

The background of the slide is a photograph of a SuperCDMS detector component. It is a square-shaped, copper-colored metal frame containing a white, circular, concentric ring pattern. A stainless steel ruler is placed diagonally across the top left corner of the frame for scale. The ruler has markings in inches and centimeters, with the text "STAINLESS STEEL" and "MADE IN U.S.A." visible.

# SuperCDMS: The Coolest Particle Detectors in Physics



Michael H. Kelsey, Texas A&M



Physics Colloquium, UT Dallas  
28 April 2021

# Overview

SuperCDMS is a large experiment, using semiconductor crystals cooled near absolute zero, to search for dark matter passing through the Earth. It will be installed in a deep mine in Ontario, to start running in 2023.

- Dark Matter and How to Find It
- The SuperCDMS Experiment
- A Bit of Solid State Physics
- Detector Response and Signals
- Future Developments



The background of the slide is a deep space image showing a vast field of galaxies, some appearing as bright, fuzzy clouds and others as thin, elongated streaks. A prominent, bright star with a four-pointed diffraction pattern is located in the upper right quadrant. The overall color palette is a mix of deep blues, purples, and whites from the starlight.

# **Dark Matter and How To Find It**

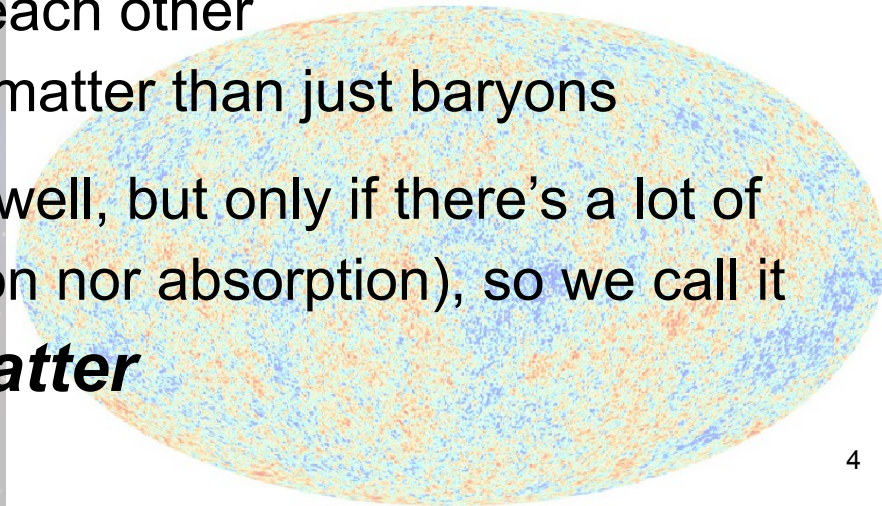
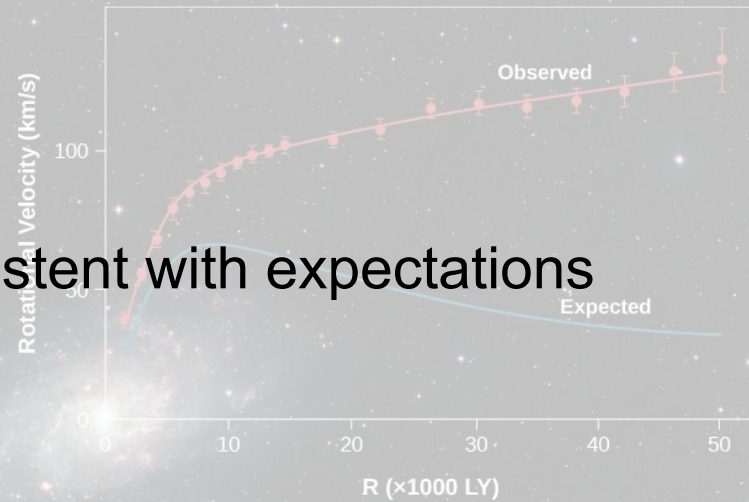
# What is “Dark Matter”?

Some astrophysical observations inconsistent with expectations

- Galaxies in clusters moving “too fast”
- Individual galaxies rotating “too fast”
- Galaxy clusters “pass through” each other
- Big Bang produced much more matter than just baryons

We can explain these observations well, but only if there’s a lot of matter we can’t see (neither emission nor absorption), so we call it

***Dark Matter***





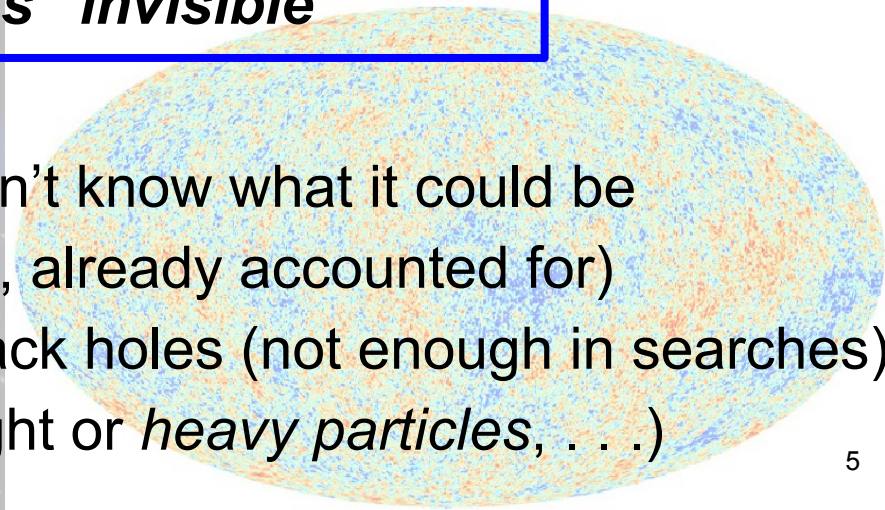
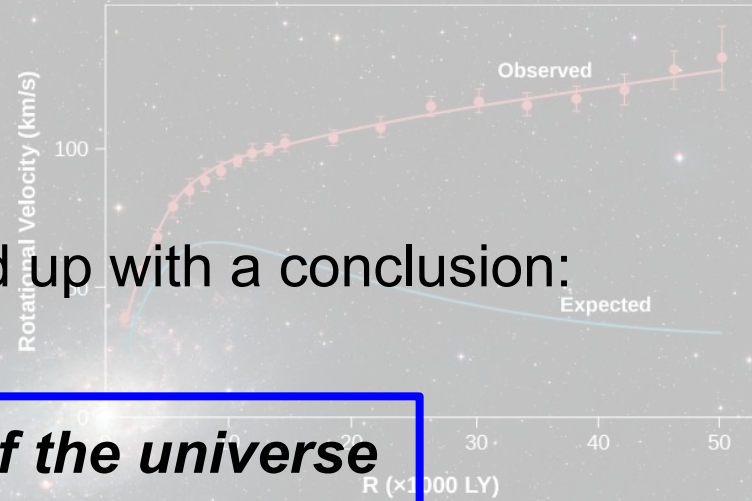
# Indirect Evidence

Assuming known physics processes, end up with a conclusion:

***Around 80% of the mass of the universe  
on large scales is “invisible”***

Something must be there, but we didn't know what it could be

- ✗ Gas or dust (would affect spectra, already accounted for)
- ✗ Rogue planets, brown dwarfs, black holes (not enough in searches)
- ✓ New kinds of particles (axions, light or *heavy particles*, . . .)



# Direct Evidence

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The background of the slide is a deep space image showing a vast field of stars and galaxies. A particularly bright star with a prominent four-pointed diffraction pattern is located in the upper right quadrant. The text "Dark Matter Particles?" is centered in a large, bold, black font.

# Dark Matter Particles?

# New Particle Physics

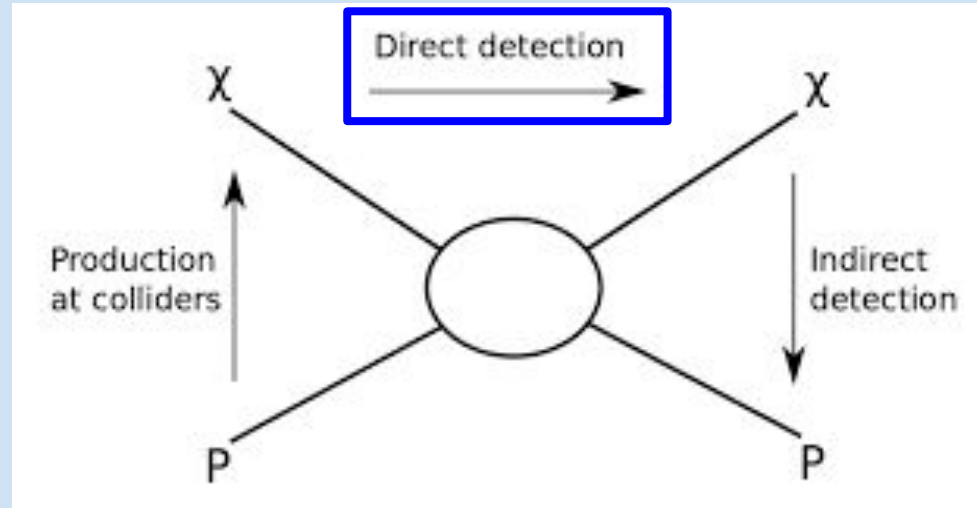
- Light, stable, unique kind of particle
  - Axion or “axion-like particle”; behaves similarly (mixes) to photons
  - Prediction of particle physics (CP symmetry in strong interactions)
- Heavy, stable, unique kind of particle
  - WIMPs (**w**eakly **i**nteracting **m**assive **p**articles)
  - Prediction of particle physics (supersymmetry)
- Parallel “zoo” of particles with own interactions
  - “Dark sector”: particles, “atoms”, “molecules”, etc.
  - Limited or no coupling to ordinary (standard model) particles

**SuperCDMS's Target**



# Looking for New Particles

Dark matter (whatever it is)



Ordinary matter (protons, neutrons, etc.)

# Looking for New Particles

Dark matter doesn't appear to interact, cross-section must be tiny

Use large **active mass**

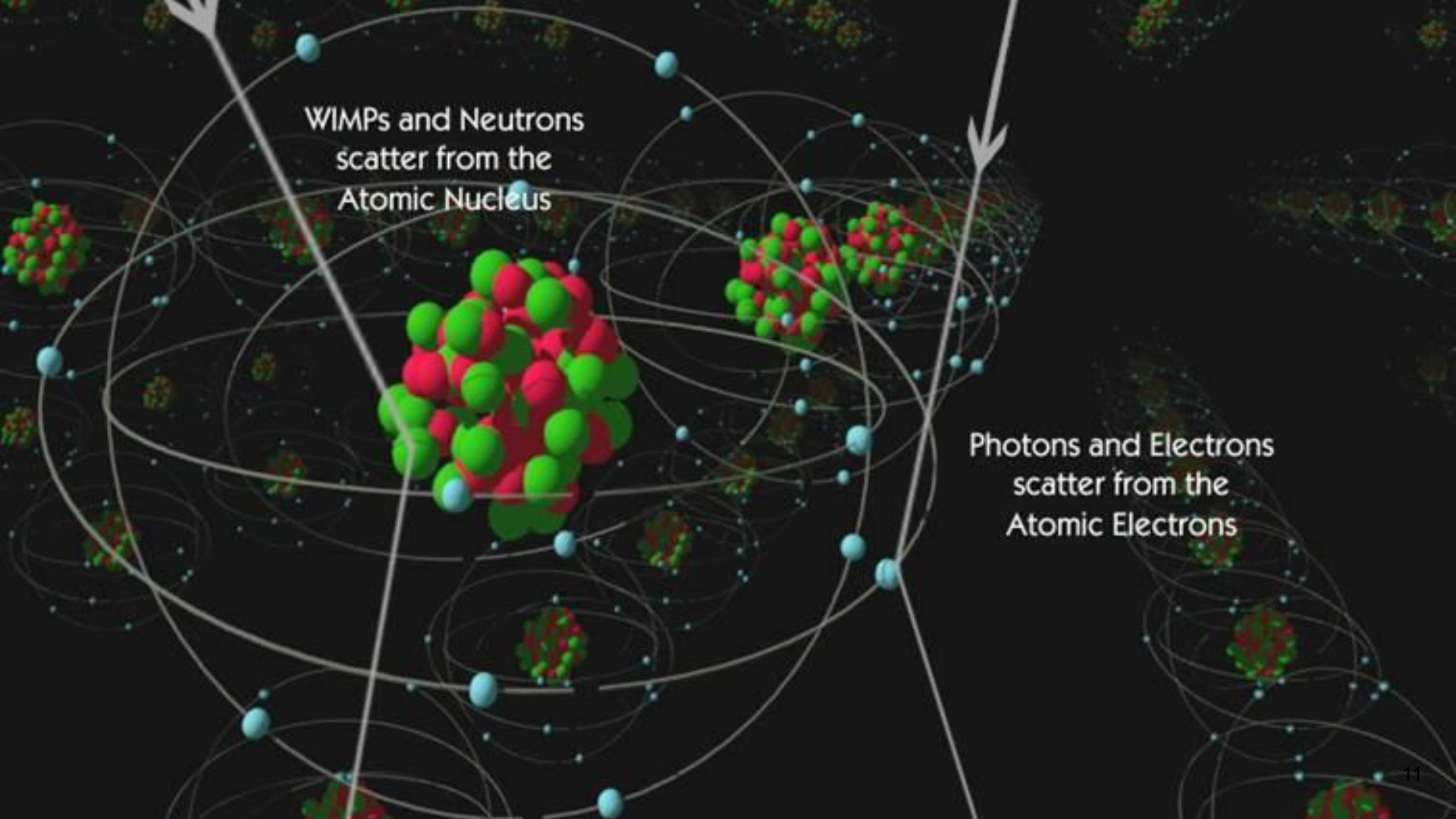
- Many heavy atoms, where response can be directly measured
- Various options: Liquid xenon, sodium iodide, **semiconductors**

**Deep underground** to shield from cosmic rays

Low radioactivity materials for everything, shielding from rock (U/Th)

Turn on . . . and wait . . . and wait . . . and wait . . .





The diagram illustrates an atom with a central nucleus composed of red and green spheres. Surrounding the nucleus are several concentric elliptical orbits, each containing small blue spheres representing electrons. Two white arrows originate from the top of the frame: one points towards the nucleus, and the other points towards the electron orbits. Text labels are placed near these arrows to describe the scattering processes.

WIMPs and Neutrons  
scatter from the  
Atomic Nucleus

Photons and Electrons  
scatter from the  
Atomic Electrons

A photograph of the SuperCDMS experiment detector assembly. The central component is a circular silicon wafer with a complex, white, meander-like pattern of conductive traces. This wafer is mounted within a custom-built, octagonal copper frame. The frame has several small, rectangular electronic components and gold-colored solder joints attached to its inner edge. A stainless steel ruler is placed vertically to the left of the detector for scale, showing measurements in inches and centimeters. The ruler is marked with "STAINLESS STEEL" and "MADE IN U.S.A.". The entire assembly is resting on a light-colored, textured surface.

# SuperCDMS Experiment



# SuperCDMS Experiment History

**Cryogenic Dark Matter Search** experiment, deep underground

25 kg of large semiconductor crystals cooled to 50 millikelvins

- 1998–2002: CDMS-I, Stanford (shallow tunnels)

- 2006–2008: CDMS-II, Soudan Iron Mine, Minnesota (713.8 m)

- 2011–2015: SCDMS, Soudan (713.8 m)

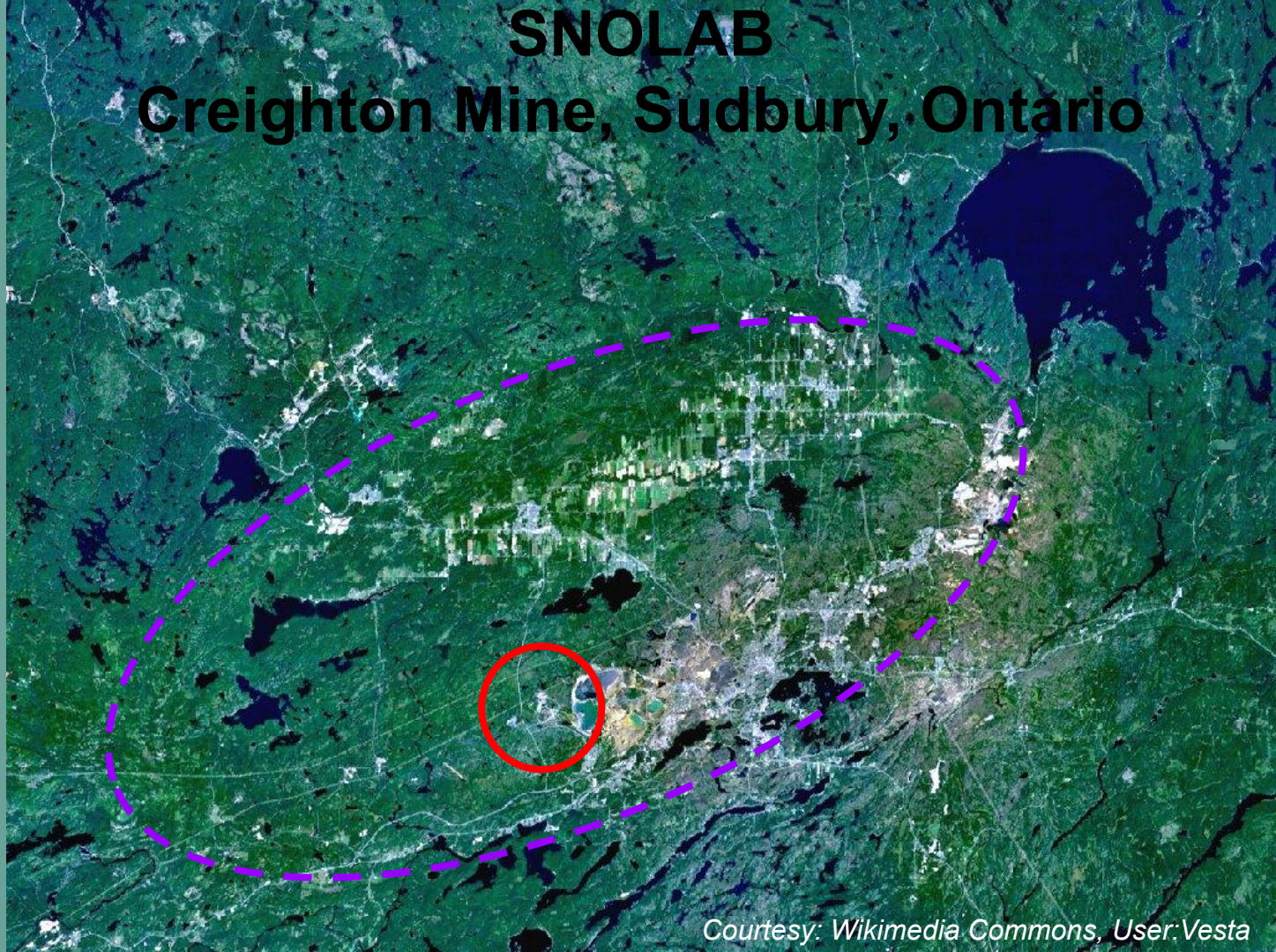
- 2023–2026: SuperCDMS, SNOLAB, Ontario (2070 m)

Detector assembly, installation at SNOLAB (4950 ft deep)  
underway



# SNOLAB

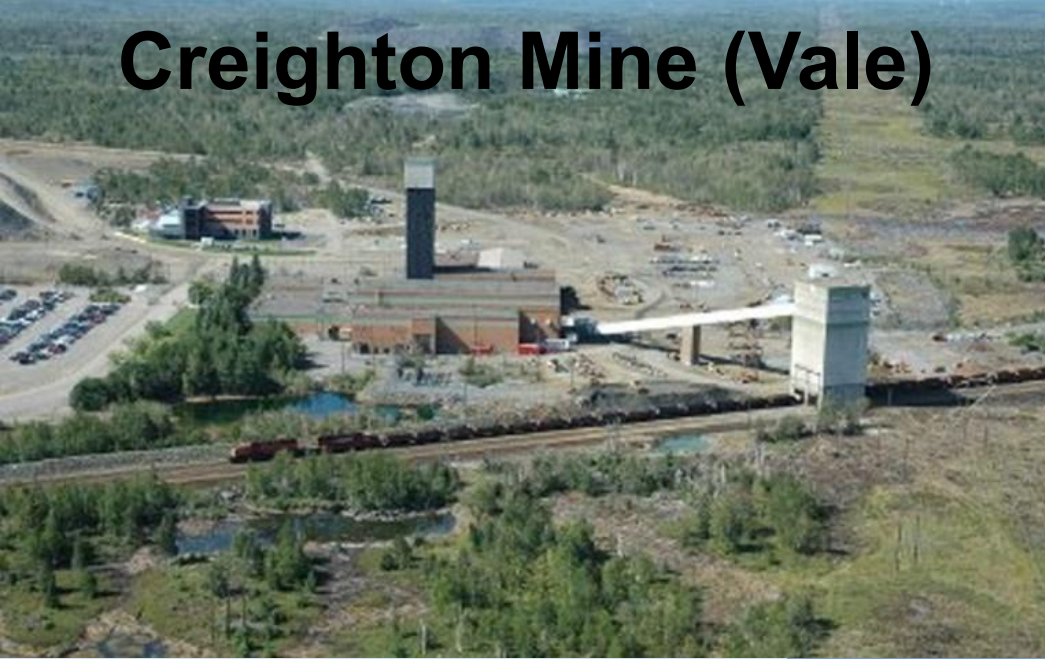
## Creighton Mine, Sudbury, Ontario



*Courtesy: Wikimedia Commons, User:Vesta*



# Creighton Mine (Vale)



*Courtesy: Vale, via CIM Magazine*

*Courtesy: SNOLAB*



## SNOLAB Offices



2km Overburden  
Creighton #9 shaft

Underground Lab:

37,000 m<sup>3</sup> volume

5000 m<sup>2</sup> Class 2000

0.27μ/m<sup>2</sup>/day

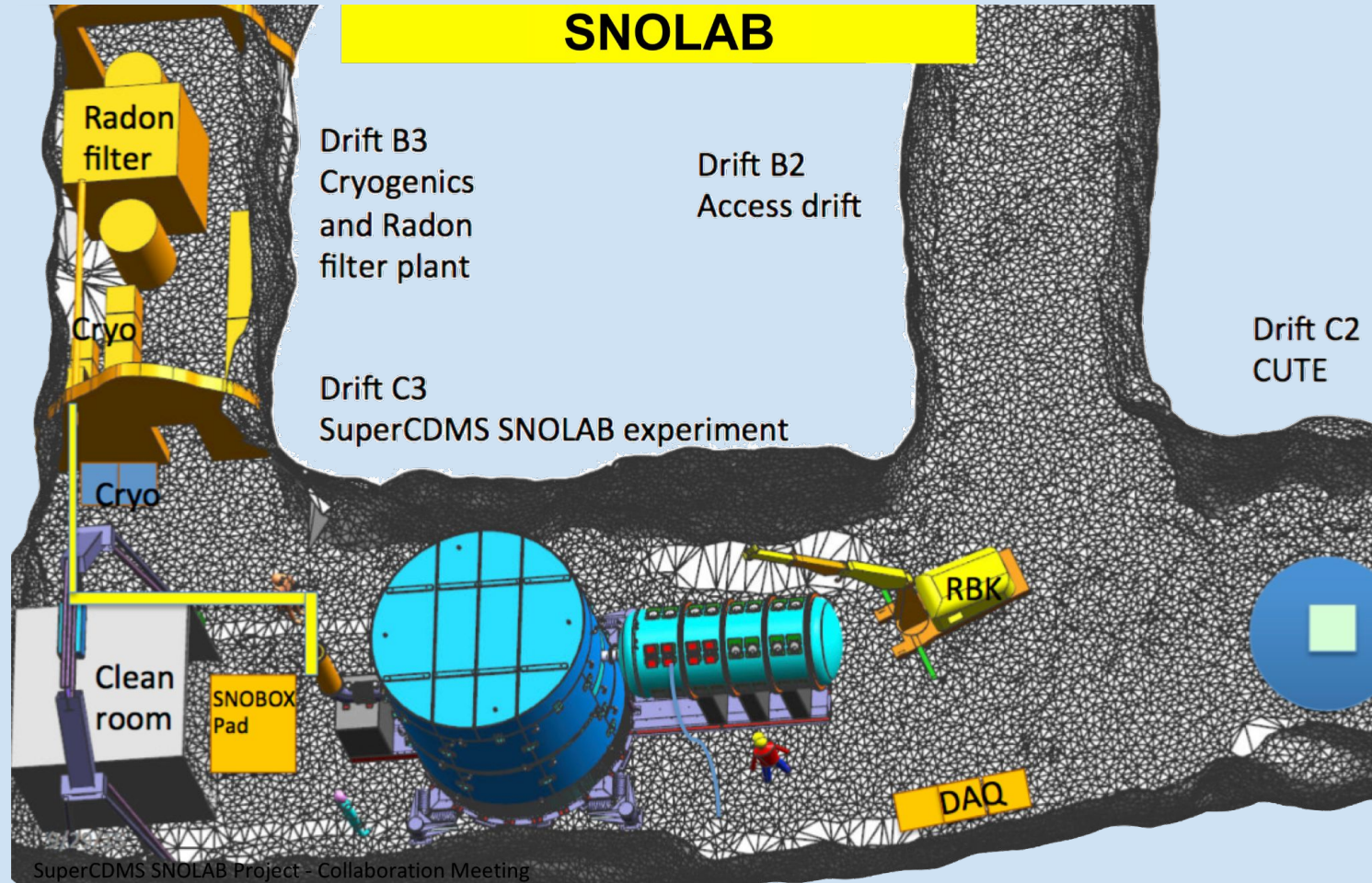




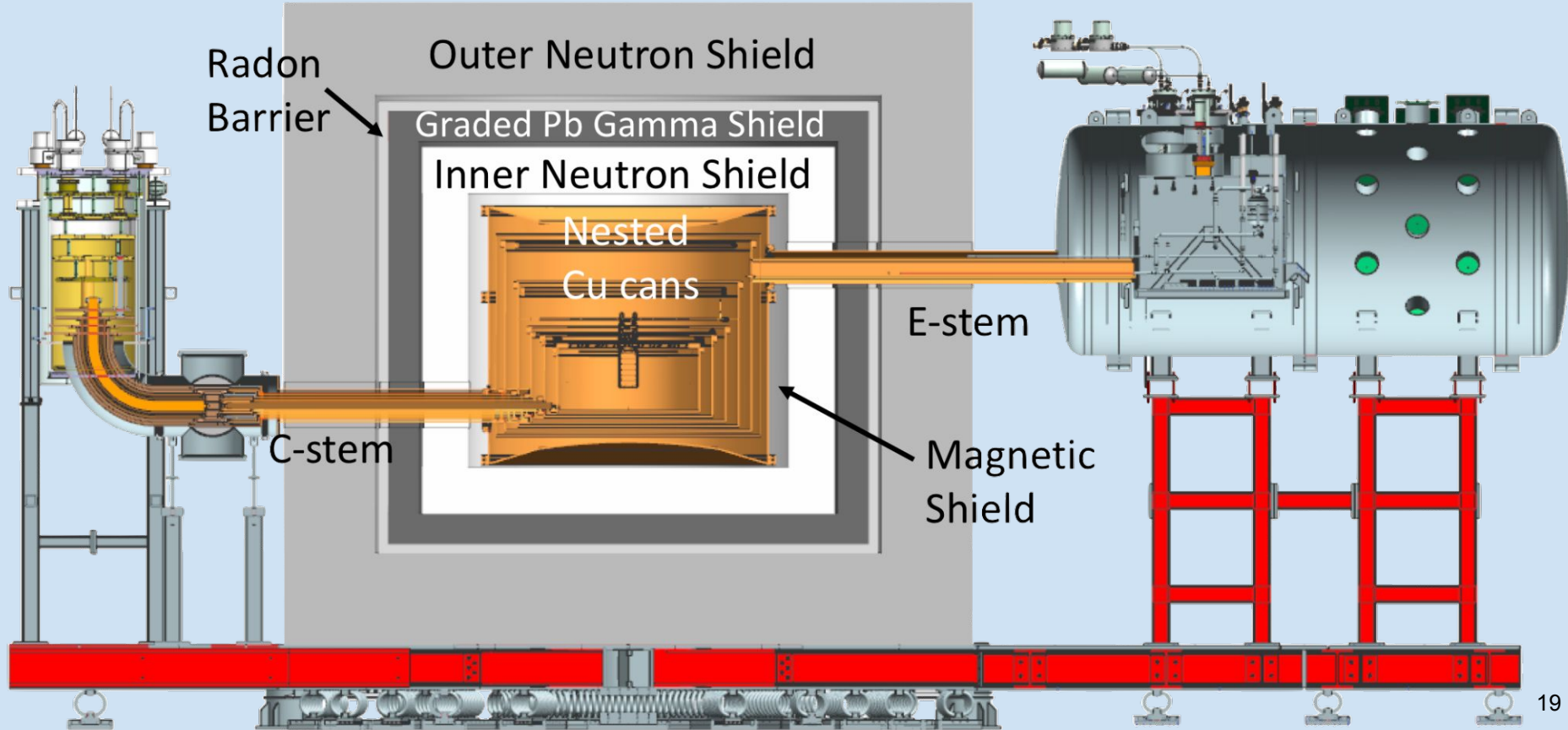
# SNOLAB Cavern Layout



# SuperCDMS Tunnel and Adits



# SuperCDMS Experiment







**Progress of Installation Today**



# Detector Towers

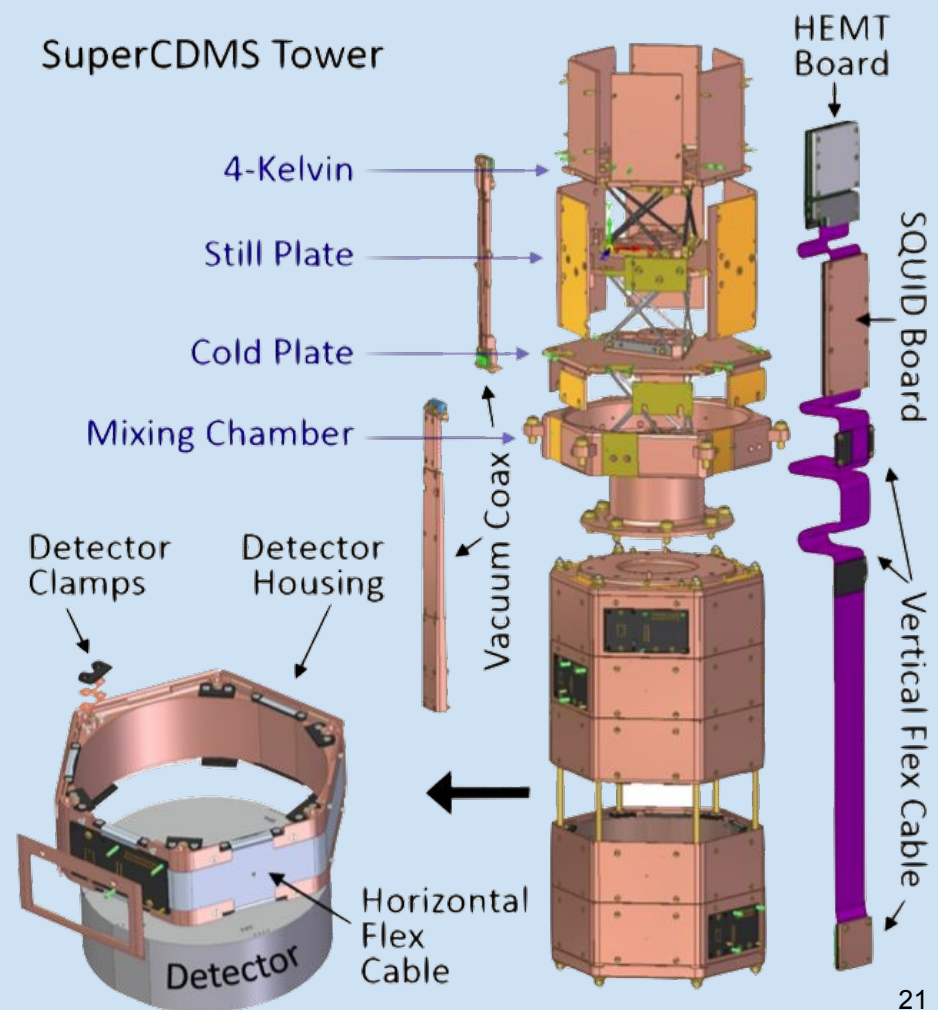
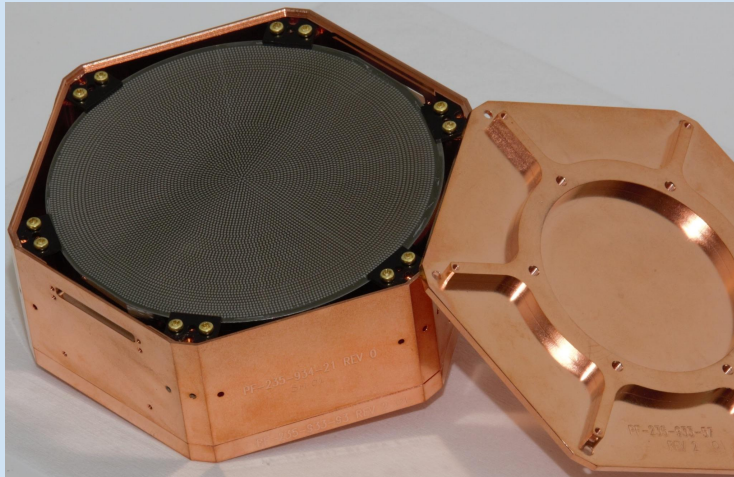
50 mK base temperature, 6-stage fridge

4 towers, 6 detectors each

Germanium, silicon detectors

High (100V) and low (4V) voltage

Charge and phonon sensors



A photograph of a SuperCDMS detector component, which is an octagonal copper housing containing a white, circular, meandered circuit board. A stainless steel ruler is placed vertically to the left of the component for scale. The ruler has markings in inches and centimeters, with the text "STAINLESS STEEL" and "MADE IN U.S.A." visible. The detector housing has several gold-colored electrical contacts along its perimeter.

# SuperCDMS Detectors



# SuperCDMS Detectors

High purity single crystals, 100×33 mm thick, 0.6 (Si), 1.5 (Ge) kg

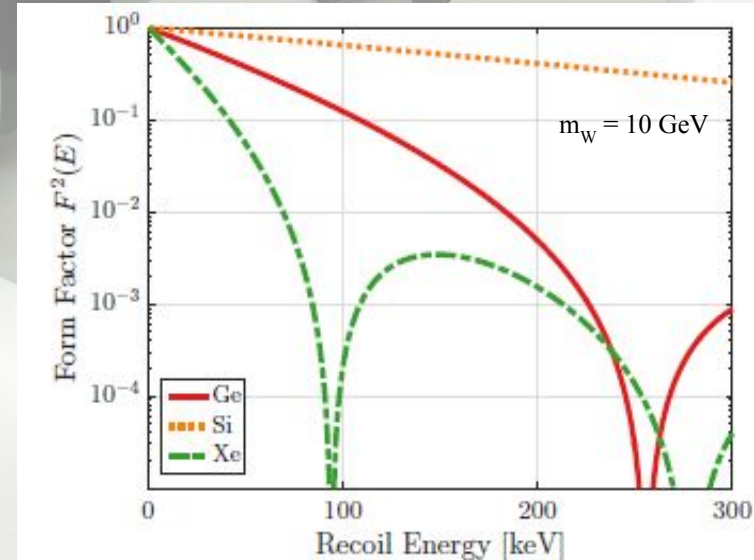
Precise crystal orientation, machined and polished dimensions

Some germanium, some silicon

- Different atomic masses will produce different recoil signals
- Protons vs. neutrons, nuclear spin, may be sensitive to specific theoretical interactions

Cooled to 50 millikelvins

- Suppresses thermal noise
- Sensors and readout superconducting





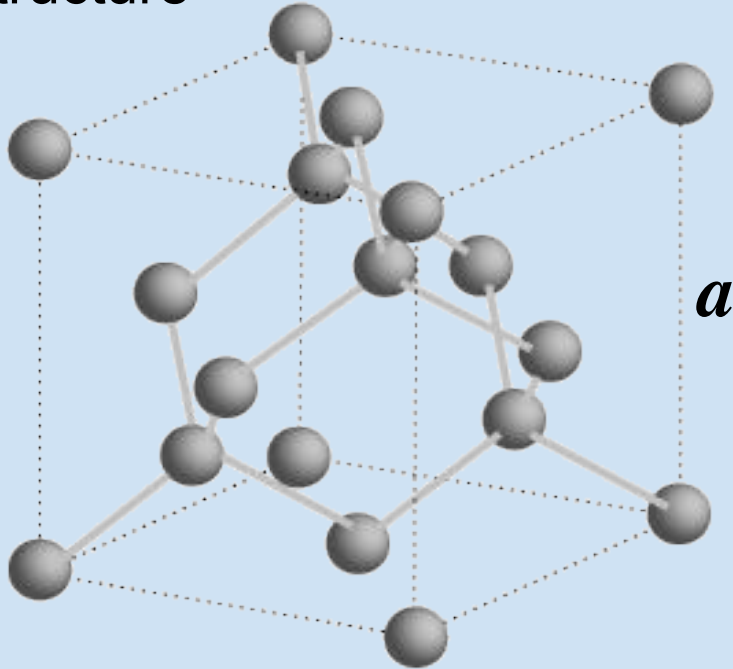
# A Bit of Solid State Physics

*for our detectors*



# Atoms in a Crystal

Silicon and germanium both have diamond cubic lattice structure



	Ge	Si
Unit cell ( $a$ )	5.658 Å	5.431 Å
$V_{\text{sound}}$ (L)	5.3 km/s	9.0 km/s
$V_{\text{sound}}$ (T)	3.3 km/s	5.4 km/s
Band gap	0.74 eV	1.17 eV
Electron “effective mass”	$1.59 m_e$	$0.95 m_e$
Hole “effective mass”	$0.35 m_e$	$0.50 m_e$

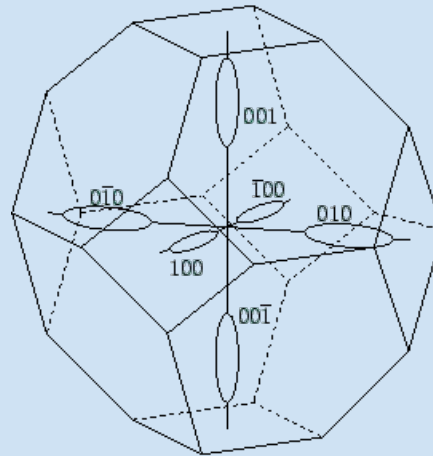
# Charge Transport, Scattering and Valleys

Incident particles promote electrons to conduction band, also creates holes (positive charge carriers)

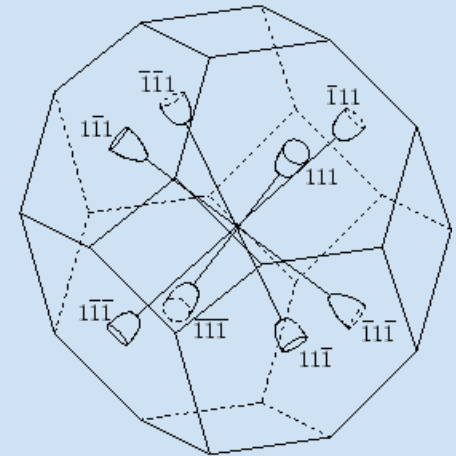
Lowest energy bands have particular orientations, “valleys”

Electrons travel along these directions, with some scattering

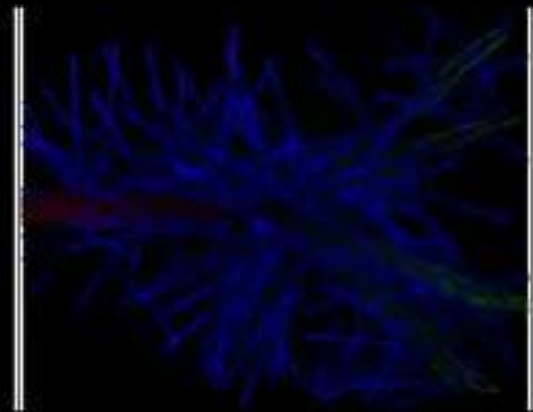
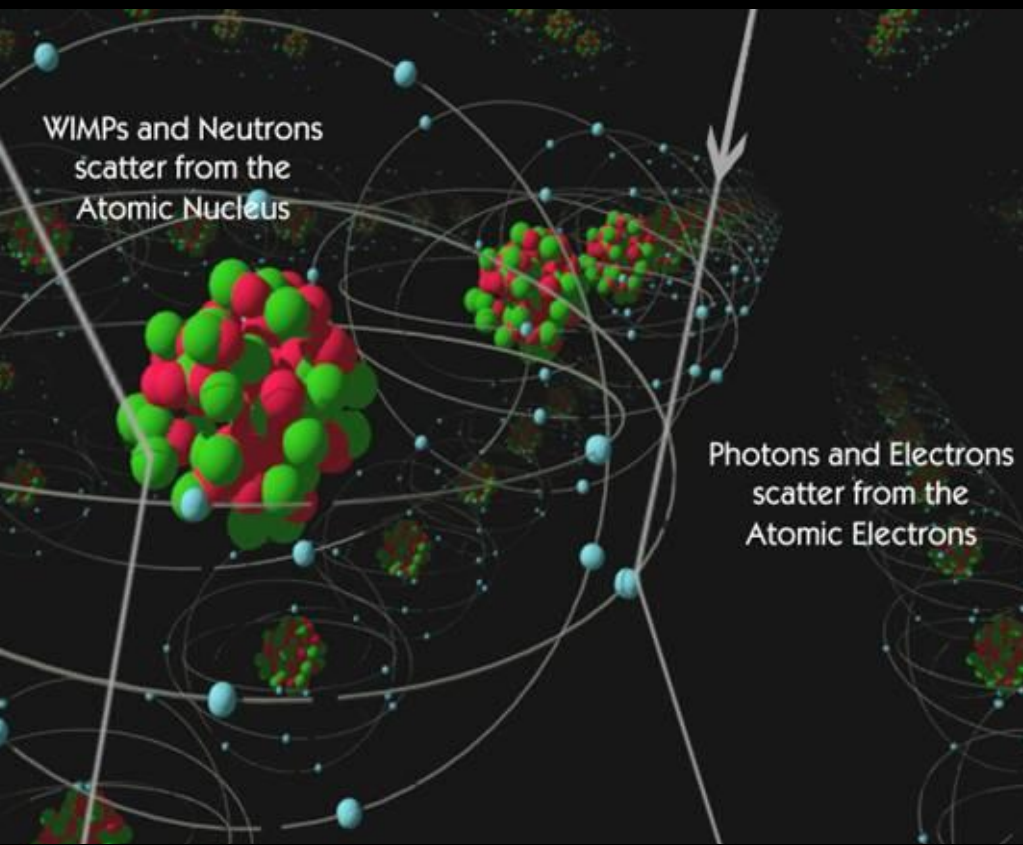
Charges accelerated in electric field radiate phonons



**Silicon**



**Germanium**



1.824  $\mu\text{s}$



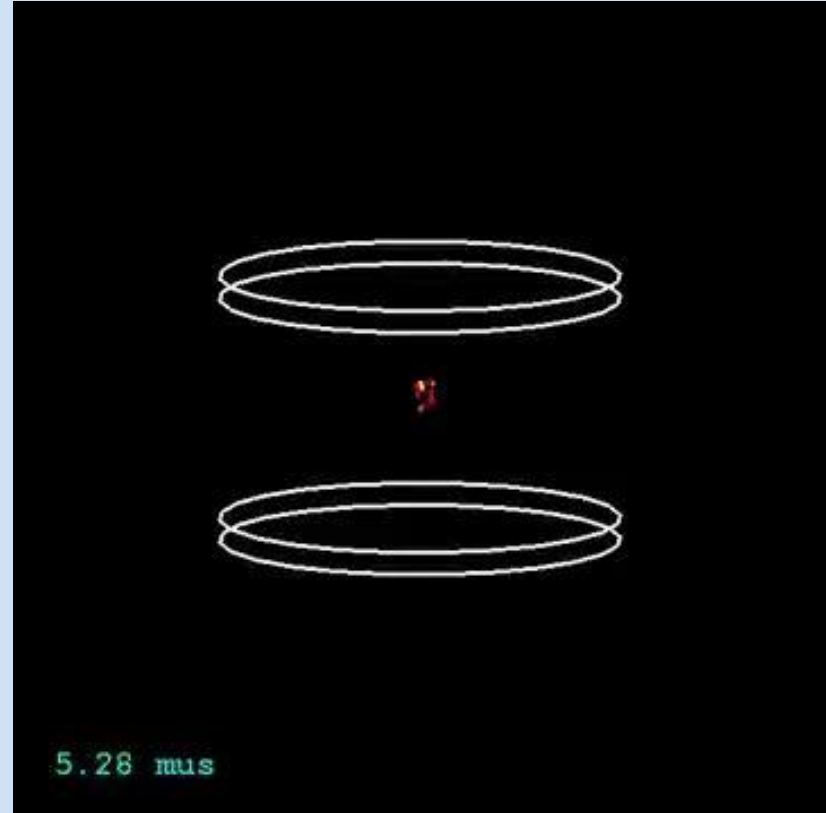
# Phonons: Scattering and Equipartition

Higher energy (tens of meV) phonons scatter off of impurities, different isotopes, crystal defects

Scatter and transform from one mode to another, rate  $\sim E^4$

Some split into two lower energy phonons, rate  $\sim E^5$

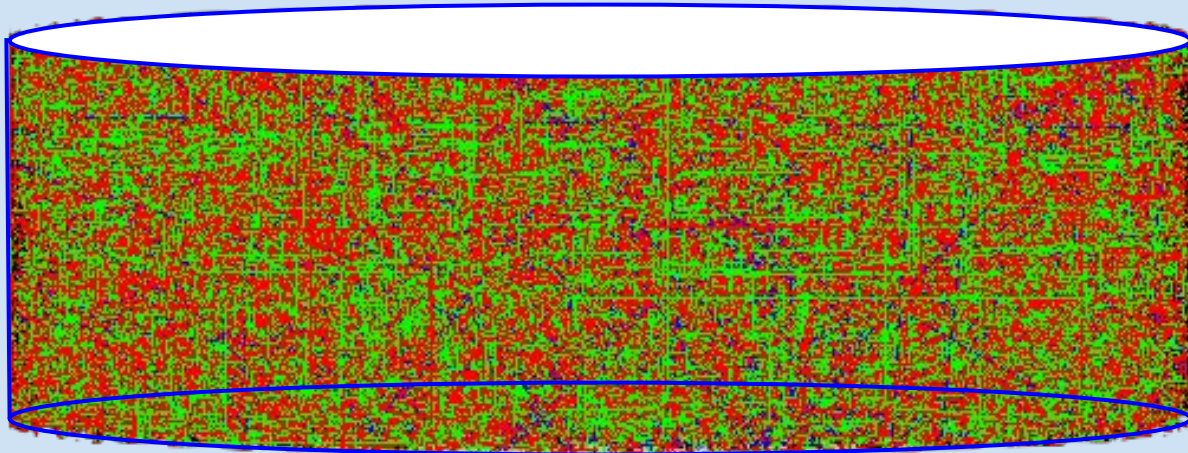
Low energy phonons rarely scatter



# Phonons: Scattering and Equipartition

After energy deposit, crystal filled with “gas” of low energy ( $\lesssim$  meV) phonons, with all modes represented, moving in all directions

Sensors on top and bottom can absorb phonons to measure energy



# QET: SuperCDMS's “enhanced” TES

*Quasiparticle trap assisted Electrothermal feedback*

*Transition edge sensor*

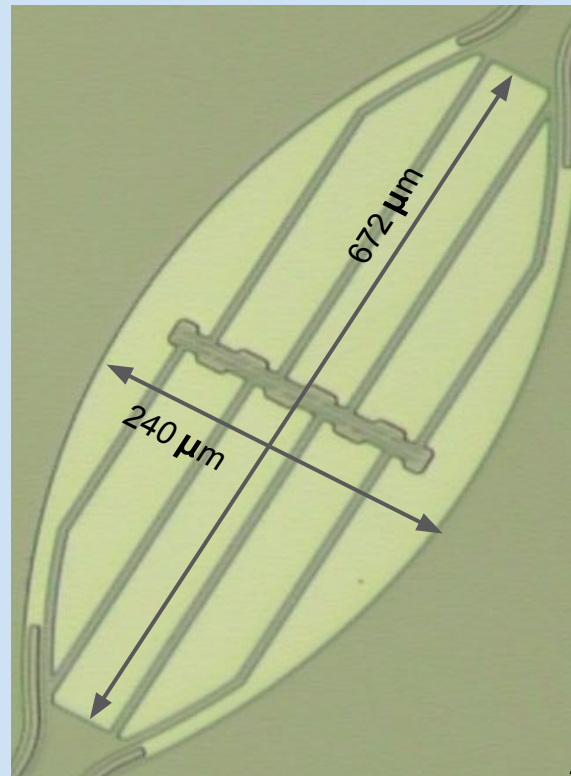
Absorbs phonons, produces change in current

Thin tungsten TES connected to readout lines

- On edge of superconducting transition
- Small  $\delta T \Rightarrow$  large  $\delta R \Rightarrow$  measurable  $\delta I$

Attached to superconducting aluminum fins

- Phonons incident on Al break Cooper pairs
- Recombination re-emits phonons within Al





A photograph of a detector assembly. It consists of a copper-colored octagonal frame housing a white substrate with a complex, symmetrical, maze-like pattern of fine white lines. A stainless steel ruler is placed vertically to the left of the assembly for scale. The ruler has markings in inches (0 to 2) and centimeters (0 to 56). Text on the ruler includes "STAINLESS STEEL" and "MADE IN U.S.A.". The assembly is mounted on a copper-colored base with visible solder joints and electrical contacts along the edges.

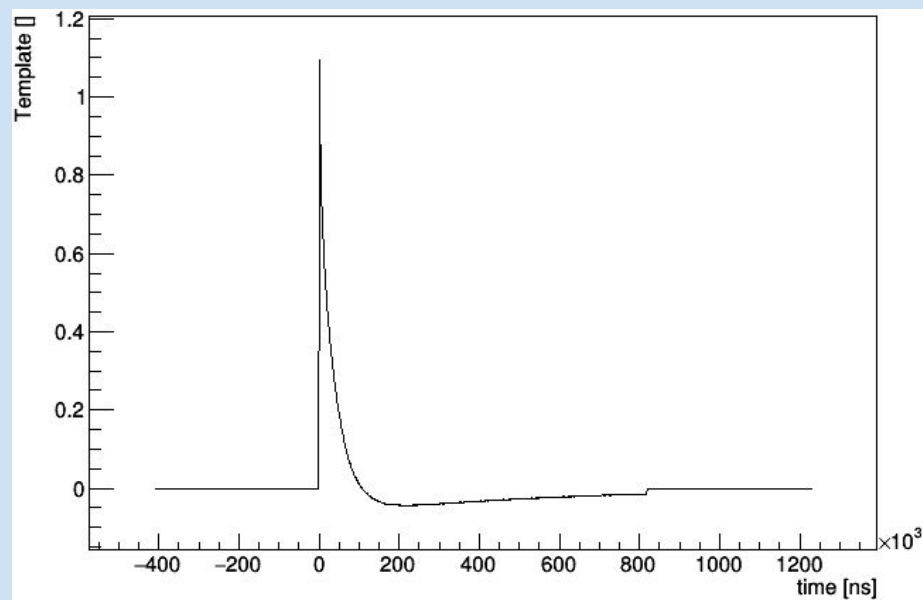
# Detector Response

# Charge Signals

Particles incident on detector create electrons (-ve) and holes (+ve)

Voltage bias carries charges to electrodes on opposite sides

- Charges travel much faster ( $\sim 30$  km/s) than readout (800 ns)
- Integral Shockley-Ramo theorem
- Voltage spike proportional to total charge collected at electrode



# Phonon Signals

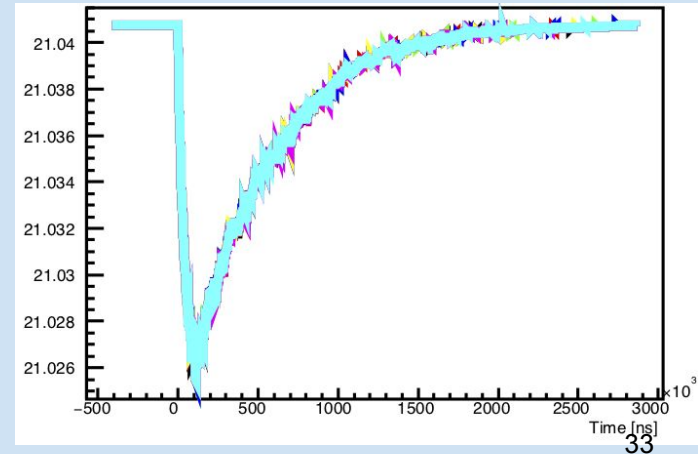
Charges gain energy in voltage, radiate phonons as they move

Phonons near surfaces arrive quickly, maximum when charges arrive

Long tail of low-energy phonons “bouncing around” in detector

Integral measures total energy deposit

*Superconducting sensor has less current when warm (after energy absorbed)*





# How Do We Find a Signal?

Looking for maybe a few events per year

- Signal consistent with nuclear recoil
- In just one detector, nothing else around

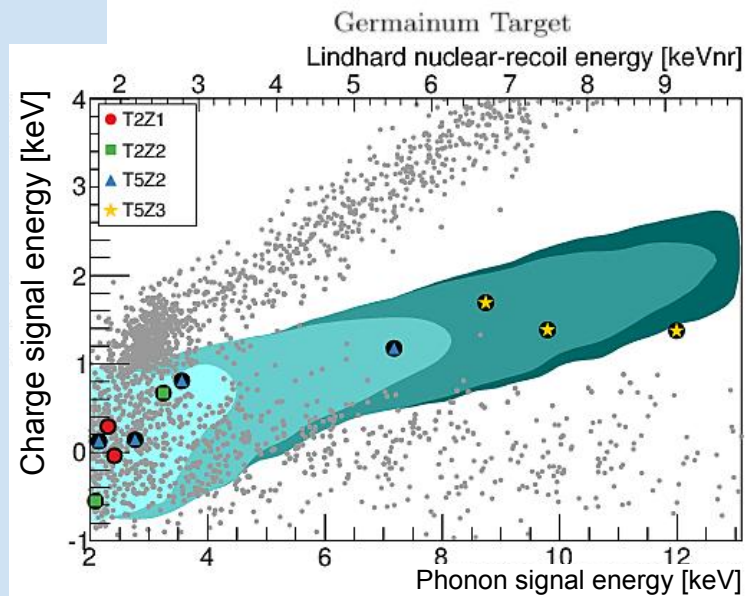
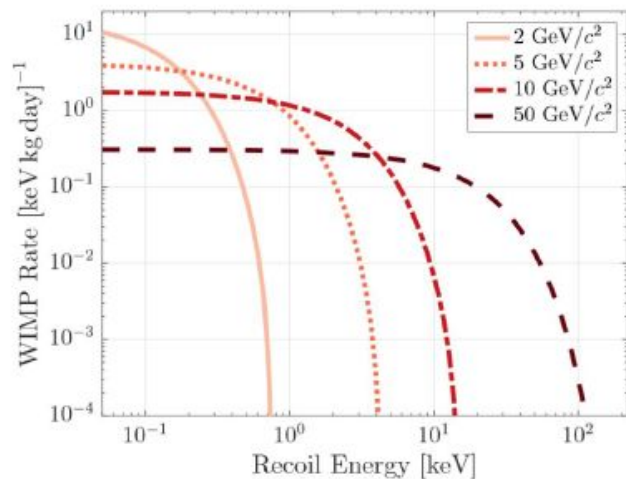
**Background** rate of few per second

- Physical shielding, low-activity materials

Spend most of our time characterizing detector response

- **Calibrations**, simulations

Event selection, filtering, fits, maybe find something interesting



# Backgrounds, Backgrounds, Backgrounds

Detectors are made of natural germanium and silicon

- Radioisotopes ( $^{32}\text{Si}$ , 172 y;  $^3\text{H}$ , 12.3 y) part of mix
- Neutron calibrations can induce radioactivity ( $^{71}\text{Ge}$ , 11.4 d)

Mounted in copper housings, with cables, circuit boards, etc.

- Built of low radioactivity materials, but always some contaminants

Lead and polyethylene shielding excludes external radiation

- $^{210}\text{Pb}$  in shield; U, Th in cavern walls; neutrons from cosmic rays

# Calibration: Properly Interpreting Signals

Readouts are “ADC counts” (arbitrary units) not energy or charge

Want events with known energy to convert units into physical values

Radioactive sources, exposing single detectors or whole experiment

$^{55}\text{Fe}$      5.9 keV gamma

$^{133}\text{Ba}$      356 keV gamma, other gammas at known energies

$^{71}\text{Ge}$      10.37 keV gamma, from activating natural Ge in detector

$^{252}\text{Cf}$      Neutrons from spontaneous fission



# Another Approach: LUX-ZEPPELIN (LZ)

*Courtesy: LZ Collaboration*

7000 kg liquid xenon

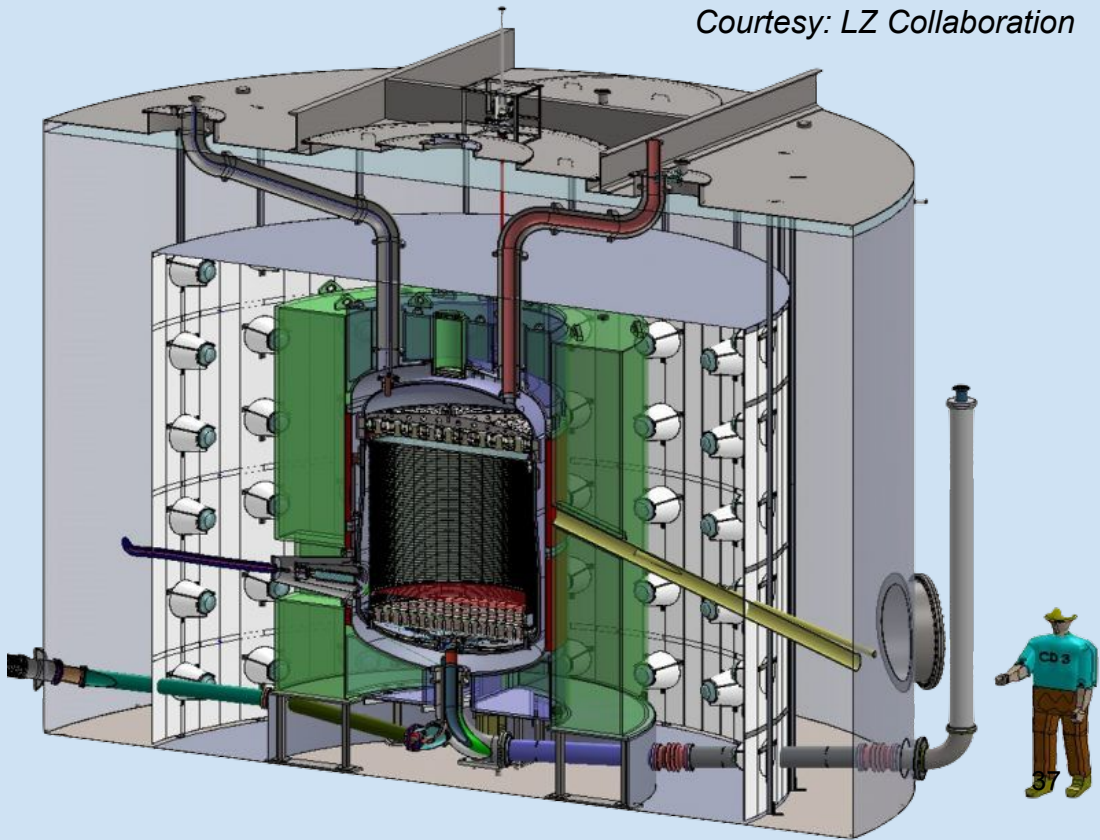
- PMTs for scintillation light
- Electric field: light from electrons

Surrounding water veto

Sensitive to WIMPs

Under construction

- Sanford Underground Lab
- Homestake Mine, South Dakota



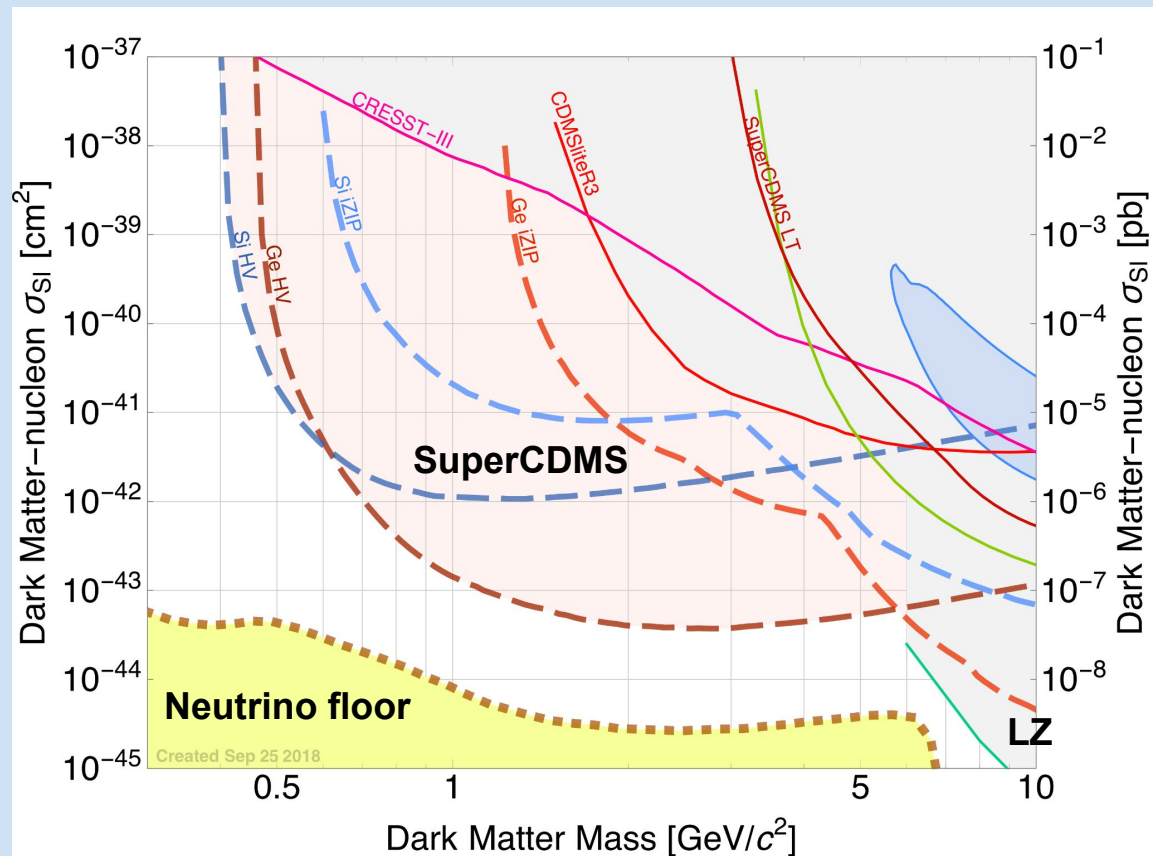
# Dark Matter Search Limits

Sensitivity depends on both DM mass and cross-section

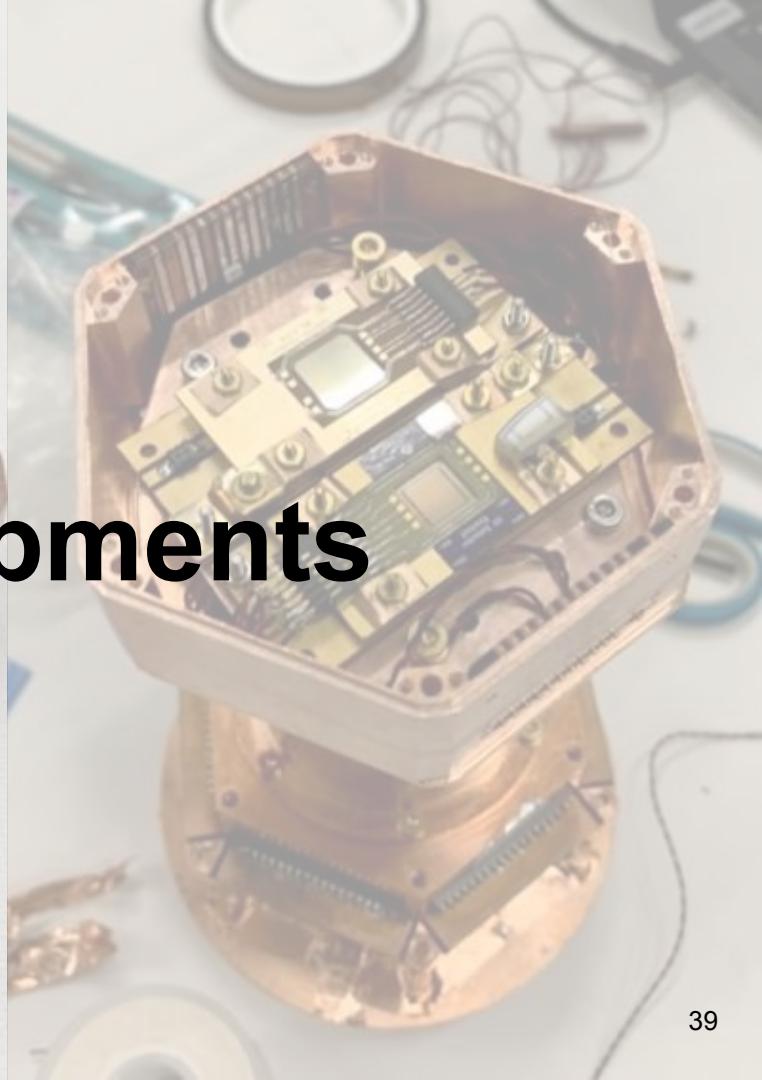
SuperCDMS can push to lower masses ( $\sim 500$  MeV)

- Different detector types have different strengths

LZ sensitive to higher masses, much lower cross-sections

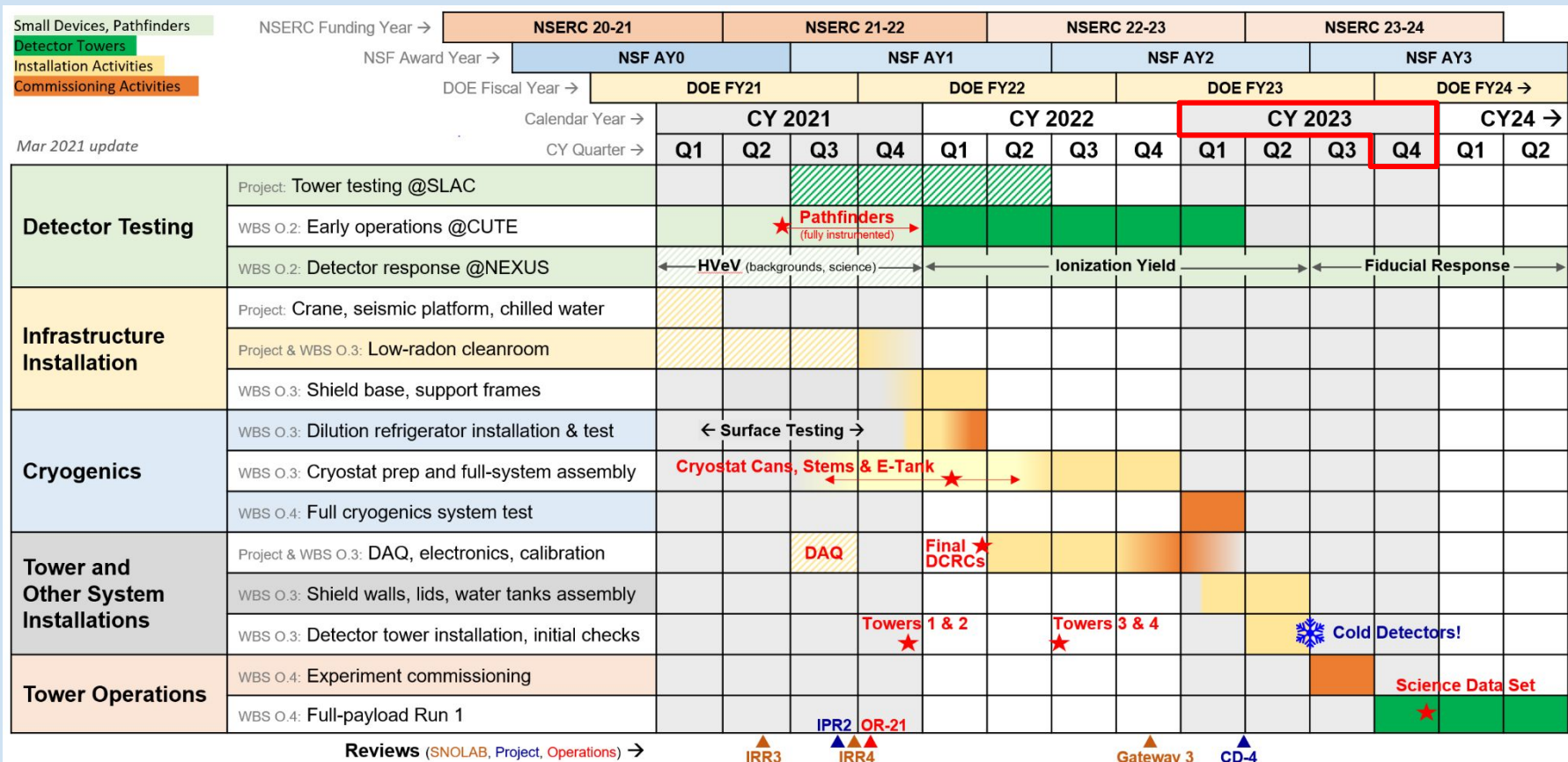


# Future Developments





# SuperCDMS Installation and Startup



# LAPD : Large Area Photon Detector

Thin Si wafer, 75×1 mm, 11 g (vs. CDMS 0.6 kg)

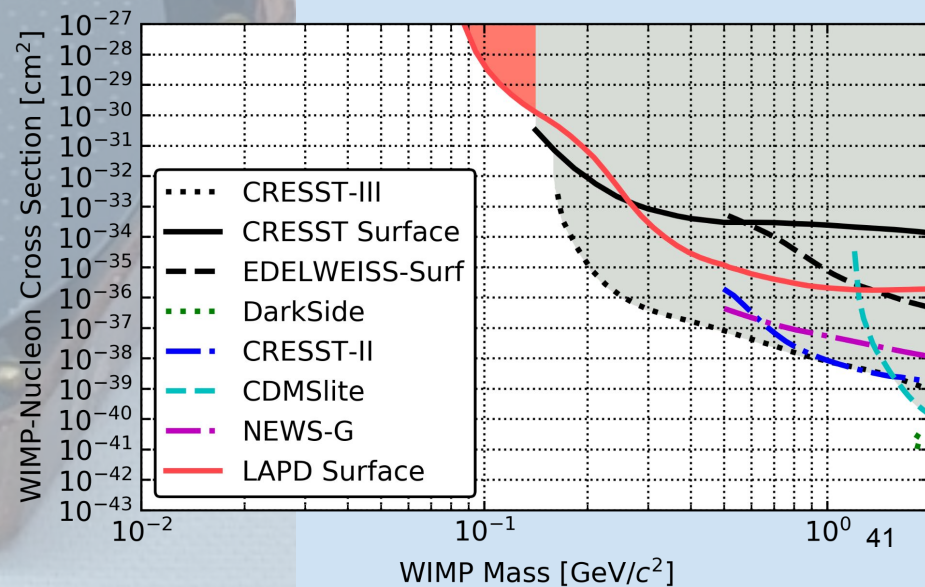
- Sparse array of QET phonon sensors
- Sensitive to 3.5 eV energy deposit

Science run ~10 g · day exposure

- Limits on  $m_{\text{DM}}$  93–140 MeV/ $c^2$

I. Alkhatib *et al.*, arXiv:2007.14289

(submitted to PRL, in review)



# HVeV : High Voltage, eV resolution

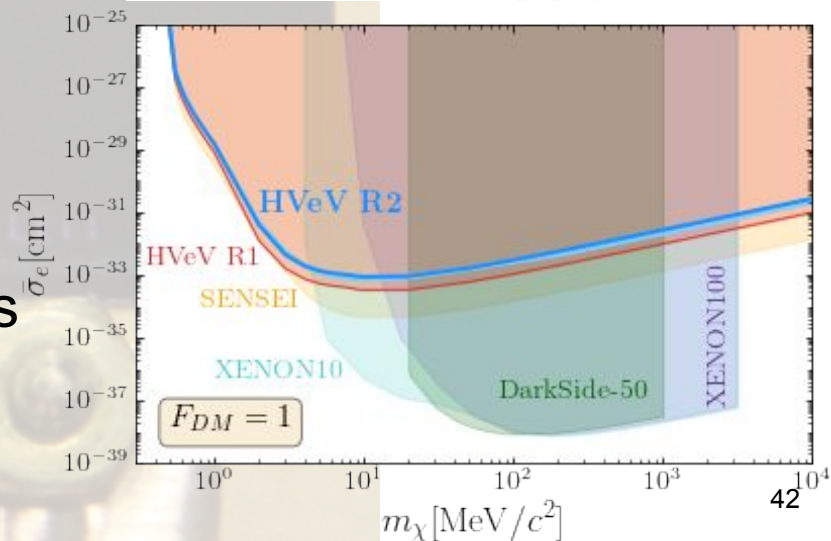
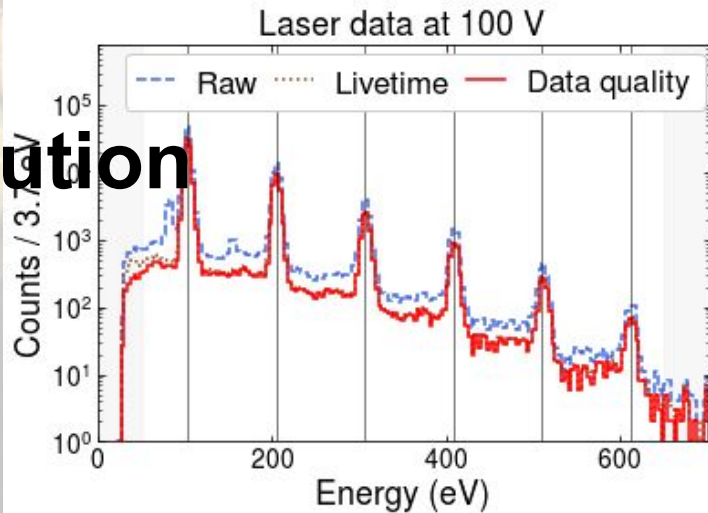
Si chip, 10×10×4 mm, 0.93 g

- Dense array of QETs, two channels
- 100V bias for phonon amplification
- Sensitive to individual charges

Science run just 1.2 g · day exposure

- Limits on  $m_{\text{DM}} \gtrsim 50 \text{ keV}/c^2$
- Competitive with other experiments
- Work is continuing

D.W.Amaral *et al.*, *Phys. Rev. D* 102, 091101 (2020)





# Closing

Dark matter is a compelling mystery at the junction of cosmology, astronomy and particle physics

Numerous efforts are underway to try to discover it

SuperCDMS is the coolest experiment (semiconductor detectors with superconducting sensors) to search for dark matter

Construction and installation underway to start next phase in 2023

Expecting big results in a few years!

# Backup Slides

The background of the slide is a deep space image showing a vast field of galaxies. In the center, there is a very bright, white star-like object with a prominent four-pointed diffraction pattern. Surrounding this central object are numerous smaller, distant galaxies, some appearing as bright, fuzzy blobs and others as more elongated, spiral or elliptical shapes. The overall color palette is a mix of deep blues, purples, and whites, typical of astronomical imagery.

# **Evidence for Dark Matter**

# Galaxy Clusters

Large collection of galaxies, bound together by gravity

- Not “in orbit” around each other
- Moving within large region defined by their collective mass
- Velocity distribution limited by total mass (escape if too fast)

Measured velocities are “too fast” if total mass only due to galaxies themselves, or even galaxies plus intergalactic gas (about one atom per cubic meter)

Velocities are reasonable if total mass 4 to 5 times larger



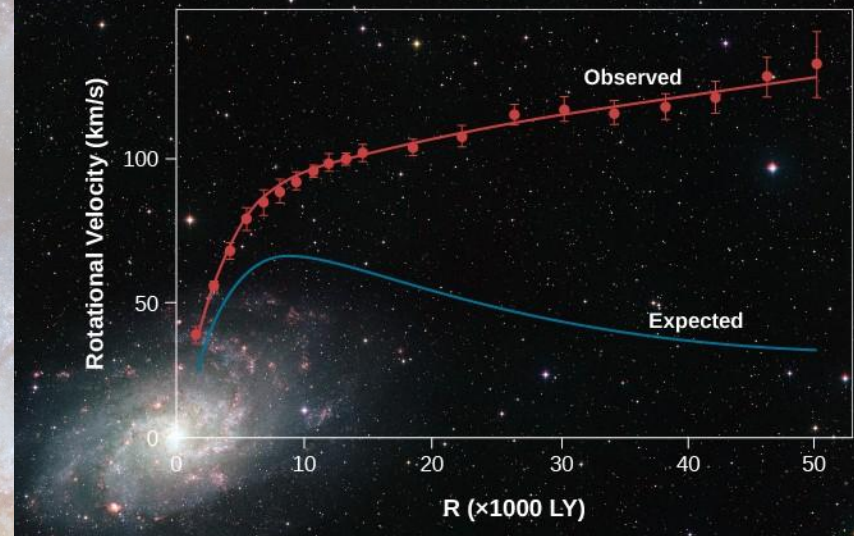
# Galaxy Rotation Curves

Measure speed of stars at distances from galaxy center, hydrogen gas in halo around luminous galaxy

If mass is due to stars and gas (mass-luminosity relationship), expect speeds to get slower with increasing radius

Observe constant or even increasing speed with distance!

Need “solid” (continuous) halo of at least 2 to 5 times additional mass, surrounding and including visible galaxy to explain speeds



# Mass Separation (Bullet Clusters)

Observations of multiple colliding clusters of galaxies

- Gravitational lensing (Hubble), X-ray emission from gas (Chandra)

Most cluster mass seems to pass through without interaction (blue)

Intracuster gas compresses and heats along collision region, producing X-ray emission

Visible mass (galaxy luminosity, emitting gas) about 10-15% of total including gravitational lensing mass

Abell 370

Abell 2744

ZwCl 1358+62



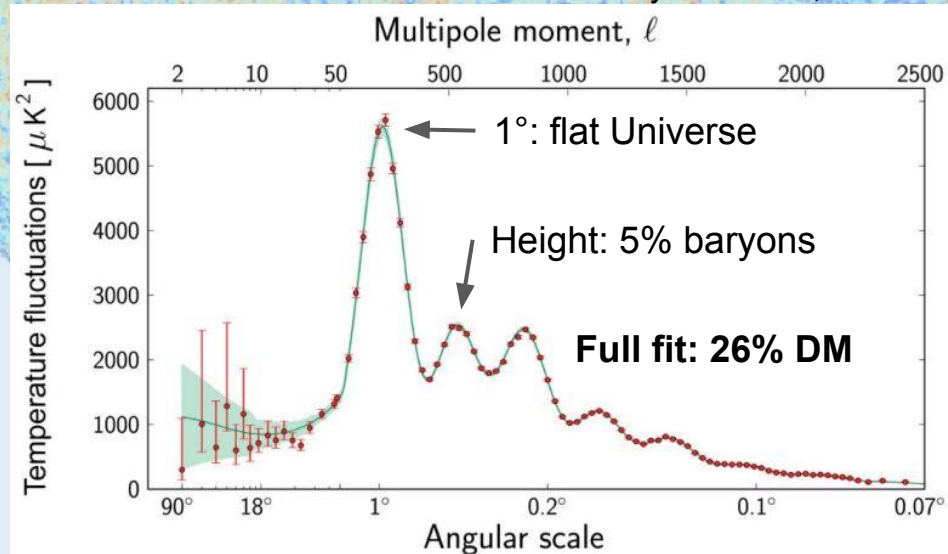
# CMB and Nucleosynthesis

*Planck* measured cosmic microwave background on small scales

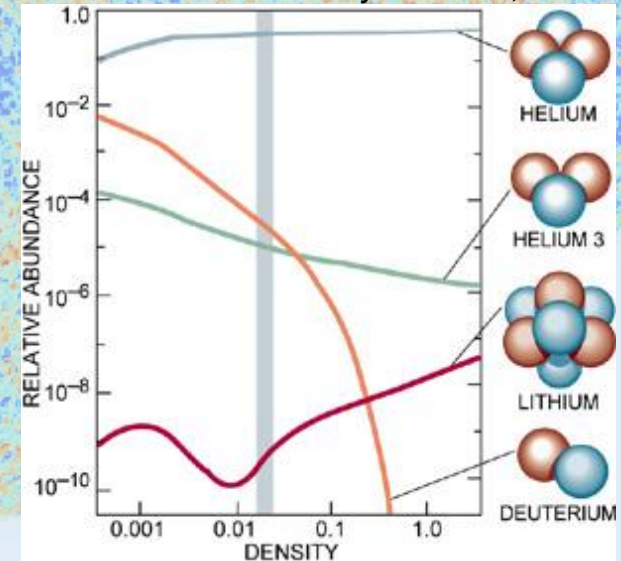
- Fit to angular power spectrum says 5% baryons, 26% non-baryonic matter

Primordial abundances consistent with baryons 3~5% of total

Courtesy: K. Freese, Caltech



Courtesy: M. White, UCB



The background of the slide is a light yellow color, densely populated with numerous faint, grey Feynman diagrams. These diagrams represent various particle interactions, including vertex corrections, self-energy loops, and multi-particle production and decay processes. They are scattered across the entire slide, creating a complex, technical texture.

# Dark Matter Hypotheses



# What Could Dark Matter Be?

- Neutrinos: non-zero mass, don't interact much
  - Unlikely; density predicted from CMB included in “matter content”
- Primordial (low mass) black holes
  - Possible, but not seen in microlensing surveys
- Planets, brown/black dwarves, other hard to see **objects**
  - Possible, but not enough seen in microlensing surveys
- Unknown/unobserved elementary particles
  - Possible, attractive candidate for **direct detection** or production

# New Particle Physics

Other “anomalies” in Standard Model hint at new particles

- Unexpected resonances (“X, Y, Z”) at BES and other colliders
- Muon  $g-2$  anomaly, from virtual particle contributions

As with supersymmetry or axions, it would be “elegant” if resolving a problem in one area also contributed to resolving another

*Whether the Universe is elegant or concise is a different question*



# Weakly-Interacting Massive Particles (WIMPs)

- Like neutrinos, but with neutron/proton-scale mass
- No electric charge, non-baryonic (no strong interactions)
- Weak interaction ( $W^\pm$ ,  $Z^0$ ) mediates e.g. radioactive decay

Supersymmetry predicts “superpartner” for each Standard Model particle

- Heavy “superpartners” would decay into lighter ones
- Lightest superpartner (“LSP”) would be stable
- If LSP is partner of  $W^\pm$  or  $Z^0$  would interact only weakly

LSP should have been produced at LHC by now, maybe less likely



The background of the slide is a deep-field astronomical image, likely from the Hubble Space Telescope, showing a vast field of galaxies. In the upper center, there is a particularly bright, large, and irregularly shaped galaxy, possibly a massive elliptical galaxy or a galaxy cluster core, which is the primary focus of the image. It has a bright, glowing center with a complex, filamentary structure extending outwards. Surrounding this central galaxy are hundreds of other galaxies of various shapes and sizes, including spiral, elliptical, and irregular forms. Some are very bright and clear, while others are faint and distant. The overall color palette is dominated by blues, greys, and whites, with some hints of yellow and orange from the light of the galaxies. The text 'Other Dark Matter Searches' is overlaid in the center of the image in a large, bold, black font.

# Other Dark Matter Searches

# Axion-like Particles (ADMX)

Nearly massless, would “mix” with photons

- Strong magnetic field could transform axion into photon

Empty resonant cavity could trap photon

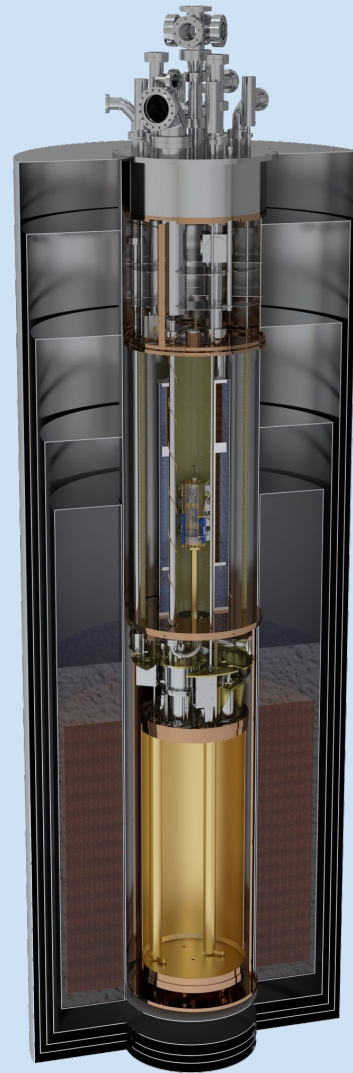
Tune cavity (frequency scan) to match axion mass

- Look for signal above baseline noise

Results exclude axions with mass 2.66 to 3.33  $\mu\text{eV}$

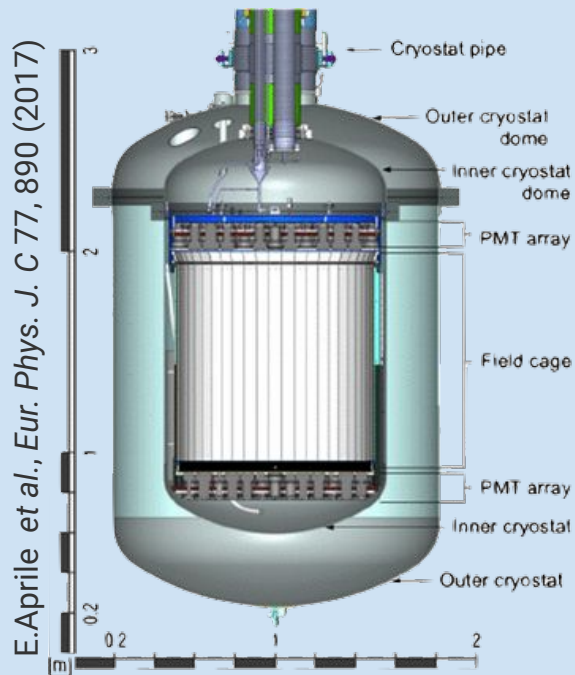
N.Du *et al.*, Phys. Rev. Lett. 120, 151301 (2018)

T.Braine *et al.*, Phys. Rev. Lett. 124, 101303 (2020)



Courtesy: ADMX Collaboration/FNAL

# Liquid Xenon Detectors: XENON1T



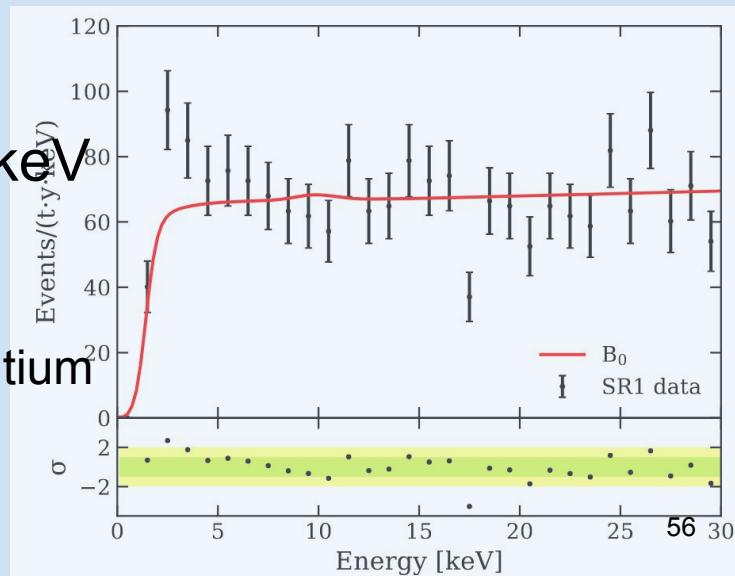
3500 kg liquid xenon

- PMTs for scintillation light
- Electric field: light from electrons

Sensitive to WIMPs

Excess events in 1-7 keV

- Close to threshold
- Only  $3.5\sigma$  significance
- Also consistent with tritium



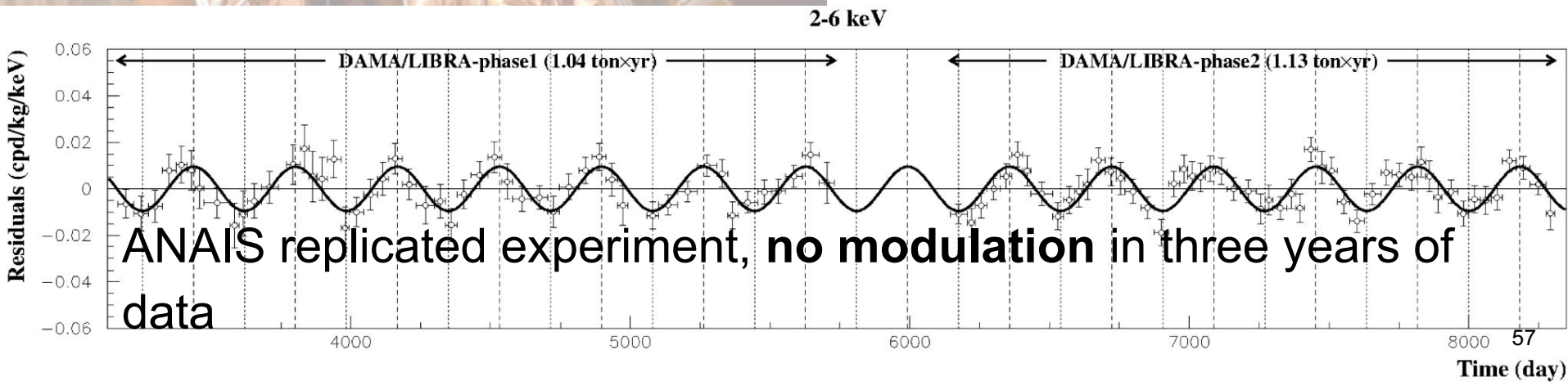
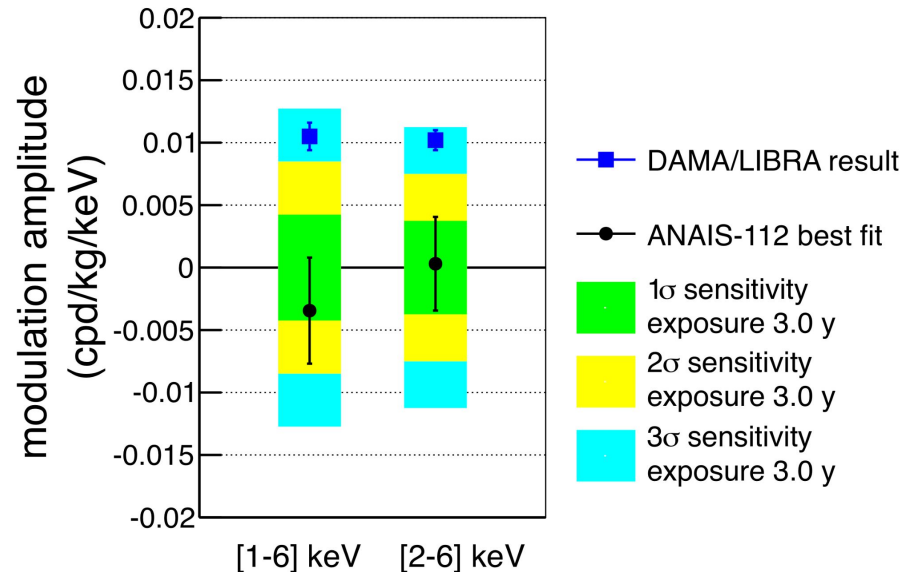
E. Aprile et al., *Phys. Rev.* **D102**, 072004 (2020)



# DAMA/LIBRA vs. ANAIS

Gran Sasso underground lab

- 250 kg of NaI(Tl) crystals
- Clear ( $\sim 13\sigma$ ) annual modulation
- Strong indication of dark matter
- Inferred DM exceeds other limits



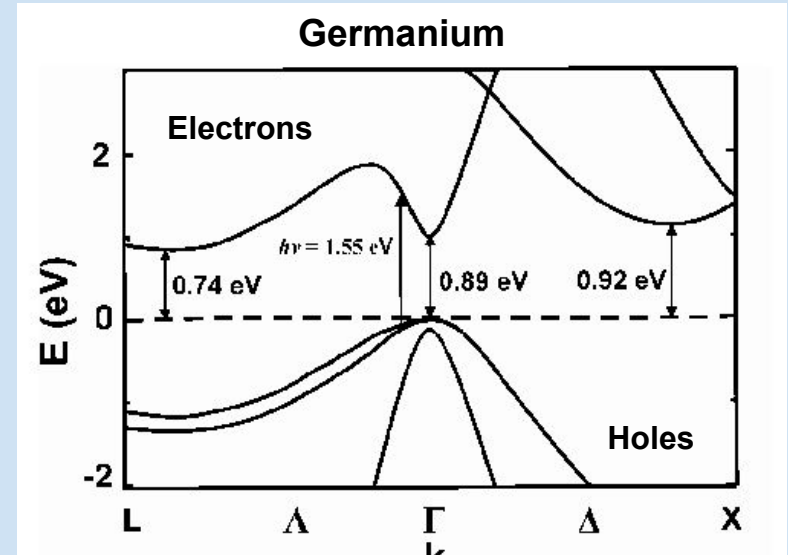


# Solid State Physics

# Band Structure (Electrons and Holes)

Energy deposit above bandgap creates a conduction electron and a hole

Energy depends on direction vector  
(Brillouin zone: L for Ge, X for Si)

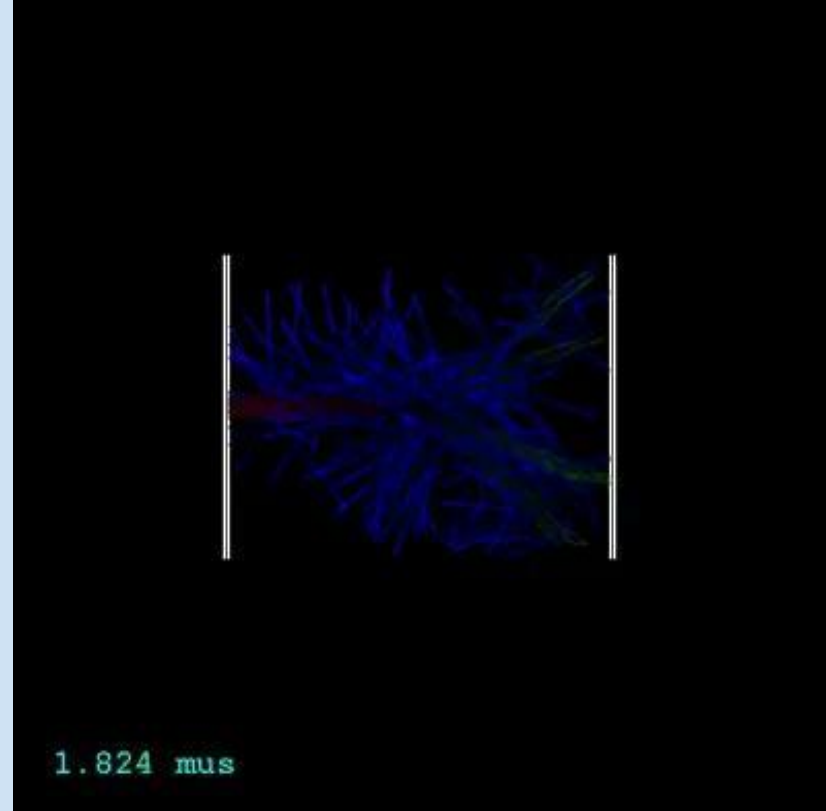


# Charge Transport, Scattering and Valleys

Lowest energy bands have particular orientations, “valleys”

Electrons travel along these directions, with some scattering

Charges radiate phonons during acceleration in field





# Charge Transport and Phonon Amplification

Accelerate charges across bias voltage

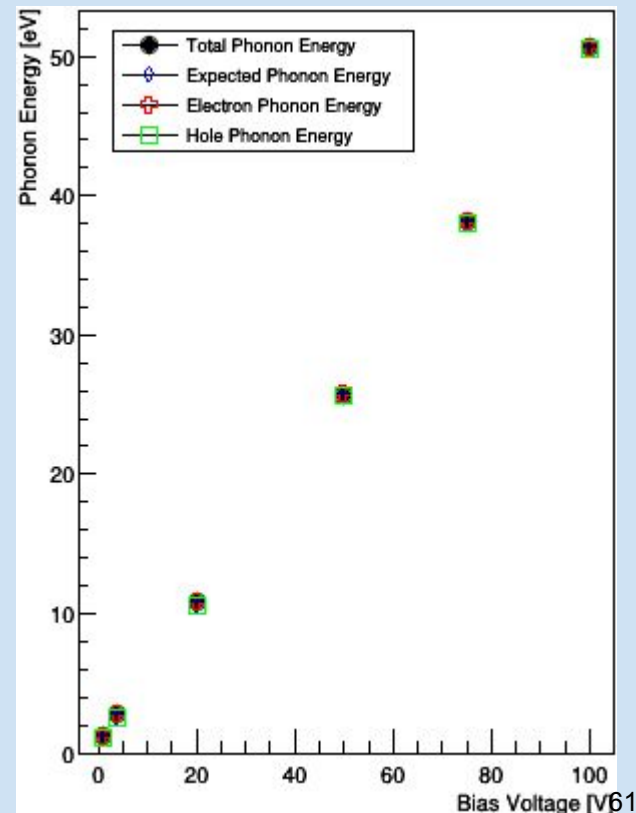
- Charges scatter, have steady “drift speed”
- Typically 20~30 km/s

Phonon emission by charges for  $v > v_{\text{sound}}$

Phonon emission scales with voltage

Total signal can exceed energy deposit

⇒ Amplifies low-energy signals



# Lattice Vibrations (Heat and Sound)

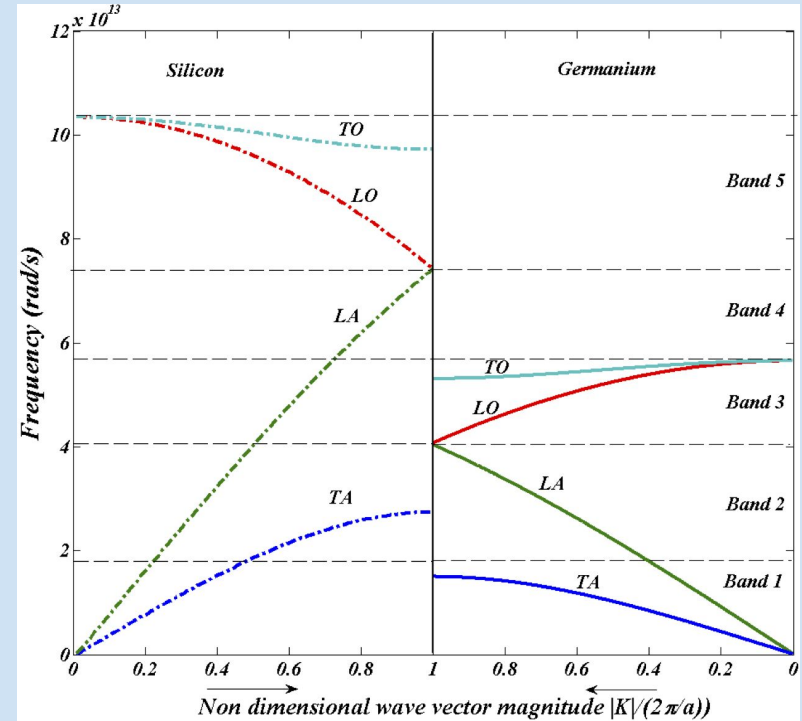
Crystal has strong, covalent bonds

High speed of sound (like metals)

Longitudinal or transverse vibrations

At low temperatures, only low frequency modes (“acoustic”) are significant

Quantized vibrations are **phonons**



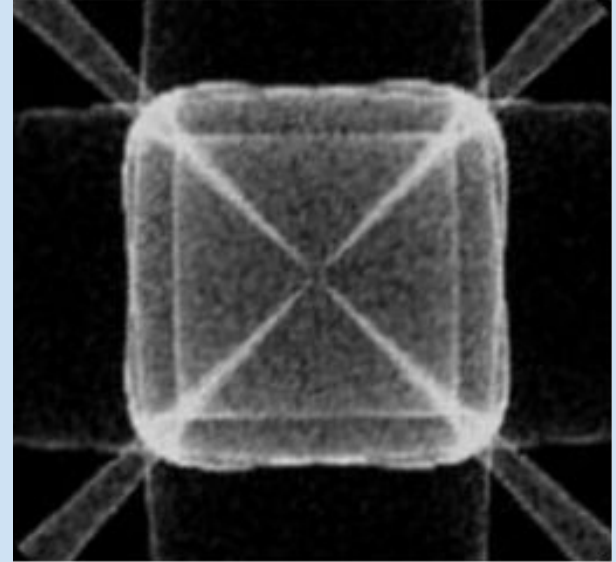
# Phonons: Caustics

Phonons are guided in particular directions by the lattice structure

Different modes have different vector dispersion relations

Complex pattern of focusing for low energy (below few meV) non-scattering phonons

Experimentally, can launch low-energy phonons at a point, detect where they hit opposite face of crystal





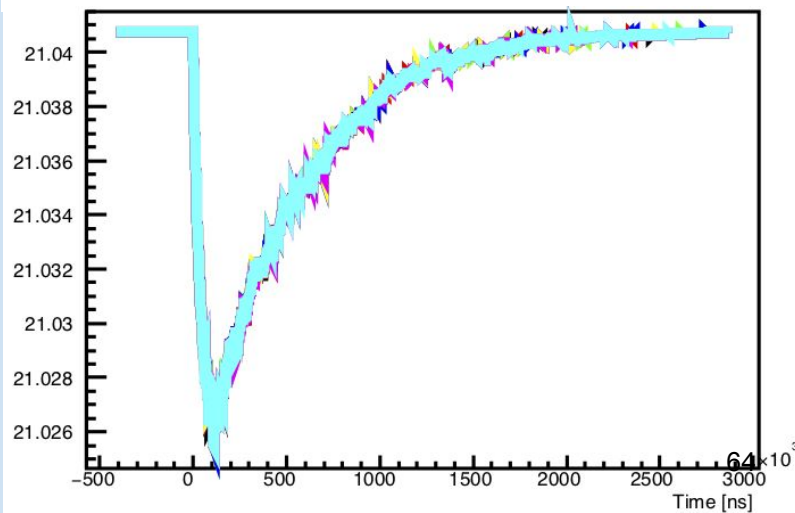
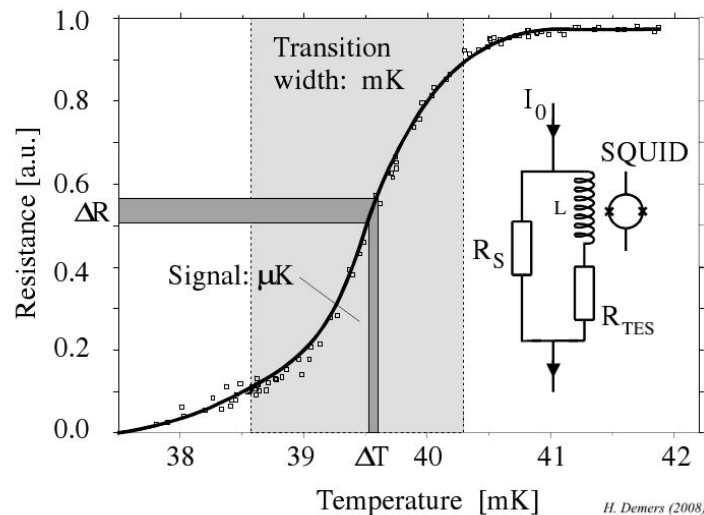
# Transition Edge Sensors

Superconducting films have finite width  $\delta T$  for transition from normal to superconducting state

Operate within transition region

- Tiny ( $\ll 1$  mK) temperature change
- Large resistance, lower current

Fast ( $< 1$   $\mu$ s) response, fast readout



A photograph of a detector assembly, likely a silicon strip detector, housed in a copper-colored metal frame. The detector is a circular silicon wafer with a complex, concentric, spiral-like pattern of white lines etched onto its surface. A stainless steel ruler is placed vertically to the left of the detector for scale, showing measurements in inches and centimeters. The ruler has markings for inches (0 to 2) and centimeters (0 to 50). The detector is mounted on a copper-colored metal base with several gold-colored pins or connectors visible along the edges. The background is a plain, light-colored surface.

# Understanding the Detectors

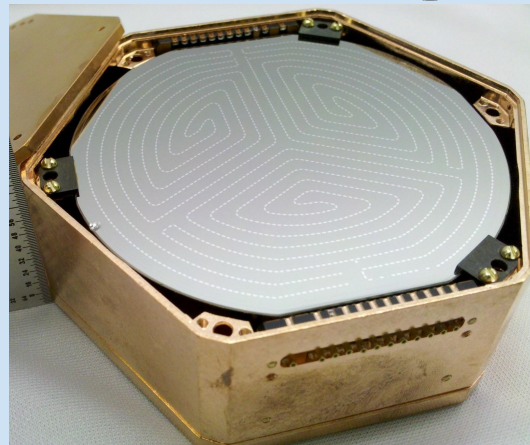
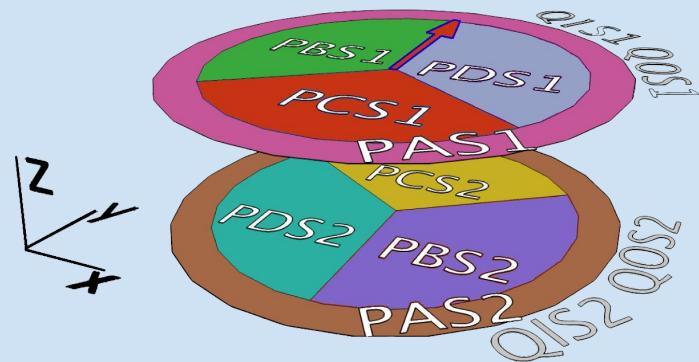
# Readout Channels (Multiple Designs)

Sensor patterns on top and bottom faces

- **Phonons:** center and outer ring(s)
- **Charges:** center disk and outer ring

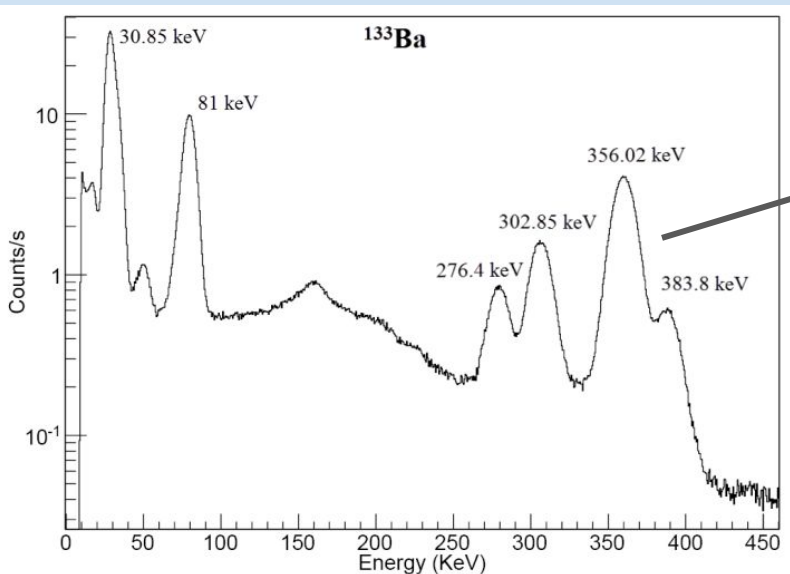
**Soudan:** eight phonon channels, four charge channels

**SNOLAB:** twelve phonon channels (four middle, two rings), four charge channels



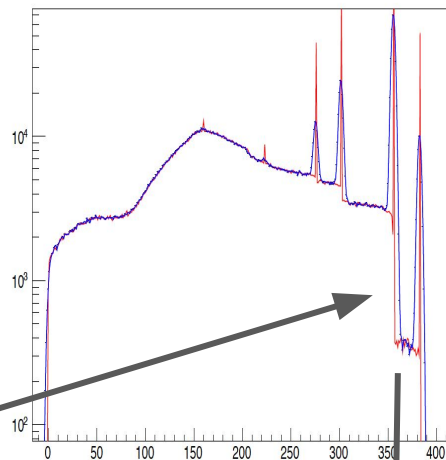


# Example: $^{133}\text{Ba}$



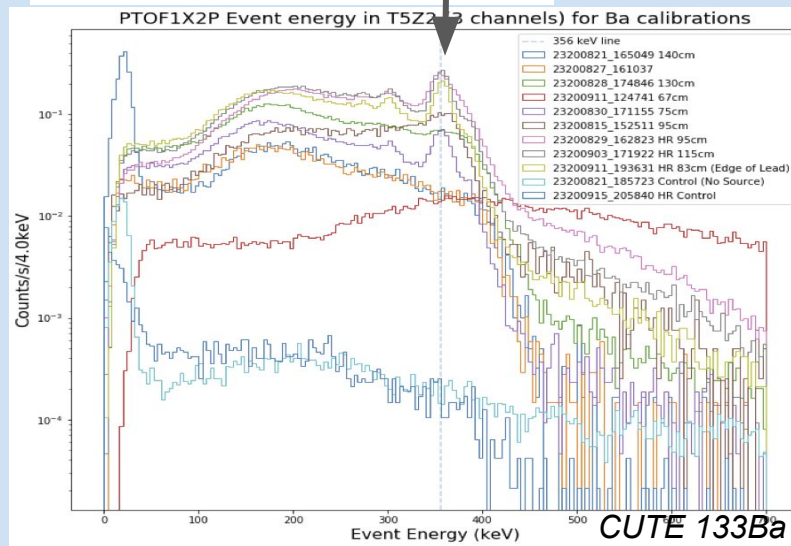
Courtesy: D-L.Zhang/ResearchGate

Smearred BulkERSingles from all zips



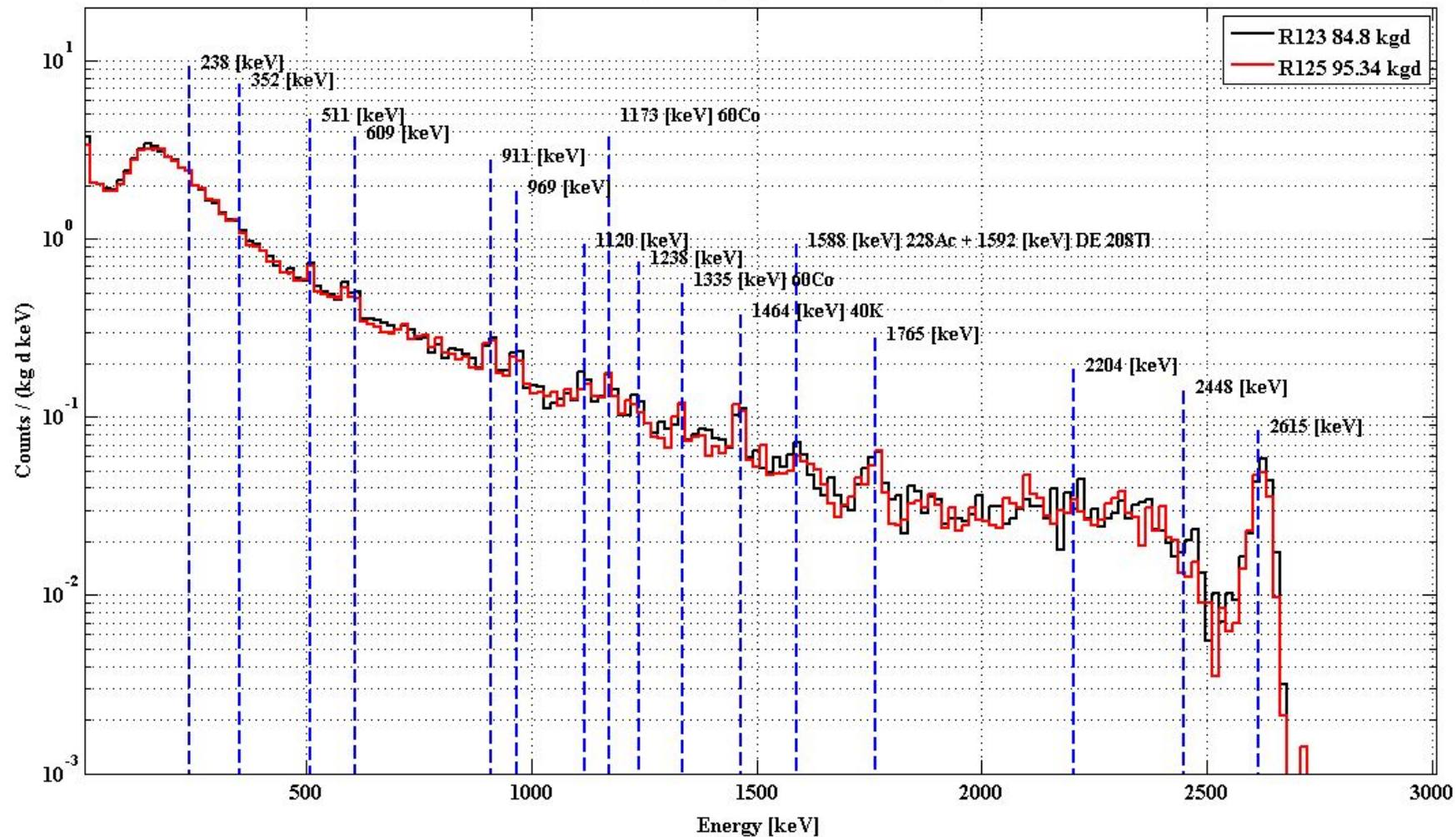
Simulation of detector with “perfect”  $^{133}\text{Ba}$  source

Real detector, source in different locations



CUTE  $^{133}\text{Ba}$  Source Study

Gamma spectrum, T5 germanium ZIPs only



# How Do We Interpret Signal or Set Limit?

$$\text{Rate} = \frac{\rho_{DM} v_{vir}}{m_{DM}} \times \frac{N_A m_{det}}{m_{nuc}} \times \sigma_{DM}$$

$$v_{vir} = 220 \text{ km/s}, \rho_{DM} \sim 0.35 \text{ GeV}/c^2/\text{cm}^3, m_{nuc} = 28 \text{ (Si)}, 72.64 \text{ (Ge)}$$

Exposure (mass  $\times$  time) converts rate into event count (2.3 for limit)

DM and nuclear mass determine recoil energy

- Detector energy sensitivity equivalent to a minimum  $m_{DM}$

Mass and cross-section are both unknown

- Limits or detections define regions of  $m_{DM}$ - $\sigma_{DM}$  plane