This slide was left
intentionally dark

Contents

1) Motivation for dark matter

   DM production: Weakly-Interacting Massive Particles (WIMPs)
   (see also the course by Francesc Ferrer)

2) DM (WIMP) detection

   - Indirect searches

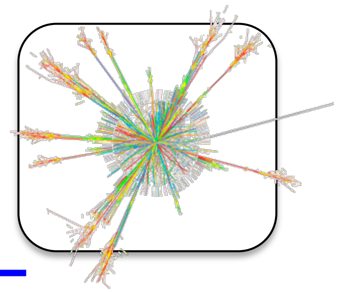
   - direct searches
     - Searches in SuperCDMS)
     - reconstruction of DM parameters

   - collider searches

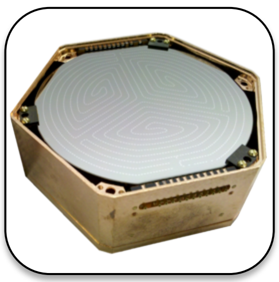
3) (some) DM models

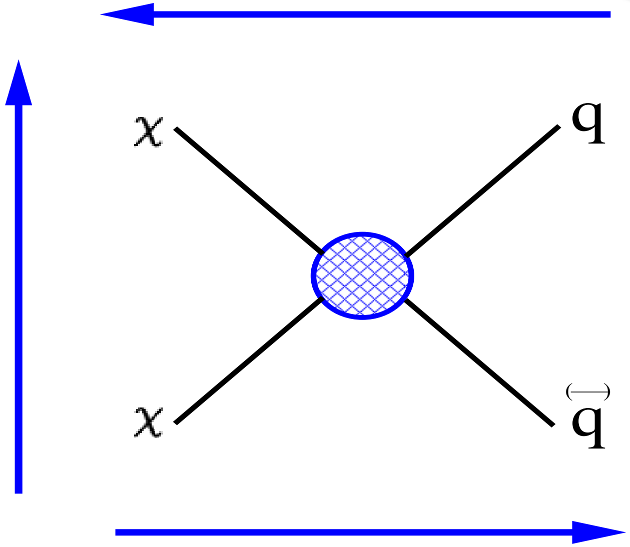
... probing **DIFFERENT** aspects of their interactions with ordinary matter

Accelerator Searches (production)



Direct Detection (scattering)

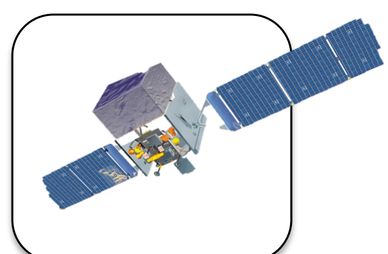




Constraints in one sector affect observations in the other two.

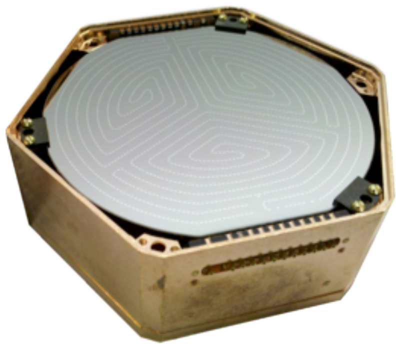
"**Redundant**" detection can be used to extract DM properties.

Indirect Detection (annihilation or decay)

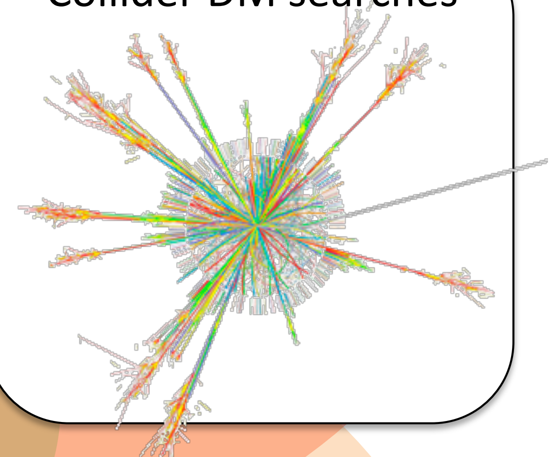


Dark matter **MUST BE** searched for in different ways...

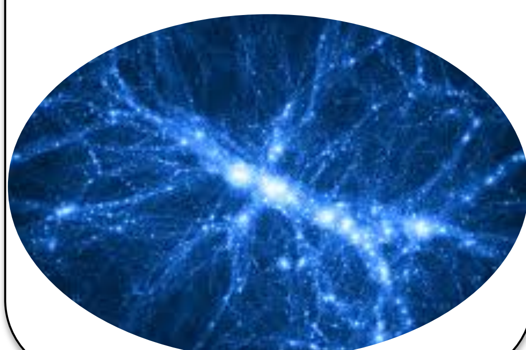
Direct DM detection



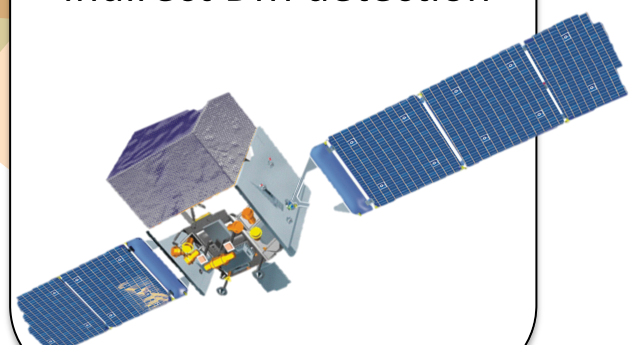
Collider DM searches



Astro/Cosmo probes

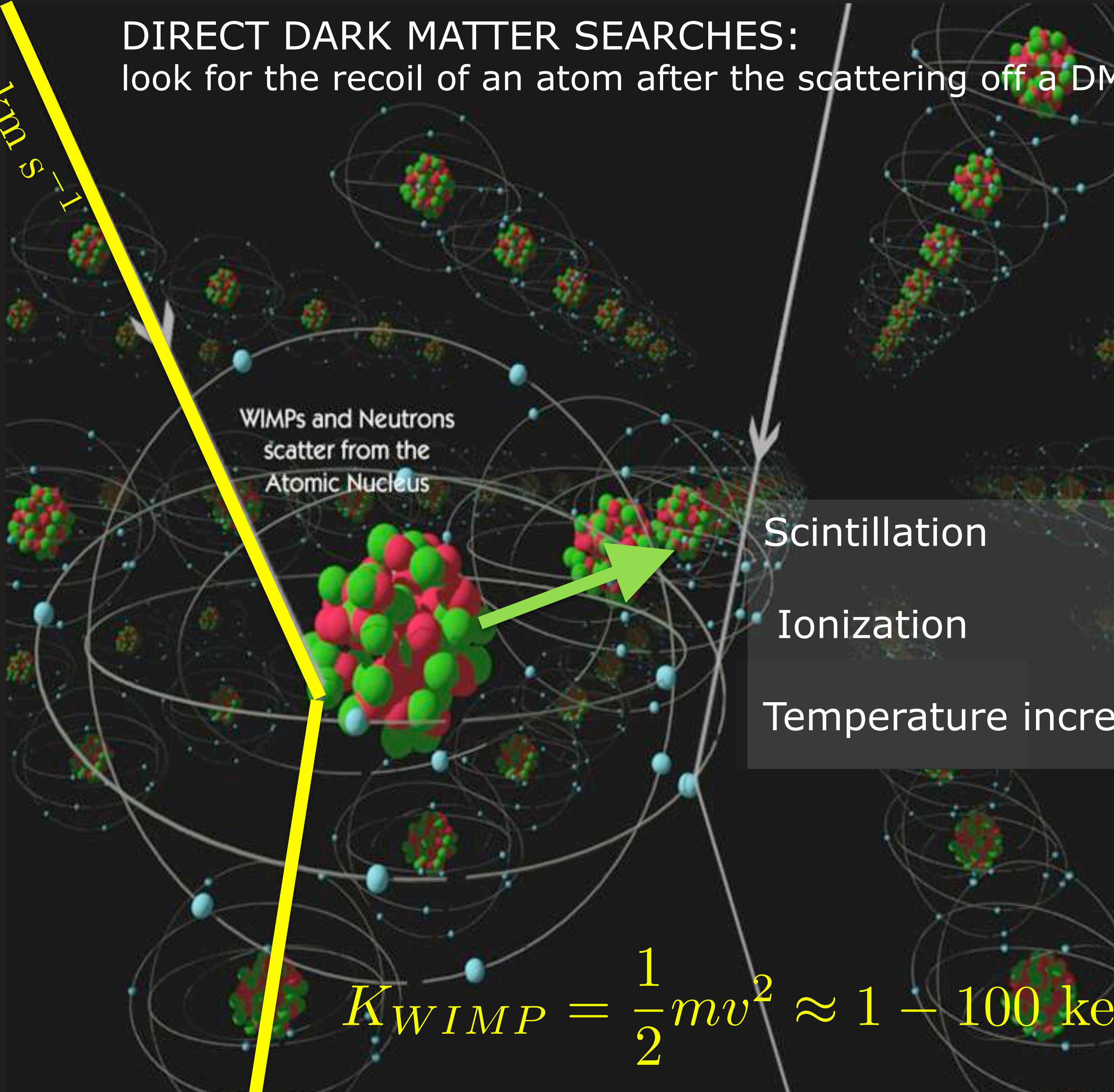


Indirect DM detection



DIRECT DARK MATTER SEARCHES:

look for the recoil of an atom after the scattering off a DM particle



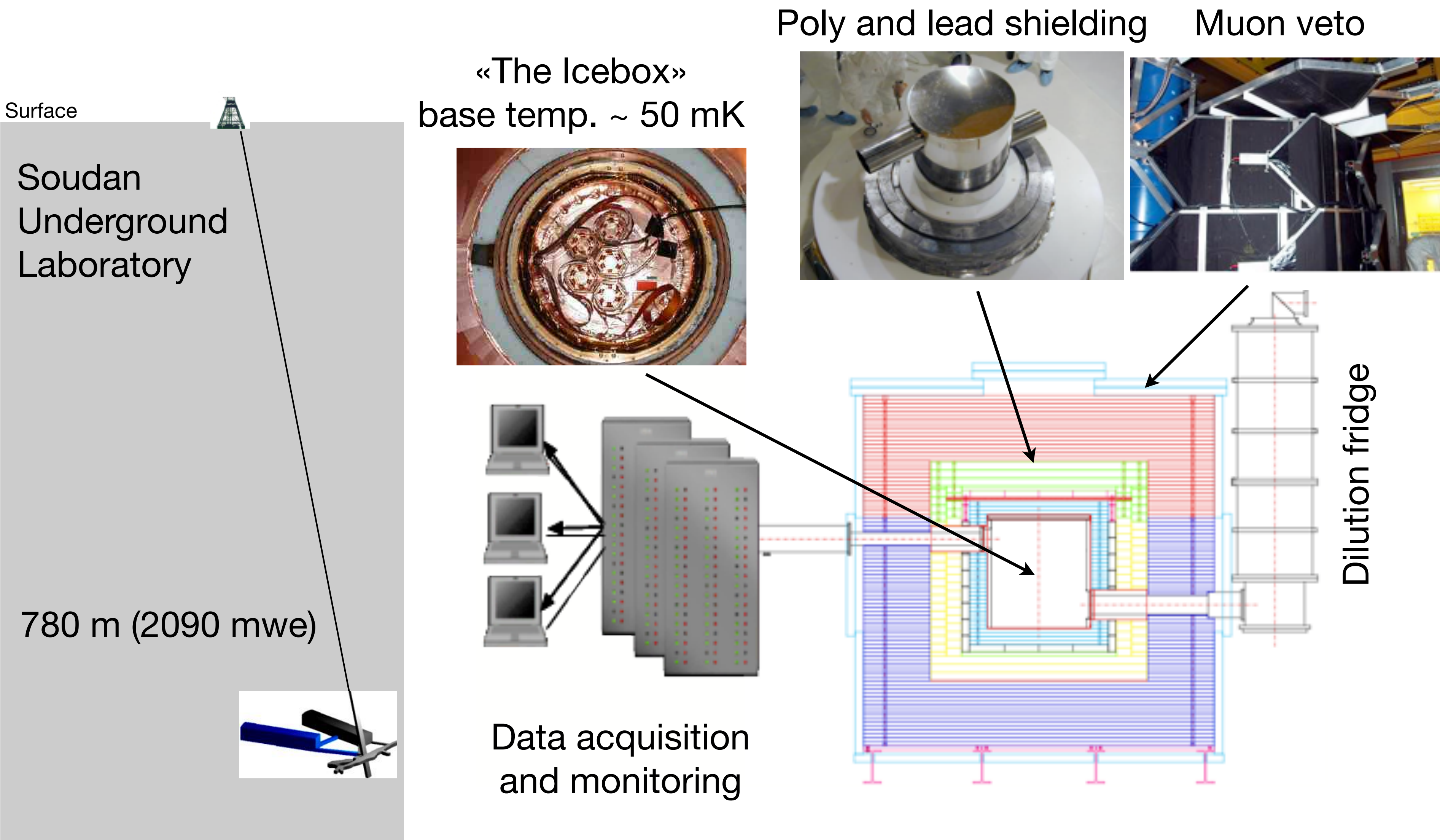
Scintillation

Ionization

Temperature increase

$$K_{WIMP} = \frac{1}{2} m v^2 \approx 1 - 100\ \mathrm{keV}$$

The experimental setup

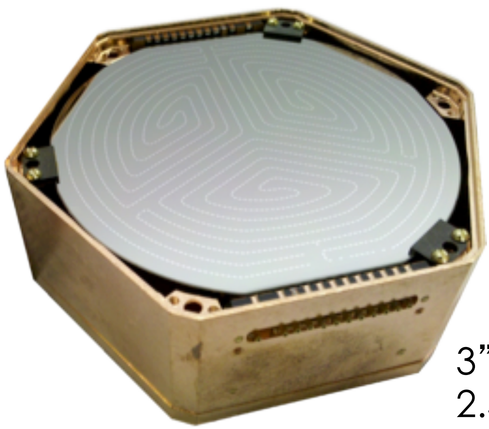


SuperCDMS at SOUDAN

Operational since March 2012

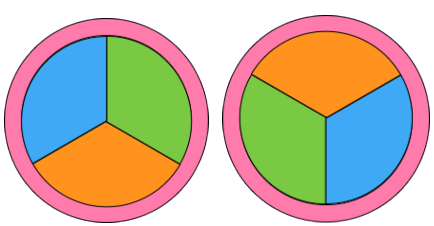
iZIP

interleaved Z-sensitive
Ionization & Phonon detectors

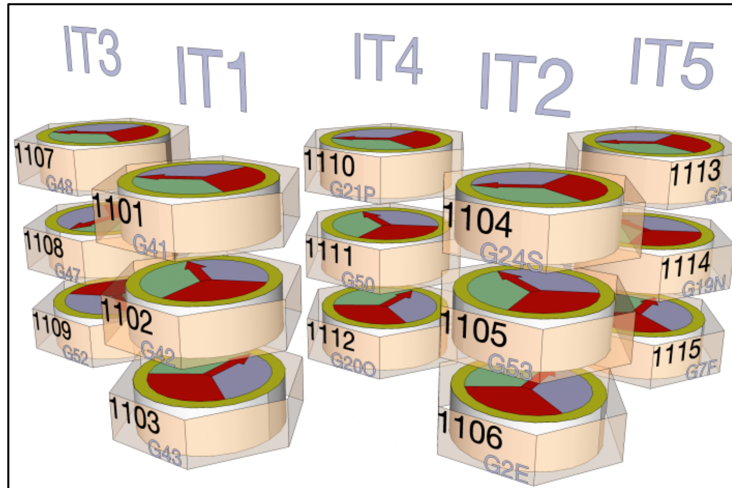


3” Diameter
2.5 cm Thick

Instrumented on both sides with
2 charge+ 4 phonon sensors



Side 1 Side 2



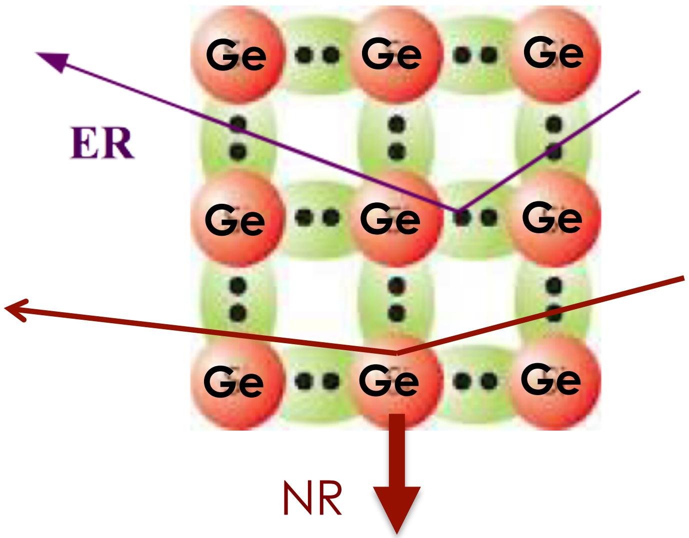
9.0 kg Ge (15 iZIPs x 600g)

Data for this analysis:

577 kg-days
taken from Mar 2012 – July 2013
7 iZIPs with lowest trigger threshold

The detection principle in CDMS

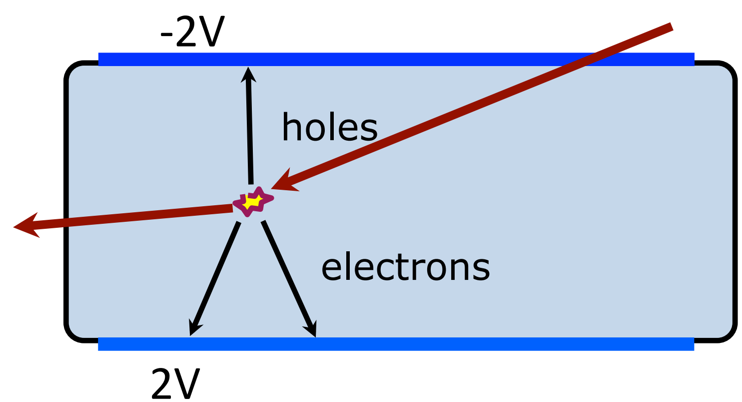
The scattering of an incident particle can induce a recoil of a nucleus (neutrons and WIMPs) or an electron (elecrons and gammas)



The recoiling particle produces

- Lattice vibrations (Phonons)
- Electron-hole pairs (Ionization)

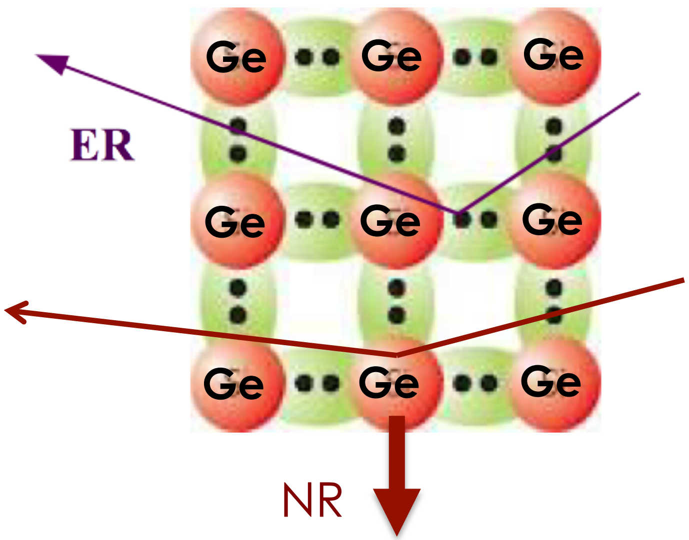
Charge carriers can propagate inside the crystal volume by applying an external electric field.



Kinetic energy of propagating charge carriers is released into additional phonons (Luke phonons)

The detection principle in CDMS

The scattering of an incident particle can induce a recoil of a nucleus (neutrons and WIMPs) or an electron (elecrons and gammas)

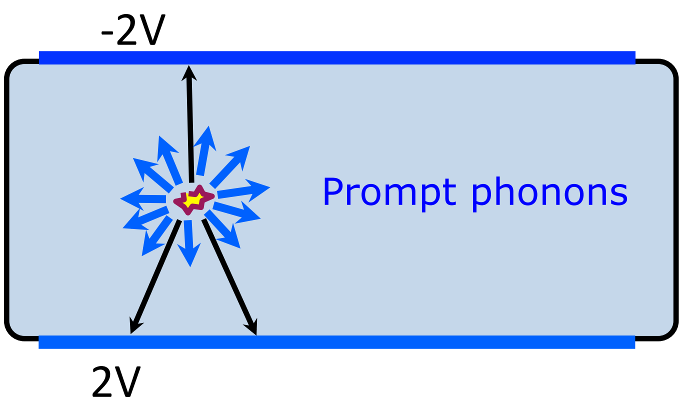


The recoiling particle produces

- Lattice vibrations (Phonons)
- Electron-hole pairs (Ionization)

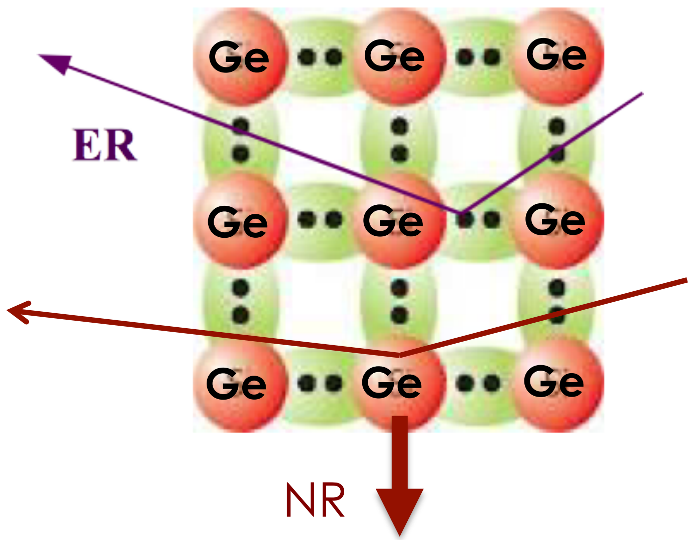
Charge carriers can propagate inside the crystal volume by applying an external electric field.

Kinetic energy of propagating charge carriers is released into additional phonons (Luke phonons)



The detection principle in CDMS

The scattering of an incident particle can induce a recoil of a nucleus (neutrons and WIMPs) or an electron (elecrons and gammas)

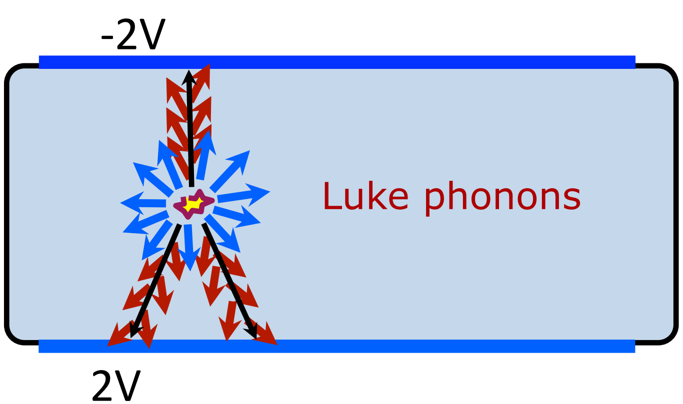


The recoiling particle produces

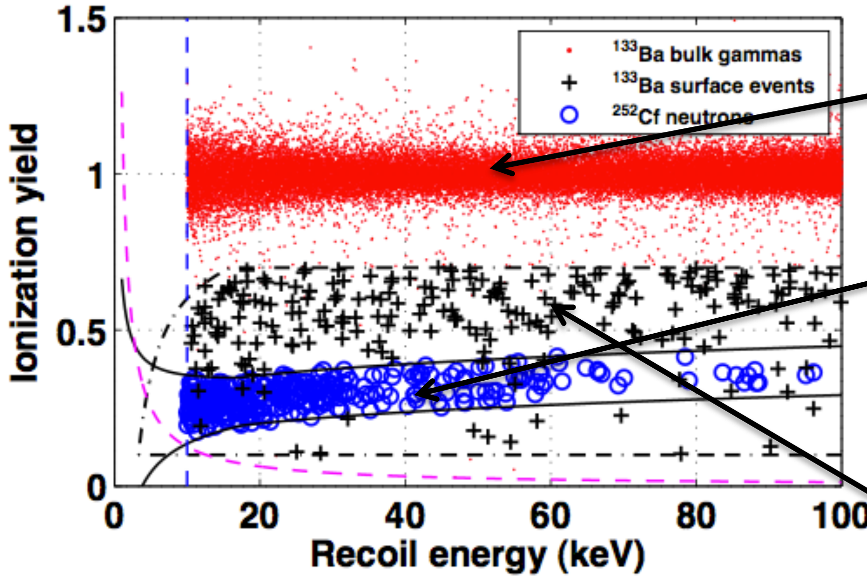
- Lattice vibrations (Phonons)
- Electron-hole pairs (Ionization)

Charge carriers can propagate inside the crystal volume by applying an external electric field.

Kinetic energy of propagating charge carriers is released into additional phonons (Luke phonons)



Background rejection in CDMS II (using ionization and phonons)

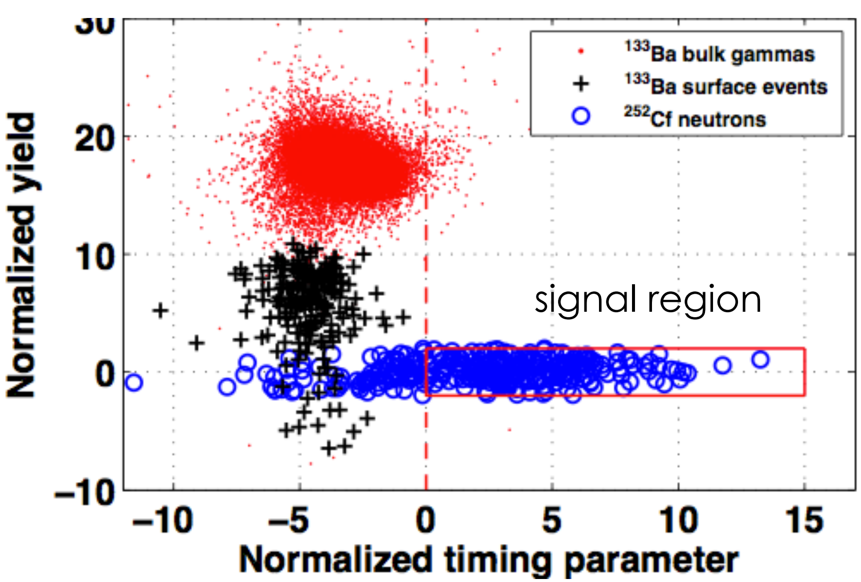


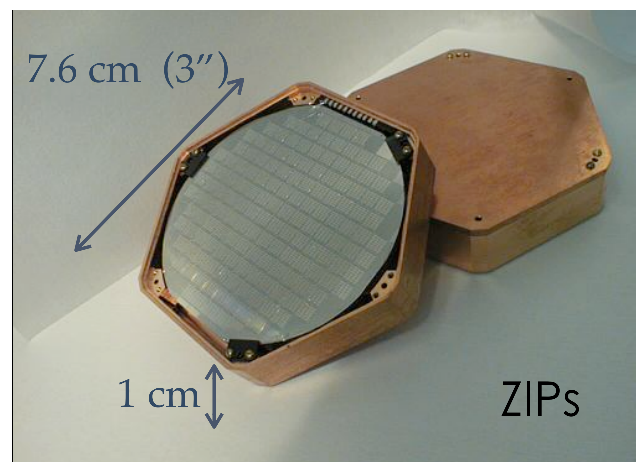
Most backgrounds (e.γ) produce electron recoils with Yield~1

Nuclear recoils produce a lower yield (~0.3) in a known band (from calibration with ^{252}Cf)

For surface events the charge collection is not complete and the yield can be lower.

They are distinguished using a timing cut.





Flux of DM particles

We can easily estimate the flux of DM particles through the Earth. The DM typical velocity is of the order of $300\,\mathrm{km\,s^{-1}} \sim 10^{-3}\,c$. Also, the local DM density is $\rho_0 = 0.3\,\mathrm{GeV\,cm^{-3}}$, thus, the DM number density is $n = \rho/m$.

$$\phi = \frac{v\rho}{m} \approx \frac{10^7}{m}\,\mathrm{cm^{-2}\,s^{-1}} \tag{3.1}$$

Kinematics

$$E_R = \frac{1}{2} m_\chi v^2 \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} \frac{1+\cos\theta}{2}$$

$$E_R^{max} = \frac{1}{2} m_\chi v^2 = \frac{1}{2} m_\chi \times 10^{-6} = \frac{1}{2}\left(\frac{m_\chi}{1\,\mathrm{GeV}}\right)\,\mathrm{keV}$$

Master formula for direct detection

We want to determine the number of nuclear recoils as a function of the recoil energy

$$\frac{dN}{dE_R} = t\, n\, v\, N_T\, \frac{d\sigma}{dE_R}\,.$$

n = DM number density
t = time
v = DM speed
NT = number of targets

The DM speed is not unique, it is distributed according to f(v)

$$\frac{dN}{dE_R} = t\, n\, N_T \int_{v_{min}} v f(\vec{v})\, \frac{d\sigma}{dE_R}\, d\vec{v}\,,$$

$$v_{min} = \sqrt{m_\chi\, E_R/2\mu_{\chi N}^2}$$

Using $N_T = M_T/m_N$

$n = \rho/m_\chi$

$\epsilon = t\, M_T$

$$\frac{dN}{dE_R} = \epsilon\, \frac{\rho}{m_\chi\, m_N} \int_{v_{min}} v f(\vec{v})\, \frac{d\sigma}{dE_R}\, d\vec{v}\,.$$

Conventional direct detection approach

$$R = \int_{E_T} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

Experimental setup

Target material (sensitiveness to different couplings)

Detection threshold

Astrophysical parameters

Local DM density

Velocity distribution factor

Theoretical input

Differential cross section

(of WIMPs with quarks)

Nuclear uncertainties

Conventional direct detection approach

$$R = \int_{E_T} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

Experimental setup

Target material (sensitiveness to different couplings)

Detection threshold

Astrophysical parameters

Local DM density

Velocity distribution factor

Theoretical input

Differential cross section

(of WIMPs with quarks)

Nuclear uncertainties

Experimental challenges:

- Discriminating Nuclear and Electron recoils
- Reduction of backgrounds
- Increment Target Size
- **Low Energy threshold**

WIMP expected fingerprint:

- Exponential spectrum
- Annual Modulation of the signal
- Directionality

Conventional direct detection approach

$$R = \int_{E_T} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}} v f(v) \boxed{\frac{d\sigma_{WN}}{dE_R}(v, E_R)}\, dv$$

Experimental setup

Target material (sensitiveness to different couplings)

Detection threshold

Astrophysical parameters

Local DM density

Velocity distribution factor

Theoretical input

Differential cross section

(of WIMPs with quarks)

Nuclear uncertainties

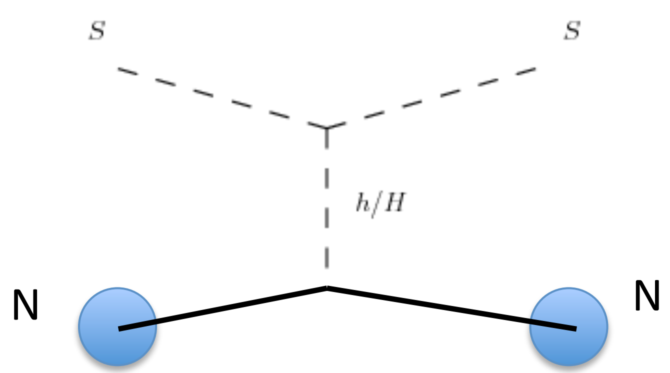
$$\boxed{\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}}$$

Spin-independent and **Spin-dependent** components, stemming from different microscopic interactions leading to different coherent factors

Detecting Dark Matter through elastic scattering with nuclei

We want to describe the (elastic) scattering cross section of DM particles with nuclei

$$\frac{d\sigma_{WN}}{dE_R}(v, E_R)$$



But our microscopic theory generally provides the interaction with quarks and gluons

Quarks → Nucleons (protons and neutrons)

Nucleons → Nucleus Nuclear models (encoded in a Form Factor)

The WIMP-nucleus cross section has two components

$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

Spin-independent contribution: scalar (or vector) coupling of WIMPs with quarks

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q + \alpha_q^V \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

Total cross section with Nucleus scales as A^2

Present for all nuclei (favours heavy targets) and WIMPs

Spin-dependent contribution: WIMPs couple to the quark axial current

$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

Total cross section with Nucleus scales as J/(J+1)

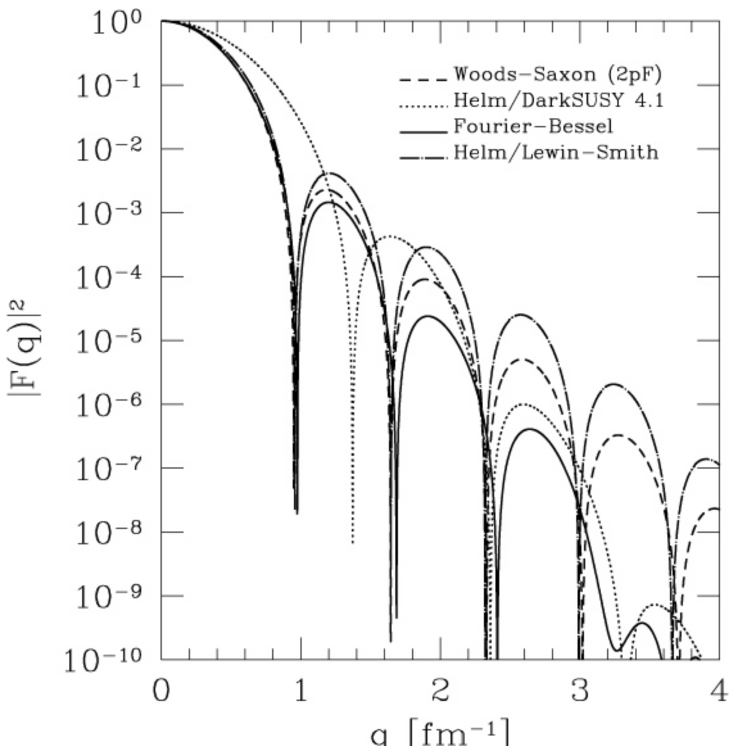
Only present for nuclei with J≠ 0 and WIMPs with spin

WIMP-nucleus (elastic) scattering cross section

$$\frac{\mathrm{d}\sigma^{WN}}{\mathrm{d}E_R} = \frac{m_N}{2{\mu_N}^2 v^2}\left({\sigma_0}^{SI,N} F_{SI}^2(E_R) + {\sigma_0}^{SD,N} F_{SD}^2(E_R)\right)$$

Where the spin-independent and spin-dependent contributions read

$$\begin{aligned}{\sigma_0}^{SI,N} &= \frac{4\mu_N^2}{\pi}[Zf_p + (A-Z)f_n]^2,\\ {\sigma_0}^{SD,N} &= \frac{32\mu_N^2 G_F^2}{\pi}[a_p S_p + a_n S_n]^2\left(\frac{J+1}{J}\right)\end{aligned}$$



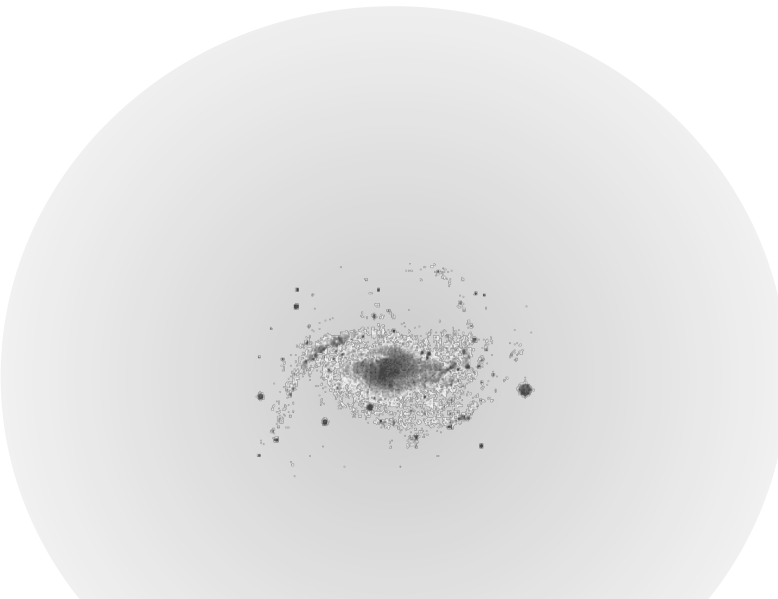
The Form factor encodes the loss of coherence for large momentum exchange

$$F^2(q) = \left(\frac{3j_1(qR_1)}{qR_1}\right)^2 \exp(-q^2 s^2)$$

For ~keV energies, F(q)~1

Detecting Dark Matter through elastic scattering with nuclei

$$\frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$



Minimal DM velocity for a recoil of energy E_R

$$v_{min}(E_R) = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}.$$

Isothermal spherical halo

$$f(\vec{v} + \vec{v}_{lag}) = \frac{1}{(2\pi)^{\frac{3}{2}}\sigma^3} exp\left(-\frac{(\vec{v} + \vec{v}_{lag})^2}{2\sigma^2}\right)$$

$$\sigma = 150\ \mathrm{km\, s^{-1}}$$

$$v_{lag} = 230\ \mathrm{km\, s^{-1}}$$

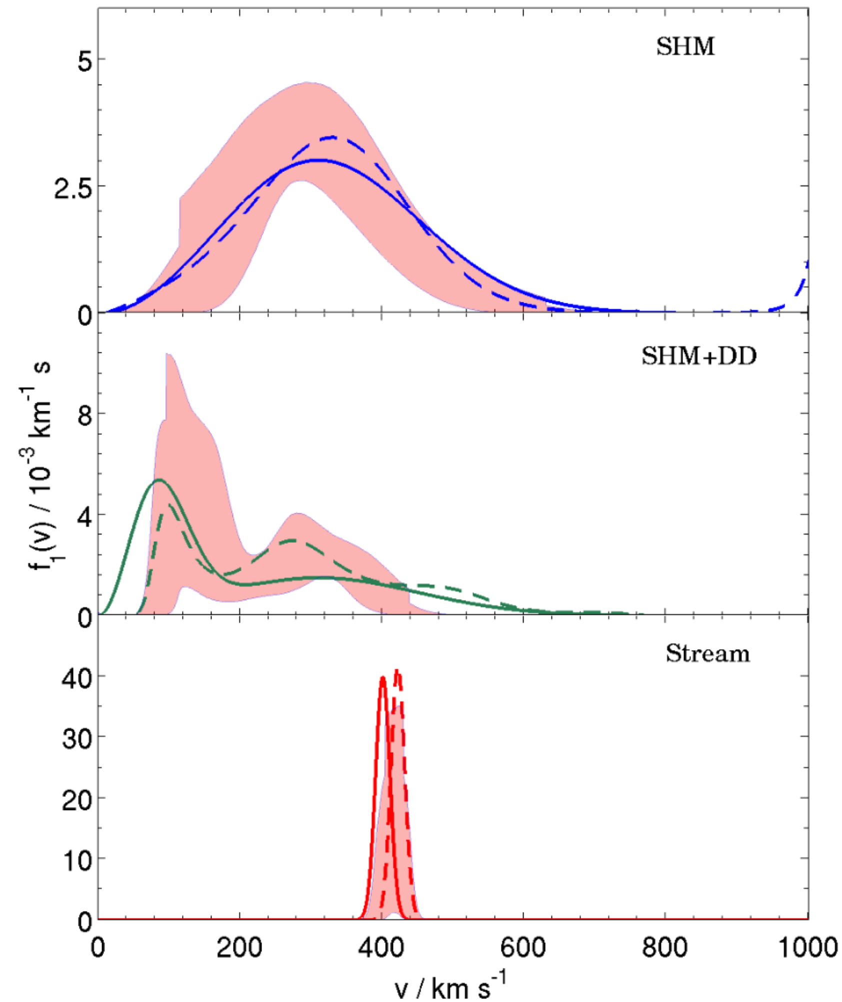
Astrophysical parameters

Local DM density

Velocity distribution factor

Uncertainties in the Dark Halo affect significantly the prospects for direct detection

For example, there might be non-thermalised components: dark disk or streams



Kavanagh and Green 2013

Discriminating a DM signal: ENERGY SPECTRUM

DM scattering would leave an **exponential signal** in the differential rate

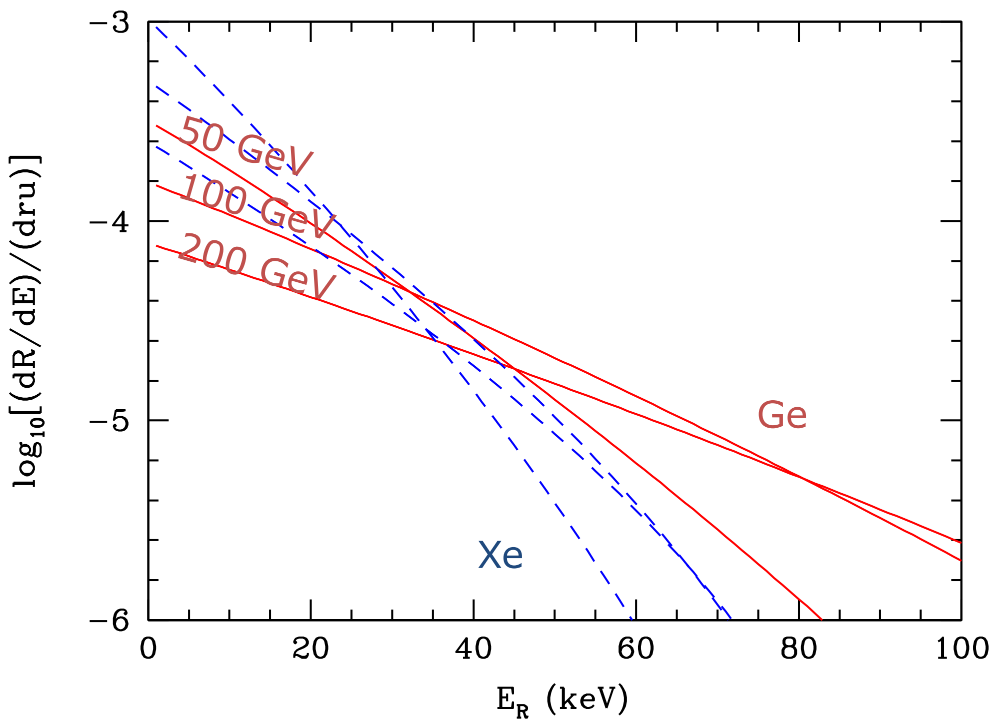
$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

The slope is dependent on the DM mass and the target mass

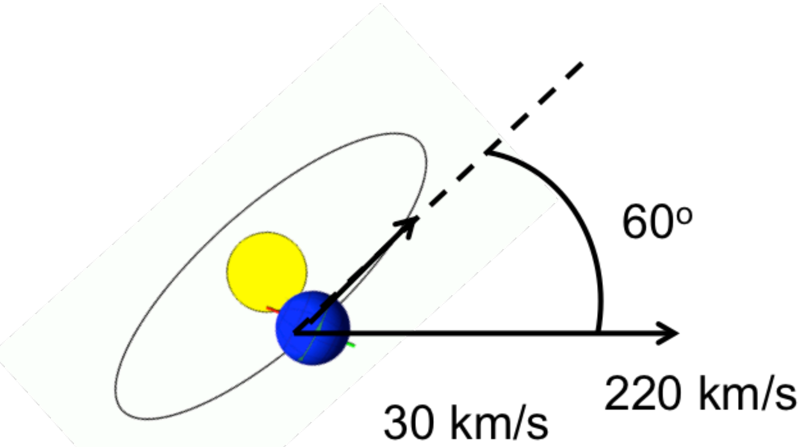
Light WIMPs expected at very low recoil energies

Favours light targets

Low-threshold searches



Discriminating a DM signal: ANNUAL MODULATION

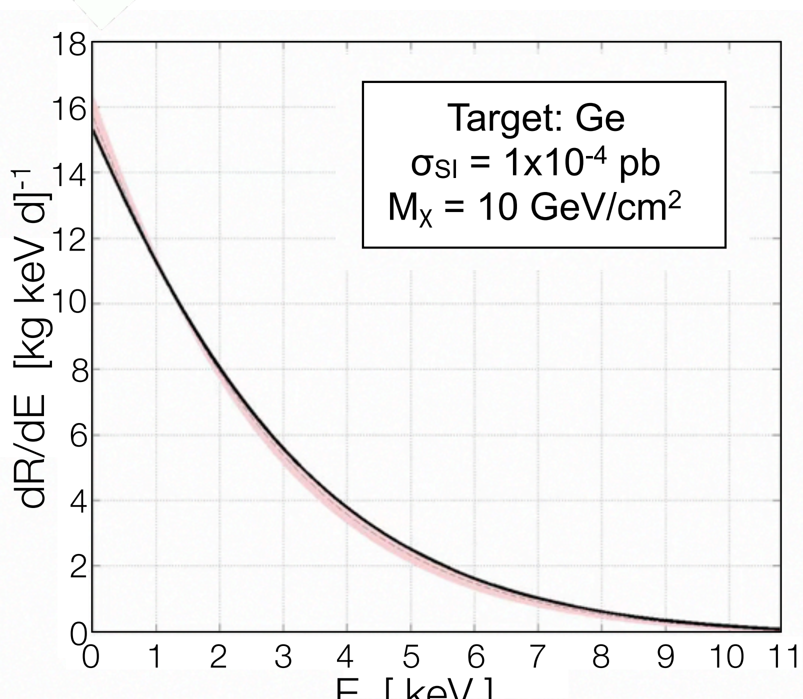


Drukier et al. 86

The relative velocity of WIMPs in the Earth reference frame has an annual modulation.

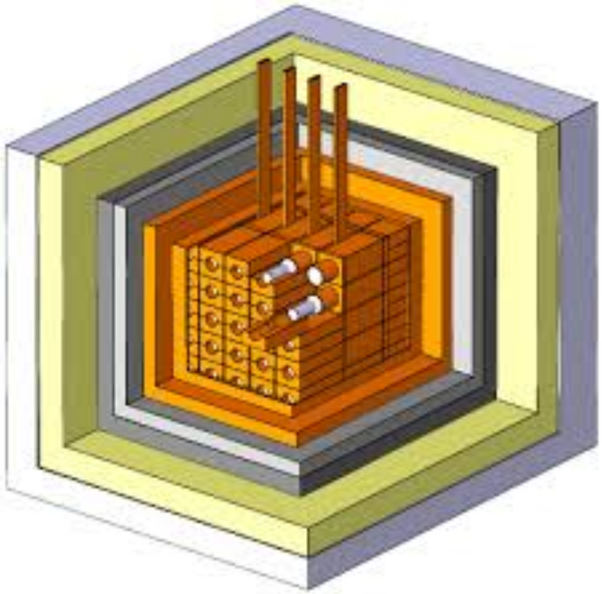
This implies a modulation in the rate.

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \approx \left(\frac{\mathrm{d}R}{\mathrm{d}E_R}\right)\left(1 + \Delta(E_R)\cos(\alpha(t))\right).$$



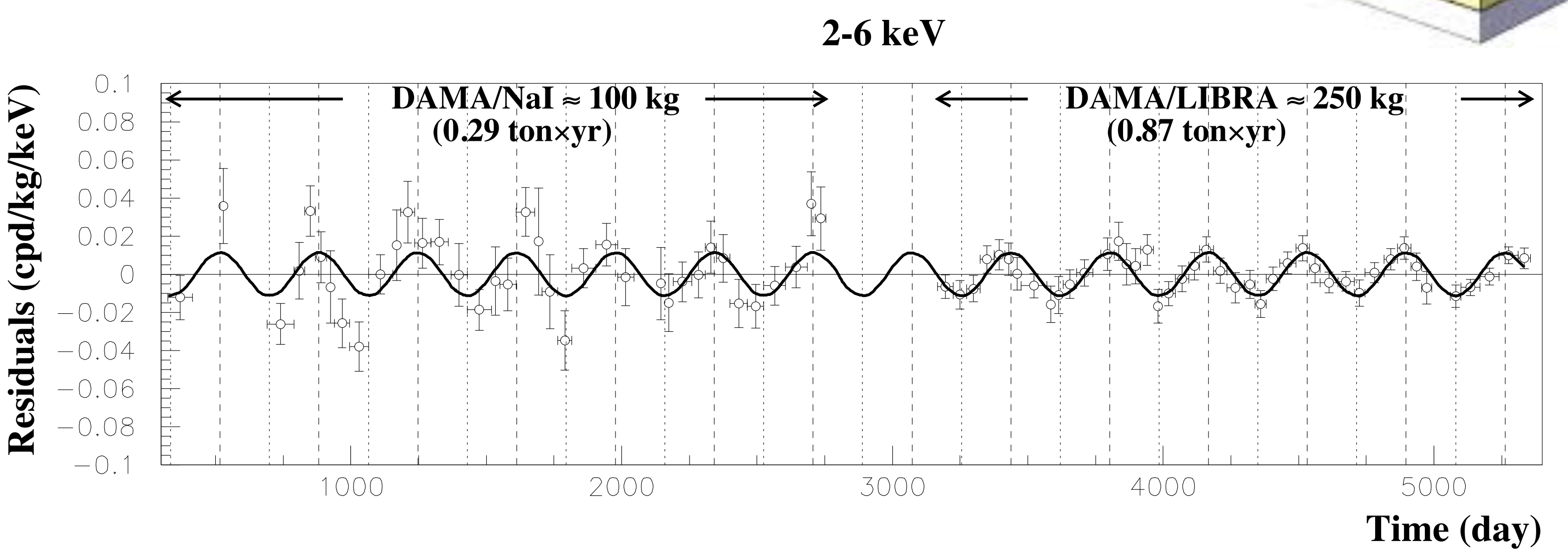
The modulation amplitude is small (~7%) and very sensitive to the details of the halo parameters

DAMA (DAMA/LIBRA) signal on annual modulation



cumulative exposure 427,000 kg day (13 annual cycles) with NaI

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \approx \left(\frac{\mathrm{d}\bar{R}}{\mathrm{d}E_R}\right)[1+\Delta(E_R)\cos\alpha(t)]$$

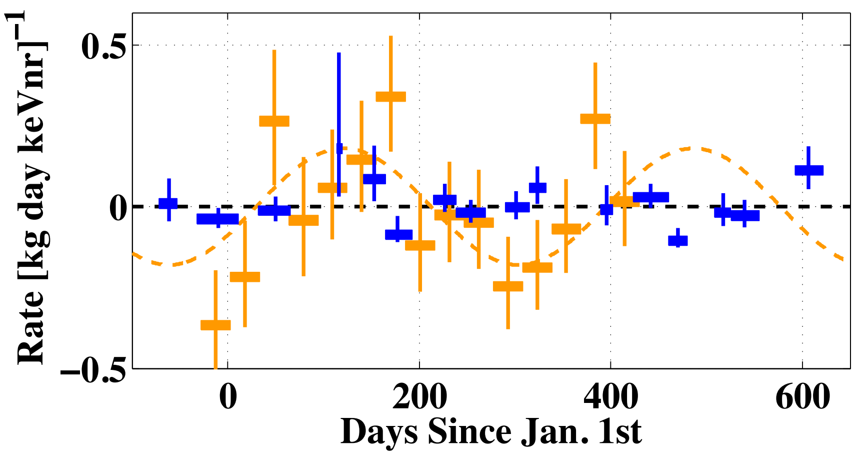


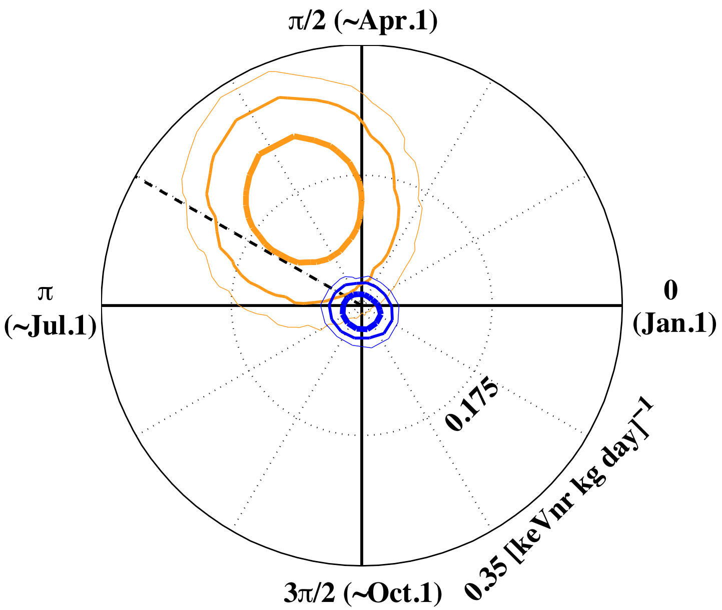
... however other experiments (CDMS, Xenon, CoGeNT, ZEPLIN, Edelweiss, ...) did not confirm (its interpretation in terms of WIMPs).

CDMS did not see annual modulation

An analysis of CDMS II (Ge) data has shown no evidence of modulation.

This means a further constraint on CoGeNT claims



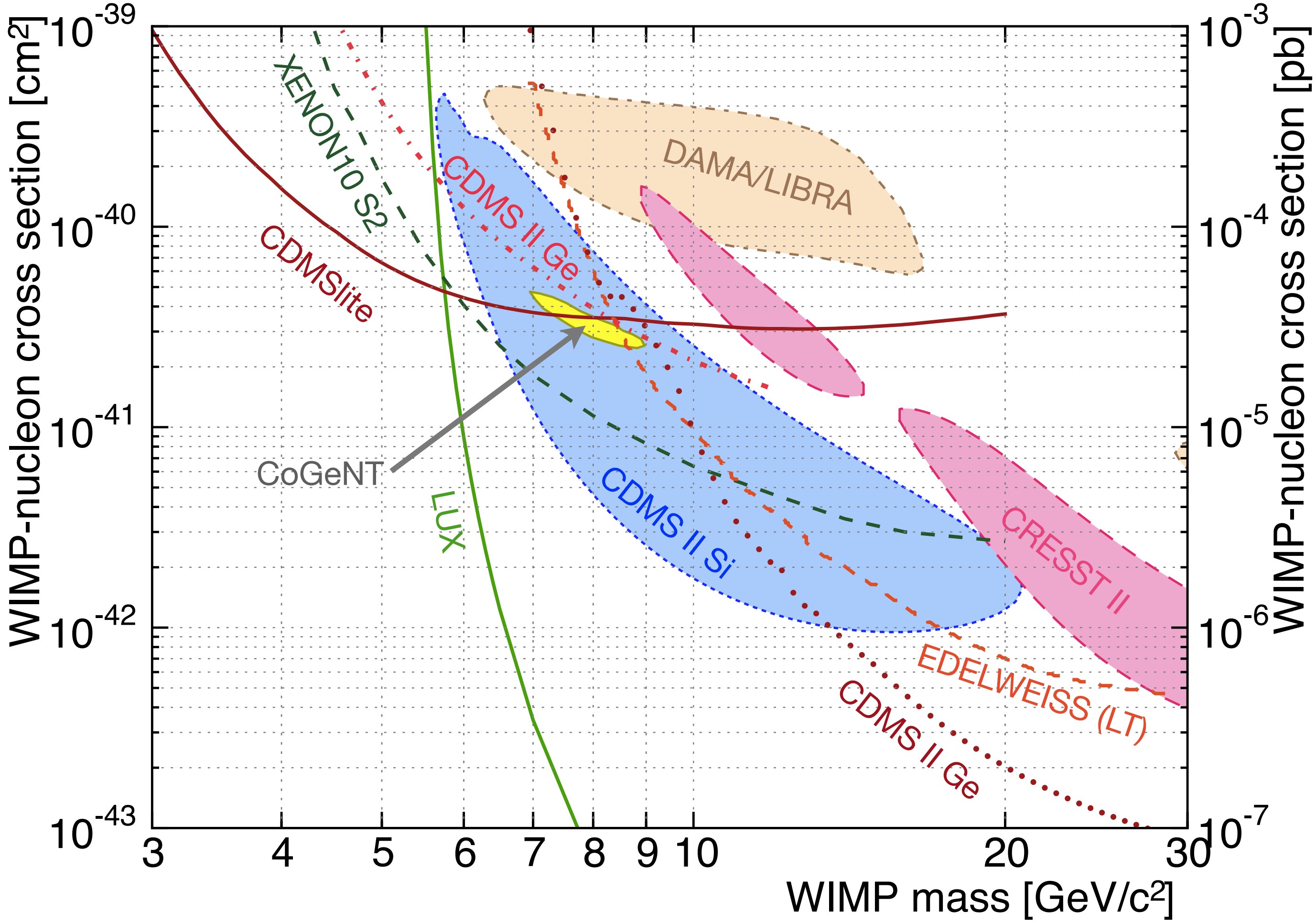


CDMS II 2012

- CoGeNT: smaller amplitude of the DM modulation signal in second year of data

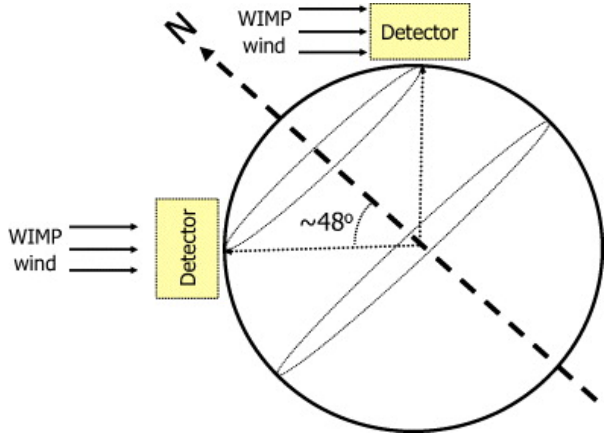
Collar in IDM 2012

The light DM puzzle



CDMS II Si: Phys.Rev.Lett. 111 (2013) 251301
CDMSlite: Phys.Rev.Lett. 112 (2014) 041302

Discriminating a DM signal: DIRECTIONALITY



Spergel '88

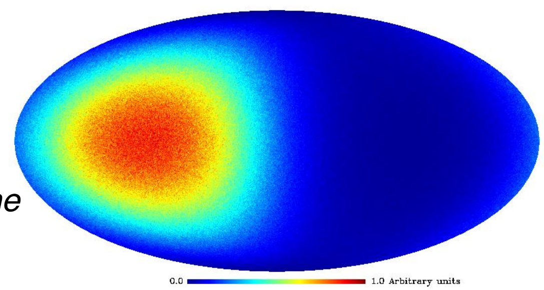
Experimental challenges

Low-pressure TPC to measure direction

Large exposure needed (from current limits)

WIMP signal (recoil map)

Angular distribution of Fluorine recoils [5;50] keV

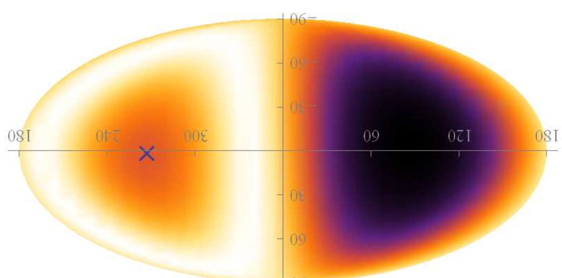


Characteristic dipole signal

- Poor resolution
- Low- number of WIMPs vs. Background

J. Billard et al., 2010

E_R= 5 keV (CS_2)
m_{WIMP} = 100 GeV



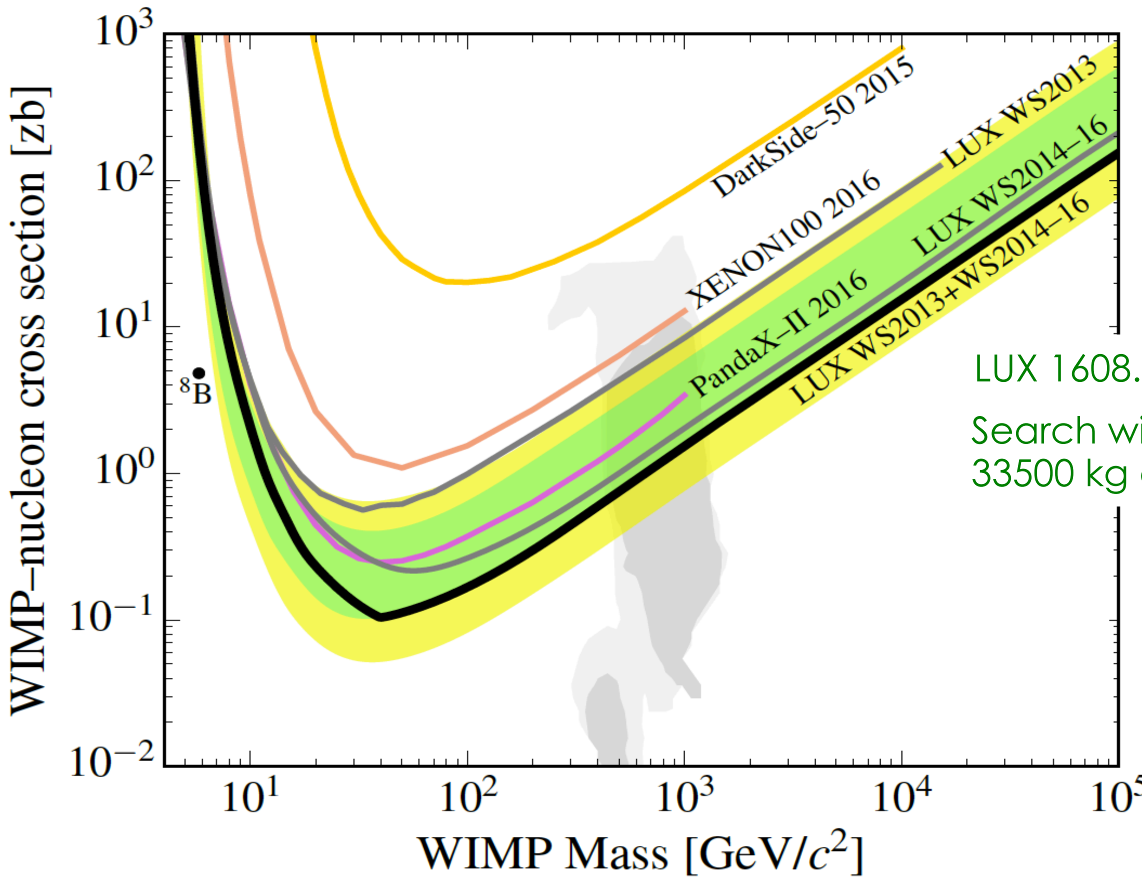
Ring-like structure

- Requires low-recoil energies and heavy WIMPs
- Also aberration due to Earth's motion

Bozorgnia et al., 2012

Constraints on the DM-nucleus scattering cross section

XENON, LUX, Panda-X (Xe), CDMSlite, SuperCDMS, Edelweiss (Ge), COUPP (CF_3I), and CRESST ($CaWO_4$) have not observed any DM signal, which constrains the DM-nucleus scattering cross section

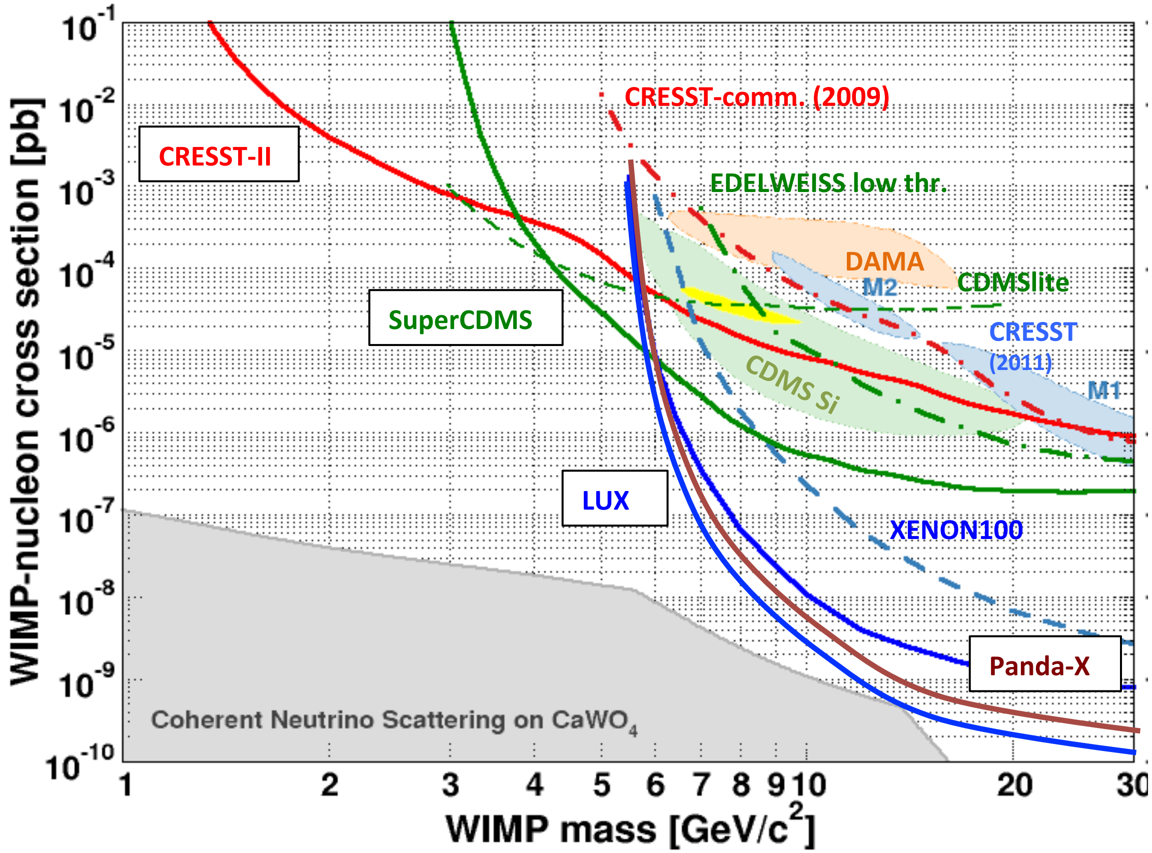


LUX 1608.07648

Search with
33500 kg day exposure of LXe

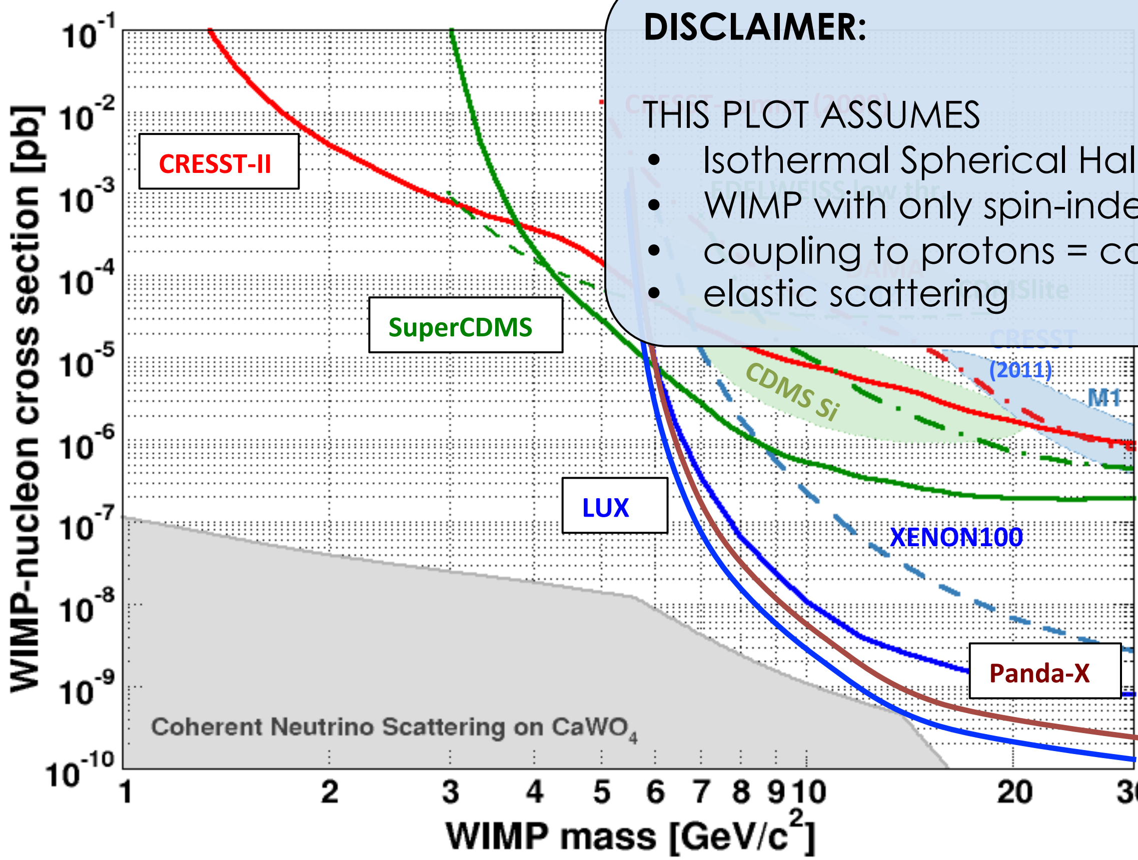
Constraints on the DM-nucleus scattering cross section

XENON, LUX, Panda-X (Xe), CDMSlite, SuperCDMS, Edelweiss (Ge), COUPP (CF_3I), and CRESST ($CaWO_4$) have not observed any DM signal, which constrains the DM-nucleus scattering cross section



Constraints on the DM-nucleus scattering cross section

XENON, LUX, Panda-X (Xe), CDMSlite, SuperCDMS, Edelweiss (Ge), COUPP (CF_3I), and CRESST ($CaWO_4$) have not observed any DM signal, which constrains the DM-nucleus scattering cross section

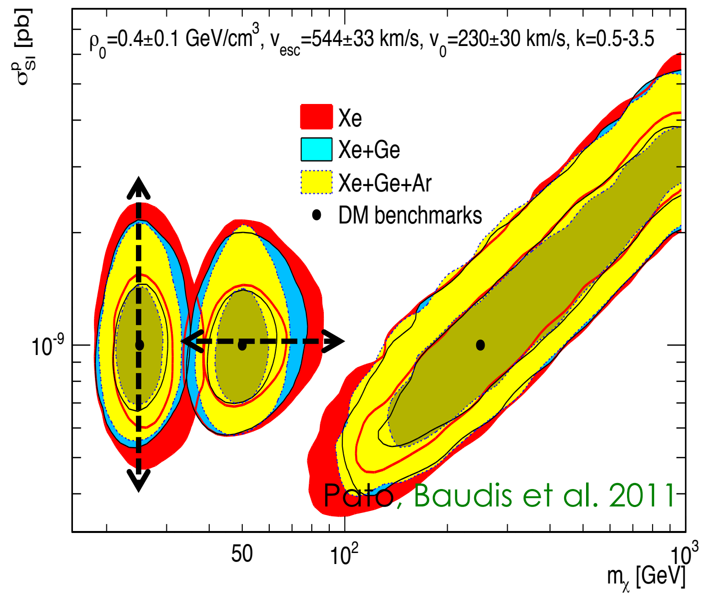


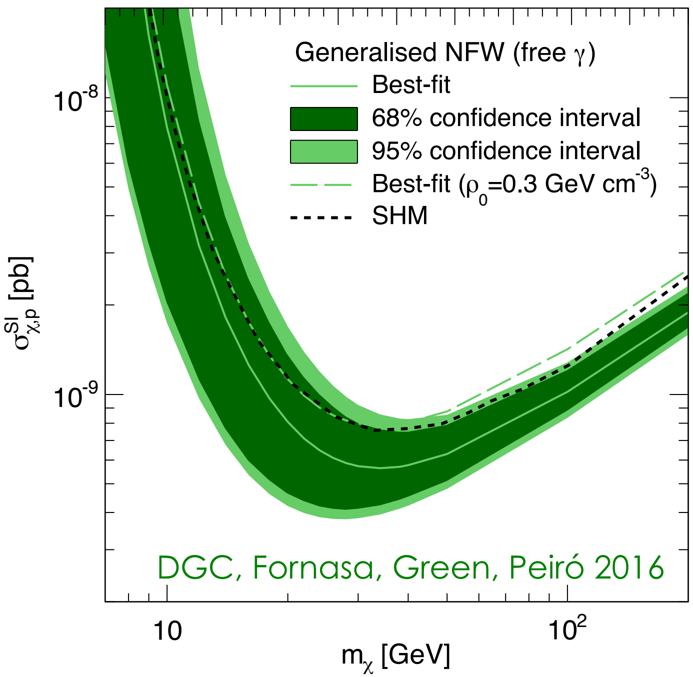
DISCLAIMER:

THIS PLOT ASSUMES
- Isothermal Spherical Halo
- WIMP with only spin-independent interaction
- coupling to protons = coupling to neutrons
- elastic scattering

Astrophysical input and uncertainties

Uncertainties in the parameters describing the Dark Matter halo affect bounds and reconstruction





- Incorporating uncertainties is crucial in order to compare results among different experiments. **Halo-independent analyses.**
- Very relevant to combine direct and indirect detection constraints.
- Low mass region is especially sensitive

Theoretical prejudice

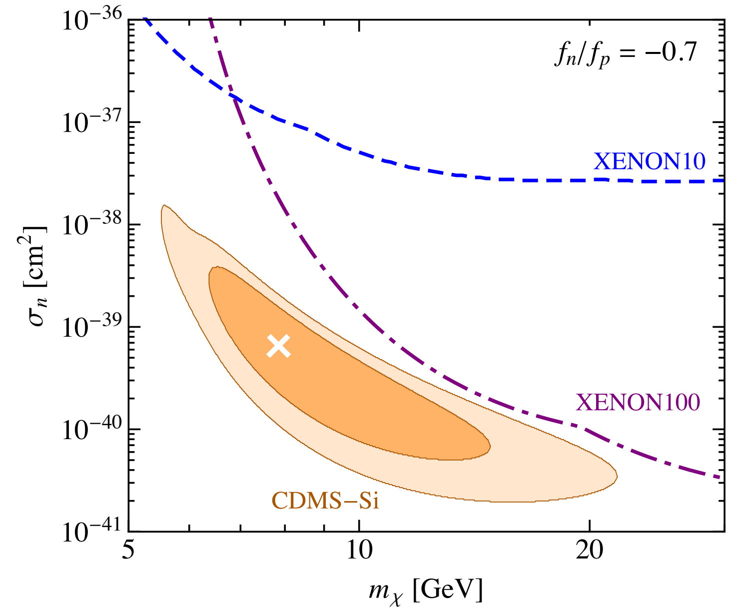
Example: "Isospin violation": the scattering amplitudes for proton and neutrons may interfere destructively

$$R = \sigma_p \sum_i \eta_i \frac{\mu_{A_i}^2}{\mu_p^2} I_{A_i} \left[Z + (A_i - Z) f_n/f_p\right]^2$$

$$f_n/f_p = -Z/(A-Z)$$

The interference depends on the target nucleus

For Xe (Z=54, A~130) → $f_n/f_p = -0.7$



XENON100 (Xe) and CDMS II (Si) results "reconciled"

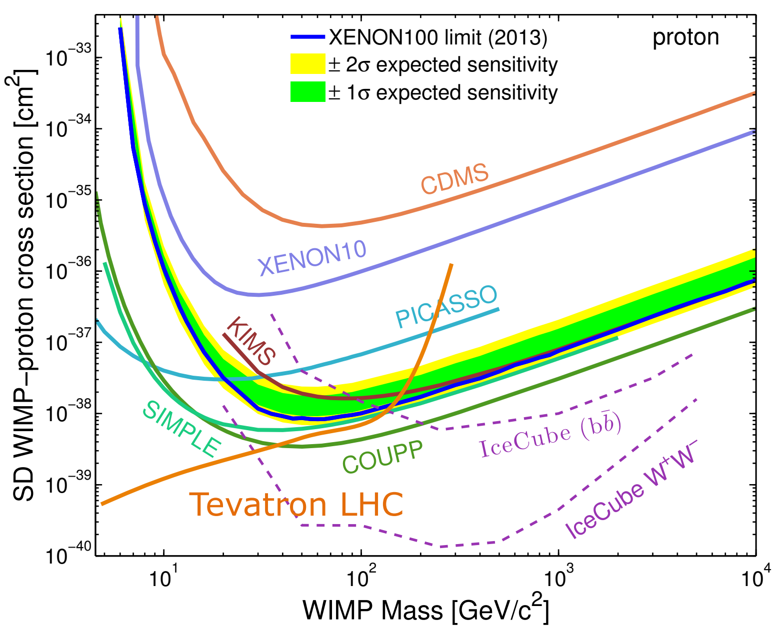
Frandsen et al. 2013

The effective interaction of DM particles with nuclei can be more diverse than previously considered

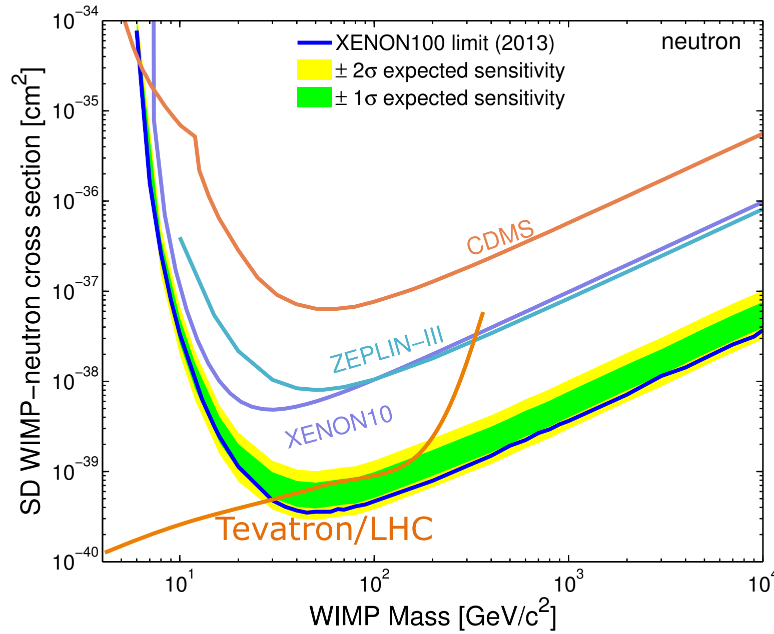
Spin-dependent searches have also become more sensitive

Although they do not impose yet strong constraints on DM models

SD coupling to protons



SD coupling to neutrons



Currently we have also understood how nuclear uncertainties in the form factors affect these constraints

CDGC, Fornasa, Huh, Peiró 2012
Cannoni 2013

Are we being too simplistic in describing WIMP-nucleus interactions?

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \boxed{\frac{d\sigma_{WN}}{dE_R}(v, E_R)}\, dv$$

$$\boxed{\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}}$$

Effective Field Theory approach

The most general effective Lagrangian contains up to 14 different operators that induce **6 types of response functions and two new interference terms**

Haxton, Fitzpatrick 2012-2014

$$\mathcal{L}_{\rm int}(\vec{x}) = c\ \Psi^*_\chi(\vec{x})\mathcal{O}_\chi\Psi_\chi(\vec{x})\ \Psi^*_N(\vec{x})\mathcal{O}_N\Psi_N(\vec{x})$$

$$\begin{aligned}
\mathcal{O}_1 &= 1_\chi 1_N \\
\mathcal{O}_3 &= i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right] \\
\mathcal{O}_4 &= \vec{S}_\chi \cdot \vec{S}_N \\
\mathcal{O}_5 &= i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right] \\
\mathcal{O}_6 &= \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right] \\
\mathcal{O}_7 &= \vec{S}_N \cdot \vec{v}^\perp \\
\mathcal{O}_8 &= \vec{S}_\chi \cdot \vec{v}^\perp \\
\mathcal{O}_9 &= i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}_{10} &= i\vec{S}_N \cdot \frac{\vec{q}}{m_N} \\
\mathcal{O}_{11} &= i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \\
\mathcal{O}_{12} &= \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right] \\
\mathcal{O}_{13} &= i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right] \\
\mathcal{O}_{14} &= i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right] \\
\mathcal{O}_{15} &= -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]
\end{aligned}$$

(x2) if we allow for different couplings to protons and neutrons (isoscalar and isovector)

Effective Field Theory approach

The most general effective Lagrangian contains up to 14 different operators that induce **6 types of response functions and two new interference terms**

Haxton, Fitzpatrick 2012-2014

$$\mathcal{L}_{\rm int}(\vec{x}) = c\ \Psi^*_\chi(\vec{x})\mathcal{O}_\chi\Psi_\chi(\vec{x})\ \Psi^*_N(\vec{x})\mathcal{O}_N\Psi_N(\vec{x})$$

Spin-Indep.

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

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

Spin-Dep.

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$

$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$

$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

(x2) if we allow for different couplings to protons and neutrons (isoscalar and isovector)

Effective Field Theory approach

The most general effective Lagrangian contains up to 14 different operators that induce **6 types of response functions and two new interference terms**

Haxton, Fitzpatrick 2012-2014

$$\mathcal{L}_{\rm int}(\vec{x}) = c\ \Psi_\chi^*(\vec{x})\mathcal{O}_\chi\Psi_\chi(\vec{x})\ \Psi_N^*(\vec{x})\mathcal{O}_N\Psi_N(\vec{x})$$

Spin-Indep.

Spin-Dep.

Momentum dependence

Velocity dependence

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

$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$

$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$

$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$

$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$

$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$

$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$

$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$

$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$

$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$

$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$

$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$

$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$

(x2) if we allow for different couplings to protons and neutrons (isoscalar and isovector)

These operators can be obtained as the non-relativistic limit of relativistic operators (e.g., starting from UV complete models)

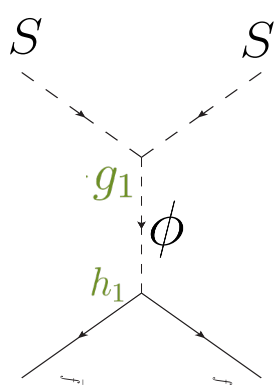
Spin-0 DM particle + scalar mediator

$$
\begin{aligned}
\mathcal{L}_{S\phi q} = {} & \partial_\mu S^\dagger \partial^\mu S - m_S^2 S^\dagger S - \frac{\lambda_S}{2}(S^\dagger S)^2 \\
& + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{m_\phi \mu_1}{3}\phi^3 - \frac{\mu_2}{4}\phi^4 \\
& + i\bar{q}\not{D}q - m_q \bar{q}q \\
& - g_1 m_S S^\dagger S \phi - \frac{g_2}{2} S^\dagger S \phi^2 - h_1 \bar{q}q\phi - i h_2 \bar{q}\gamma^5 q\phi,
\end{aligned}
$$

Microscopic Model
(relativistic description)

↓

Microscopic Model
(non-relativistic reduction)



Usual "spin-independent" contribution

$$(S^\dagger S)(\bar{q}q) \longrightarrow \left(\frac{h_1^N g_1}{m_\phi^2}\right)\mathcal{O}_1$$

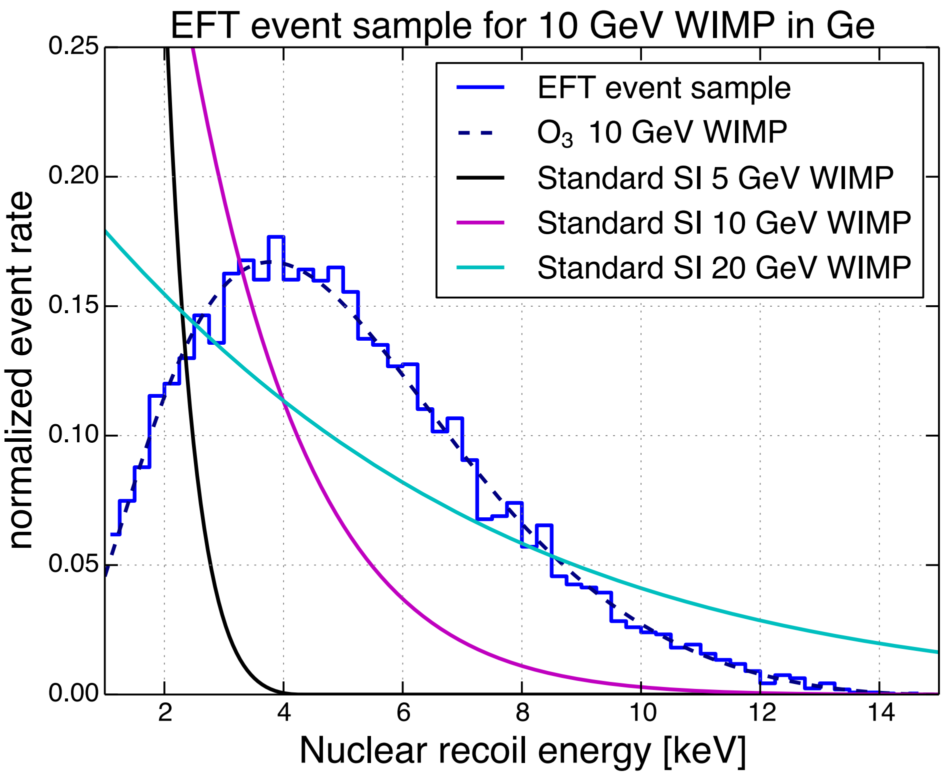
$$(S^\dagger S)(\bar{q}\gamma^5 q) \longrightarrow \left(\frac{h_2^N g_1}{m_\phi^2}\right)\mathcal{O}_{10}$$

Momentum-dependent "spin-dependent" contribution

We might MISS a DM signature

The spectrum from some interactions (momentum dependent) differs from the standard exponential signature

We might **misinterpret** a DM signature (if we reconstruct it with the usual templates)



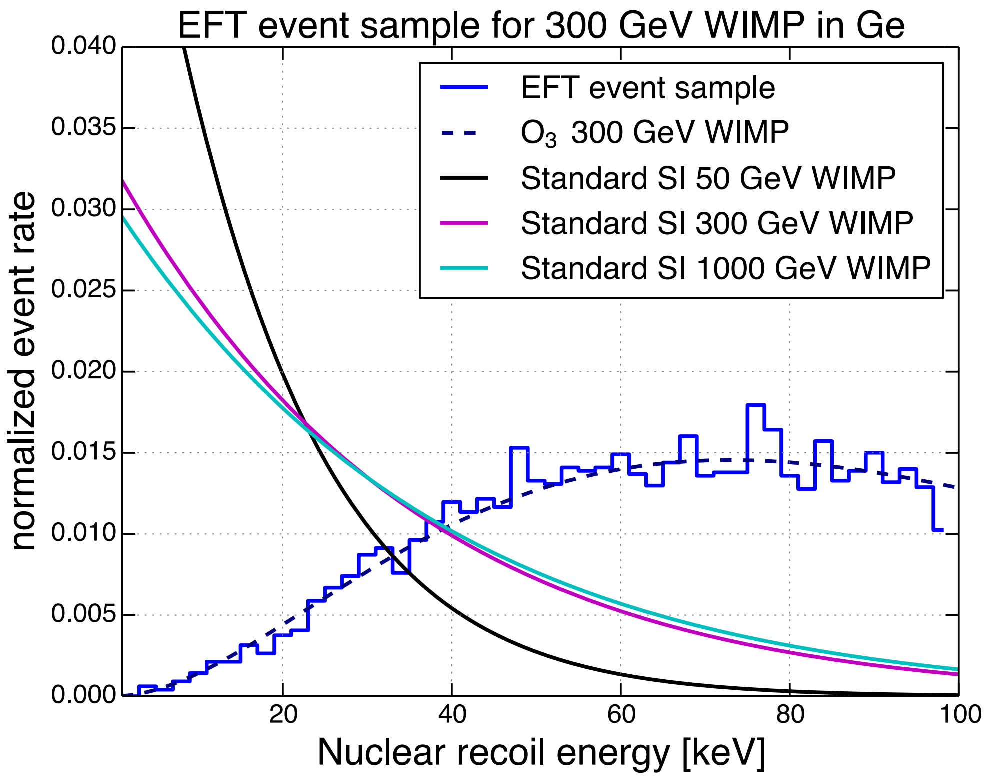
A low threshold is extremely beneficial

We might MISS a DM signature

The spectrum from some interactions (momentum dependent) differs from the standard exponential signature

We might **misinterpret** a DM signature (if we reconstruct it with the usual templates)

We might **miss** a signature (if we misidentify it as a background)

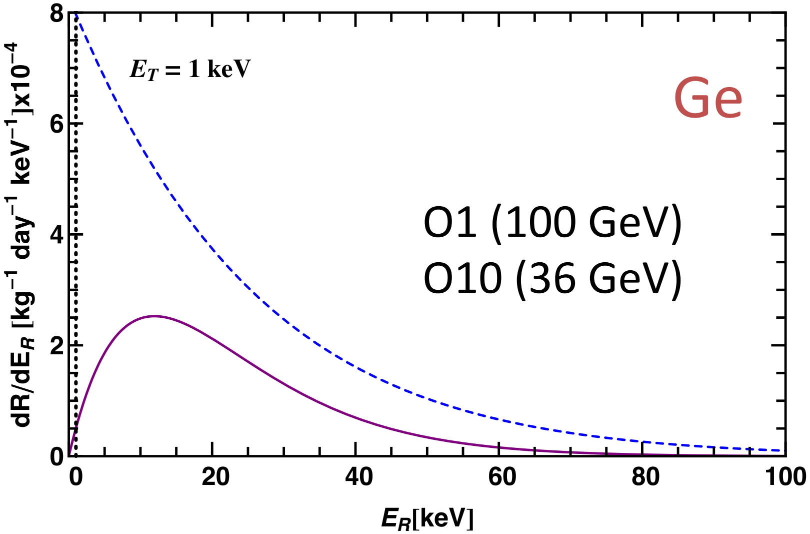


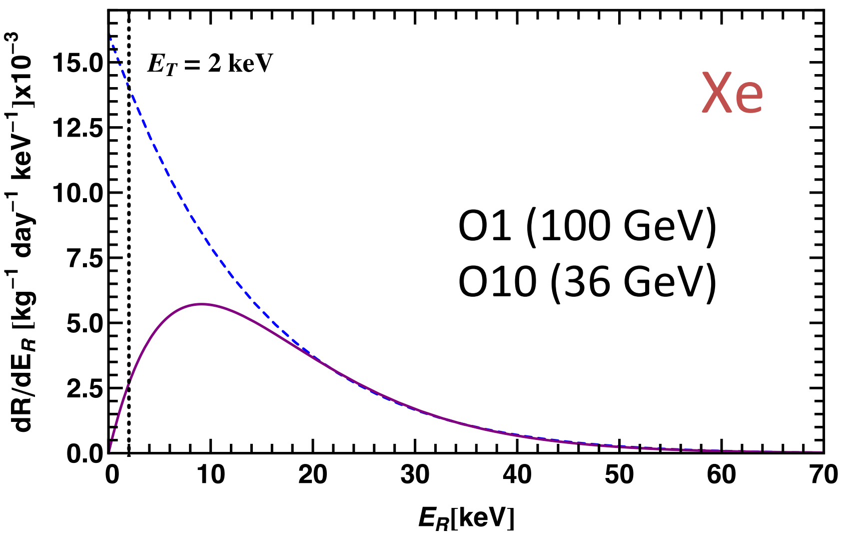
A low threshold is extremely beneficial

Disentangling operators through combined targets

Both operators have different spectrum (due to the momentum dependence)

Coefficients for O10 chosen to mimic O1 signal in Xe



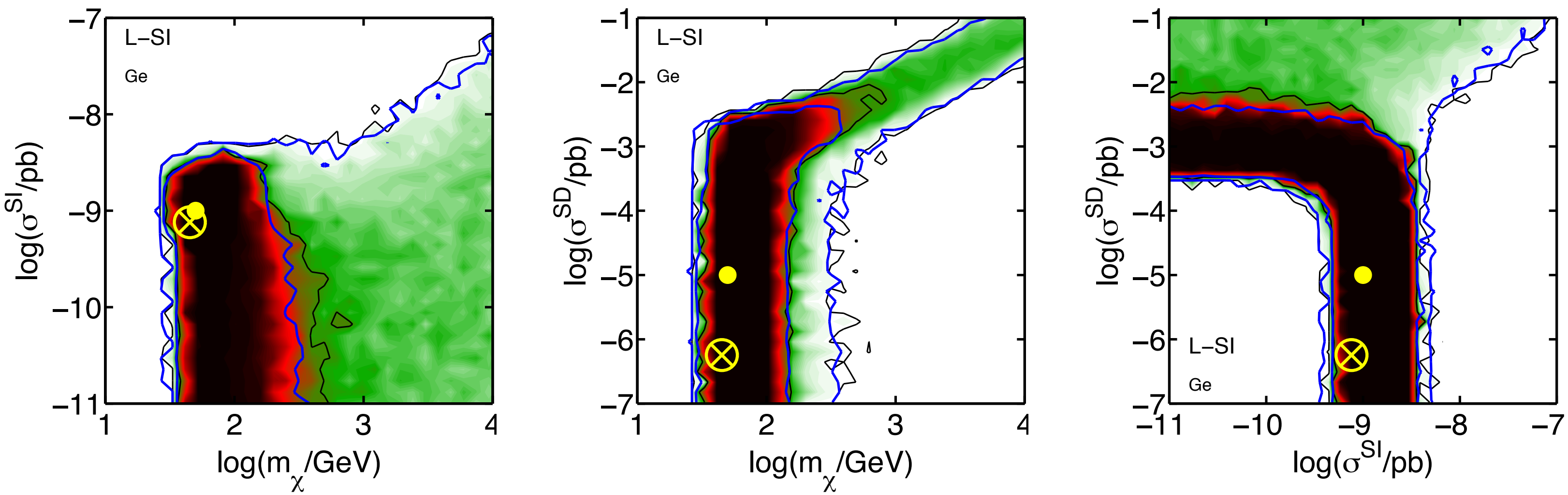


Cheek, Gerstmayr, DGC, Peiro (prelim)

Complementarity of different target materials to explore the EFT parameter space

Example: reconstruction in the usual SI-SD-mass plane

A single experiment cannot determine all the WIMP couplings, a combination of various targets is necessary.



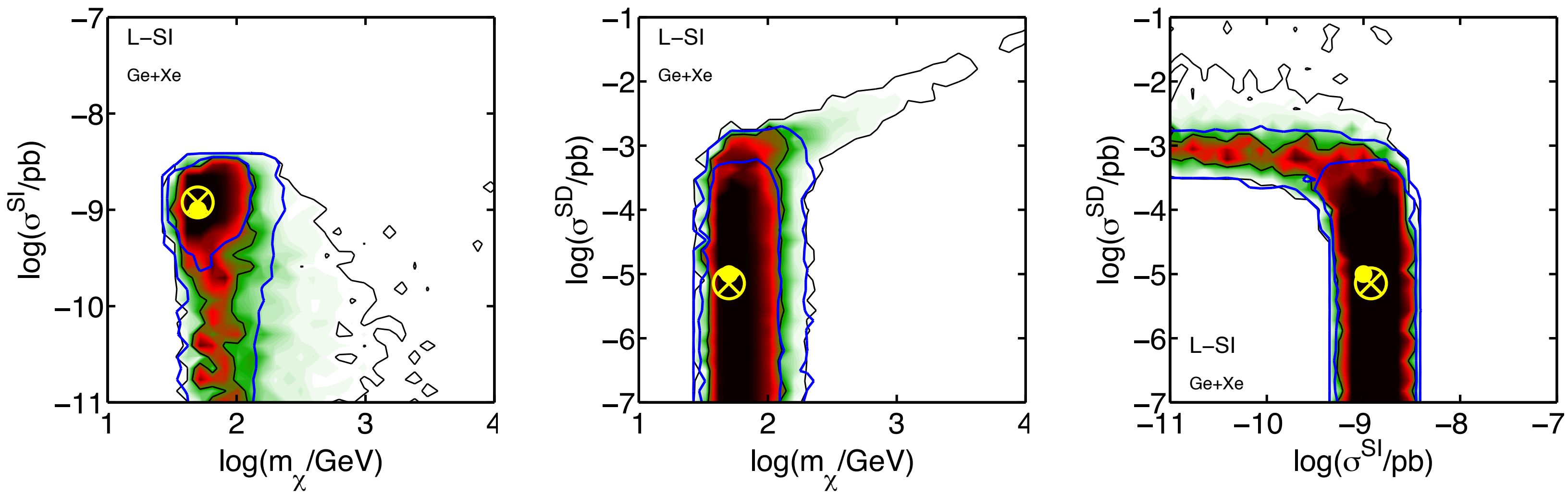
$$\sigma_0^{SI} = 10^{-9}\,\mathrm{pb}$$
$$\sigma_0^{SD} = 10^{-5}\,\mathrm{pb}$$
$$m_W = 50\,\mathrm{GeV}$$
$$\epsilon = 300\,\mathrm{kg\,yr}$$

We use simulated data to assess the reconstruction of DM parameters

Prospects for SuperCDMS (Ge)

Example: reconstruction in the usual SI-SD-mass plane

A single experiment cannot determine all the WIMP couplings, a combination of various targets is necessary.

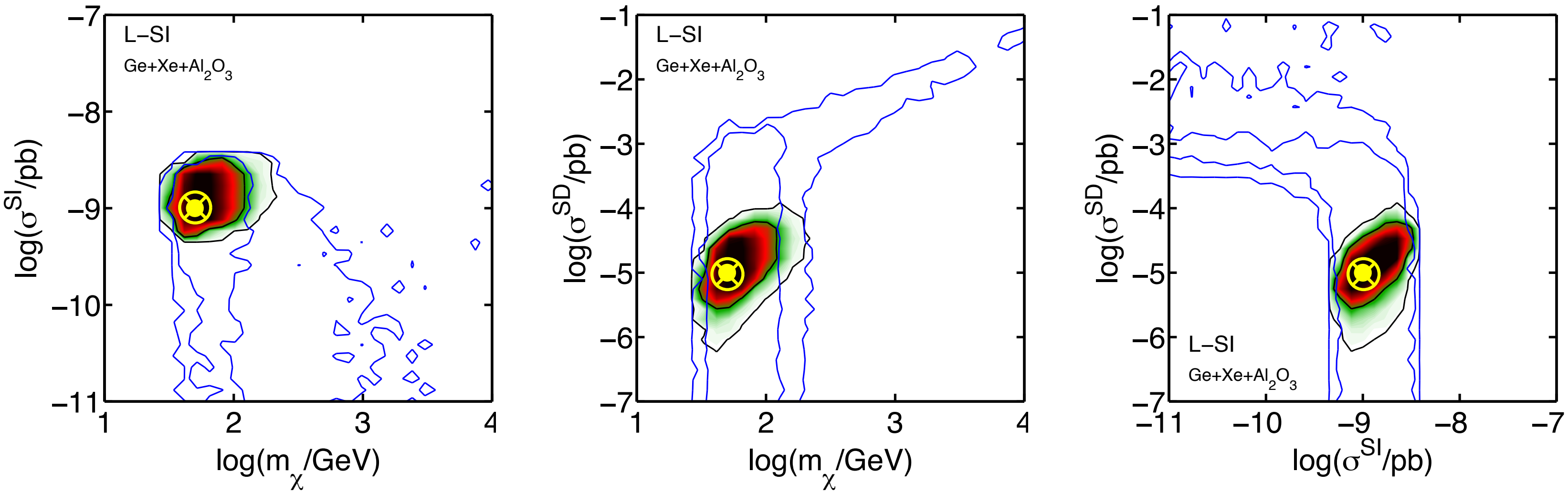


$$\sigma_0^{SI} = 10^{-9}\,\mathrm{pb}$$
$$\sigma_0^{SD} = 10^{-5}\,\mathrm{pb}$$
$$m_W = 50\,\mathrm{GeV}$$
$$\epsilon = 300\,\mathrm{kg\,yr}$$

Germanium and Xenon might not be able to fully reconstruct the DM parameters

Example: reconstruction in the usual SI-SD-mass plane

A single experiment cannot determine all the WIMP couplings, a combination of various targets is necessary.



$$\sigma_0^{SI} = 10^{-9}\,\mathrm{pb}$$
$$\sigma_0^{SD} = 10^{-5}\,\mathrm{pb}$$
$$m_W = 50\,\mathrm{GeV}$$
$$\epsilon = 300\,\mathrm{kg\,yr}$$

Germanium and Xenon might not be able to fully reconstruct the DM parameters

Targets with different sensitivities to SI and SD cross section are needed (e.g., F, Al)

Coherent neutrino scattering

The de Broglie wavelength of neutrinos can exceed the radii of heavy nuclei for neutrino energies below ~100 MeV.

- Yet **unobserved SM phenomenon**

  Extremely small cross section only within the reach of ultra-low background experiments.

- **Background** for DM experiments

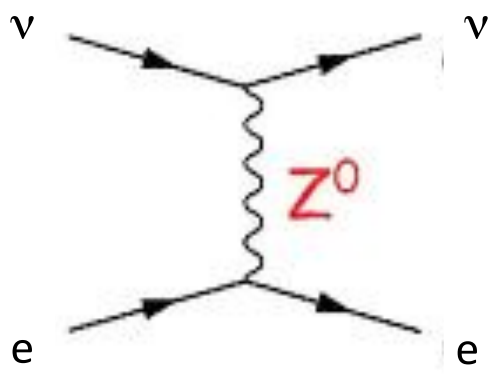
  - The signature is similar to that expected for a WIMP

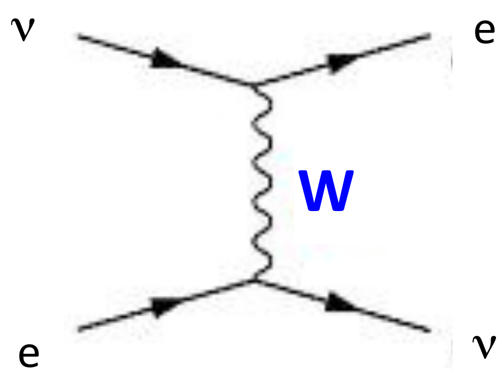
- Provides **access to fundamental quantities**

  - Measurement of sin θ_W (at low energies)

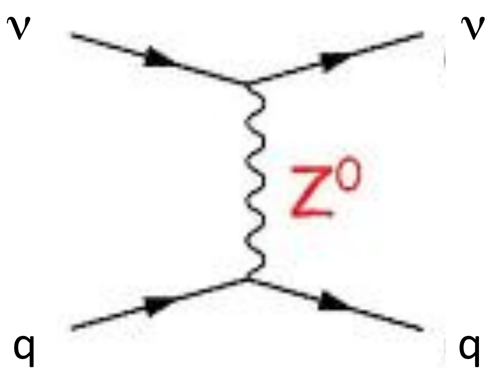
Neutrino scattering in a DM experiment

Exchange of W and Z bosons with electrons





Exchange of a Z boson with the nucleus



Neutrino scattering in a DM experiment

$$\frac{dR}{dE_R} = \frac{\epsilon}{m_T} \int dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_\nu}{dE_R}$$

Neutrino-Electron scattering (ER)

$$\frac{d\sigma_{\nu e}}{dE_R} = \frac{G_F^2 m_e}{2\pi} \left[(g_v + g_a)^2 + \quad (g_v - g_a)^2 \left(1 - \frac{E_R}{E_\nu}\right)^2 + (g_a^2 - g_v^2) \frac{m_e E_R}{E_\nu^2} \right]$$

for muon and tau only charged current $\quad g_{v;\mu,\tau} = 2\sin^2\theta_W - \frac{1}{2}; \quad g_{a;\mu,\tau} = -\frac{1}{2}.$

for electrons, charged and neutral currents $\quad g_{v;e} = 2\sin^2\theta_W + \frac{1}{2}; \quad g_{a;e} = +\frac{1}{2}$

Coherent Neutrino-Nucleus scattering (NR)

$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_v^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

$$Q_v = N - (1 - 4\sin^2\theta_W) Z$$

The form factor is the same as in WIMP-nucleus scattering.

The spectrum differs as it depends on neutrino flux.

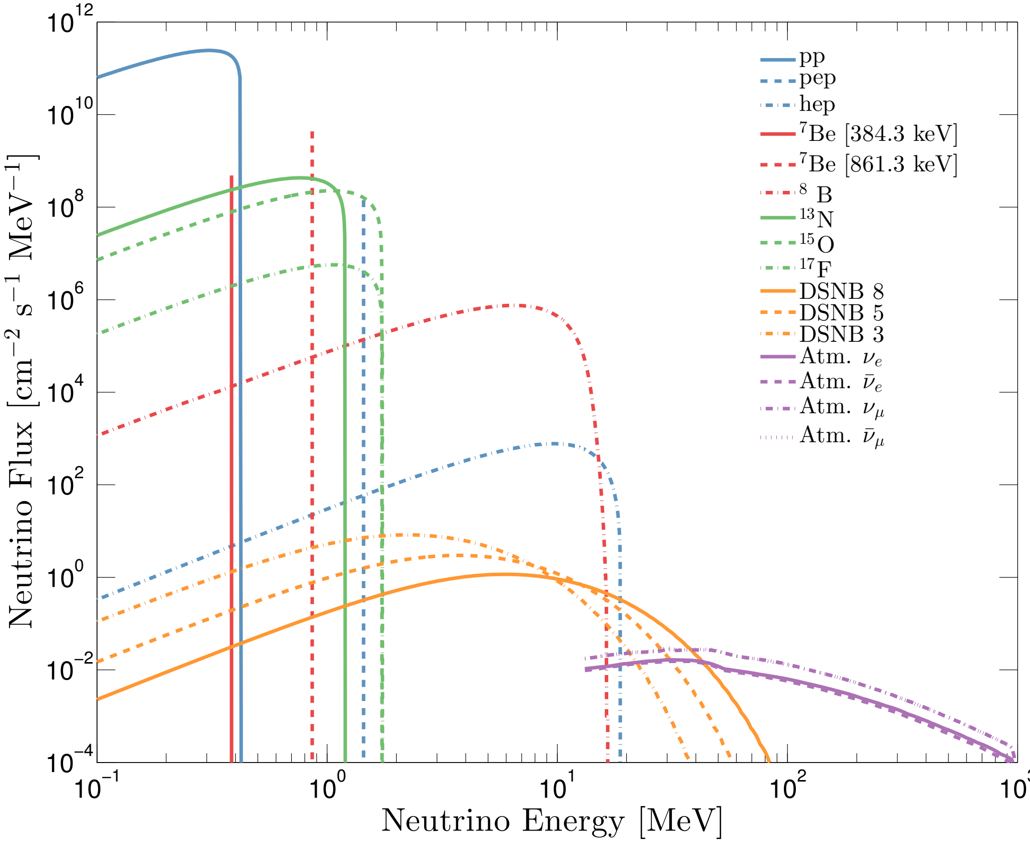
Neutrino fluxes

- Solar neutrinos dominate at low energy – the leading contribution is the pp chain below 1 MeV

- Atmospheric neutrinos contribute at higher energies but at a much smaller rate

- Diffuse Supernova Background relevant around ~20-50 MeV

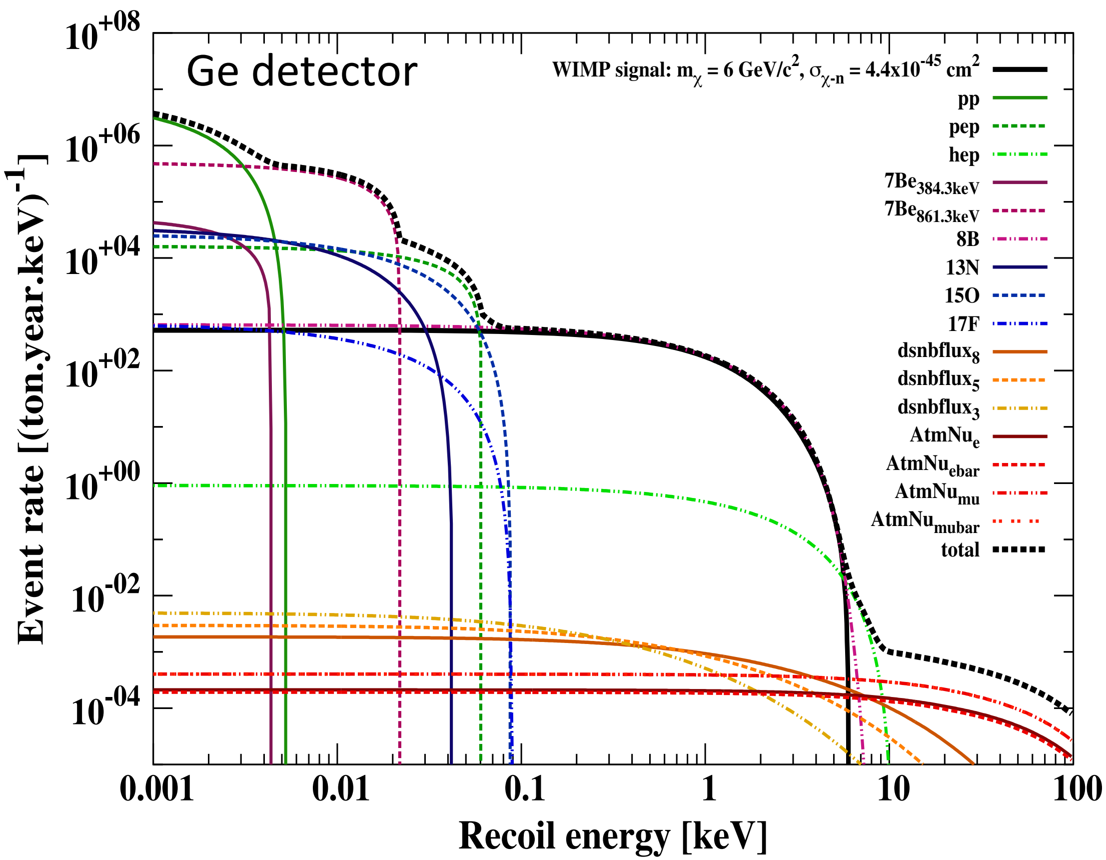
O'Hare, Green, Billard, Figueroa-Feliciano, Strigari 2015



Experimental response to CNS

Ruppin, Billard, Figueroa-Feliciano, Strigari 2014

- Solar neutrinos dominate at low energy – the leading contribution is the pp chain below 1 MeV
- Atmospheric neutrinos contribute at higher energies but at a much smaller rate
- Diffuse Supernovae Background relevant around ~20-50 MeV



Background for DM experiments

Future dark matter experiments will be sensitive to this SM process, limiting the reach for DM searches (Neutrino Floor)

Going beyond the neutrino floor:

- Spectral analysis
- Annual modulation
  Billard et al. 1307.5458
  Davis 1412.1475
- Combination of complementary targets
  Ruppin et al. 1408.3581
- Directional detection
  Grothaus et al. 1406.5047
  O'Hare et al. 1505.08061