Supermassive Dark Stars: Detectable in JWST

Katherine Freese (Univ. of Michigan)

Phys. Rev. Lett. **98**, 010001 (2008),arxiv:0705.0521
D. Spolyar , K .Freese, and P. Gondolo

PAPER 1

JCAP,11,014F (2008) arXiv:0802.1724
K. Freese, D. Spolyar, and A. Aguirre

Astrophys.J.693:1563-1569,2009, arXiv:0805.3540
K. Freese, P. Gondolo, J.A. Sellwood, and D. Spolyar

Astrophys.J.685:L101-L112,2008, arXiv:0806.0617
K. Freese, P. Bodenheimer, D. Spolyar, and P. Gondolo

Astrophys.J.705:1031-1042,2009, arXiv:0903.1724
D. Spolyar, P. Bodenheimer, K Freese, and P Gondolo

arXiv:1002.2233, K. Freese, C. Ilie, D. Spolyar, M. Valluri, and P. Bodenheimer

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

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

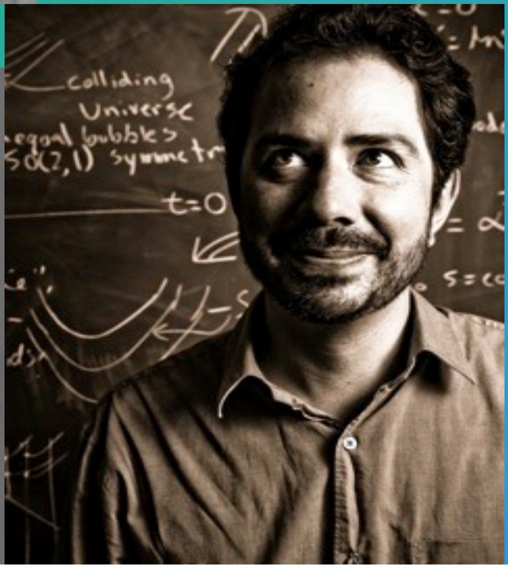
Paolo Gondolo

Doug Spolyar

Peter Bodenheimer

Naoki Yoshida

Anthony Aguirre



Monica Valluri

Cosmin Ilie

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).

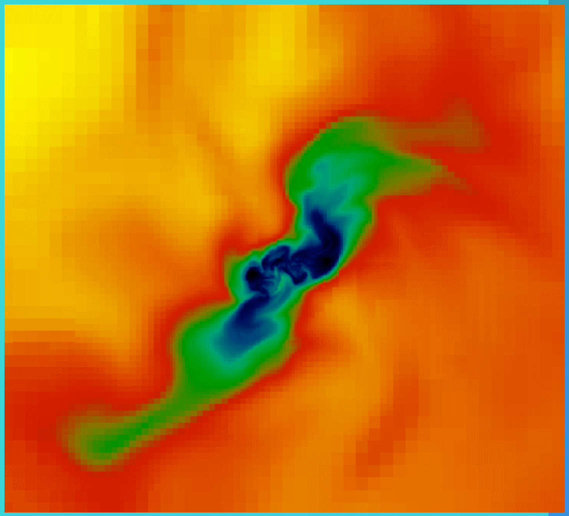
- This new phase of stellar evolution may last millions to billions of years
- Dark Stars can grow to be very large: thousands to millions of solar masses. Supermassive DS are very bright (millions to hundred billion solar luminosities) and can be seen in JWST or even HST
- Once the Dark Matter runs out, the DS has a fusion phase before collapsing to a big black hole: is this the origin of supermassive black holes?

Our Results

- Dark Matter (DM) in haloes can dramatically alter the formation of the first stars leading to a new stellar phase driven by DM annihilation.
  - Change: Reionization, Early Stellar Enrichment, Formation of early Big Black Holes.
  - Discover DM.
- Basic Properties
  - Very luminous up to ~ 10^{11} $L_\odot$
  - Relatively cool ~ 10^4 K
  - Can be very long lived ~ 10^8 years
  - Super Massive up to ~ 10^7 $M_\odot$
  - The more massive DS can be detectable with JWST

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

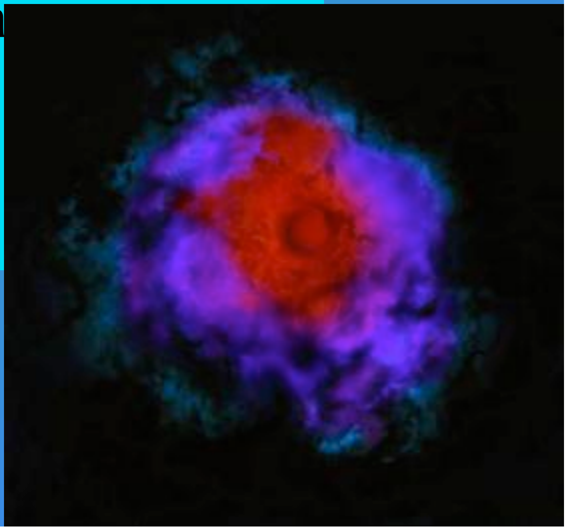
H_2

Not a very good coolant

(Hollenbach and McKee '79)

Basic Picture

- The First Stars
  - form in a DM rich environment
- Gas cools and collapses to form the first stars
  - the cloud compresses the DM halo.
- DM annihilates
  - rapidly as densities increase
- At a high enough DM density
  - the DM heating overwhelms any cooling mechanisms which stops the cloud from continuing to cool and colla

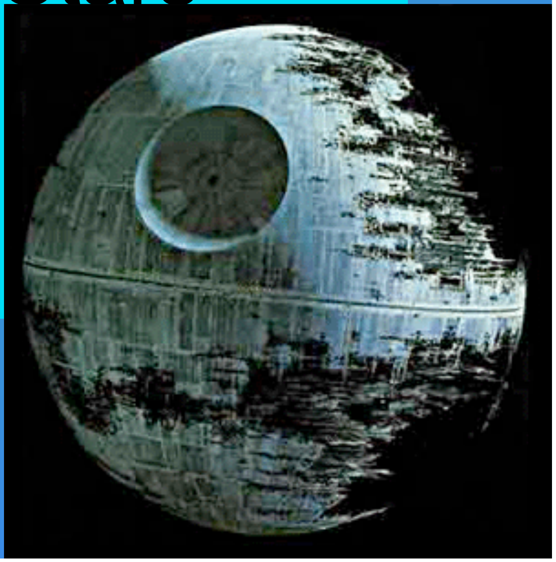


Basic Picture Continued

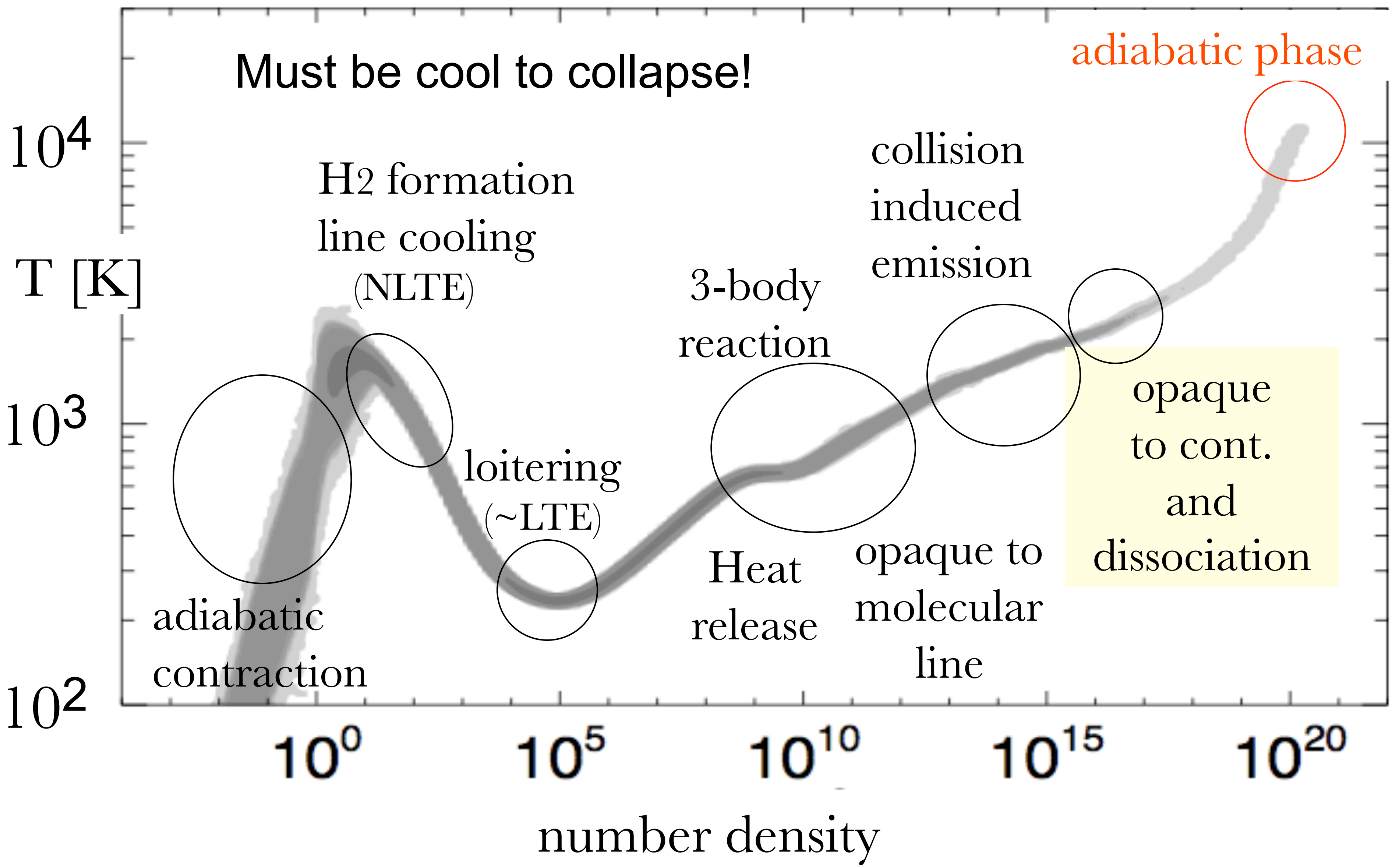
- Molecular Hydrogen core forms
  - supported by DM annihilation
- More DM and gas accretes onto the core
  - Creating a massive optically thick ionized cloud supported by DM annihilation: becomes a star in equilibrium
- If Fusion
  - Star
- But DM Powered
  - Dark Star
- DM in the star comes from 2 different mechanisms
  - Adiabatic Contraction
  - DM capture.

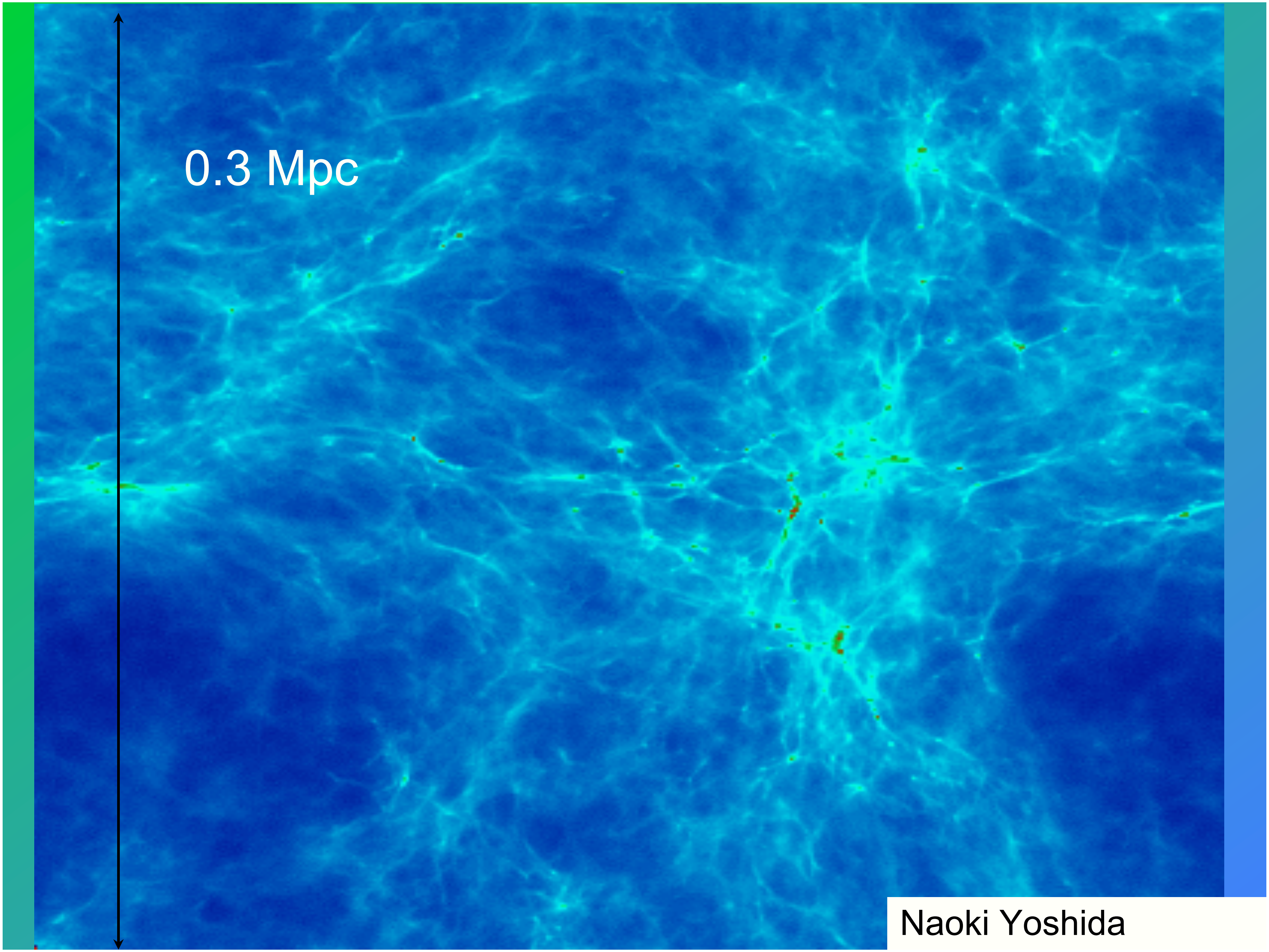
Outline

- The First Stars- standard picture
- Dark Matter
    - Particle physics-The LSP (lightest SUSY particle)
    - Astrophysics- Density Profile
- 3 Conditions for forming Dark Stars
- Properties of Dark Stars
- Supermassive DS and JWST

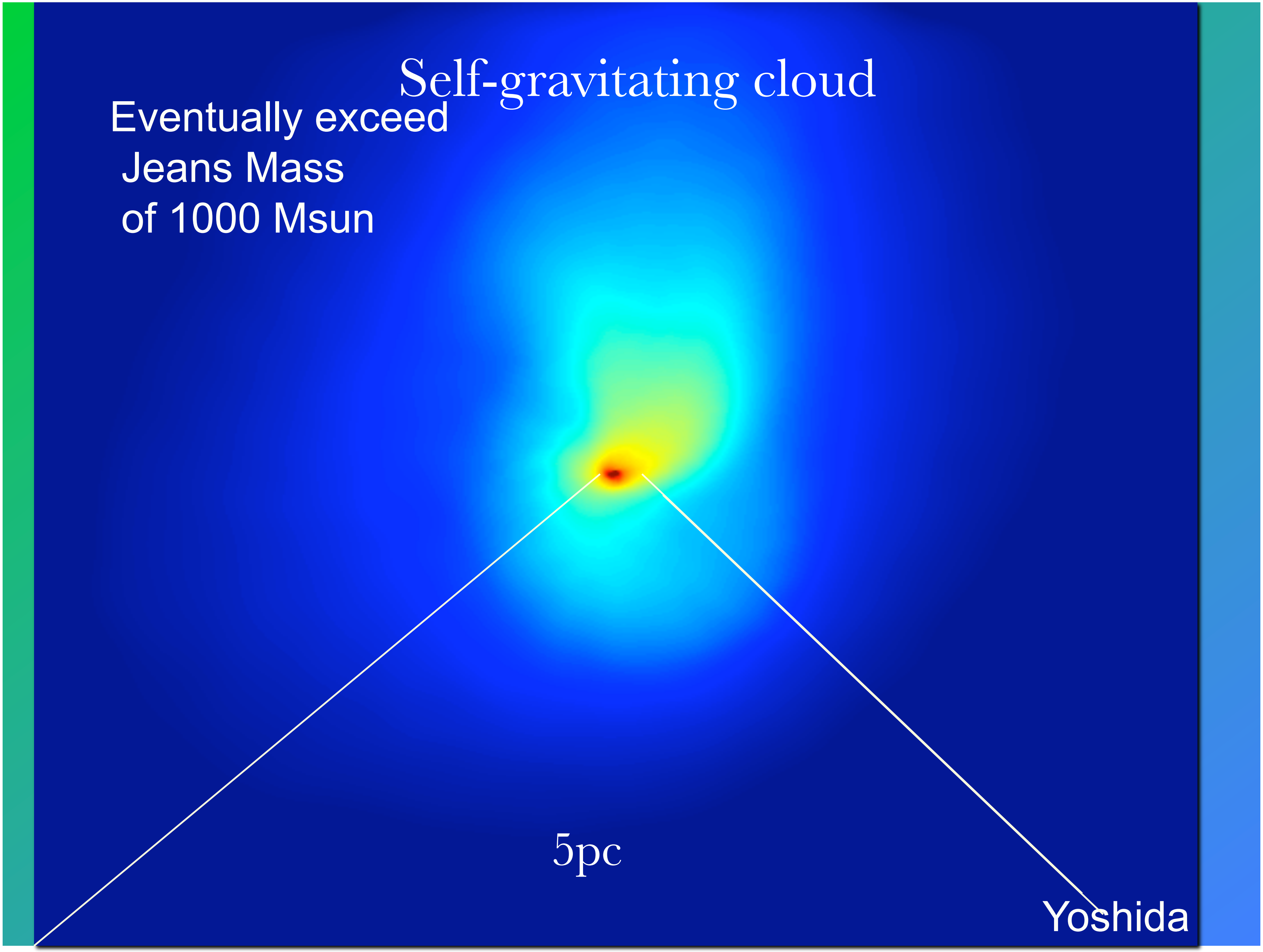


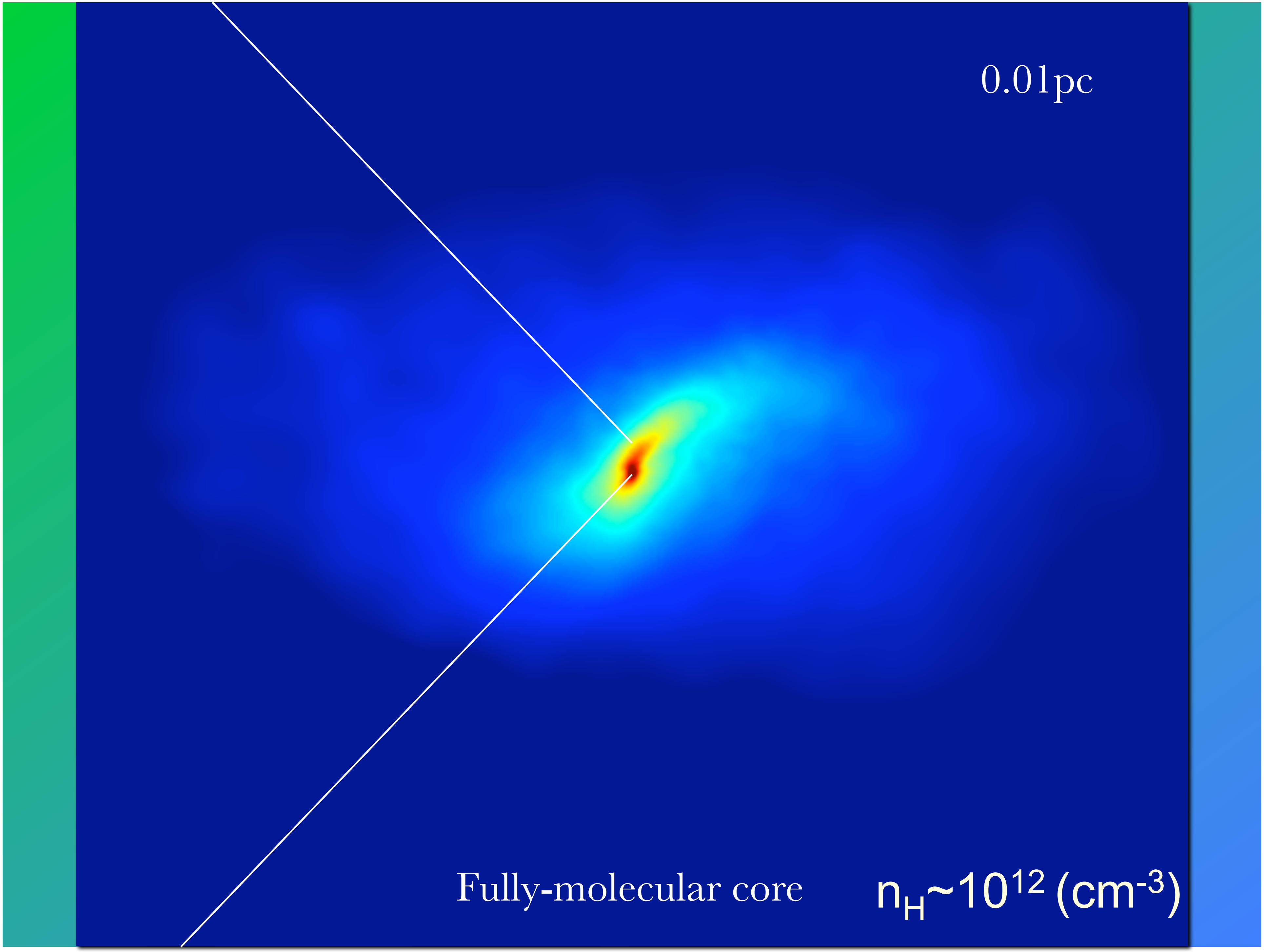
Thermal evolution of a primordial gas





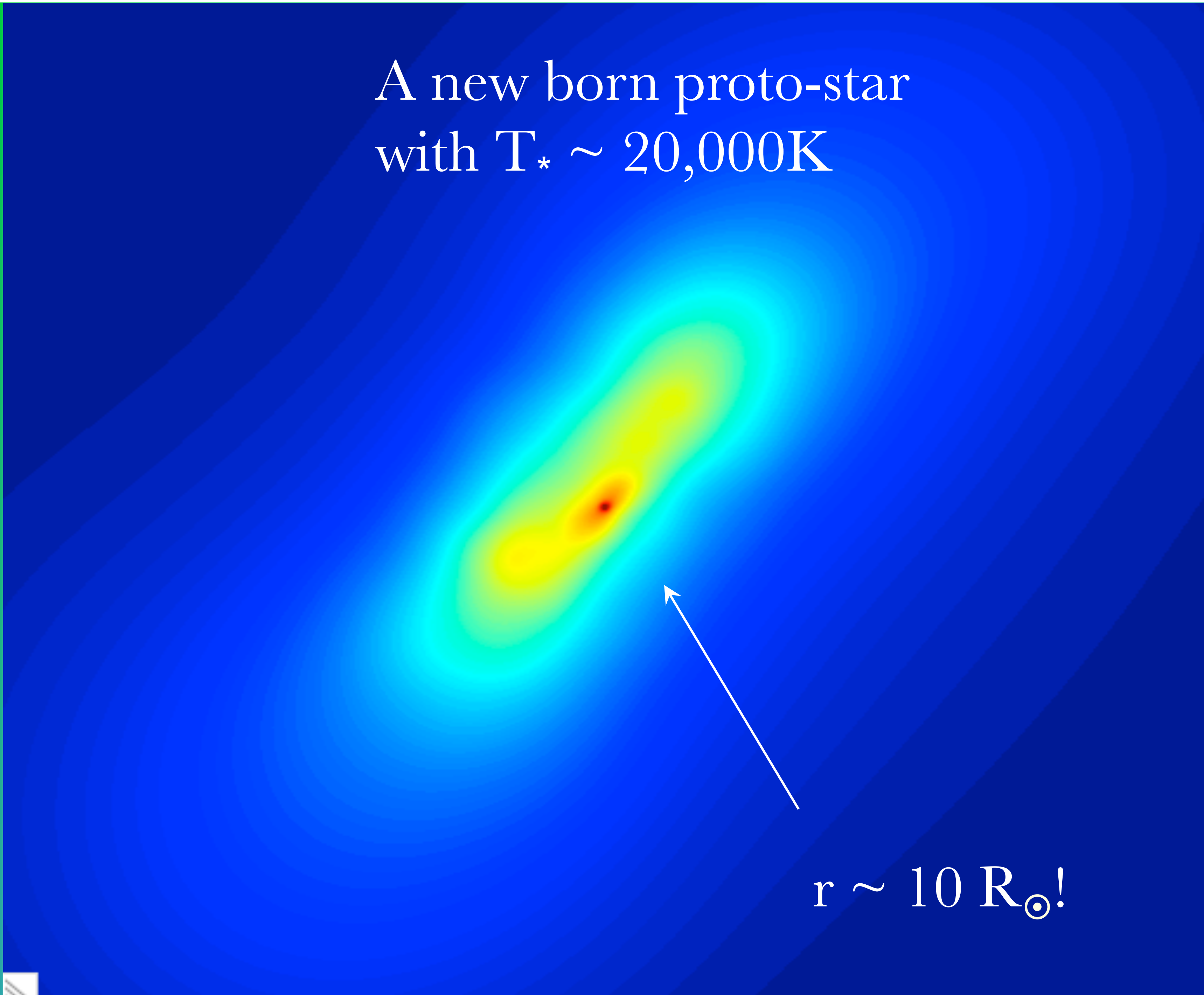
Naoki Yoshida


Self-gravitating cloud
Eventually exceed
Jeans Mass
of 1000 Msun
5pc
Yoshida



0.01pc
Fully-molecular core
$n_H \sim 10^{12}$ (cm^{-3})

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



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

$100 M_\odot$ Standard Picture

With DM heating
Much more massive

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

The best motivated dark matter particles (in order of motivation)

- WIMPs (Weakly Interacting Massive Particles):

  Supersymmetric particles or

  Kaluza Klein (extra dimensions)
- Axions
- Primordial black holes

Good news: cosmologists don't need to "invent" new particle:

- Weakly Interacting Massive Particles (WIMP)s
  - e.g. the neutralino (LSP)
  - WIMP Miracle
- Axions
  - Pecci-Quinn Solution to the strong CP problem
- Primordial Black Holes
  - First order phase transitions (GUT models, Electro-Weak Phase transition)

The Dark Matter: The WIMP Miracle

Weakly Interacting Massive Particles are the best motivated dark matter candidates. e.g.: Lightest Supersymmetric Particles (such as neutralino) are their own antipartners. Annihilation rate in the early universe determines the density today.

- The annihilation rate comes purely from particle physics and automatically gives the right answer for the relic density!

$$\Omega_\chi h^2 = \frac{3\times 10^{-27}\ cm^3/\mathrm{sec}}{<\sigma v>_{ann}}$$

WIMPs from Supersymmetry

- Particle theory designed to keep particle masses at the right values
  - Important extension of the Standard model
- Every particle we know has a partner:

photon	photino
quark	squark
electron	selectron

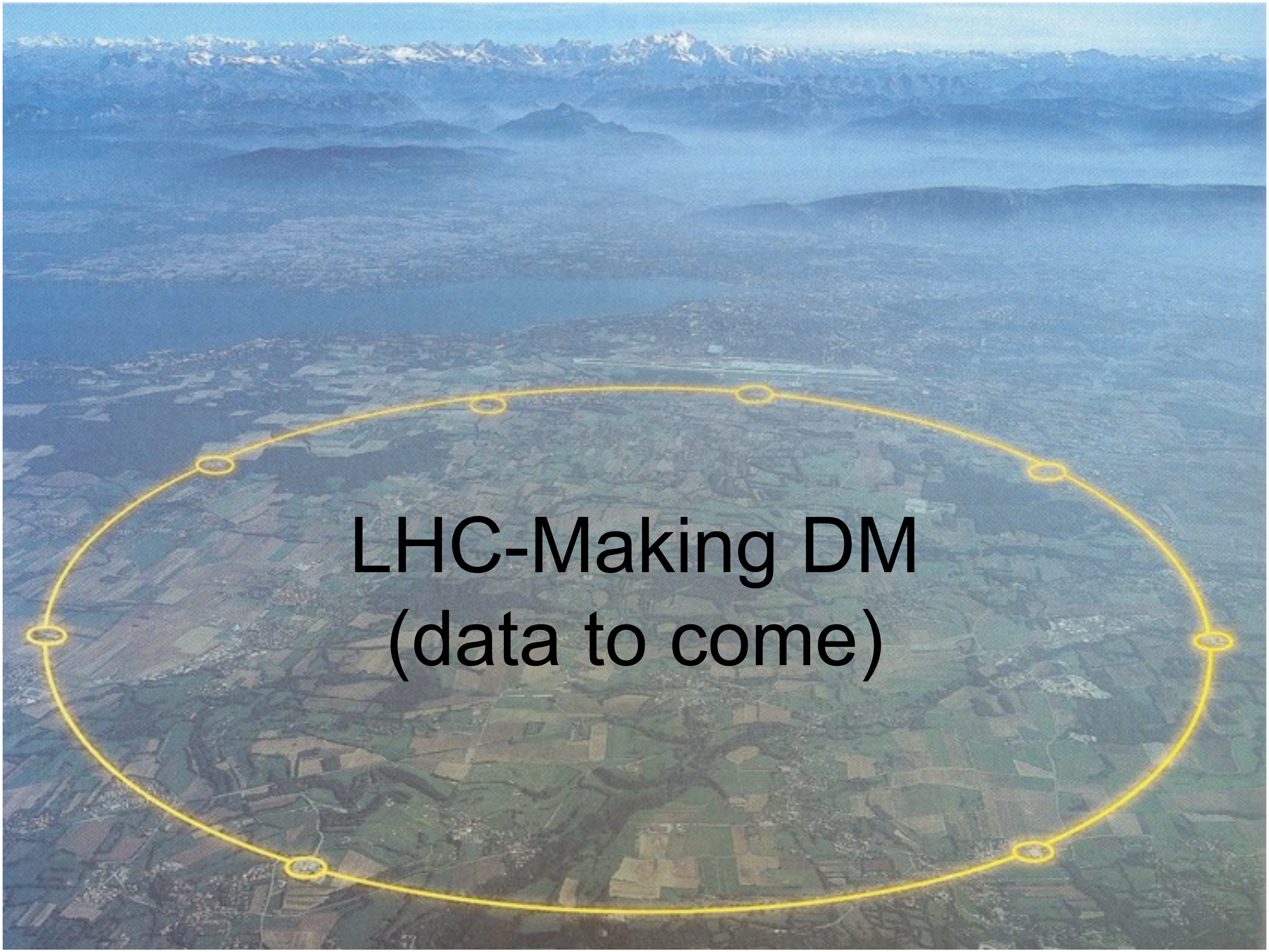
- The lightest supersymmetric partner is a WIMP dark matter candidate.

LSP
Weakly interacting DM

- Sets Mass 1Gev-10TeV (take 100GeV)
- Sets annihilation cross section (WIMPS):

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

- **On going searches**:
- Motivation for LHC at CERN: 1) Higgs 2) Supersymmetry.
- Other experiments: DAMA, CDMS, XENON, CRESST, EDELWEISS, DEEP-CLEAN, COUPP, TEXONO, FERMI, HESS, MAGIC, HEAT, PAMELA, AMANDA, ICECUBE



LHC-Making DM
(data to come)

Detecting WIMPs

- I. Direct Detection (Goodman and Witten 1986; Drukier, Freese, and Spergel 1986)
- II. Indirect Detection: uses same annihilation responsible for today's relic density:
- Neutrinos from Sun (Silk, Olive, and Srednicki 1985) or Earth (Freese 1986; Krauss and Wilczek 1986)
- Anomalous Cosmic rays from Galactic Halo (Ellis, KF et al 1987)
- Neutrinos, Gamma-rays, radio waves from galactic center (Gondolo and Silk 1999)

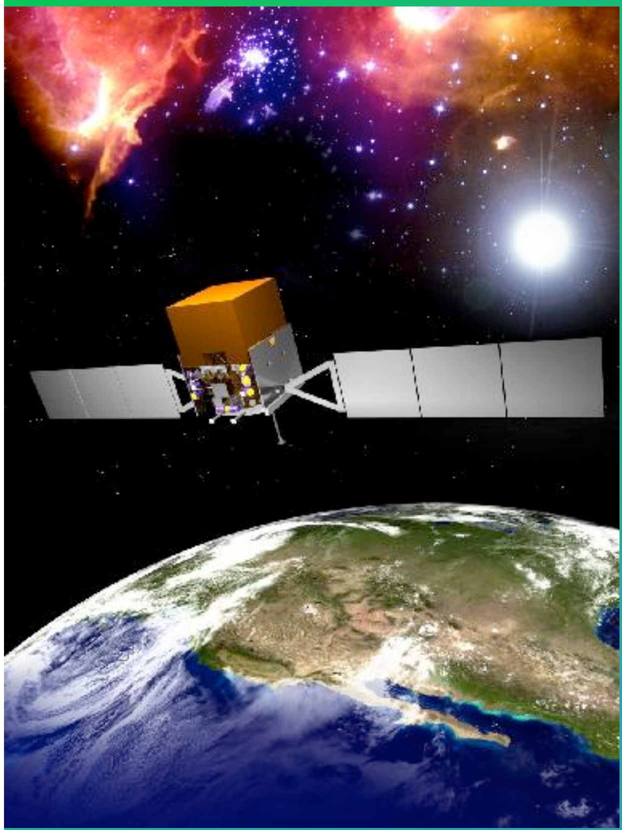
- N.B. SUSY neutralinos are their own antiparticles; they annihilate among themselves to 1/3 neutrinos, 1/3 photons, 1/3 electrons and positrons

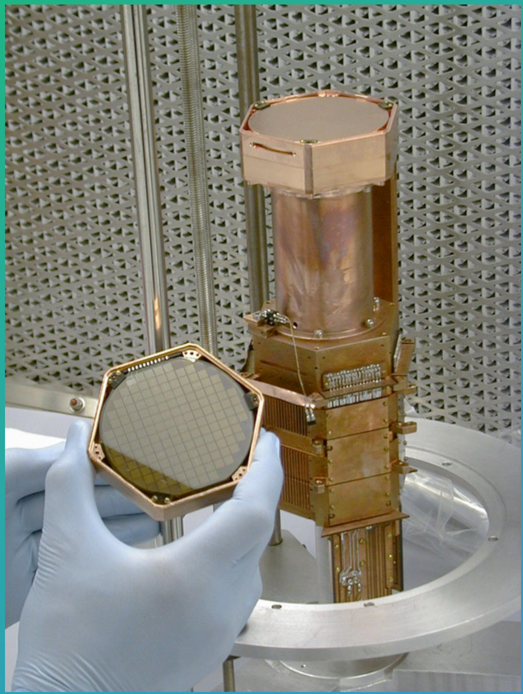
Indirect or Direct Detection

FERMI/GLAST

CDMS

ICE CUBE





photons

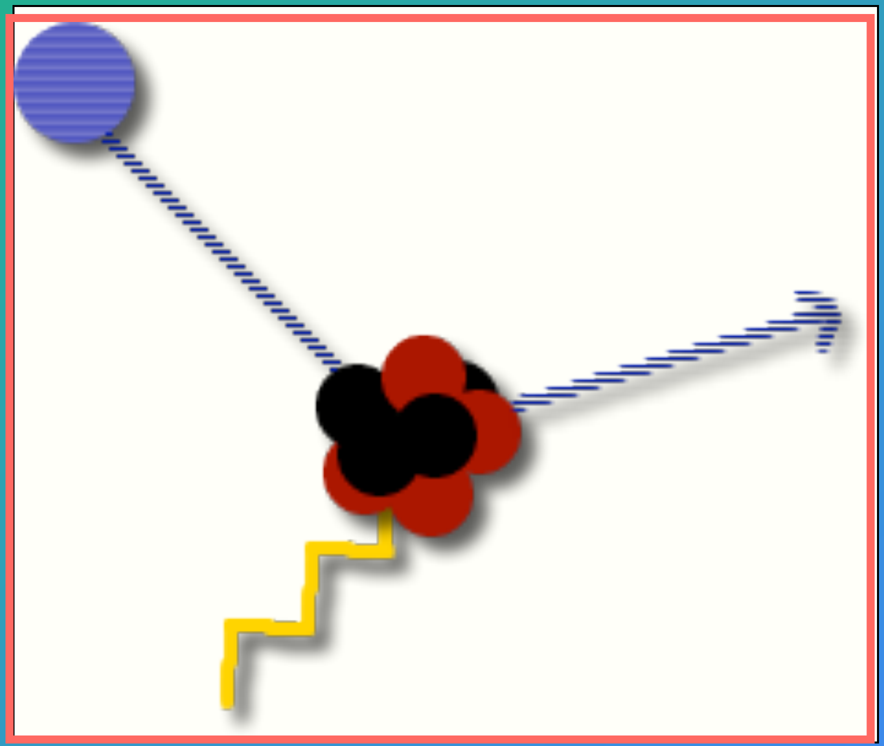
scattering

neutrinos

Direct Detection of WIMP dark matter

A WIMP in the Galaxy travels through our detectors. It hits a nucleus, and deposits a tiny amount of energy. The nucleus recoils, and we detect this energy deposit.

WIMP/NUCLEUS SCATTERING



Expected Rate: less than one count/kg/day!

The Indirect Detection of Dark Matter

1.WIMP Annihilation

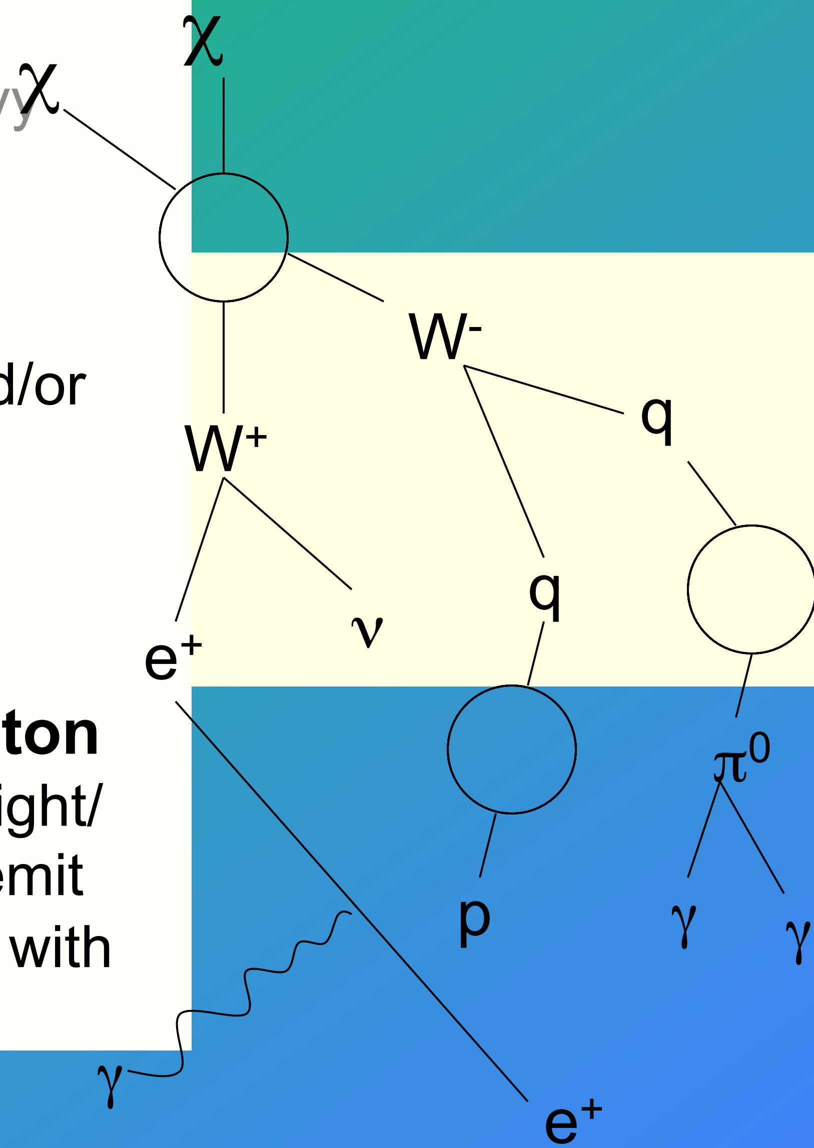
Typical final states include heavy fermions, gauge or Higgs bosons

2.Fragmentation/Decay

Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

3.Synchrotron and Inverse Compton

Relativistic electrons up-scatter starlight/ CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields



WIMP ANNIHILATION

Many claims of WIMP dark matter detection: how can we be sure?

- 1) The DAMA annual modulation
- 2) The HEAT, PAMELA, and ATIC positron excess
- 3) Gamma-rays from Galactic Center: EGRET, HESS, FERMI
- 4) WMAP Haze

HAS DARK MATTER BEEN DISCOVERED?

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); Hooper, Spolyar,Vallinotto,Gnedin 2010
- Main Sequence Stars: (Edsjo, Scott, Fairbairn 2007, 2008, 2009; Dark Stars code publicly available)

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:**

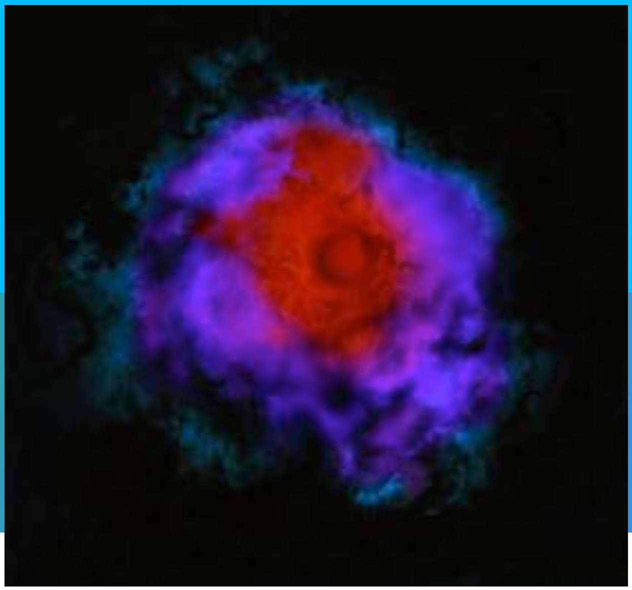
  the first stars form at high redshift,

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

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 ?



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

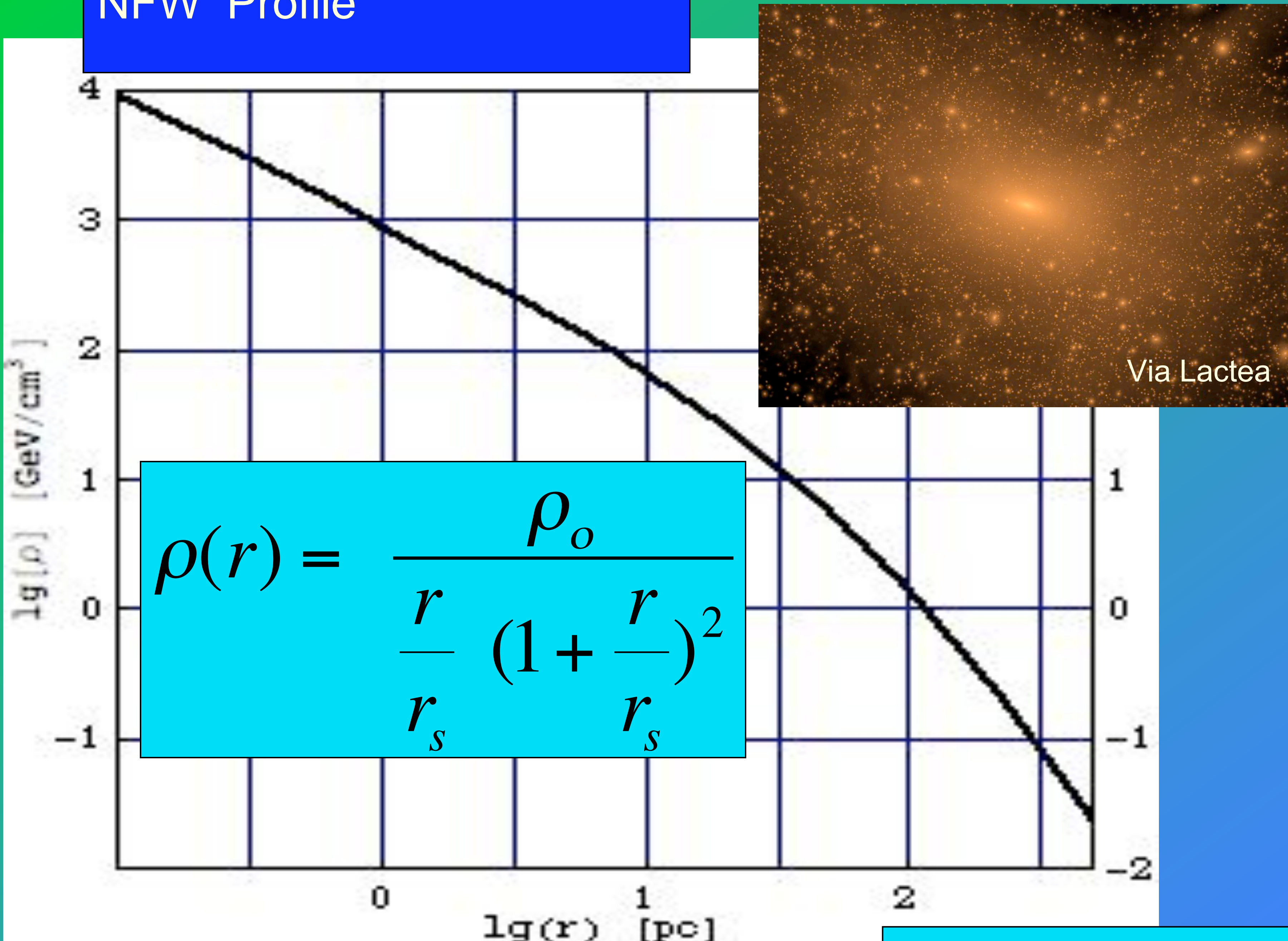
1/3 neutrinos

Depending upon the densities.

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 Profile

- As the baryons collapse into a protostar, the DM is pulled in gravitationally.Ideally we would like to determine the DM profile from running a cosmological simulation.
  – Problem: Not enough resolution to follow DM density all the way to where the star forms.
  – N-body simulation with

    Marcel Zemp

Adiabatic Contraction

- The baryons are evolving quasi statically and for much of the evolution the conditions for adiabatic contraction are indeed satisfied.
- Under adiabatic contraction phase space is conserved. We can identify three action variables which are invariant that the the distribution function depends upon.

$$f_i(\Theta_l, \Theta_r, \Theta_a) = f_f(\Theta_l, \Theta_r, \Theta_a)$$

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:

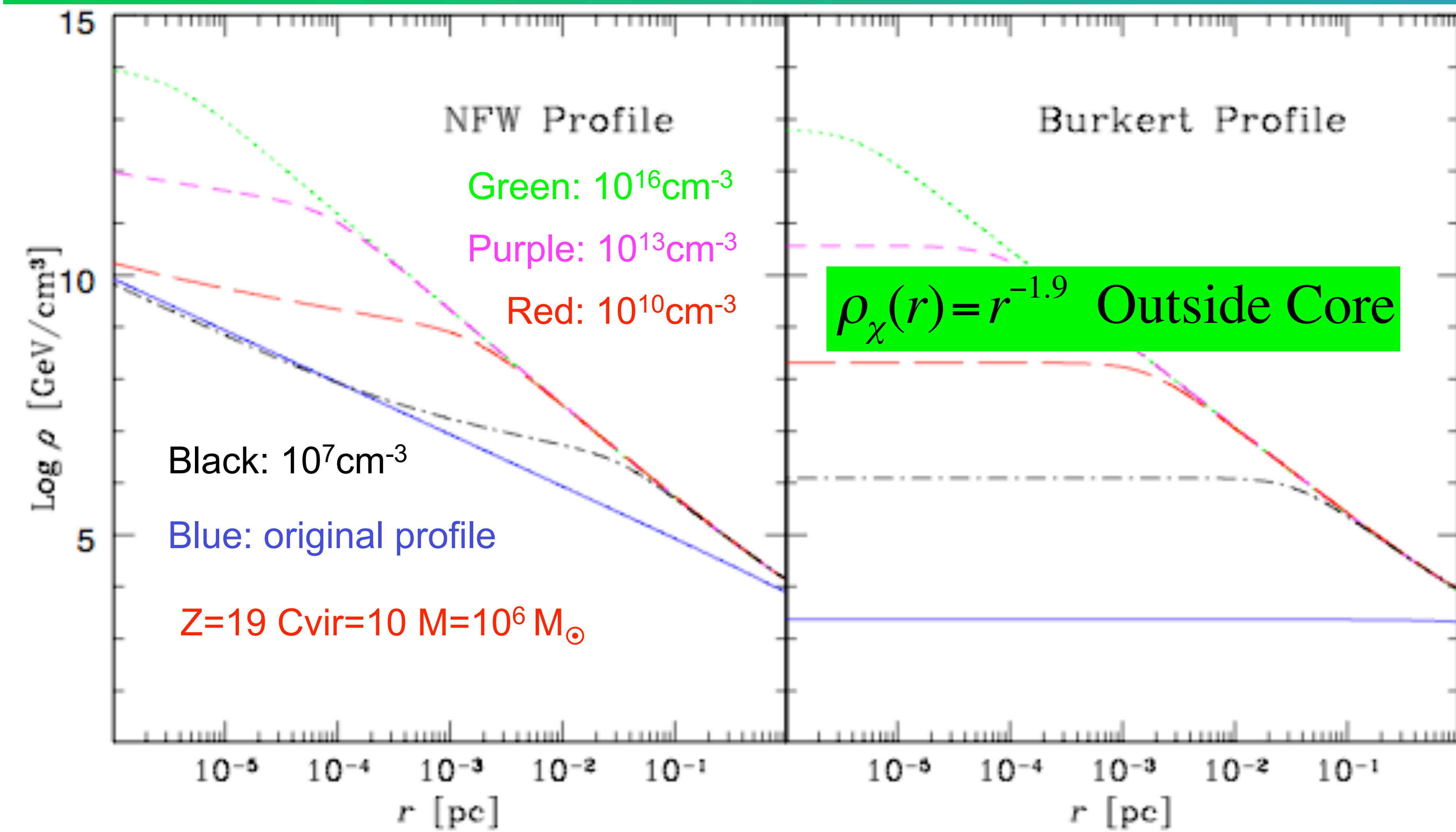
$$\rho_\chi(r) \sim r^{-1.9} \quad \text{Outside Core}$$

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

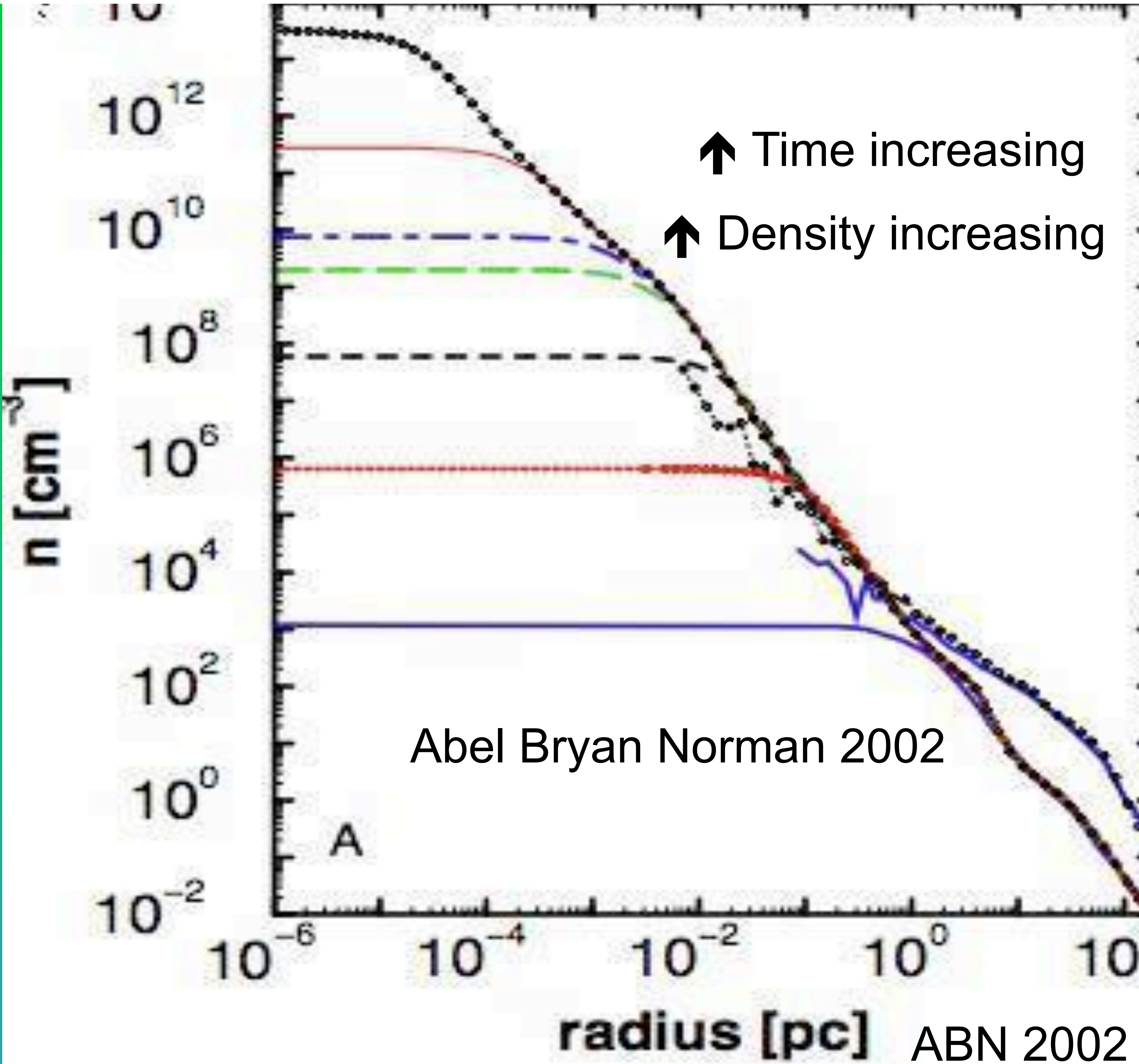
Simplistic: circular orbits only.

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

Dark Matter Profile

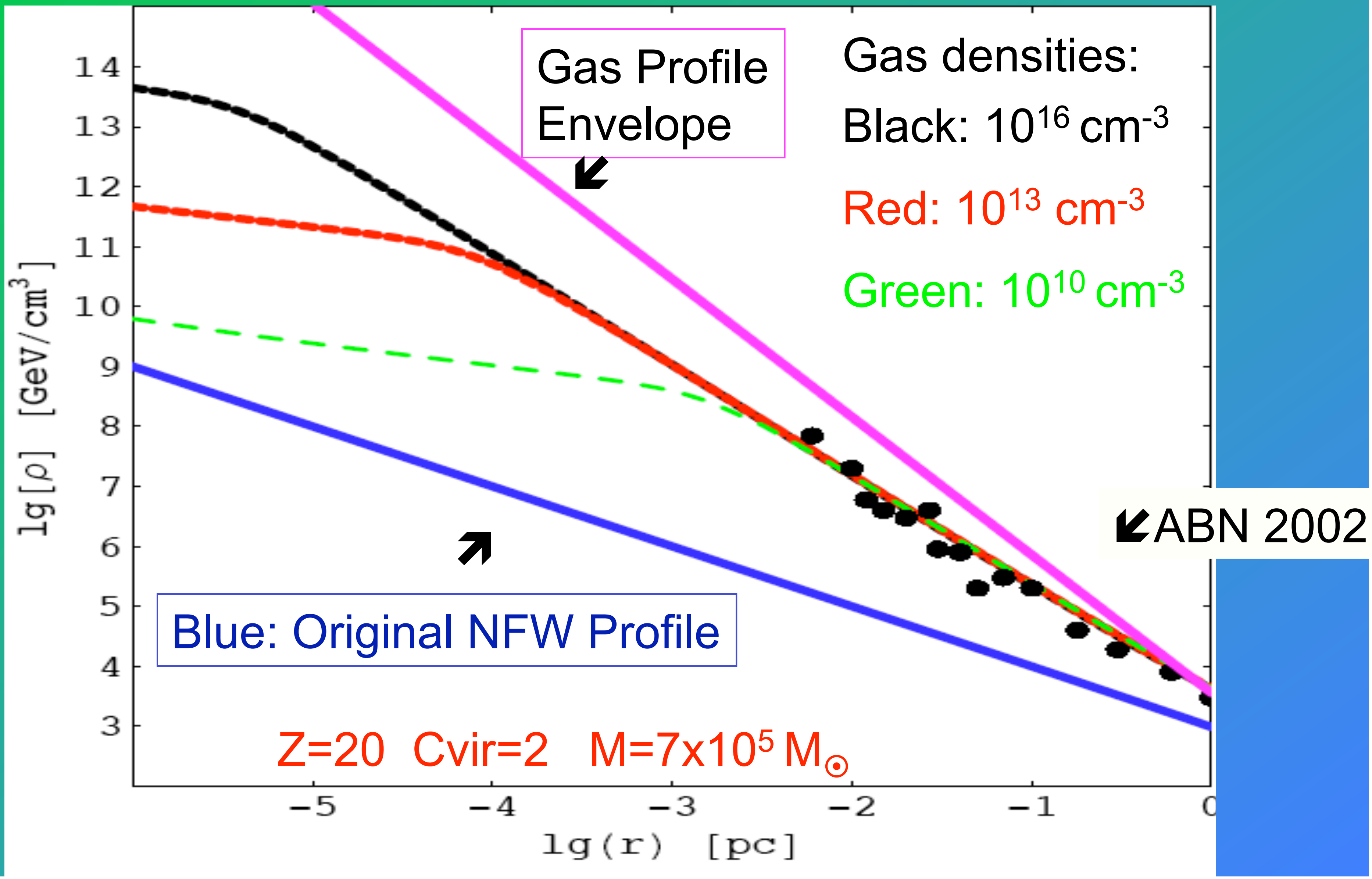


(Outer slope $r^{-1.9}$, profile matches Abel, Bryan, Norman '02)



Time increasing
Density increasing
Abel Bryan Norman 2002
A
n [cm^{-3}]
radius [pc]
ABN 2002

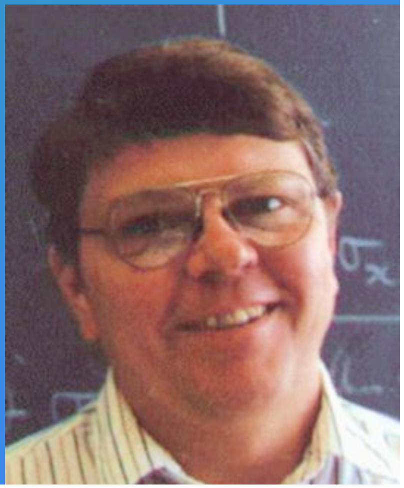
DM profile and Gas



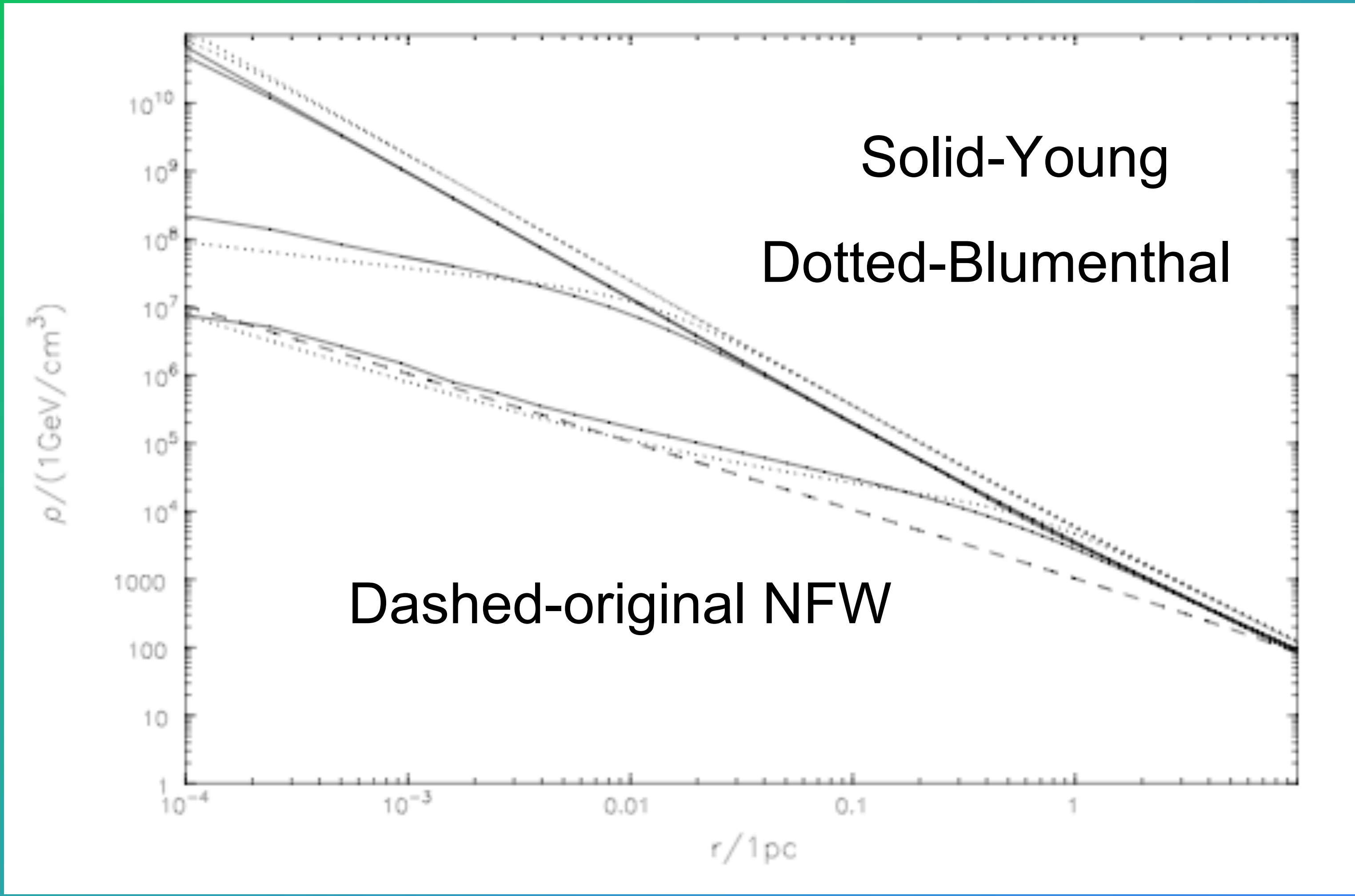
How accurate is Blumenthal method for DM density profile?

- 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
  - We have recently published a new paper.
  - If adiabaticity holds, we have found the exact solution

In collaboration with Jerry Sellwood



Within a factor of two



Further Testing of Adiabatic Contraction

See the work of Natarajan, O'Shea, and Tan (2008)

- looked at simulations and extrapolated the DM densities

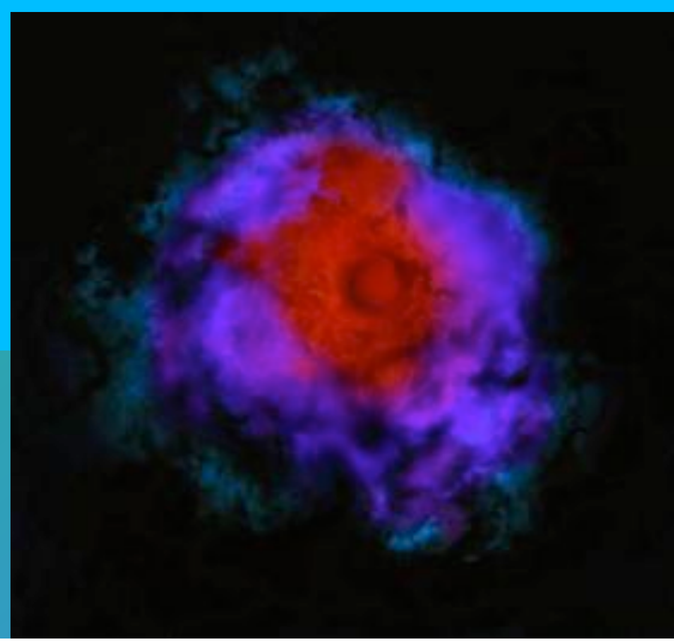
Also Iocco et al. 2008 and Sivertsson & Gondolo 2010

Find Same sort of Conclusion

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



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

Depending upon the densities.

Crucial Transition

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

$$m_\chi \approx 1\ \mathrm{GeV} \quad \rightarrow \quad n \approx 10^{9}/\mathrm{cm}^3$$

$$m_\chi \approx 100\ \mathrm{GeV} \quad \rightarrow \quad n \approx 10^{13}/\mathrm{cm}^3$$

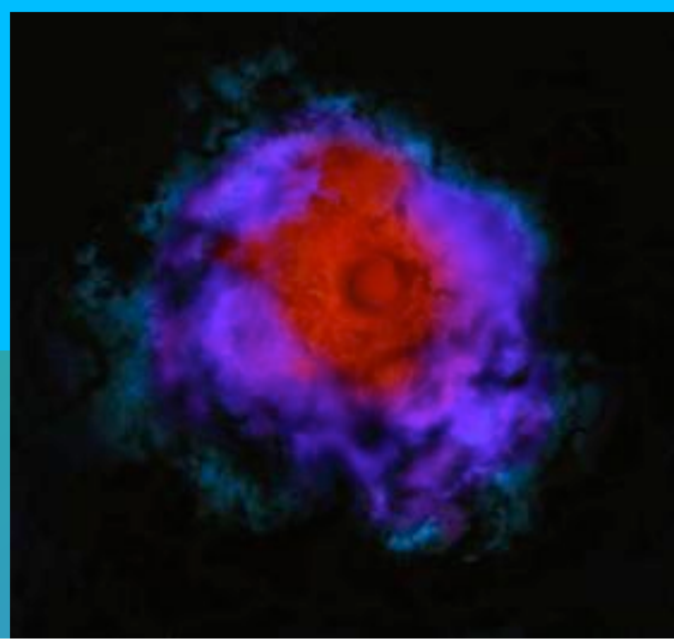
$$m_\chi \approx 10\ \mathrm{TeV} \quad \rightarrow \quad n \approx 10^{15-16}/\mathrm{cm}^3$$

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

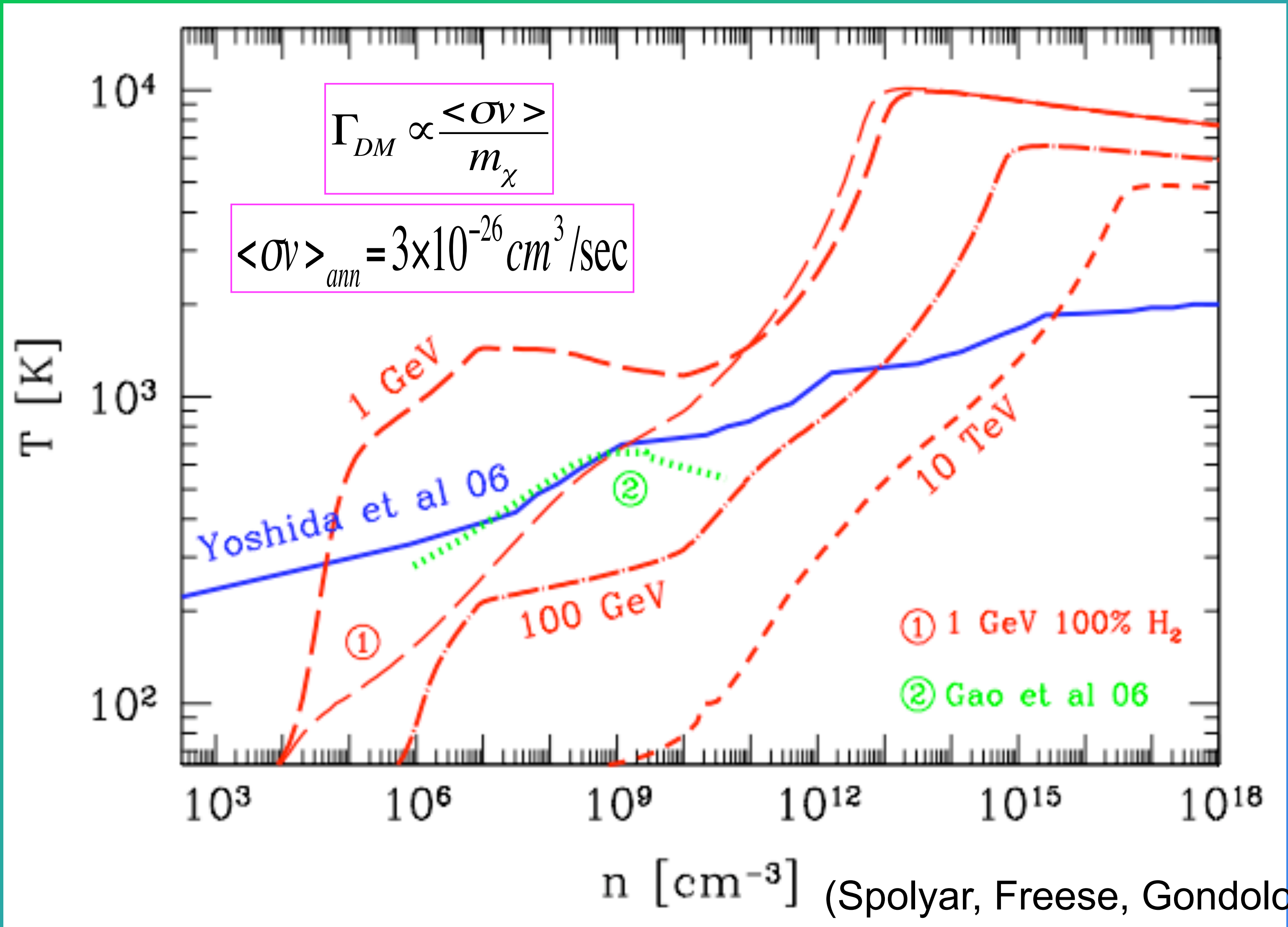
Three Conditions for Dark Stars (Paper 1)

- 1) OK! Sufficiently High Dark Matter Density
- 2) OK! Annihilation Products get stuck in star
- 3) DM Heating beats H_2 Cooling?

New Phase

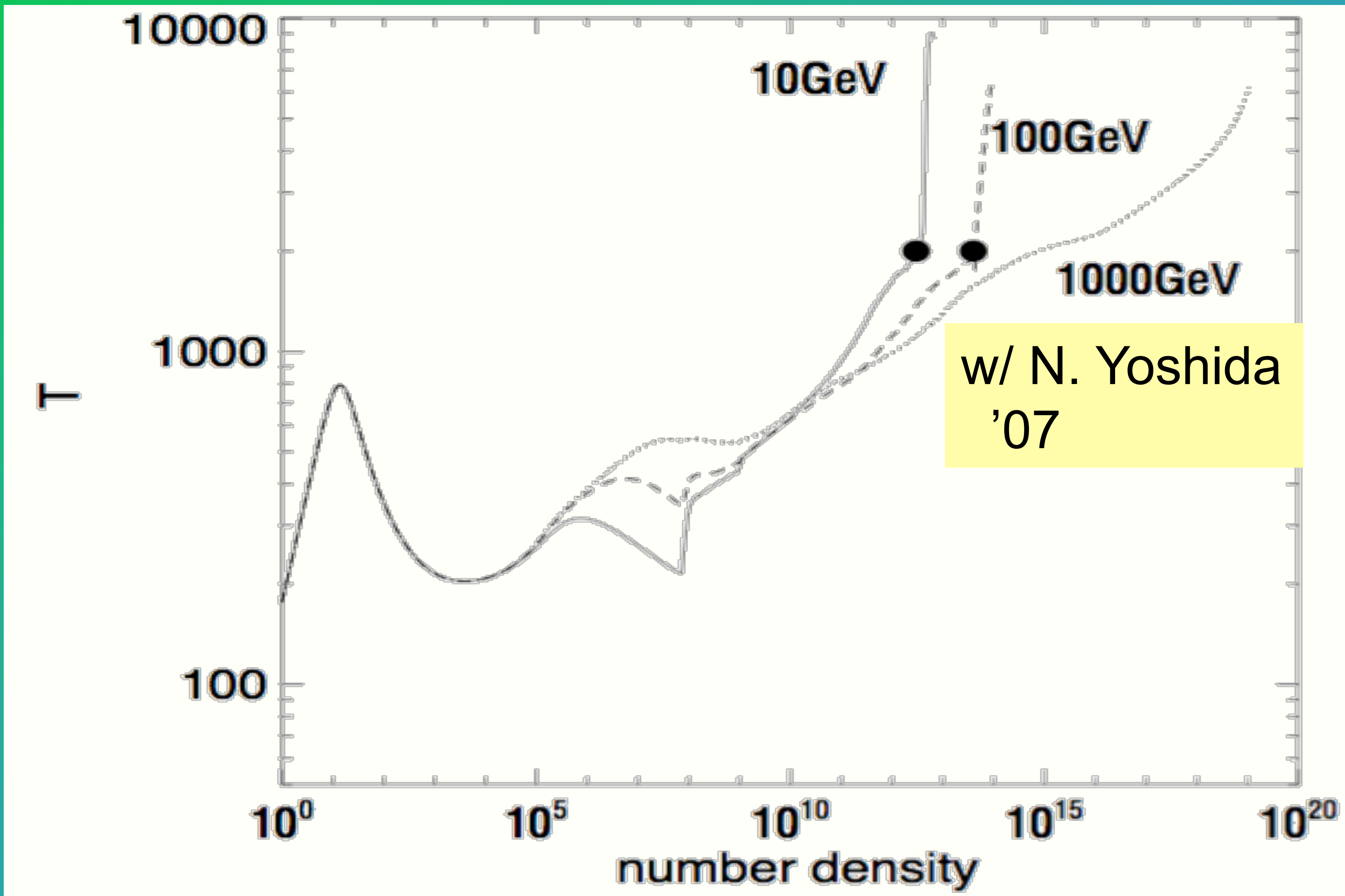


DM Heating dominates over cooling when the red lines cross the blue/green lines (standard evolutionary tracks from simulations). Then heating impedes further collapse.



(Spolyar, Freese, Gondolo April 2007)

New proto-Stellar Phase:
fueled by dark matter

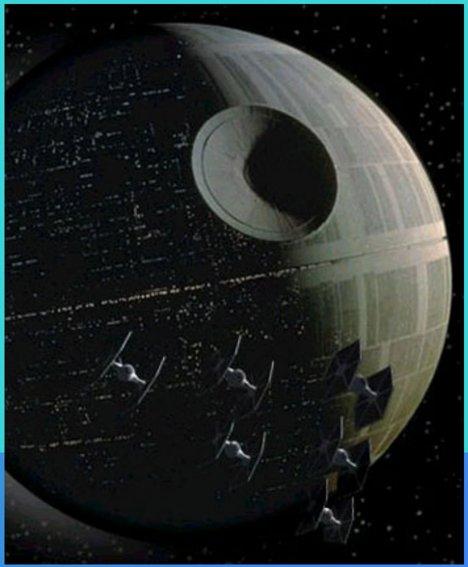


w/ N. Yoshida '07

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~$1000M_\odot$

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:

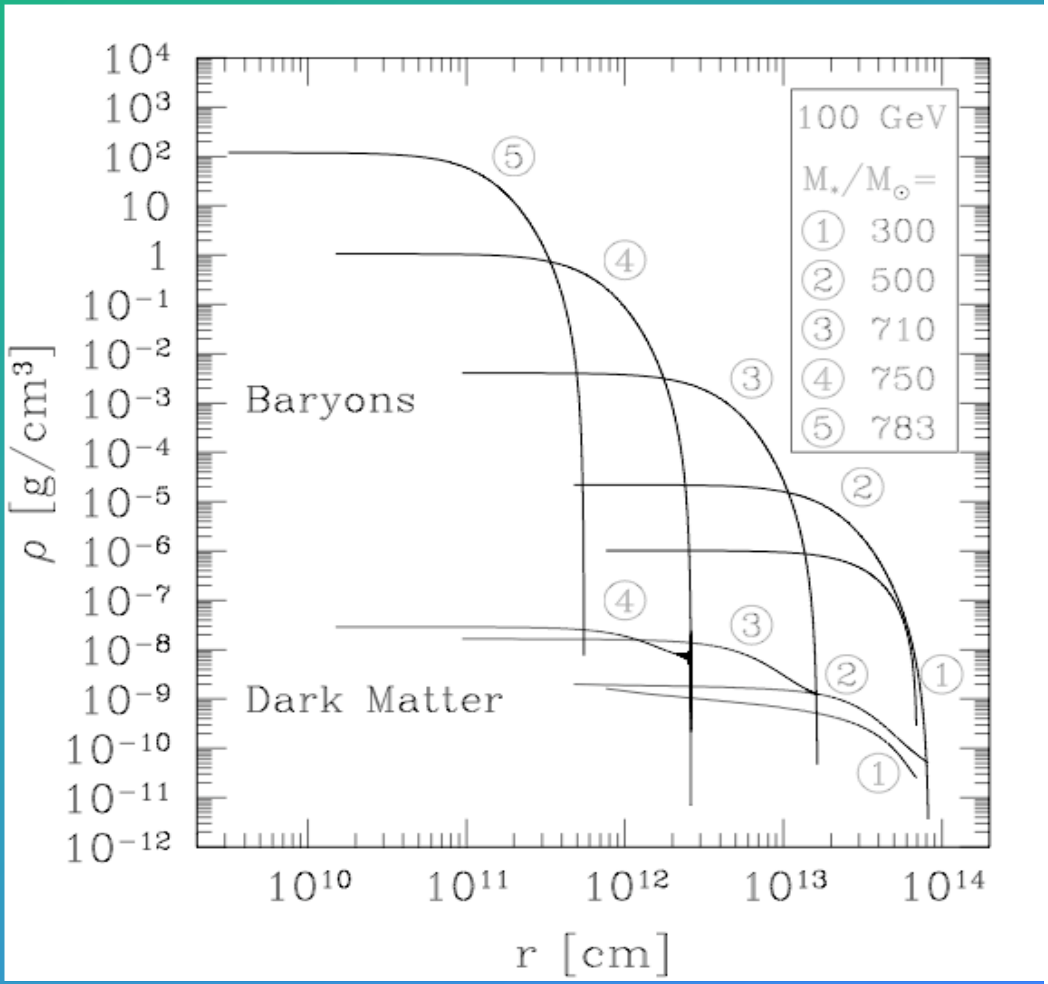
$$L_{DM} = L_*$$

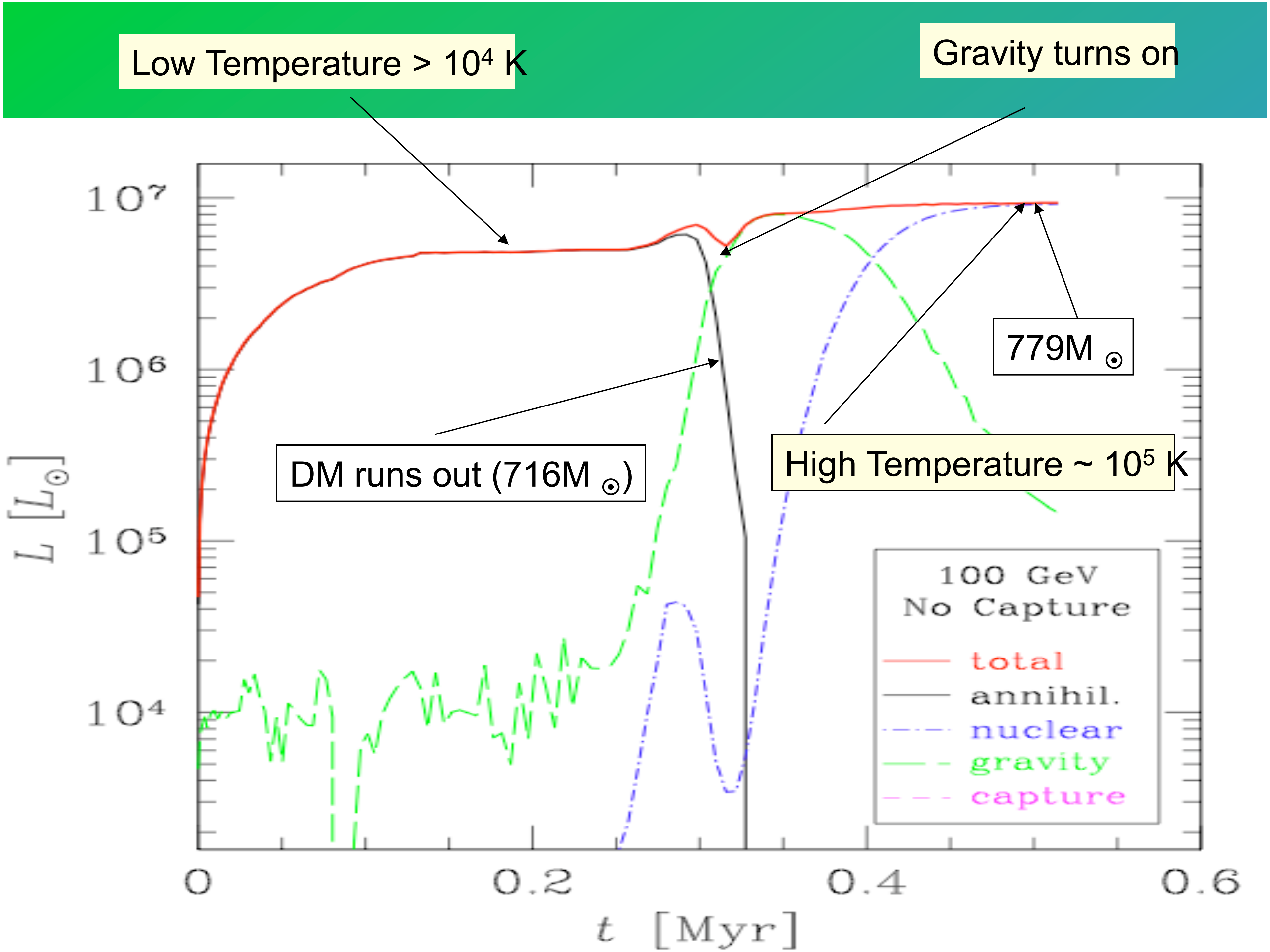
Building up the mass

- 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
- DM annihilation powered DS continues to 800 $M_\odot$.
- VERY LARGE FIRST STARS! Then, star contracts further, temperature increases, fusion will turn on, eventually make BH.

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 > 10⁴ K
Gravity turns on
779M ☉
DM runs out (716M ☉)
High Temperature ~ 10⁵ K
100 GeV
No Capture
total
annihil.
nuclear
gravity
capture
10⁷
10⁶
10⁵
10⁴
L [L☉]
0
0.2
0.4
0.6
t [Myr]

HERTZSPRUNG-RUSSELL DIAGRAM FOR DARK STARS

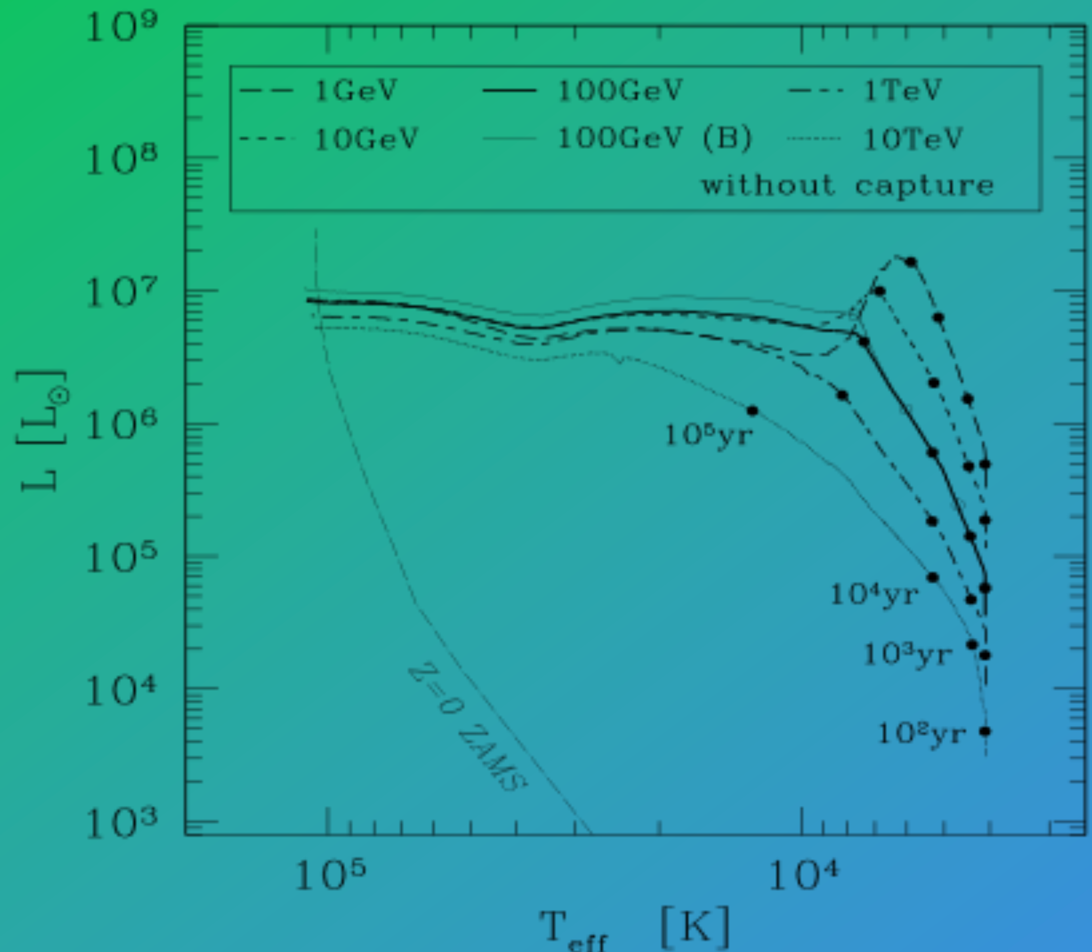


FIG. 1.— Evolution in the H-R diagram, for 5 different particle masses as indicated in the legend. The luminosity is given in solar units and the temperature is in Kelvin. The dots indicate a series of time points, which are the same for all cases. The open dots distinguish the 100 GeV (B) case from 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.

We require the DS to be in hydrostatic equilbrium,

$$\frac{dP}{dr} = -\rho \frac{GM_r}{r^2} \tag{4}$$

where $\frac{dM_r}{dr} = 4\pi r^2 \rho(r)$, $\rho(r)$ is the total density (gas plus DM) at radius r, and M_r is the enclosed mass within radius r. We use an equation of state for the gas with a mixture of ideal gas and radiation:

$$P(r) = \frac{\rho k_B T(r)}{m_u \bar{m}} + \frac{1}{3} a T(r)^4 = P_g + P_{rad} \tag{5}$$

and

$$E(r) = \frac{3 k_B T(r)}{2 m_u \bar{m}} + \frac{a T(r)^4}{\rho(r)} \tag{6}$$

DS Basic Picture (Circular Orbits Only and No Capture)

- We find that DS are:
  - Massive ~1000 $M_{\odot}$
  - Large-a few a.u.
  - Luminous ~$10^7 M_{\odot}$
  - Cool: 10,000 K vs. 100,000 K plus
    - Will not reionize the universe.
  - Long lived: ~10^6 years.
  - With Capture or nonCircular orbits, could be very different.

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 (this we knew a long time but finally ran models)

SUPERMASSIVE dark stars (SMDS) from extended adiabatic contraction

- Previously we thought dark matter runs out in a million years with 800 M_{sun} Pop III 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_{sun}, last much longer, and reach 10^9-10^{11} L_{sun}.
- Maybe visible in JWST! Leads to (as yet unexplained) big black Holes.

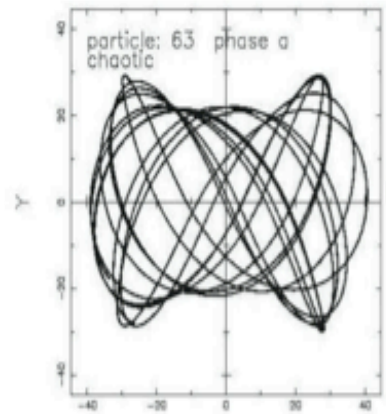
Is there enough DM?

Spherical Halos

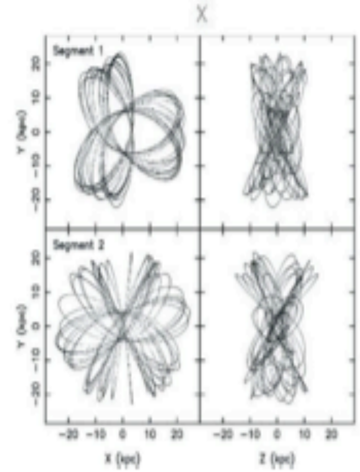
- DM orbits are planar rosettes (Binney & Tremaine '08).
- The Dark Star creates a loss cone that cannot be refilled.

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

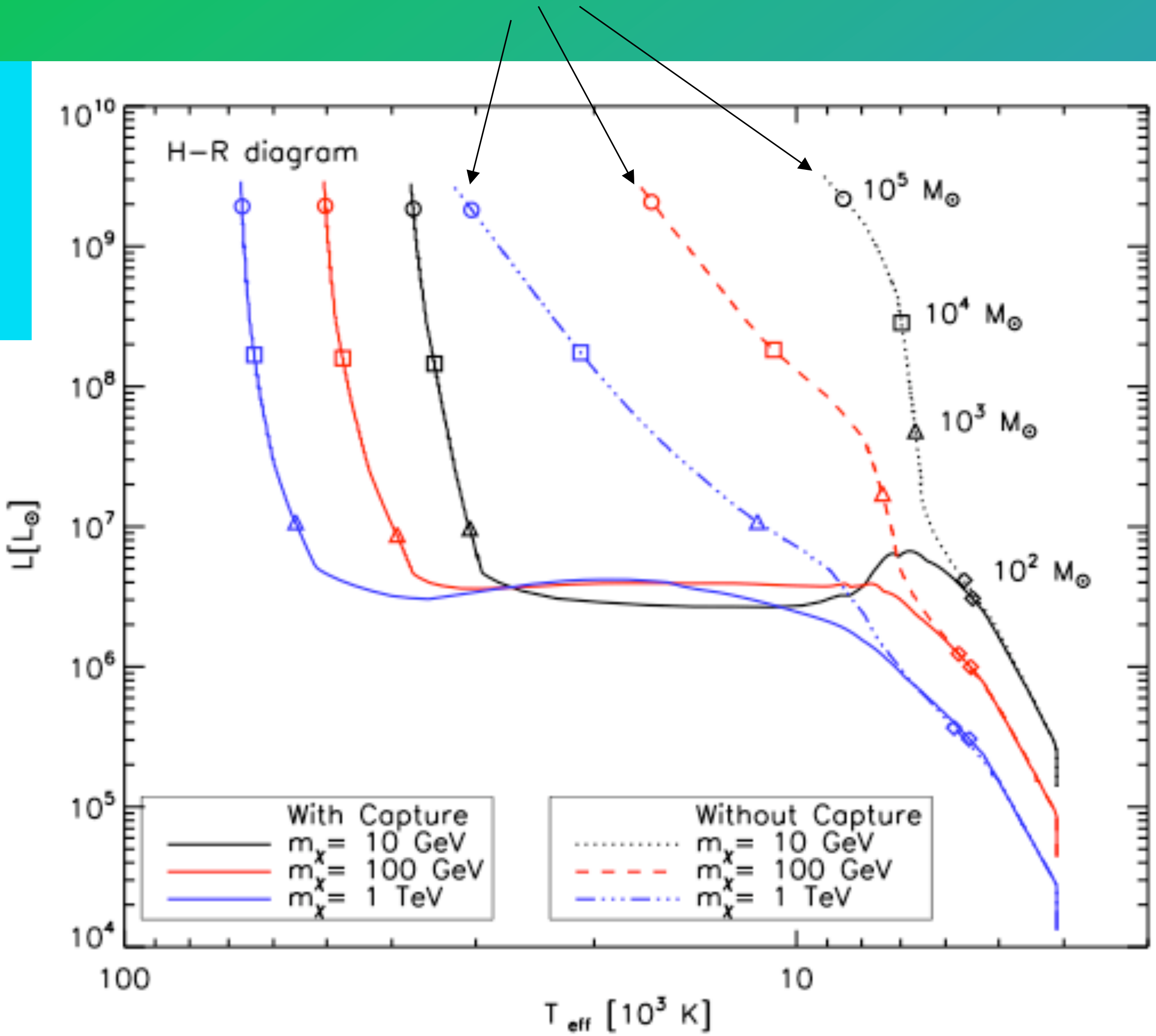


Chaotic Orbit

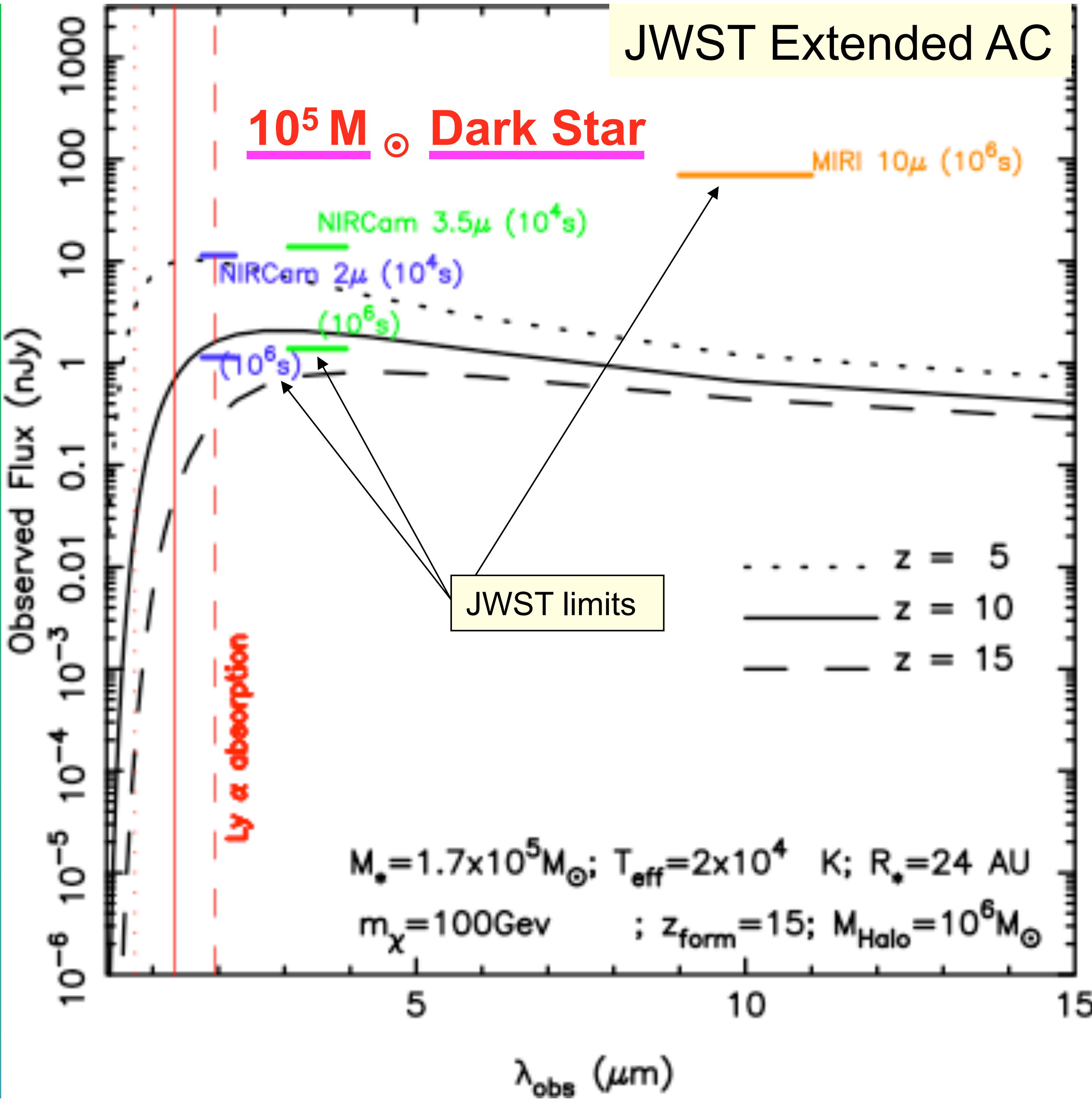
A particle that comes through the center of the DS can be annihilated. However, that particle was not on an orbit that would pass through the center again anyway. The next particle will come in from a different orbit.

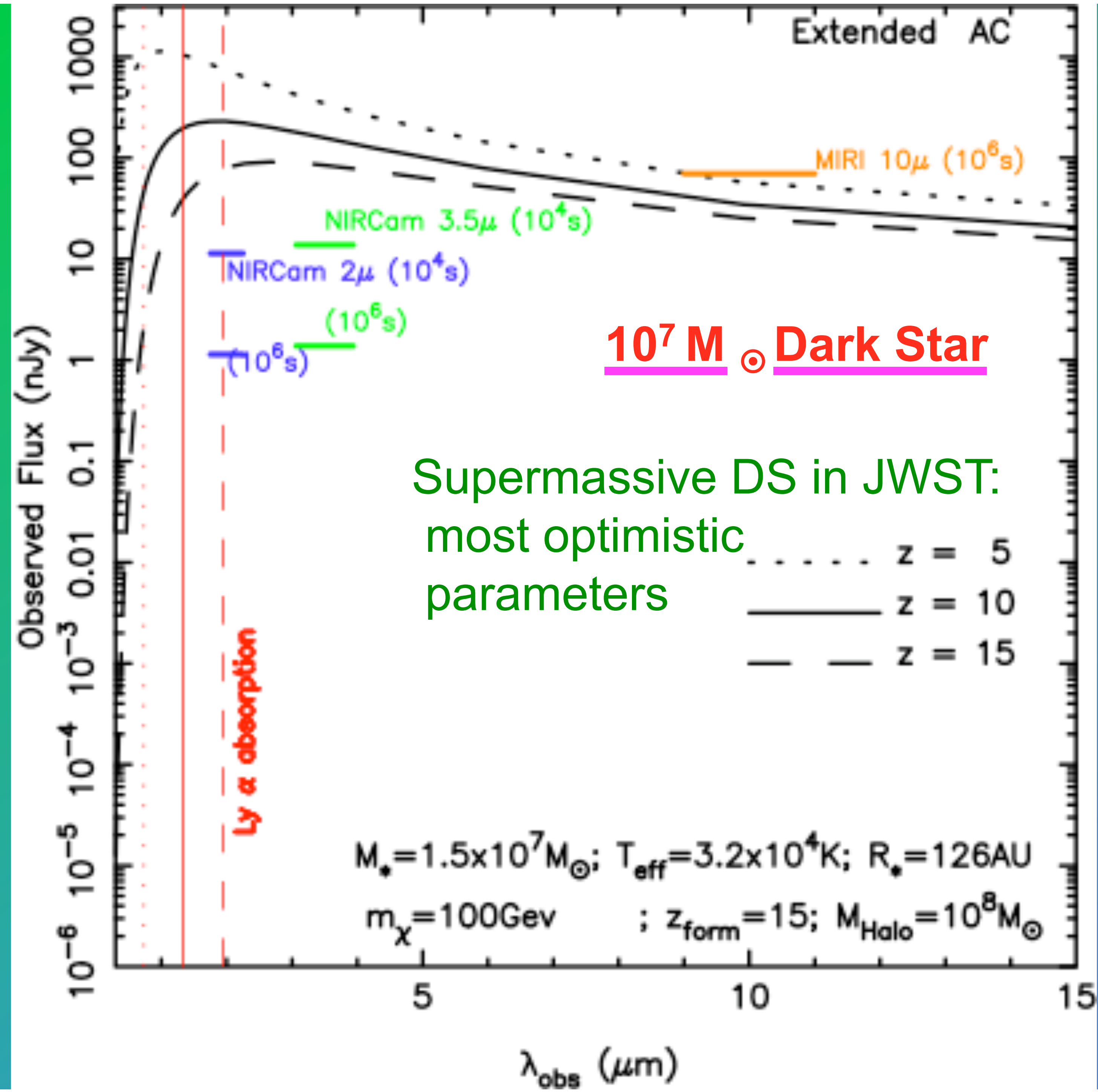
Super Massive DS due to extended adiabatic contraction since reservoir has been replenished due to orbital structure

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



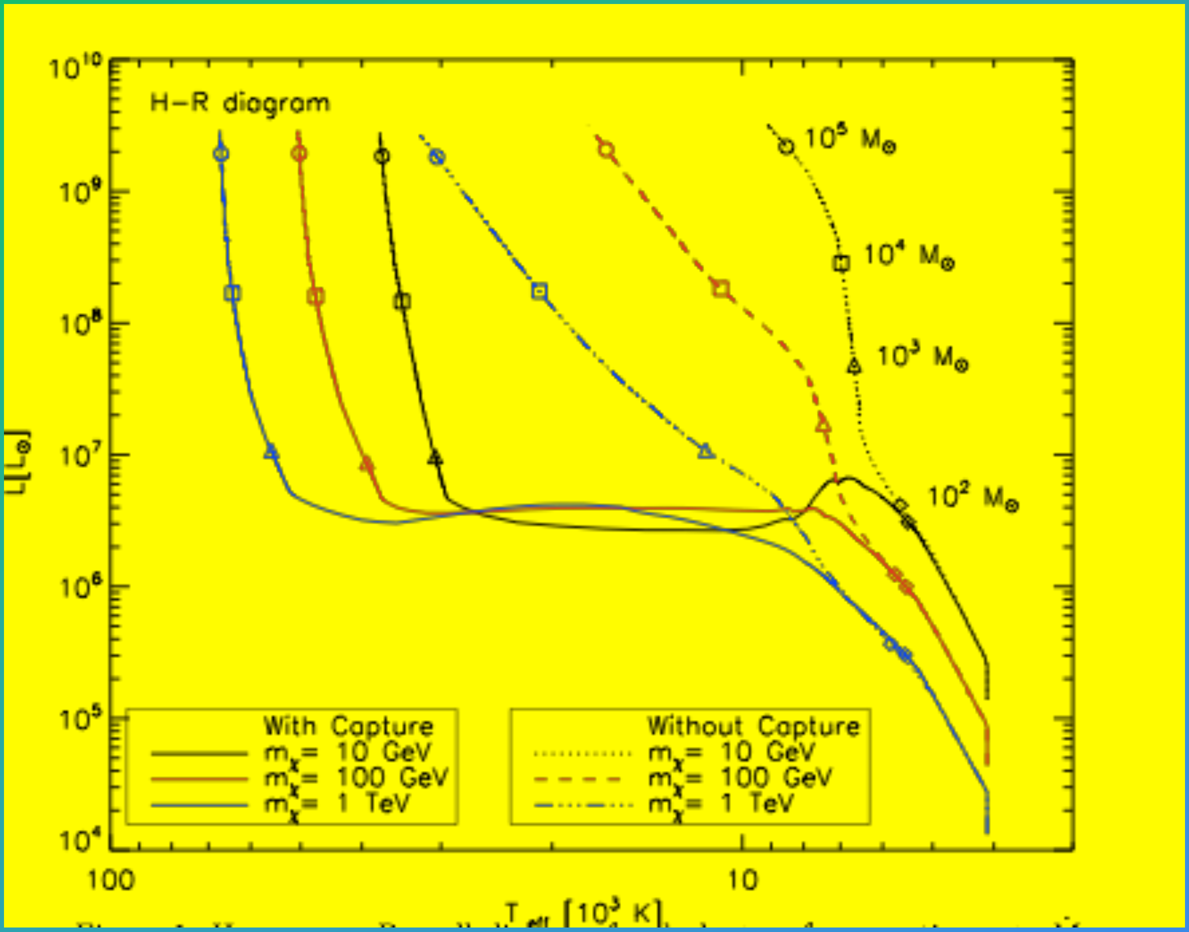
JWST Extended AC





Extended AC
MIRI 10μ (10^6s)
NIRCam 3.5μ (10^4s)
NIRCam 2μ (10^4s)
(10^6s)
(10^6s)
10^7 M ☉ Dark Star
Supermassive DS in JWST:
most optimistic
parameters
z = 5
z = 10
z = 15
Ly α absorption
M*=1.5x10^7M☉; Teff=3.2x10^4K; R*=126AU
mχ=100Gev ; zform=15; MHalo=10^8M☉
Observed Flux (nJy)
λobs (μm)

H-R diagram for SMDS



Additional possible source of DM fuel: capture

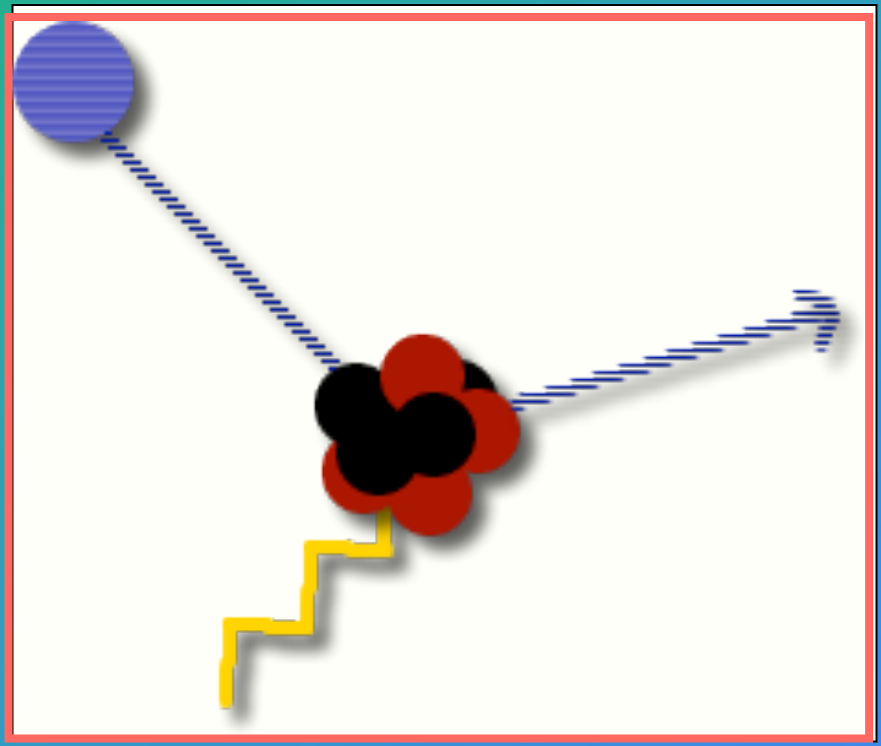
- Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured. (This it the origin of the indirect detection effect in the Earth and Sun).
- Two uncertainties:

  (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.



Capture: More DM

$$\frac{dC}{dV}(r) = \left(\frac{6}{\pi}\right)^{1/2} n(r) n_\chi(r) (\sigma_c \bar{v}) \frac{v(r)^2}{\bar{v}^2}$$

- n_χ (number density of DM) cm^{-3}
- n (number density of H) cm^{-3}
- V(r) escape velocity at a point r
- $\bar{v}$ velocity of the DM
- σ_c scattering cross section

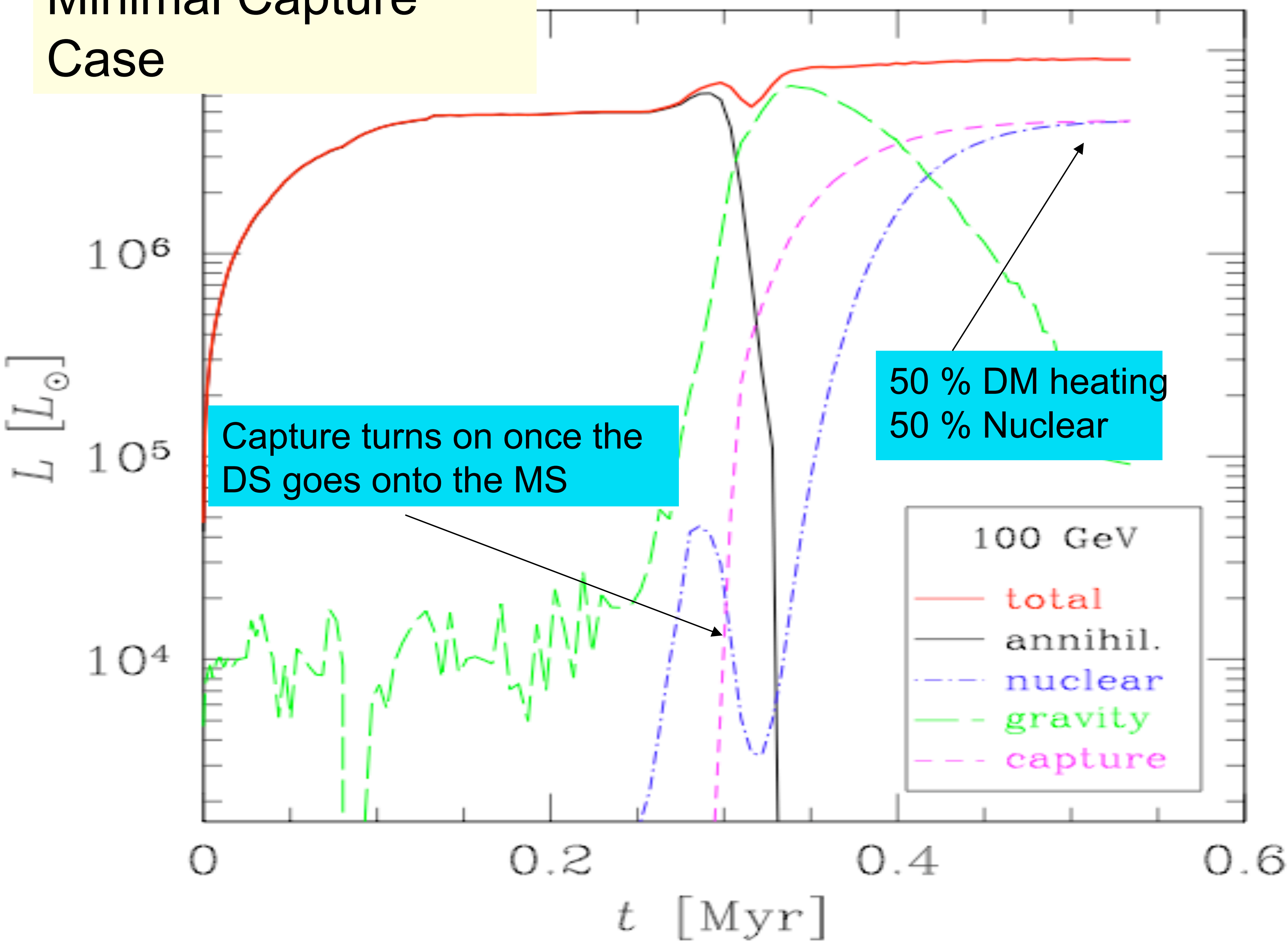
Press, Spergel 85 & Gould 88

Our Minimal Capture Case

DM mass 100GeV,

- standard annihilation cross section,
- Artificially designed to have DM power equal to fusion power inside the star
- Again reach about 800 solar masses
- spin dependant cross section $10^{-39}cm^2$
  - Bound < $10^{-38}cm^2$
- Average Background DM density of 10^{10} GeV/cm^3
  - Adiabatic contraction ~10^{14} GeV/cm^3

Minimal Capture Case



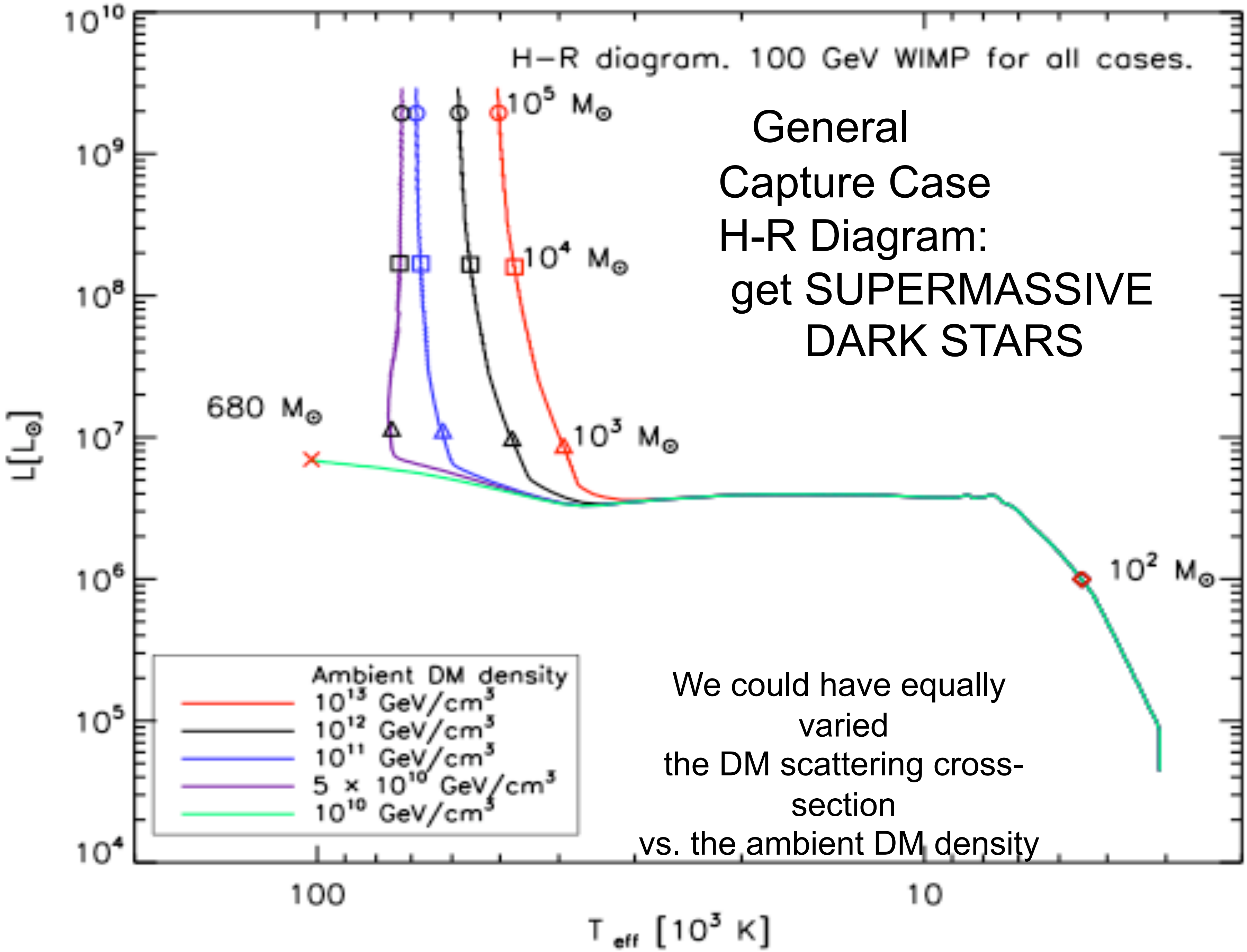
SuperMassive Dark Star w Capture

- In general one power source will dominate
  - Previously artificially matched DM heating with fusion
- If DM heating Dominates:
  - DM densities sufficiently high or scattering cross sections sufficiently large then:
    - Star cool (50,000K)
    - Very massive ($10^5 M_\odot$)
    - Very Luminous ($10^9 L_\odot$)
  - **Other related work growing very large dark stars:**
    - **Umeda, Yoshida, Nomoto, Tsuruta, Sasaki, and Ohkubo (2009)**
    - **Start with fusion already in star (not primordial DS)**
    - **Consider only capture**
  - GR Instability (not an issue: large radius in GM/R)
  - Avoids fusion and re-ionization?
    - Until DM reservoir depleted or disrupted
    - Maximum time Scale
      (10-100Myrs) due to mergers

– Other related work growing very large dark stars:

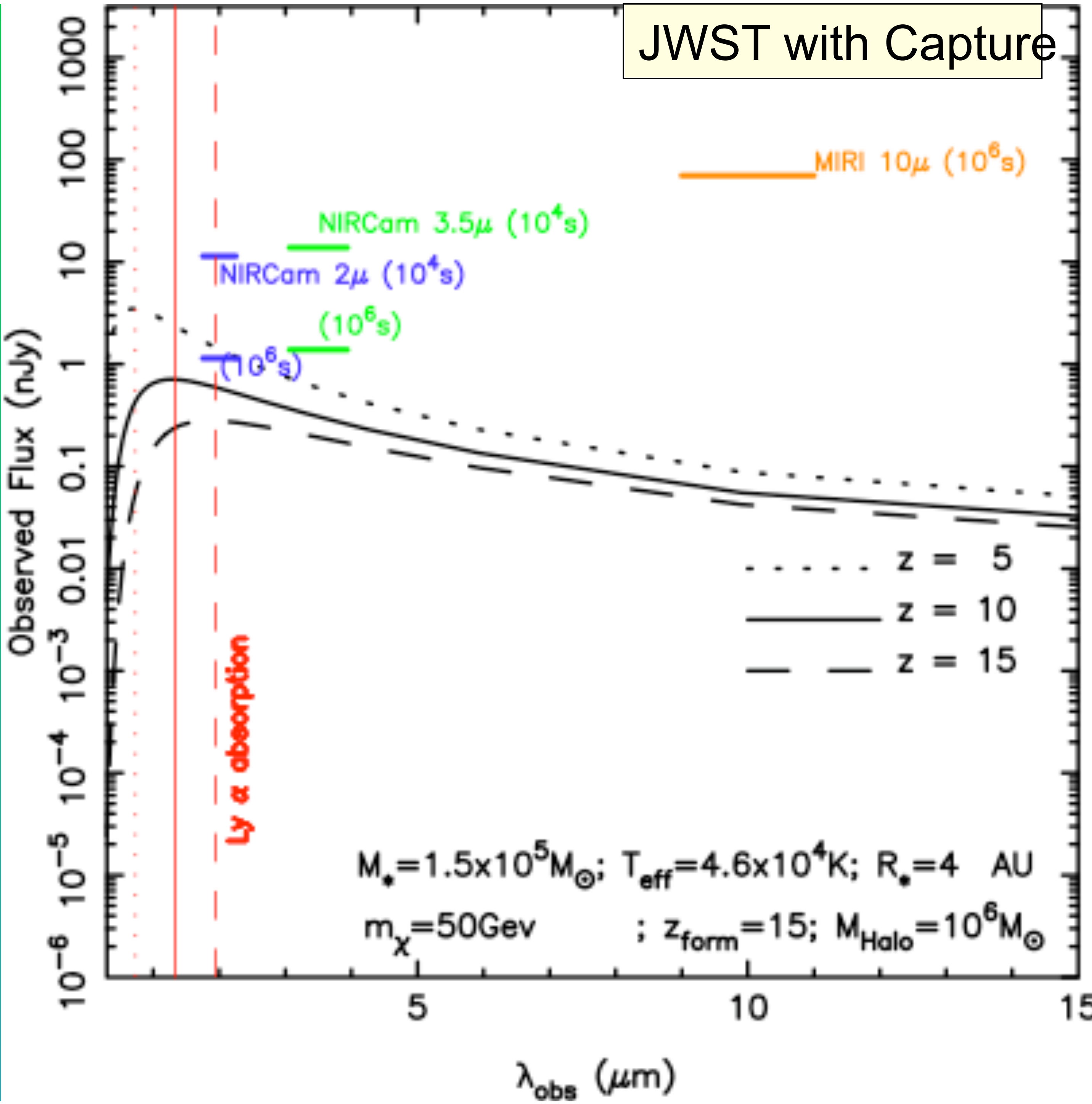
- Umeda, Yoshida, Nomoto, Tsuruta, Sasaki, and Ohkubo (2009)
- Start with fusion already in star (vs. primordial DS)
- Consider capture

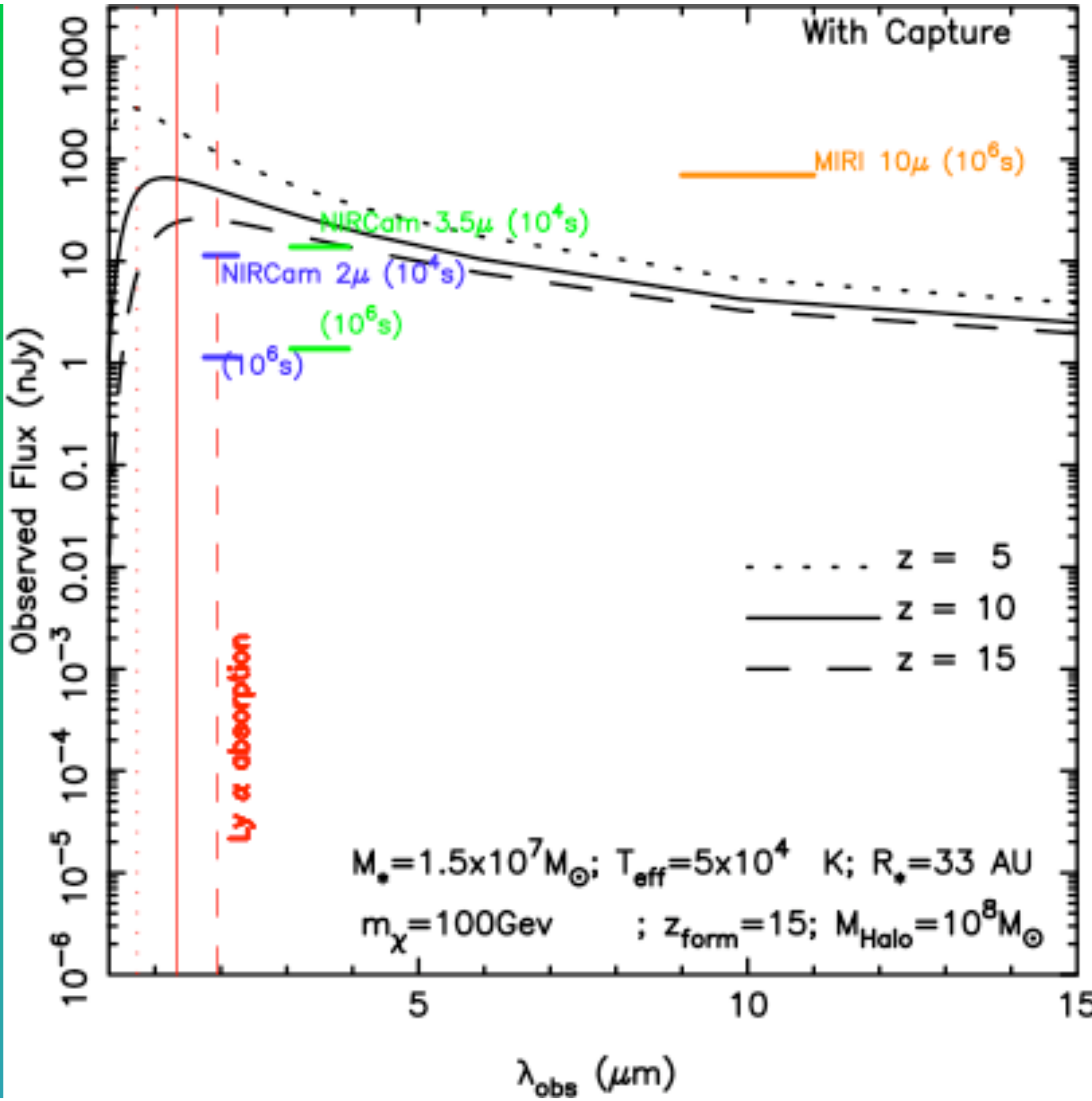
General Capture Case H-R Diagram: get SUPERMASSIVE DARK STARS



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

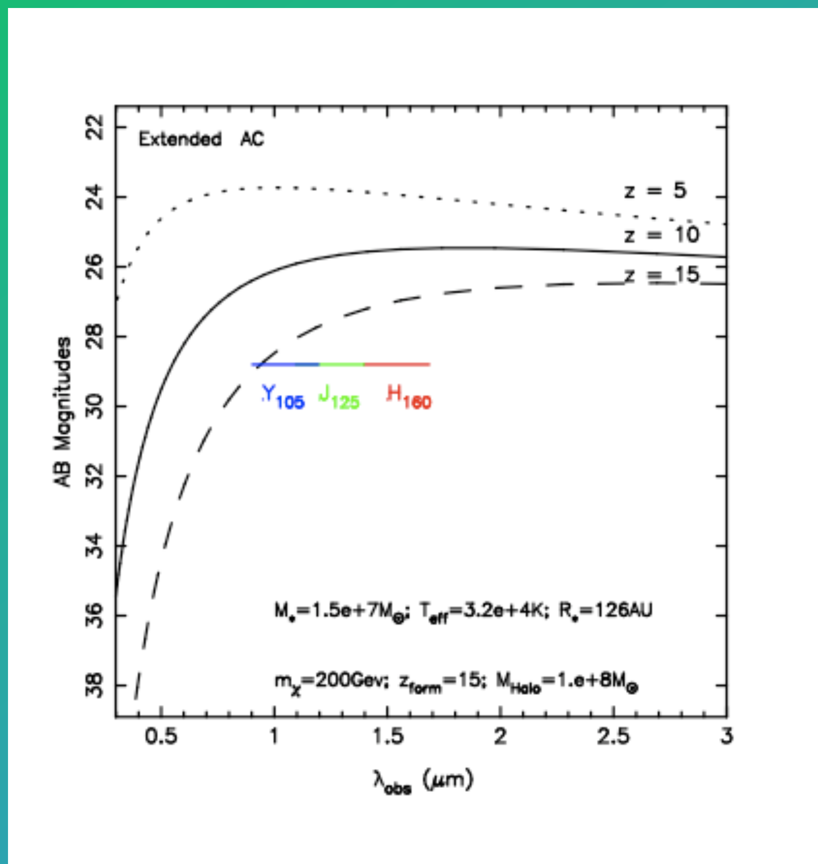
JWST with Capture





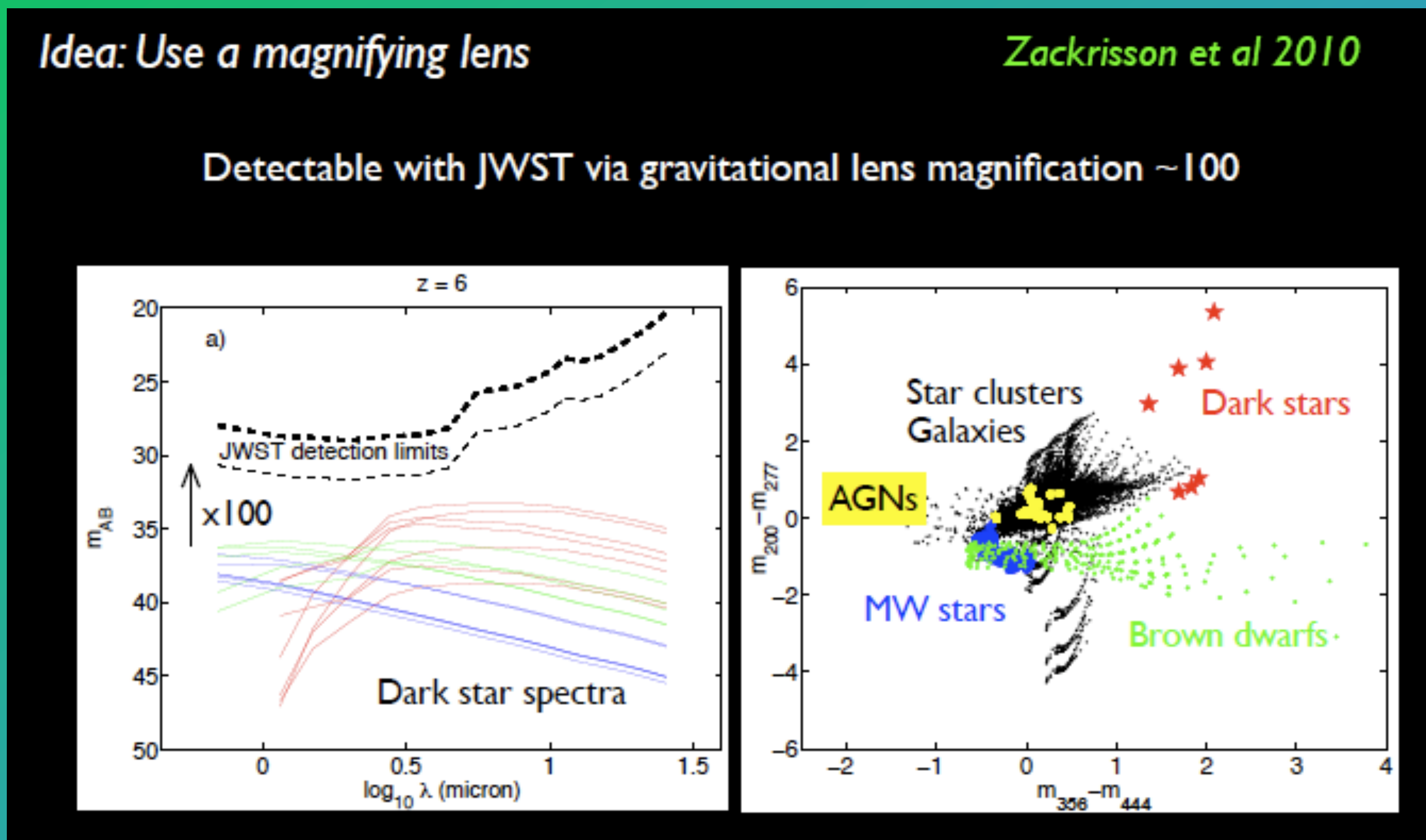
With Capture
MIRI 10μ (10^6s)
NIRCam 3.5μ (10^4s)
NIRCam 2μ (10^4s)
(10^6s)
(10^6s)
Ly α absorption
z = 5
z = 10
z = 15
M*=1.5x10^7M⊙; Teff=5x10^4 K; R*=33 AU
mχ=100Gev ; zform=15; MHalo=10^8M⊙
Observed Flux (nJy)
λobs (μm)

Could SMDS already be in HST WFC3 data?



Three z=10 objects could be dark stars or galaxies!

Enhance signal via lensing



Can even see 1000 solar mass dark stars

Lifetime of Dark Star

- SCENARIO A: The DM initially inside the star is eaten up in about a million years.
- SCENARIO B: The DS lives as long as it captures more Dark Matter fuel: millions to billions of years if further DM is captured by the star. See also work of Fabio Iocco and Gianfranco Bertone.
- 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 so that a reasonable guess for the lifetime would be tens to hundreds of millions of years tops…
- But you never know! They might exist today.
- Once the DM runs out, switches to fusion.

What happens next? BIG BLACK HOLES

- Star reaches T=10^7K, fusion sets in.
- 800 solar mass 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
- (iii) excess extragalactic radio signal in ARCADE reported at AAS meeting by Kogut (1K at 1GHz), power law spectrum could come from synchrotron radiation from accretion onto early black holes (work with Pearl Sandick)

Elemental abundances

- These very heavy SMDS will not produce pair instability SN (whose predicted even/odd element ratios are testable)
- Heger and Woosley: w/out rotation collapse directly to BH
- Okhubo etal: w/ rotation SN s.t. half the mass ends up in BH

Additional work on Dark Stars:

SEE TALK OF FABIO IOCCO

- 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
- Study of effect on stellar evolution of electron annihilation products: Ripamonti, Iocco et al 09

Next step?

- Better simulation: stellar evolution models.
  - with Alex Heger and Chris Savage.

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

NEW TOPIC

If the dark matter is primordial black holes (10^17-10^20 gm):

- Impact on the first stars:
- They would be adiabatically contracted into the stars and then sink to the center by dynamical friction, creating a larger black hole which may swallow the whole star. End result: 10-1000 solar mass BH, which may serve as seeds for early big BH or for BH in galaxies.
- (Bambi, Spolyar, Dolgov, Freese, Volonteri astro-ph 0812.0585)

March 2010 Sky and Telescope