Lecture 3: Direct Dark Matter Detection

DAVID G. CERDEÑO

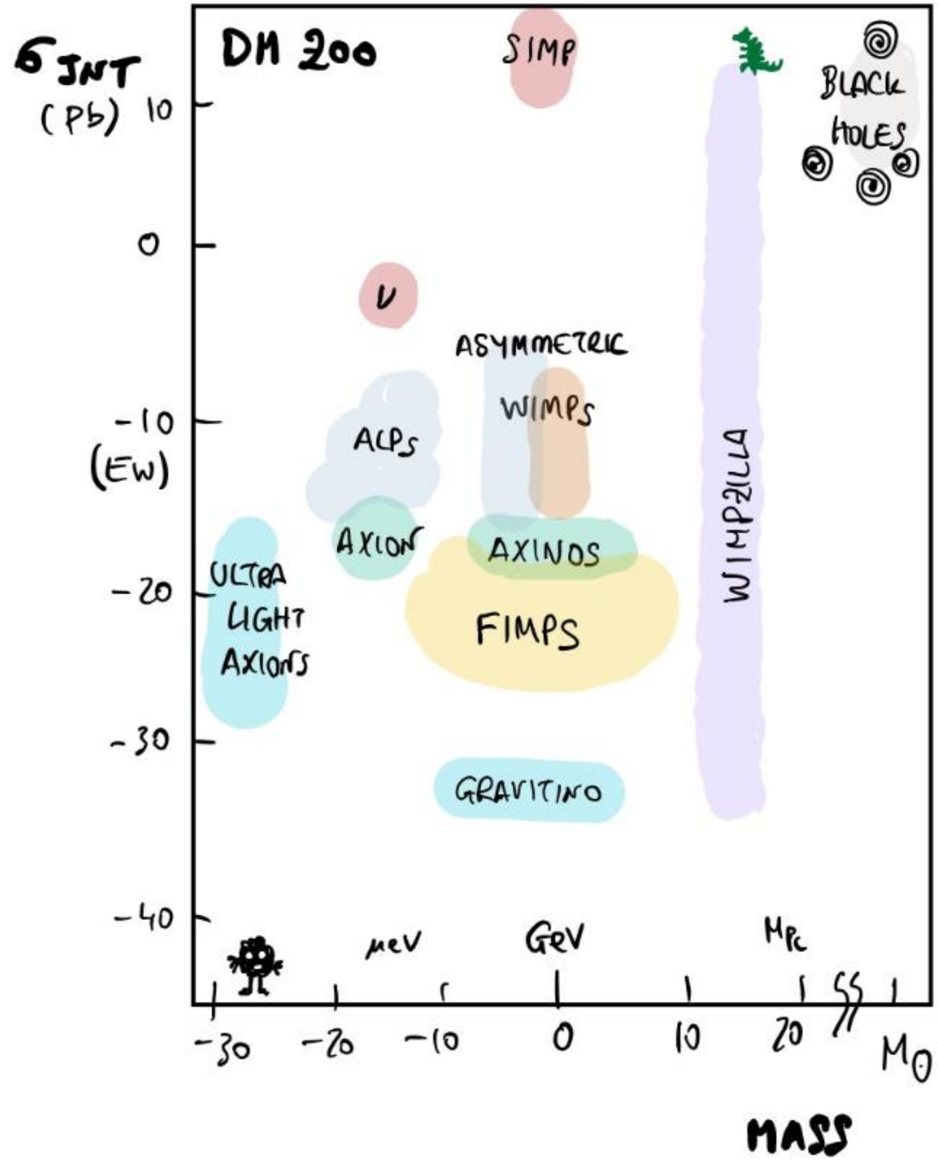
We don’t know yet what DM is... but we do know many of its properties

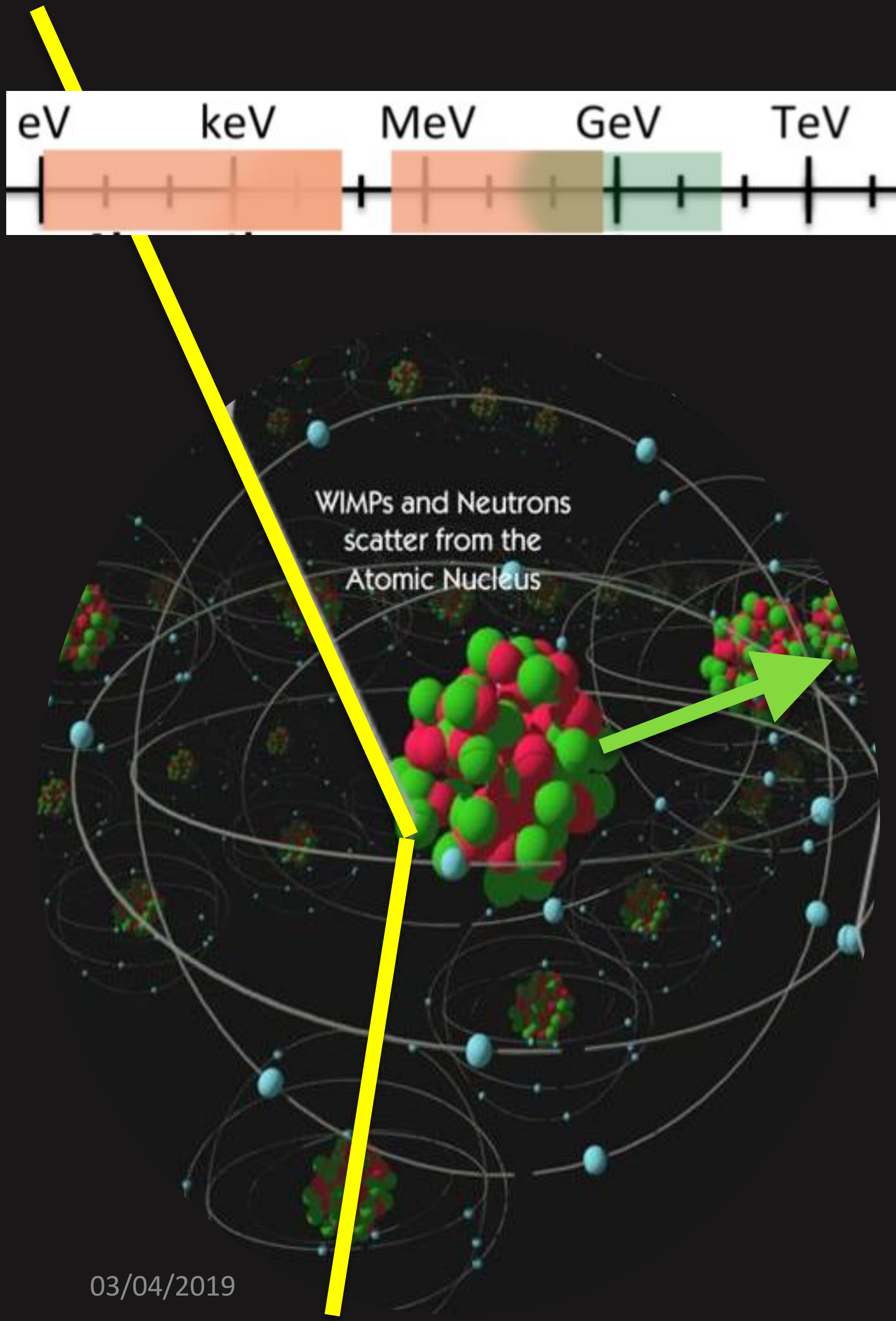
It is a NEW particle

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

Many candidates in Particle Physics

- Axions
- Weakly Interacting Massive Particles (W
- SuperWIMPs and Decaying DM
- WIMPzillas
- Asymmetric DM
- SIMPs, CHAMPs, SIDMs, ETCs...





DIRECT DARK MATTER SEARCHES:
What can we measure?

NUCLEAR SCATTERING

- "Canonical" signature
- Elastic or Inelastic scattering
- Sensitive to m >1 GeV

ELECTRON SCATTERING

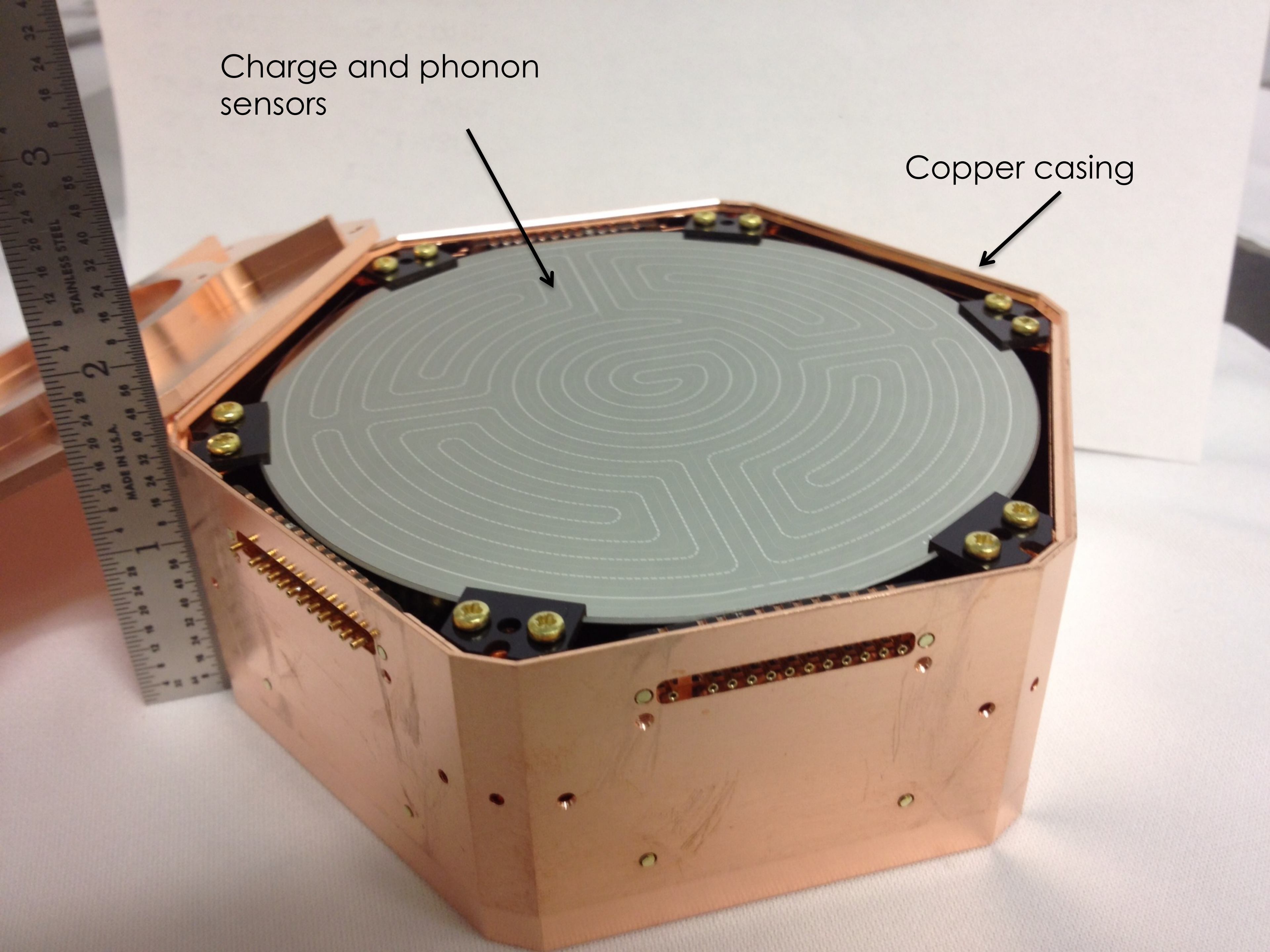
- Sensitive to light WIMPs

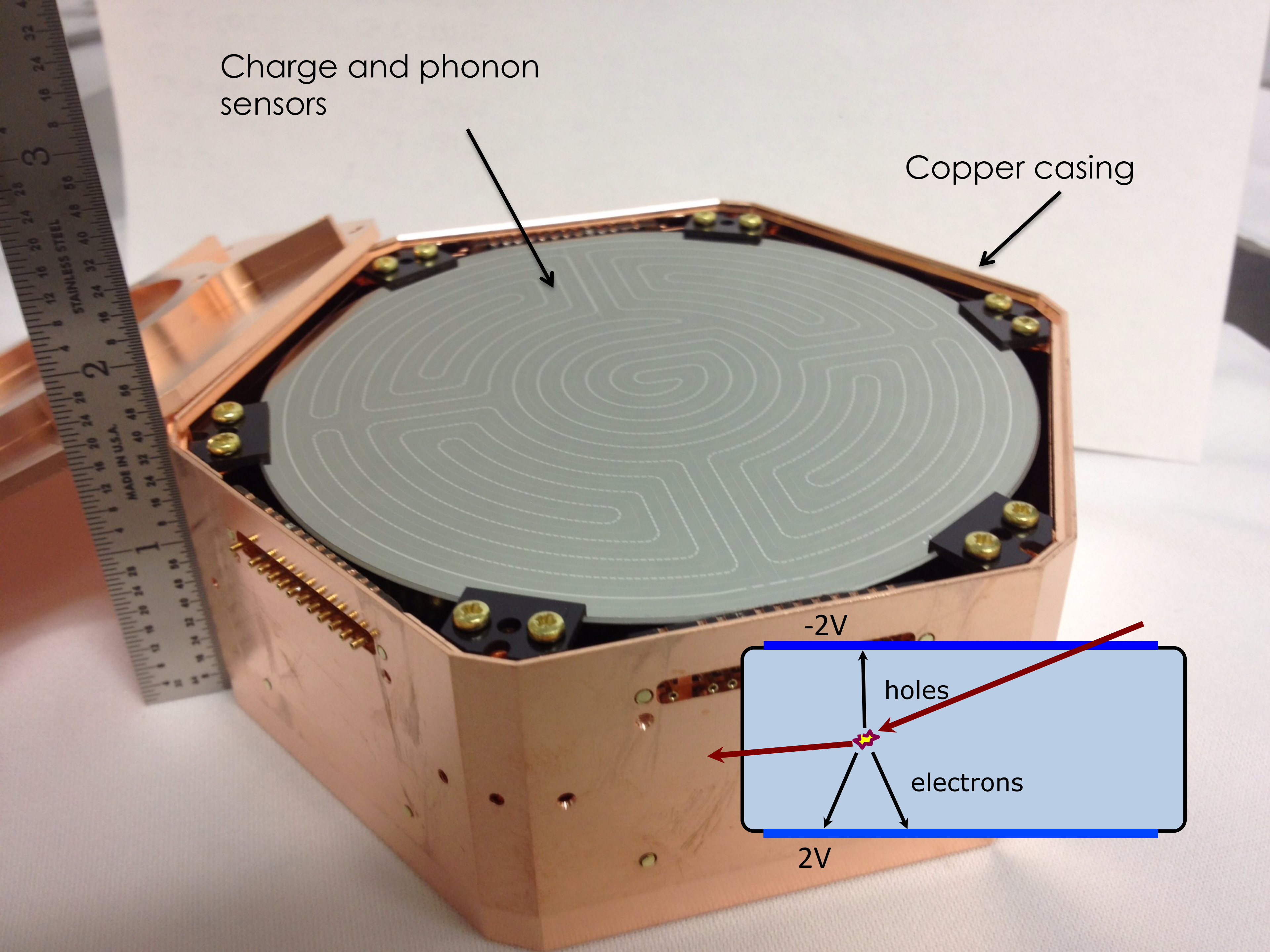
ELECTRON ABSORBPTION

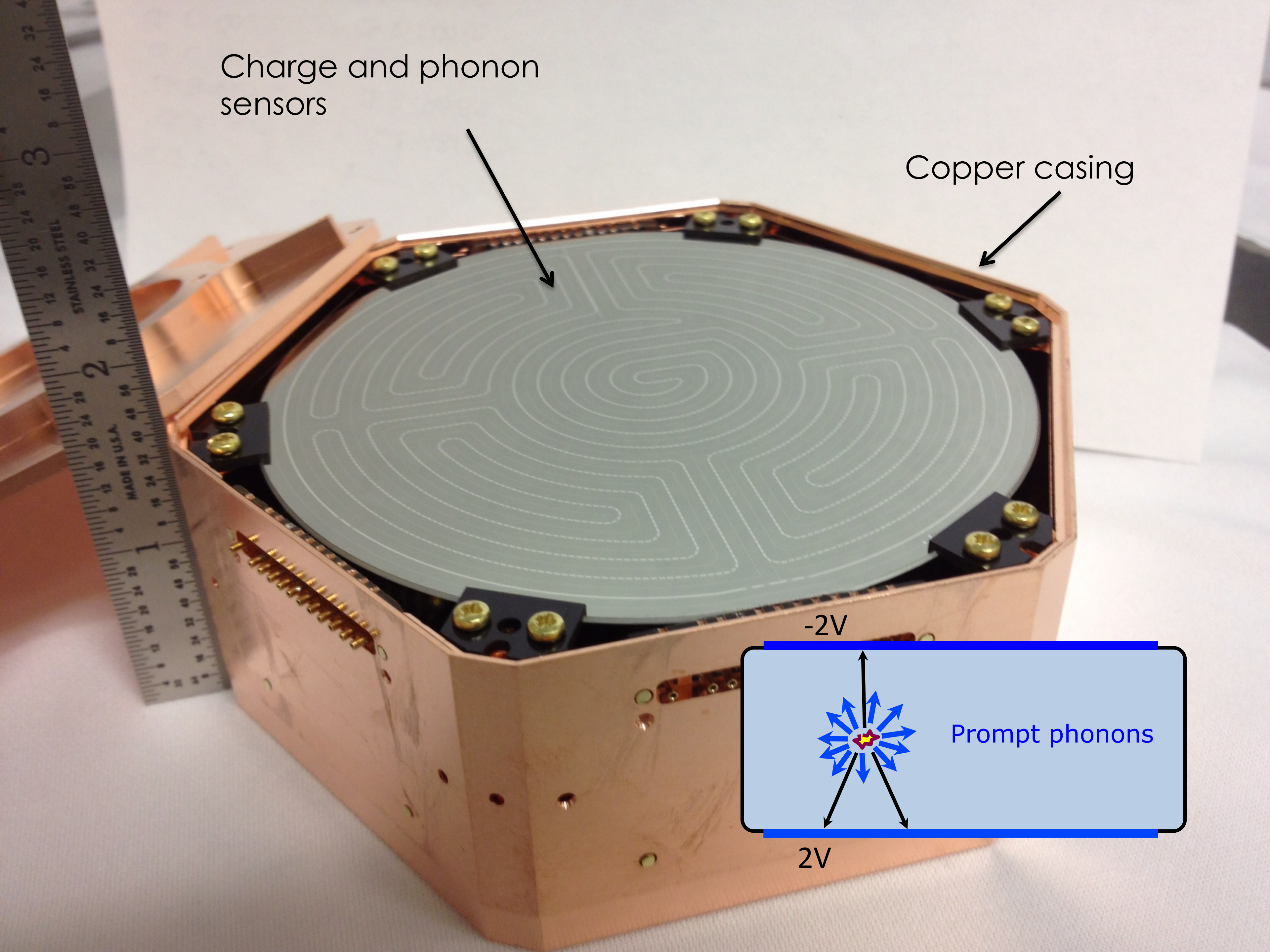
- Very light (non-WIMP)

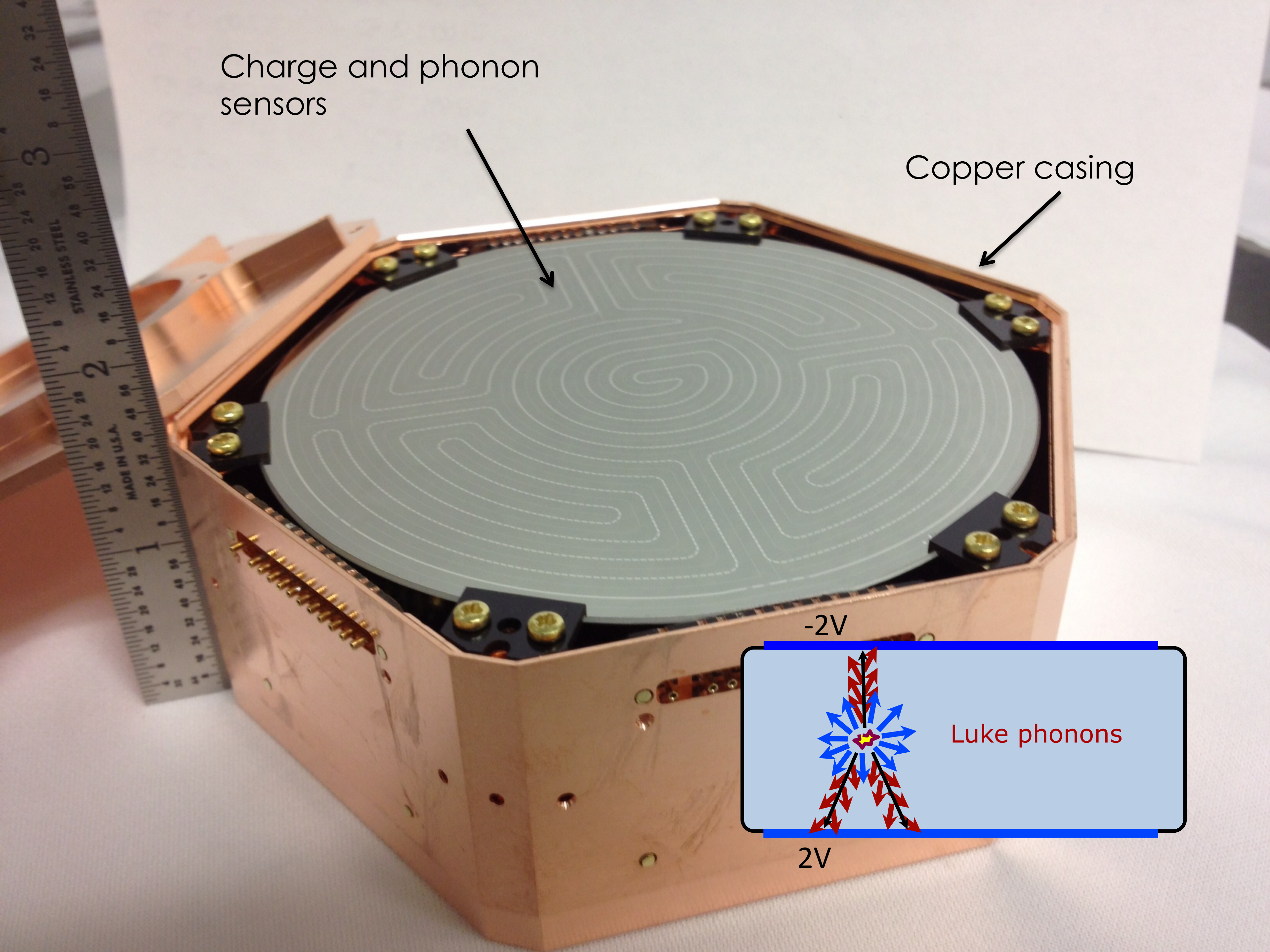
EXOTIC SEARCHES

- Axion-photon conversion in the atomic EM field
- Light Ionising Particles

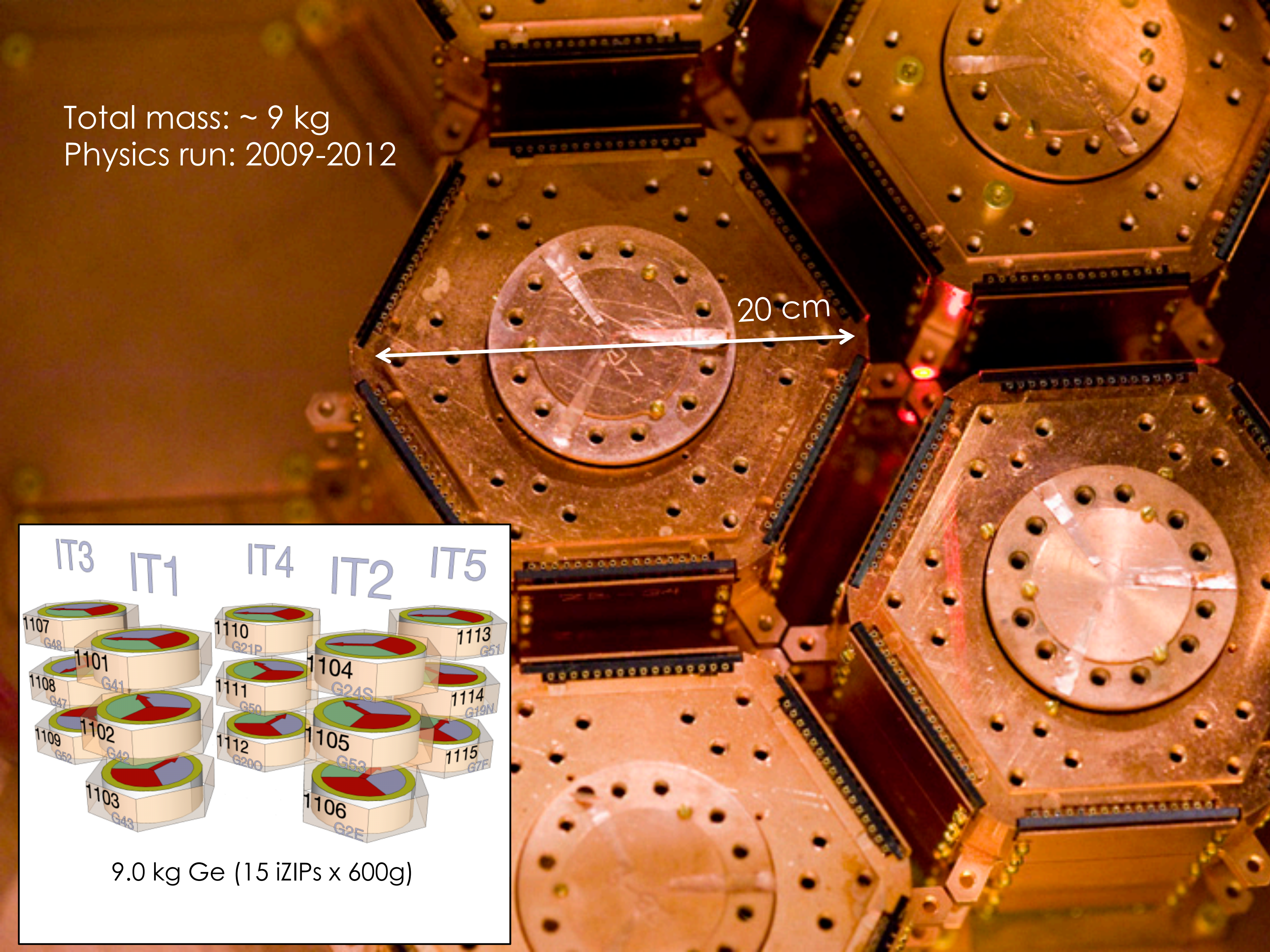

Charge and phonon sensors
Copper casing


Charge and phonon sensors
Copper casing
-2V
holes
electrons
2V


Charge and phonon sensors
Copper casing
-2V
Prompt phonons
2V



Charge and phonon sensors
Copper casing
-2V
Luke phonons
2V



9.0 kg Ge (15 iZIPs x 600g)

The SuperCDMS Experiment

High purity Germanium crystals

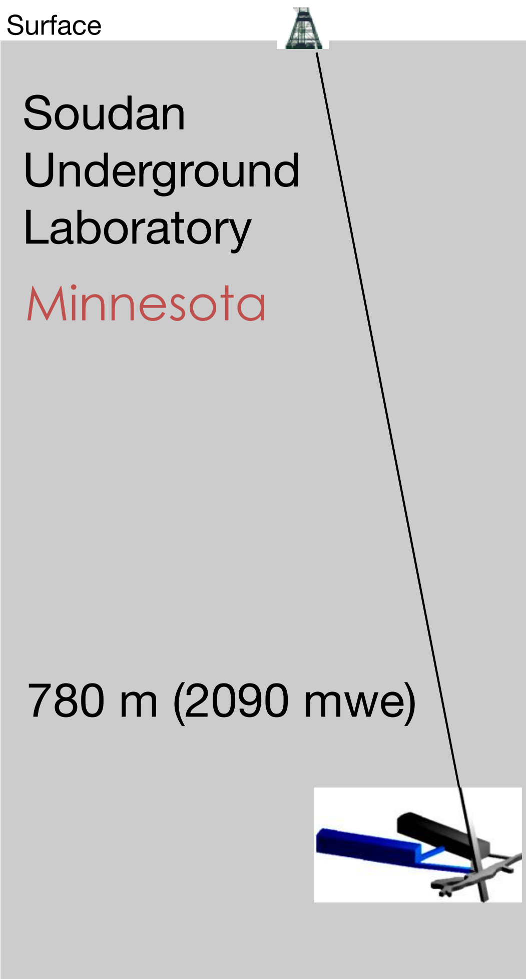
Arranged in towers

Protected by a very clean shielding

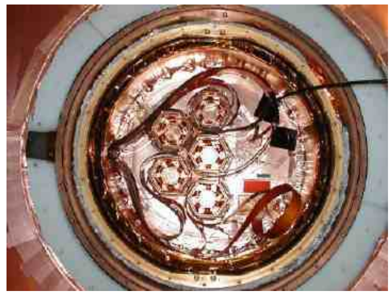
LEAD
POLYETHILENE

And an international team of ~100 scientists from 30 different instutions

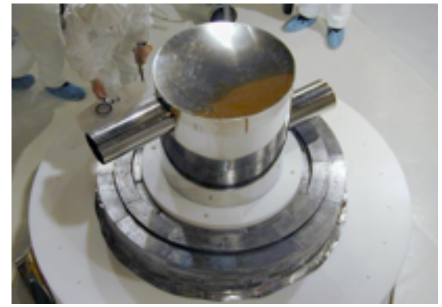
SuperCDMS at SOUDAN



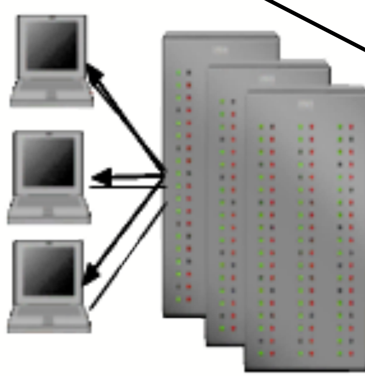
«The Icebox»
base temp. ~ 50 mK



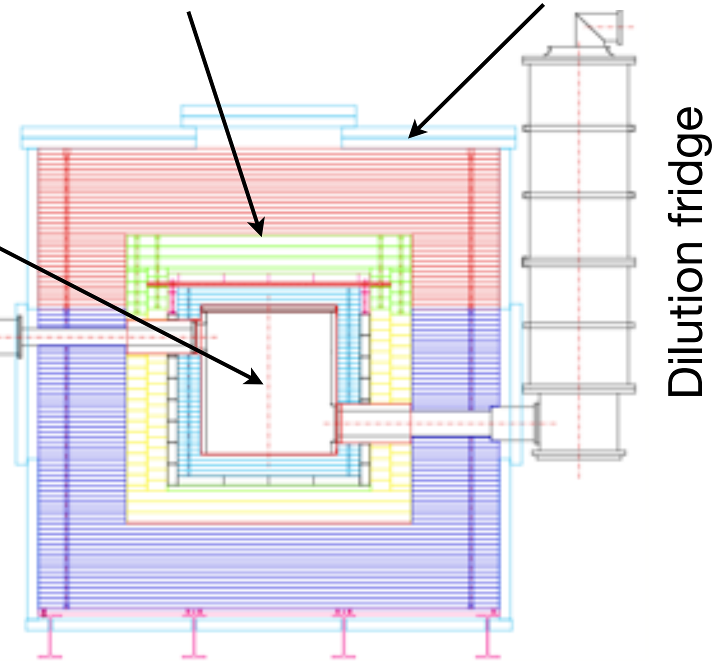
Poly and lead shielding



Muon veto



Data acquisition
and monitoring



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

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

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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)

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Theoretical input

Differential cross section

(of WIMPs with quarks)

Nuclear uncertainties

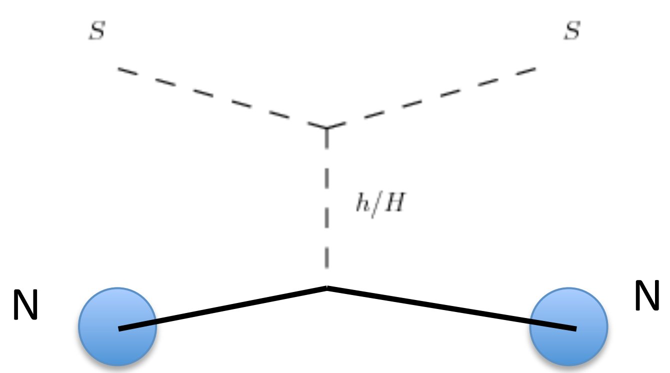
$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

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

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

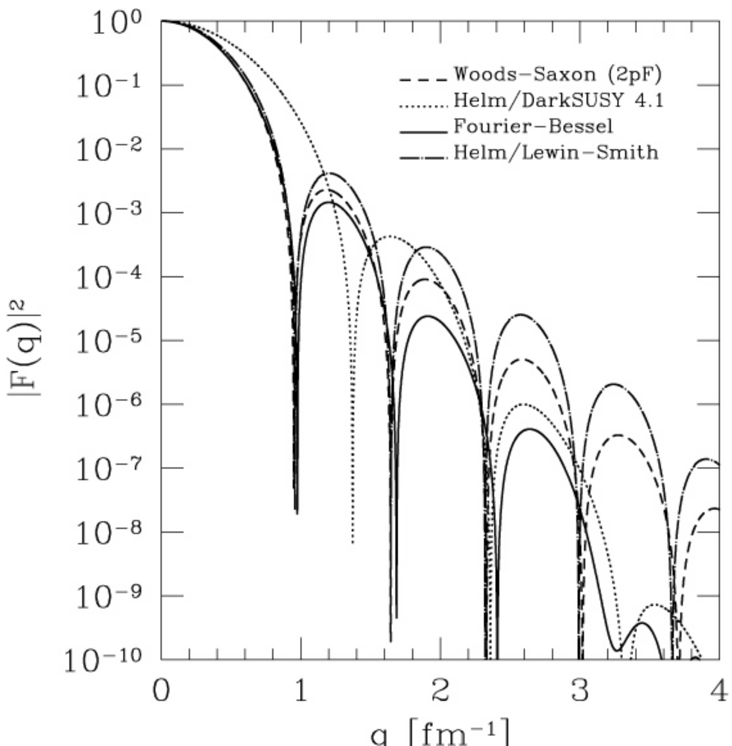
WIMP-nucleus (elastic) scattering cross section

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

Where the spin-independent and spin-dependent contributions read

$${\sigma_0}^{SI,N} = \frac{4\mu_N^2}{\pi}[Zf_p + (A-Z)f_n]^2,$$

$${\sigma_0}^{SD,N} = \frac{32\mu_N^2 G_F^2}{\pi}[a_p S_p + a_n S_n]^2 \left(\frac{J+1}{J}\right)$$



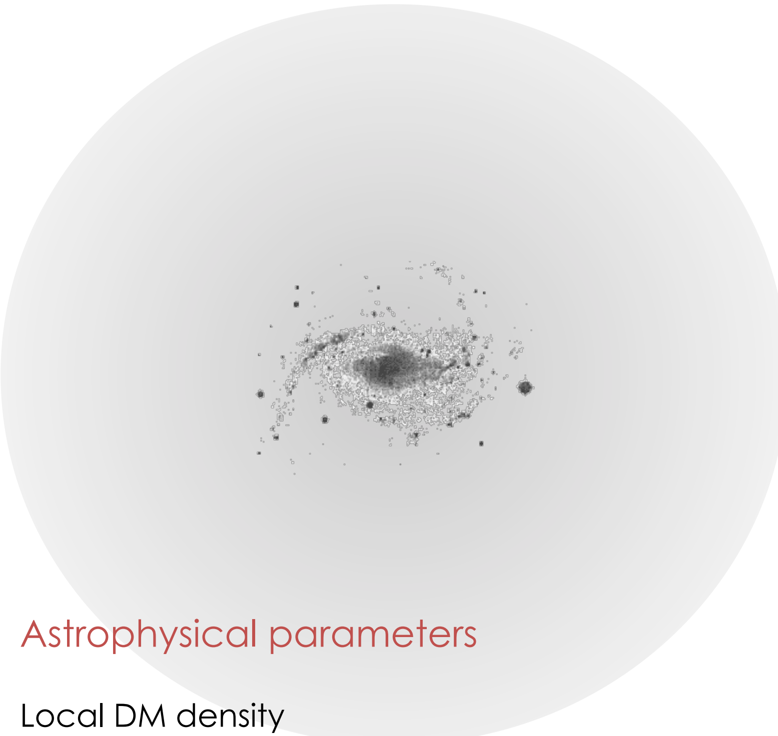
The Form factor encodes the loss of coherence for large momentum exchange

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

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

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

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

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

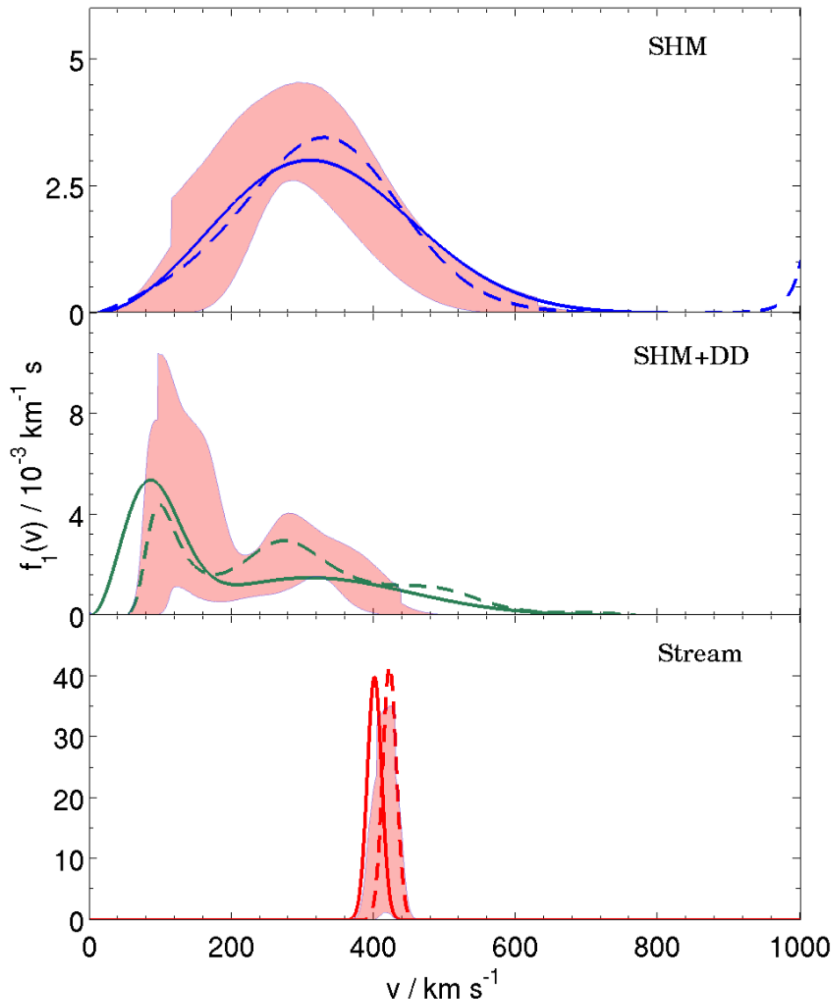
Astrophysical parameters

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

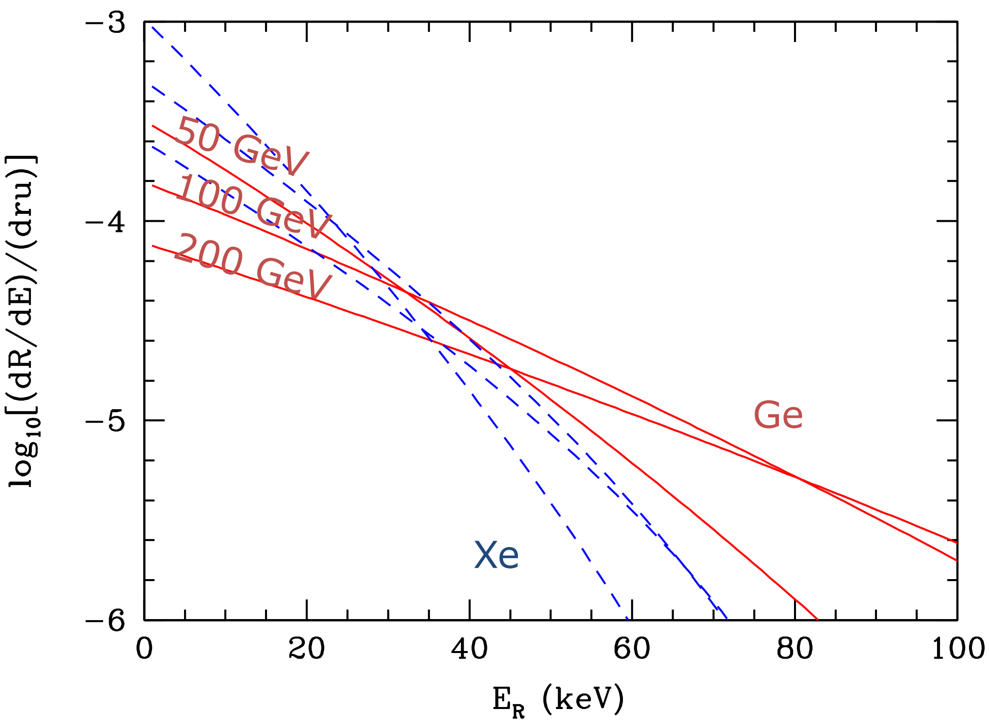
$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

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



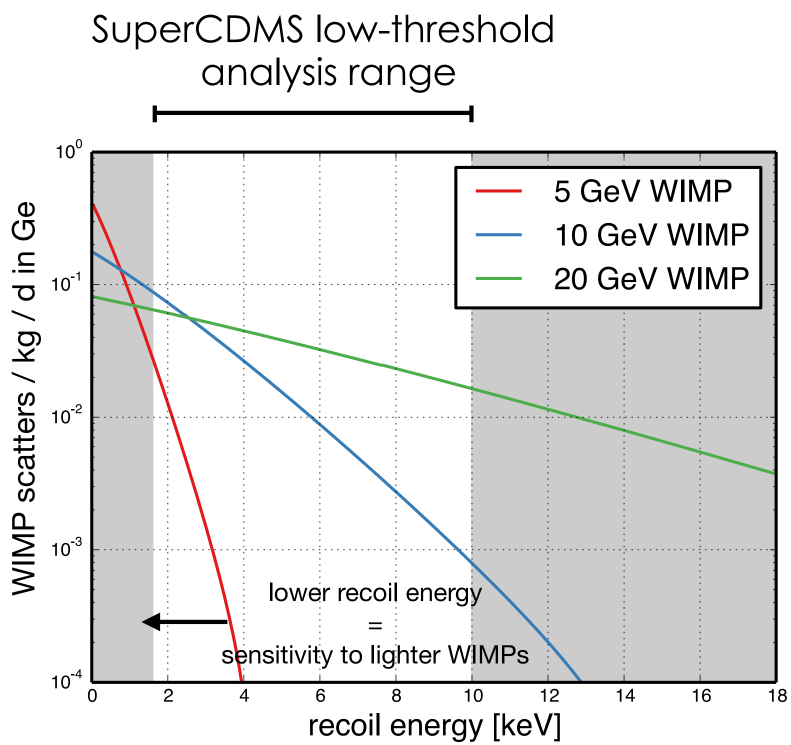
The challenge of low-mass WIMPs

- The signal is expected at very low recoil energies

  Favours light targets

  Low-threshold searches

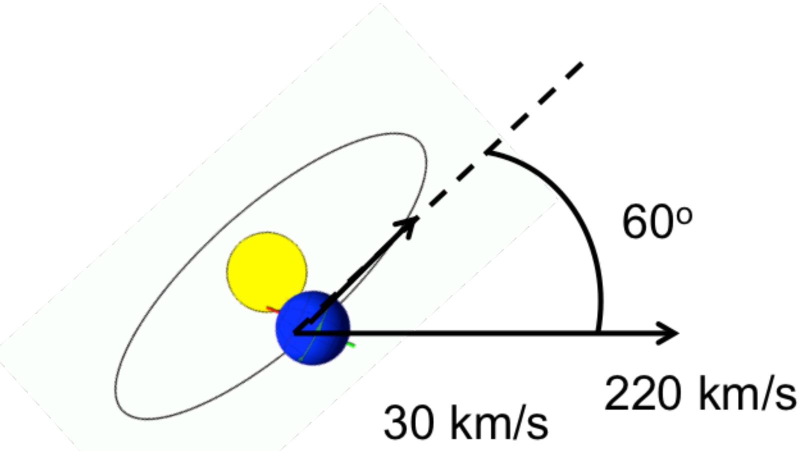
- Usual DM targets are relatively heavy so the threshold has to be significantly reduced.



- 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

Discriminating a DM signal: ANNUAL MODULATION

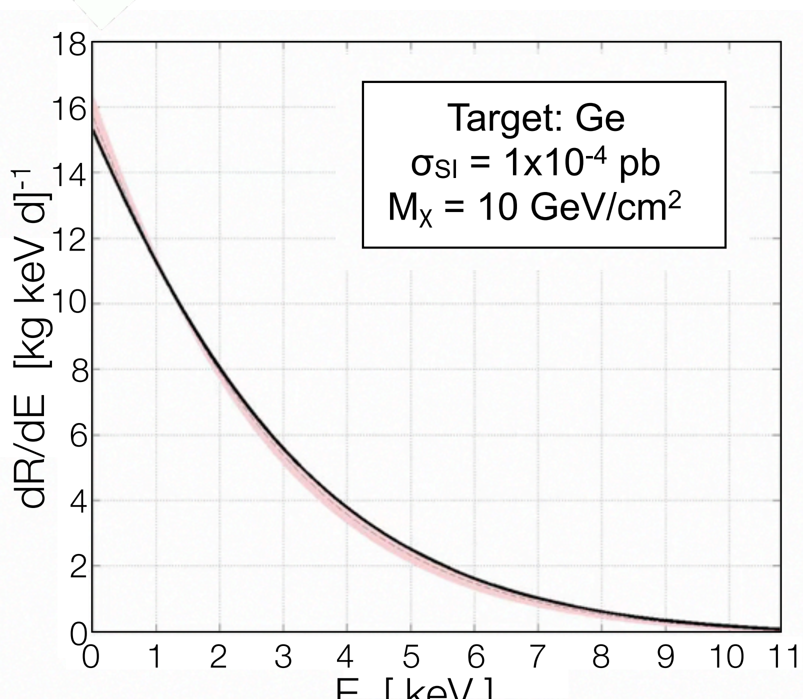


Drukier et al. 86

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

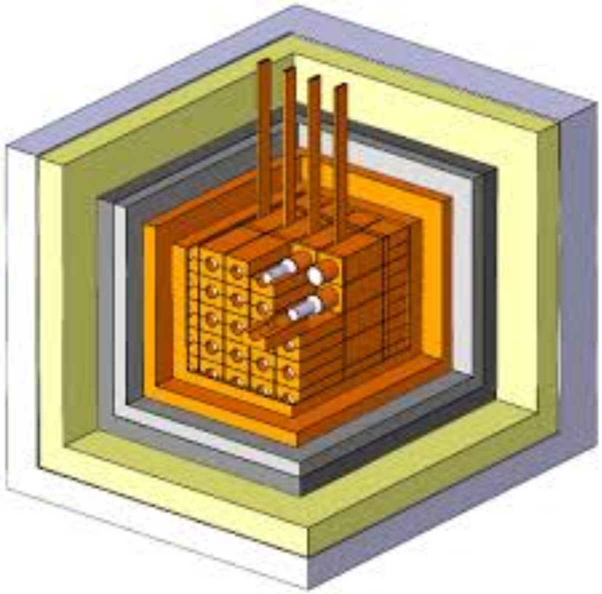
This implies a modulation in the rate.

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



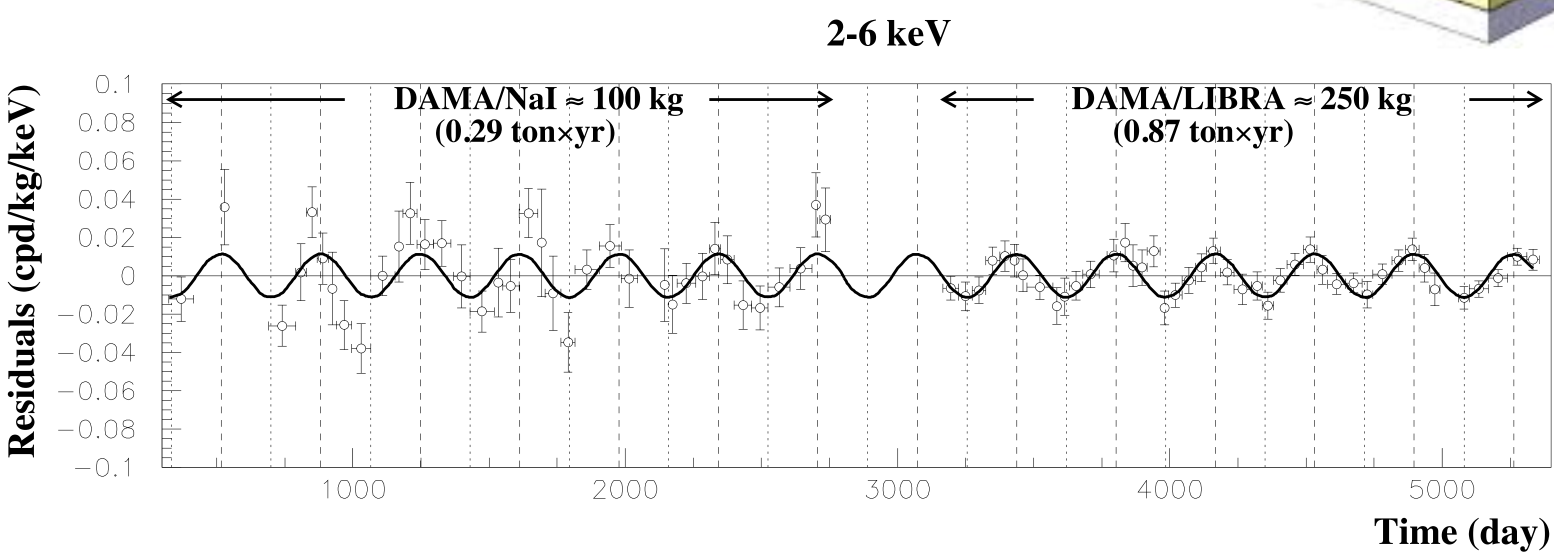
The modulation amplitude is small (~7%) and very sensitive to the details of the halo parameters

DAMA (DAMA/LIBRA) signal on annual modulation



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

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

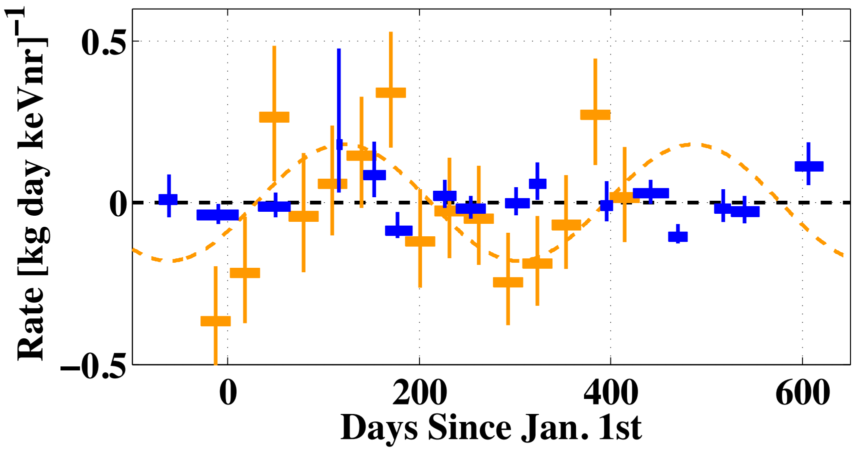


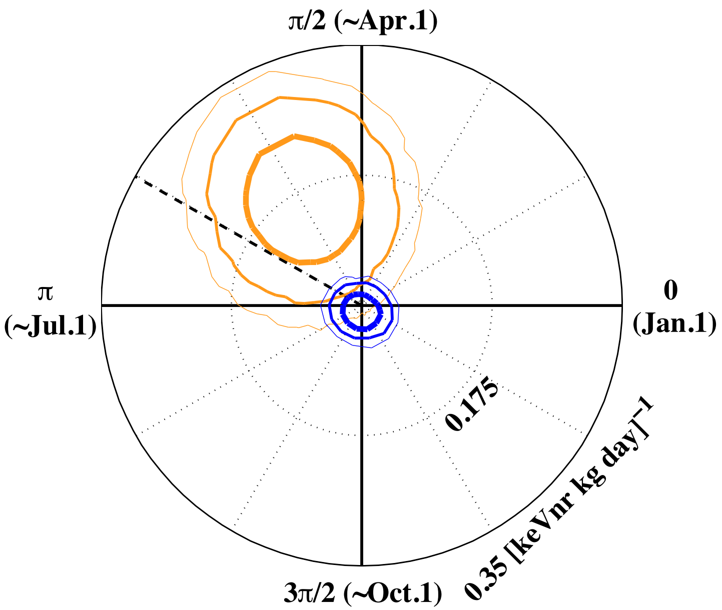
... however other experiments (CDMS, Xenon, CoGeNT, ZEPLIN, Edelweiss, ...) did not confirm (its interpretation in terms of WIMPs).

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



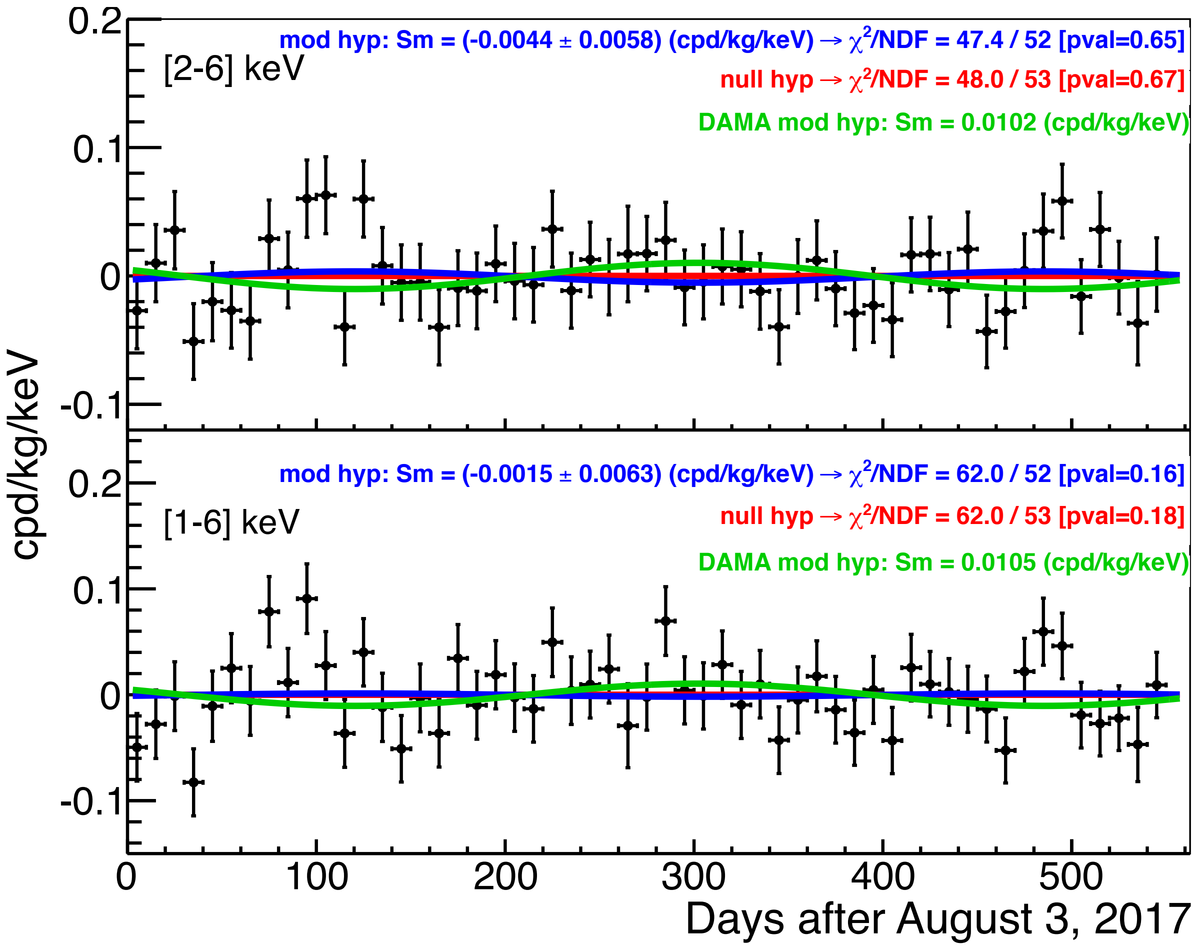


CDMS II 2012

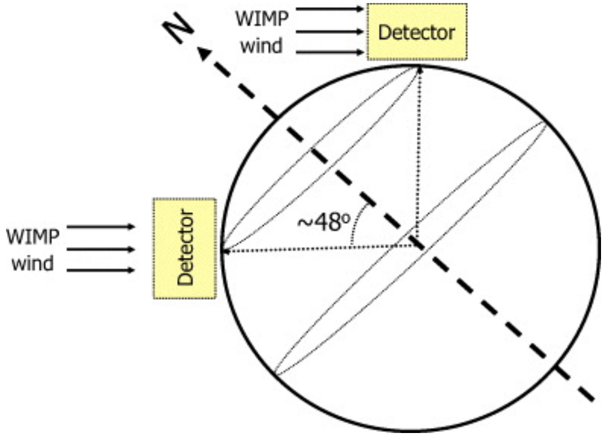
• CoGeNT: smaller amplitude of the DM modulation signal in second year of data

Collar in IDM 2012

No modulation in ANAIS



Discriminating a DM signal: DIRECTIONALITY



Spergel '88

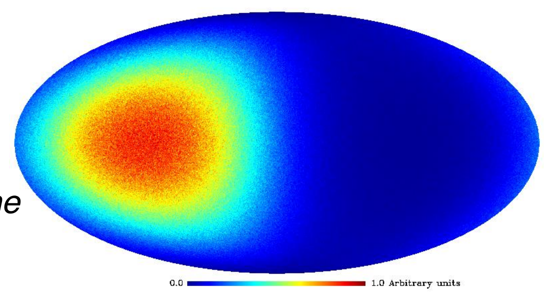
Experimental challenges

Low-pressure TPC to measure direction

Large exposure needed (from current limits)

WIMP signal (recoil map)

Angular distribution of Fluorine recoils [5;50] keV

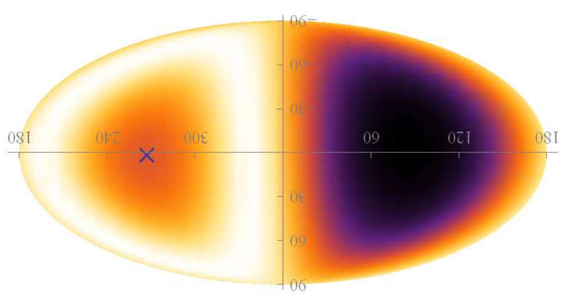


Characteristic dipole signal

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

J. Billard et al., 2010

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



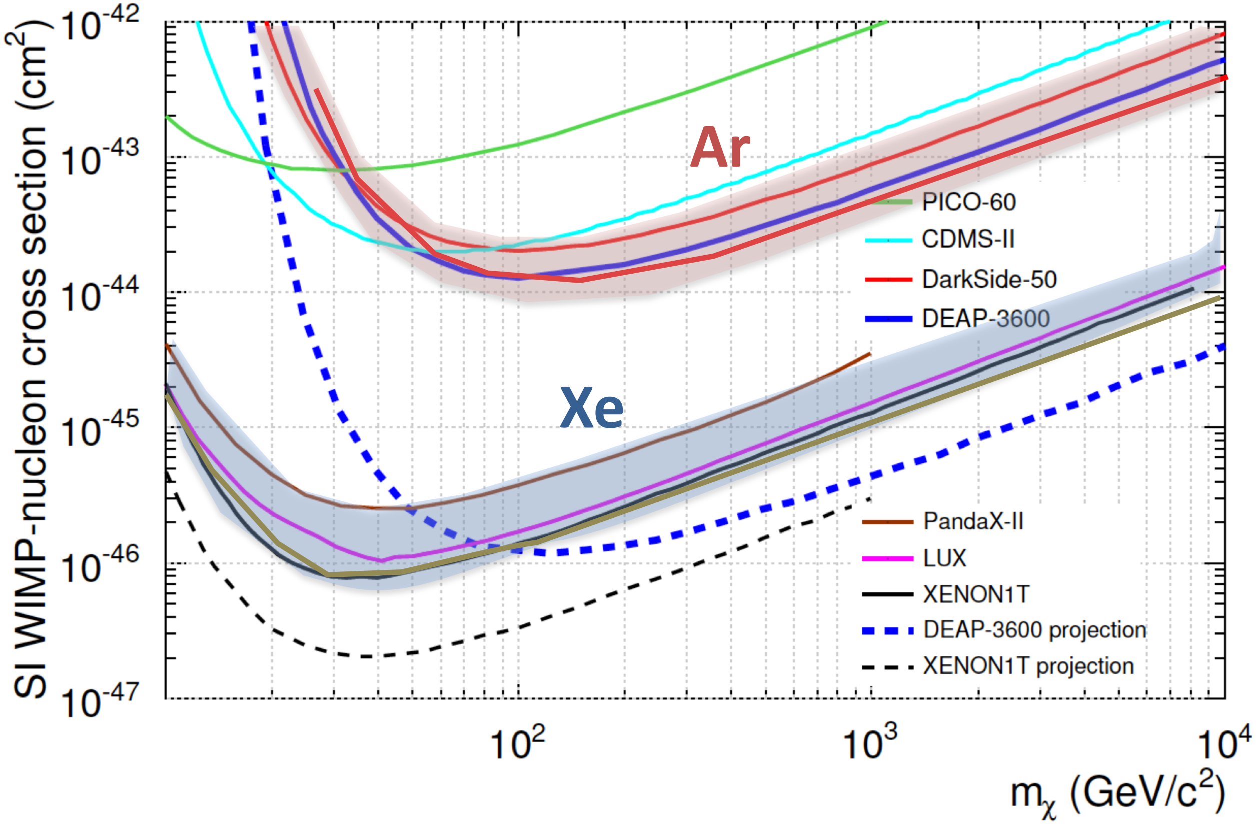
Ring-like structure

- 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

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

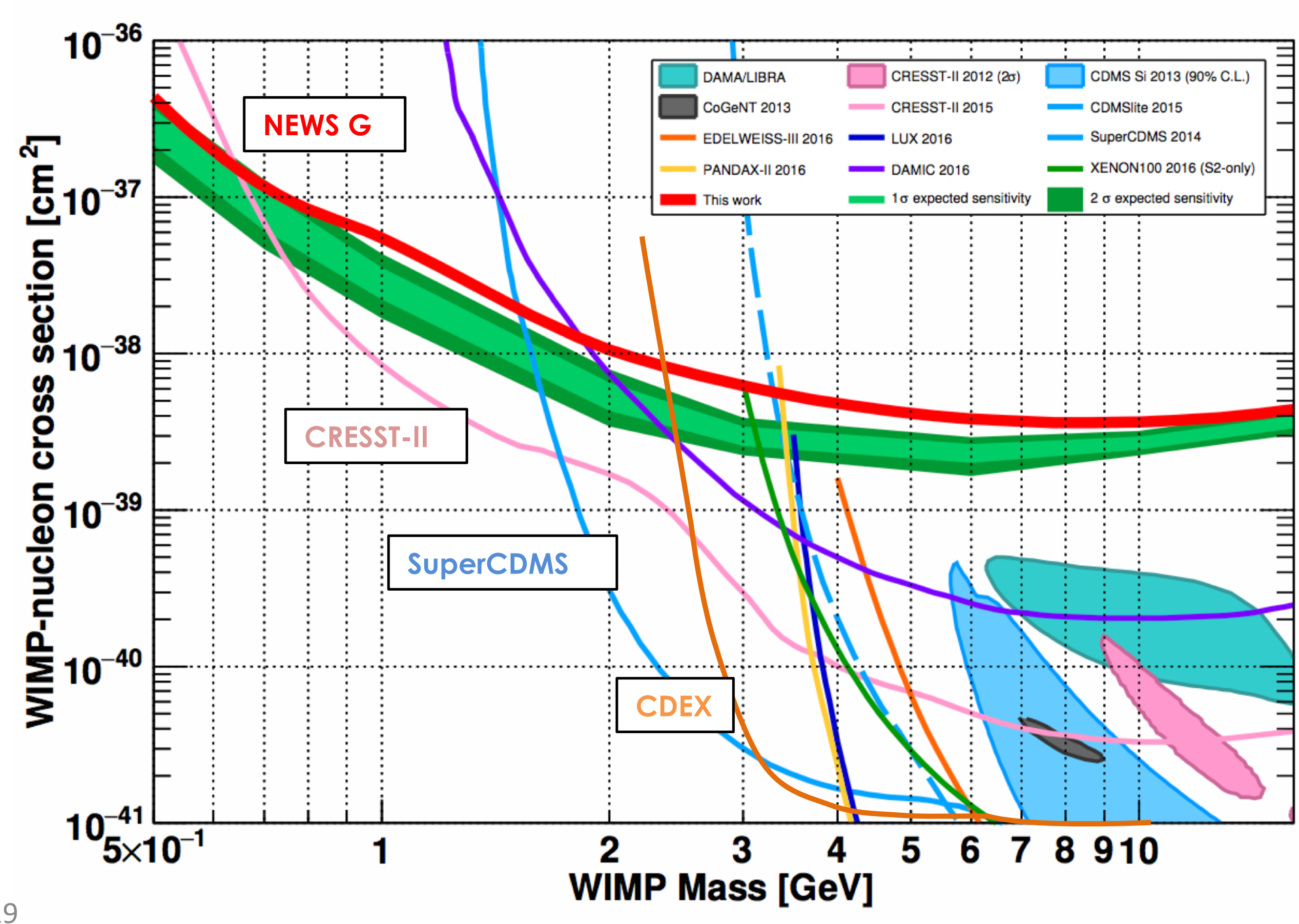
PANDAX 1708.06917
54000 kg day

LUX 1608.07648
33500 kg day

XENON1T 1705.06655
34200 kg day

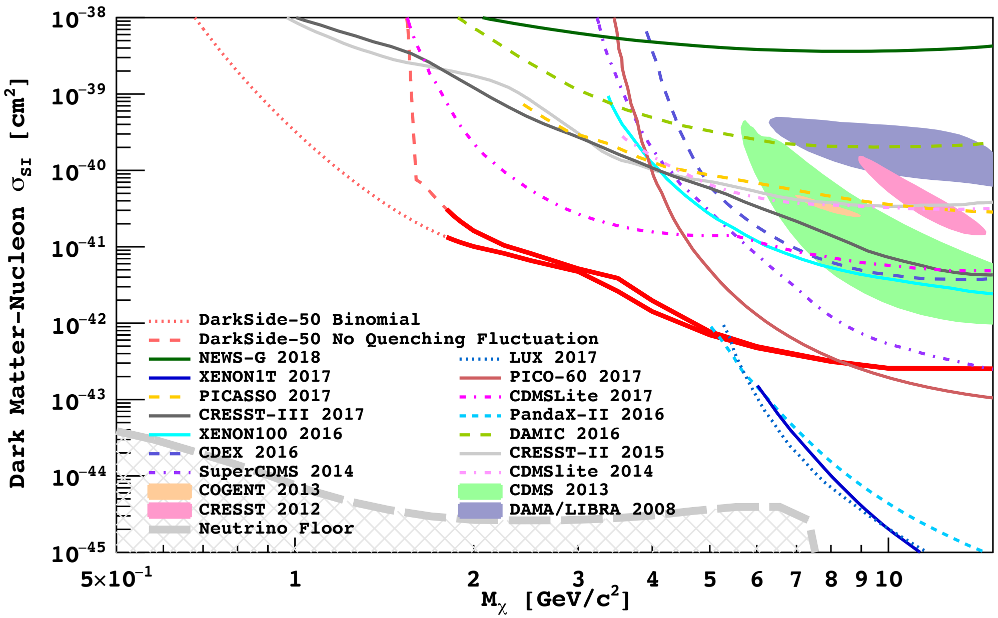
Constraints on low-mass WIMPs

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



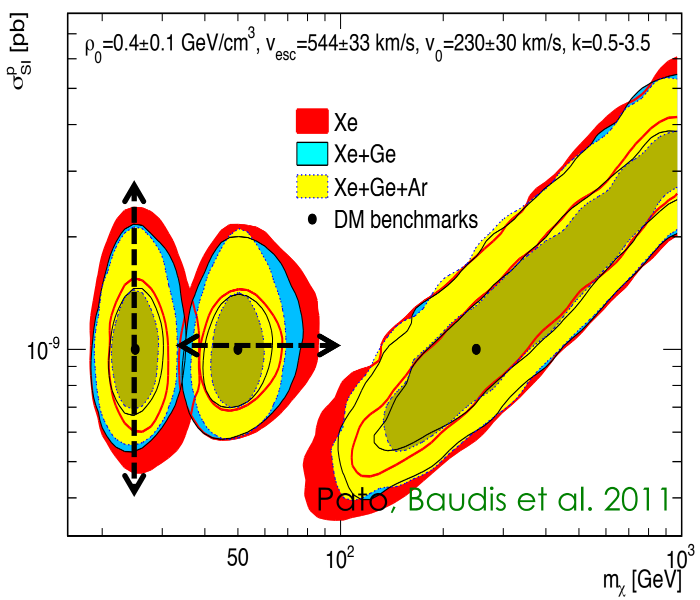
DISCLAIMER:

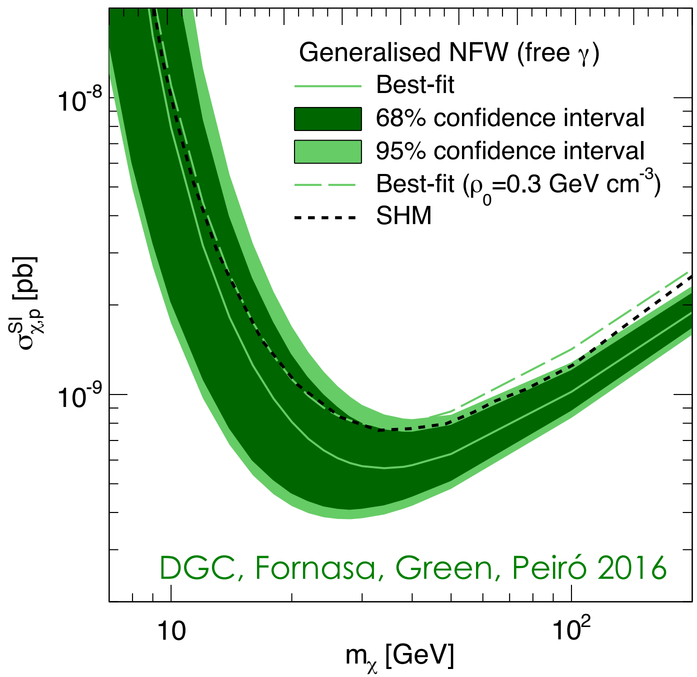
THESE PLOTS ASSUME

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

Astrophysical input and uncertainties

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



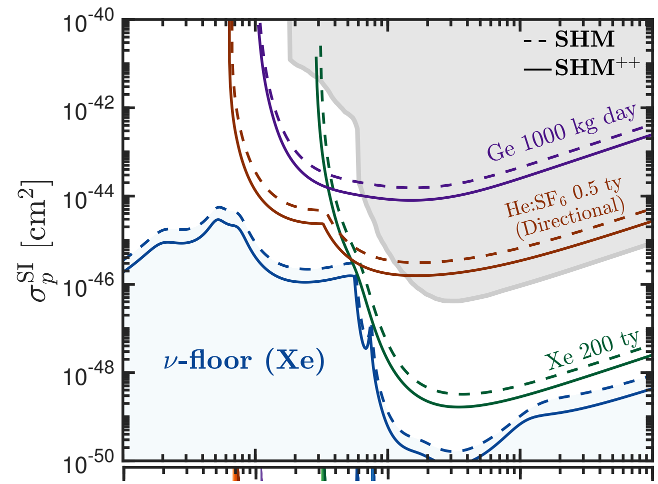


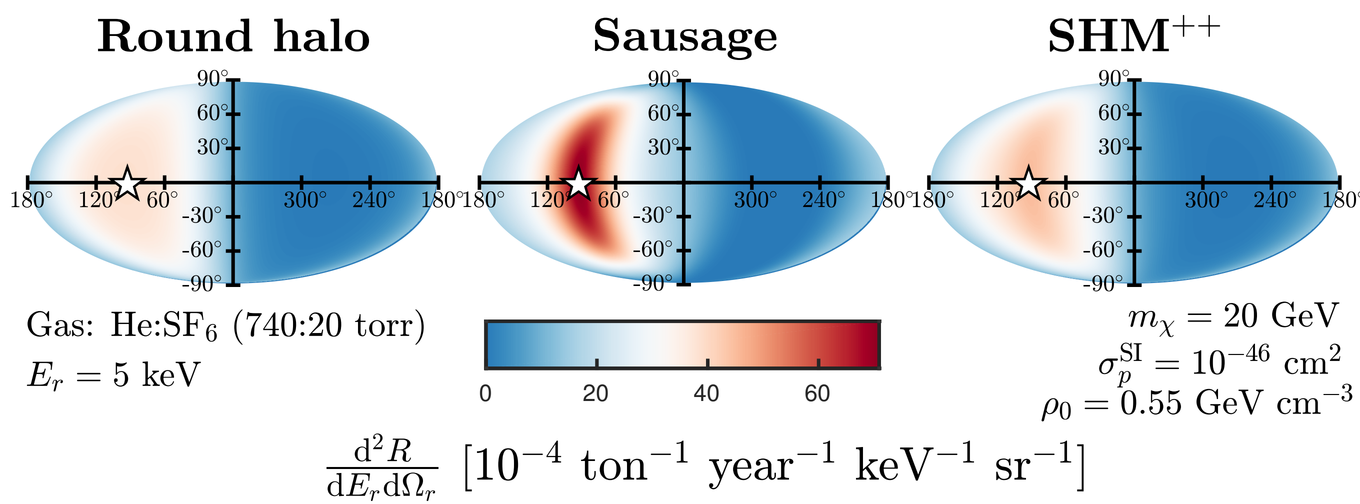
- Incorporating uncertainties is crucial in order to compare results among different experiments. **Halo-independent analyses.**
- Very relevant to combine direct and indirect detection constraints.
- Low mass region is especially sensitive

Effect of the Gaia Sausage on direct detection searches

Existing bounds are affected
(especially at low masses)

Predictions for directional searches
slightly modified
(dipole signal elongated)





Evans, O'Hare, McCabe 1810.11468

Theoretical prejudice

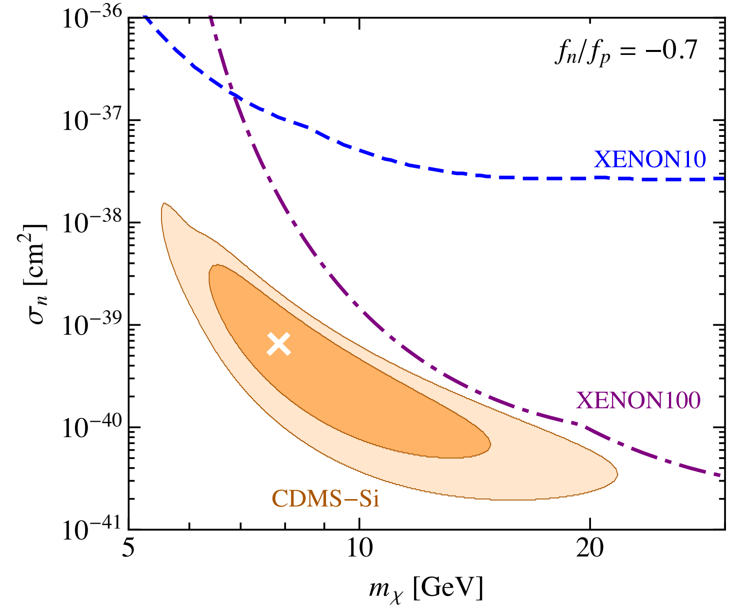
Example: "Isospin violation": the scattering amplitudes for proton and neutrons may interfere destructively

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

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

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

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

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

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

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

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

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

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

(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.

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

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Spin-Dep.

Momentum dependence

Velocity dependence

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

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(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)

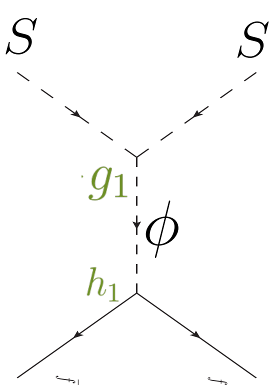
Spin-0 DM particle + scalar mediator

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

Microscopic Model (relativistic description)

↓

Microscopic Model (non-relativistic reduction)



Usual "spin-independent" contribution

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

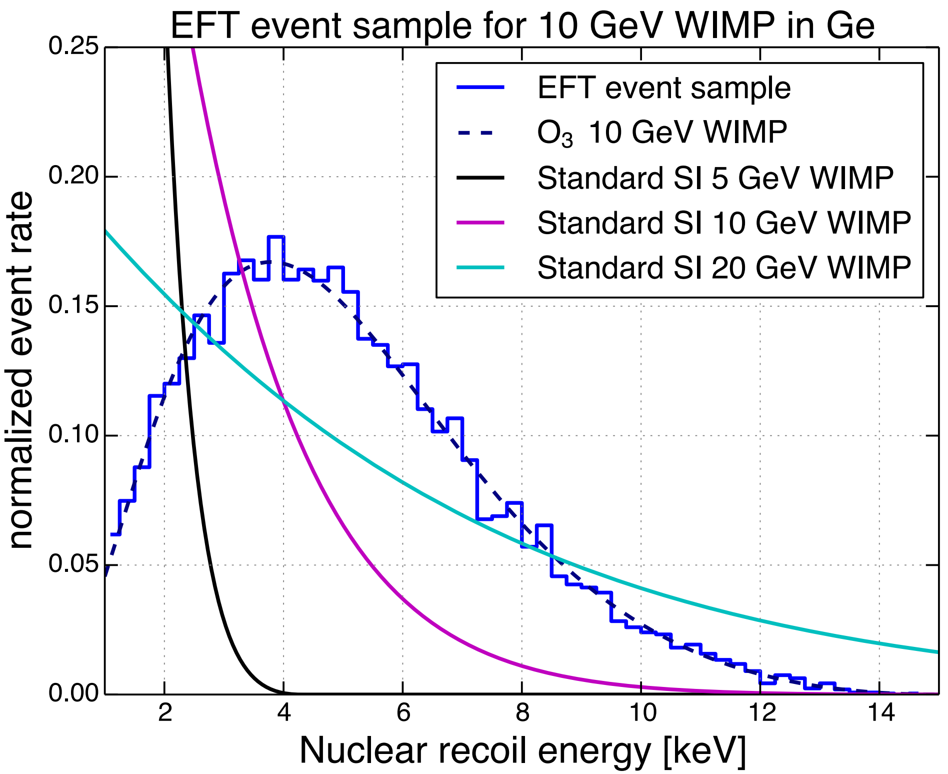
$$(S^\dagger S)(\bar{q}\gamma^5 q) \longrightarrow \left(\frac{h_2^N g_1}{m_\phi^2}\right) \mathcal{O}_{10}$$

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

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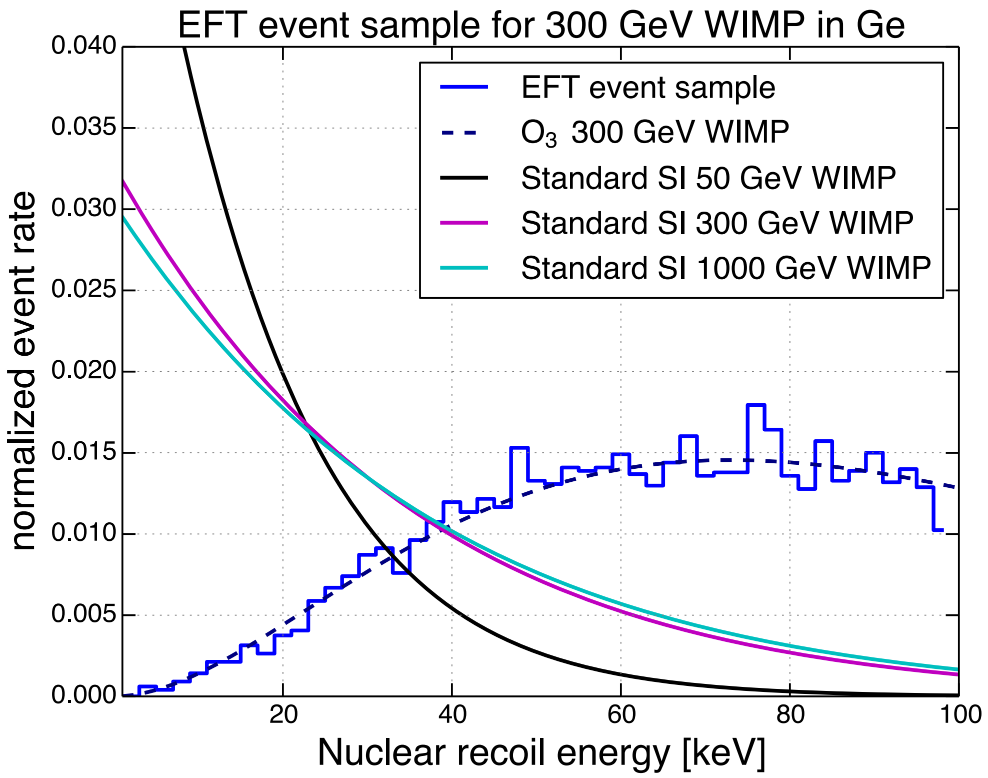
The spectrum from some interactions (momentum dependent) differs from the standard exponential signature



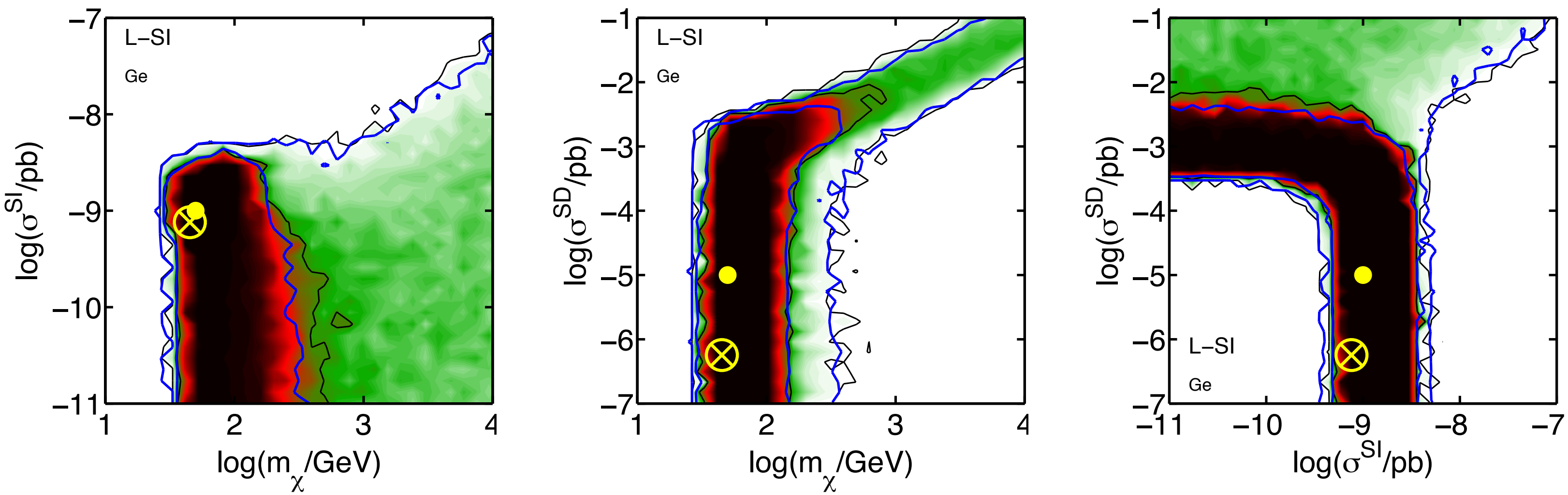
We might **misinterpret** a DM signature (if we reconstruct it with the usual templates)

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

A low threshold is extremely beneficial

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)

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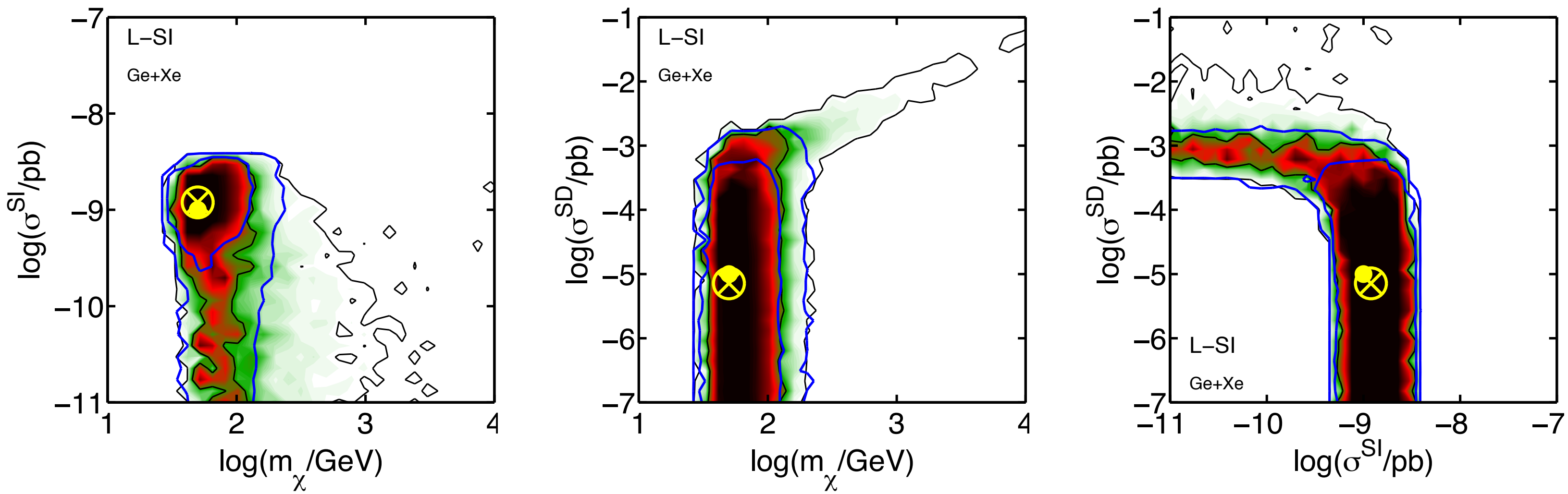

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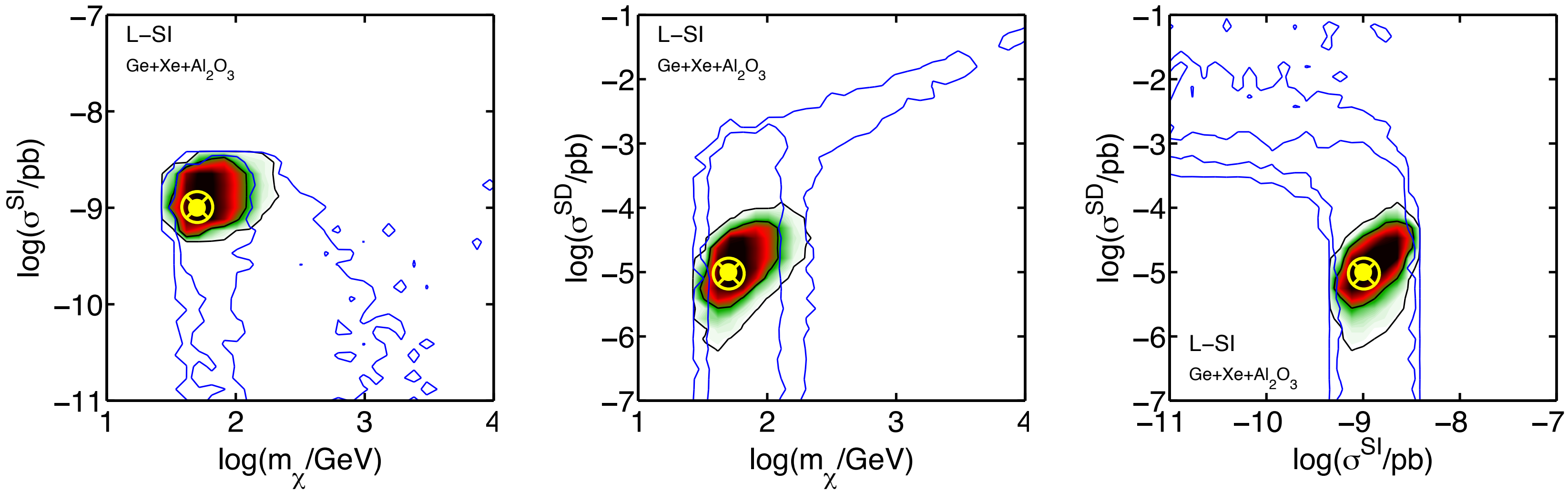

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Germanium and Xenon might not be able to fully reconstruct the DM parameters

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