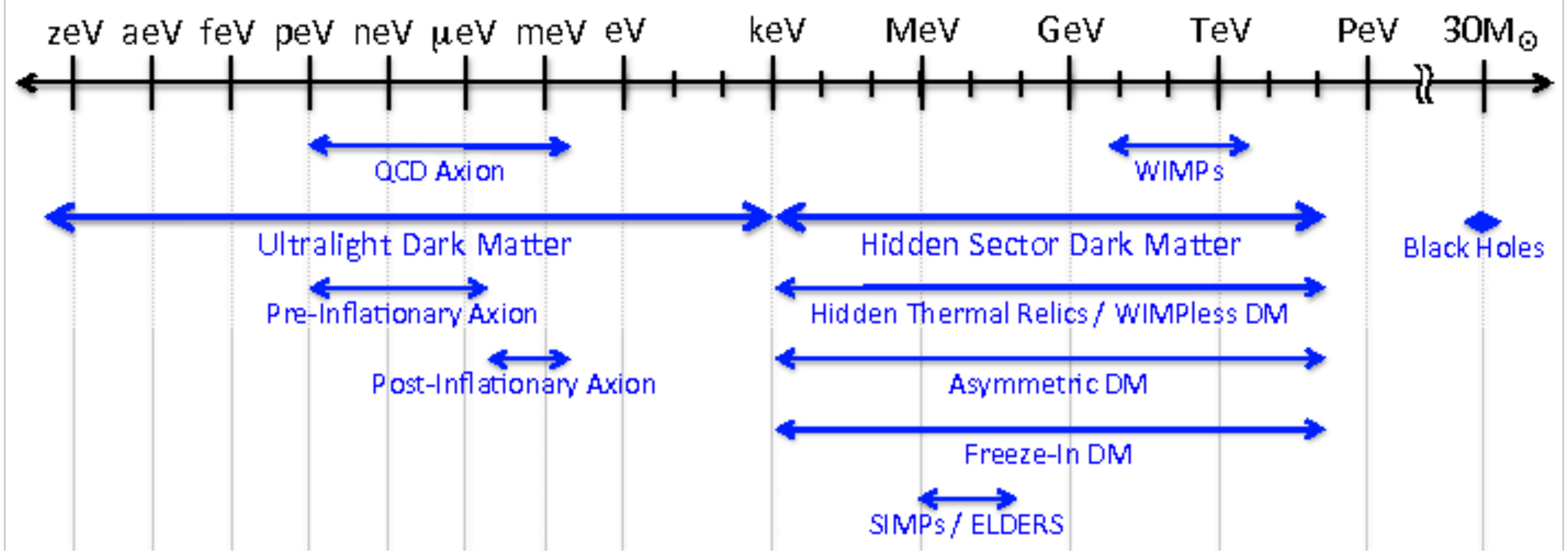
mK Detectors for Low Mass Dark Matter Searches

Jodi Cooley
SMU / SuperCDMS

The Case for Low Mass Dark Matter

Mass Range for dark matter and mediator force candidates.

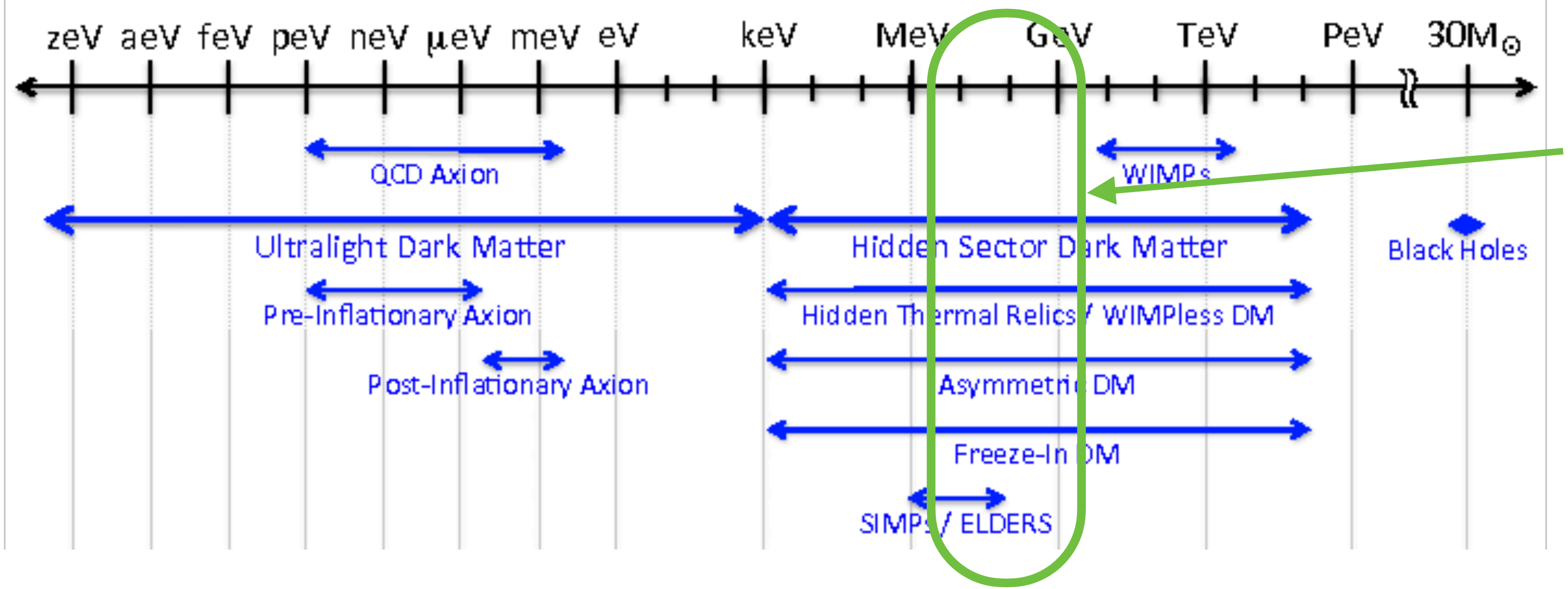


US Cosmic Visions: arXiv:1707.04591

- Much work has gone into looking for the canonical WIMP
    - No evidence from direct searches and no evidence of SUSY from LHC
- If we broaden our thoughts and loosen our cosmology or theory priors, we still have reasonable dark matter candidates — many with lower masses!

The Case for Low Mass Dark Matter

Mass Range for dark matter and mediator force candidates.



Focus of this talk.

US Cosmic Visions: arXiv:1707.04591

- Much work has gone into looking for the canonical WIMP
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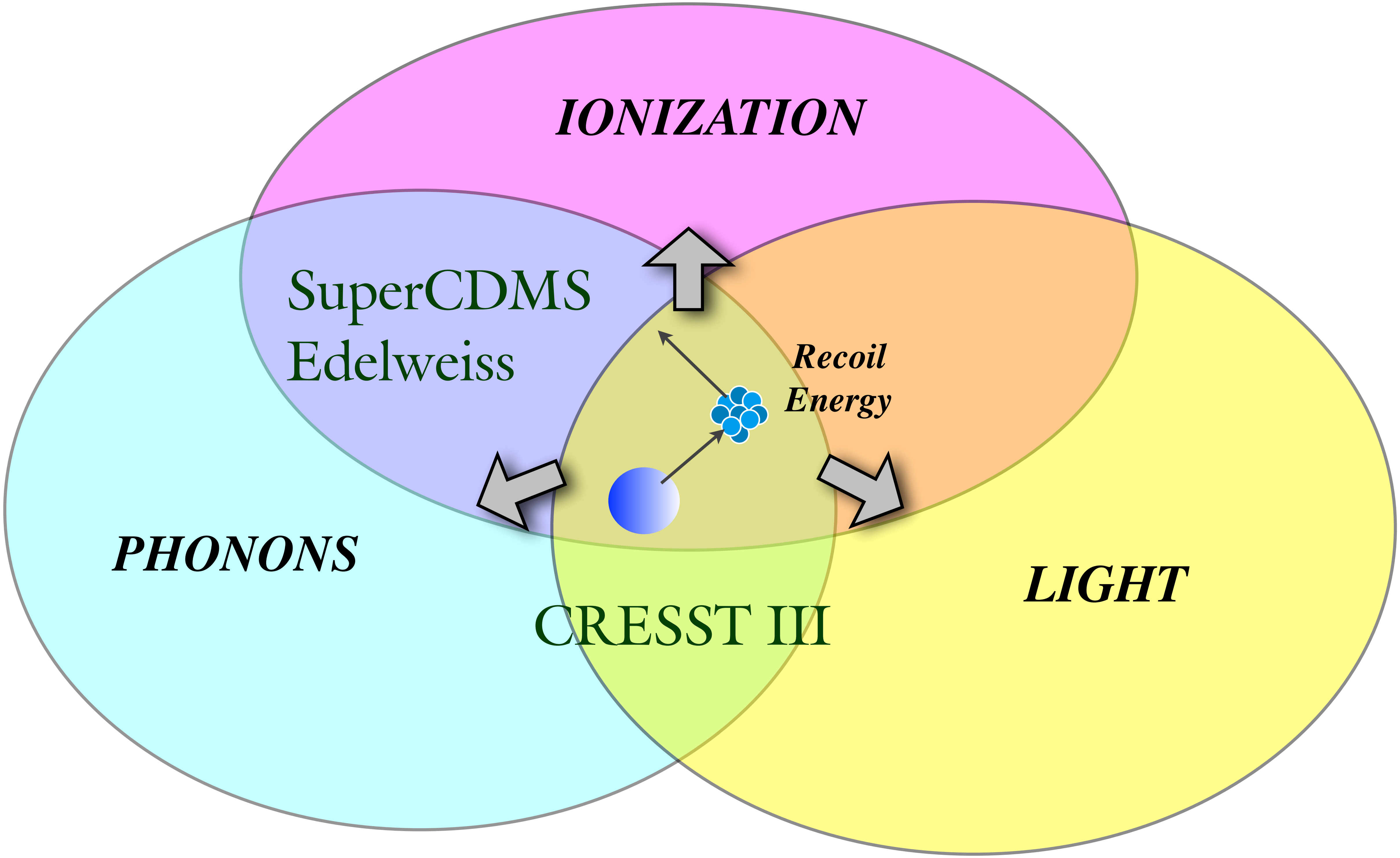
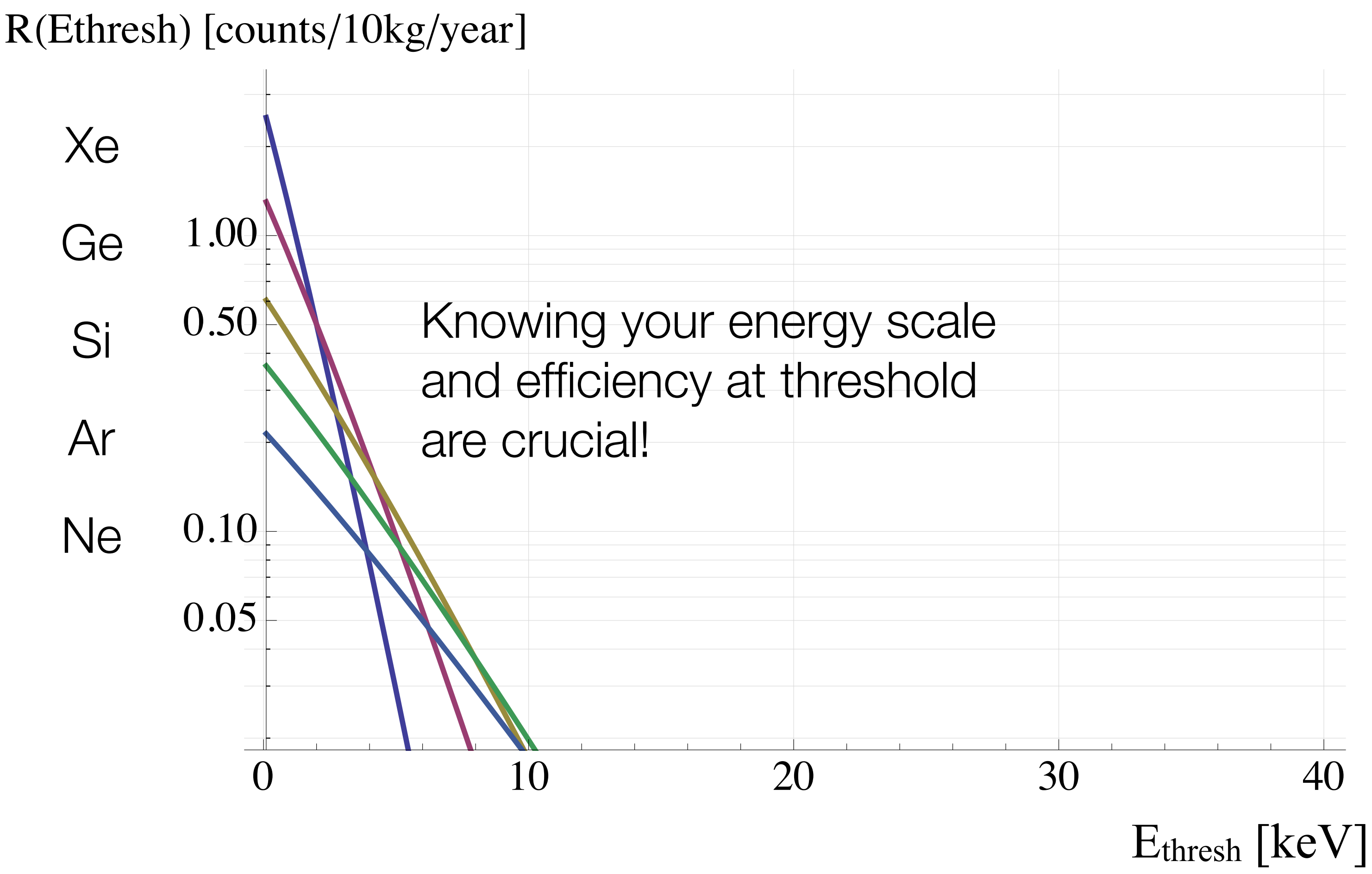
- If we broaden our thoughts and loosen our cosmology or theory priors, we still have reasonable dark matter candidates — many with lower masses!

Operating Principles



Dark Matter Event Rates

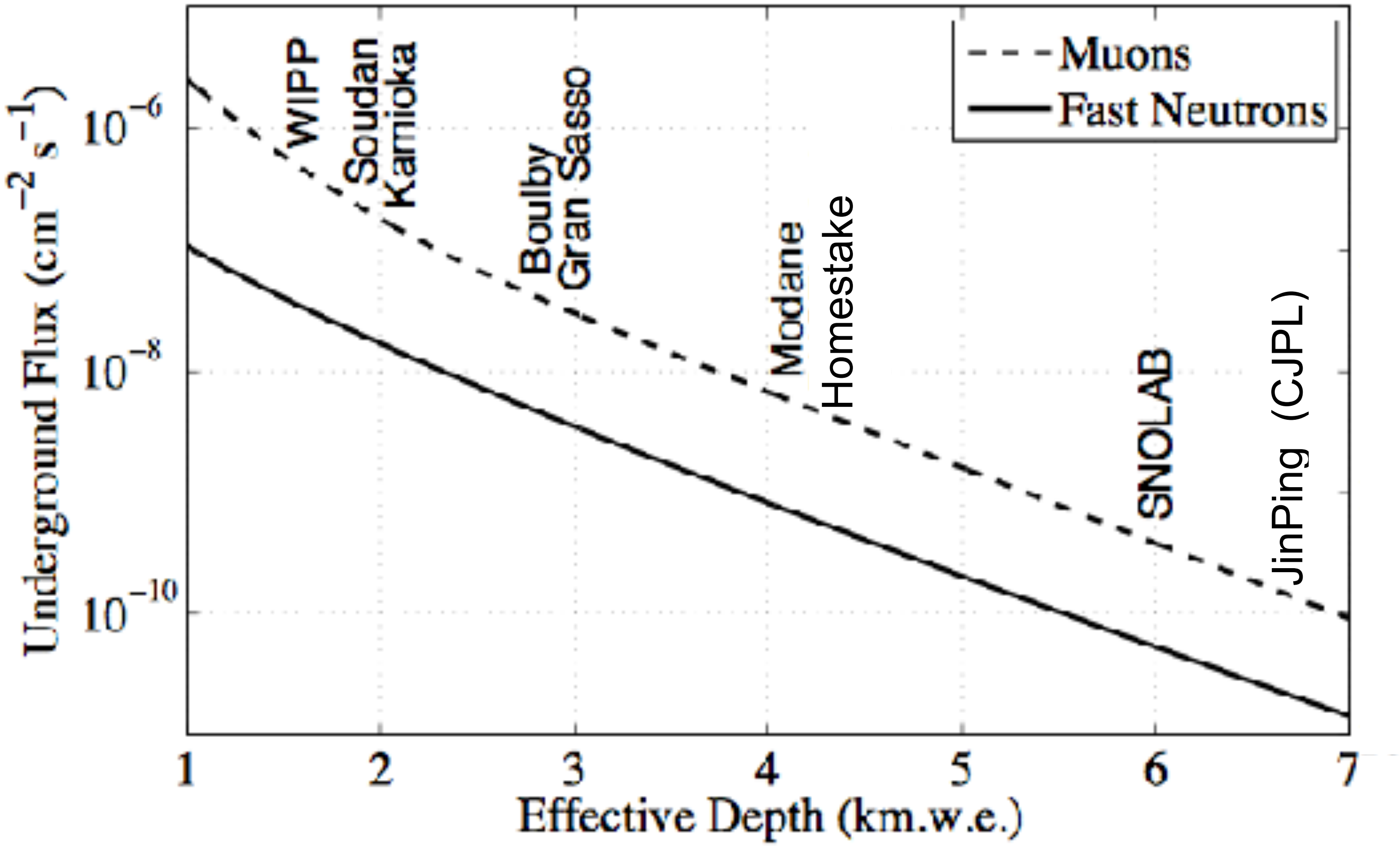
- Elastic scattering of WIMP deposits small amounts of energy into a recoiling nucleus (~few 10s of keV)
- Featureless exponential spectrum with no obvious peak, knee, break ...
- Event rate is very, very low.

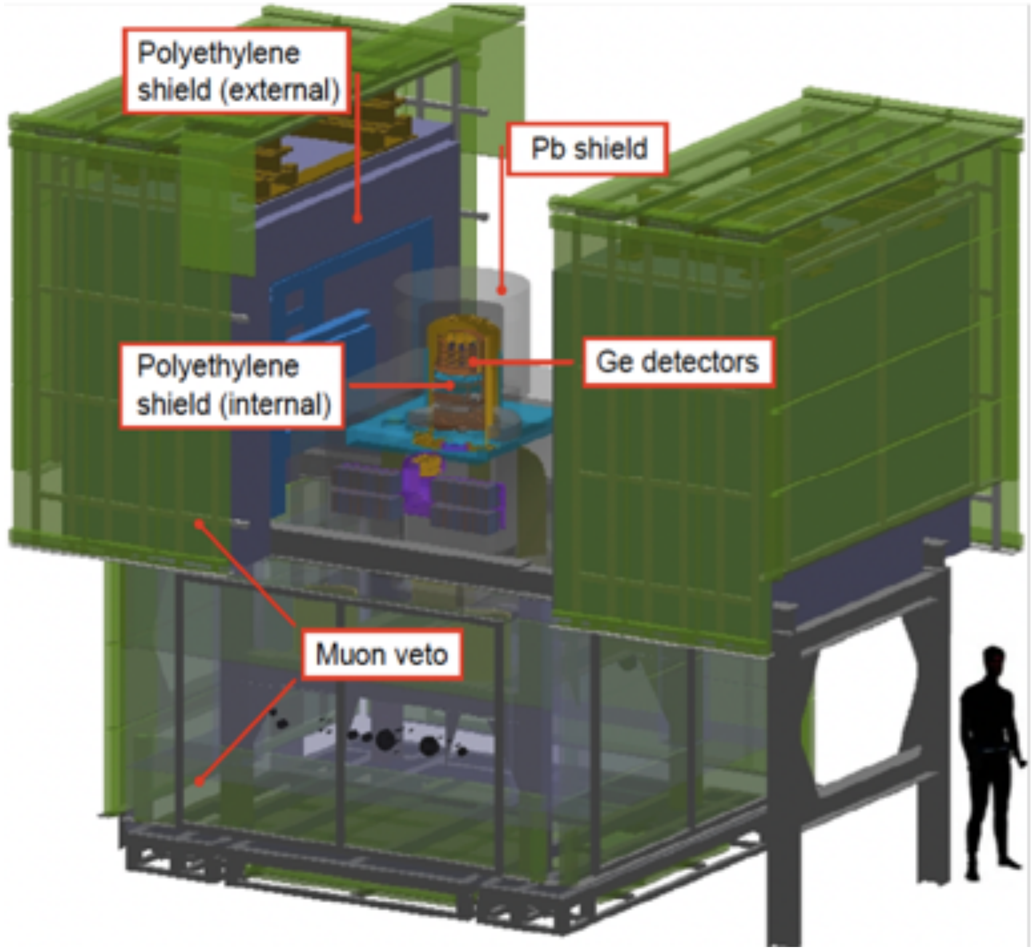


Knowing your energy scale and efficiency at threshold are crucial!

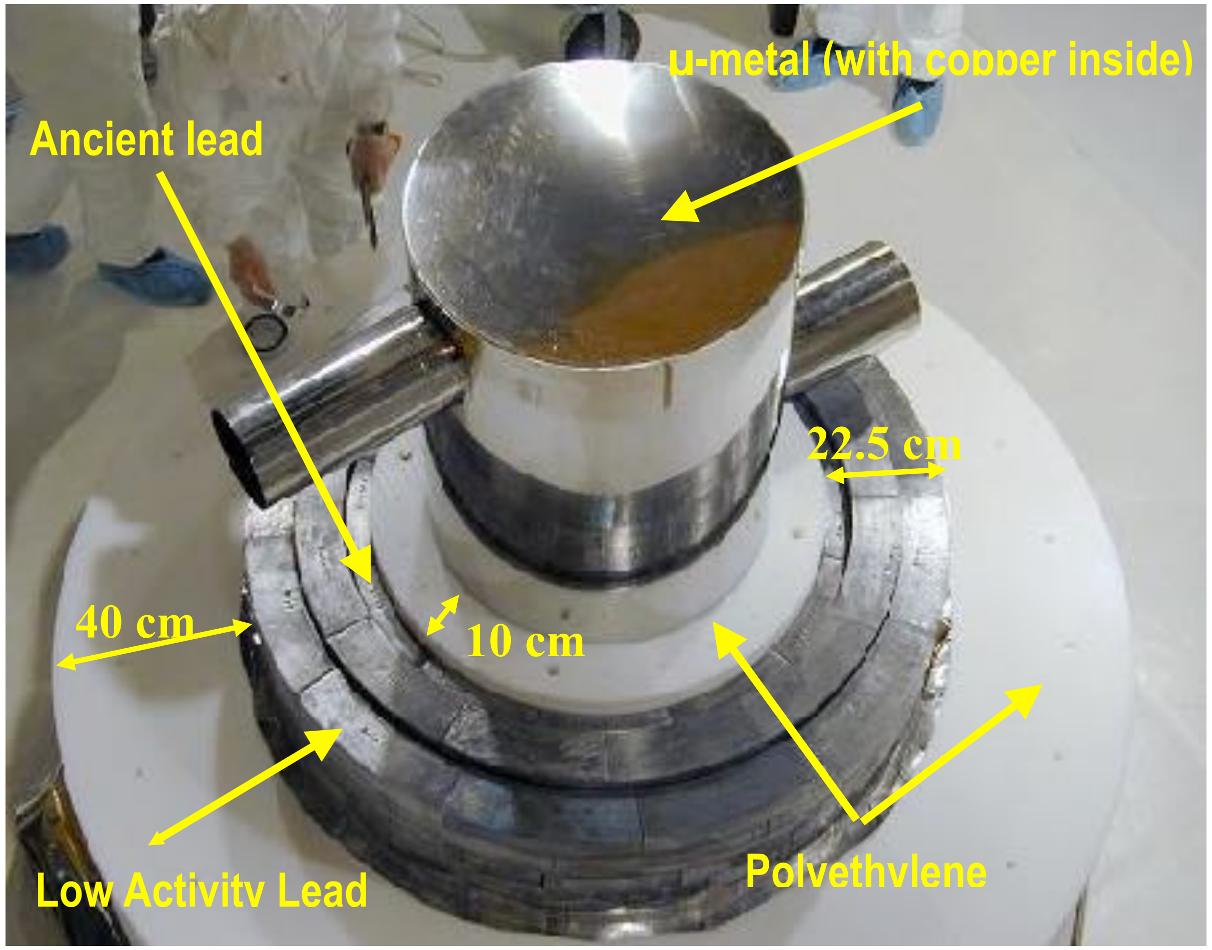
- Radioactive background of most materials is higher than the event rate.

- Experiments are sited underground to reduce cosmic induced backgrounds
- Active and passive shielding are used too reduce backgrounds resulting from radioactivity in the environment.
- Materials are carefully selected/ screened before use.





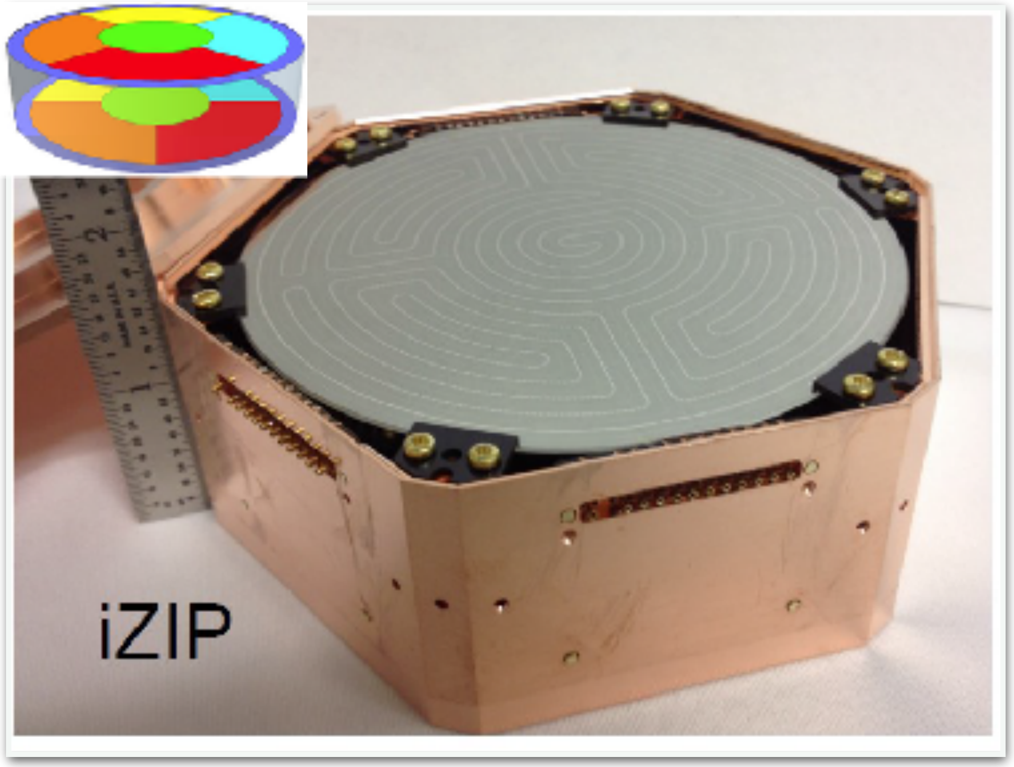
Edelweiss Active Muon & Passive Shield

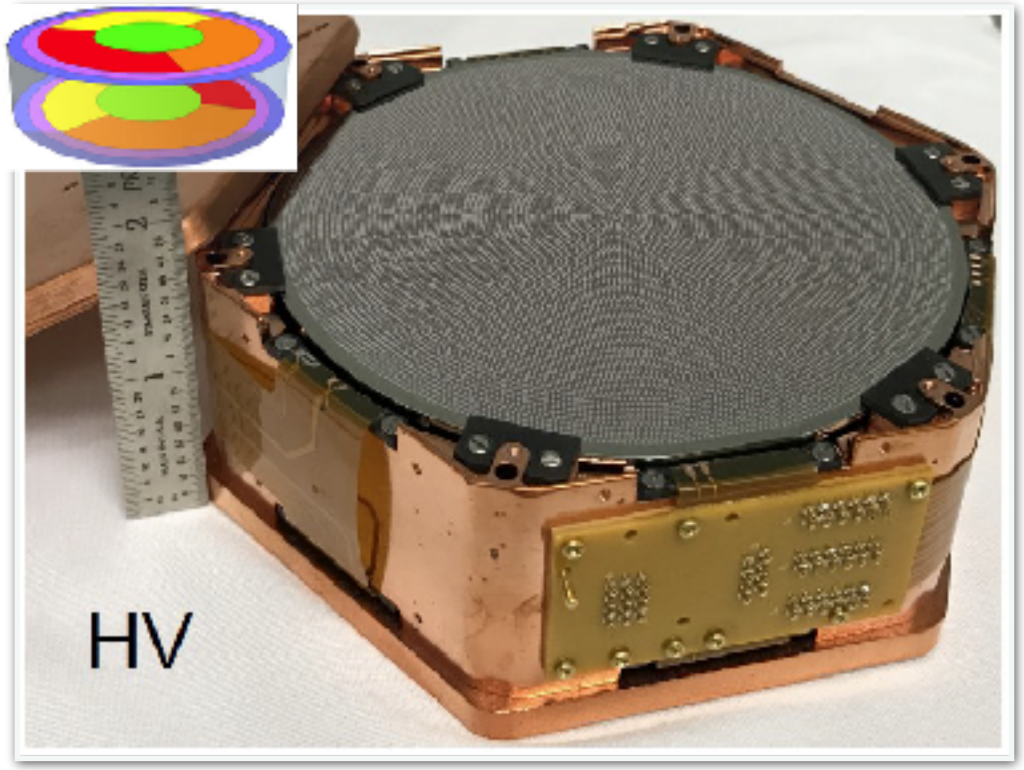


SuperCDMS Soudan Passive Shield

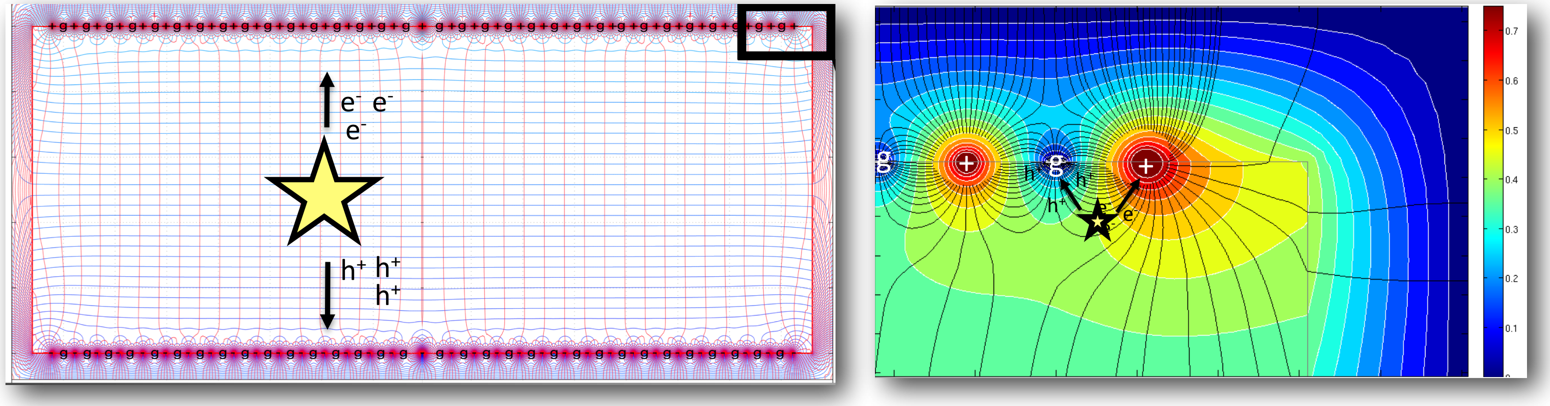
SuperCDMS

SuperCDMS Technology

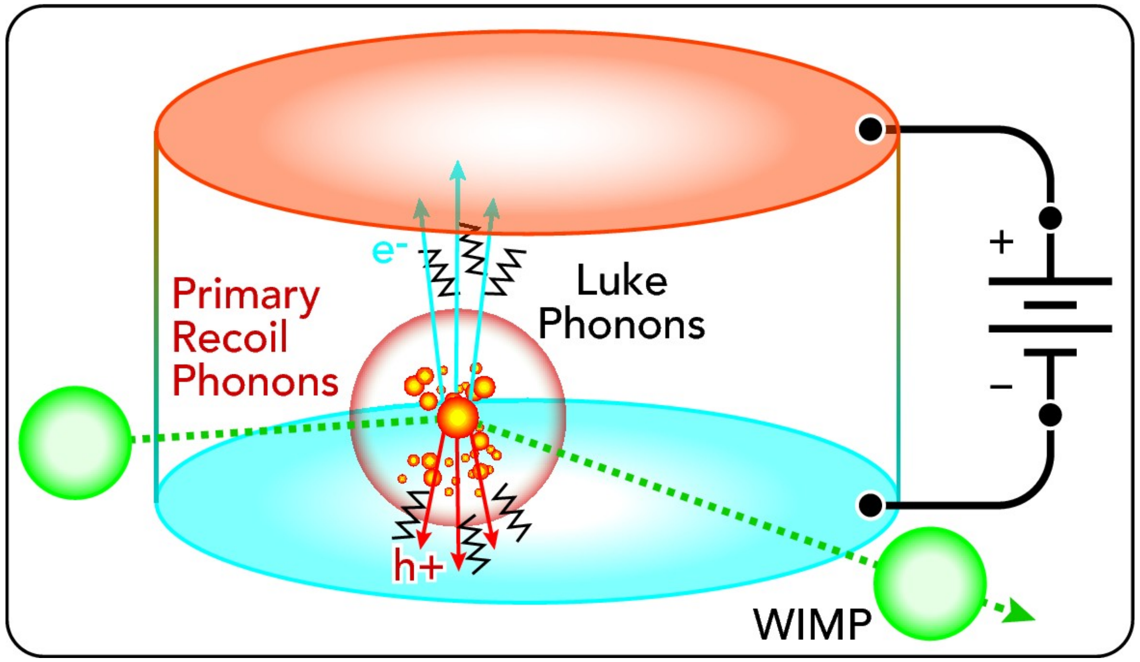




- Ultra-pure ~kg Ge and Si crystals operated at 10's of mK
- Measure athermal phonon signal via transition edge sensor
- Multiple channels give position info
- Outer "guard" rings fiducialize high radius events
- **Surface/Bulk** event discrimination via charge face symmetry



Detection Principles



Standard iZIP Mode:

- Primary (prompt) phonon and ionization signals allow for discrimination between NR and ER events

CDMSlite HV Mode:

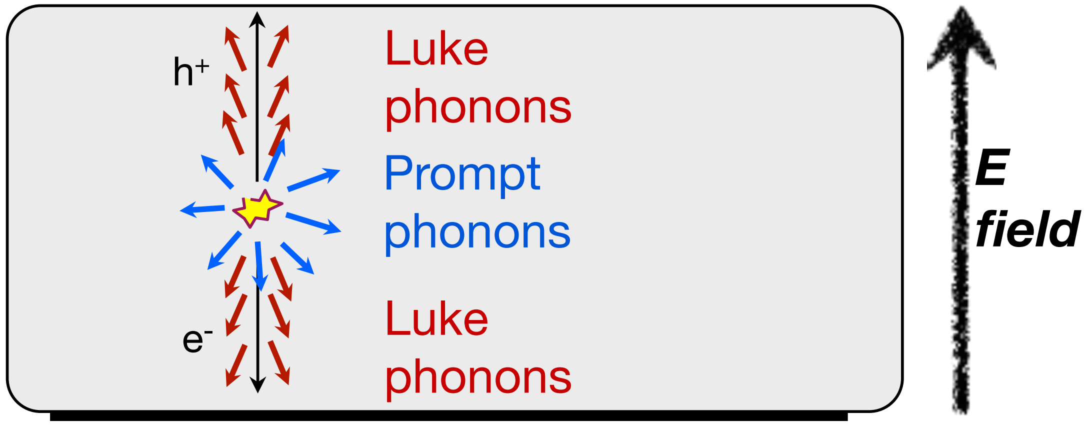
- Drifting electrons across a potential (V) generates a large number of phonons (Luke phonons).

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

total phonon energy

primary recoil energy

Luke phonon energy



- Enables very low thresholds!
- Trade-off: No NR/ER discrimination

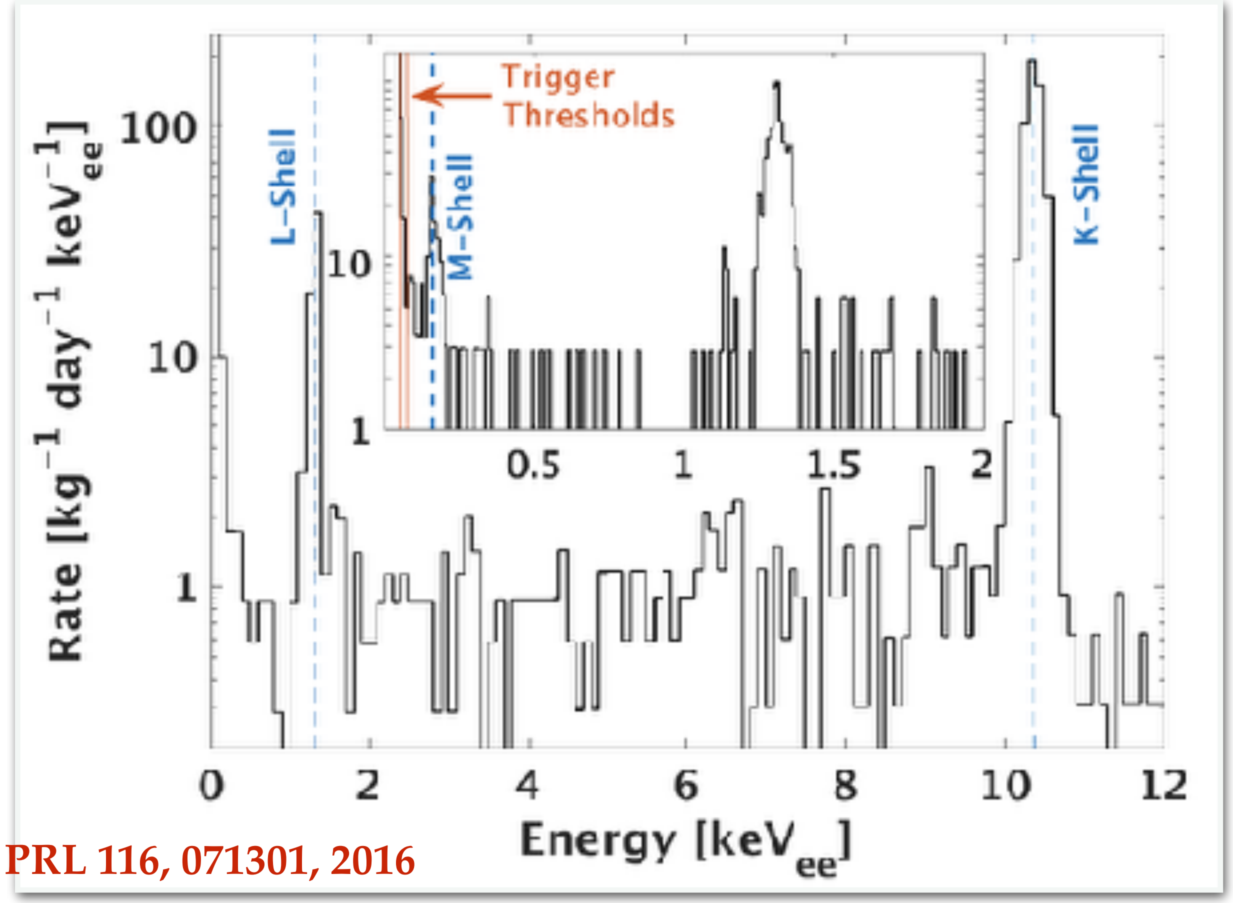
SuperCDMS Detector Advantages

High Voltage => Low Threshold

- Ultra high resolution indirect charge measurement
- Thresholds 75 eV_{ee} and 56 eV_{ee}
- No yield or detector face discrimination

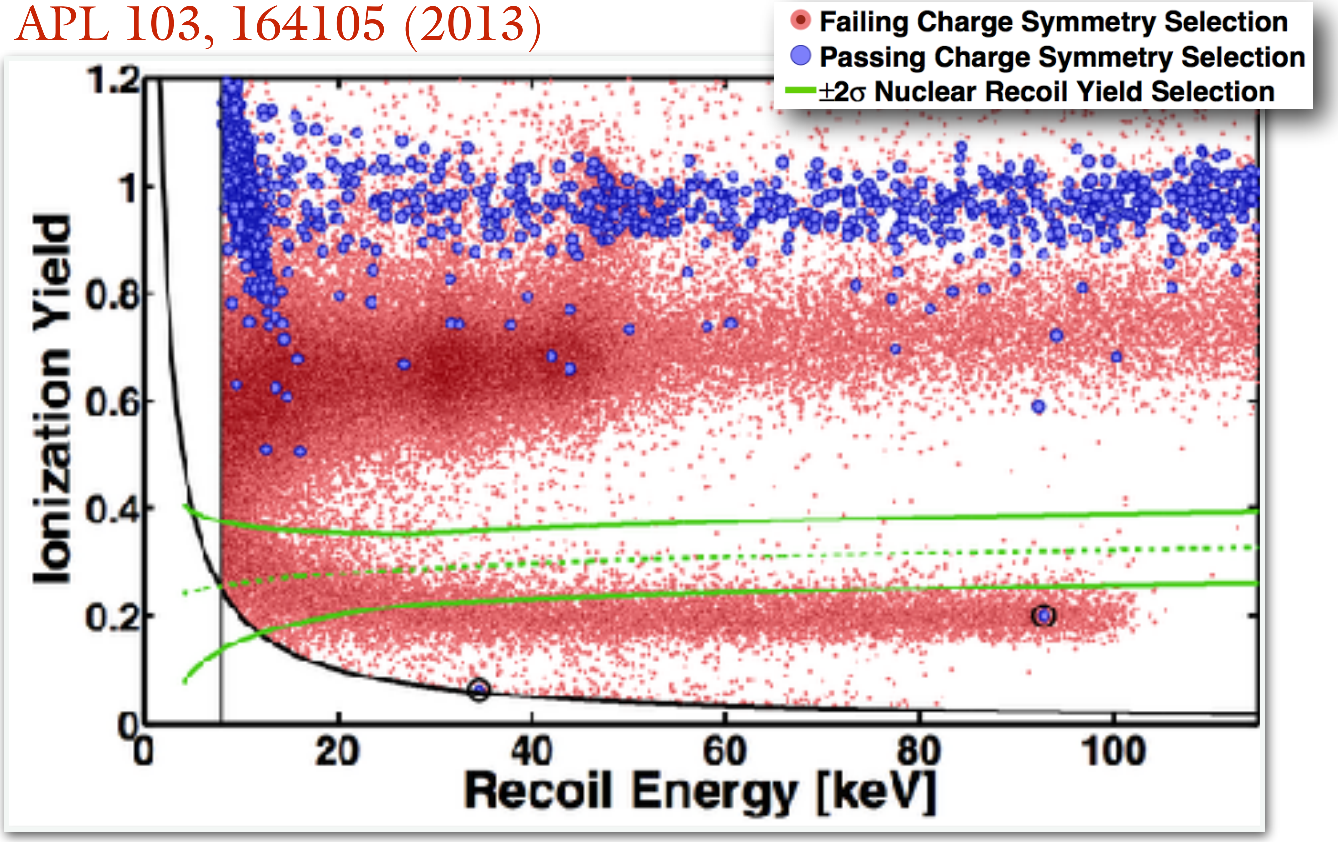
iZIPs=> Low Background

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

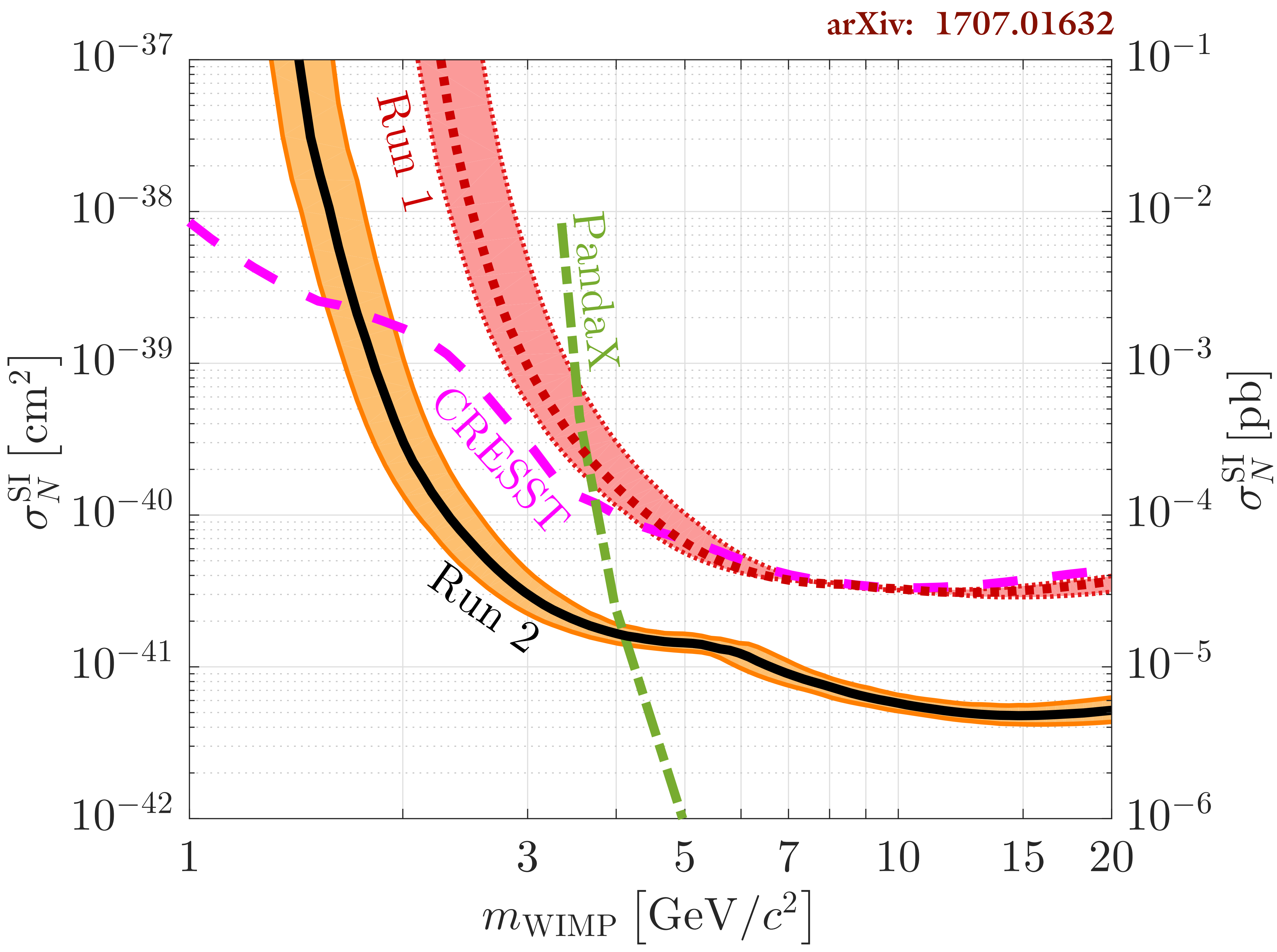


PRL 116, 071301, 2016

APL 103, 164105 (2013)

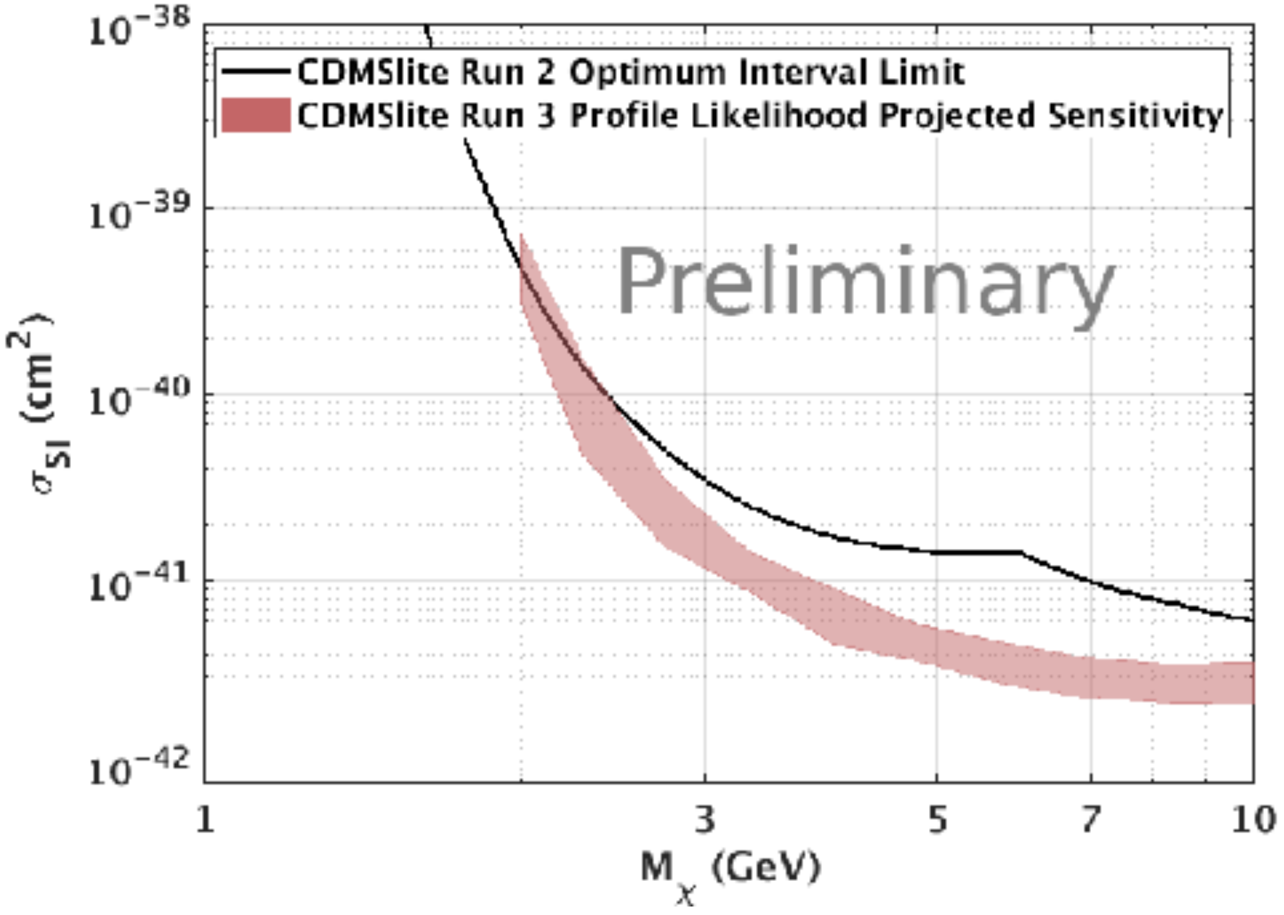


Recent Results



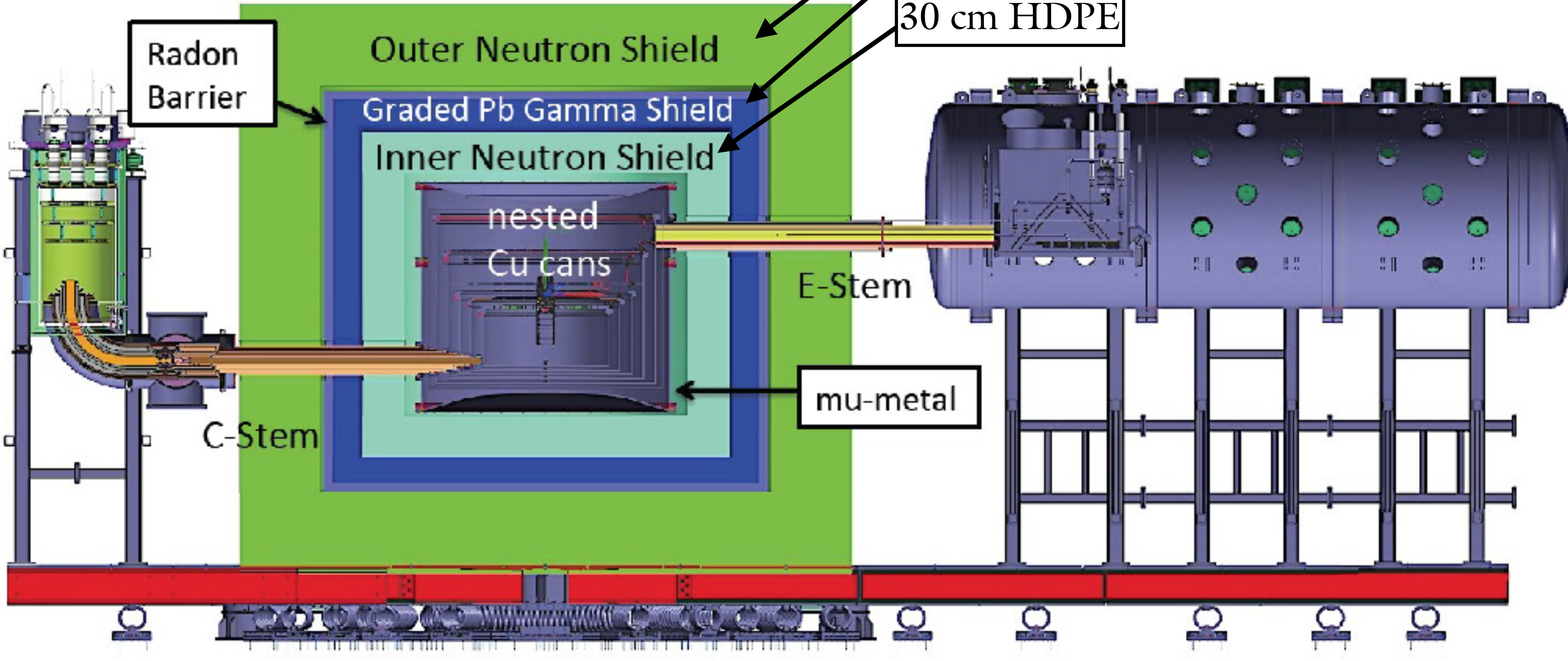
Future Prospects:CDMSlite Run 3

- Different detector, similar threshold, livetime
- Focus on improving analysis techniques
- Data blinded by “salting” fake signal-like events into data
- Improving detector response and background modeling
- Likelihood estimate allows some background rejection
- Expect factor ~3 improvement over previous results



SuperCDMS SNOLAB

Initial payload 4 towers, each w/6 detectors:
2 HV (4 Ge + 2 Si)
2 iZIP (6 Ge & 4 Ge + 2 Si)



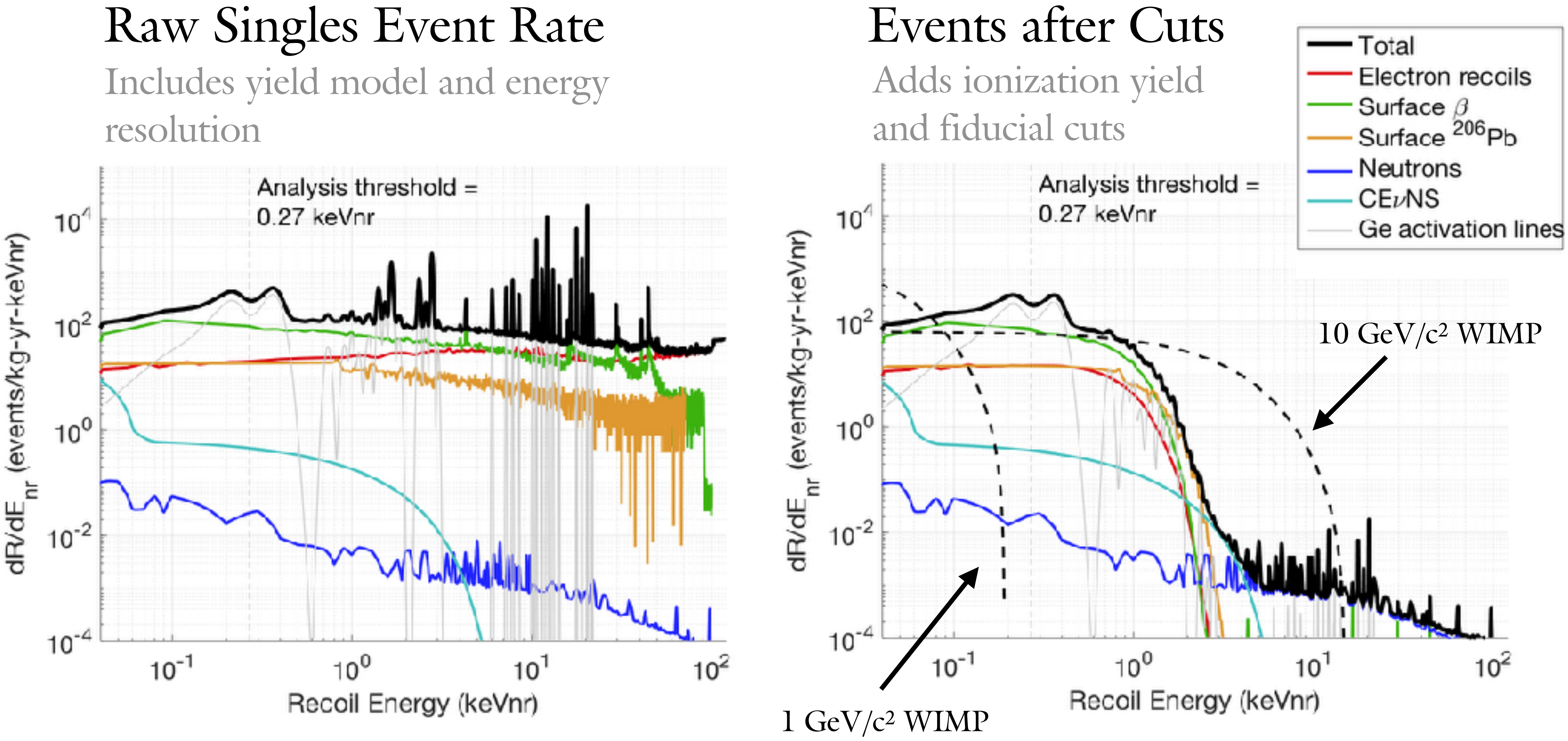
60 cm water
20 cm Pb
30 cm HDPE

Outer 10 cm: new lead
9 cm < 19 Bq/kg ^{210}Pb
1 cm < 0.08 Bq/kg ^{210}Pb

Fridge, cryostat capable of 31 towers, nominal 15 mK

Background Model

SuperCDMS SNOLAB anticipated background spectra (Ge iZIPs)



Raw Singles Event Rate

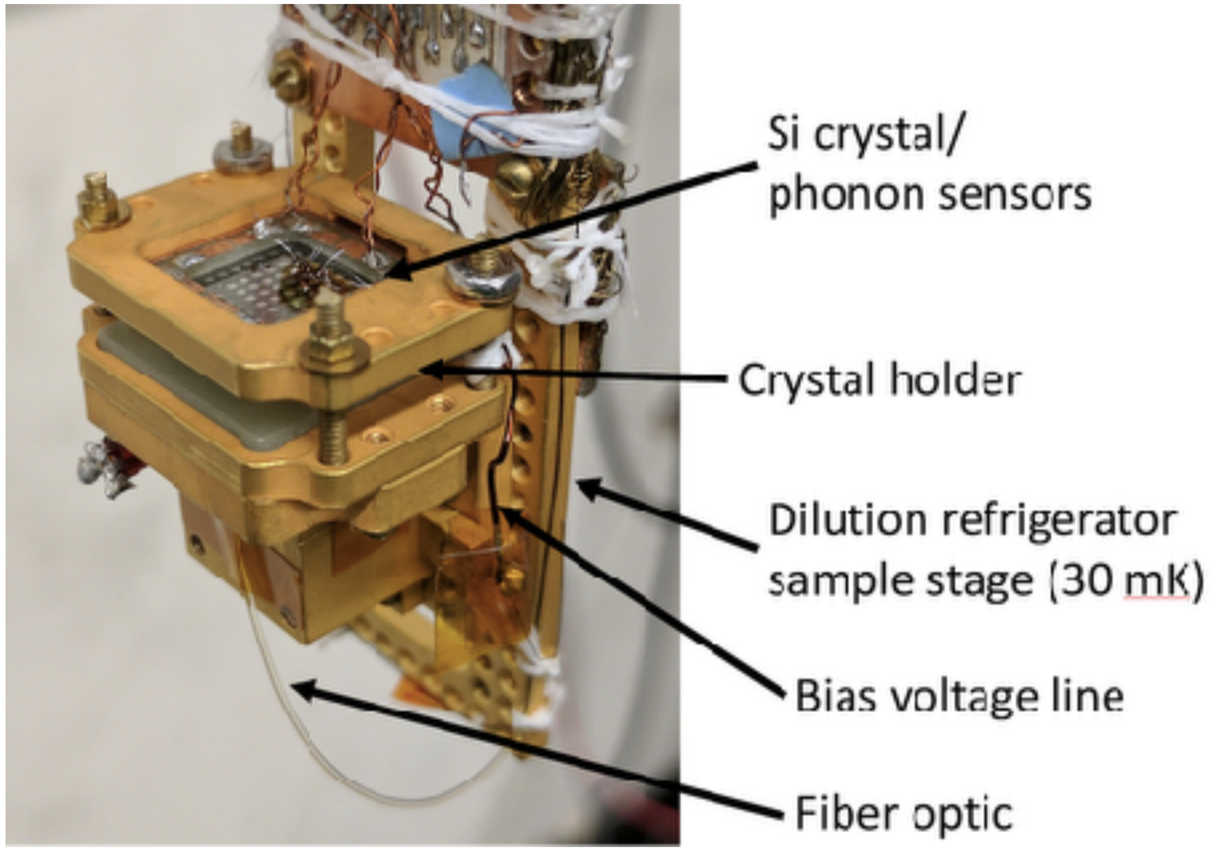
Includes yield model and energy resolution

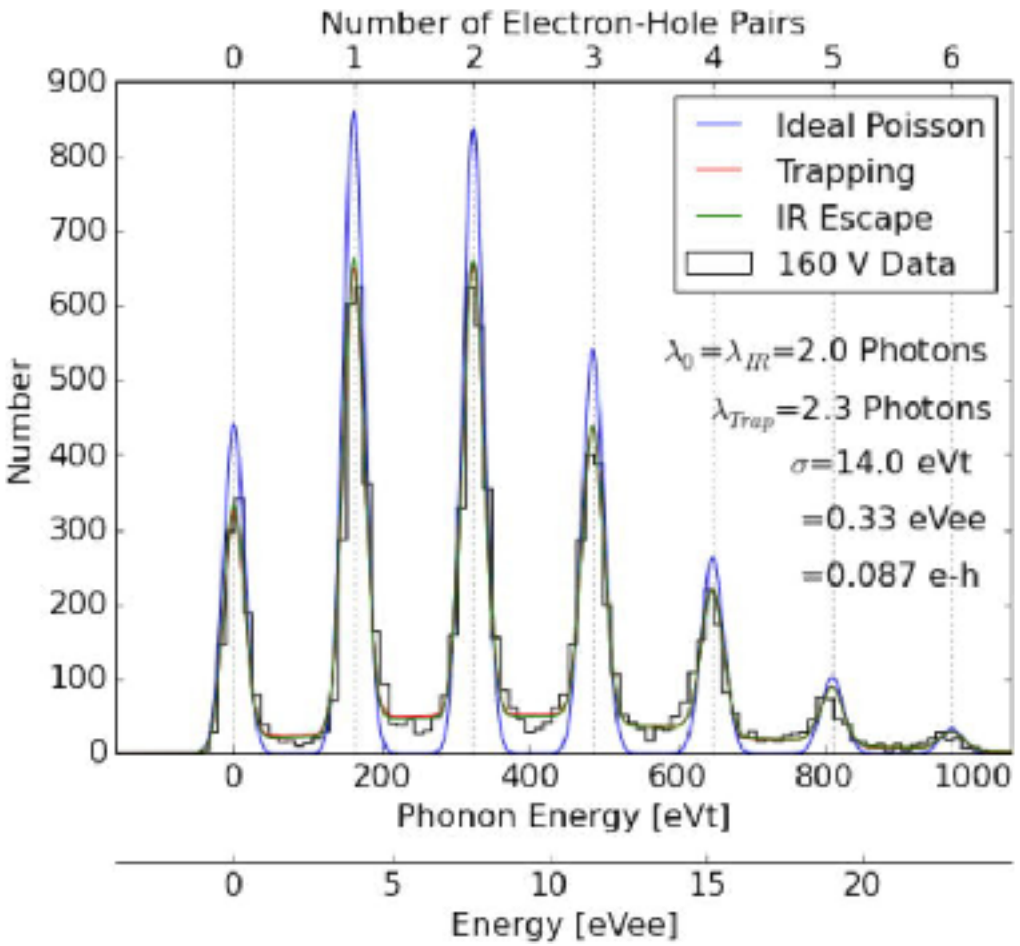
Events after Cuts

Adds ionization yield and fiducial cuts

Prototype HVeV Detector

Appl. Phys. Lett. 112, 043501



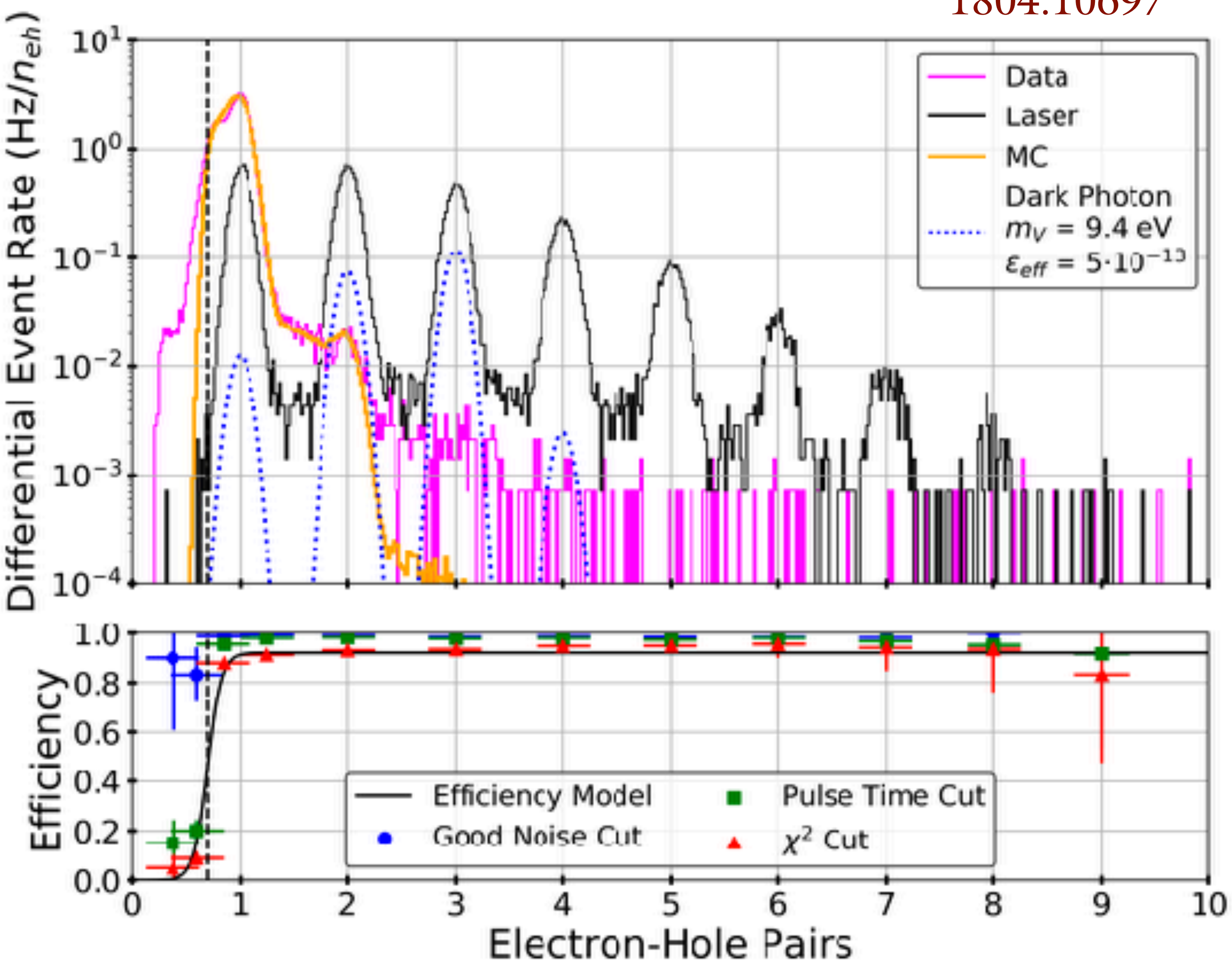


- Single e/h-pair resolution goal of SuperCDMS SNOLAB
- Single e/h-pair sensitivity has been recently demonstrated in 0.93 g Si crystal
- Such devices will have sensitivity to a variety of sub-GeV DM models with g*d exposures

Prototype HVeV Detector

- 0.93 g Si crystal (1 x 1x 0.4 cm^3) operated at 33-36 mK at a surface test facility.
- Exposure: 0.49 gram-days (16.1 hours)
  - operation voltage: 140 V
  - energy resolution: $\sigma_{ph} \sim 14$ eV
  - charge resolution: $\sigma_{eh} \sim 0.1$ e^-h^+
- Calibrations with in-run monochromatic 650 nm laser.

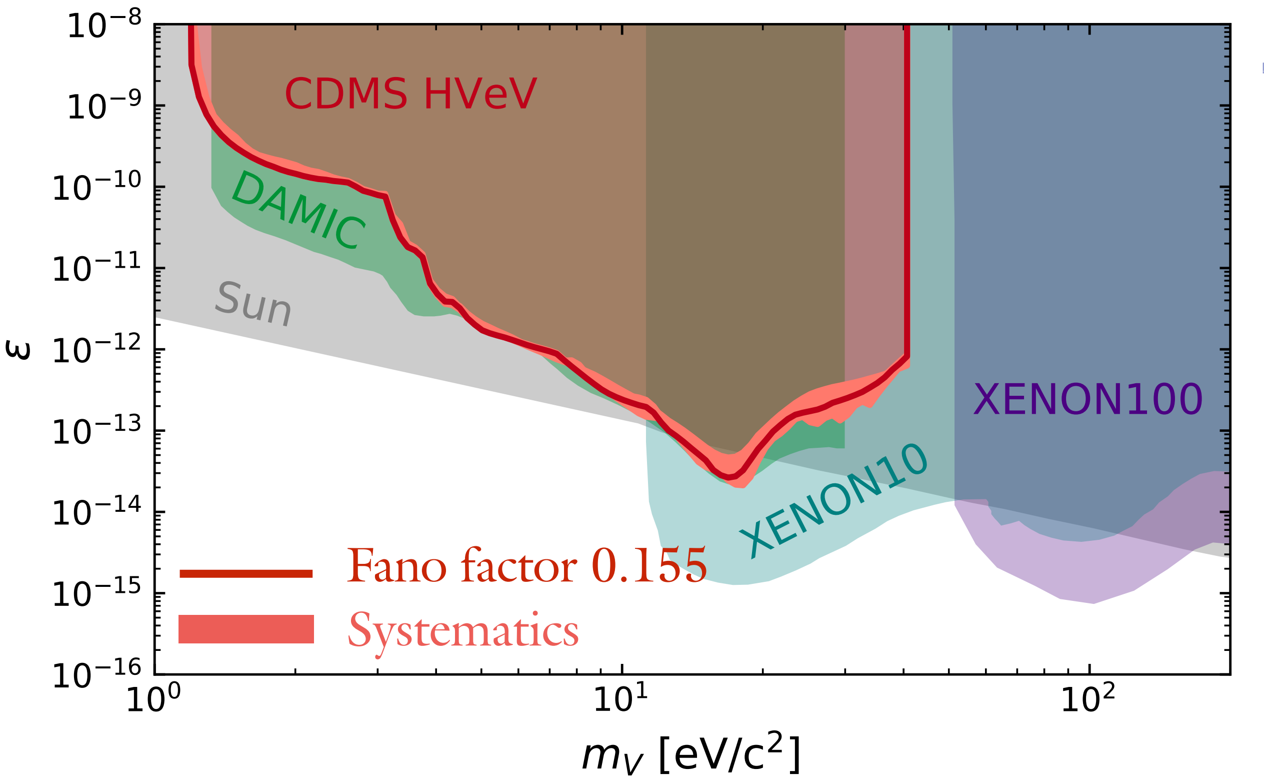
1804.10697



- Data selection criteria were applied to remove periods of poor detector performance.

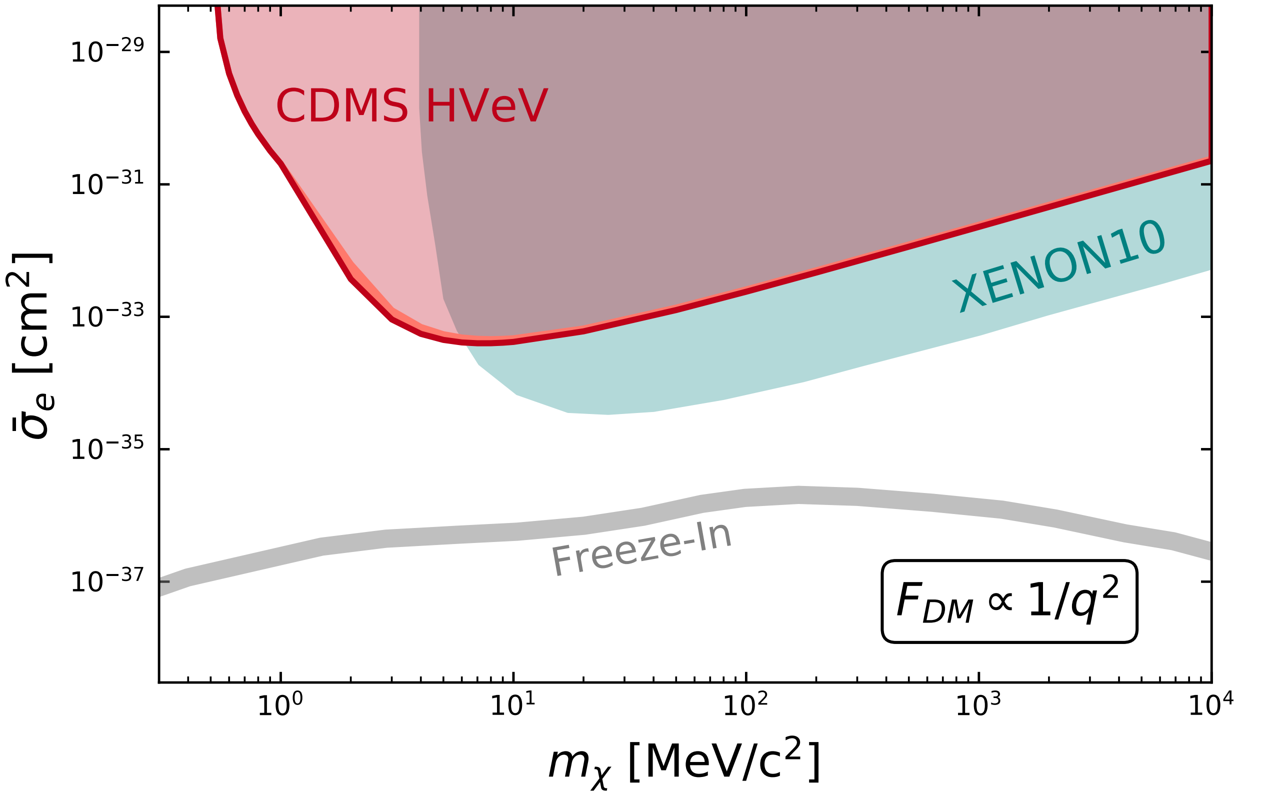
Results

Dark Photon Absoption

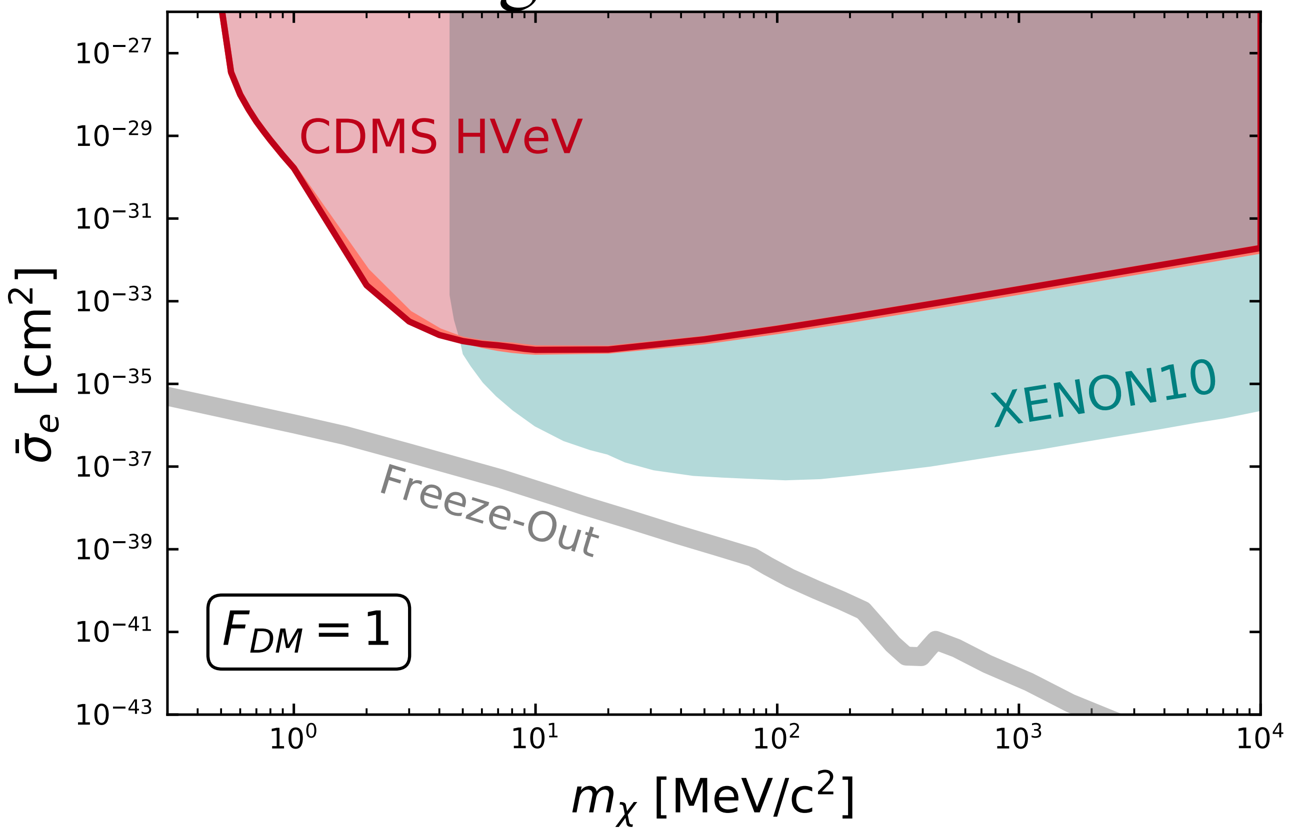


ERDM Heavy Mediator

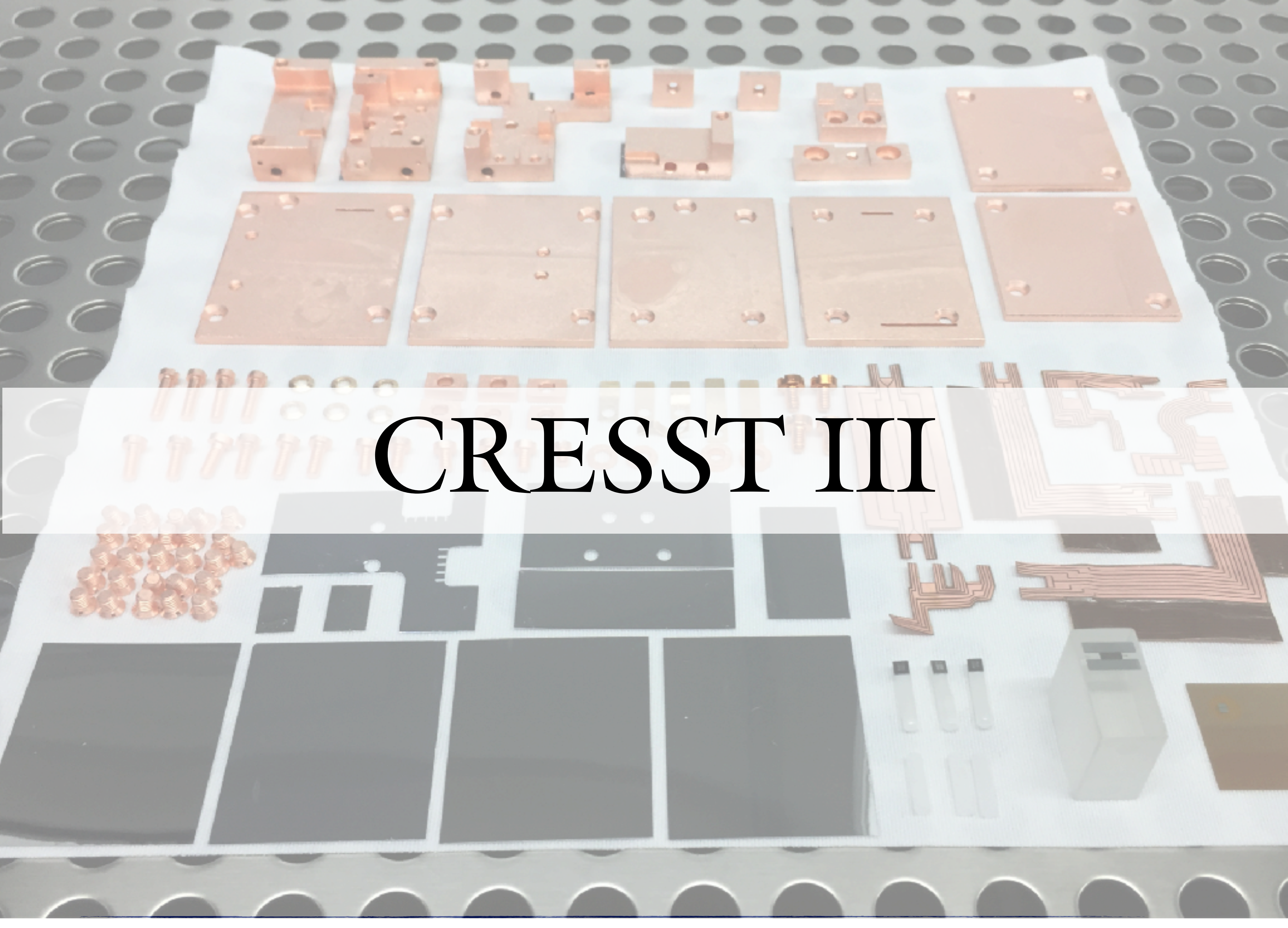
1804.10697



ERDM Light Mediator

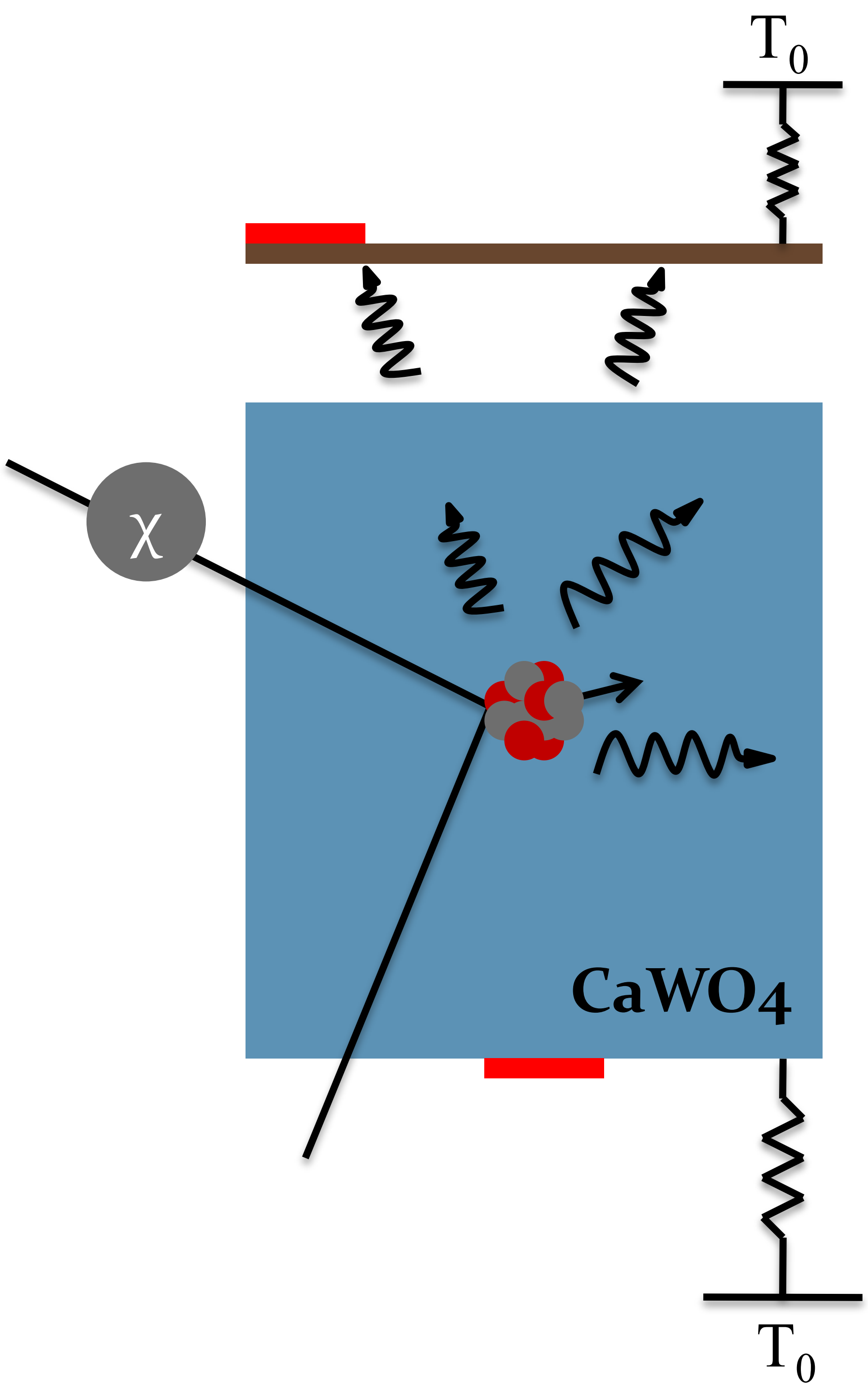


- 90% CL w/o background subtraction using optimum interval method.
- Systematics include varying Fano factor, and uncertainties in photoelectric cross section

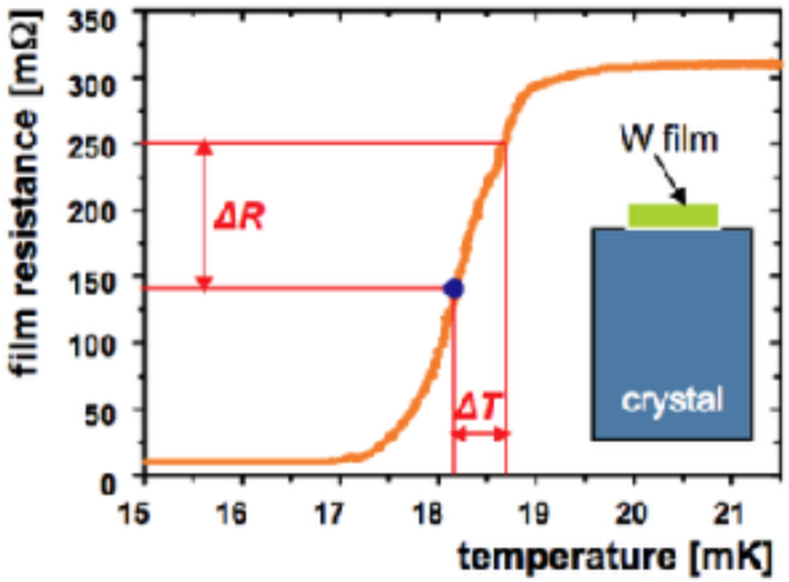


CRESST III

CRESST Technology

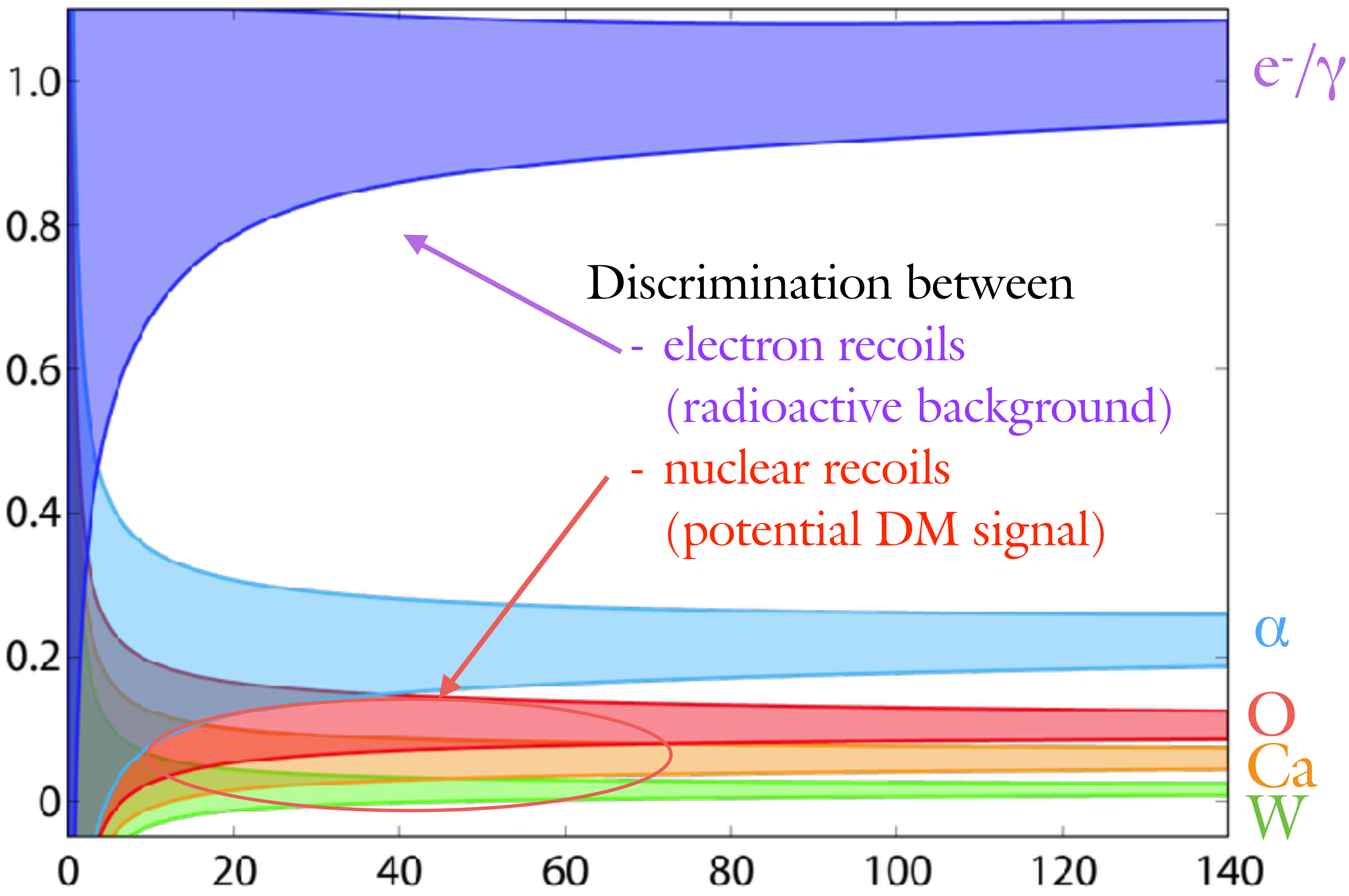


- Scintillating 24 g $CaWO_4$ crystals as target
- Collect both phonon and scintillating signals.
  - Tungsten TES reads out phonon signal (similar to SuperCDMS)
  - Light absorber (Si on sapphire) collects scintillation signal.



Particle Identification

The scintillation light is particle dependent!

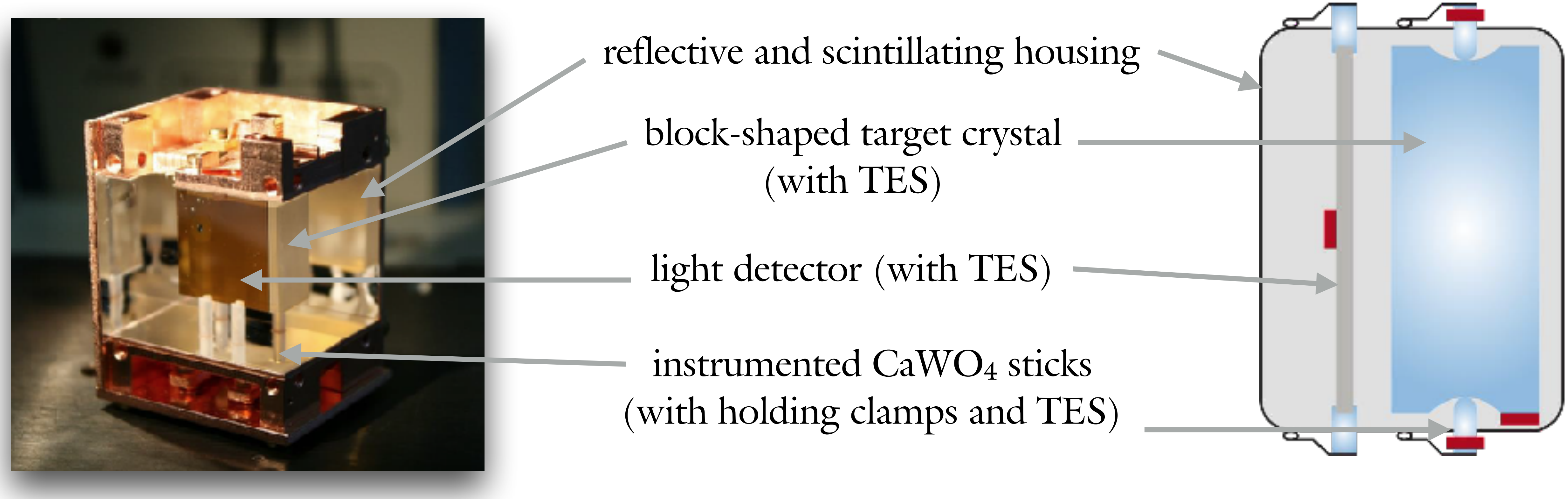


Discrimination between

- electron recoils (radioactive background)
- nuclear recoils (potential DM signal)

Recent Detector Progress

New Optimized Detector Design for Low Mass



reflective and scintillating housing

block-shaped target crystal
(with TES)

light detector (with TES)

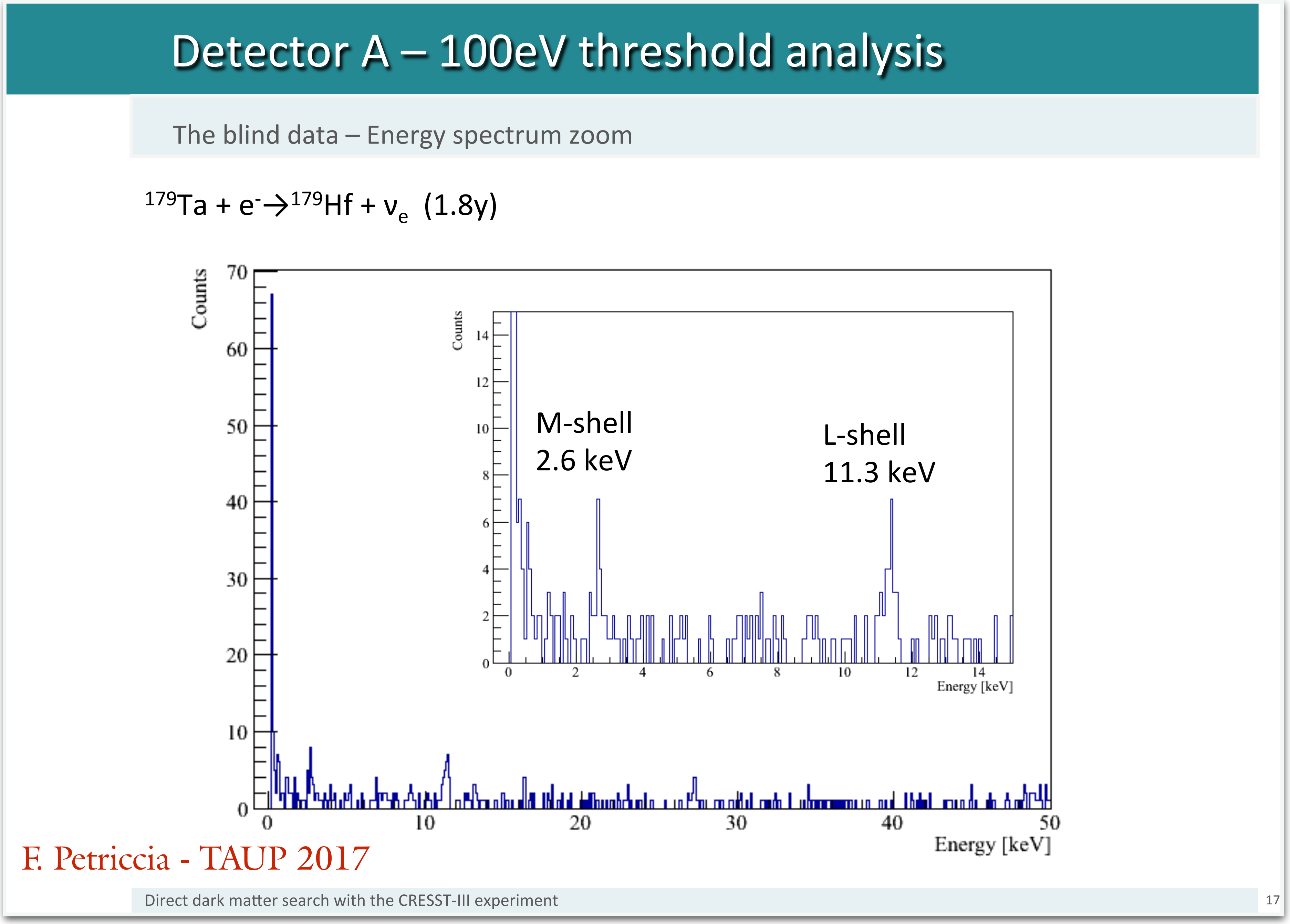
instrumented $CaWO_4$ sticks
(with holding clamps and TES)

- Cuboid crystal (20 mm x 20 mm x 10 mm) ~ 24 g
- Goal: detection threshold of **100eV**
- Self-grown crystal with low total background of ~3 keV^{-1}kg^{-1}d^{-1} [1-40 keV]
- Veto against surface related background: fully scintillating housing and instrumented sticks (“iSticks”)

H. Kluck - UCLA 2018

First Results

5 detectors met design goals - first results only on detector A



Detector A – 100eV threshold analysis

The blind data – Energy spectrum zoom

$^{179}\mathrm{Ta} + e^- \rightarrow {}^{179}\mathrm{Hf} + \nu_e$ (1.8y)

F. Petriccia - TAUP 2017

Direct dark matter search with the CRESST-III experiment

17

Total Exposure:
2.34 kg-days

Exposure after Cuts:
2.21 kg-days

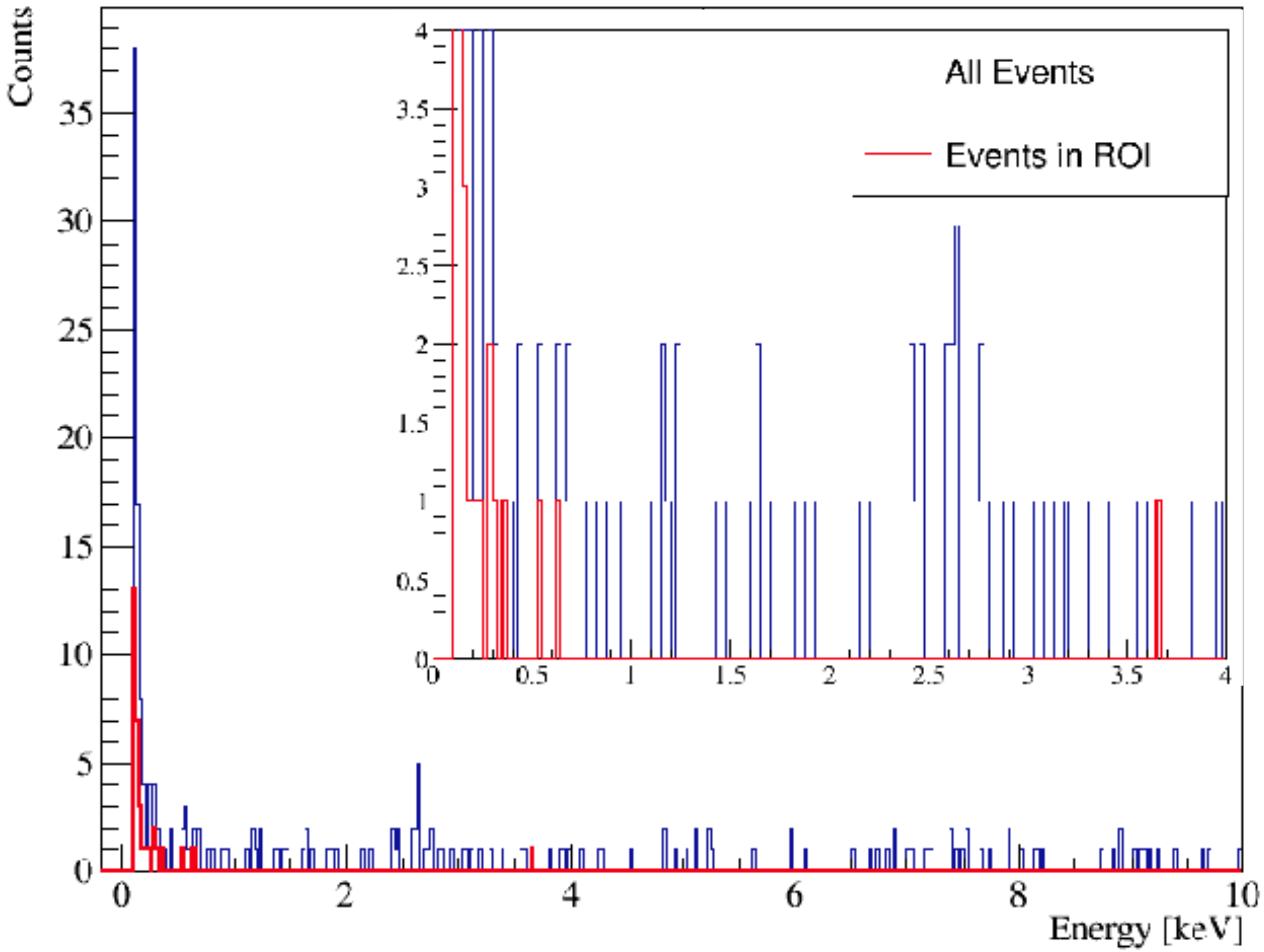
Total Mass:
24 g

Analysis Threshold:
100 eV

Background Rate:
~3.5 kev/kg/keV/d

Accepted Events

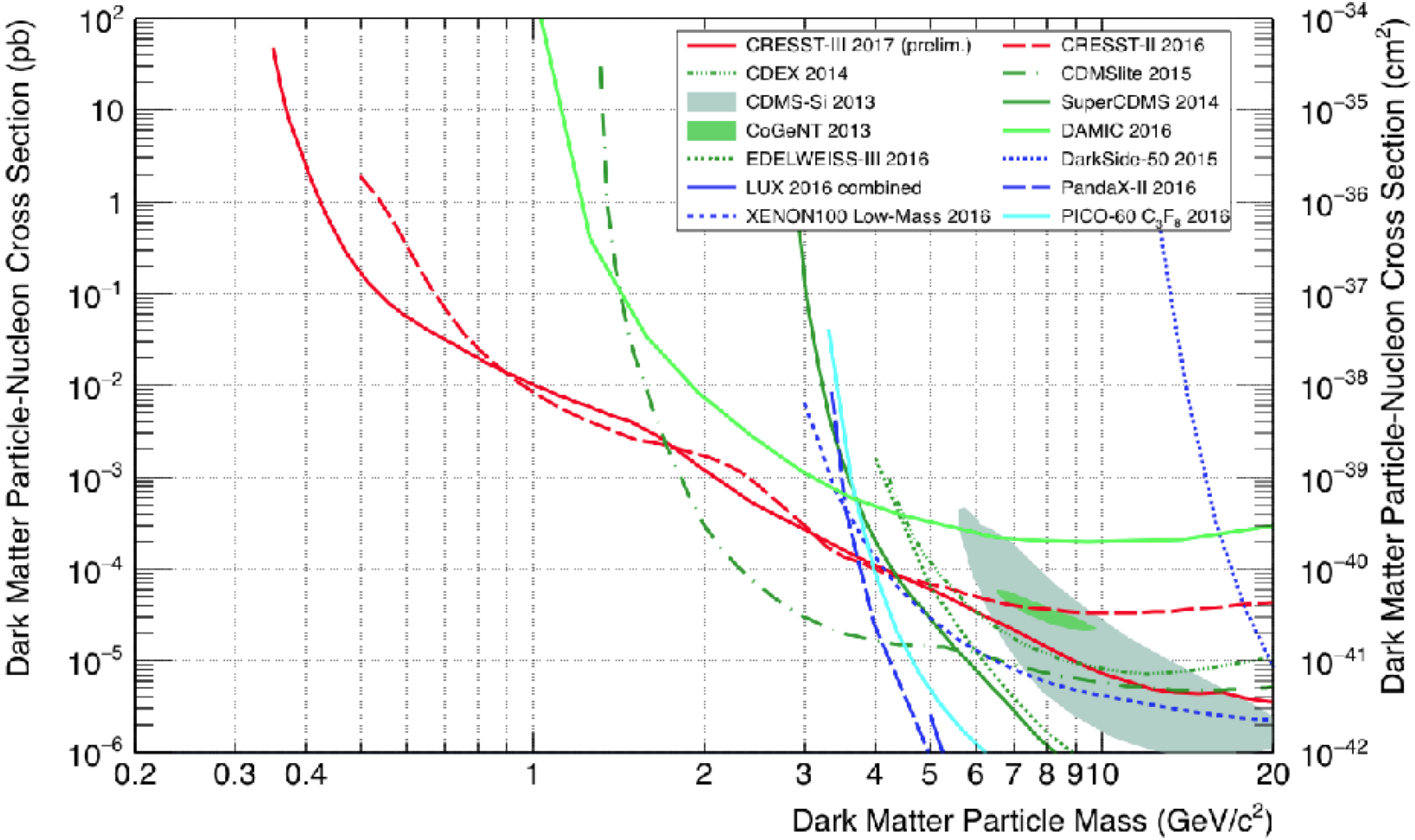
arXiv:1711.07692



Assume all accepted events result from dark-matter interactions.
Use Yellin optimum interval method to set an exclusion limit.

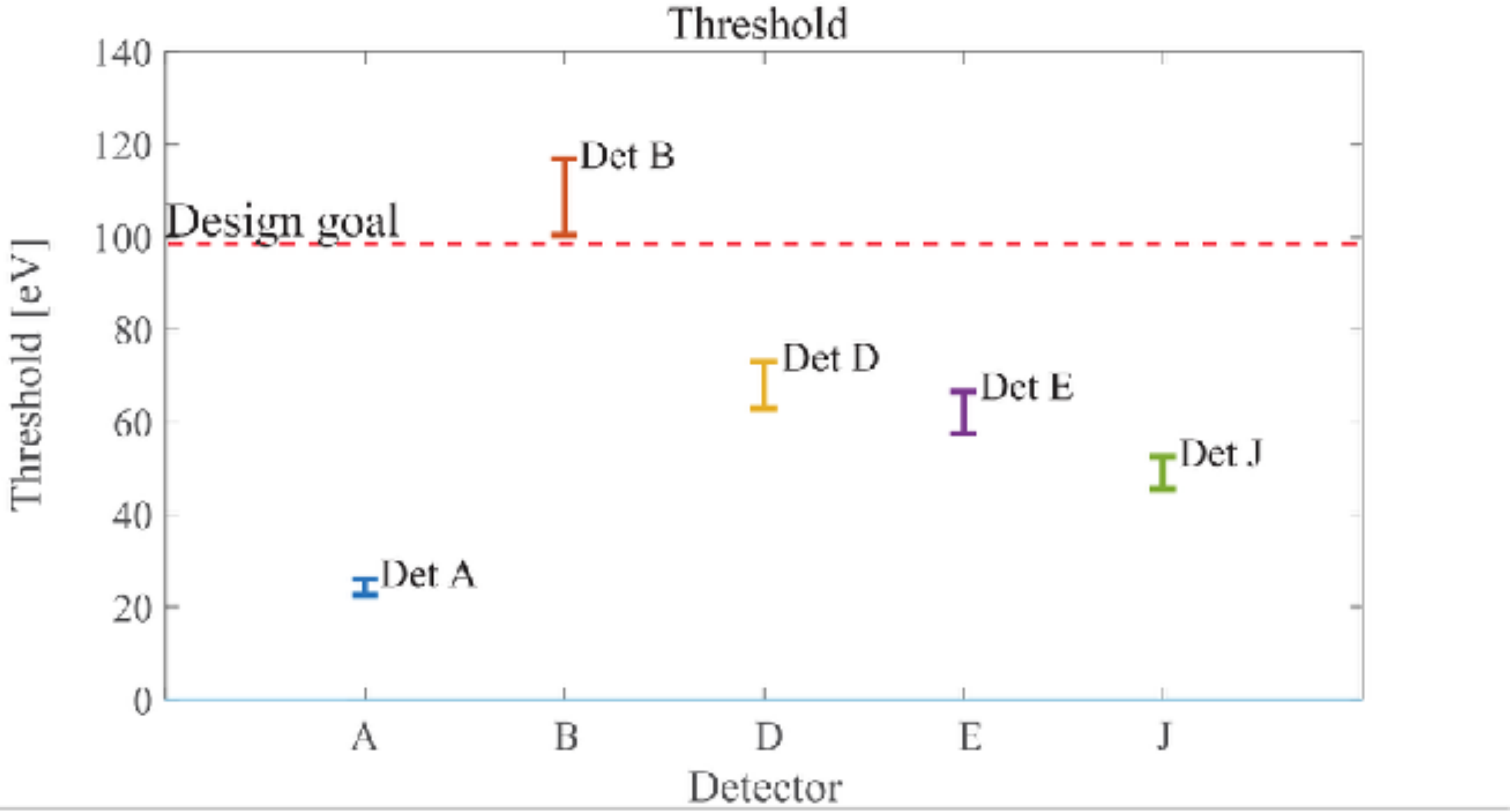
CRESST III Results

arXiv:1711.07692



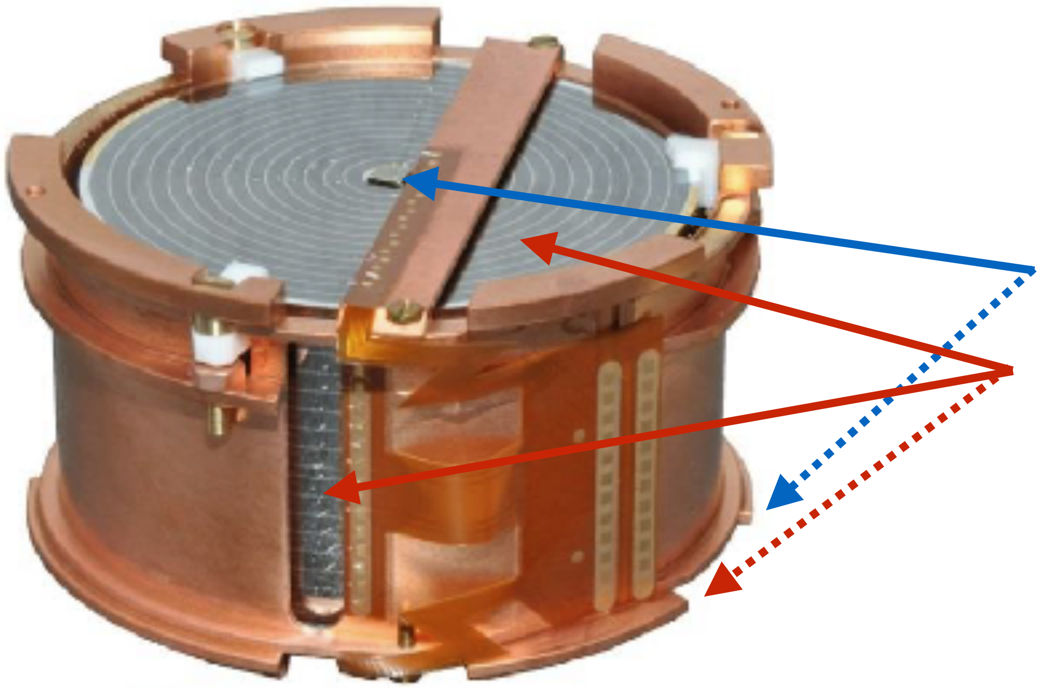
CRESST Outlook

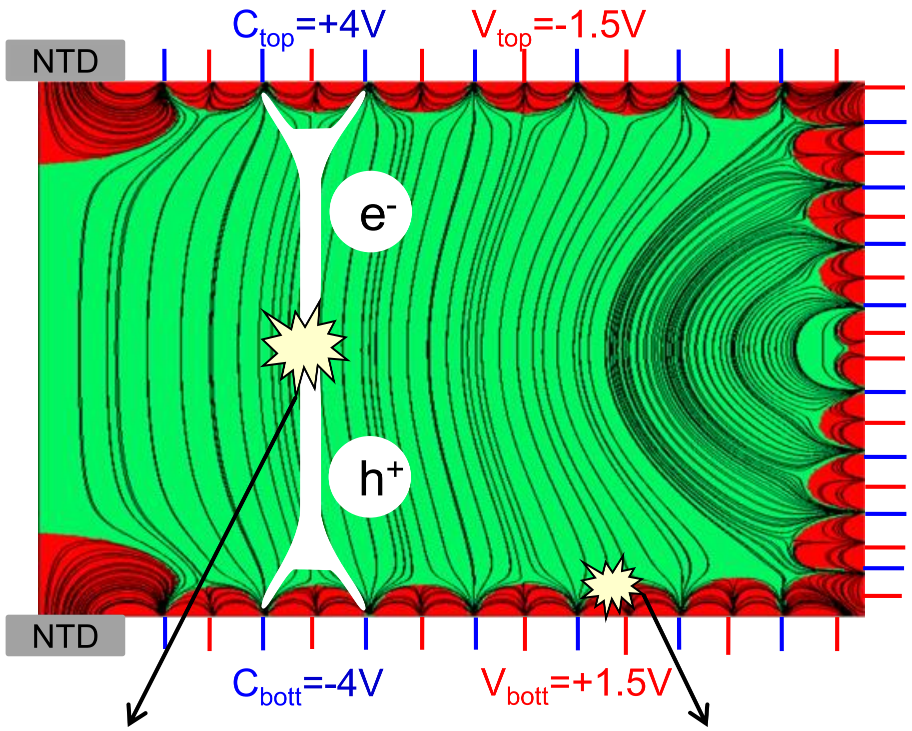
- continue data taking —> better understanding of backgrounds
- 3 more detectors with threshold « 100eV
- 3 times lower optimum threshold for detector



Edelweiss

Edelweiss Technology



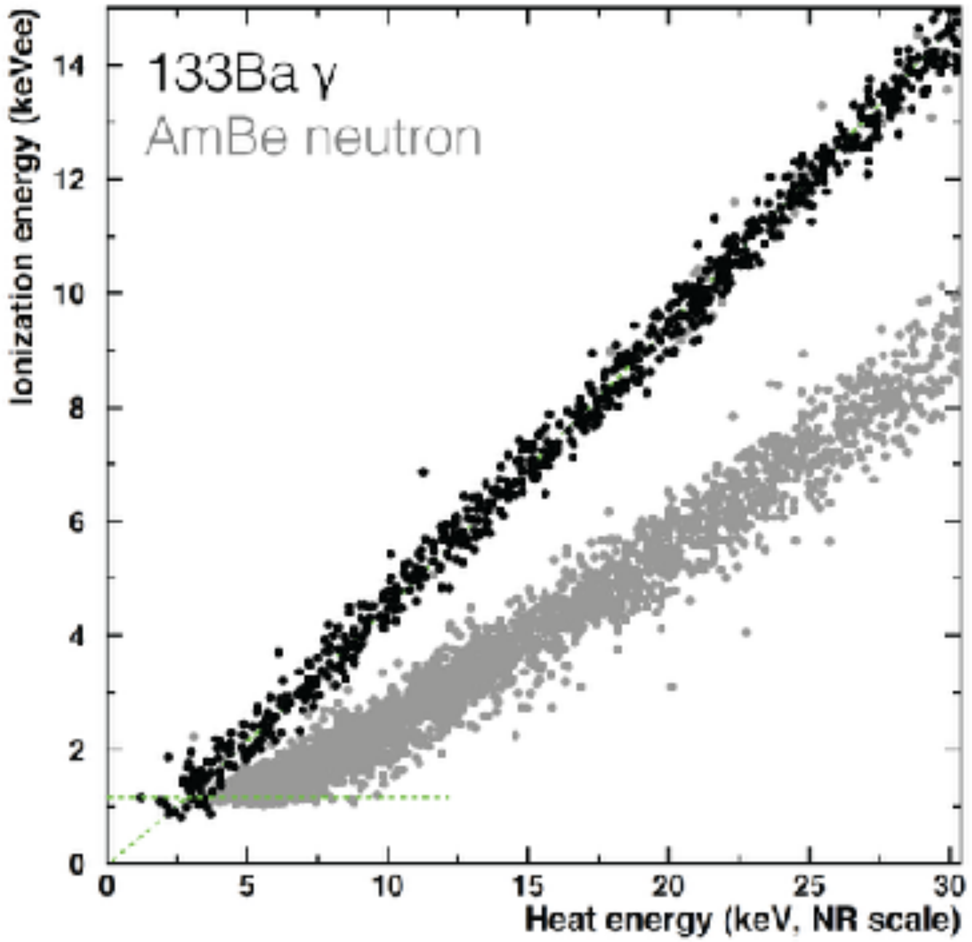


- Fully InterDigitized (FID) technology.
- Ge crystal target: ~870 g each
- 2 Ge NTDs heat sensor per detector
- Electrodes: concentric Al rings (2 mm spacing) covering all faces
- XeF_2 surface treatment to ensure low leakage current (<1 fA) between adjacent electrodes

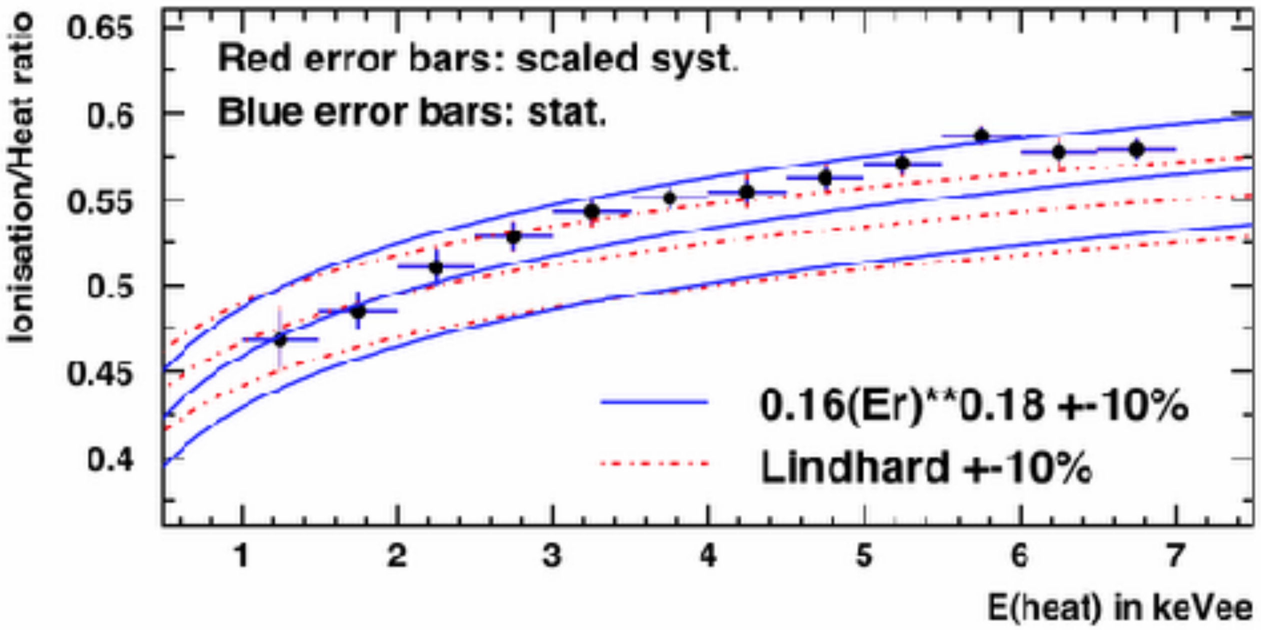
Surface & Bulk Event Rejection:

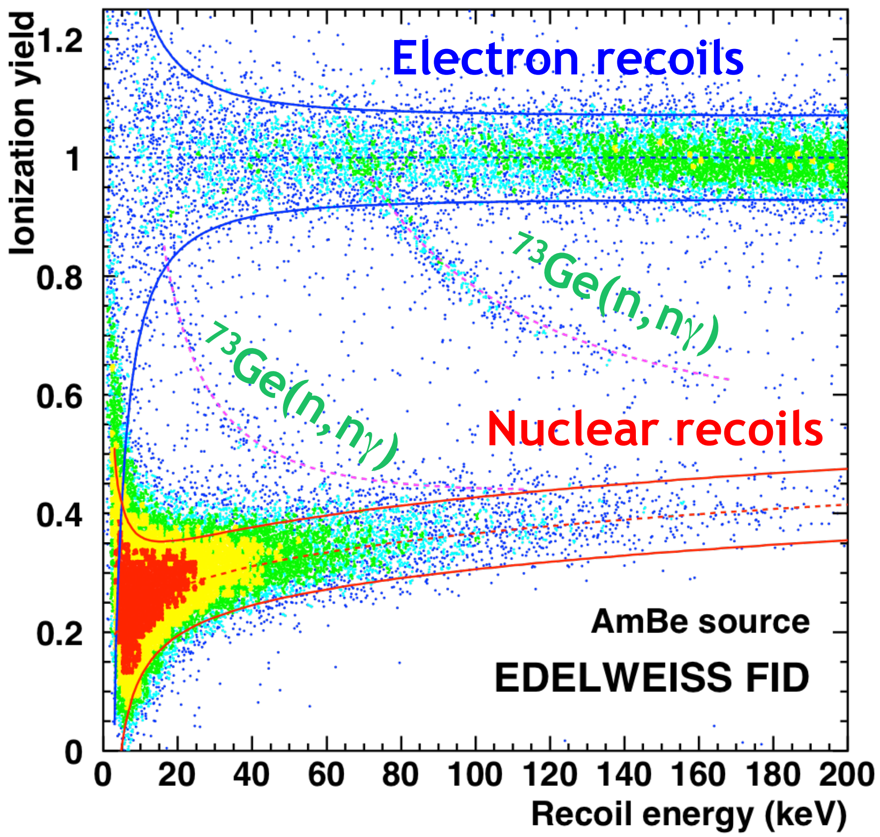
- Surface event: Signal on C_{bott}&V_{bott} or C_{top}&V_{top}
- Bulk/Fiducial event: Signal on C_{top}&C_{bott}

Detector Performance



- Event-by-event separation down to 5 keV energy recoils
- Response to nuclear recoils calibrated down to the analysis threshold for low mass WIMP searches (1 keV_{ee} heat = 2.5 keV nuclear recoil)

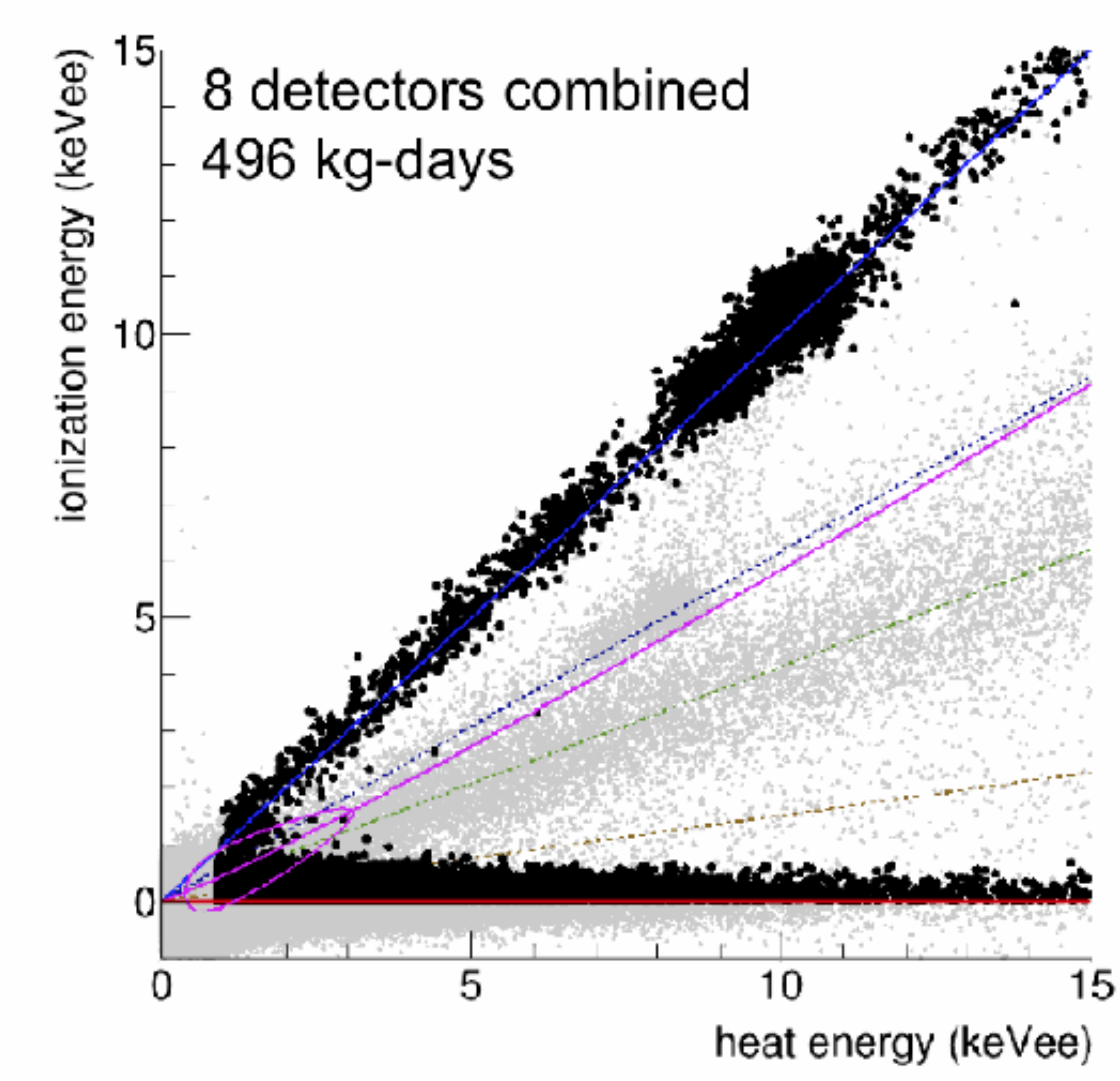




[arXiv:1706.01070]

Recent Data Analysis

- Analysis with Boosted Decision Tree (JCAP05 (2016) 019)
- Analysis with Profile Likelihood (EPJC 76 (2016) 548)



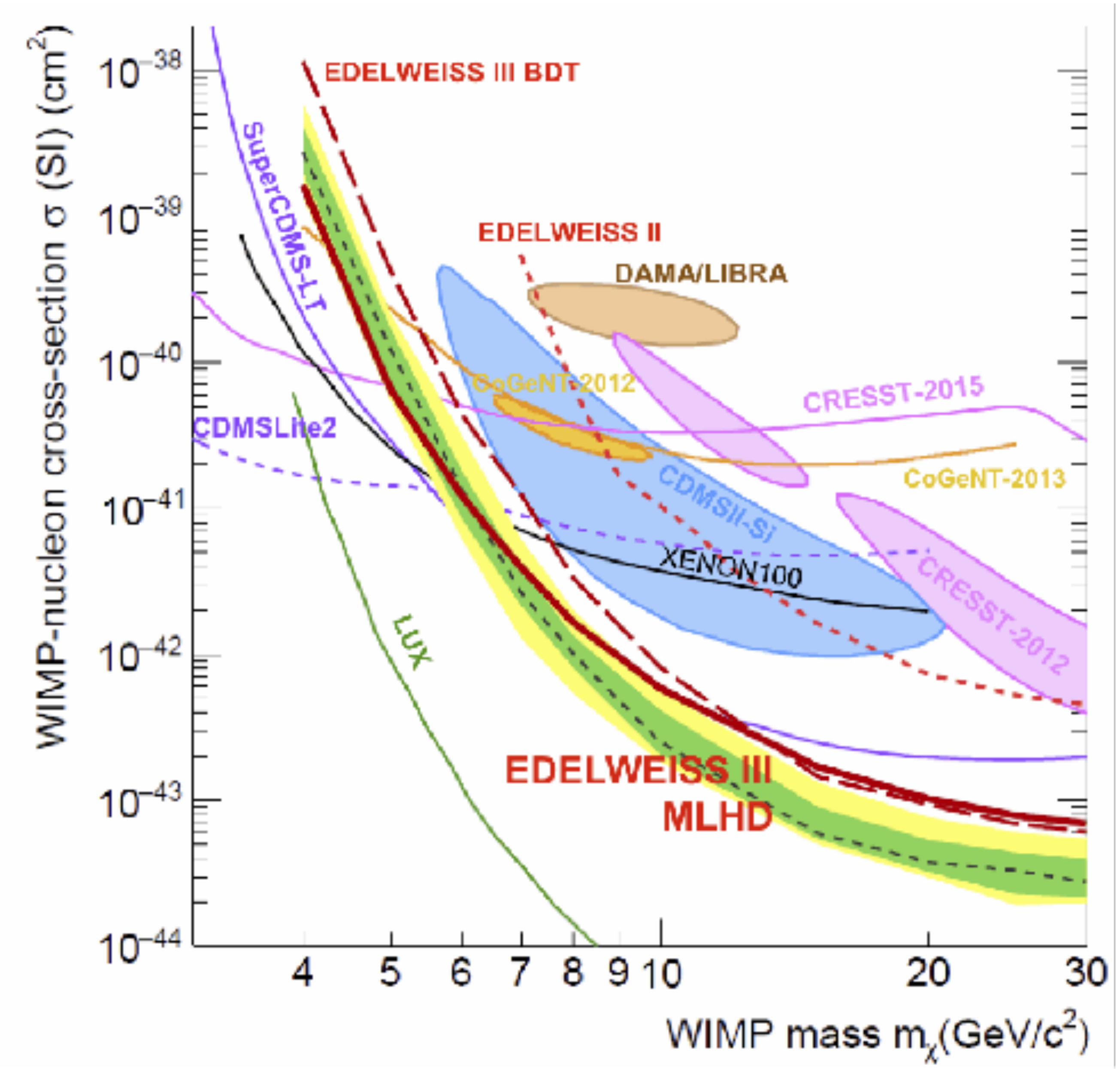
Data driven background models using sidebands.

Bulk electron recoils
Neutrons
Surface Betas, Pb
Heat only events

J. Gascon - Taup 2017

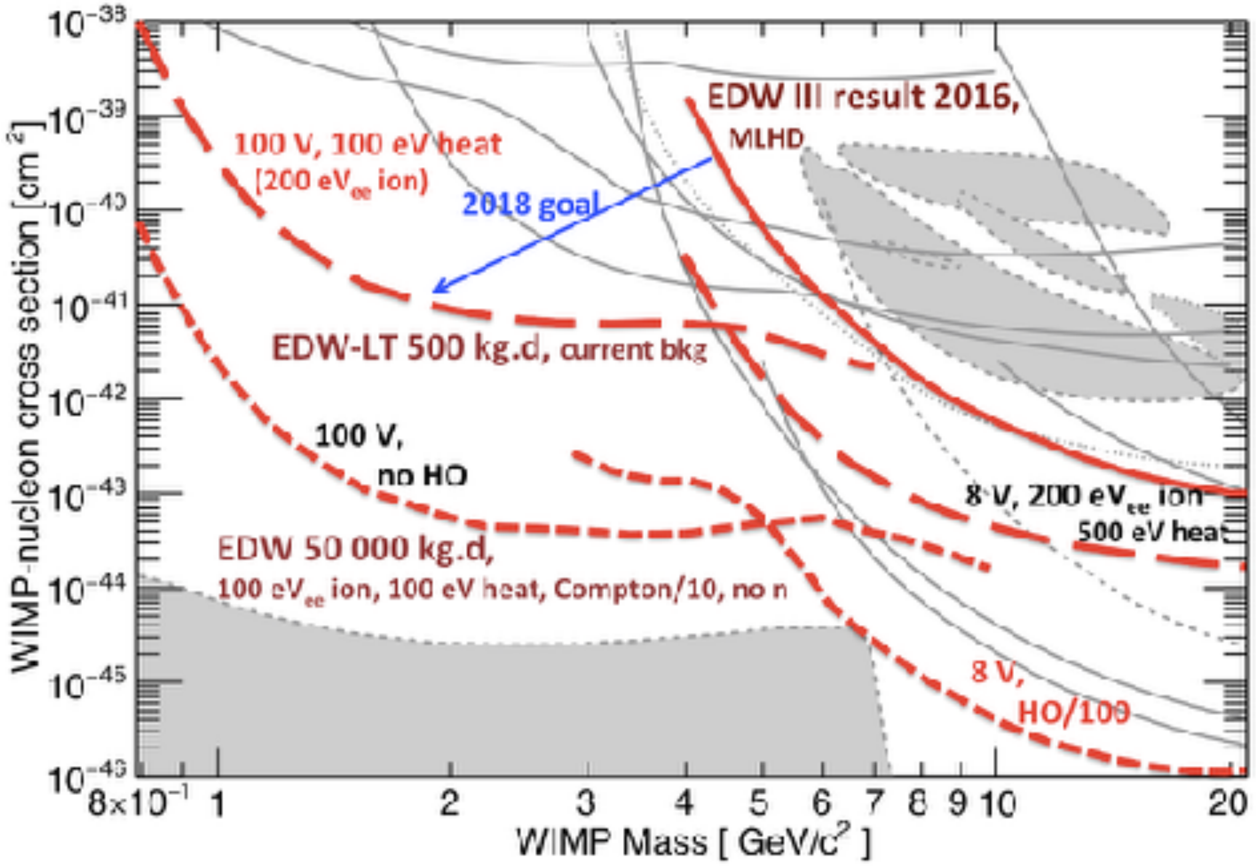
Edelweiss Results

- Analysis with Boosted Decision Tree (JCAP05 (2016) 019)
- Analysis with Profile Likelihood (EPJC 76 (2016) 548)



Edelweiss Outlook

Completed study based on present measured backgrounds and resolutions vs possible improvements (arXiv: 1707.04308).



- ☑ Use of Luke-Neganov boost to lower thresholds (up to 100V bias)
- ☑ Improve heat resolution: σ_{heat} = 500 eV → 100 eV (x5 gain in sensitivity already achieved on 200 g detectors)
- ☐ Reduction x100 of heat-only background
- ☐ Improve ionization resolution σ_{ion} = 200 eV$_{ee}$ → 100/50 eV$_{ee}$

Conclusions

- Dark matter search experiments have been very successful in ruling out a number of favored candidates. No compelling evidence for the detection of DM currently exists.
- mK detectors have been making fast progress in pushing their technologies to lower thresholds and smaller cross sections. We are now able to access parameter space we had not conceived possible a decade ago.
- Stay tuned! Current experiments are producing results at a fast pace and larger, more sensitive experiments are soon to come online.

The Future is Bright!