# Dark Matter in the Sun: scattering off Electrons vs Nucleons

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in collaboration with

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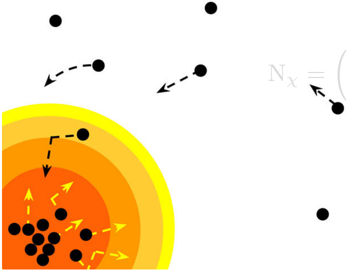
# Outline

# Introduction

- If DM ($\chi$) has a non vanishing $\sigma_{\chi T}$, it can be captured in the Sun.
  Press and Spergel '85, Griest and Seckel '86, Gould '87
- Dynamics governed by the equation

$$\frac{dN_\chi}{dt} = C_\odot - E_\odot N_\chi - A_\odot N_\chi^2$$

$$N_\chi = \left(\frac{C_\odot}{A_\odot}\right)^{1/2} \frac{\tanh\left(\kappa t_\odot/\tau\right)}{\kappa + \frac{1}{2} E_\odot \tau \tanh\left(\kappa t_\odot/\tau\right)}.$$



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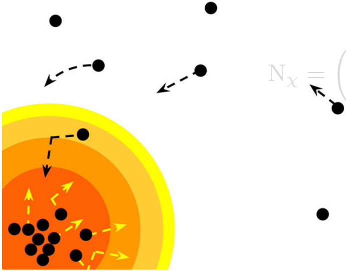

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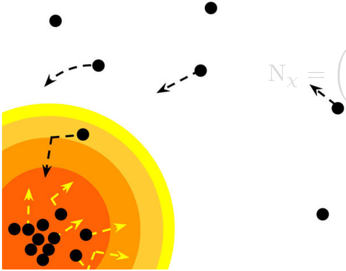

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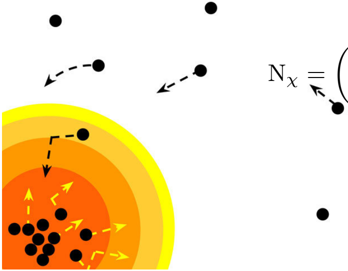

# Introduction: Scattering cross sections

The usual SI and SD cross sections for DM-nucleon interactions:

$$\sigma_{i,0}^{\mathrm{SD}} = \left(\frac{\tilde{\mu}_{A_i}}{\tilde{\mu}_p}\right)^2 \frac{4\,(J_i+1)}{3\,J_i} \, |\langle S_{p,i}\rangle + \langle S_{n,i}\rangle|^2 \, \sigma_{p,0}^{\mathrm{SD}} \, ,$$

$$\sigma_{i,0}^{\mathrm{SI}} = \left(\frac{\tilde{\mu}_{A_i}}{\tilde{\mu}_p}\right)^2 A_i^2 \, \sigma_{p,0}^{\mathrm{SI}} \, .$$

Types of scattering cross sections considered here:

$$\frac{d\sigma_{i,\mathrm{const}}(v_{\mathrm{rel}}, \cos\theta_{\mathrm{cm}})}{d\cos\theta_{\mathrm{cm}}} = \frac{\sigma_{i,0}}{2} \, ,$$

$$\frac{d\sigma_{i,v_{\mathrm{rel}}^2}(v_{\mathrm{rel}}, \cos\theta_{\mathrm{cm}})}{d\cos\theta_{\mathrm{cm}}} = \frac{\sigma_{i,0}}{2} \left(\frac{v_{\mathrm{rel}}}{v_0}\right)^2 \, ,$$

$$\frac{d\sigma_{i,q^2}(v_{\mathrm{rel}}, \cos\theta_{\mathrm{cm}})}{d\cos\theta_{\mathrm{cm}}} = \frac{\sigma_{i,0}}{2} \frac{(1 + \mathrm{m}_\chi/m_i)^2}{2} \left(\frac{q}{q_0}\right)^2 \, .$$

# Capture of Dark Matter by the Sun

- For velocity and momentum independent cross section (with $T = 0$), energy loss should be at least

$$\frac{\Delta E}{E} \geq \frac{\omega^2 - v^2}{\omega^2},$$

and from kinematics

$$0 \leq \frac{\Delta E}{E} \leq \frac{\mu}{\mu_+^2},$$

$$C_\odot = \int_0^{R_\odot} 4\pi r^2 dr \int_0^\infty du \left(\frac{\rho_\chi}{m_\chi}\right) \frac{f_\odot(u)}{u} \omega(r) \int_0^{\nu_e} R^-(\omega \to \nu) d\nu.$$

- Typical 3-momentum transfer is $\mathcal{O}\left(KeV\right)$.

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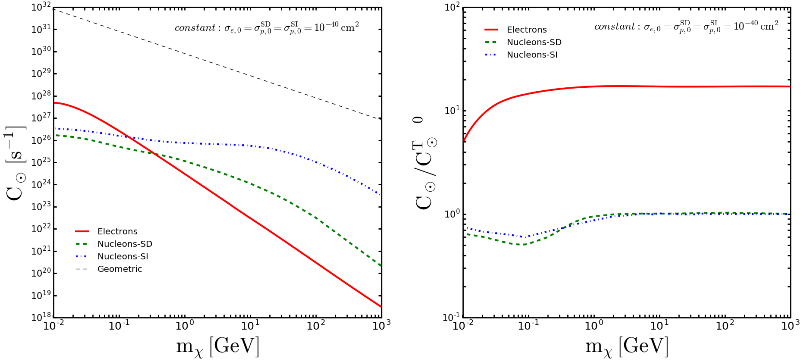
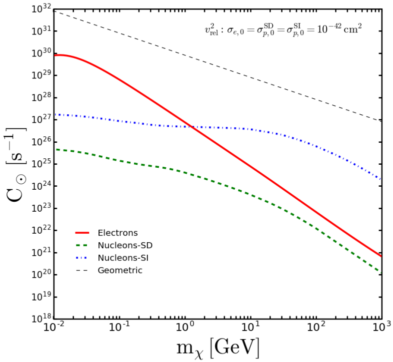
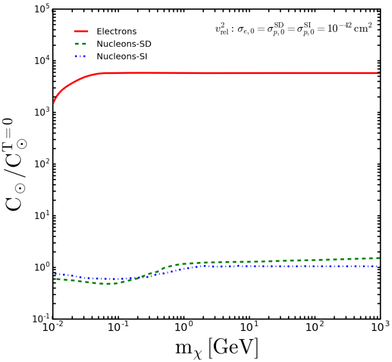
The standard case:



# Capture of Dark Matter by the Sun: $v_{rel}^2$

New !



# Capture of Dark Matter by the Sun: $q^2$

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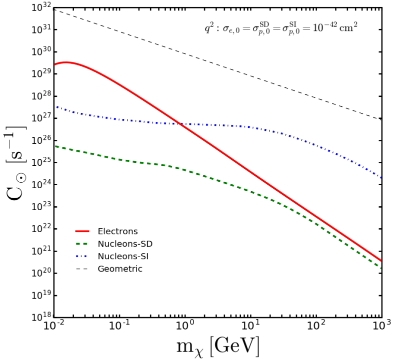


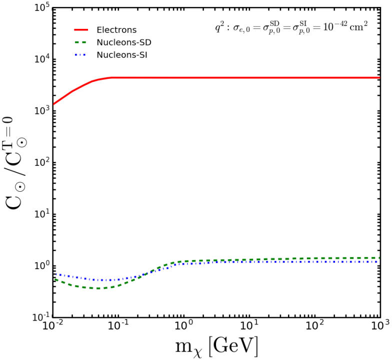

The velocity distributions of target and DM particles can be assumed to have Maxwell-Boltzmann form with a cut-off at escape velocity. Gould and Raffelt '90

$$
\begin{aligned}
f_i(\boldsymbol{u}, r) &= \frac{1}{\sqrt{\pi^3}} \left(\frac{m_i}{2\,T_\odot(r)}\right)^{3/2} e^{-\frac{m_i\,u^2}{2\,T_\odot(r)}} , \\
f_\chi(\boldsymbol{w}, r) &= \frac{e^{-w^2/v_\chi^2(r)}\ \Theta(v_c(r) - w)}{\sqrt{\pi^3}\, v_\chi^3(r)\ \left(\mathrm{Erf}\left(\frac{v_c(r)}{v_\chi(r)}\right) - \frac{2}{\sqrt{\pi}}\,\frac{v_c(r)}{v_\chi(r)}\, e^{-v_c^2(r)/v_\chi^2(r)}\right)} ,
\end{aligned}
$$

$T_\odot(r)$ and $v_\chi(r) \equiv \sqrt{2\,\mathrm{T}_\chi(r)/\mathrm{m}_\chi}$ are the solar temperature and the thermal DM velocity at a distance $r$ from the center of the Sun

# Dark matter distribution in the Sun: radial

- LTE:

$$n_{\chi,\mathrm{LTE}}(r,t) = n_{\chi,\mathrm{LTE},0}(t) \left(\frac{T_\odot(r)}{T_\odot(0)}\right)^{3/2} \exp\left(-\int_0^r \frac{\alpha(r')\frac{\mathrm{d}T_\odot(r',t)}{\mathrm{d}r'} + \mathrm{m}_\chi \frac{\mathrm{d}\phi(r')}{\mathrm{d}r'}}{T_\odot(r')}\,\mathrm{d}r'\right) ,$$

- Isothermal:

$$n_{\chi,\mathrm{iso}}(r,t) = N_\chi(t) \frac{e^{-\mathrm{m}_\chi\phi(r)/\mathrm{T}_\chi}}{\int_0^{R_\odot} e^{-\mathrm{m}_\chi\phi(r)/\mathrm{T}_\chi}\,4\pi r^2\,\mathrm{d}r} .$$

# Evaporation

- Evaporation depends on the DM distribution in the Sun. Isothermal profile and Local thermodynamic equilibrium profile.

$$E_\odot = \int_0^{R_\odot} s(r)\, n_\chi(r,t)\, 4\pi r^2\, \mathrm{d}r \int_0^{v_c(r)} f_\chi(\boldsymbol{w}, r)\, 4\pi w^2\, \mathrm{d}w \int_{v_e(r)}^{\infty} R_i^+(w \to v)\mathrm{d}v \;.$$

$$s(r) = \eta_{\rm ang}(r)\, \eta_{\rm mult}(r)\, e^{-\tau(r)}$$

$$n_\chi(r,t)\, f_\chi(\boldsymbol{w}, r) = \mathfrak{f}(K)\, n_{\chi,\rm LTE}(r,t)\, f_{\chi,\rm LTE}(\boldsymbol{w}, r) + (1-\mathfrak{f}(K))\; n_{\chi,\rm iso}(r,t)\, f_{\chi,\rm iso}(\boldsymbol{w}, r) \;,$$

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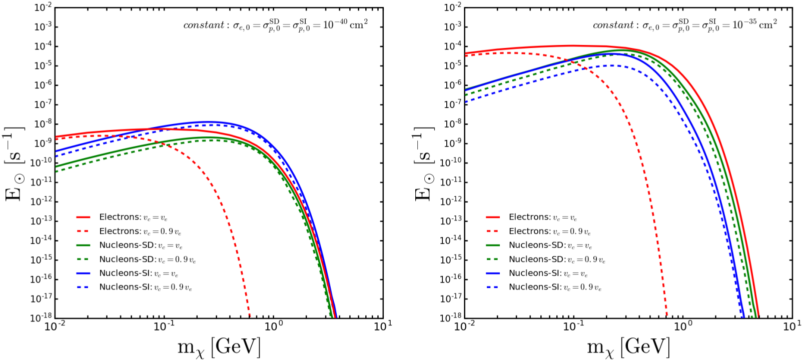
# Evaporation: Const.

The usual case:



# Evaporation: $v_{rel}^2$

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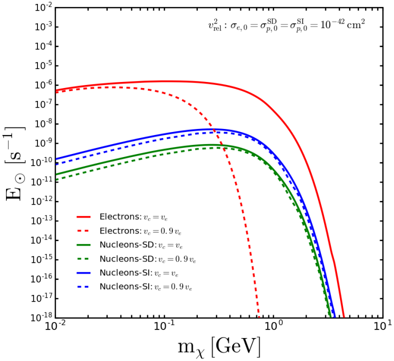


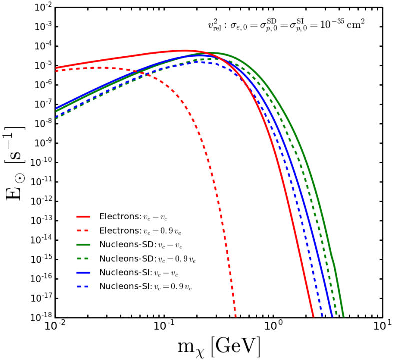

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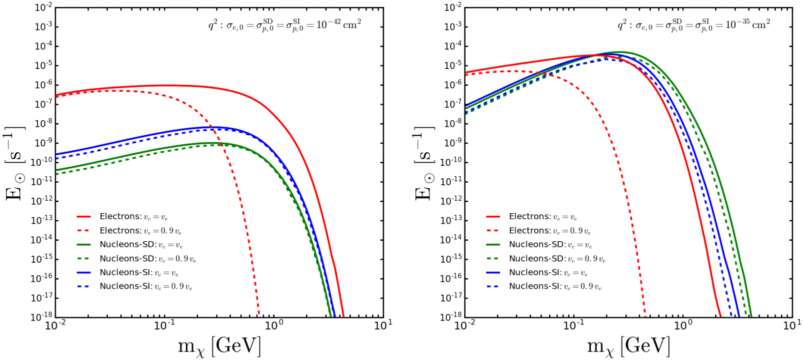


# Evaporation mass

Busoni et.al. '14

$$\left| N_\chi(m_{\rm evap}) - \frac{C_\odot(m_{\rm evap})}{E_\odot(m_{\rm evap})} \right| = 0.1\, N_\chi(m_{\rm evap}) \ ,$$

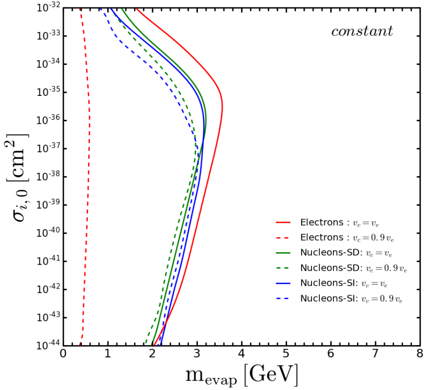
In the limit when equilibrium has been reached, i.e., $\kappa\, t_\odot \gg \tau_{\rm eq}$, it can be written as

$$E_\odot(m_{\rm evap})\, \tau_{\rm eq}(m_{\rm evap}) = \frac{1}{\sqrt{0.11}} \ .$$

$$\kappa = \left(1 + \left(\frac{E_\odot \tau}{2}\right)\right)^2$$

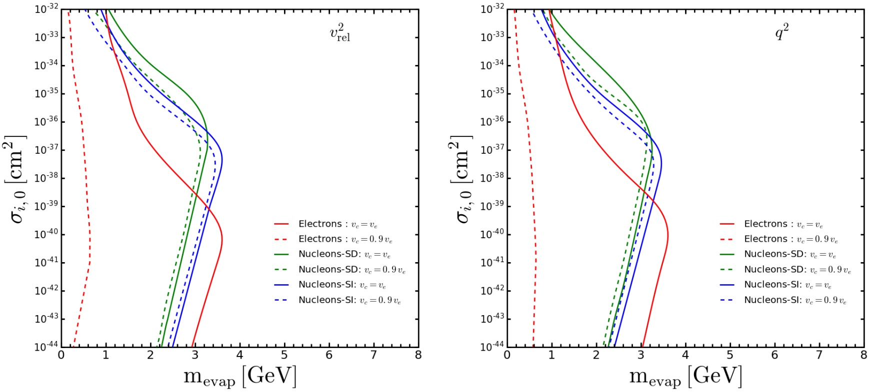
# Evaporation mass: Const.

New !



# Evaporation mass: $v_{rel}^2$ and $q^2$

New !



# Annihilation and the total Annihilation rate

- Again, annihilation depends on the DM distribution in the Sun.

$$A_\odot = \langle \sigma \nu \rangle \frac{\int \mathrm{d}V \; n_\chi^2}{\left(\int \mathrm{d}V \; n_\chi\right)^2}$$

  Only s-wave annihilation, with $\langle \sigma \nu \rangle = 3 \cdot 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$

- Finally, the total annihilation rate is

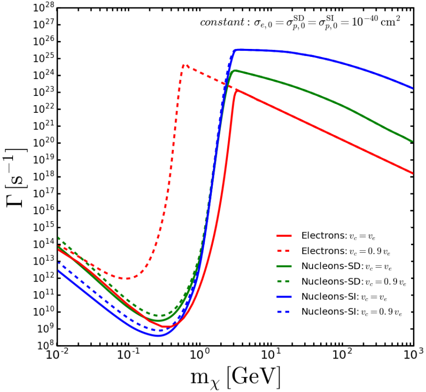
$$\Gamma = \frac{1}{2} A_\odot N_\chi^2.$$

- Neutrino flux at detector:

$$\frac{d\Phi^{\nu_j}}{dE_{\nu_j}}(E_{\nu_j}) \;\; = \;\; \frac{1}{4\pi d_\odot^2} \Gamma(m_\chi, \sigma_\chi) \left( \Sigma P(\nu_i \to \nu_j) \frac{dF}{dE_{\nu_j}}(E_{\nu_j}) \right)$$

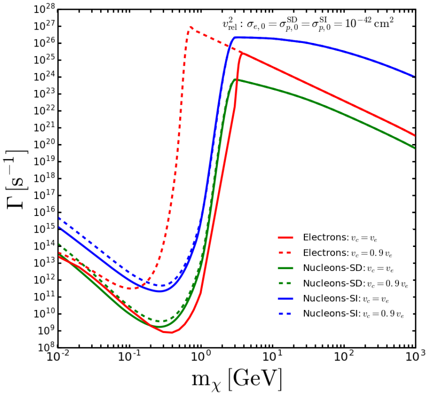
# The total annihilation rate: Const.

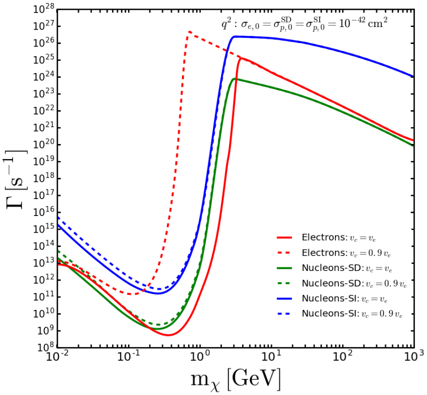
New !



# The total annihilation rate: $v_{rel}^2$ and $q^2$

New !



# Conclusion and Outlook

- Dark Matter annihilation in the Sun: A good test for "Particle dark matter" paradigm.
- Phenomenology of Dark Matter - electron scattering in the Sun is interesting. Most relevant for leptophilic models.
- Complete exploration of leptophilic Dark Matter models in progress.
- Monte Carlo to resolve the ambiguity in the cut-off of DM distribution in the Sun in progress.

# Dark matter distribution in the Sun: DM Effective temperature

Without cut-off , Press and Spergel '85

$$\sum_i \int_0^{R_\odot} \epsilon_i(r, \mathsf{T}_\chi, T_c)\, 4\pi r^2\, \mathrm{d}r = 0 \ ,$$

$$\begin{aligned}\epsilon_i(r, \mathsf{T}_\chi, T_c) \ \equiv \ & \int \mathrm{d}^3\boldsymbol{w}\, n_{\chi,\mathrm{iso}}(r, t_\odot)\, f_{\chi,\mathrm{iso}}(\boldsymbol{w}, r) \\ & \int \mathrm{d}^3\boldsymbol{u}\, n_i(r)\, f_i(\boldsymbol{u}, r)\, \sigma_{i,0}\, |\boldsymbol{w} - \boldsymbol{u}|\, \langle \Delta E_i \rangle \ ,\end{aligned}$$

# Dark matter distribution in the Sun: DM Effective temperature

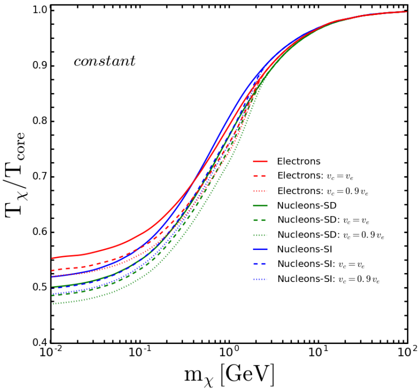
With cut-off , correction to Press and Spergel '85

$$\sum_i \int_0^{R_\odot} \epsilon_i(r, \mathsf{T}_\chi, T_c)\, 4\pi r^2\, \mathrm{d}r = \sum_i \int_0^{R_\odot} \epsilon_{\mathrm{evap},i}(r, \mathsf{T}_\chi, T_c)\, 4\pi r^2\, \mathrm{d}r \ ,$$

$$\begin{aligned} \epsilon_{\mathrm{evap},i}(r, \mathsf{T}_\chi, T_c) &= \int_0^{v_c(r)} n_{\chi,\mathrm{iso}}(r,t)\, f_{\chi,\mathrm{iso}}(\boldsymbol{w}, r)\, 4\pi w^2\, \mathrm{d}w \\ & \int_{v_e(r)}^{\infty} K_i^+(w \to v)\, \mathrm{d}v \ . \end{aligned}$$

$$\begin{aligned} K_i(w \to v) &= \int n_i(r)\, \frac{\mathrm{d}\sigma_i}{\mathrm{d}v}\, |\boldsymbol{w} - \boldsymbol{u}|\, \Delta E_i\, f_i(\boldsymbol{u}, r)\, \mathrm{d}^3\boldsymbol{u} \\ &= \Delta E_i\, R_i(w \to v) = \frac{\mathrm{m}_\chi}{2}\, \left(v^2 - w^2\right)\, R_i(w \to v) \ . \end{aligned}$$

# Dark matter distribution in the Sun: DM Effective temperature



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