WIMP dark matter annihilation in the first stars

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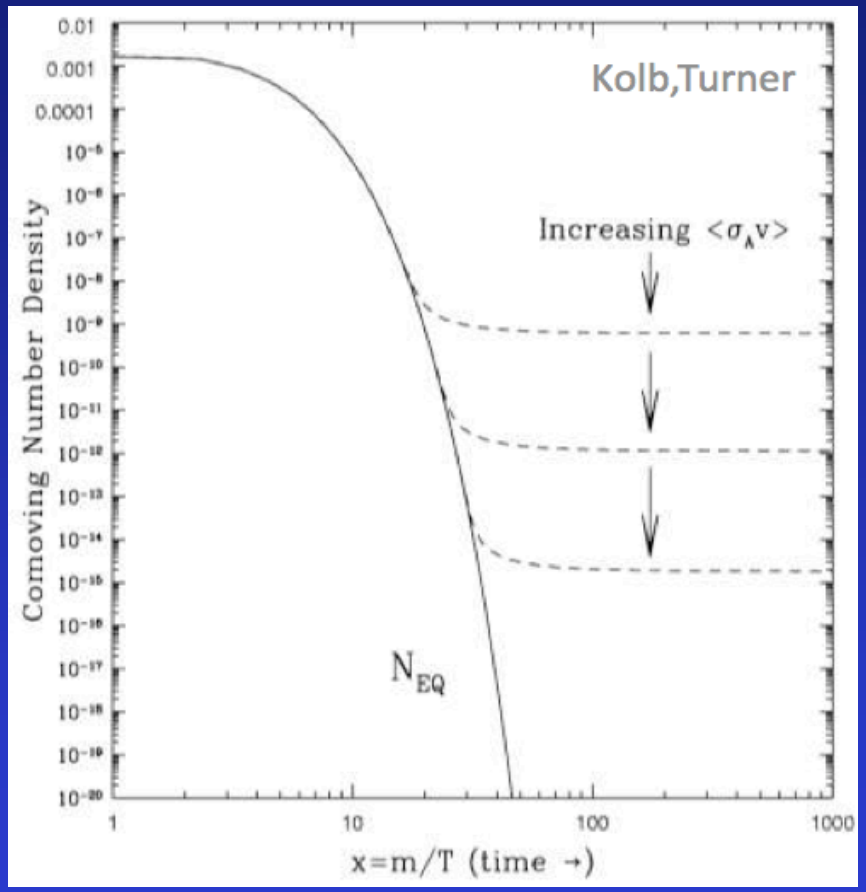
IAP, 2/2/09

Few properties of neutralinos: a *sexy* SUSY candidate



$$\Omega_\chi h^2 = \frac{3\times10^{-27}\ cm^3/\mathrm{sec}}{<\sigma v>_{ann}} \approx 0.1$$

from observations

Lightest R-parity conserving SUSY partner

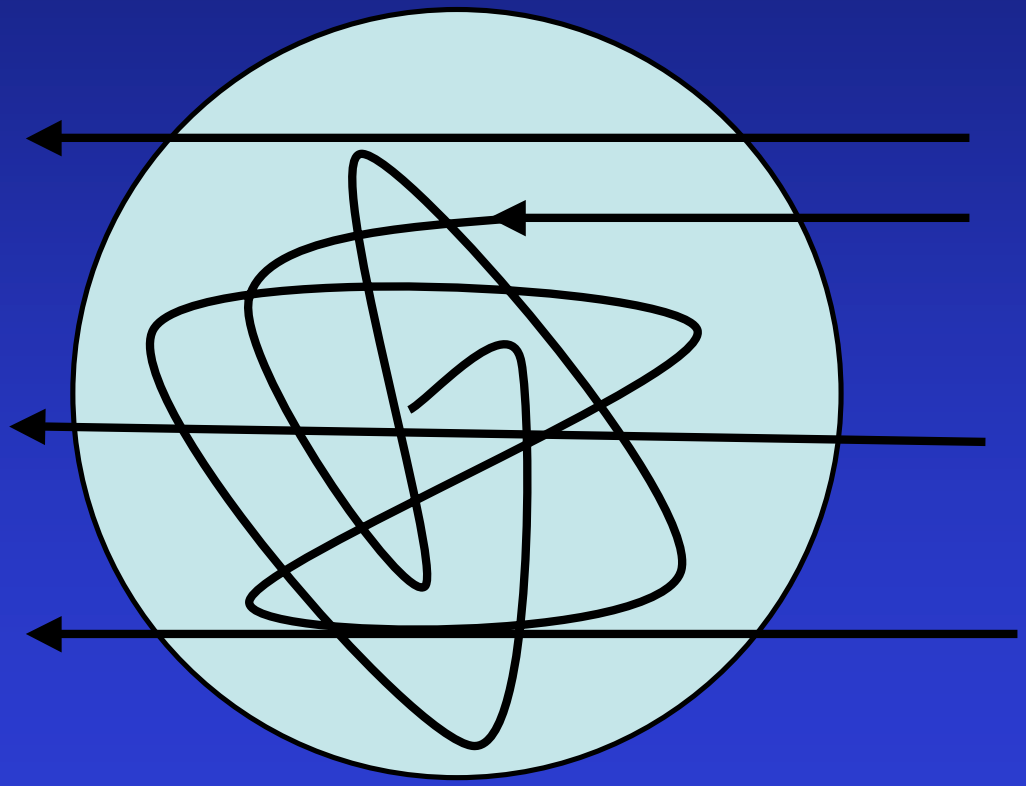
Stable, self-annihilating

Weakly coupled to baryonic matter

"Naturally", electroweak cross sections lead to $<\sigma v> \approx 3 \times 10^{-26}\ cm^3 s^{-1}$

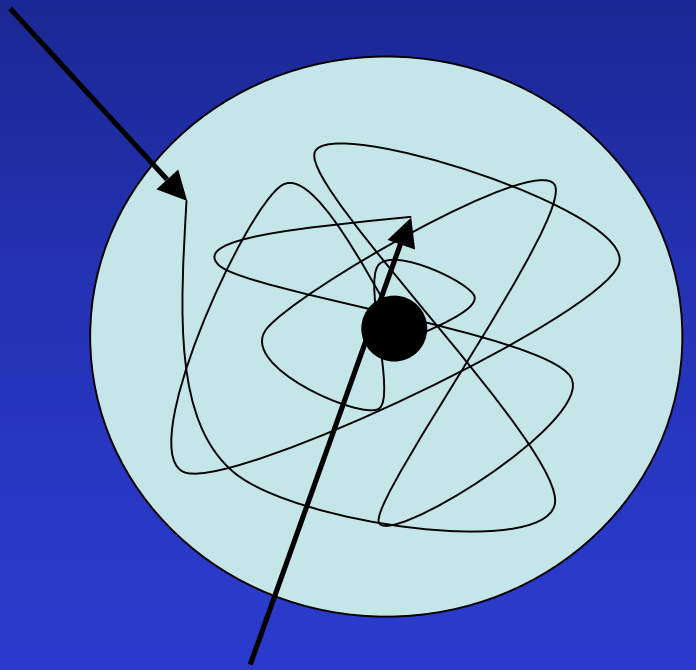
Scattering and capture

Halo WIMPs (originally outside the star) are captured



by scattering off the gas of the star

Captured WIMPs accumulate inside the star, thermalizing (need some time)



“sinking” to the center (most of annihilations is there)

DM and stars: scattering and capture

Capture rate C

$$C \propto \frac{\sigma_0 \rho}{\bar{v}} \frac{M_*^2}{R_*} \frac{1}{m_\chi}$$

"Dark Luminosity" inside the star

$$L_{DM} = 4\pi \langle \sigma v \rangle m_\chi \int n_\chi^2(r) r^2 dr$$

WIMPs thermally relaxed within the star

$$n_\chi(R) = n_\chi^c \exp(-R^2/R_\chi^2)$$

At equilibrium

$$L_{\rm DM} = C m_\chi$$

Weak dependence on self-annihilation rate <σv>

WIMP annihilation ≈ point-source $R_\chi \approx 10^9$cm$<R_c$

Equilibrium timescales

$$\tau_{\rm th} = \frac{4\pi}{3\sqrt{2G}} \frac{m_\chi}{\sigma_0} \frac{R_*^{7/2}}{M_*^{3/2}}$$

$$\tau_\chi = \left(\frac{\pi^{3/2} R_\chi^3}{C \langle \sigma v \rangle} \right)^{1/2}$$

At ZAMS $t_{kh} >> \tau_{th} > \tau_\chi$

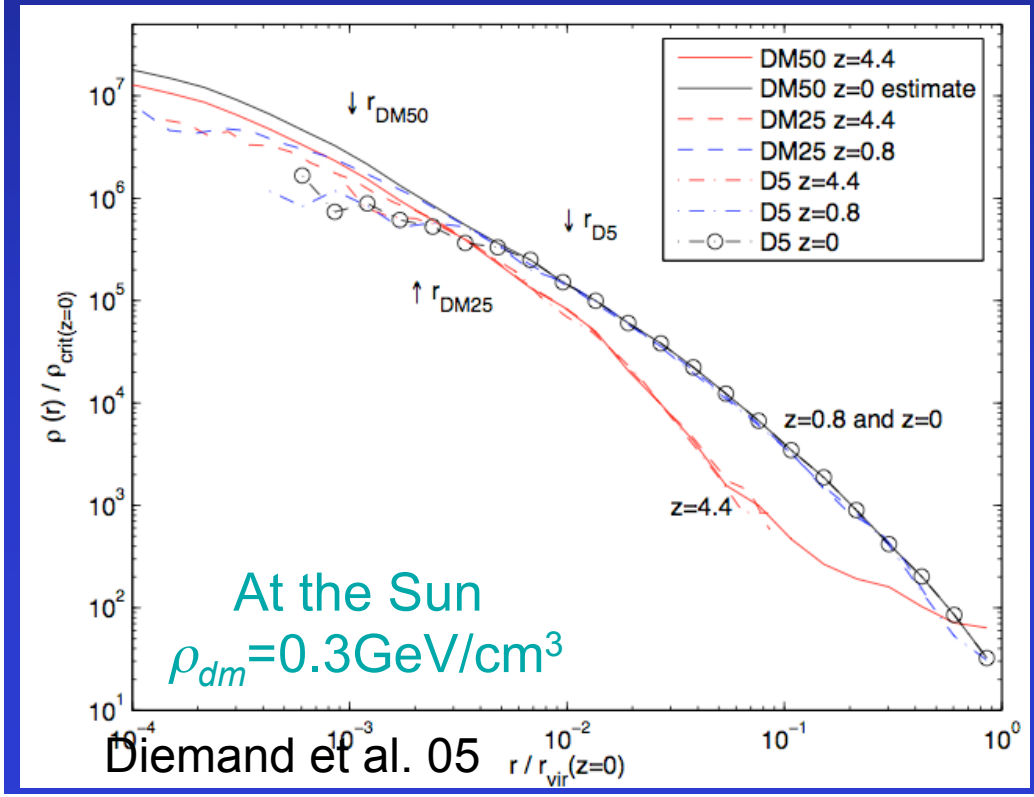
Seminal literature by: Gould, Griest, Press, Raffelt, Salati, Seckel, Spergel

Where does this happen?

(efficiently)

NFW universal profile: simulations

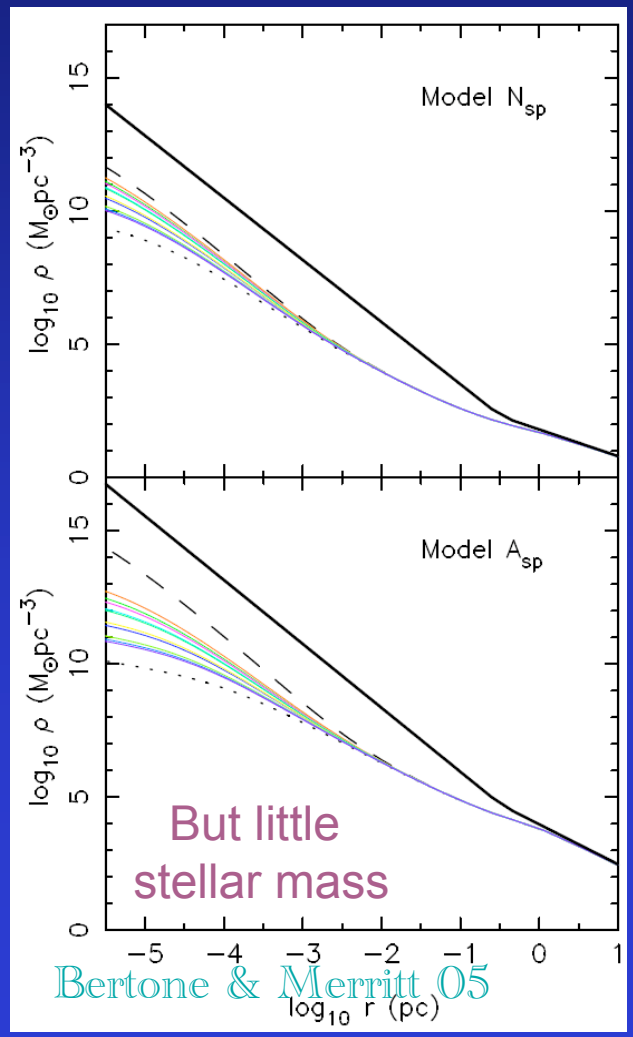
$$\rho_\chi(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^\gamma \left[1+\left(\frac{r}{r_s}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}}$$



At the Sun ρ_{dm}=0.3GeV/cm^3

Diemand et al. 05

Galactic Center is dense in DM!



But little stellar mass

Bertone & Merritt 05

The Sun: little WIMP effects over transport mechanisms

Weak particles have huge mean free paths

$$\frac{1}{l_\chi(r)} = \sum_i \sigma_i X_i(r) \frac{\rho(r)}{m_i}$$

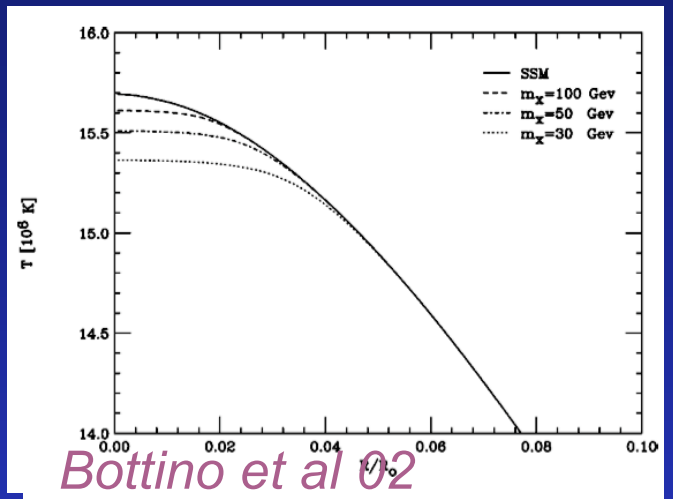
but they are *weak*, in fact

$$\epsilon_\chi = 8\sqrt{\frac{2}{\pi}} n_\chi n_n \sigma_0 \frac{m_\chi m_n}{(m_\chi + m_n)^2} \left(\frac{m_n k T_\chi + m_\chi k T_n}{m_\chi m_n}\right)^{1/2} k(T_n - T_\chi)$$

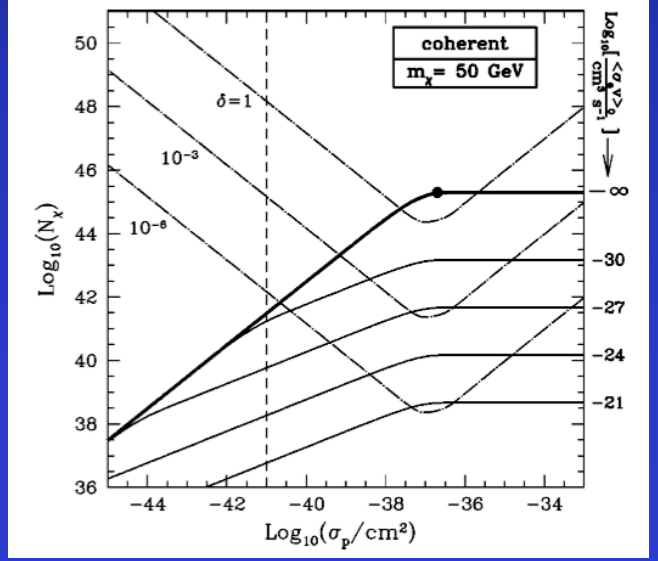
In principle suppresses convection

WIMPs are deep down: helioseismology can probe the inner Sun

$$\delta = \lim_{r\to 0} \frac{L_\chi(r)}{L(r)} \qquad \delta = \left[\frac{1}{(K/K_0)^2+1}\right] \frac{\kappa_\gamma(0)}{\kappa_\chi(0)}$$



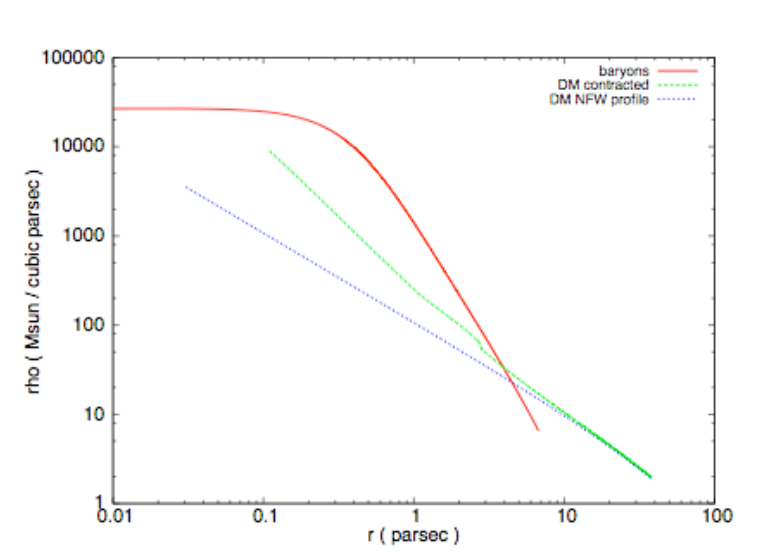
Bottino et al 02

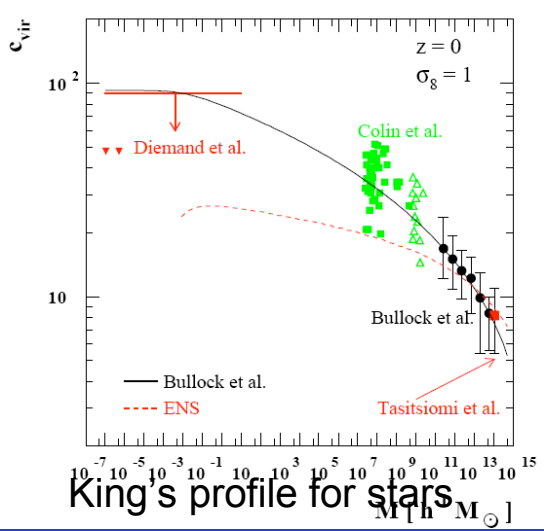


WIMP induced change in sound speed much smaller than present helioseismic uncertainties

Compact Objects

How much DM in Globular Clusters?





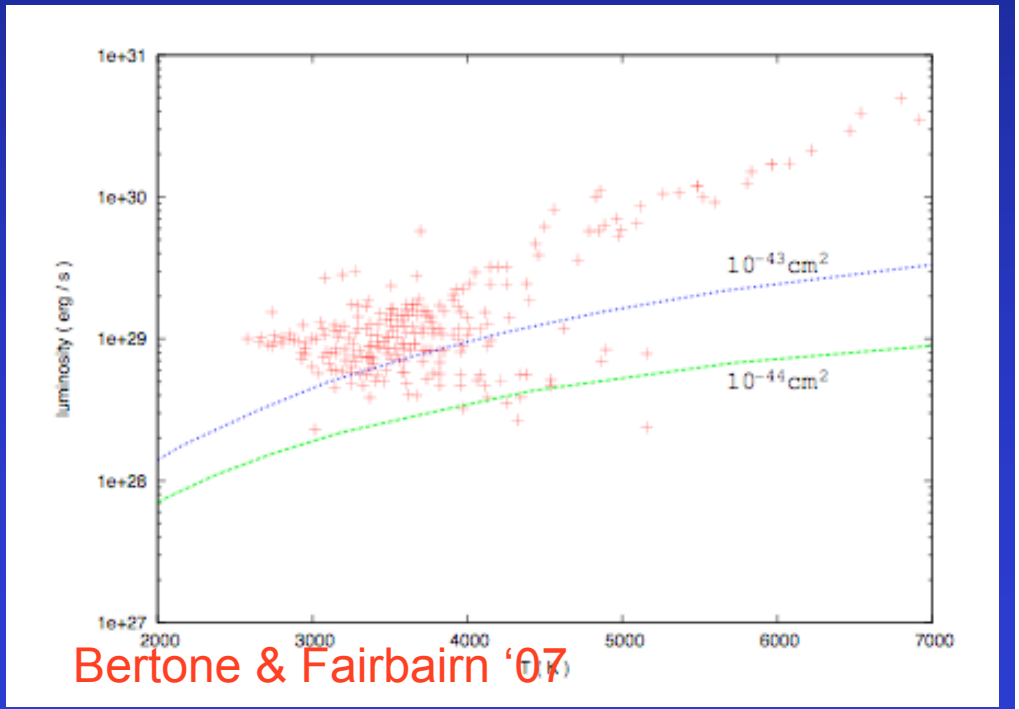
King's profile for stars

Colafrancesco et al. 05

What effects on WD from DM?

WD Blackbody emitters:
Radius-T/L relation

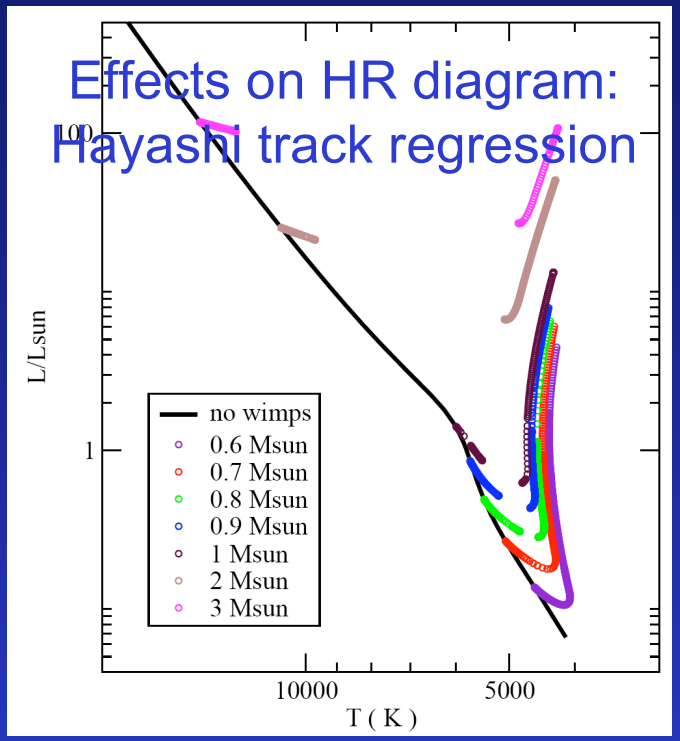
$$r = r_\odot \sqrt{\frac{L}{L_\odot}} \left(\frac{T_\odot}{T}\right)^2$$



Bertone & Fairbairn '07

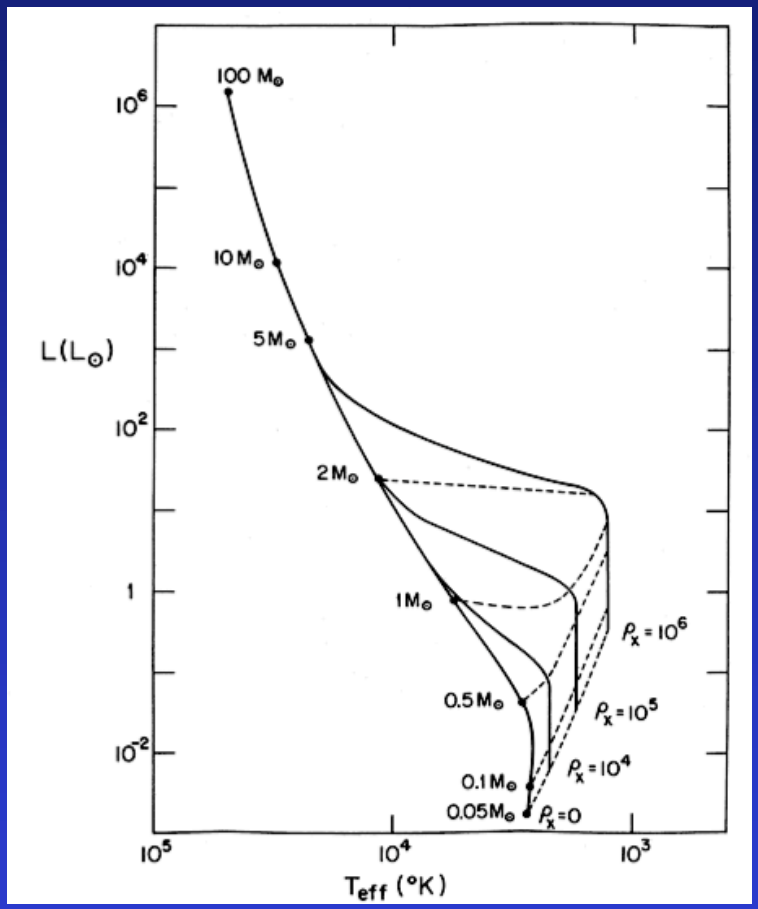
Preliminary estimates by Moskalenko & Wai 07

WIMP burning



Fairbairn, Scott & Edsjo 08

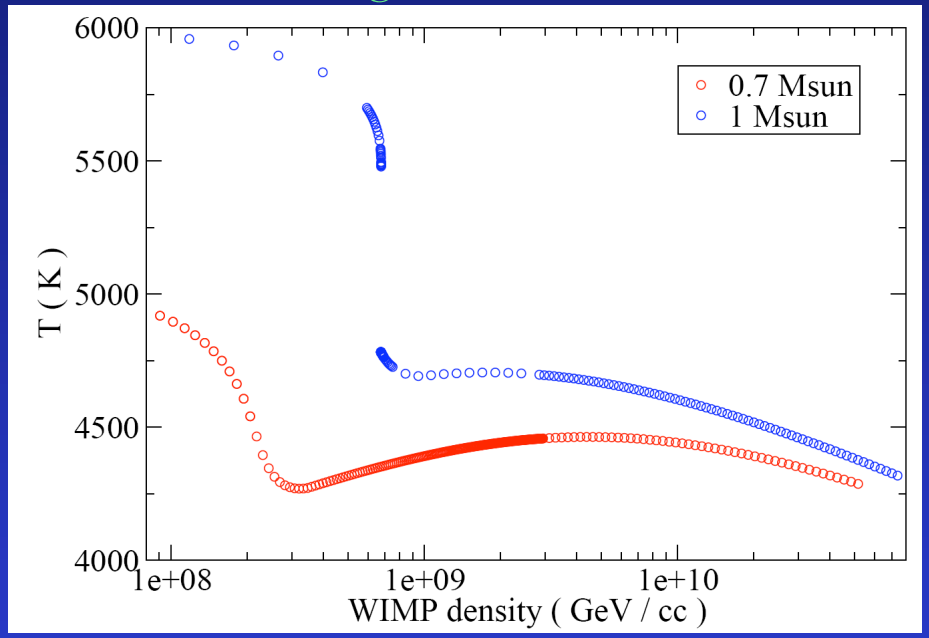
"Cool things start happening at about 10^8GeV/cm^3"
($\sigma_0=10^{-38}$cm^2)
M. Fairbairn



Salati & Silk 1989

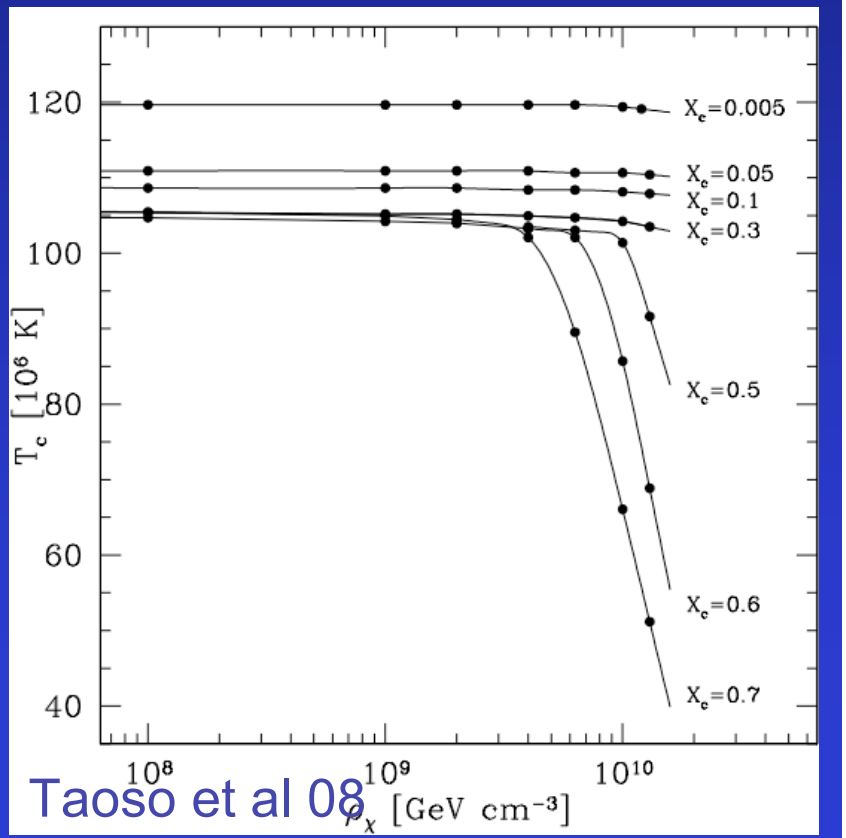
WIMP burning

Stars have negative specific heat:
feed them energy,they will cool down



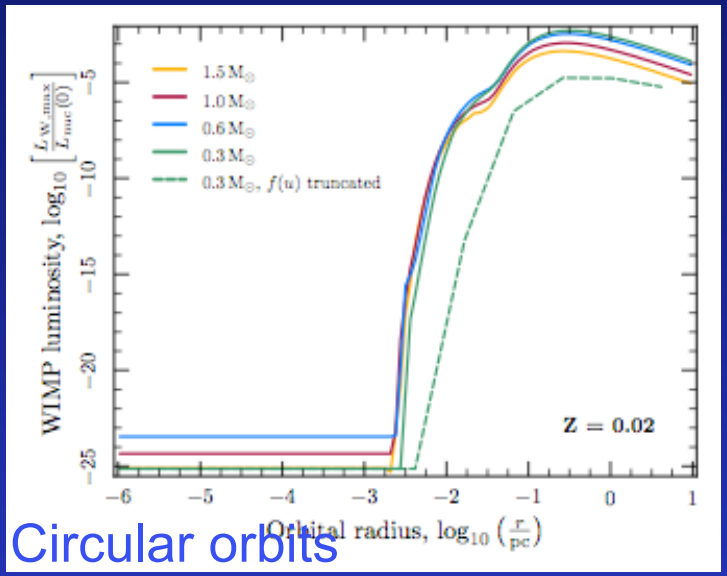
Fairbairn et al. 07

Nuclear burning switch-off
(take-over of DM)

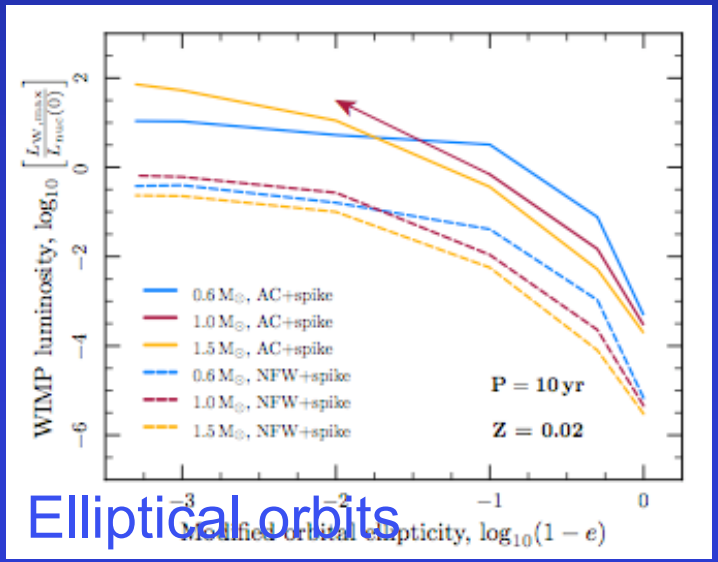


Taoso et al 08

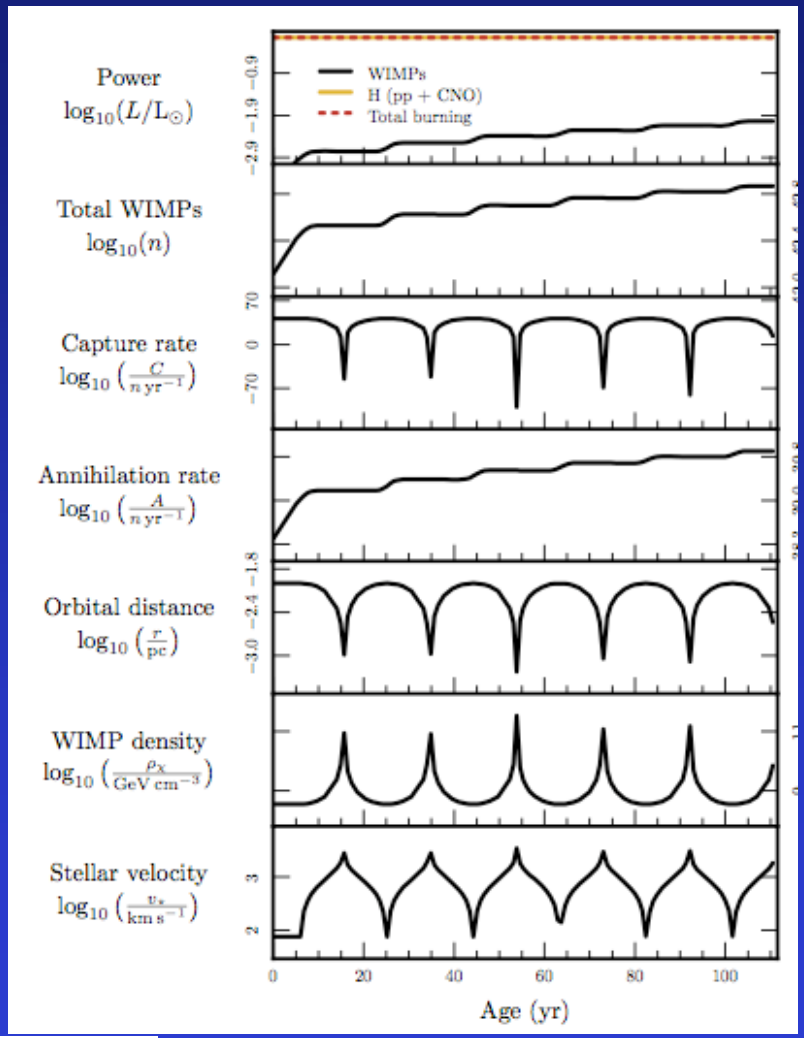
DM burning at the Galactic Center



Circular orbits



Elliptical orbits



$\sigma_{\rm SI} = 10^{-44}\,{\rm cm}^2$

$\sigma_{\rm SD} = 10^{-38}\,{\rm cm}^2$

Scott et al. 08

The first stars (Population III)

Form in halos of $M_h \approx 10^6 M_{sun}$ at $z \approx 20$ ($T_{vir} < 10^4$K)

First Stars $\Rightarrow$ primordial chemical composition
(BBN: no C,N,O -- A > 7)

Weak cooling: H_2 vs CO $\Rightarrow$ big masses
No fragmentation: big masses
Live fast, die young (30-300Msun go SNe)
Hot: first engines for IGM Reionization
(possibly) seed BH, correlated to quasars

$$M_J \propto T^{3/2}$$

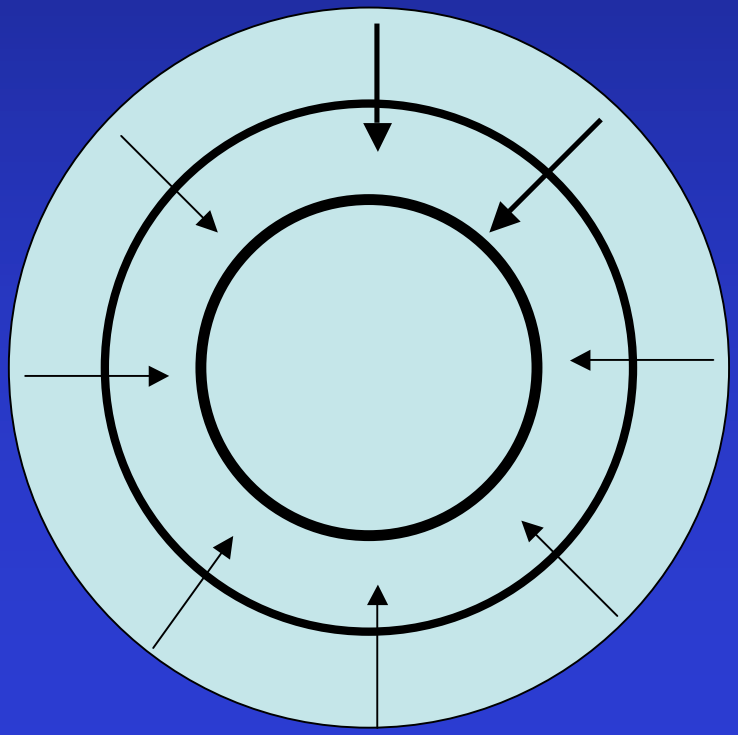
One star per halo, at its very center!

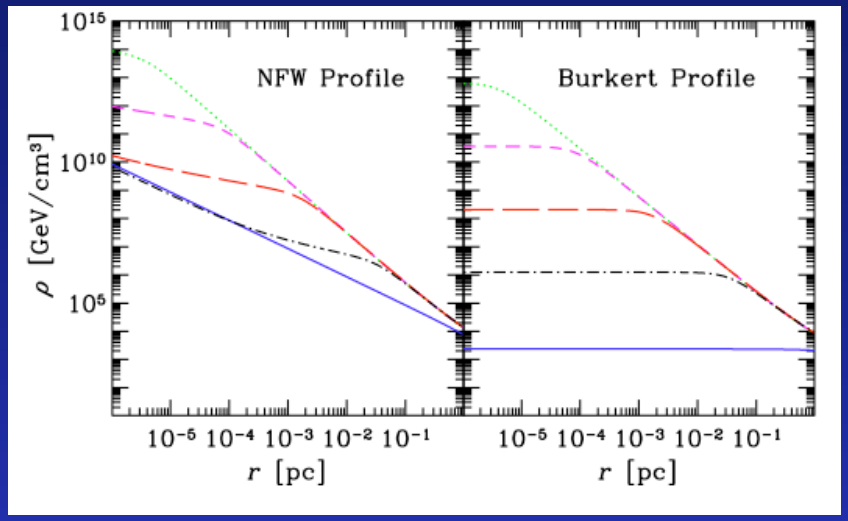
As of now, we have
(very likely) not seen one yet

Simulations!

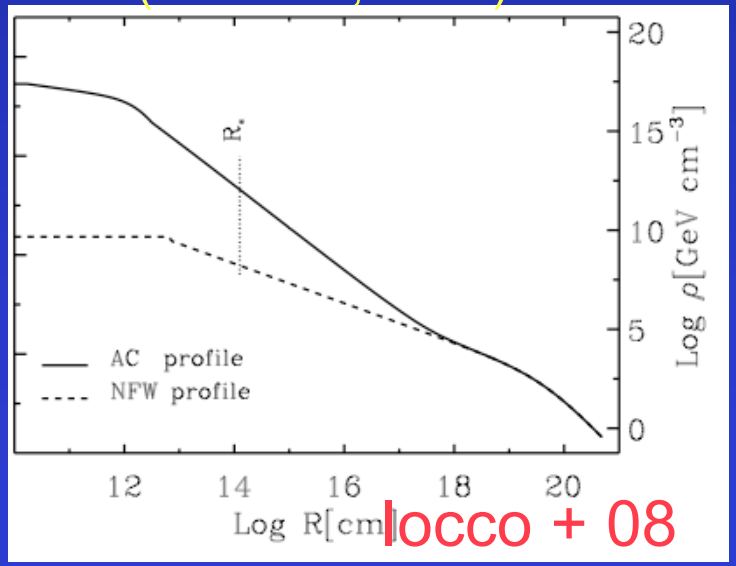
Building the DM cusp

Gas (collisional) cooling
and collapsing to the center
"pulling in" DM (gravitationally)
(modeled through adiabatic contraction)





Spolyar, Freese & Gondolo 07
(PRL 100, 2008)



Iocco + 08

(also Freese+ 08)

Powering the structure (with DM)

Energy production

$$\frac{dL_{\rm DM}}{dV} = \frac{\rho^2}{m_\chi}\langle\sigma v\rangle$$

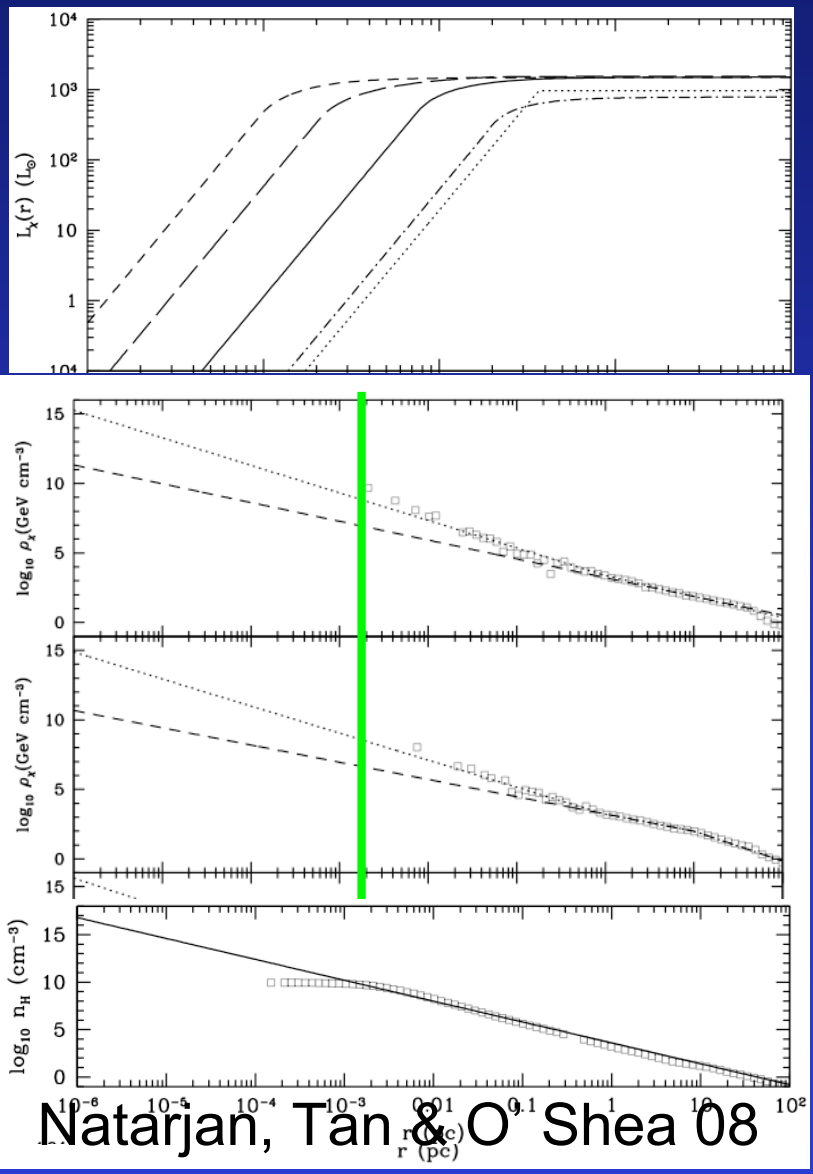
DM profile critical!

+

Energy deposition

Energy repartition for WIMP annihilation:
1/3 electrons
1/3 photons
1/3 neutrinos (lost)

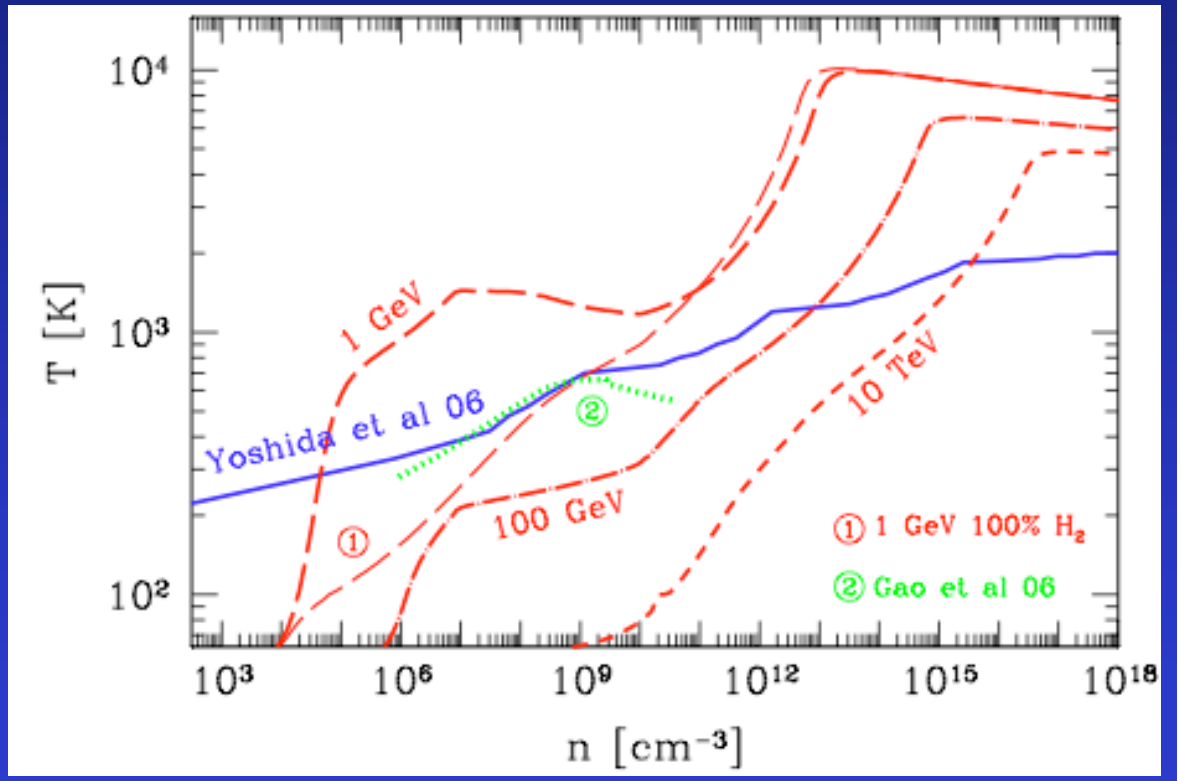
Absorption:
Gas profile critical!



Natarjan, Tan & O'Shea 08

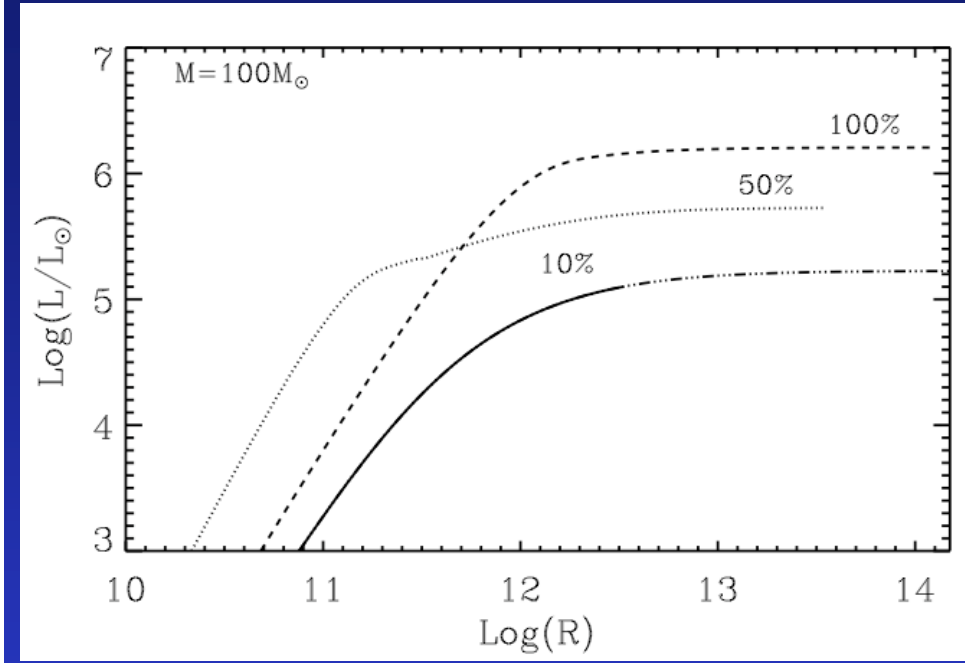
(only) *First Stars can do it !*

At n_{gas}~10^{12} #/cm^3
(and above)
structure opaque
to annihilation products

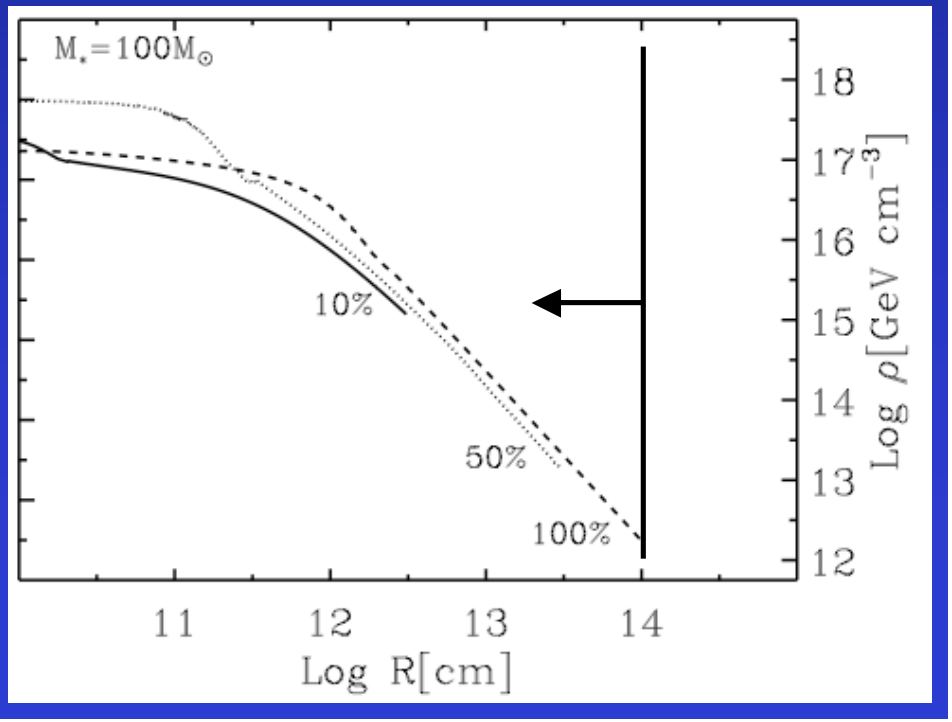


Spolyar, Freese & Gondolo 07
(PRL 100, 2008)

What happens, then?



100 Msun
initial conditions:
$R=10^{14}$cm
$n_{gas}=10^{16}$ #/cm3



delicate equilibrium
between accretion
(or DM cusp build-up)
and annihilation

Dark Star (à la Freese)

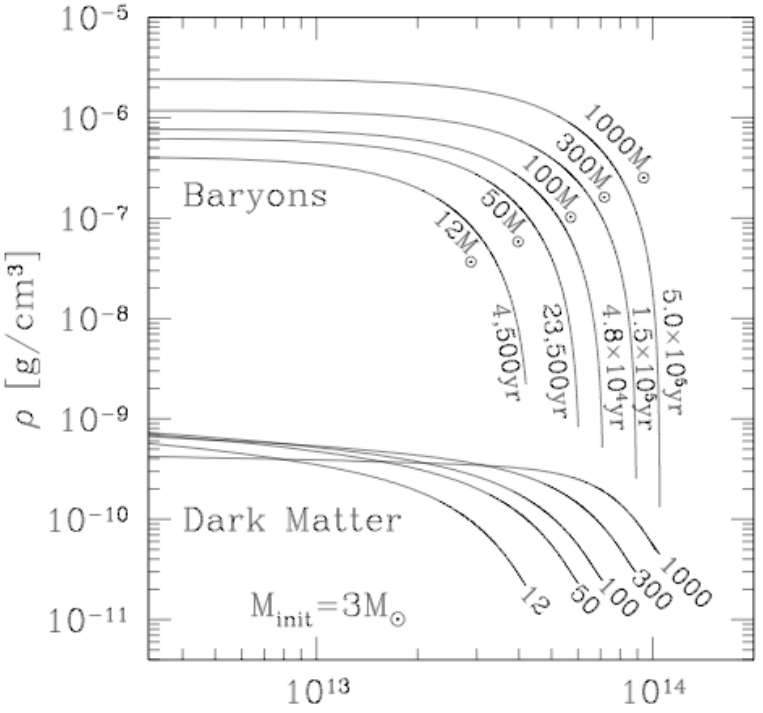
Polytropic EoS for the gas

Mass accretion≈10^{-3}Msun/yr

T≈10^5 K, t≈10^6yr, R≈10^{14}cm

$$\frac{dL_{\rm DM}}{dV} = \frac{\langle\sigma v\rangle}{m_\chi}\rho^2$$

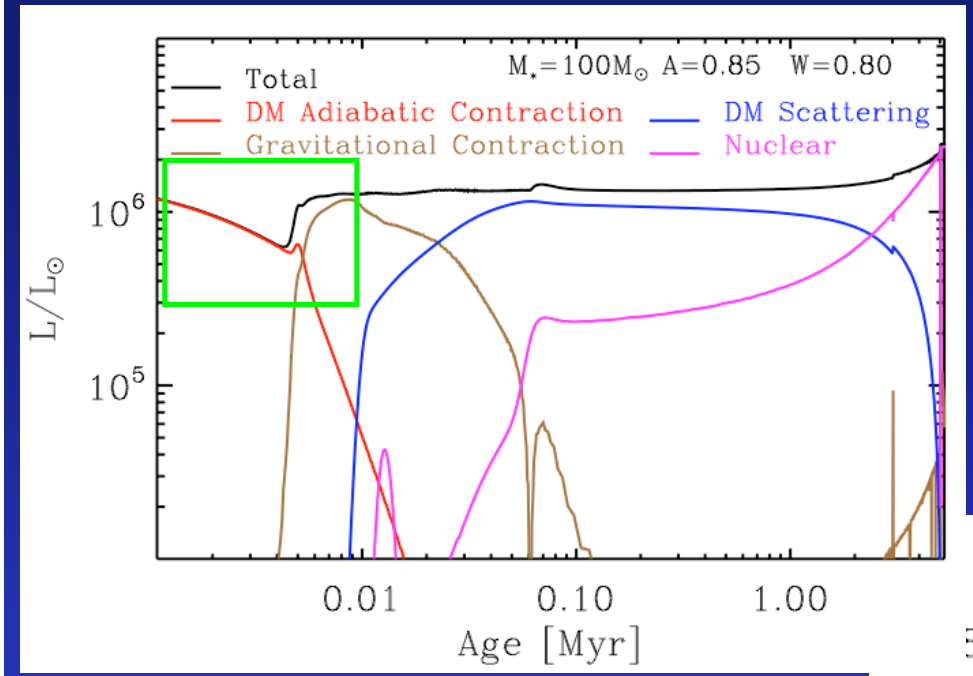
$$\langle\sigma v\rangle = 3\times10^{-26}\frac{cm^3}{s}$$
$$m_\chi = 100GeV$$



Freese et al, 08

M_* ($M_\odot$)	T_c (10^5K)	R_S (10^{13}cm)	ρ_c (gm/cm^3)	$\rho_{\chi,c}$ (gm/cm^3)	L_* ($L_\odot$)	T_{eff} (10^3K)	M_{DM} (gm)	t (yr)
12	1.3	4.2	4.1×10^{-7}	1.1×10^{-9}	1.1×10^5	4.3	2.8×10^{31}	6×10^3
50	2.7	6.0	6.2×10^{-7}	1.2×10^{-9}	4.2×10^5	5.0	9.1×10^{31}	2.5×10^4
100	3.5	7.1	7.7×10^{-7}	1.1×10^{-9}	7.8×10^5	5.3	1.6×10^{32}	5×10^4
300	5.3	9.0	1.2×10^{-6}	8.2×10^{-10}	1.9×10^6	6.0	3.6×10^{32}	1.5×10^5
1000	8.5	10	2.4×10^{-6}	4.5×10^{-10}	3.9×10^6	6.6	7.3×10^{32}	5×10^5

Evolving "Dark Stars"

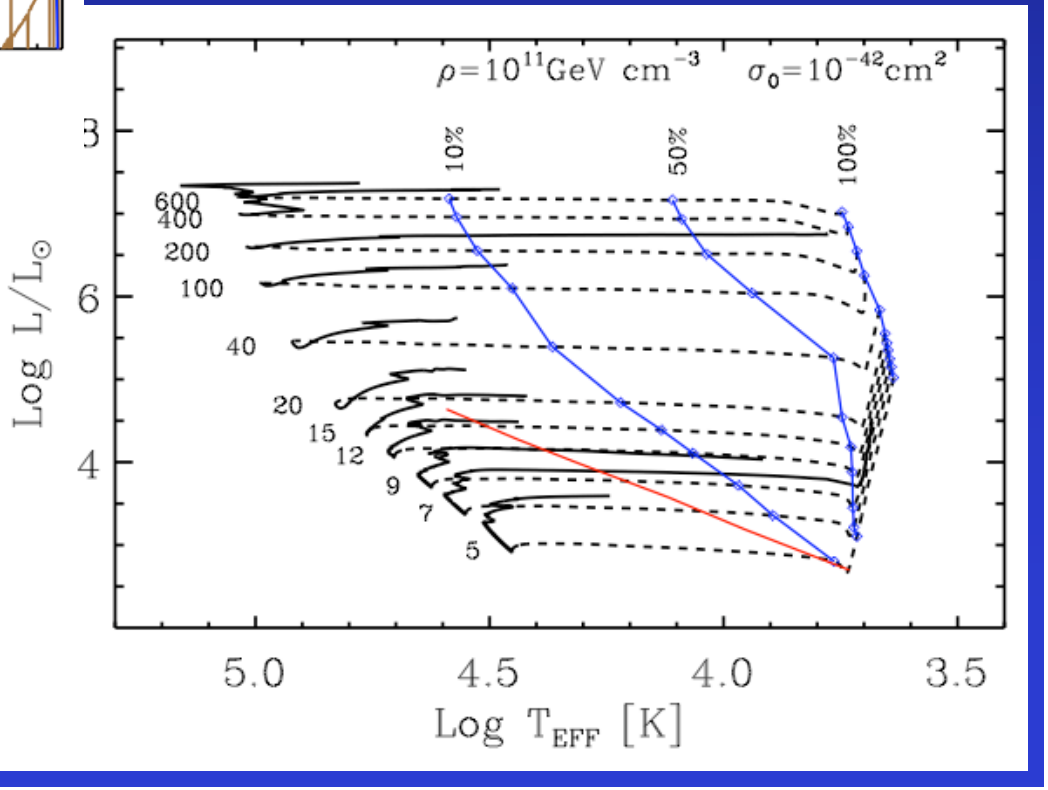


Adiabatic Contraction phase
Acts at proto-stellar stages
(or early pre-MS)
at T≈ 5000 K

Adopted
fiducial values:

$$\langle \sigma v \rangle = 3 \times 10^{-26} \frac{cm^3}{s}$$

$$m_\chi = 100 GeV$$



AC: a transient phase

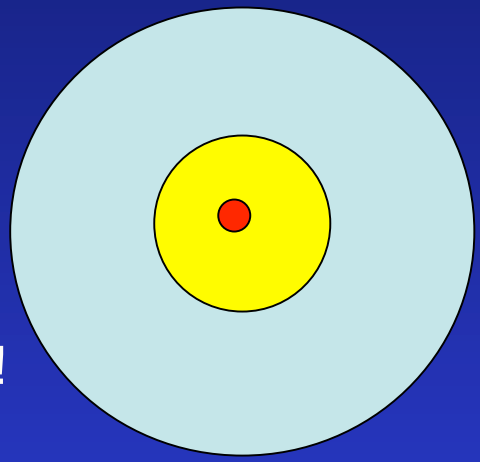
All groups agree!

(aside details)

Scattering (DM burning): once more

Capture rate depends on stellar characteristics

$$C \propto \frac{\sigma_0 \rho}{\bar{v}} \frac{M_*^2}{R_*} \frac{1}{m_\chi}$$



And environemt (continuously capturing halo WIMPs)!

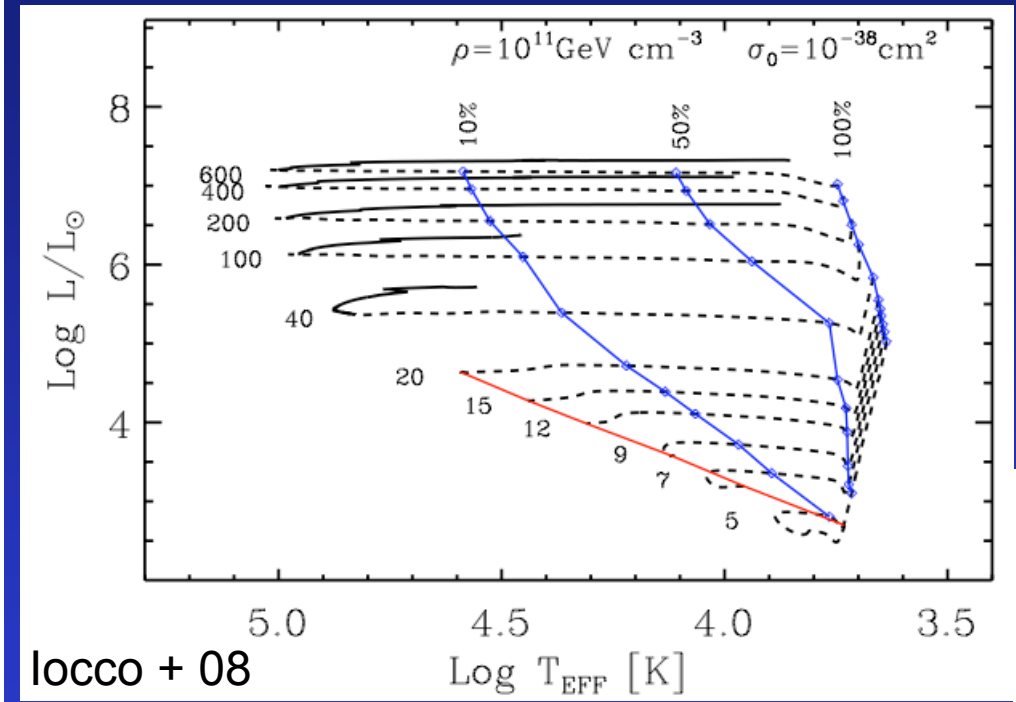
Dark Matter annihilation inside first stars can overpower nuclear

$$L_{\rm DM} = C m_\chi$$

Needs continous replenishment!!!!

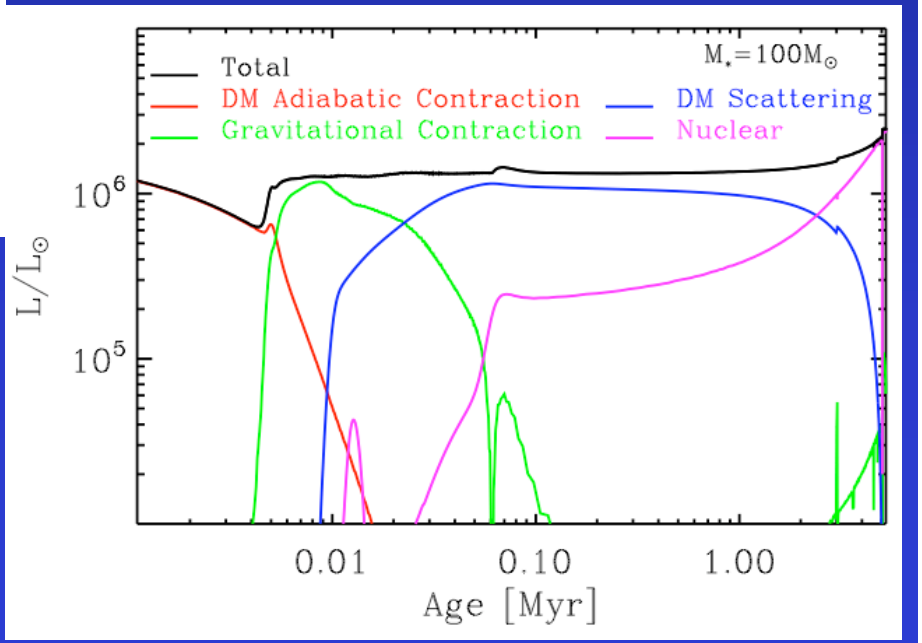
Scott, Fairbairn & Edsjo 08
also excellent review

So what, once they become "DM burners" ?



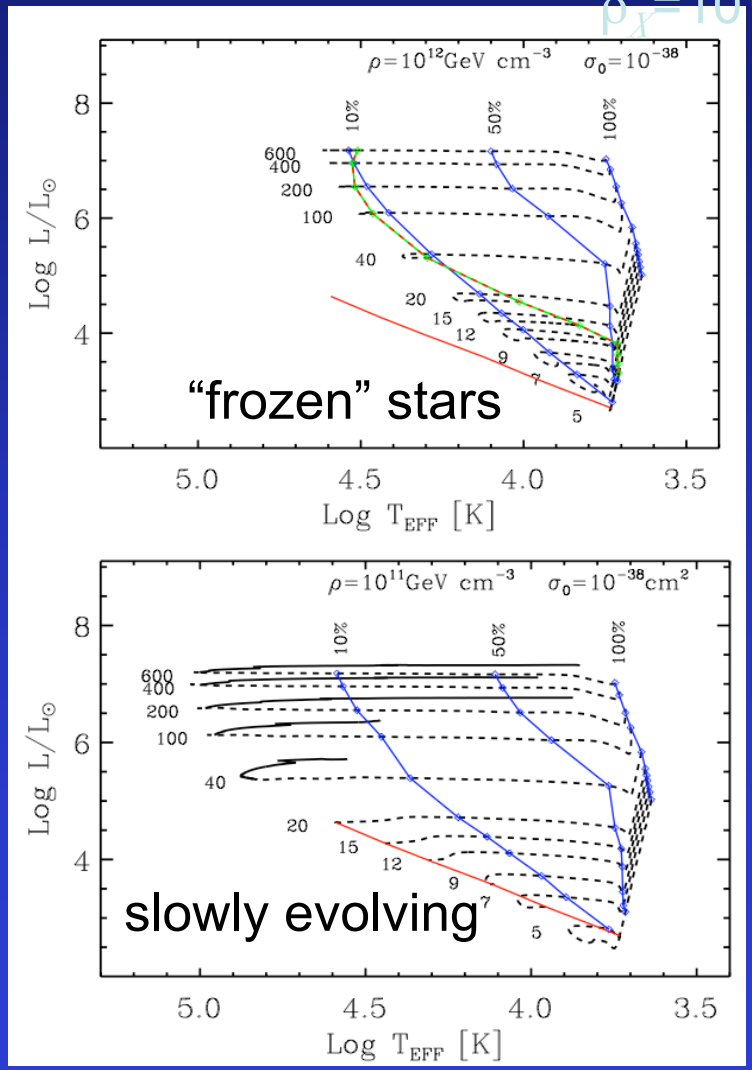
Iocco + 08

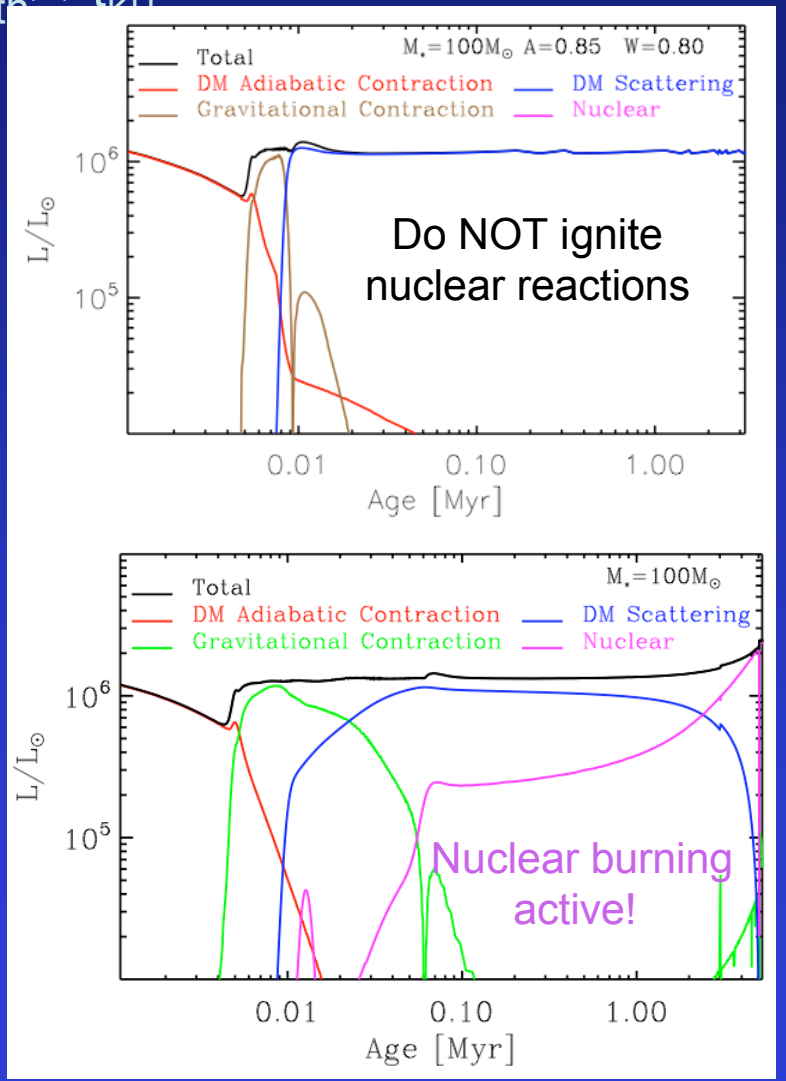
Active in late stages of pre-MS on Hayashi track $\tau_{KH} < \tau_{DM}$



DM burning: effects on the pre-MS

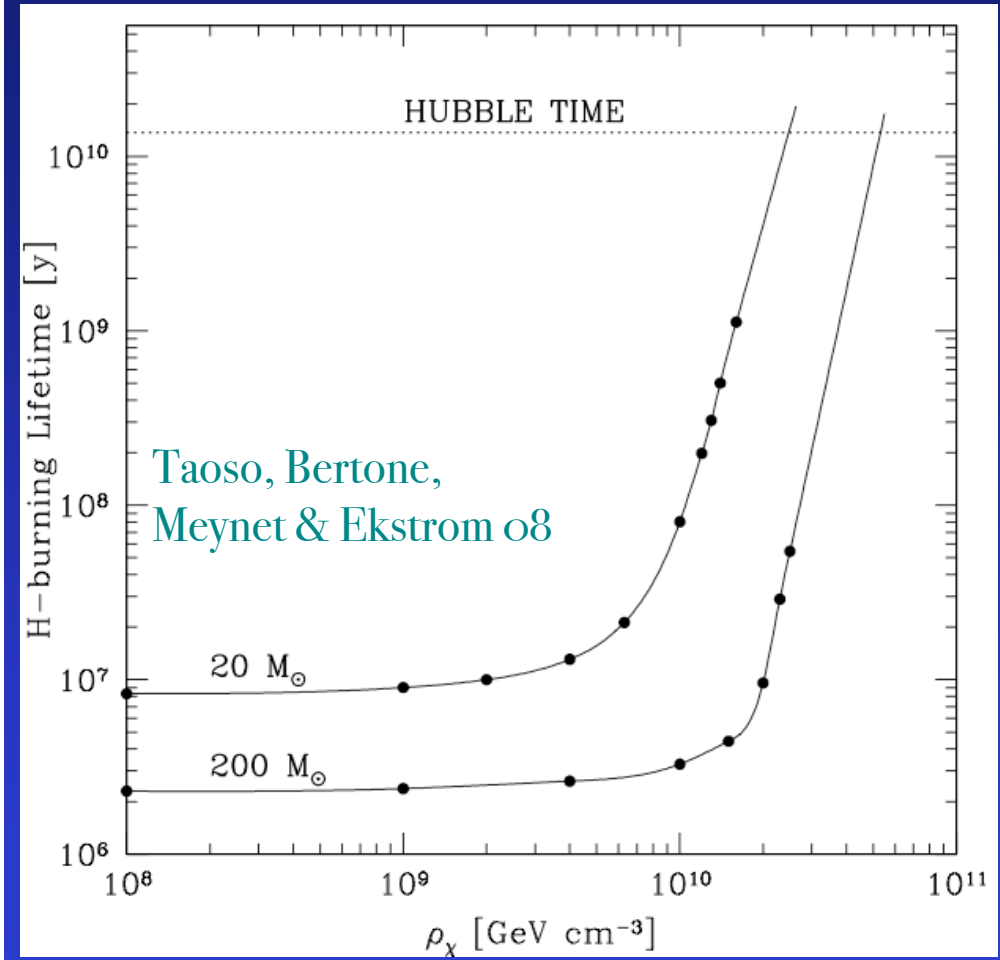
During AC phase $100M_{sun}$
$R=1.2\times10^{14}$cm, $L_X\approx10^{37}$erg/s,
$\rho_X=10^{12}$GeV/cm^3, $\tau_{th}>>t_{KH}$





Iocco, et al., MNRAS in press; arXiv:0805.4016

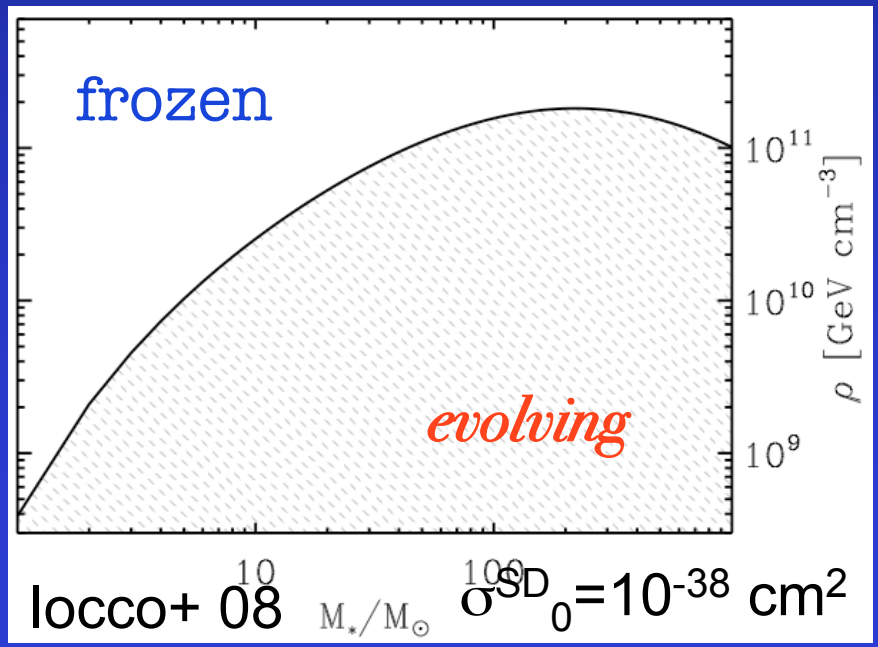
Prolonged lifetimes



Taoso, Bertone, Meynet & Ekstrom 08

DM powered stars are "*frozen*"

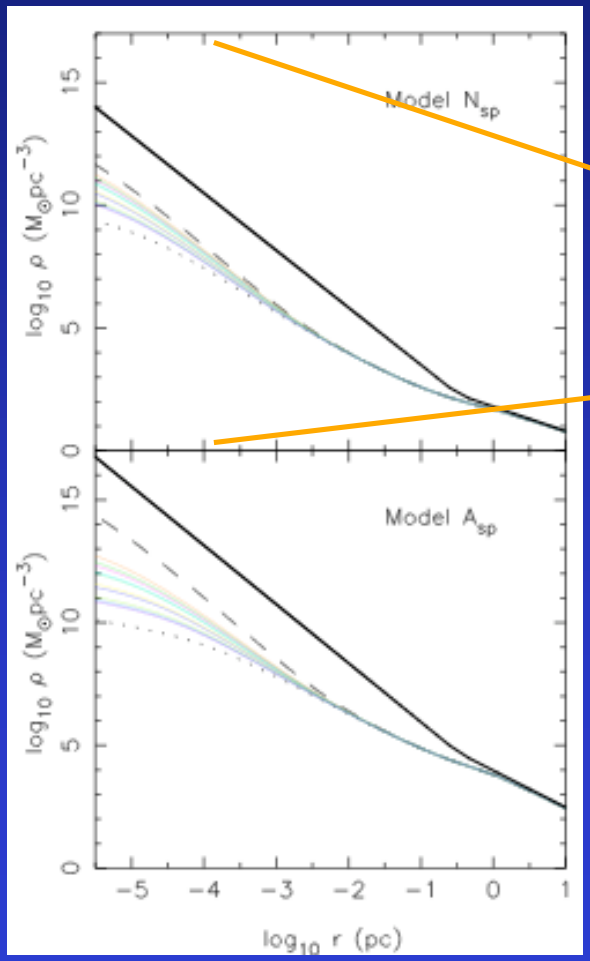
as long as environmental DM stays supecritical



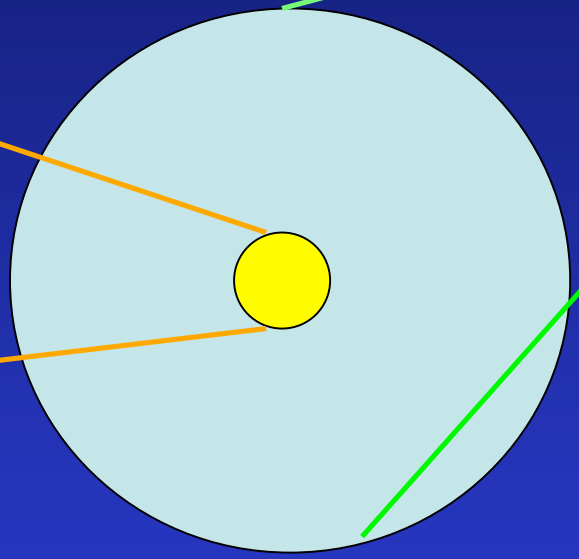
Iocco+ 08 $\sigma^{SD}_0=10^{-38}$ cm^2

Direct observation?

(surviving the ages)



Bertone & Merritt 05

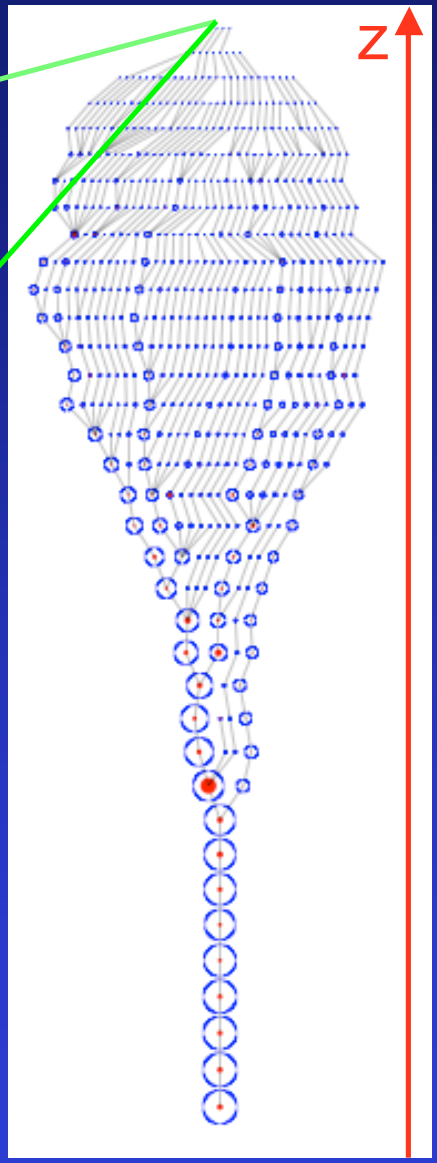


(not actual size)

Halo merger

DM cusp erosion

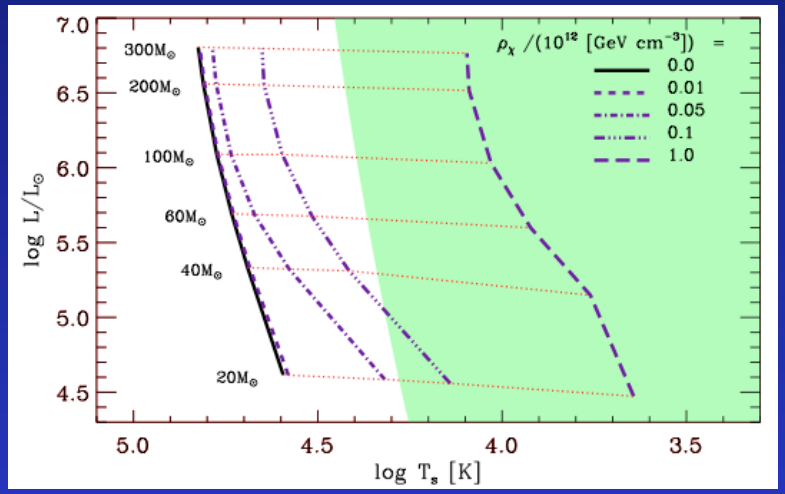
(baryons + self-annihilation)

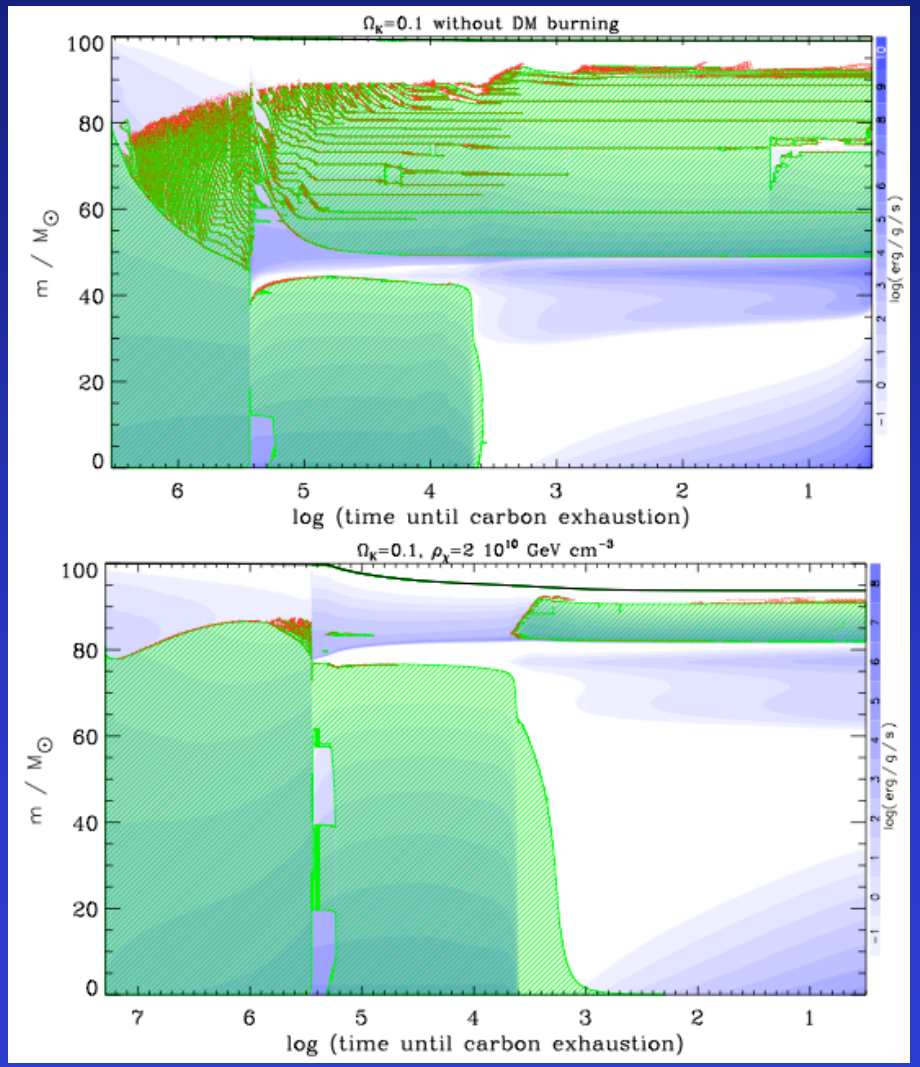


Wechsler + 02

Some more properties

(useful for indirect detection)





ionizing photons!

(tricky: increase or decrease depending on DM density)

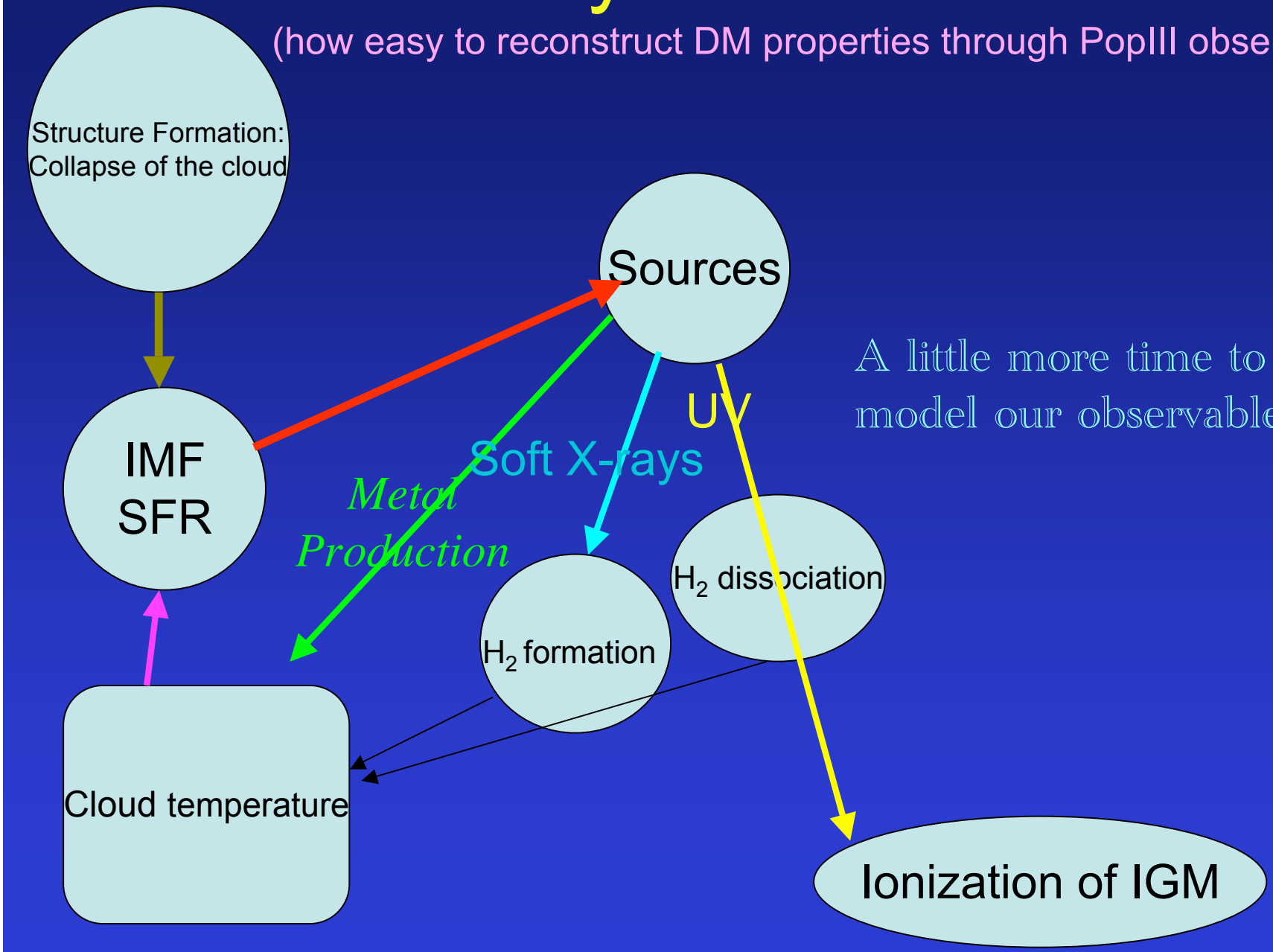
Chemistry

(yeah: analize that!)

Yoon, Iocco & Akiyama 08

The Physics of Reionization

(how easy to reconstruct DM properties through PopIII observations)



A little more time to model our observables…

Concluding:

In the early Universe…

TWO phases of DM annihilation in stars

AC stalling phase (Dark Star) is transient,
details yet to be understood

DM burning prologes stellar lifetimes
(up to freezing them)

No direct chemical signatures by DM burning

Which effects on local feedback and Reionization?

Dark Stars?

(praising against)

Short lived, lots of chemicals. DM PopIII live forever, only H and He