Searching for Low-Mass Dark Matter Particles

Cryogenic Detector

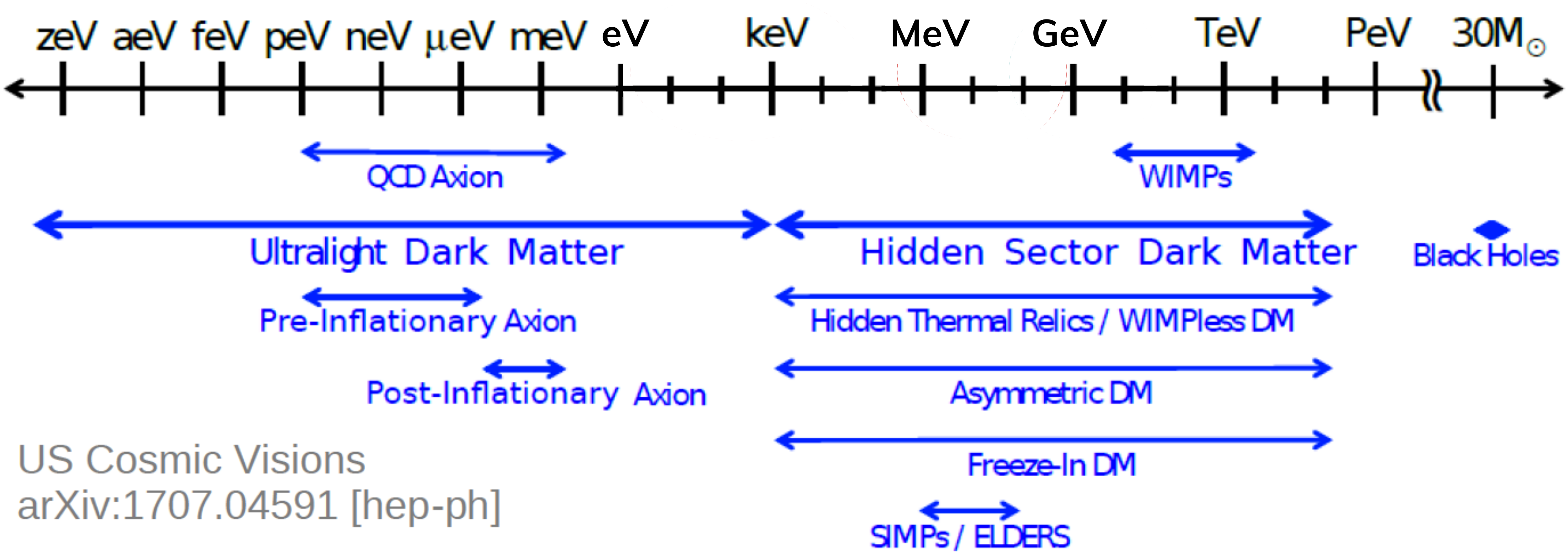
Silvia Scorza

2019/03/26

Aspen Winter Conference 2019

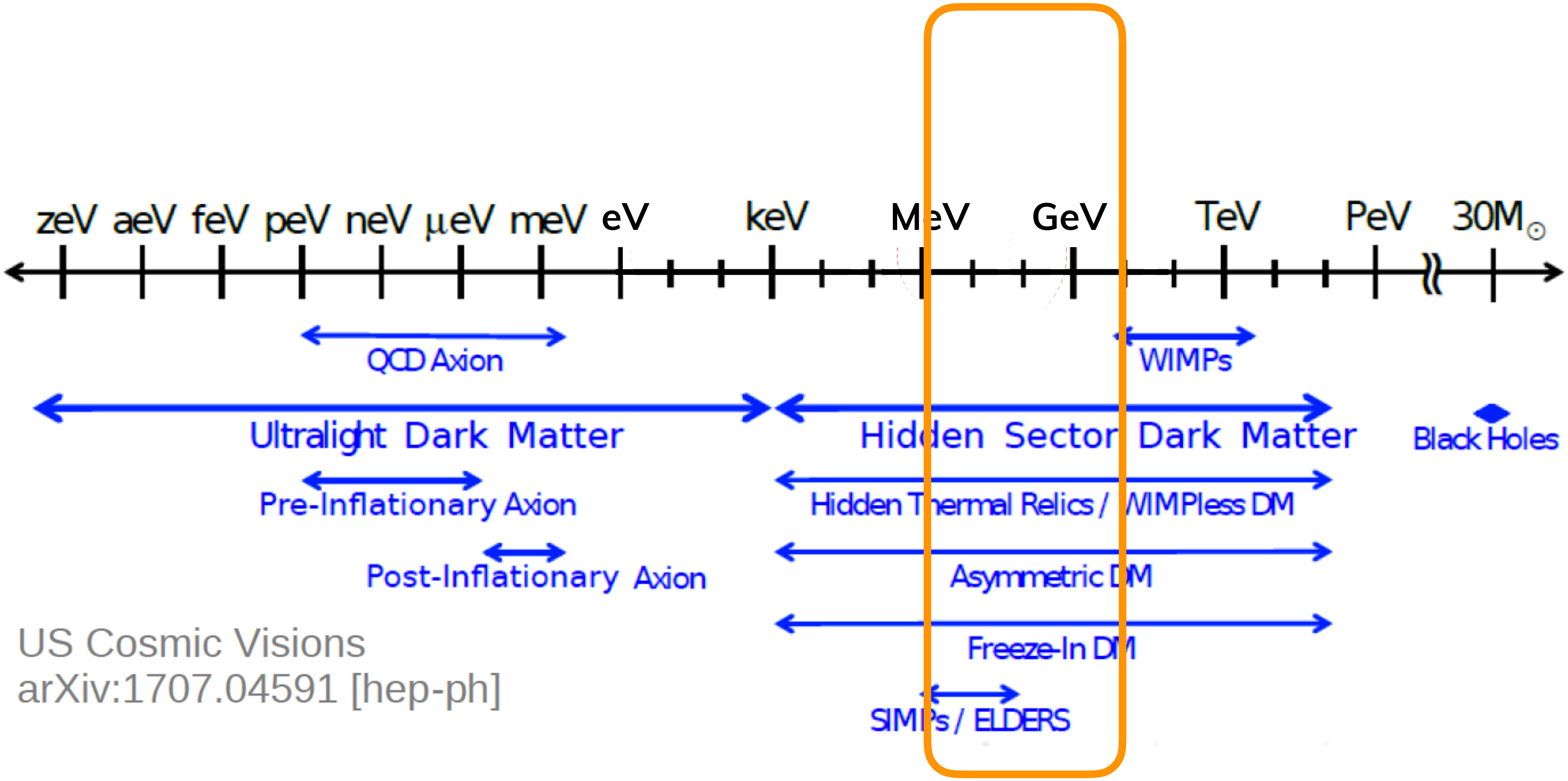
SNOLAB

Light Dark Matter Scenario



US Cosmic Visions
arXiv:1707.04591 [hep-ph]

Light Dark Matter Scenario

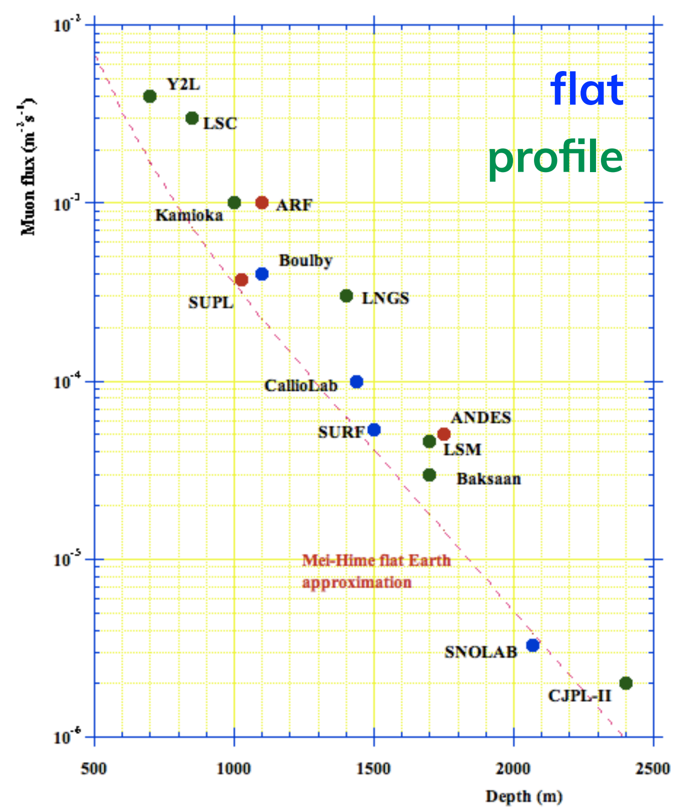


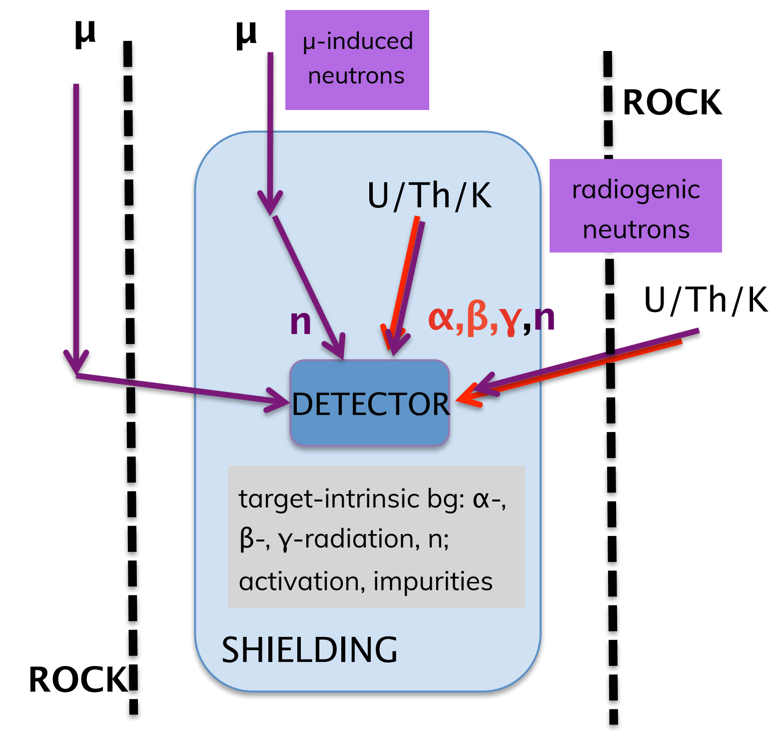
US Cosmic Visions
arXiv:1707.04591 [hep-ph]

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.

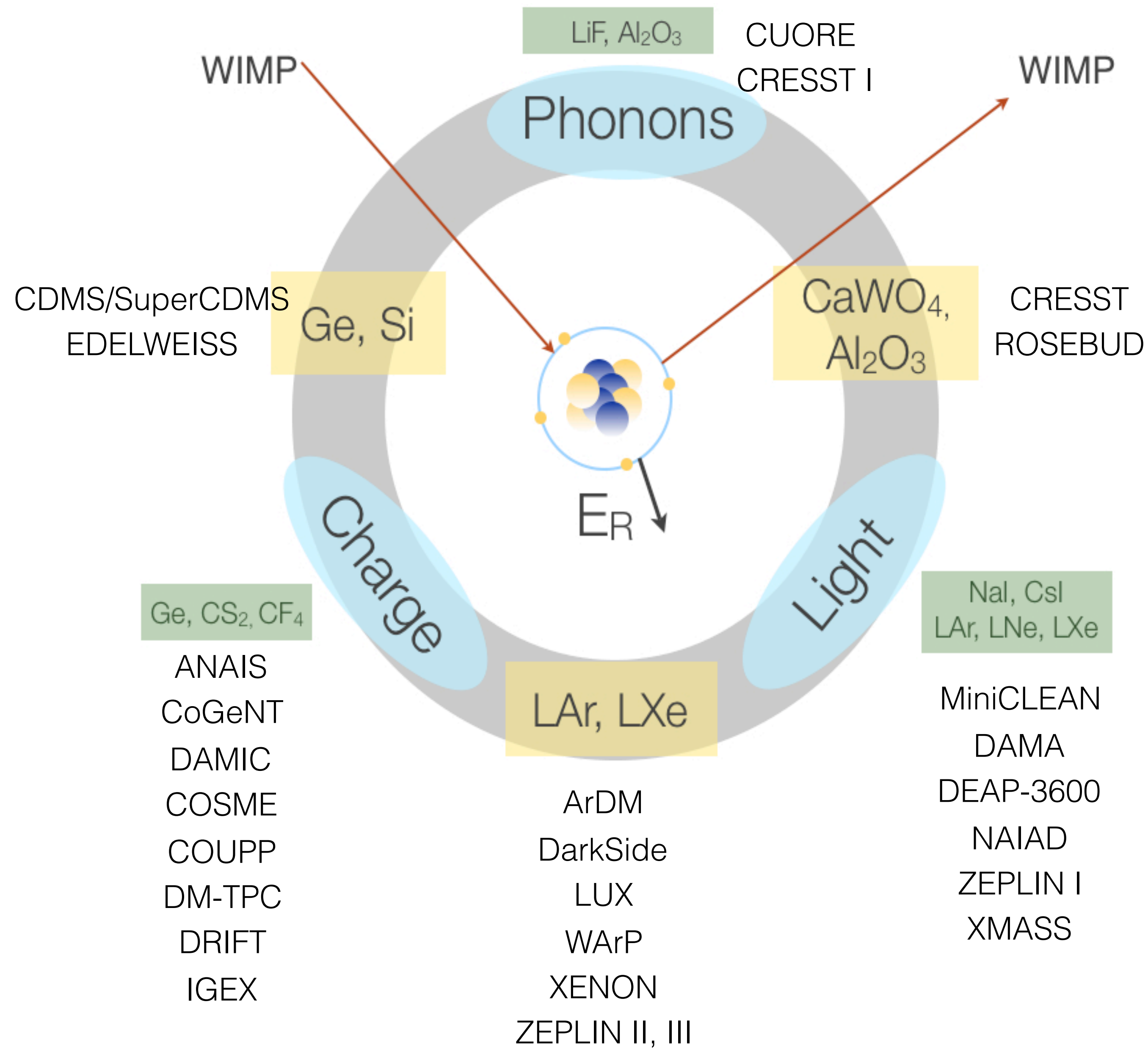




Passive/Active shielding
Reduce backgrounds from natural (^{238}U, ^{232}Th, ^{40}K) radioactivity

Direct DM Search - Challenges

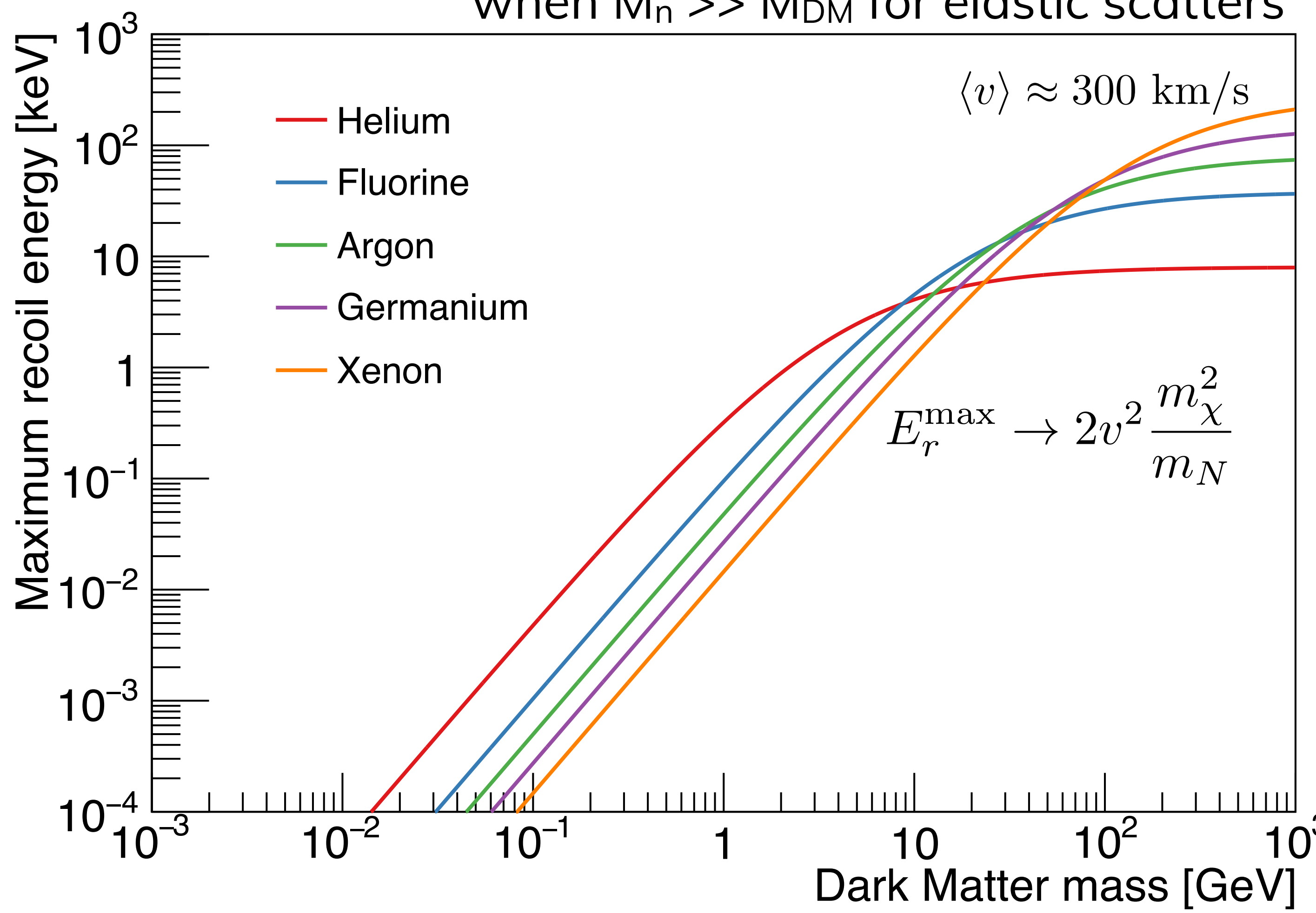
- **Low** and **controlled** backgrounds
- **Discrimination** between signal and background
  - Simultaneous measurements of two signals allows ER/NR discrimination on an event-by-event basis
  - Detector technology background rejection
- **Large exposure** *(few events per ton-year)*
- **Low energy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



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 te[illegible]ackground rejection
- **Large exposure** *(few events per ton-year)*
- **Low energy threshold**

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



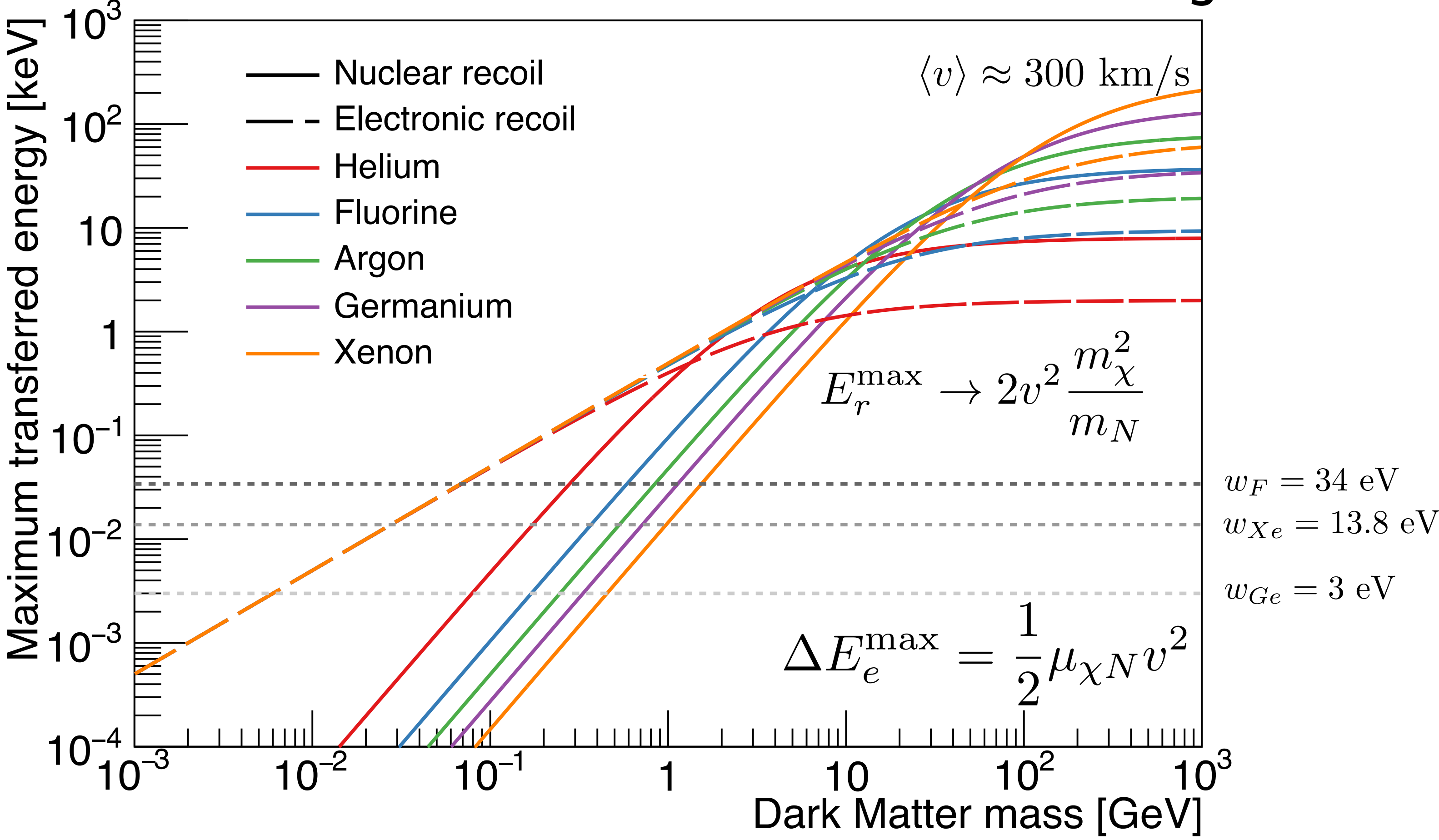
Direct detection of Sub-100 MeV dark matter via nuclear recoil is nearly impossible !

Direct DM Search - Challenges

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

- **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**

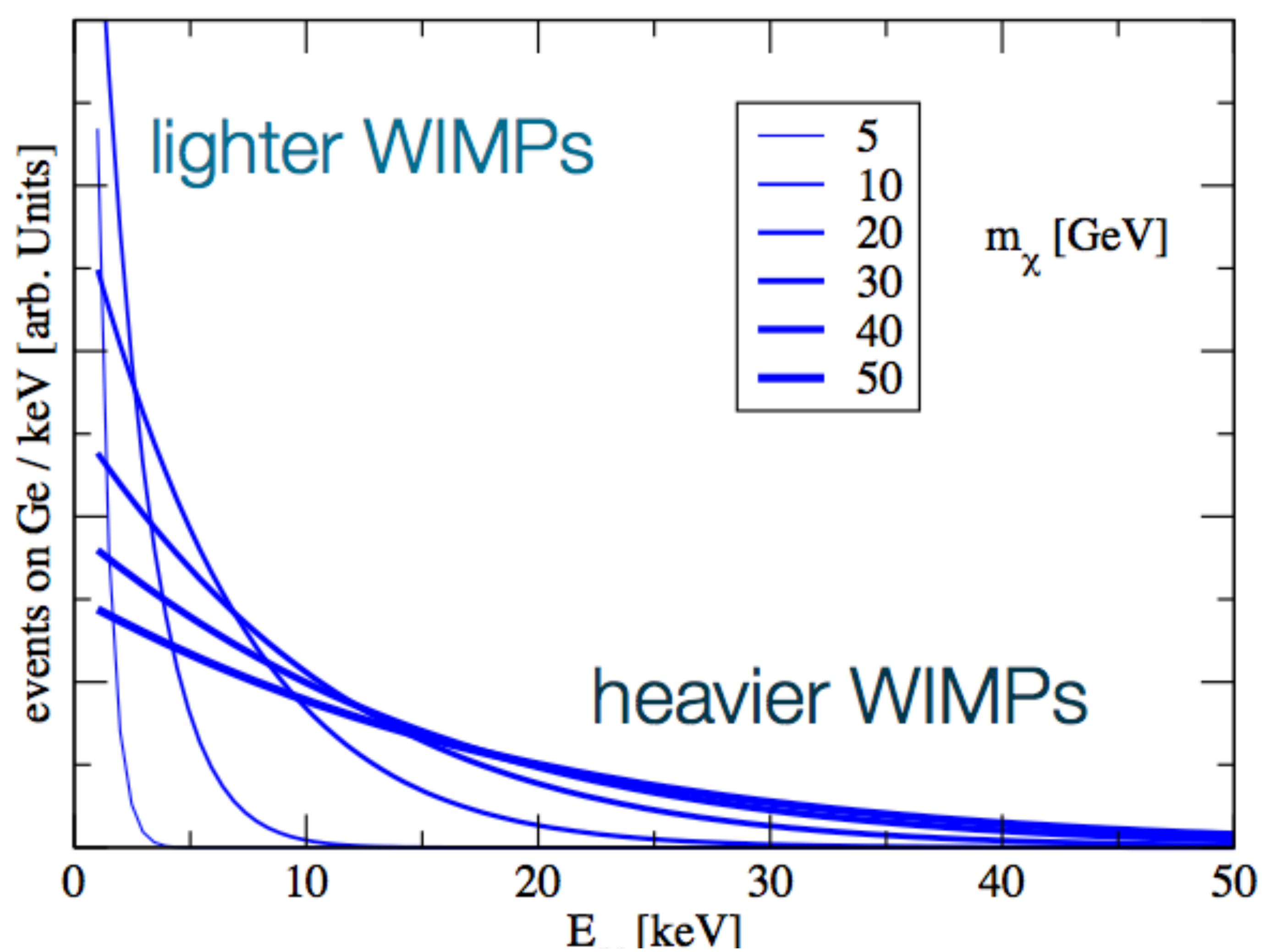
Dark Matter - electron scattering



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

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**



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**

$$\frac{dR}{dE_r} = \frac{1}{2m_r^2}\overbrace{\frac{\sigma_0}{m_\chi}}^{\text{Particle Physics}}\overbrace{F^2(E_r)}^{\text{Nuclear Physics}}\overbrace{\rho_0\int\frac{f(\vec{v})}{v}d^3v}^{\text{Astrophysics}}$$

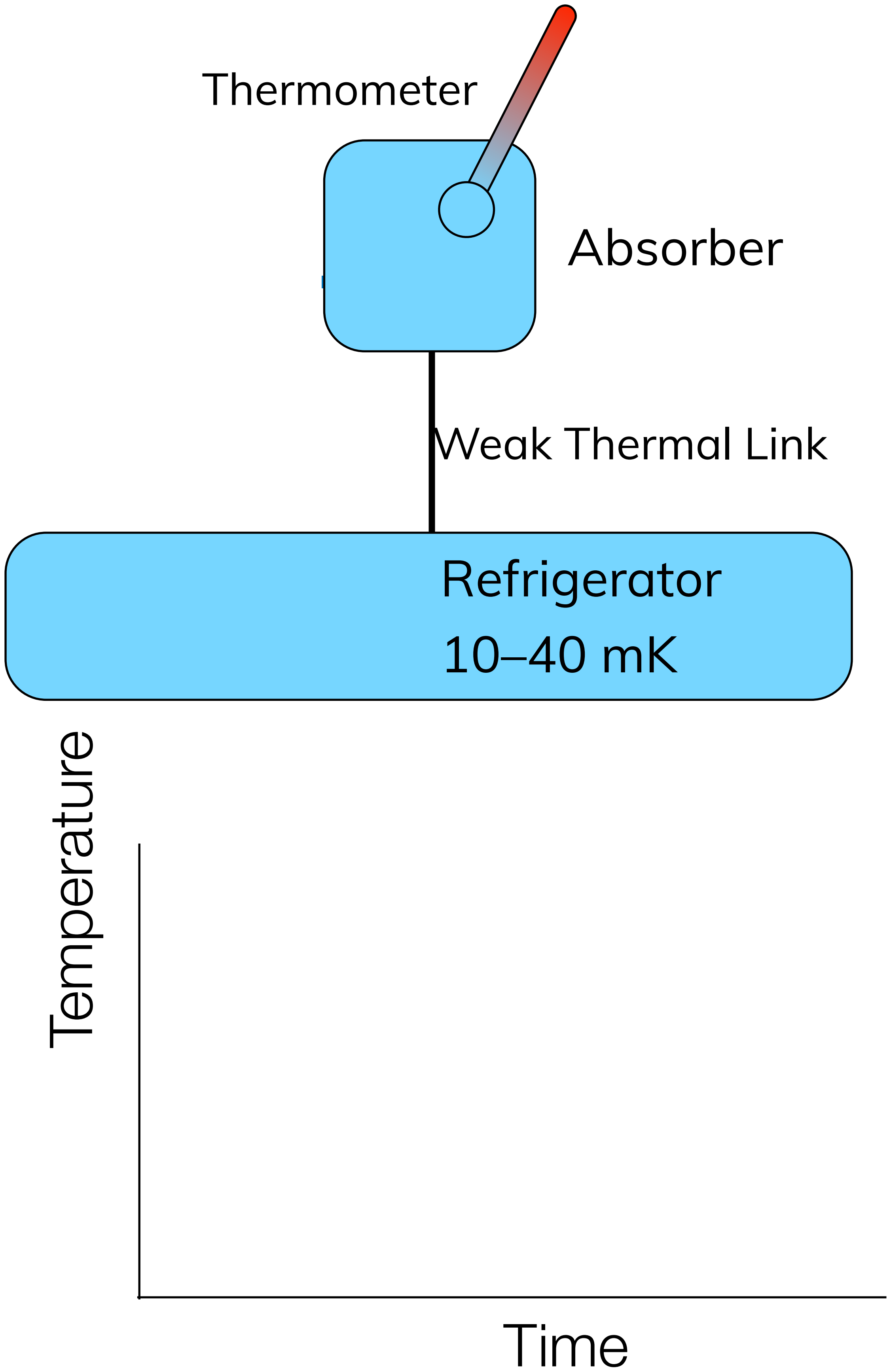
Interaction rate scales as $1/m_\chi$

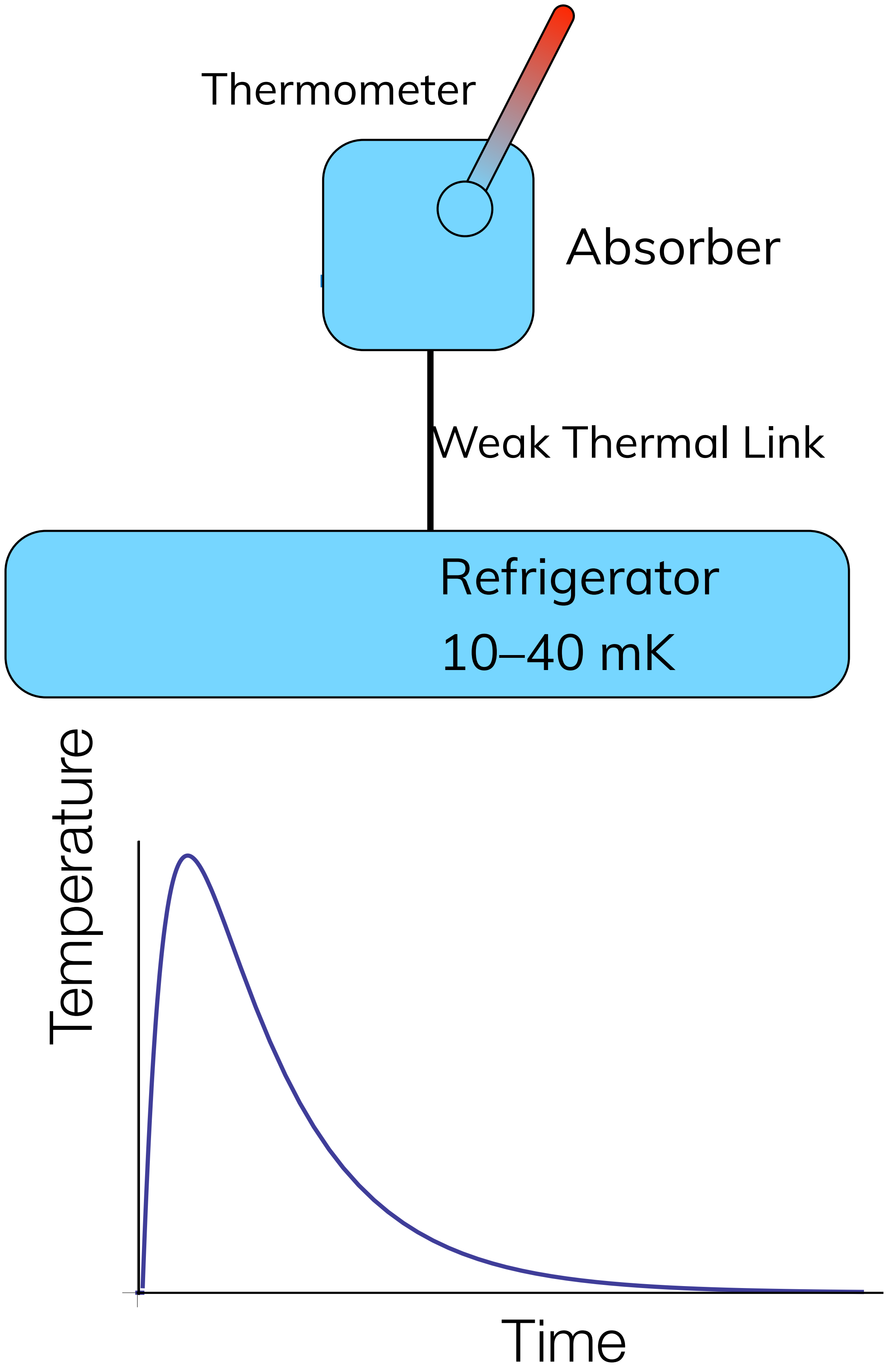
Liquid noble experiments need 10 tons to get to 10^{-47} cm^2 at 100GeV

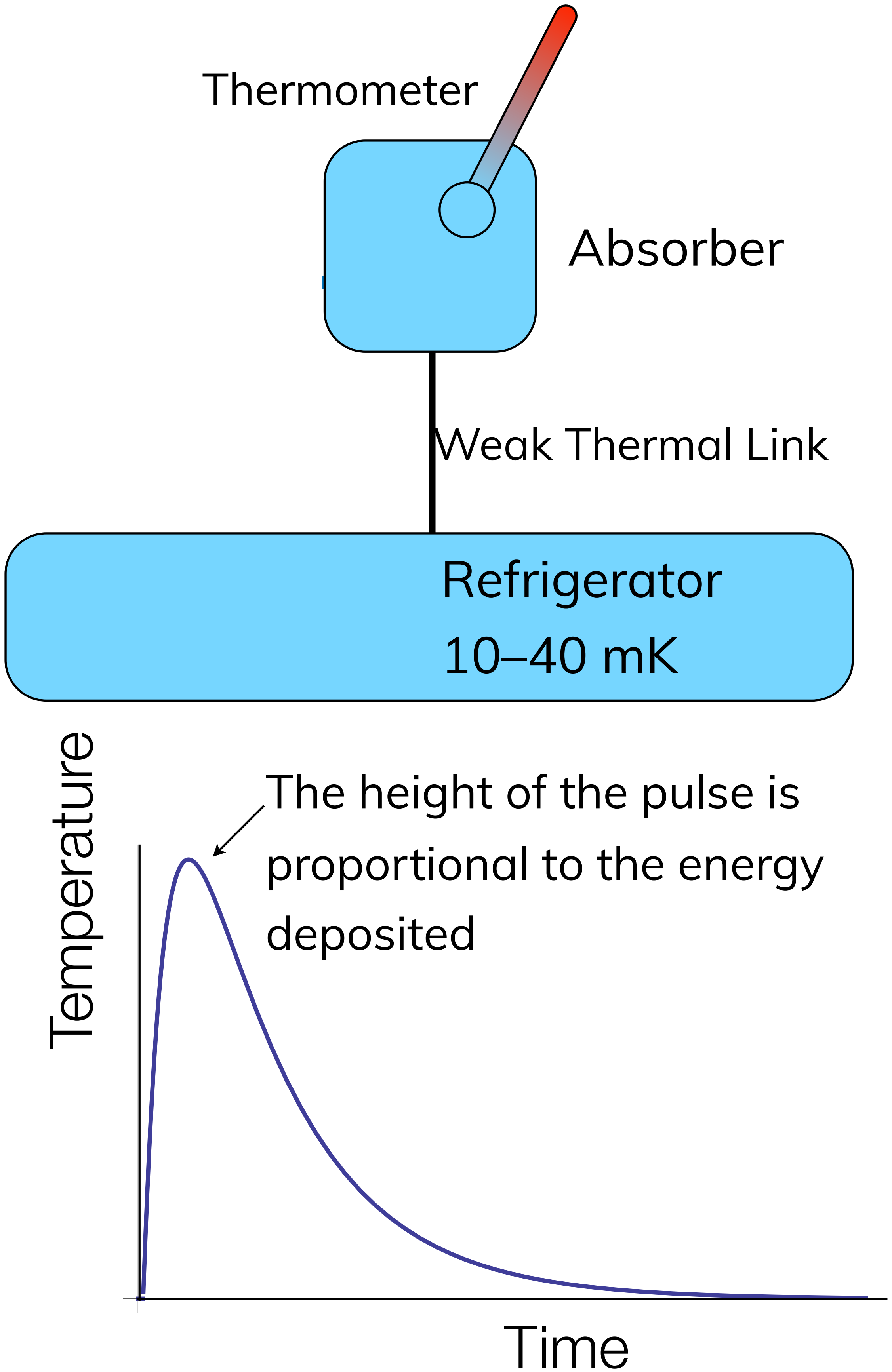
Solid-state experiments only needs 10kg to reach the same level at 100MeV

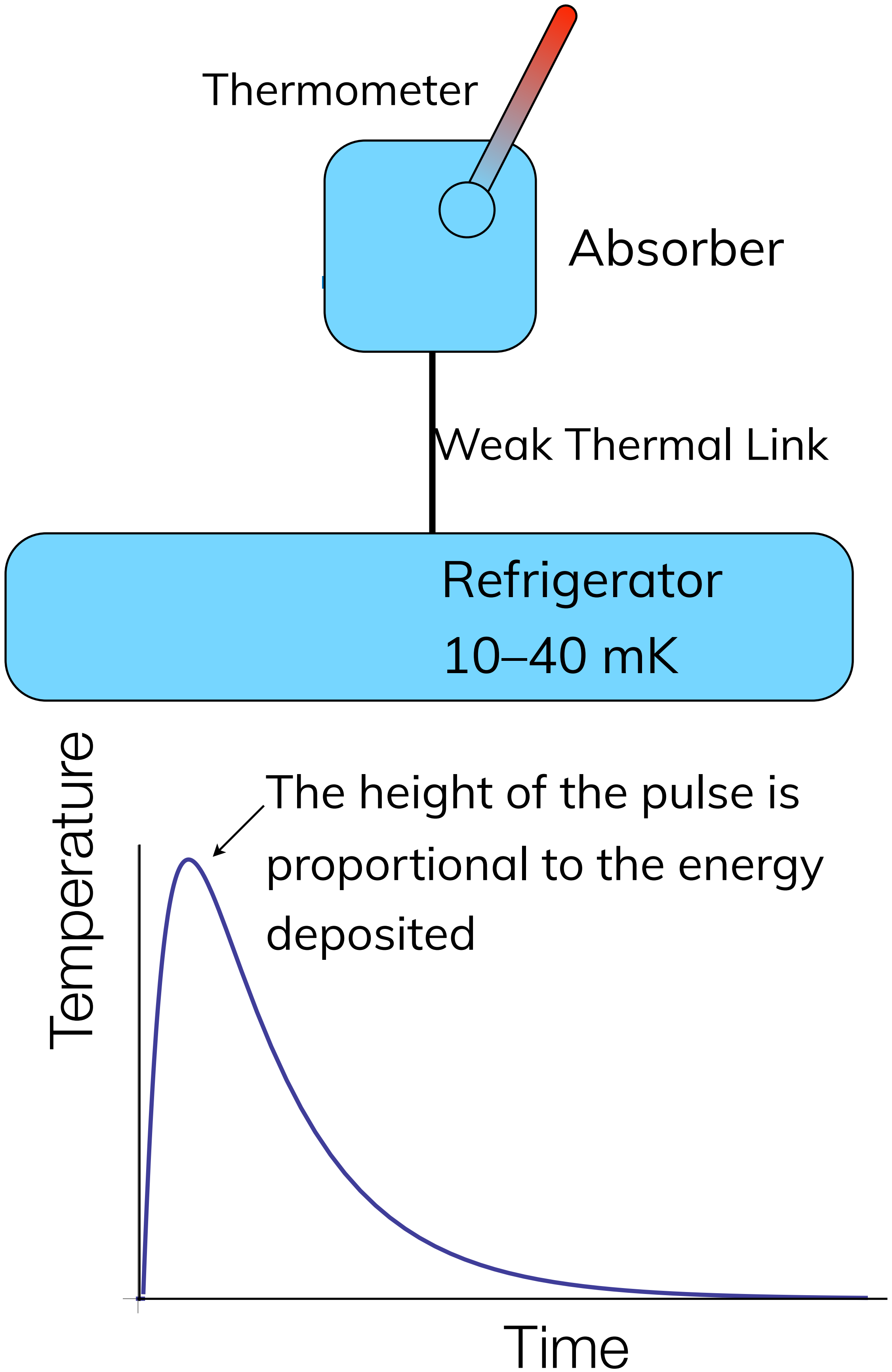
→ **energy sensitivity**

Cryogenic Detectors


Thermometer
Absorber
Weak Thermal Link
Refrigerator
10–40 mK
Temperature
Time


Thermometer
Absorber
Weak Thermal Link
Refrigerator
10–40 mK
Temperature
Time


Thermometer
Absorber
Weak Thermal Link
Refrigerator
10–40 mK
The height of the pulse is proportional to the energy deposited
Temperature
Time

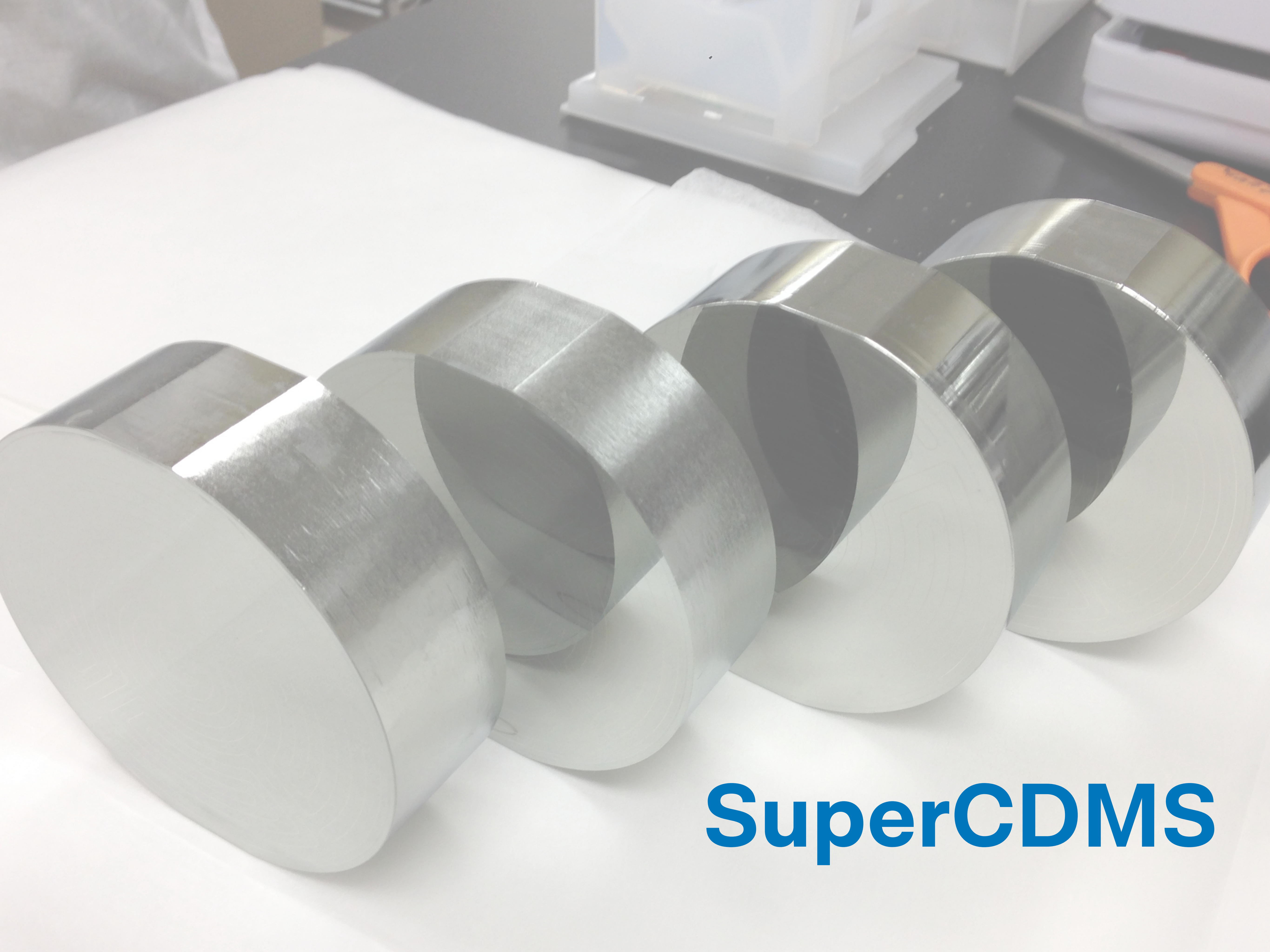


Advantages of phonon readout:

- 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**),
- Low threshold enables sensitivity to lower DM masses + larger rate/kg for large WIMP masses.

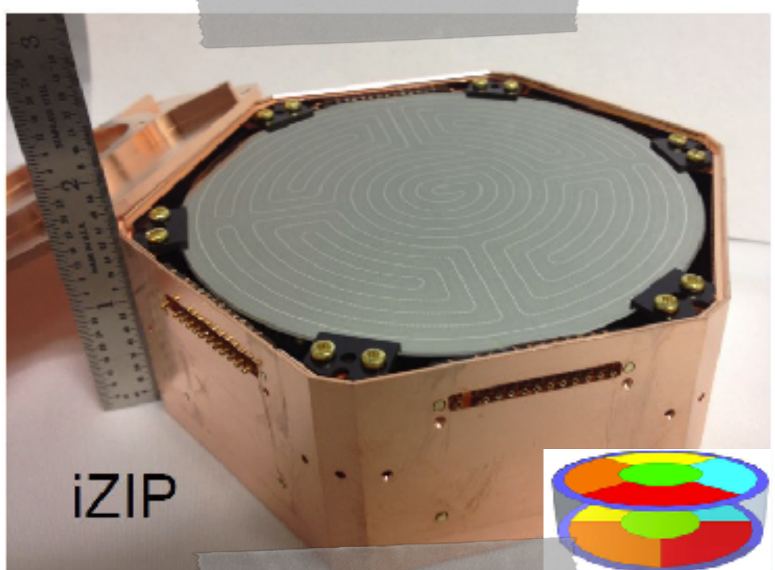
Phonon Readout

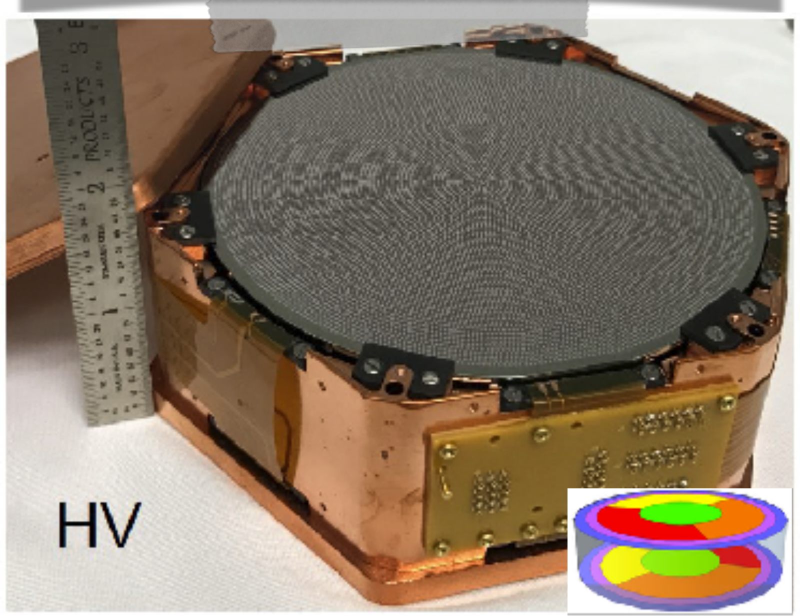
- Thermal measurement (EDELWEISS)
- Athermal measurement (SuperCDMS/ CRESST)


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

Detectors Advantages

iZIP Detector

(10 Ge, 2 Si)

heat+ionization

ER/NR discrimination

Full fiducialisation

M_{DM} >5GeV/c^2

HV Detector

(8 Ge, 4 Si)

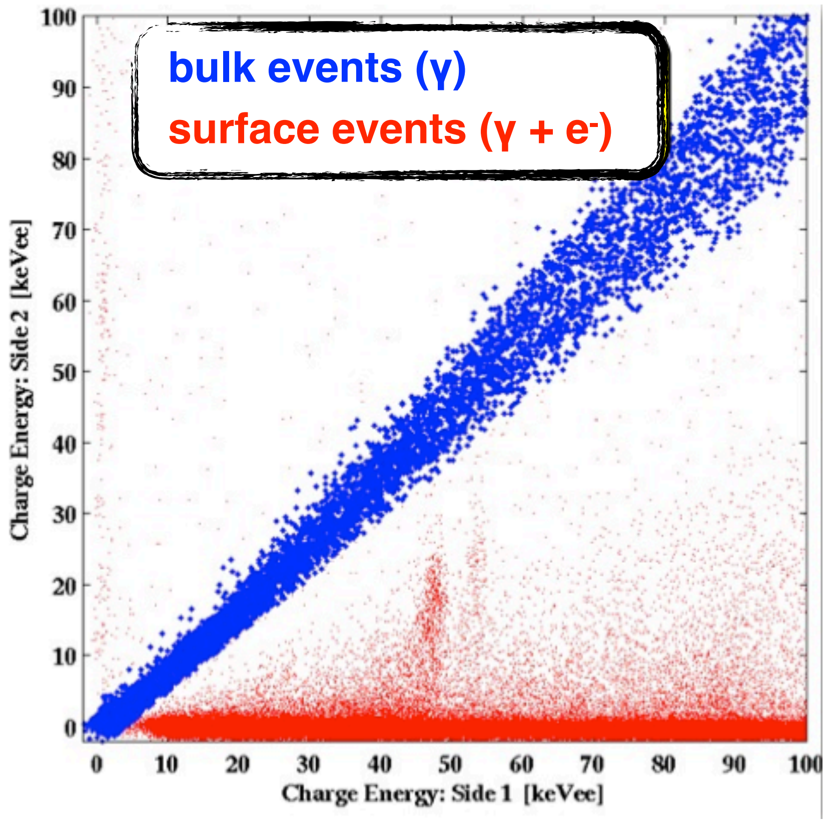
heat+ionization

Radial fiducialisation

Lower thresholds

(75 eV_{ee} and 56 eV_{ee})

M_{DM} <5GeV/c^2



Detectors Advantages

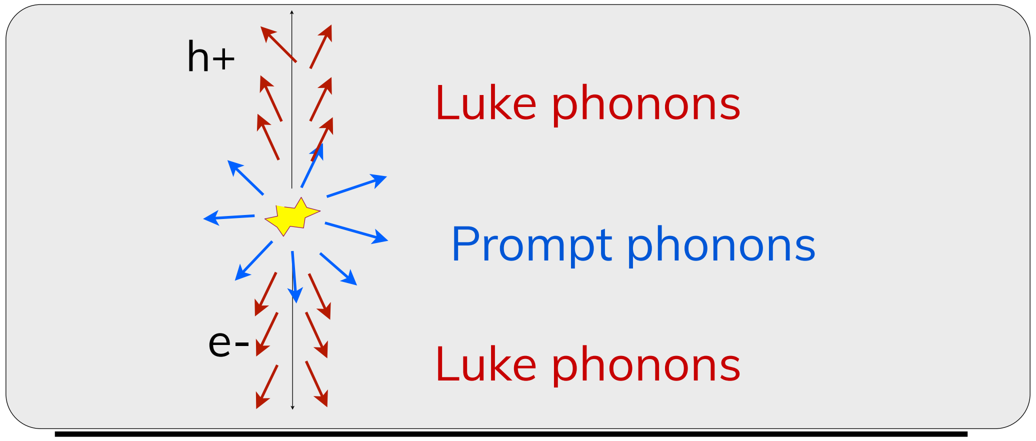
iZIP Detector
(10 Ge, 2 Si)
heat+ionization

- ER/NR discrimination
- Full fiducialisation
- $M_{DM} > 5 GeV/c^2$

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

- Radial fiducialisation
- **Lower thresholds**
  (75 eV_{ee} and 56 eV_{ee})
- $M_{DM} < 5 GeV/c^2$

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



Detectors Advantages

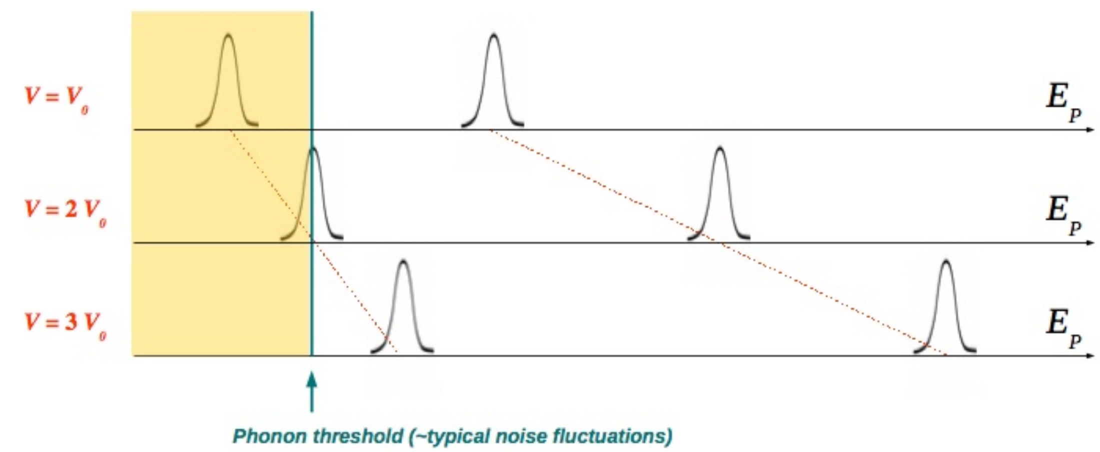
iZIP Detector
(10 Ge, 2 Si)
heat+ionization

ER/NR discrimination
Full fiducialisation
$M_{DM} > 5 GeV/c^2$

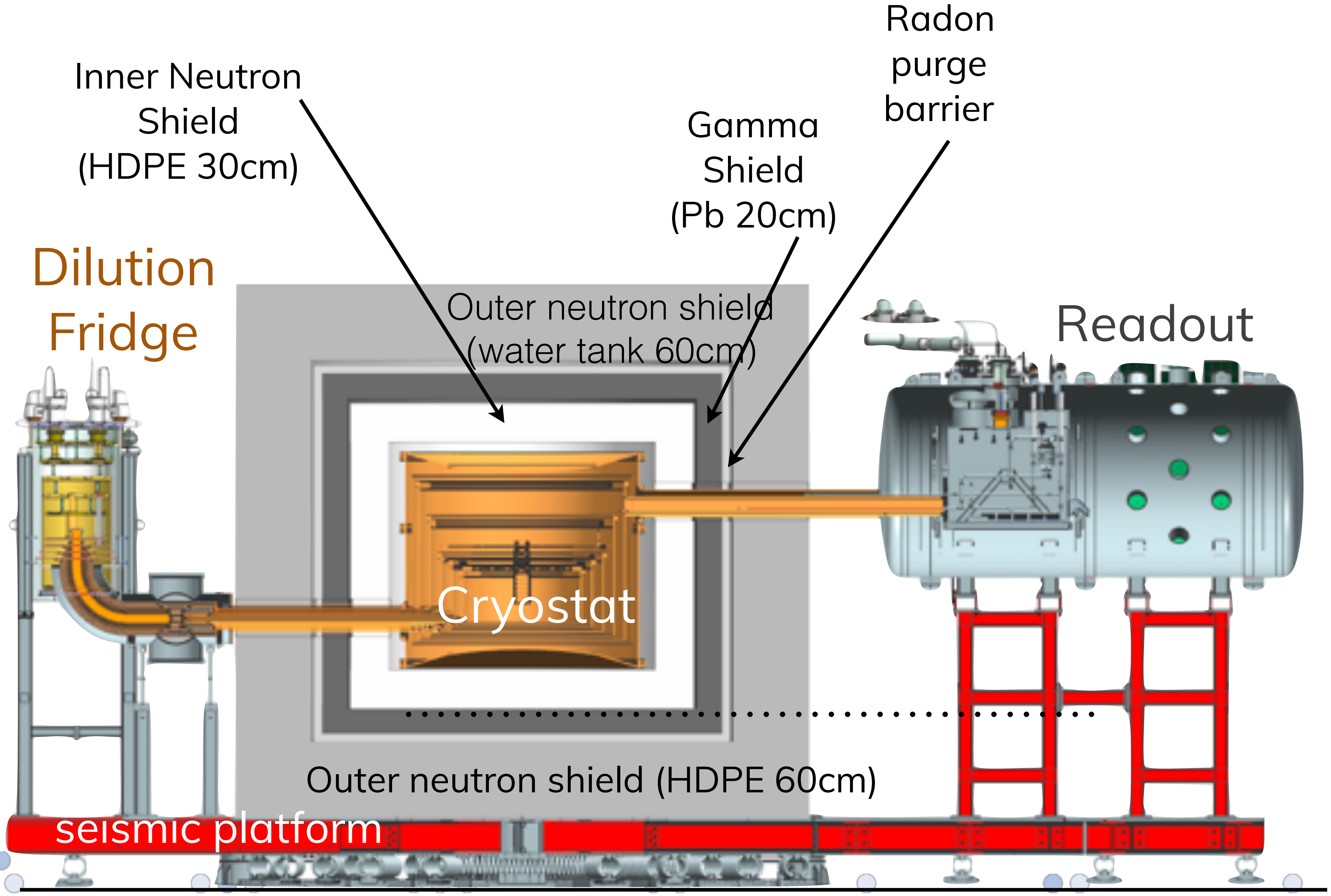
HV Detector
(8 Ge, 4 Si)
~~heat+ionization~~

Radial fiducialisation
Lower thresholds
(75 eV_{ee} and 56 eV_{ee})
$M_{DM} < 5 GeV/c^2$

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



SuperCDMS SNOLAB



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

2 HV Towers

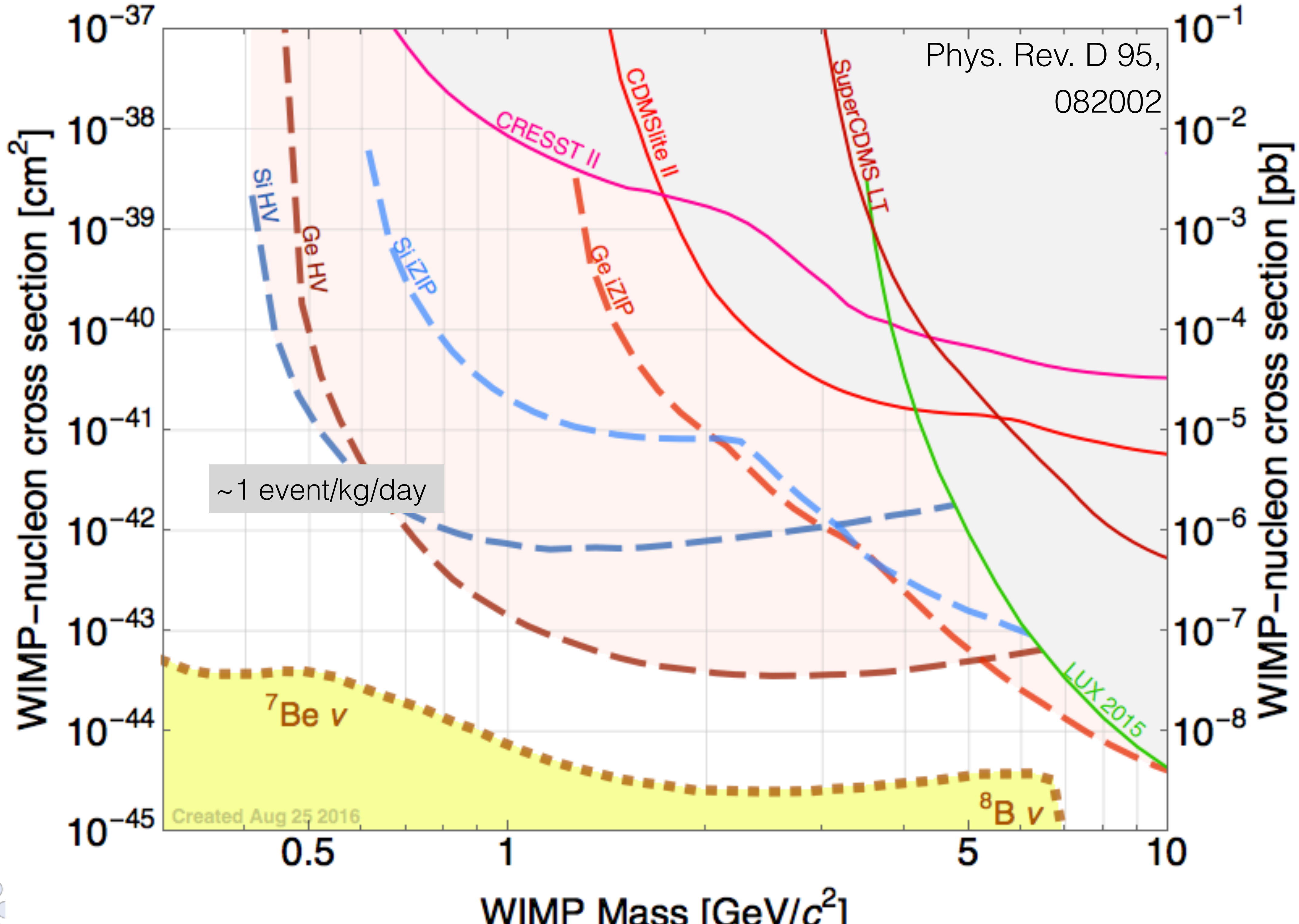
(4 Ge + 2 Si)

2 iZIP Towers

(6 Ge & 4 Ge + 2 Si)

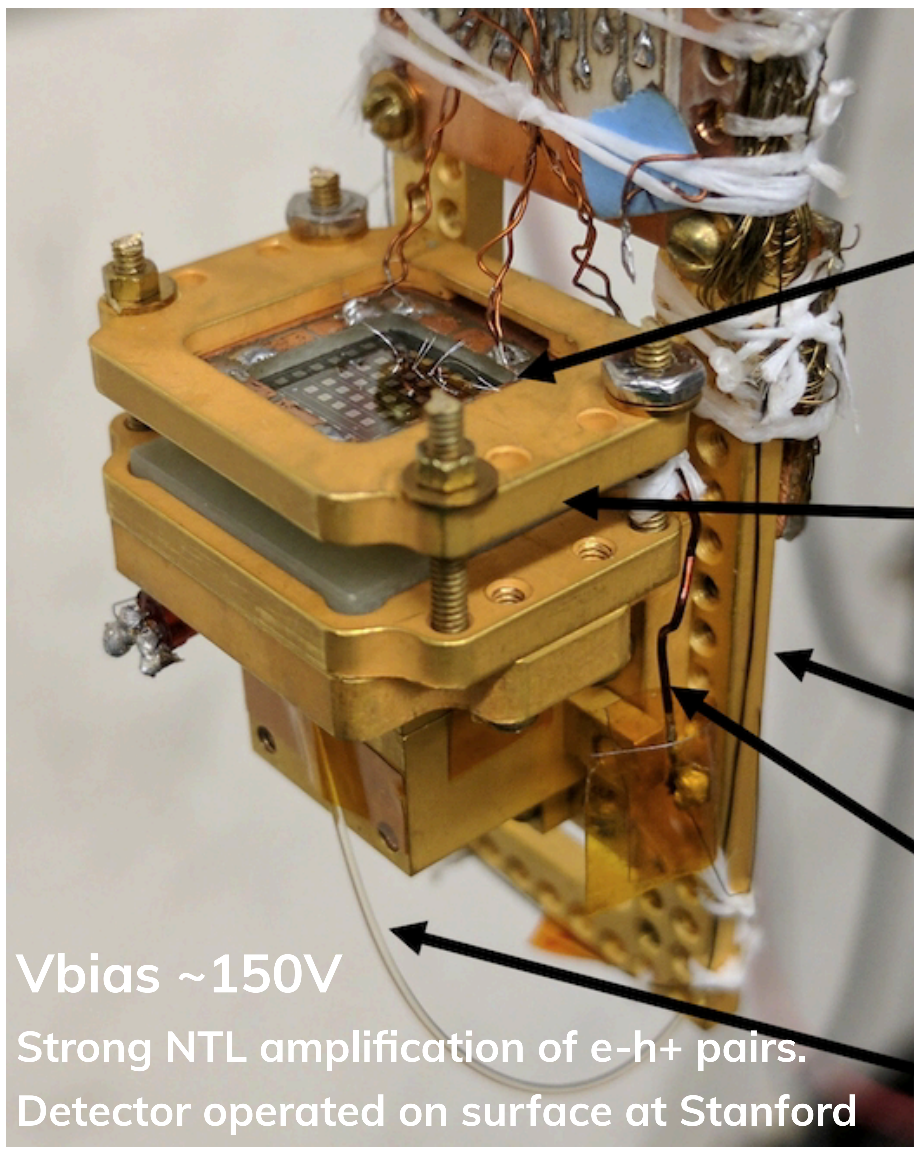
Predicted Sensitivity

Initial program: beginning operation in 2020, operating for 5 years



Prototype HVeV Detector

Appl. Phys. Lett. 112, 043501



Si crystal/
phonon sensors

Crystal holder

Dilution refrigerator
sample stage (30mK)

Bias voltage line

Fiber optic

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

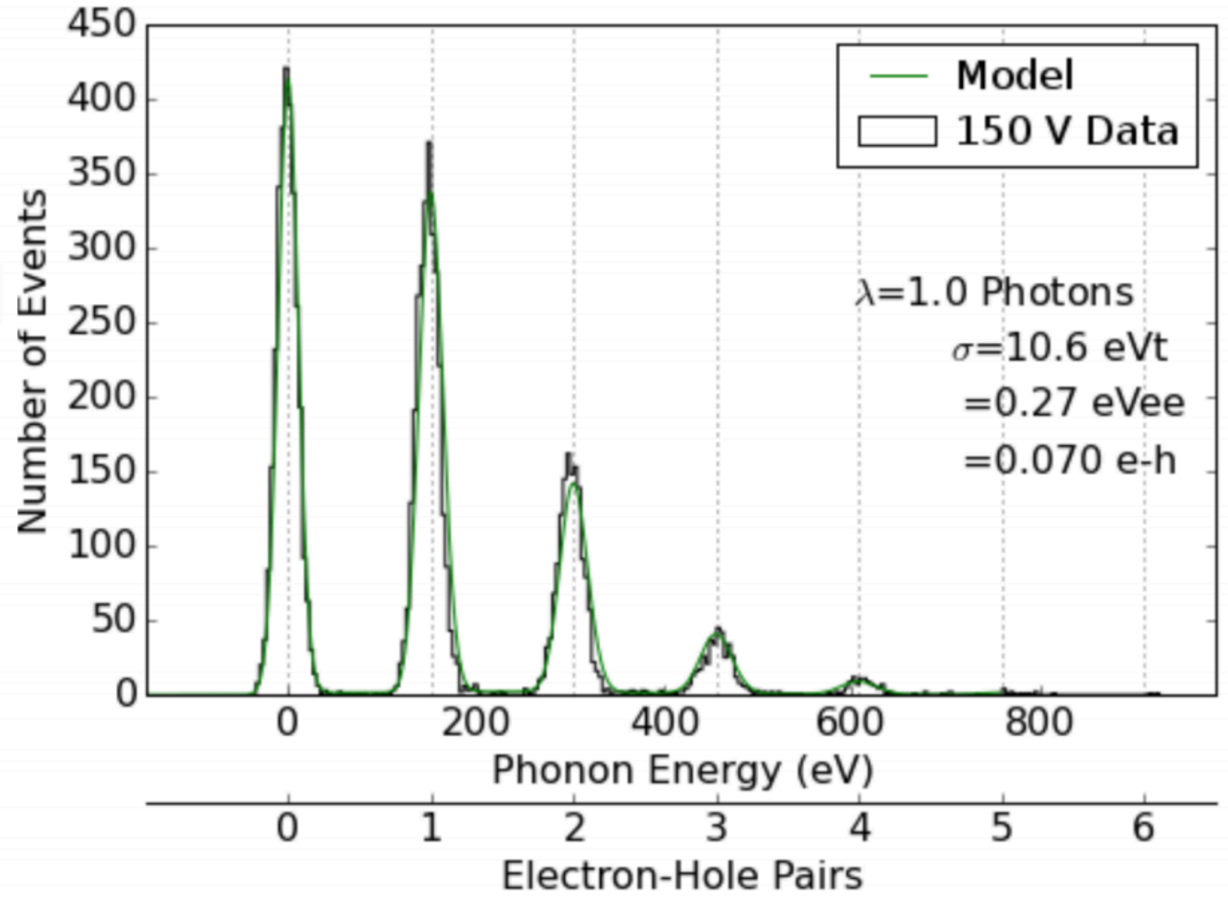
Prototype for SuperCDMS SNOLAB

- ~35mK operational temp
- 1 $cm^2 \times$ 4 mm Si, 0.93g
- One-sided detector readout

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

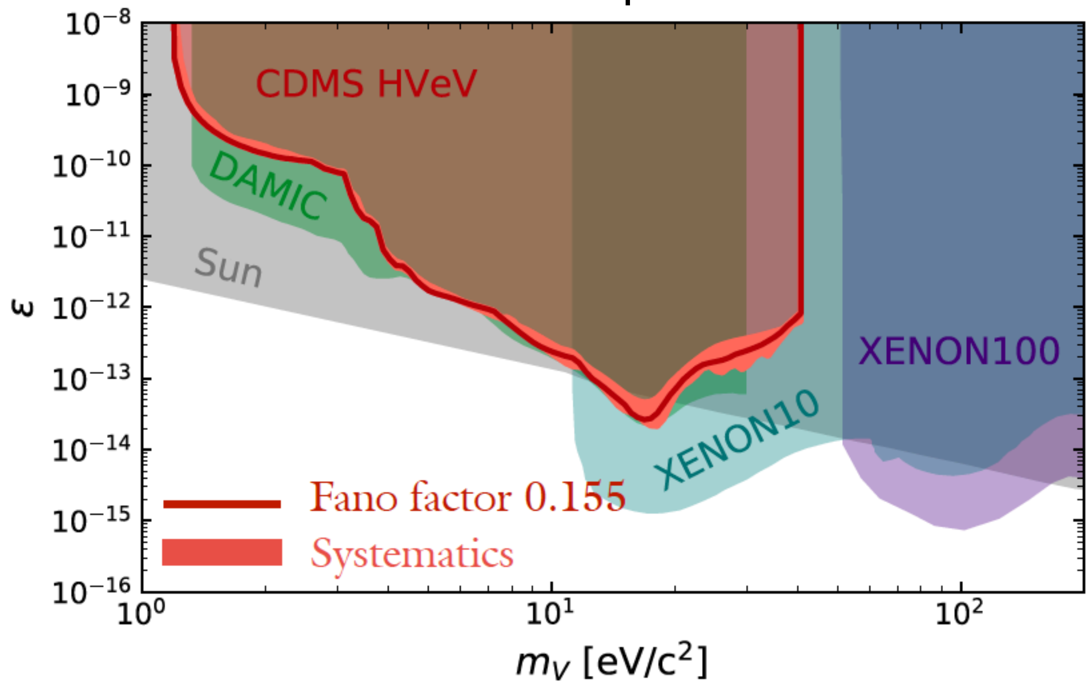
Prototype HVeV Detector

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.

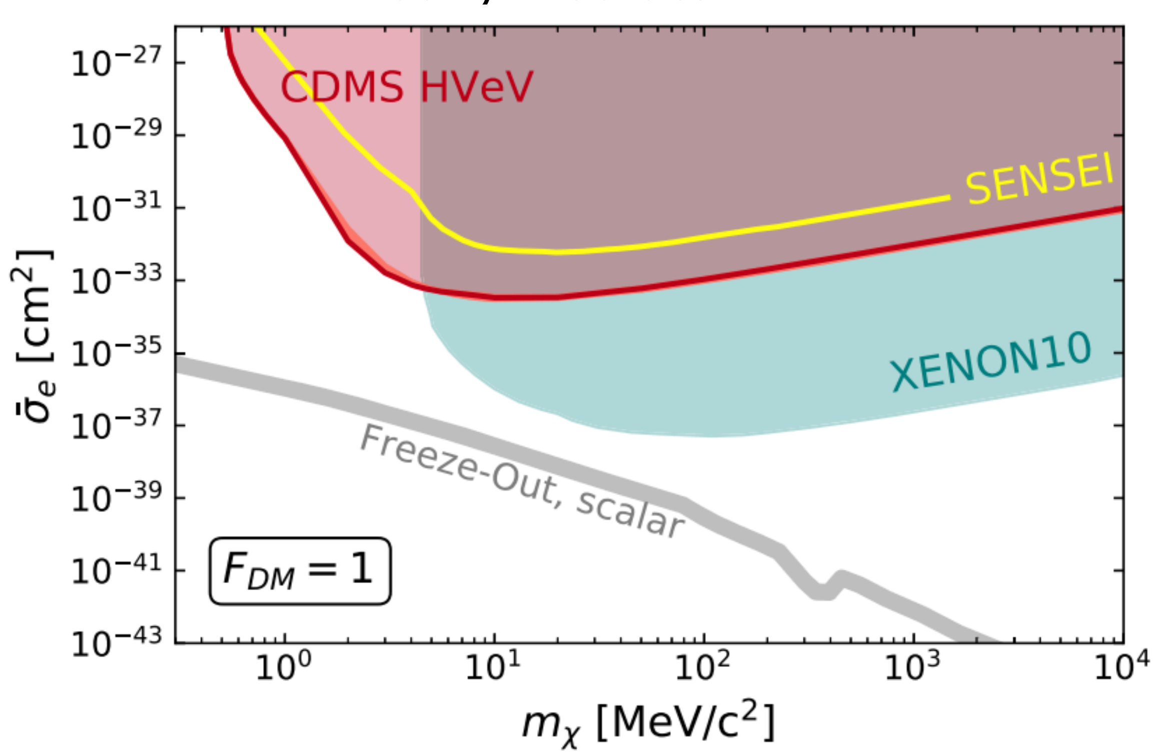
Dark Photon Absorption



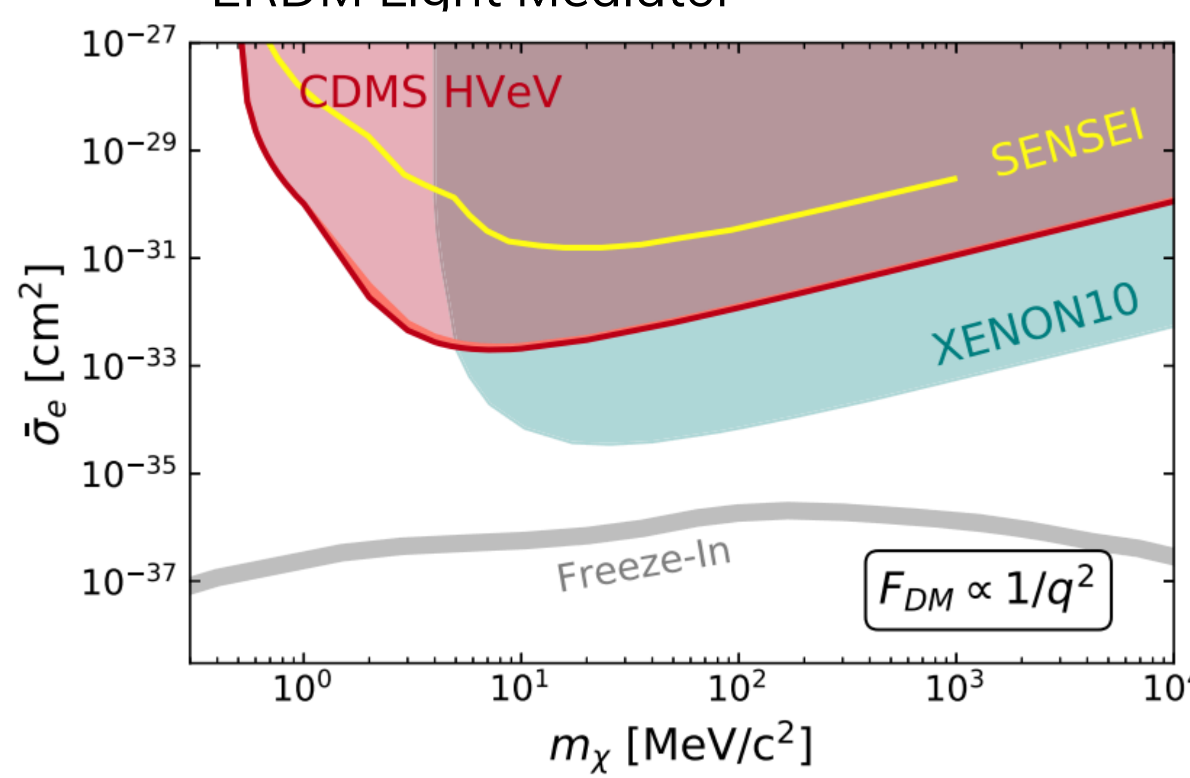
- 90% CL w/o background subtraction using optimum interval method.
- Systematics include varying Fano factor, and uncertainties in photoelectric cross section

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

ERDM Heavy Mediator



ERDM Light Mediator



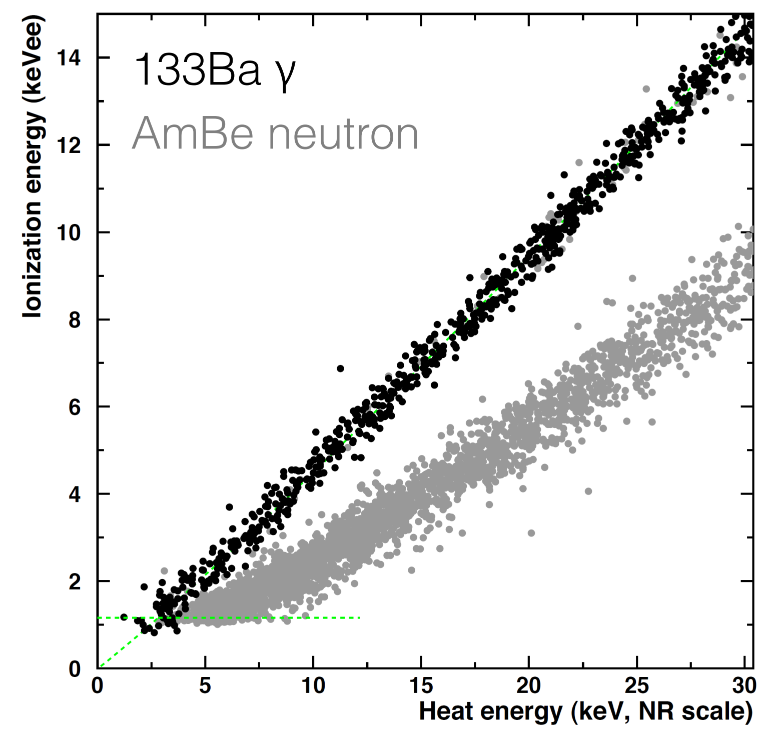
EDELWEISS III

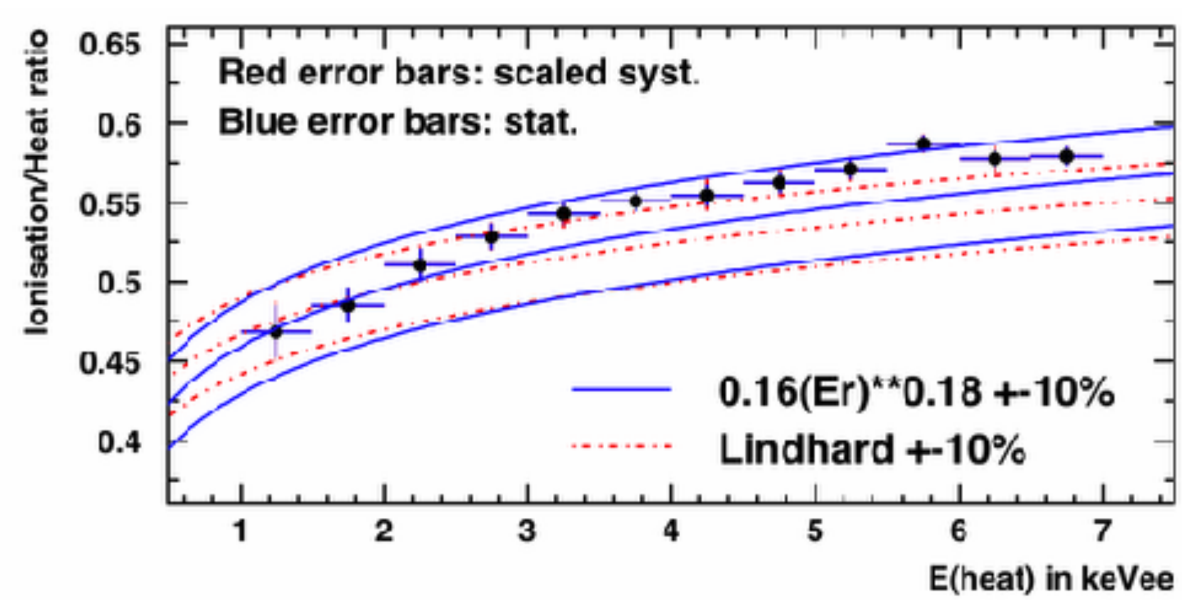
EDELWEISS Results

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.





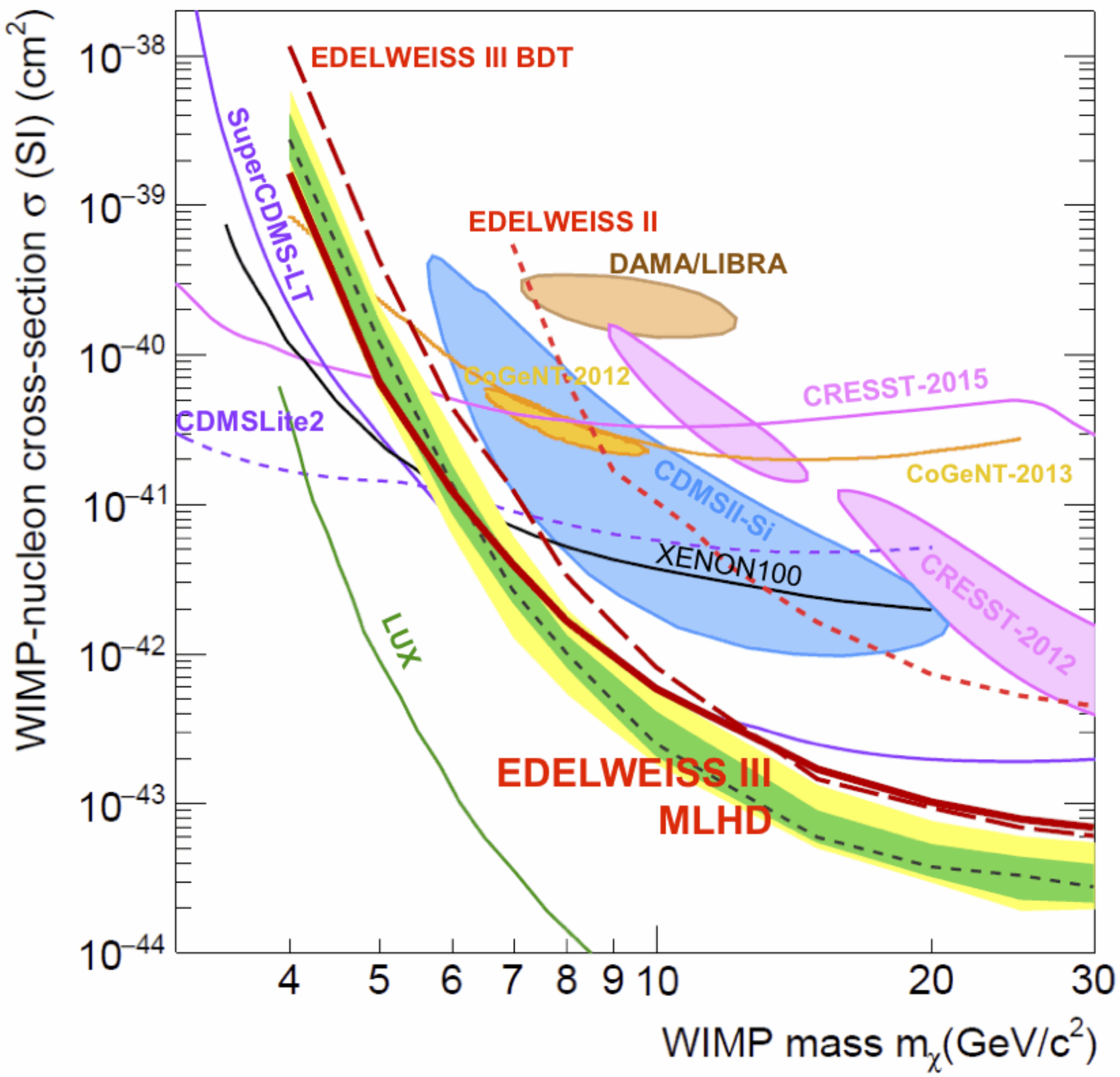
EDELWEISS Results

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]

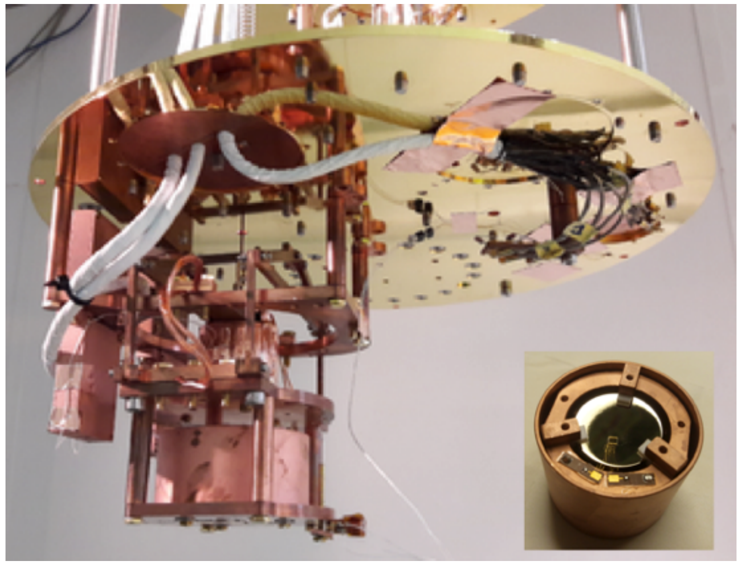


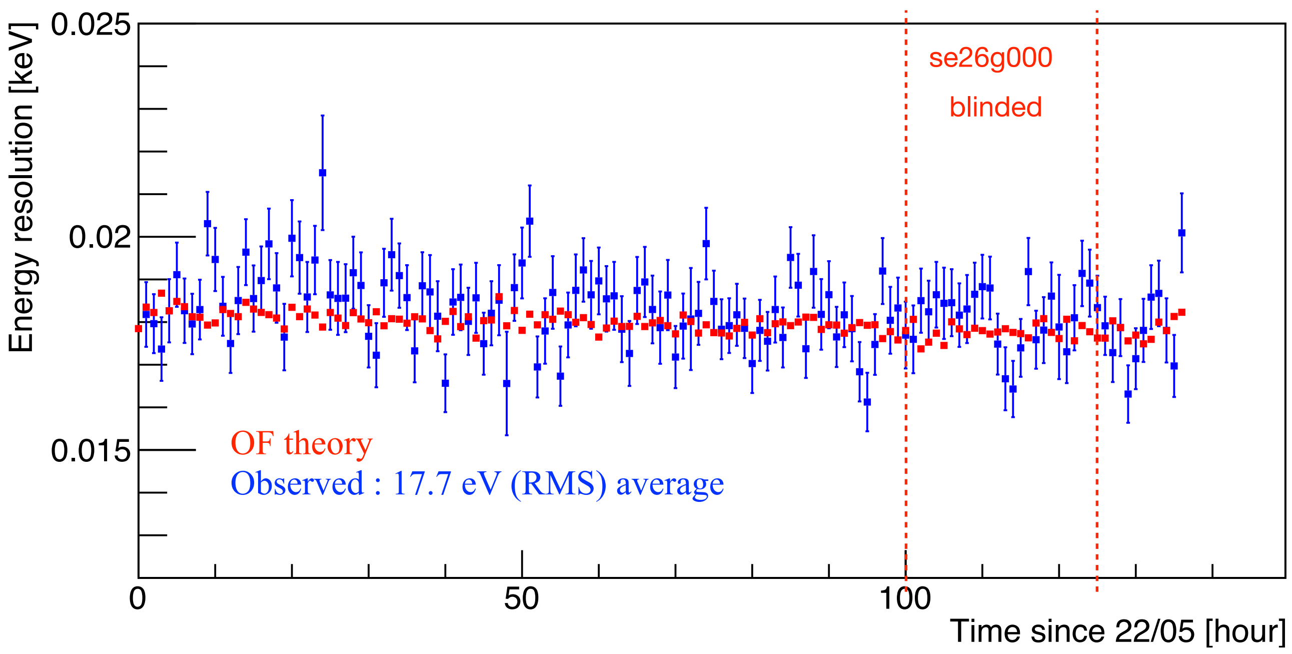
EDELWEISS-Surf

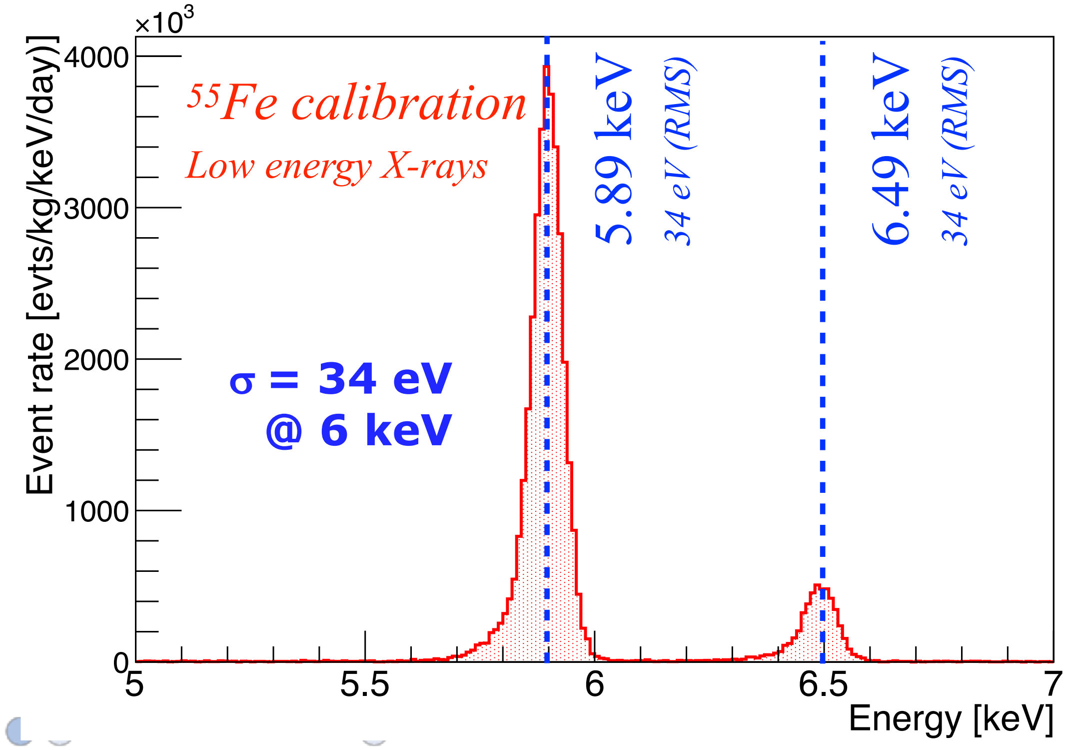
Technique: Heat Only

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]







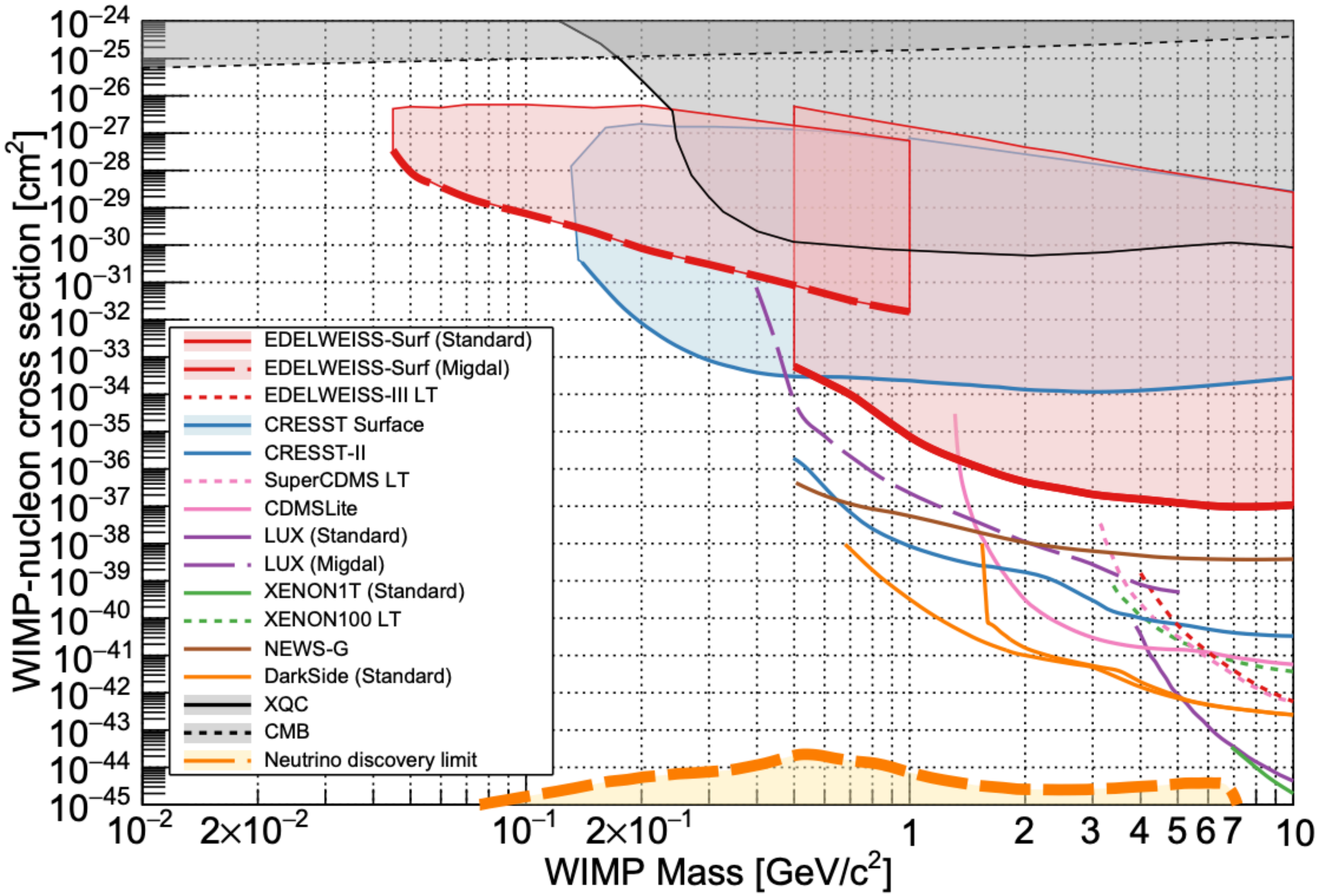
EDELWEISS-Surf

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




CRESST

CRESST Detector

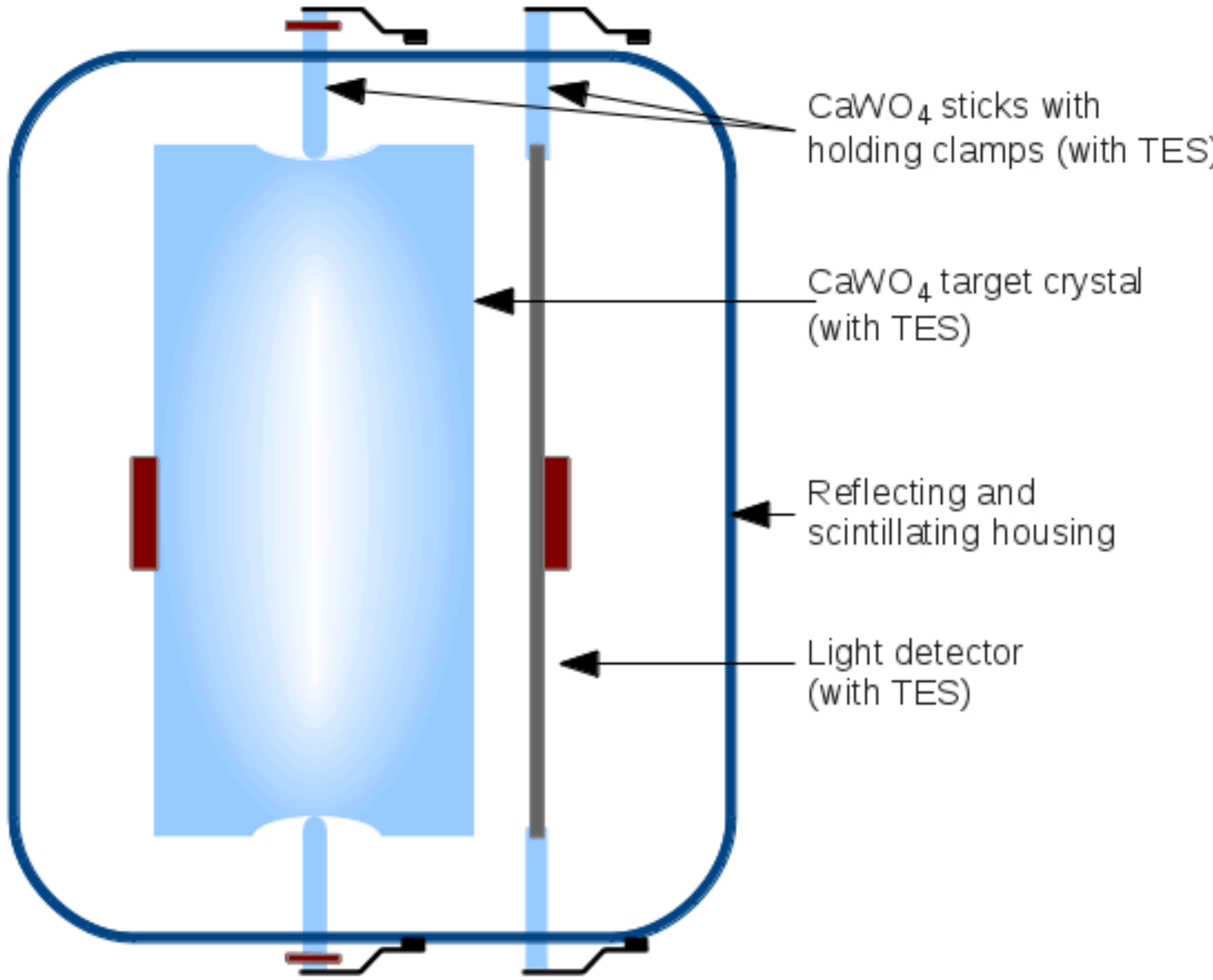
Technique: Heat+Scintillation

Scintillating $CaWO_4$ crystals as target

Target crystals operated as cryogenic calorimeters (~15mK)

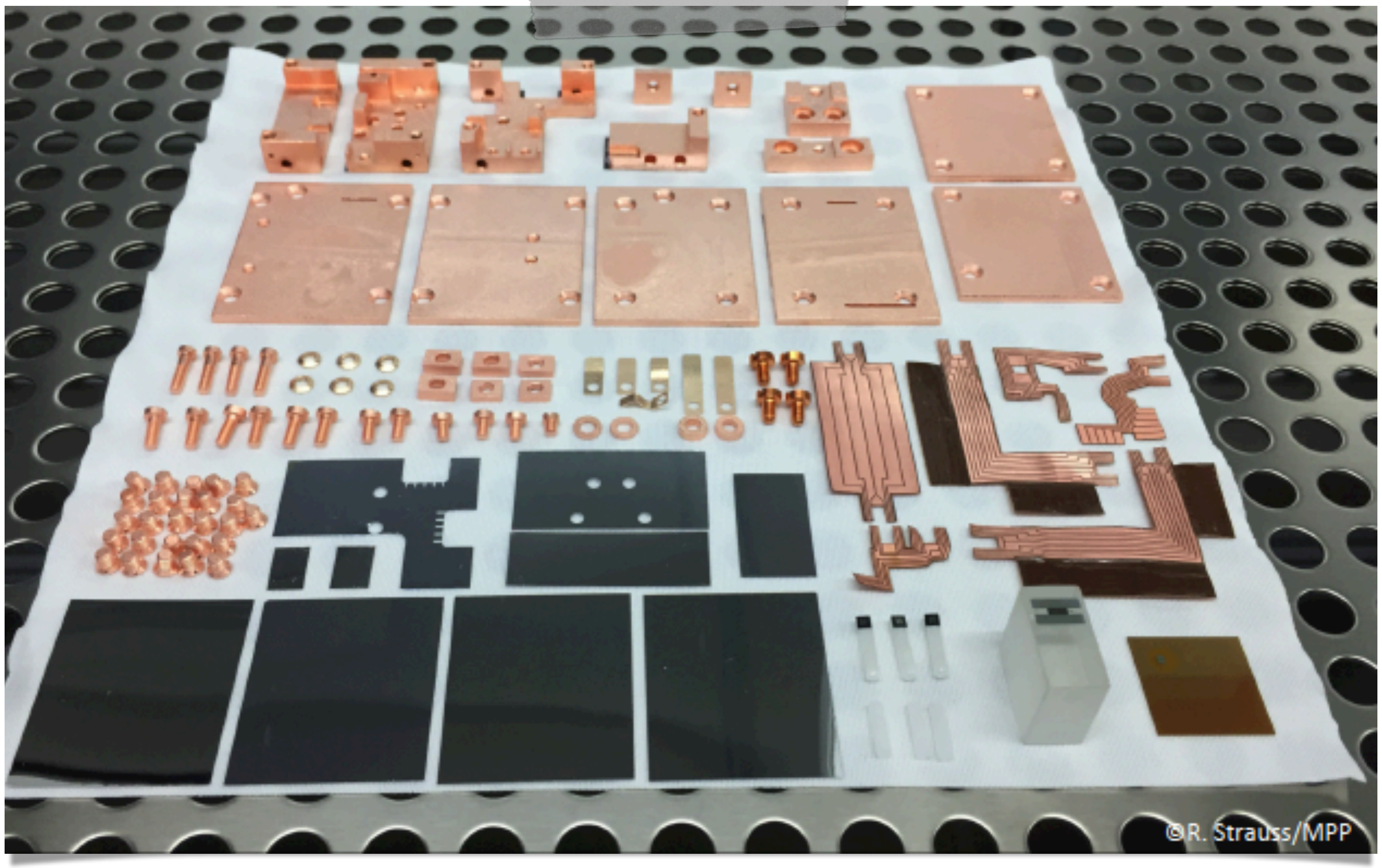
Collect both phonon and scintillating signals.

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



CRESST Detector

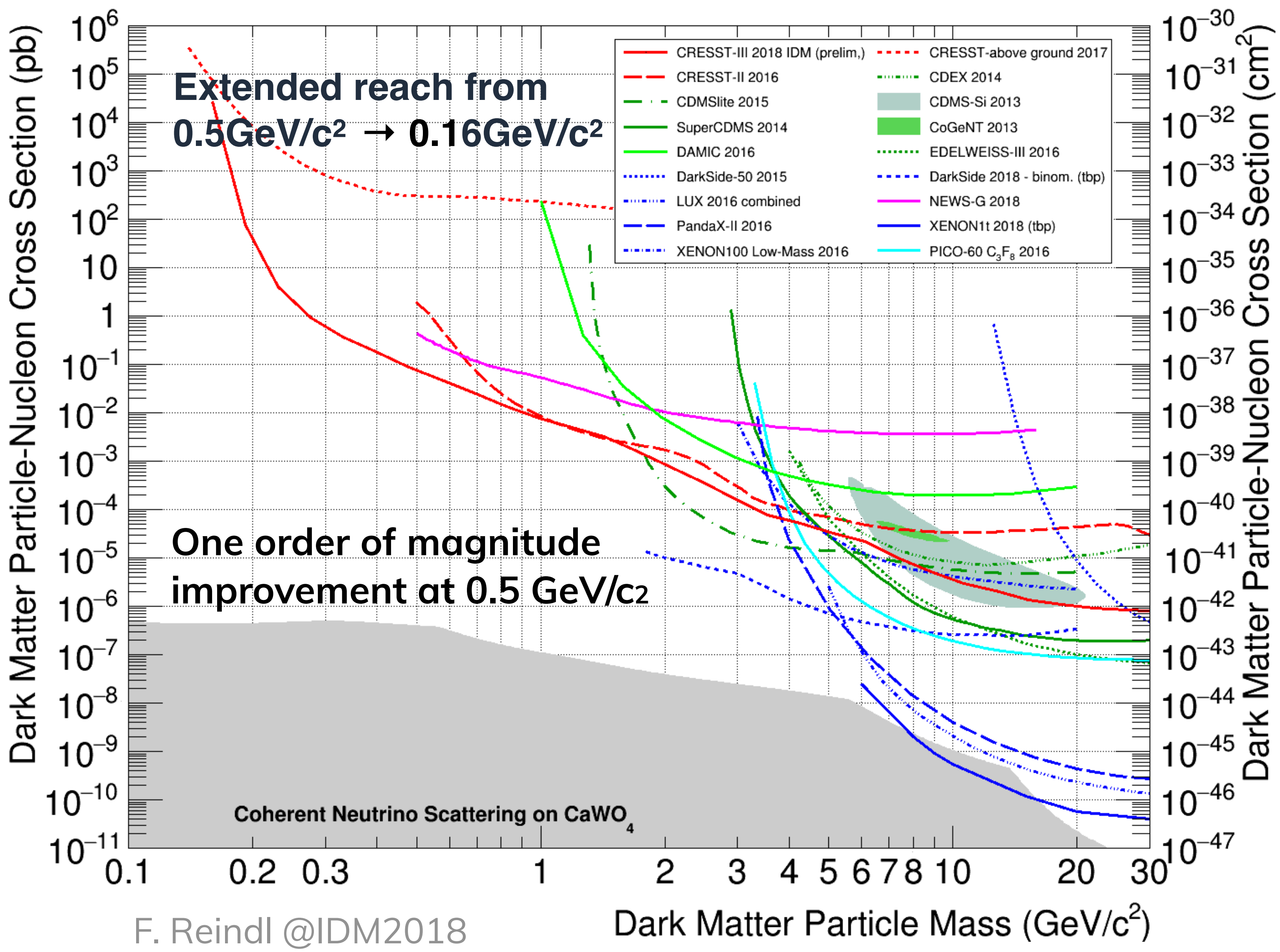
Technique: Heat+Scintillation



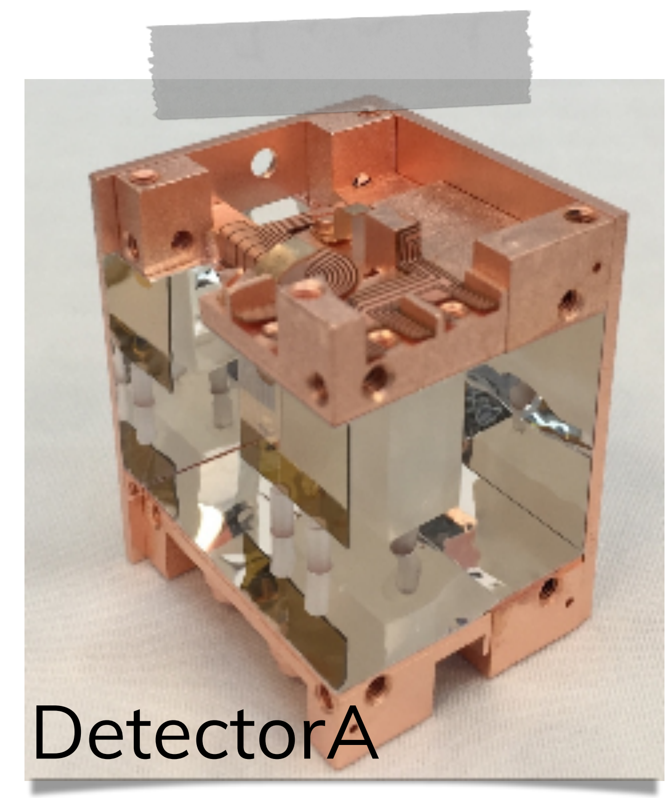
- Cuboid crystal (20 mm x 20 mm x 10 mm) ~ 24 g
- Goal: detection threshold of **100 eV**
- Self-grown crystal with low total background of ~**3 dru** [1-40 keV]
- Veto against surface related background: **fully scintillating housing** and instrumented sticks ("iSticks")

Results - Detector A

Technique: Heat+Scintillation



F. Reindl @IDM2018



Data taking period: 10/16 –01/18

Target crystal mass: 24g

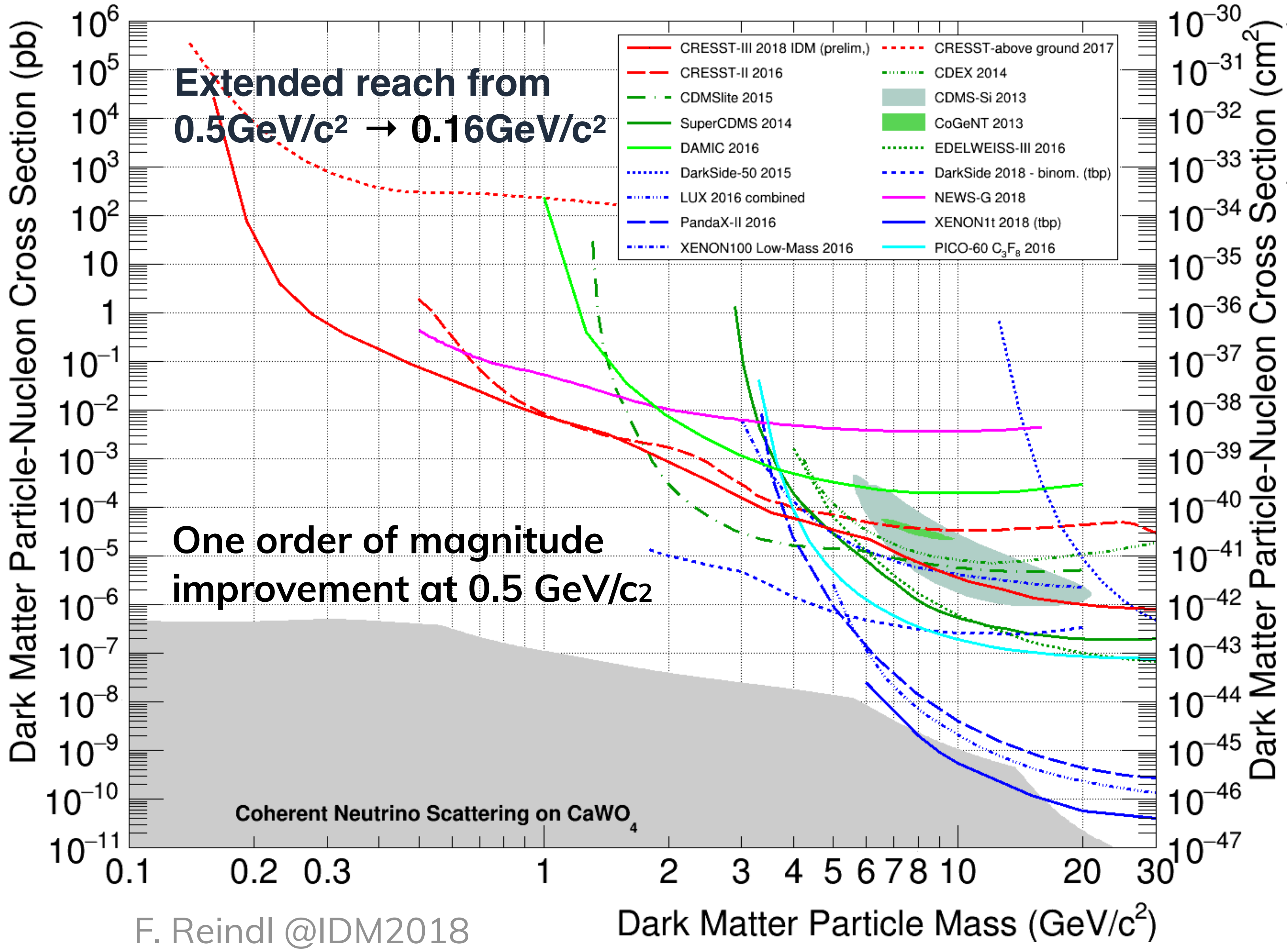
Gross exposure: 5.7 kg days

Nuclear recoil threshold: 30.1 eV

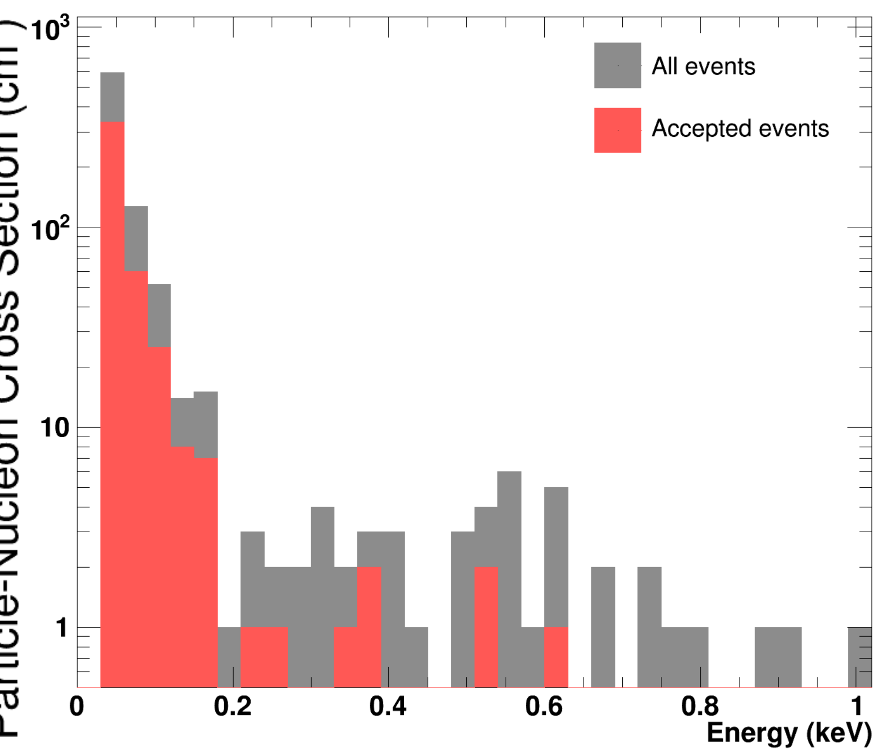
Results - Detector A

Technique: Heat+Scintillation

F. Reindl @IDM2018



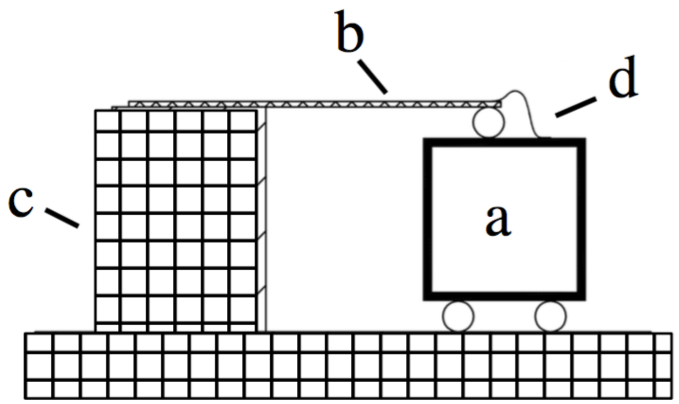
F. Reindl @IDM2018

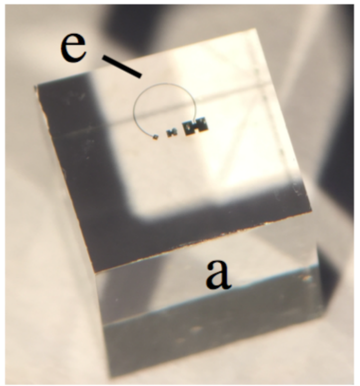


Unexpected rise of event rate < 200eV

CRESST Detector

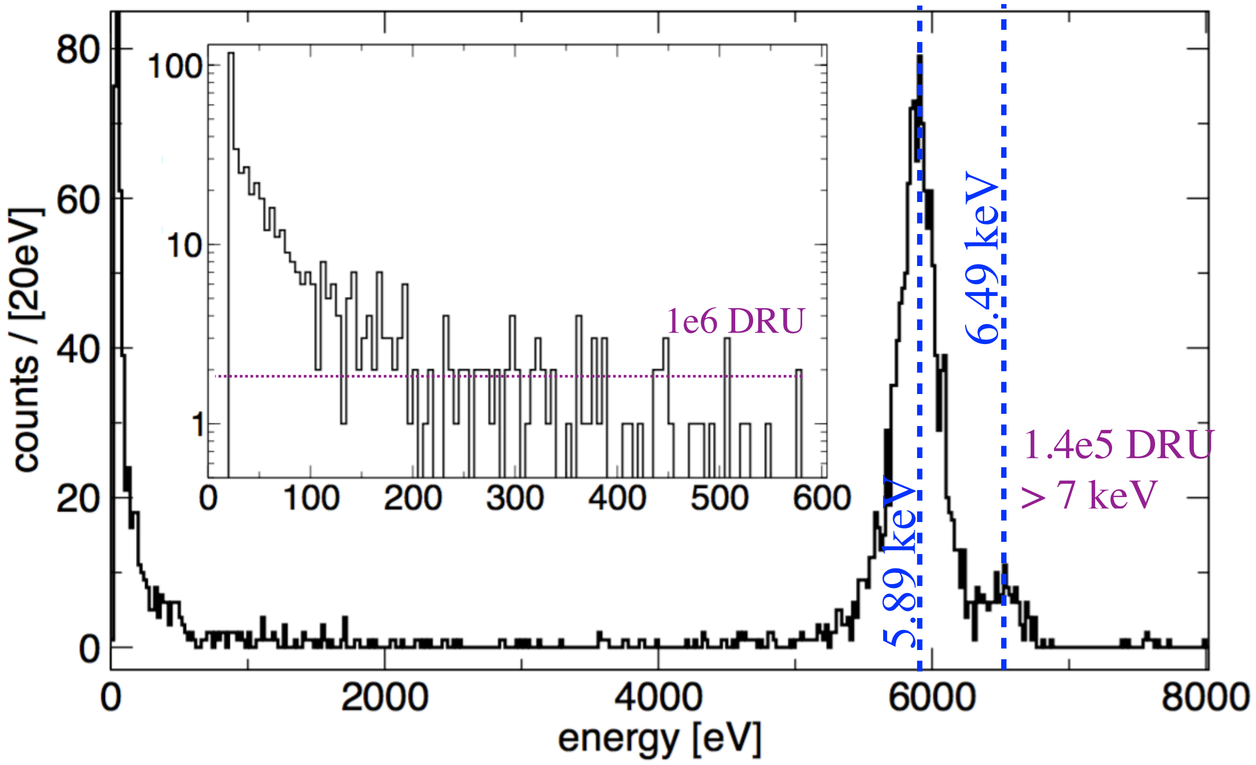
Technique: Heat Only





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 **19.7 eV** energy threshold
- **Above ground operation** at MPI in Munich with no passive / active shielding
- Non-blind analysis with no event selection cut, only stability cuts (62 % efficiency)

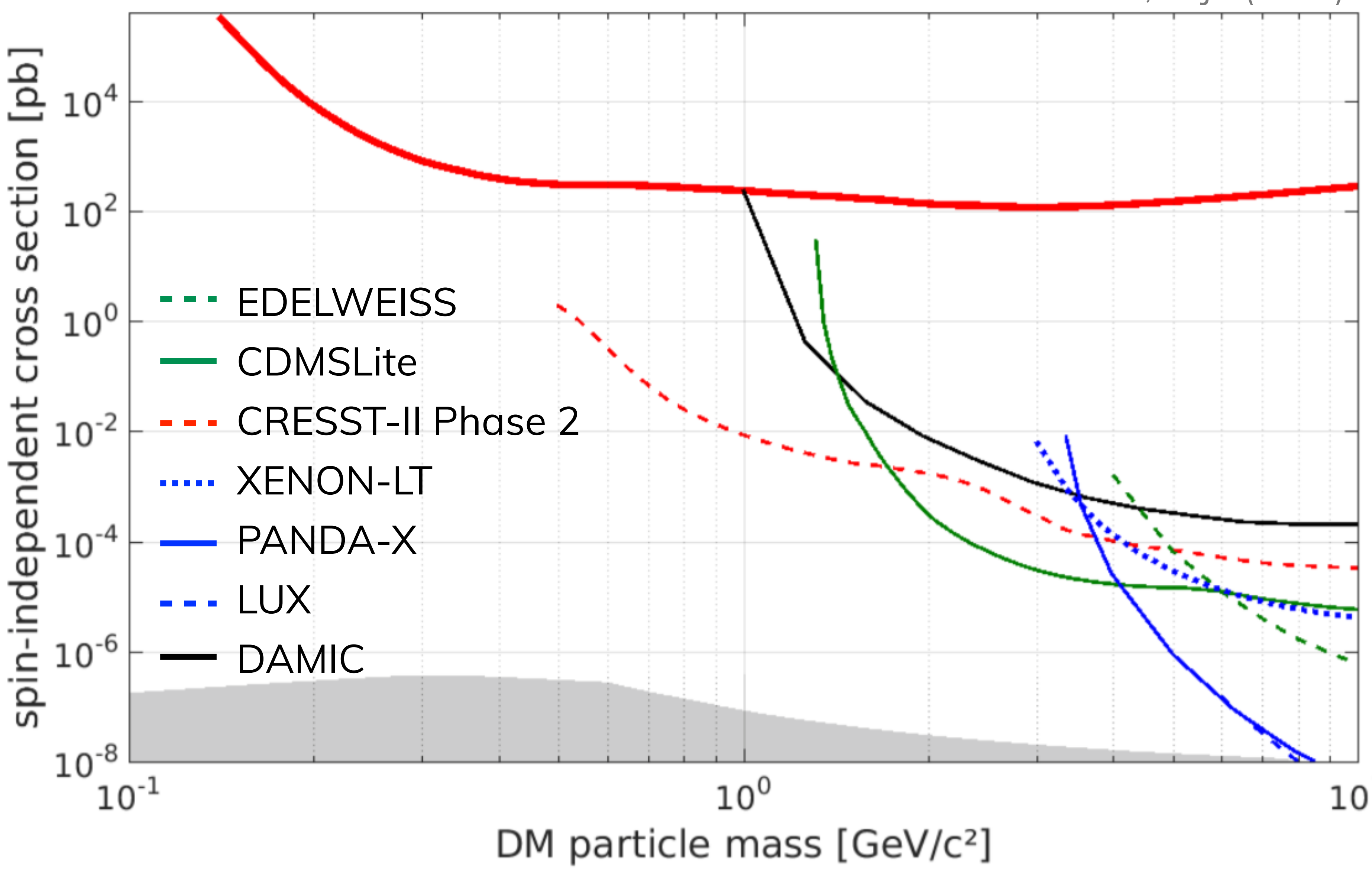


R. Strauss et al., EPJC 2017

CRESST Detector

Technique: Heat Only

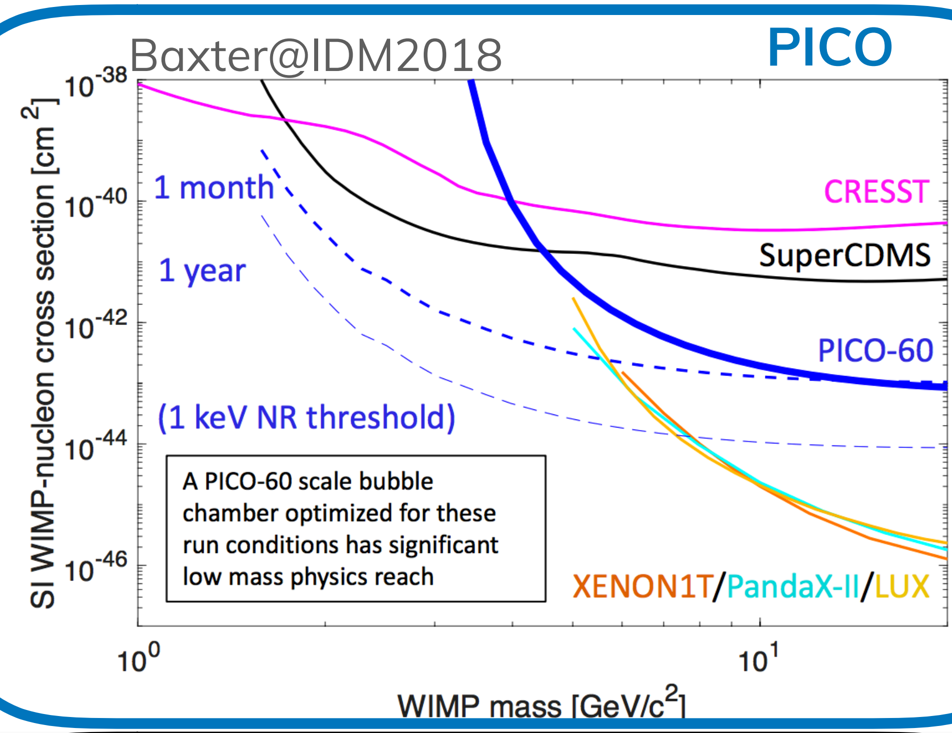
CRESST Coll., EPJC (2017)

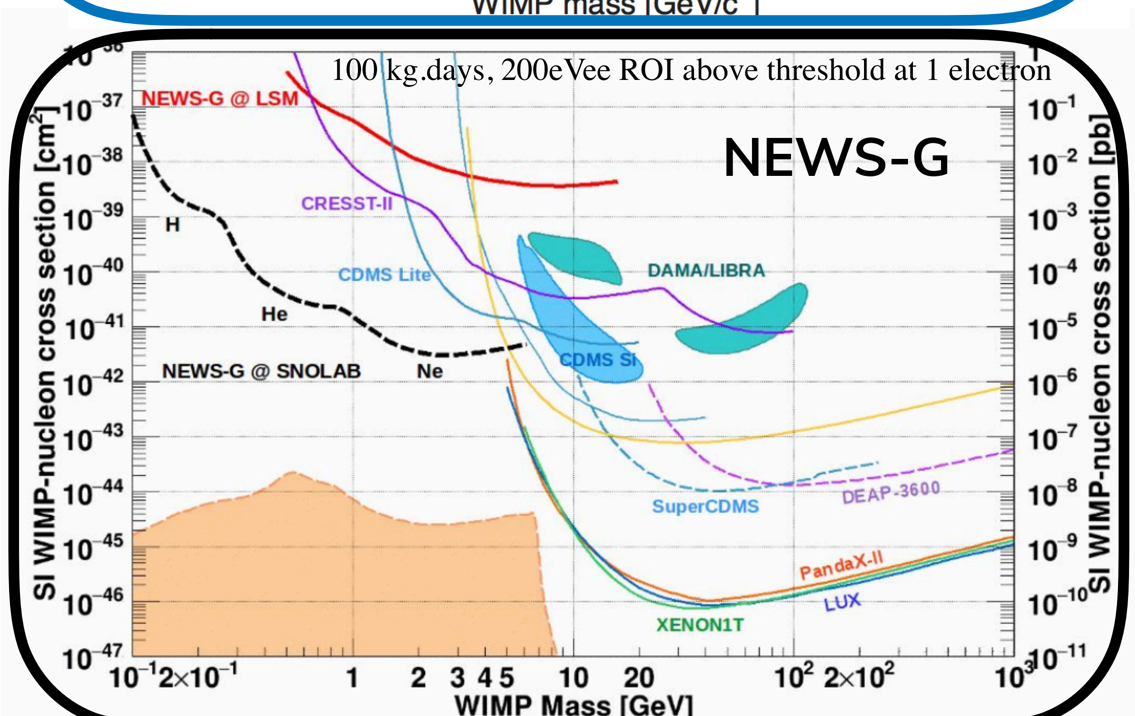


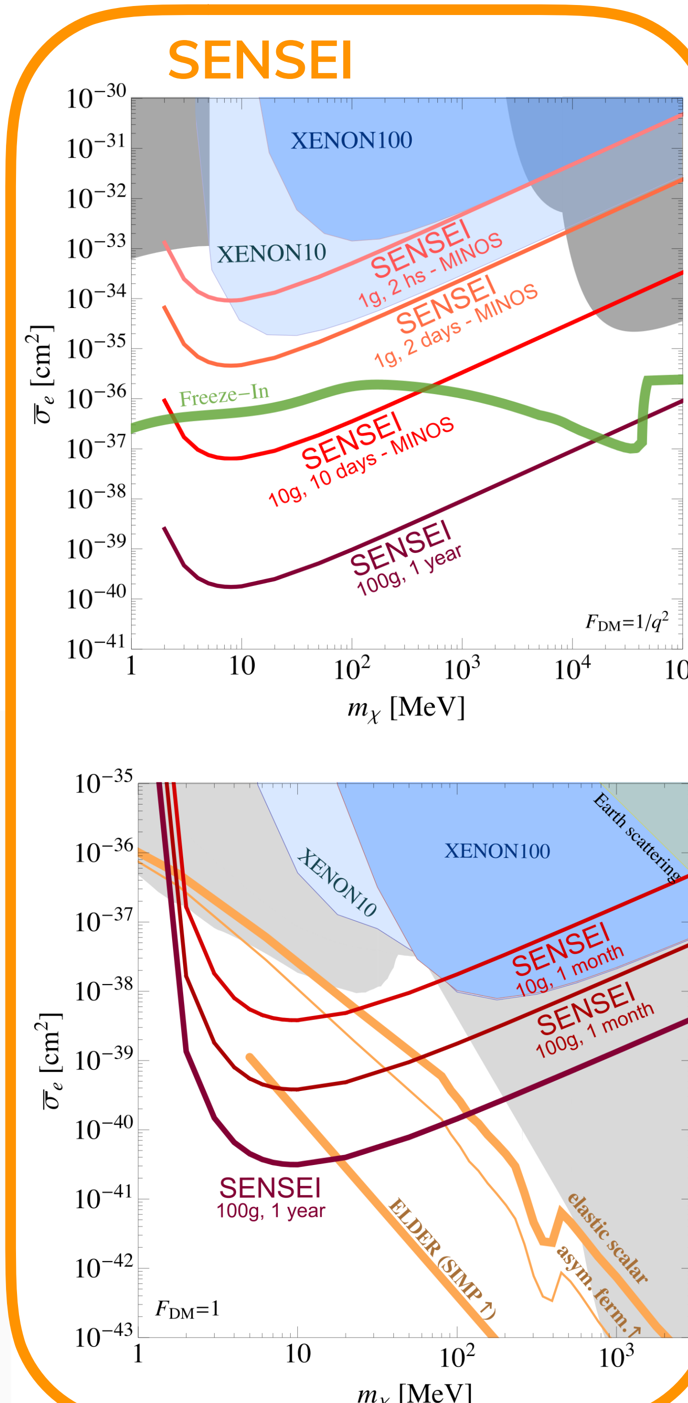
Leading limit from 500 MeV to 140 MeV

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

There is More…

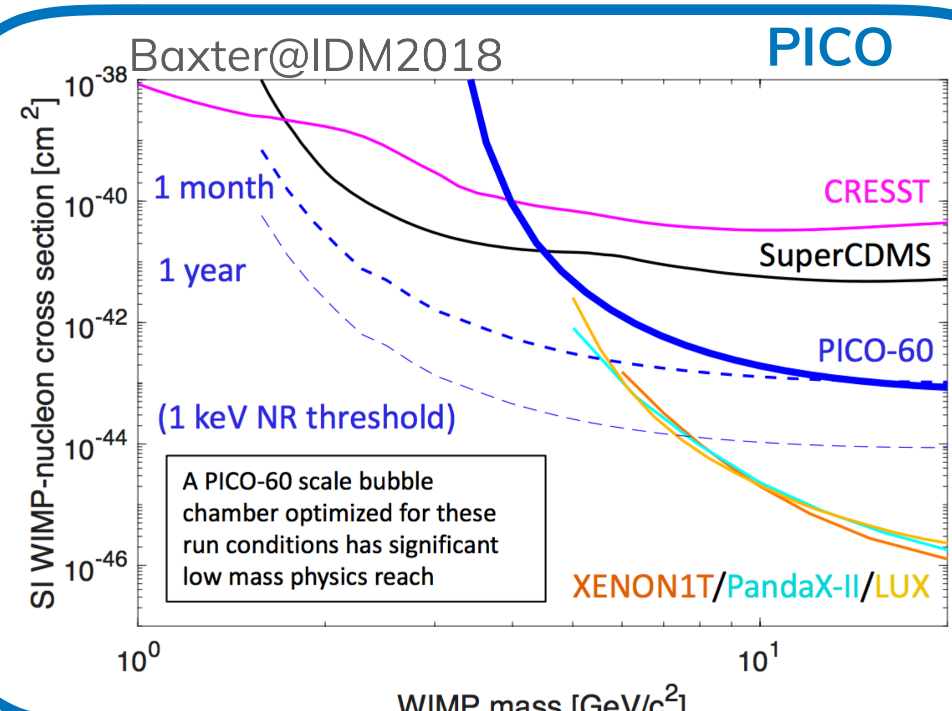




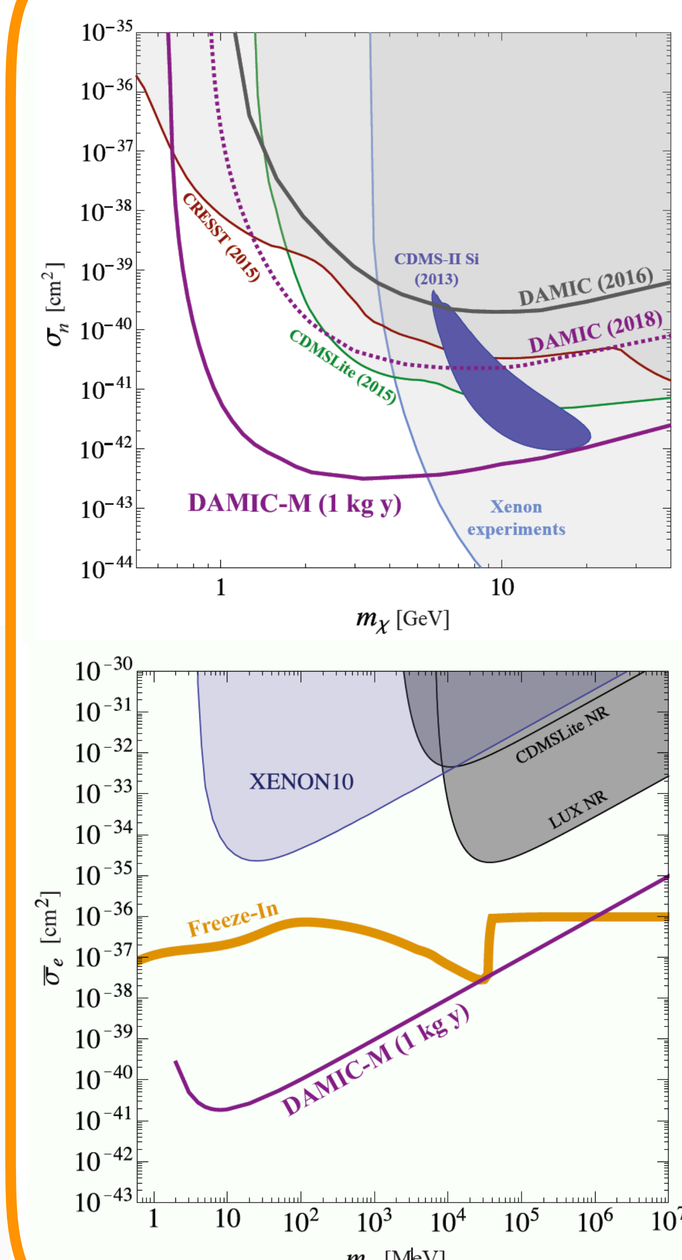


There is More…

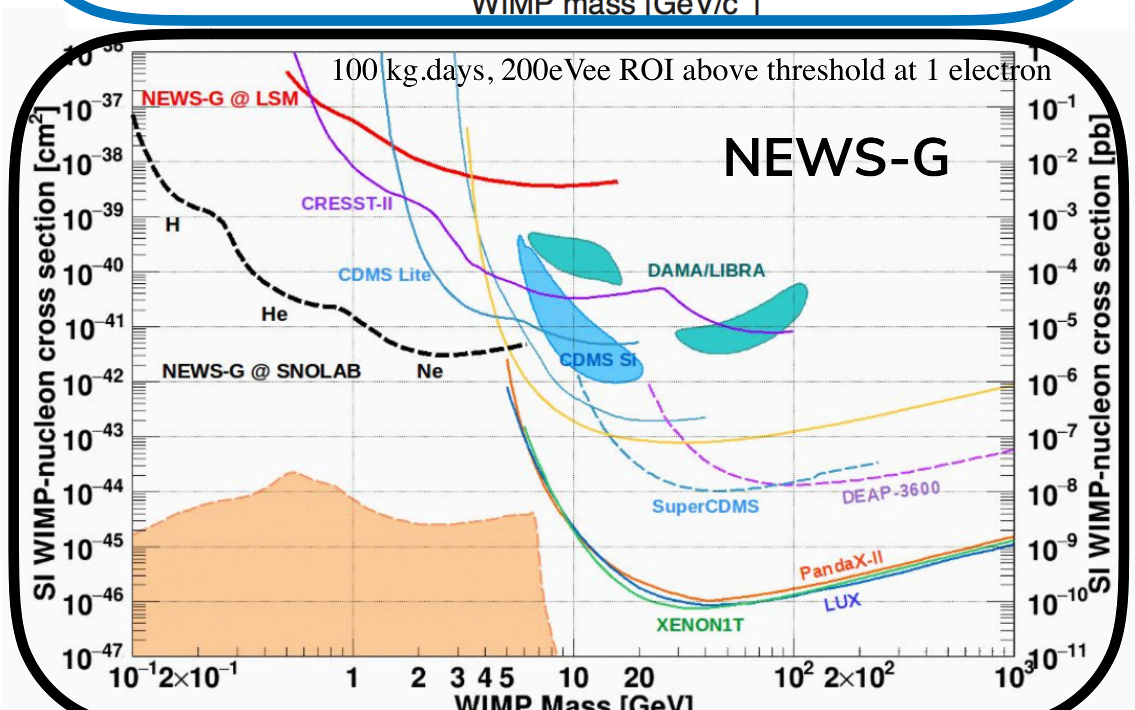
PICO



DAMIC-M



Grayson C. Rich @IDM2018



Arnaud@LLWI2018

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!