DARK MATTER DIRECT DETECTION OF CLASSICAL WIMPS – LECTURE 3

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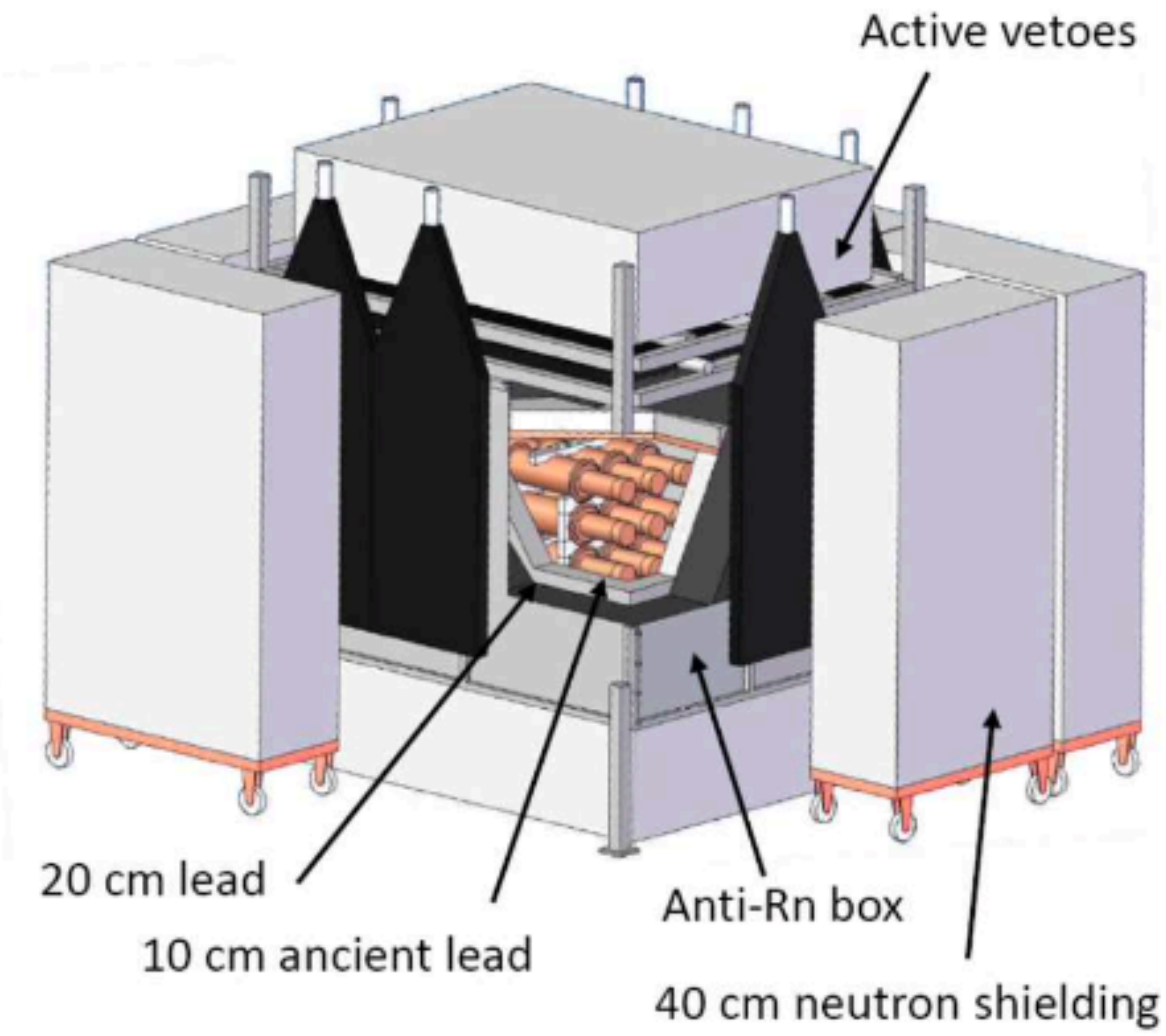
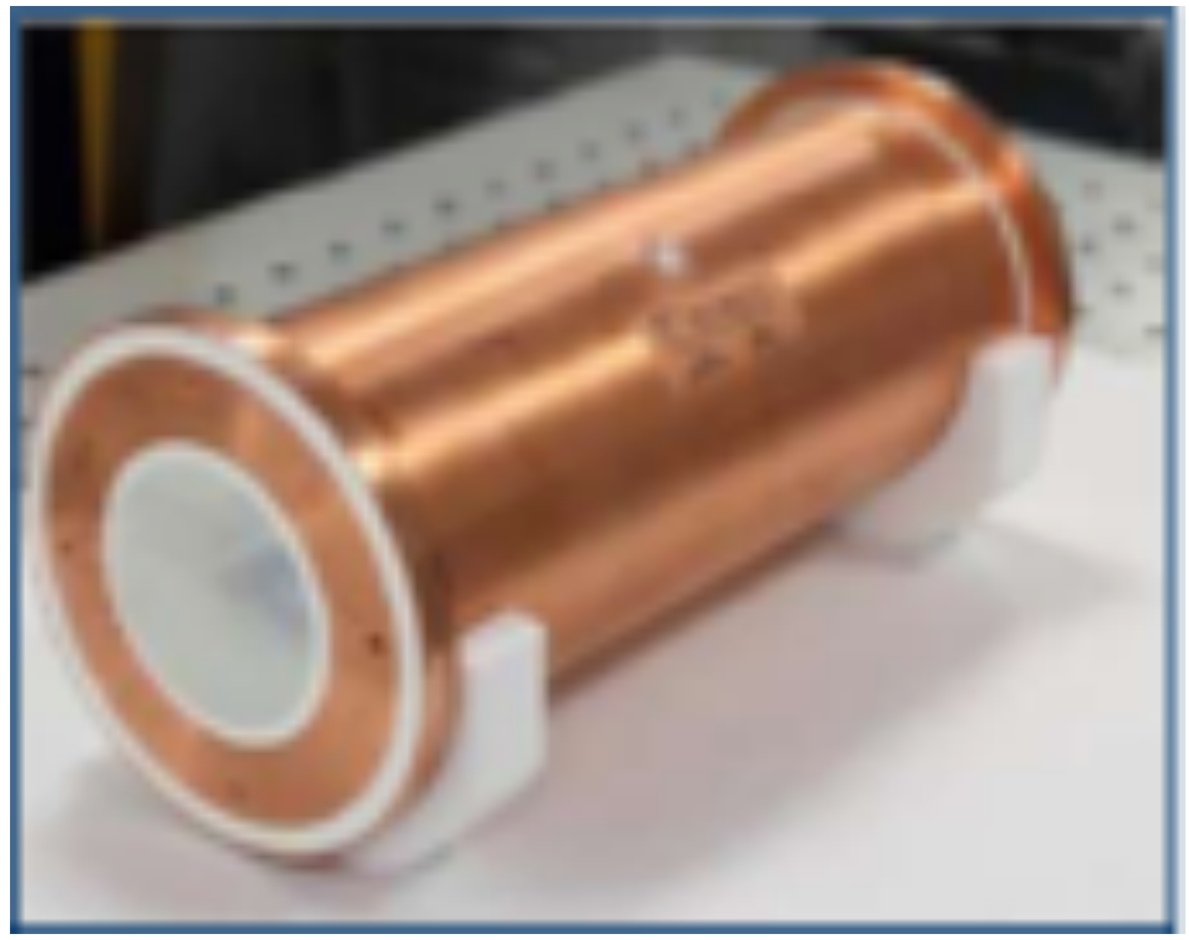
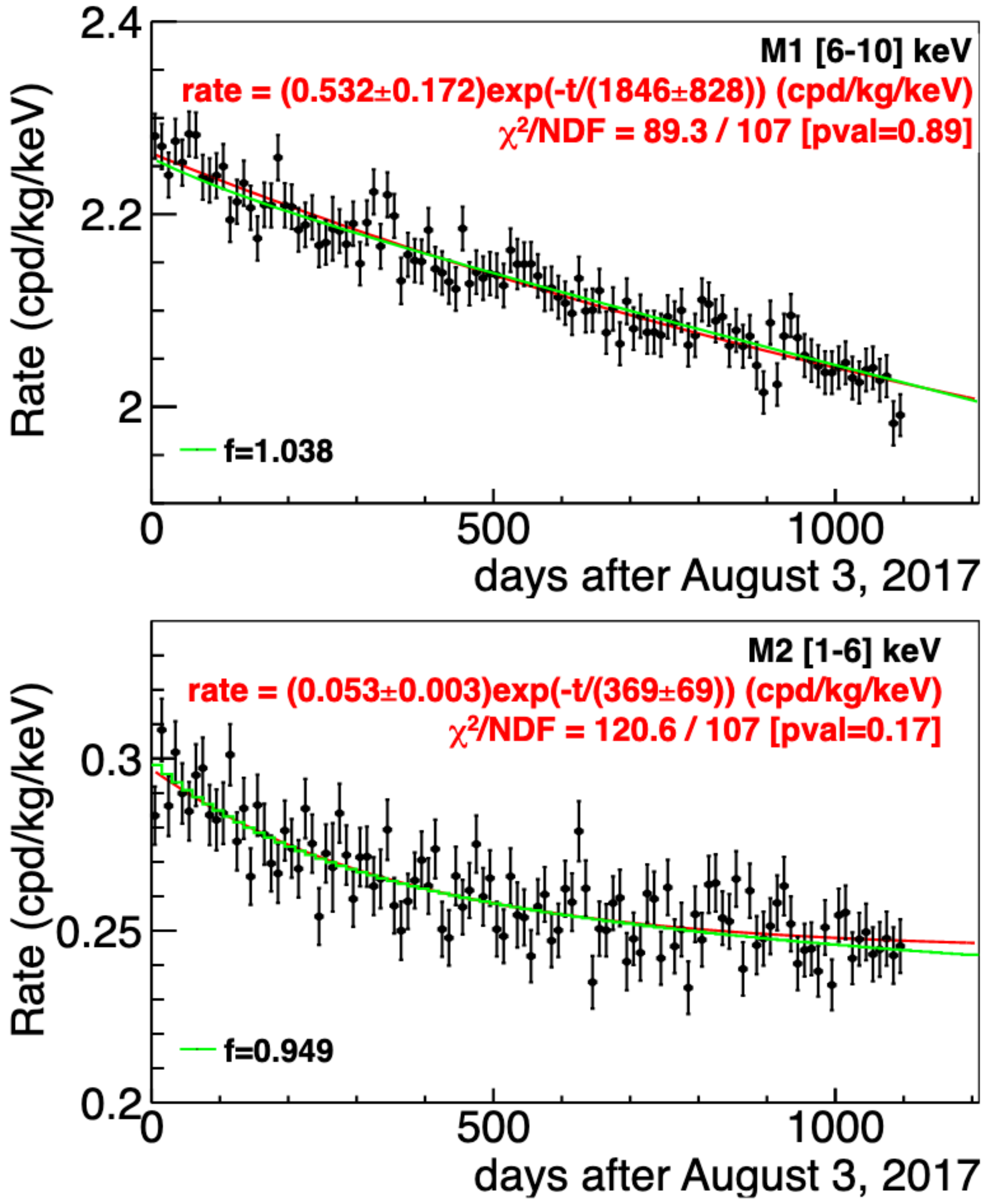
Phys. Rev. D 103, 102005

ANAIS 112





- Located in Hall B at the Canfranc Laboratory (2450 mwe).
- NaI(Tl) crystals (12.5 kg each) grown from ultra pure NaI powder and housed in OFE copper.
    - 112.5 kg of NaI(Tl), distributed in a 3×3 array of modules.
- Mylar window for low energy calibration
- Two Hamamatsu R12669SEL2 photomultipliers
    - Low background, high quantum efficiency.

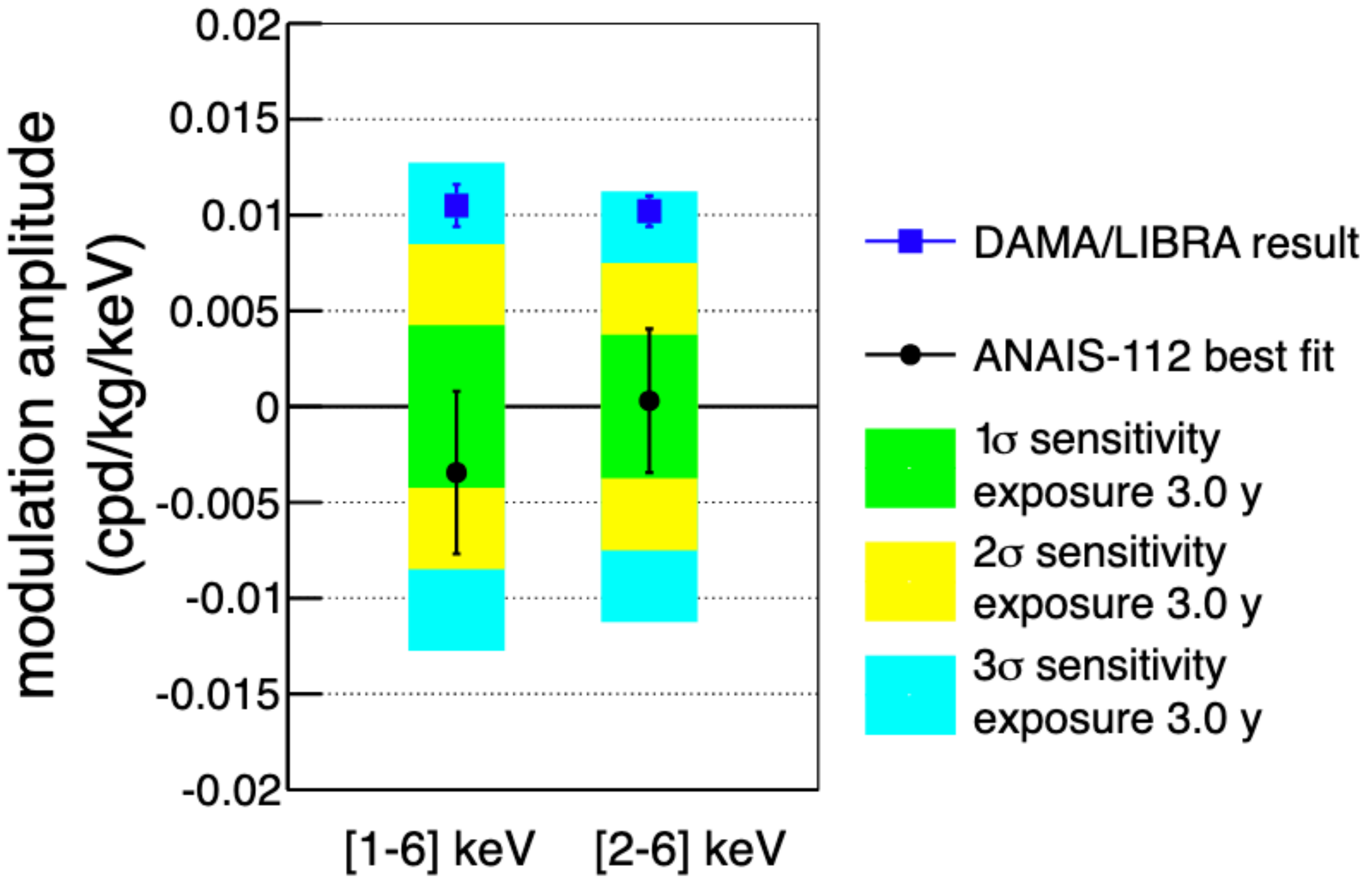


ANAIS112: 3-YEAR BACKGROUND MODELS:

- Three independent background modeling procedures:
  - Exponetinally decaying background
  - Probability distribution function derived from background mode
  - Probability distribution function for every detector to account for possible systematic effects related with the different backgrounds and efficiencies of the different modules.

ANAIS 112: 3 YEAR RESULTS

Energy region	Model	χ^2/NDF null hyp	nuisance params	S_m cpd/kg/keV	p-value mod	p-value null
[1-6] keV	1	132 / 107	3	-0.0045±0.0044	0.051	0.051
	2	143.1 / 108	2	-0.0036±0.0044	0.012	0.013
	3	1076 / 972	18	-0.0034±0.0042	0.011	0.011
[2-6] keV	1	115.7 / 107	3	-0.0008±0.0039	0.25	0.27
	2	120.8 / 108	2	0.0004±0.0039	0.17	0.19
	3	1018 / 972	18	0.0003±0.0037	0.14	0.15



- Data support the absence of modulation in both energy region and three background models.
- Best fits are incompatible with DAMA/LIBRA at 3.3σ in the [1-6] keV region and 2.6σ in the [2-6]keV region

LIQUID NOBLE EXPERIMENTS

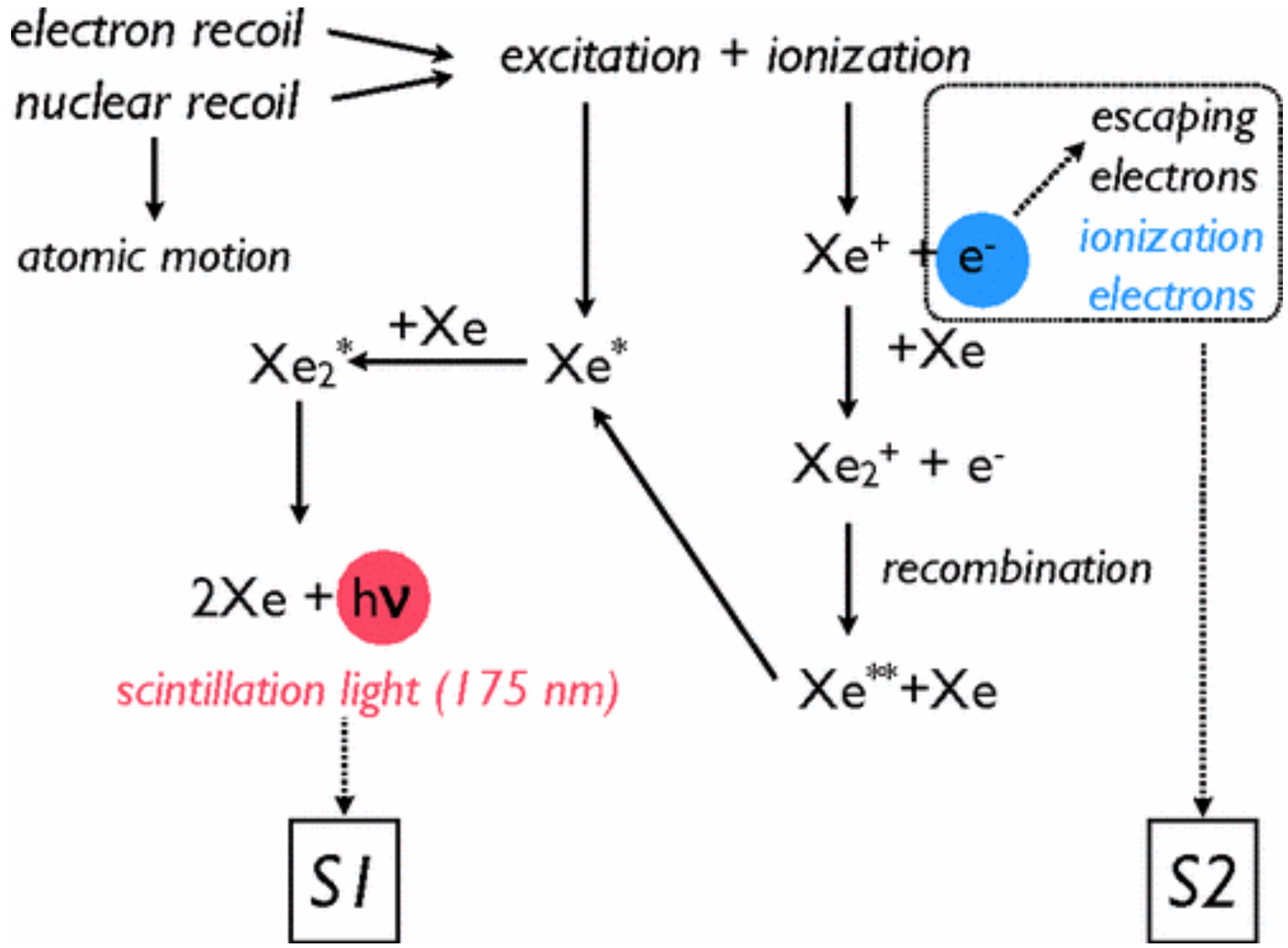
LIQUID NOBLE PROPERTIES

Property (unit)	Xe	Ar	Ne
Atomic Number	54	18	10
Mean relative atomic mass	131.3	40.0	20.2
Boiling Point T_b (K)	165.0	87.3	27.1
Melting Point T_m (K)	161.4	83.8	24.6
Liquid density at T_b (g cm^{-3})	2.94	1.40	1.21
Volume fraction in Earth's atmosphere (ppm)	0.09	9340	18.2
Scintillation light wavelength (nm)	175	128	78
Triplet lifetime (ns)	27	1600	15000
Singlet lifetime (ns)	3	7	<18
Electron mobility (cm^2 V^{-1} s^{-1})	2200	400	low
Scintillation yield (photons/keV)	42	40	30

Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
W values (eV)	26.4[a]	24.2[a]	22.0[a]
Liquid			
Gap energy (eV)	14.3	11.7	9.28
W value (eV)	23.6±0.3[b]	18.4±0.3[c]	15.6±0.3[d]

- Three different noble liquids have been considered for dark matter detection over the past few decades.
- Properties of the noble liquids determine many practical aspects of the detectors. For example, Xe has a high density and a large target mass (favorable) but it is not very abundant in the atmosphere (more expensive).
- The energy loss of an incident particle in noble liquids is shared between excitation, ionization and sub-excitation electrons liberated in the ionization process
- The average energy loss in ionization is slightly larger than the ionization potential or the gap energy, because it includes multiple ionization processes
- As a result, the ration of the W-value (= average energy required to produce an electron-ion pair) to the ionization potential or gap energy = 1.6 - 1.7

LIQUID NOBLE SIGNAL PRODUCTION

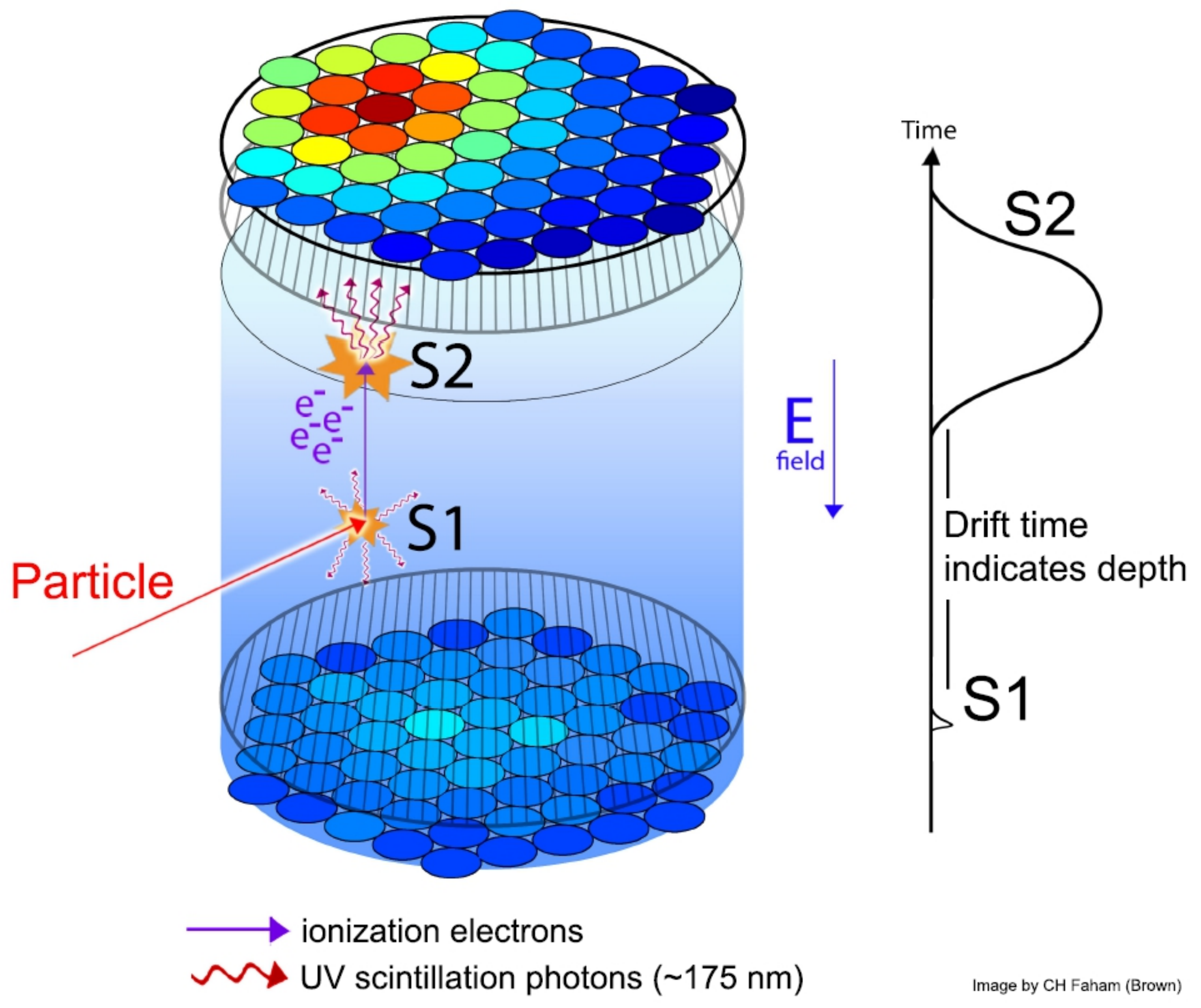


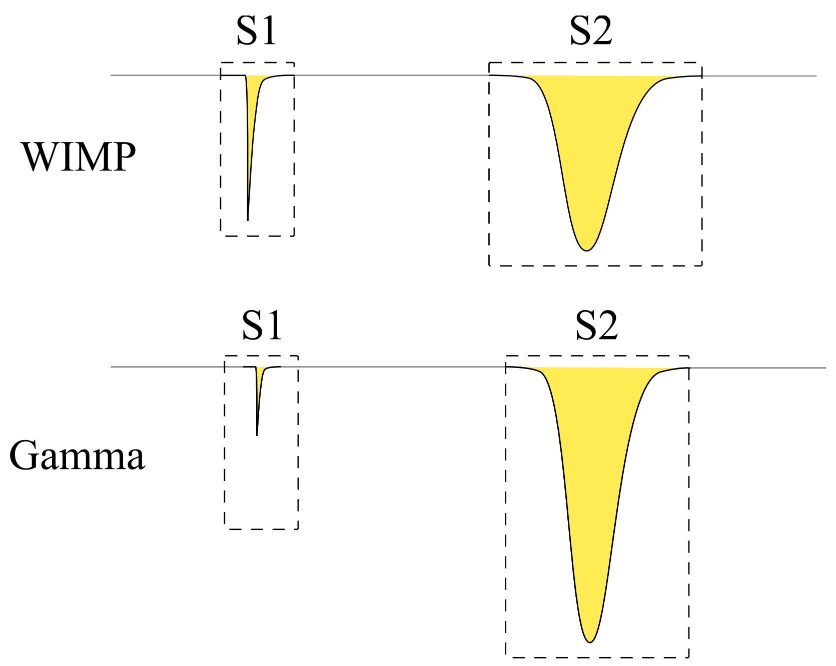
- Energy is transferred to a particle by excitation, ionization or heat (atomic motion).

$e^- + R \to R^* + e^-$	*impact excitation*
$R^* + R \to R_2^{*,v}$	*excimer formation*
$R_2^{*,v} + R \to R_2^* + R$	*relaxation*
$R_2^* \to R + R + h\nu$	*VUV emission*

$e^- + R \to R^+ + 2e^-$	*ionization*
$R^+ + R + R \to R_2^+ + R$	
$e^- + R_2^+ \to R^{**} + R$	*recombination*
$R^{**} + R \to R^* + R + \text{heat}$	
$R^* + R + R \to R_2^* + R + \text{heat}$	
$R_2^* \to R + R + h\nu$	*VUV emission*

LIQUID NOBLE DETECTORS

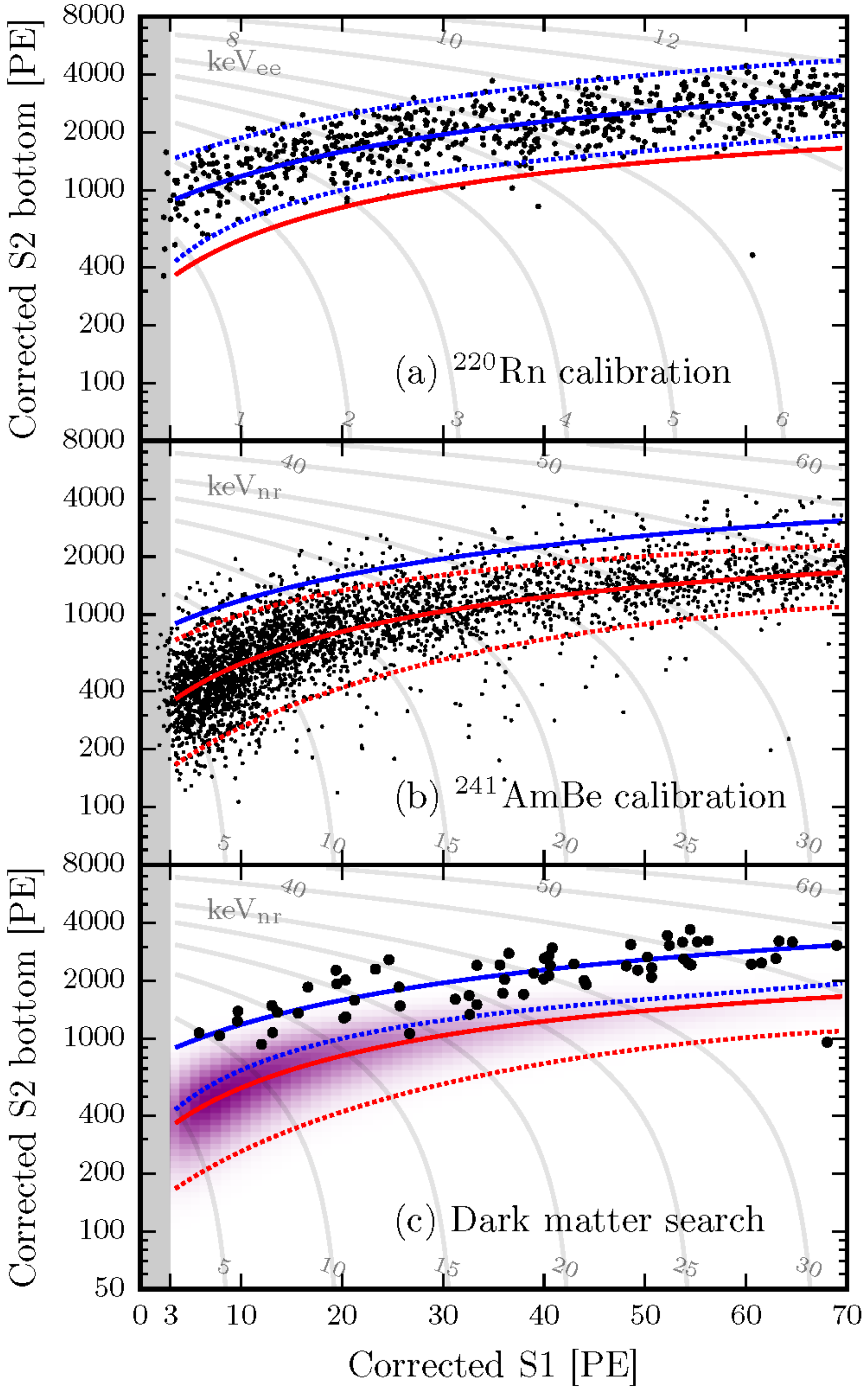




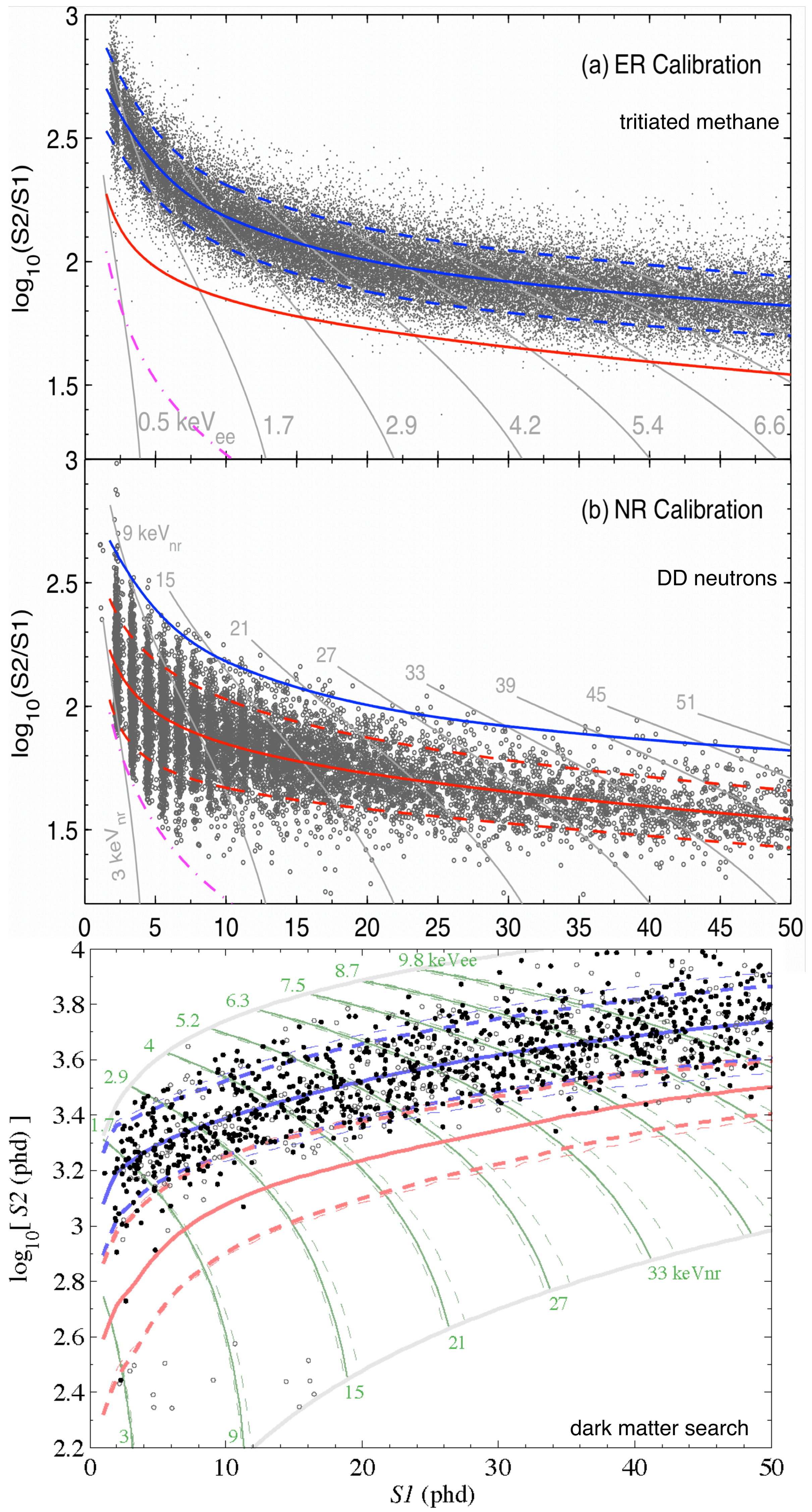
Dual Phase TPCs (XENON, LUX/LZ, Darkside PandaX, etc)

- Interactions in the liquid produce excitation and ionization.
- Excitation leads to scintillation light emission
- Ionization electrons are drifted with an applied electric field into the gas phase (S1).
- In the gas phase, electrons are further accelerated producing proportional scintillation (S2).
- PMTs on the bottom and top of the chamber record scintillation signals.
- Distribution of S2 give xy coordinates, drift time gives z coordinates
- Ratio of S2/S1 discriminates electron and nuclear recoils

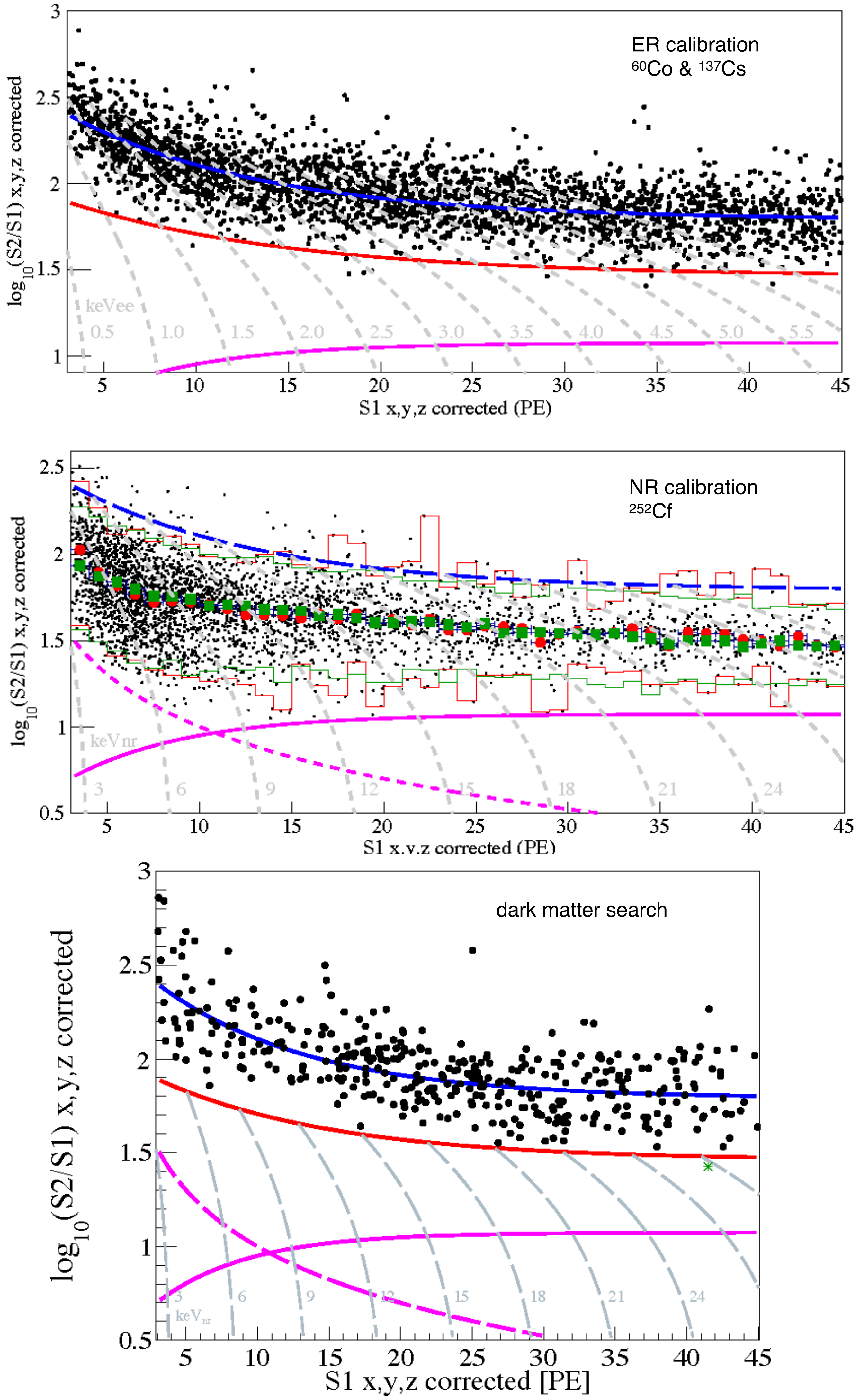
Xenon1T



LUX



PandaX-II



ENERGY

Nuclear recoils are measured through a combination of scintillation light and ionization. The nuclear recoil energy is related to S1 by

$$\underbrace{E_{nr}}_{[\mathrm{keV_{nr}}]} = \frac{\overbrace{S1}^{\text{observed scintillation [PE]}}}{\underbrace{L_y}_{\substack{\text{light yield}\\ [\mathrm{PE/keVee}]}} \underbrace{L_{eff}}_{\substack{\text{scintillation efficiency}\\ \text{of NR in LXe}}}} \times \frac{S_e}{S_r}$$

suppression of scintillation signal from electric field for ER and NR events

L_{eff} accounts for the quenching of the scintillation signal for a nuclear recoil.

$$L_{eff} \equiv \frac{S1(E_{nr})/E_{nr}}{S1(122keV_{ee})/122keV_{ee}}$$

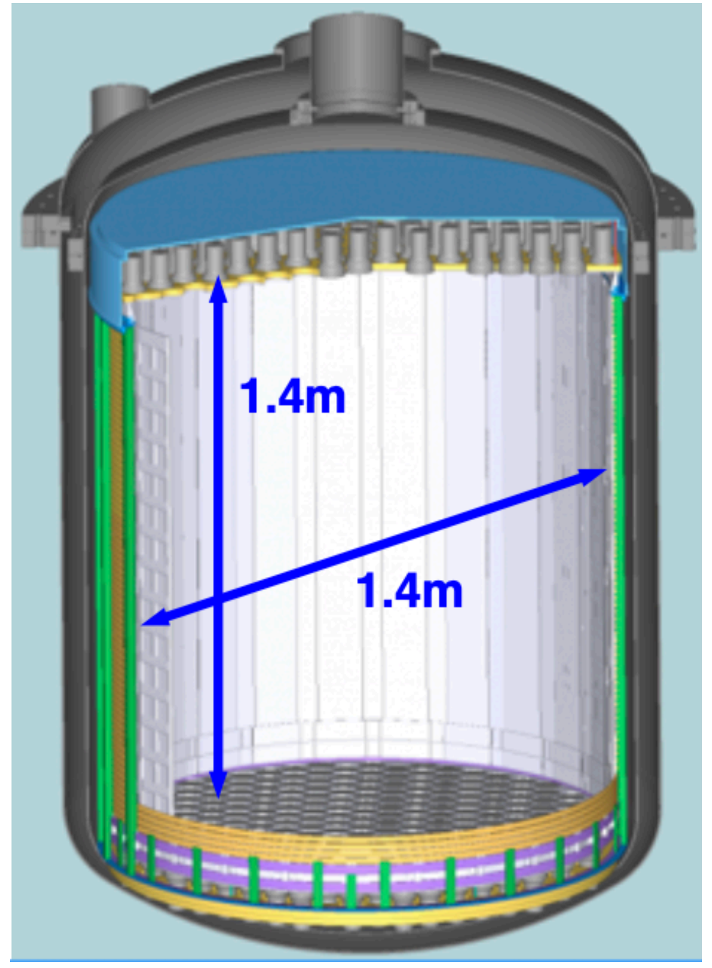
122 γ line from ^{57}Co source

The nuclear recoil energy is related to S2 by

$$\underbrace{E}_{[\mathrm{keV_{nr}}]} = \frac{\overbrace{S2}^{\text{observed scintillation [PE]}}}{\underbrace{Y}_{\substack{\text{secondary amplification factor}\\ [\mathrm{pe/e^-}]}}} \frac{1}{\underbrace{Q_y(E)}_{\substack{\text{number of free electrons}\\ \text{per unit energy}}}}$$

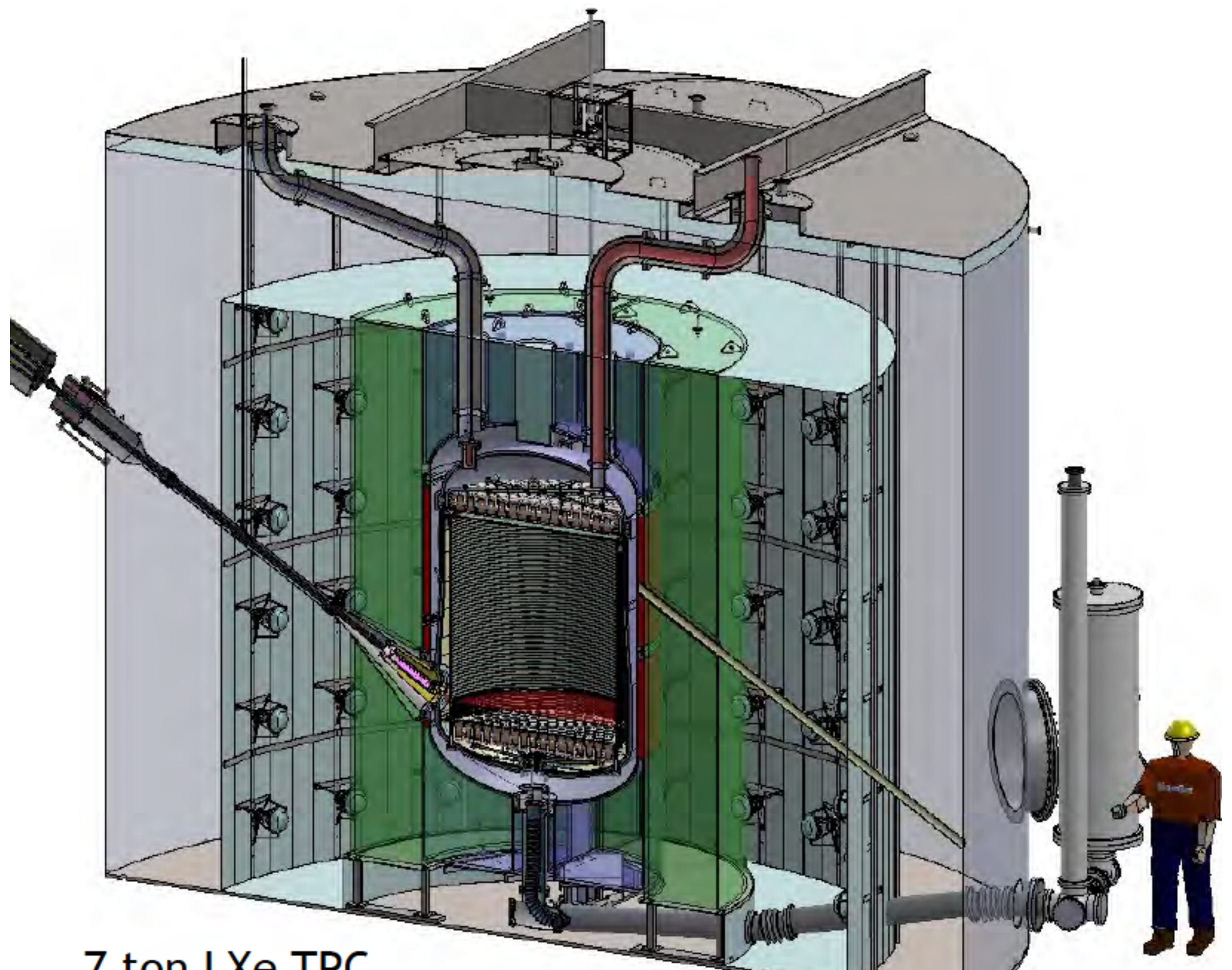
STATUS OF CURRENT TPC DARK MATTER EXPERIMENTS

XENONnT



Data Taking
2019-2025
8t LXe

LZ



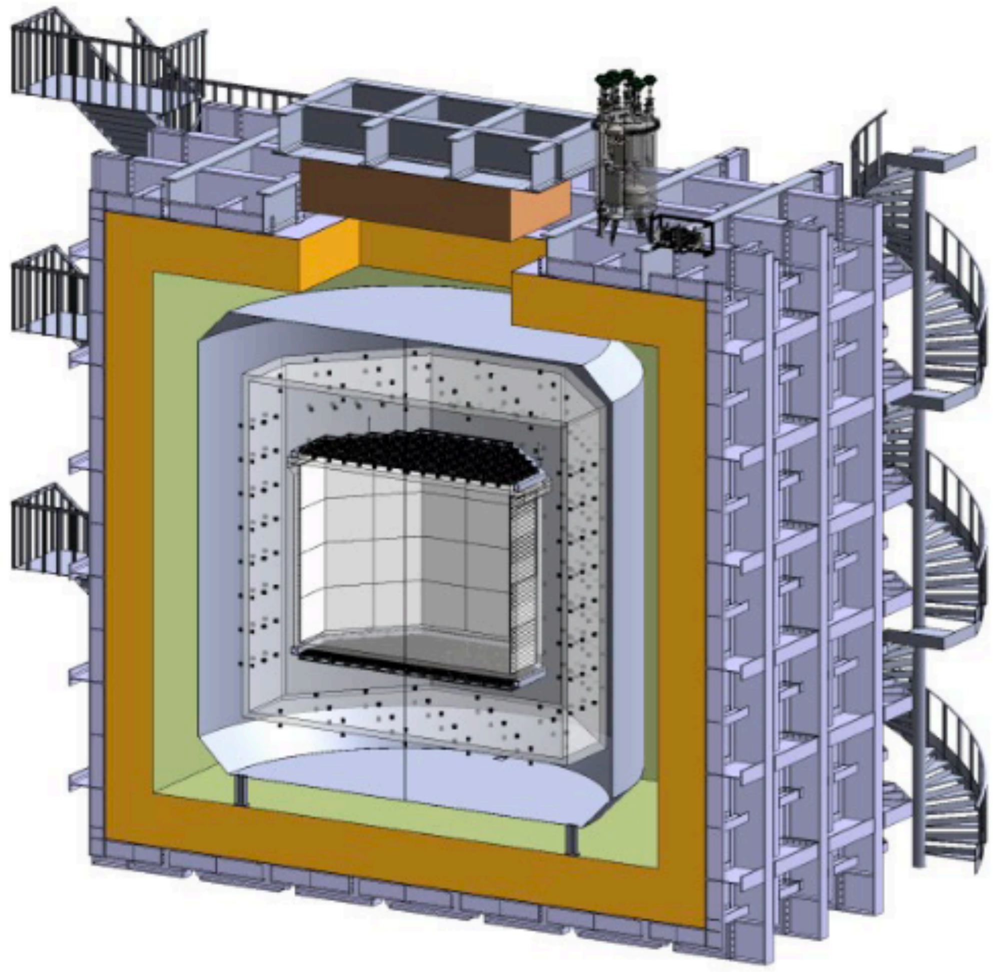
7 ton LXe TPC
(10 tons LXe total)

Commissioning
2019-2025 ?
7t LXe

PandaX-4T

Commissioning
2019 - ?
4t LXe

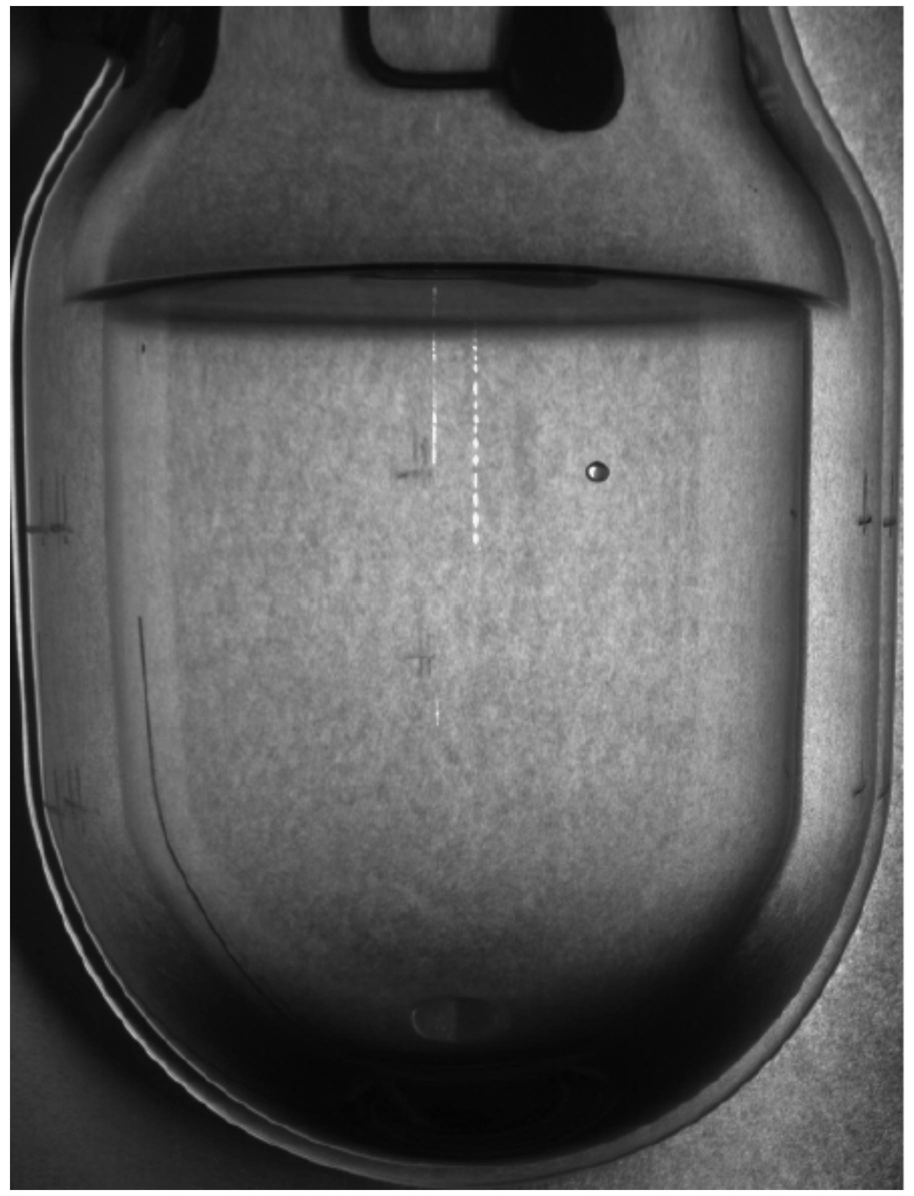
DarkSide-20K

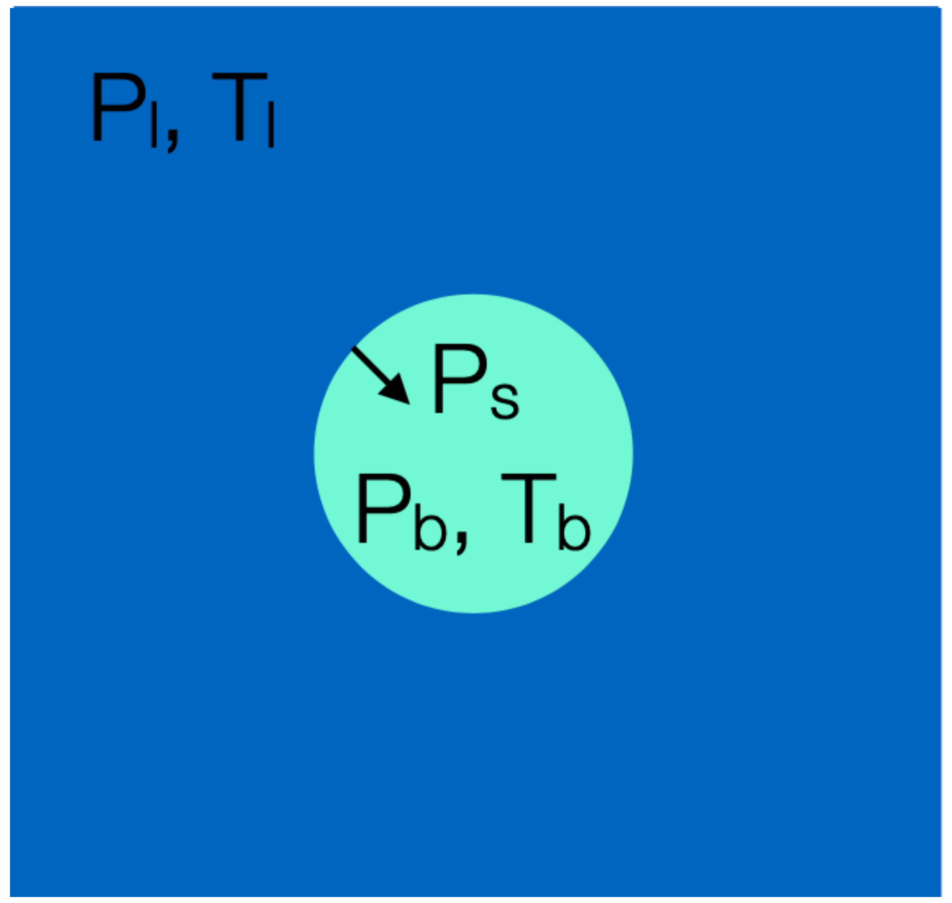


Under Design
50t LAr

BUBBLE CHAMBERS

HOW DO BUBBLE CHAMBERS WORK?





- The threshold for bubble nucleation is given by

$$E_T = r\pi r_c^2\left(\sigma - T\left[\frac{d\sigma}{dT}\right]_\mu\right) + \frac{4\pi}{3}r_c^3\rho_b(h_b - h_l) - \frac{4\pi}{3}r_c^3(P_b - P_l)$$

surface energy | *bulk energy* | *reversible work*

ρ = *density and* h = *specific heat*

- Start with a bubble in a liquid in thermal and chemical equilibrium

$$T_l = T_b$$

- If $P_b > P_l$ the bubble will expand (assuming no surface tension).
- Include surface tension, $P_s = 2\sigma/r$, bubble grows when

$$P_b > P_l + P_s$$

$$\text{and} \qquad r > r_c = \frac{2\sigma}{P_b - P_l}$$

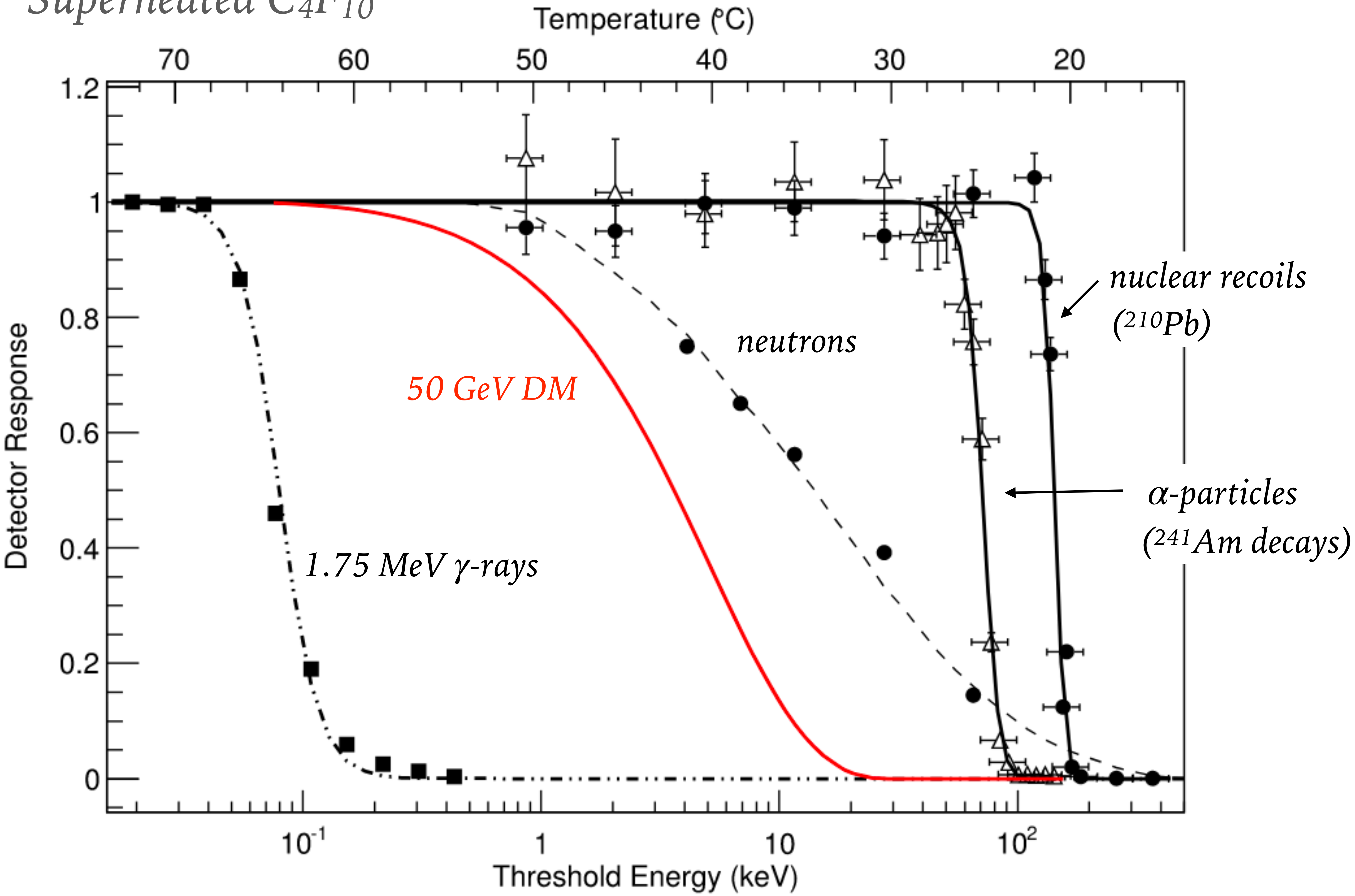
- Bubbles that do not meet this criteria collapse

Physics Letters B 711 (2012) 153–161

DETECTOR RESPONSE

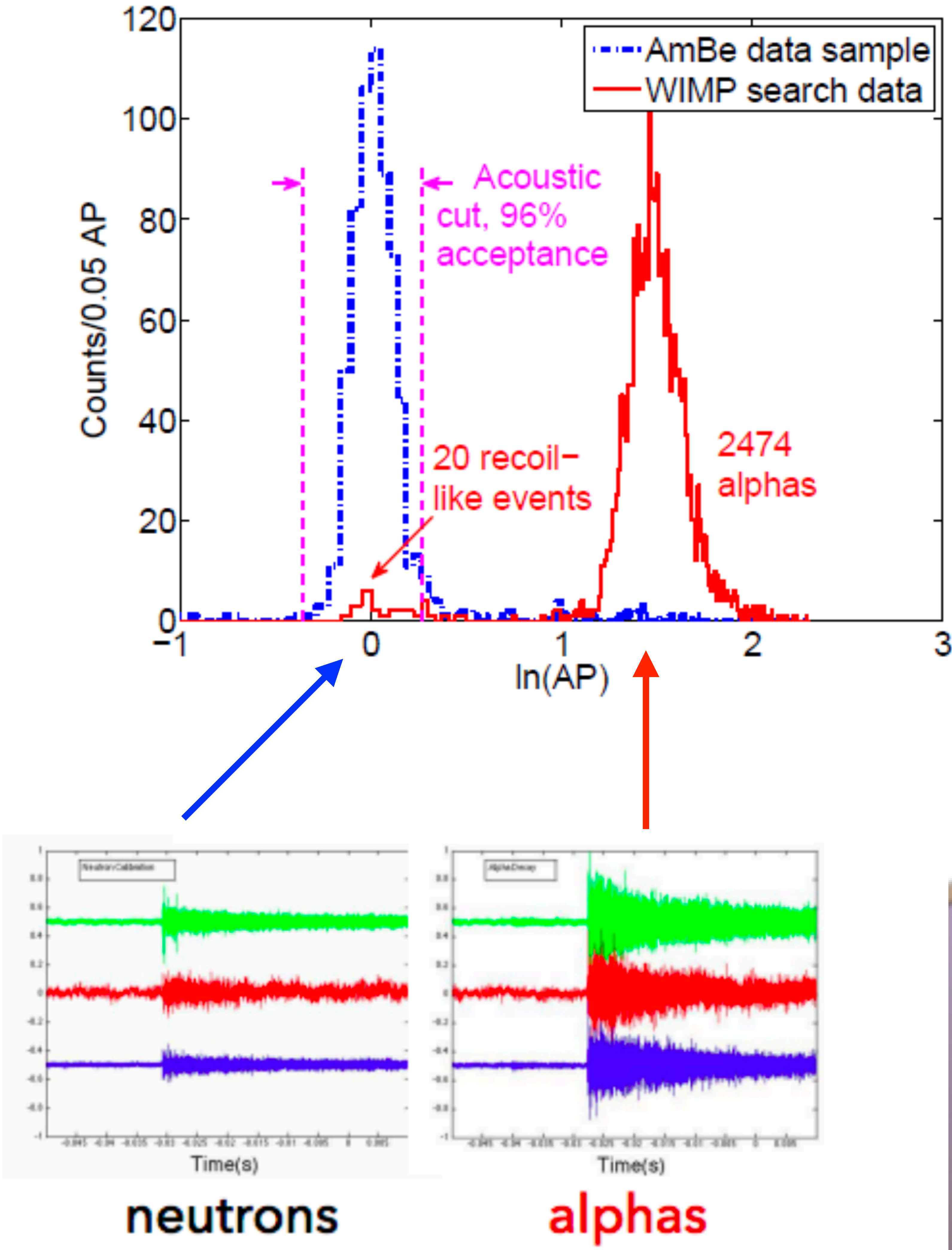
- Heavier particles have higher thresholds
- Tune the chamber to be unresponsive to most backgrounds(ER).
- Underground location and shielding to mitigate neutrons.
- But what about alphas?

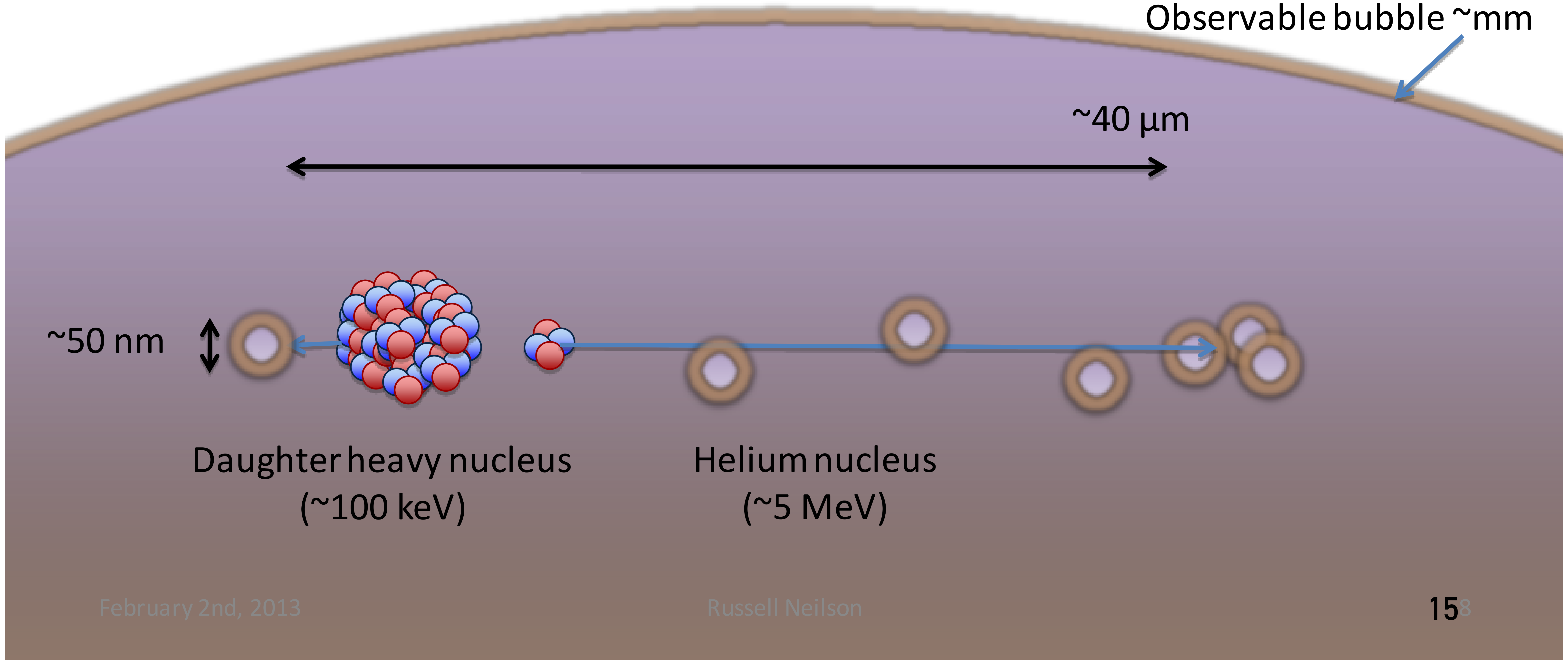
Superheated C_4F_{10}



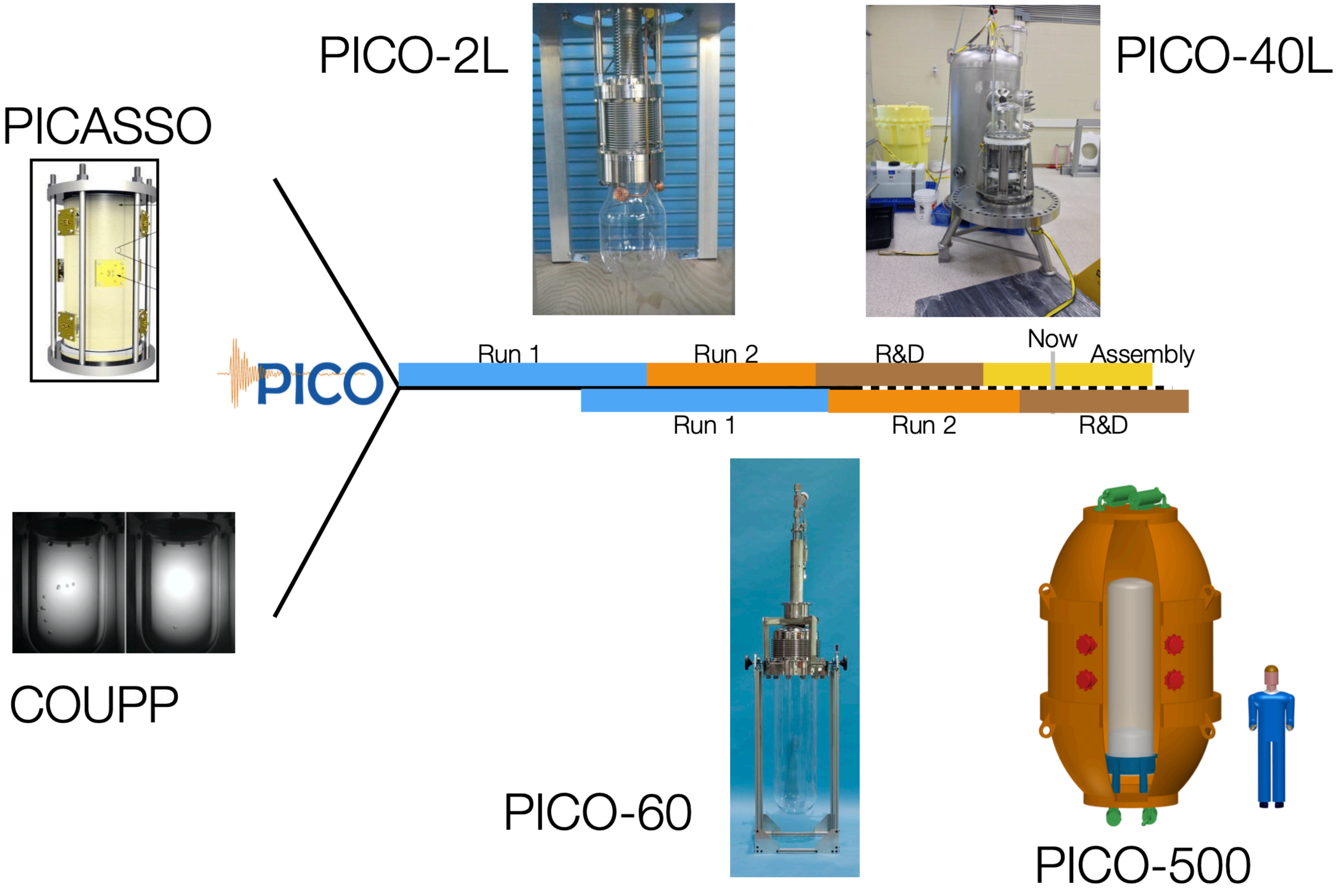
ACOUSTIC DISCRIMINATION

- Alphas deposit their energy over 10s of microns
- Nuclear recoils deposit their energy over 10s of nanometers
- Alpha particles are ~4 times louder than NR. This can be measured by piezoelectric sensors



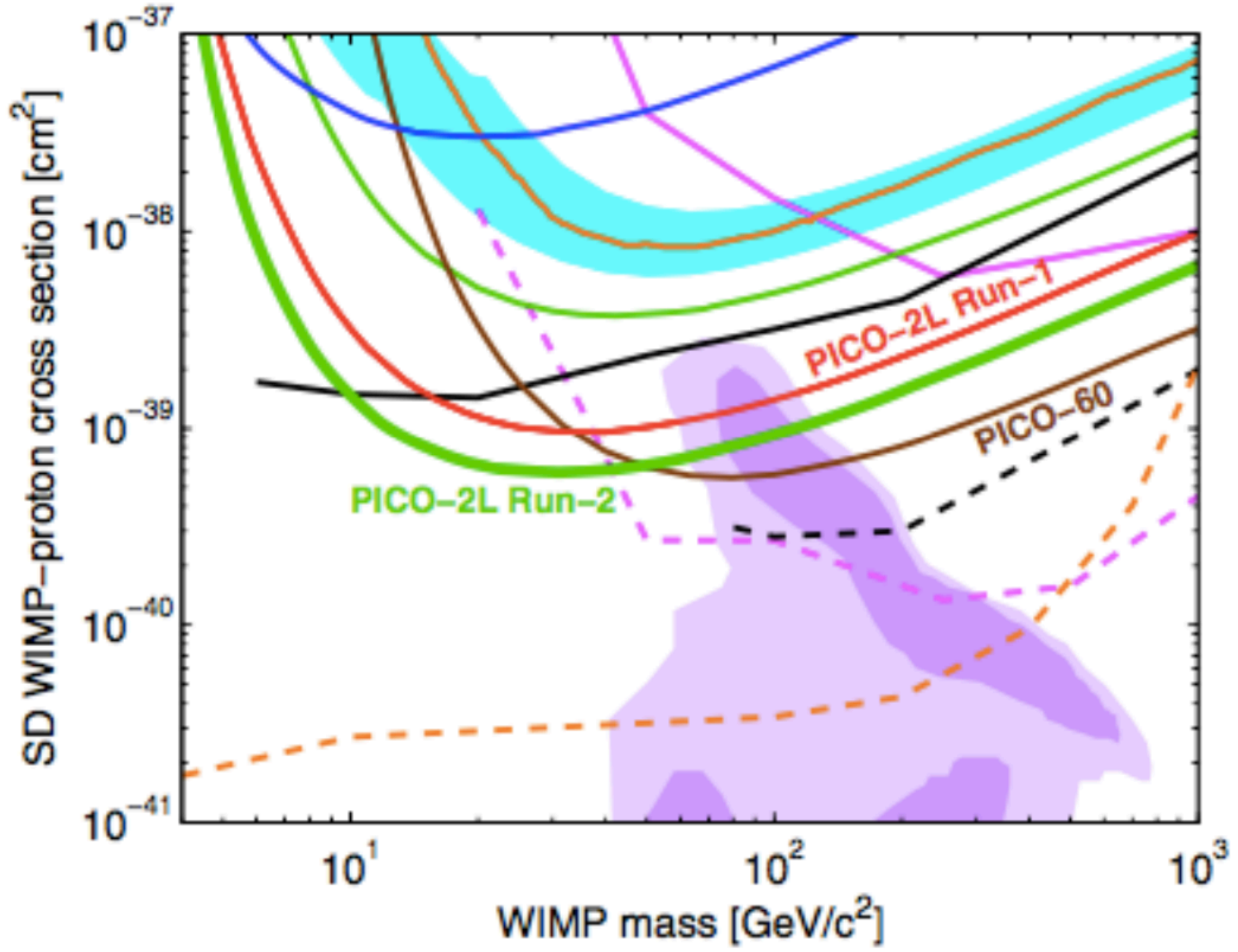


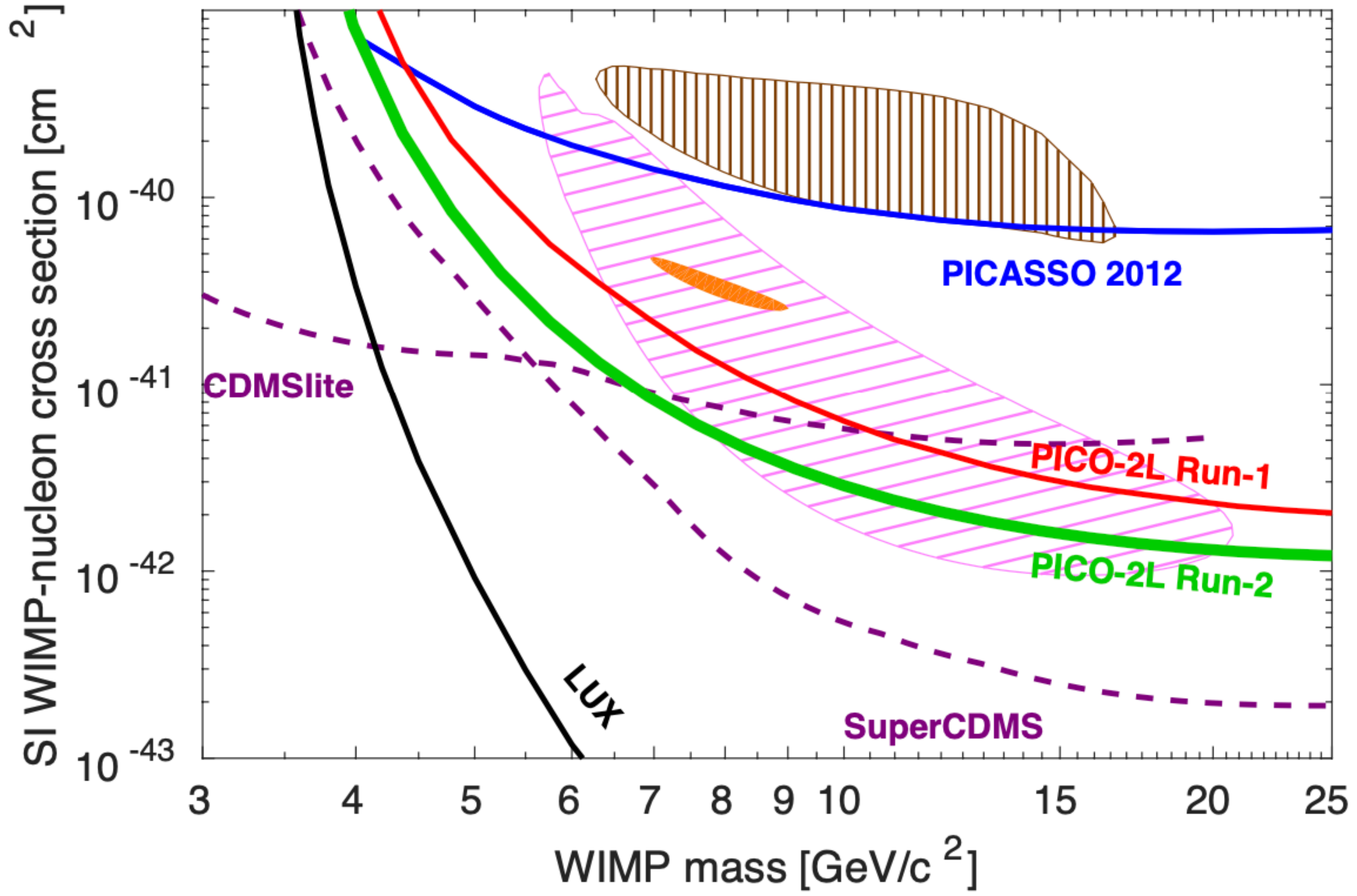
PICO PROGRAM



Ken Clark

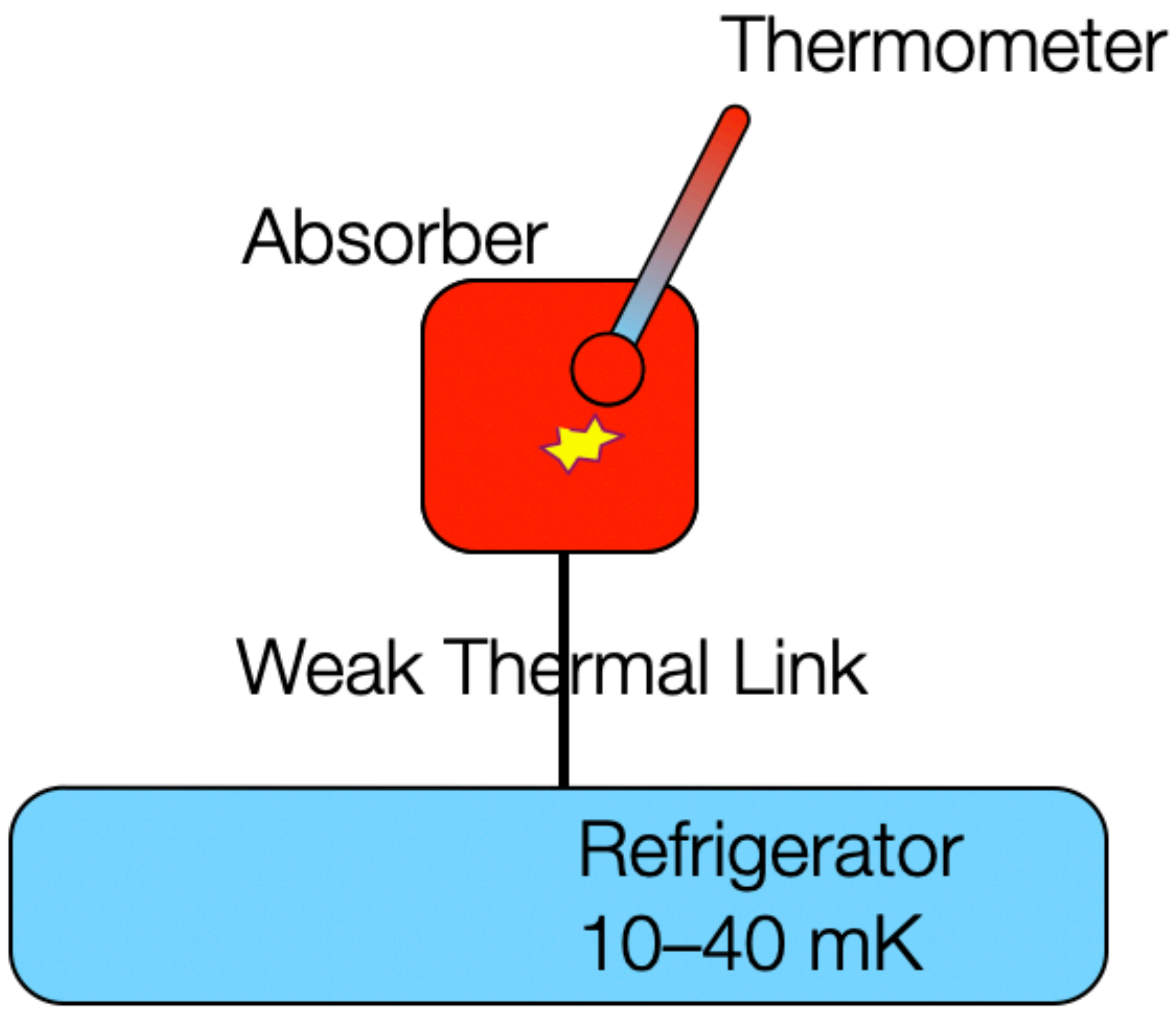
PICO-2L Results

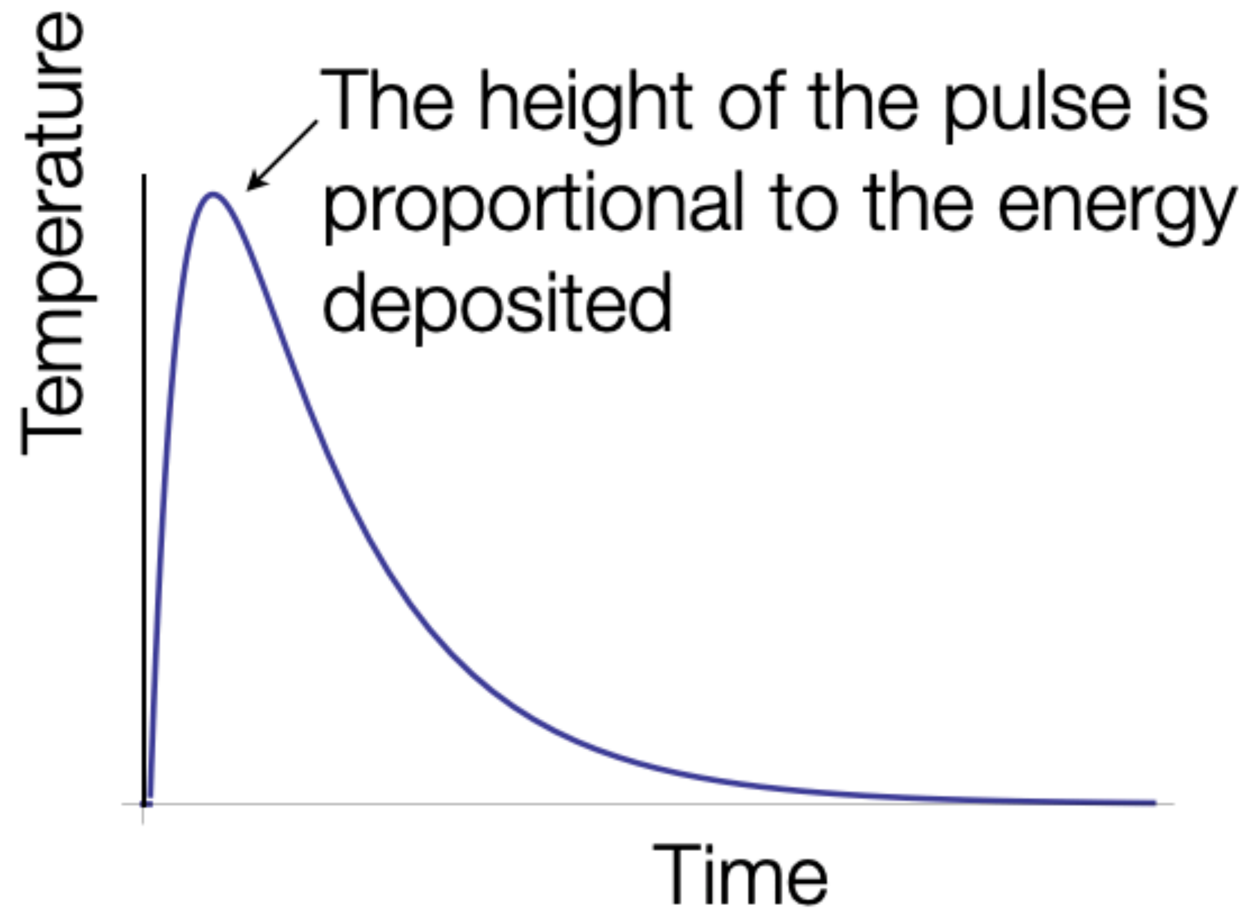




CRYOGENIC SOLID STATE DETECTORS

CRYOGENIC DETECTORS: PHONON AND HEAT SIGNALS





$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$

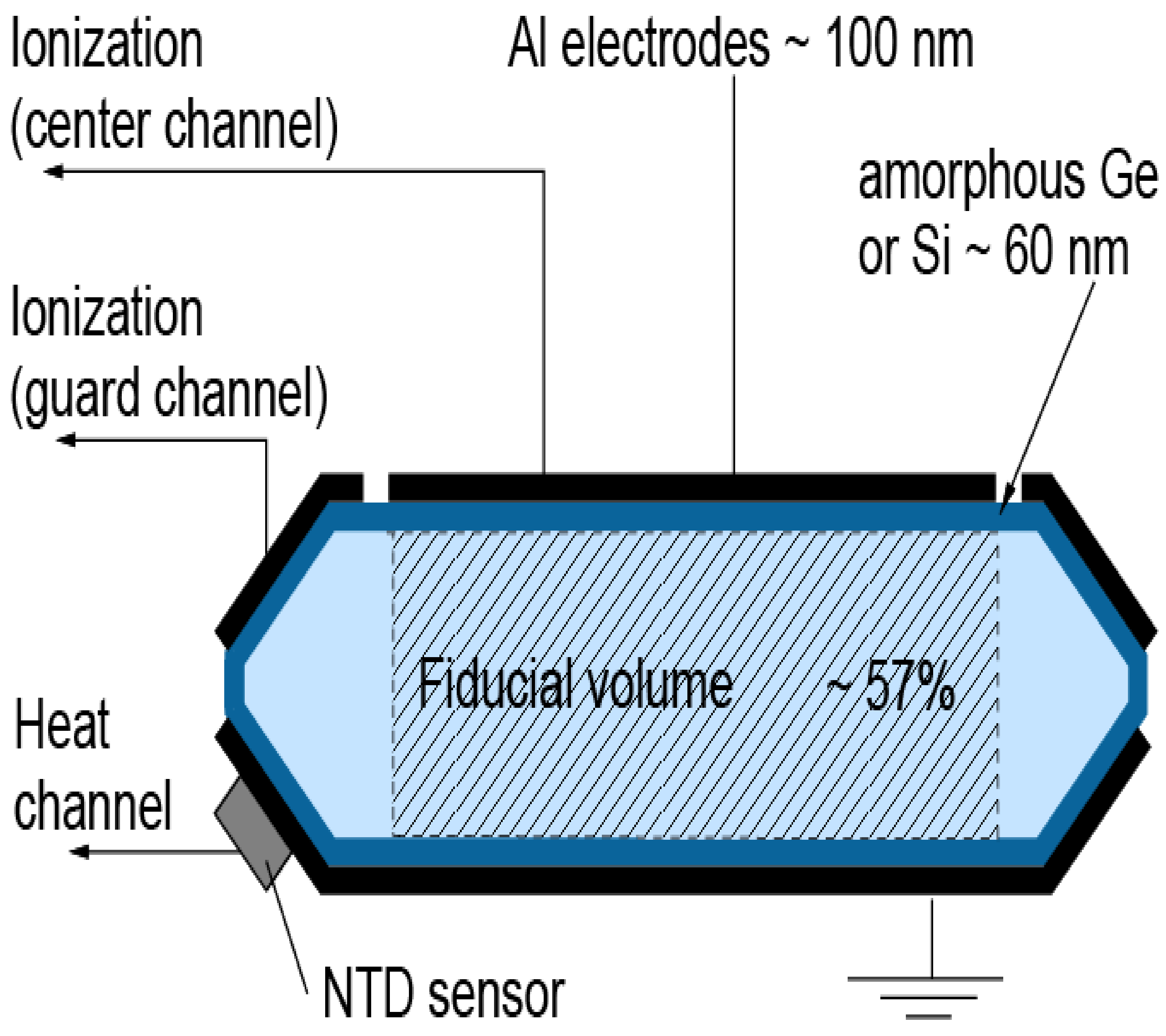
$$\tau = \frac{C(T)}{G(T)}$$

$C(T)$ = *heat capacity of absorber*

$G(T)$ = *thermal conductance of the link between absorber and reservoir a T_{0}*

- Two families of sensors for phonon signal: themal and athermal
  - Thermal sensors - wait for the full thermalization of the phonons within the bulk of the detector and the sensor itself
  - Athermal sensors detect fast, non-equilibrium phonons
- Temperature increase is equal to the deposited energy over the heat capacity of the system.
- Two most widely used technologies to measure these signals are neutron doped germanium sensors (NTD) and transition edge sensors (TES)

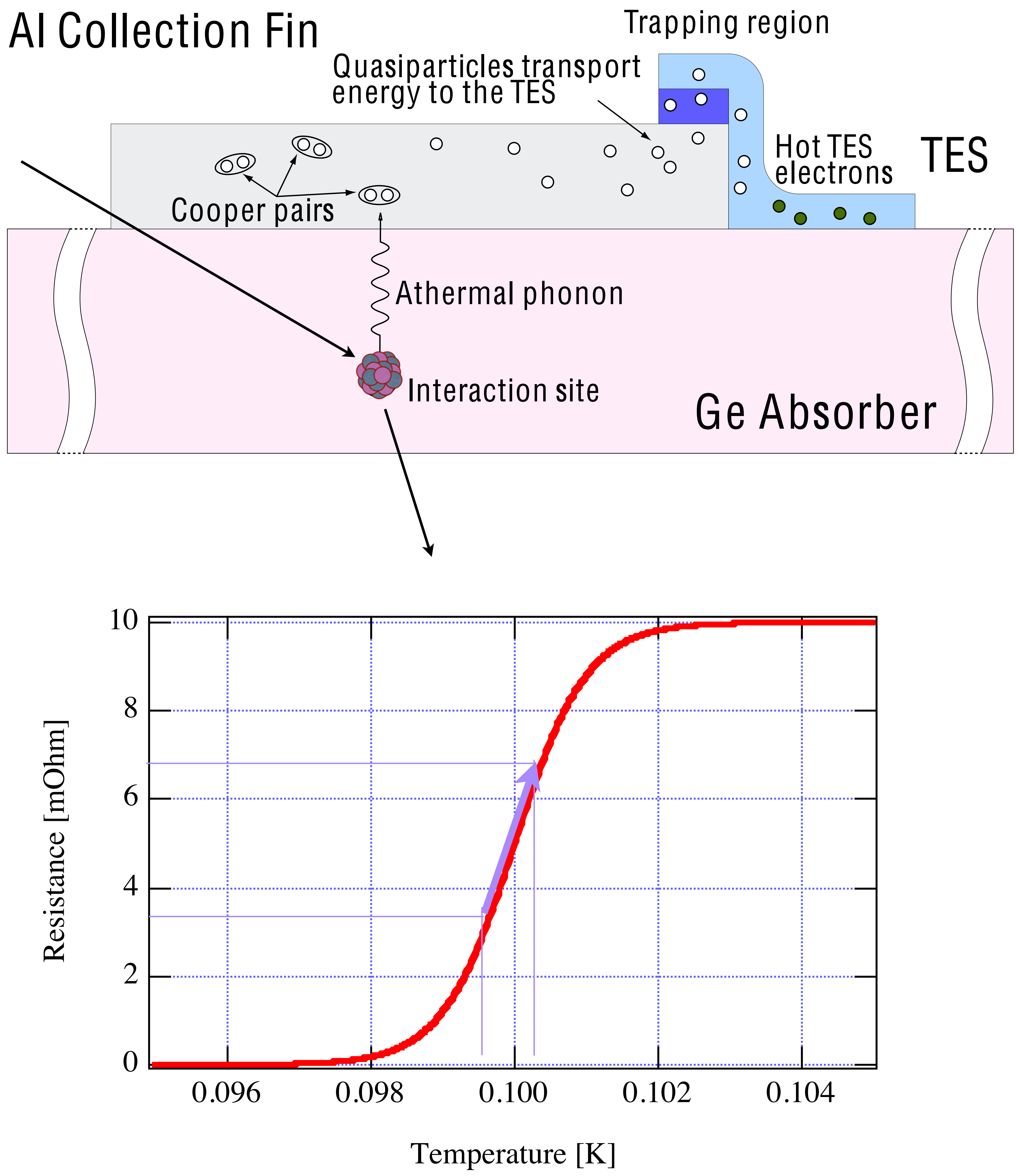
NTDS



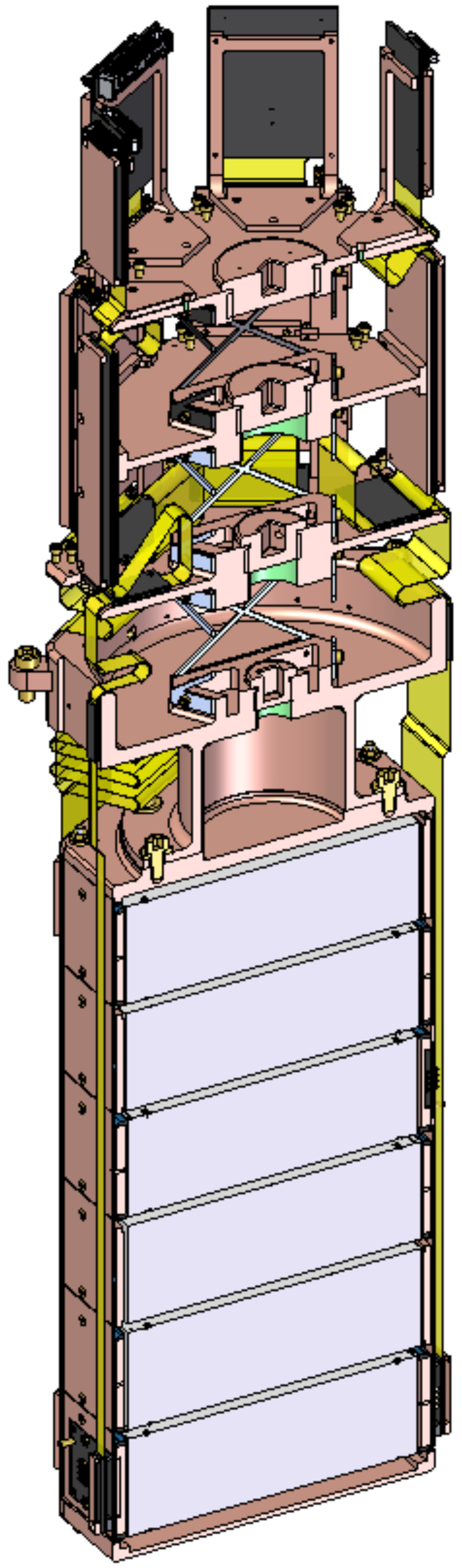
Schematic “Ge-NTD”
EDELWEISS detector

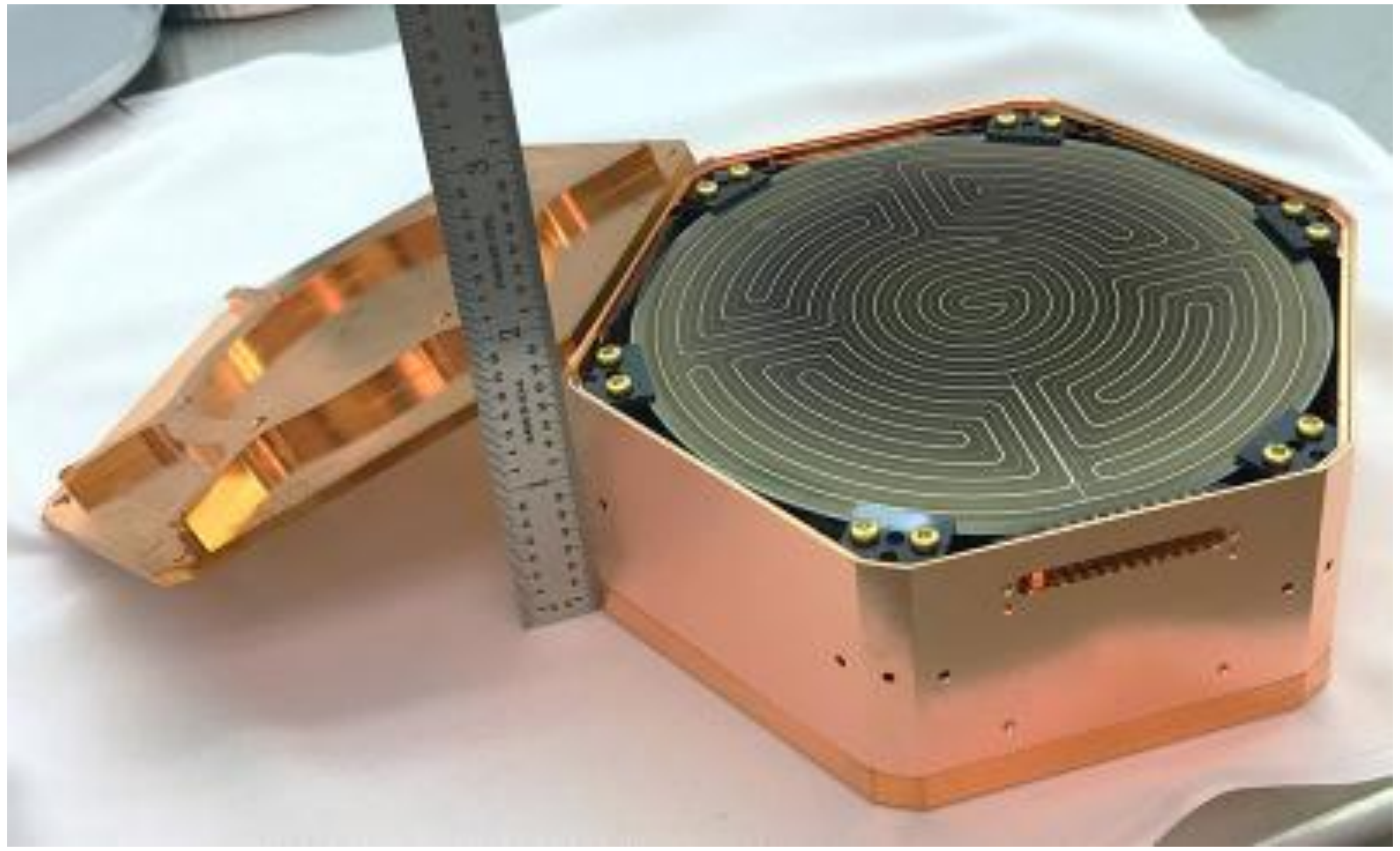
- NTDs are small Ge semiconductor crystals that have been exposed to a neutron flux to make a large, controlled density of impurity.
- NTD measures small temperature variations relative to $T_{0,}$ which is set to be on the transition from superconducting and resistance regime with dependence of the resistance with temperature T
- Resistance is continuously measured by flowing current through it and measuring the resulting voltage.
- Sensors are glued onto detector.

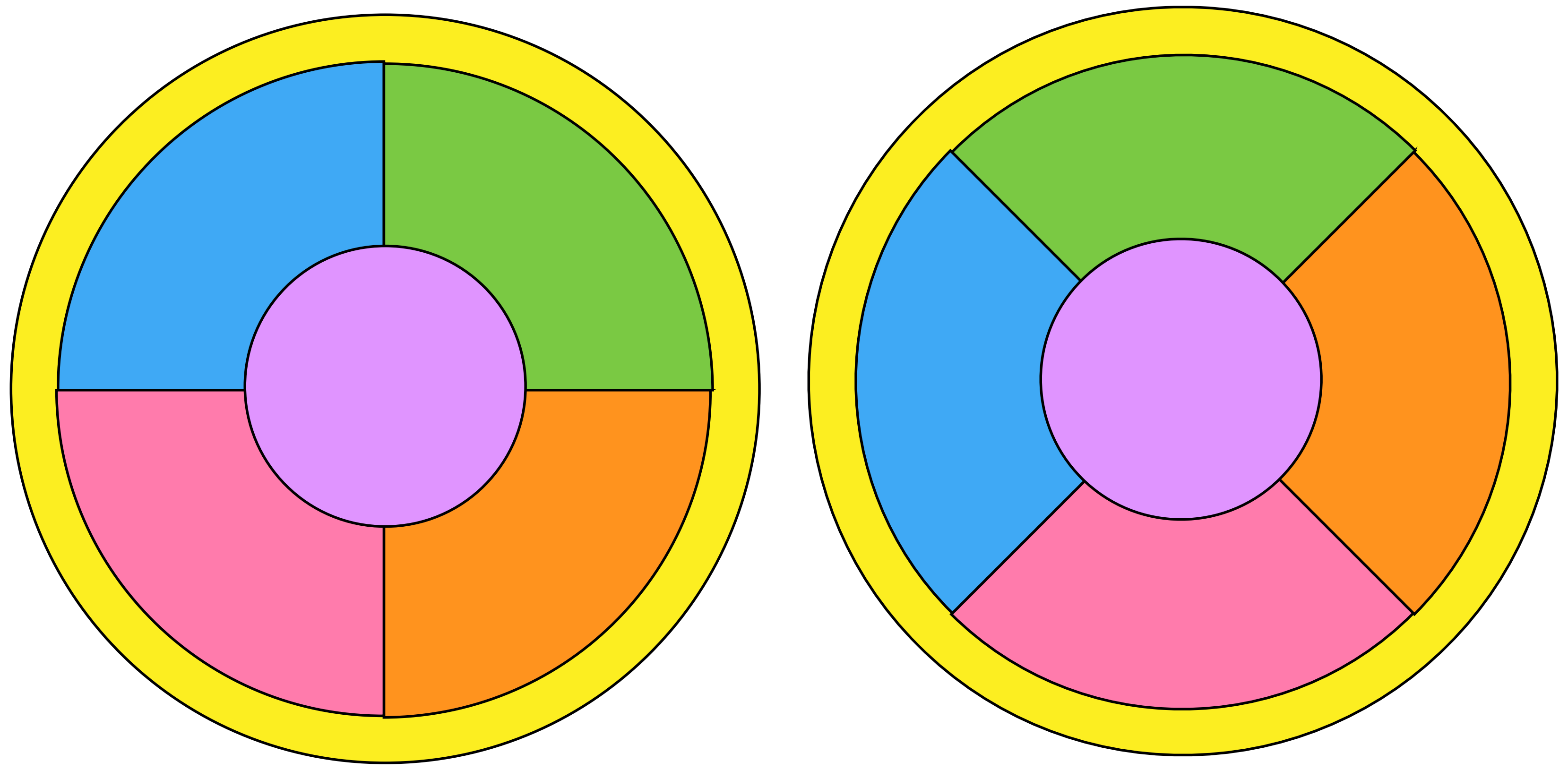
TRANSITION EDGE SENSORS



- TES is a thin superconducting film operated near its T_c.
- Refrigerator temperature needs to be close to absolute zero.
- A heater with an electothermal feedback system maintains temperature at superconducting edge.
- Temperature changes are detected by a change in the feedback current, collected by a SQUID.



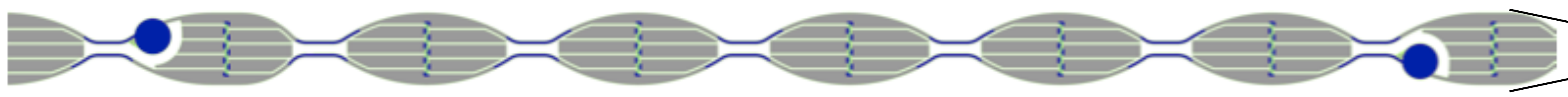


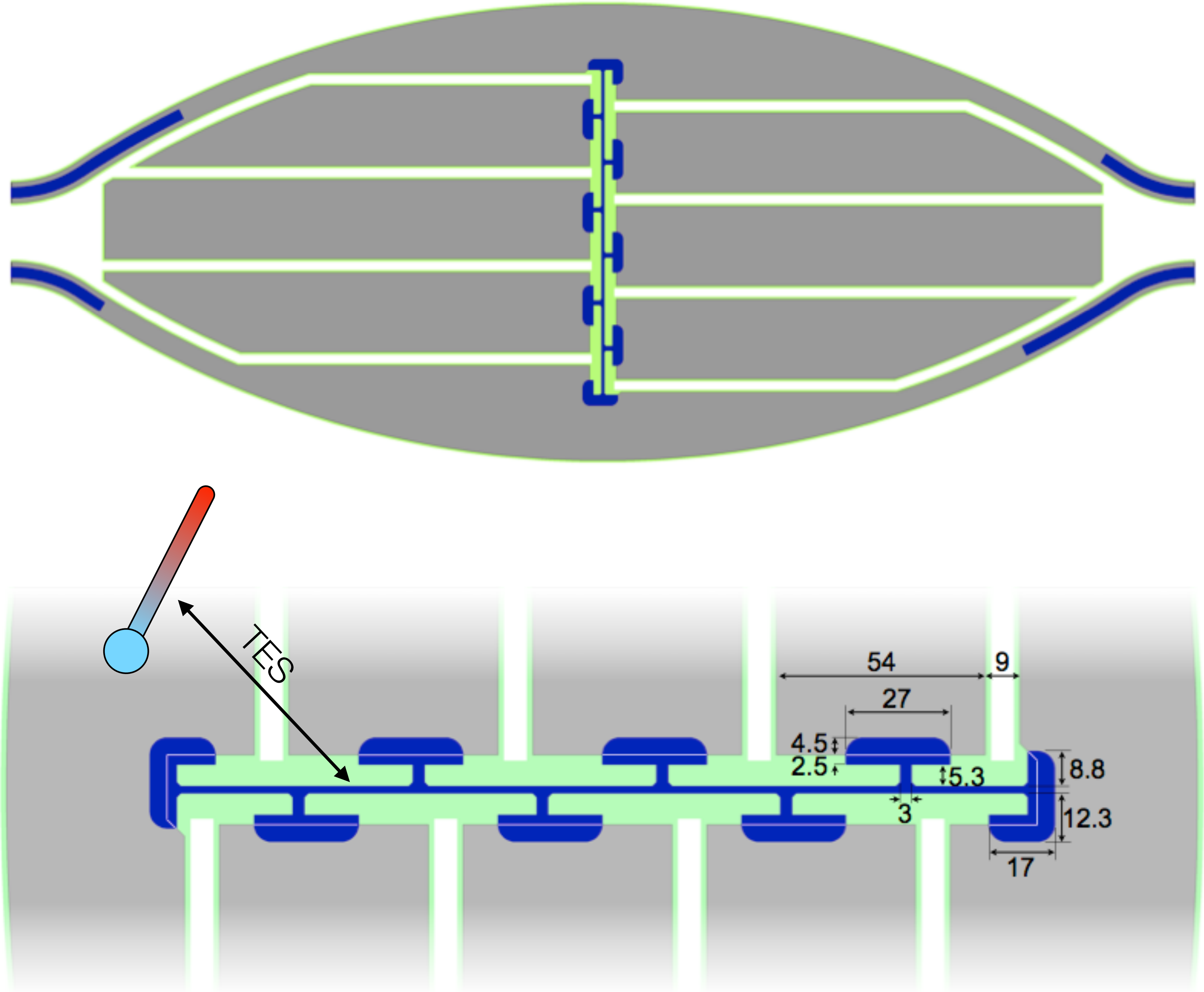


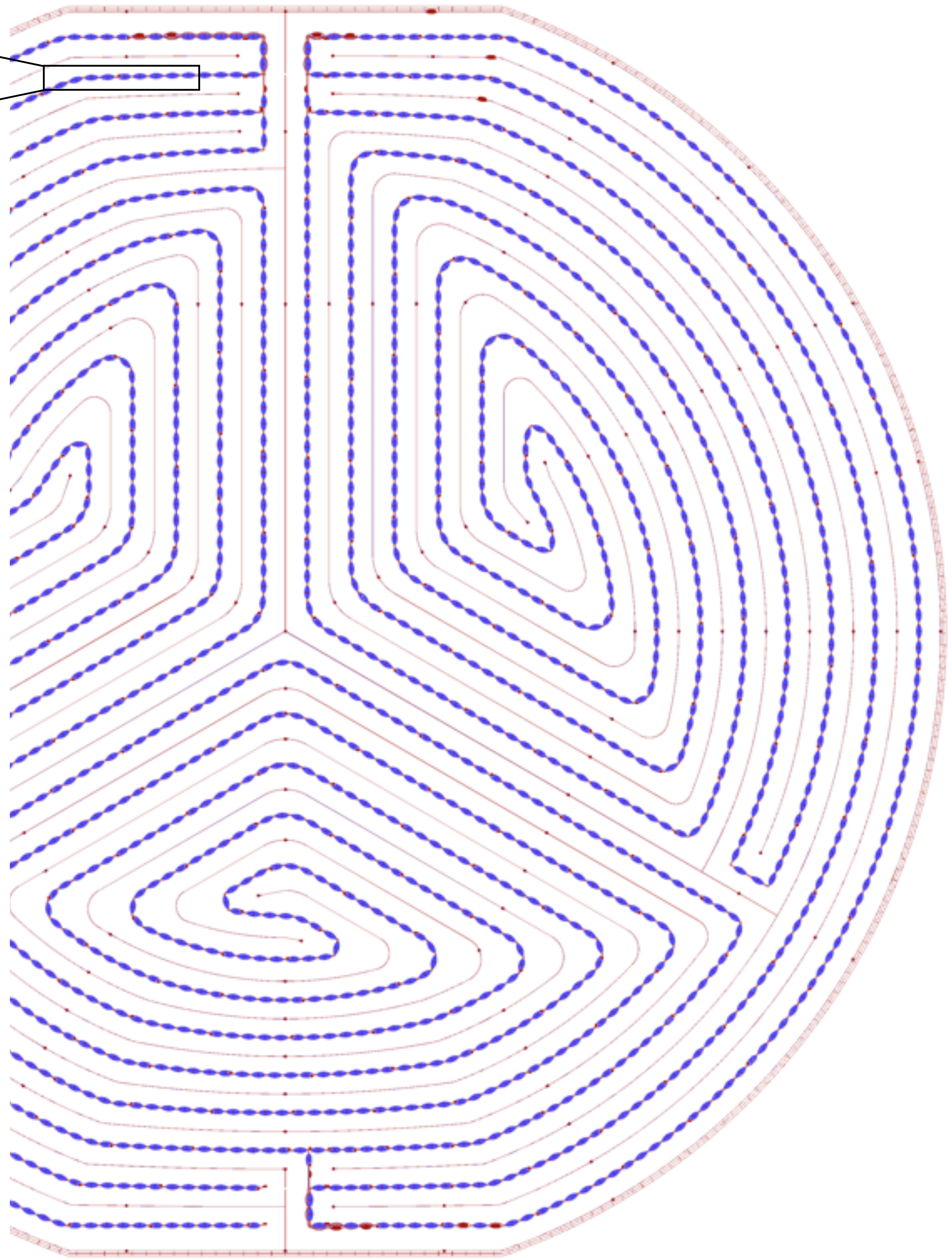
SUPERCDMS SNOLAB DETECTORS

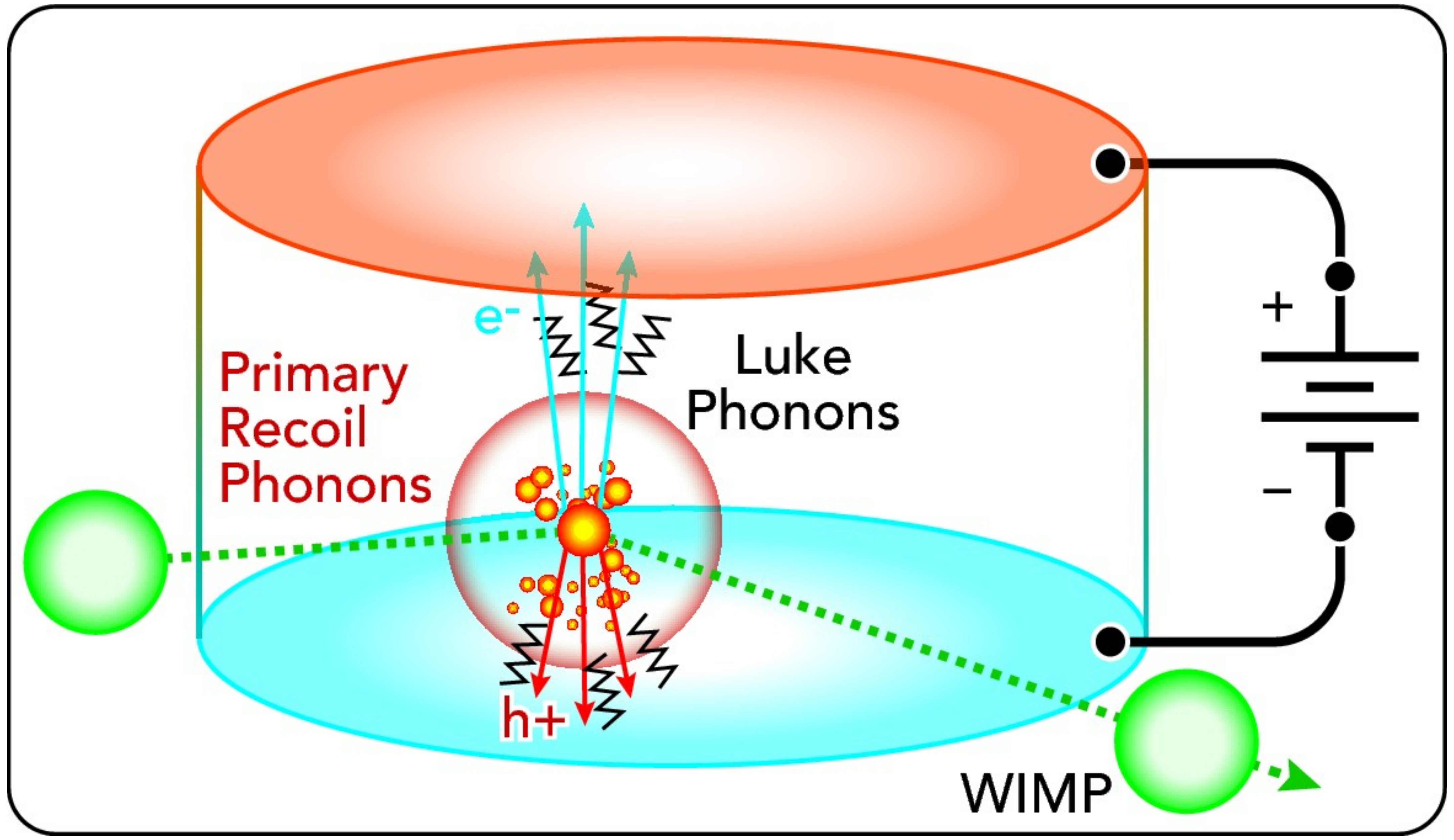
- Initial payload 4 towers, each w/6 detectors (1.39 kg Ge crystals, 0.61 kg Is crystals) each 100 mm diameter, 33.3 mm thick:
  - 2 HV (4 Ge + 2 Si)
  - 2 iZIP (6 Ge & 4 Ge + 2 Si)
- iZIP detectors
  - 8 phonon channels + 2 charge sensors each side
- HV detectors
  - 6 phonon channels on each side

IZIP DETECTOR









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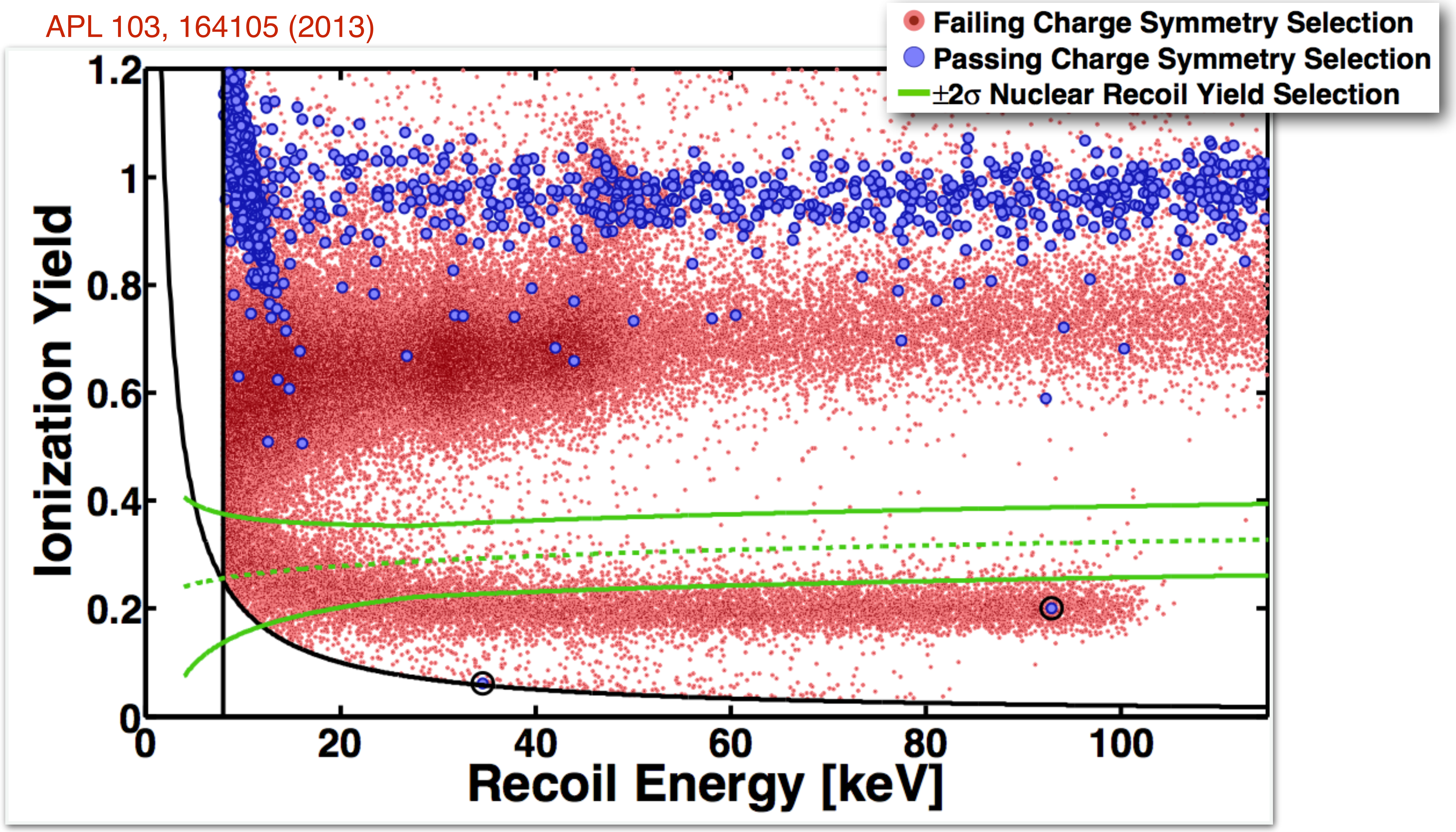
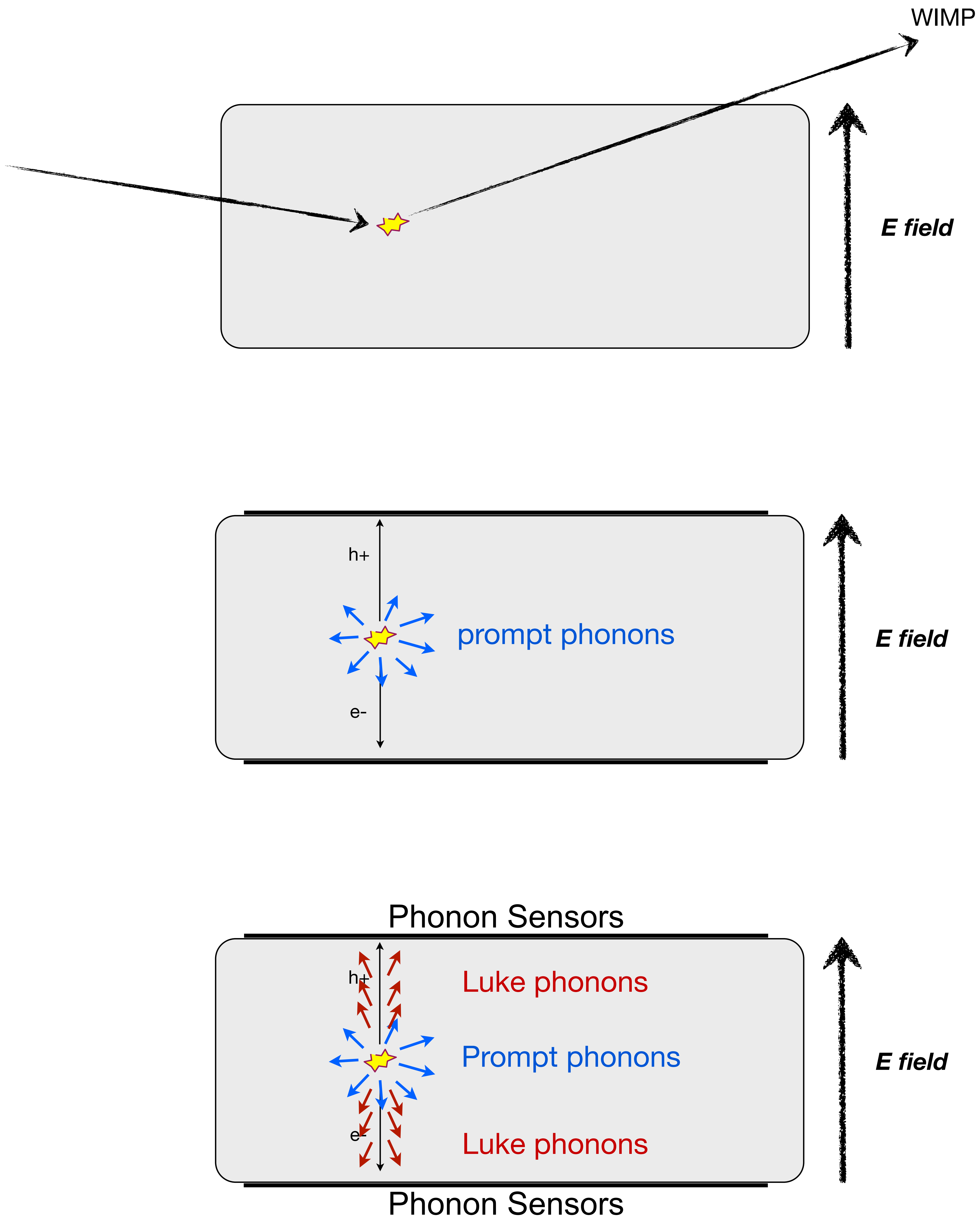


SUPERCDMS – STANDARD IZIP MODE

- Primary (prompt) phonon and ionization signals allow for discrimination between NR and ER events
- High resolution phonon and charge readout
- All surface and ER backgrounds above a few keV can be easily removed with selection criteria.



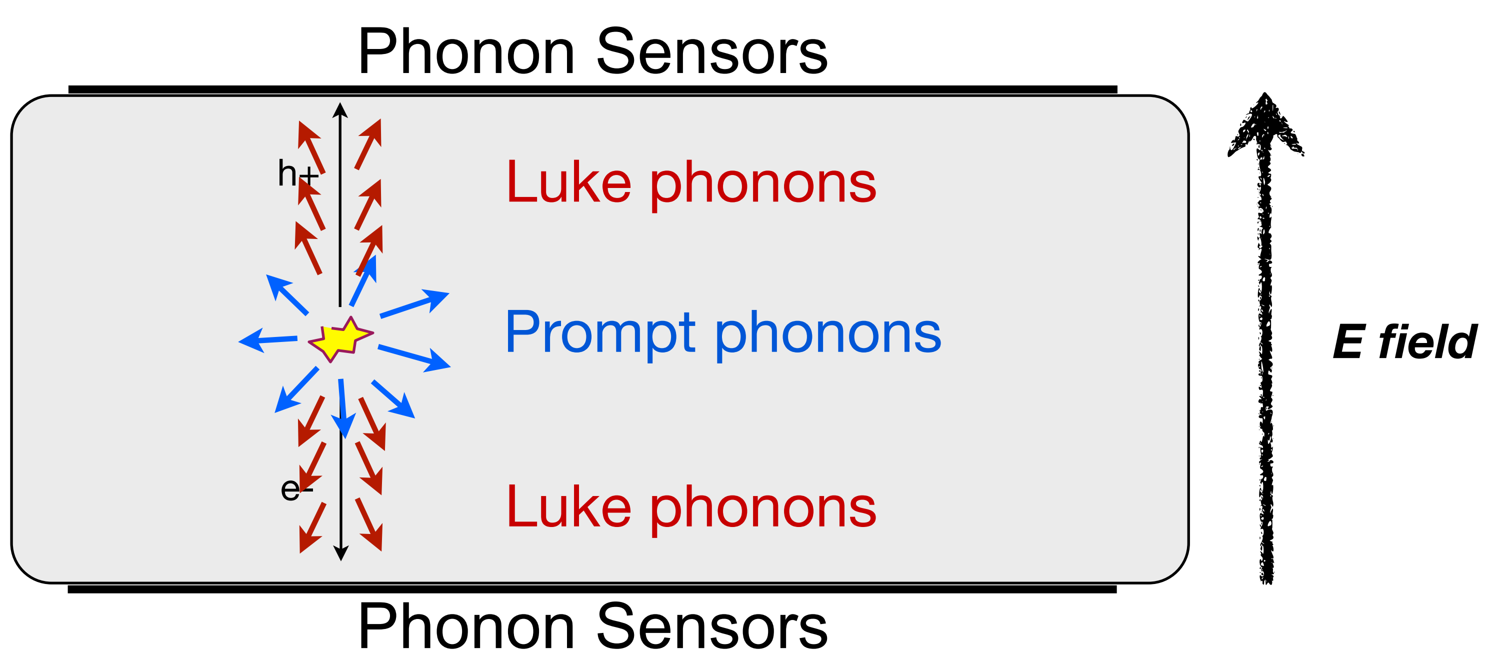
SUPERCDMS HIGH-VOLTAGE DETECTORS

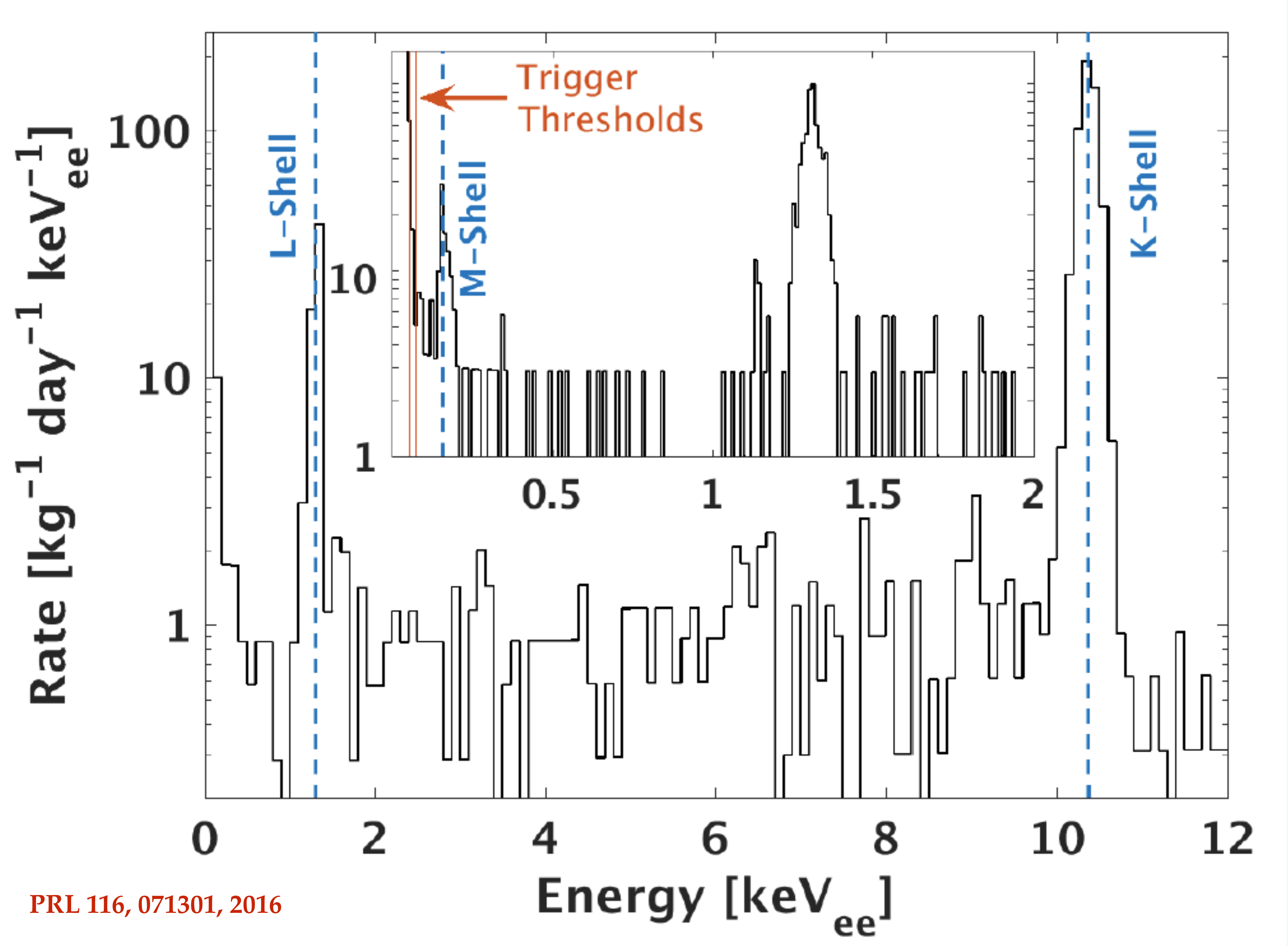
- Drifting electrons across a potential (V) generates a large number of phonons (NLT phonons)

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

total phonon energy *primary recoil energy* *Luke phonon energy*

SUPERCDMS HIGH-VOLTAGE DETECTORS





PRL 116, 071301, 2016

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

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

total phonon energy *primary recoil energy* *Luke phonon energy*

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

ON UNITS

We know that NTL phonon energy is given by

$$E_{NTL} = N_{eh} V_b$$

The number of electron hole pairs generated in an interaction is given by

$$N_{eh} = \frac{E_r}{\epsilon} \qquad \epsilon_{Ge} = 3.0 \text{ eV}$$

The total energy (phonon) is given by

$$E_t = E_r + eV_b N_{eh}$$

NR produce eh-pairs less efficiently than ER. Take this into account, define $Y \equiv 1$ for ER.

$$N_{eh} = Y(E_r)\frac{E_r}{\epsilon}$$

The total energy can then be written

$$E_{tot} = E_r\left(1 + Y(E_r)\frac{eV_b}{\epsilon}\right)$$

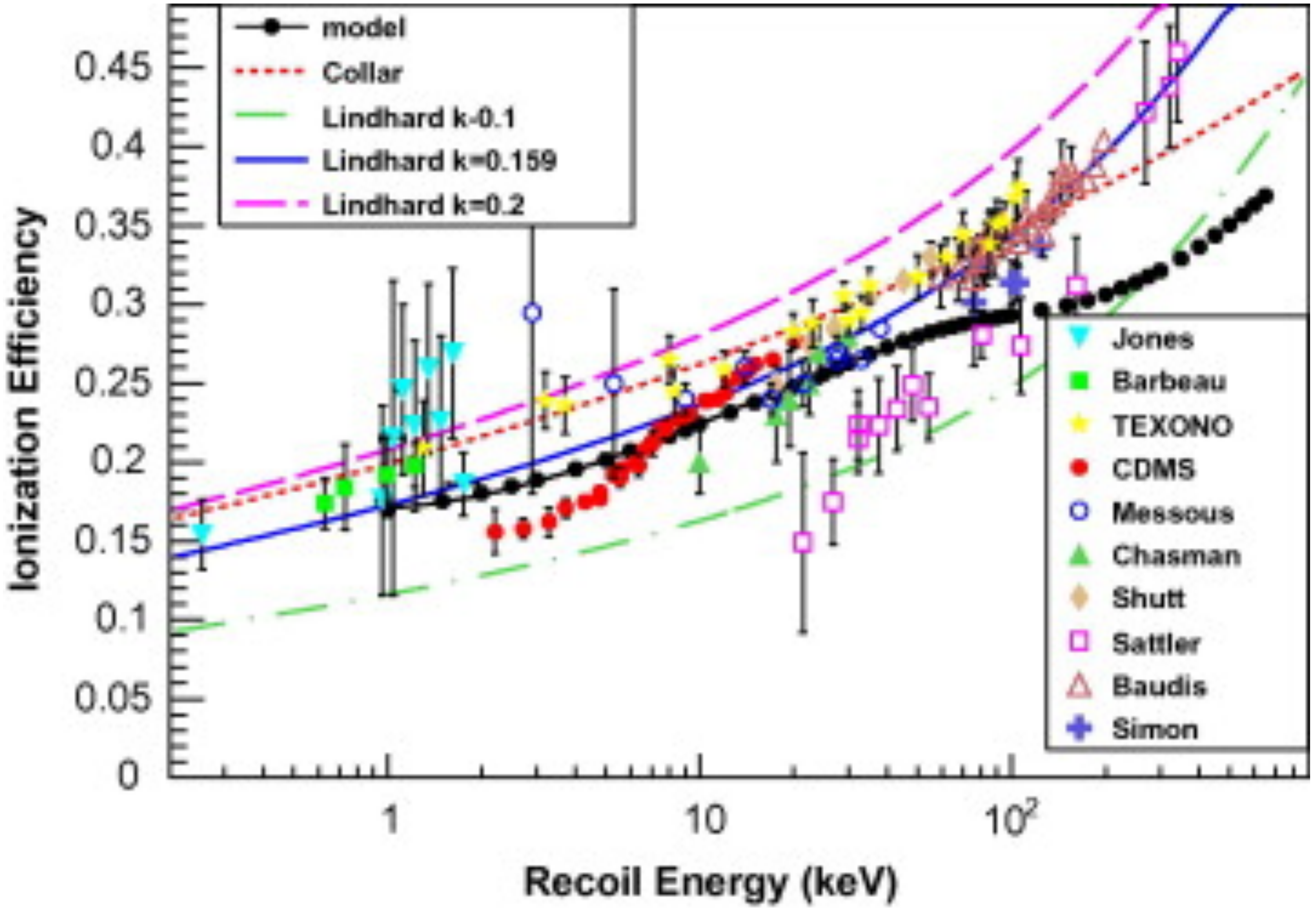
If we calibrate detectors using ER, the resulting energy scale is keV_{ee} to convert to keV_{nr} equate for NR and ER.

$$E_{nr}\left(1 + Y(E_{nr})\frac{eV_b}{\epsilon}\right) = E_{ee}\left(1 + \underbrace{Y(E_{ee})}\frac{eV_b}{\epsilon}\right)$$

recall $Y = 1$ *for ER*

$$E_{nr} = E_{ee}\left(\frac{1 + eV_b/\epsilon}{1 + Y(E_{nr})eV_b/\epsilon}\right)$$

HOW TO DETERMINE Y?



- Either you need to measure it directly or model it.
- The most utilized model is from Lindhard.

$$Y(E_{nr}) = \frac{k \cdot g(\epsilon)}{1 + k \cdot g(\epsilon)}$$

where

$$g(\epsilon) = 3\epsilon^{0.15+0.7\epsilon^{0.6}+\epsilon}$$

$$\epsilon = 11.5E_{nr}(keV)Z^{-7/3}$$

$$Z = atomic\ number$$

ASIDE: ENERGY

The total energy (phonon) is given by

recoil energy [keV$_{nr}$]

$$E_{tot} = E_r + \underline{eV_b N_Q}$$

total phonon energy

Neganov-Luke Phonons

- Assuming that an event is an ER and that the detector bias voltage is 3V, the recoil energy in [keV$_{ee}$] can be expresses as

$$E_r = E_{tot} - eV_b N_Q$$
$$= E_{tot} - eV_b \frac{E_Q}{\epsilon}$$
$$= E_{tot} - E_Q$$

$\epsilon_{Ge} = 3.0$ eV

- Assuming that an event is a NR, a smaller correction for the Luke phonons is applied. The mean ionization energy for nuclear recoils ($\mu_{Q,nr}(p_t)$) is determined using calibration data from a 252Cf source.

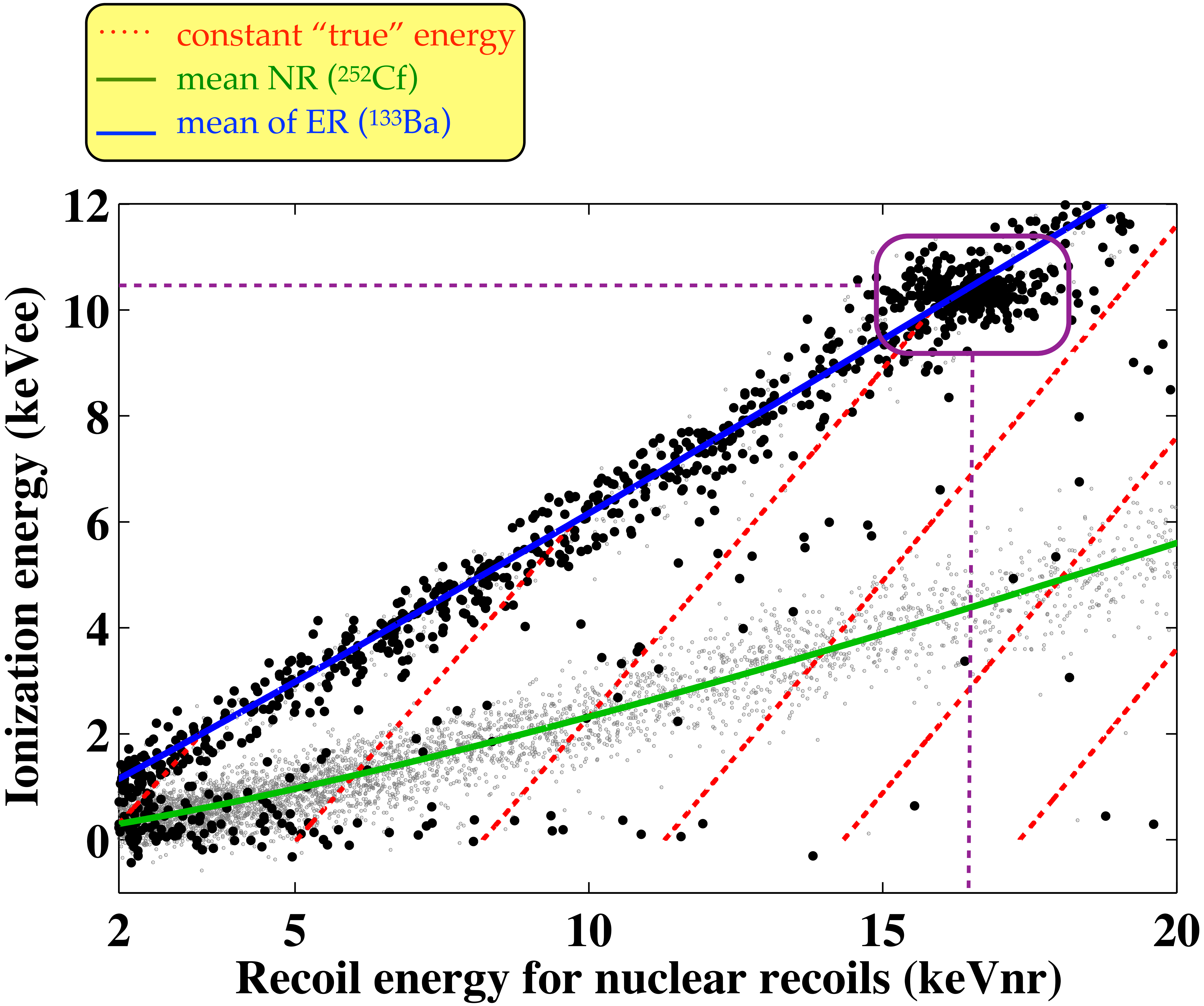
$$E_r(p_t) = p_t - \mu_{Q,NR}(p_t)$$

[keV$_{nr}$]

total phonon energy - Luke energy

where $\mu_{Q,NR} = AE_r^B$

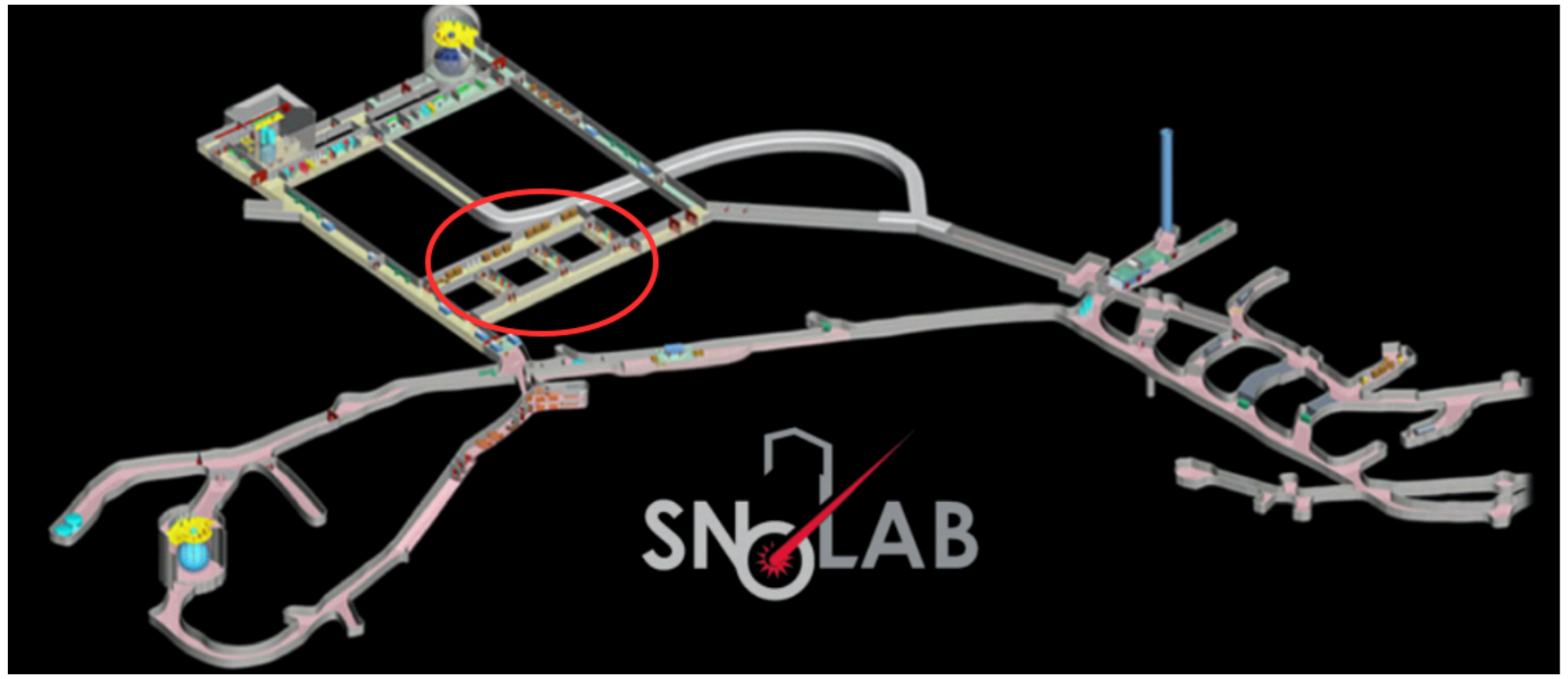
KEV$_{EE}$ VS KEV$_{NR}$

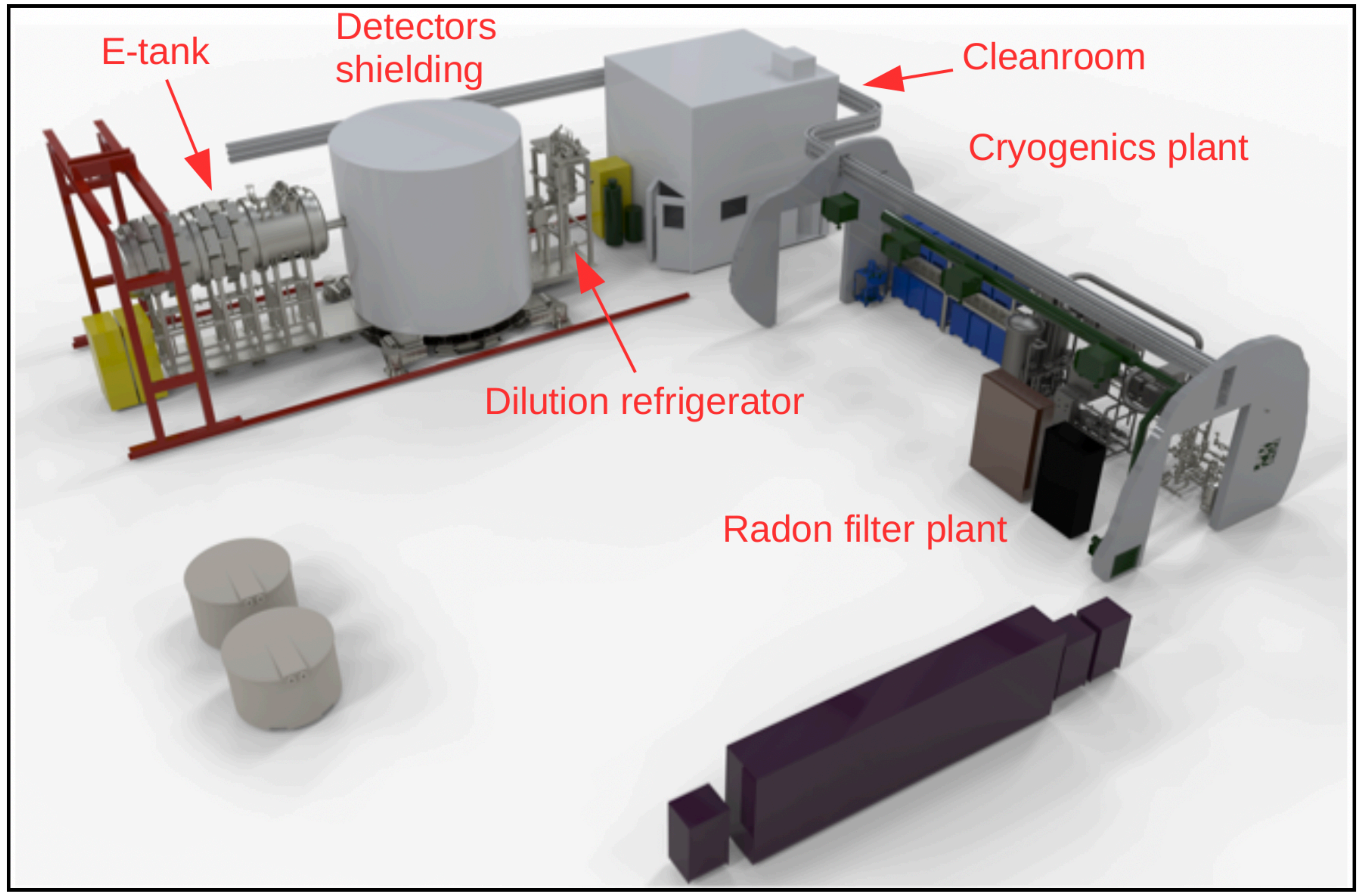


- Ionization energy vs recoil energy assuming NR scale consistent with Luke phonon contributions for NR.
  - ER recoils are pushed to higher energies using the NR scale.
  - Example - 10.4 keV$_{ee}$ ER line appears at ~16 keV$_{nr}$

*A good reference is David Moore's thesis, Chapters 3 and 4
http://thesis.library.caltech.edu/7043/

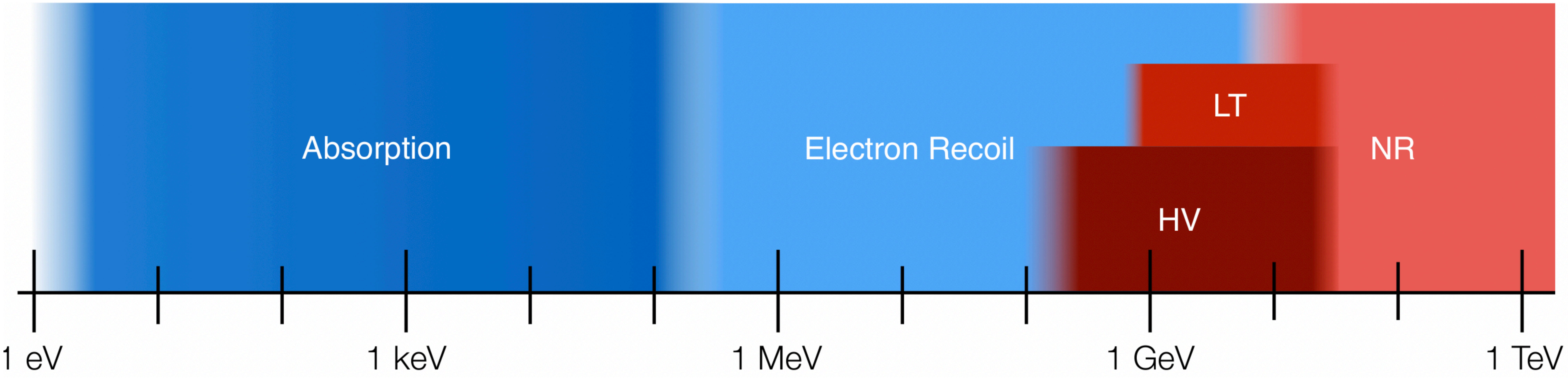
SUPERCDMS SNOLAB





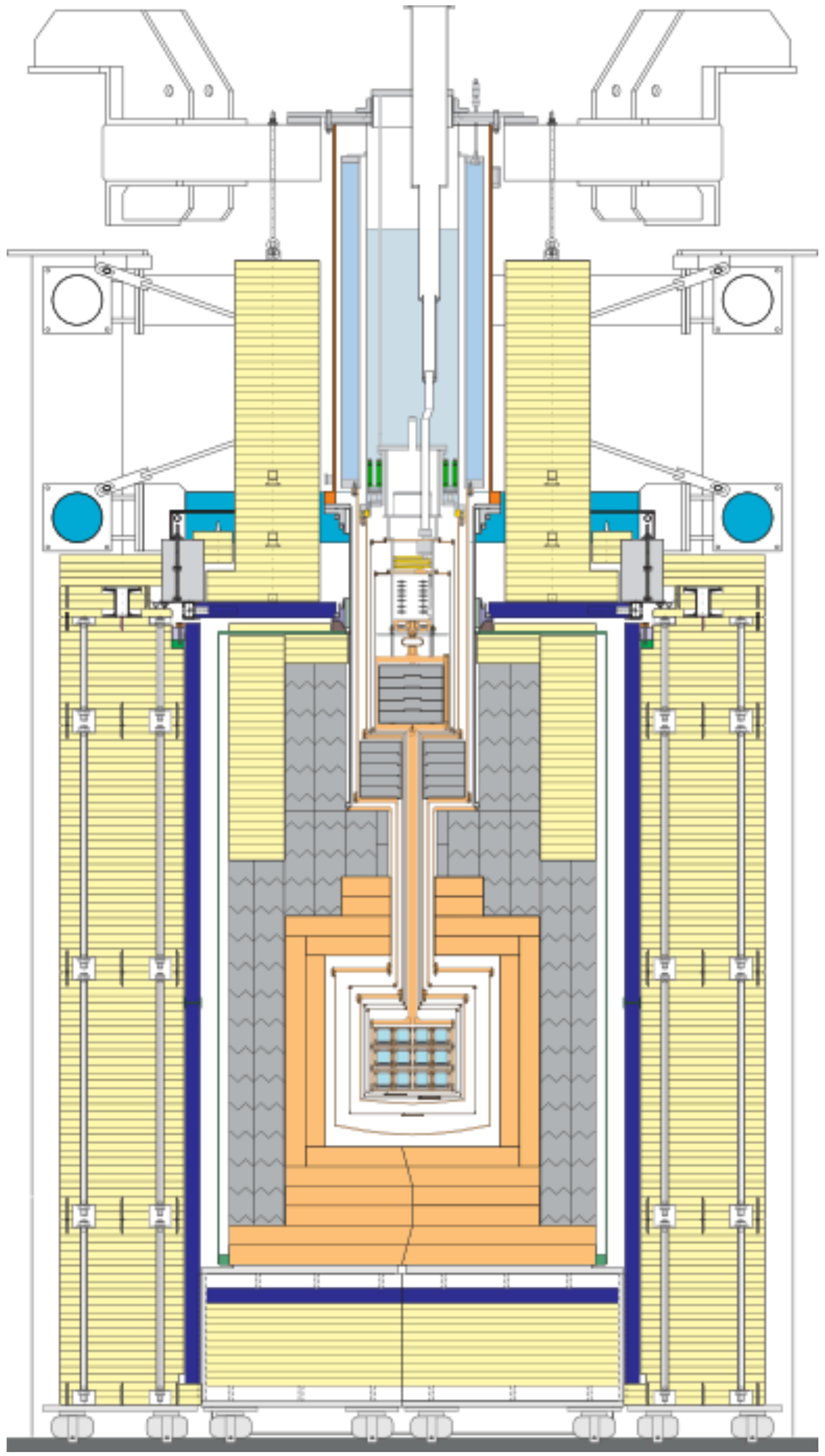
- Generation-2 dark matter experiment under construction at SNOLAB
- Infrastructure:
  - depth ~6900 mwe (results in a factor 100 reduction in muon flux from cosmic rays as compared to Soudan)
  - class 2000 or better cleanroom
  - Cryostat will be able to accommodate up to 7 towers
  - (0.1) dru gamma background
  - 15 mK base temperature
  - vibration isolation
- Initial payload: ~ 30 kg total, 4 towers with 6 detectors per tower (12 iZIP, 12 HV)

SUPERCDMS DARK MATTER SENSITIVITY

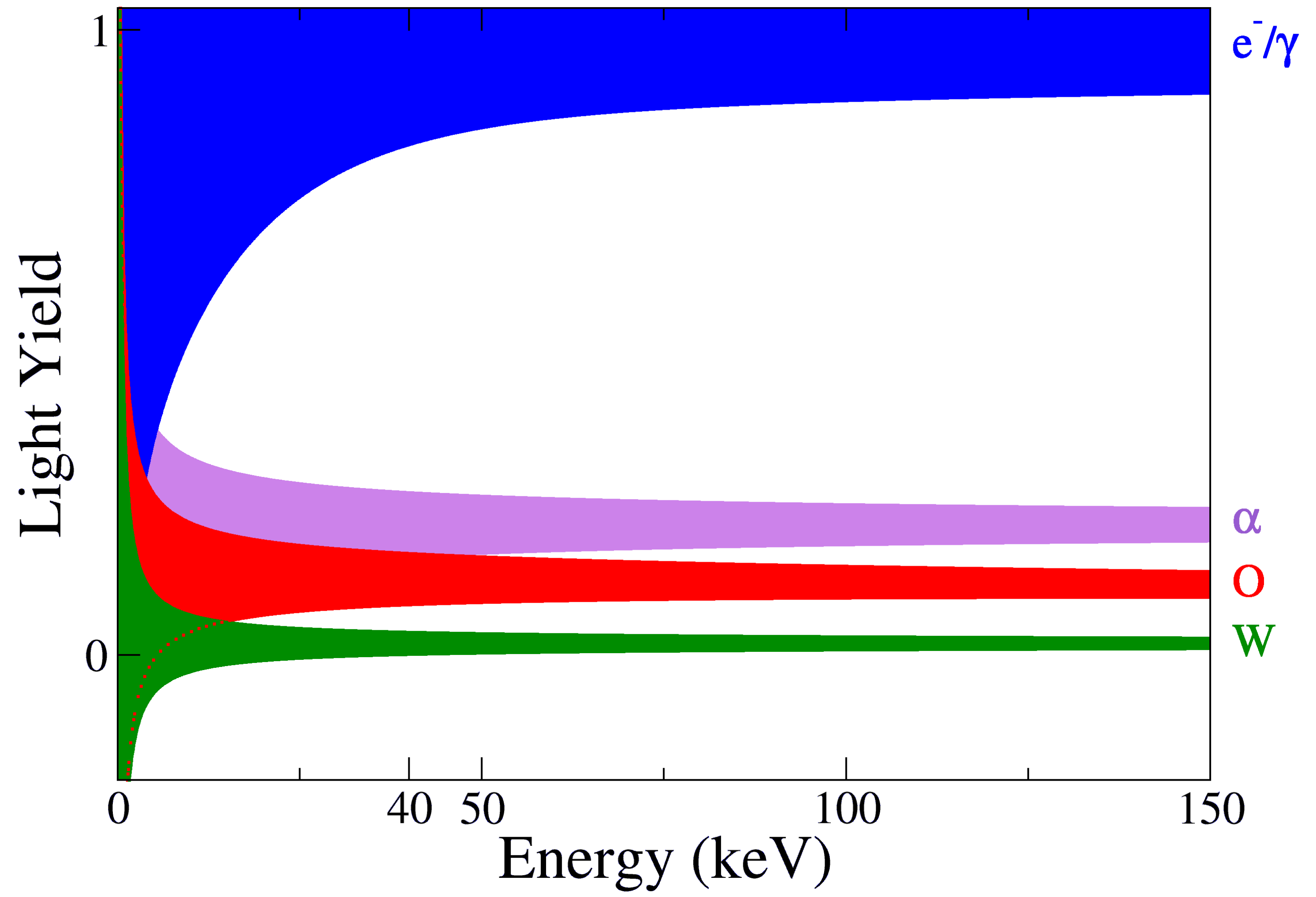


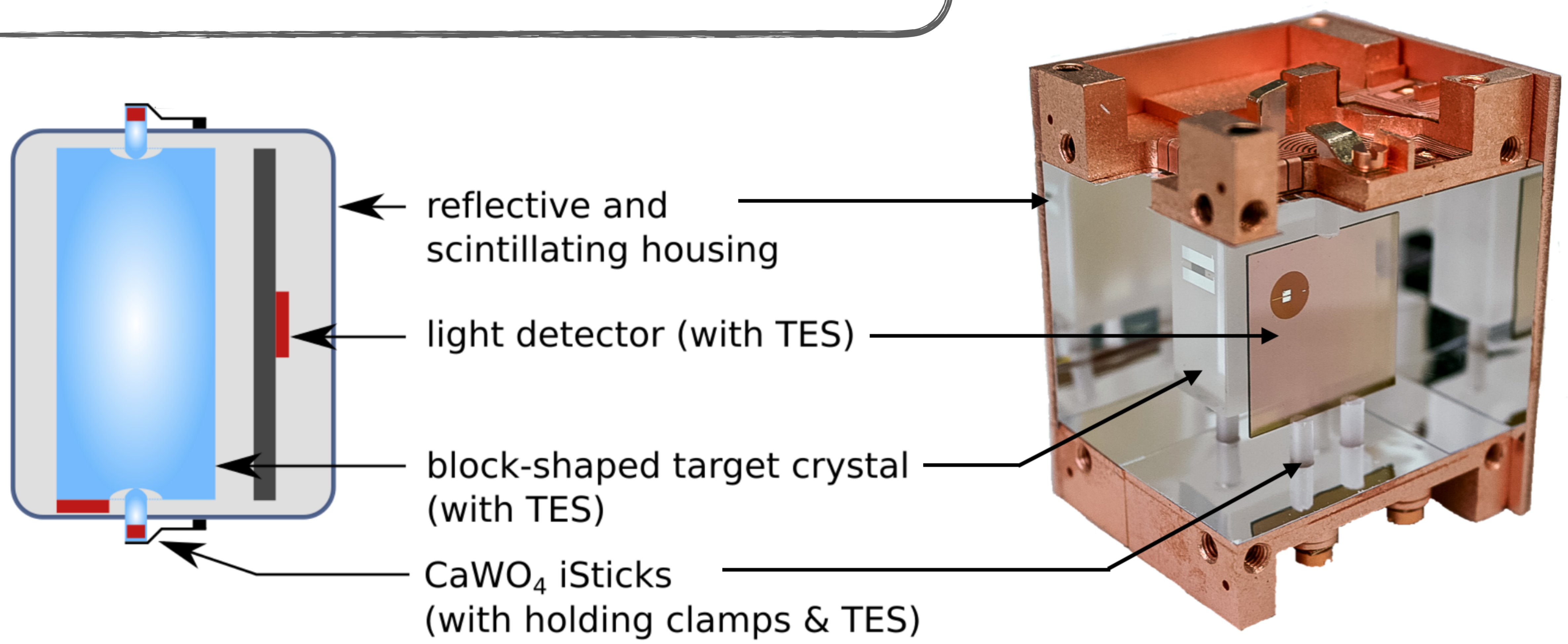
Traditional NR:	iZIP, Background free	>5 GeV
Low Threshold NR:	iZIP, limited discrimination	>1 GeV
HV Mode:	HV, no discrimination	~0.3 - 10 GeV
Electron Recoil:	HV, no discrimination	~0.5 MeV - 10 GeV
Absorption (Dark Photons, ALPs)	HV, no discrimintion	~1 eV - 500 keV (peak search)

CRESST EXPERIMENT OPERATION PRINCIPLES



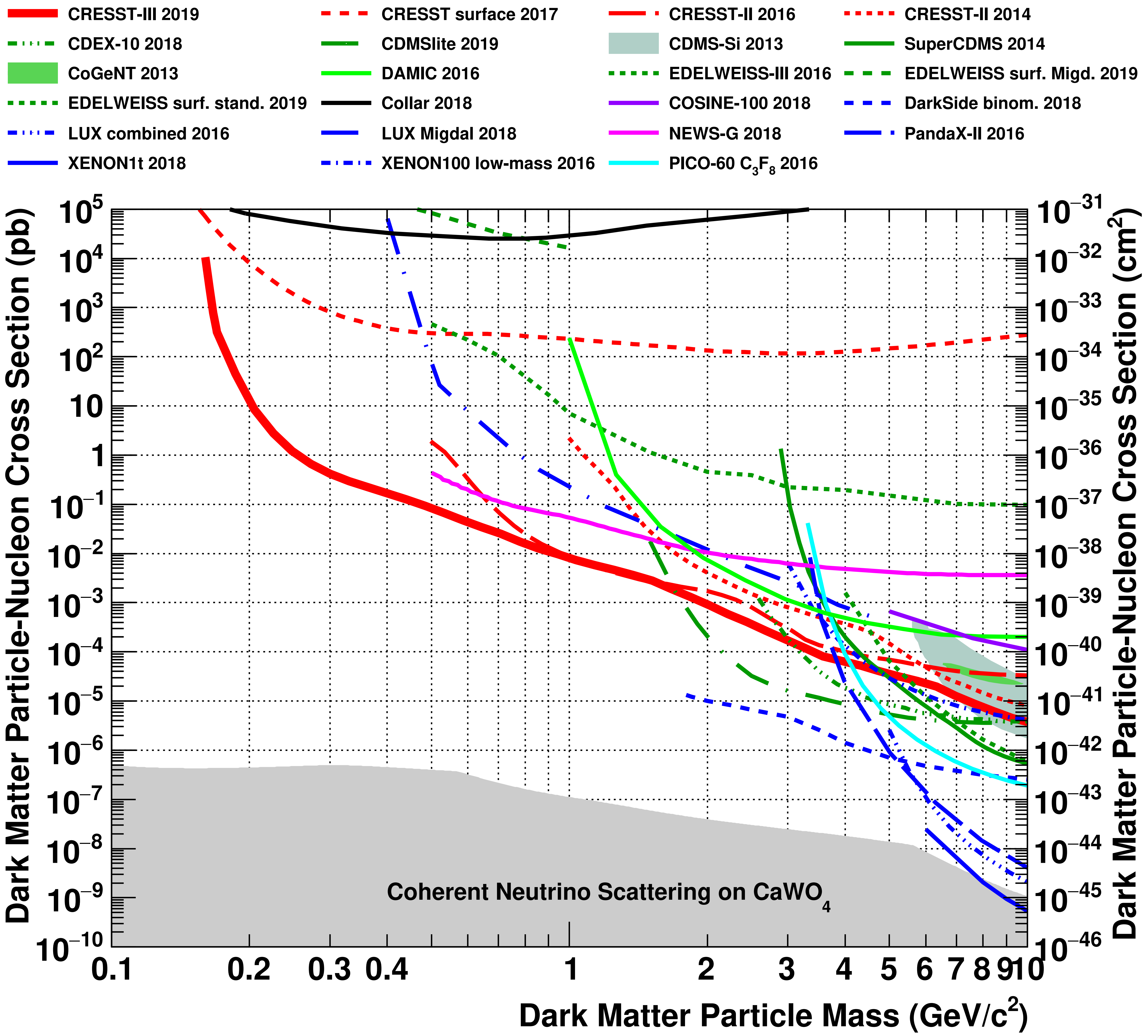
- Search of light DM direct interactions with $CaWO_4$ cryogenic detectors
- Operating temperature ~15 mK
- Second cryogenic detector to collect emitted scintillation light: particle identification
- Single detector mass ~24 g
- Energy Threshold: 30 eV



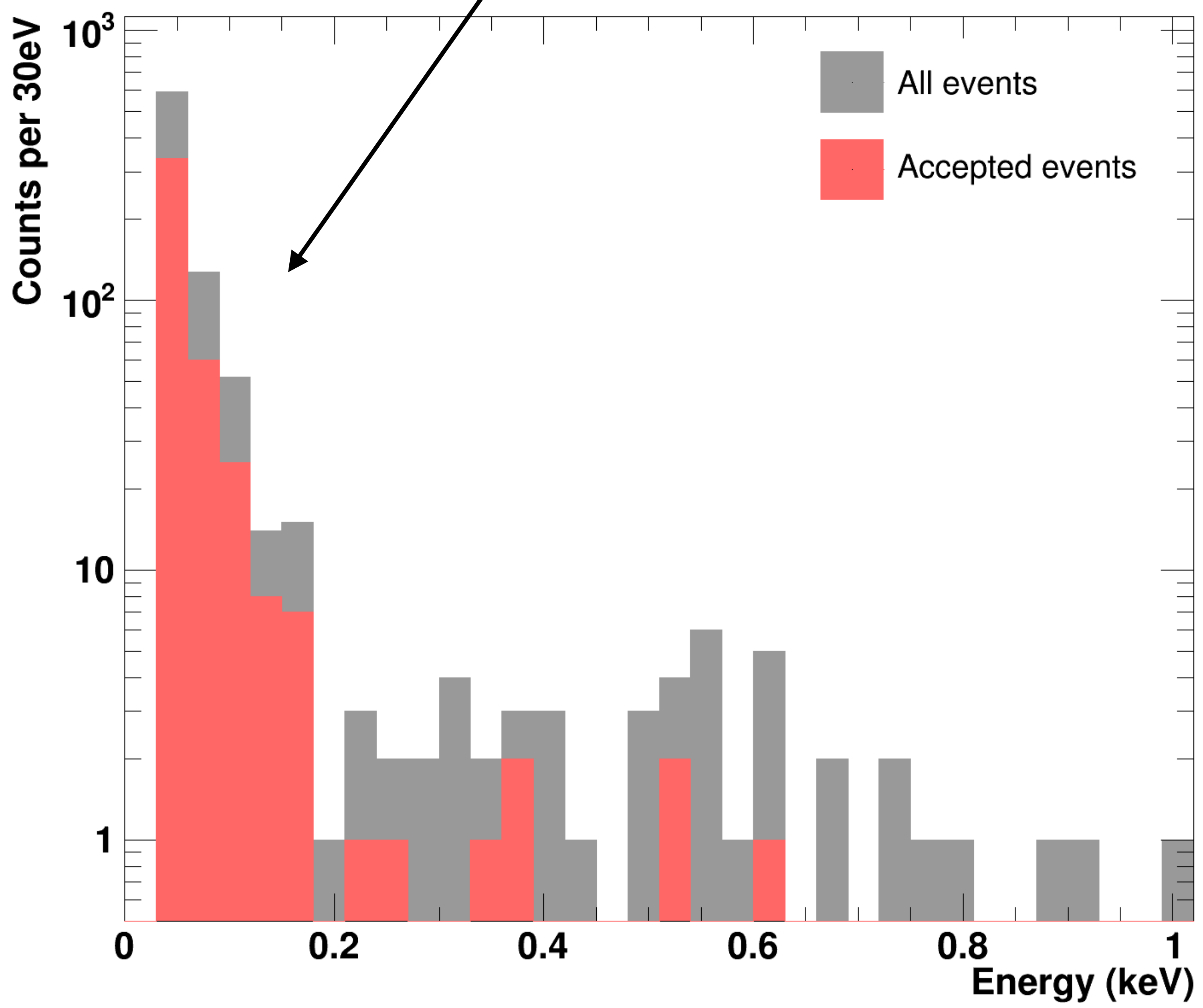


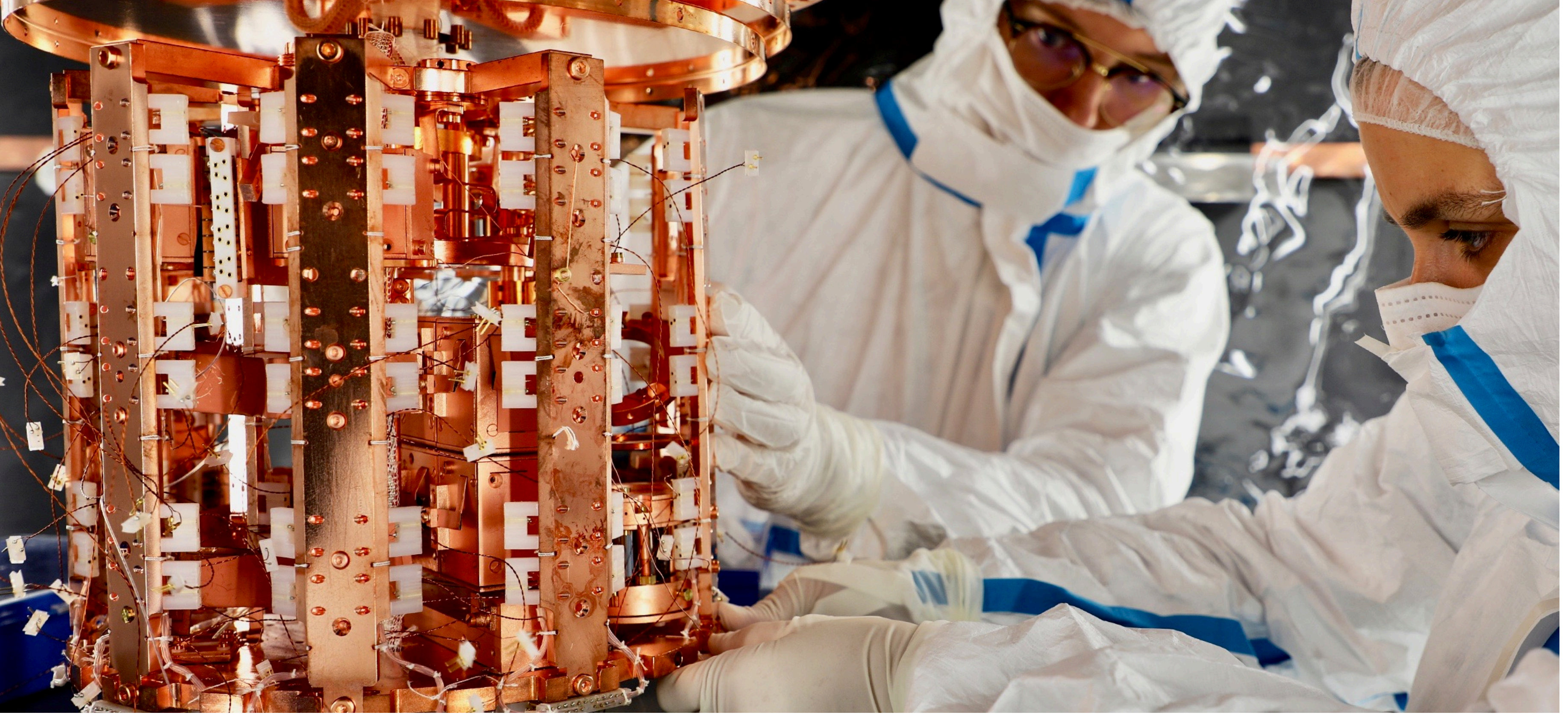
Phys. Rev. D 100, 102002 (2019)

LIMITATIONS: CRESST-III RECENT RESULTS



- More than one order of magnitude improvement at 0.5 GeV/c2
- Extended reach from 0.5 GeV/c2 to 0.16 GeV/c2
- Sensitivity limited by unknown background below 200 eV





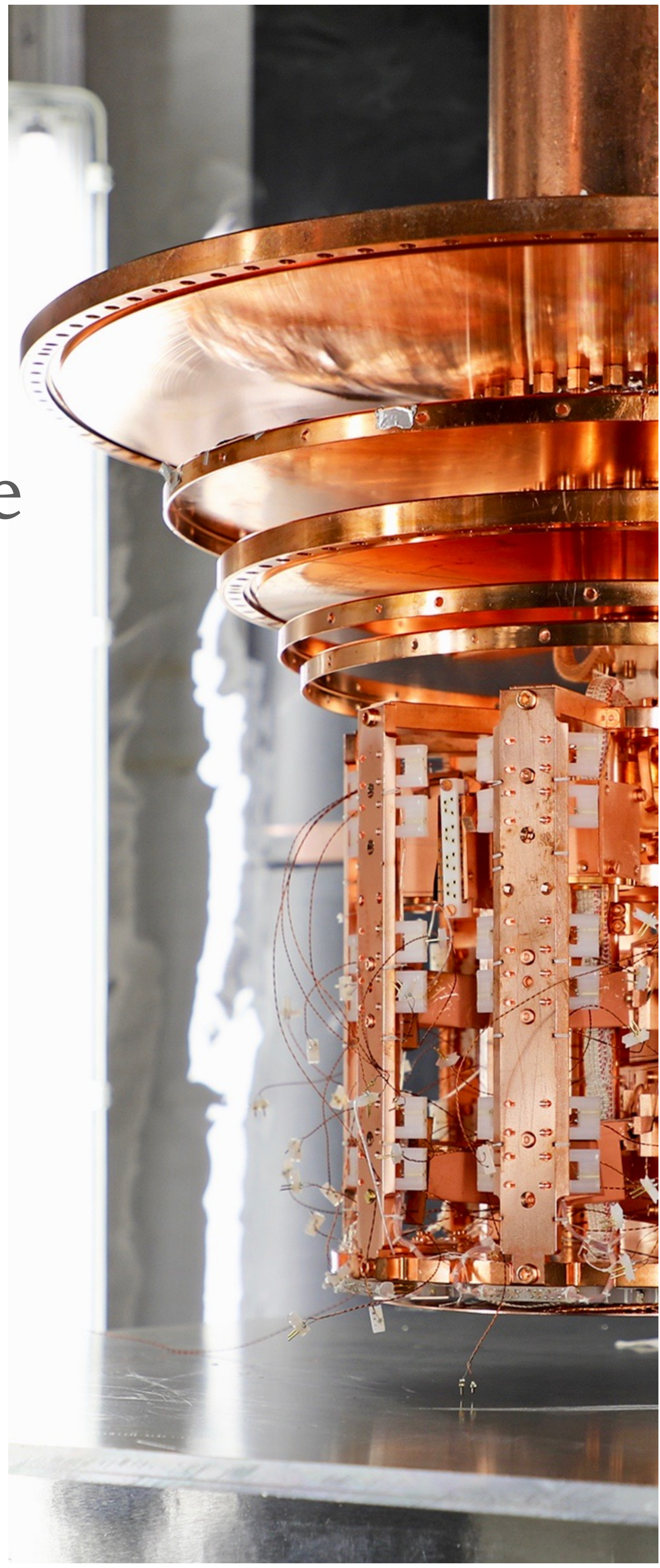
CRESST-III FUTURE PLANS

Run3
2020 - 2021

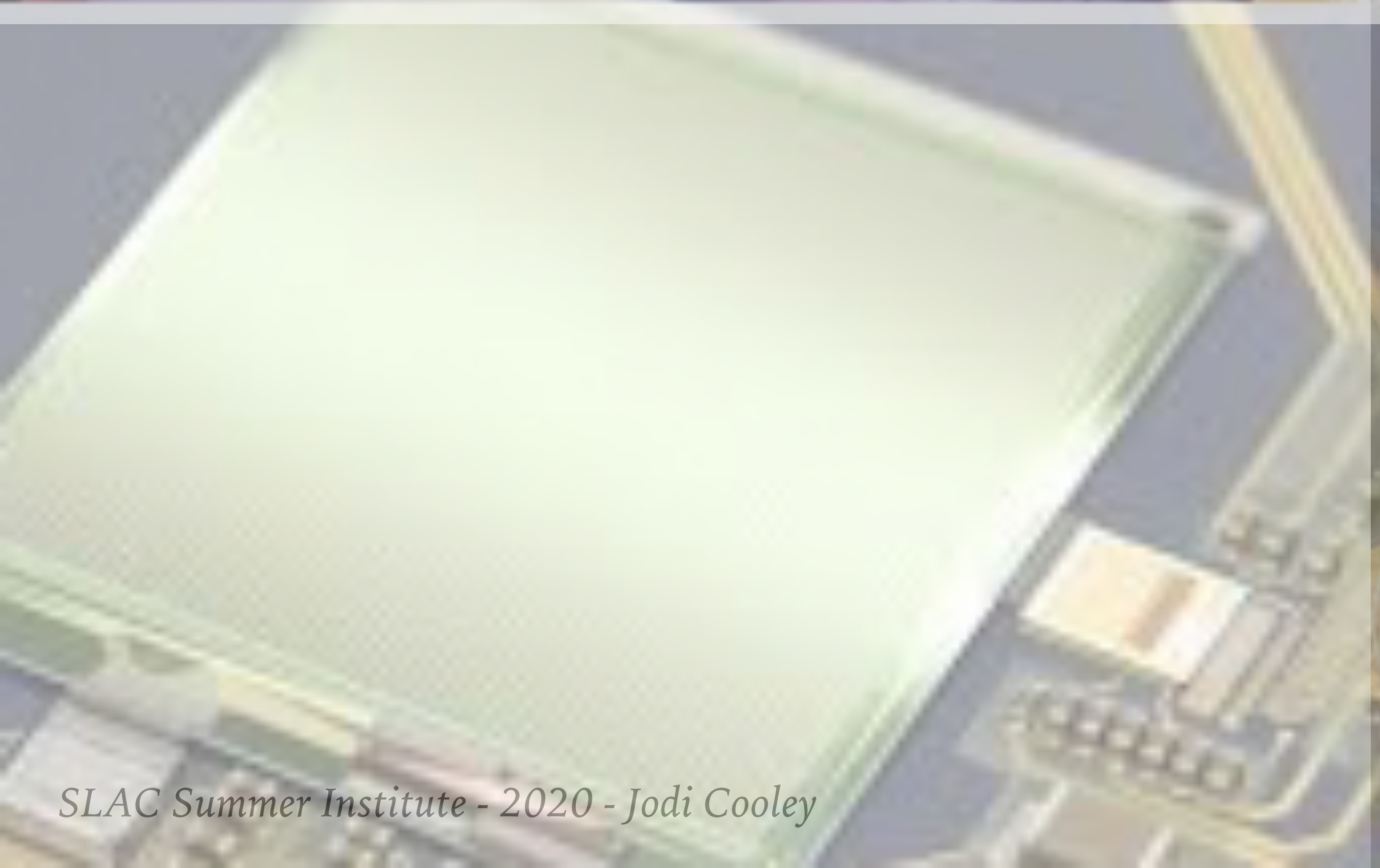
- 2nd round with additional modifications
- Successful cool-down in 03/2020, but stopped due to Corona virus pandemic
- Cool-down started July 20, 2020
- Detetor commissioning Aug - Oct 2020
- November 5, 2020 science data!
  - Preliminary analysis of calibration data is very promising!

CRESST Upgrade
2020 - 2023

- Upgrade to 288 readout channels to accommodate 100 modules for O(2 kg) target mass
- Final planning, prototyping and testing of SQUID read-out electronics, biasing system and DAQ
- Sensor development to further push detector threshold (10 eV)
- Complementary detector materials ($LiAlO_2$, Al_2O_3) which also yield sensitivity for spin-dependent interactions
- 2023 science data taking starts!



Single e-/h+ Pair Sensitivity



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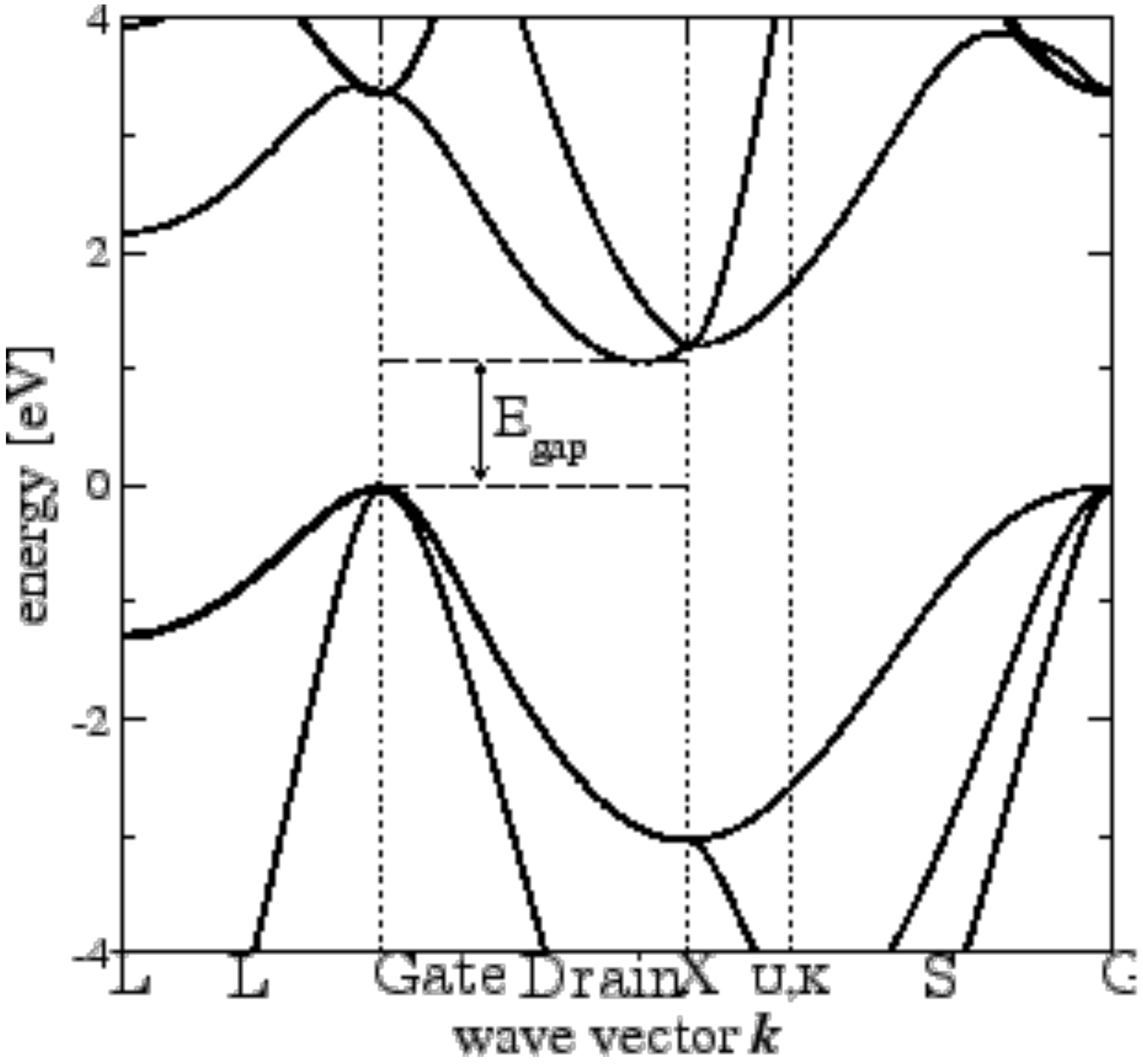
ENERGY SCALE IN SEMICONDUCTORS

Band Diagram for Si



- e- excitation momentum and energy scales in semiconductors can be exploited to search for light mass dark matter
- Si $E_{gap} \sim 1.2$ eV
  - Indirect band gap requires phonon for transition to happen.
  - Temperature dependent
- $\varepsilon_{Si} \sim 3.6$ eV
  - Average energy to produce e/h pair
  - Temperature dependent
- Sensitive to energy deposits of $\mathcal{O}$(eV) (electron scattering) to $\mathcal{O}$(10 eV) (nuclear scattering)

REALM OF SOLID STATE PHYSICS

Solid state physics	Particle physics
$E < 30$ eV	$E >$ keV
Multi-body system	Free particles
Allowed energies/momenta given by dispersion relation	$E = p^2/2m$
Particles may have effective masses	Particle masses well defined

CHALLENGES

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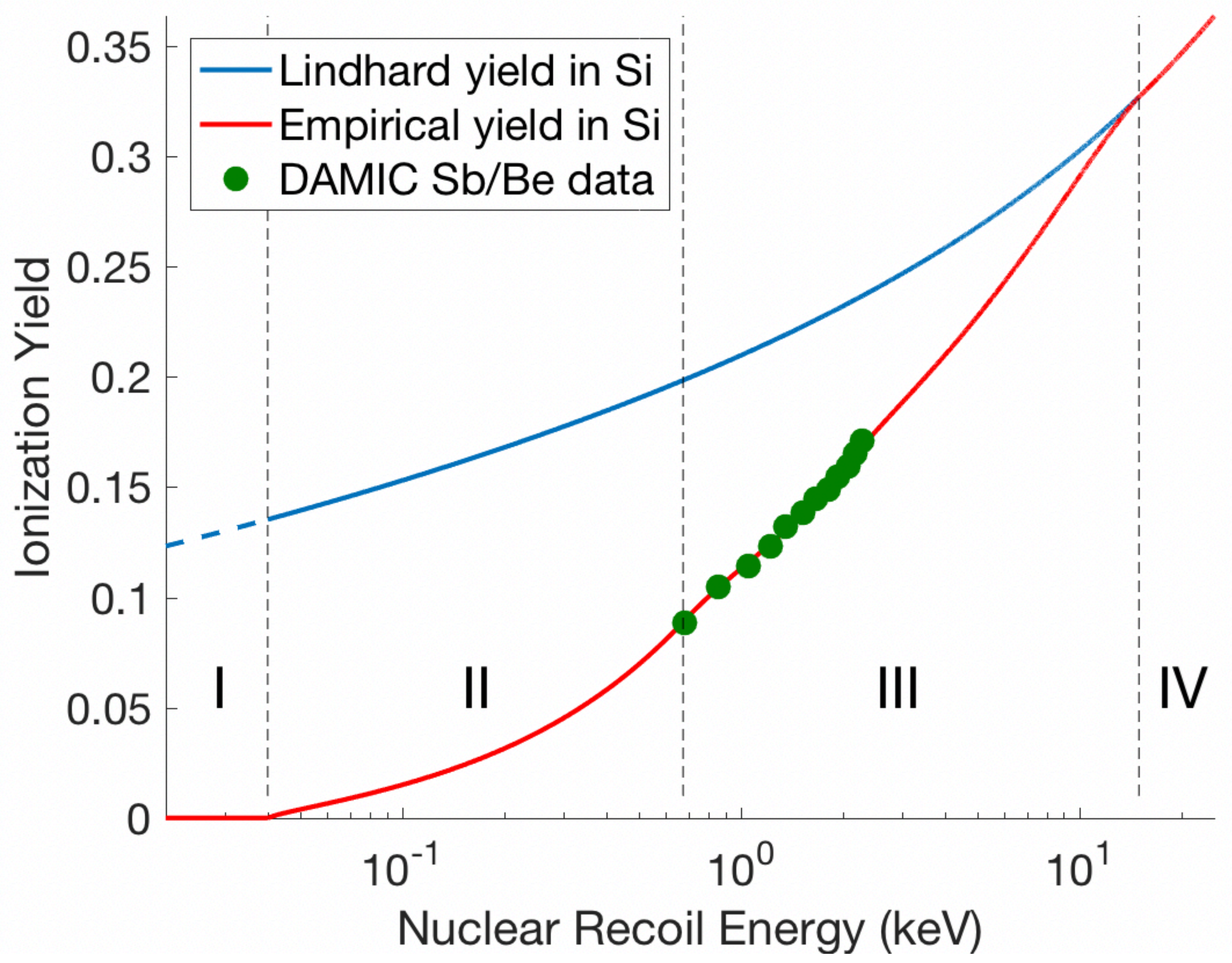

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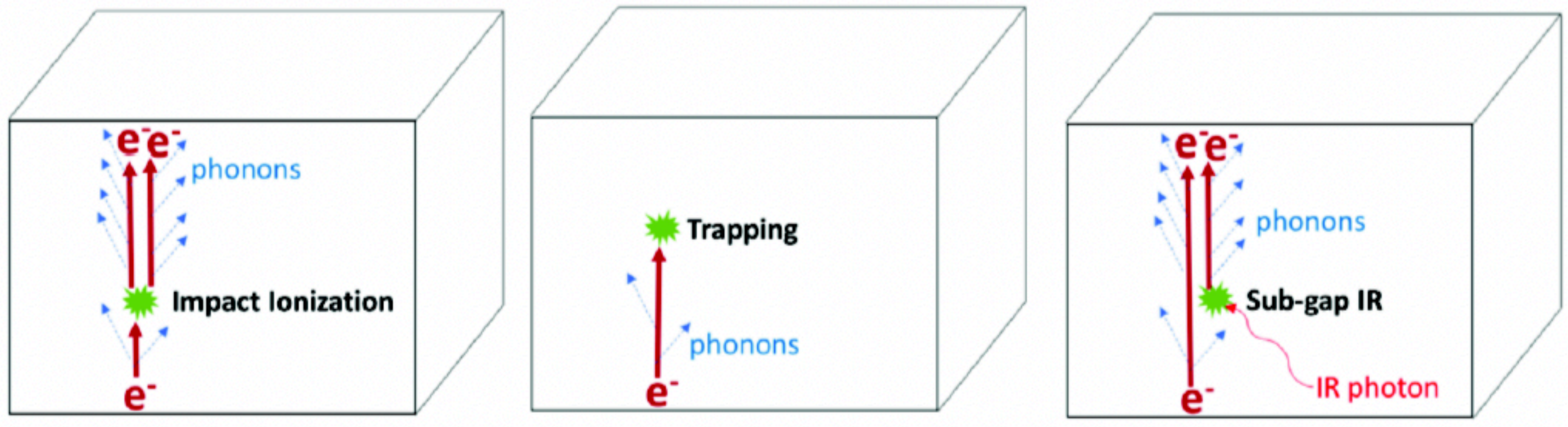

Figure: R.K. Romani

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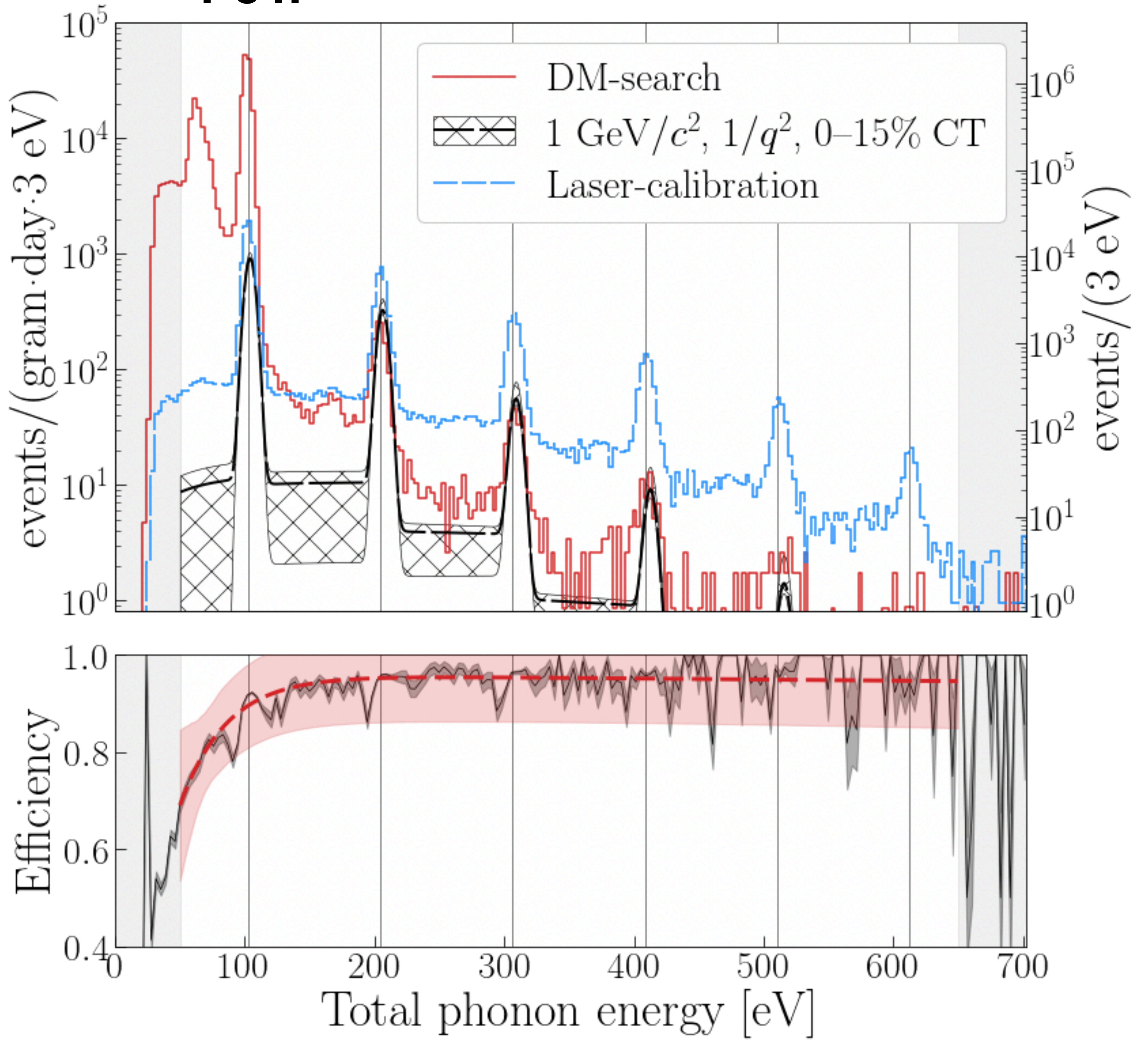
- **Backgrounds**
  - Spectral information about radioactive decays at eV scale required.
    - Relevance is exposure dependent
  - IR and optical photons become significant backgrounds at lowest energies.
  - Dark/leakage current can be significant, dominant background at lowest energies.

HVEV DETECTORS

arXiv:2005.14067
PRL 121, 051301 (2018)
APL 112, 043501 (2018)
NIM A 963, 163757 (2020)

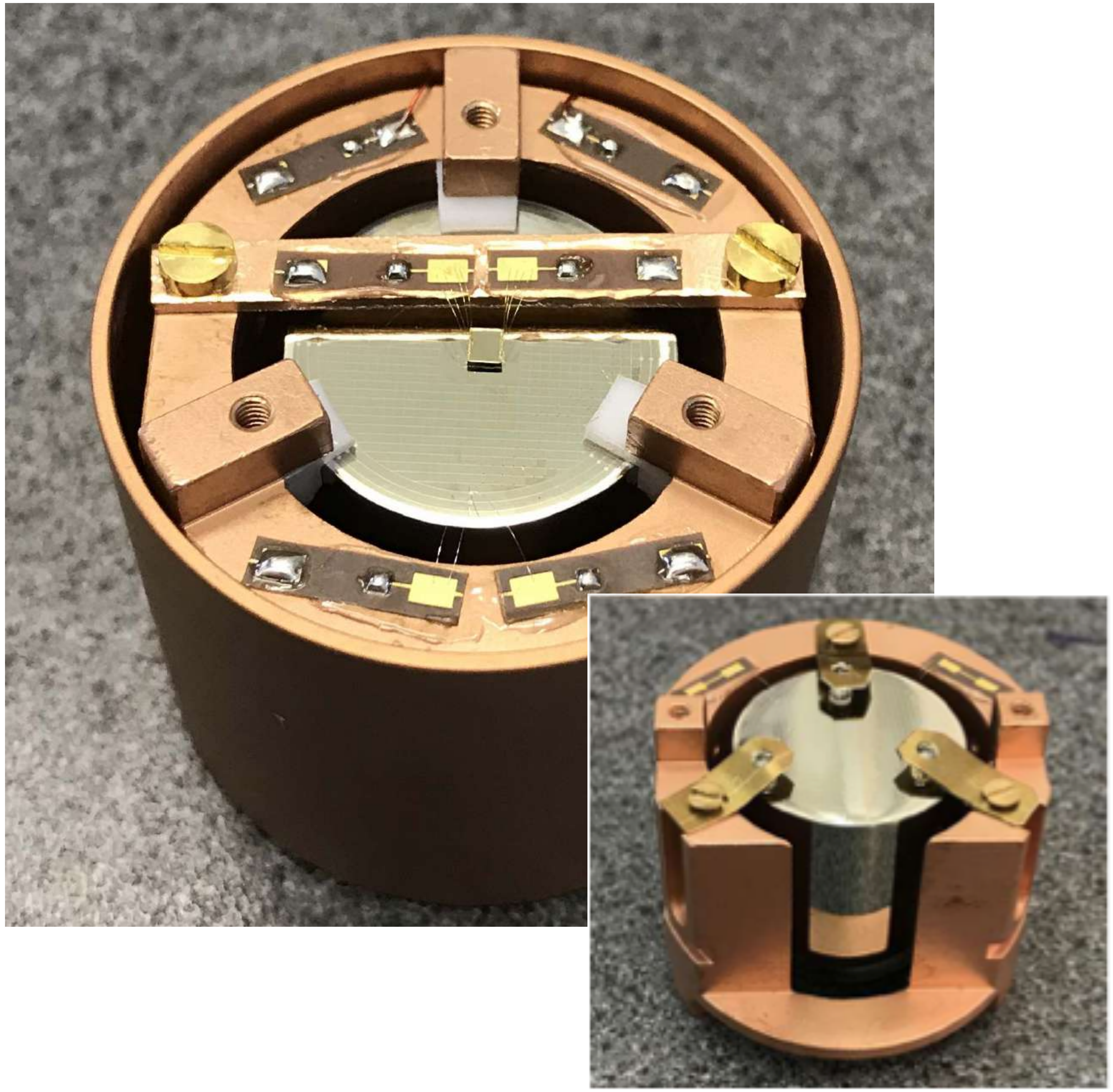
- Single-hole e/h-pair resolution devices will have sensitivity to a variety of sub-GeV DM models with g*d exposures
- 0.93 g Si crystal (1 x 1x 0.4 cm³) operated at 50-52 mK at a surface test facility.
- Exposure: 3.0 gram-days (collected over 3 days)
  - operation voltage: 100 V
  - energy resolution: σ_{ph} = 3 eV
  - charge resolution: σ_{eh} = 0.03 e^-h^+
- Calibrations with in-run monochromatic 635 nm laser fiber-coupled to room temperature.
- Data selection criteria were applied to remove leakage and surface events.

1 e^-h^+



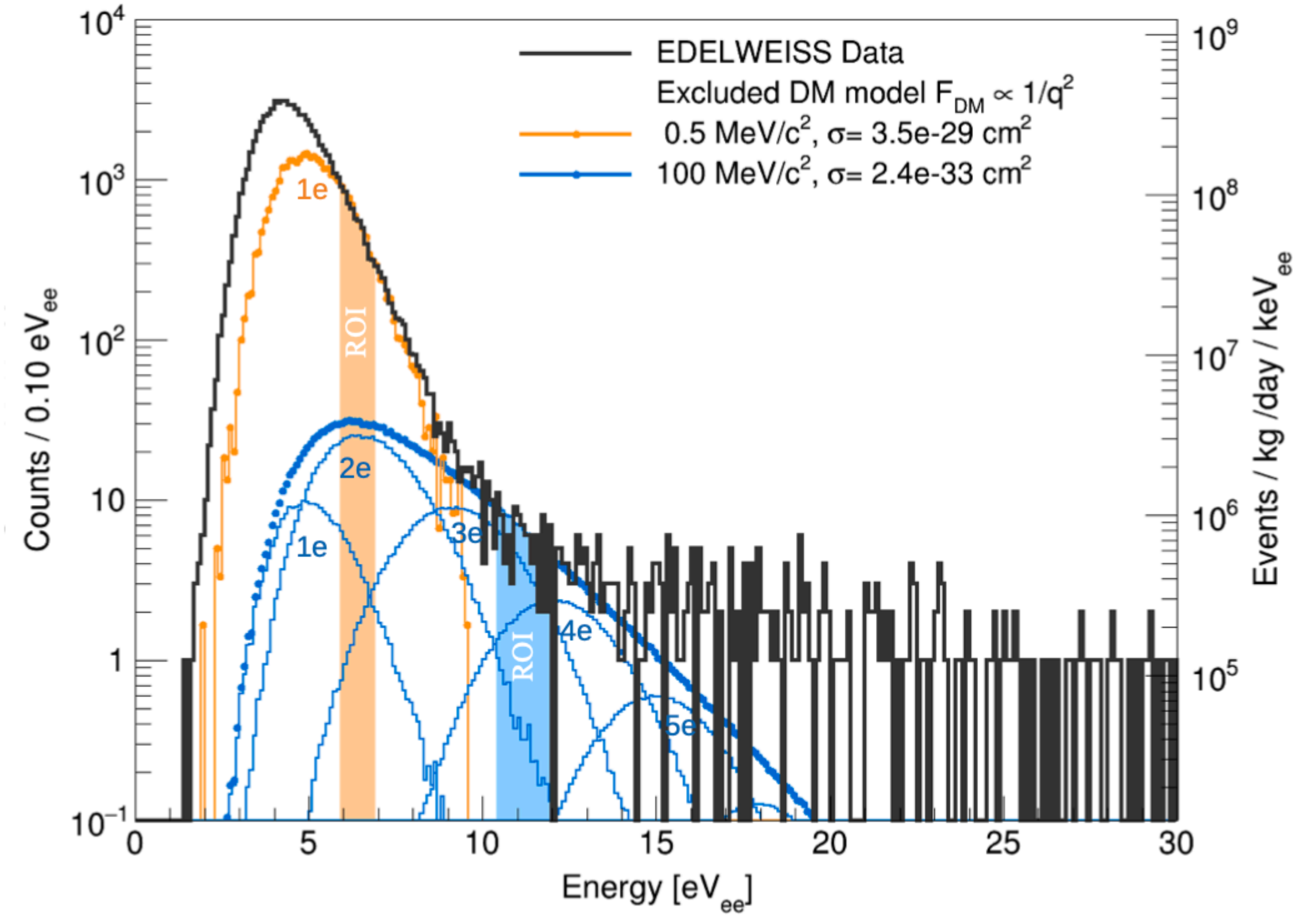
EDELWEISS RED 30 DETECTOR: HV OPERATION

- 33.4 g (20 x 20 mm) Ge bolometer with NTD sensor and electrodes operated in LSM (5 μ/m2/d)
- Exposure: 2.44 days
  - operation voltage: 78 V
  - energy resolution: σ_{ph} = 44 eV (1.6 eVee)
  - charge resolution: σ_{eh} = 0.53 e-h+
- Calibrations using 71Ge KLM (0.16, 1,30 and 10.37 keV) activation lines from AmBe neutron source.
- Data selection criteria were applied to remove events occurring in the NTD (instead of the crystal).



EDELWEISS RED 30 DETECTOR: HV OPERATION

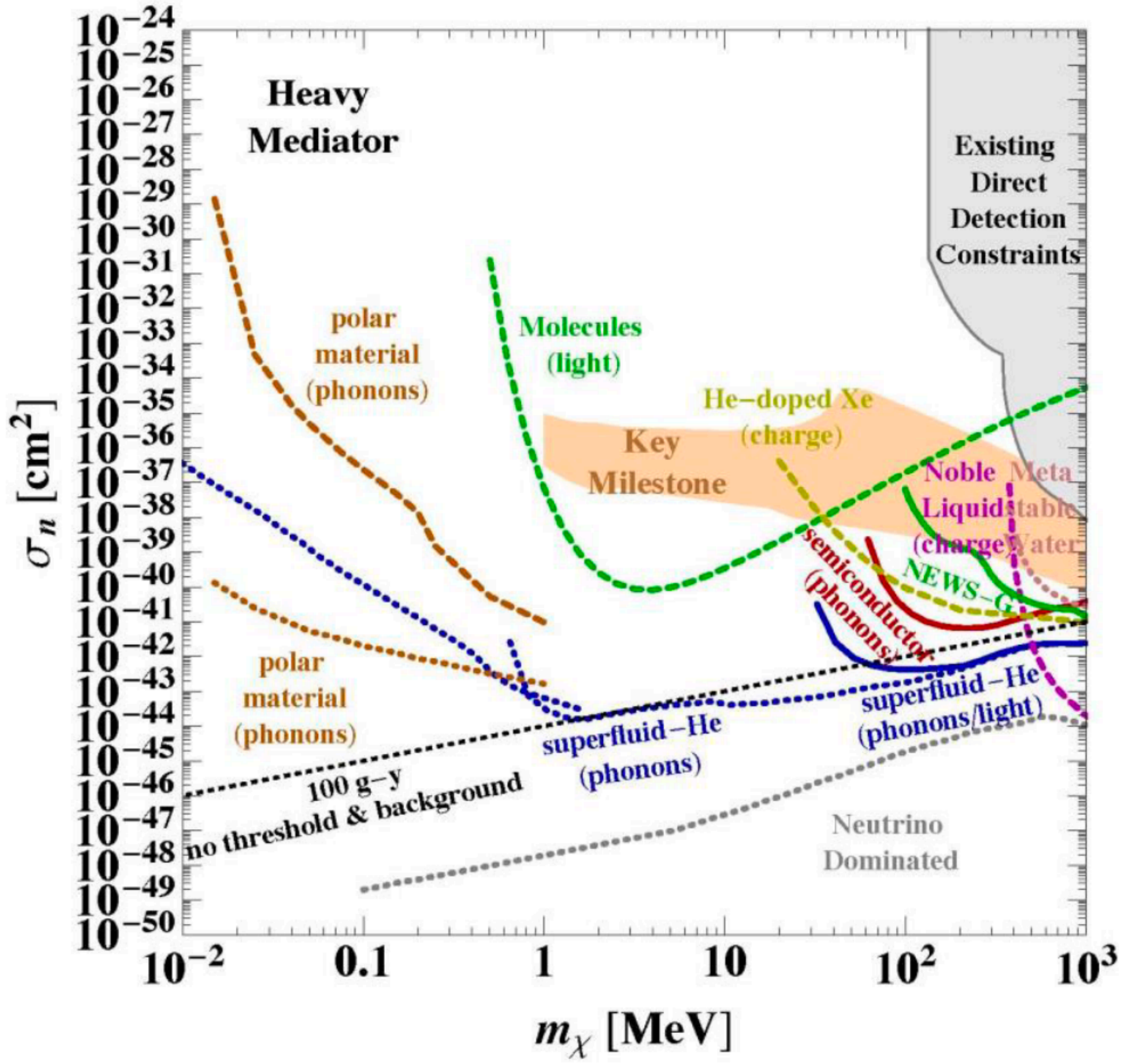
- Heat only events (those not affected by NTL amplification) are the main source of backgrounds.
  - 10^6 DRU @ 10 eVee
  - 1.5×10^5 DRU @ 25 eVee
- Dominant limitation for >3 e- signals
- May hypothesis have been studied as to the origin. No single contributor has been found.
  - These events are probably multiple sources.



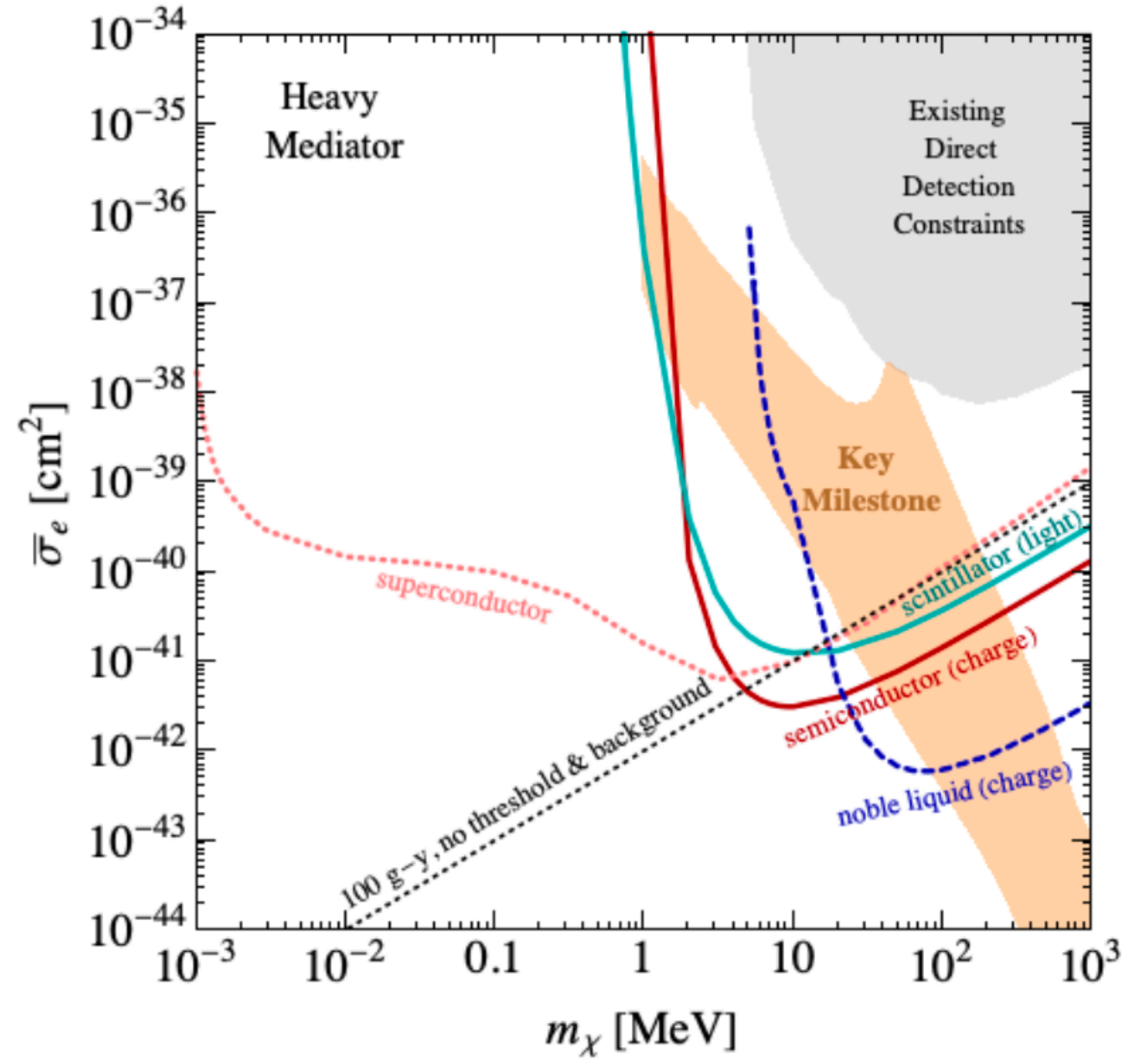
(dru = event/day/keV/kg)

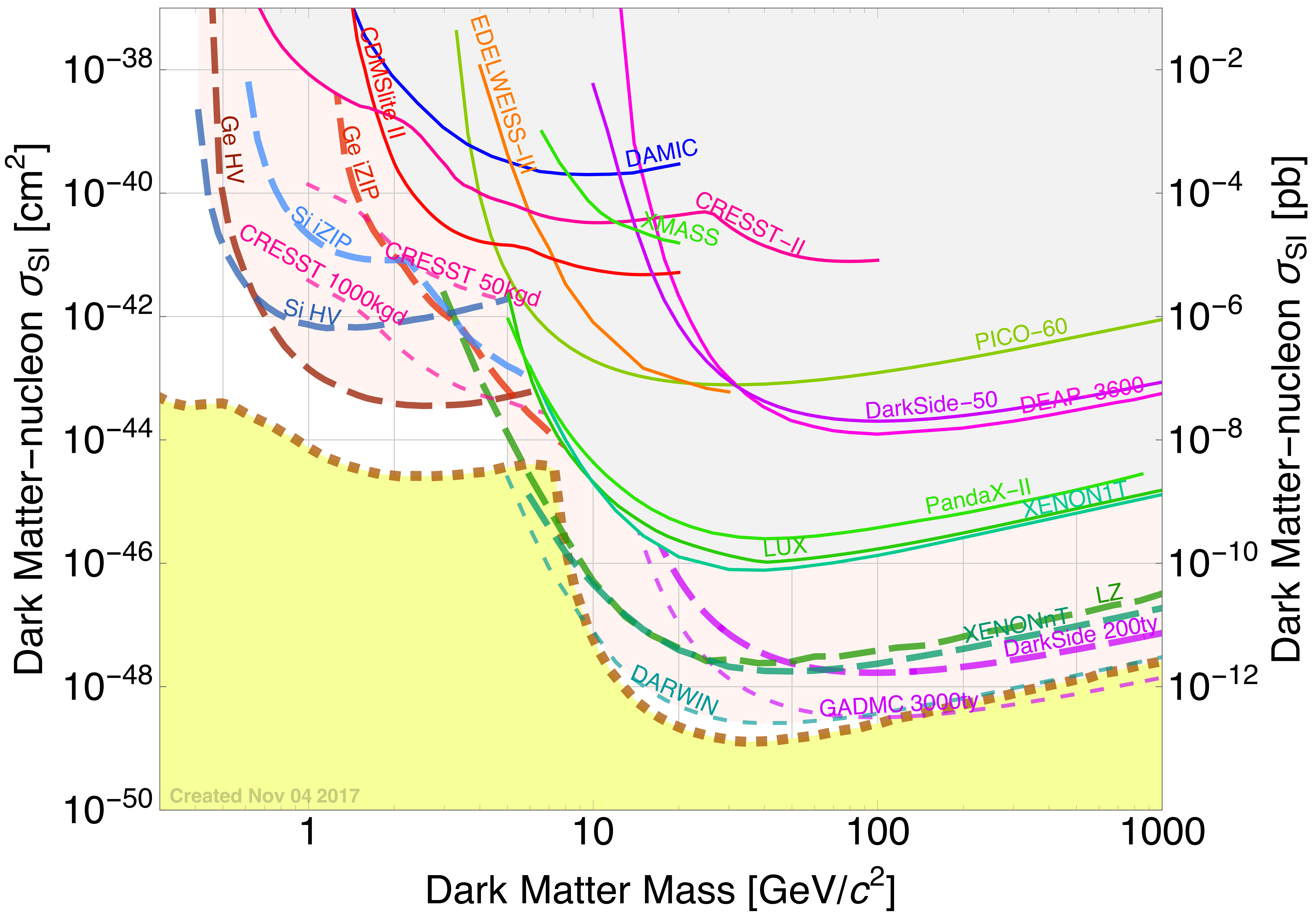
WHERE ARE WE GOING?

Scattering off nuclei



Scattering off electrons





CONCLUSIONS

- The next decade will be very exciting for dark matter direct detection. Various G2 Experiments will come online, covering a lot of new parameter space.
- Although WIMPs remain a very interesting dark matter candidate, other scenarios are gaining traction in the theoretical community, while new ideas for direct searches have been proposed and are gaining momentum.
- Given the wealth of theoretical possibilities, a diversity of experimental designs and targets will be needed to constrain the theory and couplings of any discovered signal.