SuperCDMS SNOLAB and the hunt for low-mass dark matter

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For the EIEIOO school 2024

2024/0/13

SuperCDMS at SNOLAB

- **C**ryogenic
- **D**ark
- **M**atter
- **S**earch

Talk Overview

1. Fascination with the cold and how it is possible to achieve mK temperatures
2. Rare-event search landscape for cryogenic experiments
3. Status of the SuperCDMS at SNOLAB
4. Prospects for the SuperCDMS experiment at SNOLAB

Fascination with the cold

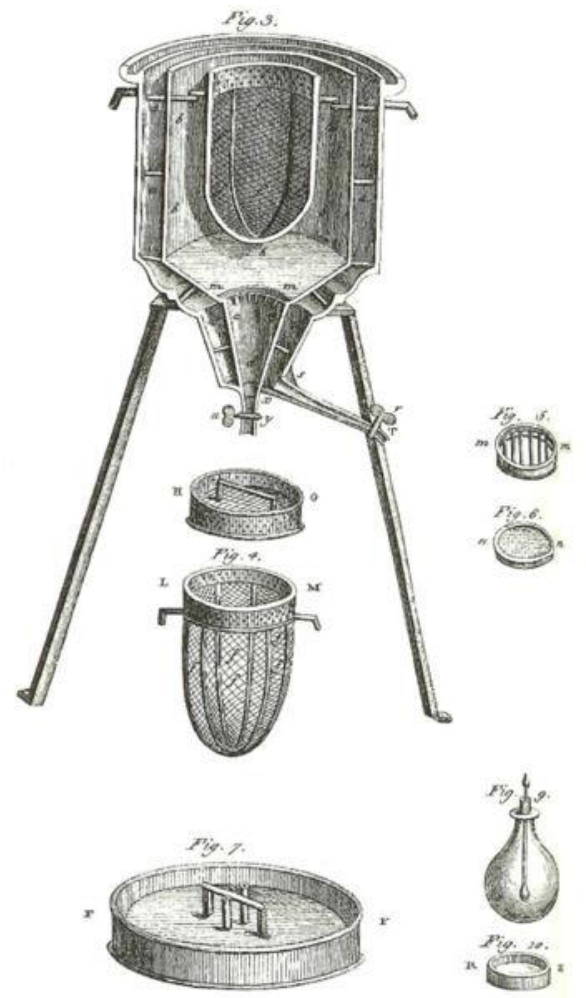
Out in the Cold

Detectors operated at mK temperatures

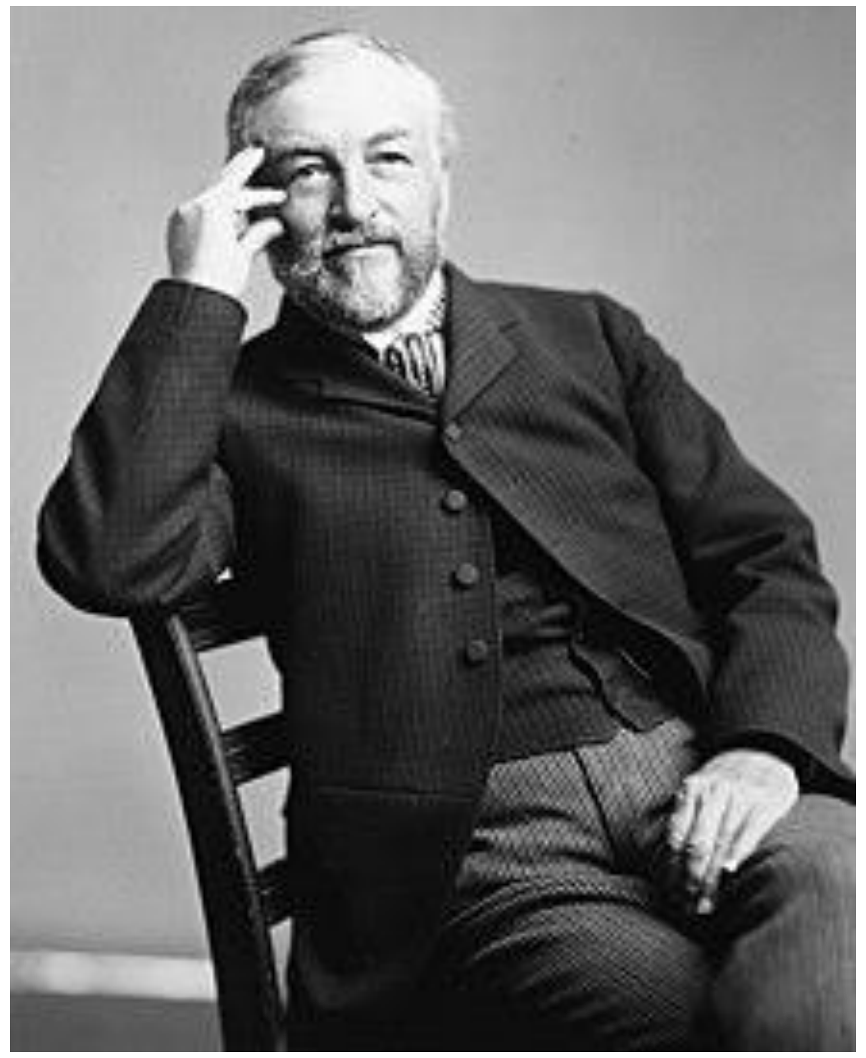
SNOLAB

Brief (very incomplete) History of Cryogenic Detectors

https://doi.org/10.1016/S0168-9002(00)00812-3



1780's Black, Lavoisier and Laplace develop the first Ice calorimeters



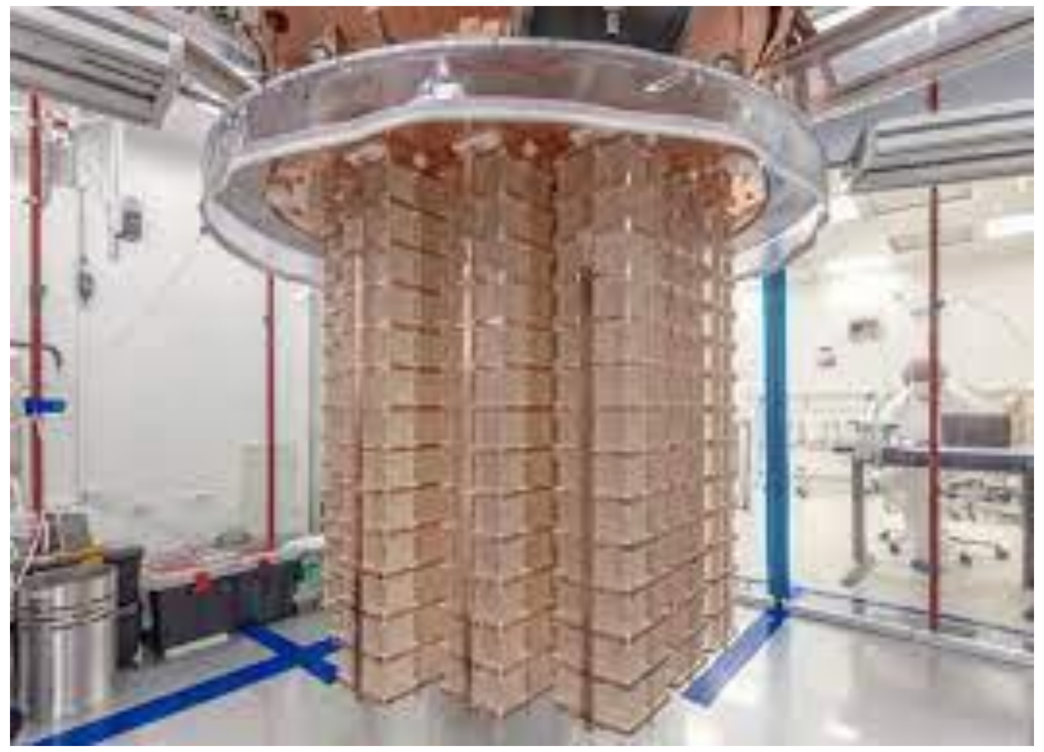
1878 S.P Langley invented the Bolometer (Sun)

$^{210}\mathrm{Bi} \rightarrow \beta^{-} + {}^{210}\mathrm{Po} + \overline{\nu}_e$

1903-1930 Microcalorimeters where used to measure radioactivity for the first time (β-decay of Bi-210)

1935 F. Simon suggested the idea of cryogenic calorimeters for the first time

1951 Heinz London proposes the dilution refrigerator

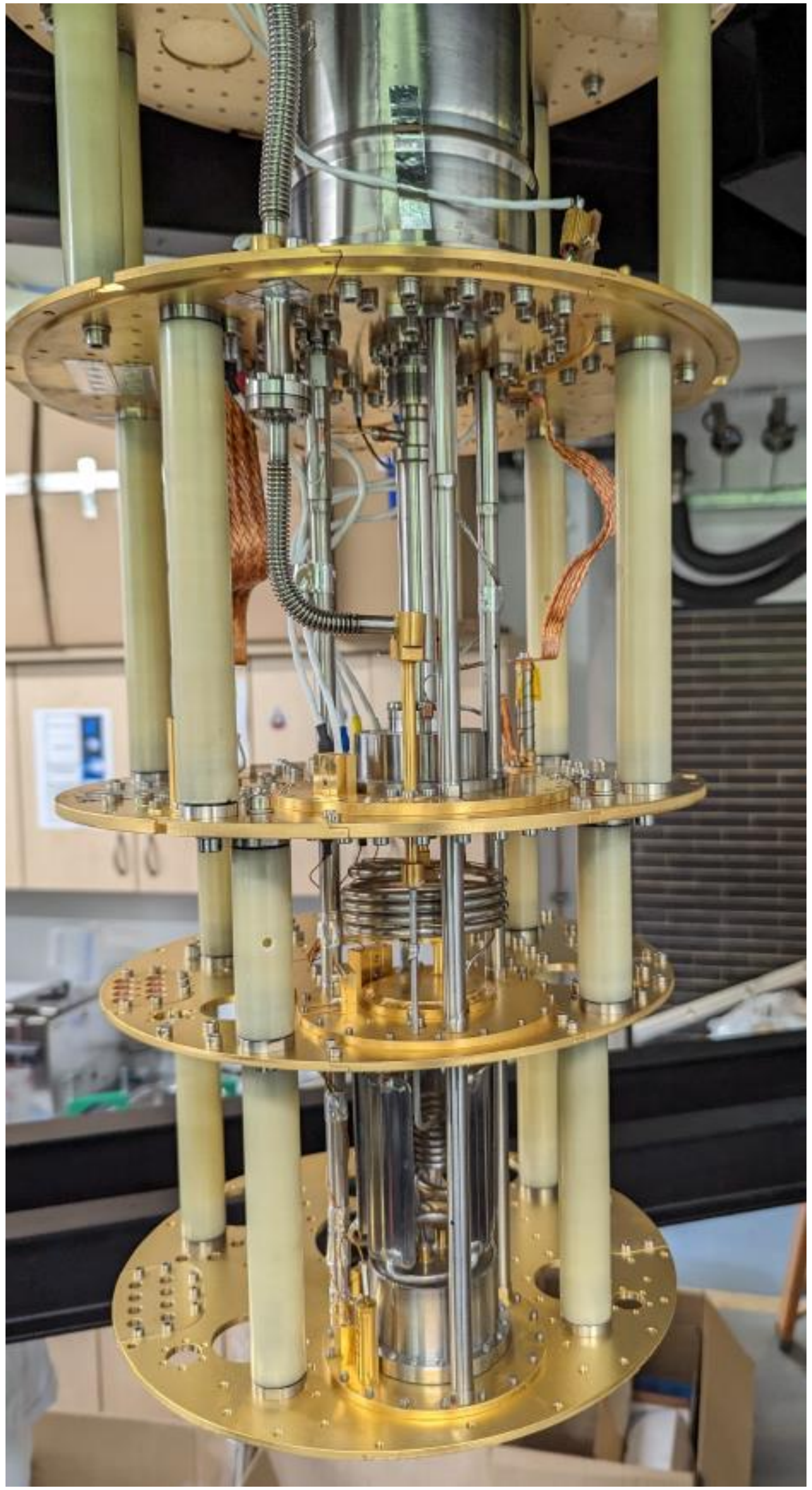


1983 E. Fiorini and T.O. Niinikoski explored the idea of cryogenic calorimeters for searching for neutrinoless double-beta decay

Today

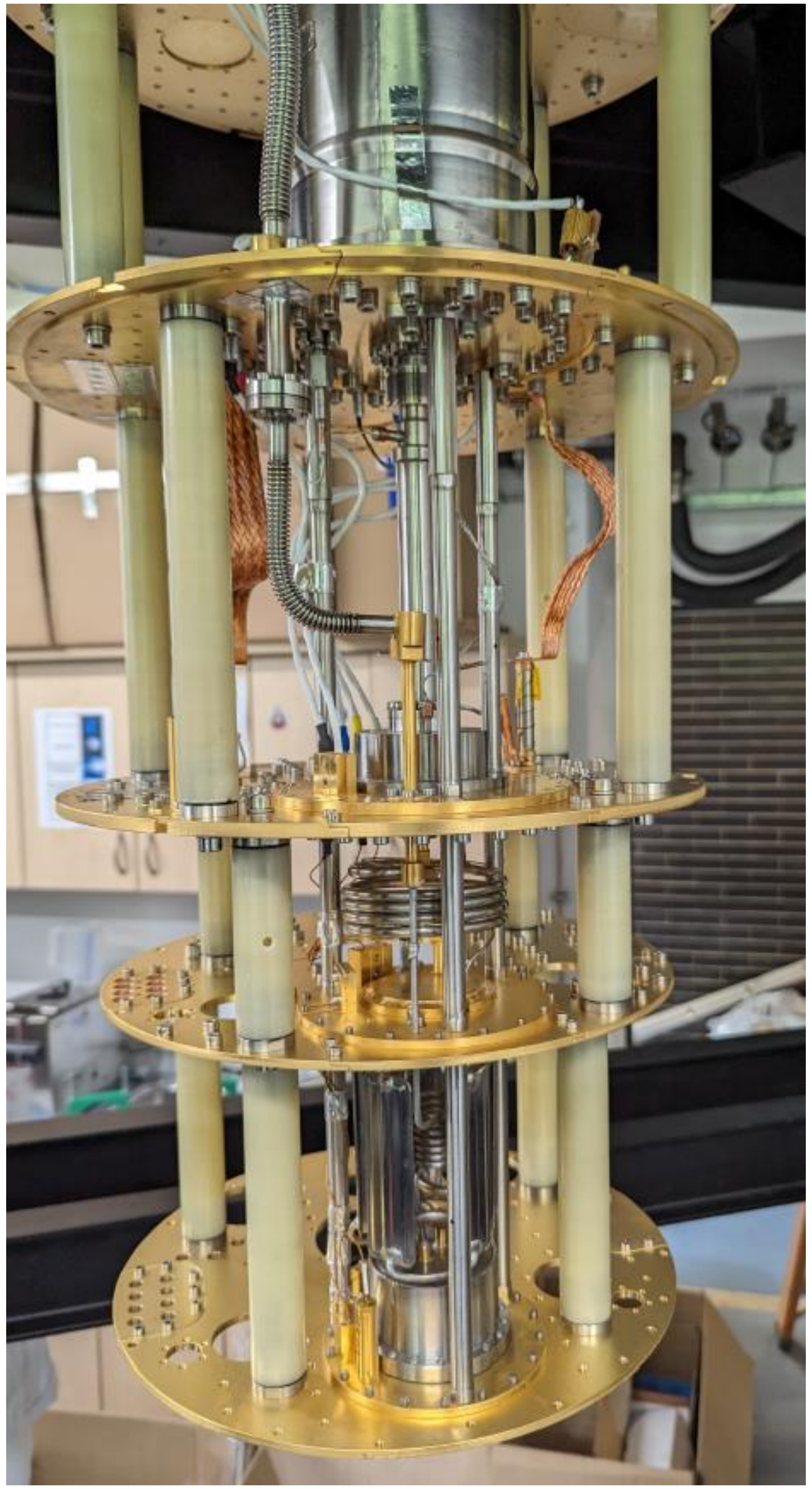
Understanding Refrigeration

- Cryostats (fridge): Are devices used to maintain a very low temperature
- Cooling Principles
  - Wet Dilution Refrigerator
    - Pre-cools (< 4K) using the cooling power of continuously flowing liquid helium. Low vibrations
  - Dry Dilution Refrigerator
    - Pre-cooling is done using direct mechanical cooler (pulse-tube)



Refrigeration Terminology (Dry Fridge)

- Dilution Refrigerators are able to change the temperature over 4 orders of magnitude
- The sound!!!!!



Pulse Tube First Stage (60 K)

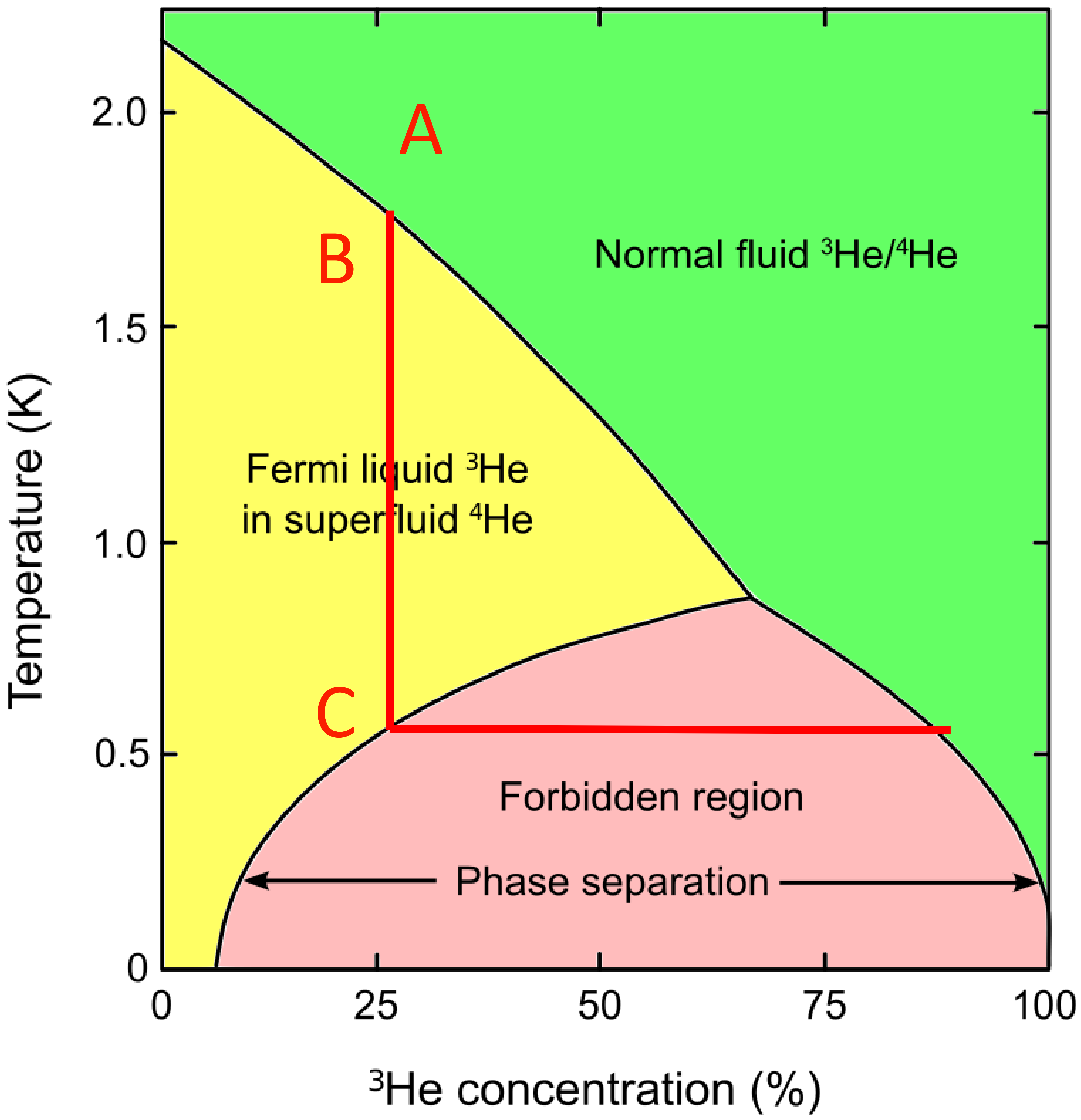
Pulse Tube Second Stage (4 K)

Still Plate (1 K)

Cold Plate (100 mK)

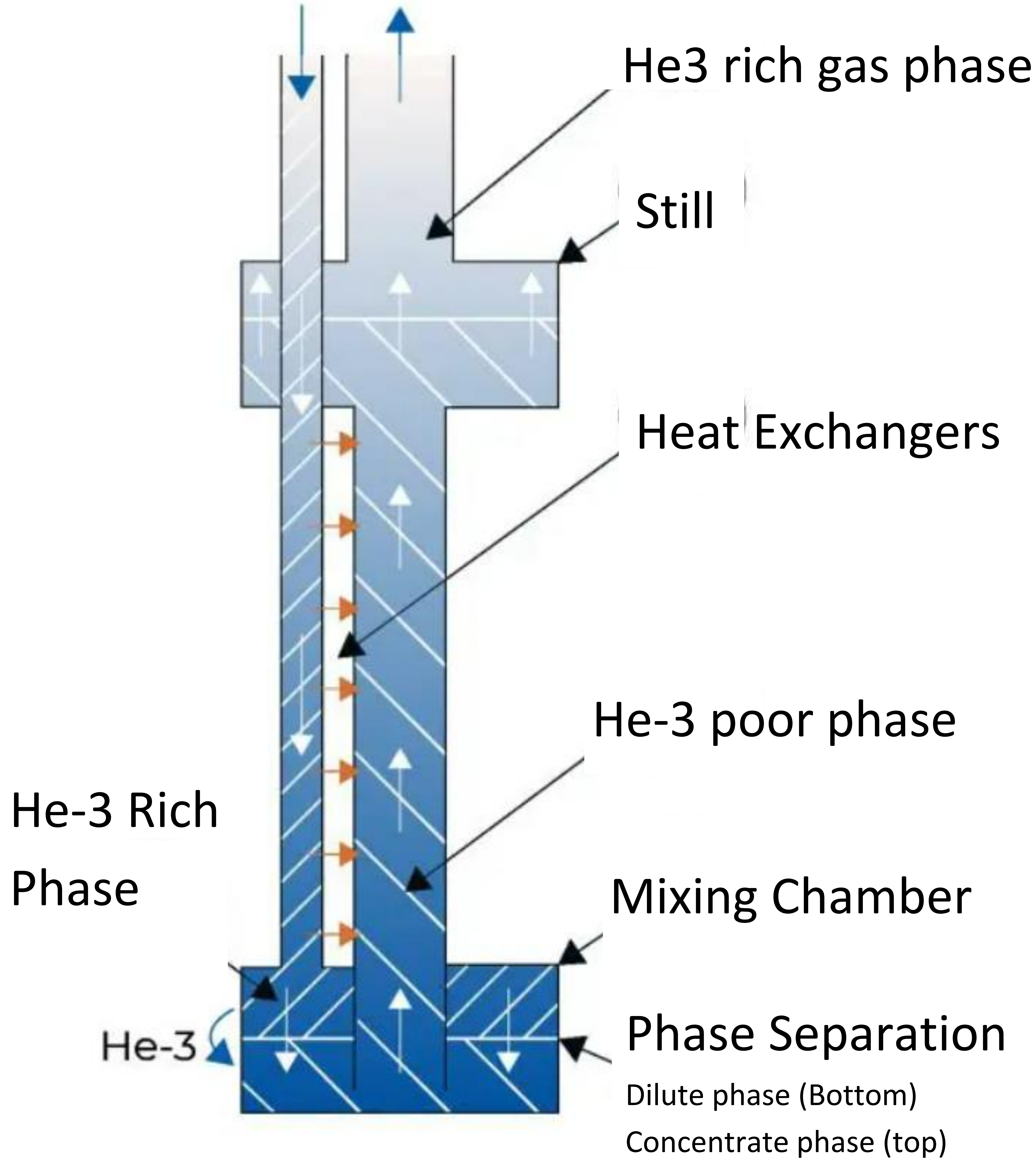
Mixing Chamber Plate (10 mK)

How to reach mK: Dilution Technique?



- Dilution refrigeration utilizes the properties of ^3He-^4He mixtures to achieve mK cooling
- ^4He obeys Bose statistics while ^3He obeys Fermi statistics.
- Mixing the two isotopes together is what allows mK temperature to be achieved
- A mix of He3/He4 starts at temperature A
- If the temperature is lowered below point B that mix is now a superfluid
- When lower then point C ^3He-^4He separate into dilute and concentrated phases.
- This happens in the mixing chamber
- Concentrated phase will "float" on-top of the dilute phase
- It takes energy to move ^3He from the dilute to concentrated phase which is taken from well isolated environment providing the cooling

How to reach mK?

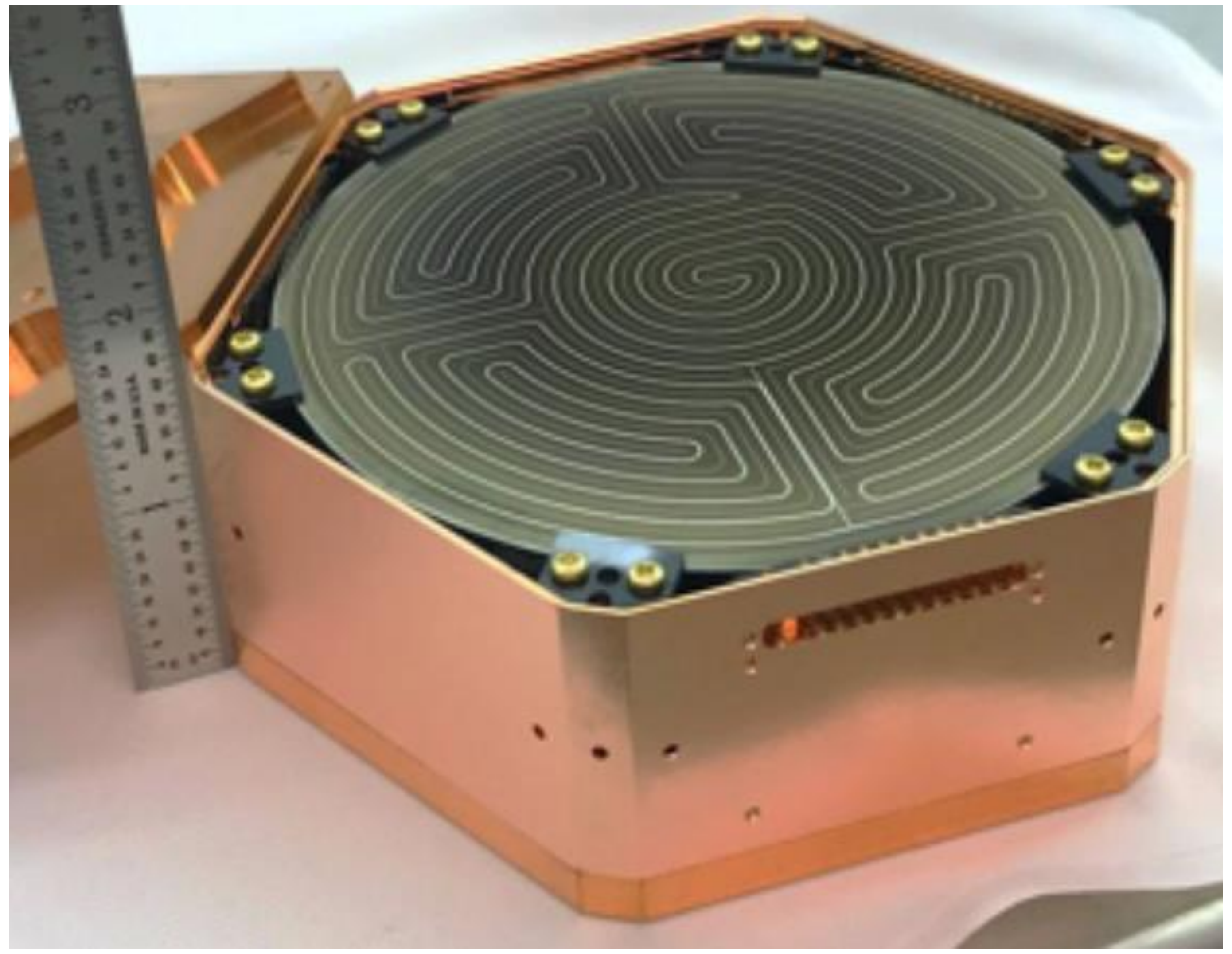


1. He-3 enters the dilution unit pre-cooled by the pulse tube at around 3K
2. It proceeds to the mixing chamber and is cooled by the heat exchangers
3. In the mixing chamber the phase separation occurs
4. He3 is pumped out to the still causing He3 to move from the concentrated phase to the dilute phase. Which takes energy from the system, thus providing the cooling
5. The He3 that was pumped out provides the cooling for the incoming He3
6. In the still He3 is evaporated and the cycle begins again

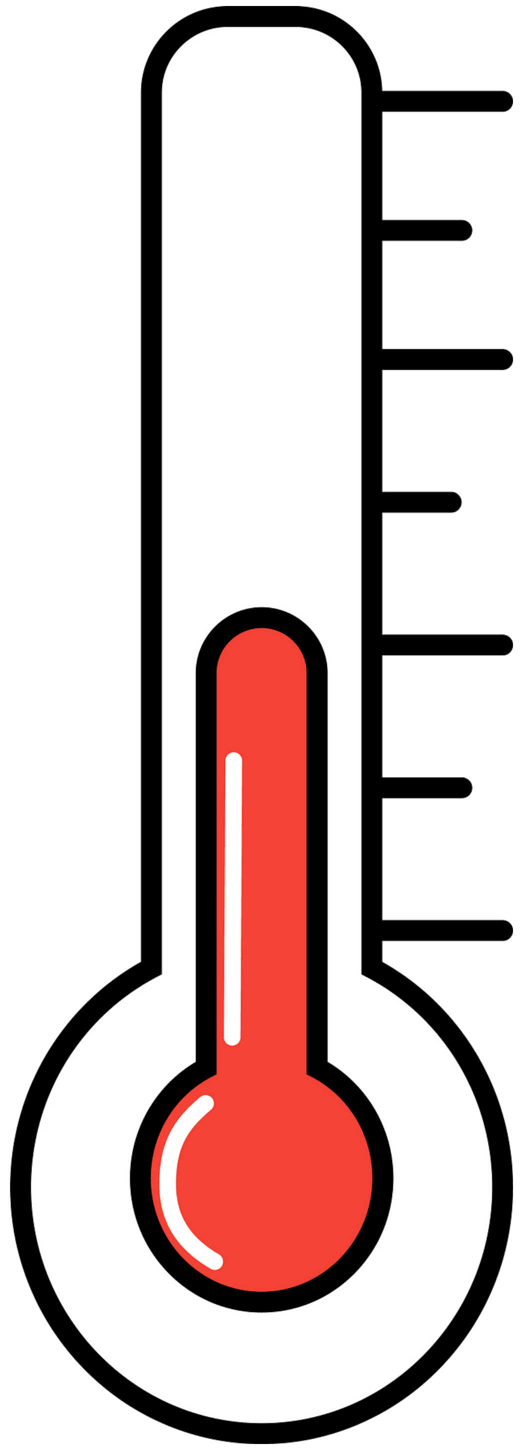
Rare Event Landscape for Cryogenic Detection

World of Cryogenic Experiments: Basic Requirements

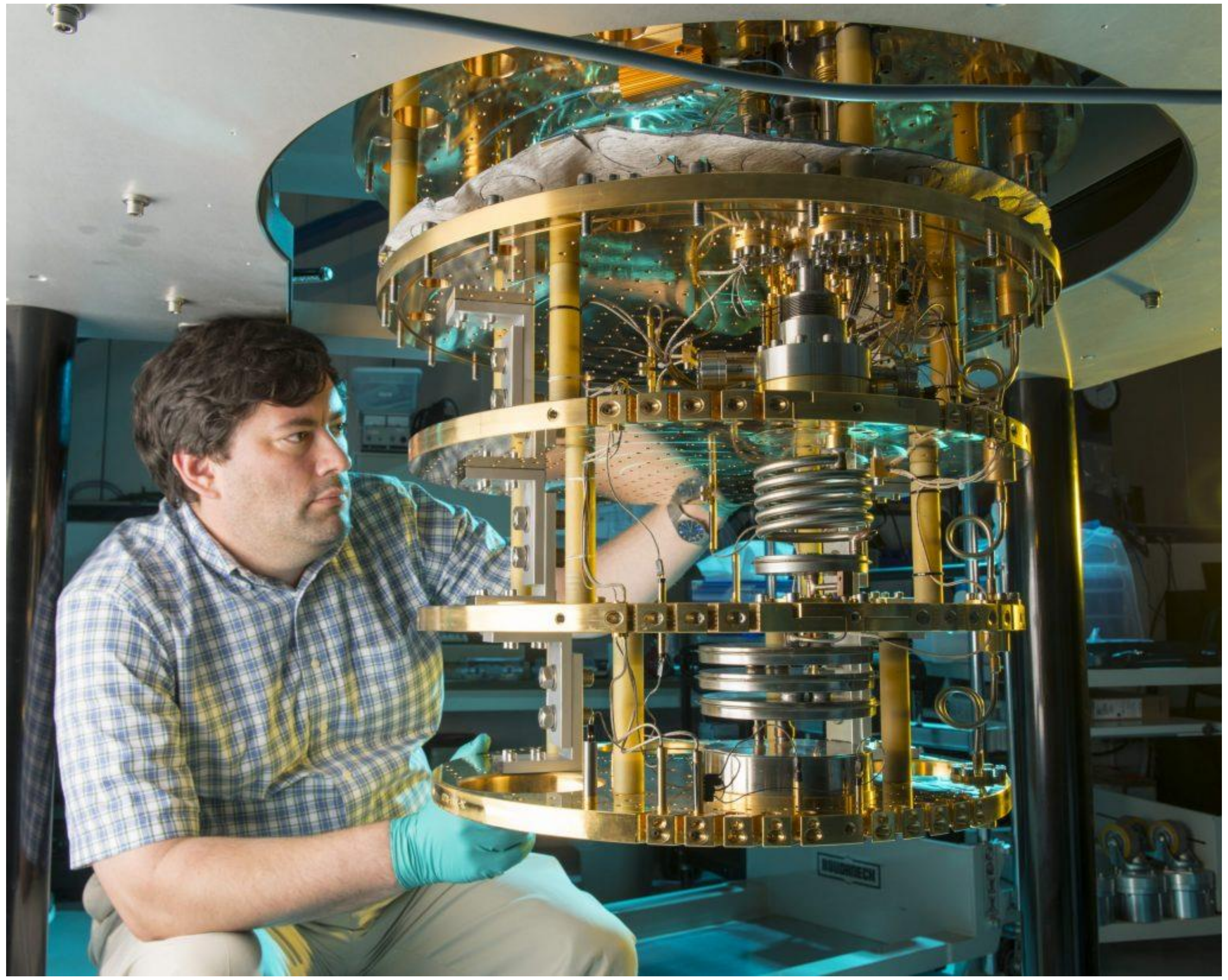
1) Absorber



2)Measuring Device



3)Refrigerator



4) People

World of Cryogenic Experiments: Questions?

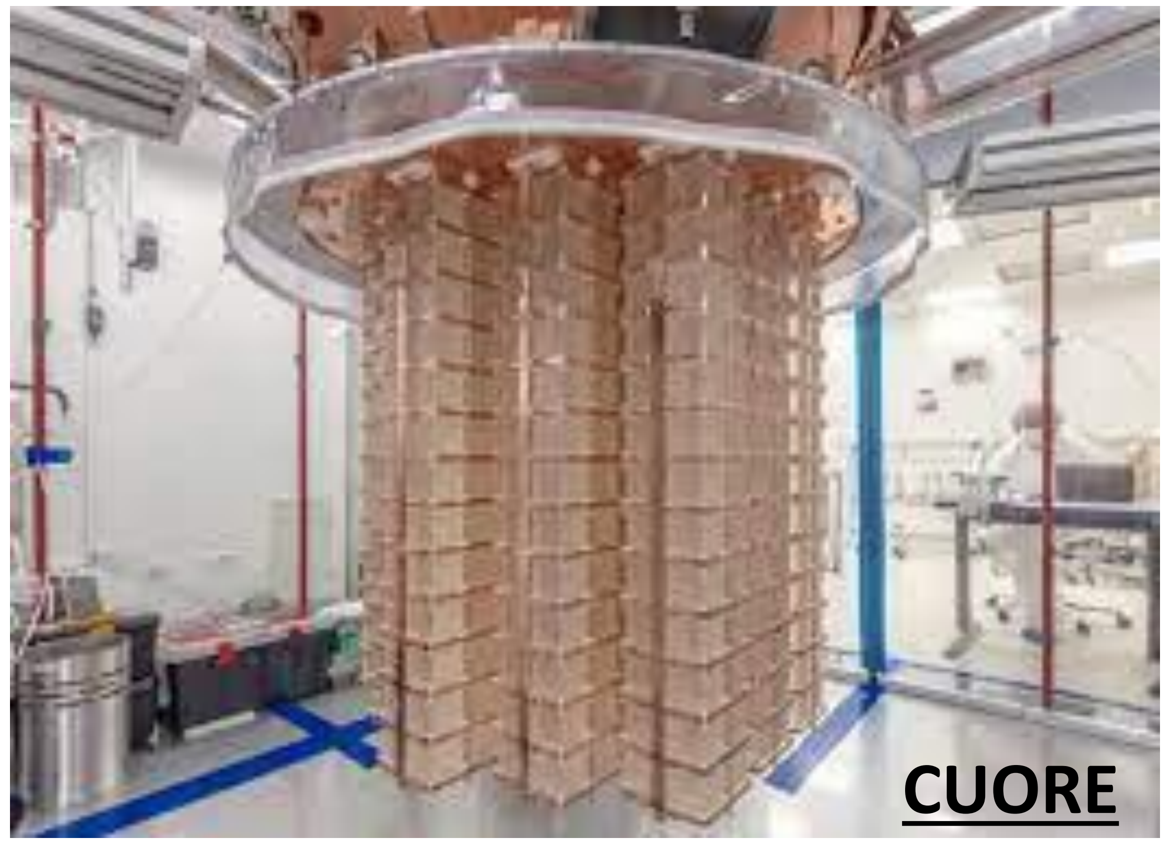
SNOLAB

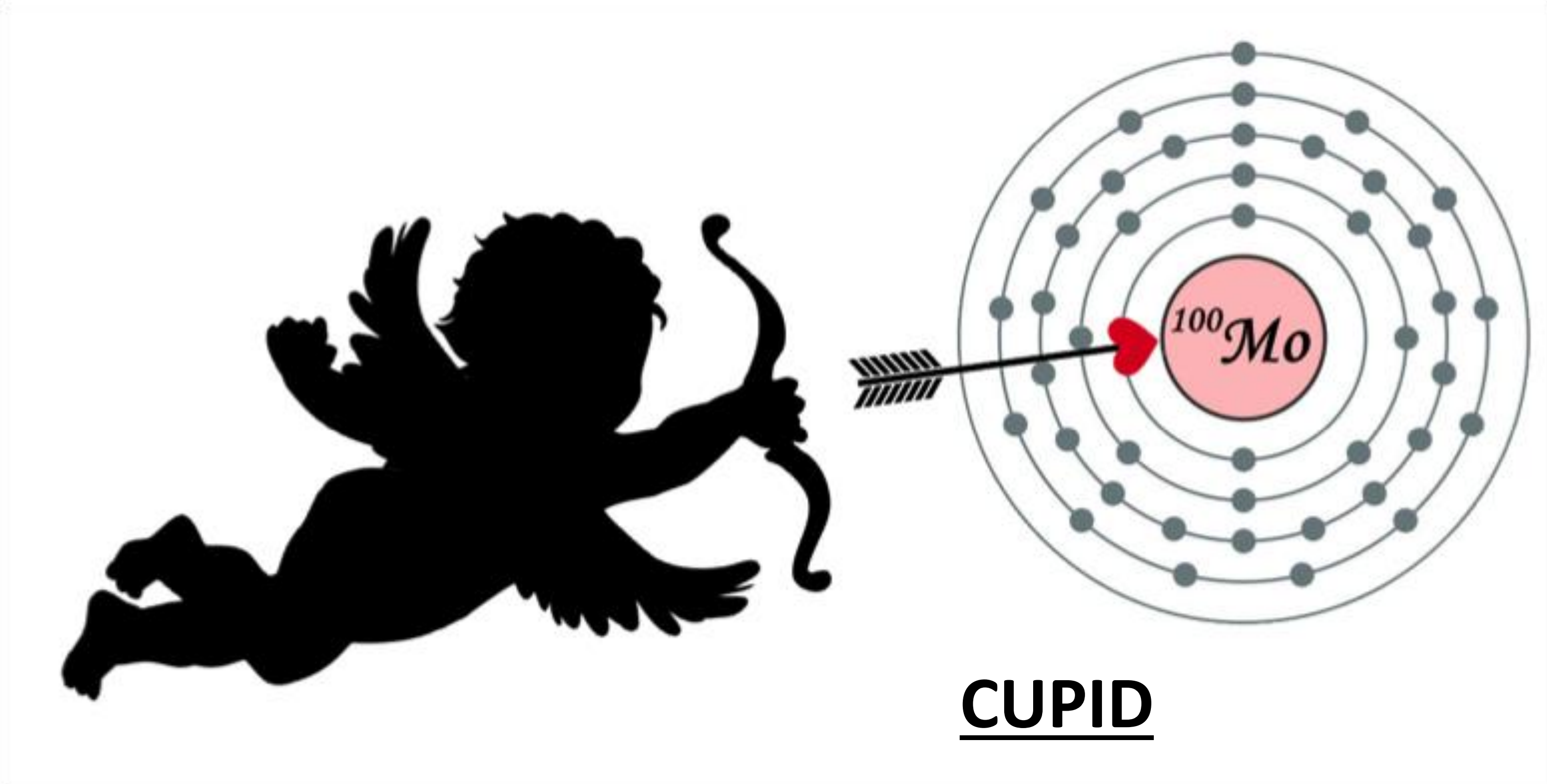
Dark Matter Searches

CRESST
Cryogenic Rare Event Search
with Superconducting Thermometers

SPICE/HERALD

Neutrinoless Double Beta Decay





CEvNS

nucleus
EXPERIMENT

RICOCHET

Quantum Computing

Supernova Detection

RES - NOVA

+ many more I have missed

World of Cryogenic Experiments: Questions?

SNOLAB

Dark Matter Searches

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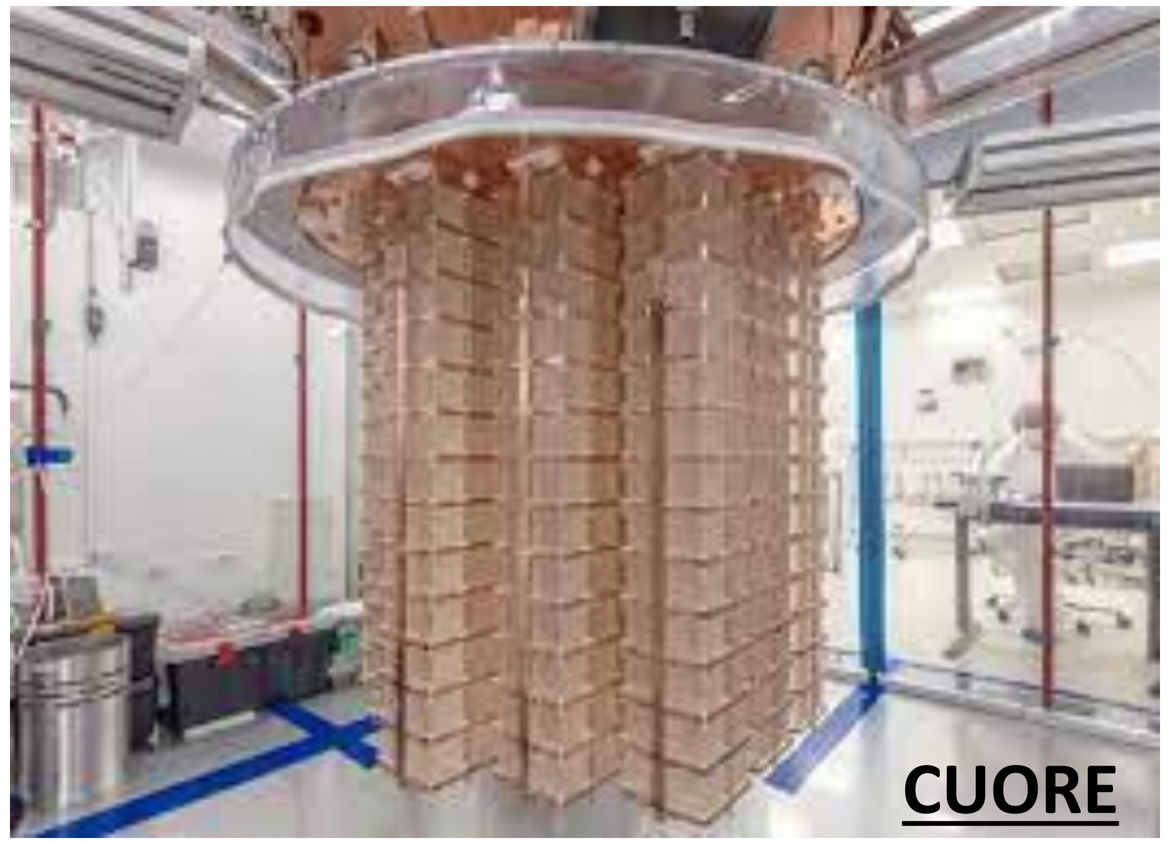
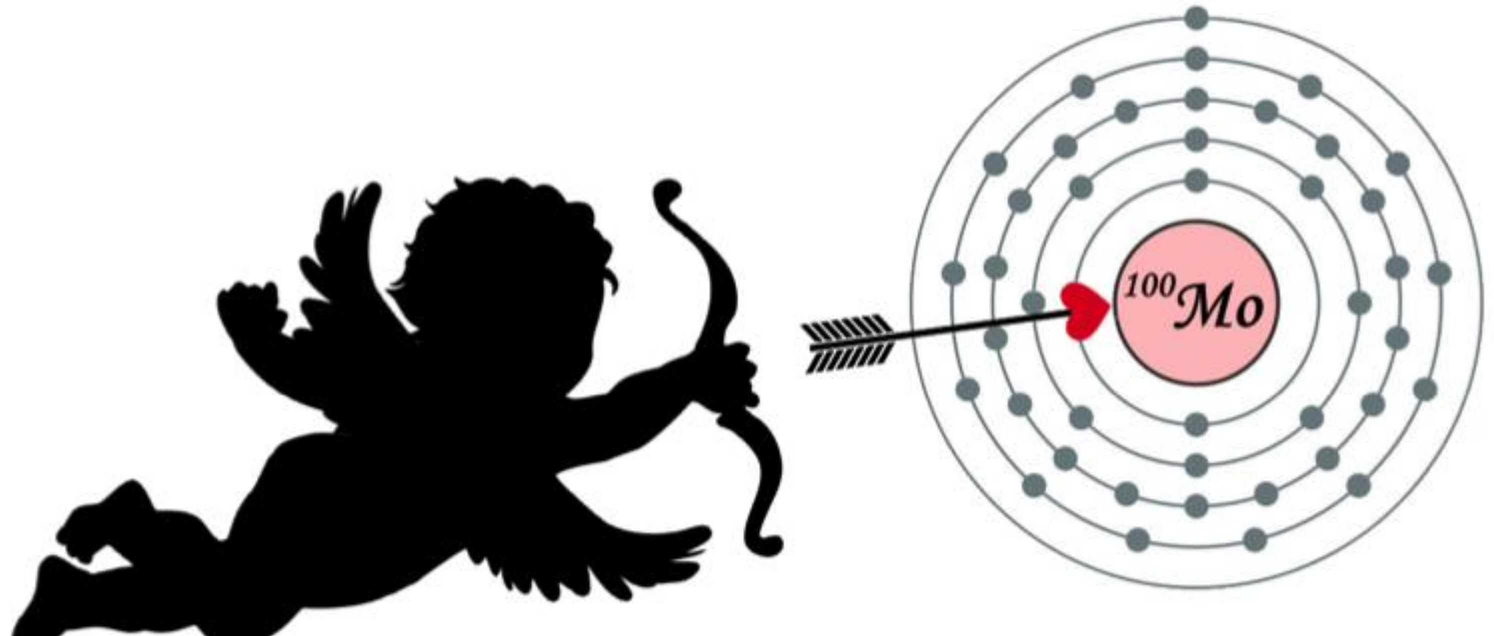
SPICE/HERALD

Neutrinoless Double Beta Decay



CUORE



CUPID

CEvNS

nucleus

EXPERIMENT

RICOCHET

Quantum Computing

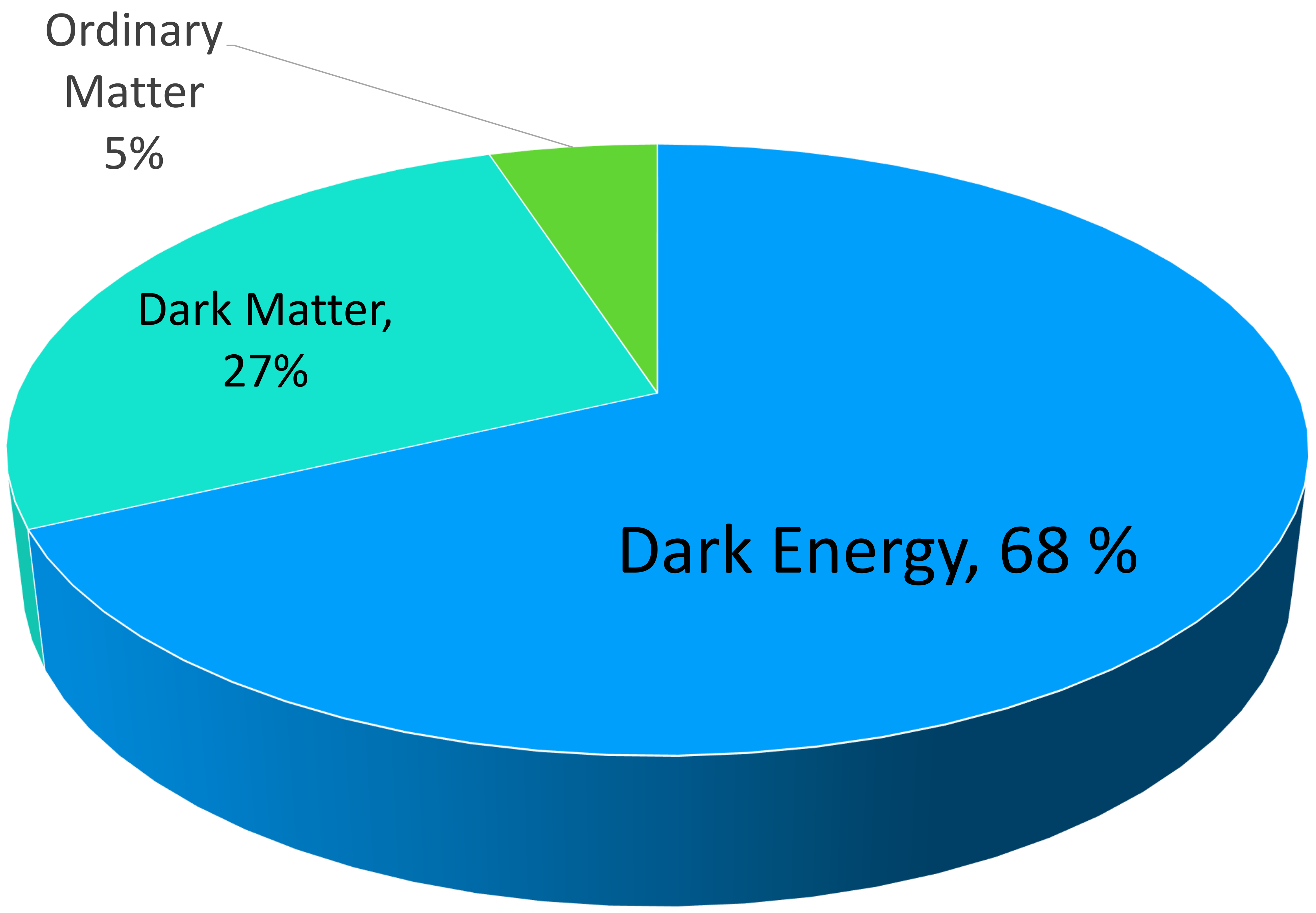
CUTE

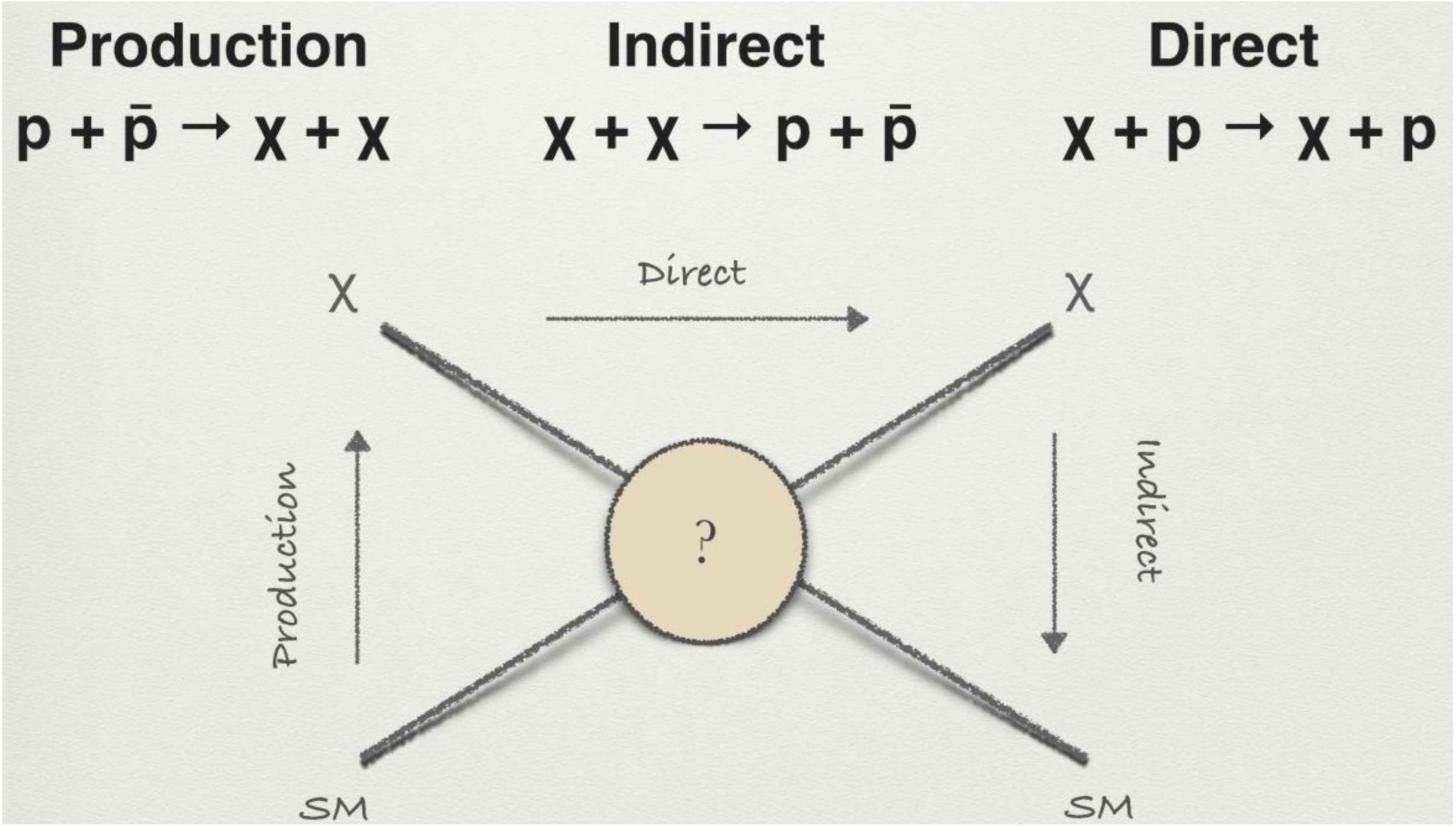
Supernova Detection

RES - NOVA

\+ many more I have missed

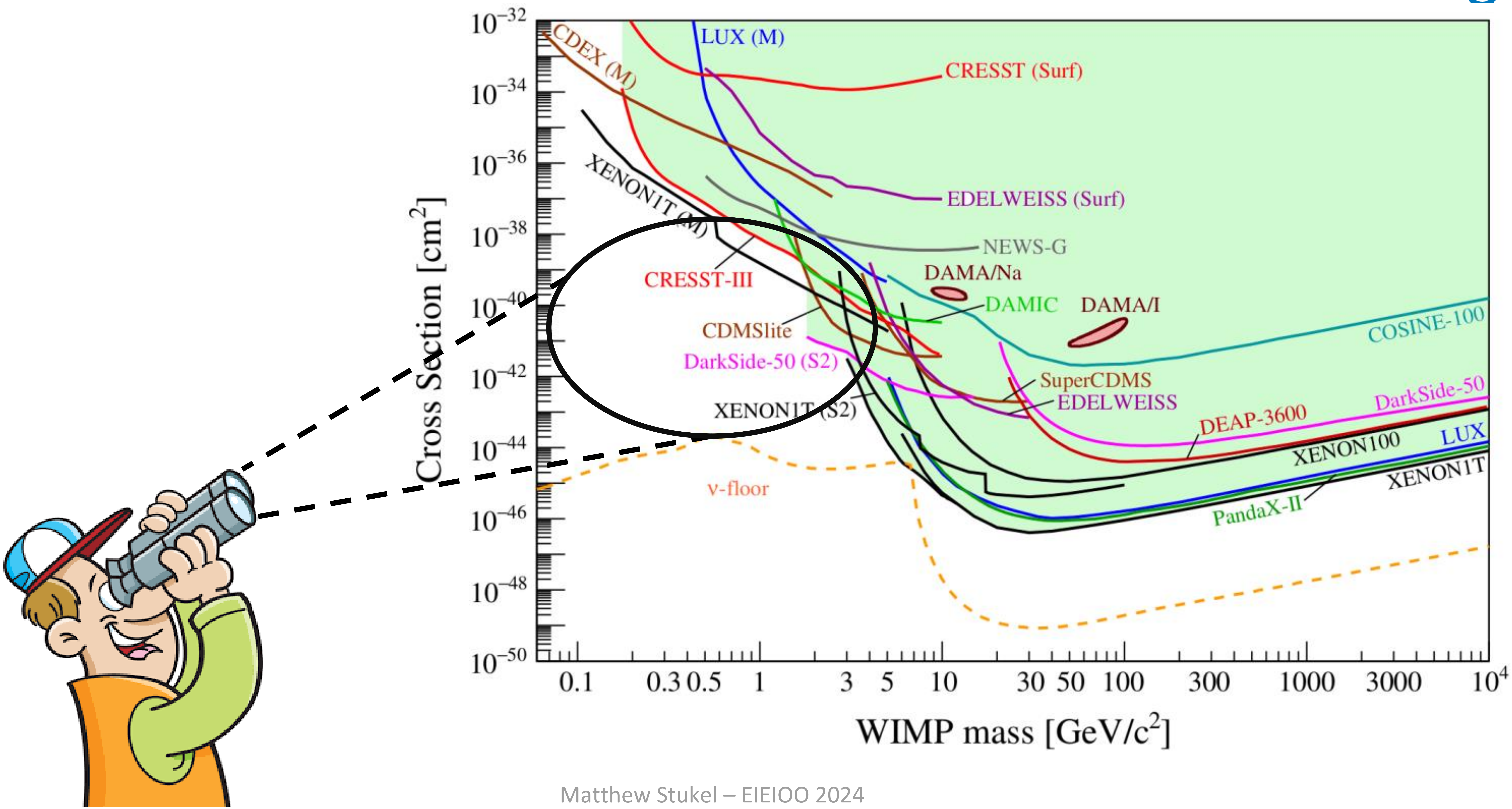
Dark Matter



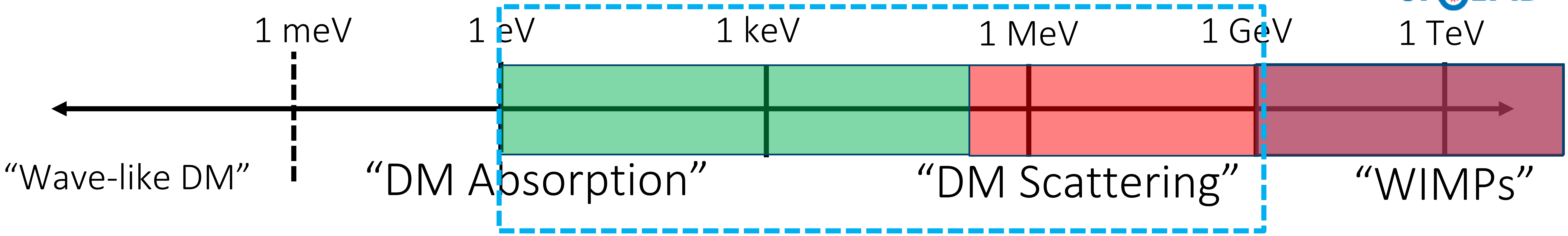


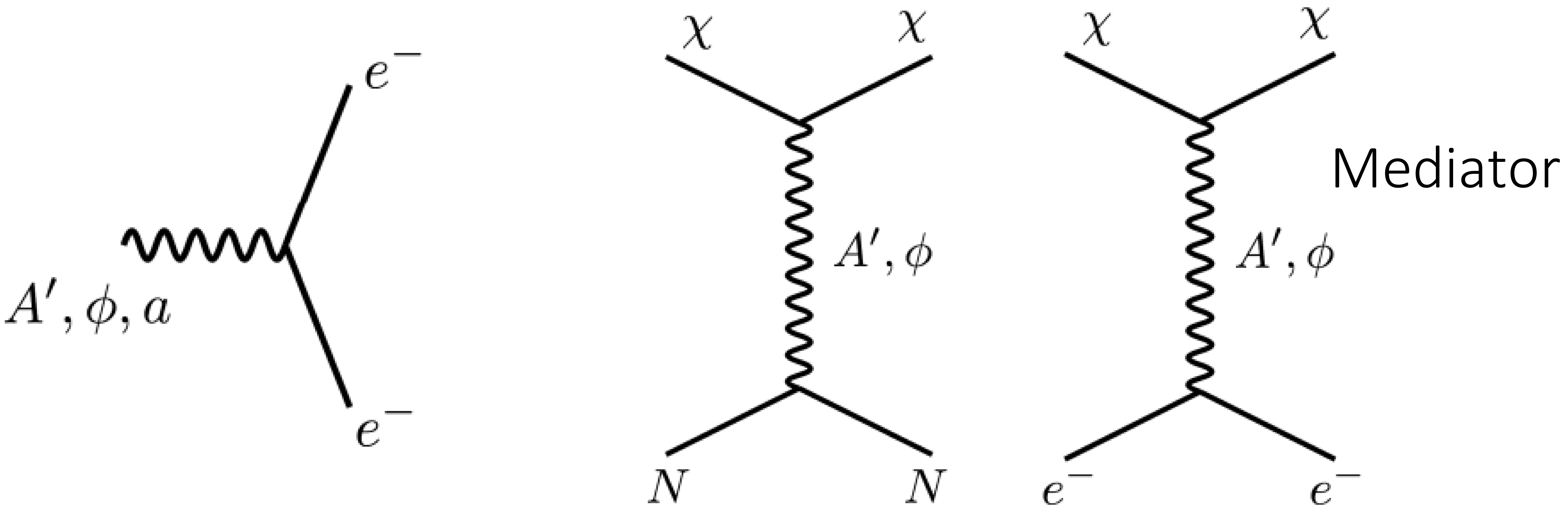
- Evidence includes: Rotation curves of galaxies, weak gravitational lensing, cosmological modelling
- Many experiments that employ many techniques!
- Direct Detection: Nuclear or electric recoils

Dark Matter: The Current Search



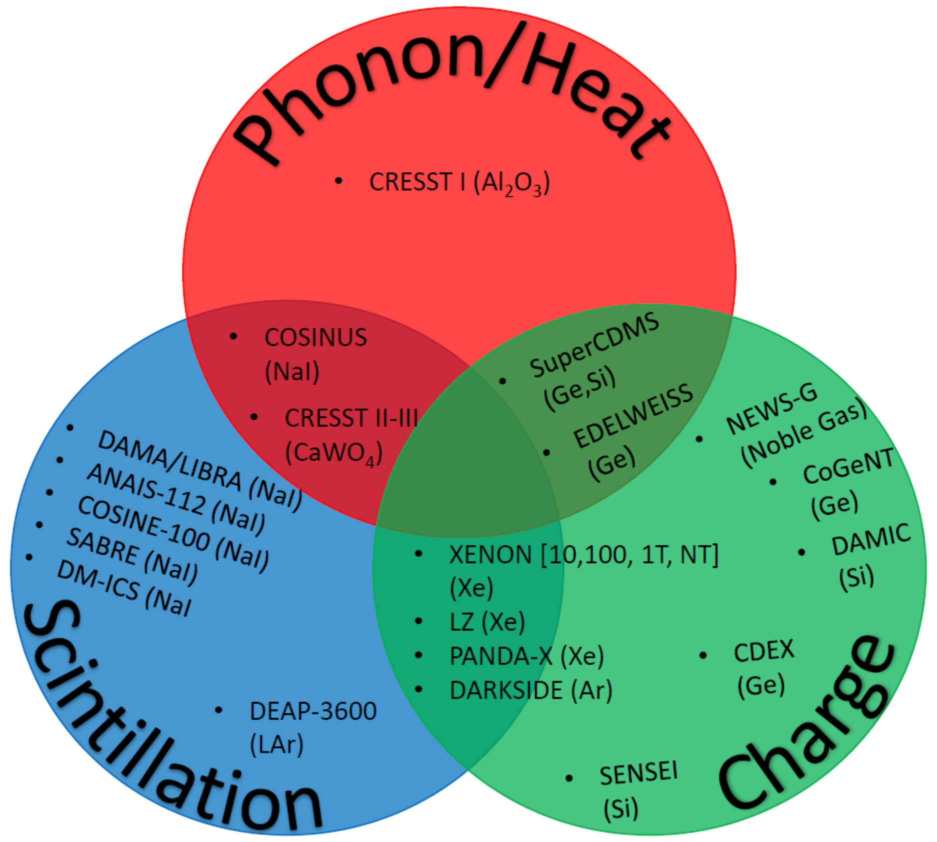
Sub-GeV Dark Matter Detection Channels



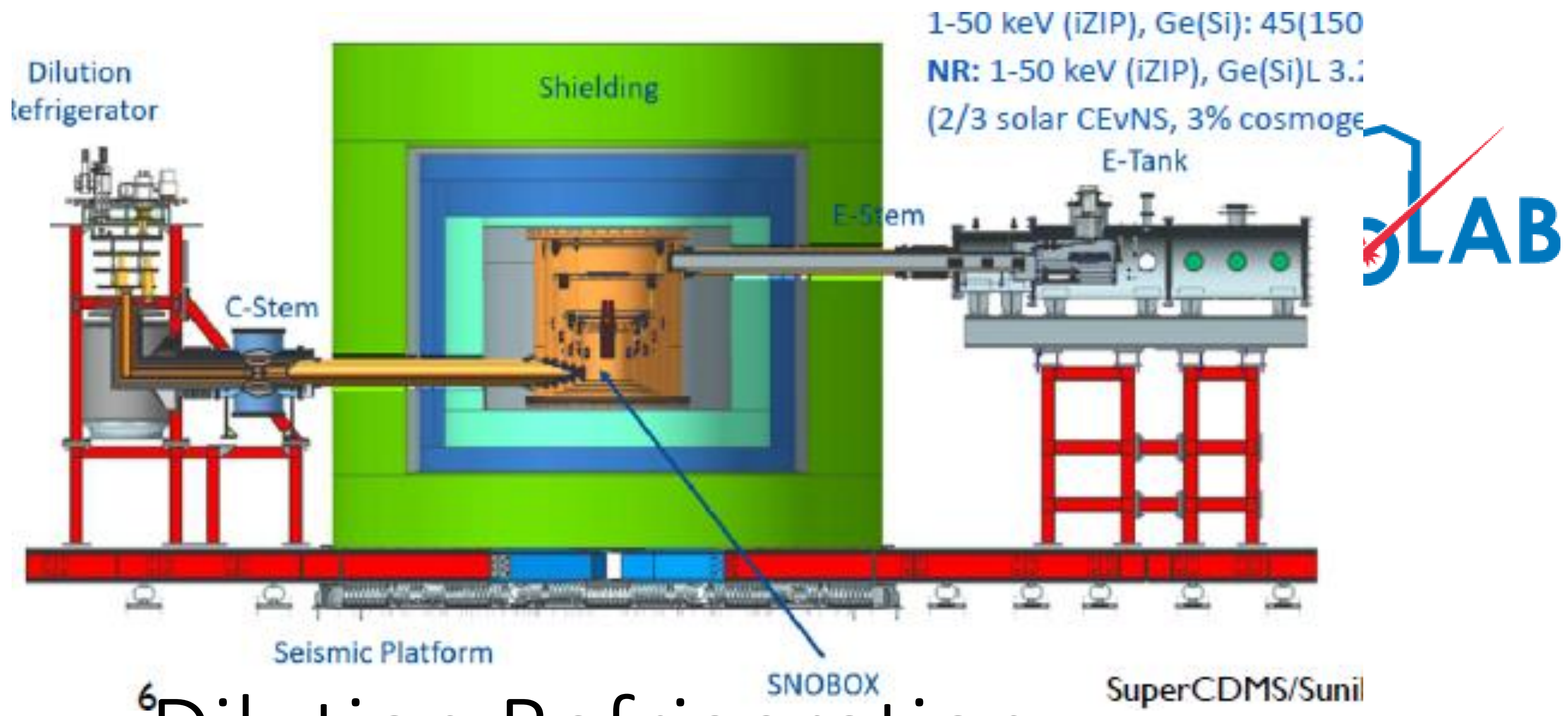


Adapted From: https://indico.cern.ch/event/1188759/contributions/5044015/

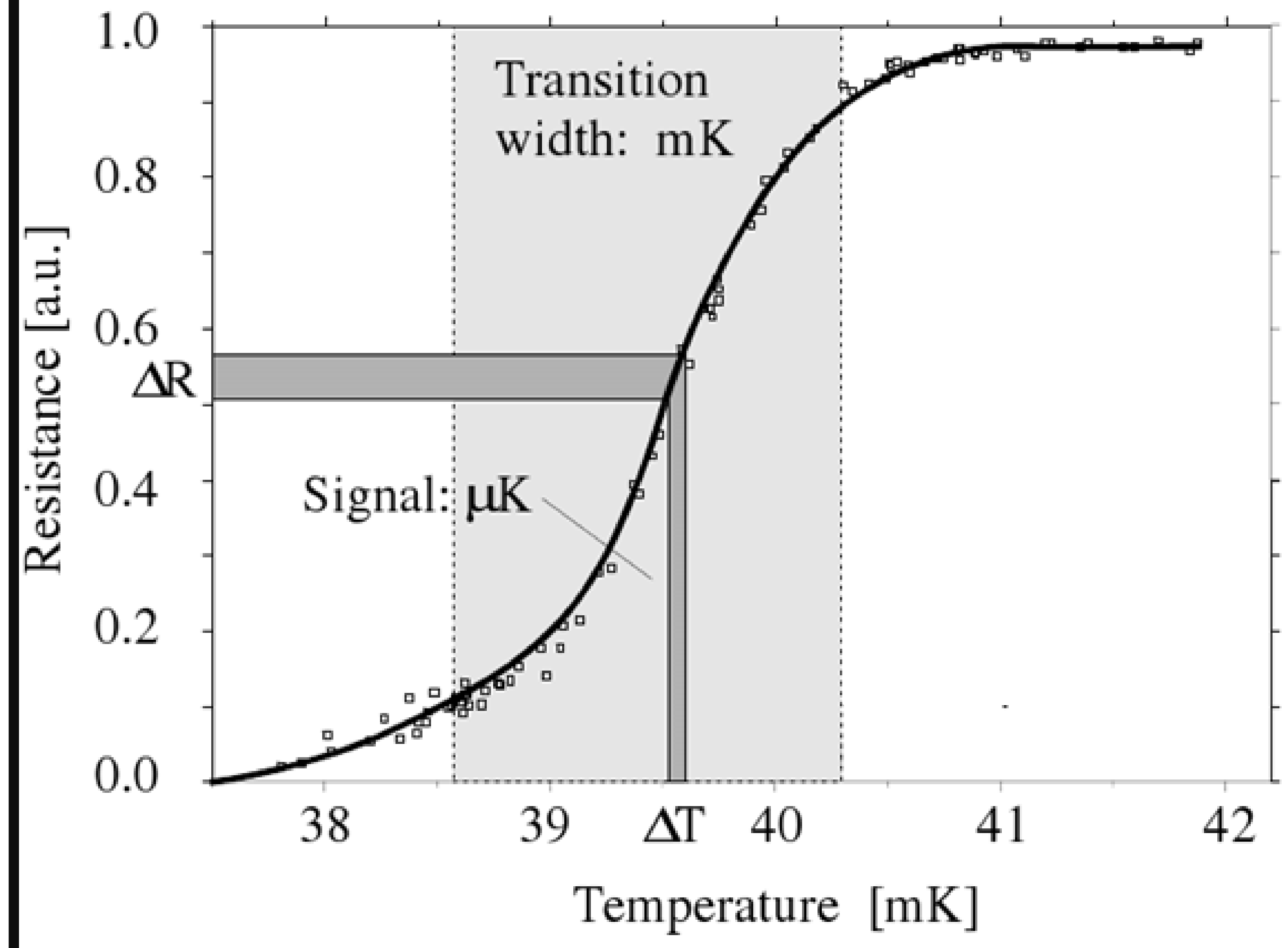
SuperCDMS



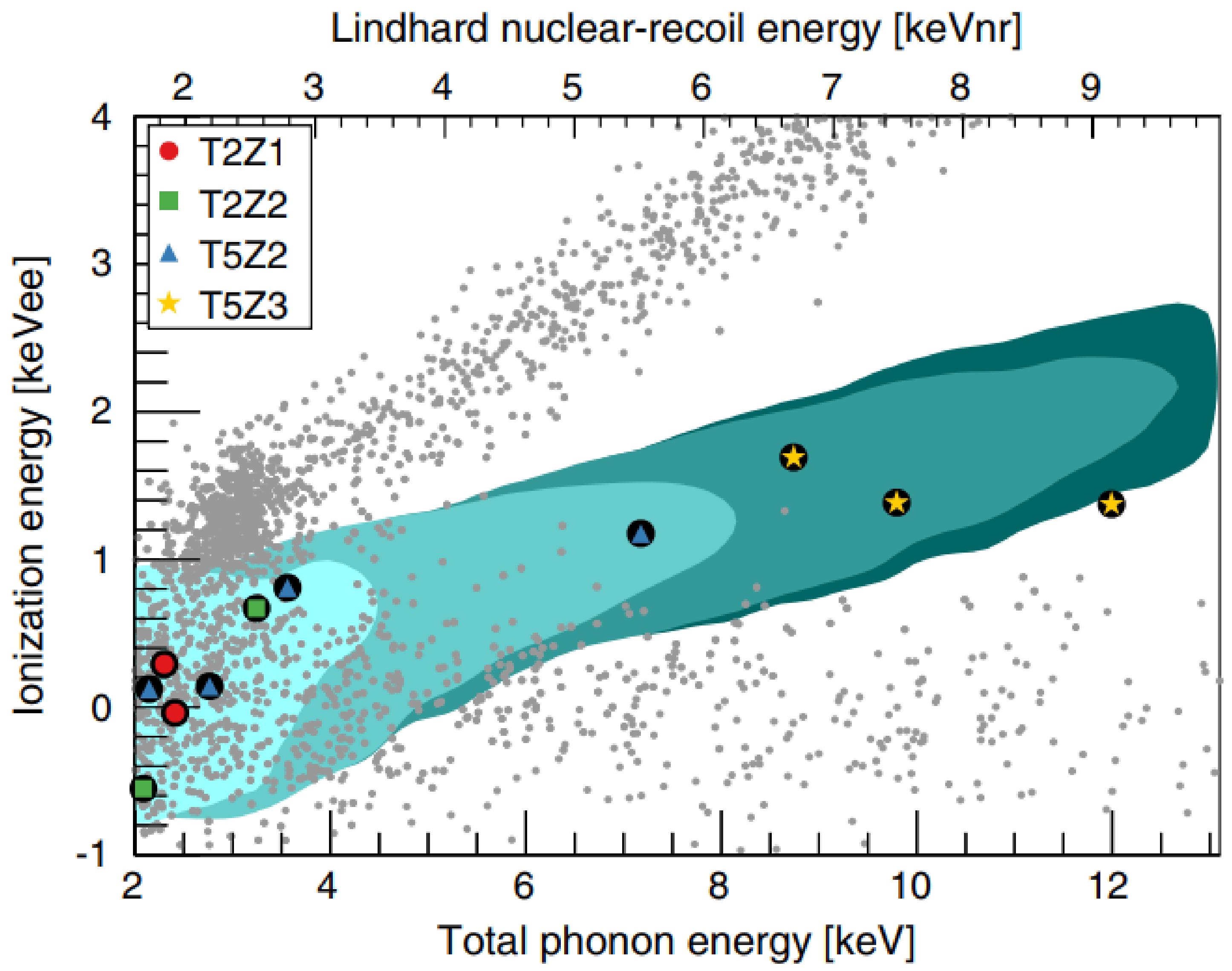
Dual-channel readout



Dilution Refrigeration



Transition Edge Sensors



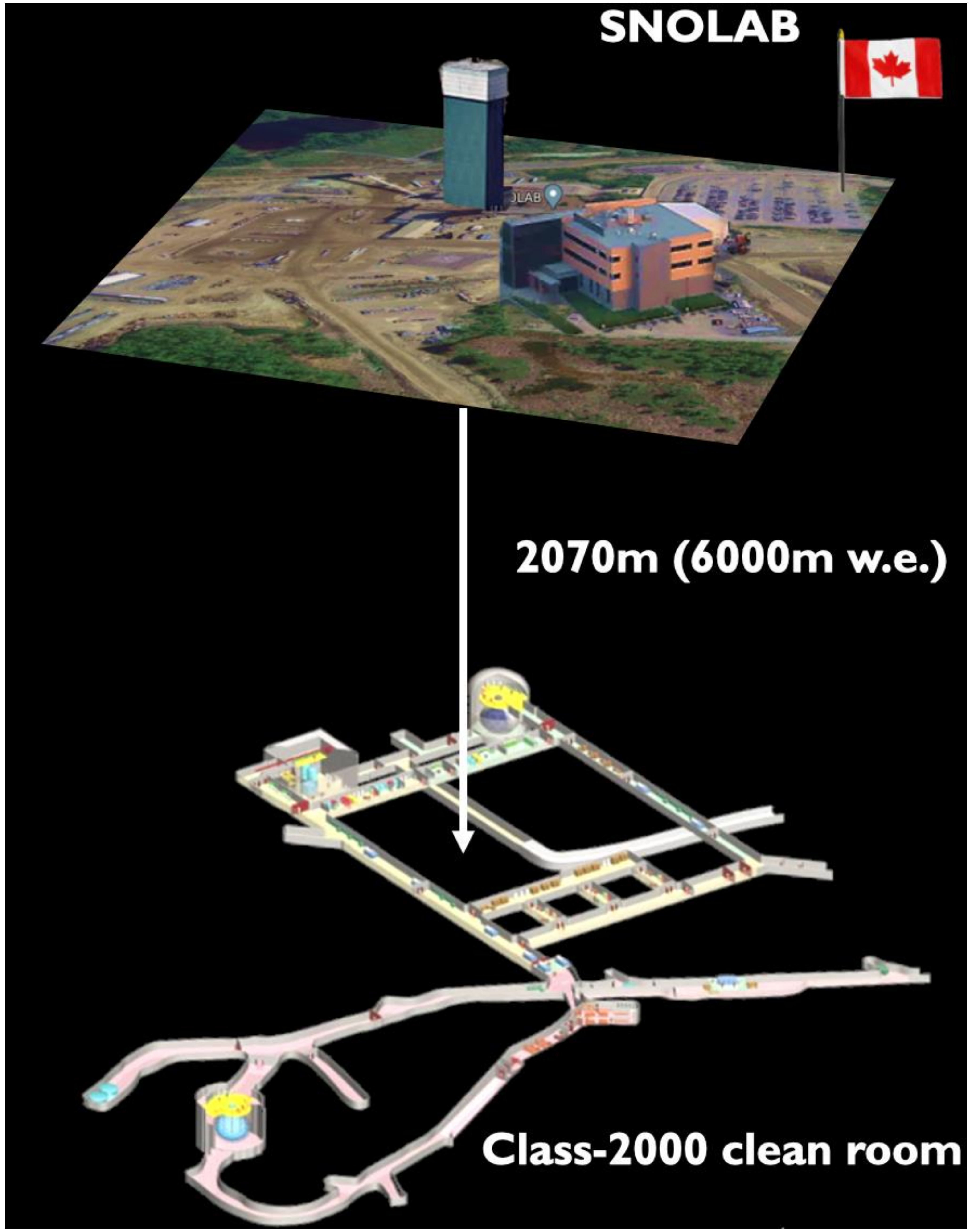
Particle Discrimination

Underground Laboratory

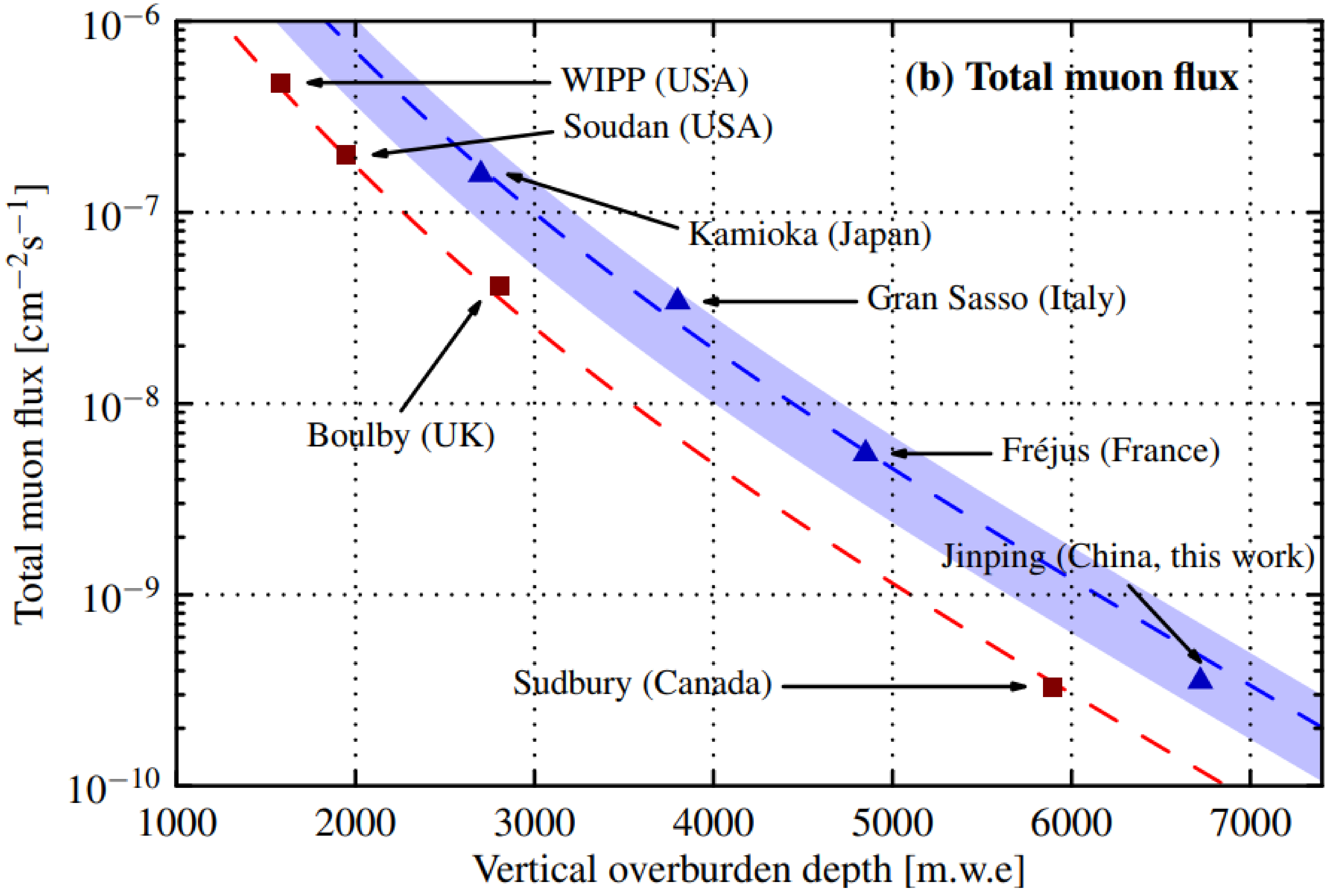
SuperCDMS at SNOLAB

Where is SNOLAB?

- SNOLAB is located at the Vale-Creighton mine just outside Sudbury
- On the traditional territory of the Robinson-Huron Treaty of 1850
- It is 2 km deep and operates as a class-2000 clean room
- Host to numerous particle physics experiments



Advantage at SNOLAB



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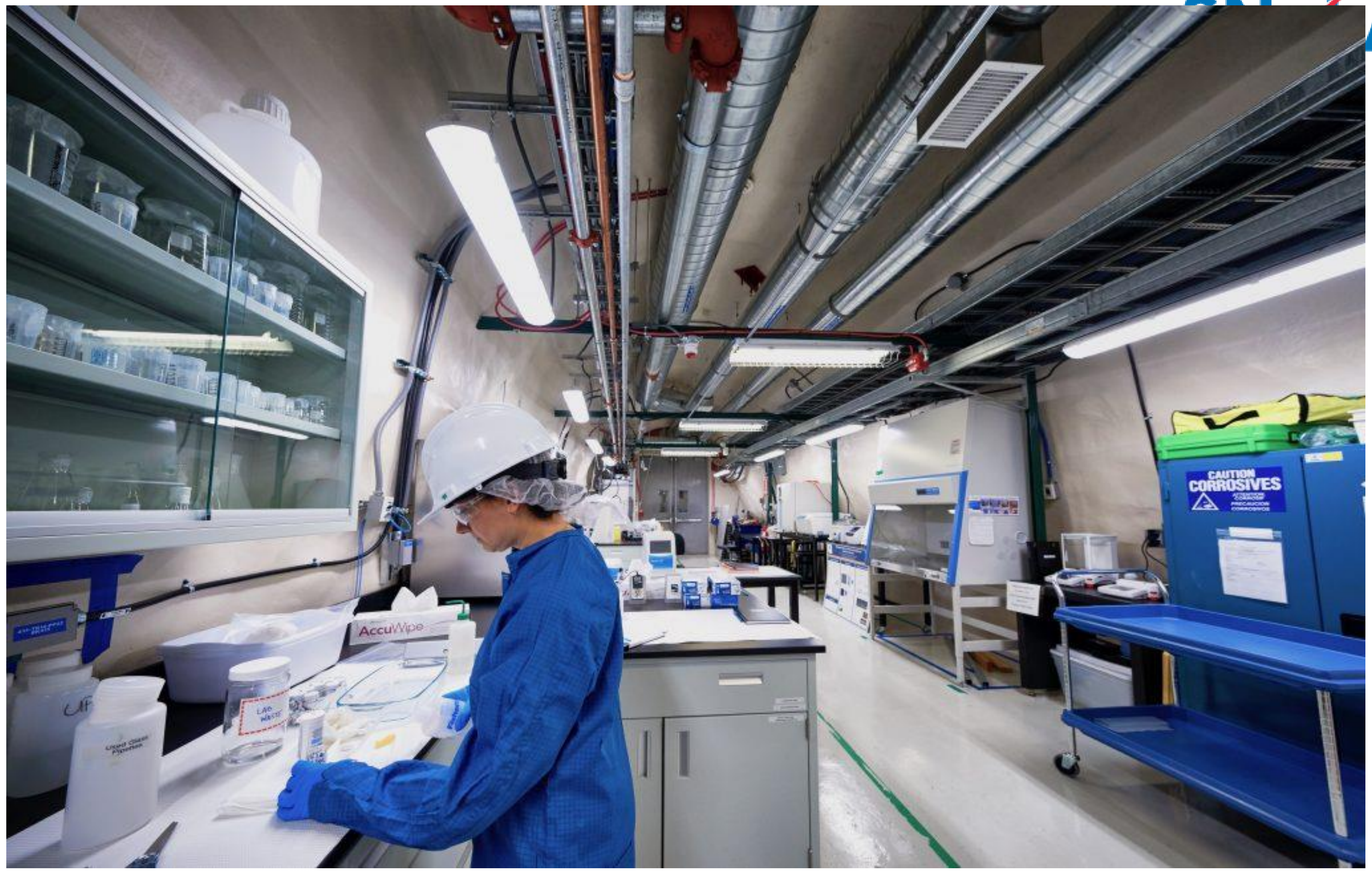


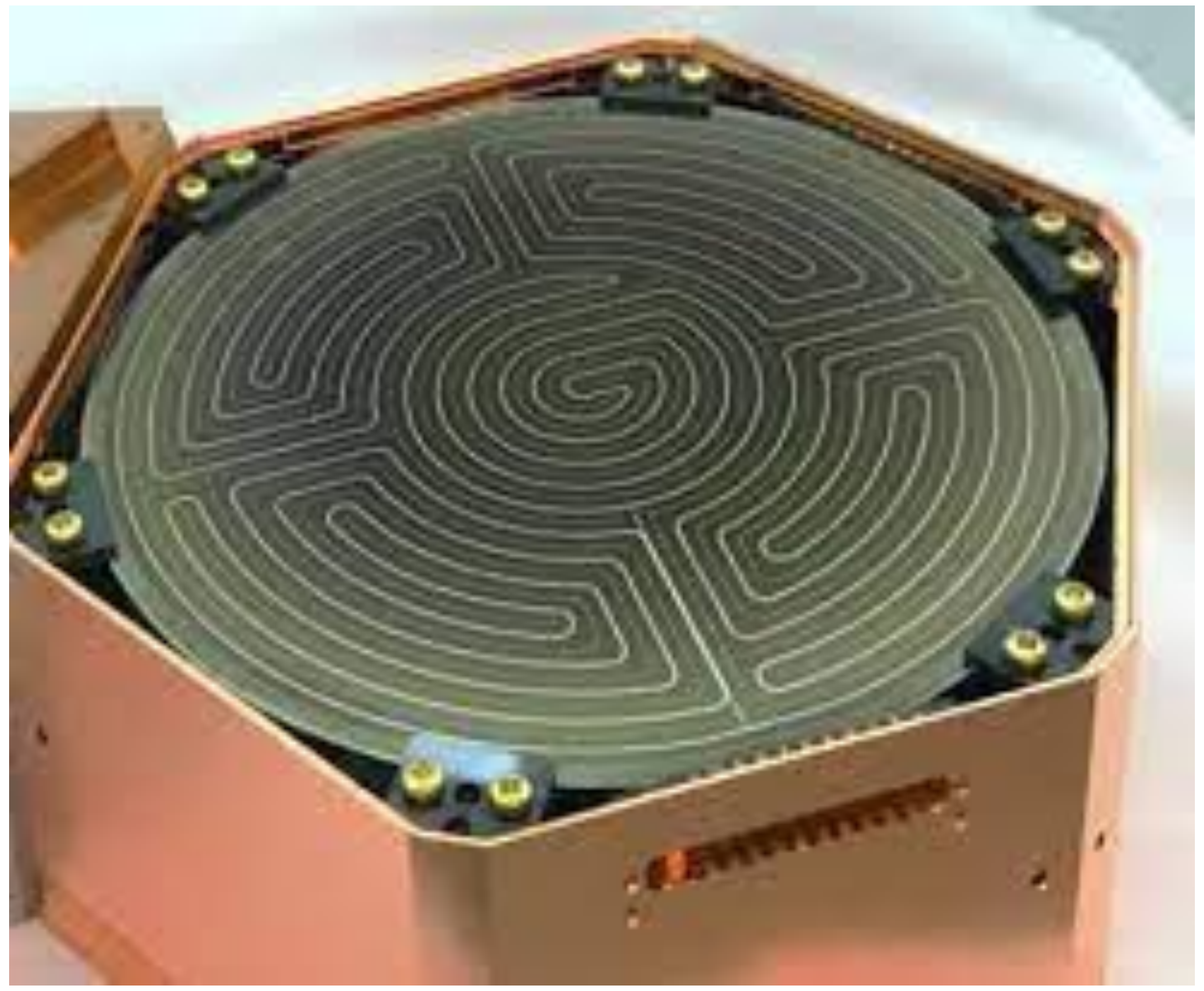
- One of the lowest muon flux in the world
- Class-2000 clean-room
- <2000 particle >0.5µm in diameter per cubic feet

SuperCDMS Collaboration

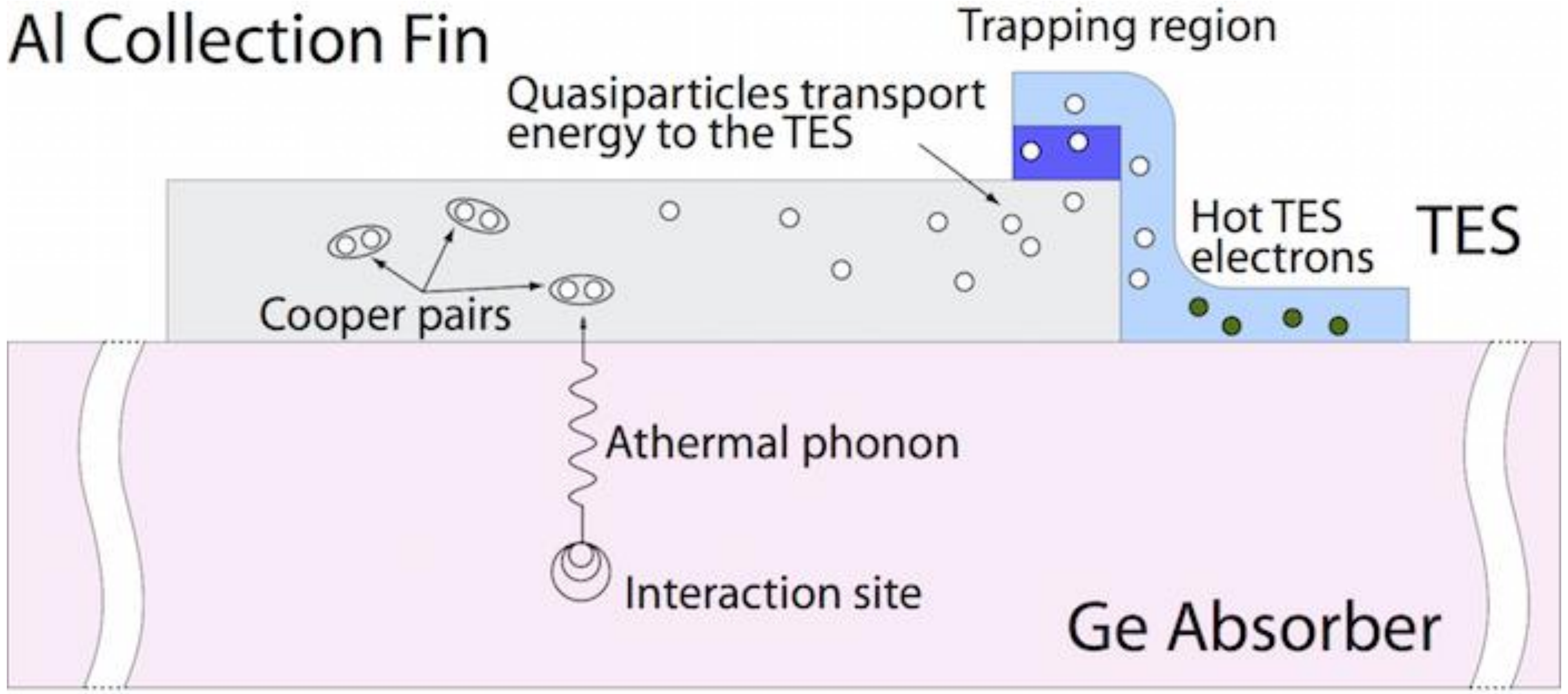
+1 (I just joined in January)

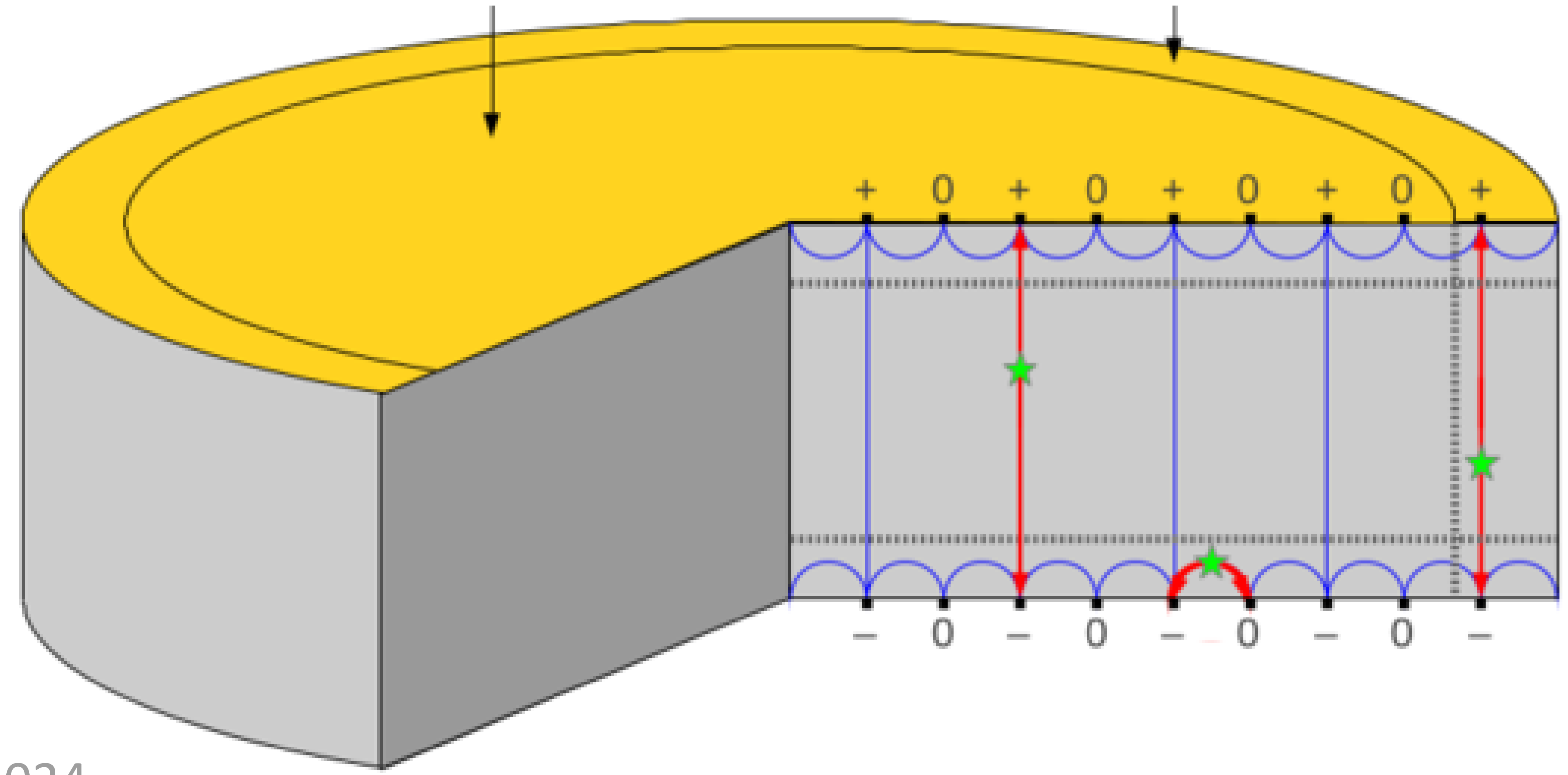
$\sim$ 100 scientists at 27 institutions from 6 countries

SuperCDMS Detectors

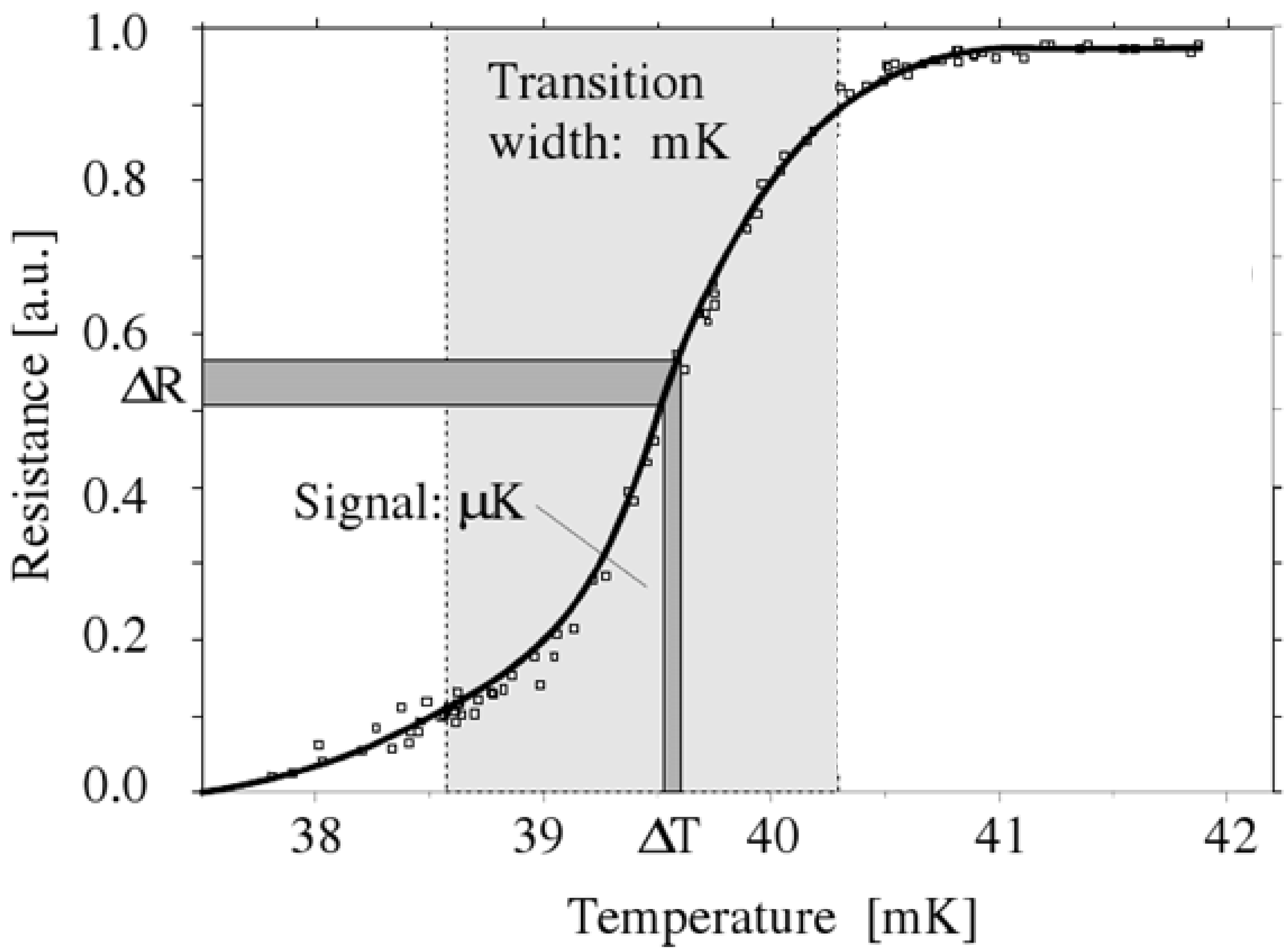


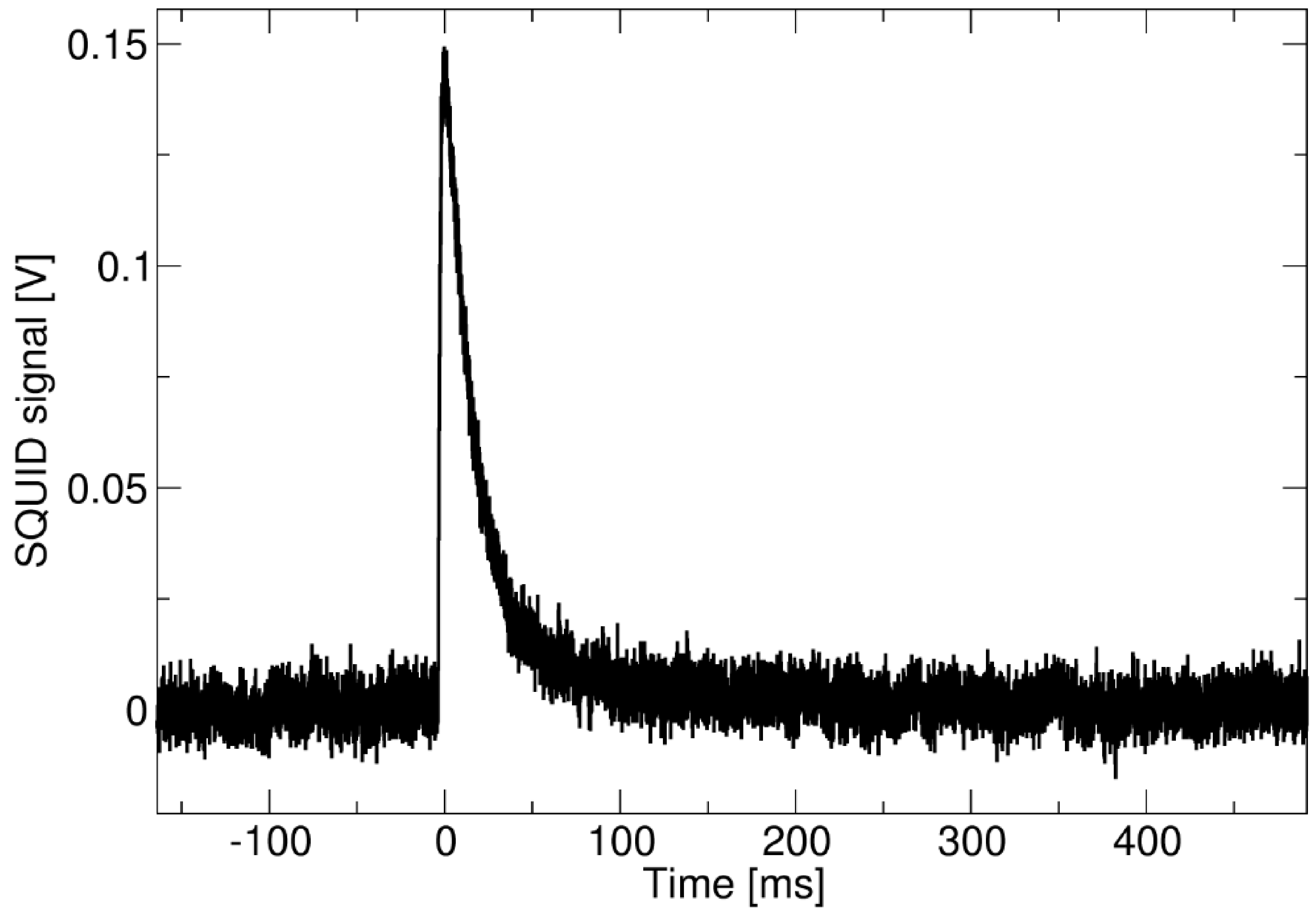
- Upgrade from CDMS and SuperCDMS Soudan (bigger and higher purity)
- Si(0.6 kg)/Ge (1.4 kg) cryogenic detectors
- Measure of **heat (phonon)** and **ionization**
- Heat is measured through Quasi-particle trap assisted electrothermal Feedback Transition Edge sensors
- Charge is measured through interleaved electrodes





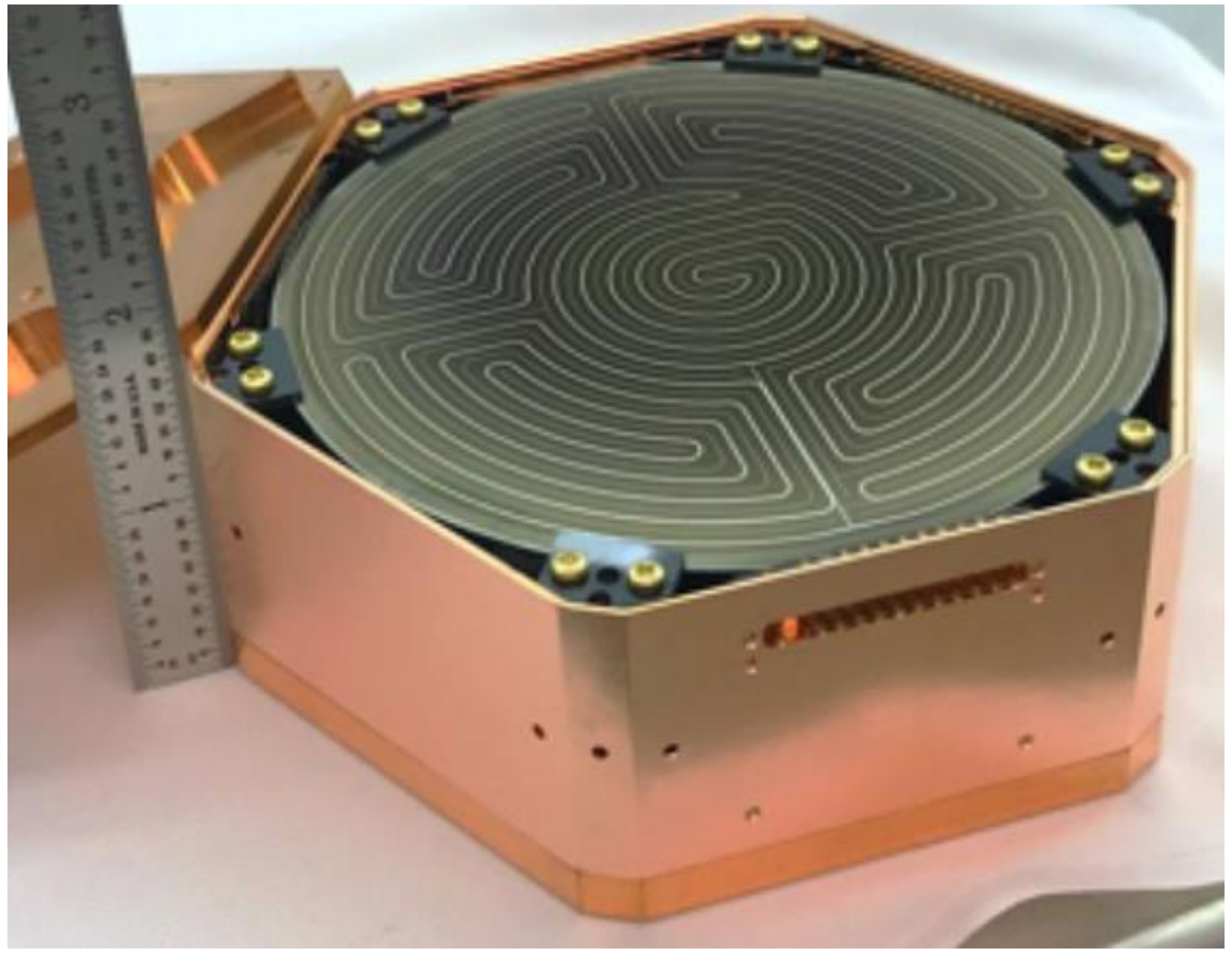
Transition Edge Sensors (TES)



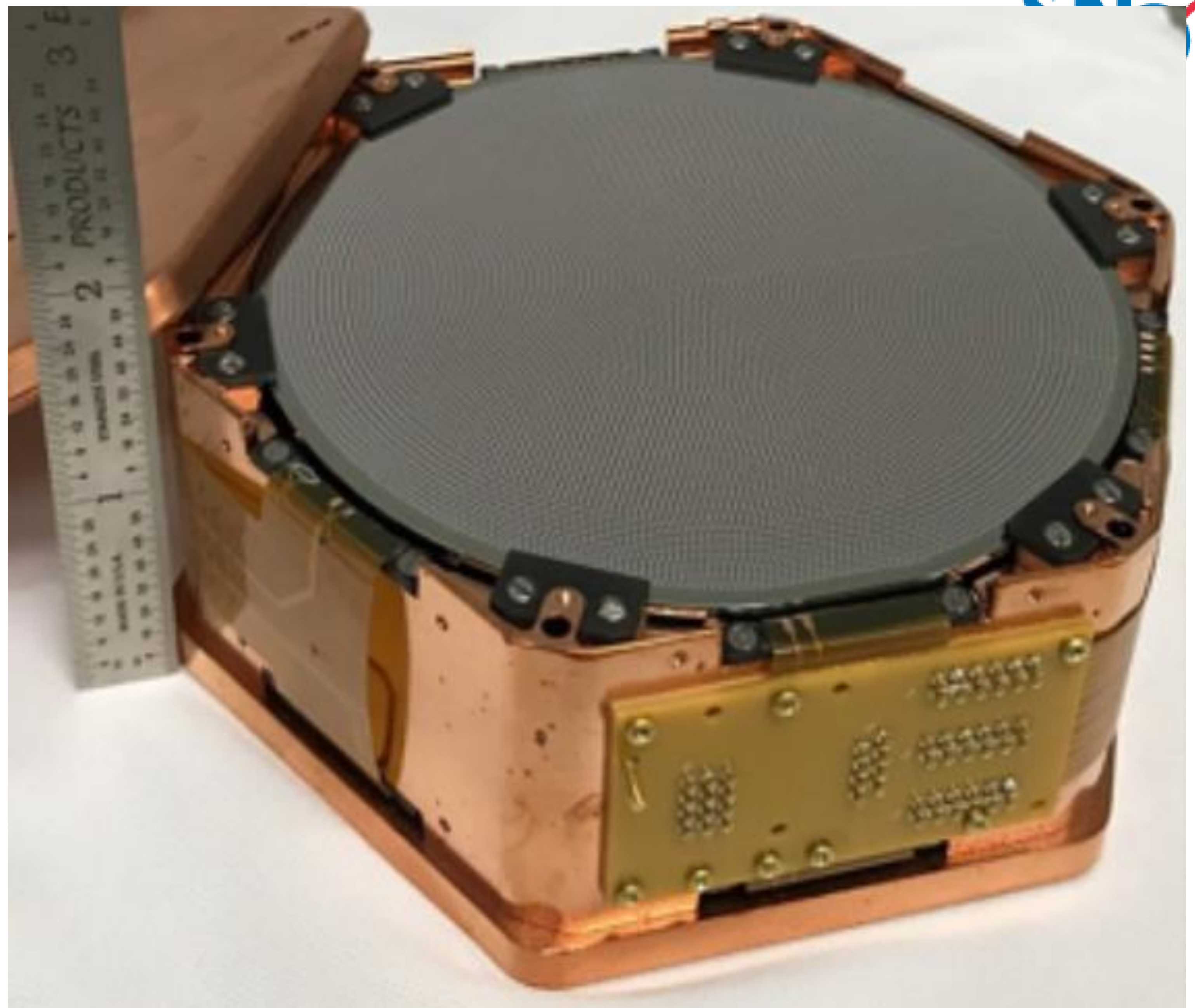


- Deposition of energy → Lattice vibrations (**Phonons)** → Change of temperature → Change in resistance → Signal
- Critical temperature reduced from 90 mk (Soudan) to 40 mk.
- Resolution will scale T_c^3
- TES are widely used in the field of rare event searches

iZIP and HV SuperCDMS Detectors

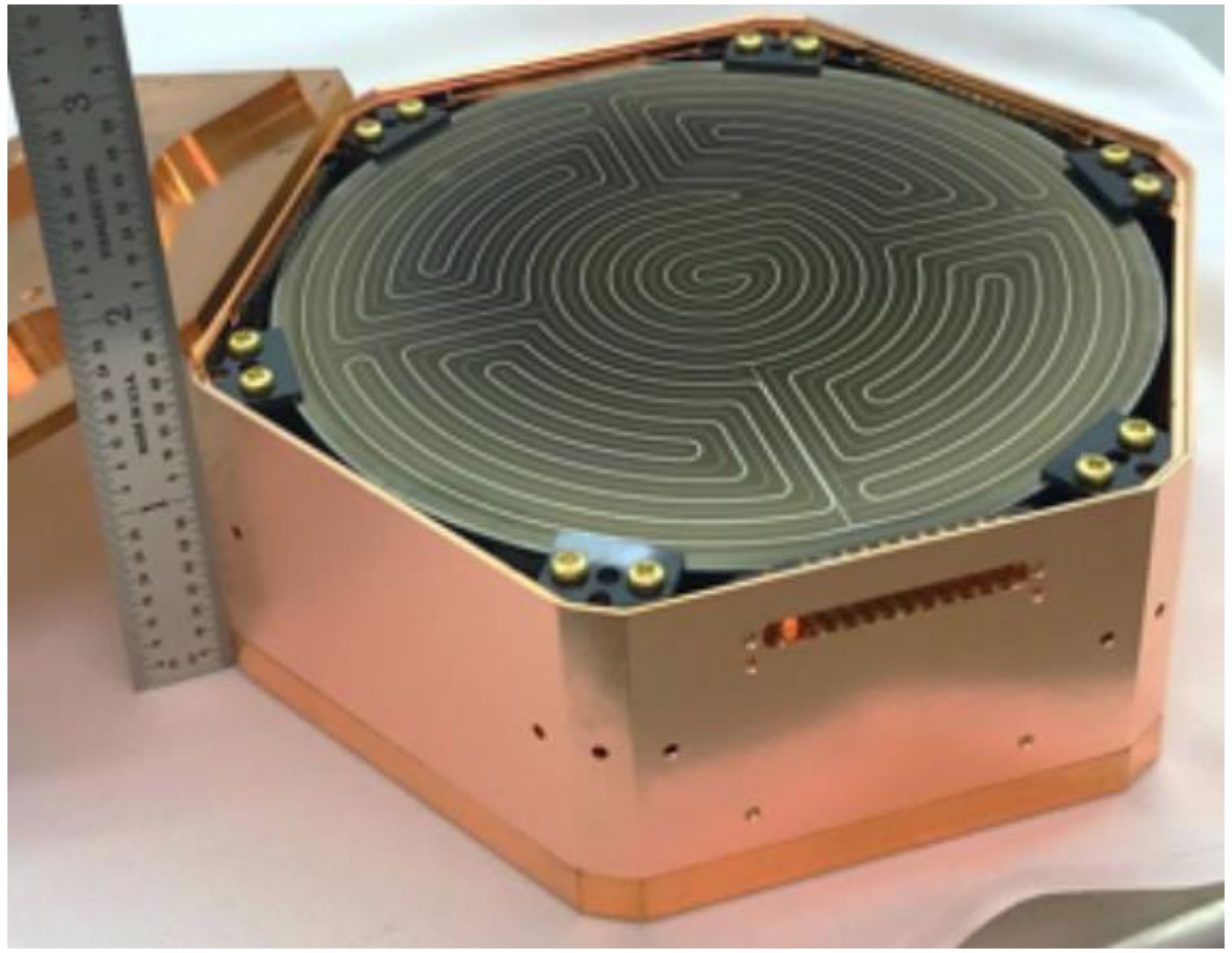


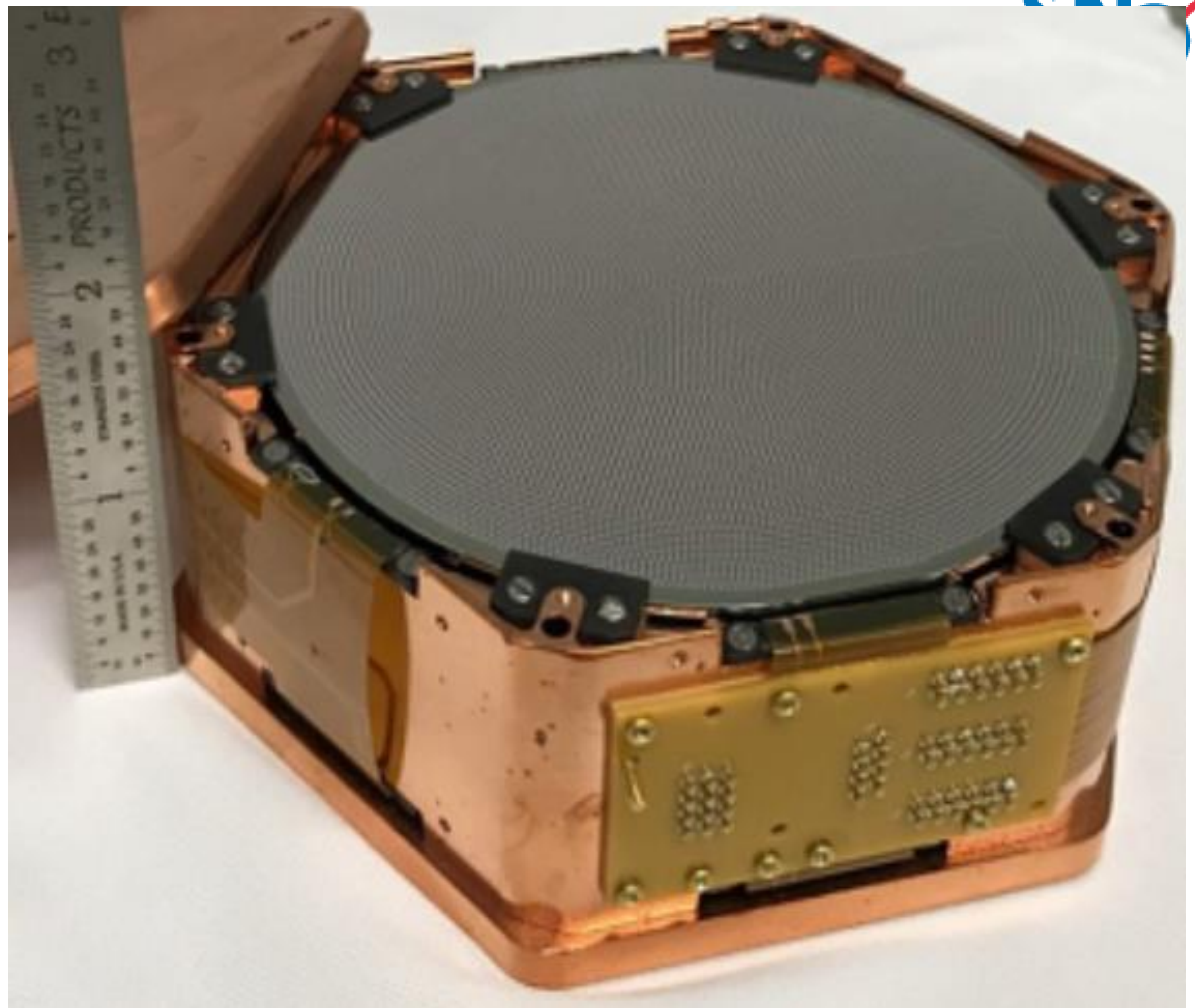
- iZIP (interleaved Z-sensitive Ionization and Phonon detector)
- 12 phonon, 4 charge channels
- Phonon and ionization channel allow for particle discrimination ER vs. NR



- HV (High Voltage detector)
- 12 phonon channels
- 100 V across the detector to exploit the Neganov-Trofimov-Luke (NTL) Effect

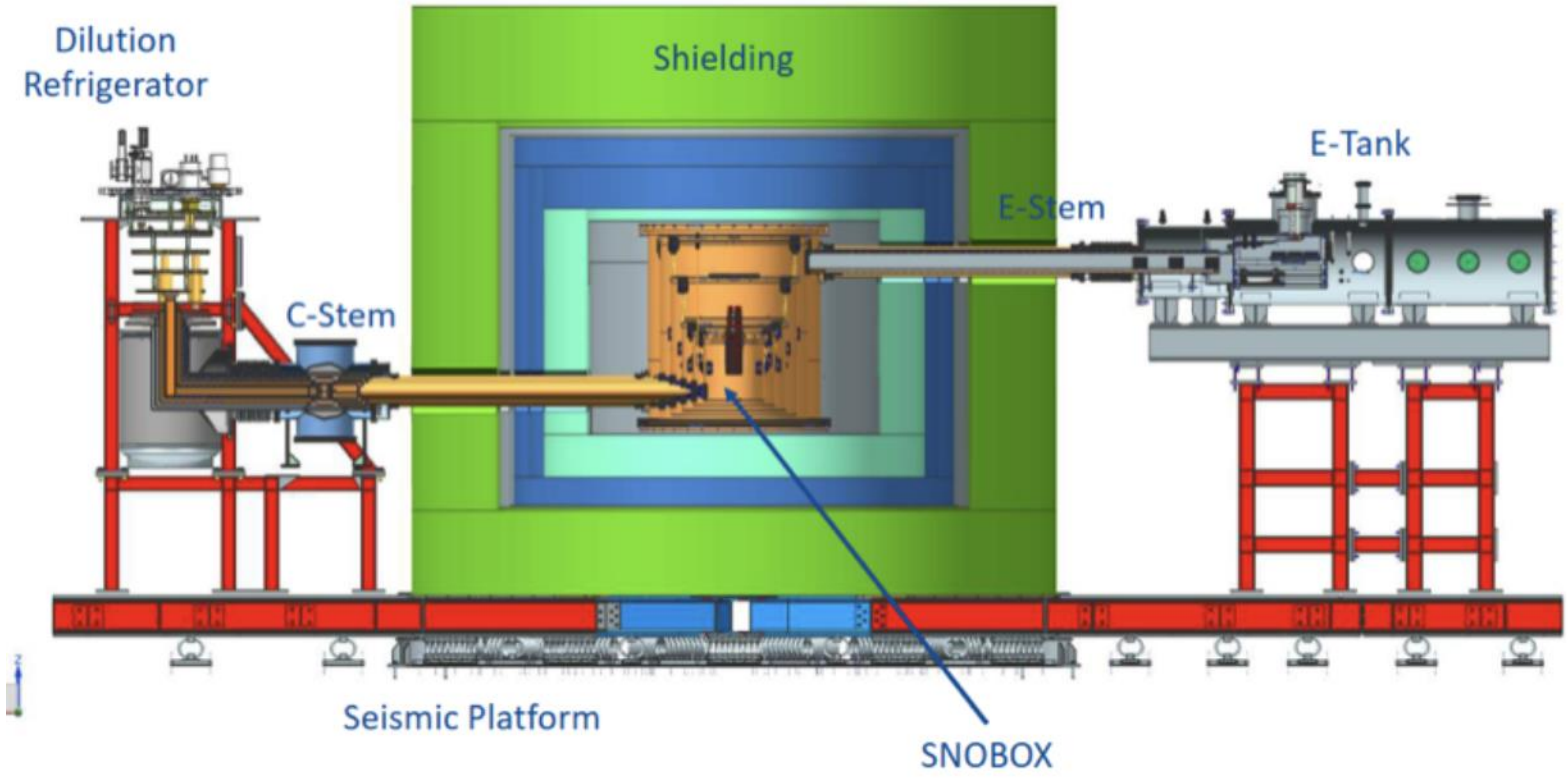
iZIP and HV SuperCDMS Detectors





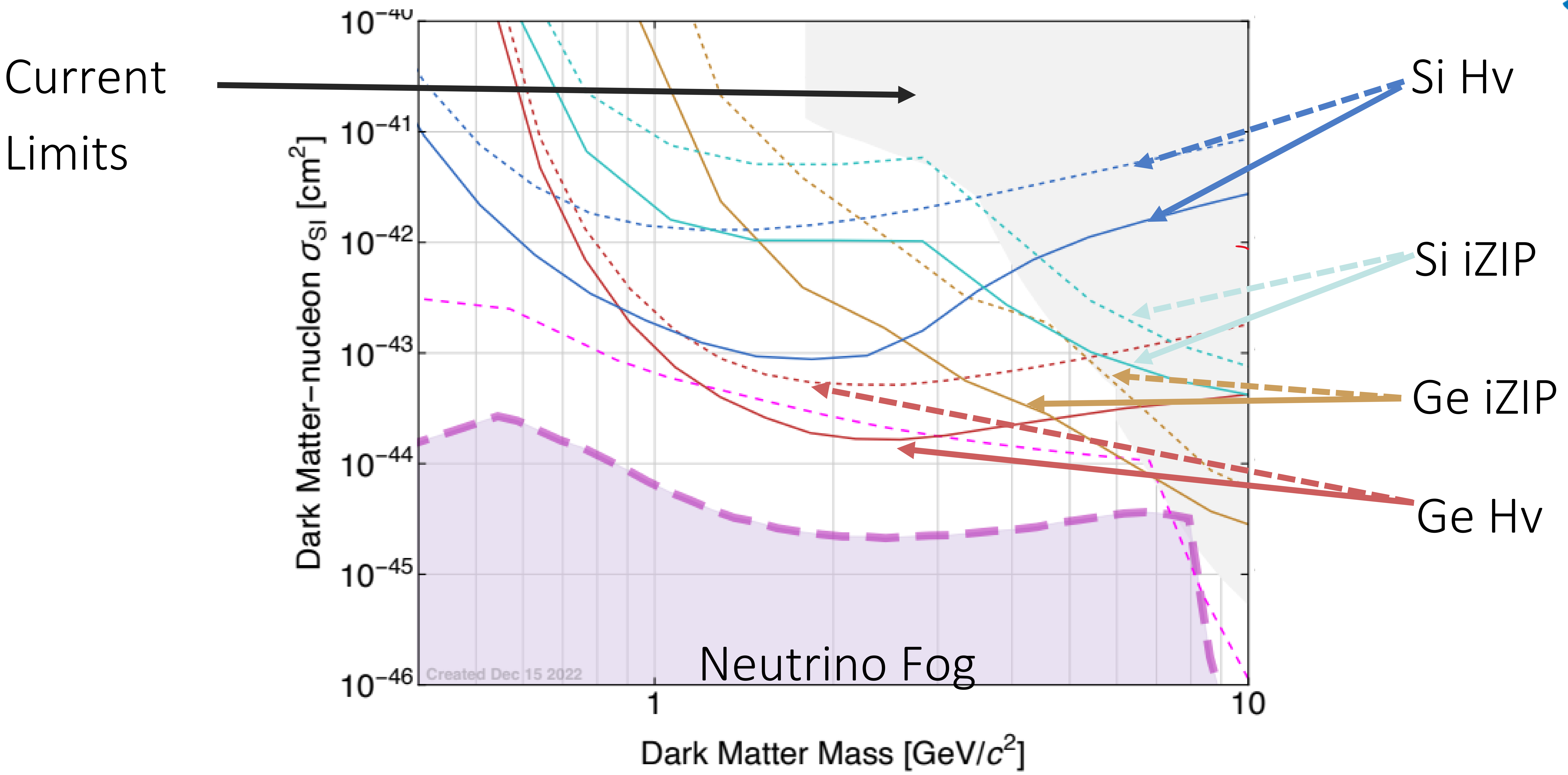
	iZIP		HV	
	Ge	Si	Ge	Si
Number of detectors	10	2	8	4
Total exposure [kg·yr]	45	3.9	36	7.8
Phonon resolution [eV]	33	19	34	13
Ionization resolution [eV_{ee}]	160	180	–	–
Voltage Bias ($V_+ - V_-$) [V]	6	8	100	100

SuperCDMS Experimental Setup



- Four towers (6 detectors each) will be used in the initial physics run, 30 kg total
- Towers will consist of Si and Ge targets iZIP (x12) and HV (x12) detectors

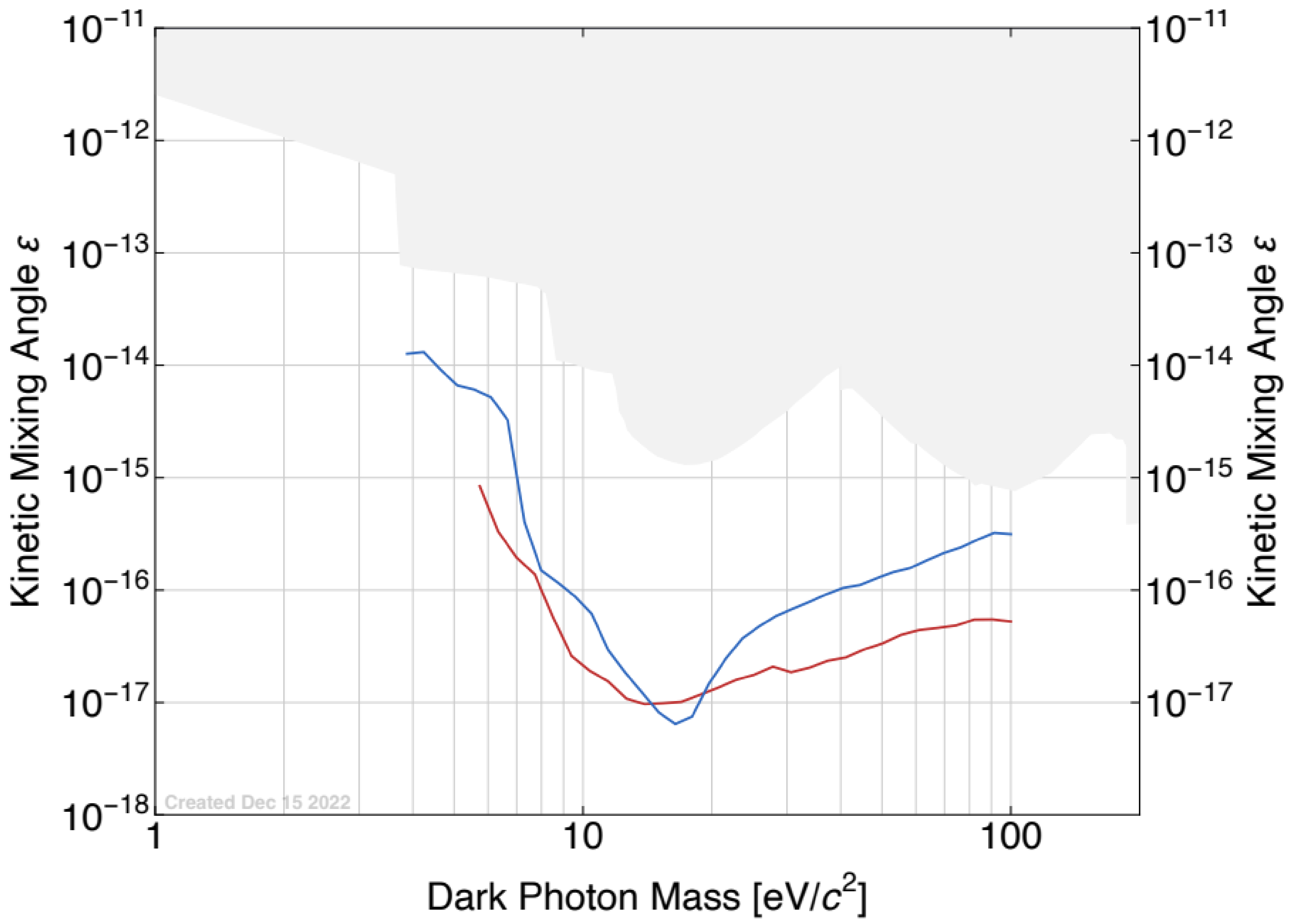
Dark Matter Sensitivity (4 year exposure)

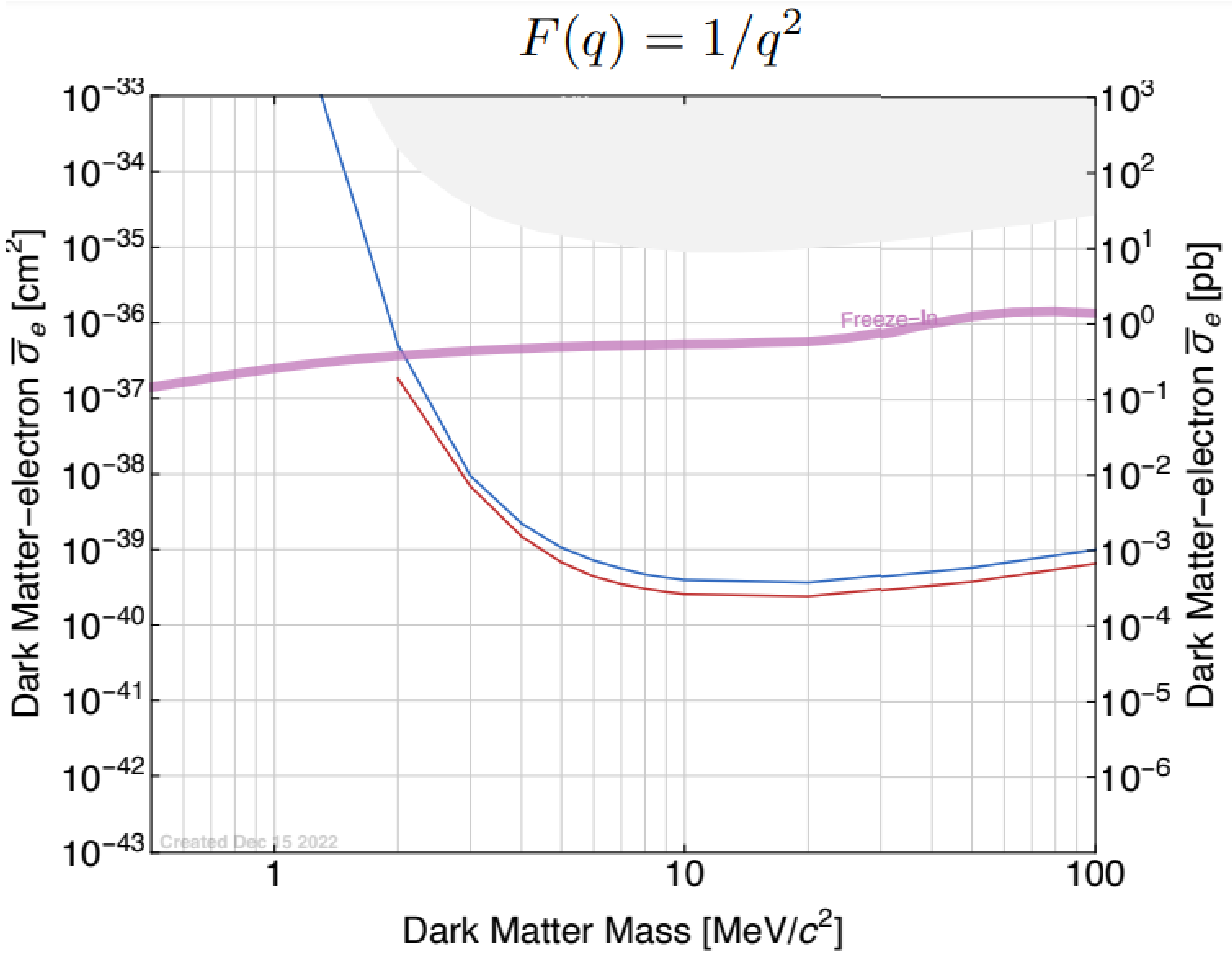


- 90% C.L exclusion sensitivity for the Yellin-Optimal method (dashed) and profile likelihood ratio (solid)

Non-WIMP Dark Matter Sensitivities

- SuperCDMS can probe even further by looking for dark photon (O(eV)) absorption or electron scattering light DM (O(MeV))

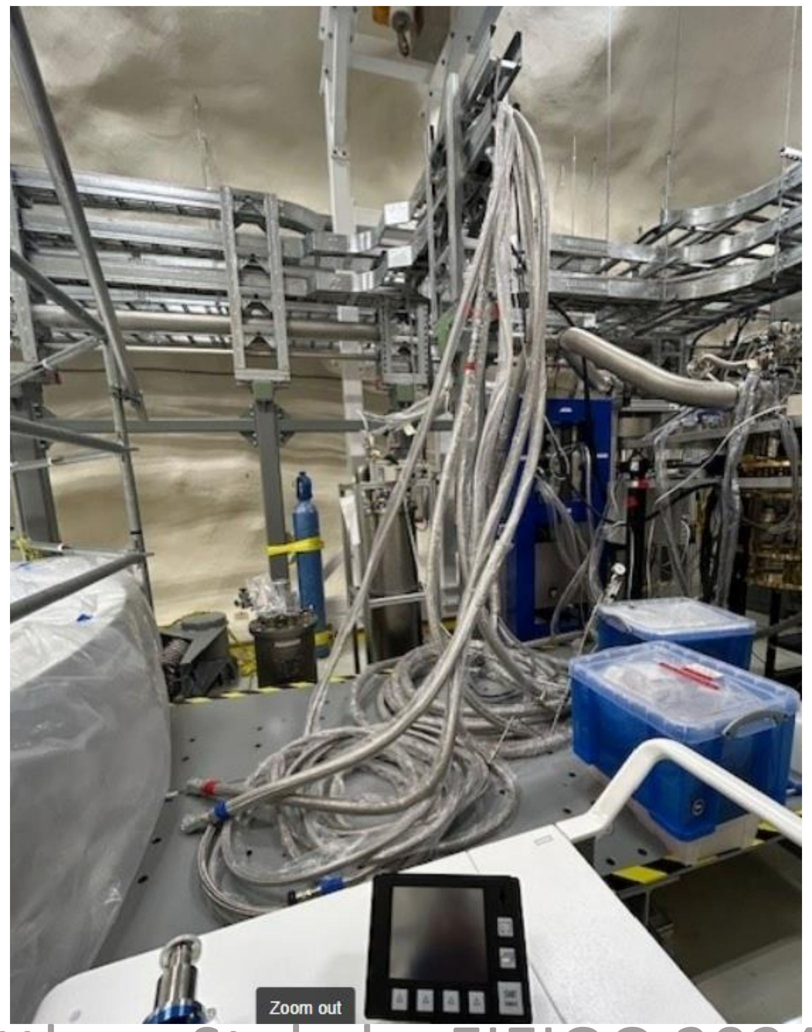




Current Construction

Tuesday

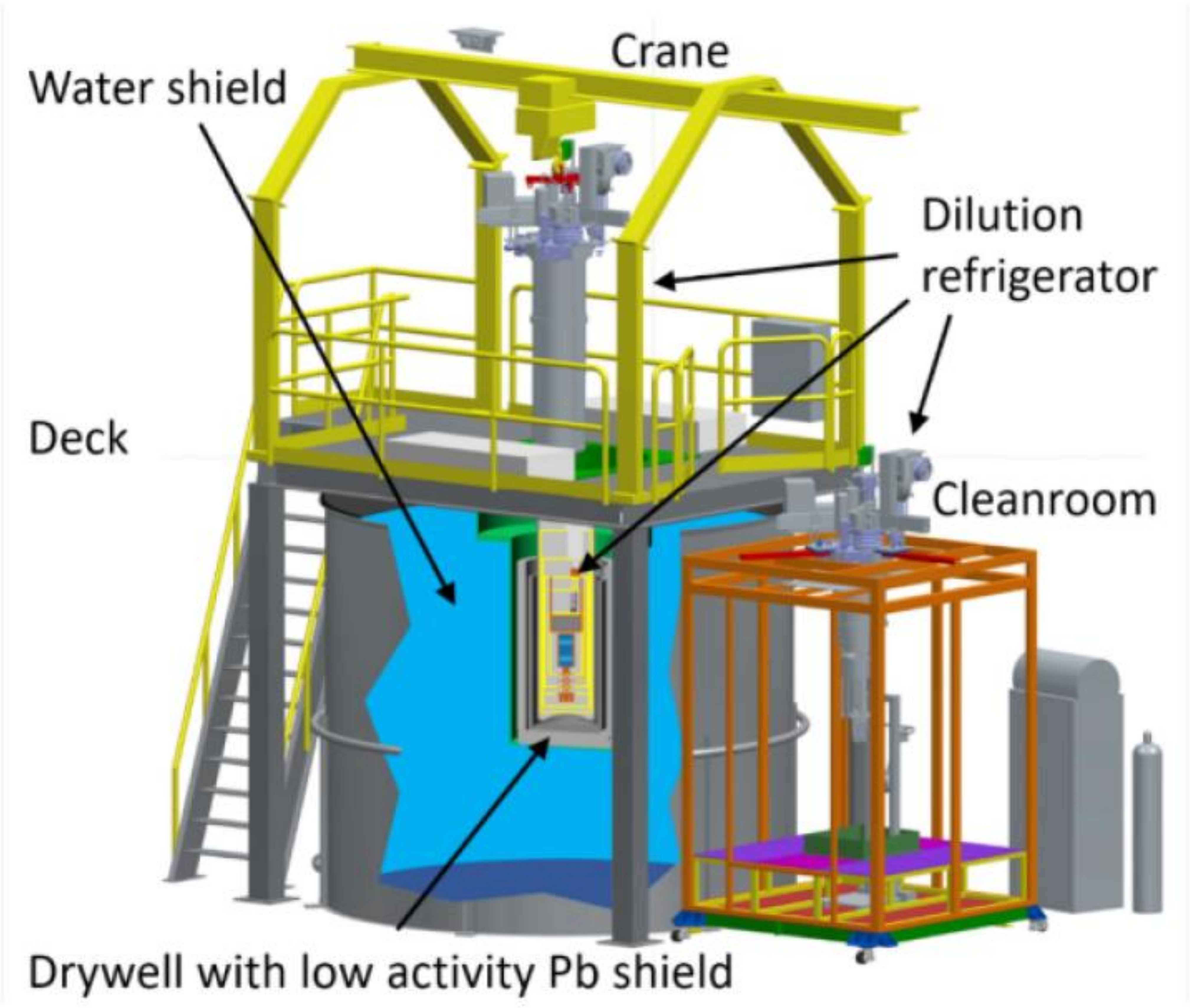
Thursday



Science data taking to begin next year!!!

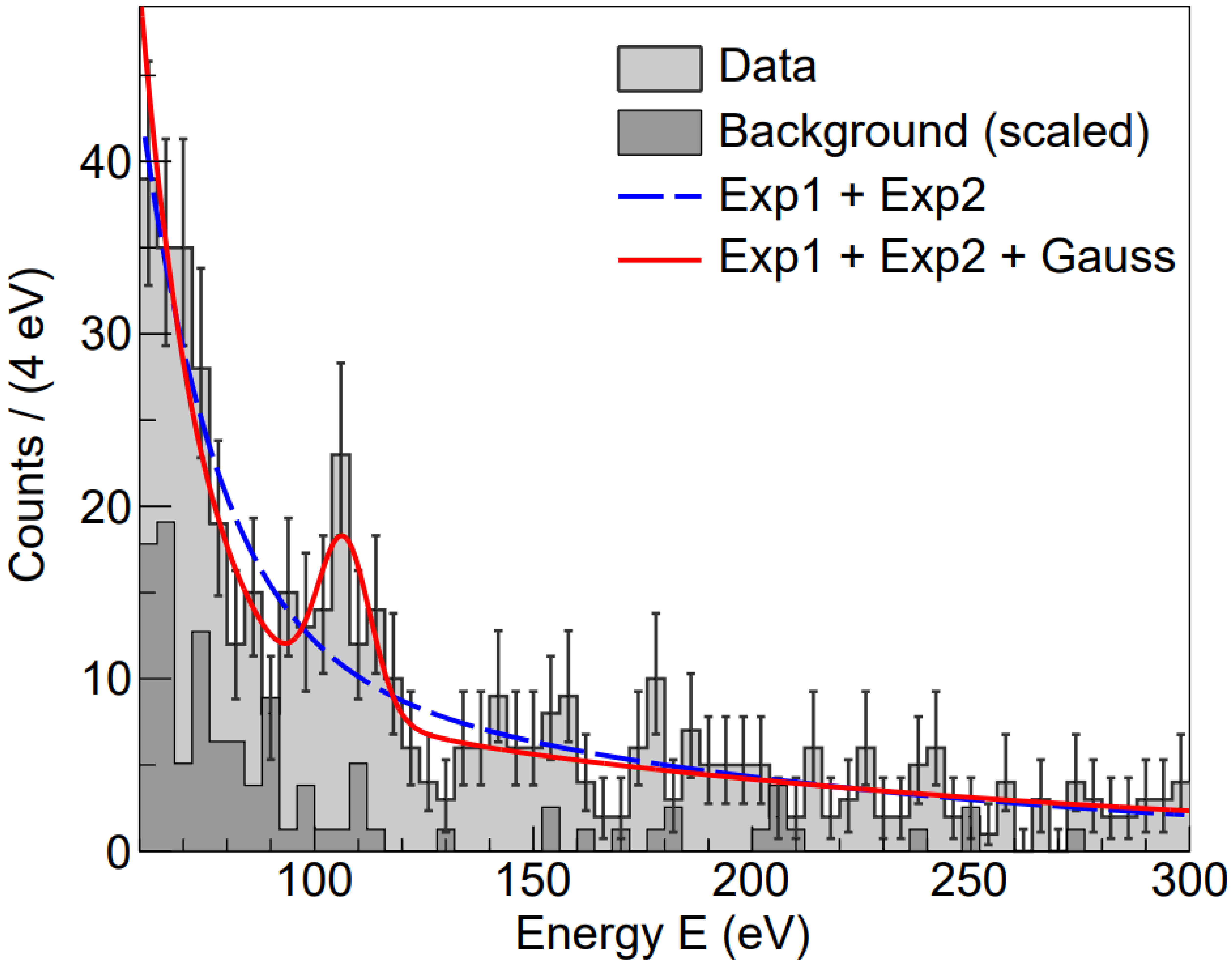
Testing at the CUTE Facility

- Cryogenic Underground TEsting Facility
- One full HV tower was placed into CUTE and operated for 6 months
- Allowed for detector characterization (SQUIDs, Tc etc.),Noise modelling, calibration, Pulse shape characterization, data pipeline testing, HV operation and more
- Currently HVeV detector is inside to test low energy excess



Challenges and Conclusions

Calibration Challenges



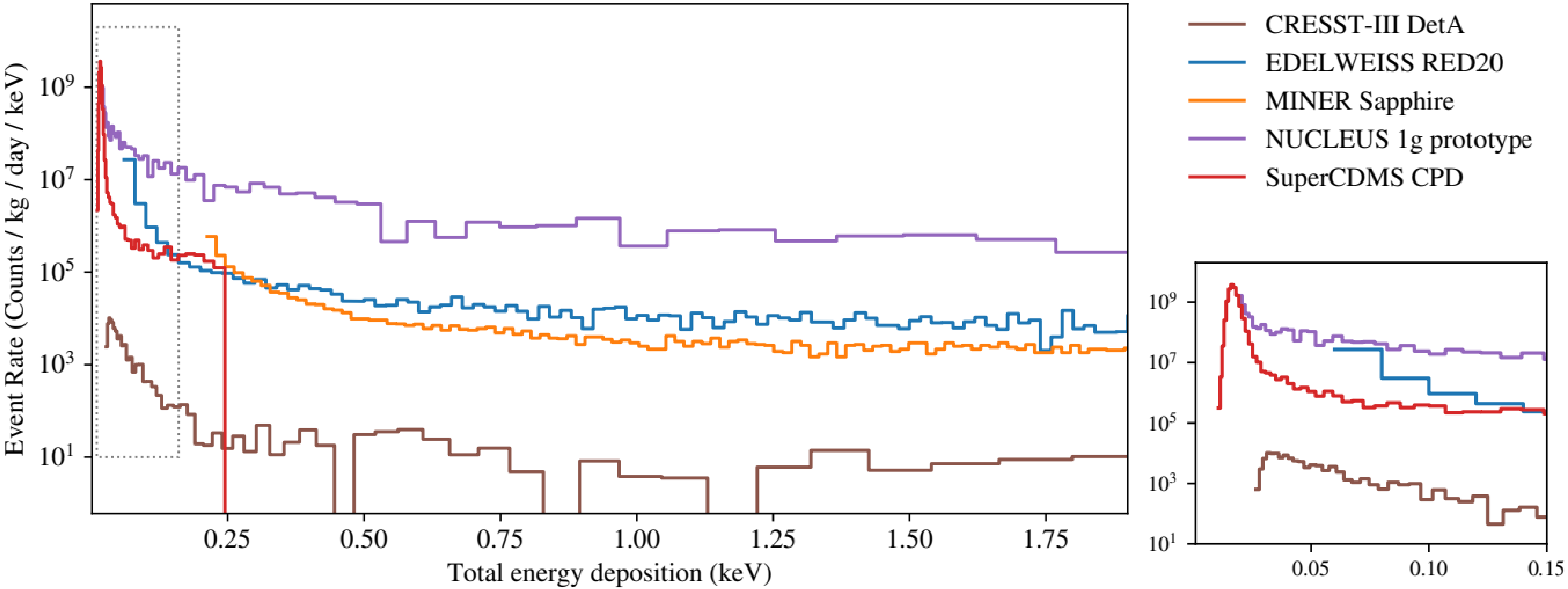
Low energy Compton scattering

Laser and LED photon absorption

CRAB (Calibrated nuclear Recoils for Accurate Bolometry)

- Thermal neutron capture -> Recoil induced from the de-excitation
- $CaWO_4$ 112.4 eV peak

Low Energy Excess



- Low-energy excess observed in a variety of experiments over a variety of conditions
- Common origin? Understanding the low energy frontier

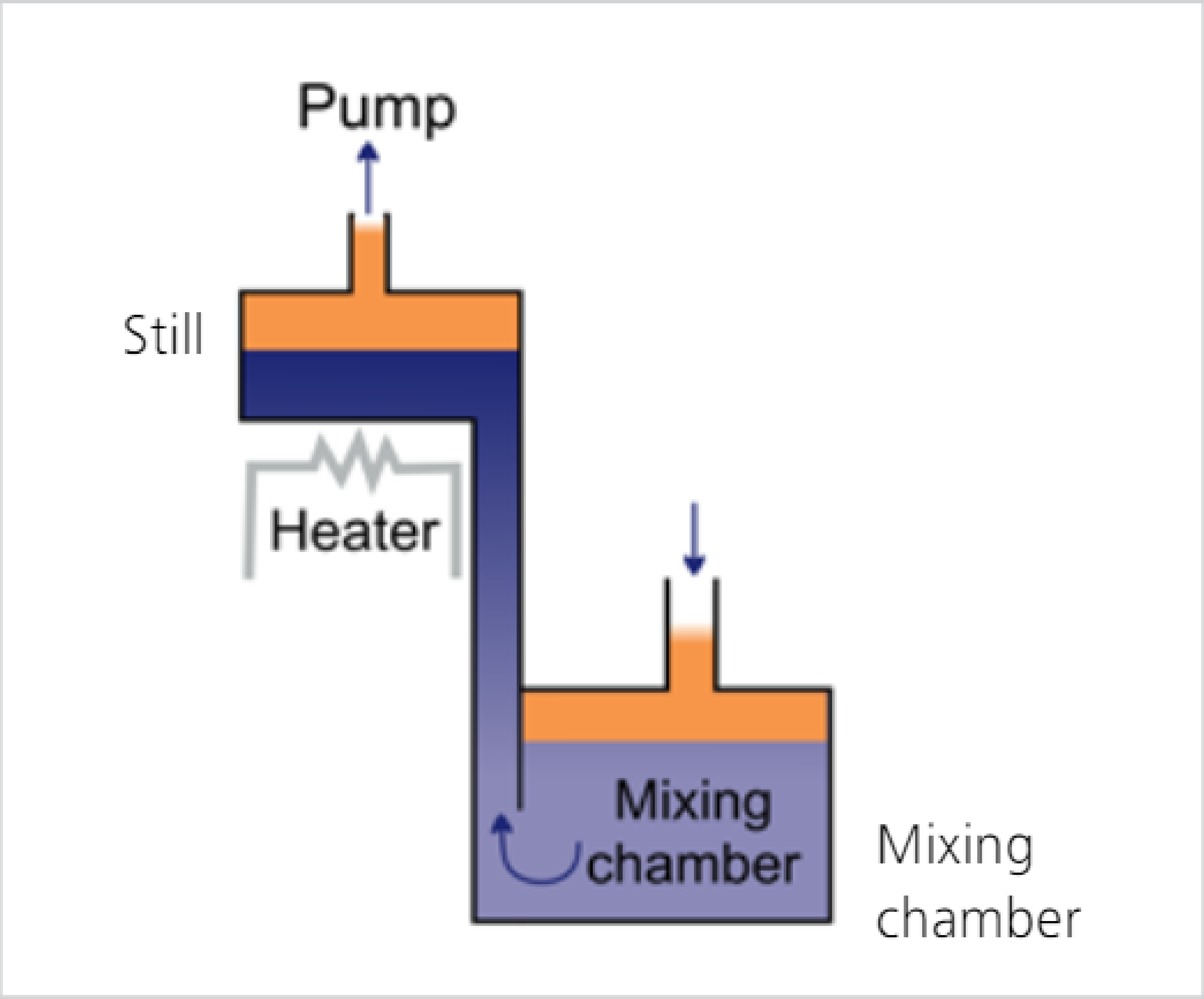
Conclusion

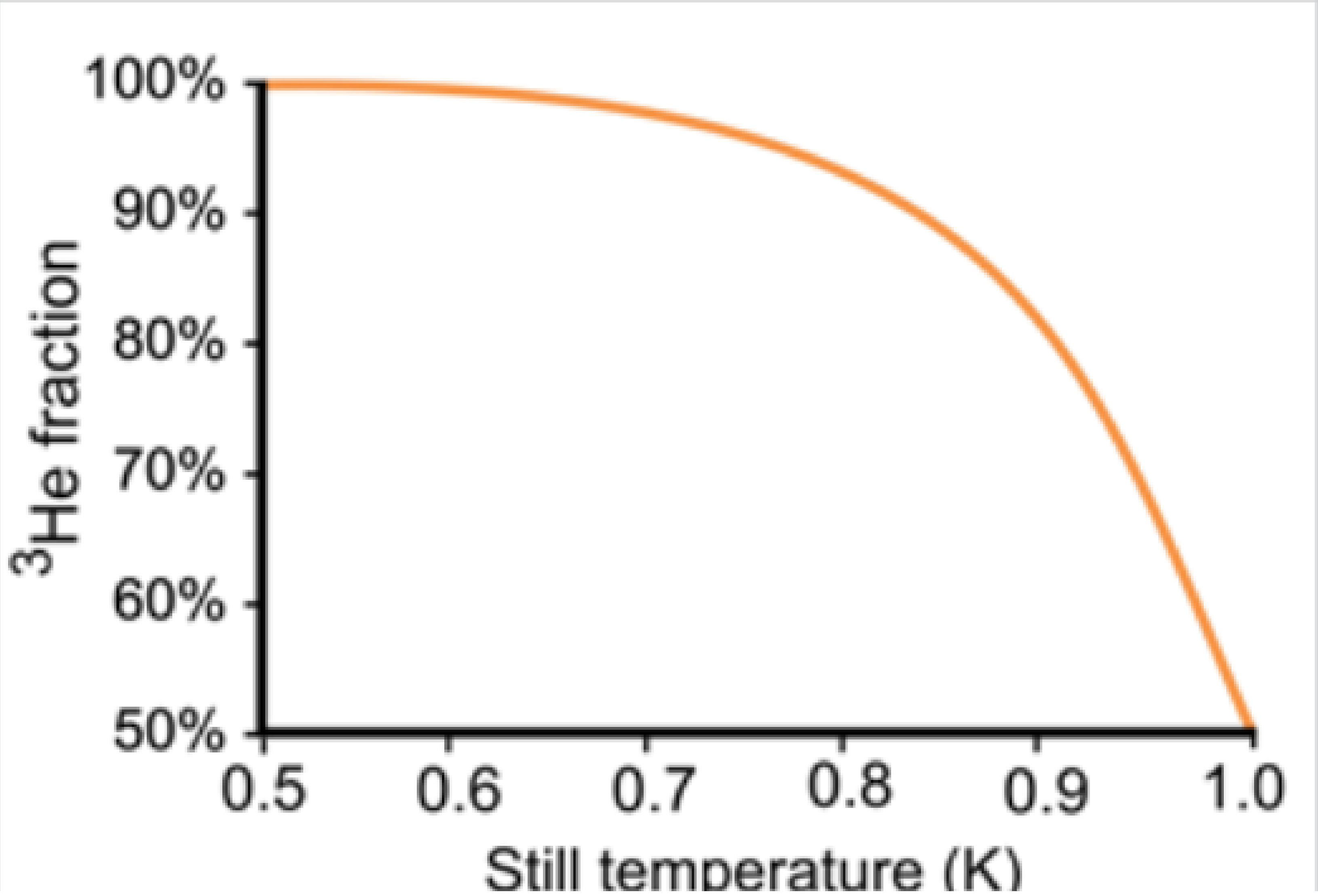
- Cryogenic detectors are powerful tools, that can be designed to try and answer the most challenging problems in particle physics
- Basic Design: 1) Absorber 2) Thermometer 3) Refrigerator
- Six month tower testing completed at SNOLAB
- SuperCDMS will push the boundaries of Sub-GeV dark matter searches at SNOLAB
- 30 kg of Si and Ge detectors. 4 towers with 6 detectors in each
- 12 iZIP and 12 HV detectors
- Currently experiment is under construction with data taking expected to begin next year

Extra Slides

How to remove only ^{3}He from diluted ^{4}He

- The mixing chamber connects to a distiller ('still'), which distils the ^{3}He from the ^{4}He due to the difference in vapour pressure
- Heat is applied to the still (otherwise it will quickly cool to a temperature where the vapour pressure is so low that the circulation stops)
- More power to the still means a higher circulation rate, which means more cooling power
- On the other hand, if the still temperature is too high, the vapour pressure of ^{4}He will become significant. Circulating too much ^{4}He will reduce the dilution process efficiency
- In practice, a ^{3}He fraction of ~90% in the circulated gas is acceptable, resulting in an optimal still temperature of 0.7 - 0.8 K. The approximate relationship between still temperature and ^{3}He fraction is shown in the figure (right)



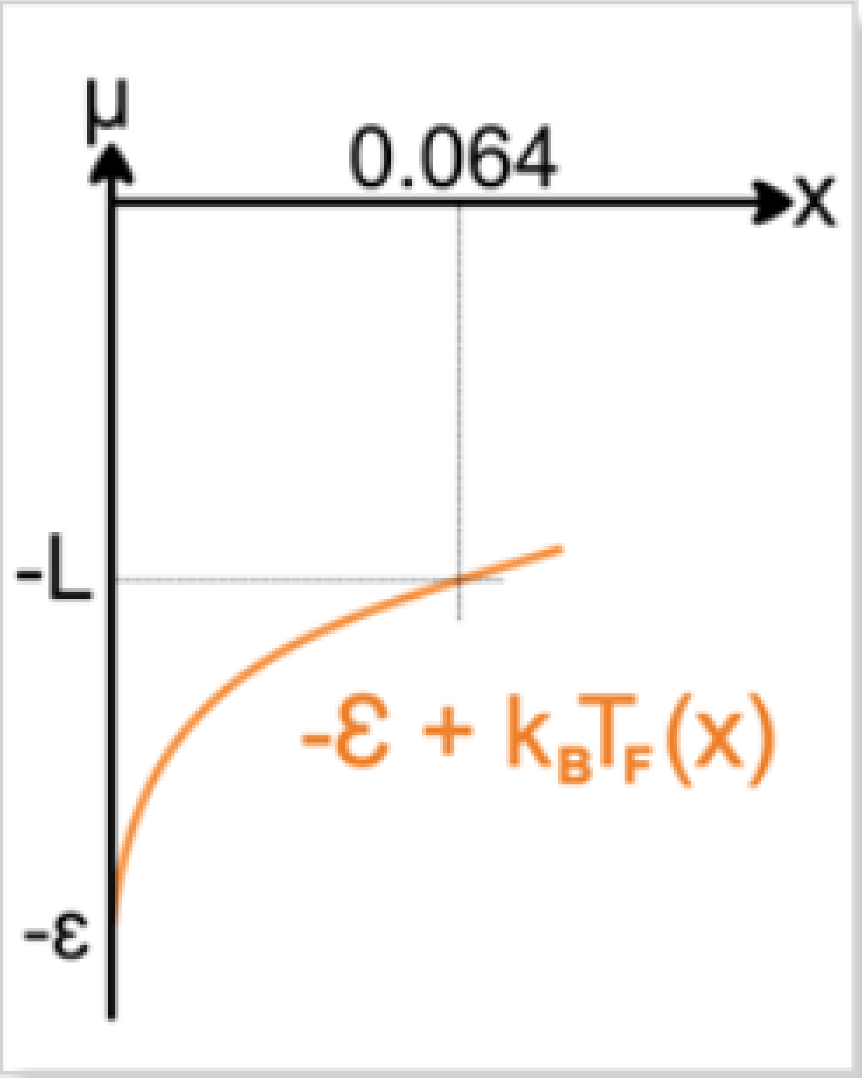


https://nanoscience.oxinst.com/assets/uploads/NanoScience/Brochures/Principles%20of%20dilution%20refrigeration_Sept15.pdf

Finite solubility of ^3He in ^4He explained

Imagine we could cool two containers of pure ^3He and pure ^4He separately to 0 K before they are allowed to interact. The first ^3He atom to venture across the boundary will consider whether to stay in the ^4He environment or to go back.

- ^3He is the lighter of the two isotopes. This means it has a larger zero-point motion, in other words it will occupy a larger volume
- The ^3He atom will find itself closer to surrounding ^4He atoms than to surrounding ^3He atoms
- Because the binding between the atoms is due to van der Waals forces, the shorter distance results in ^3He being more strongly bound in ^4He than in pure ^3He
- Since the ^3He atom is more strongly bound in ^4He it will 'prefer' to stay in the ^4He liquid. This is the reason for the finite solubility at 0 K
- To understand why the finite solubility is 6.4%, we need to look in more detail at the binding energy. Consider the chemical potential μ of ^3He in ^4He and let's say the binding energy of a single ^3He atom in ^4He is ε
- The binding energy of ^3He in ^3He is equal to the latent heat of evaporation of pure ^3He, L, so ε must be greater than L as shown in the figure below right
- The first two ^3He atoms will occupy the lowest energy state – ε with anti-parallel spins
- Additional ^3He atoms have to obey the Pauli Exclusion principle and therefore occupy increasingly higher energy states (described by the wave function solutions to the Schrodinger equation of a 'particle in a box')
- The Fermi energy $k_B T_F$ will increase with the He concentration x, as shown in the figure
- At a concentration of 6.4%, the chemical potential equals that of a ^3He atom in pure ^3He. This is therefore the finite solubility of ^3He in ^4He at 0 K



https://nanoscience.oxinst.com/assets/uploads/NanoScience/Brochures/Principles%20of%20dilution%20refrigeration_Sept15.pdf