Has JWST discovered Dark Stars?

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DAVID GRANT presents
A JOHN CARPENTER film

From
ALAN DEAN FOSTER
FIRST
2001 : A SPACE ODYSSEY
THEN
THE POSEIDON ADVENTURE
NOW

DARK STAR

A

bombed out in space
with a spaced out bomb!

n OPPIDAN ENTERTAINMENTS Release of a JACK H. HARRIS Production Starring DAN O'BANNON and BRIAN NARELLE Produced & directed by JOHN CARPENTER

Collaborators

Doug Spolyar

Paolo Gondolo

Peter Bodenheimer

Pearl Sandick

Tanja Rindler-Daller

This work

Cosmin Ilie

Colgate University

Jillian Paulin

See her poster on this work.

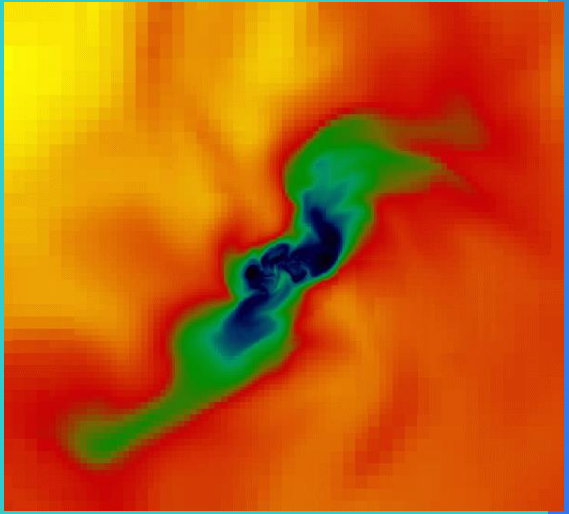
Dark Stars

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?**

First Stars: Standard Picture

- Formation Basics:
  - First luminous objects ever.
  - At z = 10-50
  - Form inside DM haloes of ~10^6 $M_\odot$
  - Baryons initially only 15%
  - Formation is a gentle process



Made only of hydrogen and helium from the Big Bang. No other elements existed yet

Dominant cooling Mechanism is

H_2

Not a very good coolant

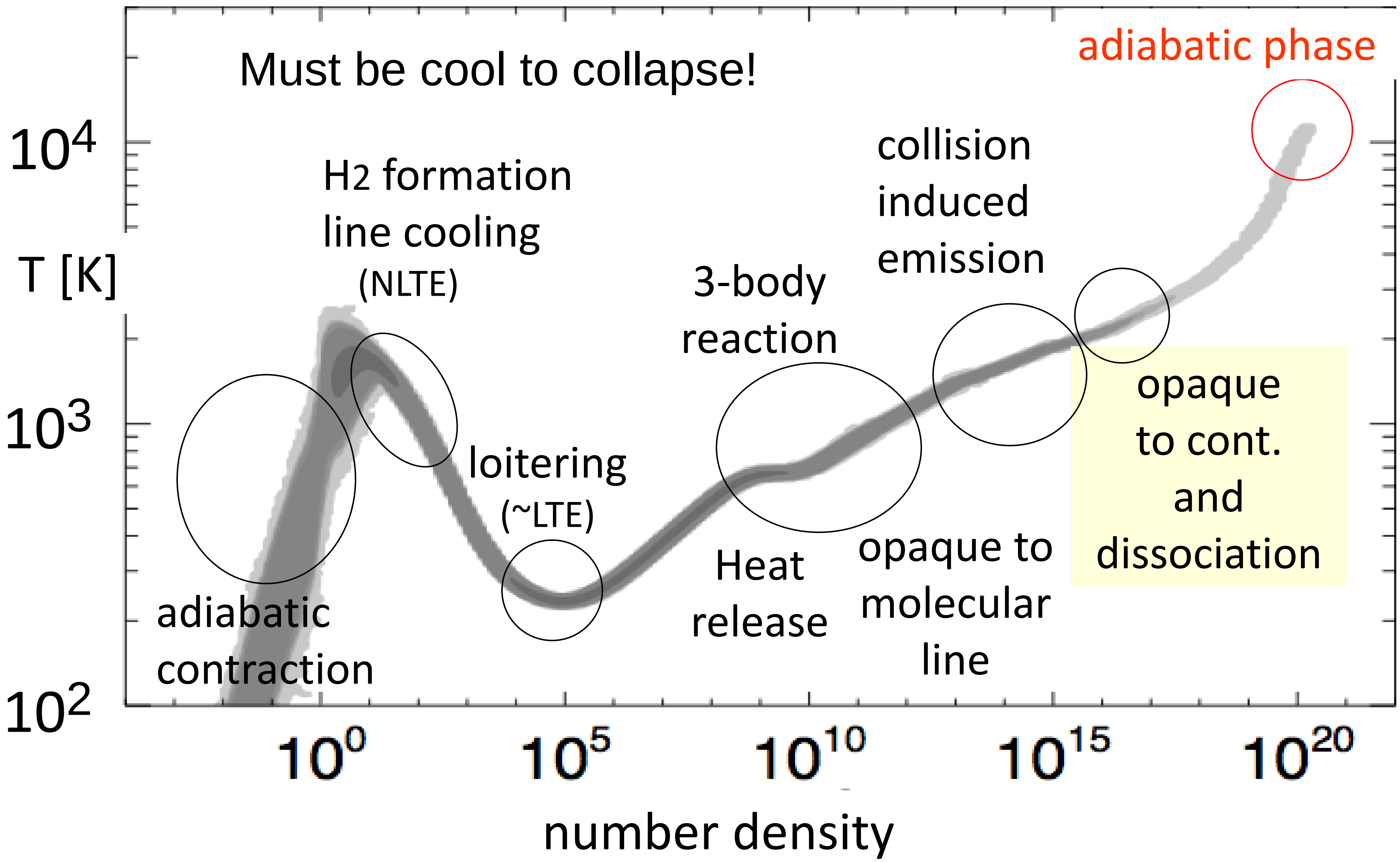
(Hollenbach and McKee '79)

Scale of the Halo

- Cooling time is less than Hubble time.
- First useful coolant in the early universe is H_2 .
- H_2 cools efficiently at around 1000K
- The virial temperature of $10^6\ M_\odot$

~1000K

Thermal evolution of a primordial gas



Must be cool to collapse!

adiabatic phase

H_2 formation
line cooling
(NLTE)

collision
induced
emission

3-body
reaction

loitering
(~LTE)

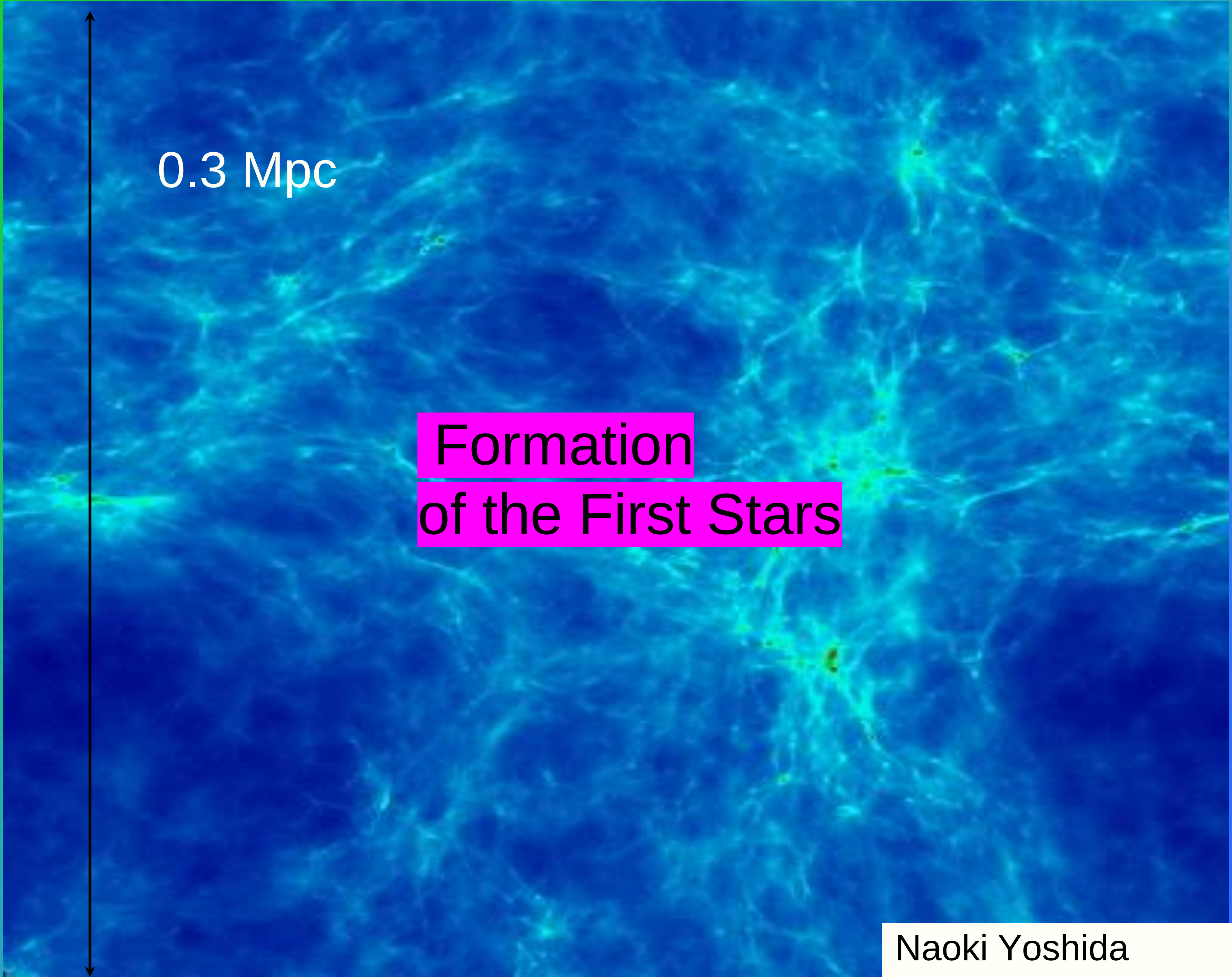
adiabatic
contraction

Heat
release

opaque to
molecular
line

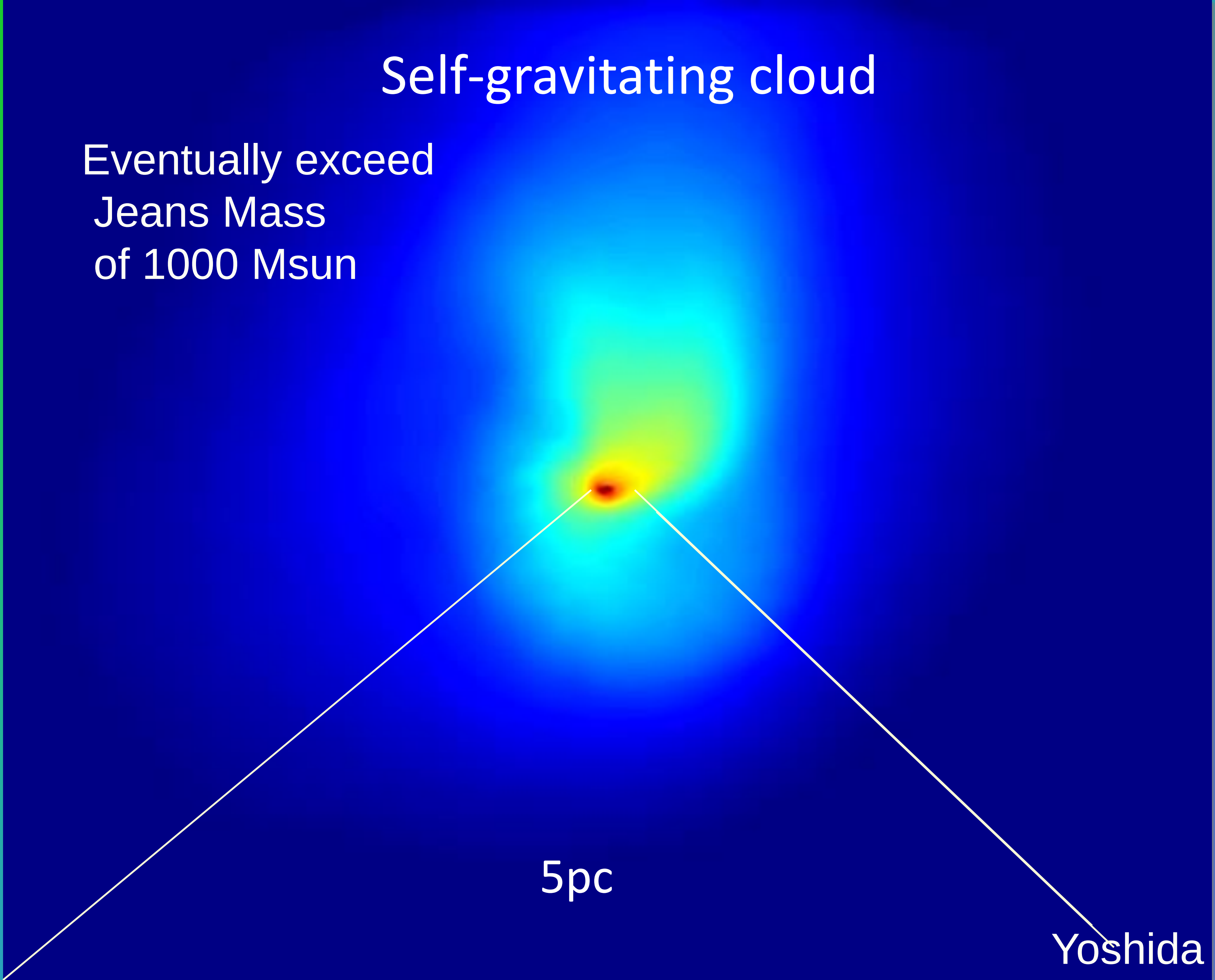
opaque
to cont.
and
dissociation

Formation of the First Stars



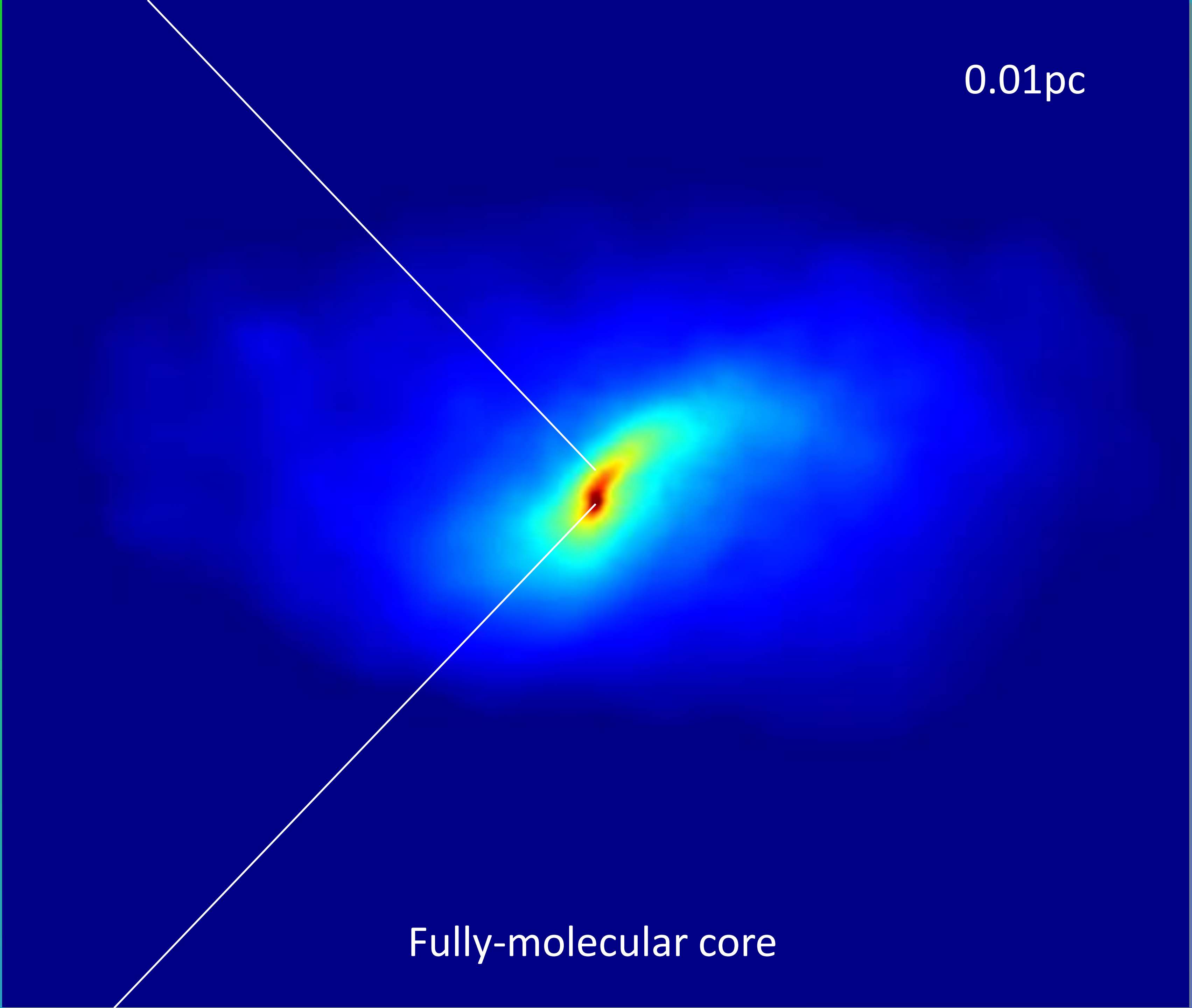
Naoki Yoshida

Self-gravitating cloud



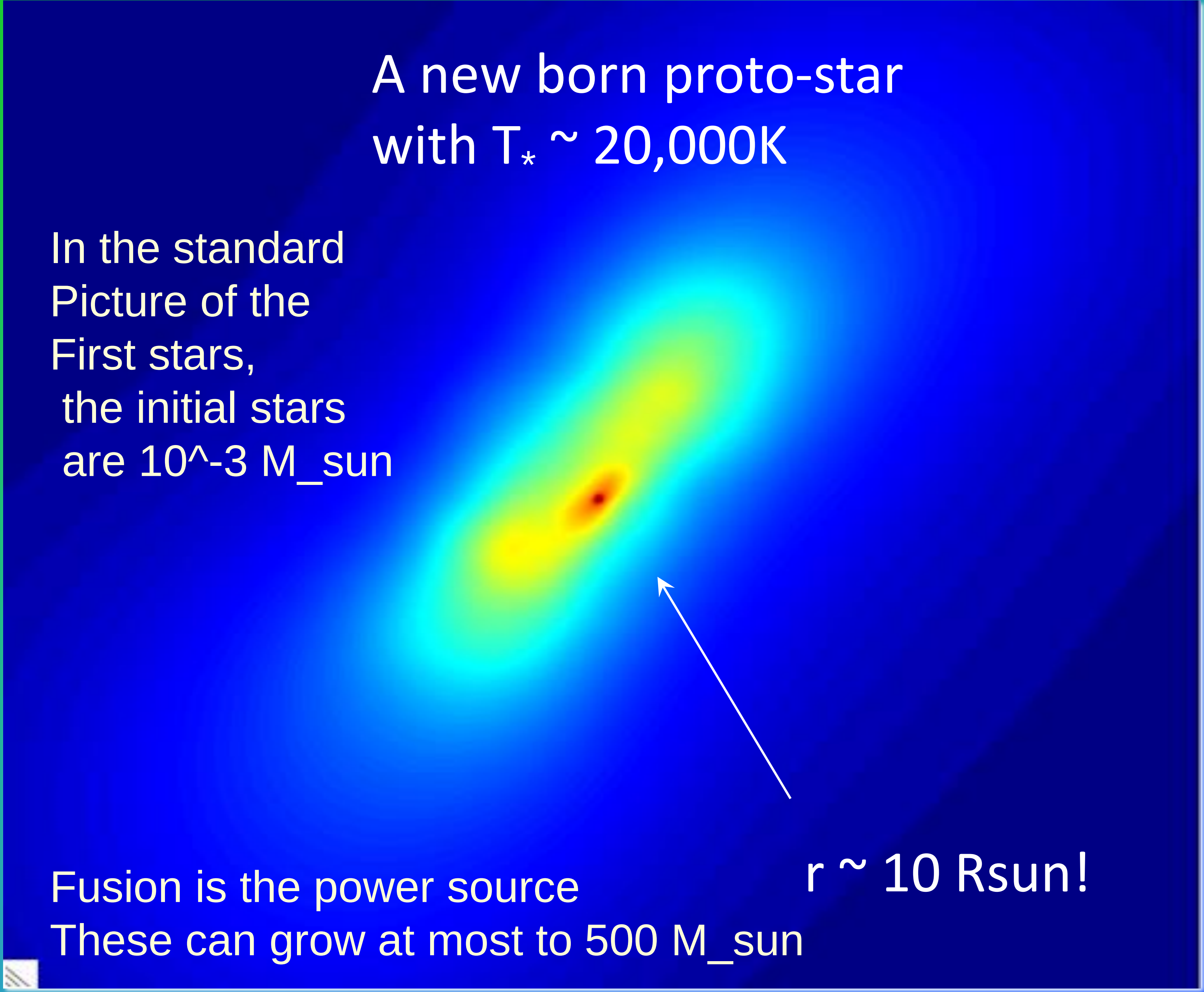
Eventually exceed
Jeans Mass
of 1000 Msun

Yoshida



Fully-molecular core

A new born proto-star with $T_* \sim$ 20,000K



In the standard
Picture of the
First stars,
the initial stars
are 10^-3 M_sun

r ~ 10 Rsun!

Fusion is the power source
These can grow at most to 500 M_sun

Scales

- Halo Baryonic Mass ~ $10^5\ M_\odot$

(Halo Mass $10^6\ M_\odot$)

↓

- Jeans Mass ~ $10^3\ M_\odot$

↓

- Initial Core Mass ~ $10^{-3}\ M_\odot$

↓ Accretion

Final stellar Mass??

feedback effects
McKee and Tan 2008

With DM heating
Much more massive

$500 M_\odot$ Standard Picture

10^3 - $10^7\ M_\odot$ Dark Star

The role of WIMPs

Mass 1Gev-10TeV (canonical 100GeV)

Annihilation cross section (WIMPS):

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

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

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

Why DM annihilation in the first stars is more potent than in today's stars: higher DM density

- **THE RIGHT PLACE**:

  one single star forms at the center of a million solar mass DM halo

- **THE RIGHT TIME:**

  the first stars form at high redshift,

  z = 10-50, and density scales as (1+z)^3

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.

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.

Dark Matter Heating

Heating rate:

$$Q_{ann} = n_c^2 < sv > ´ \; m_c$$

$$= \frac{r_c^2 < sv >}{m_c}$$

Fraction of annihilation energy deposited in the gas:

$$G_{DMHeating} = f_Q \, Q_{ann}$$

$f_Q :$

1/3 electrons

1/3 photons

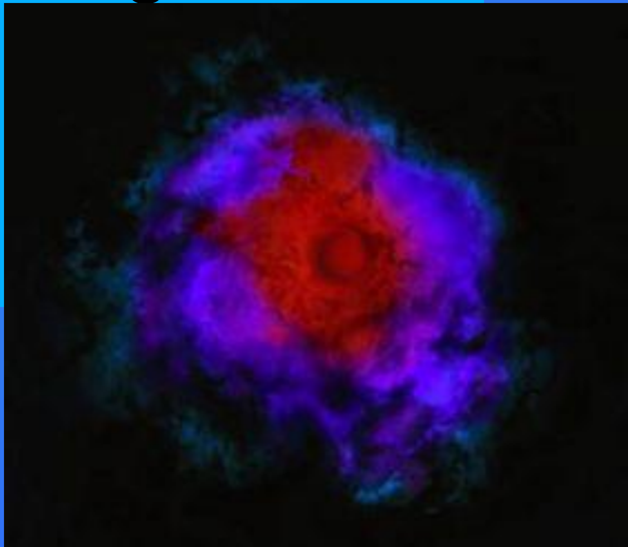
1/3 neutrinos

Three Conditions for Dark Stars

(Spolyar, Freese, Gondolo 2007 aka Paper 1)

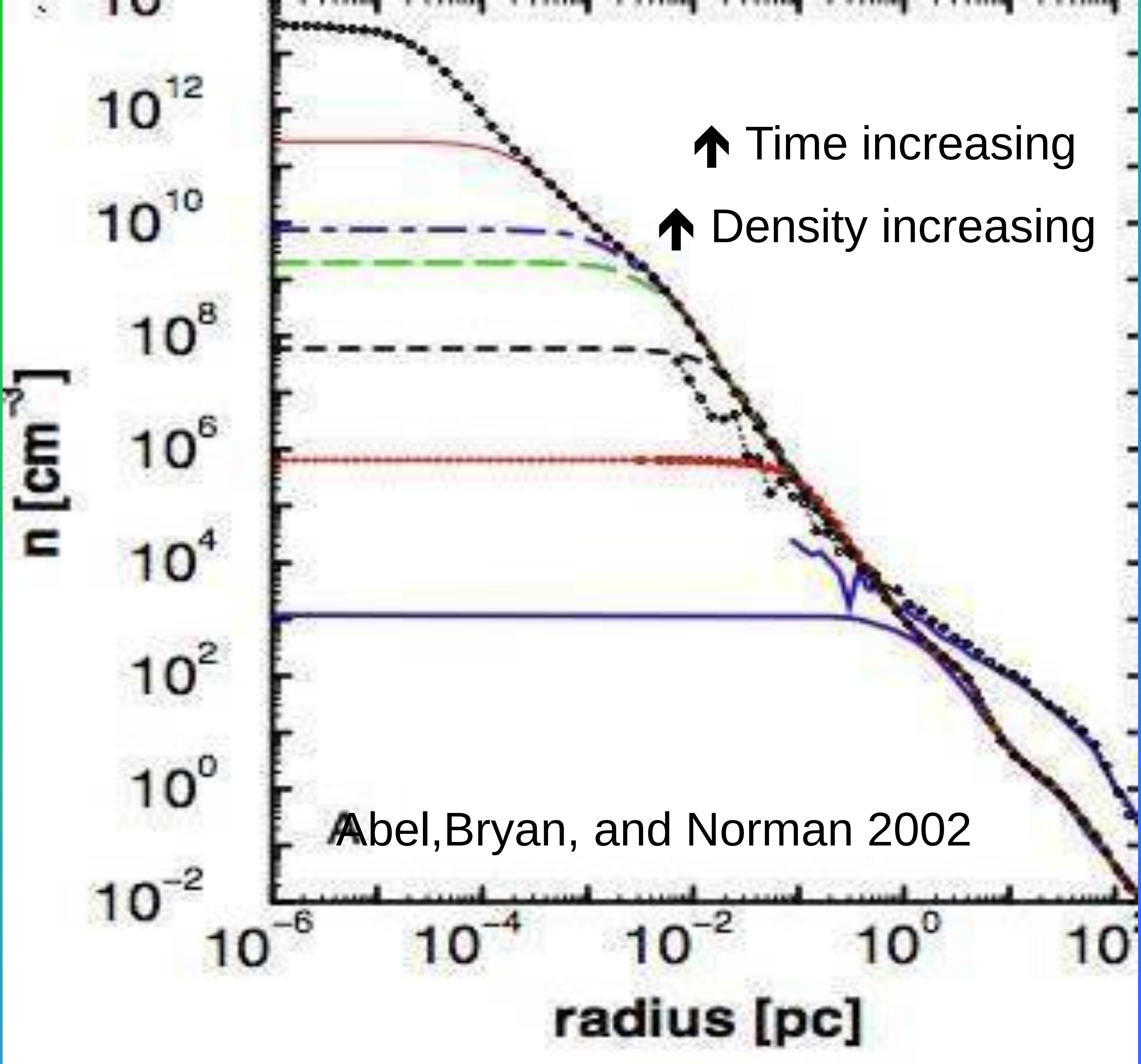
- I) Sufficiently High Dark Matter Density ?
- 2) Annihilation Products get stuck in star ?
- 3) DM Heating beats H2 Cooling ?

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).

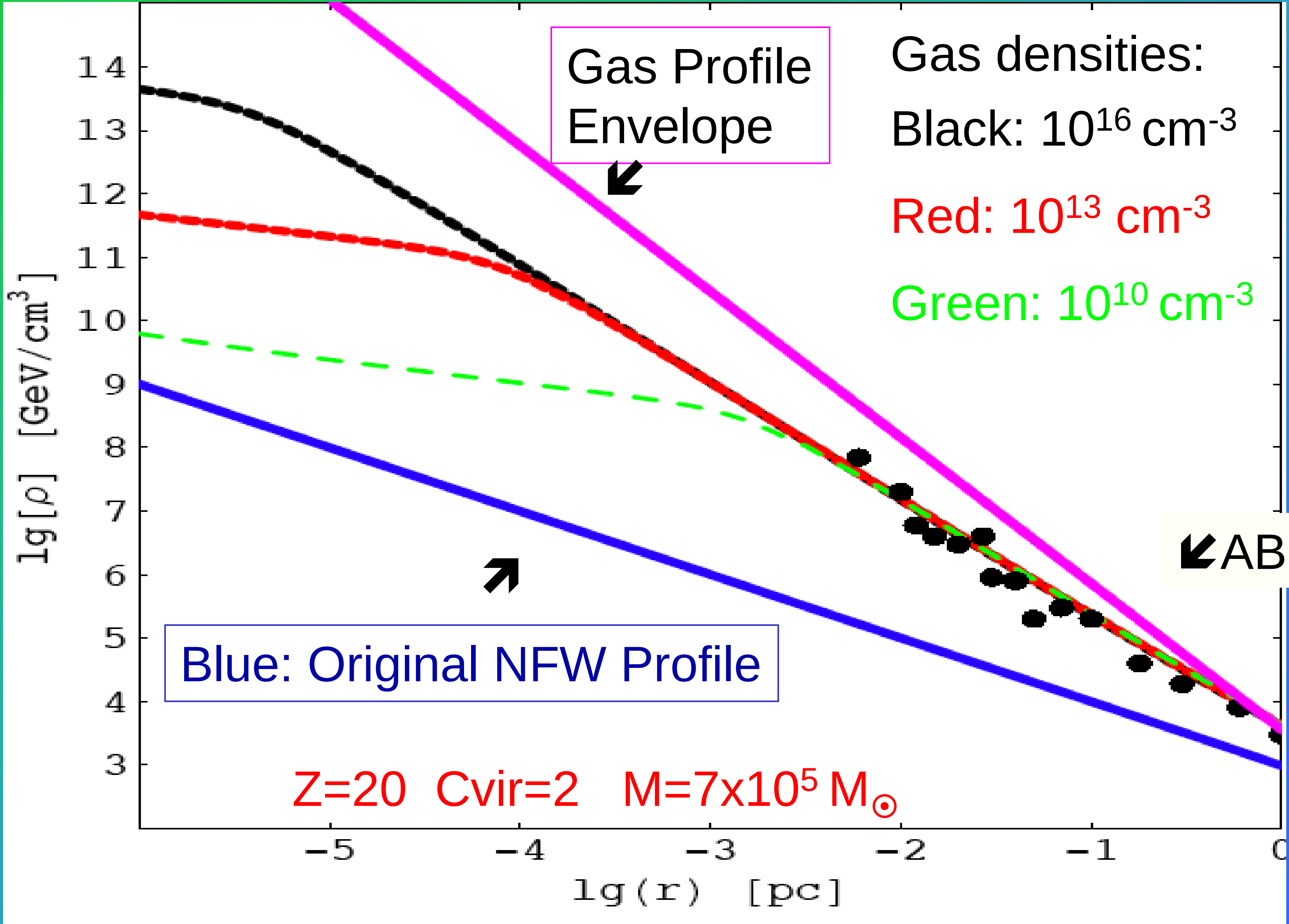


↑ Time increasing

↑ Density increasing

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=7×10^{5} $M_{\odot}$

Three Conditions for Dark Stars

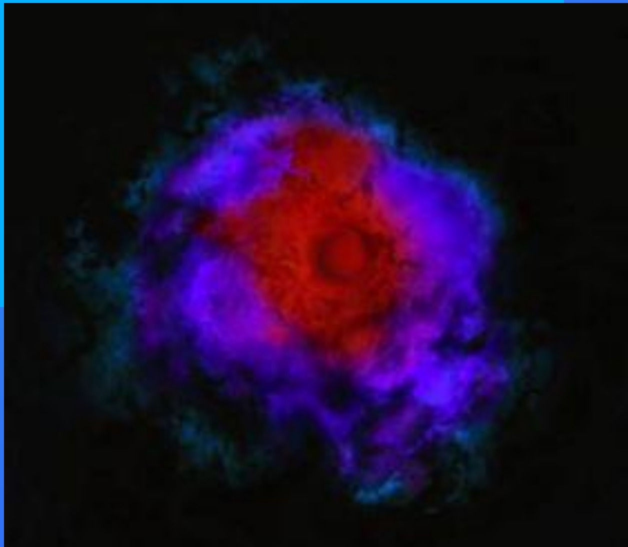
(Spolyar, Freese, Gondolo 2007 aka Paper 1)

- I) Sufficiently High Dark Matter Density

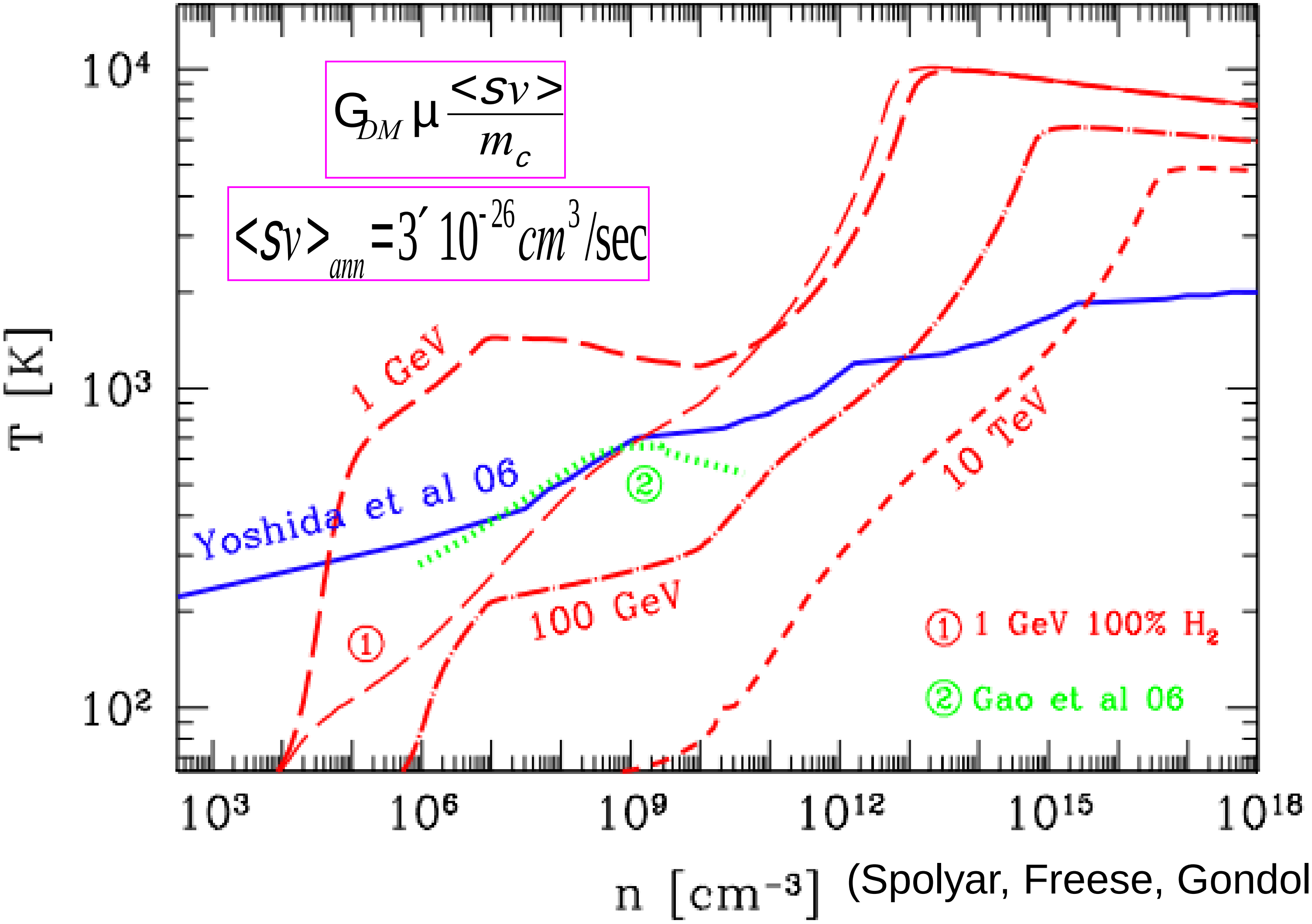
  YES
- 2) Annihilation Products get stuck in star ? YES: we used Pythia and Demanded 80 radiation lengths
- 3) DM Heating beats

  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.



$$G_{DM}\,\mu\,\frac{<sv>}{m_c}$$

$$<sv>_{ann} = 3' \, 10^{-26} \, cm^3/sec$$

(Spolyar, Freese, Gondolo April 2007)

DS Basic Properties

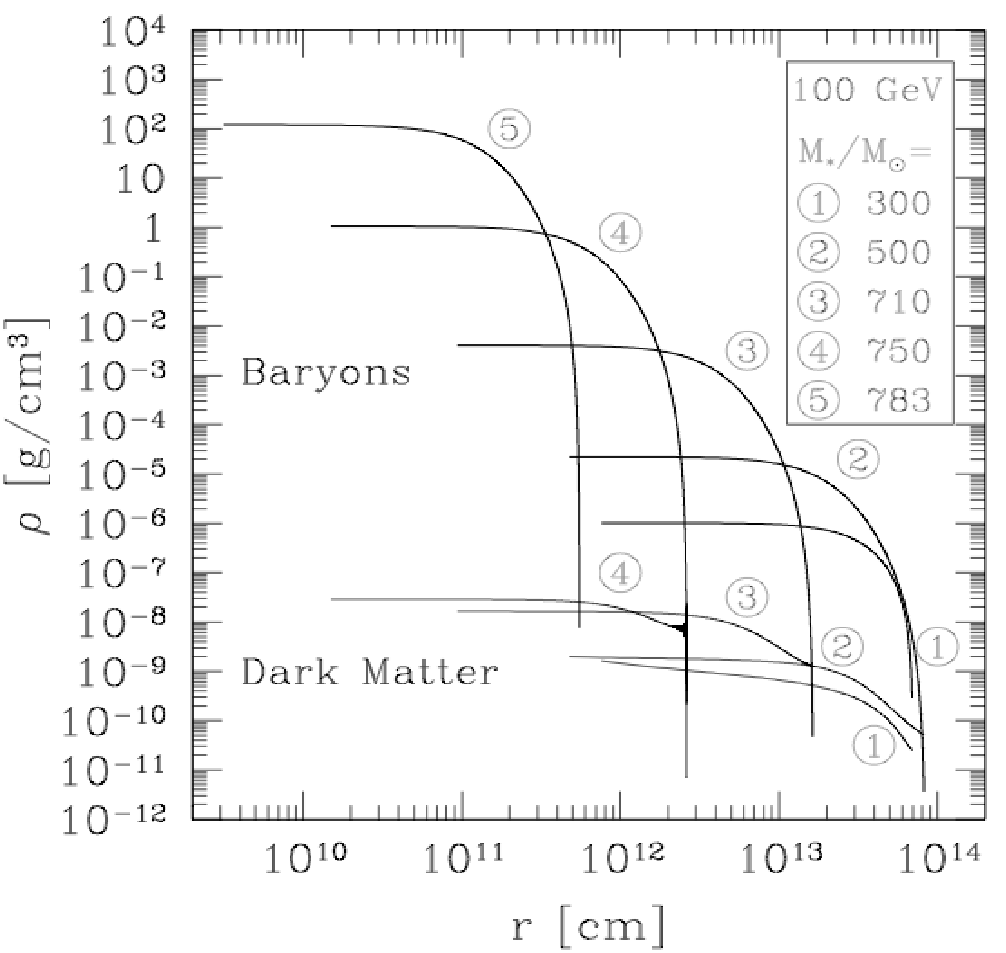
- We find that DS are big puffy objects:
  - Massive: can grow to $10^7 \, M_\odot$
  - Large- 10 a.u. (radius of Earth’s orbit around Sun)
  - Luminous: up to $10^{10} \, L_\odot$
  - Cool: 10,000 K vs. 100,000 K plus
    - Will not reionize the universe.
  - Long lived: more than 10^6 years, even till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

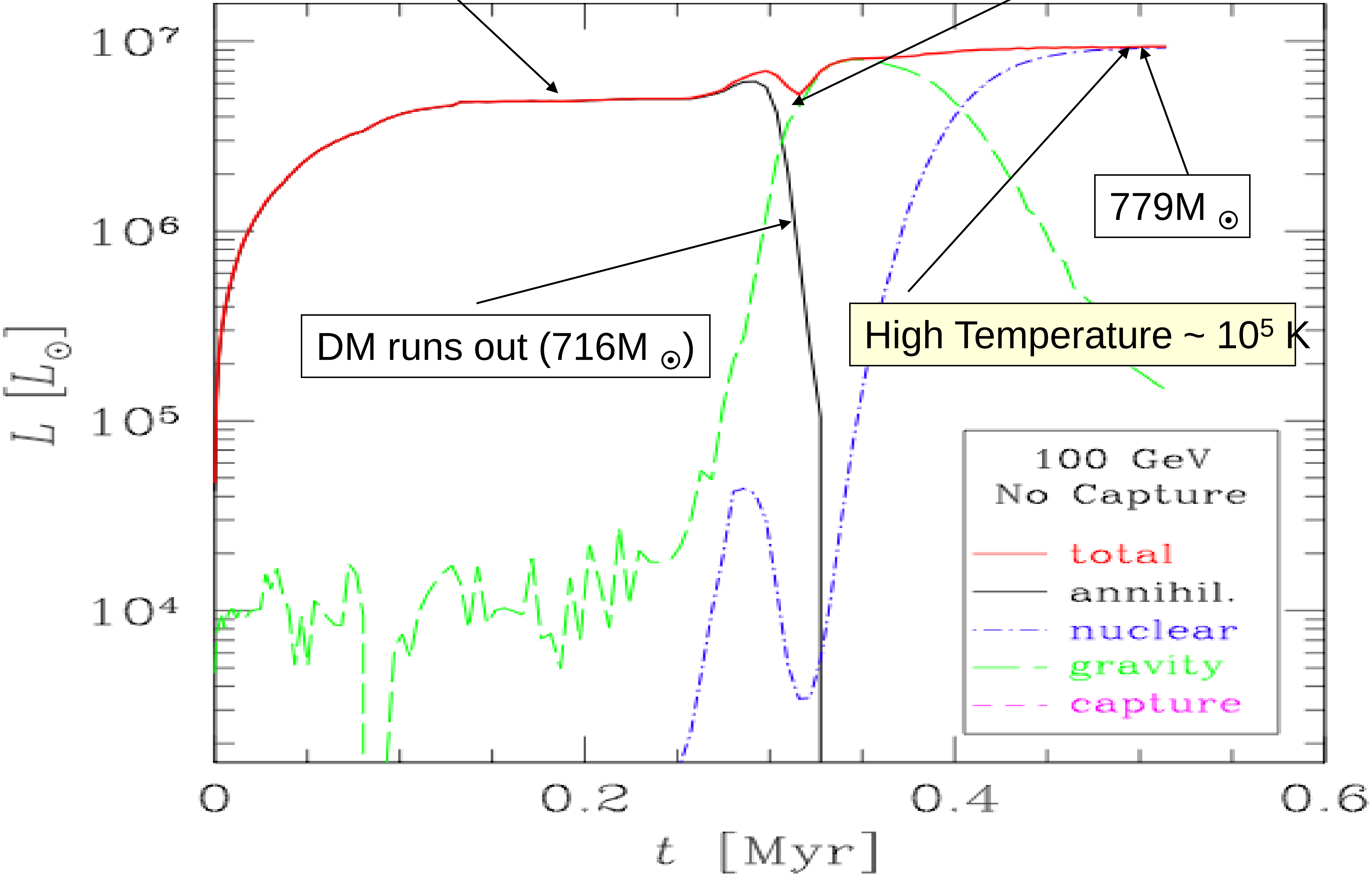
Following DS Evolution

- 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



DM runs out ($716M_{\odot}$)

High Temperature ~ 10^5 K

$779M_{\odot}$

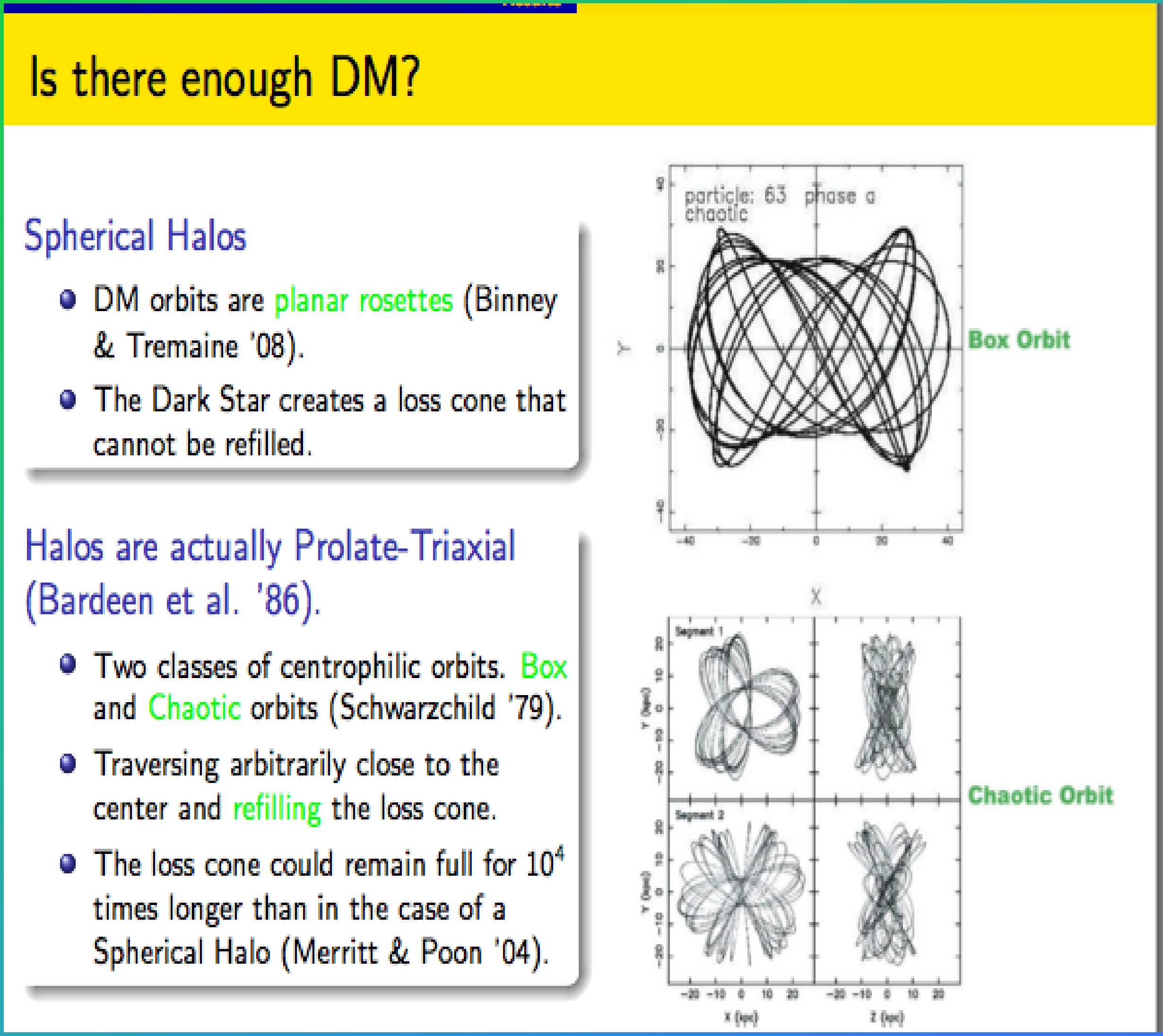
How big do Dark Stars get?

- KEY POINT: **As long as the star is Dark Matter powered, it can keep growing** because its surface is cool: surface temp 10,000K (makes no ionizing photons)
- Therefore, baryons can keep falling onto it without feedback.
- Previously, we considered spherical haloes and thought the dark matter runs out in the core, making a small hole in the middle with no dark matter. We made 1000 solar mass DS.
- Wrong: Haloes are triaxial! MUCH MORE DM is available and the DS can end up Supermassive up to ten million solar masses.
- Second mechanism to bring in more dark matter: capture

SUPERMASSIVE dark stars (SMDS)

- Previously we thought dark matter runs out in a million years with 800 $M_\odot$ stars: end up with a donut, i.e., big spherical halo of dark matter with hole in the middle
- But, triaxial haloes have all kinds of orbits (box orbits, chaotic orbits) so that much more dark matter is in there. Dark stars can grow much bigger and make supermassive stars, 10^5-10^7 $M_\odot$, last much longer, and reach 10^9-10^{11} $L_\odot$. Some may live to today
- Visible in James Webb Space Telescope.
- Leads to (as yet unexplained) big black Holes.

Additional mechanism: see Umeda etal (JCAP 2009)



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.

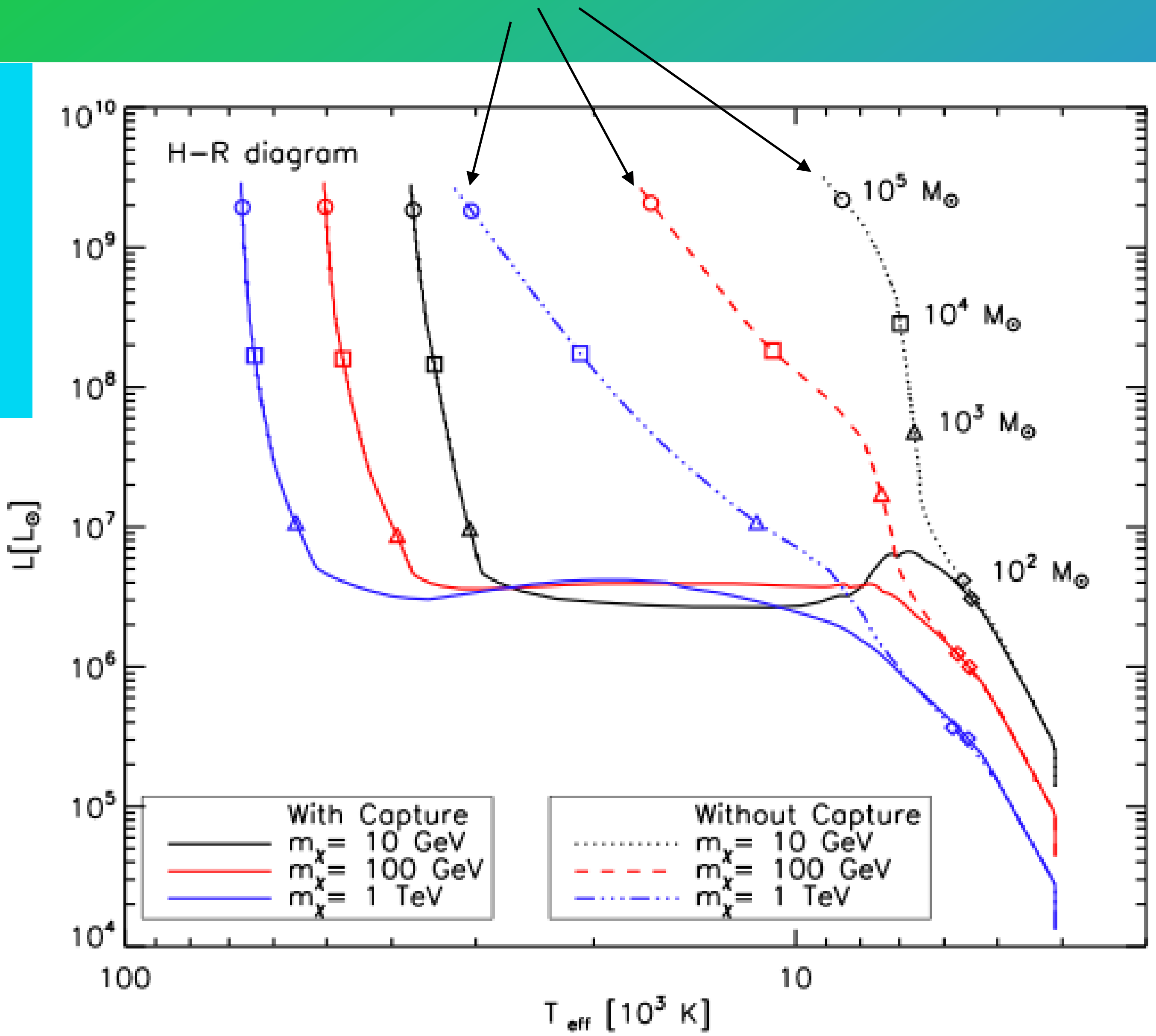
Halos are actually Prolate-Triaxial (Bardeen et al. '86).

- 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 the case of a Spherical Halo (Merritt & Poon '04).

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.

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



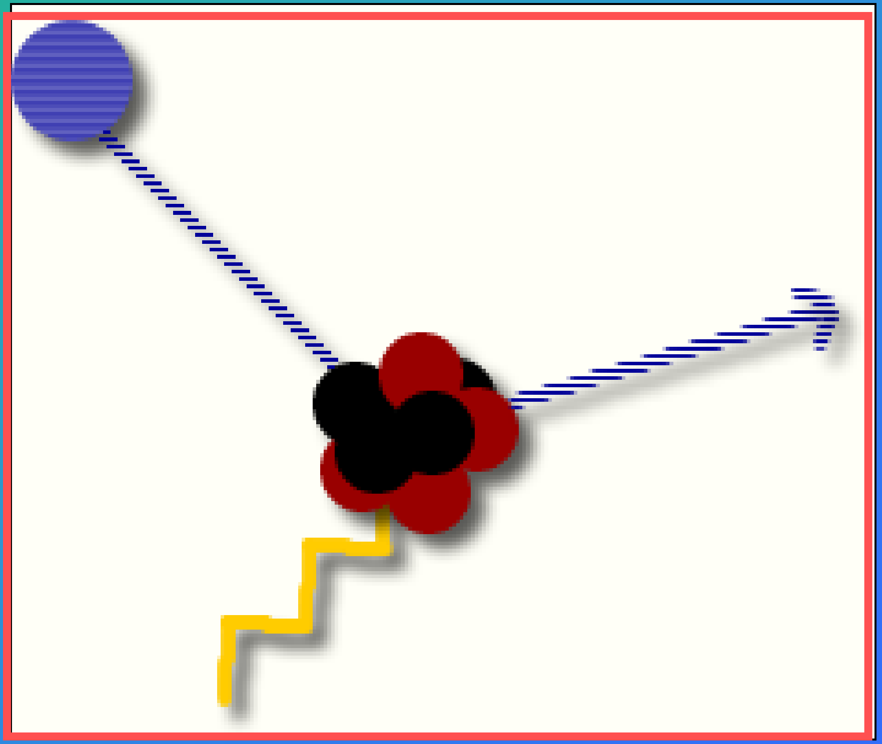
Additional possible source of DM fuel: capture

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

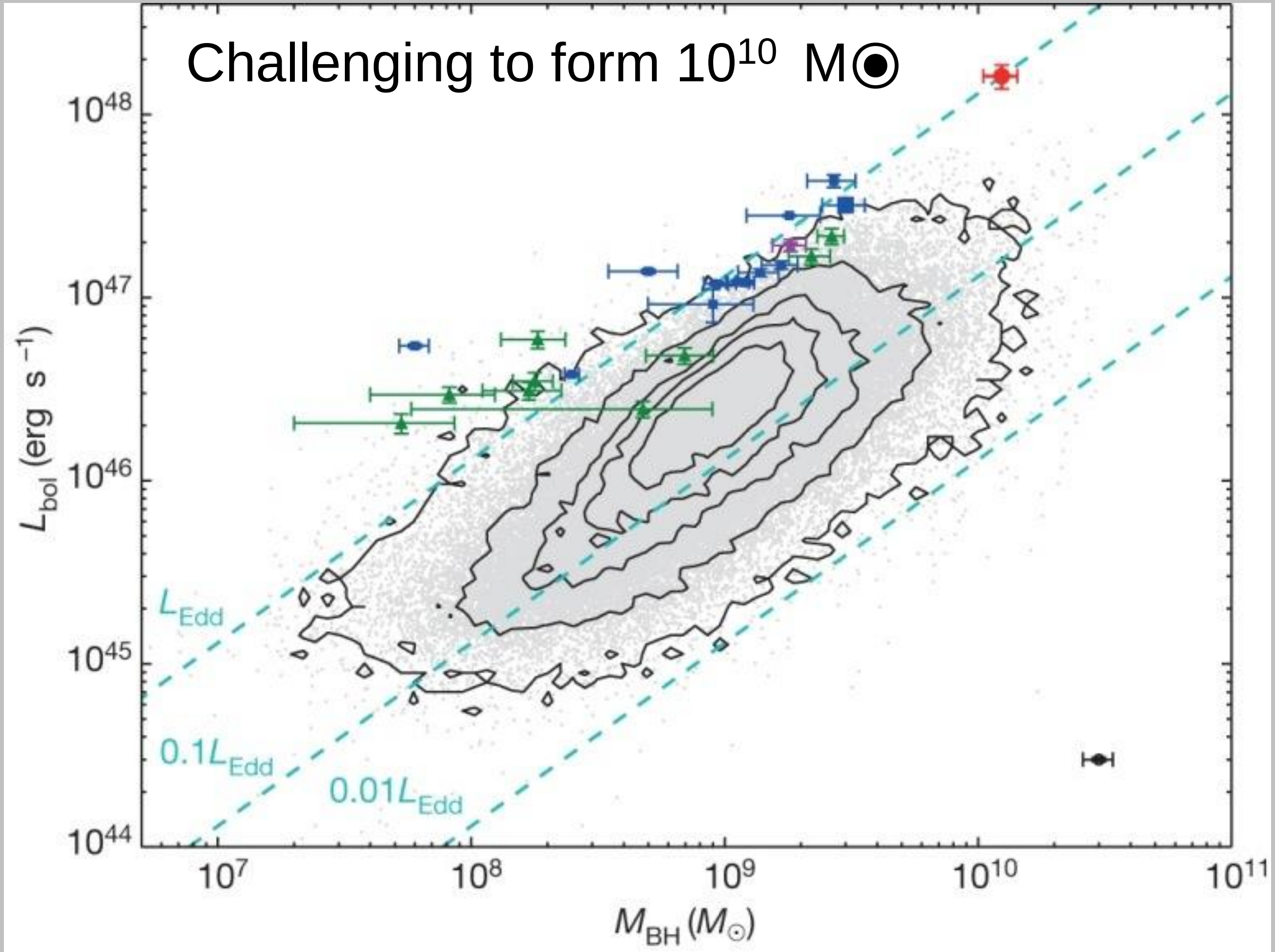
What happens next?
BIG BLACK HOLES

- 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

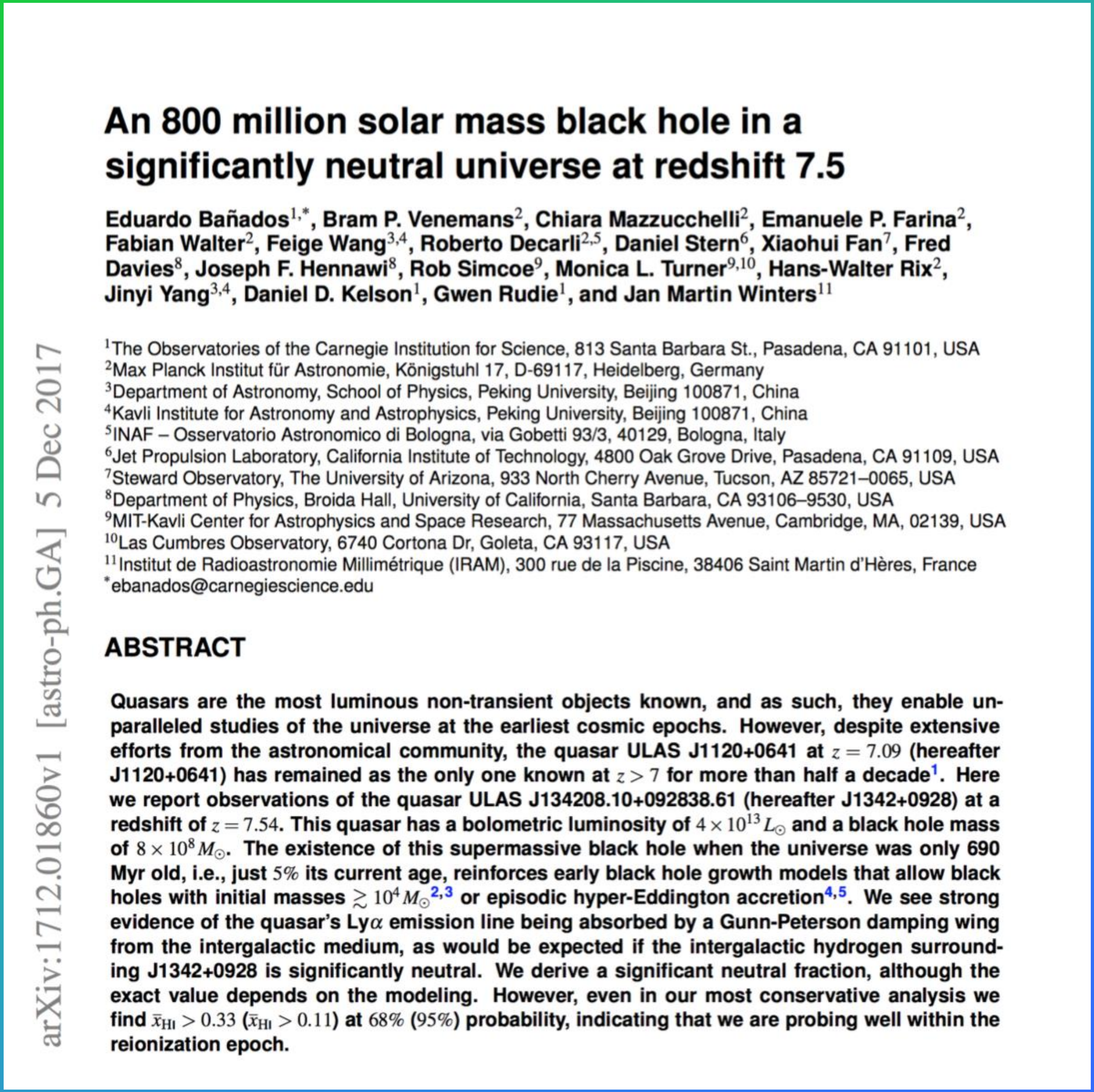
Very Massive progenitor Million Solar Masses

No other way to form supermassive BH this early z=6



Challenging to form 10^{10} M$\odot$

X-B Wu *et al. Nature* **518**, 512-515 (2015) doi:10.1038/nature14241



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]

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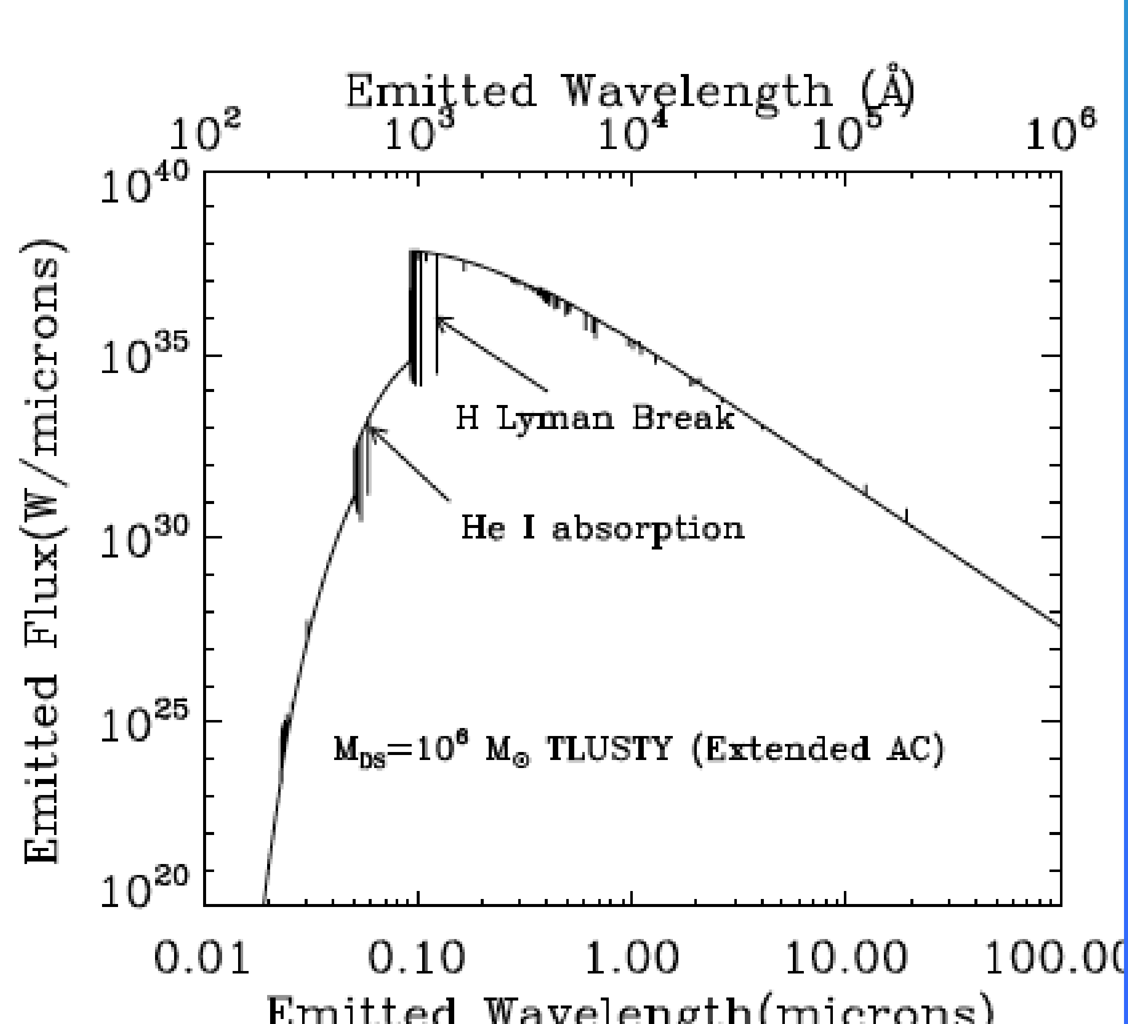
ABSTRACT

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 Lyα 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 $\bar{x}_{\rm HI} > 0.33$ ($\bar{x}_{\rm HI} > 0.11$) at 68% (95%) probability, indicating that we are probing well within the reionization epoch.

OBSERVING DARK STARS

DS Spectrum from TLUSTY (stellar atmospheres code)

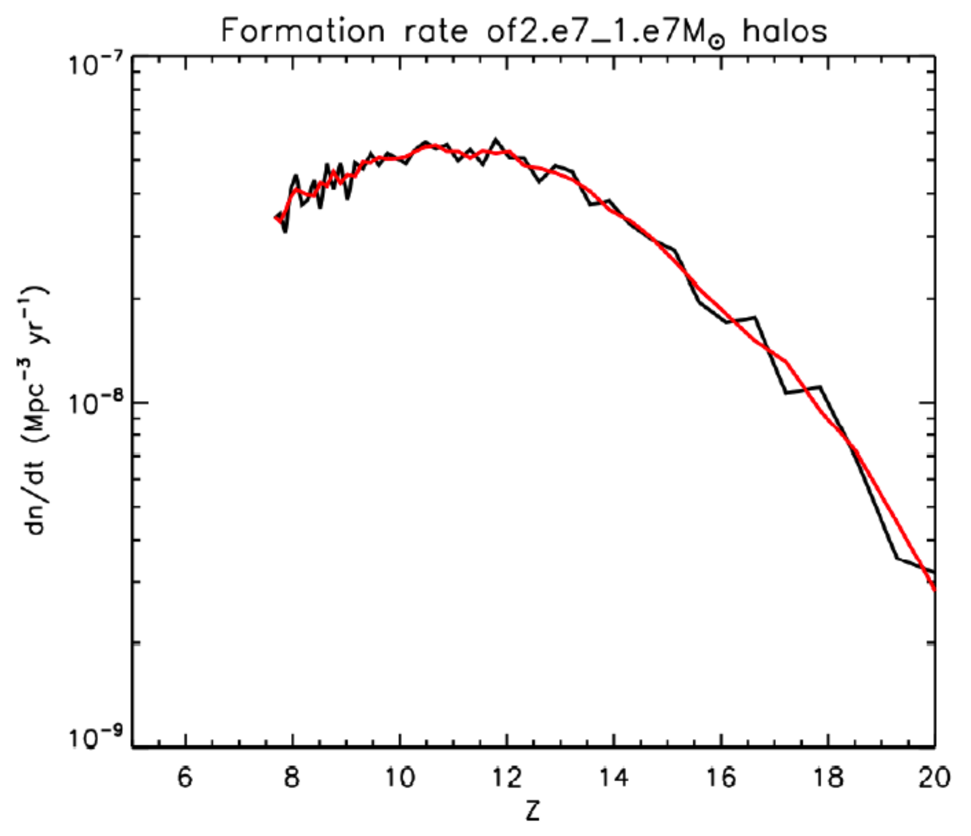


n.b. DS are made of hydrogen and helium only

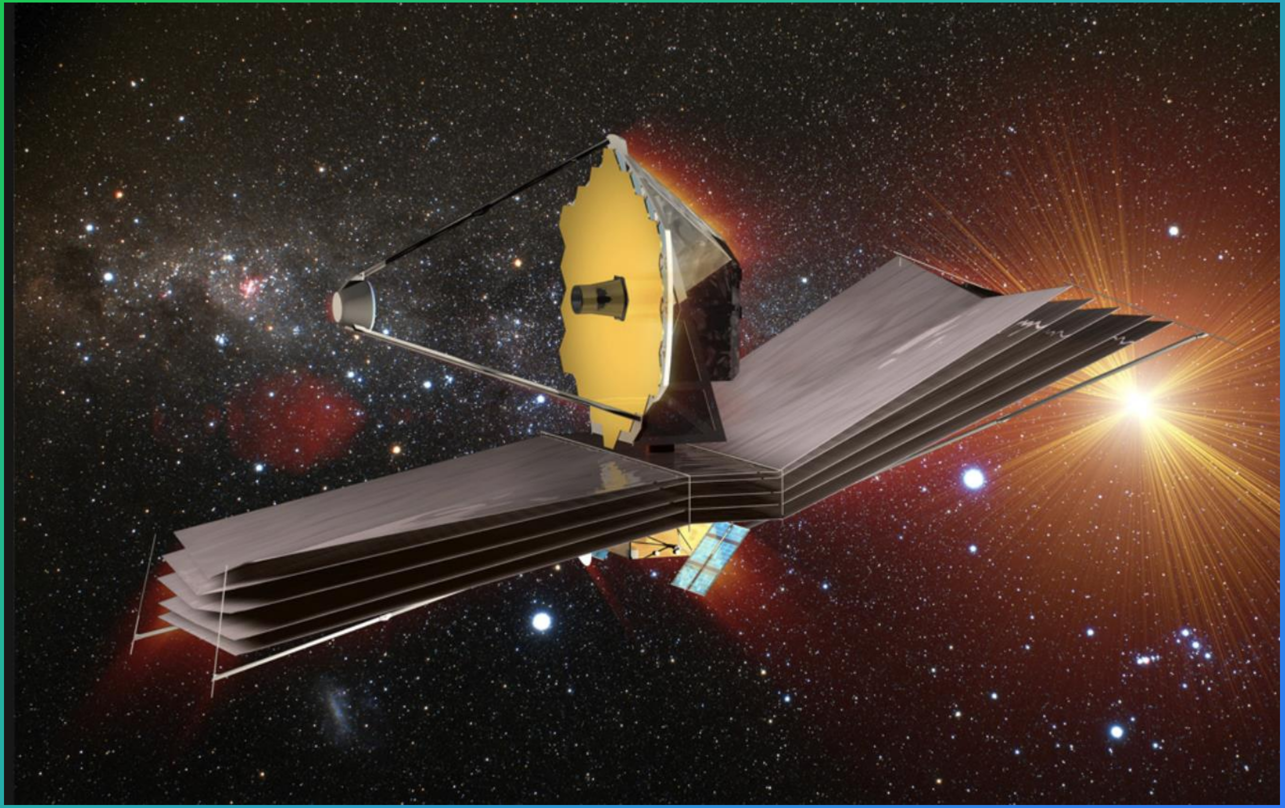
How many Dark Stars?

Start with Minihalo formation rate

Paul Shapiro

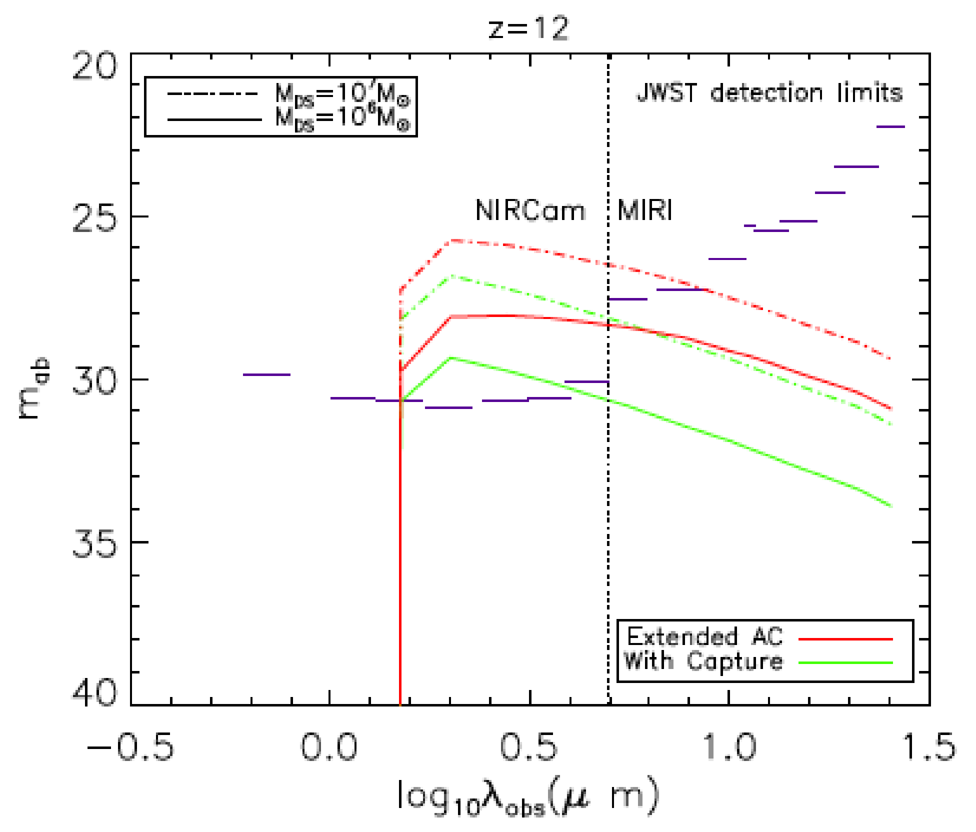


James Webb Space Telescope

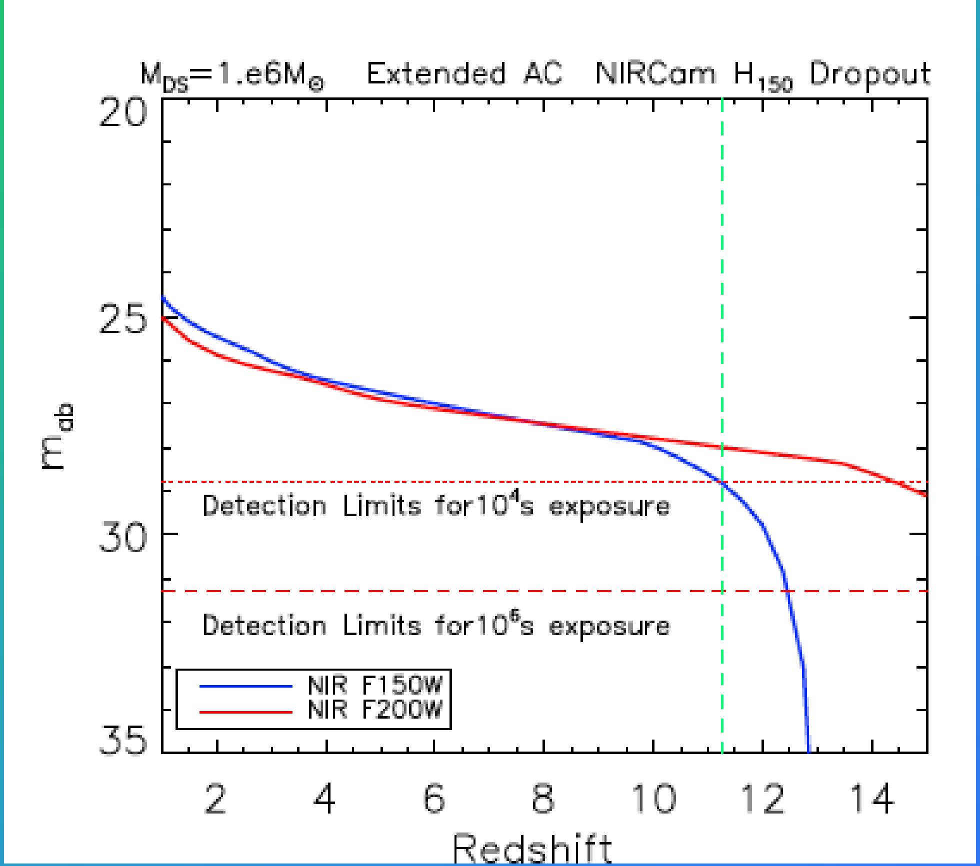


Supermassive Dark Stars:
They would be a billion times brighter than the Sun
But the same temperature as the Sun.

Dark Stars in JWST



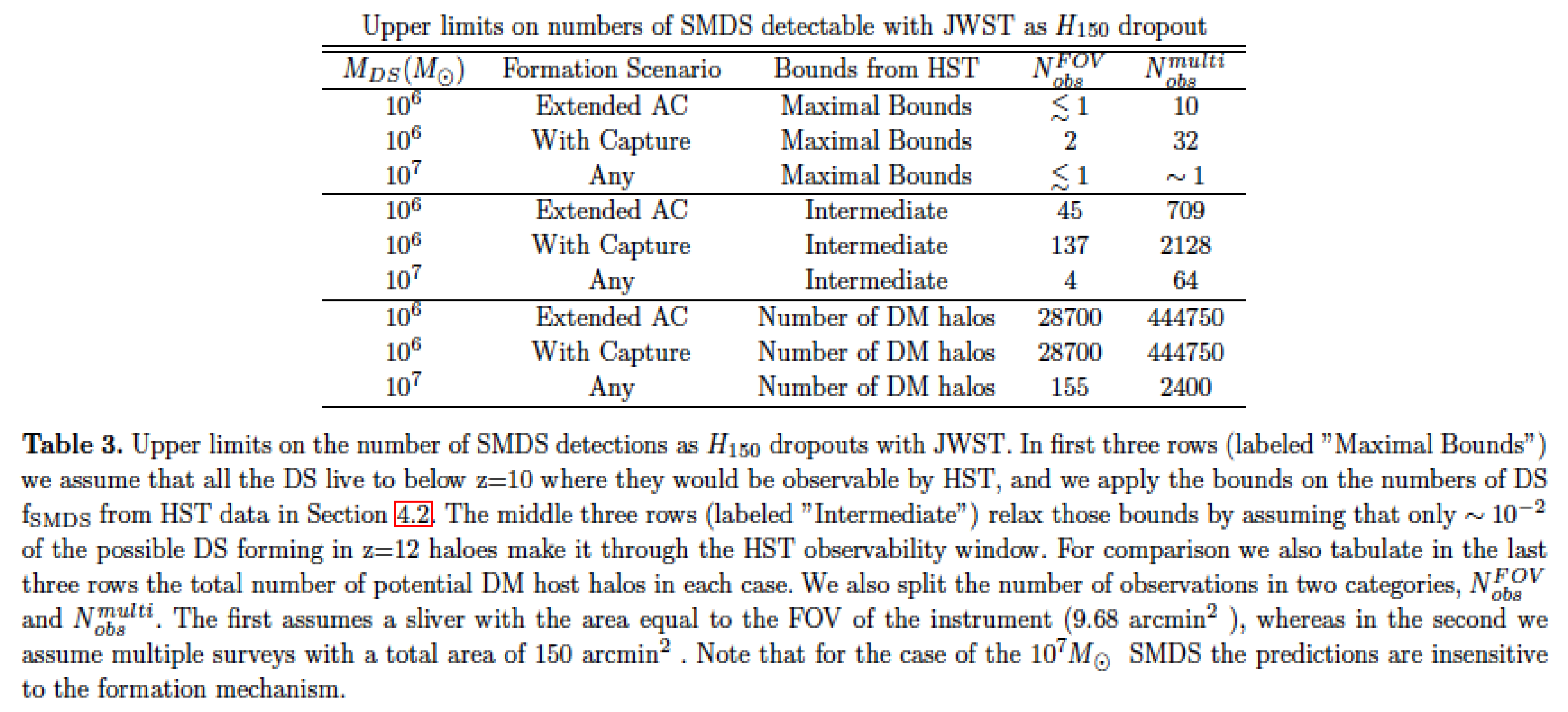
Million solar mass SMDS as H-band dropout



(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)

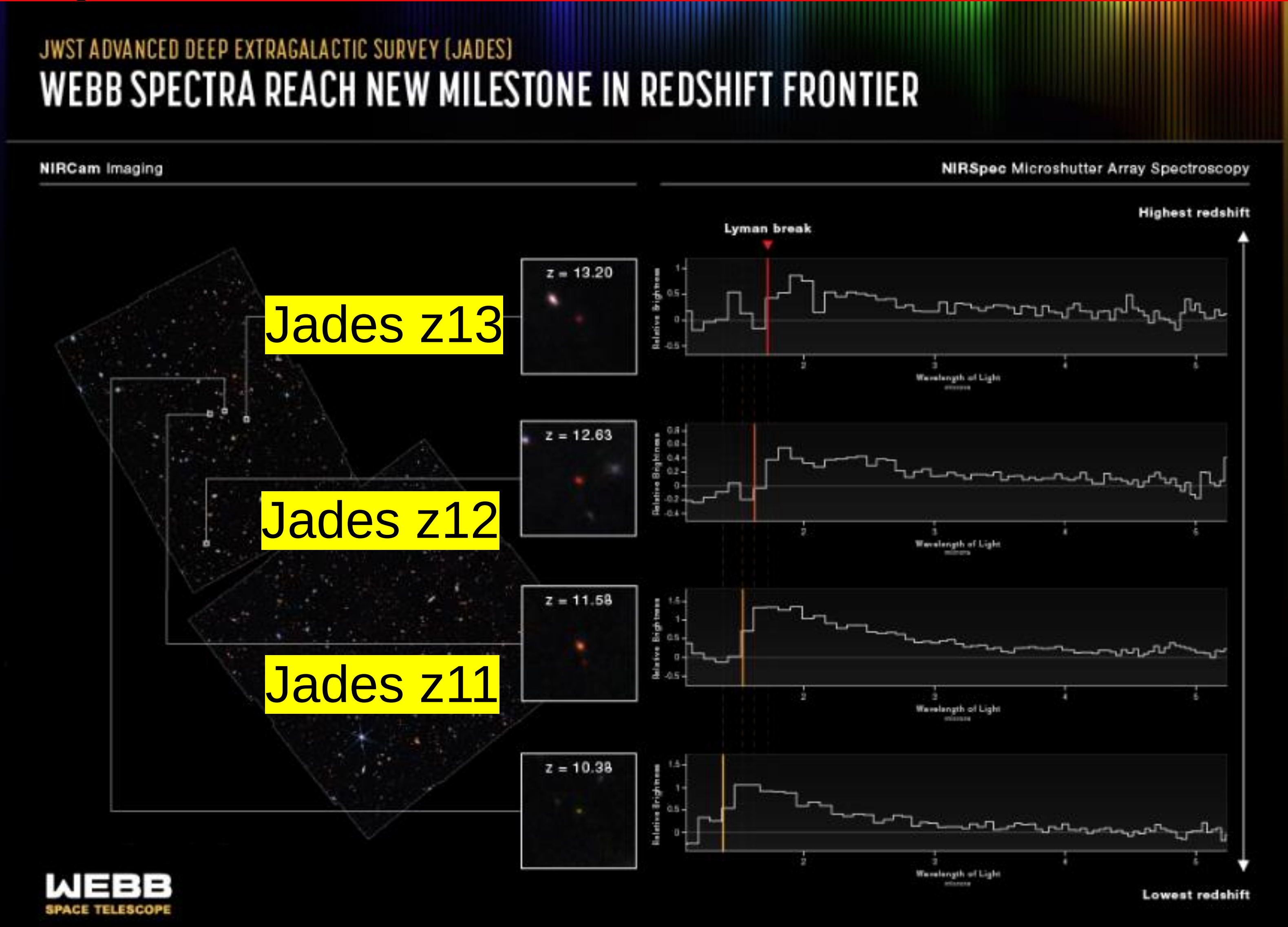


Upper limits on numbers of SMDS detectable with JWST as H_{150} dropout

$M_{DS}(M_\odot)$	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	$\lesssim 1$	~ 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.

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



Jades z13

Jades z12

Jades z11

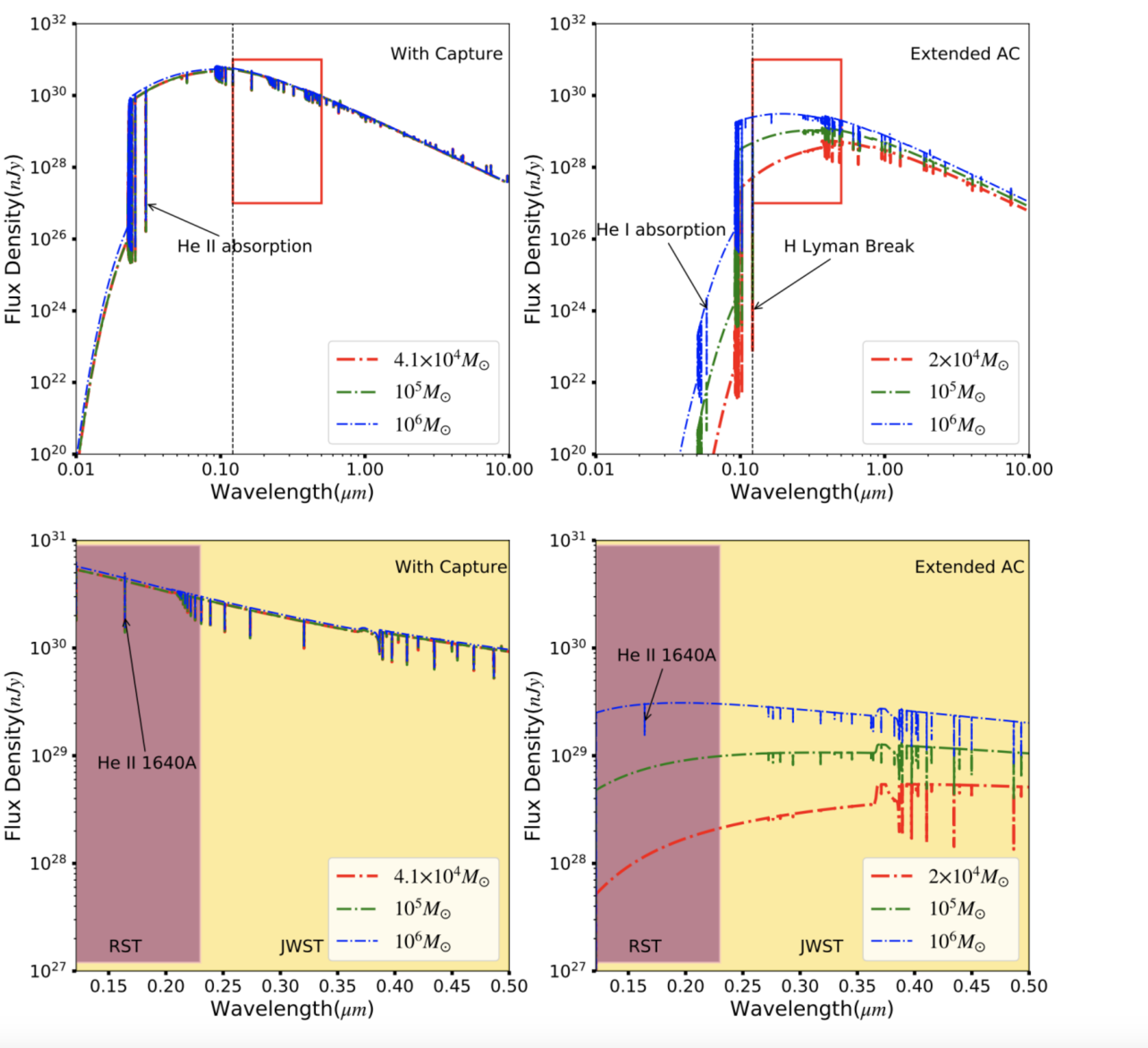
Criteria for hi-z objects to be Supermassive Dark Star candidates

- 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

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)

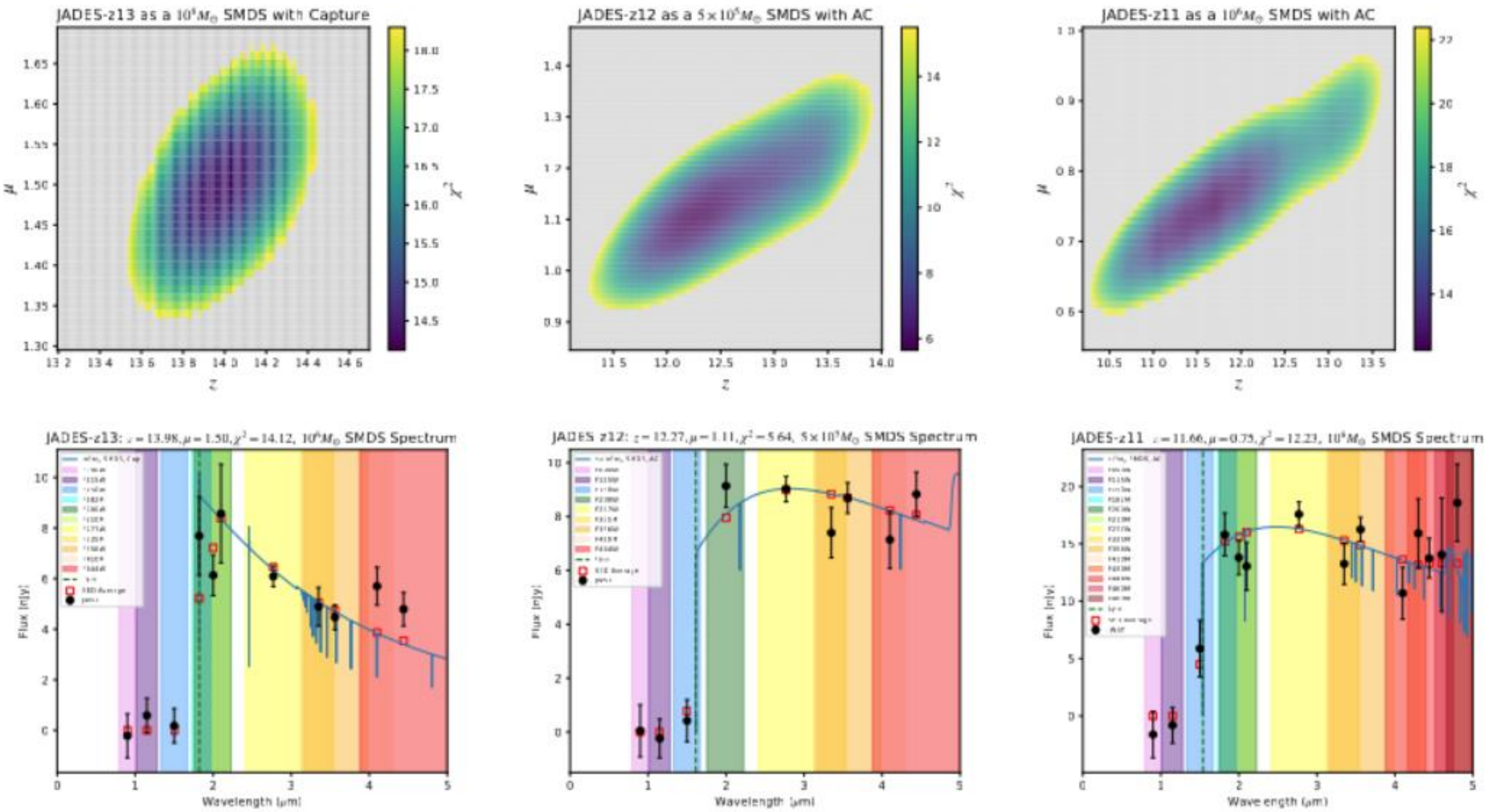
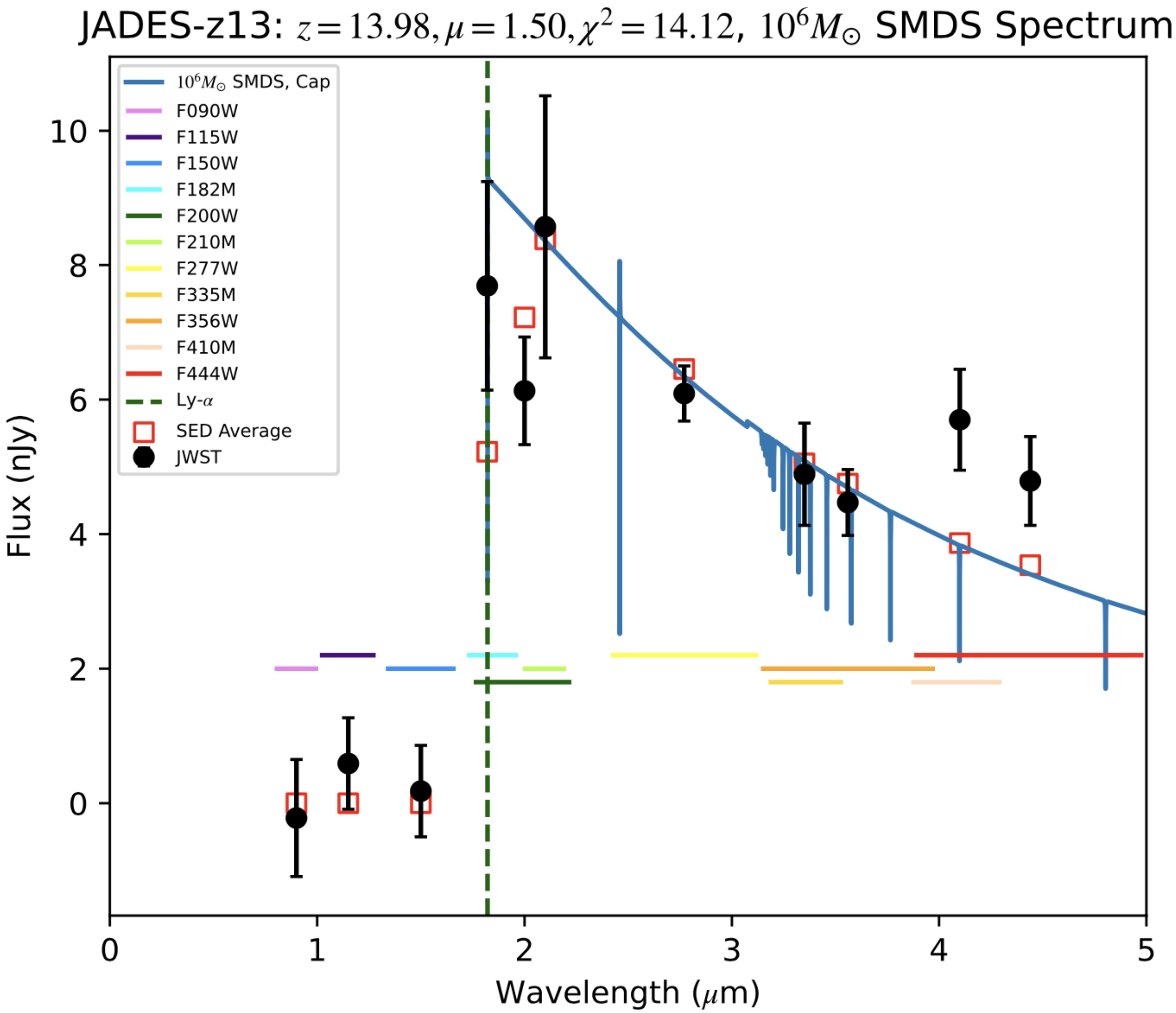


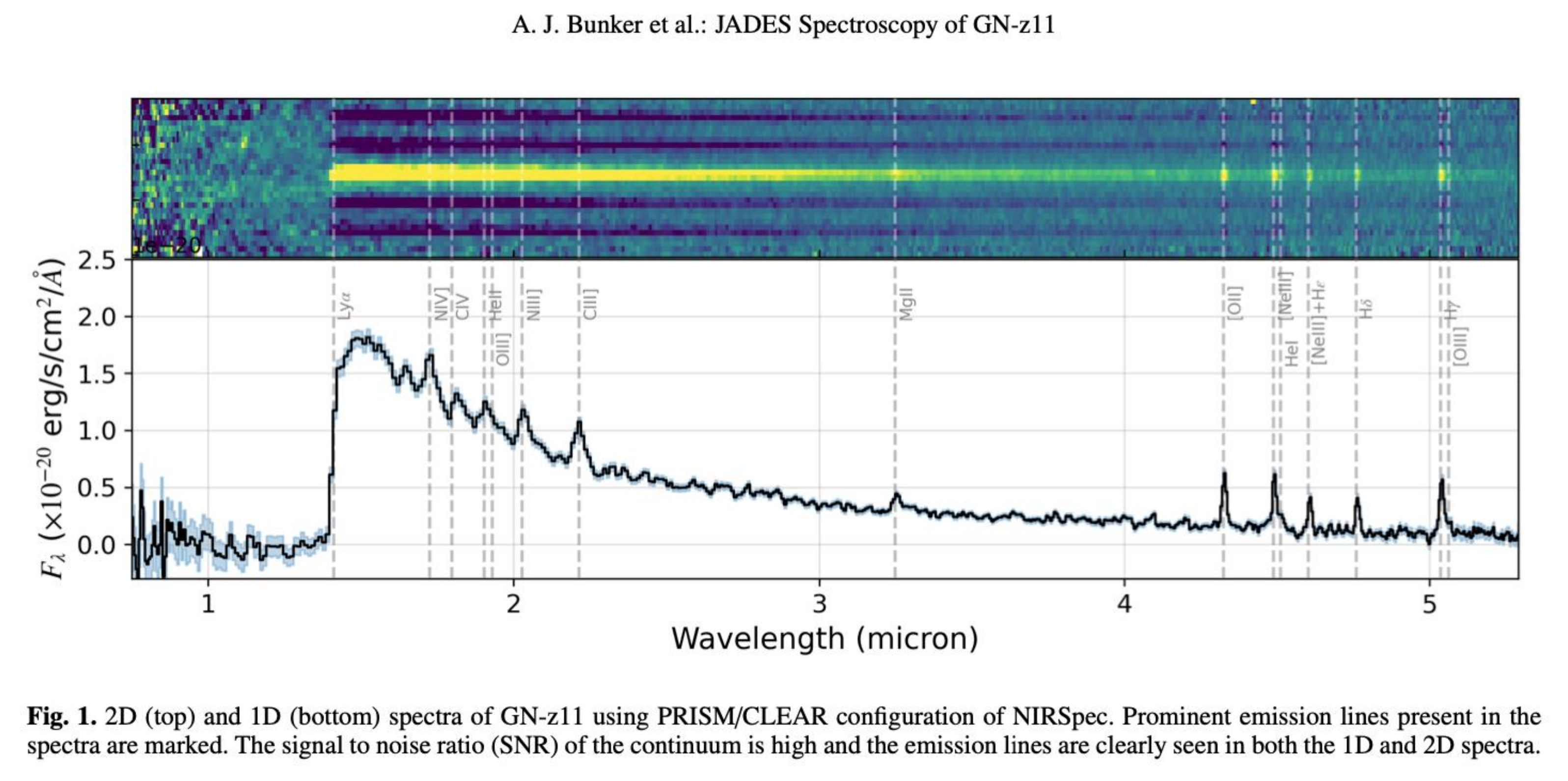
FIG. 1. (Top Row) Optimal fit regions in the z vs μ (magnification) parameter space for Supermassive Dark Star fits to JADES-GS-z11-0 , JADES-GS-z12-0 , and JADES-GS-z13-0 photometric data. The heatmap is color coded according to the value of the χ^2, and is cut off (grayed out) at the critical value 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
$10^6 M_\odot$ SMDS, Cap
F090W
F115W
F150W
F182M
F200W
F210M
F277W
F335M
F356W
F410M
F444W
Ly-α
SED Average
JWST
Flux (nJy)
10
8
6
4
2
0
Wavelength (μm)
0
1
2
3
4
5

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 and for brightest highly magnified objects.

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) and Cosmin Ilie arxiv:2306.11606

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