University of Colorado **Denver**

CU IN THE CITY

SuperCDMS in 10 Minutes

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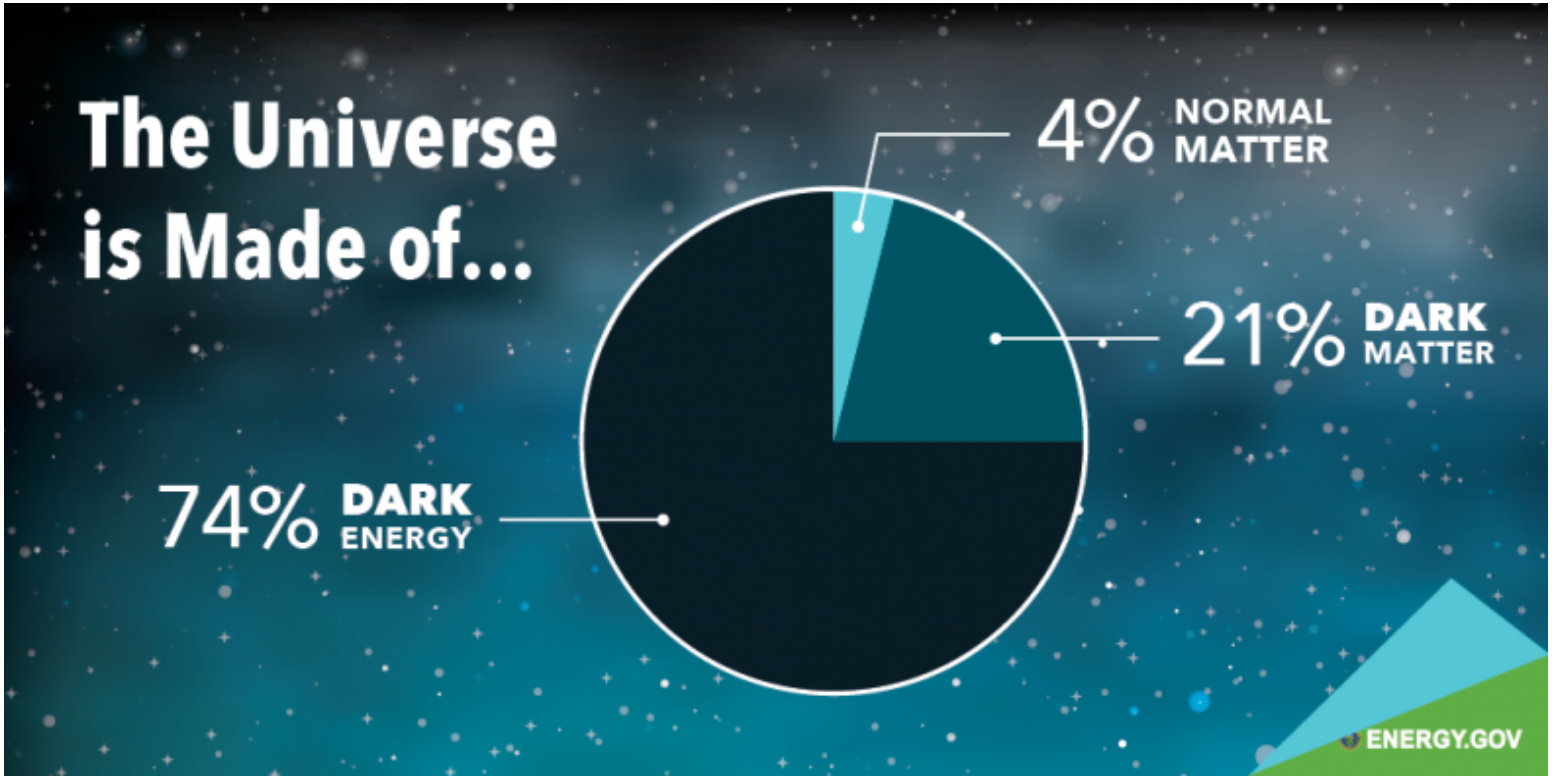
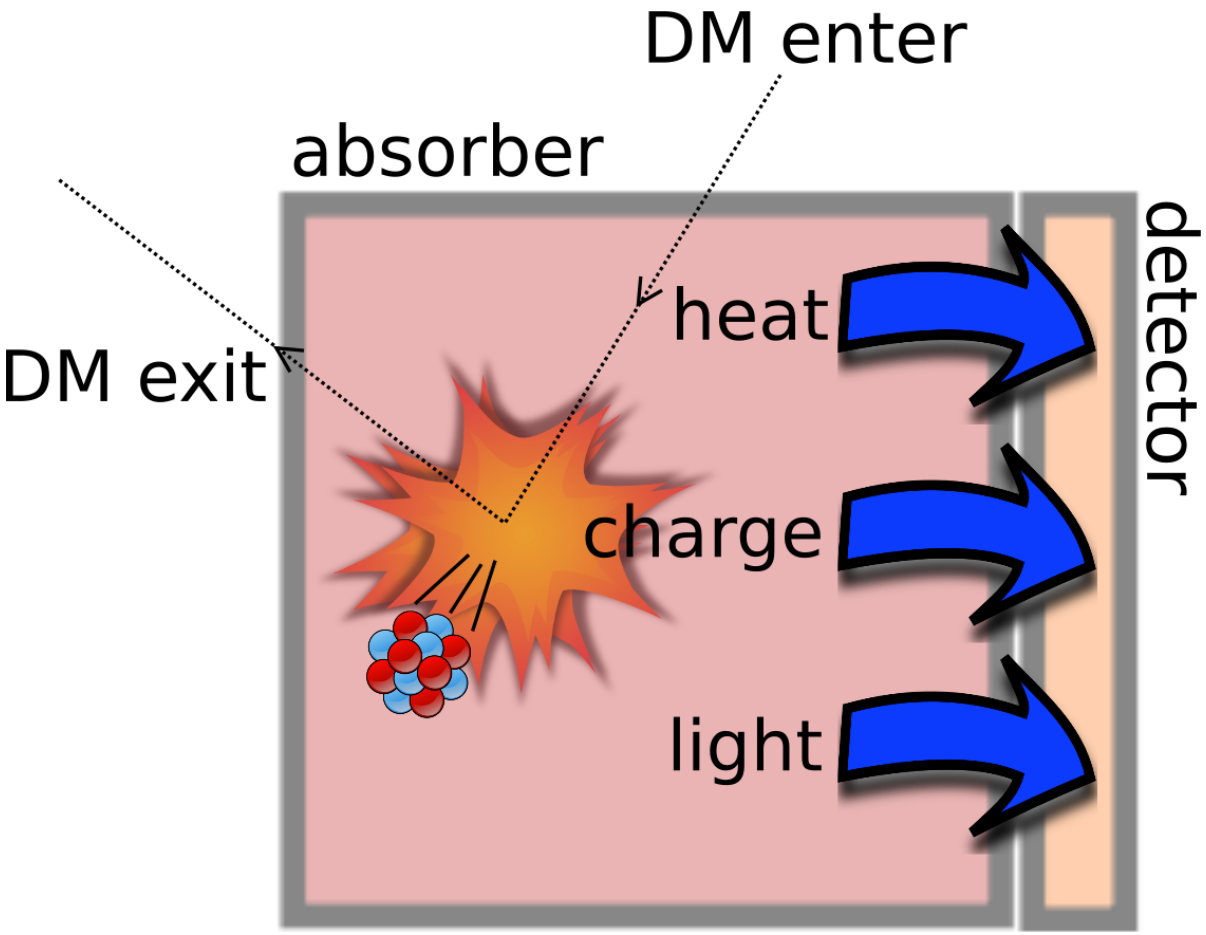
So What's Our Story?



One thing is clear: if dark matter is particulate it may the most challenging form of matter to detect. We (all) really want to directly measure this stuff, so how does SuperCDMS try to do this?

Dark Matter May Elastically Scatter



- **Elastic scattering on nuclei** is a possibility that allows energy deposition of dark matter directly into the detector
- This is our **connection** to dark matter interactions
- We can design **detector technology** around this

Dark Matter Mass Ranges

Very low recoil energy threshold!

Material: germanium/silicon crystals

DM mass range: 1—10x mass of proton

Readout: ionization and phonons (heat)

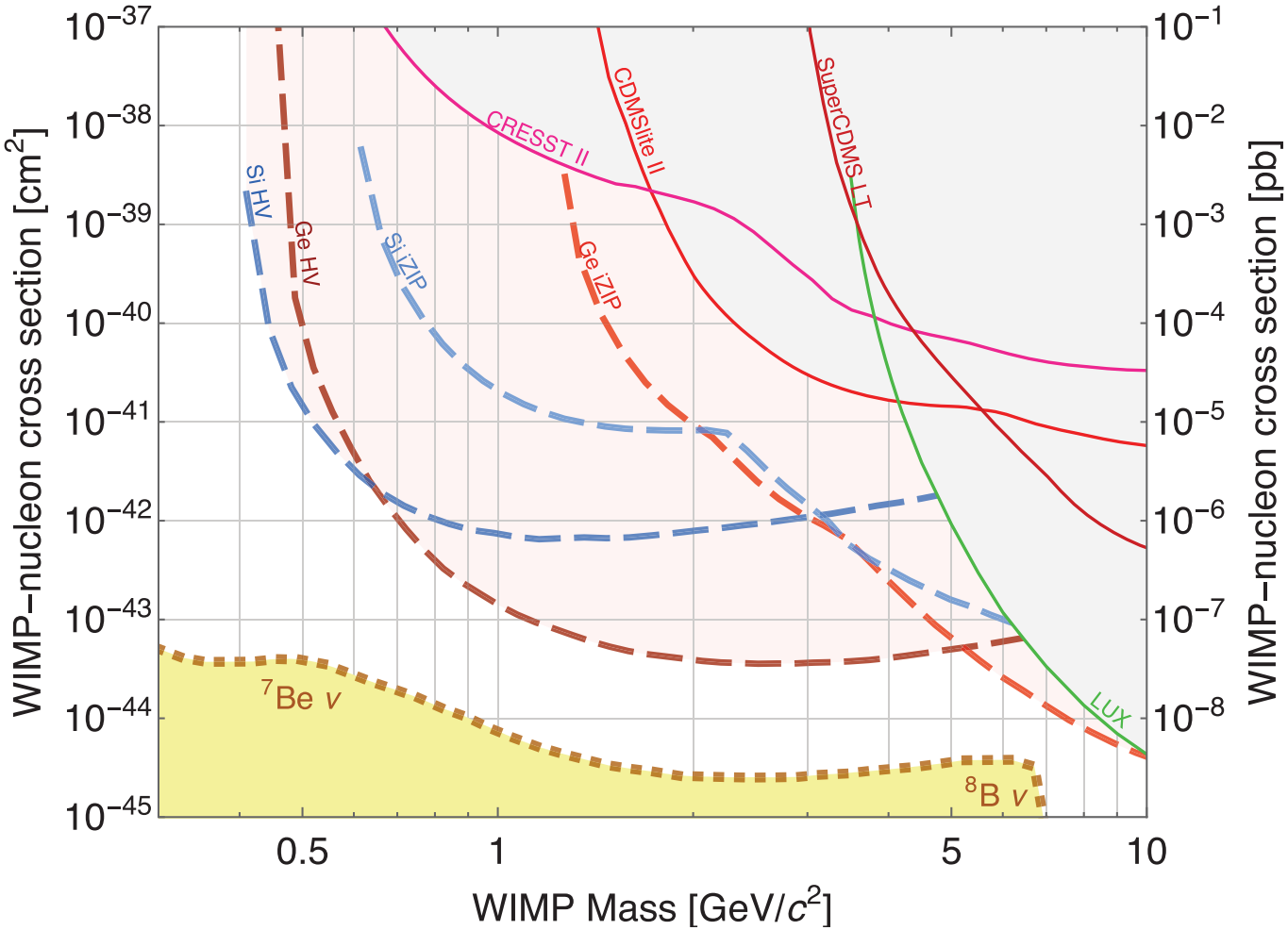
Very large detector!

Material: liquid xenon

DM mass range: 10—1000x mass of proton

Readout: ionization and scintillation (light)

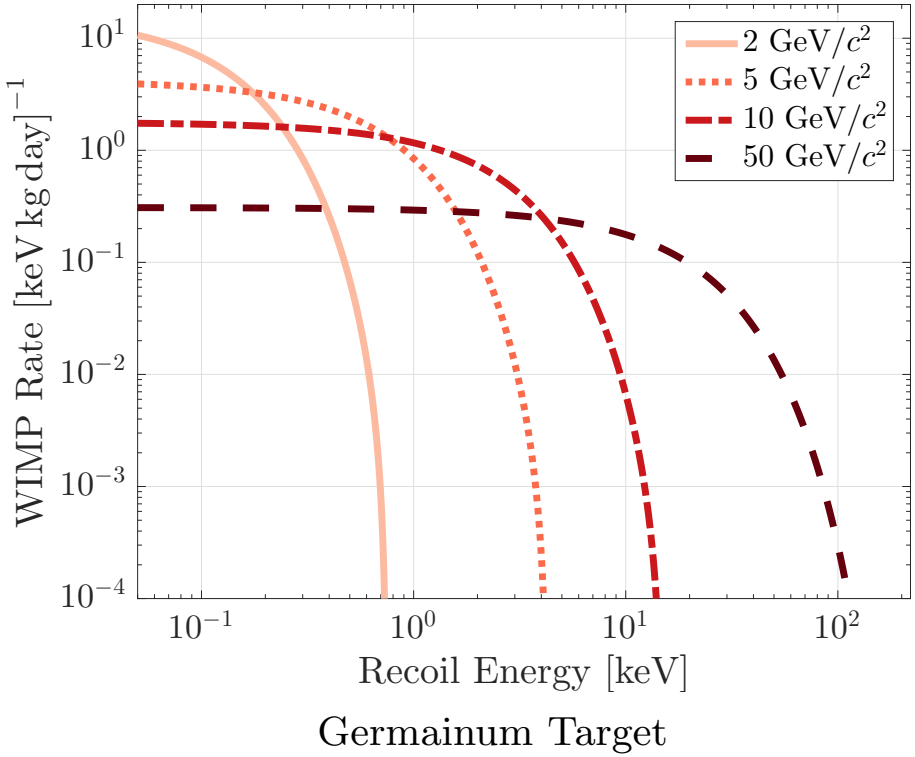
SuperCDMS at Low Mass



SNOLAB Projected Sensitivity (dashed lines) from:
Agnese et al., PRD **95**, 08002 (2017)

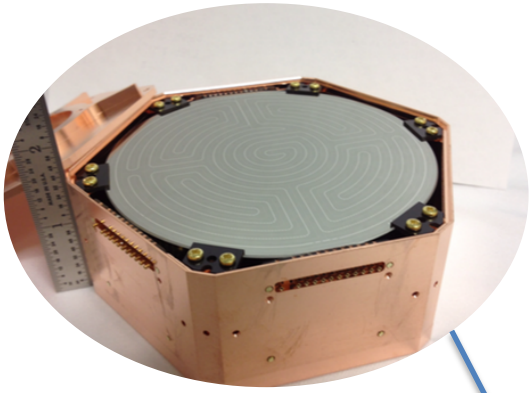
Spectrum Biased Toward Low Energy

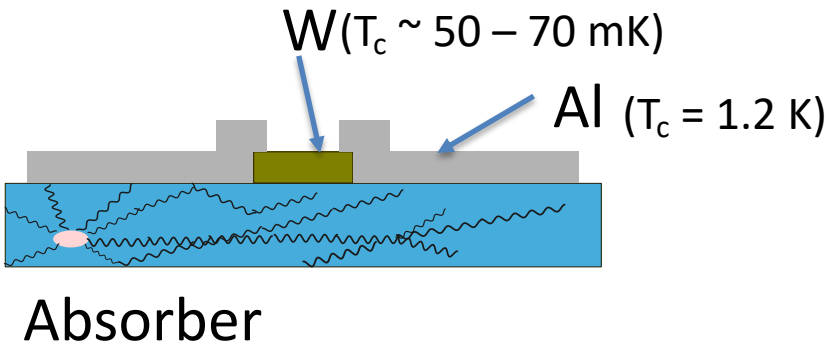
figure from:
M. Pepin, PhD thesis, U. Minnesota (2016)

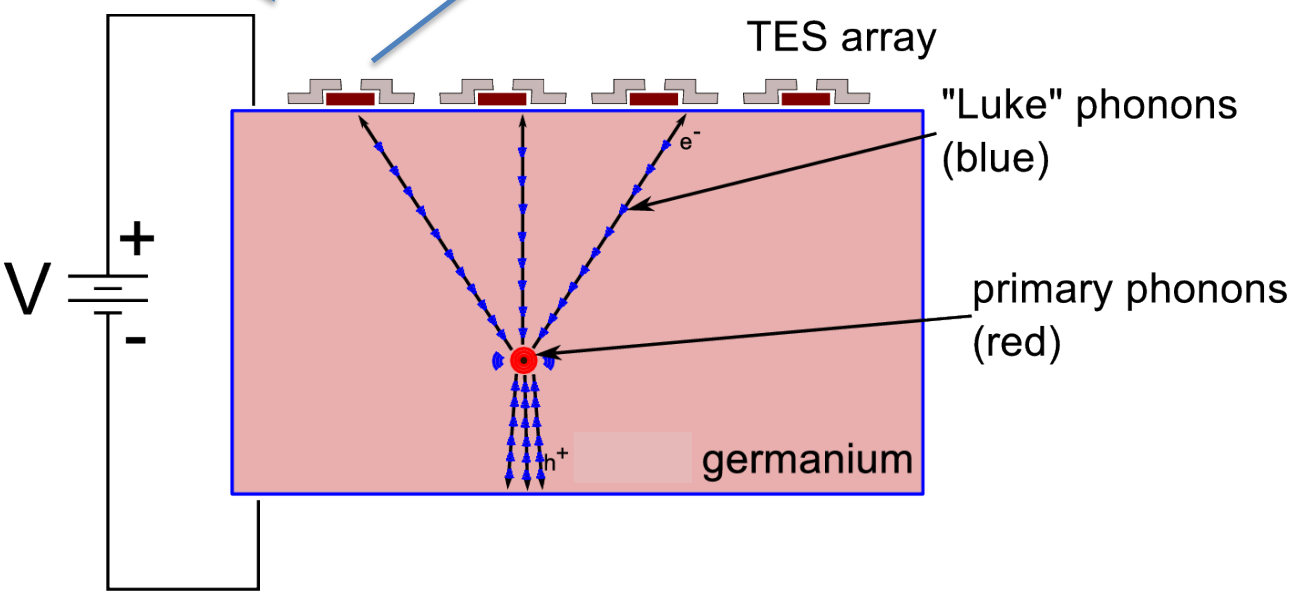


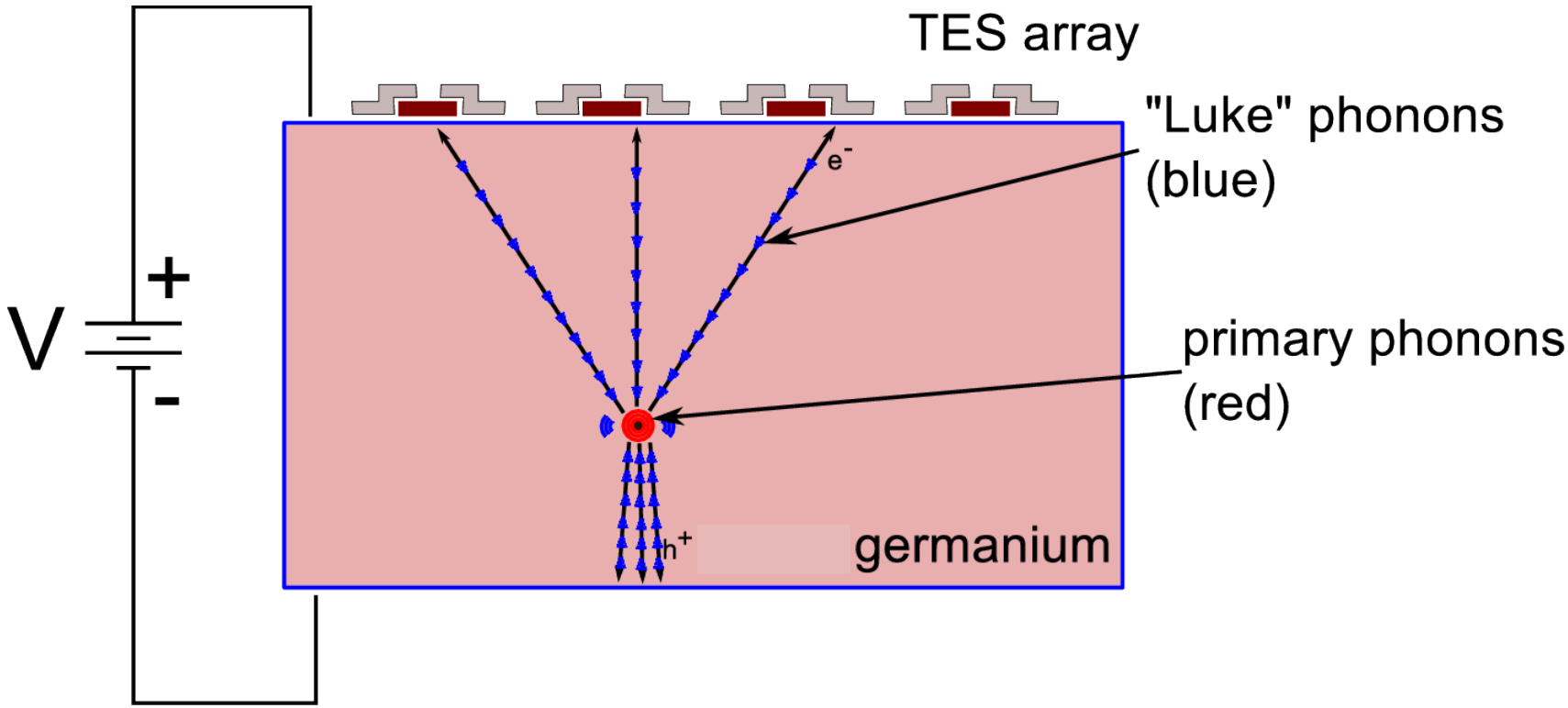
- Interested in **low mass**
- Use trial cross section to find differential recoil energy rate (left)
- "Standard" halo assumptions are used, like a Maxwellian distribution with some escape velocity

SuperCDMS Detectors









1. The event site is very small (~microns)
2. Charge carries (e^-/h^+) and primary phonons created immediately
3. e^-/h^+ drift along field lines with no charge multiplication
4. Charges drift through the potential and create phonons along the way called “Luke” phonons, proportional to voltage

Summing the Phonon Energy

Total potential traversed by e/h pairs

Abs. electron charge

True recoil energy

Number of e/h pairs

$$E_p = \underbrace{E_r}_{\text{“direct” contribution}} + \underbrace{eVN_q}_{\text{”Luke” contribution}}$$

Total phonon energy of event

$$N_q \propto E_r \,(\text{for electron recoils})$$

Rearranging The Energy Equation

$$E_p = E_r \left(1 + \frac{eV}{\epsilon_\gamma} Y(E_r)\right)$$

Average energy required to create a single e/h pair

Yield function $Y(E_r)$ is 1 for electron recoils, and nonlinear nuclear recoils

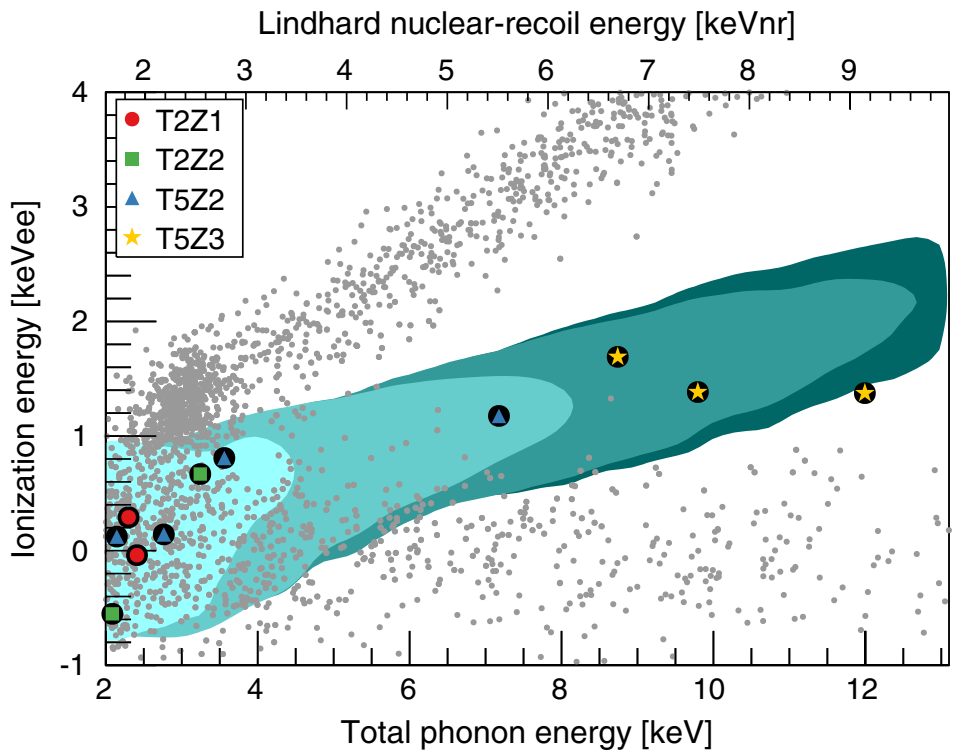
Rearranging The Energy Equation

$$E_p = E_r + \frac{eV}{\epsilon_\gamma} Y(E_r) E_r$$

$$E_p = E_r + \frac{eV}{\epsilon_\gamma} E_q$$

Yield function $Y(E_r)$ is 1 for electron recoils (ER), and nonlinear nuclear recoils (NR)

SNOLAB (low Threshold)



- In the low-threshold mode we have excellent ER/NR discrimination
- Down to where bands overlap we have nearly zero-background experiment
- This will make the two iZIP towers (10 Ge and 2 Si) ***livetime limited***

Low-Threshold Band Structure from:
Agnese et al., PRL **112**, 241302 (2014)

The Energy Equation

For *very low threshold* measurements with "CDMSlite" we measure phonons which (at our high voltages: 10 – 100V) are mostly produced by charge moving across the detector potential (Luke phonons)

Abs. electron charge

Total potential traversed by e/h pairs

Ionization "yield"

True recoil energy

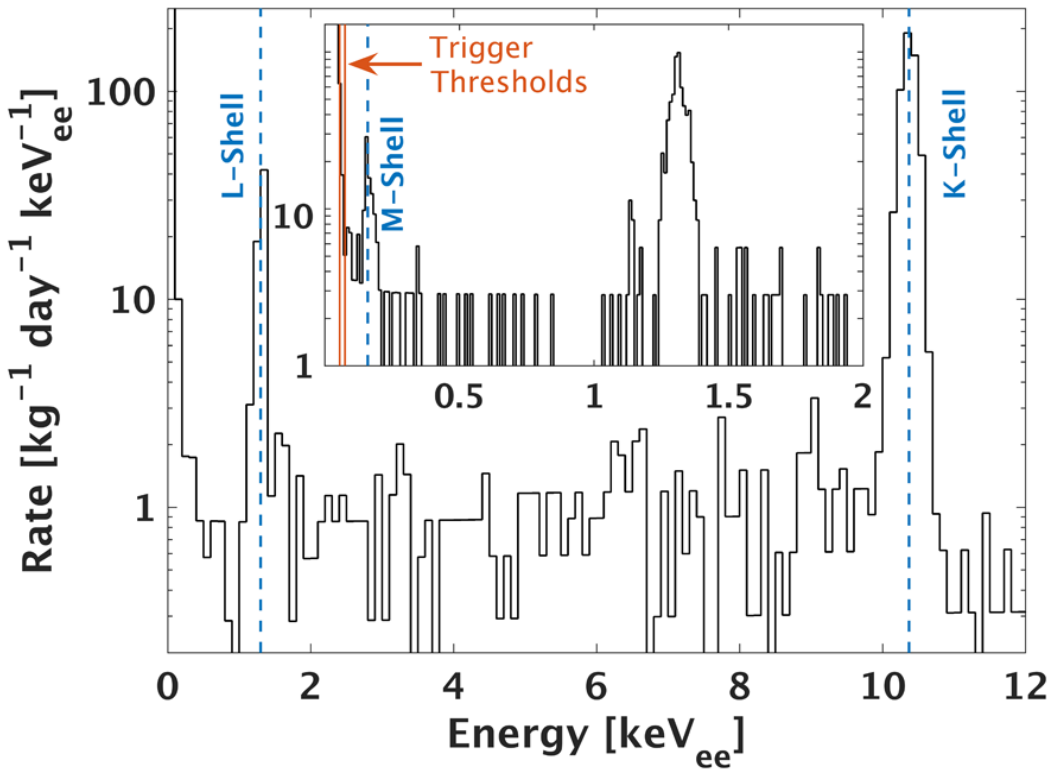
$$E_p = E_r \left(1 + \frac{eV}{\epsilon_\gamma} Y(E_r)\right)$$

Avg. recoil energy per e/h pair

Total phonon energy of event

Yield function $Y(E_r)$ is 1 for electron recoils, and nonlinear for nuclear recoils

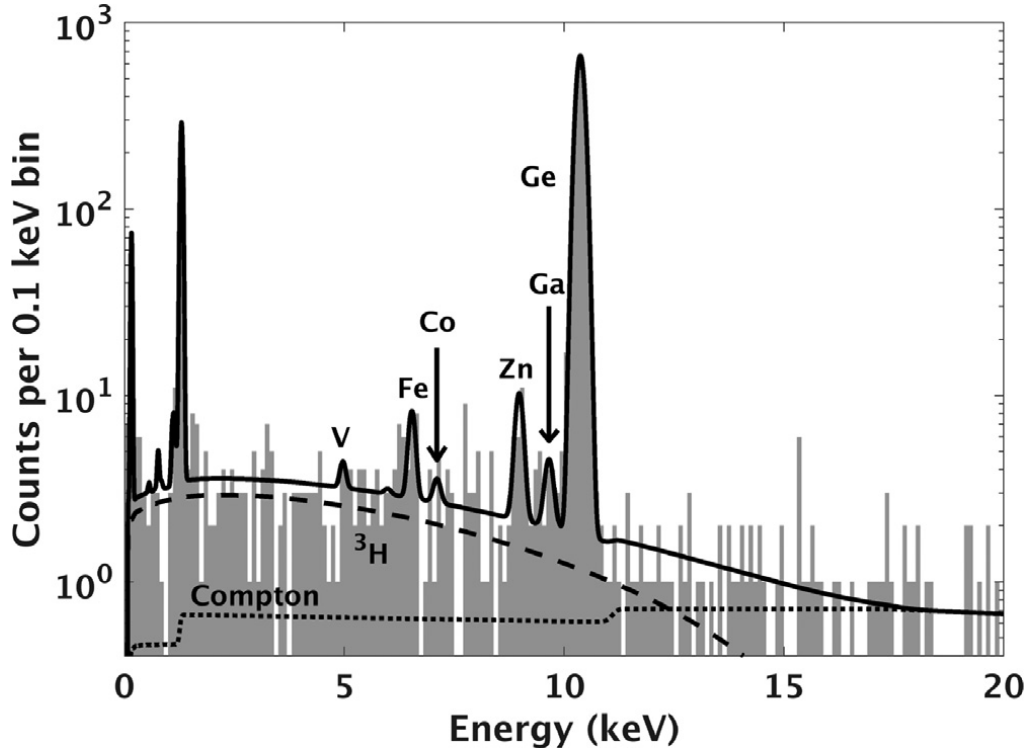
SNOLAB HV



- In the HV mode we have no ”Yield” measurement
- We do have astonishingly low threshold (< 80 eVnr at SNOLAB)
- This will make the two HV towers (8 Ge and 4 Si) ***background limited***

HV-type Spectrum from:
Agnese et al., PRL **116**, 071301 (2016)

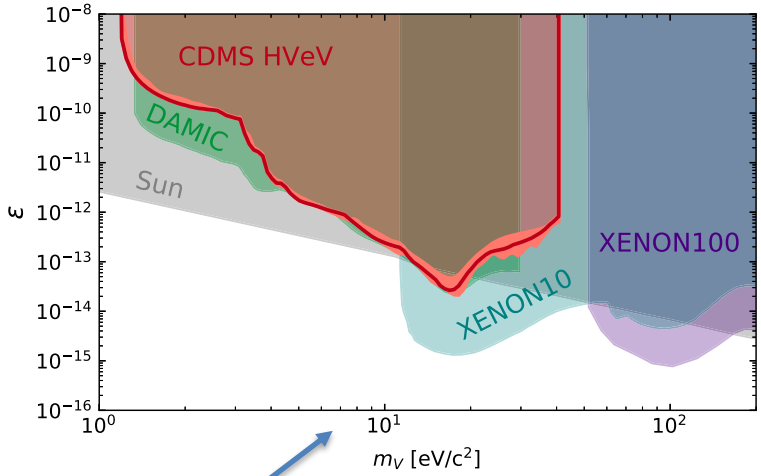
SNOLAB Bulk "ER" Backgrounds



Background analysis from:
Agnese et al., Astropart. Phys. **104**, pp 1--12 (2019)

- In the HV mode since we have no "Yield" backgrounds are ***super important***
- For Ge, the ^{3}H background is most concerning because it is in the bulk of the detector and pretty spread out in energy
- For Si, we have ^{32}Si background (not shown)

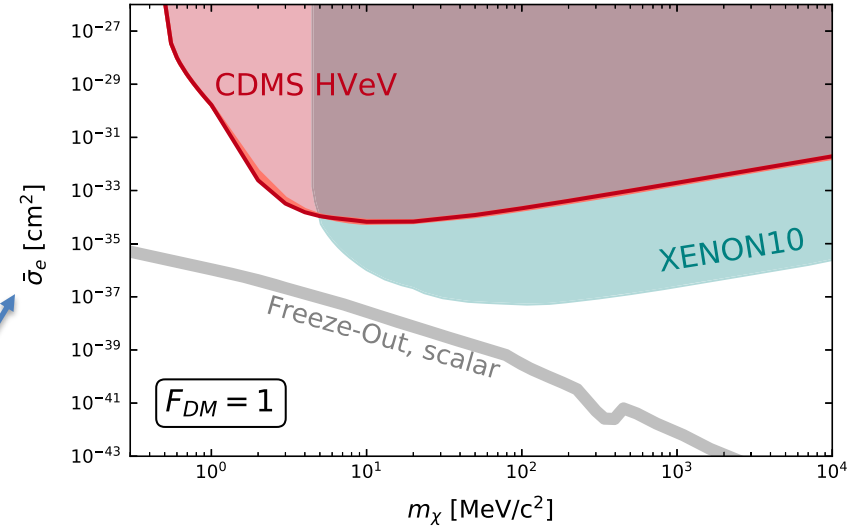
Electron Recoil DM

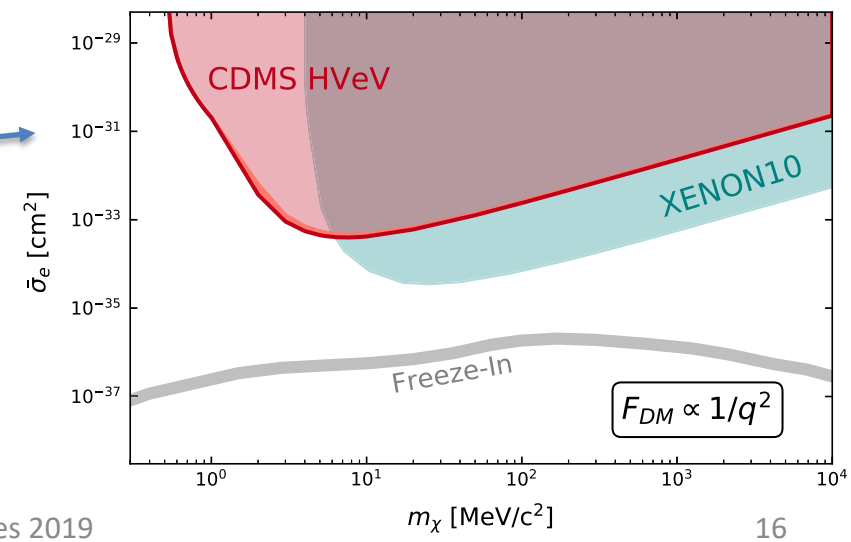


Axio-electric: a + Z → e⁻ + Z⁺

Z: neutral atomic state
χ: light dark matter particle

Electron elastic: e⁻ + χ → e⁻ + χ





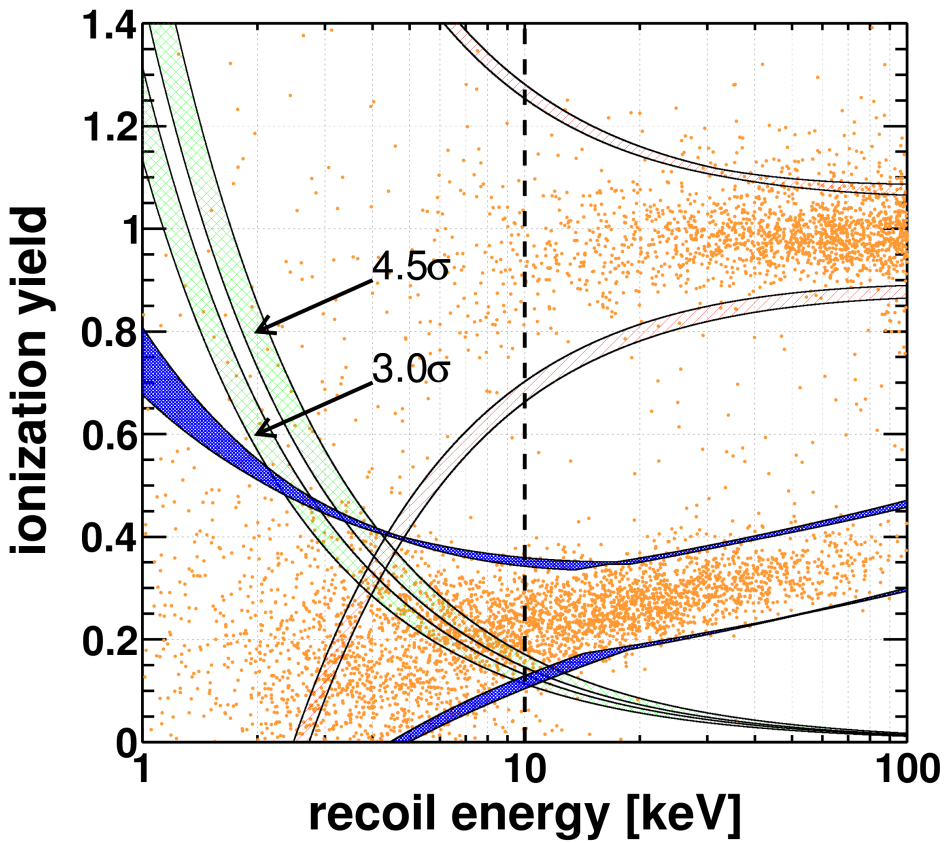
Electron Recoil Limits from:
Agnese et al., PRL **121**, 051301 (2018)

So, What Did We Learn?

- We want to explore new mass space for dark matter → low threshold detectors
- At the ultimate ionization resolution, making sense of the spectra is challenging too, because we're not measuring energy! → study the microphysics for low-energy recoils!
- SuperCDMS SNOLAB will use the best of our technology→ intermediate and low mass reach
- Learning about the new particle mechanisms combined with the SNOLAB instrument will yield an incredible opportunity for growth of dark-matter direct-detection!

Appendix: Traditional CDMS Yield Variable

Measuring the Yield: Traditional CDMS

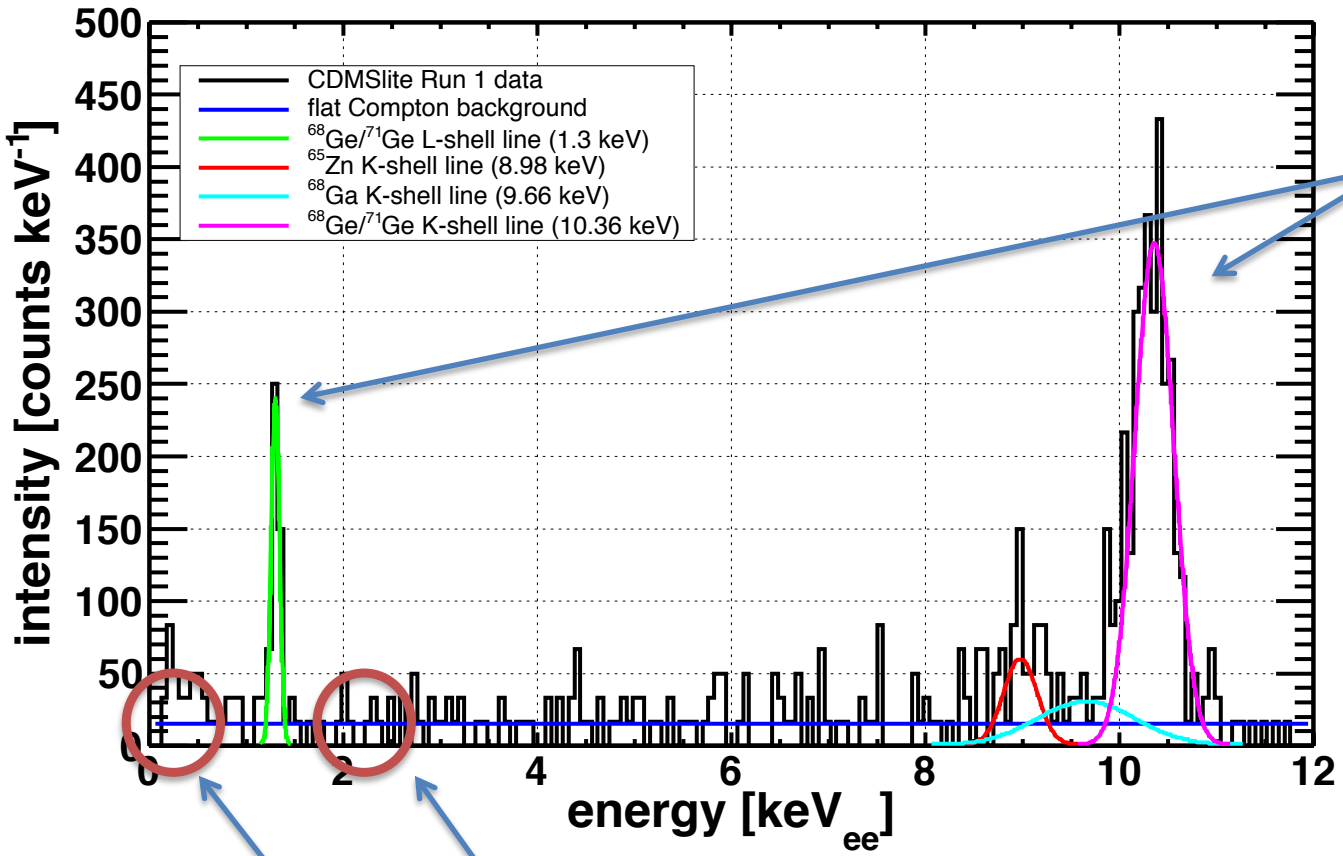


$$Y = \frac{E_p}{E_p - \frac{eV}{\epsilon_\gamma} E_q}$$

- Want to lower threshold by increasing V, can do that but:
- Electron and Nuclear Bands will overlap and make this style impossible because of charge resolution

Appendix: Yield Measurements

What if $Y(E_r)$ Sharply Decreases?



Electron recoil calibration standards

Here is where a 1.0 keV nuclear recoil would show up

Here is where a 10.0 keV nuclear recoil would show up

Our calibration standards are mostly electron recoil, but dark matter may produce mostly nuclear recoils, which behave **very differently: the yield is dramatically lower**

Yield Model and Measurements

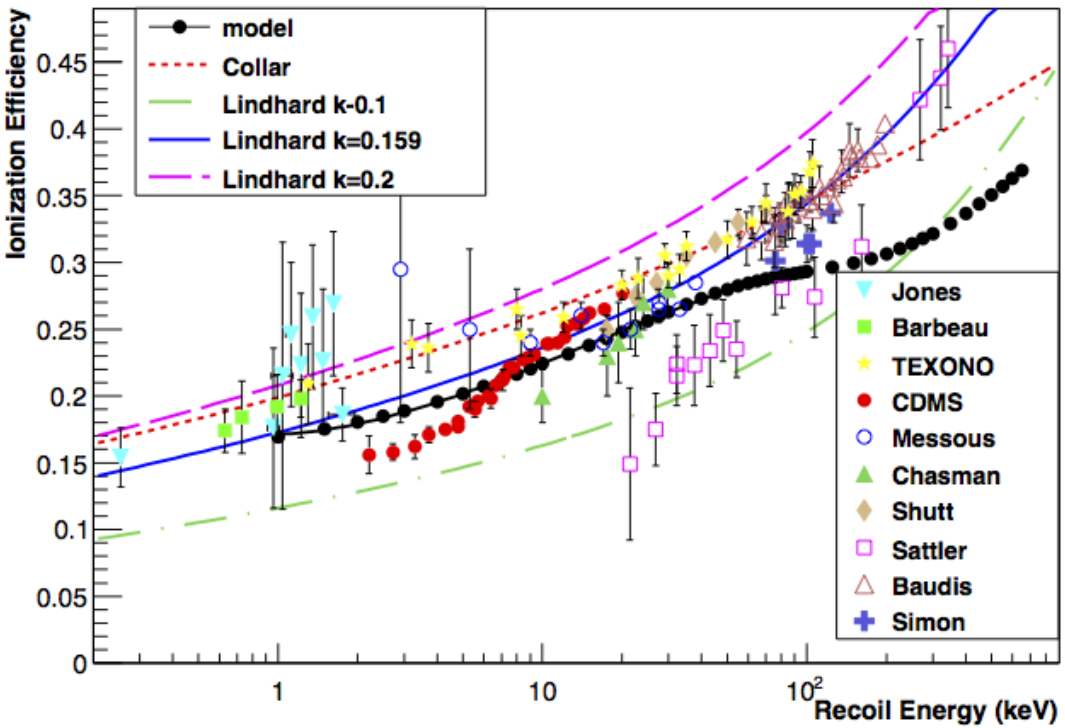
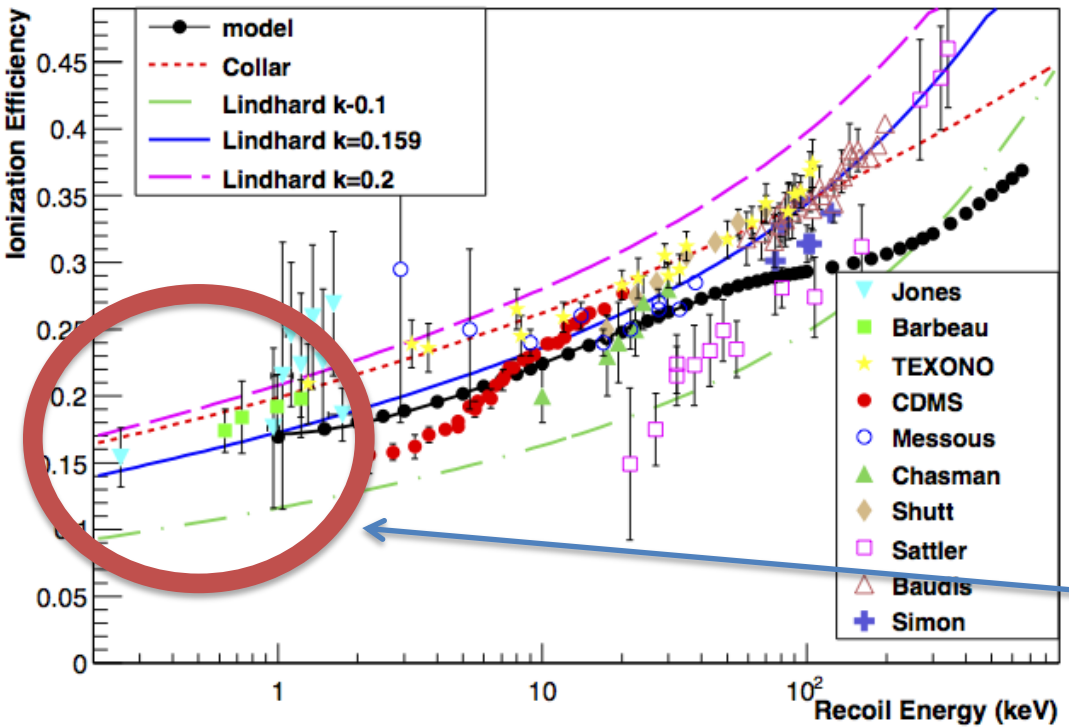


Figure and model from:
Barker, D. et al., Astroparticle Physics **48**, 8 (2013)

Most relevant low-energy data from:
Jones et al., PRA **11**, 1347 (1975)

- In fact the ionization yield in germanium has been measured and modeled (left)
- Nuclear recoils produce **less ionization** than electron recoils of the same energy
- N of charges Modeled as **Poisson Distributed**—only the average is measured

Yield Model and Measurements



Poorly measured in the region most relevant for low-mass dark matter searches!

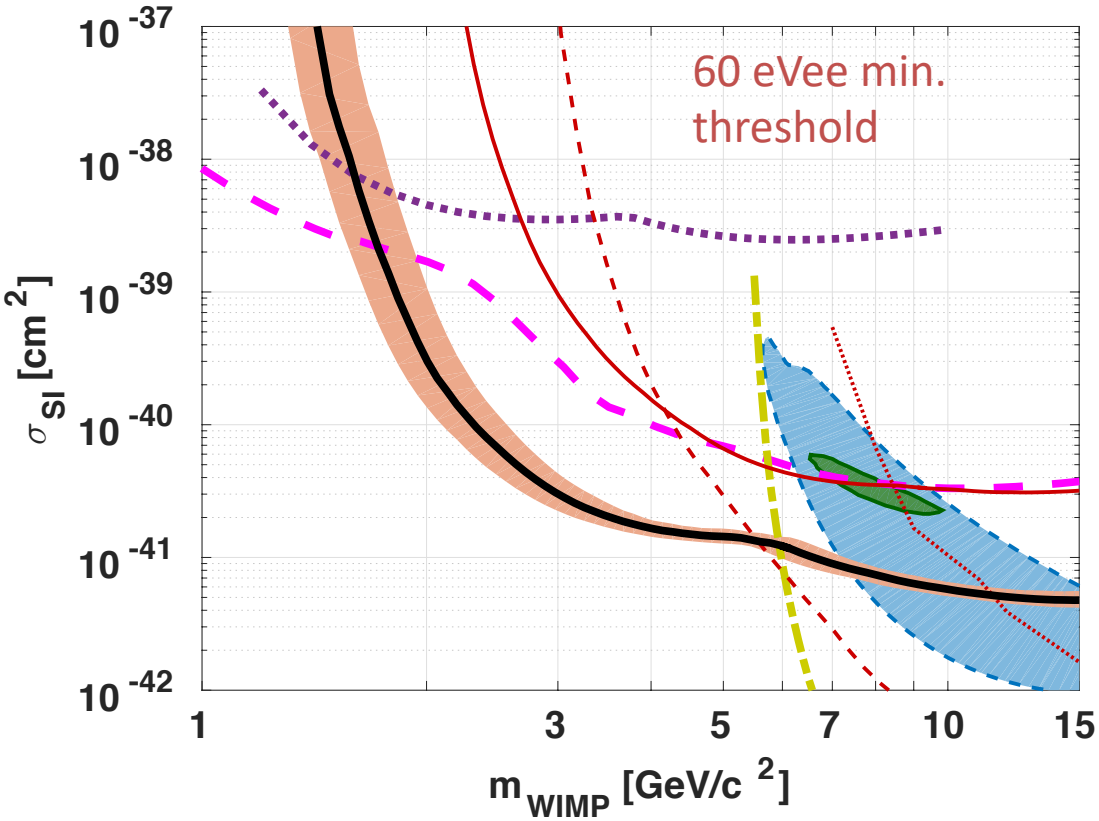
Figure and model from:
Barker, D. et al., Astroparticle Physics **48**, 8 (2013)

Most relevant low-energy data from:
Jones et al., PRA **11**, 1347 (1975)

Energy Scale Impact

CDMSlite (HV) running pushes to incredibly low thresholds (60 eVee a Soudan) :

- Best CDMSlite limit shown at right (black curve, 90% C.L.)
- The red band quantifies the dominant systematic NR yield uncertainty
- This uncertainty also affects expected background calculations

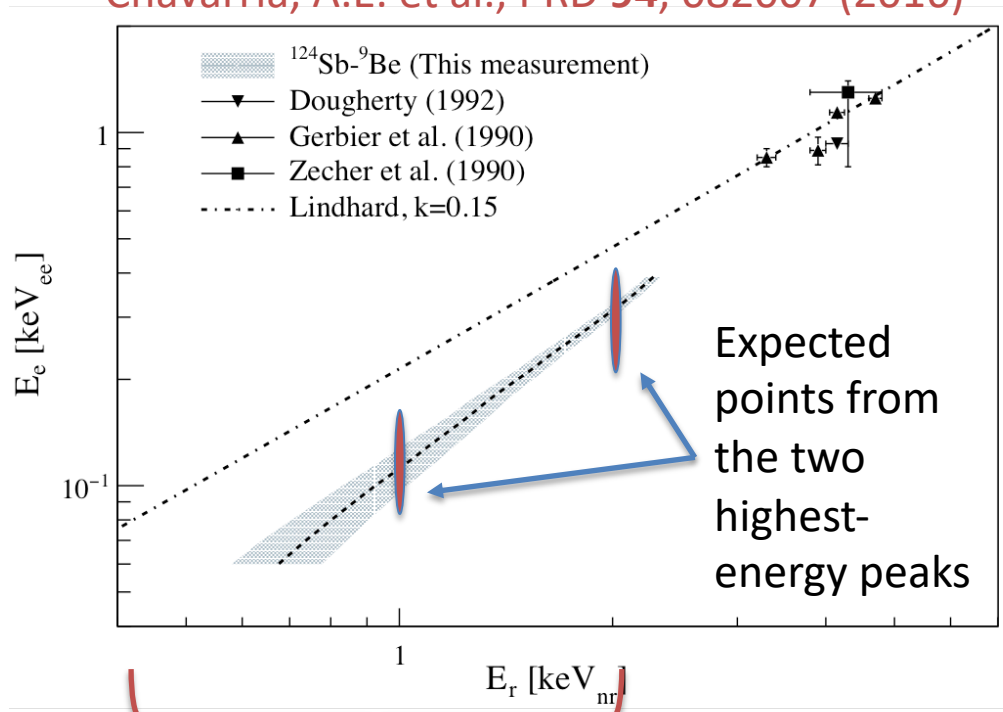


CDMSlite run 2:
Agnese et al, PRL **116**, 071301 (2016)

Expected Results (Si)

- The amount of charge produced in semiconductors is a non-linear function of recoil energy
- In silicon, some of the energy range is well-measured
- Below 700 eV measurements are so far absent and difficult to make

Figure from:
Chavarria, A.E. et al., PRD **94**, 082007 (2016)



Silicon neutron capture calibrations can measure this energy range well

Appendix: Add’l. References

WIMPs and Nuclear Recoils

WIMPs (Weakly Interacting Massive Particles; a kind of dark matter) are generally assumed to interact dominantly with nuclei; some recent trends are challenging this (considering either low-mass WIMPs or very low energy thresholds)

Light WIMPs → very low energy thresholds

because particles lighter (or heavier!) than the target nuclei have inefficient energy transfers

For semiconductor detectors!

Very low energy thresholds → Luke amplification

because we then control an extra gain factor for the phonon signal directly proportional to the voltage bias across the detector

For CDMS detectors!

Luke amplification → CDMSlite (see publications)

In our "CDMSlite" mode the detectors are configured to give the largest amplification of the phonon signals, so we can easily see recoils down to 100's of eVee (eV electron equivalent) energies

A First Course: SuperCDMS

Akerib et al., PRD **82**, 122004 (2010)

great introduction to detector technology and analysis techniques of classic (CDMS) ZIP detectors

Agnese et al., Appl. Phys. Lett. **103**, 164105 (2013)

an overview of the more modern (SuperCDMS) iZIP detector and description of its surface-event rejection capability in standard voltage mode

Agnese et al., PRL **112**, 241302 (2014)

a first science run in our high-voltage (CDMSlite) running mode

Agnese et al., PRL **116**, 071301 (2016)

extended science reach and improved analysis for the CDMSlite running mode; this displays our best phonon energy resolution and threshold to date and has sparked a lot of activity in the **"Low Recoil Energy Frontier"**