Dark Matter and Dark Stars

Katherine Freese

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- 1. Dark Stars: new dark matter powered phase of stellar evolution
- 2. Dark Matter Detection Status

--- direct detection

--- indirect detection

Dark Stars: Dark Matter Annihilation in the First Stars.

Katherine Freese (Univ. of MI)

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

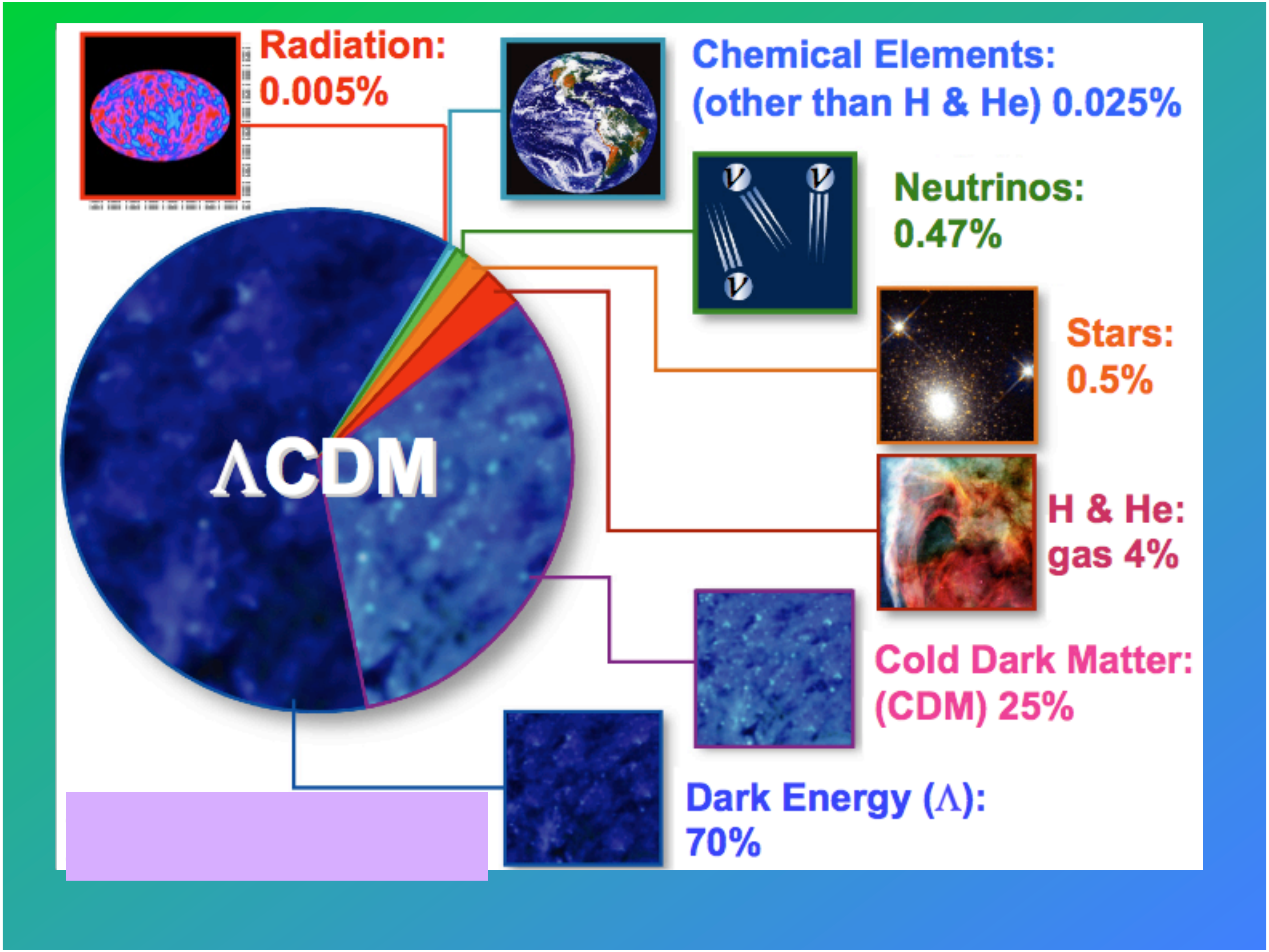
PAPER 1

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%
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

Spiritual Leader

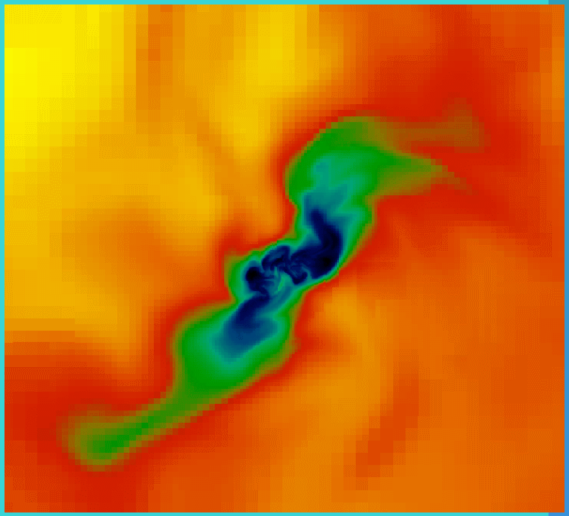
Dark Stars

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 = 10-50
  - 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)

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.

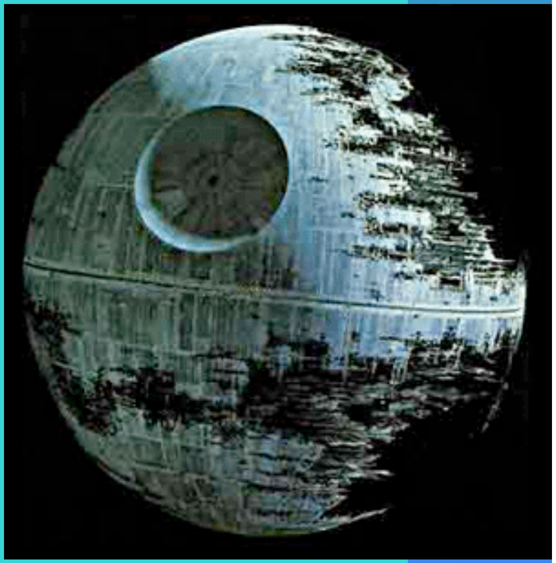
Basic Picture Continued

- 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

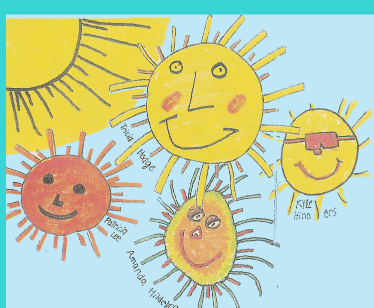
Smallest objects form first (earth mass)

Merge to ever larger structures

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

Merge → galaxies

Merge → clusters



→

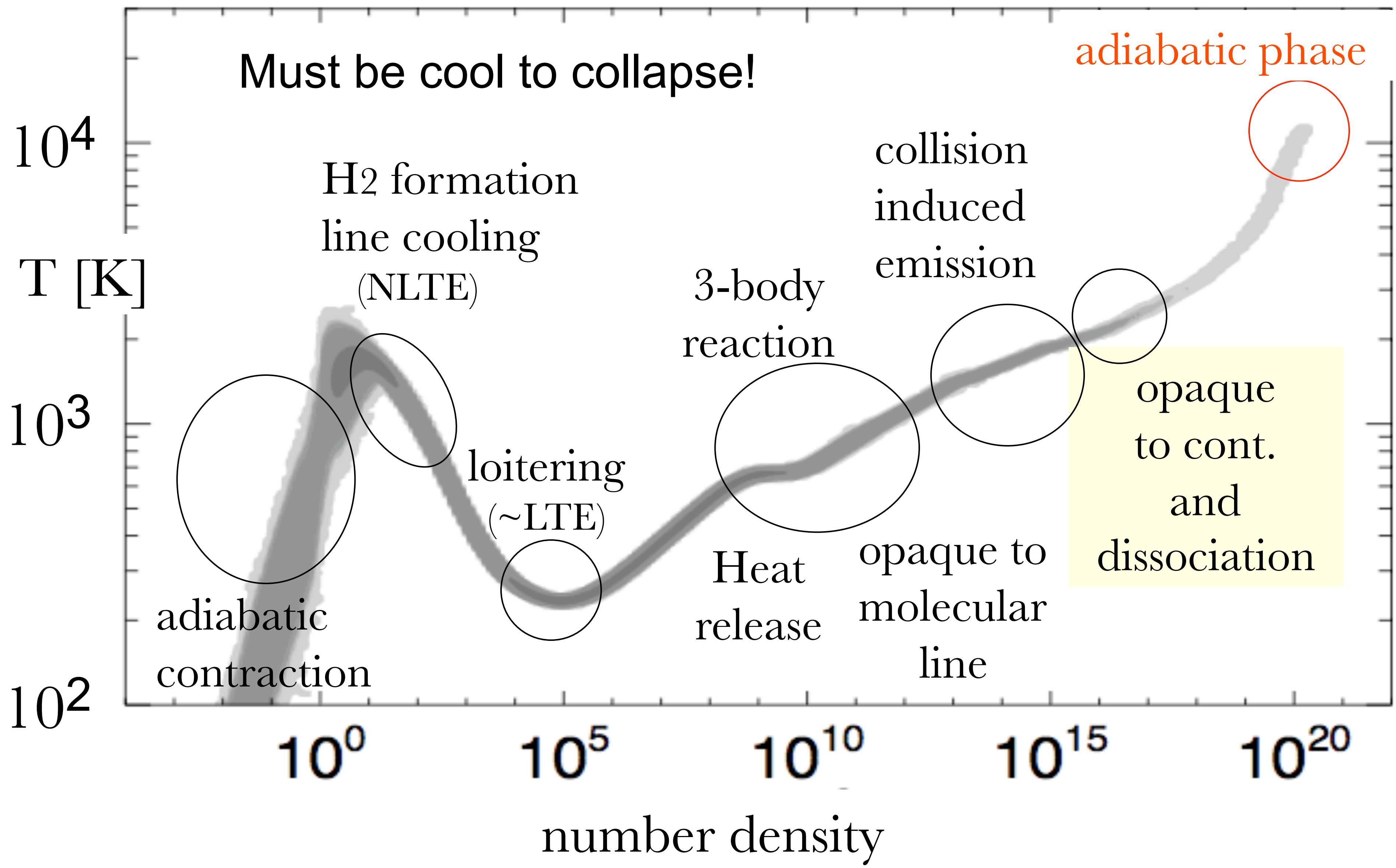
→

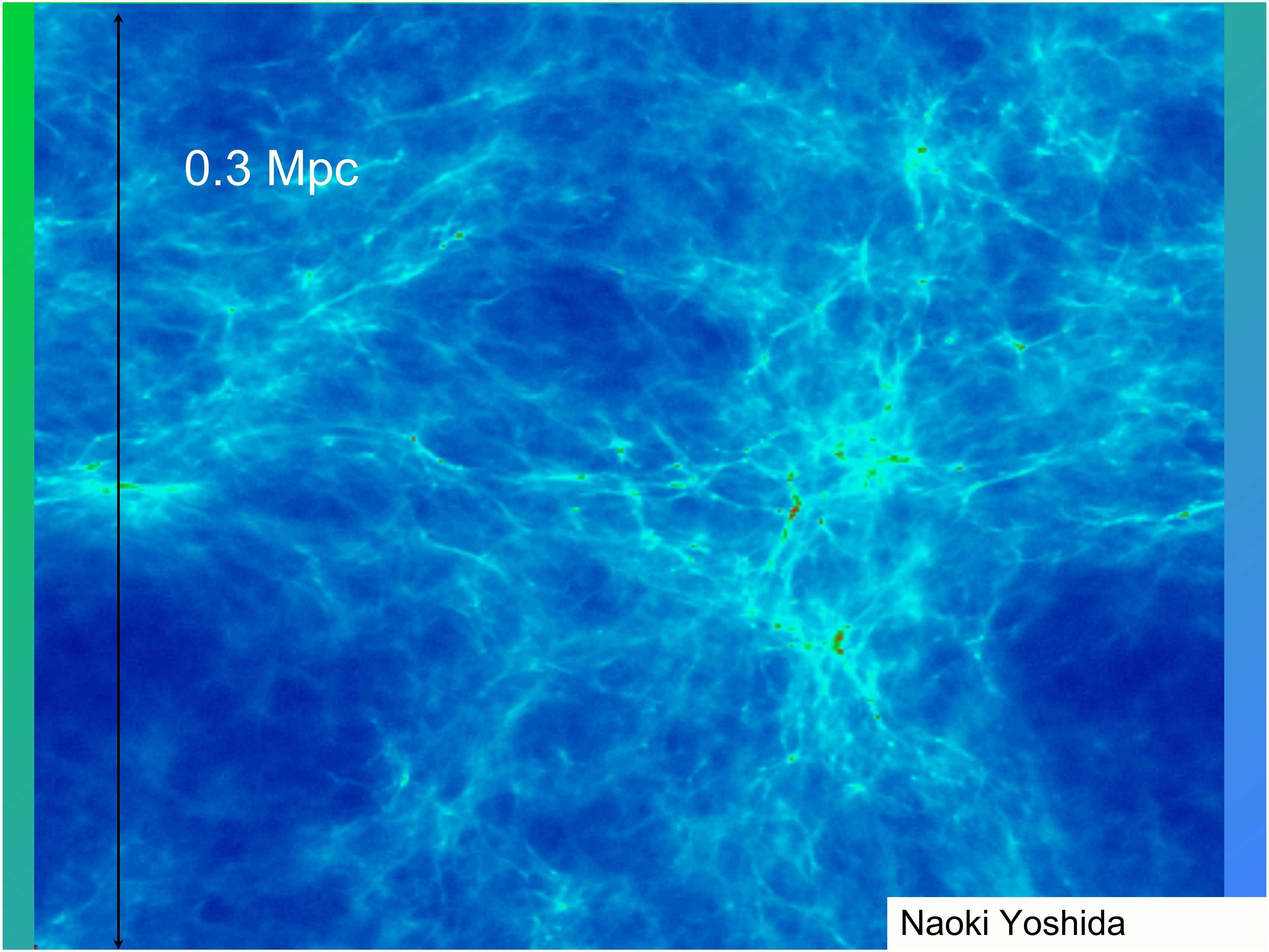
Scale of the Halo

- 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





0.3 Mpc
Naoki Yoshida

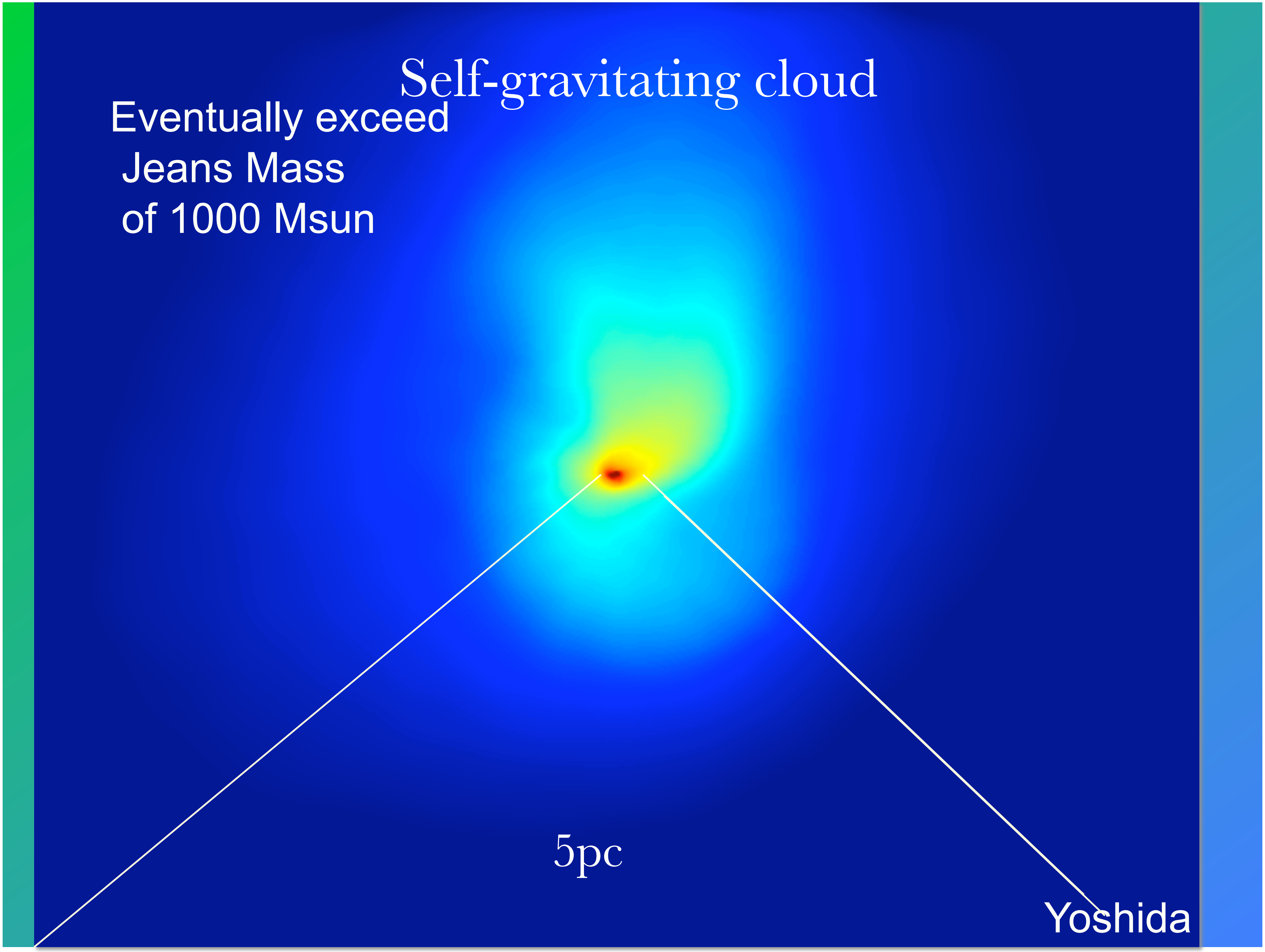
H_2 Cooling and Collapse

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 $\dfrac{\text{Molecular H}}{\text{Atomic H}} \propto 10^{-3}$


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

Cooling

3-Body Reaction

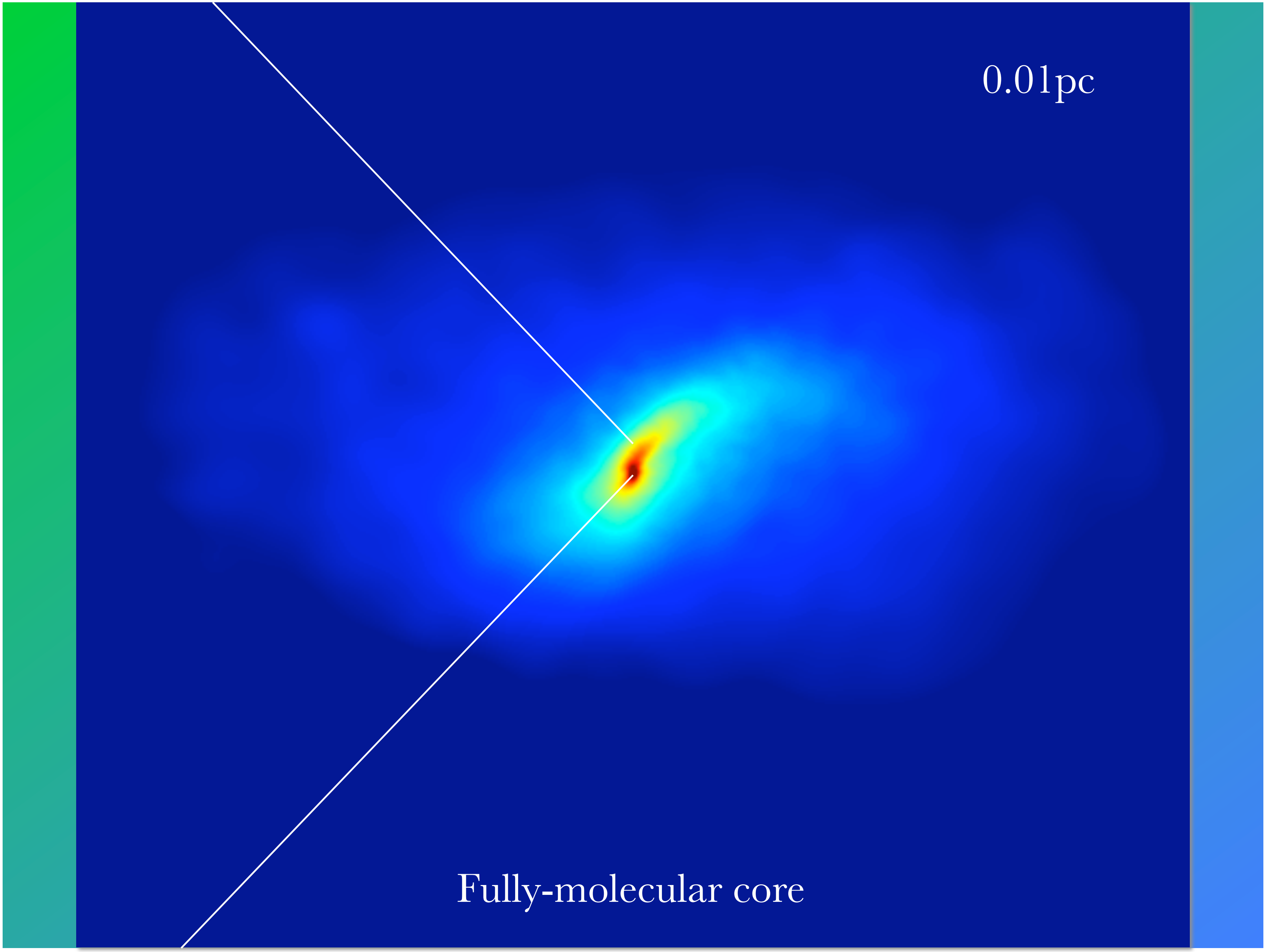
$$n \approx 10^{8} cm^{-3}$$

H+H+H → H_2+H

Becomes 100% molecular

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

Opacity → less efficient cooling


0.01pc
Fully-molecular core

Cooling to Collapse

Other cooling processes

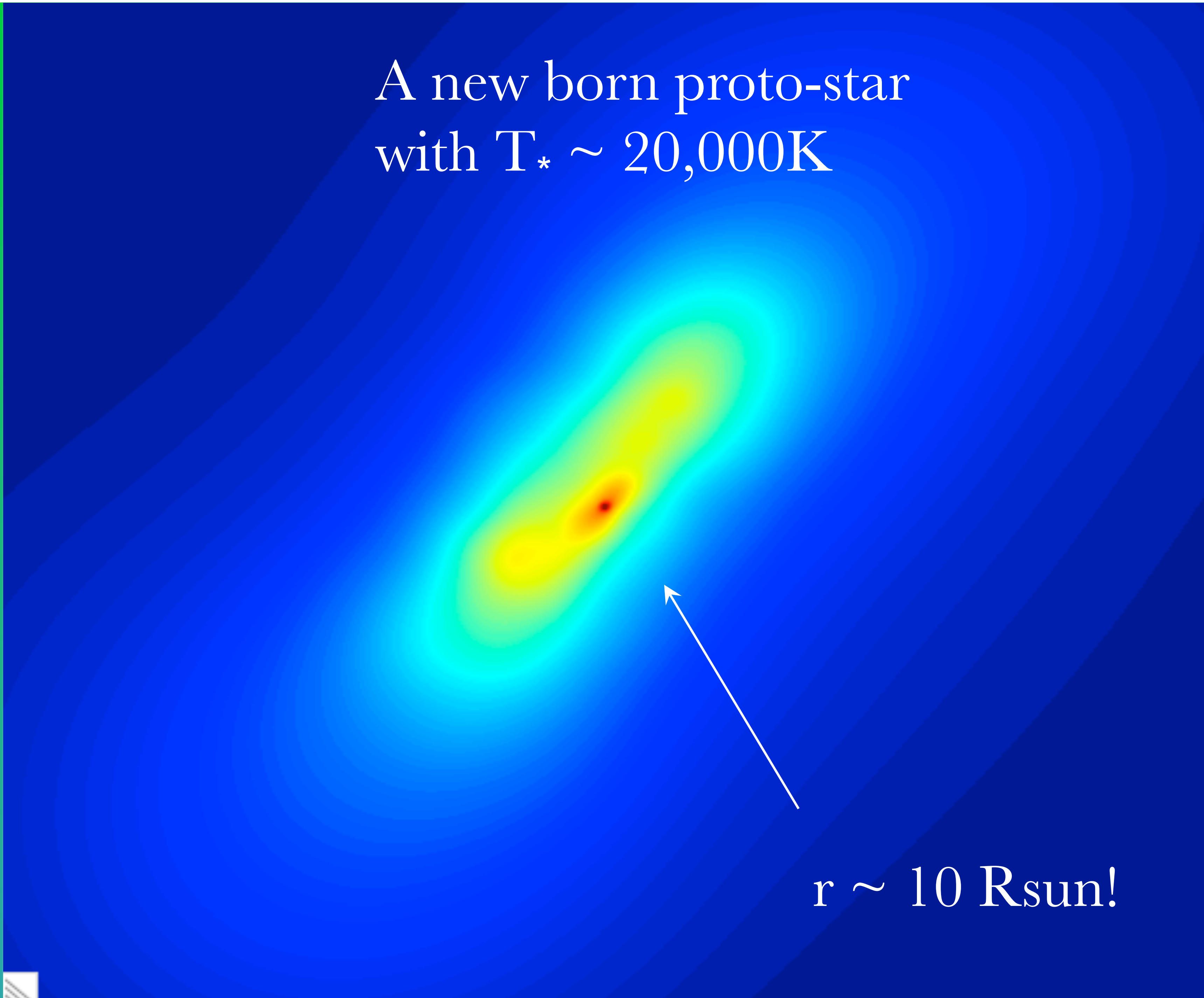
$10^{14}\,cm^{-3}$ CIE

$10^{15}\,cm^{-3}$ 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* ~ 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

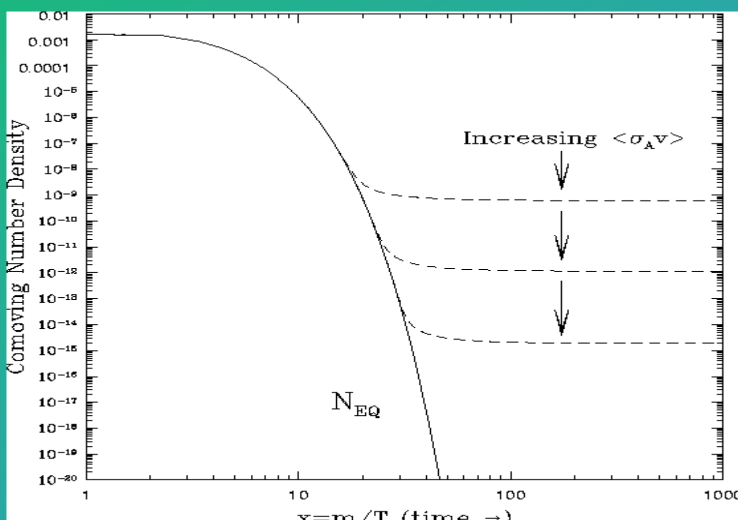
The best motivated dark matter particles

- 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~$10^{-(3-6)}$ 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!

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

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, GLAST, HESS, MAGIC, HEAT, PAMELA, AMANDA, ICECUBE


LHC-Making DM
Coming Soon
(We hope)

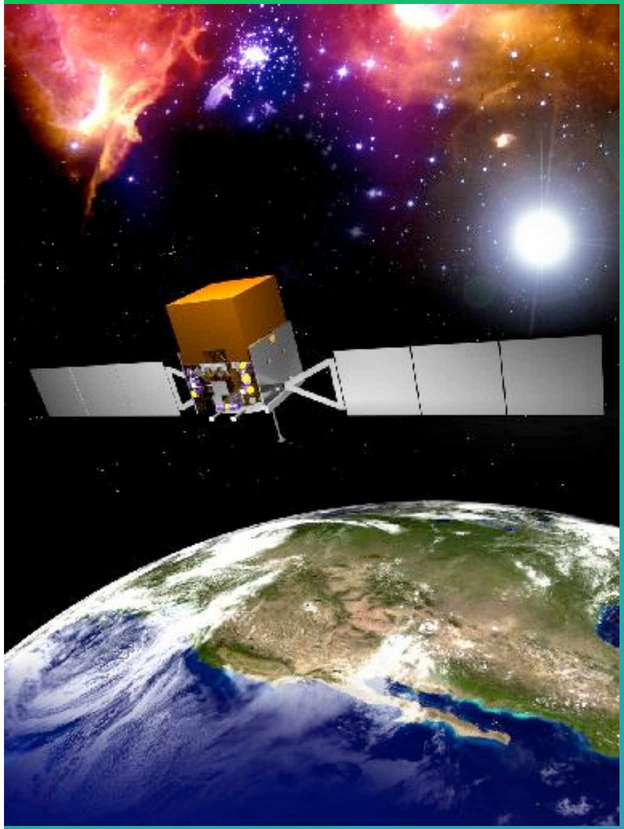
Searching for dark WIMPs

- 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

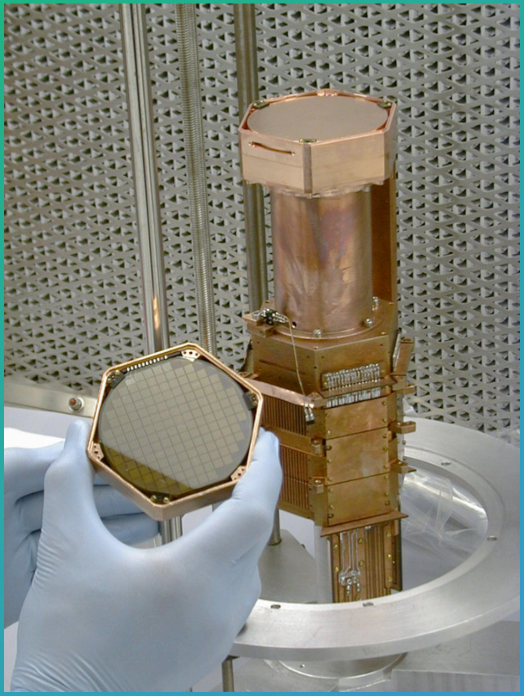
Indirect or Direct Detection

FERMI/GLAST



photons

CDMS



scattering

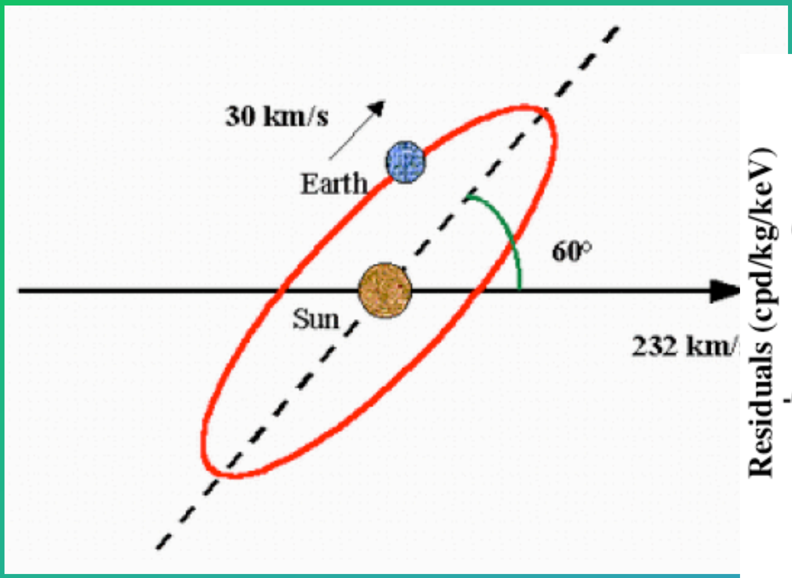
ICE CUBE

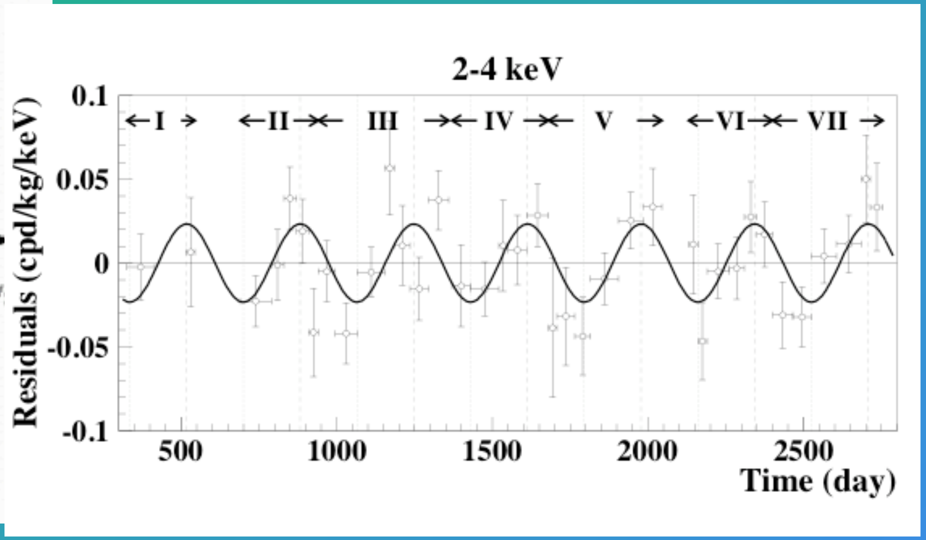
neutrinos

DAMA annual modulation

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

Bernabei et al 2003

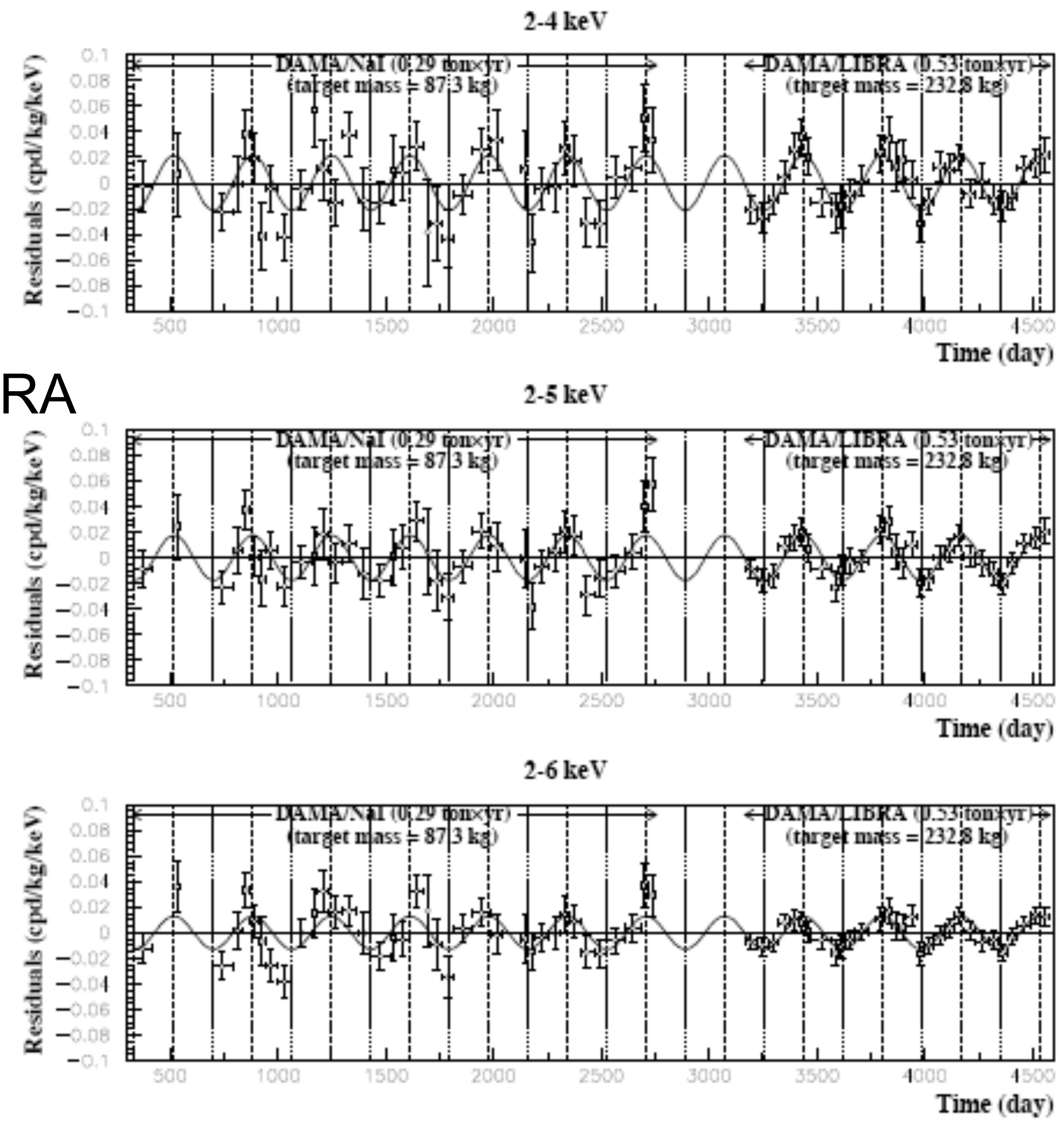




Data do show a 8σ modulation

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

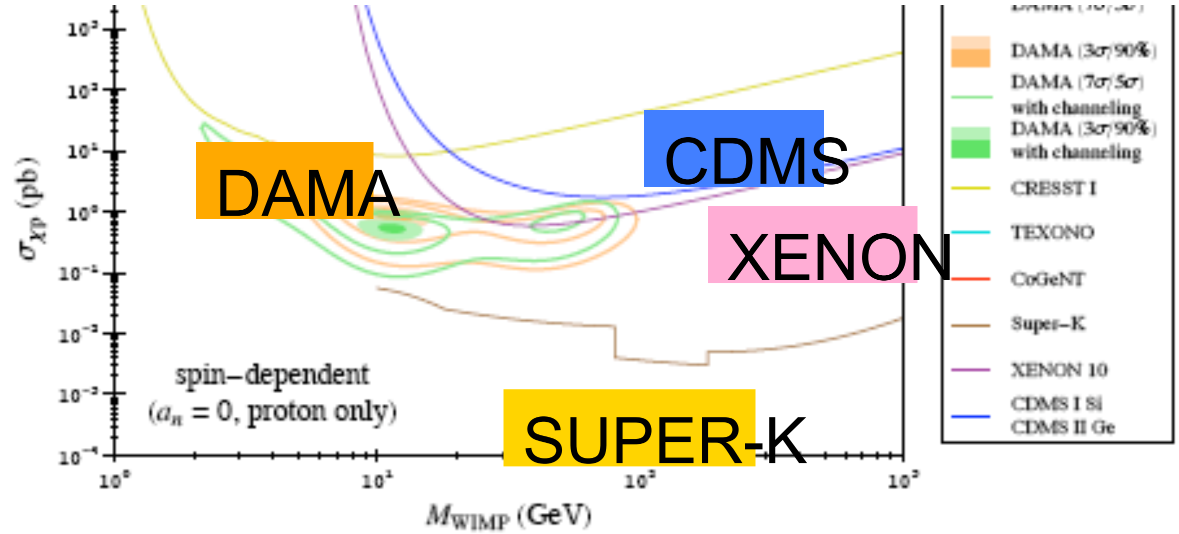
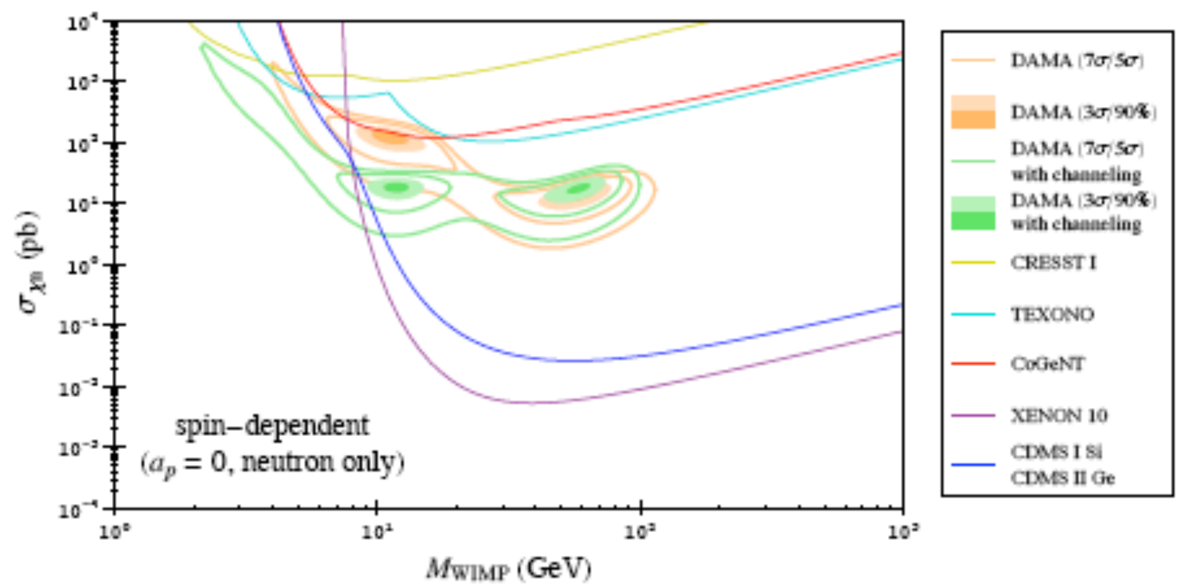


FIG. 6: Experimental constraints and DAMA preferred parameters for SD proton-only scattering. The DAMA preferred regions are determined using the likelihood ratio method with (green) and without (orange) the channeling effect. The CoGeNT and TEXONO constraints are too weak to fall within the shown region.



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

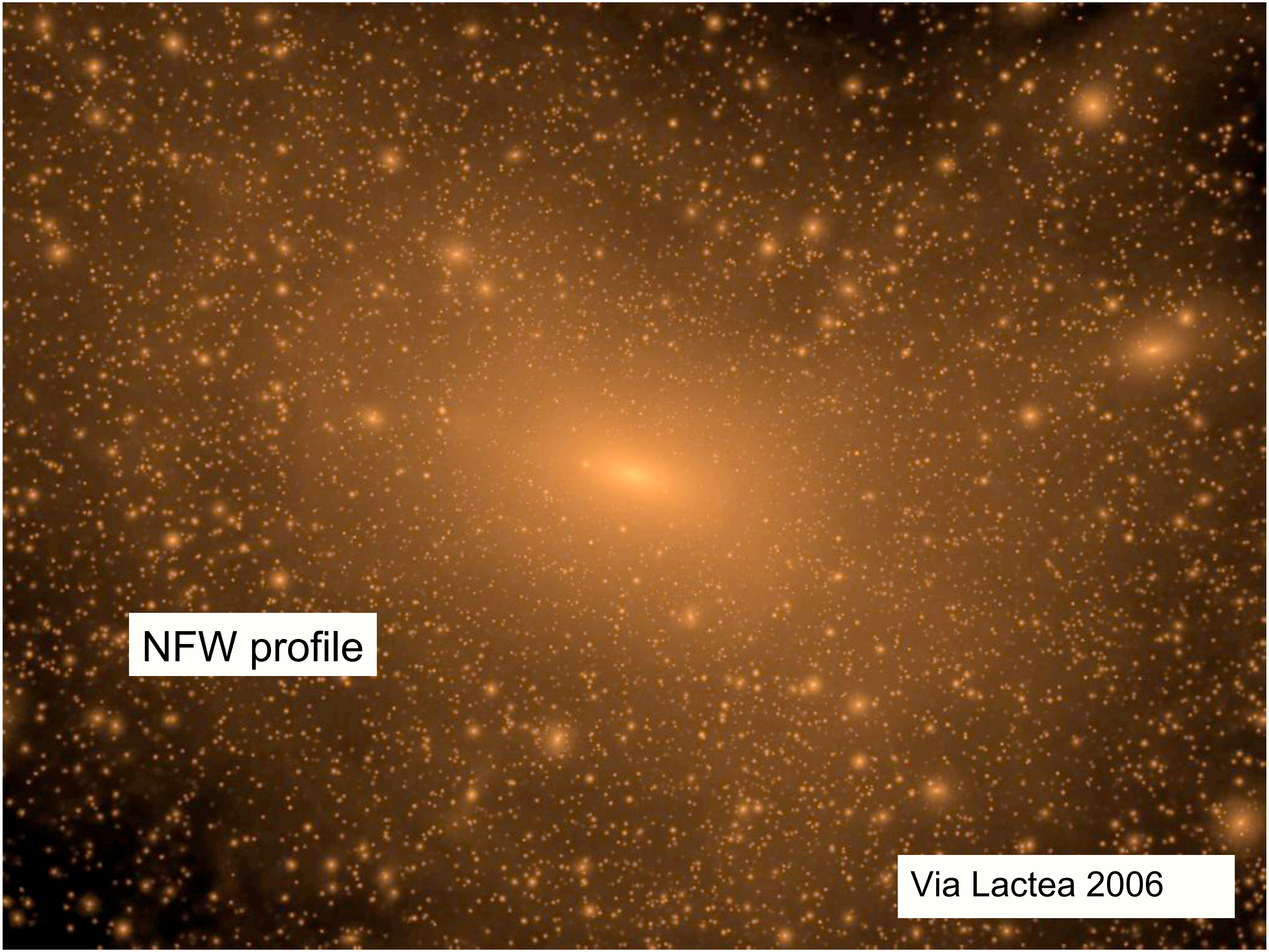
1/3 neutrinos

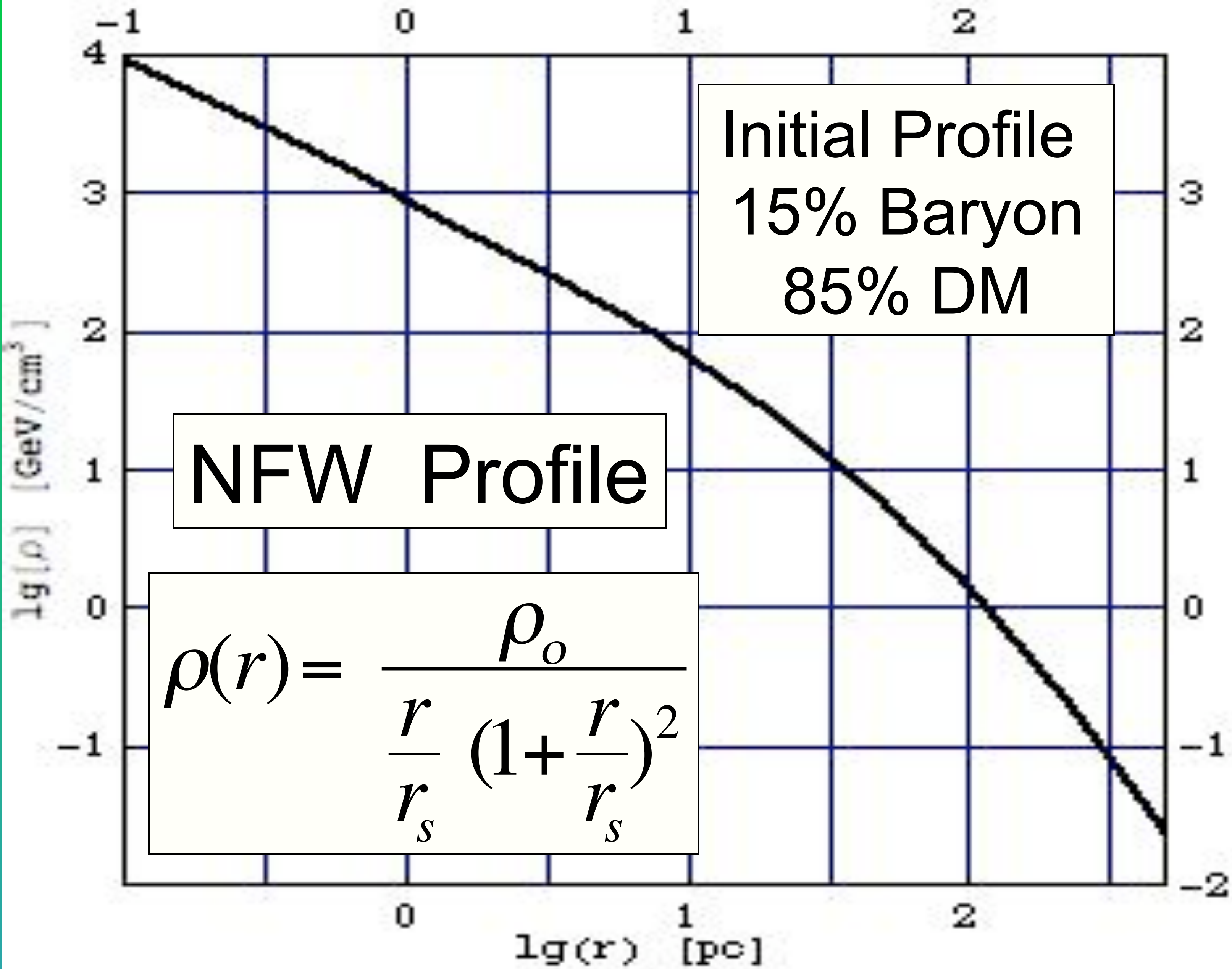
Depending upon the densities.

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 ↗





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

(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:

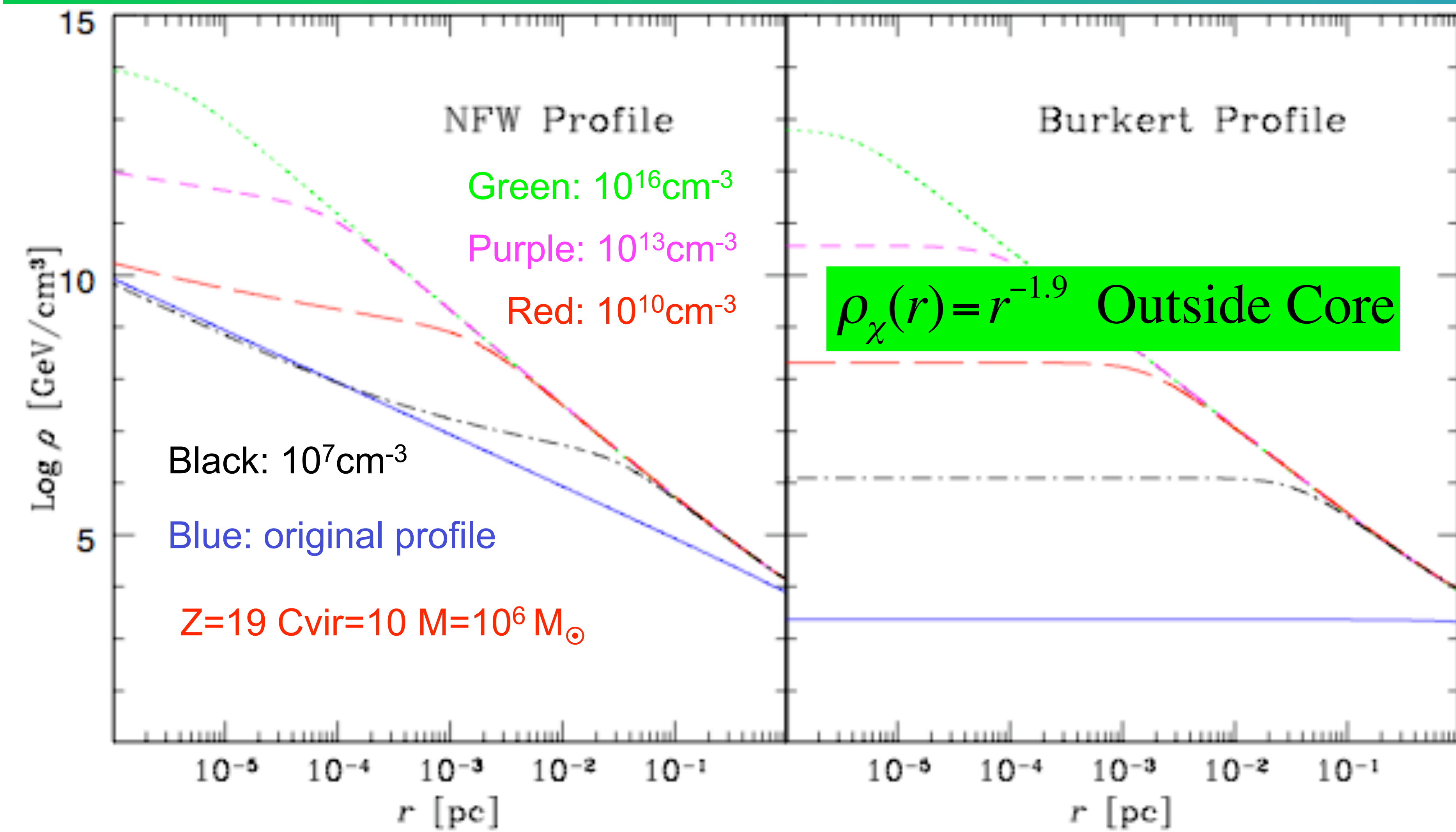
$$\rho_\chi(r) \sim r^{-1.9} \quad \text{Outside Core}$$

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

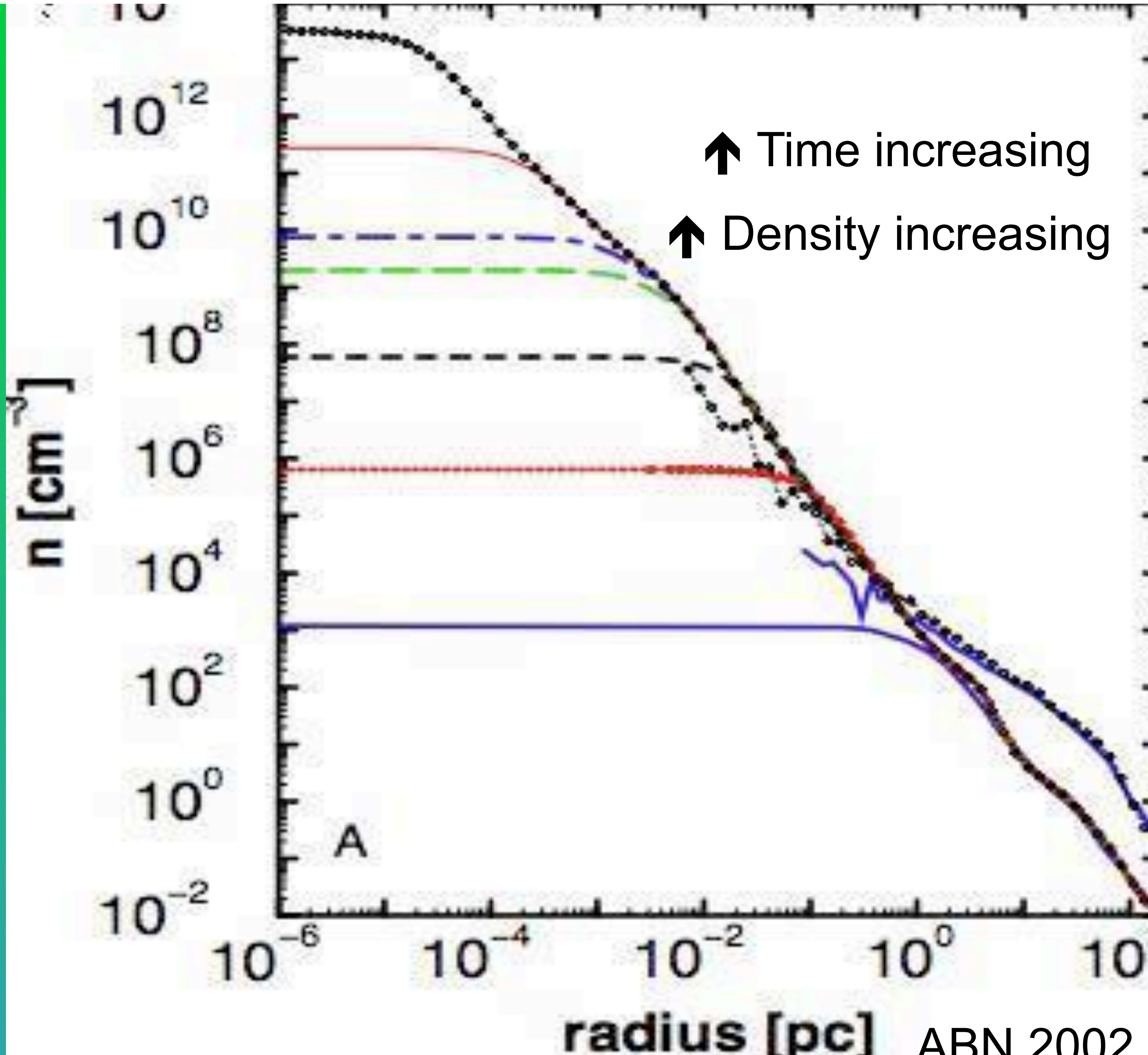
Simplistic: circular orbits only.

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

Dark Matter Profile



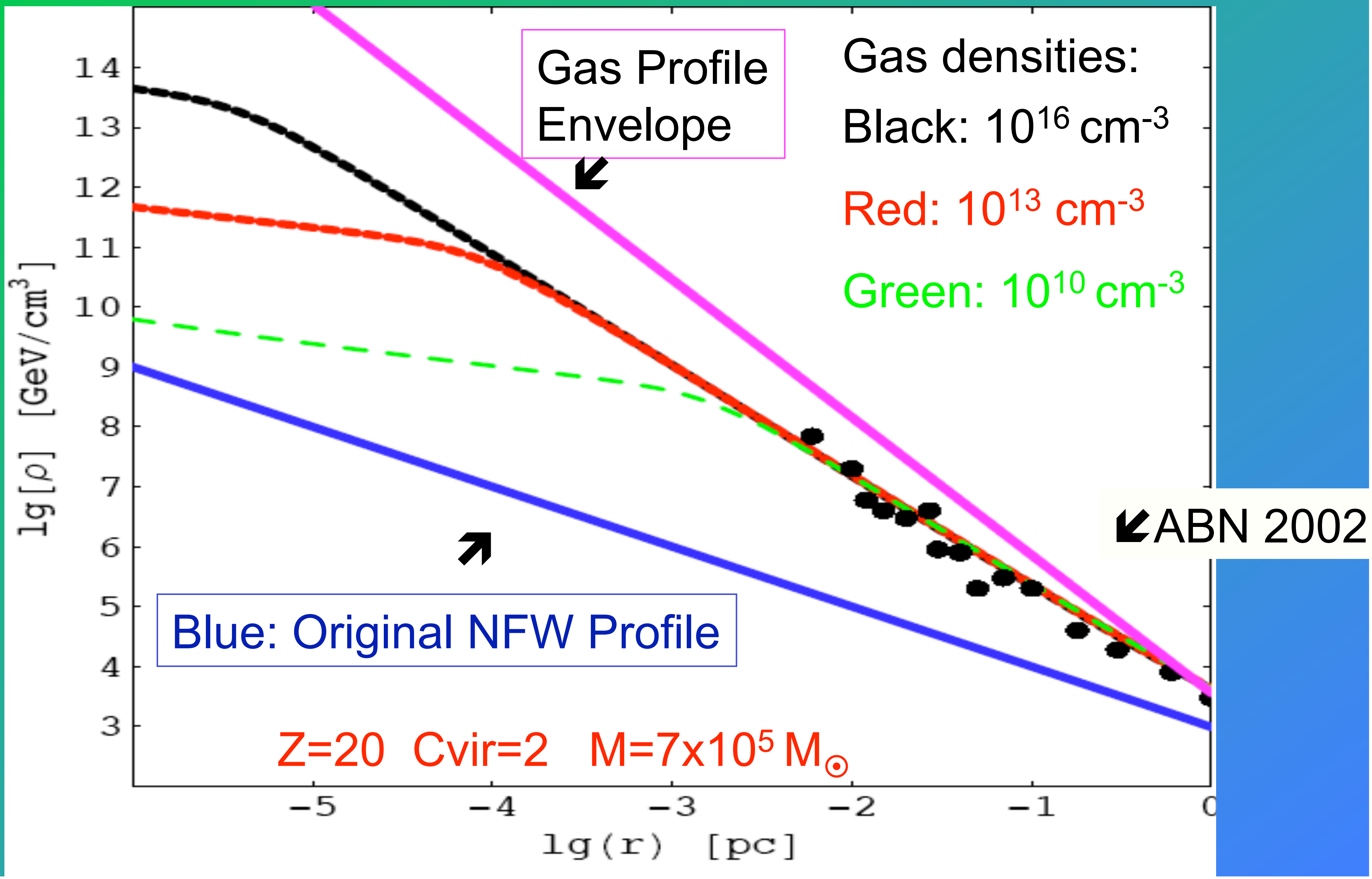
(Outer slope $r^{-1.9}$, profile matches Abel, Bryan, Norman '02)



Time increasing
Density increasing
n [cm^-3]
radius [pc]
A
10^12
10^10
10^8
10^6
10^4
10^2
10^0
10^-2
10^-6
10^-4
10^-2
10^0

ABN 2002

DM profile and Gas



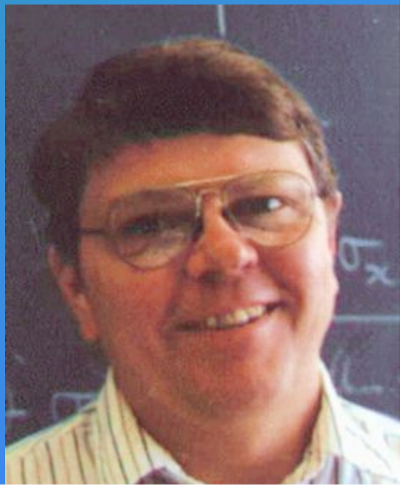
Dark Matter Densities in the Stars

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

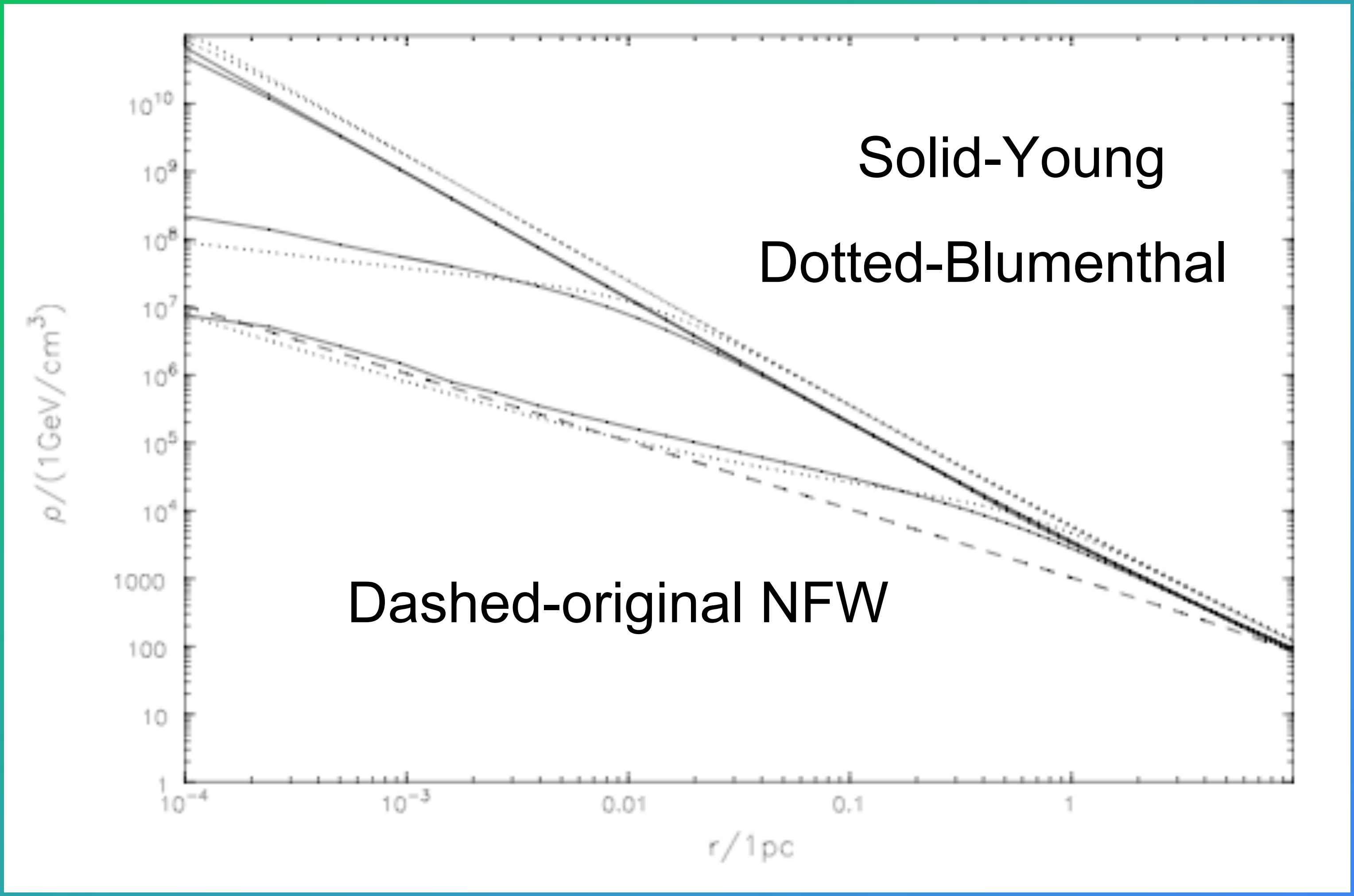
How accurate is Blumenthal method for DM density profile?

- 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



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:

$$Q_{ann} = n_\chi^2 < \sigma v > \times \, m_\chi$$

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

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:

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

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

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

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

Three Conditions for Dark Stars (Paper 1)

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- 2) Annihilation Products get stuck in star
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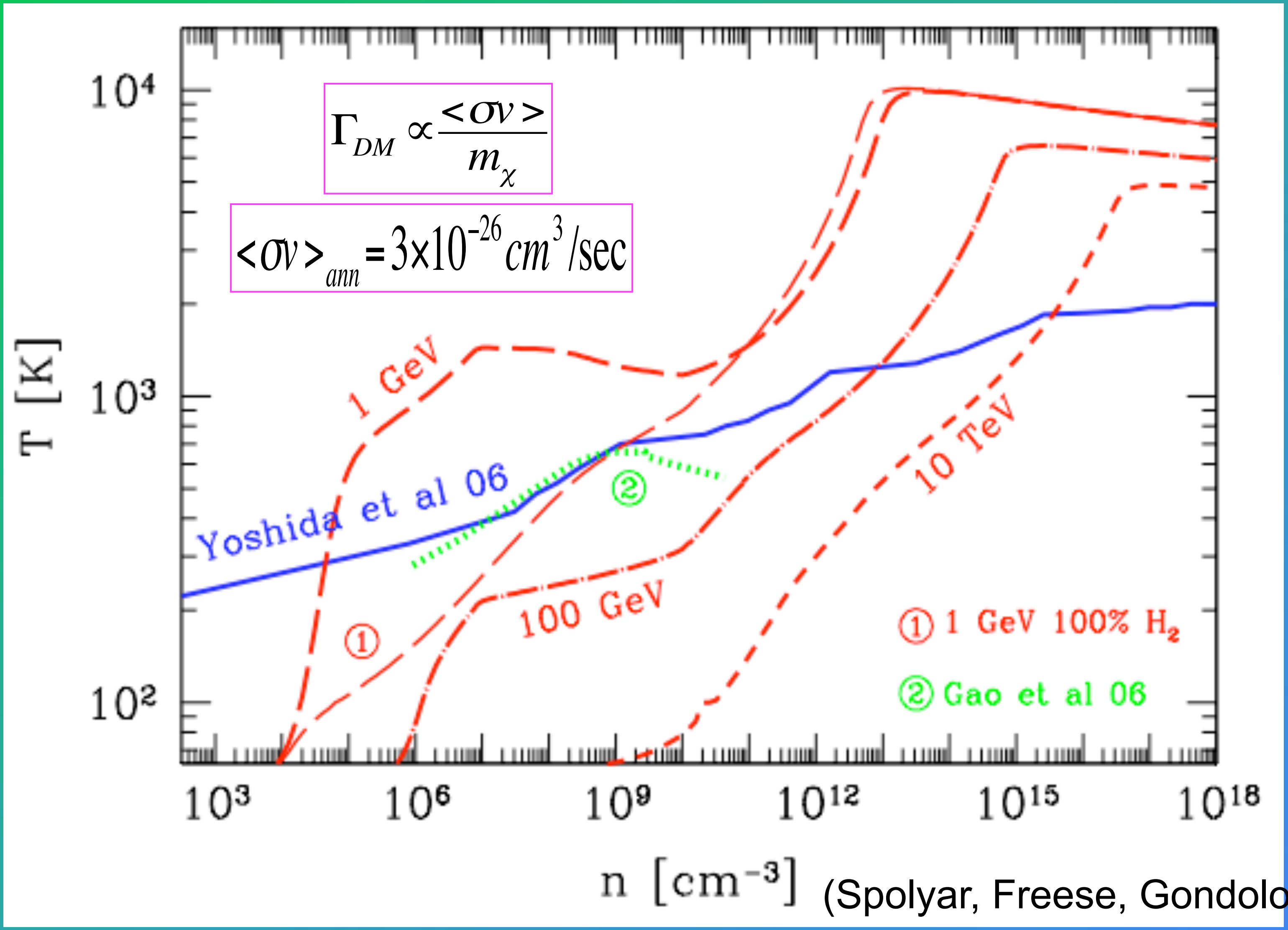
DM Heating beats H2 Cooling

- Leads to New Phase

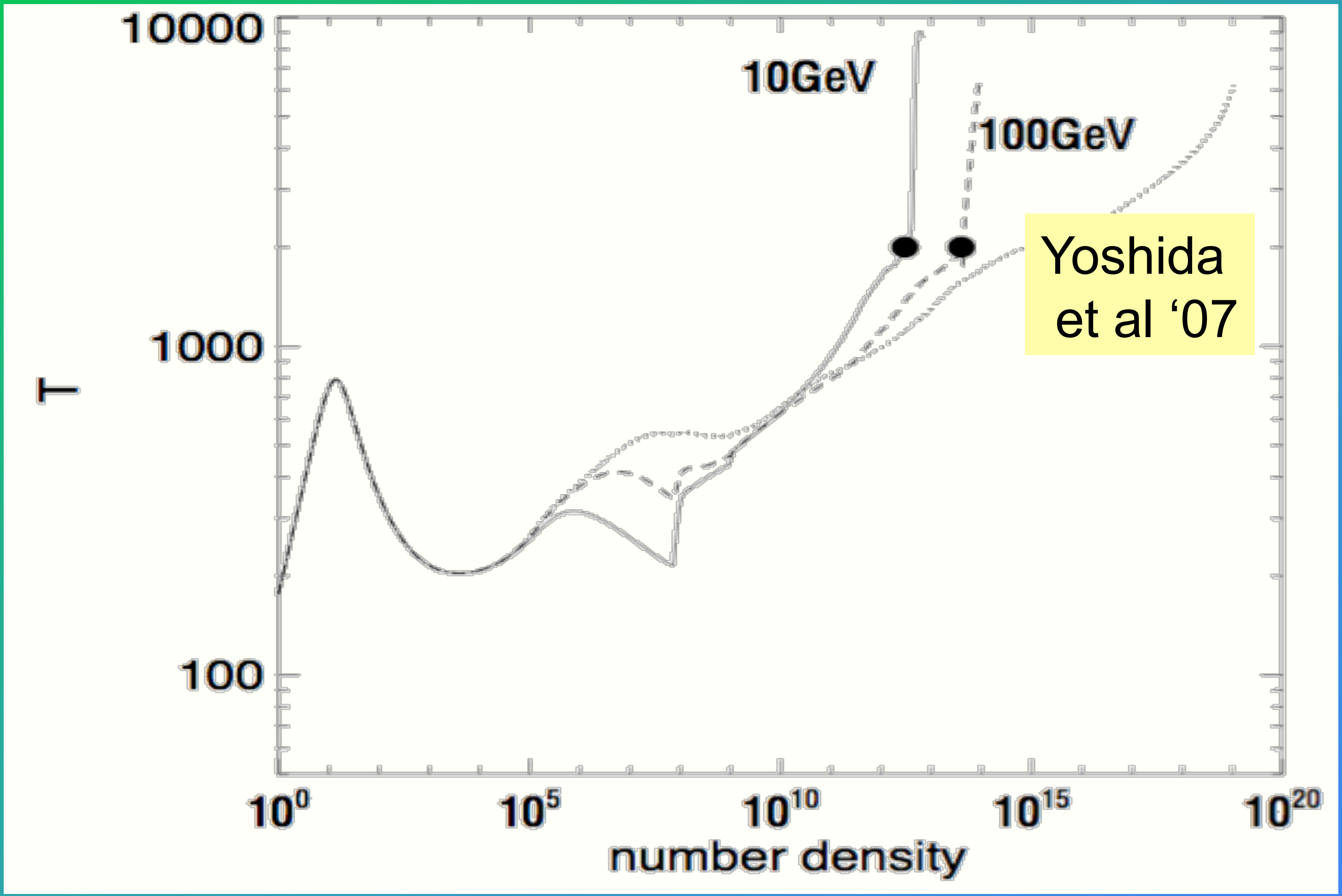
DM Heating dominates over cooling when the red lines cross the blue/green lines (standard evolutionary tracks from simulations). Then heating impedes further collapse.



(Spolyar, Freese, Gondolo April 2007)

New proto-Stellar Phase:

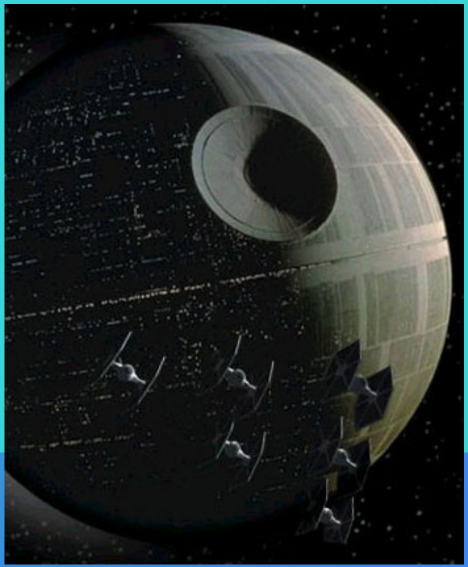
fueled by dark matter



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

$m_\chi \approx 1$ GeV — core radius 960 a.u. — Mass 11 $M_\odot$

$m_\chi \approx 100$ GeV — core radius 17 a.u. — Mass 0.6 $M_\odot$

- THE POWER OF DARKNESS: DM is only 1% of the mass of the star but provides the heat source
- Dark stars are powered 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)

- 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:

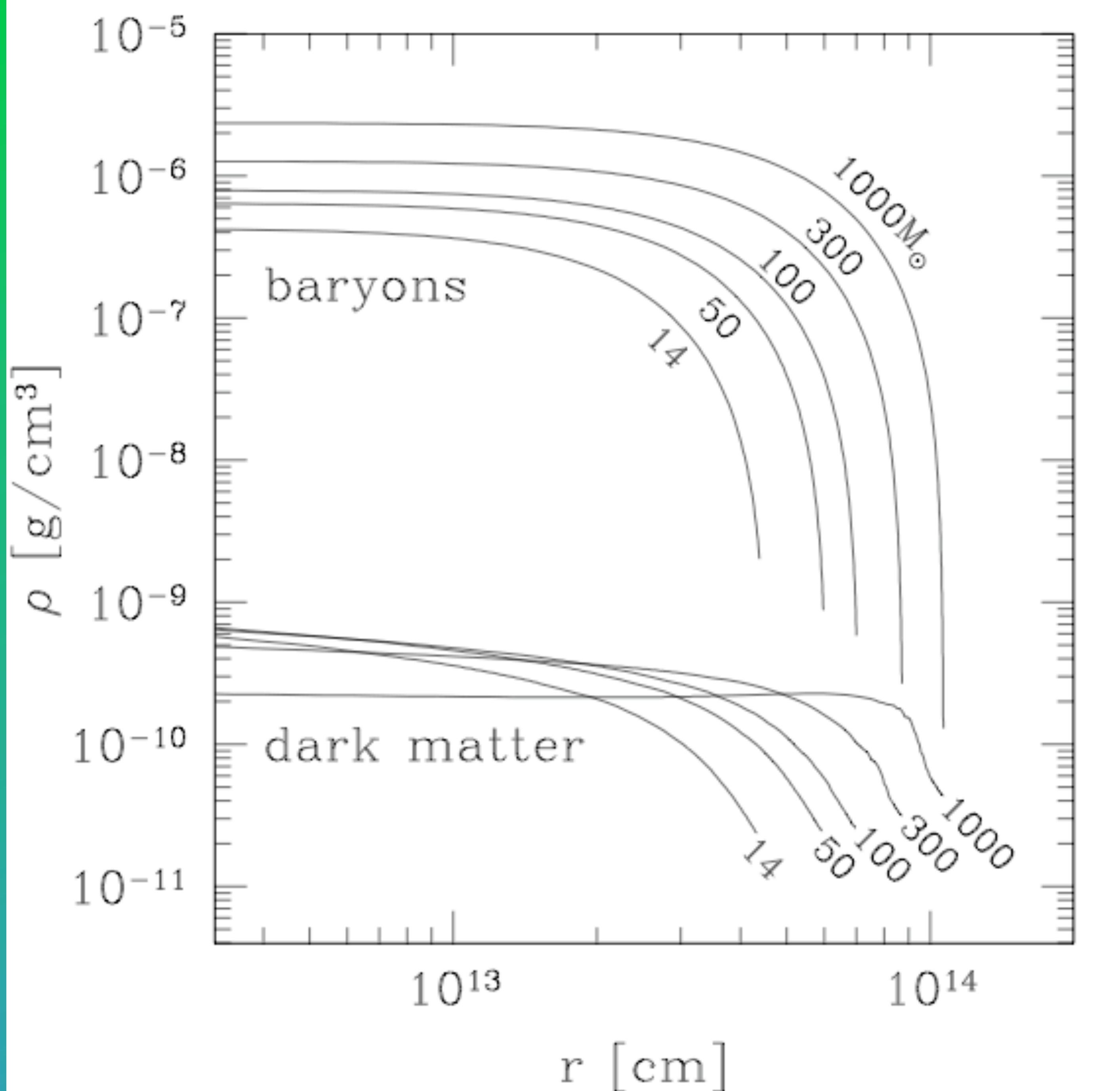
$$L_{DM} = L_*$$

Building up the mass

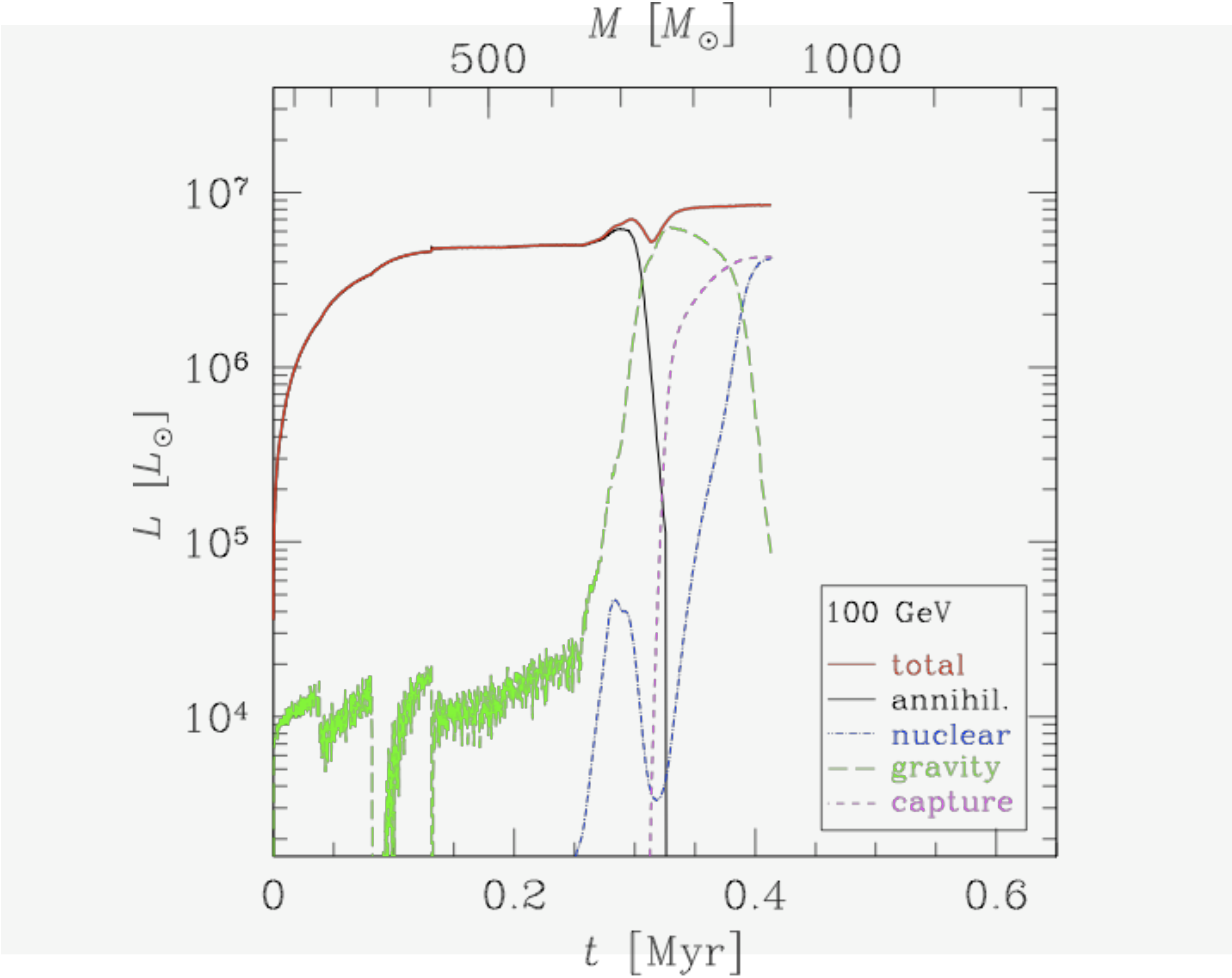
- Start with a few $M_\odot$ Dark Star, find equilibrium solution
- Accrete mass, one $M_\odot$ at a time, always finding equilibrium solutions
- N.b. as accrete baryons, pull in more DM, which then annihilates
- Continue until you run out of DM fuel
- DM annihilation powered DS continues to 800 $M_\odot$.
- VERY LARGE FIRST STARS! Then, star contracts further, temperature increases, fusion will turn on, eventually make BH.

Why much larger stars than in standard picture?

- Fusion powered stars are hot: 10^7K in the core, 50,000-100,000 K (>13.6eV) at the surface. They produce ionizing photons. These photons produce feedback onto the accretion disk that prevents further accretion.
- Dark Stars, on the other hand, are cool, with surface temperatures 6000K like the Sun. No ionizing photons, no feedback, accretion can continue as long as dark matter powers the star.



10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
ρ [g/cm^3]
baryons
dark matter
1000M$_\odot$
300
100
50
14
1000
300
100
50
14
10^{13}
10^{14}
r [cm]



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

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 (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?

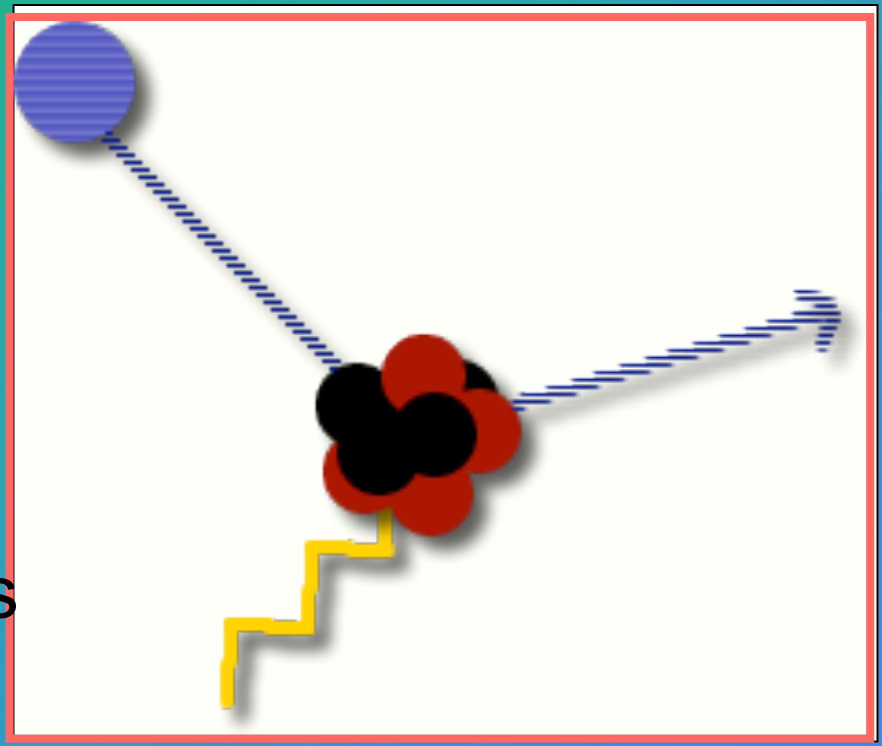
- Star reaches T=10^7K, fusion sets in.
- 800 solar mass Pop III star lives a million years, then becomes a Black Hole
- Very high mass: can avoid Pair instability SN which arise from 140-260 solar mass stars (and whose chemical imprint is not seen)
- Helps explain observed black holes:
- (I) in centers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

New Ideas: SUPERMASSIVE dark stars

- 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 M_sun, last much longer, and reach 10^9 L_sun.
- Maybe visible in JWST! Leads to (as yet unexplained) big black Holes.

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.
n.b. this is the same process as in direct detection experiments



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!

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

- 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.
- 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.

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?

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 (800-10^5 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)

Detecting WIMP Dark Matter Particles

- Collider Searches
- 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 (Ellis, KF et al ‘87)
  - Galactic Center (Gondolo and Silk 2000)
  - Anomalous signals seen in HEAT, PAMELA (e+), HESS, CANGAROO, WMAP, EGRET, etc.

EXCITING TIMES

- We made WIMP phenomenology proposals twenty years ago:
- It is coming to fruition!
- My personal prediction: one of the anomalous results is right and we will know very soon.

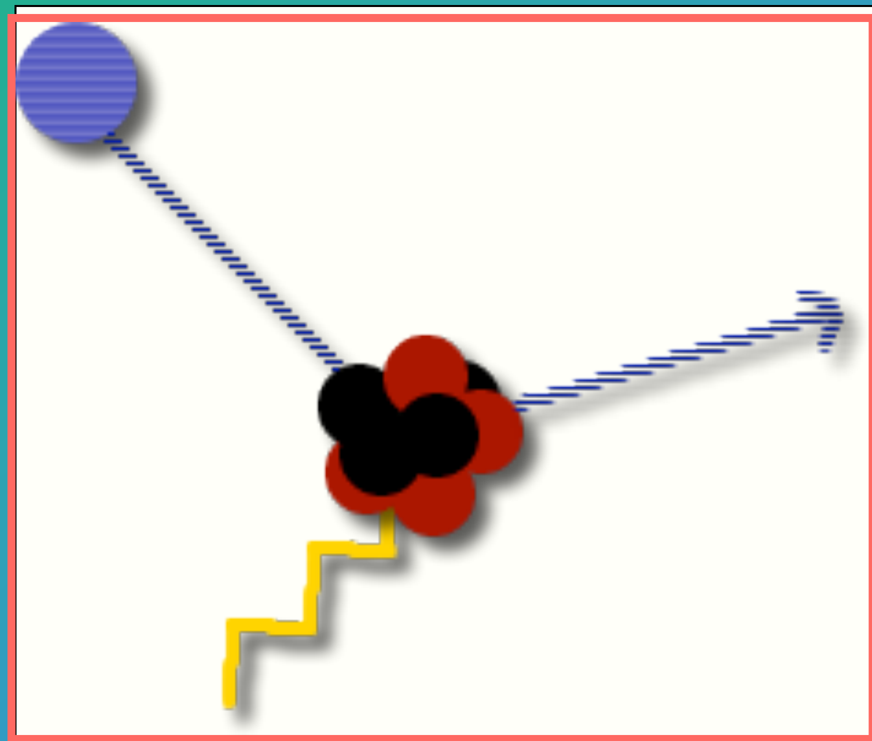

LHC-Making DM
Coming Soon
(We hope)

Supersymmetric Particles in LHC

- Signature: missing energy when SUSY particle is created and some energy leaves the detector
- Problem with identification: degeneracy of interpretation
- SUSY can be found, but, you still don’t know how long the particle lives: fractions of a second to leave detector or the age of the universe if it is dark matter
- Proof that the dark matter has been found requires astrophysical particles to be found

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.



Expected Rate: fractions of a count/kg/day

WIMP Dark Matter Phenomenology: History

- Looking for neutrinos (Drukier and Stodolsky)
- First paper suggesting direct detection: Goodman and Witten 1986
- Second paper on direct detection: we
- (I) took into account WIMP distribution in galaxy and (ii) suggested annual modulation (Drukier, Freese, and Spergel 1986).
- (iii) discussed spin-independent and spin-dependent
- A followup paper (Freese, Frieman, Gould 1988) suggested using annual modulation to pull out signal from background. This is how the only current claim for direct detection was done (DAMA experiment).

Event rate

(number of events)/(kg of detector)/(keV of recoil energy)

$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nv\, f(v,t)\, d^3v$$

$$= \frac{\rho \sigma_0 F^2(q)}{2m\mu^2} \int_{v > \sqrt{ME/2\mu^2}} \frac{f(v,t)}{v} d^3v$$

Spin-independent $\sigma_0 = \frac{A^2 \mu^2}{\mu_p^2} \sigma_p$

Spin-dependent $\sigma_0 = \frac{4\mu^2}{\pi} \left| \langle S_p \rangle G_p + \langle S_n \rangle G_n \right|^2$

unit detector mass for a WIMP mass m, typically given in units of cpd/kg/keV (where cpd is counts per day), can be written as:

$$\frac{\mathrm{d}R}{\mathrm{d}E} = \frac{\sigma(q)}{2m\mu^2}\,\rho\,\eta(E,t) \tag{1}$$

where $q = \sqrt{2ME}$ is the nucleus recoil momentum, $\sigma(q)$ is the WIMP-nucleus cross-section, ρ is the local WIMP density, and information about the WIMP velocity distribution is encoded into the mean inverse speed $\eta(E,t)$,

$$\eta(E,t) = \int_{u>v_{\mathrm{min}}} \frac{f(\mathbf{u},t)}{u}\,\mathrm{d}^3u\,. \tag{2}$$

Here

$$v_{\mathrm{min}} = \sqrt{\frac{ME}{2\mu^2}} \tag{3}$$

represents the minimum WIMP velocity that can result in a recoil energy E and $f(\mathbf{u},t)$ is the (time-dependent) distribution of WIMP velocities $\mathbf{u}$ relative to the detector

Canonical DM distribution in halo

use a Maxwellian distribution, characterized by an rms velocity dispersion σ_v, to describe the WIMP speeds, and we will allow for the distribution to be truncated at some escape velocity $v_{\rm esc}$,

$$\tilde{f}(\mathbf{v}) = \begin{cases} \frac{1}{N_{\rm esc}} \left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2}, & \text{for } |\mathbf{v}| < v_{\rm esc} \\ 0, & \text{otherwise.} \end{cases}$$

Here

$$N_{\rm esc} = \mathrm{erf}(z) - 2z\exp(-z^2)/\pi^{1/2},$$

with $z \equiv v_{\rm esc}/\overline{v}_0$, is a normalization factor. The most probable speed,

$$\overline{v}_0 = \sqrt{2/3}\,\sigma_v,$$

Typical particle speed is about 270 km/sec.

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
- 4) WMAP Haze

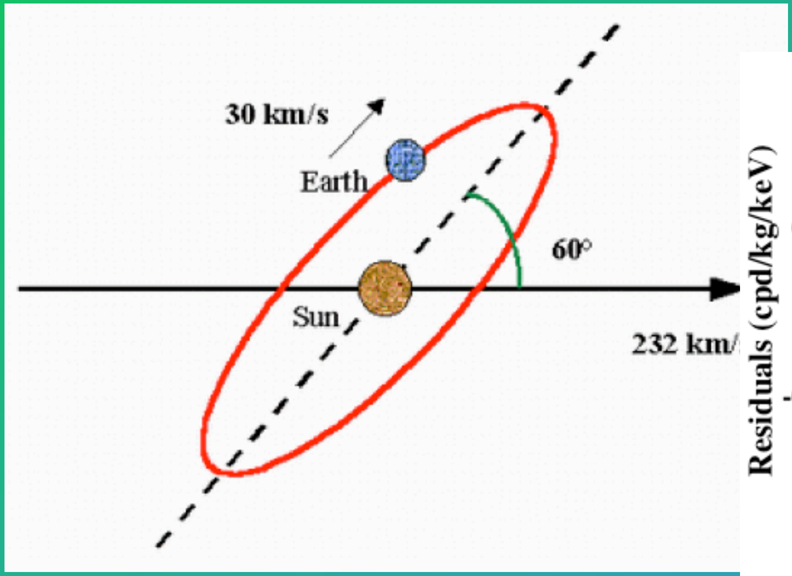
HAS DARK MATTER BEEN DISCOVERED?

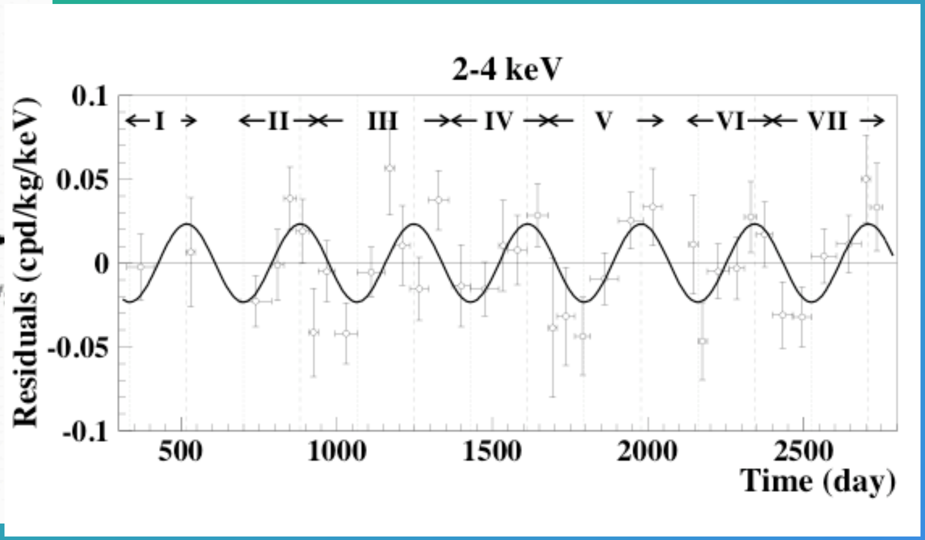
The DAMA Annual Modulation

DAMA annual modulation

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

Bernabei et al 2003

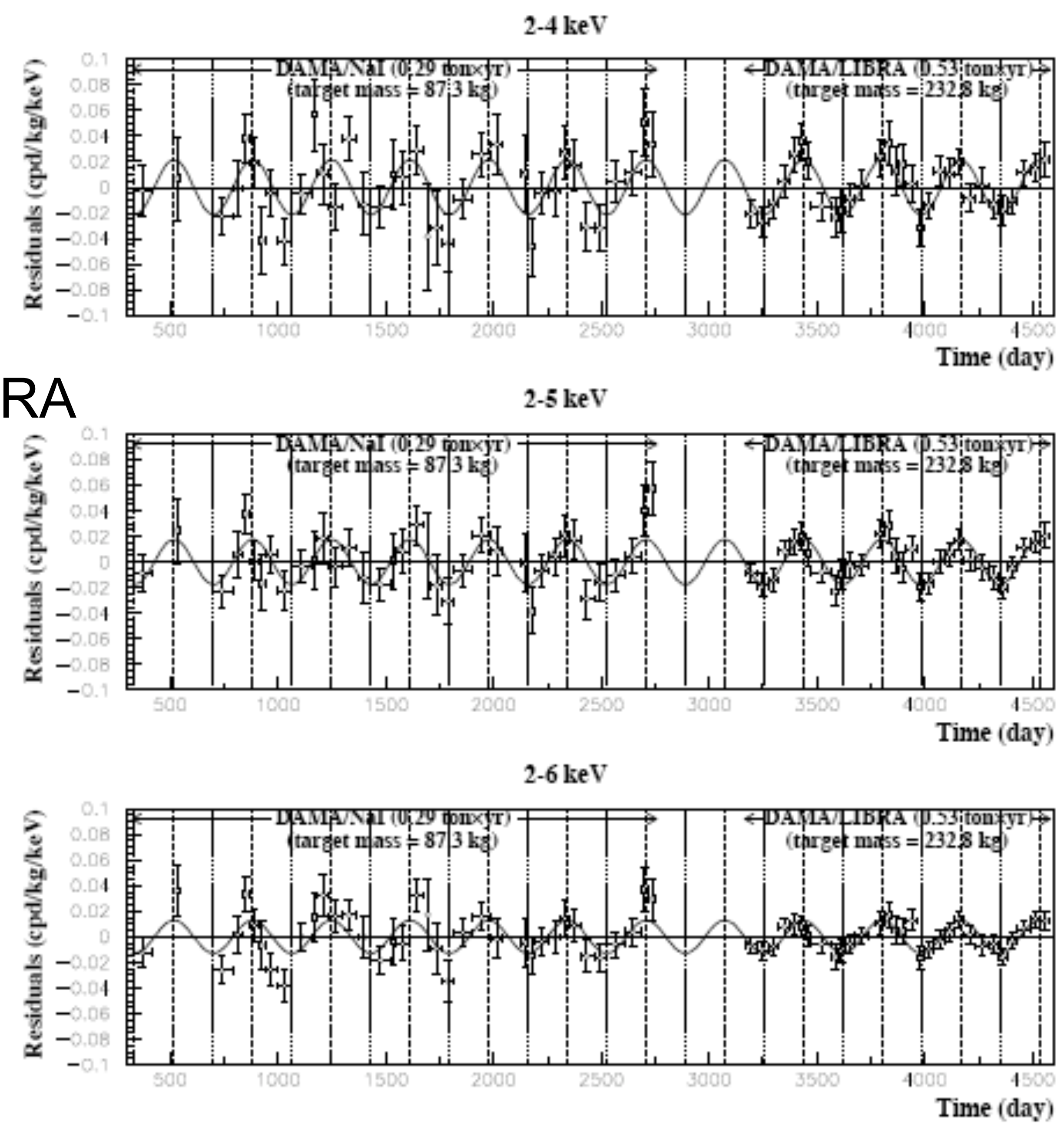




Data do show a 8σ modulation

WIMP interpretation is controversial

DAMA/LIBRA
(April 17, 2008)
8 sigma



Can the positive signal in DAMA be compatible with null results from other experiments?

Experiment	Element	Exposure [kg-day]	Energies [keVee]	Quenching Factor (Q)
DAMA	NaI	2.99×10^5	2–20	0.3, 0.09 (‡)
CDMS	Si	6.58	5–55	1 (§)
	Ge	397.8	10–100	1 (§)
CoGeNT	Ge	8.38	0.23–4.1	0.2
CRESST I	Al_2O_3	1.51	0.6–20	1 (§)
TEXONO	Ge	0.338	0.2–8	0.2
XENON10	Xe	316.4	6.1–36.5	1 (§)

Savage, Gelmini, Gondolo, and Freese, arxiv:0808:3607
(see also papers by Hooper and Zurek; Fairbairn and Schwetz; Chang, Pierce and Weiner 2008)

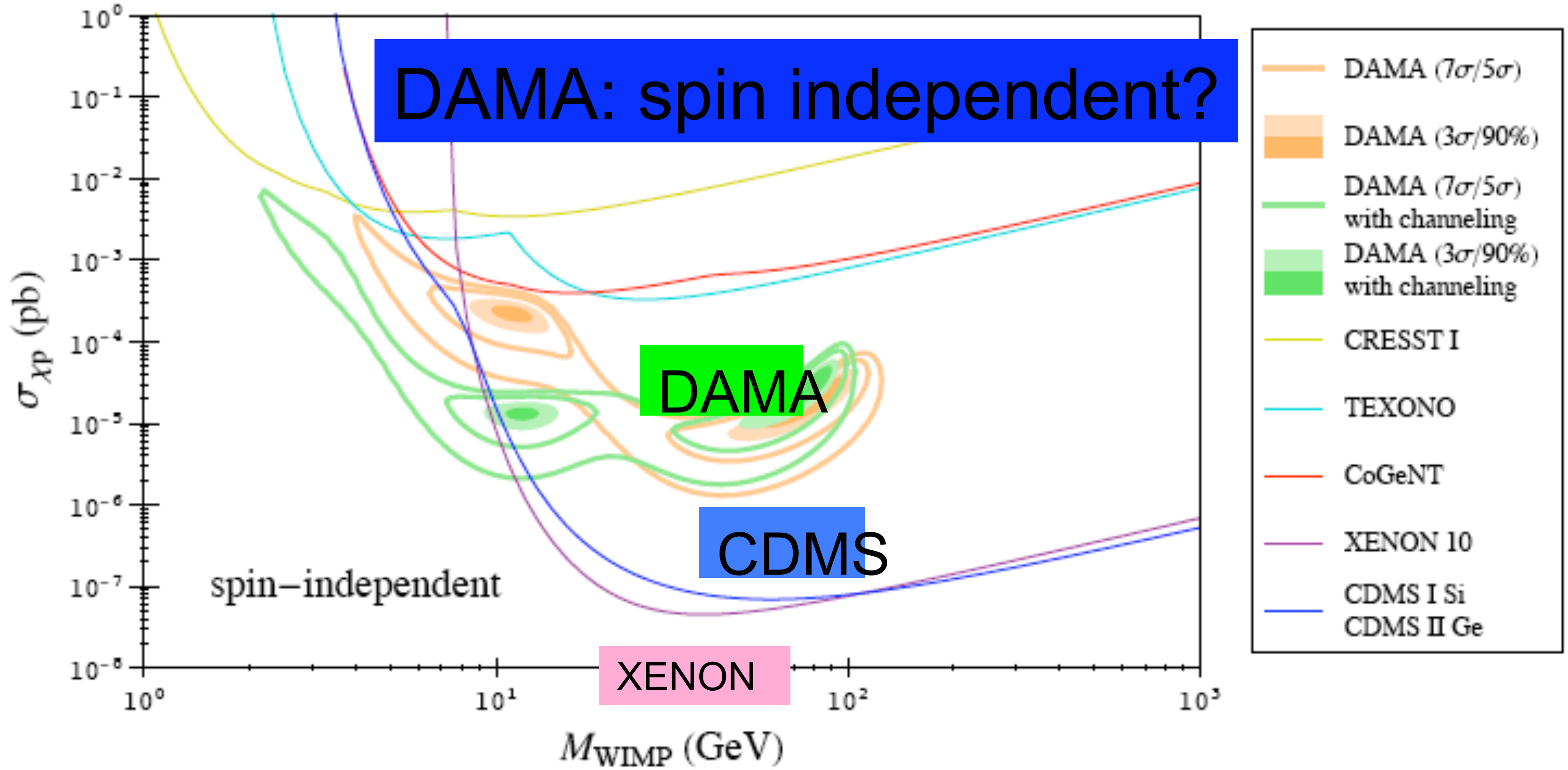
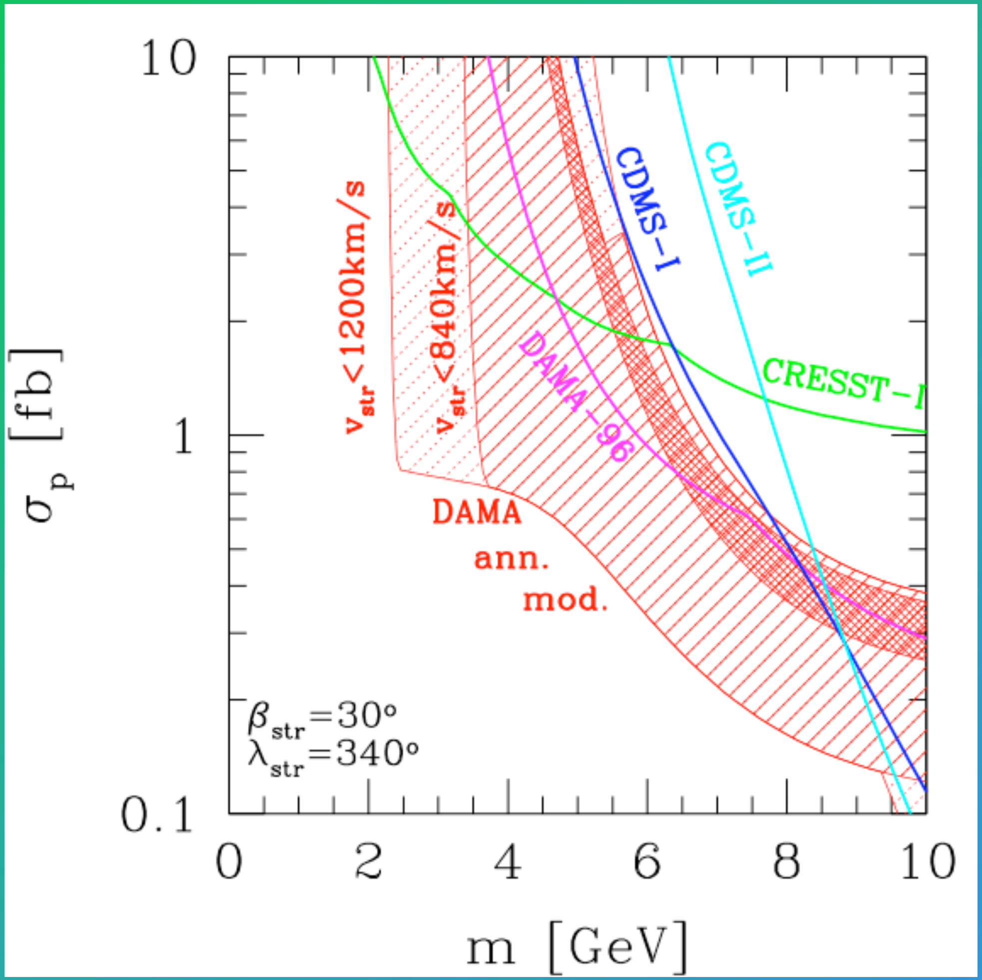


FIG. 5: Experimental constraints and DAMA preferred parameters for SI only scattering. The DAMA preferred regions are determined using the likelihood ratio method with (green) and without (orange) the channeling effect.

Small remaining region at 10 GeV WIMP mass

DAMA: spin-independent?



Gondolo, Gelmini 2004

- Possible at small masses with
  - canonical halo and Maxwellian distribution
  - Galactic or extragalactic dark matter streams

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

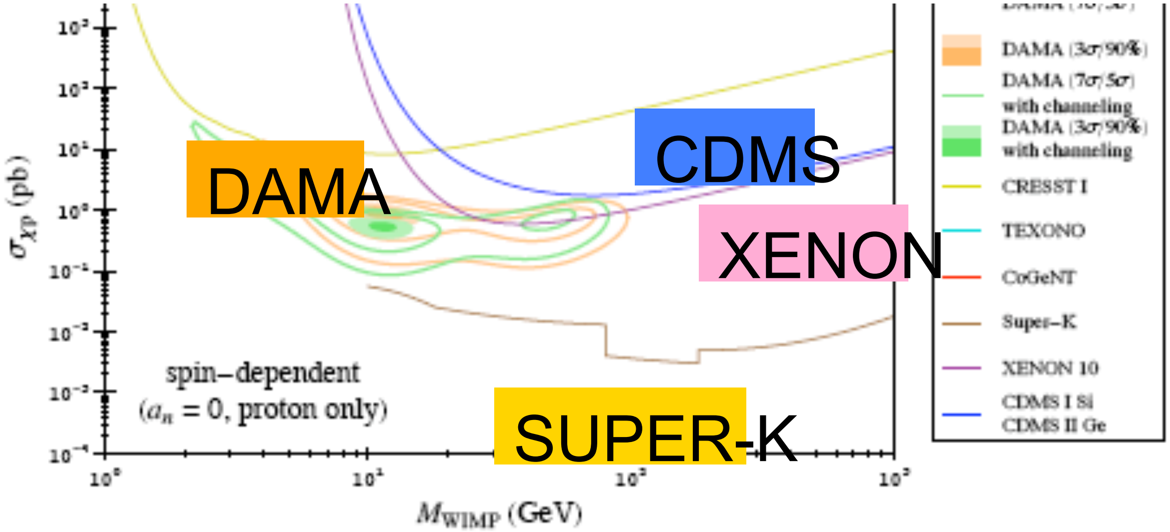
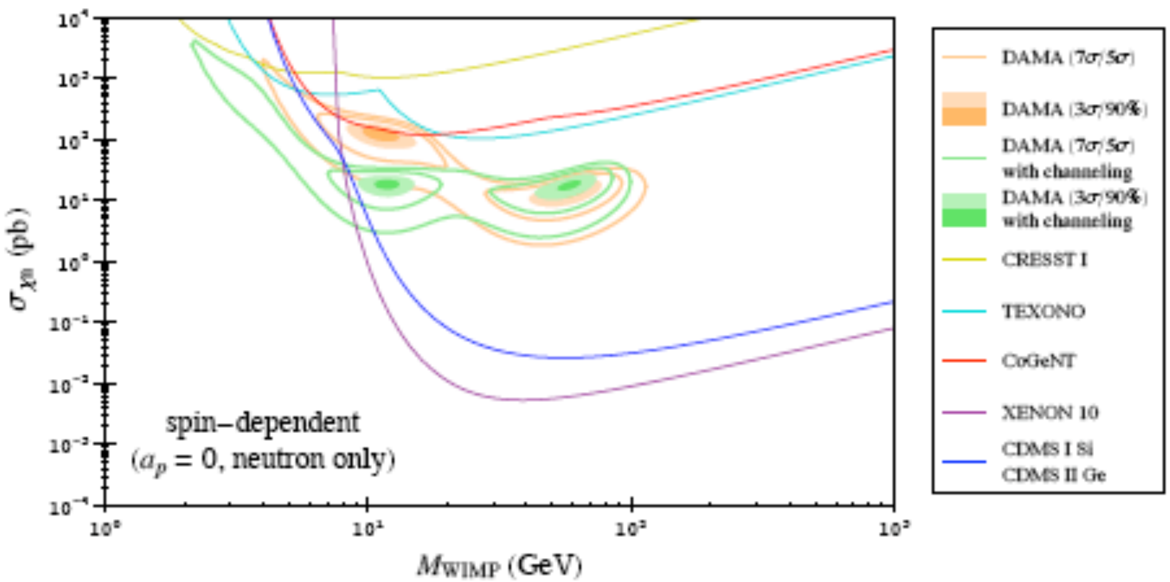


FIG. 6: Experimental constraints and DAMA preferred parameters for SD proton-only scattering. The DAMA preferred regions are determined using the likelihood ratio method with (green) and without (orange) the channeling effect. The CoGeNT and TEXONO constraints are too weak to fall within the shown region.



Alternatives to explain DAMA plus all other data

1. Low mass 5-10 GeV WIMPs

1. For some reason can ignore SuperK bounds (which are from annihilation, not scattering)

2. WIMPs with inelastic scattering?

Different kinematics for Ge vs. NaI

Weiner, Finkbeiner, Pierce

4. Dark Sector with Heirarchy of Masses like our own?

Finkbeiner, Arkani-Hamed, Slatyer, Weiner

Direct Detection

- In past two years, two orders of magnitude increase in sensitivity:

  (i) CDMS

  (ii) XENON-10

  New technology: liquid noble gases

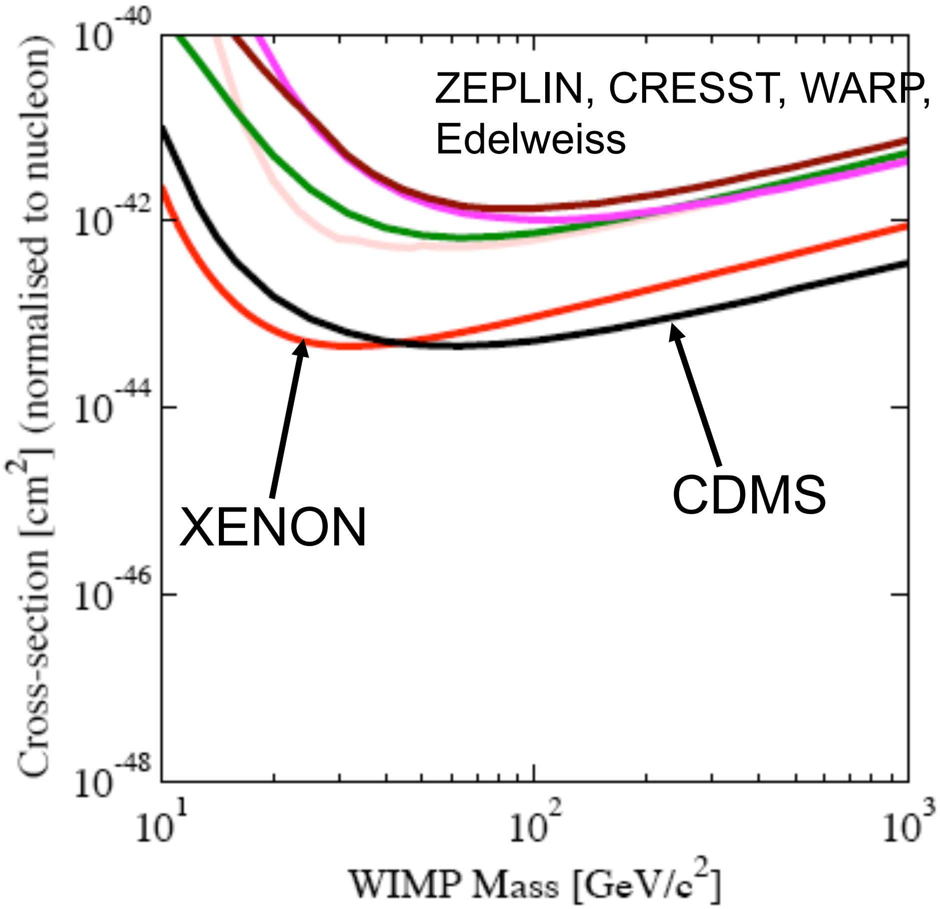
  XENON, LUX

  WARP (argon)

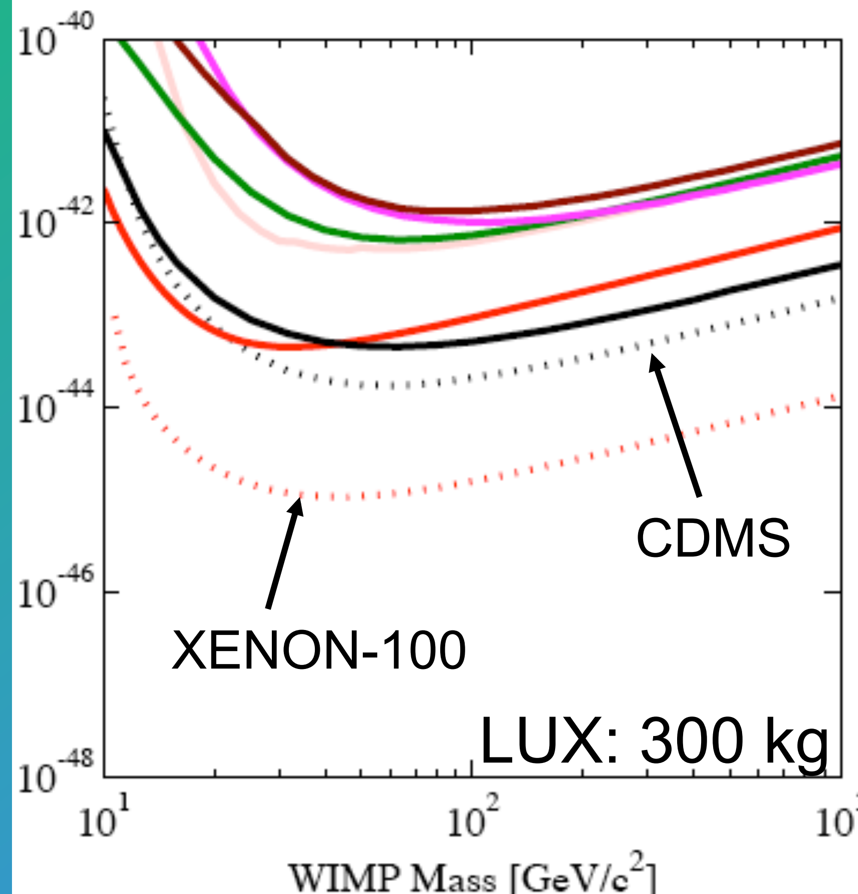
  DEEPCLEAN (argon and neon)

Direct Detection Experiments

Current Status



Near Future



The future: one ton detectors! XENON, LUX, CRESST/ EDELWEISS, DEEP-CLEAN, SUPERCDMS

The HEAT and PAMELA Positron Excess

The Indirect Detection of Dark Matter

1.WIMP Annihilation

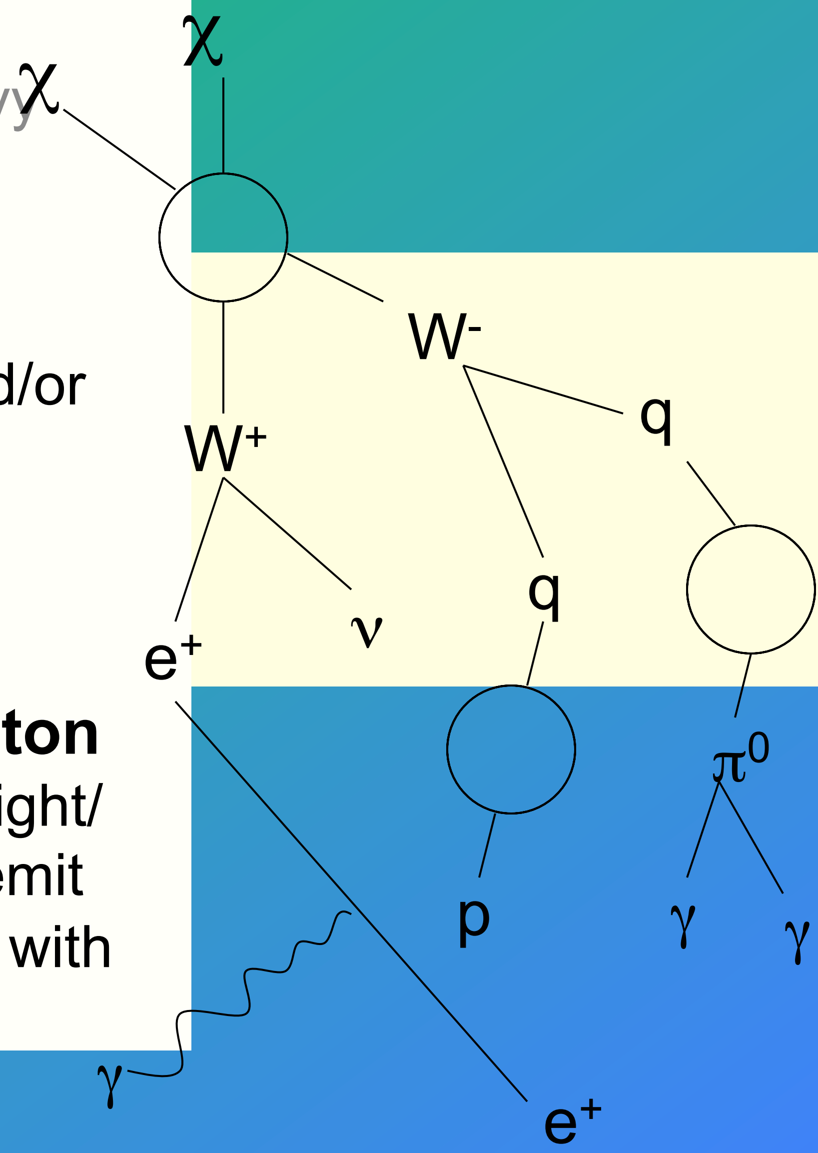
Typical final states include heavy fermions, gauge or Higgs bosons

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



Annihilation Products

- 1/3 electron/positrons
- 1/3 gamma rays
- 1/3 neutrinos
- Typical particles have energies roughly 1/10 of the initial WIMP mass
- All of these are detectable!

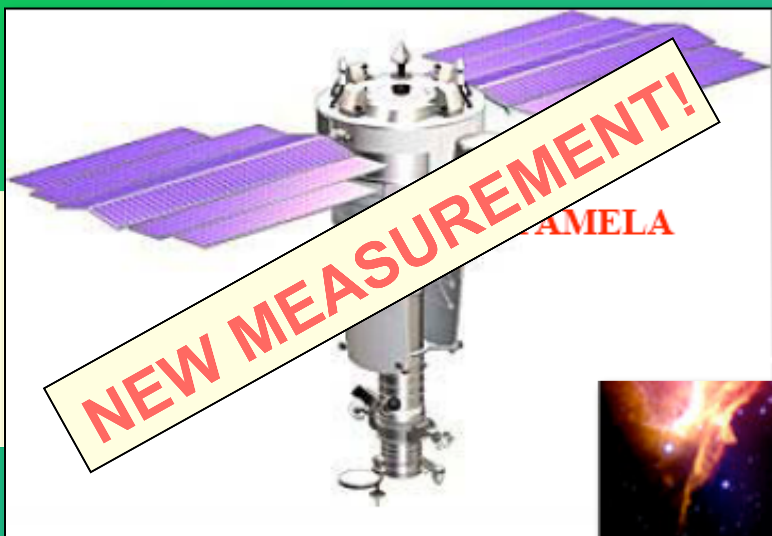
Indirect Detection History

- 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.

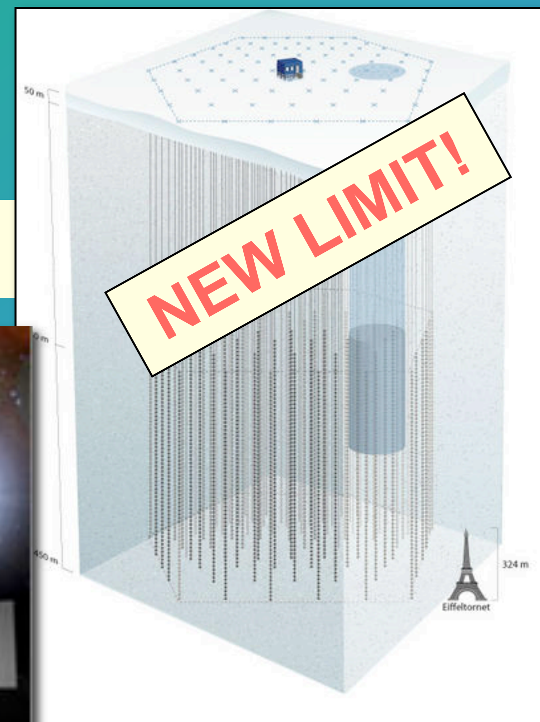
New Indirect Detection Results!

(When it rains it pours)

Pamela

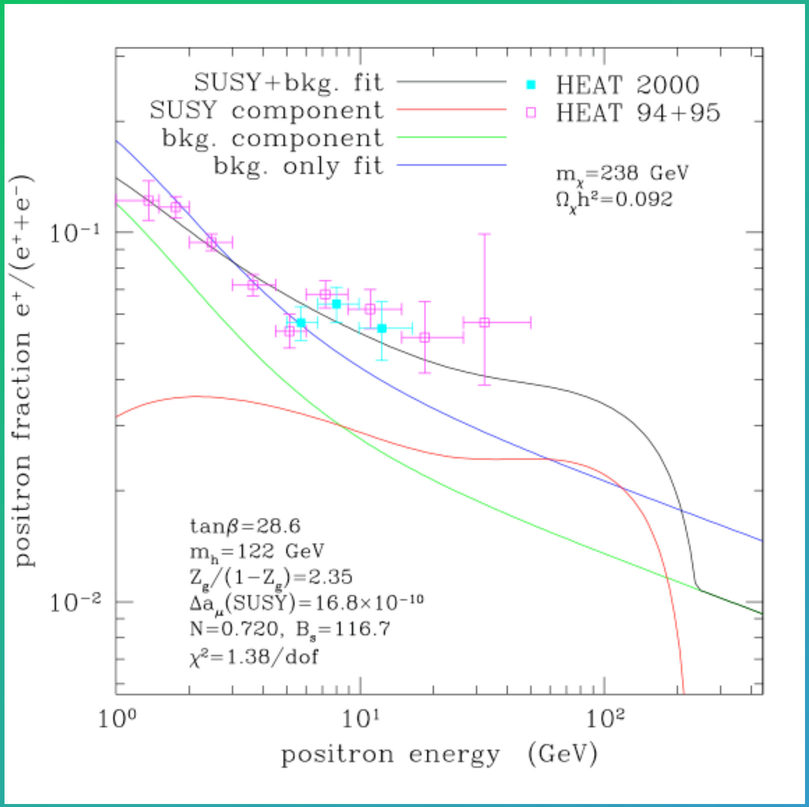


IceCube



FERMI

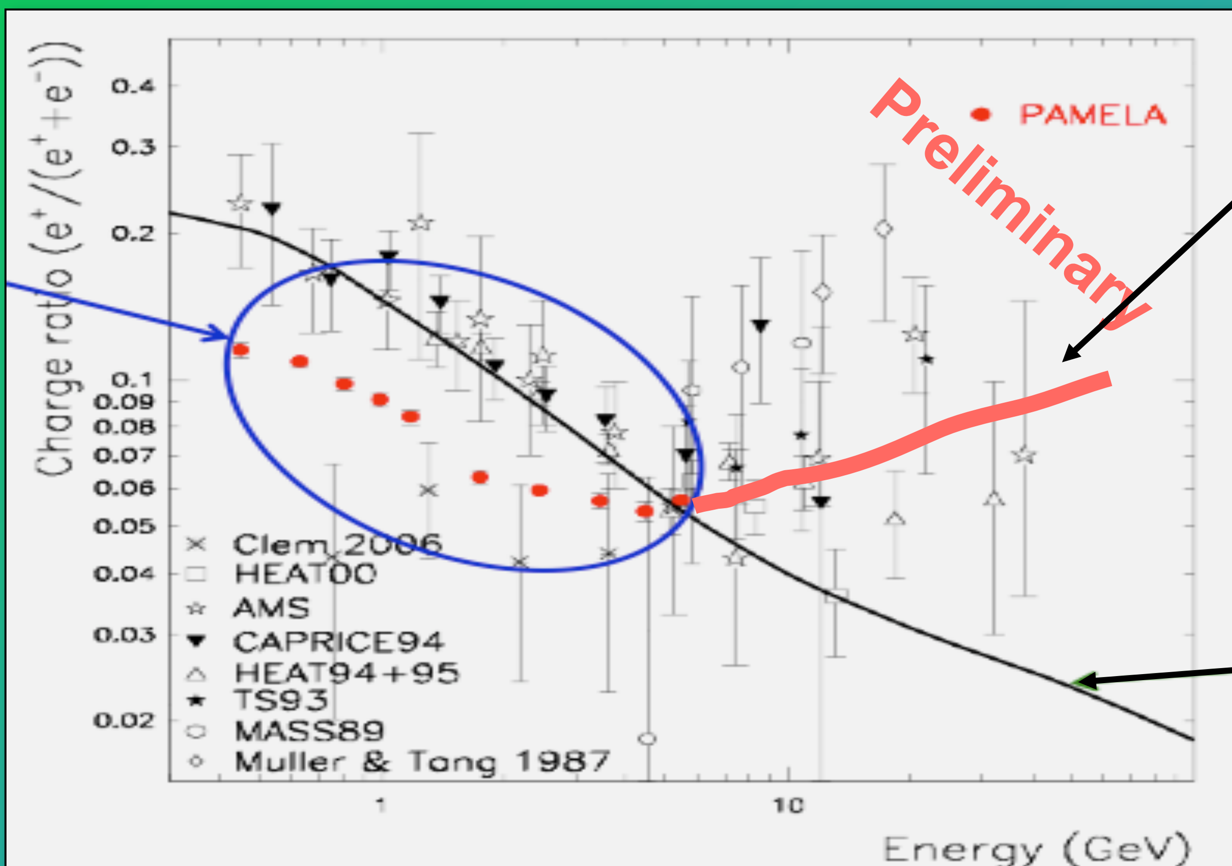
Positron excess



- HEAT balloon found anomaly in cosmic ray positron flux
- Explanation 1: dark matter annihilation
- Explanation 2: we do not understand cosmic ray propagation

Baltz, Edsjo, Freese, Gondolo 2001

Pamela's New Positron Measurement

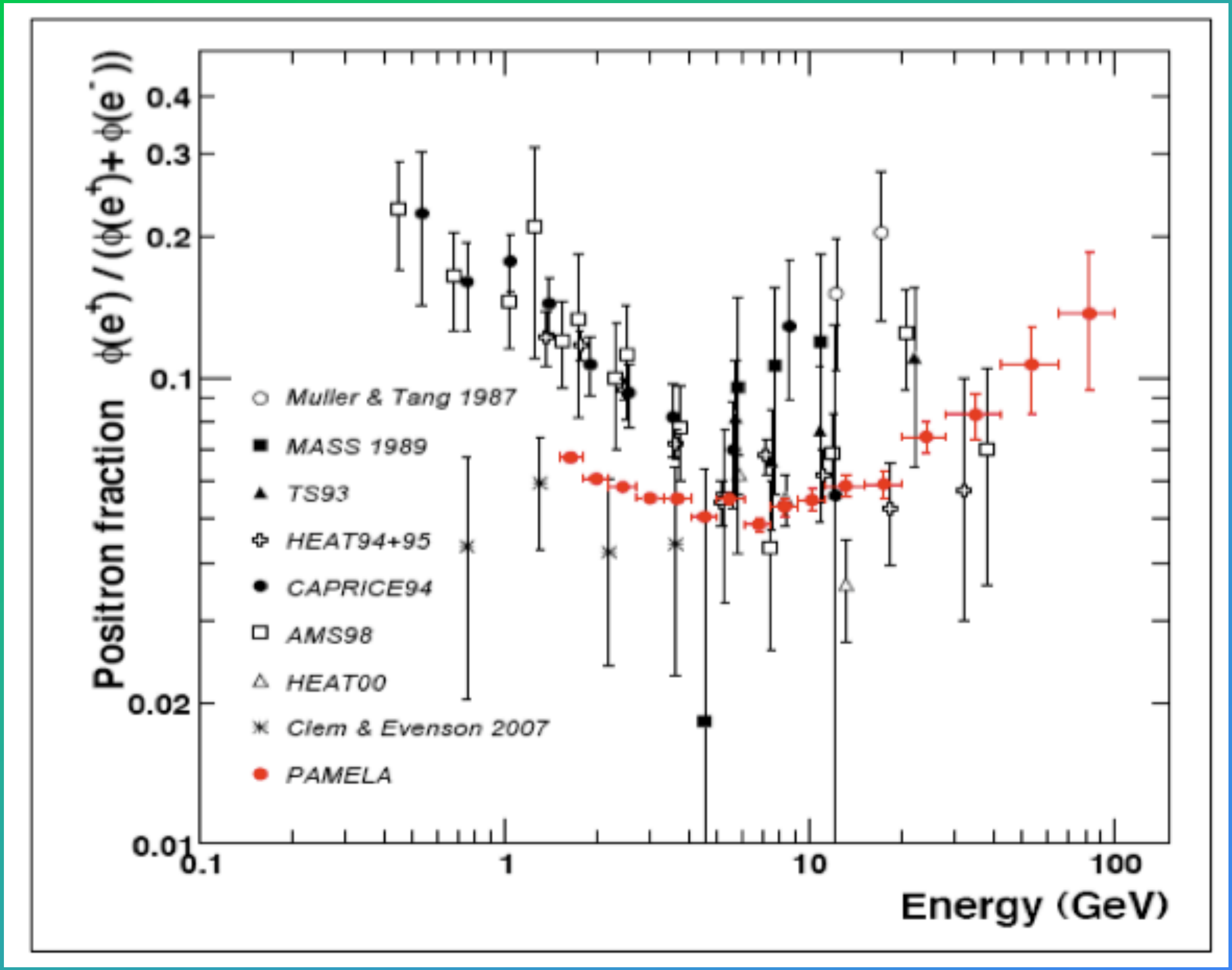


- The positron content of the comic ray spectrum begins to rise at 8-10 GeV, and climbs to ~10% at 60 GeV

Astrophysical expectation (secondary production)

M. Boezio, ICHEP08

PAMELA EXCESS OF POSITRONS

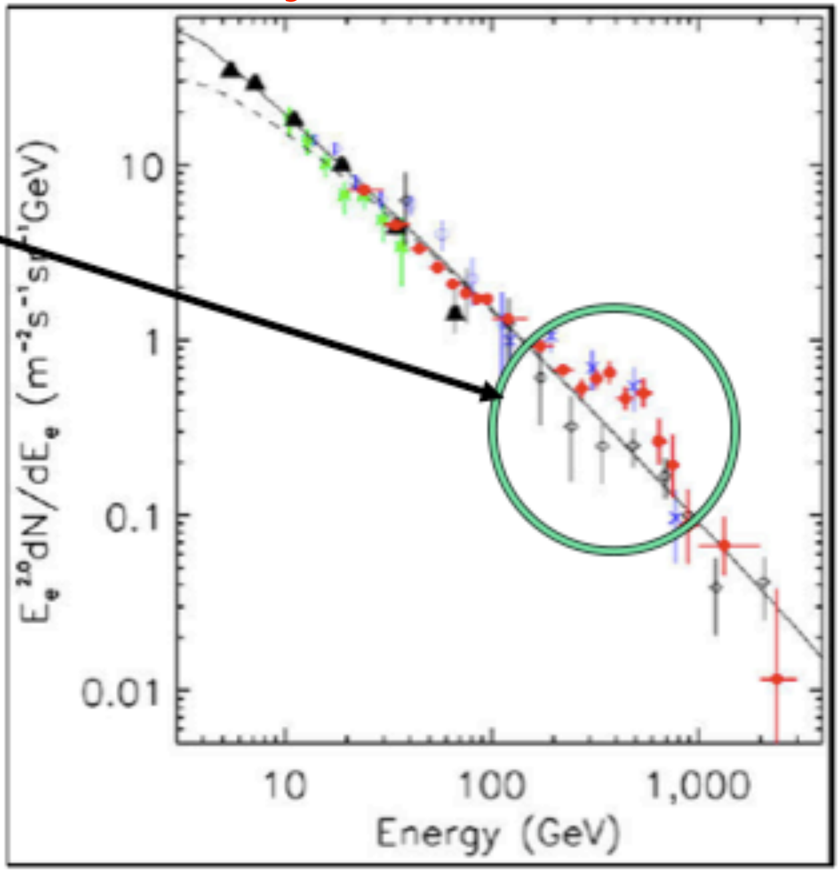


The New Cosmic Ray Electron Spectrum From ATIC

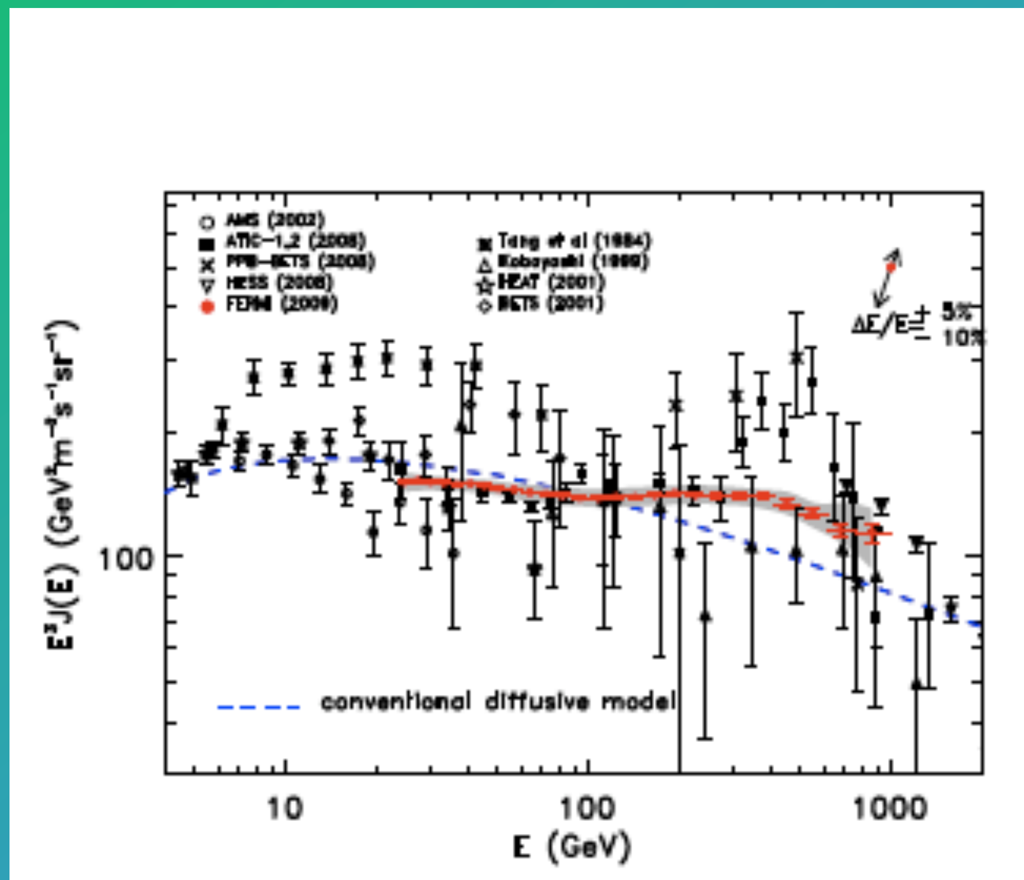
Eun-Suk Seo

Ruled out by FERMI ??

- In a series of balloon flights, ATIC has measured a 4-5σ excess of cosmic ray electrons between 300 and 800 GeV (Nature, Nov. 21, 2008)
- This requires a ***local*** source of cosmic ray electrons/positrons (within ~1 kpc)
- If we extrapolate the Pamela positron fraction up to higher energies, the ATIC result approximately matches



FERMI/LAT electron spectrum

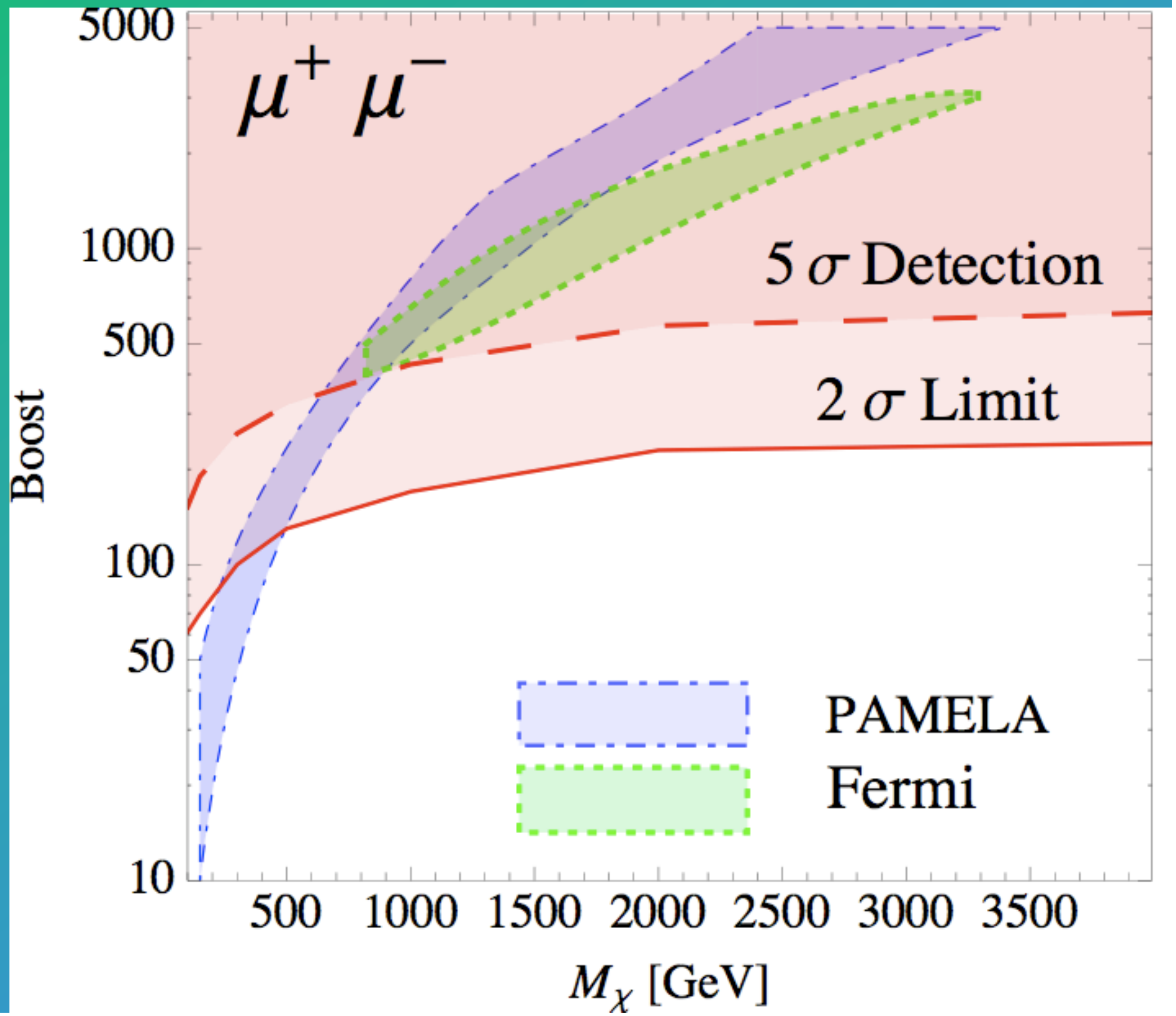


How to understand positron excess?

- 0) Pulsars: the best bet?
- 1) Astrophysics. Propagation of charged particles in the galaxy poorly understood. See Delahaye and Salati 08.
- 2) proton background (misidentified as positrons), is known to rise with energy. PAMELA doesn’t identify each event (HEAT did)
- 3) We happen to live in a hot spot of high dark matter density (boosted by at least factor 10)
- 4) nonstandard WIMPs: e.g., nonthermal WIMPs; Kaluza Klein particles. MUST HAVE BOOSTED ANNIHILATION CROSS SECTION AND LEPTOPHILIC PRODUCTS
- WHO KNOWS?

ICECUBE will see neutrinos in five years if PAMELA is right

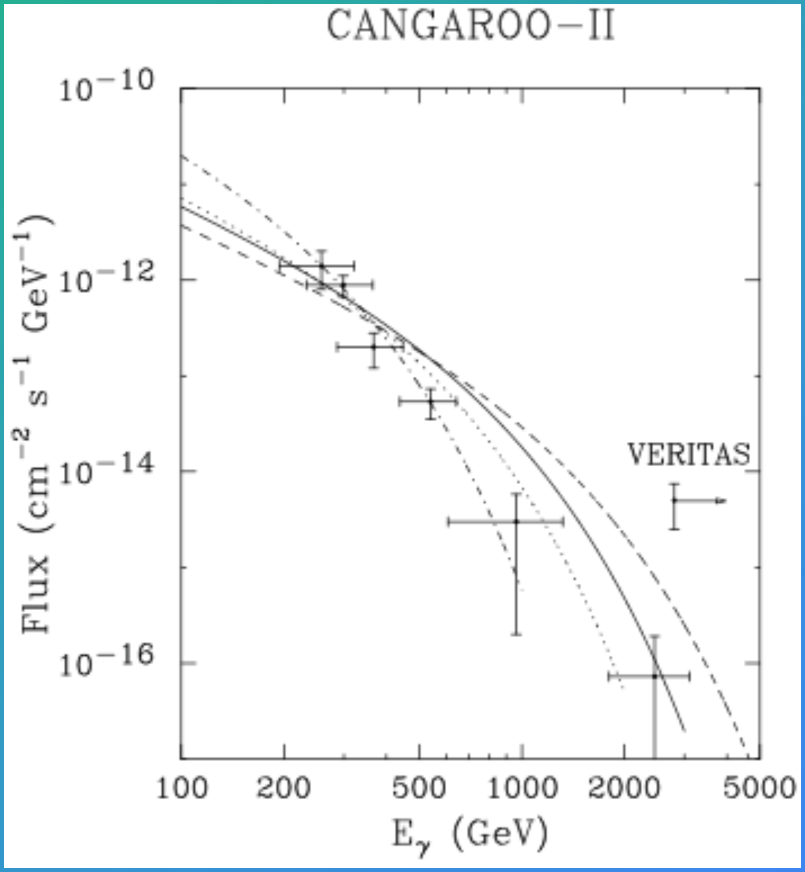
Spolyar,
Buckley,
Freese,
Hooper,
Murayama
2009



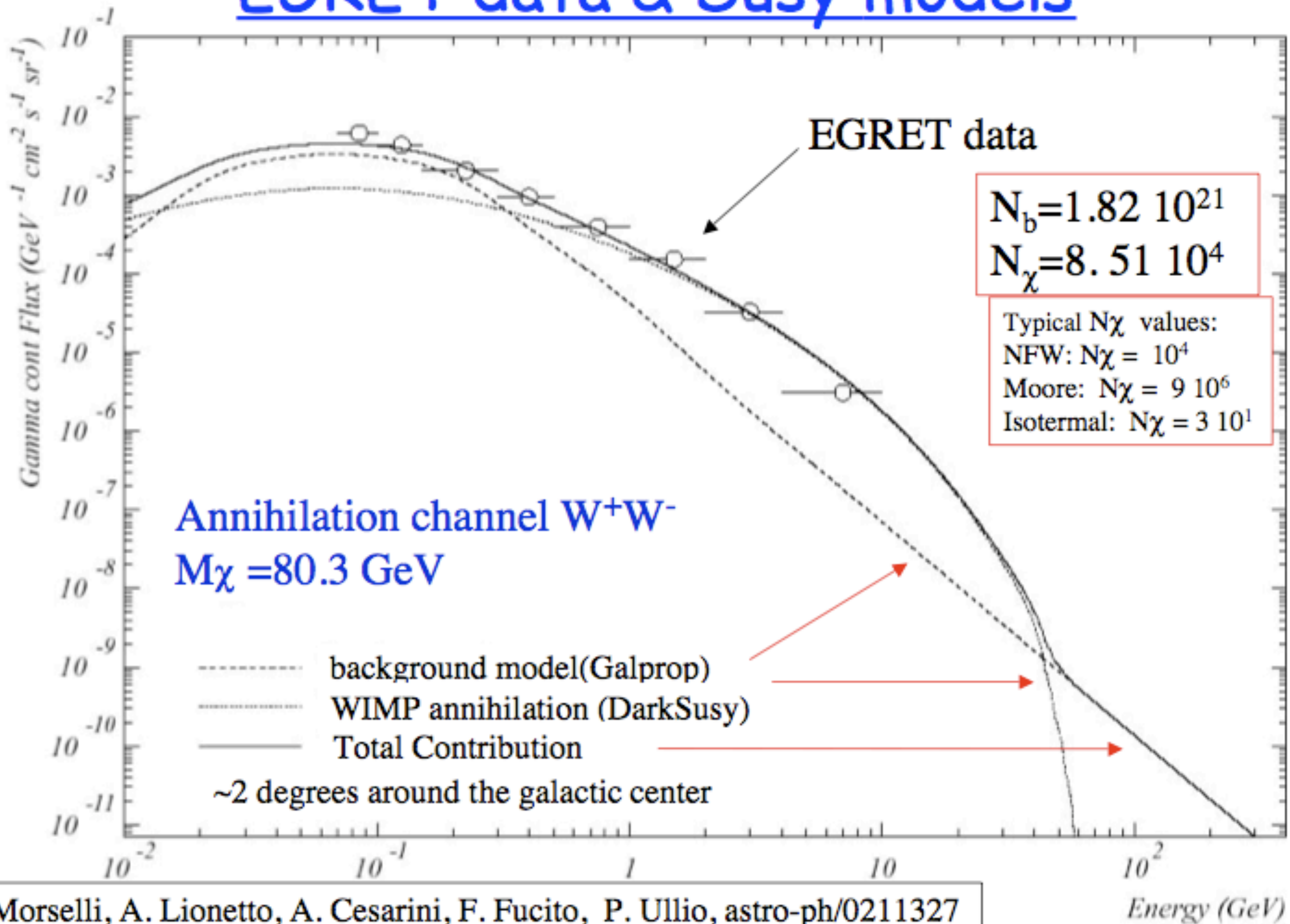
Gamma-rays from the Galactic Center

Dark Matter at Galactic Center?

- CANGAROO observations of gamma-rays from Galactic Center
  Tsuchiya et al 2004
- Possible interpretation in terms of WIMP annihilation
  Hooper et al 2004



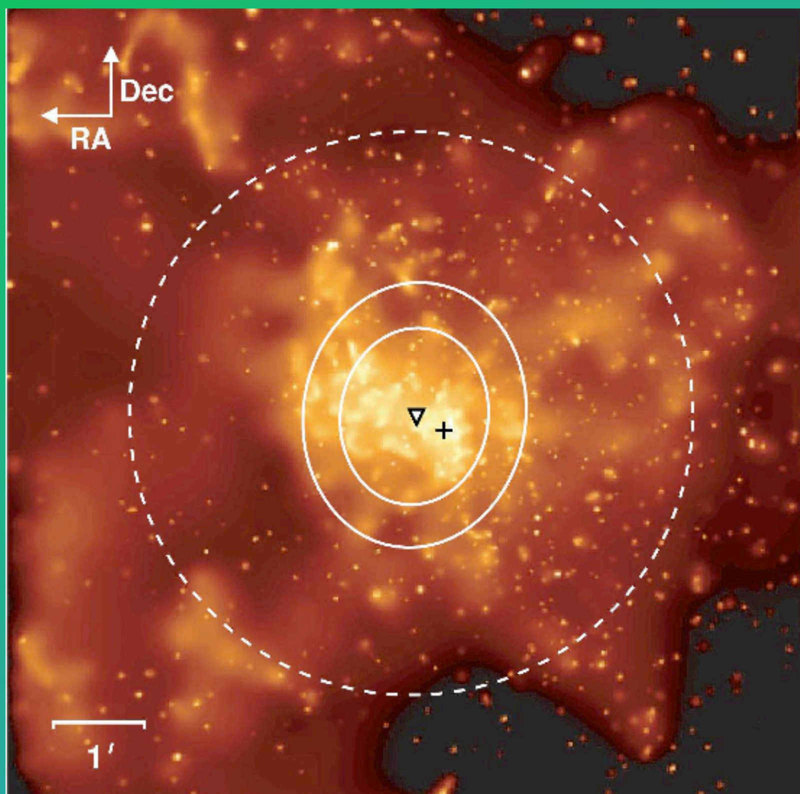
EGRET data & Susy models

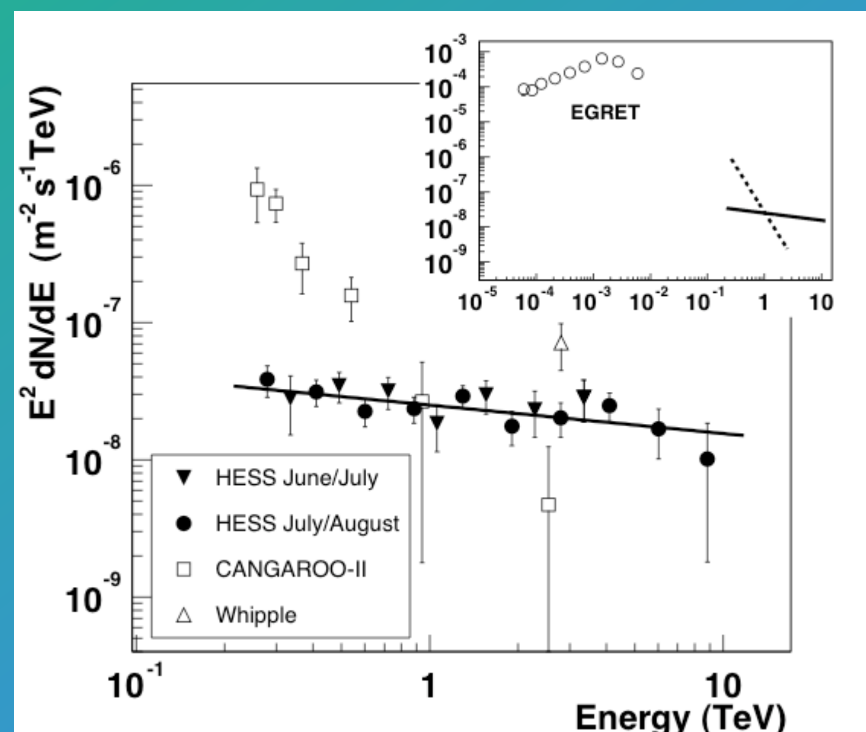


A.Morselli, A. Lionetto, A. Cesarini, F. Fucito, P. Ullio, astro-ph/0211327

HESS Gamma-ray Data

Aharonian et al 2004

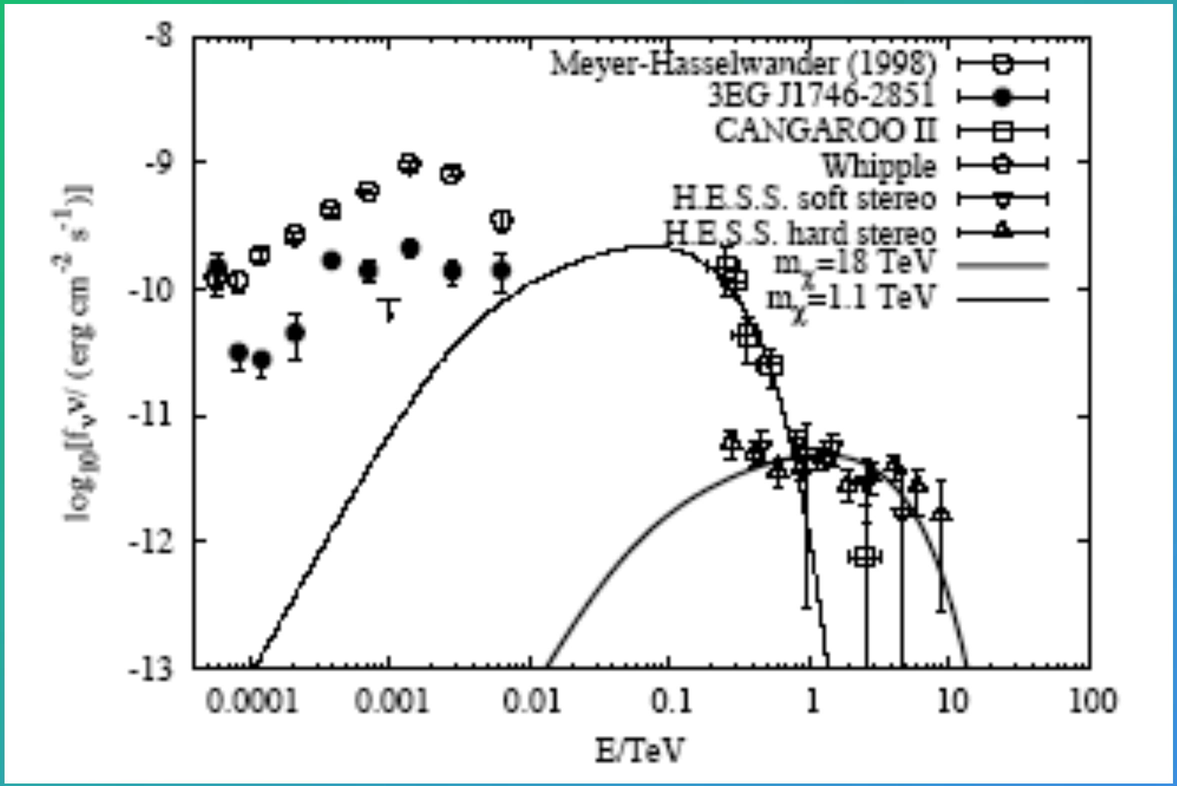




WIMPs at Galactic Center?

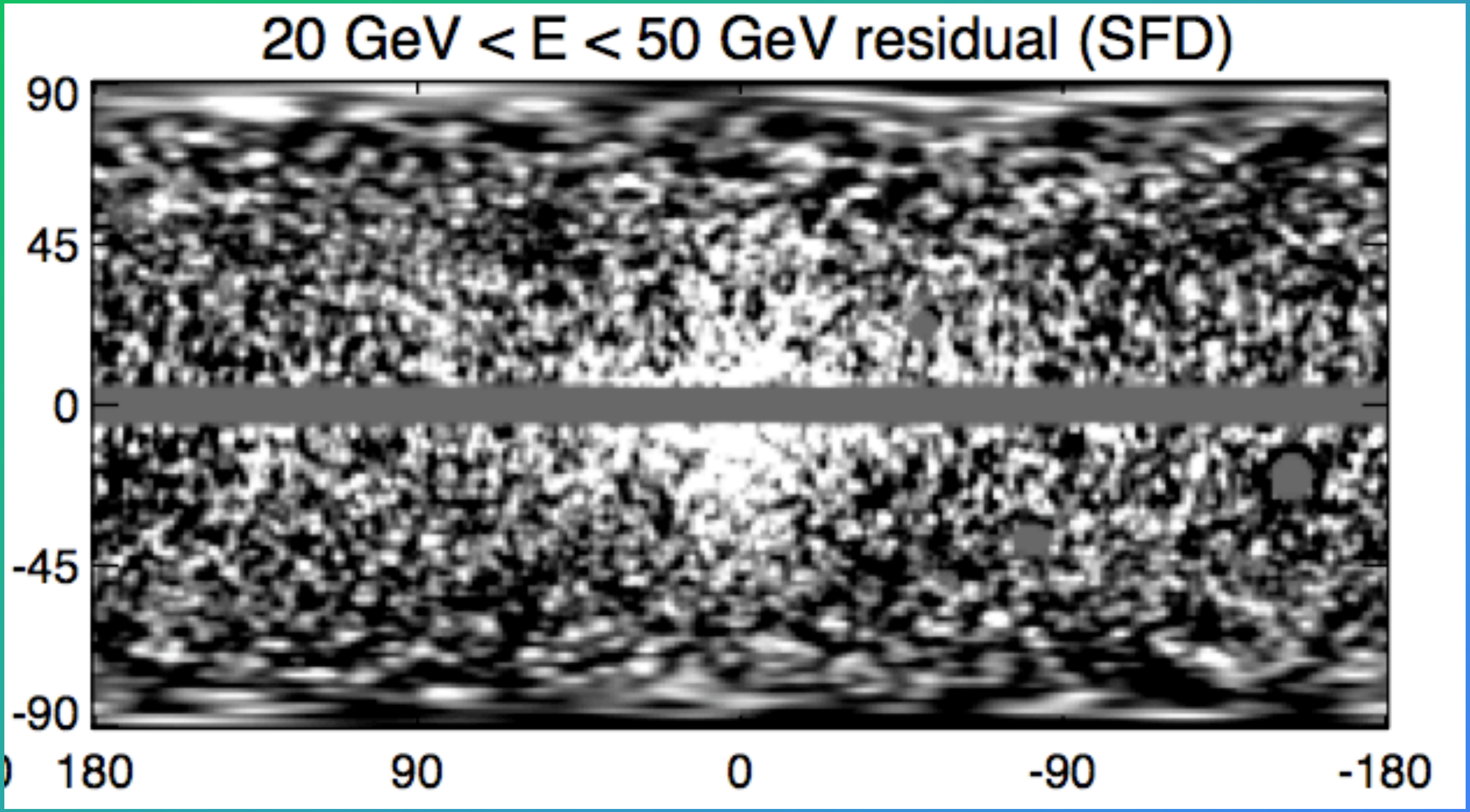
One can fit either CANGAROO and HESS spectra (but not both)

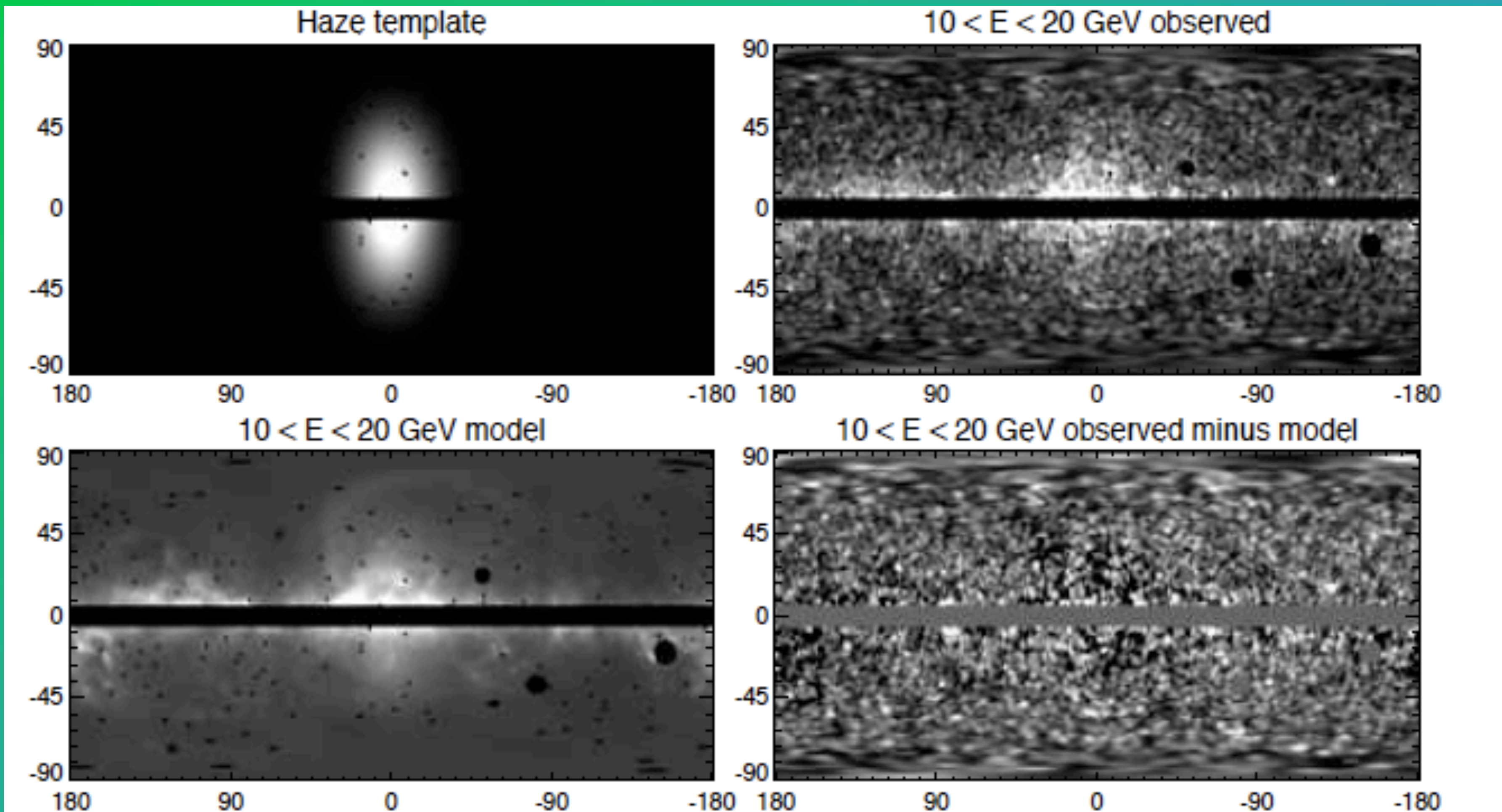
Horns 2004



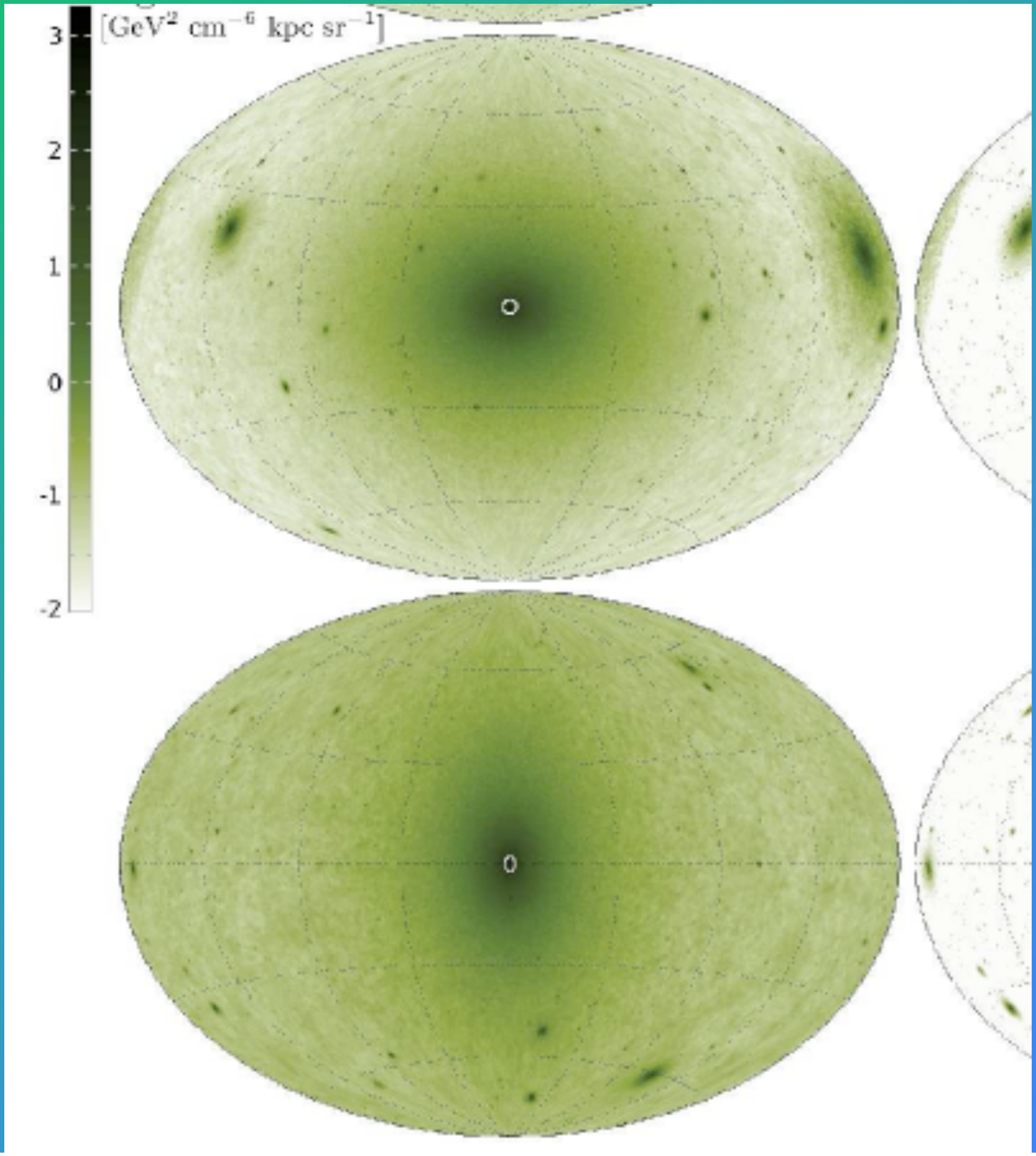
Dobler, Finkbeiner, Slatyer, Cholis, Weiner

FERMI HAZE




Haze template
10 < E < 20 GeV observed
10 < E < 20 GeV model
10 < E < 20 GeV observed minus model
90
45
0
-45
-90
180
90
0
-90
-180

Via Lactea II (Diemand, Kuhlen, Madau)



Gamma Ray Status: from WIMP annihilation in Galactic Center?

- CANGAROO: possible detection up to 10TeV
- HESS: different power law
- Can explain with astrophysics?
- Not easy to get intensity in SUSY
- New decay channel for Kaluza-Klein particles
- CACTUS observed Draco (nearby dwarf galaxy).

WMAP microwave emission interpreted as dark matter annihilation in inner galaxy?

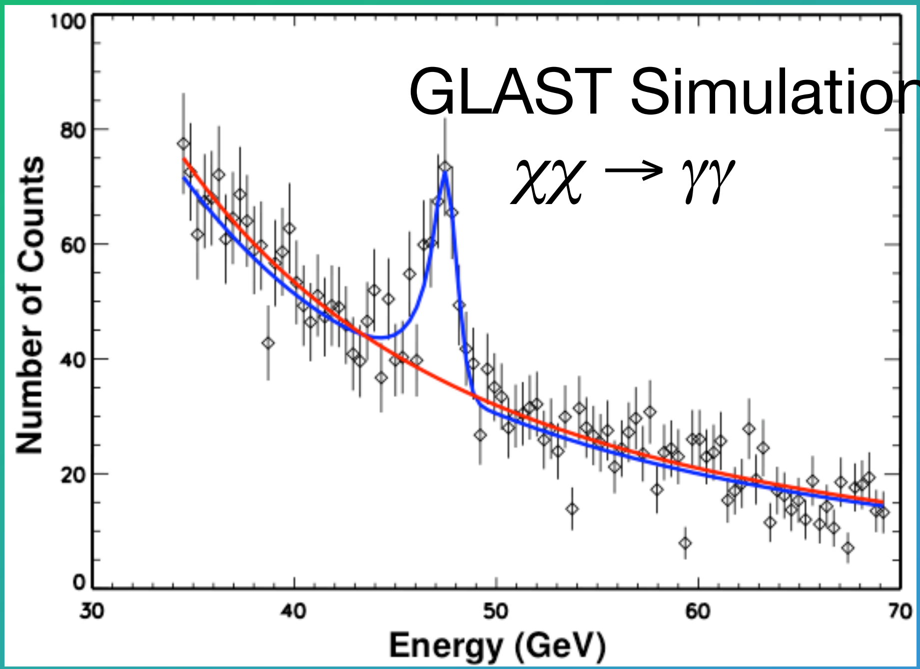
Excess microwave emission observed in the inner Galaxy (inner $\sim 1-2$ kpc) is consistent with synchrotron emission from highly relativistic e^+e^- pairs produced by dark matter particle annihilation. More conventional sources for this emission, such as free-free (thermal bremsstrahlung), thermal dust, spinning dust, and the softer Galactic synchrotron traced by low-frequency surveys, have been ruled out.

Consistent with 100 GeV WIMPs.

Finkbeiner 2005; Hooper, Dobler 2007

Gamma-ray line

- Characteristic of WIMP annihilation
- Need good energy resolution



- GLAST may do it below ~80 GeV

Bergstrom, Ullio and Buckley 1998

Possible evidence for WIMP detection already now:

- The DAMA annual modulation
- The HEAT/PAMELA positron excess
- Gamma-rays from Galactic Center
- WMAP haze

- Theorists are looking for models in which these results are consistent with one another (given an interpretation in terms of WIMPs)

Upcoming Data: will the Dark Matter be found in 2010?

- LHC (find SUSY)

- Indirect Detection due to annihilation:
- FERMI (GLAST) first light June 2008 (gamma rays)
- PAMELA (positrons)
- ICECUBE (neutrinos)
- GAPS (antideuterons)

- Direct Detection: CDMS (December 18??), LUX, XENON, DEEP-CLEAN, WARP, CRESST-EDELWEISS, ZEPLIN, COUPP, KIMS …

Conclusion

- WIMP phenomenology is getting hot
- If WIMPs are right, annihilation can power stars and produce new phase of stellar evolution: massive puffy cool bright Dark Stars