Dark Matter
And
The First Stars

A new phase of stellar evolution

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Our Results

- Dark Matter (DM) in proto-stellar haloes can dramatically alter the formation of the first stars
- The LSP (lightest supersymmetric particle) provides a heat source that prevents the protostar from further collapse, leading to a new stellar phase:
- The first stars in the universe are giant (> 1 A.U.) H/He stars powered by dark matter annihilation rather than by fusion

The First Stars

- Basic Properties:
  - Made only of H/He
  - Form inside DM haloes of $(10^5$-$10^6)\ M_\odot$
  - At $z = 10 - 50$
- Important for:
  - End of Dark Ages.
  - Reionize the universe.
  - Provide enriched gas for later stellar generations.
  - May be precusors to black holes which power quasars.

Dark Matter + Pop III Stars

- DM in protostellar haloes alters star formation of PopIII stars:
  - Dark Matter annihilation heats the collapsing gas cloud preventing further collapse, which halts the march toward the main sequence.
  - A “Dark Star” may result forming

    (a new Stellar phase)

Outline

- Dark Matter
  - The LSP (lightest SUSY particle)
  - 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:
  - At z = 10-50
  - Form inside DM haloes of $(10^5\text{-}10^6)\ M_\odot$
  - Baryons initially only 15%

- Dominant cooling Mechanism to allow collapse into a star is H_2

(Hollenbach and McKee '79)

H_2 Cooling and Collapse

Gas Density:

$n \leq 10^4\, cm^{-3}$ $\qquad \Gamma_{cool} \propto n^2$

$n \geq 10^4\, cm^{-3}$ $\qquad \Gamma_{cool} \propto n$

n.b fraction of $\dfrac{\text{Molecular H}}{\text{Atomic H}} \propto 10^{-3}$

Cooling

3-Body Reaction

$$n \approx 10^{8} cm^{-3}$$

$H+H+H \rightarrow H_2+H$

Becomes 100% molecular

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

Opacity → less efficient cooling

Cooling to Collapse

Other cooling processes

$10^{14}\,cm^{-3}$	CIE
$10^{15}\,cm^{-3}$	Disassociation
$10^{18}\,cm^{-3}$	Atomic

Mini Core Forms at $n \approx 10^{22}\,cm^{-3}$

(Omukai and Nishi '98)

Two Scales

- Jeans Mass ~ 1000 $M_\odot$

  at $n \approx 10^4\, cm^{-3}$

- Central Core Mass (requires cooling)

  ↓ accretion

  Final stellar Mass??

Lightest Super Symmetric Particle: neutralino

- Most popular dark matter candidate.
- Mass 1Gev-10TeV

  (canonical value 100GeV)
- Self 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!

Dark Matter Annihilation

- Annihilation mediated by weak interaction.
- Thus for the standard neutralino (WIMPS):

$$\Omega_\chi h^2 = \frac{3\times10^{-27}\ cm^3/\mathrm{sec}}{<\sigma v>_{ann}}$$

- **On going searches**: LHC, CDMS XENON, GLAST, ICECUBE

Dark Matter

Our Canonical Case: $<\sigma v>_{ann} = 3\text{x}10^{-26} cm^3/\sec$

$M_\chi = 100 GeV$

Minimal supergravity (SUGRA)

- Mass 50GeV-2TeV
- $<\sigma v>_{ann}$ can be an order of magnitude bigger

Nonthermal relics

- $<\sigma v>_{ann}$ can be much larger!

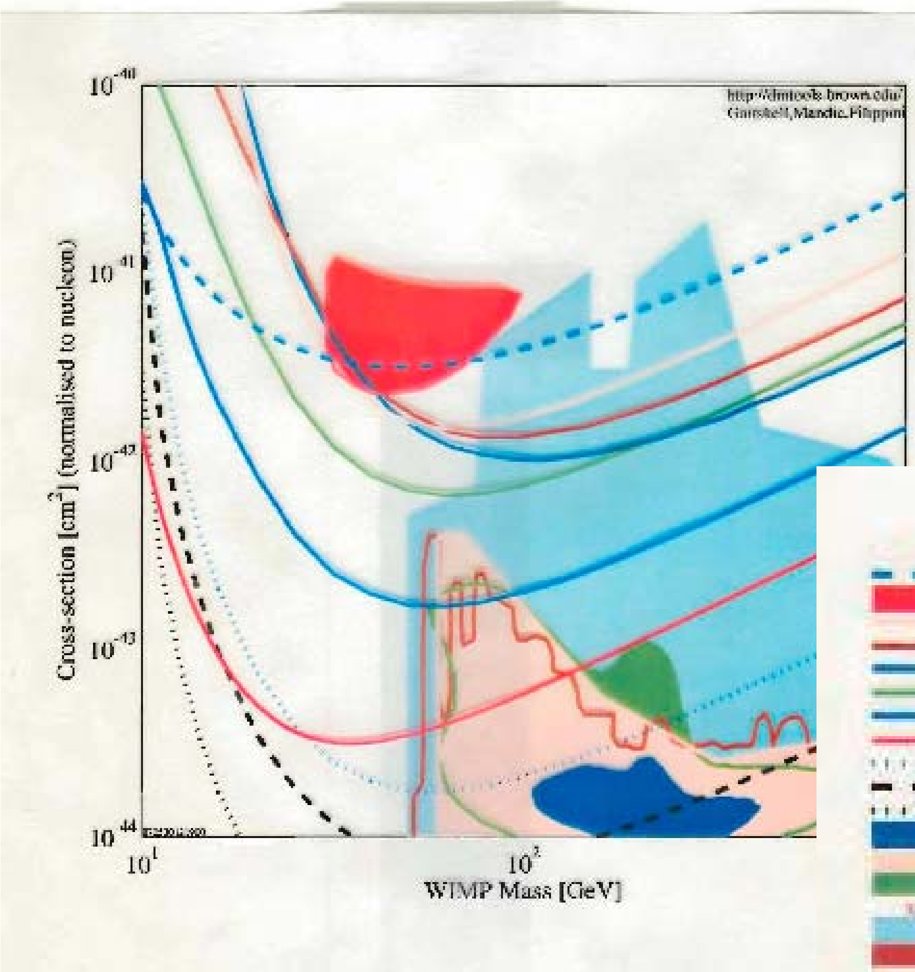
Dark Matter

- We consider a range:
  - Mass: 1GeV-10TeV
  - a range of Cross sections
- Results apply to other candidates
  - Sterile ν
  - K-K particles

Detecting Dark Matter Particles

- Accelerators
- Direct Detection
- Indirect Detection (Neutrinos)
    - Sun (Silk,Olive,Srednicki '85)
    - Earth (Freese '86; Krauss, Srednicki, Wilczek '86)
- Indirect Detection (Gamma Rays, positrons)
    - Milky Way Halo
    - Galactic Center
    - Anomalous signals seen in HEAT (e+), HESS, CANGAROO, WMAP, EGRET, etc.

Status of Direct Detection Experiments



Red region: DAMA experiment claimed detection via annual modulation (Drukier Freese, Spergel 1986; Freese,Frieman, Gould 1987); hard to explain in light of null results from other experiments. Spin-dependent Interactions still possible.

The future: 1 ton XENON detector.

Hierarchical Structure Formation

Smallest objects form first

Pop III stars ($10^5 M_\odot$)

Merge → galaxies

Merge → clusters etc.

Numerical Simulations

- NFW Profile (Navarro,Frank,white ‘96)

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

$\rho_o =$ “Central Density”

$\rho(r_s) = 1/4\ \rho_o$

$r_s =$ “Scale Radius”

Other Variables

- We can exchange

$$\rho_o, r_s \quad \rightarrow \quad M_{vir}, C_{vir}$$

$$C_{vir} = \frac{R_{vir}}{r_s}$$

$$M_{vir} = 200 \frac{4\pi}{3} R_{vir}^3 \rho_{crit}(z)$$

- R_{vir} radius at which

$$\rho_{DM} = 200 \times$$

The DM density of the universe at the time of formation.

Dark Matter Density Profile

- Adiabatic contraction (a prescription):
  - As baryons fall into core, DM particles respond to potential well.

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

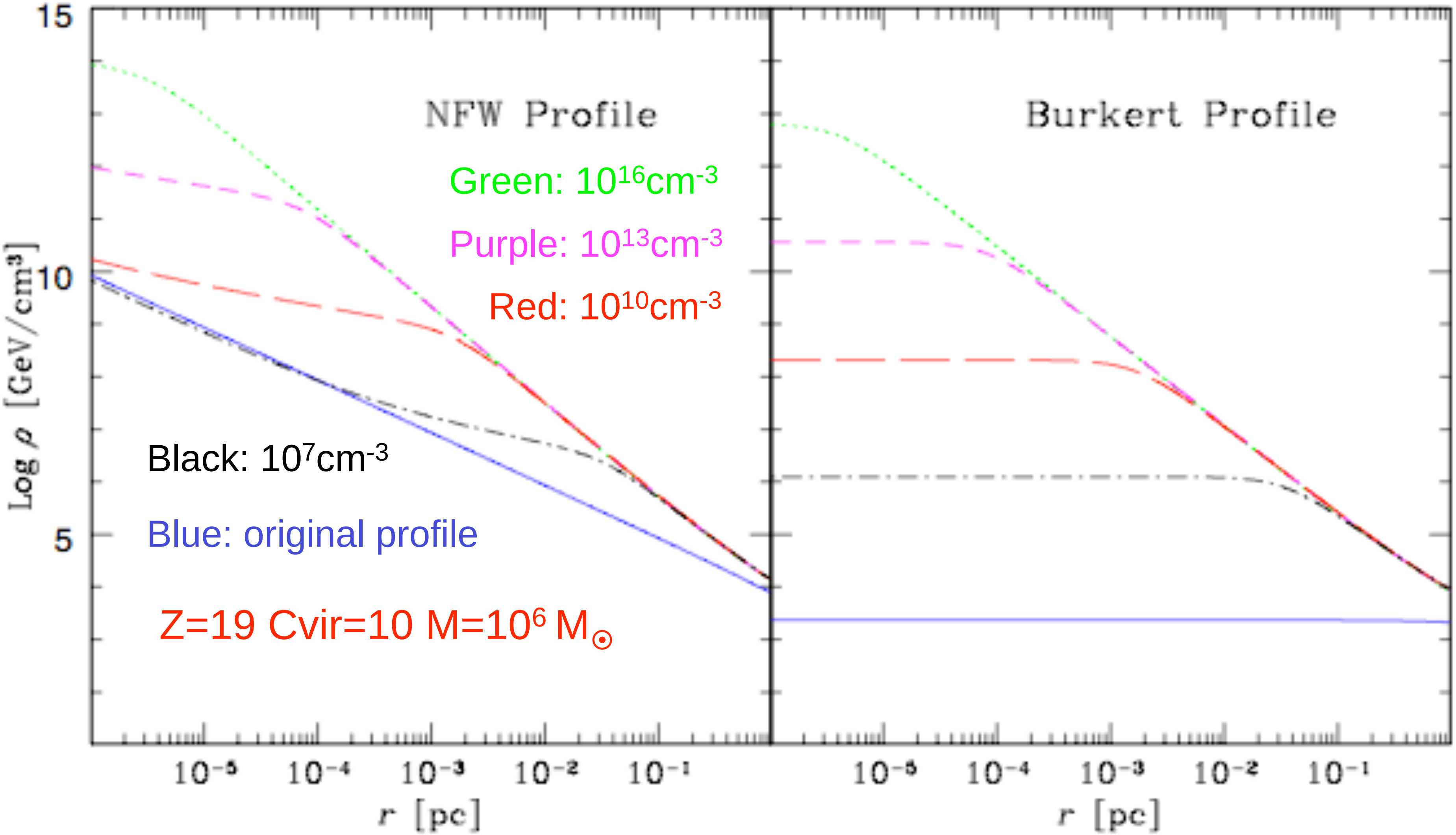
- Profile that we find:

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

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

(using prescription from Blumenthal, Faber, Flores, and Primack ‘86)

Dark Matter Profile



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

Adiabatic Conditions

- Dynamical time vs. orbital time
- Caveat: Spherical symmetry vs. mergers
- Matches simulated profiles in relevant regime even of large baryon density
- In the context of describing galactic dark matter haloes, adiabatic contraction has been wildly successful even beyond the regime where it should be valid.

On: Adiabatic Contraction

- Peebles ‘72 Young ‘81: simulations of black hole with collisionless baryons. Found density profile $r^{-1.5}$. Doesn’t apply here: 1) point source BH 2) isothermal sphere for collisionless matter is a bad approximation (vs NFW).
- Merritt ‘03: Starting with collisionless matter with density r^{0}-r^{-2} responding to central black hole, numerically found final profile $r^{-2.25}$-$r^{-2.5}$, i.e., much steeper.
- Case of merging black holes and effect on profile of collisionless matter has not been studied numerical due to spurious relaxation.
- We are working on this.

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

Crucial Transition

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

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

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

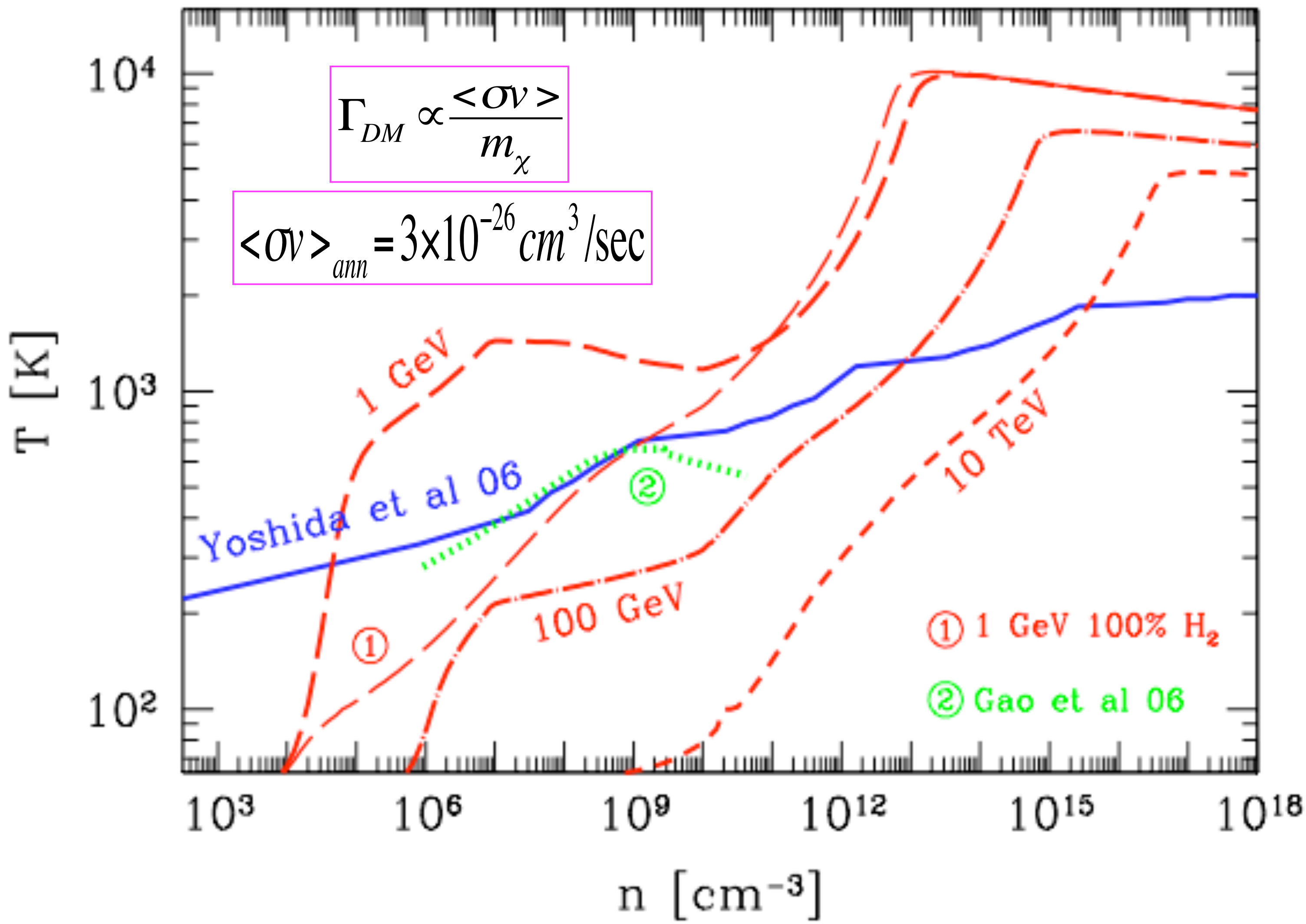
$$m_\chi \approx 10\ \mathrm{TeV} \rightarrow n \approx 10^{15-16}/\mathrm{cm}^3$$

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

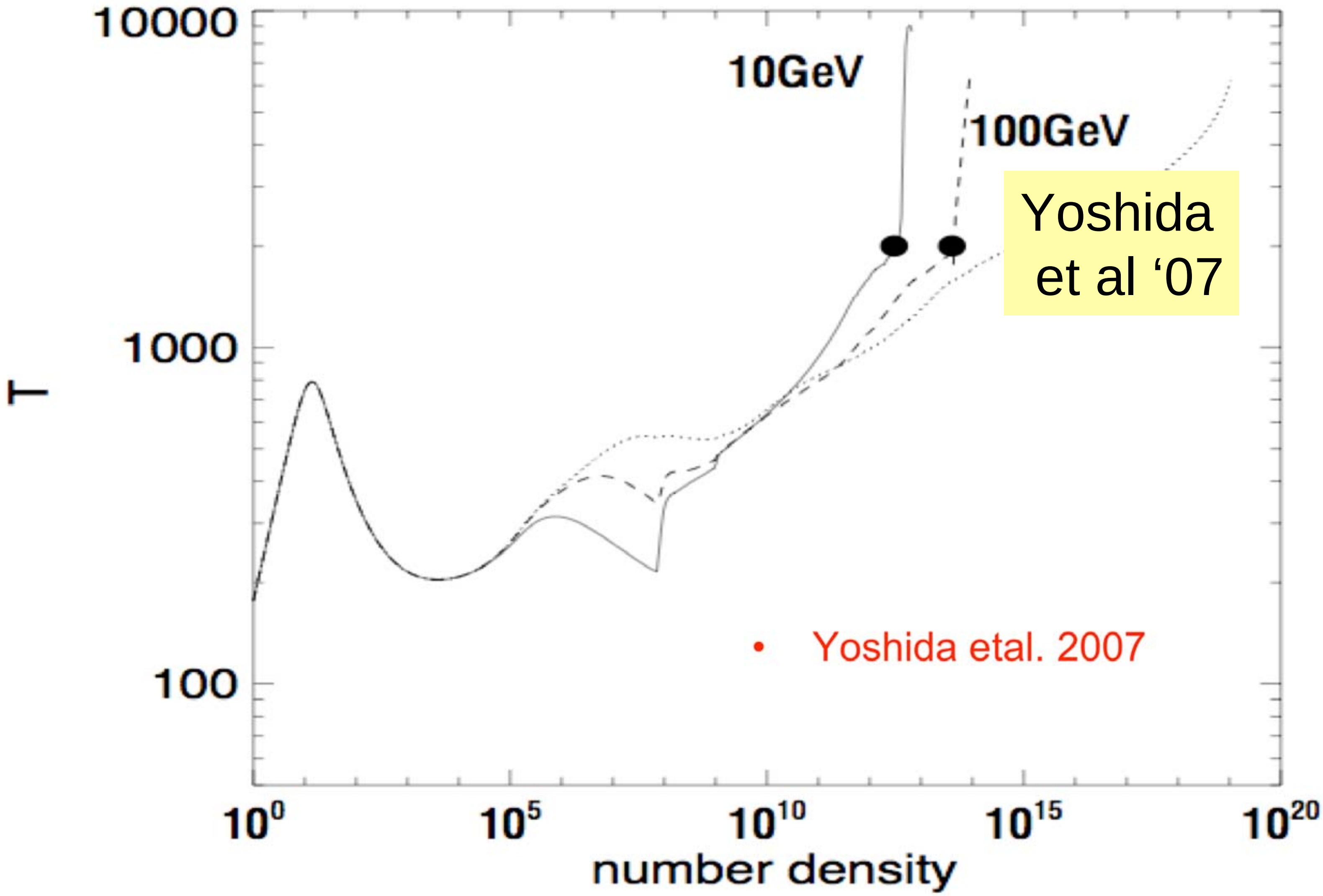
Dependence on concentration

- N.b. For Cvir = 1 at z=19, the DM density is lower by a factor of 4, annihilation rate by factor of 16, s.t. have 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)

DM 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



Possible Outcomes

- "Dark Star" supported by DM annihilation rather than fusion:

$m_\chi \approx 1\ \mathrm{GeV}$	core radius 960 a.u.	Mass 0.6 $M_\odot$
$m_\chi \approx 100\ \mathrm{GeV}$	core radius 17 a.u.	Mass 11 $M_\odot$

- Could still exist today.
- Would not re-ionize the universe.
- Would not produce the heavy elements

Lifetime

- Life time:

$$T_e \approx \frac{m_\chi}{\rho_\chi < \sigma v >}$$

- For example for our canonical case:

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

- v.s. dynamical time of <10^{3}yr:

  the core may fill in with DM again s.t. annihilation heating continues for a longer time

Second Possibility
Dark Stellar phase

- Shorter than current lifetime of the universe.
- 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.

- Which is the most likely outcome?

work with N. Yoshida

Possible effects

- Reionization: Delayed due to later formation of Pop III stars? Sped up by DM annihilation products?
- --
- Pop III initial mass function:

  Nuggets of $10^{-3}\ M_{\odot}$ form as usual, but DM at Eddington luminosity could slow prevent spherical accretion → different stellar mass distribution
- Make Larger objects? Accrete to make $10^{9}\ M_{\odot}$ BH observed at z~6.
- Accretion process (Tan and McKee ‘03)

Observables

- Dark stars are giant objects with core radii > 1 a.u.
  - Find them with lensing? JWST?
- ν annihilation products in AMANDA or ICECUBE.
- γ in GLAST, HESS, VERITAS, MAGIC, etc.
- Reionization of the universe affected
  - 21 cm line.

Observables (continued)

- Can neutralinos be discovered this way or can we learn more about their properties?

Summary

- DM annihilation heating in Pop III protostars can delay/block their production.
- A new stellar phase DARK STARS
  - Produced by DM annihilating and not by fusion.

New Effect:
Annihilation in the First Stars!

- Today's stars do not Form in DM Haloes.
- The first stars do!
- As the first stars contract they bring DM in with them.
    - Densities with interesting annihilation rates.