution (n.b. JWST also goes to higher wavelength and hence higher  $z$ ).
- Paper with Saiyang Zhang (student) in progress

# Dark Stars (conclusion)

- The dark matter can play a crucial role in the first stars. Though made of hydrogen and helium, they may be powered by DM heating rather than fusion
- Dark stars may be very massive (up to ten million  $M_{\odot}$ ) and bright (up to ten billion solar luminosities), and can be precursors to Supermassive Black Holes
- SMDS may already have been discovered by JWST; need to find He absorption line as smoking gun
- SMDS are also detectable in Roman Space Telescope
- WIMPs and their properties could first be detected by discovering Dark Stars