# The SuperCDMS SNOLAB Experiment

## A Broadband Dark Matter Search

CIPANP 2022

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University of Florida

SUPER CDMS
Cryogenic Dark Matter Search

# Outline

- ~~Fundamental Principles of Dark Matter Detection:~~
  ~~How dark matter interacts~~
- The SuperCDMS Detectors:
  - The principles behind measuring DM signal and minimizing background
  - The road to low mass / energy resolution
- The SuperCDMS Experiment in Action:
  - SuperCDMS @ SNOLAB
  - Current results and Future Reach


# The SuperCDMS Collaboration

# I. The SuperCDMS Detectors

A DM particle walks into a detector?

# SuperCDMS Detector Technology

**Low Background** ~~iZIP~~ **Detector:**

- Prompt phonon and ionization signals allow for discrimination between nuclear and electron recoil events

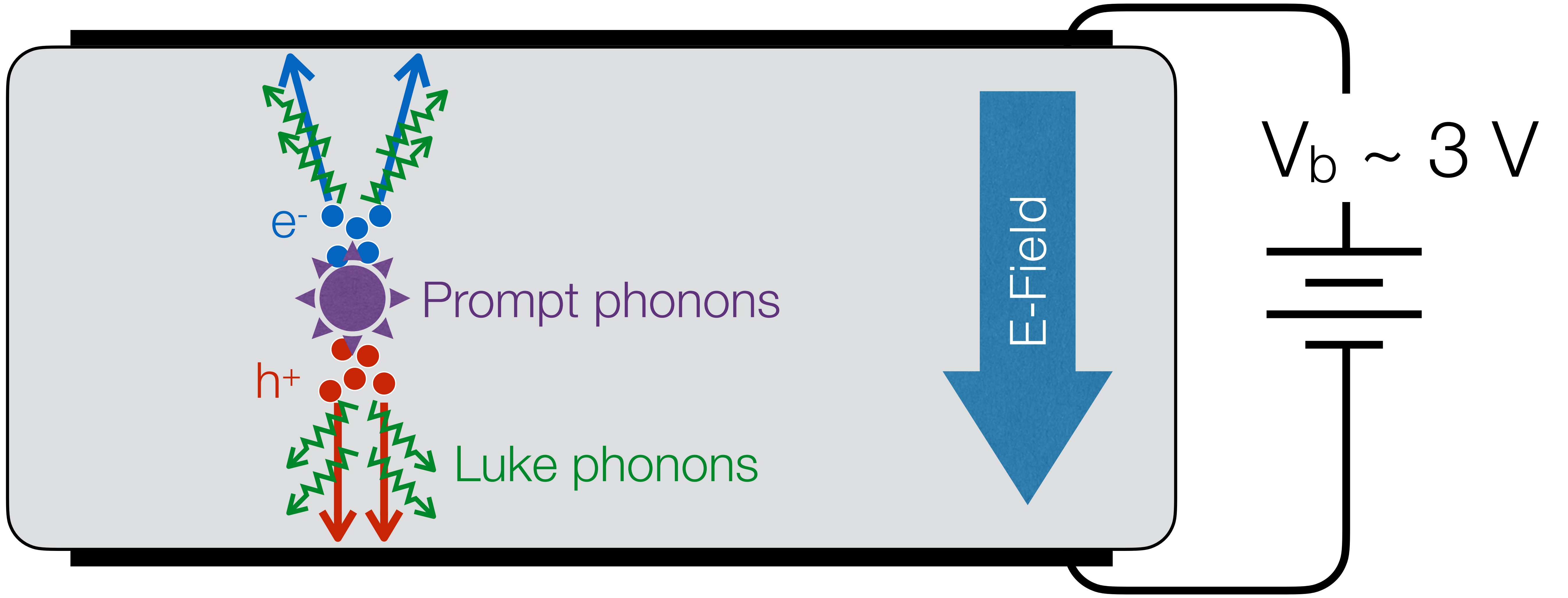
**Low Threshold** ~~HV~~ **Detector:**

- Drifting electrons/holes across a potential ($V_b$) generates a large number of phonons (Luke phonons).
  - Enables very low thresholds!
  - Trade-off: No event-by-event NR/ER discrimination

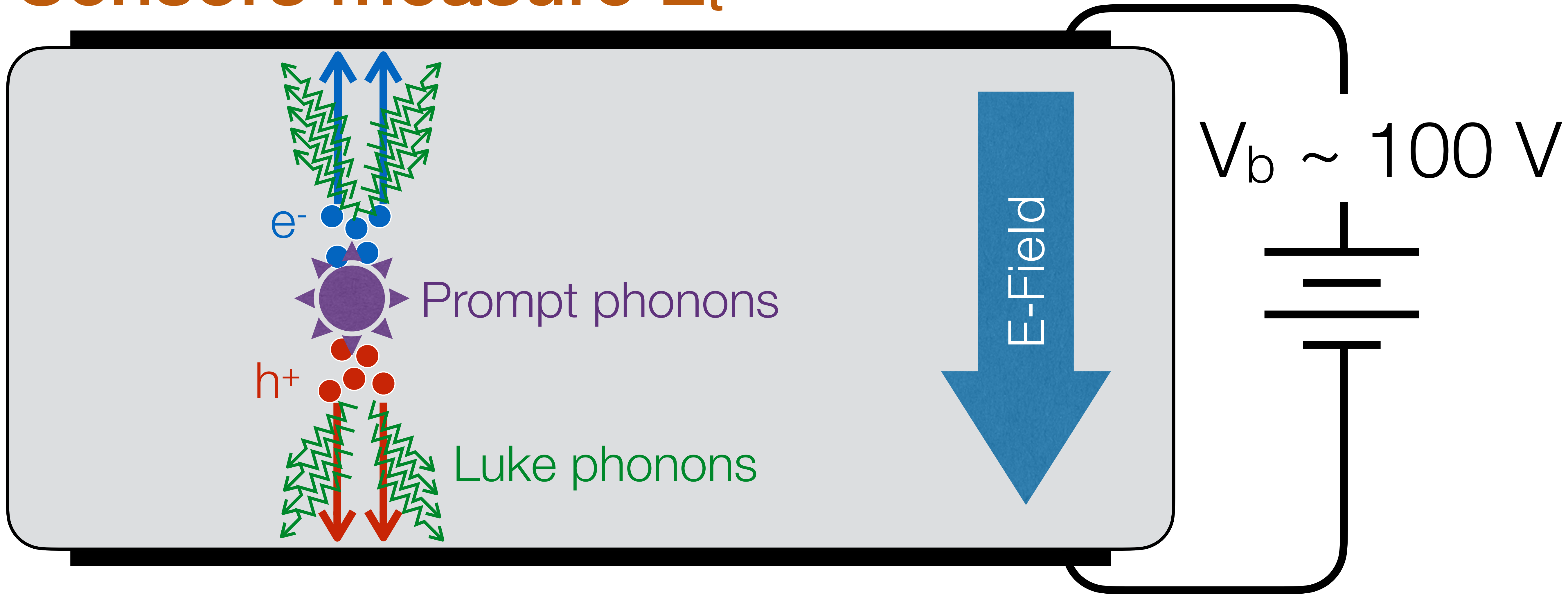
$$E_t = E_r + N_{eh} e V_b$$

*total phonon energy* ($E_t$), *primary recoil energy* ($E_r$), *Luke phonon energy* ($N_{eh} e V_b$)

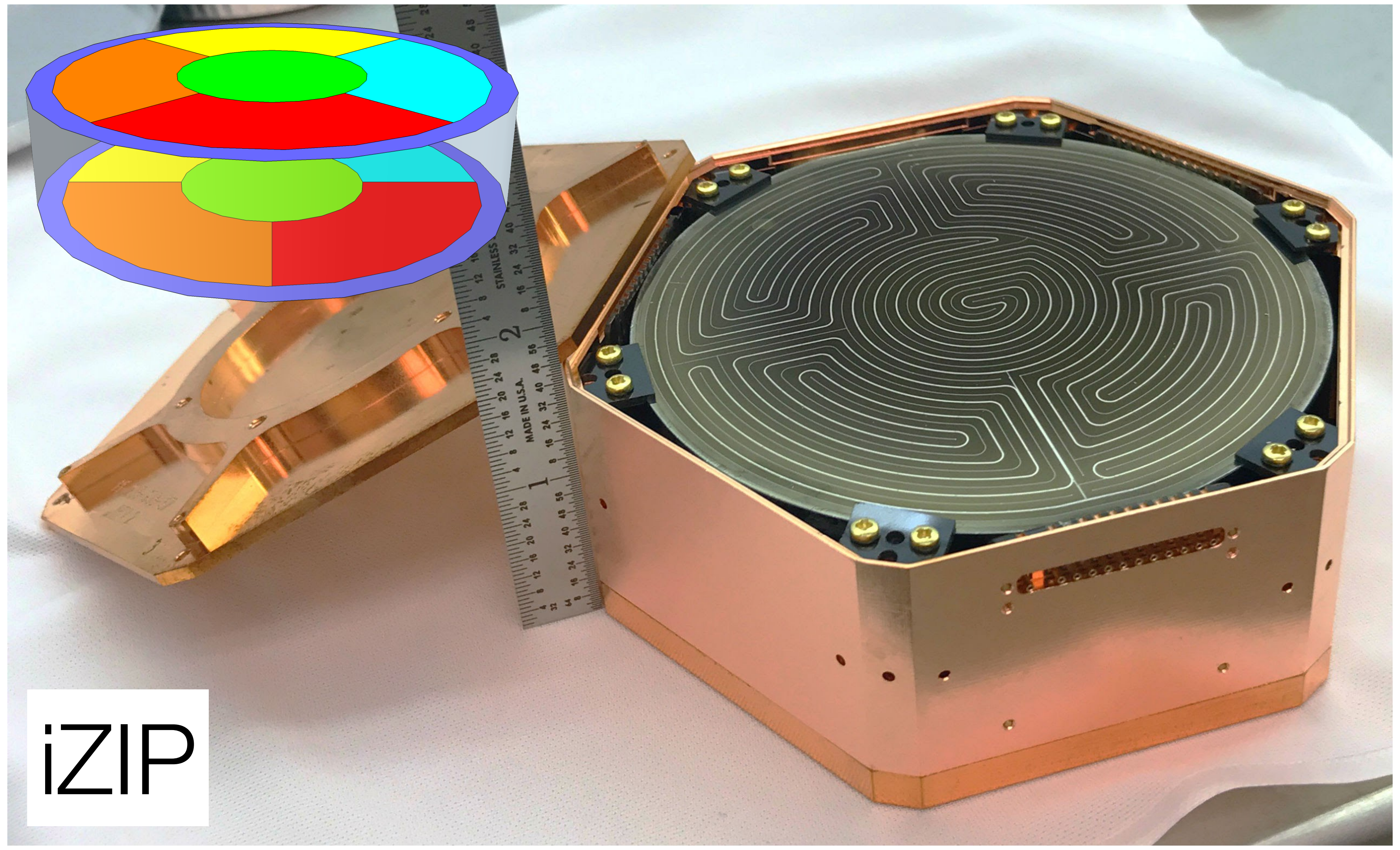
**Sensors measure $E_t$, and $n_{eh}$**

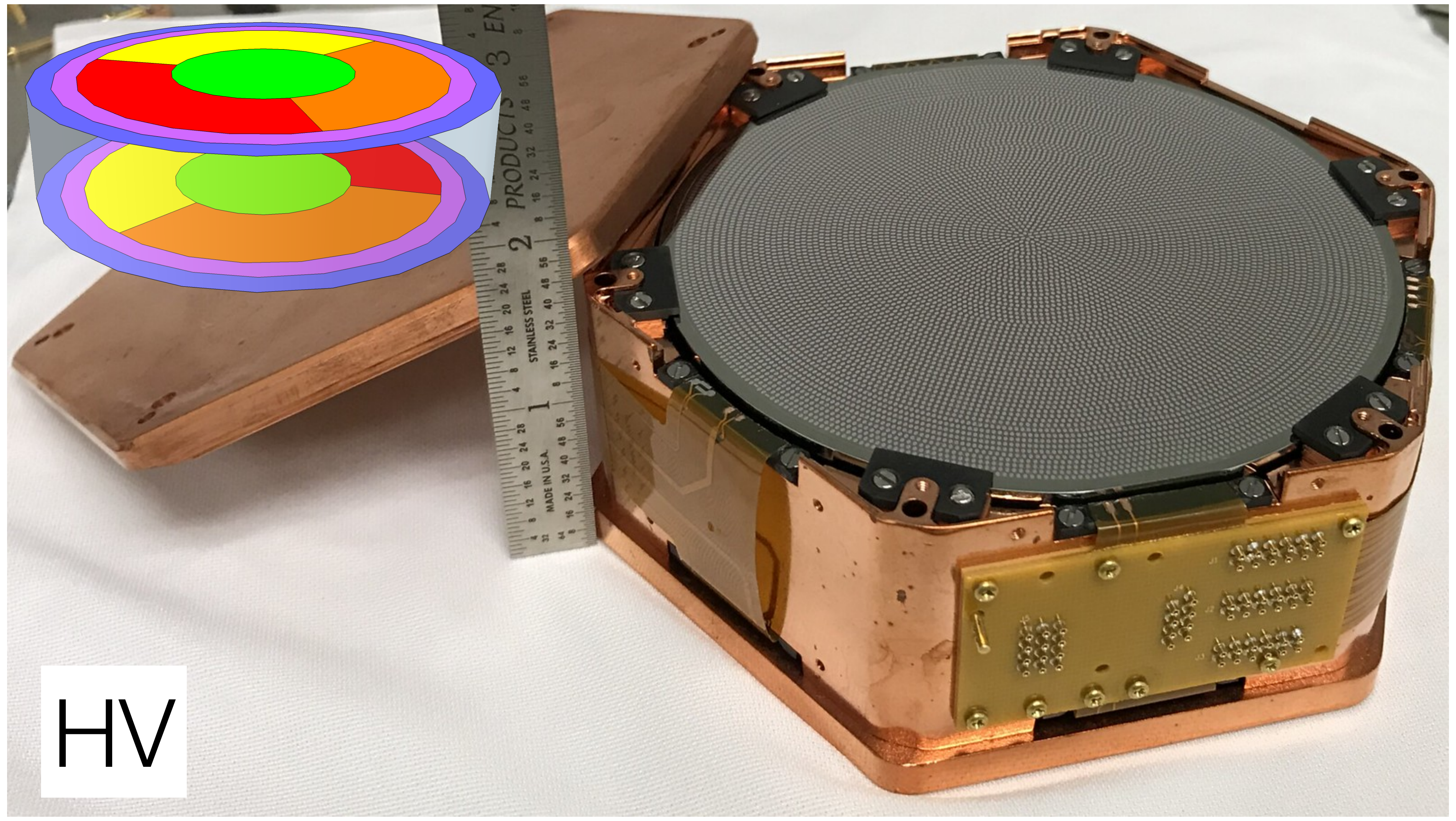



**Sensors measure $E_t$**



# SuperCDMS Detectors: Posing for the Cameras

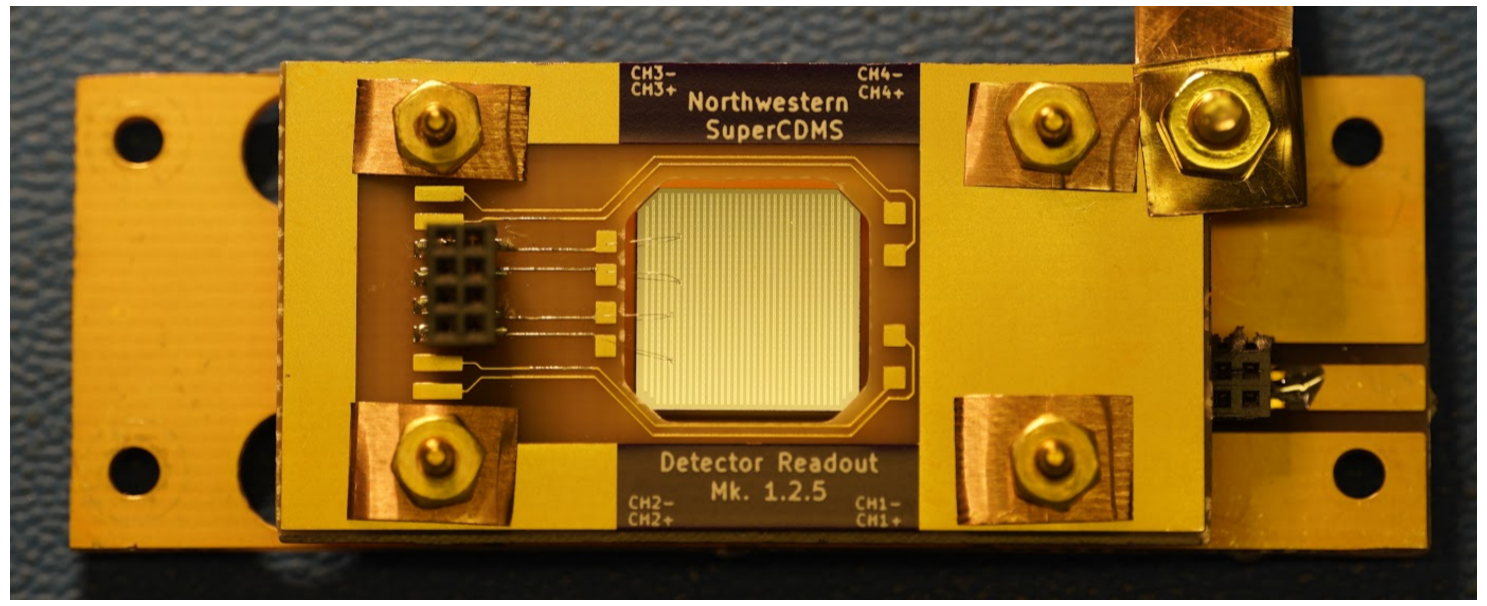


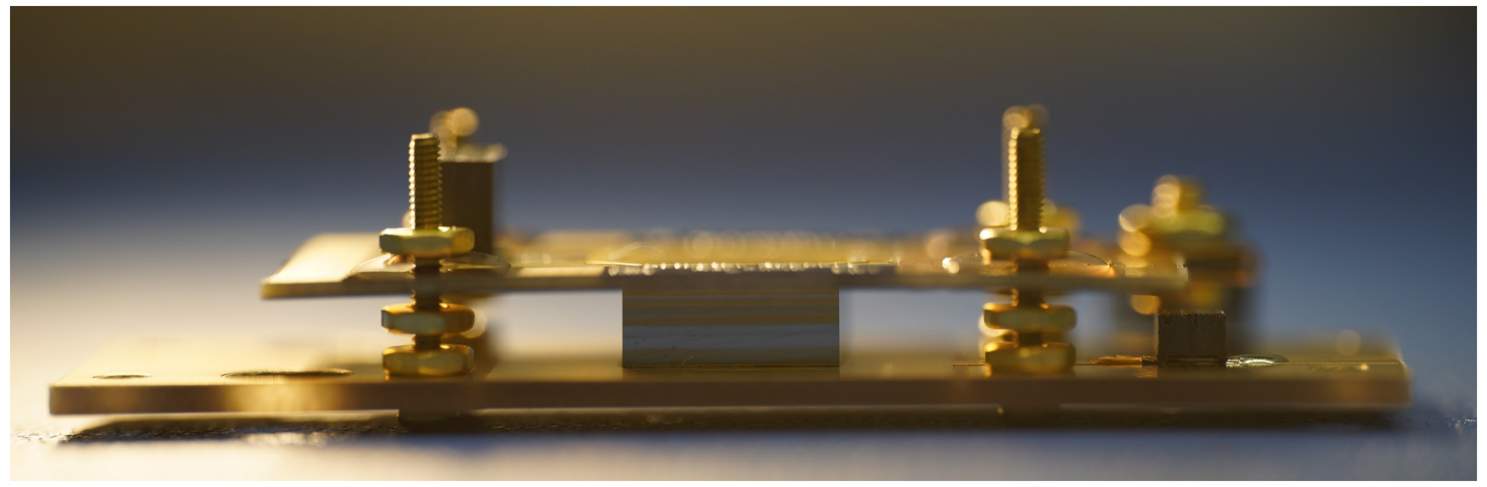



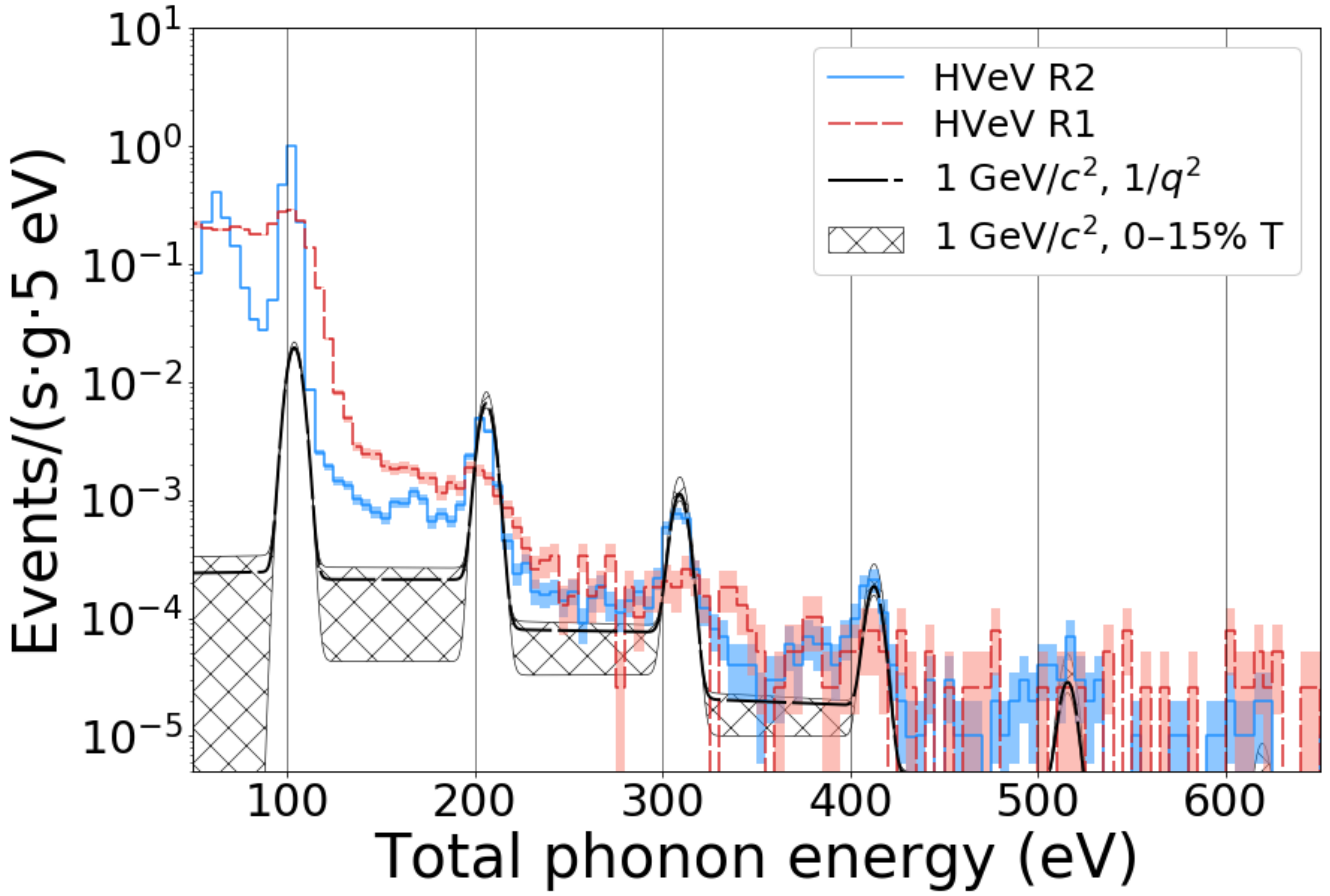

- Detectors made of high-purity Ge and Si Crystals
  - Si (0.6 kg) provides sensitivity to lower dark matter masses, Ge (1.5 kg) provides sensitivity to lower dark matter cross-sections
- Low operation temperature: ~15mK
  - Athermal phonon measurement with TESs
  - Ionization measurement (iZIP) with HEMTs
- Multiple channels per detector to identify event position
- Initial payload will consist of 4 towers
  - 6 detectors each
  - 2 iZIP: 10 Ge / 2 Si
  - 2 HV: 8 Ge / 4 Si

# ~~Small~~, ~~Mini~~, ~~Micro~~, HVeV Detectors

- SuperCDMS has also developed gram scale R&D detectors
  - Single electron-hole pair resolution devices will have sensitivity to a variety of sub-GeV DM models with gram*day exposures
  - Largest “quantum resolution” detectors available
  - Powerful tool for low-energy rare event searches
- 0.93 g Si crystal (1x1x0.4 $cm^3$) operated at a surface test facility.
- Exposure: 0.49 gram-days (16.1 hours)
  - energy resolution: $\sigma_{ph}$ ~ 3 eV
  - charge resolution: $\sigma_{eh}$ ~ 0.03 $e^- h^+$
  - operation voltage: 0–100 V






PRD 102, 091101, 2020

# SuperCDMS Detectors & Dark Matter Mass Scales

- Dark Matter Mass Ranges
  - "Traditional" Nuclear Recoil: Full discrimination, $\gtrsim$ 5 GeV
  - Low Threshold NR: Limited discrimination, $\gtrsim$ 1 GeV
  - CDMSlite: HV, no discrimination, ~0.3 – 10 GeV
  - Migdal & Bremsstrahlung: no discrimination, ~0.01 – 10 GeV
  - Electron recoil: HV, no discrimination, ~0.5 MeV – 10 GeV
  - Absorption (Dark Photons, ALPs): HV, no discrimination, ~1 eV – 500 keV (“peak search”)

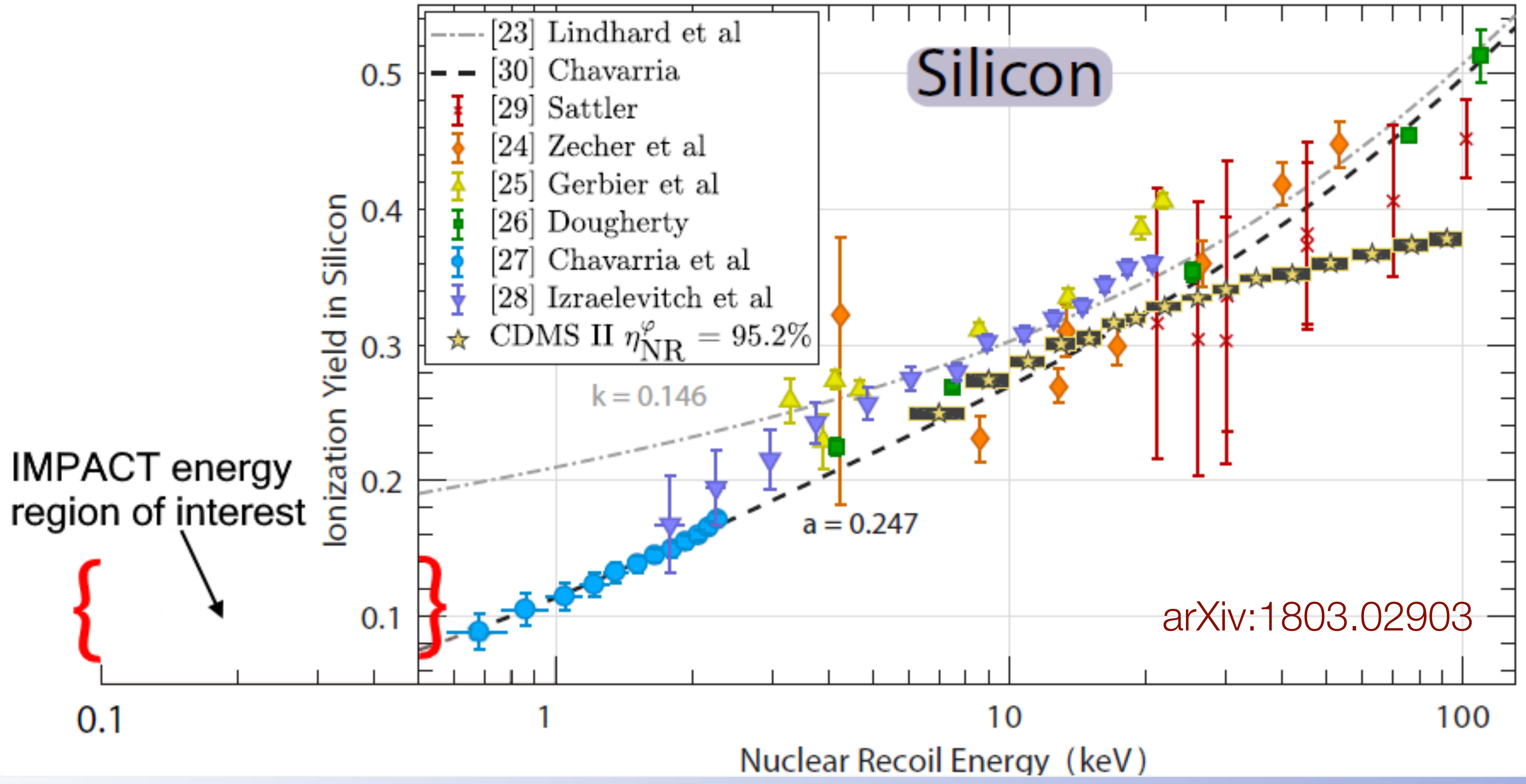
# III. The Neutron Beam Measurement in Si

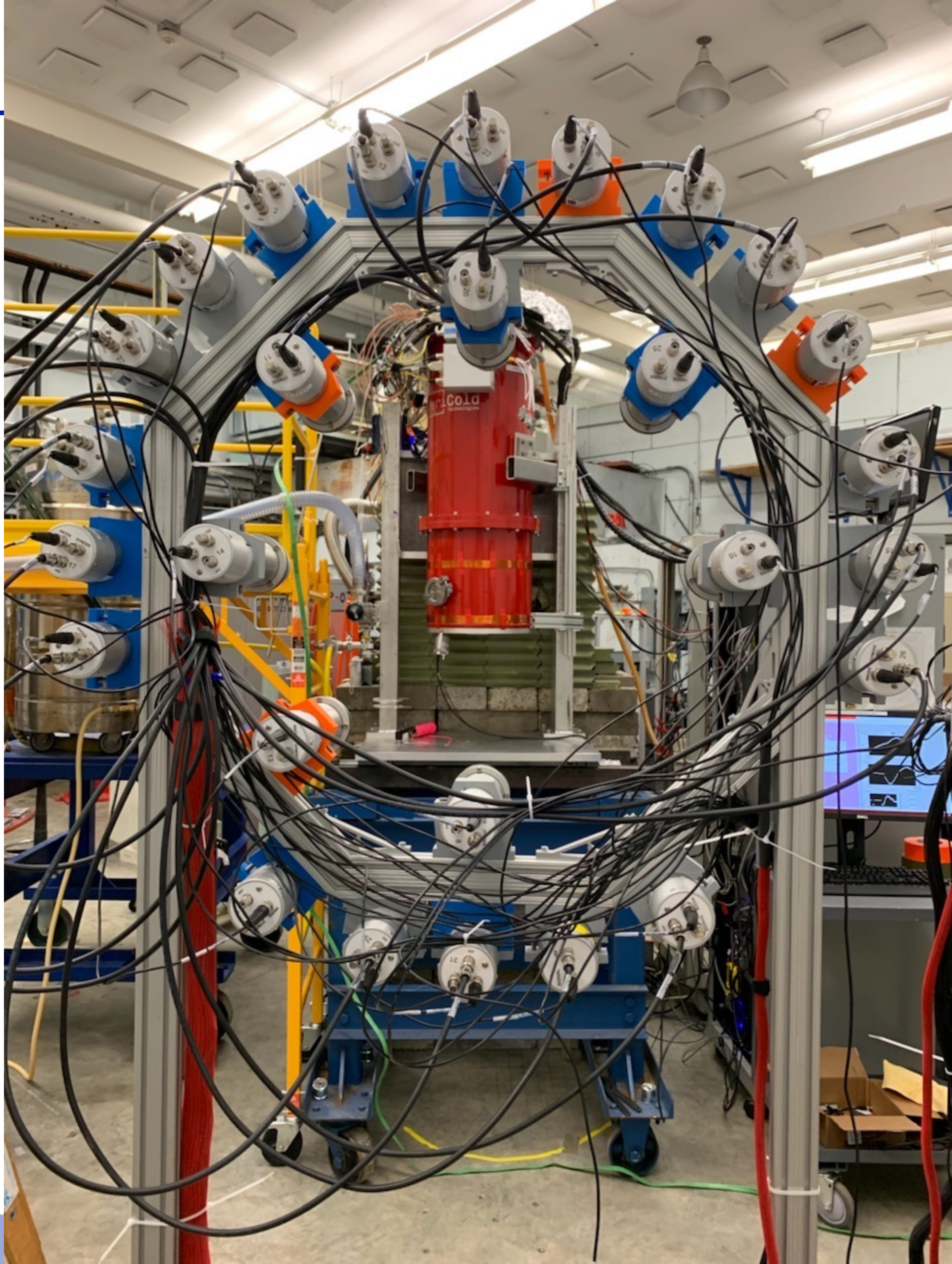
A proton, a Li atom, and a neutron ….

# IMPACT

*I*onization *M*easurement with *P*honons *a*t *C*ryogenic *T*emperatures

- A measurement of the nuclear recoil ionization yield down to 100 eV recoil
  - Essential to understanding the response of the HV detectors to nuclear recoils
  - Current state of knowledge in Si:



# How To Impact

IMPACT

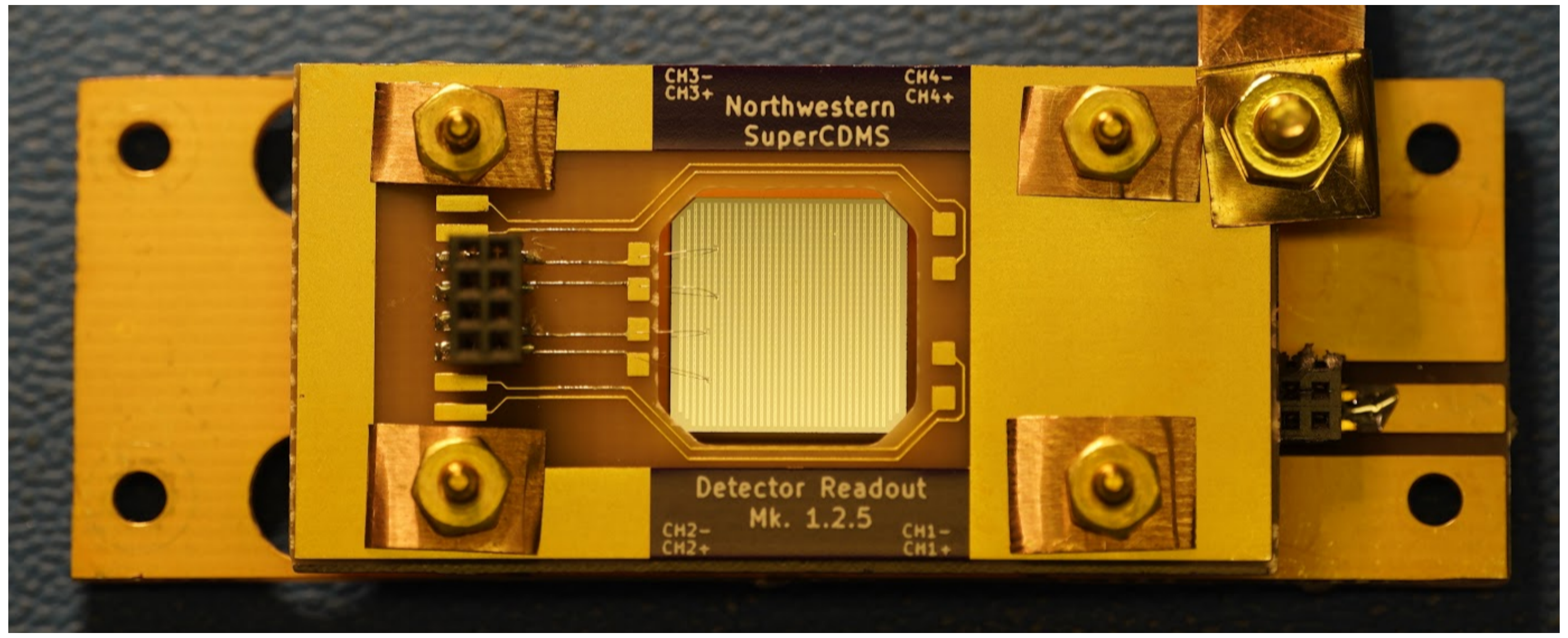
- Determination of yield via measurement of the total phonon energy in the detector and kinematic measurement of the recoil energy via a coincident detection of the scattered neutron

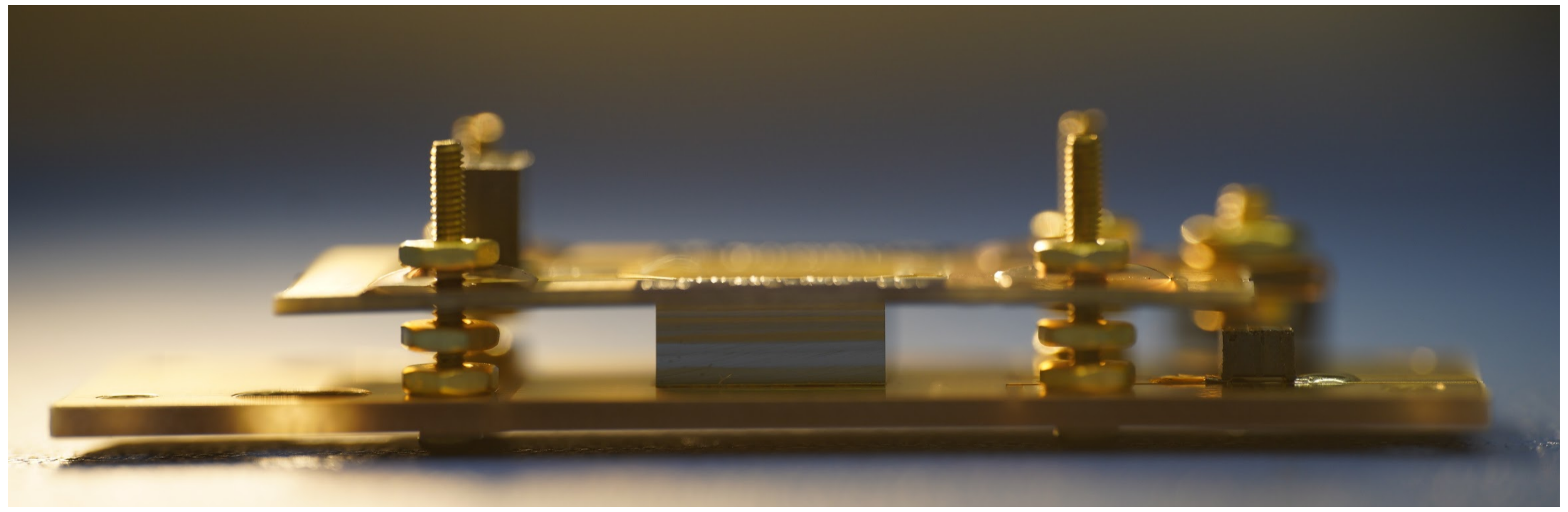
$$E_r = 2E_{\mathrm{n}} \frac{M_{\mathrm{n}}^2}{(M_{\mathrm{n}} + M_{\mathrm{T}})^2} \left( \frac{M_{\mathrm{T}}}{M_{\mathrm{n}}} + \sin^2\theta - (\cos\theta)\sqrt{\left(\frac{M_{\mathrm{T}}}{M_{\mathrm{n}}}\right)^2 - \sin^2\theta} \right)$$

- Neutrons courtesy of Triangle Universities Nuclear Laboratory
  - 1.889 MeV protons with 2.5 MHz pulsing
  - LiF-on-Ta target
  - Aim for $^{28}$Si elastic scattering resonance at 55.7 keV

TUNL
Triangle Universities Nuclear Laboratory

- Same HVeV detector used for HVeV DM Run 2
  - 1x1x0.4 cm$^3$ Si crystal (0.93 g)
  - 2 channel TES readout
  - Energy resolution: $\sigma_{ph}$ ~ 3 eV
  - Charge resolution: $\sigma_{eh}$ ~ 0.03 $e^-h^+$



# How To Impact

- Neutron detectors
  - EJ-301/309 liquid scintillators, sensitive to neutrons down to 10 keV
  - 26 detectors focused on 100 eV, 220 eV, and 460 eV recoil energy points measure y in new parameter space
  - Three detectors at 0.75 keV, 2 keV, and 3.8 keV to overlap with existing measurements

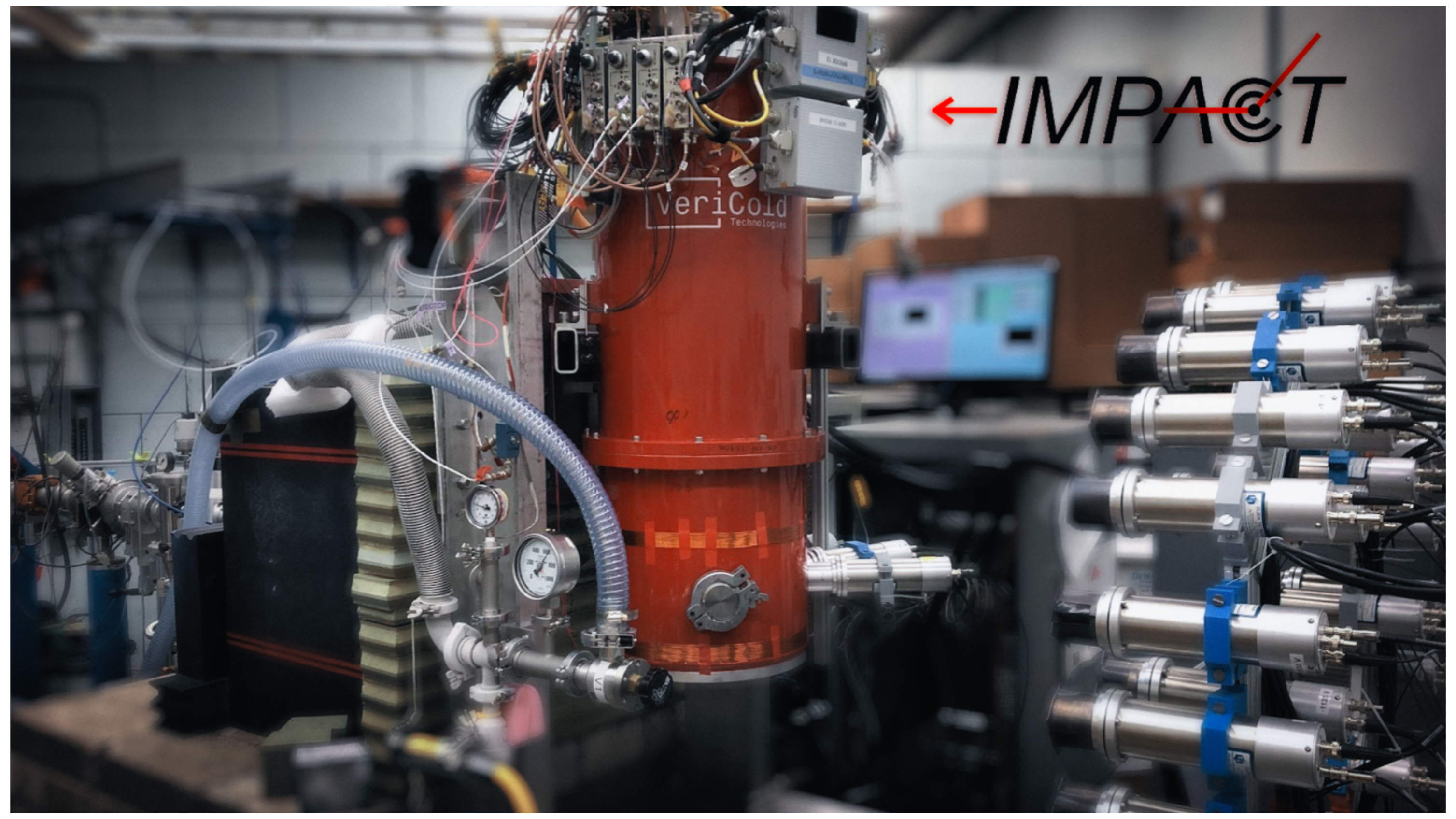


Image credit: Tom Ren

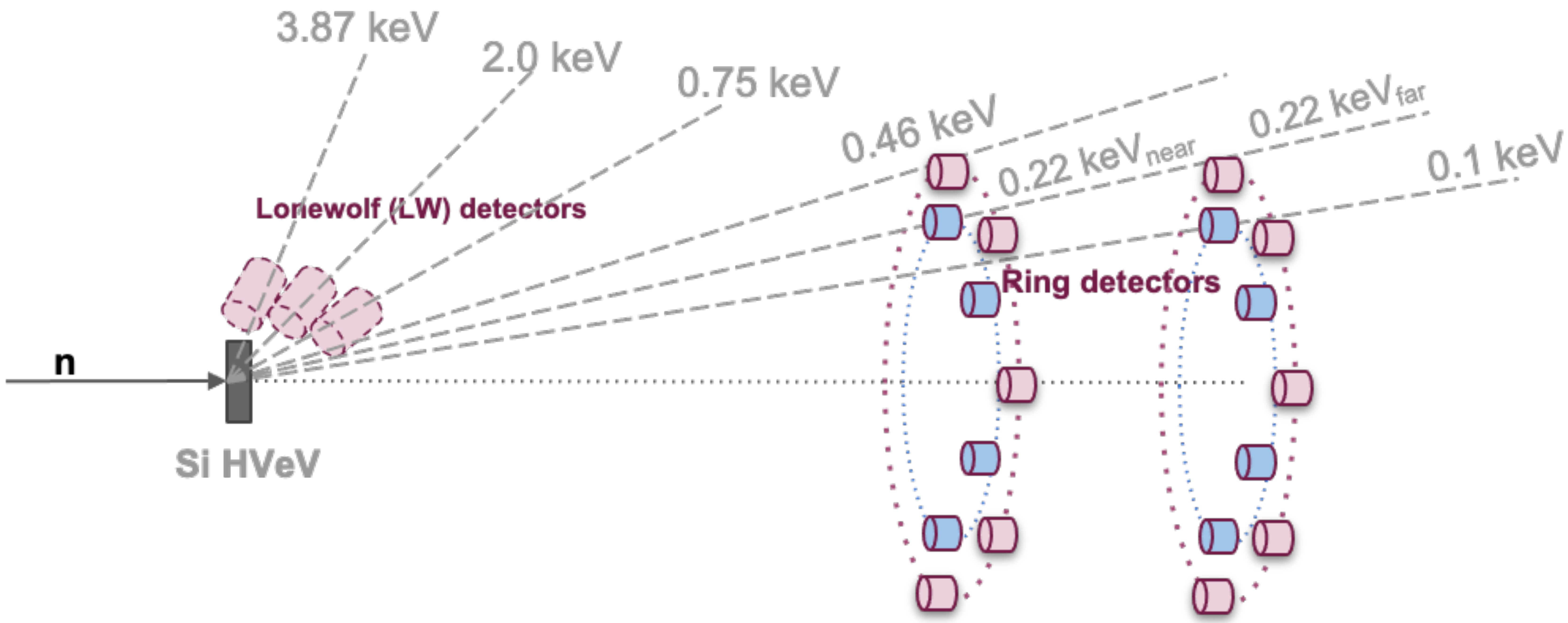


Image credit: Tom Ren

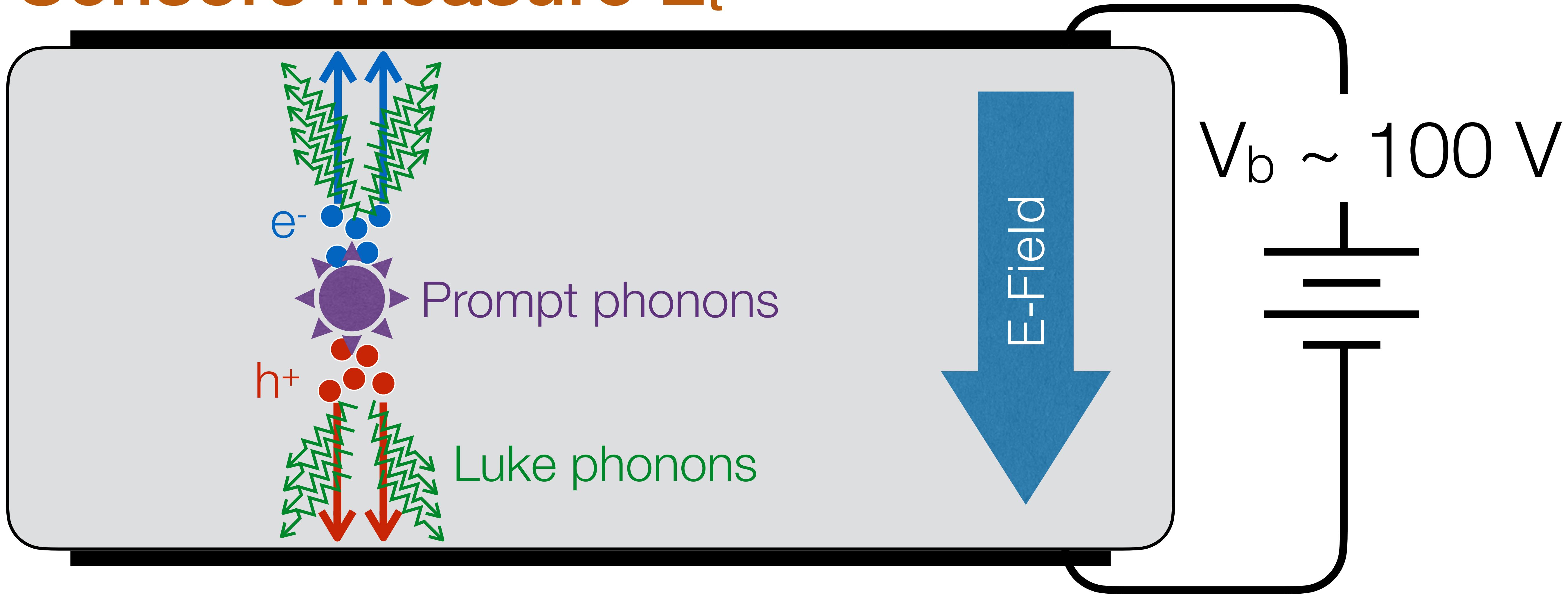
# How To Impact

IMPACT @TUNL

- Data
  - 3 weeks of data taking at 50% duty cycle
  - Two days at 0 V for tuning cuts and validating HVeV—scintillator neutron coincidence technique
  - Data taken at 20, 100, and 180 V for exploring yield dependence on the electric field

$$E_{total} = E_{recoil} + n_{eh}eV_b$$
$$= E_{recoil}(1 + eV_b/\epsilon_{eff} \cdot Y)$$

**Sensors measure $E_t$**




➡0V mode $V_b = 0$: Total energy = Recoil energy
➡HV mode $V_b \neq 0$: Total energy = Recoil energy + NTL energy

# IMPACT Analysis Scheme in 1 Slide

1. **Measurement:**
   Total phonon energy spectrum for events coincident between HVeV and PMT

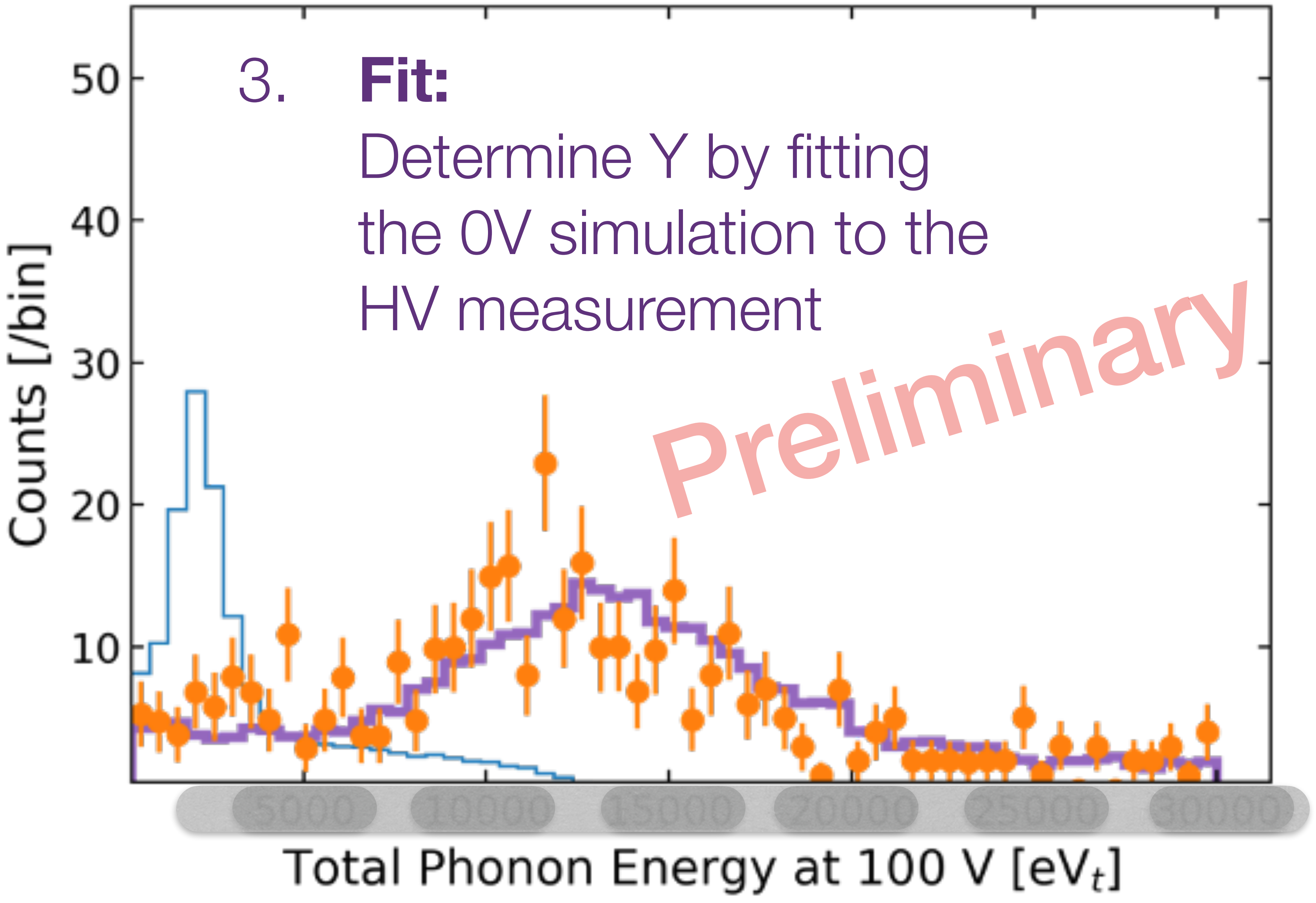
$$E_{total} = (1 + eV_b/\epsilon_{eff} \cdot Y)\ E_{recoil}$$

HV

0V

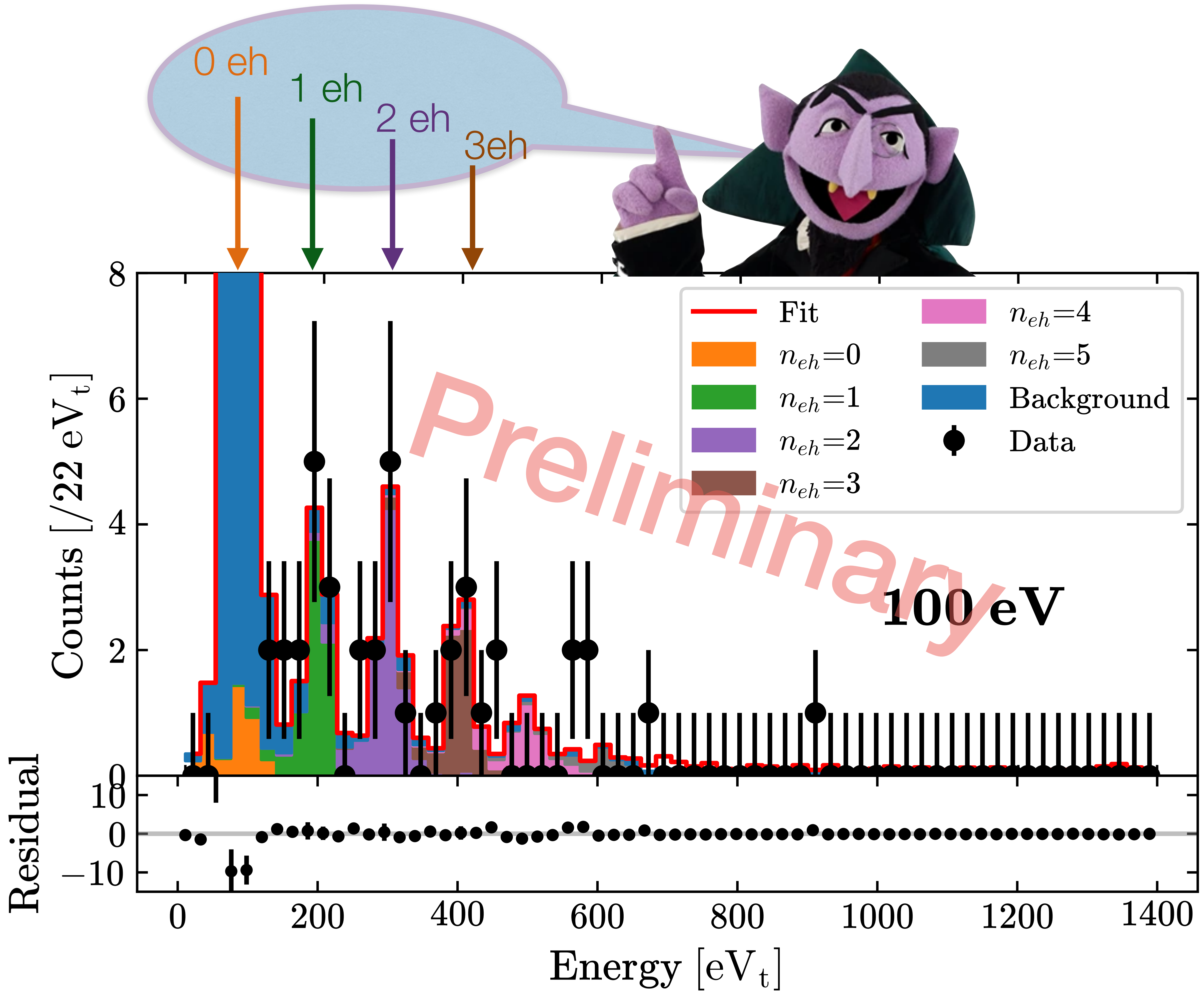
2. **Simulation:**
   Geant4 simulation of recoil energy spectrum for events coincident between HVeV and PMT

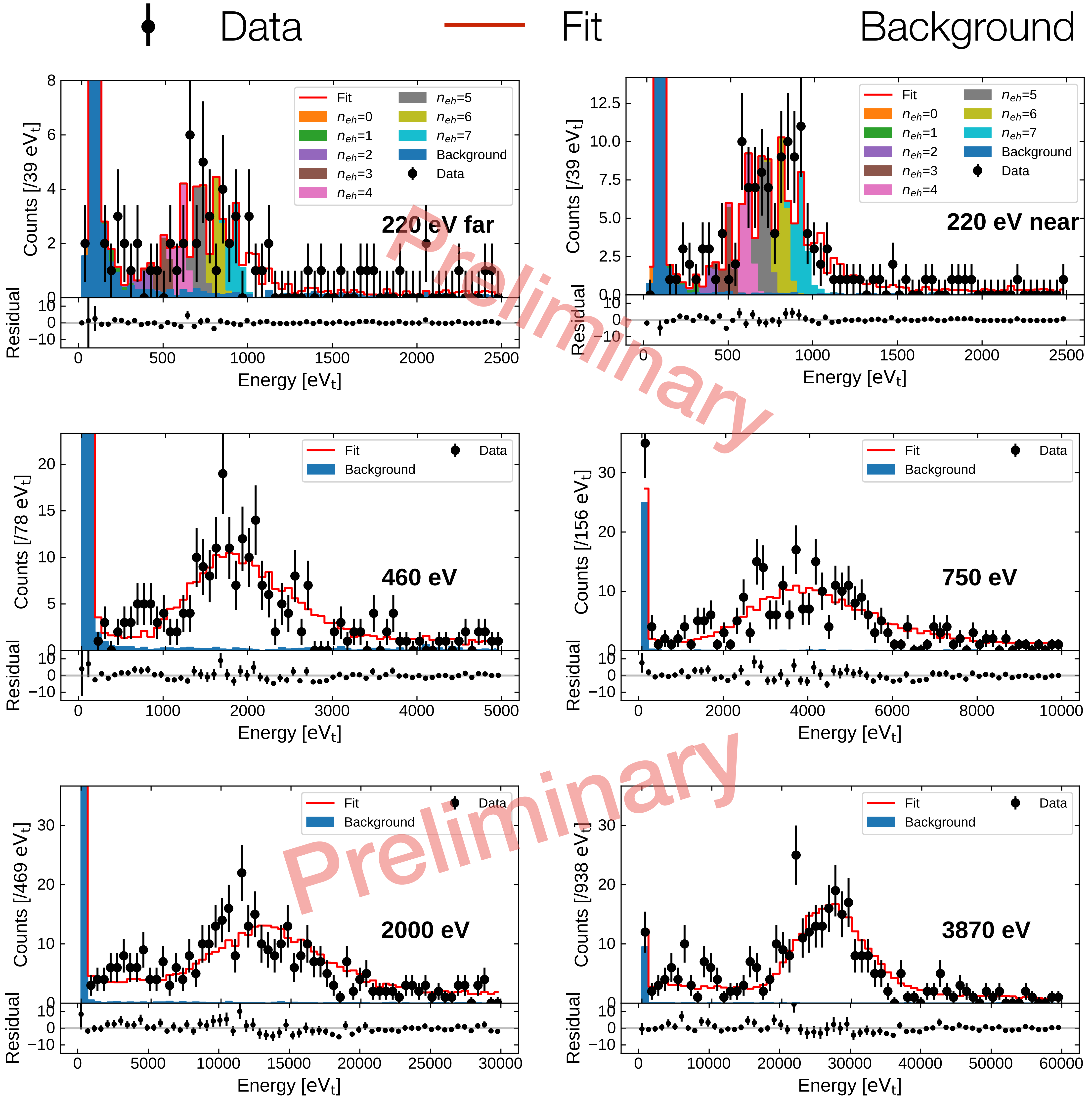
3. **Fit:**
   Determine Y by fitting the 0V simulation to the HV measurement



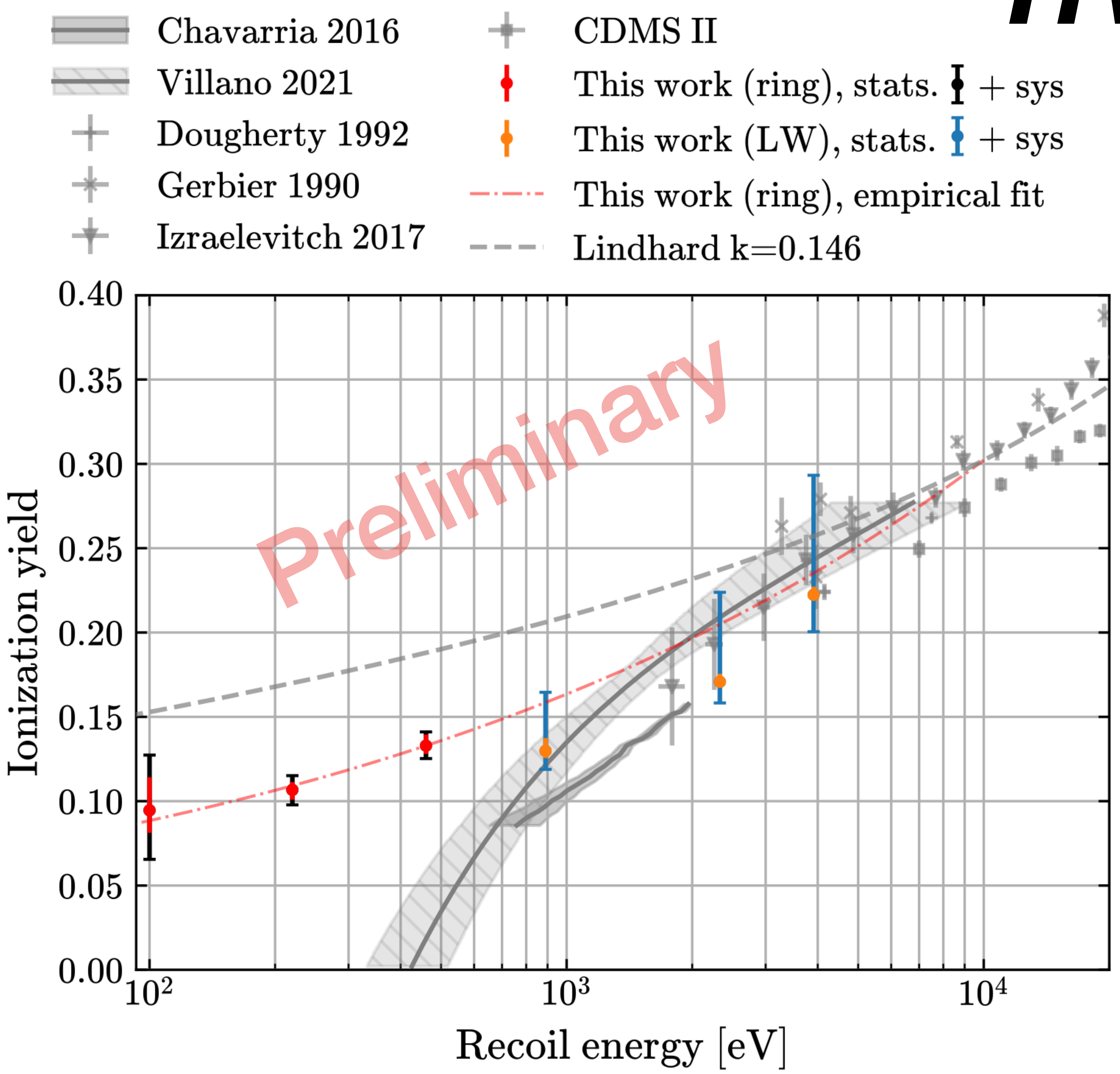

4. **Systematic Uncertainty:**
   - Coincidence timing window
   - Time of flight window
   - Neutron beam energy
   - Detector energy calibration
   - Impact ionization / Charge trapping
   - Fano factor

# Results of Ionization Yield Fit



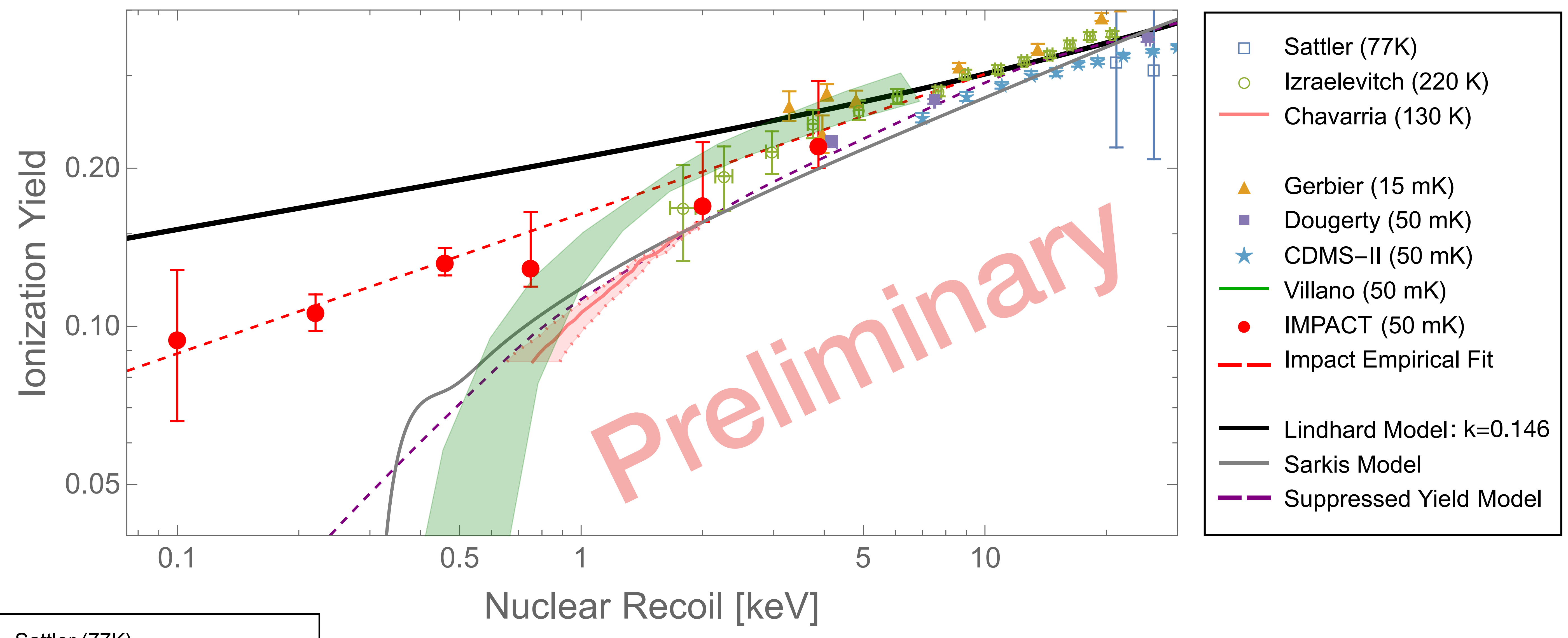
# IMPACT@TUNL Si Yield



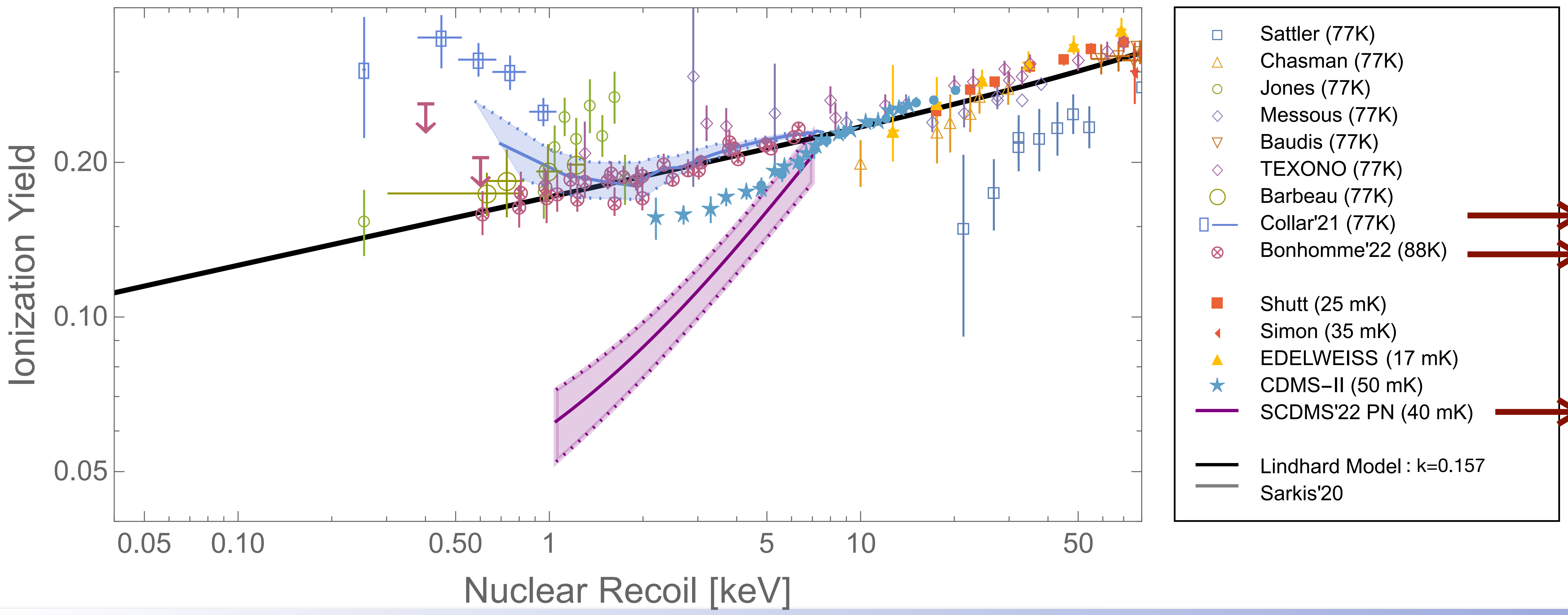
# IMPACT in Context

- Evidence of continued ionization production down to 100 eVr has significant impact for low mass reach of SuperCDMS and other Si based DM experiments
- Variability observed among measurements below 1 keV
- Currently studying effect of electric field using 180 V data
- Plan to repeat with Ge HVeV

Ionization Yield Values in Si




Ionization Yield Values in Ge




arXiv:2102.10089

arXiv:2202.03754

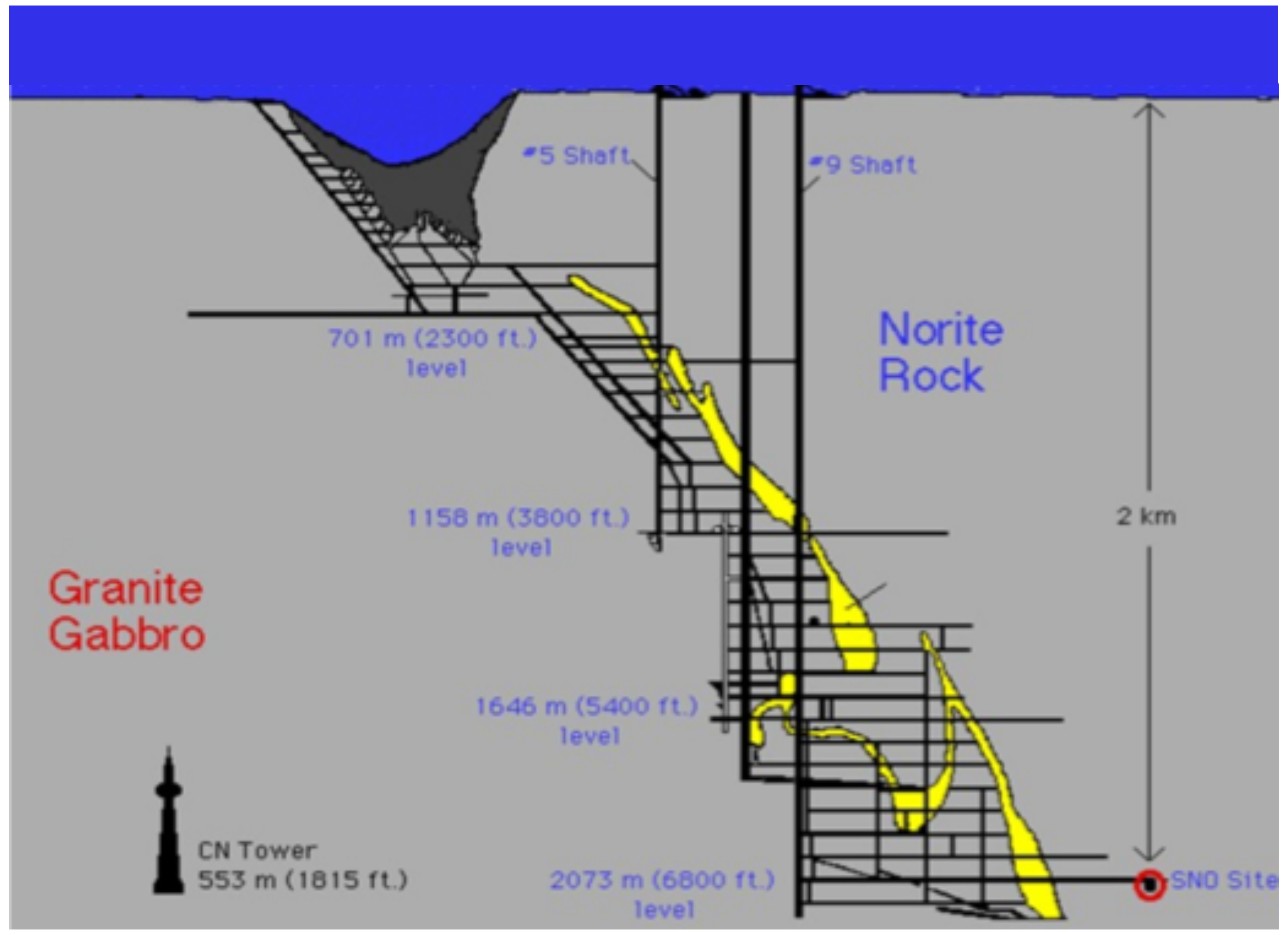
arXiv:2202.07043

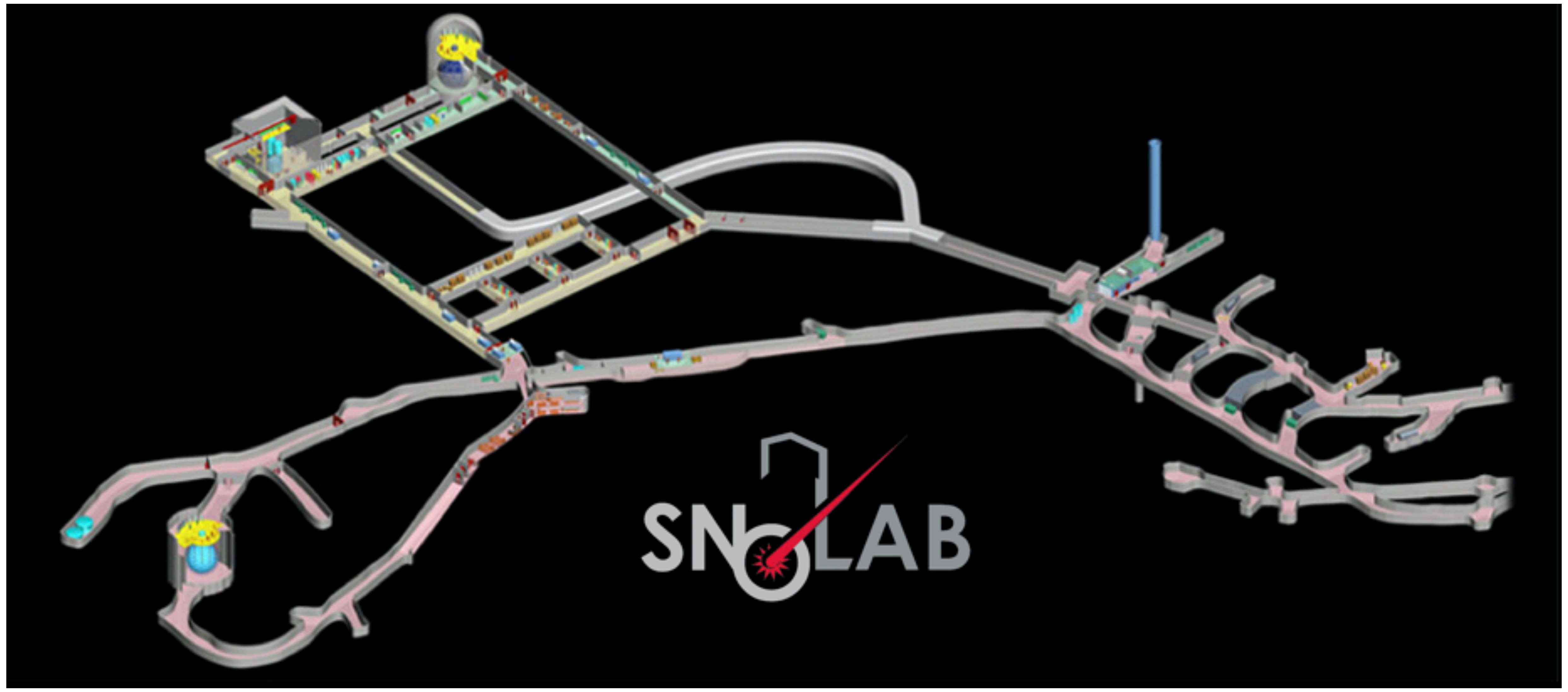
# II. The SuperCDMS Experiment

SuperCDMS @ SNOLAB

# SNOLAB

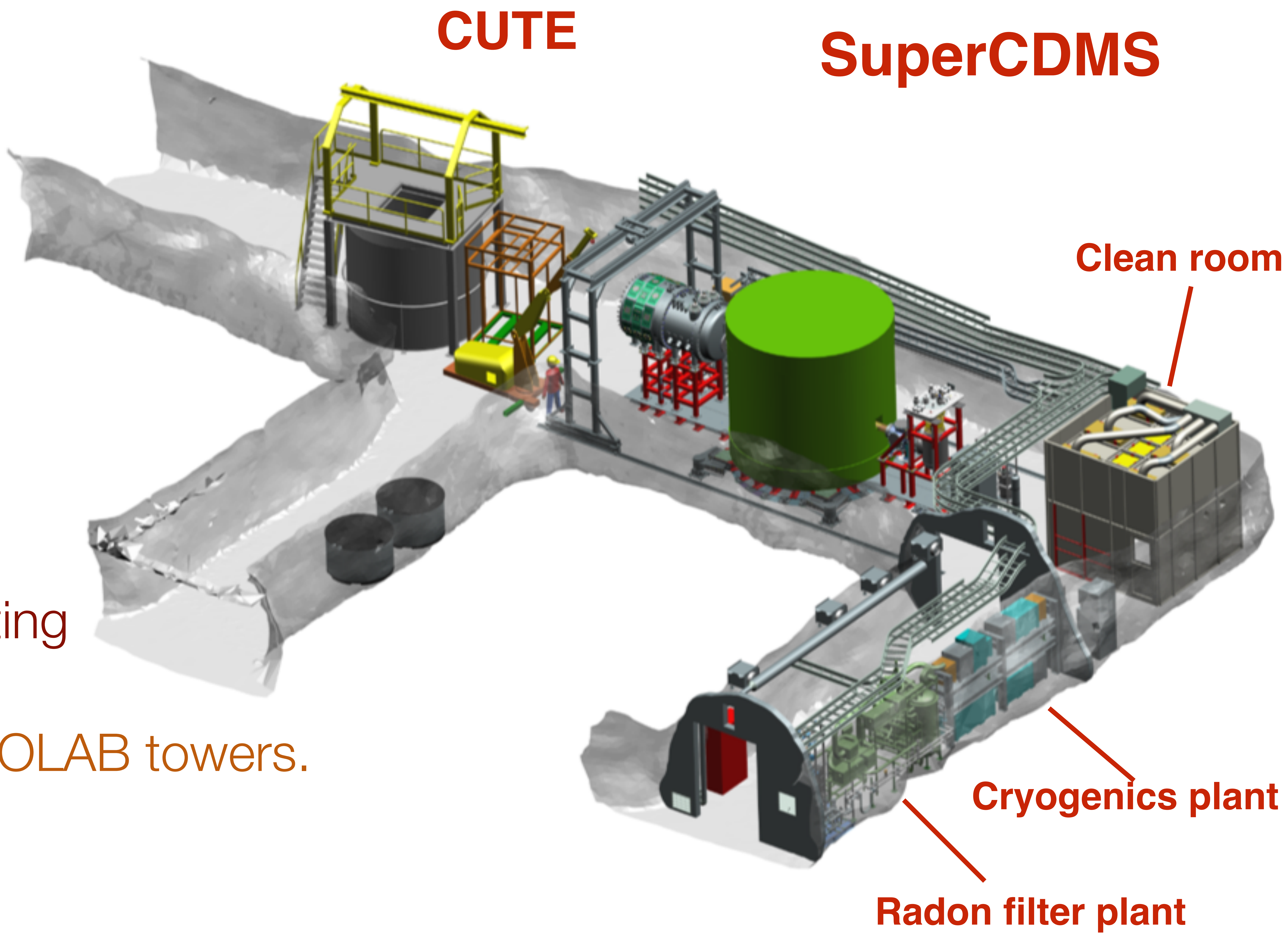
- 2 km underground (6000 m water equiv.)
- Cleanroom (class 2000 or better)
- Large lab (~5,000 $m^2$)
- Cosmic radiation: muon rate reduced by ~$10^6$
- Surface facilities, support staff (>100)



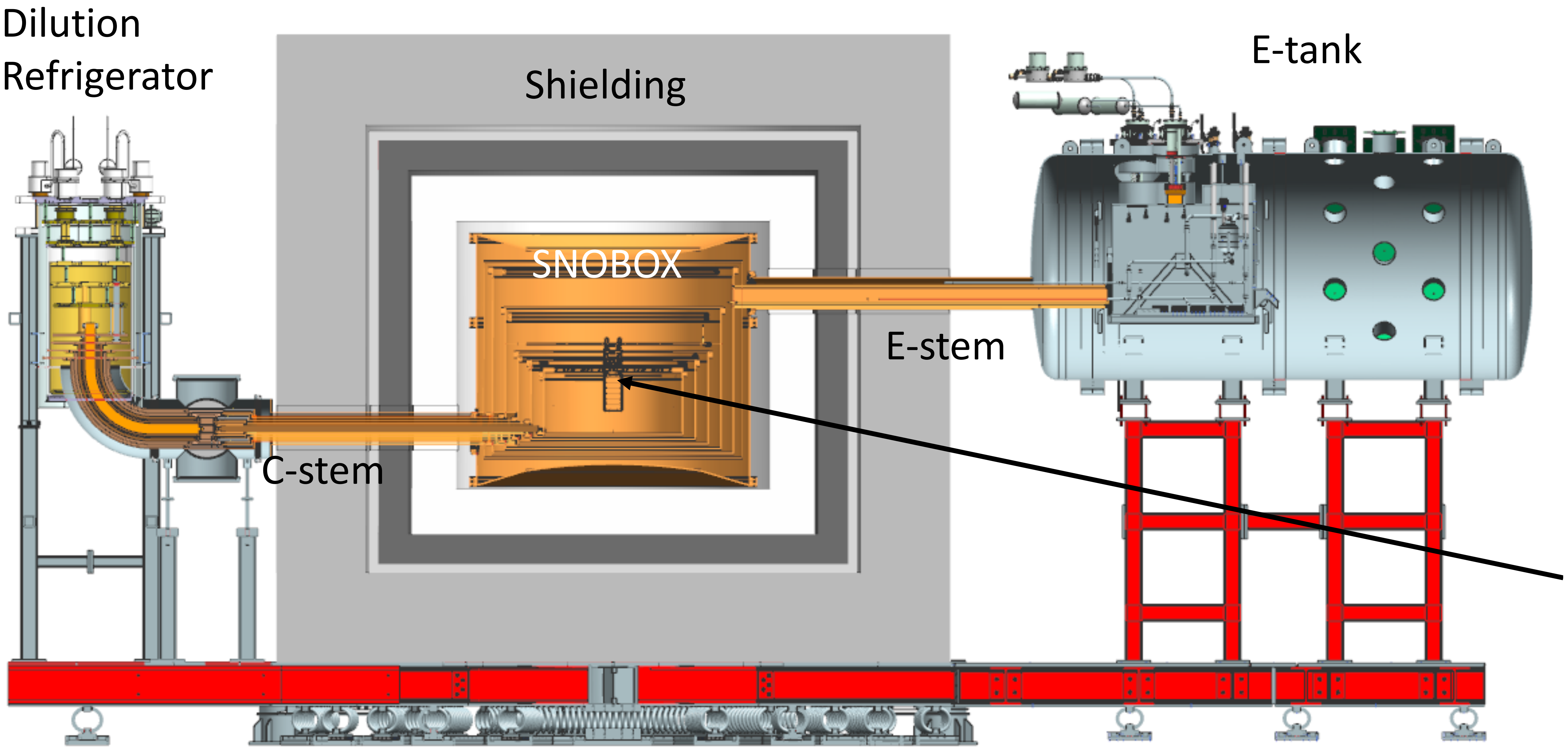




# SuperCDMS @ SNOLAB

- Low-radon clean-room
- Collaborating with:
  - Cryogenic *U*nderground *TE*st facility (CUTE)
  - Rapid-turn around detector testing
  - First data from SuperCDMS SNOLAB towers.



# The SuperCDMS SNOLAB Experiment




Facility:

- 6800 m.w.e. overburden
- 15 mK base temperature
- Initial Payload: ~30 kg total
  4 towers (2 iZIP, 2 HV)

Electron Recoil Backgrounds:

- External and facility: O(0.1 /keV/kg/d)
- Det. setup: O(0.1(Ge)-1(Si) /keV/kg/d)
- Total: O(0.1-1 /keV/kg/d)

Solar ν-dominated NR background

Vibration isolation:

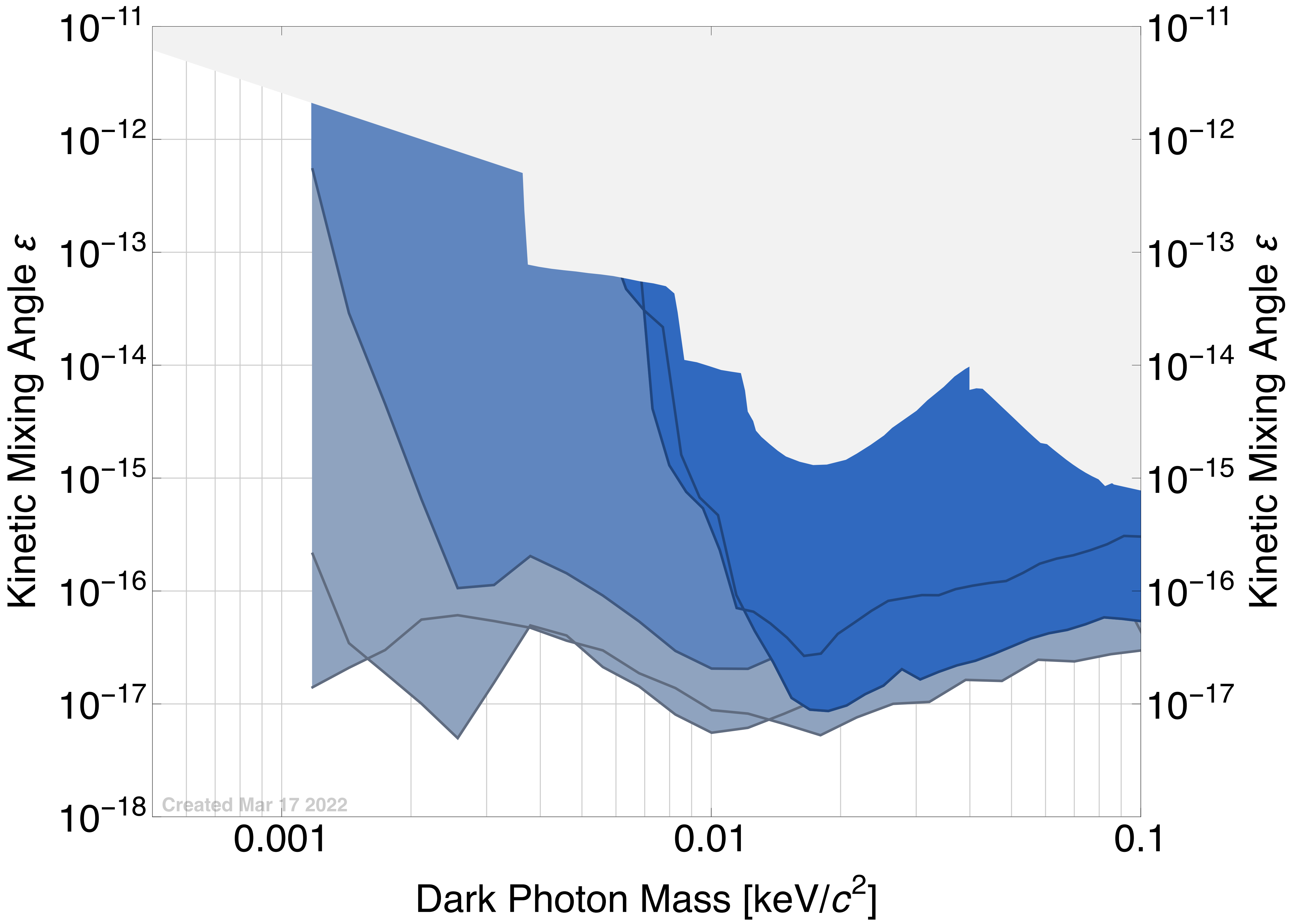
- Seismic: spring loaded platform
- Cryo coolers: soft couplings (braids, bellows)
- Copper cans: hanging on Kevlar ropes

# III. The SuperCDMS Experiment

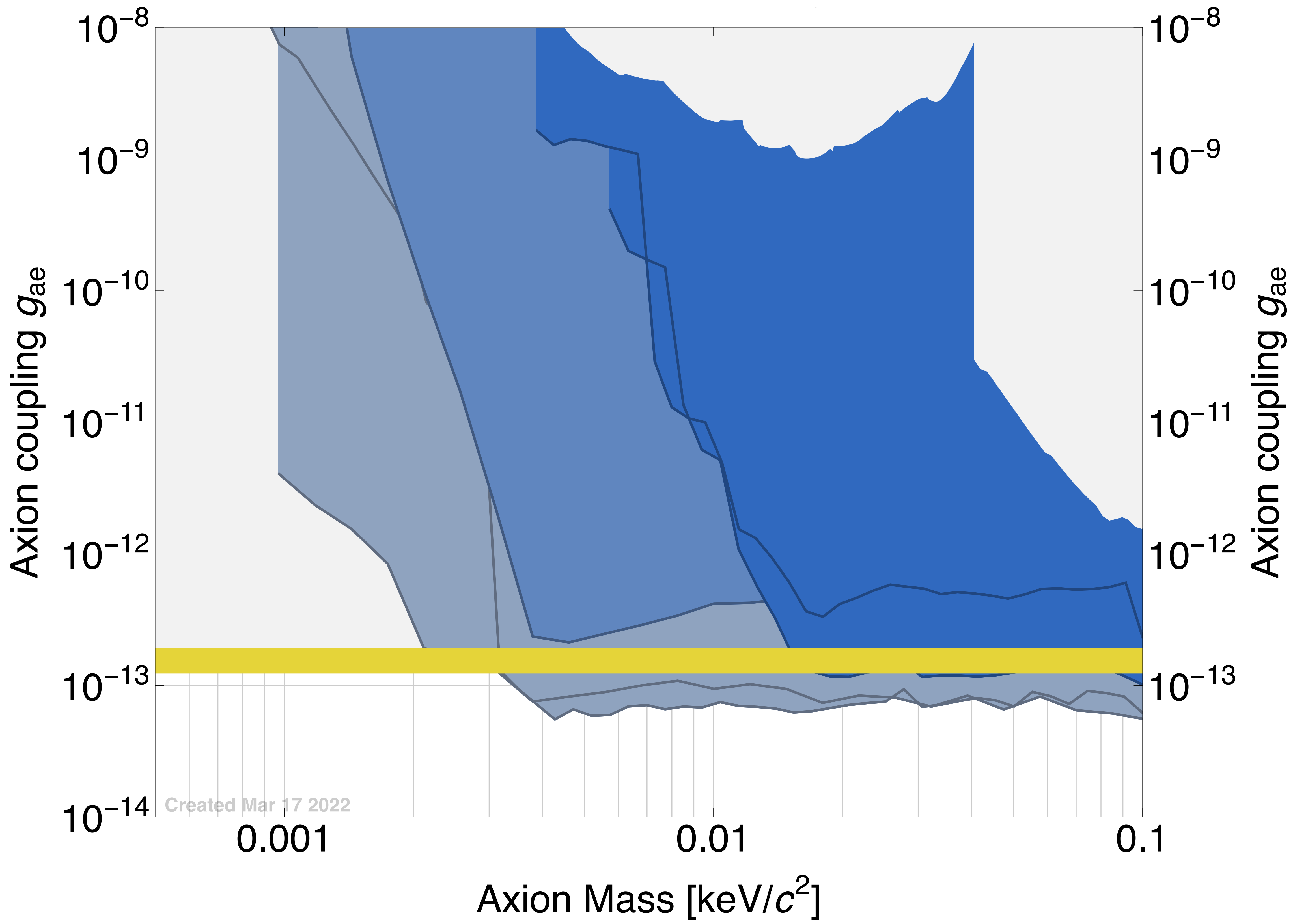
Dark Matter Search Results … and future reach

# Low Mass: Dark Photon & ALP Searches

Dark Photon Searches



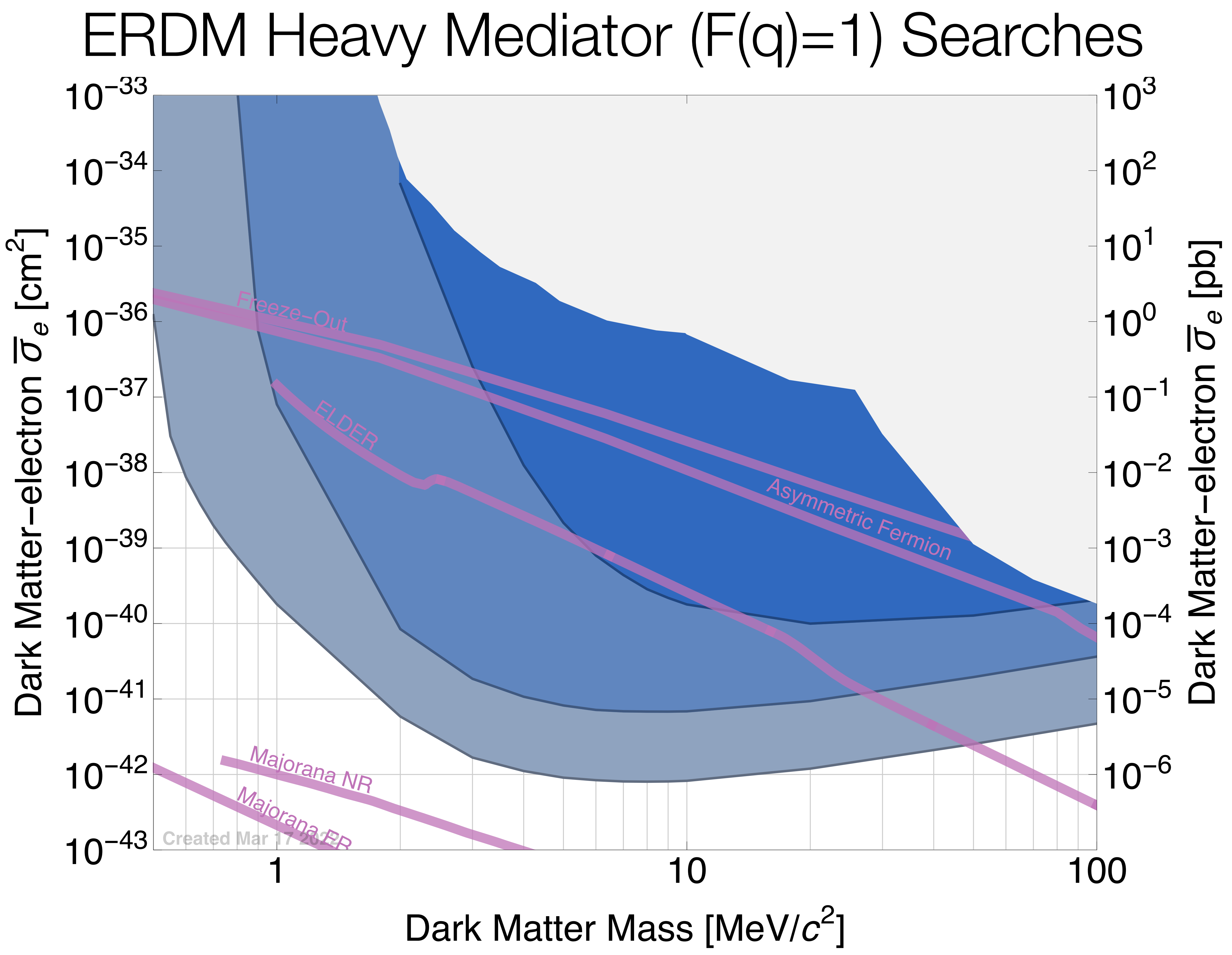

Axion-Like Particle Searches

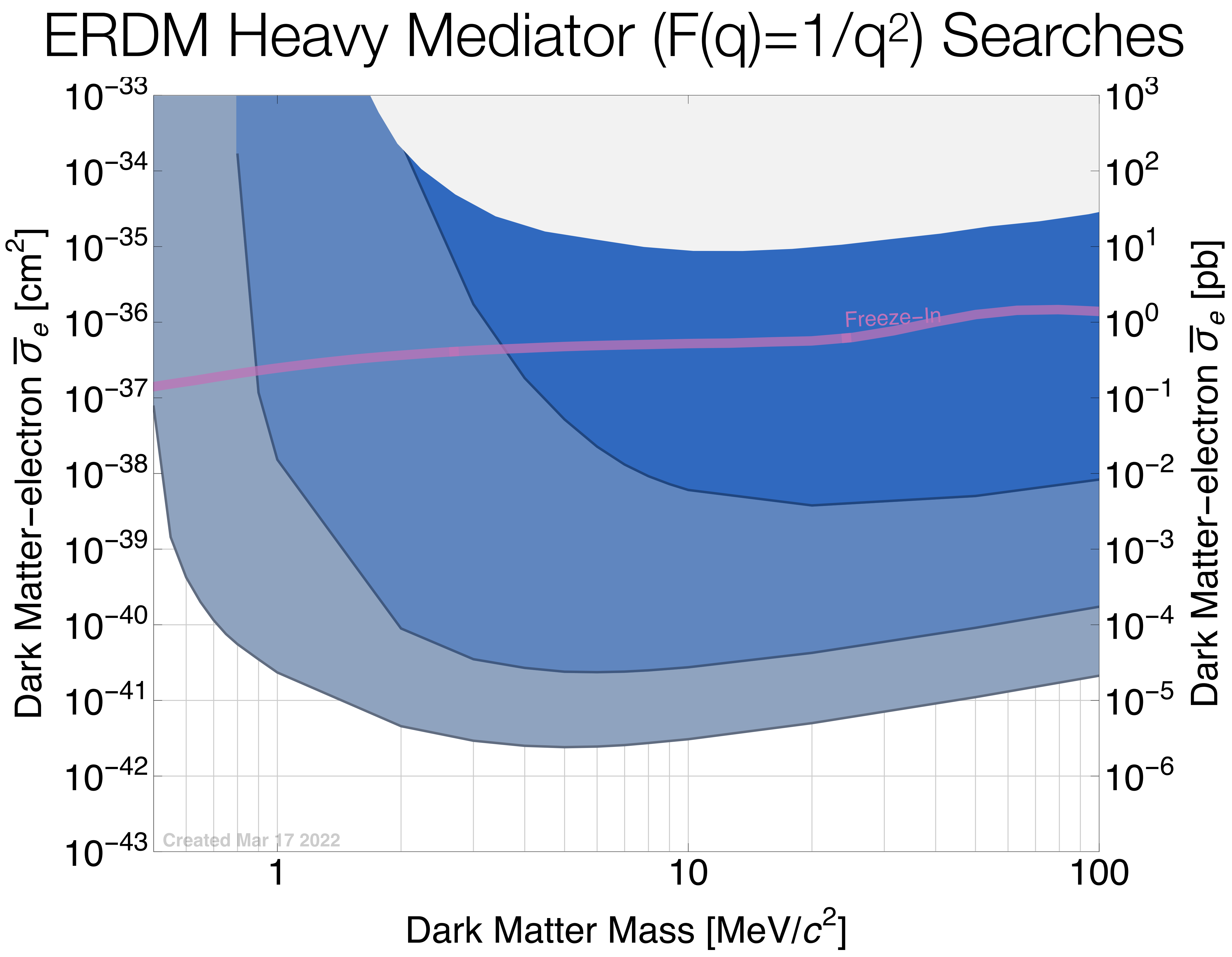



- Currently excluded region of parameter space
- Expected reach of SuperCDMS@SNOLAB experiment
- Expected reach of improved backgrounds with in-hand detector performance
- Expected reach of SNOLAB facility with background and detector performance improvements

arXiv.2203.08463: A Strategy for Low-Mass Dark Matter Searches with Cryogenic Detectors in the SuperCDMS SNOLAB Facility

# Mid Mass: Electron Recoil Dark Matter Searches

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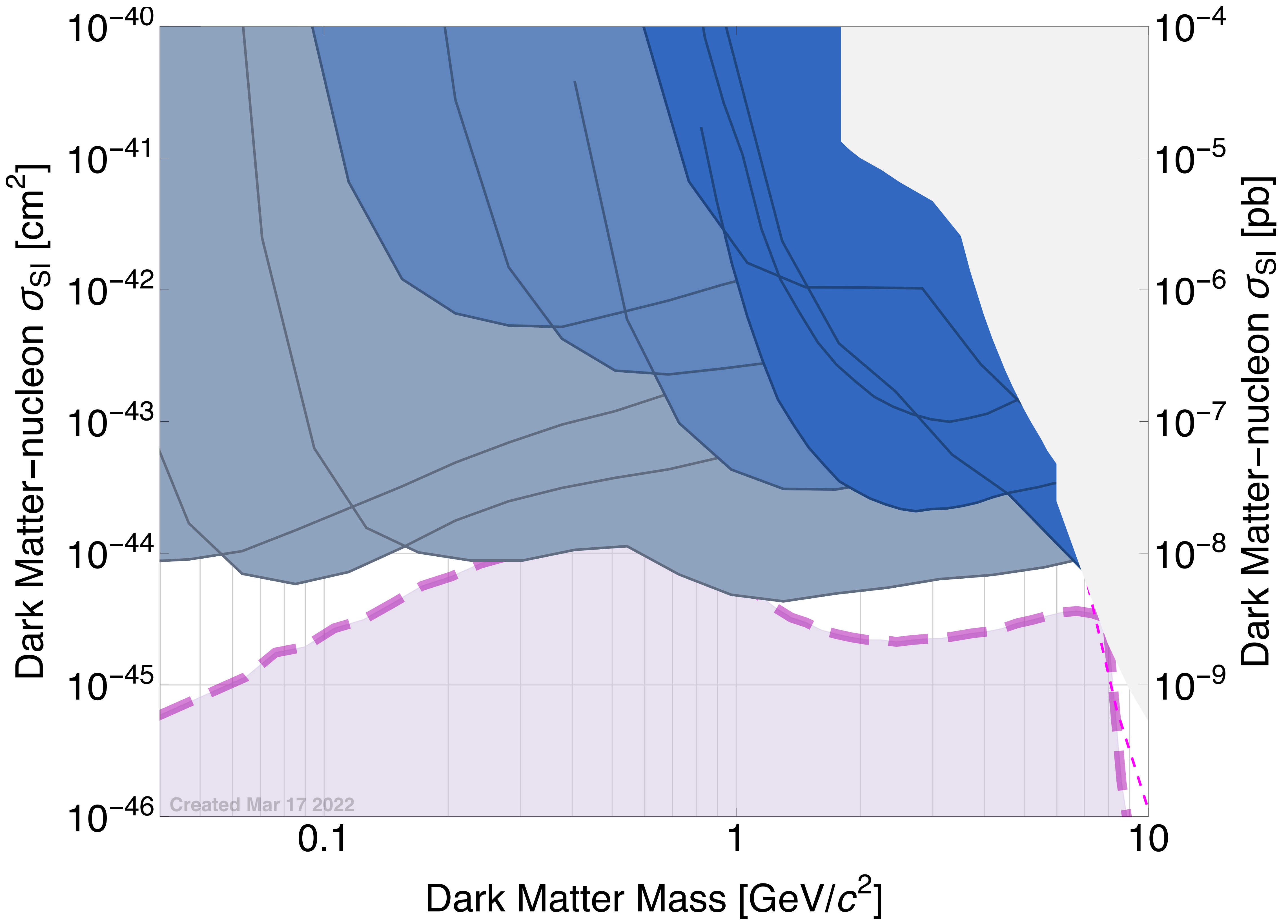
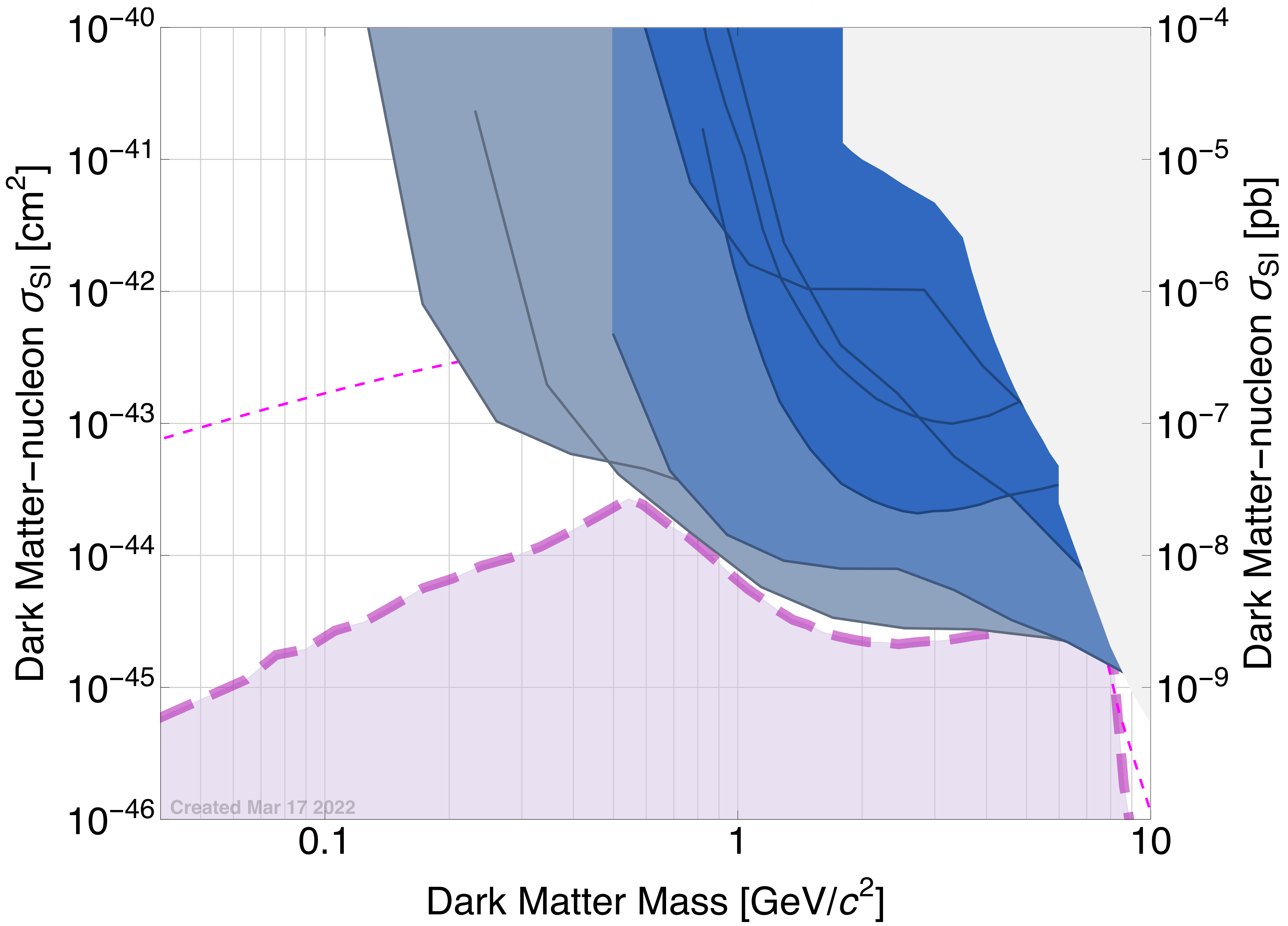
# High Mass: Nuclear Recoil Dark Matter Searches

NRDM Searches w/ High Res Detectors




NRDM Searches w/ Discriminating Detectors




- Currently excluded region of parameter space
- Expected reach of the SuperCDMS@SNOLAB experiment
- Expected reach of SNOLAB facility with in-hand detector performance and improved backgrounds
- Expected reach of SNOLAB facility with detector performance background and improvements

arXiv.2203.08463: A Strategy for Low-Mass Dark Matter Searches with Cryogenic Detectors in the SuperCDMS SNOLAB Facility

# Conclusion

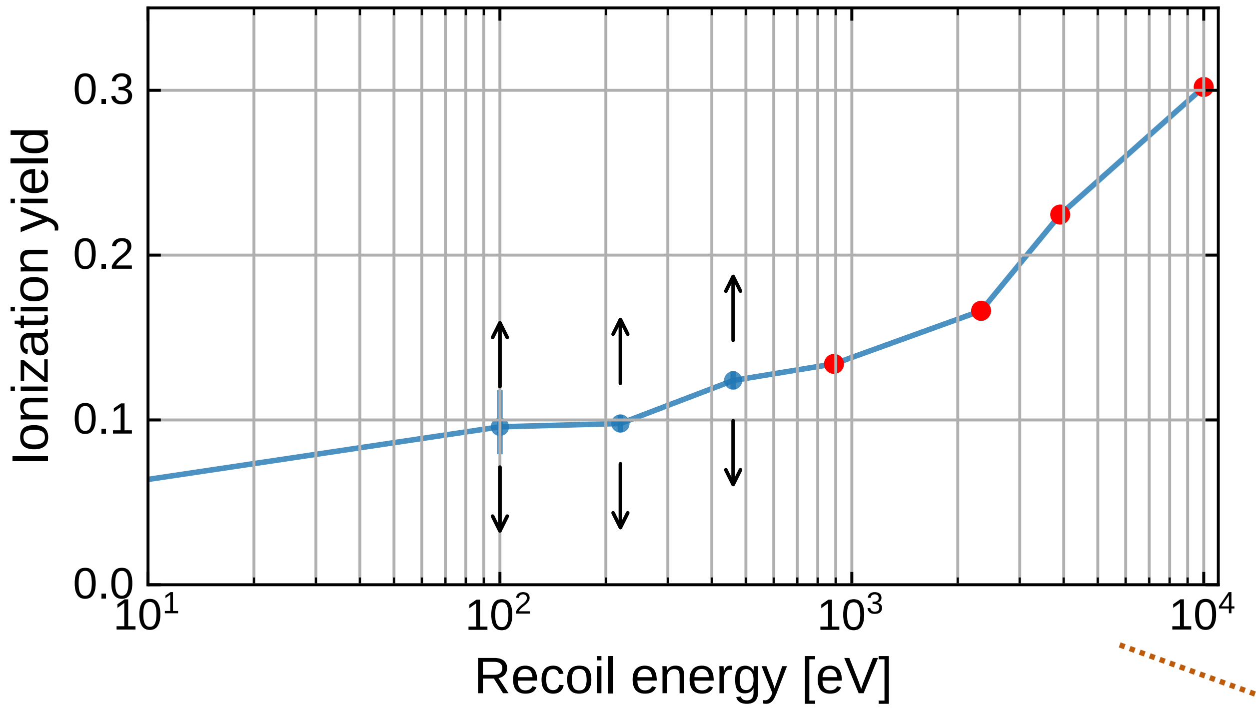
... the end

# Conclusions

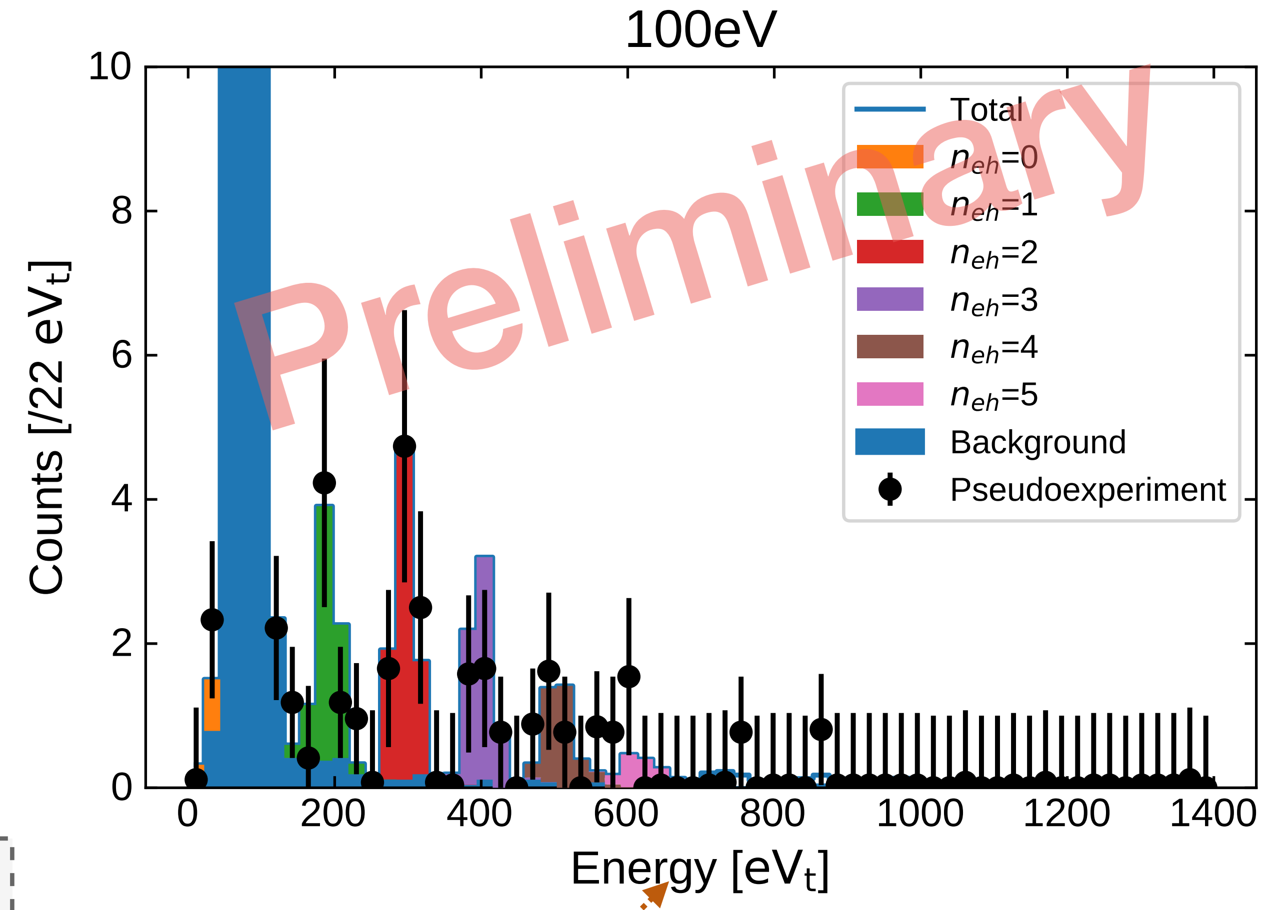
- SuperCDMS detectors aiming to reach "neutrino floor" in 1-10 GeV NR mass range
- Technology being adapted in smaller detectors to search for light dark matter, down to
  - $\mathcal{O}(10)$ MeV via inelastic Nuclear recoil channels (Migdal, Bremsstrahlung)
  - $\mathcal{O}(1)$ MeV via Electron recoil channels and
  - $\mathcal{O}(1)$ eV via Dark Photon Absorption channels
    - With sensitivity to Axion dark matter in the same range
- SuperCDMS designed a powerful complex cryogenic system that is being installed at SNOLAB
  - NEXUS operates HVeV devices at shallow depth for detector calibration and ERDM searches
  - CUTE is operational – deepest dilution fridge in the world
    - Plans for early science reach with CUTE facility
  - SuperCDMS Detector installation – next spring/summer
    - Initial run – late 2022
- SuperCDMS is particularly competitive at low masses, including electronic interactions.
- Stay tuned! Installation of and commissioning of experiment ongoing, exciting news on the horizon.

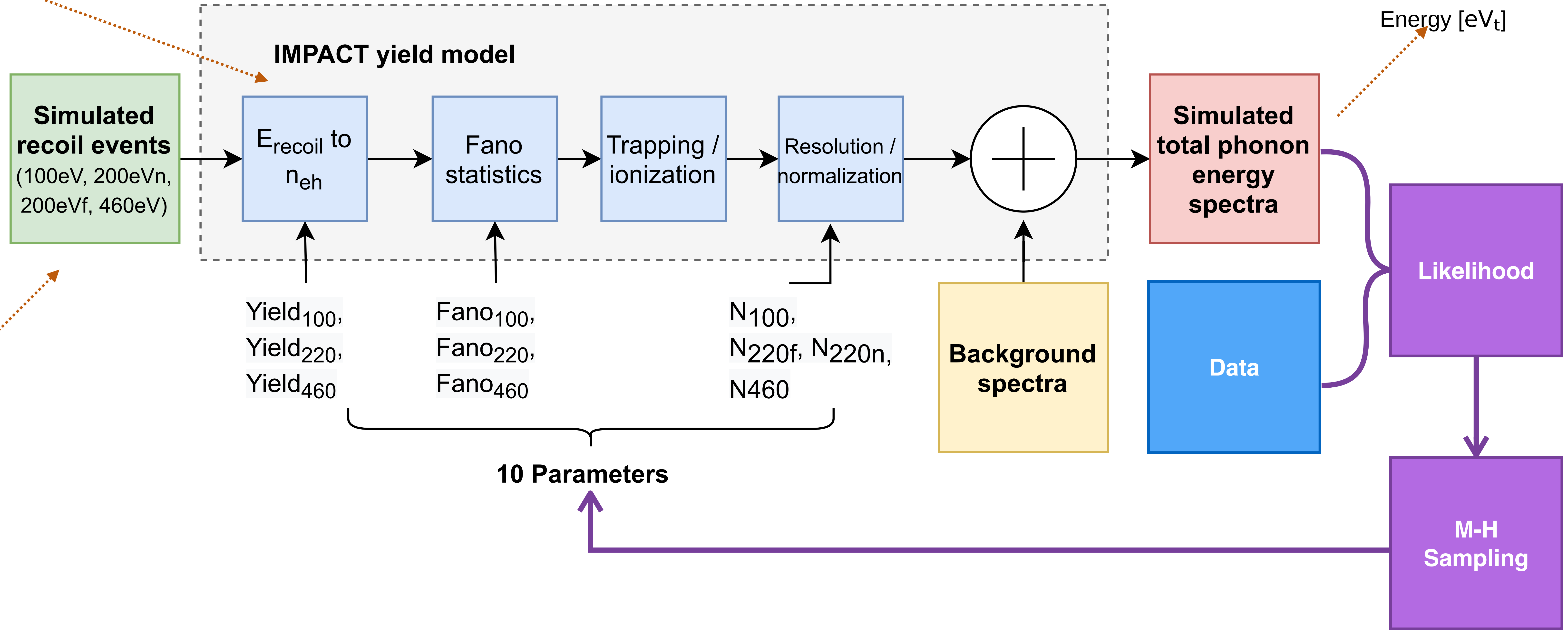
# Backup Slides

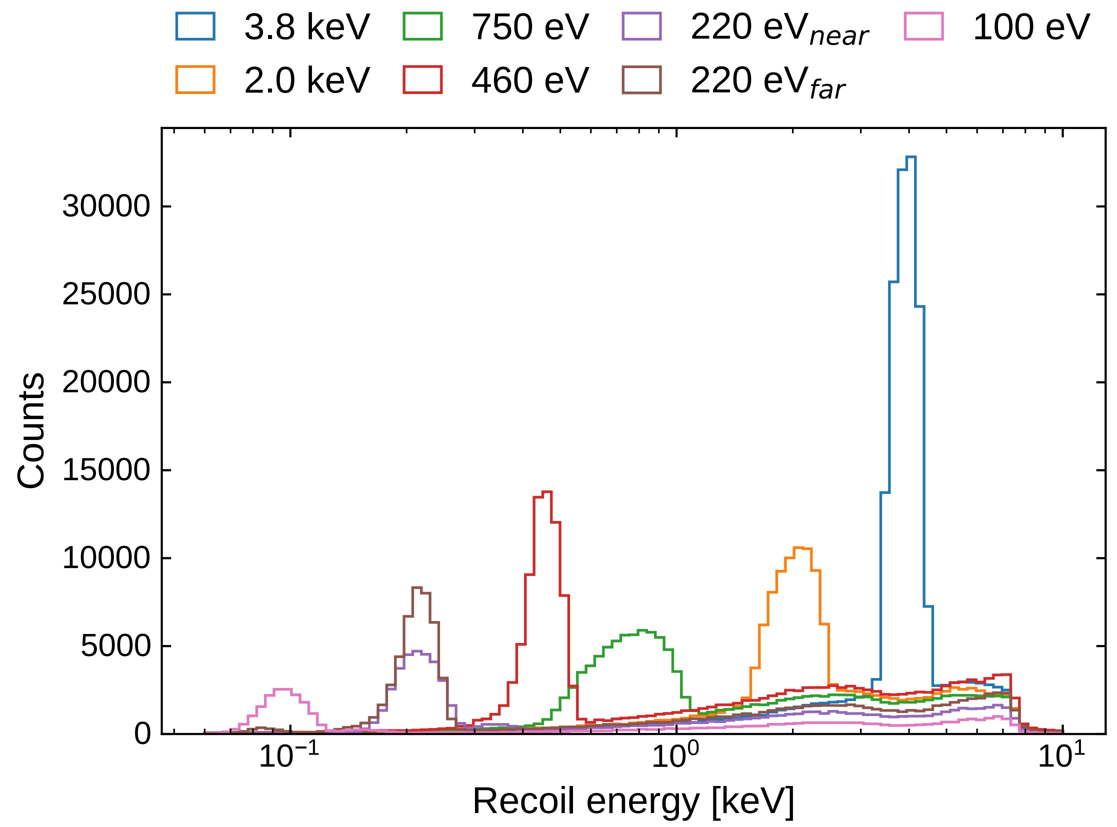
# IMPACT Analysis Scheme in 2 Slides




- Linear interpolation between points
- Yield(0 eV) = 0
- Yield(10 keV and LWs) = $Y_{Chavarria}$

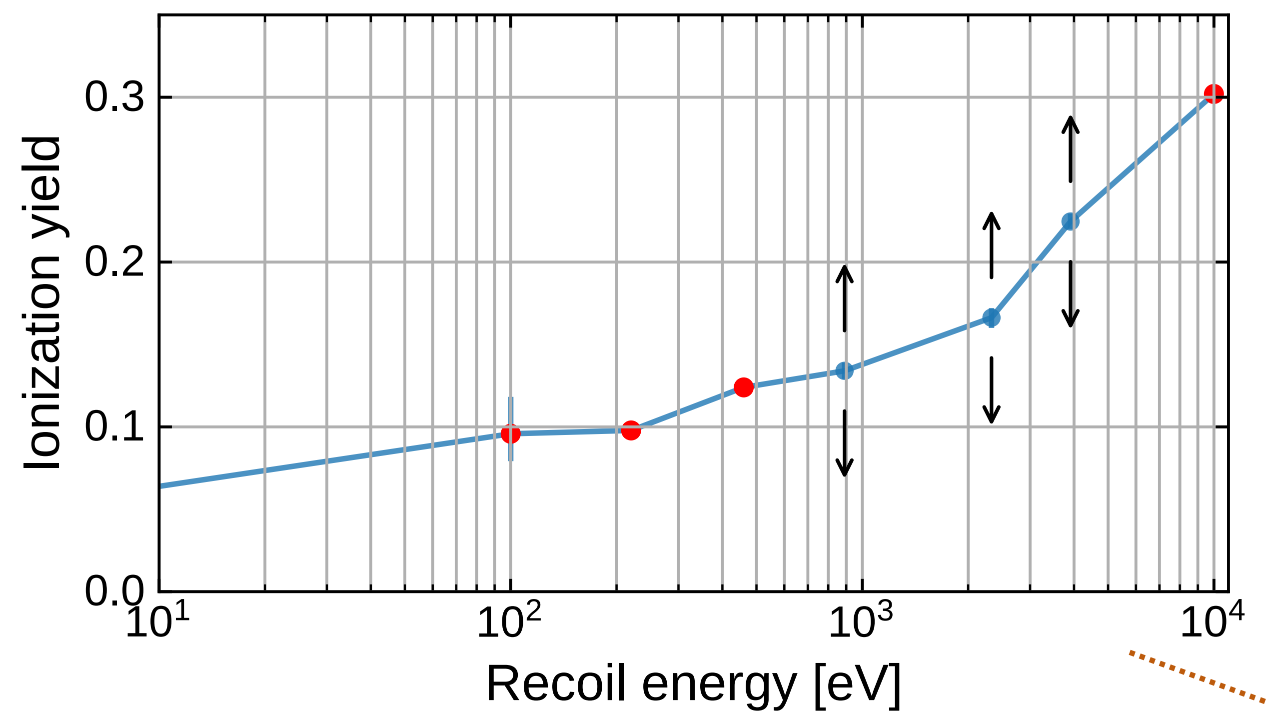



- We fit to the Ring detectors first

# IMPACT Analysis Scheme in 2 Slides

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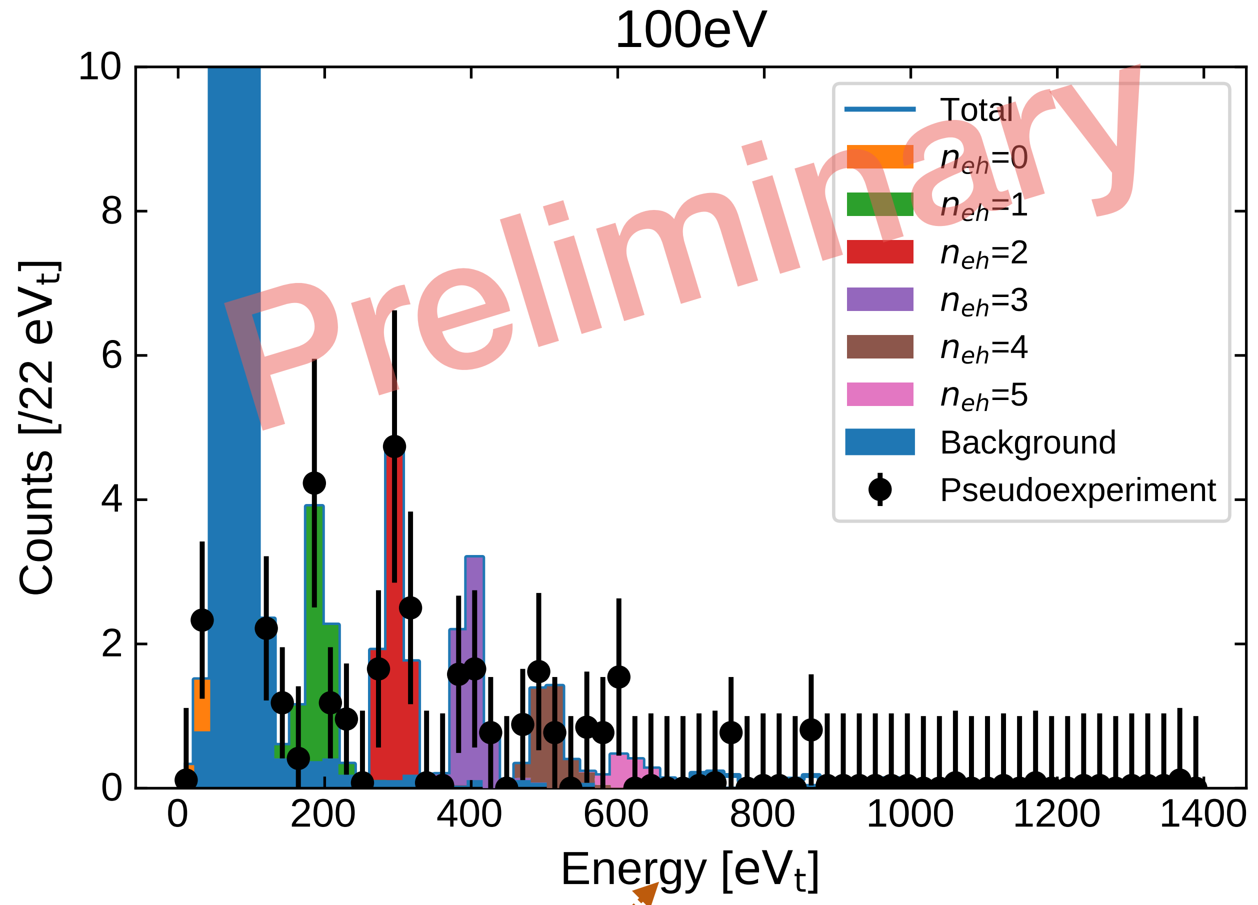
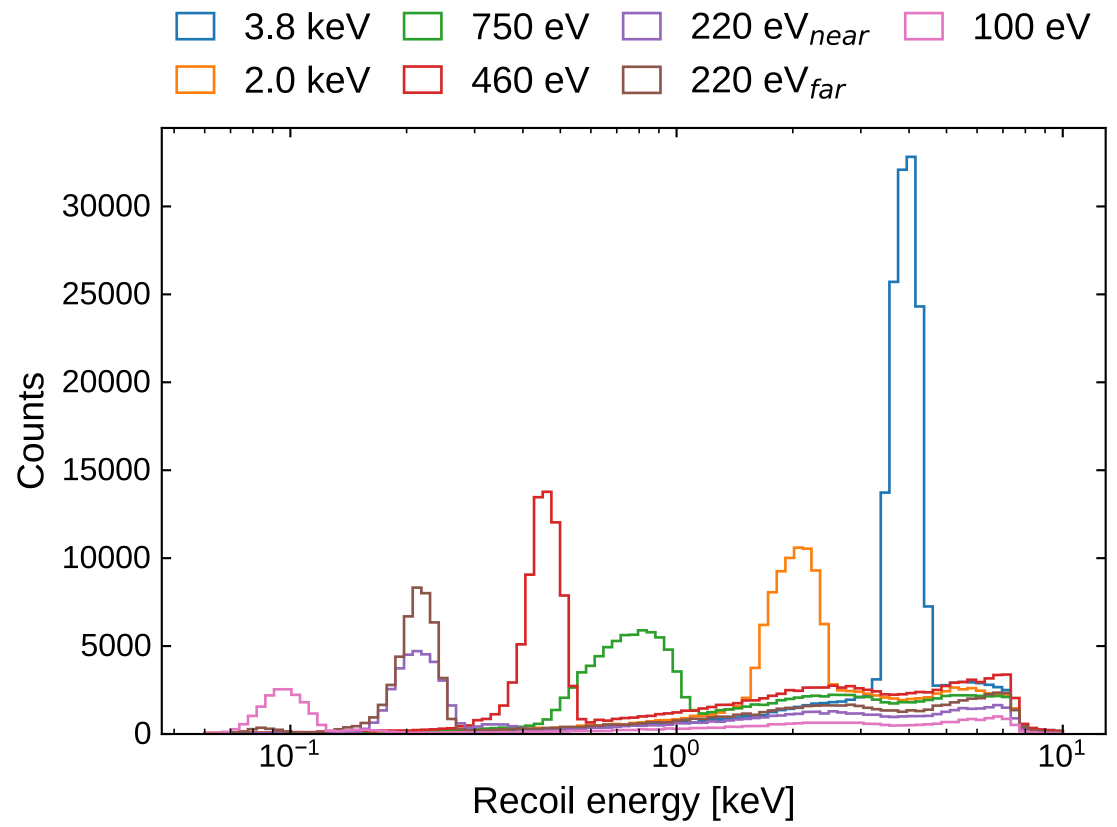
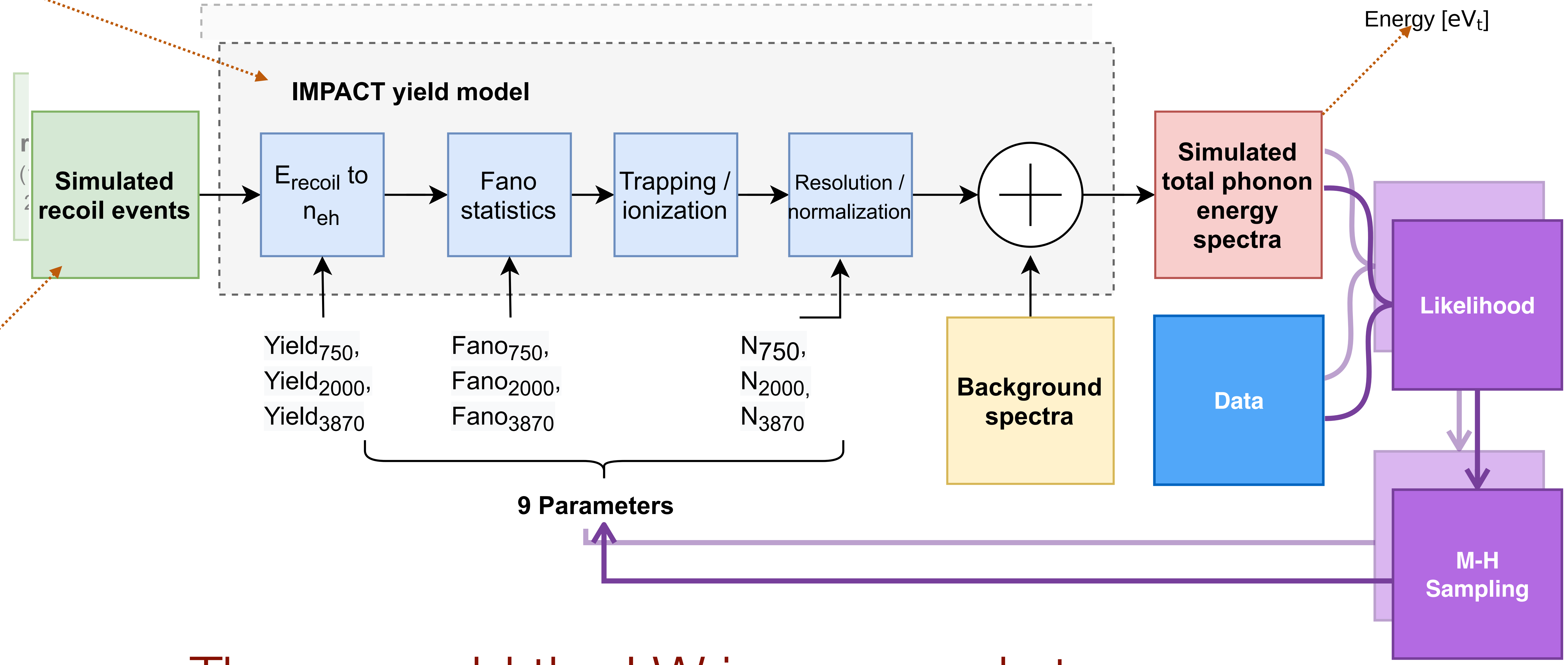
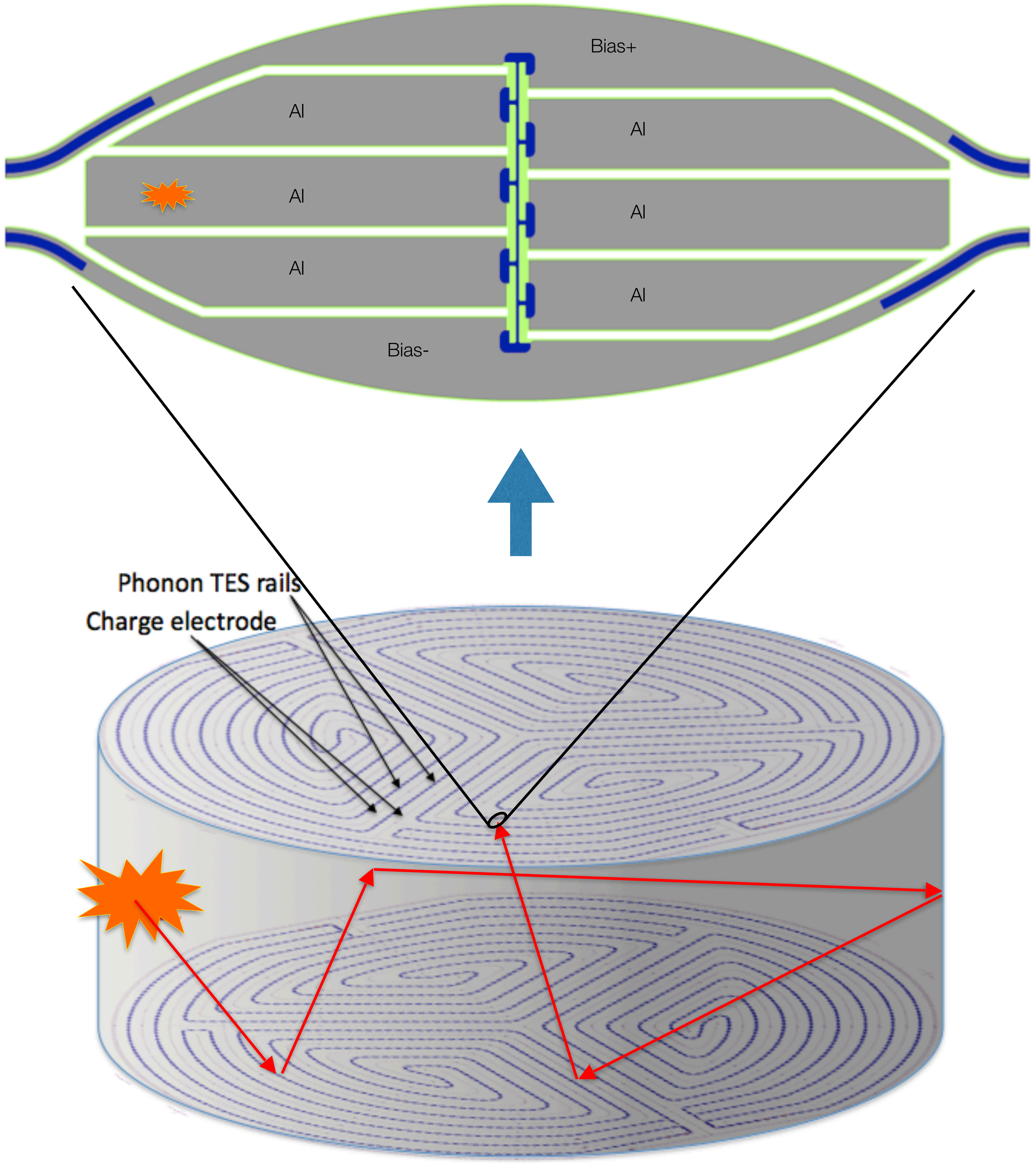


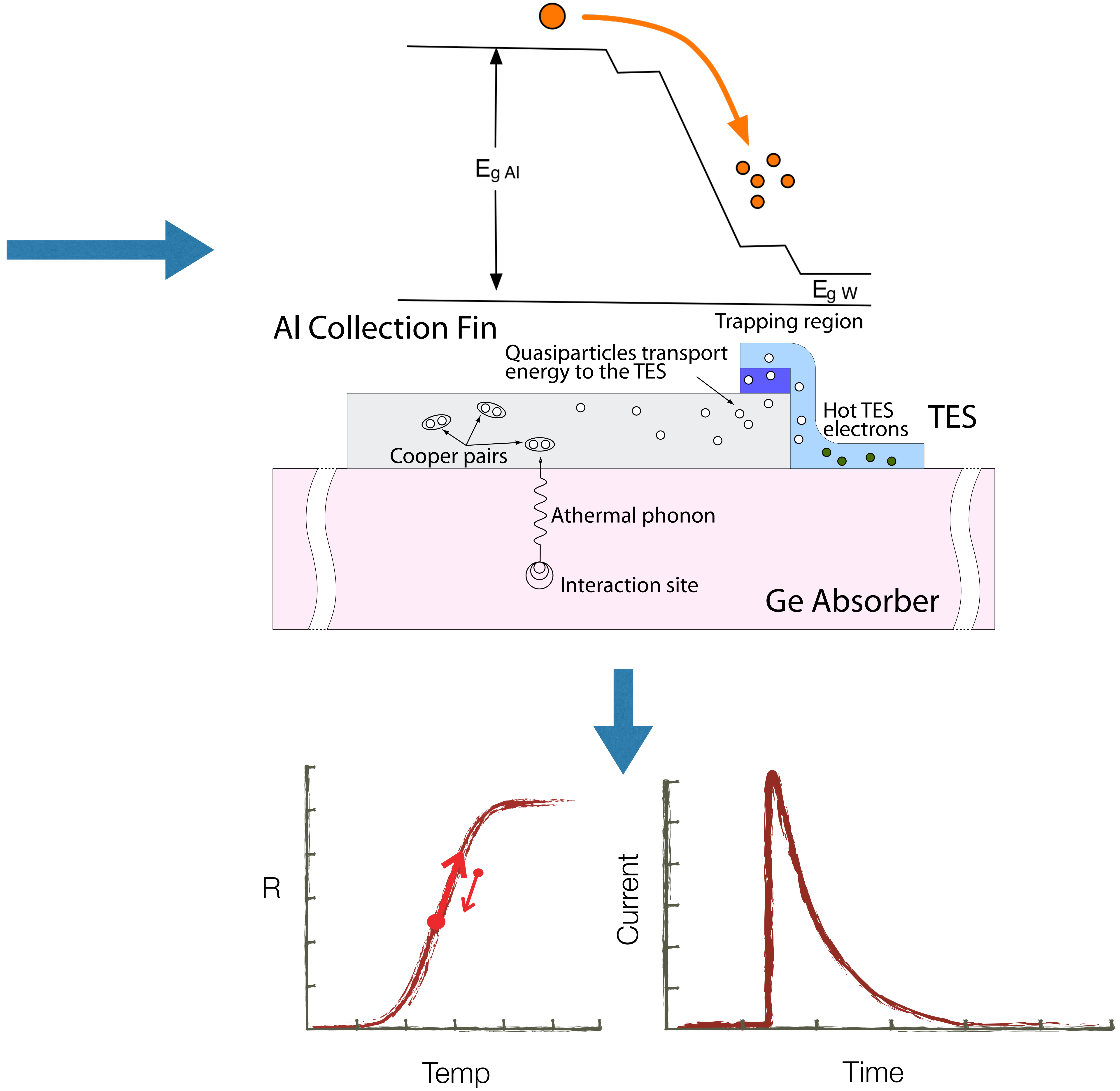




- Then we add the LW in a second step

# SuperCDMS Signal Readout



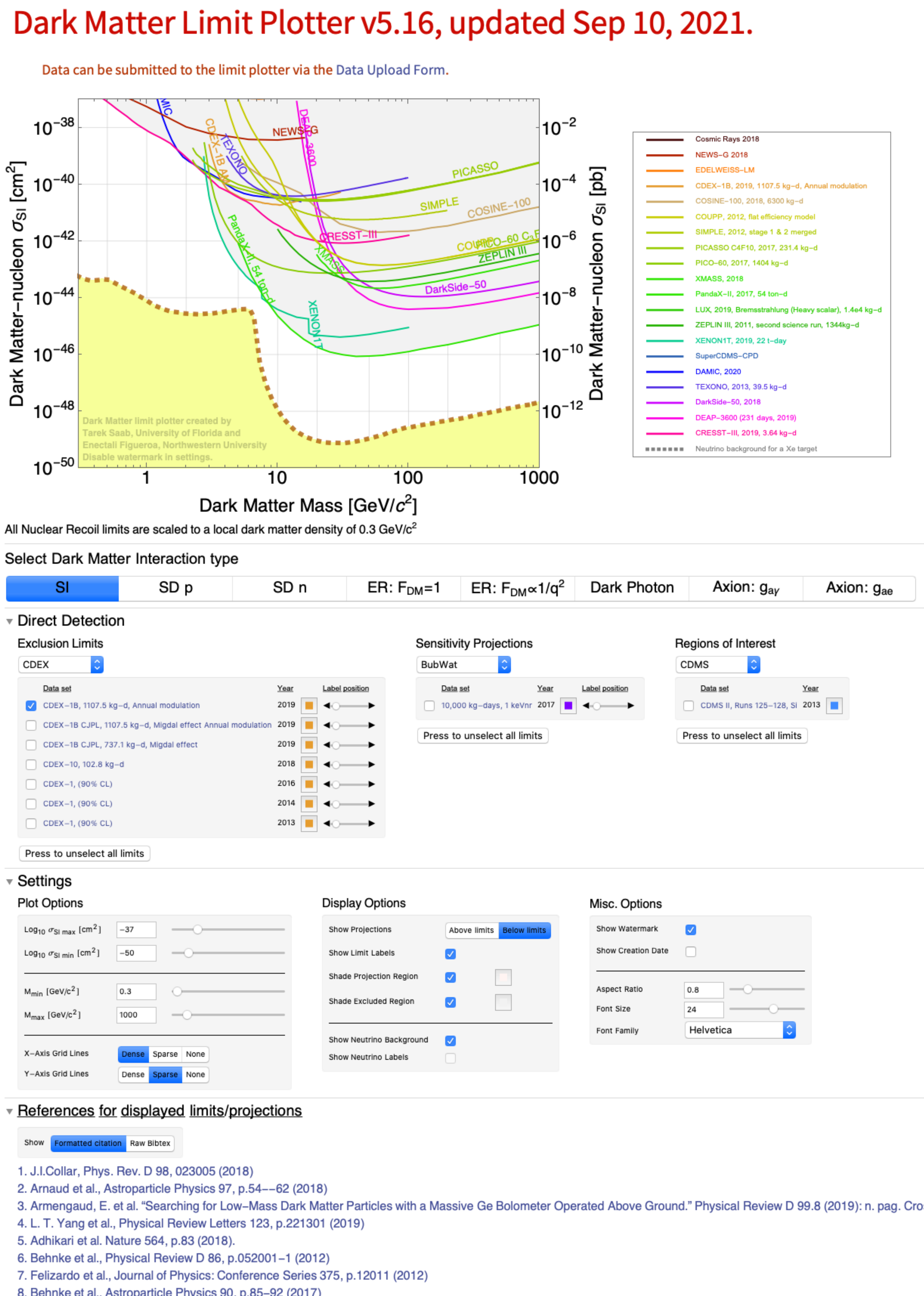



# Rapidly Growing Catalog of Limits and Projections

- Central repository for cataloging data & references, and plotting dark matter limits
    - Includes limits from several “Dark Matter” channels, i.e. **Nuclear recoil**, **Electron recoil**, **Dark Photon** and **Axion** interactions

- Downloadable, runs locally*
    - https://supercdms.slac.stanford.edu/dark-matter-limit-plotter

- Submissions welcome from all experiments
    - https://ufl.qualtrics.com/jfe/form/SV_9KVMNlMhbVg0cPb




*you can even run it on your iPad if you are so inclined, but I don’t recommend it

# The SuperCDMS Dilution Refrigerator