Neutrino non-standard interactions (NSI) and DM direct searches

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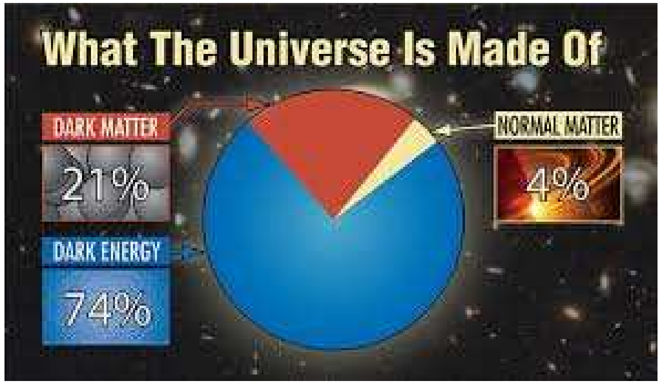
Introduction



Evidence for DM supported by:

- Galaxy rotation curves
- Velocity dispersion of galaxies
- Galaxy clusters and gravitational lensing...

Everything what we know is inferred from its gravitational effects in visible matter

Properties (simplified)

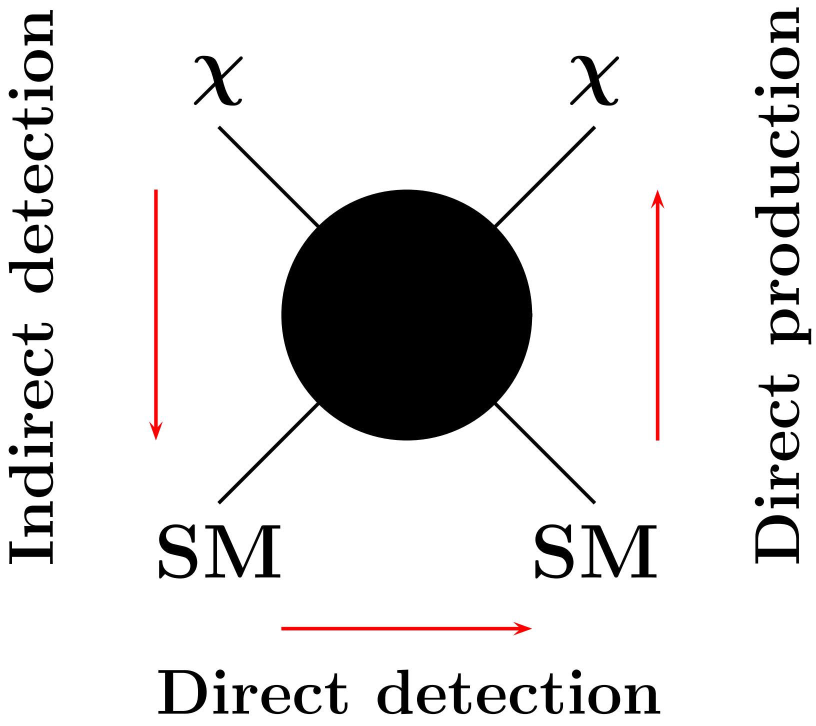
- DM is not observed to interact with light, electrically neutral
- The bulk of DM is either Cold or Warm

At the onset of GF$[\mathscr{O}(T)\sim$ keV$]$ $\begin{cases} \text{CMD: is non-relativistic} \Rightarrow m_{\text{DM}} \gg \text{keV} \\ \text{WMD: is becoming non-relativistic} \end{cases}$

- DM has attractive F_g and is stable or long-lived $\tau_{\text{DM}} \gtrsim 10^{26}$ sec
- DM is dissipationless and collisionless

DM searches

Searches are done in three possible ways



Direct searches

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

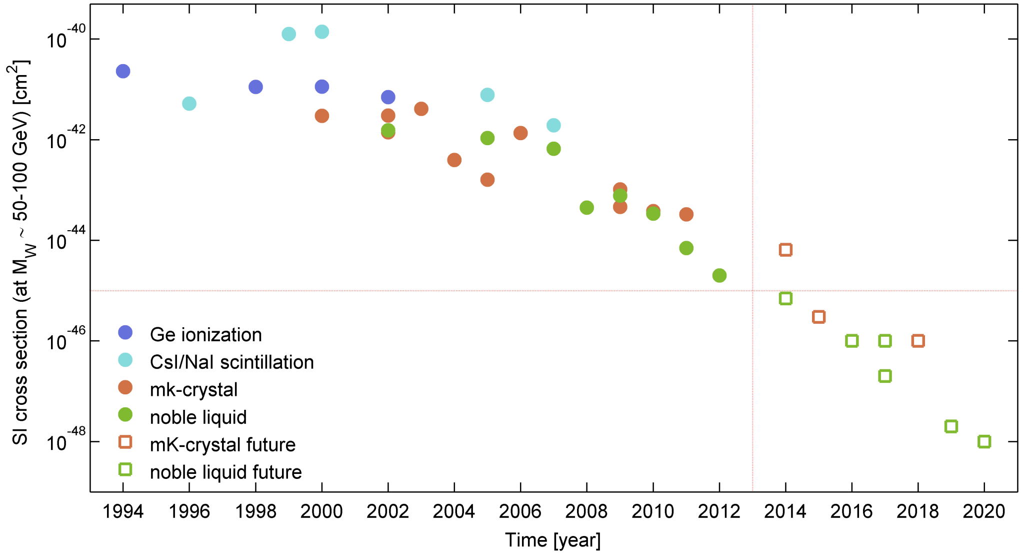
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

$$E_R \simeq m_\chi v_0^2 \frac{m_\chi m_N}{(m_\chi + m_N)^2}$$

$$m_\chi \subset [1, 10^3] \text{ GeV}$$

$$E_R \subset [1, 10^2] \text{ keV}$$

L. Baudis, 2012



LZ: $\sigma^{\text{SI}}_{\chi-n} \lesssim 1.6 \cdot 10^{-48}$ cm^2 for $m_\chi \simeq 40$ GeV

The ultimate background

Increase sensitivity to Ton-size detectors: LZ **(talk by Hall Carter)**, XenonNT, DARWIN

CνNES: $\nu N \to \nu N$ background matters!

$$E_R \lesssim 100 \text{ keV} \;\Rightarrow\; q \lesssim 10^2 \text{ MeV}$$

$$\sigma \simeq 4.2 \times 10^{-45} N^2 \left(\frac{E_\nu}{1\text{MeV}}\right)^2 \text{cm}^2$$

The BG fakes WIMP signals

E_R measurements only

cannot discriminate!!

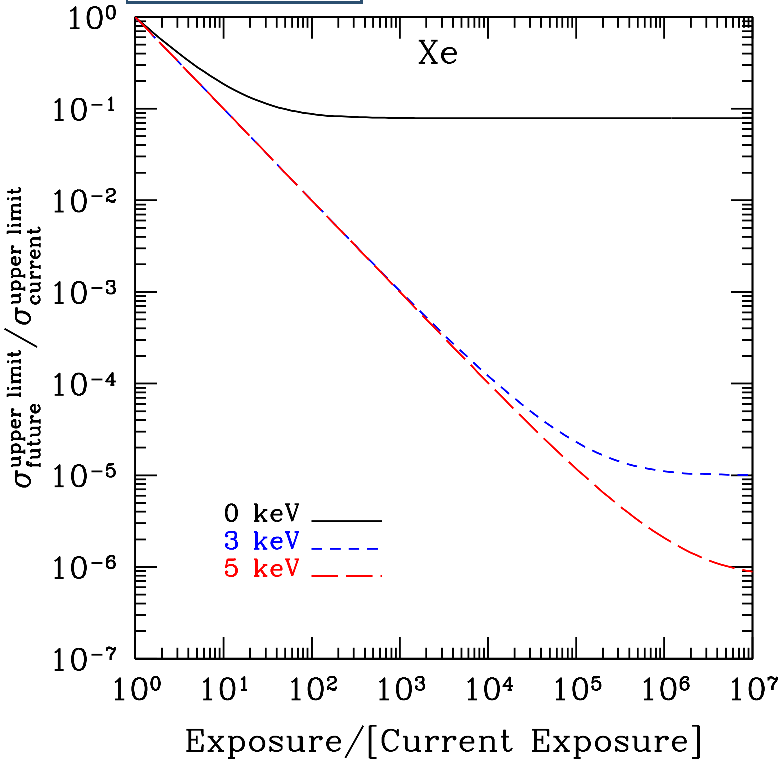
ν-floor: The values of WIMP parameters for which the ν-BG becomes important

For ^{131}Xe nuclear target detector

$$R_\nu \sim N_N \times \Phi_\nu \times \sigma_{\nu-N}$$

$$R \sim 18 \left(\frac{\Phi}{10^6 \text{cm}^{-2}\text{s}^{-1}}\right)\left(\frac{\sigma}{10^{-40}\text{cm}^2}\right)\frac{\text{events}}{\text{ton}\cdot\text{year}}$$

Strigari, 2009

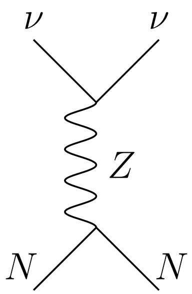


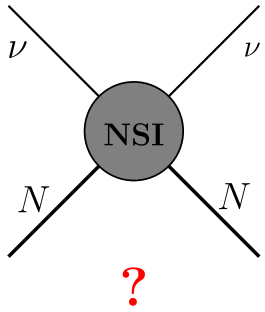
Anatomy of the ν background

DM and ν rates

Talk by Louis Strigari!

Differential rate for ν-nuclei elastic scattering





$$\frac{dR}{dE_R} = N_N \int_{E_\nu} \frac{d\Phi_\nu}{dE_\nu} \times \frac{d\sigma_\nu}{dE_R}\, dE_\nu$$

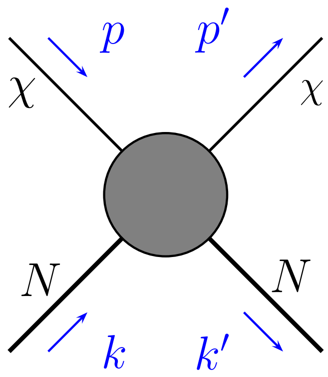
dN/dE_ν: Solar, Atmospheric, Diffuse SN fluxes

σ_ν: σ_{SM} **Freedman, 1974**

σ_{NSI} **Barranco, Miranda, Rashba, 2005**

Differential rate for WIMP-nuclei elastic scattering

Lewis & Smith, 1996



$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_\chi} \int_{v_{\text{min}}}^{v_{\text{max}}} dv\, f(v)\, v\, \frac{d\sigma}{dE_R}$$

$\rho_0, f(v), v$: Astrophysics

m_χ, σ: Particle and nuclear physics

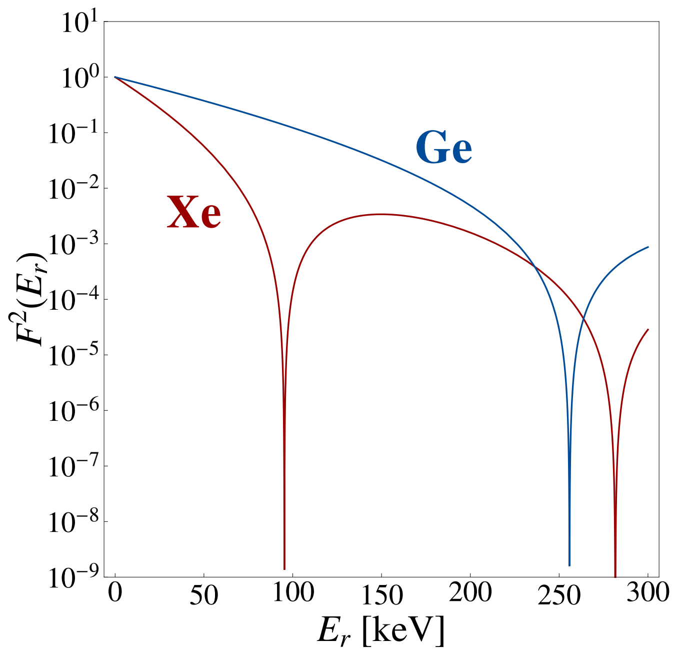
N_N, E_R: Detector physics

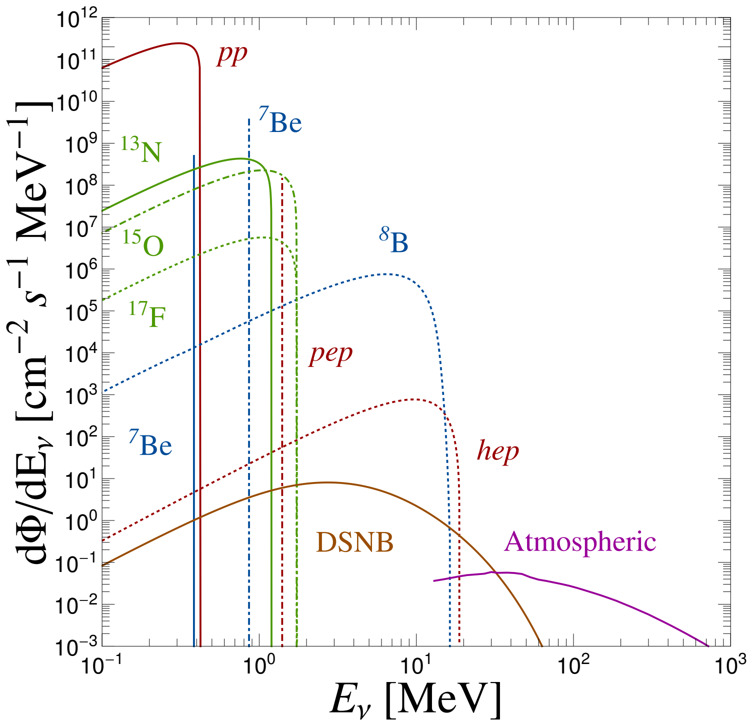
Freedman, 1974

$$\frac{d\sigma_\nu}{dE_R} = \frac{G_F^2}{4\pi} Q_{\text{SM}}^2 m_N \left(1 - \frac{E_r m_N}{2E_\nu^2}\right) \underbrace{F^2(E_r)}_{\text{Form factor}}$$

$$Q_{\text{SM}}^2 = N - (1 - s_W^2) Z$$

Helm, 1956





CνNES process

$$\lambda \gtrsim R_N \quad \Rightarrow \quad q \lesssim 100 \text{ MeV} \quad \Rightarrow \quad E_\nu \lesssim 100 \text{ MeV}$$

Neutrino Sources

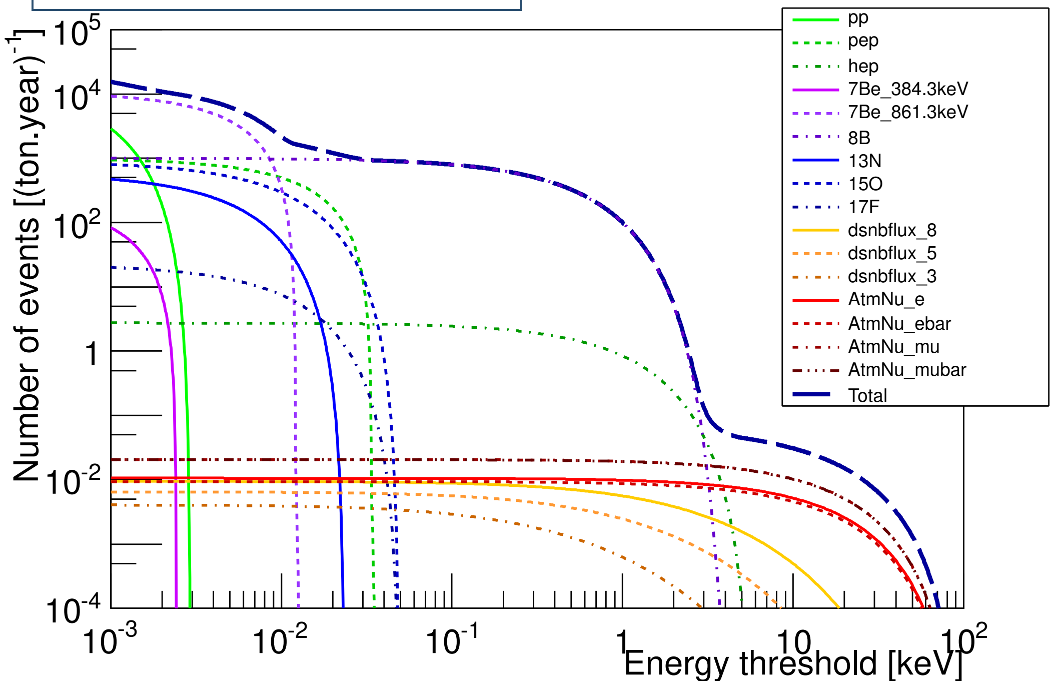
- $\nu_\odot$: pp chain (and CNO!): $E_\nu \lesssim 20$ MeV
- ν_{Atm}: $\pi \to \mu + \bar{\nu}_\mu \to e + \bar{\nu}_e + \nu_\mu$: $E_\nu \lesssim 100$ MeV
- DSNB: Neutrinos from past history of CCSN

Number of ν events

- Consider the full neutrino spectrum: Solar + Atmospheric + DSNB:
  - ↪ Solar neutrinos ⇒ Limit sensitivities for $m_\chi \lesssim 10$ GeV
  - ↪ Atm neutrinos ⇒ Limit sensitivities for $m_\chi \gtrsim 10$ GeV
- Assume 100% efficiency, fix $N =$ **Xe**, $E_r^{\text{th}} = [10^{-3}, 10^2]$ keV

$$R_\nu = \sum_{i=\Phi_\nu} \int_{E_r^{\text{th}}}^{E_r^{\text{max}}} \frac{dR_{\nu_i}}{dE_r} dE_r$$

Billard, Figueroa, Strigari, 2013

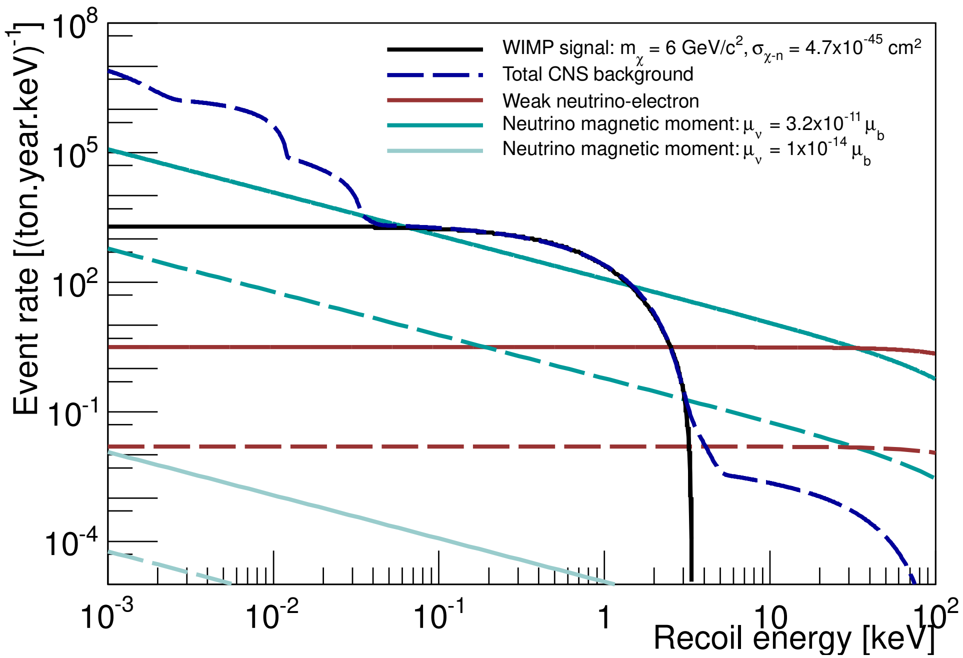


Mimicking WIMPS

With sufficient neutrino events a WIMP-like signal can be mimicked.

Billard, Figueroa, Strigari, 2013

- Calculate dR_{WIMP}/dE_R as a function of E_R
- Compare dR_{WIMP}/dE_R with dR_ν/dE_R. Best match gives the WIMP paramaters that lead to $dR_{\text{WIMP}}/dE_R = dR_\nu/dE_R$



Solar ν

$m_\chi = 6$ GeV and $\sigma_{\chi-N} \simeq 4.4\times10^{-45}$ cm^2

Atmospheric ν

$m_\chi = 100$ GeV and $\sigma_{\chi-N} \simeq 10^{-48}$ cm^2

Constructing the ν floor

Billard, Figueroa, Strigari, 2013

Goal: Determine the **best background-free sensitivity** achievable at each WIMP mass for an exposure of one neutrino event

Sensitivity

$$\sigma_{\chi-n} = \frac{R_\chi}{\mathscr{E}(E_R^{\text{th}}) \int_{E_R^{\text{th}}}^{E_R^{\text{max}}} dR_\chi/dE_R|_{\sigma_{\chi-n}=1} \, dE_R}$$

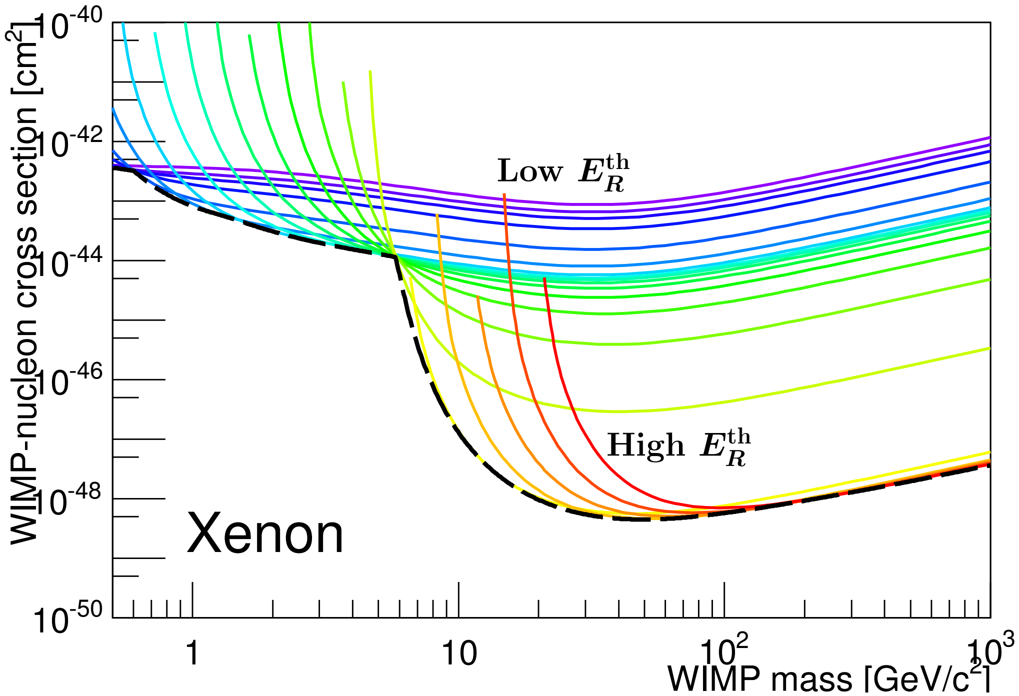
Exposure

$$\mathscr{E}(E_R^{\text{th}}) = \frac{\#\,\text{neutrino events}}{\int_{E_R^{\text{th}}} dR_\nu/dE_R dE_R}$$

Strategy

- Fix target (**Xe**), calculate sensitivities in $E_R^{\text{th}} = [10^{-2}, 10^2]$ keV. Fix $R_\chi = 2.3$ (90% CL)
- Optimize the calculation so each isocontour involves a single neutrino:
  - ✓ Small $E_R \Rightarrow$ Large Φ_ν ($\mathscr{E}$ small) $\Rightarrow$ Large $\sigma_{\chi-n}$ for small m_χ
  - ✓ Large $E_R \Rightarrow$ Small Φ_ν ($\mathscr{E}$ large) $\Rightarrow$ small $\sigma_{\chi-n}$ for large m_χ
- For each sensitivity isocontour (each E_R^{th}) select $\{m_\chi, \sigma_{\chi-N}|_{\text{min}}\}$, fit the points and *voilà*

The result



Low WIMP mass region $m_\chi \lesssim 10$ GeV:

Challenge: measure $\sigma_{\chi-n} \lesssim 10^{-45}\,\text{cm}^2$

High WIMP mass region $m_\chi \gtrsim 10$ GeV:

Challenge: measure $\sigma_{\chi-n} \lesssim 10^{-48}\,\text{cm}^2$

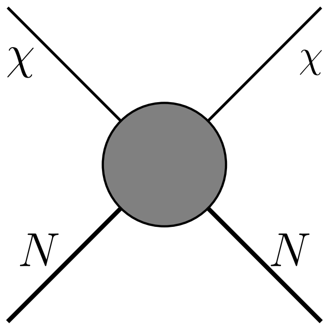
Various experimental techniques can be used to “evade” the discovery limit saturation point

What does theory has to say?

Beyond “standard” WIMPs

DD non-relativistic EFT approach

Adopt a more generic approach for DM direct detection: Non-relativisitic EFT



$q \lesssim 100$ MeV $\Rightarrow \Lambda \gtrsim$ few$\times$ q

$$\mathscr{L}_{\text{Eff}} = \sum_{\mathcal{N}=n,p} \sum_i \mathscr{C}_i^{(\mathcal{N})} \mathscr{O}_i \bar{\chi}\chi\overline{\mathcal{N}}\mathcal{N}$$

$\mathscr{C}_i^{(\mathcal{N})}$ determined by the underlying physics

Operators from Galilean+T+Hermitian vecs: q/m_N, $v^\perp = v + q/\mu_N$, S_N, S_χ **Haxton et. al, 2012**

$\mathscr{O}_1 = 1_\chi 1_N$

$\mathscr{O}_2 = (v^\perp)^2$

$\mathscr{O}_3 = i S_N \cdot (\frac{q}{m_N} \times v^\perp)$

$\mathscr{O}_4 = S_\chi \cdot S_N$

$\mathscr{O}_5 = i S_\chi \cdot (\frac{q}{m_N} \times v^\perp)$

$\mathscr{O}_6 = (\frac{q}{m_N} \cdot S_N)(\frac{q}{m_N} \cdot S_\chi)$

$\mathscr{O}_7 = S_N \cdot v^\perp$

$\mathscr{O}_8 = S_\chi \cdot v^\perp$

$\mathscr{O}_9 = S_\chi \cdot (S_N \times \frac{q}{m_N})$

$\mathscr{O}_{10} = i \frac{q}{m_N} \cdot S_N$

$\mathscr{O}_{11} = i \frac{q}{m_N} \cdot S_\chi$

$\mathscr{O}_{12} = S_\chi \cdot (S_N \times v^\perp)$

$\mathscr{O}_{13} = (S_\chi \cdot v^\perp)(\frac{q}{m_N} \cdot S_N)$

$\mathscr{O}_{14} = (S_N \cdot v^\perp)(\frac{q}{m_N} \cdot S_\chi)$

$\mathscr{O}_{15} = -(S_\chi \cdot \frac{q}{m_N})((S_N \times v^\perp) \cdot \frac{q}{m_N})$

In particular models q- or v-dependent operators can be leading

What kind of models??

Simplified models

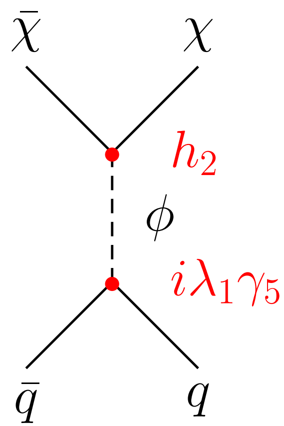
UV completions of these operators can be worked out systematically for $s = 0, 1/2, 1$ DM, at least in simplified models

Dent, Krauss et. al, 2015

Simplified model $\Rightarrow$ Integrate out mediator

$\mathcal{O}_q \sim \bar{q}\Gamma q \rightarrow \mathcal{O}_N \sim \bar{N}\Gamma N$ $\Rightarrow$ Take non-relativistic limit

Fermion DM and scalar mediator



$$\mathcal{L}_{\text{Sim}} = h_2\bar{\chi}\chi\phi + i\lambda_1\bar{q}\gamma_5 q + \cdots$$

$$\mathcal{L}_{\text{Eff}}^{\text{R}} = \frac{h_{\text{Eff}}}{m_\phi^2}\bar{\chi}\chi\bar{q}\gamma_5 q$$

$$\langle N|\bar{q}\gamma_5 q|N\rangle + \text{NR limit}:$$

$$\mathcal{L}_{\text{Eff}}^{\text{NR}} \sim i\frac{q}{m_N}\cdot S_N = \mathcal{O}_{10}$$

Direct detection driven by momentum-dependent operator

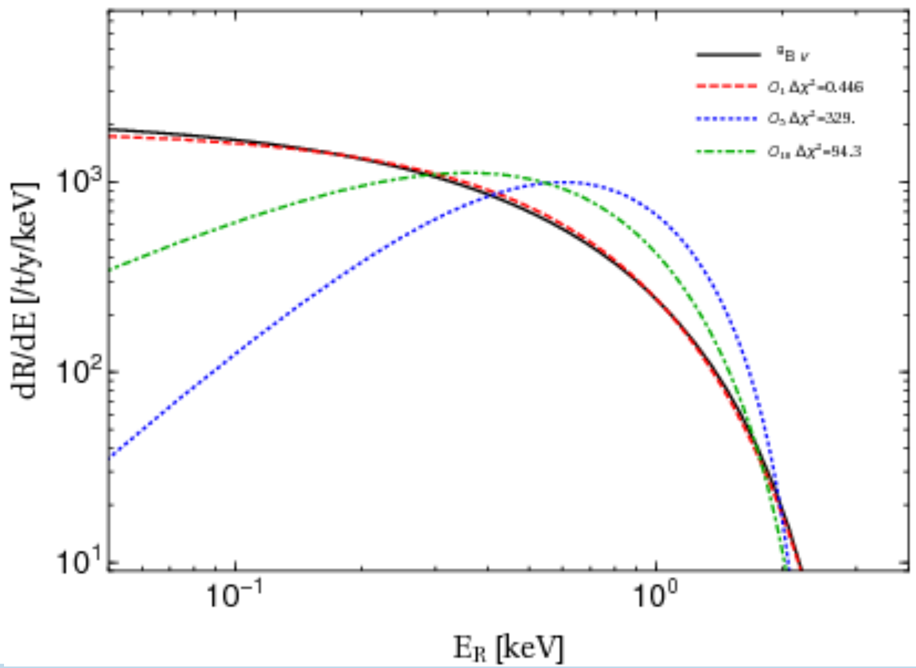
Evading the ν floor

WIMP interactions with the same Lorentz structure than $\nu - q$ lead to strongly overlapping spectra otherwise not

$$\mathscr{L}_{\text{Eff}} \sim \bar{\nu}\gamma_\mu(1-\gamma_5)\nu\,\bar{q}\gamma^\mu(g_V^q + g_A^q\gamma_5)q$$

$$\mathscr{L}_{\text{Eff}} \sim \underbrace{\bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q}_{\mathscr{O}_1} \quad ✘$$

$$\mathscr{L}_{\text{Eff}} \sim \underbrace{\bar{\chi}\chi\,\bar{q}\gamma_5 q}_{\mathscr{O}_{10}} \quad ✔$$



Dent, Dutta et. al, 2016

For most operators ($\chi - q$ interactions) the WIMP signal can be distinguished in experiments with good spectra resolution

All but $\mathscr{O}_{1,4}, \mathscr{O}_{7,8}$

If the CEνNS is subject to **new interactions** same effect MIGHT be present

WIMP SI interaction $\Rightarrow$ **BSM $\nu - q$ interaction**

Possible effects

- The new physics depletes the CEνNS number of events
- The new physics changes CEνNS recoil spectrum
- Even if effects aren't sizable use the analysis to place constraints on $\mathscr{P}$

COHERENT data still allow sizable effects

Talk by Grayson Rich

Start such a "program" with neutrino NSI

Dutta et. al. 2017

DAS et. al. 2017

Gonzalez-Garcia et. al. 2018

The rôle of NSI

NSI

Non-standard interactions parametrized in a model-independent and phenomenological way

Wolfenstein, 1978

$$\mathcal{L} \sim \sum_{q=u,d} G_F \bar{\nu}_i (1-\gamma_5)\gamma_\mu \nu_j \bar{q}(\epsilon_{ij}^{qV} - \epsilon_{ij}^{qA}\gamma_5)\gamma^\mu q$$

Phenomenological constraints from forward coherent scattering (matter potentials) DIS and COHERENT data

Scenarios

Gonzalez-Garcia et. al, 2017

- For $m_X^2 \ll q^2$ contributions of NSI to DIS are suppressed, $q^2_{\text{DIS}} \gtrsim (10\text{GeV})^2$
- Light mediator scenarios: $M_X \subset [10, 10^3]$ MeV $\Rightarrow$ DIS constraints evaded
- Heavy mediator scenarios: $M_X \subset [1, 10^3]$ GeV all constraints apply

Constraints in light mediator scenarios are weaker

For DIS bounds derived from CHARM and NuTeV data

Gonzalez-Garcia et. al, 2017

Light mediators
Oscillation+COHERENT
$\epsilon^u_{ee} \subset [0.028, 0.6]$
$\epsilon^u_{\mu\mu} \subset [-0.088, 0.37]$
$\epsilon^u_{\tau\tau} \subset [-0.09, 0.38]$
$\epsilon^u_{e\mu} \subset [-0.073, 0.044]$
$\epsilon^u_{e\tau} \subset [-0.15, 0.13]$
$\epsilon^u_{\mu\tau} \subset [-0.01, 0.009]$

Gonzalez-Garcia et. al, 2017

Heavy mediators
Oscillation+COHERENT+DIS
$\epsilon^u_{ee} \subset [0.033, 0.45]$
$\epsilon^u_{\mu\mu} \subset [-0.088, 0.005]$
$\epsilon^u_{\tau\tau} \subset [-0.015, 0.04]$
$\epsilon^u_{e\mu} \subset [-0.05, 0.03]$
$\epsilon^u_{e\tau} \subset [-0.15, 0.13]$
$\epsilon^u_{\mu\tau} \subset [-0.006, 0.005]$

For the ν background larger effects found in the light mediator case

Theory limits

Strategy: Start with a gauge-invariant effective approach

consider 59 SM dim-6 effective operators

$$\mathcal{O}^{(1)}_{ij} = \left(\bar{\ell}_i \gamma^\mu P_L \ell_j\right)\left(\bar{Q}_1 \gamma^\mu P_L Q_1\right) \qquad \mathcal{O}^{(2)}_{ij} = \left(\bar{\ell}_i \gamma^\mu P_L Q_1\right)\left(\bar{Q}_1 \gamma^\mu P_L \ell_j\right)$$

$$\mathcal{O}^{(3)}_{ij} = \left(\bar{\ell}_i \gamma^\mu P_L \ell_j\right)\left(\bar{u} \gamma^\mu P_R u\right) \qquad \mathcal{O}^{(4)}_{ij} = \left(\bar{\ell}_i \gamma^\mu P_L \ell_j\right)\left(\bar{d} \gamma^\mu P_R d\right)$$

NSI parameters

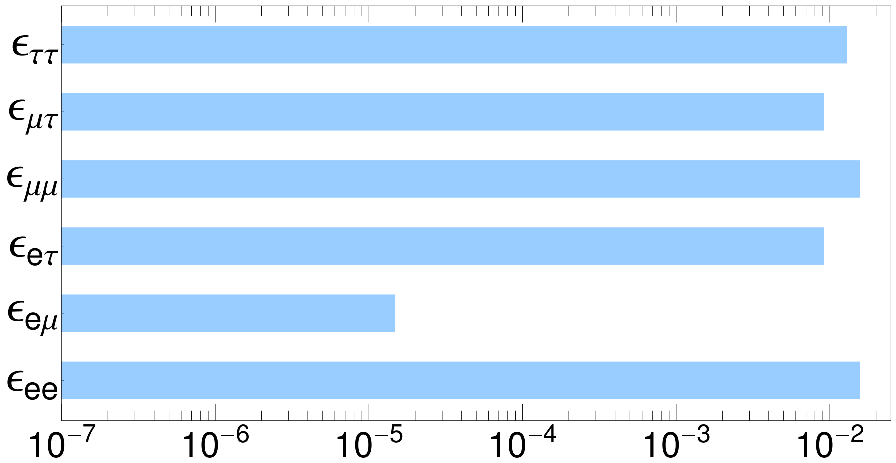
$$\epsilon^u_{ij} = \frac{\mathcal{C}^{(1)}_{ij} + \mathcal{C}^{(2)}_{ij} + \mathcal{C}^{(3)}_{ij}}{2\sqrt{2}G_F}$$

$$\epsilon^d_{ij} = \frac{\mathcal{C}^{(1)}_{ij} + \mathcal{C}^{(4)}_{ij}}{2\sqrt{2}G_F}$$

Wilson coefficients are also constrained by

LFV: $\mu - e$ conversion in nuclei, rare τ decays

Contact interactions $e^+ e^- \bar{q} q$ (LEP), EW universality



From theory point of view effects are small

Adopt a phenomenological approach!

Propagation effects (I)

NSI induce additional matter potentials ⇒ Affect propagation

$$H_{\text{mat}} \to G_F \, \epsilon_{ij}^{q} \, n_e(r) \, Y_q(r)$$

For solar neutrinos propagation can be analyzed in the two-flavor regime:

$$\tilde{\nu}_e \simeq \nu_e \qquad \tilde{\nu}_\mu \simeq \cos\theta_{23}\nu_\mu - \sin\theta_{23}\nu_\tau$$

The averaged survival probability can be calculated **Analytically**

$$\mathscr{P}_{ee}(E_\nu, r) = \cos^4\theta_{13}\,\mathscr{P}_{\text{eff}}(E_\nu, r) + \sin^4\theta_{13}$$

Guzzo, et. al, 2001

Friedland et. al, 2004

$$\mathscr{P}_{\text{eff}}(E_\nu, r) = \frac{1 + \overbrace{\cos 2\theta_M(r, \epsilon_{ij})}^{\theta \text{ matter}} \cos 2\theta_{12}}{2}$$

Dependence on the neutrino path

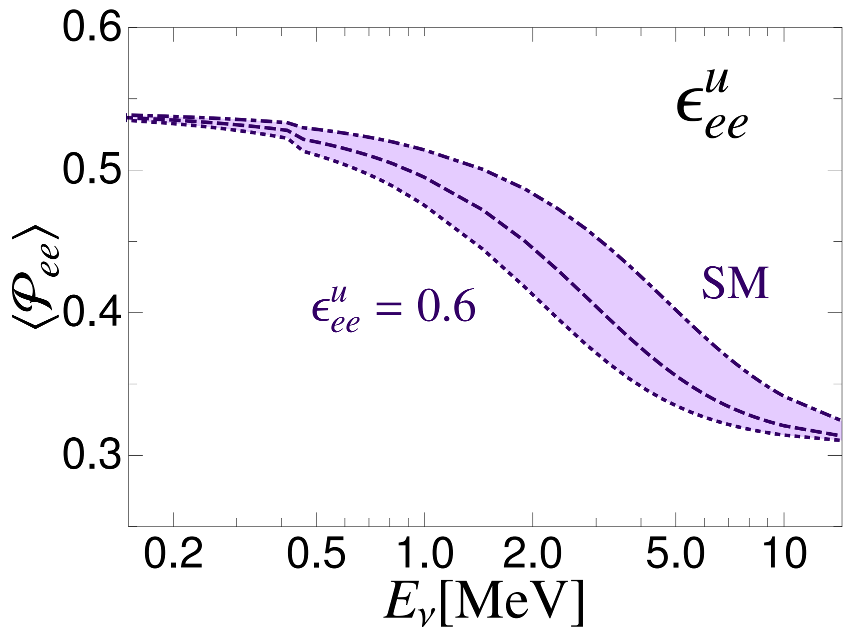
⇒ integration over distribution

of neutrino production in the Sun (BSM05)

$$\langle \mathscr{P}_{ee}(E_\nu)\rangle = \frac{\sum_\alpha \Phi_\alpha(E_\nu) \int_0^1 dr\, \rho_\alpha(r)\, \mathscr{P}_{ee}(E_\nu, r)}{\sum_\alpha \Phi_\alpha(E_\nu)}$$

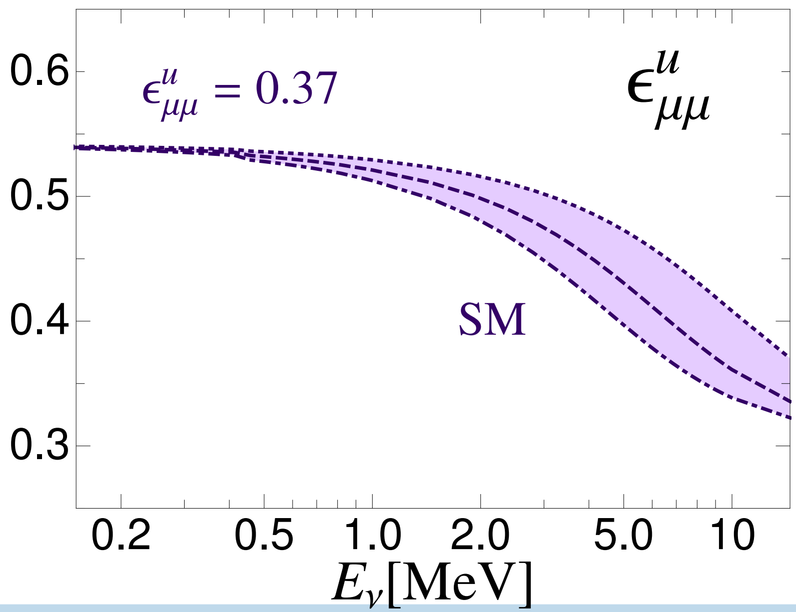
Propagation effects (II)

DAS, Rojas, Tytgat, 2017



ϵ_{ee} NSI effects deplete the oscillation probability

DAS, Rojas, Tytgat, 2017



$\epsilon_{\mu\mu}$ NSI effects enhance the oscillation probability

CEνNS in the presence of NSI

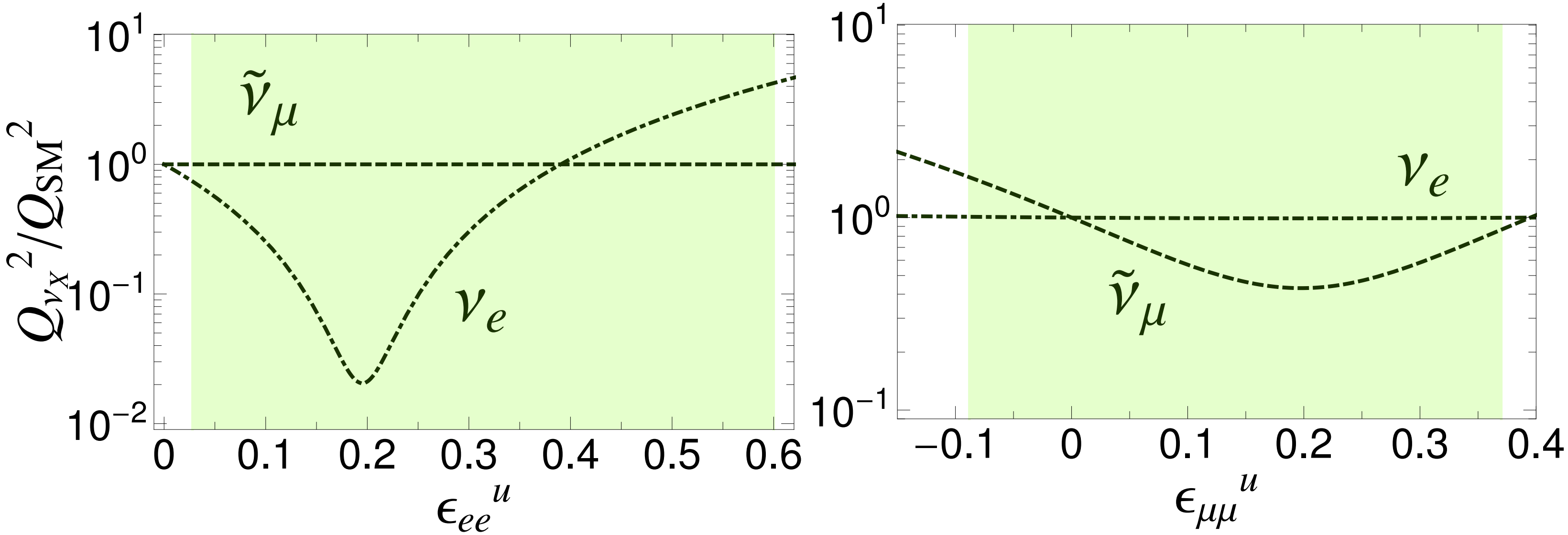
The presence of NSI affect the $\nu - N$ cross section $\Rightarrow$ Affect detection

$$\frac{d\sigma_{\nu_i}}{dE_r} = \frac{G_F^2}{4\pi} Q_{\nu_i}^2 \, m_N \left(1 - \frac{E_r}{E_r^{\max}(E_\nu)}\right) F^2(E_r)$$

Barranco, Miranda, Rashba, 2005

$$Q_{\nu_i}^2 = 4\left[-\frac{Q_{\rm SM}}{2} + N(\epsilon_{ii}^u + 2\epsilon_{ii}^d) + Z(2\epsilon_{ii}^u + \epsilon_{ii}^d)\right]^2 + \sum_{j\neq i} 4\left[N\left(\epsilon_{ij}^u + 2\epsilon_{ij}^d\right) + Z\left(2\epsilon_{ij}^u + \epsilon_{ij}^d\right)\right]^2$$

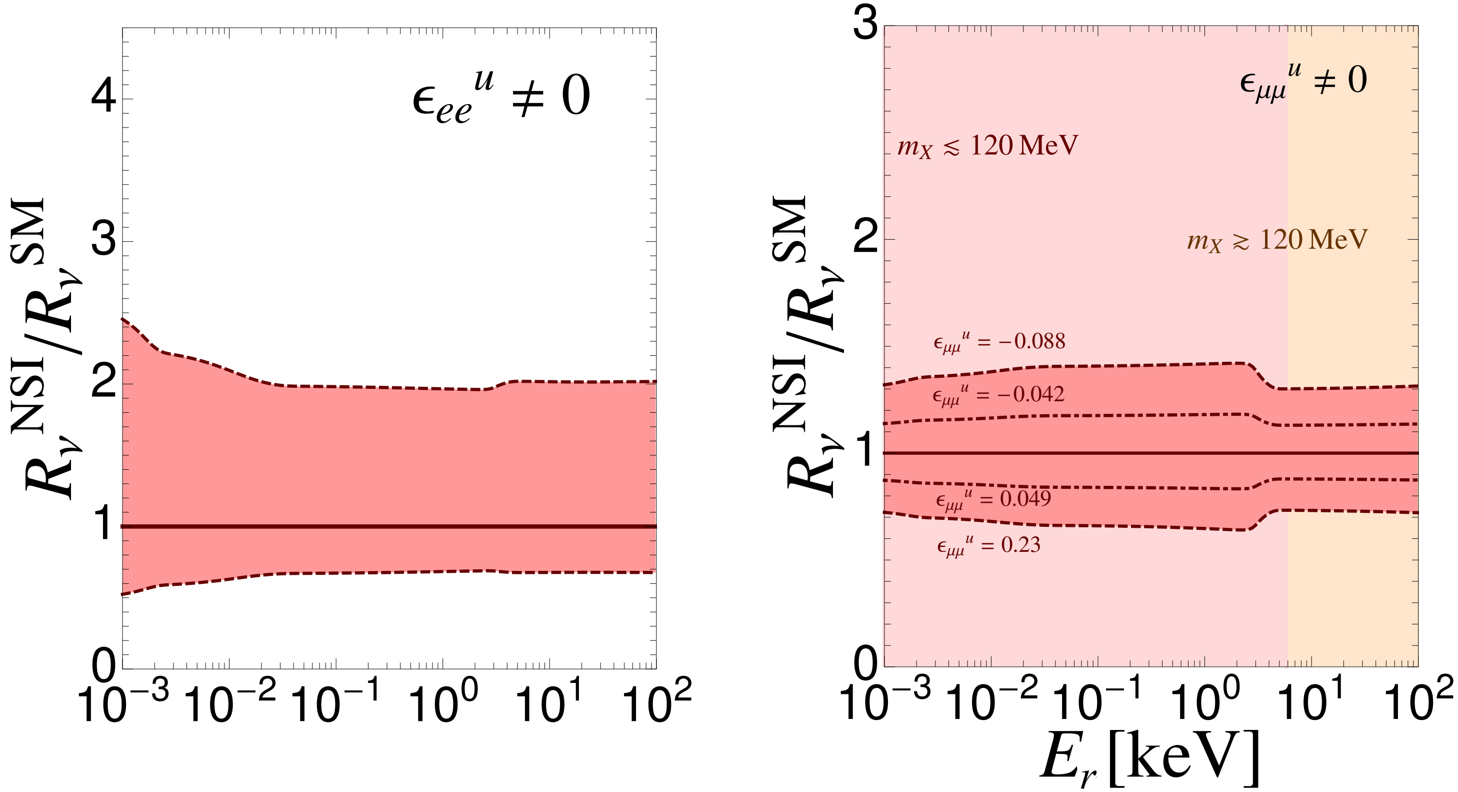
DAS, Rojas, Tytgat, 2017



Event rates

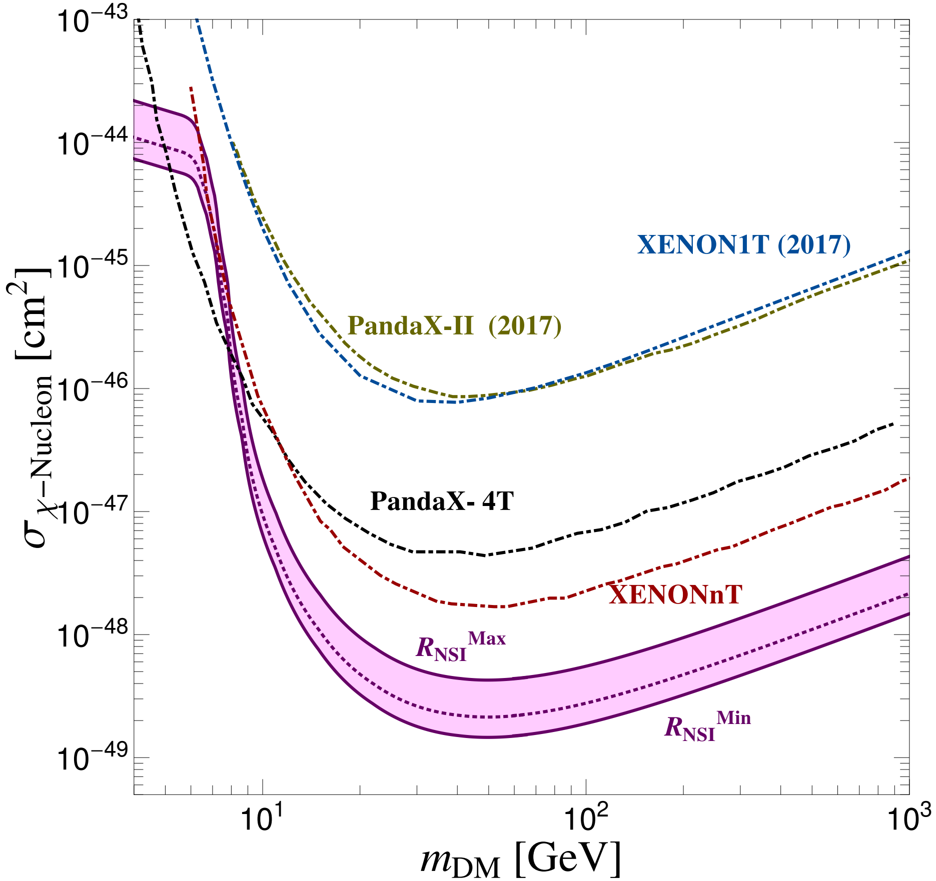
$$\frac{dR_\nu^\odot}{dE_r} = N_T \sum_\alpha \int_{E_{\rm min}}^\infty \Phi_\alpha(E_\nu)\left[\langle\mathscr{P}_{ee}\rangle \frac{d\sigma_{\nu_e}}{dE_r} + (1-\langle\mathscr{P}_{ee}\rangle)\frac{d\sigma_{\tilde{\nu}_2}}{dE_r}\right] dE_\nu$$

DAS, Rojas, Tytgat, 2017



Background-free sensitivities

The results can be summarized in the WIMP parameters space by calculating the background-free sensitivities



Summary

Résumé

- Near future DD experiments will be challenged by irreducible ν backgrounds.
- Ideally, understanding of the background requires considering all possible effects/uncertainties:
  - If DM-N is induced by “exotic” interactions the ν-floor may be evaded in detectors with good spectra resolution.
  - If ν are subject to ν NSI interactions, sensitivities can be either enhanced or further diminished
  - BSM $\nu - q$ interactions might improve the discovery reach by changing the $\nu - N$ spectra
- BSM $\nu - N$ interactions are still sizable and should be considered in the analysis of near future DD experimental data

Thanks for your attention!