Dark Stars: Dark Matter Annihilation in the First Stars.

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

PAPER 1

arXiv:0802.1724
K. Freese, D. Spolyar, and A. Aguirre

arXiv:0805.3540
K. Freese, P. Gondolo, J.A. Sellwood, and D. Spolyar

arXiv:0806.0617
K. Freese, P. Bodenheimer, D. Spolyar, and P. Gondolo

DS, PB, KF, PG arXiv:0903.3070

And N. Yoshida

Radiation:
0.005%

Chemical Elements:
(other than H & He) 0.025%

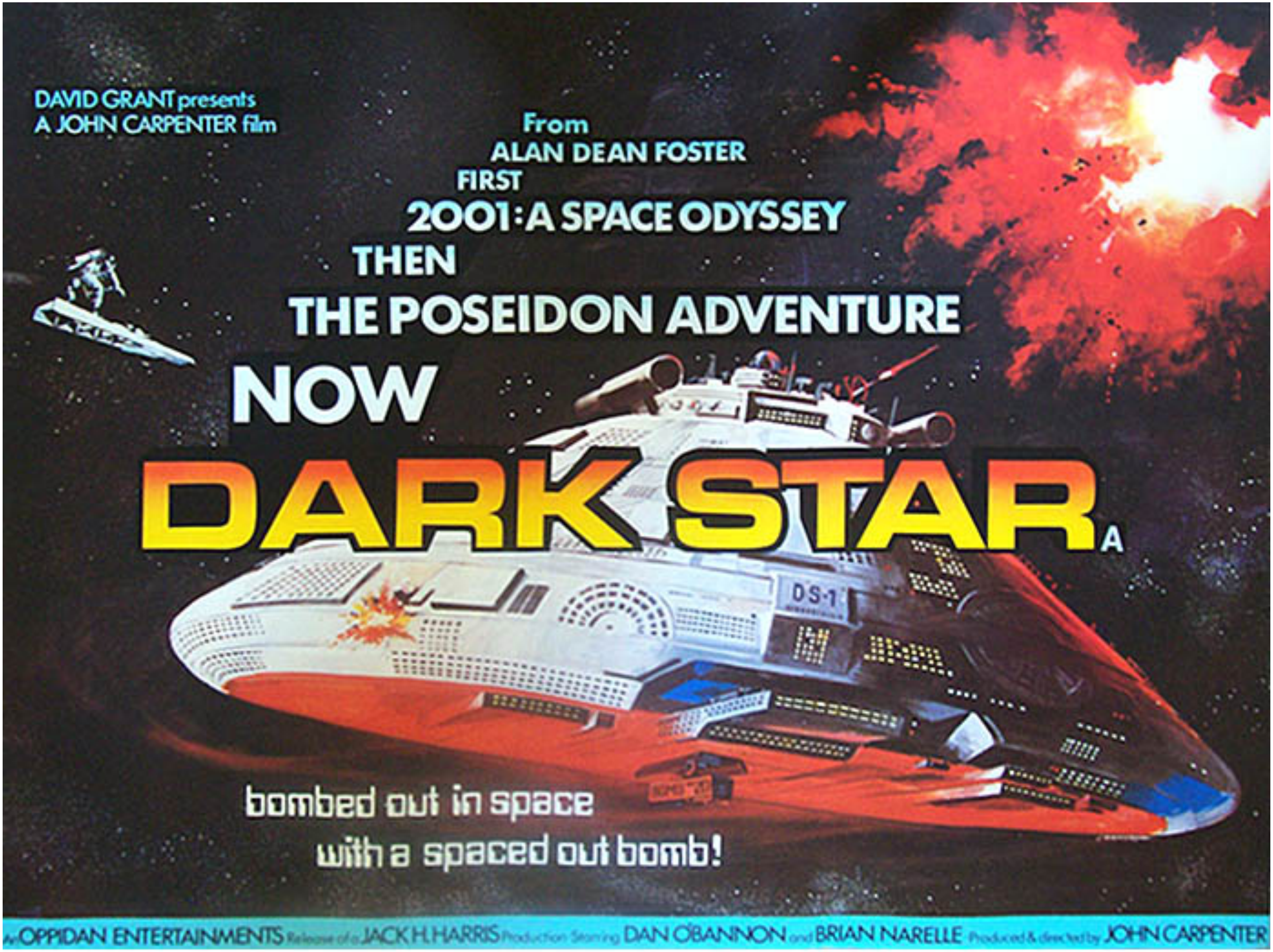
Neutrinos:
0.47%

Stars:
0.5%

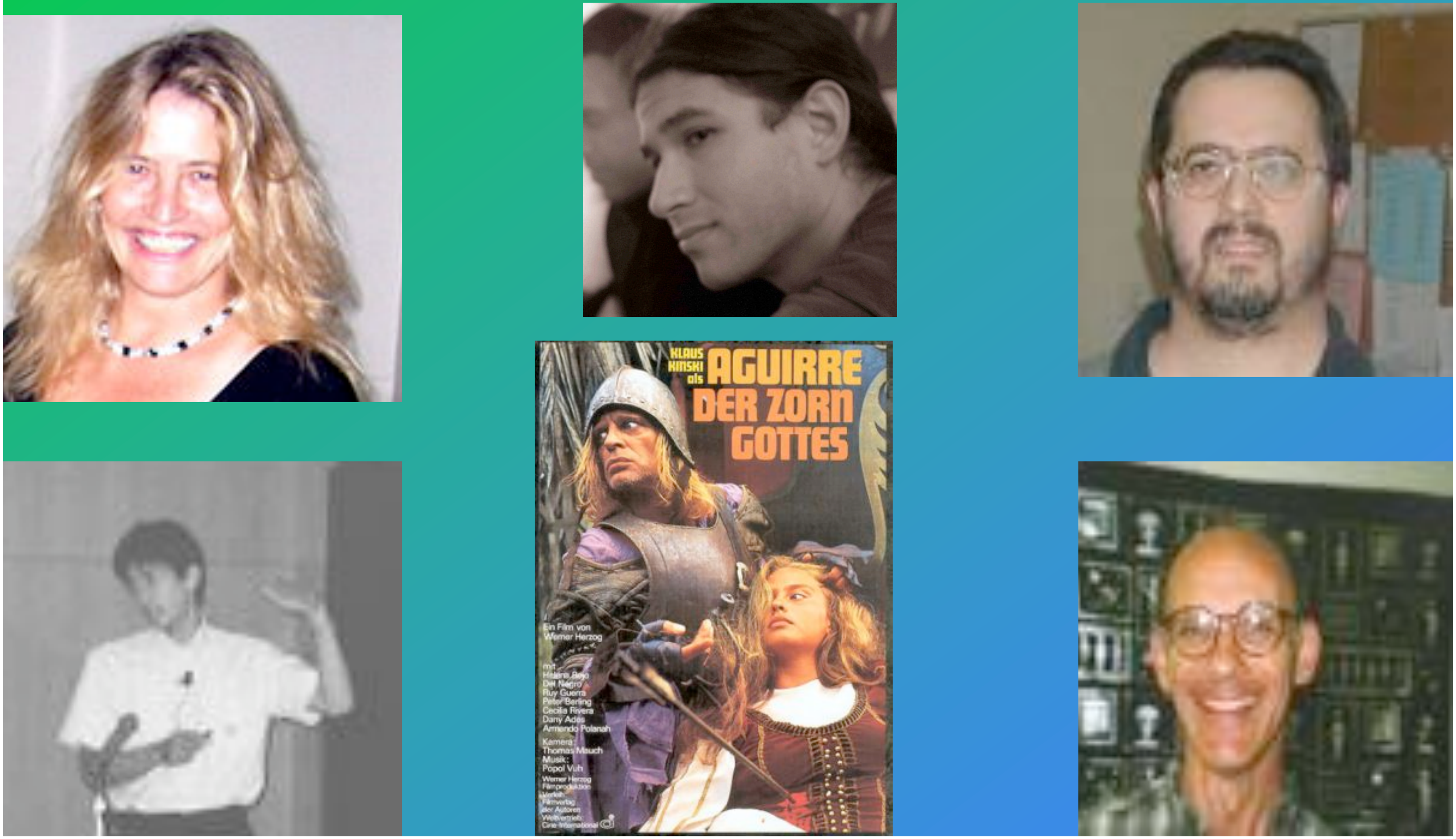
H & He:
gas 4%

Cold Dark Matter:
(CDM) 25%

Dark Energy (Λ):
70%


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



Spiritual Leader

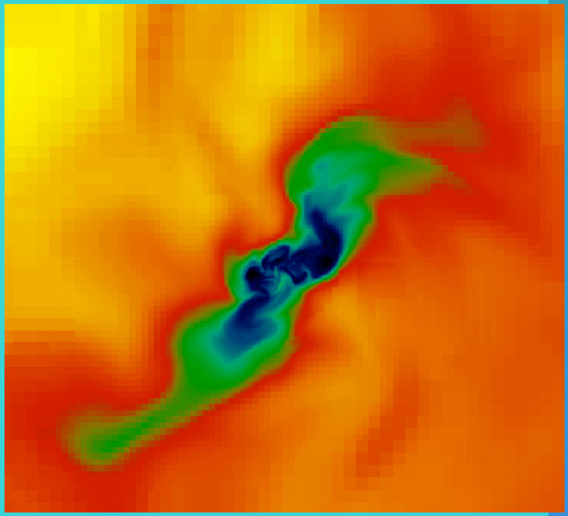
Dark Stars

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 over a million years

First Stars: Standard Picture

- Formation Basics:
  - First luminous objects ever.
  - At $z = 10\text{-}50$
  - Form inside DM haloes of $\sim 10^6 M_\odot$
  - 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

The First Stars
Also The First Structure

- Important for:
    - End of Dark Ages.
    - Reionize the universe.
    - Provide enriched gas for later stellar generations.
    - May be precursors to black holes which power quasars.

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.
- Hence the name- Dark Star (DS)
- Change: Reionization, Early Stellar Enrichment, Early Big Black Holes.
- Discover DM.

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 as the gas cloud collapses.
- DM annihilates more and more rapidly as its densities increase
- At a high enough DM density, the DM heating overwhelms any cooling mechanisms which stops the cloud from continuing to cool and collapse.

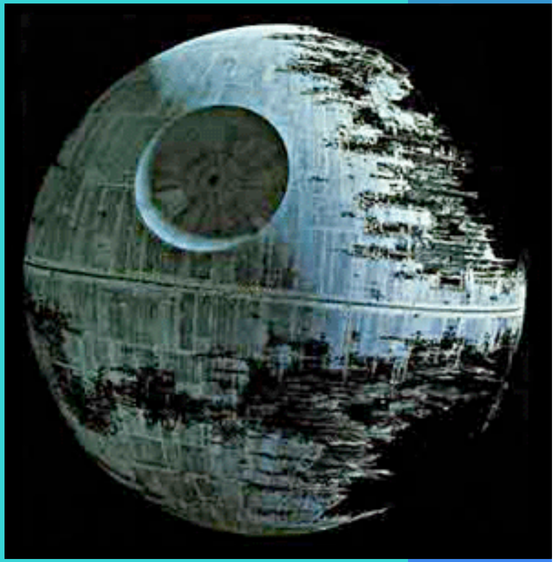
Basic Picture Continued

- Thus a gas cloud forms which is supported by DM annihilation
- More DM and gas accretes onto the initial core which potentially leads to a very massive gas cloud supported by DM annihilation.
- If it were fusion, we would call it a star.
- Since it is DM annihilation powered, we call it a Dark Star
- DM in the star comes from Adiabatic Contraction and DM capture.

Outline

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

  Life in the Roaring 20's
- Dark Star Born
- Stellar structure
- Return of the Dark Star during fusion era



Hierarchical Structure Formation

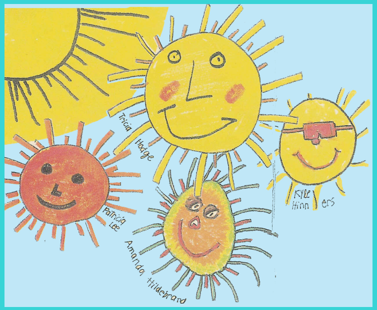
Smallest objects form first (earth mass)

Merge to ever larger structures

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

Merge → galaxies

Merge → clusters



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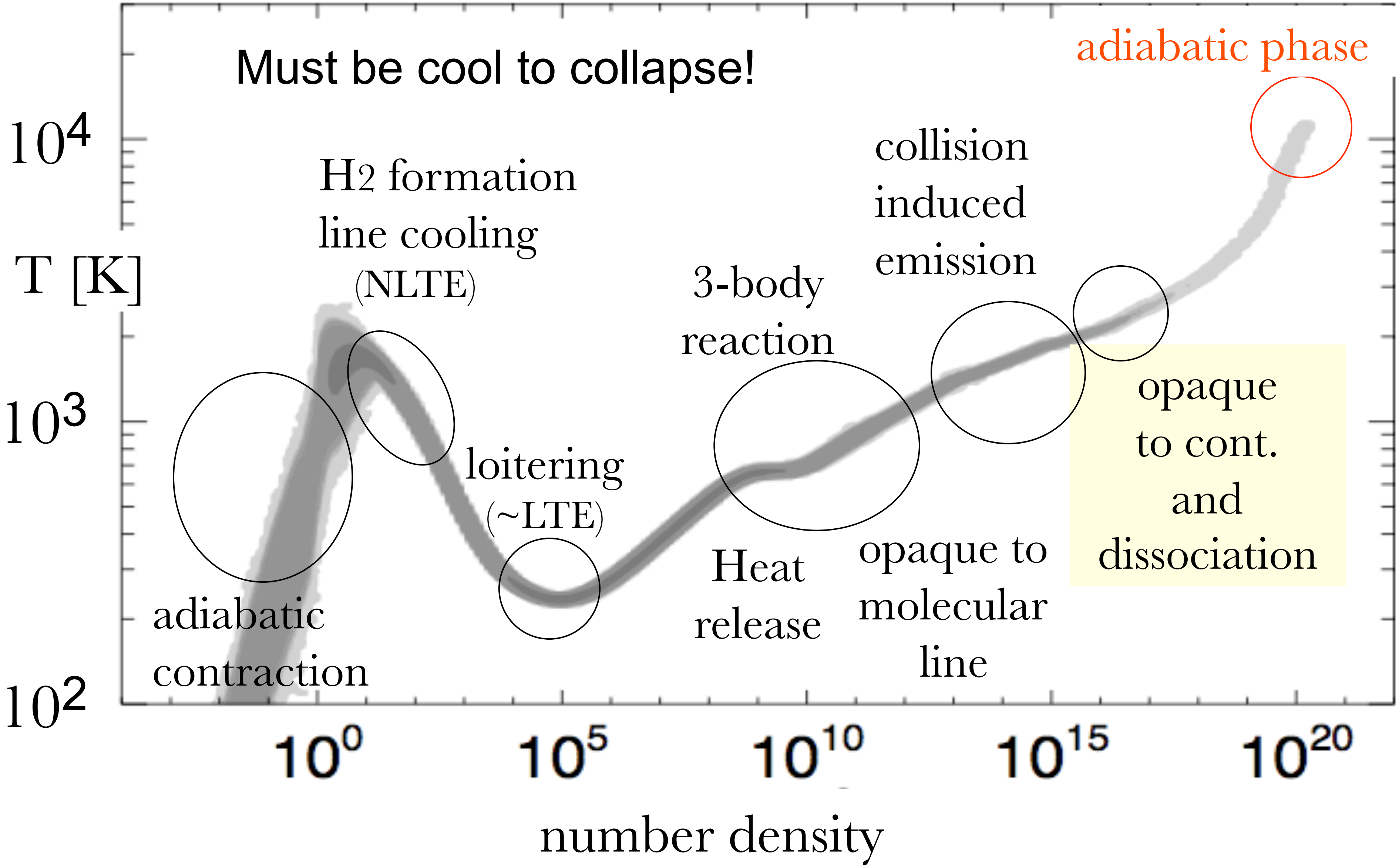
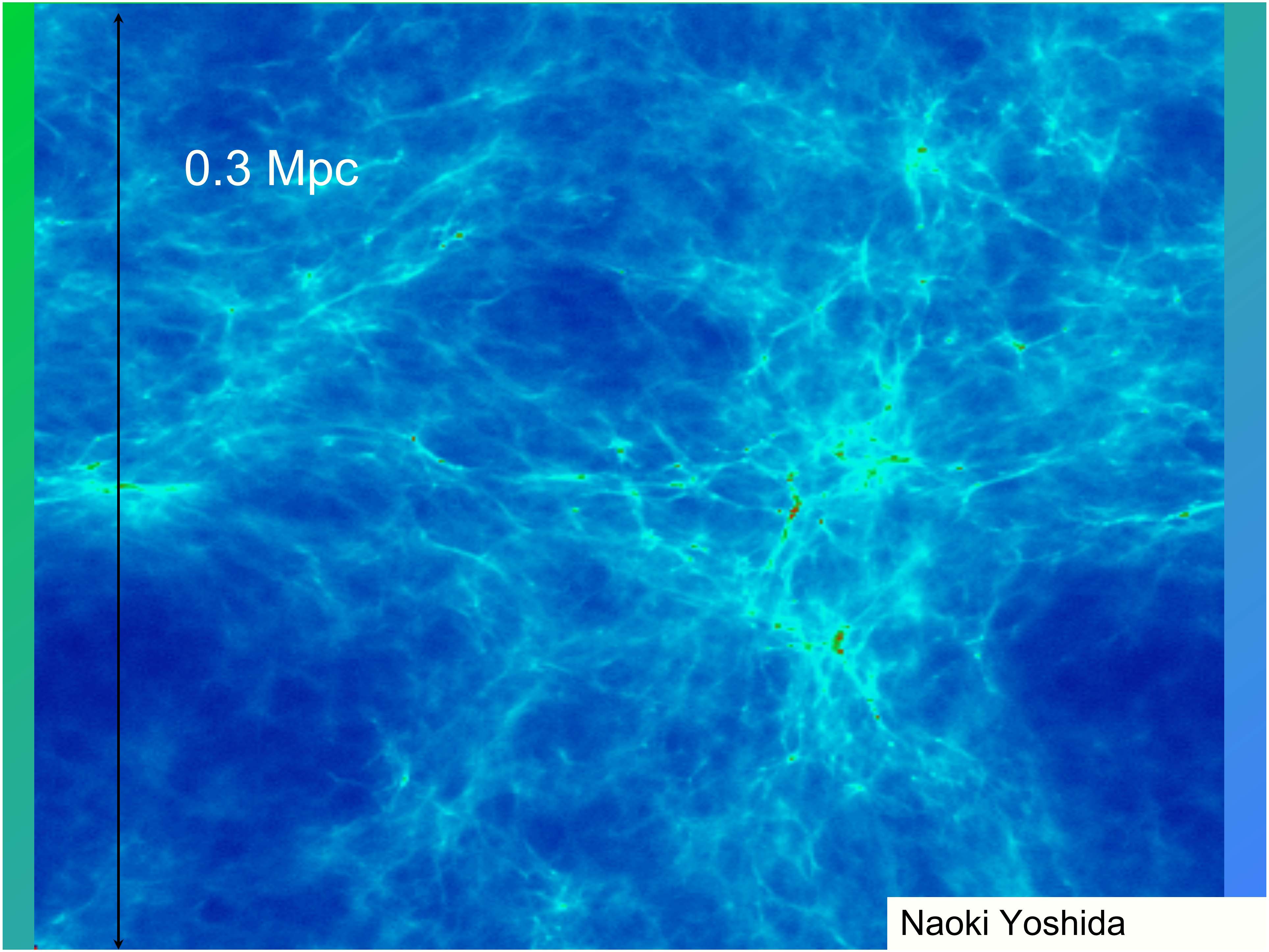
Scale of the Halo

- 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

H_2 Cooling and Collapse

Gas Density:

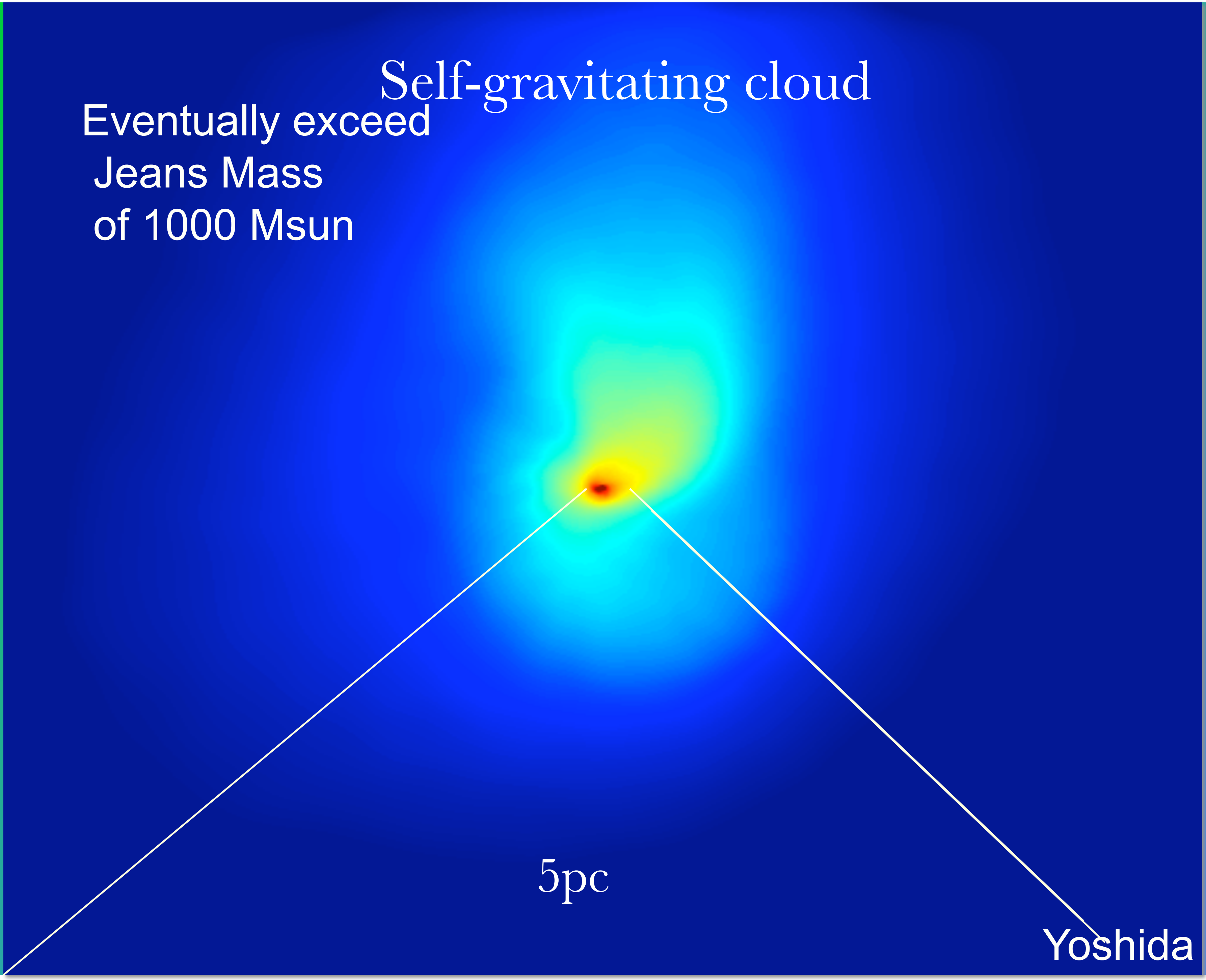
$n \leq 10^4 cm^{-3}$ $\Gamma_{cool} \propto n^2$

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

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

Self-gravitating cloud

Eventually exceed
Jeans Mass
of 1000 Msun



Yoshida

Cooling

3-Body Reaction

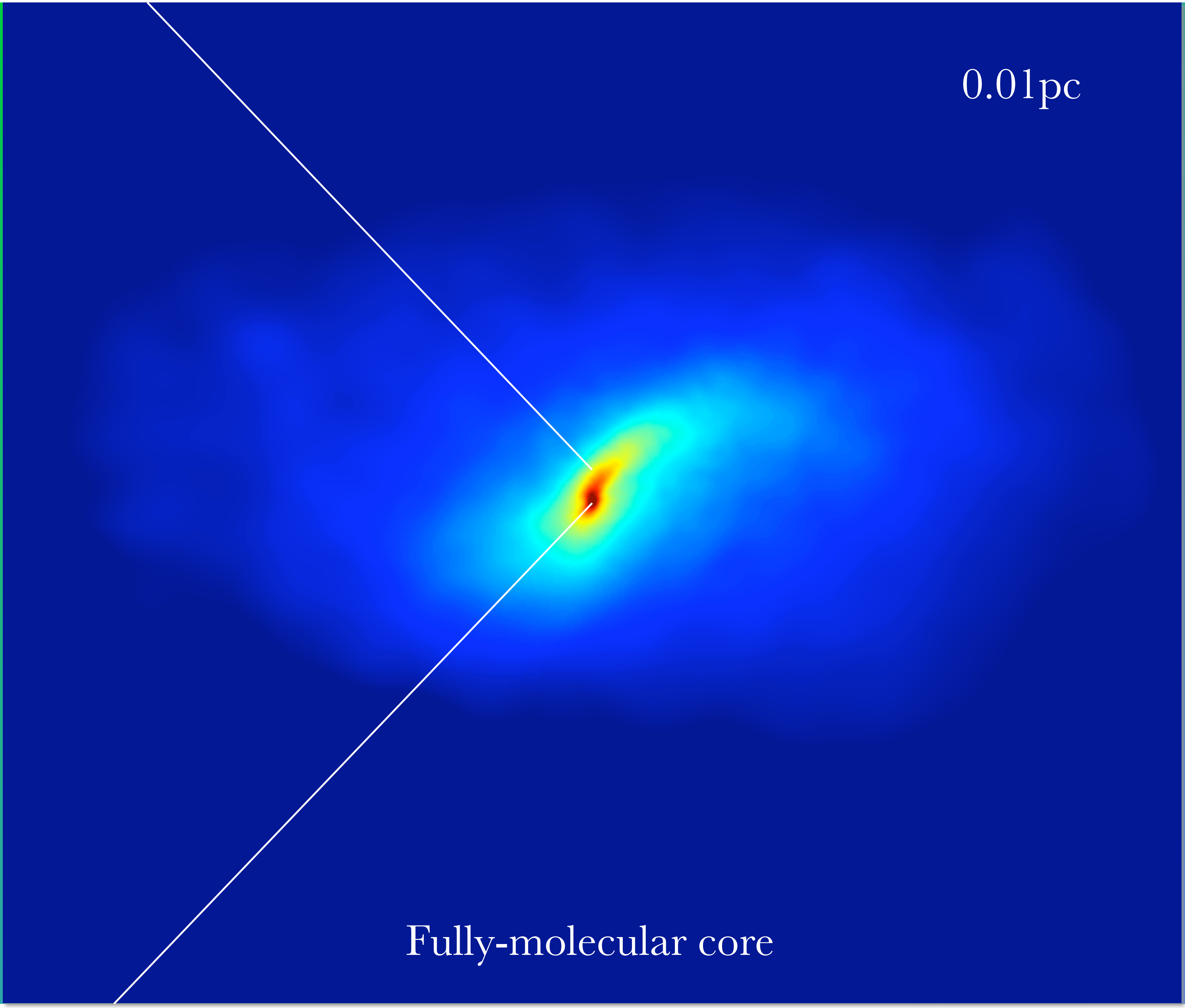
$$n \approx 10^{8}\,cm^{-3}$$

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

Becomes 100% molecular

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

Opacity → less efficient cooling



Fully-molecular core

Cooling to Collapse

Other cooling processes

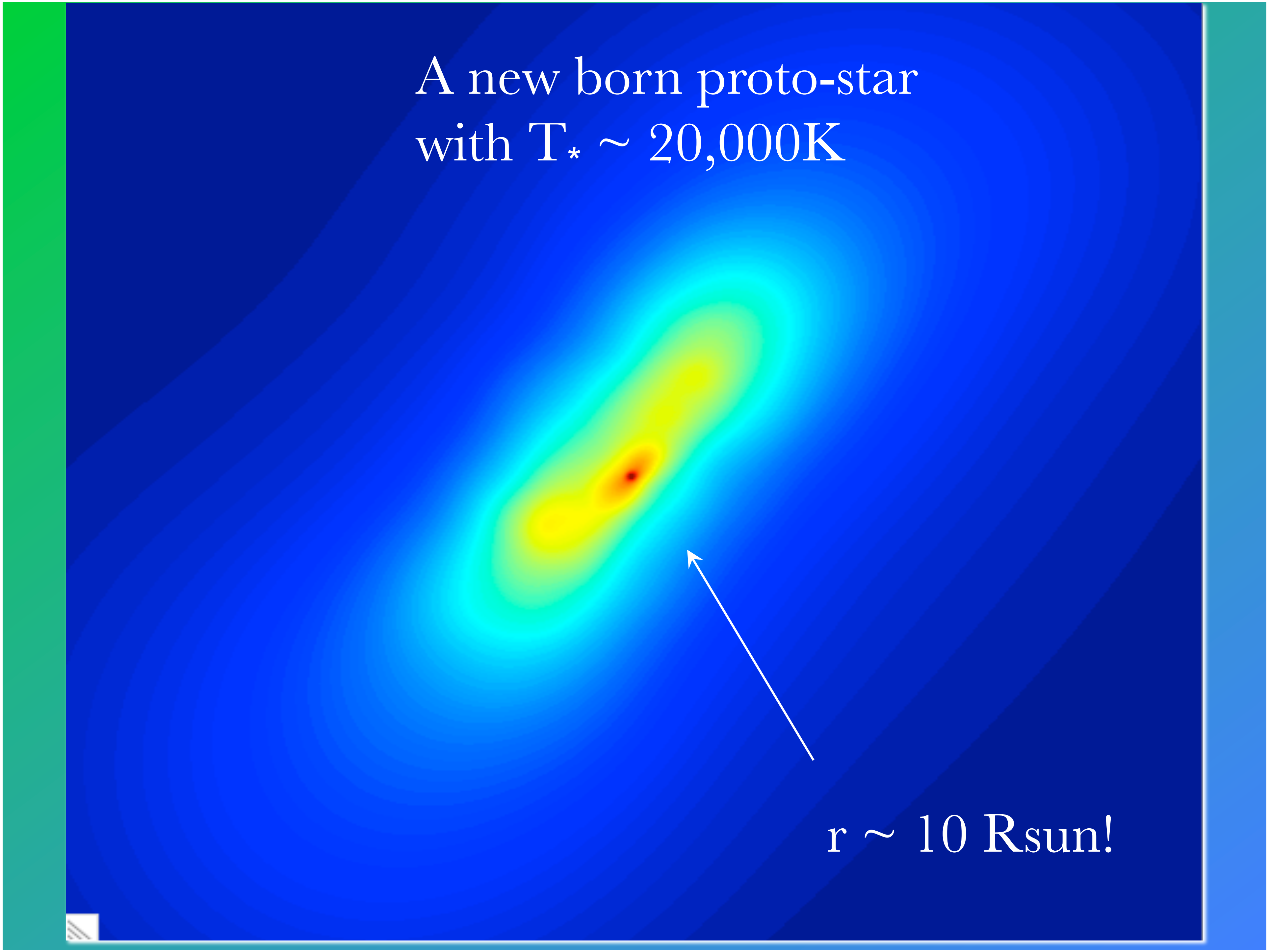
$10^{14}\,cm^{-3}$ CIE

$10^{15}\,cm^{-3}$ Disassociation

$10^{18}\,cm^{-3}$ Atomic

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

(Omukai and Nishi ‘98)



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

r ~ 10 Rsun!

Scales

- Jeans Mass ~ 1000 $M_\odot$

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

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

↓ accretion

Final stellar Mass??

$\sim 100 M_\odot$ in standard picture

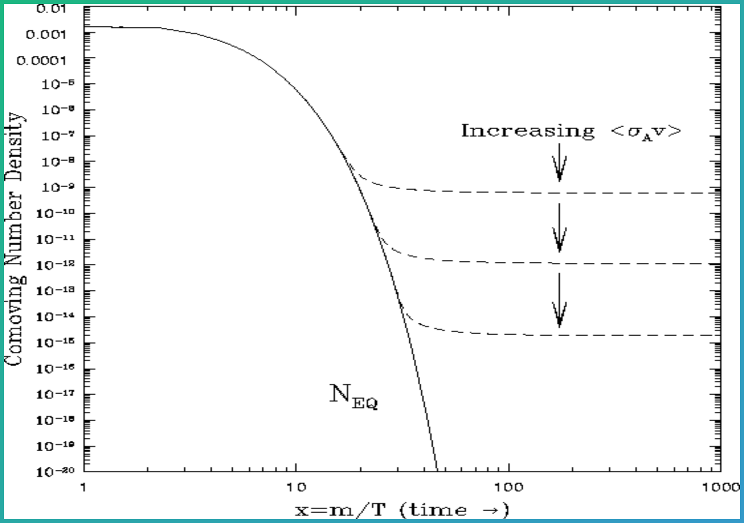
The best motivated dark matter particles

- WIMPs (Weakly Interacting Massive Particles),

  e.g. supersymmetry or Kaluza Klein particles (extra dimensions)
- Axions (Weinberg; Wilczek)
- Primordial black holes

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

- Weakly Interacting Massive Particles (WIMPS). e.g.,neutralinos



- Axions

$m_a \sim 10^{-(3\text{-}6)}$ eV

arises in Peccei-Quinn solution to strong-CP problem

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!

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

LSP
Weakly interacting DM

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

$$<\sigma v>_{ann} = 3\times10^{-26}\,cm^3/\sec$$

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

LHC-Making DM Coming Soon (We hope)

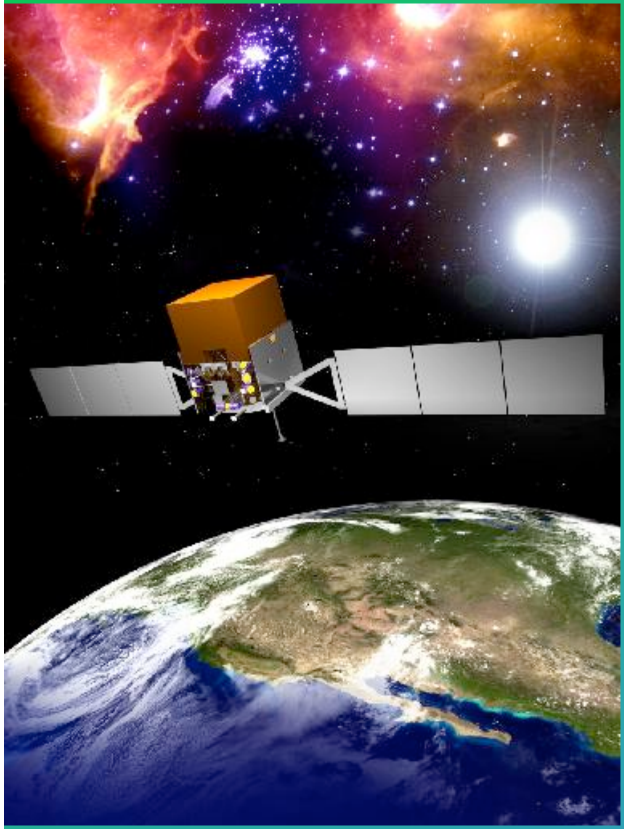
Searching for dark WIMPs

- Direct Detection (Goodman and Witten 1986; Drukier, Freese, and Spergel 1986)
- 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 WIMPs are their own antiparticles; they annihilate among themselves to 1/3 neutrinos, 1/3 photons, 1/3 electrons and positrons

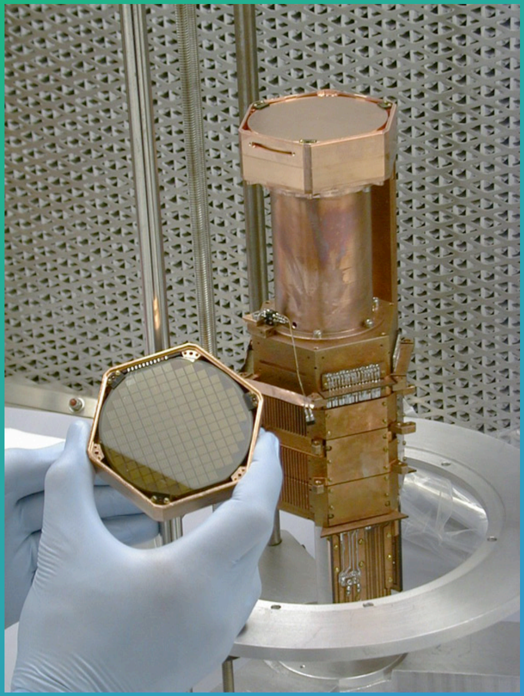
Indirect or Direct Detection

FERMI/GLAST



photons

CDMS



scattering

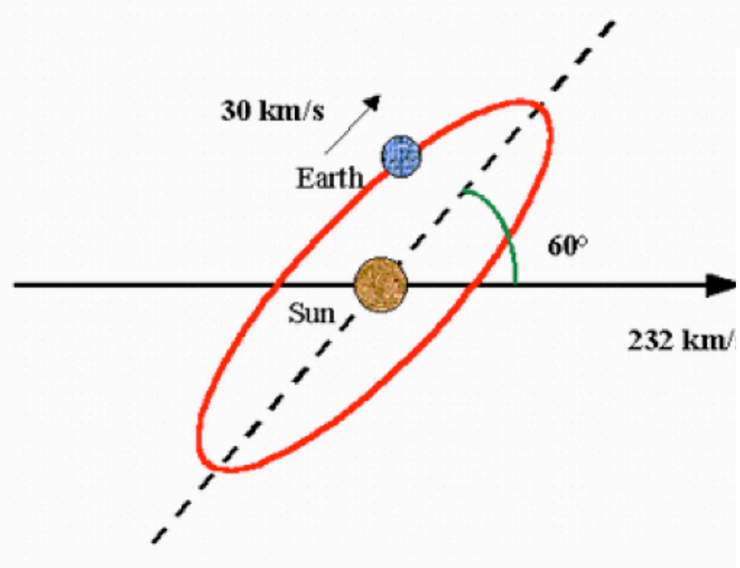
ICE CUBE

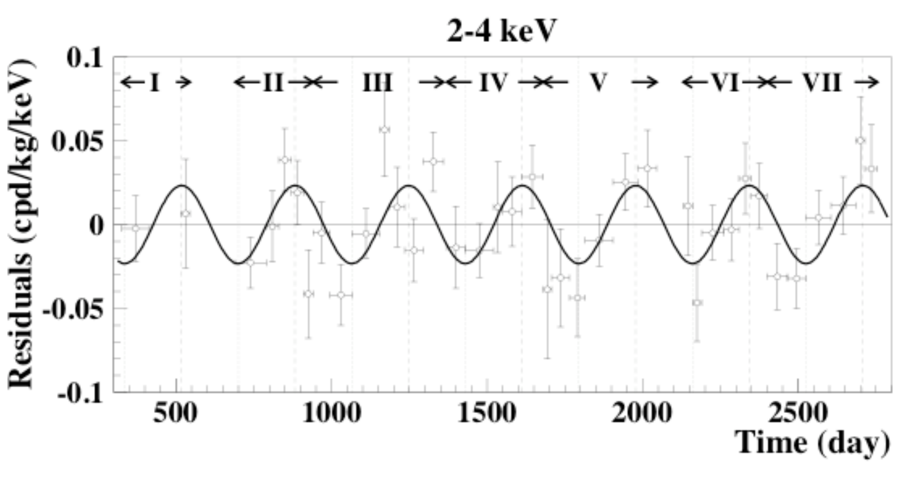
neutrinos

DAMA annual modulation

Drukier, Freese, and Spergel (PRD 1986);
Freese, Frieman, and Gould (PRD 1988)

Bernabei et al 2003

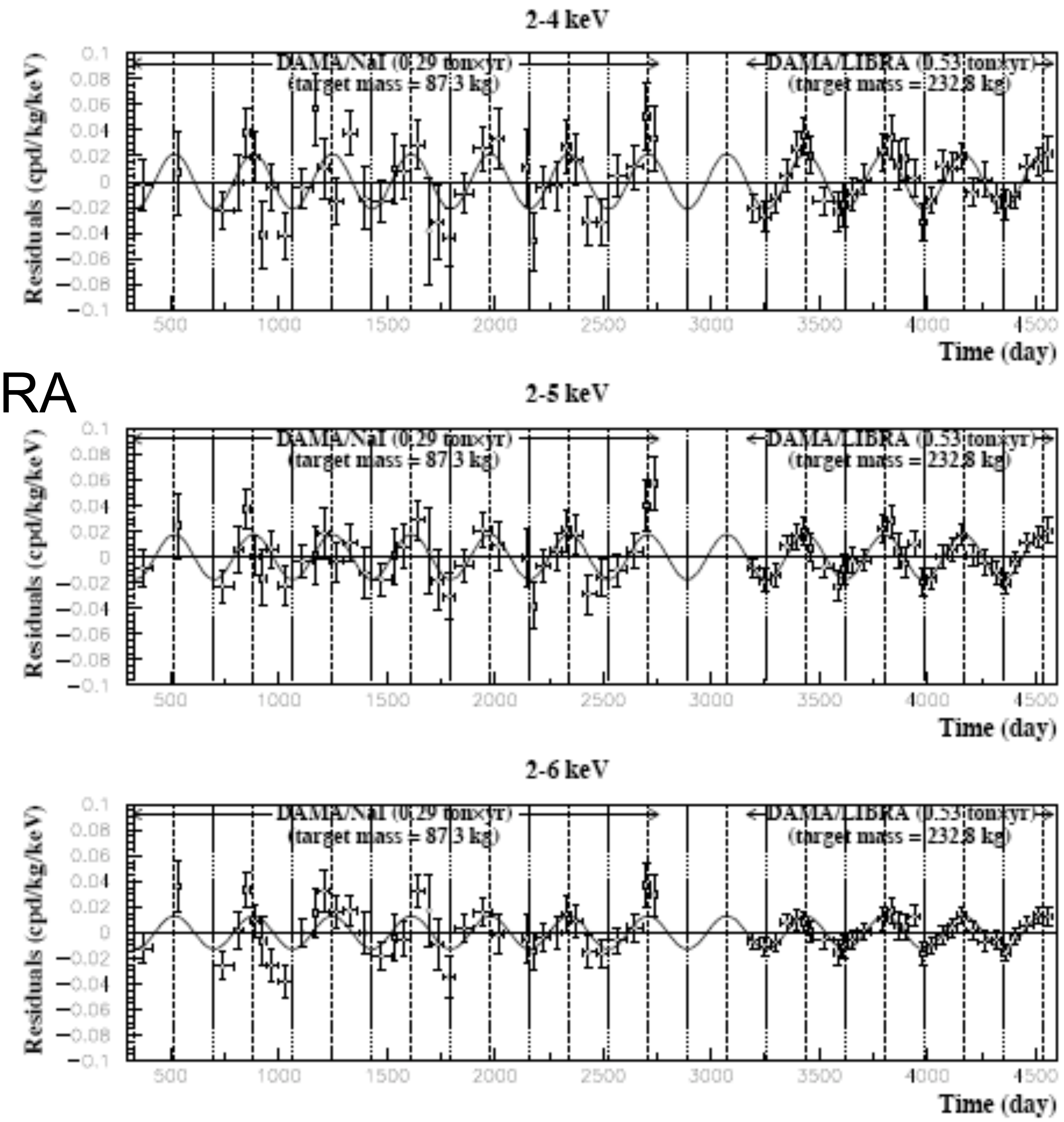




Data do show a 8σ modulation

WIMP interpretation is controversial

DAMA/LIBRA
(April 17, 2008)
8 sigma



DAMA and Spin-dependent cross sections

Remaining window around 10 GeV.

Removing SuperK: WIMP mass up to 70 GeV allowed

Savage, Gelmini, Gondolo, Freese 0808:3607

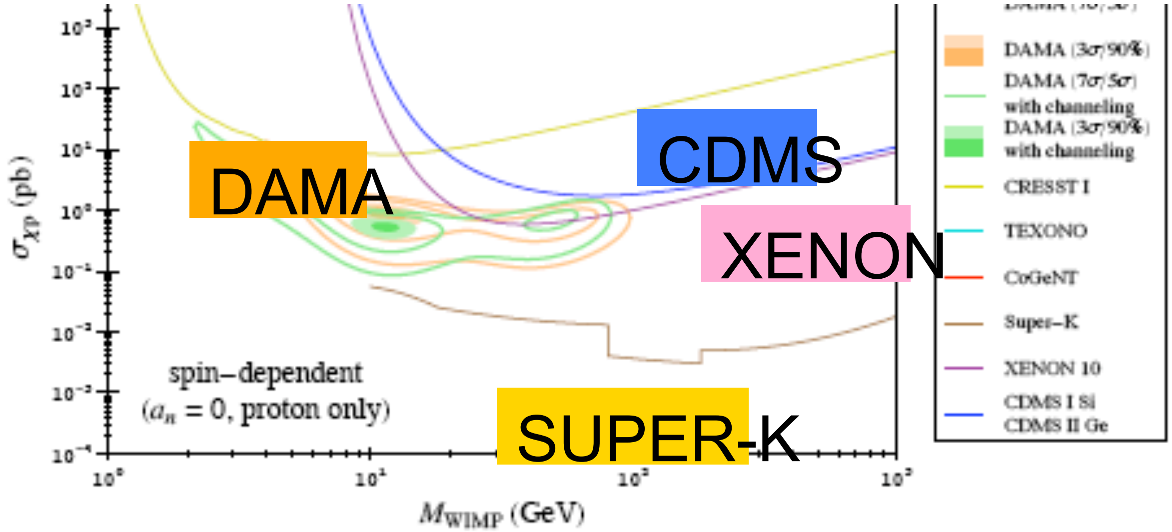
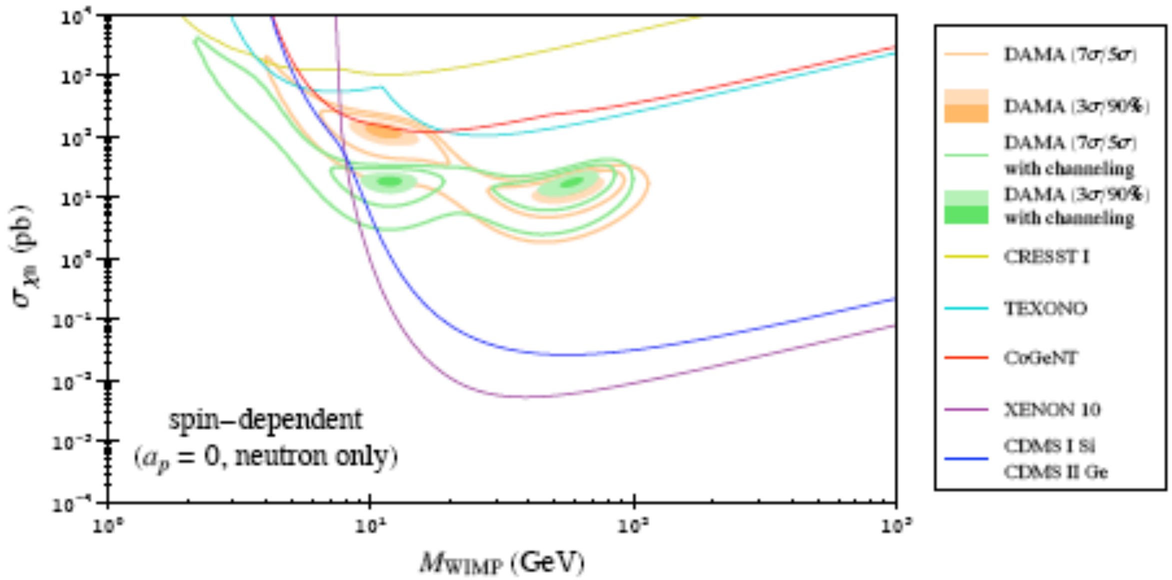


FIG. 6: Experimental constraints and DAMA preferred parameters for SD proton-only scattering. The DAMA preferred regions are determined using the likelihood ratio method with (green) and without (orange) the channeling effect. The CoGeNT and TEXONO constraints are too weak to fall within the shown region.



Other Anomalous Signals

- Excess positrons: HEAT, PAMELA
- Excess gamma rays towards GC: EGRET, HESS, FERMI/GLAST will check
- Excess microwaves towards GC
- Hard to explain all signals with a single particle

Three Conditions for Dark Stars
(Spolyar, Freese, Gondolo 2007 aka Paper 1)

- I) Sufficiently High Dark Matter Density to get large annihilation rate
- 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

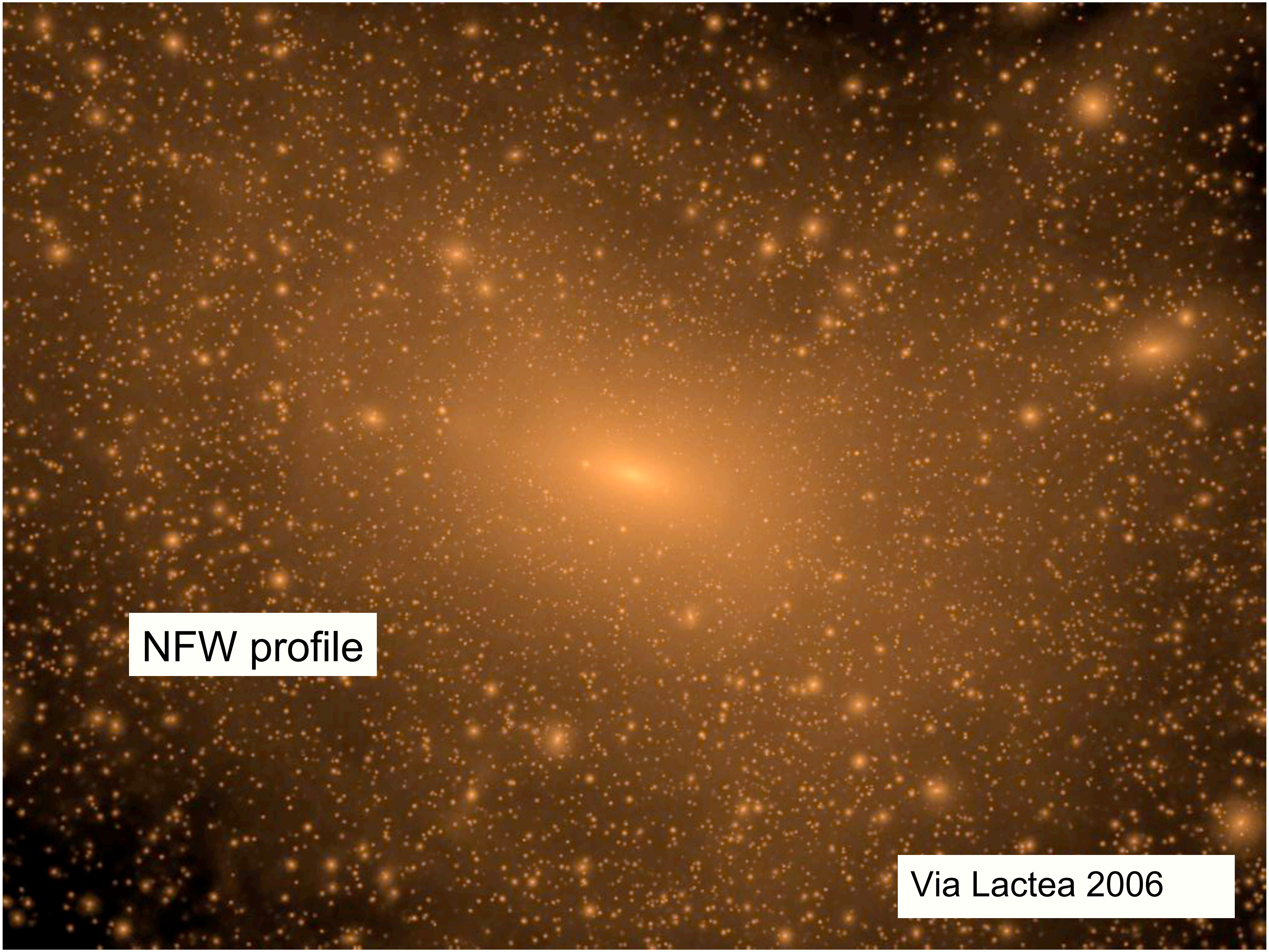
1/3 neutrinos

Depending upon the densities.

First Condition: Large DM density

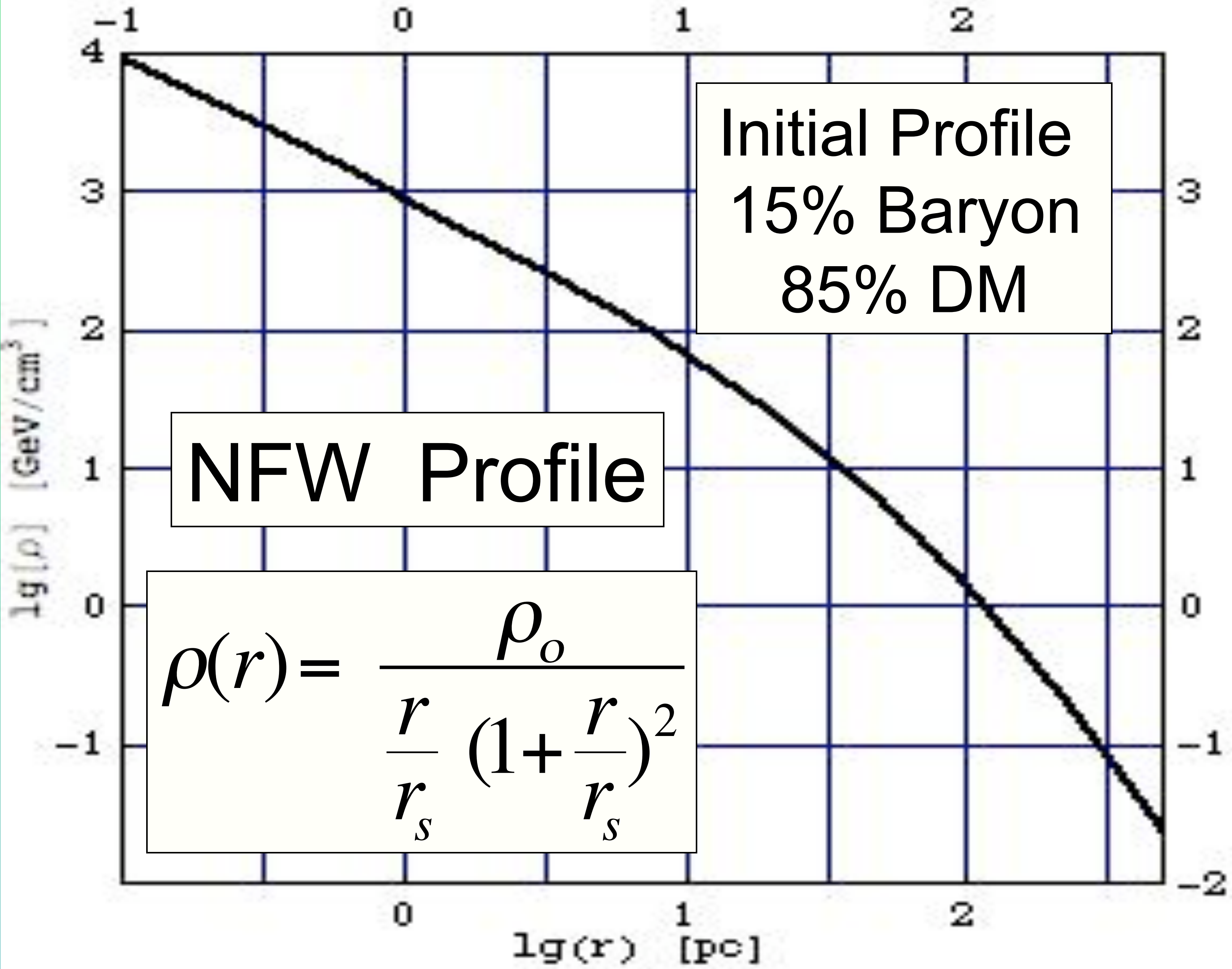
- DM annihilation rate scales as DM density squared, and happens wherever DM density is high. The first stars are good candidates: good timing since density scales as $(1+z)^3$ and good location at the center of DM halo
- Start from standard NFW profile in million solar mass DM halo.
- As star forms 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).

Substructure ➚



NFW profile

Via Lactea 2006



Initial Profile
15% Baryon
85% DM

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 via Blumenthal method:
  - As baryons fall into core, DM particles respond to potential, conserve Angular Momentum but only take circular orbits

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

Overly simplistic but basically correct.

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

DM Density Profile Conserving Phase Space

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

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

- Profile that we find:

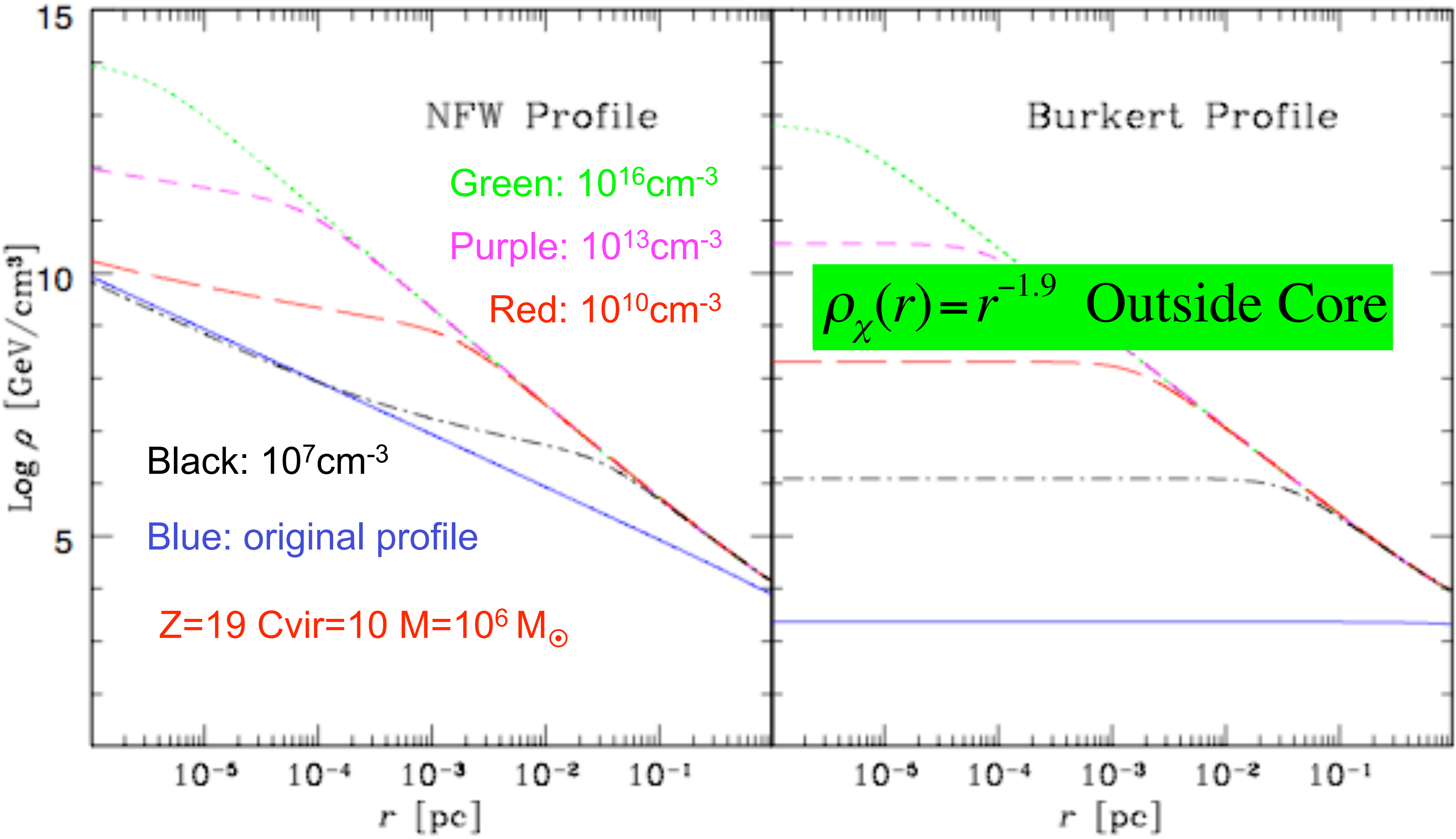
$$\rho_\chi(r) \sim r^{-1.9} \text{ Outside Core}$$

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

Simplistic: circular orbits only.

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

Dark Matter Profile



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

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

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

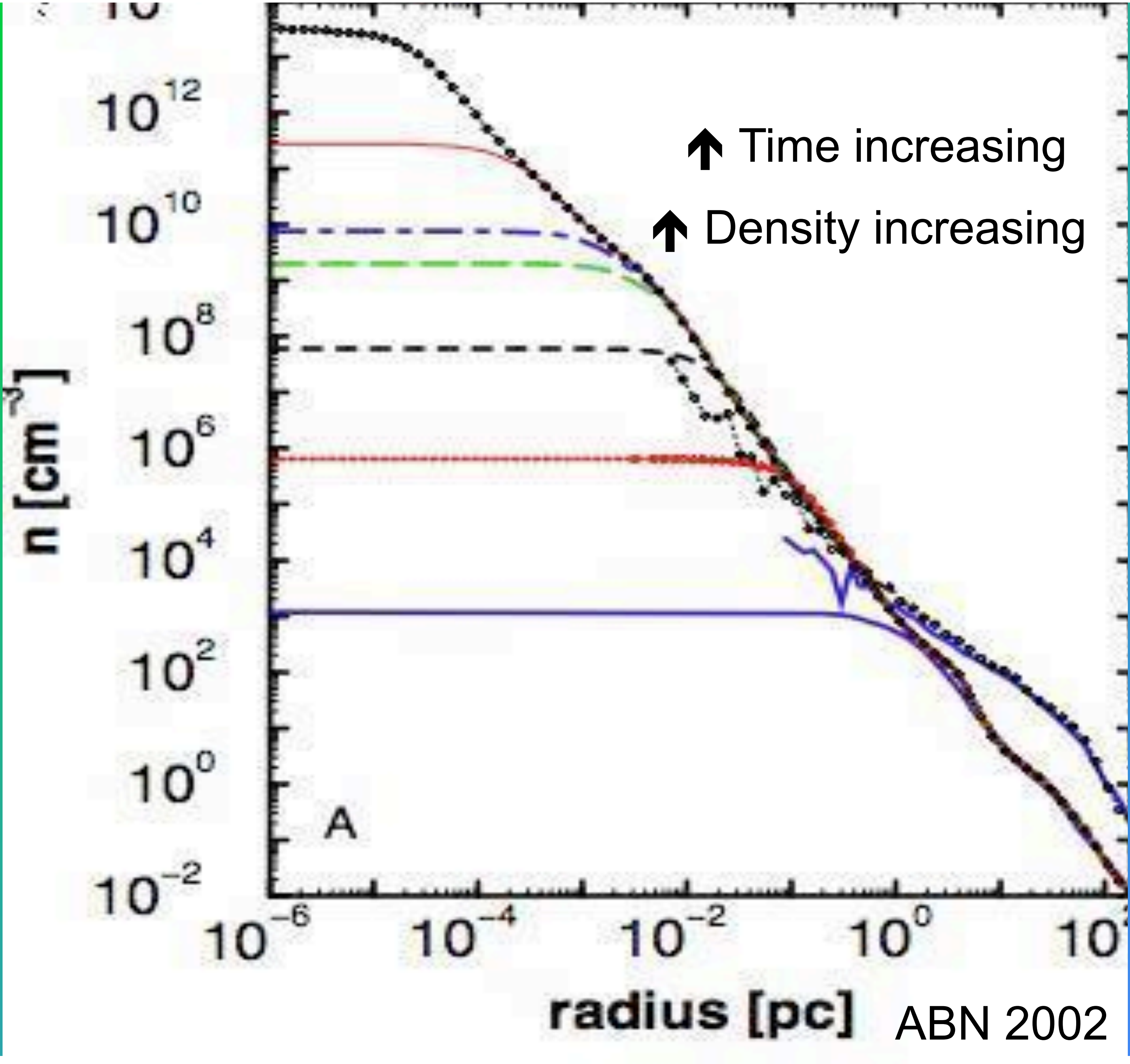
Black: 10^{7}cm^{-3}

Blue: original profile

Z=19 Cvir=10 M=10^{6} $M_\odot$

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

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

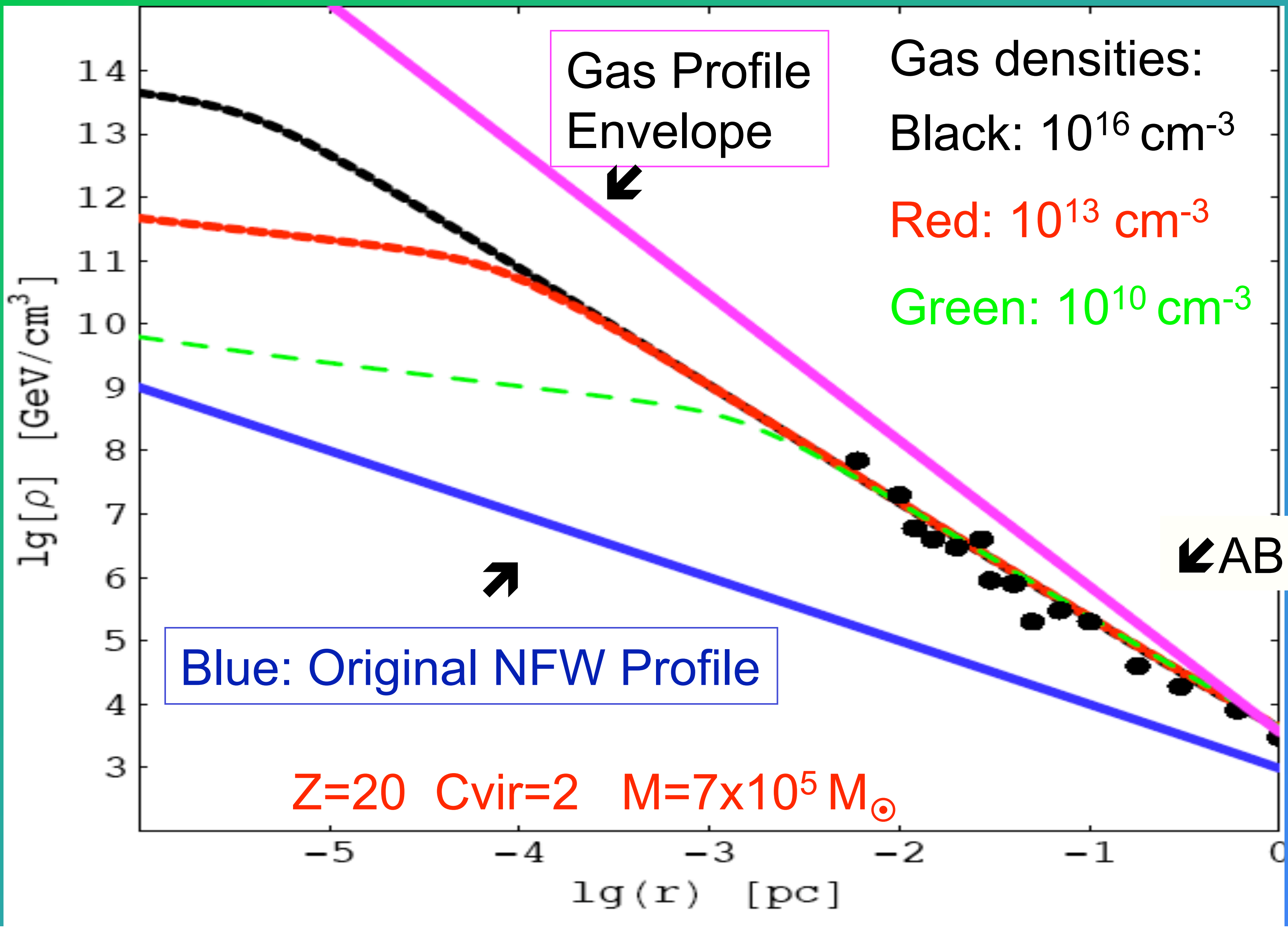


↑ Time increasing

↑ Density increasing

ABN 2002

DM profile and Gas



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=7x10^5 $M_\odot$

ABN 2002

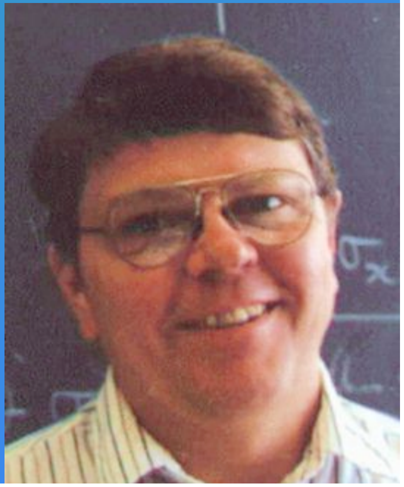
Dark Matter Densities in the Stars

- Adiabatic Contraction
- See also work of Natarajan, O’Shea and Tan 2008, taking simulation results and extrapolating to also find large densities

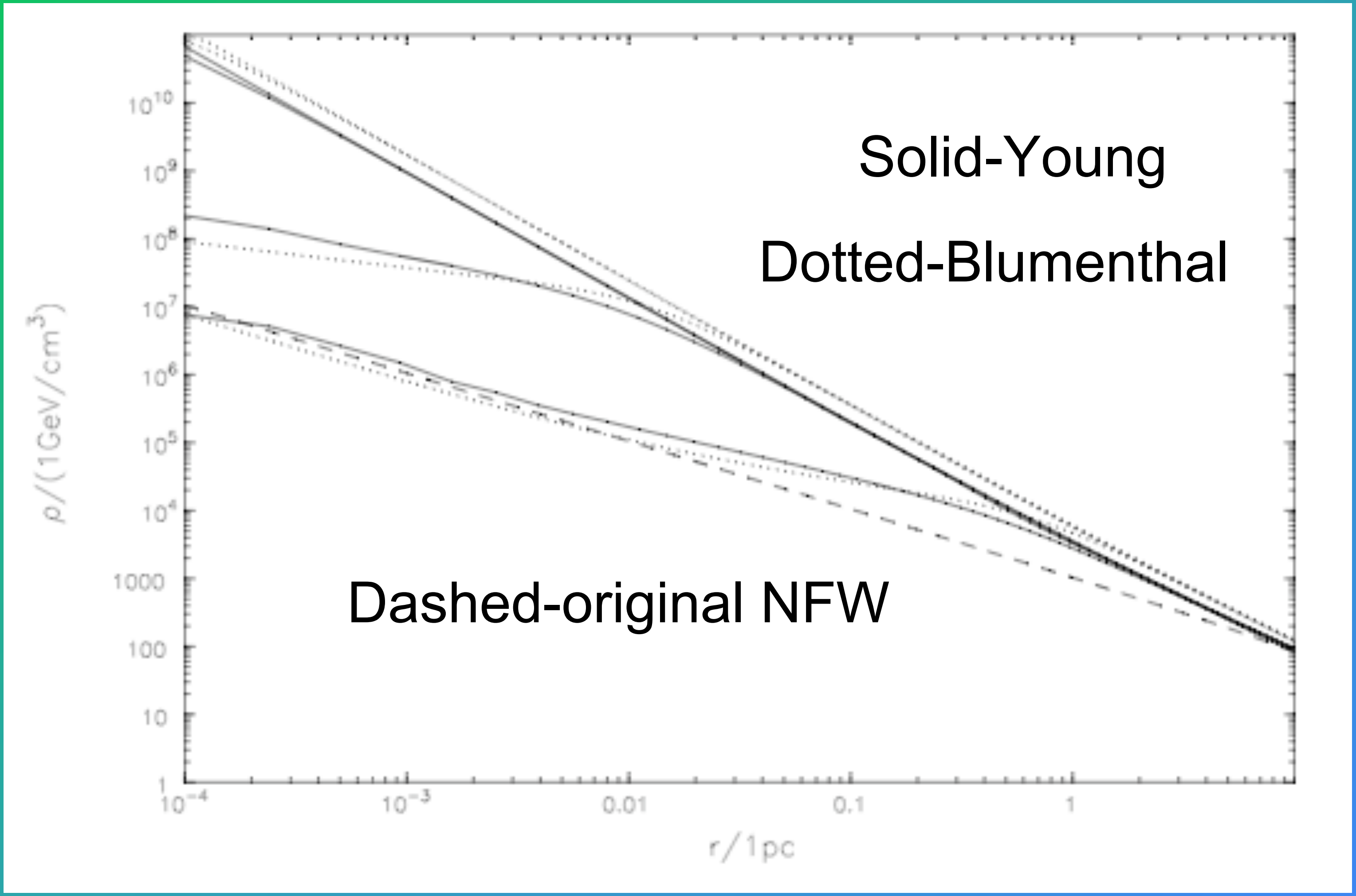
How accurate is Blumenthal method for DM density profile?

- 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



Solid-Young

Dotted-Blumenthal

Dashed-original NFW

Three Conditions for Dark Stars (Paper 1)

- I) Sufficiently High Dark Matter Density to get large annihilation rate: OK!
- 2) Annihilation Products get stuck in star
- 3) DM Heating beats H2 Cooling

- Leads to New Phase

Dark Matter Heating

Heating rate:

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$$= \frac{\rho_\chi^2 < \sigma v >}{m_\chi}$$

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:

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

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

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

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

Three Conditions for Dark Stars (Paper 1)

- I) Sufficiently High Dark Matter Density to get large annihilation rate
- 2) Annihilation Products get stuck in star
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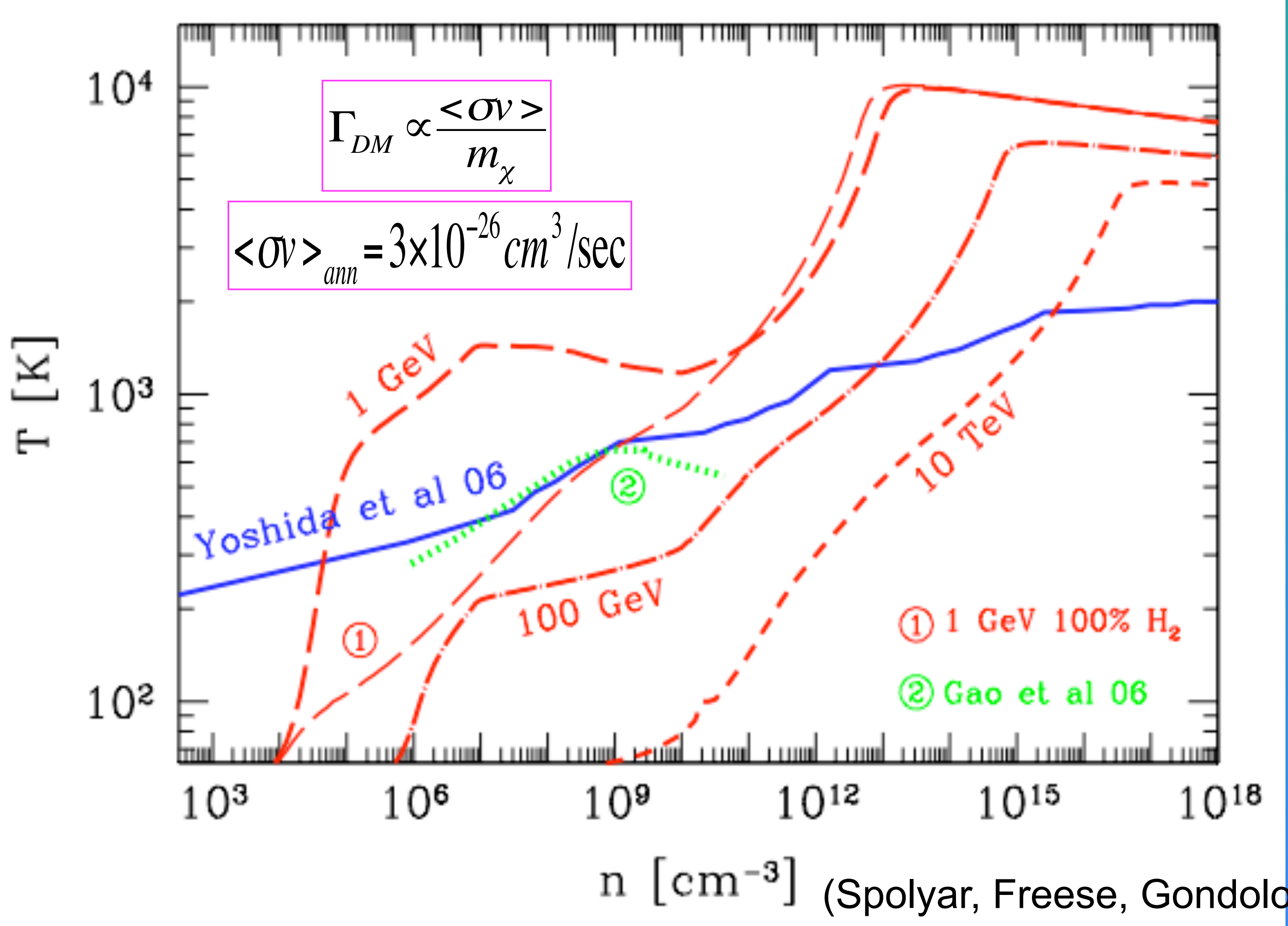
DM Heating beats H2 Cooling

- Leads to 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.



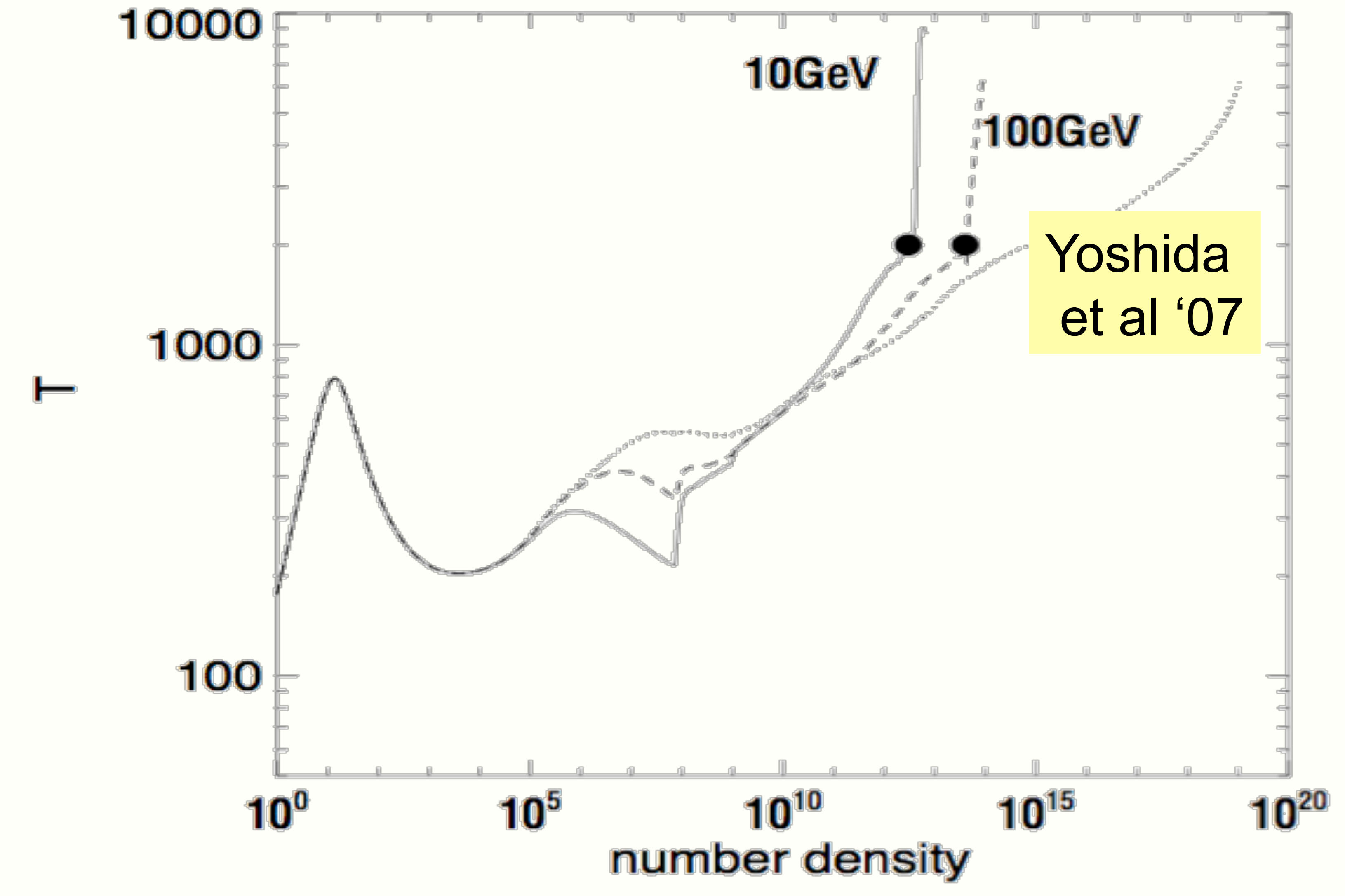
$$\Gamma_{DM} \propto \frac{<\sigma v>}{m_\chi}$$

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

(Spolyar, Freese, Gondolo April 2007)

New proto-Stellar Phase:

fueled by dark matter

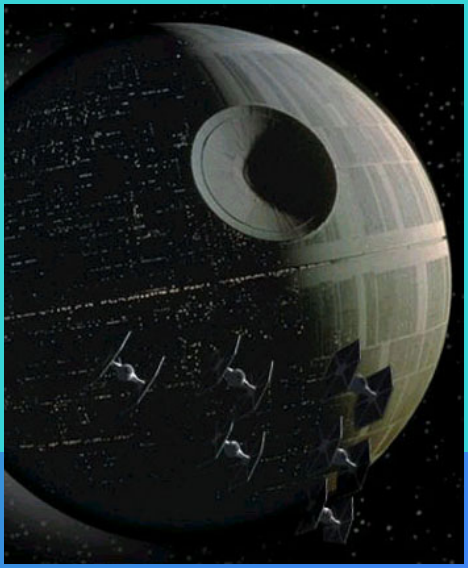


Yoshida
et al ‘07

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 made of 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,

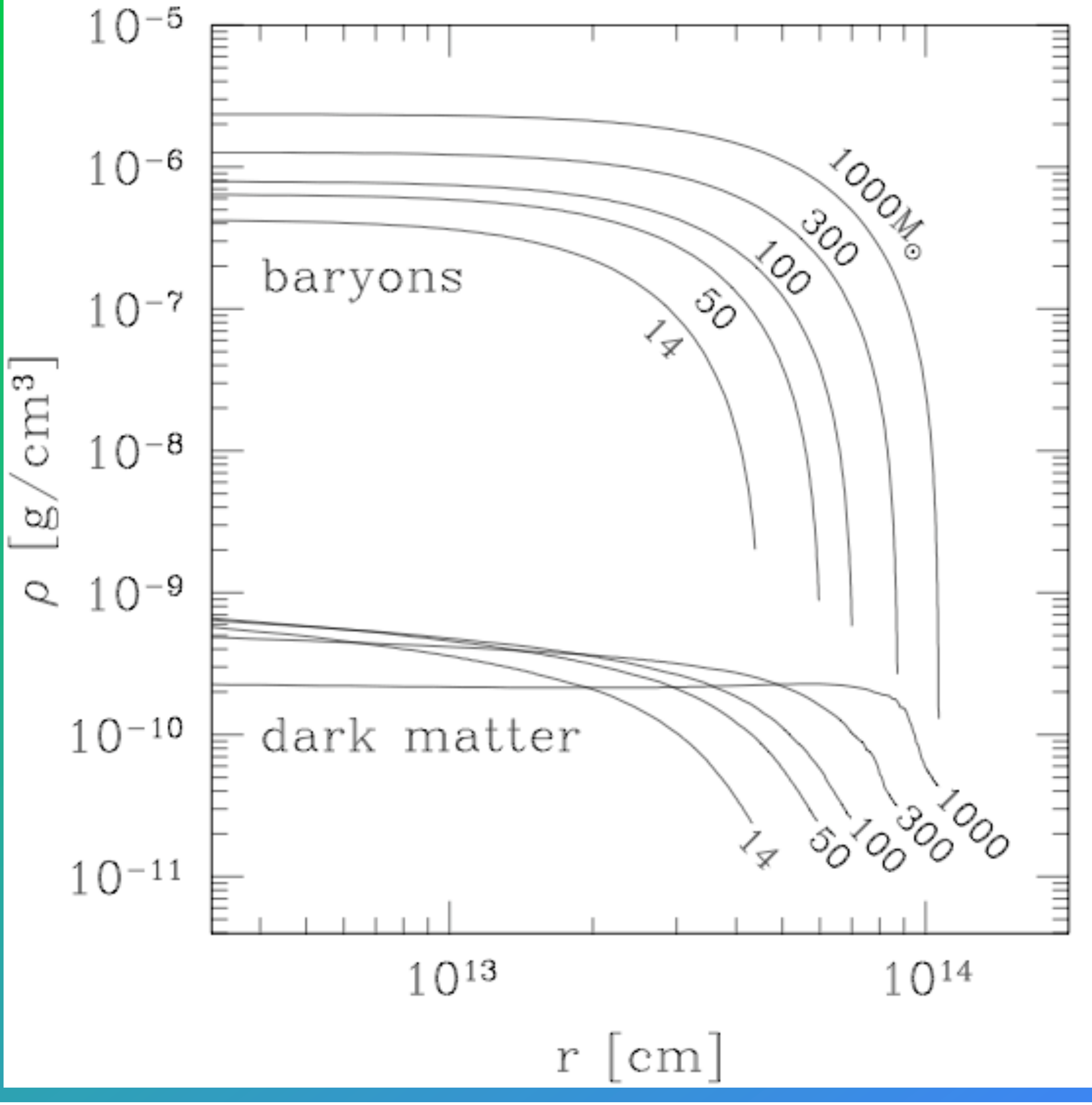
  for high mass n=3 radiative

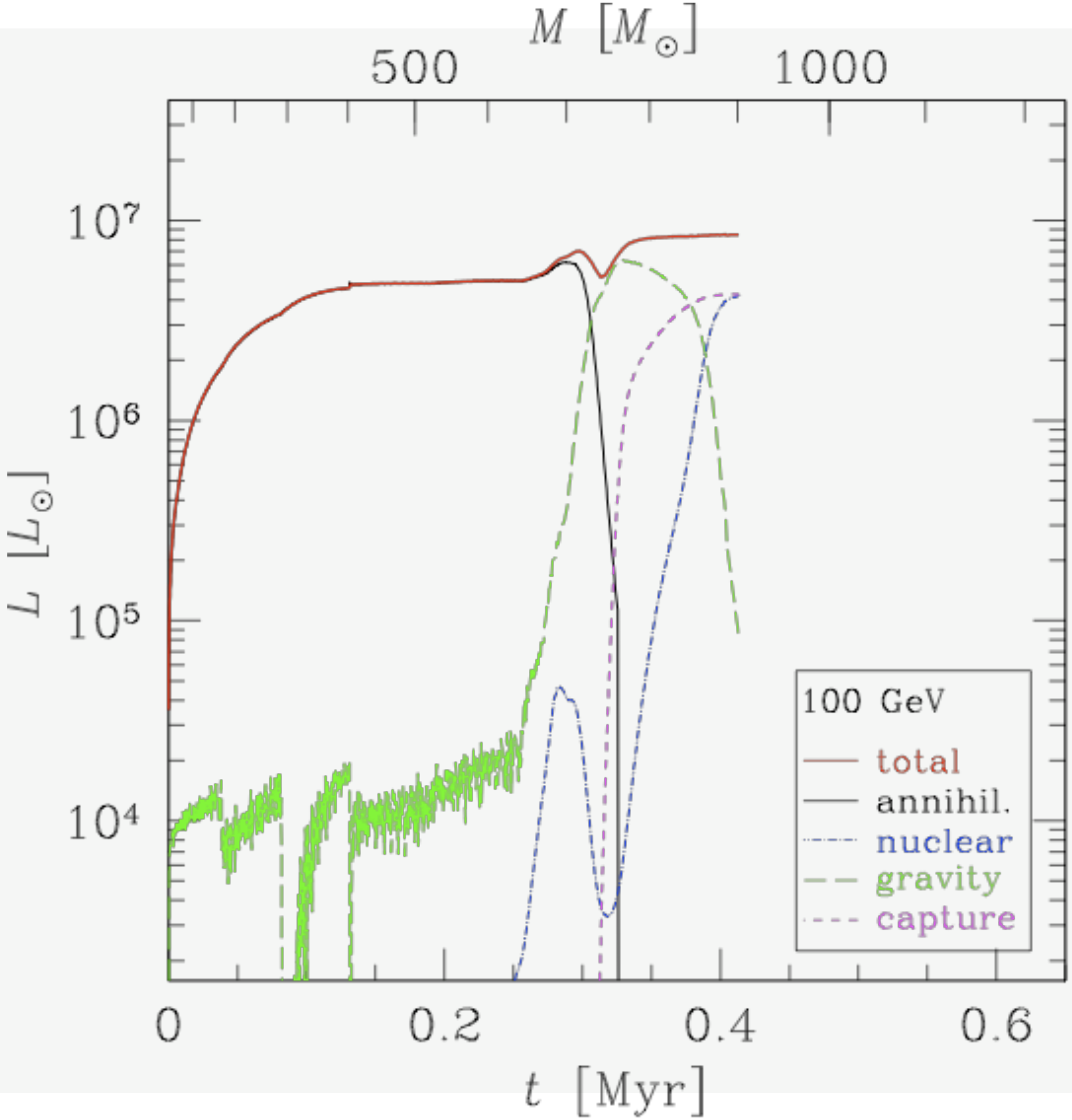
  (transition at 100-400 $M_\odot$)
- Start with a few solar masses, guess the radius, see if DM luminosity matches luminosity of star (photosphere at roughly 6000K). If not adjust radius until it does. Smaller radius means larger gas density, pulls in more DM via adiabatic contraction, higher DM density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

$$L_{DM} = L_*$$

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.


10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
ρ [g/cm³]
baryons
1000M☉
300
100
50
14
dark matter
1000
300
100
50
14
10^13
10^14
r [cm]



M [$M_\odot$]
500
1000
L [$L_\odot$]
10^7
10^6
10^5
10^4
0
0.2
0.4
0.6
t [Myr]
100 GeV
total
annihil.
nuclear
gravity
capture

Predictions for Dark Stars

  - Very luminous between $10^6 L_\odot$ and $10^7 L_\odot$
  - Cool: 6,000-10,000 K vs. 30,000 K plus in standard Pop III
    - Very few ionizing photons, just too cool.
  - Directly observable? Hard to see these in JWST
  - Indirect signatures: Leads to very massive first Main Sequence stars: 800 $M_\odot$
  - Helps with formation of large early black holes
  - Atomic and molecular hydrogen lines
- Reionization: Can study with upcoming measurements of 21 cm line.
  - Heat Gas, but not ionize until DS phase finishes

Observables

- Dark stars are giant objects with 6000K and $10^6 L_\odot$
  - Find them with JWST?

    NASA's 4 billion dollar sequel to HST: unlikely
- ν annihilation products in AMANDA or ICECUBE? Can neutralinos be discovered via dark stars or can we learn more about their properties? (work with Pearl Sandick)
- Very high mass: can avoid Pair instability SN which arise from 140-260 solar mass stars (and whose chemical imprint is not seen)

Lifetime of Dark Star

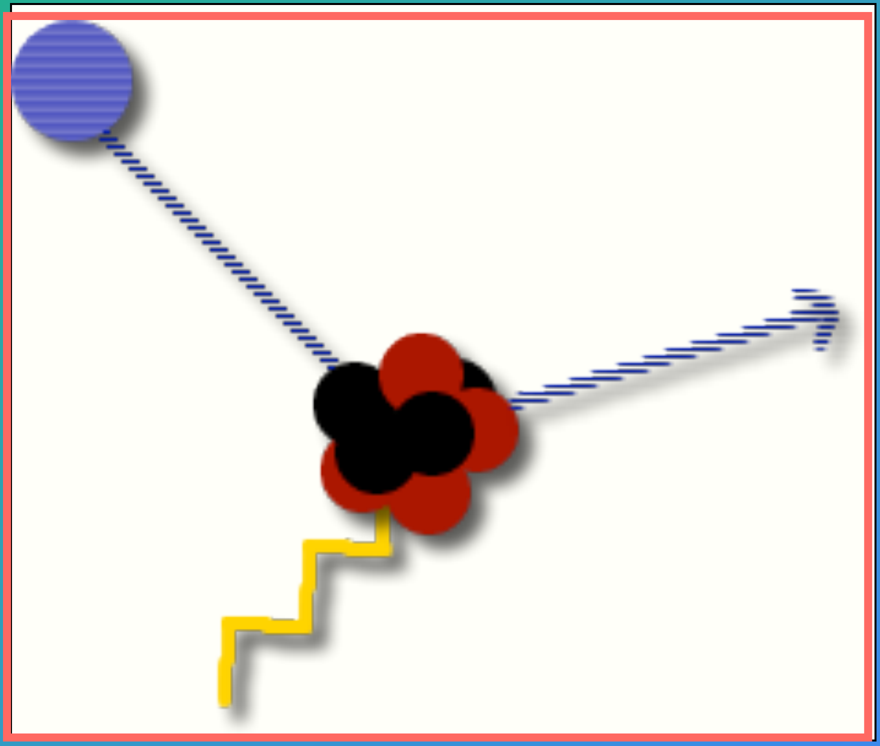
- SCENARIO A: The DM initially inside the star is eaten up in about a million years.
- SCENARIO B: The DS lives as long as it captures more Dark Matter fuel: millions to billions of years if further DM is captured by the star. See also work of Fabio Iocco and Gianfranco Bertone.
- The refueling can only 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?

- Star reaches T=10^7K, fusion sets in.
- 800 solar mass Pop III star lives a million years, then becomes a Black Hole
- Very high mass: can avoid Pair instability SN which arise from 140-260 solar mass stars (and whose chemical imprint is not seen)
- 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)

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.



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.

Bounds on scattering cross section from experiment:

- Spin-independent WIMPs (DAMA, XENON):

$$\sigma_c < 10^{-44}\mathrm{cm}^2$$

- Spin-dependent WIMPs (SuperKamiokande) (Savage, Freese, Gondolo) This dominates in hydrogen (which has spin).

$$\sigma_c < 10^{-38}\mathrm{cm}^2$$

- Value needed for capture to be interesting:

$$\sigma_c > 10^{-40}\mathrm{cm}^2$$

Theory allows a wide range: unknown!

Possible DM scattering off of gas leads to capture

- Scattering cross section is unknown
- Two cases:
- 1) If $\sigma_c < 10^{-41}\mathrm{cm}^2$ then scattering is unimportant. The 800 solar mass star proceeds through ordinary MS to BH
- 2) If $\sigma_c >> 10^{-41}\mathrm{cm}^2$ then the star can capture additional DM from scattering on the star, the DM is in thermal distribution with velocity distribution. DM annihilation can be more powerful than fusion.

L_{DM} versus $L_{\star}$

- We compare the DM luminosity against fusion luminosity of zero metallicity stars half way through H burning (on the main sequence) for various masses. (using stellar models of Heger,Woosley)
  - H burning represents the largest fraction of a star's life.
- DM luminosity wins for a sufficiently high DM density.

$$\boxed{\rho_{\chi} > 2 \times 10^{11} GeV/cm^{3}}$$

$$\boxed{L_{DM} > L_{\star}(\mathrm{FirstStars})}$$

Similar and Simultaneous Work

- Within a few days of each other, we and **Fabio Iocco** posted the same basic idea:
  - Both groups found that the DM luminosity can be larger than fusion for the first stars.

(Freese, Spolyar, Aguirre 08;
Iocco 08)

Uncertainties: scattering cross section, amount of DM in the ambient medium to capture from

Return of the Dark Star

- Even once the first stars reach the main sequence, DM annihilation can still be very important.
  - DM Can again be the dominant heat source.
  - DM heating may also determine the mass of the first stars.

(Freese, Spolyar, Aguirre 08; Iocco 08)

Capture Rate per Unit Volume

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

Press, Spergel 85 & Gould 88

- 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

We can neglect the term in the brackets because the DM velocity is much less than the escape velocity for the first stars, which makes B big.

If the star moves relative to the DM halo, the term in the brackets changes. Luckily, we can still neglect the term.

Lifetime of Dark Star

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- 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 (Iocco).
- Once the DM runs out, switches to fusion.

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
- 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.

    Speculation: can DS grow ever larger if capture continues its lifetime, producing supermassive 10^5 solar mass stars and thus BH of this mass?
  - Caveat: GR instability

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 (800 solar masses)

In closing

- We are presently working on the Life and Times of the Dark Star. We should be able to determine how the properties of the Dark Star depends upon the underlining particle physics, which may have interesting observable consequences.
- Connection between particle physics and astrophysics grows !!!

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)

Indirect Detection History

- Indirect Detection (Neutrinos)
  - Sun (Silk,Olive,Srednicki ‘85)
  - Earth (Freese ‘86; Krauss, Srednicki, Wilczek ‘86)
- Indirect Detection (Gamma Rays, positrons)
  - Milky Way Halo (Ellis, KF et al ‘87)
  - Galactic Center (Gondolo and Silk 2000)
  - Anomalous signals seen in HEAT (e+), HESS, CANGAROO, WMAP, EGRET, PAMELA.