Dark Matter and the First Stars

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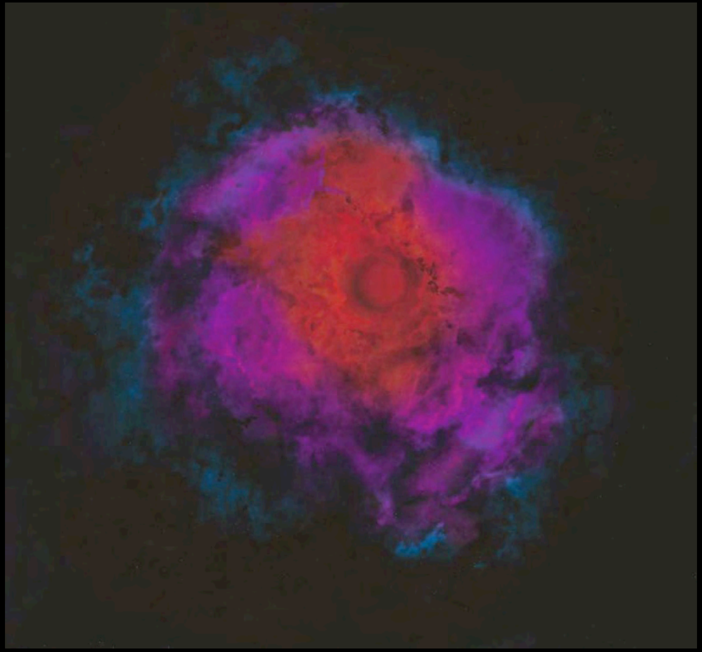
Based on:

Spolyar, Freese, Gondolo, arxiv:0705.0521, Phys. Rev. Lett. 100, 051101 (2008)
Freese, Gondolo, Sellwood, Spolyar, arxiv:0805.3540
Freese, Bodenheimer, Spolyar, Gondolo, arxiv:0806.0617

Results

The first stars to form in the universe may be powered by dark matter annihilation rather than nuclear fusion

They are *dark matter-powered stars* or for short



Dark Stars

Artist's impression of a dark star

Some implications

- Dark Stars modify the *reionization history of the universe*, and thus the expected signals in future 21 cm surveys
- Dark Stars change the production of heavy elements and the *chemical abundances of the oldest stars*
- Dark Stars may evolve into *intermediate-mass or supermassive black holes*, providing a mechanism for their early formation
- Dark Stars are a *new indirect detection method* to search for WIMPs

Collaborators

Pierre Salati
(Spiritual Leader)

Katherine Freese

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Jerry Sellwood

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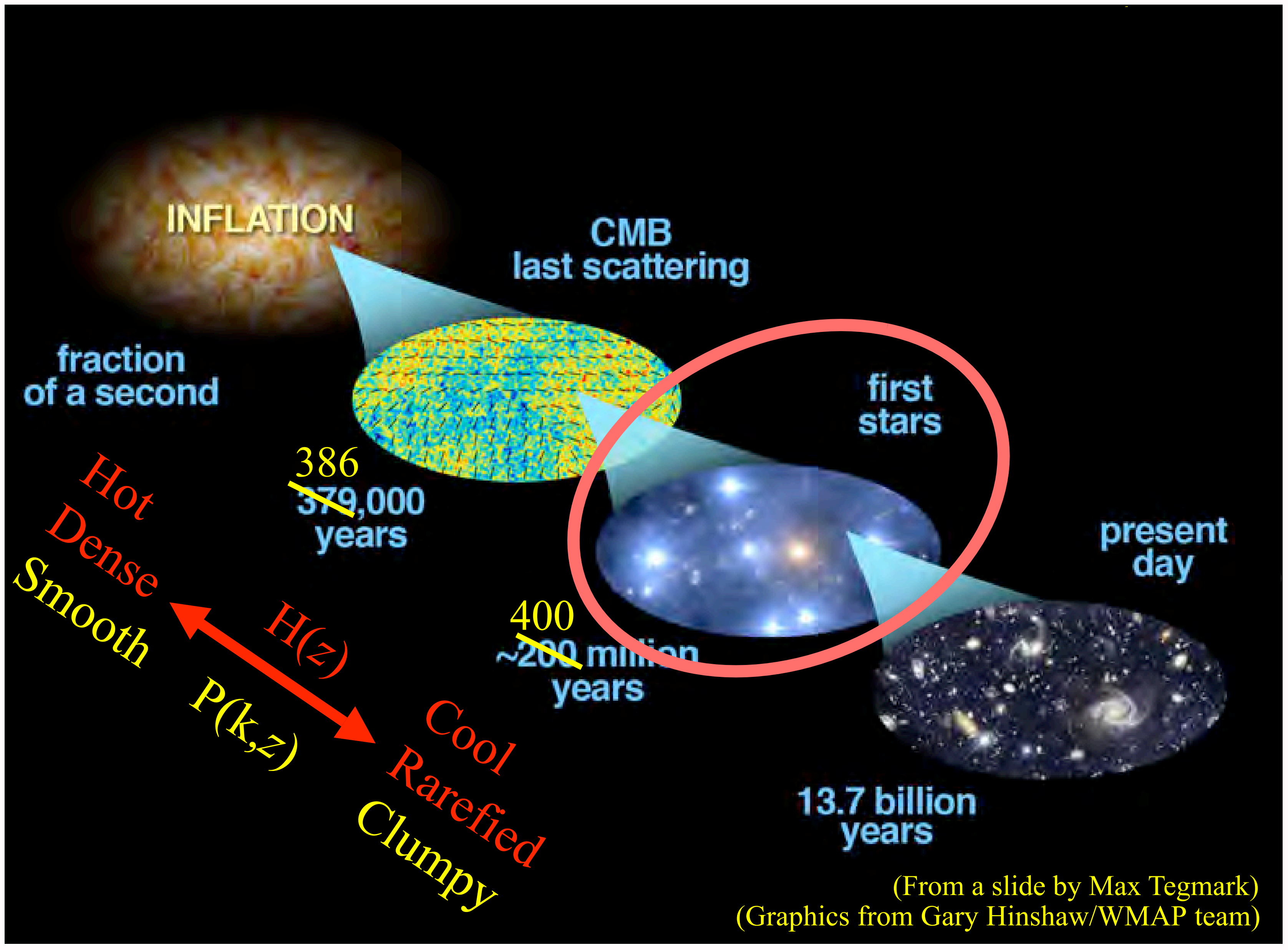
Naoki Yoshida

Anthony Aguirre

The First Stars (Population III stars)



(From a slide by Max Tegmark)
(Graphics from Gary Hinshaw/WMAP team)

The First Stars (Population III stars)

- Basic properties
  - made only of H/He
  - form inside DM halos of 10^5-10^6 $M_\odot$
  - at redshift z=10-50

- Important for
  - end of Dark Ages
  - reionize the universe
  - provide enriched gas for later stellar generations

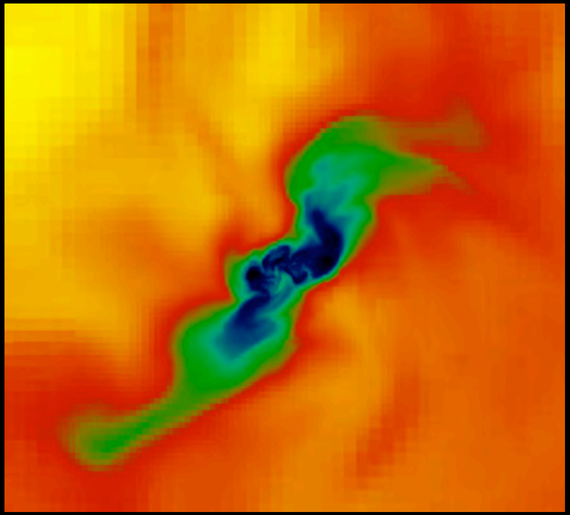
Dark Matter in Pop III Stars

- DM in protostellar halos alters the formation of Pop III stars
  - dark matter annihilation heats the collapsing gas cloud impeding its further collapse and halting the march toward the main sequence
- a new stellar phase results, powered by DM annihilation instead of nuclear fusion

Outline

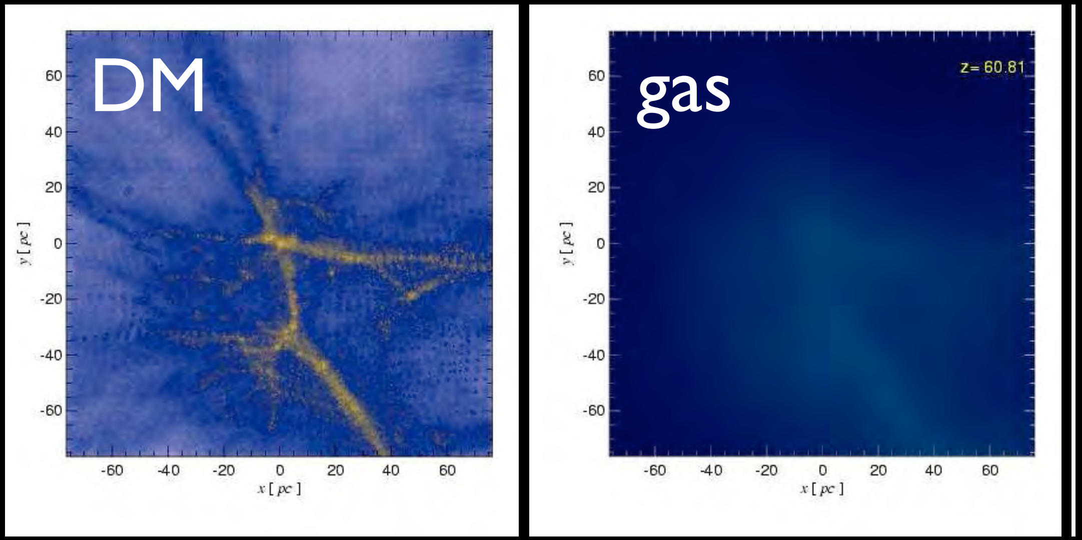
- The First Stars
- Dark Matter
  - The magnificent WIMP
  - Density Profile
- DM annihilation: a heat source that overwhelms cooling in Pop III star formation
- Outcome: a new stellar phase
- Observable consequences

First Stars: Standard Picture



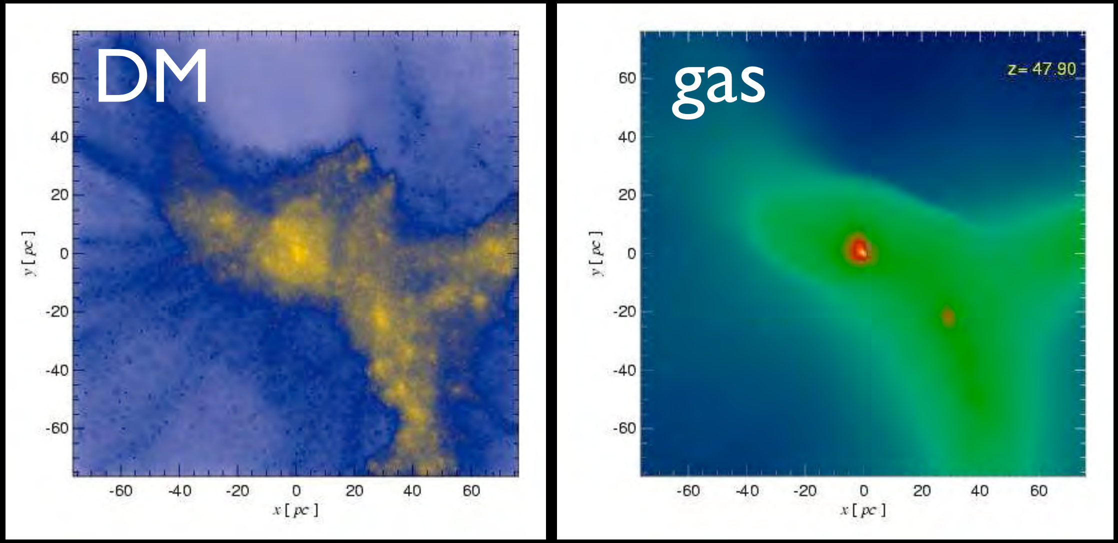
- Formation Basics
  - first luminous objects ever
  - made only of H/He
  - form inside DM halos of 10^5-10^6 $M_\odot$
  - at redshift z=10-50
  - baryons initially only 15%
  - formation is a gentle process
- Dominant cooling mechanism to allow collapse into star is H_2 cooling (Hollenbach & McKee 1979)

First Stars: Simulations



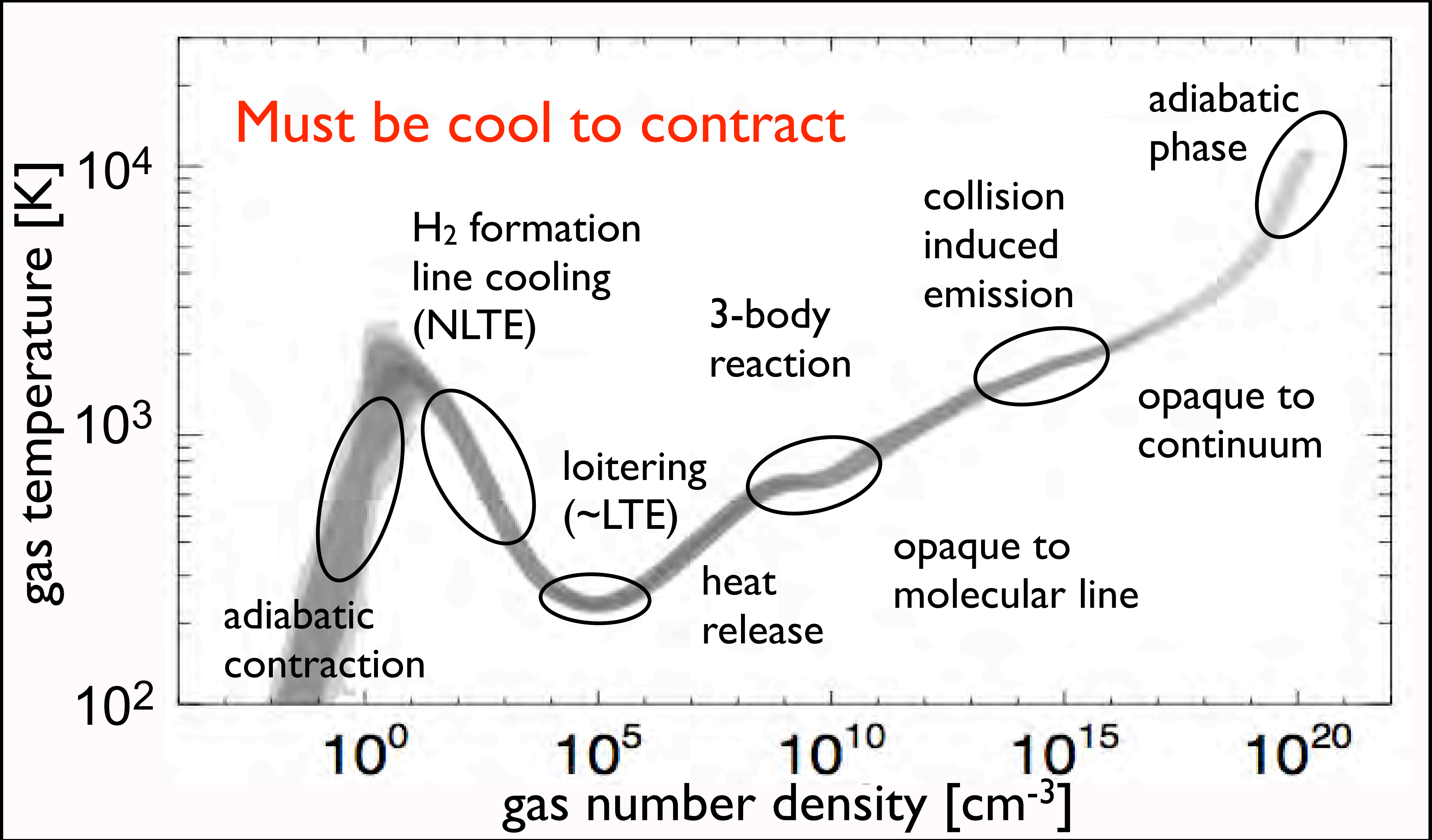
z=60

z=48



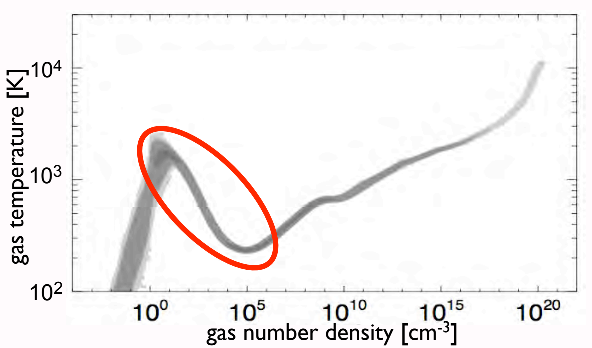
Gao, Abel, Frenk, Jenkins, Springel, Yoshida 2006

Thermal evolution of Pop III protostar



Courtesy of N.Yoshida

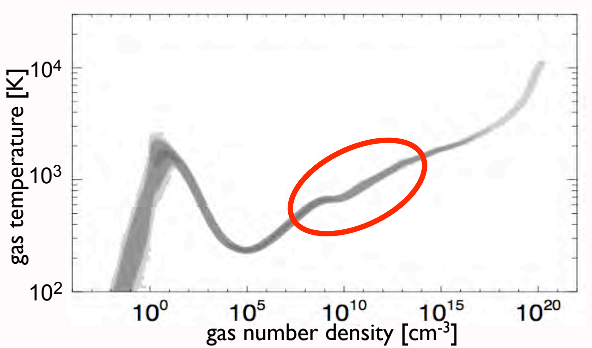
H_2 Cooling and Collapse



Gas number density	Cooling rate
$n \lesssim 10^4 \mathrm{cm}^{-3}$	$\Gamma_{\mathrm{cool}} \propto n^2$
$n \gtrsim 10^4 \mathrm{cm}^{-3}$	$\Gamma_{\mathrm{cool}} \propto n$

$$\text{Number fraction of } \frac{\text{Molecular H}}{\text{Atomic H}} \sim 10^{-3}$$

Cooling



3-body reaction

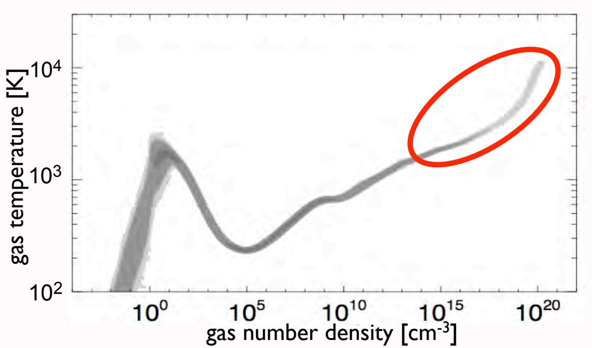
$$n \approx 10^8 \mathrm{cm}^{-3} \qquad H + H + H \rightarrow H_2 + H$$

becomes 100% molecular

$$n \approx 10^{10} \mathrm{cm}^{-3}$$

opacity → less efficient cooling

Cooling to Collapse



Other cooling processes

$10^{14}\mathrm{cm}^{-3}$	collision-induced emission
$10^{15}\mathrm{cm}^{-3}$	dissociation
$10^{18}\mathrm{cm}^{-3}$	atomic

Mini-core forms at $n \approx 10^{22}\mathrm{cm}^{-3}$ T ~ 20,000 K

Omukai, Nishi 1998

Mass scales

- Jeans mass

  $1000 M_\odot$ at $n \approx 10^4 \mathrm{cm}^{-3}$

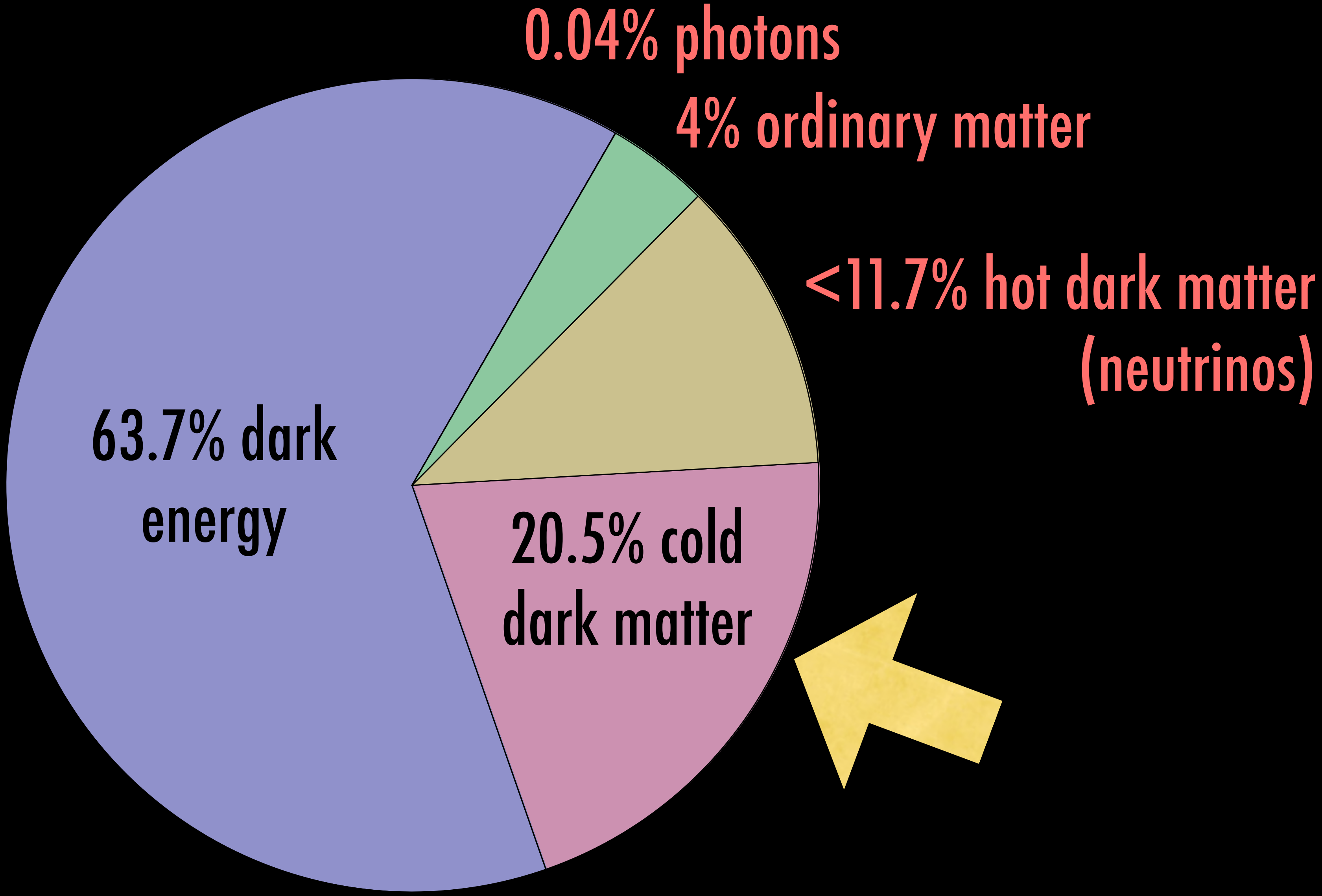
- Central core mass

  $\sim 10^{-3} M_\odot$ (requires cooling)

- Final stellar mass

  $\sim 100 M_\odot$ in standard scenario

Cold Dark Matter



Cold Dark Matter

WMAP+SN+BAO (Hinshaw et al. 2008)

Cosmological constant	$\Omega_\Lambda h^2 = 0.354 \pm 0.008$
Matter ($p \approx 0$)	$\Omega_\mathrm{m} h^2 = 0.1369 \pm 0.003$
Radiation ($p = \rho/3$)	$\Omega_\mathrm{r} h^2 = 2.47 \times 10^{-5}$

Matter $\left\{ \begin{array}{ll} \text{ordinary matter} & \Omega_b h^2 = 0.02265 \pm 0.00059 \\ \text{neutrinos} & \Omega_\nu h^2 < 0.065 \text{ (95\% C.L.)} \\ \text{cold dark matter} & \Omega_c h^2 = 0.1143 \pm 0.0034 \end{array} \right.$

(Units are 1.879×10^{-29} g/cm^3 = 18.79 yg/m^3)

The magnificent WIMP

Weakly Interacting Massive Particle

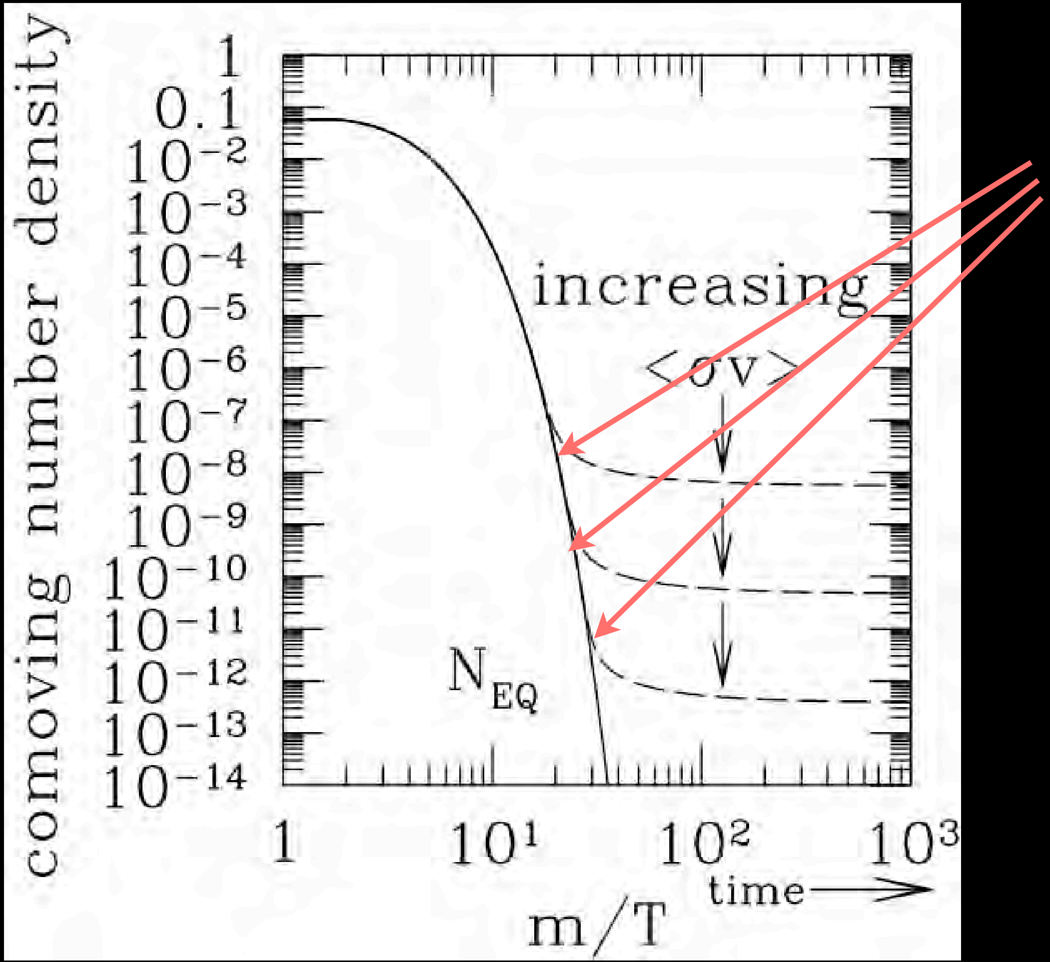
A WIMP in chemical equilibrium in the early universe naturally has the right density to be Cold Dark Matter

- At early times, WIMPs are produced in e^+e^-, $\mu^+\mu^-$, etc collisions in the hot primordial soup [*thermal production*].

$$\chi + \chi \leftrightarrow e^+ + e^-, \mu^+ + \mu^-, \mathrm{etc.}$$

- WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate [*freeze-out*].
- After freeze-out, the number of WIMPs per photon is constant.

The WIMP annihilation cross section determines its cosmological density



freeze-out

$$\Gamma_{\text{ann}} \equiv n\langle\sigma v\rangle \sim H$$

annihilation rate *expansion rate*

$$\Omega_\chi h^2 \simeq \frac{3\times10^{-27}\text{cm}^3/\text{s}}{\langle\sigma v\rangle_{\text{ann}}}$$

$$\Omega_\chi h^2 = \Omega_{\text{cdm}} h^2 \simeq 0.1143$$

for $\langle\sigma v\rangle_{\text{ann}} \simeq 3\times10^{-26}\text{cm}^3/\text{s}$

(weak interactions)

Lightest Supersymmetric Particle: Neutralino

- “Supersymmetry, supersymmetry, supersymmetry” (David Gross)
- Most popular WIMP dark matter candidate
- Mass 1GeV-10TeV
- They are their own antiparticles and thus annihilate with themselves
- The annihilation rate comes purely from particle physics and automatically gives the right answer for the relic density!

Current searches for WIMP Dark Matter

- Accelerators
- Direct detection
- Indirect detection (neutrinos)
  - Sun
  - Earth
- Indirect detection (gamma-rays, positrons, antiprotons)
  - Milky Way halo
  - External galaxies
  - Galactic Center

LHC

CDMS

XENON

Fermi (GLAST)

IceCube

PAMELA

The magnificent WIMP

- A WIMP in chemical equilibrium in the early universe naturally has the right density to be Cold Dark Matter
- The same annihilation cross section that determines the WIMP relic density fixes the rate of WIMP annihilation in indirect searches (but for kinematical factors)
- WIMP annihilation is important wherever the dark matter density is high:
  - Early universe (gives the right relic density)
  - Earth, Sun, Galaxy, the first stars!

WIMP Cold Dark Matter

Our canonical case:

$$\langle \sigma v \rangle_{\mathrm{ann}} = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s} \qquad m_\chi = 100\ \mathrm{GeV}$$

- We consider
  - a range of masses (1 GeV - 10 TeV)
  - a range of cross sections
- Our results apply to various WIMP candidates
  - neutralinos
  - Kaluza-Klein particles
  - sneutrinos

Three conditions for Dark Stars

Spolyar, Freese, Gondolo, April 2007, aka Paper I

Started working on this in 2006

(1) Sufficiently high dark matter density to get large annihilation rate

(2) Annihilation products get stuck in star

(3) Dark matter heating beats H_2 cooling

Leads to new stellar phase

Several papers on Dark Stars after our Paper I

- Freese, Spolyar, Aguirre 2008
- Iocco 2008
- Iocco, Bressan, Ripamonti, Schneider, Ferrara, Marigo 2008
- Yun, Iocco, Akiyama 2008
- Freese, Spolyar, Bodenheimer, Gondolo 2008
- Taoso, Bertone, Meynet, Ekstrom 2008
- Natarajan, Tan, O'Shea 2008
- Schleicher, Banerjee, Klessen 2008

Effects of dark matter annihilation on stellar evolution were considered as early as 1989 (Salati, Silk) and continue to be considered today (e.g., Moskalenko, Wai 2006; Fairbairn, Scott, Edsjo 2007). Here we focus on the effects on the first stars.

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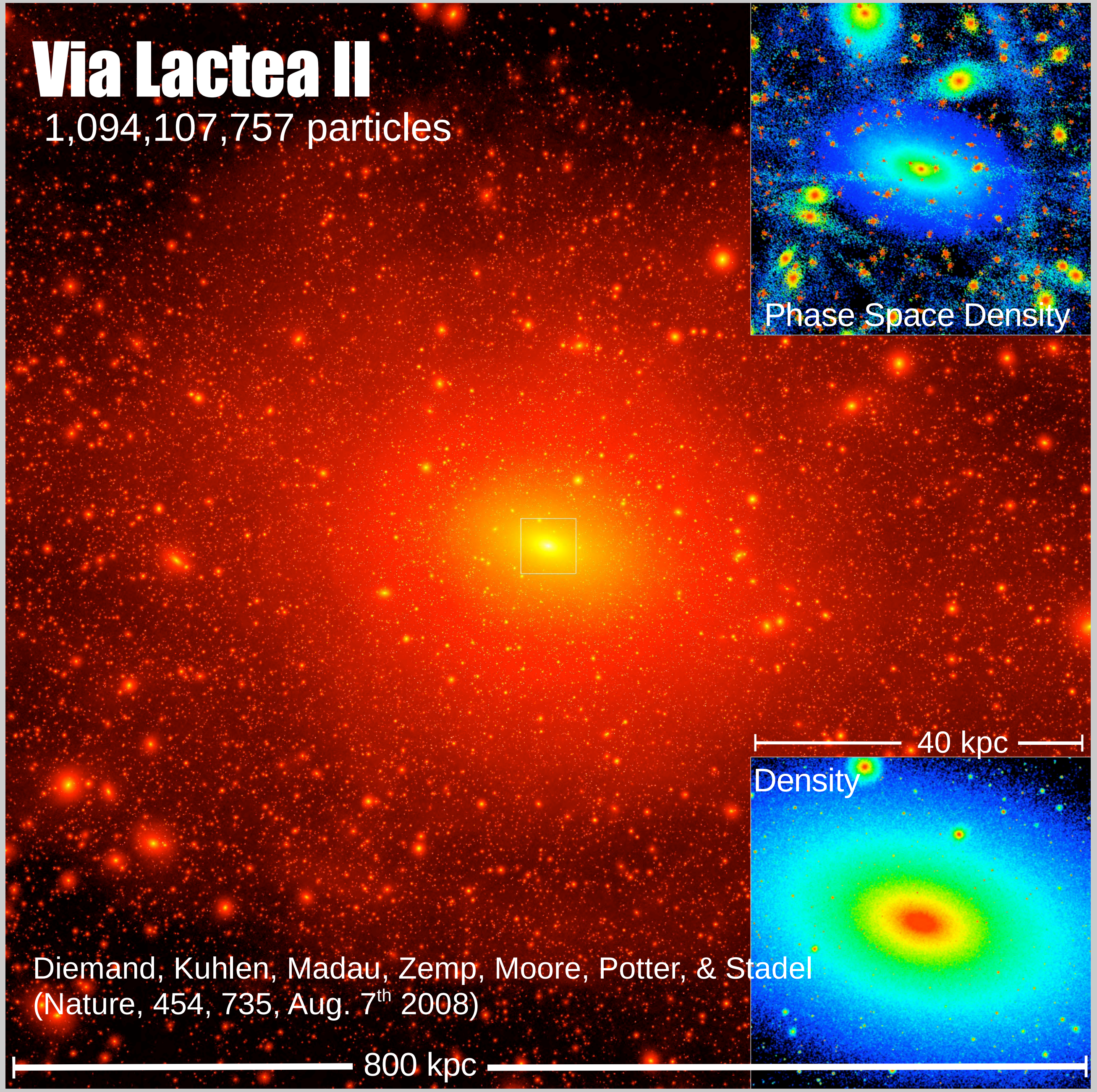
Two ways of concentrating dark matter

- *Gravitationally*: when object forms, dark matter is dragged in into deeper and deeper potential
  - adiabatic contraction of galactic halos due to baryons (e.g. Blumenthal et al 1986)
  - dark matter concentrations around black holes (Gondolo, Silk 1999)
  - dark matter contraction during formation of first stars (Spolyar, Freese, Gondolo 2007)

- *Through collisions*: dark matter scatters elastically off baryons and is eventually trapped
  - Sun and Earth, leading to indirect detection via neutrinos
  - stars embedded in dense dark matter regions ("dark matter burners" of Moskalenko & Wai 2006, Fairbairn, Scott, Edsjo 2007)
  - dark matter in late stages of first stars (Freese, Spolyar, Aguirre; Iocco; Iocco et al; Taoso et al 2008)

Dark matter halos



Diemand, Kuhlen, Madau, Zemp, Moore, Potter, & Stadel
(Nature, 454, 735, Aug. 7th 2008)

Dark Matter Density Profile

- Initially: NFW profile (Navarro, Frenk, White 1996) with 15% baryons

$$\rho(r) = \frac{\rho_0}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

$\rho_0 =$ "central density"

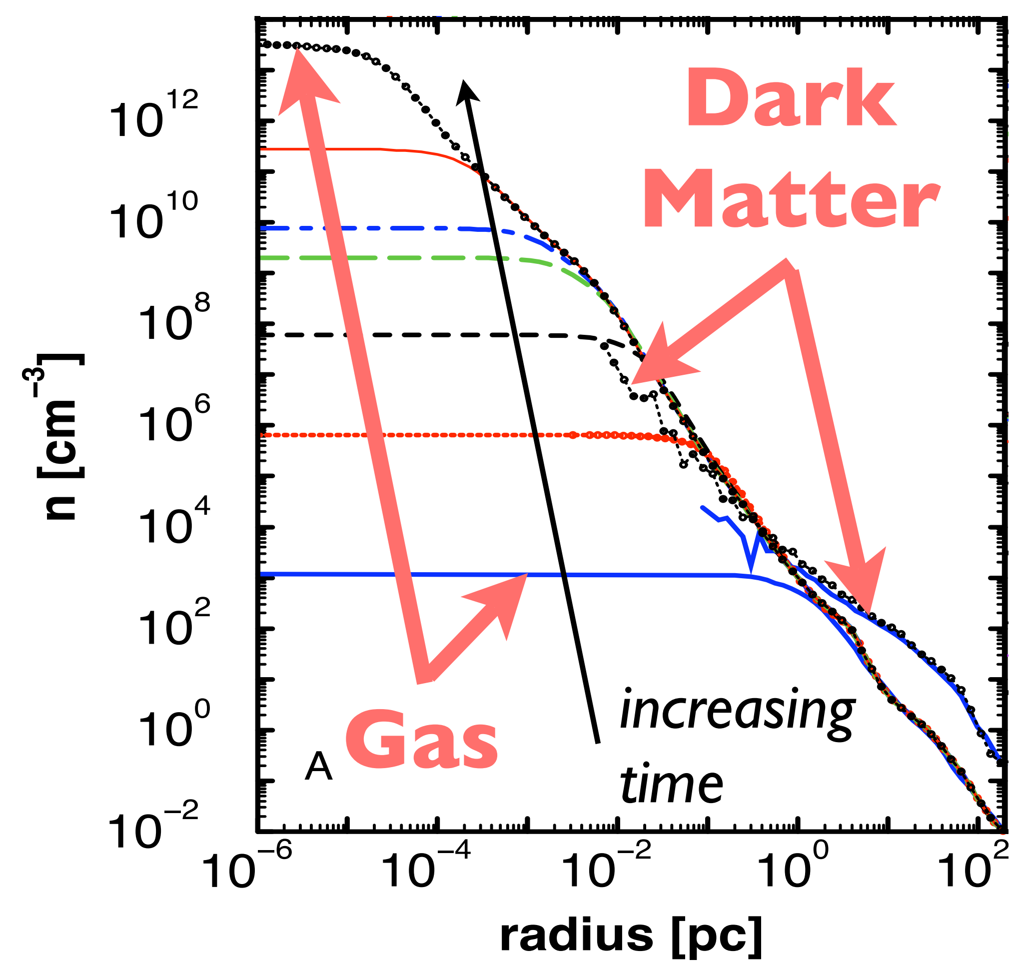
$\rho(r_s) = \rho_0/4$

$r_s =$ "scale radius"

- As gas contracts, dark matter is dragged in

Dark Matter Density Profile: Simulations

Numerical simulations of DM stop at 0.01 pc



Abel, Bryan, Norman 2002

Other variables

- We can exchange

$$\rho_0, r_s \longrightarrow M_{\rm vir}, c_{\rm vir}$$

$$c_{\rm vir} = \frac{R_{\rm vir}}{r_s} \qquad M_{\rm vir} = 200\frac{4\pi}{3}R_{\rm vir}^3\rho_{\rm crit}(z_{\rm f})$$

- $R_{\rm vir}$ radius at which

$$\rho_{\rm DM} = 200\times\left(\begin{array}{c}\text{the DM density of the universe}\\ \text{at the time of formation}\end{array}\right)$$

Dark Matter Density Profile

- Adiabatic contraction
  - as baryons fall into core, DM particles respond to potential well
  - using prescription from Blumenthal, Faber, Flores, & Primack 1986

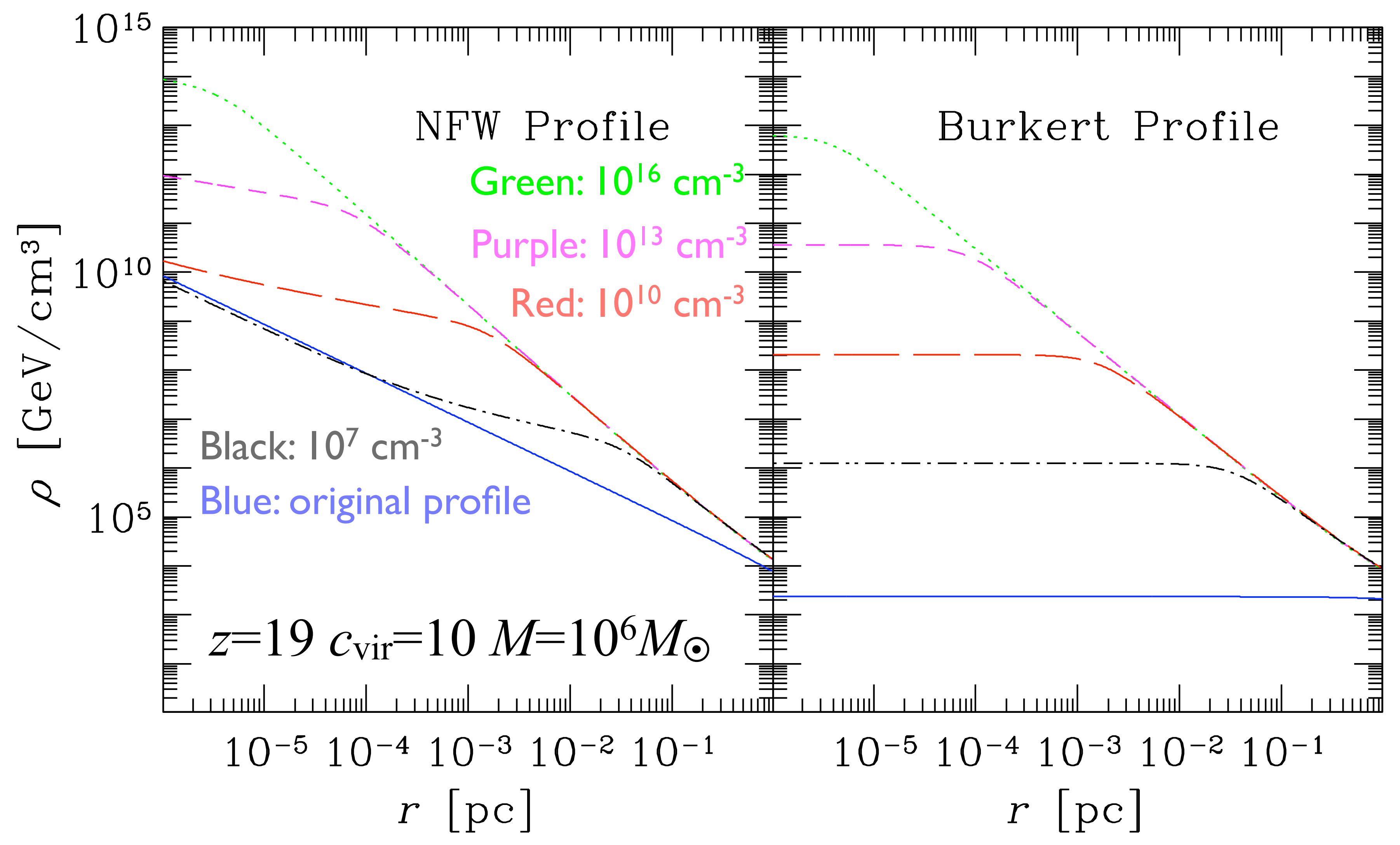
$$r\,M(r) = \text{constant}$$

- We find a contracted profile

$$\rho_\chi(r) = k r^{-1.9} \quad \text{outside core}$$

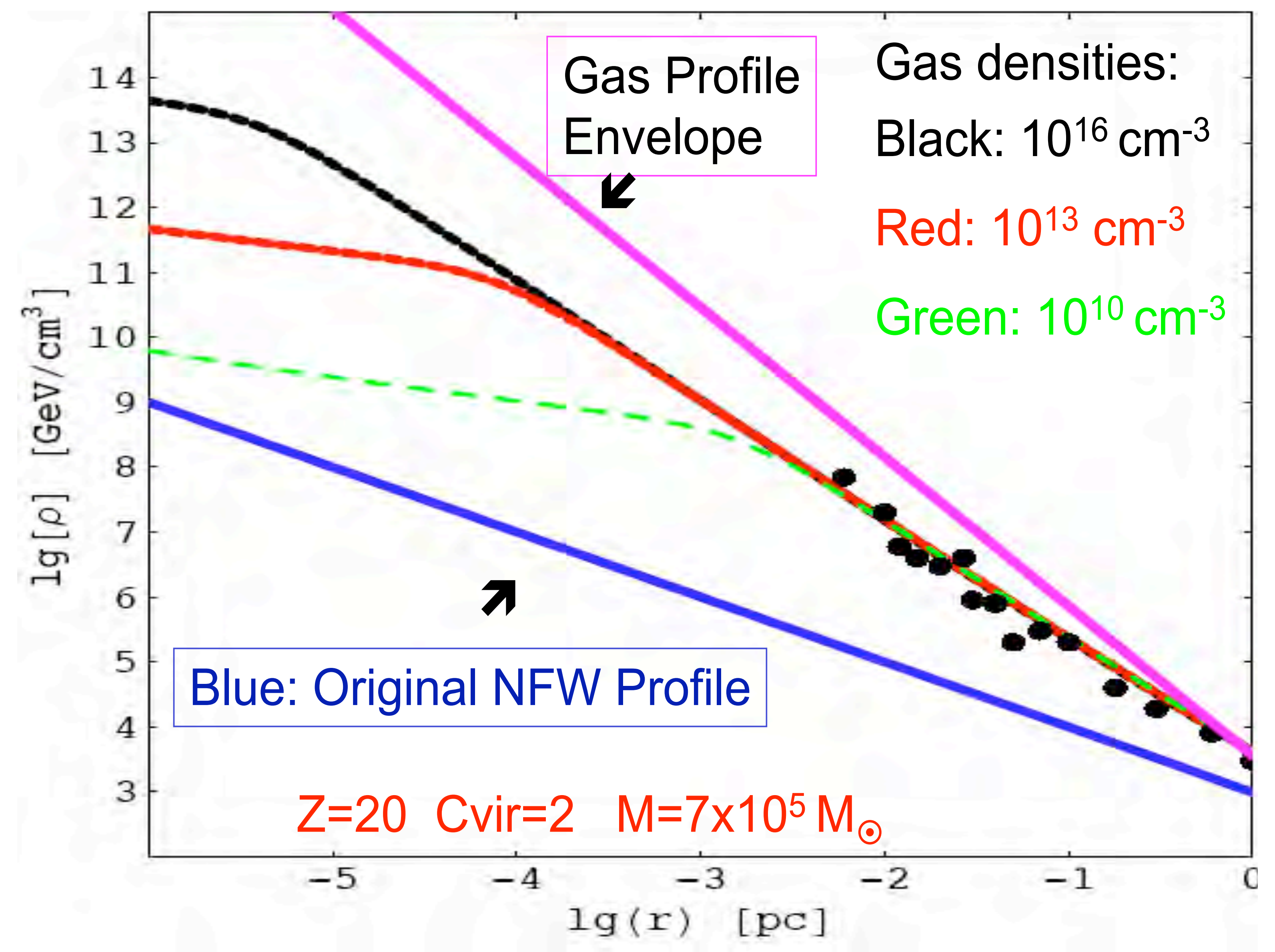
$$\rho_\chi(\text{core}) = 5\,\frac{\text{GeV}}{\text{cm}^3}\left(\frac{n}{\text{cm}^{-3}}\right)^{0.8}$$

Dark Matter Profile: Adiabatic Contraction



Outer profile matches Abel, Bryan, & Norman 2002

DM Profile: Analytic Matches Numerical



Gas Profile Envelope

Gas densities:

Black: 10^{16} cm^{-3}

Red: 10^{13} cm^{-3}

Green: 10^{10} cm^{-3}

Blue: Original NFW Profile

Z=20 Cvir=2 M=7×10^5 $M_\odot$

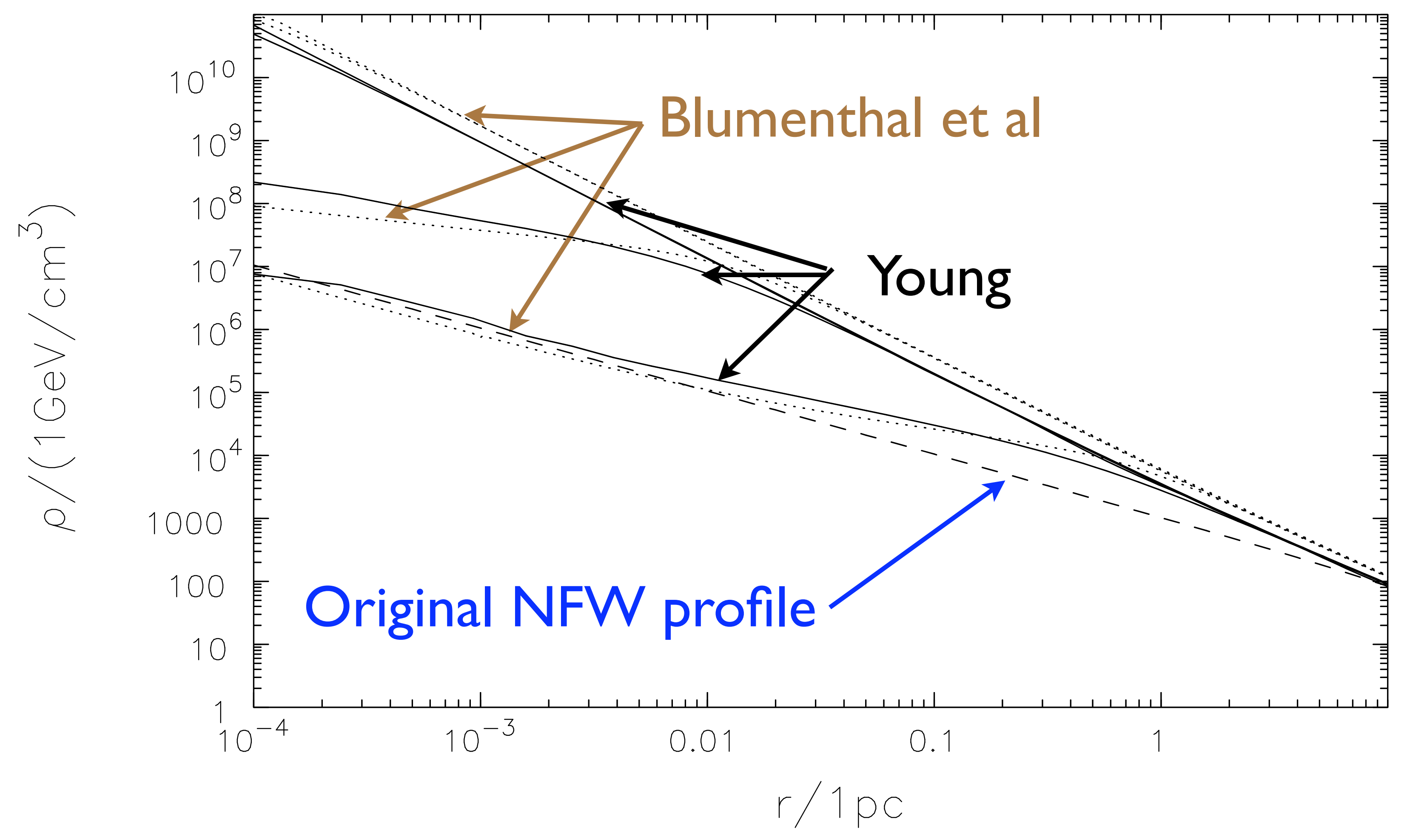
On Adiabatic Contraction

- Dynamical time vs orbital time
- Caveat: spherical symmetry vs mergers
- Matches simulated profiles in relevant regime even at large baryon density
- In the context of describing galactic dark matter halos, adiabatic contraction has been wildly successful even beyond the regime where it should be valid
- Sellwood & McGaugh 2005: adiabatic contraction is only off by O(1) even for radial orbits, disks, bars
- We have performed a full phase-space analysis a la Young 1980
- N-body simulations are in progress (with M. Zemp)

Adiabatic contraction a la Young

Freese, Gondolo, Sellwood, Spolyar 2008

within factor of 2 of Blumenthal et al



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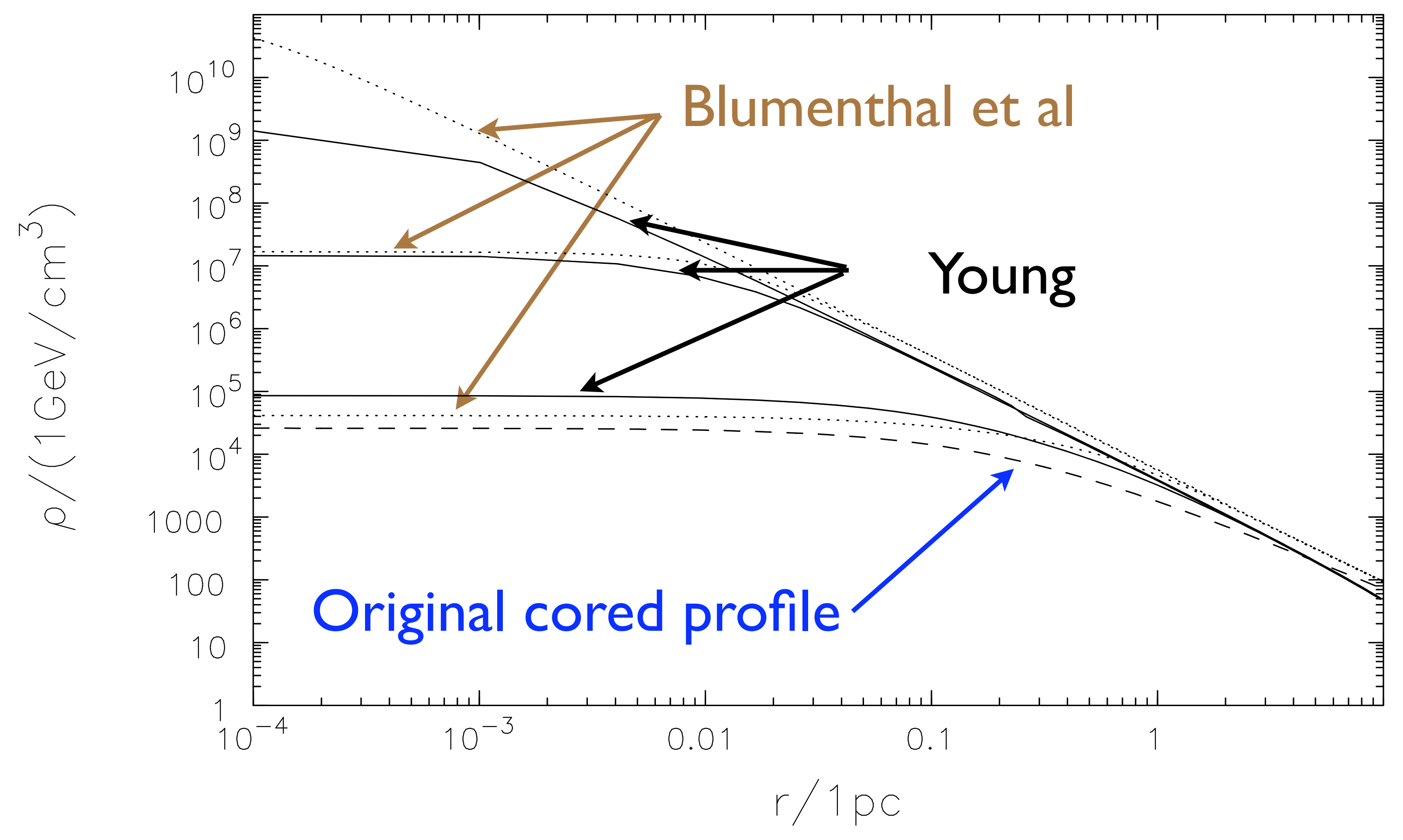

Three conditions for Dark Stars

Spolyar, Freese, Gondolo 2007 aka Paper I

(1) Sufficiently high dark matter density to get large annihilation rate

(2) Annihilation products get stuck in star

(3) Dark matter heating beats H_2 cooling

Leads to new stellar phase

Dark Matter Heating

Heating rate $\Gamma_{\rm DM\ heating} = f_Q\, Q_{\rm ann}$

Rate of energy production from annihilation $Q_{\rm ann} = n_\chi^2 \langle \sigma v \rangle m_\chi = \dfrac{\rho_\chi^2 \langle \sigma v \rangle}{m_\chi}$

Fraction of annihilation energy deposited in gas f_Q (see next slide)

Previous work noted that at $n \leq 10^4$ cm^{-3} annihilation products simply escape (Ripamonti, Mapelli, & Ferrara 2007)

Annihilation energy deposited into gas

Estimate f_Q (better calculation in progress)

- 1/3 neutrinos, 1/3 photons, 1/3 electrons/positrons
- Neutrinos escape
- Electrons $\gtrsim E_\mathrm{c} \approx 280\ \mathrm{MeV} \rightarrow$ electromagnetic cascades
  $\lesssim E_\mathrm{c} \approx 280\ \mathrm{MeV} \rightarrow$ ionization
- Photons $\gtrsim 100\ \mathrm{MeV} \rightarrow$ electromagnetic cascades
  $\lesssim 100\ \mathrm{MeV} \rightarrow$ Compton/Thomson scattering

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Leads to new stellar phase

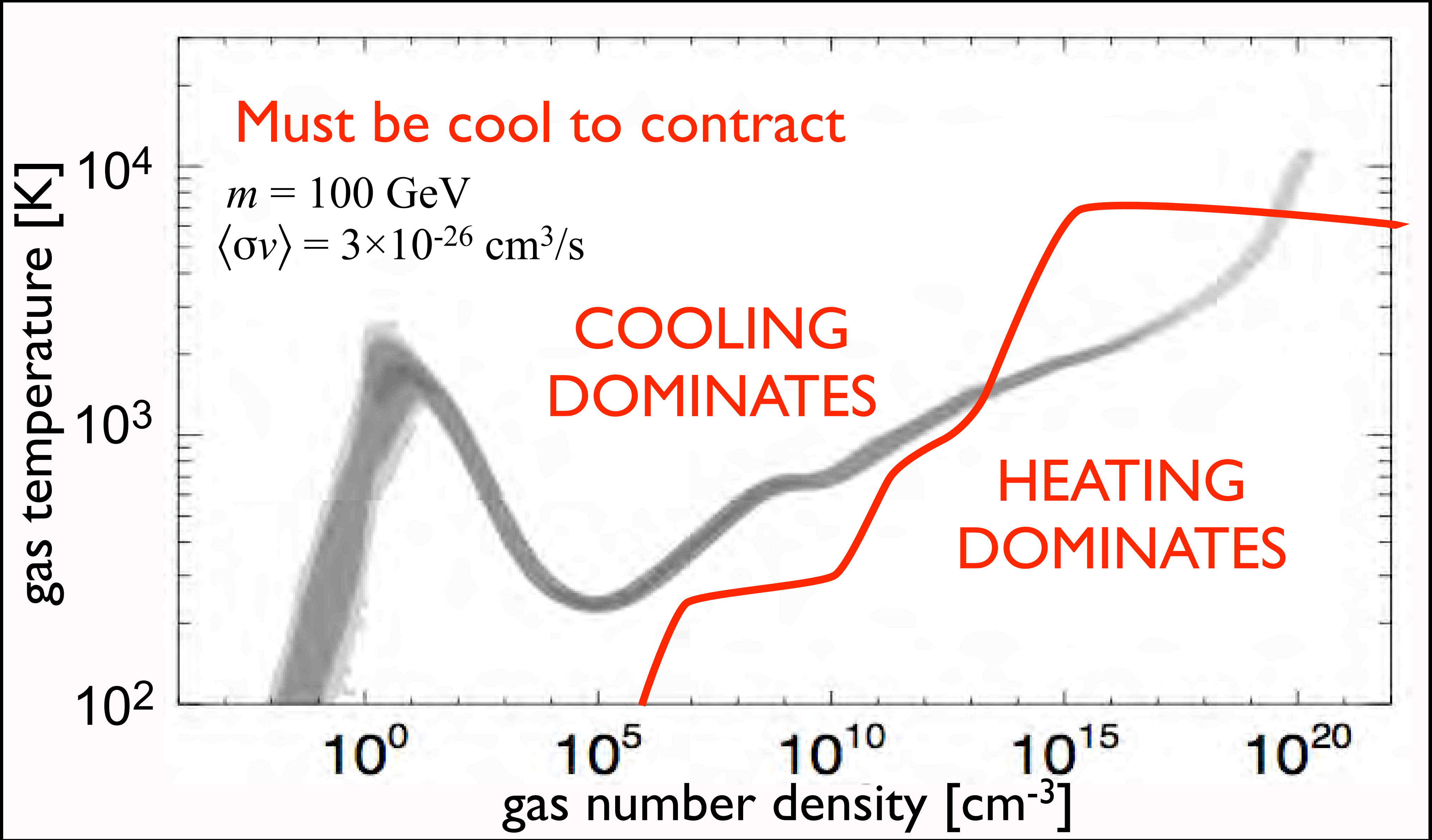
Crucial transition

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

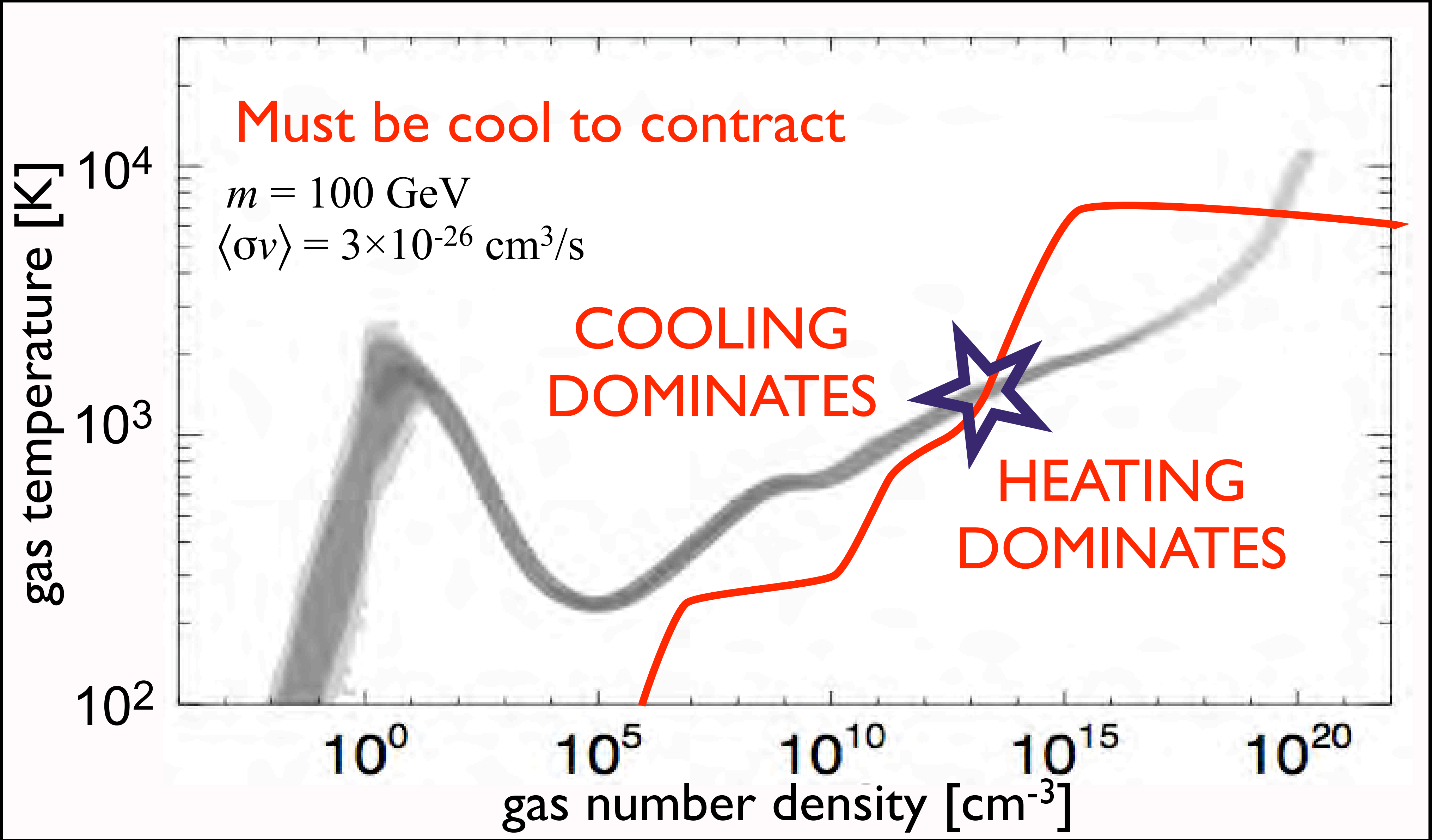
$$
\begin{aligned}
m_\chi &\approx 1\ \mathrm{GeV} & &\longrightarrow & n &\approx 10^{9}\mathrm{cm}^{-3}\\
m_\chi &\approx 100\ \mathrm{GeV} & &\longrightarrow & n &\approx 10^{13}\mathrm{cm}^{-3}\\
m_\chi &\approx 10\ \mathrm{TeV} & &\longrightarrow & n &\approx 10^{15.5}\mathrm{cm}^{-3}
\end{aligned}
$$

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

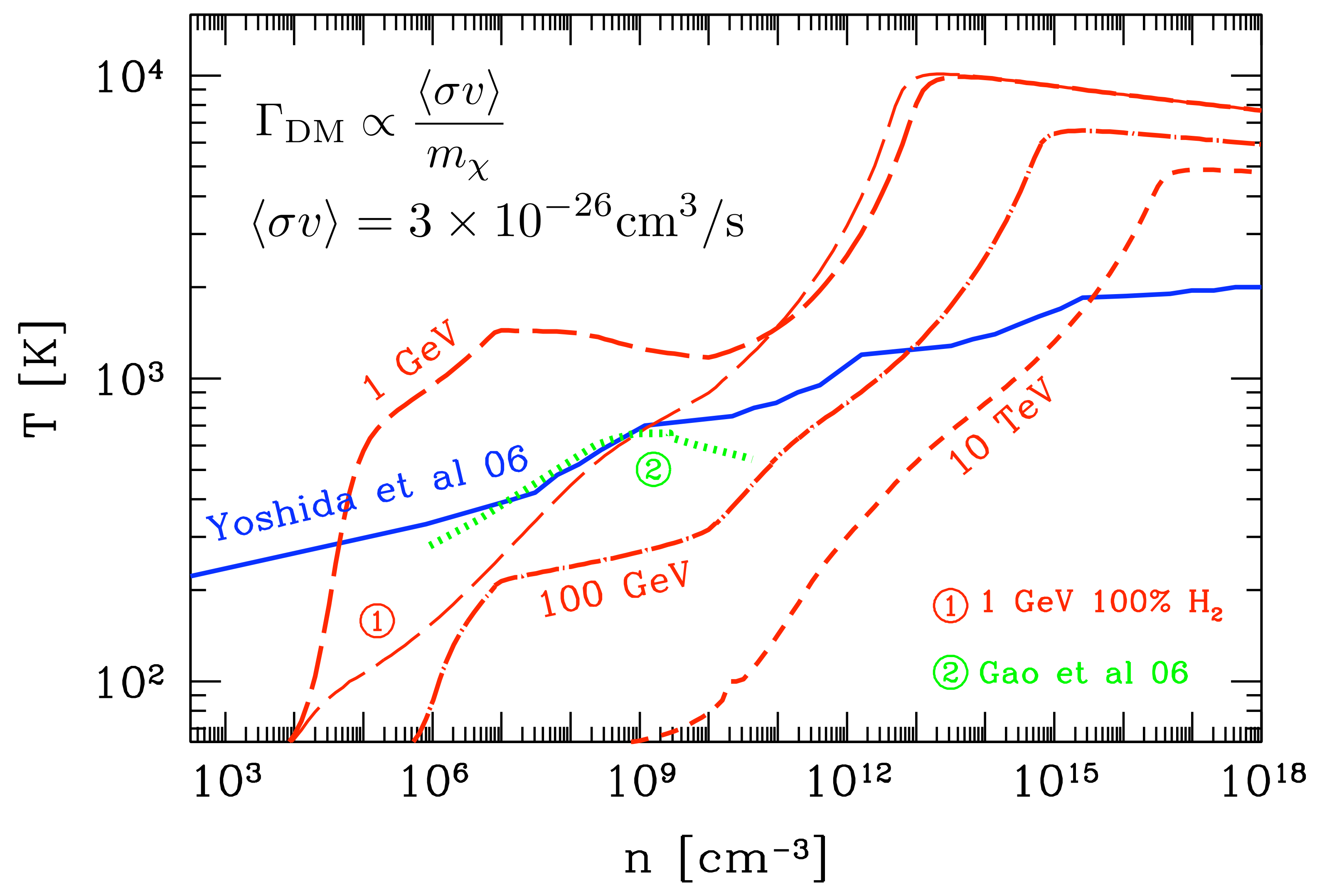
Crucial transition



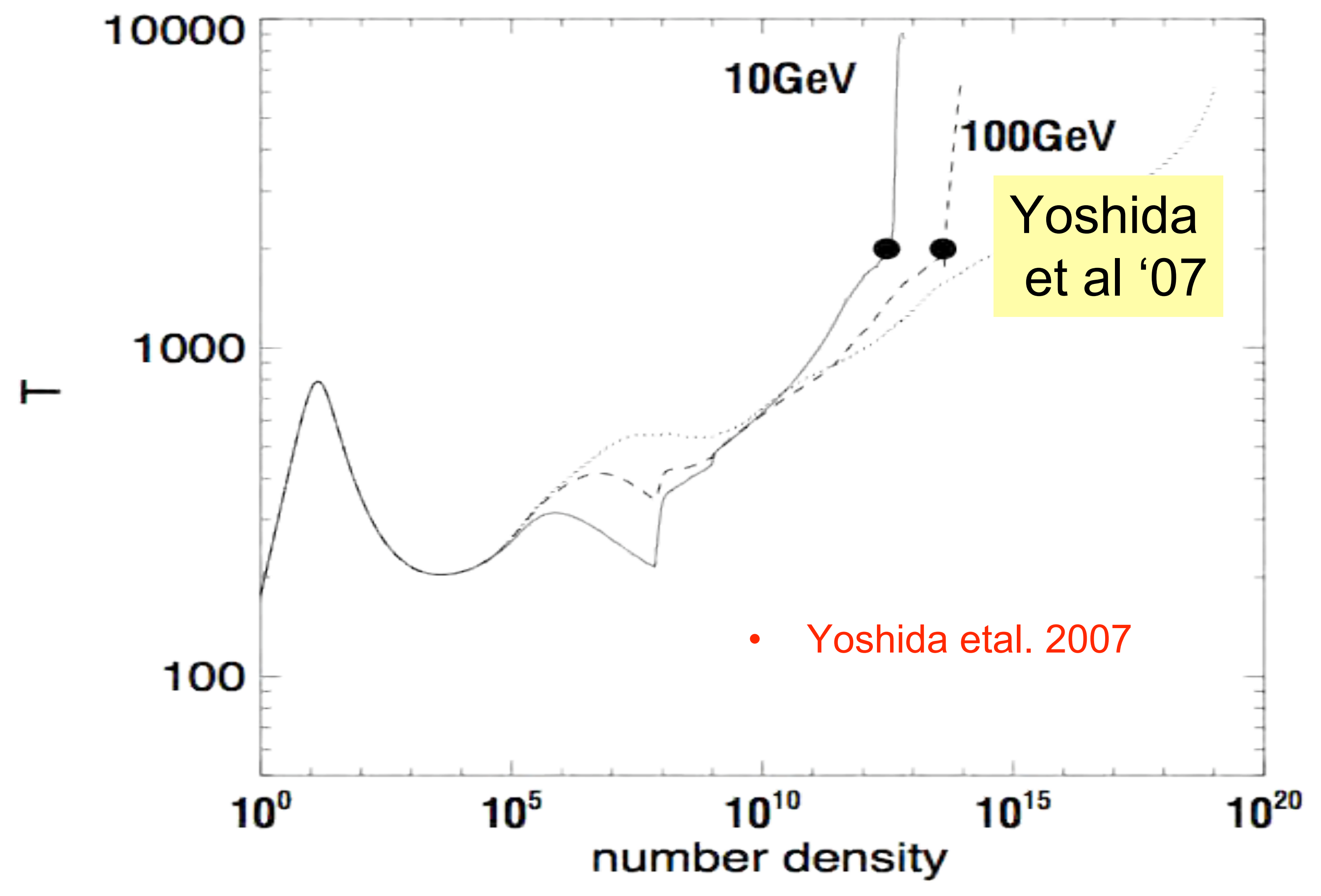
Crucial transition



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



New stellar phase, fueled by dark matter



Yoshida et al '07

- Yoshida etal. 2007

New stellar phase

- Dark Star supported by DM annihilation rather than fusion
- DM is less than 2% of the mass of the star but provides the heat source (The Power of Darkness)
- Dark Stars are not dark: they shine
- Initially, they are giant stars that fill Earth's orbit

$m_\chi \approx 1$ GeV	core radius 960 AU	mass 11 $M_\odot$
$m_\chi \approx 100$ GeV	core radius 17 AU	mass 0.6 $M_\odot$

- What is their subsequent evolution?
  How long does the dark star phase last?

Key Question: Lifetime of Dark Stars

- How long does it take the DM in the core to annihilate away?

$$t_{\rm ann} = \frac{m_\chi}{\rho_\chi \langle \sigma v \rangle}$$

- For example, for our canonical case

$$t_{\rm ann} \approx \text{600 million years for } n \approx 10^{13} {\rm cm}^{-3}$$

- Compare with dynamical time of $<10^3$ yr. The core may fill in with DM again so that annihilation heating continues for a long time

A First Phase of Dark Star Evolution

Freese, Bodenheimer, Spolyar, Gondolo 2008

- DM heating dissociates molecular hydrogen and then ionizes the gas
- The protostar has now become a star
  - Initial star is a few solar masses
  - Accrete more baryons up to the Jeans mass $\sim 1000 M_\odot$
  - Becomes very luminous, between $10^6 L_\odot$ and $10^7 L_\odot$
  - Cool: 6,000-10,000 K vs usual 30,000 K and plus Very few ionizing photons - just too cool
  - Lifetime: a few million years

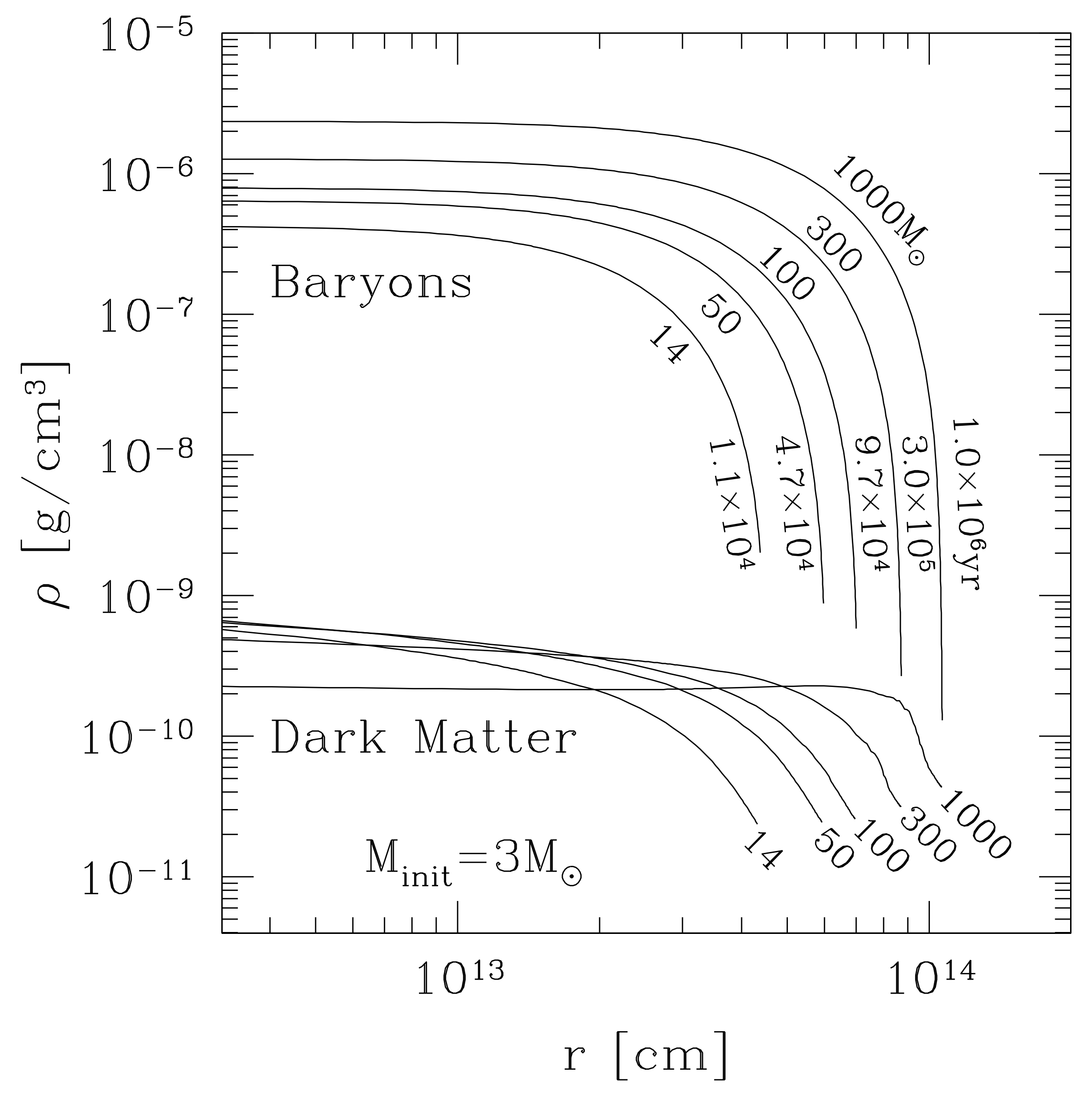
A First Phase of Dark Star Evolution

Freese, Bodenheimer, Spolyar, Gondolo 2008

- Polytrope with index 3/2 (convection dominated) or 3 (radiation dominated)
- Dark matter adiabatically contracted from NFW
- Slow evolution
    - Find hydrostatic equilibrium solution such that star luminosity equals energy produced per unit time

A First Phase of Dark Star Evolution

Freese, Bodenheimer, Spolyar, Gondolo 2008



What happens next?

- Outer material accretes onto core
  - Accretion shock
- Once $T \sim 10^6$ K,
  - Deuterium burning, pp chain, Helmholz contraction, CNO cycle
- Star reaches main sequence
  - Pop III star formation is delayed

Possible effects

- Reionization
  - Delayed due to later formation of Pop II stars?
  - Sped up by DM annihilation products?
  - Achieved by other Pop III stars that are not "dark"?

  Can be studied with upcoming measurements of 21 cm line

- Early Black Holes
  - Accrete to make $10^9\ M_\odot$ black holes observed at z~6
  - Accretion process (Tan & McKee 2003)

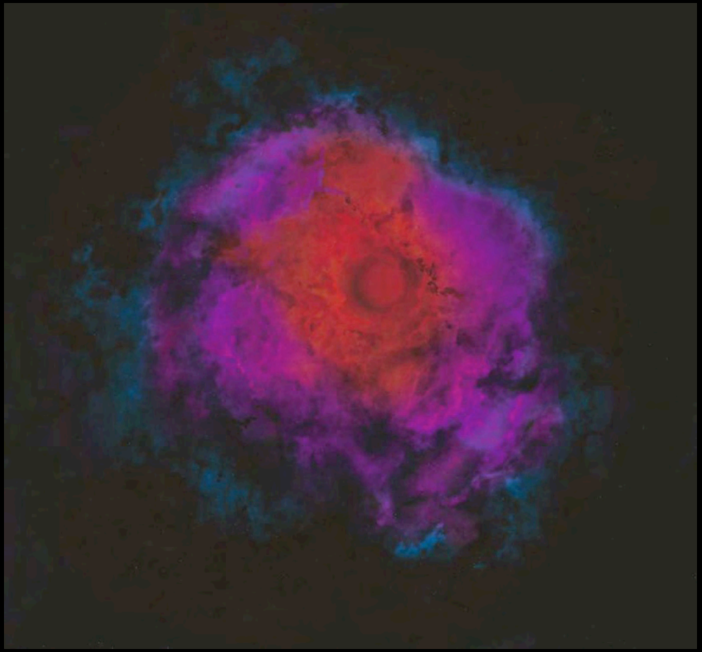
Observables

Dark stars are giant objects at redshift 10-20, with radii ~ 1 AU, luminosities ~10^6 $L_\odot$, and masses ~10^3 $M_\odot$

- Find them with JWST?
- Detect annihilation products?
- Perhaps WIMPs may be discovered via dark stars
  Perhaps we can learn more about their properties

Summary

- Dark matter annihilation heating in Pop III protostars can delay/block their formation
- A new stellar phase can arise: Dark Stars powered by dark matter annihilation and not by fusion



Artist's impression of a dark star