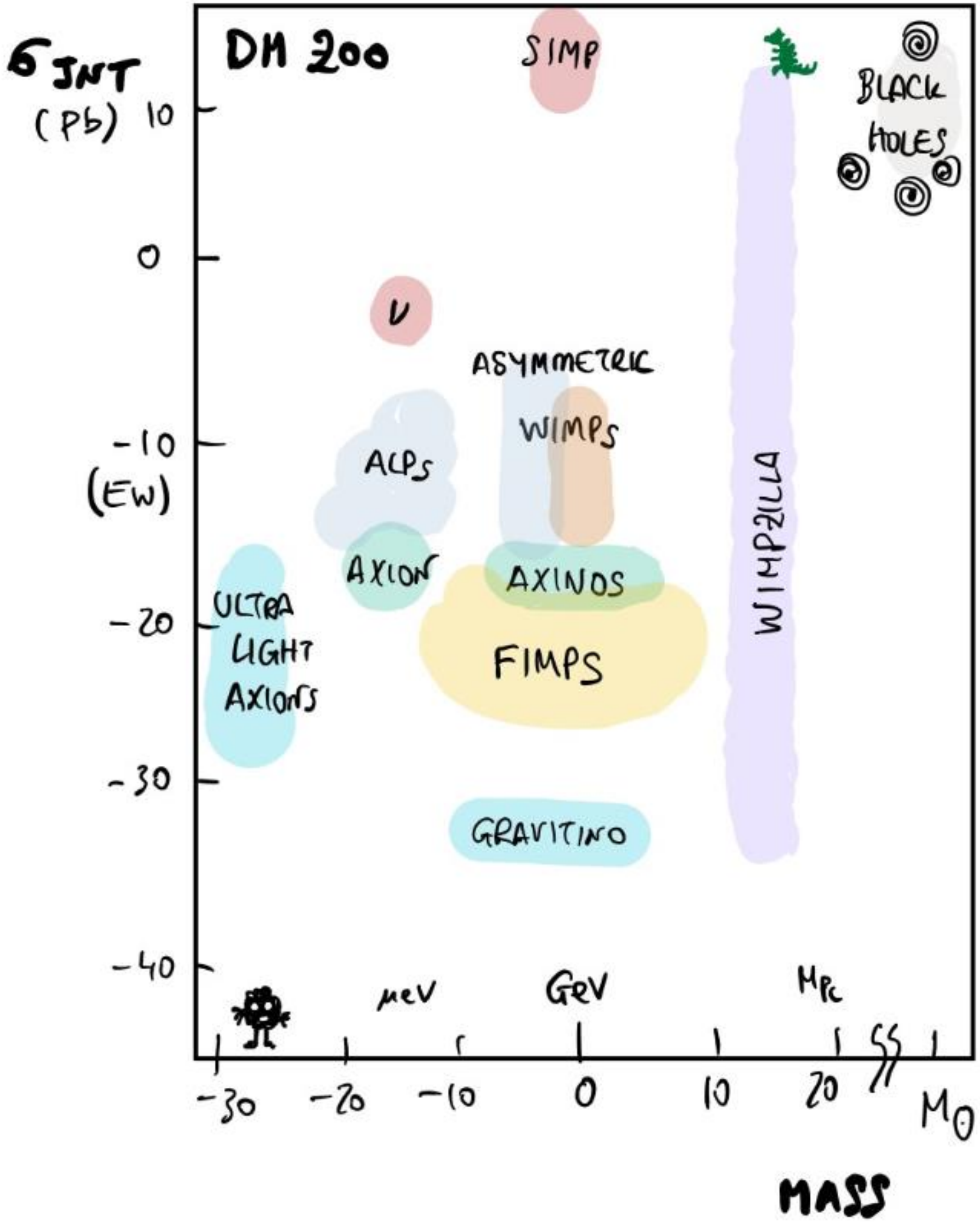
SuperCDMS update

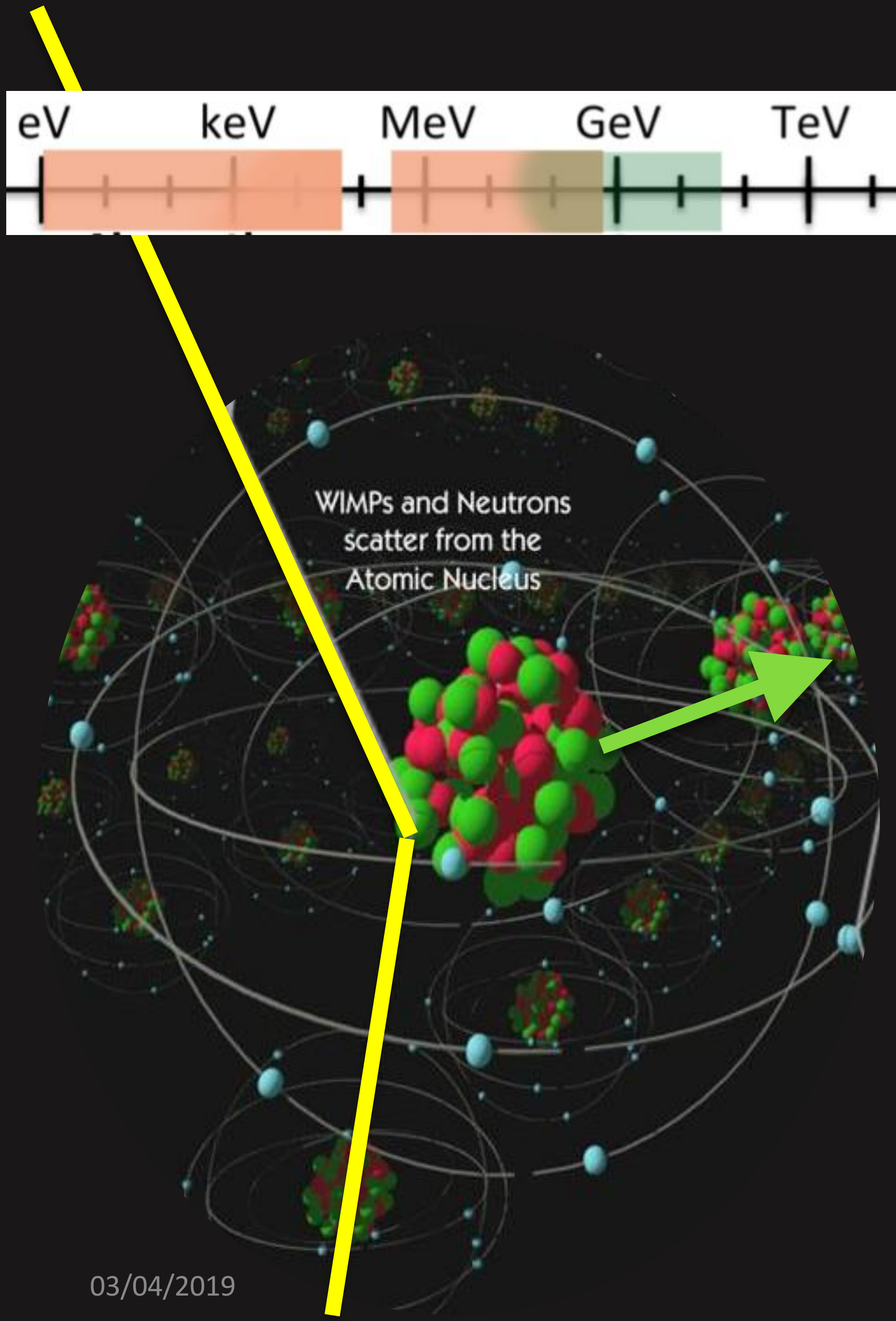
David G. Cerdeño, Elías López Asamar

Durham University IP3 LIP

XV MultiDark workshop, Zaragoza, 4th of April 2019



σ INT
(Pb)
DM ZOO
SIMP
BLACK HOLES
10
0
ν
ASYMMETRIC
WIMPS
-10
(EW)
ALPS
WIMPZILLA
AXION
AXINOS
ULTRA LIGHT AXIONS
-20
FIMPS
-30
GRAVITINO
-40
meV
GeV
MPL
-30
-20
-10
0
10
20
M⊙
MASS



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

SuperCDMS Collaboration

Caltech NIST Pacific Northwest NATIONAL LABORATORY SLAC SOUTH DAKOTA M SCHOOL OF MINES & TECHNOLOGY

SNOLAB UBC Cal UF UNIVERSITY OF SOUTH DAKOTA

NSF NISER

Durham group in SuperCDMS

D. G. Cerdeno
Elias Lopez-Asamar **(in Coimbra (LZ) since Feb 2019)**
Marina Penalver **(MSc Student 2016)**
Andrew Cheek
Elliott Reid
Dorian Praia do Amaral

Analysis

- **Effective Field Theory**: Dark Matter parameter reconstruction
- **Coherent neutrino scattering and Electron Recoil**
  Very light dark matter and new physics in the neutrino sector.

Numerical Tools

- **Surrogate Models**: Numerical tools to speed-up reconstruction
- **Machine learning tools:** Applied to discriminate the neutrino floor

Event Reconstruction for SuperCDMS SNOLAB

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)

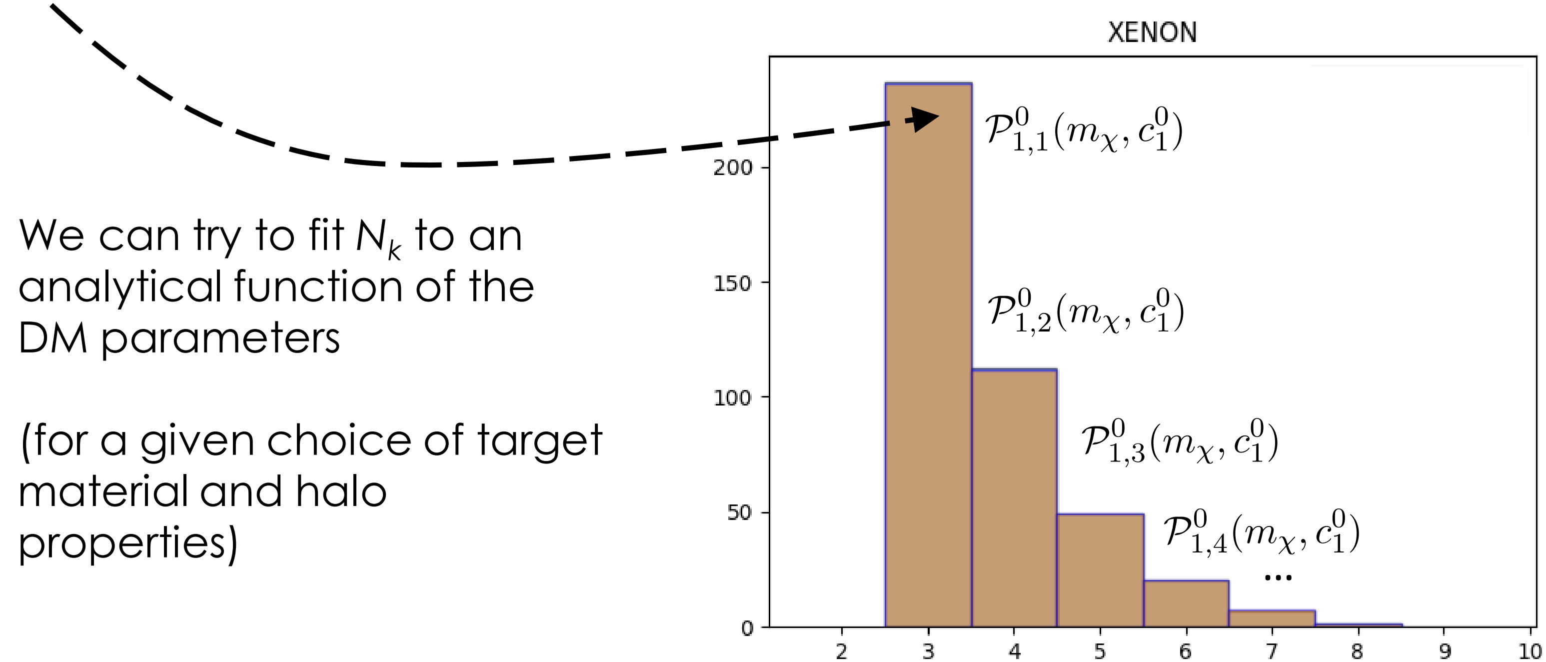
A surrogate model for direct dark matter detection

DGC, Cheek, Reid, Schulz 2018

Speeding up **the reconstruction of DM parameters:**

The number of DM events **for a given energy bin** is, in the simplest cases, a smooth function of the scattering cross section and the DM mass

$$N_k = \frac{\rho_0}{m_N\, m_\chi} \int_{E_k}^{E_{k+1}} dE_R\, \epsilon(E_R) \int_{E'_R} dE'_R\, Gauss(E'_R, E_R) \int_{v_{min}} d\vec{v}\, v f(\vec{v})\, \frac{d\sigma_{WN}}{dE'_R}\,,$$



We can try to fit N_k to an analytical function of the DM parameters

(for a given choice of target material and halo properties)

Surrogate models for direct detection (RAPIDD)

We have used the **PROFESSOR** tool to obtain an analytical approximation (**in terms of polynomials**) for the expected DM rate in each energy bin (k)

$$N_k = \frac{\rho_0}{m_N\, m_\chi} \int_{E_k}^{E_{k+1}} dE_R\, \epsilon(E_R) \int_{E'_R} dE'_R\, Gauss(E'_R, E_R) \int_{v_{min}} d\vec{v}\, v\, f(\vec{v})\, \frac{d\sigma_{WN}}{dE'_R}\,,$$

$$= \int_{E_k}^{E_{k+1}} dE \frac{\rho_0 m_T}{32\pi^2 m_\chi^2 m_N^2} \left\langle \frac{1}{v} \sum_{ij} \sum_{\tau,\tau'=0,1} c_i^{(\tau)} c_j^{(\tau')} \mathcal{F}_{i,j}^{(\tau,\tau')}(v^2, q^2) \right\rangle$$

$$\sim \sum_{ij} \sum_{\tau,\tau'=0,1} \mathcal{P}_{ij,k}^{(\tau\tau')}(c_i, c_j, m_\chi, \alpha, \beta, \ldots)$$

RAPIDD is trained for an initial random population of points, which determines the coefficients of the polynomials.

Astrophysical (and nuclear) uncertainties can be added as extra variables in the polynomials.

Examples:

This reconstruction works well, provided that the dependence on the parameters is smooth

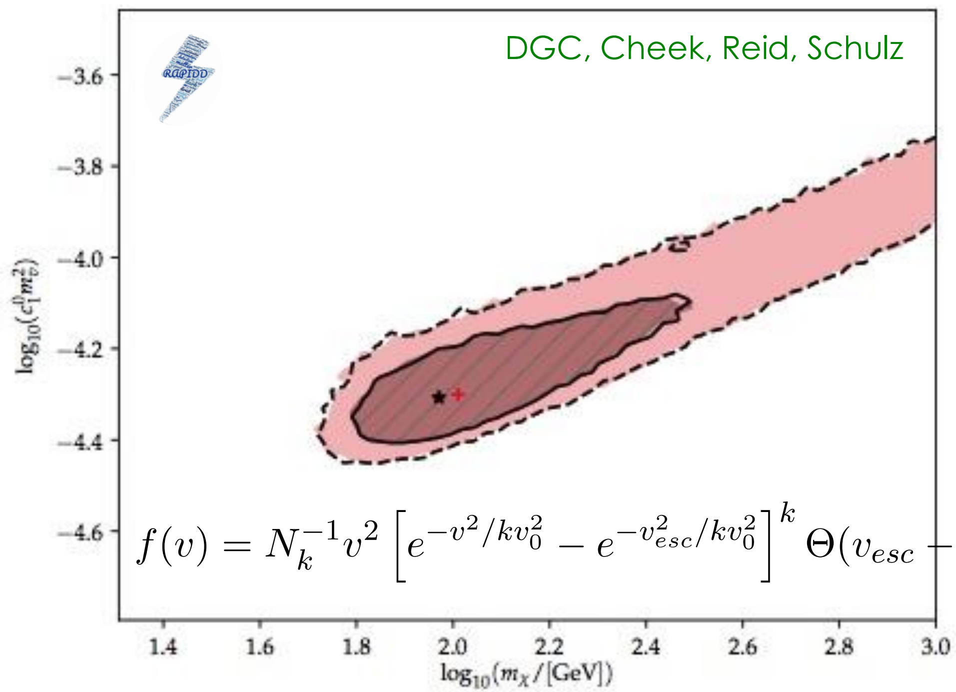
Potential problems appear at low DM masses and in interference regions (these are solved by using more than one polynomial)

2-D example: $(m_\chi, \, c_1^0)$

Spin-independent scattering

We achieve a good reconstruction in 1/200th of the time

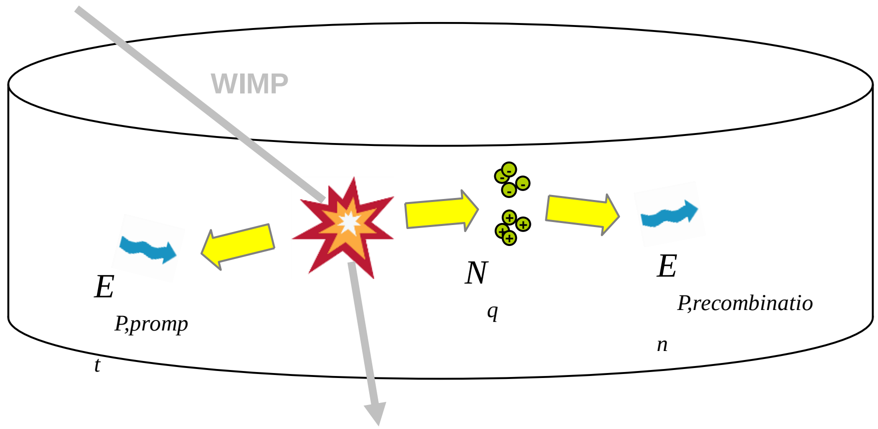
Results are also consistent when uncertainties in the DM halo are included (5D scan)



$$f(v) = N_k^{-1} v^2 \left[e^{-v^2/kv_0^2} - e^{-v_{esc}^2/kv_0^2} \right]^k \Theta(v_{esc} - v)$$

The SuperCDMS approach

Measure phonons (E_P) and charge carriers (N_q) produced by recoiling Ge nucleus



$$N_q = Y\frac{E_R}{\epsilon}, \quad \epsilon(\mathrm{Ge}) = 3.0\ eV$$

$$E_P = E_{P,prompt} + E_{P,recombination} = E_R$$

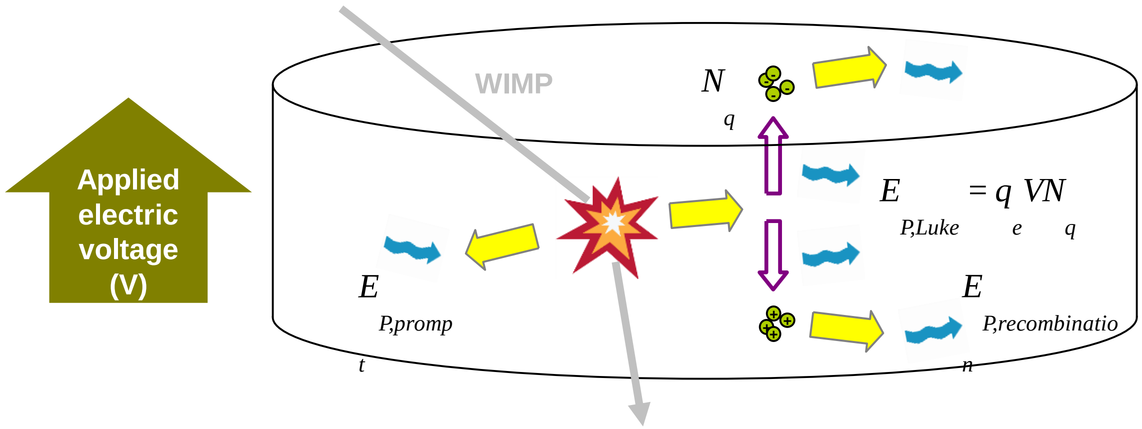
E_R : Recoil energy, related to WIMP mass
Y: Charge yield, depends on recoiling particle

	Y
Recoiling electron	1
Recoiling Ge nucleus	~0.3

It is possible to know (E_R, Y) from (E_P, N_q)

The SuperCDMS approach

Measure phonons (E_P) and charge carriers (N_q) produced by recoiling Ge nucleus



$$N_q = Y \frac{E_R}{\epsilon}, \quad \epsilon(\mathrm{Ge}) = 3.0\ eV$$

$$E_P = E_R + q_e V N_q = E_R \left(1 + Y \frac{q_e V}{\epsilon}\right)$$

Additional contribution to E_P called "Luke phonons"

E_R : Recoil energy, related to WIMP mass
Y : Charge yield, depends on recoiling particle

	Y
Recoiling electron	1
Recoiling Ge nucleus	~0.3

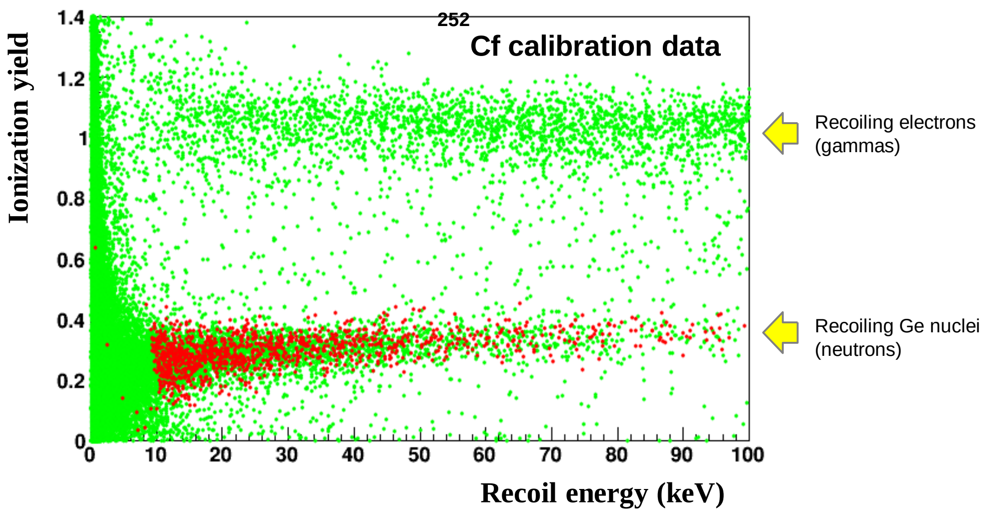
It is possible to know (E_R, Y) from (E_P, N_q)

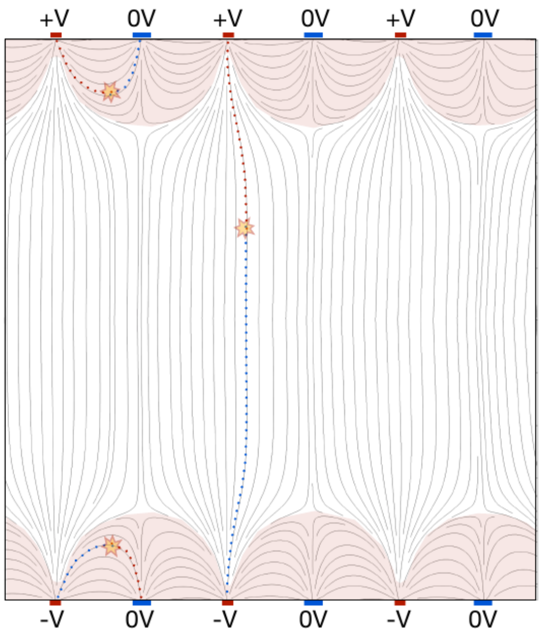
The SuperCDMS approach

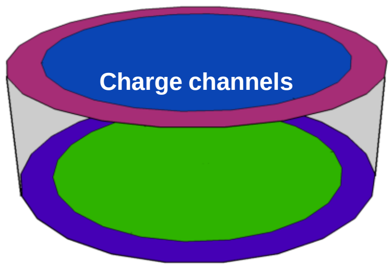
The iZIP ("interleaved z-sensitive ionization and phonon sensors") approach:

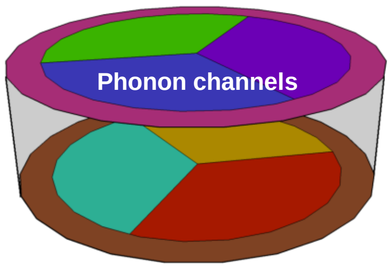
Measuring *Y* → NR/ER discrimination

Applied electric field (4 V) + segmented readout → full fiducialization









The SuperCDMS approach

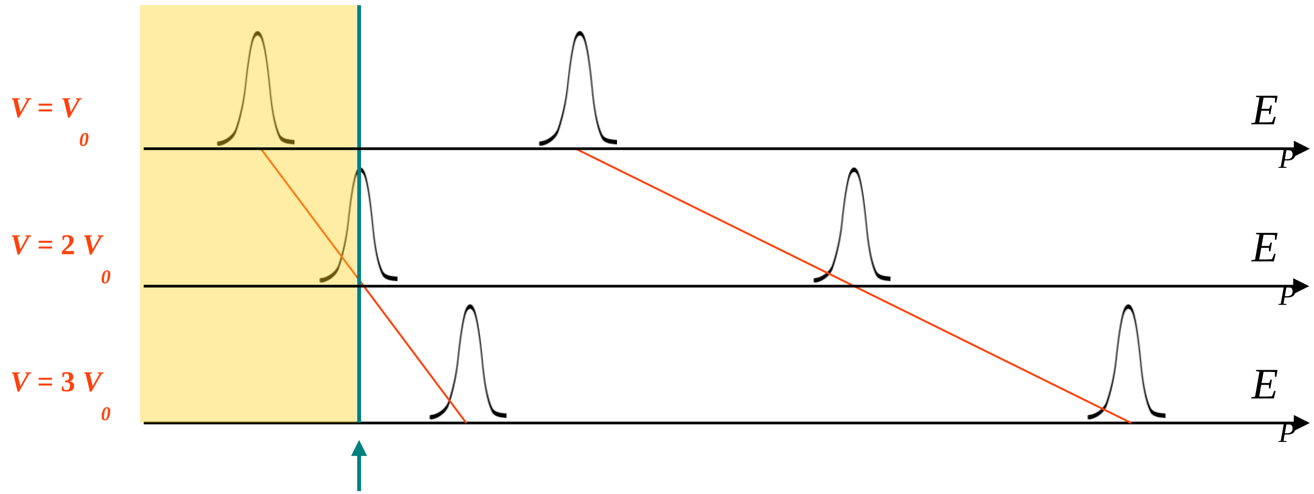
The HV ("high-voltage operation", a.k.a. CDMSlite) approach:

Increased applied voltage (*V*) enables to effectively decrease threshold

$$E_P = E_R + q_e V N_q = E_R(1 + Y\frac{q_e V}{\epsilon}) = g(V) E_R$$

Contribution from applied electric field

$g(V) > 1$



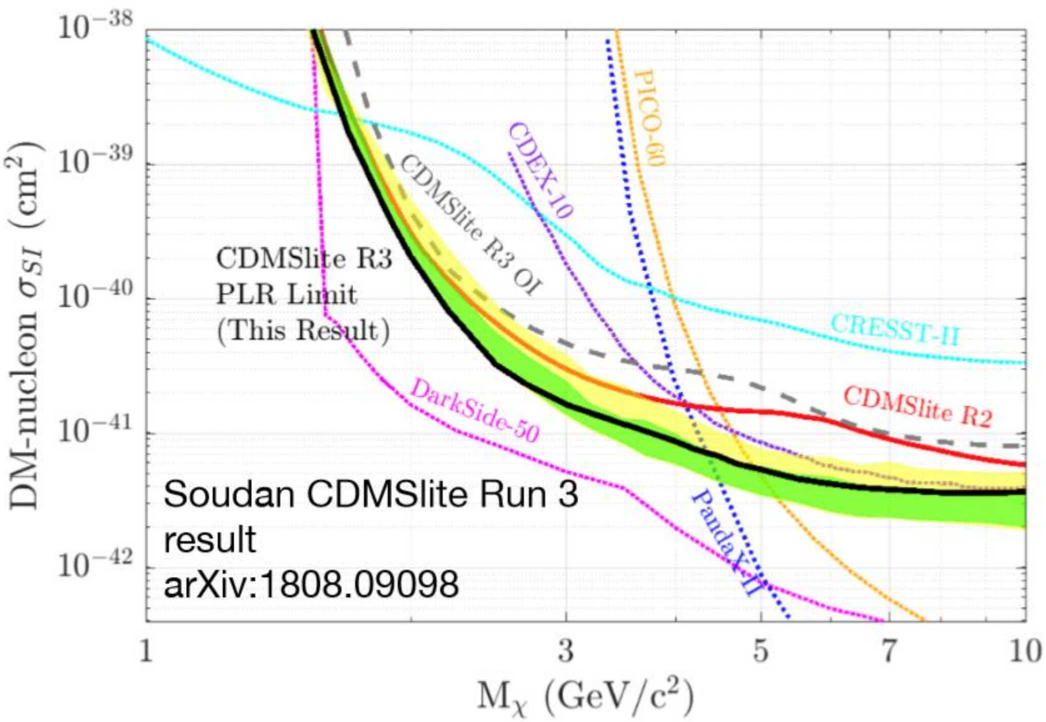
However N_q remains below threshold Þ charge signal is useless

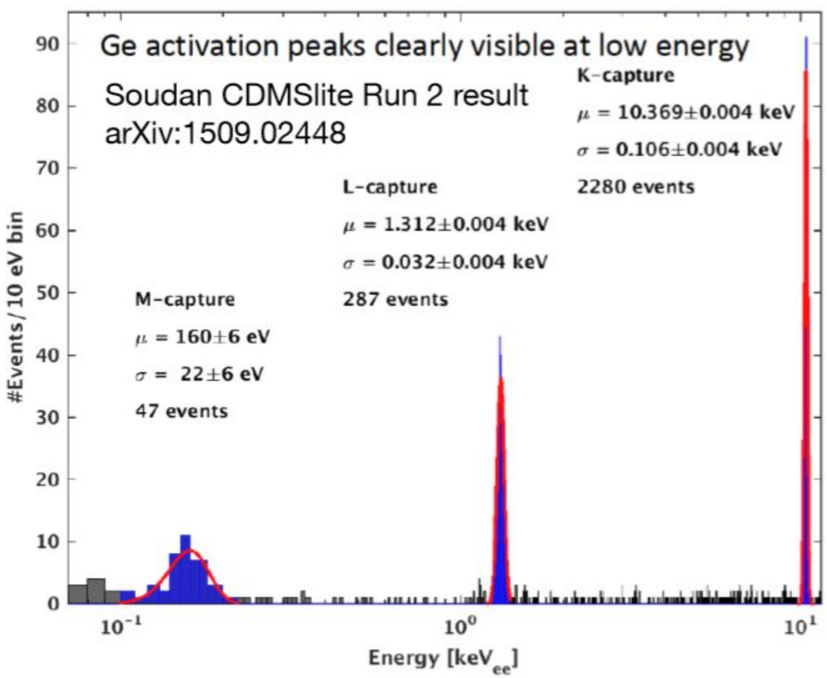
CDMSlite3 Results

15 cylindrical Ge detectors, 9.2 kg total

Deployed at Soudan Underground Laboratory (US, 714 m depth)

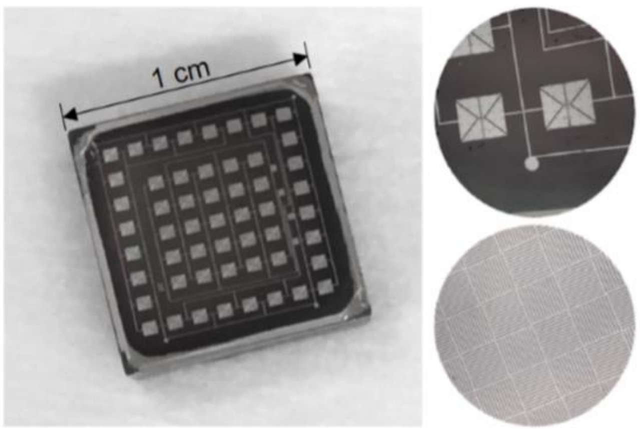
Operated between March 2012 and November 2015





SuperCDMS HVeV

Using the SuperCDMS QET technology, but optimising for resolution

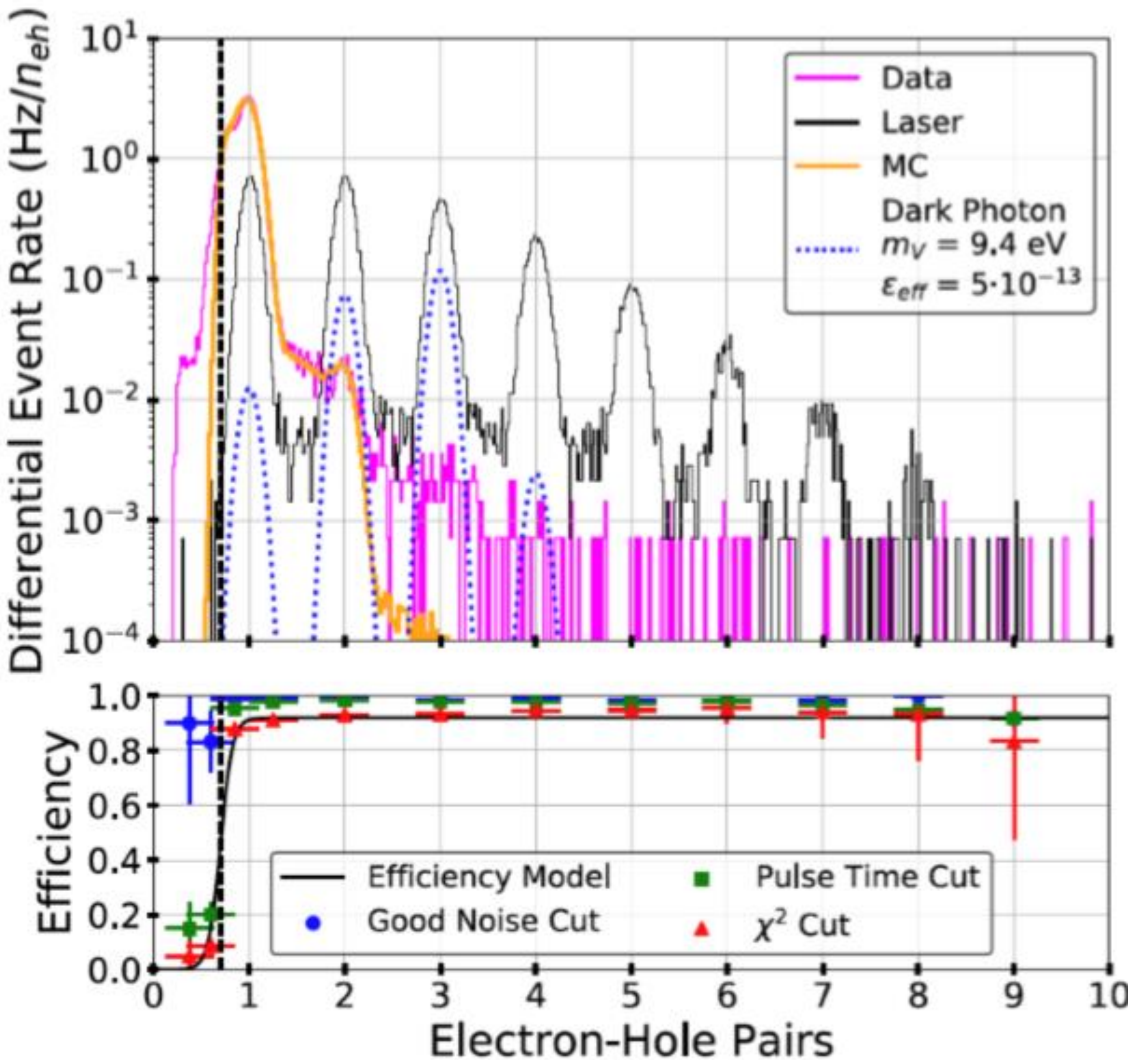


cm2 sized Si detectors operating at high voltage with eV-scale phonon resolution

They are sensitive to single e-h+ pair resolution (effectively lowering the detection threshold to eV scale)

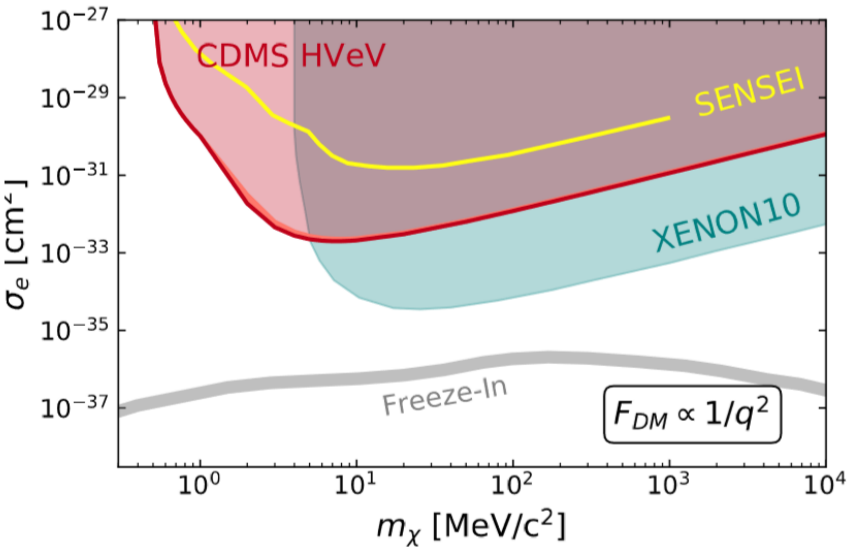
1cm x 1cm x 0.4 cm device running for 27+9 hours with a bias voltage of 140V for a total exposure of 0.49 g day

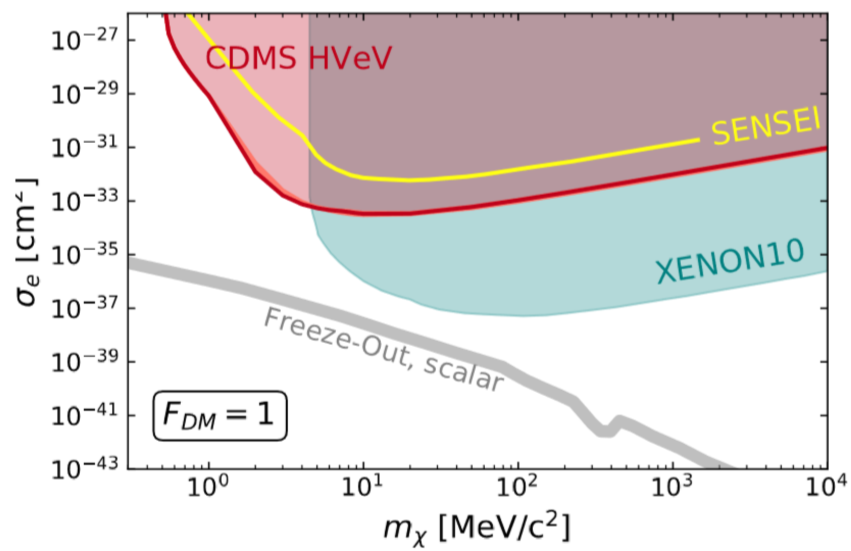
SuperCDMS HVeV



Bounds on dark matter with electron recoils

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





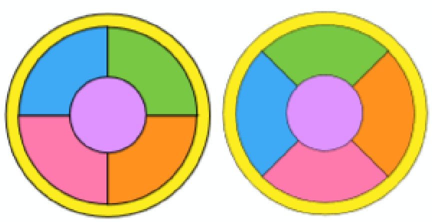
Phys.Rev.Lett. 121 (2018)

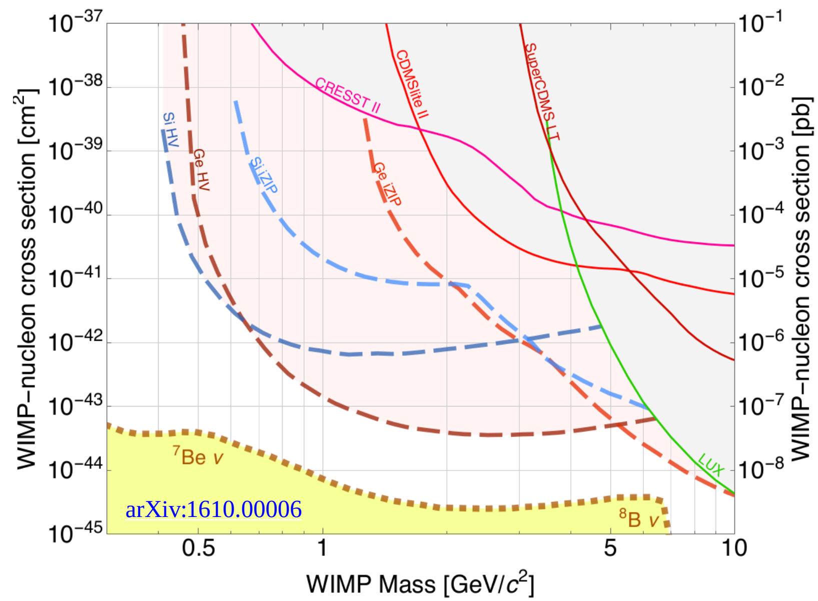
SuperCDMS SNOLAB

Project proposal:

- **iZIP detectors (full background rejection capabilities): 14 kg Ge, 1.2 kg Si**
- **HV detectors (lowered energy threshold): 10 kg Ge, 2.4 kg Si**

In construction phase since project review on January 2018





Planned to start operations in 2020, expecting ~5 years of data taking

Development of the event reconstruction

Event reconstruction: Processing of the raw event data to obtain information of the particle interactions (recoil enery, position, etc...)

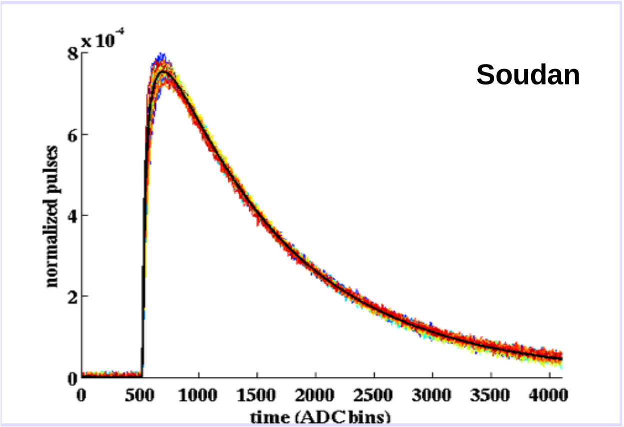
Raw data ⇨ Reduced quantities ⇨ Physics result

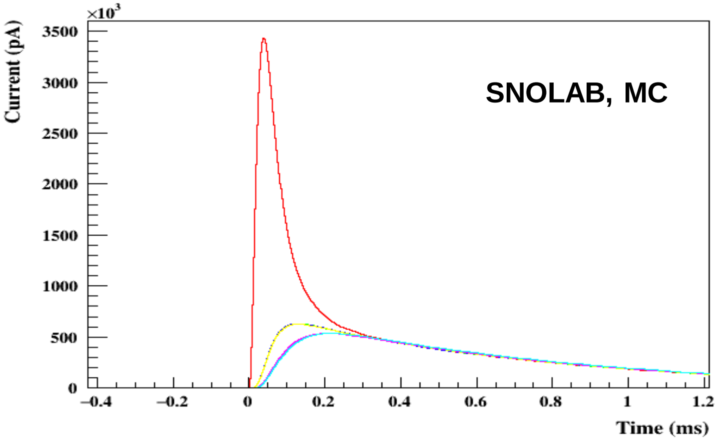
(reconstruction) (analysis)

Traditionally: Fit measured pulses to fixed templates, in Fourier space (to filter noise)

(Information derived from pulse amplitudes)

But: Large position dependence in SuperCDMS SNOLAB





Development of the event reconstruction

For this reason:

- **Proposed to create a working group in the SuperCDMS Collaboration to develop the event reconstruction of SuperCDMS SNOLAB (Aug. 2017)**
- **The SNOLAB Reconstruction working group was created on Sep. 2017**
- **SNOLAB Reconstruction working group was coordinated by MultiDark member (Elías López Asamar) between Sep. 2017 and Jan. 2019**

Achievements:

- **Carried out studies to assess the performance of different fitting algorithms**
- **Established that standard reconstruction algorithms need to be preceded by an initial stage that provides an approximate reconstruction**
- **Developed a prototype implementation to fully reconstruct the noise signal, based on a simultaneous multi-template fit**
- **Started to study machine learning methods to filter noise**

There has been coordination with other SuperCDMS collaborators to ensure that the activity of the SNOLAB Reconstruction working group will continue

MultiDark participation in LZ

Elías López Asamar left the SuperCDMS Collaboration on Jan. 2019, and joined the LZ Collaboration via the group at LIP-Coimbra (as postdoc)

Main activities of the LIP-Coimbra group:

- **Analysis of ultra-rare (2-beta) nuclear decays: ^{134}Xe, ^{136}Xe, etc**
- **Backgrounds (the backgrounds studies in LZ are coordinated by a member of LIP-Coimbra)**
- **Slow-control of the detector**

Summary

- **SuperCDMS based on semiconductor technology, measuring phonon and charge signal**
- **SuperCDMS SNOLAB under construction, expected to start operations on 2020**

- **Since Sep 2017-Jan 2019 the group coordinated the event reconstruction for SuperCDMS SNOLAB**

- **The IPPP group is now involved mainly in developing numerical tools and analysis of Effective Field Theories**

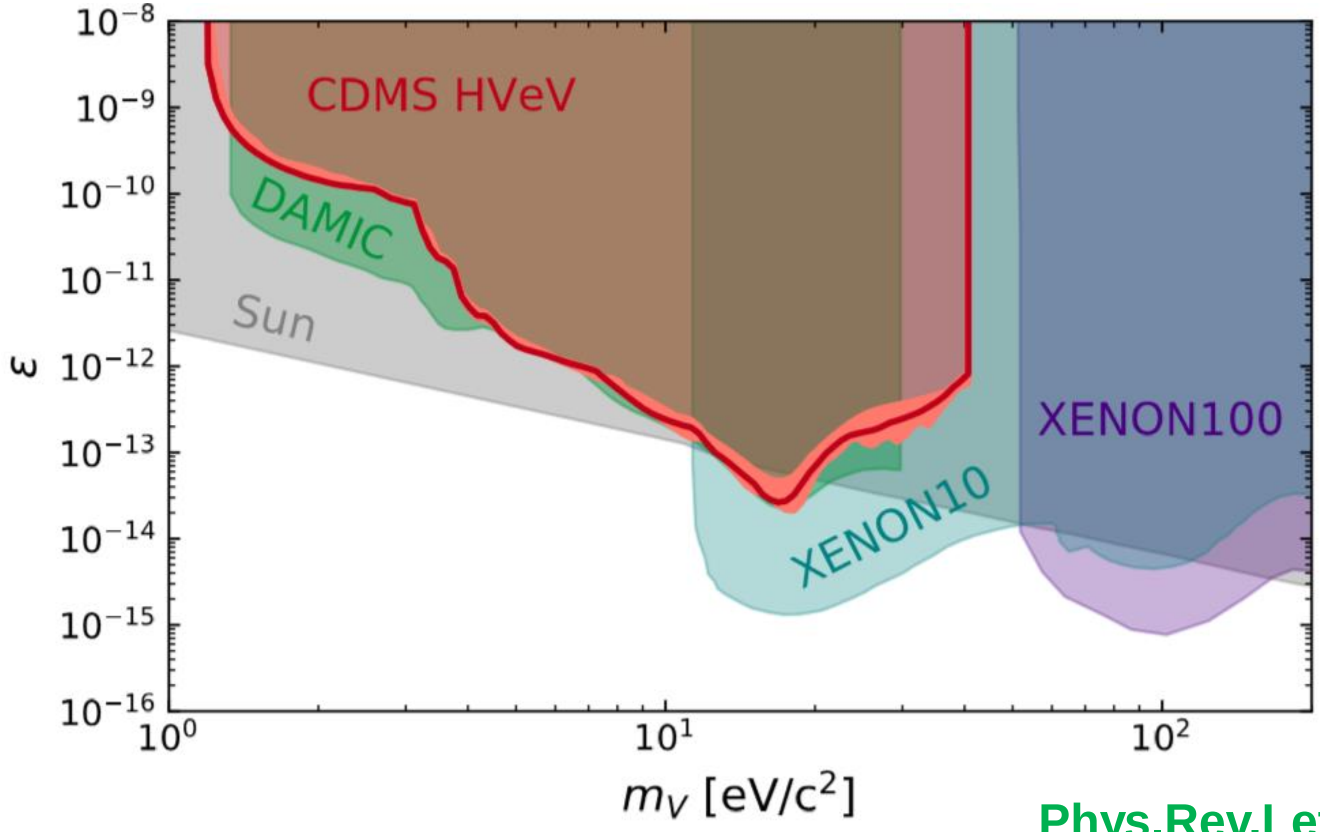
- **Now MultiDark has also presence in LZ**

Thank you for your attention...

Bounds on dark photons

"Heavy" photon with kinetic mixing with the SM photon.

$$R = V_{det} \frac{\rho_{DM}}{m_V} \varepsilon^2_{eff}(m_V, \tilde{\sigma}) \sigma_1(m_V).$$



Phys.Rev.Lett. 121 (2018)