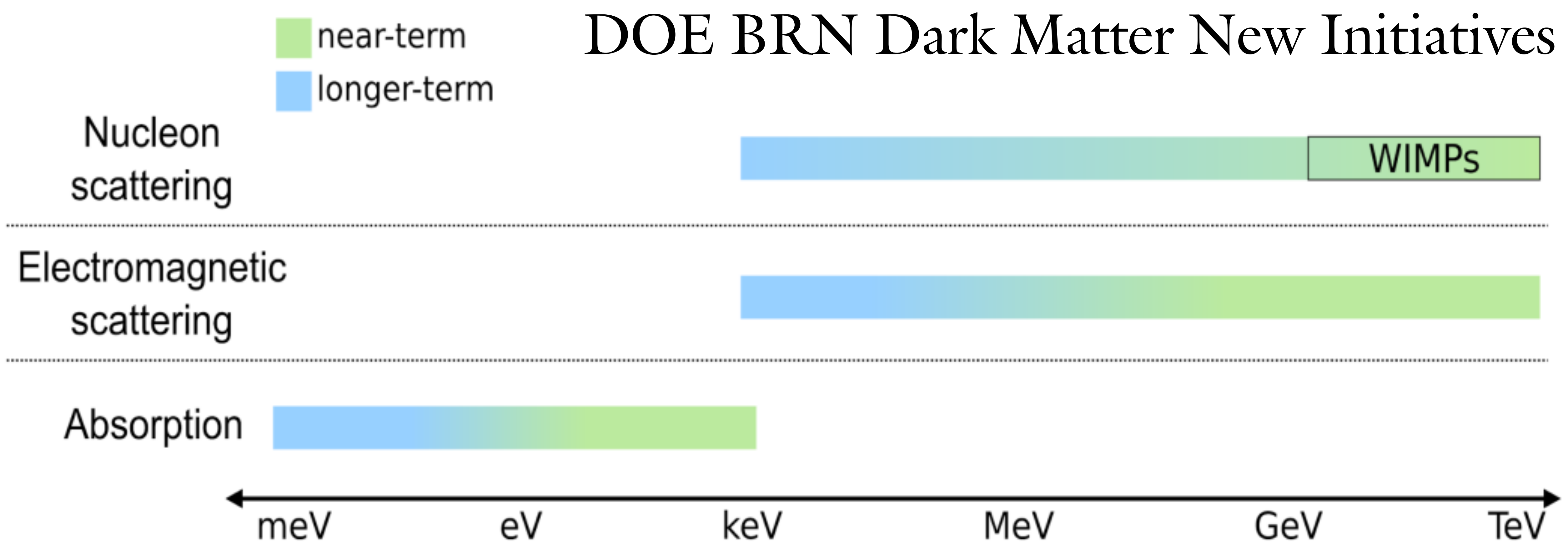
Future Dark Matter Experiments with Cryogenic Detectors

Jodi Cooley - SMU

Direct Detection Needs

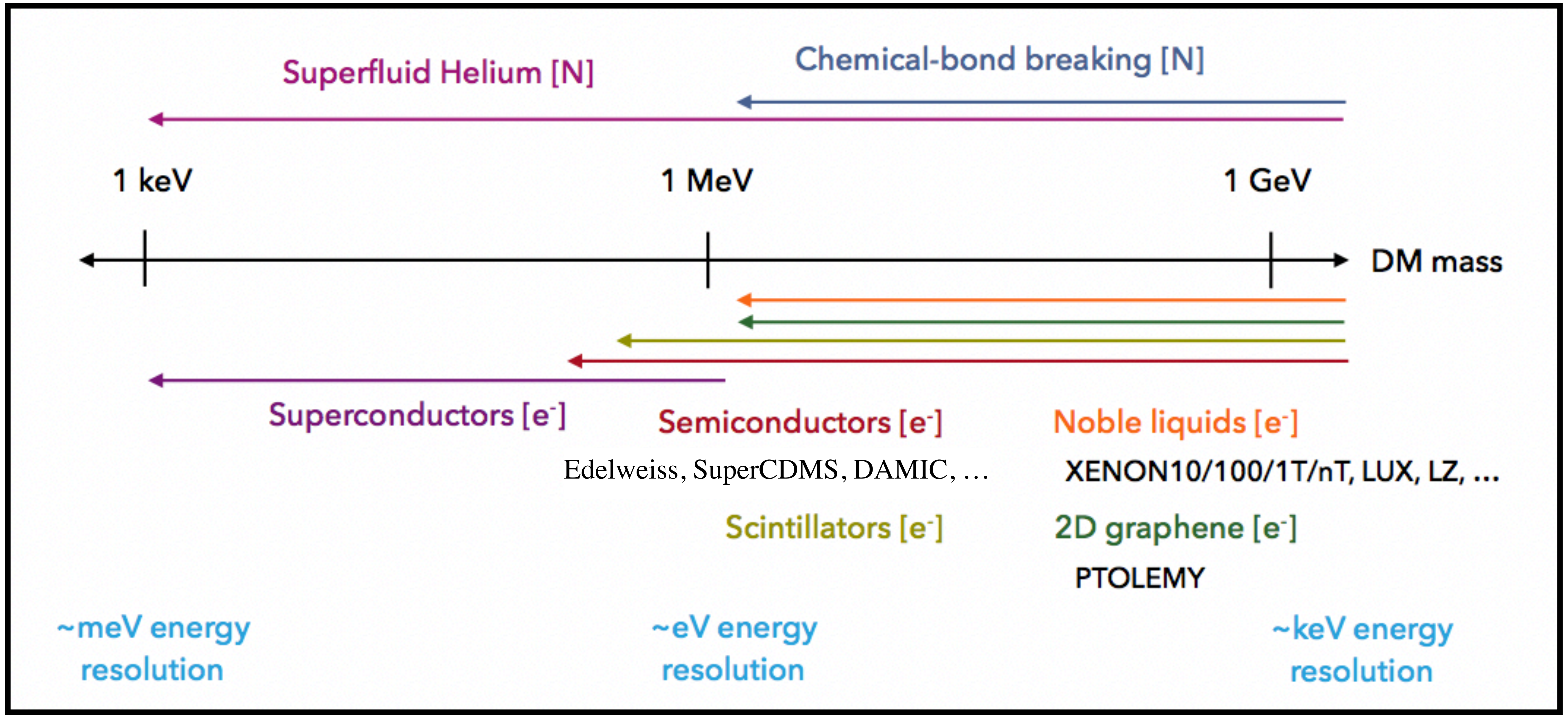
- Ability to detect low energy dark matter-nucleon couplings
  - Detect small energy depositions requires low threshold detectors.
  - Radiogenically pure
  - Difference between electronic recoils & nuclear recoils
  - Difference between alphas and nuclear recoils
- Ability to detect dark matter-electron couplings.
  - Detect extremely small energy depositions require even lower thresholds.
  - Ultra pure targets
- Noise
  - Environmental and instrumental
- Shielding from radiogenic and cosmogenic backgrounds
  - Position reconstruction and fiducialization



There are a number of existing experiments and new ideas covering a large amount of space. In this talk, I will only be able to highlight a few.

Detection Media for Low Mass Searches

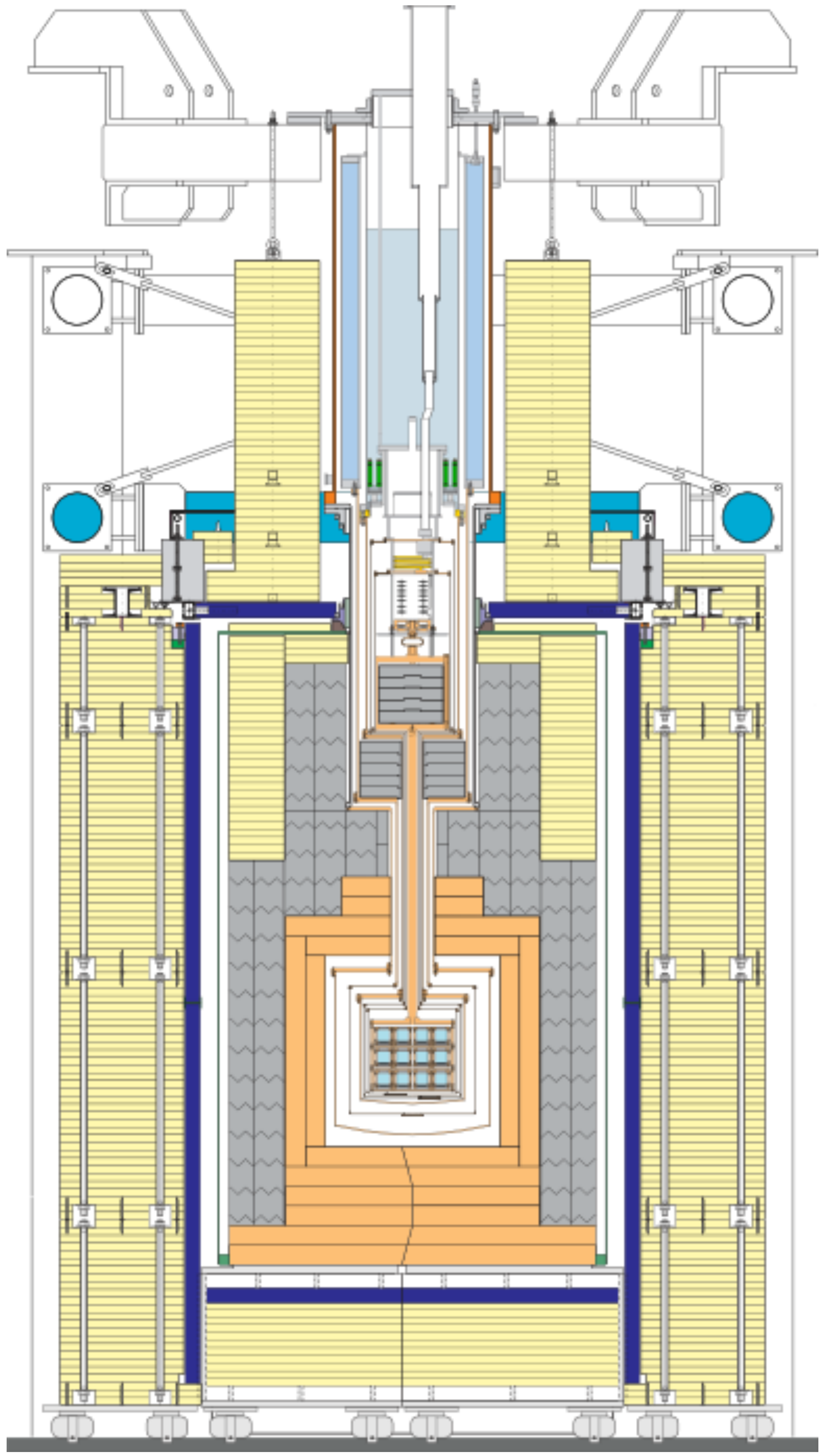
- A lot of work has gone into searching for the canonical WIMP and we have excluded large swaths of parameter space.
- There are many plausible dark matter candidates below 10 GeV/c².
- Future cryogenic technologies include a mix of materials with small but non-zero band gaps to limit dark counts and maximize energy to carrier conversion.
- Extent of arrows driven by fundamental limitations from kinematics and material properties. Assumes large hurdles can be overcome in energy and charge noise across all experiments.



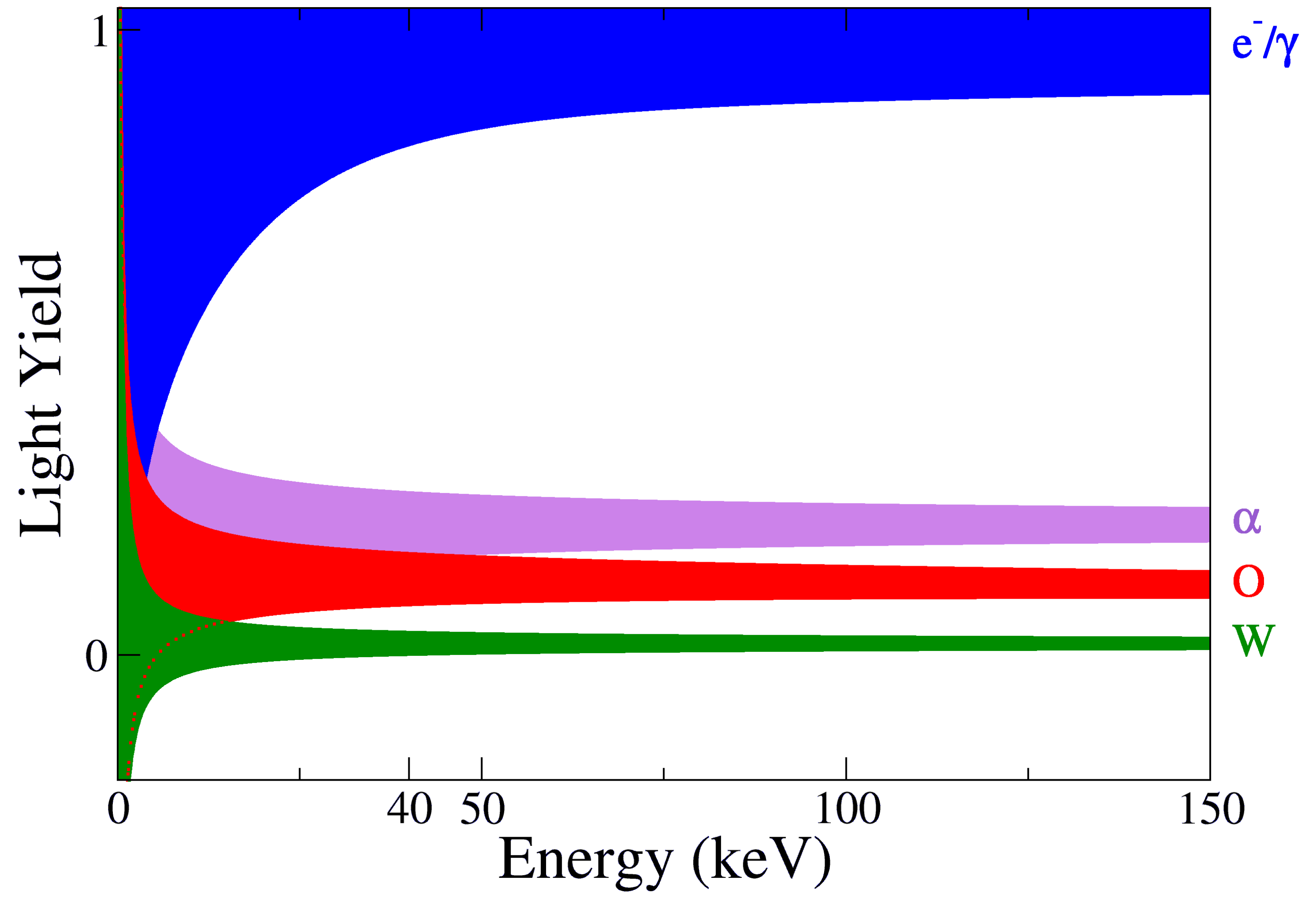
Noah Kurinsky

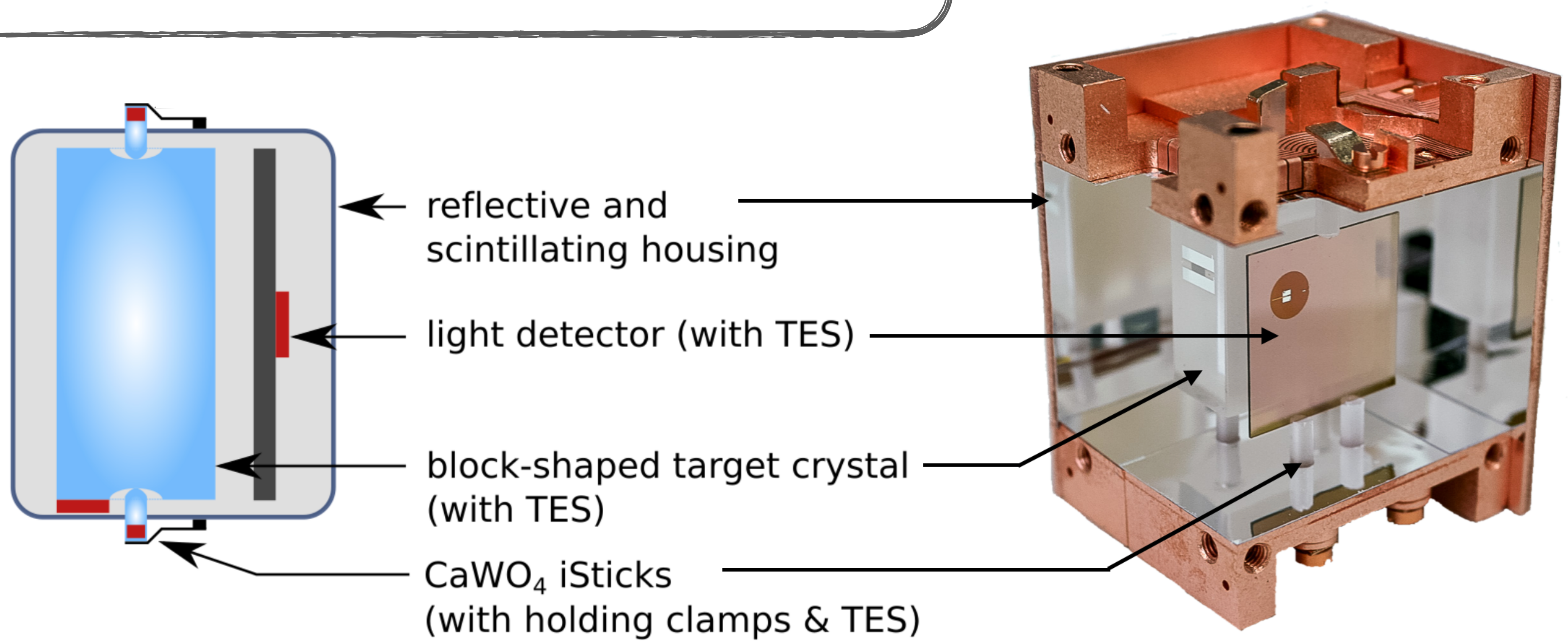
CRESST III

CRESST Experiment Operation Principles



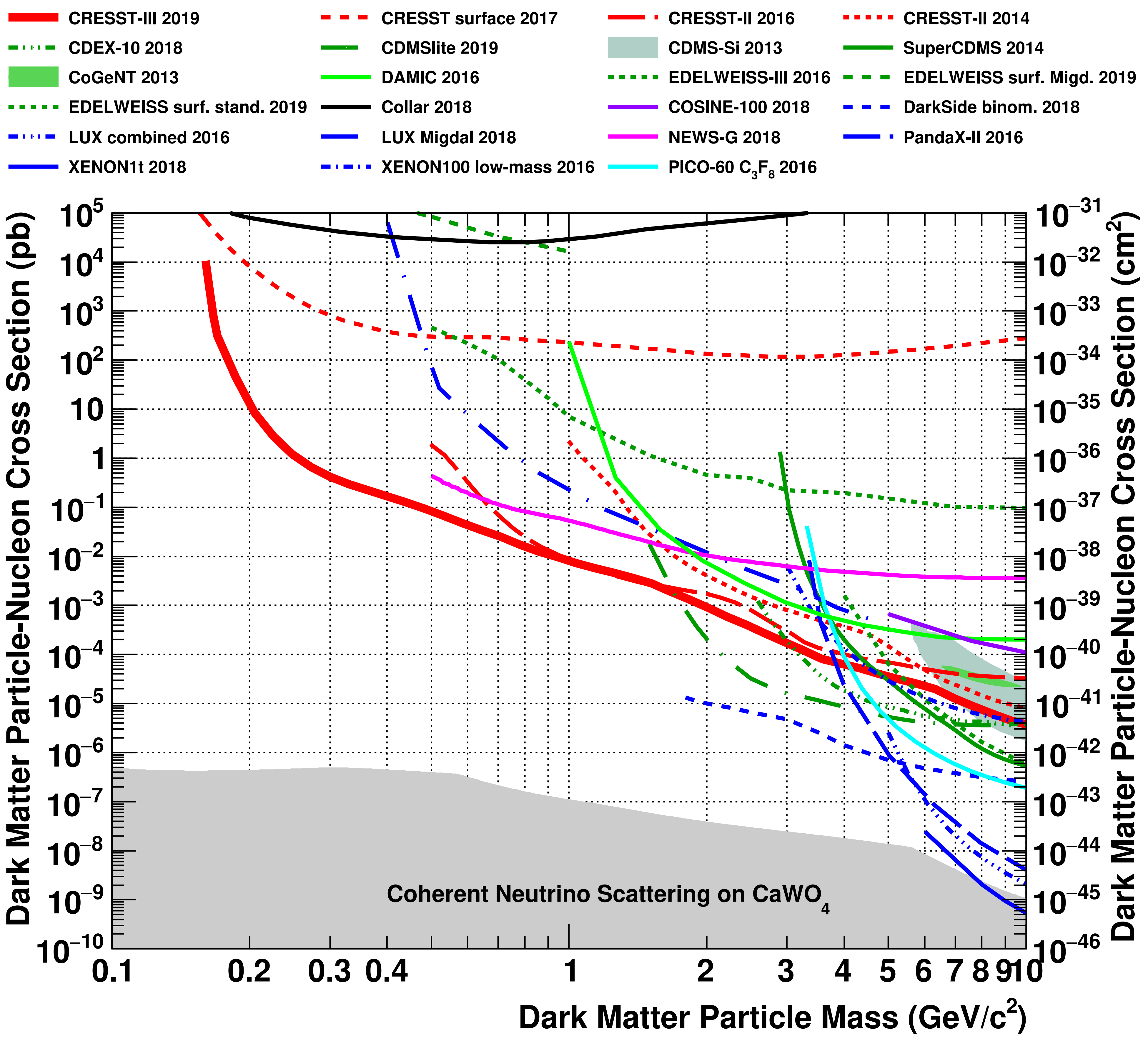
- Search of light DM direct interactions with $CaWO_4$ cryogenic detectors
- Operating temperature ~15 mK
- Second cryogenic detector to collect emitted scintillation light: particle identification
- Single detector mass ~24 g
- Energy Threshold: 30 eV





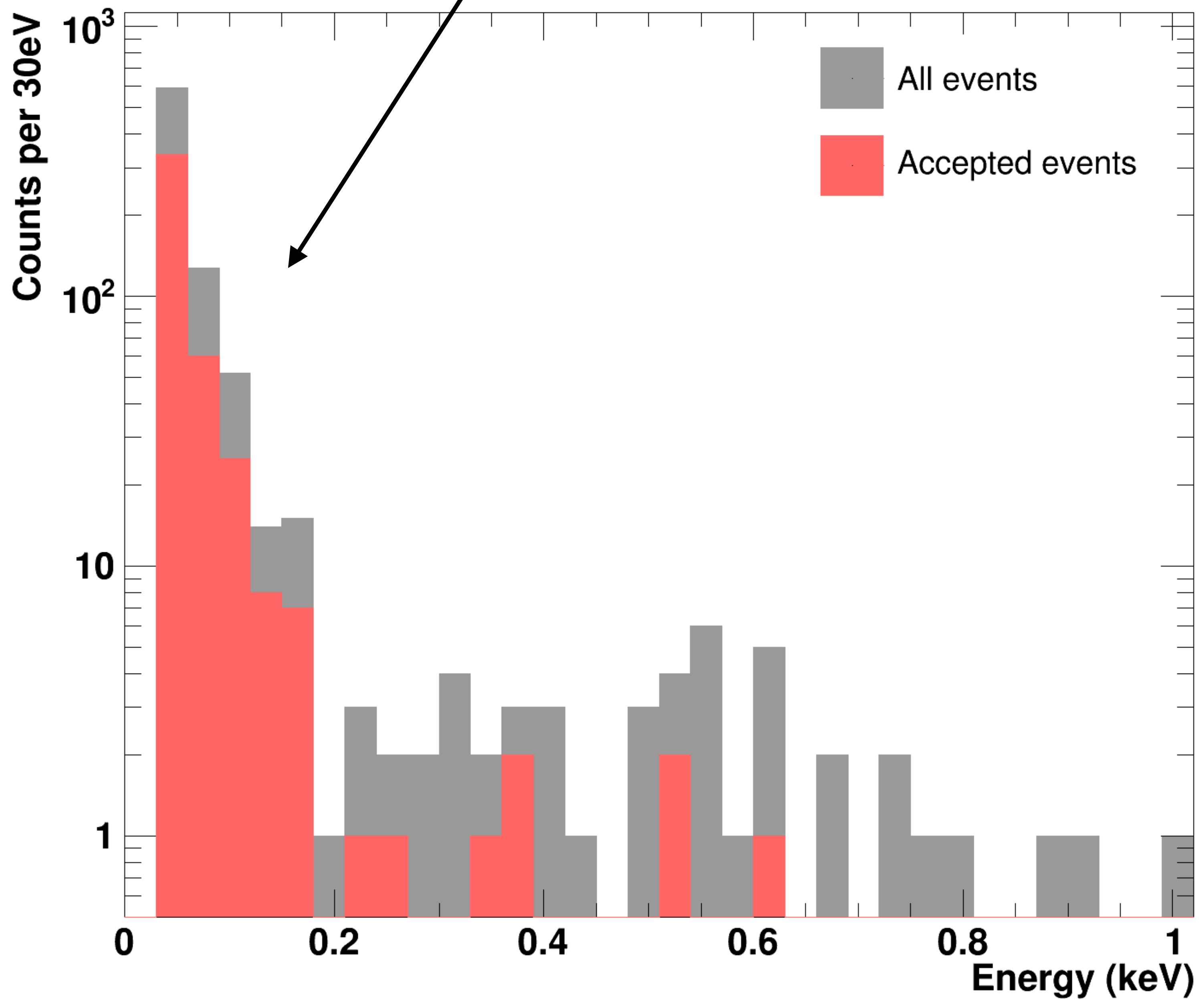
Phys. Rev. D 100, 102002 (2019)

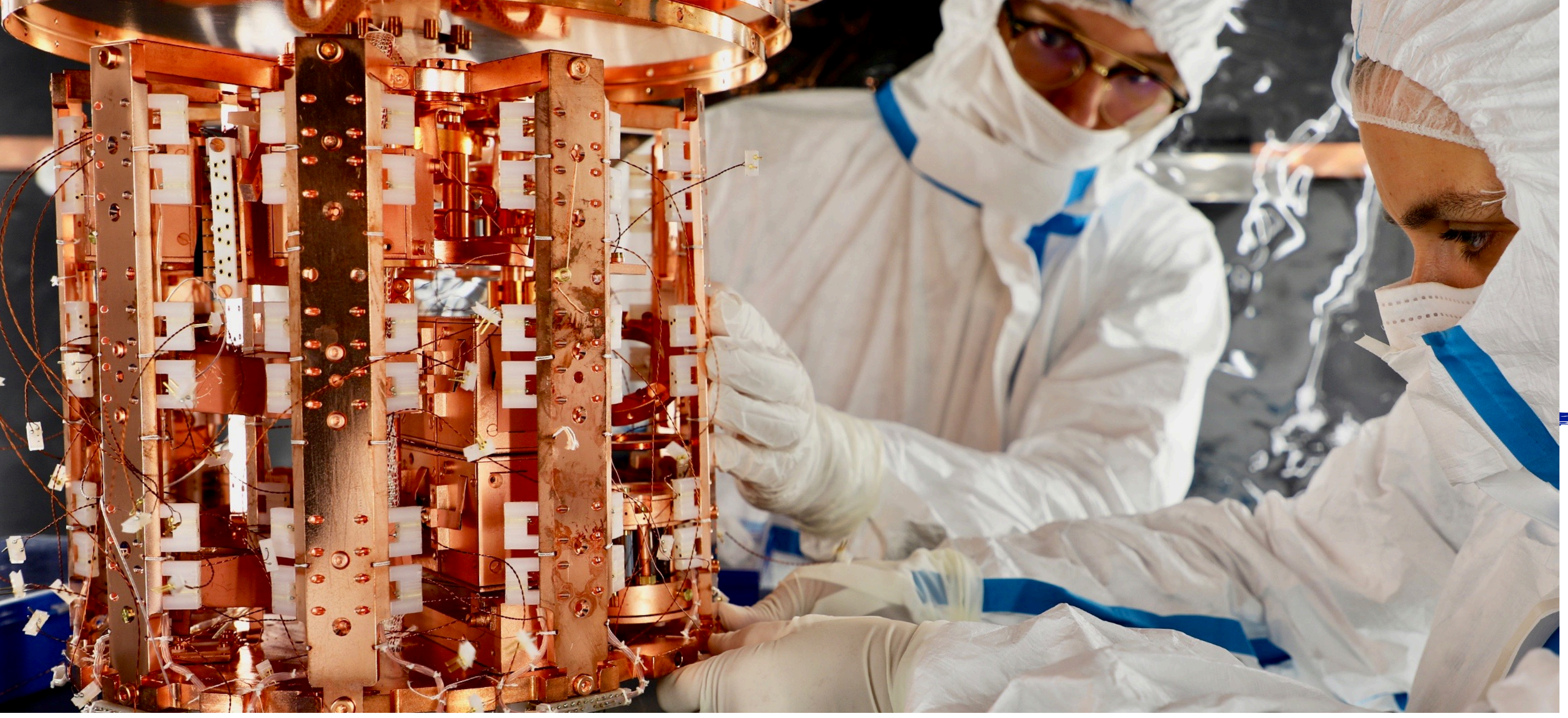
Limitations: CRESST-III Recent Results



Data taking period:	2016 – 2018
Target crystal mass:	23.6 g
Gross exposure (before cuts):	5.689 kg days
Nuclear recoil threshold:	30.1 eV

- 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





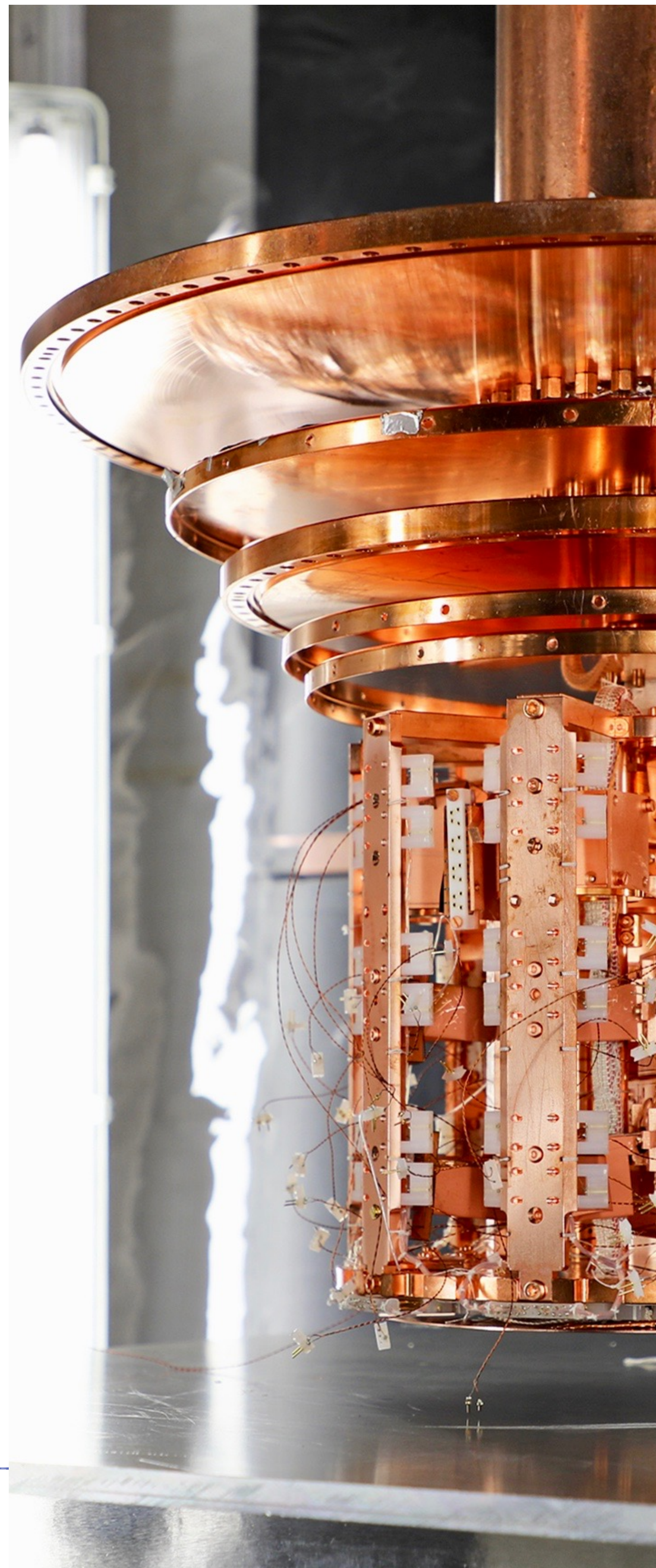
CRESST-III Future Plans

Run3
07/2020

- 2nd round with additional modifications
- Successful cool-down in 03/2020, but stopped due to Corona virus pandemic
- Next cool-down started Monday, July 20!!!

CRESST Upgrade
2020/2021

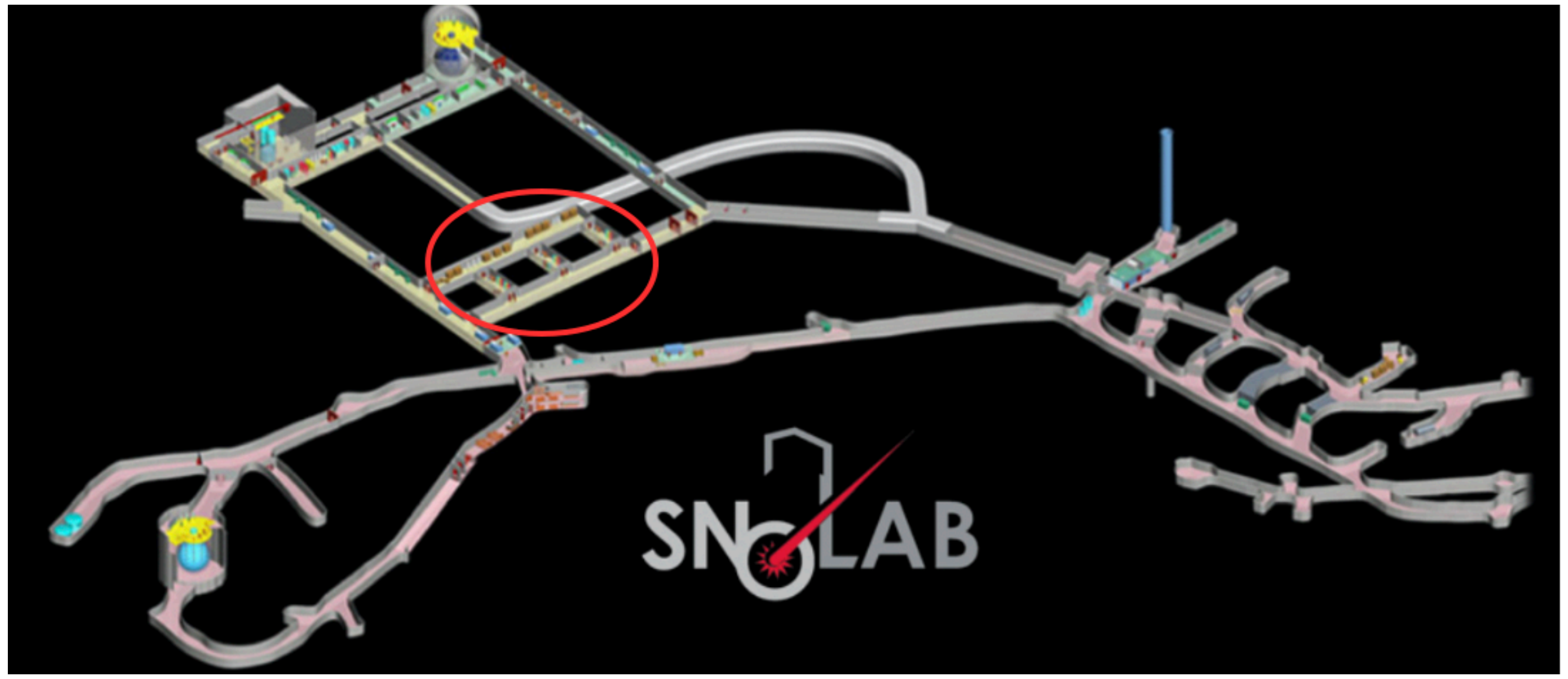
- Upgrade to 200 readout channels to accommodate 100 modules for O(2 kg) target mass
- New cryostat cabling designed and prototyped
- Sensor development to further push detector threshold (10 eV)
- Continuation of studies with alternative detector materials ($LiAlO_2$, Al_2O_3) which also yield sensitivity for spin-dependent interactions

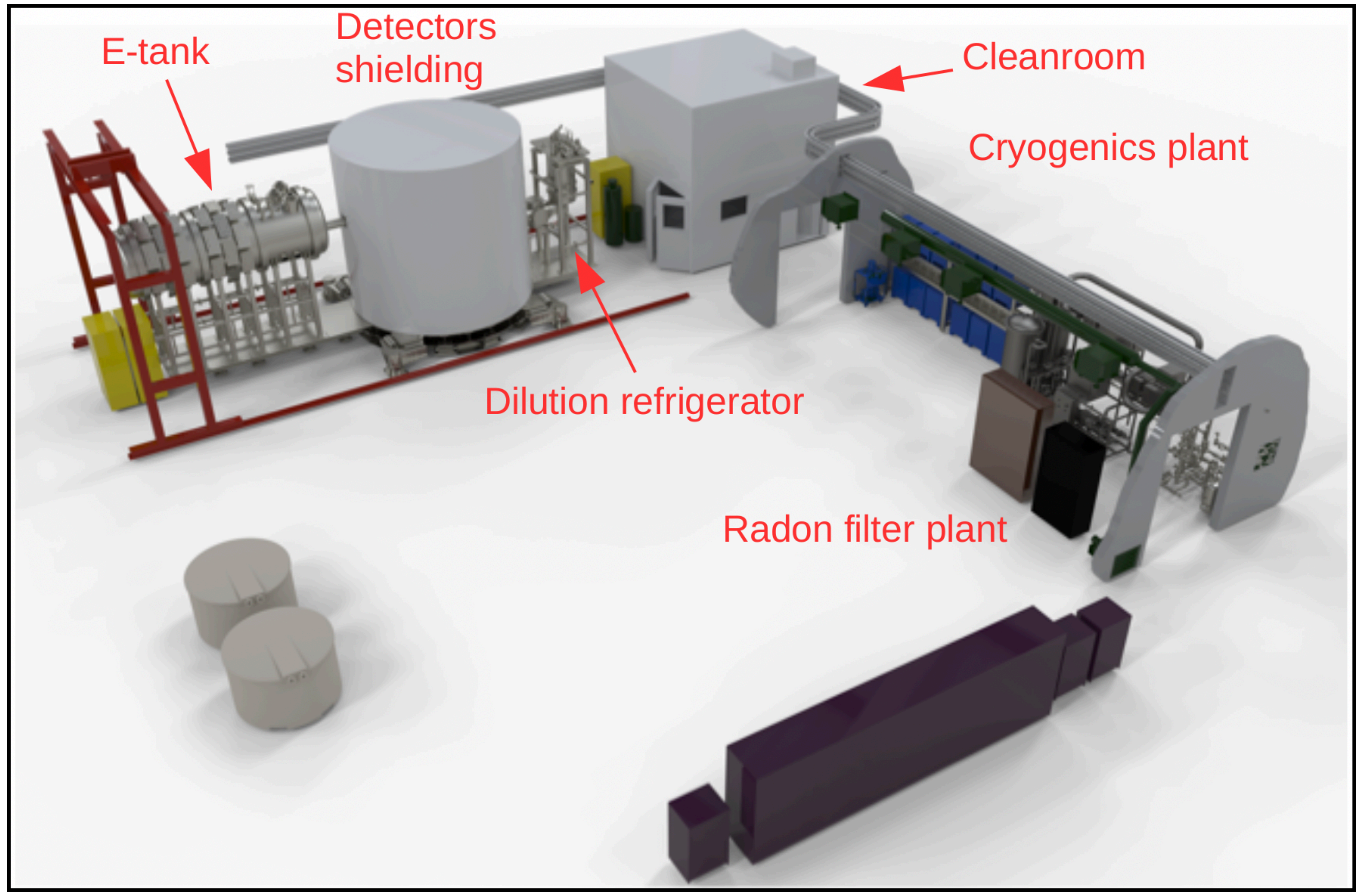


SuperCDMS & Edelweiss

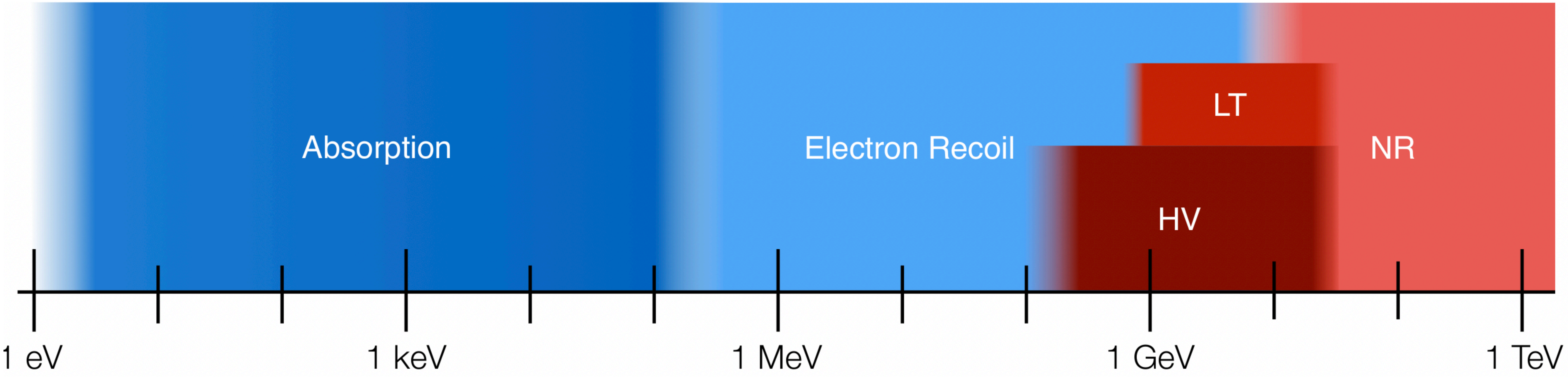
SuperCDMS SNOLAB Experiment

- 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
  - $\mathcal{O}(0.1)$ 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

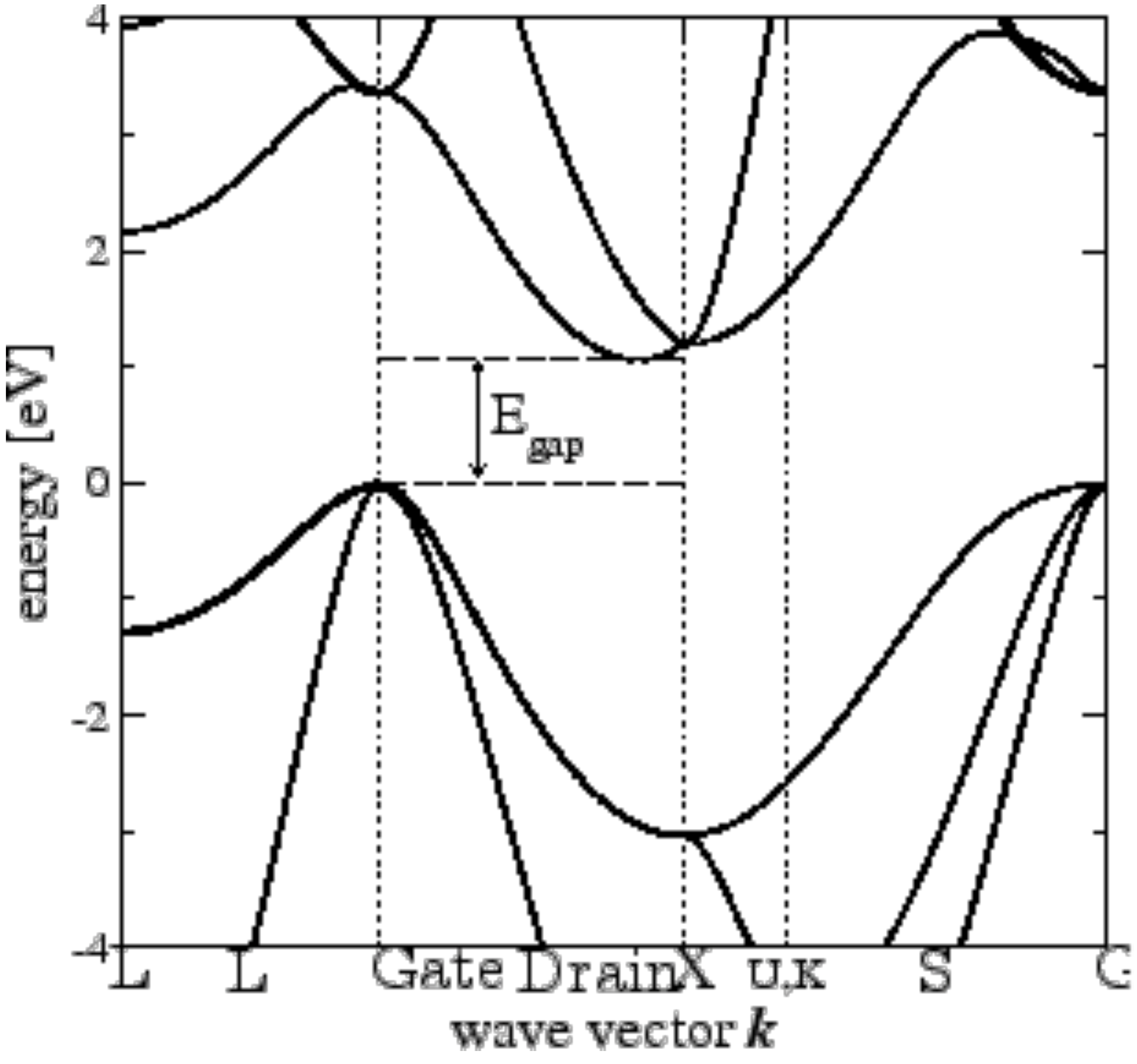


Traditional NR:	iZIP, Background free	>5 GeV
Low Threshold NR:	iZIP, limited discrimination	>1 GeV
HV Mode:	HV, no discrimination	~0.3 - 10 GeV
Electron Recoil:	HV, no discrimination	~0.5 MeV - 10 GeV
Absorption (Dark Photons, ALPs)	HV, no discrimintion	~1 eV - 500 keV (peak search)

Single e^-/h^+ Pair Sensitivity

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} ~ 1.2 eV
  - Indirect band gap requires phonon for transition to happen.
  - Temperature dependent
- ε_{Si} ~ 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

Table: A. E. Robinson

Challenges

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  - Details of the band structure become increasingly important

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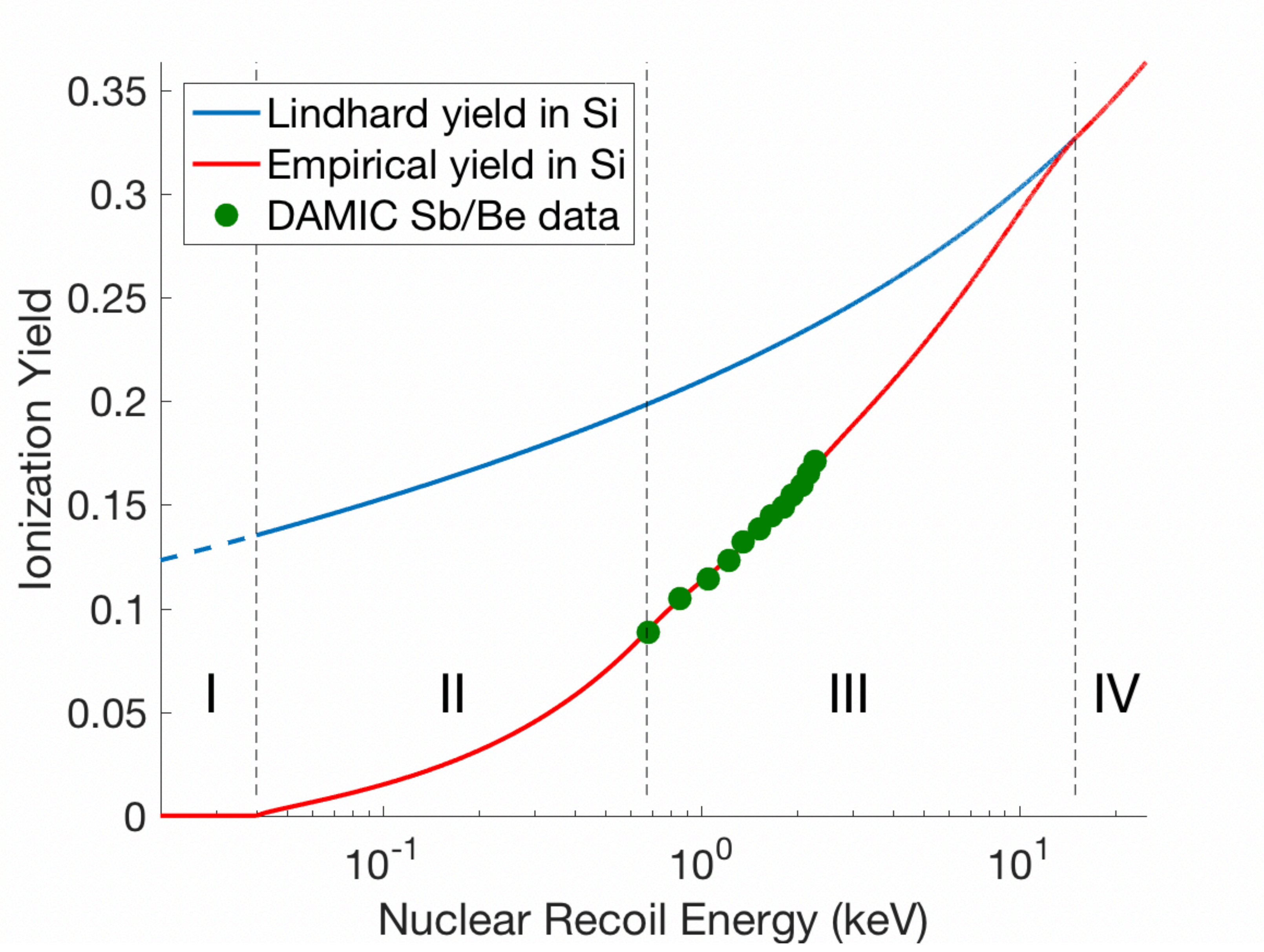
  - PDF to get the numbers of e/h pairs given an energy deposition required, $P(n_{eh}|E_{dep})$
    - Fano statistics (dispersion probabilities - ignored or simplified in many pdfs, ongoing efforts)
    - For NR: quenching (ionization yield < 1, not in agreement at low energies, lack of data)



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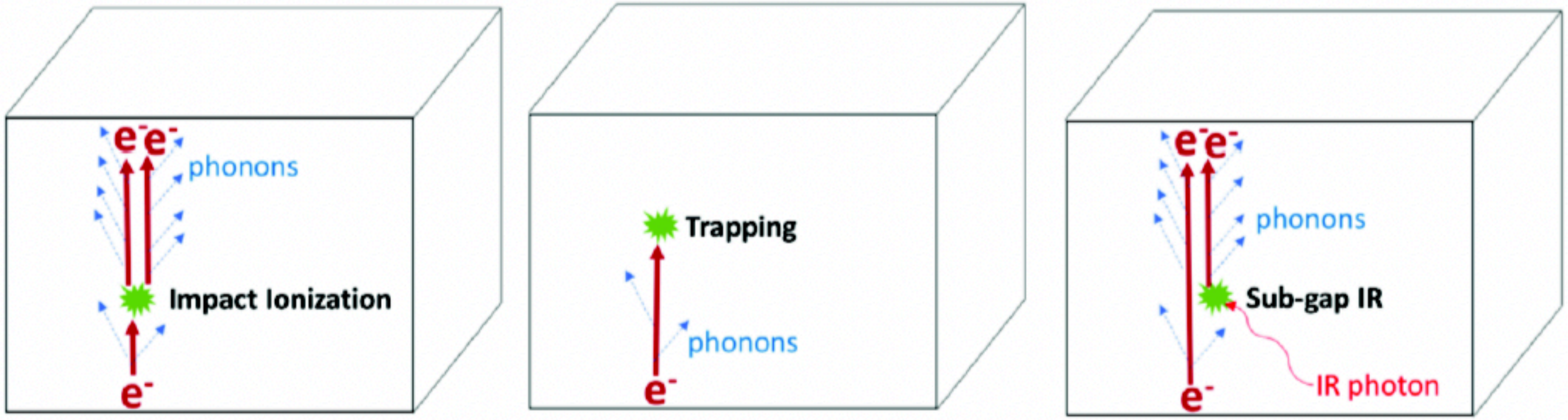

Figure: R.K. Romani

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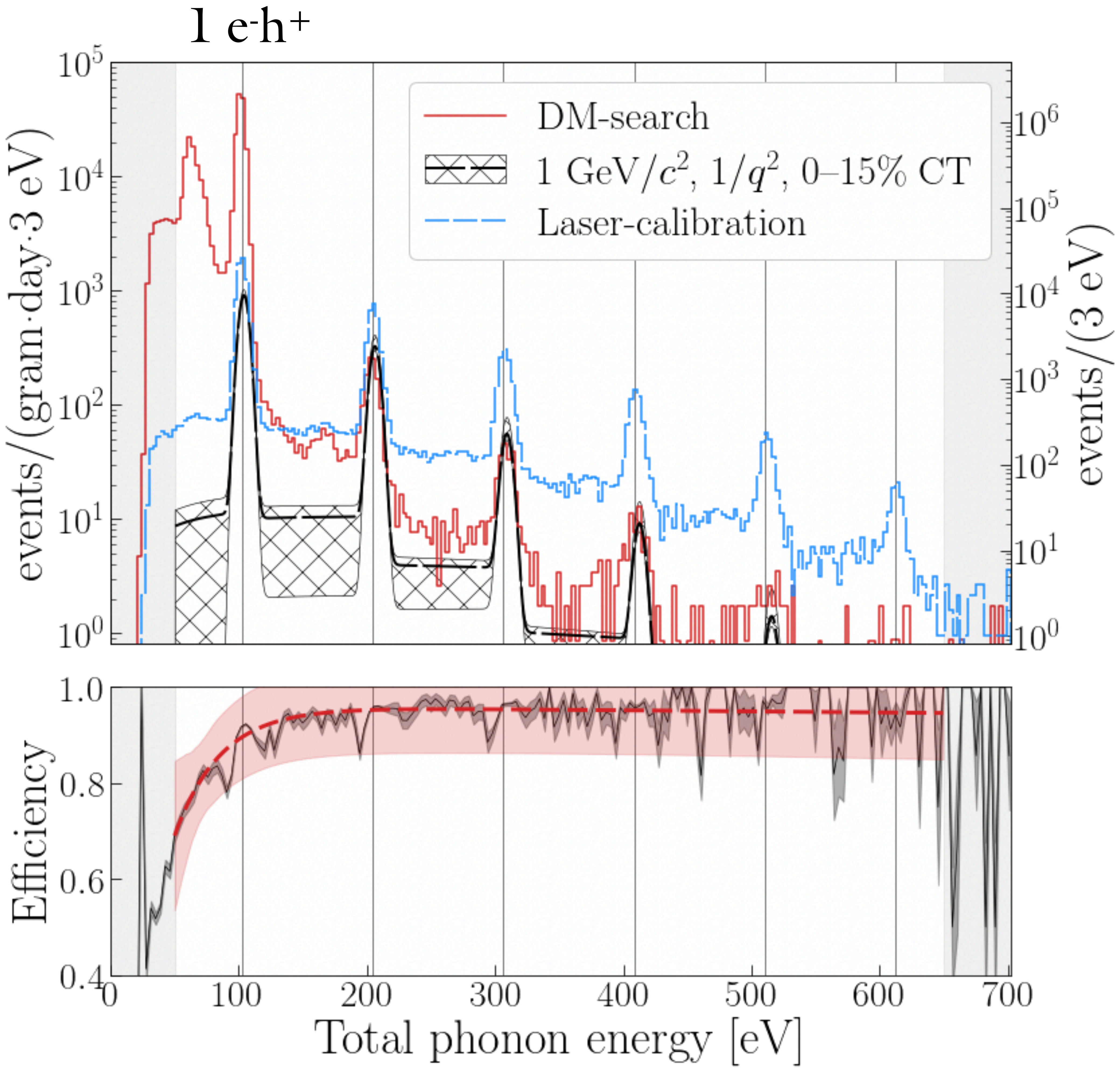
- Backgrounds
  - Spectral information about radioactive decays at eV scale required.
    - Relevance is exposure dependent
  - IR and optical photons become significant backgrounds at lowest energies.
  - Dark/leakage current can be significant, dominant background at lowest energies.

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

HVeV Detectors

- 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.

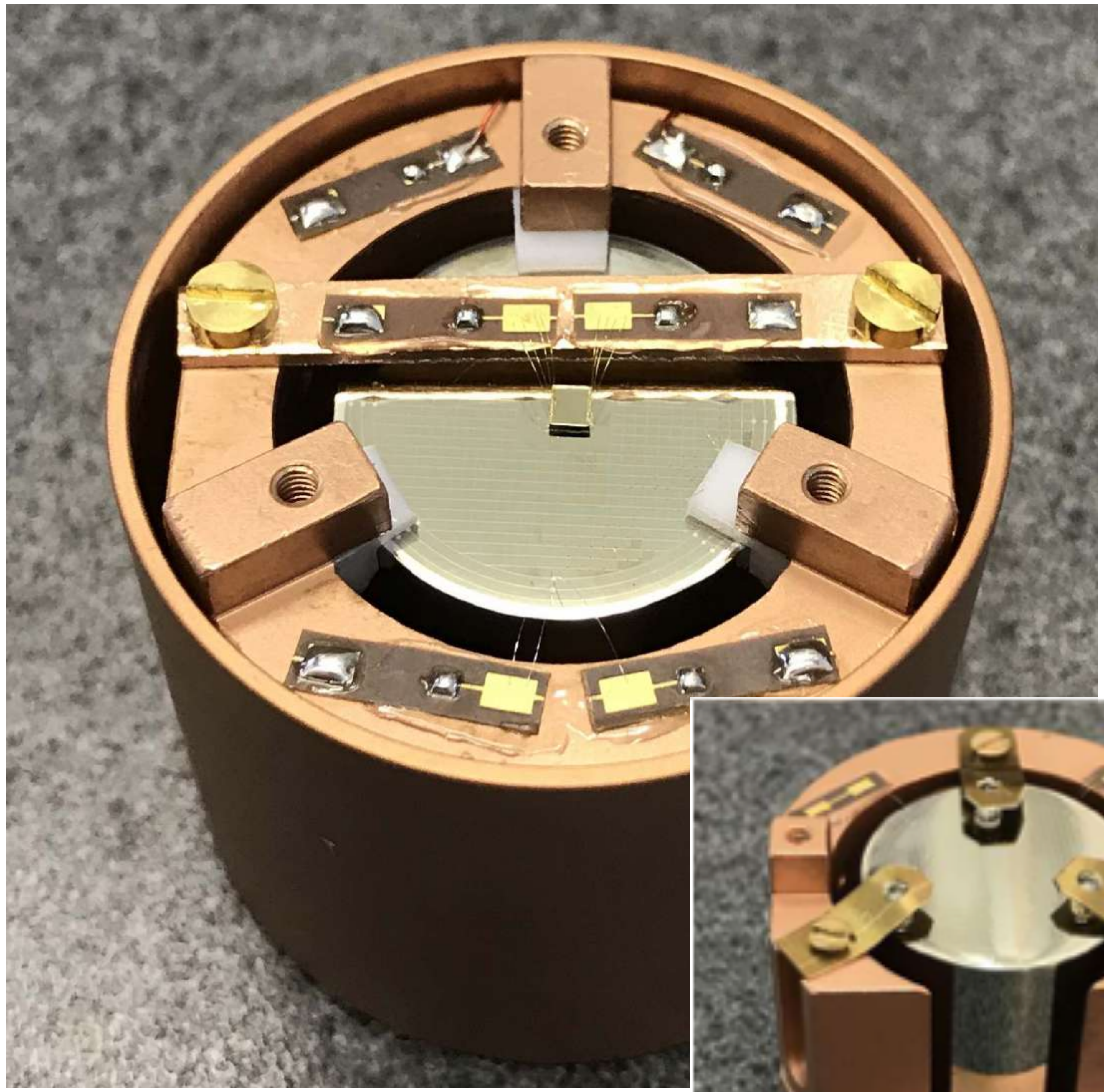


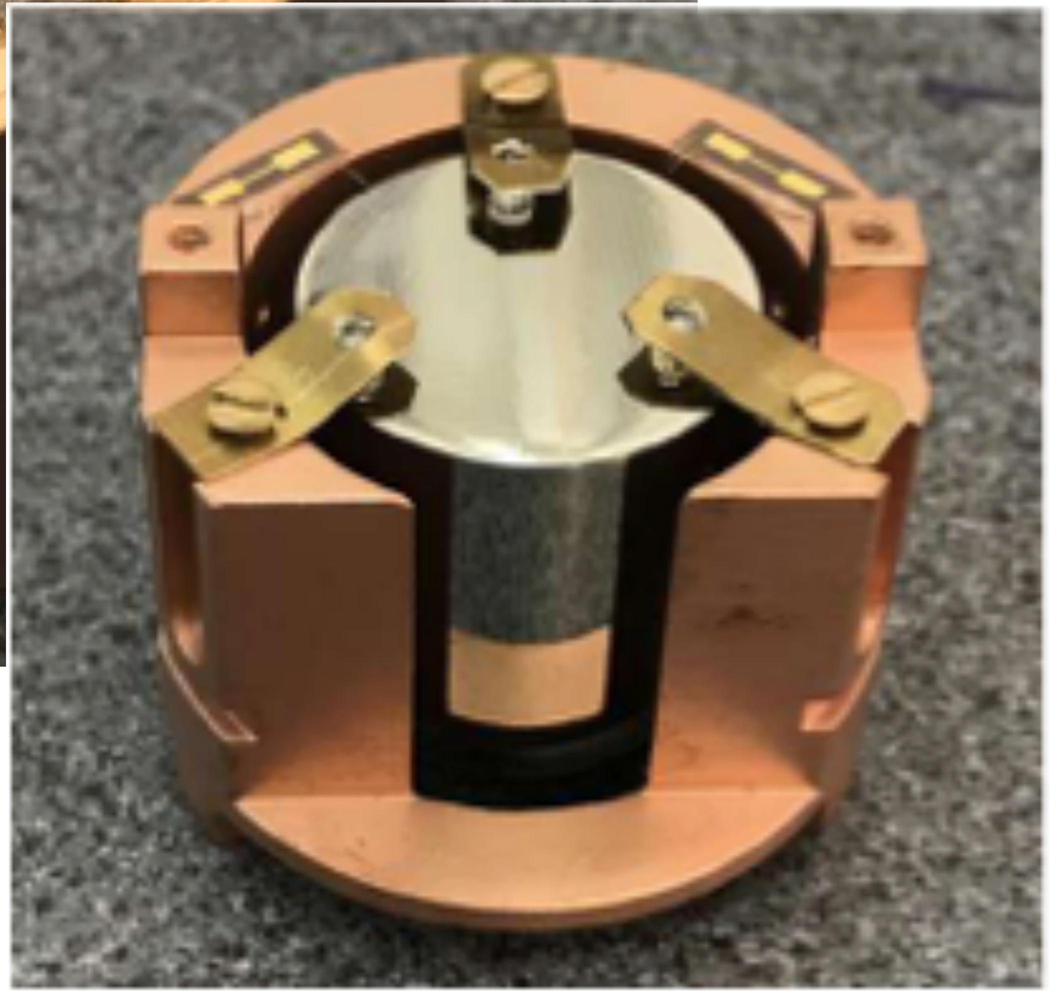
- Impact ionization and charge trapping were incorporated into DM signal models.

arXiv:2003.01046

Edelweiss RED 30 Detector: HV operation

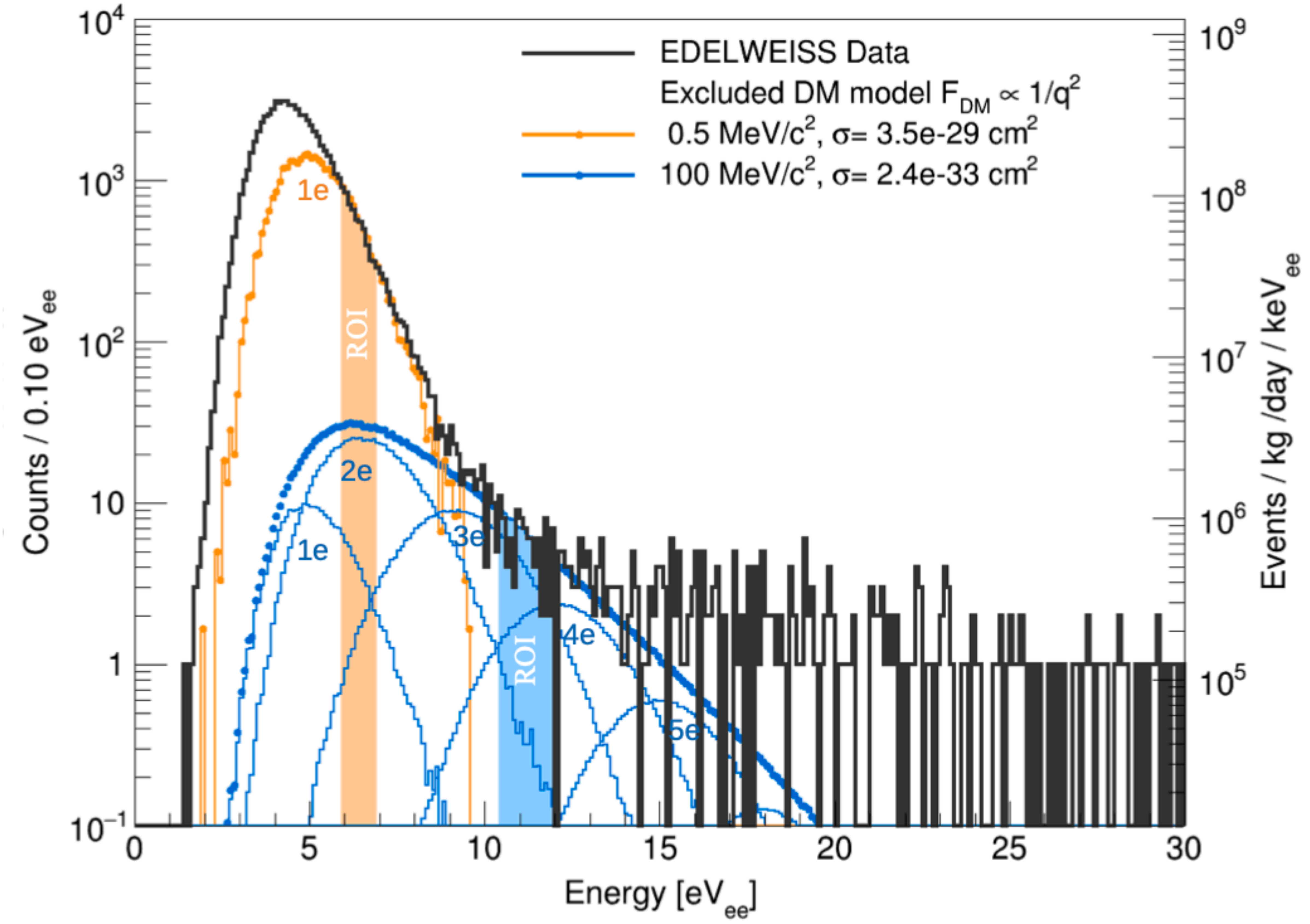
- 33.4 g (20 x 20 mm) Ge bolometer with NTD sensor and electrodes operated in LSM (5 **μ**/m²/d)
- Exposure: 2.44 days
  - -operation voltage: 78 V
  - -energy resolution: σ_{ph} = 44 eV (1.6 eV_{ee})
  - -charge resolution: σ_{eh} = 0.53 e^-h^+
- Calibrations using ^{71}Ge KLM (0.16, 1,30 and 10.37 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

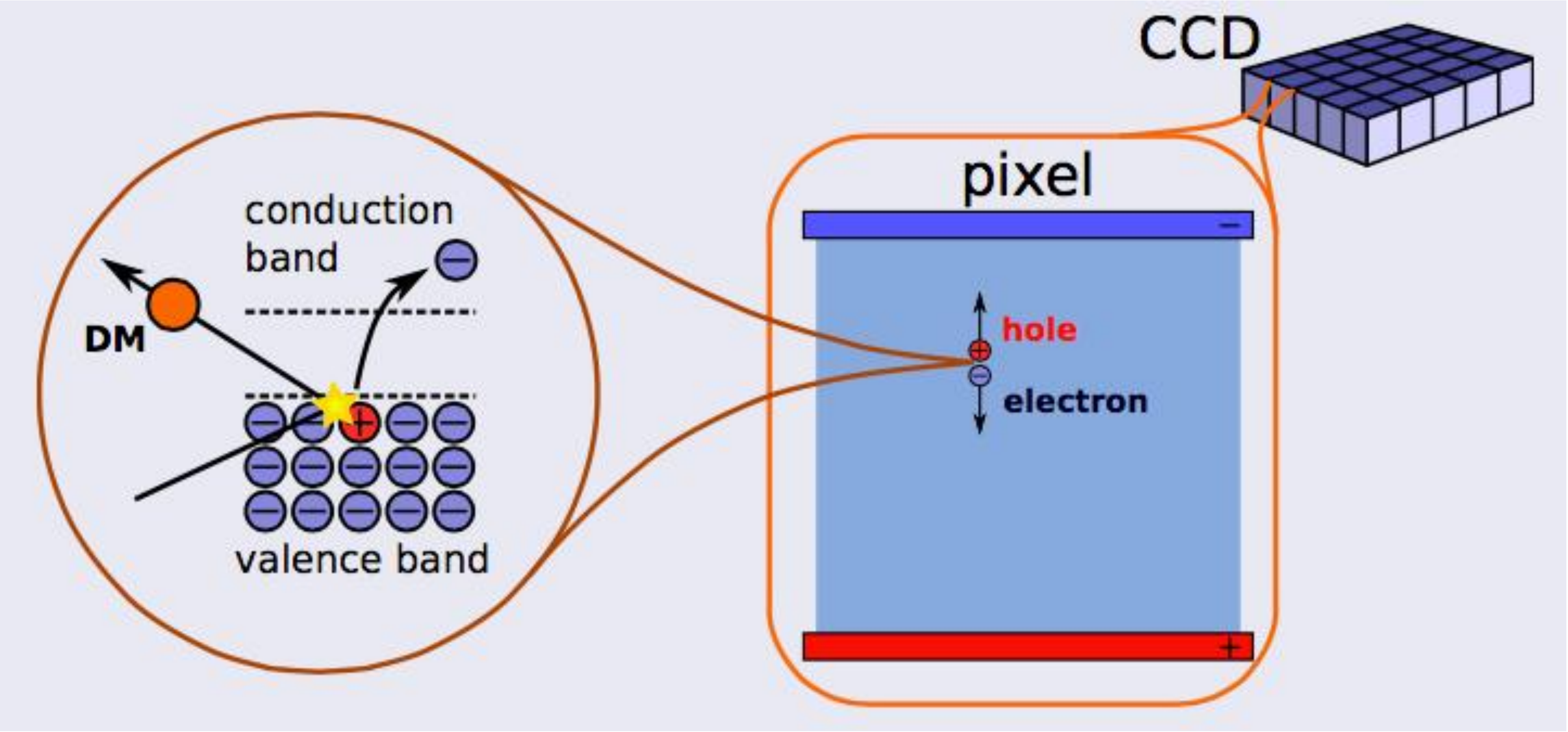
- Heat only events (those not affected by NTL amplification) are the main source of backgrounds.
  - 10^6 DRU @ 10 eV_{ee}
  - 1.5 x 10^5 DRU @ 25 eV_{ee}
- Dominant limitation for >3 e- signals
- May hypothesis have been studied as to the origin. No single contributor has been found.
  - These events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



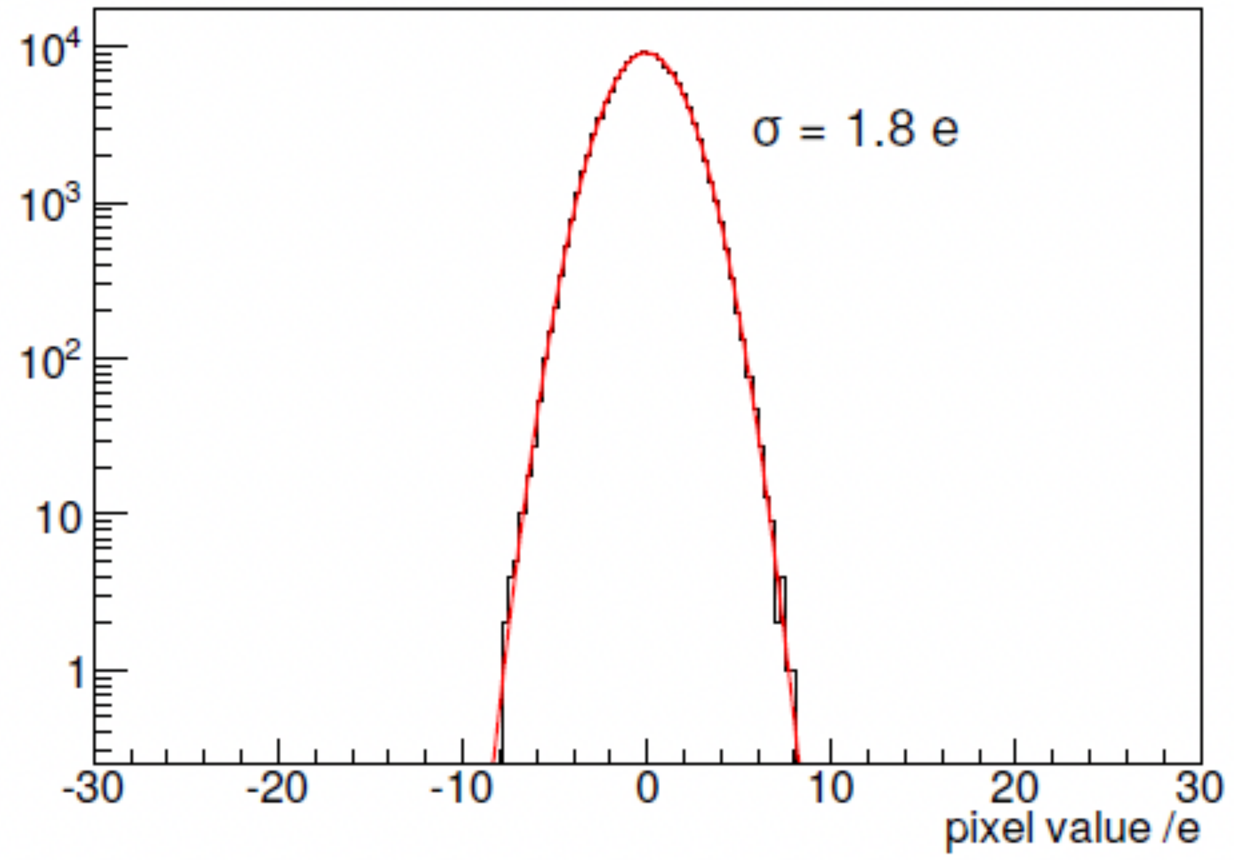
arXiv:2004.11378

SENSEI

- Skipper-CCD designed by LBNL MSL, fabricated by DALSA
- High-resistivity silicon 675 μm thick, 1.59 × 9.42 cm2, 1.925 g active mass
- Sub-electron noise with skipper readout makes single electron resolution possible.

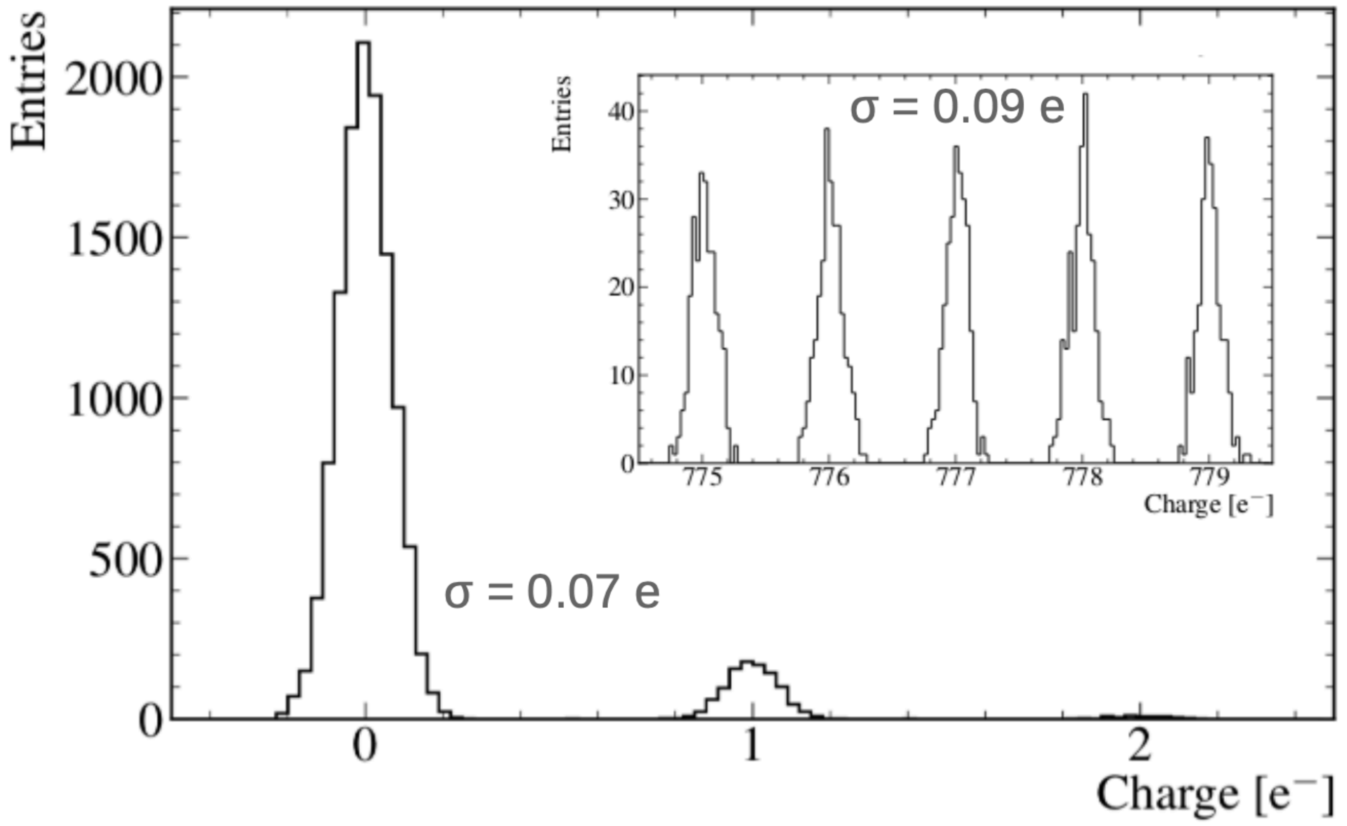


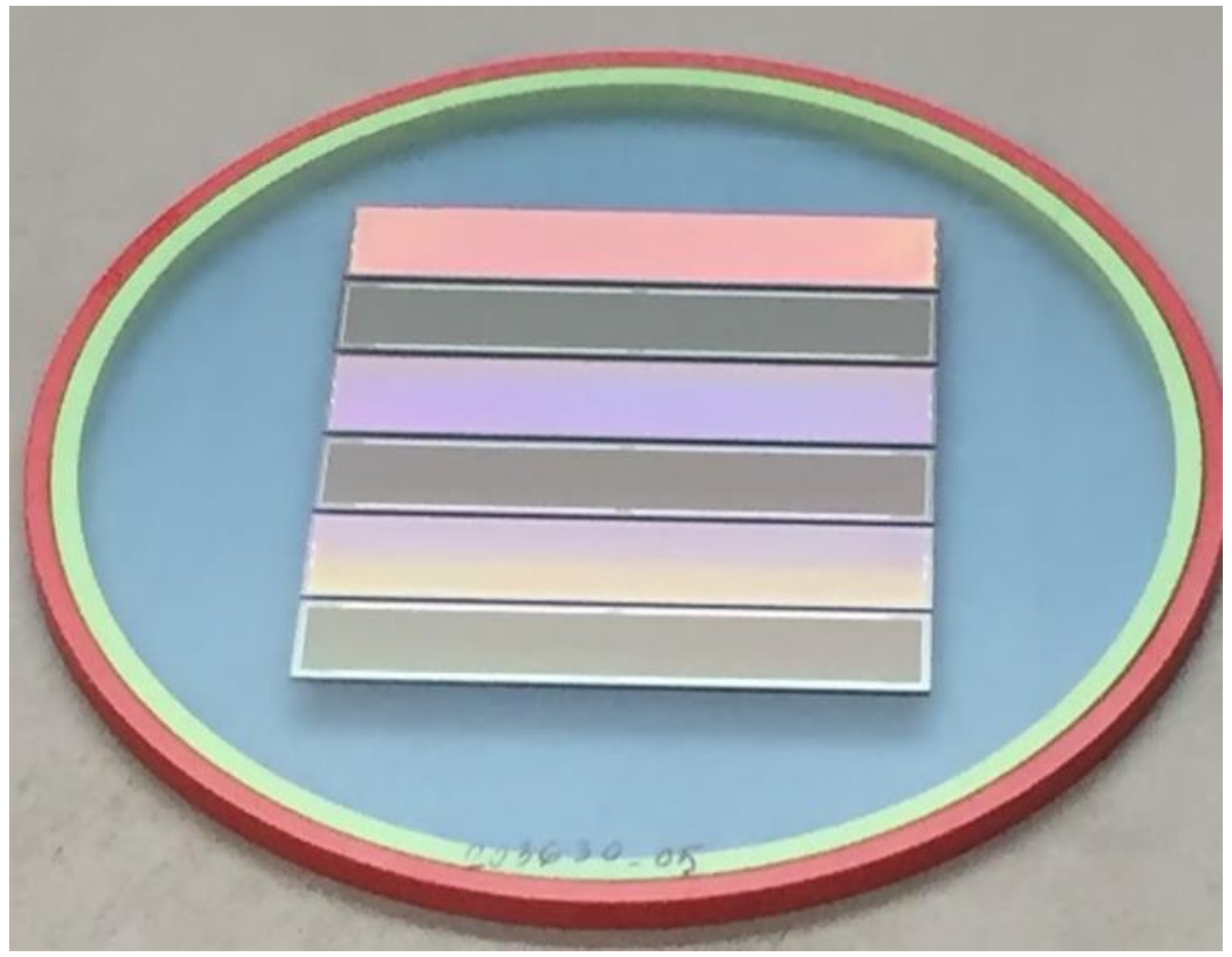
Readout noise, regular CCD



Sub-electron noise, skipper readout

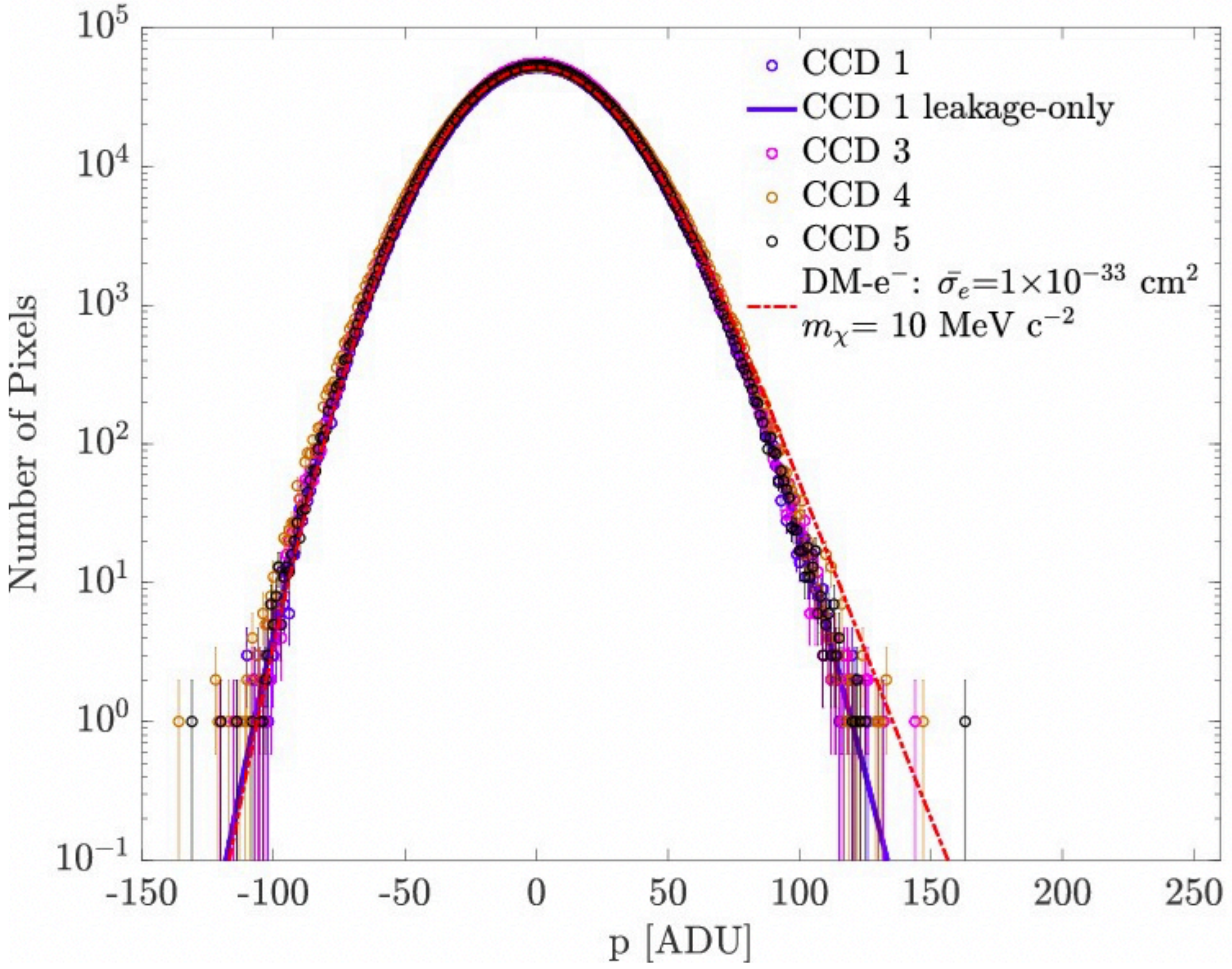
J. Tiffenberg *et al*, Phys. Rev. Lett. **119**, 131802 (2017) [arXiv:1706.00028]





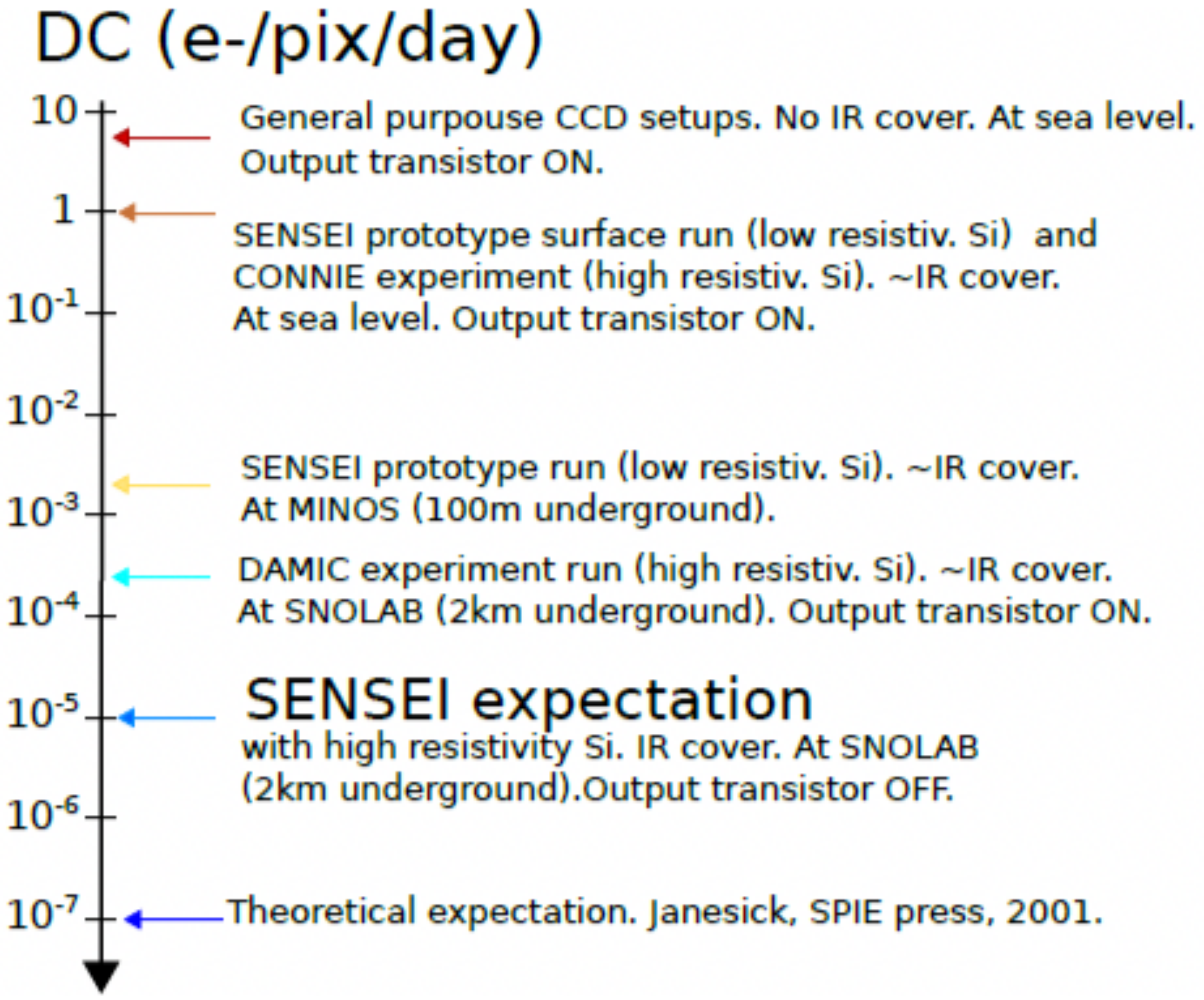
arXiv: 1907.12628

DAMIC-SNOLAB



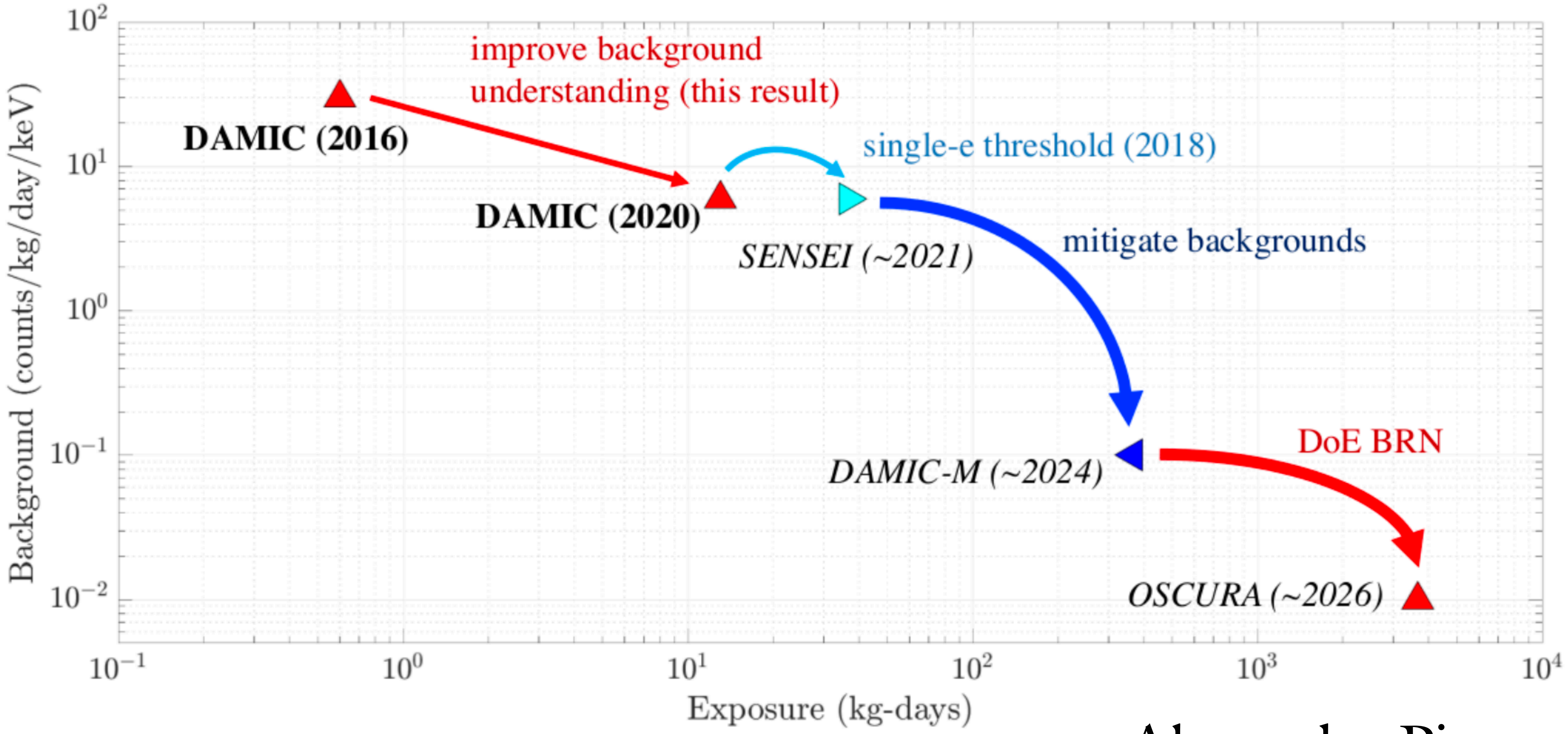
- 7 fully depleted CCDs
- Each CCD is 675 μm thick, 15 x 15 μm² pixel size
- 4k x 4k pixels (6.0 g)
- **σ**' = 2 e^- —> not yet sensitive to e^-/h^+ pair
- Lowest dark count to date

CCD Dark Count Progress



Skipper CCD Plans

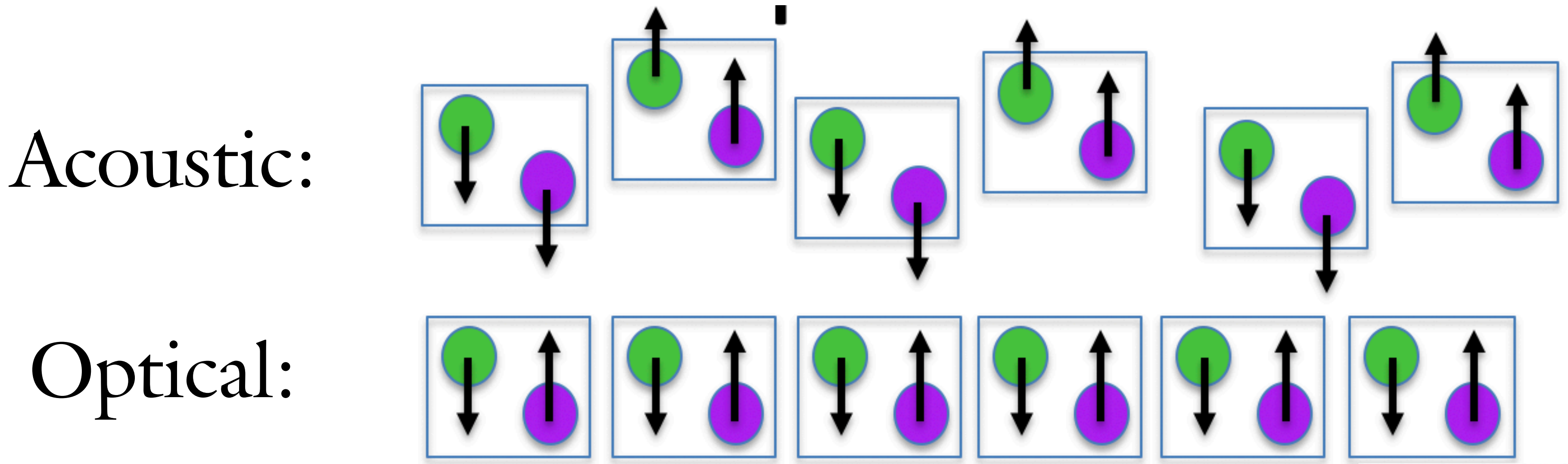
- SENSEI has moved to SNOLAB.
  - “Phase 1” system is operational
  - Complete exeperiment will contain 100 grams.
- DAMIC-M at MODANE
  - 1 kg mass
  - 6k x 6k pixels over 9x9 cm2 with 1mm thickness (20 g mass)
  - Integration of skipper readout
- Oscura
  - 10 kg of skipper CCDS

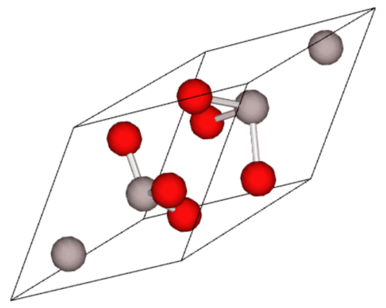


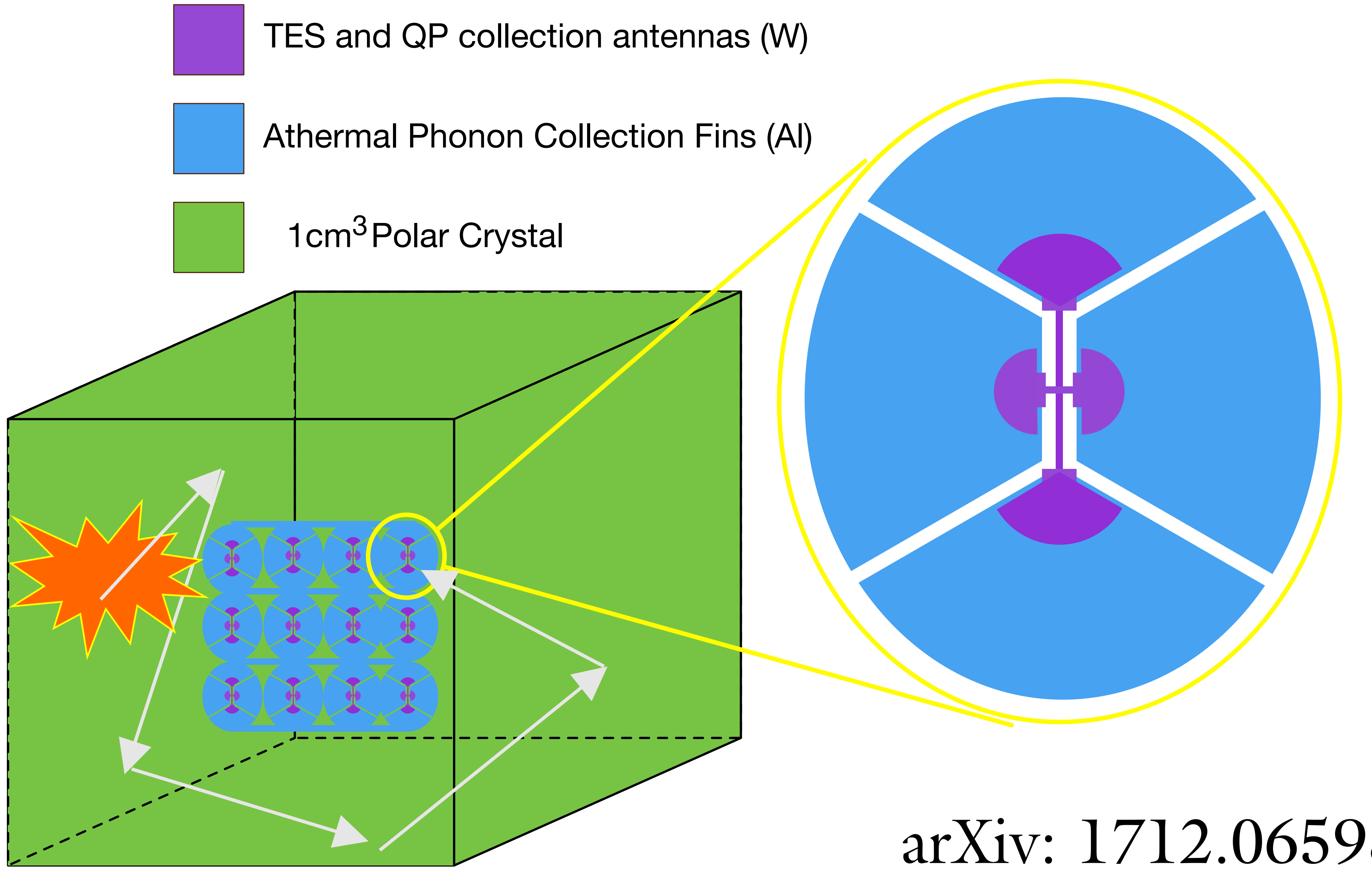
Alexander Piers

SPICE: Sub-ev Polar Interactions in Cryogenic Experiments

- In ionic crystals, optical photons are oscillating electric dipoles.
- Very large coupling to photons (black in the IR) and very large couplings to dark photons
- 30-100 meV phonon sensitivity required.
- An effort is underway in polar crystal R&D using a variety of substrates.
  - GaAs, Al_2O_3 (Saphire), SiO_2
  - Energy Sensitivity R&D
  - 10-20 mK Tc W Films
  - Environmental Noise Reduction
  - Low Stress/ Low Parasitic Heating Crystal Support design

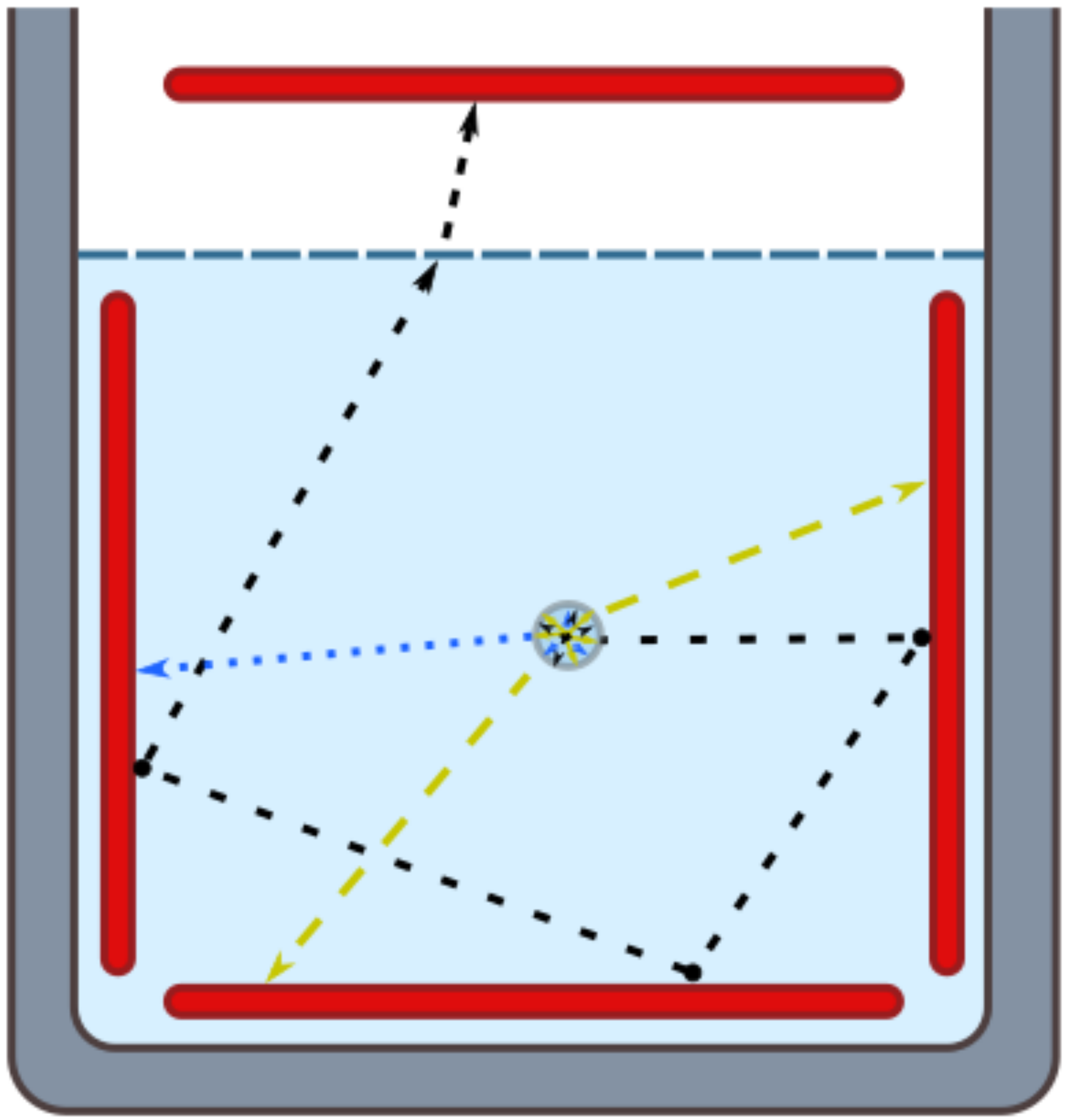






arXiv: 1712.06598
arXiv: 1910.10716

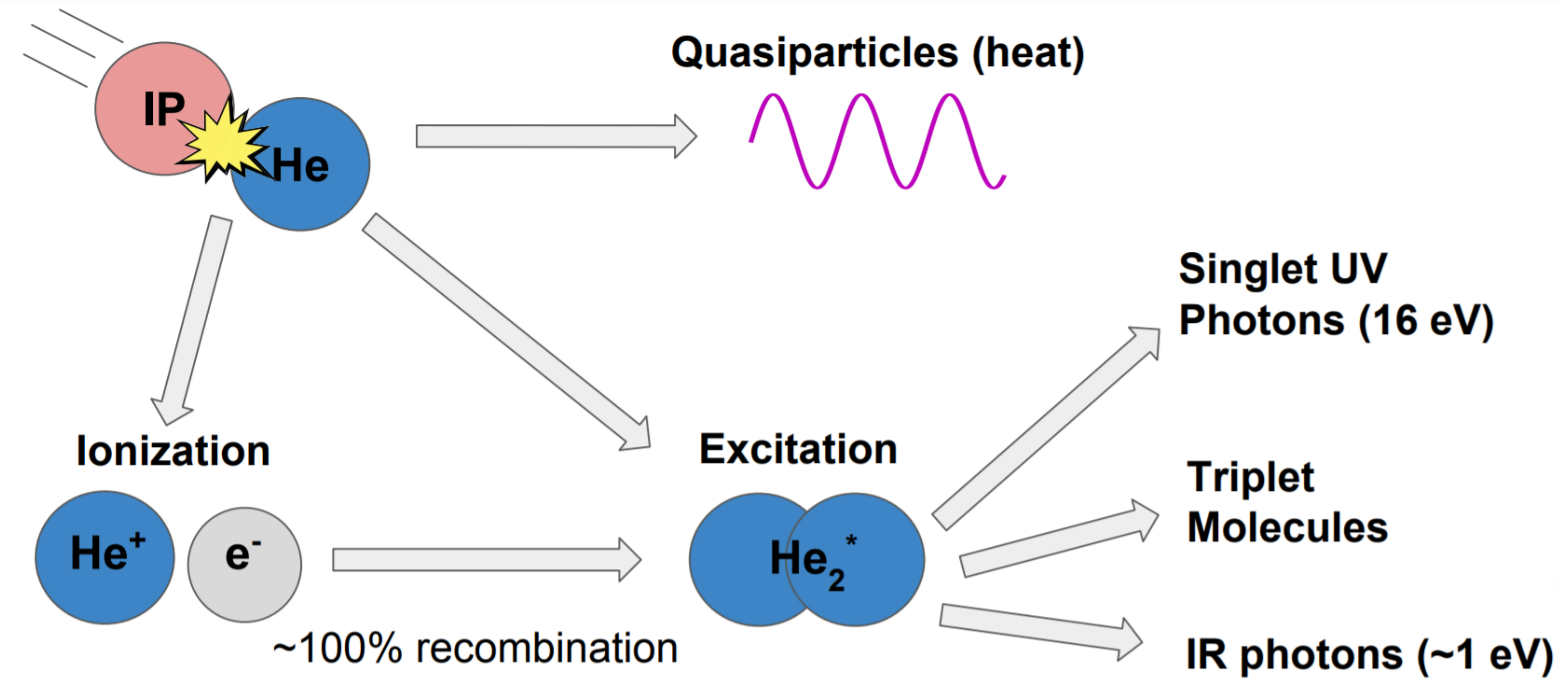
HeRALD: Helium Roton Apparatus of Light Dark Matter



R.K. Romani

1 kg of superfluid ^{4}He at ~50 mK

- Quasiparticle excitations (phonon, roton)
- Atomic excitations (singlet photons, triplet excimer)
- Both wet and dry calorimeter readout via TES arrays.



Conclusions

- Cryogenic technologies are making quick progress towards lighter and lighter dark matter.
- There is a healthy mix of existing experiments currently upgrading and running that will produce results in the near term.
- Single e-/h+ detection has been achieved by multiple technologies. There is still R&D needed in order to probe the maximal parameter space.
- There is a large theory space to explore in the next decade!