The SuperCDMS SNOLAB Experiment

Mining Dark Matter in Northern Canada

16th Marcel Grossman Meeting

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Outline

- Fundamental Principles of Dark Matter Detection:
  How dark matter interacts

- Dark Matter Detection Techniques:
  The principles behind the SuperCDMS approach
  The road to low mass / energy resolution

- The SuperCDMS Experiment in Action:
  - Current results
  - Future Plans

The SuperCDMS Collaboration

Detection Principles

How dark matter interacts with material

Dark Matter Interactions & Detector Physics

- Interactions fall into three categories, with differing energy scales
  - **Nuclear recoils** - particle interacts with the nucleus
    - Traditional “WIMP” Dark matter signal
    - Neutron and neutrino backgrounds
  - **Electron recoils** - particle interacts with atomic electrons
    - Electron recoil, Dark Photon and Axion signals
    - Most background sources
  - **Excitation recoils** - particle interacts with background excitations in target material
    - i.e. Phonons, Cooper pairs, …

- Detector response often is different for the three categories. Can be used to reject some backgrounds

- Energy scale of the interaction dictates detection approach

- Backgrounds and detection techniques drive science reach

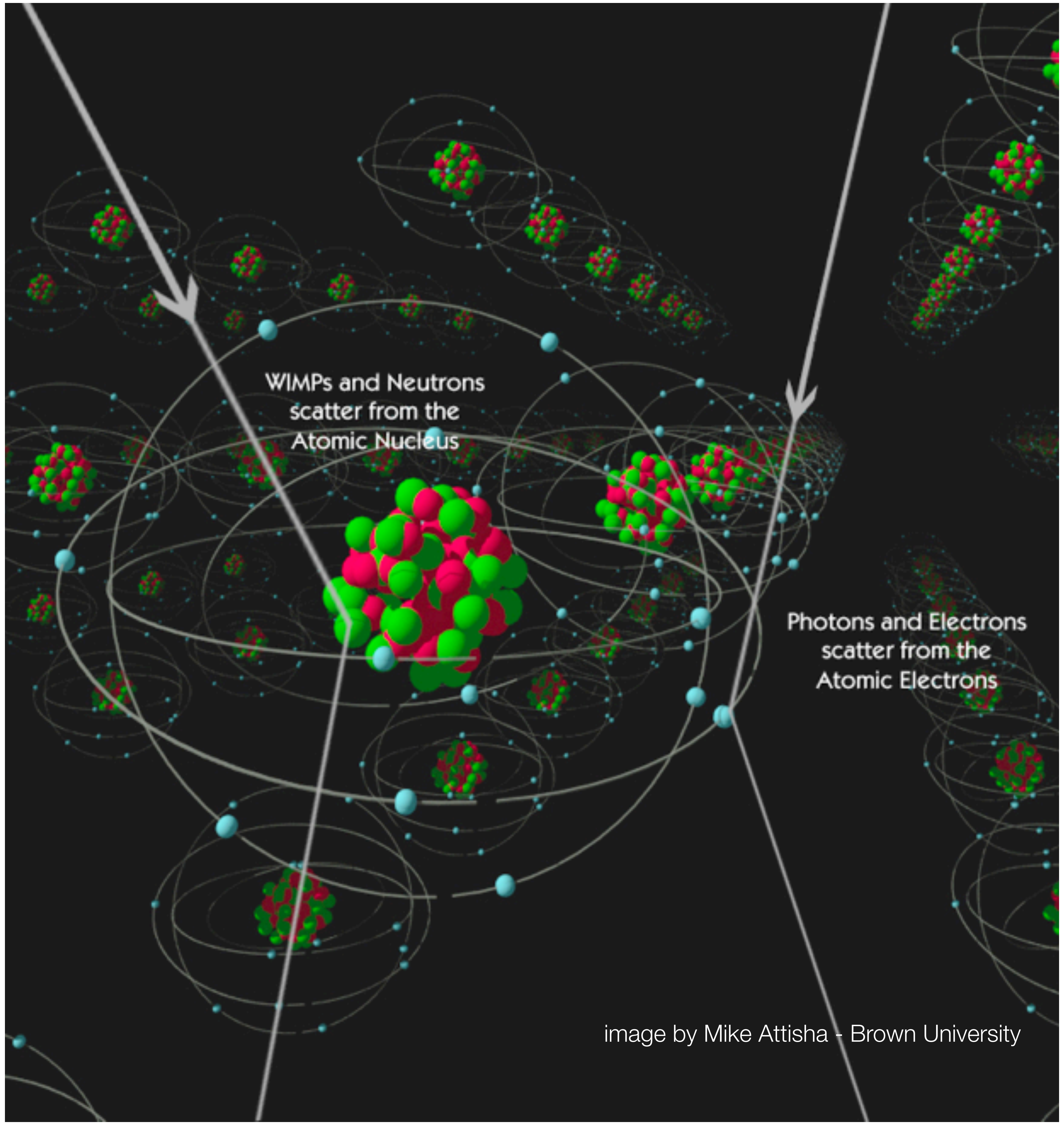
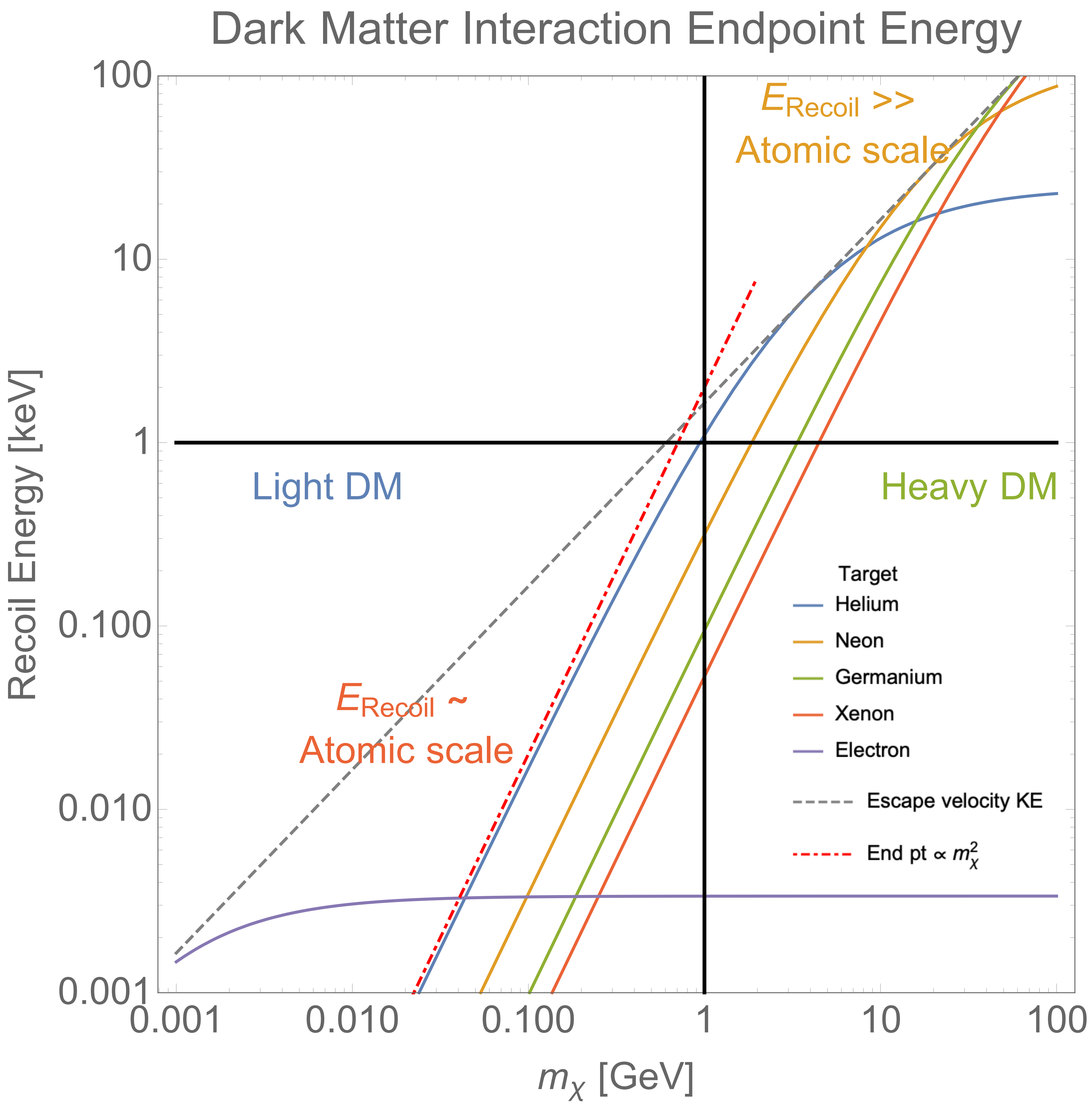


image by Mike Attisha - Brown University

Dark Matter Interaction

- Heavy DM
    - Nuclear Scattering
        - Recoil energies >> atomic energies
        - Simple elastic collisions
        - Nucleus mass determines DM mass sensitivity
        - Long exposure time, limited by detector mass
- Mid-weight DM
    - Nuclear Scattering & Electron Scattering
        - Recoil energies ~ atomic energies
        - Inelastic collisions dominated by orbital mechanics
        - Mass reach determined by band gap
          Short exposure time, limited by background
- Light DM
    - Absorption
        - Recoil energies ~ atomic energies
        - Inelastic collisions dominated by orbital mechanics
        - Mass reach determined by band gap
          Short exposure time, limited by background



The SuperCDMS Detectors

What happens when DM interacts with a detector?

SuperCDMS/EDELWEISS Detector Technology

Discriminating
~~iZIP~~ Detector:

- Prompt phonon and ionization signals allow for discrimination between nuclear and electron recoil events

Low Threshold
~~HV~~ Detector:

- Drifting electrons/holes across a potential (V_b) generates a large number of phonons (Luke phonons).
  - Enables very low thresholds!
  - Trade-off: No event-by-event NR/ER discrimination

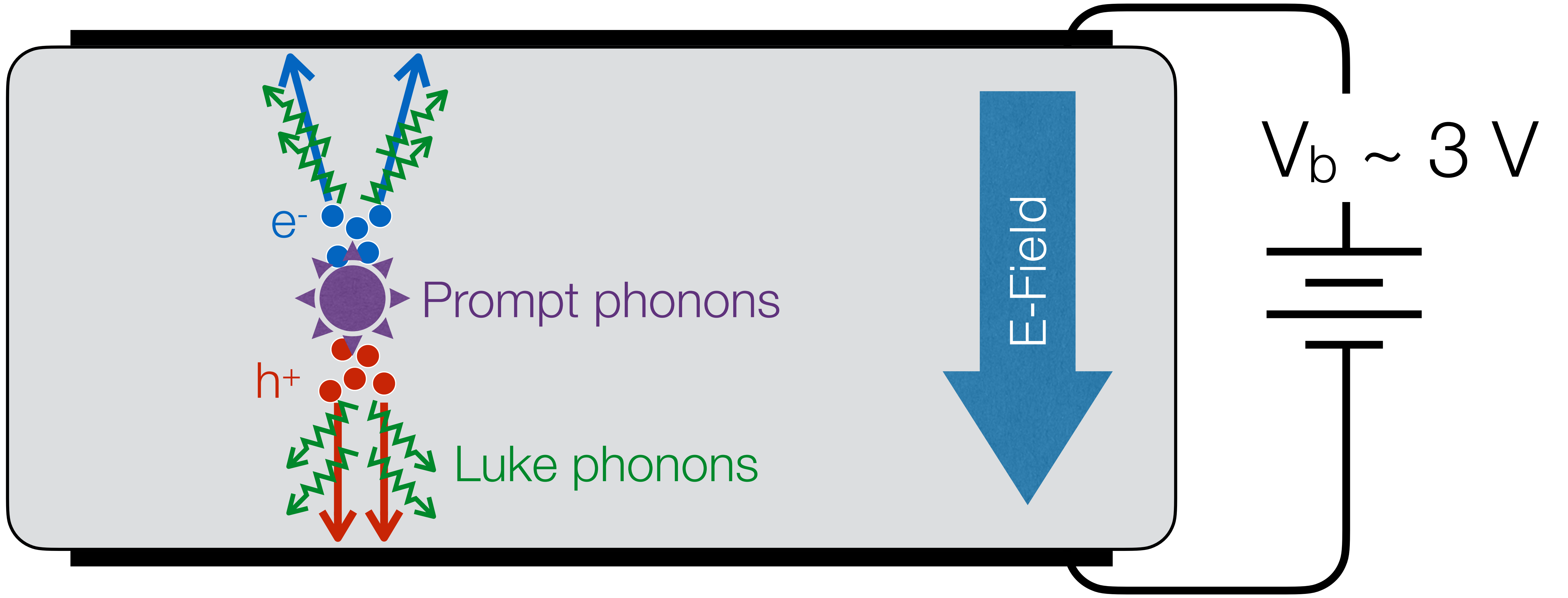
$$E_t = E_r + N_{eh} e V_b$$

total phonon energy

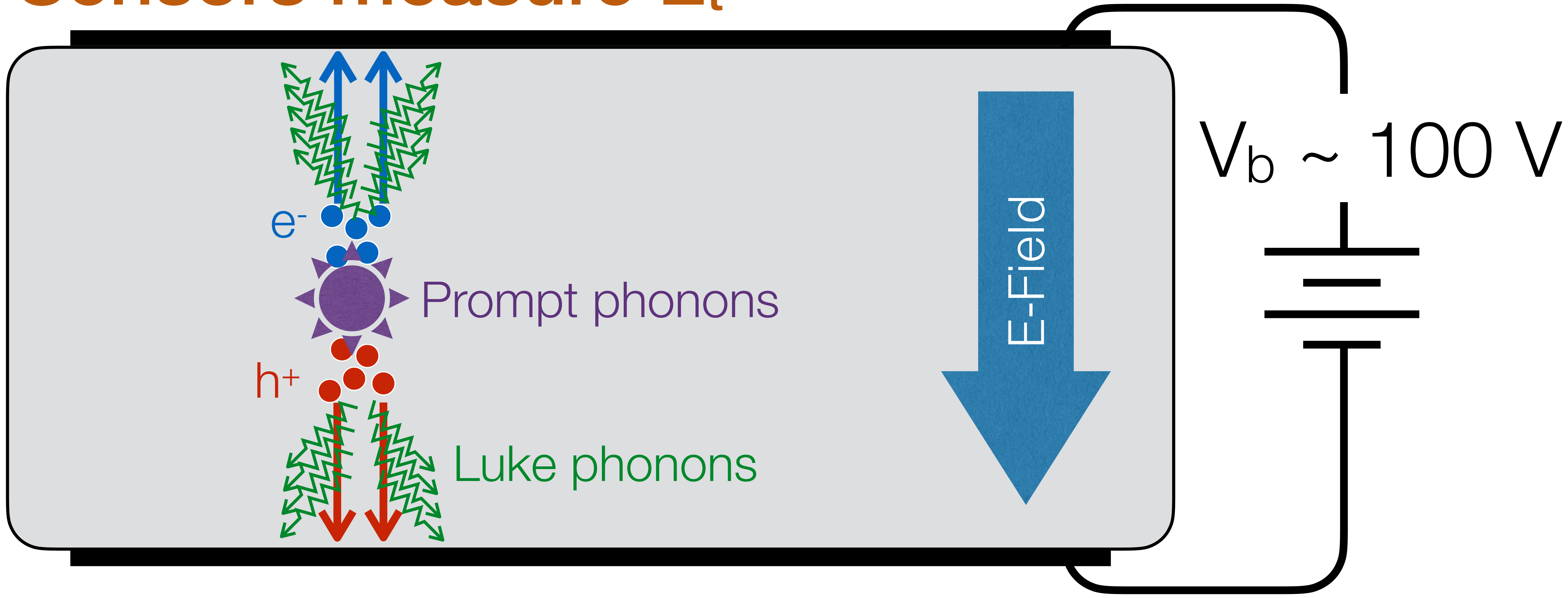
primary recoil energy

Luke phonon energy

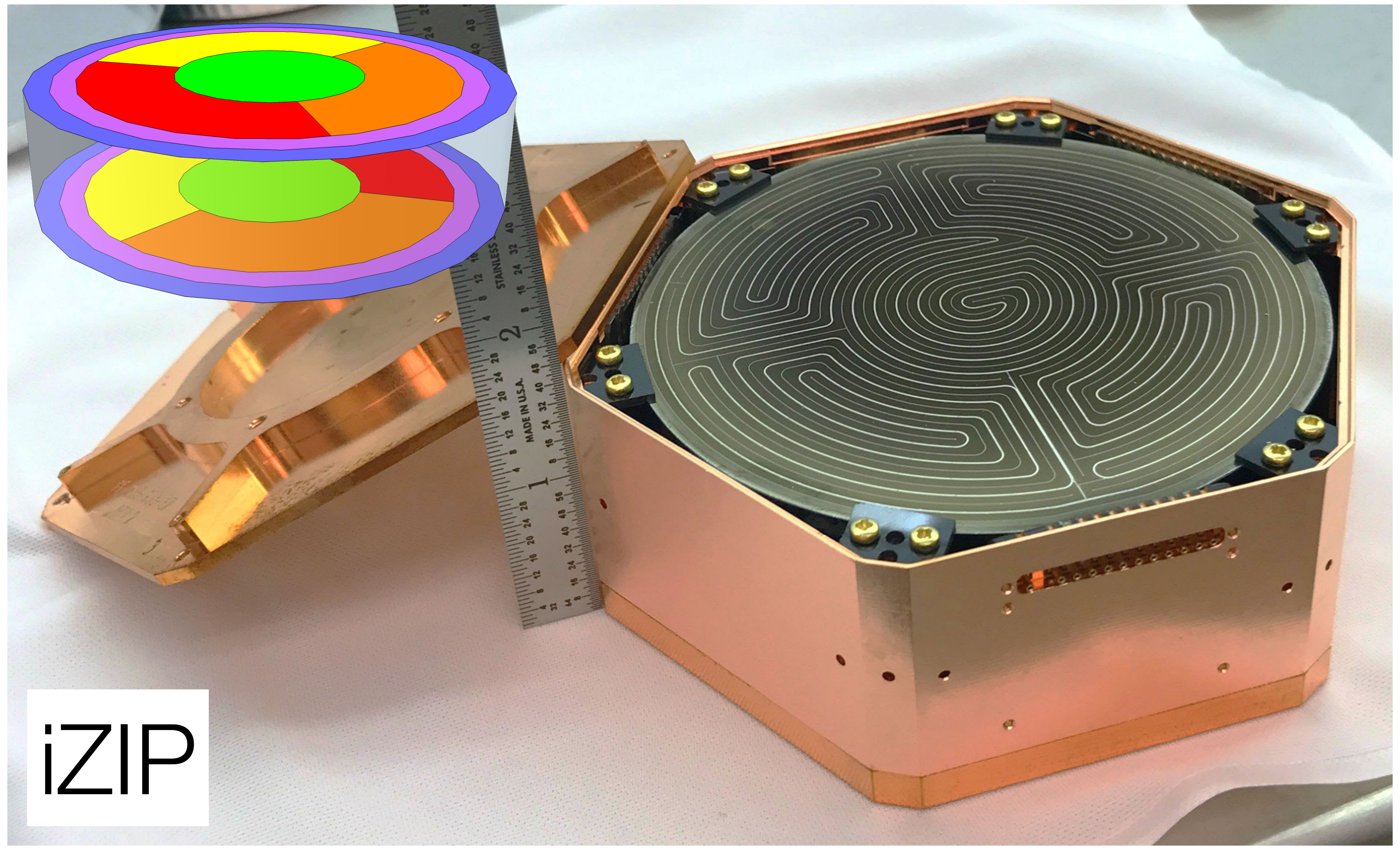
Sensors measure E_t, and n_{eh}

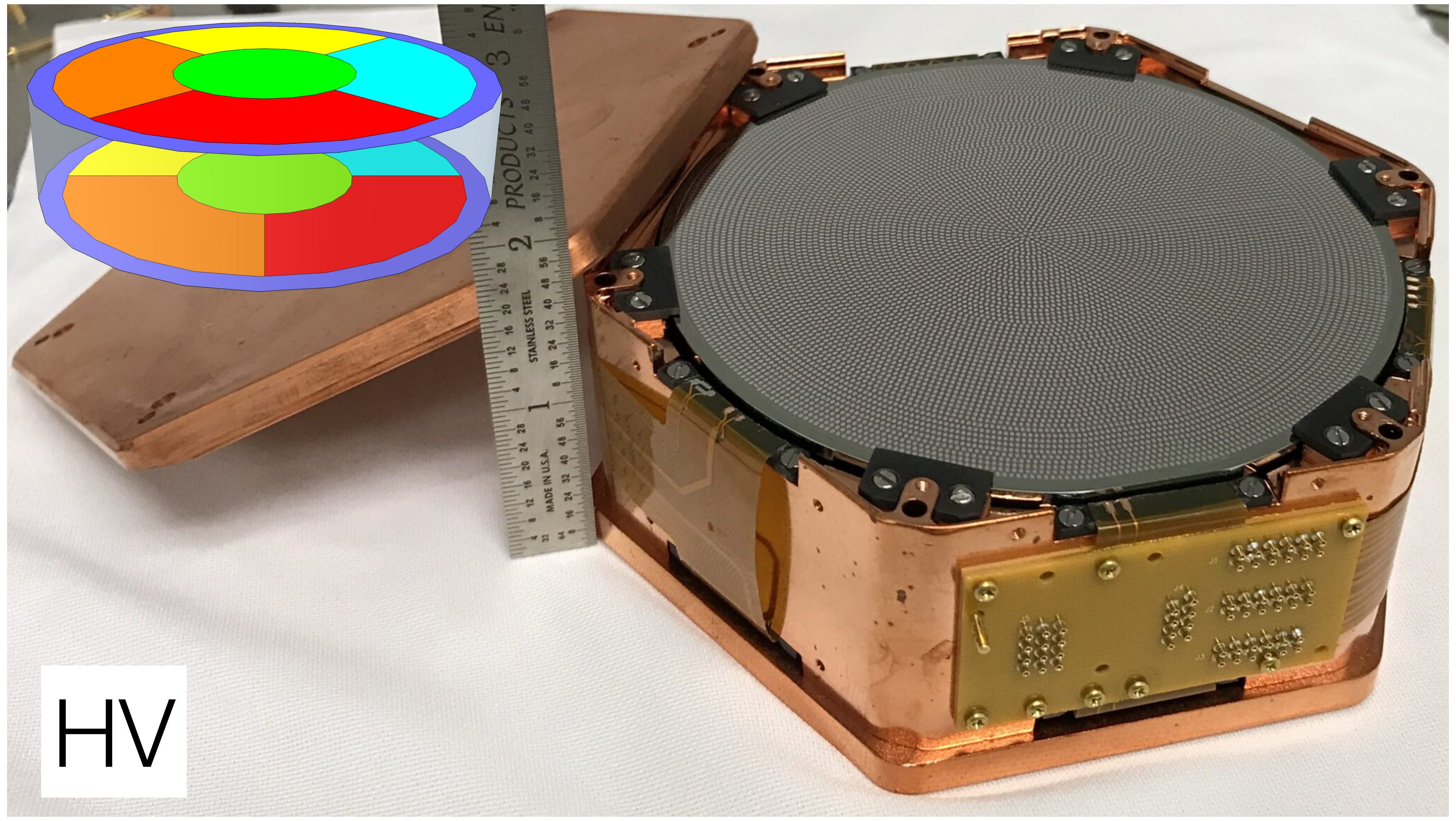


Sensors measure E_t



SuperCDMS Detectors: Posing for the Cameras



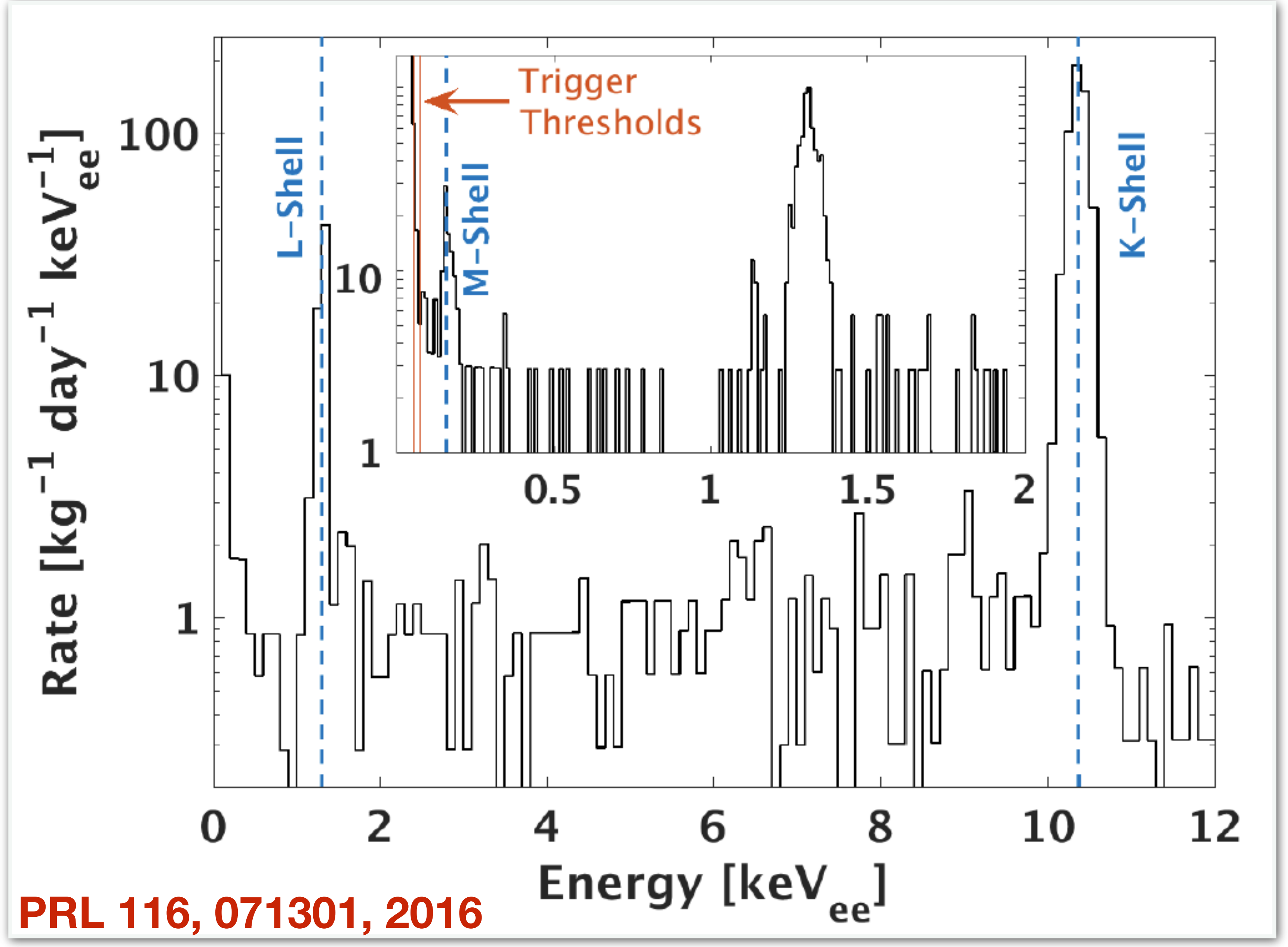


- Detectors made of high-purity Ge and Si Crystals
  - Si (0.6 kg) provides sensitivity to lower dark matter masses, Ge (1.5 kg) provides sensitivity to lower dark matter cross-sections
- Low operation temperature: ~15mK
  - Athermal phonon measurement with TESs
  - Ionization measurement (iZIP) with HEMTs
- Multiple channels per detector to identify event position
- Initial payload will consist of 4 towers
  - 6 detectors each
  - 2 iZIP: 10 Ge / 2 Si
  - 2 HV: 4 Ge / 4 Si

Comparison of Low Threshold vs Discrimination Modes

HV ⟶ Low Threshold

- Ultra high resolution indirect charge measurement
- Thresholds 75 eVee and 56 eVee
- No yield or detector face discrimination

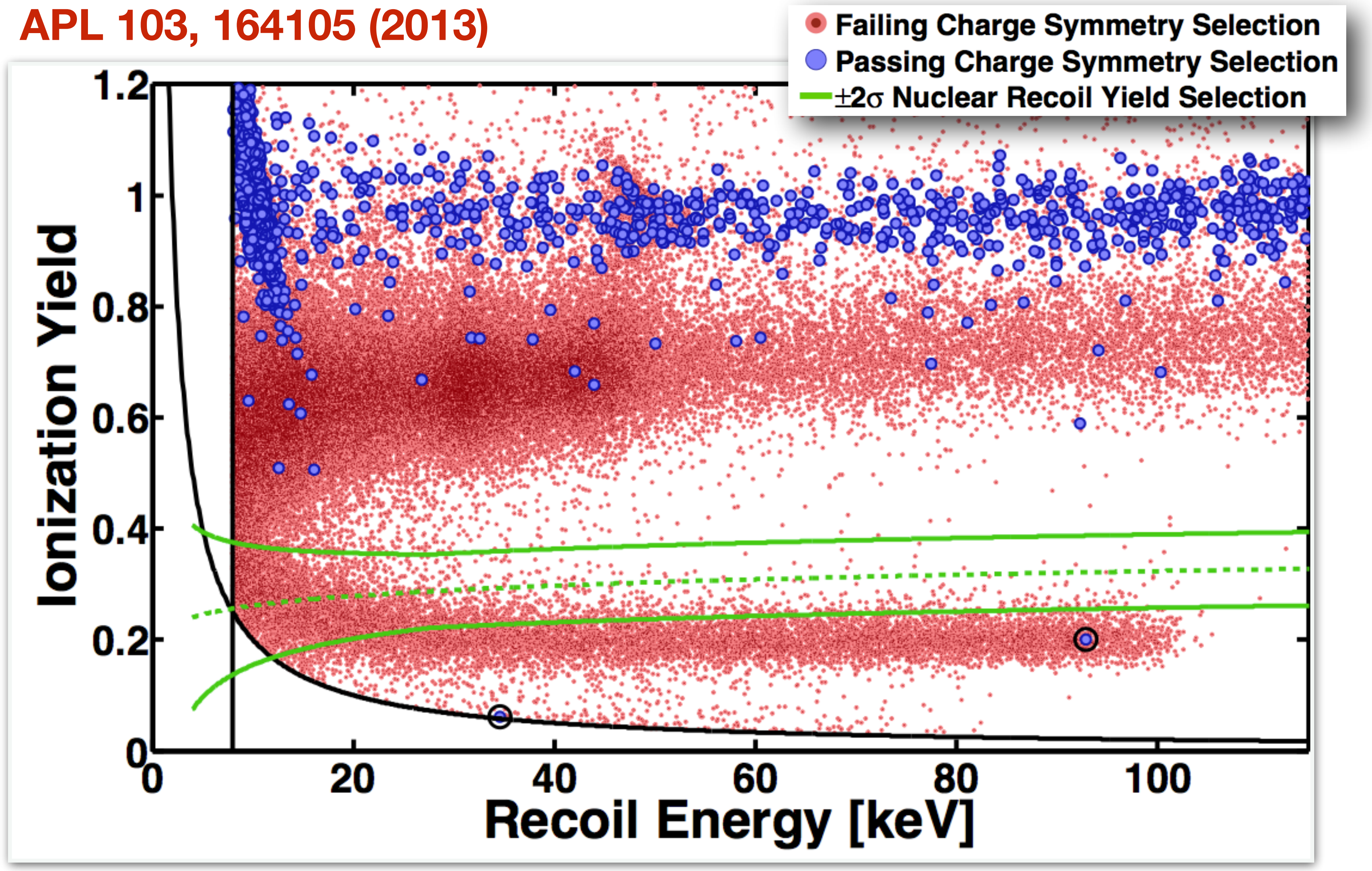


PRL 116, 071301, 2016

iZIPs ⟶ Low Background

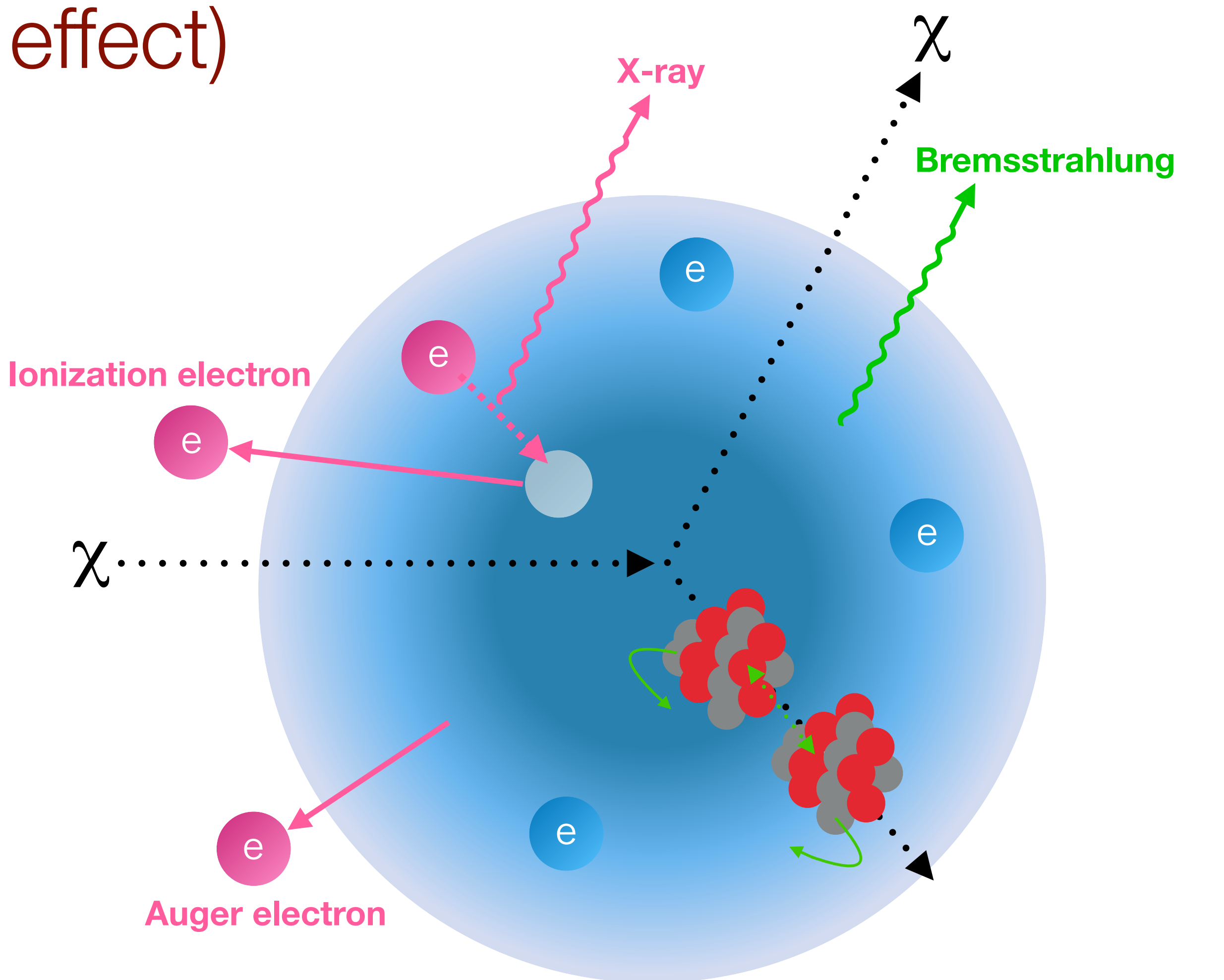
- High resolution phonon and charge readout
- All surface and ER backgrounds above few keV removed (red dots)

APL 103, 164105 (2013)

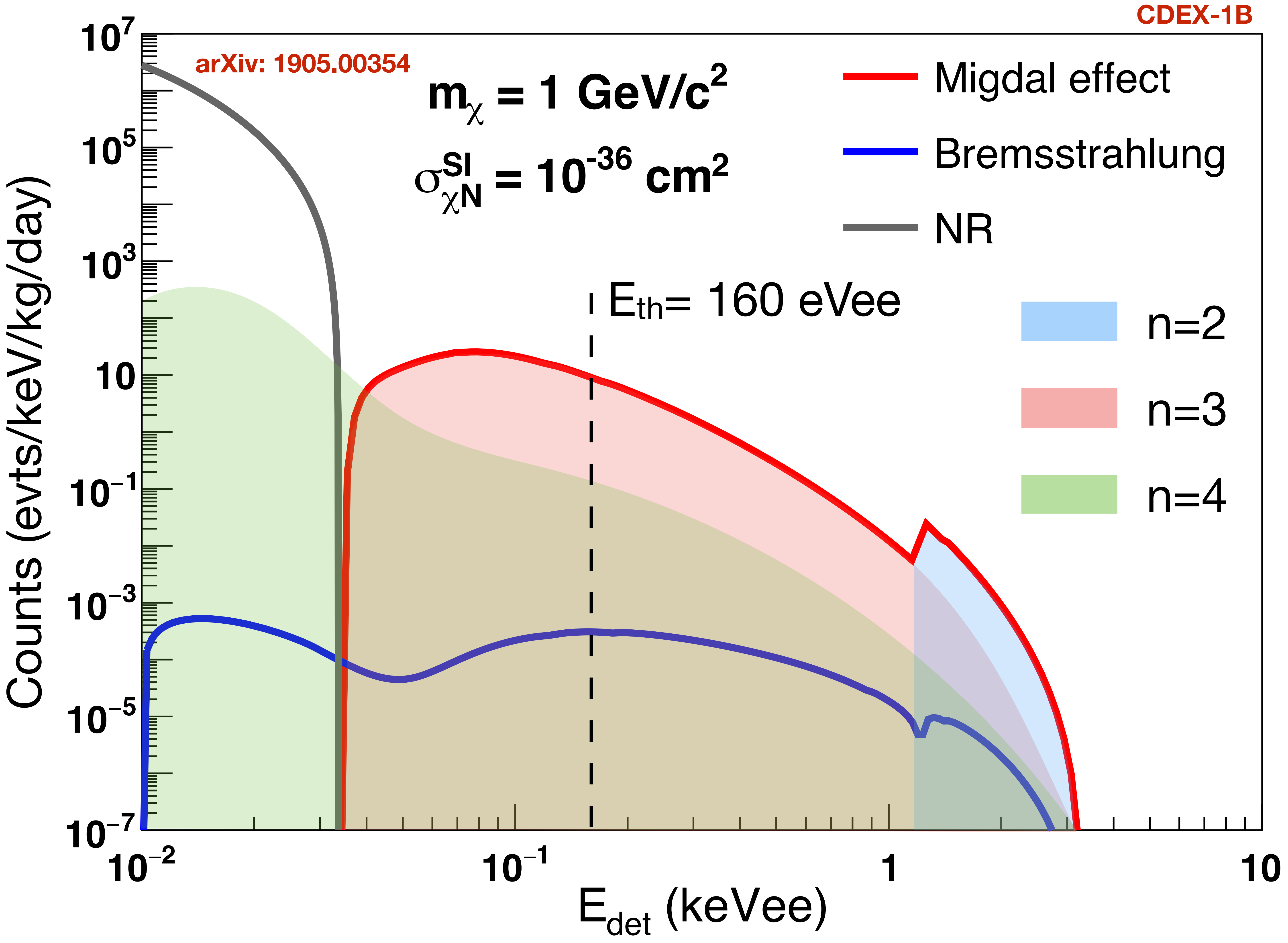


Inelastic Nuclear Recoils: Migdal and Bremsstrahlung Effect

- Given a dark matter elastic scatter with nucleus:
  - Induces “instantaneous” change in momentum of nucleus wrt orbital electrons
  - Results in a kinematic boost of the electrons.
  - Leads to Bremsstrahlung emission and
  - Ionization and/or excitation of the atom (Migdal effect)



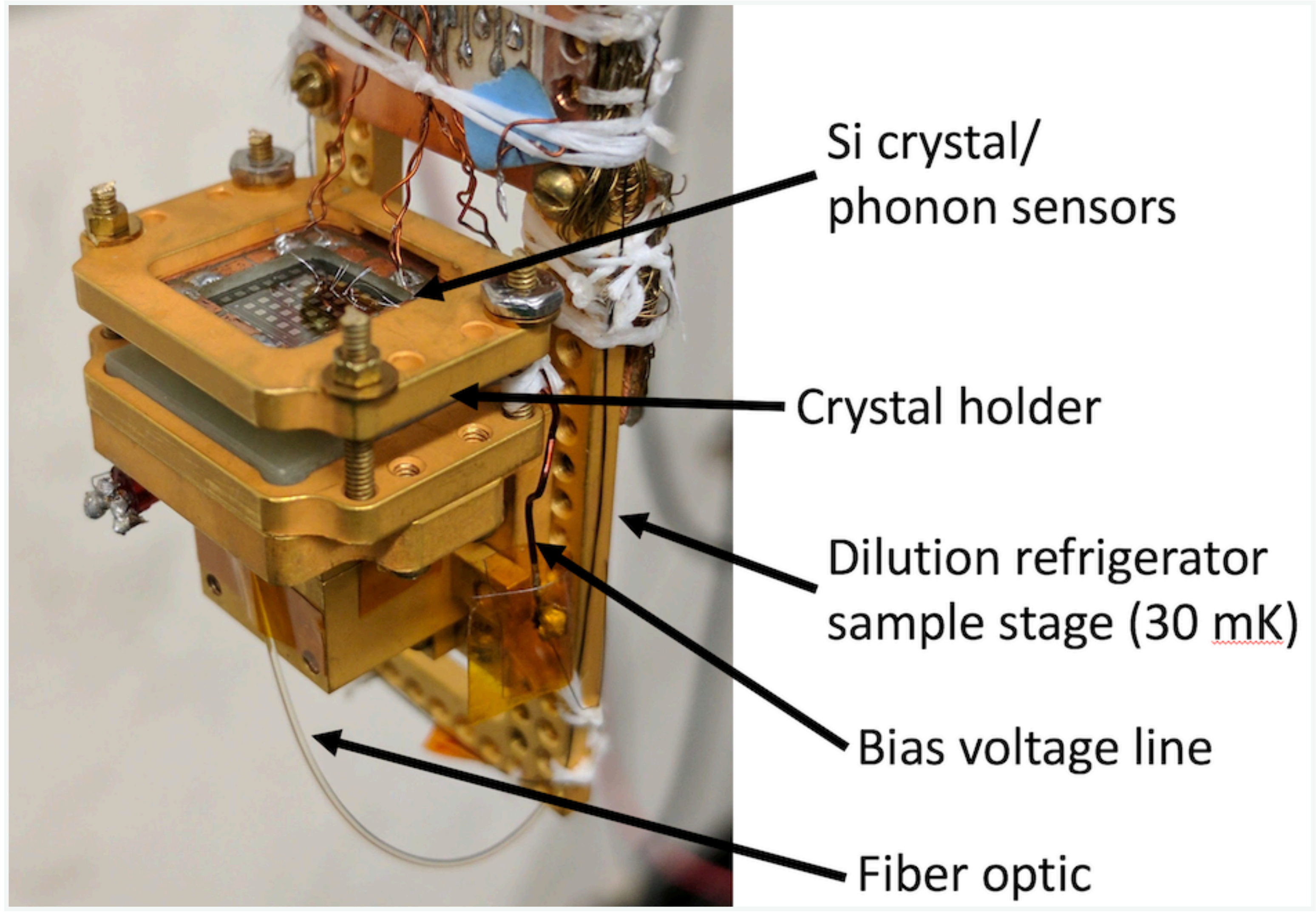
arXiv: 1907.12771



A. B. Migdal, J. Phys.(USSR) 4, 449 (1941).
C. Kouvaris and J. Pradler, Phys. Rev. Lett. 118, 031803 (2017).
M. Ibe, W. Nakano, Y. Shoji, and K. Suzuki, JHEP 03, 194 (2018).
M. J. Dolan, F. Kahlhoefer, and C. McCabe, Phys. Rev. Lett. 121, 101801 (2018).

~~Small~~ , ~~Mini~~ , ~~Micro~~ , HVeV Detectors

arXiv: 1710.09335

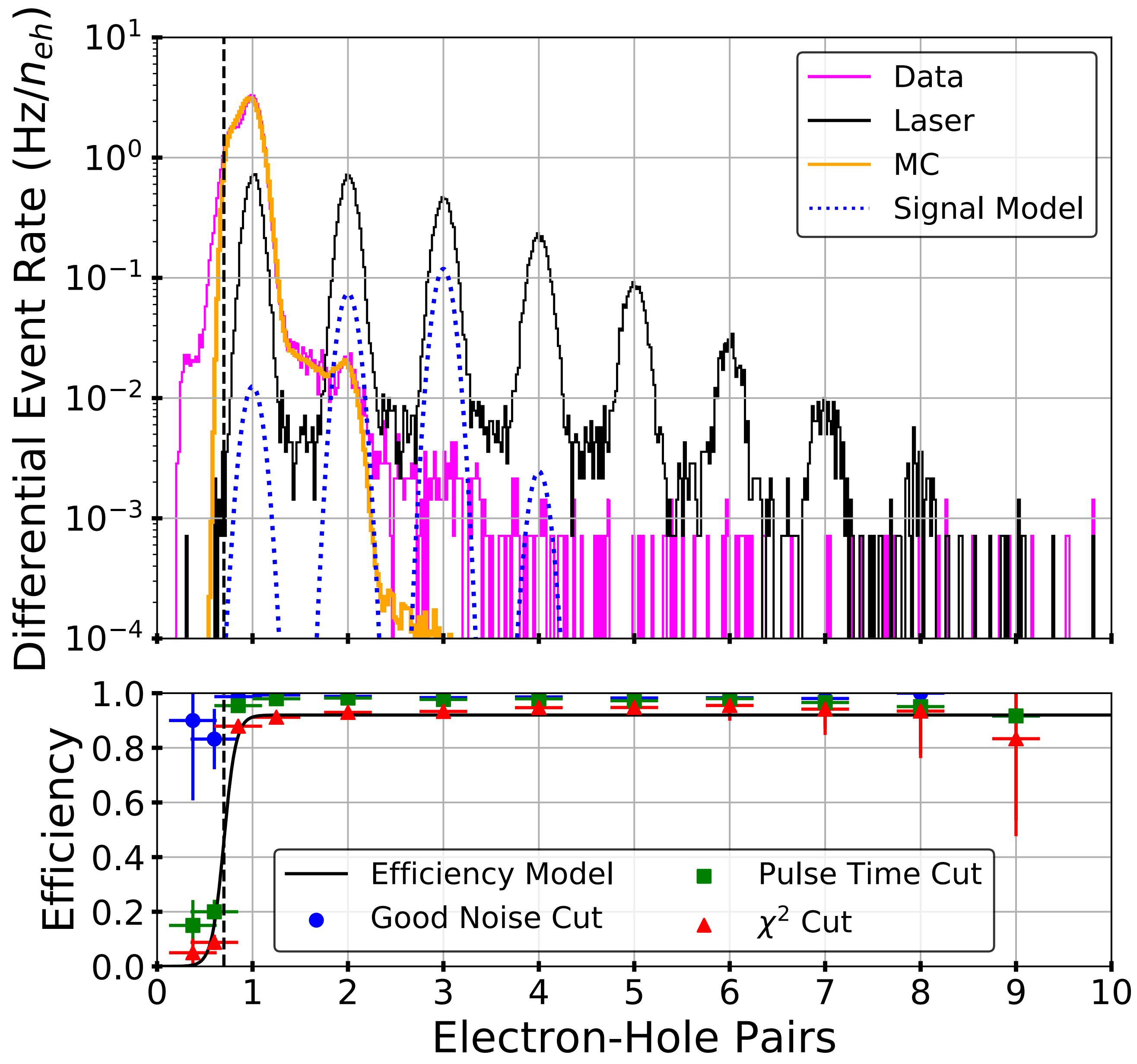


- SuperCDMS has also developed gram scale R&D detectors
  - Single electron-hole pair resolution devices will have sensitivity to a variety of sub-GeV DM models with gram*day exposures
  - Largest "quantum resolution" detectors available
  - Powerful tool for low-energy rare event searches

- 0.93 g Si crystal (1x1x0.4 cm^3) operated at 33-36 mK at a surface test facility.

- Exposure: 0.49 gram-days (16.1 hours)
  - energy resolution: σ_{ph} ~ ~~14 eV~~ → $\sigma_{ph} \sim 3$ eV
  - charge resolution: σ_{eh} ~ ~~0.1 e-h+~~ → $\sigma_{eh} \sim 0.06$ e^-h^+
  - operation voltage: ~~140 V~~ → $V_{bias} \sim 50$ V

arXiv: 1903.06517



arXiv: 1804.10697

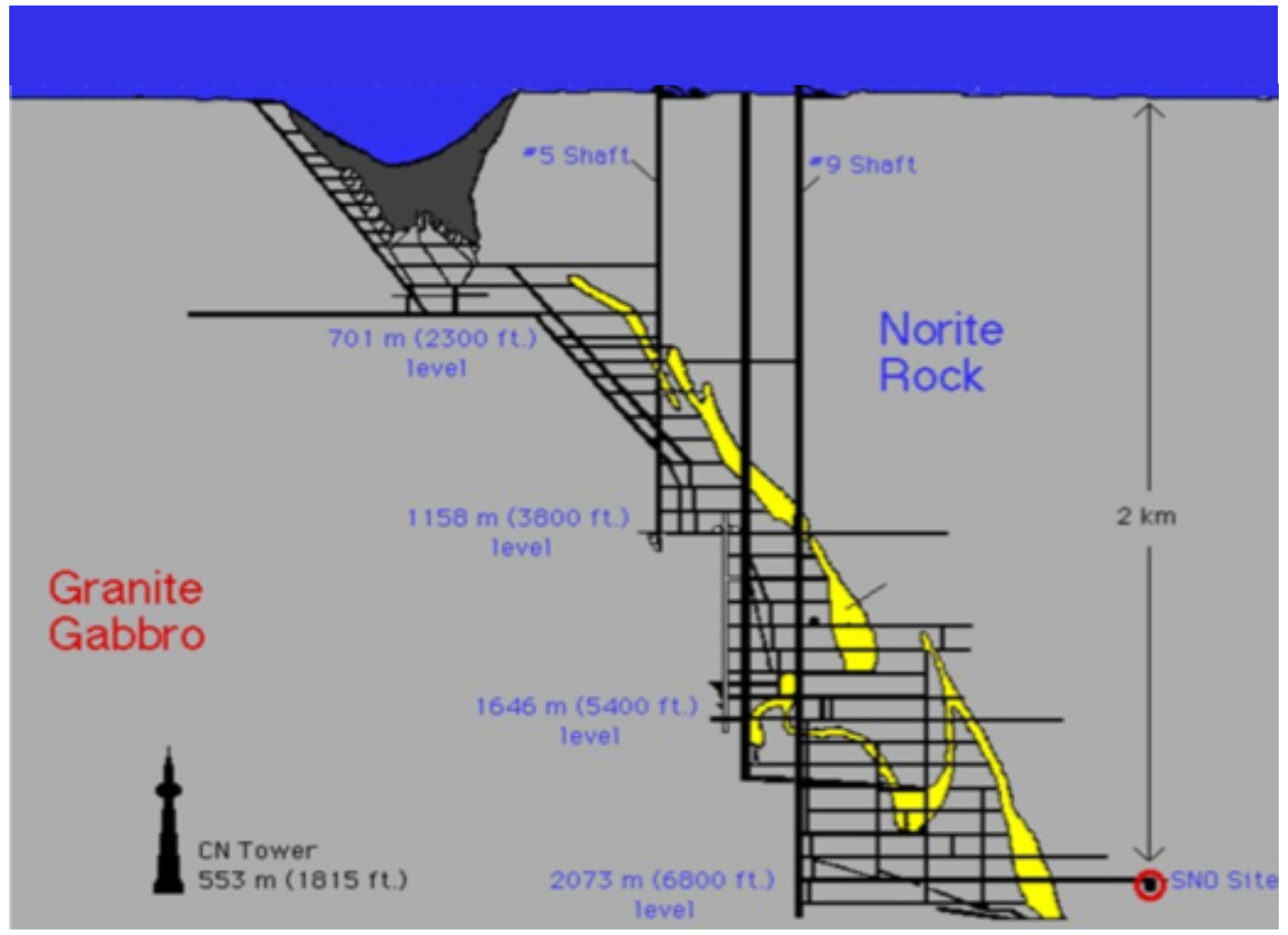
SuperCDMS Detectors & Dark Matter Mass Scales

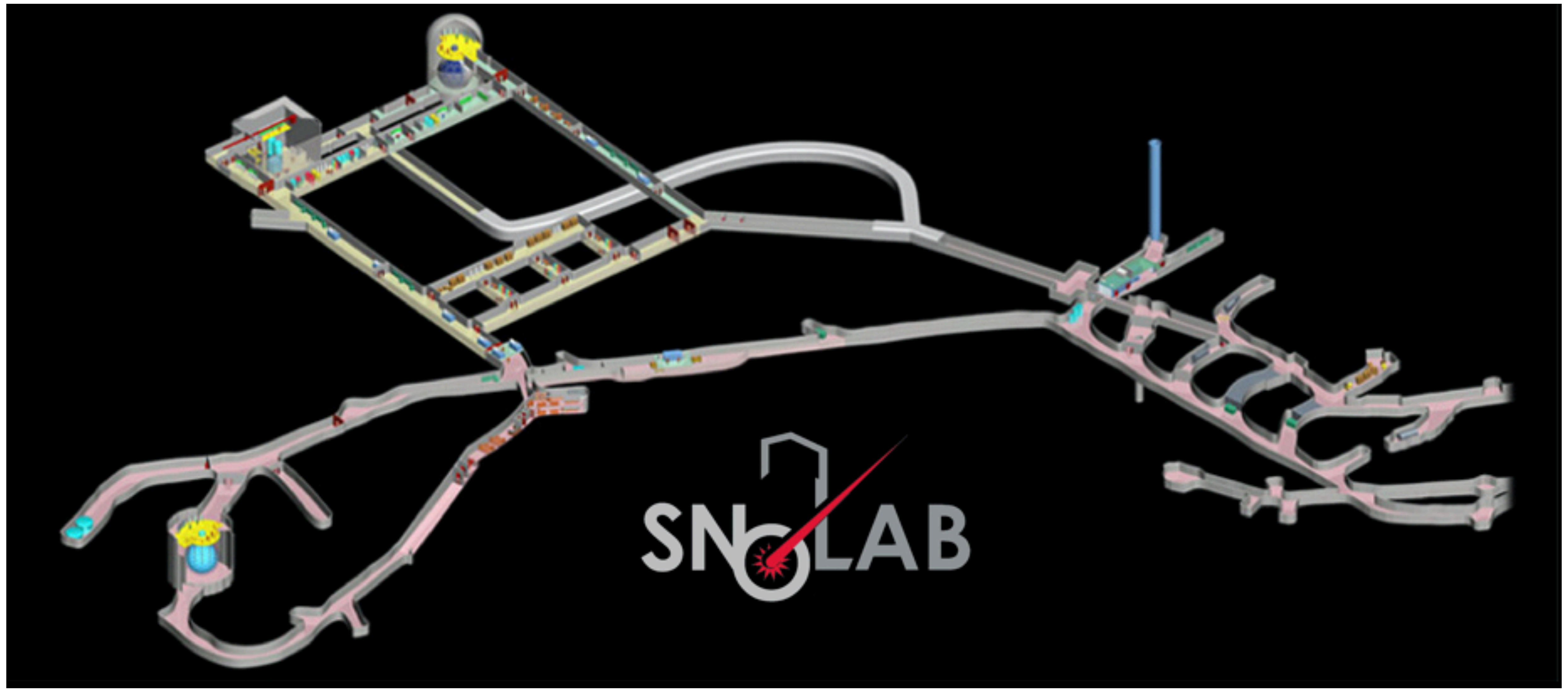
- Dark Matter Mass Ranges

"Traditional" Nuclear Recoil:	Full discrimination,	≳ 5 GeV
Low Threshold NR:	Limited discrimination,	≳ 1 GeV
CDMSlite:	HV, no discrimination,	~0.3 – 10 GeV
Migdal & Bremsstrahlung:	no discrimination,	~0.01 – 10 GeV
Electron recoil:	HV, no discrimination,	~0.5 MeV – 10 GeV
Absorption (Dark Photons, ALPs):	HV, no discrimination,	~1 eV – 500 keV ("peak search")

SNOLAB

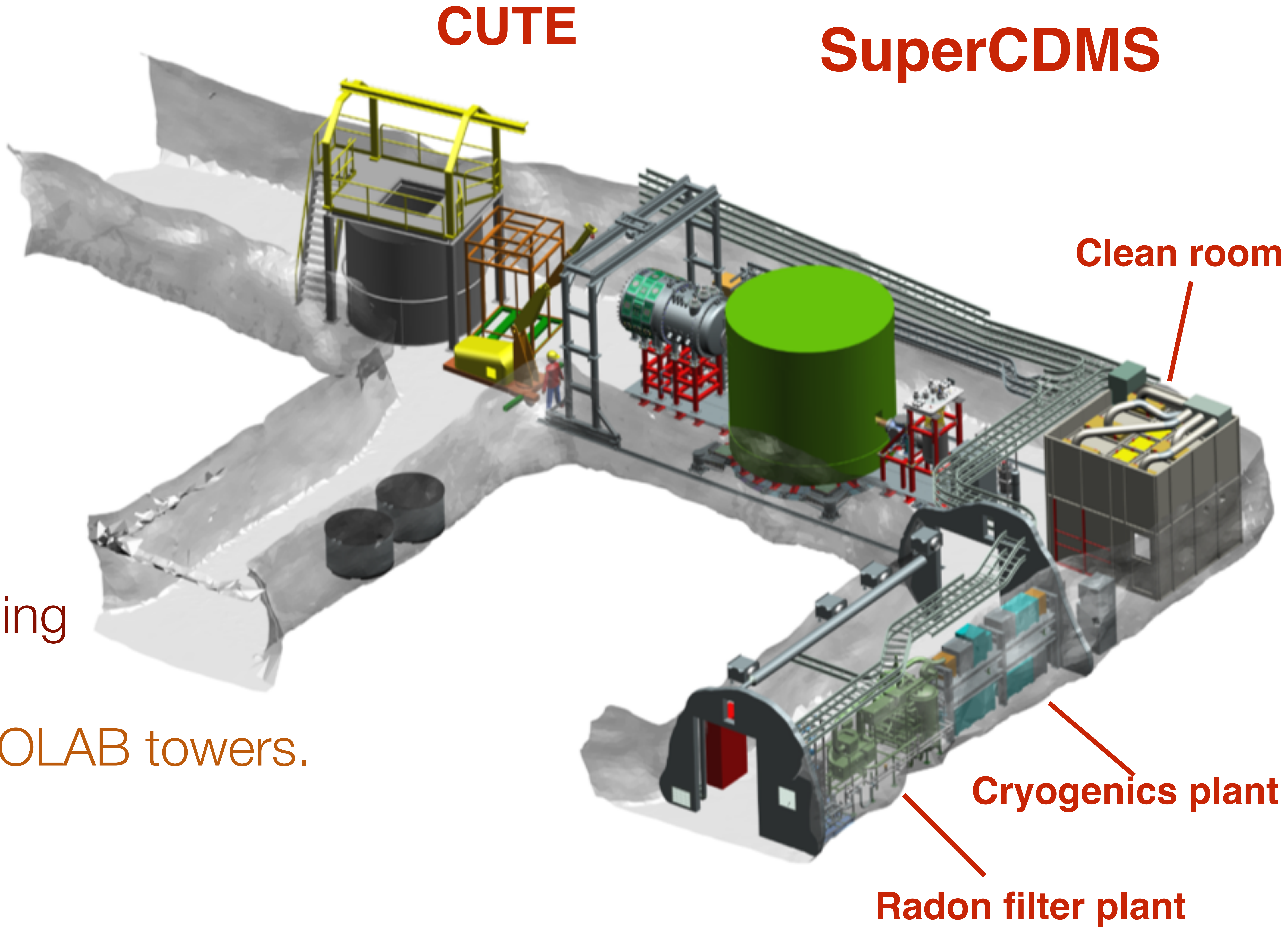
- 2 km underground (6000 m water equiv.)
- Cleanroom (class 2000 or better)
- Large lab (~5,000 m²)
- Cosmic radiation: muon rate reduced by ~10^6
- Surface facilities, support staff (>100)



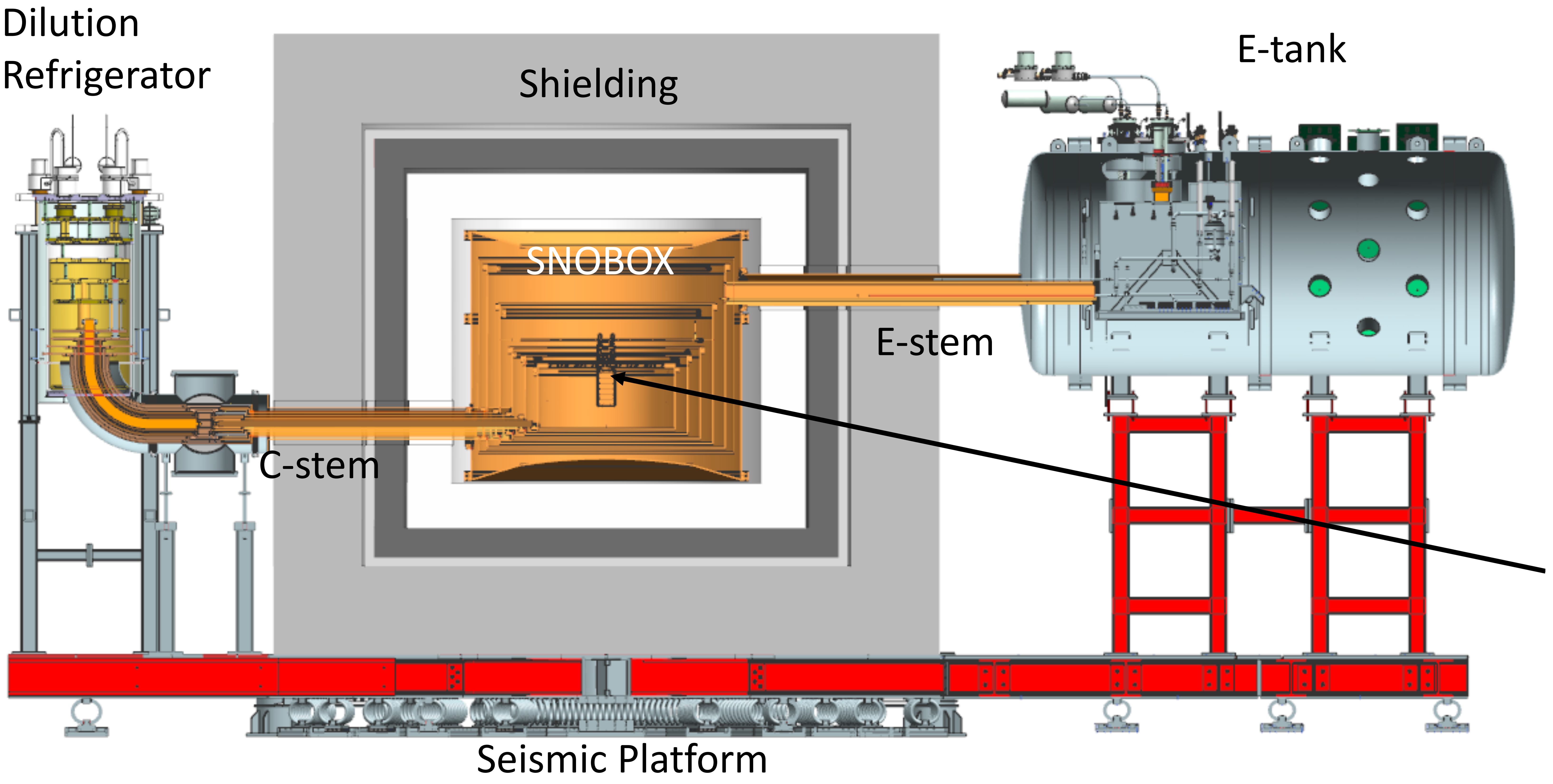


SuperCDMS @ SNOLAB

- Low-radon clean-room
- Collaborating with:
  - Cryogenic Underground TEst facility (CUTE)
  - Rapid-turn around detector testing
  - First data from SuperCDMS SNOLAB towers.



The SuperCDMS SNOLAB Experiment



Facility:

- 6800 m.w.e. overburden
- 15 mK base temperature
- Initial Payload: ~30 kg total 4 towers (2 iZIP, 2 HV)

Electron Recoil Backgrounds:

- External and facility: O(0.1 /keV/kg/d)
- Det. setup: O(0.1(Ge)-1(Si) /keV/kg/d)
- Total: O(0.1-1 /keV/kg/d)

Solar ν-dominated NR background

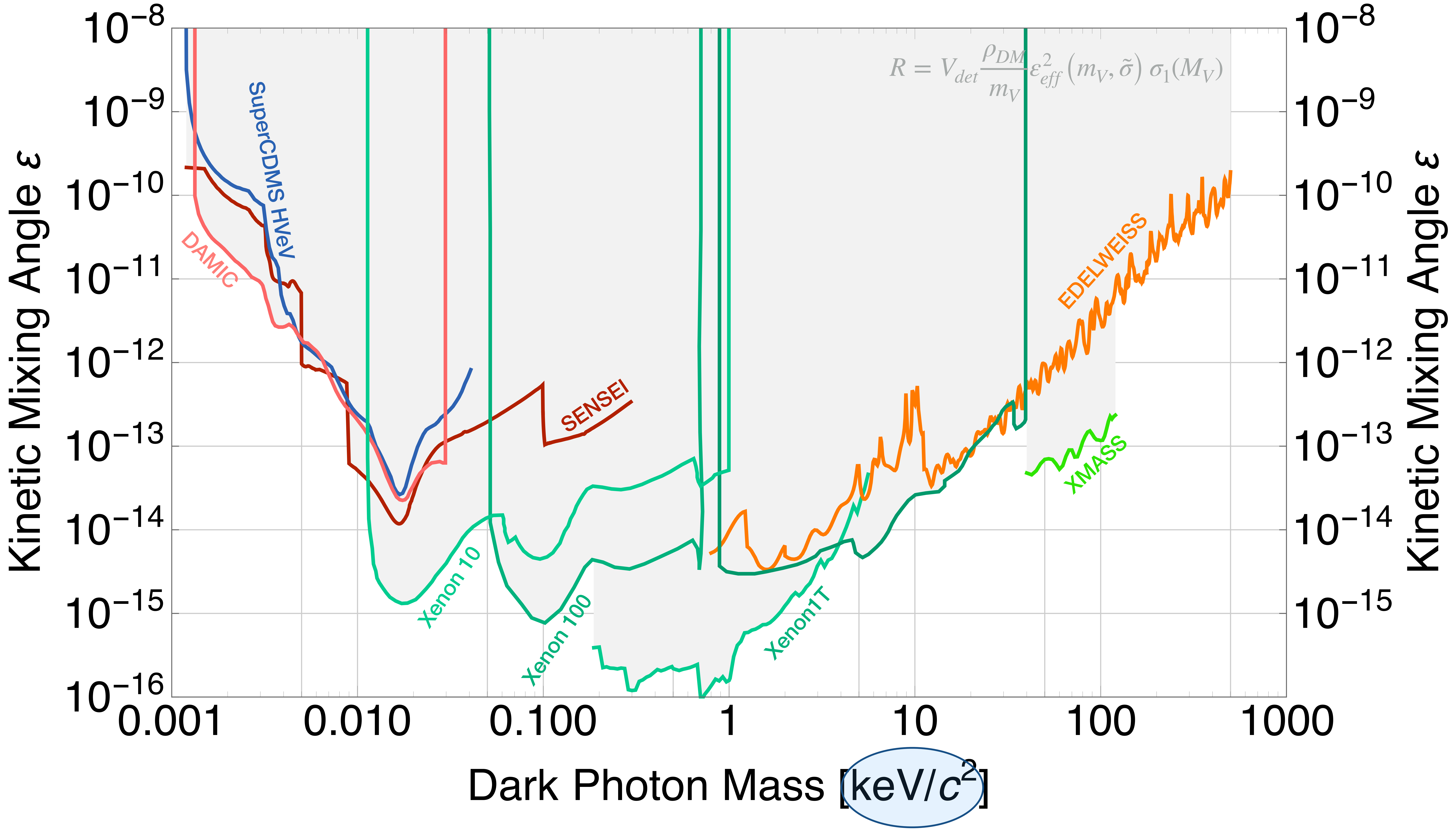
Vibration isolation:

- Seismic: spring loaded platform
- Cryo coolers: soft couplings (braids, bellows)
- Copper cans: hanging on Kevlar ropes

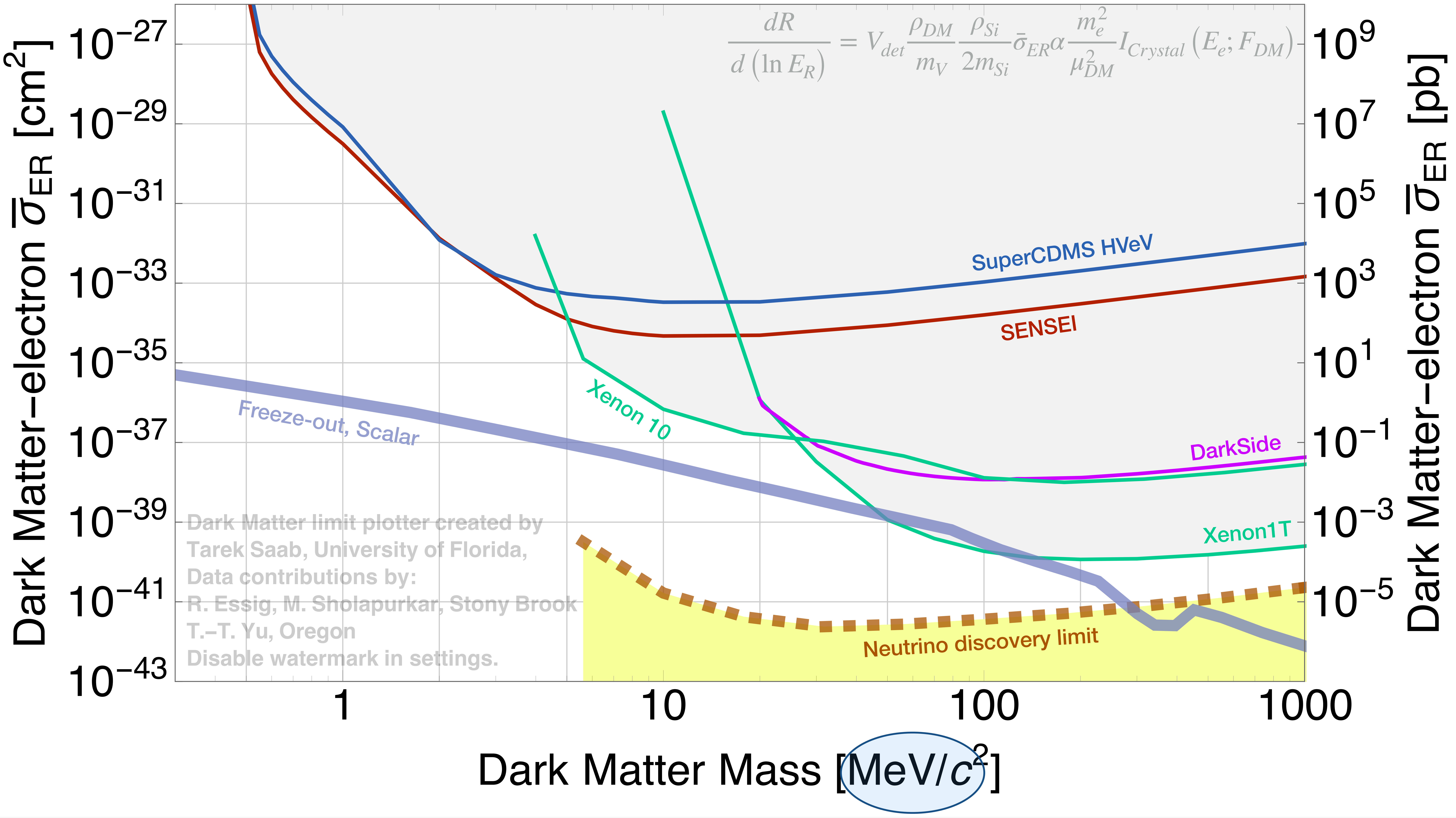
Dark Matter Search Results

… and future reach

Low Mass: Dark Photon Searches

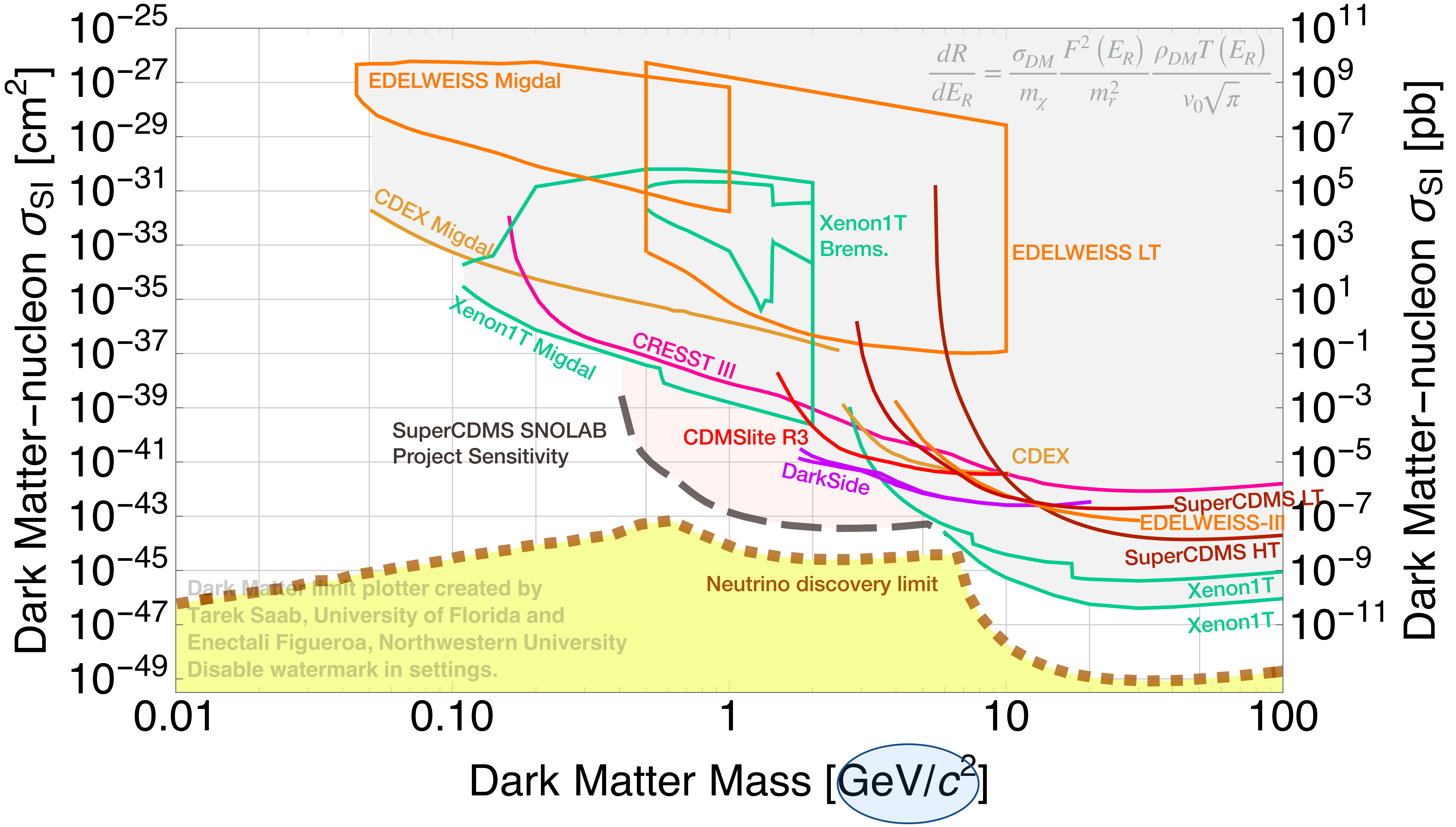


Mid Mass: Electron Recoil Dark Matter Searches



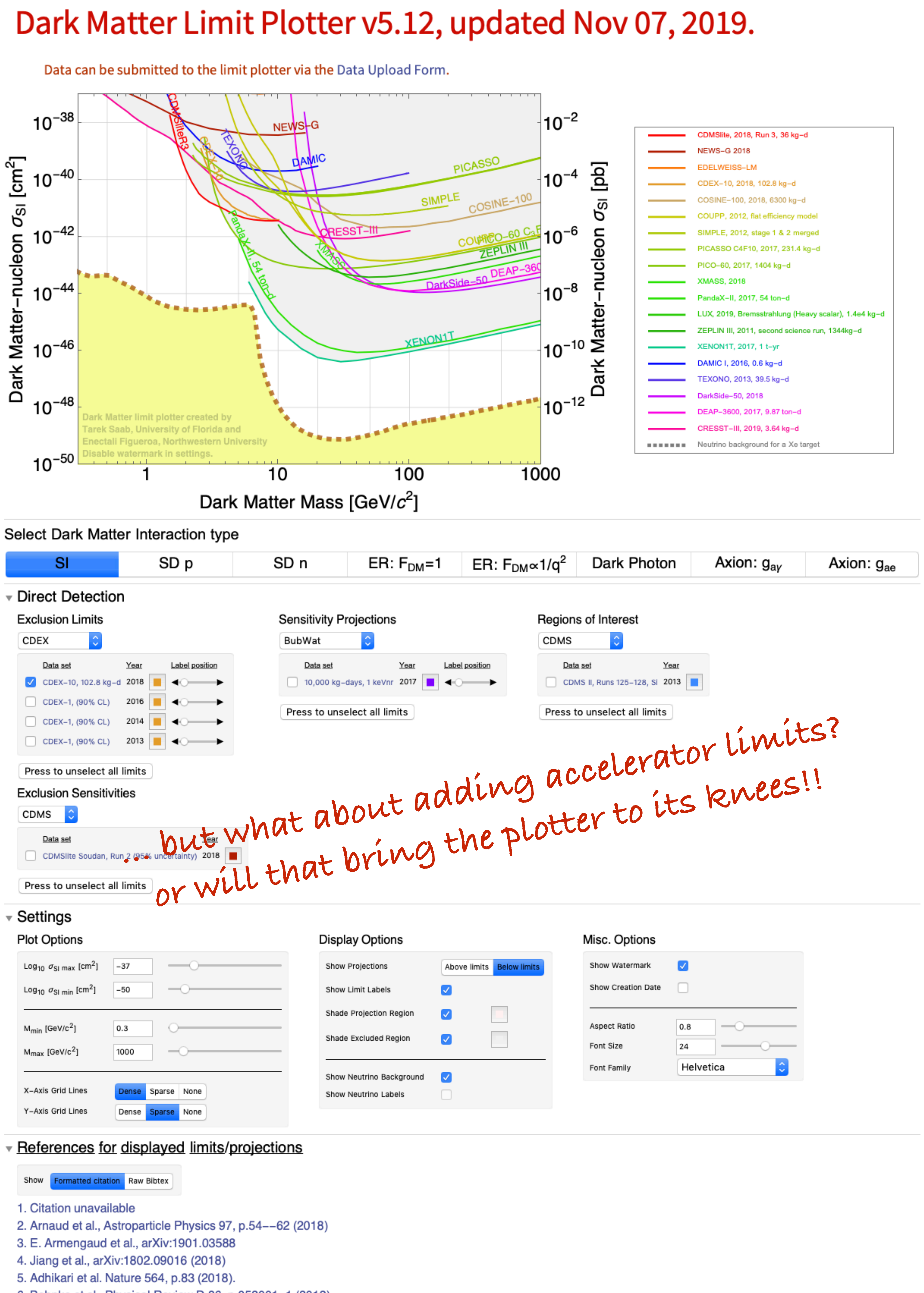
$$\frac{dR}{d\left(\ln E_R\right)} = V_{det}\frac{\rho_{DM}}{m_V}\frac{\rho_{Si}}{2m_{Si}}\bar{\sigma}_{ER}\alpha\frac{m_e^2}{\mu_{DM}^2}I_{Crystal}\left(E_e; F_{DM}\right)$$

High Mass: Nuclear Recoil Dark Matter Searches



Rapidly Growing Catalog of Limits and Projections

- Central repository for cataloging data & references, and plotting dark matter limits
  - Includes limits from several “Dark Matter” channels, i.e. **Nuclear recoil**, **Electron recoil**, **Dark Photon** and **Axion** interactions
  - Downloadable, runs locally*
    - https://supercdms.slac.stanford.edu/dark-matter-limit-plotter
  - Submissions welcome from all experiments
    - https://ufl.qualtrics.com/jfe/form/SV_9KVMNlMhbVg0cPb



Dark Matter Limit Plotter v5.12, updated Nov 07, 2019.

Data can be submitted to the limit plotter via the Data Upload Form.

Select Dark Matter Interaction type

▾ Direct Detection

Exclusion Limits

CDEX

	Data set	Year	Label position
☑	CDEX–10, 102.8 kg–d	2018	🟧
☐	CDEX–1, (90% CL)	2016	🟧
☐	CDEX–1, (90% CL)	2014	🟧
☐	CDEX–1, (90% CL)	2013	🟧

Press to unselect all limits

Sensitivity Projections

BubWat

	Data set	Year	Label position
☐	10,000 kg–days, 1 keVnr	2017	🟪

Press to unselect all limits

Regions of Interest

CDMS

	Data set	Year	
☐	CDMS II, Runs 125–128, Si	2013	🟦

Press to unselect all limits

Exclusion Sensitivities

CDMS

	Data set	Year	
☐	CDMSlite Soudan, Run 2 (95% uncertainty)	2018	🟥

Press to unselect all limits

... but what about adding accelerator limits?
or will that bring the plotter to its knees!!

▾ Settings

Plot Options

$\text{Log}_{10}\ \sigma_{SI\ max}$ [cm^2] -37
$\text{Log}_{10}\ \sigma_{SI\ min}$ [cm^2] -50
M_{min} [GeV/c^2] 0.3
M_{max} [GeV/c^2] 1000
X–Axis Grid Lines: Dense
Y–Axis Grid Lines: Sparse

Display Options

Show Projections: Below limits
Show Limit Labels ☑
Shade Projection Region ☑
Shade Excluded Region ☑
Show Neutrino Background ☑
Show Neutrino Labels ☐

Misc. Options

Show Watermark ☑
Show Creation Date ☐
Aspect Ratio 0.8
Font Size 24
Font Family Helvetica

▾ References for displayed limits/projections

Show: Formatted citation

1. Citation unavailable
2. Arnaud et al., Astroparticle Physics 97, p.54-–62 (2018)
3. E. Armengaud et al., arXiv:1901.03588
4. Jiang et al., arXiv:1802.09016 (2018)
5. Adhikari et al. Nature 564, p.83 (2018).

*you can even run it on your iPad if you are so inclined, but I don’t recommend it

Conclusion

... the end

Conclusions

- SuperCDMS detectors aiming to reach “neutrino floor” in 1-10 GeV NR mass range
- Technology being adapted in smaller detectors to search for light dark matter, down to
  - $\mathcal{O}(10)$ MeV via inelastic Nuclear recoil channels (Migdal, Bremsstrahlung)
  - $\mathcal{O}(1)$ MeV via Electron recoil channels and
  - $\mathcal{O}(1)$ eV via Dark Photon Absorption channels
    - With sensitivity to Axion dark matter in the same range
- SuperCDMS designed a powerful complex cryogenic system that is being installed at SNOLAB
  - CUTE is operational – deepest dilution fridge in the world
    - Plans for early science reach with CUTE facility
  - SuperCDMS Detector installation – next spring/summer
    - Initial run – late 2022
- SuperCDMS is particularly competitive at low masses, including electronic interactions.
- Stay tuned! Experiments are producing results at a fast pace, more sensitive experiments are soon to come online.

Dark Matter Searches: Executive Summary

First, it was thought neutrinos can't be detected, …

And then they were (1930—1956)

But then many said Gravitational Waves will never be detected, ….

Until they were, in plenty, (1893—2015)

So, now they all ask, … when the h@#% are you going to finally see this dark matter stuff, ….

…. soon, I hope?!
Dark Matter Searches, 90 years and counting!

At least the size of potential DM parameters space isn't expanding exponentially!