Title: Dark Matter and the First Stars

Date: Jun 08, 2008 10:00 AM

URL: http://pirsa.org/08060016

Abstract:

Dark Matter and the First Stars

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Based on:

Spolyar, Freese, Gondolo, 2008, Phys. Rev. Lett. 100, 051101 [arxiv:0705.0521]
Freese, Gondolo, Sellwood, Spolyar, arxiv:0802.1724
Freese, Bodenheimer, Spolyar, Gondolo, arxiv:0806.0617

Perimeter Institute, June 8, 2008

Our Results

- Cold Dark Matter particles can dramatically alter the formation of the first stars, leading to a new stellar phase powered by CDM annihilation instead of nuclear fusion

A Dark Star

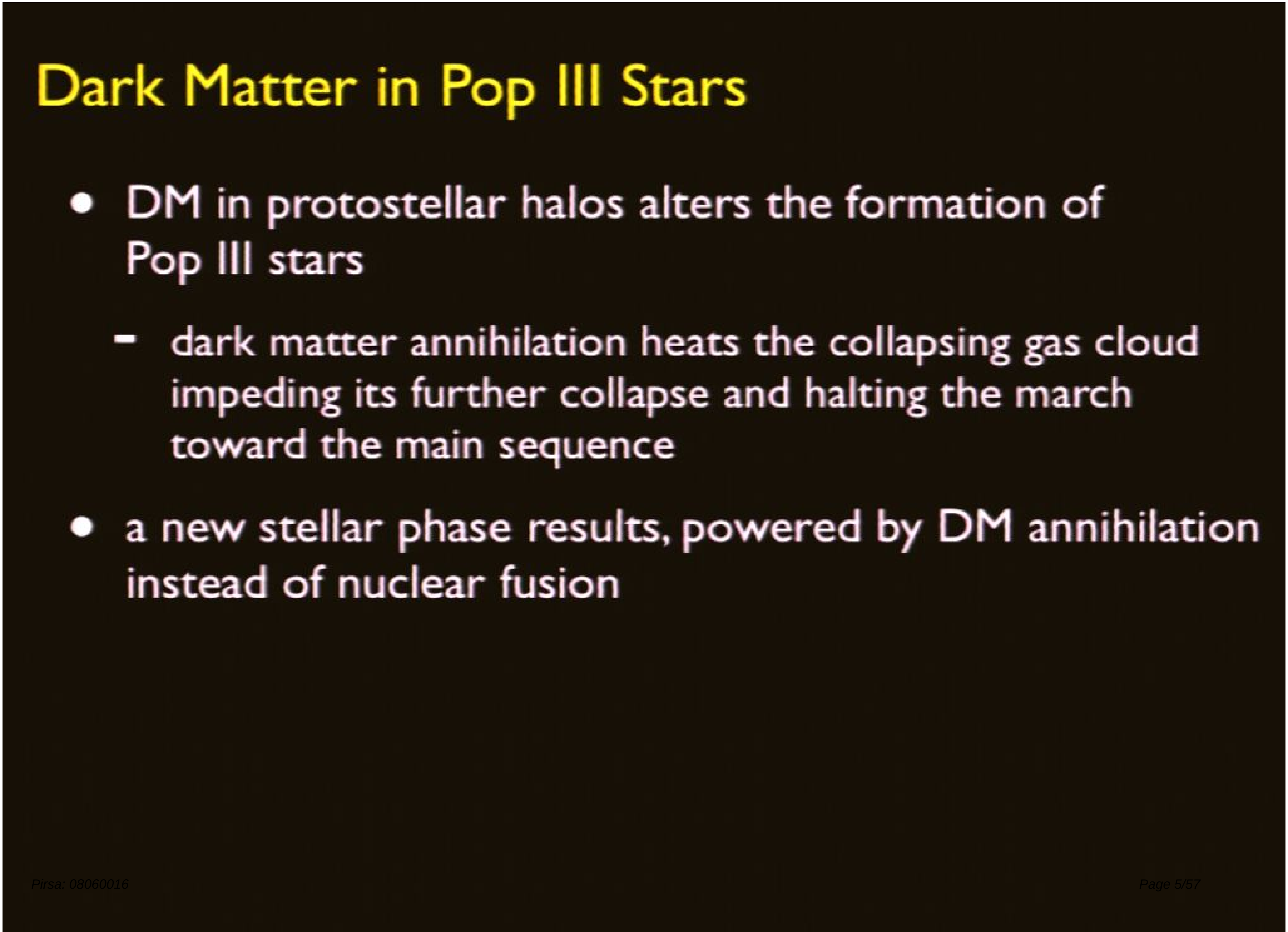
Some consequences

- Affects reionization and early stellar enrichment
- Dark stars may be precursors to the supermassive black holes that power high red-shift quasars

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



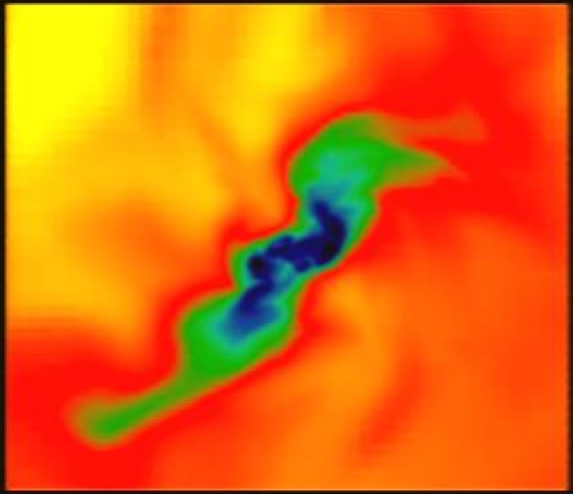
Dark Matter in Pop III Stars

- 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 wonder 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



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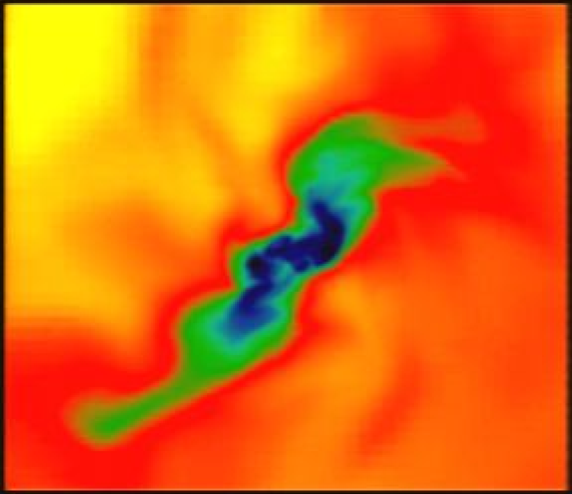
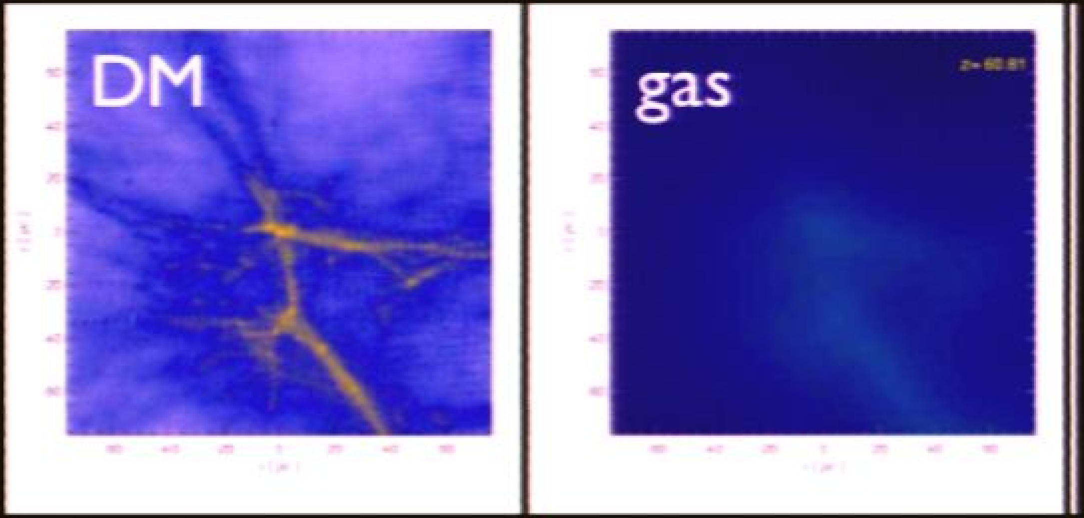


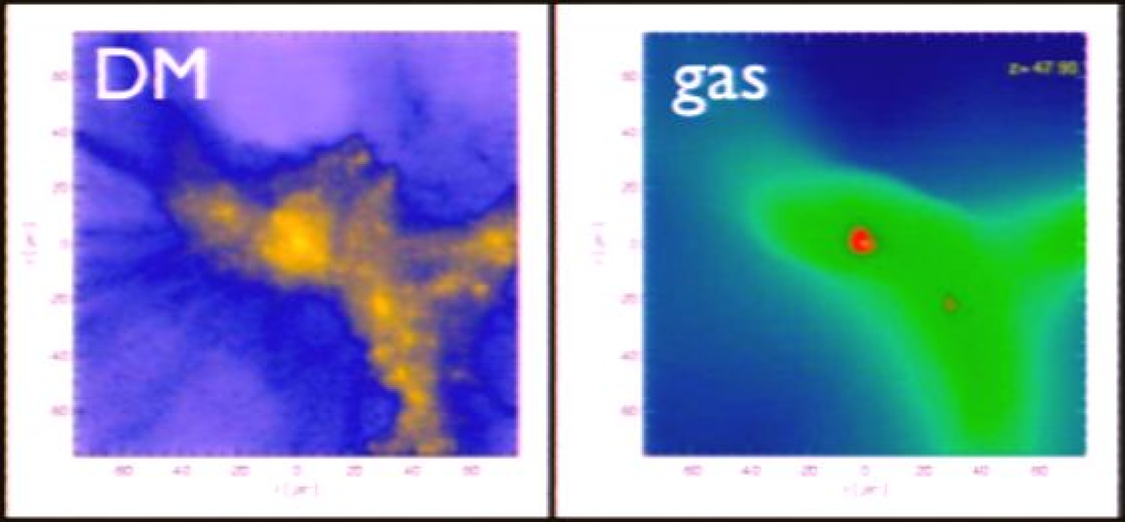
- Formation Basics
  - first luminous objects ever
  - made only of H/He
  - form inside DM halos of 10^5-10^6 $M_\odot$
  - at redshift z=10-50
  - baryons initially only 15%
  - formation is a gentle process
- Dominant cooling mechanism to allow collapse into star is H_2 cooling (Hollenbach & McKee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

First Stars: Simulations



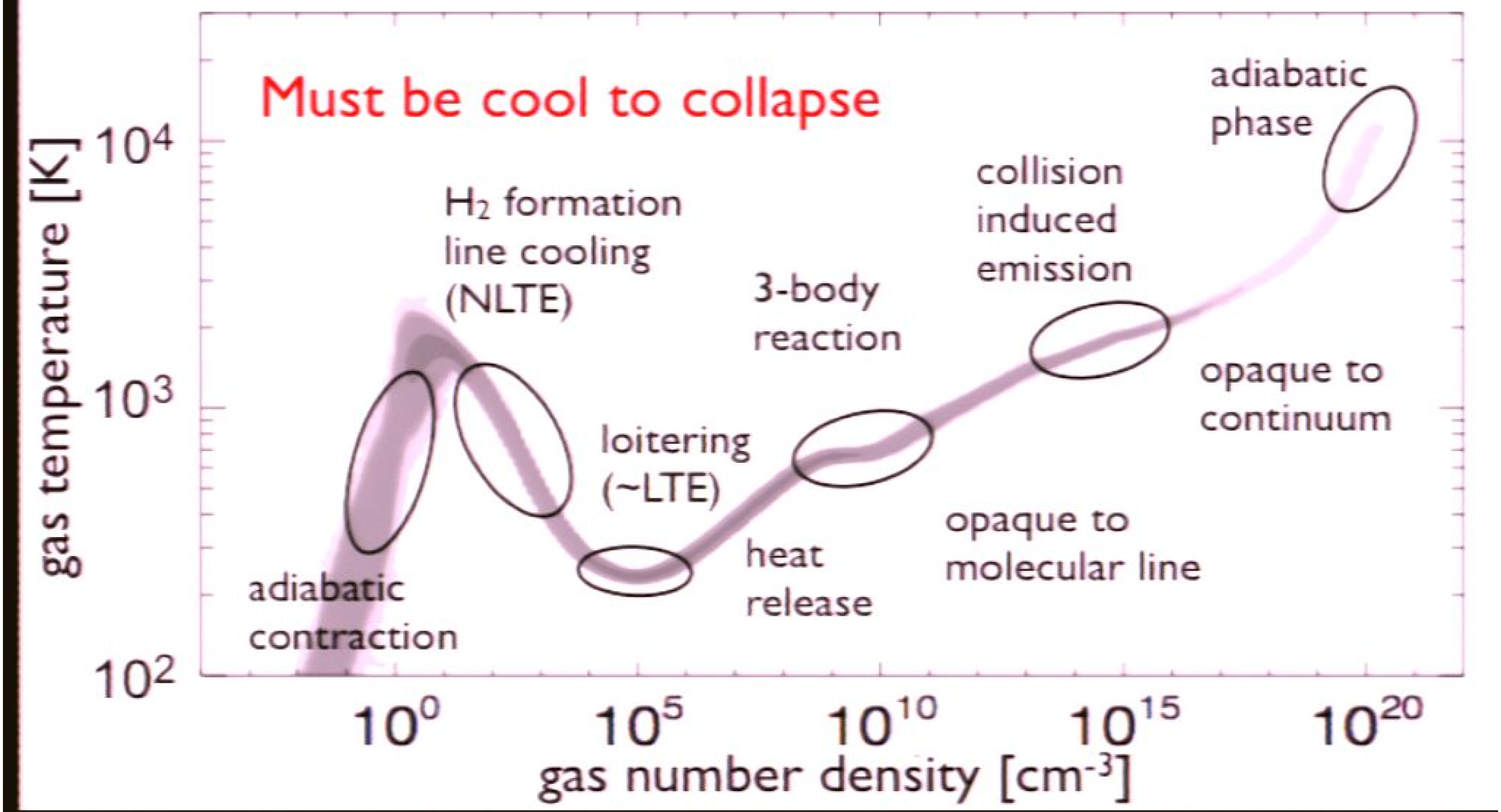
z=60

z=48



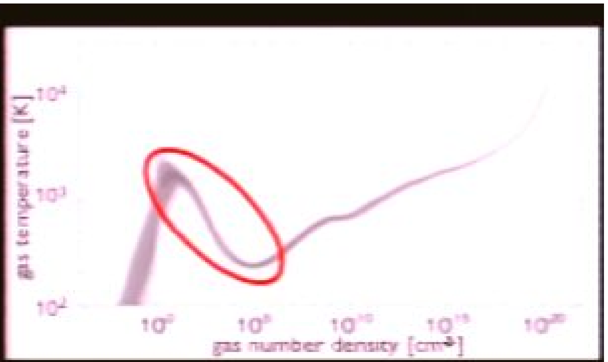
Gao, Abel, Frenk, Jenkins, Springel, Yoshida 2006

Thermal evolution of Pop III protostar



Courtesy of N.Yoshida

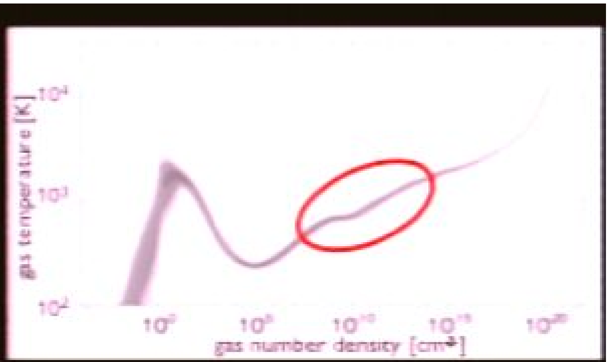
H_2 Cooling and Collapse



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

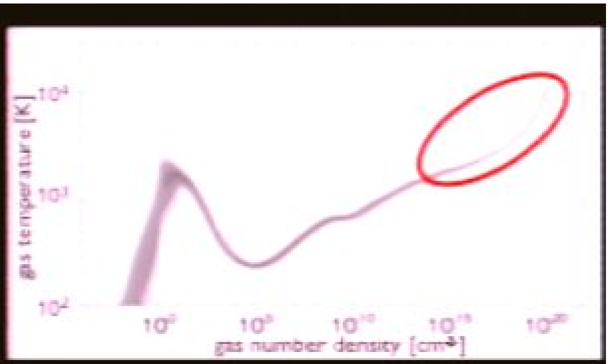
$$n \approx 10^8 \mathrm{cm}^{-3} \qquad H + H + H \rightarrow H_2 + H$$

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

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

- Central core mass

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

- Final stellar mass

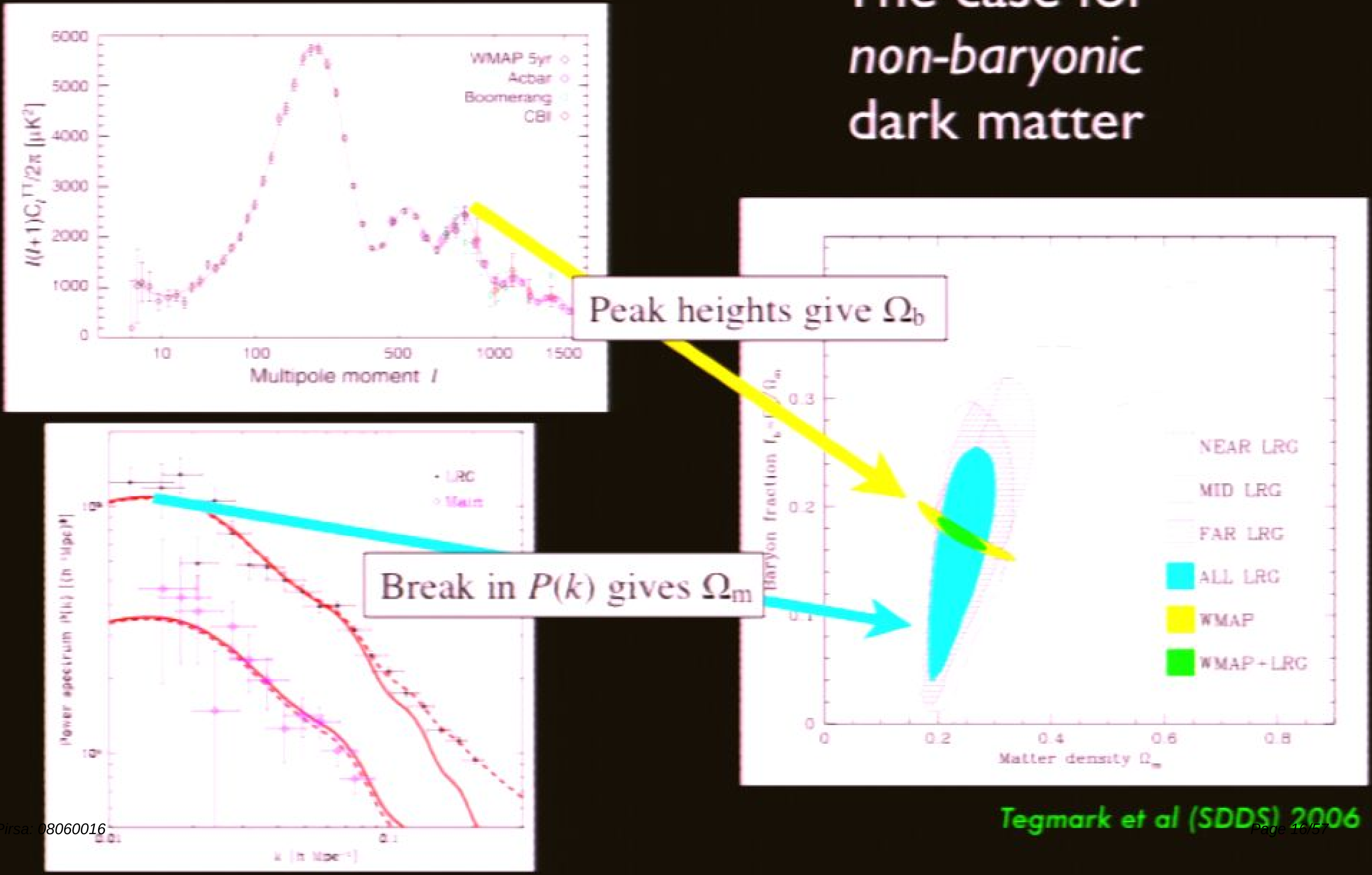
$$\sim 100 M_\odot \quad \text{in standard scenario}$$

Dark Matter

The case for
non-baryonic
dark matter

Dark Matter

The case for *non-baryonic* dark matter



Peak heights give Ω_b

Break in $P(k)$ gives Ω_m

Tegmark et al (SDDS) 2006

The wonder WIMP

Weakly Interacting Massive Particle

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

The wonder WIMP

Weakly Interacting Massive Particle

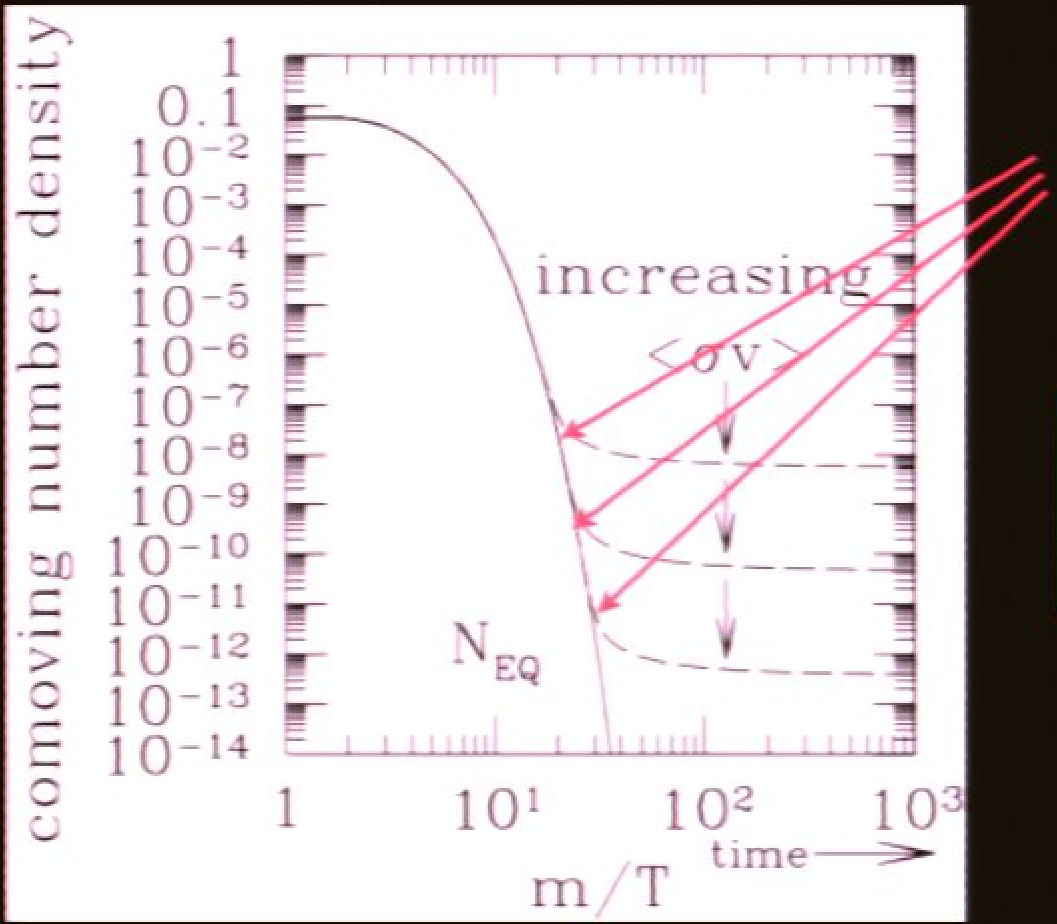
A WIMP in chemical equilibrium in the early universe naturally has the right density to be Cold Dark Matter

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

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

- 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

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

annihilation rate *expansion rate*

$$\boxed{\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle_{\mathrm{ann}}}}$$

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

for $\langle\sigma v\rangle_{\mathrm{ann}} \simeq 3\times 10^{-26}\mathrm{cm}^3/$

(weak interactions)

WIMP Cold Dark Matter

Our canonical case:

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

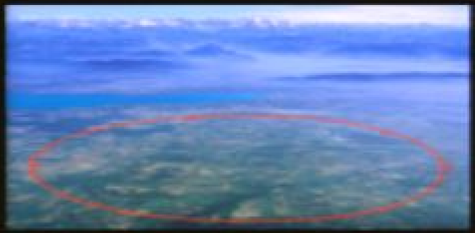
- We consider
  - a range of masses (1 GeV - 10 TeV)
  - a range of cross sections
- Our results apply to various WIMP candidates
  - neutralinos
  - Kaluza-Klein particles
  - sneutrinos

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

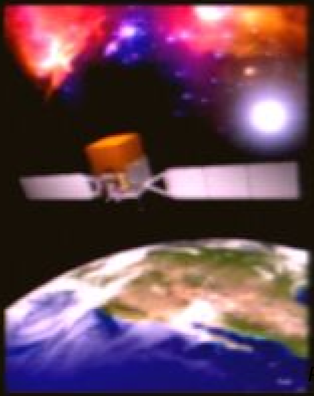
- Accelerators
- Direct detection
- Indirect detection (neutrinos)
  - Sun
  - Earth
- Indirect detection (gamma-rays, positrons, antiprotons)
  - Milky Way halo
  - External galaxies
  - Galactic Center



LHC

CDMS

IceCube



GLAST

Indirect detection

The same annihilation cross section that determines the WIMP relic density fixes the rate of WIMP annihilation in indirect searches (but for kinematical factors)

Annihilation of neutralinos is important wherever dark matter density is high:

- Early universe (gives right relic density)
- Earth, Sun, Galaxy, the first stars!

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"

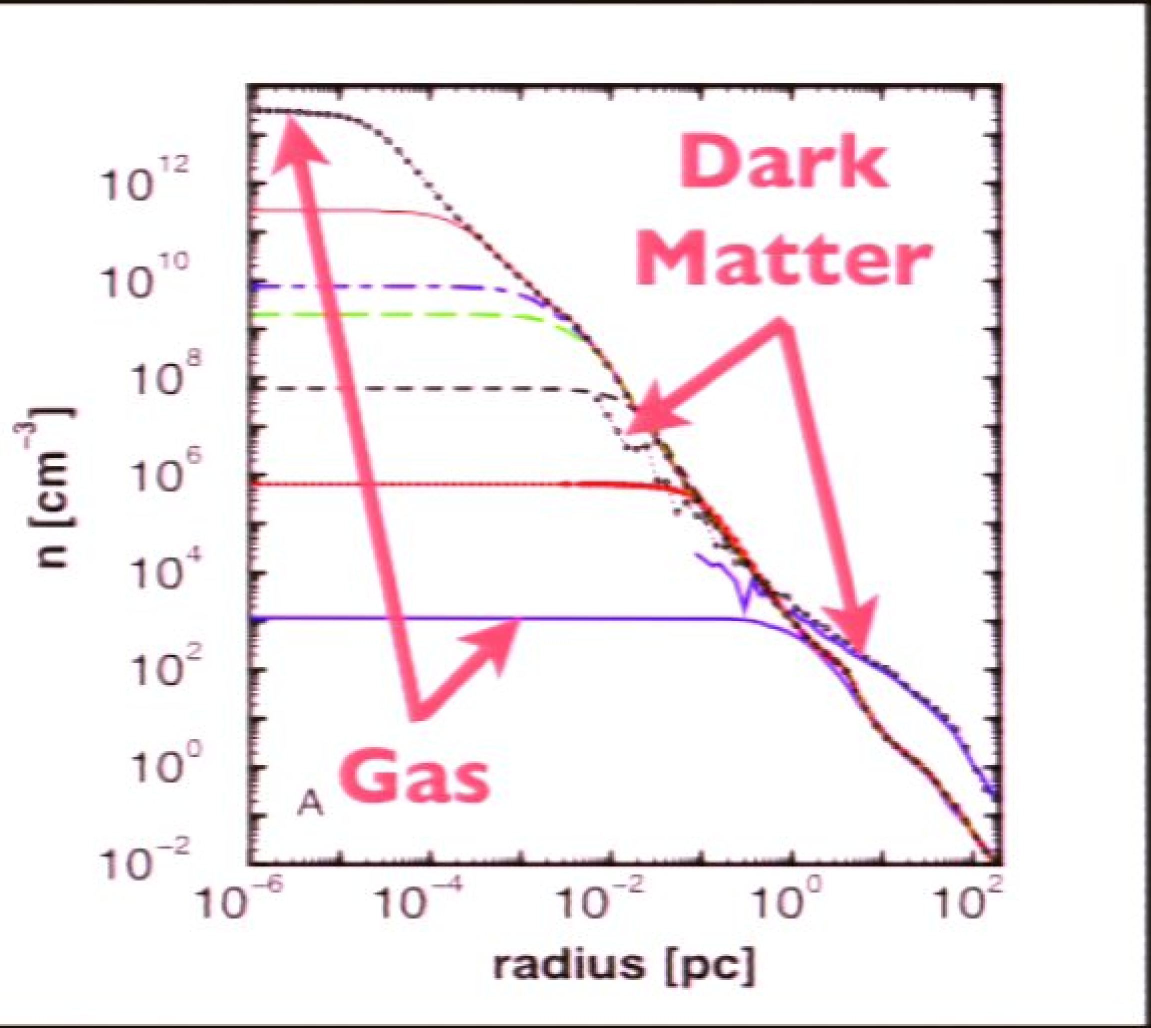
$\rho(r_s) = \rho_0/4$

$r_s =$ "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

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

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

- $R_{\rm vir}$ 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

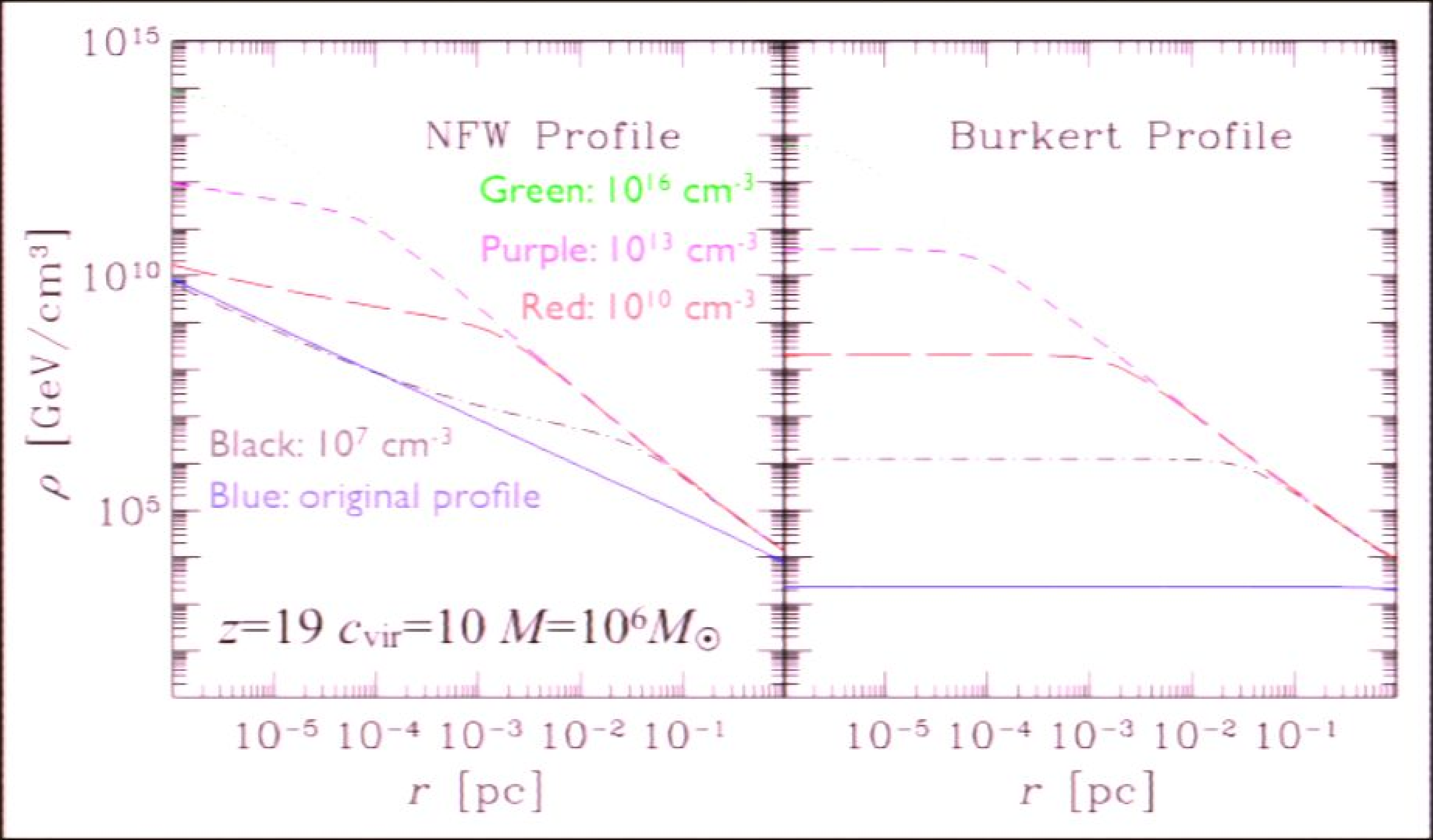
$$r\,M(r) = \text{constant}$$

- We find a contracted profile

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

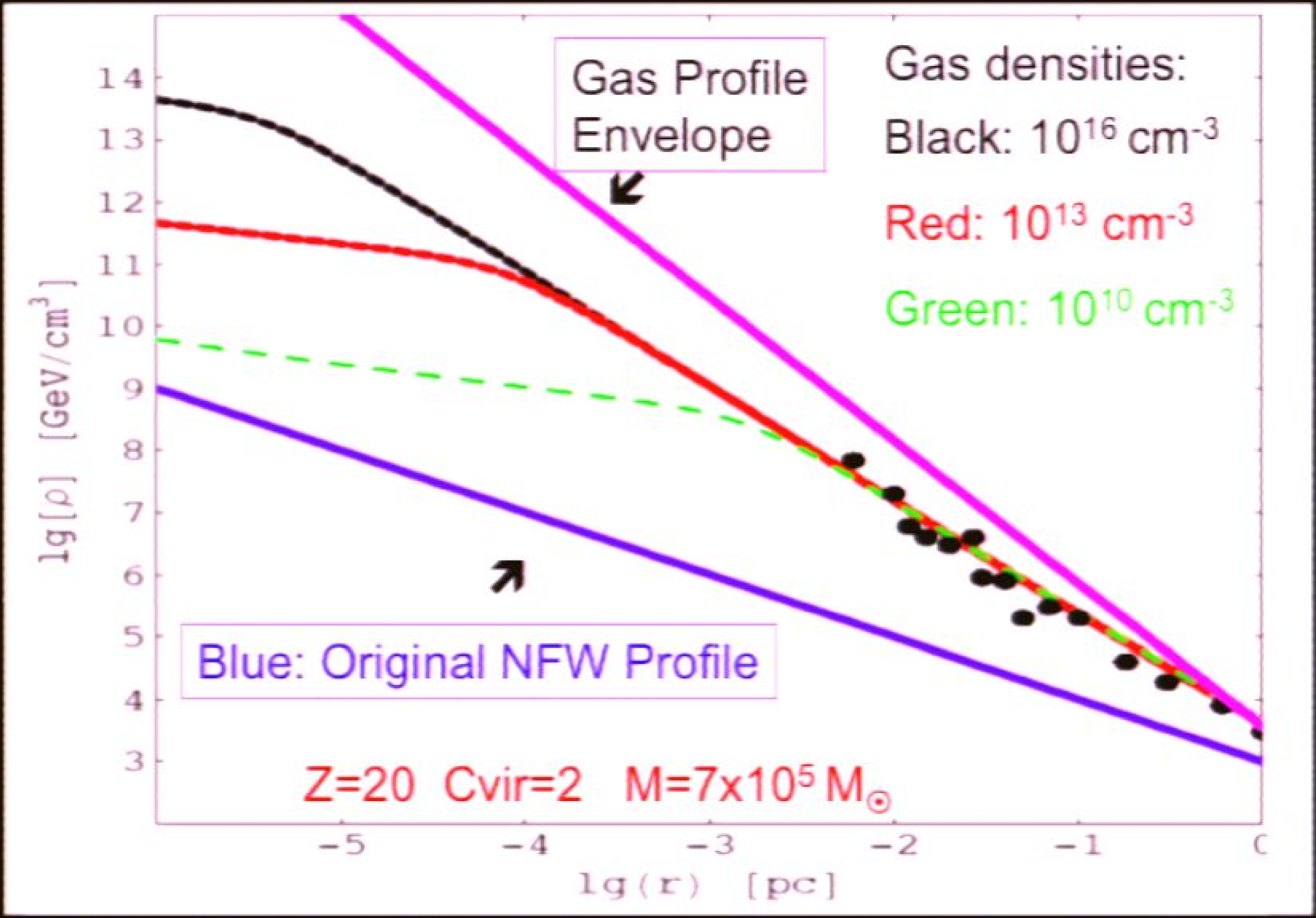
$$\rho_\chi(\text{core}) = 5\,\frac{\text{GeV}}{\text{cm}^3}\left(\frac{n}{\text{cm}^{-3}}\right)^{0.8}$$

Dark Matter Profile: Adiabatic Contraction



Outer profile matches Abel, Bryan, & Norman 2002

DM Profile: Analytic Matches Numerical



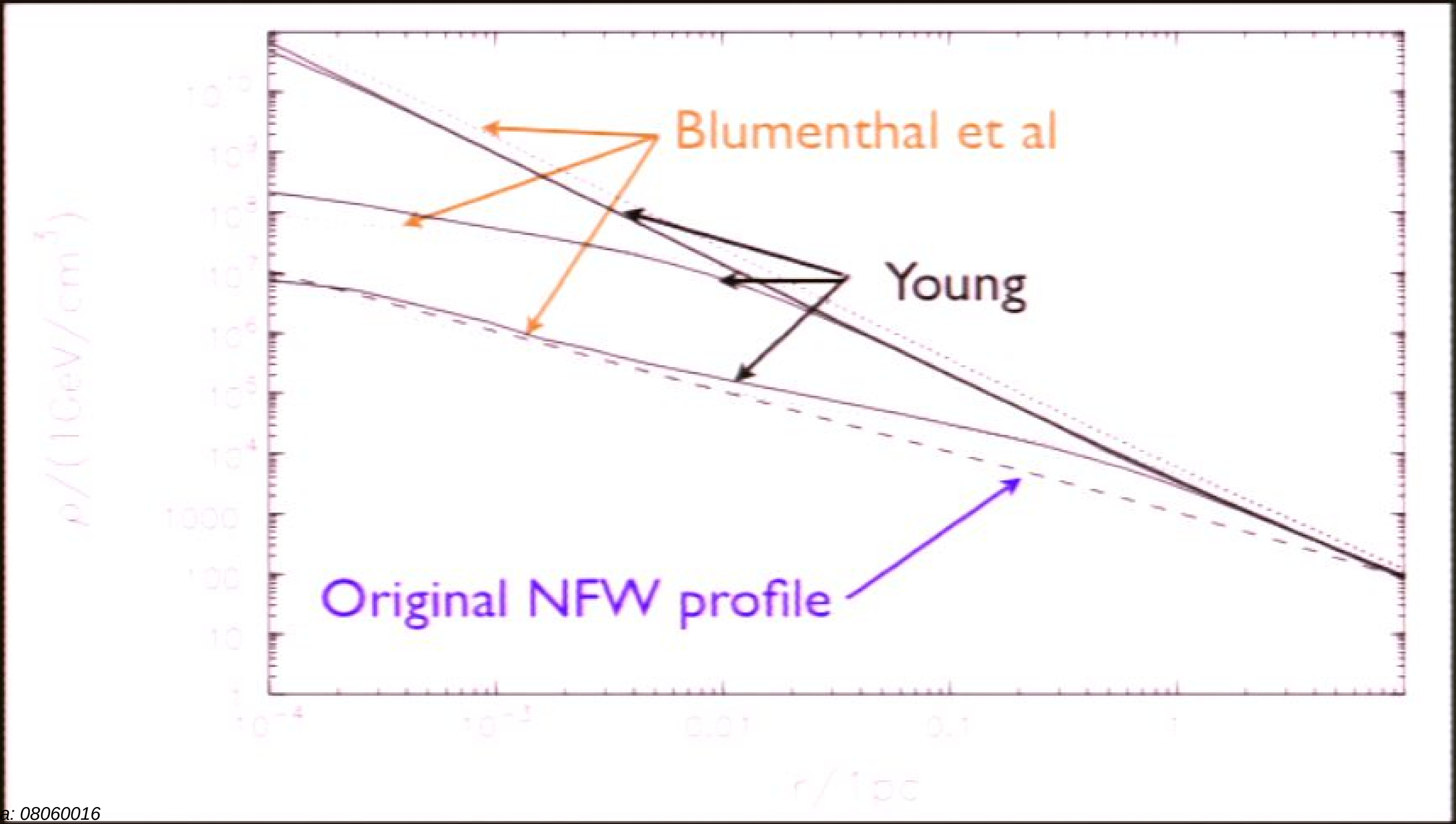
On Adiabatic Contraction

- 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 from Blumenthal et al



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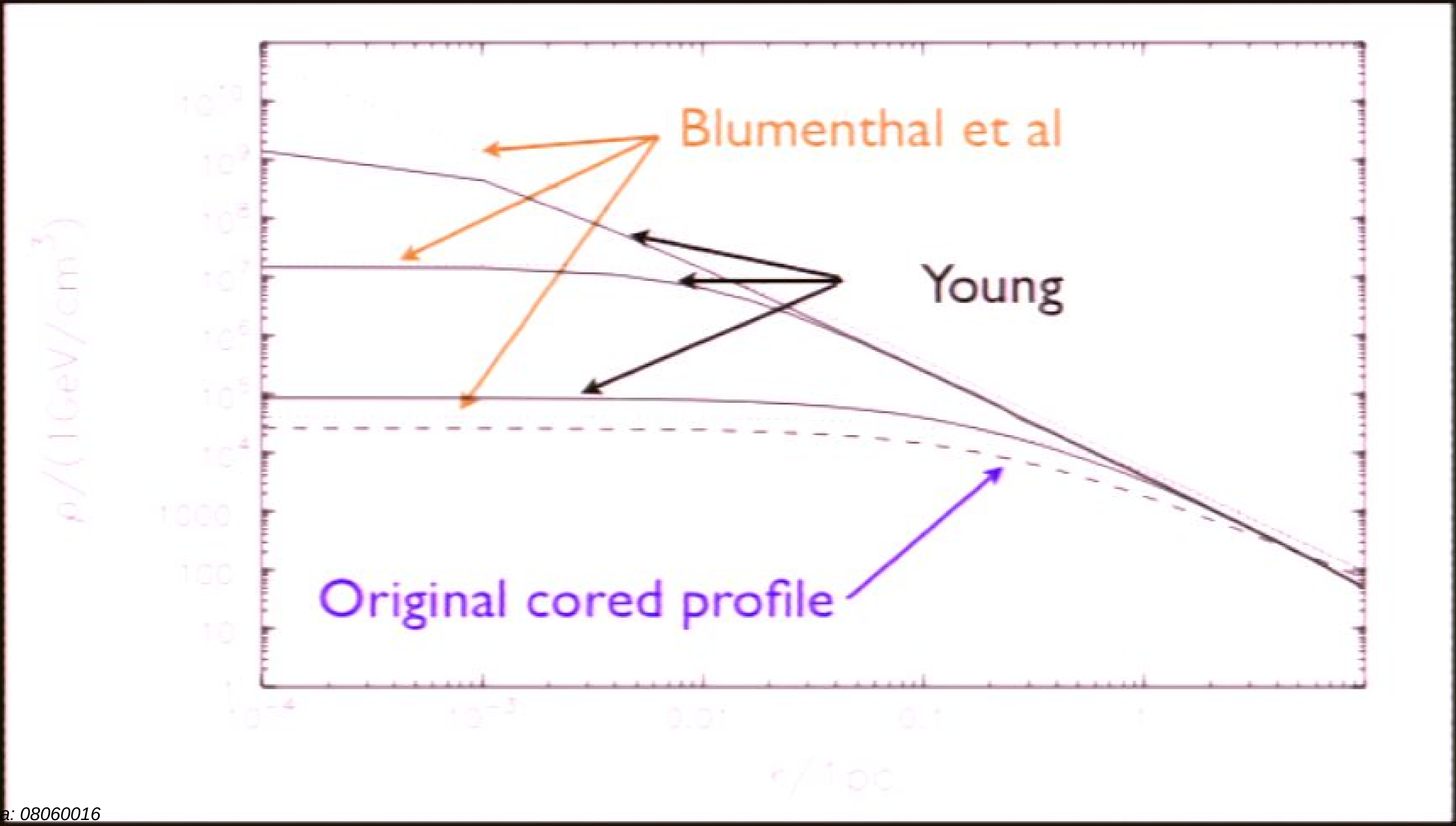


Dark Matter Heating

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

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

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

Crucial transition

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

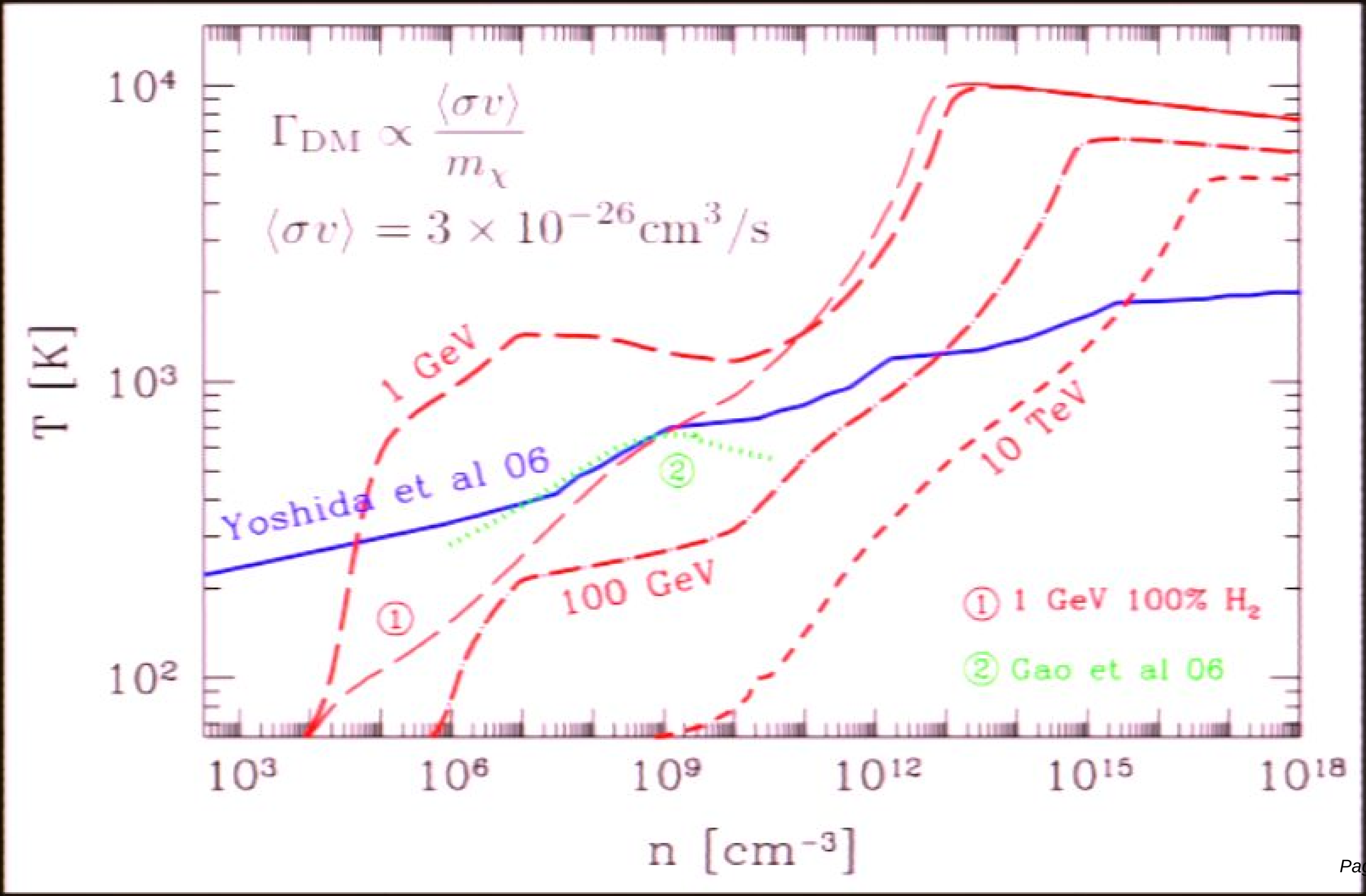
$$\begin{aligned} m_\chi &\approx 1 \text{ GeV} & \rightarrow \quad & n \approx 10^{9}\text{cm}^{-3} \\ m_\chi &\approx 100 \text{ GeV} & \rightarrow \quad & n \approx 10^{13}\text{cm}^{-3} \\ m_\chi &\approx 10 \text{ TeV} & \rightarrow \quad & n \approx 10^{15.5}\text{cm}^{-3} \end{aligned}$$

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

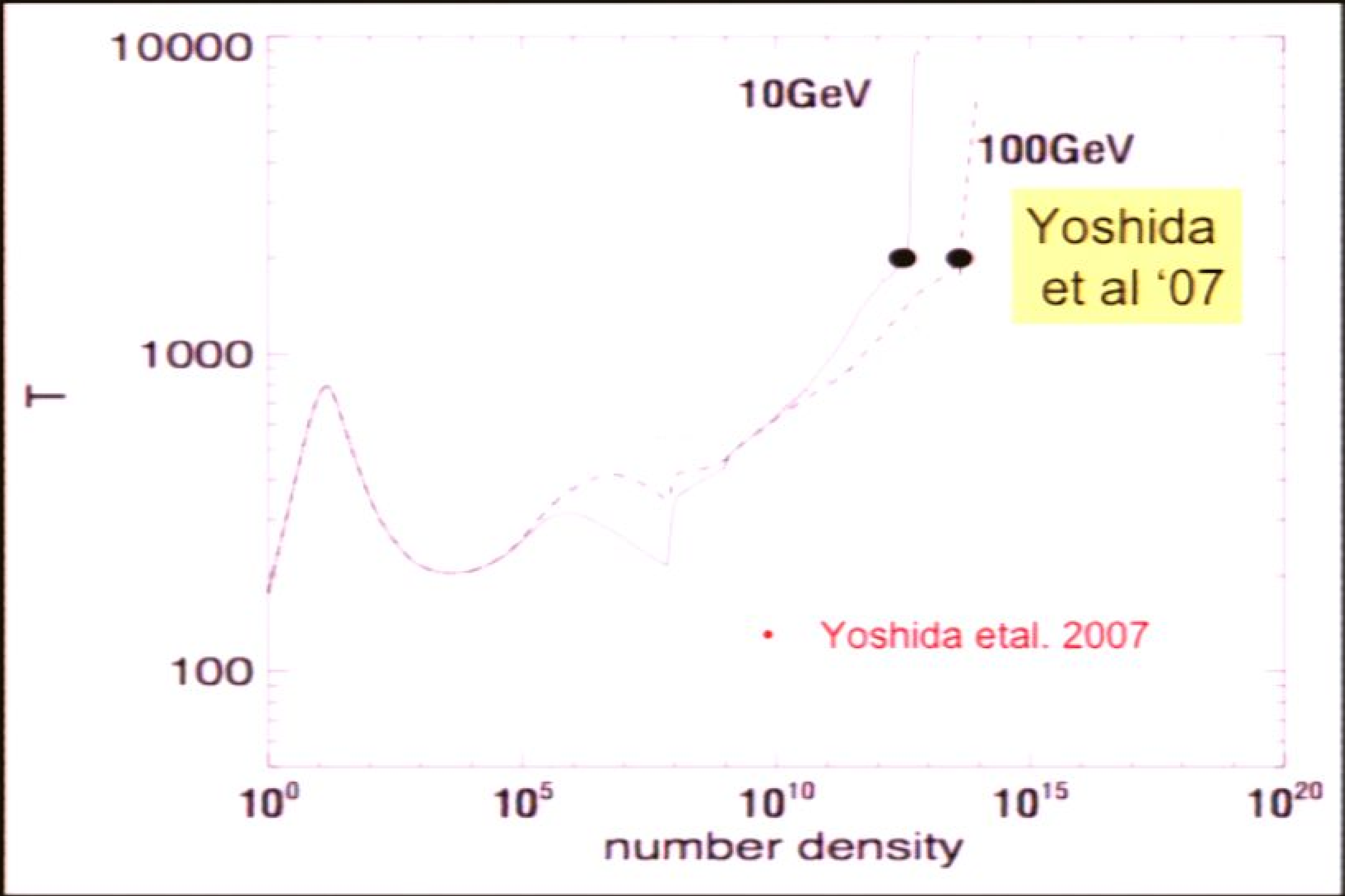
Dependence on concentration c_{vir}

- For $c_{vir}=1$ (instead of 10) at $z=19$, the DM density is lower by a factor of 4, the annihilation rate by a factor of 16, so that one needs to go to $n=10^{14}$ cm^{-3} (about an order of magnitude higher) before heating products remain stuck in protostar
- Same basic behavior (dark matter heating wins)

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



New stellar phase

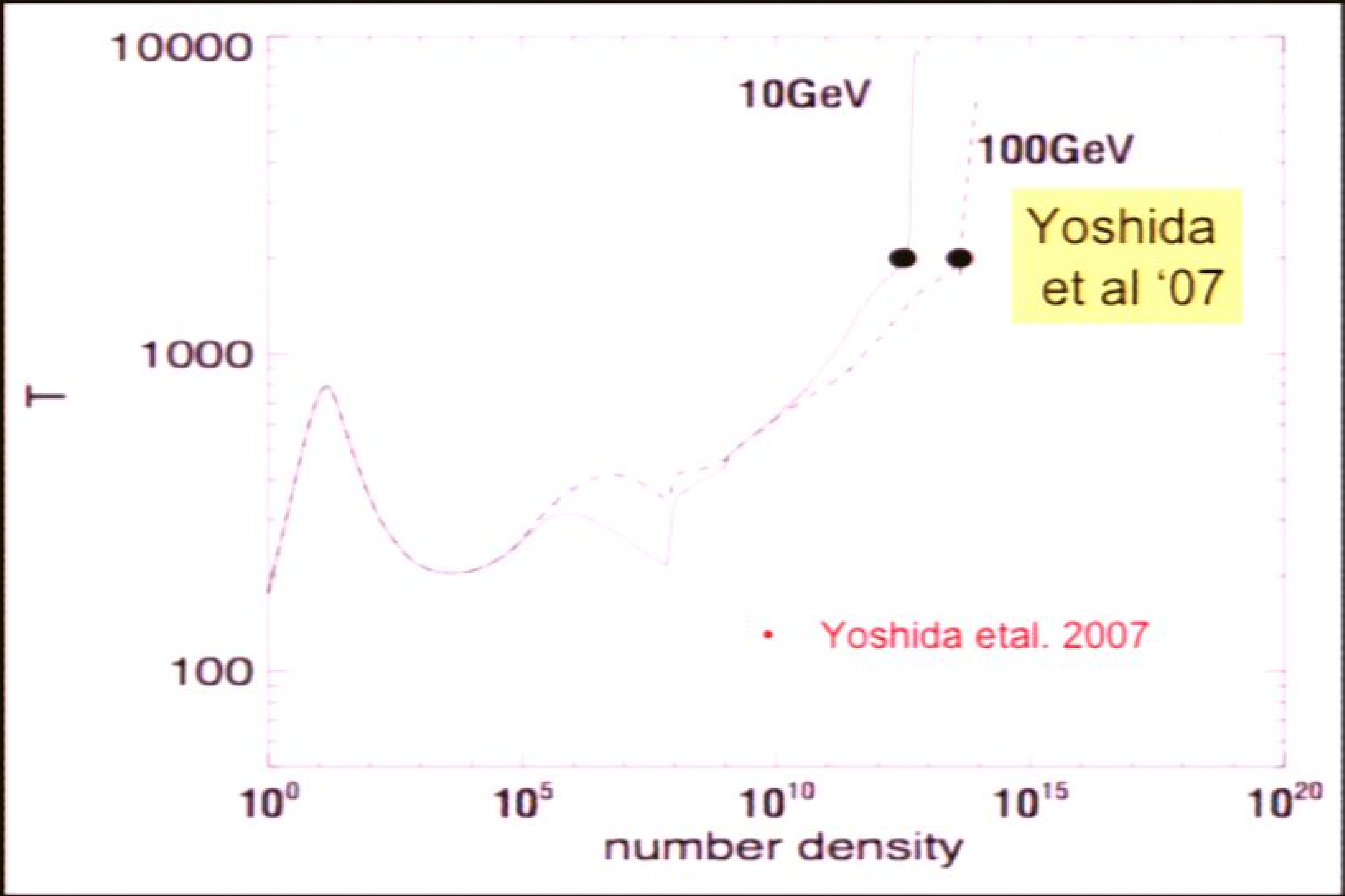
- Dark Star supported by DM annihilation rather than fusion
- DM is less than 2% of the mass of the star but provides the heat source (The Power of Darkness)
- Dark Stars are not dark: they shine
- Initially, they are giant stars that fill Earth's orbit

$m_\chi \approx 1$ 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?

New stellar phase, fueled by dark matter



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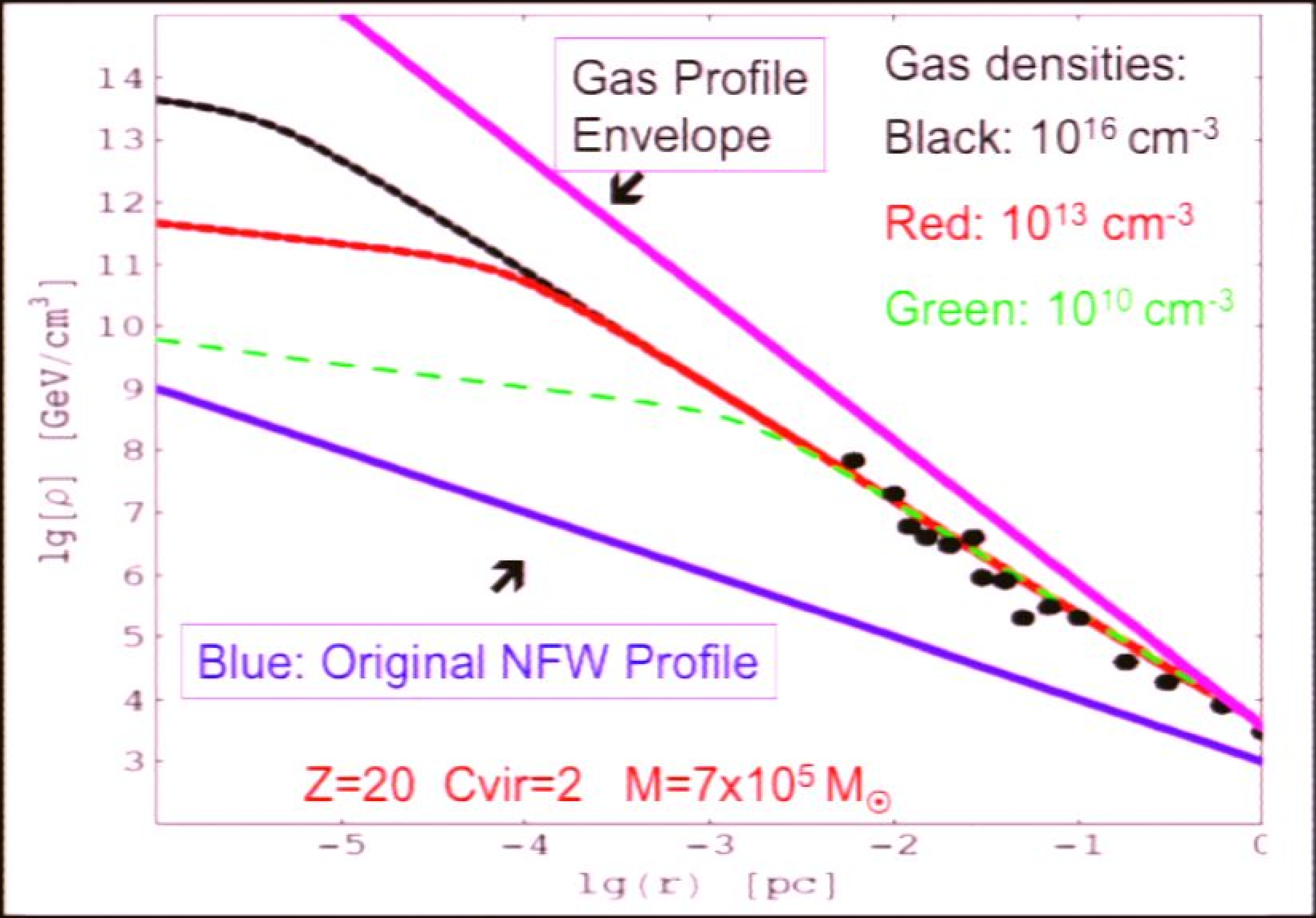

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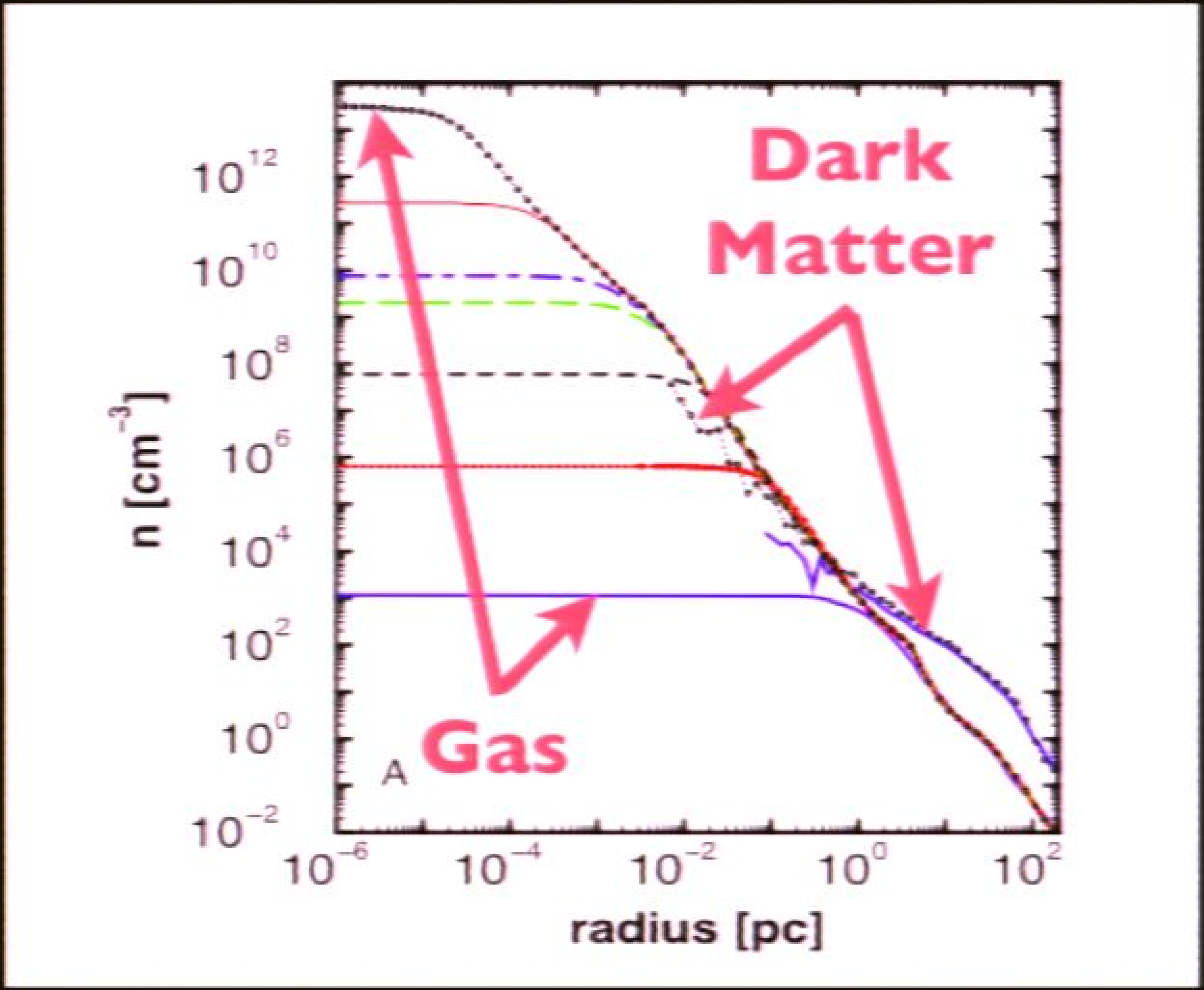

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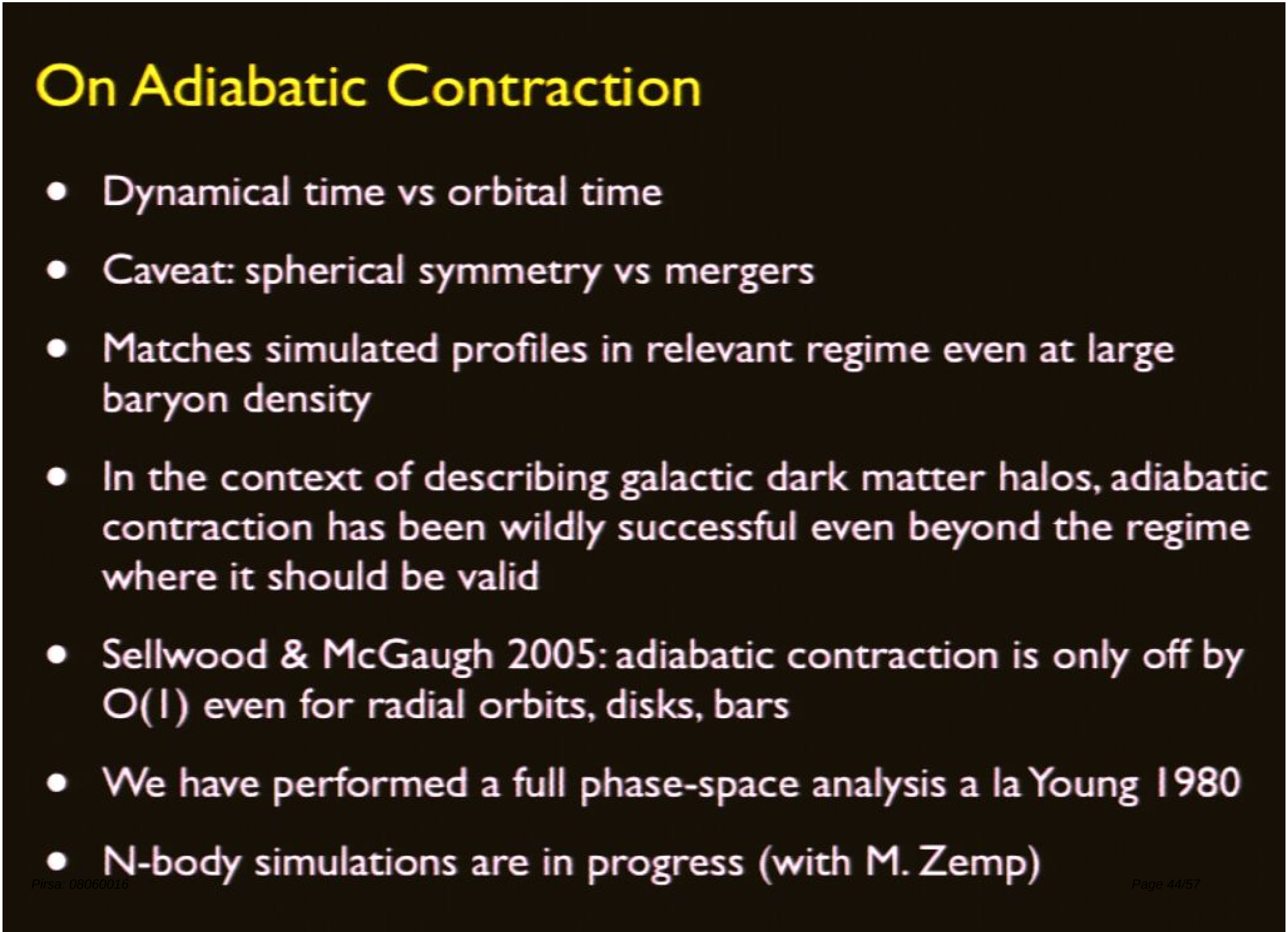

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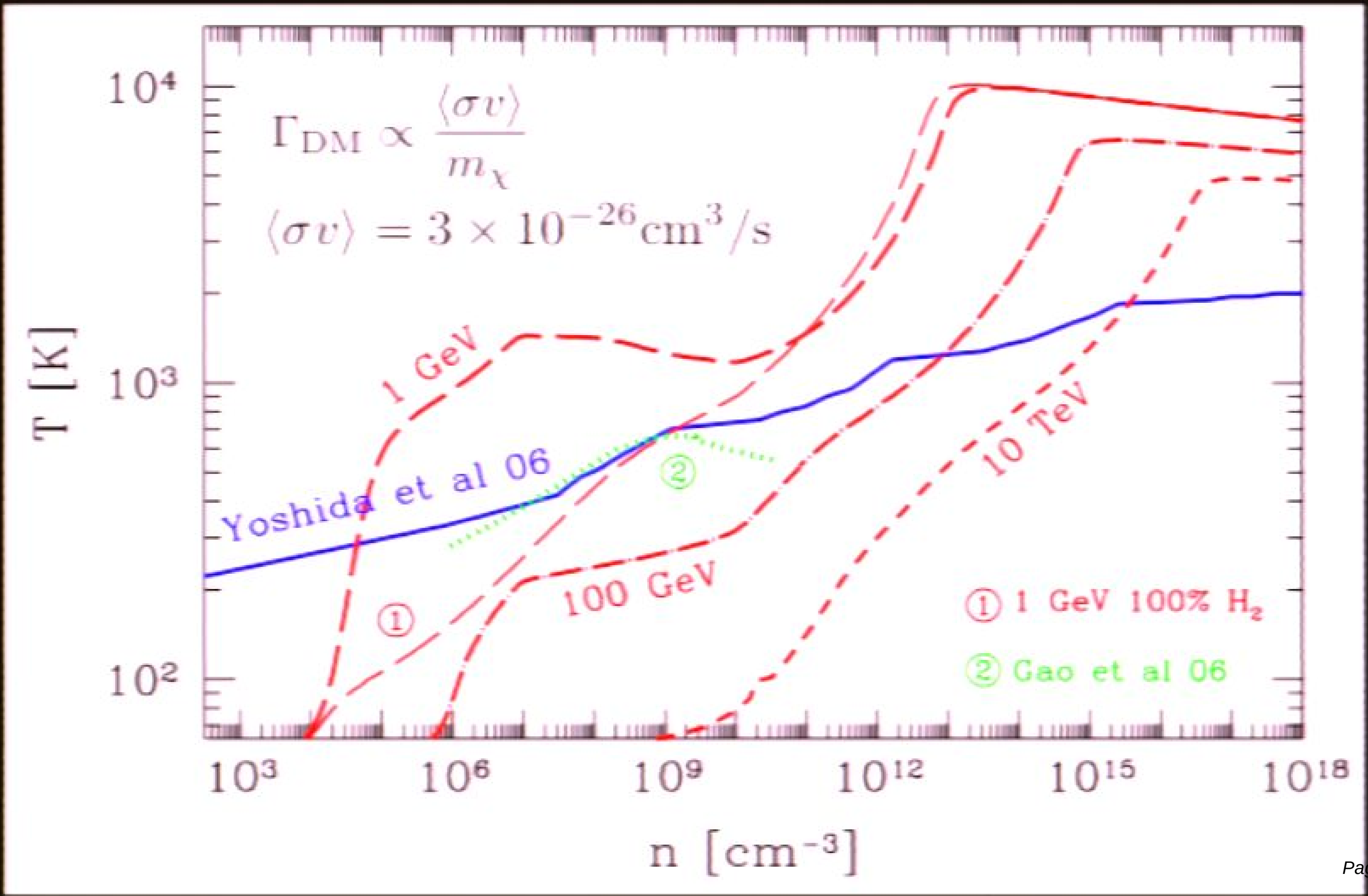

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- What is their subsequent evolution?
  How long does the dark star phase last?

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

$t_{\rm ann} \approx$ 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

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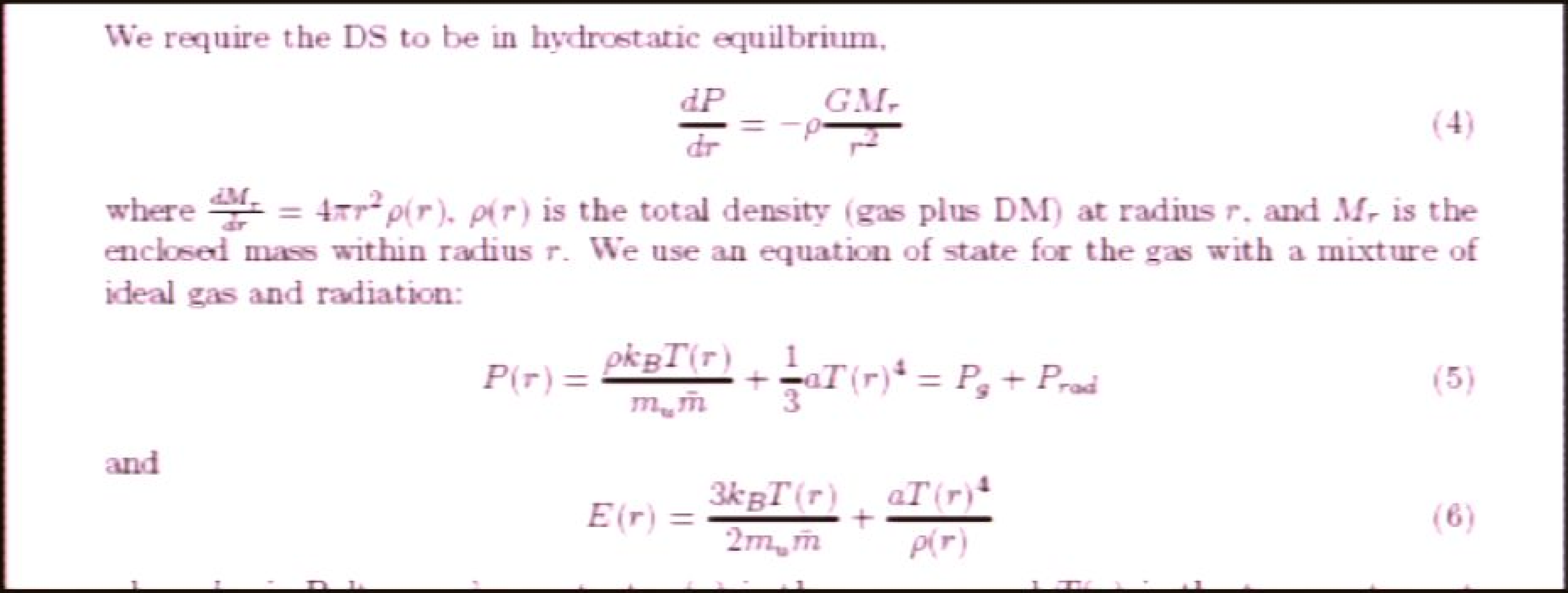


We require the DS to be in hydrostatic equilbrium,

$$\frac{dP}{dr} = -\rho \frac{GM_r}{r^2} \qquad (4)$$

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:

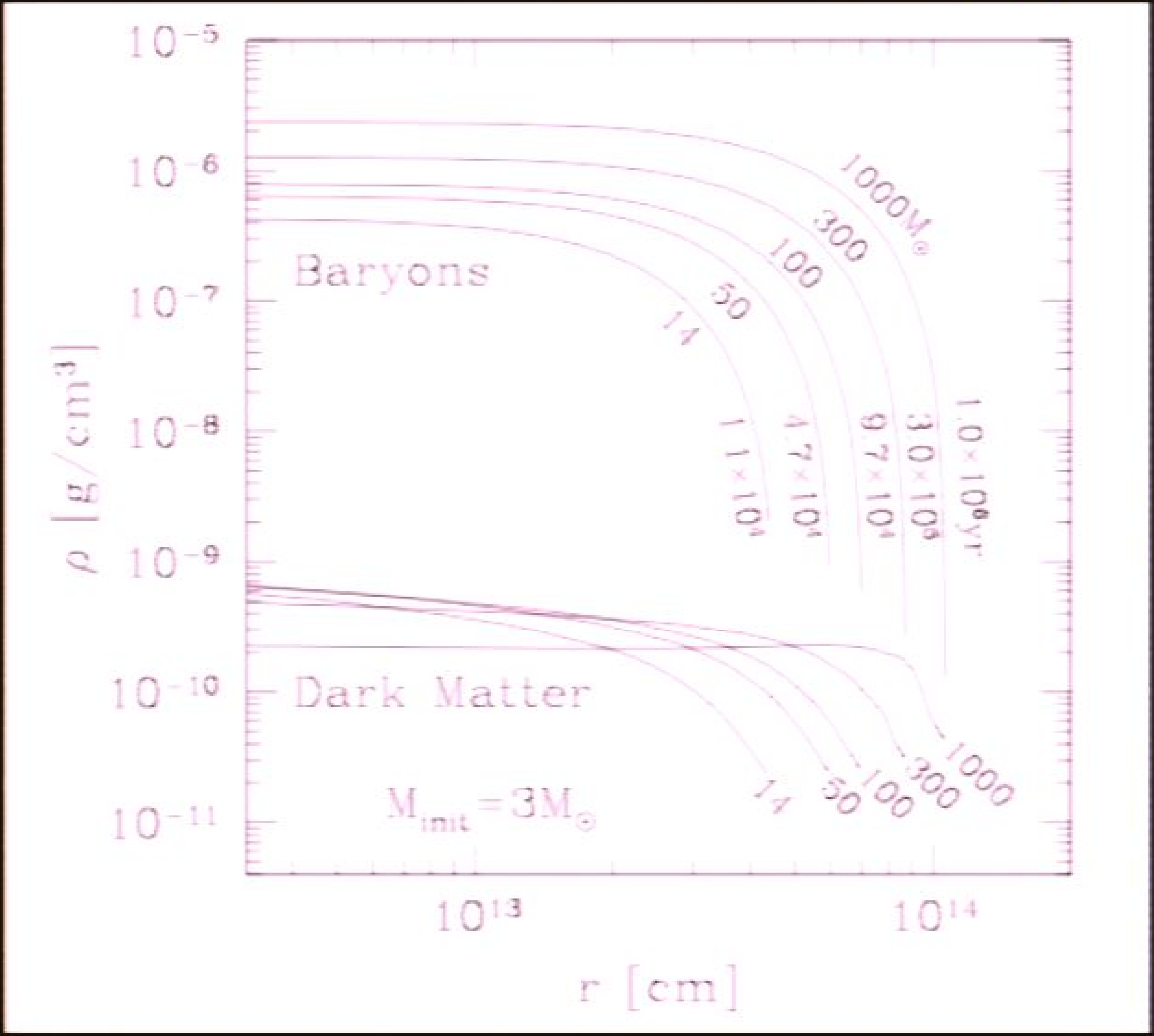
$$P(r) = \frac{\rho k_B T(r)}{m_u \bar{m}} + \frac{1}{3} a T(r)^4 = P_g + P_{rad} \qquad (5)$$

and

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

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 $z\sim6$
  - Accretion process (Tan & McKee 2003)

Observables

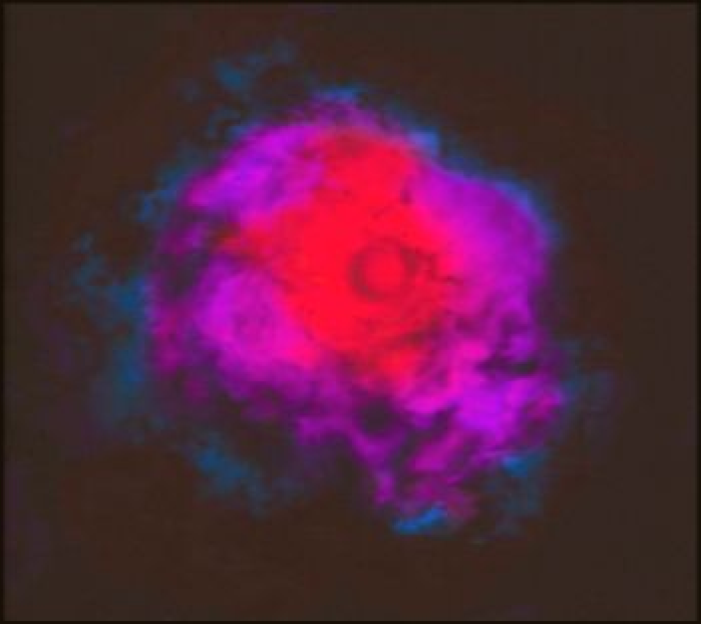
Dark stars are giant objects at redshift 10-20, with radii ~ 1 AU, luminosities ~$10^6\ L_\odot$, and masses ~$10^3\ M_\odot$

- 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