# Has JWST discovered Dark Stars?

Katherine Freese

Director, Weinberg Institute for Theoretical Physics

Kodosky Endowed Chair, Univ. of Texas, Austin

and

Professor, Stockholm University

# Collaborators



Doug Spolyar

Paolo Gondolo

Pearl Sandick

Tanja Rindler-Daller

Peter Bodenheimer

# 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 Msun 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: at the time spectra for 5 objects were on the arxiv or published.

(without spectra, can't be sure of redshift; some are low redshift interlopers)

- 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

Naoki Yoshida

Self-gravitating cloud

Eventually exceed
Jeans Mass
of 1000 Msun

5pc

Yoshida

0.01pc

Fully-molecular core
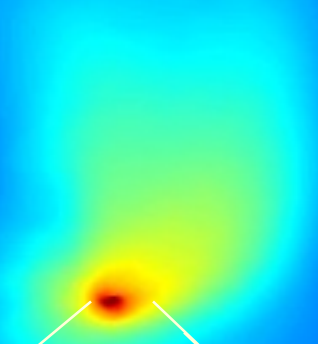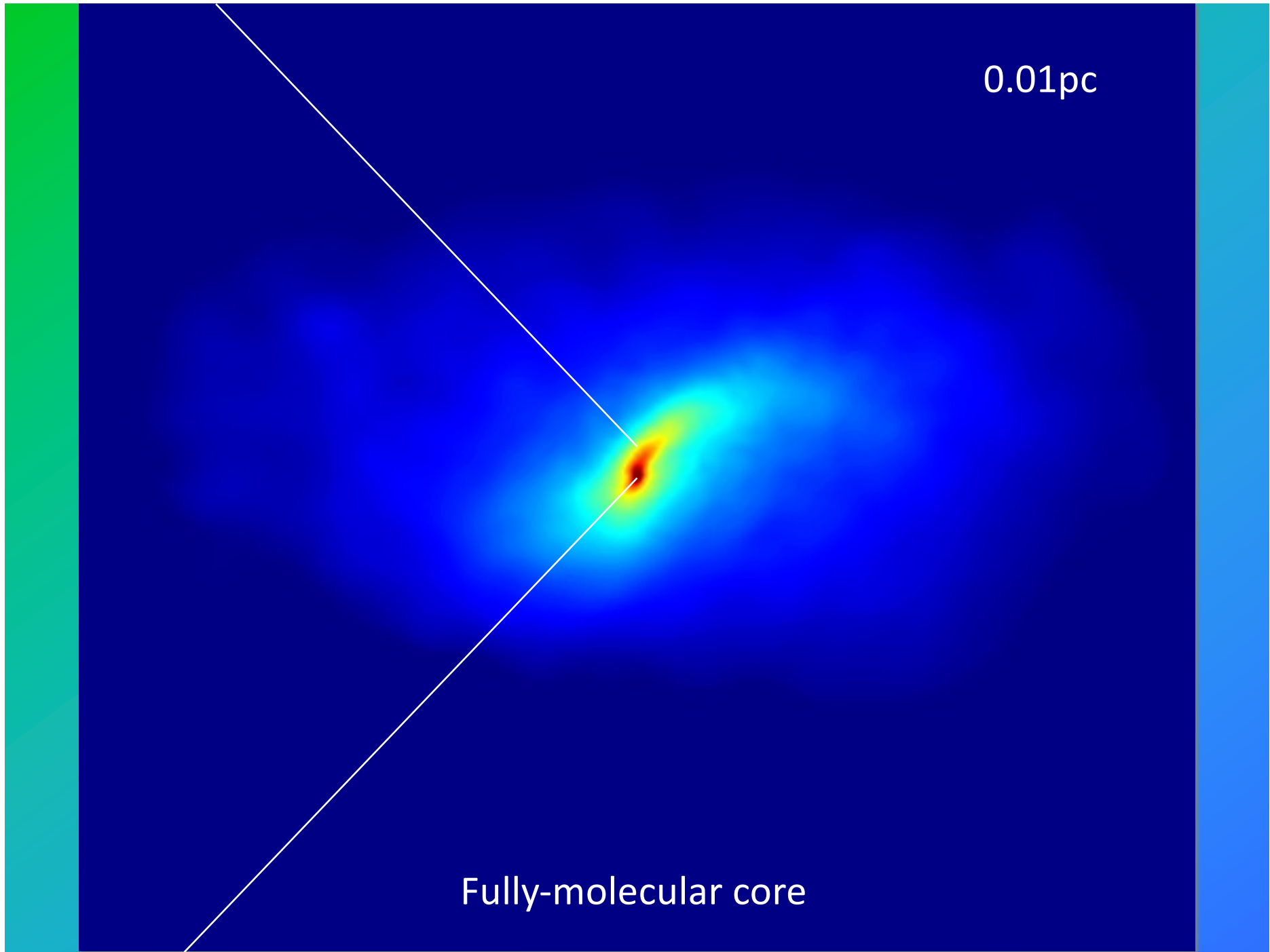
# The role of WIMPs

Mass 1Gev-10TeV (canonical 100GeV)

Annihilation cross section (WIMPS):

$$<\sigma v>_{ann} = 3 \times 10^{-26} cm^3/sec$$

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:

$$Q_{ann} = n_\chi^2 <\sigma v> \times m_\chi$$

$$= \frac{\rho_\chi^2 <\sigma v>}{m_\chi}$$

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)

- I) Sufficiently High Dark Matter Density ?

- 2) Annihilation Products get stuck in star ?

- 3) DM Heating beats H2 Cooling ?

New Phase
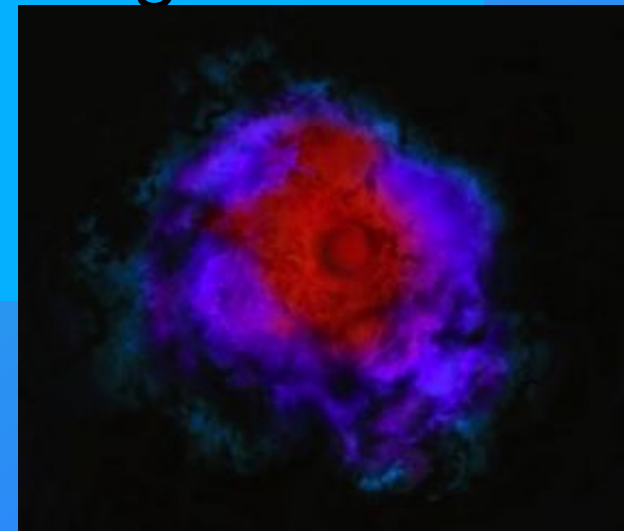
# First Condition: Large DM density

- 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).
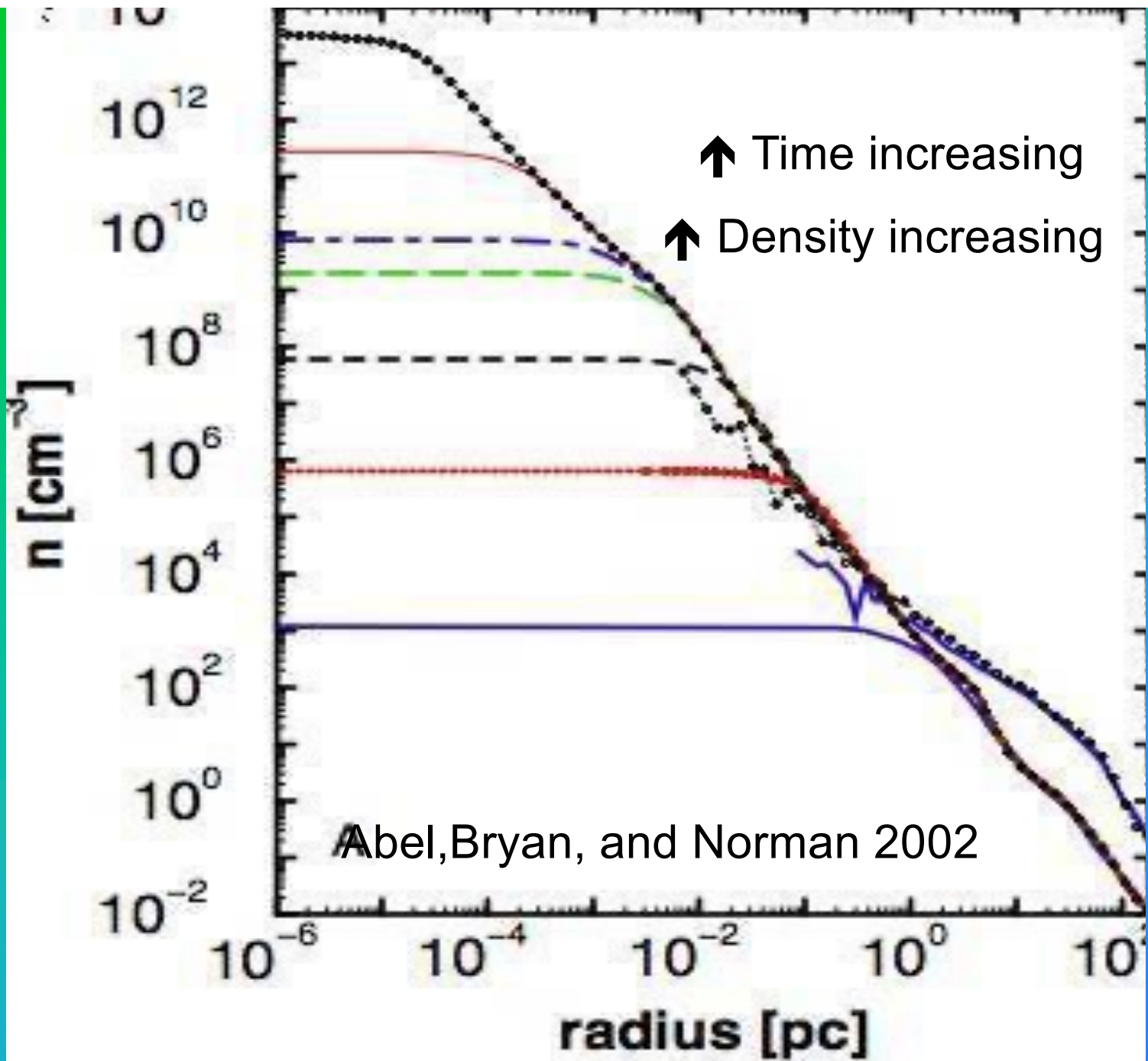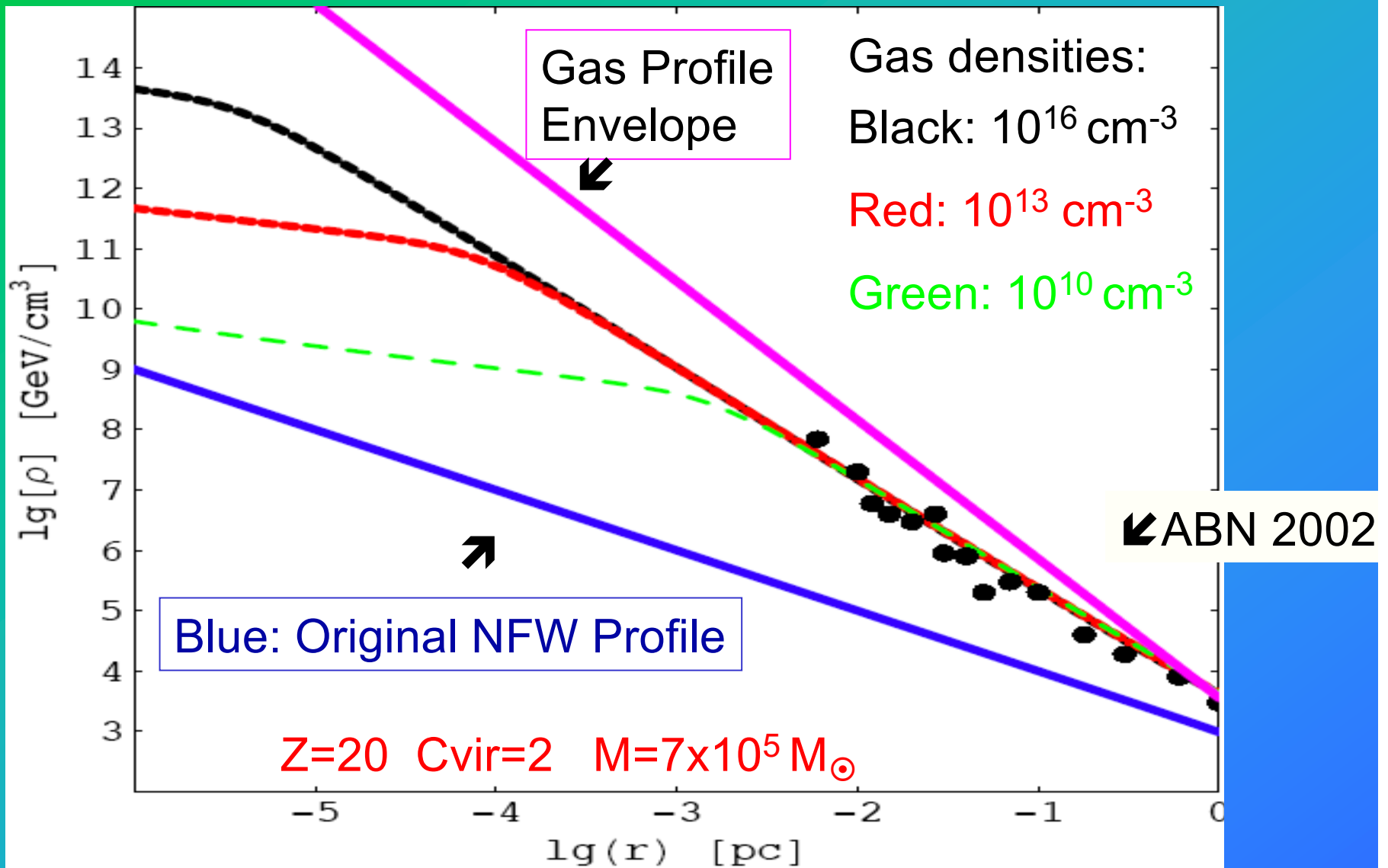
Abel, Bryan, and Norman 2002

# DM profile and Gas



Gas Profile Envelope

Gas densities:
Black: $10^{16}$ cm$^{-3}$
Red: $10^{13}$ cm$^{-3}$
Green: $10^{10}$ cm$^{-3}$

ABN 2002

Blue: Original NFW Profile

Z=20  Cvir=2   M=7x$10^5$ M$_\odot$

# Three Conditions for Dark Stars
## (Spolyar, Freese, Gondolo 2007 aka Paper 1)

- I) Sufficiently High Dark Matter Density YES
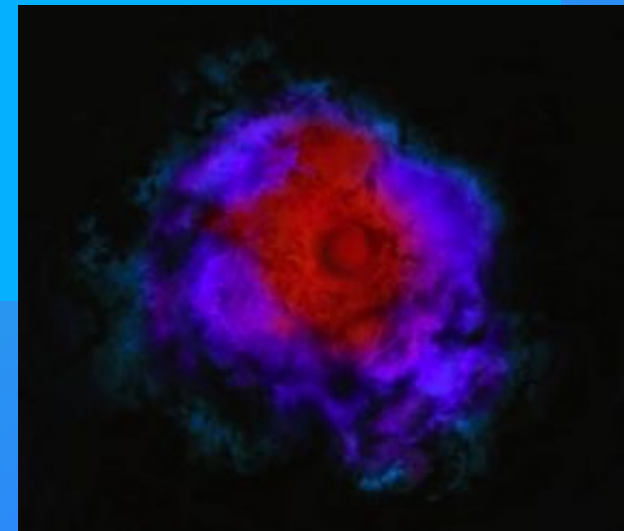
- 2) Annihilation Products get stuck in star ? YES: we used Pythia and Demanded 80 radiation lengths

- 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.



$$\Gamma_{DM} \propto \frac{<\sigma v>}{m_\chi}$$

$$<\sigma v>_{ann} = 3 \times 10^{-26} cm^3/sec$$

1 GeV

10 TeV

Yoshida et al 06

② 

100 GeV

① 1 GeV 100% $H_2$

② Gao et al 06

①

T [K]

$10^4$

$10^3$

$10^2$

$10^3$    $10^6$    $10^9$    $10^{12}$    $10^{15}$    $10^{18}$

n [cm$^{-3}$]  (Spolyar, Freese, Gondolo April 2007)
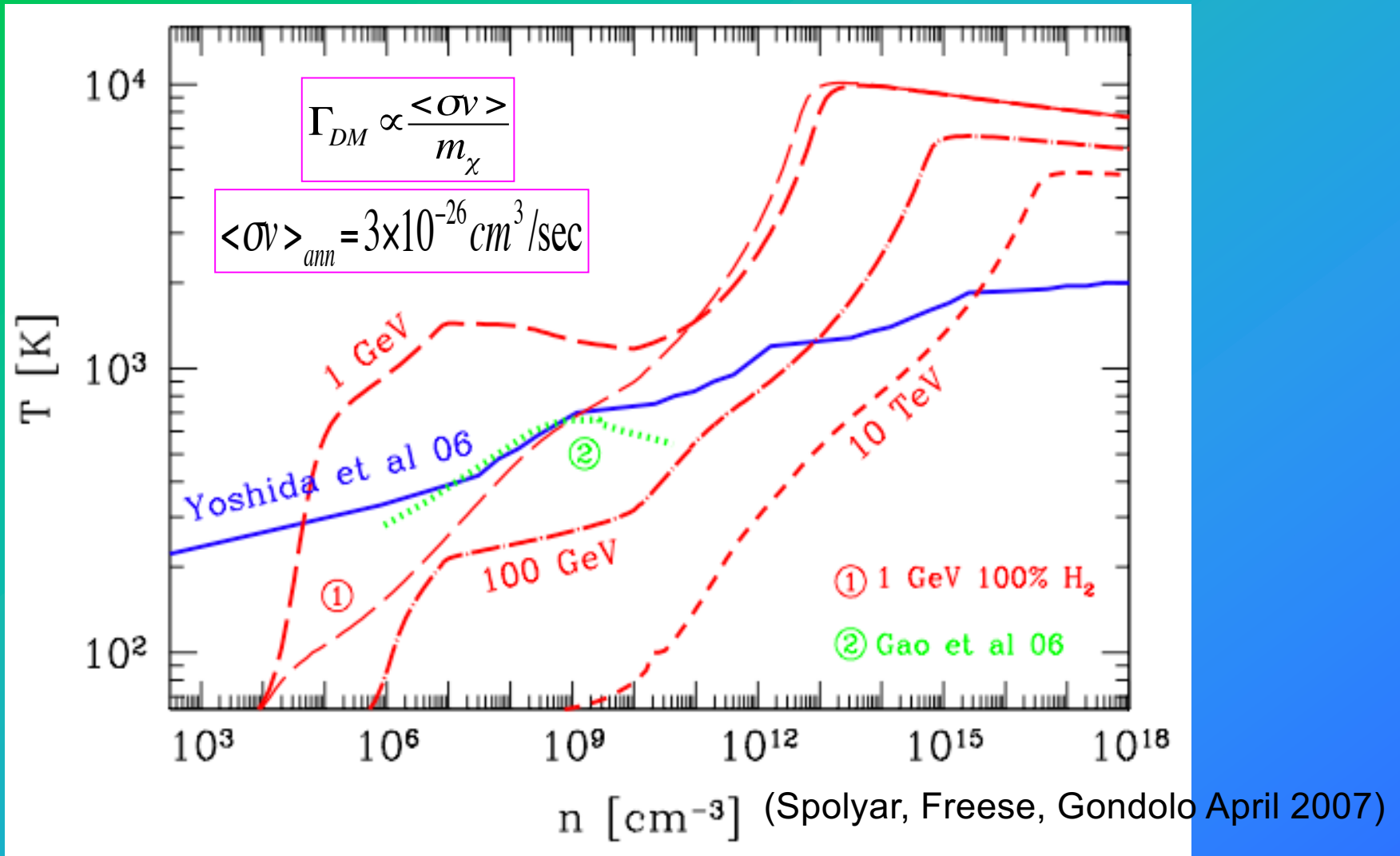
# DS Basic Properties

- 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

- Approach: first polytropes, later MESA code (same results)

- 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
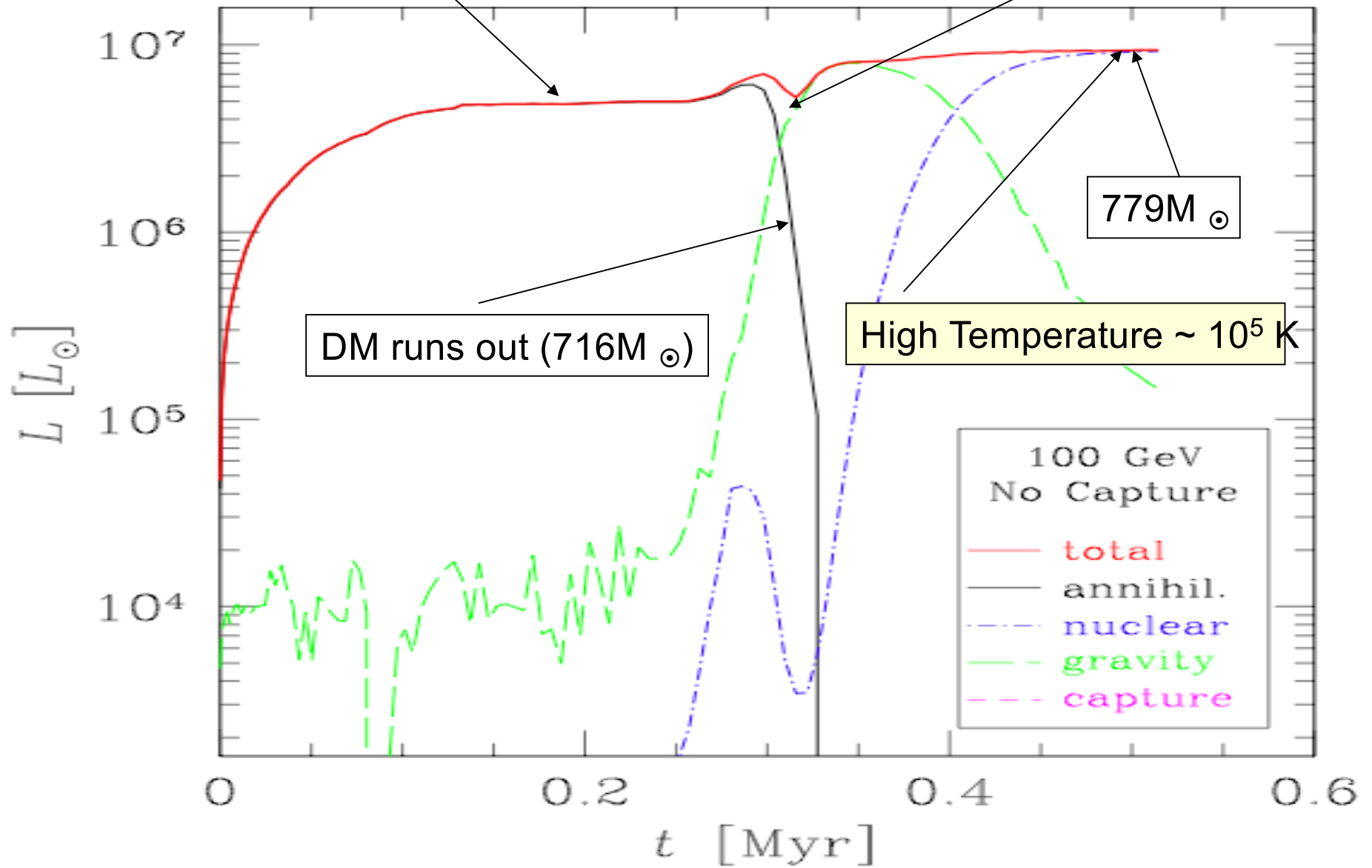
# Following DS Evolution

- 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
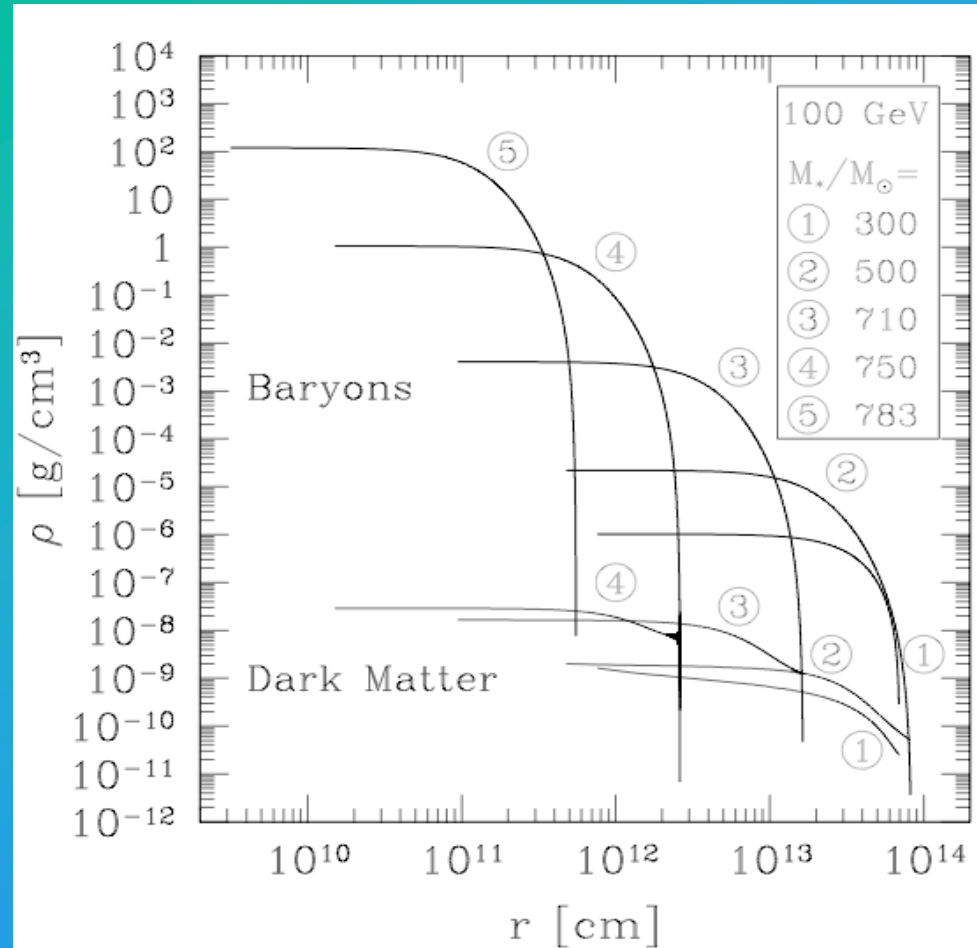
# Is there enough DM?

## Spherical Halos

- DM orbits are planar rosettes (Binney & Tremaine '08).
- The Dark Star creates a loss cone that cannot be refilled.

## Halos are actually Prolate-Triaxial (Bardeen et al. '86).

- Two classes of centrophilic orbits. Box and Chaotic orbits (Schwarzchild '79).
- Traversing arbitrarily close to the center and refilling the loss cone.
- The loss cone could remain full for $10^4$ times longer than in the case of a Spherical Halo (Merritt & Poon '04).

**Box Orbit**

particle: 63 phase a
chaotic

**Chaotic Orbit**
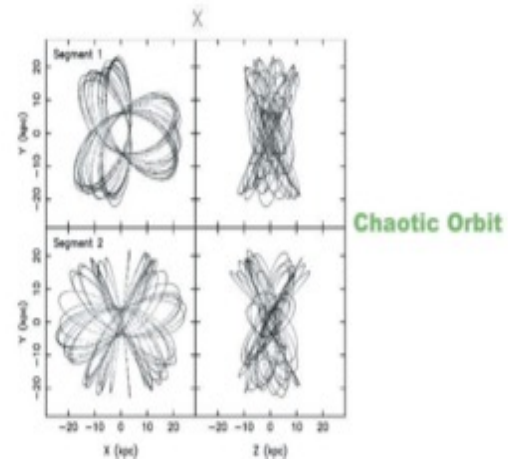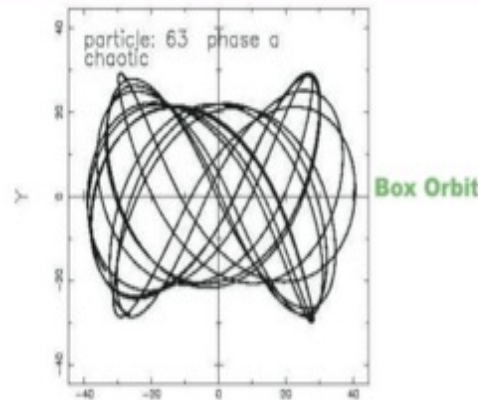
A particle that comes through the center of the DS can be annihilated. However, that particle was not on an orbit that would pass through the center again anyway. The next particle will come in from a different orbit.

Assuming all of the baryons can accrete in a $10^6$ M $_\odot$ halo



H–R diagram
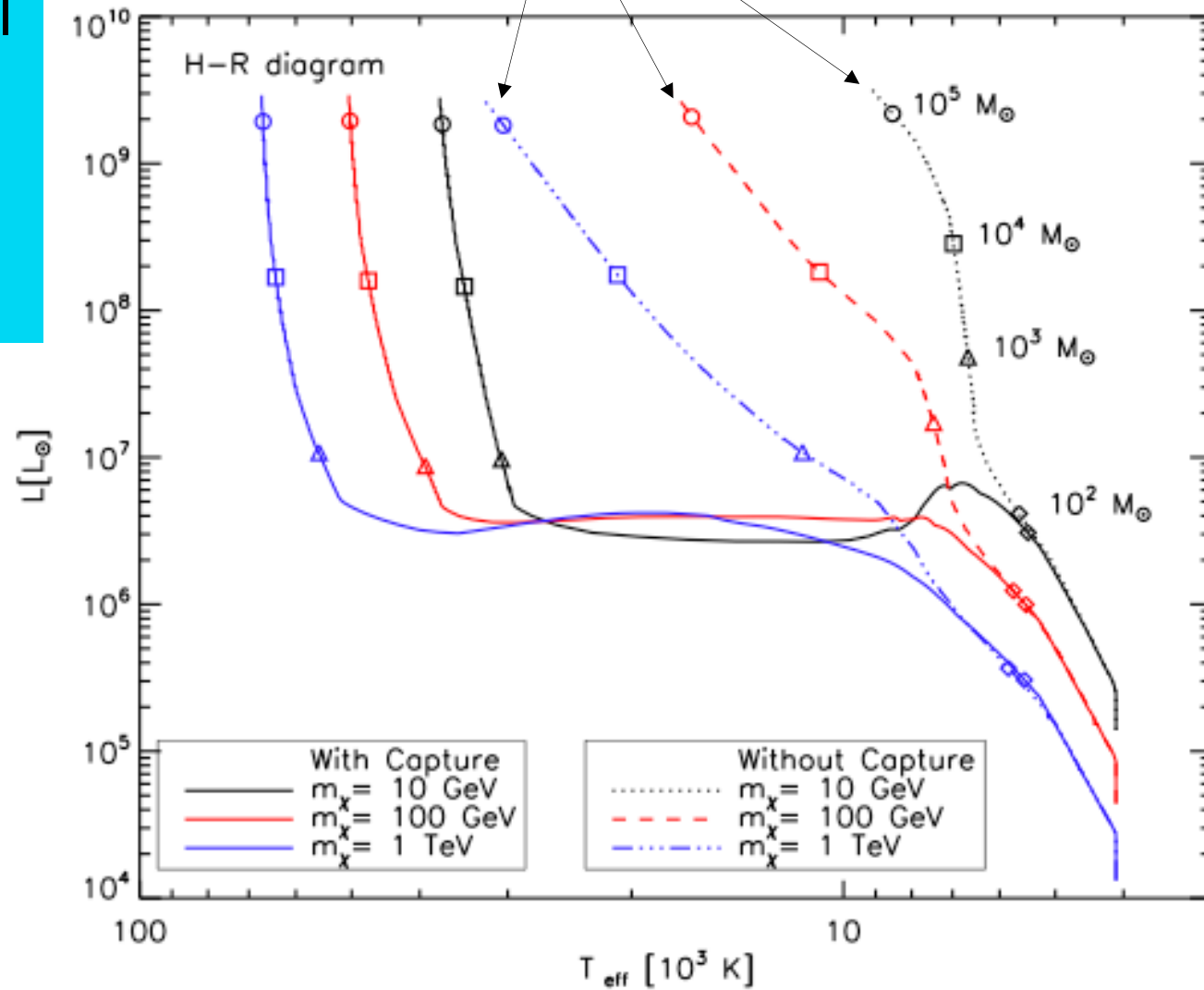
# Additional possible source of DM fuel: capture

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

Freese, Aguirre, Spolyar 08; Iocco 08
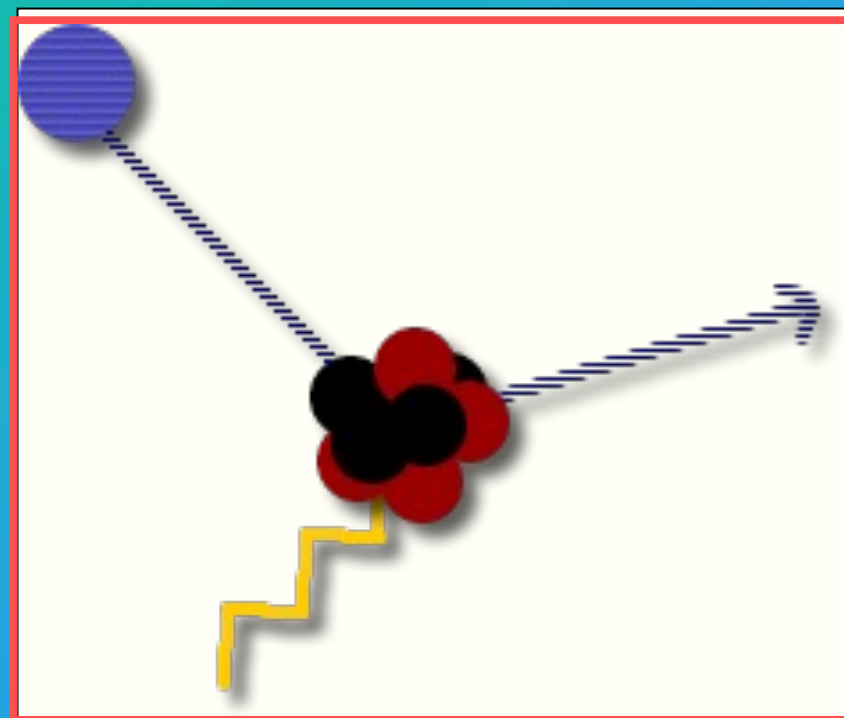
# WIMP scattering off nuclei leads to capture of more DM fuel

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=$10^7$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



Challenging to form $10^{10}$ M⊙
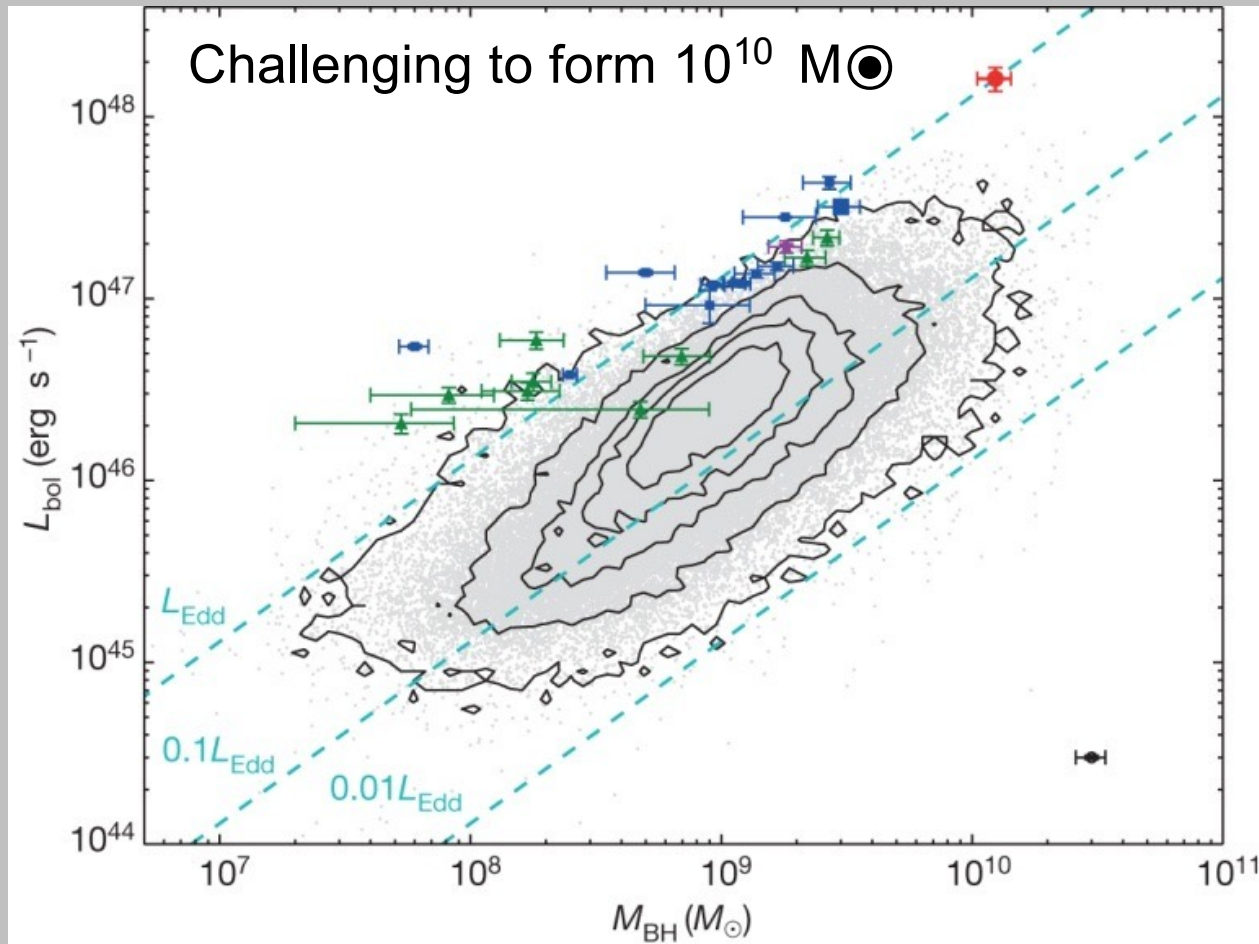
nature

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

Eduardo Bañados[1,*], Bram P. Venemans[2], Chiara Mazzucchelli[2], Emanuele P. Farina[2], Fabian Walter[2], Feige Wang[3,4], Roberto Decarli[2,5], Daniel Stern[6], Xiaohui Fan[7], Fred Davies[8], Joseph F. Hennawi[8], Rob Simcoe[9], Monica L. Turner[9,10], Hans-Walter Rix[2], Jinyi Yang[3,4], Daniel D. Kelson[1], Gwen Rudie[1], and Jan Martin Winters[11]

[1]The Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA
[2]Max Planck Institut für Astronomie, Königstuhl 17, D-69117, Heidelberg, Germany
[3]Department of Astronomy, School of Physics, Peking University, Beijing 100871, China
[4]Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China
[5]INAF – Osservatorio Astronomico di Bologna, via Gobetti 93/3, 40129, Bologna, Italy
[6]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
[7]Steward Observatory, The University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721–0065, USA
[8]Department of Physics, Broida Hall, University of California, Santa Barbara, CA 93106–9530, USA
[9]MIT-Kavli Center for Astrophysics and Space Research, 77 Massachusetts Avenue, Cambridge, MA, 02139, USA
[10]Las Cumbres Observatory, 6740 Cortona Dr, Goleta, CA 93117, USA
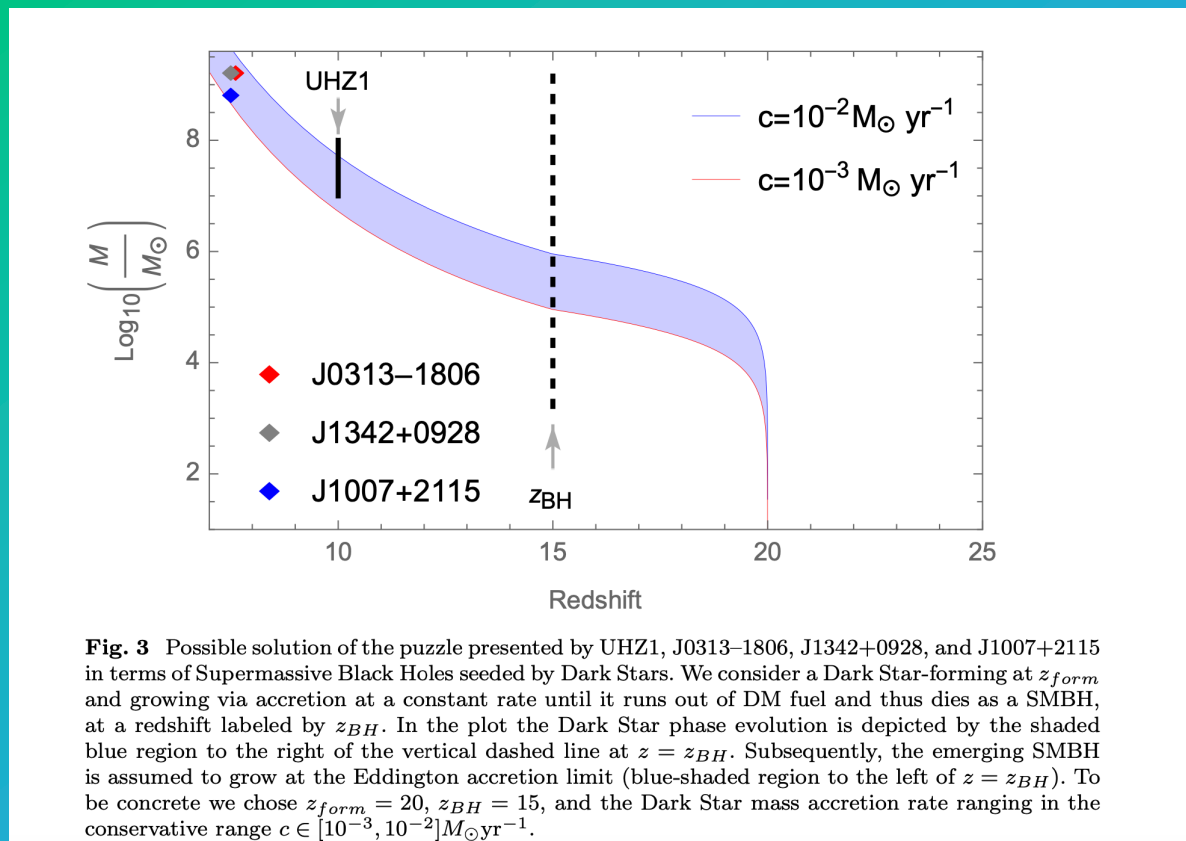[11]Institut de Radioastronomie Millimétrique (IRAM), 300 rue de la Piscine, 38406 Saint Martin d'Hères, France
*ebanados@carnegiescience.edu

## 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[1]. 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 $\gtrsim 10^4 M_\odot$[2,3] or episodic hyper-Eddington accretion[4,5]. 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 $\bar{x}_{HI} > 0.33$ ($\bar{x}_{HI} > 0.11$) at 68% (95%) probability, indicating that we are probing well within the reionization epoch.

# SMDS as origin of UHZ1 (z=10, $10^6$ M$_\odot$) and other distant quasars



**Fig. 3** Possible solution of the puzzle presented by UHZ1, J0313–1806, J1342+0928, and J1007+2115 in terms of Supermassive Black Holes seeded by Dark Stars. We consider a Dark Star-forming at $z_{form}$ and growing via accretion at a constant rate until it runs out of DM fuel and thus dies as a SMBH, at a redshift labeled by $z_{BH}$. In the plot the Dark Star phase evolution is depicted by the shaded blue region to the right of the vertical dashed line at $z = z_{BH}$. Subsequently, the emerging SMBH is assumed to grow at the Eddington accretion limit (blue-shaded region to the left of $z = z_{BH}$). To be concrete we chose $z_{form} = 20$, $z_{BH} = 15$, and the Dark Star mass accretion rate ranging in the conservative range $c \in [10^{-3}, 10^{-2}] M_\odot \text{yr}^{-1}$.
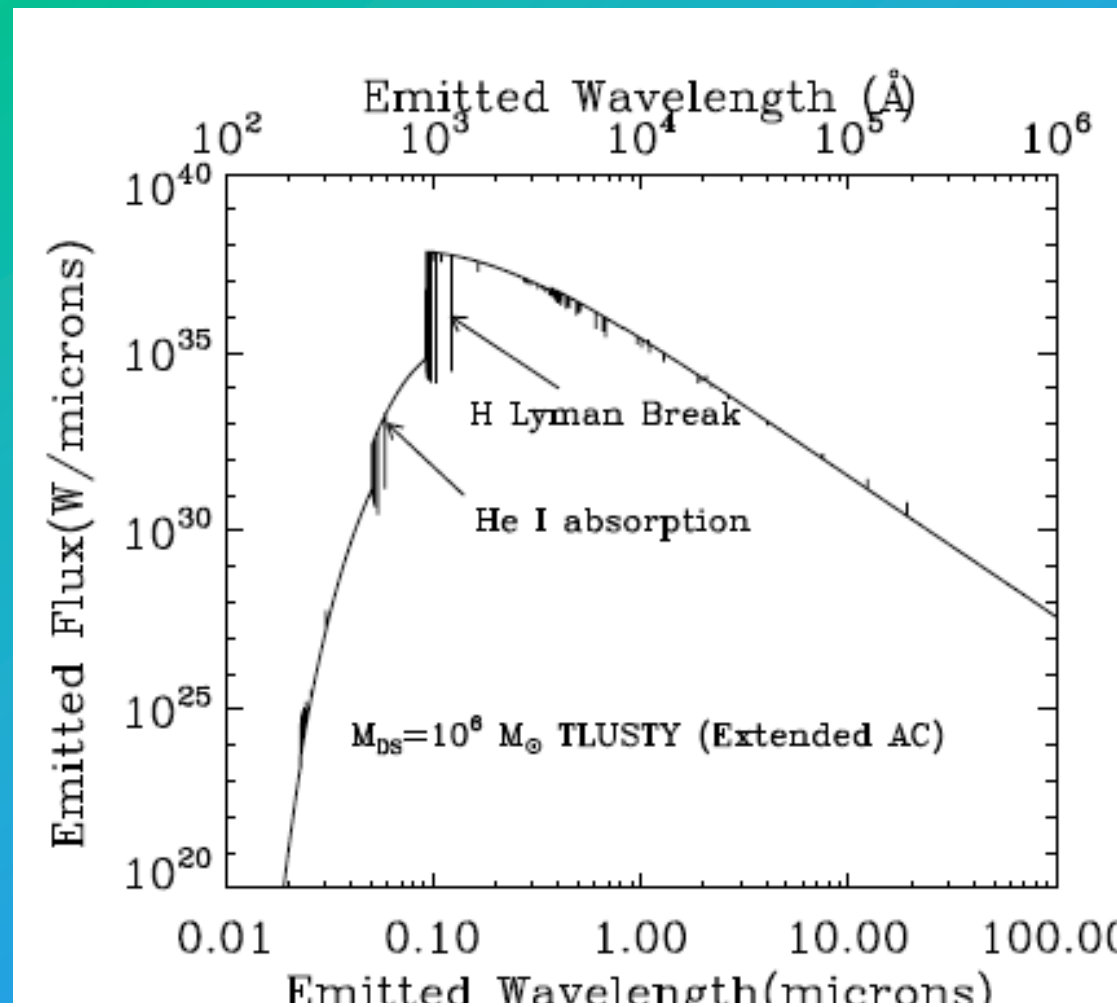
Ilie, KF, Petric, Paulin https://arxiv.org/pdf/2312.13837

# To explain both the quasars and the stellar population ($\sim 10^6$ M $_\odot$ )
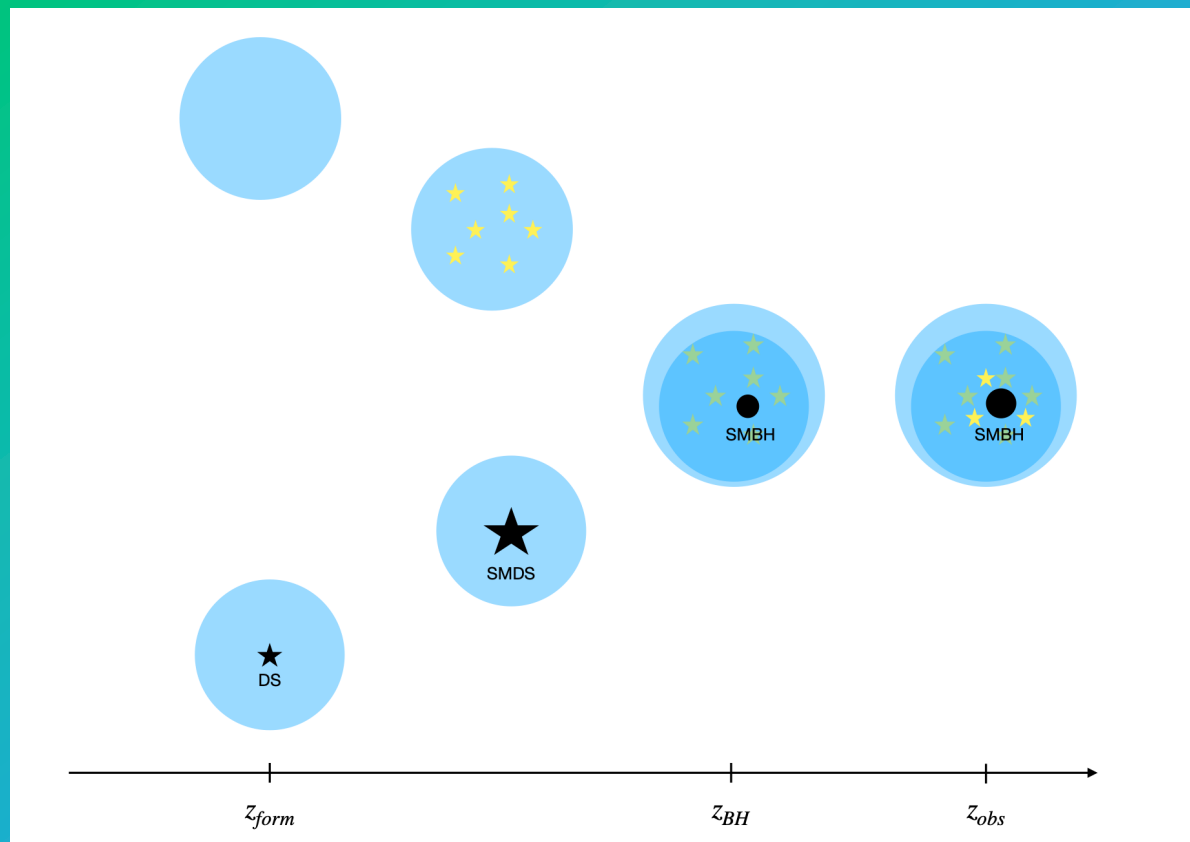
# OBSERVING DARK STARS

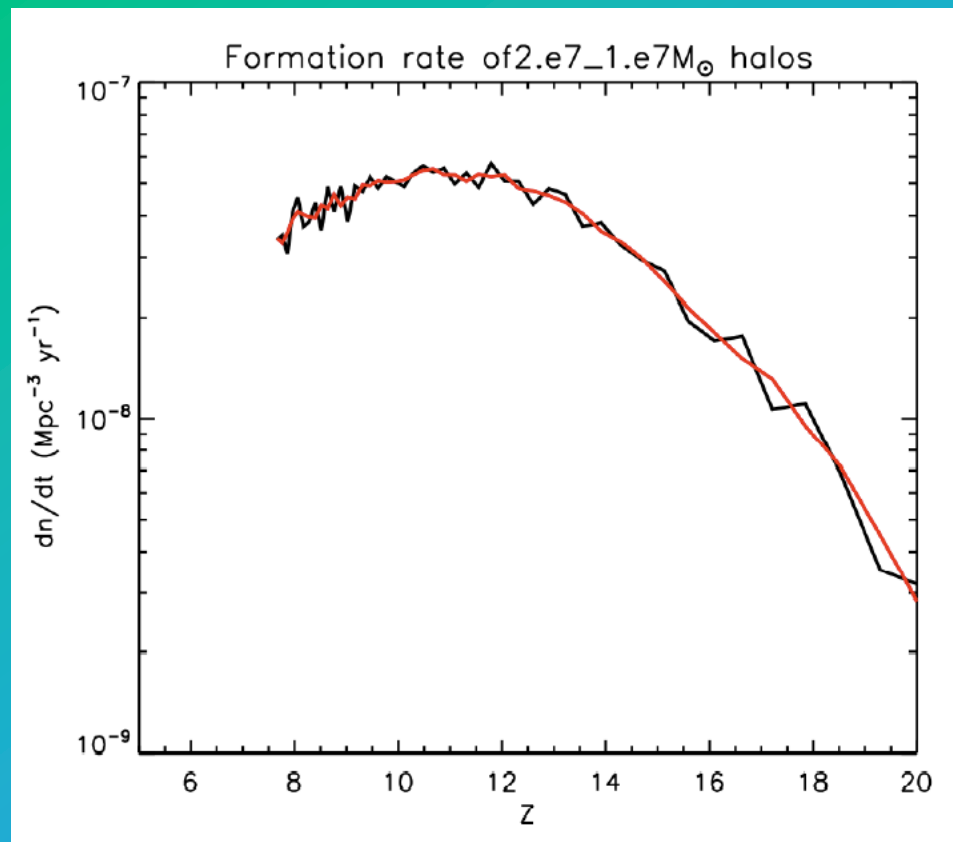## DS Spectrum from TLUSTY (stellar atmospheres code)



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

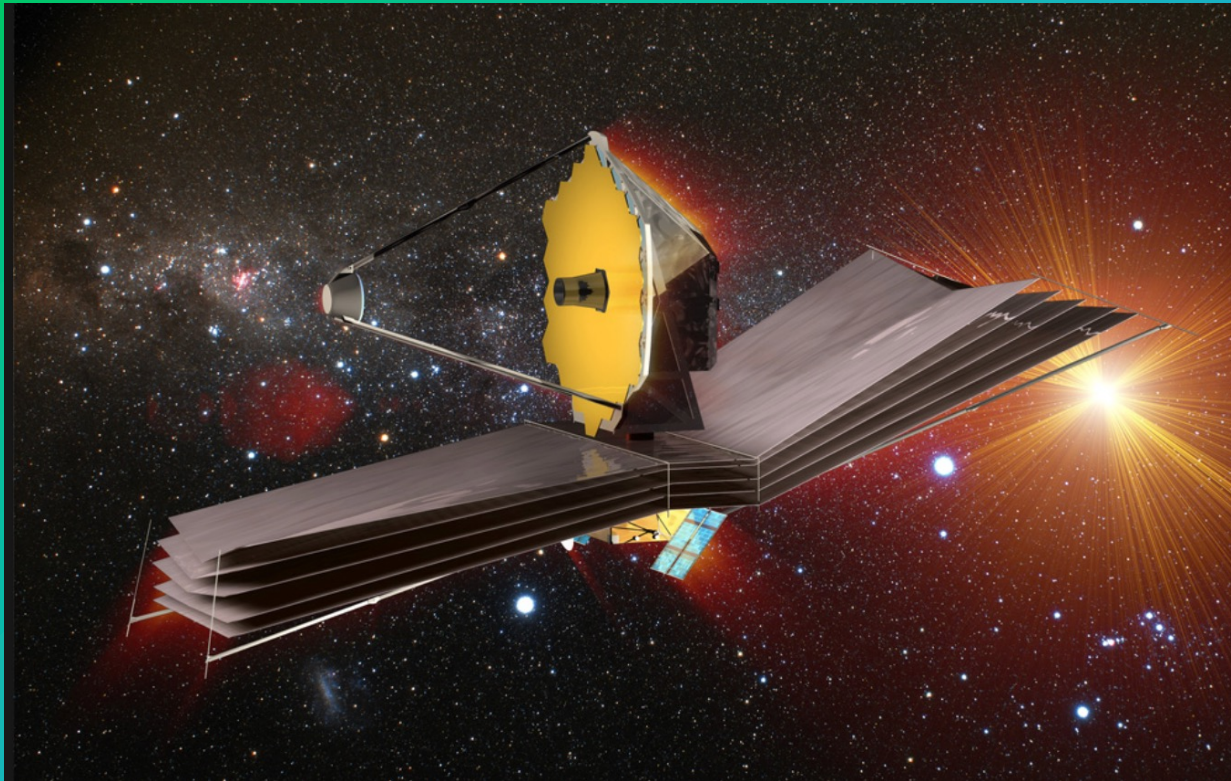# How many Dark Stars?
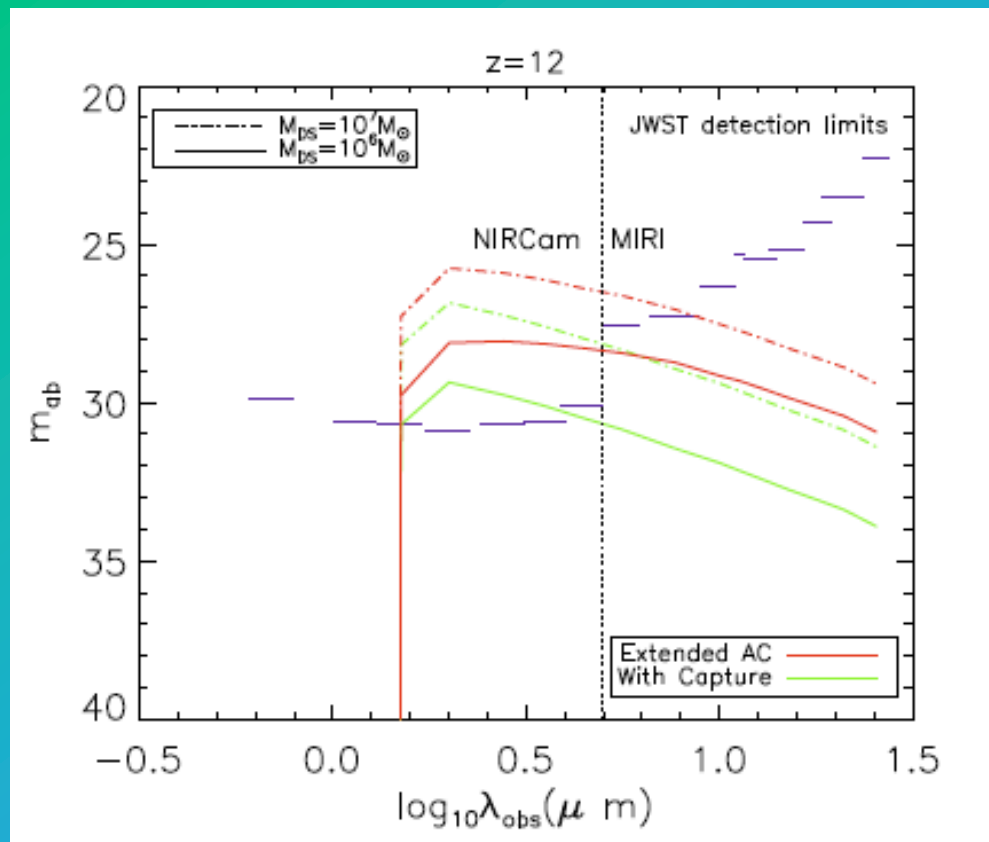## Start with Minihalo formation rate
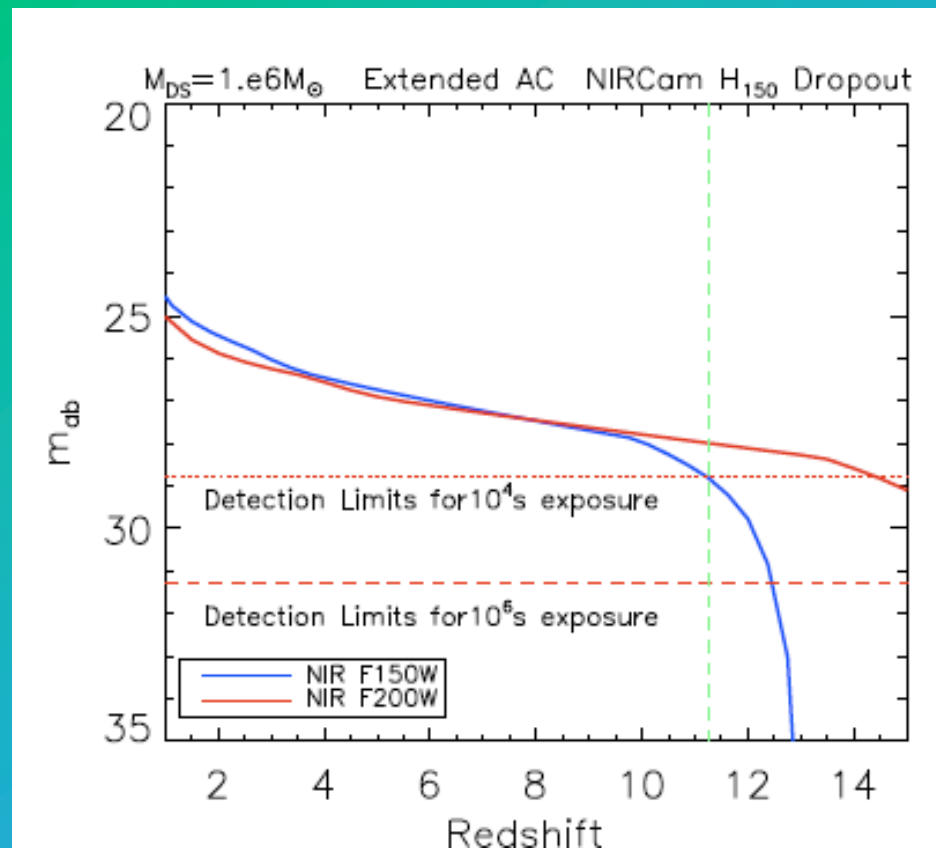


Paul Shapiro

# 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$^2$), whereas in the second we assume multiple surveys with a total area of 150 arcmin$^2$. Note that for the case of the $10^7 M_\odot$ SMDS the predictions are insensitive to the formation mechanism.

# Has JWST discovered Dark Stars?
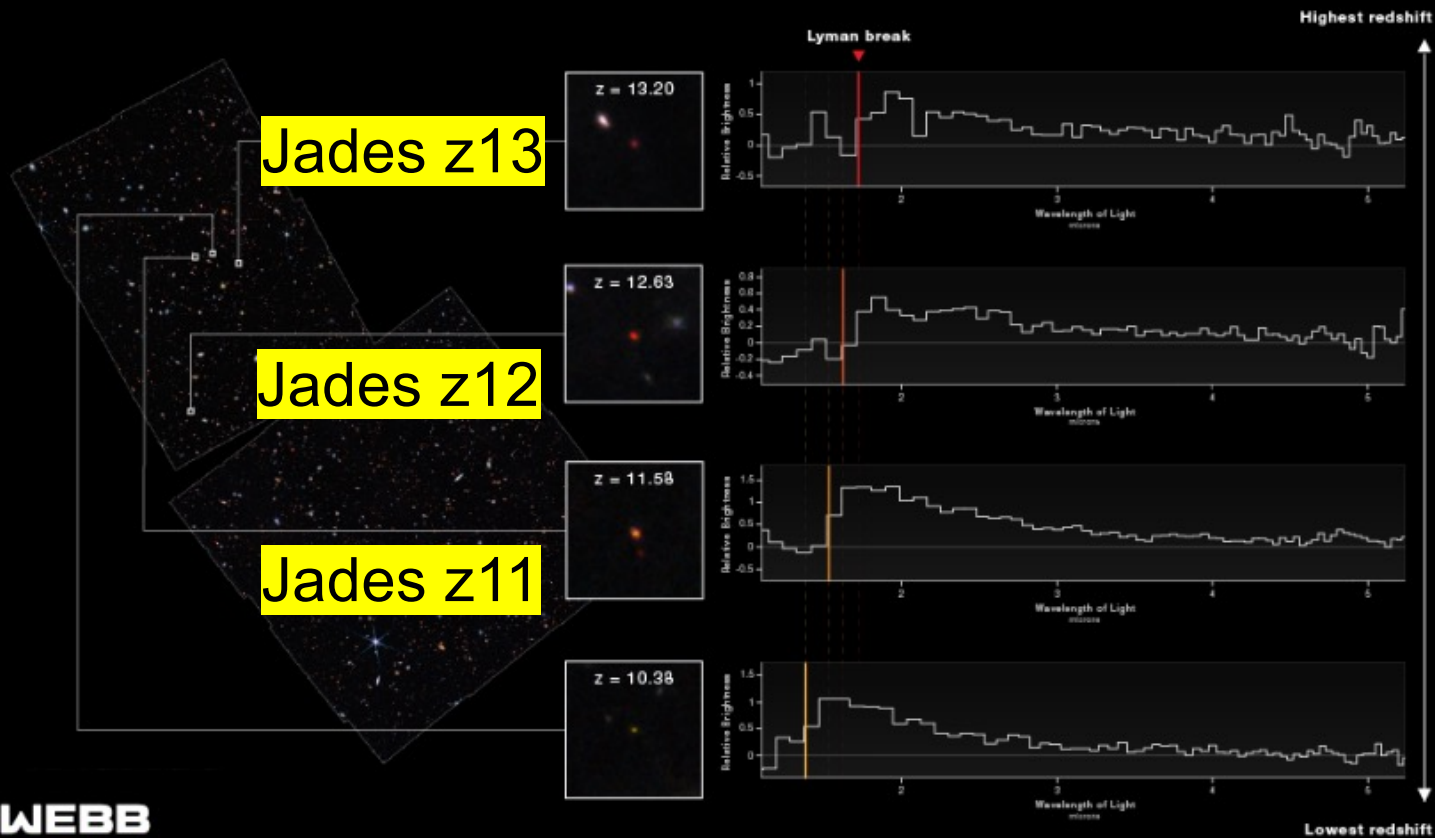
Cosmin Ilie

Colgate University

Jillian Paulin

# 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

Jades z13

Jades z12

Jades z11

WEBB
SPACE TELESCOPE

# 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", ~ the size of one NIRCam pixel, and one order of magnitude below the resolution limit ~0.1"

# Dark Star spectra
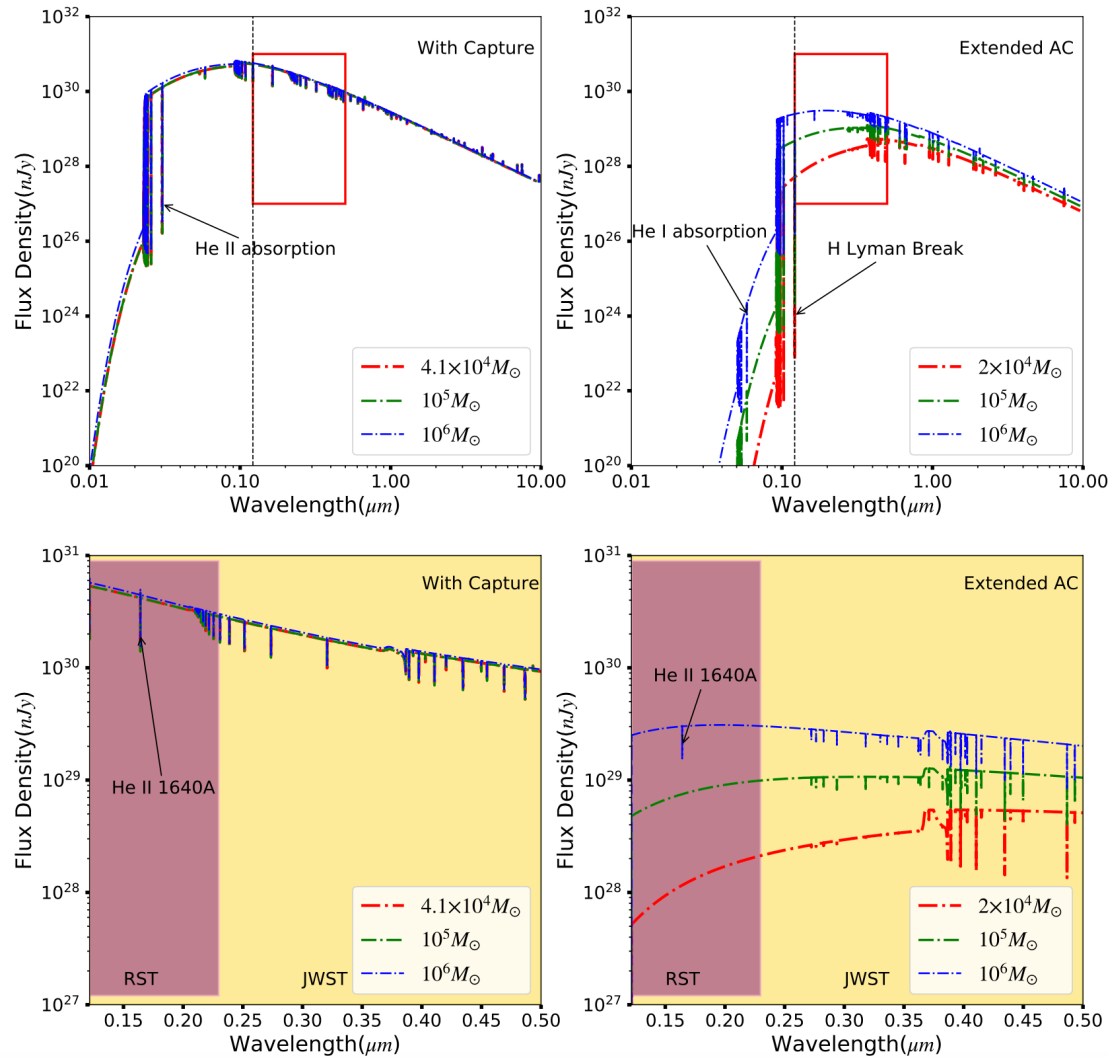


Assumes z =10 object

# 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 $T_{eff} = 4.9, 5.1, 5.1 \times 10^4$K, and radii of $R_* = 1.8, 2.7, 8.5$AU respectively. Right panels: SMDS formed via Extended AC with $M_* = 2 \times 10^4, 10^5, 10^6 M_\odot$, effective temperatures $T_{eff} = 1.0, 1.4, 1.9 \times 10^4$K, and radii of $R_* = 31, 39, 61$AU respectively. Top panels are fluxes for rest frame wavelengths up to $10\mu m$, 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 $0.1640\mu m$, marked in the standard notation as He II 1640Åin 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= 100GeV 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,
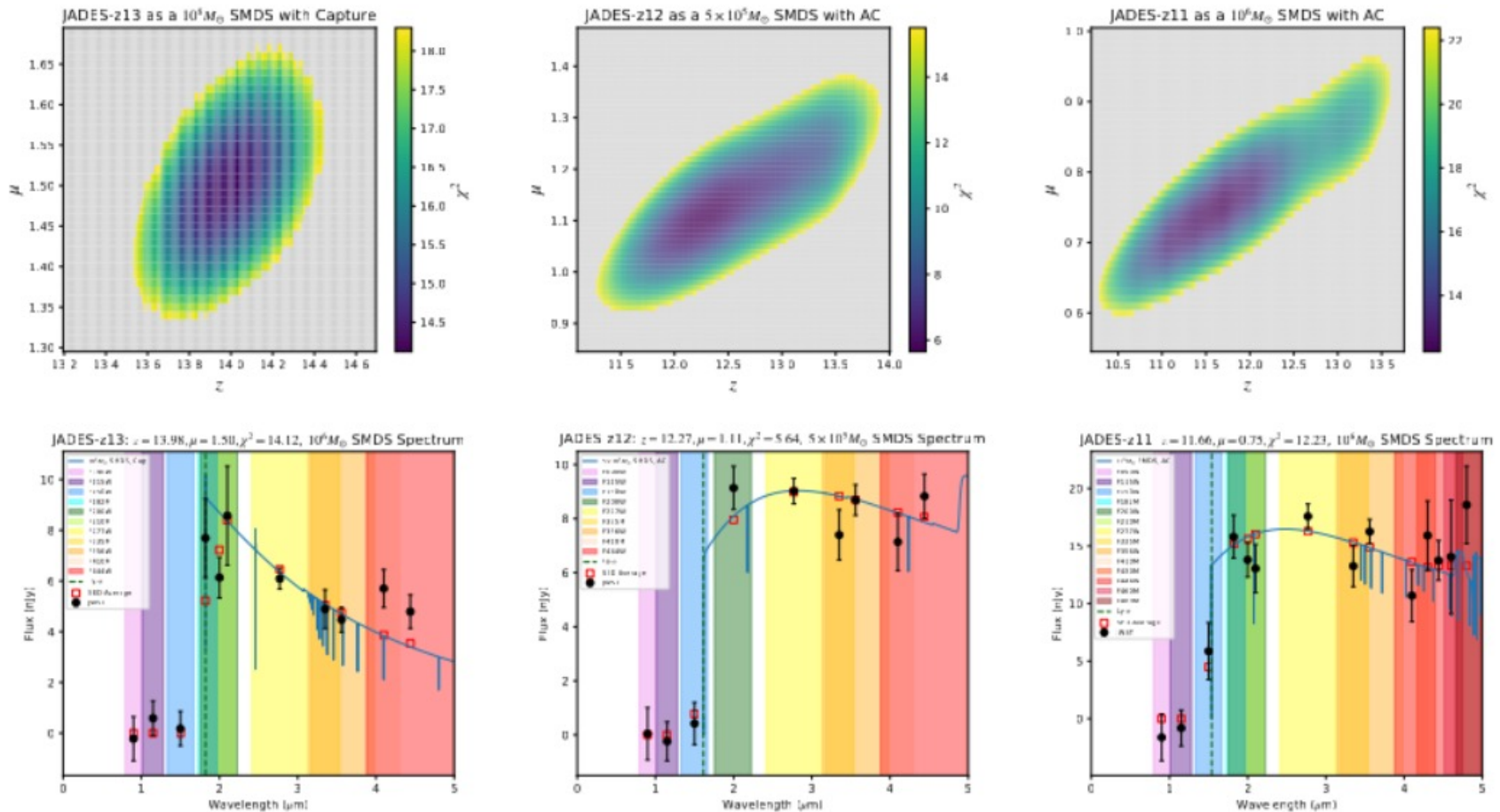
or, most lines of light have mu < 1

(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
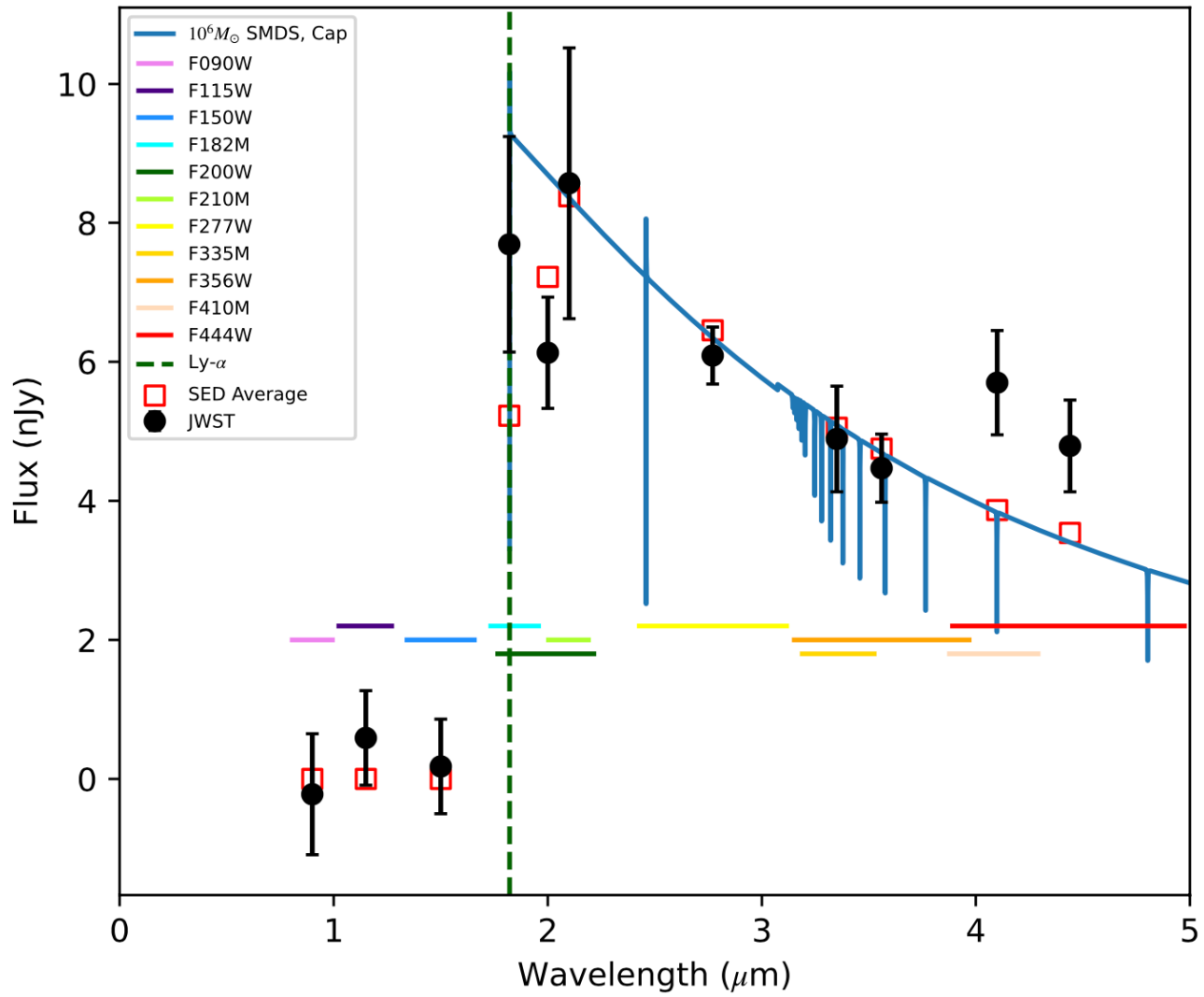
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# GNz11:    An object with beautiful spectrum: a galaxy



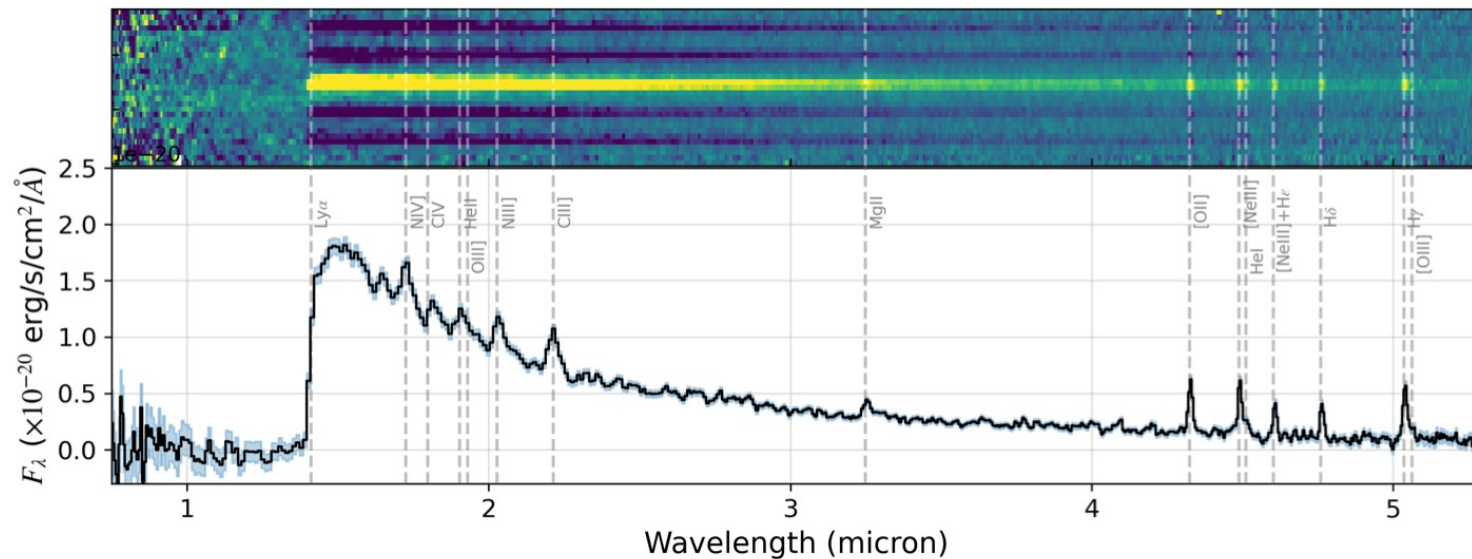A. J. Bunker et al.: JADES Spectroscopy of GN-z11

**Fig. 1.** 2D (top) and 1D (bottom) spectra of GN-z11 using PRISM/CLEAR configuration of NIRSpec. 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

- HeII 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 ~ 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 at UT)

# 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 (see work of group of Jonathan Tan)

- 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