SUPER
CDMS
Cryogenic Dark Matter Search

SuperCDMS SNOLAB Status and Prospects

Lake Louise Winter Institute
February 22, 2022
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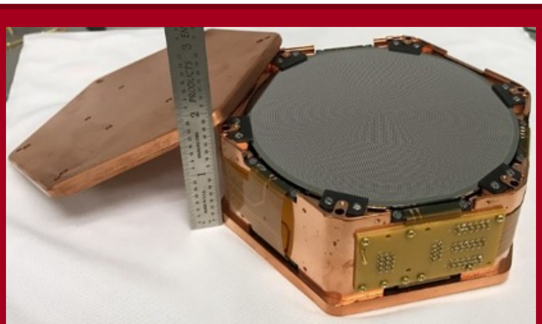
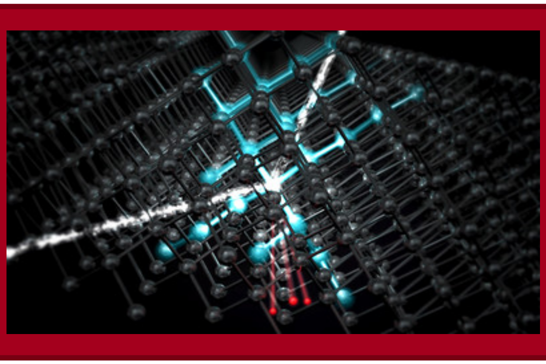
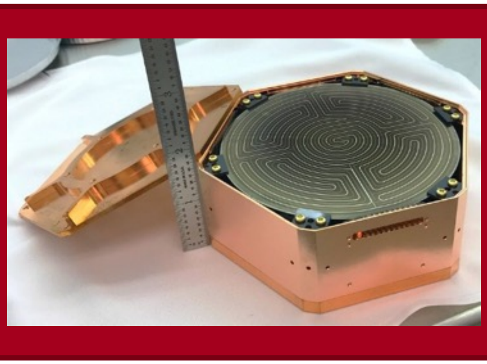
University of Minnesota

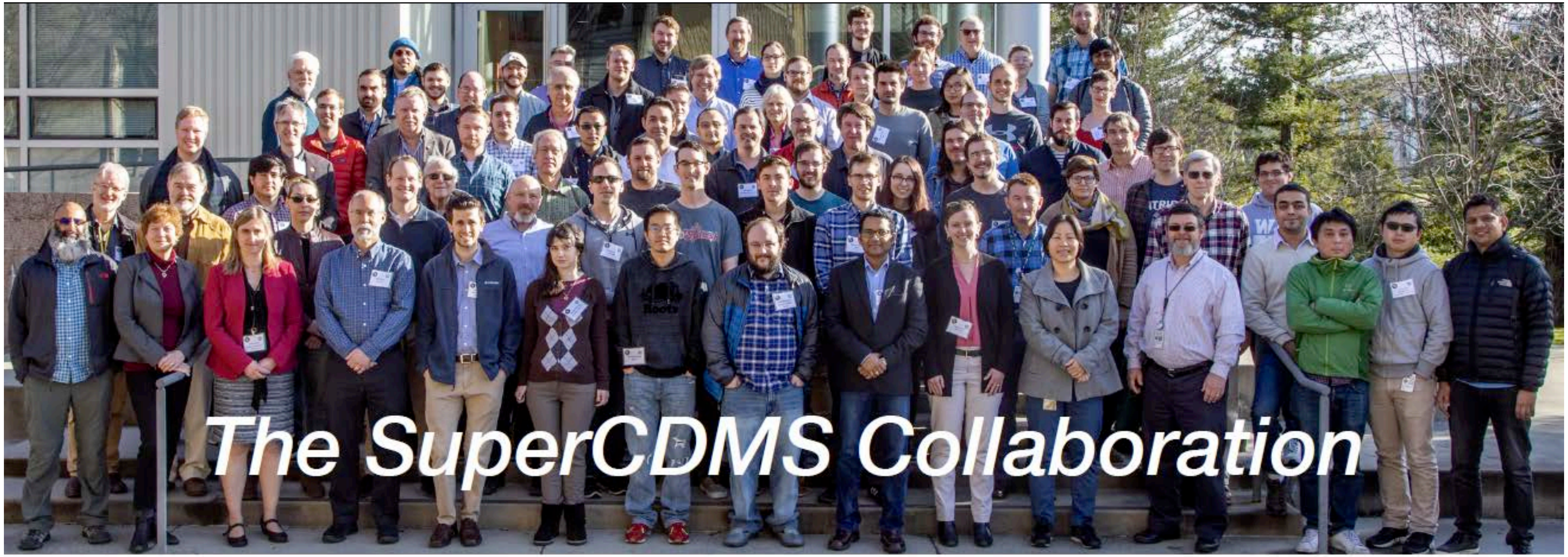




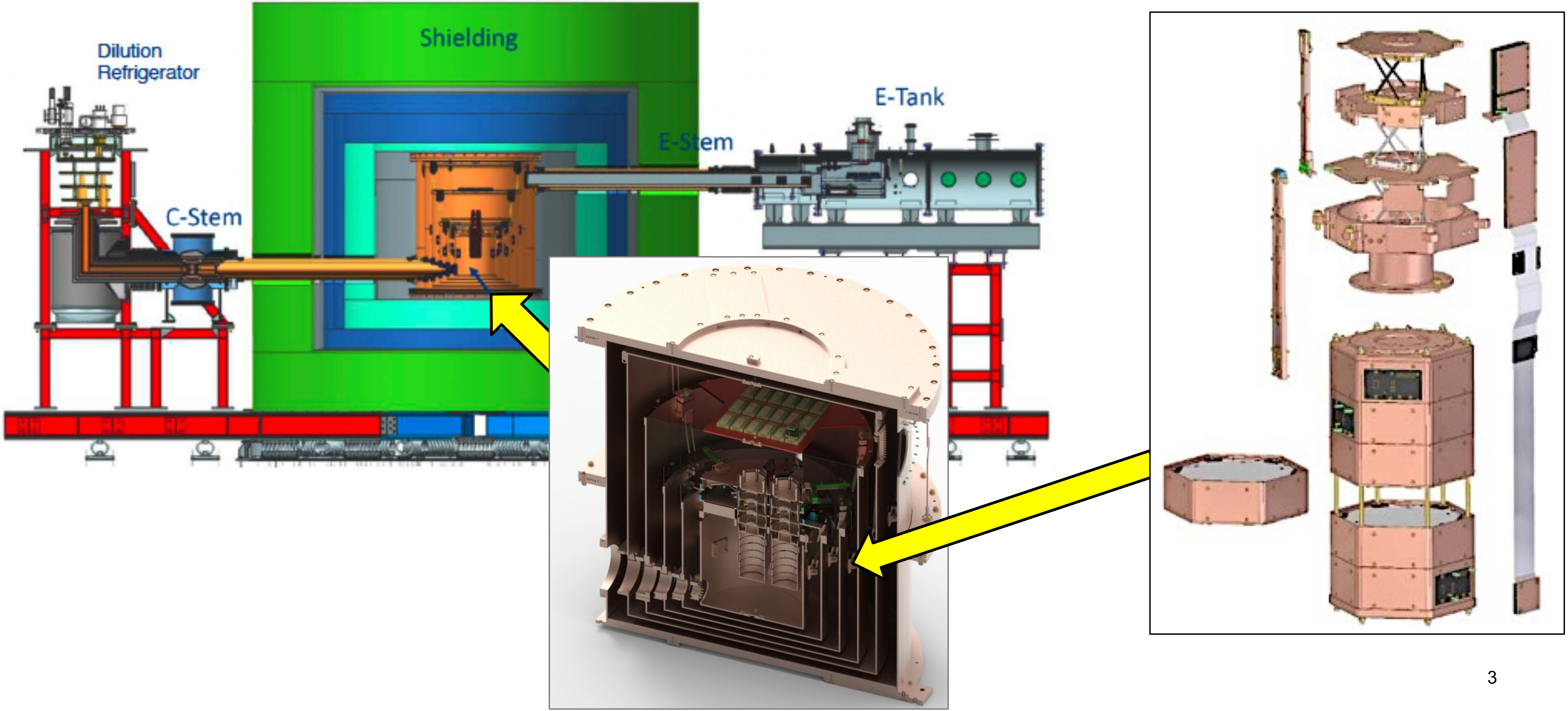


The SuperCDMS Collaboration

~100 scientists at 27 institutions including 3 US national labs and 2 Canadian labs

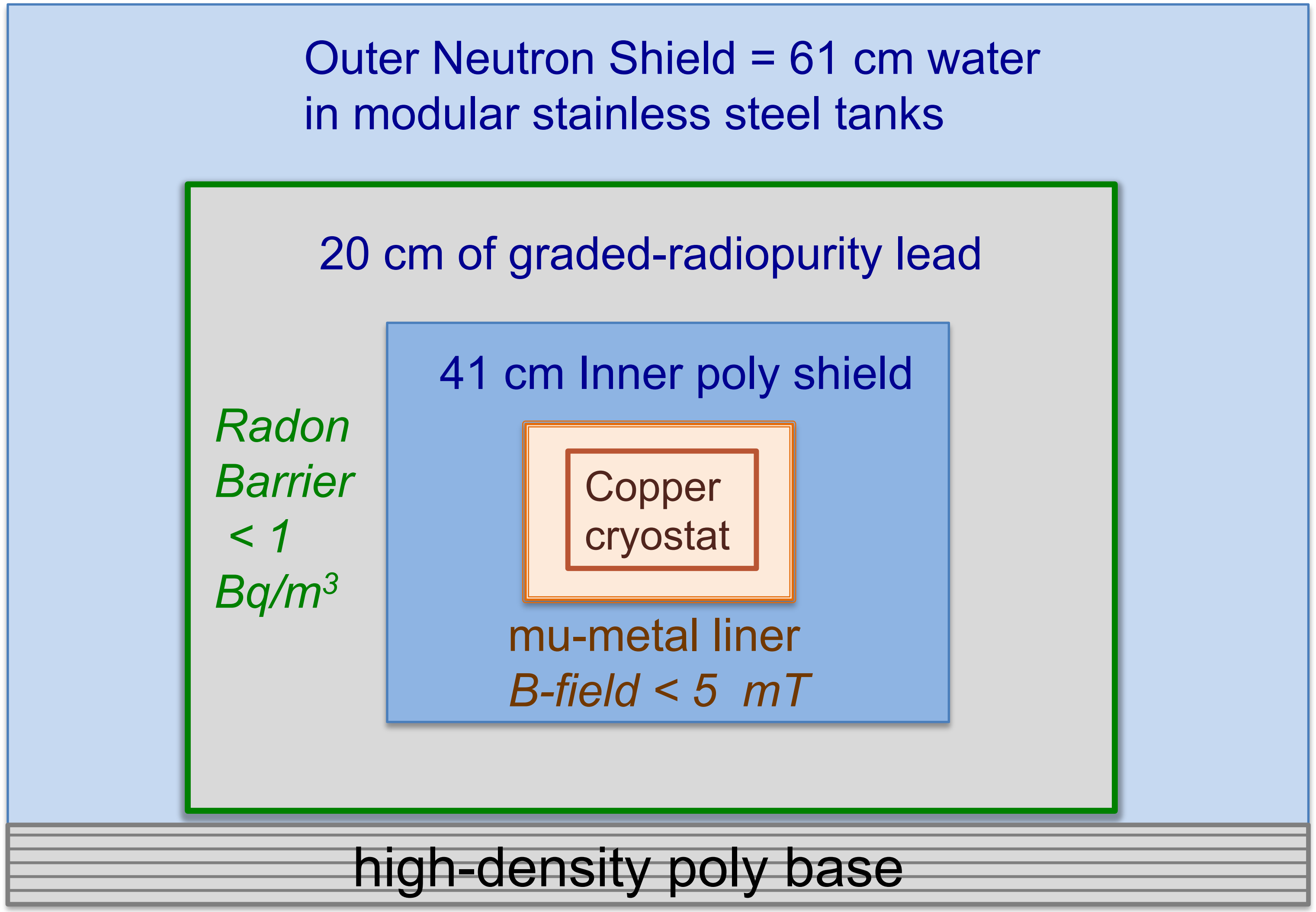


Layered approach to creating ultra low-background, 15 mK environment



Low-background lead/poly shield was out-sourced to Lemer Pax

At SNOLAB depths, there is no need for a muon veto.



Outer Neutron Shield = 61 cm water
in modular stainless steel tanks

20 cm of graded-radiopurity lead

Radon Barrier < 1 Bq/m^3

41 cm Inner poly shield

Copper cryostat

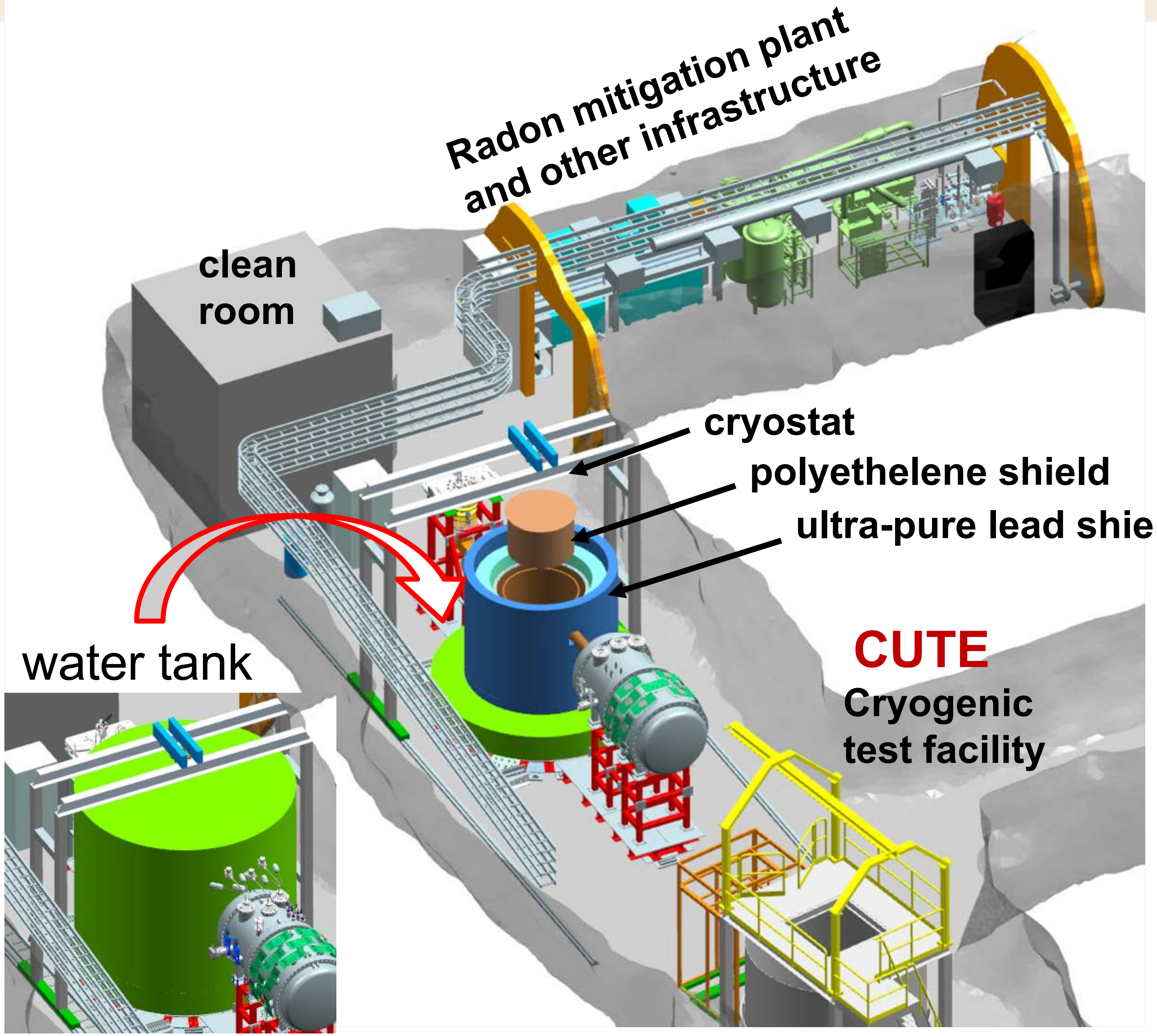
mu-metal liner
B-field < 5 mT

high-density poly base

Preassembled at Nantes Factory
Archaeological lead cast in assayed crucibles
All materials assayed by ICPMS and HPGe

Inner 1 cm of Pb: 0.08 Bq/kg ^{210}Pb, < 0.4 mBq/kg U/Th/K

SuperCDMS Experiment in SNOLAB



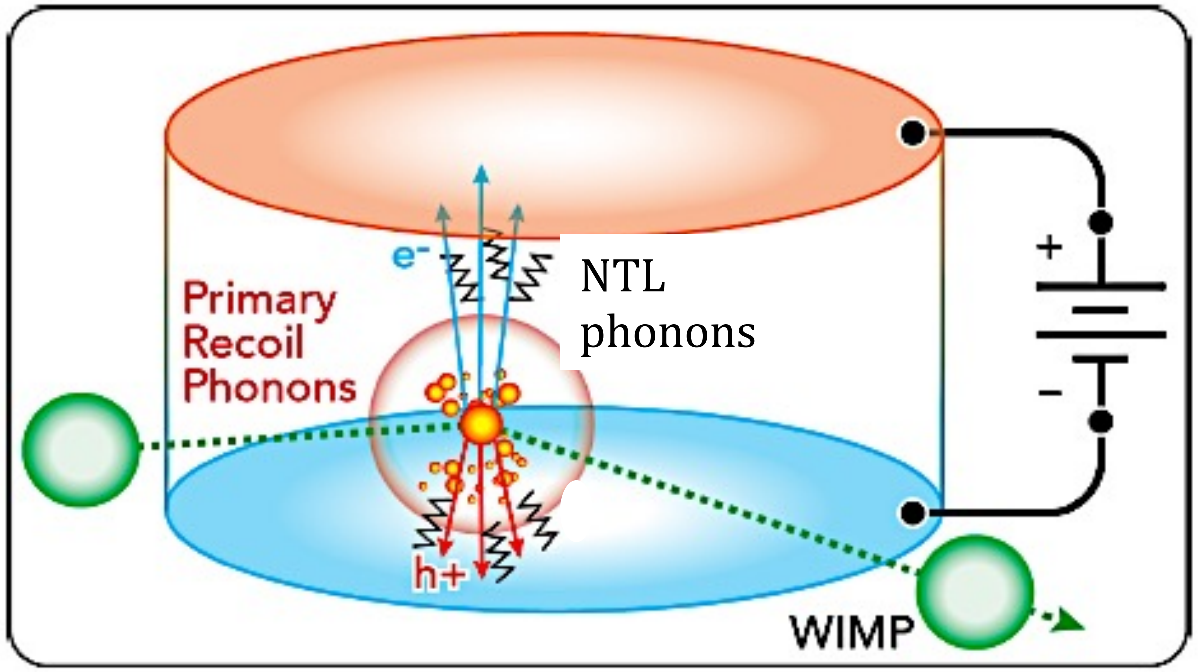
Infrastructure in place, Shield stored underground
CUTE is running now w/ small next-gen detectors

Towers 1 + 2 arrive this June
Towers 3 + 4 arrive this Sept
Early physics in CUTE

Fridge test at FNAL successful
Cryo and shield assembly this year

Anticipate all detectors cold and running
in SuperCDMS cryostat by Fall 2023.

Very Sensitive Detectors



Our signature technology

Athermal phonon sensors at cryogenic temperatures.

Transition Edge Sensors read out by SQUIDs

$$E_{tot} = E_r + N_{eh}\, e\, V_b = E_r \left(1 + \frac{Y(E_r)\, e\, V_b}{\varepsilon}\right)$$

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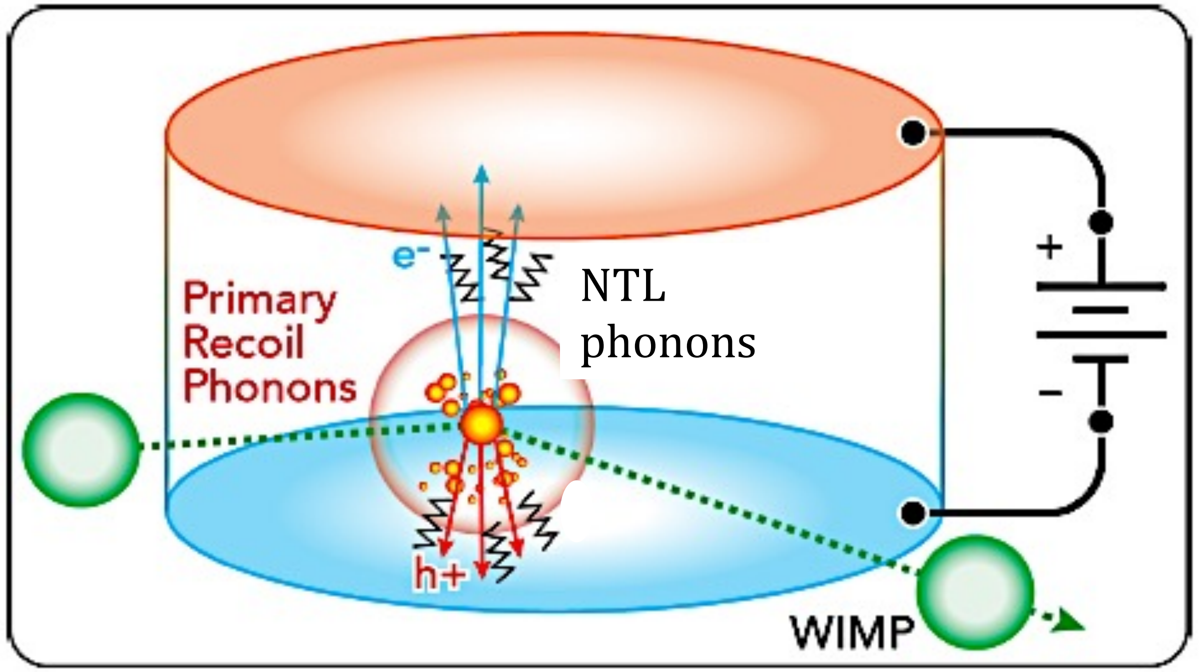

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Two different modes of operation

iZIP: Low bias voltage (~ 4 V) the original background-free mode ➔ NTL phonons negligible

Ratio of ionization to primary phonon signal is unambiguous

Interleaved phonon and charge sensors on both sides

Provides 10^6 ER/NR discrimination and surface rejection

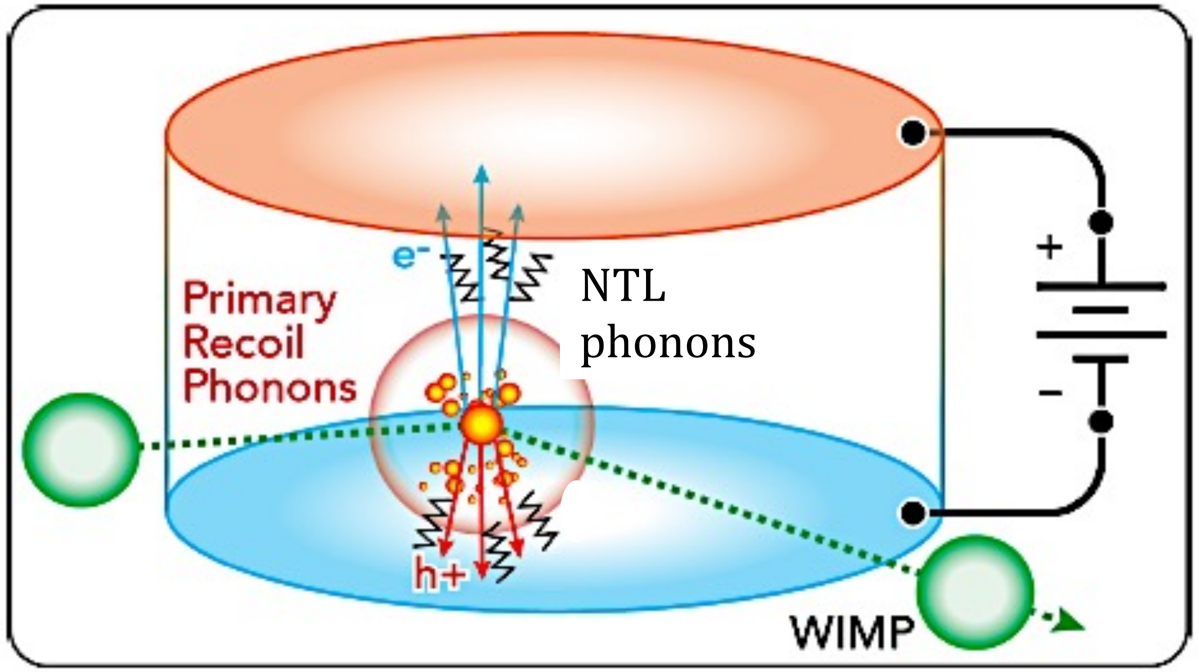
HV: High bias voltage (~ 100 V) push to lower thresholds ➔ NTL phonons dominate.

$$E_{tot} \sim E_r \frac{Y(E_r)\, e\, V_b}{\varepsilon}$$

The total phonon signal is larger (amplification means lower thresholds),

but it is essentially a measure of the charge signal read out through the phonon channel

This will be important later: **Yield** is ~ 0.3 for recoil energies 20-100 keV, but it is energy dependent and not well known at lower energies.



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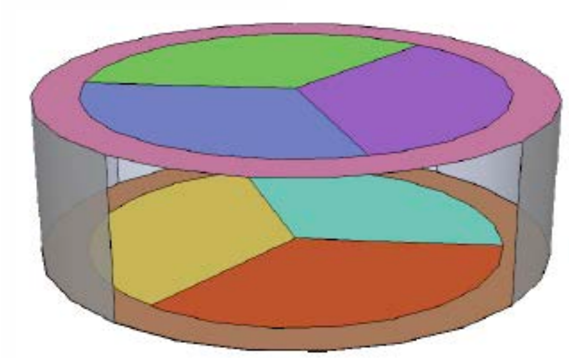
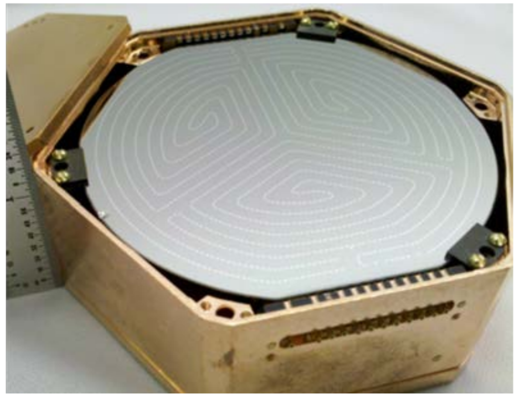
Lots of experience with this technology

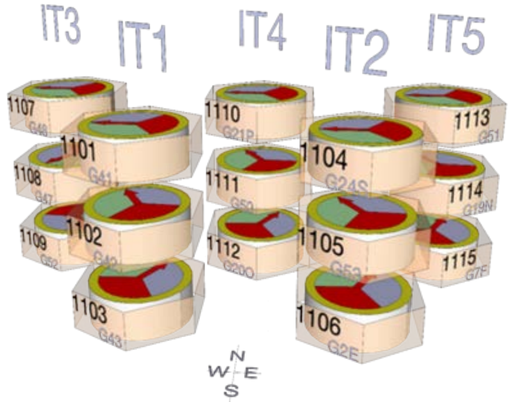
SuperCDMS Soudan Detectors

Ge iZIP (0.6 kg)
7.6 cm diameter and 2.5 cm thick





CDMS Low Ionization Threshold Experiment

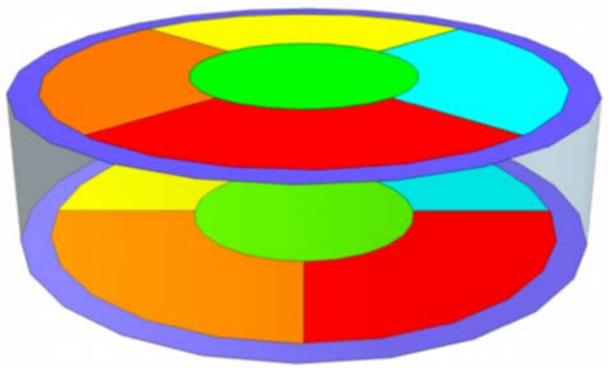


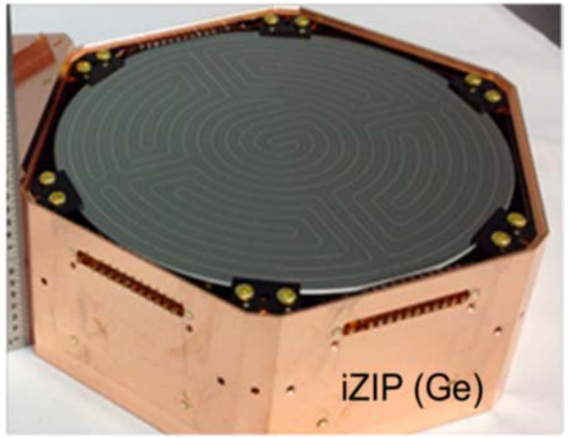
CDMSlite
Running two iZIPs in
HV mode (60-75V)

New SuperCDMS SNOLAB Detectors

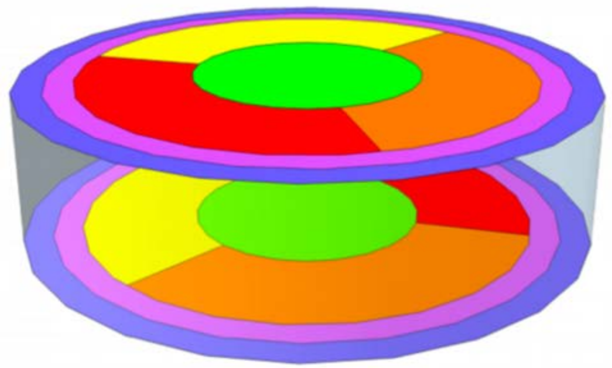
Two target materials Ge (1.4 kg) and Si (0.6 kg)
10 cm diameter and 3.3 cm thick

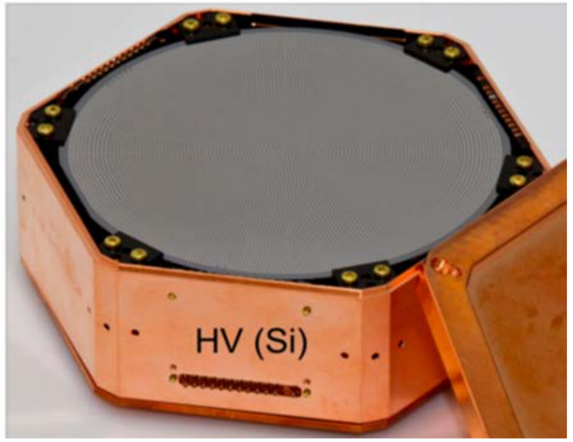
***iZIP* detector**



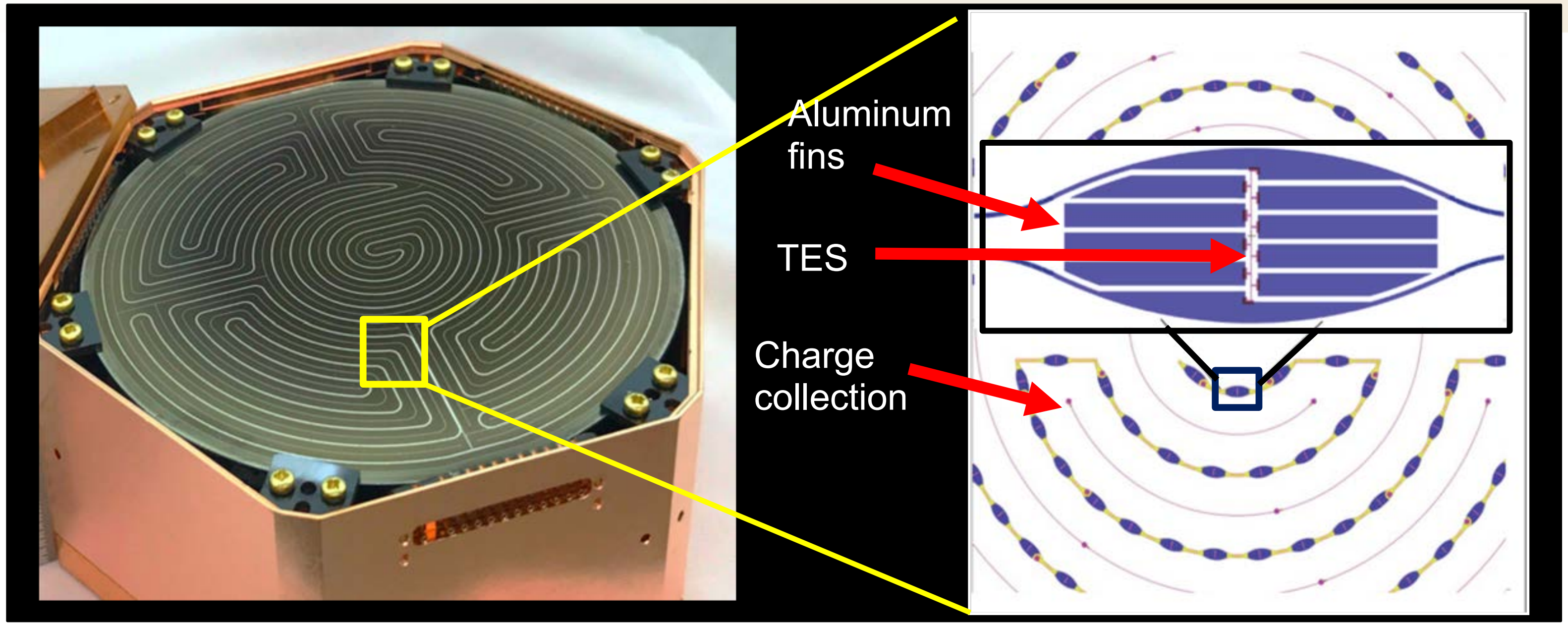


***HV* detector**



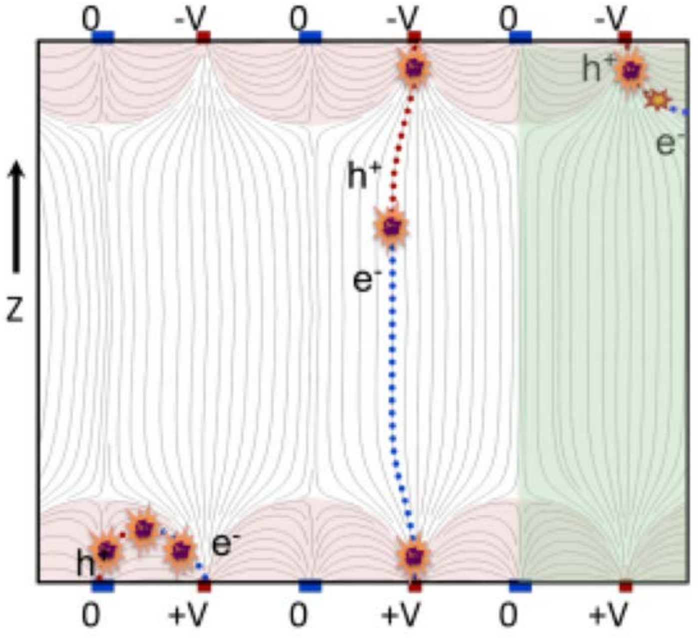


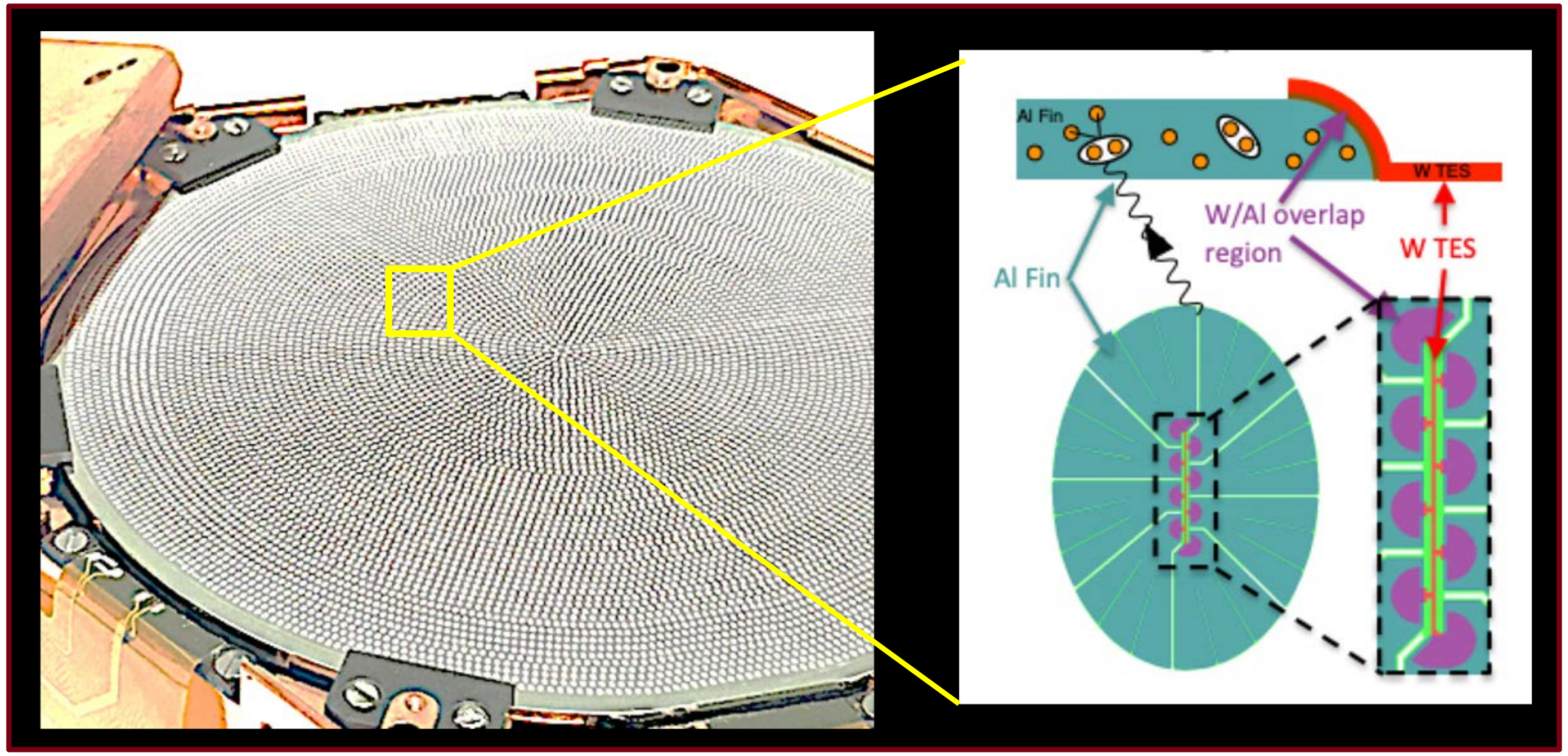
TES and collection fin design follows function



iZIP

Double-sided readout with E-field-shaping provides z-dependence and surface rejection





HV

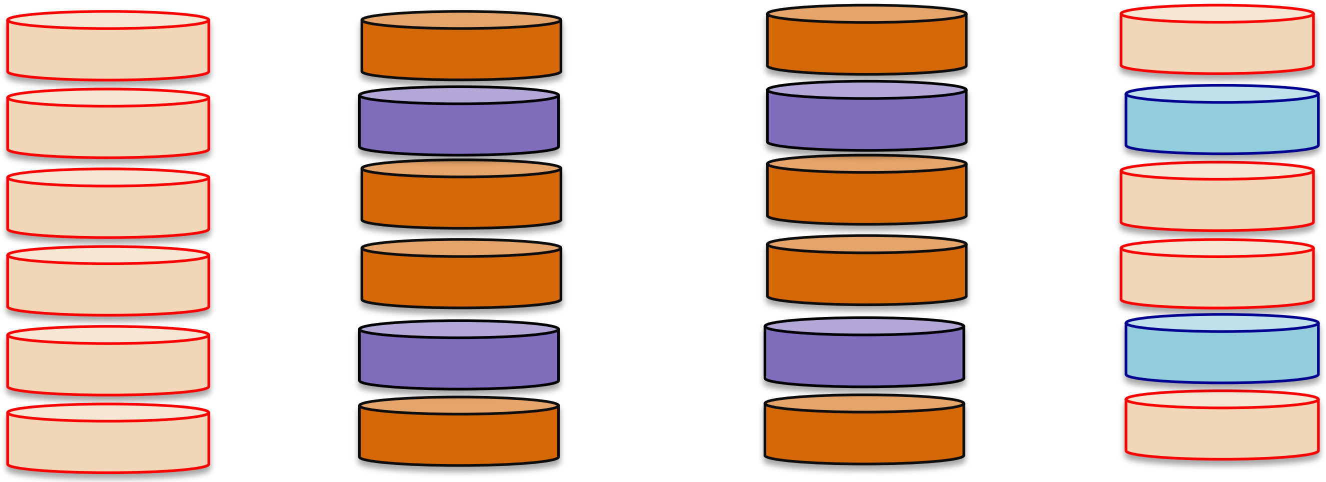
No charge readout required.

Optimized for phonon energy resolution and collection efficiency (35% coverage)

Improved position resolution and double outer ring to sharpen fiducial cut.

Strategy: Complementary Targets and Multiple Functionality

	Germanium	Silicon
HV	Lowest threshold for low mass DM Larger exposure, no ^{32}Si bkgd	Lowest threshold for low mass DM Sensitive to lowest DM masses
iZIP	Nuclear Recoil Discrimination Understand Ge Backgrounds	Nuclear Recoil Discrimination Understand Si Backgrounds

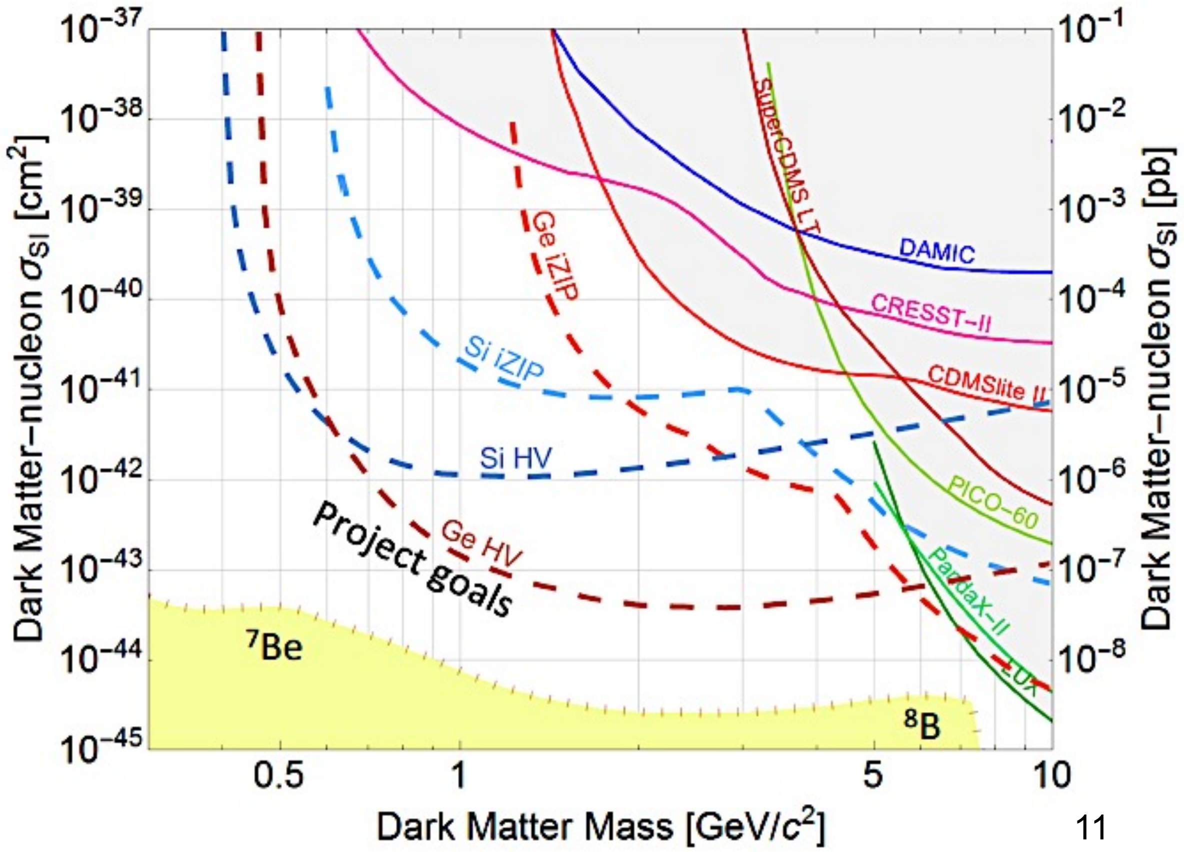


Tower 1 (iZIP)

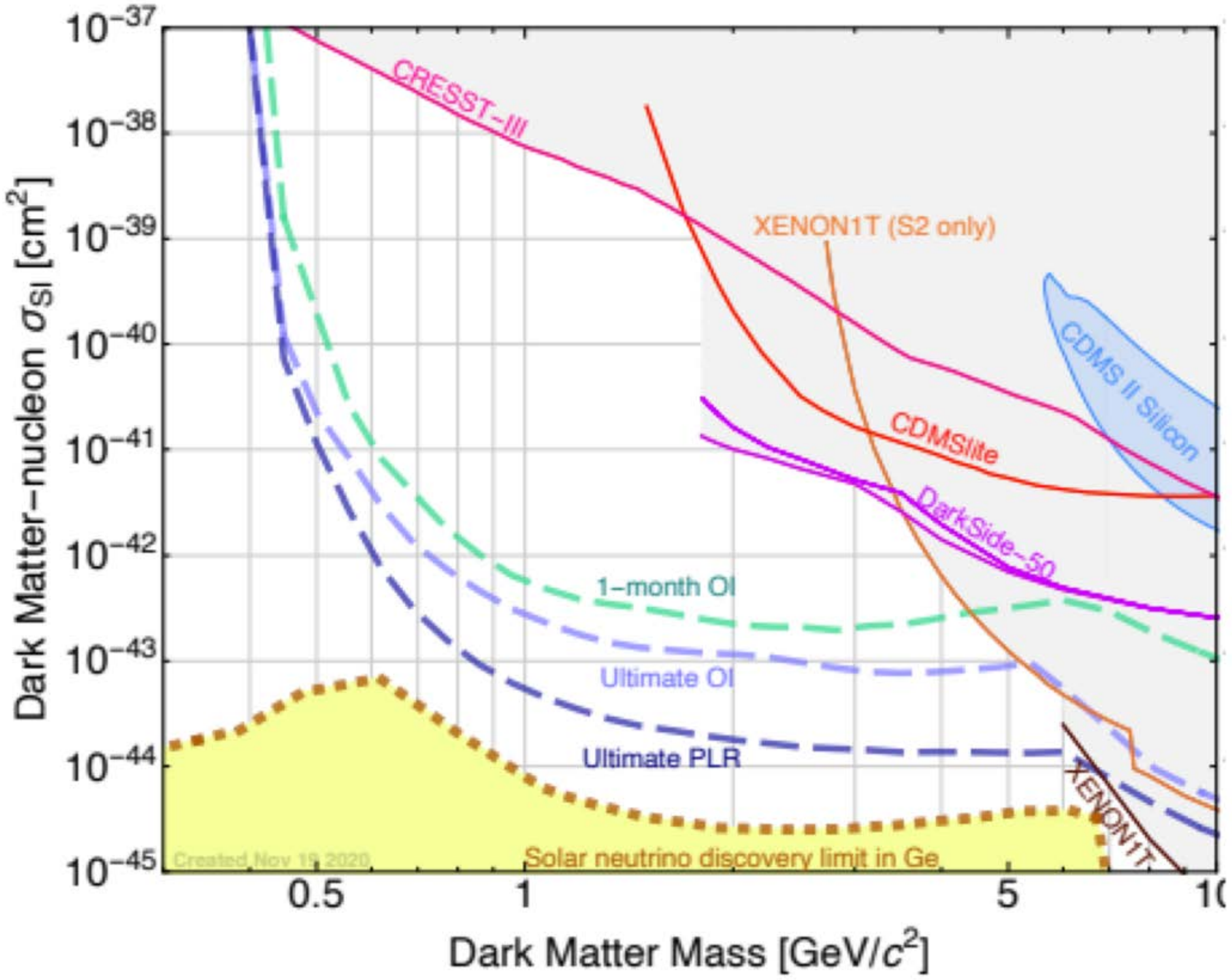
Tower 2 (HV)

Tower 3 (HV)

Tower 4 (iZIP)



Profile Likelihood extends reach beyond Project goals



Plot assumes 4 years of livetime at 80% yield

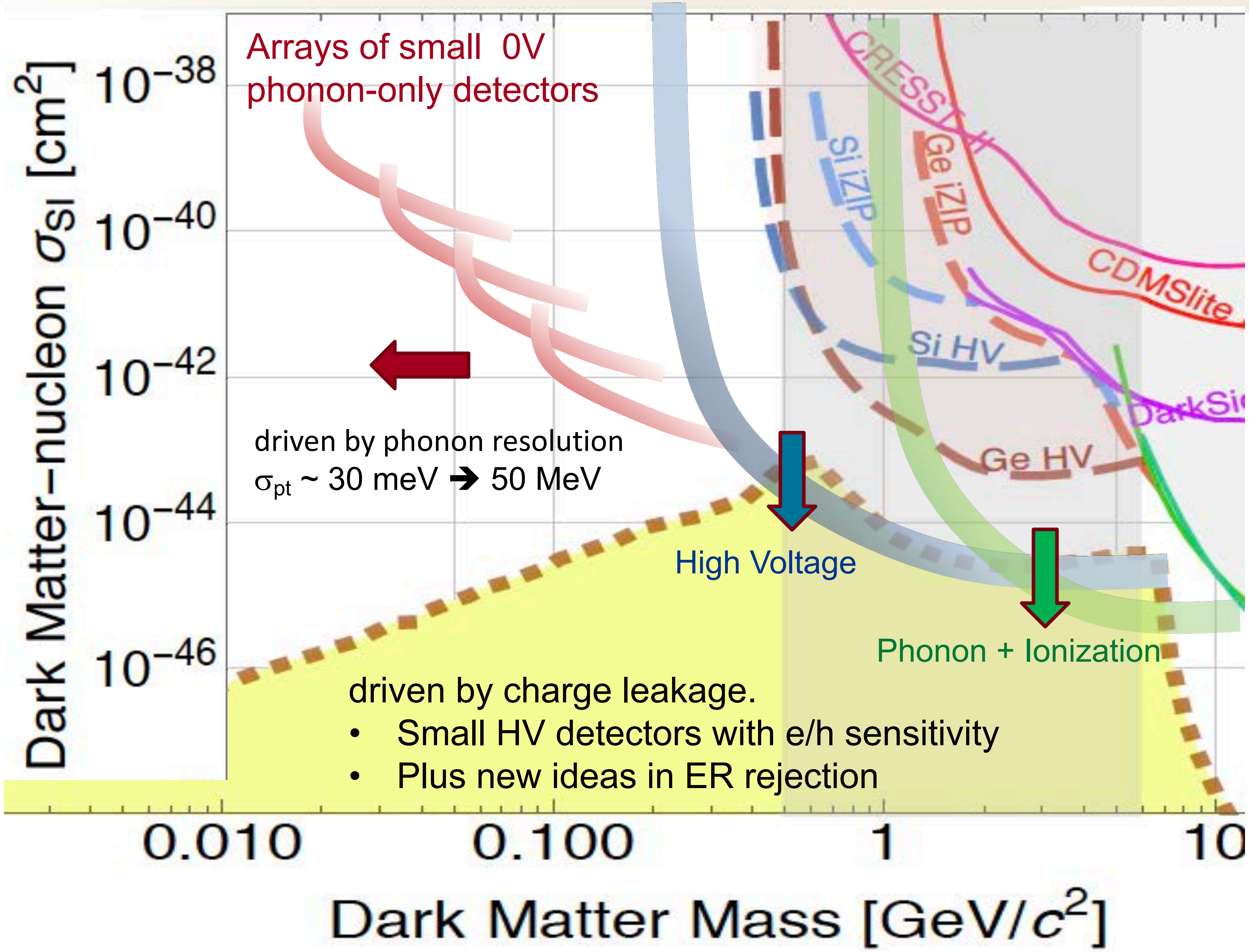
Project Goals assume Optimum Interval Method Limits assuming no prior knowledge of backgrounds

HV will be bkgd limited within 2 years
so we get close to OI goals with 1 month exposure.

To reach full potential,
We will perform a profile likelihood analysis (PLR).

The ER/NR discrimination of the iZIPs in Run 1 provides detailed data we need to include backgrounds in the PLR

Pushing even deeper into the nucleon-coupled DM landscape



Arrays of small 0V phonon-only detectors

driven by phonon resolution
σ_{pt} ~ 30 meV ➔ 50 MeV

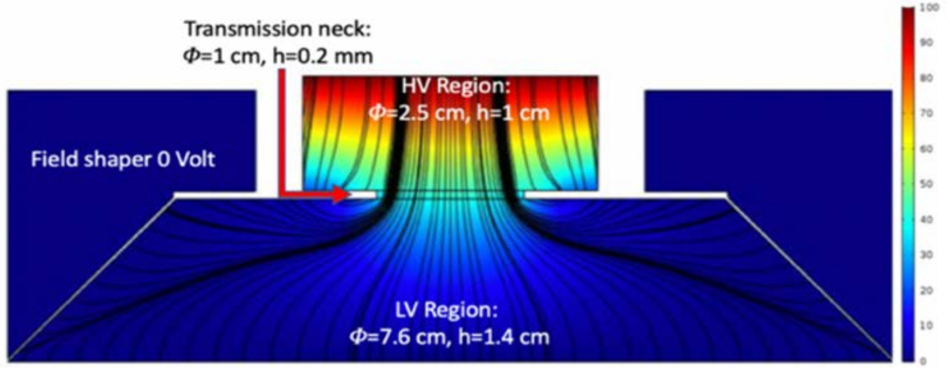
High Voltage

Phonon + Ionization

driven by charge leakage.
- Small HV detectors with e/h sensitivity
- Plus new ideas in ER rejection

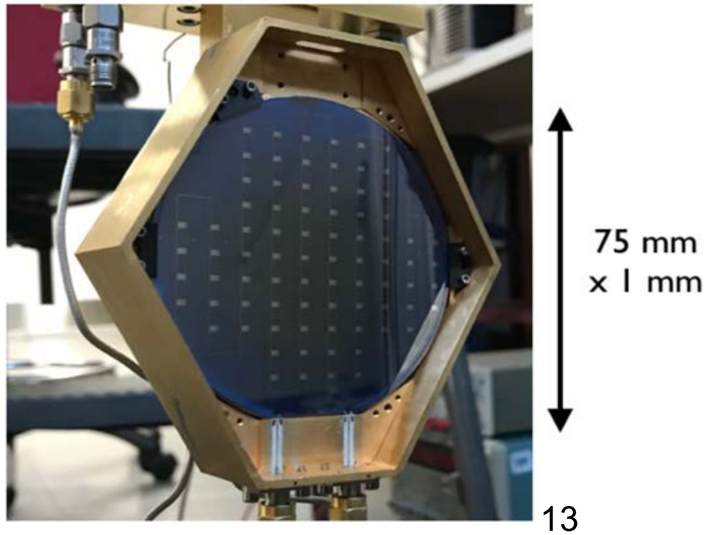
New Ideas in ER rejection

Hybrid Detector



phonon-only iZIP (piZIP)

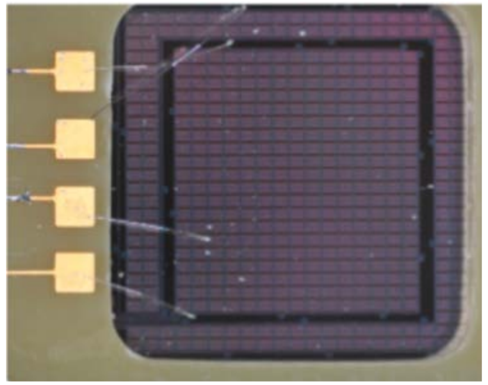
NR/ER discr. down to O(100) MeV!



We are already running the small 0 V and single eh-sensitive HV detectors

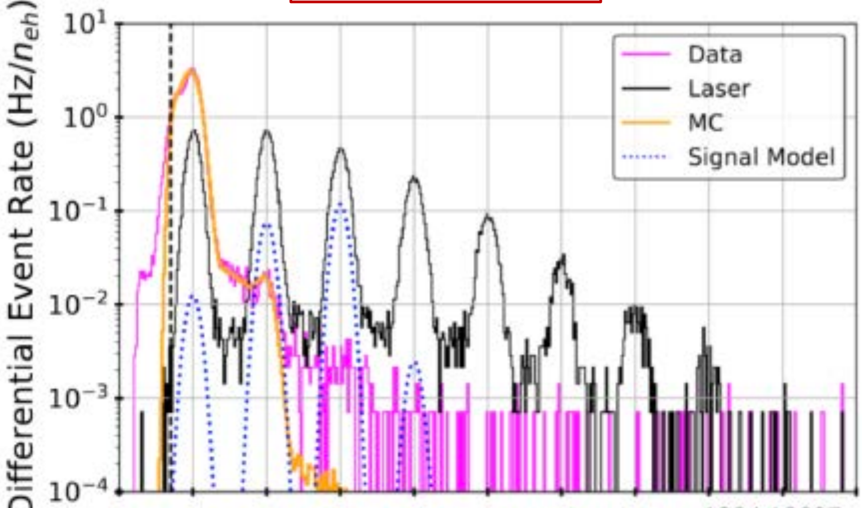
HVeV (Si or Ge, 1 x 1 cm^2 x 4 mm). 2 equal area QET sensors

R. Agnese *et al.* Phys. Rev. Lett. **121**, 051301 (2018)



- Study charge transport in Si and Ge, minimize charge leakage
- Improve phonon resolution, study single e-h devices
- Physics runs in NEXUS (FNAL) and CUTE ongoing
- Used in the TUNL ionization yield measurements.

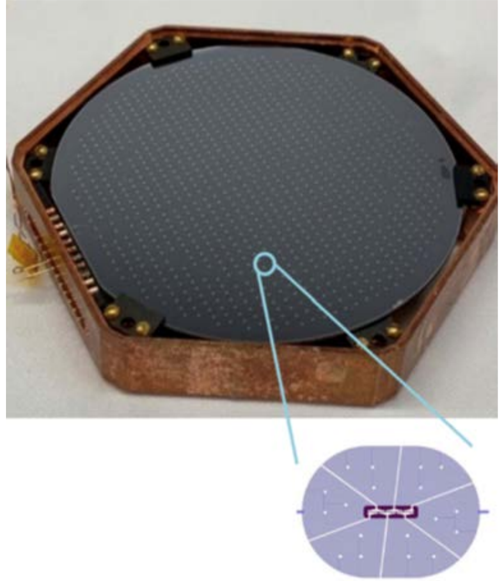
V_{bias} = 160 V



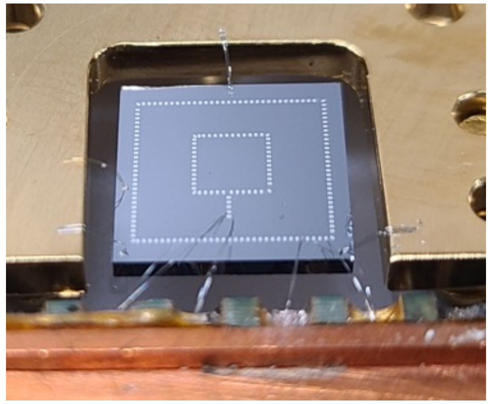
1804.10697

A mosaic of these on 2 SuperCDMS towers can get us to the ν-fog in 0.5 – 5 GeV range

0V, CPD (cryogenic photon detector) 1 mm thick (45.6 cm^2) Si wafer with CDMS phonon readout



- Study phonon resolution and test facility noise performance
  especially "environmental" sub-keV phonon-only backgrounds
- Phonon resolution in the $\sigma_{pt} \sim 1$ eV range now.
- New prototype (with new hanging support) may have σ_{pt} ~ 50 - 100 meV



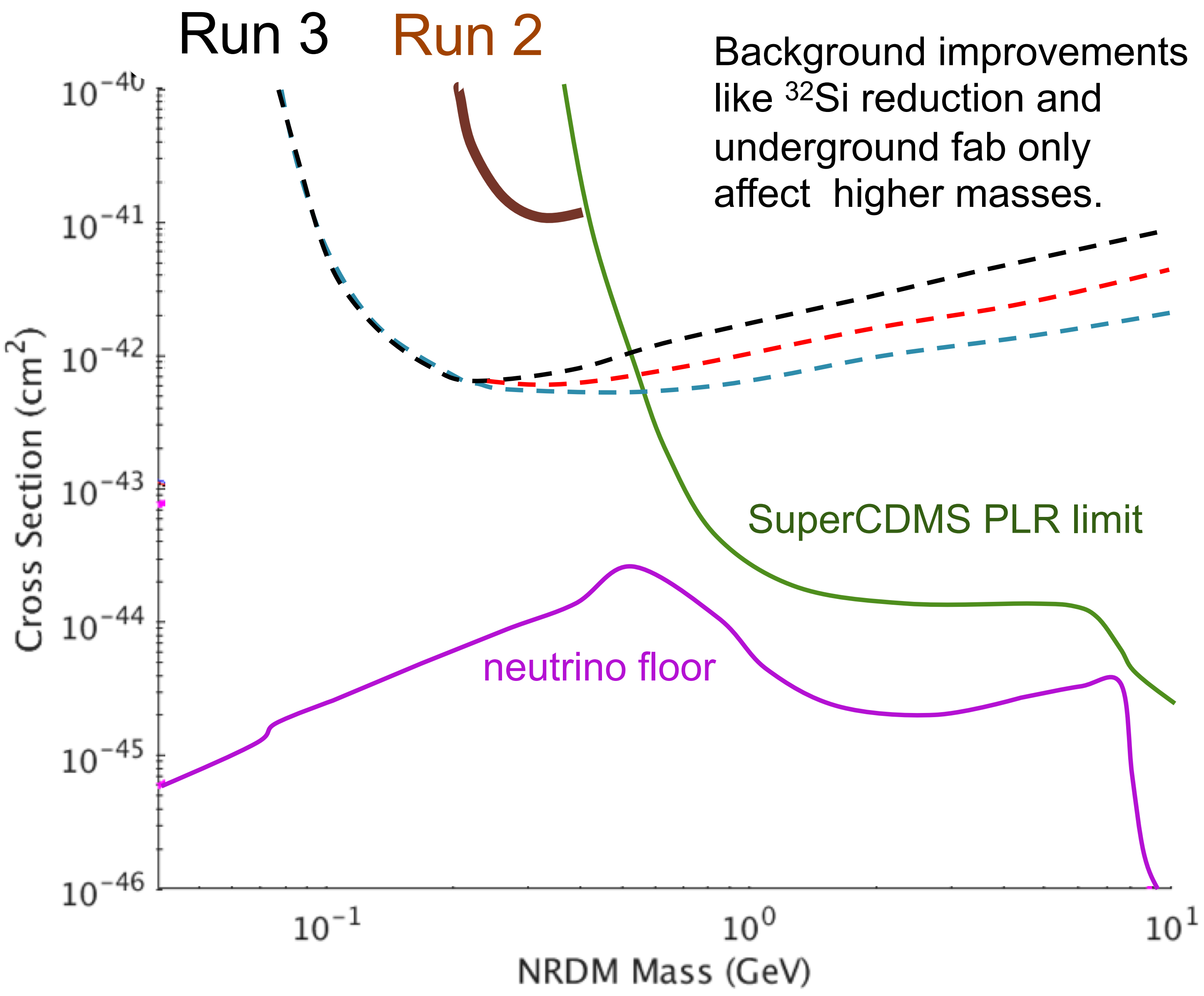
A mosaic of the current CPDs on 2 SuperCDMS towers can get us to DM masses of 100 MeV now and down to 50 MeV if the new prototype has sub-eV resolution

An example of an upgrade strategy in parallel with Project

CPD upgrade path

- Install one detector housing of 6 CPD for **Run 2**
  - *~ 1/12 of mass => x 10 higher limit*
- If successful, build 2 towers of CPD
  - CPD detectors are cheap!
  - Build new low-bkgd tower structures in parallel with running experiment
- Install CPD towers for **Run 3**
  - *144 channels for a 4 yr run*

- Still have another tower for the HVeV mosaic.

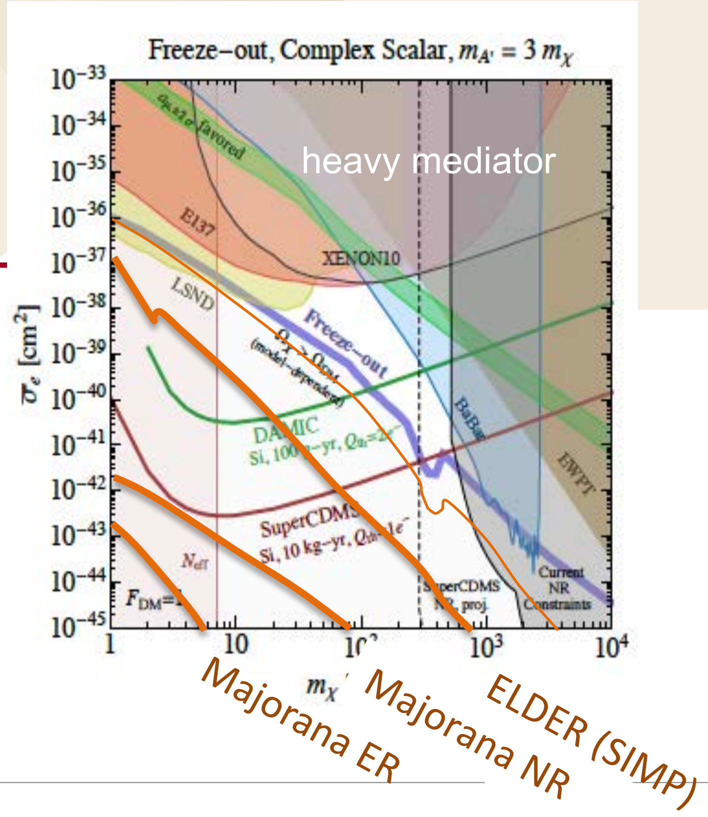


Background improvements like ^{32}Si reduction and underground fab only affect higher masses.

Explore Light DM, Dark Photon and Axion-like DM

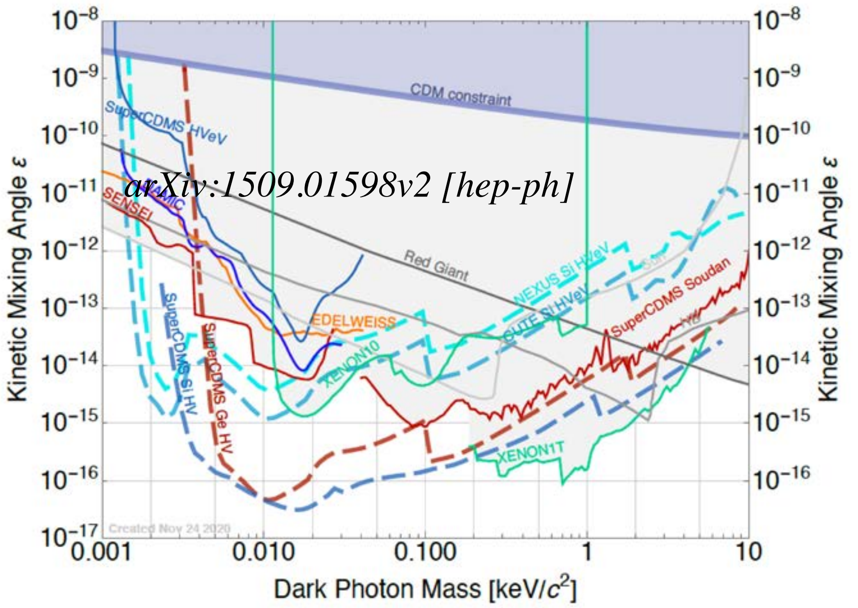
Improving reach for this science requires sensitivity to
1–100 eV deposited energy,
enabled by small bandgaps ~1 eV
and excellent energy resolution.

Achieved with SNOLAB HV and 0V, phonon-only detectors



Dark photon and axion-like dark matter in the 1-100 eV range

- Improvements in leakage and resolution drives these limits.
  - 100 times better reach in kinetic-mixing parameter ϵ
  - 1000 times better reach in g_{ae}.



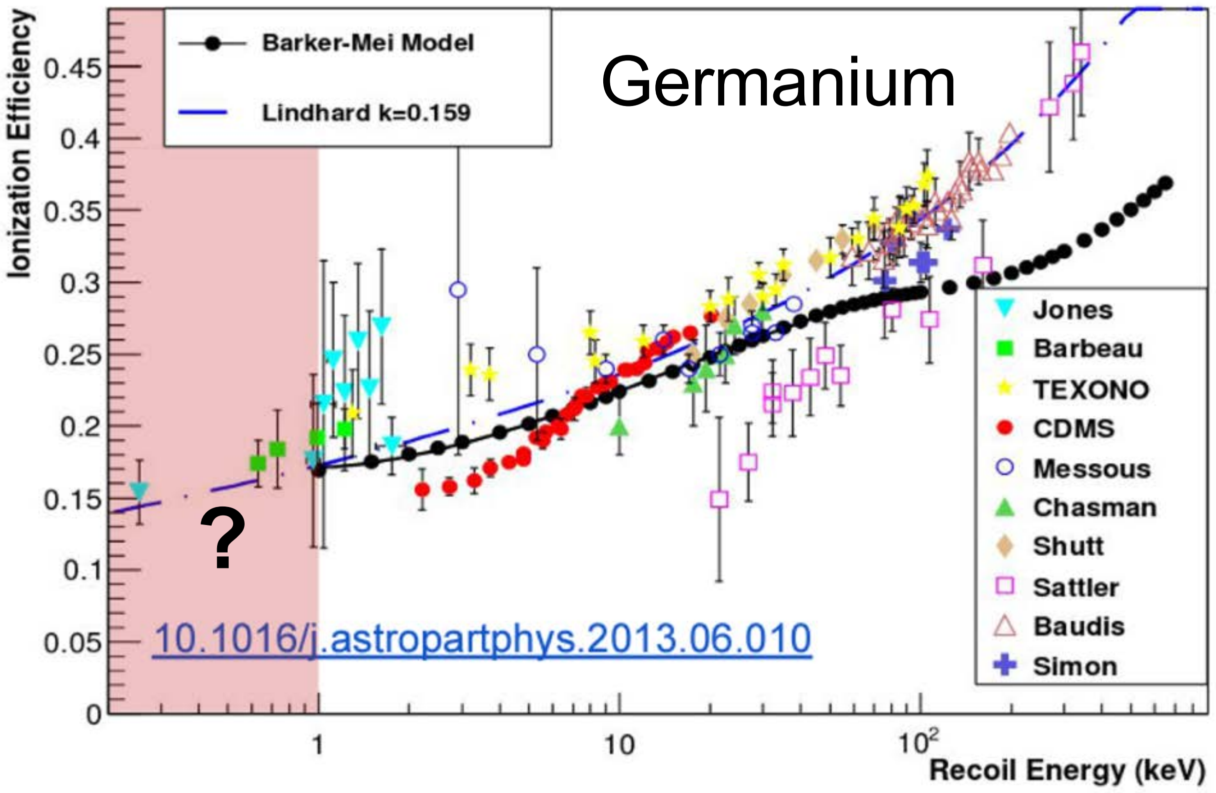
arXiv:1509.01598v2 [hep-ph]

Light DM in the 1-100 MeV range

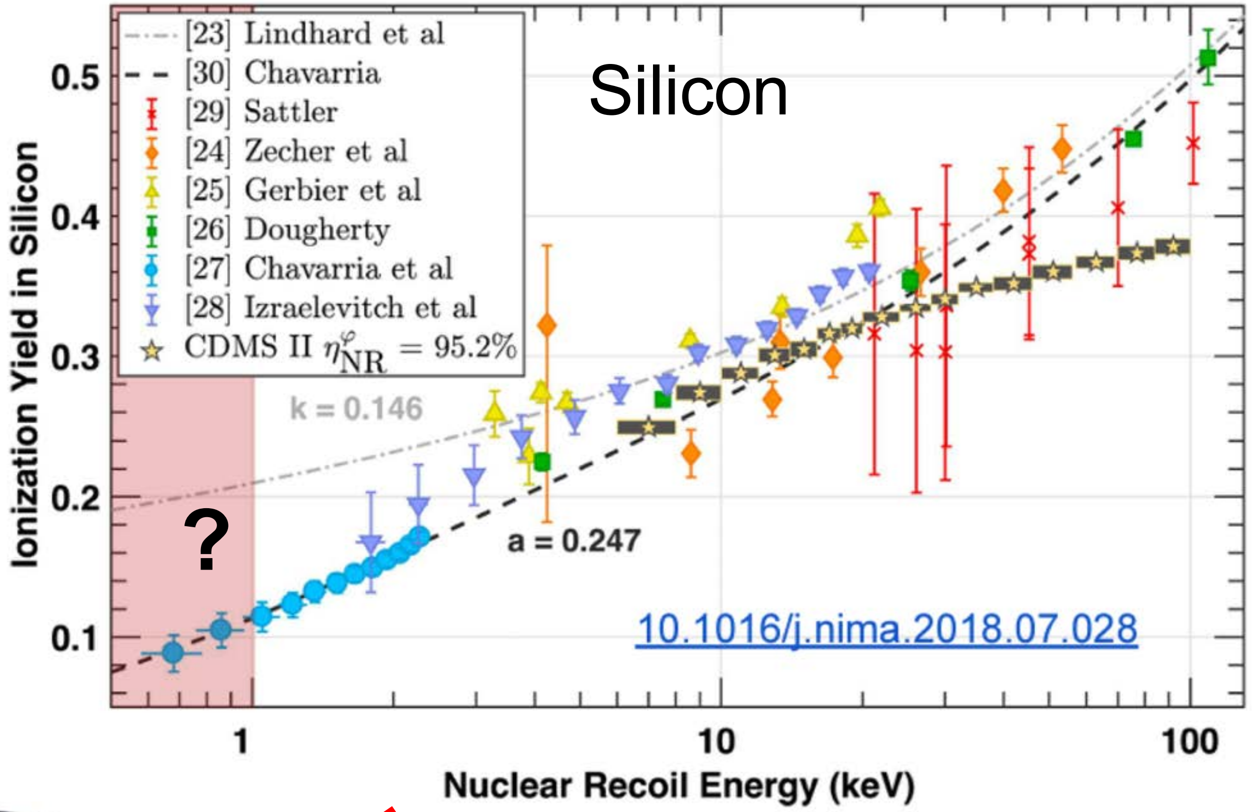
- Extend cross section by 4 - 5 orders of magnitude.

Stay tuned: Coming next month
Snowmass White Paper
will have all the new projections

Understanding the Nuclear Recoil Scale at lower energies

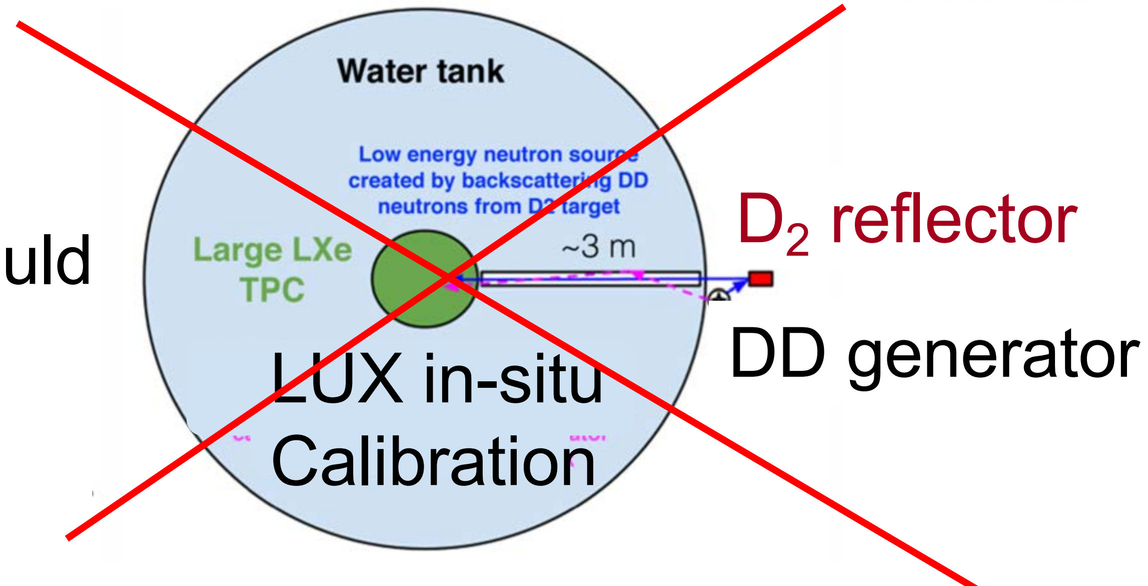


10.1016/j.astropartphys.2013.06.010



10.1016/j.nima.2018.07.028

LUX-style in-situ neutron scattering would compromise our shield and cryostat



Understanding the Nuclear Recoil Scale at lower energies

Neutron beam at the TUNL facility

- Used a “portable” ADR fridge and a Silicon HVeV
- Next campaign in 2022 with a Germanium HVeV

DD generator at NEXUS underground (~300 mwe) FNAL NUMI hall

- Compare HVeV with full-scale SuperCDMS detectors
- Use the NEXUS fridge and backing arrray

Photo-neutron Source: (^{88}Y or ^{124}Sb) gammas on ^{9}Be

- Soudan Underground Lab, iZIP run in CDMSlite mode

Developing new neutron capture technique

- SNOLAB HVs (Ge and Si) in UMN cryo lab, exposed to PuBe source of thermal neutrons

IMPACT

Ionization Measurement with Phonons at Cryogenic Temperatures

Measure $Y(E_r)$ in Silicon

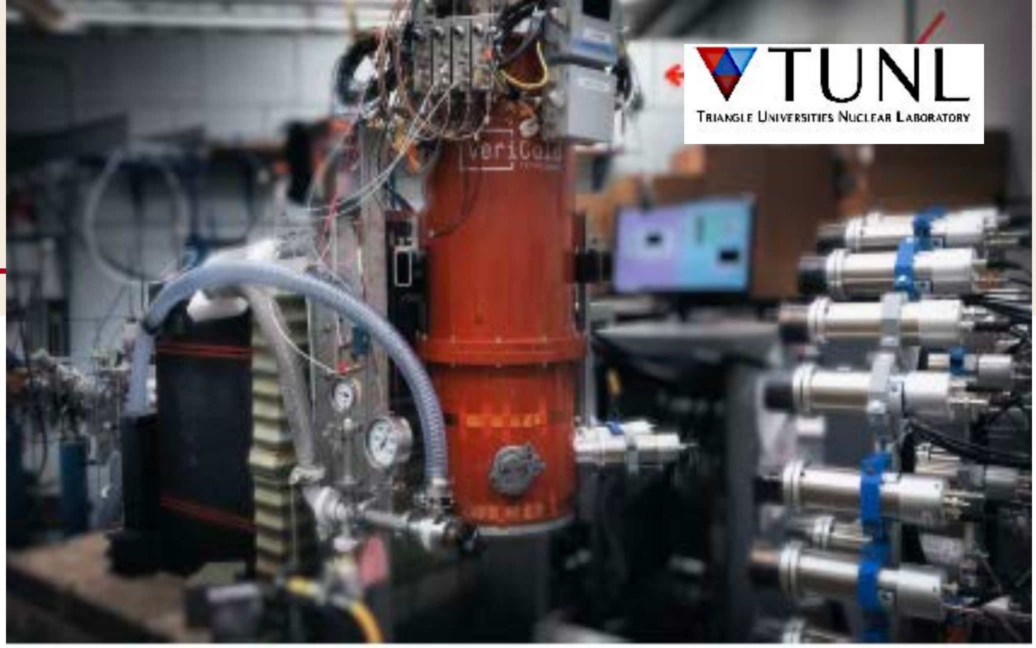

TUNL
Triangle Universities Nuclear Laboratory

Image credit: Tom Ren

Neutron Beam Energy ➔ E_n

- 1.9 MeV pulsed (2.5 MHz) protons on LiF target
- Tune to the ^{28}Si elastic scattering resonance (56 keV)

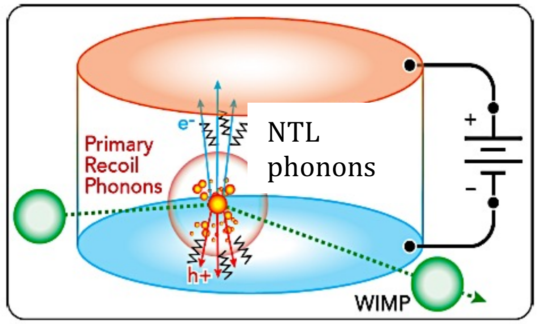
Neutron scattering angle ➔ E_r

- Backing Array (26 PMTs) at 2 distances
- 3 “lone wolf” to reference large angles
- Also measure TOF and γ backgrounds

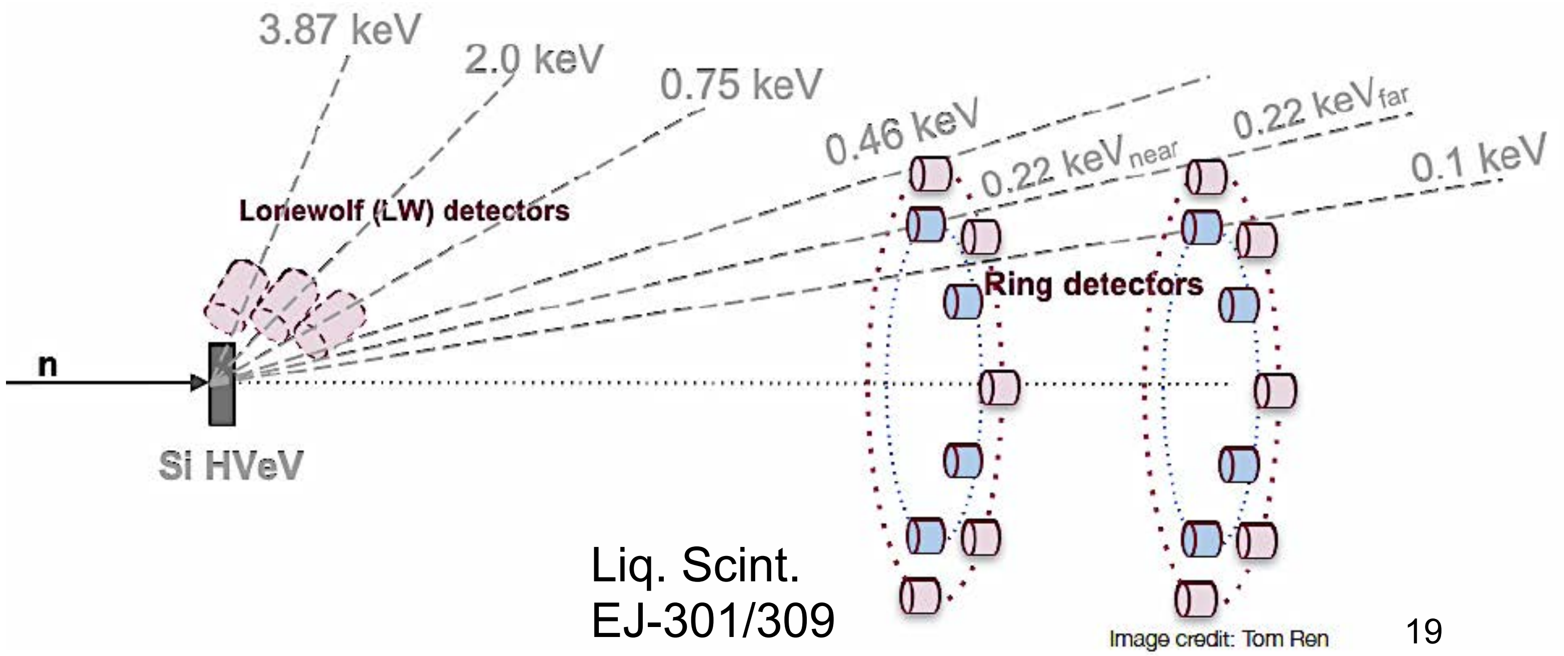
$$E_r = 2E_n \frac{M_n^2}{(M_n + M_T)^2}\left(\frac{M_T}{M_n} + \sin^2\theta - (\cos\theta)\sqrt{\left(\frac{M_T}{M_n}\right)^2 - \sin^2\theta}\right)$$

Silicon Detector ➔ total phonon energy

- HVeV (0.93 g) with 2 TES channels
- Energy Resolution: $\sigma_p \sim 3$ eV
- Charge Resolution: $\sigma_{eh} \sim 0.03$ e/h



$$E_{tot} = E_r + E_{NTL}$$



Liq. Scint.
EJ-301/309

Image credit: Tom Ren

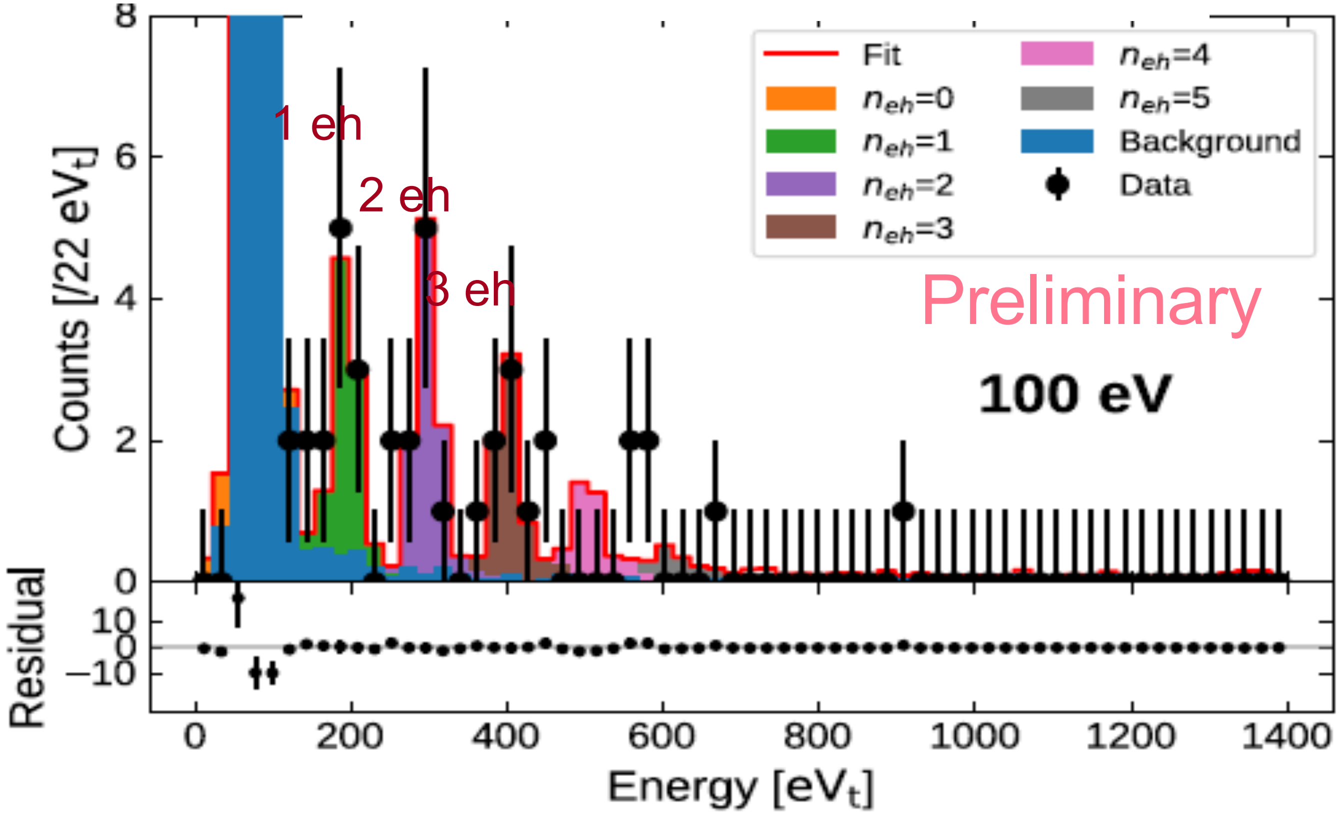
$Y(E_r)$ in Silicon Results (published soon)

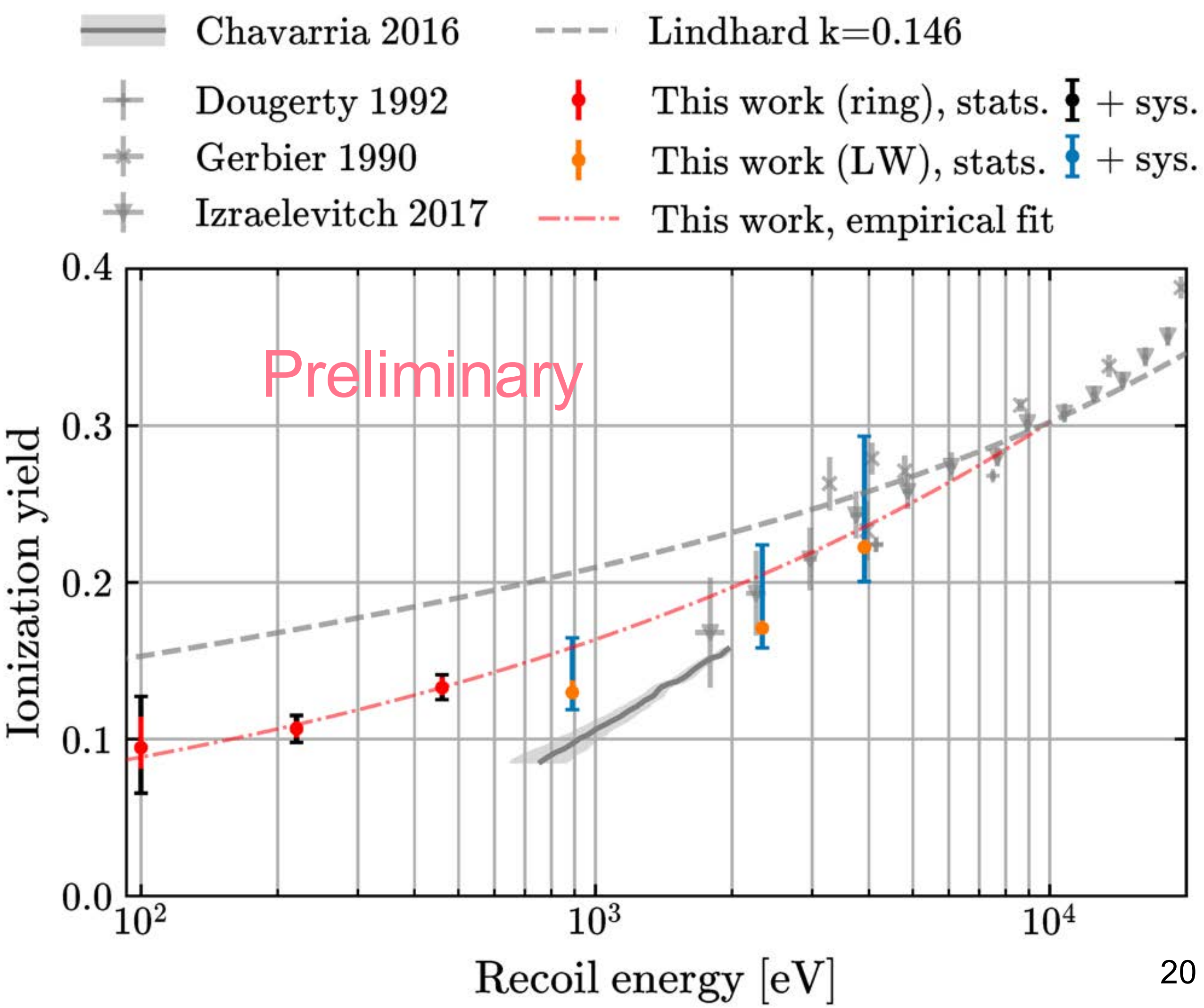
Extract Yield $E_{tot} = E_r\left(1+Y(E_r)\frac{eV_b}{\varepsilon_\gamma}\right)$ for the 6 recoil energies defined by the LS array

Took data sets with V_b = 0V, 20V, 100V, 180V

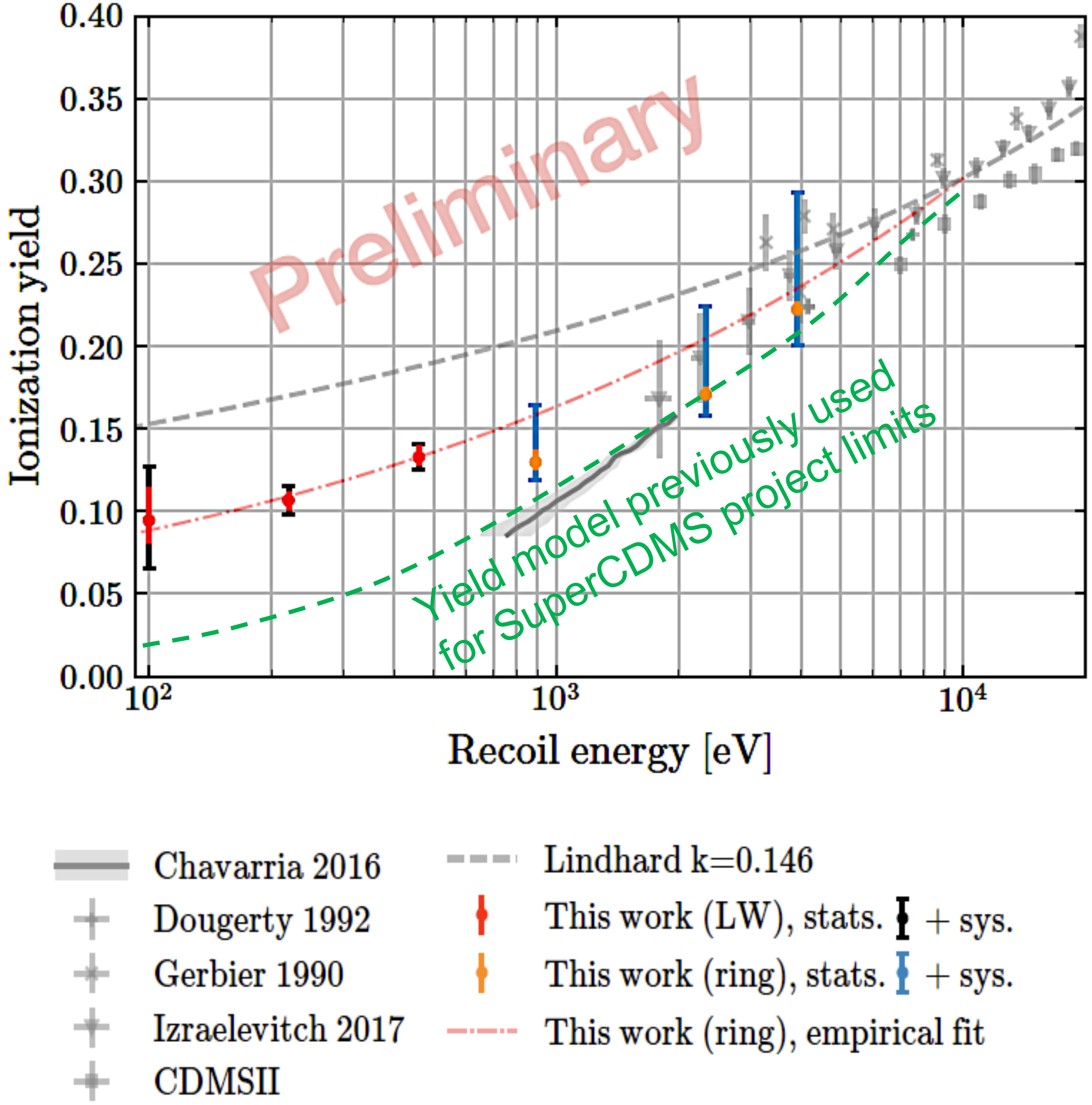
but only the 100 V data is used in this result

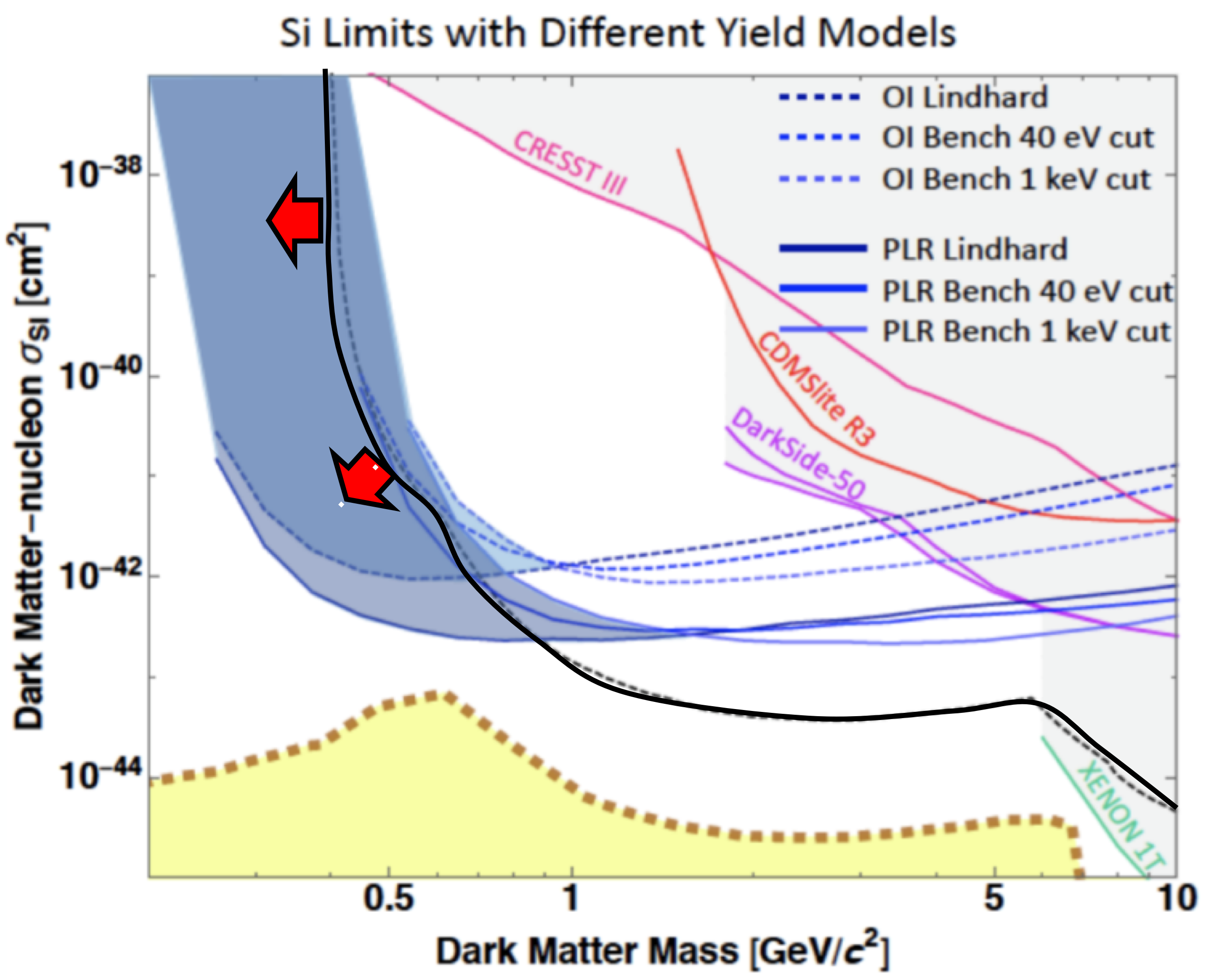
At V_b =100 V you can easily see quantization





Yield has significant consequences to our low mass reach in Silicon





All our Si project limits were based on a modified Lindhard (green)that passes through Chavarria '16

Measure Y(E_r) in Germanium: SuperCDMS Photo-Neutron Measurement

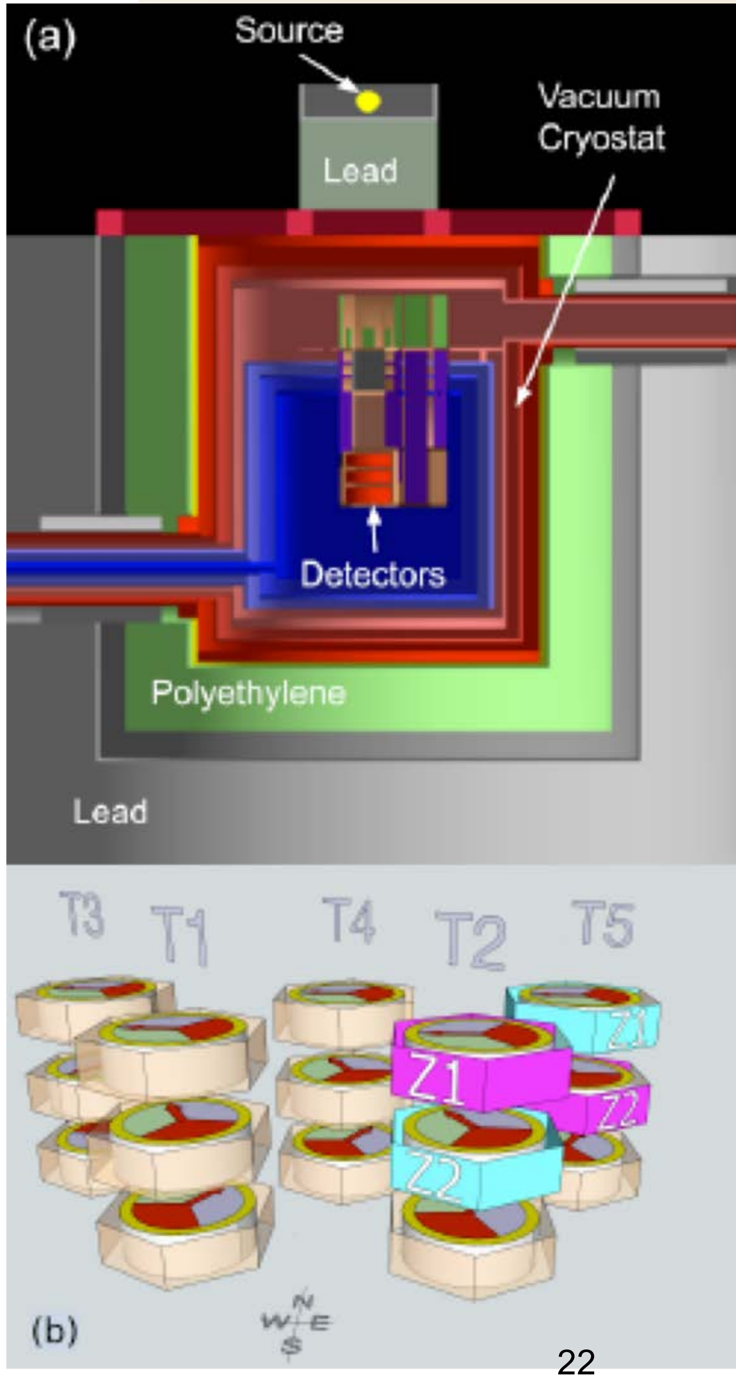
arXiv:2202.07043

Last set of runs before disassembling Soudan Facility

Illuminated the SuperCDMS array of germanium iZIPs

For each run, one iZIP was in CDMSlite HV mode.

Source	n Energy	Duration	Detector	V_b
^{124}Sb / ^{124}Sb ^{9}Be	24 keV	62 days	T5Z2	70 V
^{88}Y / ^{88}Y ^{9}Be	152 keV	42 days	T5Z2	70 V
^{88}Y / ^{88}Y ^{9}Be	152 keV	38 days	T2Z1	25 V



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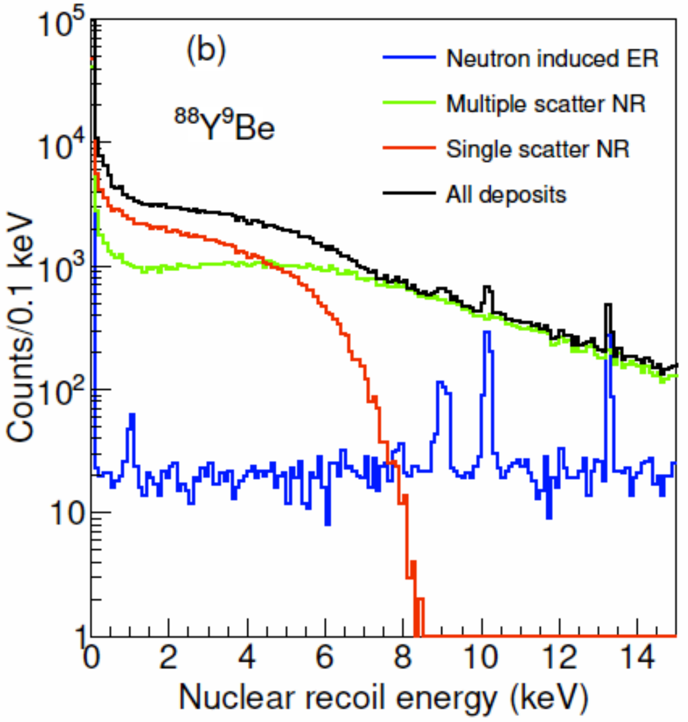
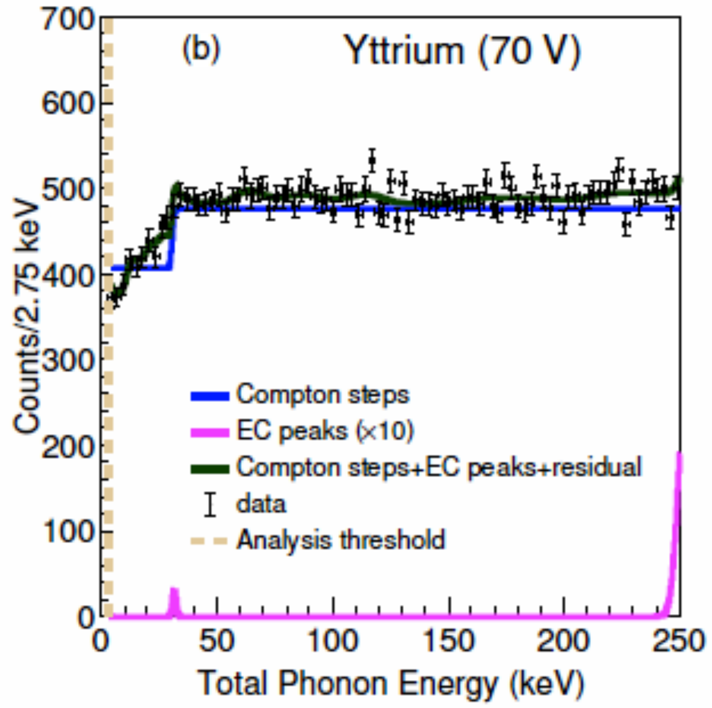
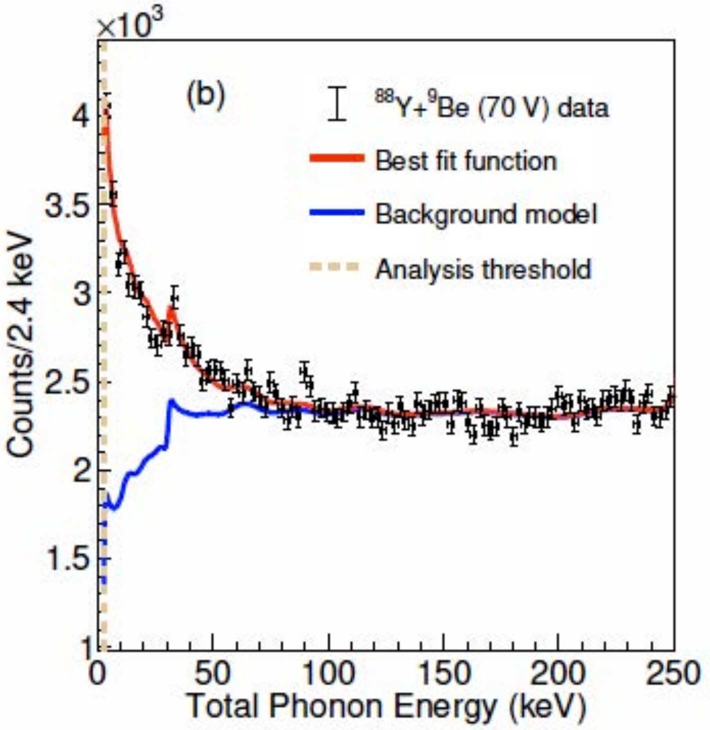
Geant4 MC

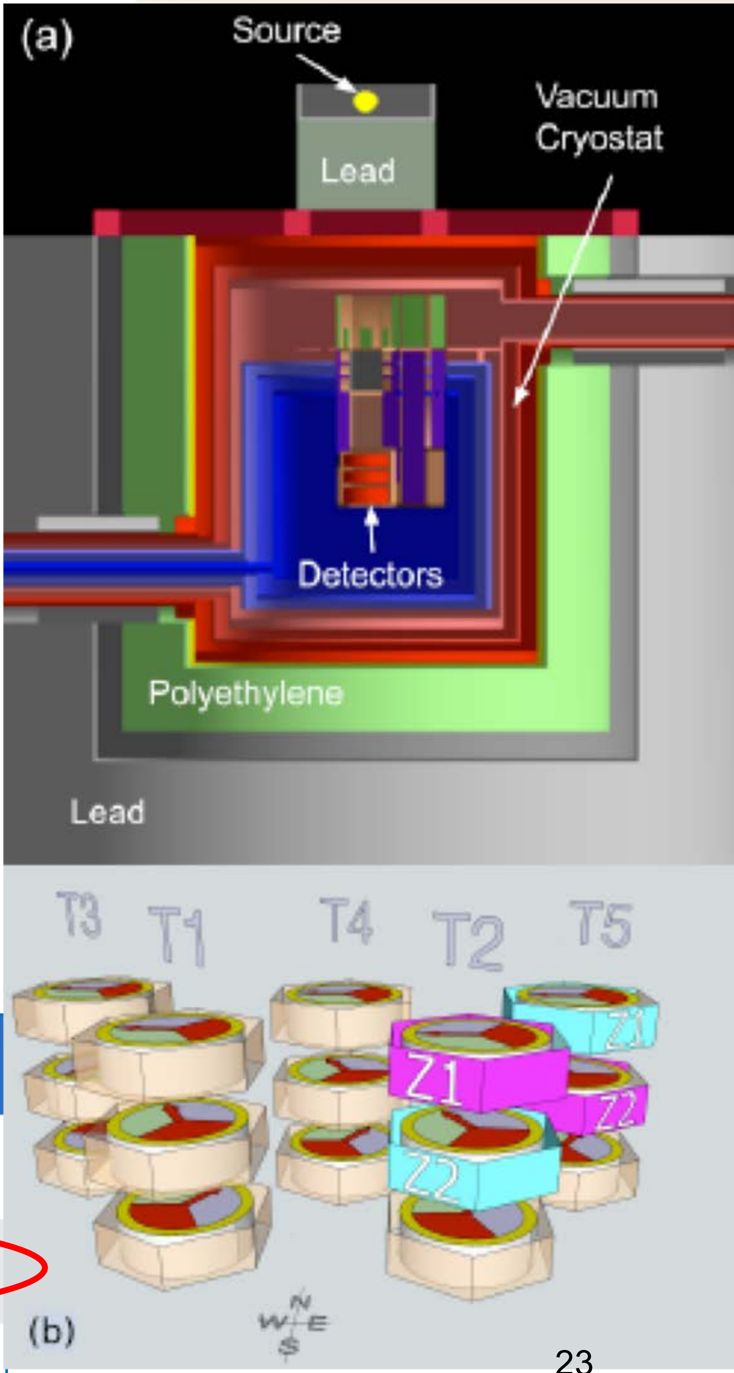


Data without Be disk



Data with Be disk





Likelihood fit to modified Lindhard, varying k-parameters and NR fraction

$$Y_r = \frac{k g(\epsilon)}{1 + k g(\epsilon)}$$

$$k(E_r) = k_{low} + \frac{k_{high} - k_{low}}{E_{high} - E_{low}}(E_r - E_{low})$$

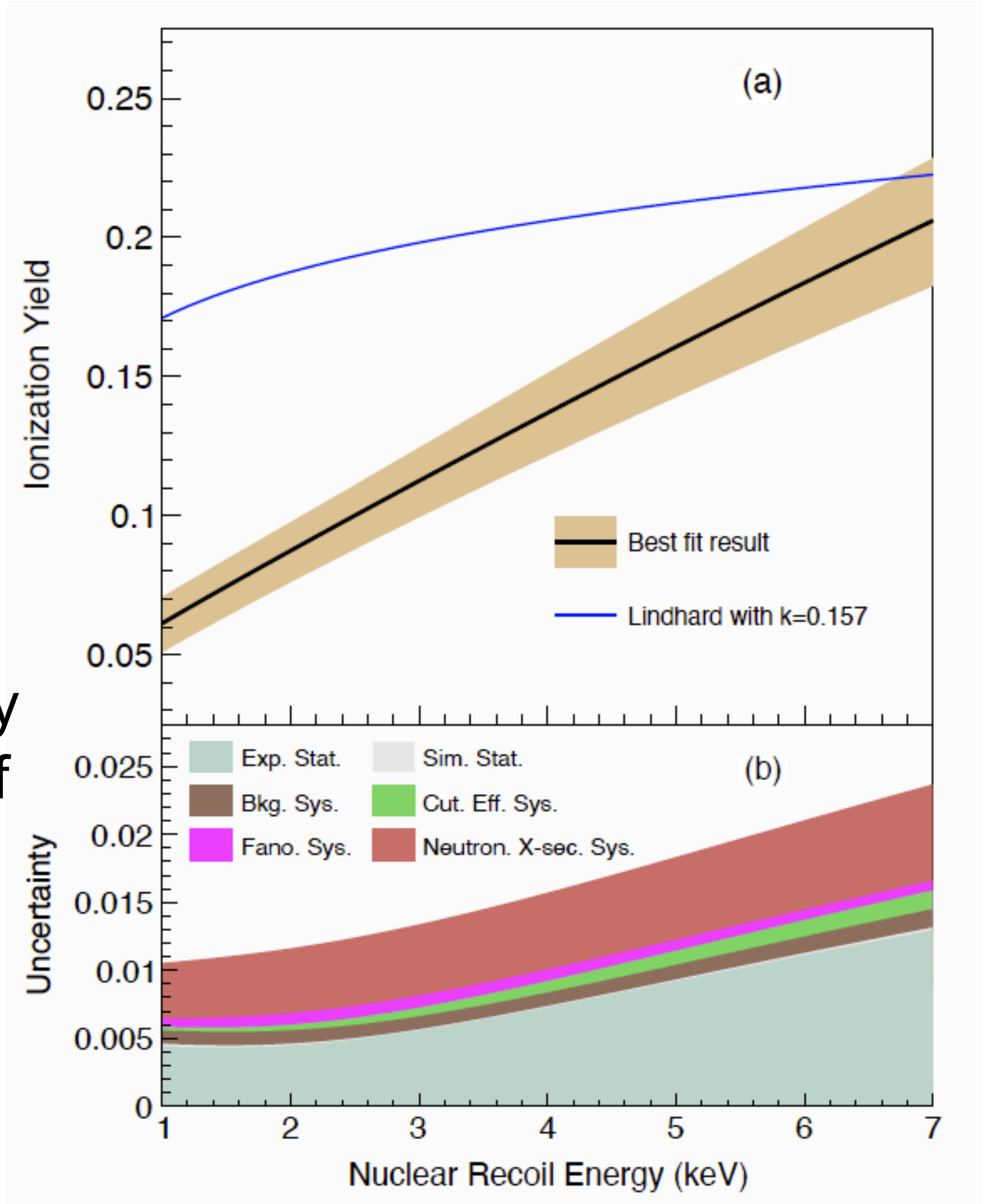
Source	n Energy	Duration	Detector	V_b
^{124}Sb / ^{124}Sb ^{9}Be	24 keV	62 days	T5Z2	70 V
^{88}Y / ^{88}Y ^{9}Be	152 keV	42 days	T5Z2	70 V
^{88}Y / ^{88}Y ^{9}Be	152 keV	38 days	T2Z1	25 V

$Y(E_r)$ in Germanium: Results also indicate suppression wrt Lindhard at a few keV

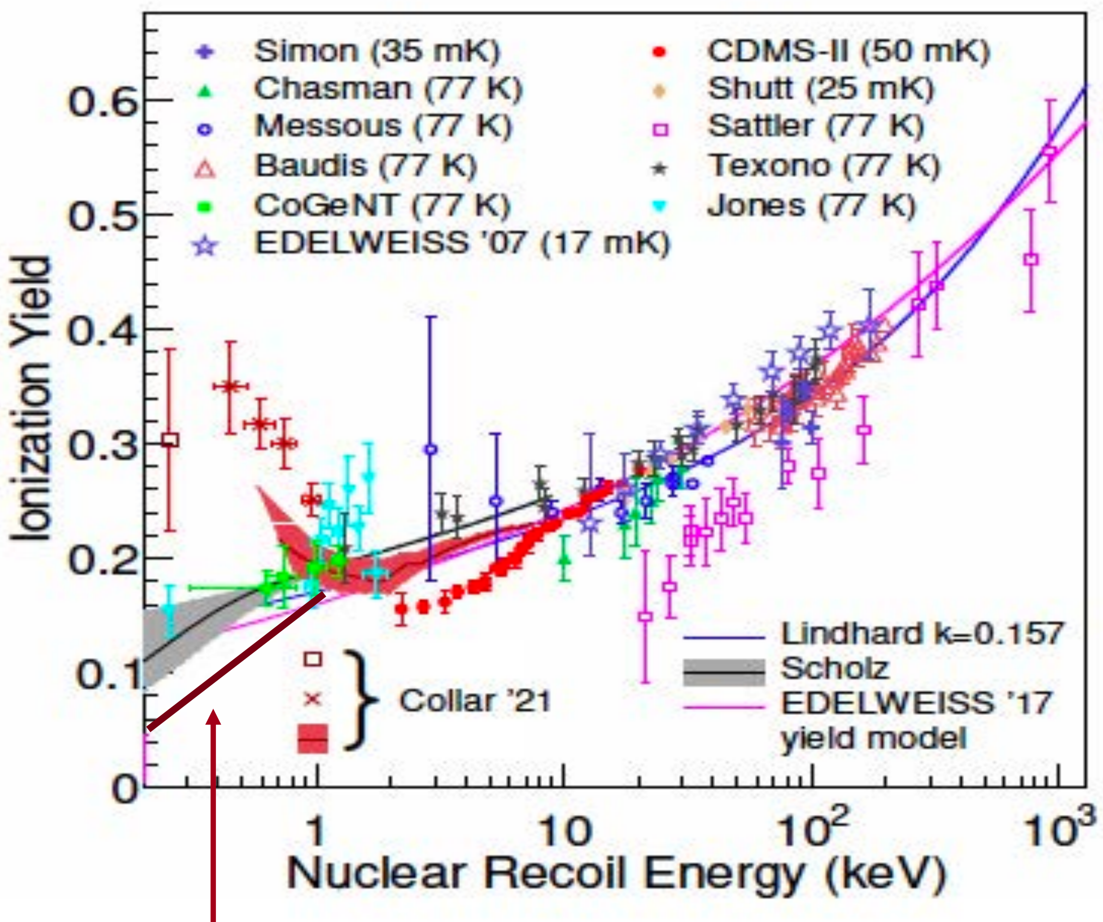
Linear combination of two k-parameters required for good fit

Inconsistent with Lindhard one-k fit

Uncertainty dominated by statistics and precision of neutron scattering cross sections



Inconsistent with recent Collar measurement.
Is Yield T-dependent?
Or modified by internal field?



CDMSlite result

SuperCDMS SNOLAB is poised to explore huge swaths of parameter space

The SuperCDMS SNOLAB Project is on track

- Detector fab is complete and SNOLAB infrastructure is well advanced
- Early science is happening now, in coordination with testing and commissioning
- Data taking at CUTE uses same software and shift structure

The Science Program is highly competitive

- The parameter space that SuperCDMS will explore is world-leading and unique
- During the delay, we have
    - made stunning technological advances
    - begun a campaign to measure the nuclear recoil scale at low energies.
- Upgrades using advanced detectors in the final payload will leap-frog our initial reach