Dark Matter capture by the Sun

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KM3NeT

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1. Big picture for Dark Matter searches

Direct search

• Search of a scattering signal between a WIMP and a nucleous (electron?).

• Conditions of very low background needed.

• XENON1T, DAMA/LIBRA, CRESST...

Inirect search

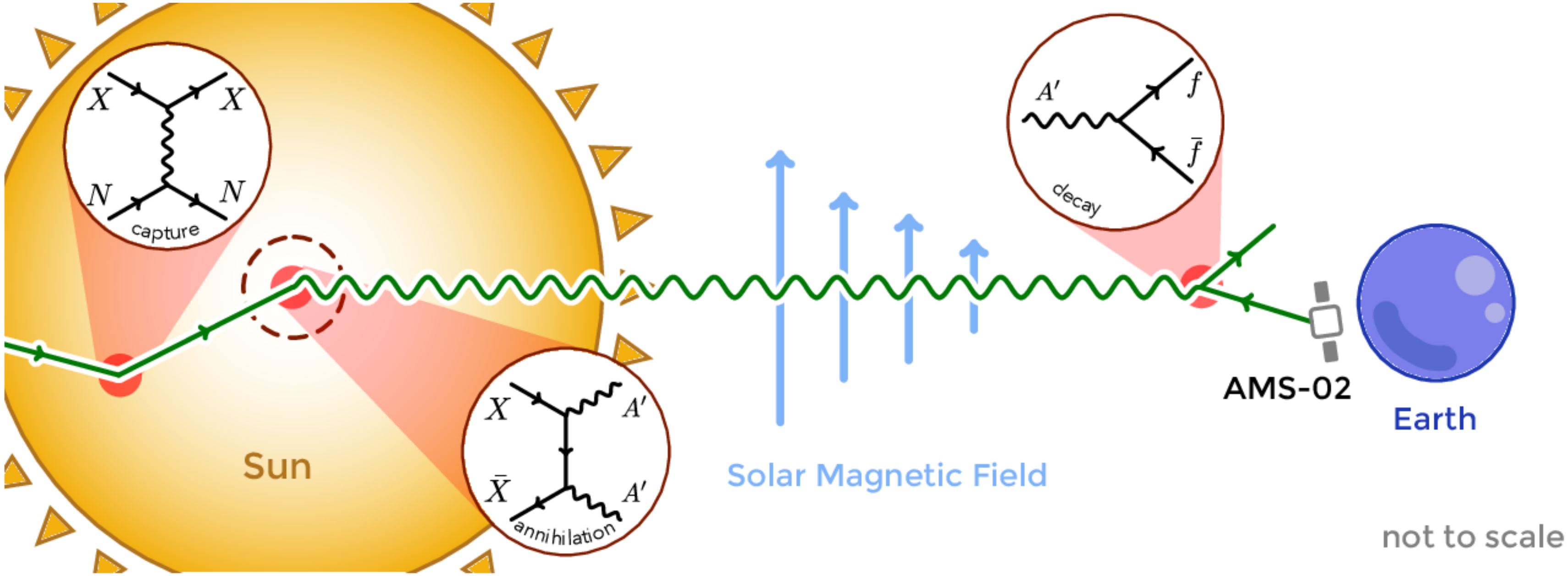
• Search of the products of Dark Matter decay/annihilation.

• The density of DM is low $\rightarrow$ it's more likely to find a signal when looking to the Sun, the Earth, the Galactic Center...

• KM3NeT, IceCube, ANTARES, MAGIC, KK...

• If no signal is found, we can set limits to the DM - proton/neutron cross section.

• For indirect search, we assume $\Gamma_R = 2C_R$. The neutrino flux emitted in DM annihilation depends on the capture rate, and therefore, on the DM - nucleous cross section.


X
X
N
N
capture
X
A′
X̄
A′
annihilation
Sun
Solar Magnetic Field
A′
f
f̄
decay
AMS-02
Earth
not to scale

2. Dark Matter velocity

• Dark Matter is present in the galactic halo with a mean velocity of $\beta \approx 10^{-3}$.
• We need to use a velocity distribution for the Dark Matter particles. We have different options:

- **Standard Halo Model (SHM)**: one single component - an isotropic and spheric distribution that takes into account the angular velocity of the Milky Way.
- **GAIA Sausage component:** it is believed that a long time ago another galaxy collided with the Milky Way. This distribution corresponds to the Dark Matter that comes from that galaxy.
- **Standard Halo Model Plus Plus (SHM++)**: a distribution that takes into account both of the components above.

- **SHM**:

$$f_R(\vec{u}) = \frac{1}{(2\pi\sigma_u^2)^{3/2} N_{R,esc}} \exp\left(-\frac{|\vec{u}|^2}{2\sigma_\mu^2}\right) \Theta(\tilde{v}_{esc} - |\vec{u}|).$$

- **GAIA Sausage component:**

$$f_S(\vec{u}) = \frac{1}{(2\pi)^{3/2}\sigma_r\sigma_\theta^2 N_{S,esc}} \exp\left(-\frac{u_r^2}{2\sigma_r^2} - \frac{u_\theta^2}{2\sigma_\theta^2} - \frac{u_\phi^2}{2\sigma_\phi^2}\right) \Theta(\tilde{v}_{esc} - |\vec{u}|).$$

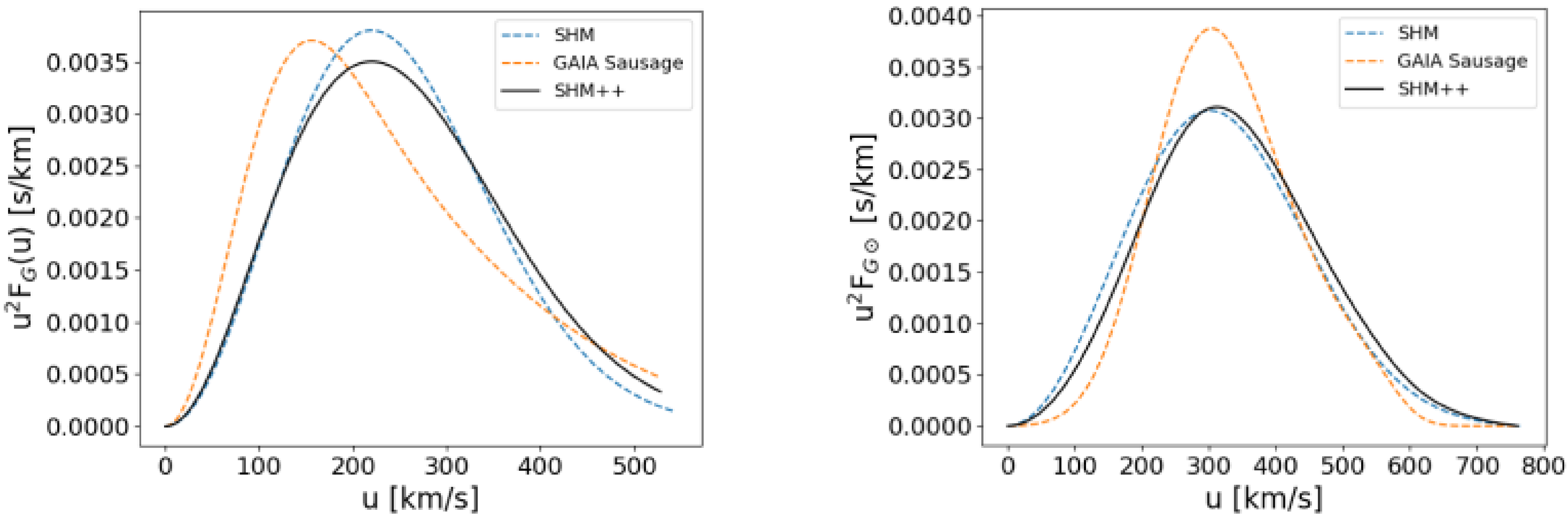
- **SHM++**:

$$f_T(\vec{u}) = (1-\eta) f_R(\vec{u}) + \eta f_S(\vec{u}).$$

- $\eta = 0.2$ is the mixing factor between the two components.
- $\tilde{v}_{esc} = 544\text{km/s}$ is the scape velocity of the galaxy.
- The other factors are (remember $v_0 \approx 220\text{km/s}$):

$$\sigma_r^2 = \frac{3v_0^2}{2(3-2\beta)}, \ \sigma_\theta^2 = \sigma_\phi^2 = \frac{3v_0^2(1-\beta)}{2(3-2\beta)},$$

with $\beta = 0.9$.

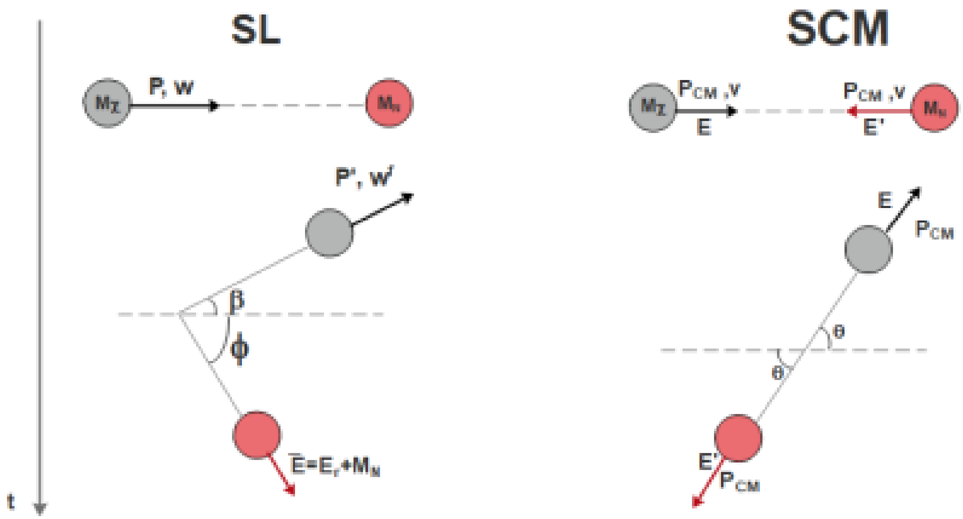

SHM
GAIA Sausage
SHM++
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
u^{2}F$_G$(u) [s/km]
0
100
200
300
400
500
u [km/s]
0.0040
u^{2}F$_{G\odot}$ [s/km]
600
700
800

3. Kinematics

• Let's consider two different scenarios: the collision of DM with a nucleus at rest and the collision with a moving nucleous.

3.1. Collision with a nucleous at rest

• A DM particle with velocity w collides with a given nucleous with mass M_N. In the system of reference of the center of mass, the emission angle of both the DM particle and the nucleous is given by θ. The scheme would be:

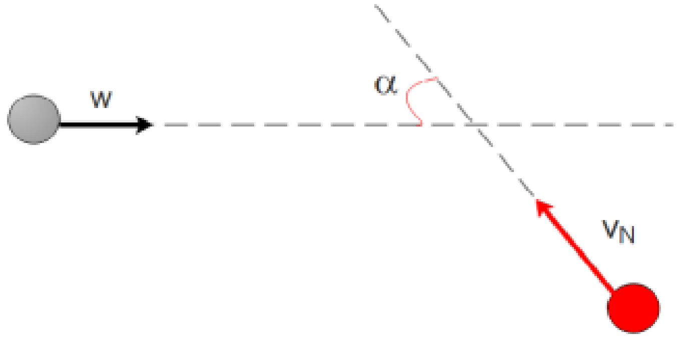


Then, the nucleous recoil energy in the non relativistic limit is given by:

$$E_r = \frac{E_{max}}{2}(1 - \cos\theta), \quad E_{max} = \frac{2M_\chi^2 M_N}{(M_N + M_\chi)^2} w^2.$$

3.2. Collision with a moving nucleous

• A DM particle with velocity w collides with a given nucleous with mass M_N and velocity $\vec{v}$. In the system of reference of the Sun, the angle of the collision is α. The scheme would be:

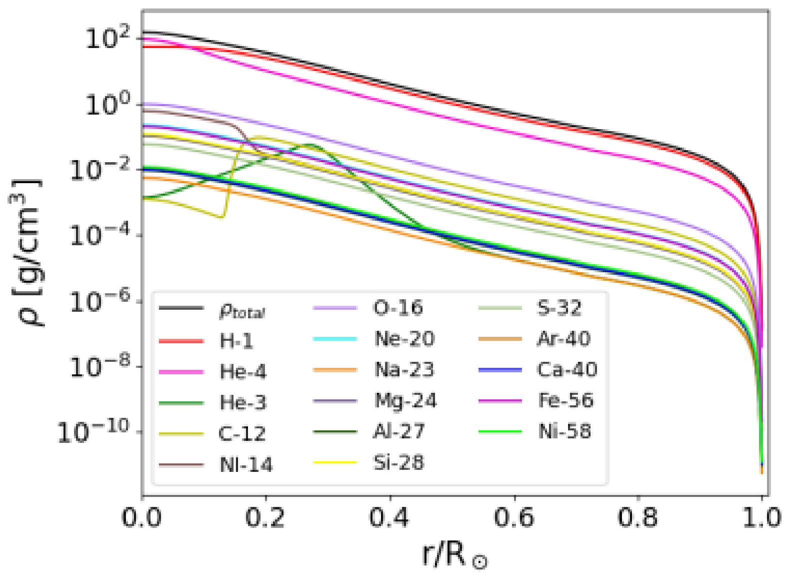


Then, the DM final velocity is given by:

$$\begin{aligned} w_x^f &= \frac{1}{M_N + M_\chi}(M_N w \cos\theta - M_N v \cos\alpha + M_\chi w), \\ w_y^f &= \frac{M_N}{M_N + M_\chi}(w \sin\theta \cos\phi + v_N \sin\alpha), \\ w_z^f &= \frac{M_N}{M_N + M_\chi} w \sin\theta \sin\phi. \end{aligned} \tag{1}$$

4. Solar model

- The composition of the Sun will be given by the AGSS09 model:

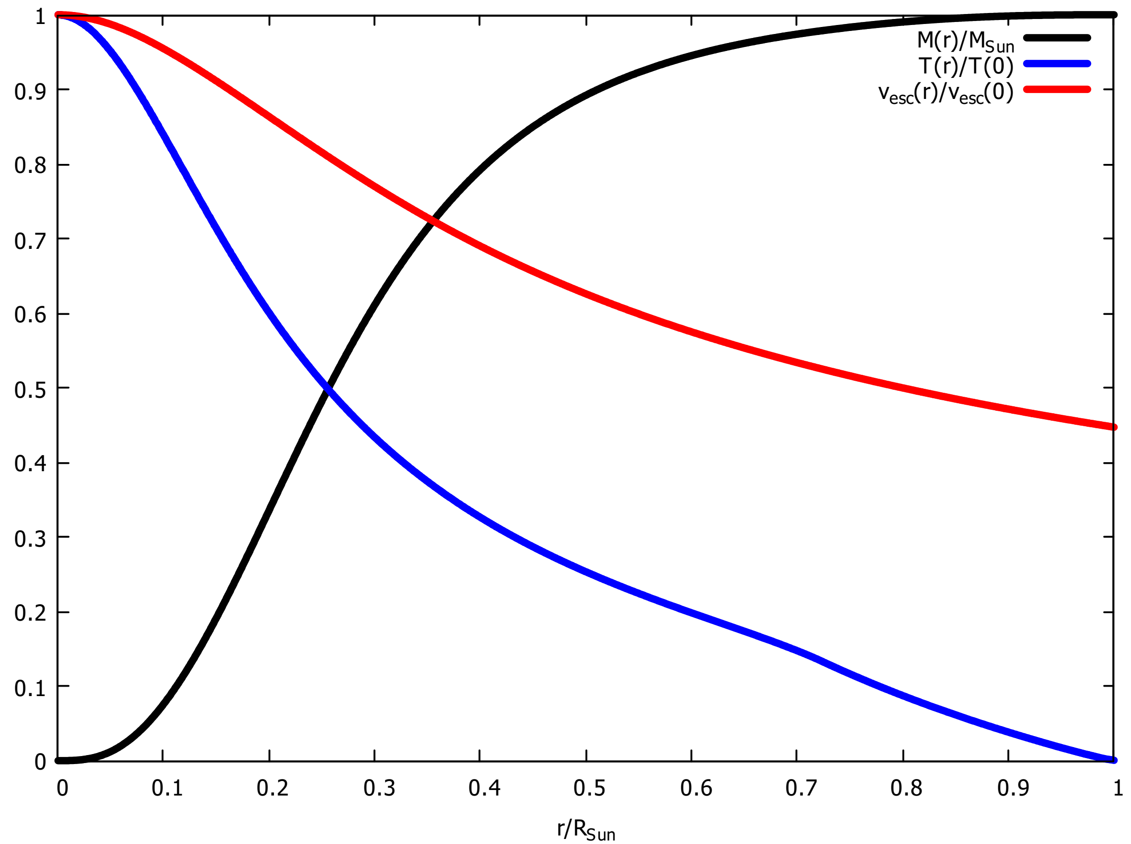


- A DM particle with velocity u that falls into the Sun will have a velocity:

$$w = \sqrt{u^2 + v_{esc}^2}.$$

With $v_{esc} = \sqrt{-2V(r)}$ being the scape velocity in the Sun:

$$V(r) = \int_r^\infty \frac{GM(r')}{r'^2} dr', \quad M(r) = \begin{cases} 4\pi \int_0^r \rho(r) dr & \text{if} \quad r < R_\odot, \\ M_\odot & \text{if} \quad r > R_\odot. \end{cases}$$



$T(0) = 1.45 \cdot 10^7$ K,

$M_\odot = 1,98 \cdot 10^{30}$ kg,

$R_\odot = 6.9 \cdot 10^5$ km,

$v_{esc}(0) = 1381$ km/s.

5. Dark Matter - nucleous interactions

• We will consider two different interactions between Dark Matter and baryonic matter (protons and neutrons): one spin-dependent and the other one spin-independent.

$$V_{SI}(\vec{r}) = c_1^i \delta^3(\vec{r}),$$

$$V_{SD}(\vec{r}) = c_4^i \delta^3(\vec{r}) \vec{S}_i \cdot \vec{S}_\chi.$$

which leads to the differential cross sections:

$$\frac{\mathrm{d}\sigma_{SI}^i}{\mathrm{d}E_r} = \frac{M_i}{2\pi w^2} |c_1^i|^2,$$

$$\frac{\mathrm{d}\sigma_{SD}^i}{\mathrm{d}E_r} = \frac{3M_i}{32\pi w^2} |c_4^i|^2.$$

with $i = p, n$.

• The DM - nucleon cross section can be used to obtain the DM - nucleous cross sections:

$$\frac{\mathrm{d}\sigma_{SI}^{N}}{\mathrm{d}E_r} = \frac{M_N}{2\pi w^2}\frac{1}{2J+1}\frac{1}{2}\sum_{\tau=0,1}\sum_{\tau'=0,1} 8\pi c_1^{\tau} c_1^{\tau'} W_M^{\tau\tau'}(y),$$

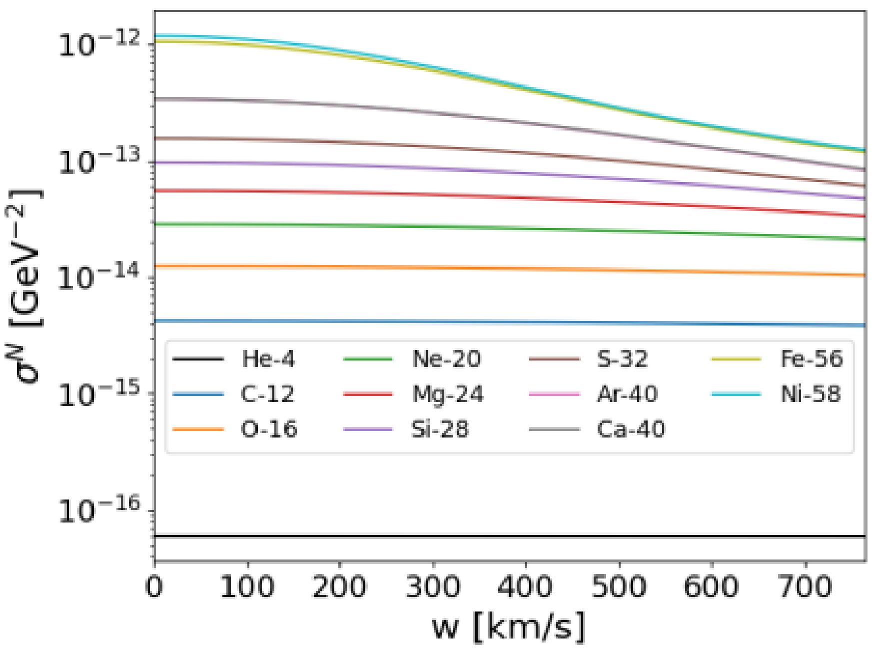
$$\frac{\mathrm{d}\sigma_{SD}^{N}}{\mathrm{d}E_r} = \frac{M_N}{2\pi w^2}\frac{1}{2J+1}\frac{1}{32}\sum_{\tau=0,1}\sum_{\tau'=0,1} 8\pi c_4^{\tau} c_4^{\tau'} (W_{\Sigma'}^{\tau\tau'}(y) + W_{\Sigma''}^{\tau\tau'}(y)).$$

Being $W_{M,\Sigma',\Sigma''}$ tabulated functions and:

$$y = \left(\frac{qb}{2}\right)^2,$$

$$b = \sqrt{\frac{2}{3}}\left(0.91\left(\frac{M_N}{\mathrm{GeV}}\right)^{1/3} + 0.3\right)\frac{1}{0.197\mathrm{GeV}},$$

$$c_{1(4)}^{0} = c_{1(4)}^{p} + c_{1(4)}^{n}, \quad c_{1(4)}^{1} = c_{1(4)}^{p} - c_{1(4)}^{n}.$$



• For the SI the constraints are obtained assuming $c_1^n = c_1^p$. The limits for the cross sections are (from XENON1T and PICO-60):

$$\sigma_{SI}^i < 2.313 \cdot 10^{-21} M_\chi^{1+\left(\frac{13}{M_\chi}\right)^2} \, [\text{GeV}^{-2}],$$

$$\sigma_{SD}^n < 3.855 \cdot 10^{-16} M_\chi^{1+\left(\frac{13}{M_\chi}\right)^2} \, [\text{GeV}^{-2}],$$

$$\sigma_{SD}^p < 1.4649 \cdot 10^{-15} M_\chi^{0.93+\left(\frac{13}{2+M_\chi}\right)^2} \, [\text{GeV}^{-2}].$$

6. Capture rate

- The capture rate for static nuclei is given by:

$$C_N = 4\pi \int_0^{R_0} n_N(r) r^2 dr \int_0^{(\tilde{v}_{esc}+v_0)} \mathrm{d}u u (u^2 + v_{esc}^2) \frac{\rho_\chi}{M_\chi} F_G(u) \int_{E_{min}}^{E_{max}} \mathrm{d}E_r \frac{\mathrm{d}\sigma^N}{\mathrm{d}E_r} \Theta(E_{max} - E_{min}),$$

with:

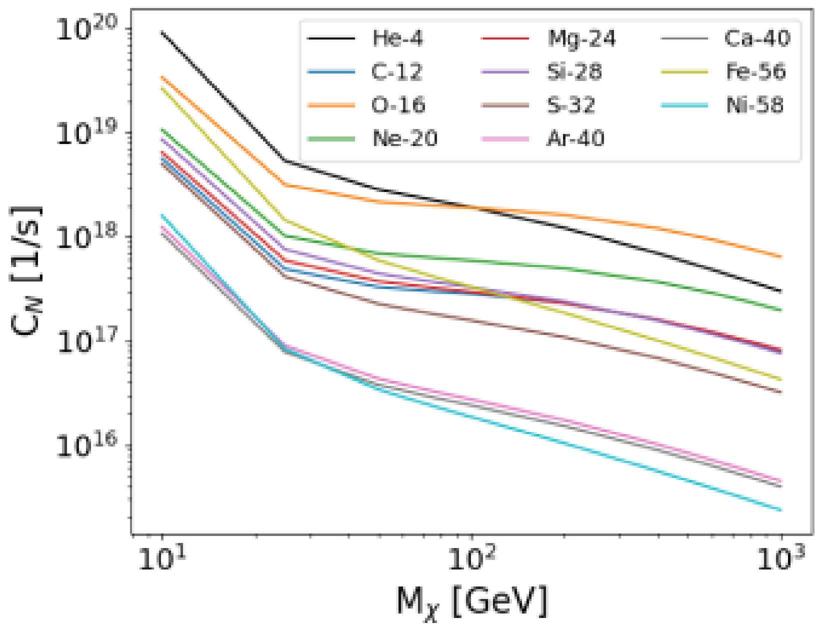
$$E_{max} = \frac{2M_\chi^2 M_N}{(M_N + M_\chi)^2} w^2, \quad E_{min} = \frac{1}{2} M_\chi u^2.$$

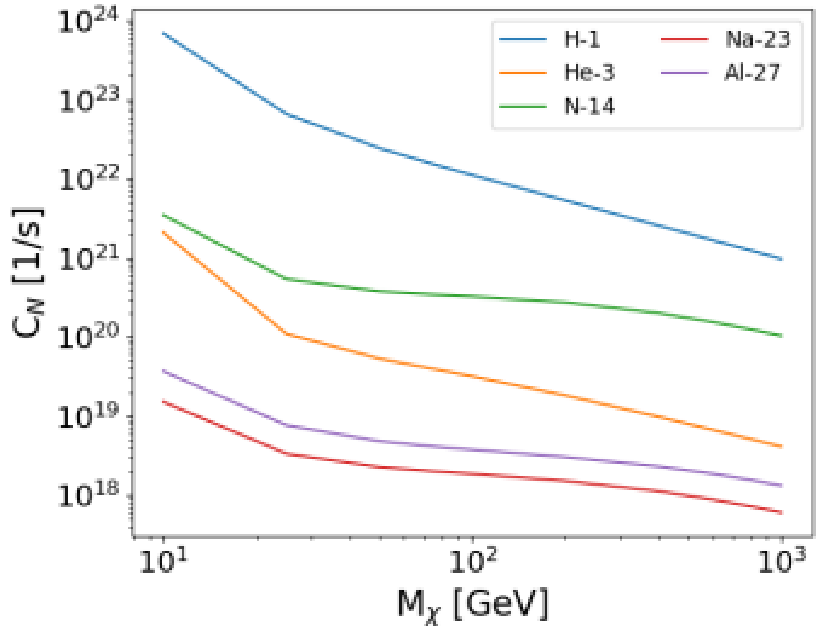
- If we consider the movement of the nuclei in the Sun:

$$C_N = 4\pi \int_0^{R_0} n_N(r) r^2 dr \int_{-1}^{1} \frac{1}{2} \mathrm{d}\cos\alpha \int_0^{(\tilde{v}_{esc}+v_0)} \mathrm{d}u u (u^2 + v_{esc}^2)^{1/2} v_\chi \frac{\rho_\chi}{M_\chi} F_G(u) \cdot$$

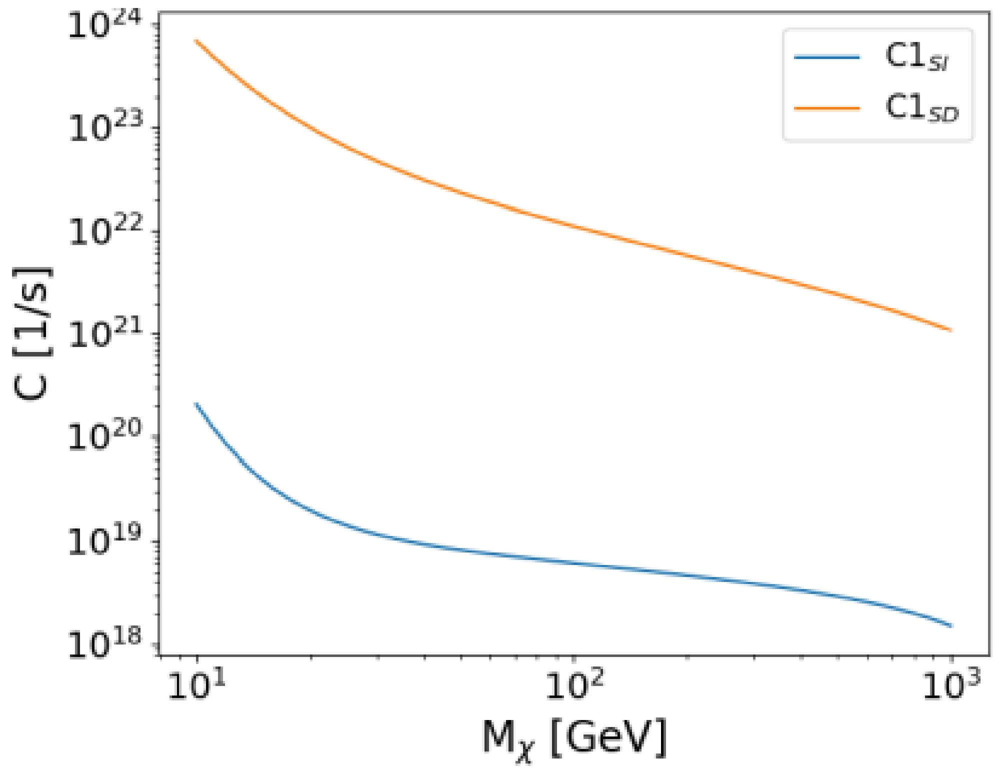
$$\cdot \int_0^{2\pi} \mathrm{d}\phi \int_{-1}^{1} \mathrm{d}\cos\theta \frac{\mathrm{d}\sigma^N}{\mathrm{d}\Omega} \Theta(v_{esc}^2 - (w^f)^2).$$

• Maximum capture rate for several nuclei. Here, we have used the SHM distribution for Dark Matter and we don't consider the movement of the targets. The elements on the left have no spin, while the elements on the right have spin.

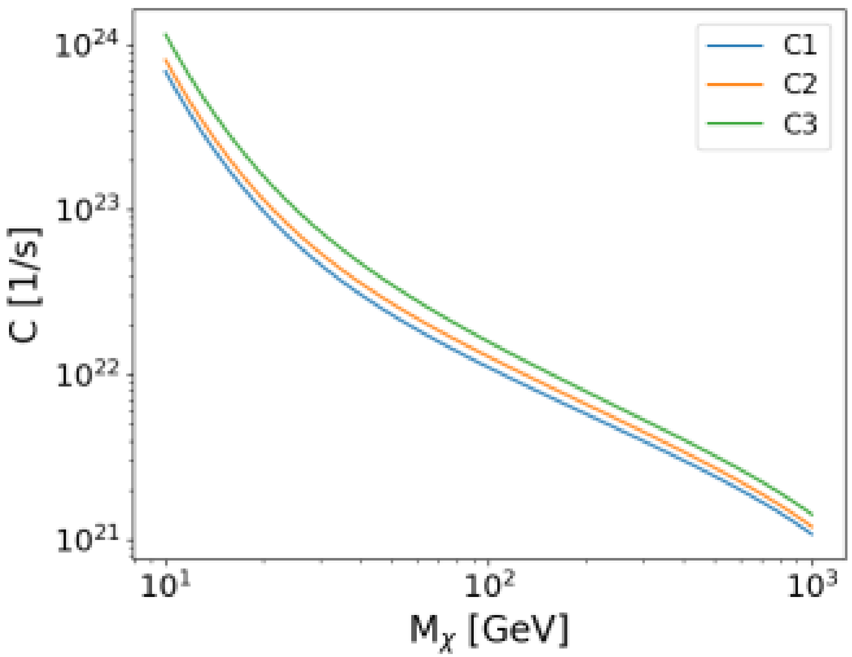


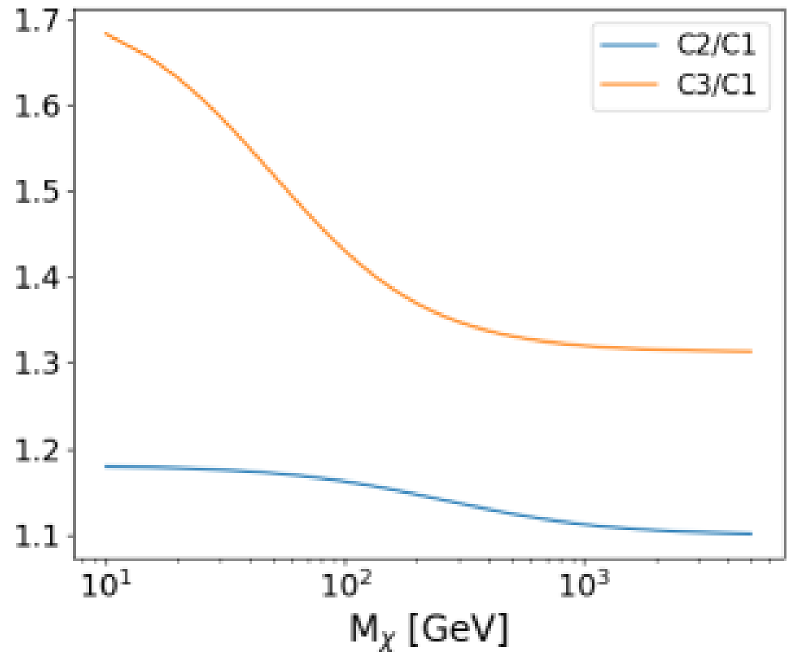


• Maximum capture rate in the Sun, C_1, considering the SHM model and $v_N = 0$.



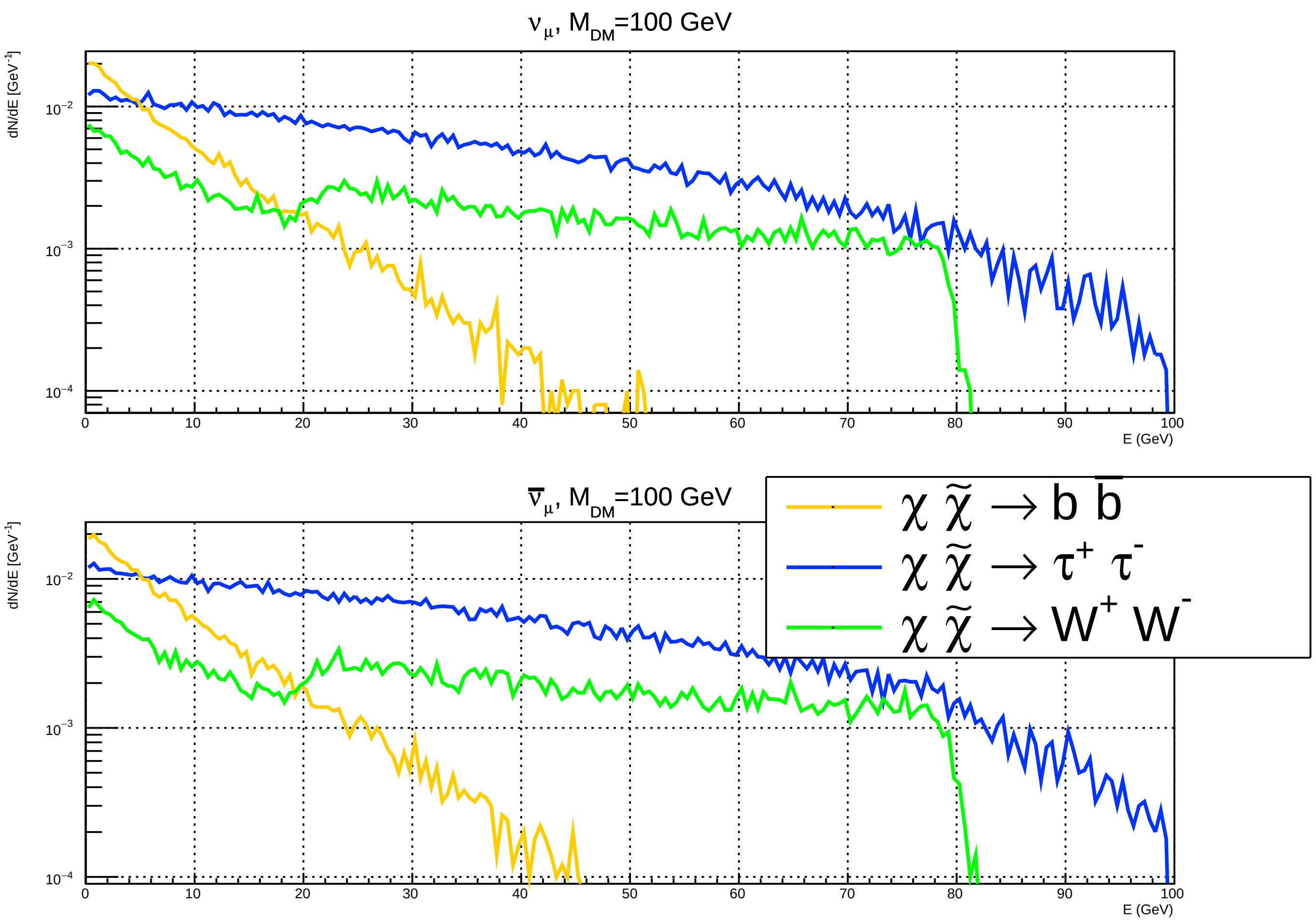
• Maximum capture rate in the Sun, C_2, considering the SHM model and $v_N \neq 0$, and C_3, considering the SHM++ model and $v_N = 0$.





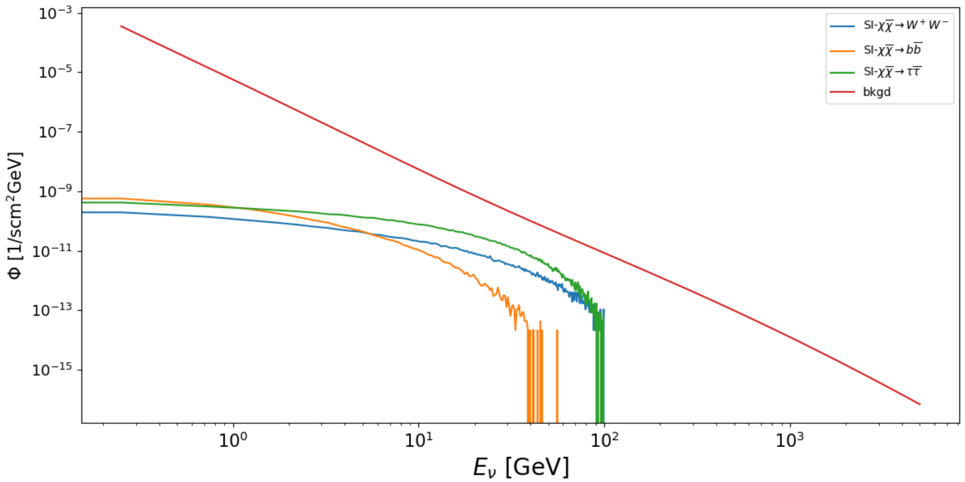
7. Neutrino flux

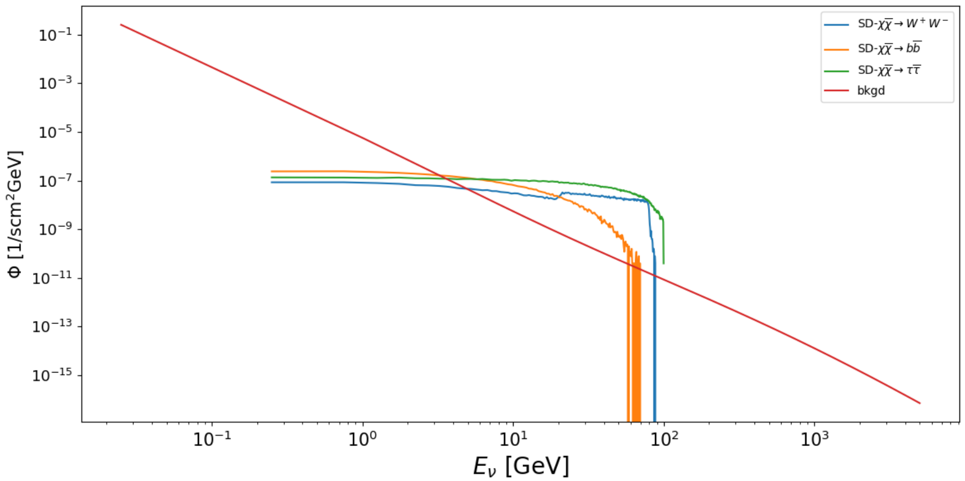
• We can obtain the WIMP annihilation yields for several channels using the software WimpSim:



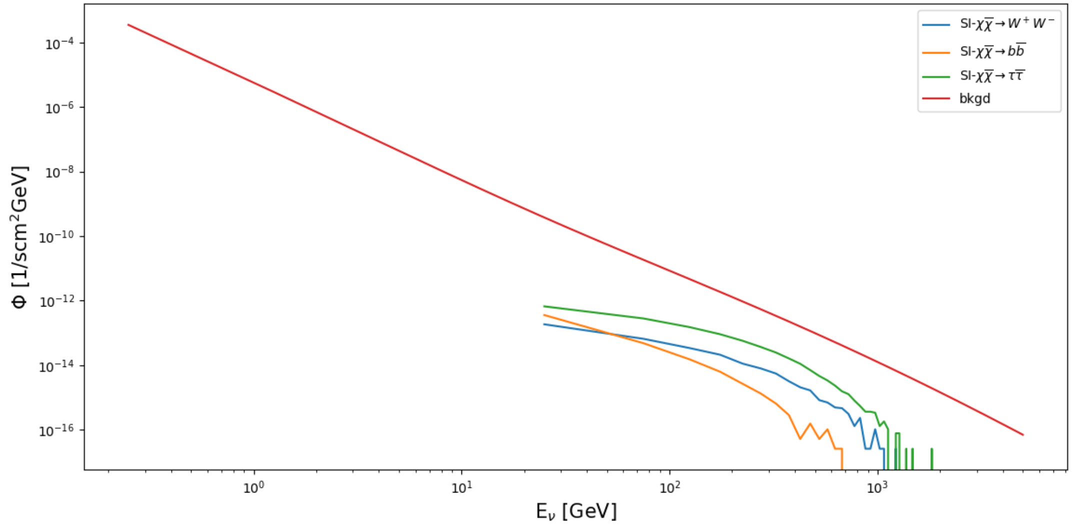
• Then, the estimated flux of neutrinos is just the annihilation rate times the annihilation yield.

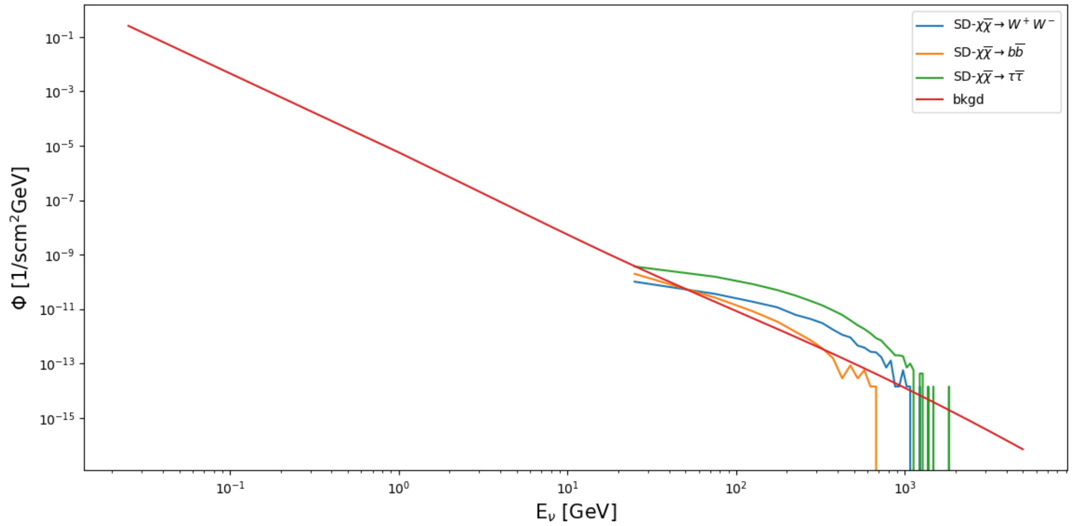
• For $m_\chi = 100\,\text{GeV}$:





- For $m_\chi = 5000\,\text{GeV}$:





8. Conclusions

• Notice that the capture rate depends strongly on the mass of the WIMP.
• The SD interaction is the leading one, being up to 4 orders of magnitude stronger than the SI.
• Althought the velocity of the targets is often ignored in this kind of analysis, we have seen that it may increase the capture rate up to a factor $\times 1.2$ for lower masses.
• The capture rate is sensible to the distribution considered for the Dark Matter: the results for the SHM++ are about 80% greater than for the SHM.
• We are not considering the inelastic cross section for the collisions, but there are works that try to estimate the influence of these interactions in the capture rate.
• As we have seen, SI interaction does not produce a flux of neutrinos above the background. However, SD interaction could produce an observable flux of neutrinos.

Thanks!