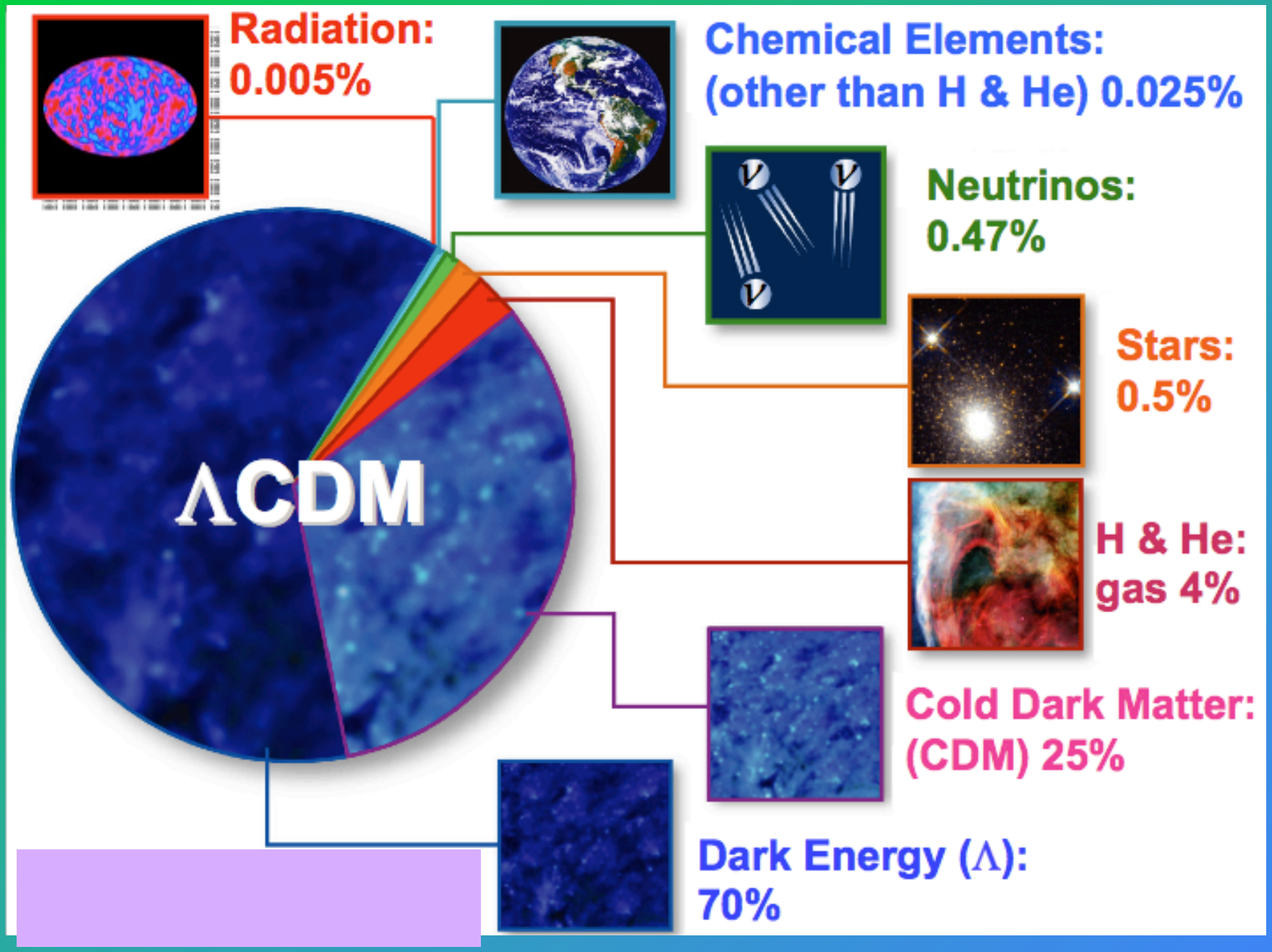
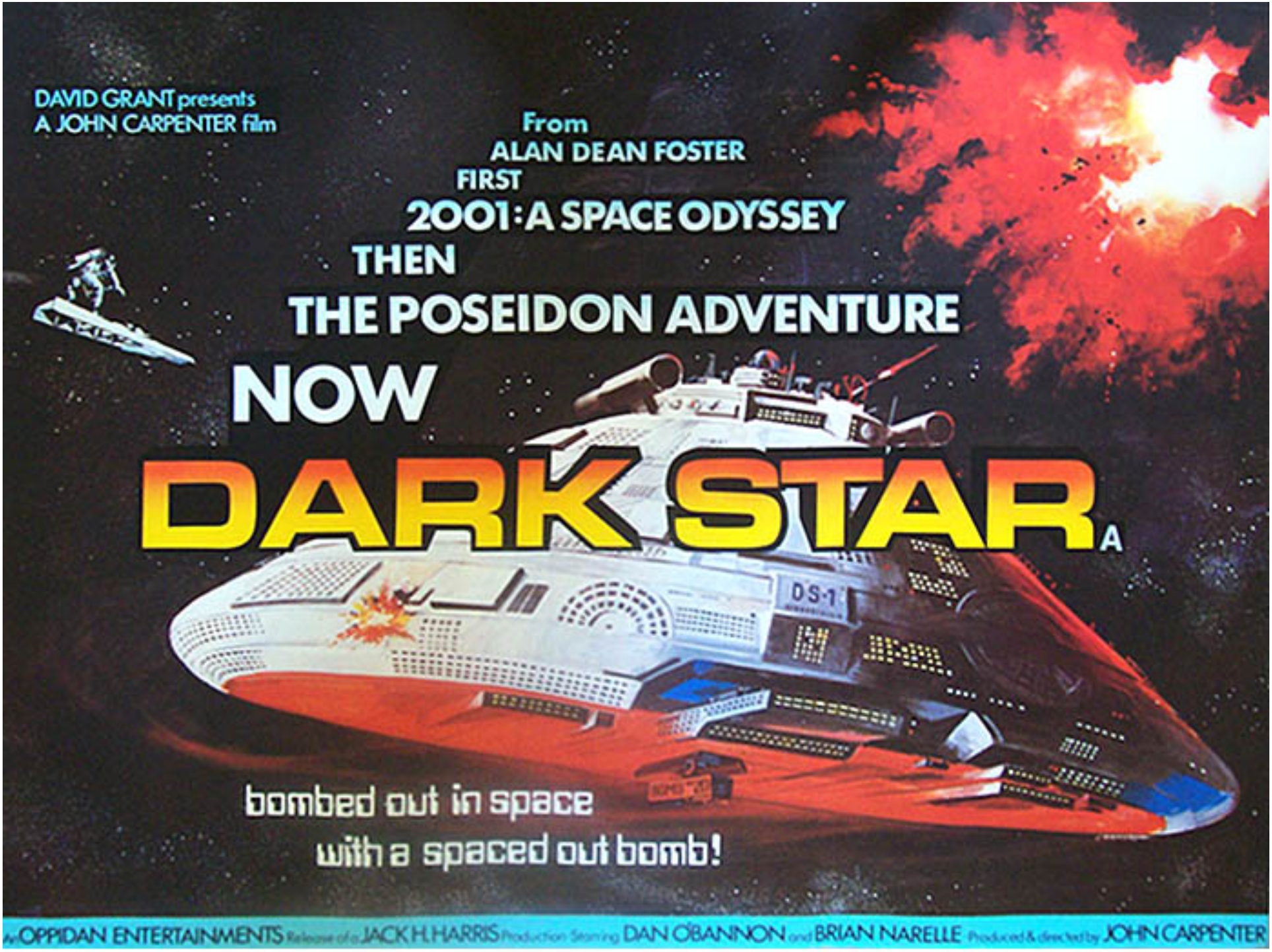
Dark Stars: Dark Matter annihilation can power the first stars

Katherine Freese
Michigan Center for Theoretical Physics
University of Michigan


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.47%
Stars:
0.5%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
ΛCDM


DAVID GRANT presents
A JOHN CARPENTER film
From
ALAN DEAN FOSTER
FIRST
2001: A SPACE ODYSSEY
THEN
THE POSEIDON ADVENTURE
NOW
DARK STAR A
DS-1
bombed out in space
with a spaced out bomb!
An OPPIDAN ENTERTAINMENTS Release of a JACK H. HARRIS Production Starring DAN O'BANNON and BRIAN NARELLE Produced & directed by JOHN CARPENTER

Collaborators

From Science et Vie: Mars 2010

REPÈRES

Faute de pouvoir être observées directement, les étoiles primitives demeurent une énigme pour les scientifiques. Aussi, le scénario de leur formation repose-t-il sur celui des étoiles connues, où la mystérieuse matière noire tient un faible rôle. Or, voilà qu'une astrophysicienne américaine émet une hypothèse audacieuse : la matière noire serait au cœur même de l'extraordinaire rayonnement de ces premiers astres titanesques.

Etoiles noires

Elles seraient les premiers astres

par Mathieu Grousson

Imaginez le spectacle : il y a plus de 13 milliards d'années, notre Univers vit sa prime jeunesse, les futures galaxies ne sont encore que des nébuleuses de poussière et, en leur centre, voici que brillent des boules de gaz mille fois plus lourdes, deux mille fois plus grandes et un million de fois plus lumineuses que ne le sera jamais notre Soleil ! Titanesques, inouïs, ces astres sont comme les phares d'un monde en gestation : les seules sources de lumière d'un espace par ailleurs obscur et glacé.

Ce spectacle sidéral de l'Univers primitif, on le doit à une physicienne américaine de l'université du Michigan, à Ann Arbor : à la lueur des équations tournant dans sa tête, Katherine Freese s'est aventurée dans les recoins sombres des premiers temps du cosmos pour en ramener une vision inédite, qui bouleverse l'image qu'en avaient jusqu'ici les astrophysiciens. Car la chercheuse en est revenue convaincue que les premiers astres qui ont illuminé l'Univers furent ces monstres stellaires nichés au cœur des nébuleuses de poussière, qui →

Extraordinairement massives et lumineuses, les étoiles noires auraient illuminé fugacement l'Univers 200 millions d'années après le big bang, avant de donner naissance aux étoiles classiques.

P.CARIL

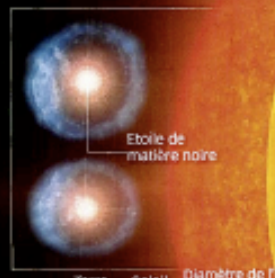
Vie et mort d'une étoile noire

La matière se concentre

Environ 200 millions d'années après le big bang, l'Univers est structuré en halos contenant de la matière "normale" (principalement de l'hydrogène) et de la matière noire.

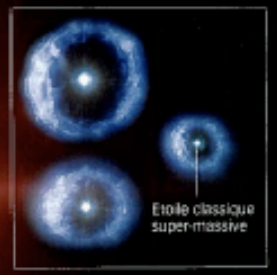
L'étoile noire s'allume...

Au centre d'un halo, les deux types de matière se concentrent. L'énorme pression provoque l'annihilation des particules de matière noire. L'astre s'enflamme, engendrant une étoile noire.



...puis se transforme...

Lorsque toute la matière noire du cœur stellaire a été épuisée, l'étoile s'effondre. Le processus de fusion nucléaire de l'hydrogène s'enclenche alors: l'astre noir se transforme en étoile classique super-massive.



...et devient un trou noir

L'hydrogène est, à son tour, rapidement consumé. L'étoile s'éteint en s'effondrant sur elle-même, donnant naissance à un trou noir géant (de 1000 à 10 000 masses solaires), autour duquel va peu à peu s'organiser une galaxie.

→ apparurent 200 millions d'années après le big bang. Monstres qu'elle a baptisés "étoiles noires". Et pour cause. Ils auraient puisé leur extraordinaire rayonnement dans une énergie qu'aucune étoile, plus tard, ne saura exploiter: la destruction de particules de matière noire présente en leur sein.

L'hypothèse semble pour le moins étrange. Car, pour tout astrophysicien qui se respecte, toutes les étoiles de l'univers sont censées briller en consumant de l'hydrogène, *via* des réactions de fusion nucléaire, et non de la matière noire. Et l'hypothèse est d'autant plus audacieuse que personne, à ce jour, n'a encore observé ne serait-ce que l'ombre d'une particule de cette fameuse matière exotique à la surface d'un détecteur – c'est même pour cette raison qu'elle a été baptisée ainsi. Pour autant, l'existence de cette hypothétique matière d'essence inconnue est désormais acceptée comme une quasi-nécessité. Sans elle, en effet, les physiciens (et, à travers eux, la théorie de la relativité d'Einstein qui décrit l'effet de gravitation) sont incapables d'expliquer la rotation des galaxies, celle des superamas ou encore la formation des grandes structures de l'Univers. En inventant le concept de matière noire et en lui prêtant des effets gravitationnels justifiant les grands mouvements cosmiques, l'énigme prend un tour acceptable. A condition toutefois de ne pas lésiner sur les moyens: les calculs montrent que la matière noire doit, dans ce cadre, compter pour 85 % de la matière totale contenue dans l'Univers! Or, c'est justement cette omniprésence qui a mis Katherine Freese sur la piste de ses "étoiles noires", prêtes à faire leur entrée fracassante dans le panthéon de l'astrophysique.

"Personne n'avait encore étudié comment la matière noire affecte la physique interne de ces astres"

KATHERINE FREESE, PHYSICIENNE, UNIVERSITÉ DU MICHIGAN, À ANN ARBOR

UN SOLEIL MONSTRUEUX

COMPOSITION
99 % de matière classique
1 % de matière noire

RAYON 2 000 fois celui du Soleil

MASSE 1 000 fois celle du Soleil

LUMINOSITÉ
1 million de fois celle du Soleil

TEMPÉRATURE DE SURFACE
Semblable à celle du Soleil

TEMPÉRATURE EN SON CENTRE
30 fois moindre que celle du Soleil

S'il est difficile d'imaginer à quoi ressemblait le ciel à cette époque reculée, les astrophysiciens pensent que les premières étoiles sont apparues relativement rapidement: ce serait en leur sein qu'ont été produits les éléments chimiques lourds entrant dans la composition des étoiles plus récentes. Mais, faute de les avoir observées directement avec leurs télescopes – les plus lointaines images recueillies montrent les galaxies telles qu'elles étaient 600 millions d'années après le big bang, soit 400 millions d'années plus tard –, ils en sont réduits à spéculer sur la nature de ces astres primitifs.

D'après les théories communément admises, la matière noire ne jouait qu'un rôle passif dans les scénarios de formation des étoiles primitives: c'est dans les zones de forte concentration de cette masse invisible, appelées halos, que ces dernières auraient été forgées. Attirée par gravitation vers le centre de ce halo, la matière ordinaire – essentiellement de l'hydrogène – se serait peu à peu concentrée, cette contraction se poursuivant jusqu'à ce que la densité soit suffisante pour que s'amorcent les réactions nucléaires dont l'énergie dégagée allume l'astre et l'empêche de s'effondrer sur lui-même.

UN RÉSULTAT INATTENDU

Mais la matière noire s'est-elle contentée de ce rôle passif de catalyseur? Rien n'est moins sûr. "*Si on sait que les premières étoiles résultent de la gravité imposée par la matière noire au sein des halos*, explique Katherine Freese, *personne n'avait encore étudié en détail la manière dont cette matière noire affecte la physique interne de ces astres primordiaux.*" Et grâce à cette spécialiste de l'astrophysique des particules, c'est désormais chose faite... avec un résultat inattendu. D'après les calculs théoriques qu'elle et ses collaborateurs ont effectués, l'effondrement de la matière ordinaire au centre du halo sous l'effet de l'attraction due à la matière noire crée, en retour, une force de gravitation qui attire encore plus de matière noire. Certes, cette matière exotique ne dépasse pas 1 % de la masse de la future étoile, mais sa densité finit par être suffisante pour que les particules qui la constituent commencent à s'entrechoquer. Or, le modèle le plus en vogue auprès des physiciens présente ces énigmatiques particules comme leurs propres antiparticules: la rencontre de deux d'entre elles entraînerait inévitablement leur annihilation totale dans une formidable explosion d'énergie lumineuse. Résultat: alors que l'étoile en formation n'est encore qu'une gigantesque boule d'hydrogène dilué incapable d'engendrer le processus de fusion nucléaire, ce processus d'annihilation des particules de matière noire serait suffisamment efficace pour enflammer l'astre et stopper l'effondrement du nuage de gaz. Sur le →

UMICH, PCARR

Dark Stars

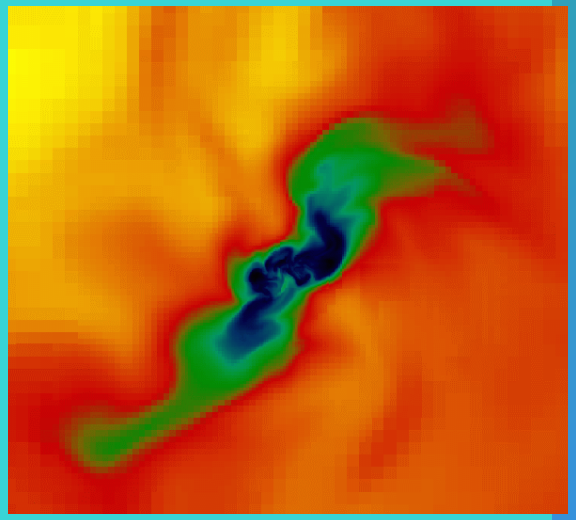
The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion (even though the dark matter constitutes less than 1% of the mass of the star).

THESE REALLY ARE STARS: atomic matter that shines due to dark matter, possibly a billion times as bright as the Sun

- This new phase of stellar evolution lasts millions to billions of years (possibly even to today)

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.

Dominant cooling Mechanism is

H_2

Not a very good coolant

(Hollenbach and McKee '79)

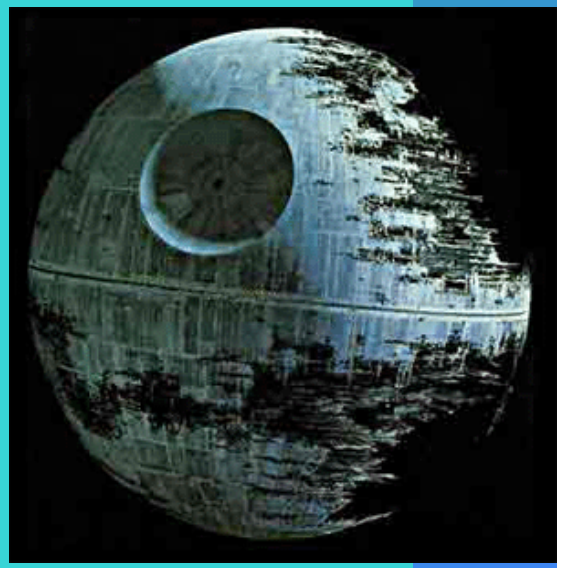
Pioneers of First Stars Research: Abel, Bryan, Norman; Bromm, Greif, and Larson; McKee and Tan; Gao, Hernquist, Omukai, and Yoshida; Klessen; Nishii

Outline

- The First Stars- standard picture
- Dark Matter
  - The LSP (lightest SUSY particle)

Life in the Roaring 20's

- Dark Star Born
- Stellar structure
- Dark Star can grow supermassive and superbright
- When a dark star dies it becomes a giant black hole (up to a billion solar masses)



Hierarchical Structure Formation

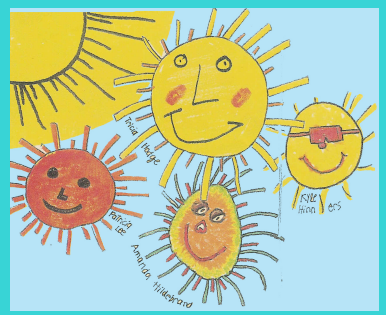
Smallest objects form first (sub earth mass)

Merge to ever larger structures

Pop III stars (inside $10^6\ M_\odot$ haloes) first light

Merge → galaxies

Merge → clusters



→

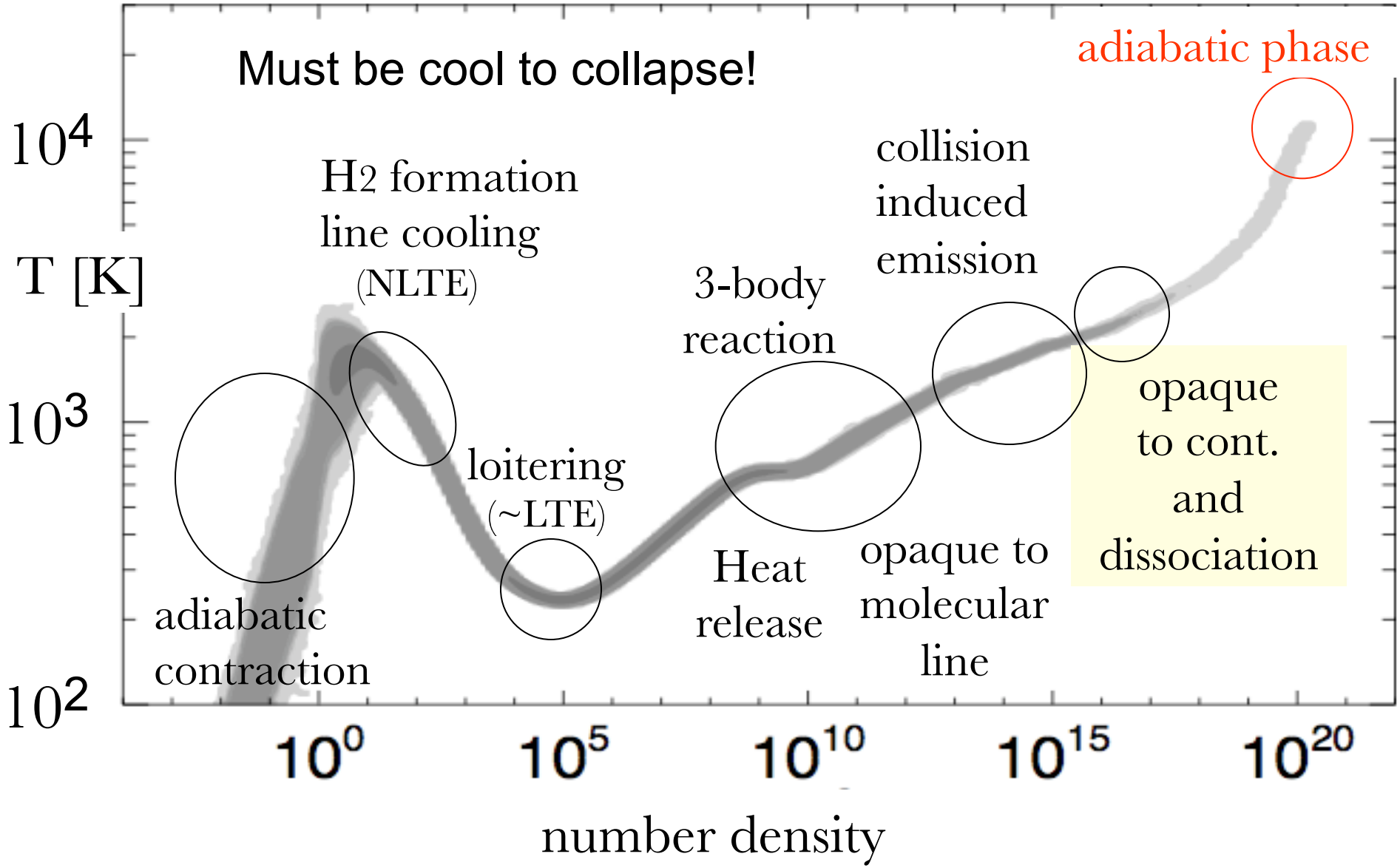
→

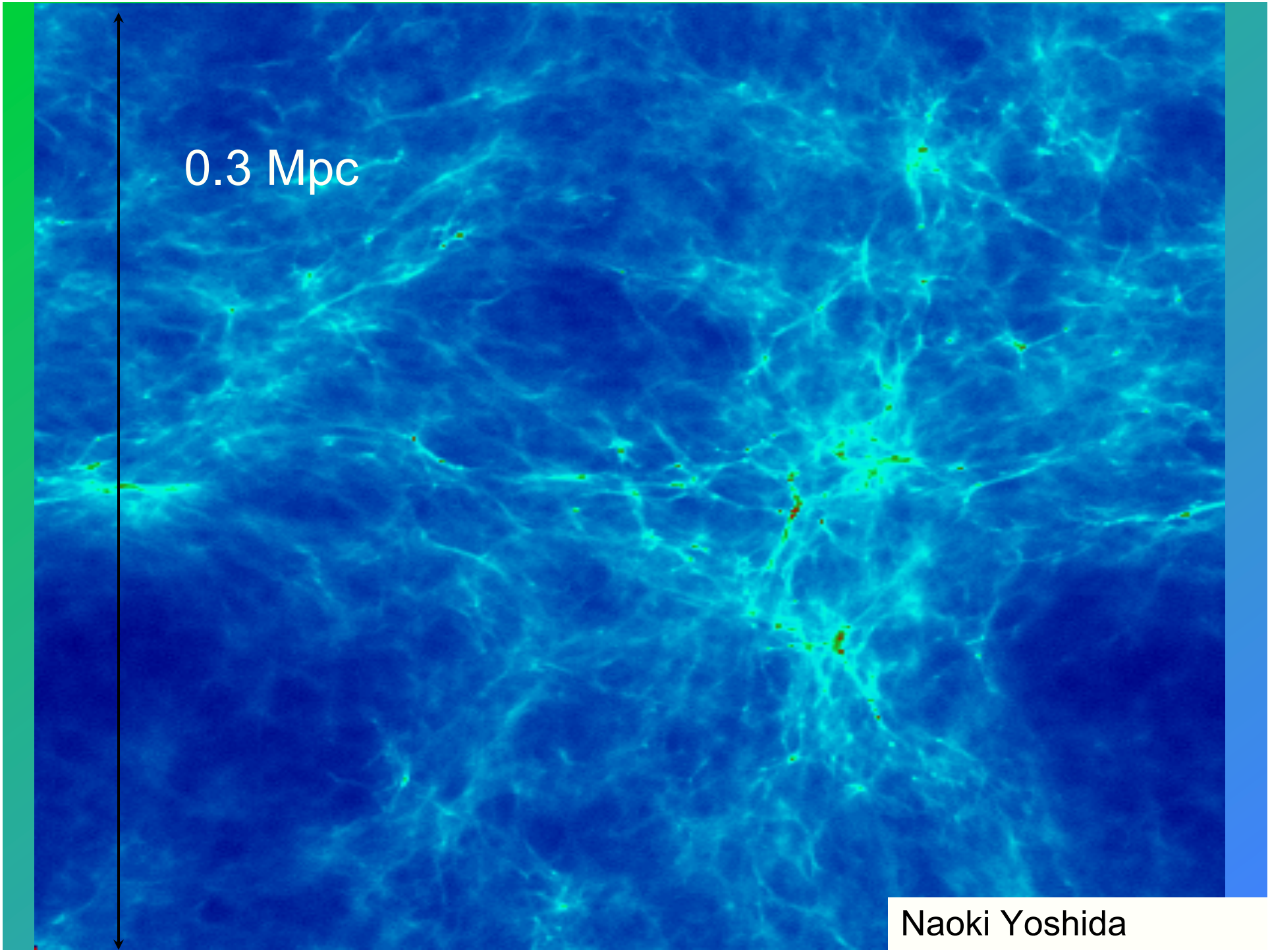
Scale of the Halo

- 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

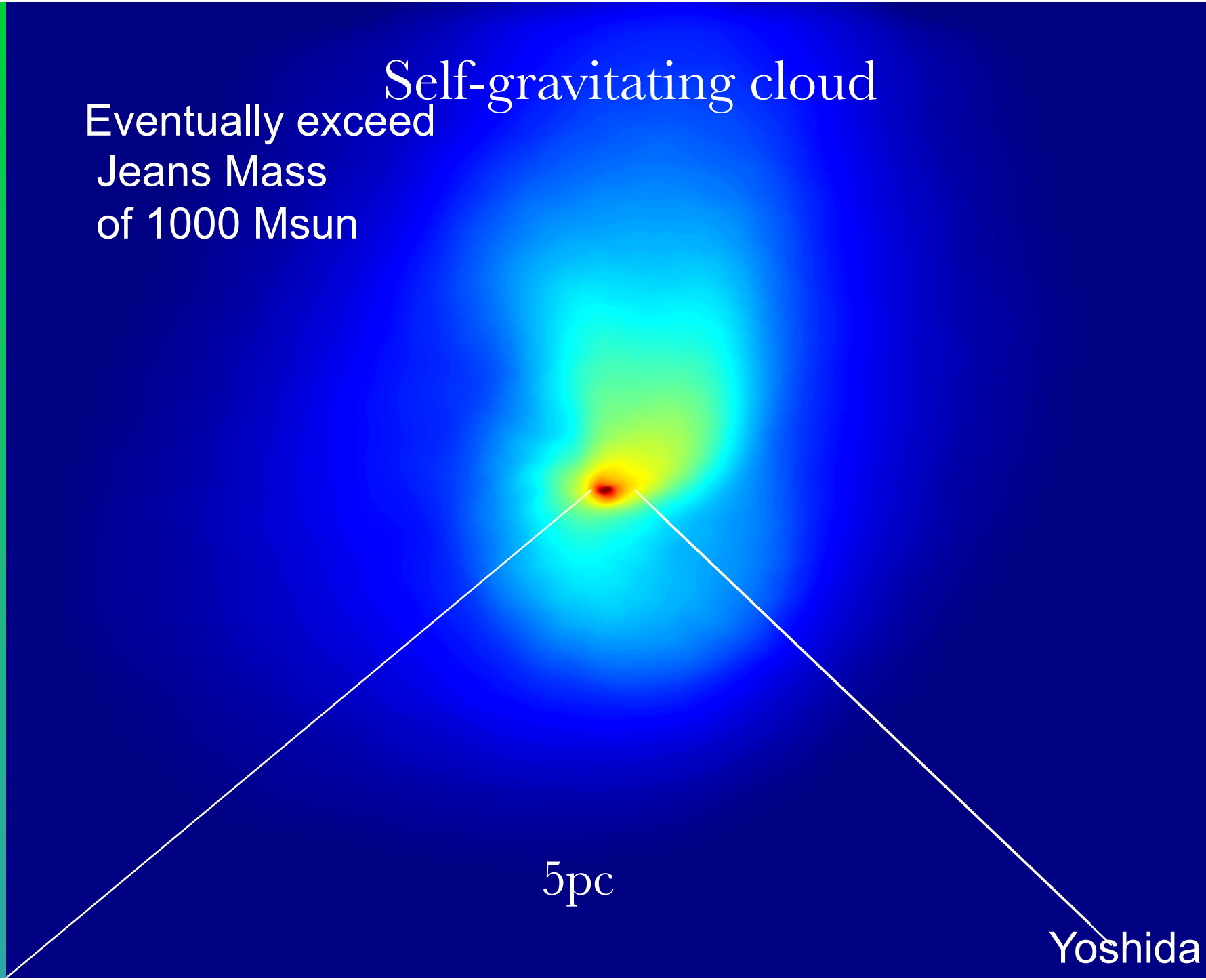


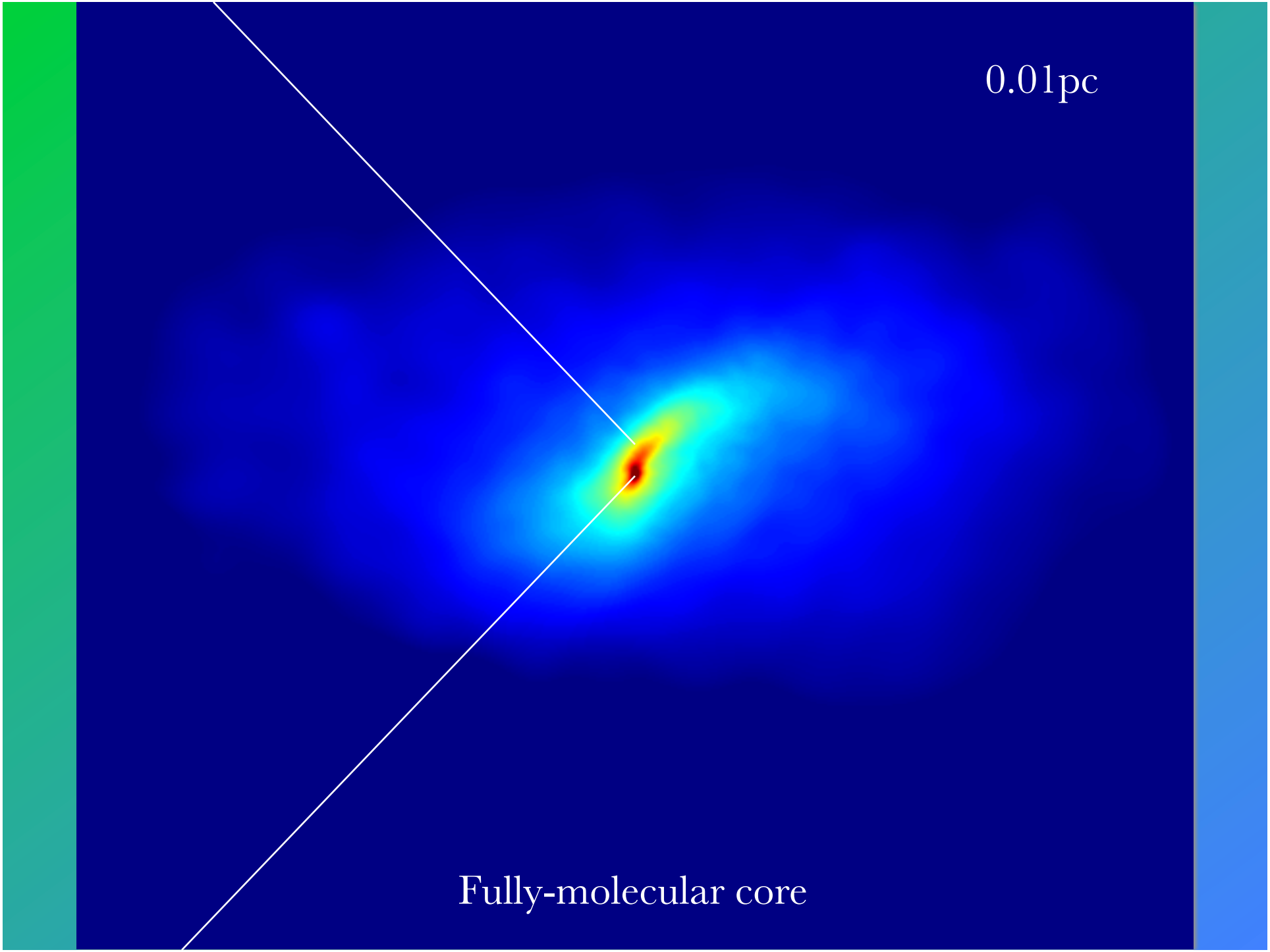


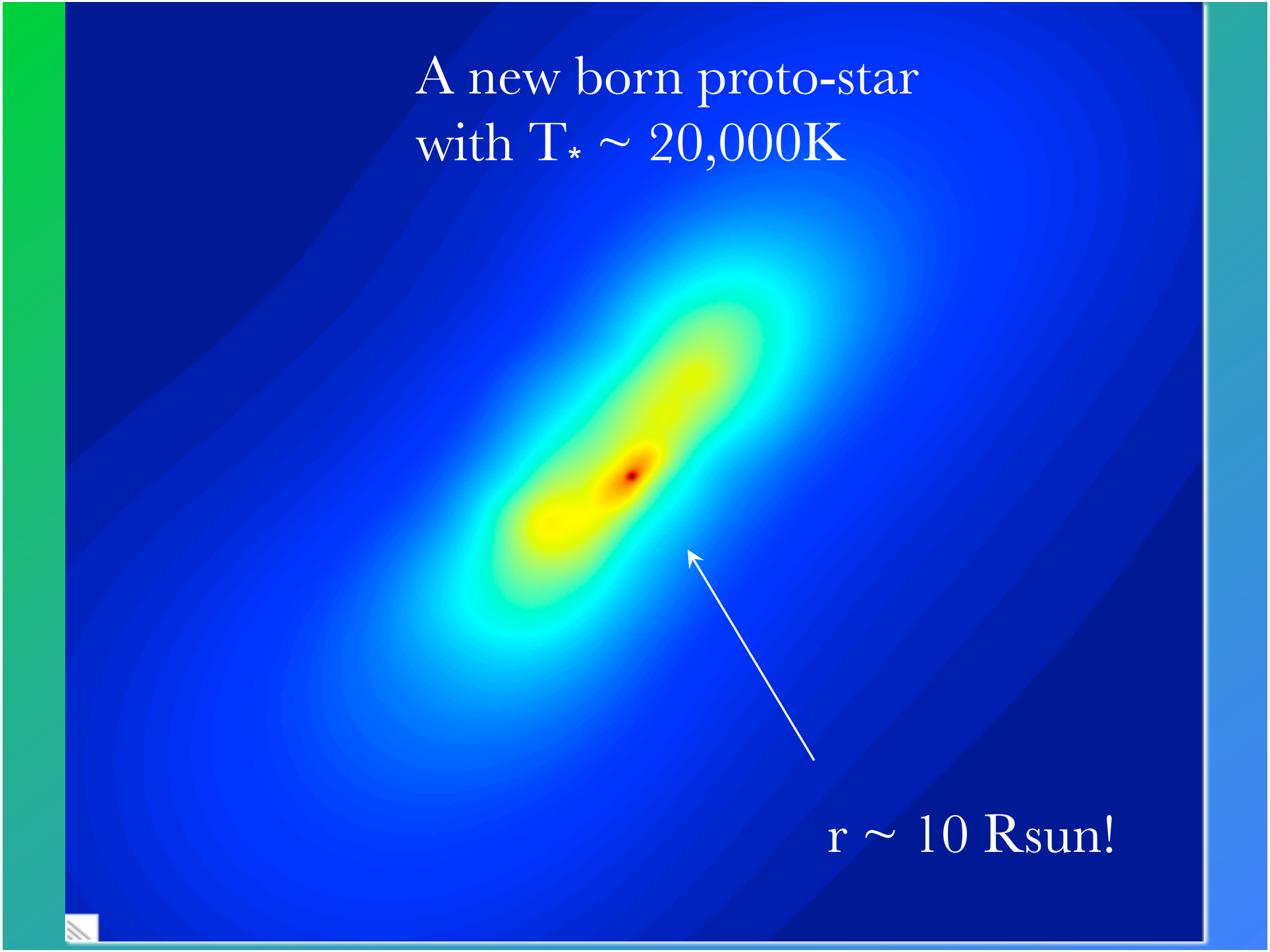
Naoki Yoshida

Self-gravitating cloud

Eventually exceed
Jeans Mass
of 1000 Msun




0.01pc
Fully-molecular core


A new born proto-star
with $T_* \sim 20{,}000K$
r ~ 10 Rsun!

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

$100M_\odot$ Standard Picture

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

Weakly interacting DM

Mass 1Gev-10TeV (take 100GeV)

Annihilation cross section (WIMPS):

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

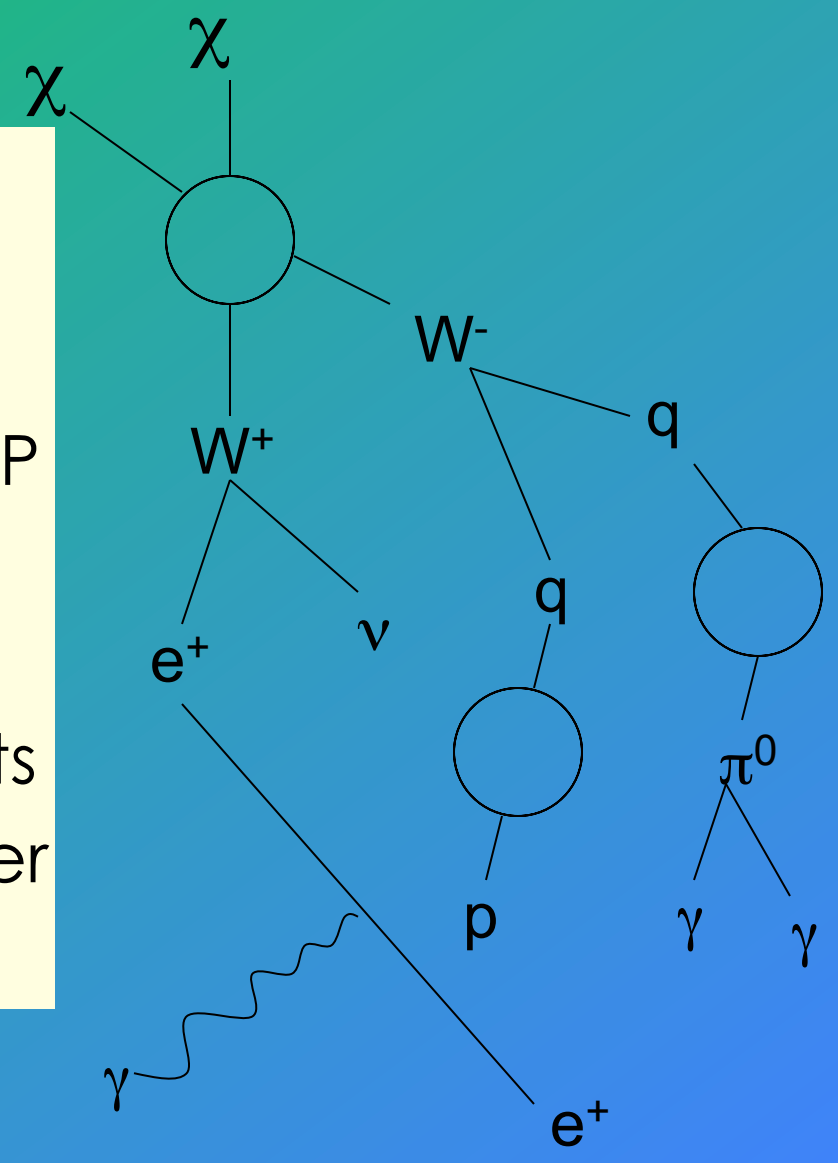
Same annihilation that leads to correct WIMP abundance in today's universe

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

WIMP Annihilation

Many WIMPs are their own antiparticles, annihilate among themselves:

- 1) Early Universe gives WIMP miracle
- 2) Indirect Detection expts look for annihilation products
- 3) Same process can power stars!



Annihilation Products

- 1/3 electron/positrons
- 1/3 gamma rays
- 1/3 neutrinos
- Typical particles have energies roughly 1/10 of the initial WIMP mass
- All of these are detectable!

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

DM annihilation in Today's Stars:

- The Sun: (Krauss, KF, Press, Spergel 1985); ICECUBE looking for neutrinos
- Stellar Structure: (Bouquet and Salati 1989; Salati and Silk 1989)
- WIMP burners: white dwarfs near the Galactic Center (Moskalenko and Wai 2007)
- Compact objects: Bertone and Fairbairn 2008)
- Main Sequence Stars: (Edsjo, Scott, Fairbairn 2007, 2008, 2009; Dark Stars code publicly available)

Basic Picture

- The first stars form in a DM rich environment
- As the gas cools and collapses to form the first stars, the cloud pulls DM in.
- DM particles are their own antipartners, and annihilate more and more rapidly as the density increases
- DM annihilates to e+/e- and photon endproducts of 100 GeV (or so) which 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.

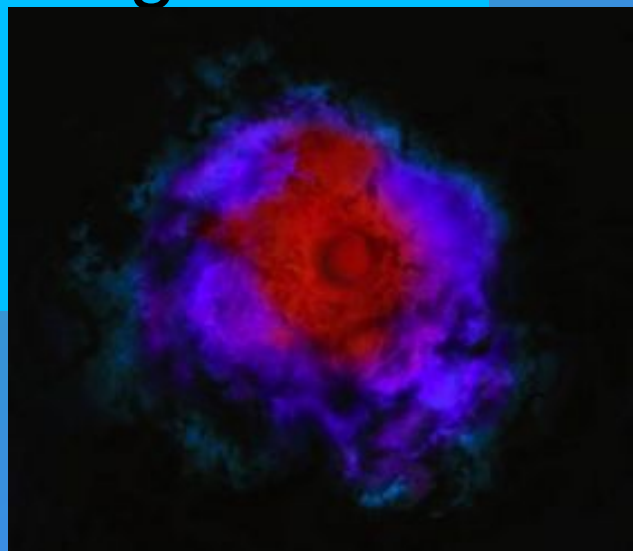
Dark Matter Power vs. Fusion

- 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.

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



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:

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

Previous work noted that at $n \leq 10^4 cm^{-3}$ annihilation products simply escape (Ripamonti,Mapelli,Ferrara 07)

f_Q:

1/3 electrons

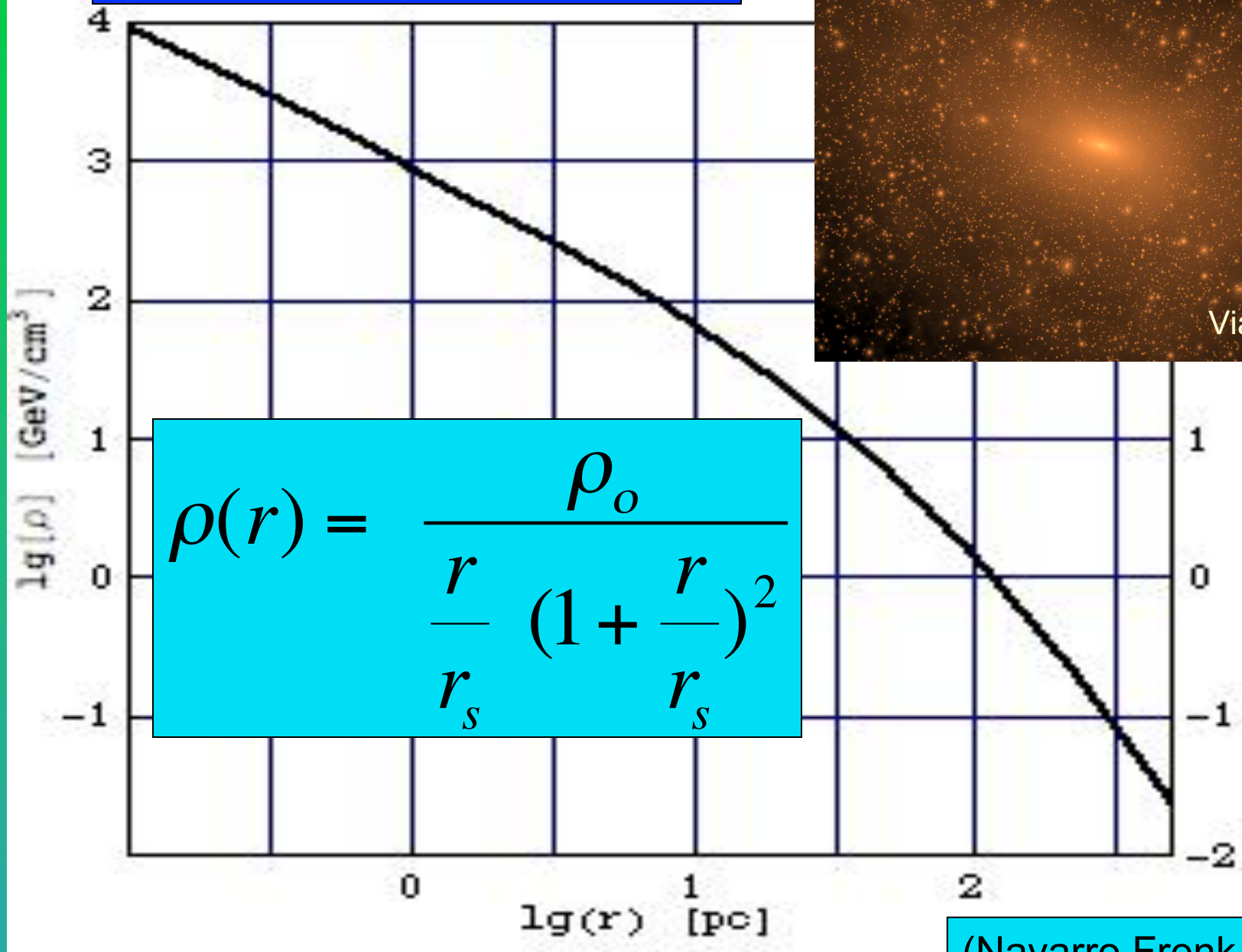
1/3 photons

1/3 neutrinos

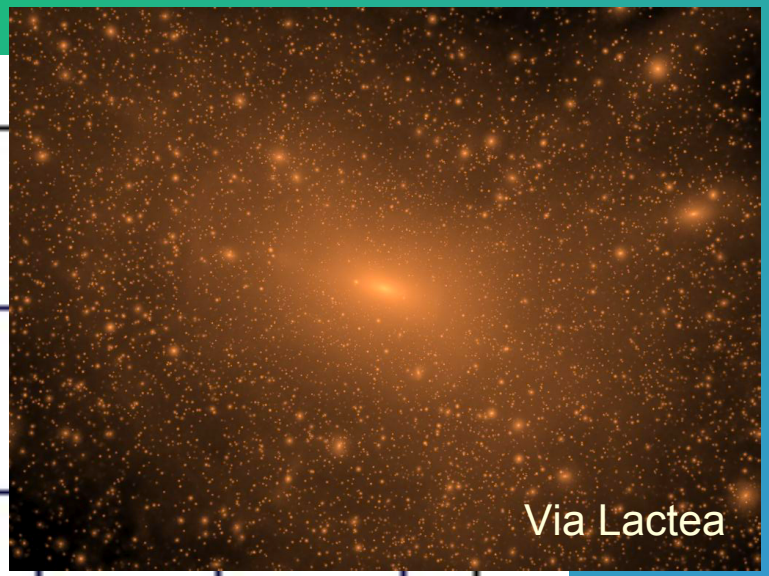
First Condition: Large DM density

- 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).

NFW Profile



$$\rho(r) = \frac{\rho_o}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$



(Navarro,Frenk,White ‘96)

DM Density Profile Conserving Phase Space

- Adiabatic contraction (Blumenthal, Faber, Flores, Primack prescription):
  - As baryons fall into core, DM particles respond to potential conserves Angular Momentum.

$$r\,M(r) = \text{constant}$$

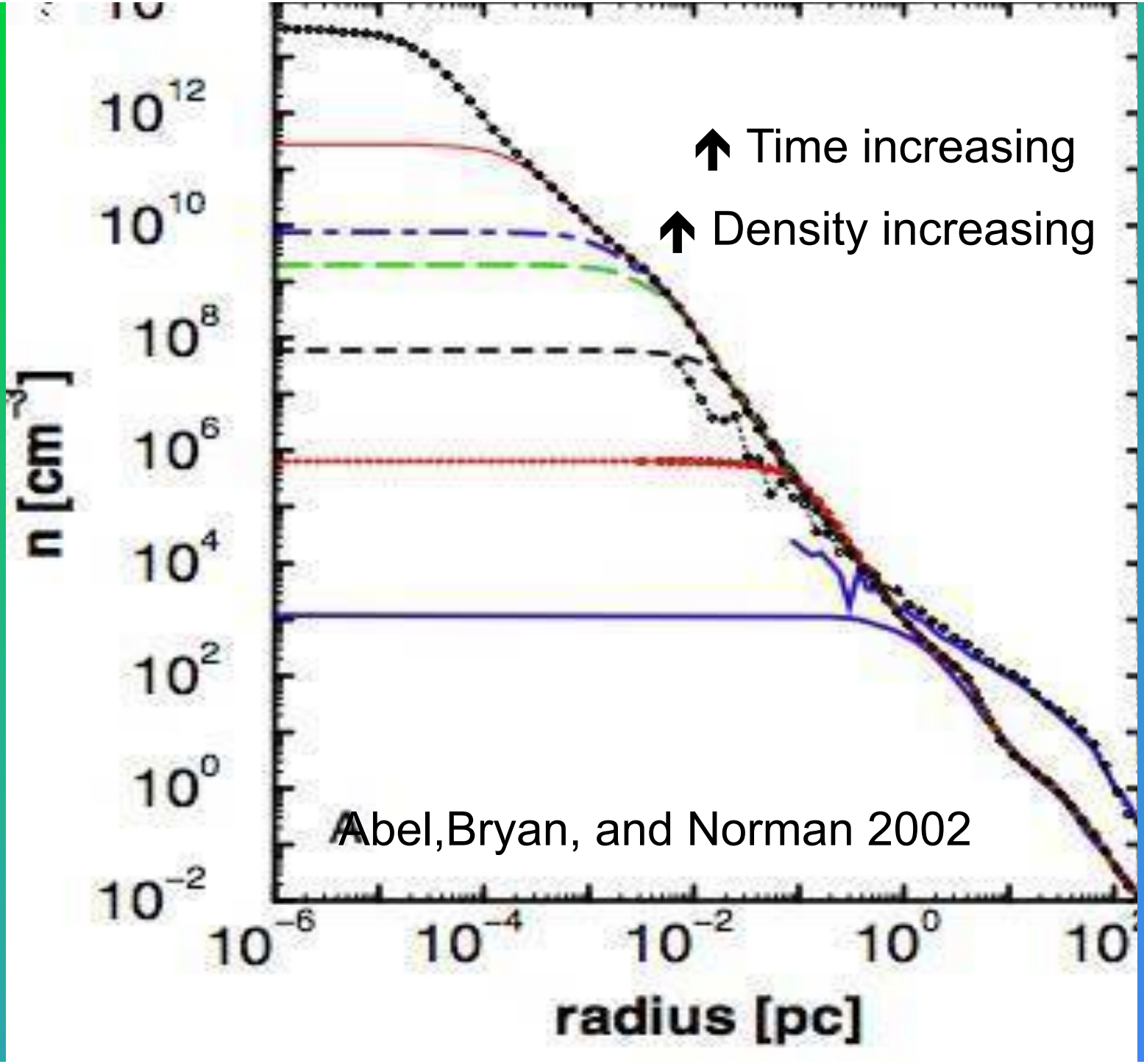
- Profile that we find:

$$\rho_\chi(r) \sim r^{-1.9} \quad \text{Outside Core}$$

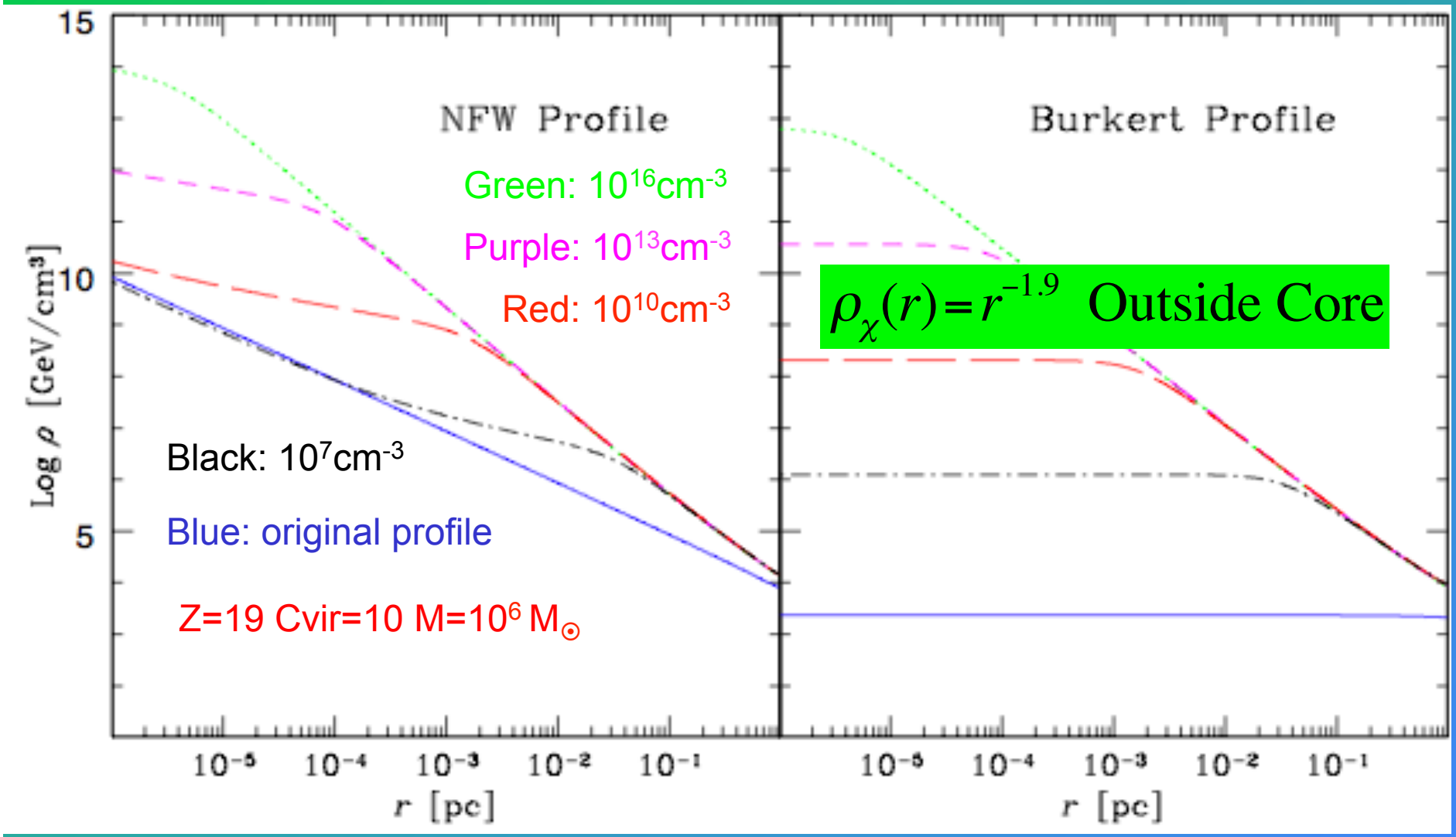
$$\rho_\chi(n) = 5\ \text{GeV}\ (n/cm^{-3})^{0.8}$$

Simplistic: circular orbits only.

(From Blumenthal, Faber, Flores, and Primack '86)

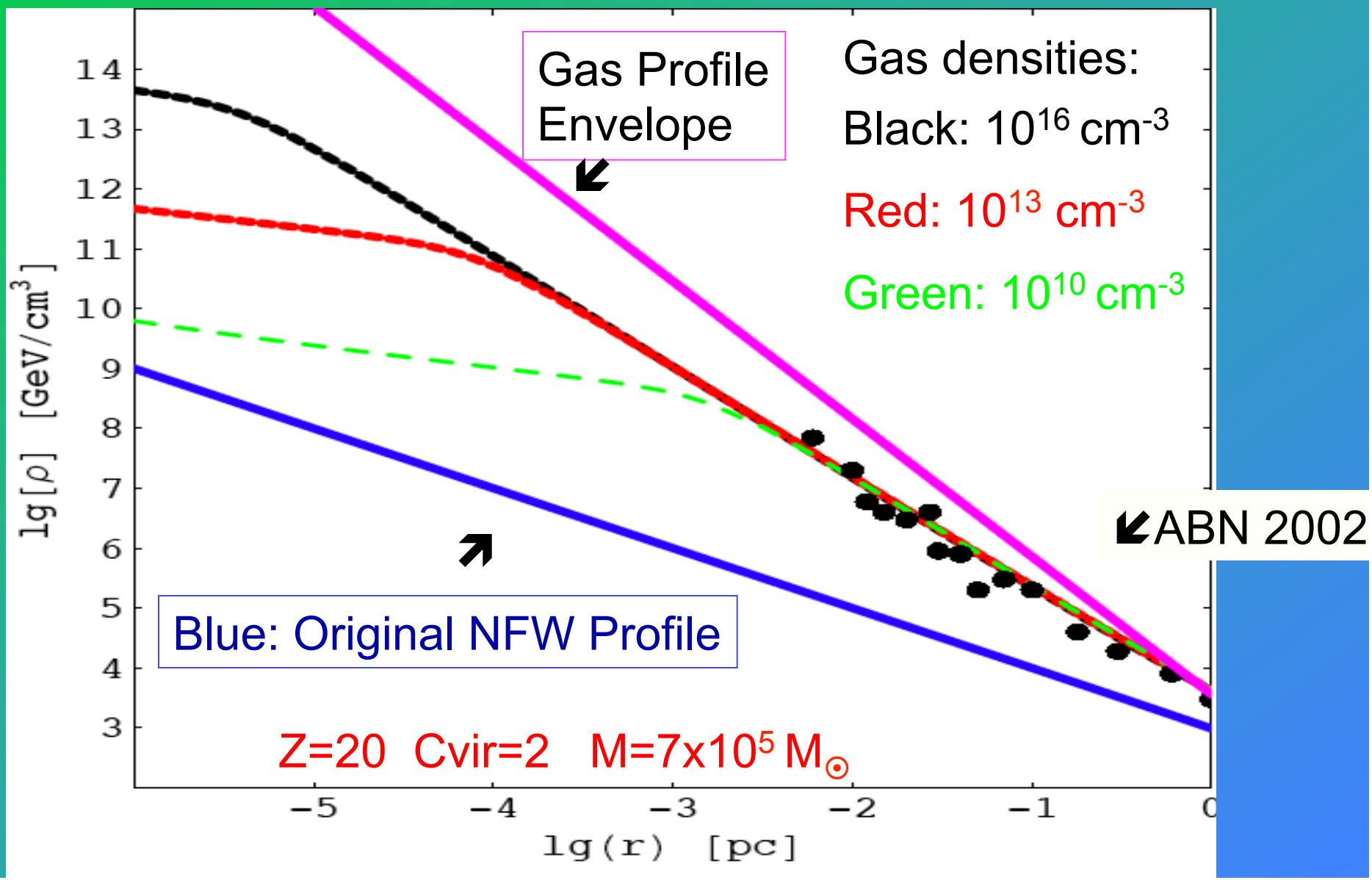

Time increasing
Density increasing
Abel,Bryan, and Norman 2002
n [cm^{-3}]
radius [pc]
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-6}
10^{-4}
10^{-2}
10^{0}

Dark Matter Profile



(Outer slope $r^{-1.9}$, profile matches Abel, Bryan, Norman '02)

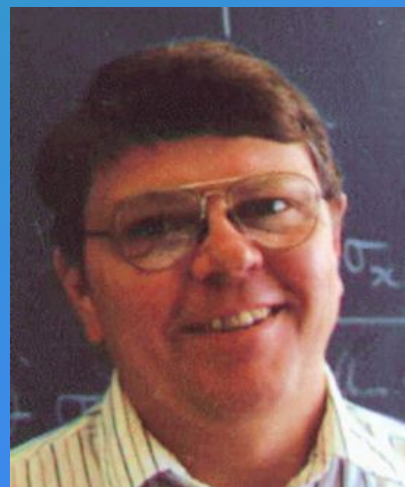
DM profile and Gas



How accurate is Blumenthal method for DM density profile?

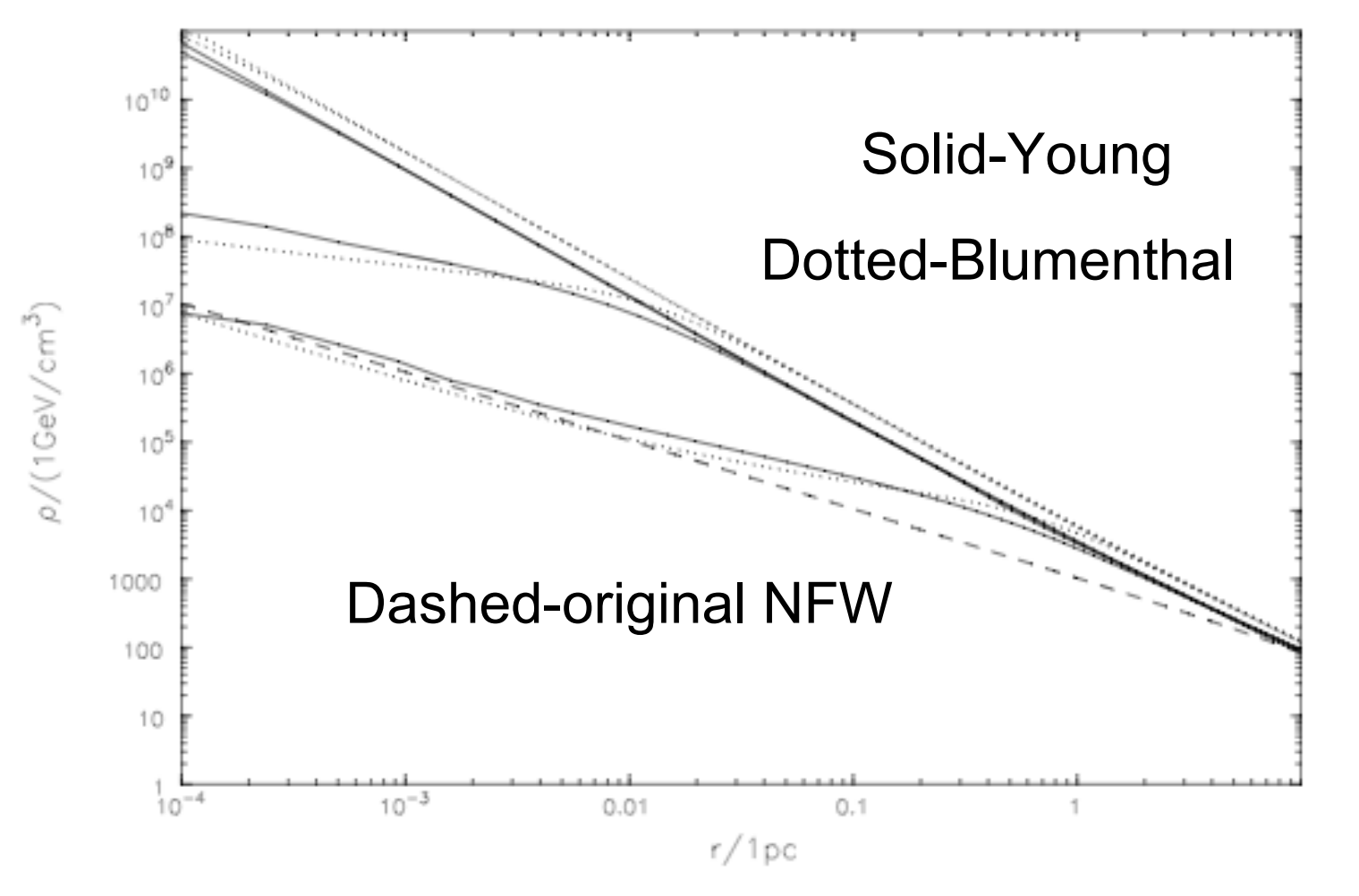
- There exist three adiabatic invariants.
- Blumenthal method ignored the other 2 invariants.
- Following a more general prescription first developed by Peter Young: includes radial orbits
  - If adiabaticity holds, we have found the exact solution

In collaboration with Jerry Sellwood



Within a factor of two

n.b. no dependence on NFW profile: even with initial Burkert profile, essentially the same result



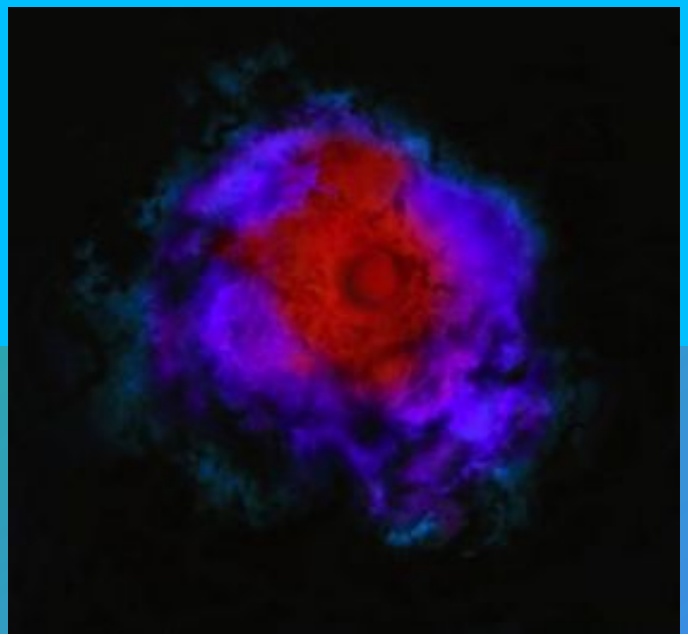
Dark Matter Densities in the Stars

- Adiabatic Contraction
- See also work of Natarajan, O'Shea and Tan 2008, taking simulation results and extrapolating to also find large densities
- See also work of Iocco etal 2008 using O. Gnedin method
- All results agree

Three Conditions for Dark Stars (Paper 1)

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

Leads to New Phase



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f_Q:

1/3 electrons

1/3 photons

1/3 neutrinos

Crucial Transition

- At sufficiently high densities, most of the annihilation energy is trapped inside the core and heats it up
- When:

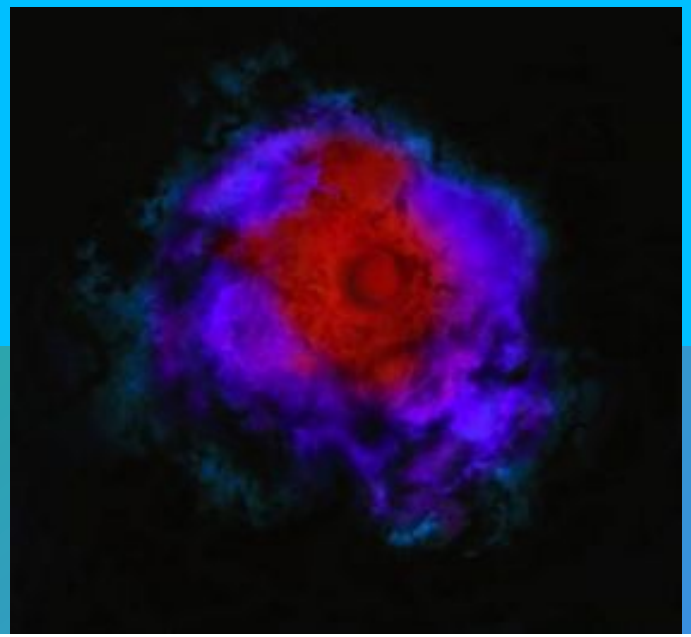
$$m_\chi \approx 1\ \mathrm{GeV} \quad \rightarrow \quad n \approx 10^{9}/\mathrm{cm}^3$$
$$m_\chi \approx 100\ \mathrm{GeV} \quad \rightarrow \quad n \approx 10^{13}/\mathrm{cm}^3$$
$$m_\chi \approx 10\ \mathrm{TeV} \quad \rightarrow \quad n \approx 10^{15\text{–}16}/\mathrm{cm}^3$$

- The DM heating dominates over all cooling mechanisms, impeding the further collapse of the core

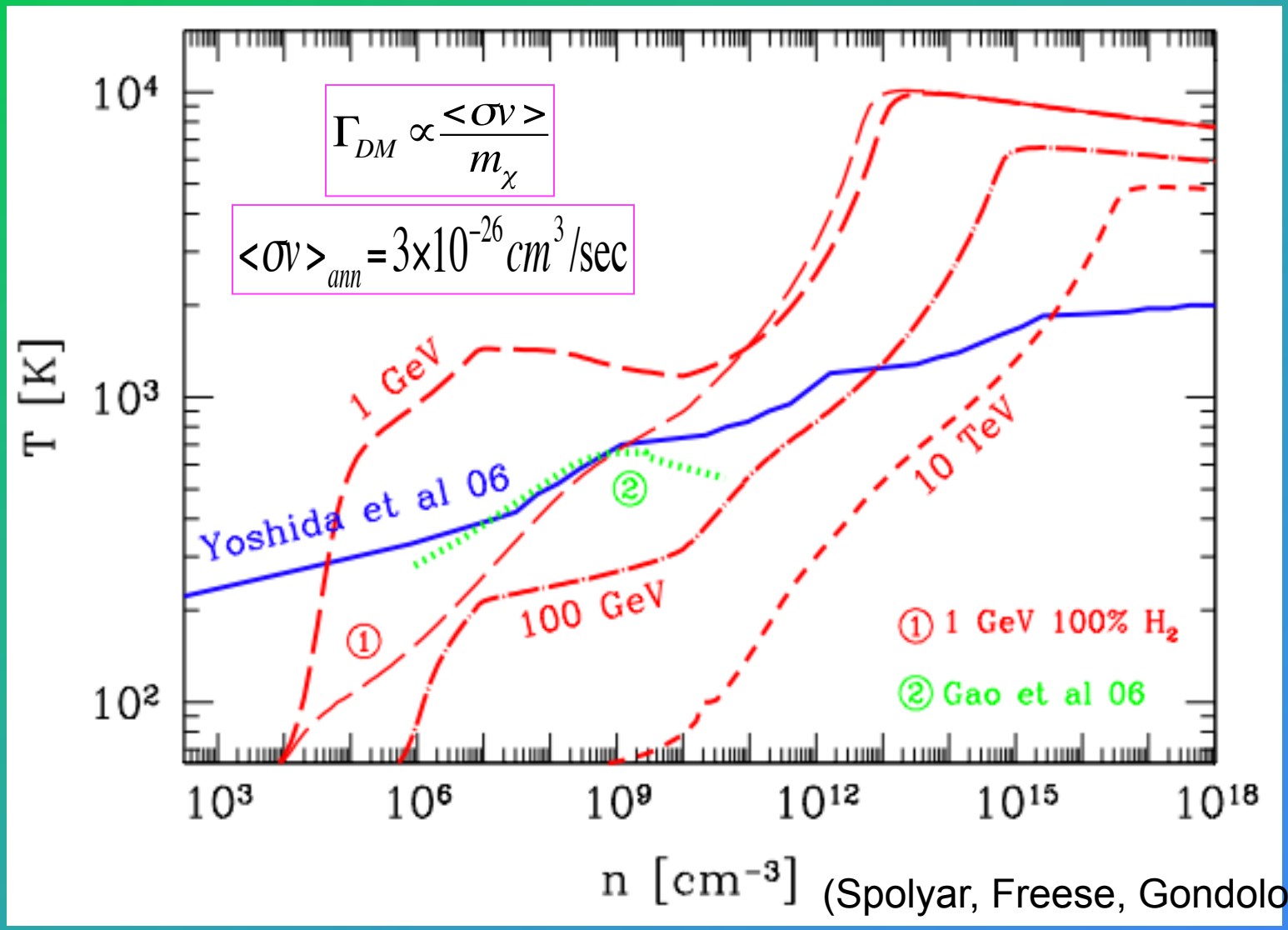
Three Conditions for Dark Stars (Paper 1)

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

New Phase

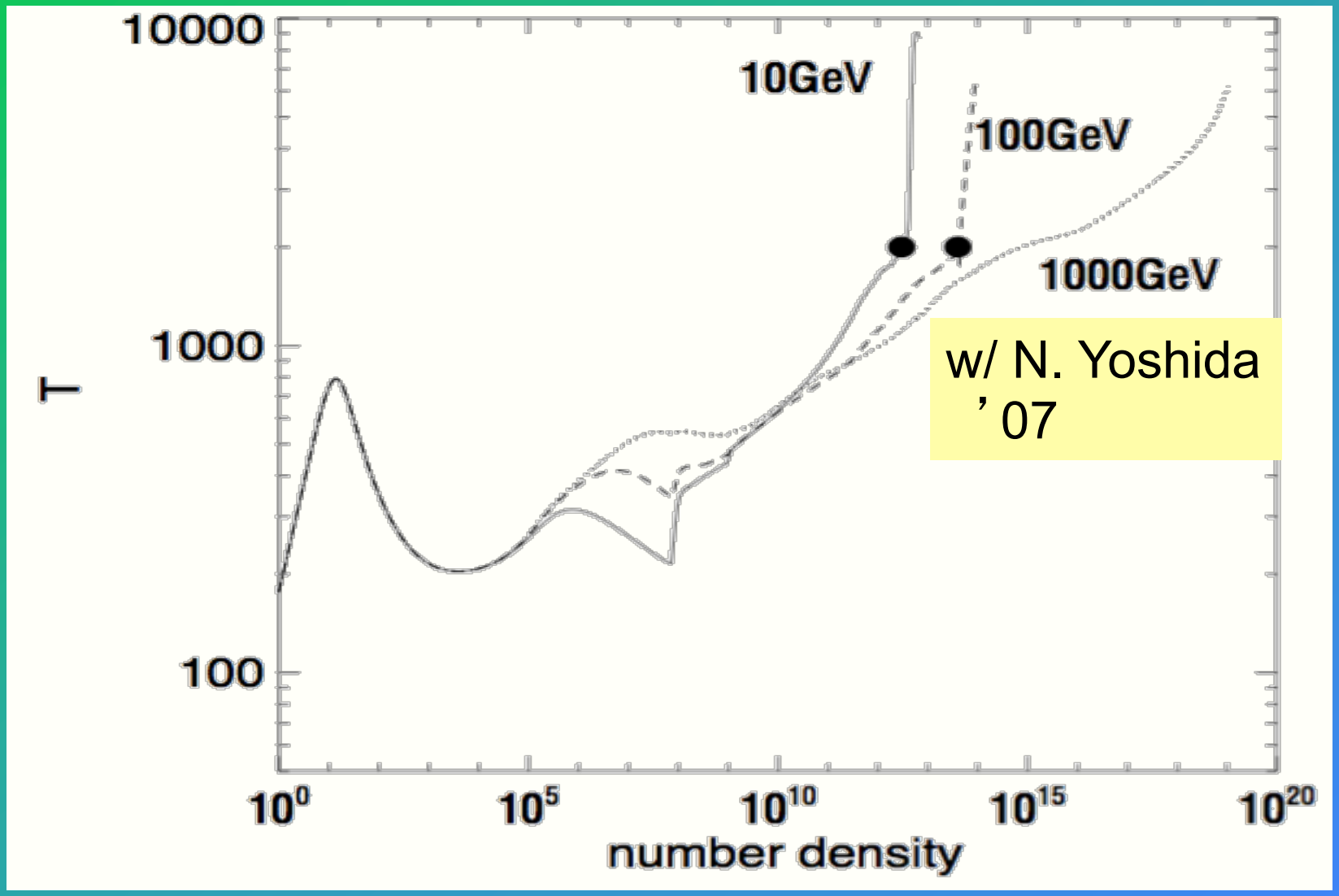


DM Heating dominates over cooling when the red lines cross the blue/green lines (standard evolutionary tracks from simulations). Then heating impedes further collapse.



(Spolyar, Freese, Gondolo April 2007)

New proto-Stellar Phase:
fueled by dark matter



Dark Matter Intervenes

- Dark Matter annihilation grows rapidly as the gas cloud collapses. Depending upon the DM particle properties, it can stop the standard evolution at different stages.
- Cooling Loses!
- A "Dark Star" is born

  (a new Stellar phase)

At the moment heating wins:

- "Dark Star" supported by DM annihilation rather than fusion
- They are giant diffuse stars that fill Earth's orbit

$m_\chi \approx 1\ \mathrm{GeV}$ core radius 960 a.u. Mass 11 $M_\odot$

$m_\chi \approx 100\ \mathrm{GeV}$ core radius 17 a.u. Mass 0.6 $M_\odot$

- THE POWER OF DARKNESS: DM is only 2% of the mass of the star but provides the heat source
- Dark stars are heated by DM but are not dark:

  they do shine, although they're cooler than early stars without DM. We find: Luminosity 140 solar

DS Evolution (w/ Peter Bodenheimer)

- DM heating disassociates molecular hydrogen, and then ionizes the gas
- Our proto star has now become a star.
  - Initial star is a few solar masses
  - Accrete more baryons up to the Jeans Mass~1000$M_\odot$

DS Evolution (w/ Peter Bodenheimer)

- Find hydrostatic equilibrium solutions
- Look for polytropic solution, $p = K\rho^{1+1/n}$

  for low mass n=3/2 convective,

  for high mass n=3 radiative

  (transition at 100-400 $M_\odot$)
- Start with a few solar masses, guess the radius, see if DM luminosity matches luminosity of star (photosphere at roughly 6000K). If not adjust radius until it does. Smaller radius means larger gas density, pulls in more DM via adiabatic contraction, higher DM density and heating. Equilibrium condition:

$$L_{DM} = L_*$$

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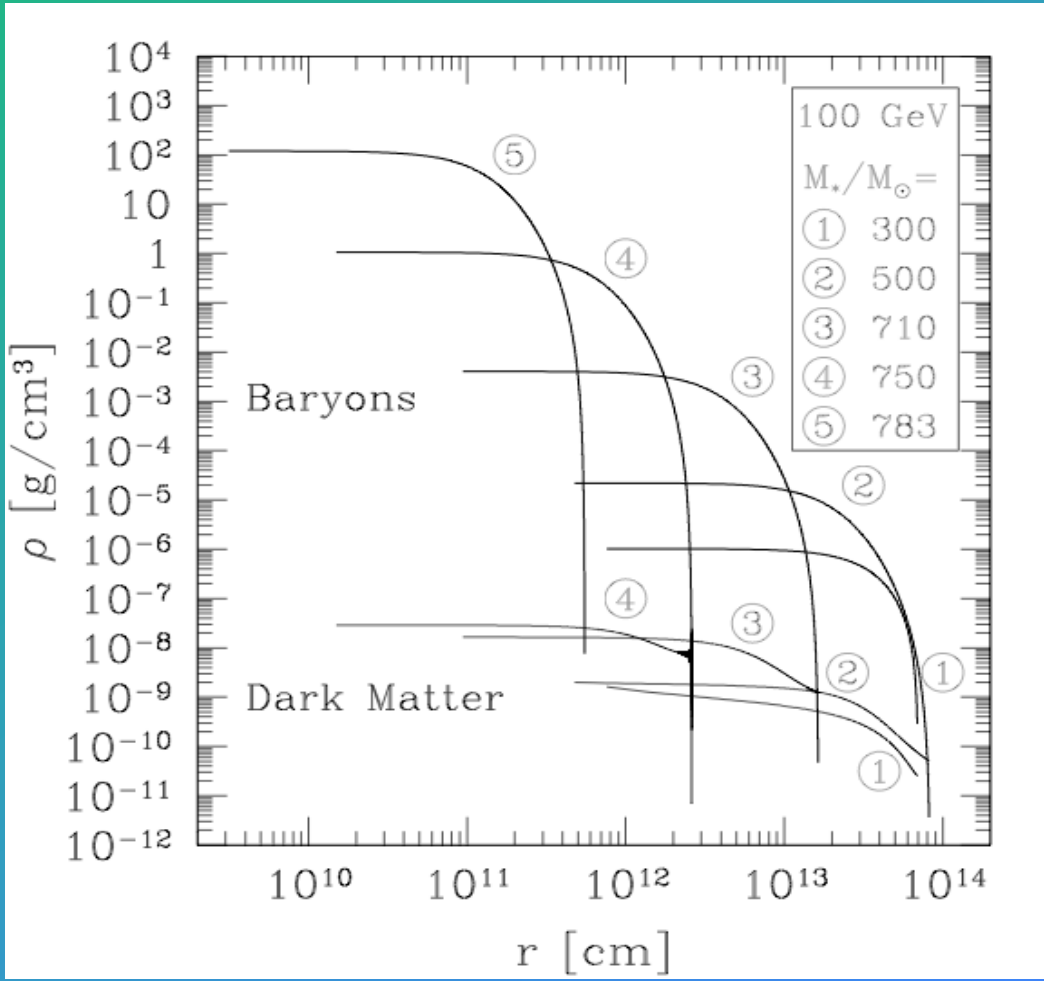
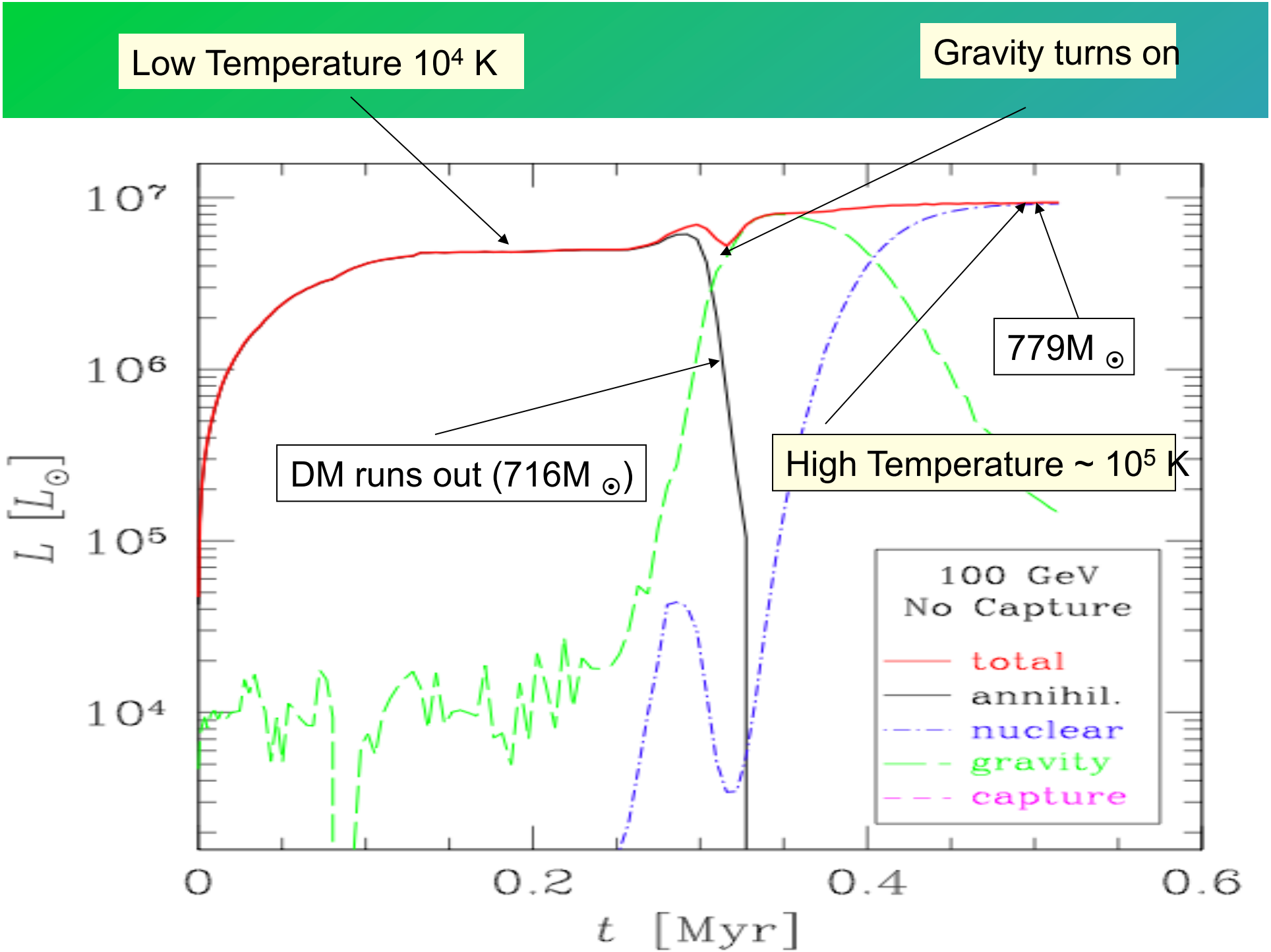
Building up the mass

- 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
779M ⊙
DM runs out (716M ⊙)
High Temperature ~ 10^5 K
100 GeV
No Capture
total
annihil.
nuclear
gravity
capture
10^7
10^6
10^5
10^4
$L\ [L_\odot]$
0
0.2
0.4
0.6
t [Myr]

HERTZSPRUNG-RUSSELL DIAGRAM FOR DARK STARS

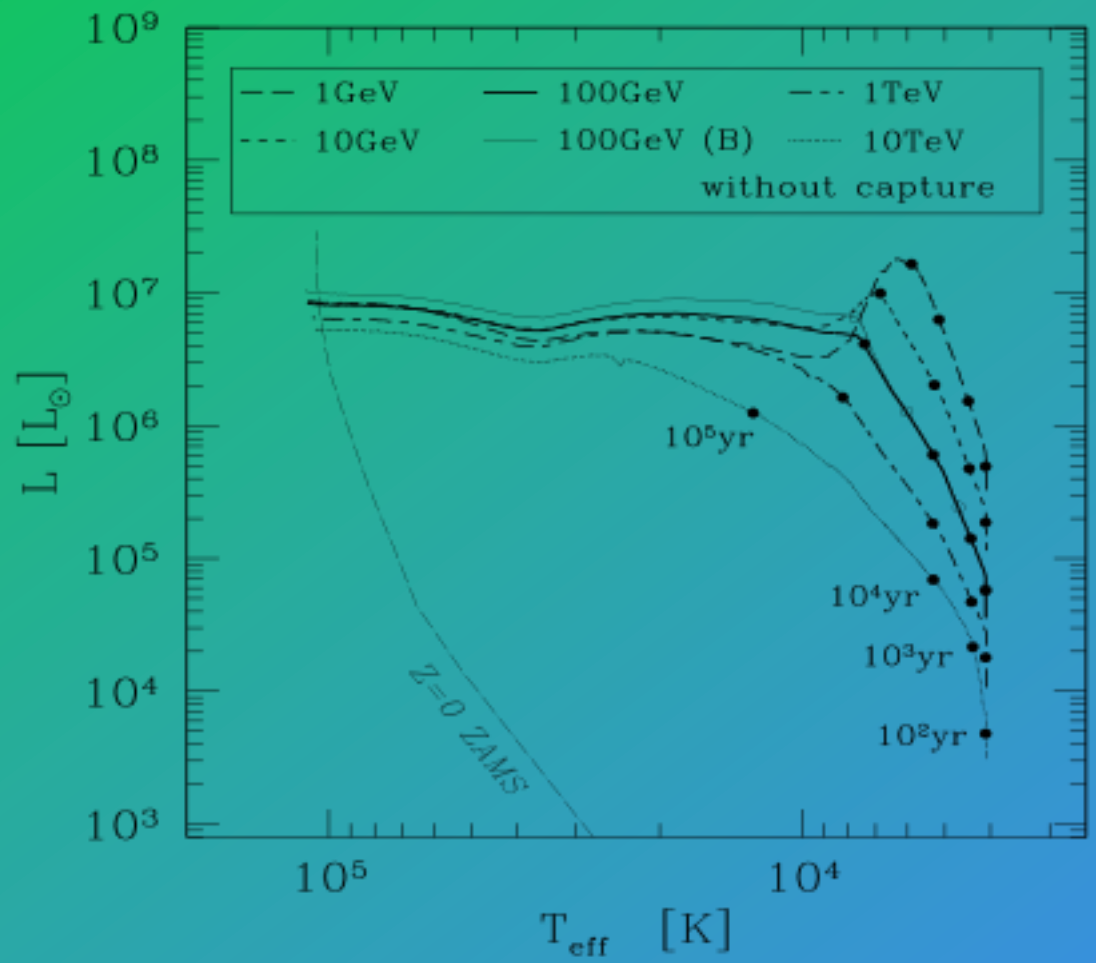


FIG. 1.— Evolution in the H-R diagram, for 5 different particle masses as indicated in the legend. The luminosity is given in solar units and the temperature is in Kelvin. The dots indicate a series of time points, which are the same for all cases. The open dots distinguish the 100 GeV (B) case from the 100 GeV case. All cases are calculated with the accretion rate given by Tan & McKee (2004) except the curve labelled 100 GeV (B), which is calculated with the rate given by O'Shea & Norman (2007). The metal-free zero-age main sequence ($Z = 0$ ZAMS) is taken from Schaerer (2002). The peak below 10^4K in the 1 GeV case is due to the overwhelming DM luminosity in this case.

DS Basic Picture

- We find that DS are:
  - Massive: more than 1000 $M_\odot$
  - Large-a few a.u. (size of Earth's orbit around Sun)
  - Luminous: more than 10^7 solar
  - Cool: 10,000 K vs. 100,000 K plus
    - Will not reionize the universe.
  - Long lived: more than 10^6 years.
  - With Capture or nonCircular orbits, get even more massive, brighter, and longer lived

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) from extended adiabatic contraction

- 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)

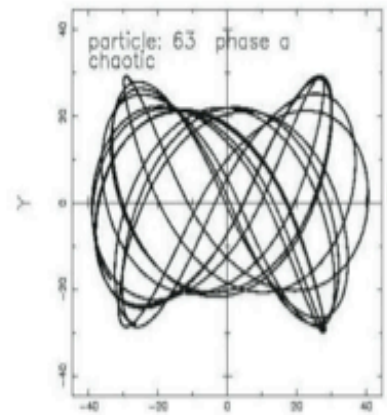
Is there enough DM?

Spherical Halos

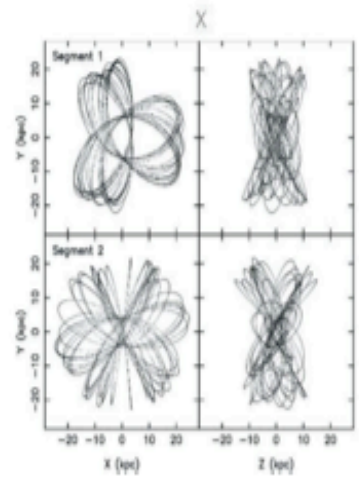
- DM orbits are planar rosettes (Binney & Tremaine '08).
- The Dark Star creates a loss cone that cannot be refilled.

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



Box Orbit

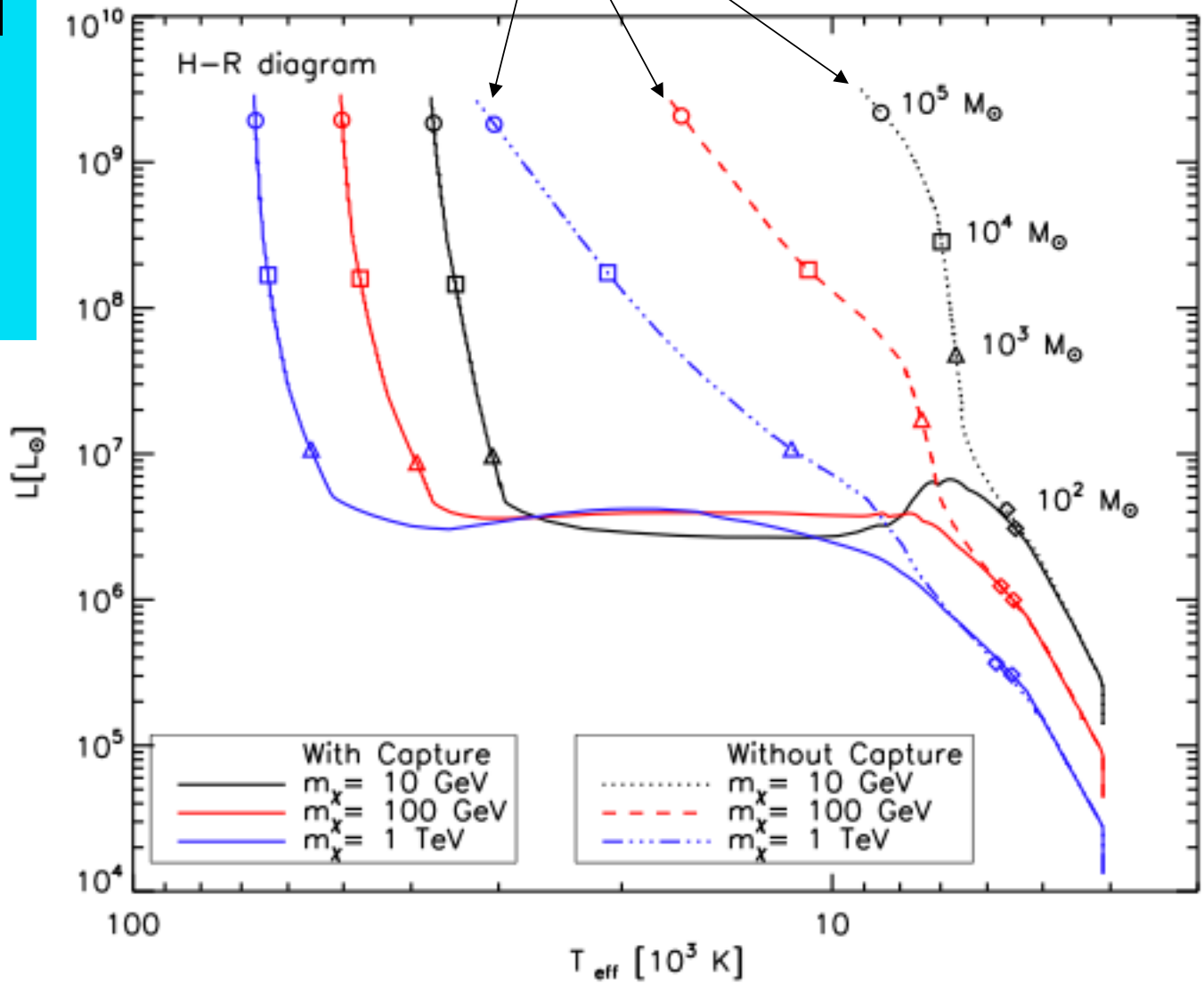


Chaotic Orbit

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.

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



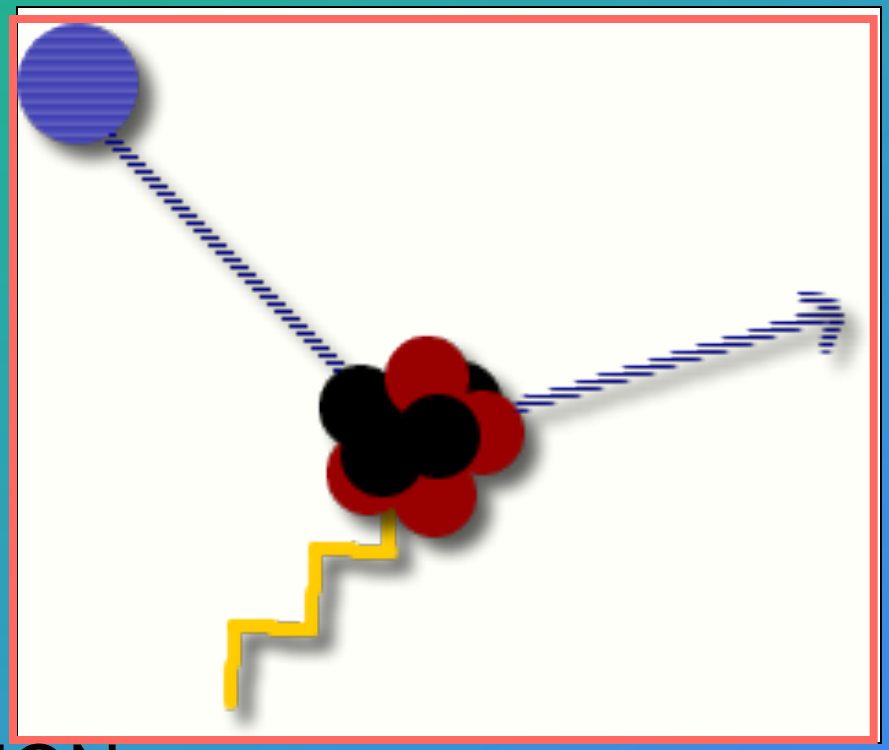
Additional possible source of DM fuel: capture

- 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.

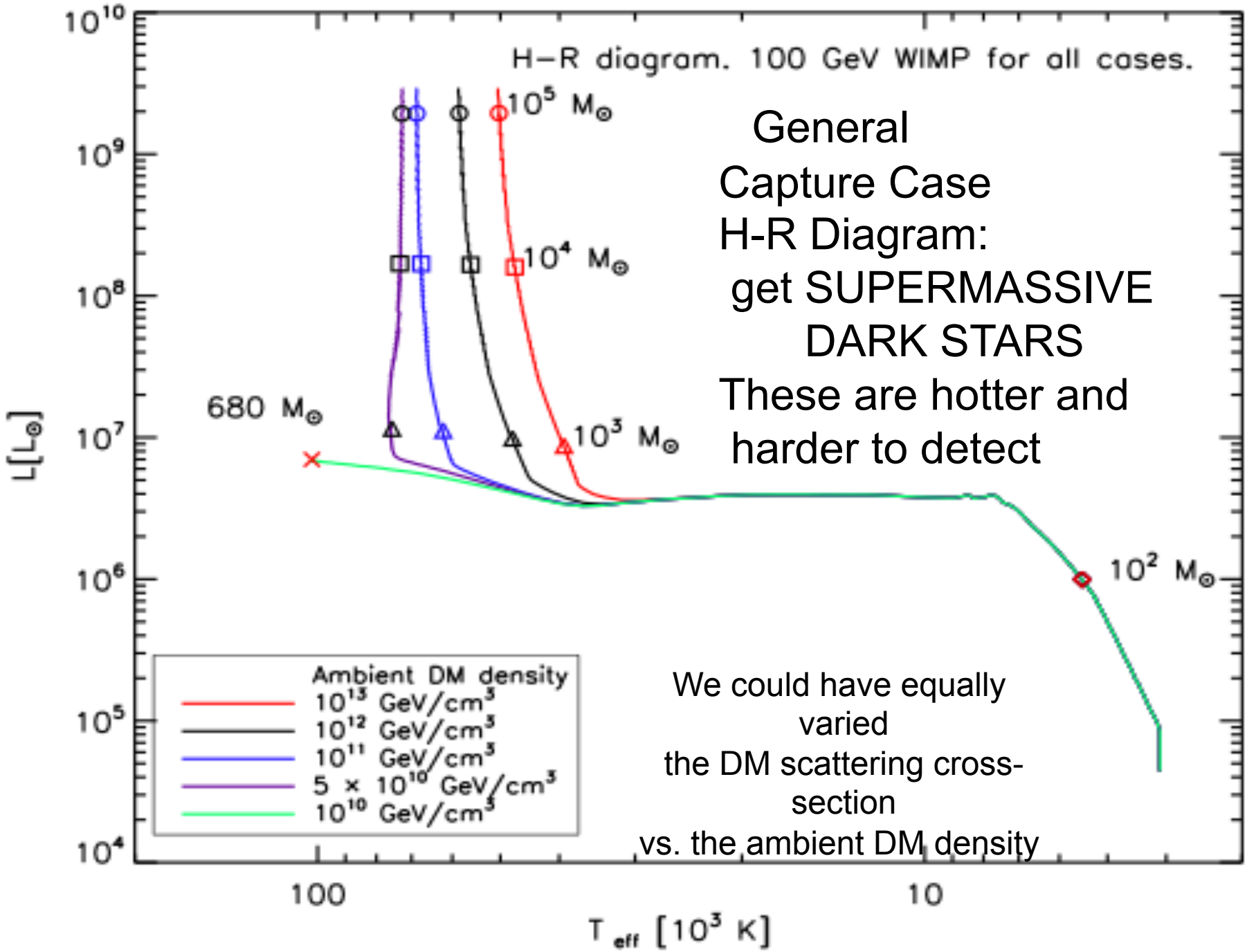
Freese, Aguirre, Spolyar 08; Iocco 08

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 COGENT, CDMS, XENON, DAMA, CRESST, etc are looking for (Direct Detection)



General
Capture Case
H-R Diagram:
get SUPERMASSIVE
DARK STARS
These are hotter and
harder to detect

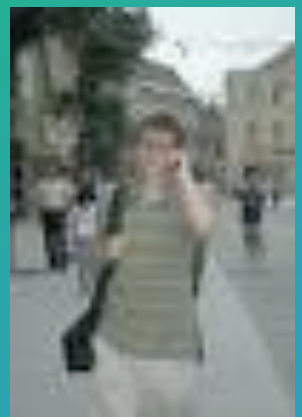
We could have equally
varied
the DM scattering cross-
section
vs. the ambient DM density

Additional work on Dark Stars:

- Dark Star stellar evolution codes with DM heating in 25-300 solar mass stars of fixed mass through helium burning: case where DM power equals fusion: Iocco, Ripamonti, Bressan, Schneider, Ferrara, Marigo 2008;Yun, Iocco, Akiyama 2008; Taoso, Bertone, Meynet, Ekstrom 2008
- Study of reionization: Schleicher, Banerjee, Klessen 2008, 2009; Scott etal 2011
- Study of important effects on stellar evolution: Ripamonti, et al 09; Ripamonti etal 10

Observing Dark Stars

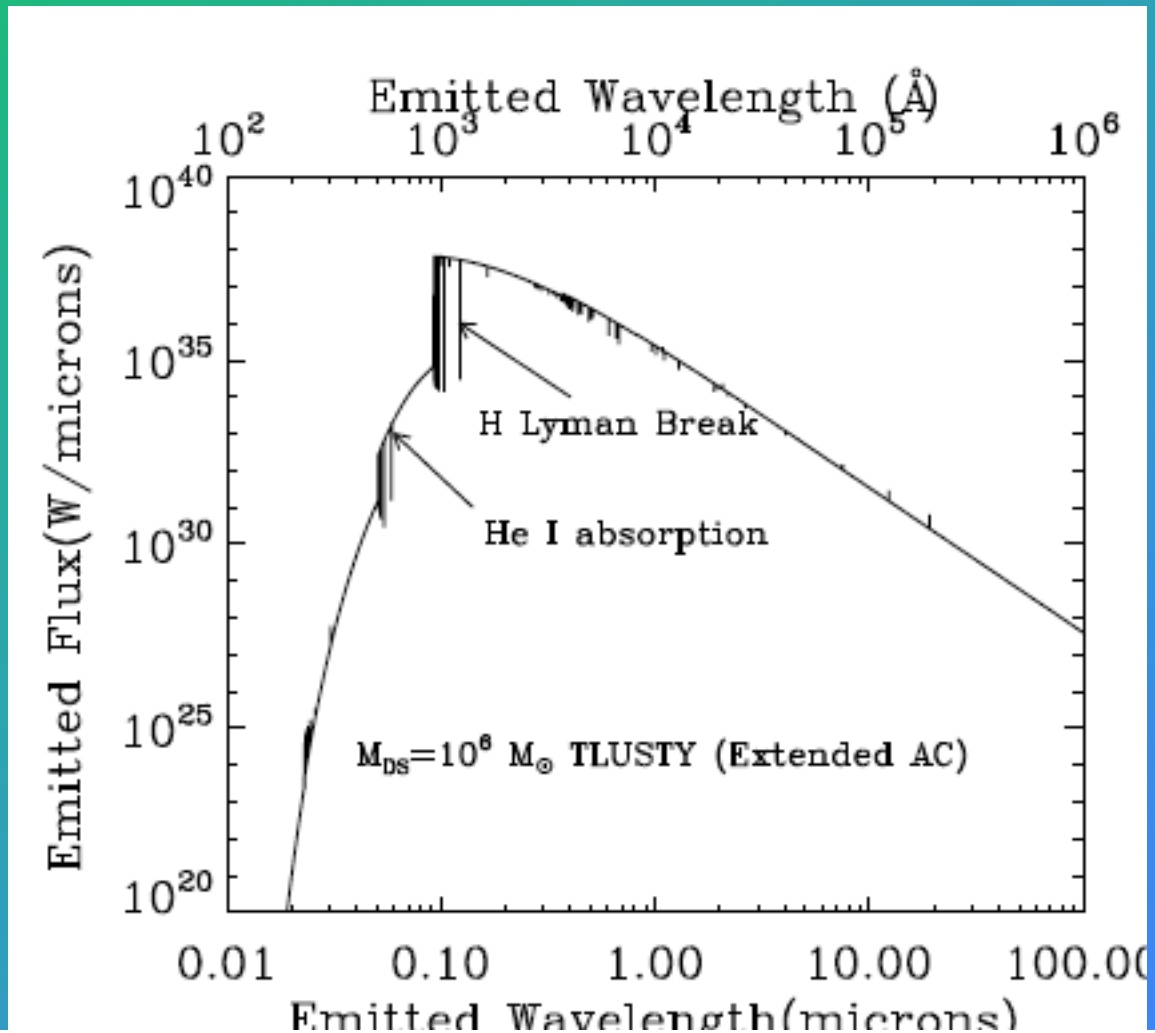
- Supermassive Dark Stars may be detected in upcoming James Webb Space Telescope
- One of JWST goals is to find first stars: only if they are dark stars is this goal realizable



Cosmin Ilie, Paul Shapiro

Pat Scott

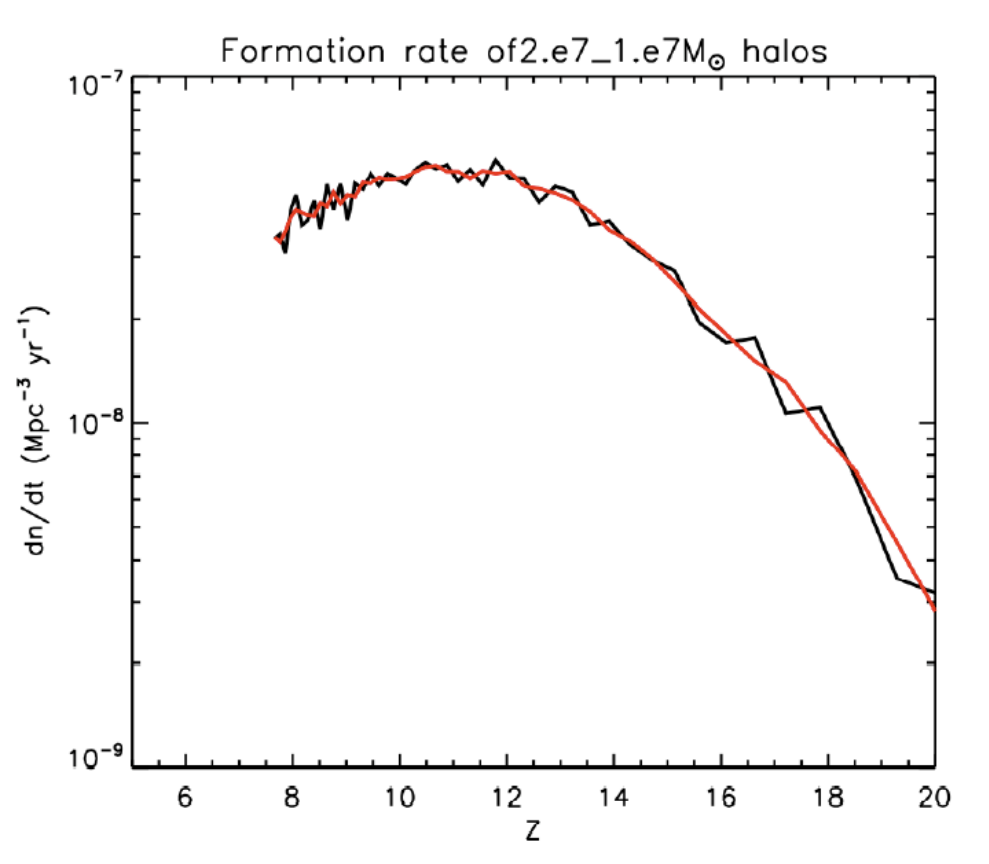
DS Spectrum from TLUSTY (stellar atmospheres code)



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

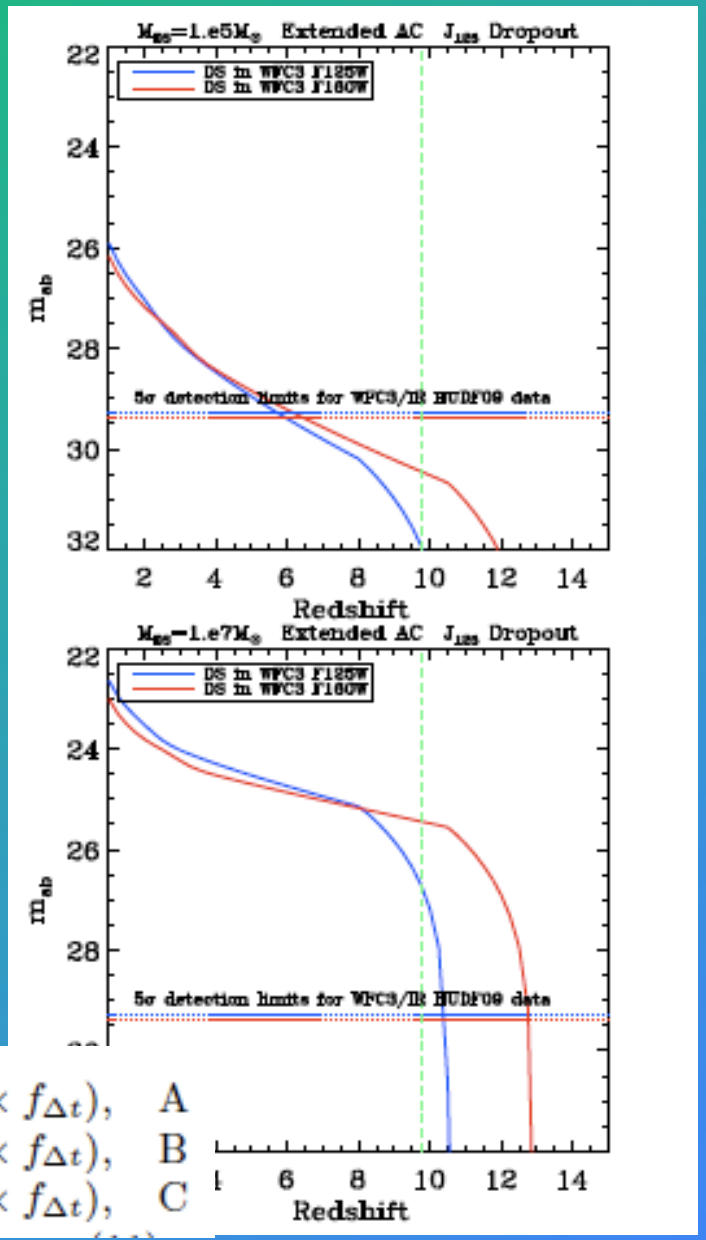
Minihalo formation rate

Shapiro, Iliev



Dark Stars in HST

Heaviest ones would be visible in HST as Jband dropouts (observable in 1.6 micron band but not in 1.25 micron band due to Ly-alpha absorption in the intervening gas), yet only one object was found at z=10.
Thus we can bound the numbers of 10^7 solar mass SMDS.



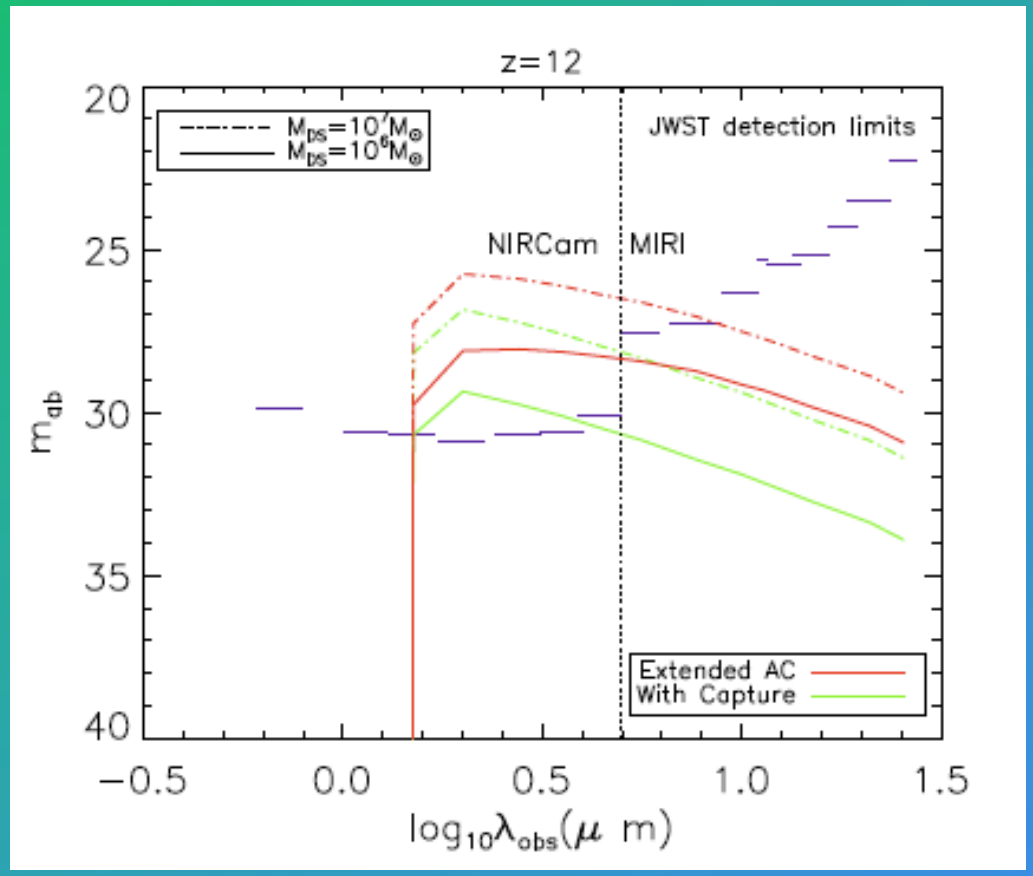
$$\log f_{smds}(M_{DS} = 10^7 M_\odot) \leqslant \begin{cases} -4.5 - \log(f_{surv} \times f_{\Delta t}), & \text{A} \\ -3.4 - \log(f_{surv} \times f_{\Delta t}), & \text{B} \\ -2.1 - \log(f_{surv} \times f_{\Delta t}), & \text{C} \end{cases}$$

A,B,C: zform=10,12,15

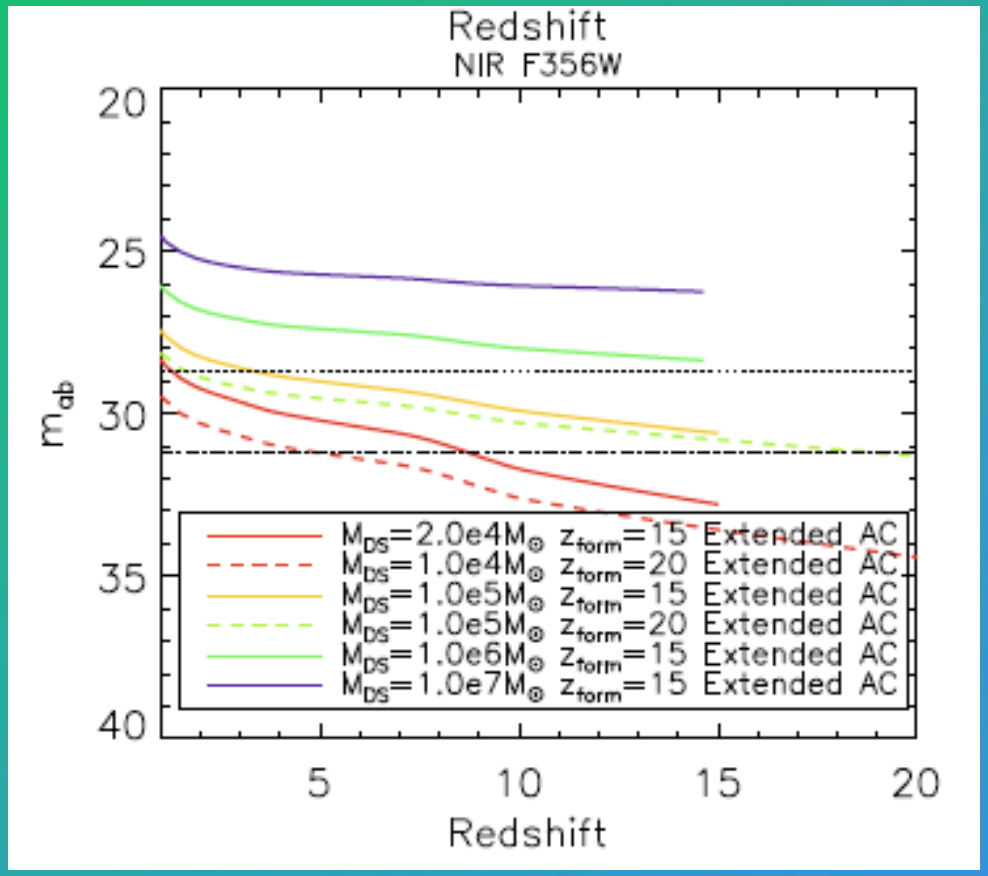
JWST filters

	Filter	λ_{center} (μm)	$\log_{10} \lambda_{center}$	$\Delta\lambda$ (μm)	m_{AB}
NIRCam	F070W	0.7	-0.15	0.175	28.1
	F090W	0.9	-0.05	0.225	28.51
	F115W	1.15	0.06	0.2875	28.72
	F150W	1.5	0.17	0.375	28.77
	F200W	2.0	0.30	0.5	28.75
	F277W	2.77	0.44	0.6925	28.67
	F356W	3.56	0.55	0.89	28.55
	F444W	4.44	0.65	1.11	27.92
MIRI	F560W	5.6	0.75	1.2	25.65
	F770W	7.7	0.89	2.2	25.28
	F1000W	10.0	1.00	2.0	24.29
	F1130W	11.3	1.05	0.7	23.32
	F1280W	12.8	1.1	2.4	23.53
	F1500W	15.0	1.18	3.0	23.26
	F1800W	18.0	1.25	3.0	22.31
	F2100W	21.0	1.32	5.0	21.56
	F2550W	25.5	1.4	4.0	20.28

SMDS in JWST

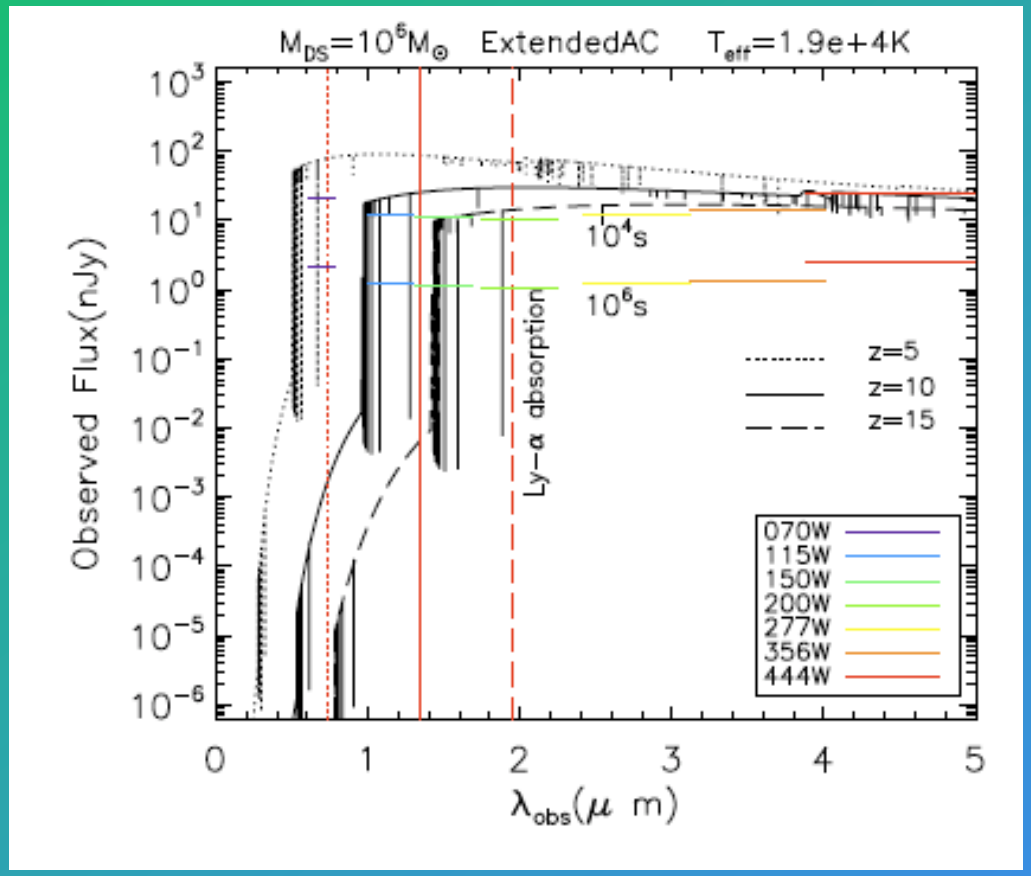

z=12
$M_{DS}=10^7 M_\odot$
$M_{DS}=10^6 M_\odot$
JWST detection limits
NIRCam
MIRI
Extended AC
With Capture
m_{ab}
20
25
30
35
40
−0.5
0.0
0.5
1.0
1.5
$\log_{10}\lambda_{obs}(\mu\ m)$

DS in JWST

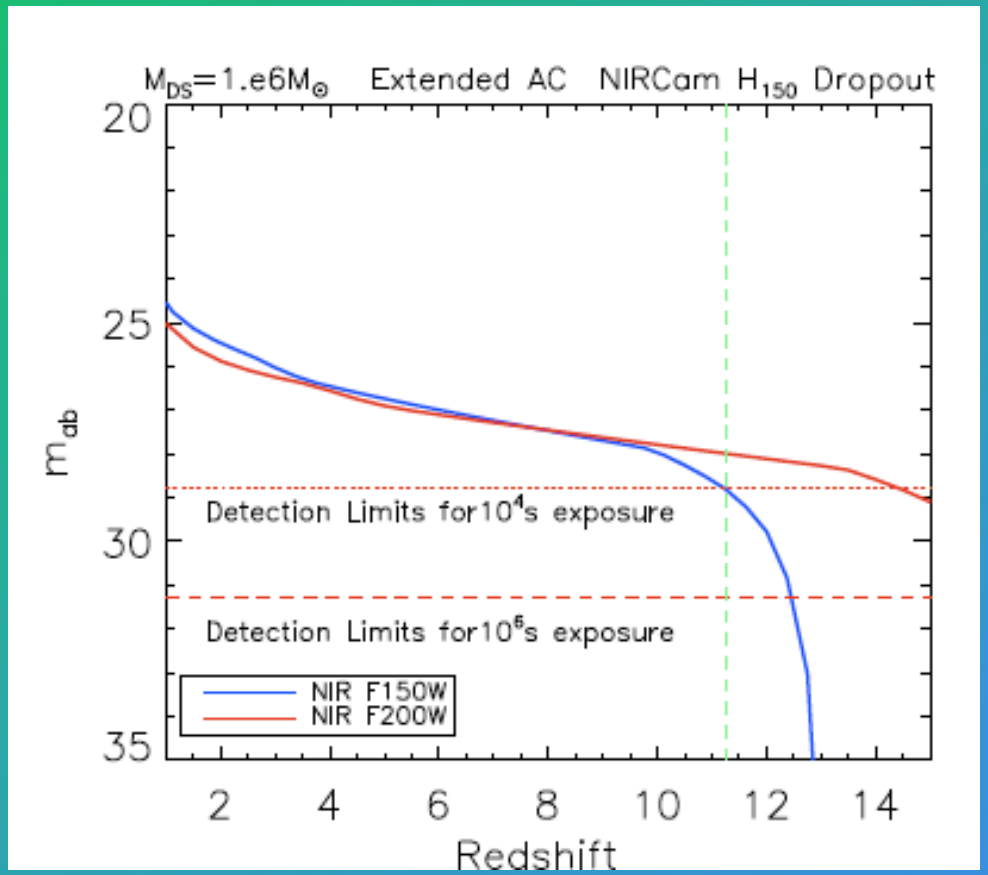


Horizontal lines:
10^4 and
10^6 sec
exposures

Million solar mass DS in JWST NirCam filters



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

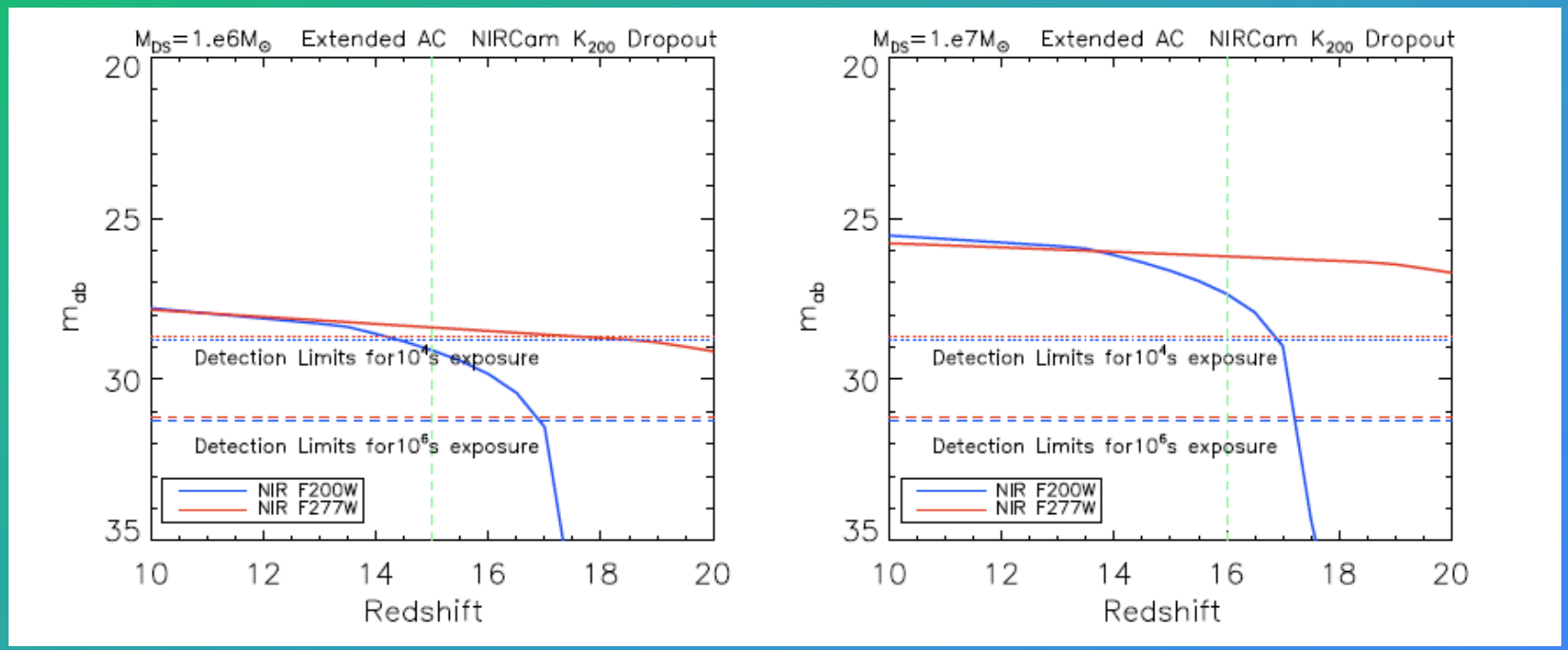
Upper limits on numbers of SMDS detectable with JWST as H_{150} dropout

$M_{DS}(M_\odot)$	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.

SMDS as K-band dropout

(see in 2.77 micron but not 2.00 micron filter, implying it's a z=15 object)



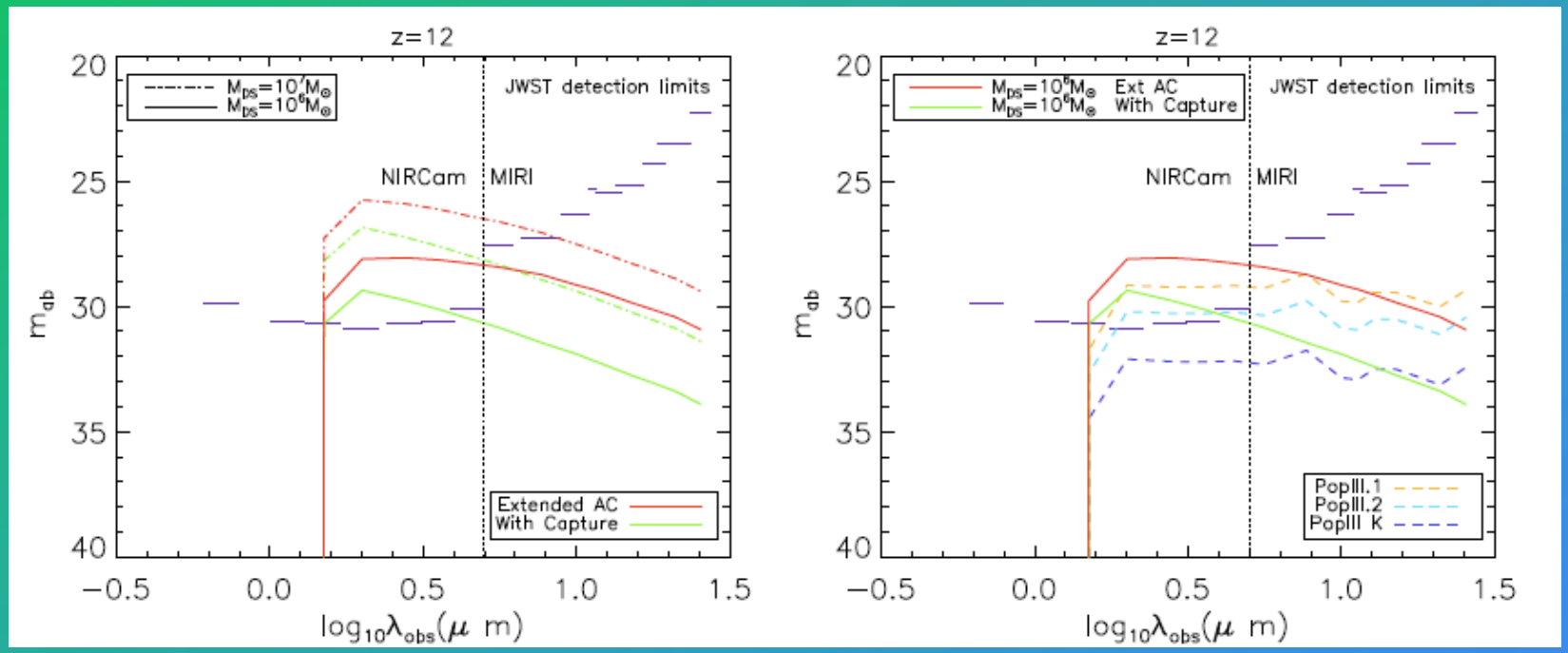
Number of SMDS detectable with JWST as K-band dropout

(see in 2.77 micron but not 2.00 micron filter, implying it's a z=15 object)

Upper limits on numbers of SMDS detectable with JWST as K_{200} dropout

$M_{DS}(M_\odot)$	Formation Scenario	Bounds from HST	N_{obs}^{FOV}	N_{obs}^{multi}
10^6	Extended AC	Maximal Bounds	$\lesssim 1$	~ 1
10^7	Any	Maximal Bounds	$\ll 1$	$\ll 1$
10^6	Extended AC	Intermediate	5	75
10^7	Any	Intermediate	$\ll 1$	$\lesssim 1$
10^6	Extended AC	Number of DM halos	4511	69900
10^7	Any	Number of DM halos	8	116

Comparison of SMDS vs. early galaxies

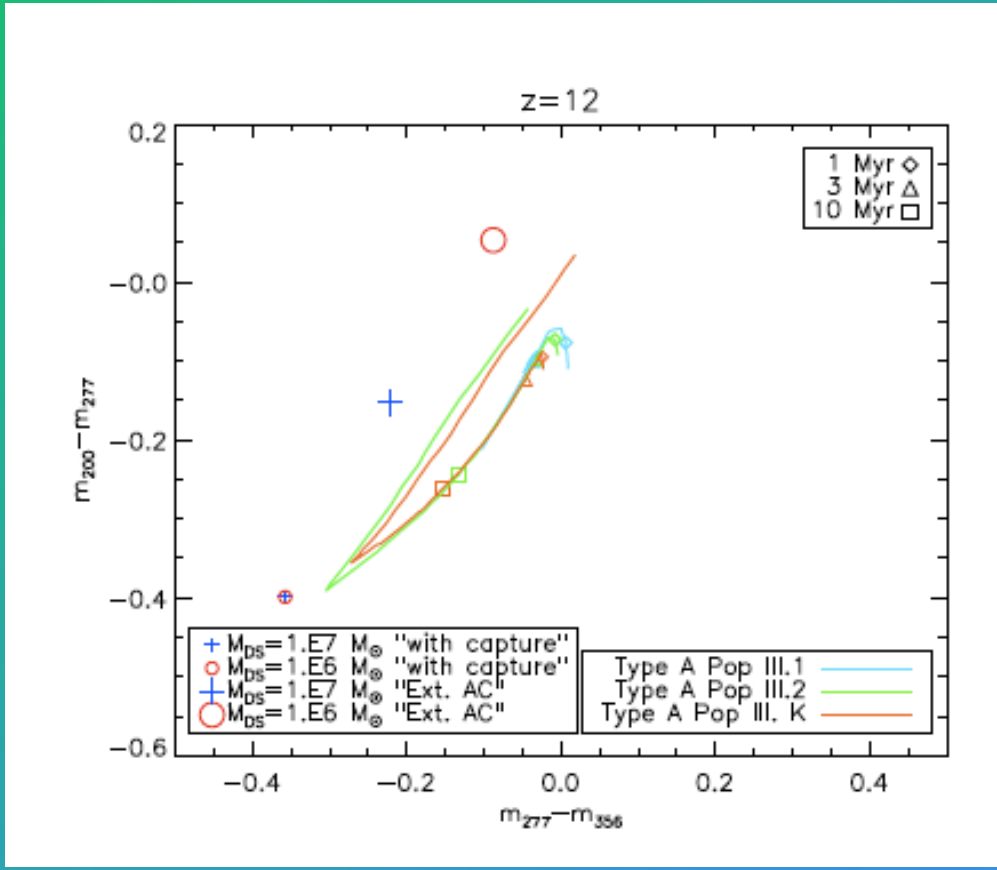


SMDS are brighter, have slightly different slope

- If followup spectroscopy is done on an object found as as dropout with JWST, the detection of a HeII1640 emission line or an H emission line would most likely indicate that the object is a Pop III galaxy with nebular emission rather than a SMDS

(Pawlik etal 2011; Zackrisson etal 2011)

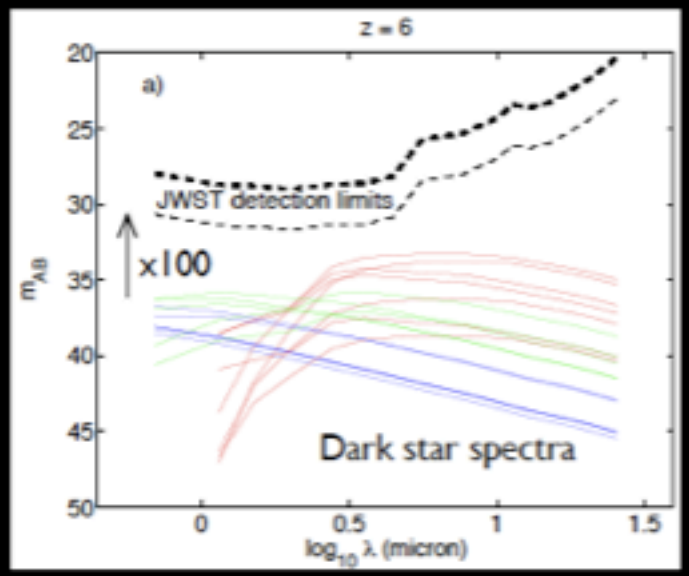
SMDS vs. early galaxies using Ygdrassil evolution code

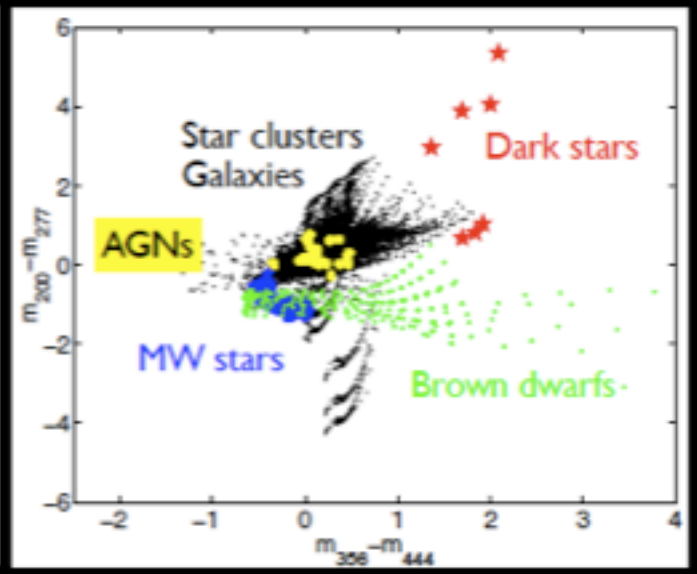


Enhance signal via lensing

Idea: Use a magnifying lens *Zackrisson et al 2010*

Detectable with JWST via gravitational lens magnification ~100





Can even see 1000 solar mass dark stars

Lifetime of Dark Star

- The DS lives as long as DM orbits continue through the DS or it captures more Dark Matter fuel: millions to billions of years.
- The refueling can only persist as long as the DS resides in a DM rich environment, I.e. near the center of the DM halo. But the halo merges with other objects.
- You never know! They might exist today.
- Once the DM runs out, switches to fusion.

What happens next?
BIG BLACK HOLES

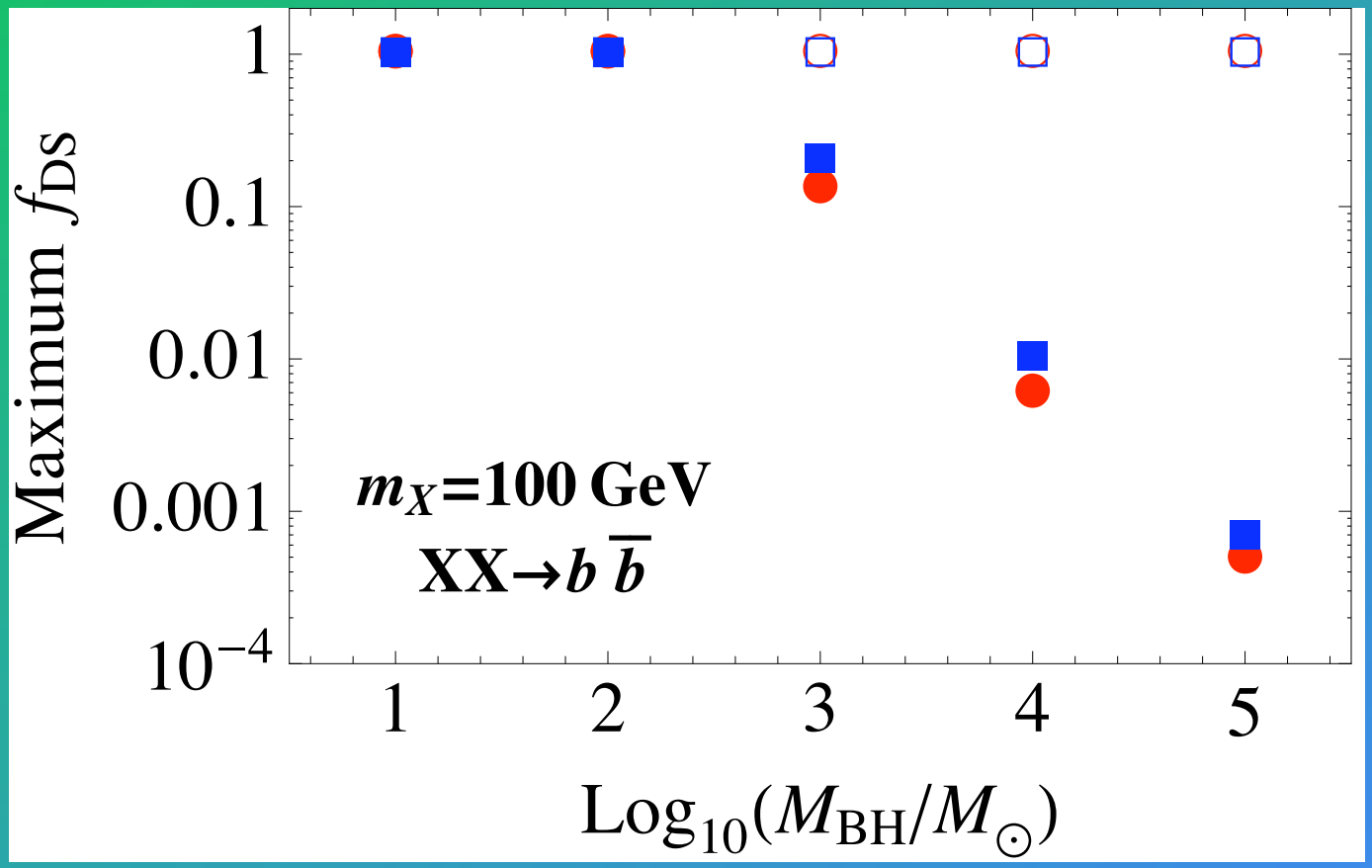
- Star reaches $T=10^7$K, fusion sets in.
- A. Heger finds that fusion powered stars heavier than 153,000 solar masses are unstable and collapse to BH
- Less massive Pop III star lives a million years, then becomes a Black Hole
- Helps explain observed black holes:
- (I) in centers of galaxies
- (ii)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

Black Hole remnants of dark stars

- These live till today, have DM spikes around them, that DM annihilates to observable signals in gamma rays and positrons (explains PAMELA?)
- FERMI has 368 unidentified point sources: can they be seeing these effects?
- Numbers of BH in Milky Way can be huge: millions between us and the GC!

FERMI bounds on the fraction of minihaloes hosting dark stars

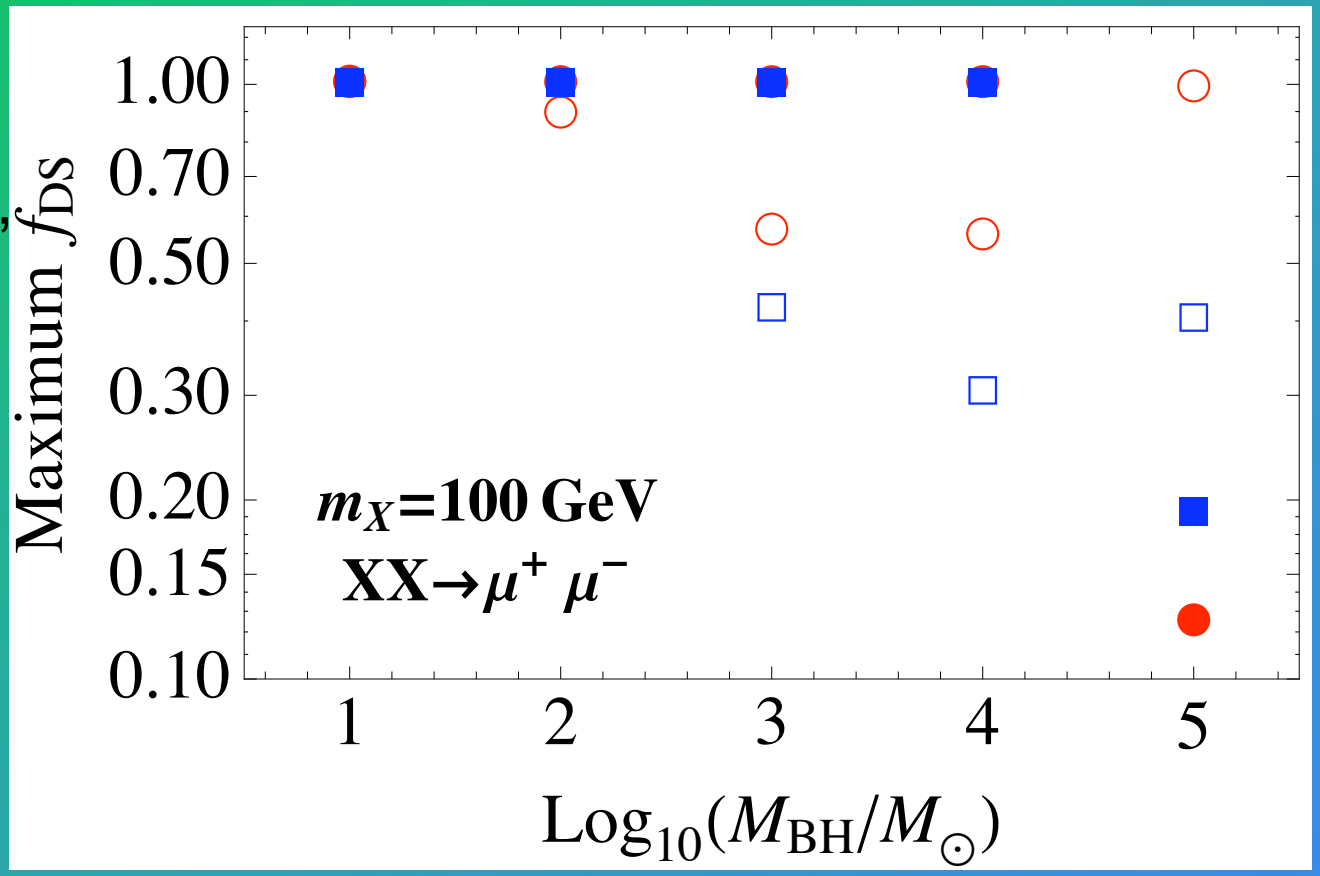
Sandick, KF, etal 2010; 2011



Solid: FERMI point sources; open: gamma ray diffuse flux

FERMI bounds on the fraction of minihaloes forming dark stars

Sandick, KF etal 2010



Solid: point source bounds; Open: diffuse gamma ray flux

Final Thoughts: *IMF*

- The IMF of the first fusion powered stars may be determined by the Dark Matter encountered by their Dark Star progenitors: as long as there is DM, the DS keeps growing
- Depends on cosmological merger details of early haloes, million to hundred million solar mass haloes

Dark Stars (conclusion)

- The dark matter can play a crucial role in the first stars
- The first stars in the Universe may be powered by DM heating rather than fusion
- These stars may be very large (1000-100,000 solar masses) and bright (million to ten billion solar luminosities) and can be detected by JWST

March 2010 Sky and Telescope

THE END