Neutrino Physics in Direct Detection Dark Matter Experiments

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Dark matter direct detection and neutrinos

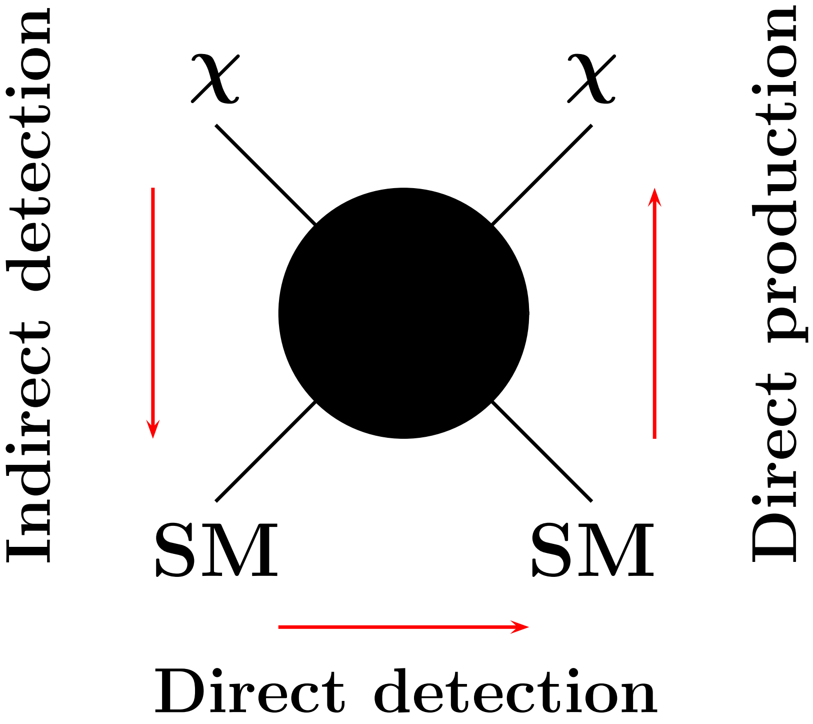
Useful references

Biased list (not biased!)

- Lewis & Smith, Astroparticle Physics 6 (1997)
- Fitzpatrick, Haxton, Katz, Lubbers & Xu (1203.3542)
- Dent, Krauss, Newstead & Sabharwal (1505.03117)
- Billard, Figueroa, Strigari (arXiv:1307.5458)

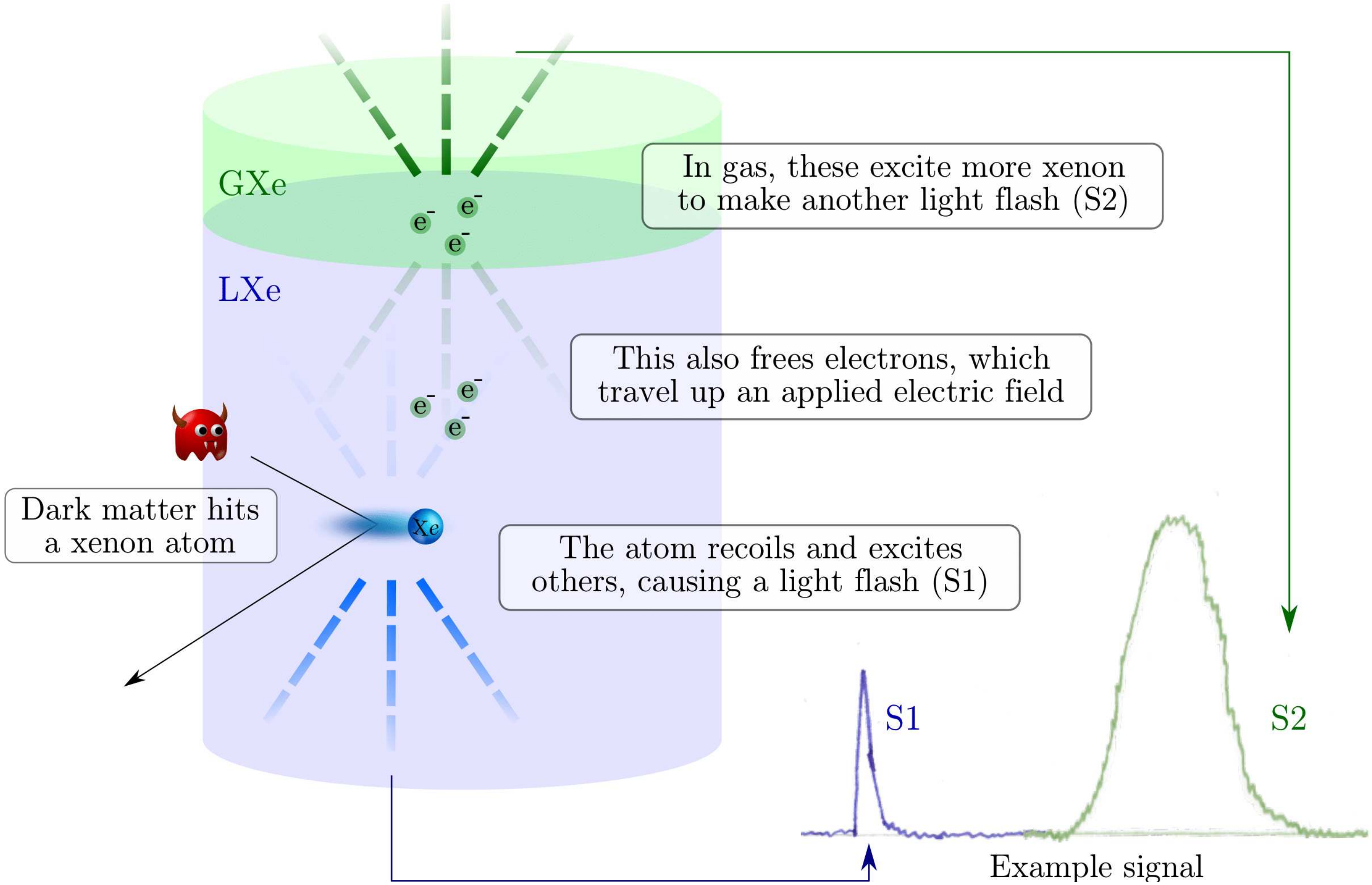
DM searches

Searches are done in three possible ways



DM direct detection: How does work?

Detection principle: The Earth moves within the dark matter halo... Statistically one expects a WIMP hitting a nucleus “stored” in a container



In gas, these excite more xenon to make another light flash (S2)

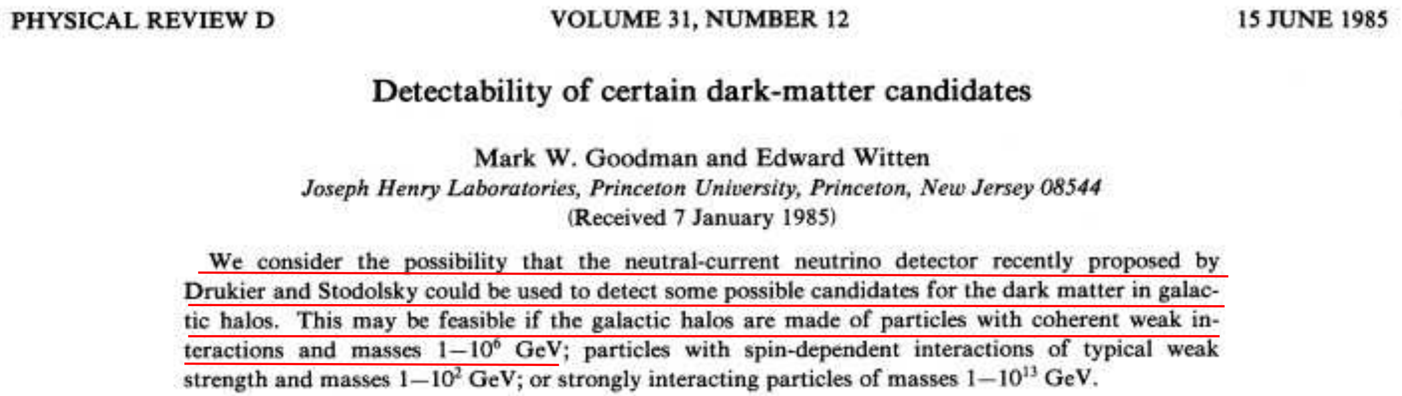
This also frees electrons, which travel up an applied electric field

Dark matter hits a xenon atom

The atom recoils and excites others, causing a light flash (S1)

Example signal

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)

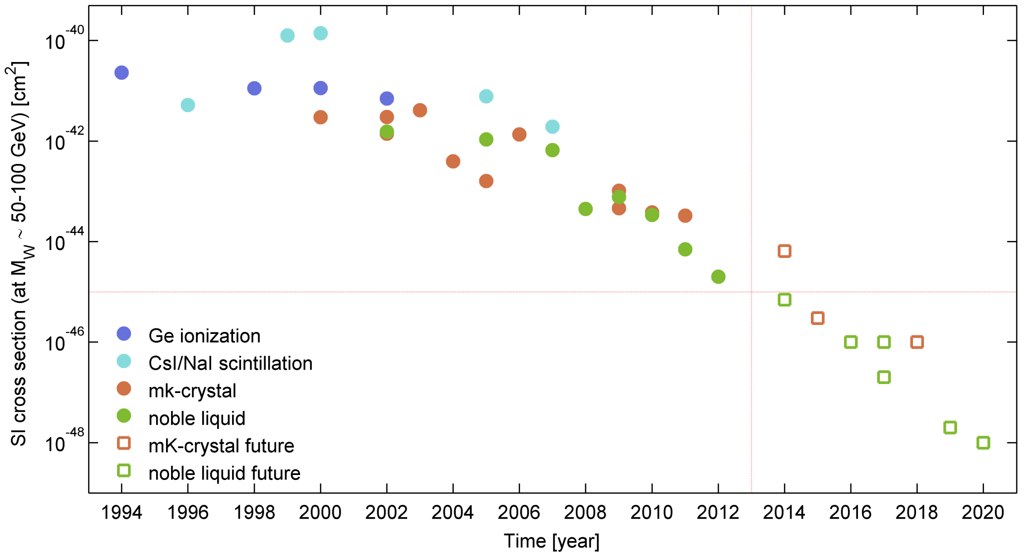
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and 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



Some experiments (limits)

Darkside-50

Laboratorio Nazionale del Gran Sasso

Material target: Argon

Detector mass: 50 kg

90%CL L: $\sigma \lesssim 10^{-44}\,\text{cm}^2$ $m_{\text{DM}} = 100\,\text{GeV}$

PANDA-XII

China Jinpeng Underground Laboratory

Material target: Xenon

Detector mass: 500 kg

90%CL L: $\sigma \lesssim 10^{-46}\,\text{cm}^2$ $m_{\text{DM}} = 40\,\text{GeV}$

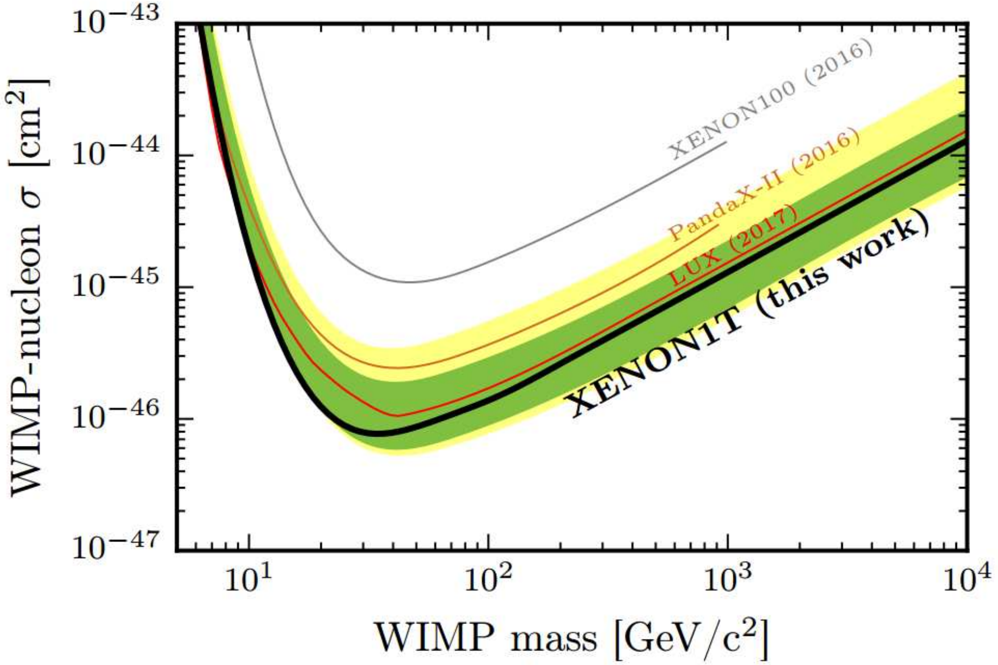
XENON-1T

Laboratorio Nazionale del Gran Sasso

Material target: Xenon

Detector mass: $\sim 2\,\text{ton}$

90%CL L: $\sigma \lesssim 7.7 \cdot 10^{-47}\,\text{cm}^2$ $m_{\text{DM}} = 30\,\text{GeV}$



The ultimate background

Increase sensitivity to Ton-size detectors: LZ, XenonNT, DARWIN

CEνNS: $\nu N \to \nu N$ 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!!

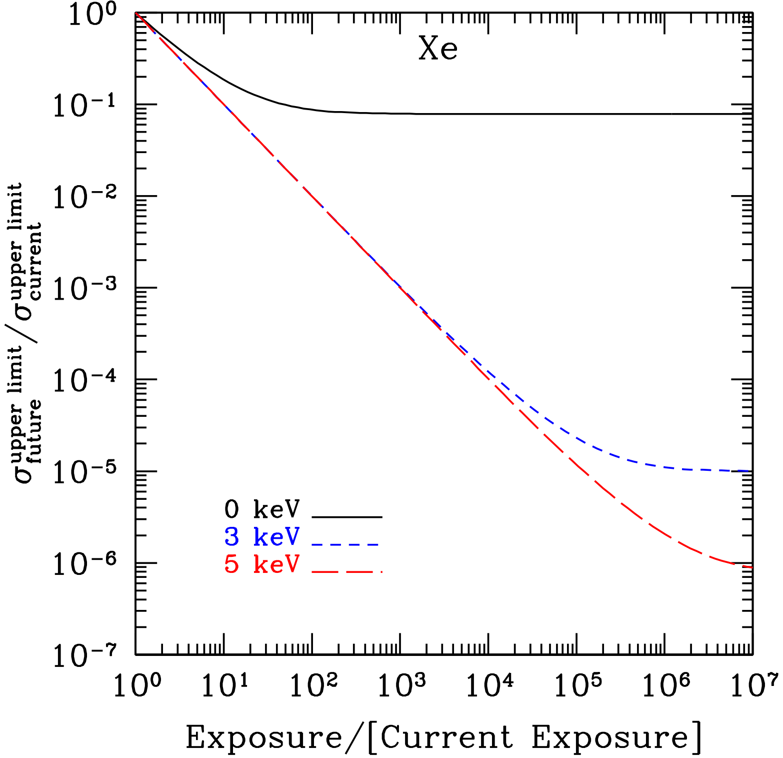
ν-floor: The values of WIMP parameters for which the ν-BG becomes important

For ^{131}Xe nuclear target detector

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

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

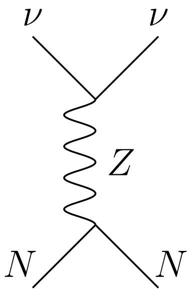
Strigari, 2009

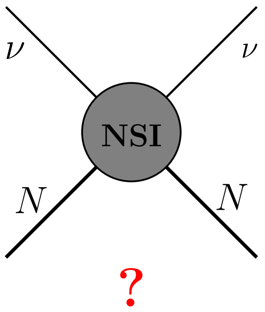


Anatomy of the ν background

DM and ν rates

Differential rate for ν-nuclei elastic scattering





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

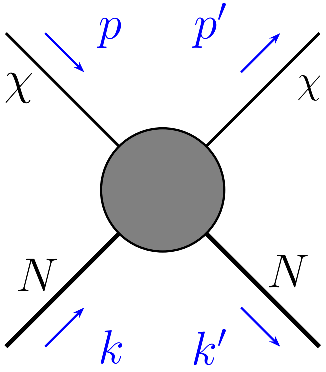
dN/dE_ν: Solar, Atmospheric, Diffuse SN fluxes

σ_ν: σ_{SM} **Freedman, 1974**

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

Differential rate for WIMP-nuclei elastic scattering

Lewis & Smith, 1996



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

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

m_χ, σ: Particle and nuclear physics

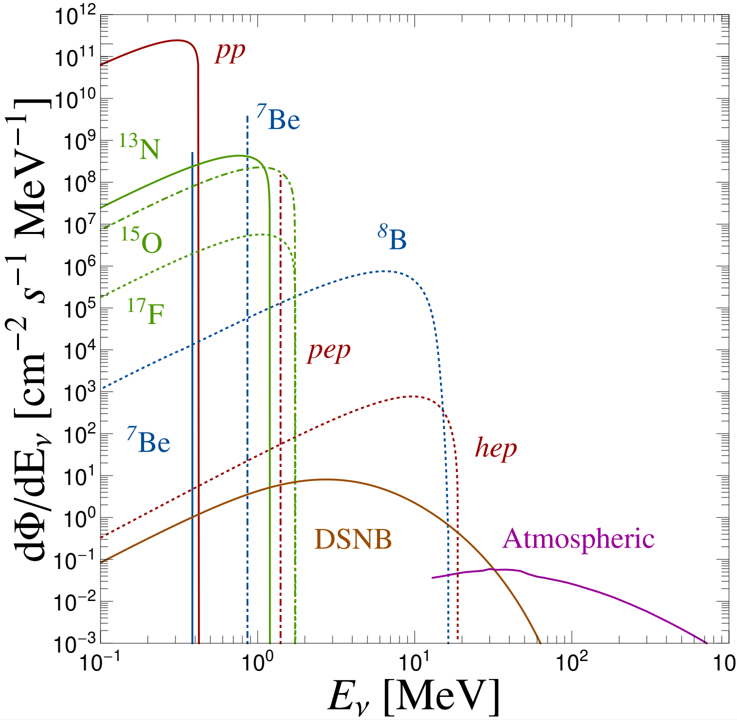
N_N, E_R: Detector physics

Neutrino Input

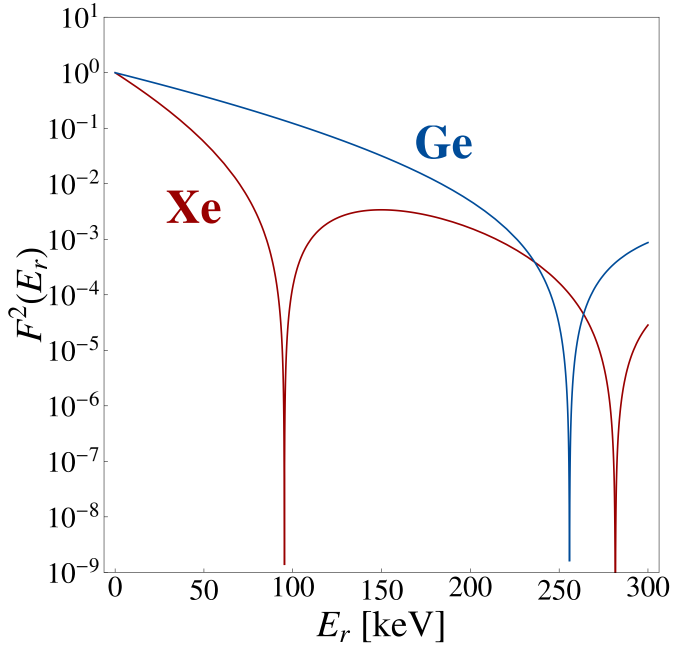
Freedman, 1974

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

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



Helm, 1956



CνNES process

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

Neutrino Sources

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

WIMP-I

Isotropic DM halo in steady state

Collisionless BEq: $\hat{L}[f] = 0$

Jeans Theorem $\Rightarrow$ Steady-state solutions

Solutions: $f(x, v)$ through integrals of motion

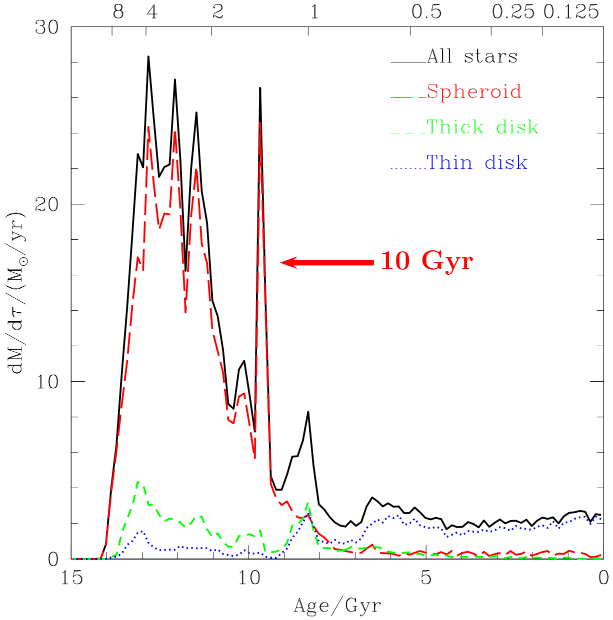
Self-gravitating isothermal gas sphere

$$\rho \propto 1/r^2 \text{ and } f(v) \propto e^{-v^2/\sigma^2}$$

Galaxy isn't in a steady state!!

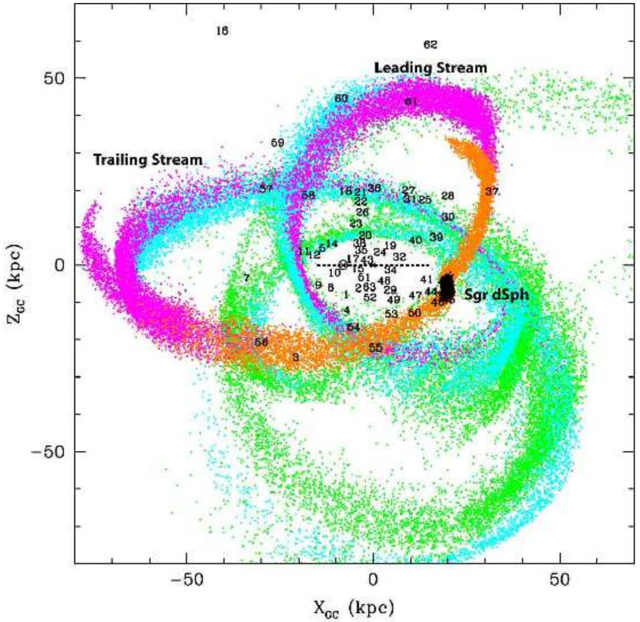
Galaxy Mergers

Mario Abadi et. al, 2002



Major mergers do not disrupt GSS!

D. Law et. al, 2010



Minor mergers do indeed **disrupt** GSS!

WIMP input-II

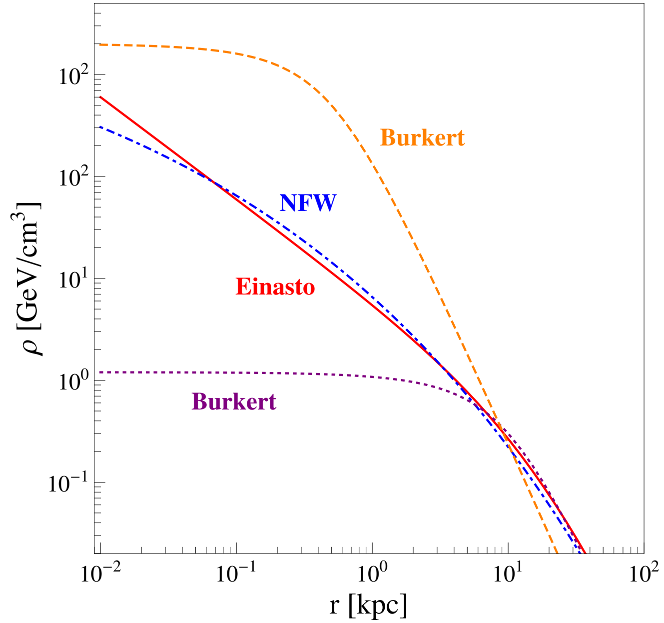
Galaxy mergers disrupte steady-state approximation!

Milky-Way-like halo simulations: VL-II, Aquarius

$$\boxed{\rho_{\text{NFW}} = \frac{\rho_0}{r/r_s(1+r/r_S)^2}}$$

Dwarf Galaxies seem to have cored profile

Core-cusp problem!

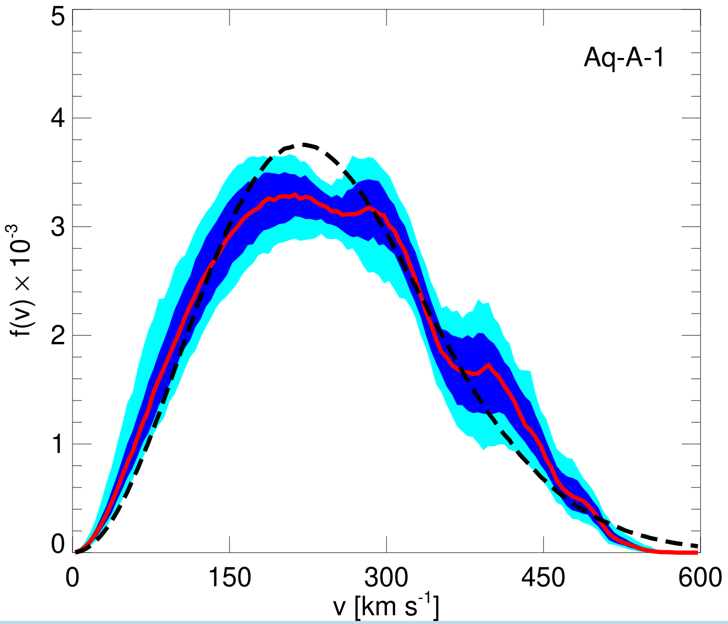


Local halo DM density **[Zemp et. el. (2008)]**

Averaging ρ_{DM} in spherical shell $R_0 \sim 8$ kpc

$$\rho_{\text{DM}} \simeq 0.3 \text{ GeV cm}^{-3}$$

Vogelsberger et al. (2008)



Velocity distribution

“Typically” calculations done in SHM

Truncated MD: $\boxed{f(v) = \frac{1}{\sqrt{2\pi}\sigma_v} e^{-v^2/2\sigma_v^2}}$

Deviations due to halo mass assembly history

Number of ν events

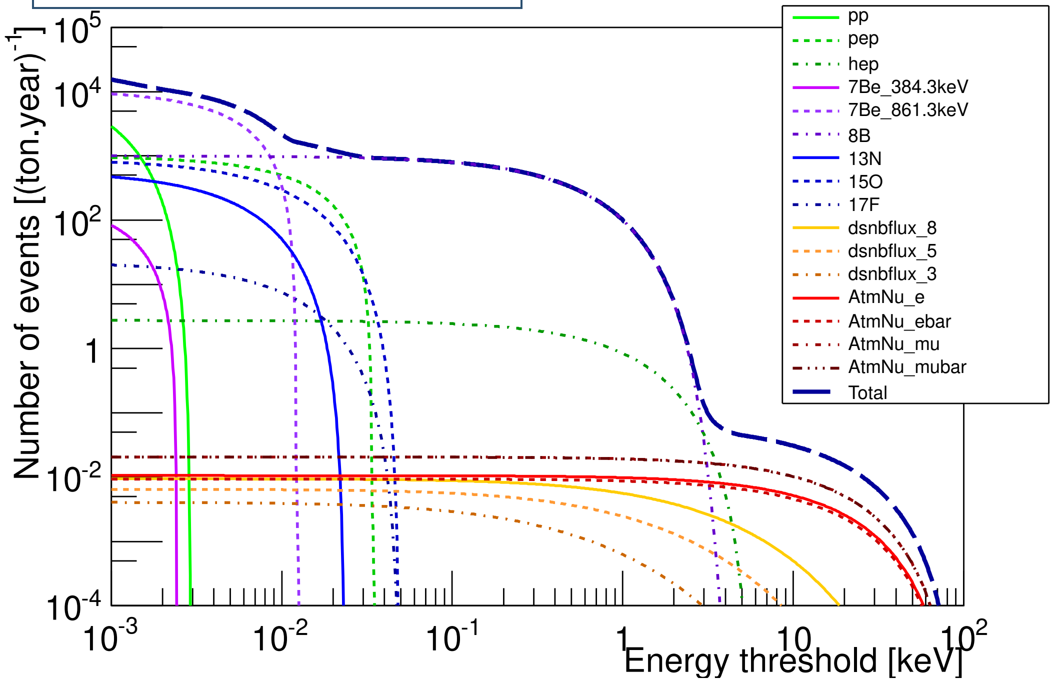
⇒ Consider the full neutrino spectrum: Solar + Atmospheric + DSNB:

- 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

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

Billard, Figueroa, Strigari, 2013



Mimicking WIMPS

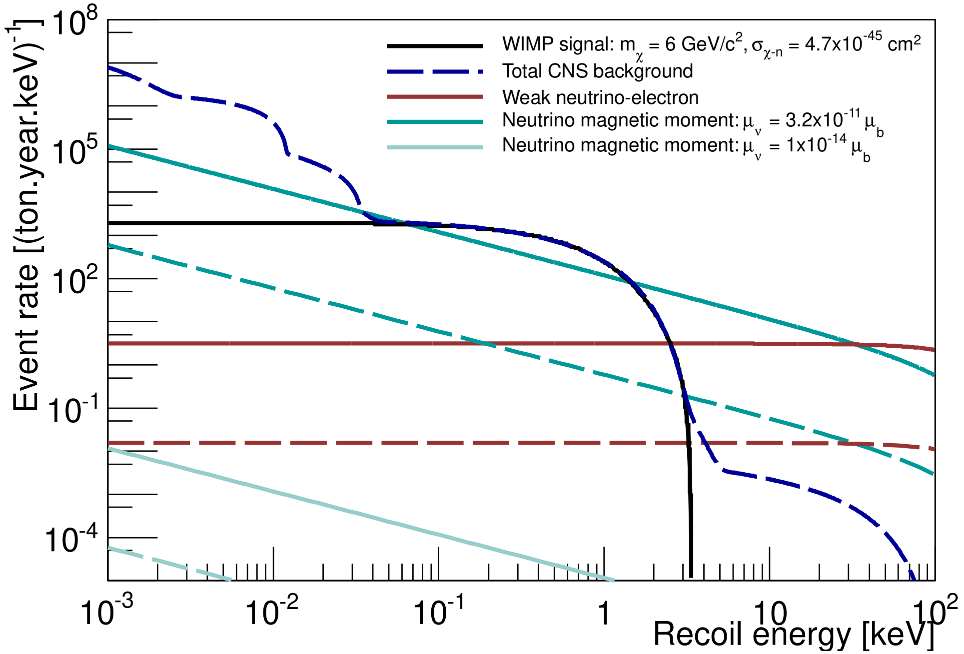
With sufficient neutrino events a WIMP-like signal can be mimicked

ν’s act as glitter: They shine as gold but aren’t

Unmask the “impostor”

⇒ Calculate dR_{WIMP}/dE_R as a function of E_R

⇒ Compare χ and ν recoil spectra ⇒ Best match gives the “impostor” mask



Solar ν

$m_\chi = 6$ GeV and $\sigma_{\chi-N} \simeq 4.4 \times 10^{-45}$ 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

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

Exposure

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

Strategy

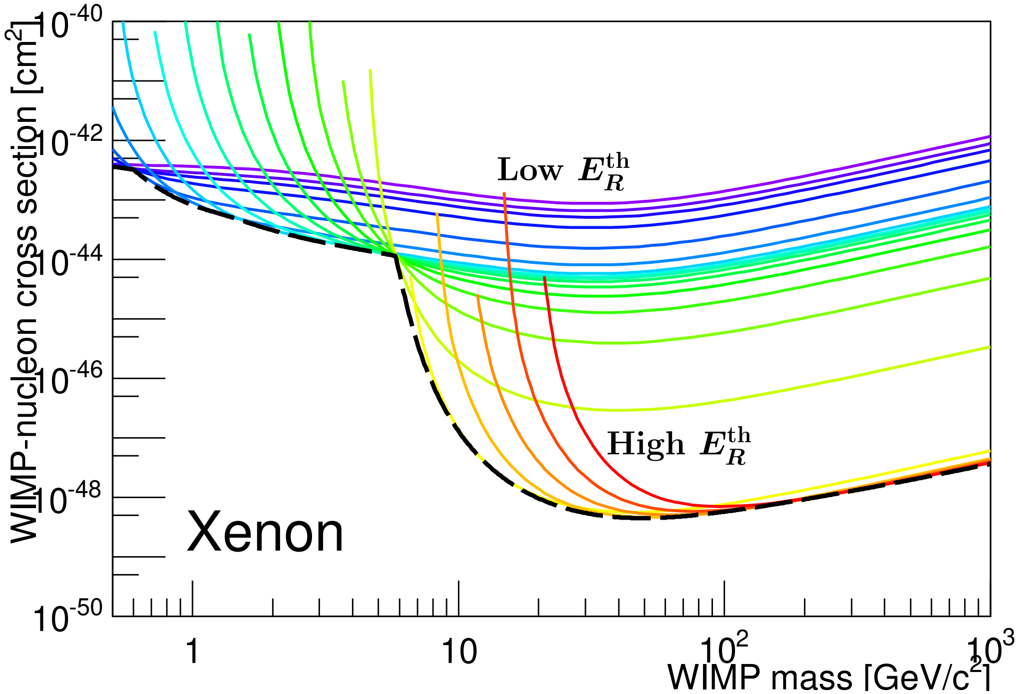
- Fix target (**Xe**), calculate sensitivities in $E_R^{\text{th}} = [10^{-2}, 10^{2}]$ keV. Fix $R_\chi = 2.3$ (90% CL)
- Optimize the calculation so each isocontour involves a single neutrino:

  ✓ Small $E_R \Rightarrow$ Large Φ_ν ($\mathcal{E}$ small) $\Rightarrow$ Large $\sigma_{\chi-n}$ for small m_χ

  ✓ Large $E_R \Rightarrow$ Small Φ_ν ($\mathcal{E}$ 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:

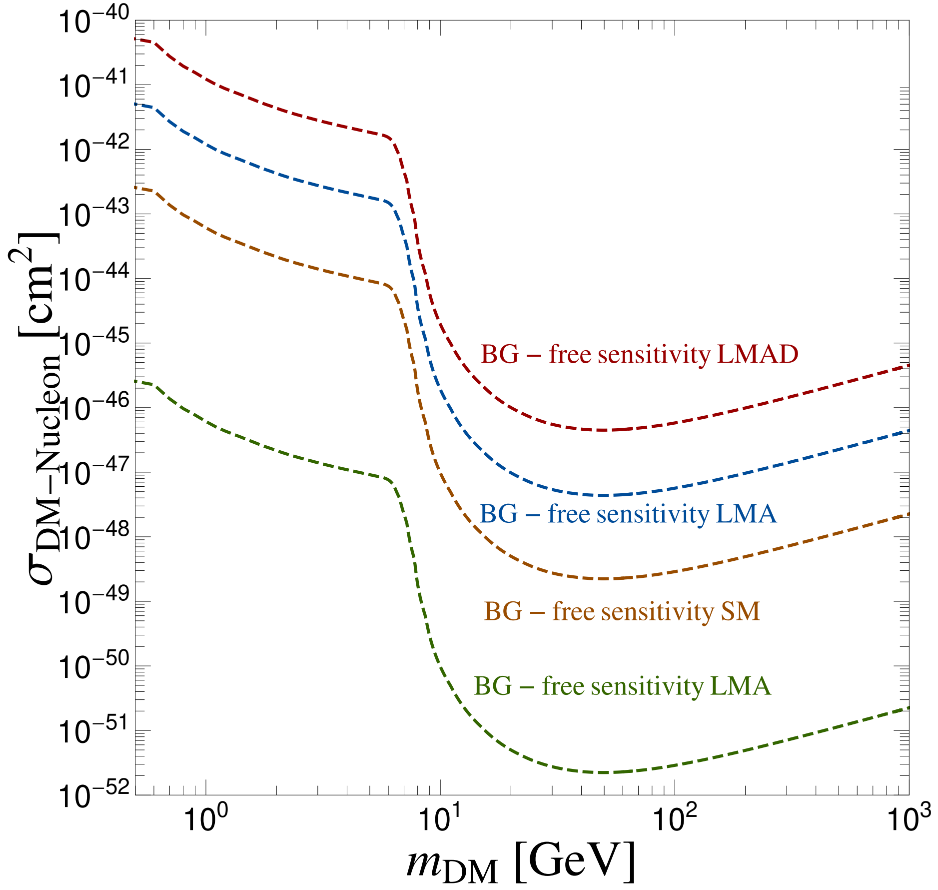
Challenge: measure $\sigma_{\chi-n} \lesssim 10^{-48}\,\text{cm}^2$

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

What does theory has to say?

Sensitivity and new physics

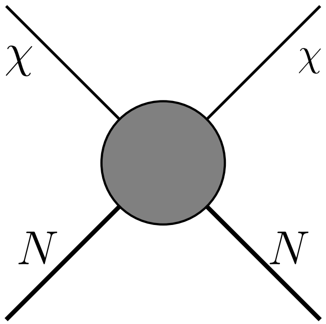
If new physics is present in the neutrino sector the “floor” (sensitivities) will be affected. Sensitivities might improve or get worse!



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

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

$\mathscr{C}_i^{(\mathcal{N})}$ 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

What kind of models??

Simplified models

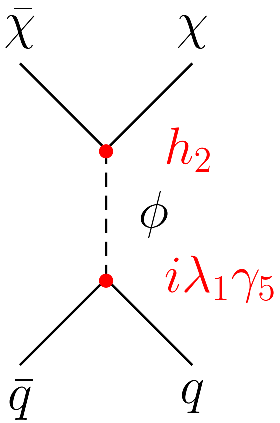
UV completions of these operators can be worked out systematically for $s = 0, 1/2, 1$ DM, at least in simplified models

Dent, Krauss et. al, 2015

Simplified model ⇒ Integrate out mediator

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

Fermion DM and scalar mediator



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

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

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

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

Direct detection driven by momentum-dependent operator

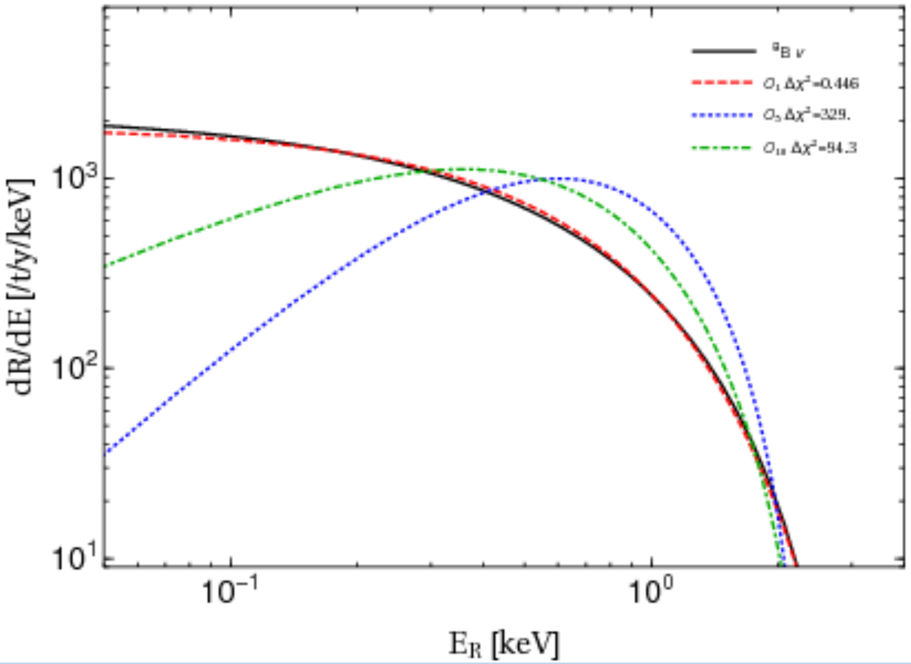
Evading the ν floor

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

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

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

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



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

Final remarks

Rèsumè

Reaching the neutrino floor

Abandon the free-bkg paradigm, but...

Does not mean looking for DM signals is over!

The neutrino bkg will be there...

two-fold use: DM+ν-physics

Tomorrow I’ll show how it can be done...!

The neutrino background offers an opportunity

complementary to that of dedicated CEvNS experiments