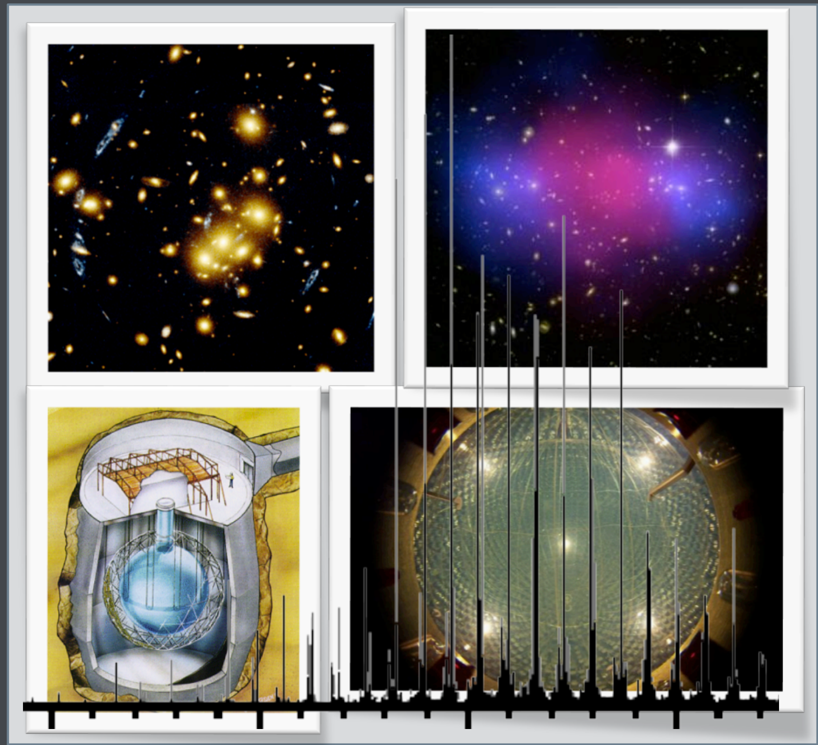
DARK MATTER IN THE SUN AND STARS

Ilídio Lopes

16 June 2010

Conference in Honor of

Professor Douglas Gough

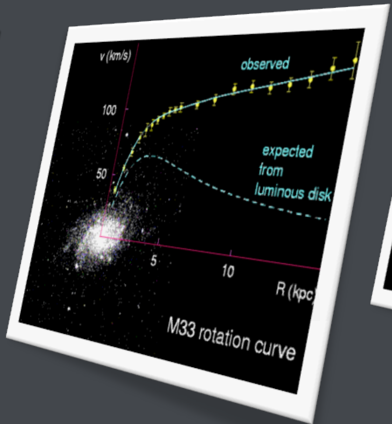


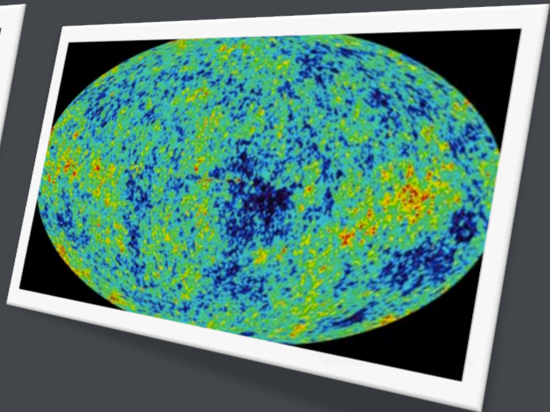
1. Present Status of DM Problem

1.1 Evidence of DM from cosmology

OBSERVATIONS: THE EVIDENCE OF DARK MATTER IN THE UNIVERSE

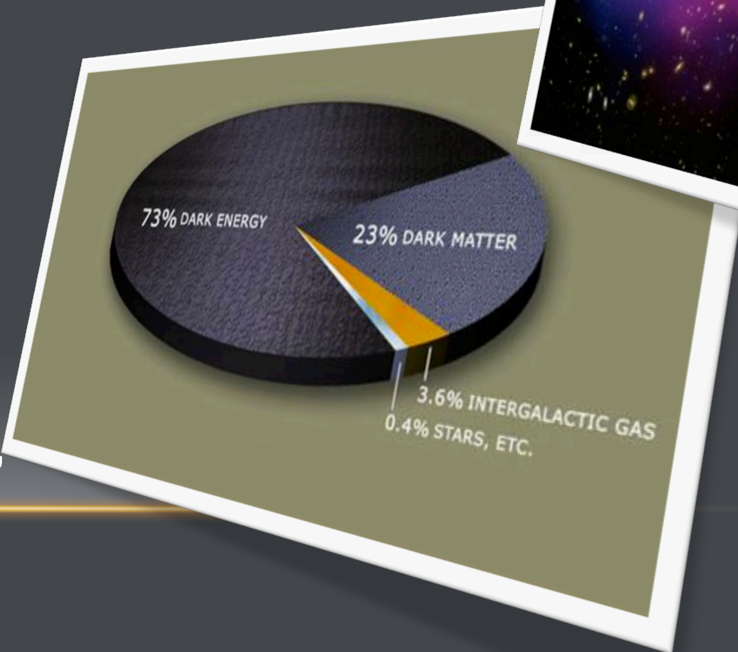
OBSERVATIONS





Since 1934, the problem of the missing mass (Fritz Zwicky):

- Velocities of galaxies in clusters
- Rotation curves of galaxies
- Gravitational lensing, such as Bullet
- Hot gas in clusters
- Others: CMB anisotropies, Oort discrepancy, velocity dispersions of dwarf spheroidal galaxies, ...



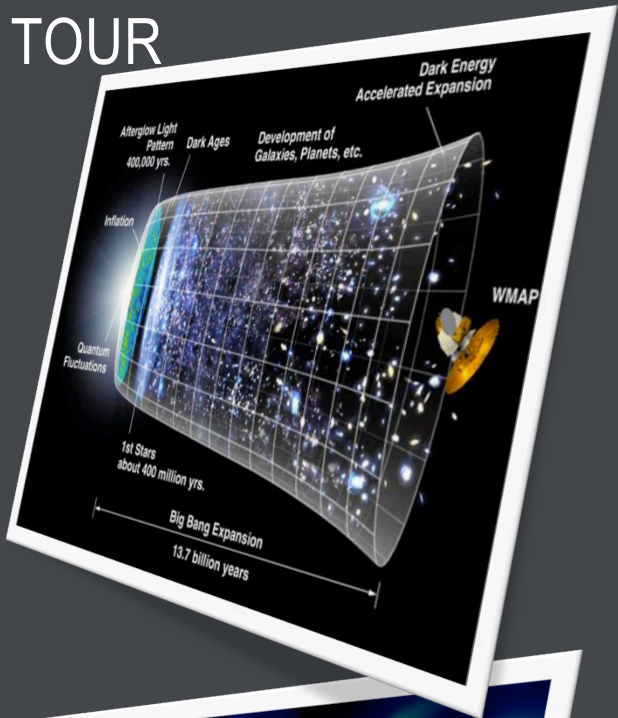
THEORY: COSMIC EVOLUTION - THE QUICK TOUR

THEORY

- The universe starts in a hot big bang and expands and cools steadily.
- Inflation makes the density distribution very (*but not perfectly*) smooth
- The first stars in the universe began forming around 400 million years after the big bang:

❑ they were exceptionally massive and bright, bringing an end to the cosmic "dark ages"

❑ the start of the evolution sequence formed galaxies, clusters and superclusters



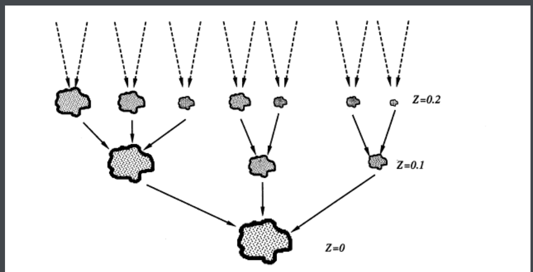
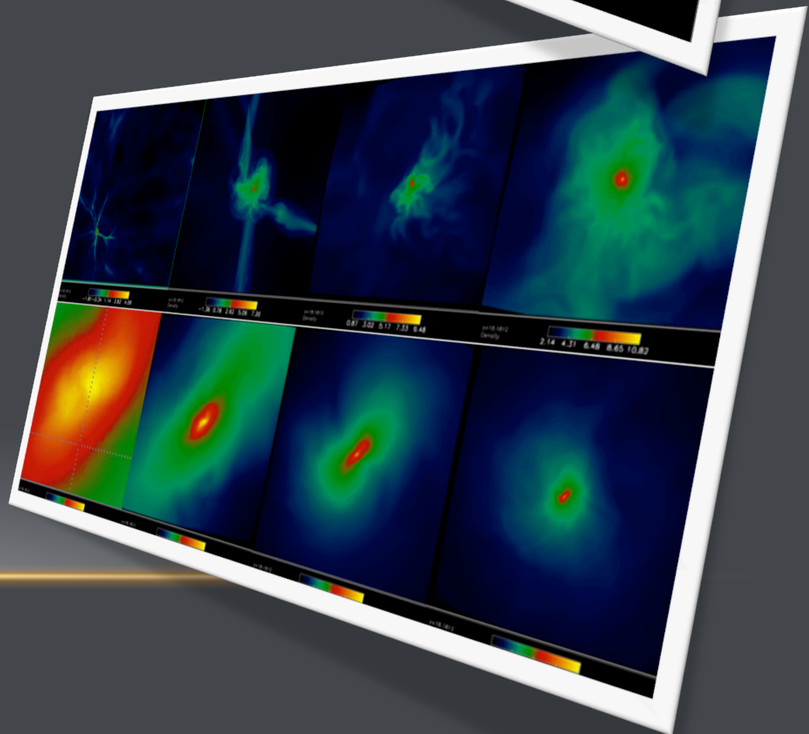


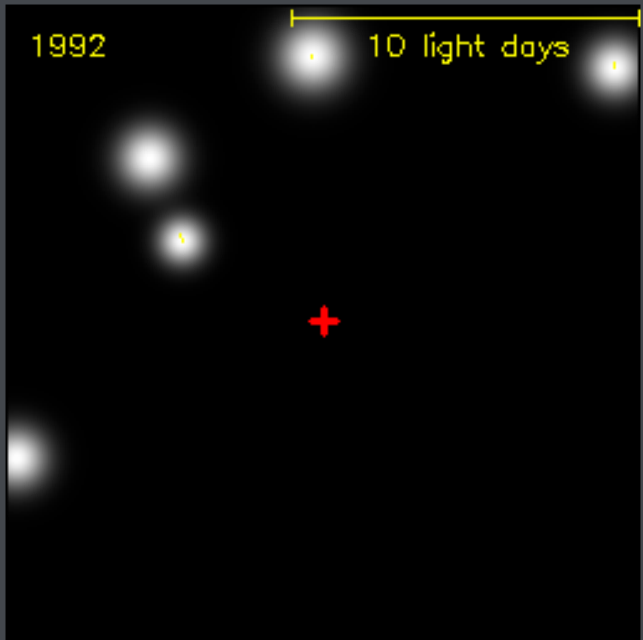
Figure 1. A schematic representation of a halo merging history 'tree'.

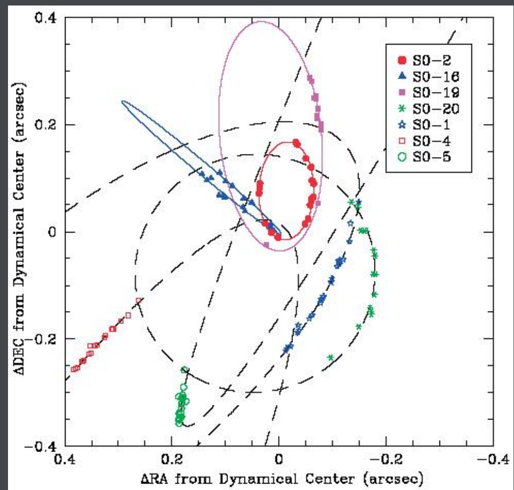
The smallest objects collapse first, bigger objects form by the merger of smaller ones

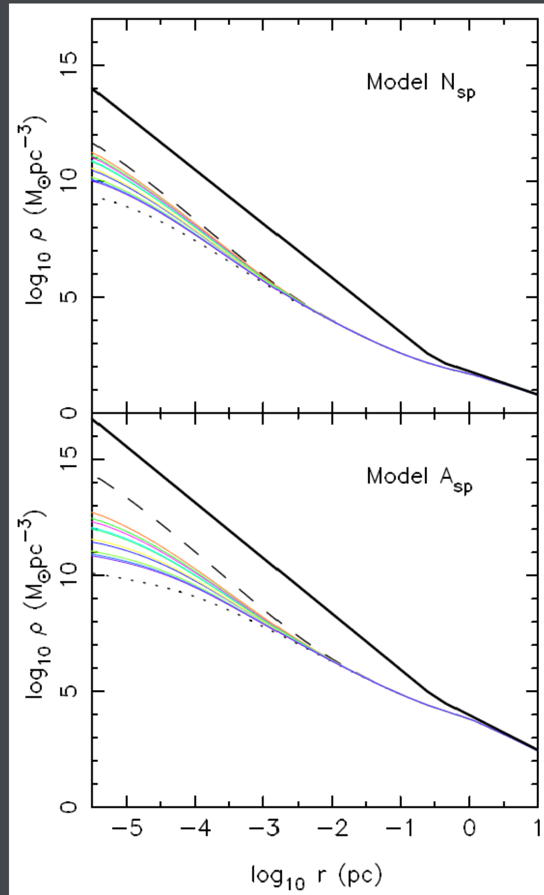


The growth of galaxies by mergers is driven by the gravity of the dark matter (non baryonic) – the baryonic matter (stars, gas) occupy a small region in the center of a much larger dark matter "halo"

STELLAR FORMATION IN THE GALACTIC CENTER
GHEZ ET AL. 2005







Ullio et al. 2001,
Bertone & Merritt 2005]

1.2 Evidence of DM from particle physics

DARK MATTER PARTICLES

WIMPs (Weakly Interacting Massive Particles)

Model of Particle Physics: SUSY

$$\langle \sigma v \rangle_{ann} \longrightarrow \Omega_\chi h^2$$

In particular, the neutralino:
(the Lightest Supersymmetric Particle in the MSSM)

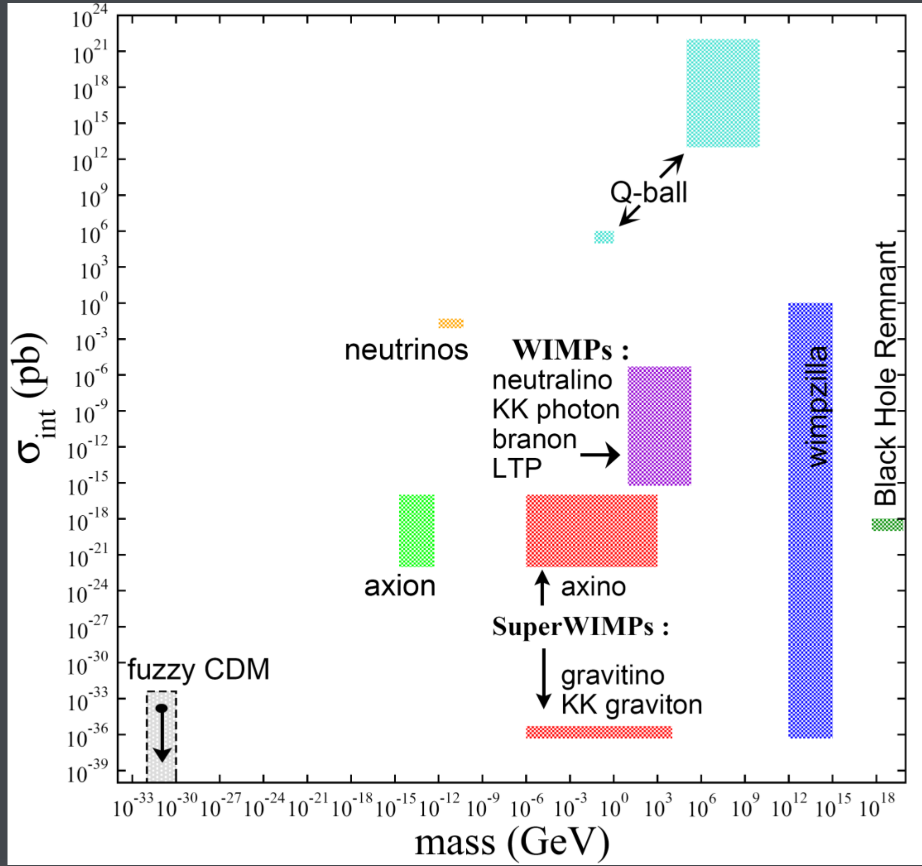
$$\chi$$

Dark Matter Particles (Search):

Direct detection: Scattering of DM particles with nucleons on a detector (e.g. ZEPLIN and CDMS)

Indirect detection of DM annihilation products: Scattering of DM particles with nucleons on a detector (e.g. PAMELA)

Candidates of Dark Matter particles:



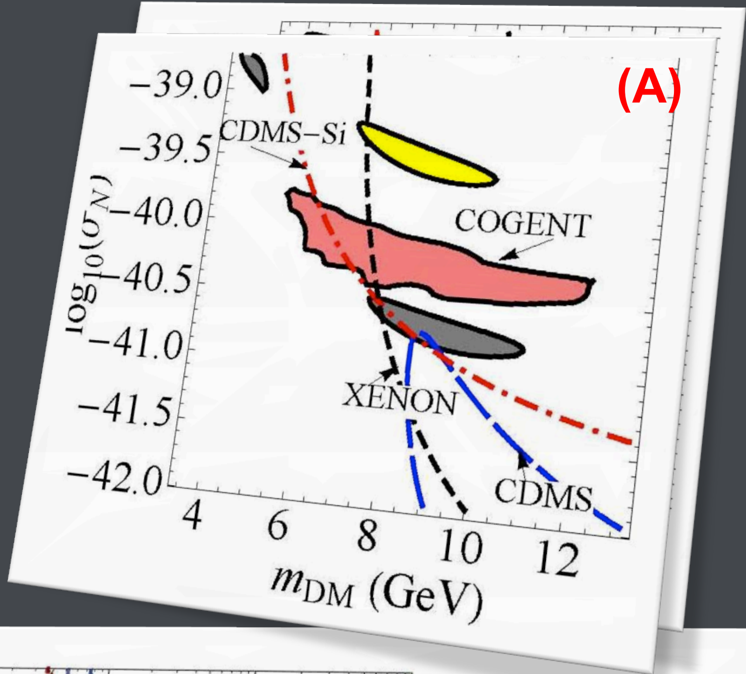
Others: neutrinos, non-luminous baryonic matter, axions, +SUSY candidates (sneutrinos, gravitinos, axinos), Kaluza Klein excitations of SM particles on extra dimensions, Wimpzillas

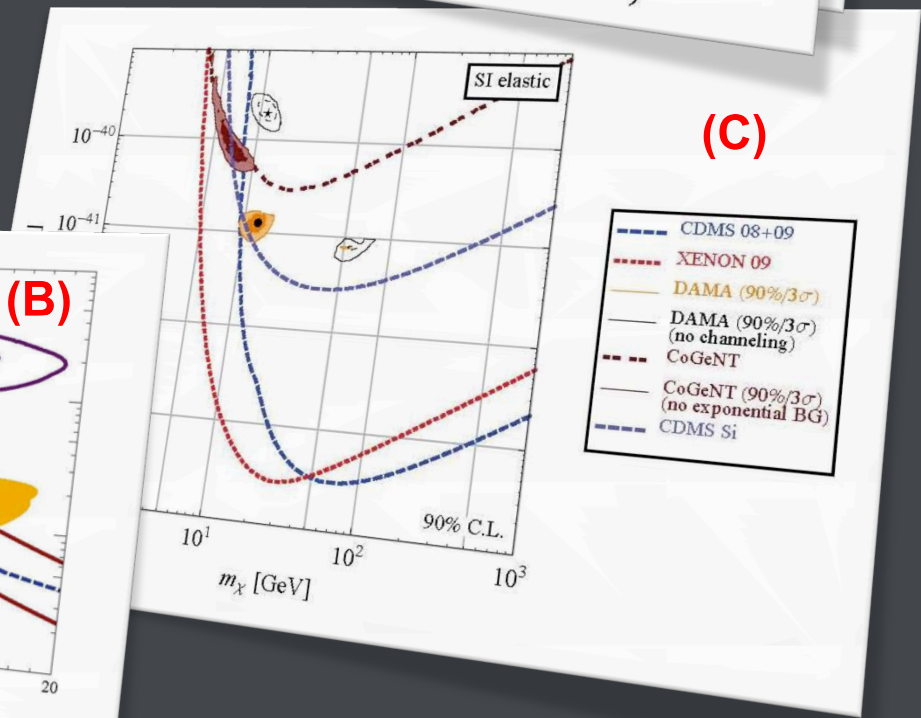

DARK MATTER SEARCH
LHC
CERN
HESS
SuperKAMIOKANDE
FERMI-
GLAST
PAMEL
XENON

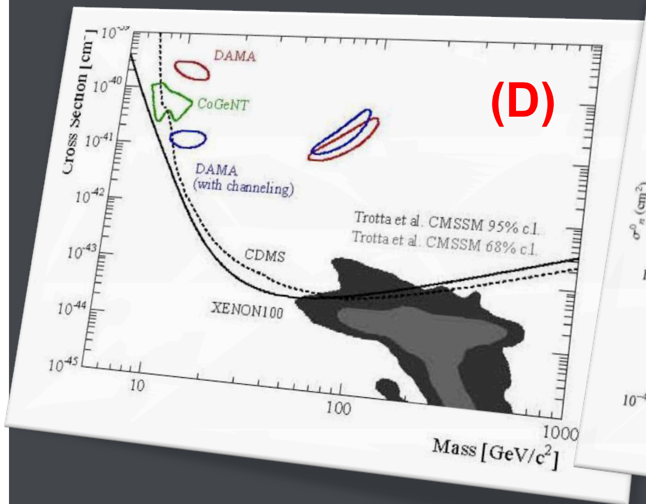
DARK MATTER SEARCH

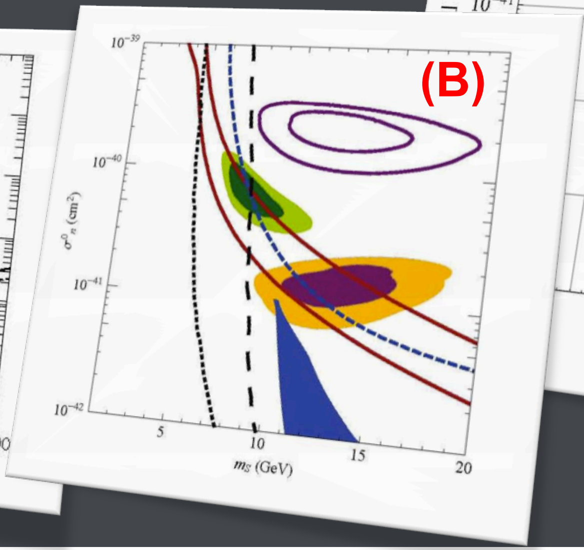
New model of particle physics
(Light DM particles):

- ❑ Implications of CoGeNT and DAMA for Light WIMP Dark Matter [hep-ph/1003.0014] **(A)**
- ❑ A light scalar WIMP through the Higgs portal and CoGeNT [hep-ph/1003.2595]. **(B)**
- ❑ Global interpretation of direct Dark Matter searches after CDMS-II results [hep-ph/0912.4264] **(C)**
- ❑First Dark Matter Results from the XENON100 Experiment [astro-ph.Co/1005.0580] **(D)**









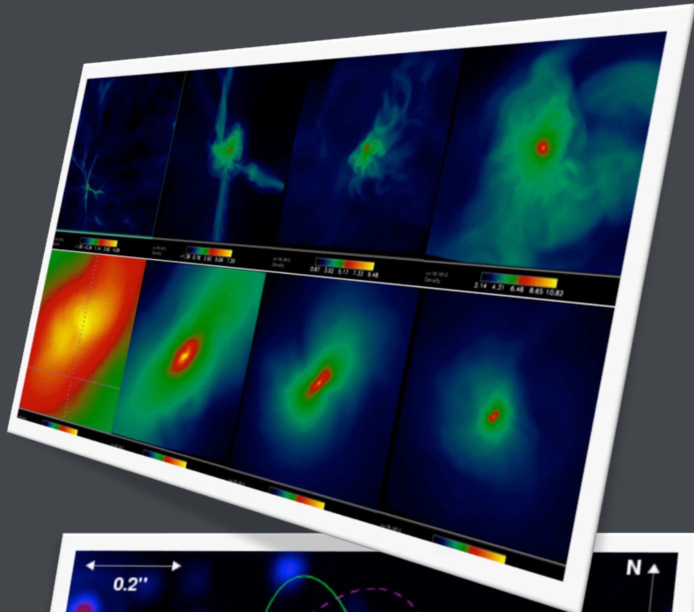
2. Goal of DM research in stars

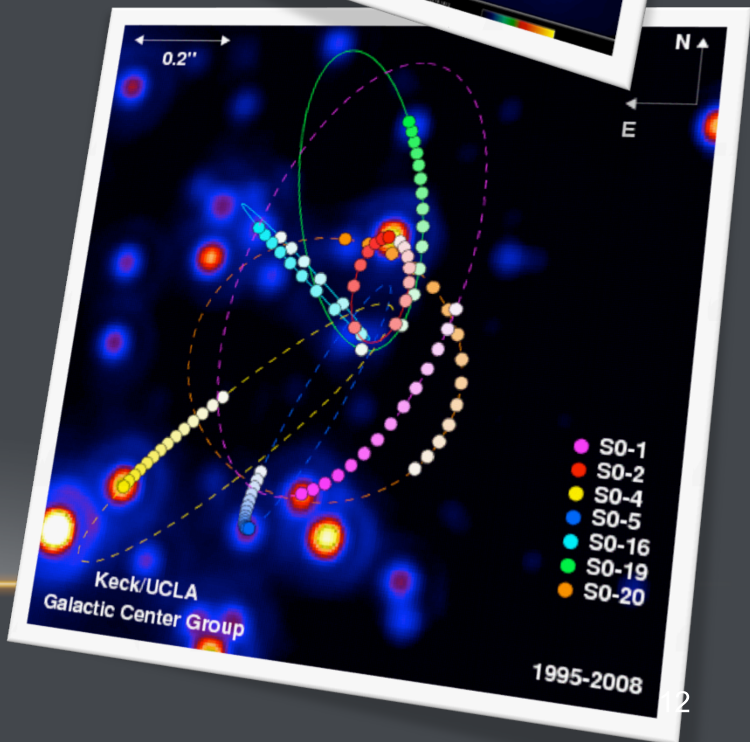
THE IMPACT OF DARK MATTER PARTICLES IN THE EVOLUTION OF THE SUN AND STARS:

A proposal with two goals:

❑ To test dark matter particle physics candidates, as suggested by particle physics theories (SUSY)

❑To explore the possibility that dark matter affected the evolution of stars in the primordial Universe (population III stars) and also in the present universe.





4. The Capture of DM particles by stars

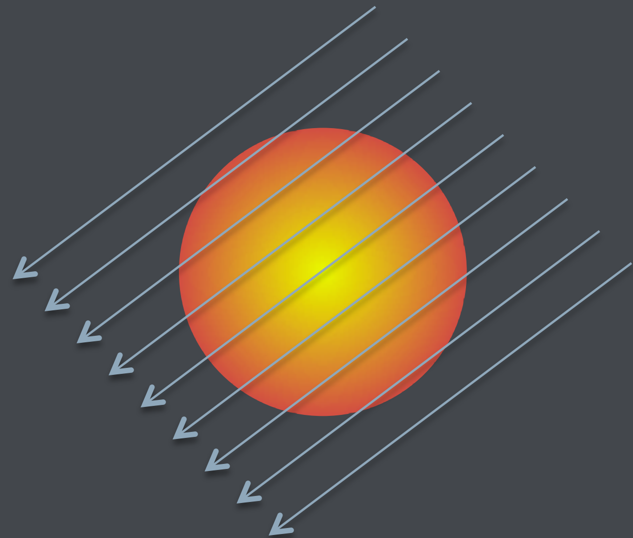
Capture of DM Particles

Calculate the number of DM particles that lose enough energy to become gravitationally bound.

[First Calculations (Cosmions): Solution to the Solar neutrino Problem, Press & Spergel 1985, Several papers 80' and 90', Douglas and others]

Wimps lose enough energy...

DM particles get gravitationally **captured** inside the star



…scattering with Hydrogen and other nucleons

Capture and annihilation of DM

$$C_\chi(t) = \sum_i \left(\frac{8}{3\pi}\right)^{1/2} \sigma_i \frac{\rho_\chi}{m_\chi} \bar{v}_\chi \frac{x_i M_\star}{A_i m_p} \frac{3v_{esc}^2}{2\bar{v}_\chi^2} \zeta$$

Casanellas & Lopes (2009),
Lopes, Casanelas, Eugenio (2911)
Gould (1987)

Dependence in particle physics, cosmology, stellar dynamics and stellar physics.

- Spin-independent scattering limits
  - CDMS II: $s_{SI}<10^{-44}cm^2$ $(^{x}A^{4})$
- Spin-dependent scattering limits
  - SuperK: $s_{SD}<10^{-38}cm^2$
- Annihilation cross-section estimate
  - $<\sigma v>\sim 3x10^{-26}cm^3s^{-1}$

Capture and annihilation of DM

Number and distribution of DM particles inside the star:

$$\frac{dN_\chi}{dt} = C_\chi - 2\Gamma_\chi$$

$$\dot{N}_\chi = 0$$

Equilibrium between Annihilating particles and Capture particles

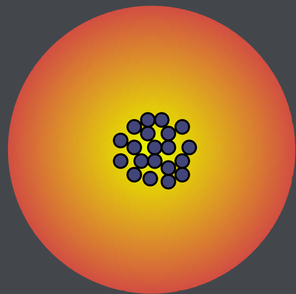
DMP's are thermalize over a time scale of

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

DMP's concentrated in the core (Gaussian distribution)

$$n_\chi(r) = \frac{N_\chi}{\pi^{3/2} r_\chi^3} e^{-r^2/r_\chi^2}$$

Characteristic radius of the DMP core



$$r_\chi \sim 0.05\ \mathrm{R}_\star$$

Core ~5 10^9cm ~ 0.05 R_{sun}

$$r_\chi = \sqrt{\frac{3\kappa T_c}{2\pi G \rho_c m_\chi}}$$

DM Particles Change Stellar Structure

The accretion of dark matter particles inside the Sun and Stars can change their evolution:

(i) By becoming an extra source of energy in the core of the Star.

$$\varepsilon_\chi(r) = f_\chi \, m_\chi \, n_\chi^2(r) \, \rho(r)^{-1} < \sigma_a v >$$

(ii) By changing the energy transport inside the Star

$$l_{\rm sp}(r) = \left[\frac{\rho(r)}{m_u}\sum \sigma_i \frac{X_i(r)}{A_i}\right]^{-1}.$$

Free mean path of DM particle

$$L_{\rm sp}(r) = -4\pi r^2 n(r)\sqrt{\frac{T(r)}{m_{\rm x}}} l_{\rm sp}(r)\nabla T(r),$$

$$L_{\rm lp}(r) = 32\sqrt{2\pi}\frac{\sigma_{\rm p}\mu_{\rm p}}{m_{\rm x}+m_{\rm p}}\int_0^r n_{\rm p}(r)\bar{T}(r)n_{\rm x}(r)r^2\,{\rm d}r,$$

Knudsen Number $K=l_x/r_x$

$K < 1$ local transport of energy (conduction regime)

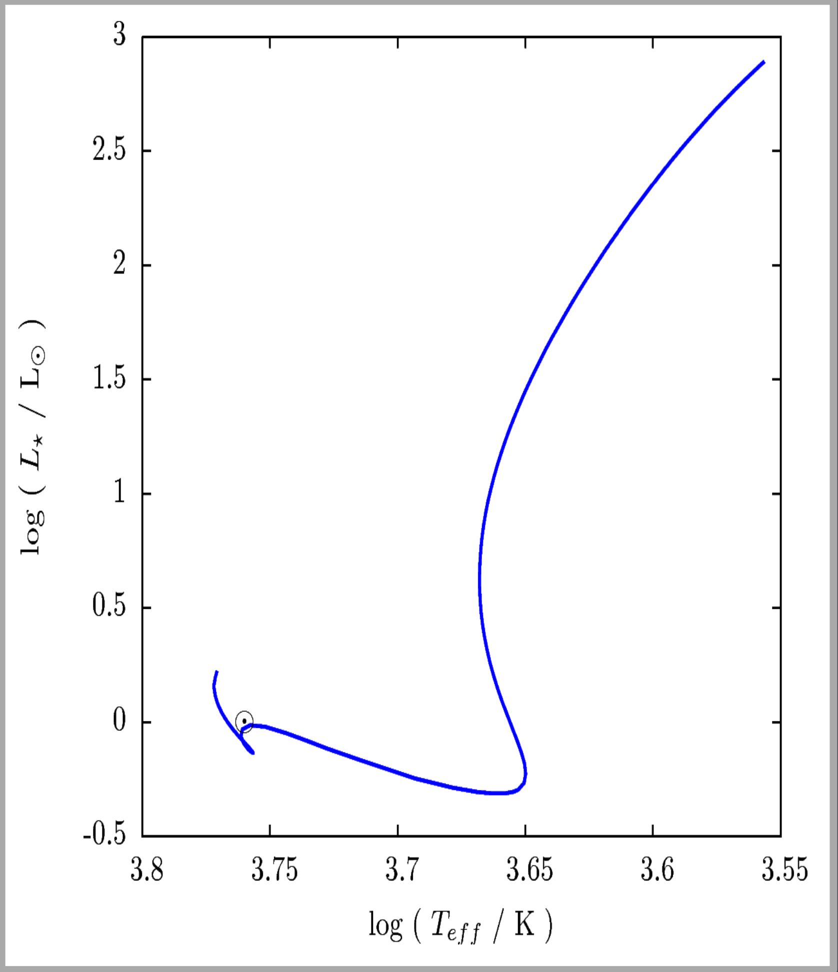
$K > 1$ no local transport of energy (Knudsen regime)

5. Evolution of low-mass stars within dense dark matter halos (energy production)

EVOLUTION OF STARS WITHIN DARK MATTER HALOS

- Stellar evolution: gravitational contraction
- + the evolution through the Main Sequence

$0.7\ \mathrm{M}_\odot < M_\star < 3\ \mathrm{M}_\odot$
$Z_0 = 0.014$
$v_\star = 220\ \mathrm{km\ s}^{-1}$



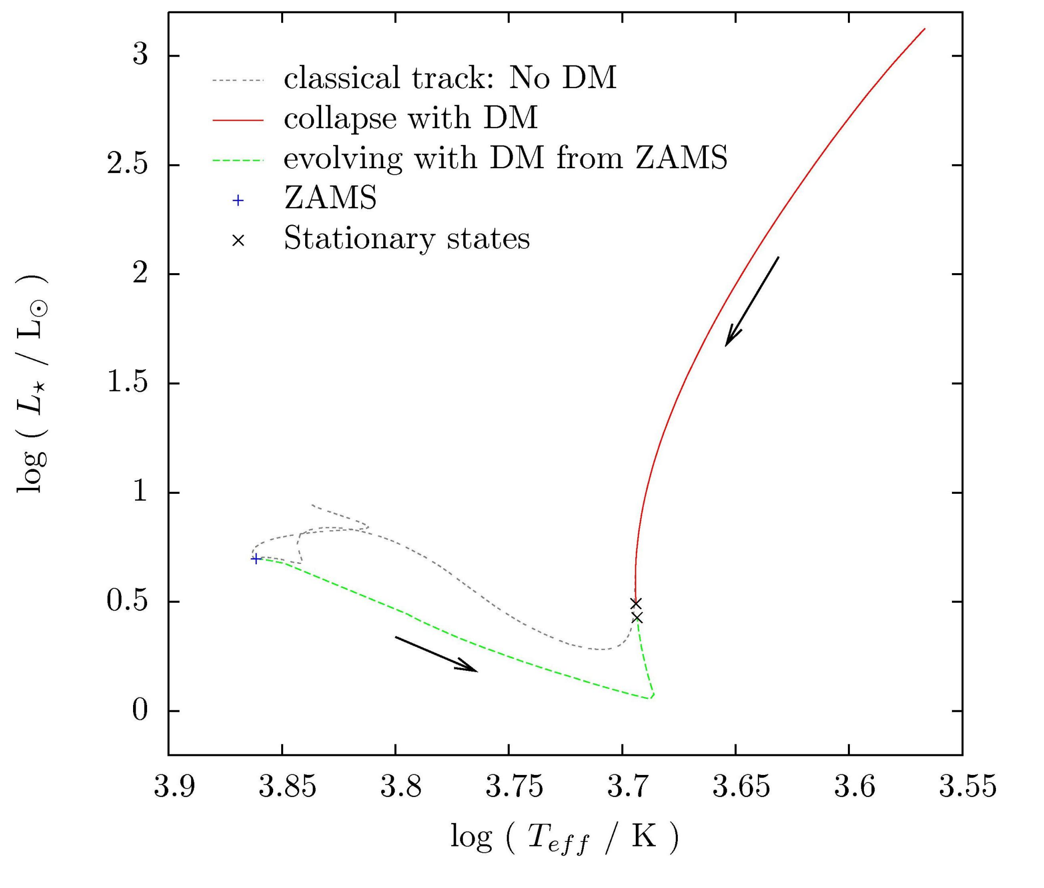
EVOLUTION OF STARS WITHIN DARK MATTER HALOS

- Compare classical stellar evolution with stellar evolution within Dark Matter halos
- Star with 1.5 Solar mass.
- We considered DM halos with:

$$0.3\ \text{GeV cm}^{-3} < \rho_\chi < 10^{12}\ \text{GeV cm}^{-3}$$
$$\bar{v_\chi} = 270\ \text{km}\ s^{-1}$$

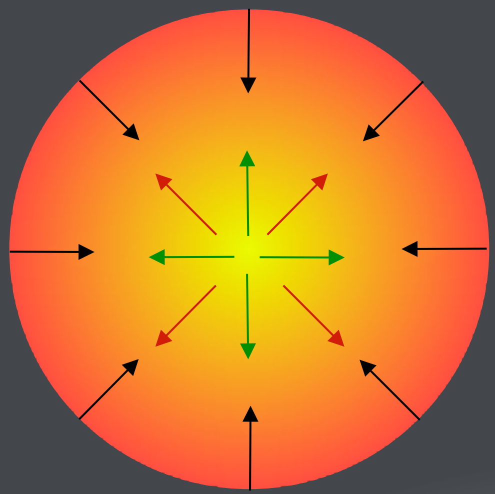
Our canonical DM particle is a WIMP, such as the neutralino, with:

$$m_\chi = 100\ \text{GeV}$$
$$\sigma_{\chi,SD} = 10^{-38}\text{cm}^2$$
$$\sigma_{\chi,SI} = 10^{-44}\text{cm}^2$$
$$< \sigma_a v >= 3 \cdot 10^{-26}\ \text{cm}^2\ \text{s}^{-1}$$



EVOLUTION OF STARS WITHIN DARK MATTER HALOS

- Within a dark matter halo ("low" DM densities) : Gravitational collapse balanced by the thermonuclear energy and energy from WIMP annihilation



$\rho_\chi = 5 \cdot 10^8$ GeV cm^{-3}

$M_\star$	ε_χ	ε_{pp+CNO}
1 $M_\odot$	70%	30%

$T_c = 12.8$ MK

DM Star

$M_\star$	ε_{pp}	ε_{CNO}
1 $M_\odot$	98%	2%

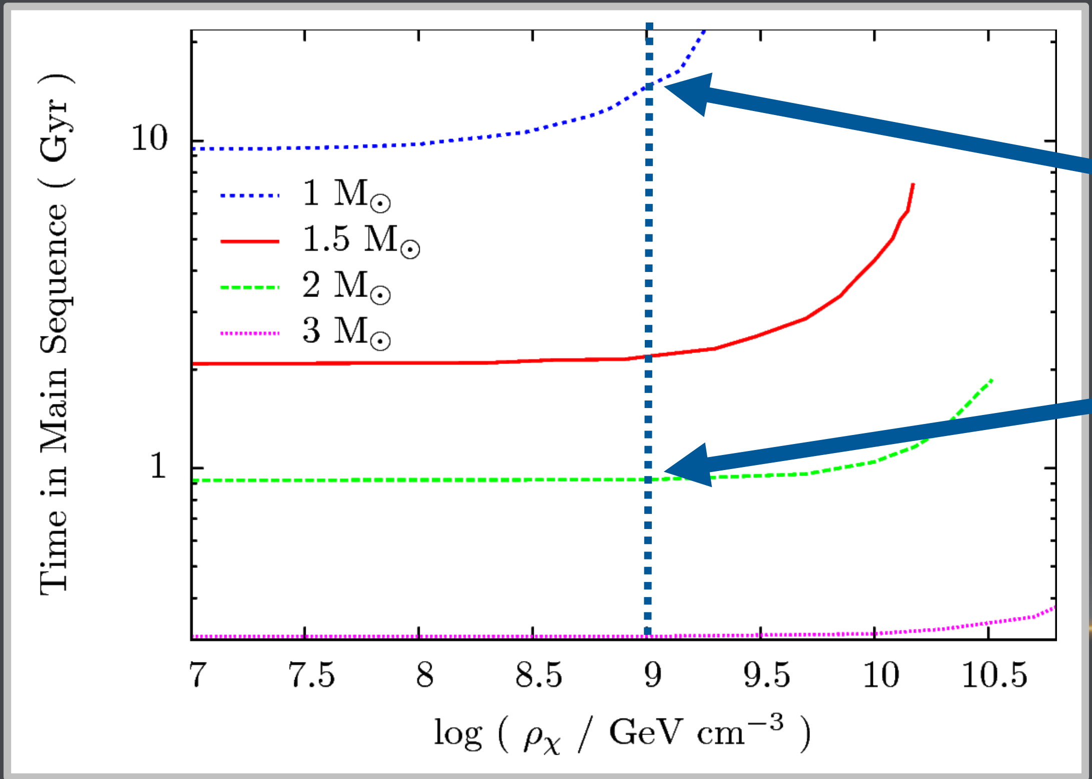
$T_c = 13.4$ MK

Classical Star

$\left(\begin{matrix}\text{when} \\ \varepsilon_{grav} < 1\%\ \varepsilon_t\end{matrix}\right)$

EVOLUTION OF STARS WITHIN DARK MATTER HALOS

- Stars evolving in halos with low DM densities:
  - - Equilibrium after collapse is reached at lower central temperatures
  - - Hydrogen is burned at a lower rate
- Time expended in Main Sequence is enlarged



A star of 1 $M_\odot$ will spend 60% more time in the MS than what expected in the classical scenario if it evolves in a halo of:

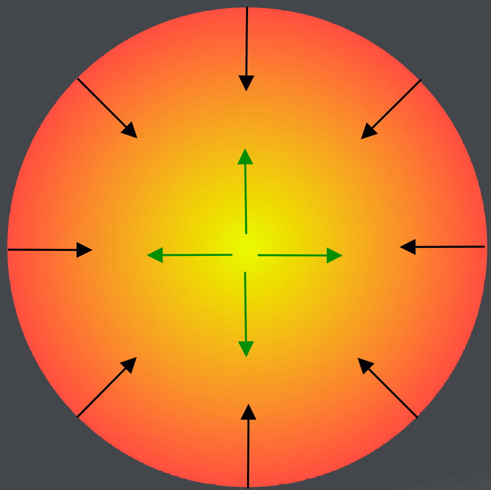
$$\rho_\chi = 10^9 \text{ GeV cm}^{-3}$$

In the same DM halo, a star of 2$M_\odot$ is not affected

This evolution scenario is qualitatively similar to that predicted by Taoso et al. (2008) for Pop. III stars

EVOLUTION OF STARS
WITHIN DARK MATTER HALOS

- Stars evolving in halos with high DM densities:
  - The gravitational collapse is balanced by the energy from WIMP annihilation
  - The star never reaches enough central temperatures to trigger hydrogen burning
  - The star is fuelled only by the DM annihilation energy



In a star of 1 $M_\odot$

$$\rho_\chi \geq 5 \cdot 10^9 \text{ GeV cm}^{-3}$$

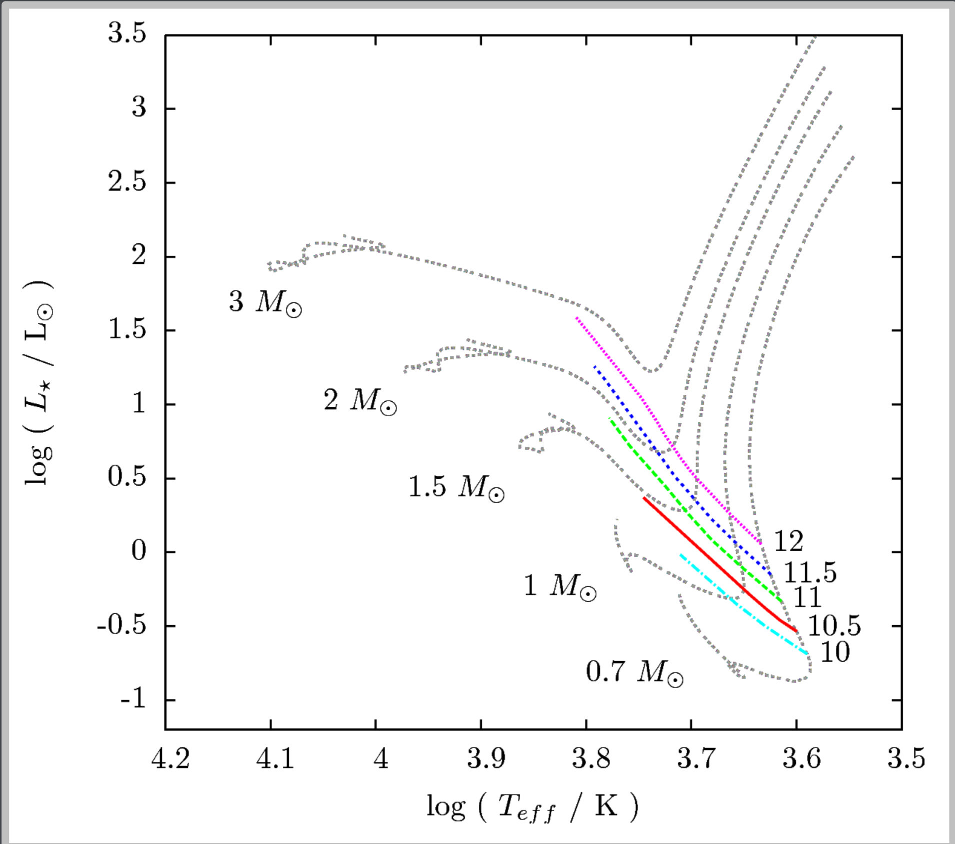
$$\varepsilon_\chi = 100\%$$

$$T_c \leq 8.0 \text{ MK}$$

This scenario is similar to that predicted by Moskalenko & Wai (2007) for white dwarfs evolving in DM halos, and by Spolyar et al. (2008) in the case of first stars that form in the center of adiabatically contracted DM halos (without DM capture).

EVOLUTION OF STARS WITHIN DARK MATTER HALOS

- Stars evolving in halos with high DM densities:
  - Given that the DM ”fuel” is constantly replenished by DM capture, the star will remain indefinitely in the same equilibrium state.



A star of $1\mathrm{M}_\odot$ evolving within a DM halo with:

$$\rho_\chi = 10^{11}\ \mathrm{GeV\ cm^{-3}}$$

will soon stop its collapse with:

$$R_\star \simeq 1.5\ \mathrm{R}_\odot$$
$$T_{eff} \simeq 4500\ \mathrm{K}$$
$$L_\star \simeq 1.3\ \mathrm{L}_\odot$$

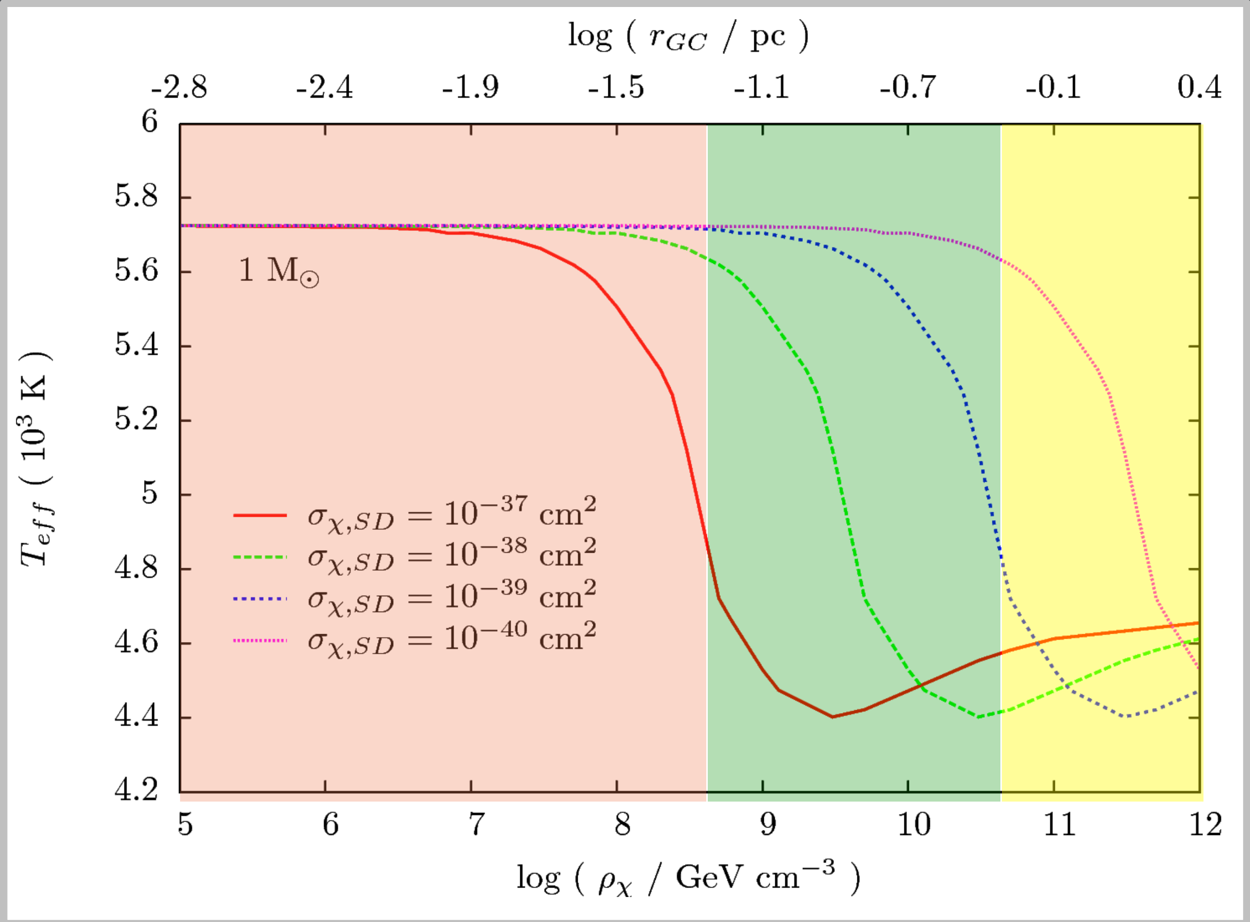
More massive stars need higher DM Densities to stop their collapse

Iocco et al. (2008) studied the collapse of first stars with DM capture.
They found the same effects at lower DM densities.

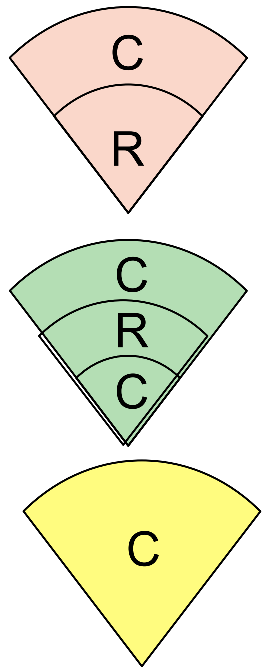
Stellar Diagnostic of Dark Matter Particles

STELLAR DIAGNOSTIC OF DARK MATTER

- Stellar evolution depend strongly on the DM density in the host halo and on the DM scattering cross sections.



Energy transport inside the star

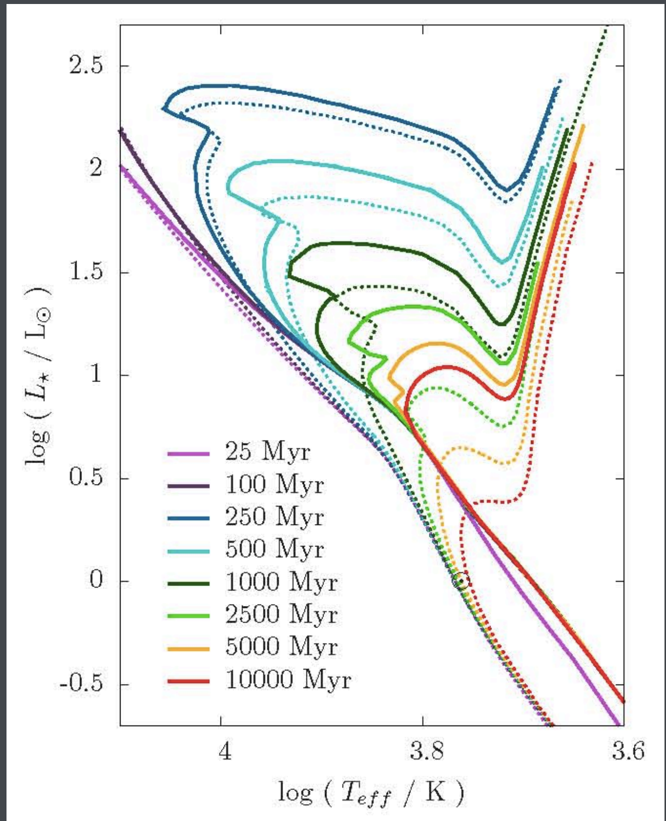


STELLAR DIAGNOSTIC OF DARK MATTER

m_χ

ρ_χ

σ_χ



The positions of the cluster stars in the H-R diagram have a brighter and hotter turn-off point than in the classical scenario without DM, therefore giving the cluster a younger appearance.

The bottom of the isochrones in the H-R diagram rises to higher luminosities, leading to a characteristic signature on the stellar cluster.

If DM halo 8GeV WIMPs (recently invoked to reconcile the results from direct detection experiments0, then this signature is predicted for halos of DM with a DM density=3·10^5 GeV cm^−3.

A stellar cluster (0 .7 M⊙ - 3.5 M⊙) within halos of DM.

Casanellas & Lopes

(ApJ 2011, MNRAS 1011)

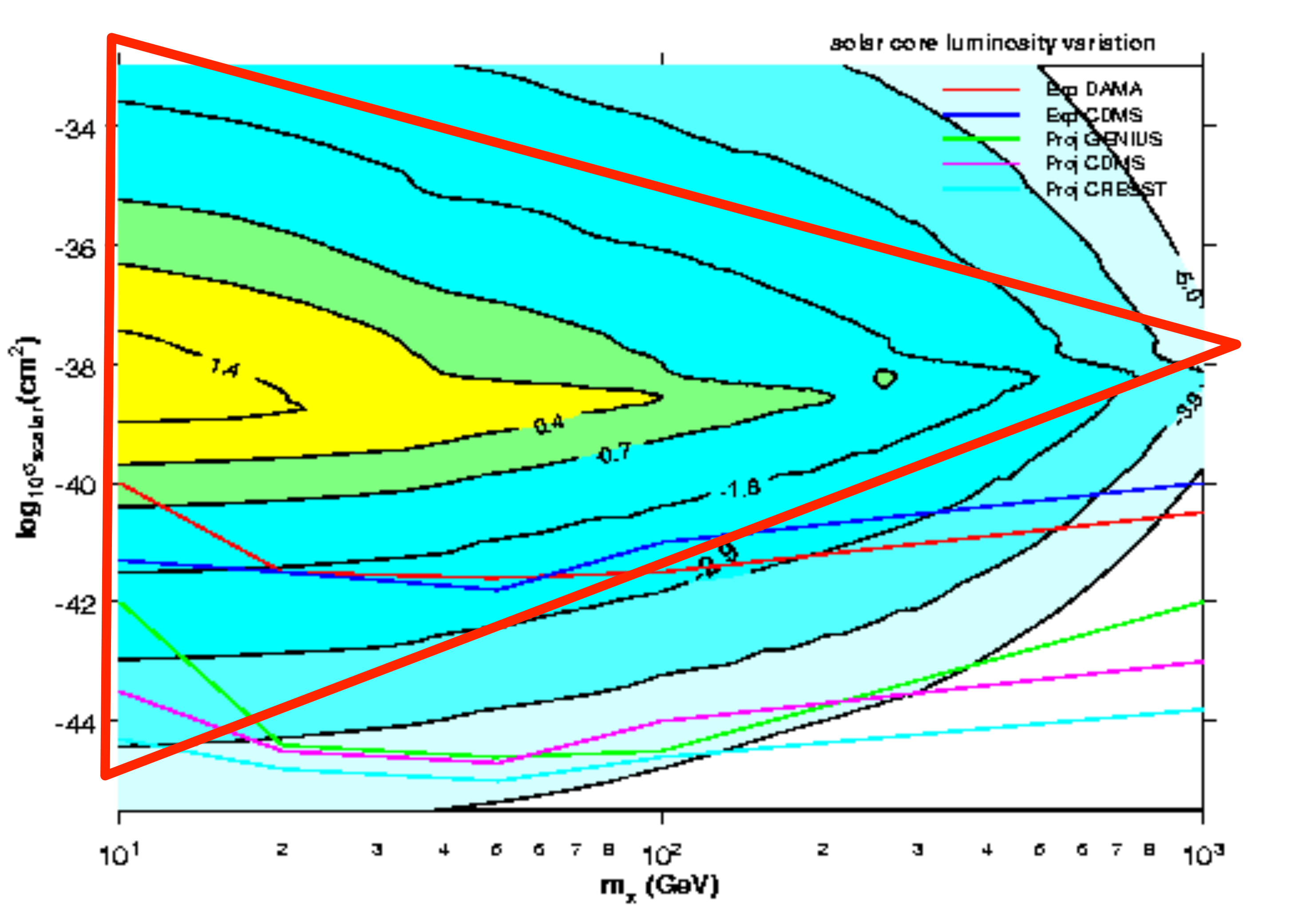
SIGNATURES OF DARK MATTER BURNING IN NUCLEAR STAR CLUSTERS

6. Evolution of low-mass stars within weak dark matter halos (energy transport)

THE SUN AND STARS AS COSMOLOGICAL TOOLS: PROBING THE ORIGIN OF DARK MATTER PARTICLES

- **Spin-independent: CDMS II: $s_{SI} < 10^{-44} cm^2$**
- **Spin-dependent: SuperK: $s_{SD} < 10^{-38} cm^2$**

Lopes, Silk & Hansen (2001)

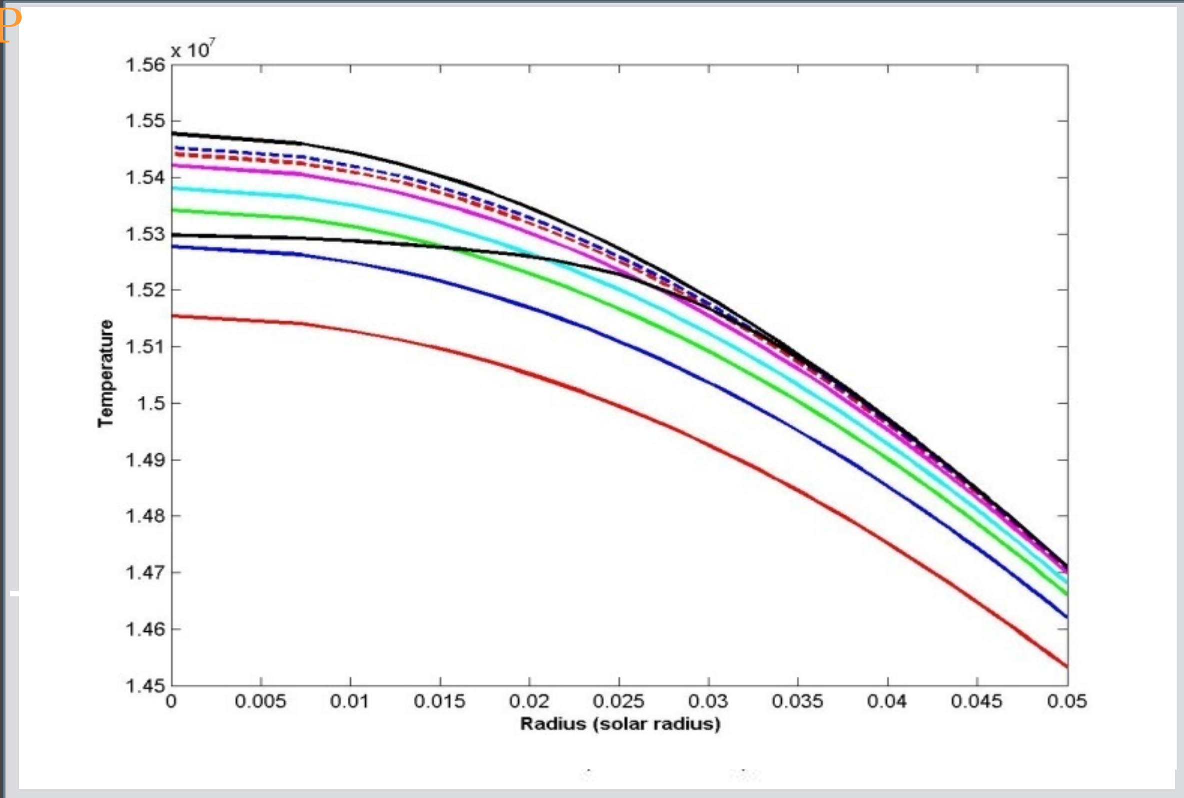


Possible DM constraints (from Sun and stars)

THE SUN AS COSMOLOGICAL TOOLS: PROBING THE ORIGIN OF DARK MATTER PARTICLES

WIMPs population in Equilibrium:
WIMP Capture balances WIMP Annihilation

- Spin-independent cross-section
- - 1.0x10^{-36} cm^2 (color curves)
- - 2.0x10^{-35} cm^2 (black curves),
- Spin-dependent cross-section
- - 10^{-40} cm^2 (negligible)
- Annihilation cross-section
- - 1.0x10^{-36} cm^3 s^{-1} (colored curves) - 1.0x10^{-50} cm^3 s^{-1} (black curves)
- [suppressed annihilation]

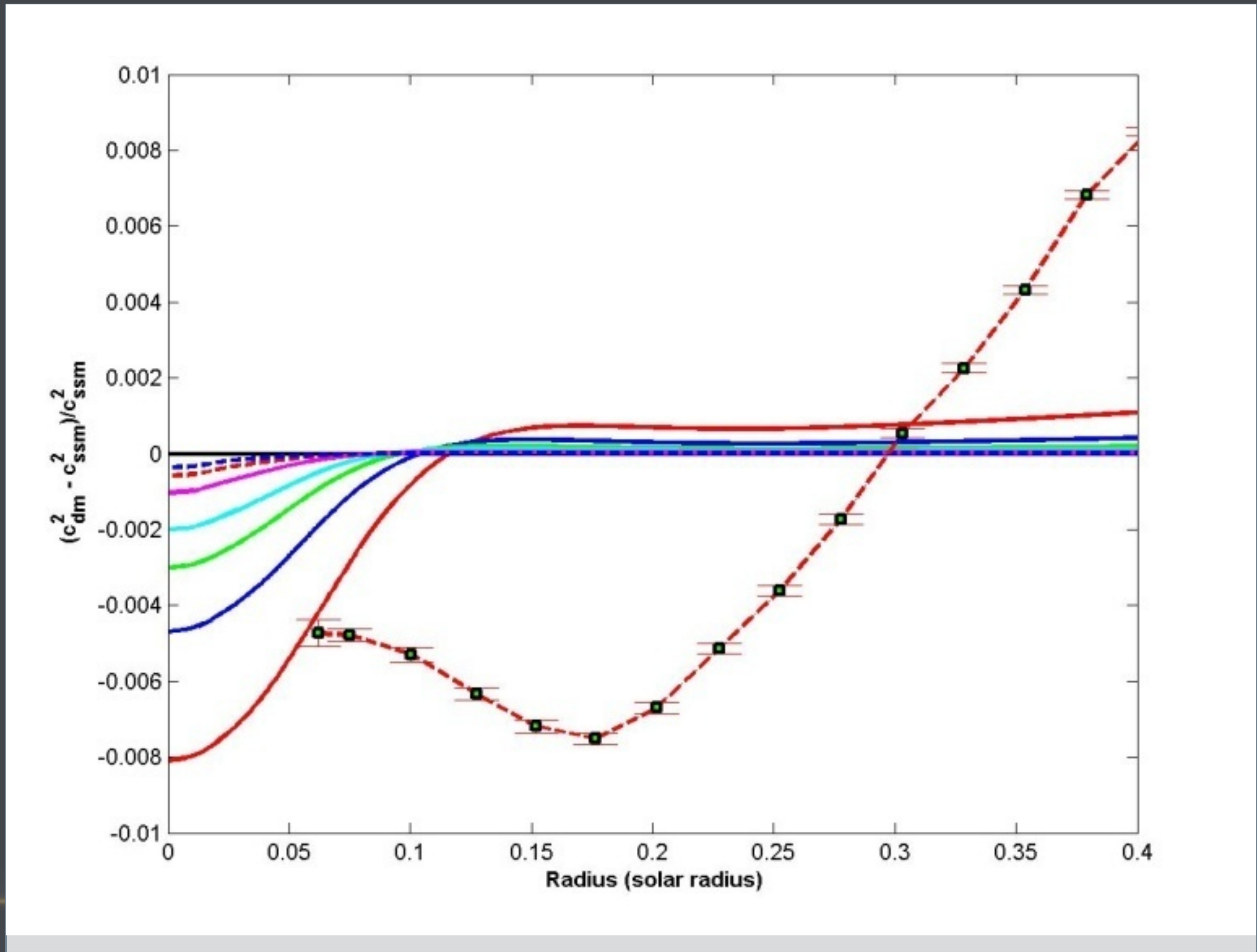


Lopes & Silk

(ApJ Let 2010)

Models with self-annihilating particles (color curves): 3 Gev (red), 4 GeV (blue), 5 GeV (green), 6 GeV (cyan), 8 GeV (magenta), 10 GeV (dotted-red) and 12 GeV (dotted-blue); (ii) non- annihilating particles (black curves, from low to higher temperature): 5 GeV, 7 GeV, 10 GeV and 50 GeV.

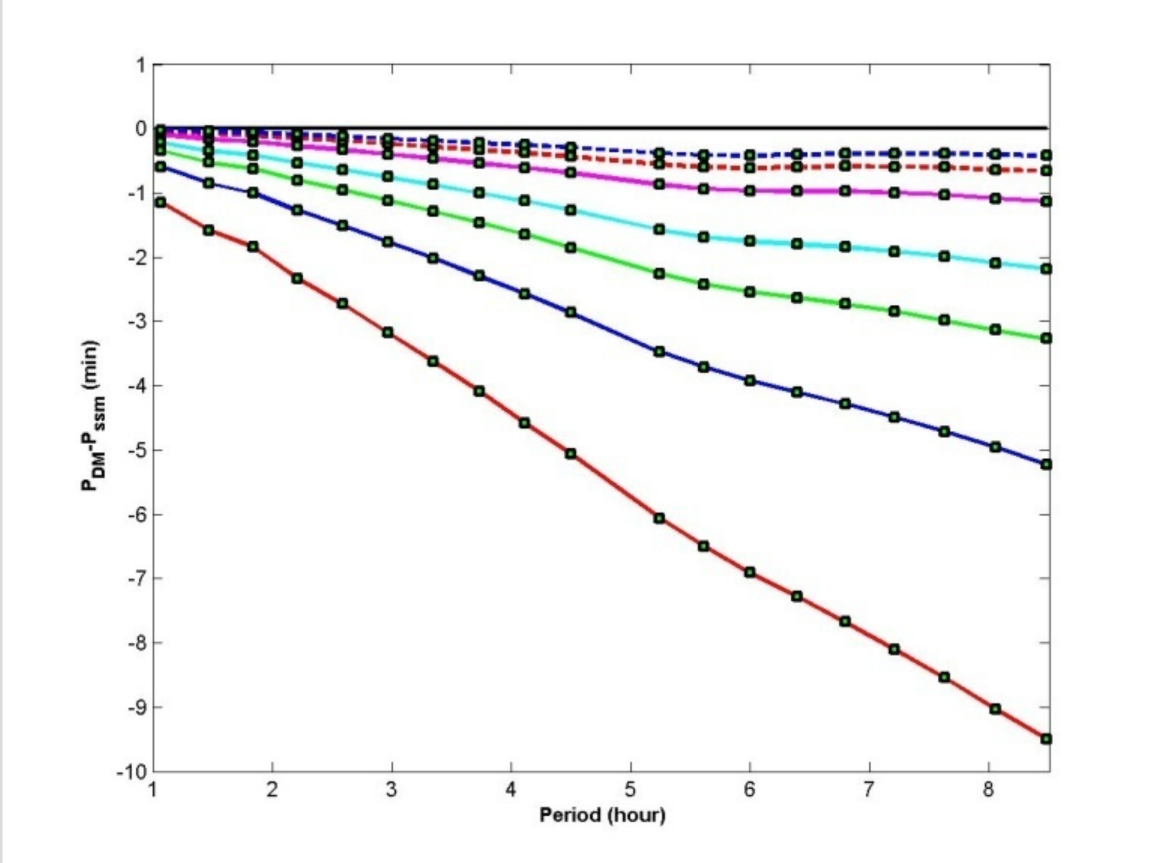
THE SUN AND STARS AS COSMOLOGICAL TOOLS: PROBING THE ORIGIN OF DARK MATTER PARTICLES



Dark Matter halos: self-annihilating particles

$\delta\nu_{ln}/\nu_{ln} = -\delta P_{ln}/P_{ln} = -\delta P_o/P_o$

THE SUN AS COSMOLOGICAL TOOLS:
PROBING THE ORIGIN OF DARK MATTER PARTICLES



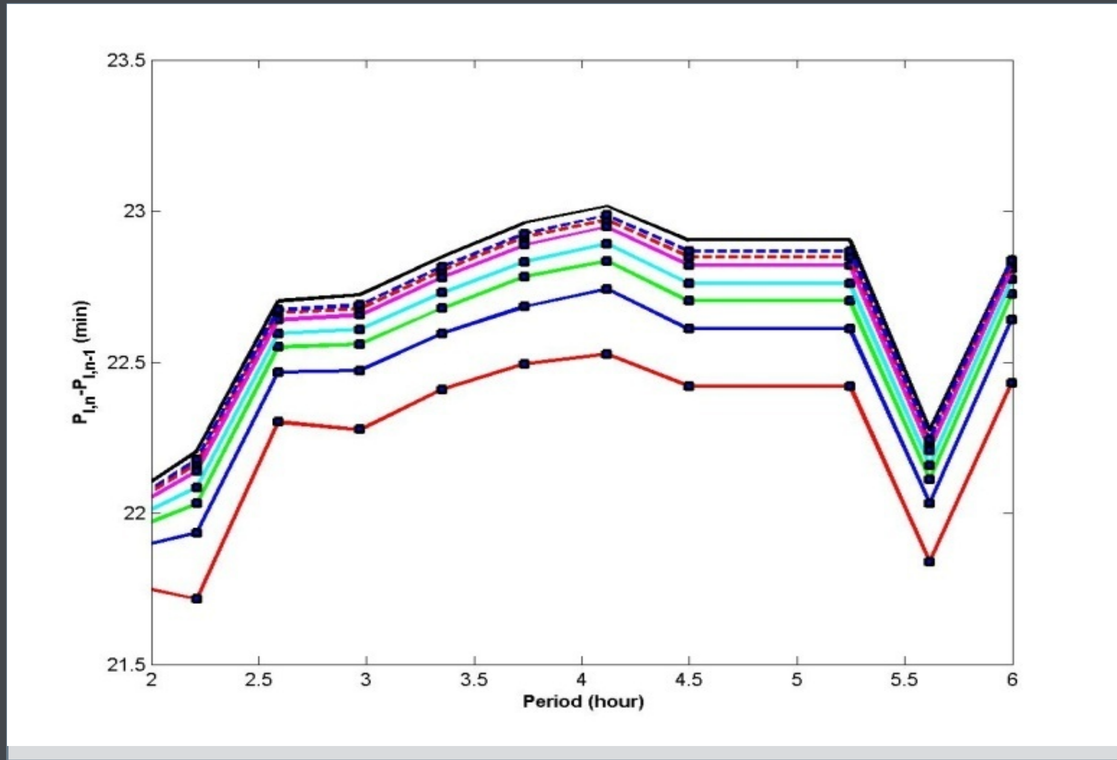
Comparison of multiplet period table between the solar standard model and models of the Sun evolving in different dark matter halos. The multiplet periods shown correspond to the dipole gravity modes. This corresponds to dark matter halos constituted by annihilating massive particles. (color curves).

THE SUN AS COSMOLOGICAL TOOLS: PROBING DARK MATTER

$$P_{l,n} = \frac{P_0}{\sqrt{l(l+1)}} \left(n + \frac{l}{2} + \phi \right) + \mathcal{O}\left(\frac{1}{P_{l,n}} \right),$$

with

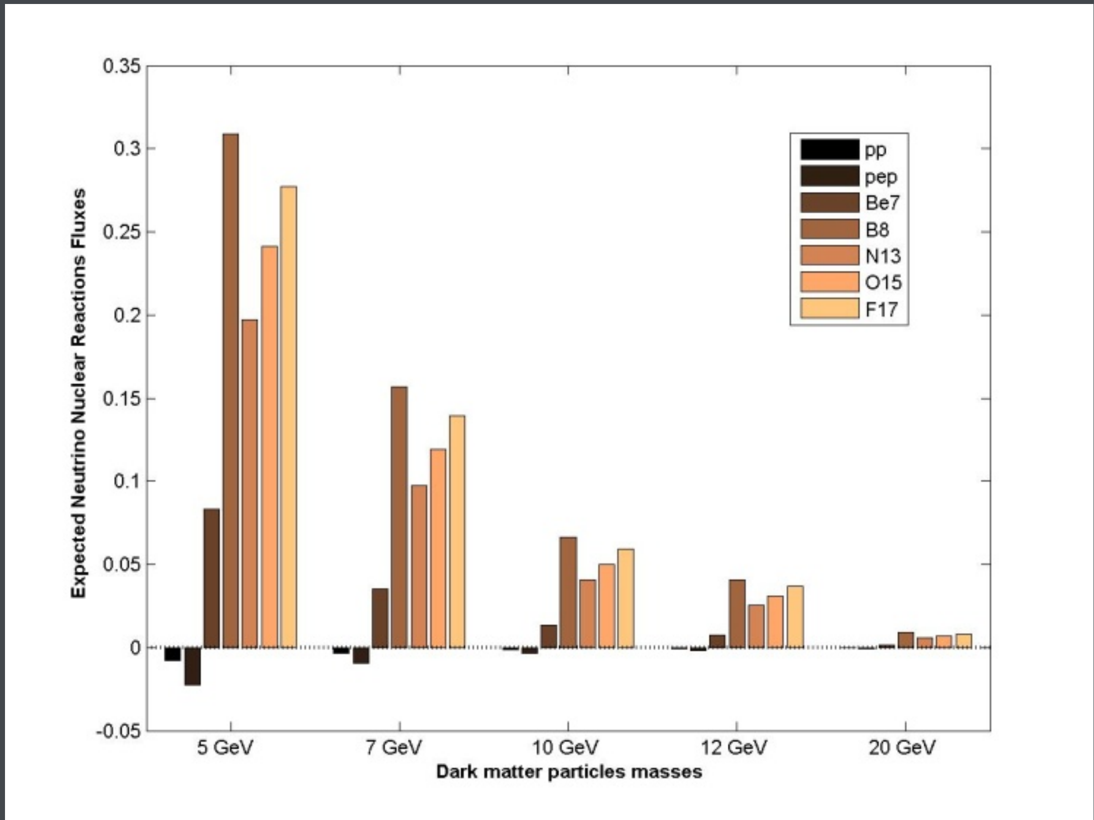
$$P_0 = 2\pi^2 \left[\int_0^R \frac{|N|}{r} dr \right]^{-1},$$

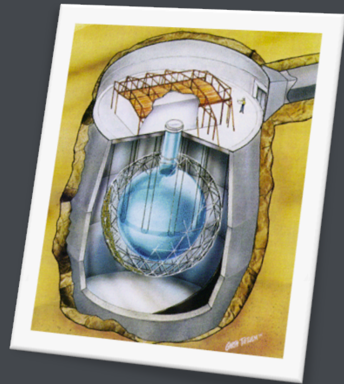


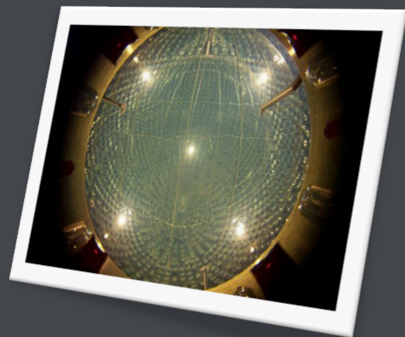
The large separation for gravity modes: This was computed for dipole gravity modes (l=1). These dark matter halos are constituted by self-annihilating massive particles.

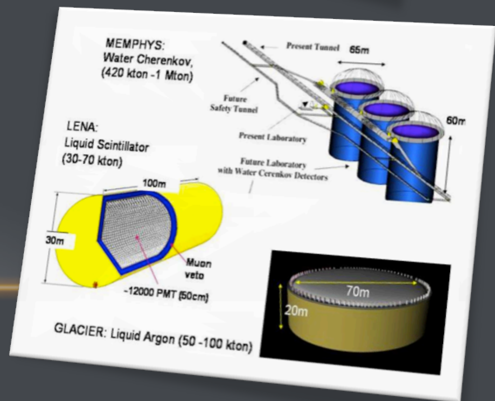
NEUTRINO SPECTROSCOPY: PROBING DARK MATTER

- In the near future, the measurements of pep and CNO neutrino fluxes will be greatly refineed through the Borexino detector or in one of the upcoming experiments SNO+ or LENA-although for LENA we need to wait a full decade.









The dark matter haloes are composed by self-annihilating massive particles, with dependent and independent scattering cross-sections with baryons of the order of 2.0×10^{-36} cm^2 and 4.0×10^{-40} cm^2. The product of the self-annihilation cross section and the relative velocity of colliding particles at freeze-out is of order 1.0×10^{-36} cm^3 s^{-1}. The Sun's dark matter models were computed in a similar way to the solar standard model. (Lopes & Silk Science 2010)

Conclusion

- DM can in principle substantially modify stellar structure.

- By now, stars in their own right are a cosmological tool to constraint the number of dark matter candidates proposed by other research fields.

With thanks to…
Jordi Casanellas and Joseph Silk

The End