Direct Dark Matter Detection

Looking for DM in all directions

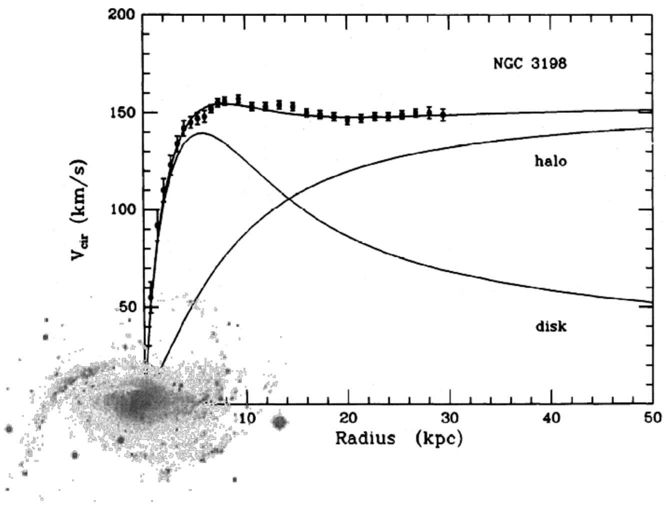
DAVID G. CERDEÑO

IP3
Durham University

Dark Matter is a necessary (and abundant) ingredient in the Universe

Galaxies

- Rotation curves of spiral galaxies
- Gas temperature in elliptical galaxies



It is one of the clearest hints of

Physics Beyond the SM

and might be accessible in the near future

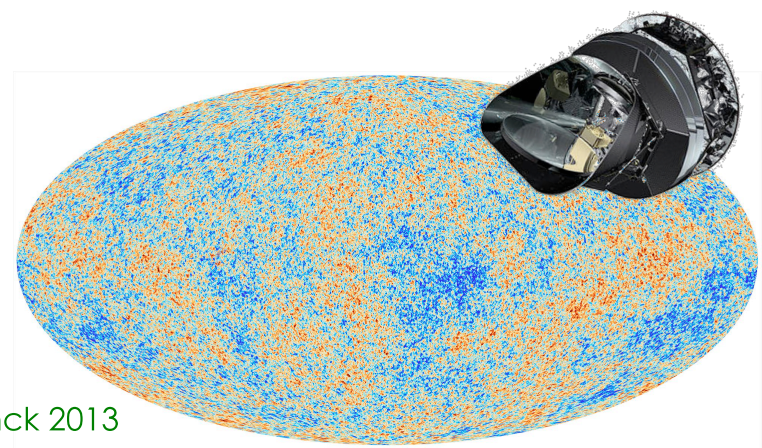
Clusters of galaxies

- Peculiar velocities and gas temperature
- Weak lensing
- Dynamics of cluster collision
- Filaments between galaxy clusters

Cosmological scales

Anisotropies in the Cosmic Microwave Background

$$\Omega_{CDM}\, h^2 = 0.1196 \pm 0.003$$



Planck 2013

The European Strategy for Particle Physics
Update 2013

j) A range of important non-accelerator experiments take place at the overlap of particle and astroparticle physics, such as searches for proton decay, neutrinoless double beta decay and dark matter, and the study of high-energy cosmic-rays. These experiments address fundamental questions beyond the Standard Model of particle physics. The exchange of information between CERN and ApPEC has progressed since 2006. *In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community's capability for unique projects in this field*.

Dark Matter only mentioned once (once more in the abstract)

Can we get a more concrete statement?

Current challenges for DARK MATTER

- **Experimental detection:**
  Does DM feel other interactions apart from Gravity?
  Is the Electro-Weak scale related somehow related to DM?
  How is DM distributed?

- **Determination of the DM particle parameters:**
  Mass, interaction cross section, etc…

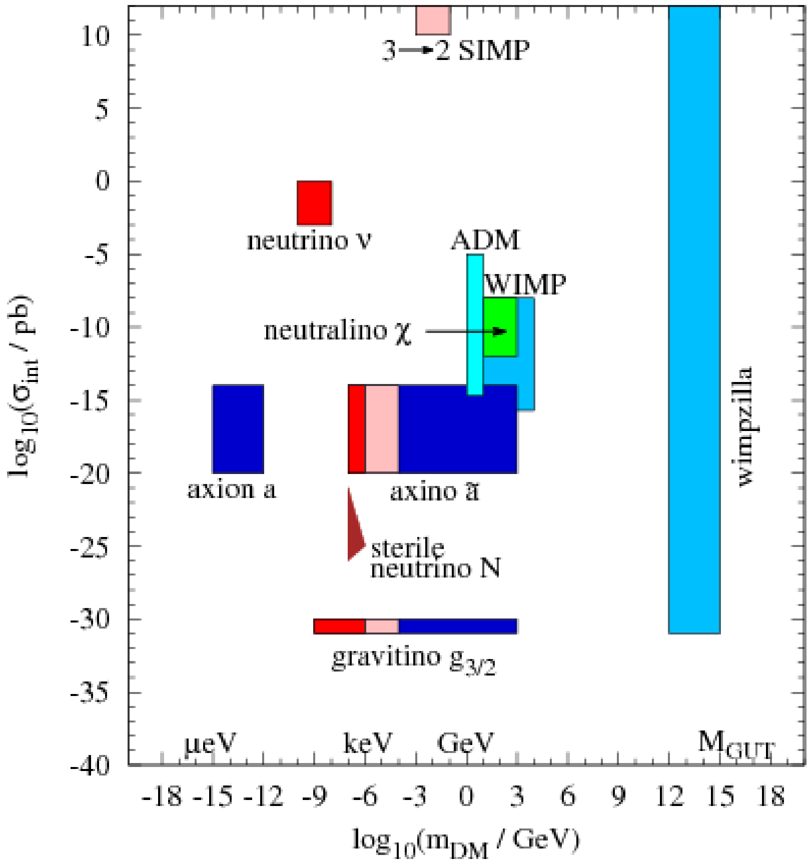
- **What is the theory for Physics beyond the SM:**
  DM as a window for new Physics
  Can we identify the DM candidate?

The **CHALLENGE**: We don't know what DM is…

Good candidates for Dark Matter have to fulfil the following conditions

- Neutral
- Stable on cosmological scales
- Reproduce the correct relic abundance
- Not excluded by current searches
- No conflicts with BBN or stellar evolution

Baer et al. 2014



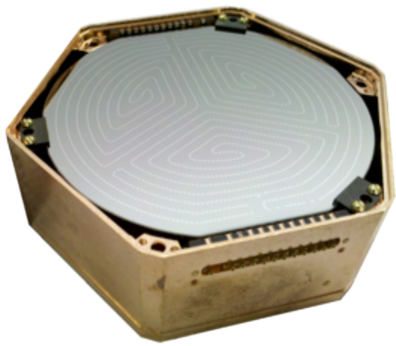
Many candidates in Particle Physics

- Axions
- Weakly Interacting Massive Particles (WIMPs)
- SuperWIMPs and Decaying DM
- WIMPzillas
- Asymmetric DM
- FIMPs, SIMPs, CHAMPs, SIDMs, ETCs…

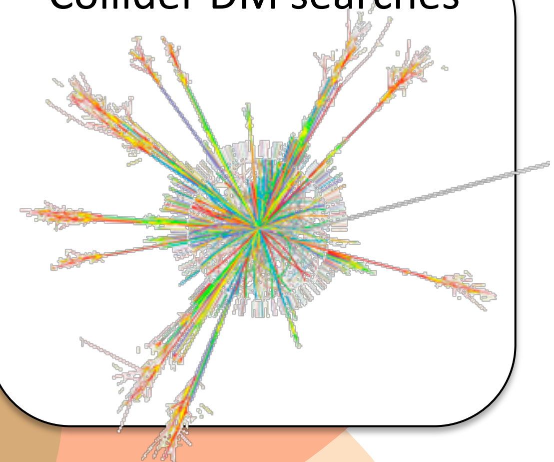
… they have very **different** properties

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

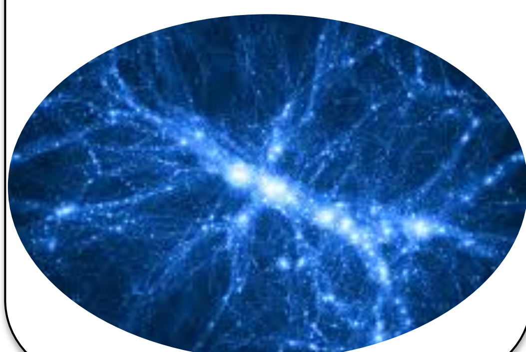
Direct DM detection



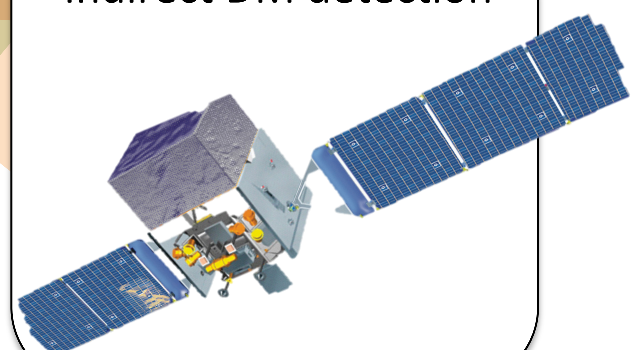
Collider DM searches



Astro/Cosmo probes

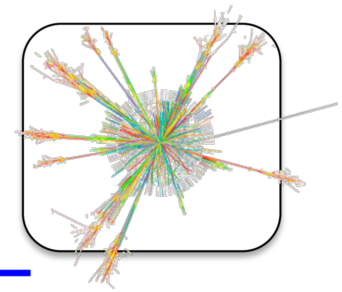


Indirect DM detection

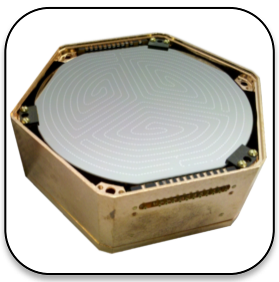


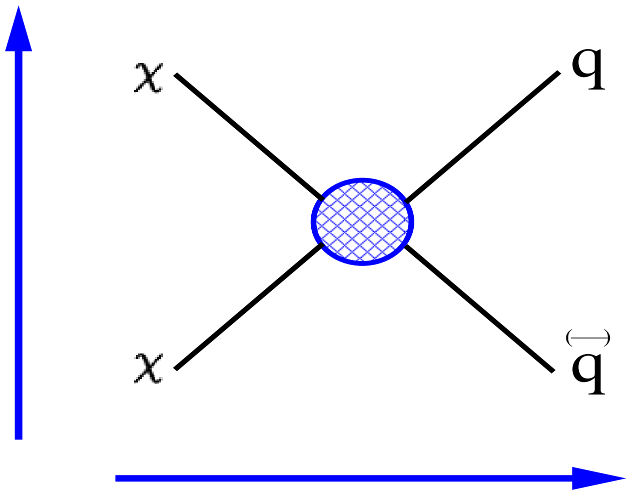
... probing **DIFFERENT** aspects of their interactions with ordinary matter

Accelerator Searches (production)



Direct Detection
(scattering)

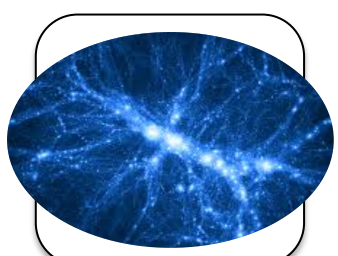


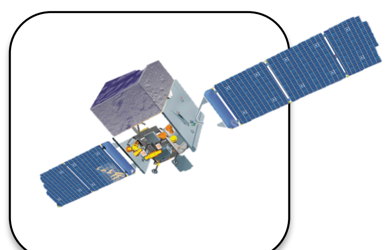


Constraints in one sector affect observations in the other two.

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

Indirect Detection
(annihilation or decay)





Looking for lost keys:

1. Check where the item should be first every time. That is, if you always put your keys by the door, look by the door first. ...

Search for "well motivated" DM models

- WIMPs can be produced in the Early Universe in the right amount and they are easily incorporated in BSM

- The parameter space for WIMPs is accessible to direct detection (but the range of interactions can still vary over many orders of magnitude − also there is no indication on the DM mass)

Looking for lost keys:

1. Check where the item should be first every time. That is, if you always put your keys by the door, look by the door first. ...
2. Clean up. ...

Experiments have become increasingly "clean", removing the (overwhelming) background in different ways (radiopurity + shielding + discrimination of recoils)

Some special signatures are also "cleaner"

- Annual Modulation
- Directionality

Looking for lost keys:

1. Check where the item should be first every time. That is, if you always put your keys by the door, look by the door first. ...
2. Clean up. ...
3. Be systematic. ...

- The dark-matter nucleus interaction might be more general than normally consider.

  Effective Field Theory approach to describe the DM-nucleus interaction.

Looking for lost keys:

1. Check where the item should be first every time. That is, if you always put your keys by the door, look by the door first. ...
2. Clean up. ...
3. Be systematic. ...
4. Check odd places. ...

Direct detection is not only looking for WIMPs

- Self-Interacting DM
- Inelastic DM
- DM-electron interactions
- Axions
- LIPs, dark photons, etc
- Neutrinos!

Looking for lost keys:

1. Check where the item should be first every time. That is, if you always put your keys by the door, look by the door first. ...
2. Clean up. ...
3. Be systematic. ...
4. Check odd places. ...
5. Look thoroughly. ...

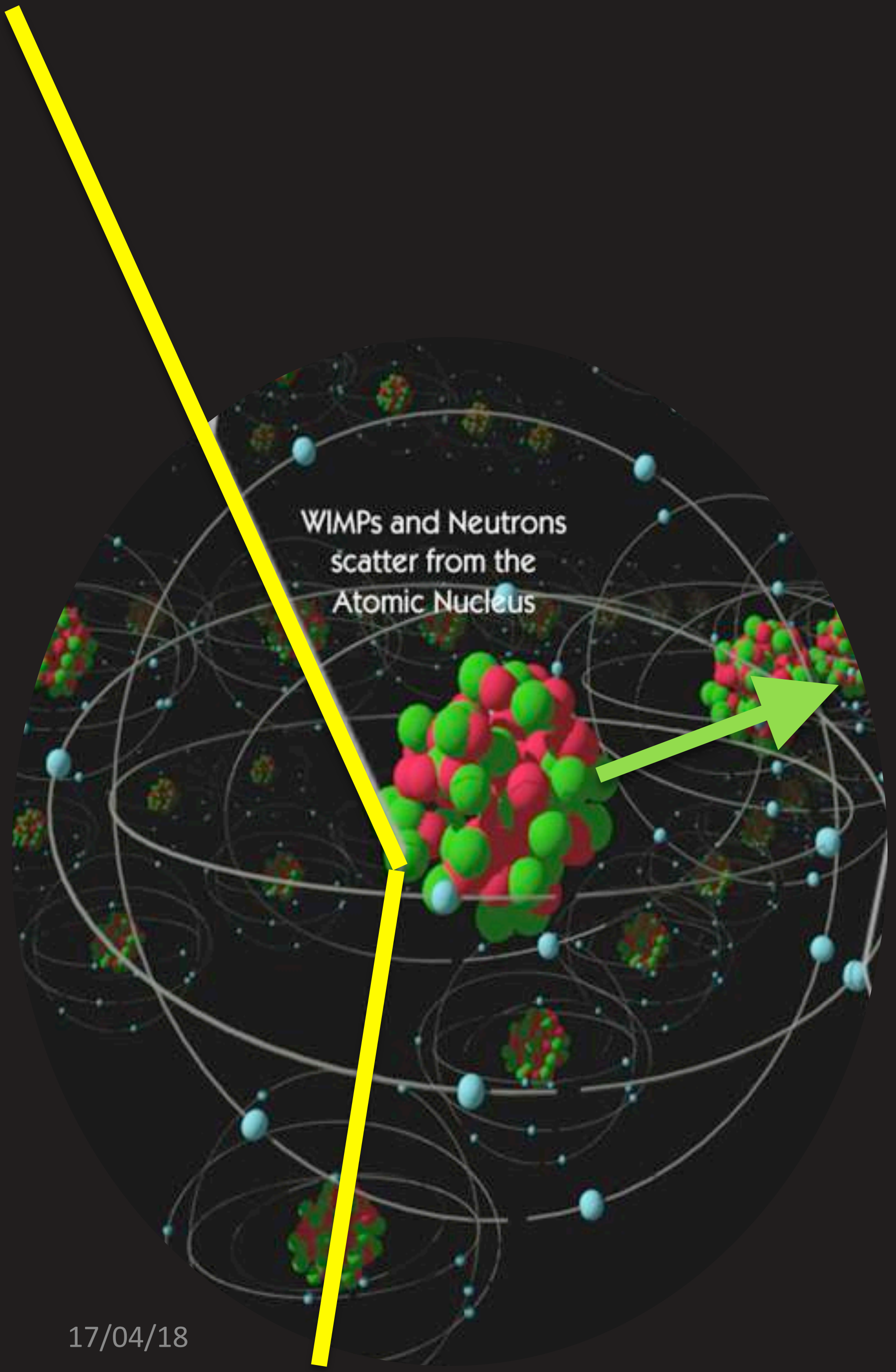
- Employ different targets, different techniques.
- Complementarity targets are not only useful to set better bounds. They are fundamental for DM parameter reconstruction in case of detection.

Looking for lost keys:

1. Check where the item should be first every time. That is, if you always put your keys by the door, look by the door first. ...
2. Clean up. ...
3. Be systematic. ...
4. Check odd places. ...
5. Look thoroughly. ...
6. Check your pockets. ...
7. Check your car. ...

Be aware of how much **astrophysical uncertainties** can affect experimental results

- Can DM be multicomponent? – This affects the detection rate (and viable parameter space of models)
- What can we learn from numerical simulations (& indirect searches)?



NUCLEAR RECOILS

- "Canonical" signature
- Elastic or Inelastic scattering
- Sensitive to m >1 GeV (keV recoils)

Conventional direct detection approach

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

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

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

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:

- Reduction of backgrounds
- **Increment Target Size**
- **Low Energy threshold**

WIMP expected fingerprint:

- Exponential spectrum (*)
- Annual Modulation of the signal
- Directionality

Conventional direct detection approach

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

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

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

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

Constraints on the DM-nucleus scattering cross section

Single or double phase noble gas detectors excel in searches at large DM masses
XENON1T, LUX, Panda-X (Xe), DARKSIDE, DEAP (Ar)
Easily scalable

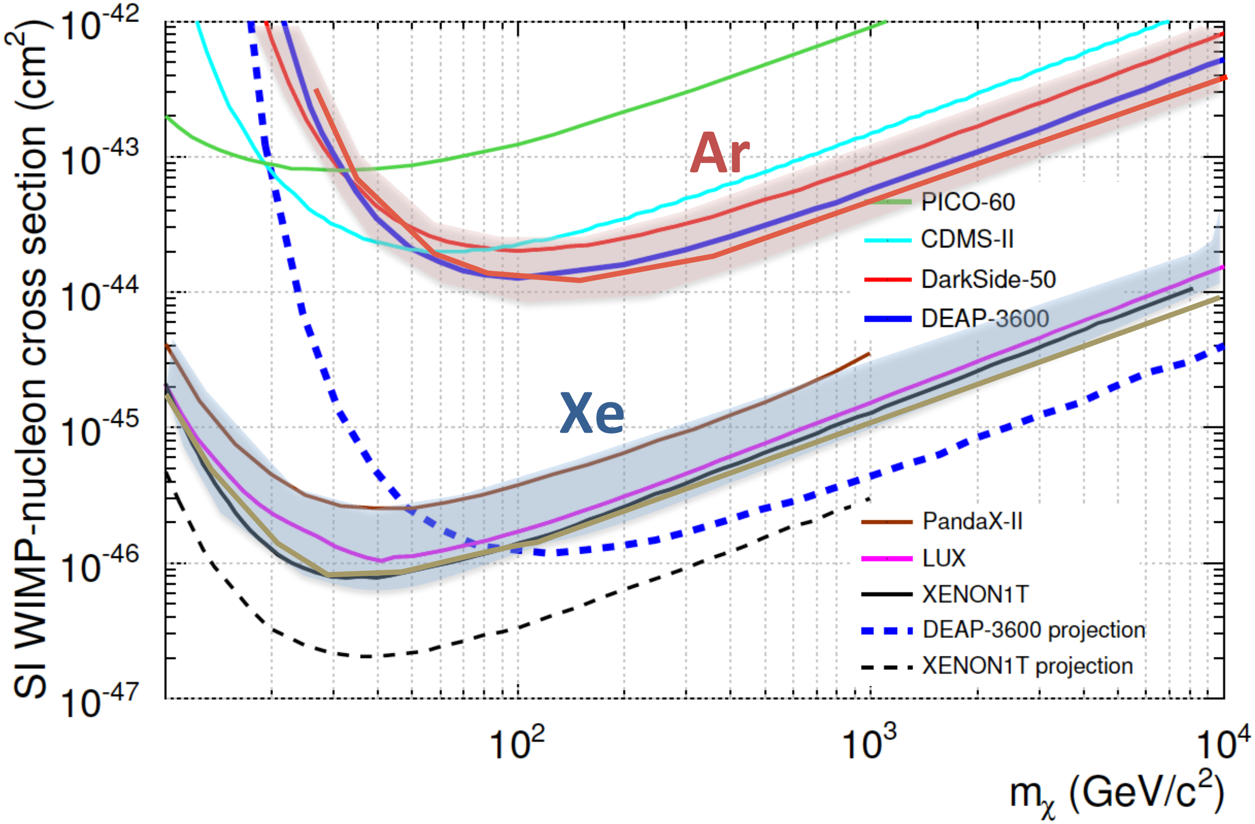
DARKSIDE 1802.07198
~10000 kg day

DEAP 1707.08042
9870 kg day

PANDAX 1708.06917
54000 kg day

LUX 1608.07648
33500 kg day

XENON1T 1705.06655
34200 kg day



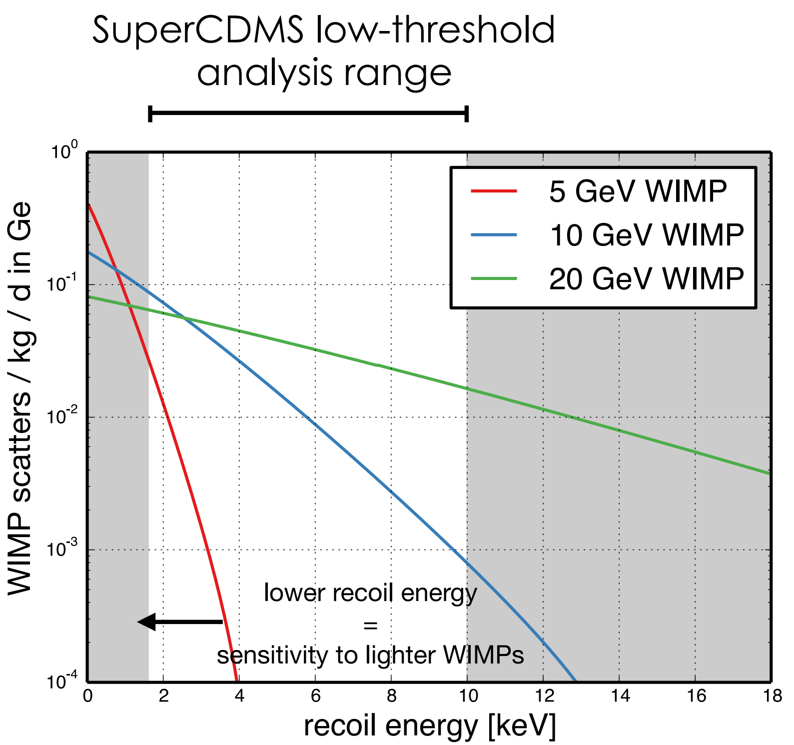
The challenge of low-mass WIMPs

- The signal is expected at very low recoil energies

    Favours light targets

    Low-threshold searches

- Usual DM targets are relatively heavy so the threshold has to be significantly reduced.

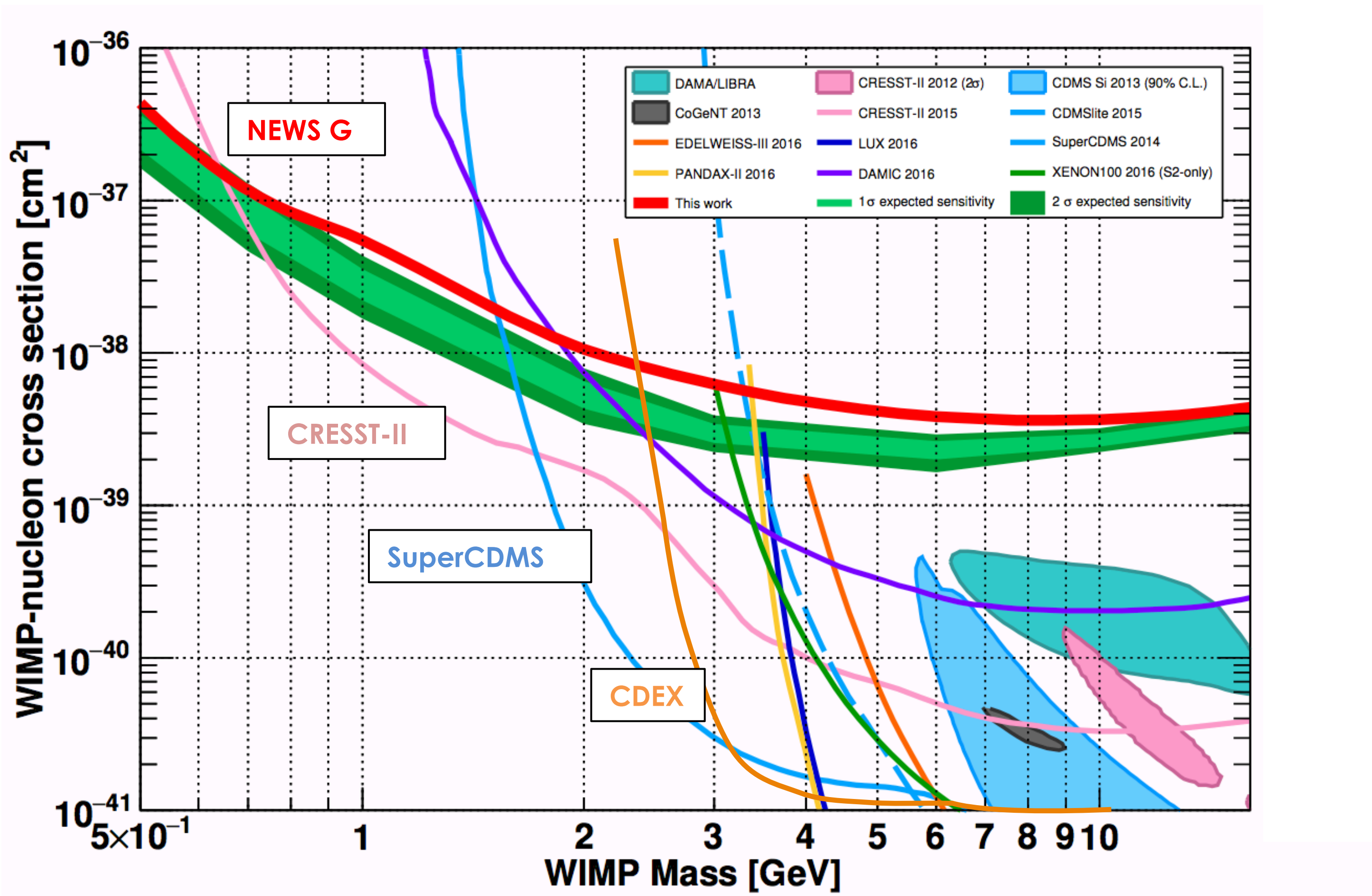


- Backgrounds are more difficult to discriminate (this is in general not a background-free search)

- Relies on the goodness of the background model and MC simulations

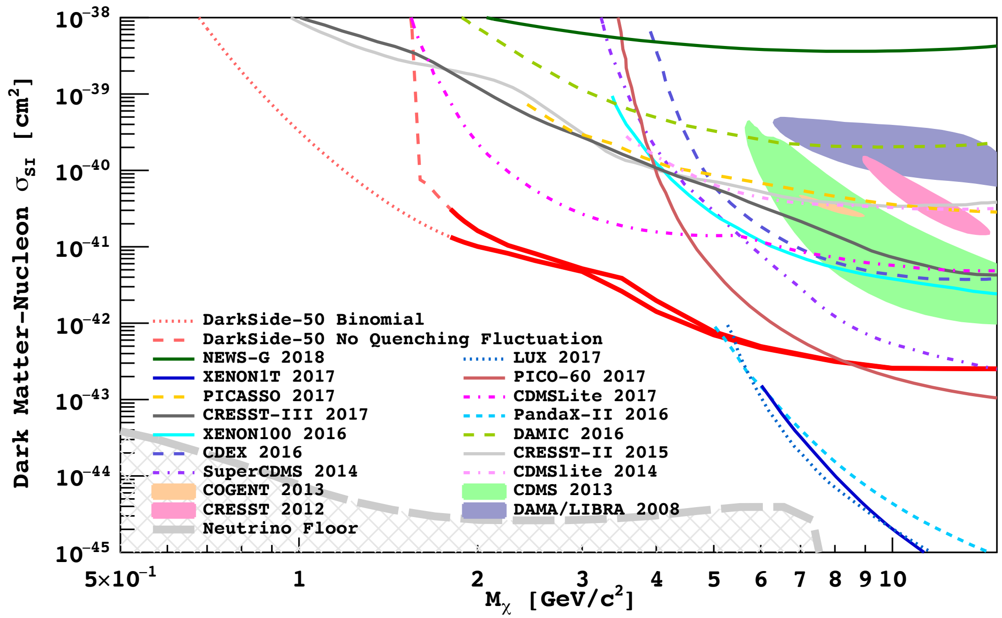
Constraints on low-mass WIMPs

CDMSlite, SuperCDMS, Edelweiss, CDEX (Ge), CRESST ($CaWO_4$), NEWS-G (Ne) complete the search for WIMPs at low masses.
Low-threshold experiments (with smaller targets) are probing large areas of parameter space



Constraints on low-mass WIMPs

Using only the ionisation signal, liquid noble gas detectors (e.g., XENON, DARKSIDE) are also advancing on the search for low-mass WIMPs

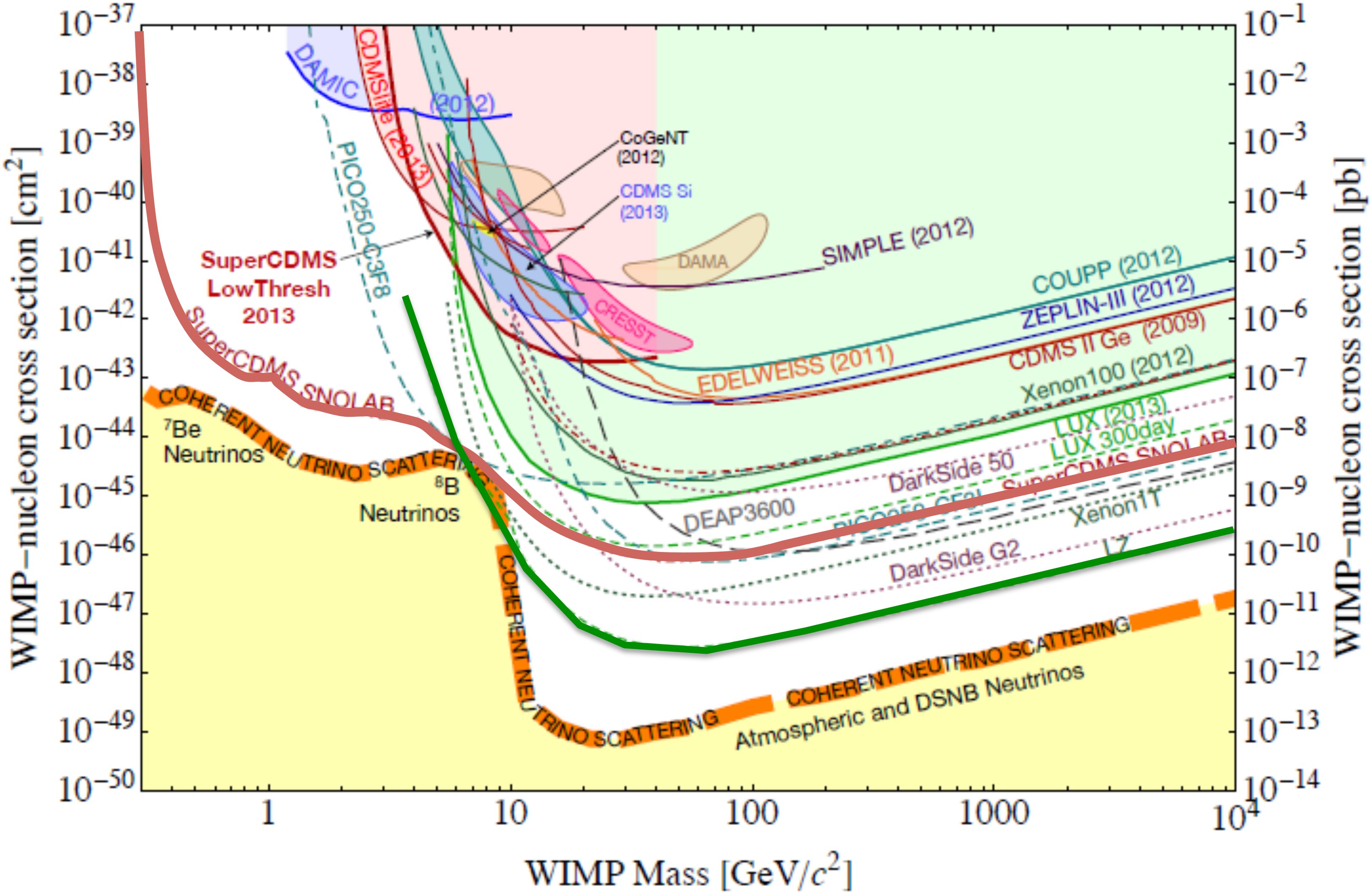


DISCLAIMER:

THESE PLOTS ASSUME

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

Future prospects

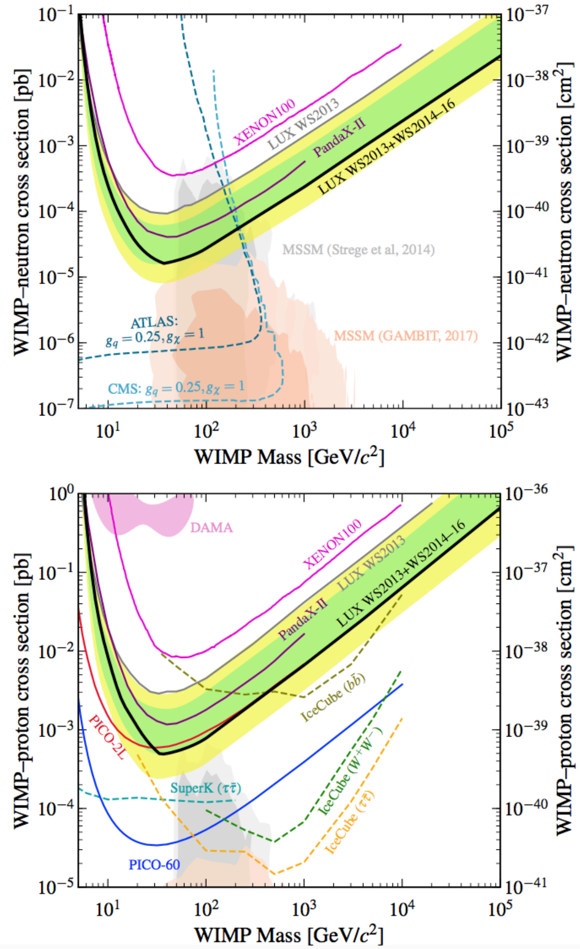


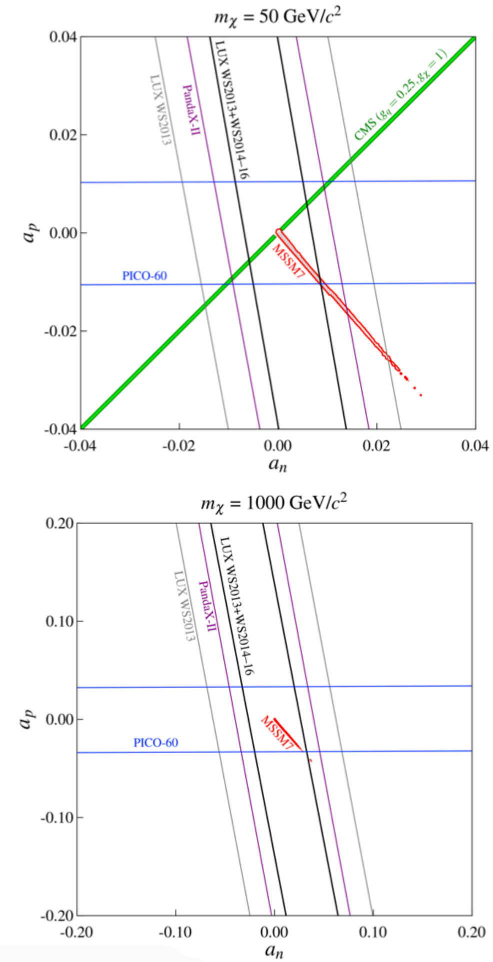
Constraints on Spin-Dependent scattering

Bounds on SD-n contribution have been derived from Xenon-based experiments (XENON1T, LUX, Panda-X)

The SD-p bounds are dominated by PICO (C_3F_8)

Important bounds from indirect searches and colliders.





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

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

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

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

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

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

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

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

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.

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

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

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

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

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

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

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

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

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

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

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

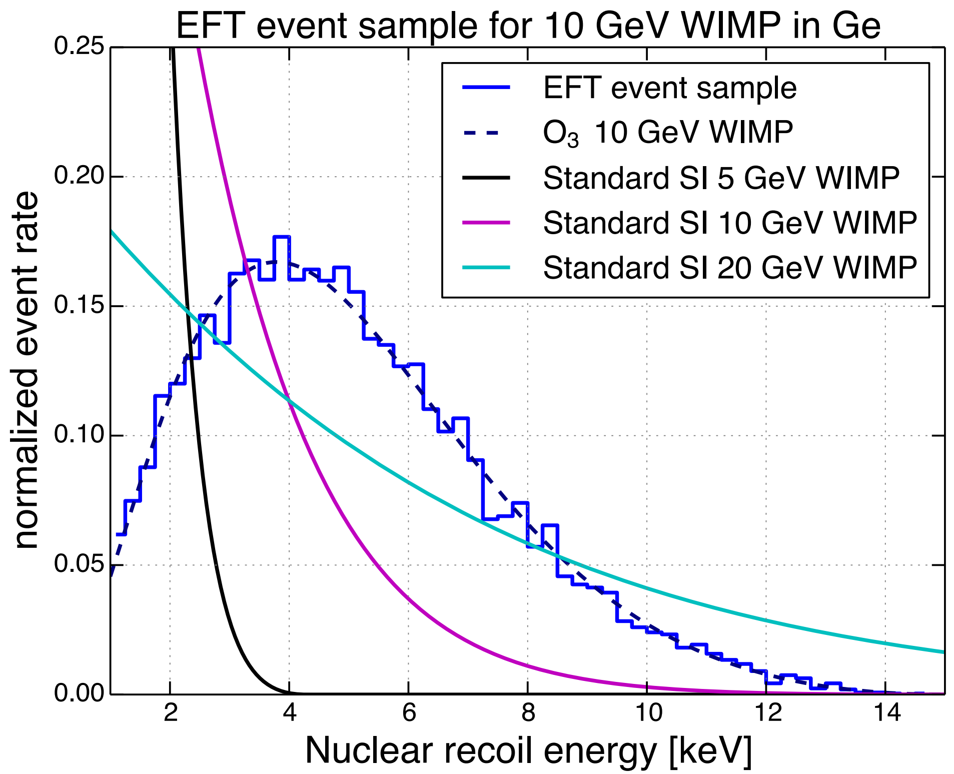
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

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

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)



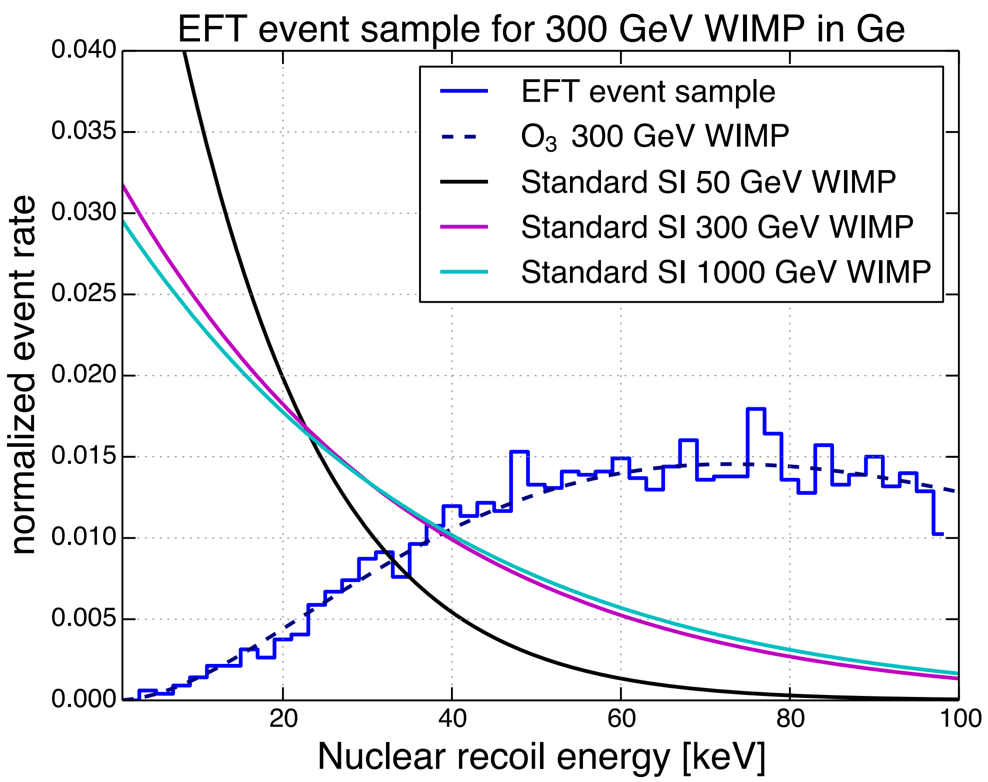
A low threshold and combined targets are extremely beneficial

We might MISS a DM signature

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

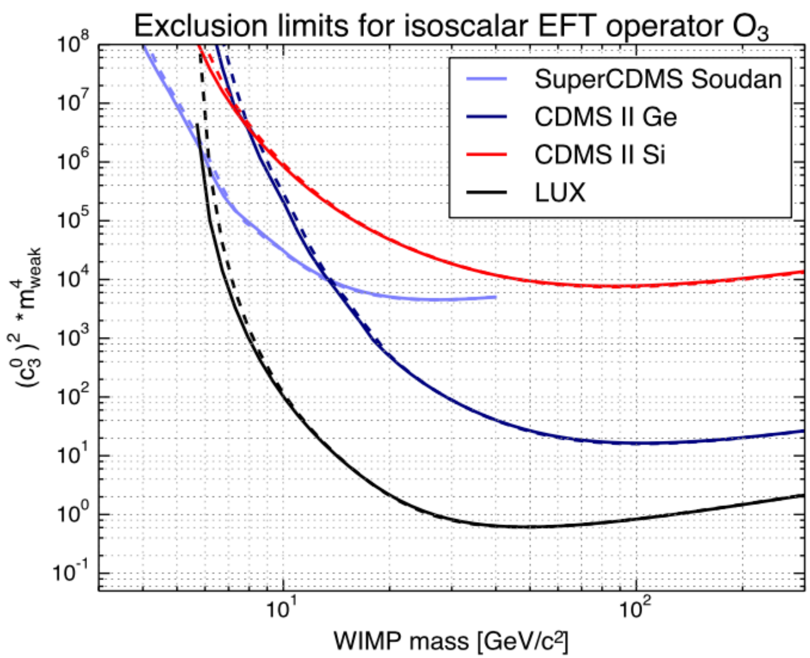
We might **misinterpret** a DM signature (if we reconstruct it with the usual templates)

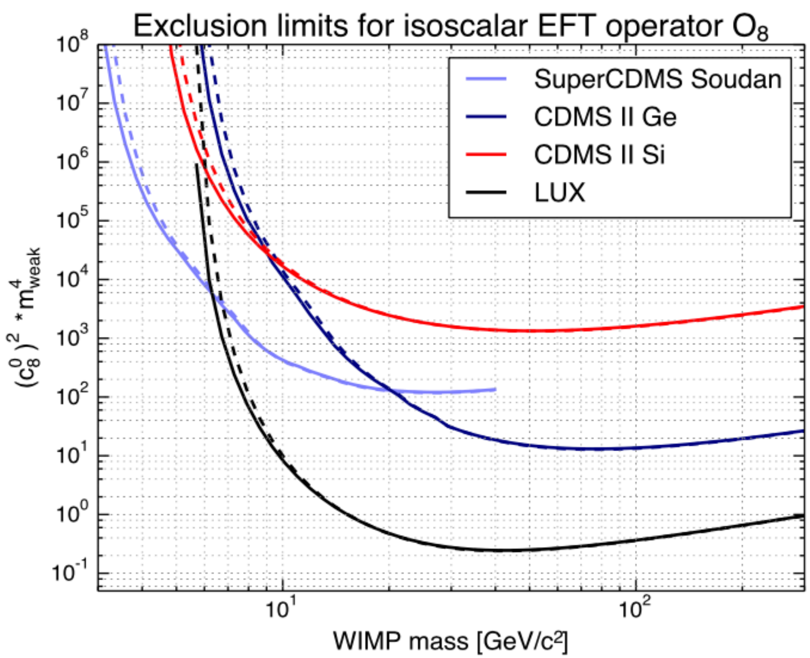
We might **miss** a signature (if we misidentify it as a background)



A low threshold and combined targets are extremely beneficial

The experimental response to these interactions is very **target dependent**



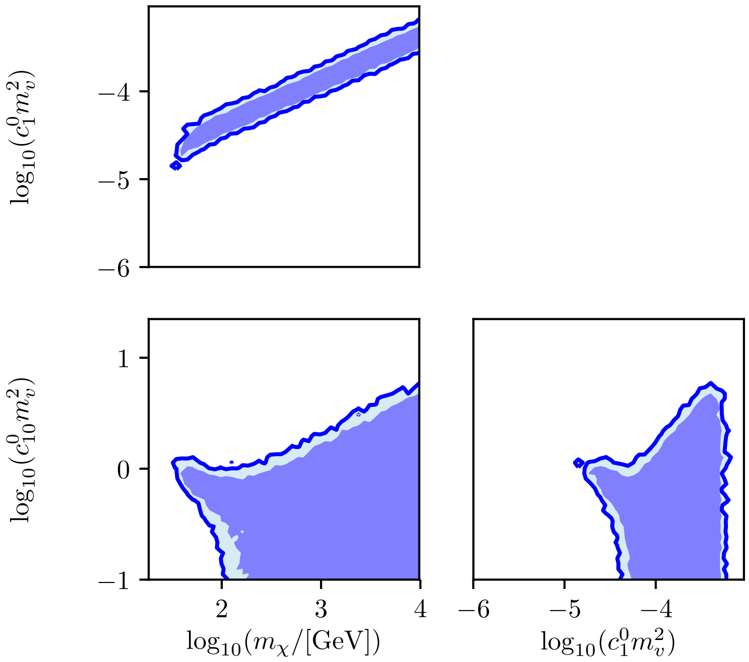


Disentangling operators through combined targets

Example: Scalar DM – Scalar Mediator
m = 100 GeV

A single target cannot determine the DM mass and couplings

Xe

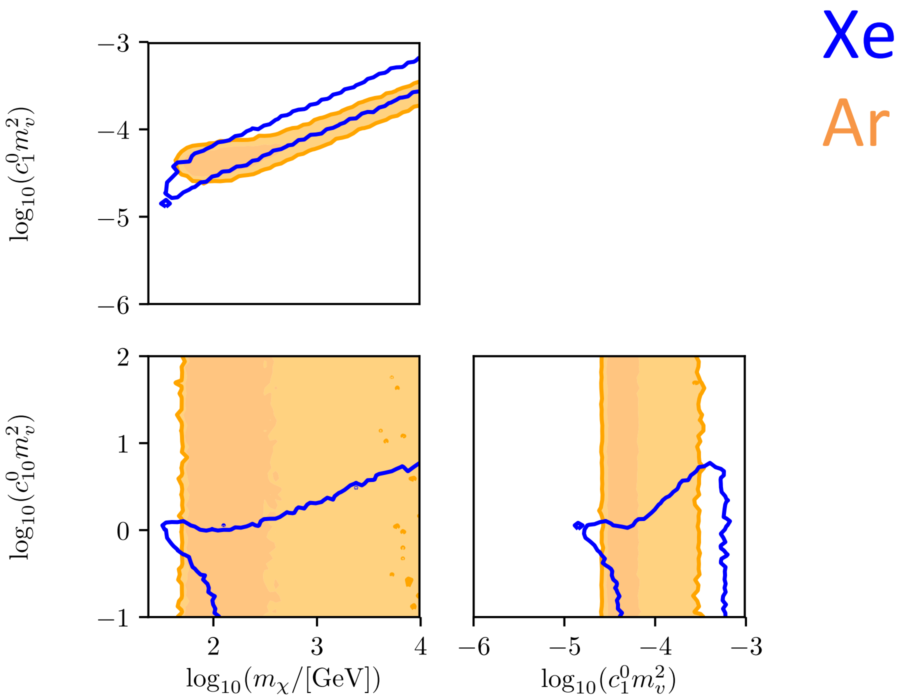


Disentangling operators through combined targets

Example: Scalar DM – Scalar Mediator
m = 100 GeV

A single target cannot determine the DM mass and couplings

The experimental response is very sensitive to the target



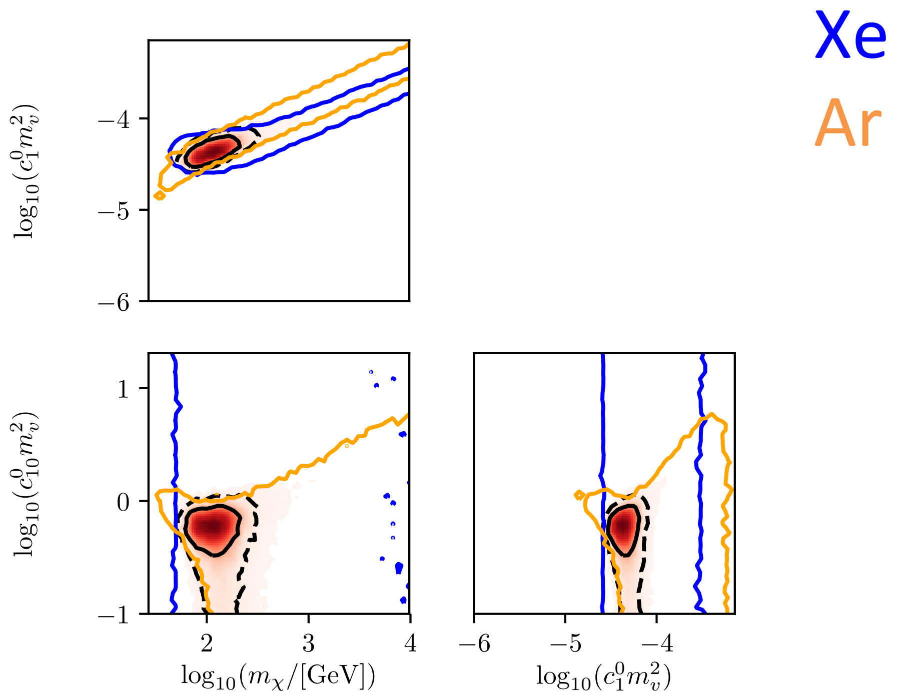
Disentangling operators through combined targets

Example: Scalar DM – Scalar Mediator
m = 100 GeV

A single target cannot determine the DM mass and couplings

The experimental response is very sensitive to the target

Combining data some degeneracies can be removed

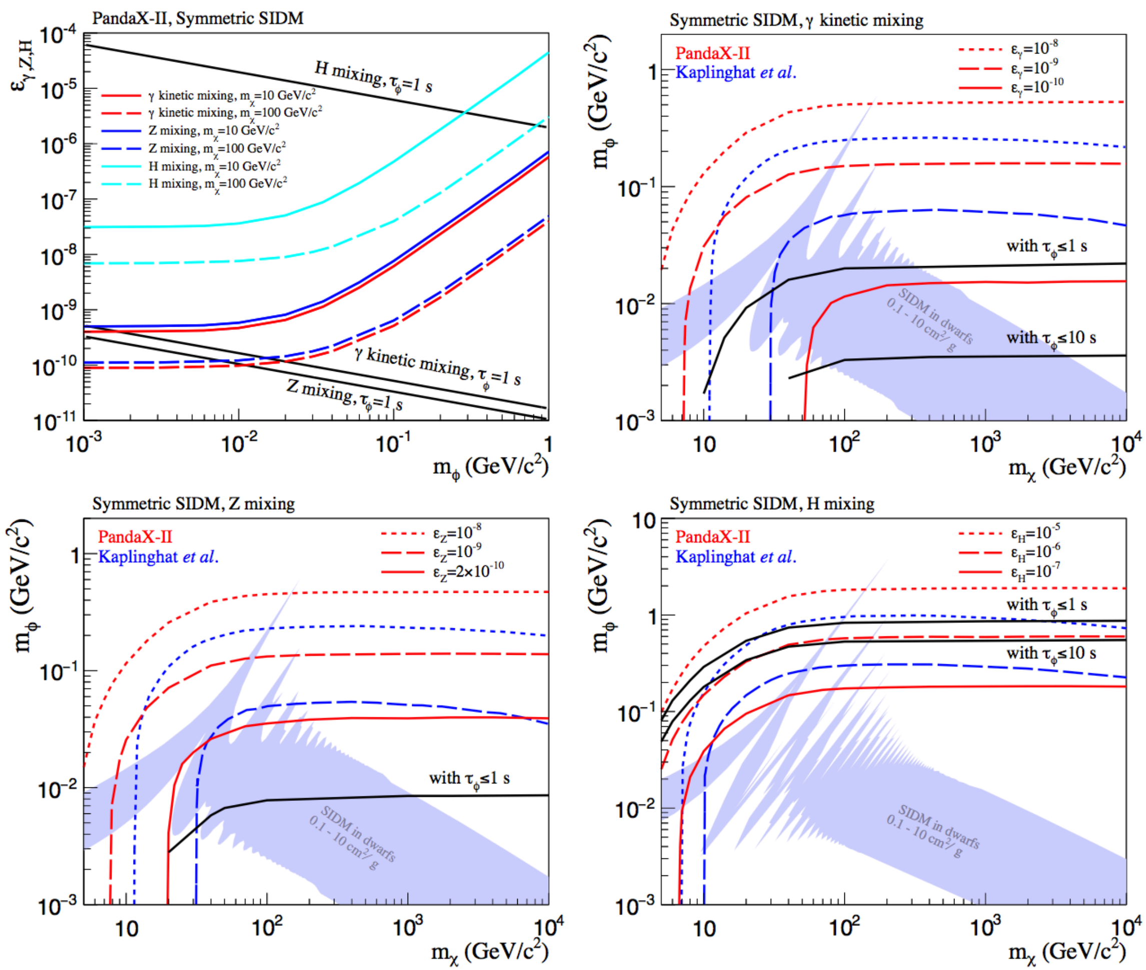


DM parameter identification requires the use of multiple targets

Going beyond the WIMP paradigm

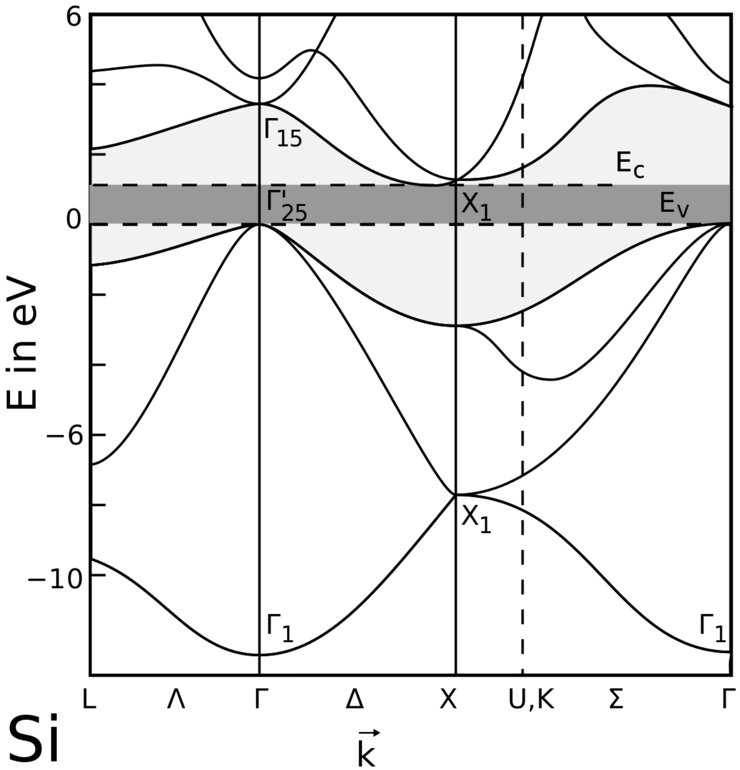
Constraints on self-interacting Dark Matter

Constraints on self-interacting DM



Panda X

Direct Detection of sub-GeV Dark Matter



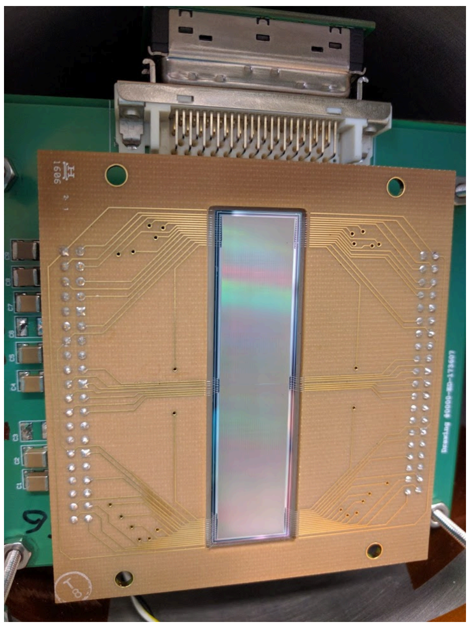
Excite bound electrons into excited states

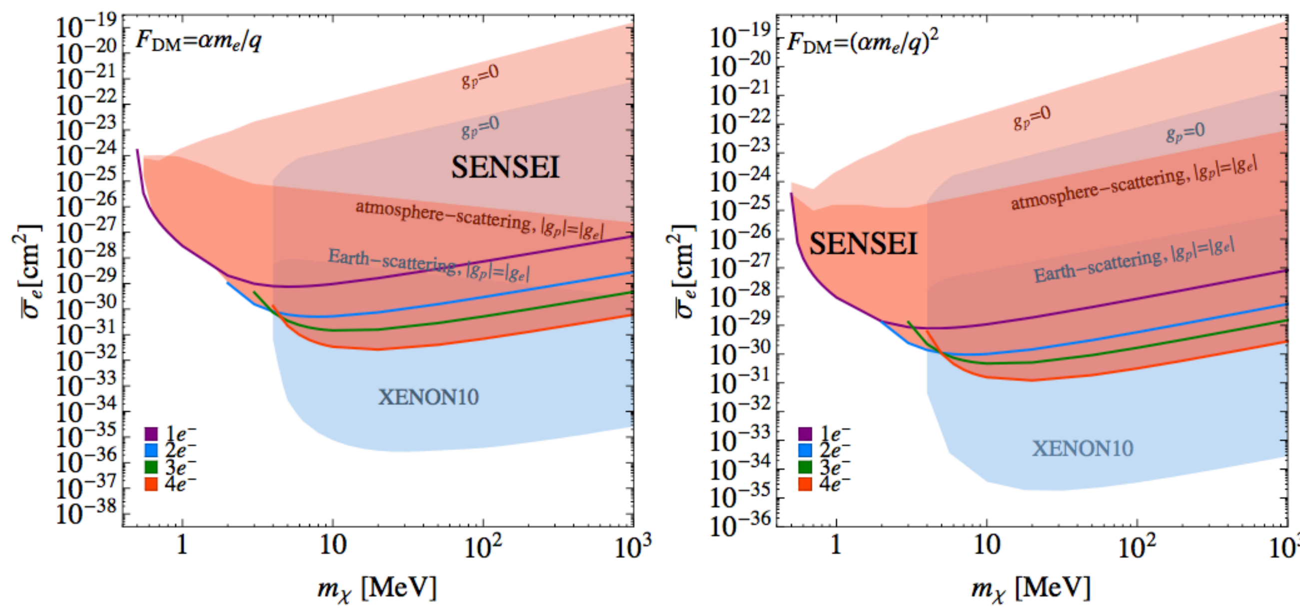
Semiconductor detectors with sensitivity to single electron-hole (e−h+) pairs can be competitive with other experimental technologies.

$$\frac{dR}{d\ln E_R} = V_{det}\frac{\rho_{DM}}{m_\chi}\frac{\rho_{\rm Si}}{2m_{\rm Si}}\bar{\sigma}_e\alpha\frac{m_e^2}{\mu_\chi^2}I_{\rm crystal}(E_e;F_\chi)$$

SENSEI

Sub-Electron-Noise Skipper CCD Experimental Instrument
CCD with a resolution to individual e-
initial active mass of 0.094g of silicon (0.019g-d exposure)

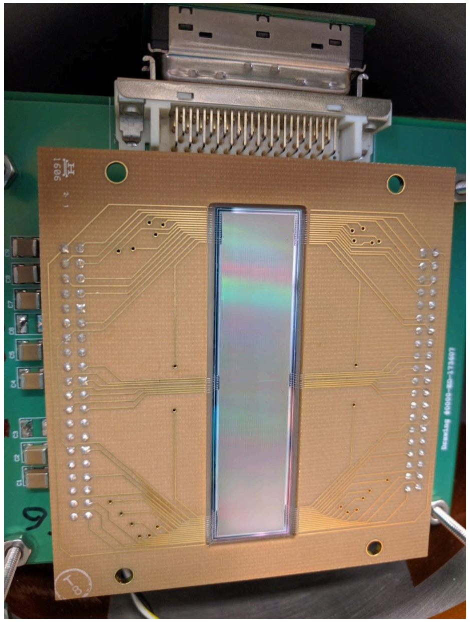


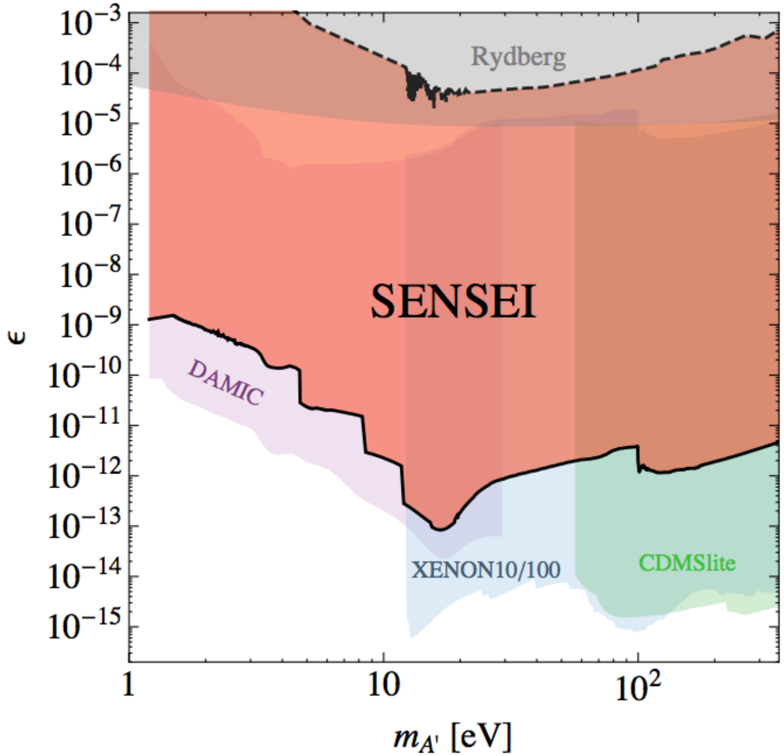


They can test DM scattering on electrons, setting bounds at very low masses

SENSEI

Sub-Electron-Noise Skipper CCD Experimental Instrument
CCD with a resolution to individual e-
initial active mass of 0.094g of silicon (0.019g-d exposure)



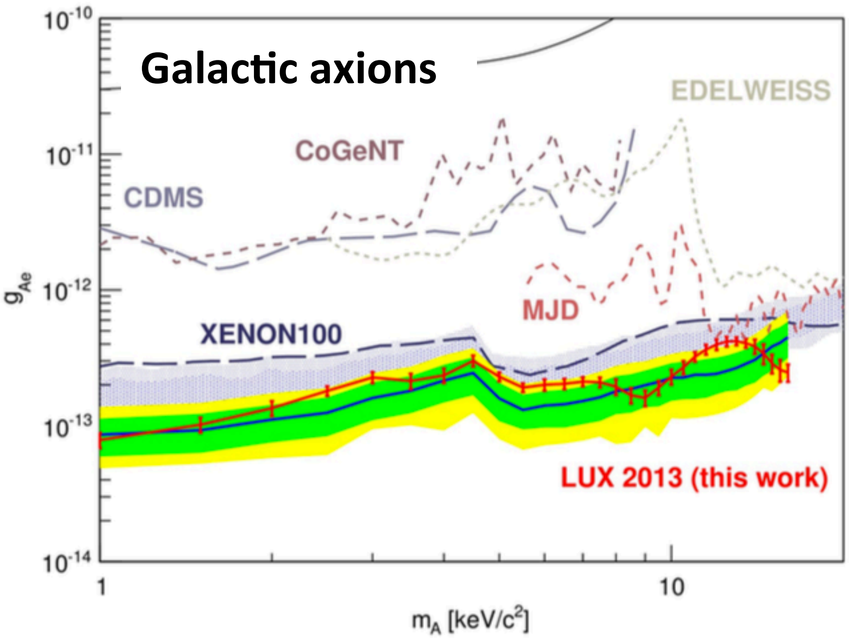


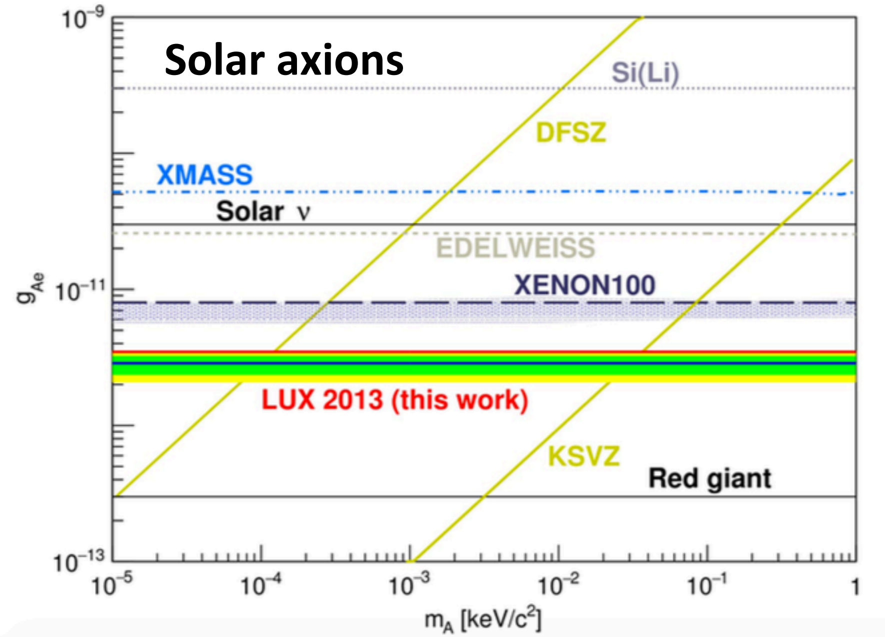
They also test Dark Photon absorption

Direct detection of axions

Axions (with keV mass) can interact with DM detectors in various ways:

- Axion-electron interactions (study ER in Xenon experiments)
- Axion-photon conversion in the EM field of the atoms (e.g. in Ge crystals)





Direct detection of ultralight scalar DM (MAGIS 100)

Ultralight dilaton DM acts as a background field (high occupation number)

Can cause small (but coherent) oscillations in Standard Model parameters

$$\mathcal{L} = +\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \sqrt{4\pi G_N}\phi\left[d_{m_e}m_e\bar{e}e - \frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}\right] + \ldots$$

DM scalar field

Electron coupling

Photon coupling

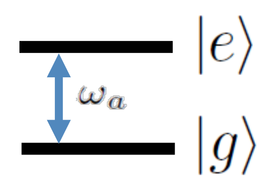
e.g., QCD

$$\phi\left(t, \mathbf{x}\right) = \phi_0 \cos\left[m_\phi(t - \mathbf{v}\cdot\mathbf{x}) + \beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right) \qquad \phi_0 \propto \sqrt{\rho_{\rm DM}}$$

DM coupling causes time-varying atomic energy levels:

$$\omega_{\rm A}(t) \simeq \omega_{\rm A} + \Delta\omega_{\rm A}\cos(m_\phi t);$$

$$\Delta\omega_{\rm A} \equiv \omega_{\rm A}\sqrt{4\pi G_N}\phi_0\left(d_{m_e} + \xi d_e\right)$$



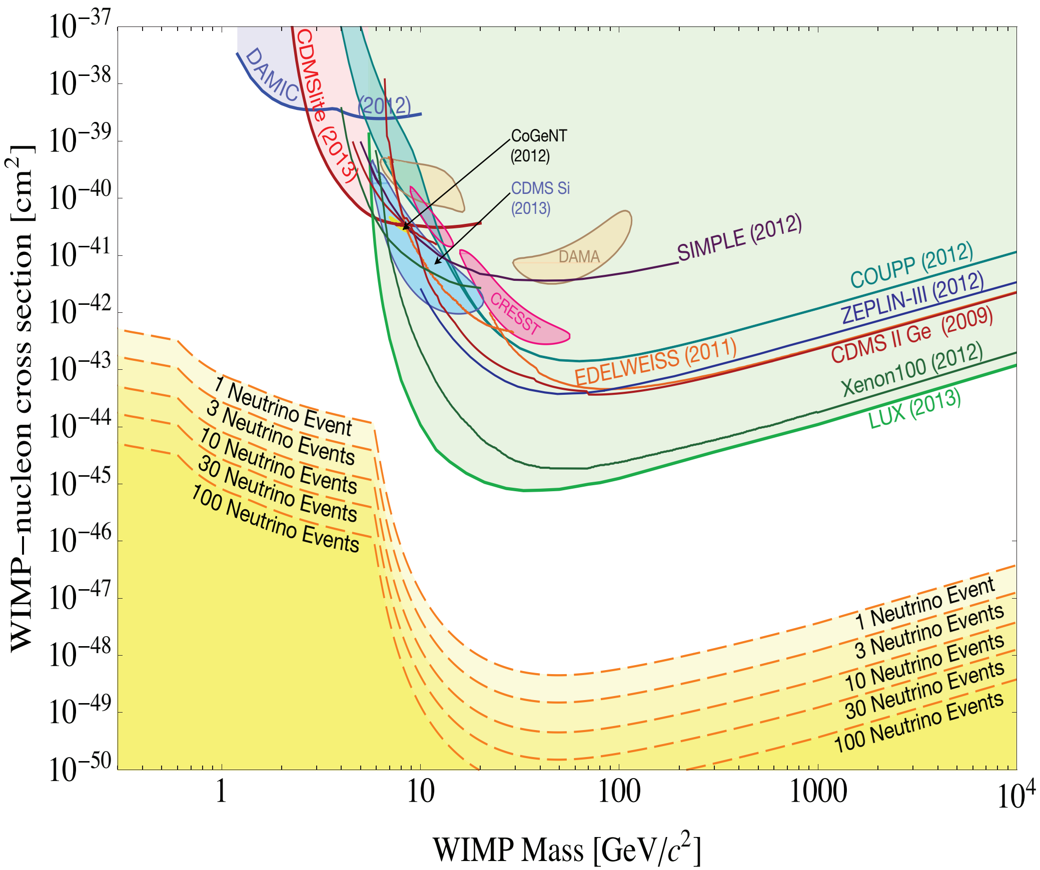
Exploring neutrino physics (Coherent Neutrino Scattering)

Future dark matter experiments will be sensitive to Coherent Neutrino Scattering, limiting the reach for DM searches (Neutrino Floor)

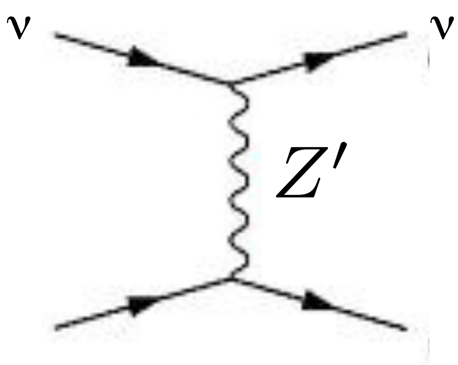
Going beyond the neutrino floor:

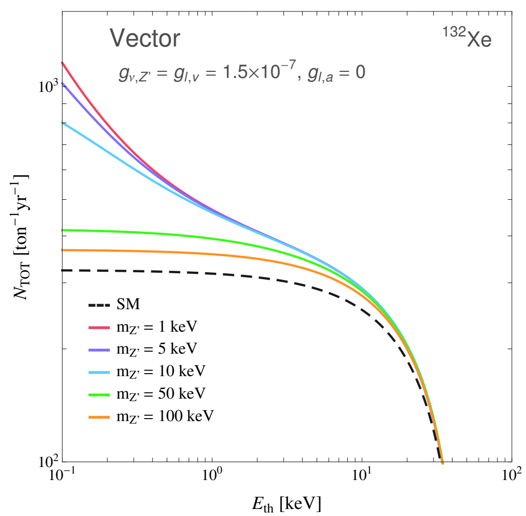
- Spectral analysis
- Annual modulation
  Billard et al. 1307.5458
  Davis 1412.1475
- Combination of complementary targets
  Ruppin et al. 1408.3581
- Directional detection

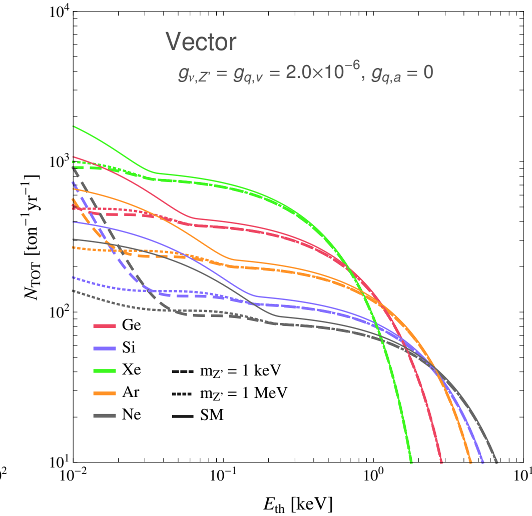
  Grothaus et al. 1406.5047
  O'Hare et al. 1505.08061



New Physics in the neutrino sector?







ER:

NR:

$$d\sigma/dE_R - d\sigma^{\rm SM}/dE_R$$

$$\frac{\sqrt{2}G_F m_e g_v g_{\nu,Z'} g_{e,v}}{\pi\left(2E_R m_e + m_{Z'}^2\right)} + \frac{m_e g_{\nu,Z'}^2 g_{e,v}^2}{2\pi\left(2E_R m_e + m_{Z'}^2\right)^2}$$

$$-\frac{G_F m_N Q_v Q'_v (2E_\nu^2 - E_R m_N)}{2\sqrt{2}\pi E_\nu^2\left(2E_R m_N + m_{Z'}^2\right)} + \frac{Q'^2_v m_N (2E_\nu^2 - E_R m_N)}{4\pi E_\nu^2\left(2E_R m_N + m_{Z'}^2\right)^2}$$

Further motivation to low-threshold direct detection experiments

Points for debate

- Direct Detection experiments are becoming **extremely sensitive** and **increasingly versatile**, probing DM models beyond the vanilla WIMP

- Probing the WIMP paradigm for masses from ~TeV to keV scale (and below), but **also looking for:**

  - SIDM, Inelastic DM, dark photons
  - Axions
  - New physics in the neutrino sector

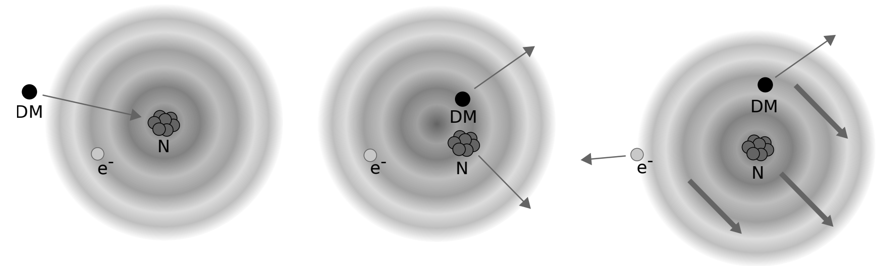
- **Bigger + Better** experiments are needed

- **Variety of targets and techniques** not only probe different DM candidates, but also crucial for DM parameter reconstruction

- **Annual Modulation and Directionality?**

The sudden acceleration of a nucleus after a collision can lead ionisation of atomic electrons (excitation much rarer)

Enhance S1 in dual phase experiments



Ibe, Nakano, Shoji, Suzuki, 1707.07258
Dolan, Kahlhofer, McCabe 1711.09906

$$\frac{\mathrm{d}^3 R_{\rm ion}}{\mathrm{d}E_{\rm R}\,\mathrm{d}E_e\,\mathrm{d}v} = \frac{\mathrm{d}^2 R_{\rm nr}}{\mathrm{d}E_{\rm R}\,\mathrm{d}v} \times |Z_{\rm ion}(E_{\rm R}, E_e)|^2$$

$$q_e = m_e\sqrt{2\,E_{\rm R}/m_N}$$