Direct Dark Matter Detection

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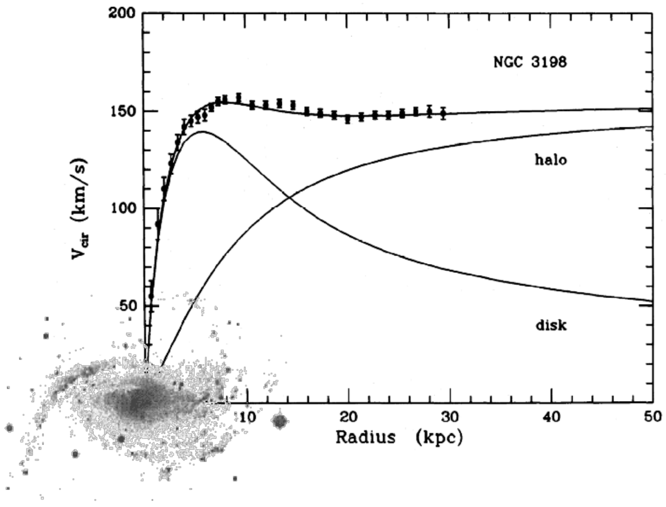
Dark Matter is a necessary (and abundant) ingredient in the Universe

It is one of the clearest hints of

Physics Beyond the SM

Galaxies

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



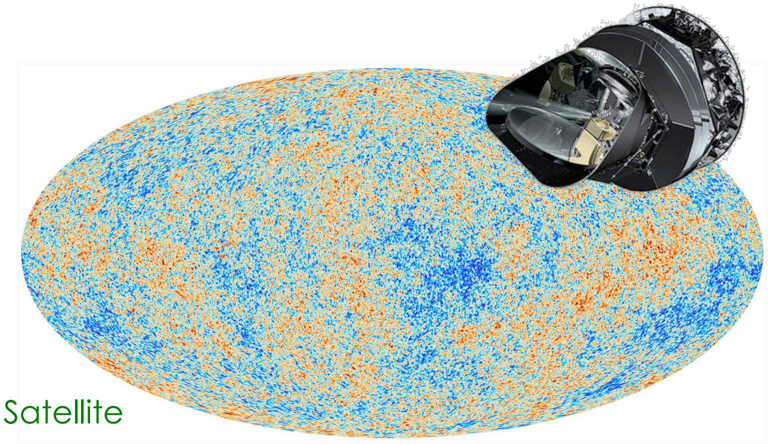
Clusters of galaxies

- 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 Satellite

Challenges for DARK MATTER in the 80's

The main questions concerning dark matter are whether it is really present in the first place and, if so, how much is there, where is it and what does it consist of.

How much. In general one wants to know the amount of dark matter relative to luminous matter. For cosmology the main issue is whether there is enough dark matter to close the universe. Is the density parameter Ω equal to 1?

Where. The problem of the distribution of dark matter with respect to luminous matter is fundamental for understanding its origin and composition. Is it associated with individual galaxies or is it spread out in intergalactic and intracluster space? If associated with galaxies how is it distributed with respect to the stars?

What. What is the nature of dark matter? Is it baryonic or non-baryonic or is it both?

van Albada, Sancisi '87

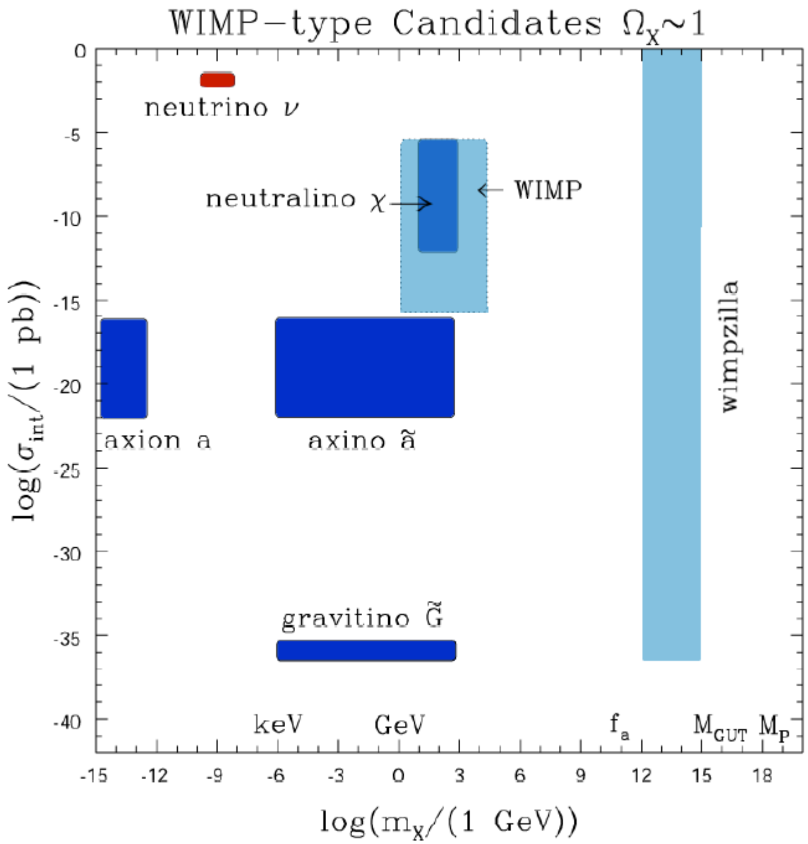
We don't know yet what DM is... but we do know many of its properties

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

Many candidates in Particle Physics

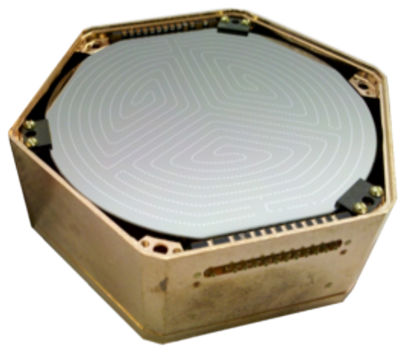
- Axions and ALPs
- Weakly Interacting Massive Particles (WIMPs)
- Sterile Neutrinos
- SuperWIMPs and Decaying DM
- WIMPzillas
- Asymmetric DM
- SIMPs, CHAMPs, SIDMs
- Bose Einstein Condensate …



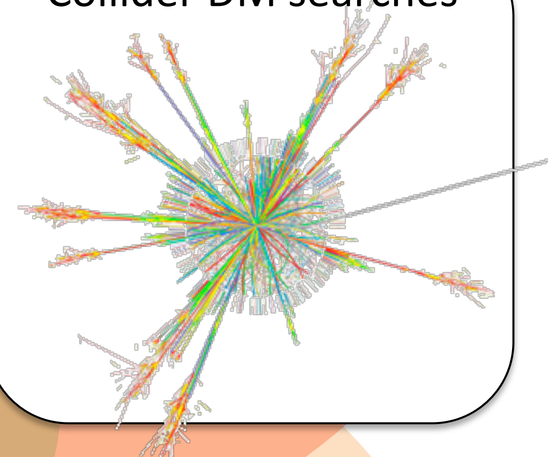
... they have very different properties

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

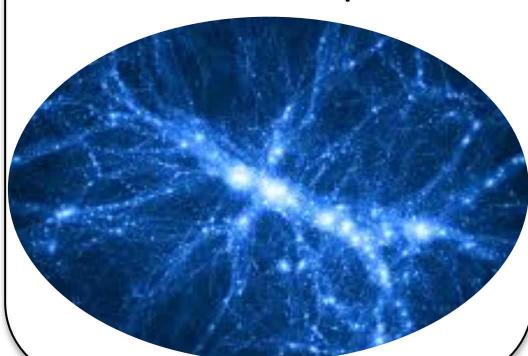
Direct DM detection



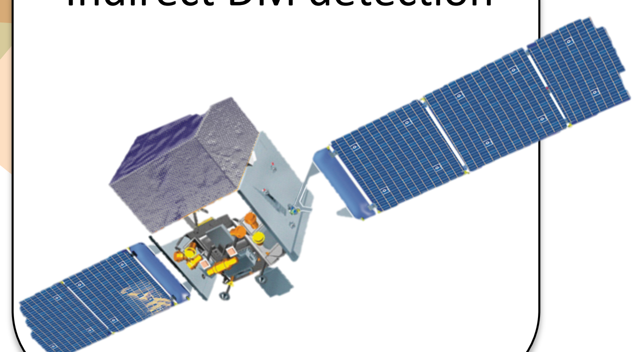
Collider DM searches



Astro/Cosmo probes

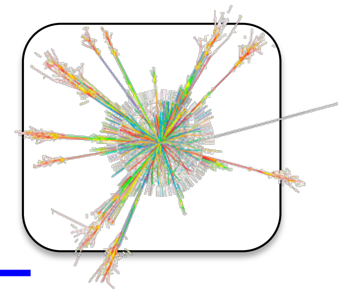


Indirect DM detection

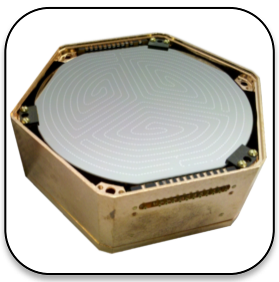


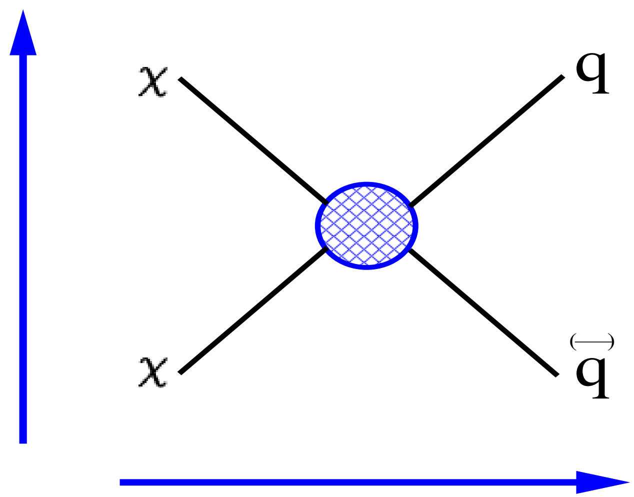
... probing **DIFFERENT** aspects of their interactions with ordinary matter

Accelerator Searches (production)



Direct Detection (scattering)

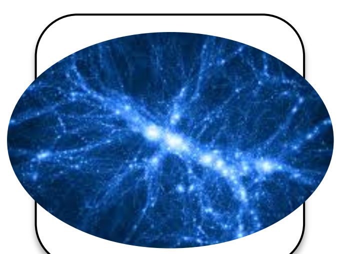


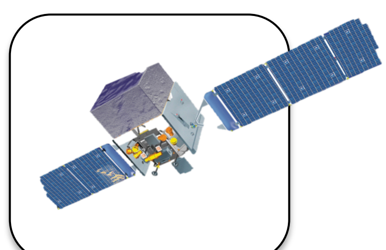


Constraints in one sector affect observations in the other two.

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

Indirect Detection (annihilation or decay)





Wish list for DARK MATTER in the ~~2000's~~ ~~2010's~~ 2020's

- Experimental **detection** (direct, indirect, collider searches)

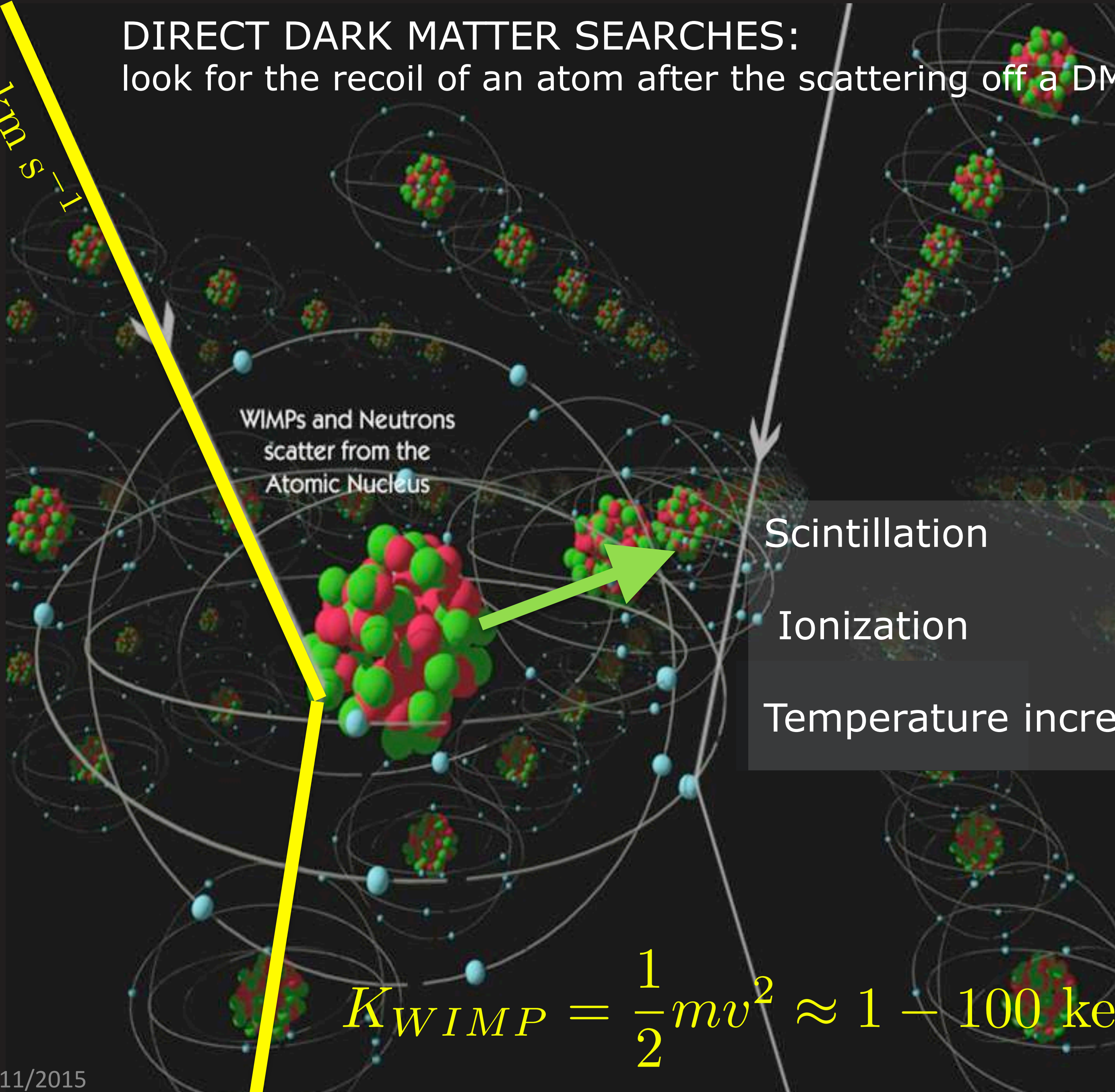
- How is DM **distributed** (in the DM halo and in larger structures)

- Determination of **DM parameters** (mass and cross sections)

- What is the model for **physics Beyond the SM**

Outstanding experimental advances → could this happen in the near future?

DIRECT DARK MATTER SEARCHES:
look for the recoil of an atom after the scattering off a DM particle



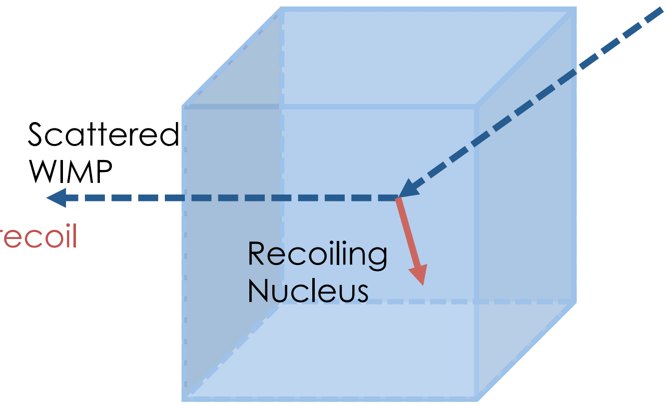
$$K_{WIMP} = \frac{1}{2} m v^2 \approx 1 - 100\ \mathrm{keV}$$

Direct DM detection

WIMP scattering with nuclei can be measured through

- Ionization
- Scintillation
- Phonons
- Bubble nucleation

For a 100 GeV WIMP, this implies recoil energies of order $E_R \sim 10$ keV



Detection rate

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

Experimental setup

Target material (sensitiveness to spin-dependent and –independent couplings)

Detection threshold

Astrophysical parameters

Local DM density

Velocity distribution factor

Theoretical input

Differential cross section (of WIMPs with quarks)

Nuclear uncertainties

WIMP-nucleus cross section traditionally separated in 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

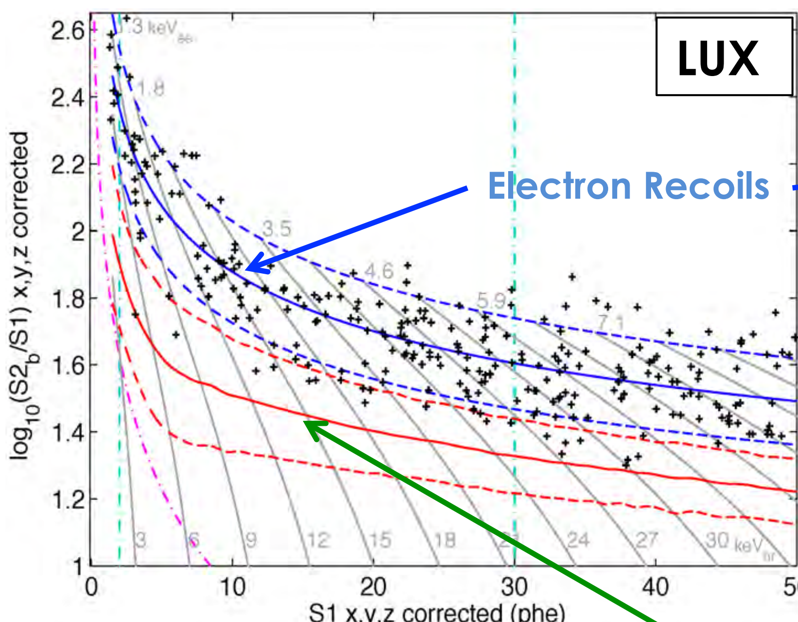
Discriminating a DM signature (from the otherwise overwhelming background)

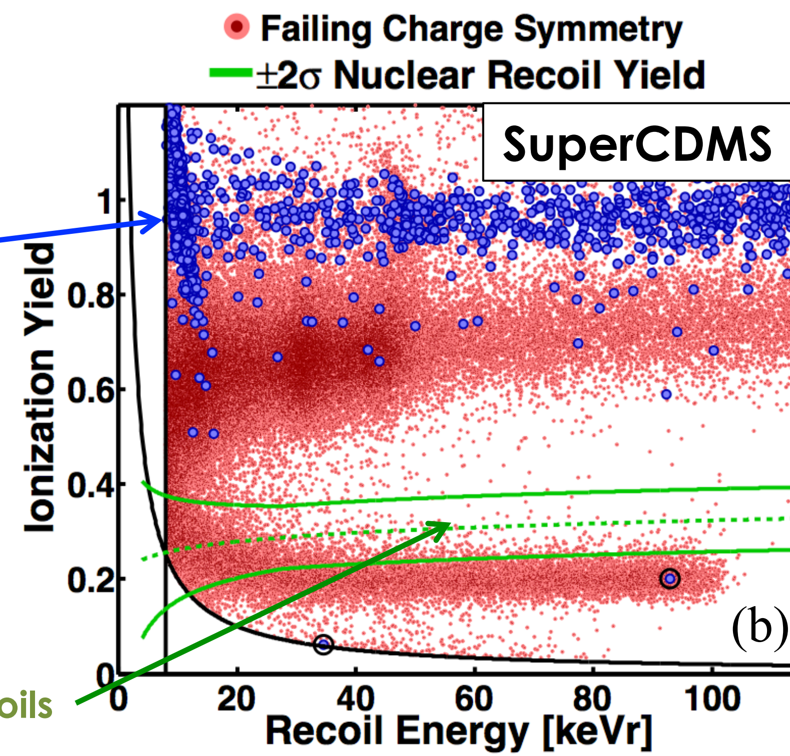
Under the hypothesis that the DM is a WIMP

- Nuclear recoils (vs. Electron recoils)
- Single scattering

(Most) experiments employ information from various channels to remove background

- Ionization/scintillation (e.g. LUX)
- Ionization/Phonons (e.g. SuperCDMS)





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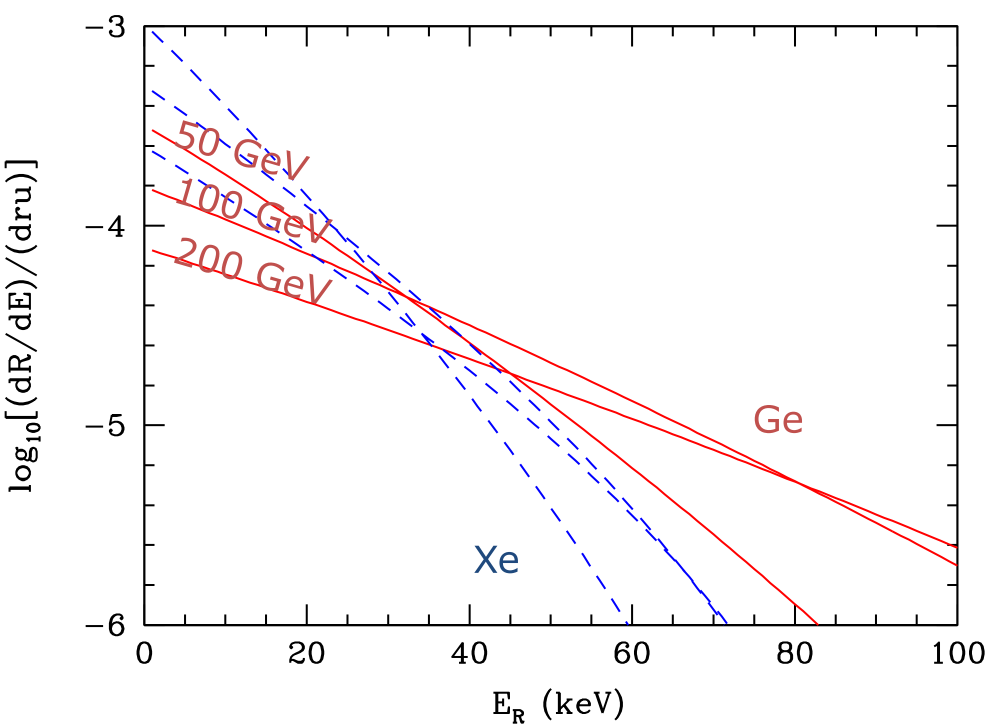
DM scattering would lead to an exponential signal

Light WIMPs expected at very low recoil energies

Favours light targets

Low-threshold searches



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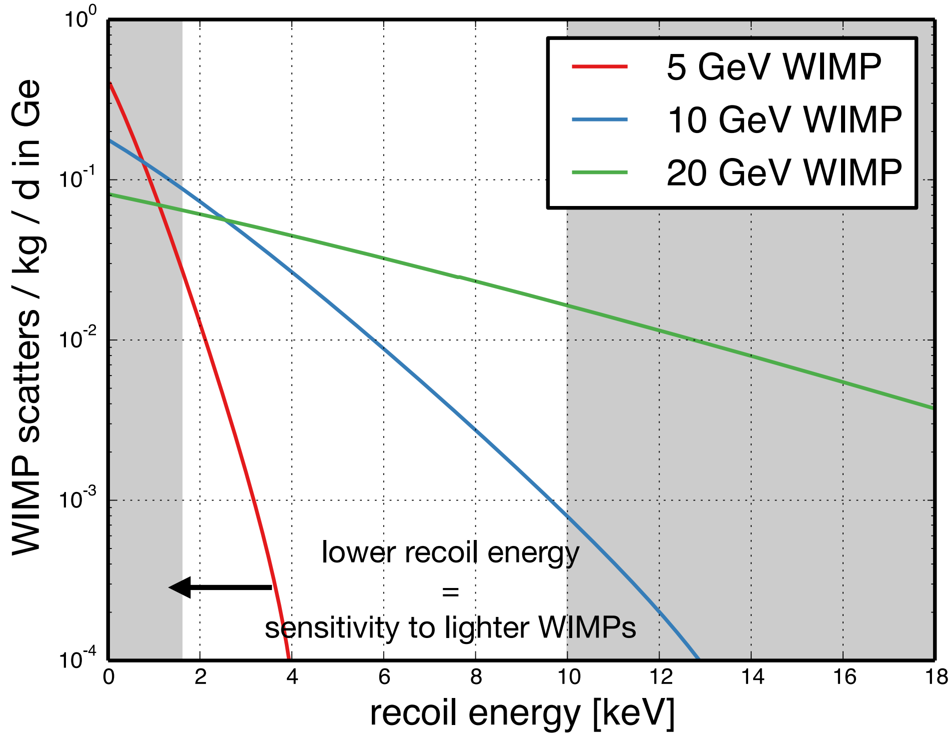
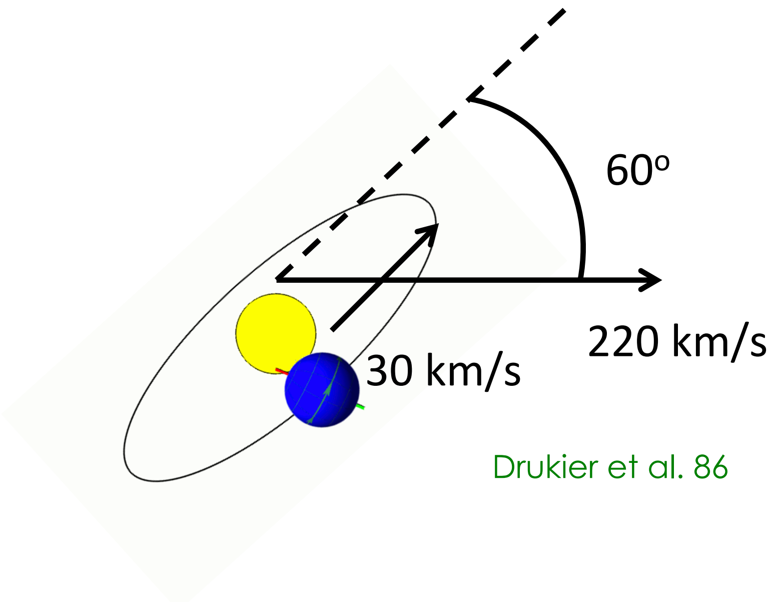


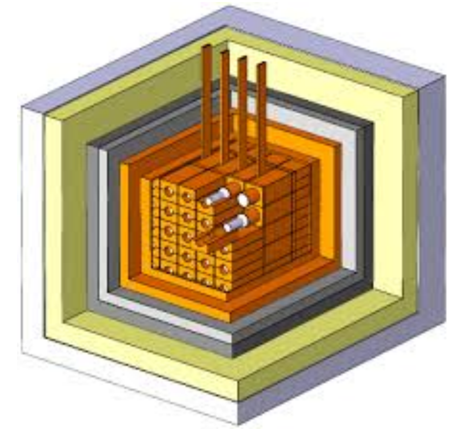
The DM rate exhibits an ANNUAL MODULATION

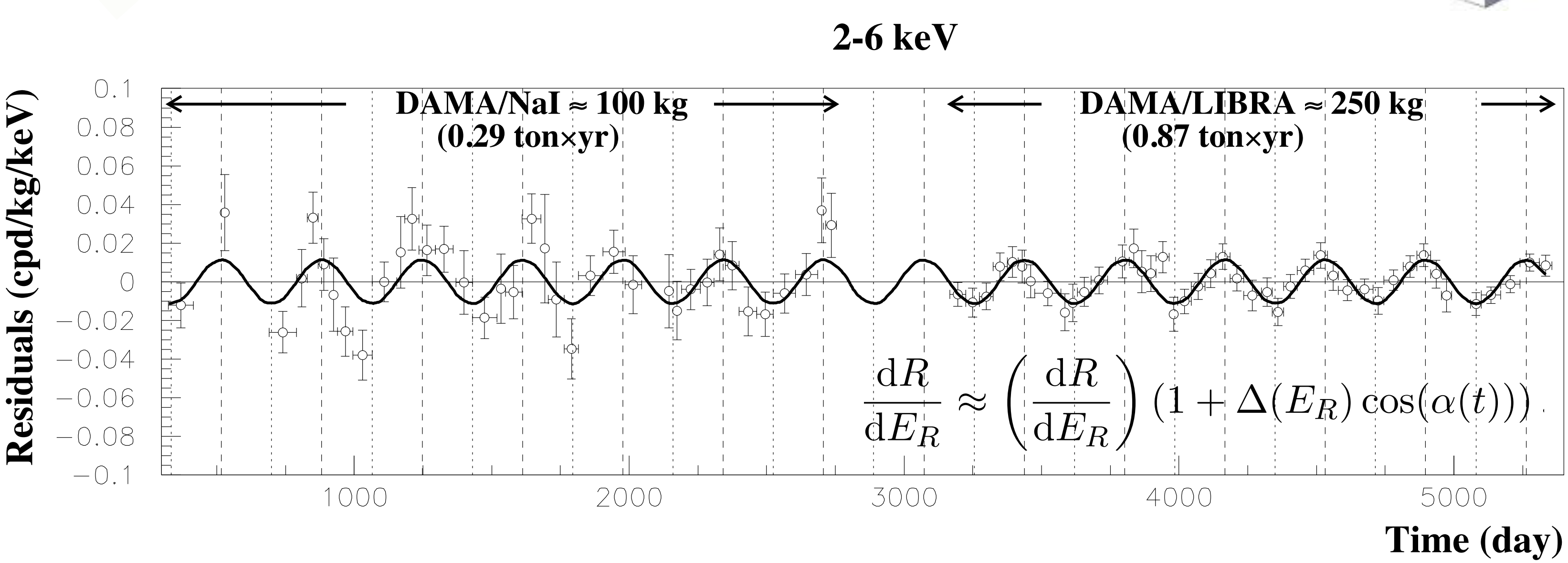


Drukier et al. 86

DAMA (DAMA/LIBRA) signal on annual modulation

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





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

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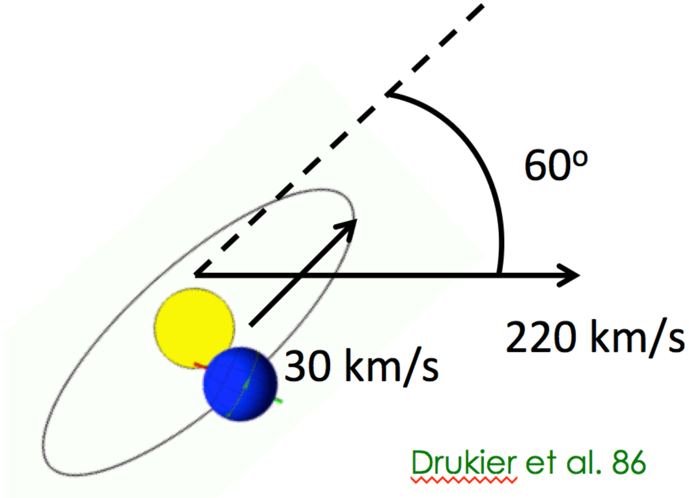

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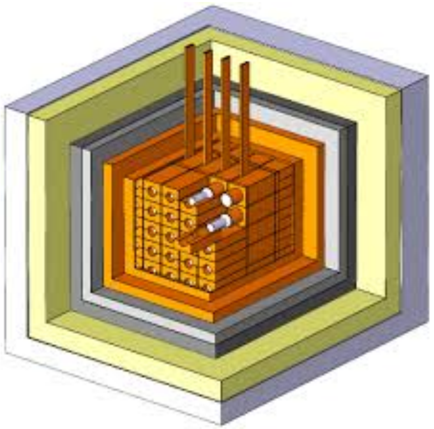
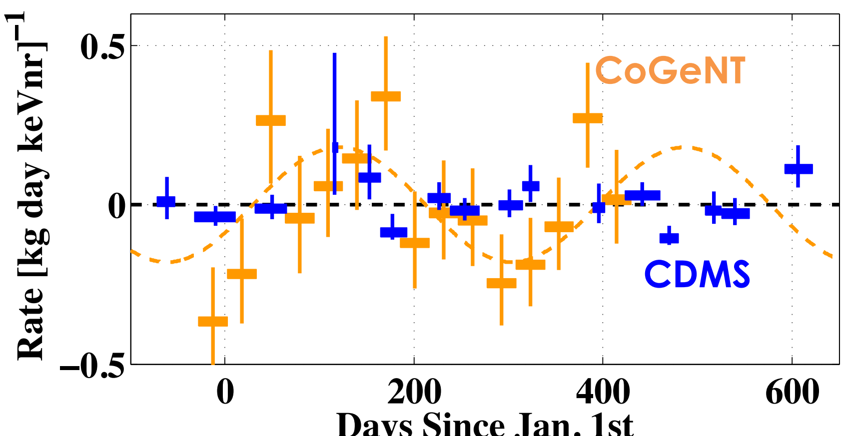
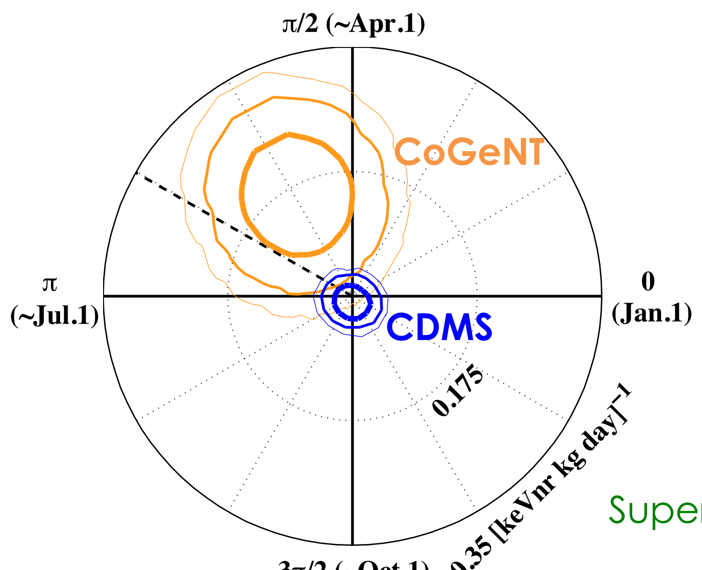


Not observed in other experiments

The WIMP interpretation is disfavoured

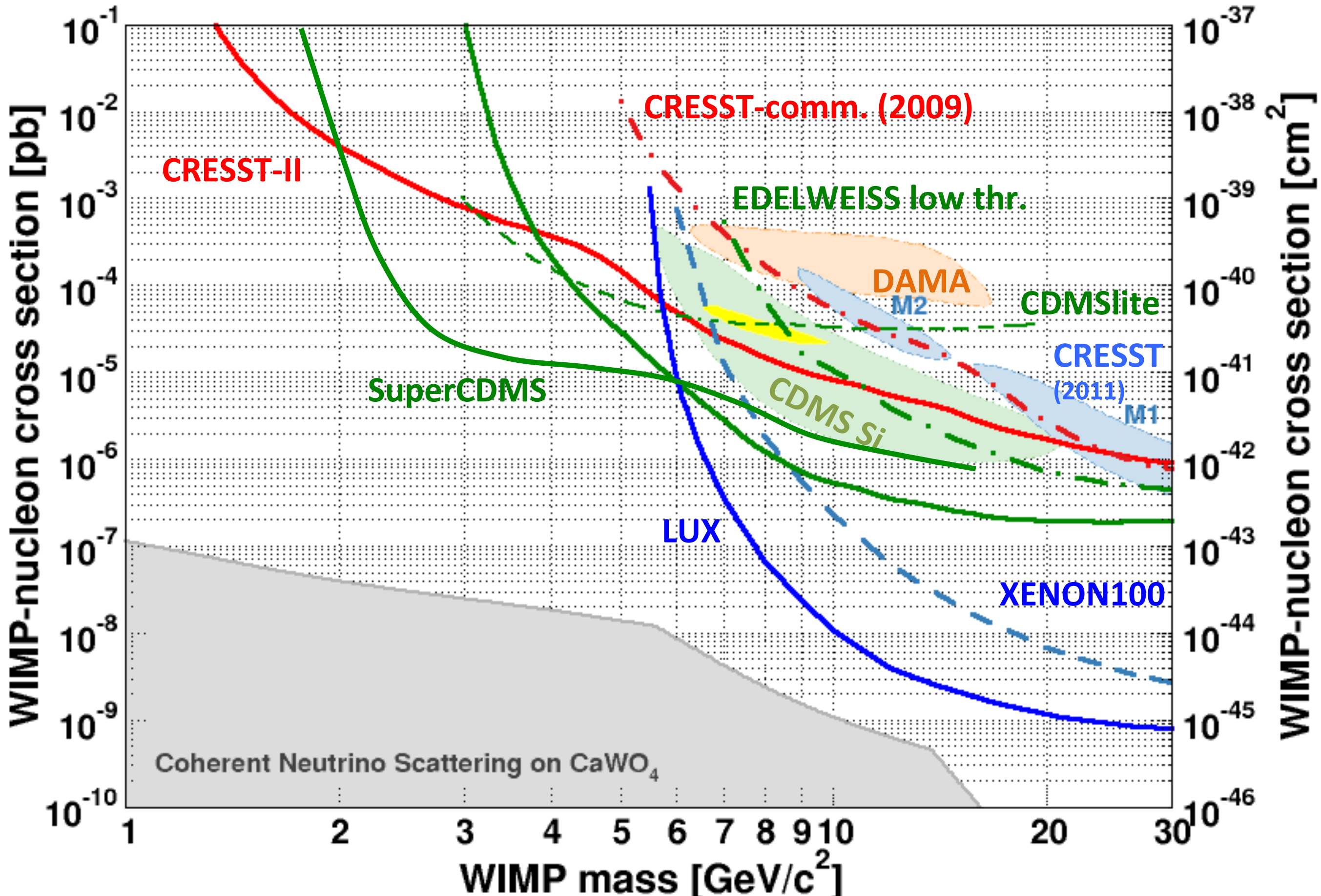




SuperCDMS 2012

Upper bounds on the SI cross section

XENON10, XENON100, LUX (Xe), CDMSlite, SuperCDMS, Edelweiss (Ge), COUPP (CF_3I), and CRESST ($CaWO_4$) have not observed any DM signal, which constrains the scattering cross section



Plot by Raimund Strauss

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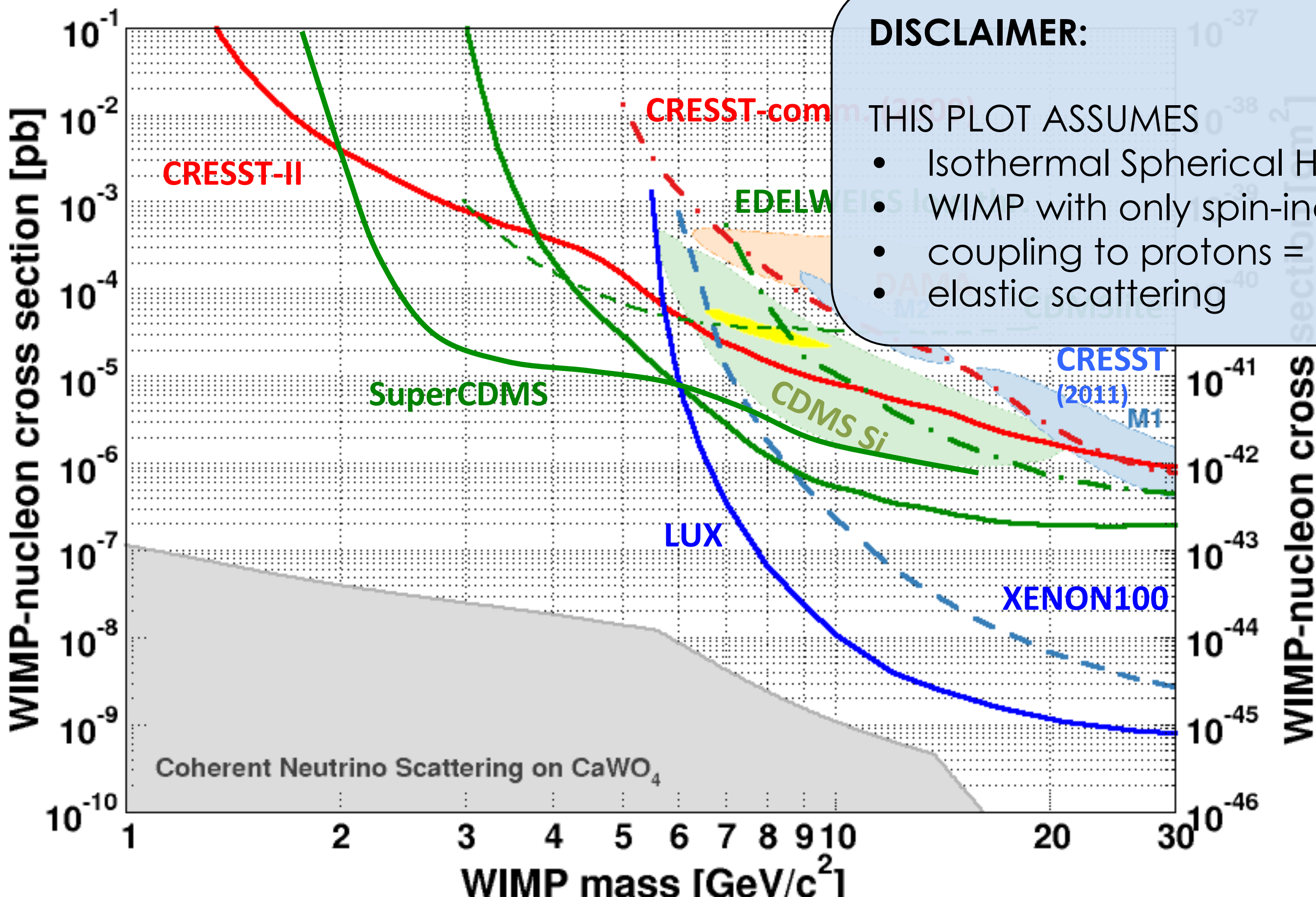


DISCLAIMER:

THIS PLOT ASSUMES

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

Plot by Raimund Strauss

Isospin-Violating Dark Matter can ease this discrepancy

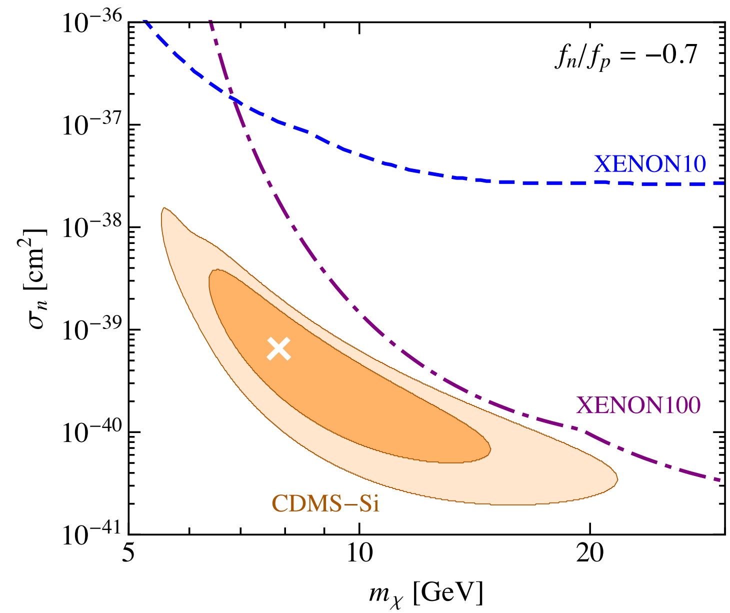
$$R = \sigma_p \sum_i \eta_i \frac{\mu_{A_i}^2}{\mu_p^2} I_{A_i} \left[Z + (A_i - Z) f_n/f_p\right]^2$$

The scattering amplitudes for proton and neutrons may interfere destructively

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

The interference depends on the target nucleus

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



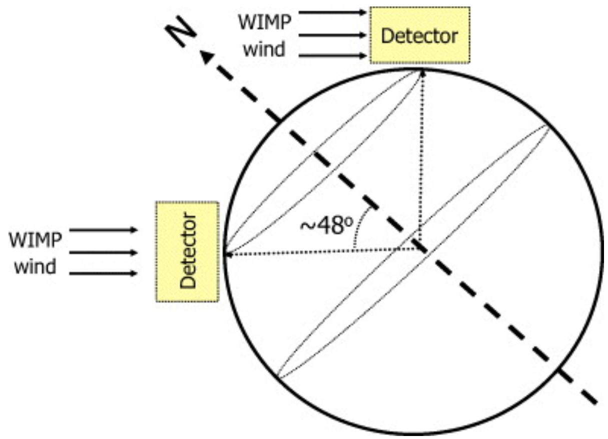
XENON100 (Xe) and CDMS II (Si) results can be "reconciled"

Frandsen et al. 2013

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

Fitzpatrick, Wick et al. 2012-2014

The direction of the DM wind has a privileged DIRECTION



Spergel '88

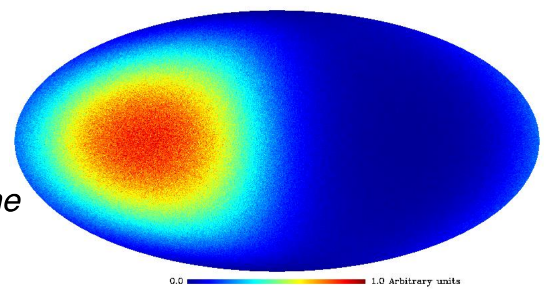
Experimental challenges

Low-pressure TPC to measure direction

Large exposure needed (from current limits)

WIMP signal (recoil map)

Angular distribution of Fluorine recoils [5;50] keV

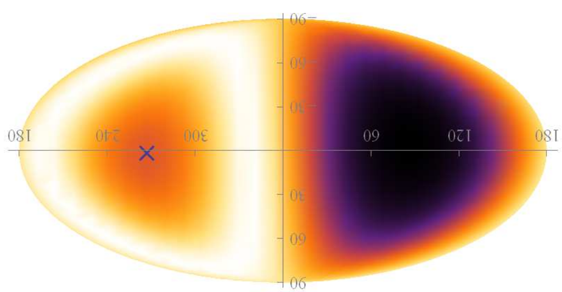


Characteristic dipole signal

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

J. Billard et al., 2010

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

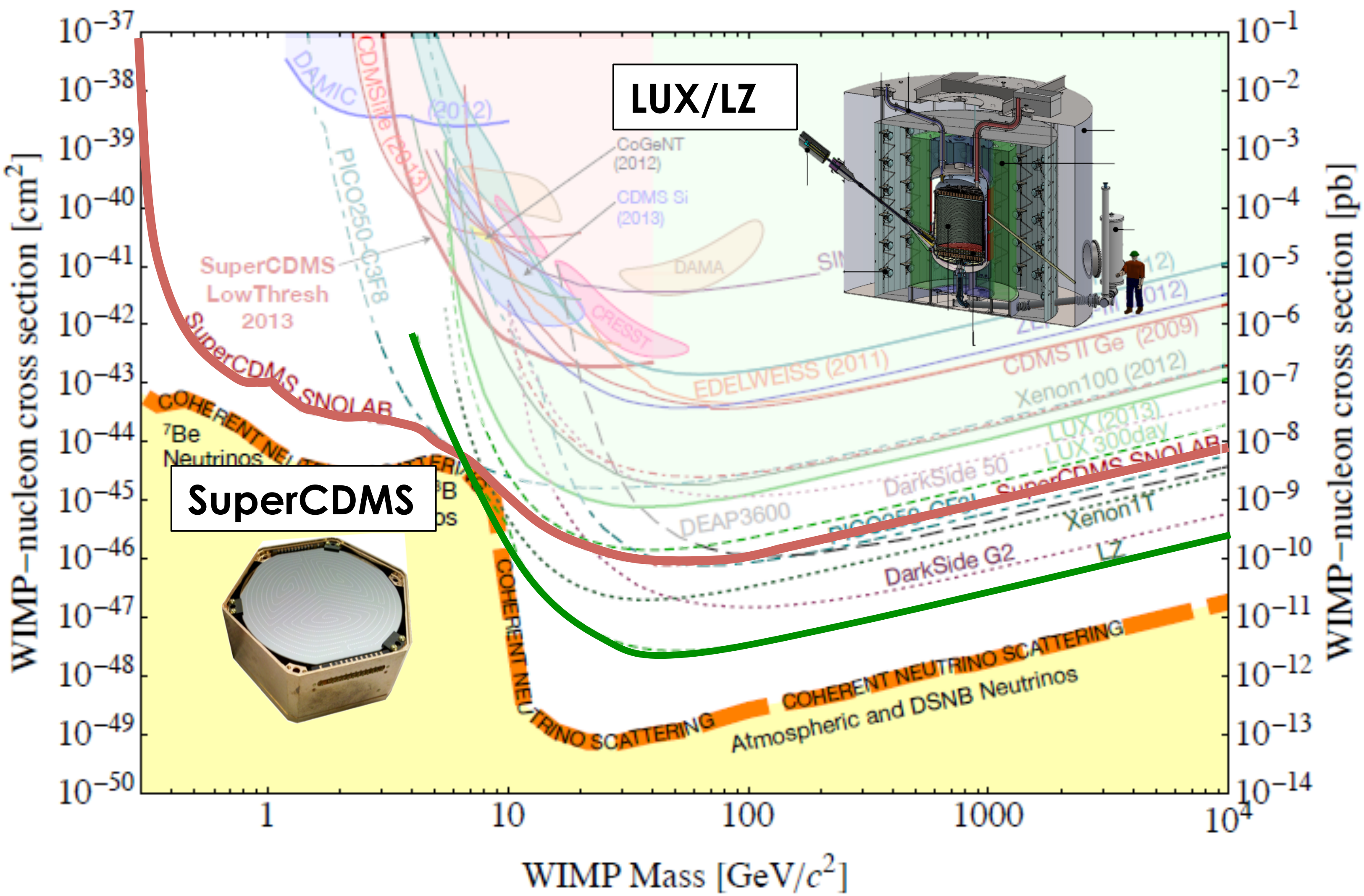


Ring-like structure

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

Bozorgnia et al., 2012

2nd Generation experiments will extend the sensitivity by over an order of magnitude.
SuperCDMS @ SNOLAB will have an excellent coverage of the light mass window.



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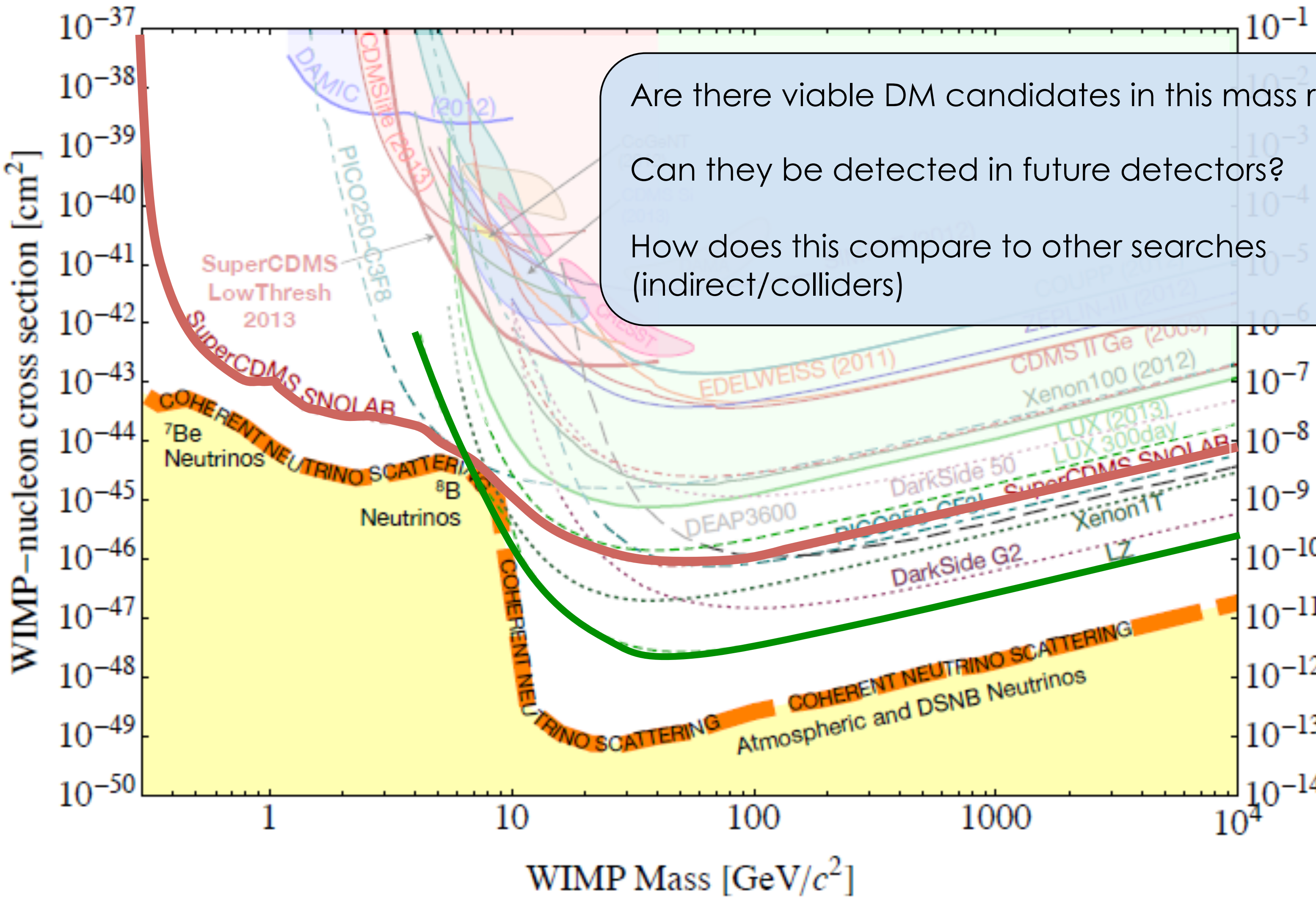


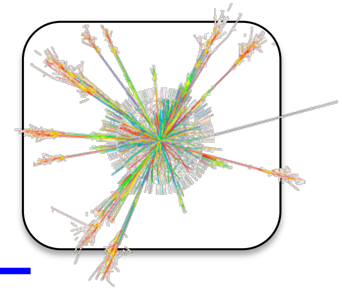
Are there viable DM candidates in this mass range?

Can they be detected in future detectors?

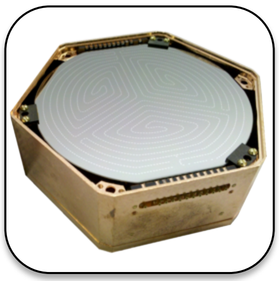
How does this compare to other searches (indirect/colliders)

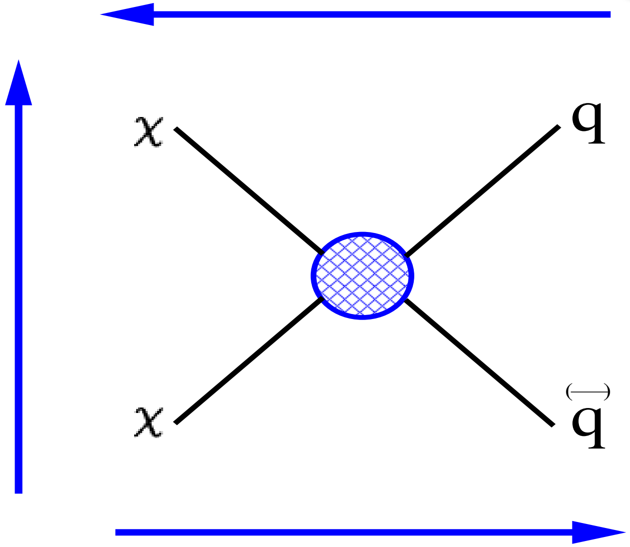
How does this compare with other searches?

Accelerator Searches (production)



Direct Detection
(scattering)

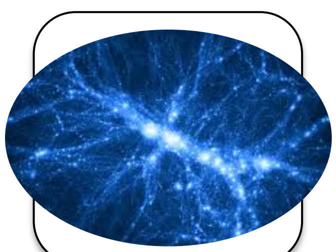


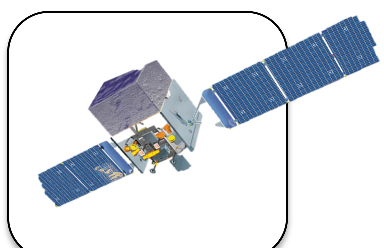


Constraints in one sector affect observations in the other two.

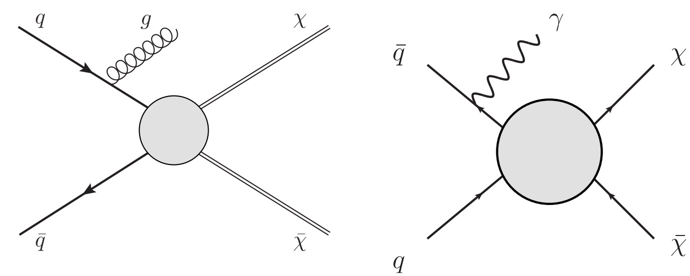
"**Redundant**" detection can be used to extract DM properties.

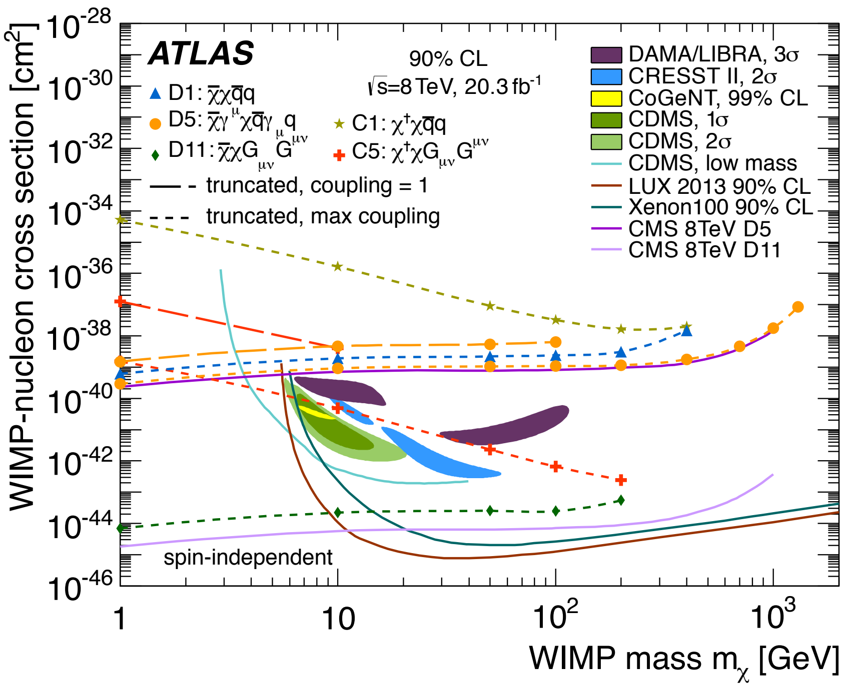
Indirect Detection
(annihilation or decay)

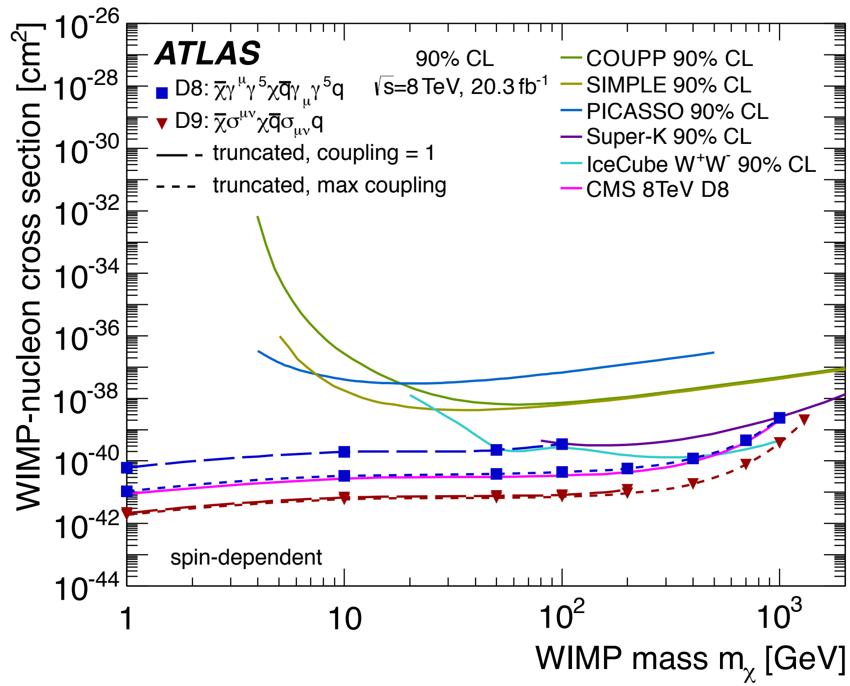




Monojet and **monogamma** constraints can be interpreted as bounds on the DM-nucleon scattering cross section.







In principle more sensitive at low masses (operator dependent)

Dependent on the mediator mass and on the validity regime of the effective theory.

Particle Physics models for dark matter

Well motivated DM models in theories beyond the Standard Model (e.g., Supersymmetry)

Minimal SUSY extension

Squarks	$\tilde{u}_{R,L}$, $\tilde{d}_{R,L}$ $\tilde{c}_{R,L}$, $\tilde{s}_{R,L}$ $\tilde{t}_{R,L}$, $\tilde{b}_{R,L}$
Sleptons	$\tilde{e}_{R,L}$, $\tilde{\nu}_e$ $\tilde{\mu}_{R,L}$, $\tilde{\nu}_\mu$ $\tilde{\tau}_{R,L}$, $\tilde{\nu}_\tau$
Neutralinos	$\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_{1,2}$
Charginos	$\tilde{W}^\pm$, $\tilde{H}^\pm_{1,2}$
Gluino	$\tilde{g}$

Neutralino

Good annihilation cross section. it is a WIMP

Goldberg '83
Ellis, Hagelin, Nanopoulos, Olive, Srednicki '83
Krauss '83

Sneutrino

Viable candidates in scenarios with Right-Handed sneutrinos

Cerdeño, Muñoz, Seto 08
Arina, Fornengo 08

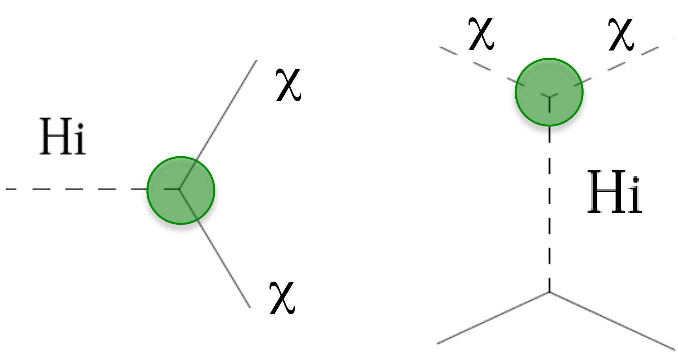
Gravitino (Superpartner of the graviton)
Axino (Superpartner of the axion)

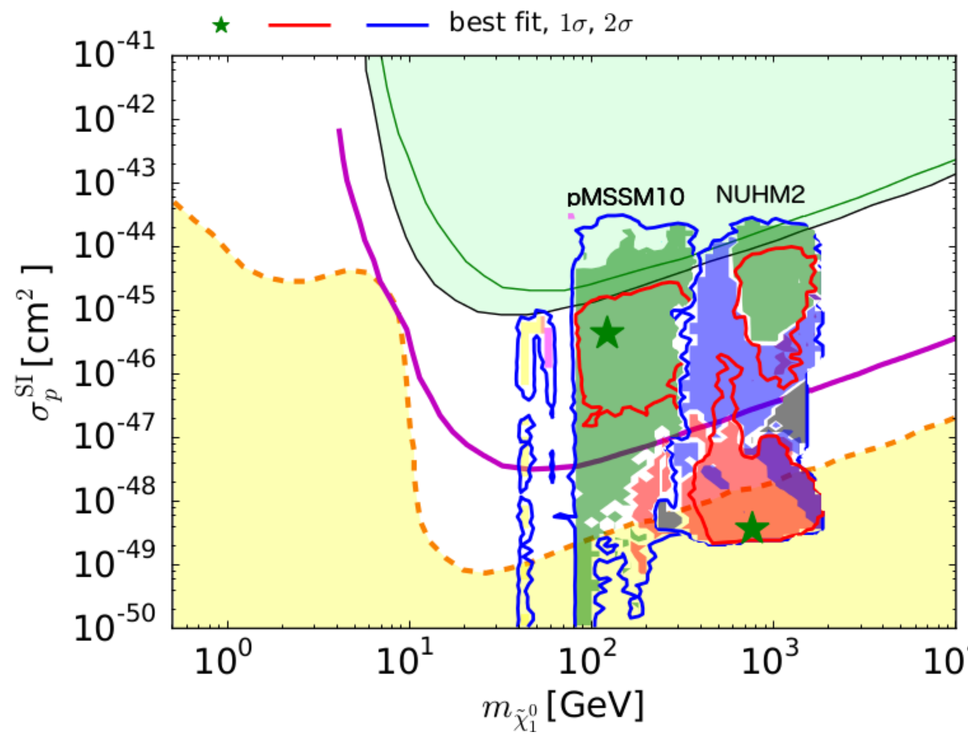
Extra-weakly interacting massive particles

Neutralino in the **MSSM**

Impose LHC1 bounds and explore the predictions of MSSM parameter space

- Bounds on SUSY masses
- Low-energy observables
- Invisible Higgs decay





MSSM after LHC1
Bagnaschi et al. 2015

The current bound on BR(H→ inv) sets constraints on the DM-Higgs coupling

This also translates into (upper) bounds for the scattering cross section of low-mass WIMPs

Neutralino in the MSSM

Impose LHC1 bounds and explore the predictions of MSSM parameter space

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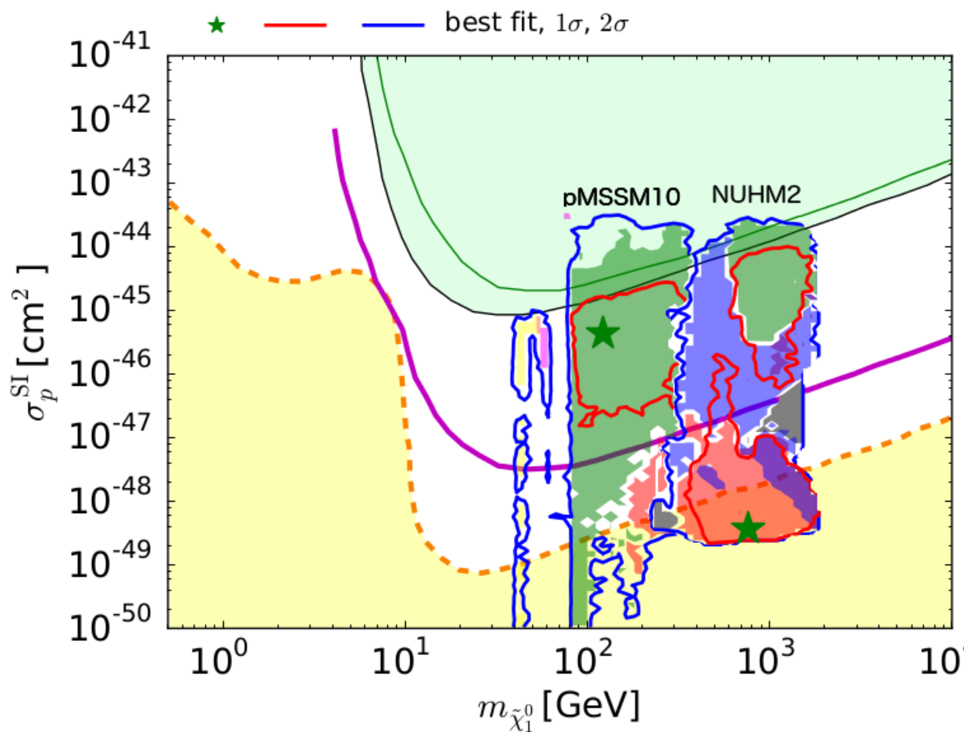
- Correct DM relic density

The predictions for the scattering cross section still span many orders of magnitude

(excellent motivation for more sensitive detectors)



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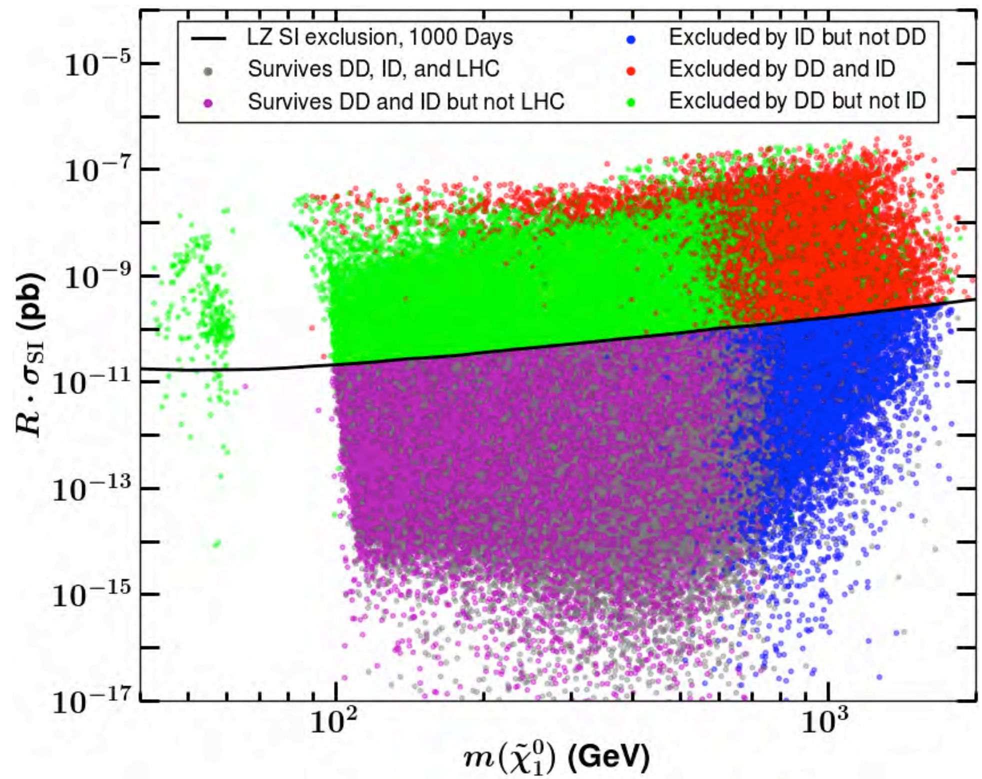


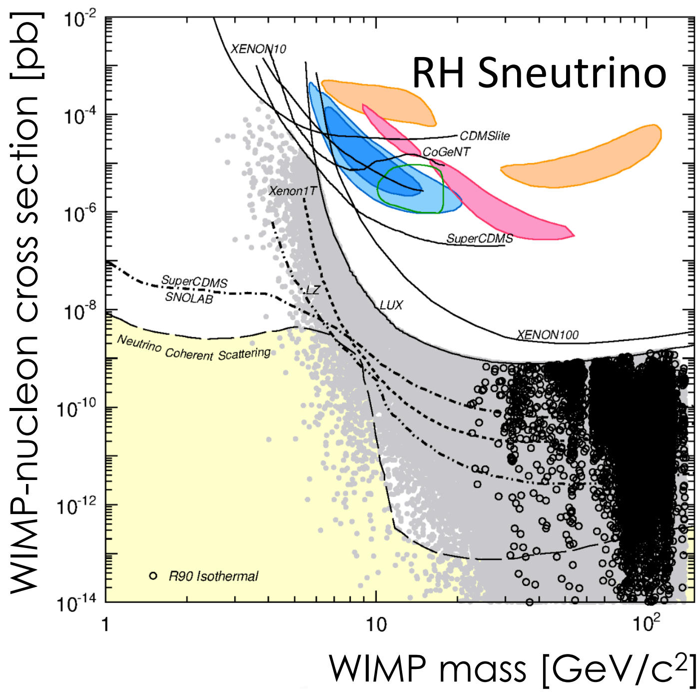
Cahill-Rowley et al. 2014

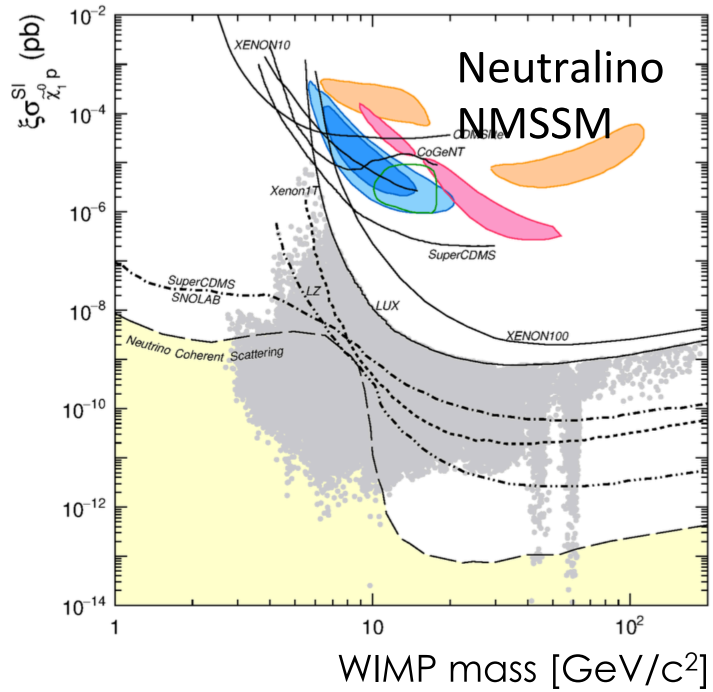
Combined with LHC + Indirect searches → excellent coverage of SUSY parameter space

Neutralino and Right-handed sneutrino in the NMSSM

Extensions of the MSSM can be more flexible (new light mediators)

Low-mass SUSY WIMPs are still viable (1-100 GeV)

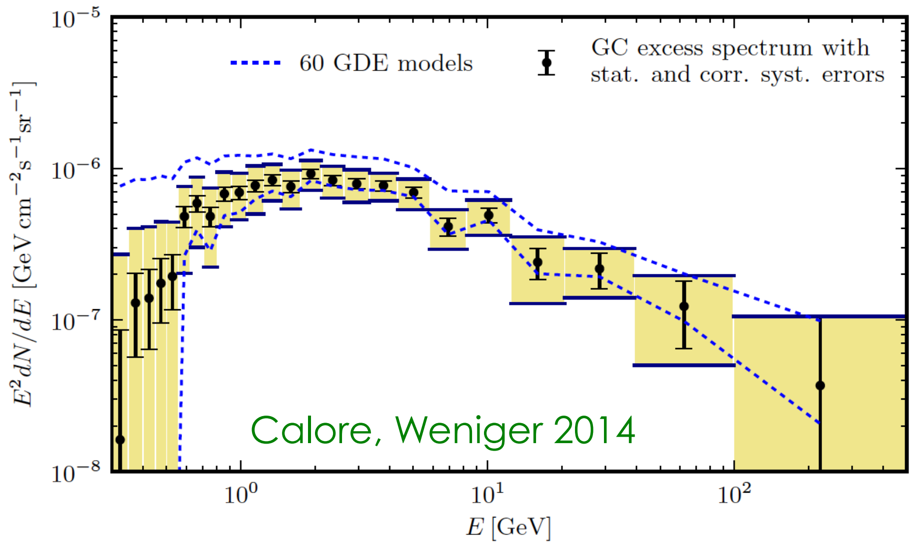


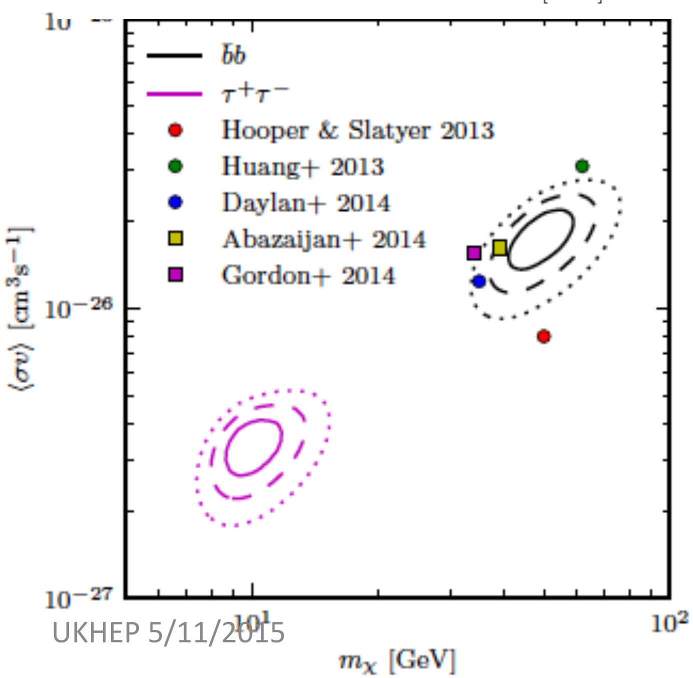


DGC, Peiró, Robles JCAP 08 (2014) 005
DGC, Peiró Robles, 2015

Excellent motivation for direct searches at low masses

The Galactic Centre Excess: An anomaly in indirect searches?





Compatible with the annihilation of a light WIMP ~10-50 GeV

Hooper, Goodenough 2010
Hooper, Linden 2011

or millisecond pulsars, cosmic ray effects or different spectrum at galactic centre.

Abazajian 1011.4275
Chernyakova 1009.2630
Boyarsky, Malyshev, Ruchayskiy, 1012.5839

Pulsars do not have the right morphology and Fermi would have seen them

Hooper, Linden 2012-2014

Fits normally done for pure annihilation channels

Compatible with WIMP DM

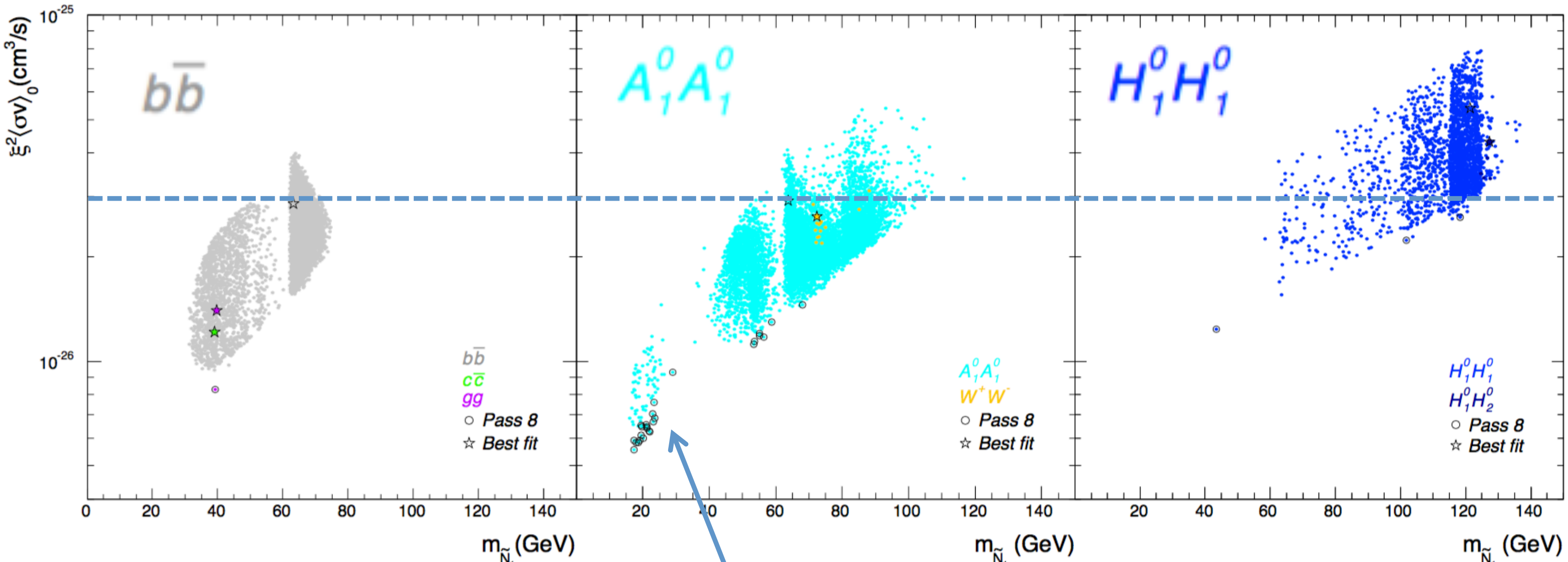
$$m_{DM} \sim 20 - 100 \text{ GeV}$$

$$\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$$

Right-handed sneutrino in the NMSSM and the Galactic Centre Emission

- Scan in the parameter space imposing all constraints (direct, indirect and colliders)
- The full final state is studied
  Do not restrict the analysis to pure annihilation channels.

Points fitting the GCE at 90% CL

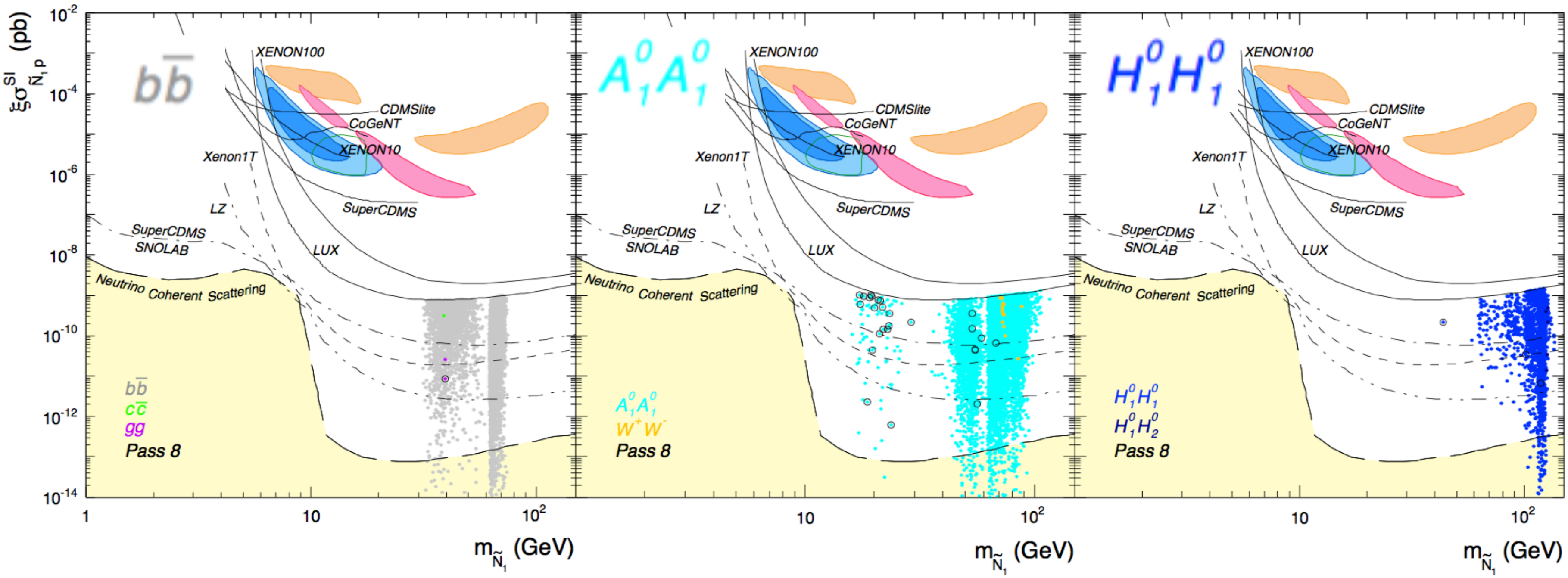


$$\boxed{\tilde{N}_1\tilde{N}_1 \rightarrow 2A_1^0 \rightarrow 4\tau}$$

DGC, Peiró, Robles JCAP 08 (2014) 005

Right-handed sneutrino in the NMSSM and the Galactic Centre Emission

- Many of these points can be checked by G2 direct detection experiments



DGC, Peiró, Robles JCAP 08 (2014) 005

Once more: Complementarity of DM searches

If there is a positive detection of DM, can we identify the underlying model?

Problem:

- Experimental data allow us to reconstruct **"phenomenological parameters"**.

$$m_\chi,\ \sigma^{SI},\ \sigma^{SD},\ <\sigma v>_{ij}$$

- Theoretical models tend to produce similar results (e.g., most WIMPs are alike)

Solution:

- Data from different experiments has to be combined in order to remove degenerate solutions (and reduce the effect of uncertainties)

Strategies that allow the identification of DM from future data

Identification of Dark Matter with direct detection experiments

Given a DM direct detection, the DM mass and couplings can be determined from the observed number of events and energy spectrum.

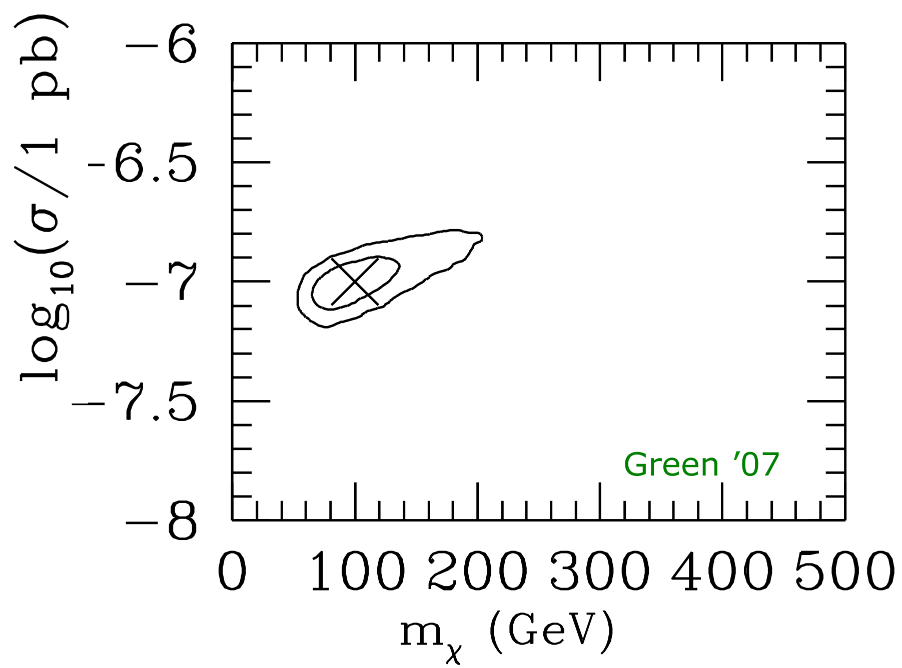
$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \boxed{\frac{d\sigma_{WN}}{dE_R}(v, E_R)}\, dv$$

$$\frac{d\sigma_{WN}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2} \left(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right)$$

Nuclear form factors

The energy spectrum depends on the WIMP mass and the mass of the target

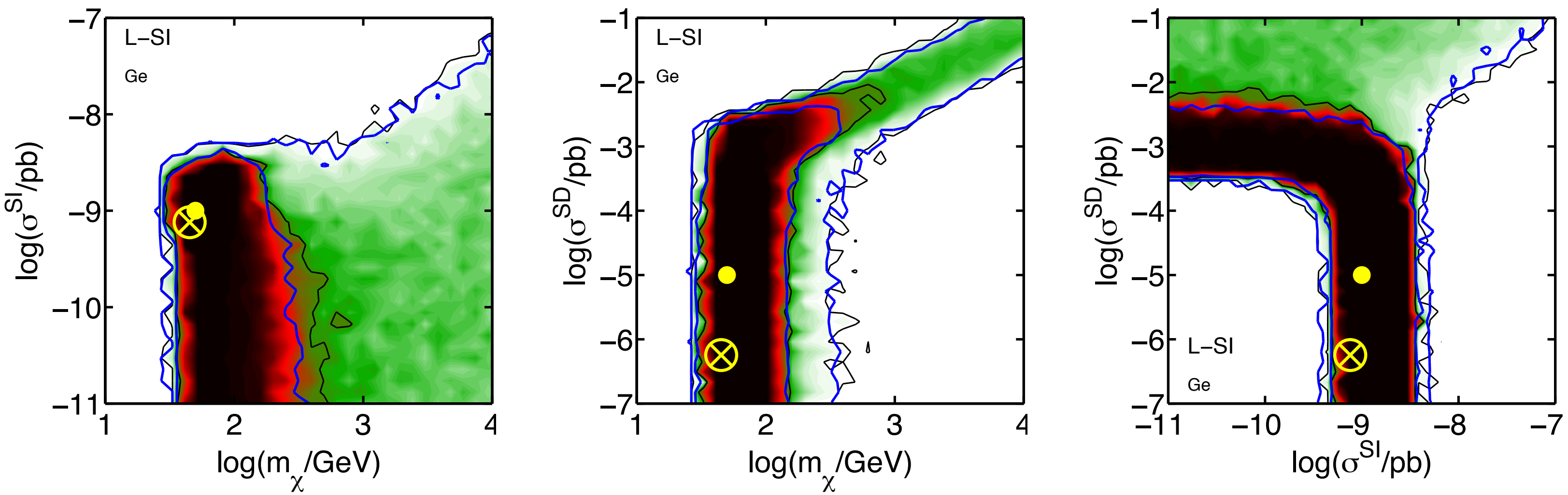
There are degenerate solutions



Example: m_χ=100 GeV
Exposure: 3000 kg day (Ge target)

We need multiple experiments (with various targets)

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



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

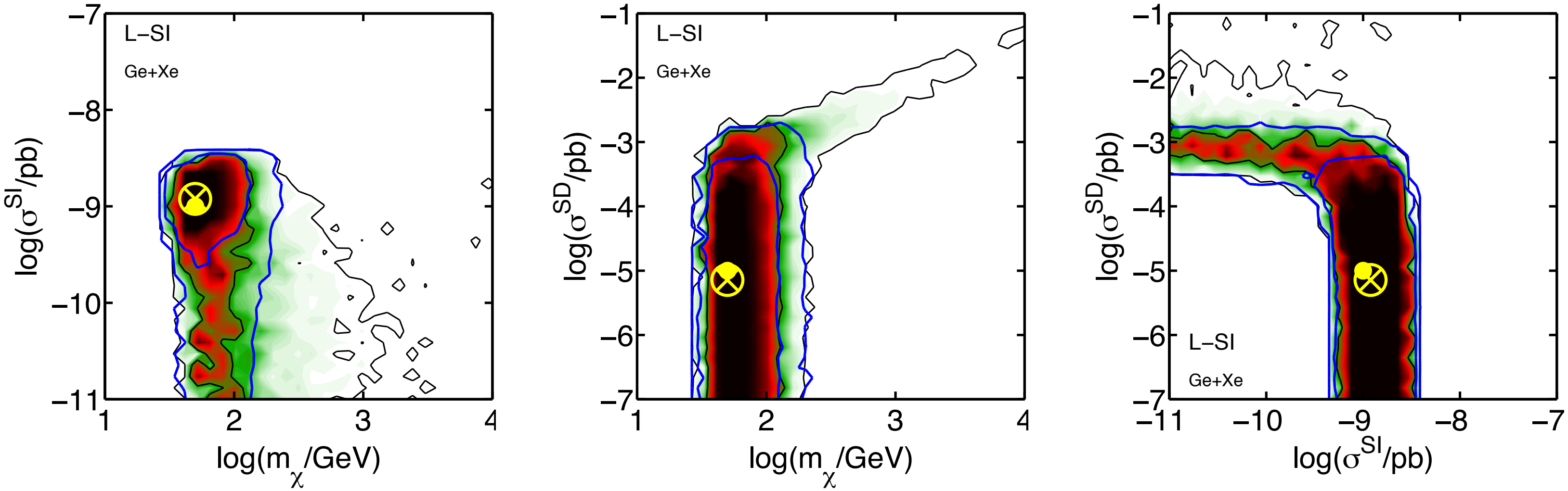
We use simulated data to assess the reconstruction of DM parameters

Astrophysical and nuclear uncertainties included

Prospects for SuperCDMS (Ge)

We need multiple experiments (with various targets)

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



A combination of **Germanium and Xenon** greatly helps in reconstructing the DM parameters

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

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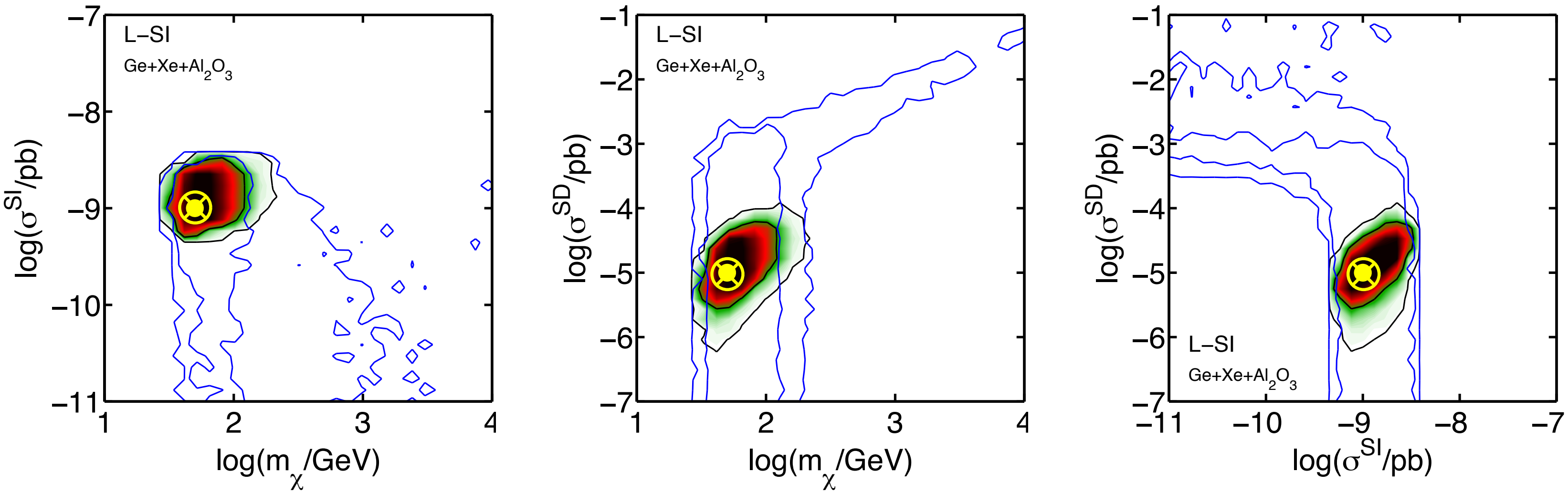


A combination of **Germanium and Xenon** greatly helps in reconstructing the DM parameters

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

This is an excellent tool to help design future experiments.

Are we being too conservative in describing DM-nucleus interactions?

The most general effective Lagrangian contains up to 14 (x2) different operators that induce six 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.

Angular momentum of unpaired nucleon

Angular momentum and spin

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

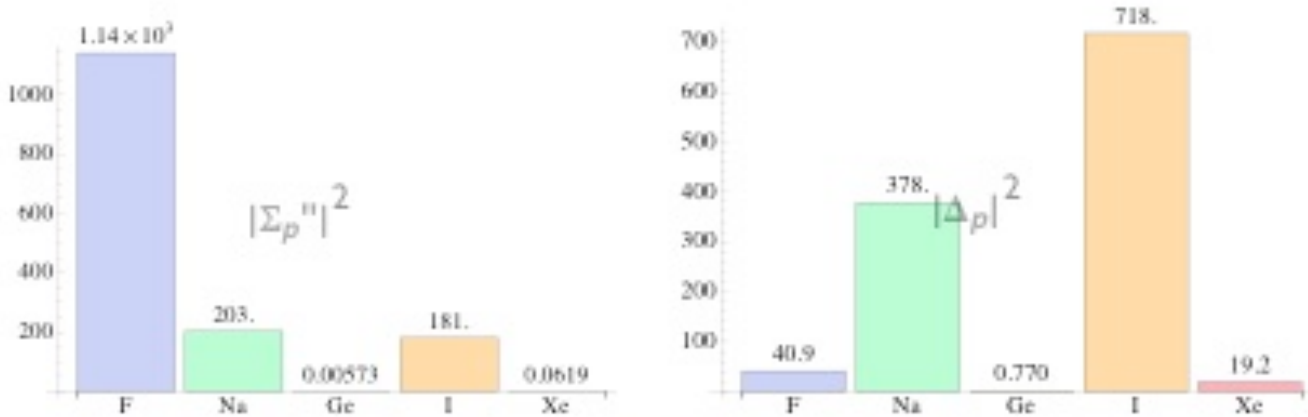
E.g., For a spin ½ particle

Scalar Mediator		
$\bar{\chi}\chi\bar{q}q$	$\longrightarrow$	$\left(\frac{h_1^N\lambda_1}{m_\phi^2}\right)\mathcal{O}_1$
$\bar{\chi}\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{h_2^N\lambda_1}{m_\phi^2}\right)\mathcal{O}_{10}$
$\bar{\chi}\gamma^5\chi\bar{q}q$	$\longrightarrow$	$\left(-\frac{h_1^N\lambda_2 m_N}{m_\phi^2 m_\chi}\right)\mathcal{O}_{11}$
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{h_2^N\lambda_2 m_N}{m_\phi^2 m_\chi}\right)\mathcal{O}_6$
Vector Mediator		
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\left(-\frac{h_3^N\lambda_3}{m_G^2}\right)\mathcal{O}_1$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\left(-\frac{2h_4^N\lambda_3}{m_G^2}\right)\left(-\mathcal{O}_7+\frac{m_N}{m_\chi}\mathcal{O}_9\right)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\left(-\frac{2h_3^N\lambda_4}{m_G^2}\right)(\mathcal{O}_8+\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\left(\frac{4h_4^N\lambda_4}{m_G^2}\right)\mathcal{O}_4$

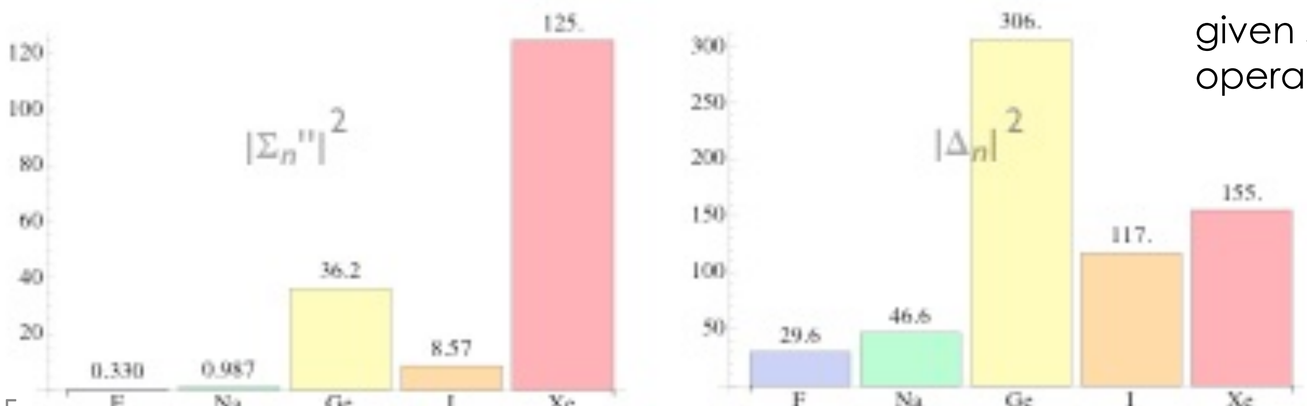
Dent, Krauss, Newstead, Sabbharwal 2015

These are extremely sensitive to the choice of target material, being crucial in the design phase of new experiments.

Vector, proton coupled: $\vec{\sigma}(i)$ vs. $\vec{\ell}(i)$



Vector, neutron coupled: $\vec{\sigma}(i)$ vs. $\vec{\ell}(i)$

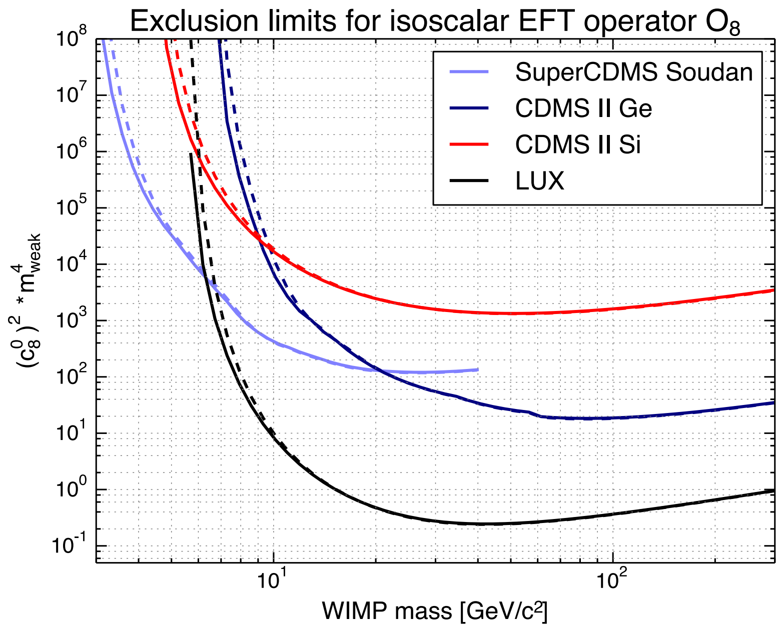


Some targets have enhanced sensitivities for a given set of operators

Limits on EFT operators (SuperCDMS)

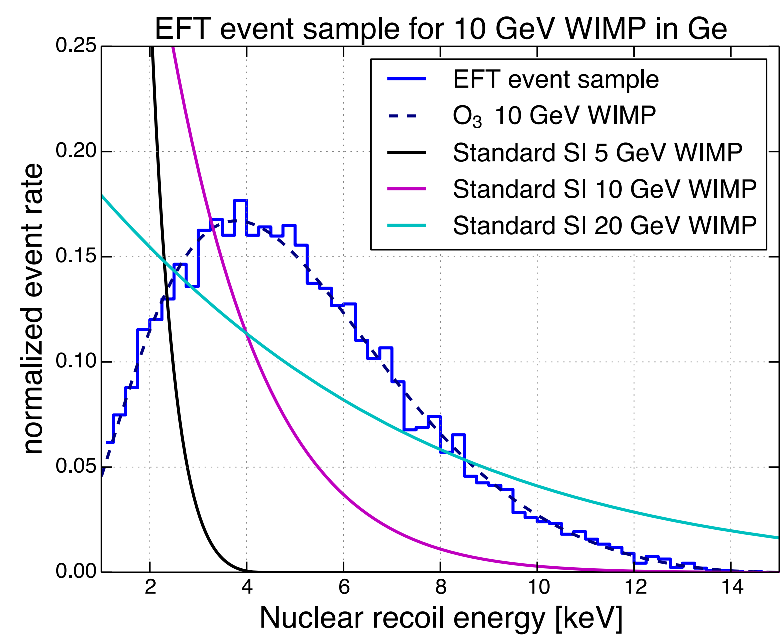
K. Schneck et al. PRD 2015

- Assume contribution from only one operator at a time
- Bounds very sensitive to the actual target
- Potential cancellations between some operators



- The spectrum differs from the expected for standard interactions

- A DM signal could be misidentified as background
- The reconstruction of a signal would point towards the wrong mass and couplings



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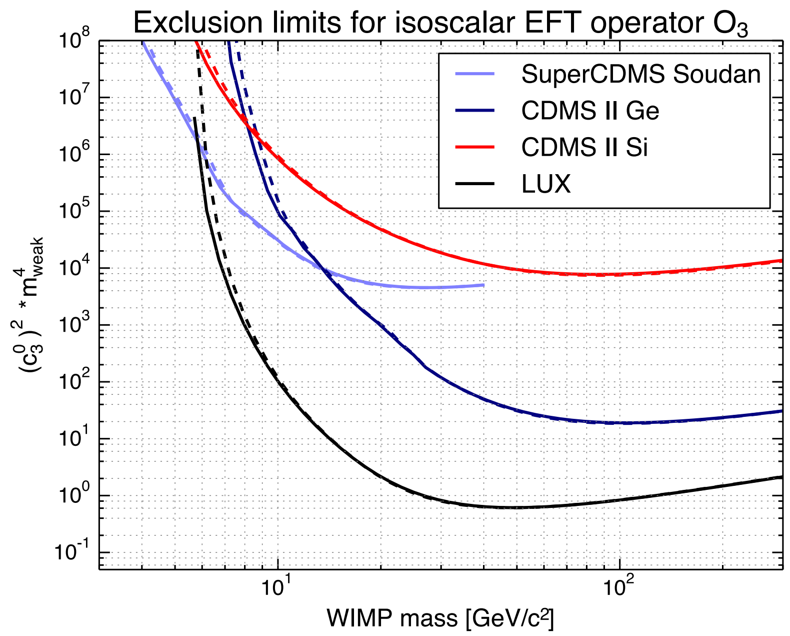

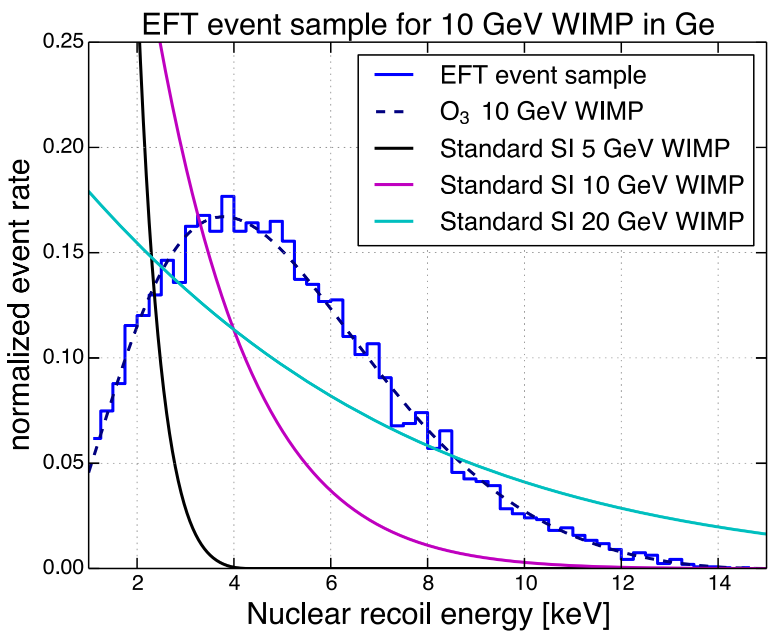

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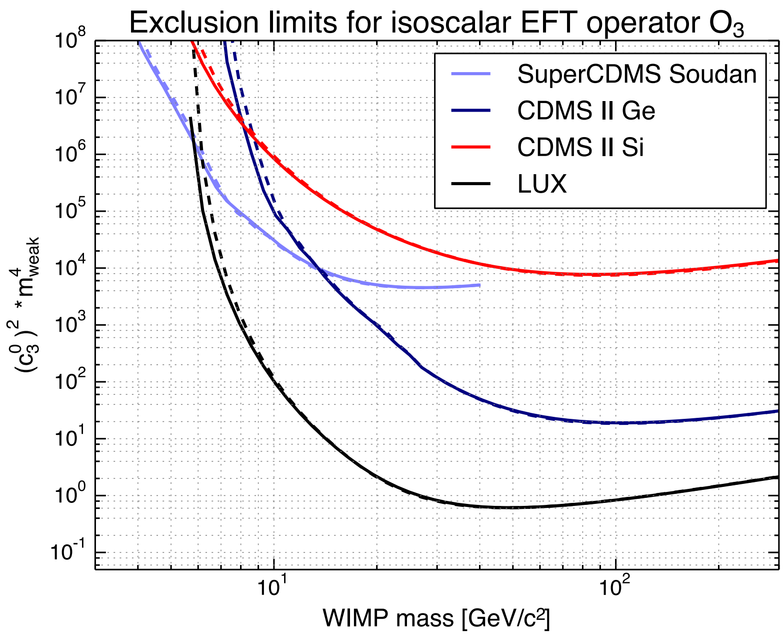

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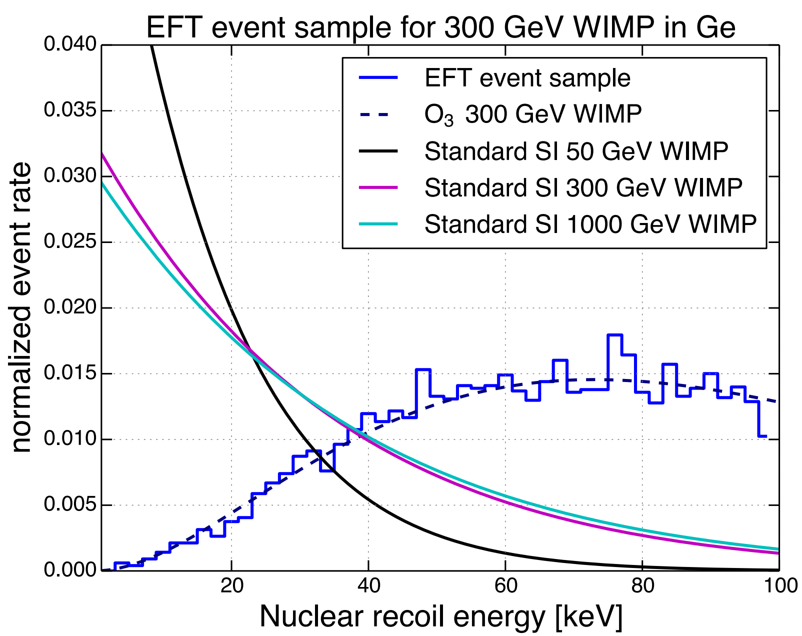


Conclusions

Exciting times ahead with future DM experiments (Generation 2)

- Good coverage for most WIMP models
- … if DM is not a WIMP? (sensitivity to axion-like particles and other exotics)

Excellent complementarity to LHC and indirect searches (testing potential signals)

- E.g., Direct detection and the Galactic Centre Excess

Future new data might provide information about the DM properties

- The use of multiple targets, or combination of different data is crucial
- Need to consider more general DM interactions and/or simplified models

Right-handed sneutrino in the NMSSM

DGC, Muñoz, Seto 2007 , DGC, Seto 2009

- Addition of TWO new superfields, ***S***, ***N***, singlets under the SM gauge group

$$\mathrm{NMSSM} \quad = \quad \mathrm{MSSM} + \hat{S} \begin{cases} 2 \text{ extra Higgs } (\mathrm{CP-even},\ \mathrm{CP-odd}) \\ 1 \text{ additional Neutralino} \end{cases}$$

$$+ N \begin{cases} 1 \text{ additional (right-handed) Neutrino} \\ \text{and sneutrino} \end{cases}$$

- New terms in the superpotential

$$W = Y_u\, H_2\, Q\, u + Y_d\, H_1\, Q\, d + Y_e\, H_1\, L\, e - \lambda\, S\, H_1 H_2 + \frac{1}{3}\kappa S^3$$

$$W \quad = \quad W_{\mathrm{NMSSM}} + \lambda_N S N N + y_N L\, H_2 N$$

- After Radiative Electroweak Symmetry-Breaking

$$\langle H_1^0 \rangle = v_1 \quad ; \quad \langle H_2^0 \rangle = v_2 \quad ; \quad \langle S \rangle = s \qquad \begin{cases} \mu\, H_1\, H_2 \\ m_N\, N\, N \end{cases}$$

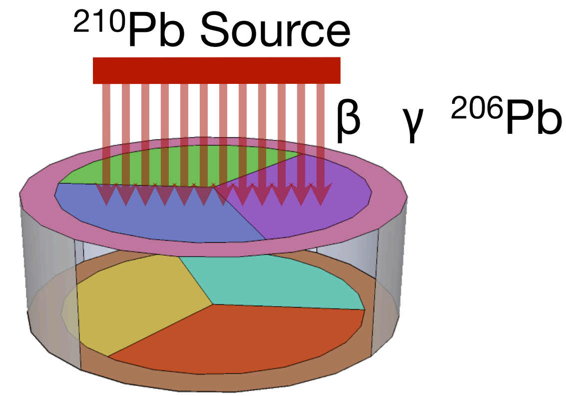
EW-scale Higgsino-mass parameter
&
Majorana neutrino mass

iZIP calibration

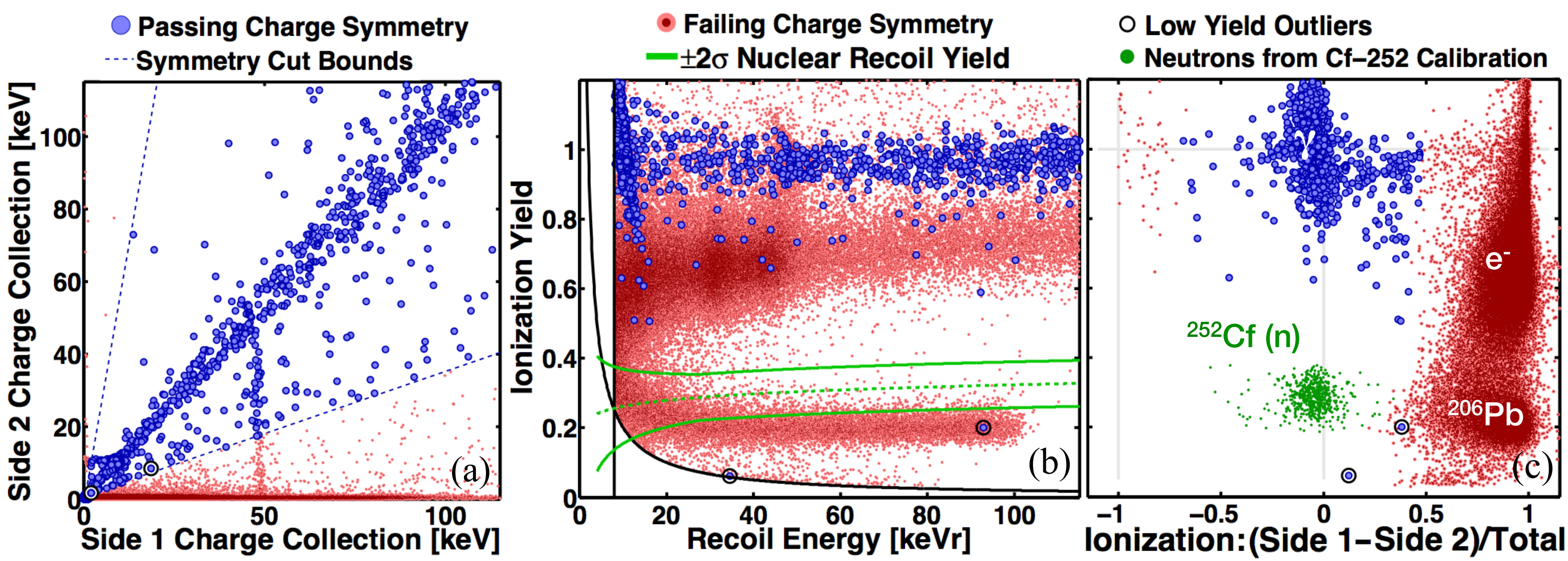
~900 live hours in T3Z1 with a ^{210}Pb source on side 1

71,525 electrons
16,258 ^{206}Pb recoils

No events leaking into the signal region (8-115 keV)



For 300 kg yr (200 kg Ge SNOLAB) the estimated leakage is < 0.6 events 90% cl



(Ionization threshold 2 keVee)