

# Giving light to Dark Matter using stars as physical laboratories

Monte Verità, January 20, 2010

Jordi Casanellas, Ilídio Lopes

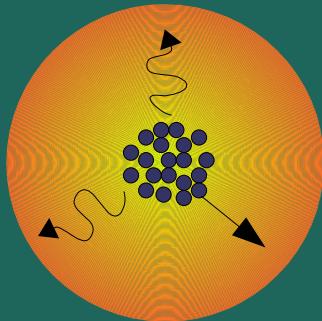
CENTRA, IST. Lisbon

CHIPP PhD Winter School 2010

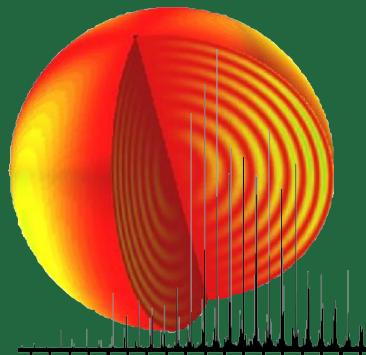
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## Motivations for Dark Matter (DM) research



Stellar evolution within dense DM halos

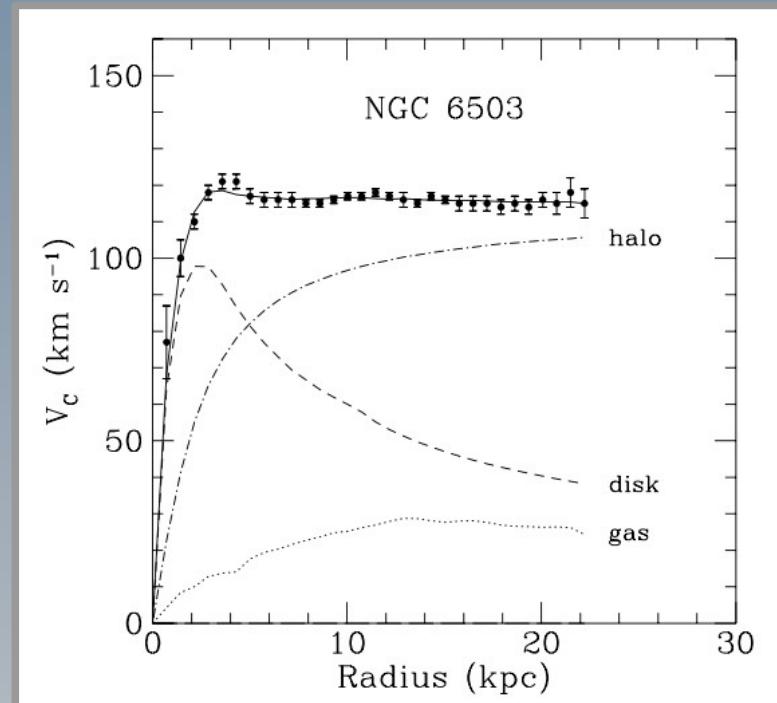


Stellar diagnostic of DM properties



## Evidences for Dark Matter in the Universe:

- Rotation curves of galaxies
- Gravitational lensing
- Velocities of galaxies in clusters
- Others:
  - Hot gas in clusters
  - CMB anisotropies
  - Velocity dispersion in dwarf spheroidal galaxies



$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

$$\rho(r) = \frac{V_0^2}{4\pi G r^2}$$

C E N  
T R AINSTITUTO  
SUPERIOR  
TÉCNICO



## Evidences for Dark Matter in the Universe:

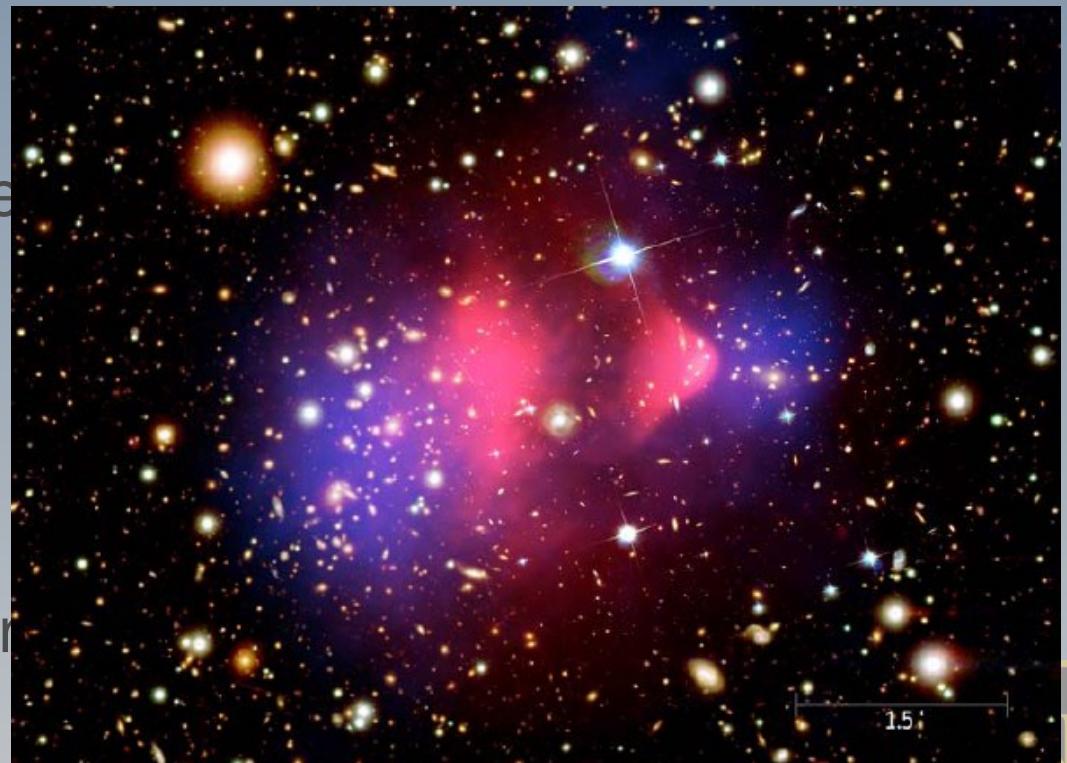
- Rotation curves of galaxies
- Gravitational lensing
- Velocity dispersion of galaxies
- Other observational evidence



GC 0024+1654 (Hubble)

cluster

dwarf



Bullet cluster (Hubble and Chandra X-ray)

T R A



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Virial theorem:

$$\langle T \rangle \geq \frac{1}{2} \langle V_{bar} \rangle$$

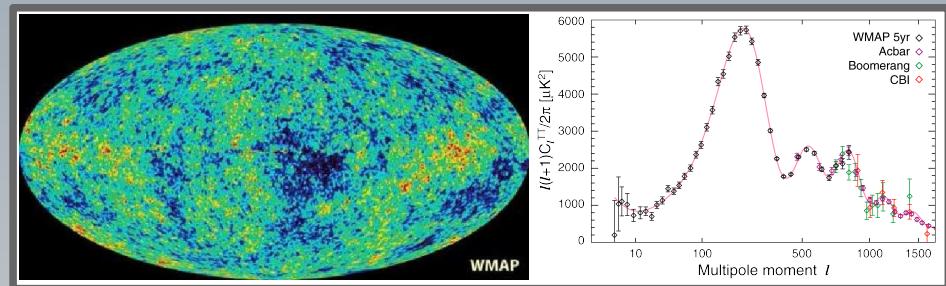
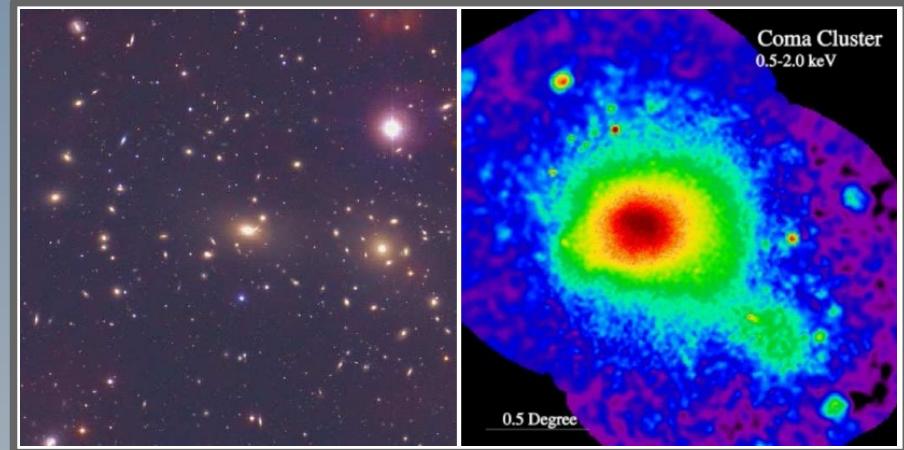
Zwicky, 1933

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Indicate the existence of:

- **invisible** matter
- interacts **gravitationally**
- **5 times** more abundant than baryonic matter





## Candidates of Dark Matter particles:

- **WIMPs** (Weakly Interacting Massive Particles)

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

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



Our test DM particle:

$$\begin{aligned}m_\chi &= 100 \text{ GeV} \\ \sigma_{\chi,SD} &= 10^{-38} \text{ cm}^2 \\ \sigma_{\chi,SI} &= 10^{-44} \text{ cm}^2 \\ \langle \sigma_a v \rangle &= 3 \cdot 10^{-26} \text{ cm}^2 \text{ s}^{-1}\end{aligned}$$

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





## Search for Dark Matter particles:

- **Direct detection**

- Scattering of DM particles with nucleons on a detector.



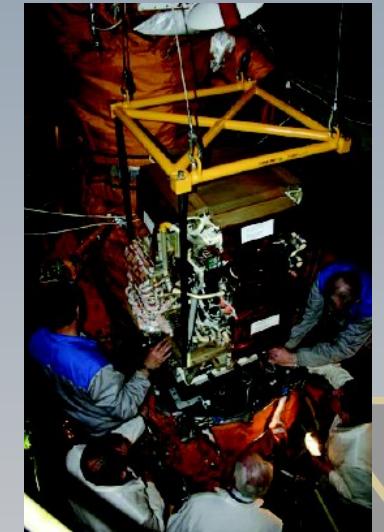
ZEPLIN



CDMS

- **Indirect detection** of DM annihilation products:

- Positrons, antiprotons (PAMELA, AMS), gammas (EGRET, Fermi-GLAST), etc. on satellites, neutrinos (Icecube)

PAMELA  
T R A

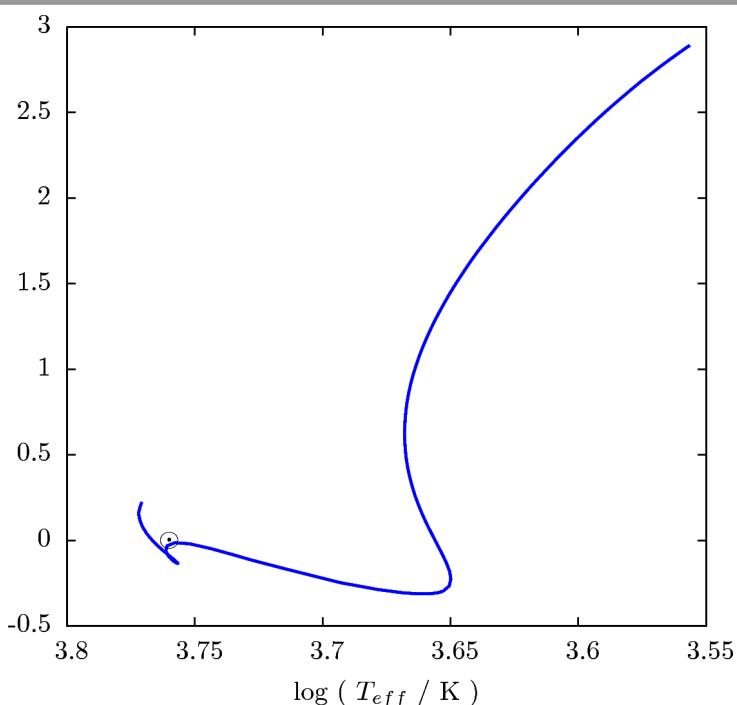
- Colliders (LHC)

Our approach:

**Compare classical stellar evolution with stellar  
evolution **within** Dark Matter halos**

Our approach:

## Compare classical stellar evolution with stellar evolution **within Dark Matter halos**



- We modified the CESAM stellar evolution code (Morel 1997) to compute the **gravitational collapse** and the evolution through the Main Sequence of stars with:

$$0.7 \text{ M}_\odot < M_\star < 3 \text{ M}_\odot$$

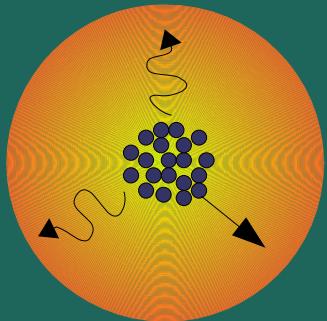
$$Z_0 = 0.014$$

$$v_\star = 220 \text{ km s}^{-1}$$

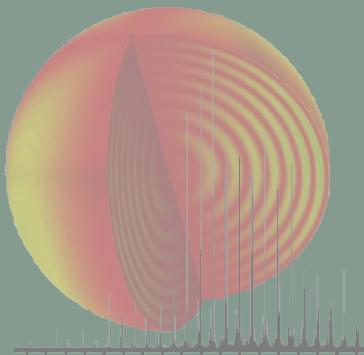
$$0.3 \text{ GeV cm}^{-3} < \rho_\chi < 10^{12} \text{ GeV cm}^{-3}$$



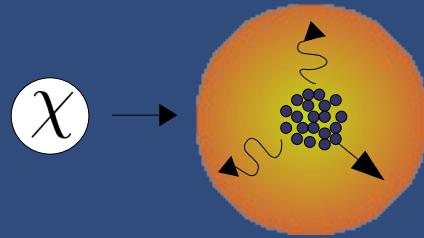
Motivations for Dark Matter (DM) research



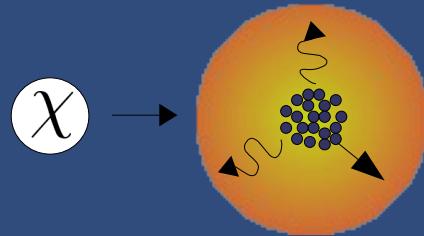
Stellar evolution within dense DM halos



Stellar diagnostic of DM properties

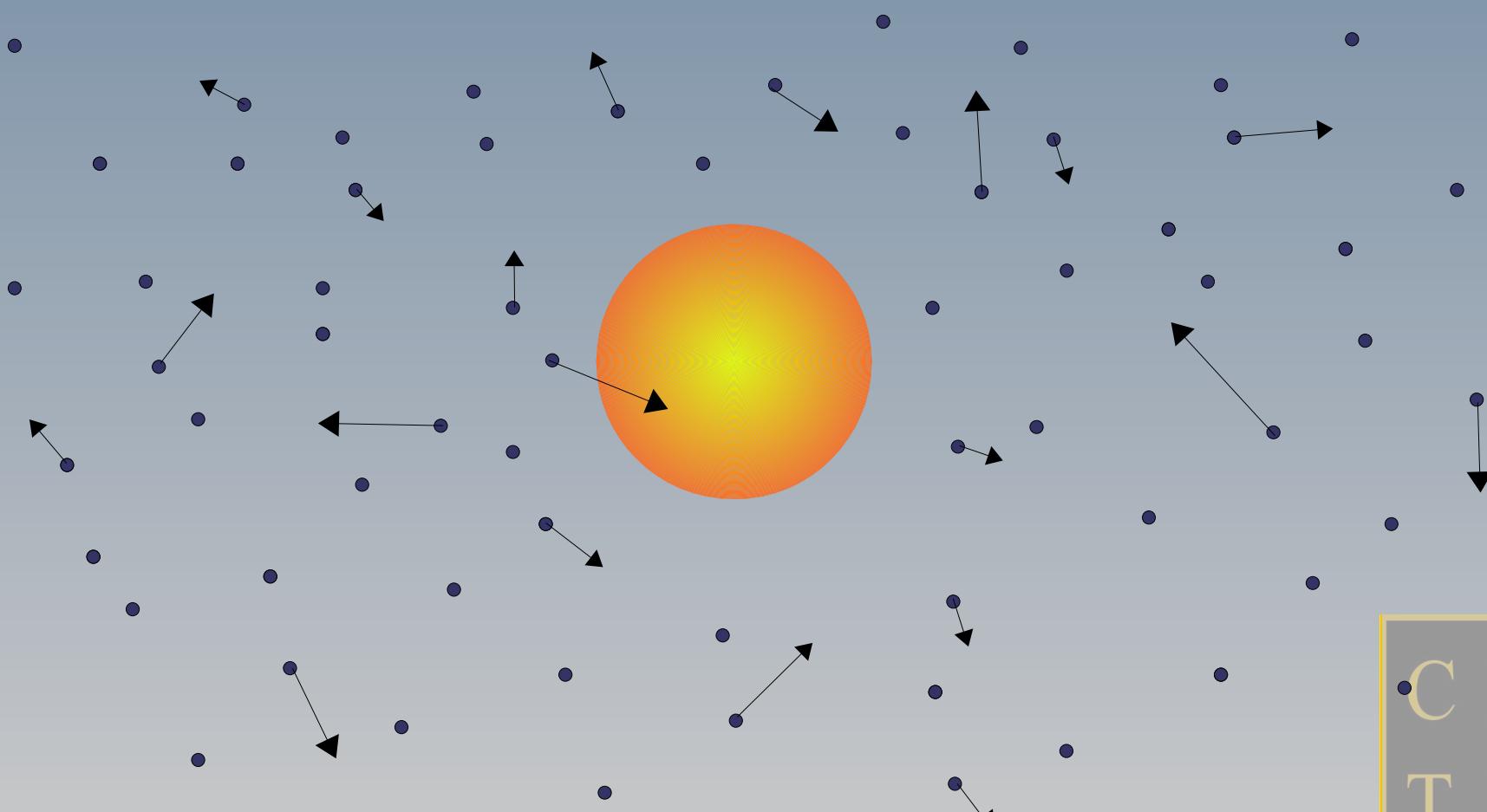


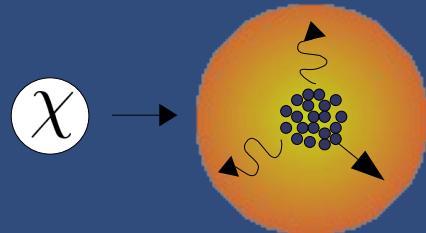
## Capture and annihilation of DM



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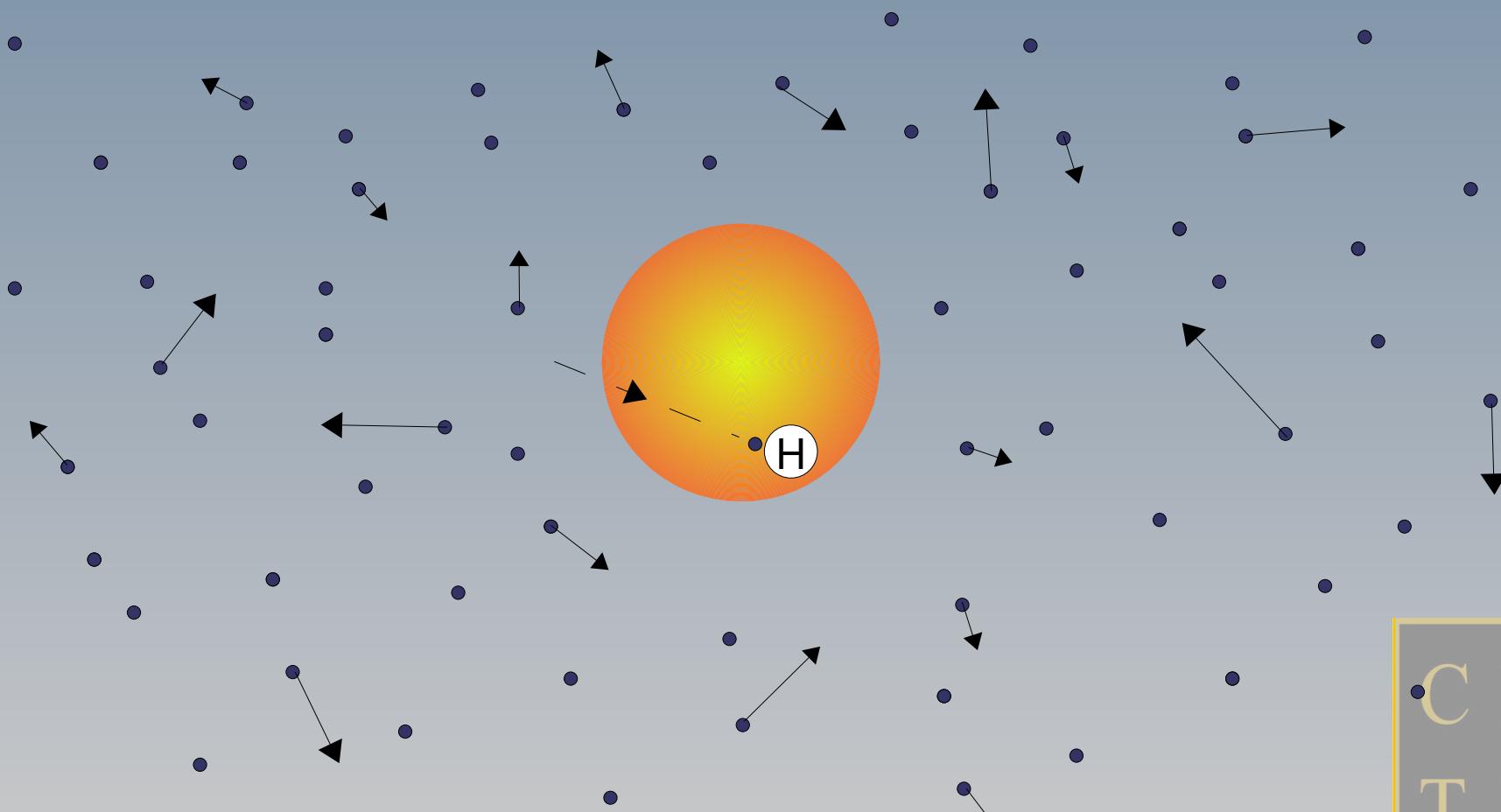
DM particles in the halo are **gravitationally** attracted by the star

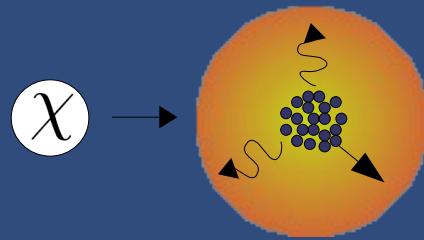




## Capture and annihilation of DM

some of them will **scatter** with nuclei inside the star

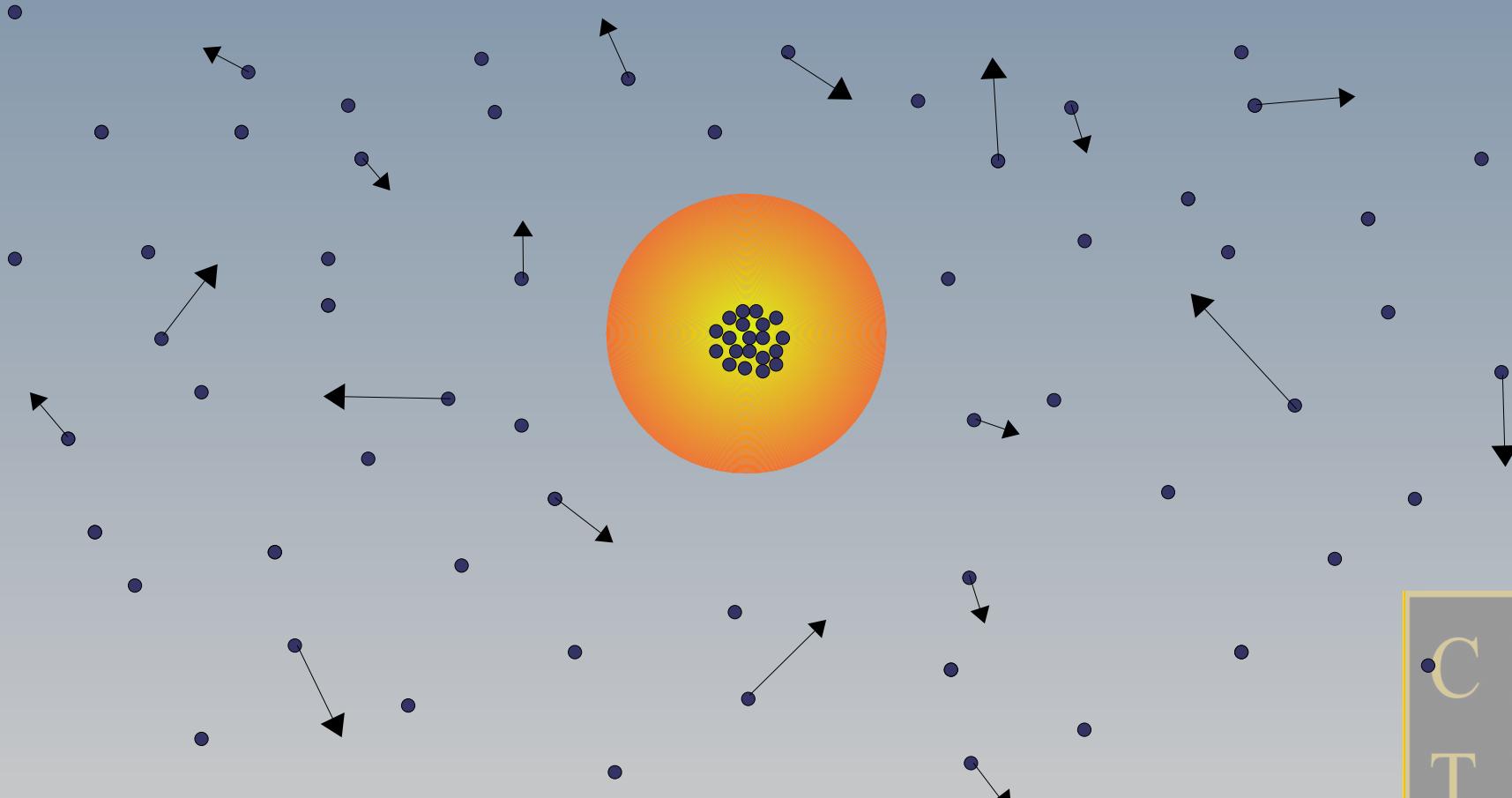


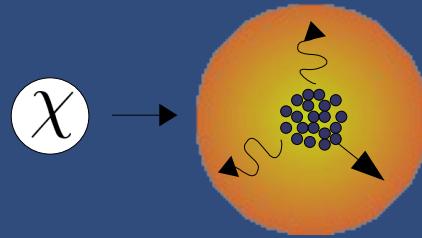


## Capture and annihilation of DM

if they lose enough energy...

they get gravitationally  
**captured** inside the star

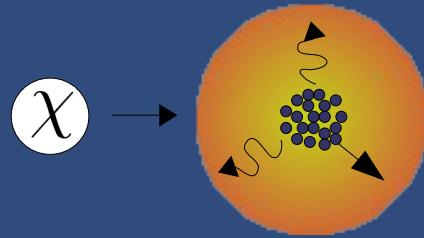




## Capture and annihilation of DM

$$C_\chi(t) = \int_0^{R_*} 4\pi r^2 \int_0^\infty \frac{f(u)}{u} w \Omega_v^-(w) du dr$$

Gould (1987)



## Capture and annihilation of DM

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Gould (1987)

$$\Omega_v^-(w) = \sum_i \frac{\sigma_i n_i(r, t)}{w} \left( v_{esc,r}^2 - \frac{\mu_{-,i}^2}{\mu_i} u^2 \right) \theta \left( v_{esc,r}^2 - \frac{\mu_{-,i}^2}{\mu_i} u^2 \right)$$

$$\mu \equiv \frac{m_\chi}{m_n}, \quad \mu_\pm \equiv \frac{\mu \pm 1}{2}$$

$$f_0(u) = \frac{\rho_\chi}{m_\chi} \frac{4}{\sqrt{\pi}} \left(\frac{3}{2}\right)^{3/2} \frac{u^2}{\bar{v}_\chi^{-3}} \exp \left( -\frac{3u^2}{2\bar{v}_\chi^{-2}} \right)$$

$$f_{v_*}(u) = f_0(u) \exp \left( -\frac{3v_*^2}{2\bar{v}_\chi^{-2}} \right) \frac{\sinh(3uv_*/\bar{v}_\chi^{-2})}{3uv_*/\bar{v}_\chi^{-2}}$$

$\sigma_\chi$

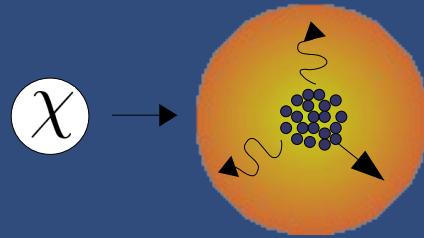
$\rho_\chi$

$m_\chi$

$V_*$

$\bar{V}_\chi$

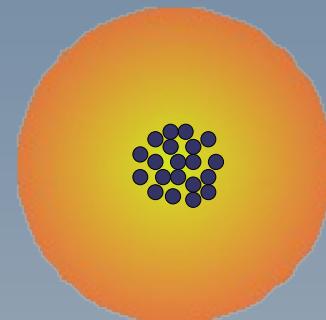
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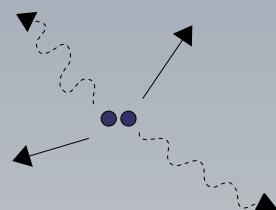
$$C_\chi(t) = \int_0^{R_\star} 4\pi r^2 \int_0^\infty \frac{f(u)}{u} w \Omega_v^-(w) du dr$$

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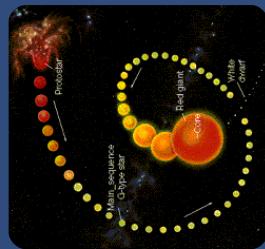


$$r_\chi \sim 0.05 R_\star$$

- The **annihilation** of DM particles provide a **new source of energy**:

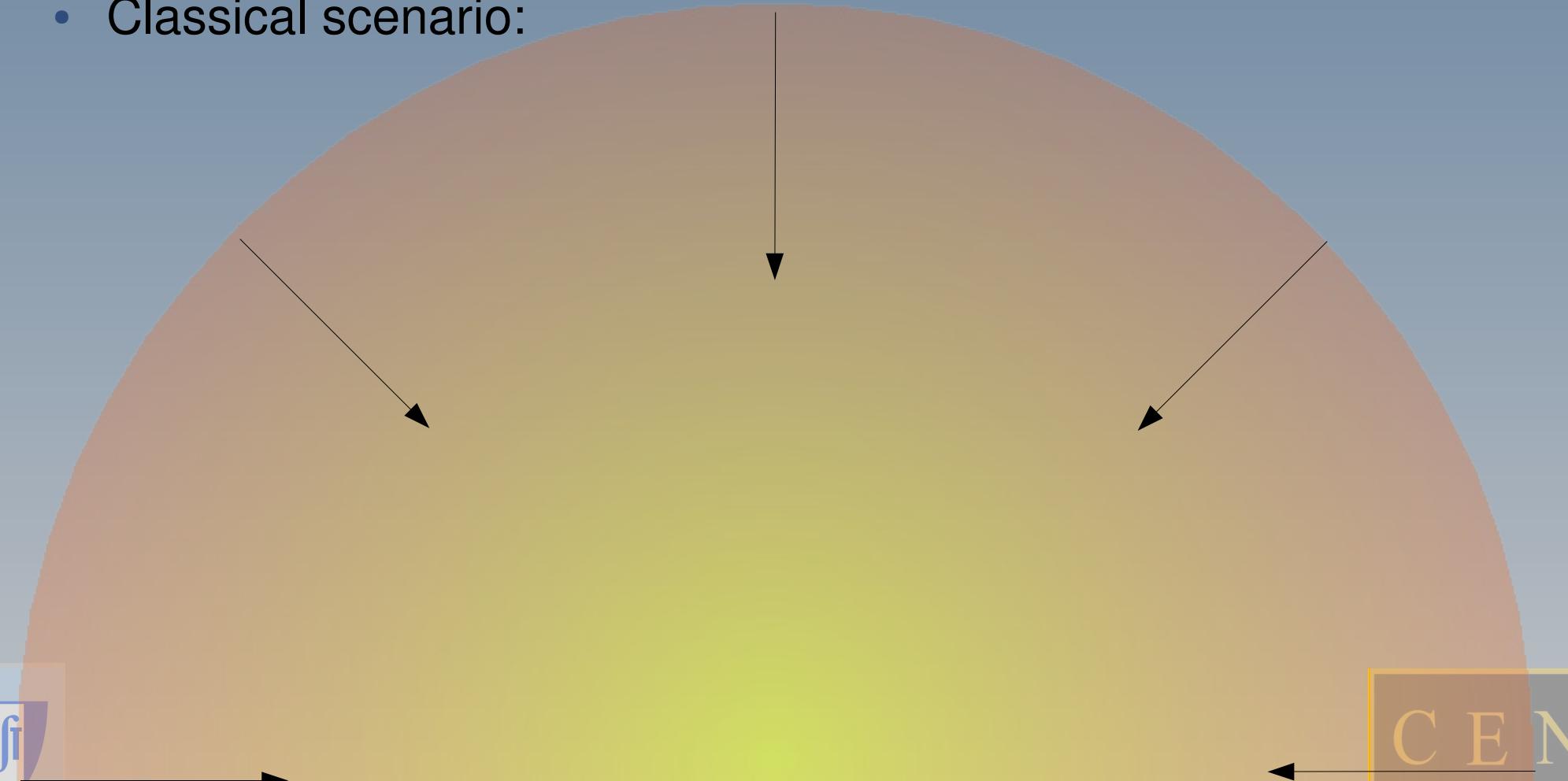


$$L_\chi = f_\chi C_\chi m_\chi$$

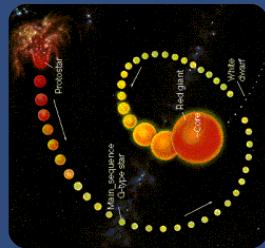


## Main impacts on stellar evolution

- Classical scenario:



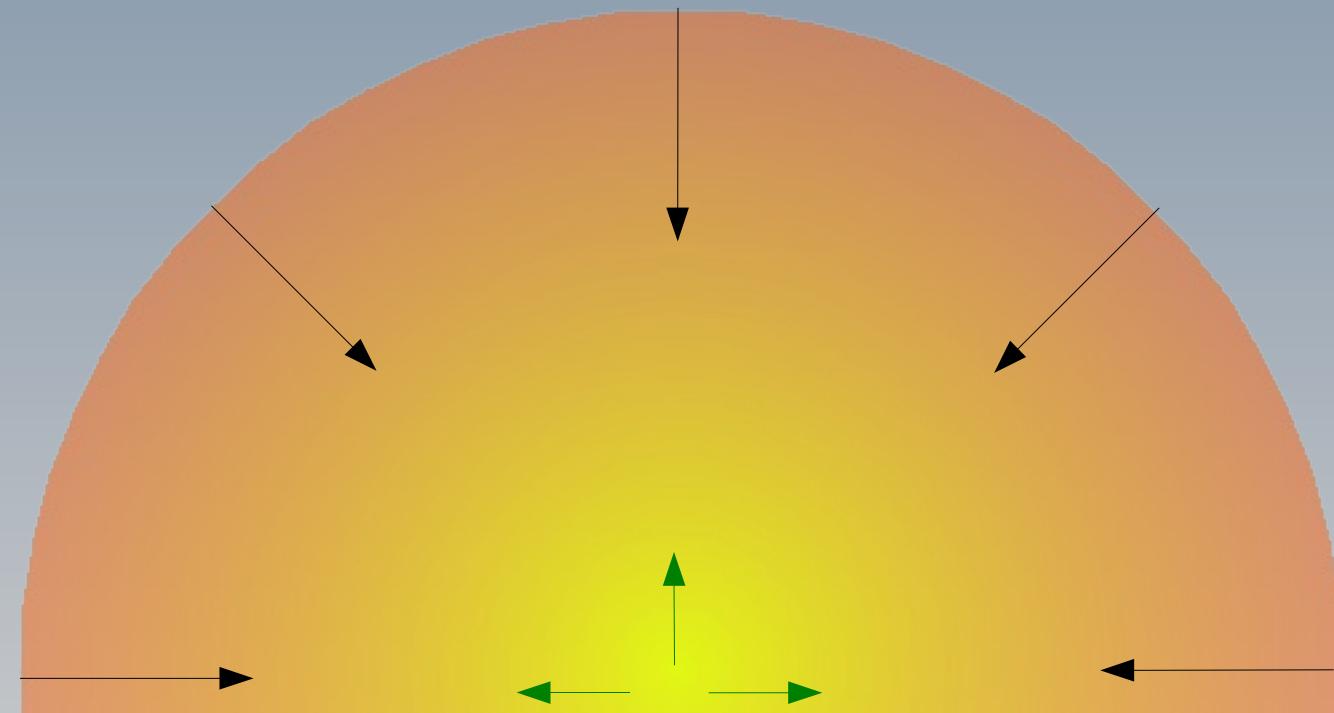
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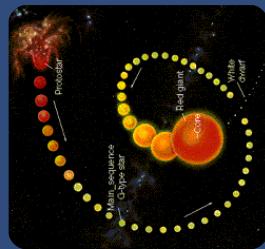


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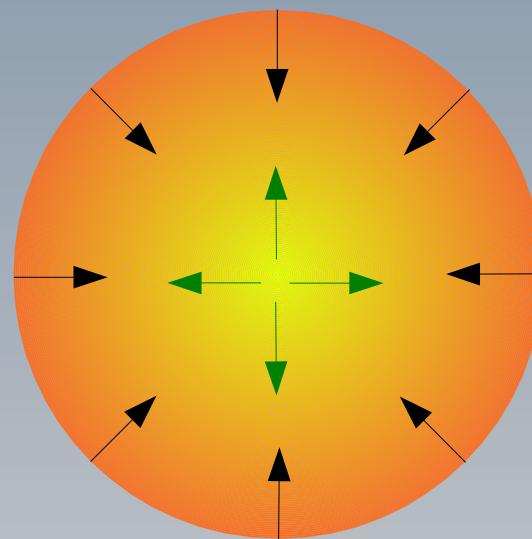
The gravitational collapse  
is balanced by the  
**thermonuclear energy**





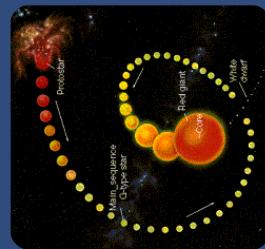
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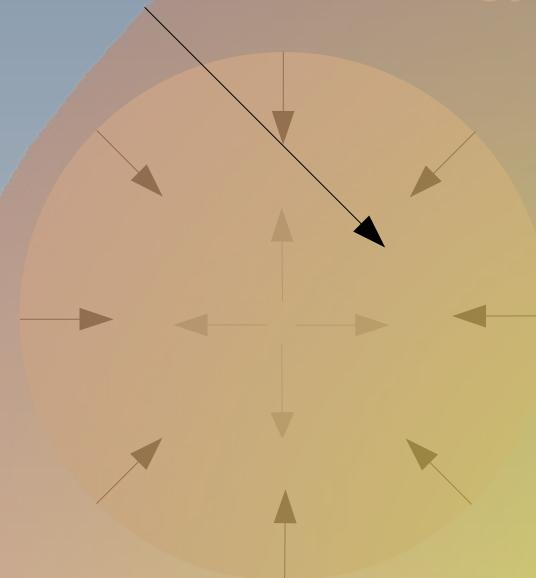
$M_\star$	$\varepsilon_{pp}$	$\varepsilon_{CNO}$
$1 M_\odot$	98%	2%
$2 M_\odot$	60%	40%
$3 M_\odot$	20%	80%

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



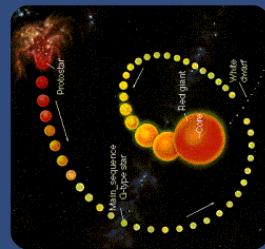
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- Classical scenario:  
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- Within a dark matter halo  
(**"low" DM densities**):



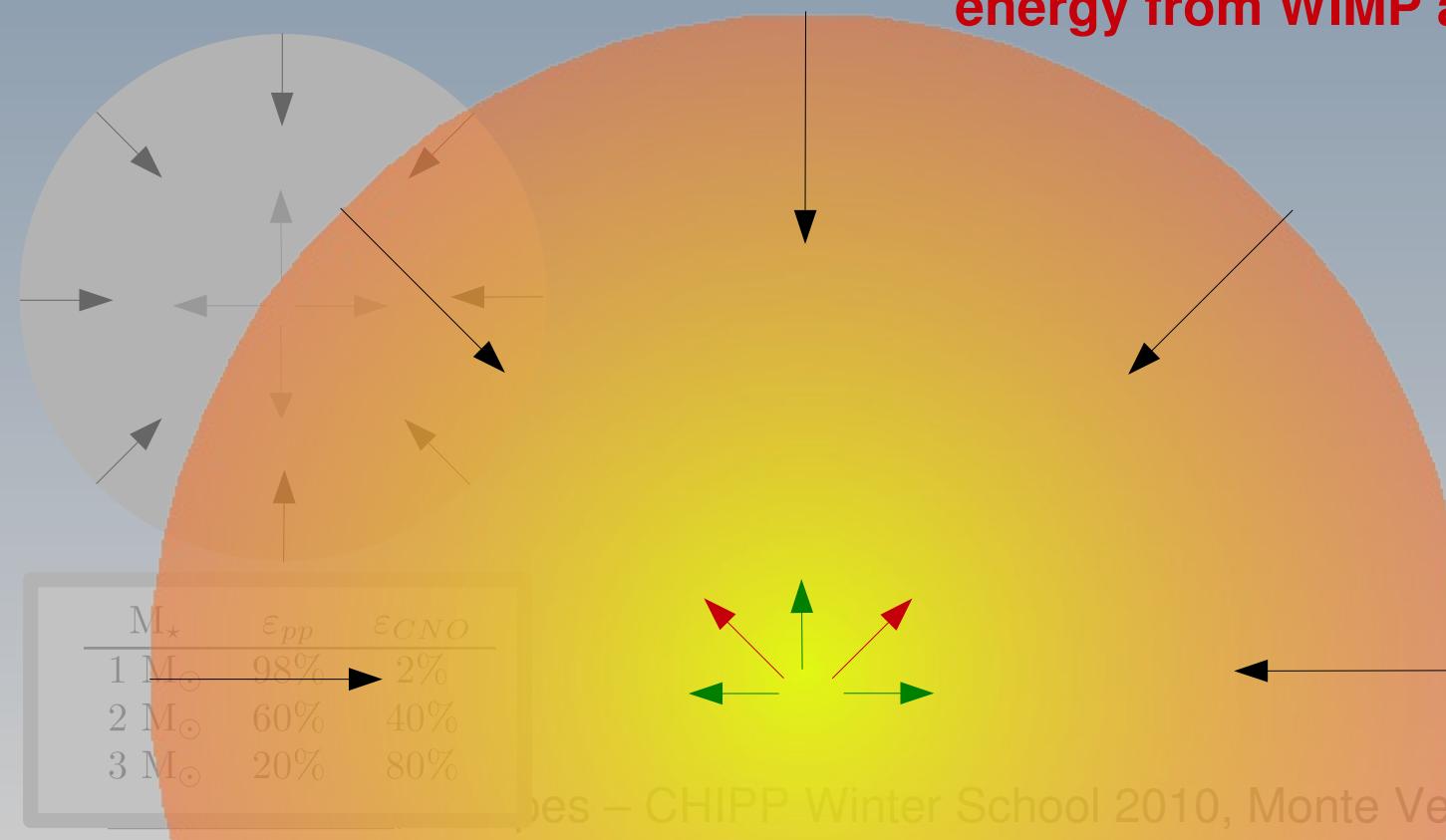
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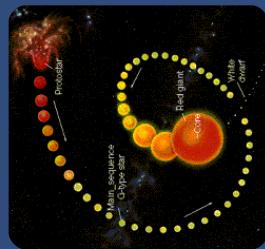


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Collapse balanced by the  
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**energy from WIMP annihilation**

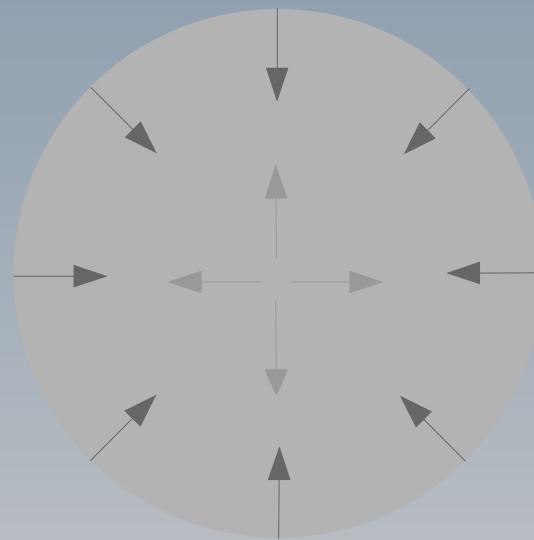


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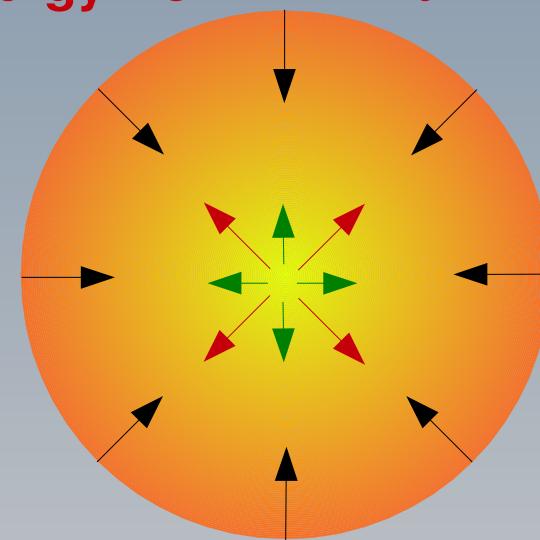
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$\frac{M_\star}{1 M_\odot}$	$\varepsilon_{pp}$ 98%	$\varepsilon_{CNO}$ 2%
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$T_c = 13.4 \text{ MK}$

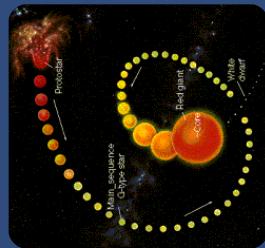
$\left( \text{when } \varepsilon_{grav} < 1\% \varepsilon_t \right)$



$\rho_\chi = 5 \cdot 10^8 \text{ GeV cm}^{-3}$	$\frac{M_\star}{1 M_\odot}$	$\varepsilon_\chi$ 70%	$\varepsilon_{pp+CNO}$ 30%
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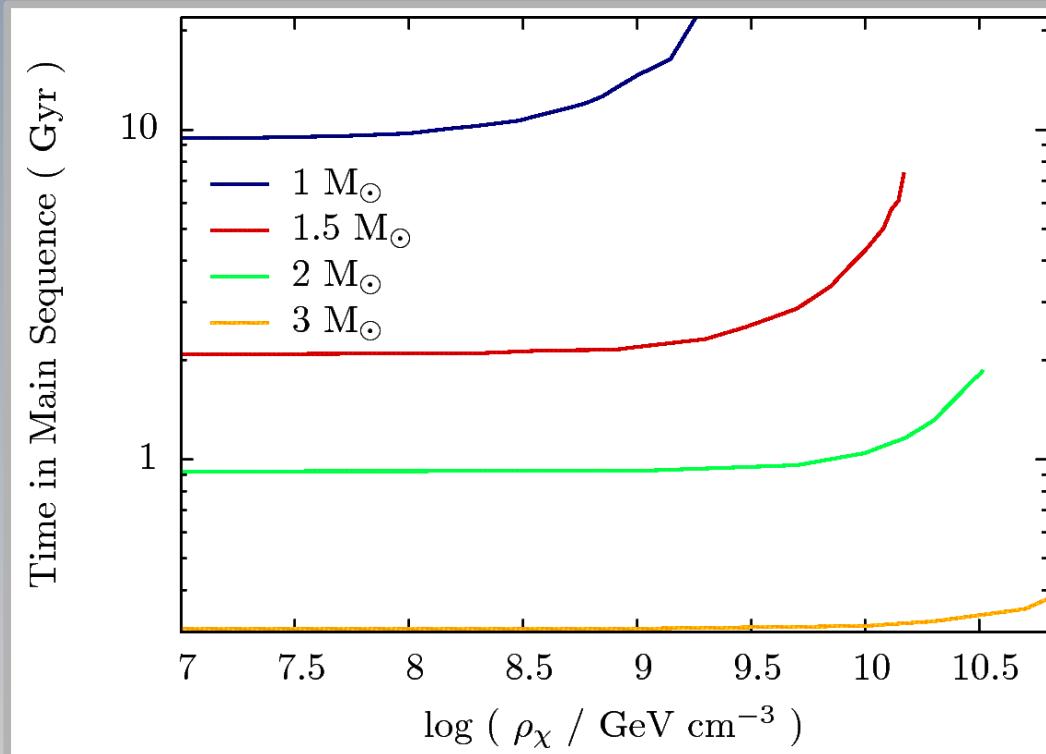
$T_c = 12.8 \text{ MK}$

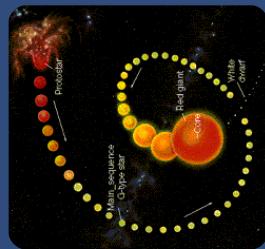
C E N  
T R A



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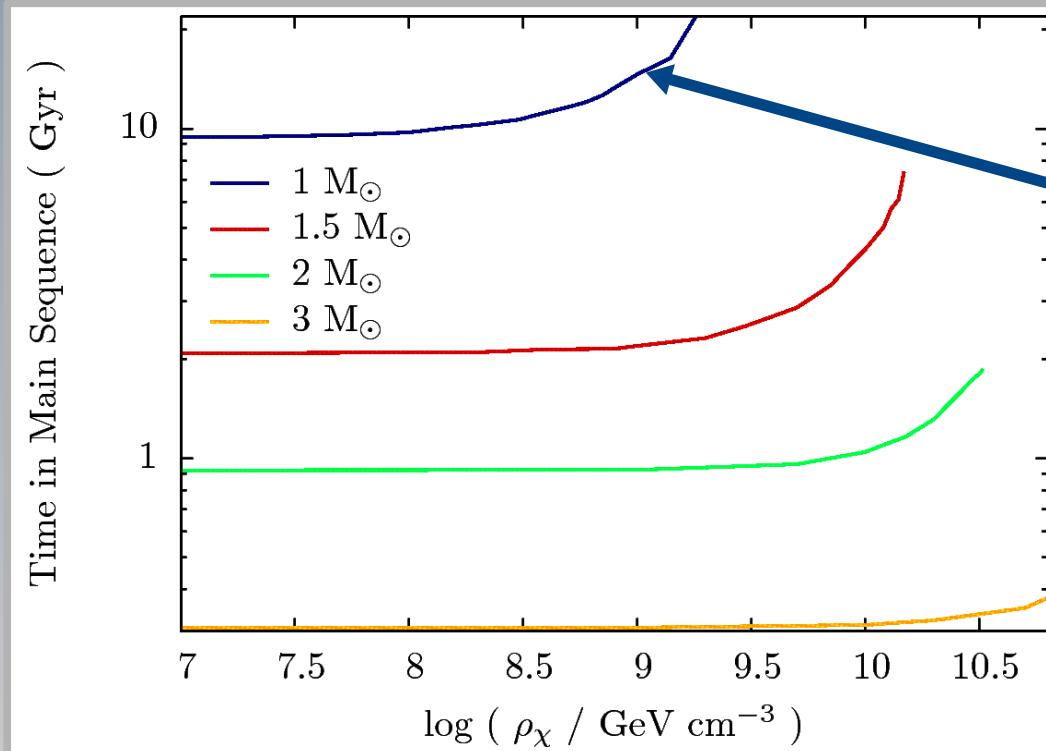
- Stars evolving in halos with **low DM densities**:
    - Equilibrium after collapse is reached at lower central temperatures
    - Hydrogen is burned at a lower rate
- **Time expended in Main Sequence is enlarged**





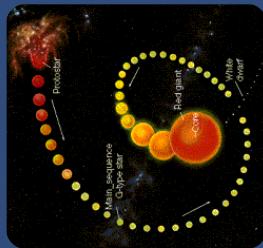
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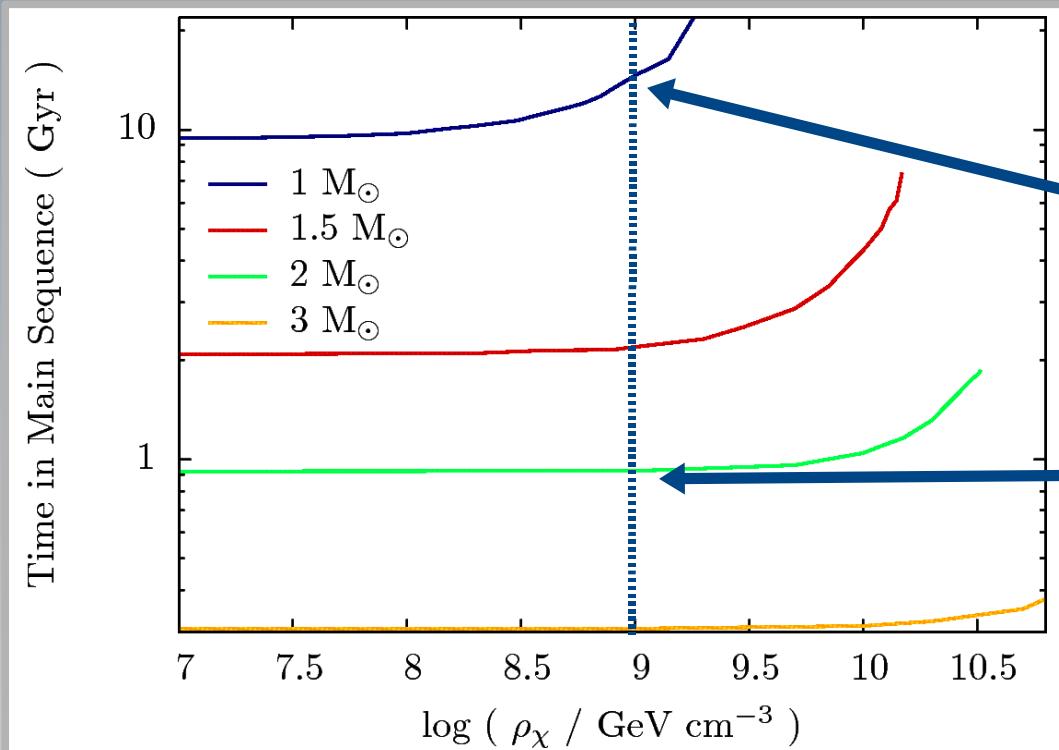
A star of  $1 M_\odot$  will spend 60% more time in the MS than what expected in the classical scenario if it evolves in a halo of:  
 $\rho_\chi = 10^9 \text{ GeV cm}^{-3}$

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T R A



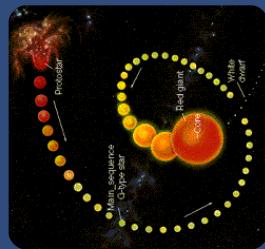
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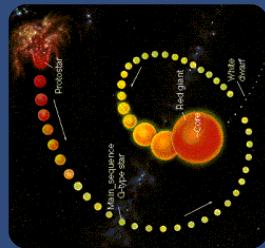
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In the same DM halo, a star of  $2 M_\odot$  is not affected



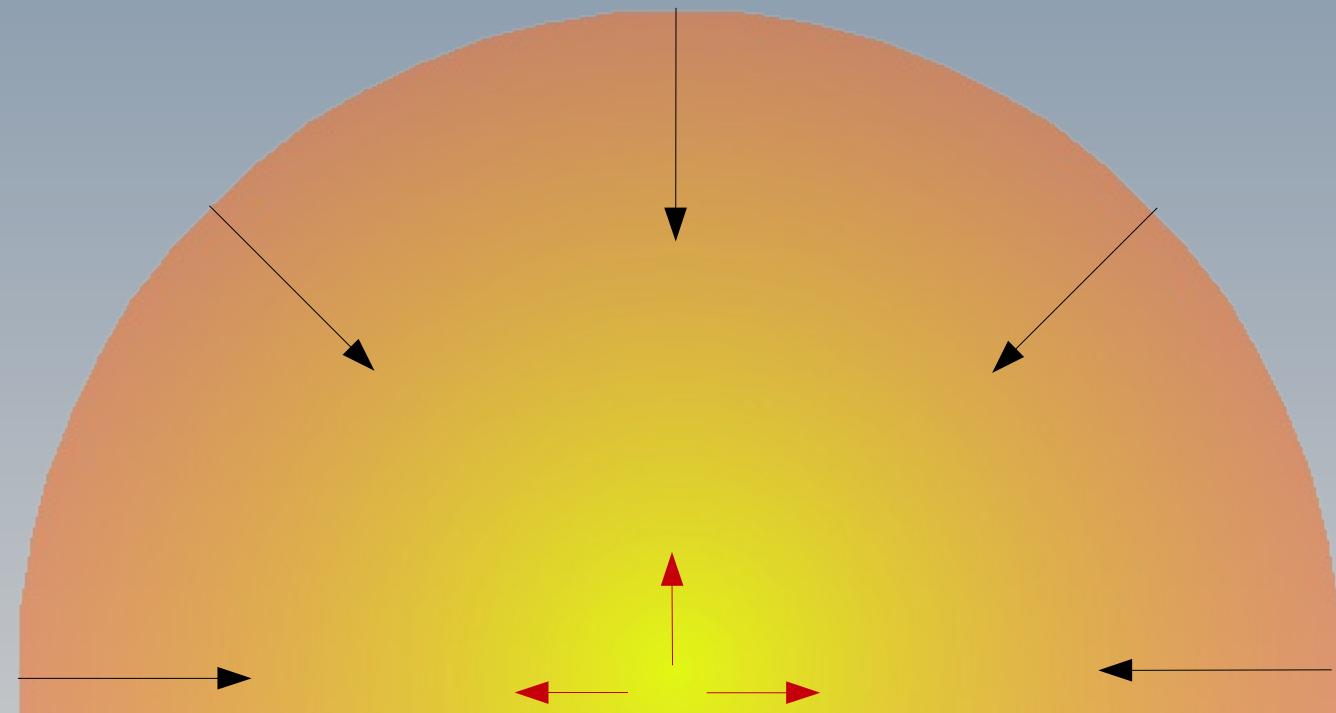
## Main impacts on stellar evolution

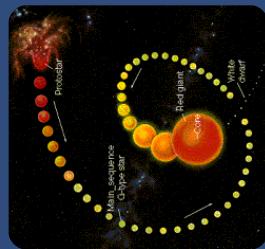
- Stars evolving in halos with **high DM densities**:



## Main impacts on stellar evolution

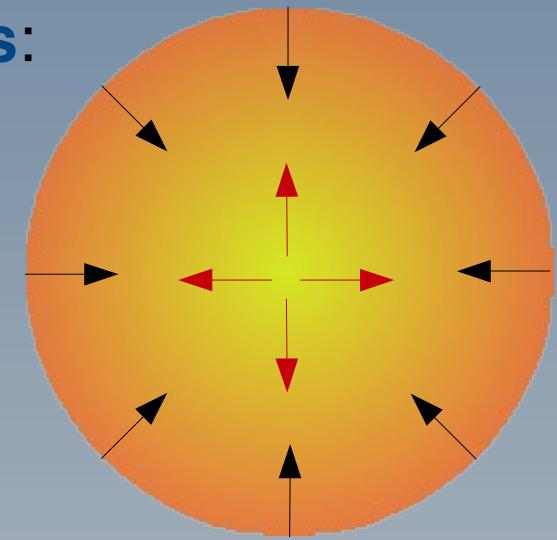
- Stars evolving in halos with **high DM densities**:
  - The gravitational collapse is balanced by the **energy from WIMP annihilation**



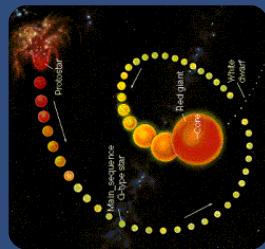


## Main impacts on stellar evolution

- 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**

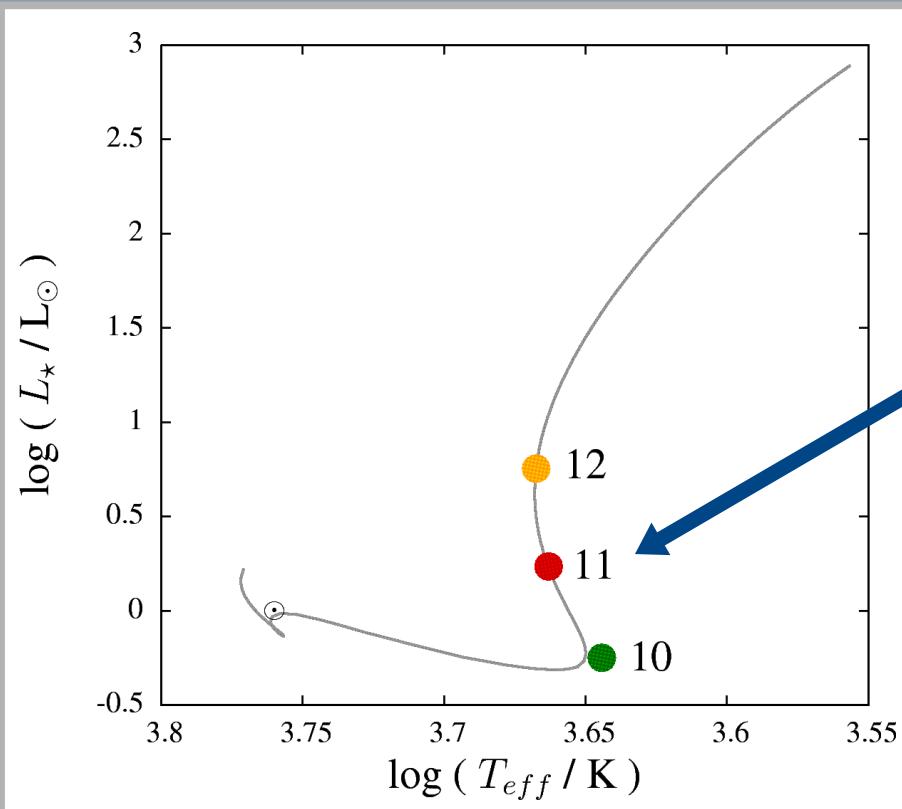


In a star of  $1 M_{\odot}$ :  
 $\rho_{\chi} \geq 5 \cdot 10^9 \text{ GeV cm}^{-3}$   
 $\varepsilon_{\chi} = 100\%$   
 $T_c \leq 8.0 \text{ MK}$



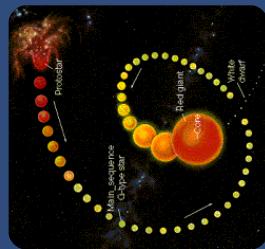
## Main impacts on stellar evolution

- 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**.



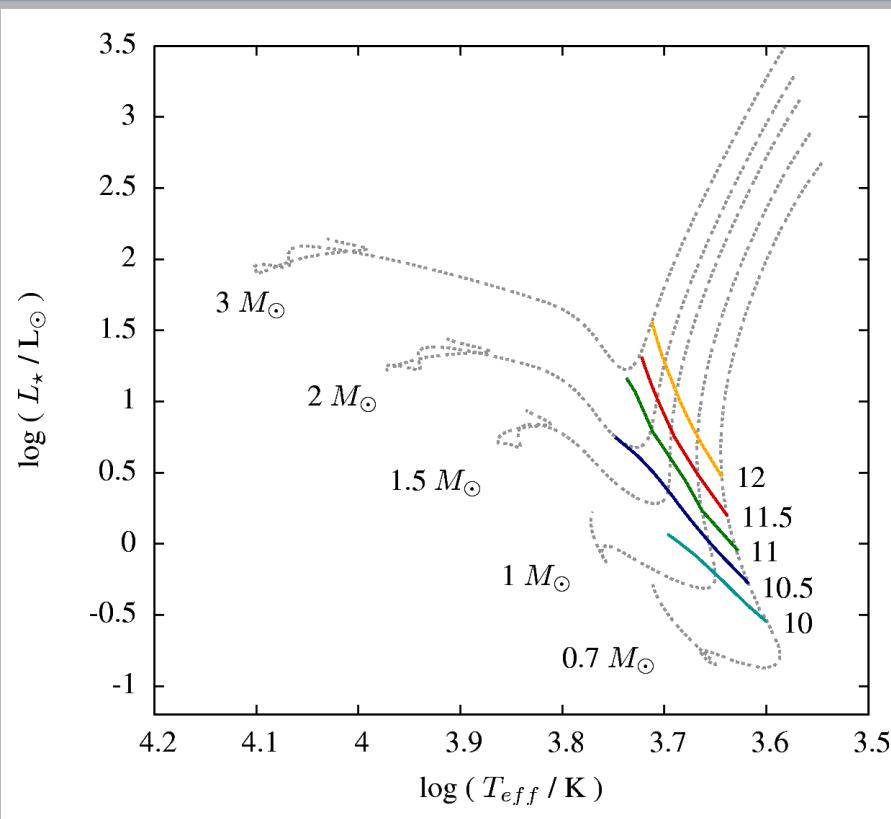
A star of  $1 M_{\odot}$  evolving within a DM halo with:  
 $\rho_{\chi} = 10^{11} \text{ GeV cm}^{-3}$   
 will soon stop its collapse with:  
 $R_{\star} \simeq 2 R_{\odot}$   
 $T_{eff} \simeq 4595 \text{ K}$   
 $L_{\star} \simeq 1.6 L_{\odot}$

Iocco et al. (2008) found similar results studying the collapse of first stars with DM capture.

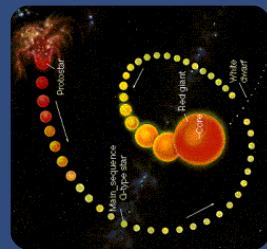


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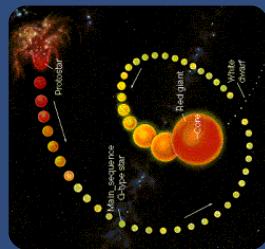


More massive stars  
need higher DM densities  
to stop their collapse



## Main impacts on stellar evolution

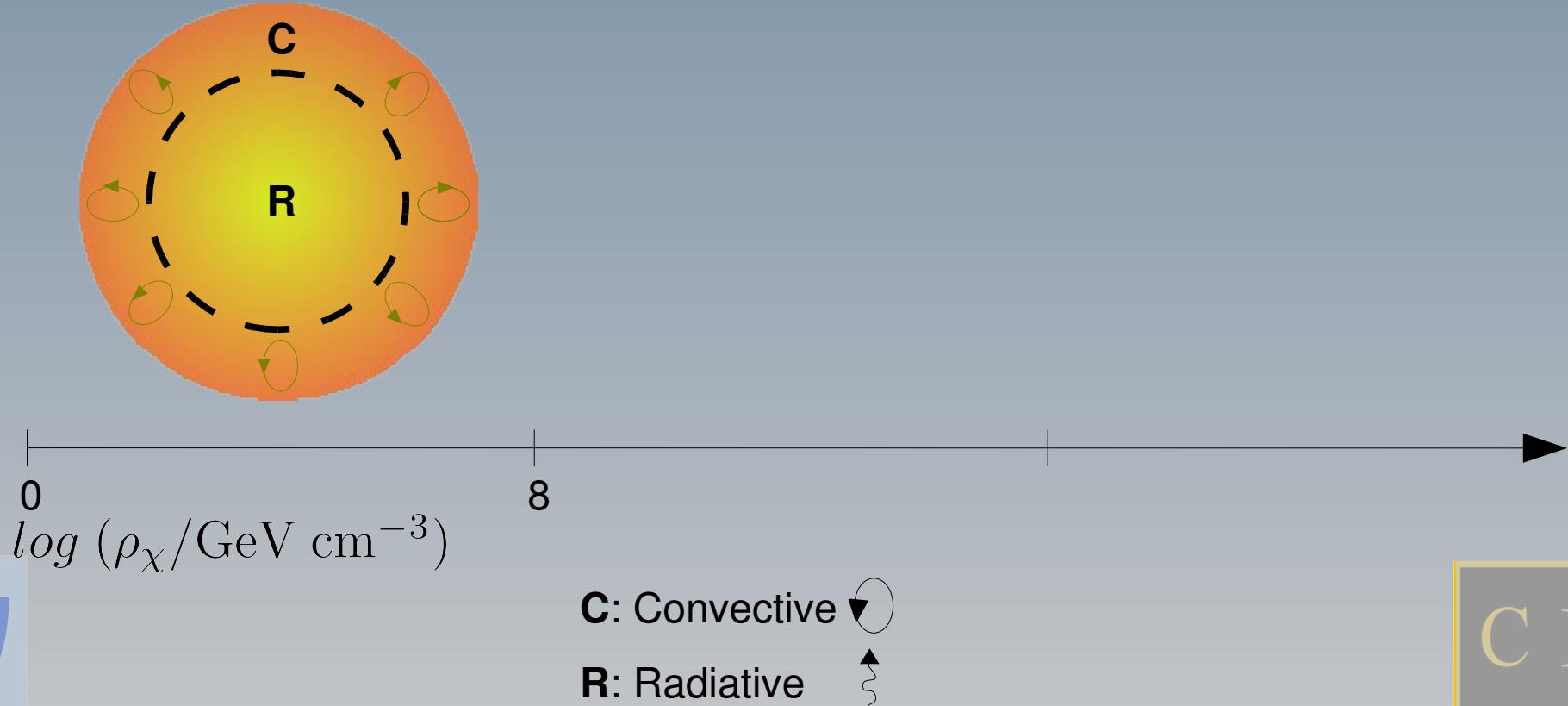
- **Energy transport** inside the star:

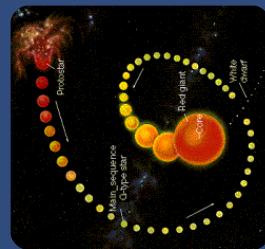


## Main impacts on stellar evolution

- **Energy transport** inside the star:

Star of  $1M_{\odot}$  in the main sequence:

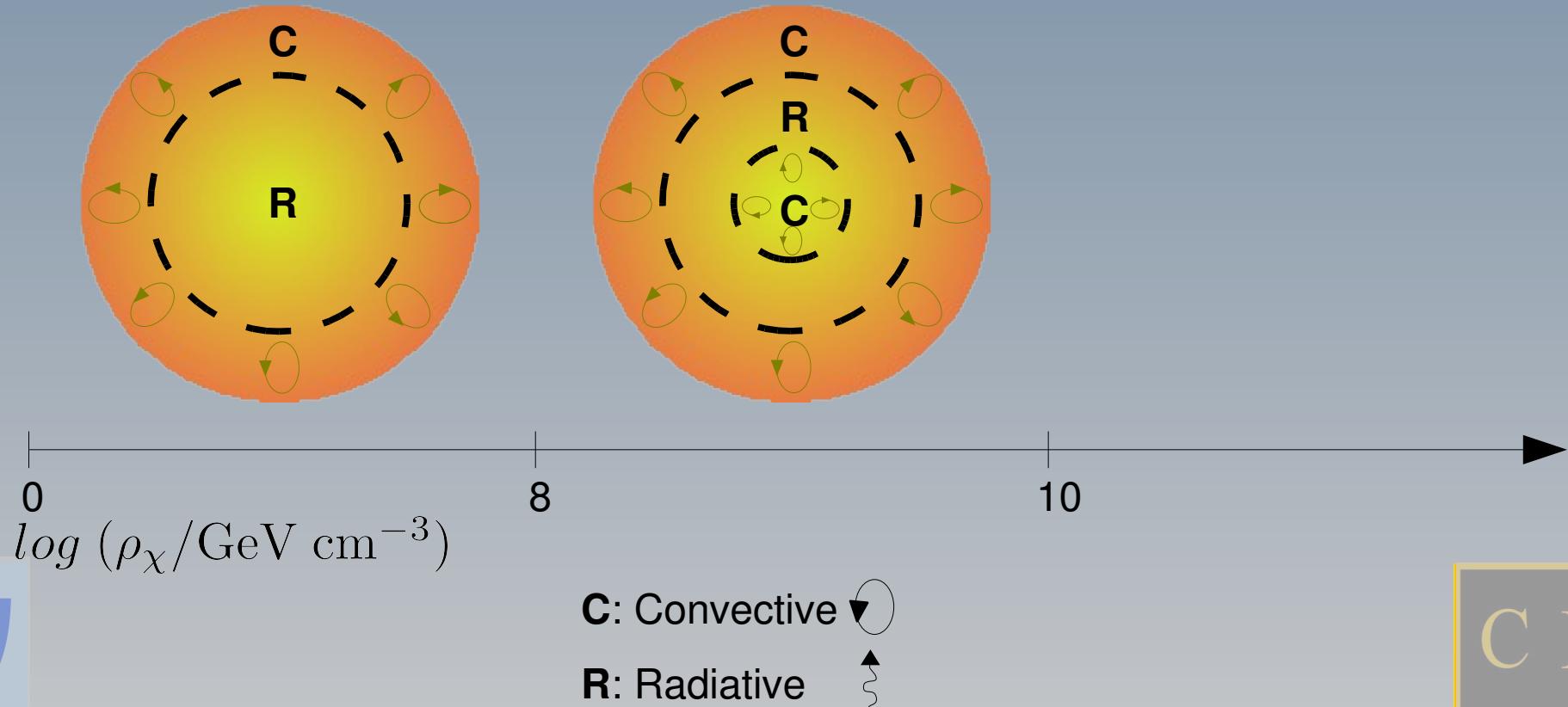


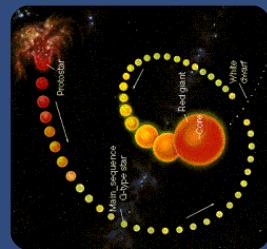


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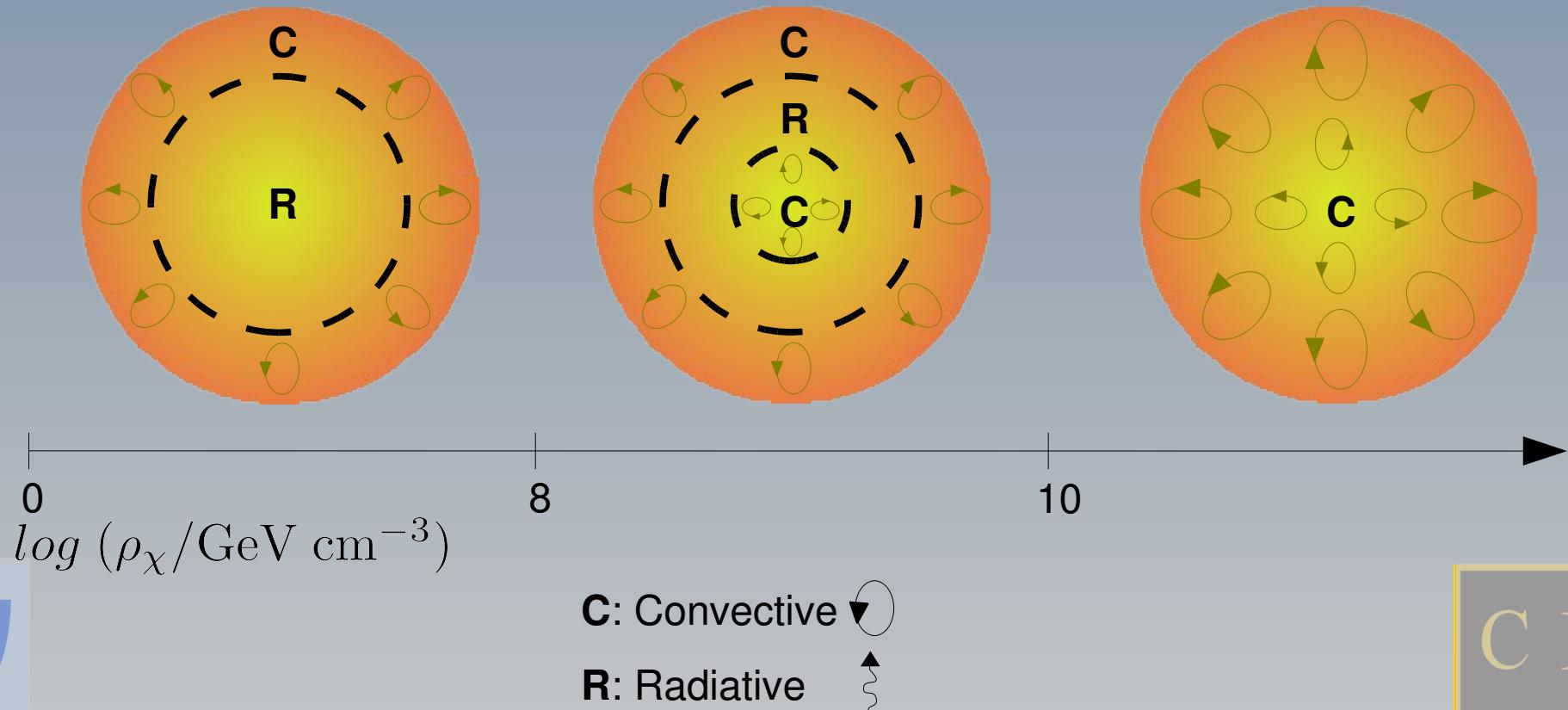




## Main impacts on stellar evolution

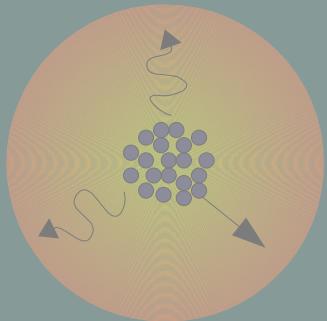
- **Energy transport** inside the star:

Star of  $1M_{\odot}$  in the main sequence:

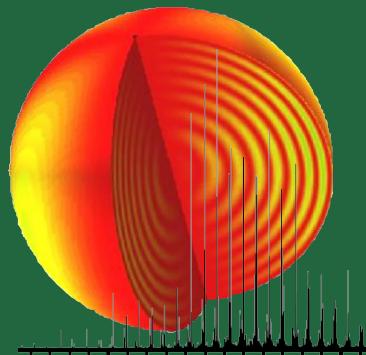




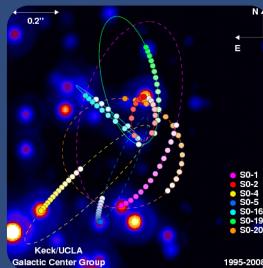
Motivations for Dark Matter (DM) research



Stellar evolution within dense DM halos

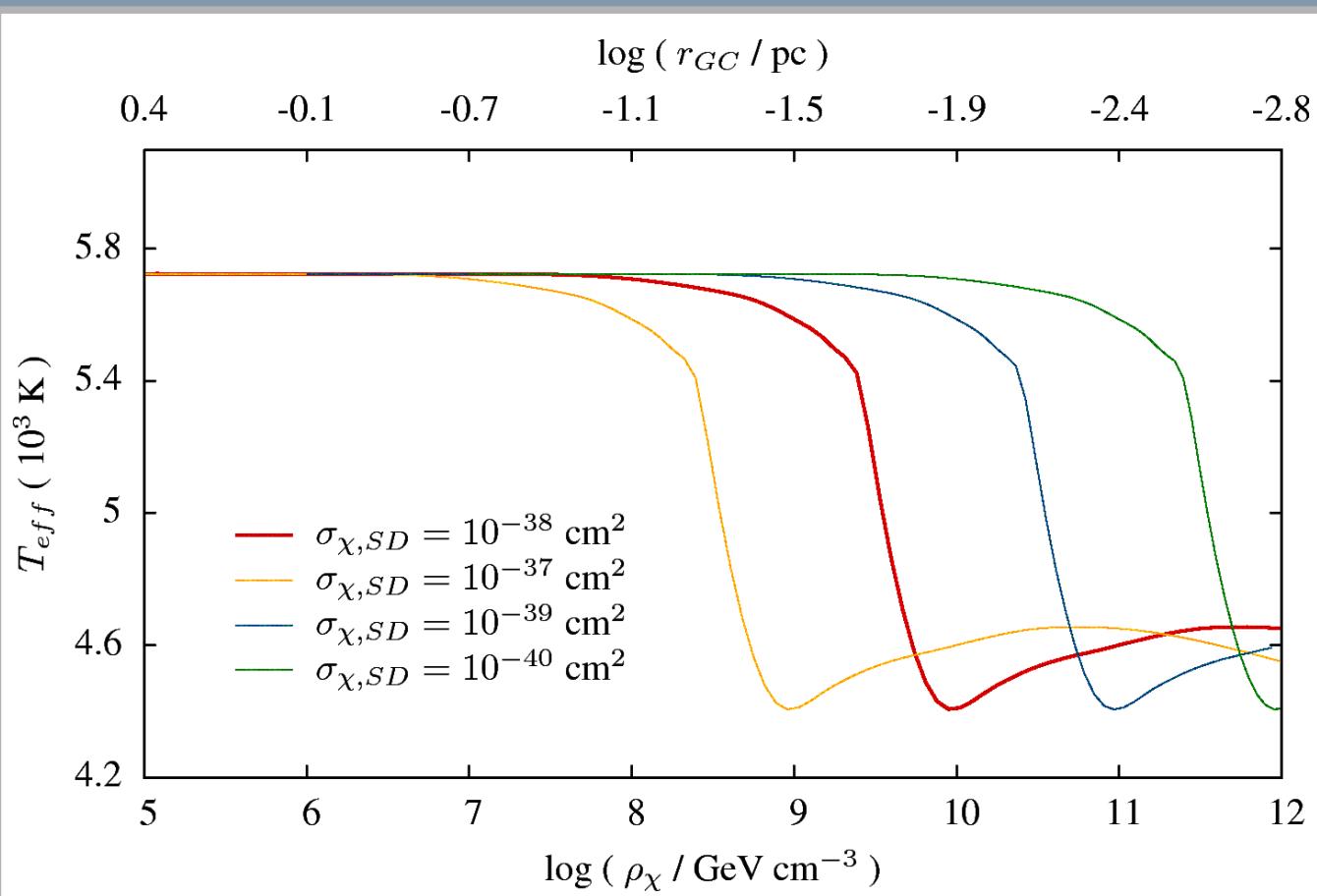


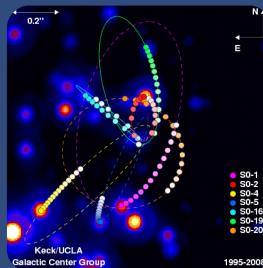
Stellar diagnostic of DM properties



## Towards observational prospects

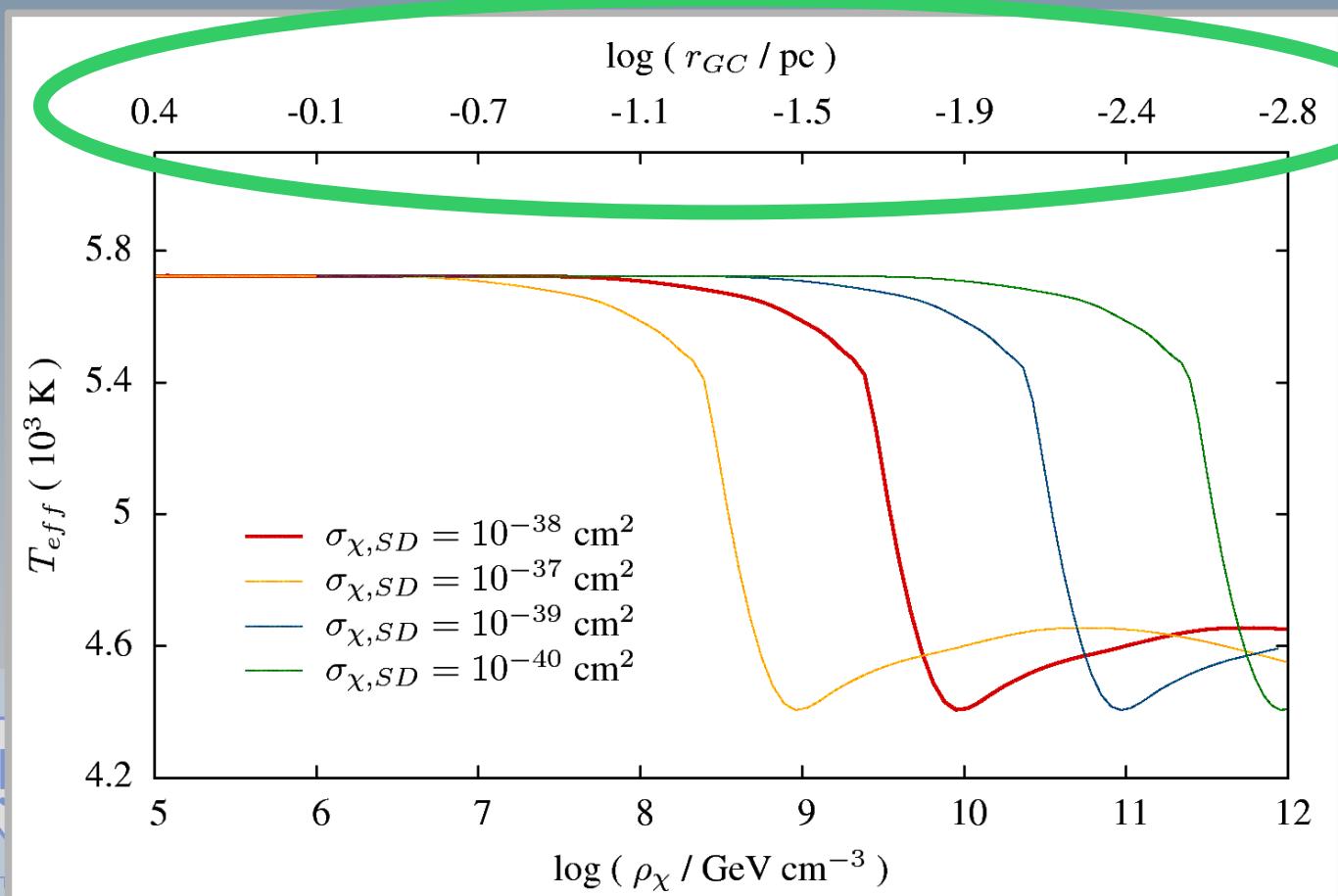
- These effects depend strongly on the **DM density** in the host halo and on the DM **scattering cross sections**.





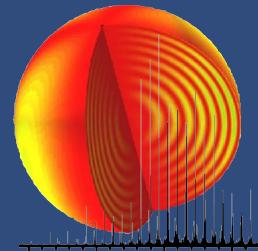
## Towards observational prospects

- These effects depend strongly on the **DM density** in the host halo and on the DM **scattering cross sections**.



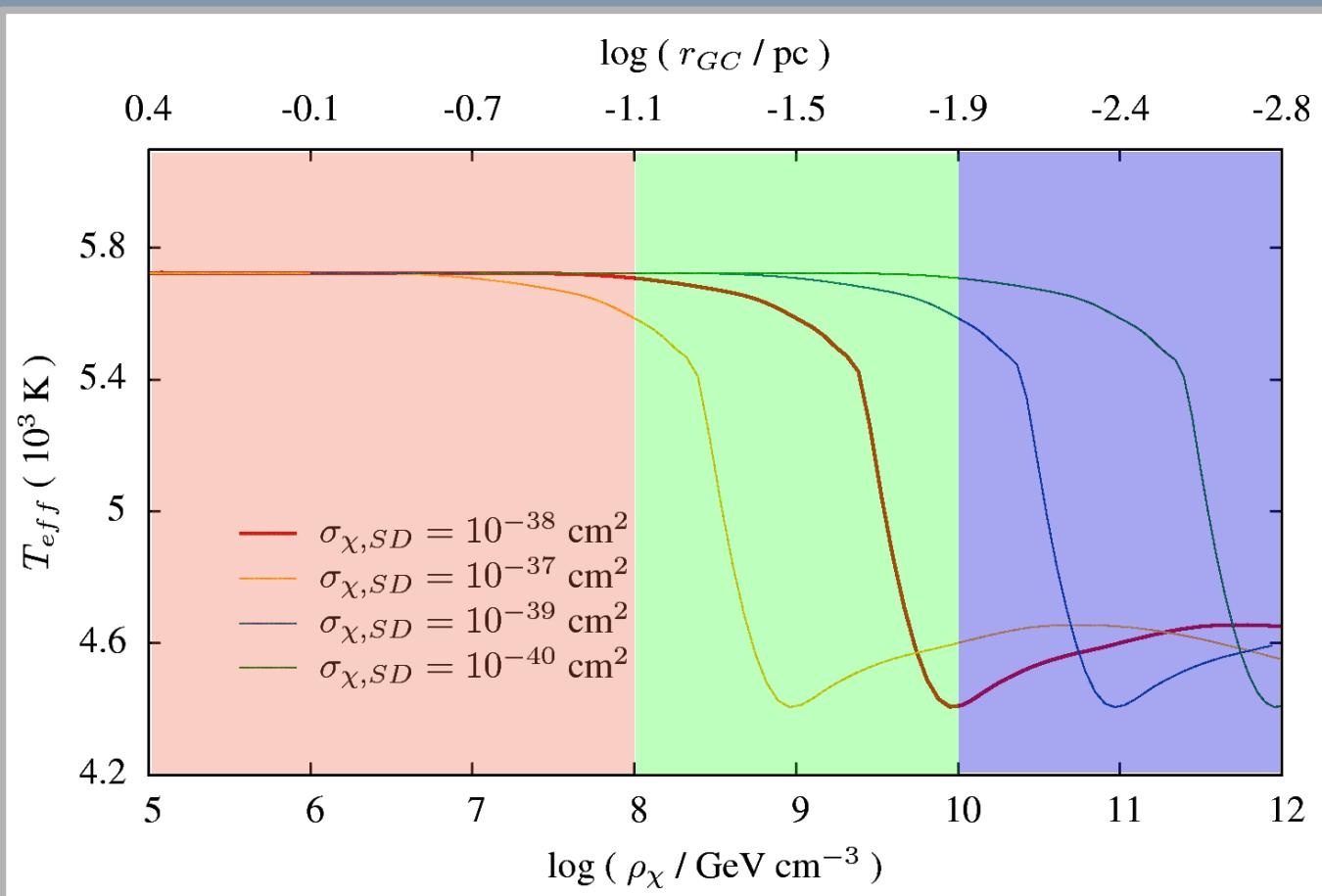
Inner parsec of the  
Milky Way

C E N  
T R A



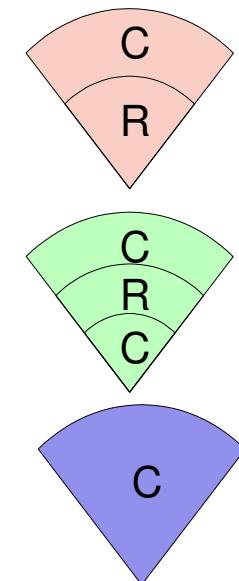
## Asteroseismology (work in progress)

- The analysis of the modes of vibration of the star is a powerful tool to **detect** the presence of **convective cores**.

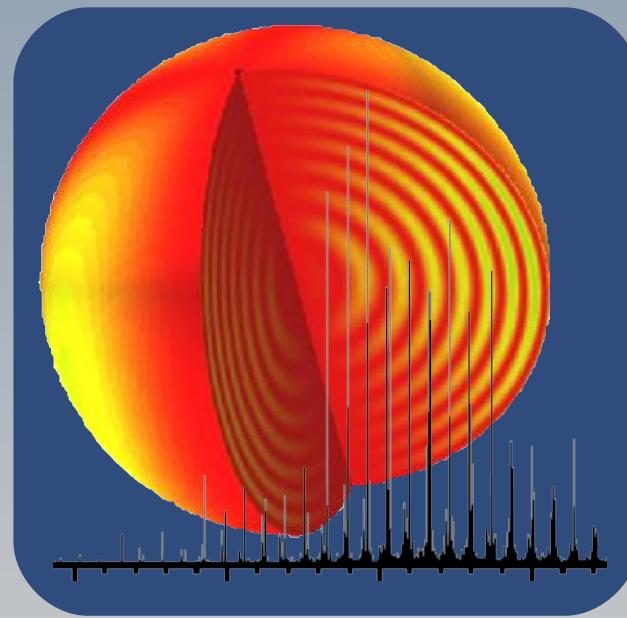
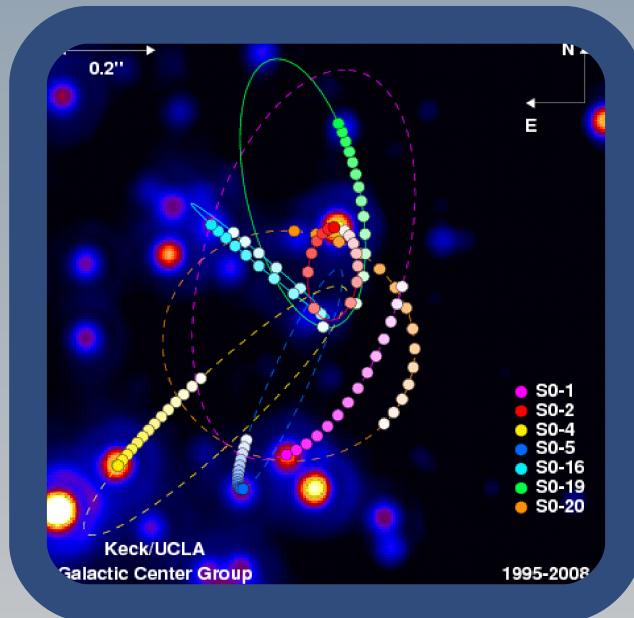


**Energy transport inside the star**

C: Convective  
R: Radiative

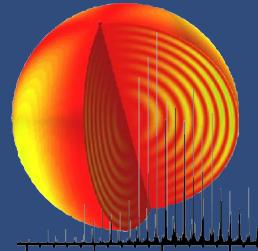


The **observation** or the **lack** of such unusual stars may provide **constraints on the DM characteristics** and help in the determination of the DM density at a given location.





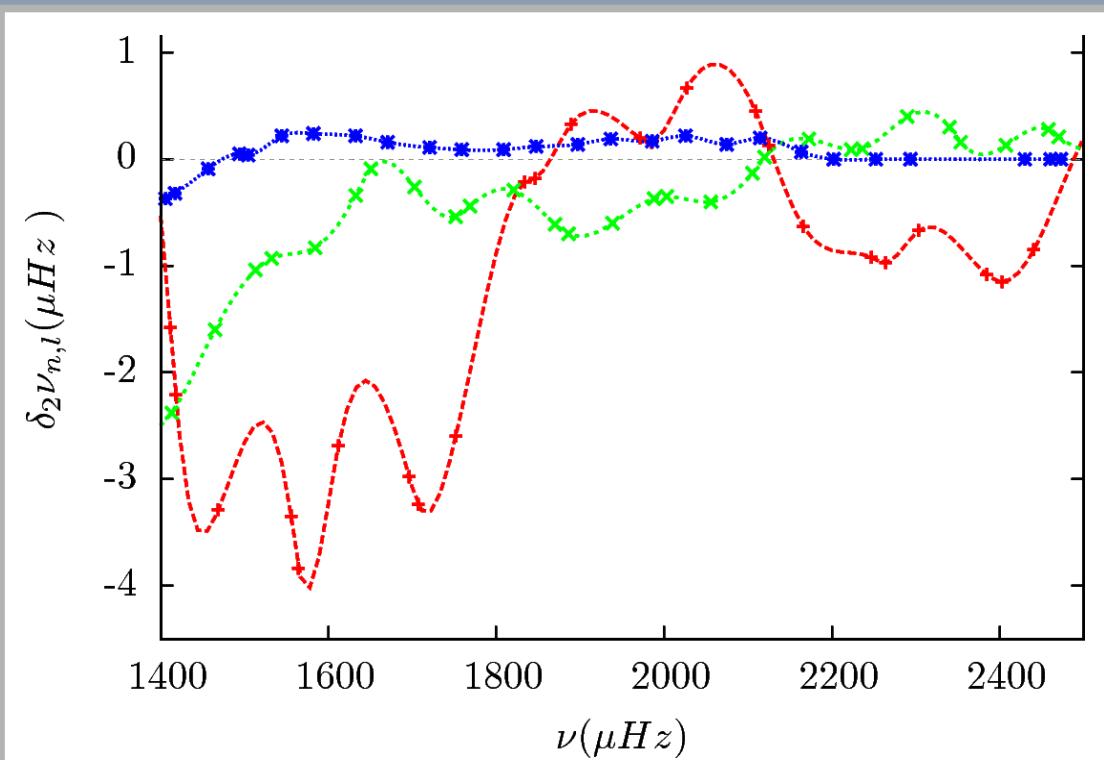
Thank you for your attention!



## Asteroseismology (work in progress)

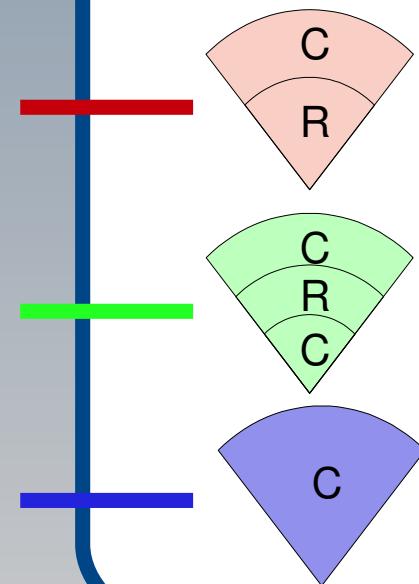
- The analysis of the modes of vibration of the star is a powerful tool to **detect** the presence of **convective cores**.

$$\delta_2 \nu_{l,n} = \nu_{l,n+1} - 2\nu_{l,n} + \nu_{l,n-1}$$



**Energy transport inside the star**

C: Convective  
R: Radiative



# Summary

Stellar evolution **within a DM halo:**

- **Classical scenario:**

Star powered by the  
**thermonuclear energy**

- **Low DM densities:**

Star powered by the  
**thermonuclear energy +**  
**energy from WIMP annihilation**

- **High DM densities:**

Collapse balanced by the  
**energy from WIMP annihilation**

$$\begin{array}{l} \rho_\chi \\ (\text{GeV cm}^{-3}) \end{array}$$

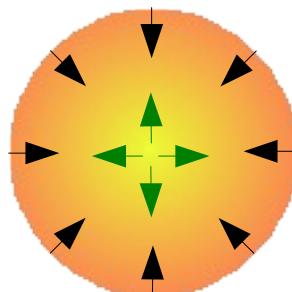
$$0.3$$

$$5 \cdot 10^{24}$$

$$\varepsilon_\chi / \varepsilon_t$$

$$0\%$$

$$M_\star = 1 M_\odot$$



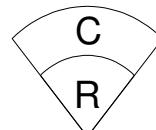
$$T_c \text{ (MK)}$$

$$13.4$$

$$t_{MS} \text{ (Myr)}$$

$$9500$$

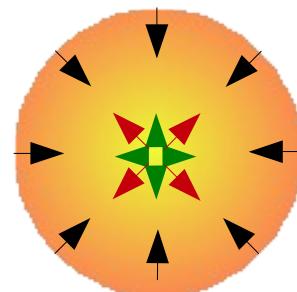
Energy  
transport



$$10^9$$

$$2 \cdot 10^{34}$$

$$85\%$$



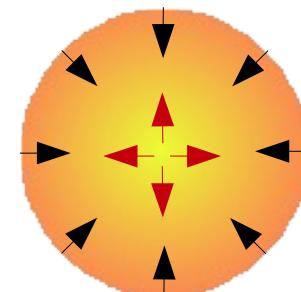
$$12.0$$

$$14150$$

$$10^{11}$$

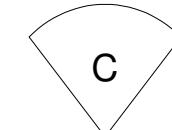
$$1 \cdot 10^{36}$$

$$100\%$$



$$5.1$$

Stop the collapse  
before the MS



- Computing the evolution of stars with different initial metallicities:  $0.0004 < Z < 0.04$

Z	$X_{in}$	$Y_{in}$	$\varepsilon_\chi$ (erg g <sup>-1</sup> s <sup>-1</sup> )	$\varepsilon_{pp}$ (erg g <sup>-1</sup> s <sup>-1</sup> )
0.0004	0.7584	0.2412	7.87 (58%)	5.76 (42%)
0.001	0.756	0.243	7.17 (57%)	5.41 (43%)
0.02	0.680	0.300	6.21 (75%)	2.07 (25%)
0.04	0.620	0.340	5.58 (77%)	1.66 (23%)

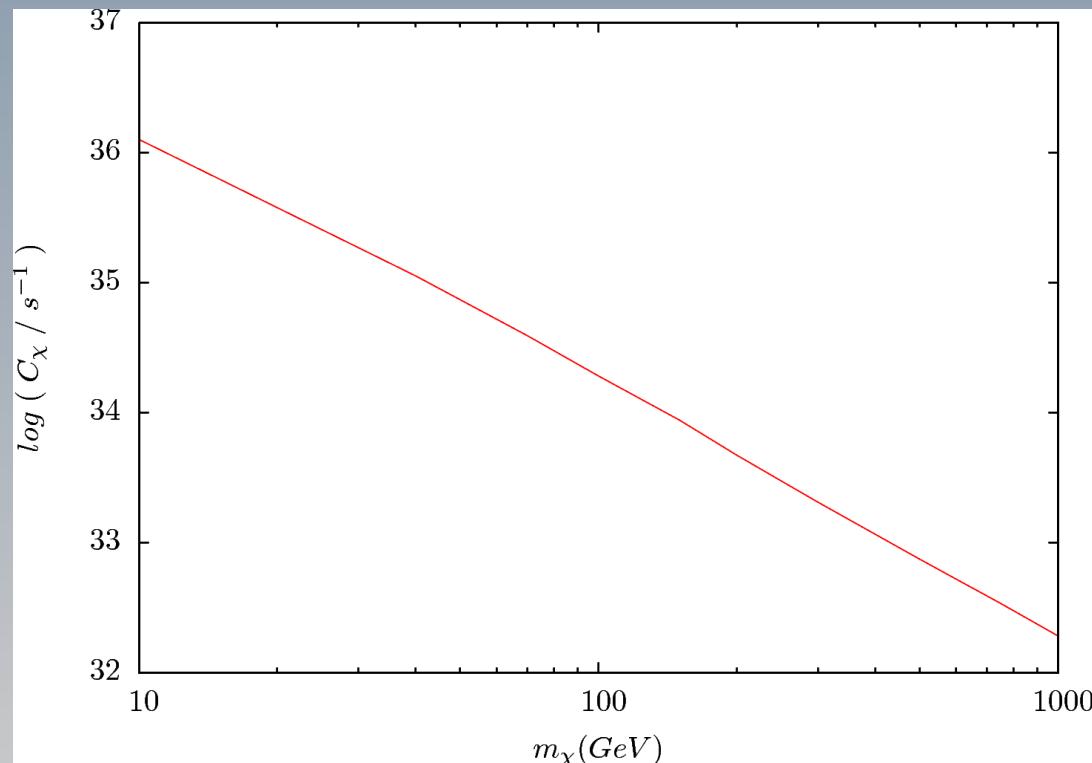
TABLE 2  
 ENERGY RATES (AND ITS PERCENTAGE OVER THE TOTAL ENERGY)  
 FOR STARS OF  $1 M_\odot$  WITH DIFFERENT INITIAL METALLICITIES,  
 EVOLVING IN A HALO WITH A DM DENSITY  $\rho_\chi = 10^8 \text{ GeV cm}^{-3}$ ,  
 AT AN AGE SUCH THAT THEIR CENTRAL HYDROGEN MASS FRACTION  
 IS  $X_c=0.60$ .

# Capture and annihilation of DM

$$C_\chi(t) = \int_0^{R_\star} 4\pi r^2 \int_0^\infty \frac{f(u)}{u} w \Omega_v^-(w) du dr$$

Gould (1987)

- Influence of the mass of the DM particles:

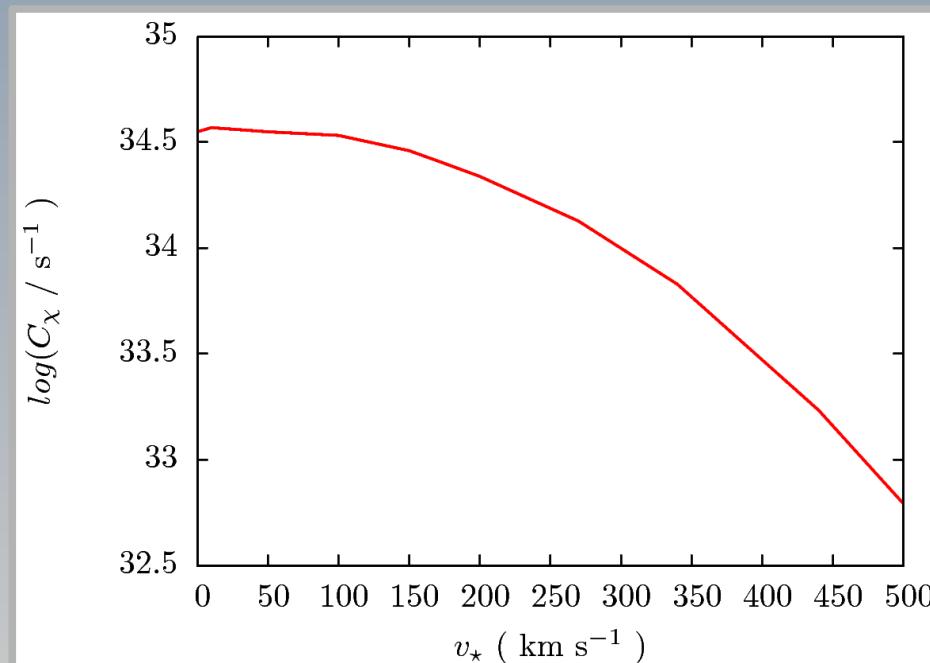


# Capture and annihilation of DM

$$C_\chi(t) = \int_0^{R_\star} 4\pi r^2 \int_0^\infty \frac{f(u)}{u} w \Omega_v^-(w) du dr$$

Gould (1987)

- Influence of the velocities:
  - Constant  $v_\chi^- = 270 \text{ km s}^{-1}$ , varying  $v_\star$ :



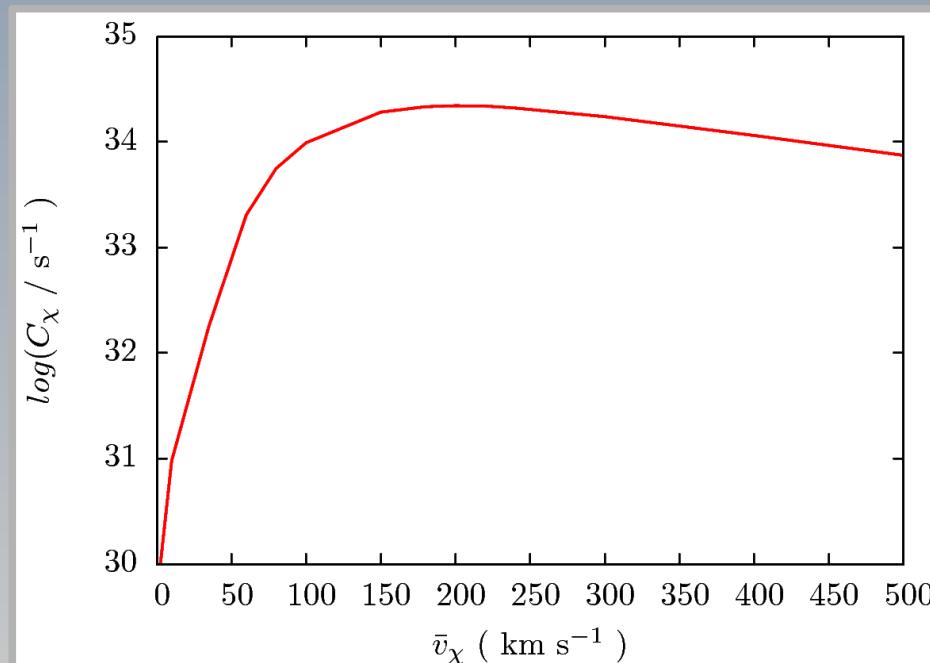
C E N  
T R A

# Capture and annihilation of DM

$$C_\chi(t) = \int_0^{R_\star} 4\pi r^2 \int_0^\infty \frac{f(u)}{u} w \Omega_v^-(w) du dr$$

Gould (1987)

- Influence of the velocities:
  - Constant  $v_\star = 220 \text{ km s}^{-1}$ , varying  $\bar{v}_\chi$ :



C E N  
T R A

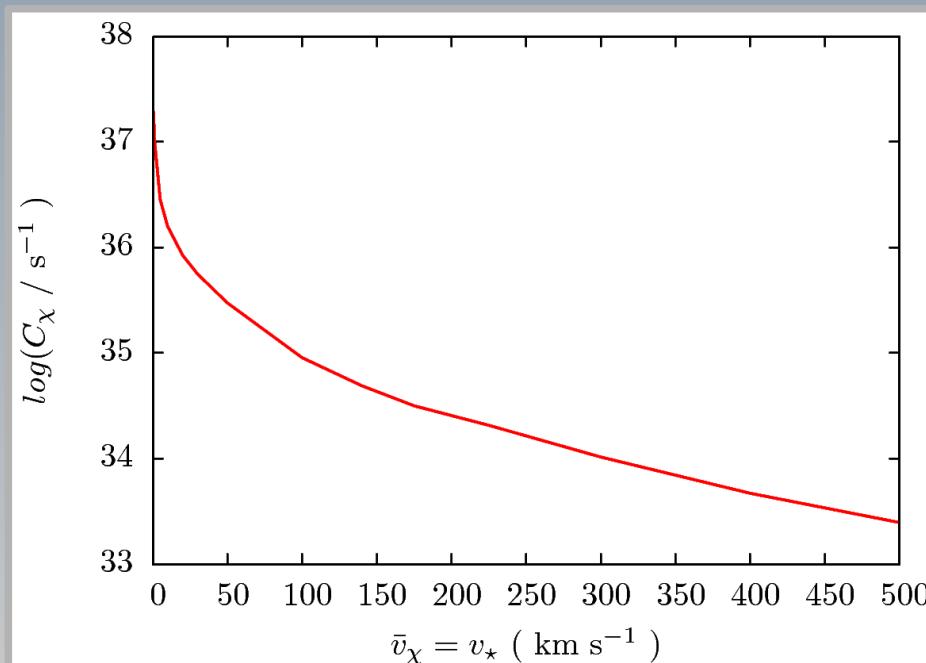
# Capture and annihilation of DM

$$C_\chi(t) = \int_0^{R_\star} 4\pi r^2 \int_0^\infty \frac{f(u)}{u} w \Omega_v^-(w) du dr$$

Gould (1987)

- Influence of the velocities:

- Keeping  $\bar{v}_\chi = v_\star$



C E N  
T R A