Searching for Low-Mass Dark Matter Particles

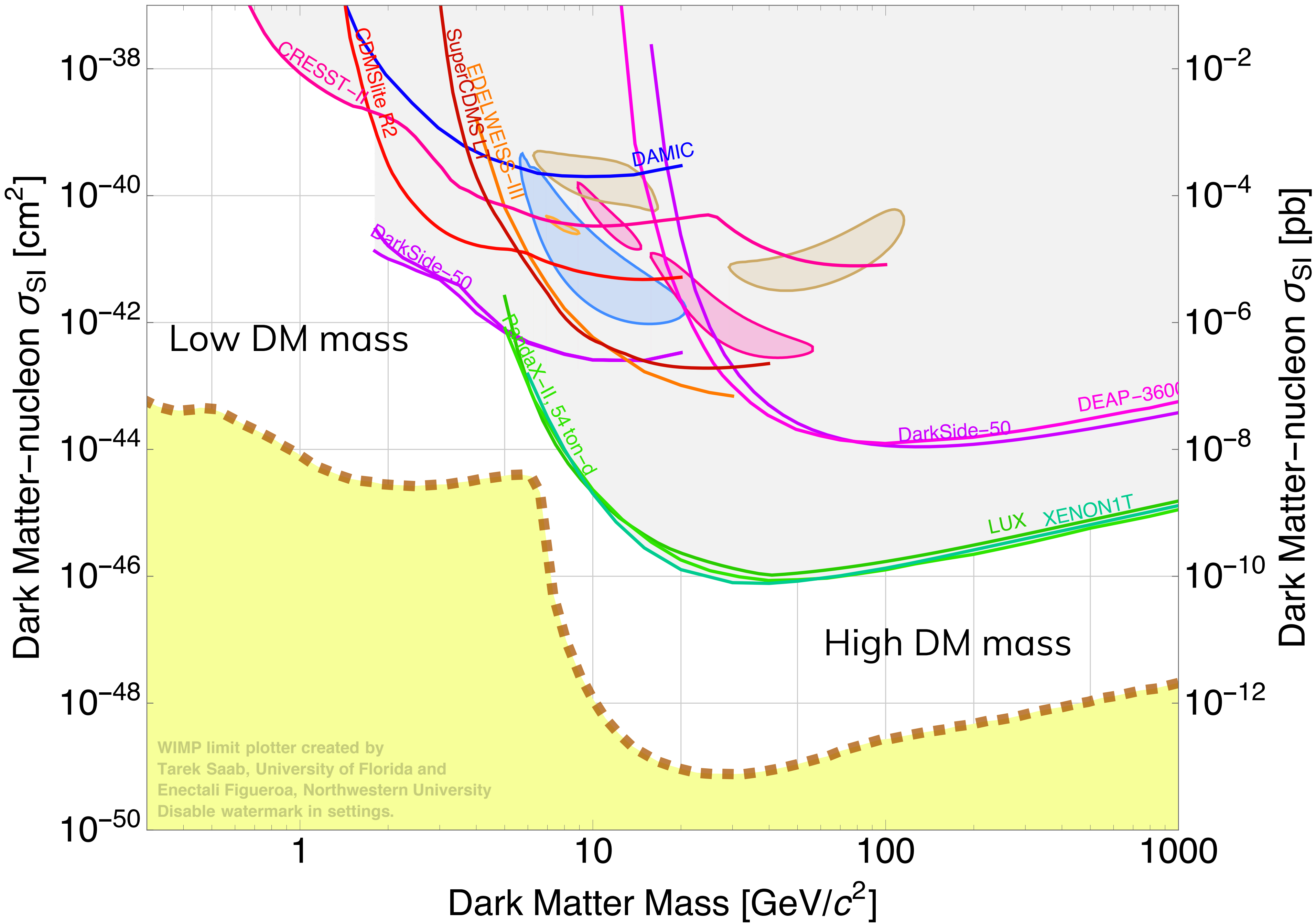
DAMIC - SuperCDMS - CRESST

2018/08/23

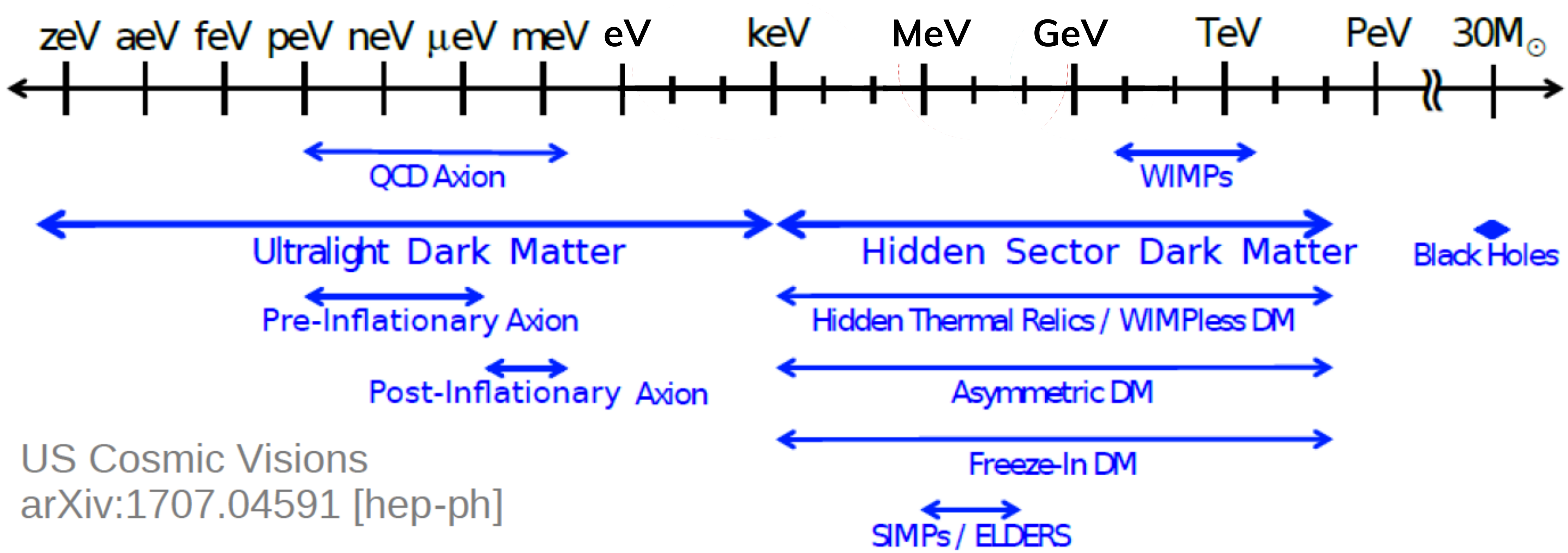
Silvia Scorza
SNOLAB

Direct DM Search - State of Art

Detection of the energy deposited due to scattering off target



Light Dark Matter Scenario



US Cosmic Visions
arXiv:1707.04591 [hep-ph]

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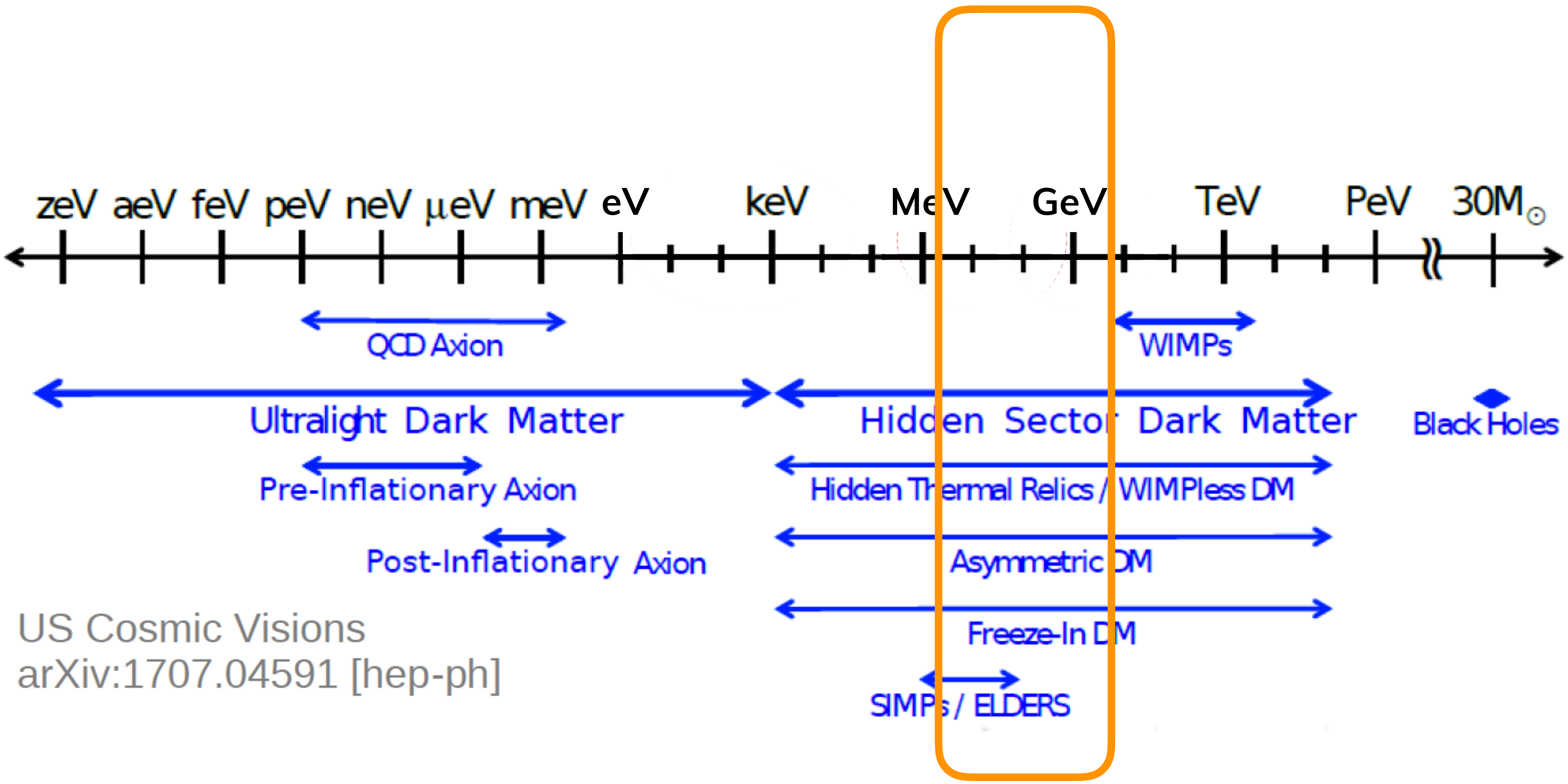

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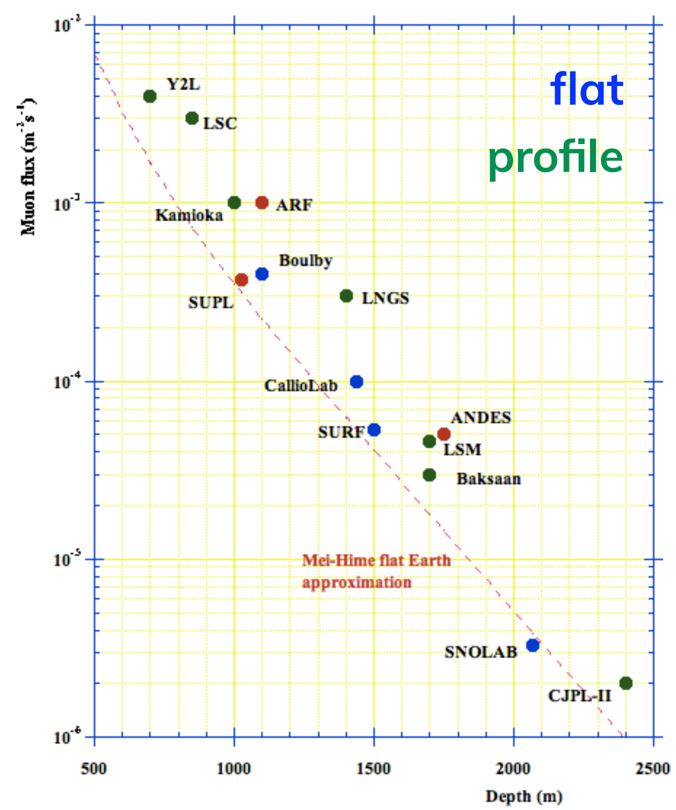
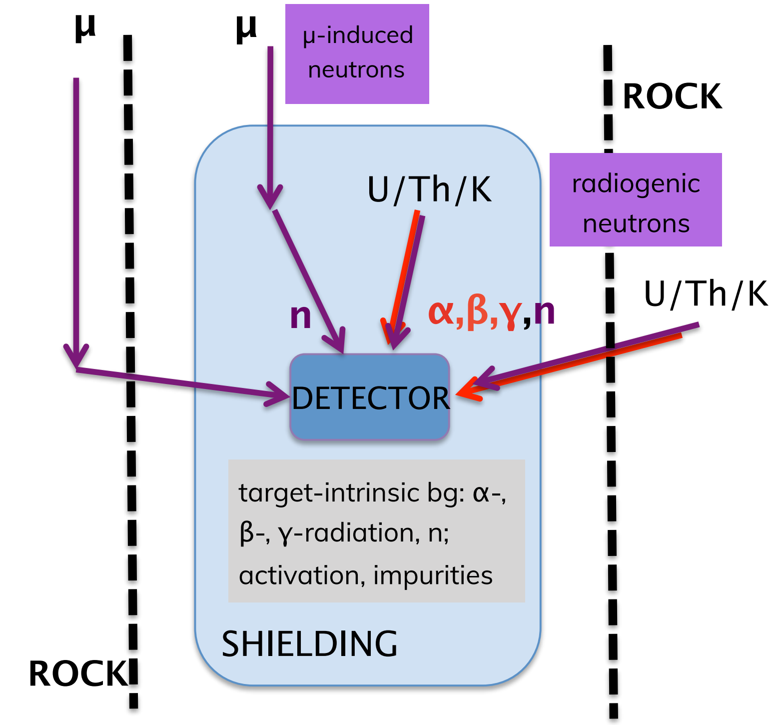
Direct DM Search - Challenges

- **Low** and **controlled** backgrounds
- **Discrimination** between signal and background
  - Simultaneous measurements of two signals allows ER/NR discrimination on an event-by-event basis
  - Detector technology background rejection
- **Large exposure** (*few events per ton-year*)
- **Low energy threshold**

Go deep underground
Fewer cosmic rays to produce neutrons.





Passive/Active shielding
Reduce backgrounds from natural (^{238}U, ^{232}Th, ^{40}K) radioactivity

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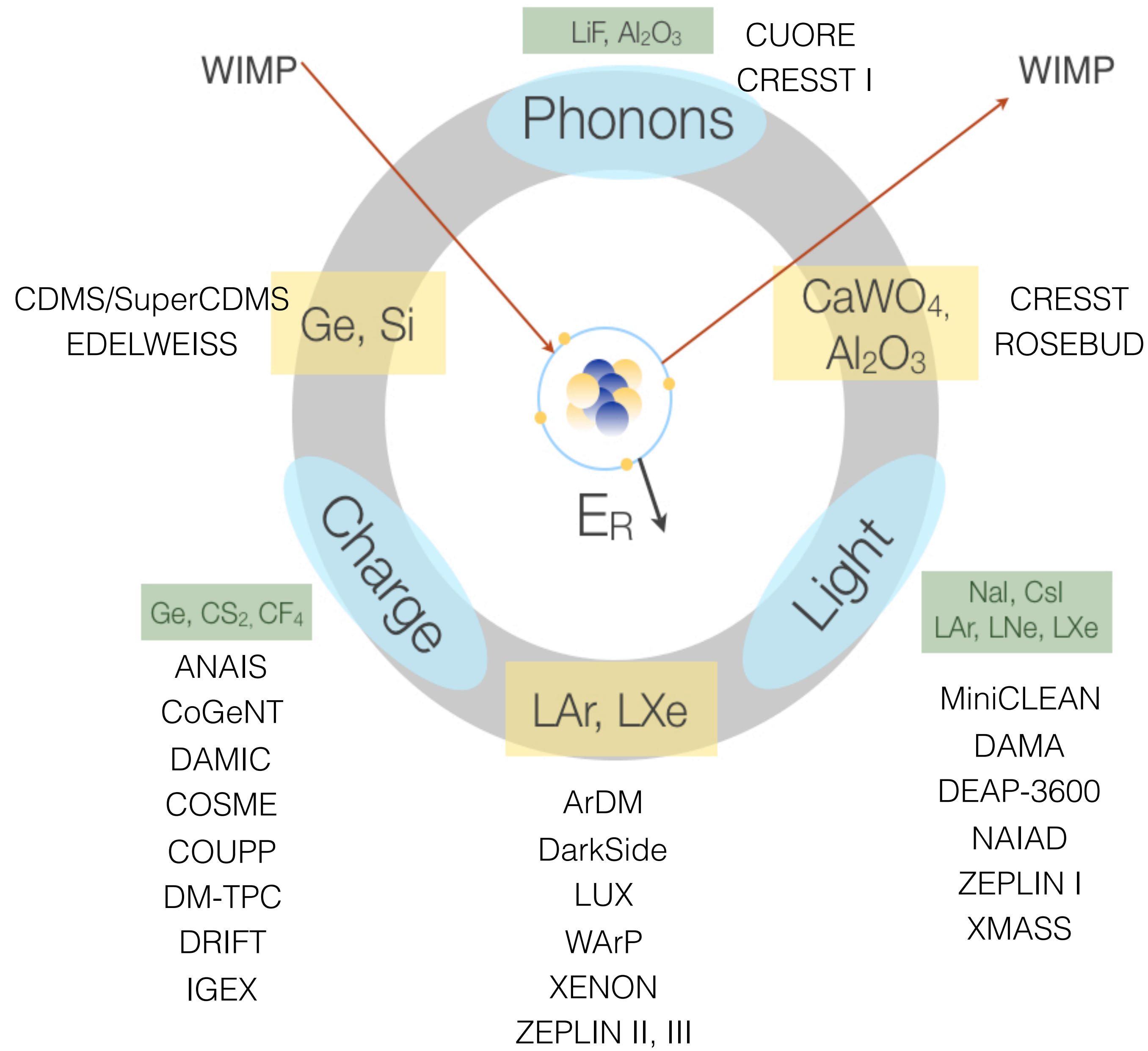

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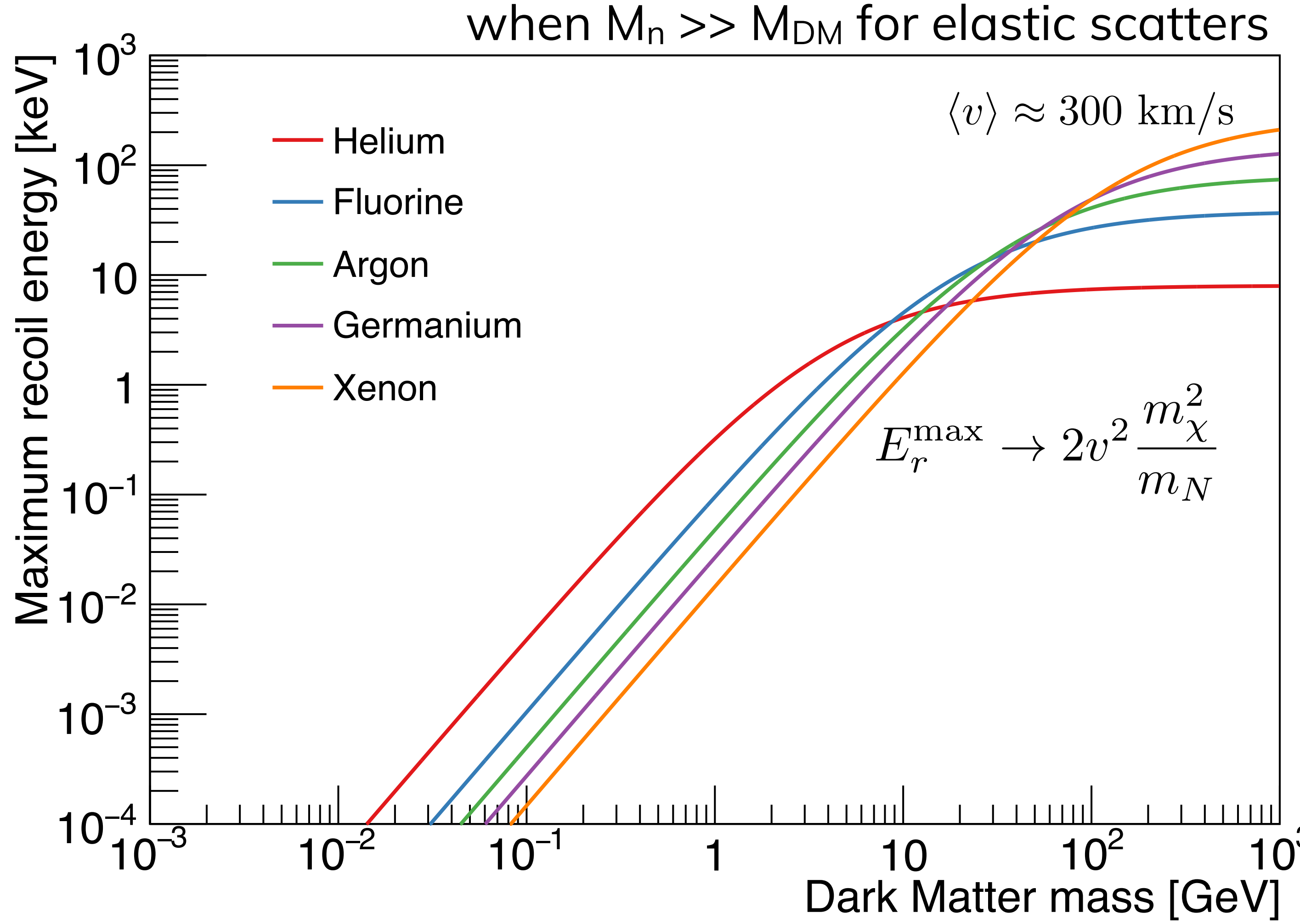
Transfer of DM kinetic energy inefficient when $M_n >> M_{DM}$ for elastic scatters



Direct detection of Sub-100 MeV dark matter via nuclear recoil is nearly impossible !

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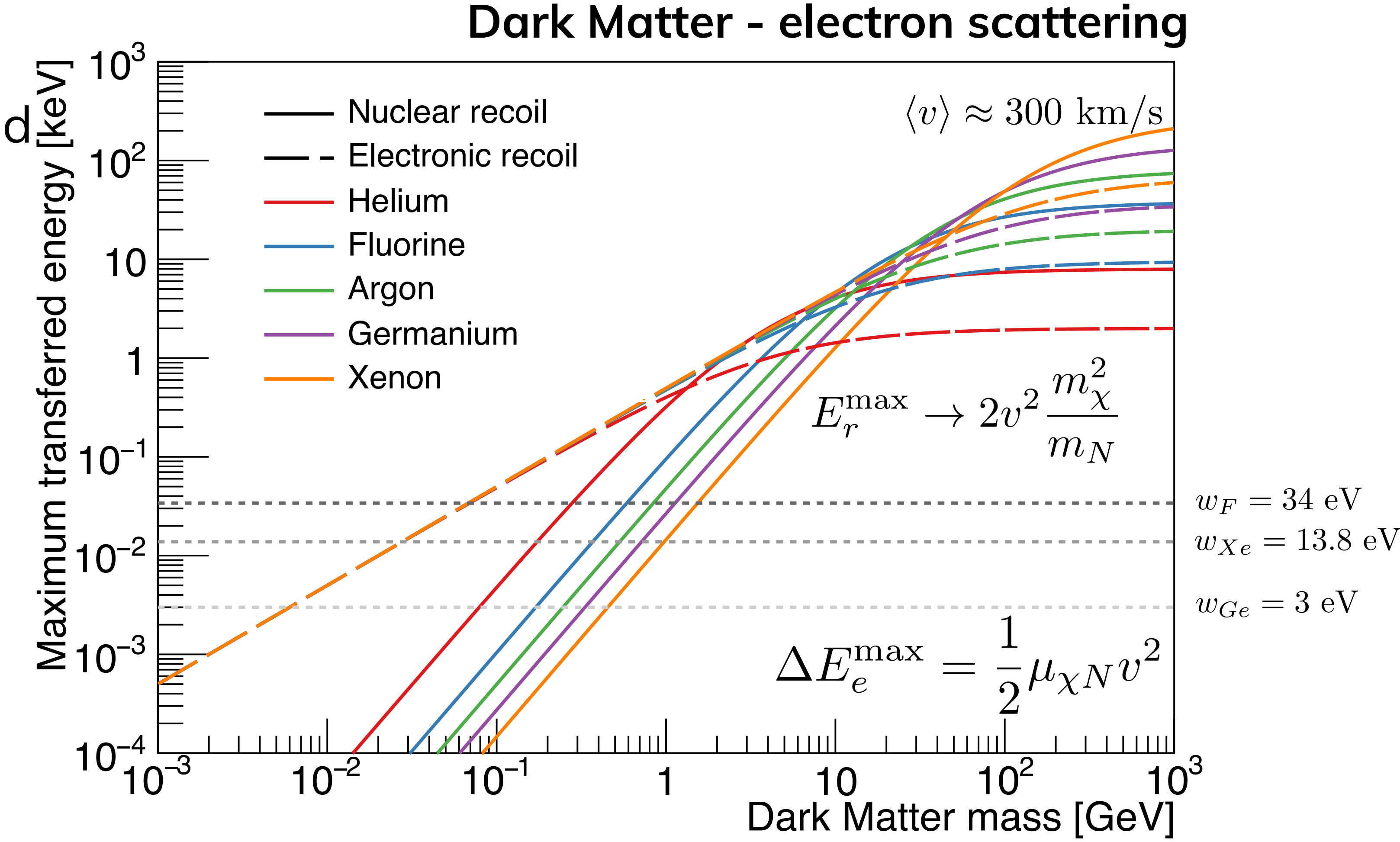

For DM masses below 100 MeV switch to DM-electron scattering searches

Direct DM Search - Challenges

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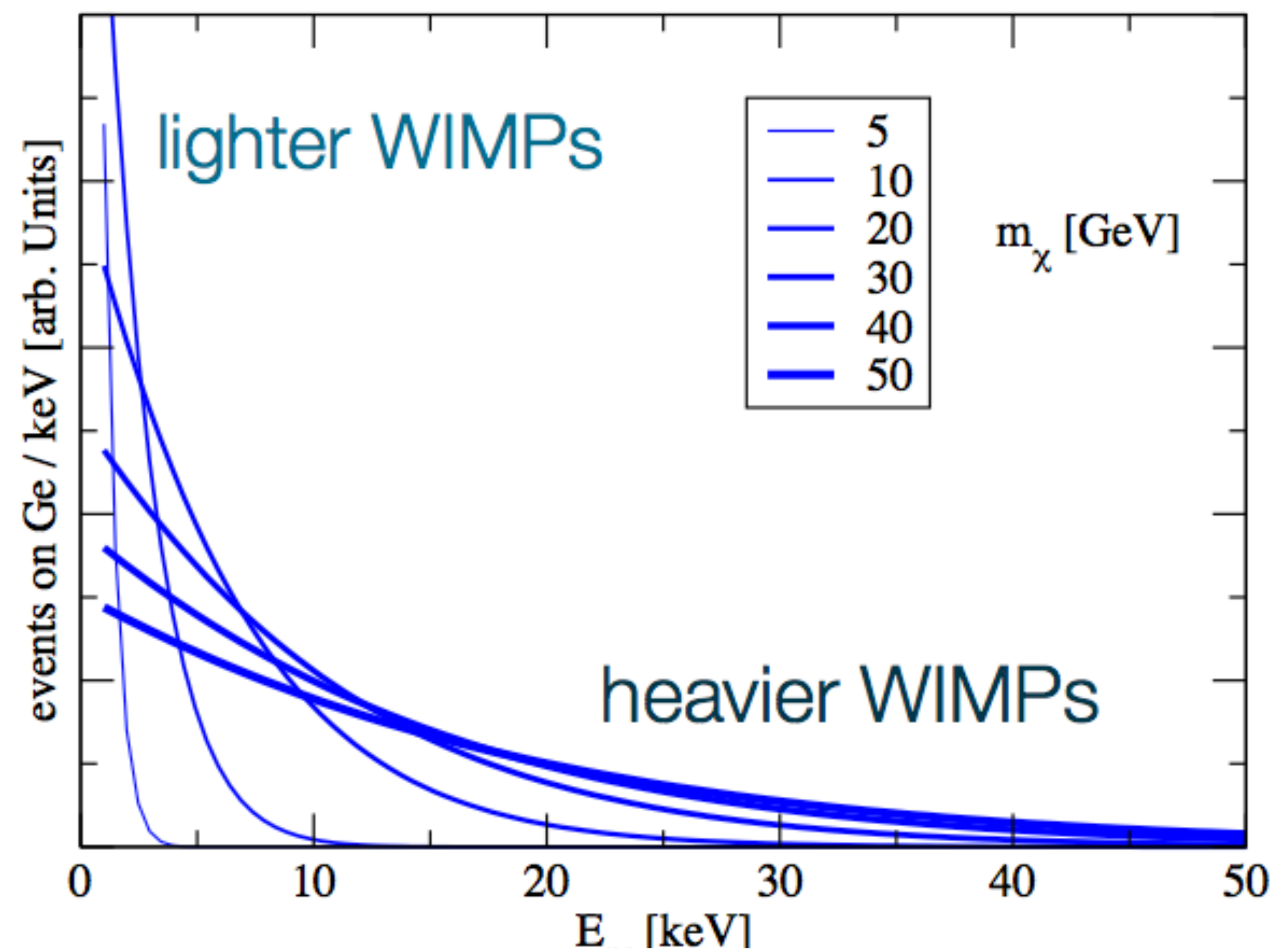

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Particle Physics | Nuclear Physics | Astrophysics

$$\frac{dR}{dE_r} = \frac{1}{2m_r^2}\frac{\sigma_0}{m_\chi} F^2(E_r)\, \rho_0 \int \frac{f(\vec{v})}{v} d^3v$$

Interaction rates scales as $1/m_\chi$

Liquid noble experiments need 10 tons to get to 10^{-47} cm^2 at 100GeV

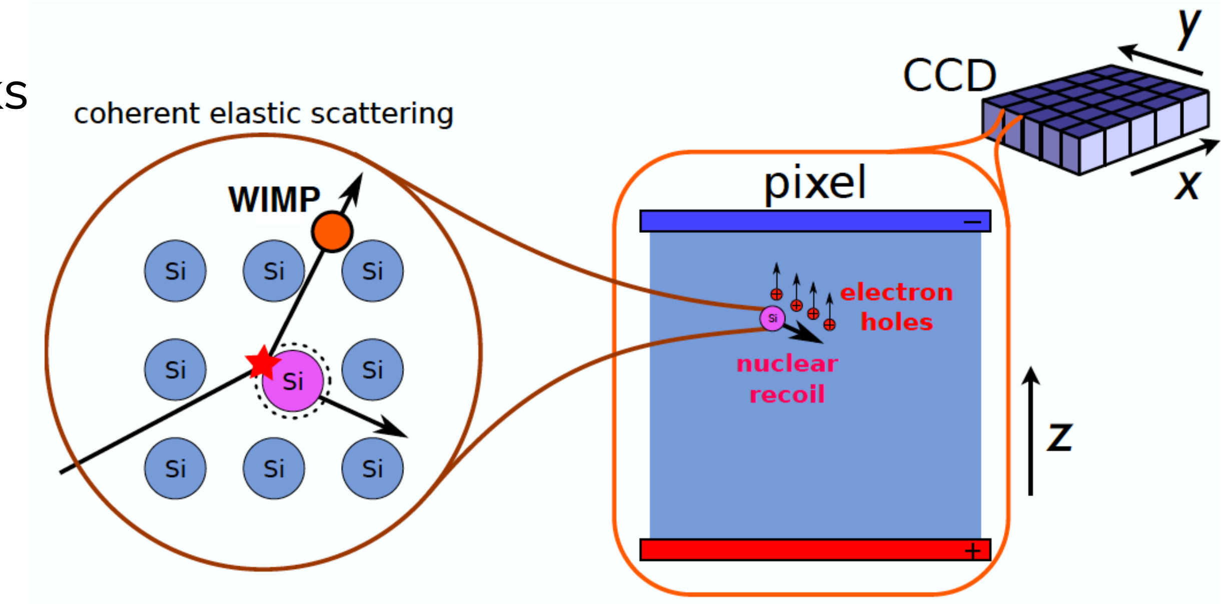
Solid-state experiments only needs 10kg to reach the same level at 100MeV

→ energy sensitivity

Charge-coupled devices (CCDs)

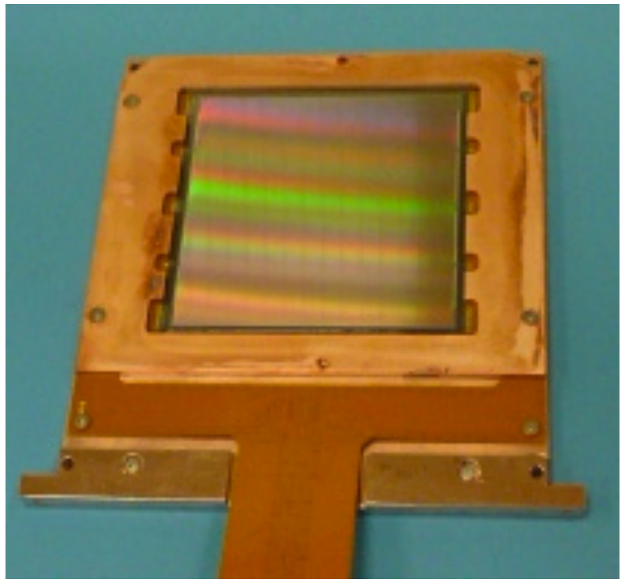
CCD Technology

- Silicon CCD technology highly advanced thanks to utility in astronomical and satellite-based imaging
- DM particles scatter coherently off of Si nuclei, which recoil and yield detectable ionization signals
- CCDs are "exposed", i.e. collect charge, for $\mathcal{O}(1$ day) and images are then read out for analysis

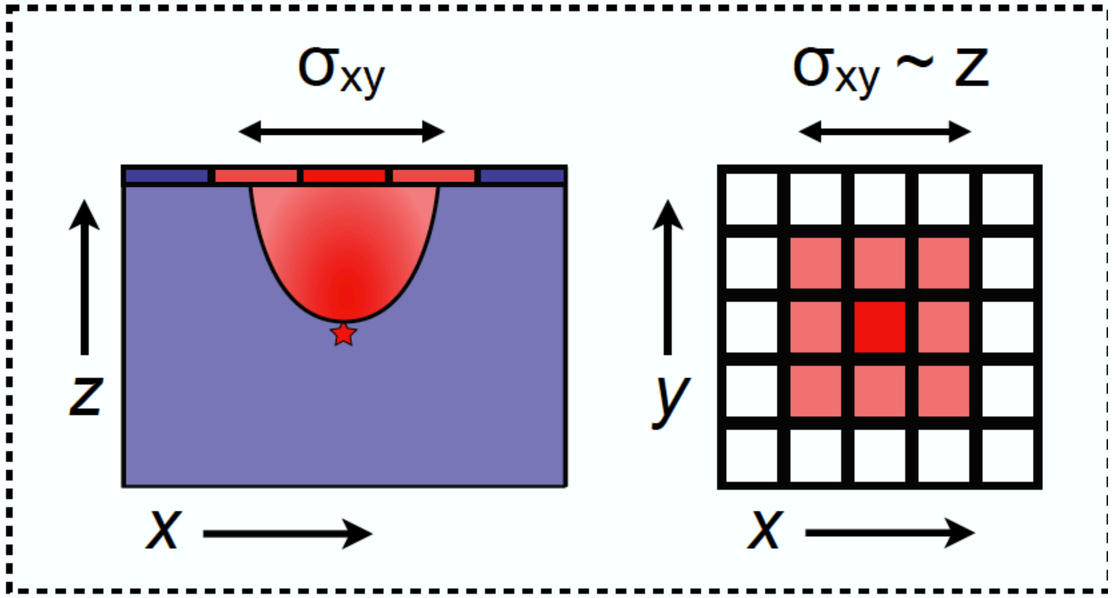


A. Aguilar-Arevalo et al., arXiv:1506.02562

16 Mpix CCD
LBNL designed
6 cm x 6 cm
15-μm pixel pitch
675-μm thick



A. Aguilar-Arevalo et al., arXiv:1607.07410

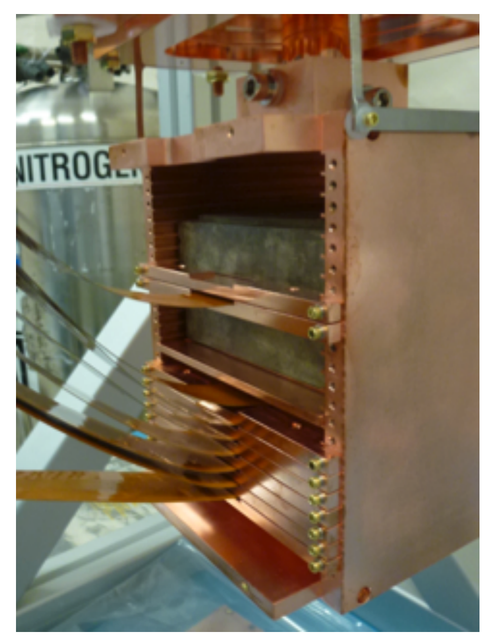


DAMIC @SNOLAB

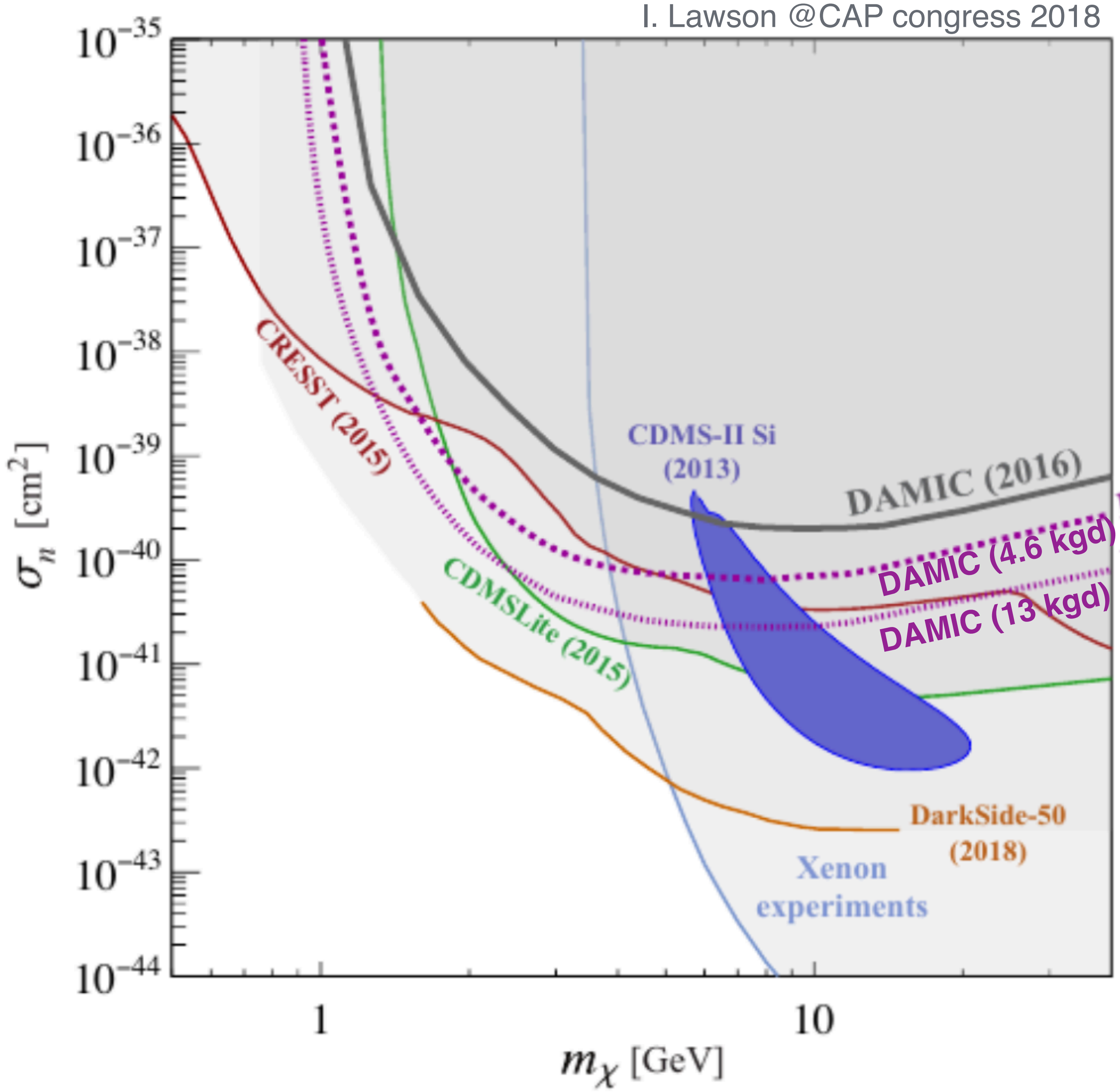
- Seven CCDs (40 g detector) in stable data taking at ~140 K since 2017;
  One CCD sandwiched in ancient lead

- 7.6 kg d “background” data with 1x1 readout

- Pixels grouped (1x100) to reduce noise for science data



DAMIC Sensitivity



Projected sensitivities assume currently realized background index of 5 dru

13 kg d exposure by end of 2018

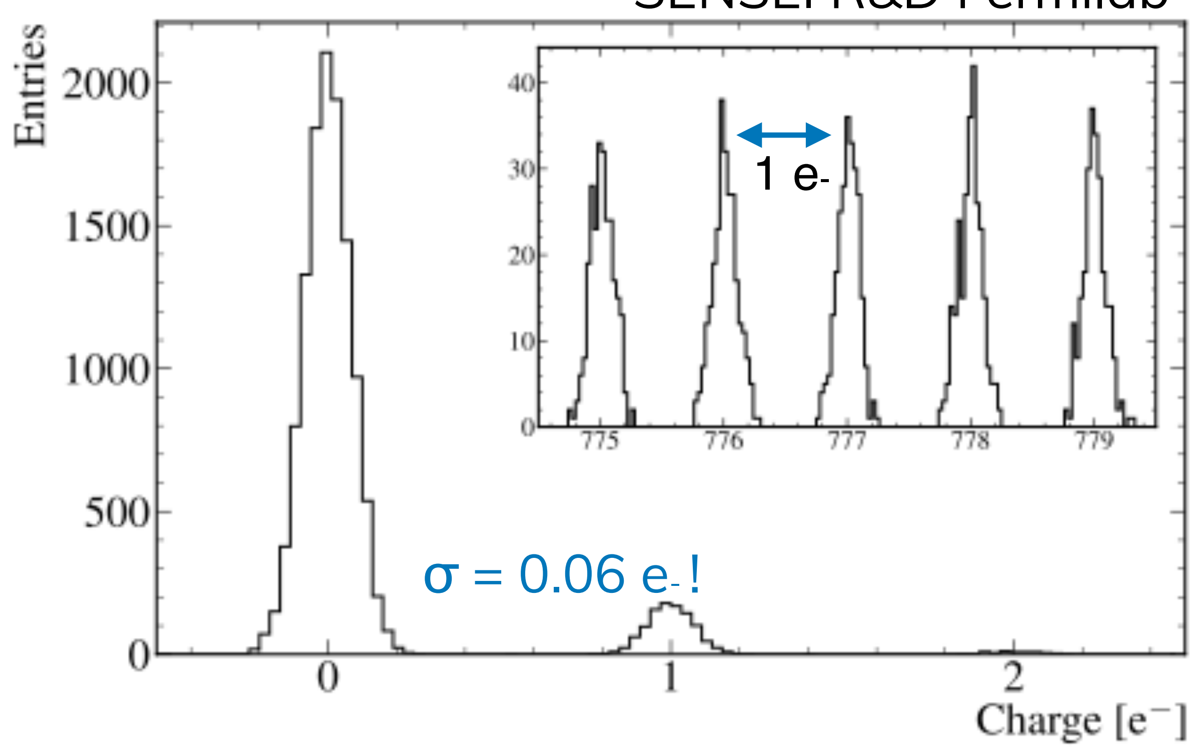
Exposure of 4.6 kgd at 03/2018

DAMIC-M @ LSM

Laboratoire Souterrain de Modane

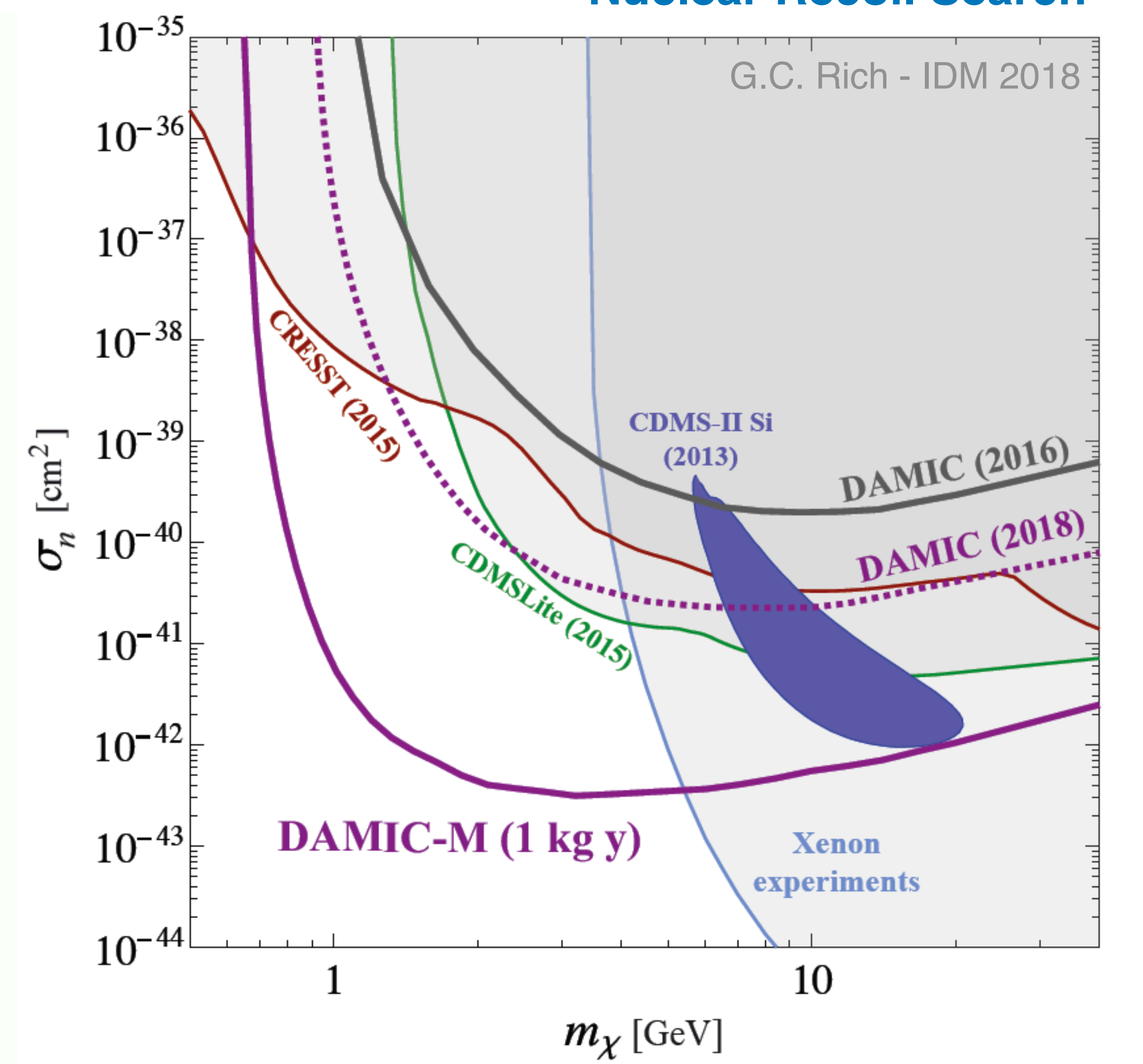
- Next stage of DAMIC to take place at LSM using 1 kg of large (20 g) DAMIC CCDs with skipper-style readout
  - Skipper readout allows for single-electron resolution, demonstrated by SENSEI [J. Tiffenberg et al., arXiv:1706.00028]
- Characterization of large skipper CCDs
- Nominal target threshold of 2 e-
  - Requires dark current ~few 10-6 e-/pix/day
  - DAMIC CCDs have previously demonstrated ~0.001 e-/pix/day (**lowest ever measured in a Si device!**), consistent with a 3 e- threshold for DAMIC-M

SENSEI R&D Fermilab

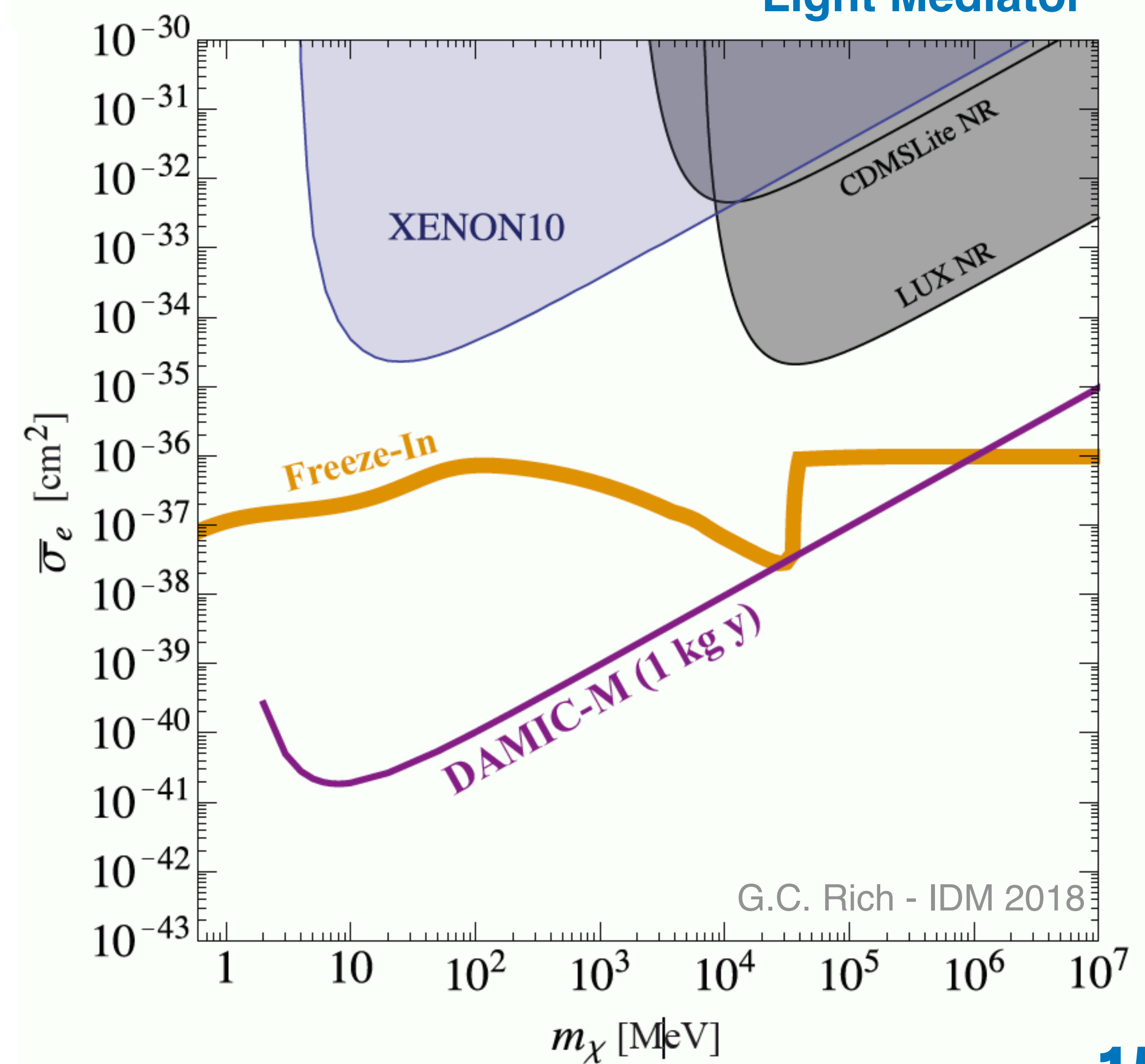


DAMIC-M Sensitivity

Nuclear Recoil Search



Electron Recoil Search
Light Mediator



DAMIC Outlook

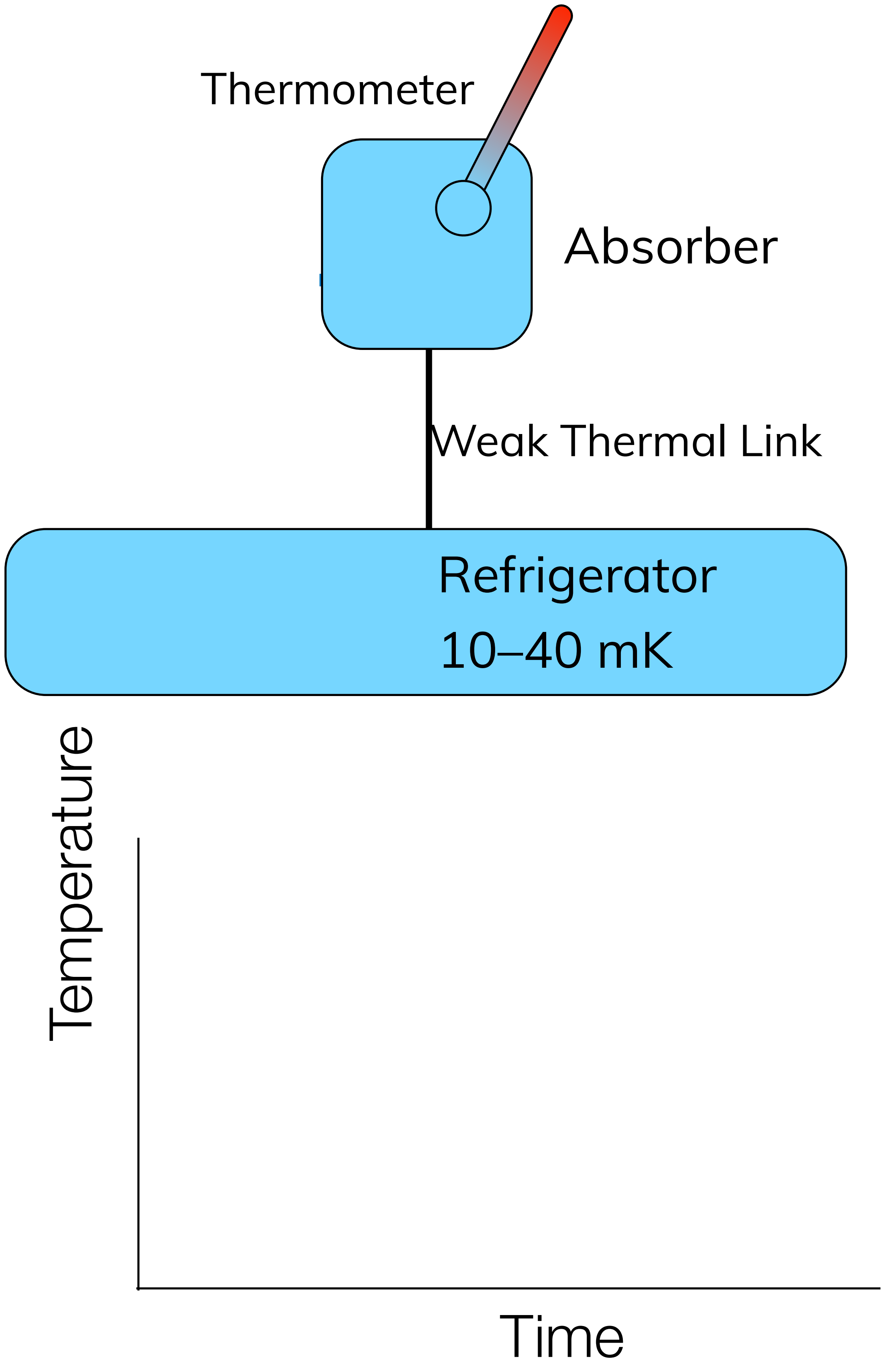
- DAMIC is collecting high quality data - few dru background and 50 eV threshold - with a 40 g CCD detector at SNOLAB. We will reach ≈ 13 kg day in 2018.

- These data will provide essential information for the next generation of silicon detectors (DAMIC-M, SuperCDMS):
    - explore spectrum below 2 keV_{ee} in silicon
    - measure cosmogenic and radiogenic backgrounds in silicon
    - measure CCD dark current at the lowest temperatures

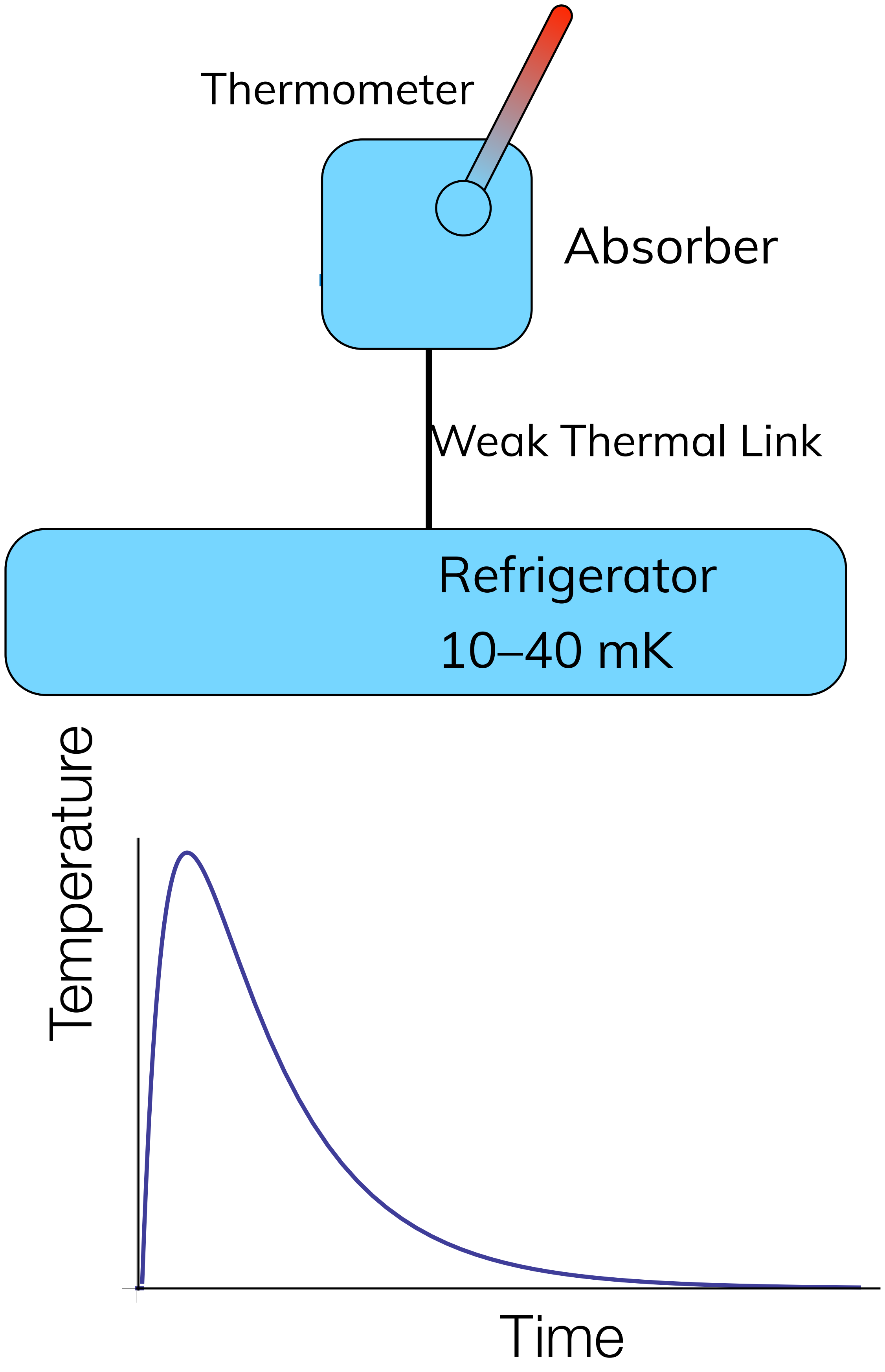
- Next stage is a kg-size DAMIC detector to be installed at the LSM in France. Continue to profit from the current setup at SNOLAB in the development stage

Cryogenic Detectors

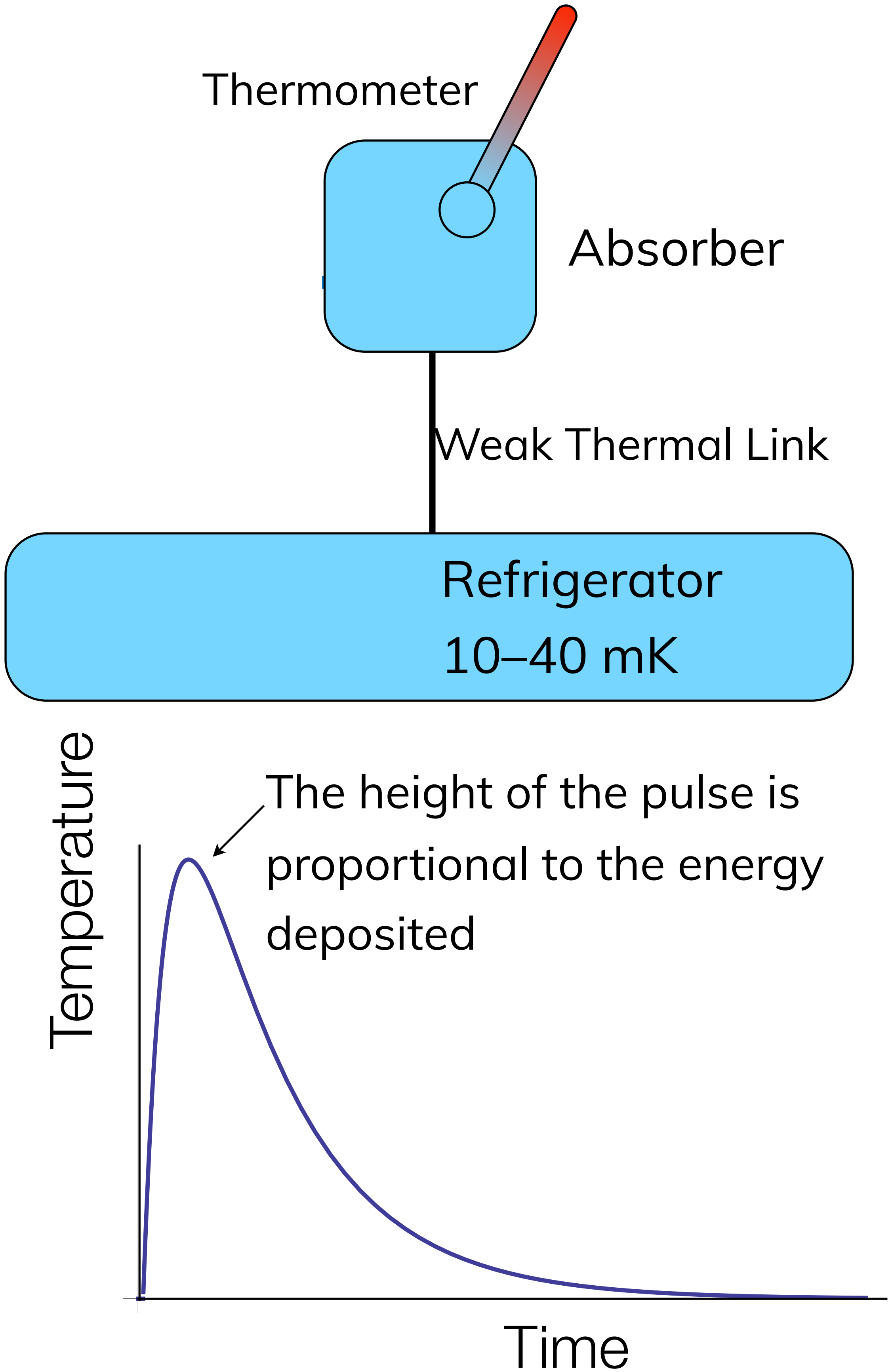
Phonon Readout



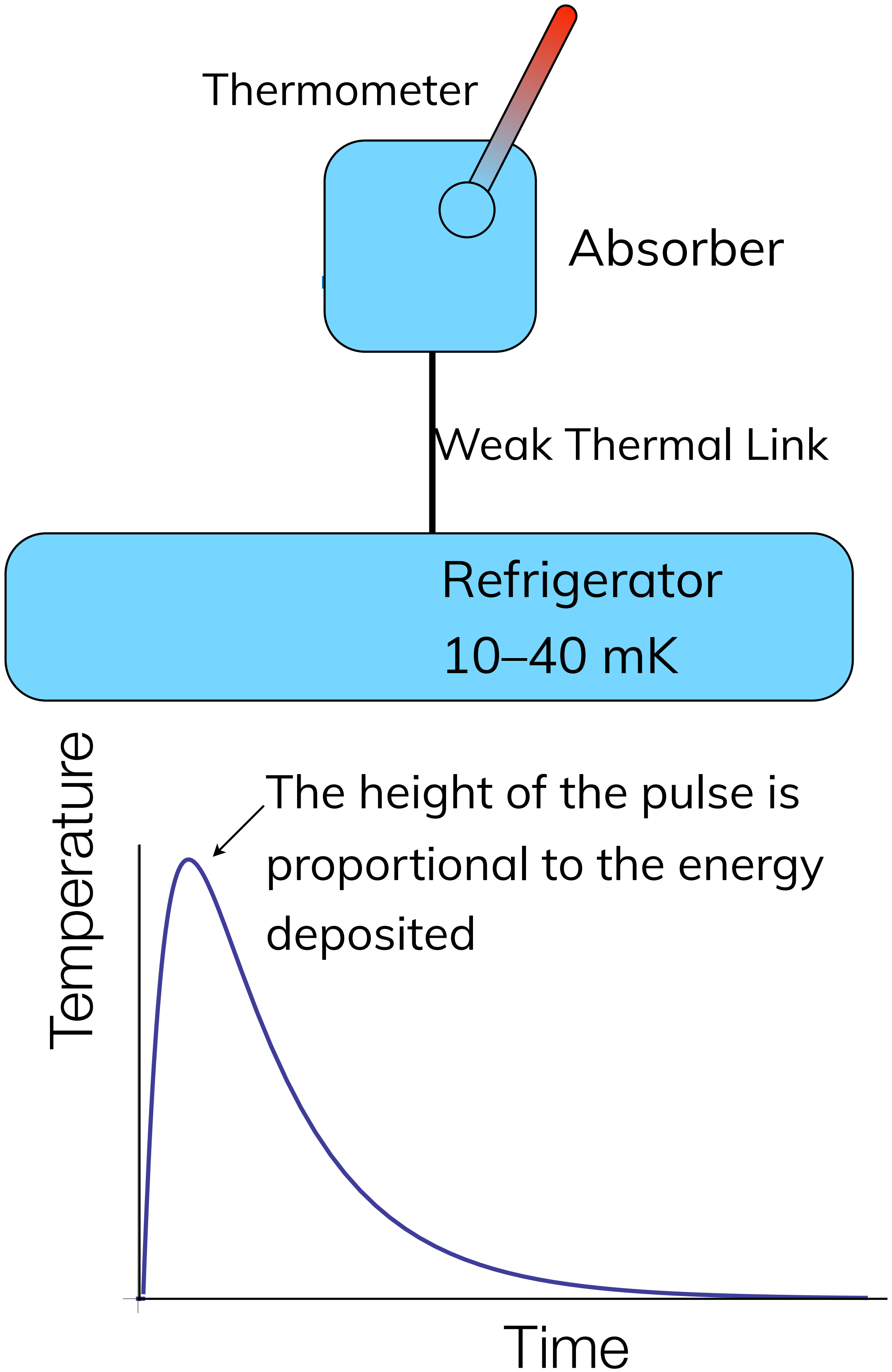
Phonon Readout



Phonon Readout

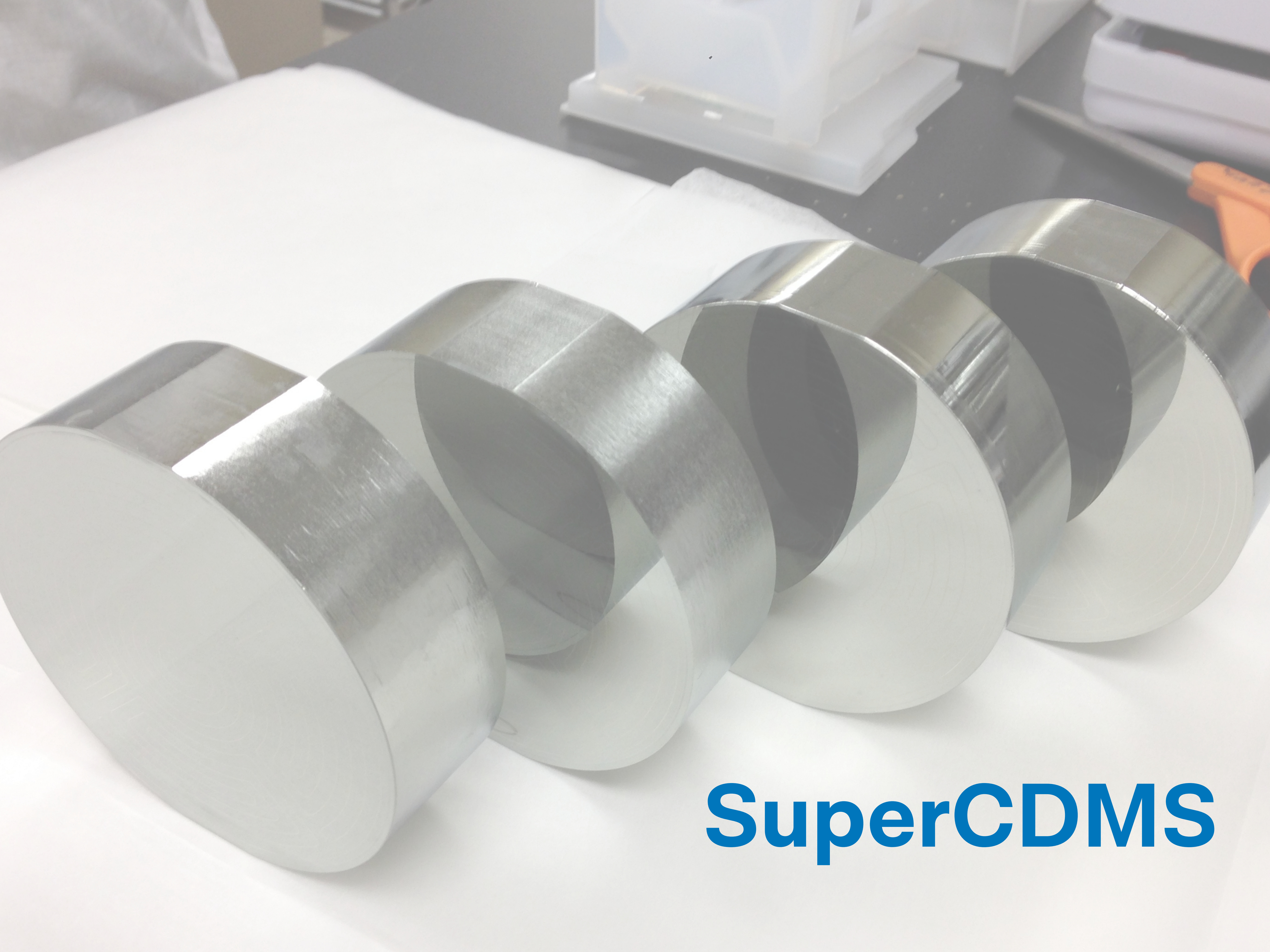


Phonon Readout



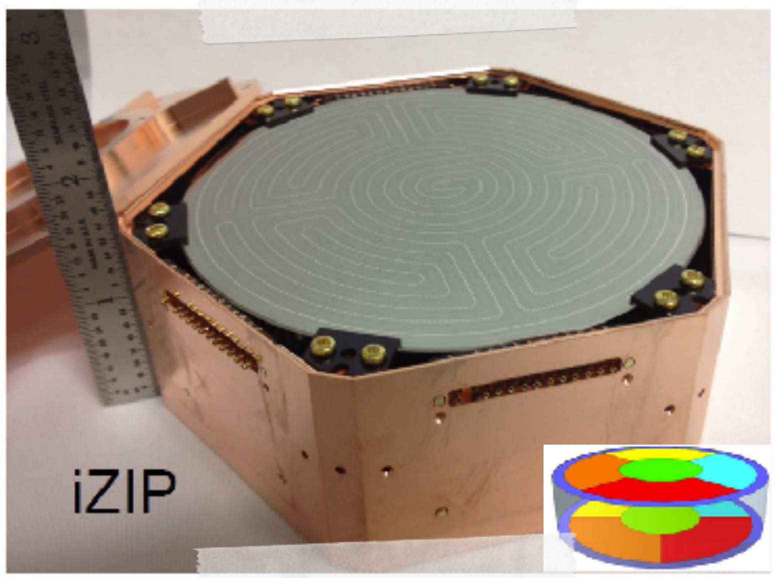
Advantages of phonon readout:

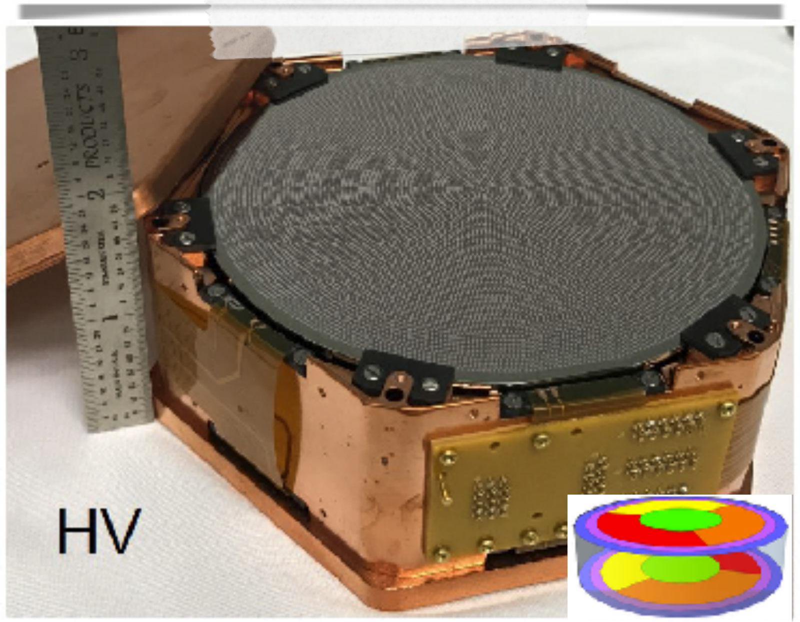
- Direct measurement of nuclear recoil energy; **no quenching factors involved**
- ~100% of the recoil energy is sensed, **allowing for low thresholds**
- Good energy resolution near threshold (**~eV (RMS) for ~ 10 g detectors**), allowing for better determination of WIMP recoil spectrum once a signal is seen
- Low threshold enables sensitivity to lower WIMP masses + larger rate/kg for large WIMP masses.


SuperCDMS

SuperCDMS Detectors

Technique: Heat+Ionization





- Ultra-pure ~kg Ge and Si crystals operated at 10's of mK

- Measure athermal phonon signal via transition edge sensor

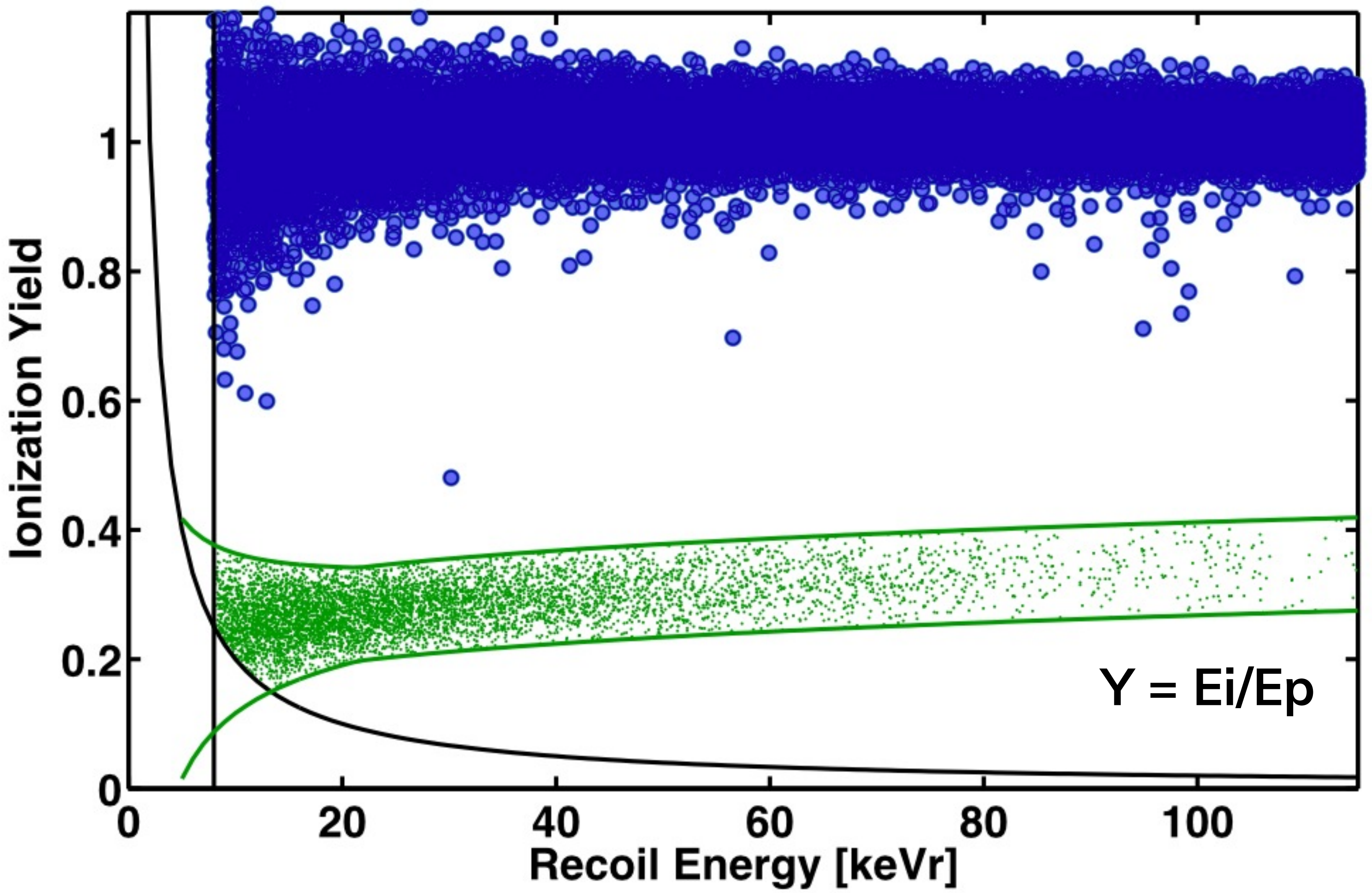
- Multiple channels give position information
- Outer "guard" rings fiducialize high radius events

- Surface/Bulk event discrimination via charge face symmetry

iZIP Technology

Background Discrimination

Electron recoils have a **higher ionization yield** than nuclear recoils



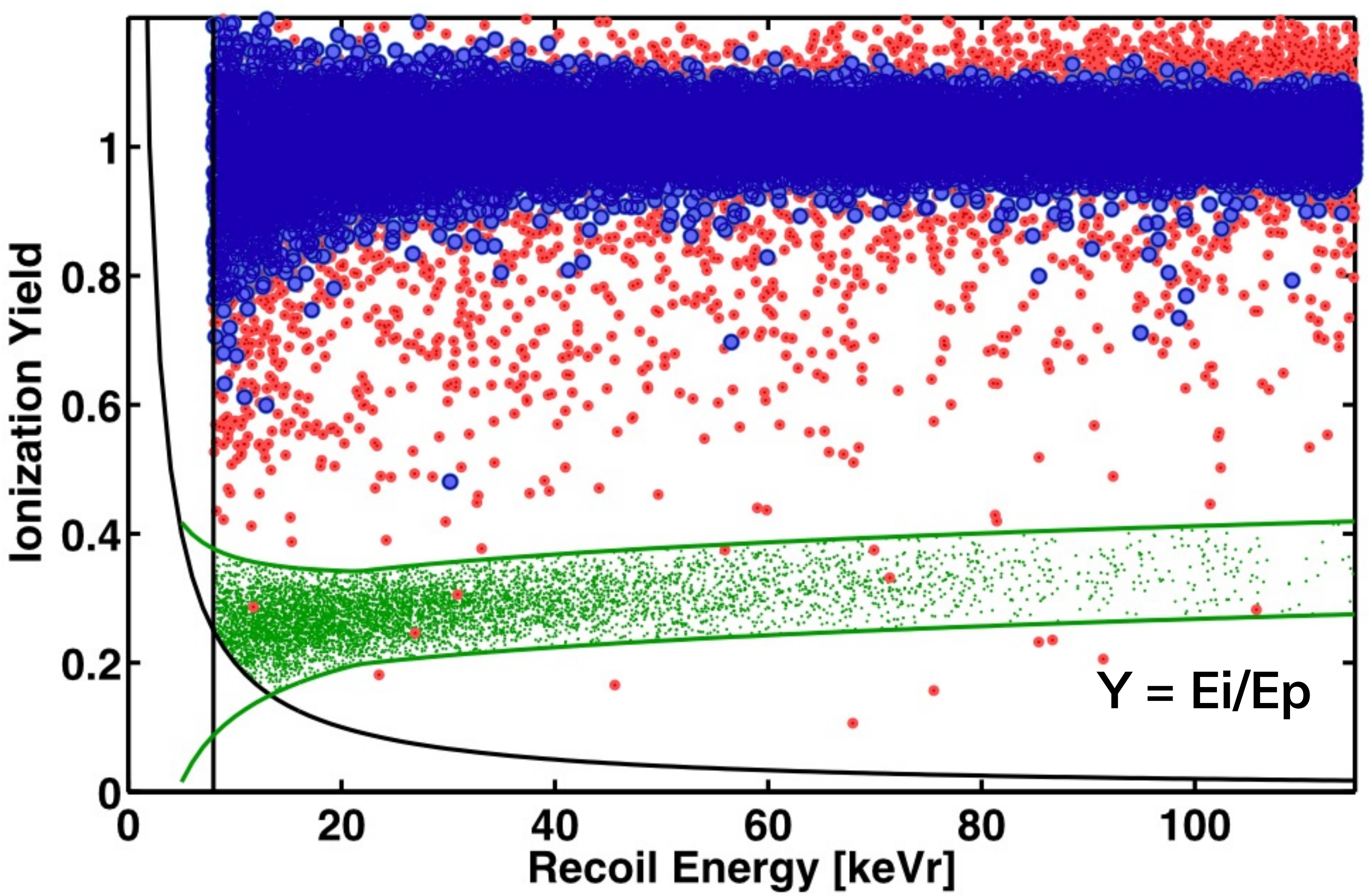
γ : ^{133}Ba calibration

n: ^{252}Cf calibration

iZIP Technology

Background Discrimination

Electron recoils have a **higher ionization yield** than nuclear recoils
Surface events have a **reduced ionization yield** and can mimic nuclear recoils



γ : ^{133}Ba calibration

^{133}Ba surface events

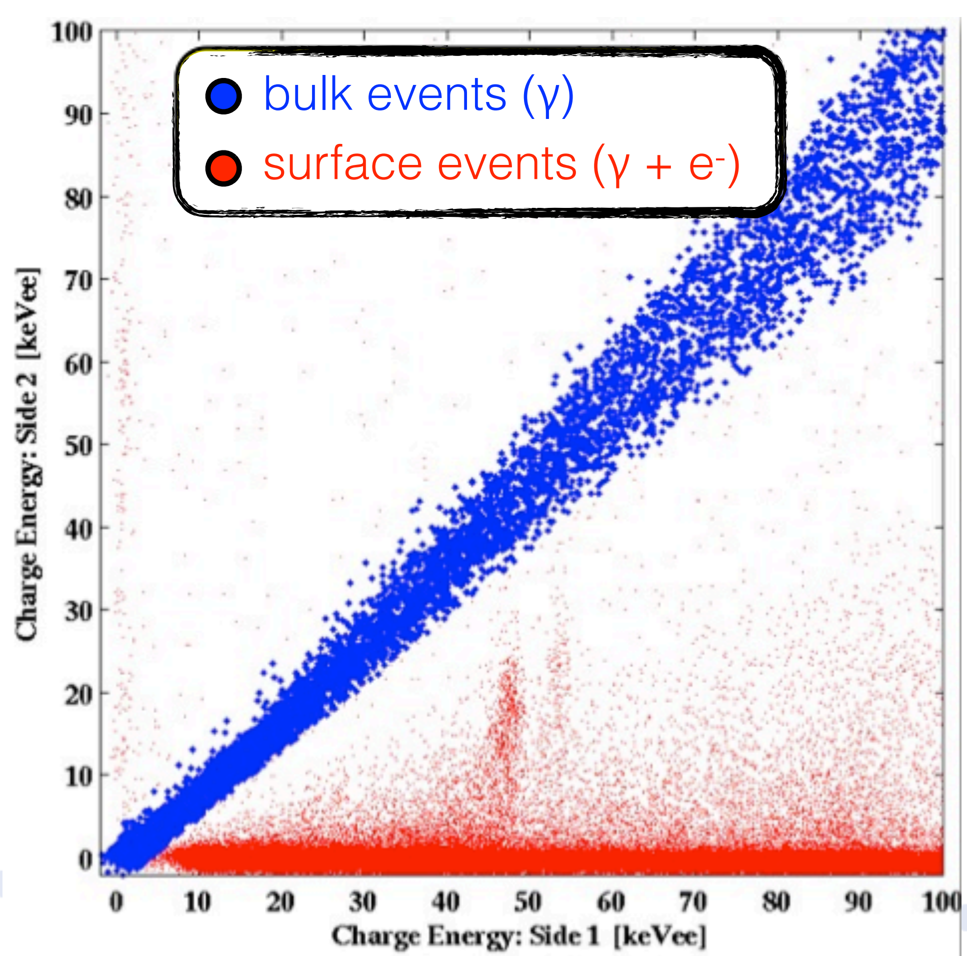
n: ^{252}Cf calibration

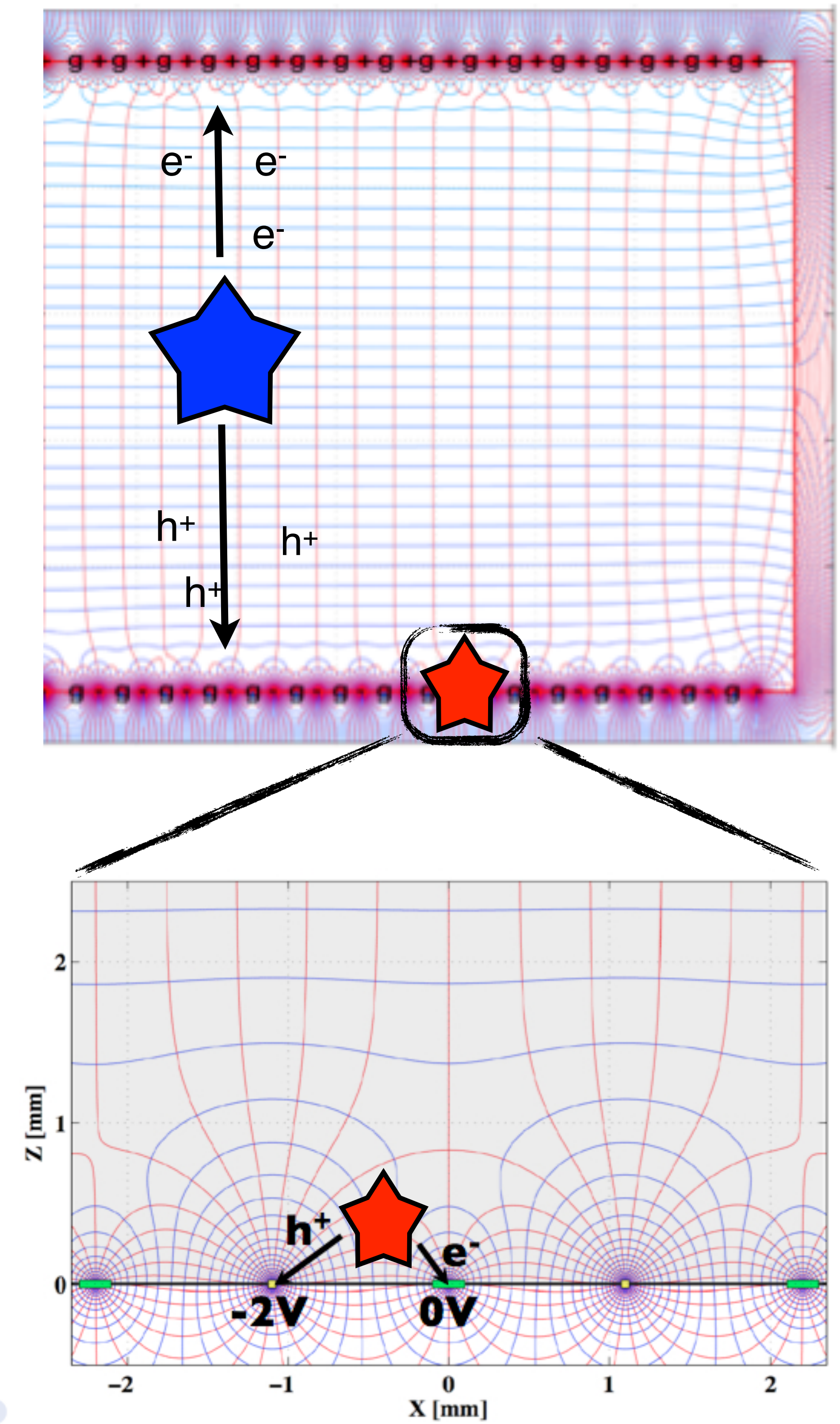
Bulk Events:

Equal but opposite ionization signal appears on both sides of each detector (symmetric)

Surface Events:

Ionization signal appears on one detector side (asymmetric)



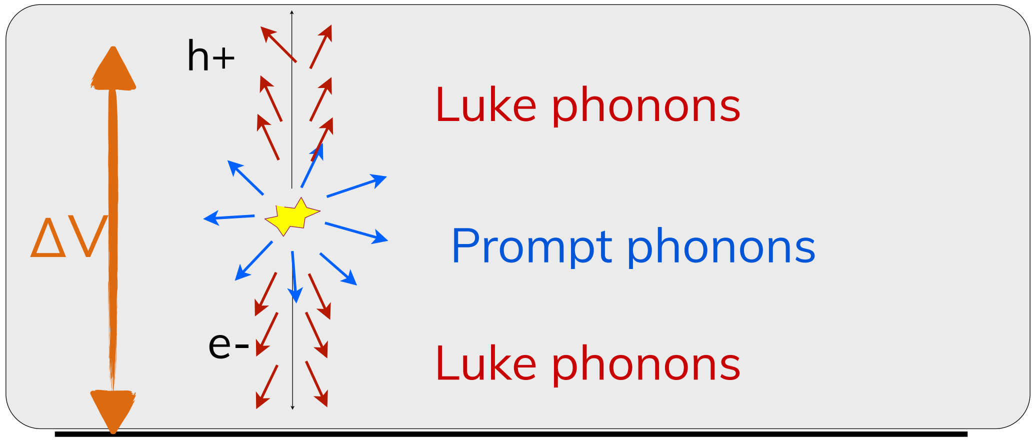


HV Technology

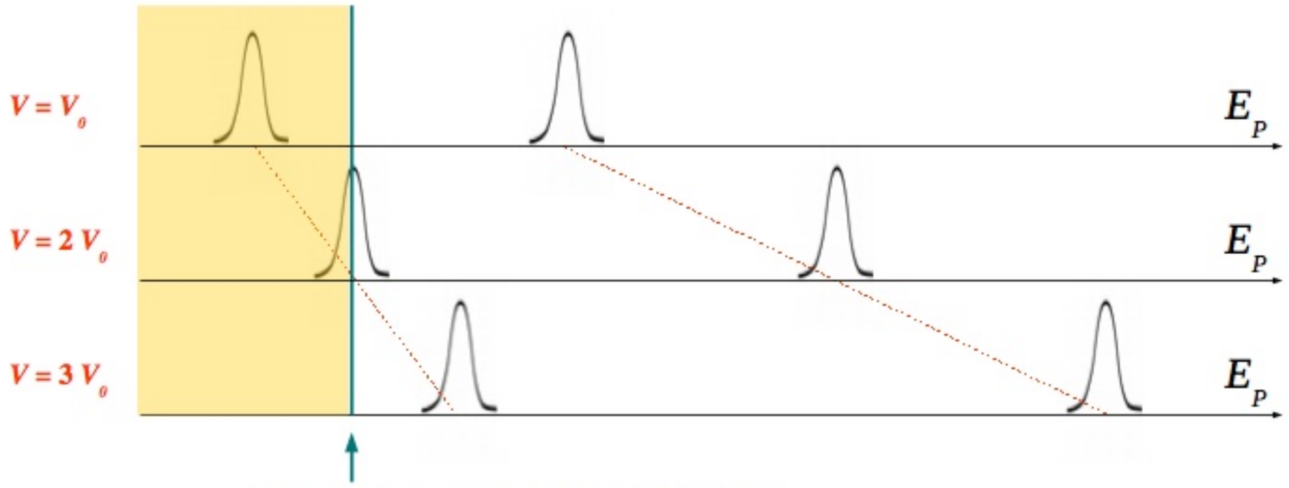
Low Energy Threshold

$$E_P = E_R + n_{eh} e \Delta V$$

Drifting charges produce large phonon signal proportional to ionization (Neganov-Luke Effect)



Heat signal boosted by Neganov-Luke effect (~Joule heating, factor [1+V/3] for Ge, factor [1+V/3.8] for Si)



Note that only E_P can be amplified, but not n_{eh}

Particle identification & fiducialisation compromised, ER reconstruction requires assumptions on Yield

Detectors Advantages

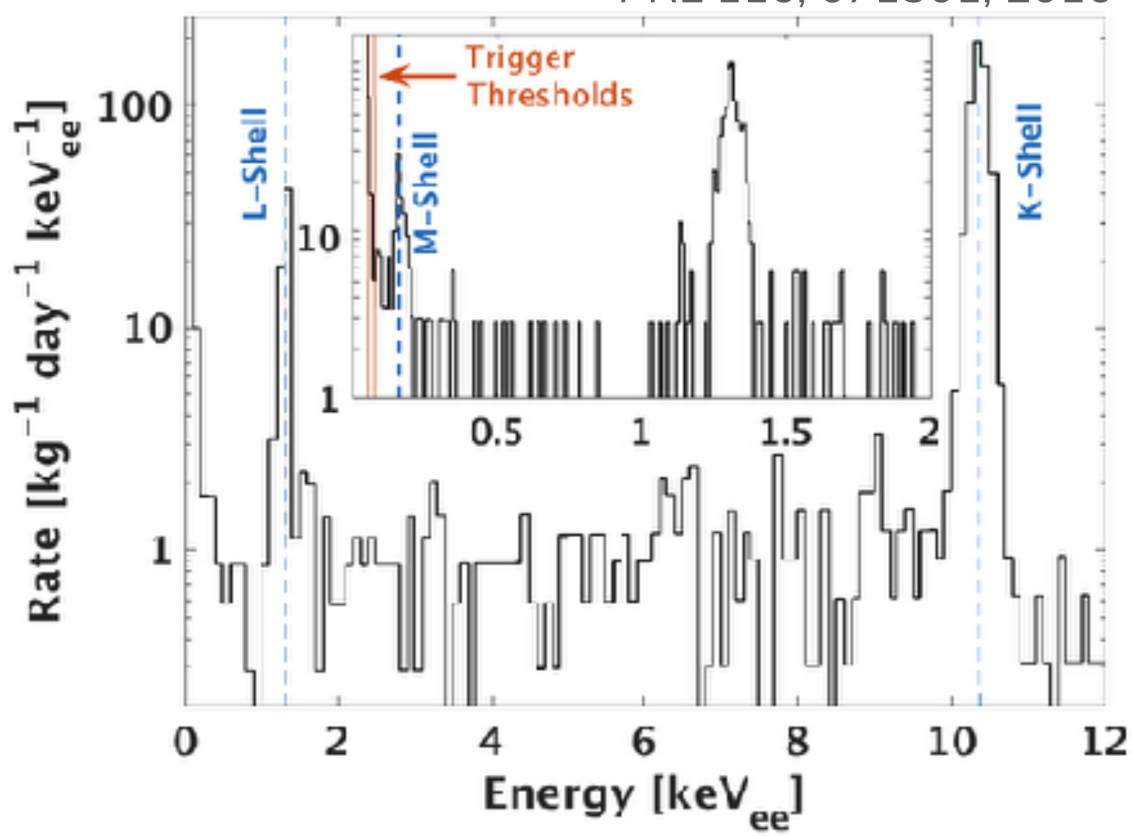
iZIP Detector
(10 Ge, 2 Si)
heat+ionization

ER/NR discrimination
Full fiducialisation
M_{DM} >5GeV/c²

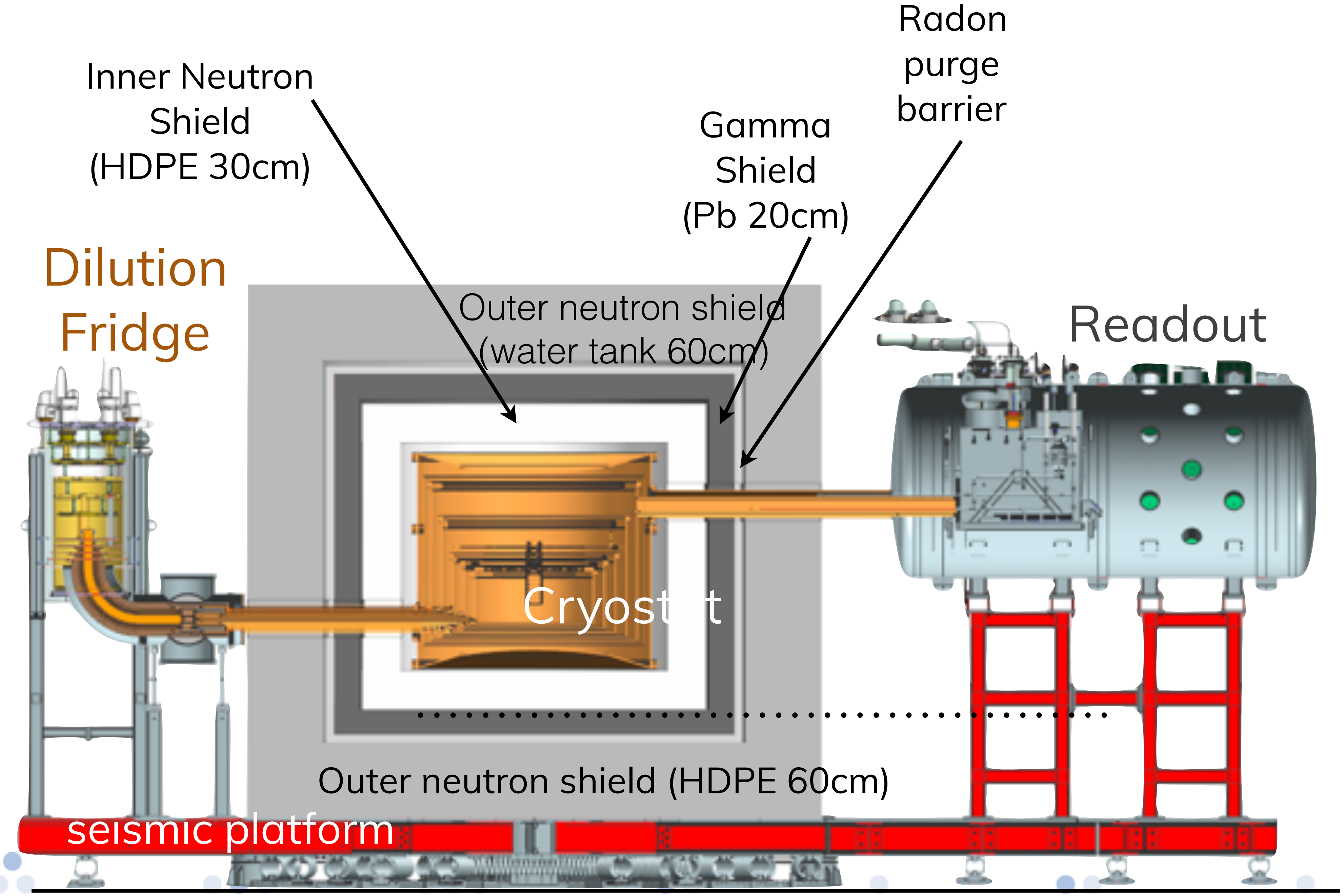
HV Detector
(8 Ge, 4 Si)
~~heat~~+ionization

Radial fiducialisation
Lower thresholds
(75 eV_{ee} and 56 eV_{ee})
M_{DM} <5GeV/c²

PRL 116, 071301, 2016



SuperCDMS SNOLAB



Initial payload of 4 towers, each w/6 detectors:

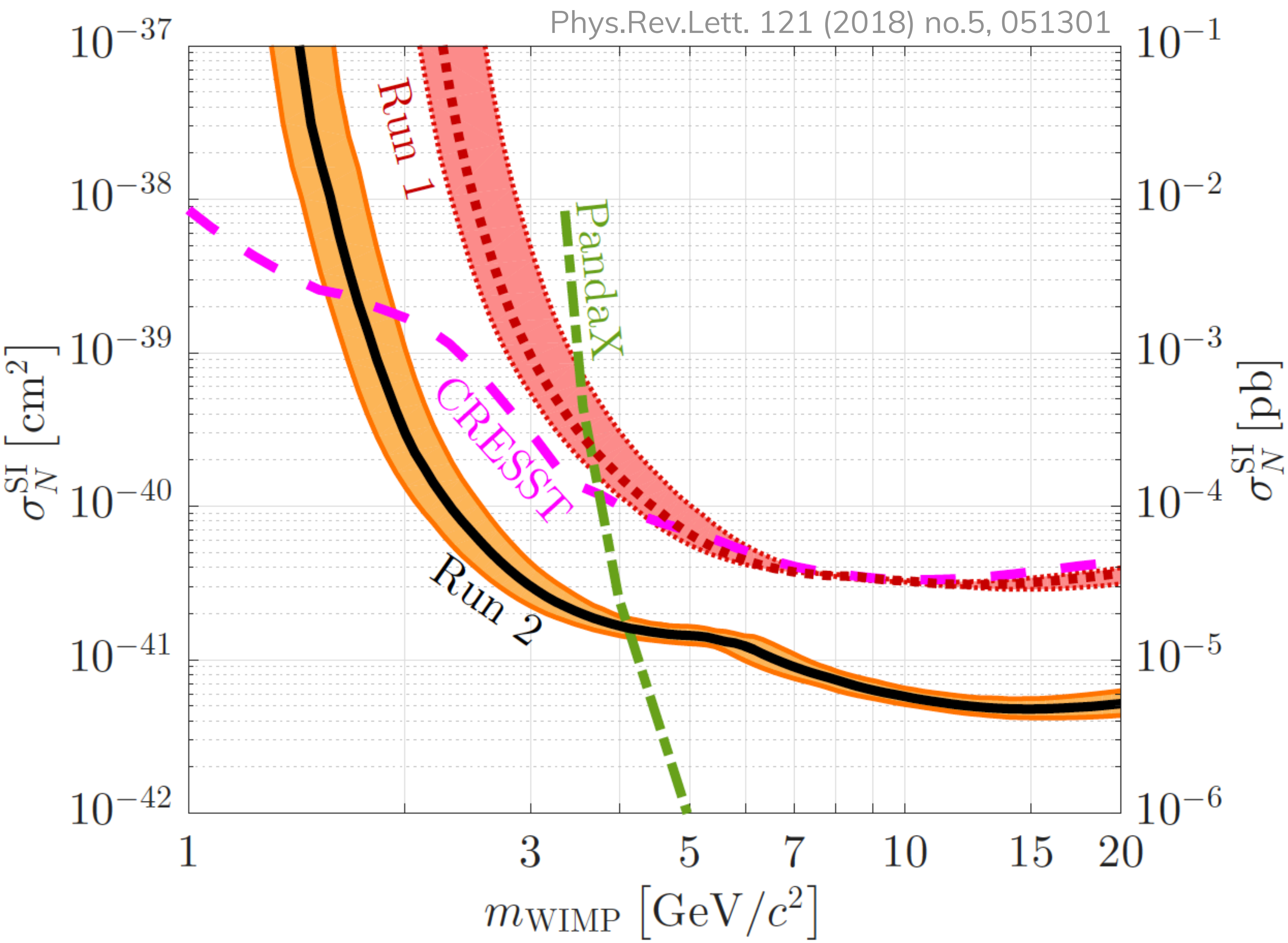
2 HV Towers

(4 Ge + 2 Si)

2 iZIP Towers

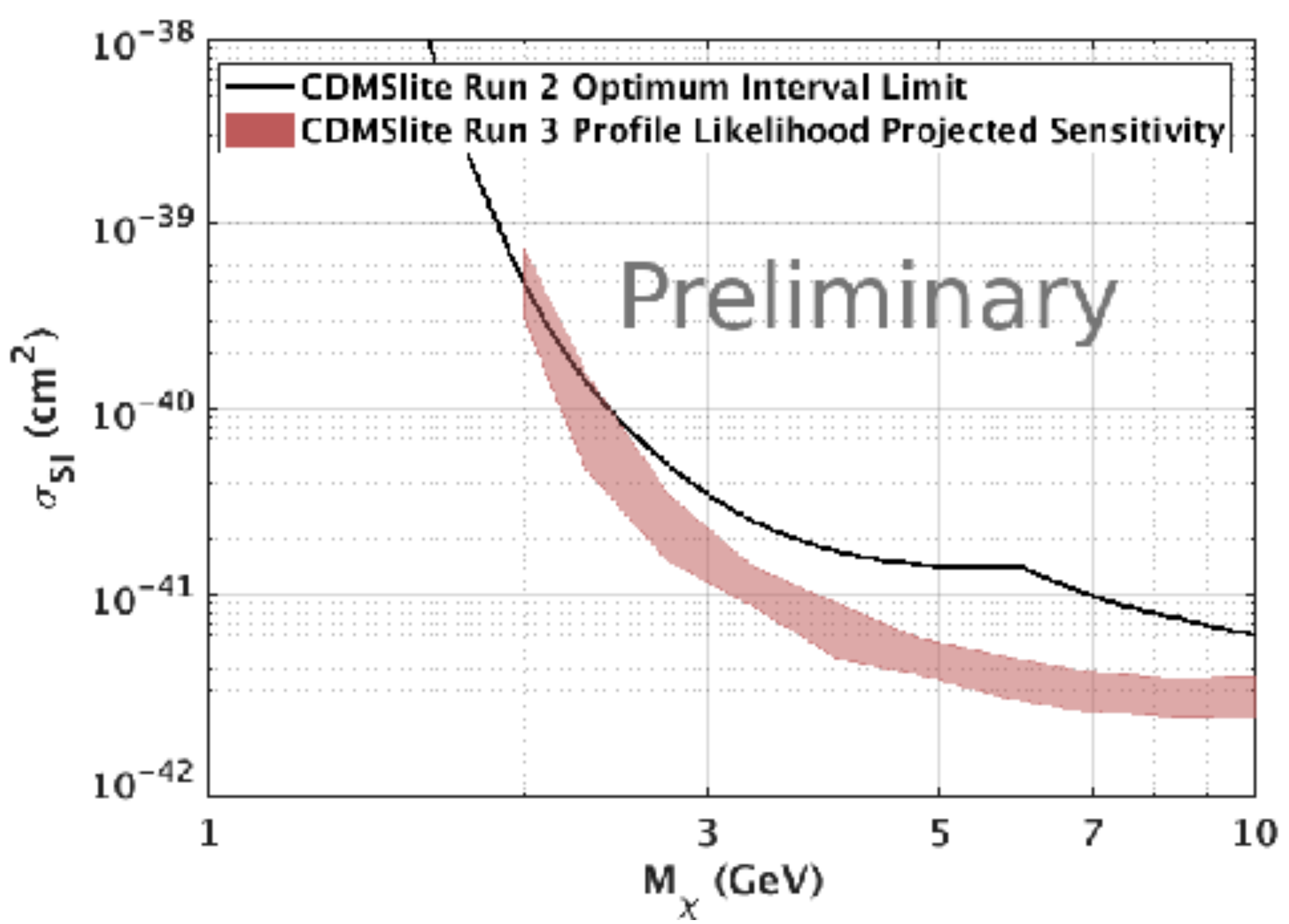
(6 Ge & 4 Ge + 2 Si)

CDMSLite (HV) - Recent Results



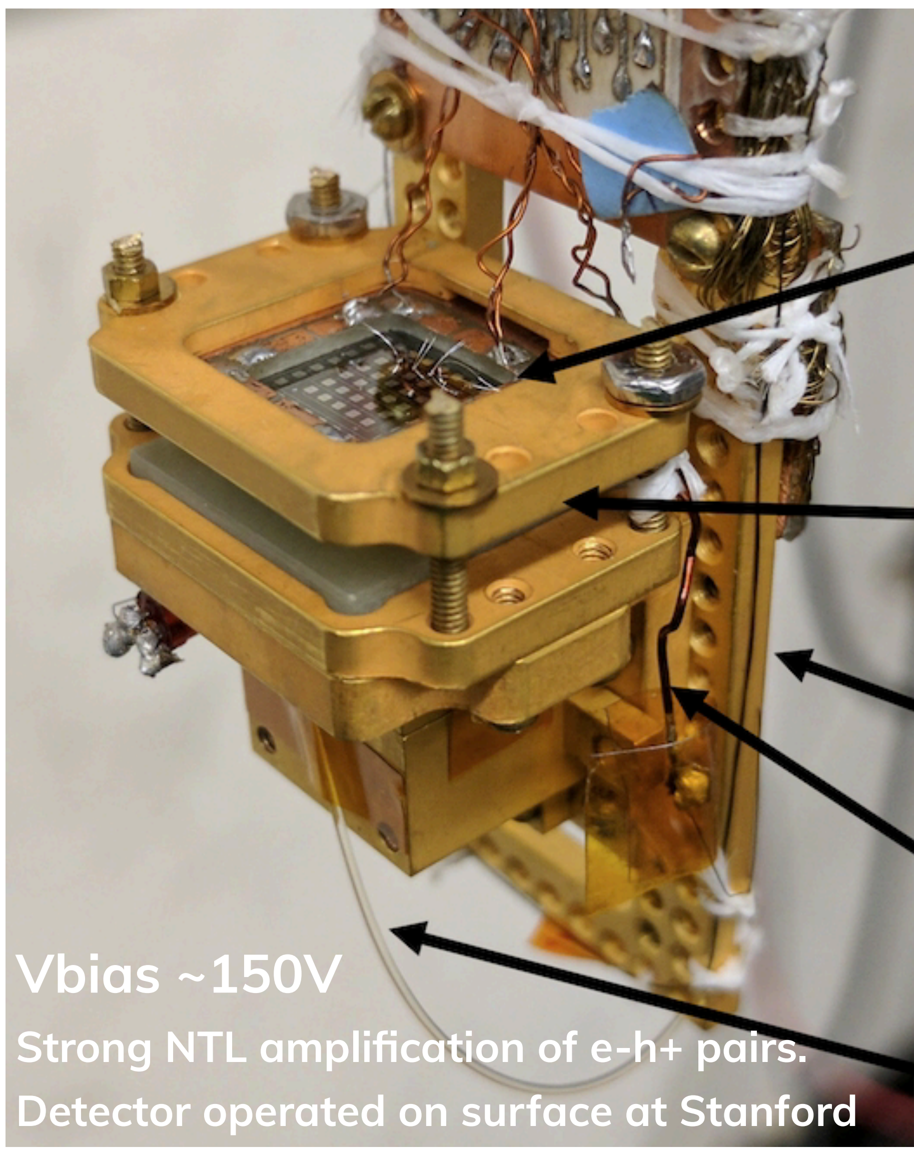
CDMSLite (HV) - Run3

- 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



Prototype HVeV Detector

Appl. Phys. Lett. 112, 043501



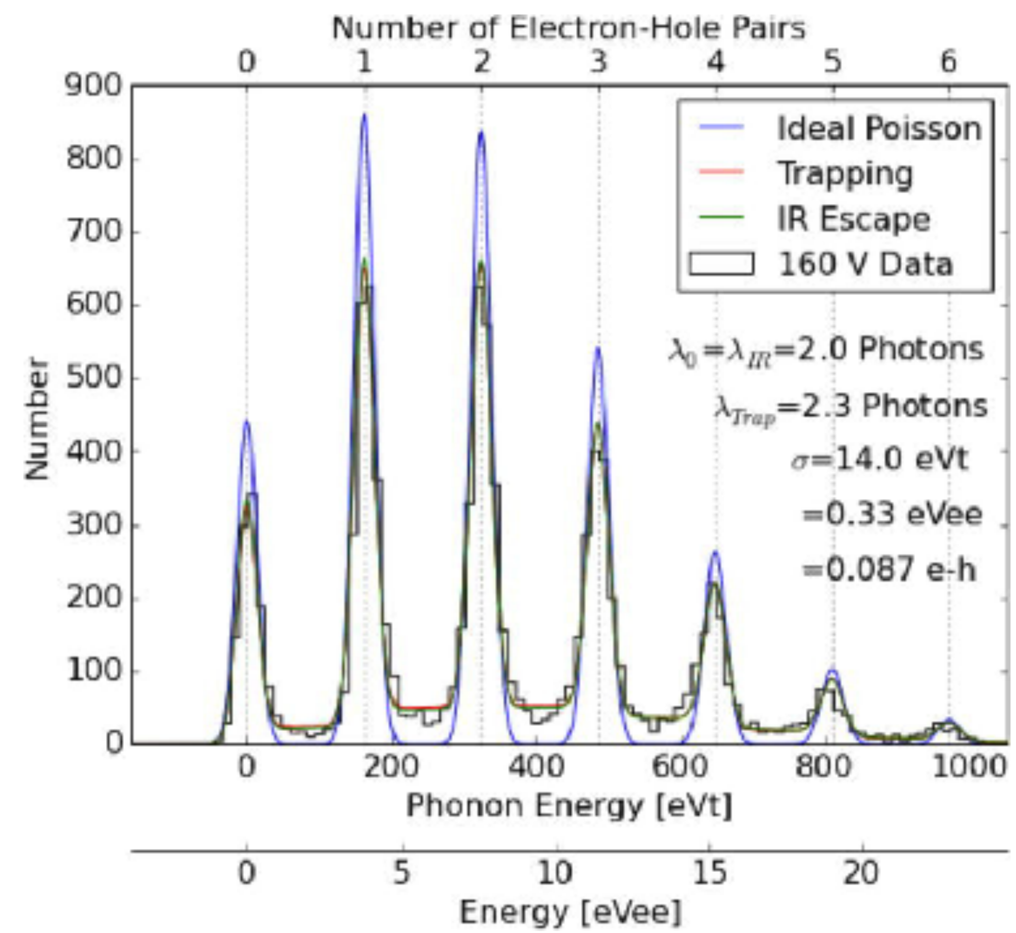
Si crystal/ phonon sensors

Crystal holder

Dilution refrigerator sample stage (3mK)

Bias voltage line

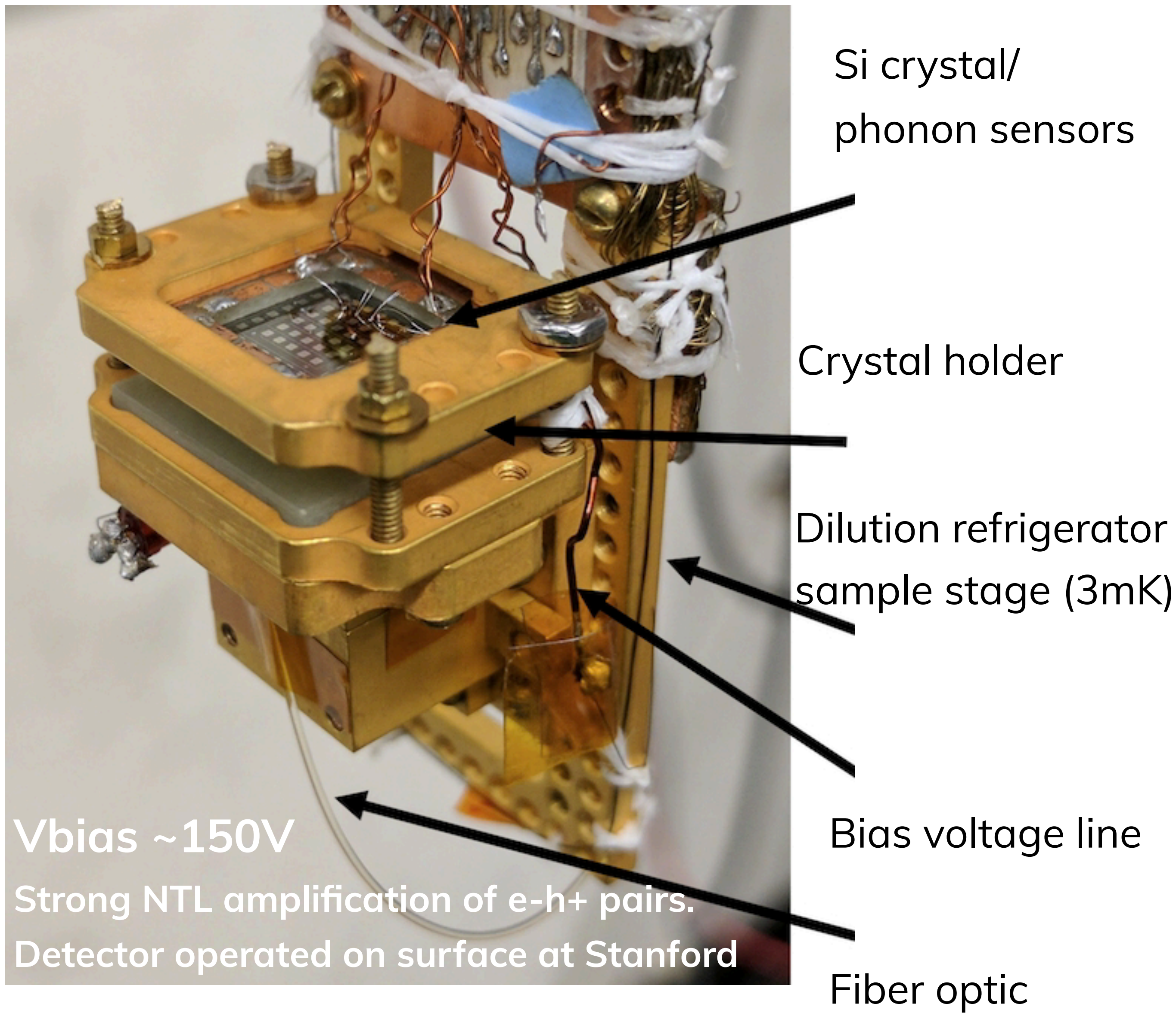
Fiber optic



Single e/h-pair sensitivity has been recently demonstrated in 0.93 g Si crystal

Sensitivity to a variety of sub-GeV DM models with g*d exposures

Prototype HVeV Detector

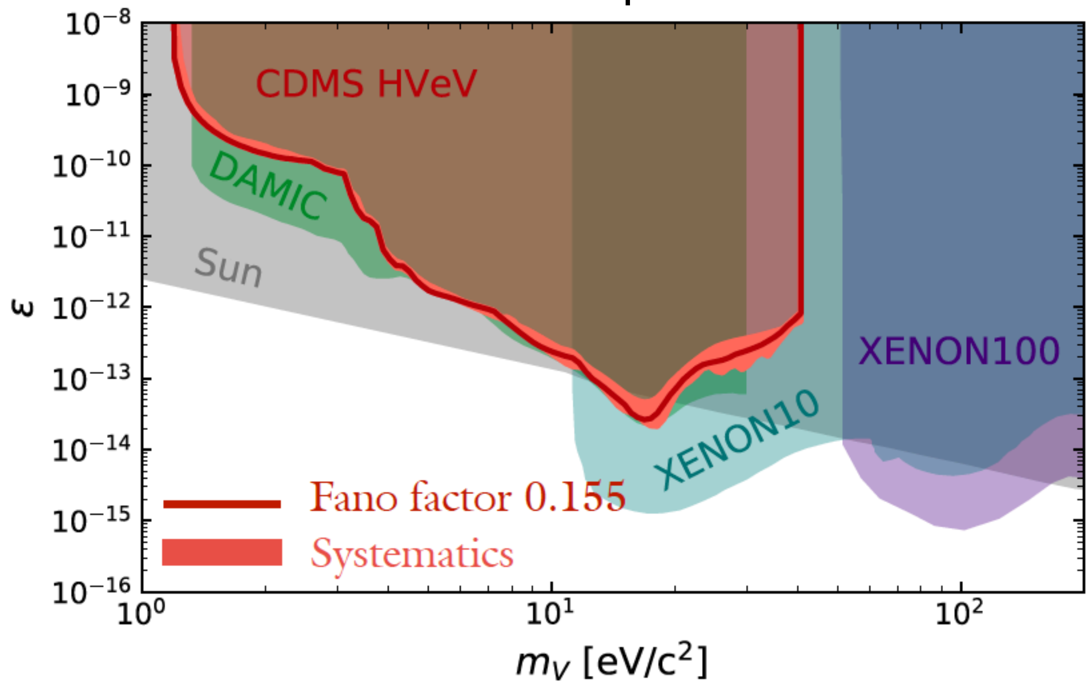


Phys. Rev. Lett. 121, 051301 (2018)

- 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: σ_{ph} ~ 14 eV
    - charge resolution: σ_{eh} ~ 0.1 e-h+
- Calibrations with in-run monochromatic 650 nm laser (1.91 eV photons).
- Data selection criteria were applied to remove periods of poor detector performance.

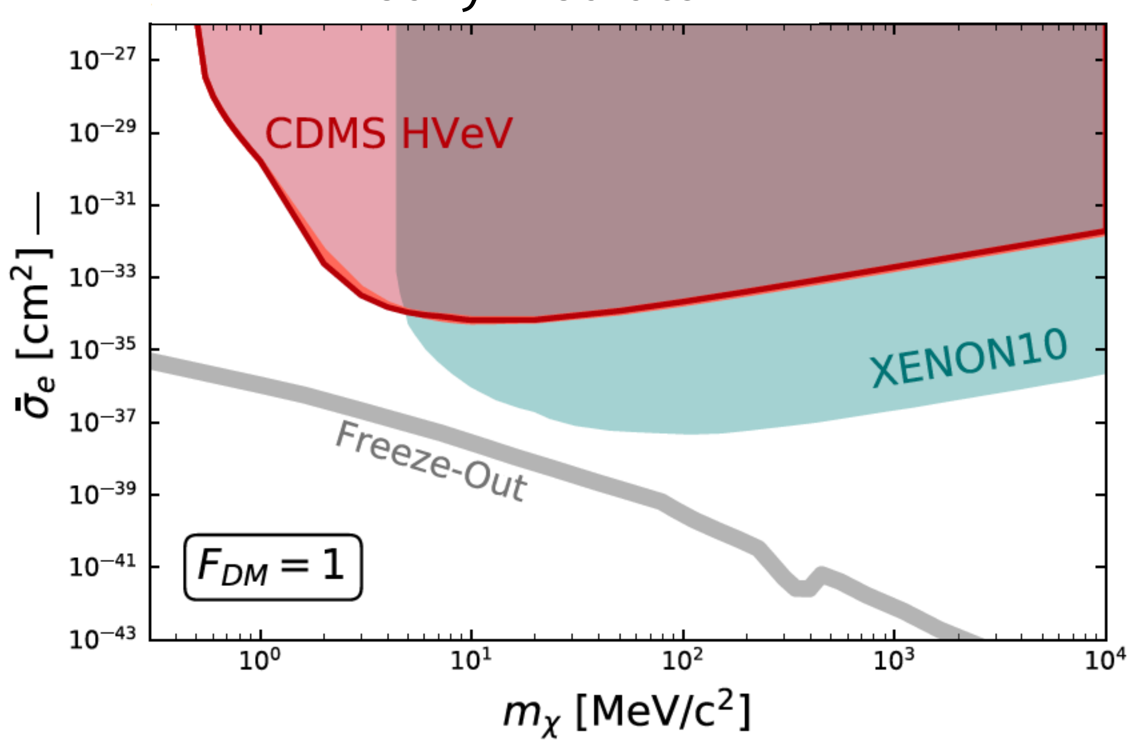
Phys. Rev. Lett. 121, 051301 (2018)

Dark Photon Absorption

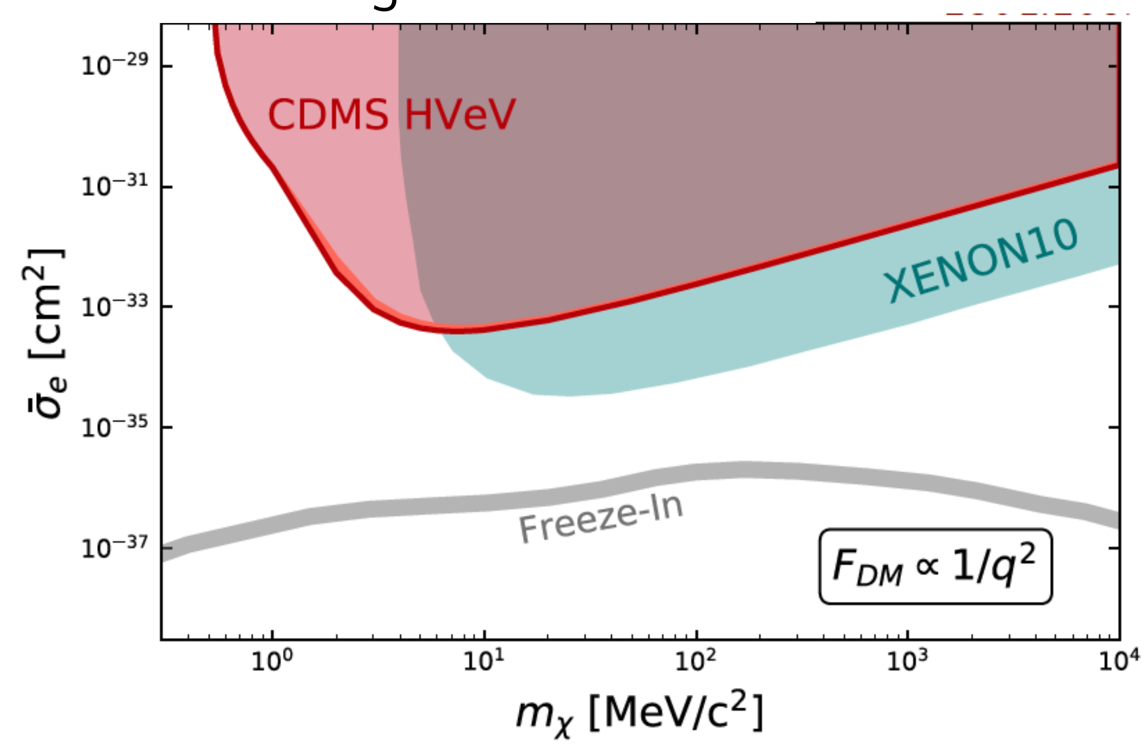


- 90% CL w/o background subtraction using optimum interval method.
- Systematics include varying Fano factor, and uncertainties in photoelectric cross section

ERDM Heavy Mediator



ERDM Light Mediator




CRESST

CRESST Detector

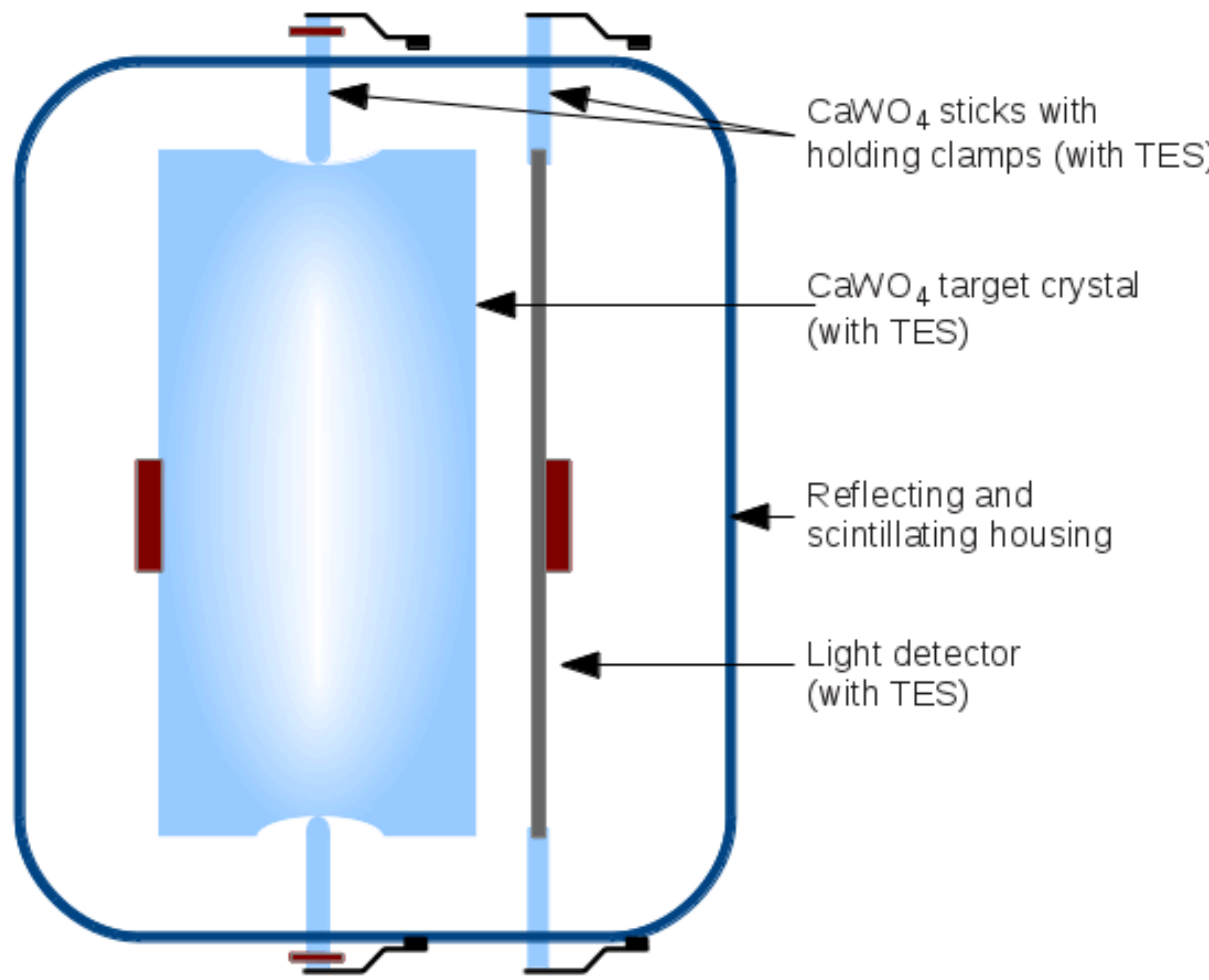
Technique: Heat+Scintillation

Scintillating $CaWO_4$ crystals as target

Target crystals operated as cryogenic calorimeters (~15mK)

Collect both phonon and scintillating signals.

- Tungsten TES reads out phonon signal
- Light absorber (Si on sapphire) collects scintillation signal.

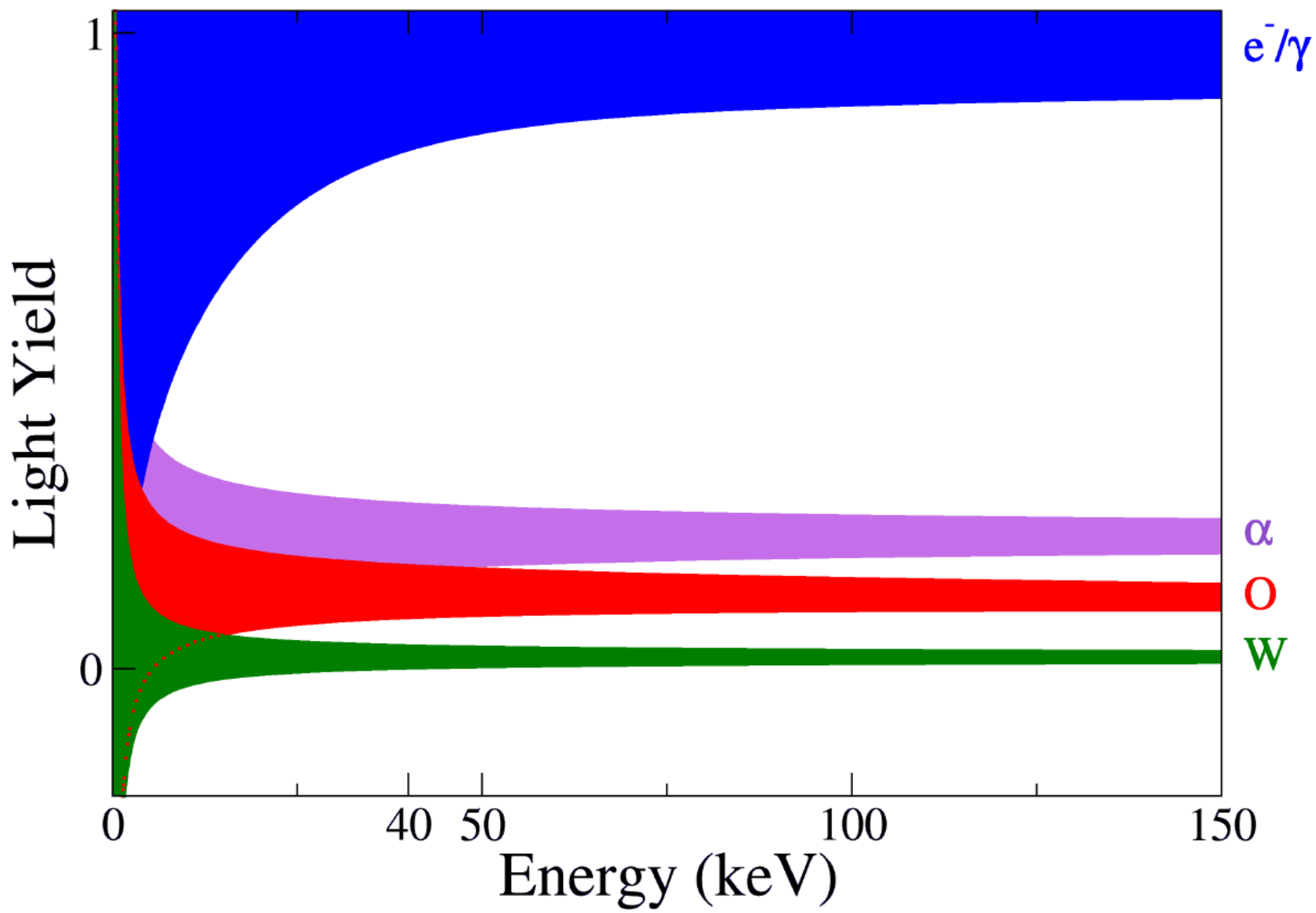


Particle Identification

Technique: Heat+Scintillation

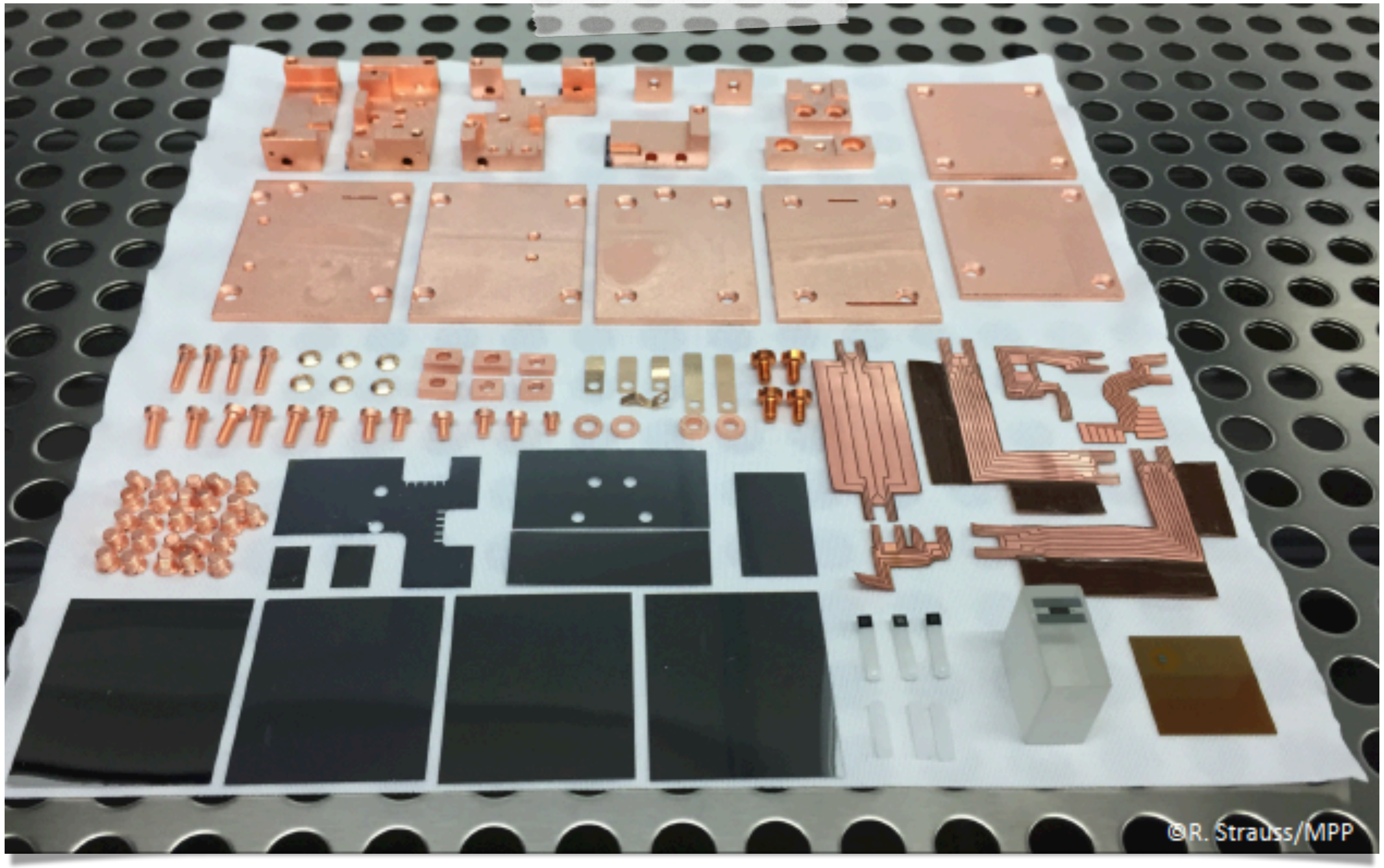
The scintillation light is particle dependent

Discrimination between
- Electron recoils (radioactive background)
- Nuclear recoils (potential DM signal)



CRESST Detector

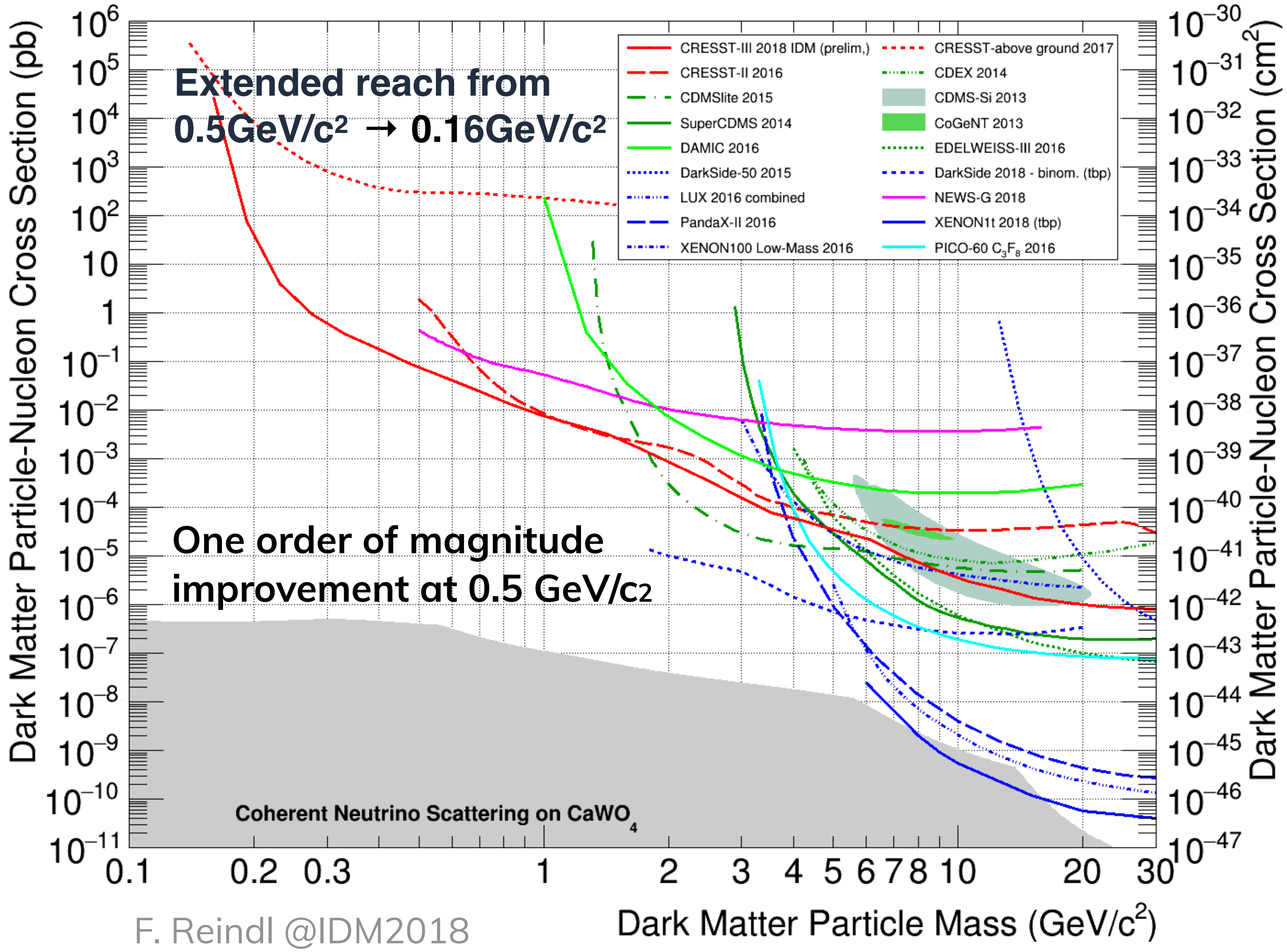
Technique: Heat+Scintillation



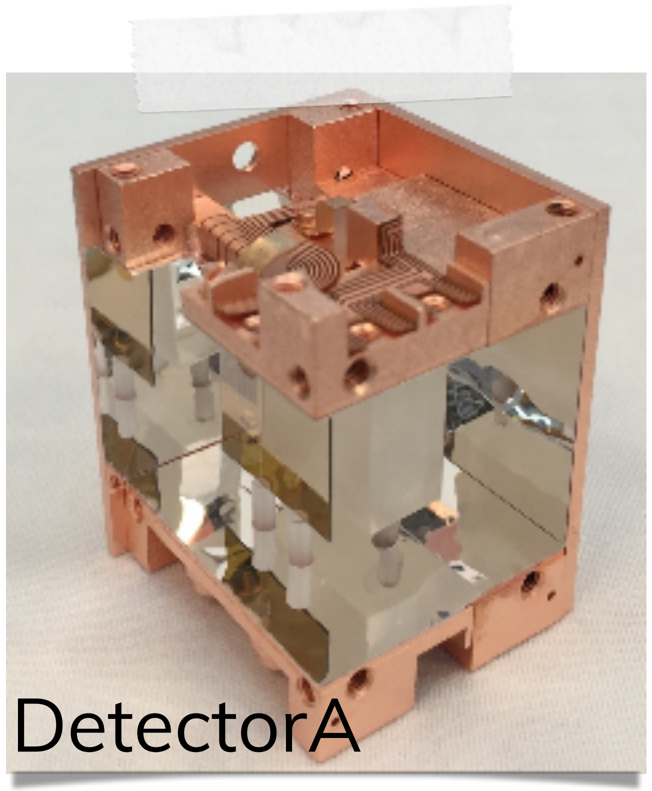
- Cuboid crystal (20 mm x 20 mm x 10 mm) ~ 24 g
- Goal: detection threshold of **100 eV**
- Self-grown crystal with low total background of ~**3 dru** [1-40 keV]
- Veto against surface related background: **fully scintillating housing** and instrumented sticks (“iSticks”)

Results - Detector A

Technique: Heat+Scintillation



F. Reindl @IDM2018



Data taking period: 10/16 –01/18

Target crystal mass: 24g

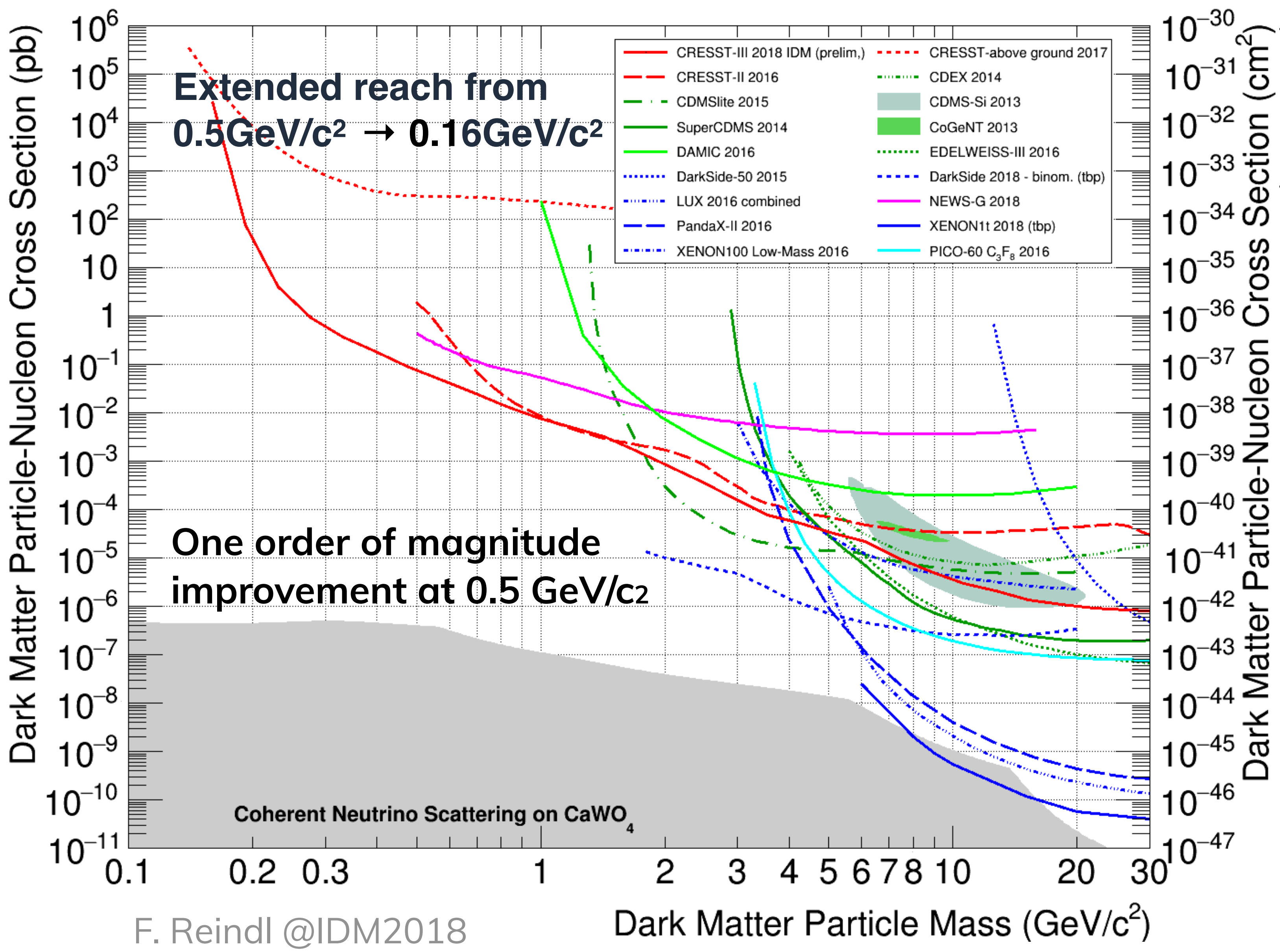
Gross exposure: 5.7 kg days

Nuclear recoil threshold: 30.1 eV

Results - Detector A

Technique: Heat+Scintillation

F. Reindl @IDM2018



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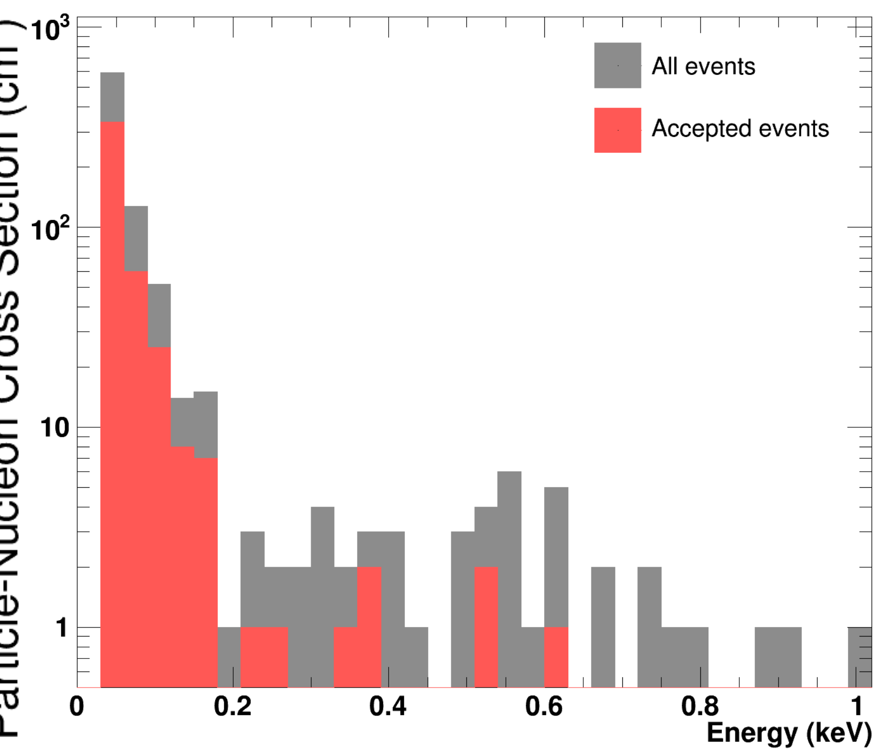
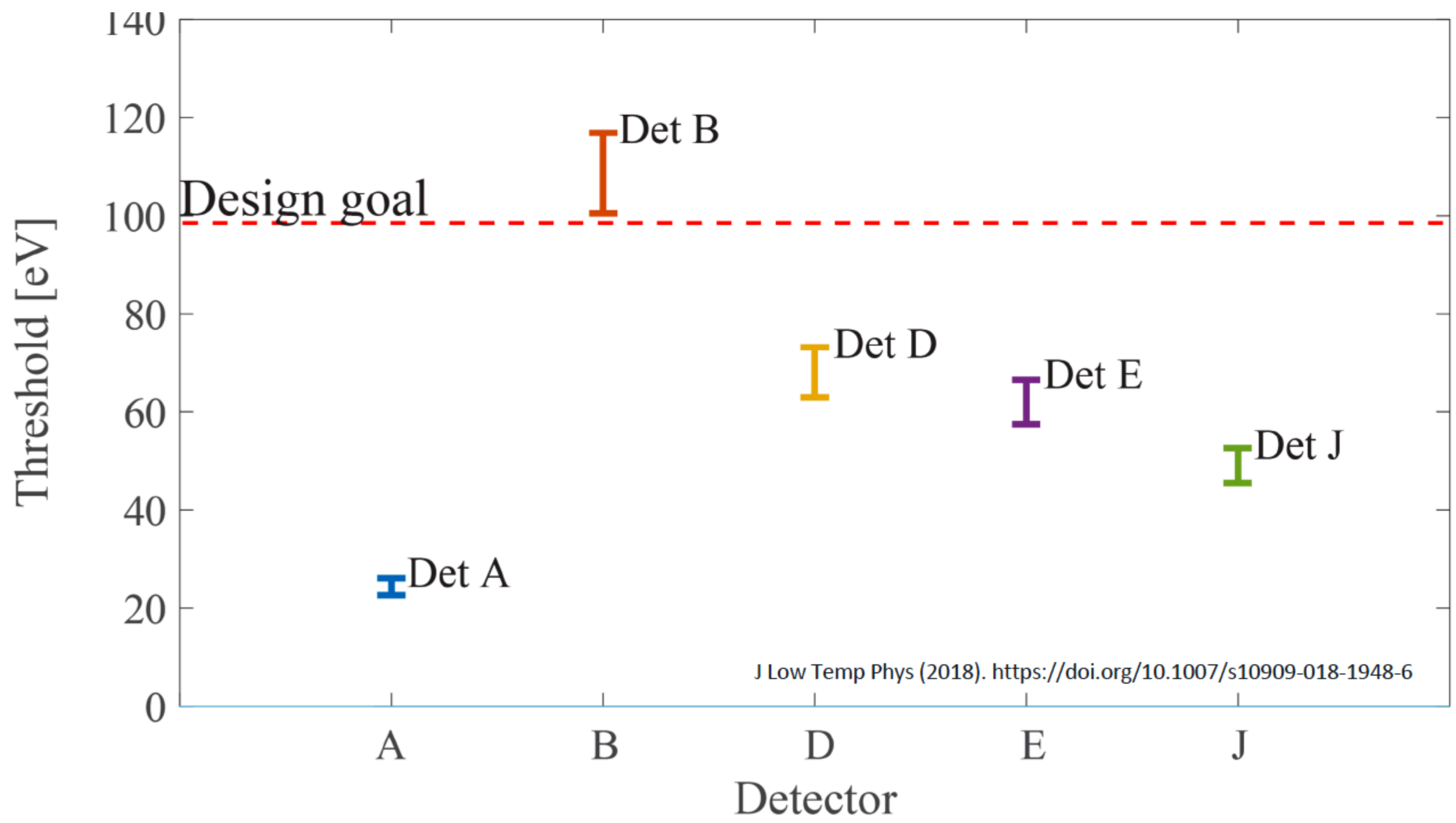


Unexpected rise of event rate < 200eV

CRESST Outlook

Continue data taking
—> better understanding of backgrounds

Three more detectors with threshold ≪ 100eV

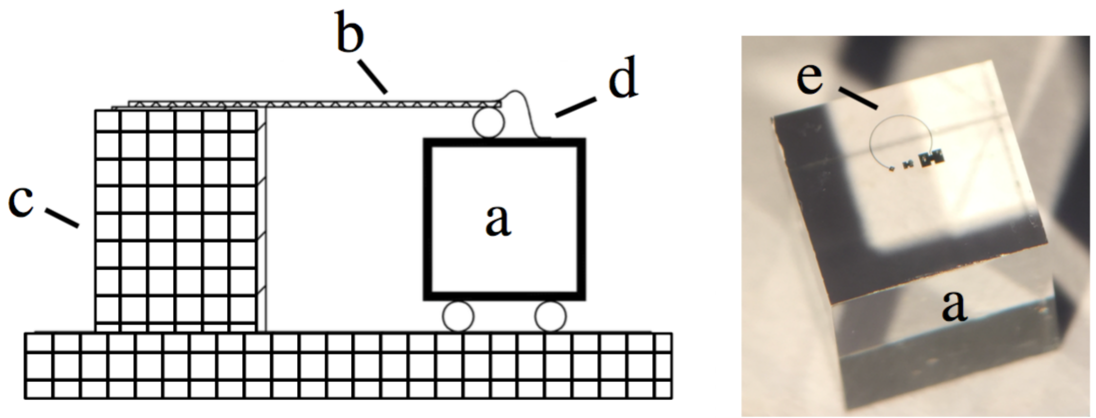


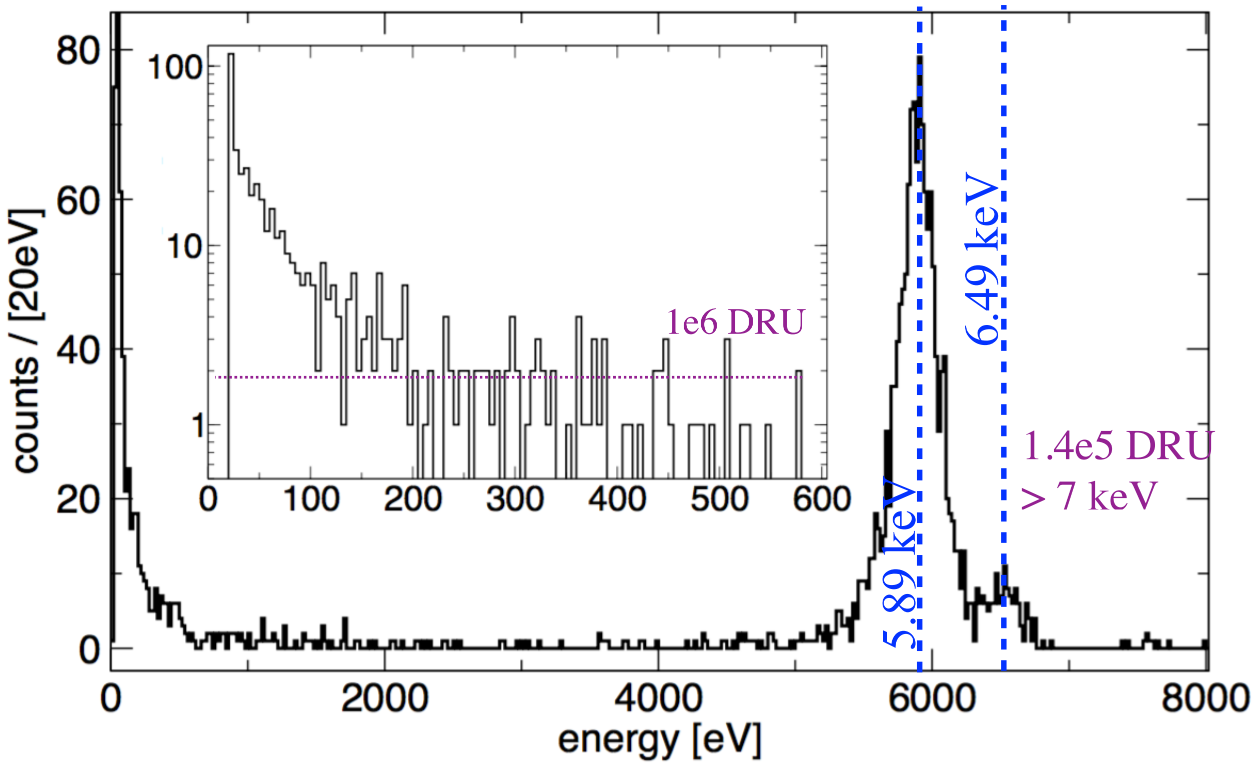
CRESST Detector

Technique: Heat Only

Detector layout optimized for **VERY low threshold**, further reduction of dimensions:

- Cuboid Al_2O_3 crystals (5 x 5 x 5) mm^3 ~ **0.49 g** with no light detector (**no particle identification**)
- Dedicated to CENNS science at nuclear reactors: NuCleus
- Achieved a **19.6 eV** energy threshold
- **Above ground operation** from MPI in Munich with no passive / active shielding
- Non-blind analysis with no event selection cut, only stability cuts (62 % efficiency)





R. Strauss et al., EPJC 2017

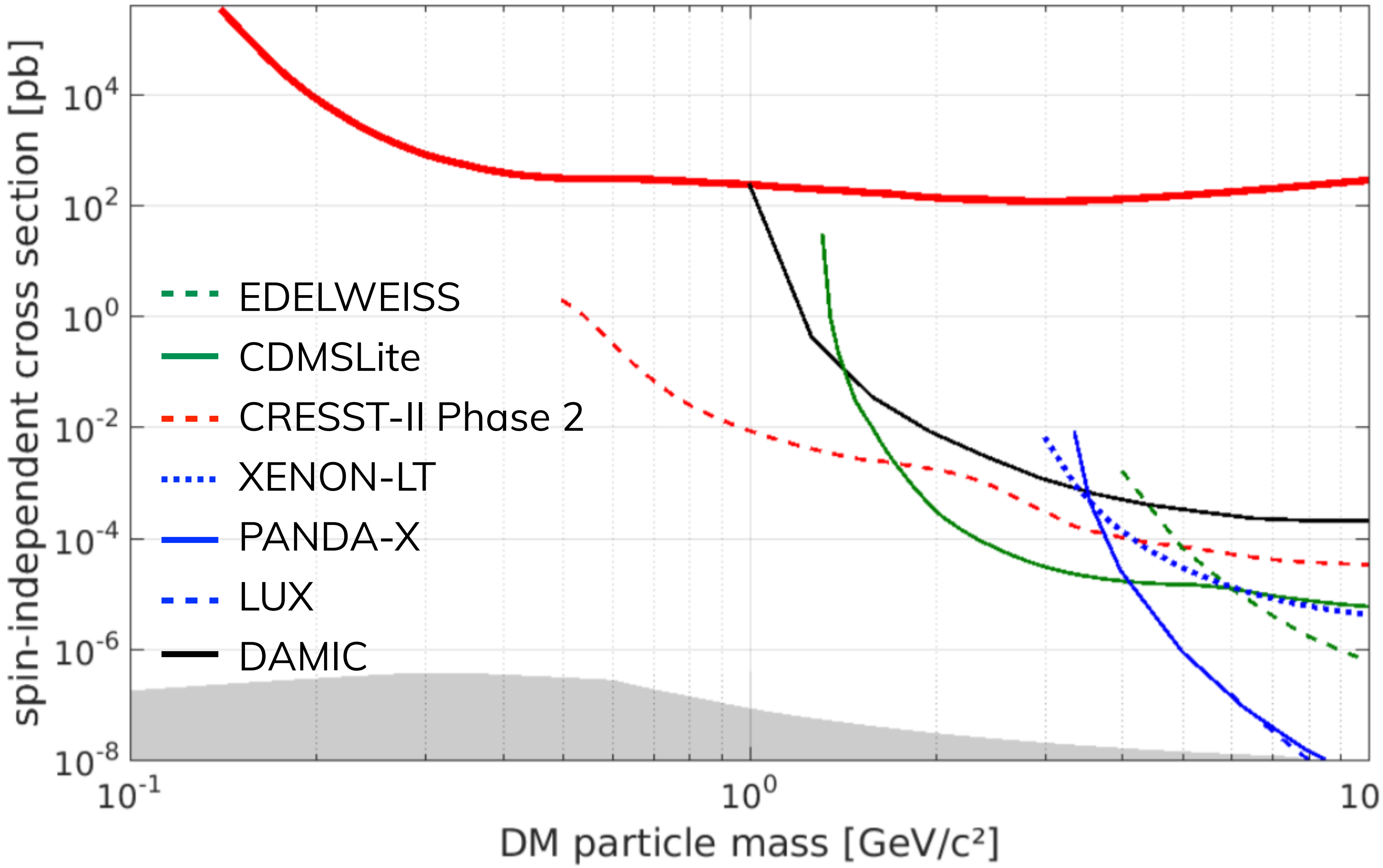
CRESST Detector

Technique: Heat Only

Leading limit from 500 MeV to 140 MeV

Above ground operation « OK »: CENNS at reactors (NuCleus)

CRESST Coll., EPJC (2017)



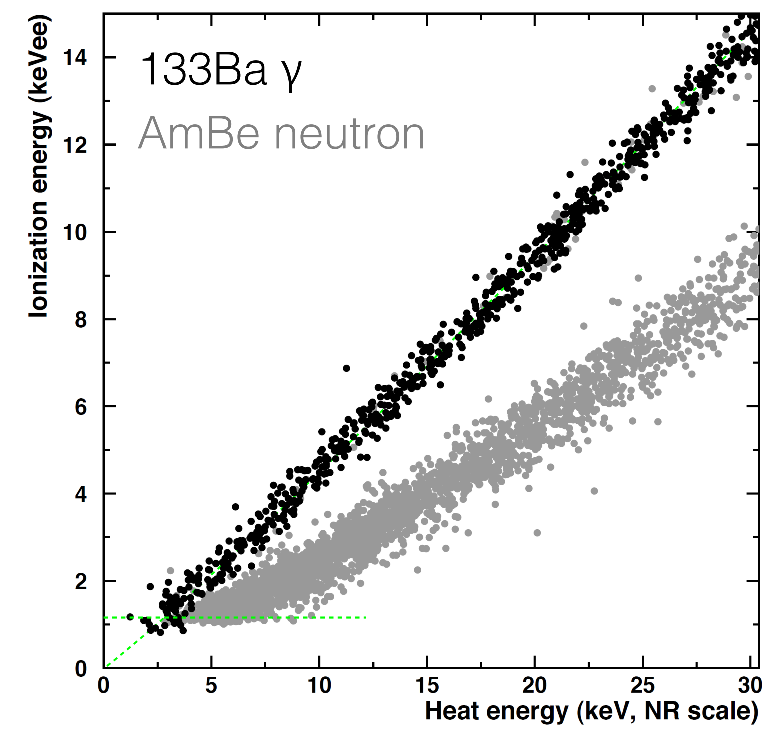

EDELWEISS III

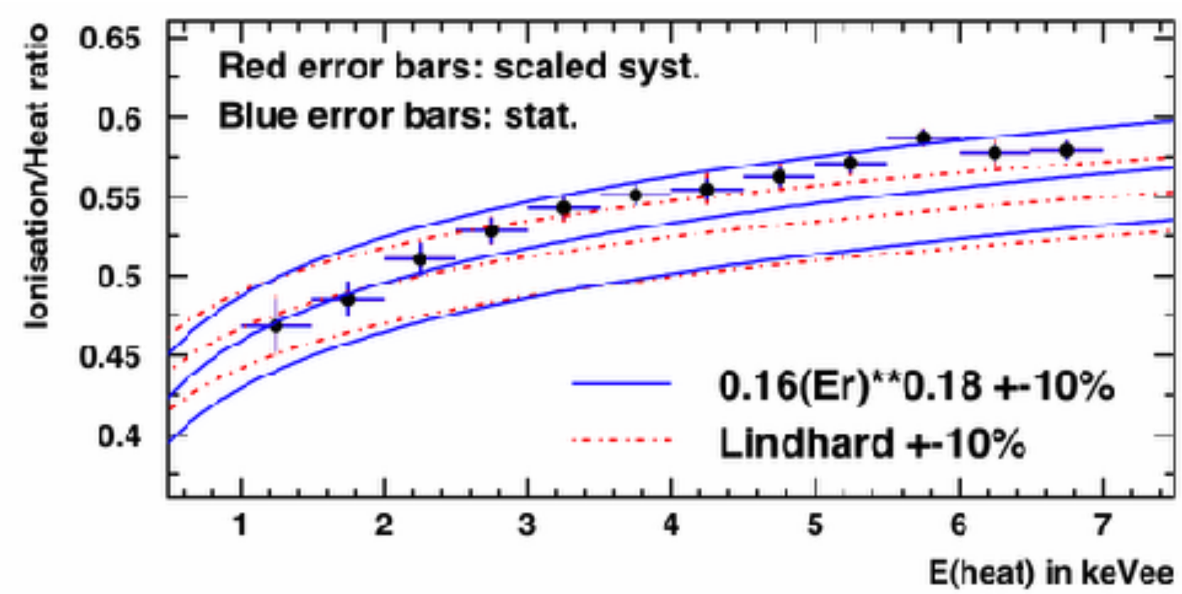
EDELWEISS Results

Robust design, good reproducibility of performances

[JINST 12 (2017) no.08, P08010]

Improved ionization resolution & thresholds lead to x40 improvement of WIMP sensitivity at ~5-10 GeV wrt EDELWEISS-II.





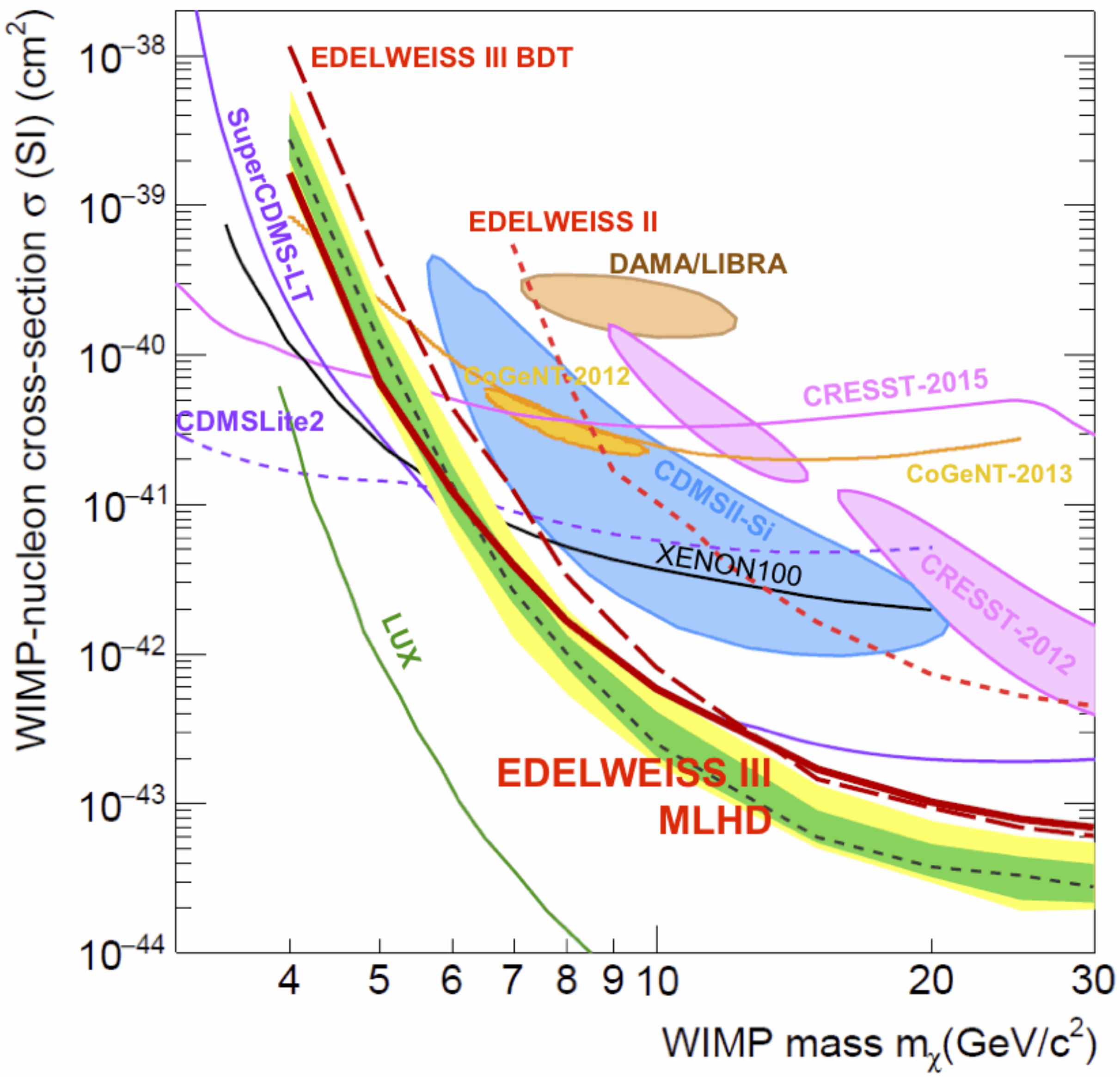
EDELWEISS Results

Robust design, good reproducibility of performances

[JINST 12 (2017) no.08, P08010]

Improved ionization resolution & thresholds lead to x40 improvement of WIMP sensitivity at ~5-10 GeV wrt EDELWEISS-II.

[JCAP05 (2016) 019] [EPJC 76 (2016) 548]

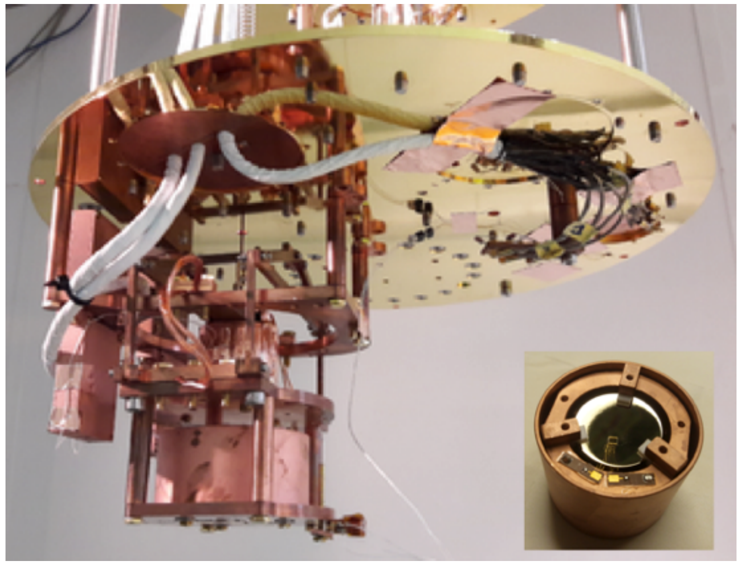


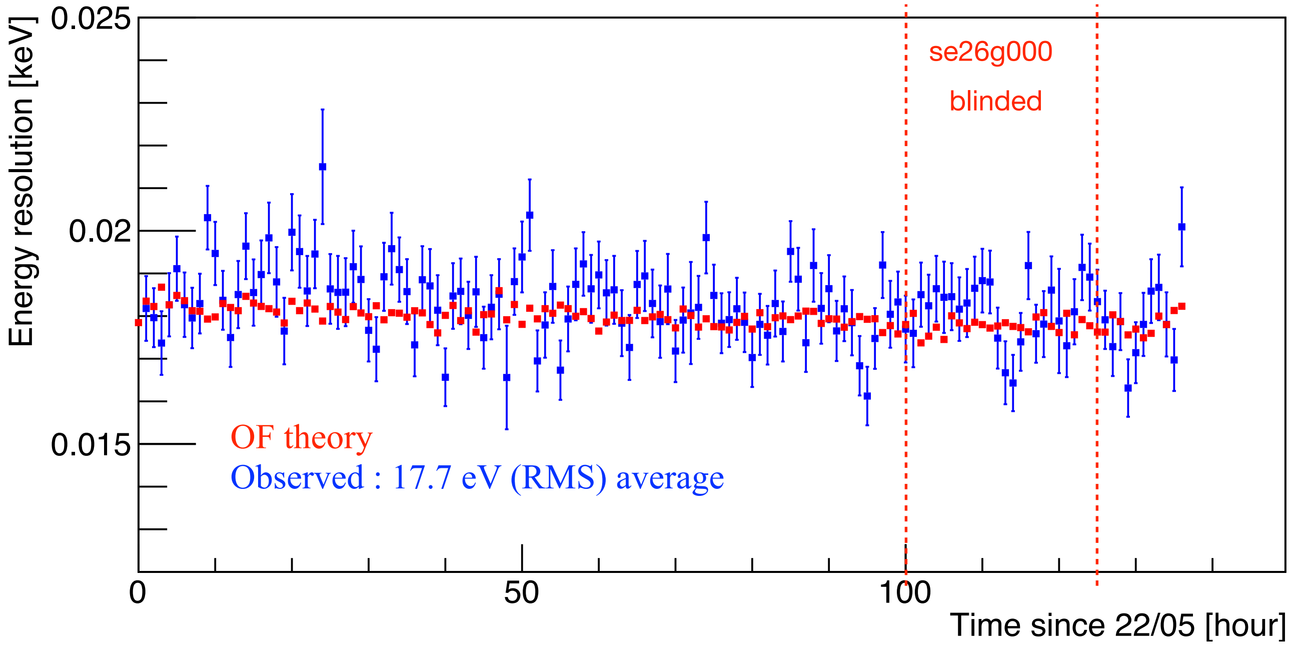
EDELWEISS-Surf

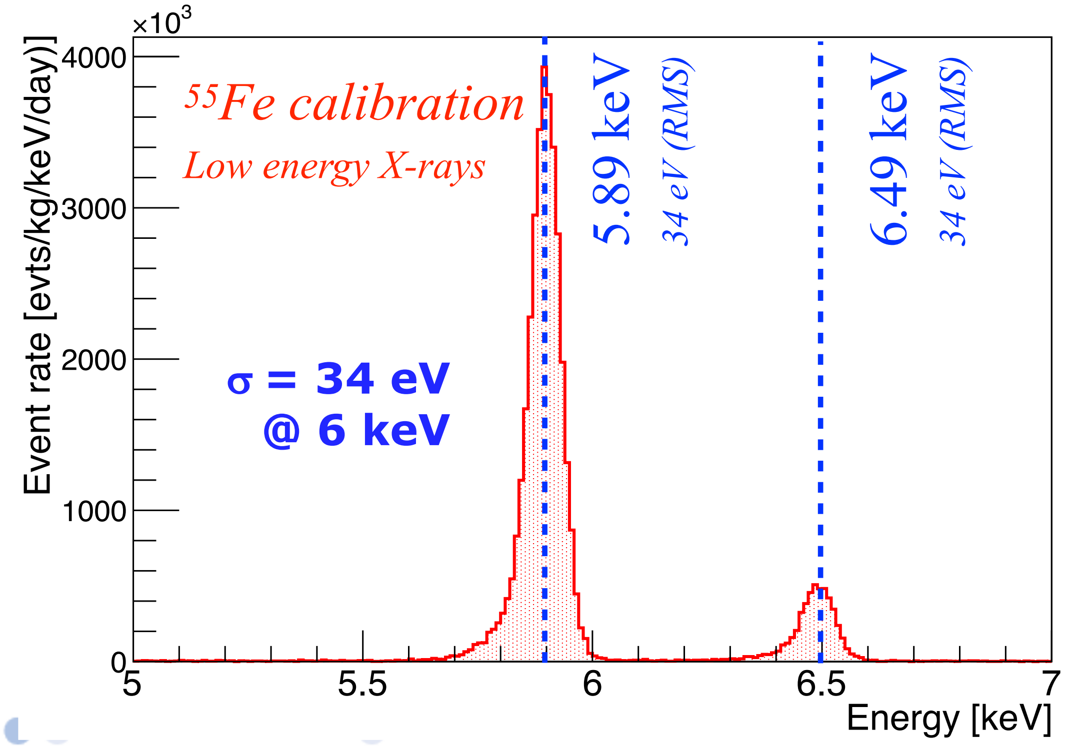
Technique: Heat Only

R&D with 32 g combined with the objective of testing the above-ground sensitivity to sub-GeV WIMPs

Kept at 17 mK in IPNL low-vibration dilution fridge [arXiv:1803.03463]







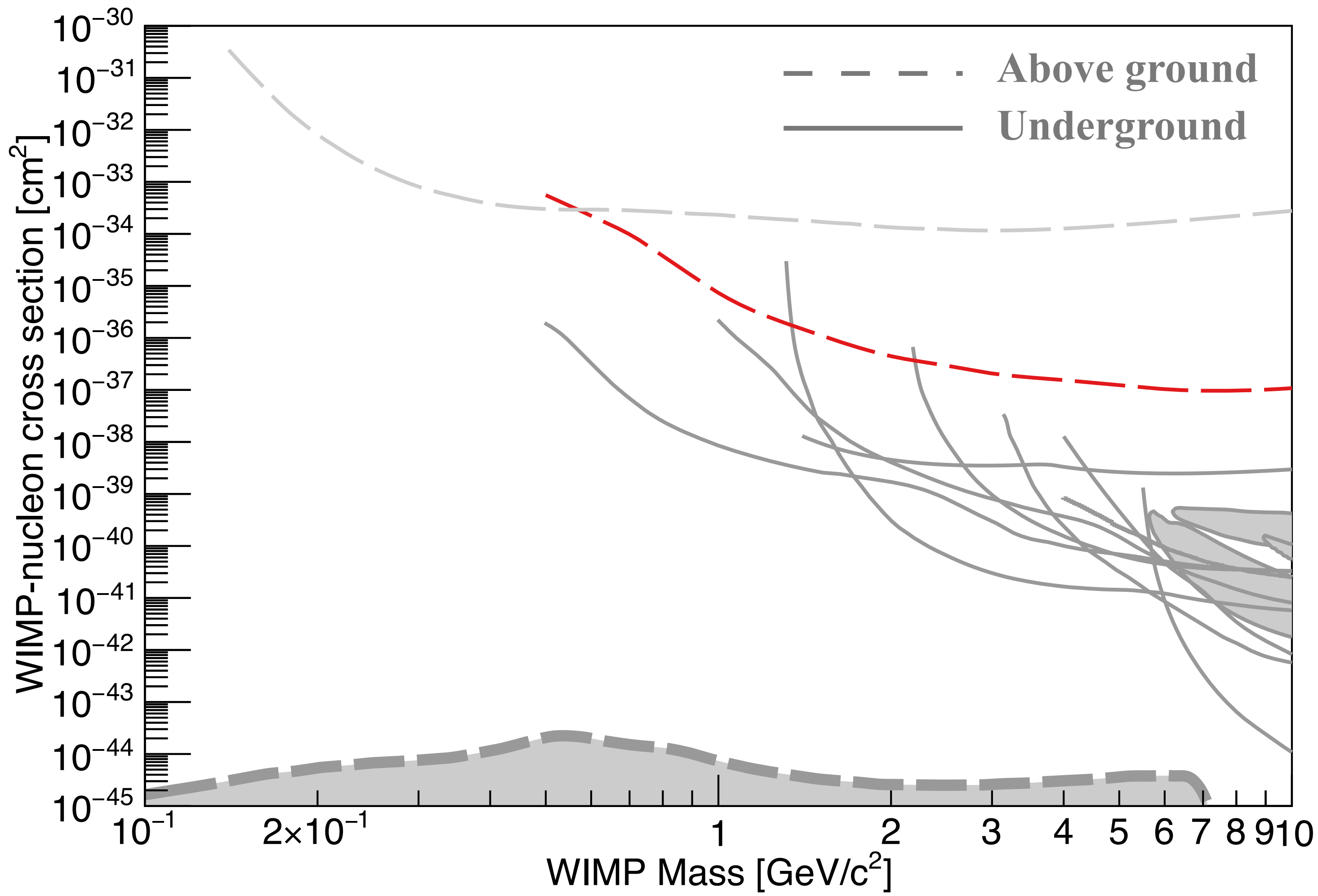
EDELWEISS-Surf

Technique: Heat Only

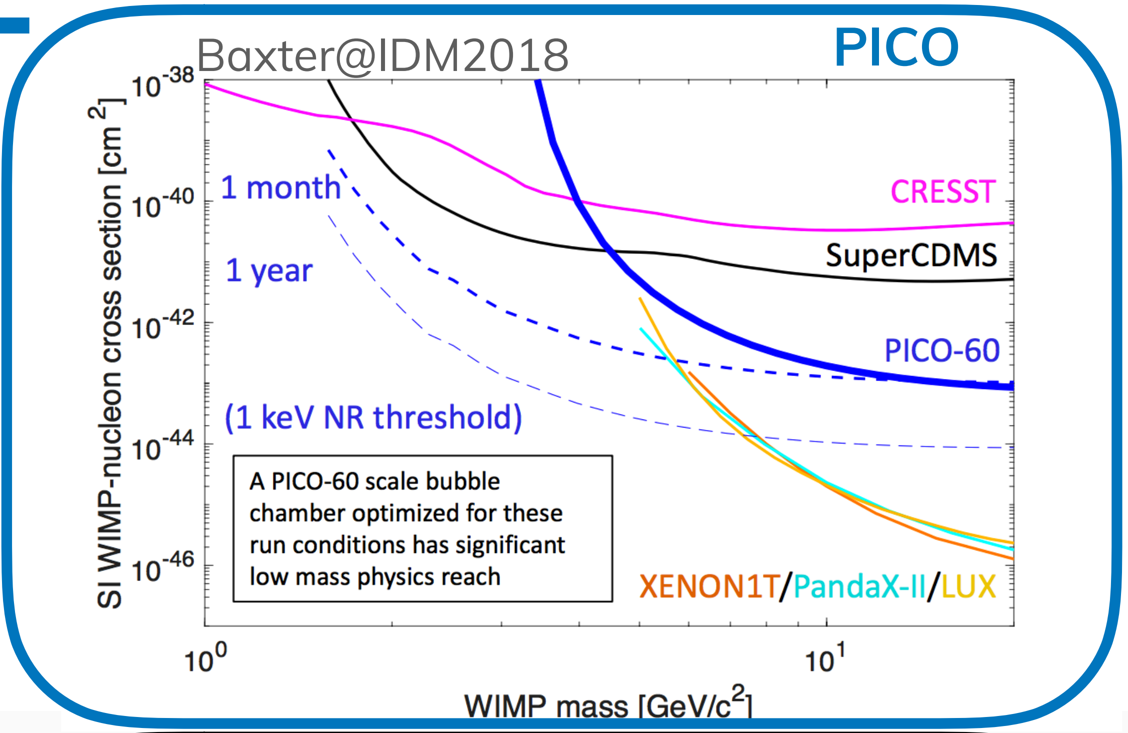
Best above-ground limit down to 600 MeV/c²

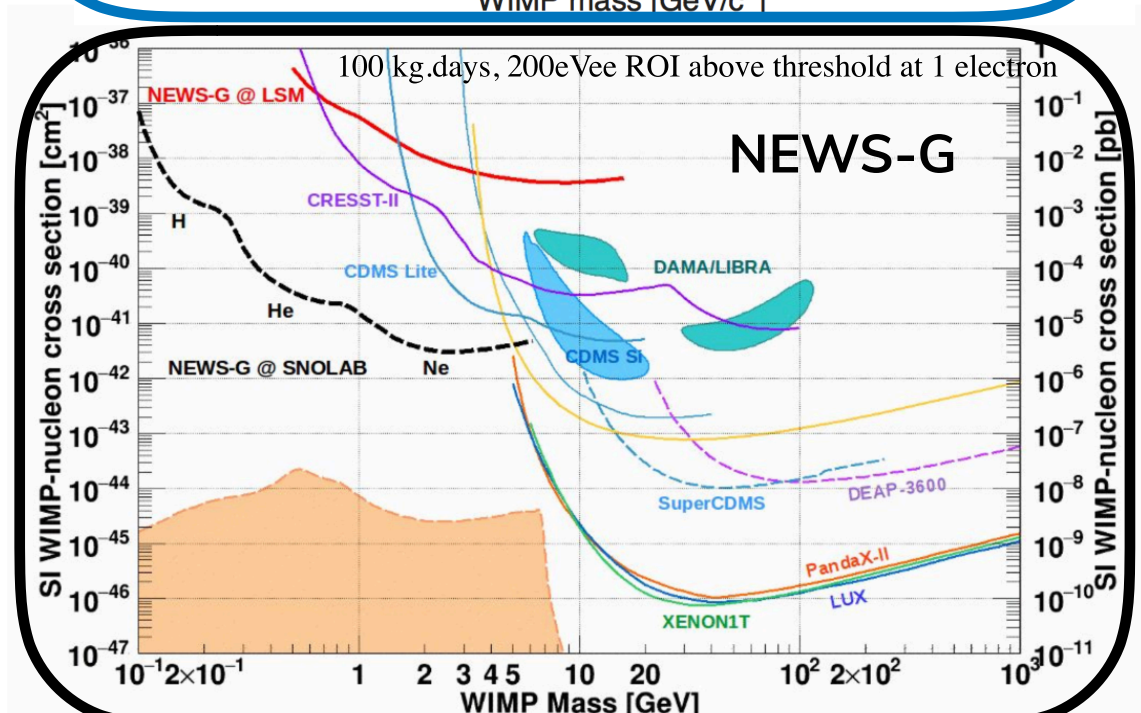
First sub-GeV limit with Ge, down to 500 MeV/c²

Opens the way for the 0.1 – 1 GeV/c² range

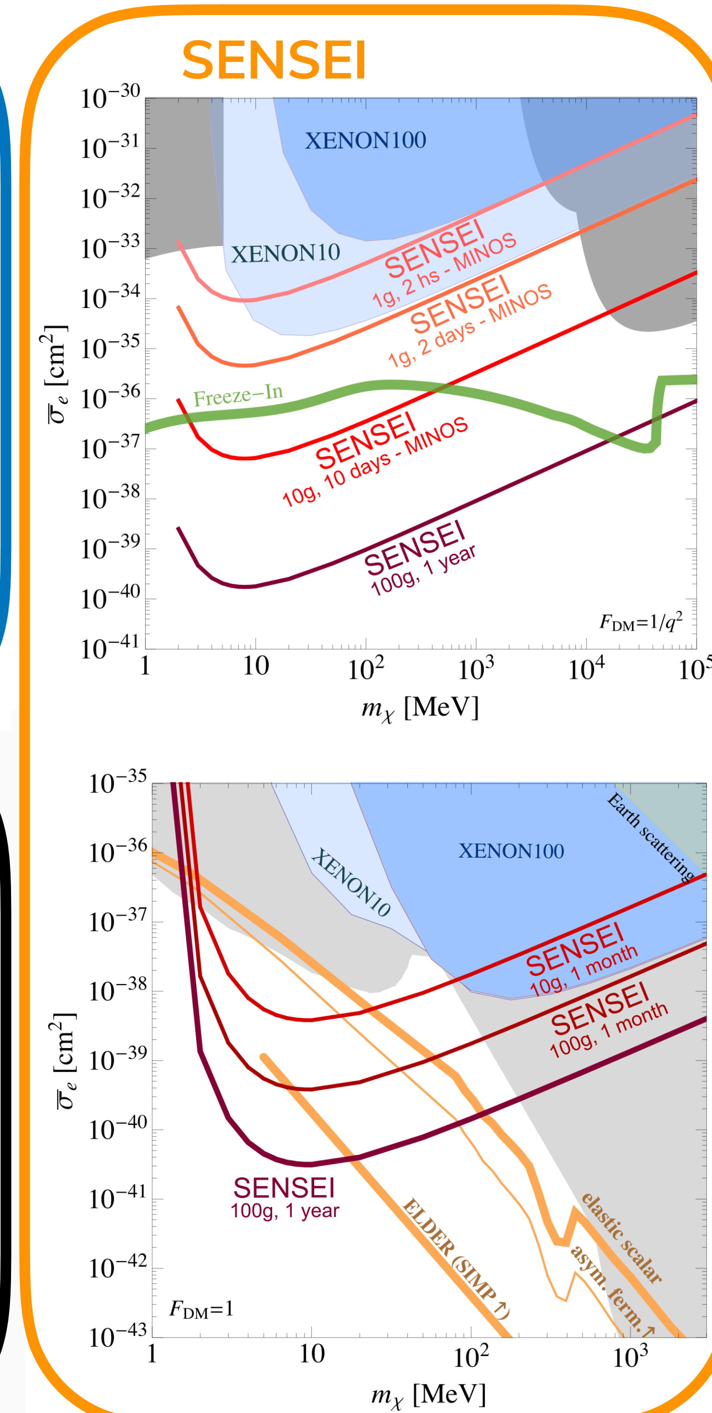


There is More…





Arnaud@LLWI2018



Phys. Rev. Lett. 121, 061803 (2018)

Conclusion

- Well motivated models of dark matter exist at a wide range of masses... we need a broad search!

- To extract all the information available through direct detection of dark matter, multiple target materials are essential

- The next generation of experiments will begin to map out the neutrino floor by detecting 8B solar neutrinos

- G2 cryogenic detectors will have unprecedented reach for dark matter masses of a few GeV, and will be an important cross check of potential signals in the high mass range

Thank You!