Title: Dark Stars: Dark Matter Annihilation can power the first stars

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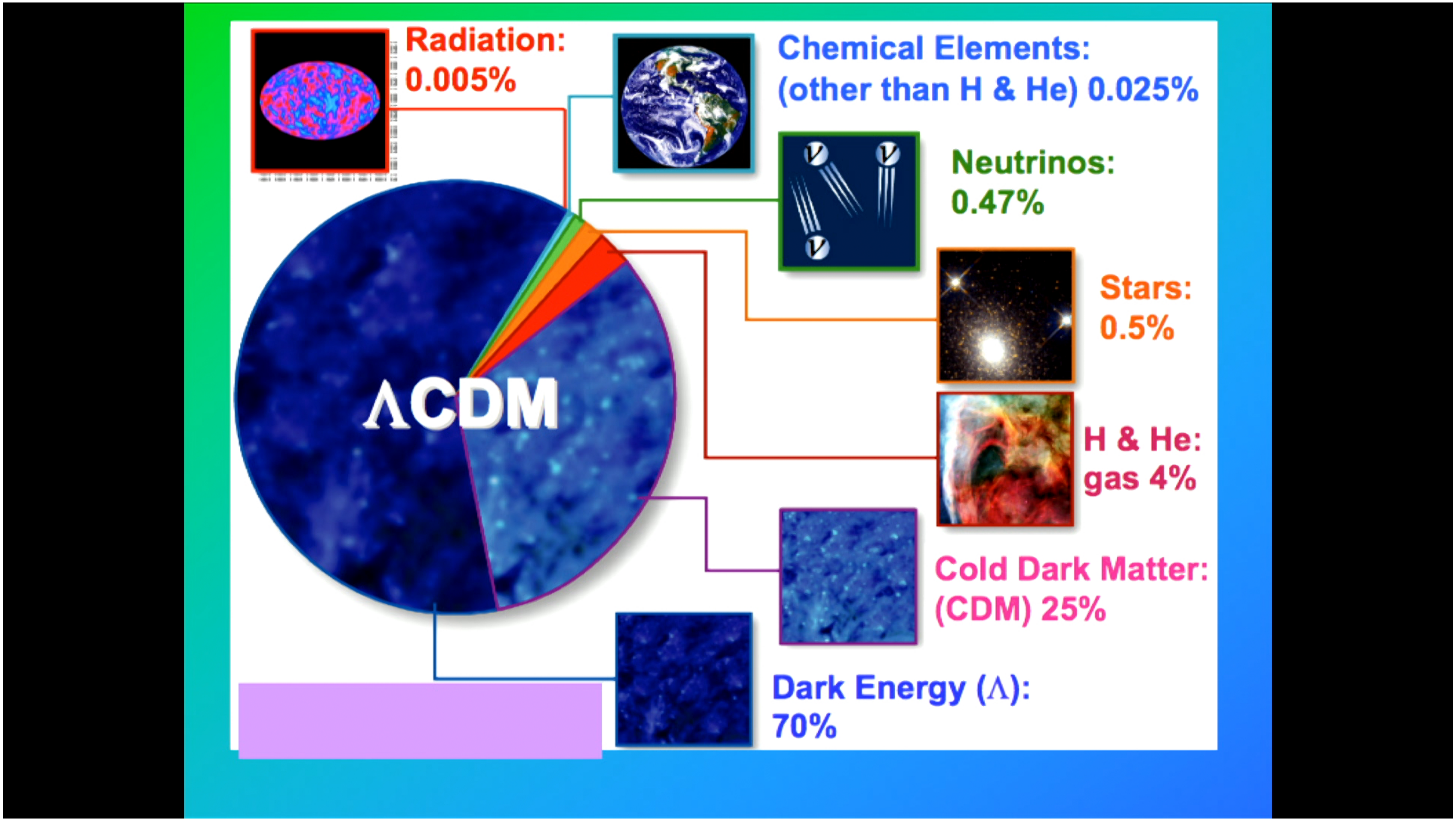
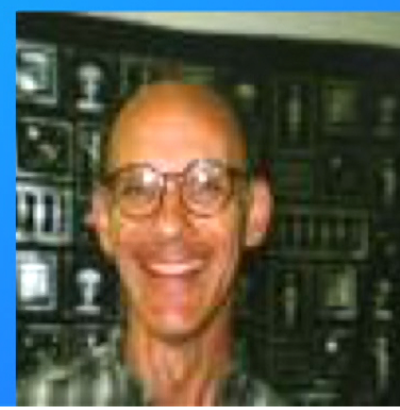
Abstract: <p>The first phase of stellar evolution in the history of the Universe may be Dark Stars (DS), powered by dark matter heating rather than by nuclear fusion. Weakly Interacting Massive Particles, which may be their own antipartners, collect inside the first stars and annihilate to produce a heat source that can power the stars. A new stellar phase results, a Dark Star, powered by dark matter annihilation as long as there is dark matter fuel, with lifetimes from millions to billions of years. Dark stars are very bright diffuse puffy objects during the DS phase, and grow to be very massive. In fact, we have found they can to grow to 10^5-10^7 solar masses with luminosities 10^9-10^11 solar luminosities. Such objects will be observable with James Webb Space Telescope (the sequel to HST). Once the dark matter fuel is exhausted, the DS becomes a heavy main sequence star; these stars eventually collapse to form massive black holes that may provide seeds for supermassive black holes observed at early times as well as in galaxies today.</p>


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%
ΛCDM

Collaborators



Dark Stars

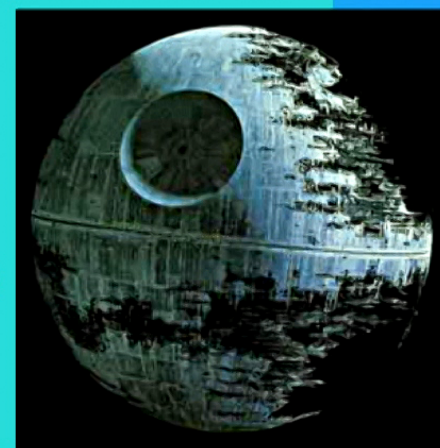
The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion (even though the dark matter constitutes less than 1% of the mass of the star).

THESE REALLY ARE STARS: atomic matter that shines due to dark matter, possibly a billion times as bright as the Sun

- This new phase of stellar evolution lasts millions to billions of years (possibly even to today)

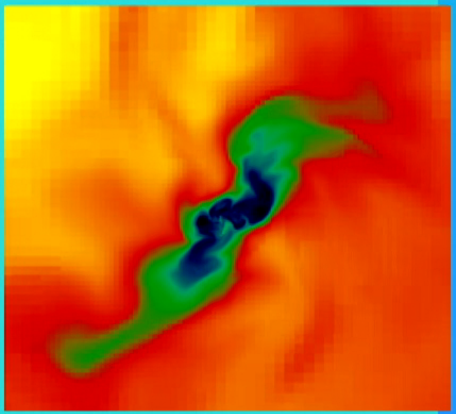
Outline

- The First Stars- standard picture
- Dark Matter
    - WIMPs
- Dark Star Born
- Stellar structure
- Dark Star can grow supermassive and superbright: see with JWST
- When a dark star dies it becomes a giant black hole (up to a billion solar masses)



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)

Hierarchical Structure Formation

Smallest objects form first (sub earth mass)

Merge to ever larger structures

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

Merge $\rightarrow$ galaxies

Merge $\rightarrow$ clusters

$\rightarrow$

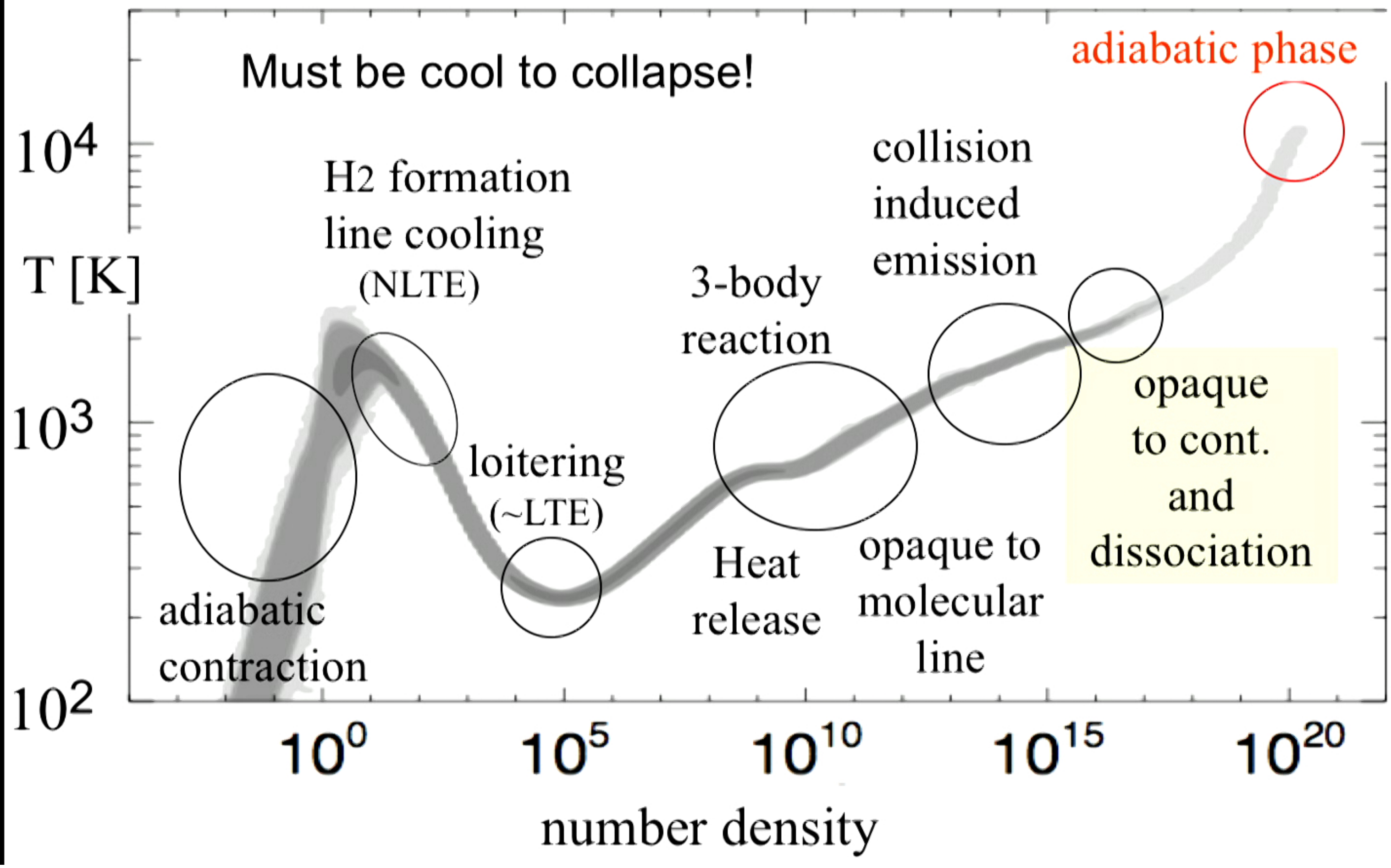
$\rightarrow$

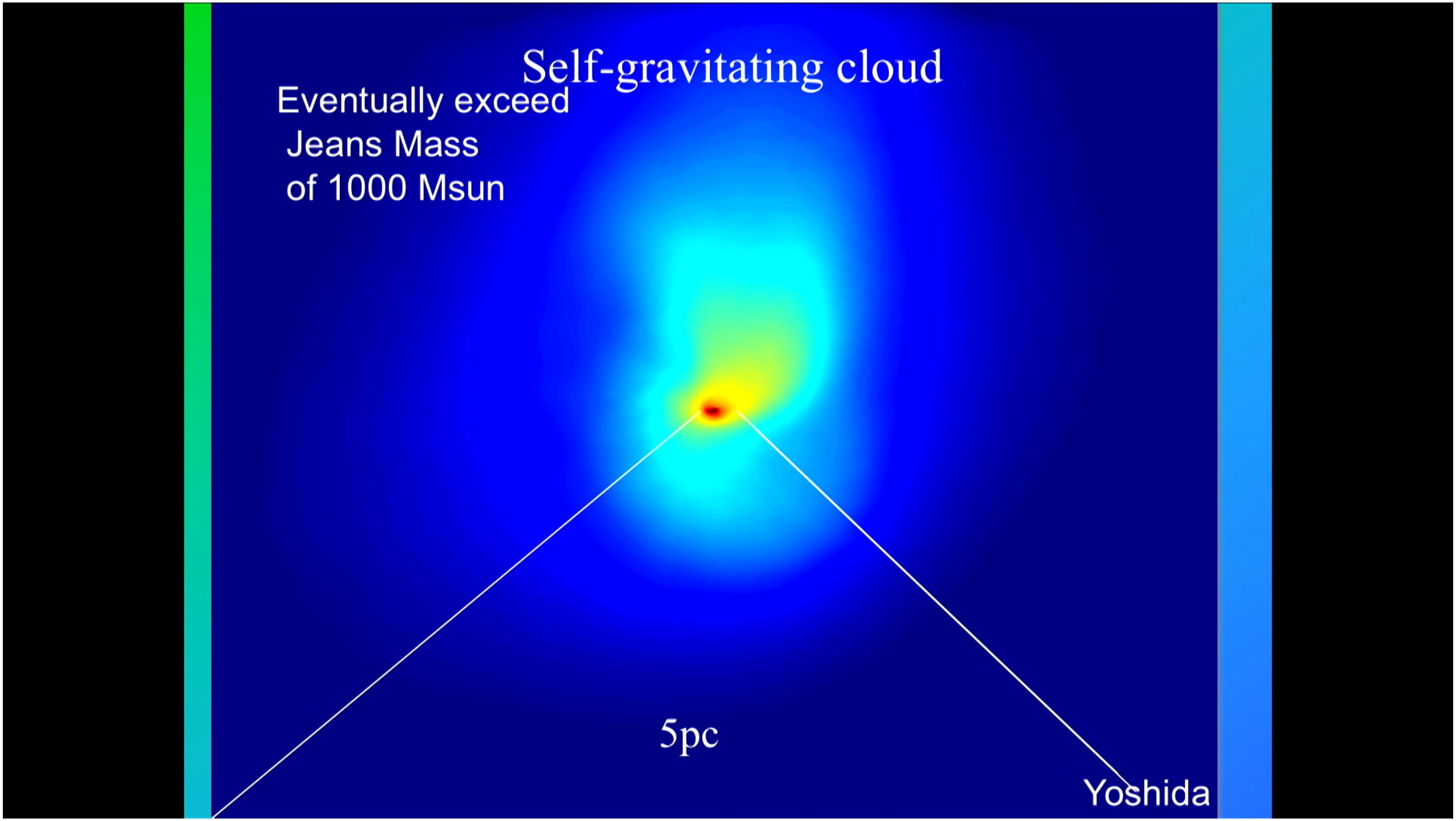
Scale of the Mini-Halo: $10^6\ M_\odot$

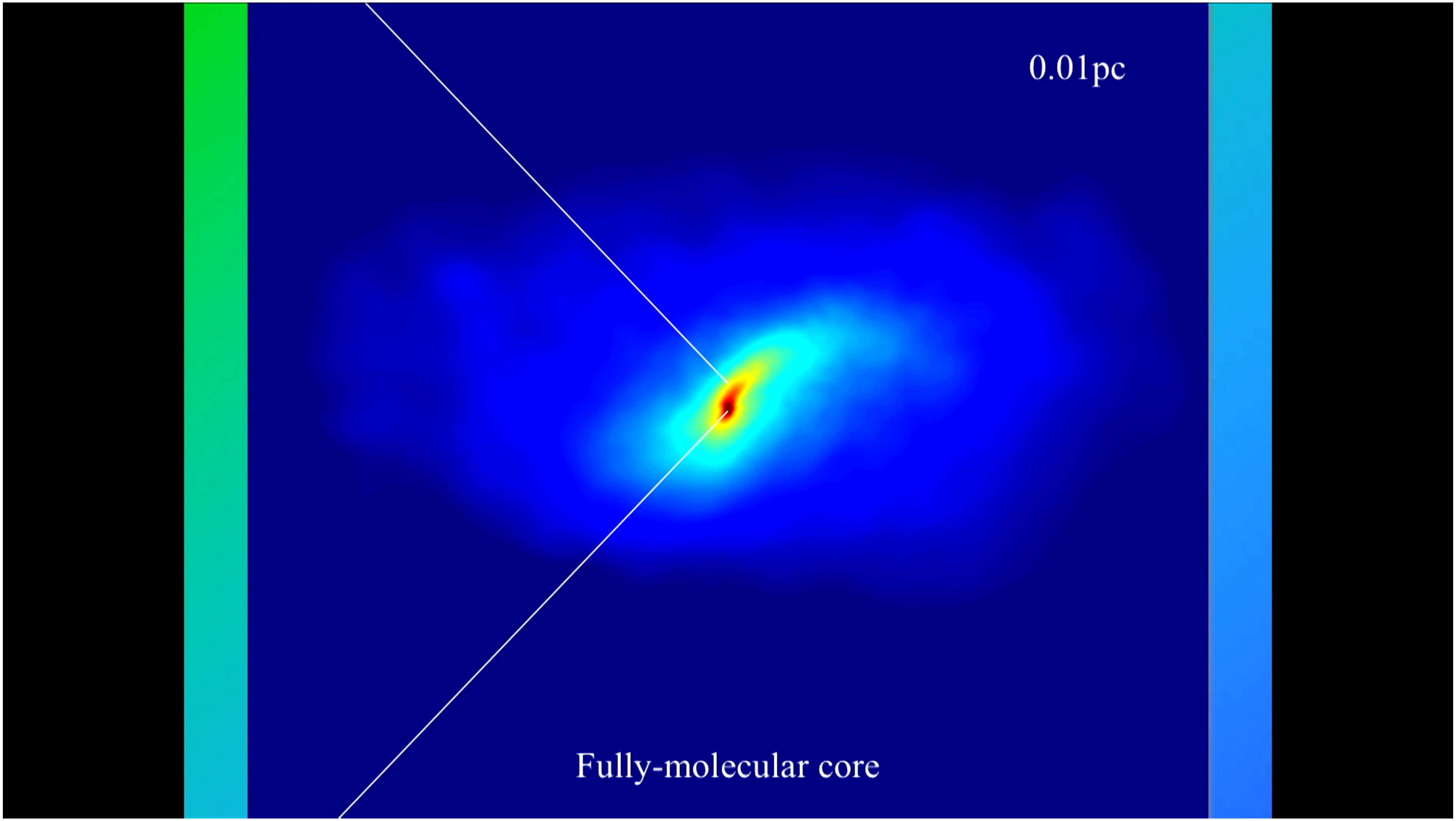
- Cooling time is less than Hubble time.
- First useful coolant in the early universe is H_2 .
- H_2 cools efficiently at around 1000K
- The virial temperature of $10^6\ M_\odot$

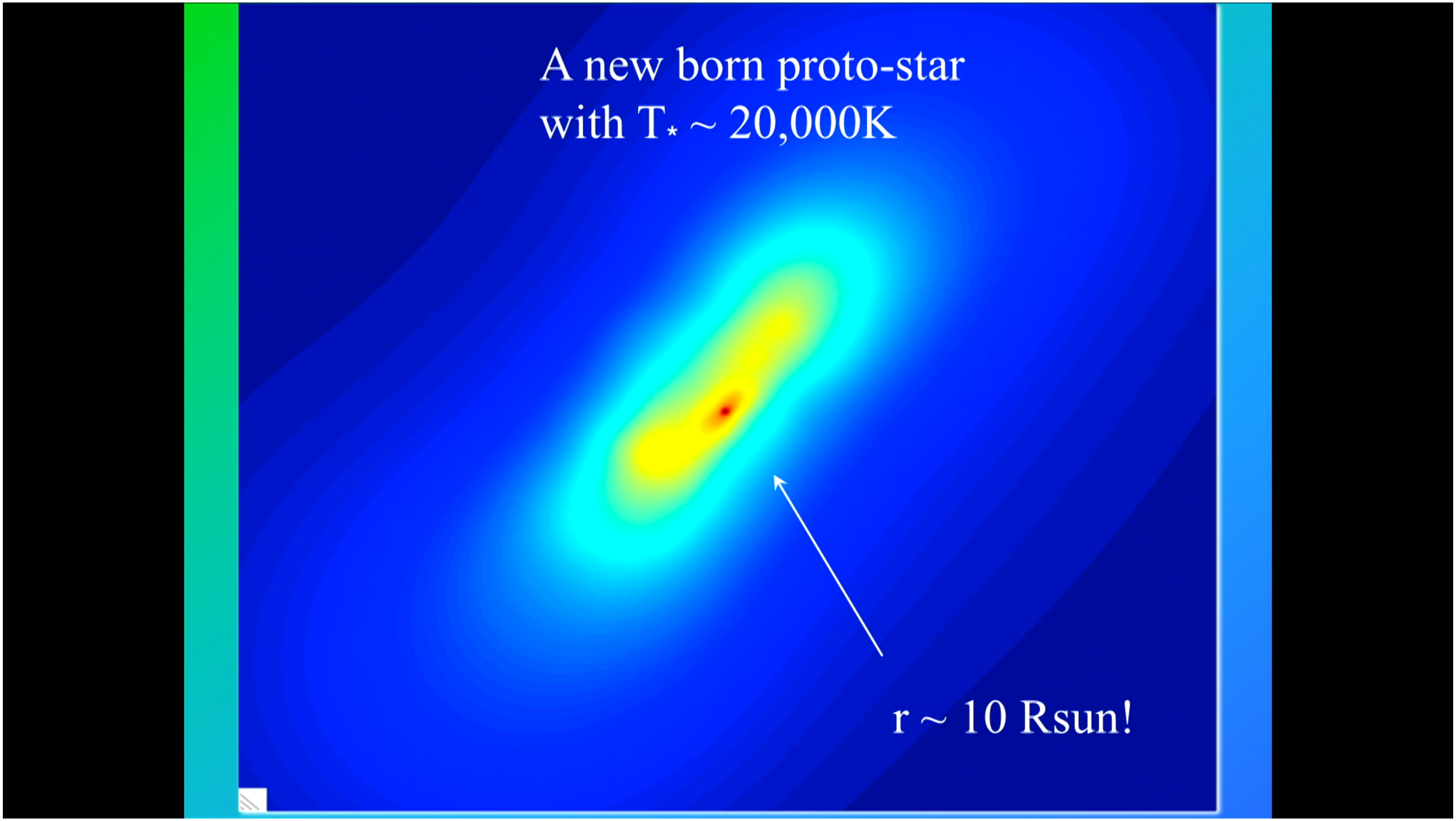
  ~1000K

Thermal evolution of a primordial gas




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


0.01pc
Fully-molecular core


A new born proto-star
with $T_* \sim 20{,}000$K
$r \sim 10$ Rsun!

Scales

- Halo Baryonic Mass ~ $10^5\ M_\odot$

(Halo Mass $10^6\ M_\odot$)

↓

- Jeans Mass ~ $10^3\ M_\odot$

↓

- Initial Core Mass ~ $10^{-3}\ M_\odot$

↓ Accretion

Final stellar Mass??

feedback effects McKee and Tan 2008

With DM heating Much more massive

$100 M_\odot$ Standard Picture

10^3 - $10^7\ M_\odot$ Dark Star

We asked:
What role does Dark Matter play in the First Stars?

- **THE RIGHT PLACE**:

  one single star forms at the center of a million solar mass DM halo

- **THE RIGHT TIME:**

  the first stars form at high redshift,

  z = 10-50, and density scales as (1+z)^3

WIMP properties

Mass 1Gev-10TeV (take 100GeV)

Annihilation cross section (WIMPS):

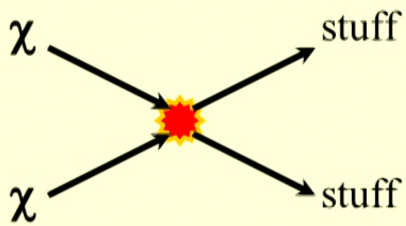
$$<\sigma v>_{ann} = 3 \times 10^{-26} cm^3 / \sec$$

Same annihilation that leads to correct WIMP abundance in today's universe

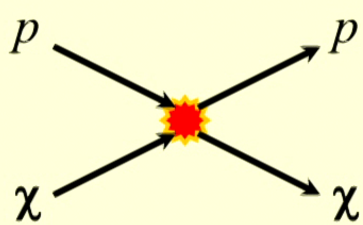
Same annihilation that gives potentially observable signal in FERMI, PAMELA, etc

THREE PRONGED APPROACH TO WIMP DETECTION

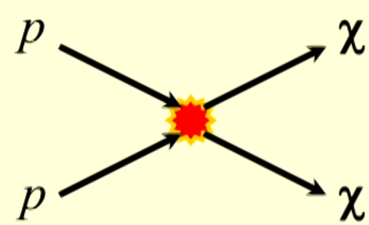
Interactions with Standard Model particles



Annihilation



Scattering



Production

Indirect Detection:
Halo (cosmic-rays), capture in Sun (ν's)

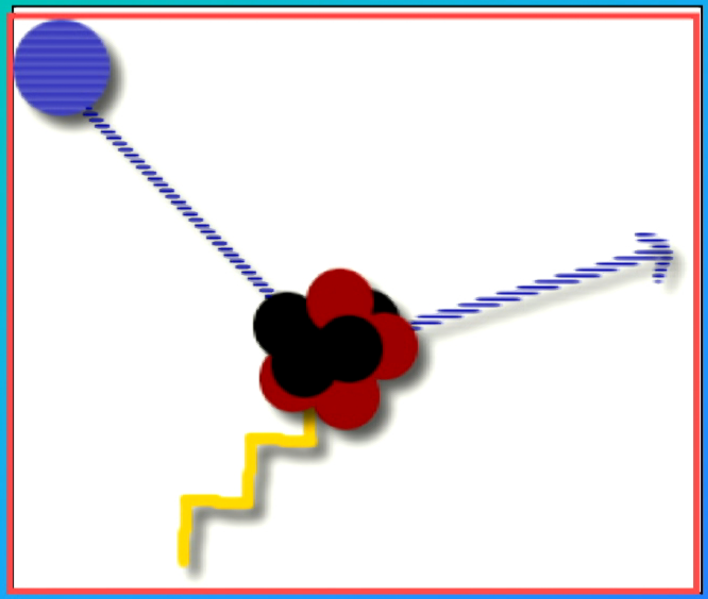
Direct Detection:
Look for scattering events in detector

Accelerators:
LHC

FOURTH PRONG: DARK STARS

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: less than one count/kg/day!

Drukier and Stodolsky (1984)

proposed neutrino detection via weak scattering off nuclei

Andrzej Drukier

Drukier, Freese, & Spergel (1986)

We studied the WIMPs in the Galaxy and the particle physics of the interactions to compute expected count rates, and we proposed annual modulation to identify a WIMP signal

Event rate

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

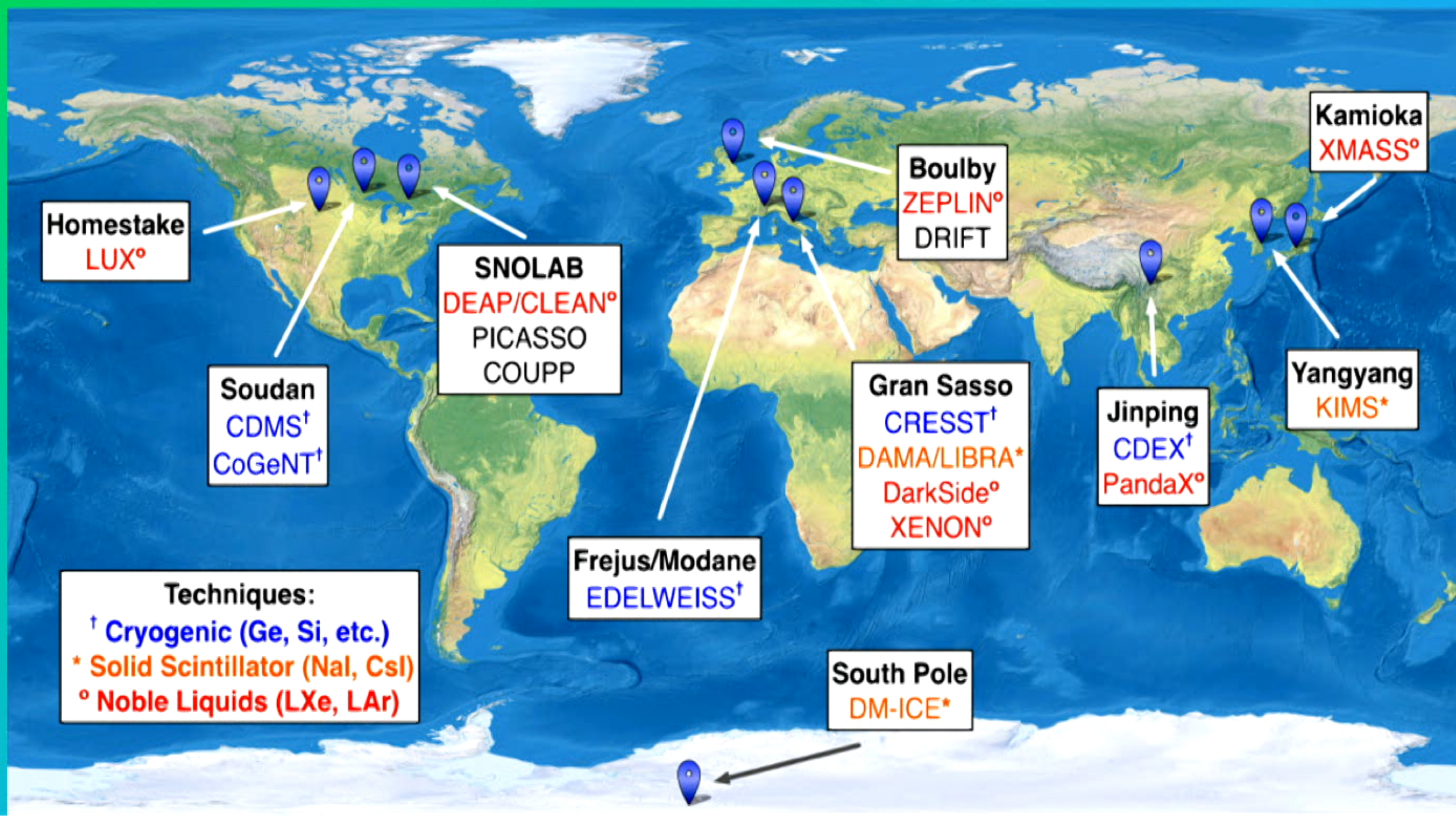
$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nv\, f(v,t)\, d^3v$$

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

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

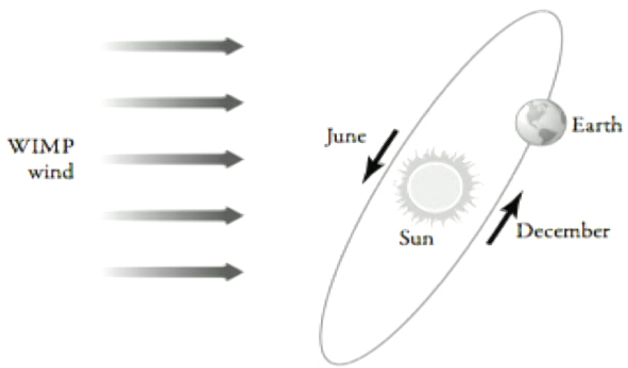
Spin-dependent $\sigma_0 = \frac{4\mu^2}{\pi} \left|\langle S_p\rangle G_p + \langle S_n\rangle G_n\right|^2$

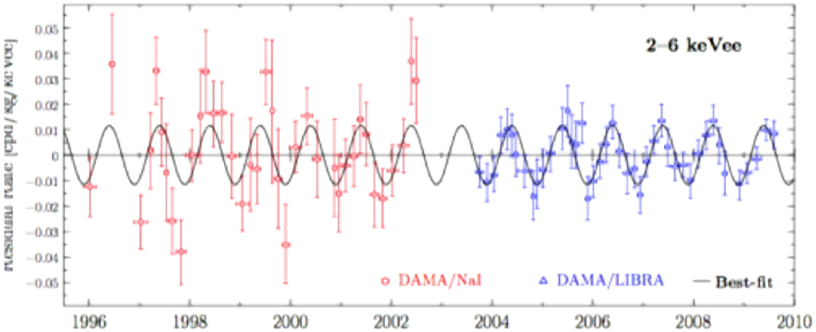
UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



DAMA annual modulation

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





NaI crystals in Gran Sasso Tunnel under the Apennine Mountains near Rome.

Data do show modulation at 9 sigma! Peak in June, minimum in December (as predicted). Are these WIMPs??

“I’ m a Spaniard caught between two Italian women”

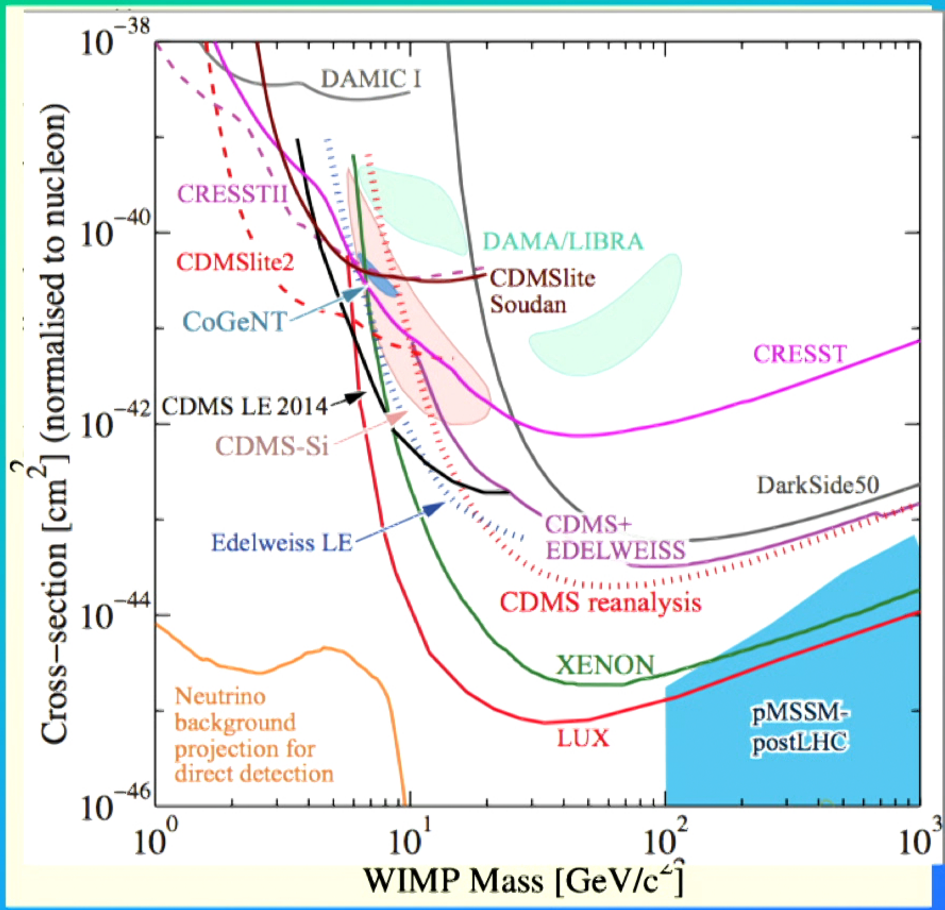
Rita Bernabei, DAMA

Juan Collar, COGENT

Elena Aprile, XENON

Bounds on Spin Independent

BUT:
--- it's hard to compare results from different detector materials
--- can we trust results near threshold?



To test DAMA

- The annual modulation in the data is still there after 13 years and still unexplained.
- Other groups are planning to use NaI crystals in the Southern Hemisphere:
- SABRE (Princeton) with Australia
- COSINE-100 (DM Ice at the South Pole joined with KIMS in Korea)
- ANAIS in Can Franc Laboratory

Another WAY TO SEARCH FOR WIMPS

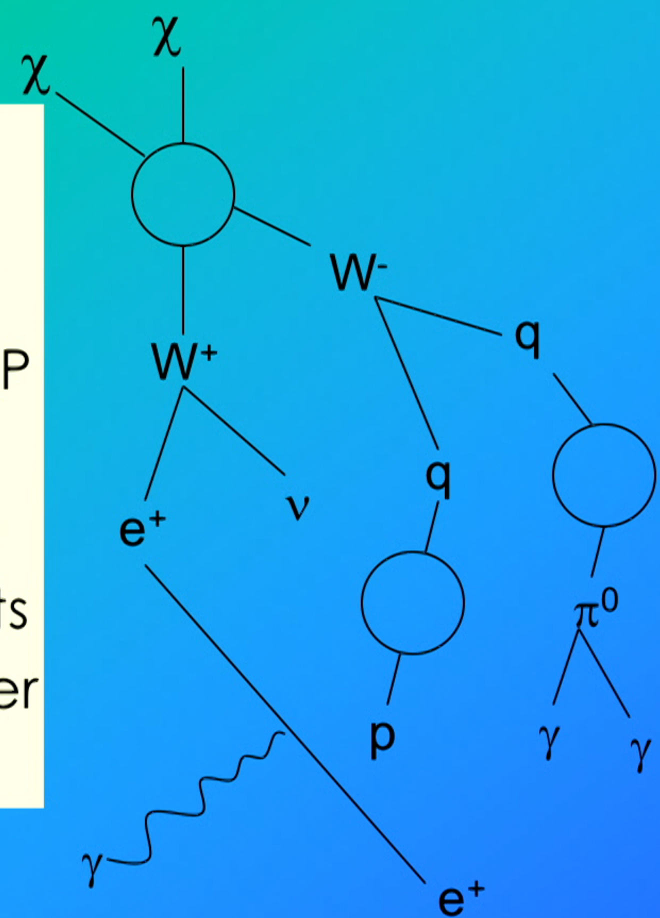
Dark Stars:

Dark Matter annihilation can power the first stars

WIMP Annihilation

Many WIMPs are their own antiparticles, annihilate among themselves:

- 1) Early Universe gives WIMP miracle
- 2) Indirect Detection expts look for annihilation products
- 3) Same process can power stars!



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.
- DM particles are their own antipartners, and annihilate more and more rapidly as the density increases
- DM annihilates to e+/e- and photon endproducts of 100 GeV (or so) which collide with hydrogen, are trapped inside the cloud, and heat it up.
- At a high enough DM density, the DM heating overwhelms any cooling mechanisms; the cloud can no longer continue to cool and collapse. A Dark Star is born, powered by DM.

Dark Matter Power vs. Fusion

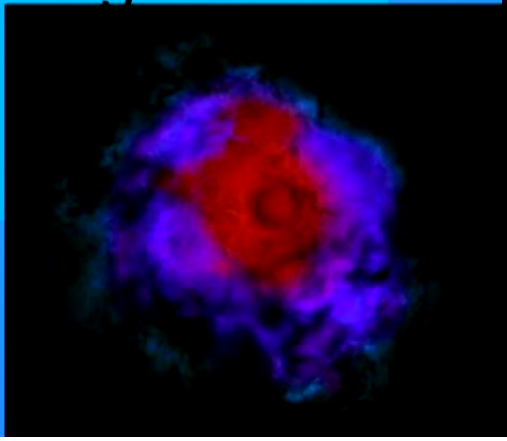
- DM annihilation is (roughly) 100% efficient in the sense that all of the particle mass is converted to heat energy for the star
- Fusion, on the other hand, is only 1% efficient (only a fraction of the nuclear mass is released as energy)
- Fusion only takes place at the center of the star where the temperature is high enough; vs. DM annihilation takes place throughout the star.

Three Conditions for Dark Stars

(Spolyar, Freese, Gondolo 2007 aka Paper 1)

- I) Sufficiently High Dark Matter Density
- 2) Annihilation Products get stuck in star
- 3) DM Heating beats H2 Cooling ?

New Phase



Dark Matter Heating

Heating rate:

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

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

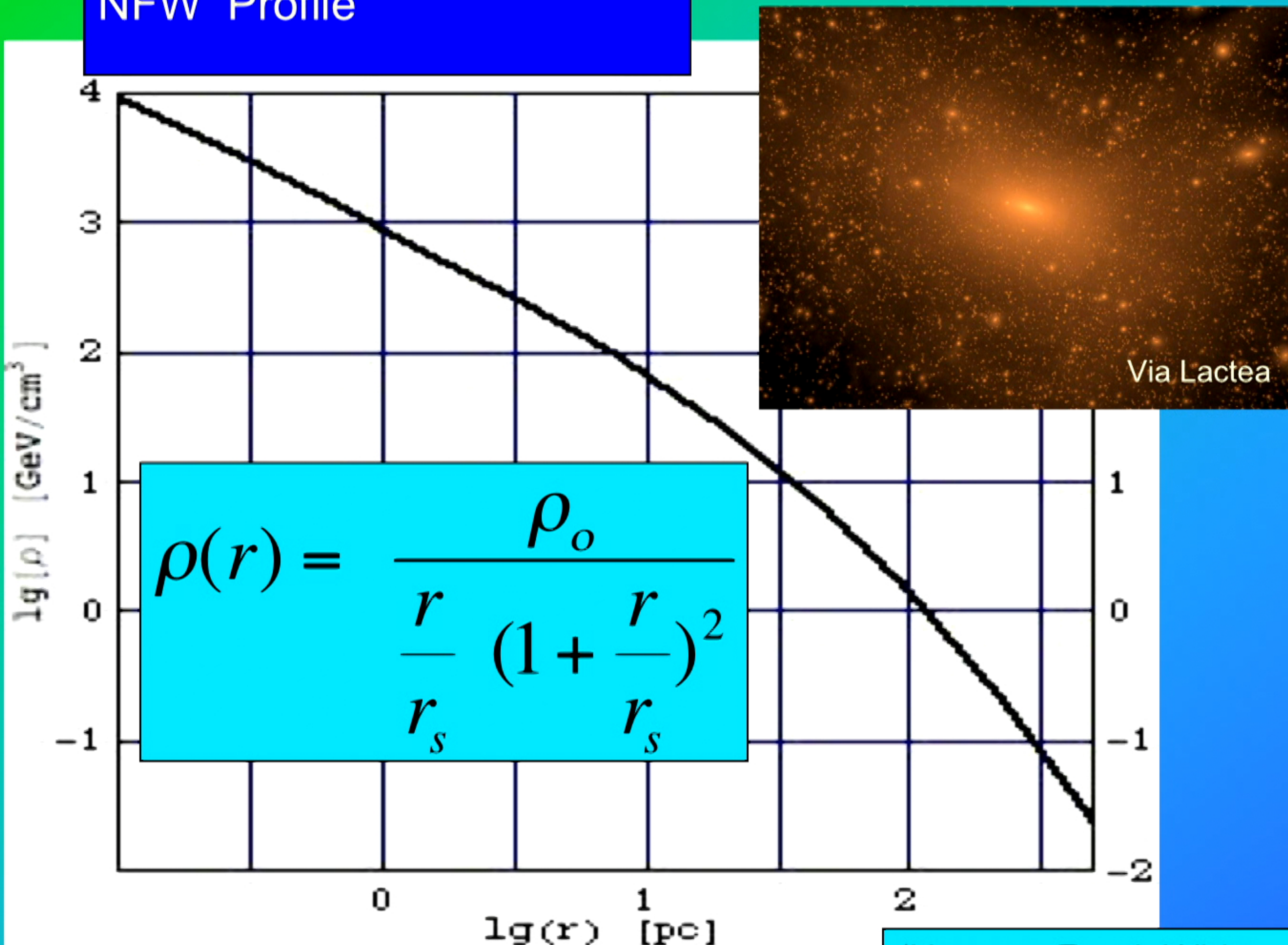
1/3 photons

1/3 neutrinos

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).

NFW Profile



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

(Navarro,Frenk,White '96

DM Density Profile Conserving Phase Space

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

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

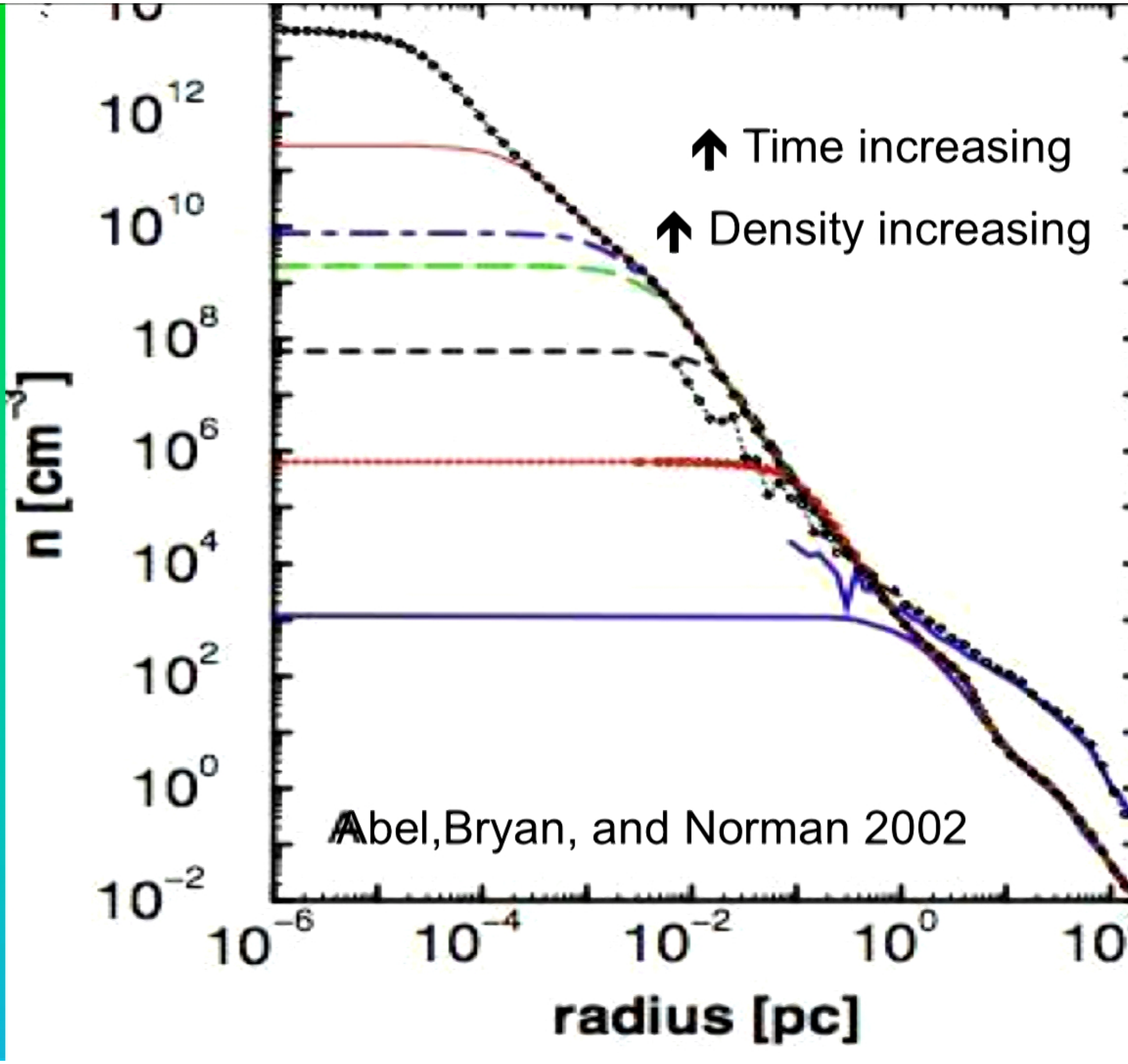
- Profile that we find:

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

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

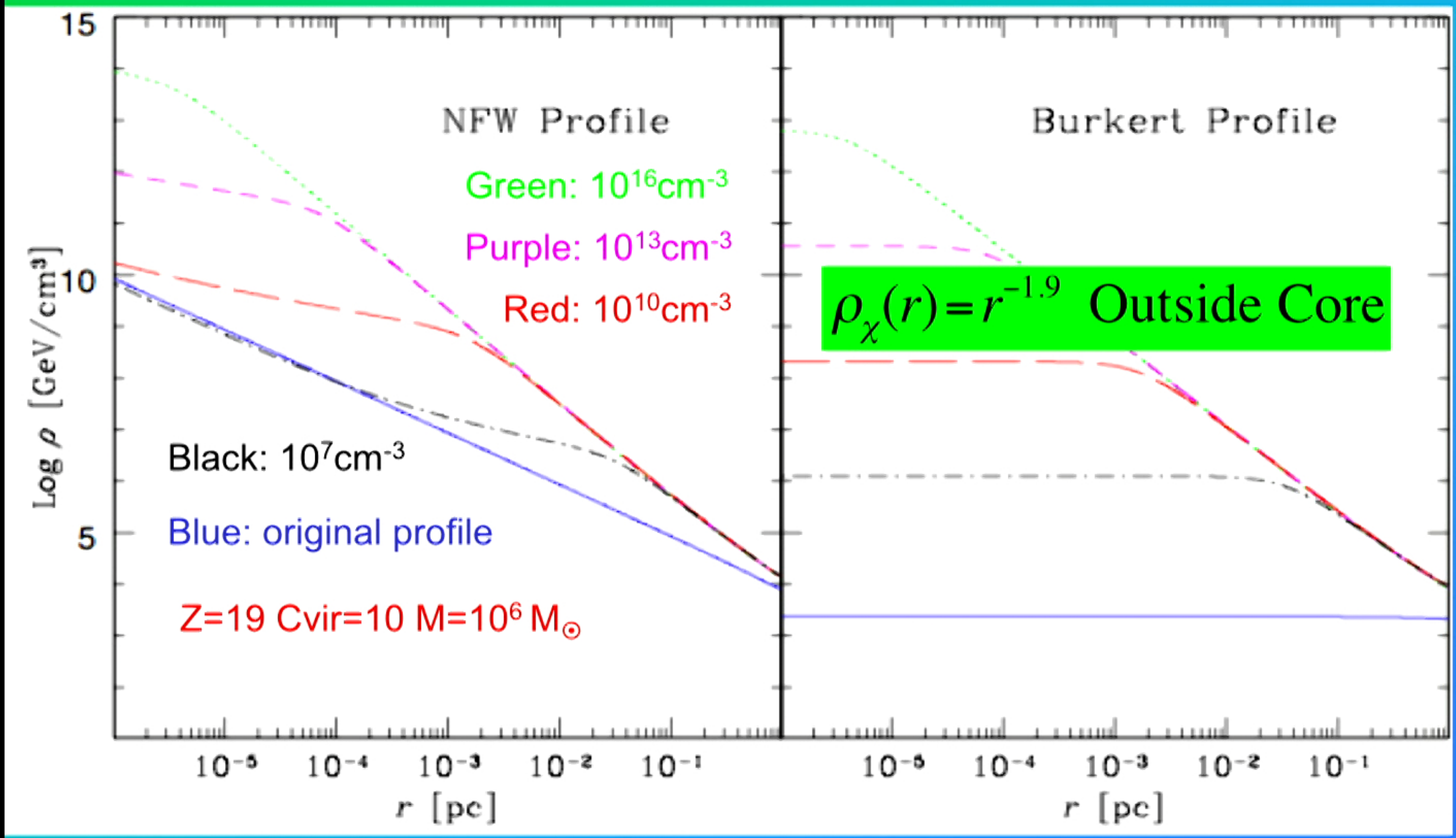
Simplistic: circular orbits only.

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



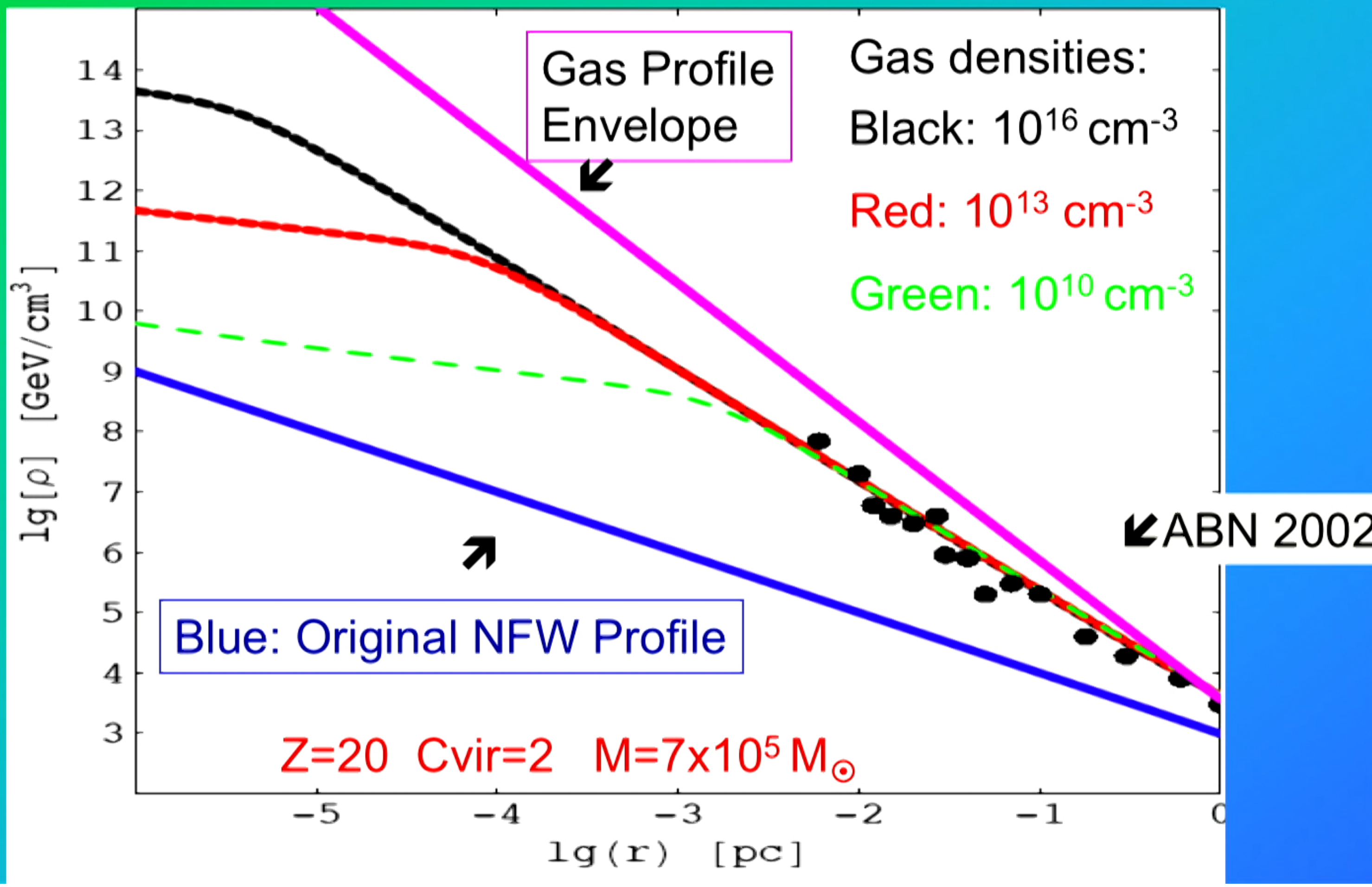
Time increasing
Density increasing
Abel,Bryan, and Norman 2002
n [cm^-3]
radius [pc]
10^12
10^10
10^8
10^6
10^4
10^2
10^0
10^-2
10^-6
10^-4
10^-2
10^0

Dark Matter Profile



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

DM profile and Gas



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
  - If adiabaticity holds, we have found the exact solution

In collaboration with Jerry Sellwood

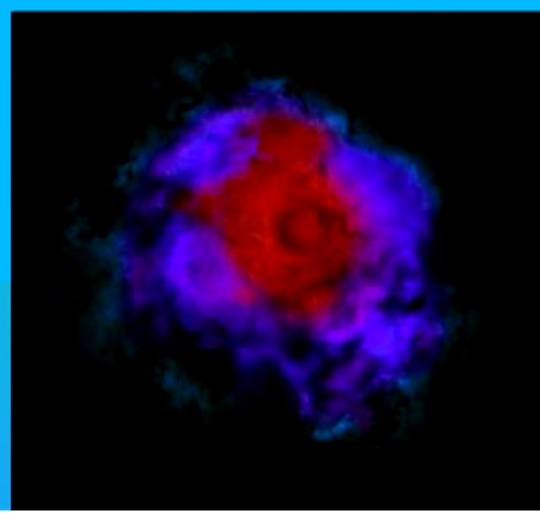
Dark Matter Densities in the Stars

- Adiabatic Contraction
- See also work of Natarajan, O' Shea and Tan 2008, taking simulation results and extrapolating to also find large densities
- See also work of Iocco etal 2008 using O. Gnedin method
- All results agree

Three Conditions for Dark Stars (Paper 1)

- I) OK! Sufficiently High Dark Matter Density
- 2) Annihilation Products get stuck in star?
- 3) DM Heating beats H2 Cooling?

Leads to New Phase



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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

Three Conditions for Dark Stars (Paper 1)

- 1) OK! Sufficiently High Dark Matter Density
- 2) OK! Annihilation Products get stuck in star
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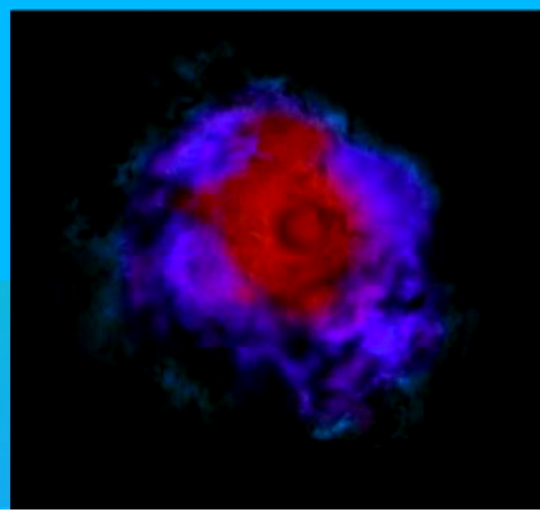
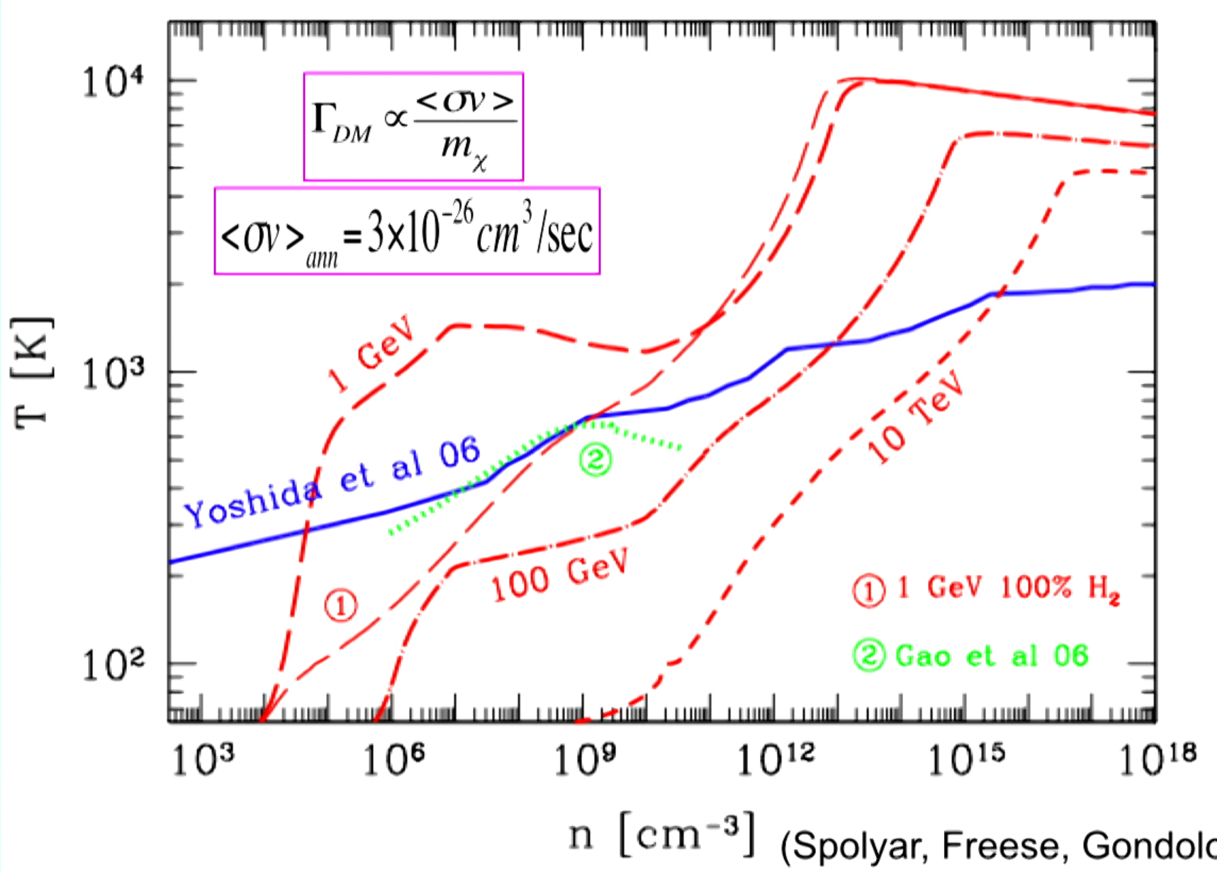
New Phase

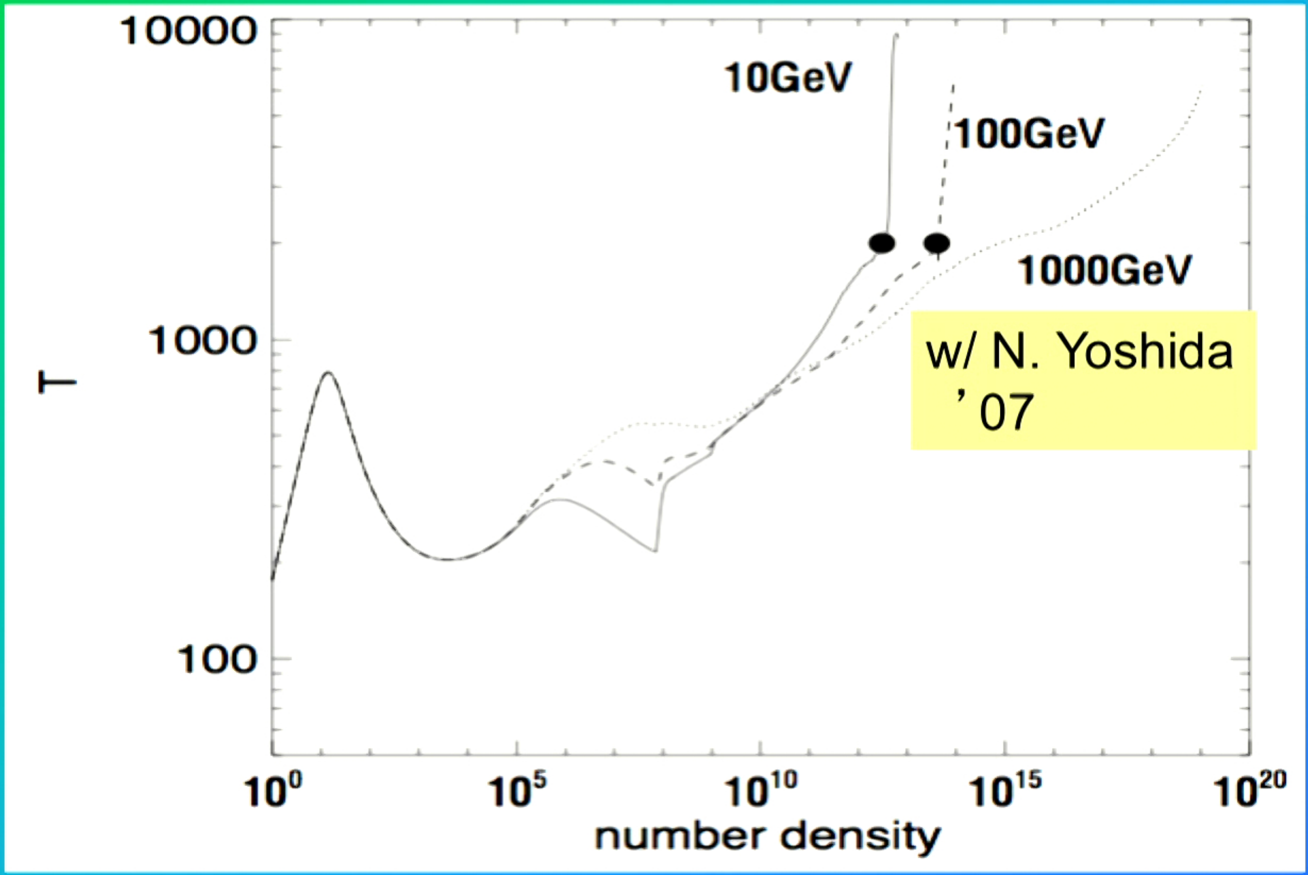


DM Heating dominates over cooling when the red lines cross the blue/green lines (standard evolutionary tracks from simulations). Then heating impedes further collapse.



(Spolyar, Freese, Gondolo April 2007)

New proto-Stellar Phase:
fueled by dark matter



w/ N. Yoshida ’07

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 <1% of the mass of the star but provides the heat source

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:

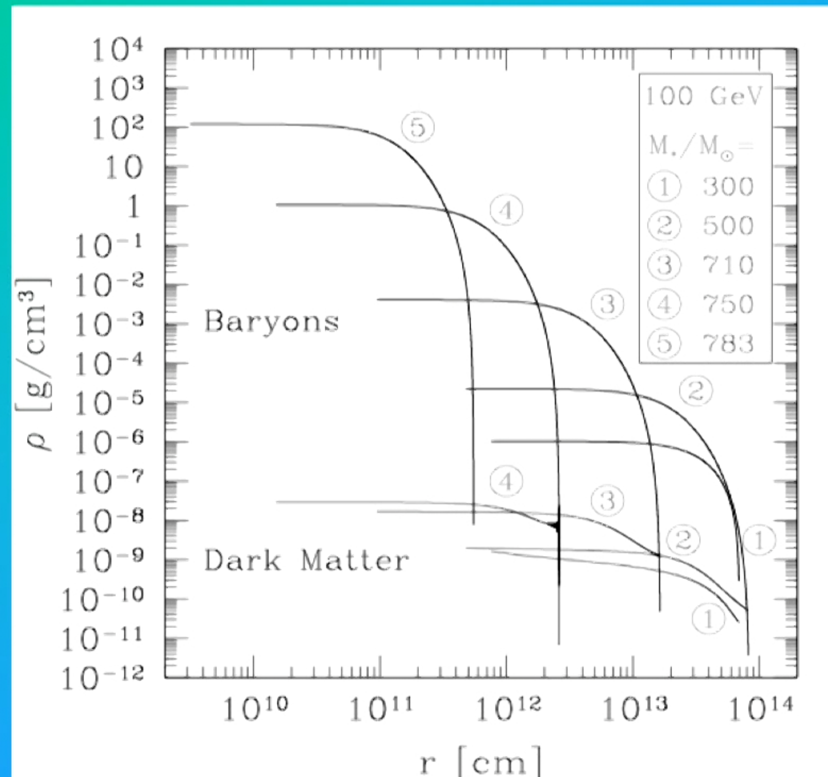
$$L_{DM} = L_*$$

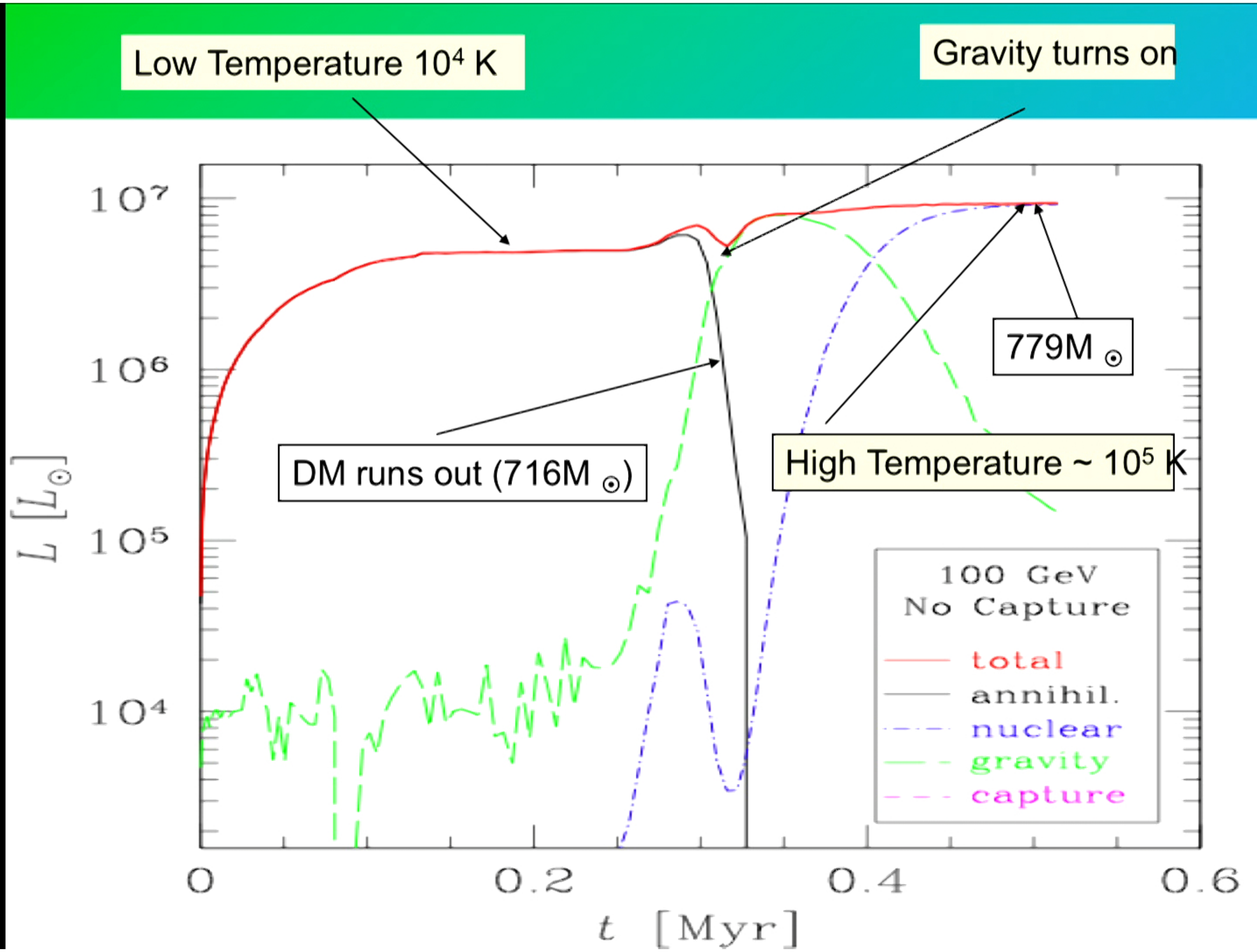
Building up the mass

- 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
- VERY LARGE FIRST STARS! Then, star contracts further, temperature increases, fusion will turn on, eventually make giant black hole

Following DS Evolution

- Gas Accretes onto molecular hydrogen Core, the system eventually forms a star.
- We then solve for stellar Structure by:
  - Self consistently solve for the DM density and Stellar structure
  - (Overly Conservative) DM in spherical halo. We later relax this condition




Low Temperature 10^4 K
Gravity turns on
DM runs out (716M ⊙)
779M ⊙
High Temperature ~ 10^5 K
100 GeV
No Capture
total
annihil.
nuclear
gravity
capture
L [L⊙]
t [Myr]
10⁷
10⁶
10⁵
10⁴
0
0.2
0.4
0.6

DS Basic Picture

- We find that DS are:
  - Massive: more than 1000 $M_{\odot}$
  - Large-a few a.u. (size of Earth orbit around Sun)
  - Luminous: more than 10^7 solar
  - Cool: 10,000 K vs. 100,000 K plus
    - Will not reionize the universe.
  - Long lived: more than 10^6 years.
  - With Capture or nonCircular orbits, get even more massive, brighter, and longer lived

How big do Dark Stars get?

- KEY POINT: **As long as the star is Dark Matter powered, it can keep growing** because its surface is cool: surface temp 10,000K (makes no ionizing photons)
- Therefore, baryons can keep falling onto it without feedback.
- Previously, we considered spherical haloes and thought the dark matter runs out in the core, making a small hole in the middle with no dark matter. We made 1000 solar mass DS.
- Wrong: Haloes are triaxial! MUCH MORE DM is available and the DS can end up Supermassive up to ten million solar masses.
- Second mechanism to bring in more dark matter: capture

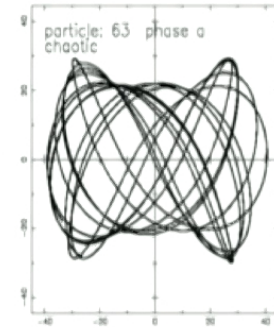
Is there enough DM?

Spherical Halos

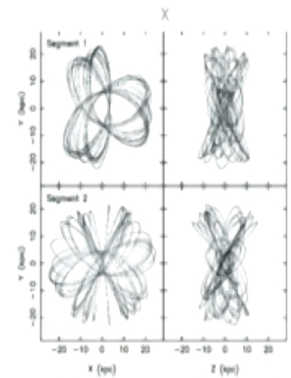
- DM orbits are planar rosettes (Binney & Tremaine '08).
- The Dark Star creates a loss cone that cannot be refilled.

Halos are actually Prolate-Triaxial (Bardeen et al. '86).

- Two classes of centrophilic orbits. Box and Chaotic orbits (Schwarzchild '79).
- Traversing arbitrarily close to the center and refilling the loss cone.
- The loss cone could remain full for 10^4 times longer than in the case of a Spherical Halo (Merritt & Poon '04).



Box Orbit



Chaotic Orbit

A particle that comes through the center of the DS can be annihilated. However, that particle was not on an orbit that would pass through the center again anyway. The next particle will come in from a different orbit.

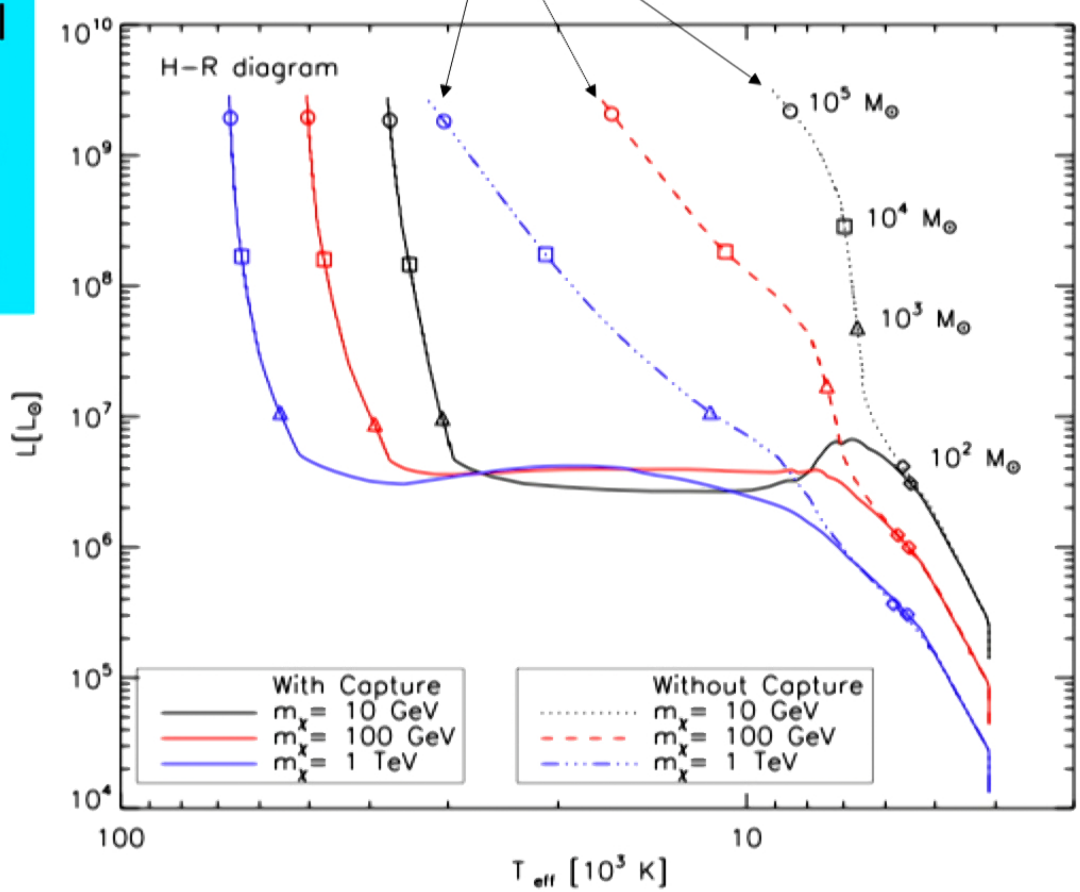
SUPERMASSIVE dark stars (SMDS) from extended adiabatic contraction

- Previously we thought dark matter runs out in a million years with 800 $M_\odot$ 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, 10^5-10^7 $M_\odot$, last much longer, and reach 10^9-10^{11} $L_\odot$. Some may live to today
- Visible in James Webb Space Telescope.
- Leads to (as yet unexplained) big black Holes.

Additional mechanism: see Umeda etal (JCAP 2009)

Super Massive DS due to extended adiabatic contraction since reservoir has been replenished due to orbital structure

Assuming all of the baryons can accrete in a $10^6 M_\odot$ halo



Additional possible source of DM fuel: capture

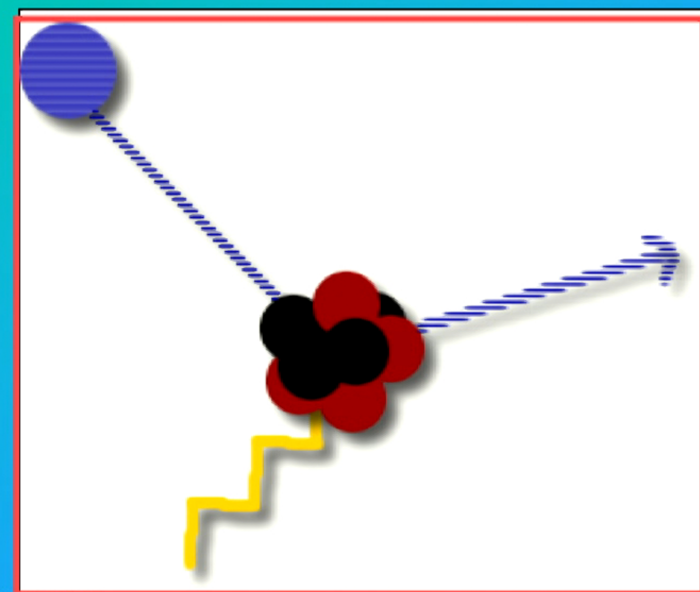
- Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured. (This it the origin of the indirect detection effect in the Earth and Sun).
- Two uncertainties:

  (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.

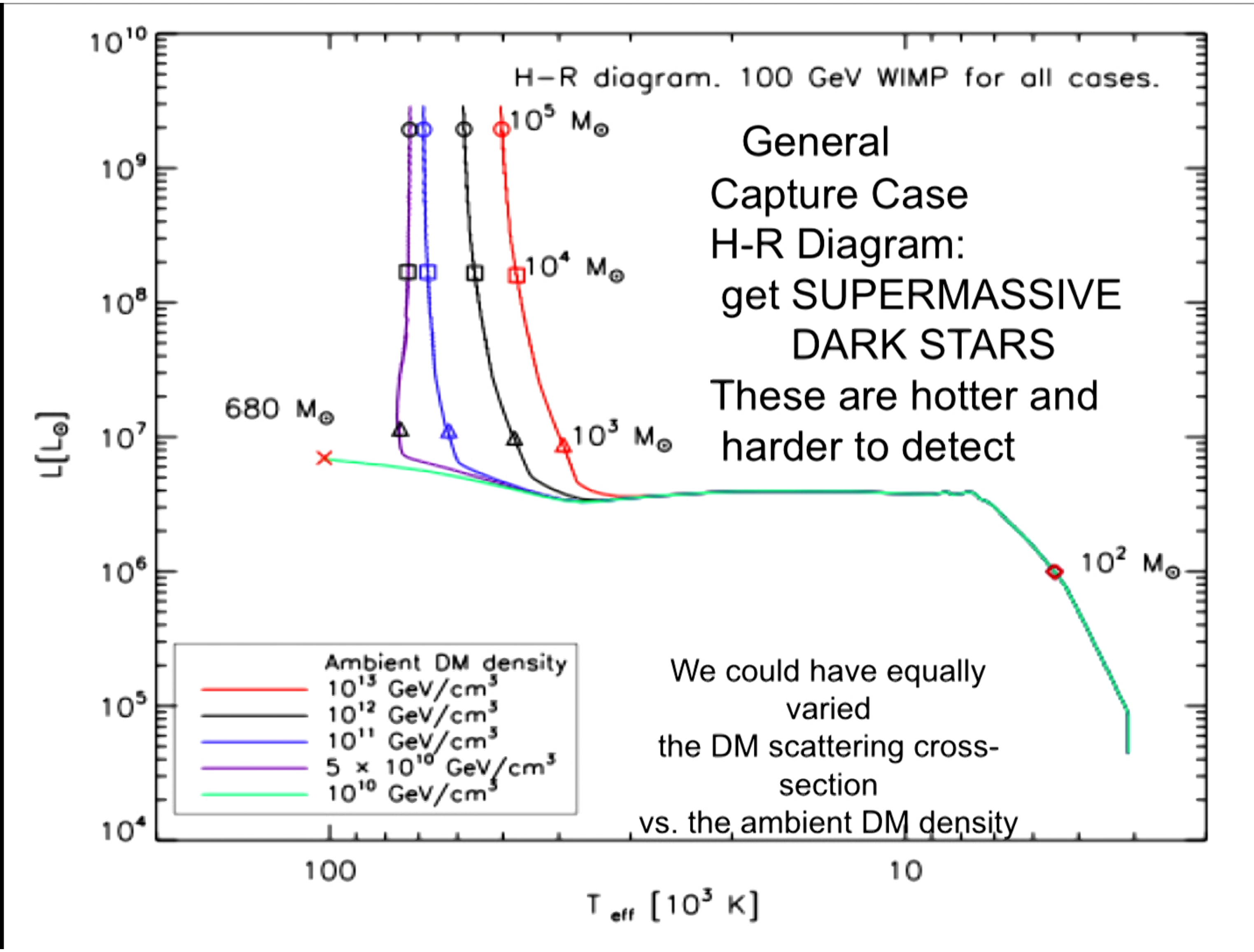
Freese, Aguirre, Spolyar 08; Iocco 08

WIMP scattering off nuclei leads to capture of more DM fuel

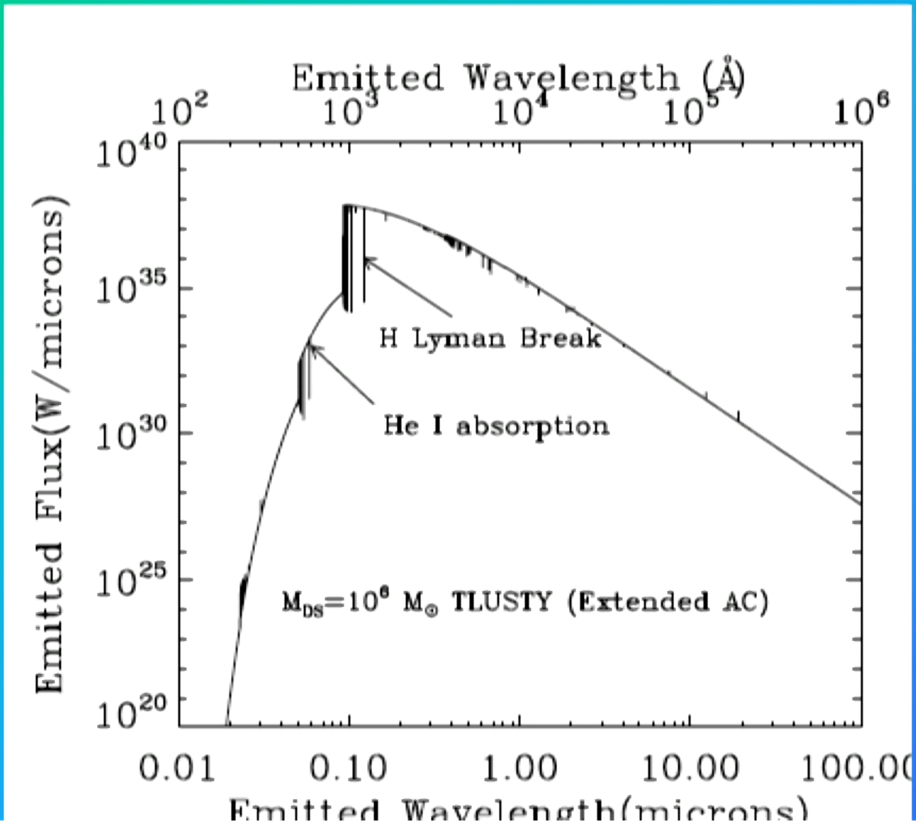
Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured.



This is the same scattering that COGENT, CDMS, XENON, DAMA, CRESST, etc are looking for (Direct Detection)


H-R diagram. 100 GeV WIMP for all cases.
10^5 $M_\odot$
10^4 $M_\odot$
680 $M_\odot$
10^3 $M_\odot$
10^2 $M_\odot$
General
Capture Case
H-R Diagram:
get SUPERMASSIVE
DARK STARS
These are hotter and
harder to detect
Ambient DM density
10^{13} GeV/cm^3
10^{12} GeV/cm^3
10^{11} GeV/cm^3
5×10^{10} GeV/cm^3
10^{10} GeV/cm^3
We could have equally
varied
the DM scattering cross-
section
vs. the ambient DM density
$L[L_\odot]$
T_{eff} [10^3 K]
100
10
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4

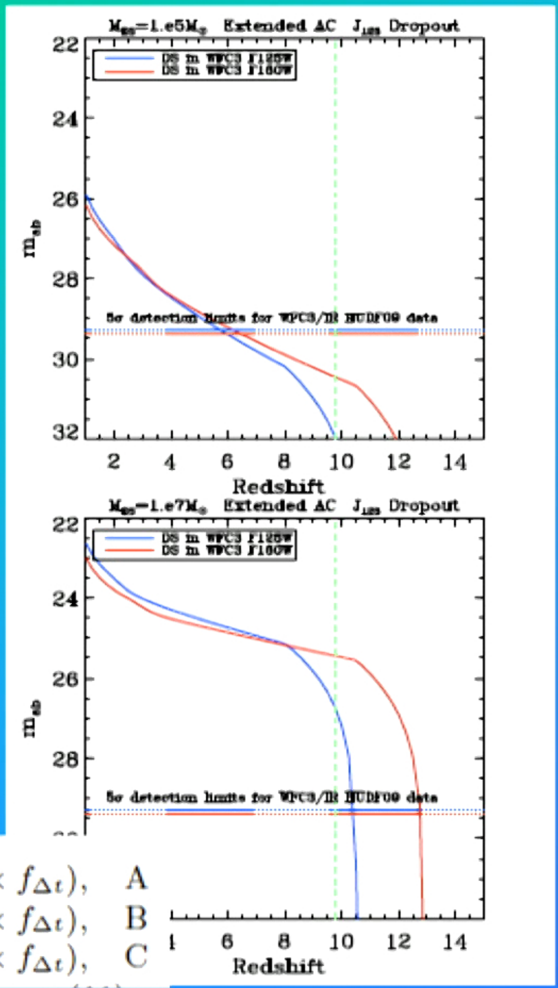
DS Spectrum from TLUSTY (stellar atmospheres code)



n.b. DS are made of hydrogen and helium only

Dark Stars in HST

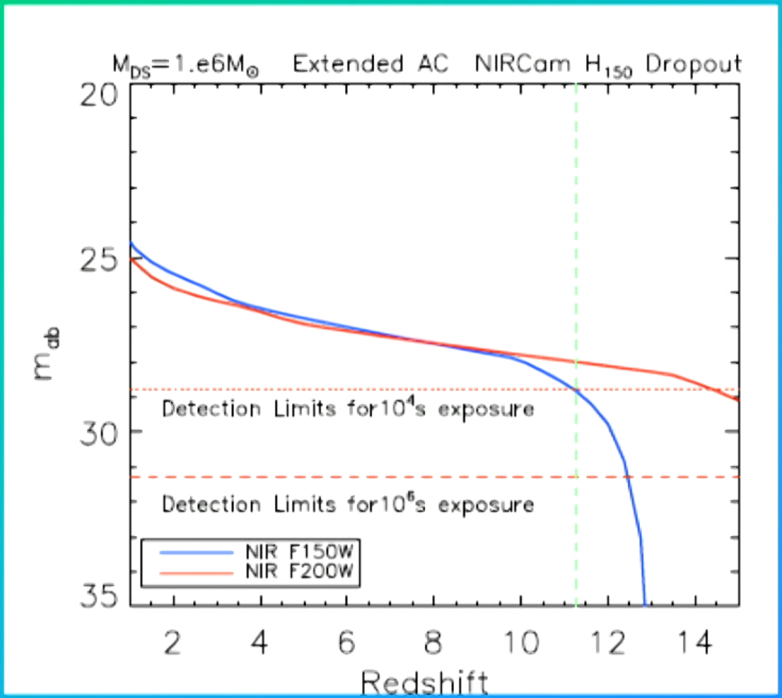
Heaviest ones would be visible in HST as Jband dropouts (observable in 1.6 micron band but not in 1.25 micron band due to Ly-alpha absorption in the intervening gas), yet only one object was found at z=10. Thus we can bound the numbers of 10^7 solar mass SMDS.



$$\log f_{smds}(M_{DS} = 10^7 M_\odot) \leqslant \begin{cases} -4.5 - \log(f_{surv} \times f_{\Delta t}), & \text{A} \\ -3.4 - \log(f_{surv} \times f_{\Delta t}), & \text{B} \\ -2.1 - \log(f_{surv} \times f_{\Delta t}), & \text{C} \end{cases}$$

A,B,C: zform=10,12,15

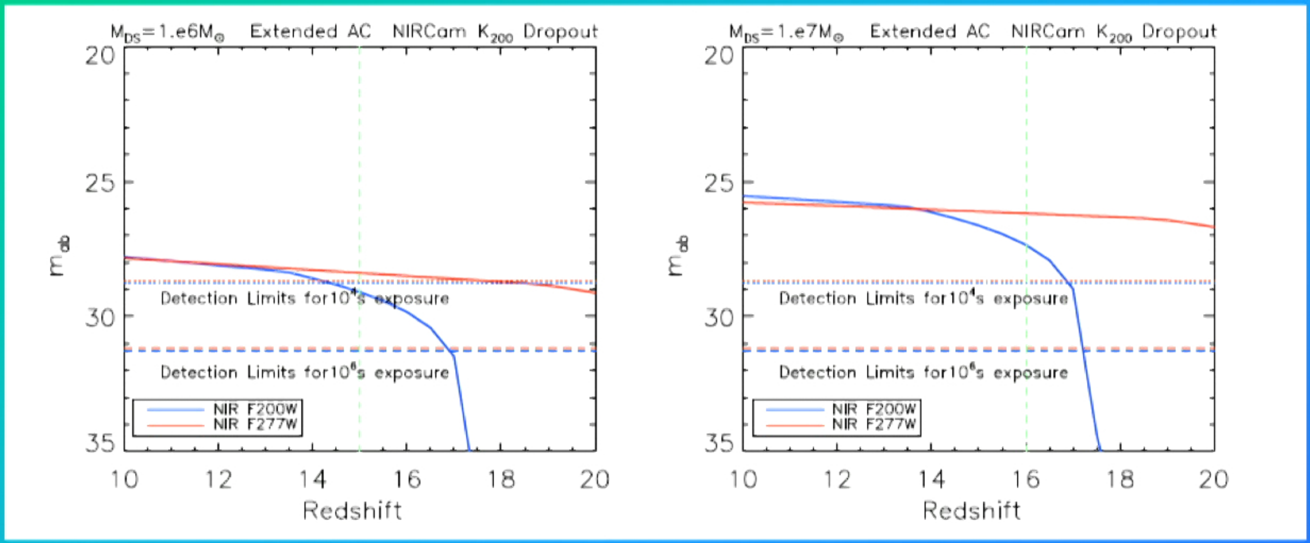
Million solar mass SMDS as H-band dropout



(see in 2.0 micron but not 1.5 micron filter, implying it's a z=12 object)

SMDS as K-band dropout

(see in 2.77 micron but not 2.00 micron filter, implying it's a z=15 object)



Numbers of SMDS detectable with JWST as H-band dropouts

(see in 2.0 micron but not 1.5 micron filter, implying it's z=12 object

Upper limits on numbers of SMDS detectable with JWST as H_{150} dropout

$M_{DS}(M_\odot)$	Formation Scenario	Bounds from HST	N_{obs}^{FOV}	N_{obs}^{multi}
10^6	Extended AC	Maximal Bounds	$\lesssim 1$	10
10^6	With Capture	Maximal Bounds	2	32
10^7	Any	Maximal Bounds	$\lesssim 1$	~ 1
10^6	Extended AC	Intermediate	45	709
10^6	With Capture	Intermediate	137	2128
10^7	Any	Intermediate	4	64
10^6	Extended AC	Number of DM halos	28700	444750
10^6	With Capture	Number of DM halos	28700	444750
10^7	Any	Number of DM halos	155	2400

Table 3. Upper limits on the number of SMDS detections as H_{150} dropouts with JWST. In first three rows (labeled "Maximal Bounds") we assume that all the DS live to below z=10 where they would be observable by HST, and we apply the bounds on the numbers of DS f_{SMDS} from HST data in Section 4.2. The middle three rows (labeled "Intermediate") relax those bounds by assuming that only $\sim 10^{-2}$ of the possible DS forming in z=12 haloes make it through the HST observability window. For comparison we also tabulate in the last three rows the total number of potential DM host halos in each case. We also split the number of observations in two categories, N_{obs}^{FOV} and N_{obs}^{multi}. The first assumes a sliver with the area equal to the FOV of the instrument (9.68 arcmin^2), whereas in the second we assume multiple surveys with a total area of 150 arcmin^2 . Note that for the case of the $10^7 M_\odot$ SMDS the predictions are insensitive to the formation mechanism.

Number of SMDS detectable with JWST as K-band dropout

(see in 2.77 micron but not 2.00 micron filter, implying it's a z=15 object)

Upper limits on numbers of SMDS detectable with JWST as K_{200} dropout

$M_{DS}(M_\odot)$	Formation Scenario	Bounds from HST	N_{obs}^{FOV}	N_{obs}^{multi}
10^6	Extended AC	Maximal Bounds	$\lesssim 1$	~ 1
10^7	Any	Maximal Bounds	$\ll 1$	$\ll 1$
10^6	Extended AC	Intermediate	5	75
10^7	Any	Intermediate	$\ll 1$	$\lesssim 1$
10^6	Extended AC	Number of DM halos	4511	69900
10^7	Any	Number of DM halos	8	116

Dark stars Pulsations

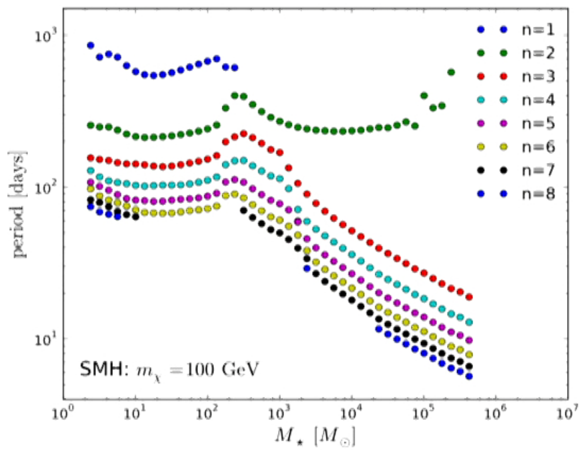


Figure 9. Radial, adiabatic pulsation periods as a function of DS mass for a WIMP mass of 100 GeV and a DS forming in SMH. The periods are given in the restframe of the DS. The curves are for different overtone number, from the fundamental radial oscillation $n = 1$ (upper-most curve) to $n = 8$ (lower-most curve); see also Ref.[16].

Finding pulsations allows differentiation in data from early galaxies
Also, someday will provide standard candles

Lifetime of Dark Star

- The DS lives as long as DM orbits continue through the DS or it captures more Dark Matter fuel: millions to billions of years.
- 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.
- You never know! They might exist today.
- Once the DM runs out, switches to fusion.

What happens next? BIG BLACK HOLES

- Star reaches $T=10^7$K, fusion sets in.
- A. Heger finds that fusion powered stars heavier than 153,000 solar masses are unstable and collapse to BH
- Less massive Pop III star lives a million years, then becomes a Black Hole
- Helps explain observed black holes:
- (I) in centers of galaxies
- (ii) billion solar mass BH at z=6 (Fan, Jiang)
- (iii) intermediate mass BH

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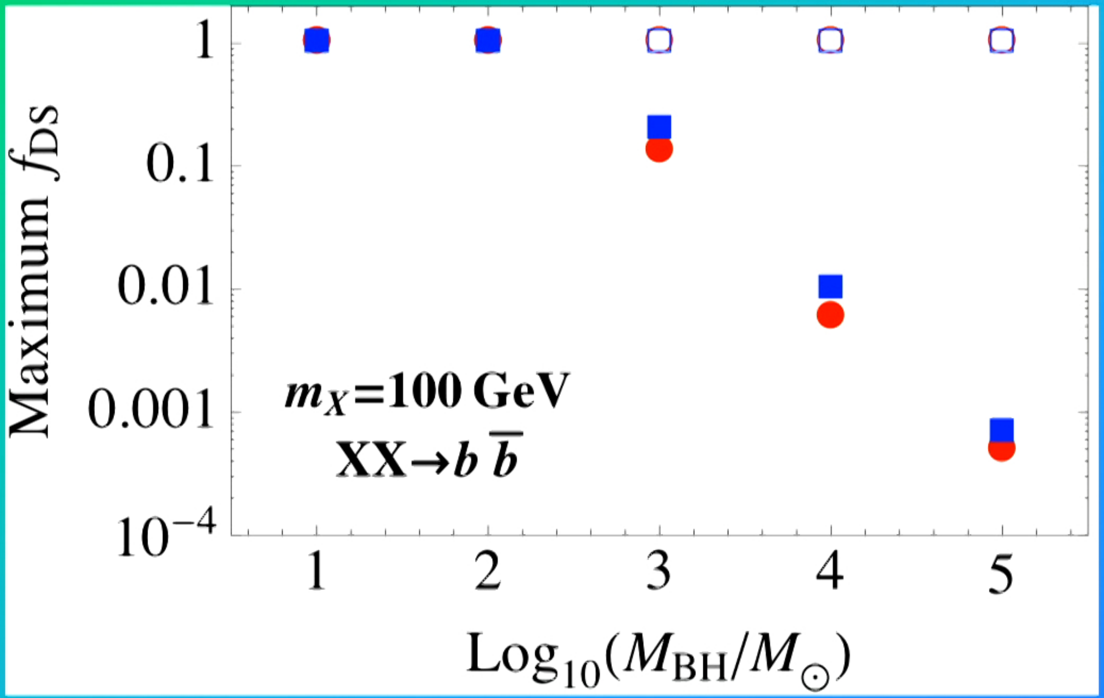
Black Hole remnants of dark stars

- These live till today, have DM spikes around them, that DM annihilates to observable signals in gamma rays and positrons (explains PAMELA?)
- FERMI has 368 unidentified point sources: can they be seeing these effects?
- Numbers of BH in Milky Way can be huge: millions between us and the GC!

FERMI bounds on the fraction of minihaloes hosting dark stars

Sandick, KF, etal 2010; 2011



Solid: FERMI point sources; open: gamma ray diffuse flux

Final Thoughts: *IMF*

- The IMF of the first fusion powered stars may be determined by the Dark Matter encountered by their Dark Star progenitors: as long as there is DM, the DS keeps growing
- Depends on cosmological merger details of early haloes, million to hundred million solar mass haloes

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 (1000-100,000 solar masses) and bright (million to ten billion solar luminosities) and can be detected by JWST