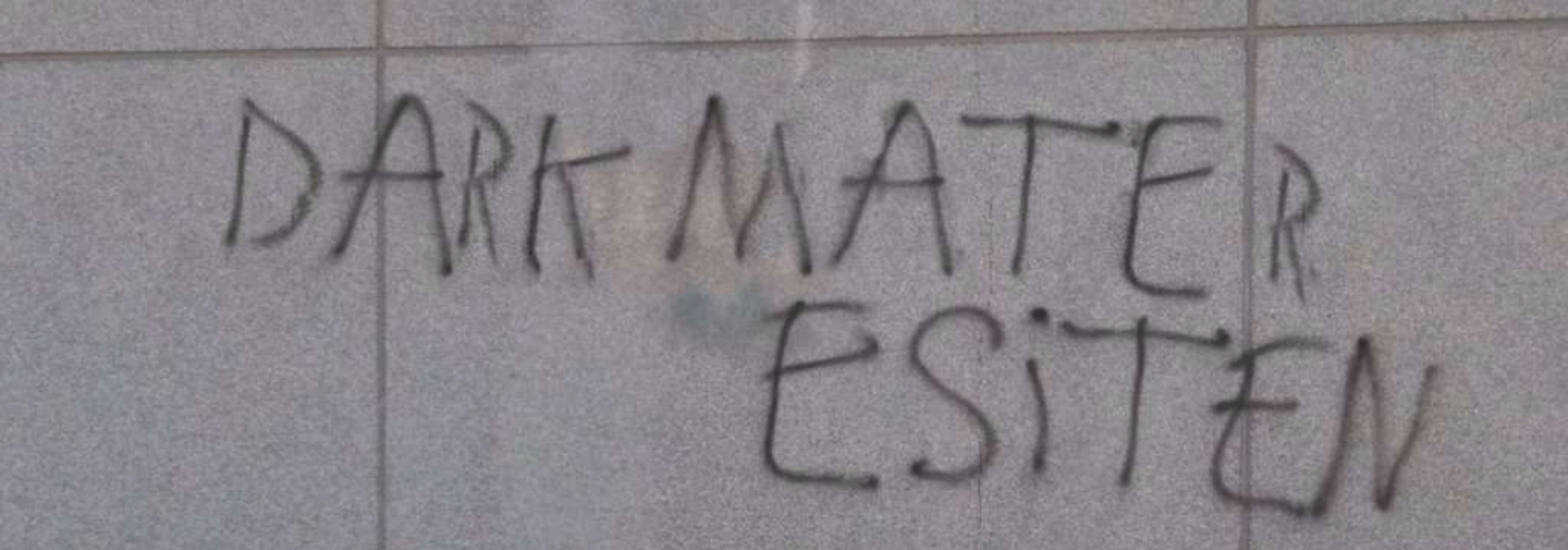

DARK MATER
ESiTEN



Direct Detection of Dark Matter

(intro and low-mass DM in SuperCDMS)

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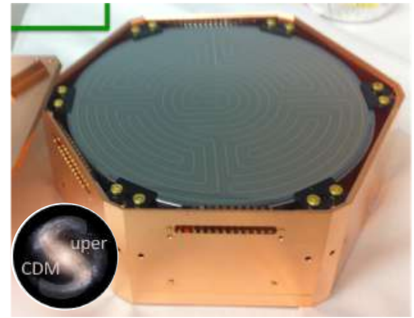
Instituto de Física Teórica UAM-CSIC

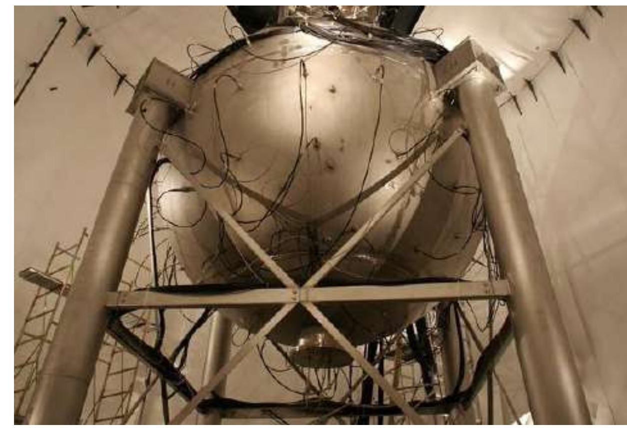
Universidad Autónoma de Madrid

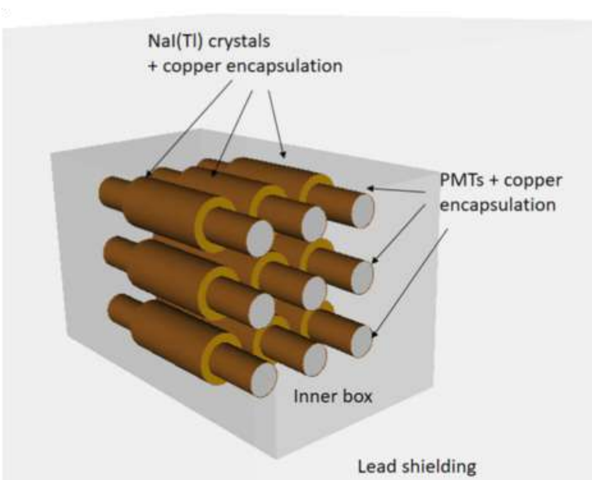
MultiDark
Multimessenger Approach for Dark Matter Detection

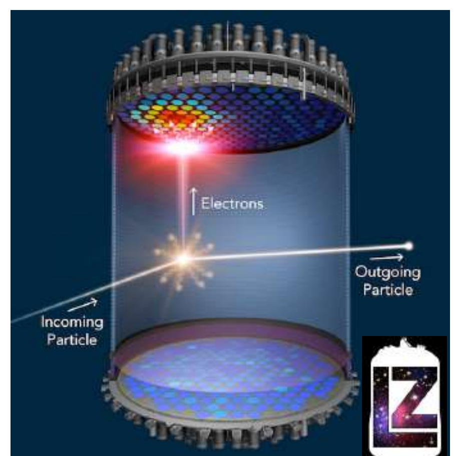
In this session…



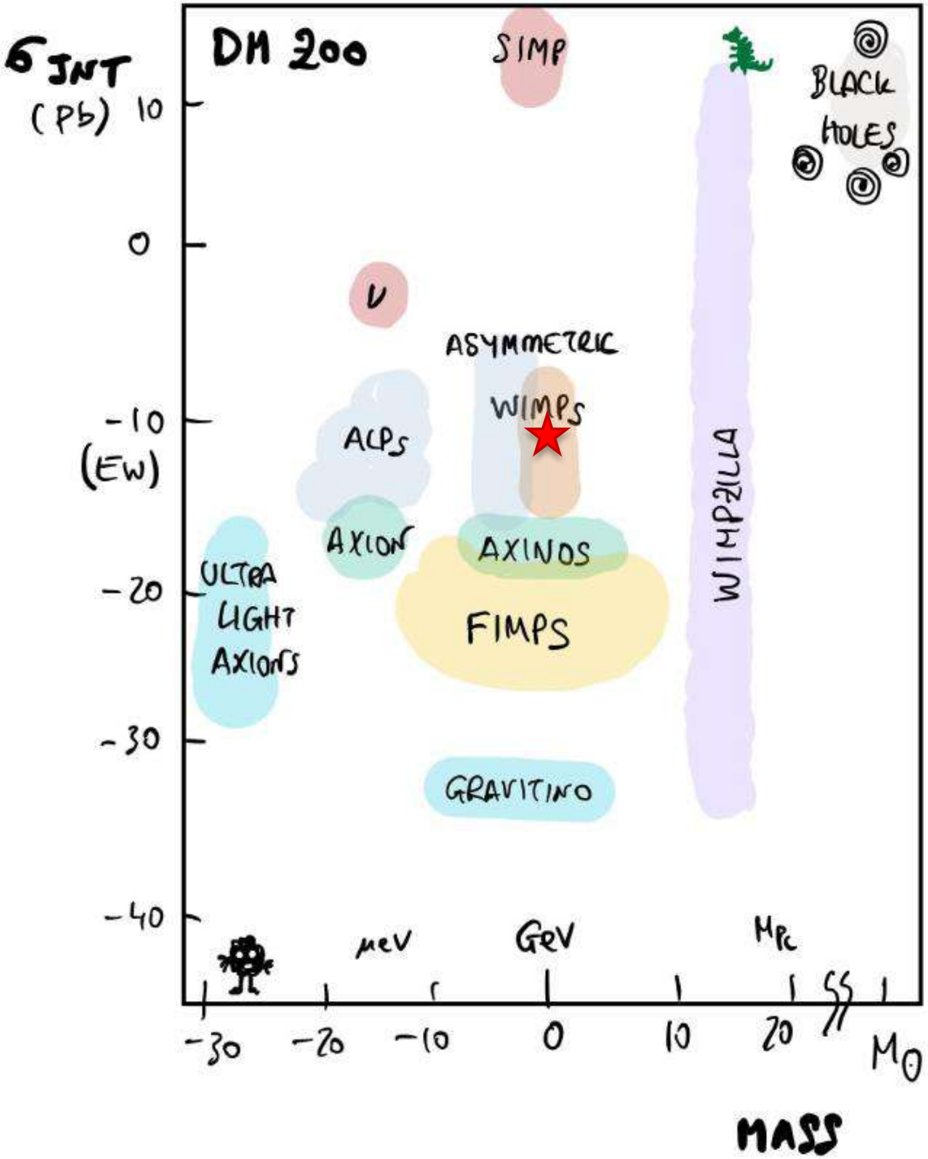
1. Introduction + SuperCDMS
2. DarkSide/DEAP/DArT – Vicente Pesudo
3. LZ and MIGDAL– Elías López Asamar
4. ANAIS – María Martínez



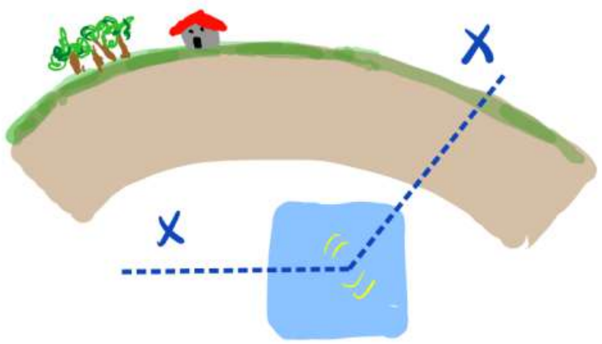




A theorist's PARADISE.... an experimentalist's PURGATORY



Direct Detection experiments



(Underground*) detectors to look for “invisibles”

- weakly-interacting (that traverse the Earth)
- Neutral (or millicharged)
- Cosmological or astrophysical origin
- Stable enough

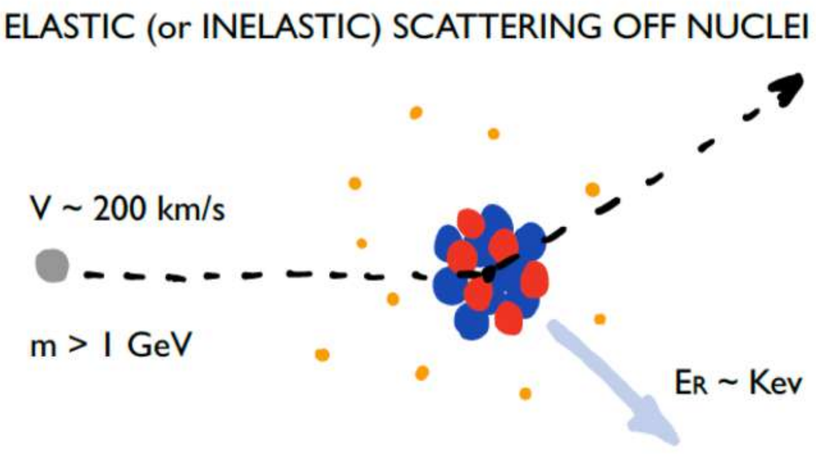
Ionisation
Scintillation
Phonons (heat)
Bubble nucleation
…

Interactions are (to say the least) rare

- Background attenuation (cleanliness + shielding)
- Increasing target size
- Increasing search window (**lower energy thresholds**)

Background/signal discrimination

- Discriminate nuclear recoils (NR) and electron recoils (ER)
- Morphology of the signal (energy spectrum)
- Time-dependence (annual modulation)
- Directionality



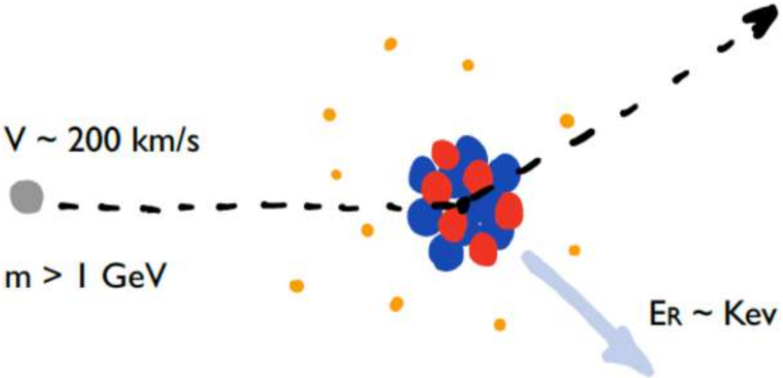
DIRECT DARK MATTER SEARCHES: What can we measure?

$$E_R = \frac{\mu_N^2 v^2 (1 - \cos\theta^*)}{m_N}$$

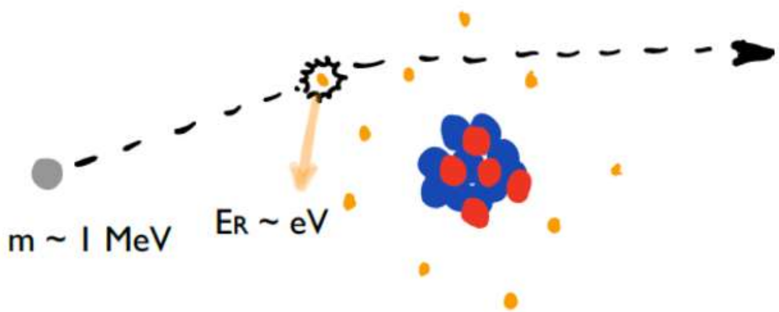
NUCLEAR SCATTERING

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

ELASTIC (or INELASTIC) SCATTERING OFF NUCLEI



INELASTIC SCATTERING WITH ELECTRONS



$$E_R = \frac{\mu_e^2 \, v^2 (1 - \cos\theta^*)}{m_e}$$

DIRECT DARK MATTER SEARCHES: What can we measure?

NUCLEAR SCATTERING

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ELECTRON SCATTERING

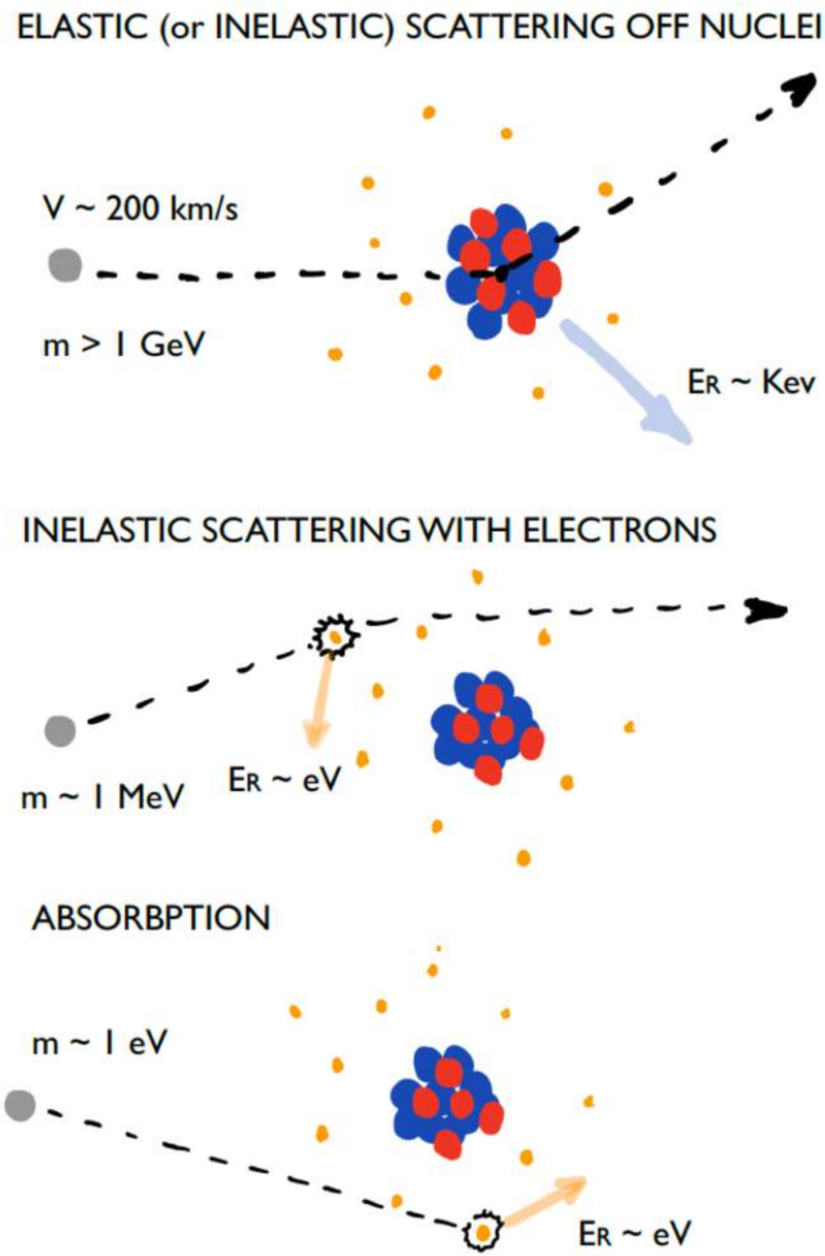
- Sensitive to light WIMPs

ELECTRON ABSORBPTION

- Very light (non-WIMP)

EXOTIC SEARCHES

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



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Conventional direct detection approach (WIMPs)

$$N = \int_{E_T} \epsilon \frac{\rho}{m_\chi m_N} \int_{v_{\min}} v f(\vec{v}) \frac{d\sigma_{WN}}{dE_R} d\vec{v}\, dE_R$$

Particle (+ nuclear) Physics

The scattering cross section contains the details about the microphysics of the DM model

The most general case can be described by means of an Effective Field Theory

$$\mathcal{L}_{\rm int} = \sum_{i=1,15} c_i \chi^* \mathcal{O}_\chi \chi \Psi_N^* \mathcal{O}_i \Psi_N$$

$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$
$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

Discriminating a DM signal… Energy Spectrum

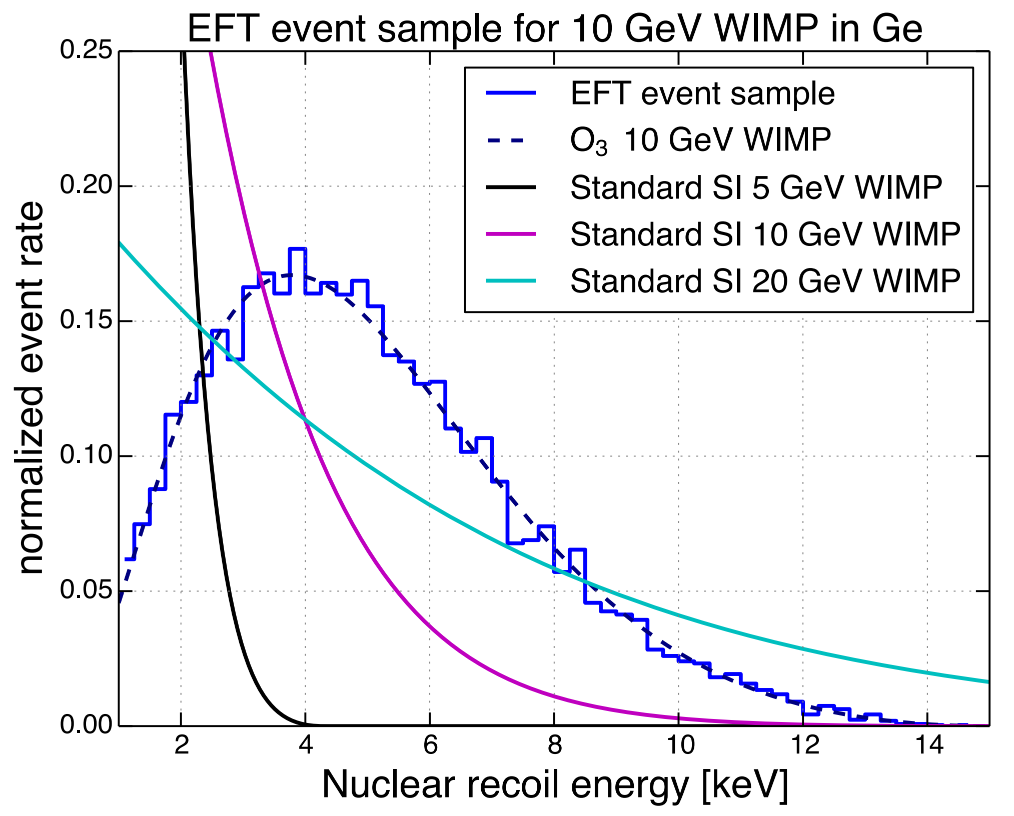
DM particles leave a recoil spectrum which is "exponential" if the interaction is momentum independent (general assumption in spin-independent analysis)

Light WIMPs expected at very low energies

Favours light targets and…

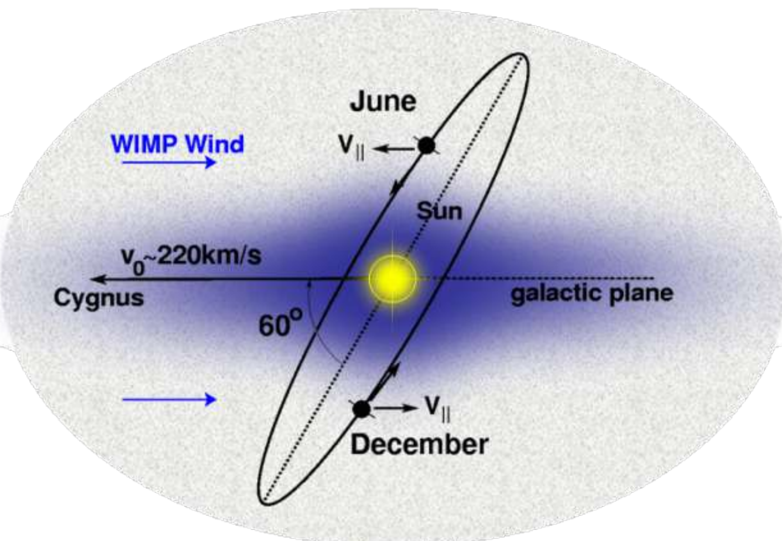
Low-threshold searches

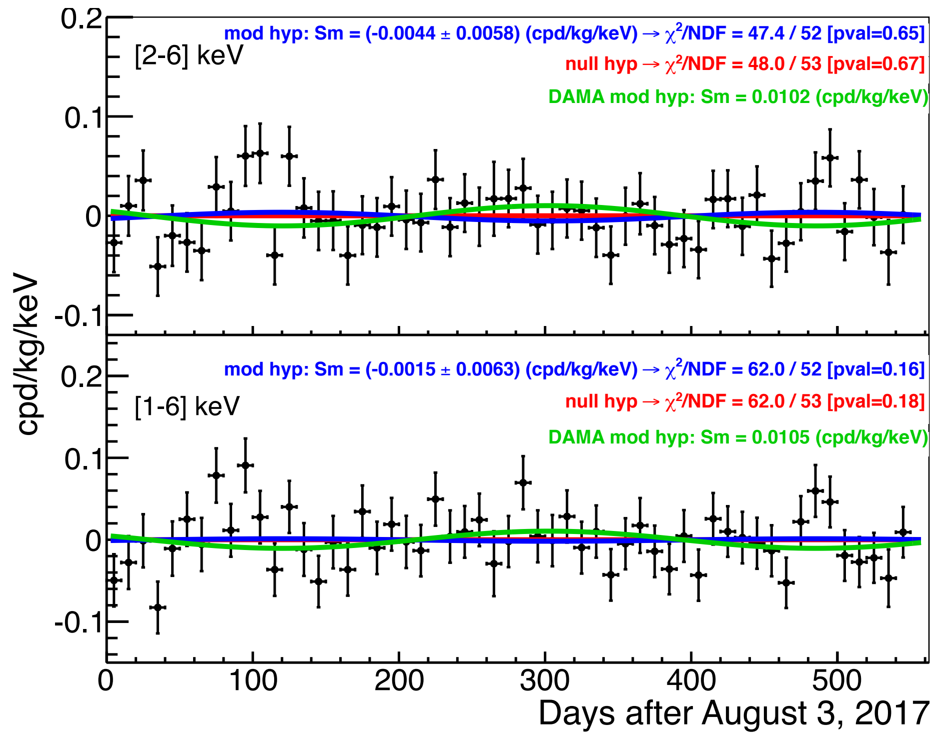
Low-threshold also useful to distinguish unconventional spectra (momentum-dependent)



Discriminating a DM signal... Annual Modulation

An annual modulation is expected due to the seasonal variation of the Earth's velocity inside the DM halo.

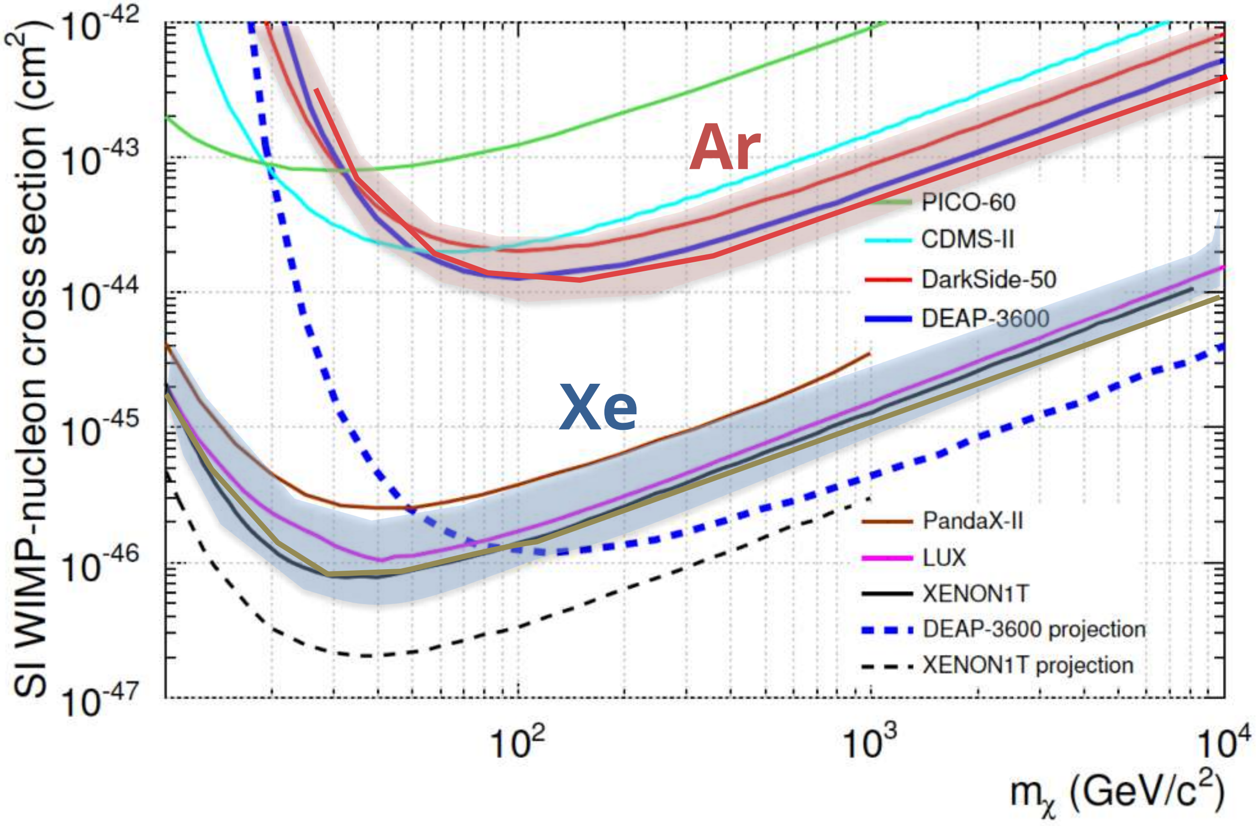




This signature is currently being currently probed by detectors such as ANAIS.

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

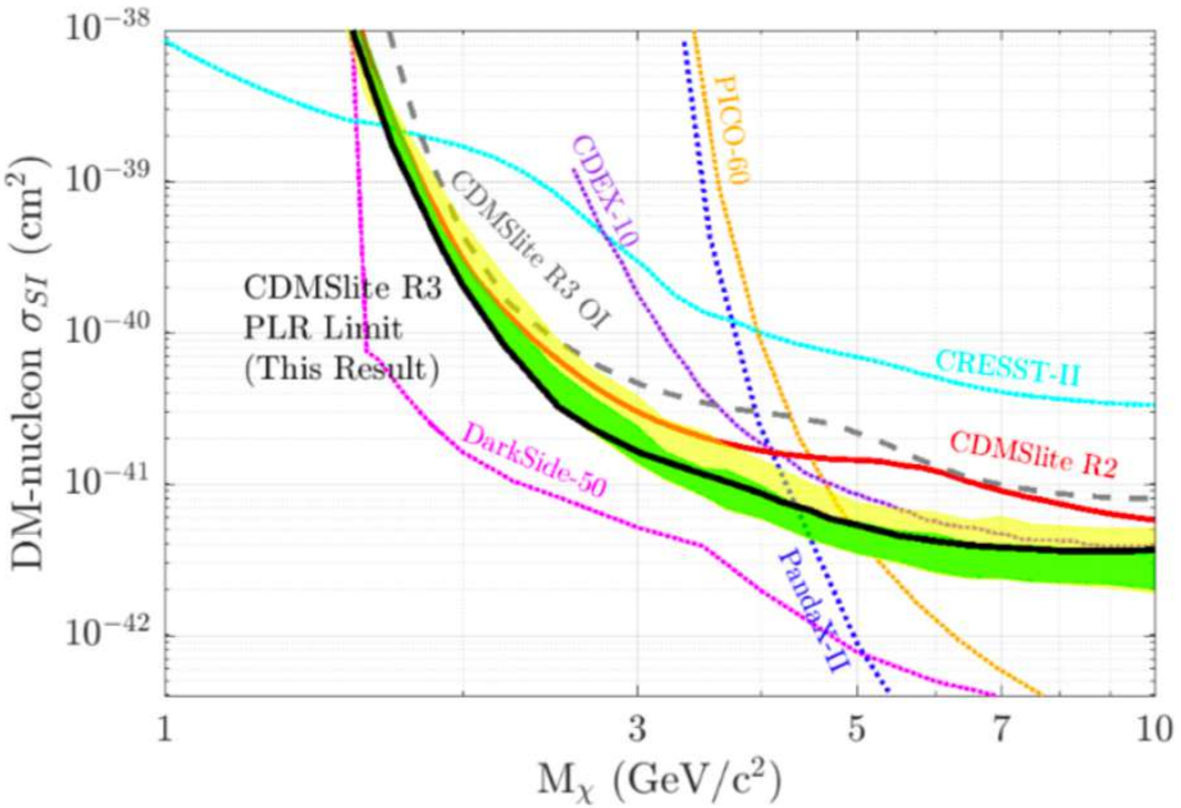
PANDAX 1708.06917
54000 kg day

LUX 1608.07648
33500 kg day

XENON1T 1805.12562
362000 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



Low-mass DM searches at SuperCDMS

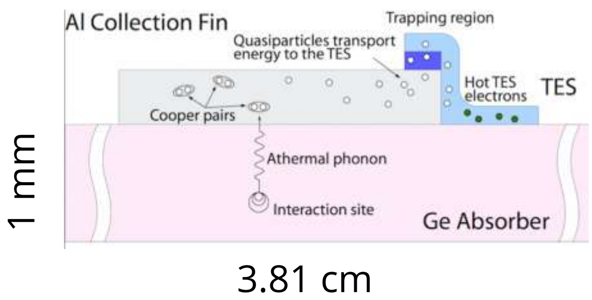
1. Athermal (Si) surface detector

2. HVeV (Si) detector

Detectors with **eV-scale** threshold can probe light WIMPS through Nuclear Recoils

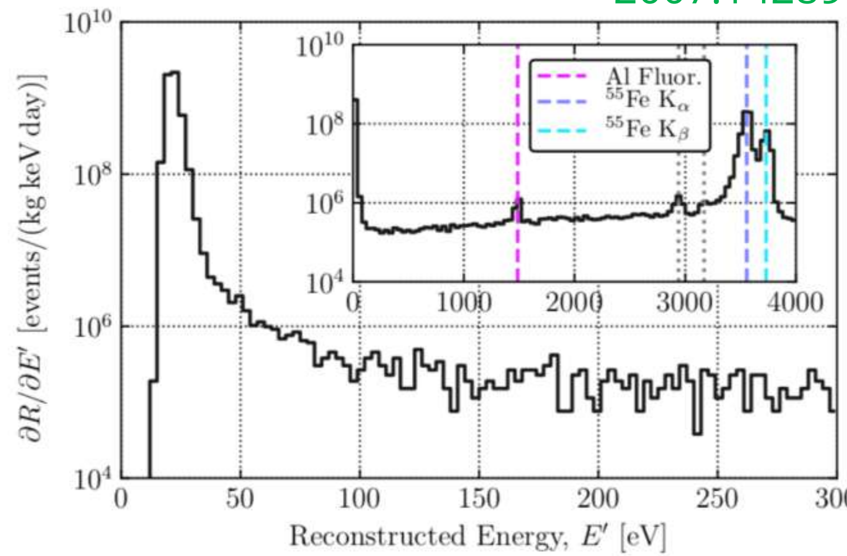
2007.14289

"Athermal" Silicon detector on surface



$\sigma_E = 4.92 \pm 0.01$ eV resolution

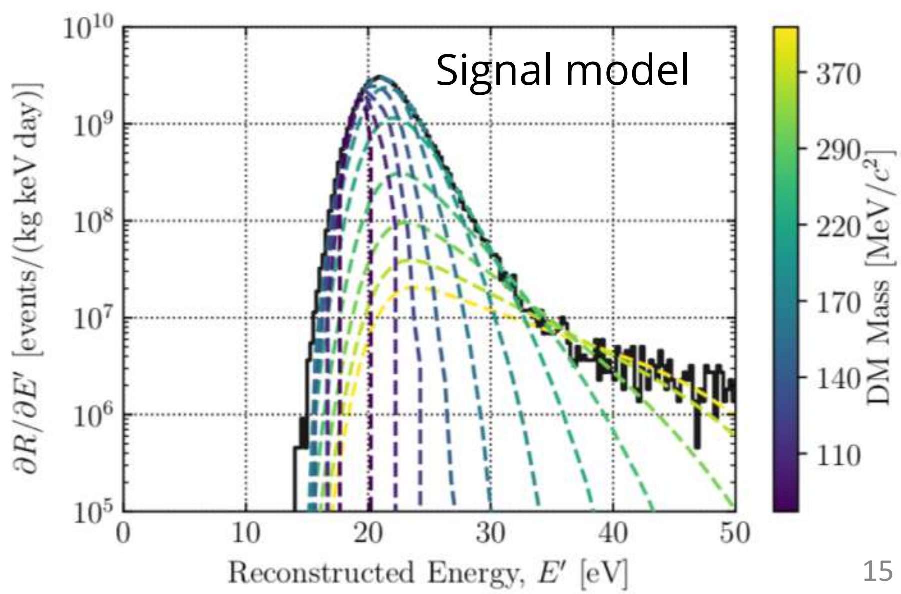
$E_T = 20.7$ eV threshold



Large (cosmogenic) backgrounds – search limited to 22h

9.9 g day exposure (SLAC Sep. 2018)

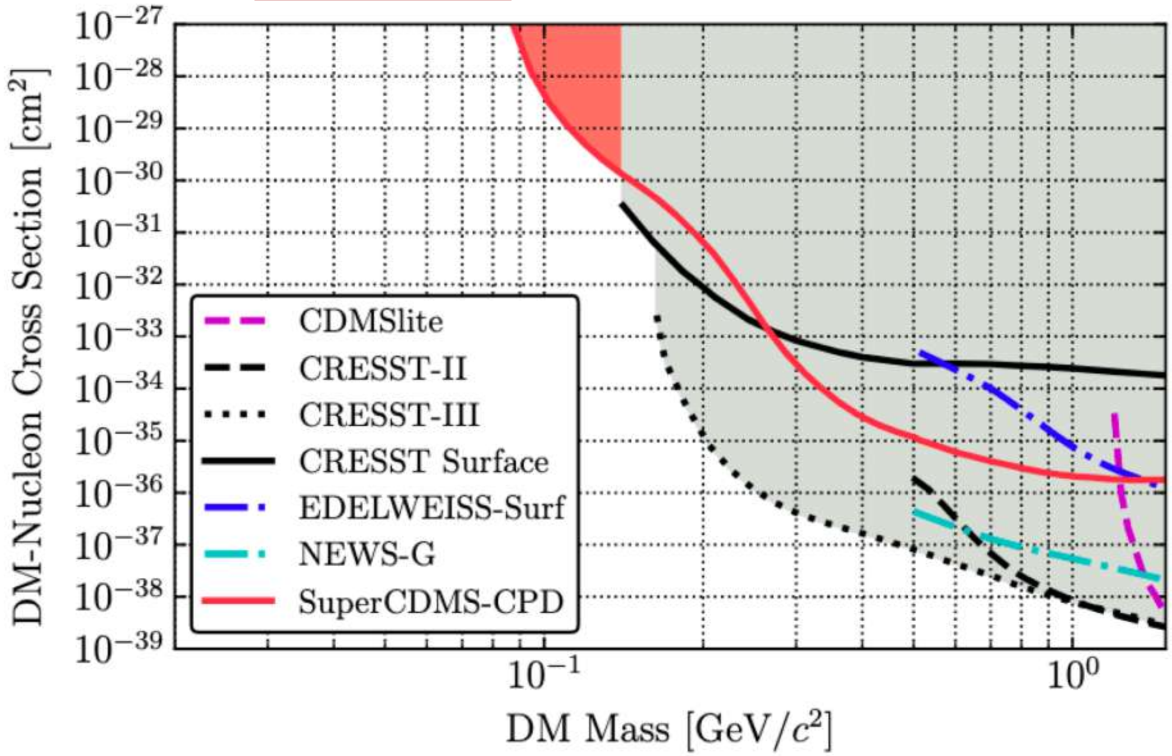
The signal model (for MeV-scale WIMP DM particles) contains trigger threshold and efficiency



Sensitivity to “WIMP” DM reaching ~10 MeV

9.9 g day (Si)

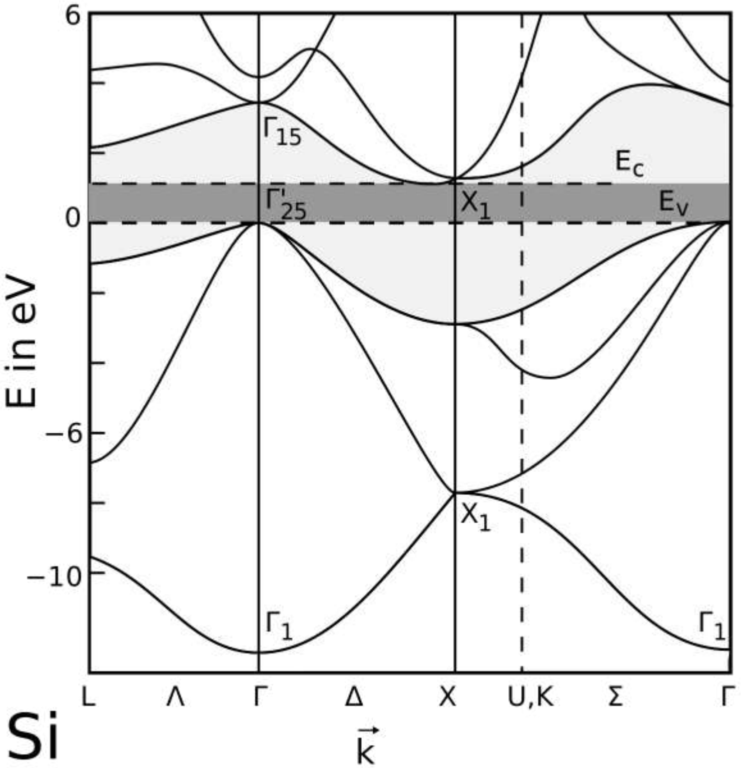
2007.14289



- Plans to operate underground to reduce Compton background
- This detector not optimal (too much surface vs volume reduces the resolution) but demonstrates the potential
- Future detectors ~ 1cm^3

Electron recoil data allows to test very low DM masses

$$E_R = \frac{m_e^2 \, v^2(1-\cos\theta^*)}{m_e}$$



DM particles with MeV mass can lead to electron recoils in the eV range

Excite bound electrons into excited states (in liquid noble gas experiments) or promote them to the conductive band (in solid state detectors)

Semiconductor detectors with sensitivity to single electron-hole (e^-h^+) pairs can be competitive with bigger experiments

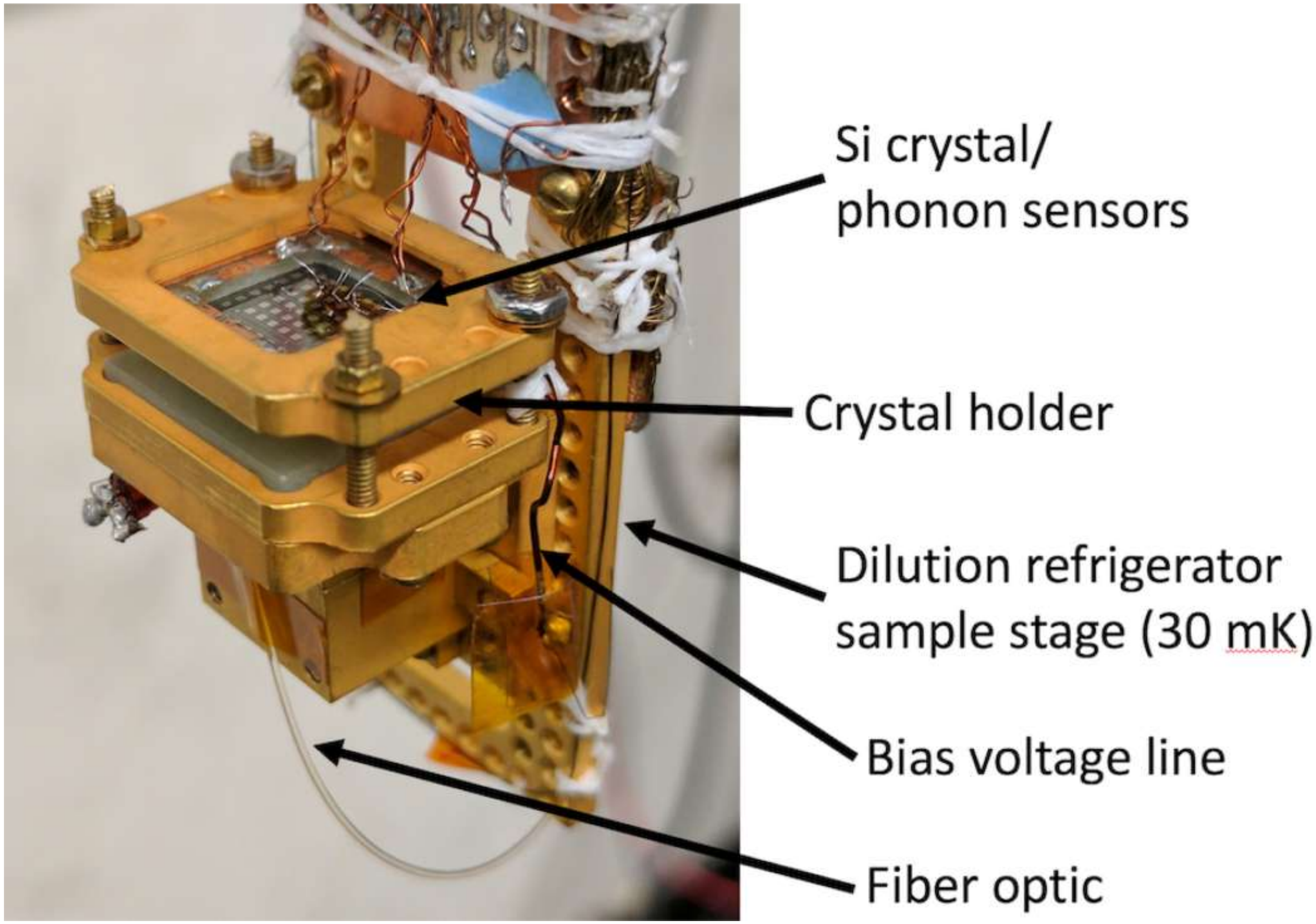
Essig et al (2016)

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

DAMIC, SuperCDMS and SENSEI

CDMS HVeV

First generation Si HVeV detector (0.93 g) - 1 x 1 x 0.4 cm^3



SuperCDMS 1804.10697

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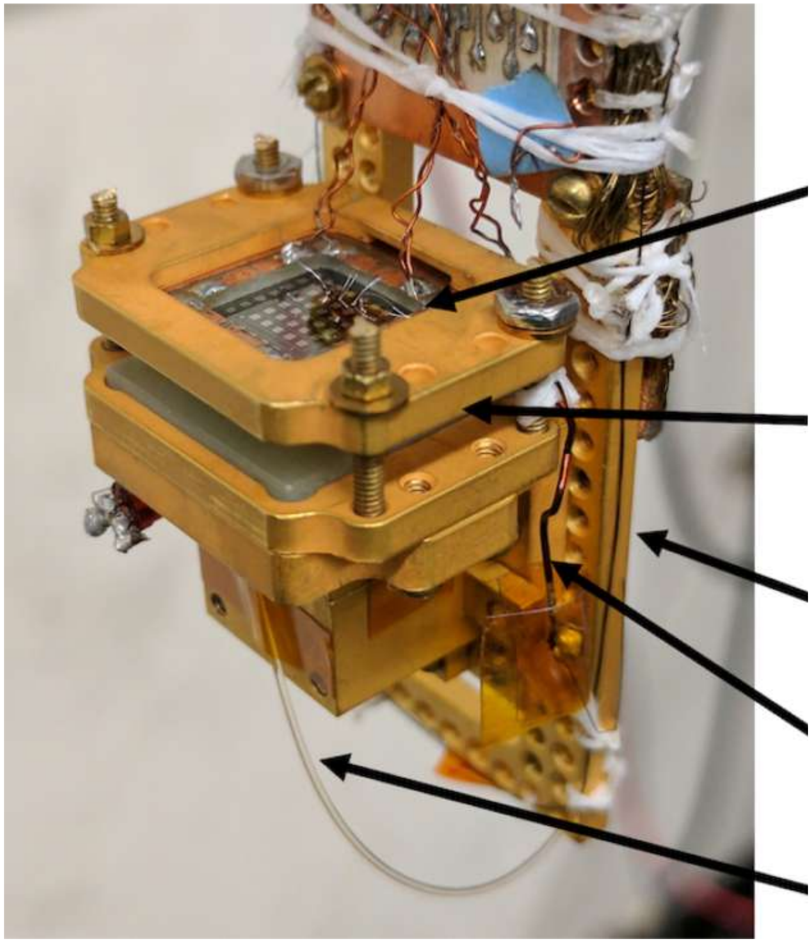
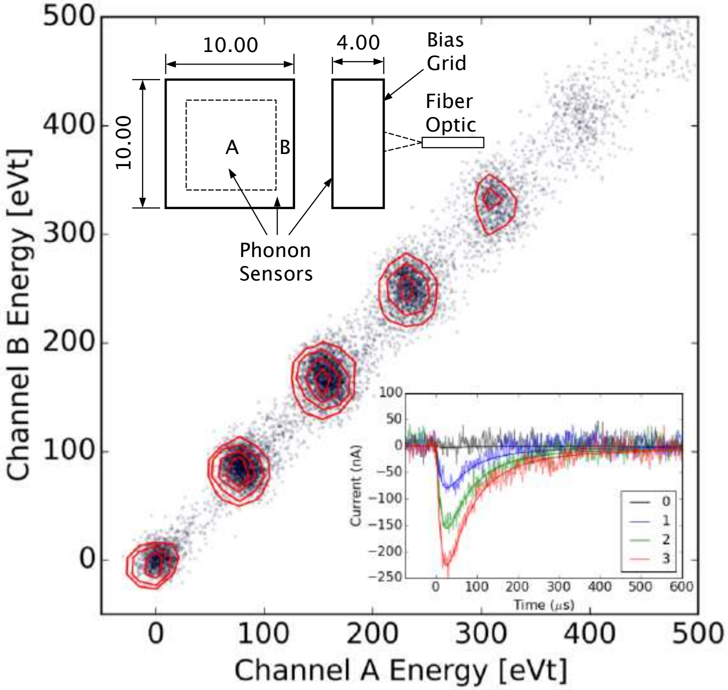




The measurement of single e^-h^+ pairs brings the threshold to the ~3 eV scale

Excellent resolution ~ 3% of single e^-h^+ pair

SuperCDMS 1804.10697

CDMS HVeV

SuperCDMS (HVeV) 2005.14067

- Above-ground Search with an improved 2nd generation detector

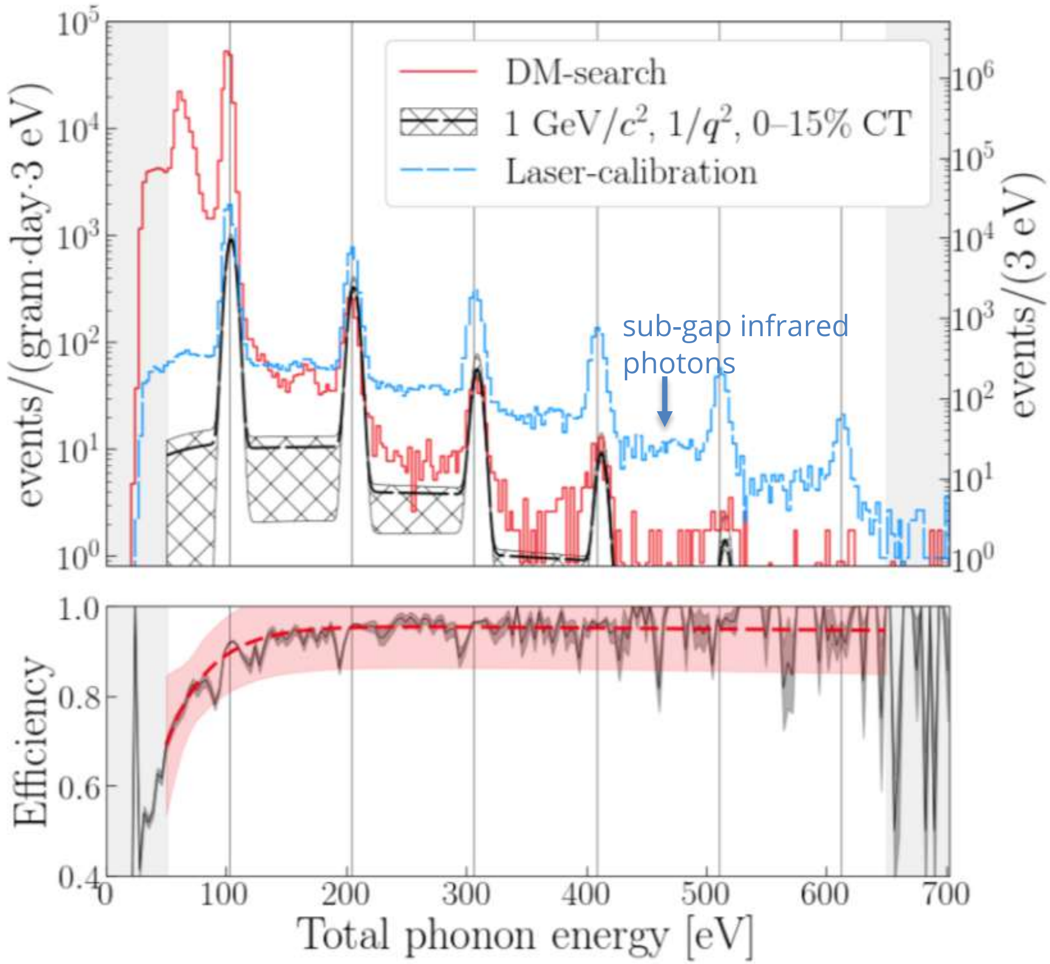
1.2 g day exposure

(North Western Apr. 2019)

$\sigma_E = 3$ eV resolution

$E_T = 0.4\ e^- h^+$ threshold

- Background events from charge leakage and sub-gap infrared photons



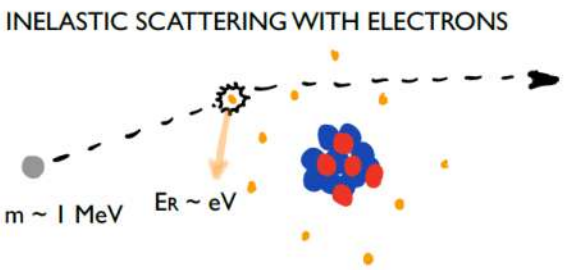
$$E_n = n(E_\gamma + e \cdot V_{\text{bias}}),$$

Direct Detection of MeV Dark Matter

DAMIC at SNOLAB 1907.12628
SuperCDMS HVeV 1804.10697
SENSEI 1901.10478
XENON10, Essig et al 1206.2644

- MeV boson or fermion DM thermally produced (e.g. secluded models)
- Light Freeze-in DM

Boehm Fayet 2004
Essig et al. 2016



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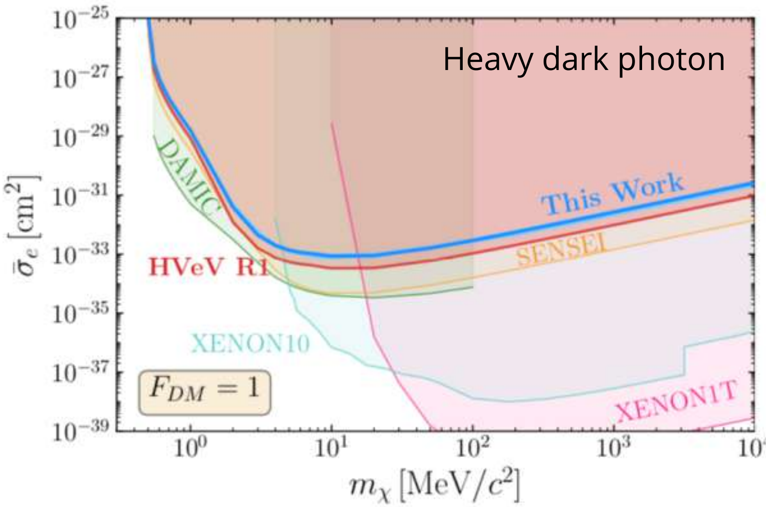

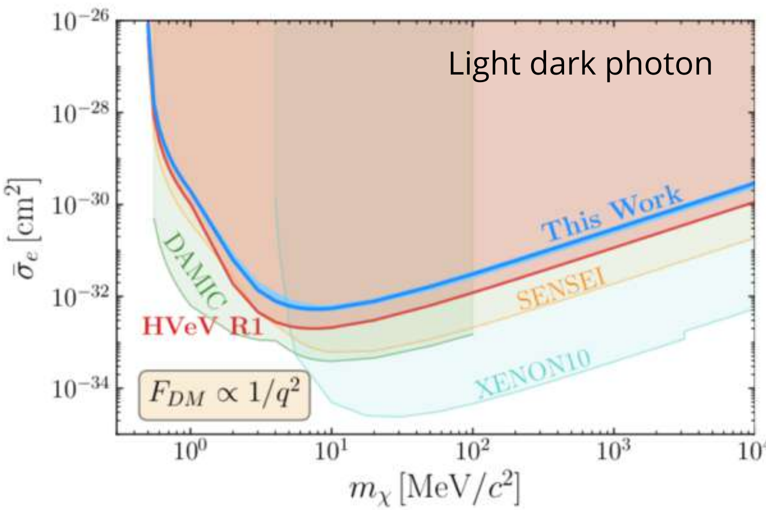

SuperCDMS (HVeV) 2005.14067

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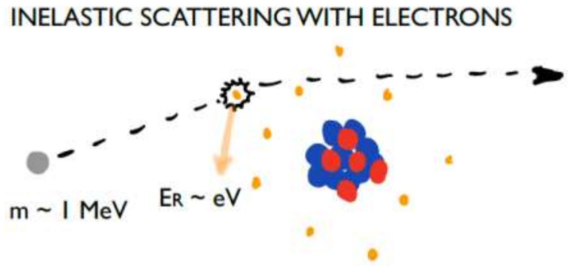
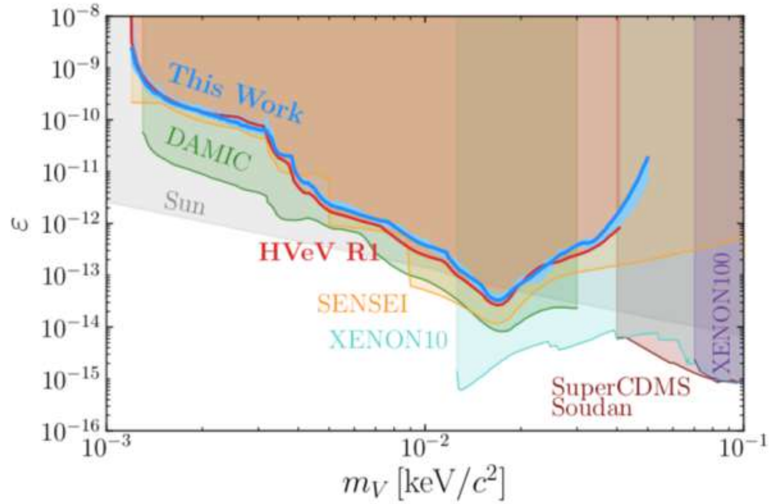
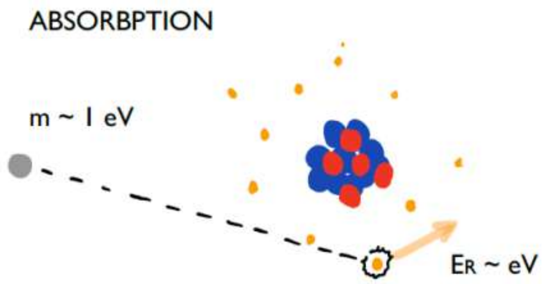
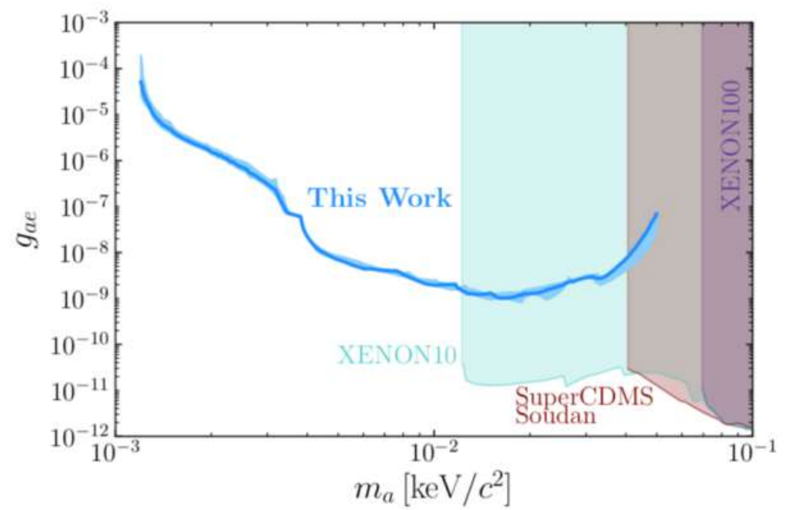




Direct Detection of eV Dark Matter

- Dark Photon (kinetic mixing and axioelectric coupling)



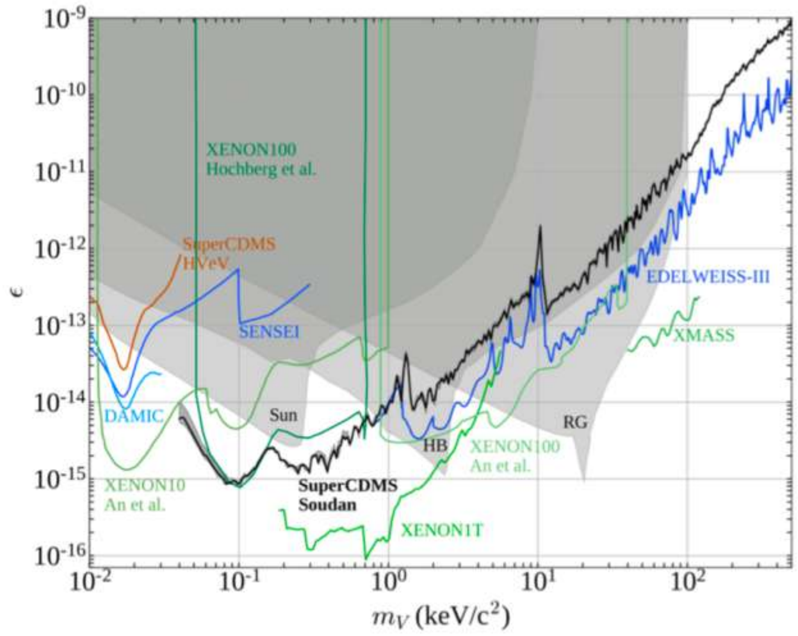


SuperCDMS (HVeV) 2005.14067

Improves previous constraints (iZIP)

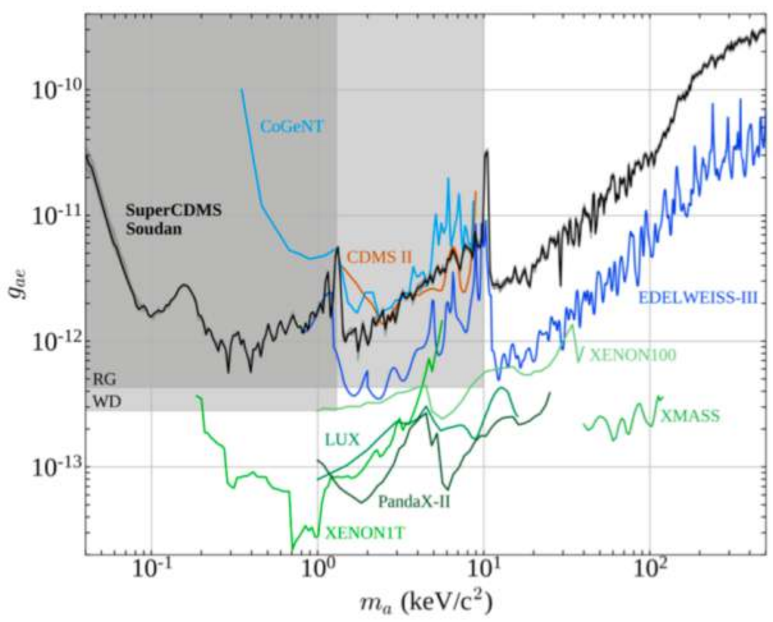
DARK PHOTONS

$$\sigma_V(E_V) = \frac{\epsilon^2}{\beta_V}\sigma_{pe}(E_V),$$



ALPS

$$\sigma_a(E_a) = \sigma_{pe}(E_a)\frac{g_{ae}^2}{\beta_a}\frac{3E_a^2}{16\pi\,\alpha\,m_e^2c^4}\left(1-\frac{\beta_a^{2/3}}{3}\right)$$



SuperCDMS (iZIP) 1911.11905

Summary

- Low-threshold devices (E_T~eV) are excellent probes of low-mass DM, testing more general models (freeze-in, ALPs, dark photons)

  - Nuclear recoil searches allow to constrain ~**10 MeV** scale DM

  - Electron inelastic scattering sets limits on **MeV** candidates

  - Electron absorption probes **eV** scale ALPs and Dark Photons


DARK MATER
ESITEN
… we'll have to keep trying
until we get a better result.