Ultimate sensitivity in DARK MATTER direct detection scenarios in presence of anomalous neutrino sources caused by DARK MATTER decay

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- What sensitivity can be reached?

Neutrino floor

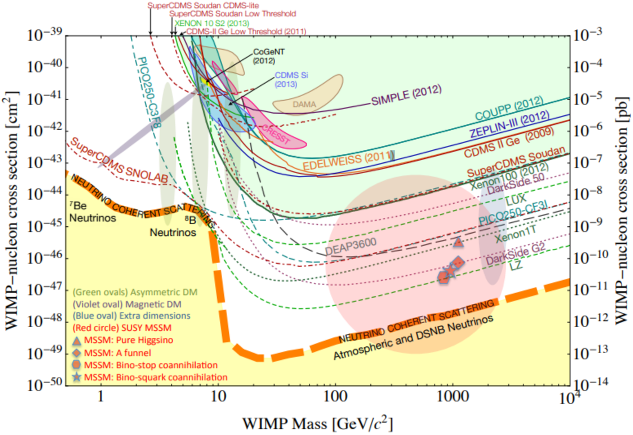

Figure 1: neutrino floor-solar, atmospheric and DSNB neutrinos [1]

Modification of Neutrino Floor by neutrinos from DM decay!

Neutrino sources

- Solar, atmospheric and DSNB neutrinos

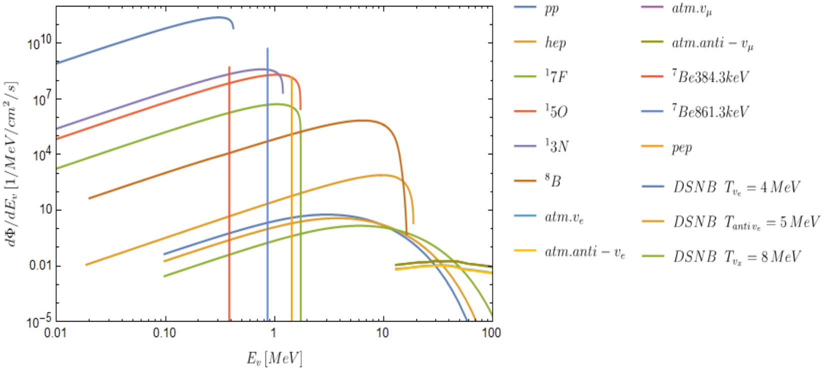

Figure 2: Flux of solar, atmospheric and DSNB neutrinos

Fluxes of DARK RADIATION from decaying DARK MATTER

Assumption: fraction of about 10% of DM decays ($\kappa = 0.1$)
lifetime of DM X: $\tau_X = 1/\Gamma_X = 1$, $\tau_X \approx 10$Gyr

- Galactic flux

$$\frac{d\Phi_{\nu,gal.}}{dE_\chi} = \frac{\kappa \Gamma_X e^{-\Gamma_X t_0}}{m_X} \frac{dN}{dE_\nu} r_\odot \rho_\odot \langle J_{dec}(\theta) \rangle, \tag{1}$$

where the J-factor is a line of sight integral

$$J_{dec}(\theta) = \frac{1}{r_\odot \rho_\odot} \int_{l.o.s} ds \rho(r(s,\theta)), \quad r(s,\theta) = \sqrt{s^2 + r_\odot^2 - 2sr_\odot \cos\theta}. \tag{2}$$

For a detector with no directional sensitivity one averages over the angles

$$\langle J_{dec}(\theta) \rangle = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} d\varphi \, d\theta \sin\theta J_{dec}(\theta), \tag{3}$$

The average J-factor is given by

$$\langle J_{dec}(\theta) \rangle = 2.1885 \tag{4}$$

obtained for NFW-profile

$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}, \quad \rho_s = 0.184 \, GeV/cm^3, r_s = 24.42 \, kpc \tag{5}$$

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  take into account that momentum of the neutrinos ν produced by DM decays is redshifted $p_{\nu,em}(z) = (1+z)p_\nu$ (em...moment at emission)

- present number density of neutrinos ν with energies in $[E_\nu, E_\nu + dE_\nu]$ emitted in a redshift interval $[z, z+dz]$

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  - $\Omega_M \approx 0.3,\ \Omega_\Lambda \approx 0.7,\ H_0 \approx 70 \mathrm{km\, s^{-1}\, Mpc^{-1}}$

$$\frac{dz}{dt} = H(z) = -H_0(1+z)\sqrt{(1+z)^3\Omega_M + \Omega_\Lambda} \tag{7}$$

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- Extragalactic flux

$$\begin{aligned}\frac{d\Phi_{\nu,e.g.}}{dE_\nu} &= c\frac{dn_X}{dE_\nu} \\ &= \Gamma_X \frac{\kappa\Omega_{dm}\rho_0}{m_X}\frac{c}{H_0}\int_0^{z_f}\frac{dz}{\sqrt{(1+z)^3\Omega_M+\Omega_\Lambda}}\frac{dN(E_{\nu,em})}{dE_\nu}e^{-\Gamma_X t(z)}\end{aligned} \tag{8}$$

- 2 body decay: assume DM X decays into 2 neutrinos ν injection spectrum

$$\left.\frac{dN}{dE_\nu}\right|_{2\text{ body}} = N_\nu \delta(E_\nu - E_{in}), \quad N_\nu = 2, \quad E_{in} = \frac{m_X}{2}$$

$$\frac{d\Phi_{\nu,e.g.}}{dE_\nu} = N_\nu \frac{\Gamma_X}{p_\nu}\frac{\kappa\Omega_{dm}\rho_0}{m_X}\frac{c}{H_0}\frac{e^{-\Gamma_X t(\alpha-1)}}{\sqrt{\alpha^3\Omega_M+\Omega_\Lambda}}\theta(\alpha-1), \tag{9}$$

where $\alpha := \frac{p_{in}}{p_\nu} \geqslant 1$

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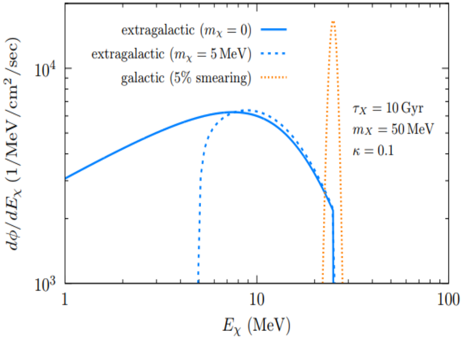
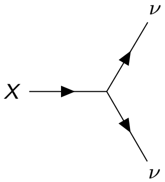


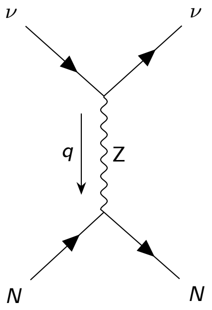


(10)

Recoil rate in a direct detection experiment

- Neutrino scatters elastically off target nuclei (coherent scattering)

$$\nu + N \rightarrow \nu + N. \tag{11}$$



(12)

- coherent cross section ($qR << 1$, where R is the radius of nucleus)

$$\frac{d\sigma(E_\nu, E_R)}{dE_R} = \frac{Q_W^2 G_F^2 m_N F(q)^2}{4\pi}\left[1 - \frac{E_R m_N}{2E_\nu^2}\right] \tag{13}$$

- m_N target mass, $m_{Xe} \approx 131 GeV$ for ^{131}Xe

Recoil rate in a direct detection experiment

- Differential recoil rate

$$\left.\frac{dR}{dE_R}\right|_{X\to\nu\nu} = N_T \int_{E_{\nu,min}}^{E_{in}} dE_\nu \sum_{i=gal.,e.g.} \frac{d\Phi_i}{dE_\nu} \frac{d\sigma(E_\nu, E_R)}{dE_R}, \tag{14}$$

  - $E_{\nu,min} = |\vec{p}\,|_{\nu,min}$ minimum energy to produce a recoil
  - $|\vec{p}\,|_{\nu,min} = \sqrt{E_R m_N/2}$ minimum momentum to produce a recoil with energy E_R
  - N_T target number density = number of target nuclei per kg detector mass

$$N_T = \frac{N_A}{A_N M}, \tag{15}$$

  where $N_A = 6.02 \cdot 10^{23} mol^{-1}$ is the Avogadro number, $M = 10^{-3} kg\ mol^{-1}$ is the molar mass constant and A_N is the nuclear mass number

- Solar, atmospheric, DSNB neutrino rate measured in detector

$$\frac{dR}{dE_R} = N_T \int_{E_{\nu,min}}^{E_\nu^{max}} dE_\nu \frac{d\Phi_\nu(E_\nu)}{dE_\nu} \frac{d\sigma(E_\nu, E_R)}{dE_R} \tag{16}$$

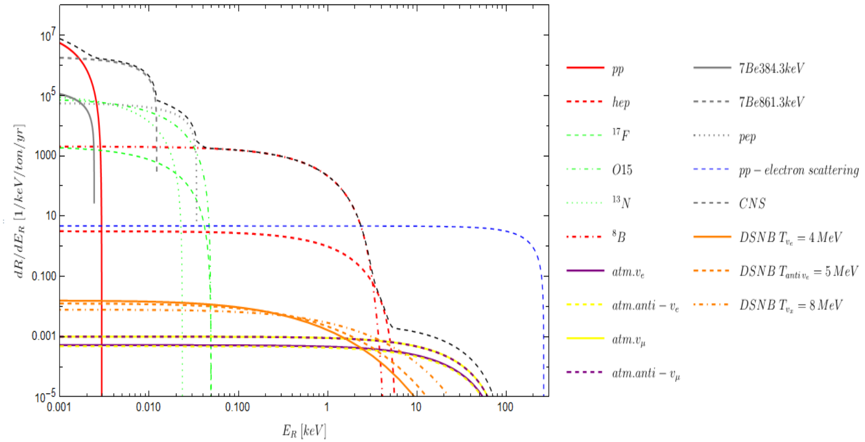


Figure 3: solar, atmospheric, DSNB neutrino differential recoil rate

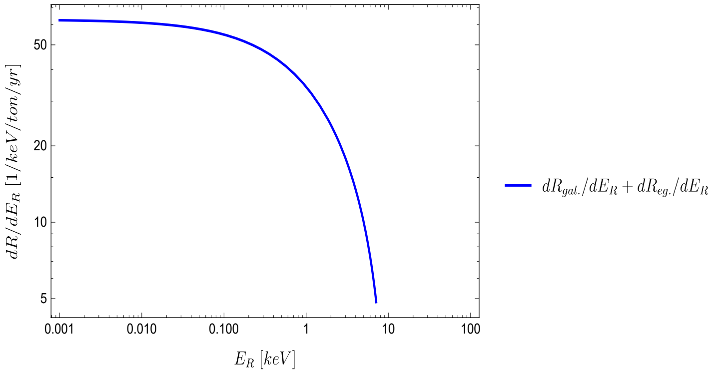


Figure 4: Neutrino differential recoil rate from DM decay

Principles of WIMP direct detection - calculation of the WIMP rate

- Direct detection differential rate

$$\frac{dR_{DM}}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} A^2 F^2(|\vec{q}|) \frac{m_N}{2\mu_{\chi,n}^2} \sigma_n \int_{v_{min}} d^3\vec{v}\, \frac{f(\vec{v})}{v} \quad (17)$$

where σ_n is the WIMP-nucleon cross section

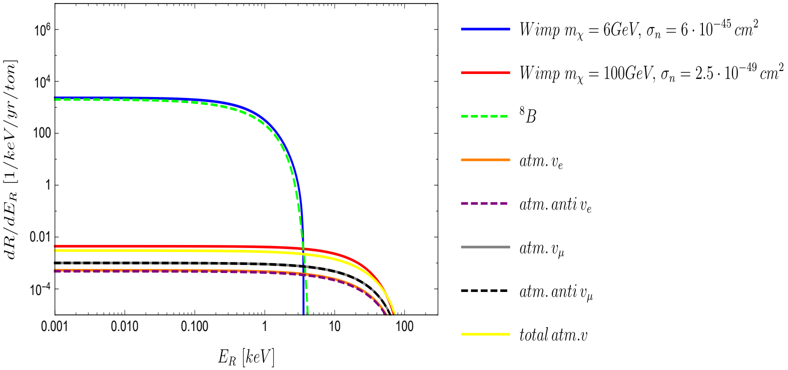
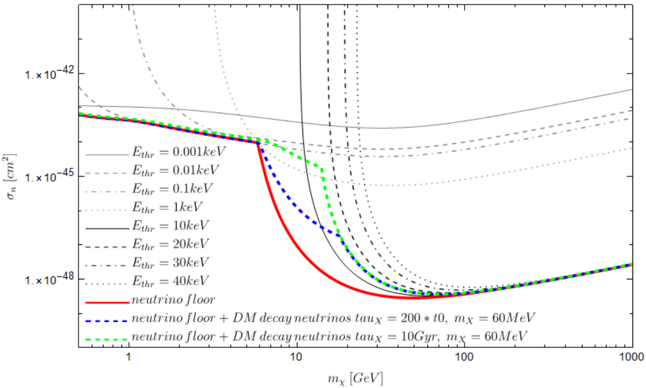


Figure 5: Differential recoil rate for elastic WIMP-Nucleus scattering

Modified neutrino floor



WIMP event rate

$$R_\nu(E_{thr}) = \epsilon_\nu(E_{thr}) \int_{E_{thr}}^{E_R^{max}} dE_R \, \frac{dR_{DM}}{dE_R}(\sigma_n, m_\chi) \qquad (18)$$

Neutrino Floor is raised by few orders of magnitude!

References I

J. Billard and E. Figueroa-Feliciano, L. Strigari*Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments*

Diffuse supernova neutrino background (DSNB)

- DSNB is a steady source of supernova neutrinos
- present number density of DSNB-neutrinos with energies in $[E_\nu, E_\nu + dE_\nu]$ emitted in a redshift interval $[z, z + dz]$

$$\begin{aligned} dn_\nu &= R_{SN}(z)(1+z)^3 \left|\frac{dt}{dz}\right| dz \, \frac{dN}{dE_\nu}\,(E_{\nu,em})\, dE_{\nu,em}(1+z)^{-3} \\ &= R_{SN}(z)(1+z) \left|\frac{dt}{dz}\right| dz \, \frac{dN}{dE_\nu}\,(E_\nu(1+z))\, dE_\nu \end{aligned} \tag{19}$$

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  - $\Psi(m) \propto m^{-2.35}$ initial mass function, mass distribution of stars comes from simulations and observations

Diffuse supernova neutrino background (DSNB)

- DSNB differential flux

$$\frac{d\Phi_\nu}{dE_\nu} = c\frac{dn_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{max}} \frac{dz}{\sqrt{(1+z)^3\Omega_M + \Omega_\Lambda}} R_{SN}(z)\frac{dN}{dE_\nu}(E_\nu(1+z)) \quad (21)$$

  - assume core collapses began at redshift $z_{max} \approx 5-6$
- R_{SN} obtained from star formation rate R_{SF} (only Type II supernovae are interesting for neutrino emission)

$$R_{SN}(z) = R_{SF}(z)\frac{\int_{8M_\odot}^{125M_\odot}\Psi(m)dm}{\int_{0.1M_\odot}^{125M_\odot}m\Psi(m)dm} \quad (22)$$

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Diffuse supernova neutrino background (DSNB)

- neutrino spectrum approximated by Fermi-Dirac spectrum

$$\frac{dN}{dE_\nu}(E_\nu) = \frac{E_{\nu,tot}}{6}\frac{120}{7\pi^4}\frac{E_\nu}{T^4}\frac{1}{(e^{E_\nu/T}+1)} \tag{23}$$

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  - $T_{\nu_e} \approx 4MeV$, $T_{\bar{\nu}_e} \approx 5MeV$, $T_{\nu_x} \approx 8MeV$

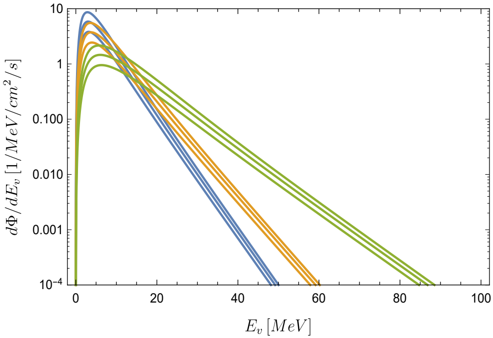

Figure 6: Flux of DSNB neutrinos for $T_{\nu_e} \approx 4MeV$, $T_{\bar{\nu}_e} \approx 5MeV$, $T_{\nu_x} \approx 8MeV$

Recoil rate in a direct detection experiment

- Solar, atmospheric, DSNB neutrino rate measured in detector

$$\frac{dR}{dE_R} = N_T \int_{E_{thr}}^{E_R^{max}} dE_R \, \frac{d\Phi_\nu(E_\nu)}{dE_\nu} \frac{d\sigma(E_\nu, E_R)}{dE_R} \tag{24}$$

  - maximal recoil energy

$$E_R^{max} = \frac{2E_\nu^2}{2E_\nu + m_N} \tag{25}$$

- Helm form factor

$$|F^{SI}(q)|^2 = \left(\frac{3j_1(qR)}{qR}\right)^3 e^{-q^2 s^2}, \tag{26}$$

where $j_1 = \frac{sin(x)}{x^2} - \frac{cos(x)}{x}$ is a spherical Bessel function, $s \approx 0.9$fm is the nuclear skin thickness and $R = \sqrt{c^2 + \frac{7}{3}\pi^2 a^2 - 5s^2}$ is the effective nuclear radius with $a \approx 0.52$fm and $c \approx (1.23A^{1/3} - 0.6)$fm

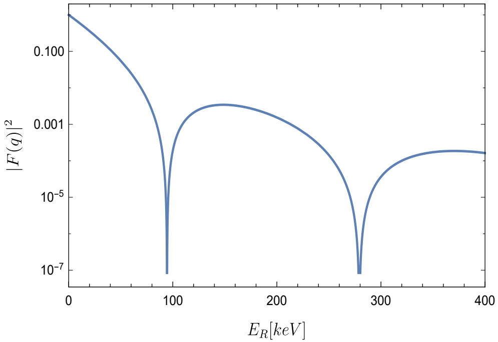

Figure 7: helm form factor

Calculation of the neutrino floor

- Calculate the recoil rate of neutrinos for several thresholds E_{thr}

$$R_\nu(E_{thr}) = \int_{E_{thr}}^{100\ keV} dE_R \, \frac{dR_\nu}{dE_R} \tag{27}$$

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- Adjust the exposure $\epsilon(E_{thr})[ton \cdot yr]$ so that $N_{\nu,ev} \stackrel{!}{=} \epsilon(E_{thr}) \cdot R_\nu(E_{thr}) = 1$ (exposure is chosen so that you measure one neutrino event)

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- Calculate exclusion limits of DM-nucleon cross section σ_n ($N_{DM,ev} \overset{!}{=} 2.3$ for 90% exclusion)

$$\begin{aligned} N_{DM,ev} &= \epsilon(E_{thr}) \cdot \int_{E_{thr}}^{100keV} dE_R \, \frac{dR_{DM}}{dE_R} \\ &= \epsilon(E_{thr}) \cdot N_T \frac{\rho_\chi}{m_\chi} \int_{E_{thr}}^{100keV} dE_R \int_{v_{min}} d^3\vec{v}\, f(\vec{v}) \frac{d\sigma}{dE_R} v, \quad v_{min} = \frac{\sqrt{2E_R m_N}}{2\mu_{\chi,N}} \\ &= \epsilon(E_{thr}) \cdot N_T A^2 F^2(|\vec{q}|) \frac{\rho_\chi}{m_\chi} \frac{m_N}{2\mu_{\chi,n}^2} \boxed{\sigma_n} \int_{v_{min}} d^3\vec{v}\, \frac{f(\vec{v})}{v} \overset{!}{=} 2.3 \end{aligned} \tag{28}$$

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- Neutrino floor is the minimum of all exclusion limits of σ_n

Principles of WIMP direct detection - calculation of the WIMP rate

- Direct detection differential rate

$$\frac{dR_{DM}}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \left\langle \frac{d\sigma}{dE_R} v \right\rangle = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{min}} d^3\vec{v}\, f(\vec{v}) \frac{d\sigma}{dE_R} v \tag{29}$$

- Maxwell-Boltzmann-Distribution

$$f(\vec{v}+\vec{v}_{lab}) = \begin{cases} \frac{1}{N_{esc}(2\pi\sigma_v^2)^{3/2}} \exp[\frac{-(\vec{v}+\vec{v}_{lab})^2}{2\sigma_v^2}] & \text{for } |\vec{v}+\vec{v}_{lab}| < v_{esc} \\ 0 & \text{for } |\vec{v}+\vec{v}_{lab}| \geqslant v_{esc} \end{cases} \tag{30}$$

$\vec{v}$...WIMP velocity in the target frame (Earth)

$\vec{v}_{lab}$...Earth velocity in the Galaxy rest frame $|\vec{v}_{lab}| \approx 232 \frac{km}{s}$

$\vec{v}_{esc}$...escape velocity $|\vec{v}_{esc}| \approx 540 \frac{km}{s}$

$\vec{v}_{\chi,gal}$...WIMP velocity in the Galaxy frame

$$\vec{v}_{\chi,gal} = \vec{v} + \vec{v}_{lab} \tag{31}$$

Principles of WIMP direct detection - calculation of the WIMP rate

- Spin independent scattering expressed in terms of the cross section at zero momentum transfer σ_0^{SI} (coherent $\rightarrow$ proportional to A^2)

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu_{\chi,N}^2 v^2} \sigma_0^{SI} F^2(|\vec{q}|), \quad \sigma_0^{SI} = A^2 \left(\frac{\mu_{\chi,N}}{\mu_{\chi,n}}\right)^2 \sigma_n \tag{32}$$

where σ_n is the WIMP-nucleon cross section

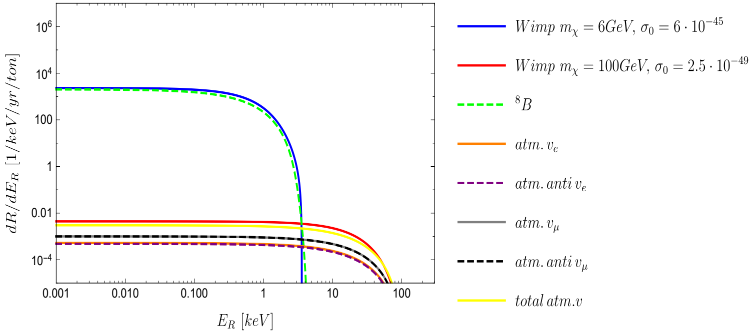

Figure 8: Differential recoil rate for elastic WIMP-Nucleus scattering