Exciting recent developments in low threshold detectors and low mass dark matter direct detection

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Southern Methodist University/SuperCDMS

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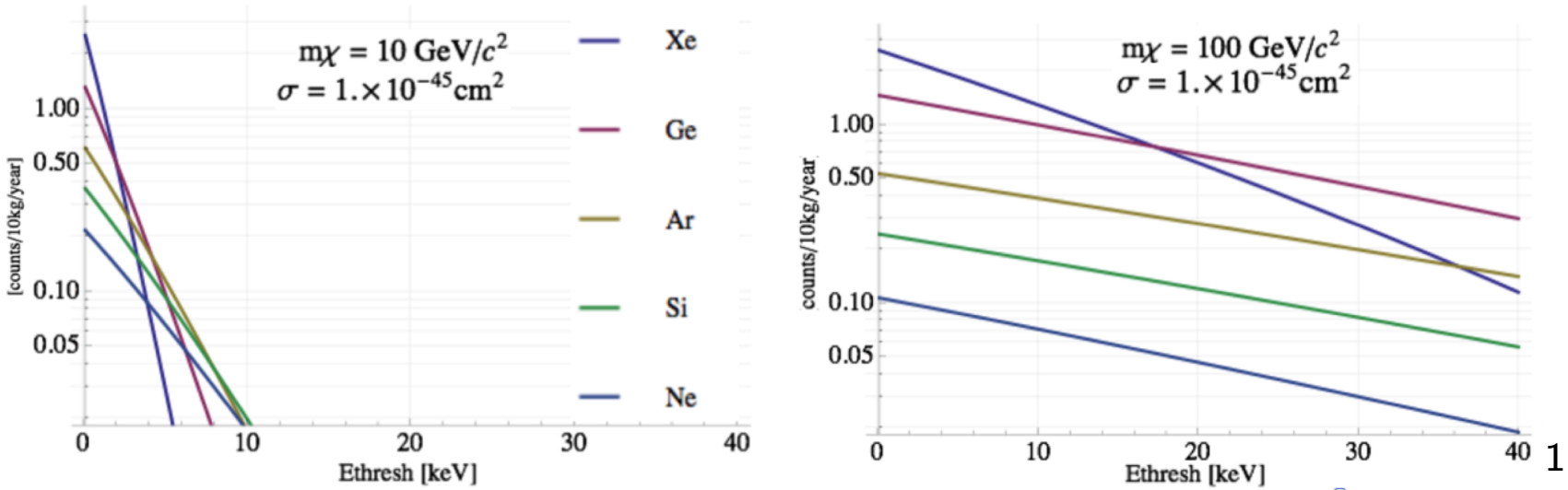
Choice of target material

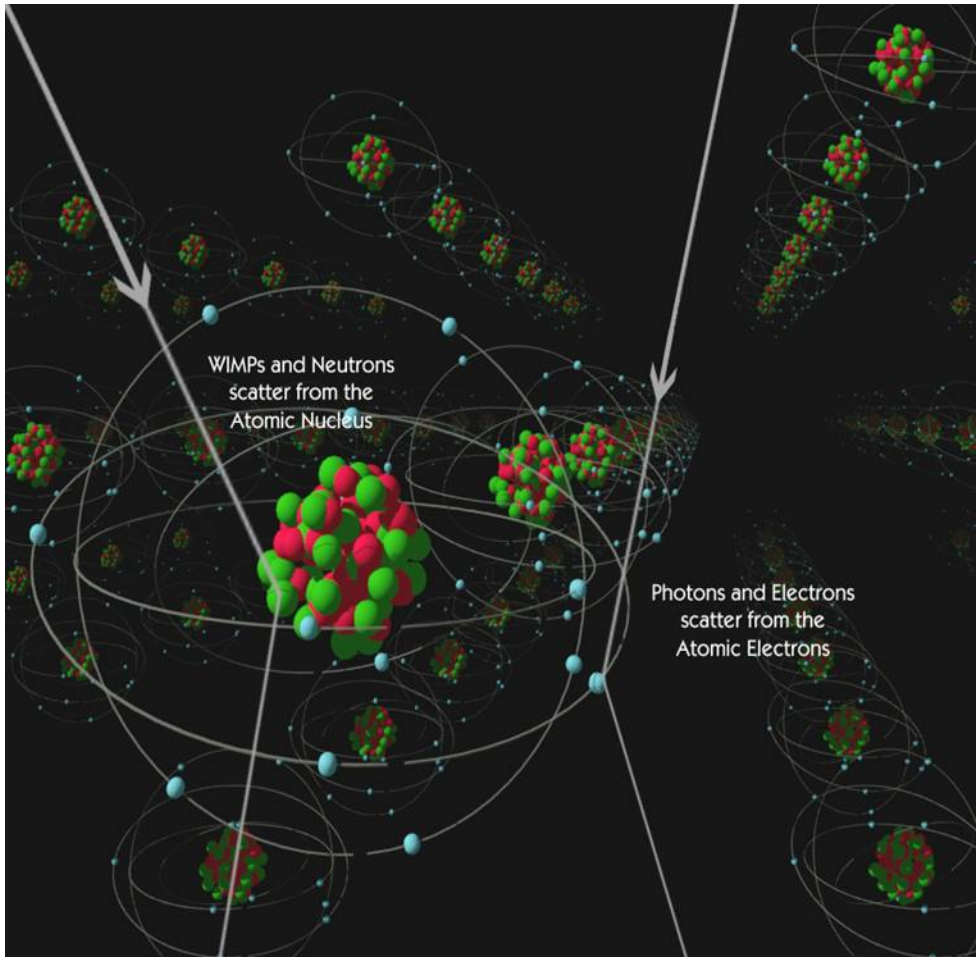


[1]

- Event rates depend on WIMP and target nuclei mass
- Thresholds matter a lot, especially for low masses!
- Up-turn in limit plots at low masses caused by this
- Spin-dependent interactions add a whole additional layer of complexity

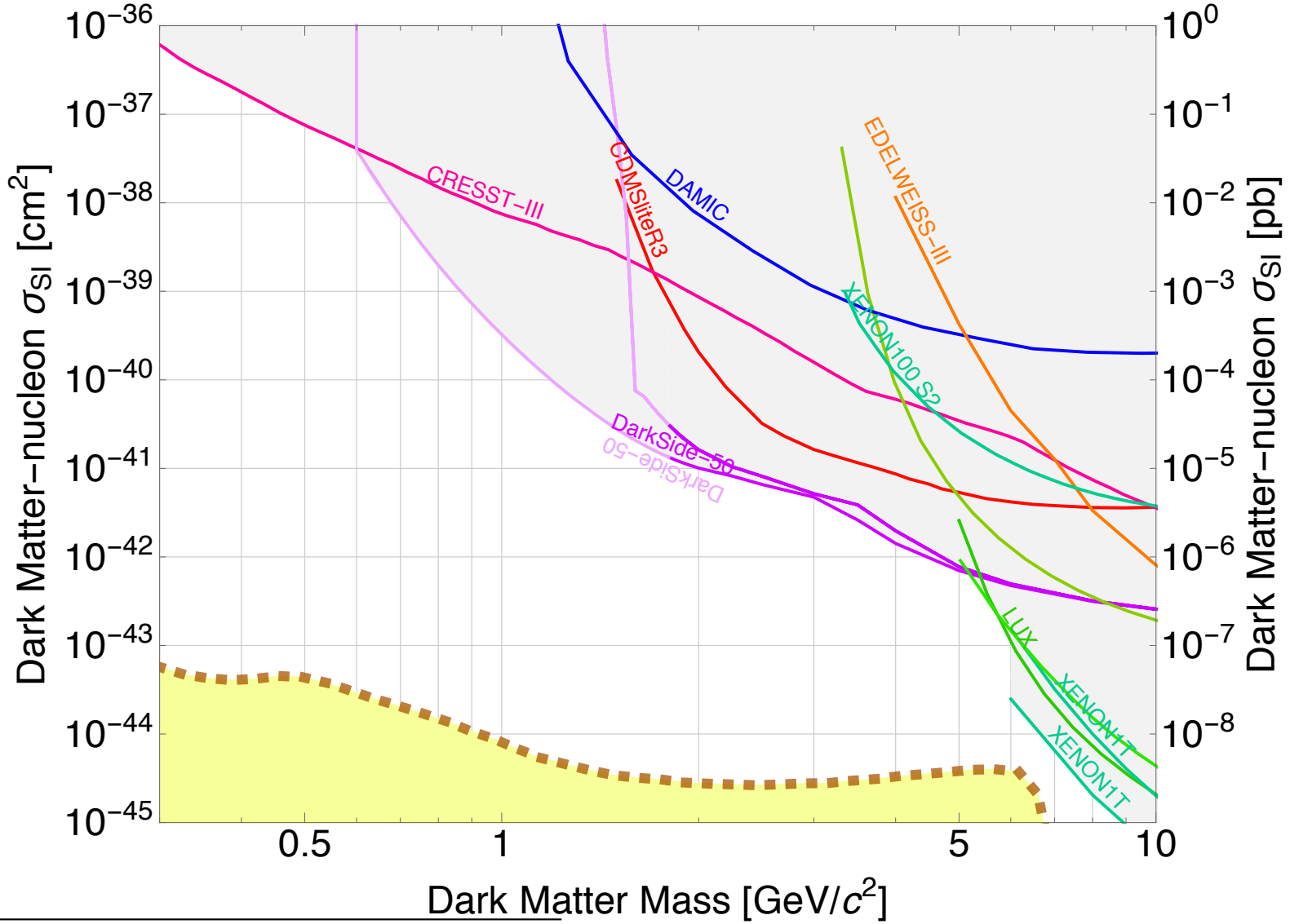
[1] arXiv:1308.0044 [astro-ph.IM]

WIMP-nucleus interactions



- Interactions come in two types
  1. Nuclear recoil (NR) - recoils against nucleus
  2. Electron recoil (ER) - recoils against surrounding electrons

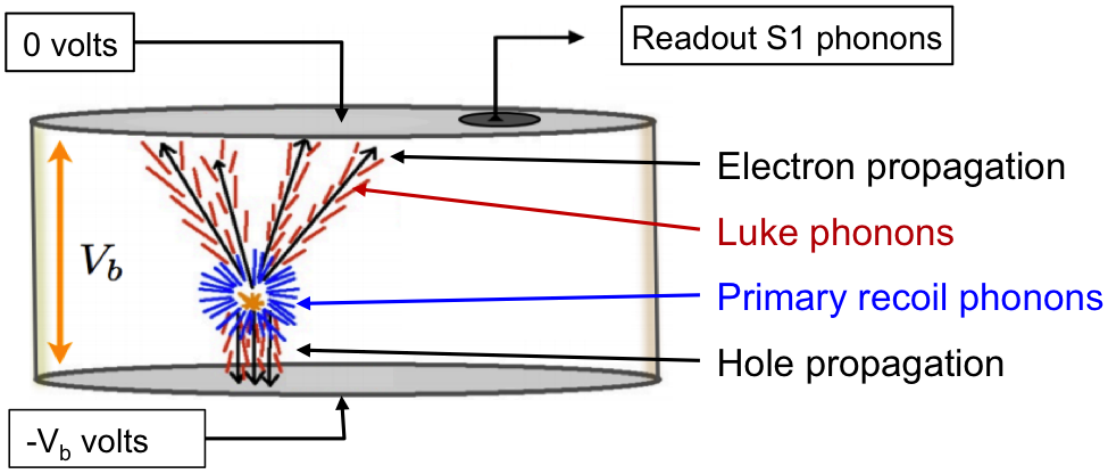
State of the low mass WIMP

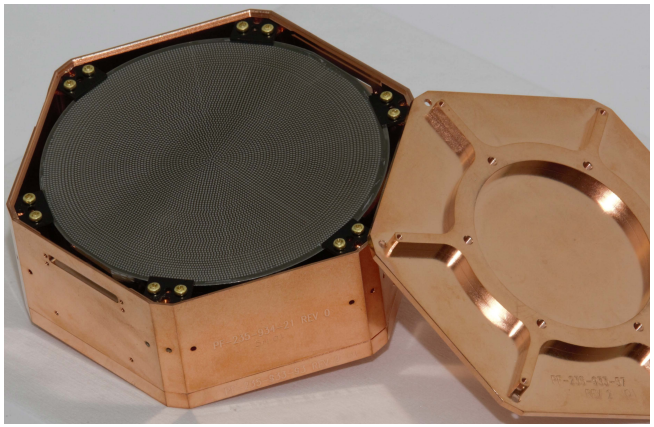


[2]

[2] Apologies to any experiments overlooked

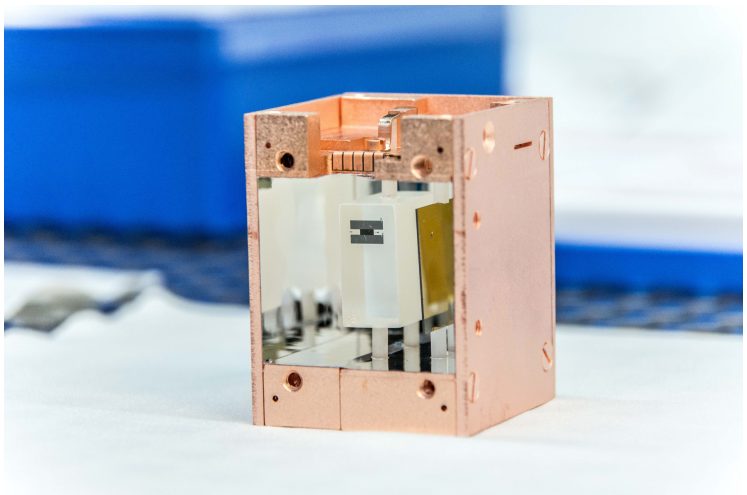
HV Biasing of crystals - SuperCDMS

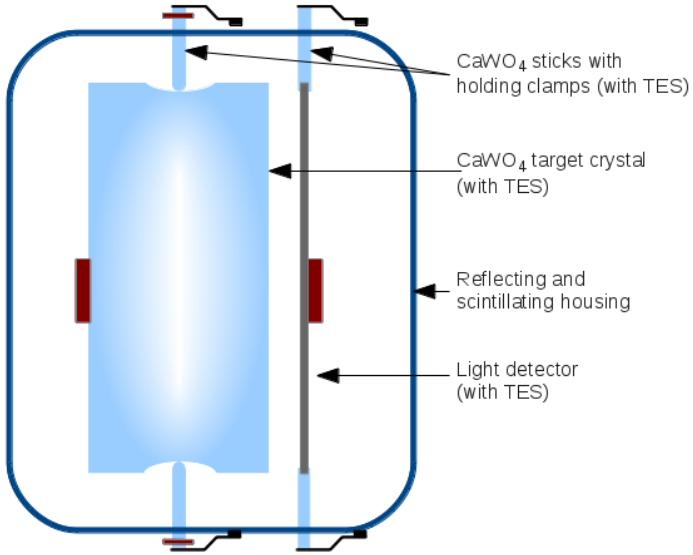




- Phonons are created from charges passing through a crystal through Neganov-Trofimov-Luke effect
- The contribution to total phonon energy goes as $N_{e/h}eV_b$: proportional to bias voltage V_b
- High bias voltage allows us to measure small amount of charges through phonon signal - amplification
- Trade-off: no separate measurement of primary phonon signal, sacrifices ER/NR discrimination

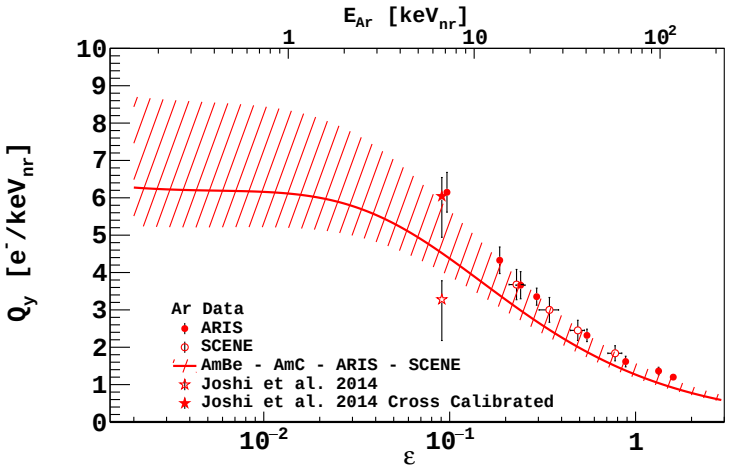
CRESST-III

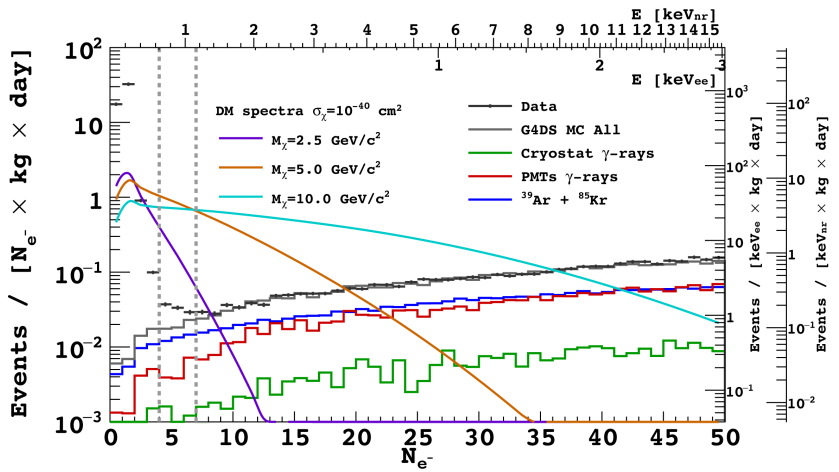


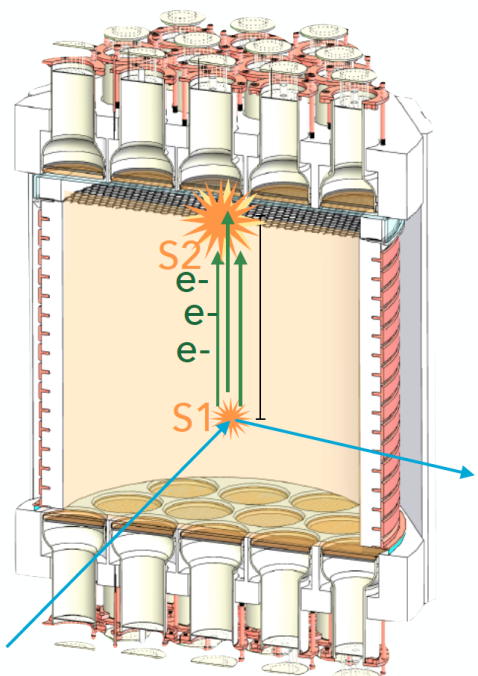


- CRESST had issues with clamps in the past but now resolved
- Crystal is $CaWO_4$ which provides light nuclei targets - sensitivity to low masses
- Looks for scintillation light using TES based photon sensors

Darkside-50 (and liquid nobles in general)- Phys. Rev. Lett. 121, 081307

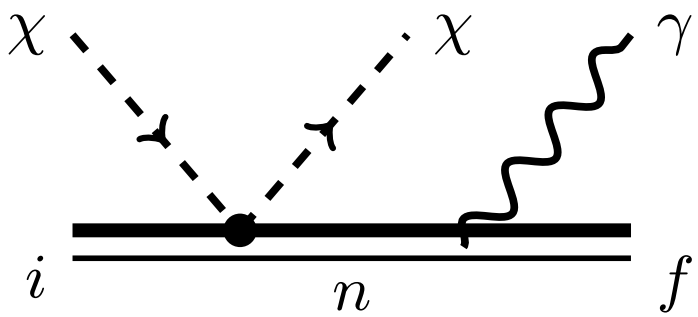


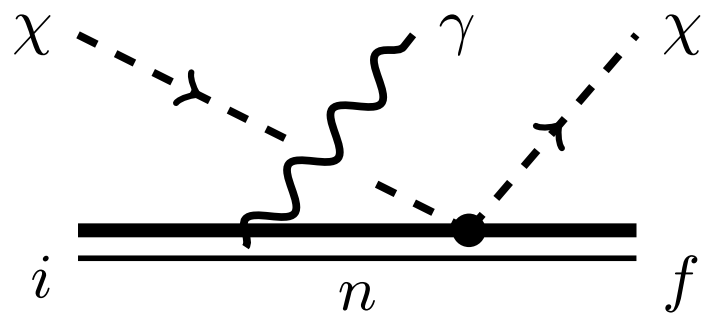


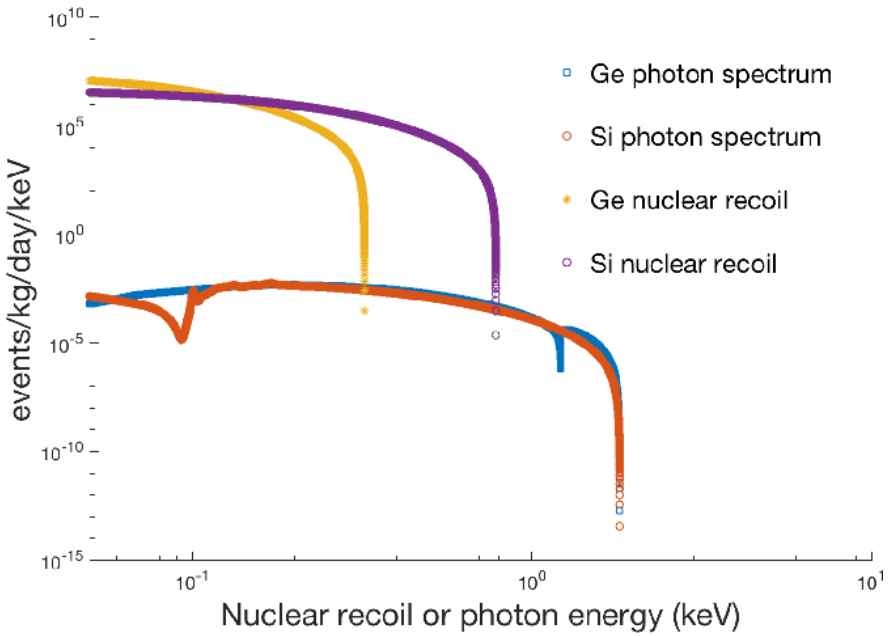


- Operate as TPC - charges drift in E-field and are amplified by transition radiation
- S2-channel is similar to NTL amplification
- Experimental difficult in understanding light yield at low recoil energies Crystals have this difficulty too

Bremsstrahlung - Kouvaris and Pradler Phys. Rev. Lett. 118, 031803





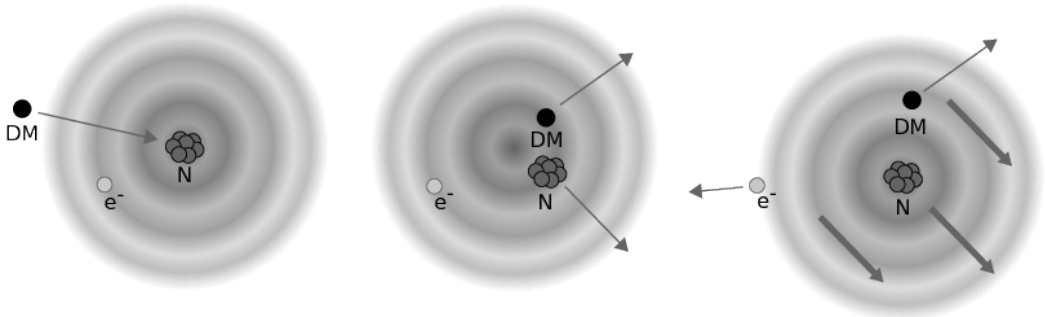


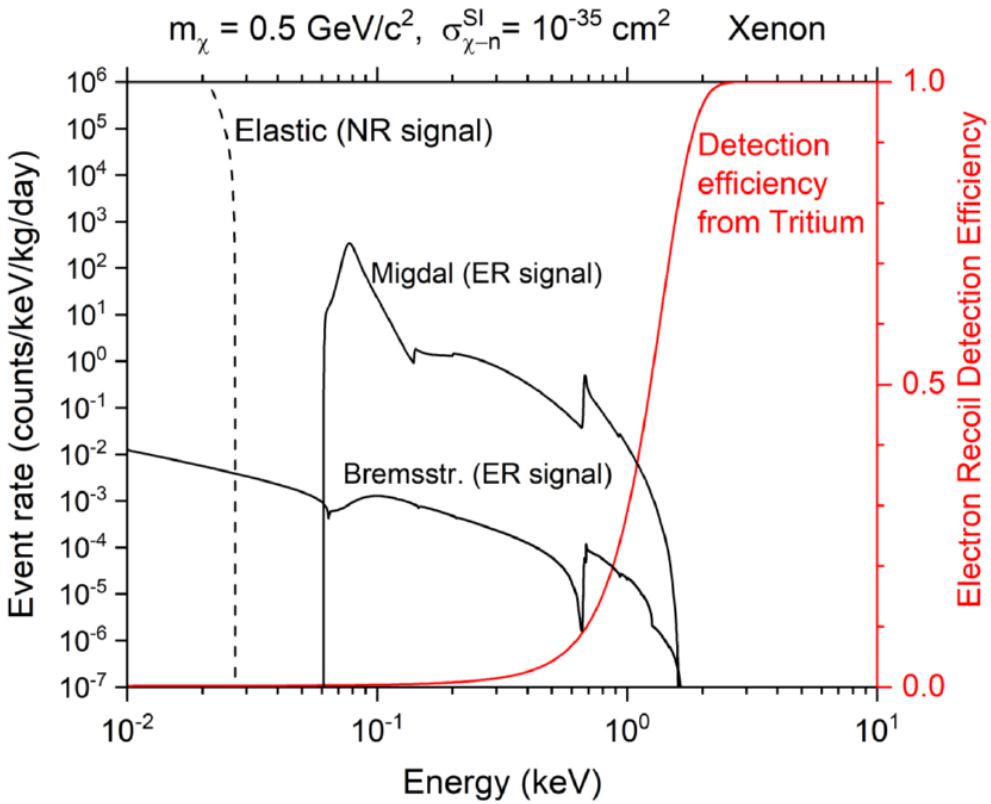
1 GeV WIMP

- Recoiling nucleus can emit a photon as it slows down in material
- Energy of this photon can extend to higher energies than NR
- Photon acts as probe to low mass WIMP scattering below detector threshold

Migdal effect - Ibe, Nakano, Shoji and Suzuki JHEP 1803 (2018) 194;

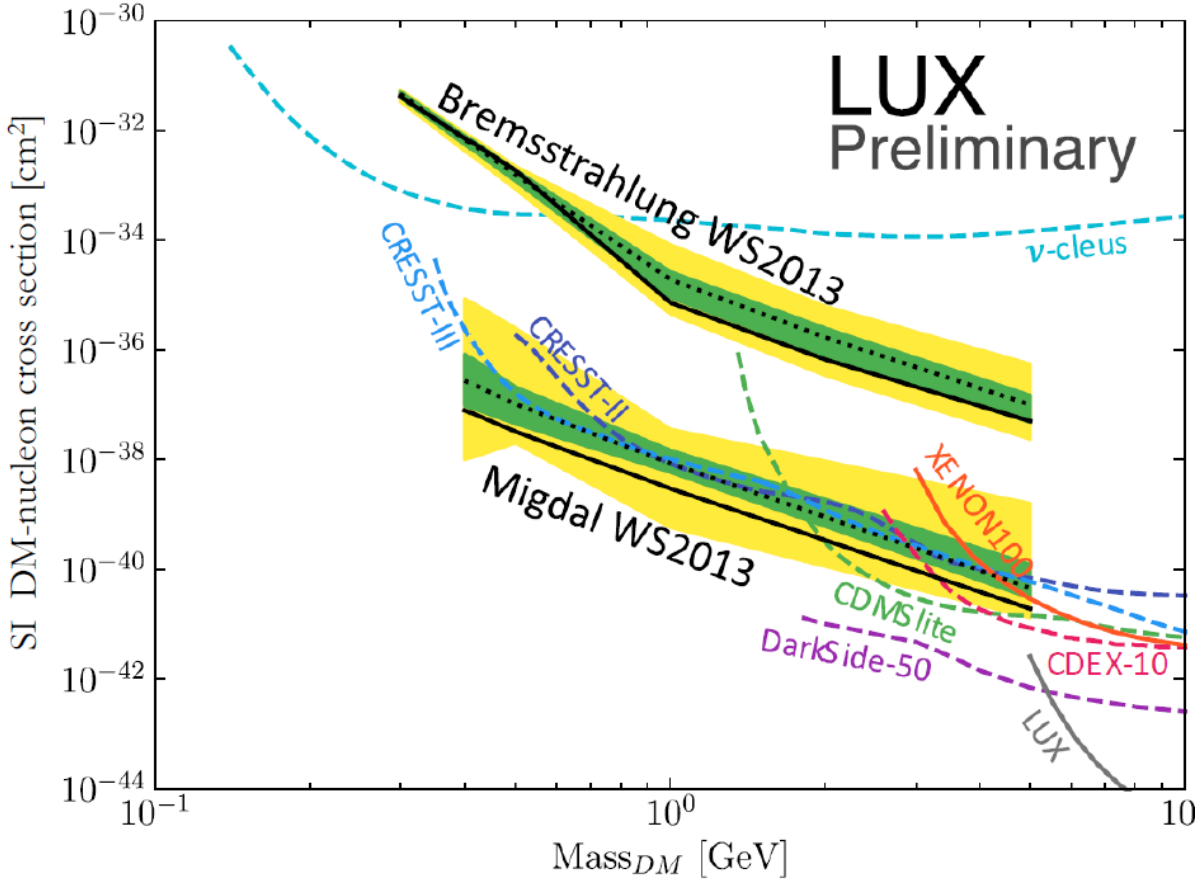
Dolan, Kahlhoefer, and McCabe Phys. Rev. Lett. 121, 101801 (2018)





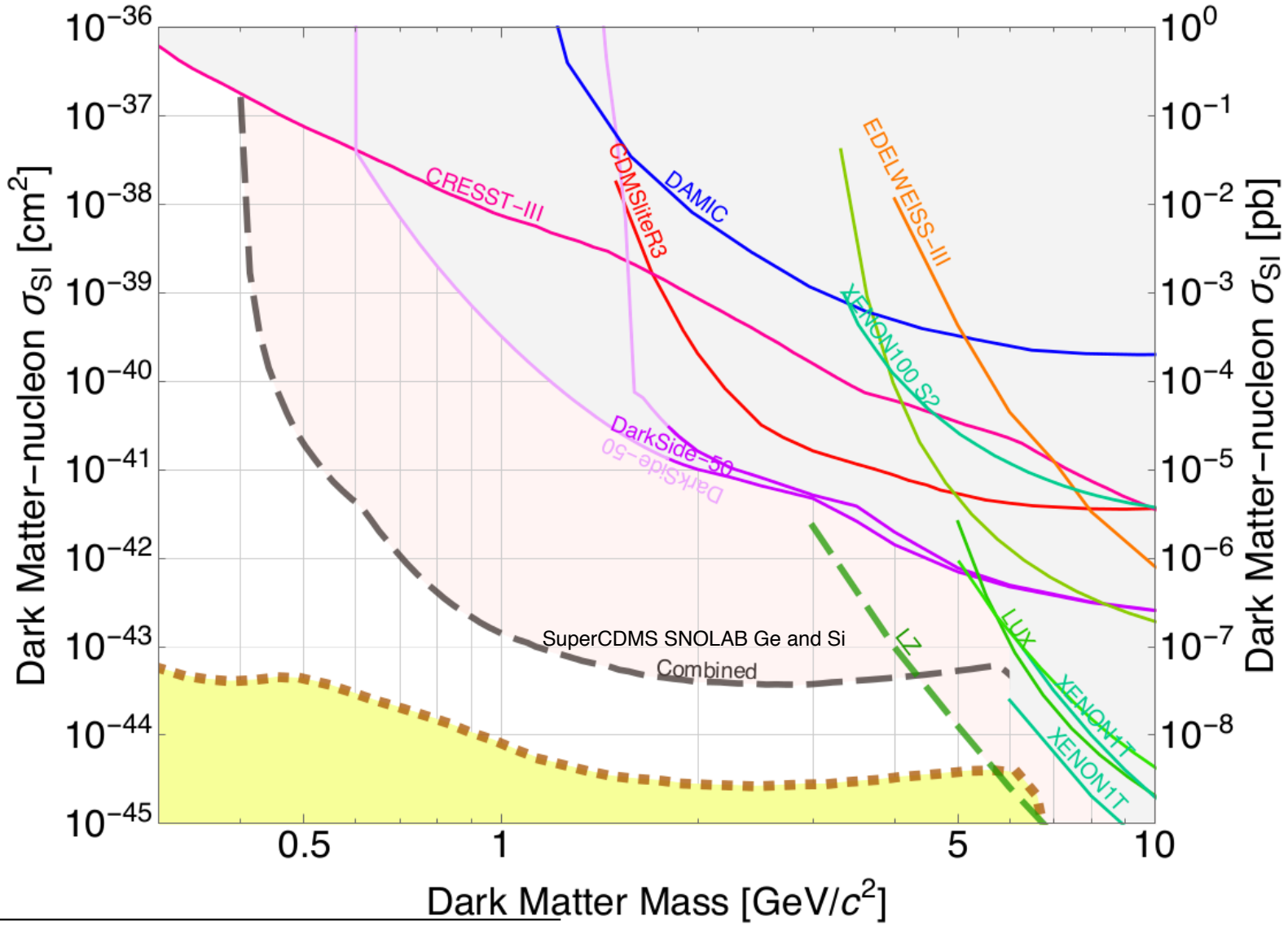
- Like Bremsstrahlung, electron and photon emission created by nucleus
- Spectrum of emission extends higher than NR
- Nuclear recoils, electron cloud is perturbed
- Higher cross-section that Bremsstrahlung since you don't have to create any particles

Migdal effect - LUX IDM 2018



- Allows high threshold detectors to be competitive at low masses
- Caveat : Migdal effect has not been observed experimentally

State of the low mass WIMP - projections



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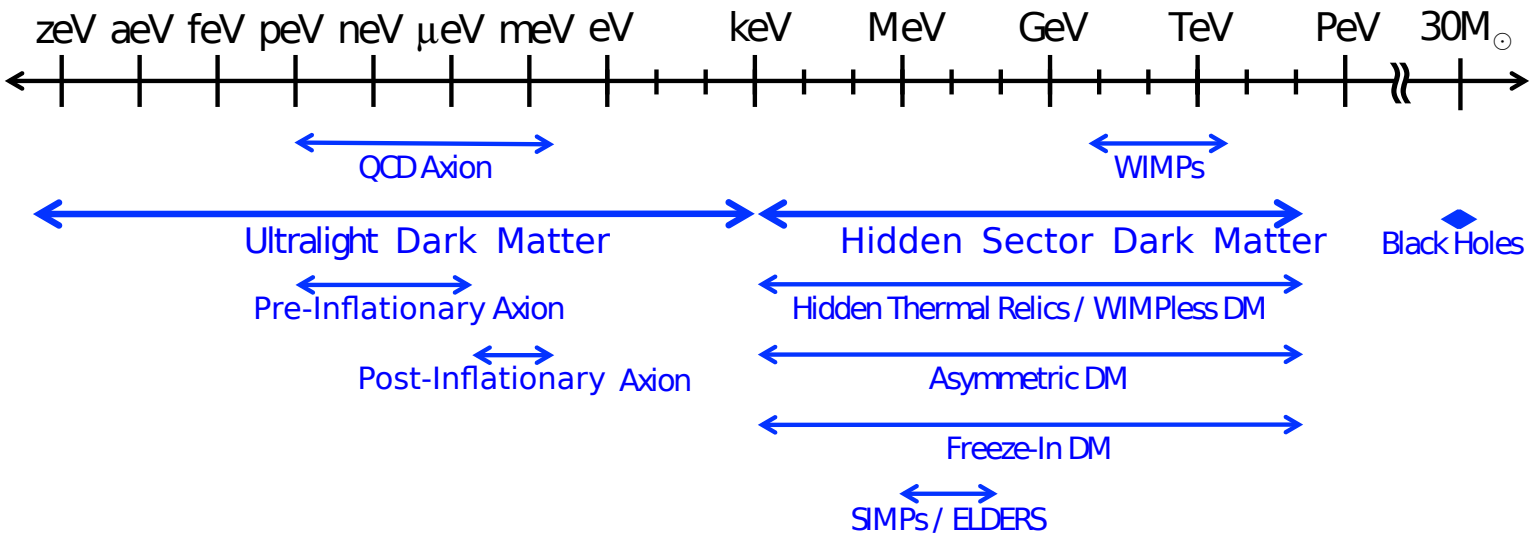
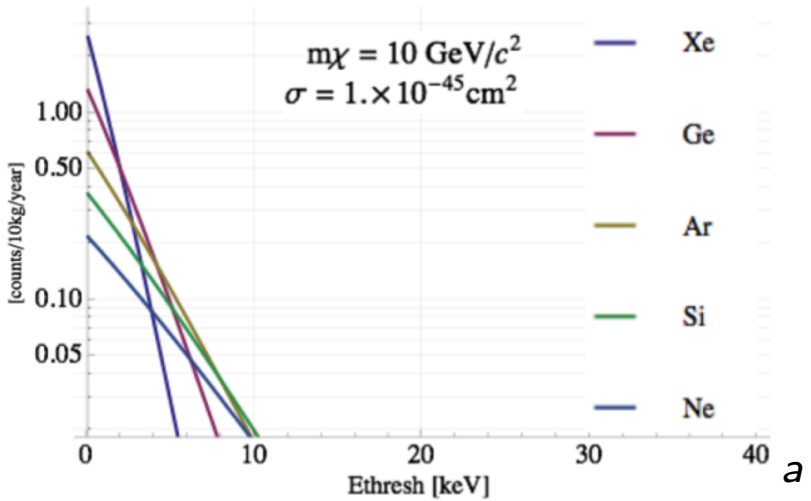
[3] Apologies to any experiments overlooked

Beyond the WIMP Battaglieri et al. arXiv:1707.04591

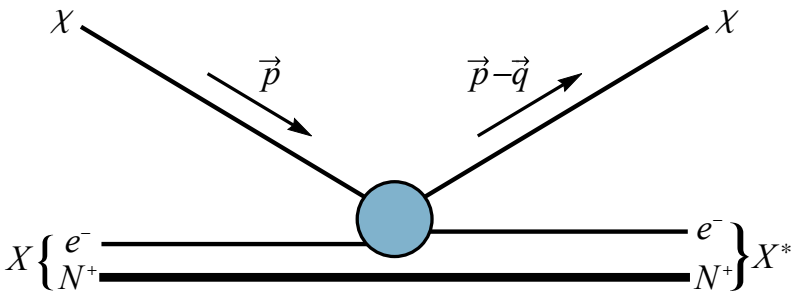


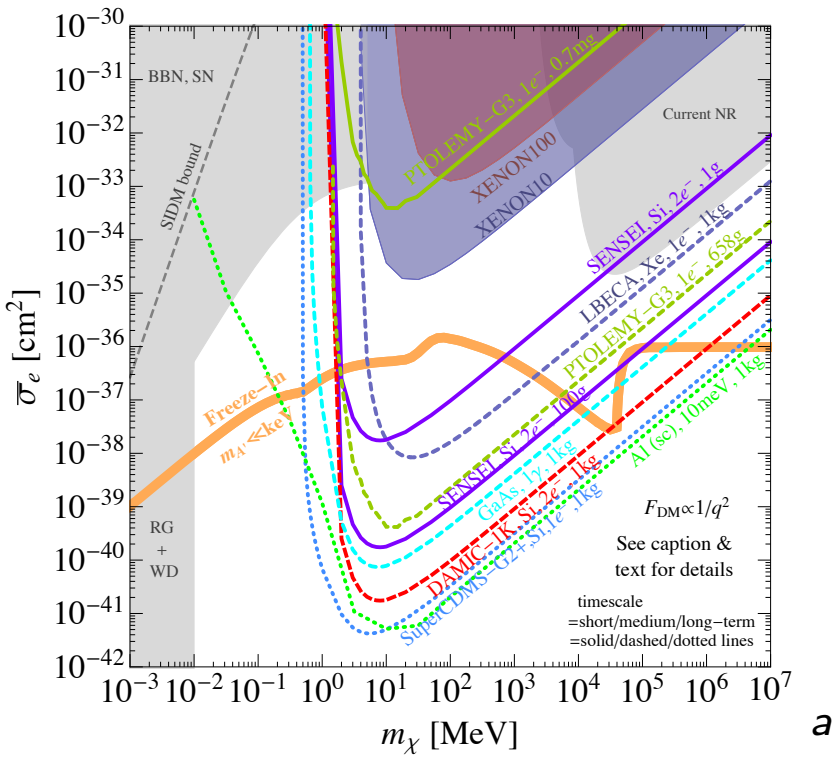
- WIMPs are just one possibility
- Kinematics for light masses dis-favorable, sensitivity driven by threshold
- Need new ideas and approaches to probe these low masses



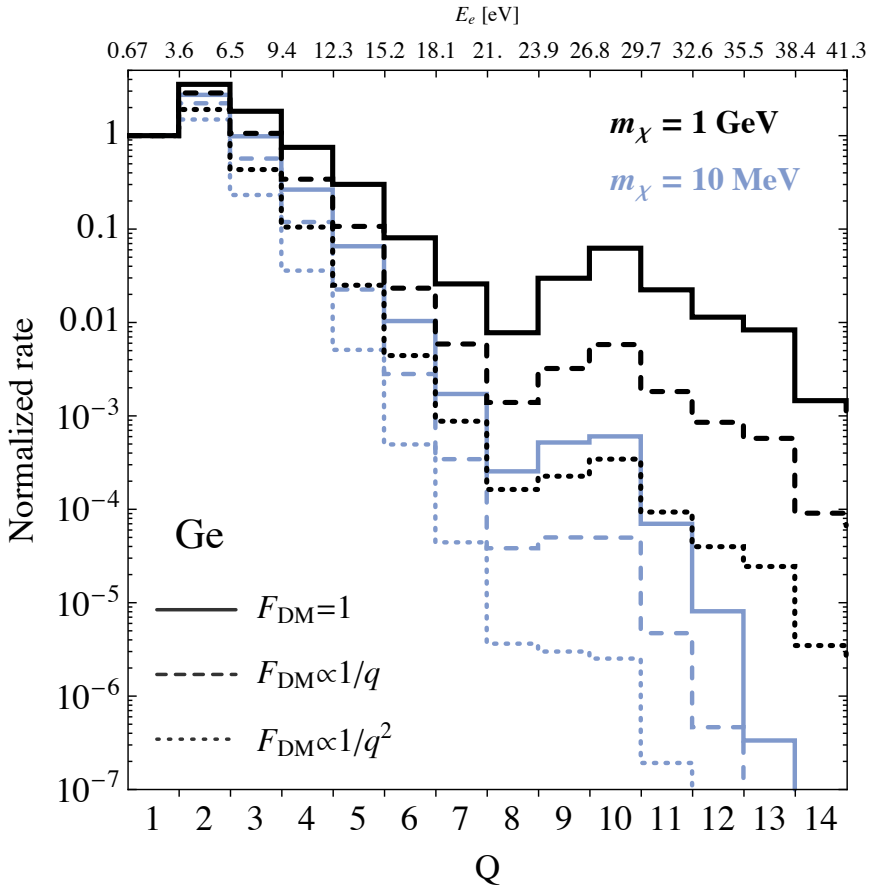
[a] Mirabolfathi - arXiv:1308.0044

DM-electron scattering - Essig et al. JHEP 1605 (2016) 046





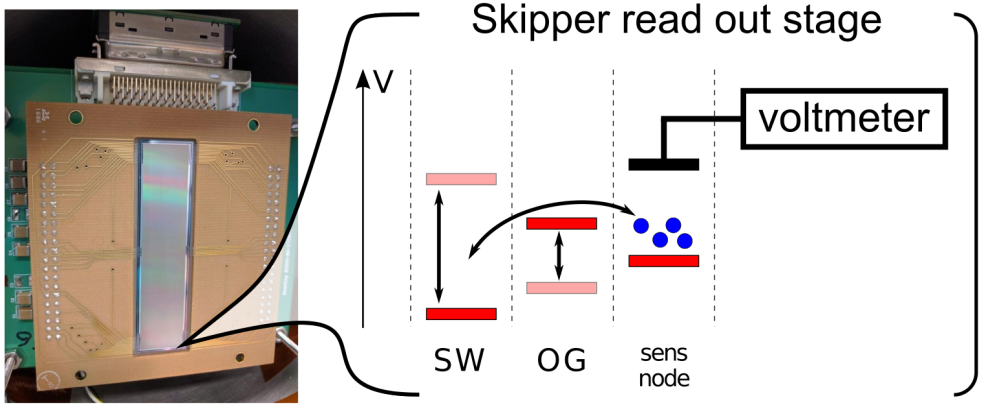
[a]

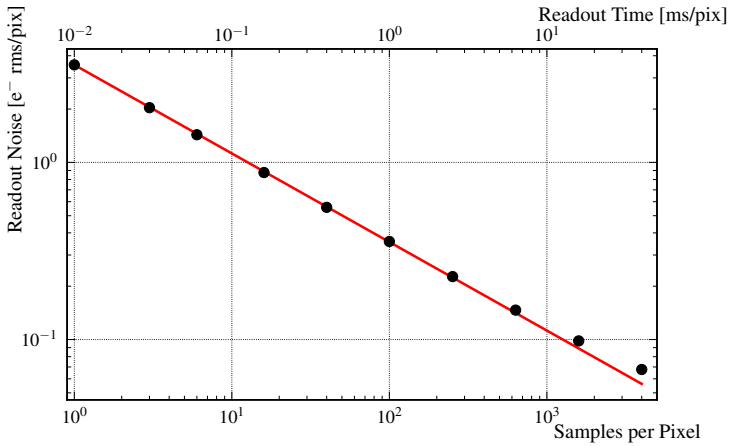


- Sensitivity driven by thresholds
- Search requires good knowledge of electronic structure of target

[a] Battaglieri et al. arXiv:1707.04591

SENSEI - Phys. Rev. Lett. 121, 061803



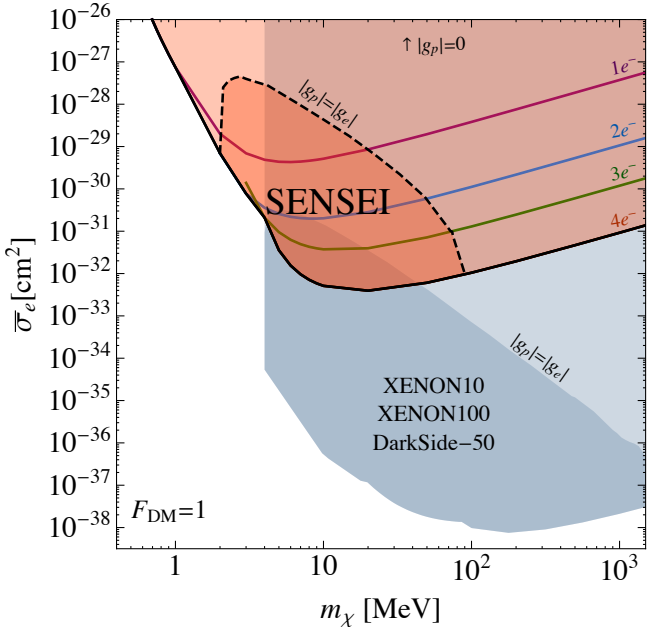


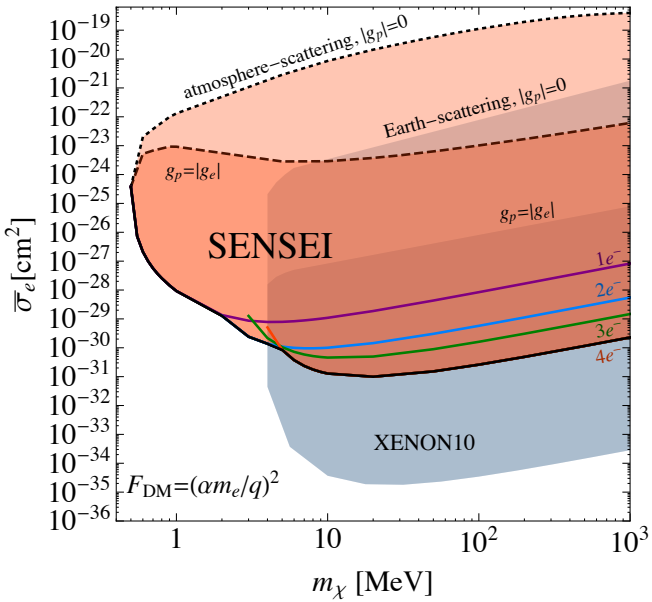
4

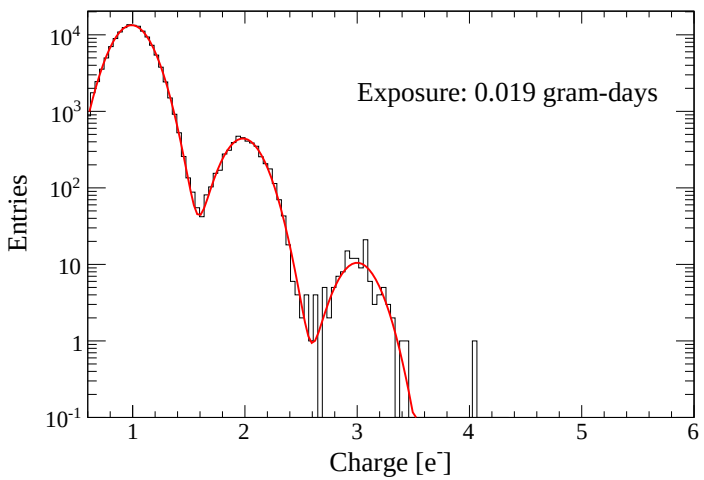
- Skipper CCD based technology - Si target - $\approx$ 3k pixels
- Charges are passed back and forth which reduces sampling noise
- Allows precise measurement of charge in sensor array
- Drawback is that this takes time to readout which means dead-time/loss of exposure

[4] https://home.fnal.gov/ javiert/sensei/

SENSEI - Phys. Rev. Lett. 121, 061803

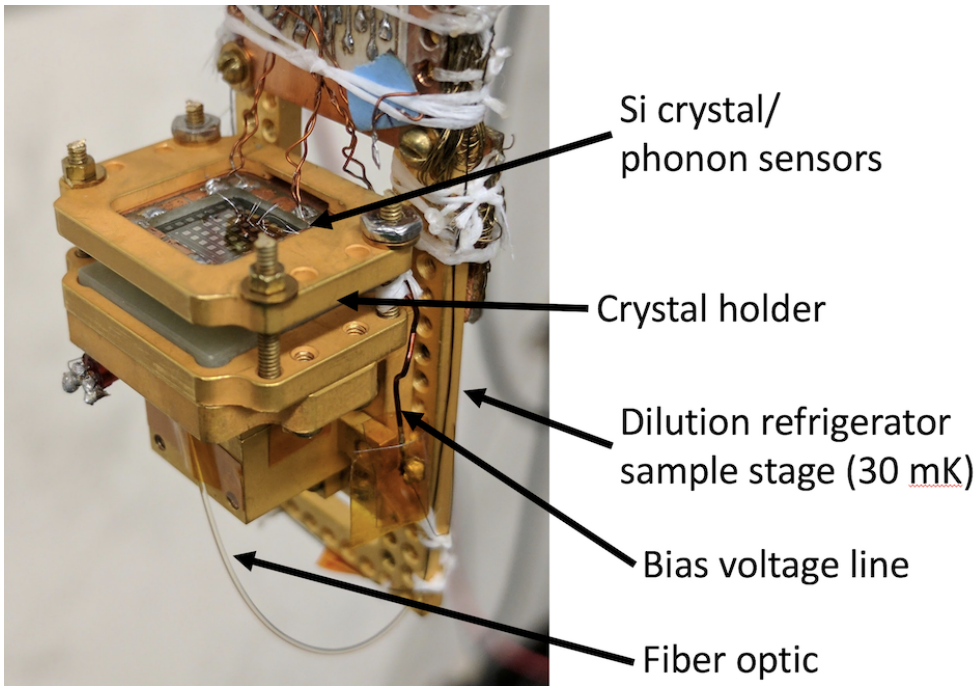


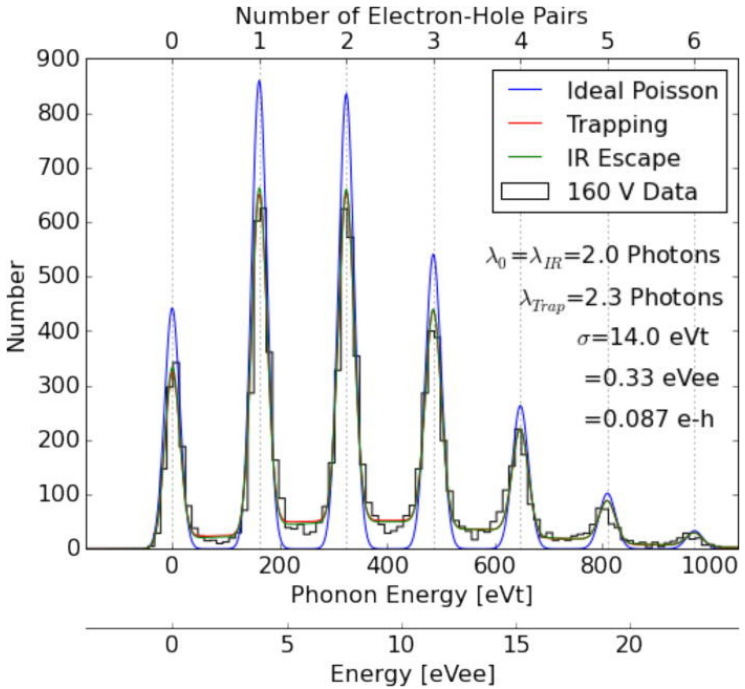




- Sensitivity down to single e/h-pairs
- Band gap for Si is 1.1 eV
- Dark current background on order of $1e^-$/pixel/day

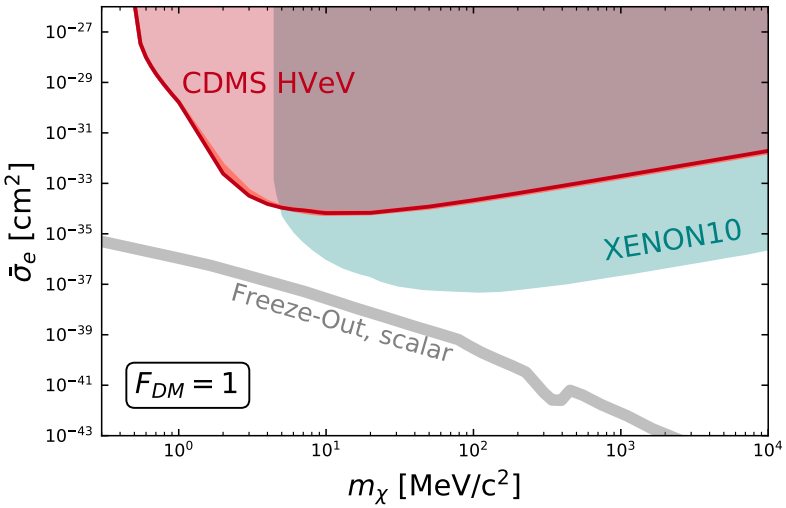
Single e/h device - SuperCDMS arXiv:1804.10697 [hep-ex]

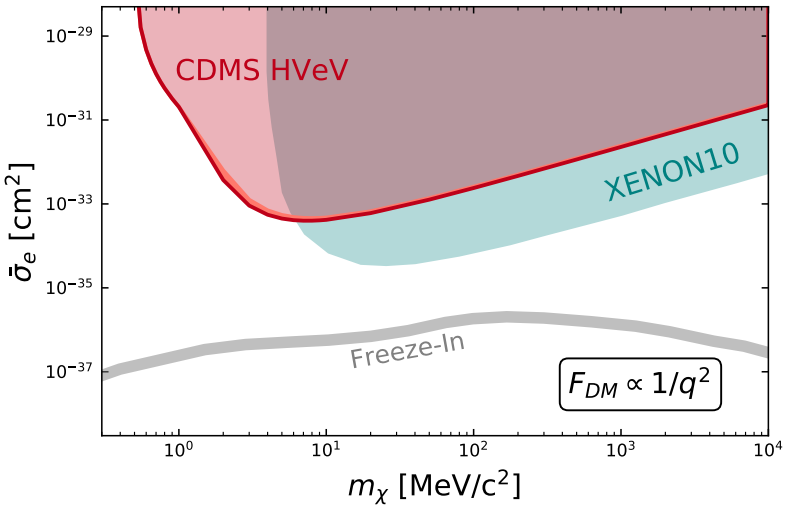


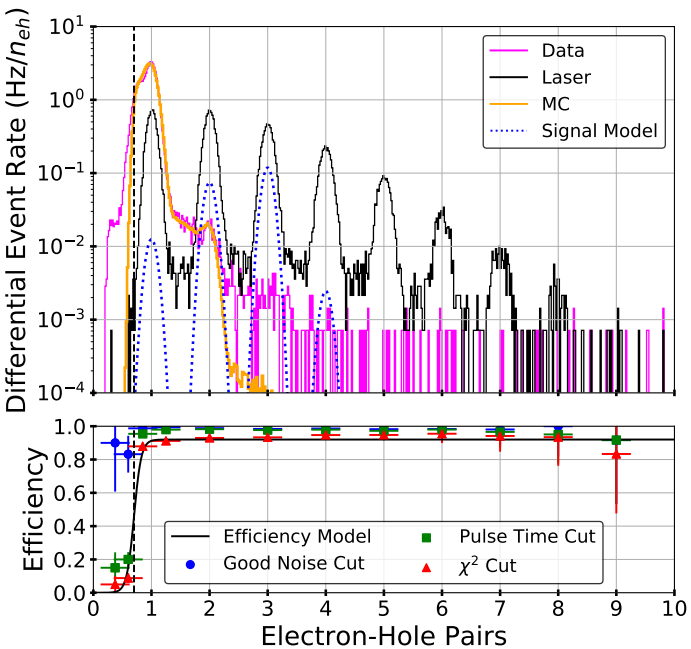


- Single e/h-pair sensitivity has been demonstrated in 0.93g Si crystal
- Single e/h-pair resolution goal of SuperCDMS SNOLAB
- Such devices will have sensitivity to a variety of sub-GeV DM models with $\sim$g*d exposures

Single e/h device - SuperCDMS Phys.Rev.Lett. 121 (2018) no.5, 051301

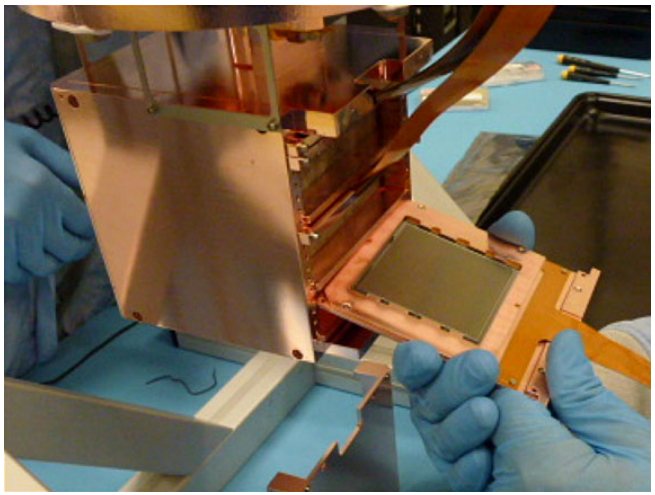


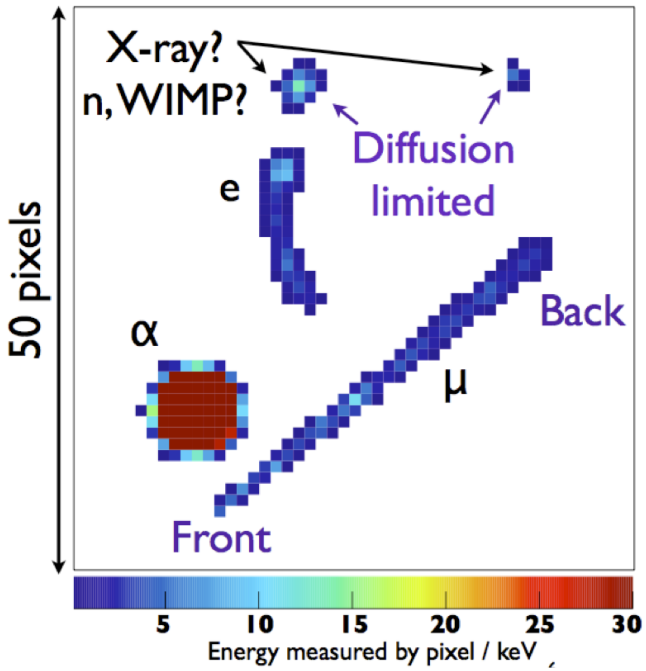


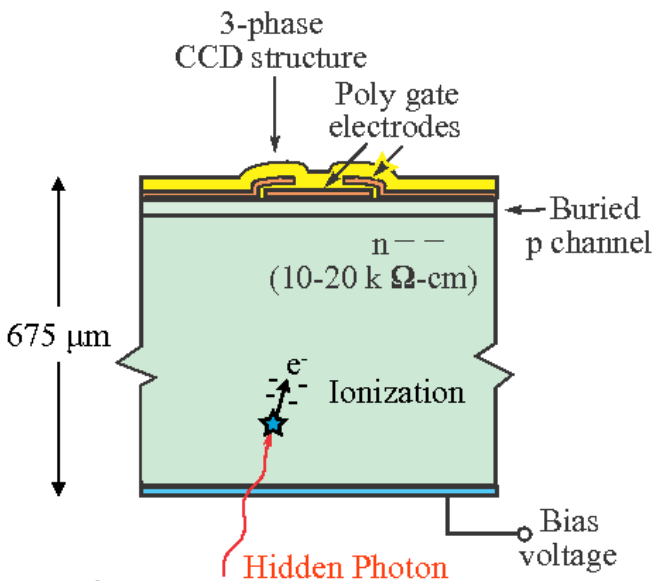


- Operated on surface for raw exposure on the order of days
- Utilizes traditional TES sensors
- New sensor designs being worked on and new chips being operated

DAMIC - Phys.Rev.Lett. 118 (2017)

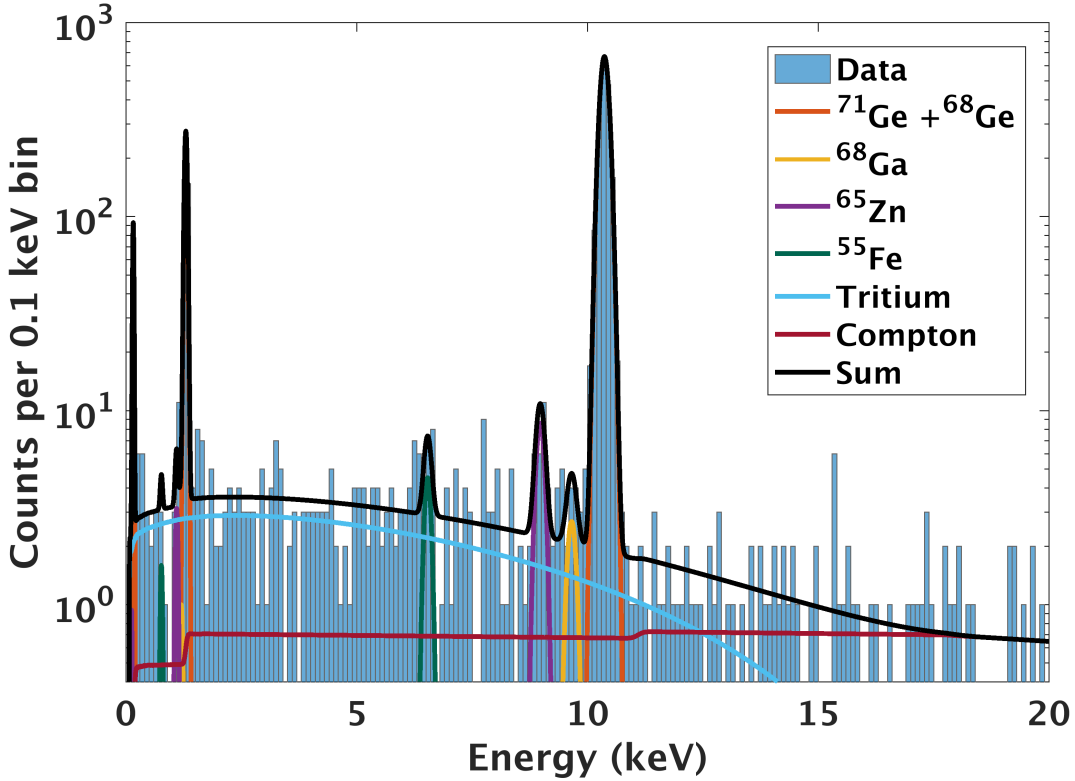






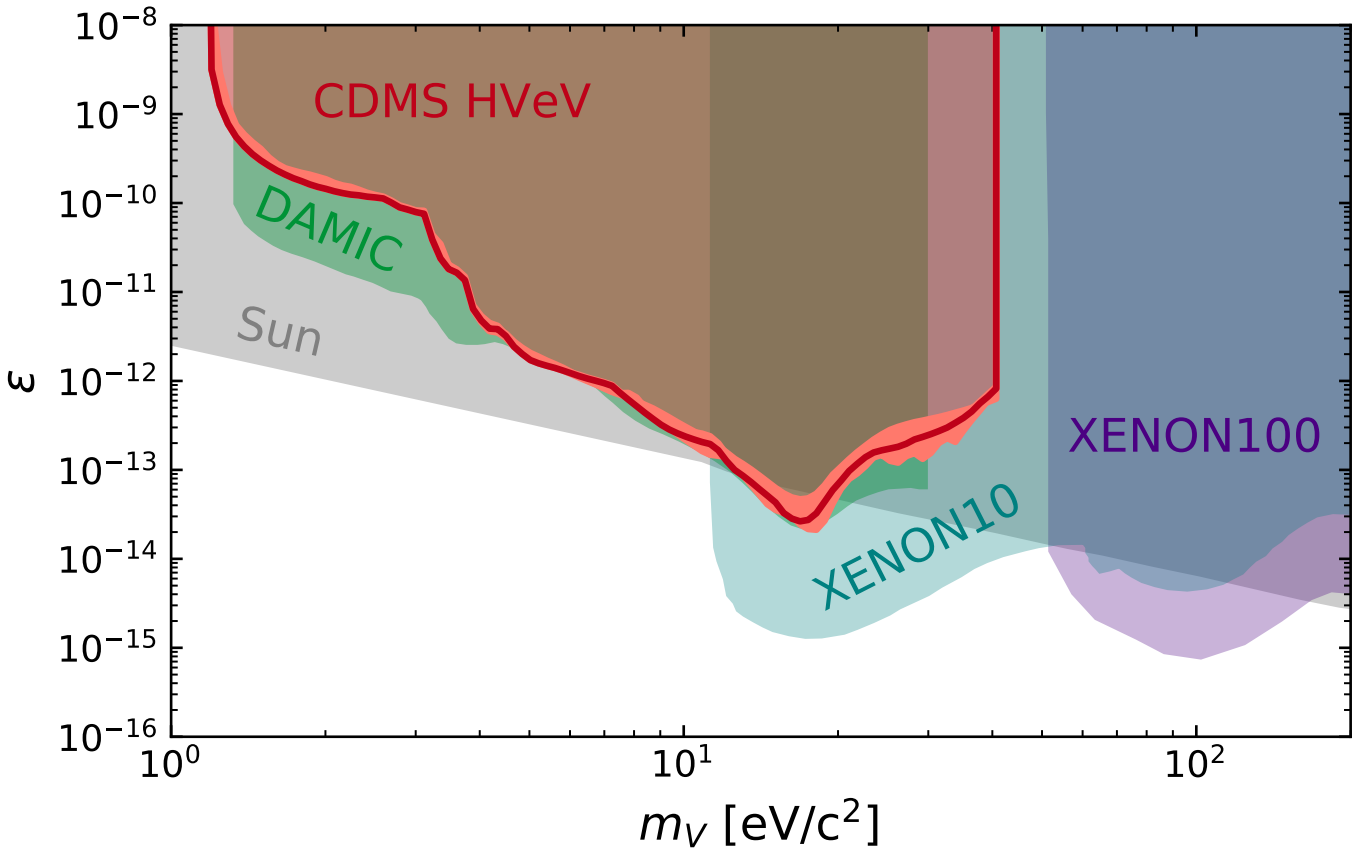
- Stacked CCD detector array
- Images interaction - provides event discrimination
- Timing information can also be used to discriminate

Dark photon absorption with CDMSlite data



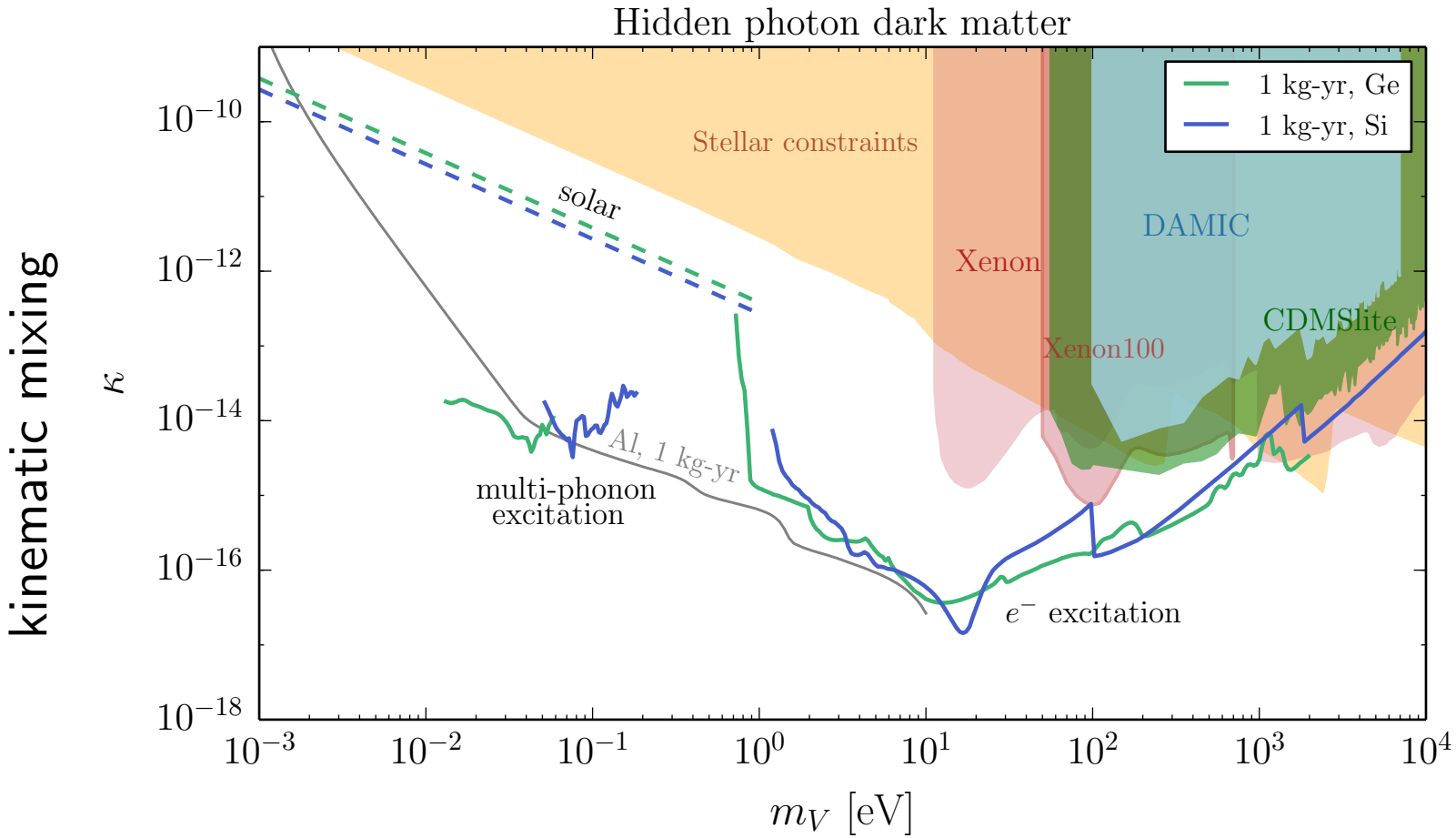
- Mediator between standard model and dark matter with finite mass ($m_{A'}$)
- Absorption rate, $R \simeq \frac{\rho_{DM}}{m_{A'}c^2}\epsilon^2\sigma_{p.e.}(E_{gamma} = m_{A'})c$
- Signal is mono-energetic electron with $E = m_{A'}$
- Search strategy is a bump-hunt in our spectrum!

Dark photons - Phys.Rev.Lett. 118 (2017) ,



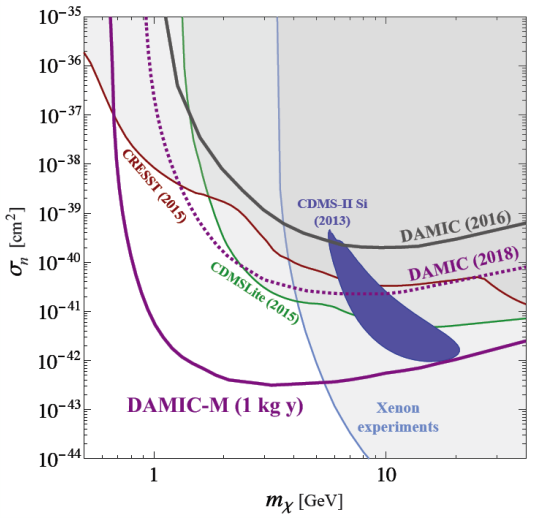
- Sensitivity down to light mass because of low threshold detectors

Dark photons outlook - Hochberg, Lin and Zurek Phys. Rev. D 95, 023013

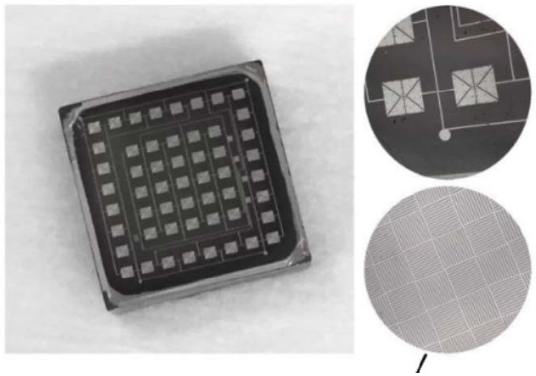


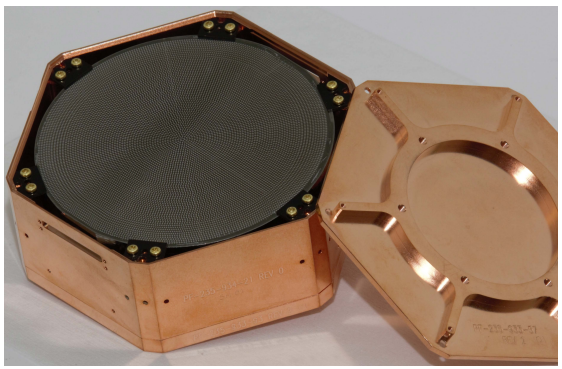
- Sensitivity extends down to band gap (Ge .7 eV, Si 1.1 eV)

Closing thoughts and outlook for the future



[5]



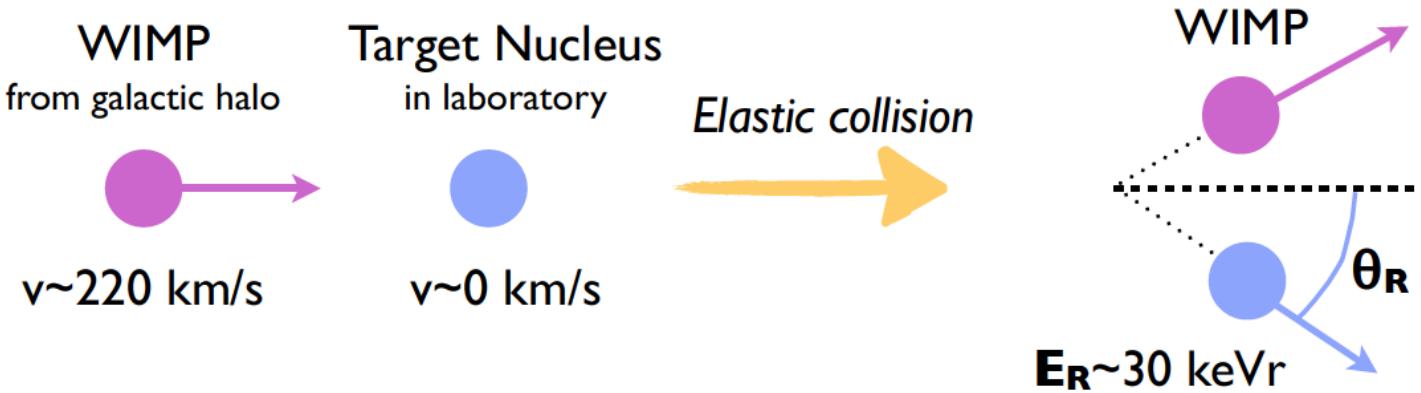


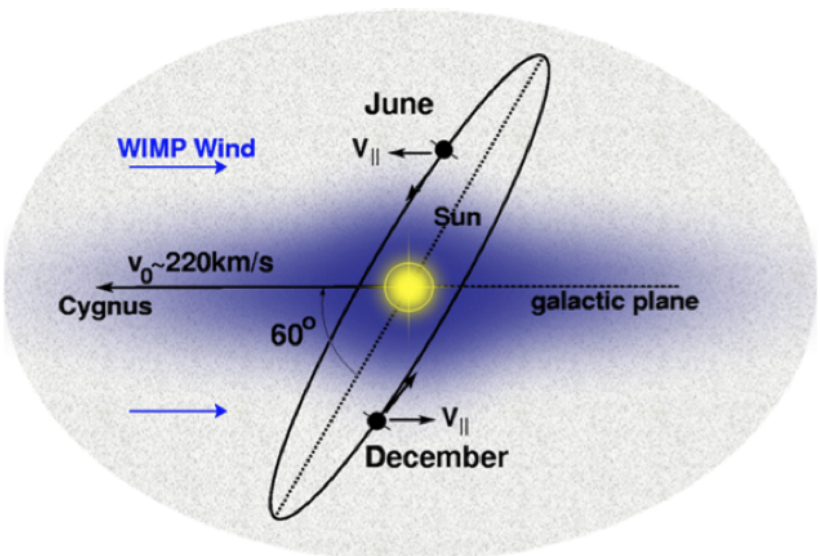
- Field is being driven by technology advances
- Semi-conductor detectors are really the drivers of these searches
- Lot of parameter space can be explored with modest exposures - lots of quick results possible
- Challenge will be scaling up and understanding detector behavior

[5] DAMIC IDM 2018

Backup slides

Direct detection event rates





- Direct detection experiments rely on having a target material, wait for 220 km/s WIMP wind to blow
- Expect a local DM density of ≈ 0.4 GeV/cm^3
- Rate should modulate annually due to Earth's motion around Sun [a]

[a] DAMA/LIBRA claims to have seen this signal

Direct detection event rates

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

With:

$$E_R = \frac{\mu_N^2 v^2 (2 - cos\theta)}{m_N} \text{ - recoil energy}$$

$f(v)$ - normalized WIMP velocity distribution in detector frame

$$u_N = \frac{m_\chi m_N}{m_\chi + m_N} \text{ - reduced mass}$$

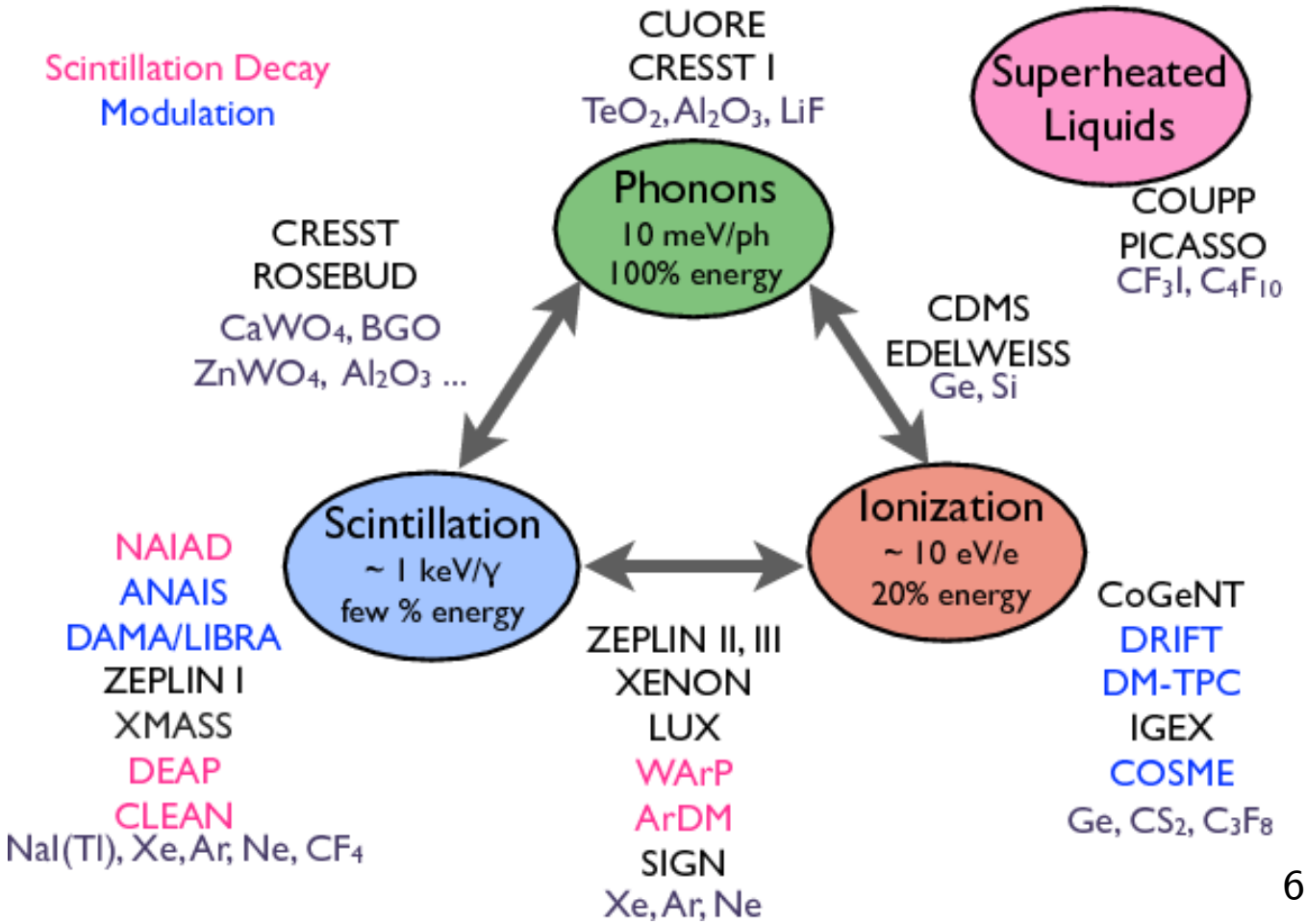
$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}} \text{ - minimum velocity for recoil energy } E_R$$

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

- Contributions for particle, nuclear and astro physics
- We expect just a few events every year from WIMPs

reference : arXiv:1002.1912 [astro-ph.CO]

Overview of direct detection approaches



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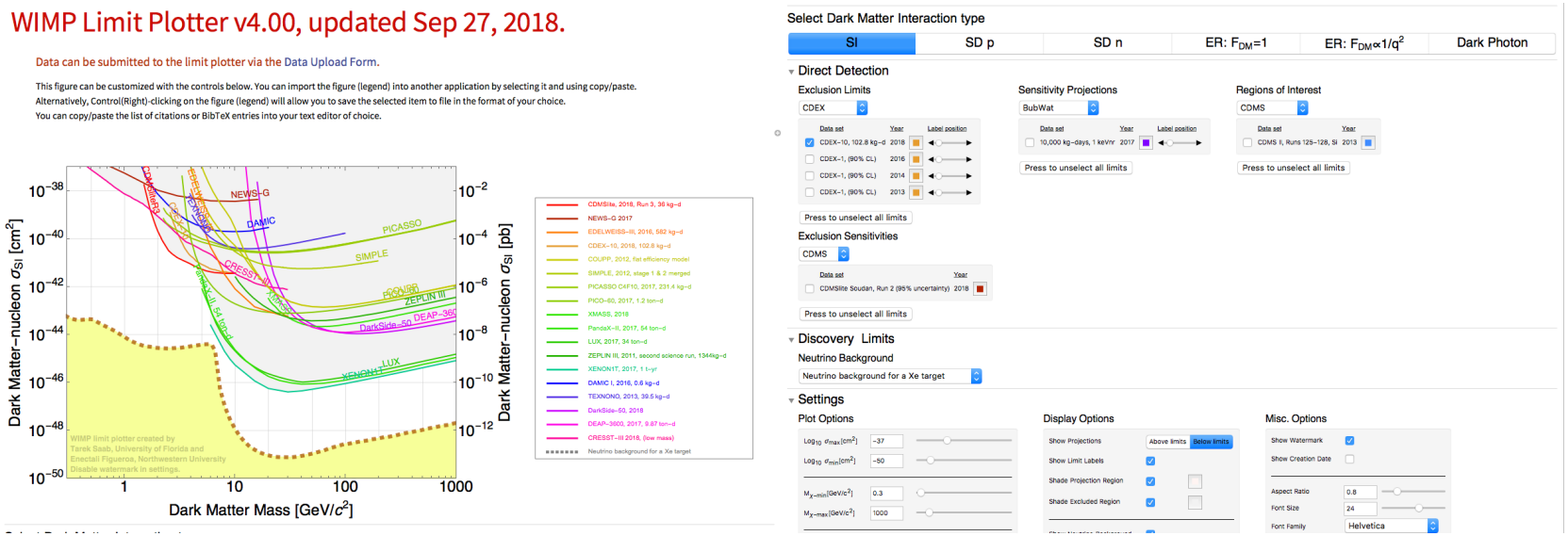
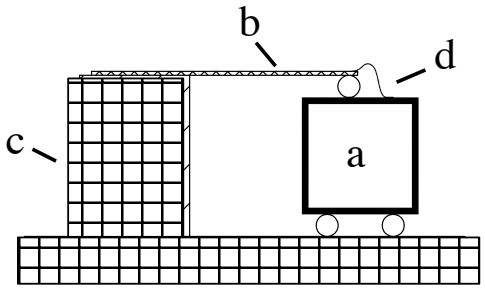
[6] arXiv:1203.2566 [physics.ins-det]

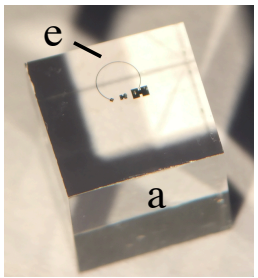
DM limit plotter - shameless advert

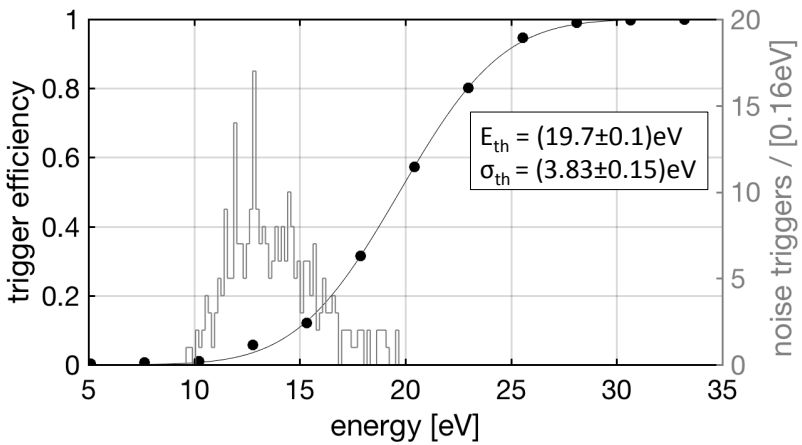


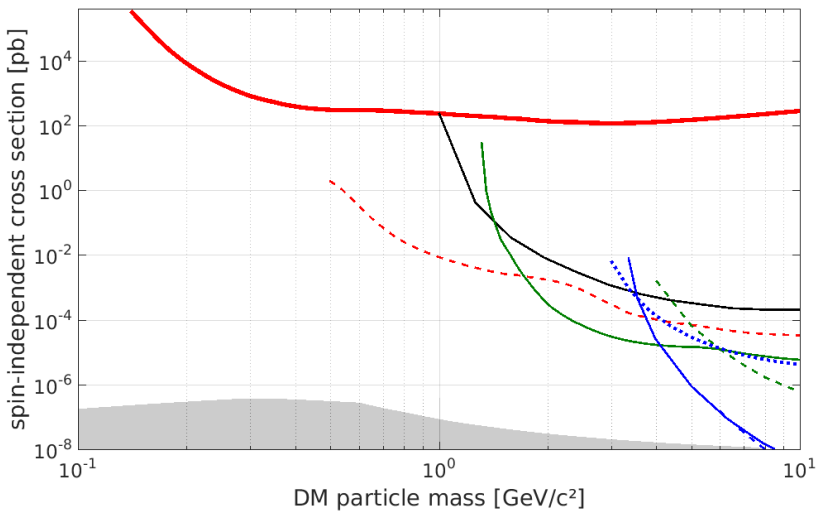
- Make your own limit plots with your preferences
- `http://cdms.berkeley.edu/limitplots/mm/WIMP_limit_plotter.html`
- SuperCDMS maintains a limit plotter - use it!
- Template available for adding new limit curve - submit them!
- Recently expanded ER DM options

Sapphire - Eur.Phys.J. C77 (2017) no.9, 637



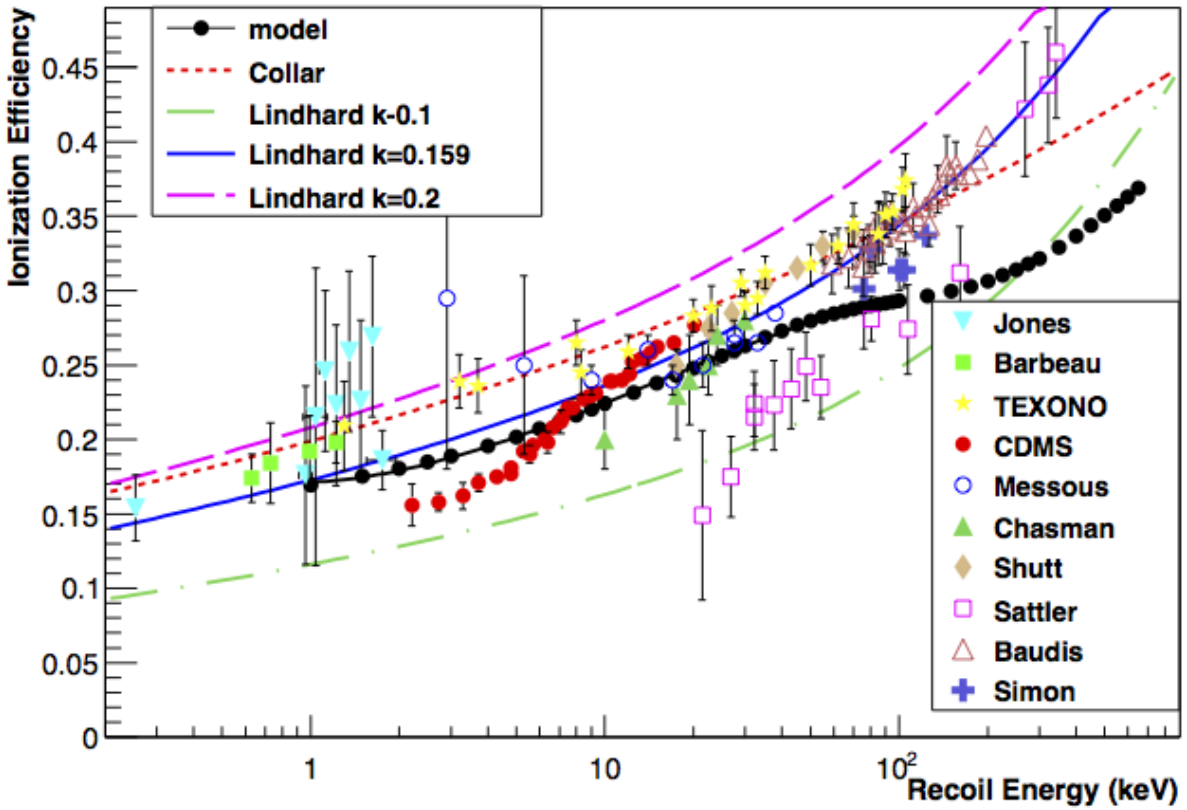






- Offshoot device from CRESST using a sapphire crystal
- Gram scale detector with a threshold around 20 eV
- Limited cross section reach but pushes into low mass territory

Nuclear recoils in crystals



[7]

- Nuclear recoils have only a fraction of their energy in ionization
- Can be reasonably modeled using Lindhard model

[7] arXiv:1304.6773 [physics.ins-det]