SuperCDMS: The Coolest Particle Detectors in Physics

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Physics Colloquium, UT Dallas
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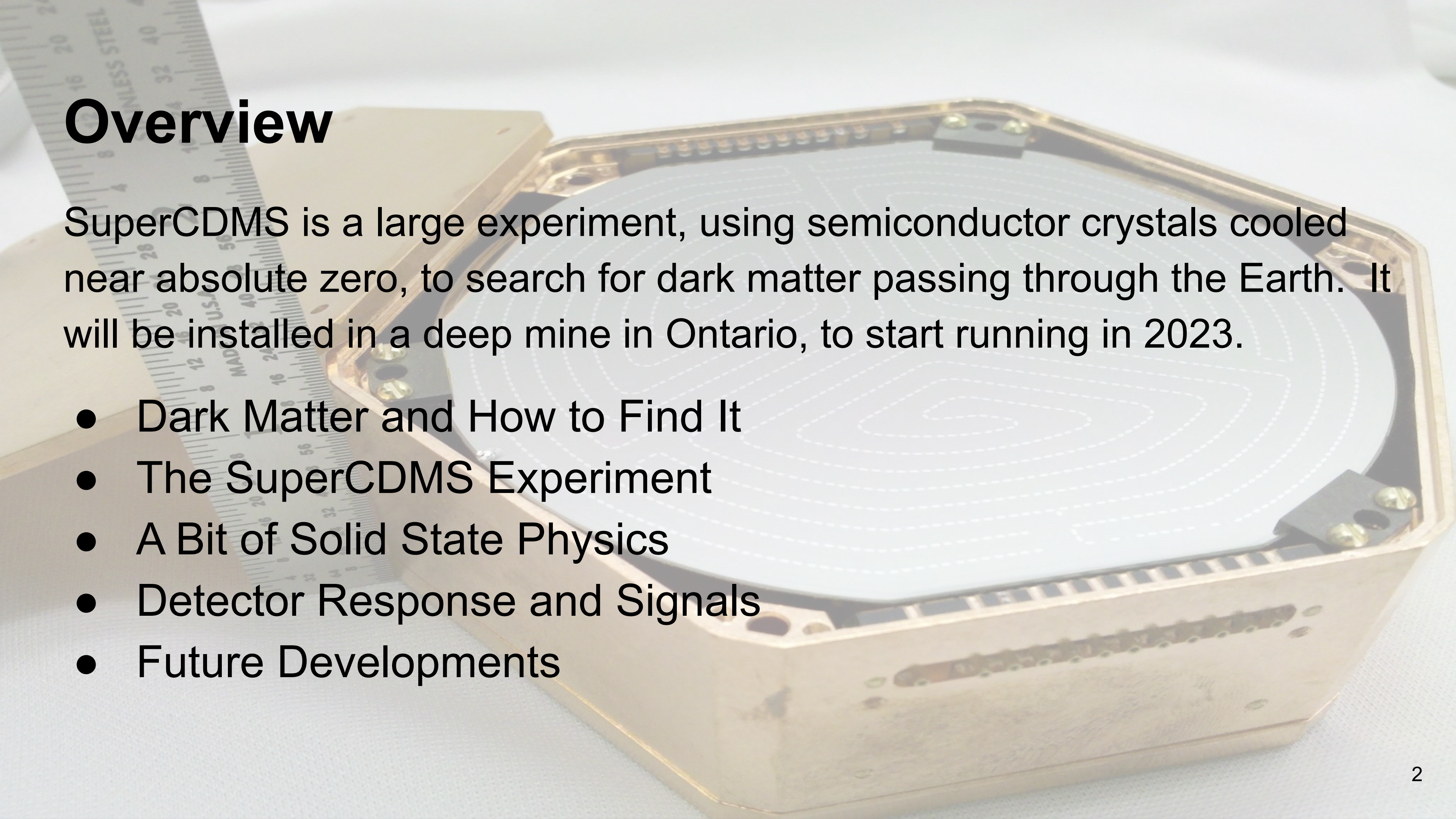


Overview

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

Dark Matter and How To Find It

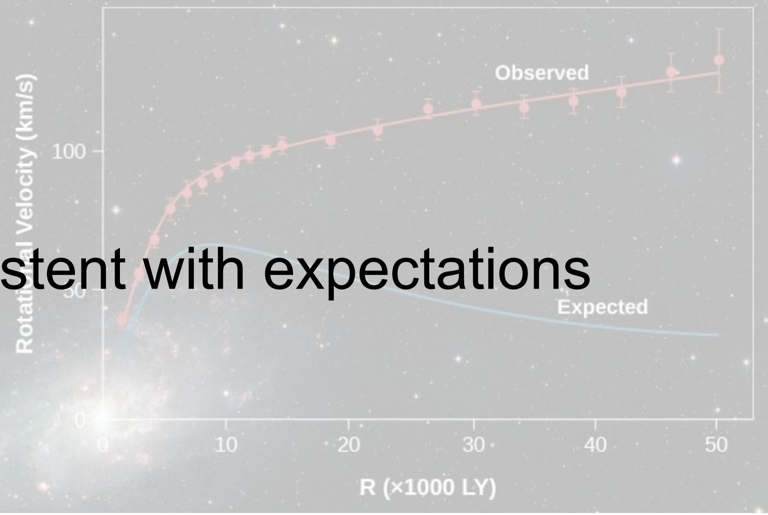
What is “Dark Matter”?

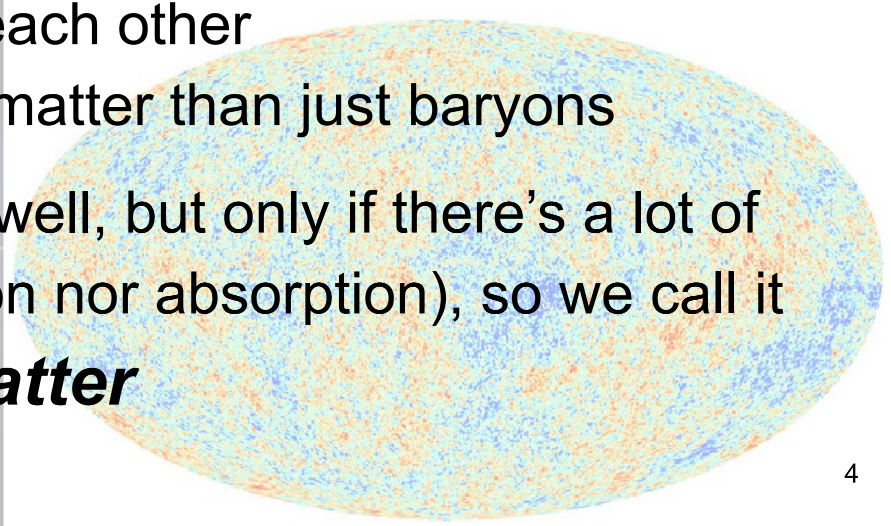
Some astrophysical observations inconsistent with expectations

- 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

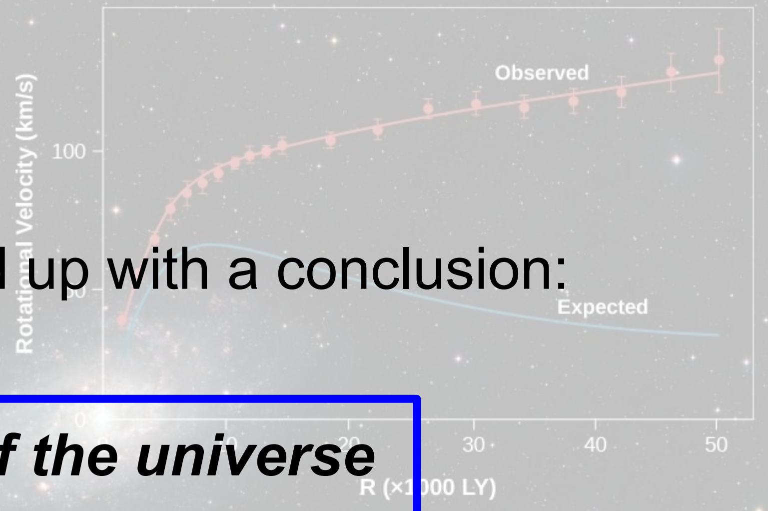
We can explain these observations well, but only if there’s a lot of matter we can’t see (neither emission nor absorption), so we call it

Dark Matter



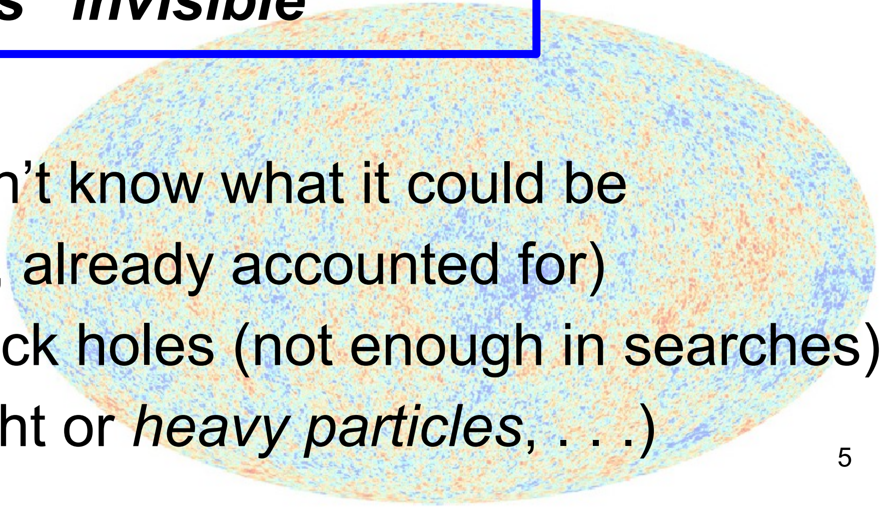


Indirect Evidence



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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Dark Matter Particles?

New Particle Physics

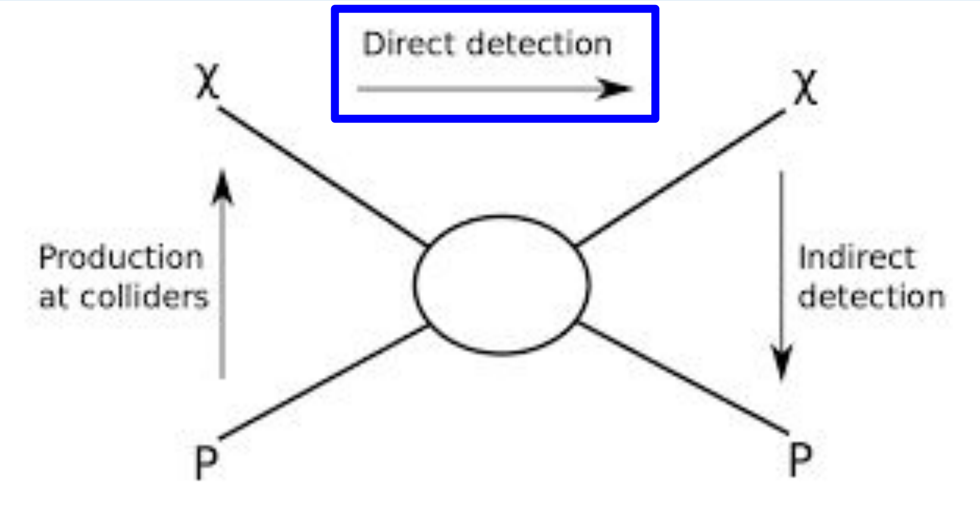
- Light, stable, unique kind of particle
  - Axion or “axion-like particle”; behaves similarly (mixes) to photons
  - Prediction of particle physics (CP symmetry in strong interactions)
- Heavy, stable, unique kind of particle
  - WIMPs (***w****eakly* ***i****nteracting* ***m****assive* ***p****articles*)
  - Prediction of particle physics (supersymmetry)

SuperCDMS’s Target

- Parallel “zoo” of particles with own interactions
  - “Dark sector”: particles, “atoms”, “molecules”, etc.
  - Limited or no coupling to ordinary (standard model) particles

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

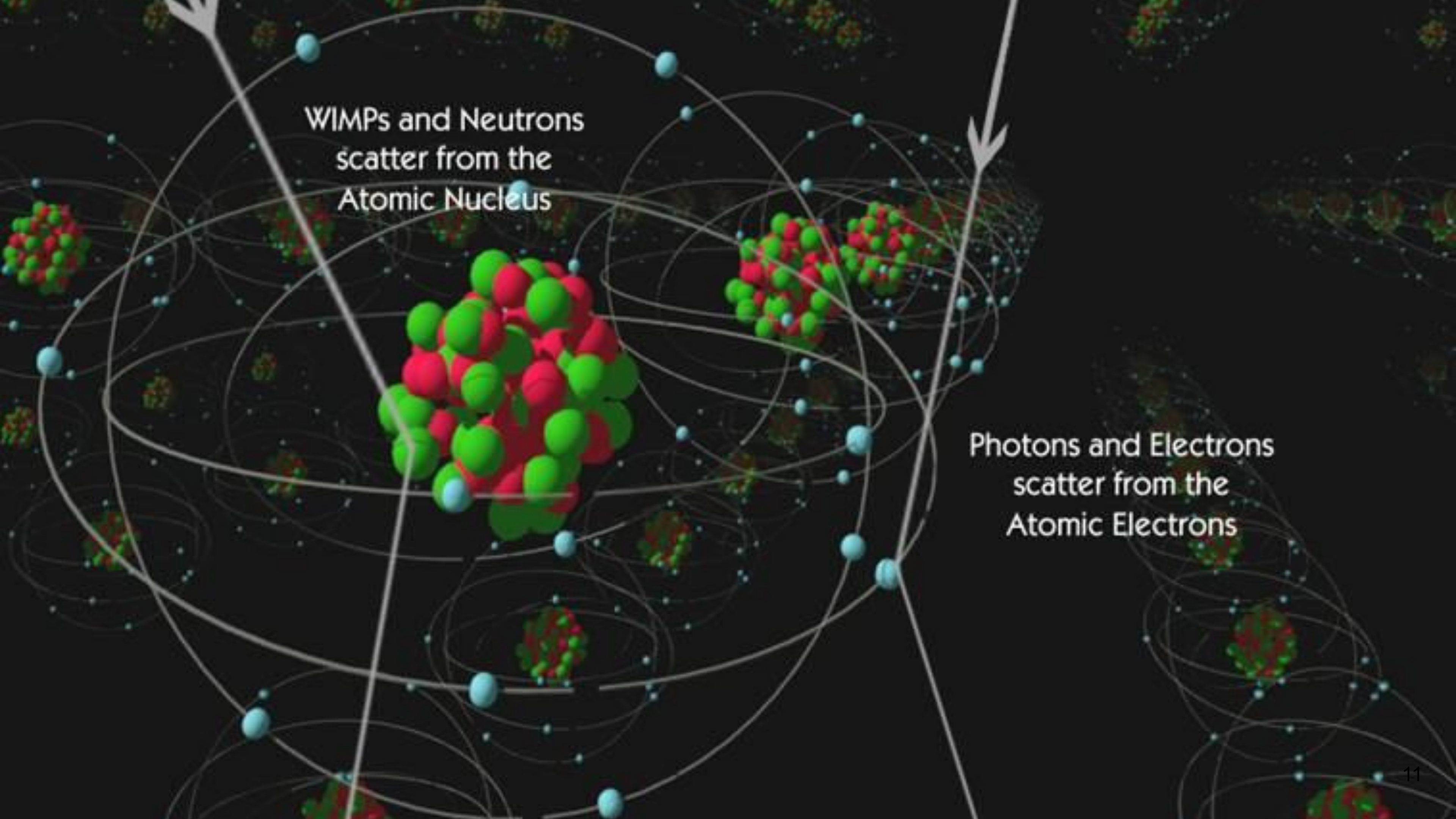
Use large **active mass**

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

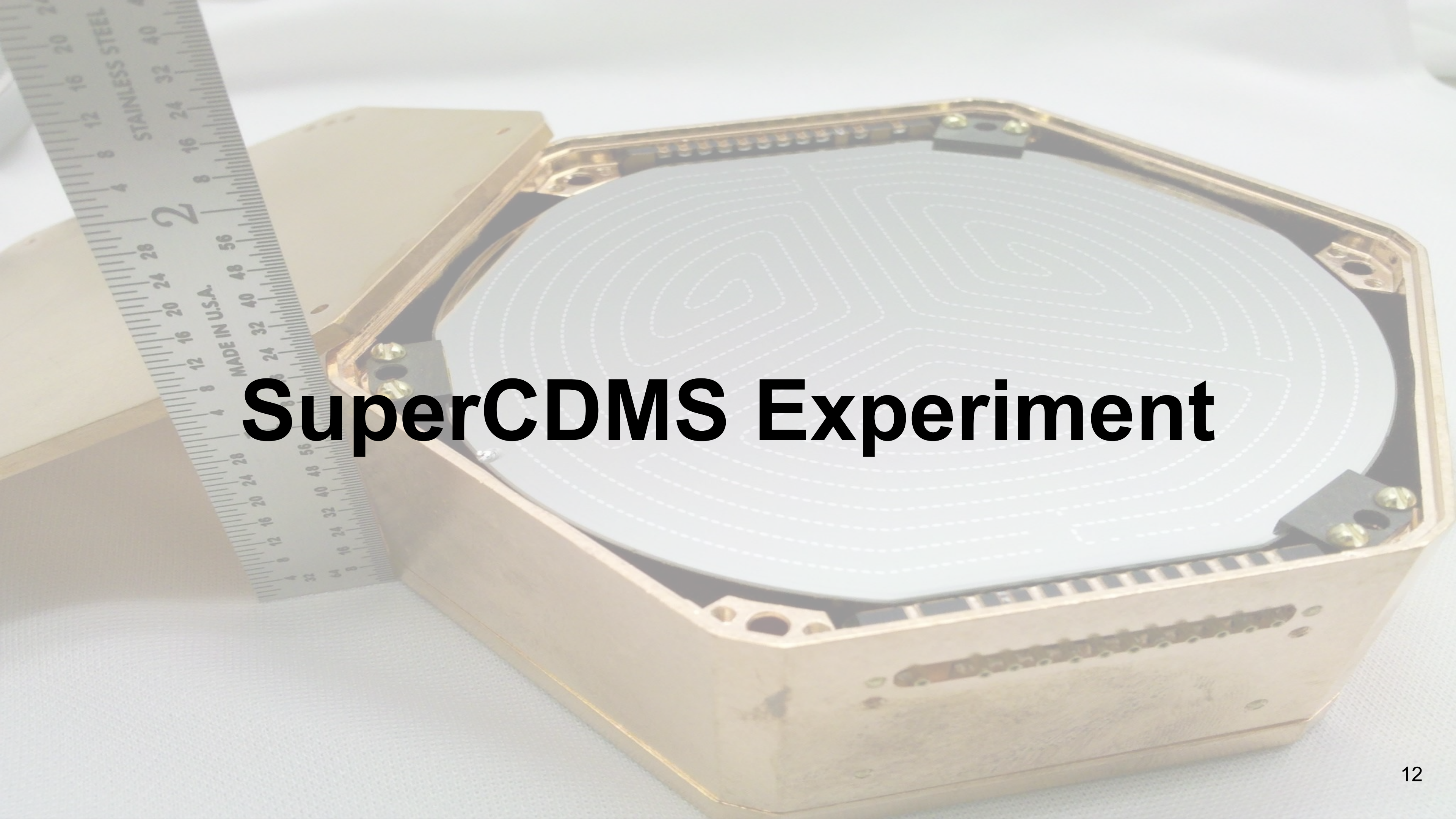
Deep underground to shield from cosmic rays

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

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


WIMPs and Neutrons scatter from the Atomic Nucleus
Photons and Electrons scatter from the Atomic Electrons

SuperCDMS Experiment



SuperCDMS Experiment History

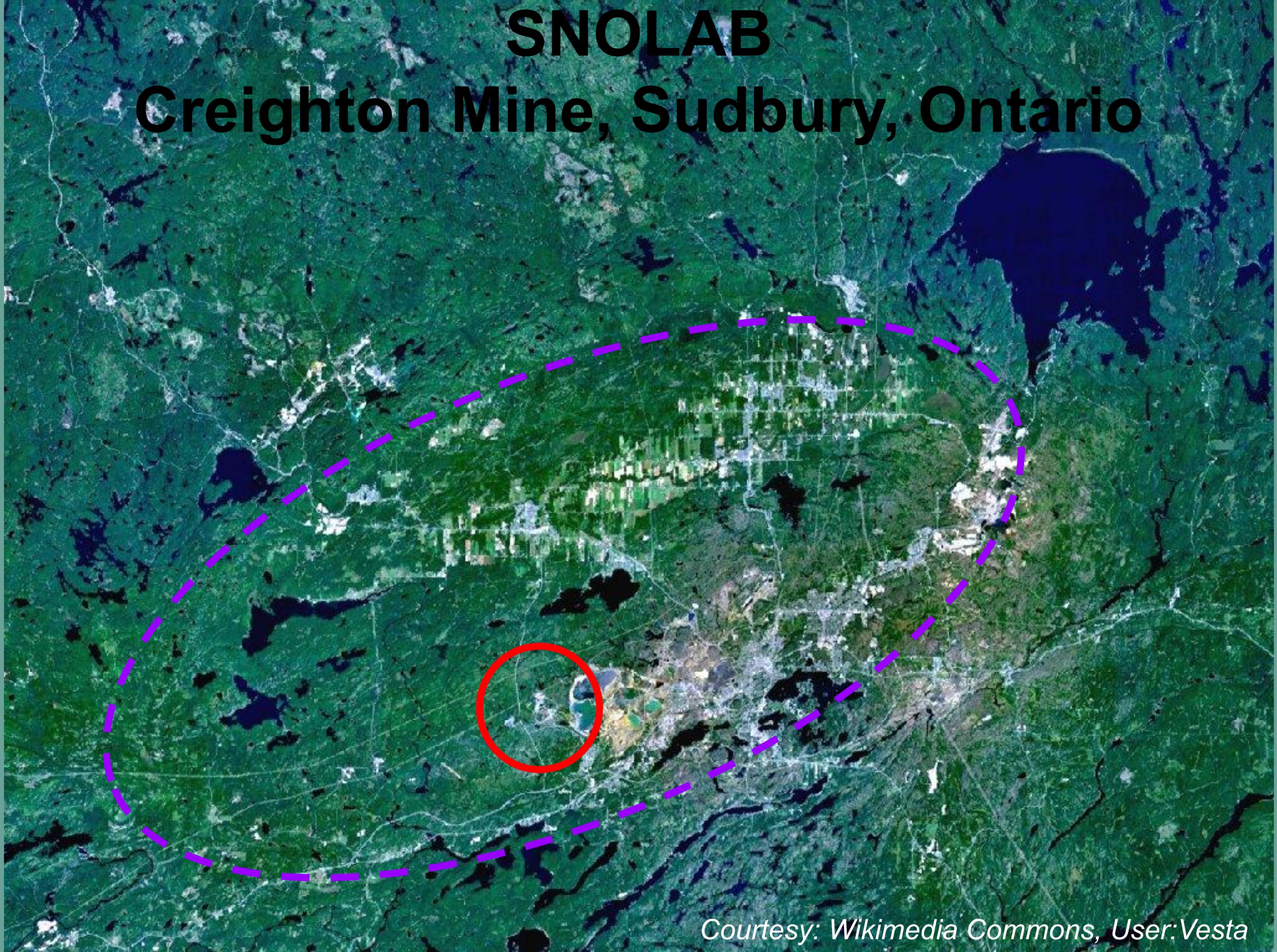
Cryogenic **D**ark **M**atter **S**earch experiment, deep underground

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)

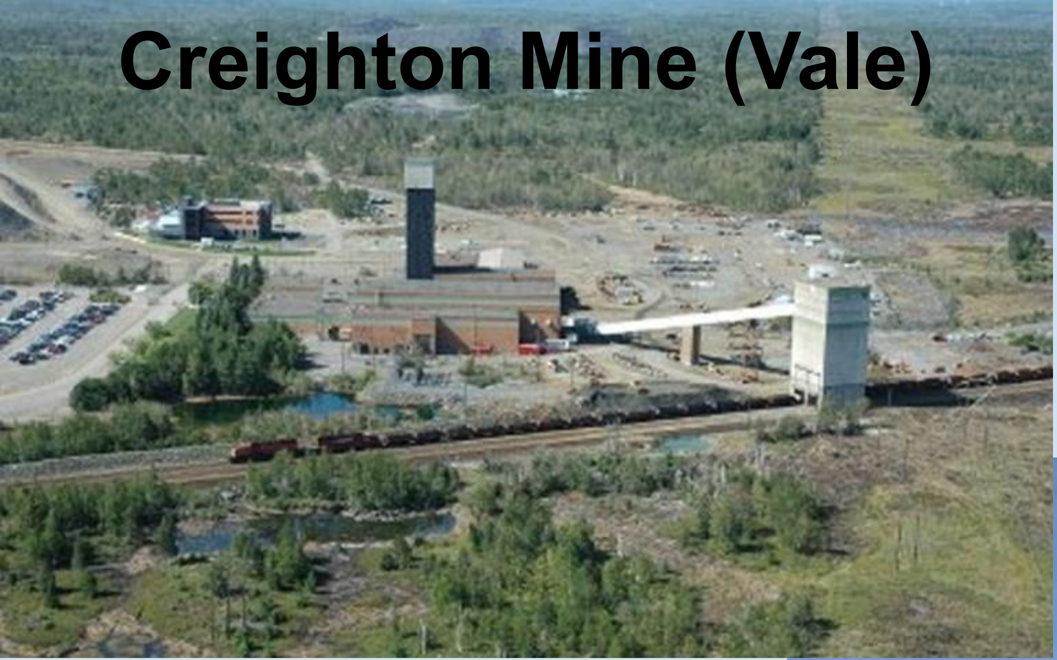
Detector assembly, installation at SNOLAB (4950 ft deep) underway

SNOLAB
Creighton Mine, Sudbury, Ontario



Courtesy: Wikimedia Commons, User:Vesta

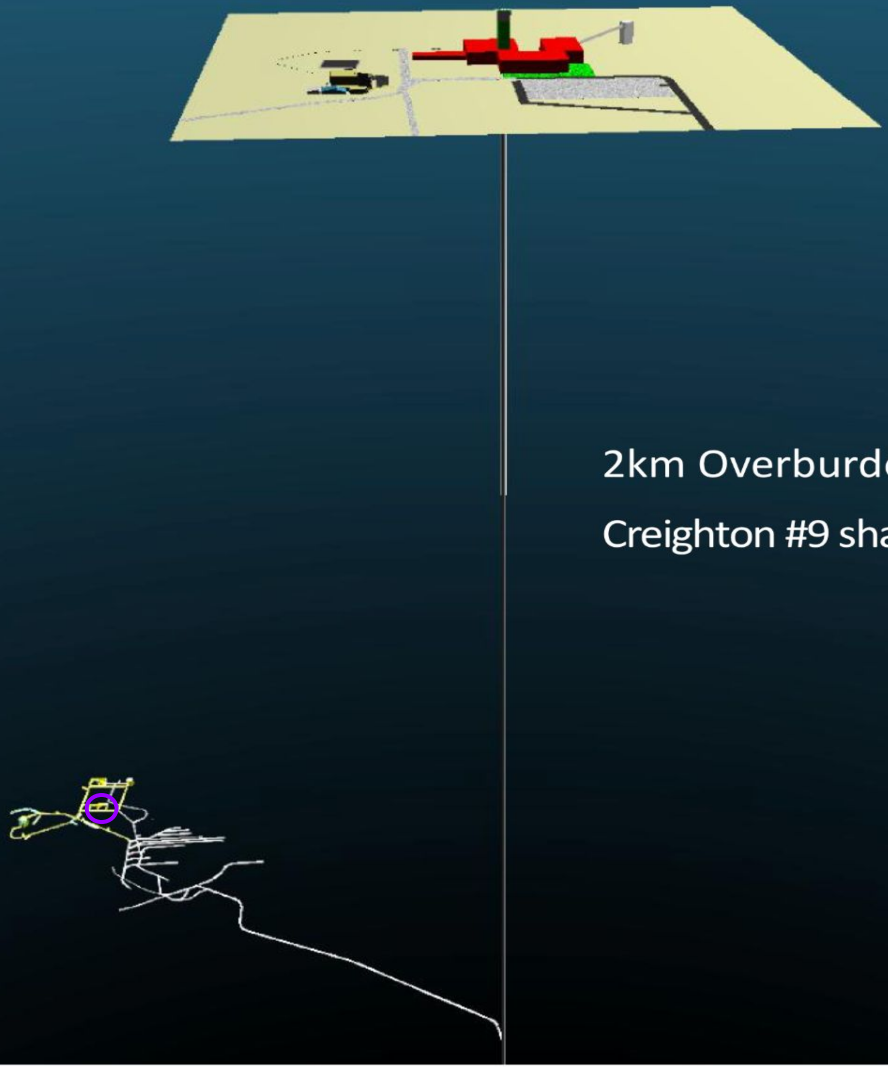
Creighton Mine (Vale)



Courtesy: Vale, via CIM Magazine

Courtesy: SNOLAB

SNOLAB Offices



Underground Lab:

37,000 m^3 volume

5000 m^2 Class 2000

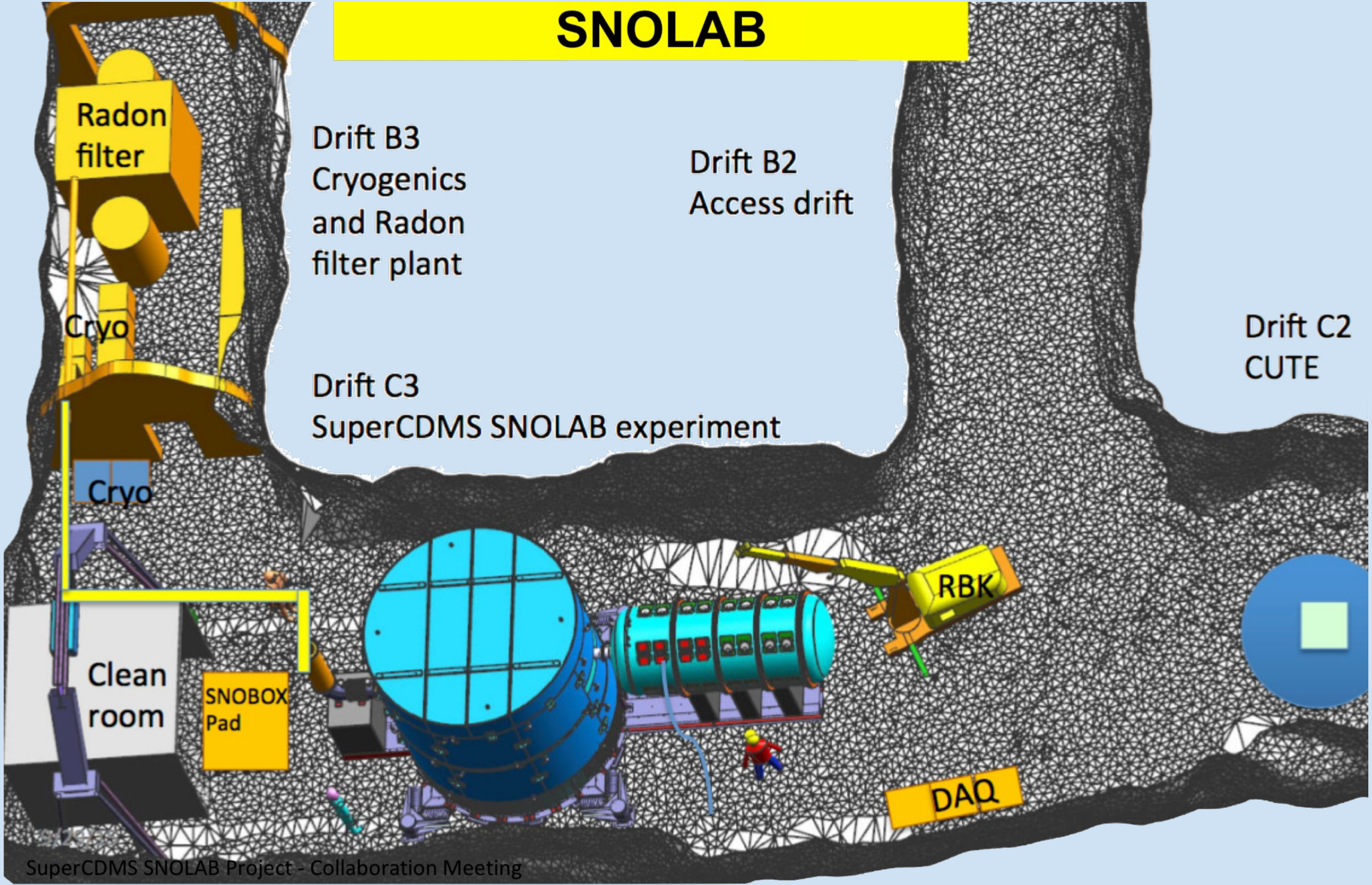
0.27μ/m^2/day

Courtesy: SNOLAB

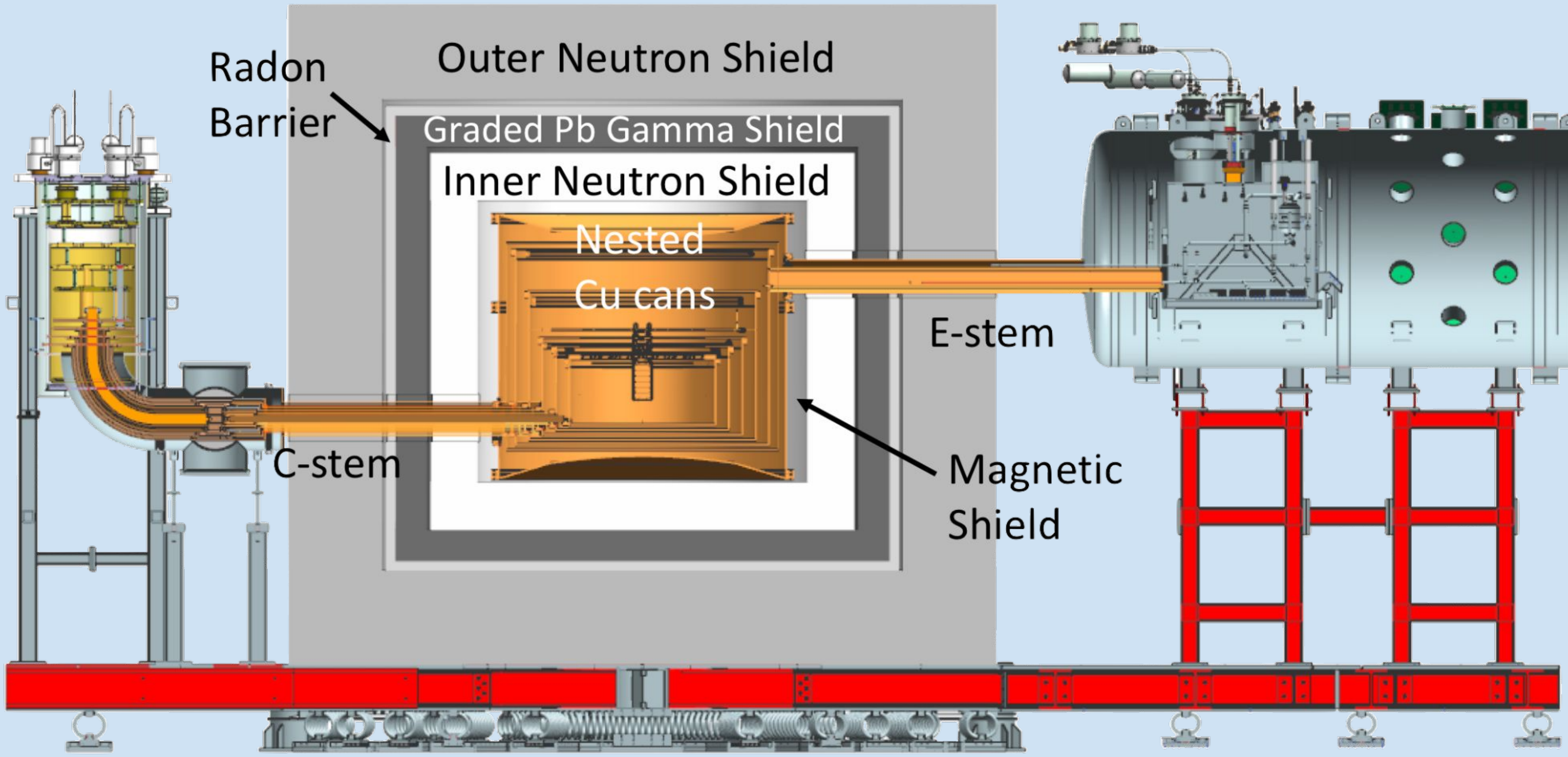
SNOLAB Cavern Layout

Courtesy: SNOLAB

SuperCDMS Tunnel and Adits



SuperCDMS Experiment



Progress of Installation Today

Detector Towers

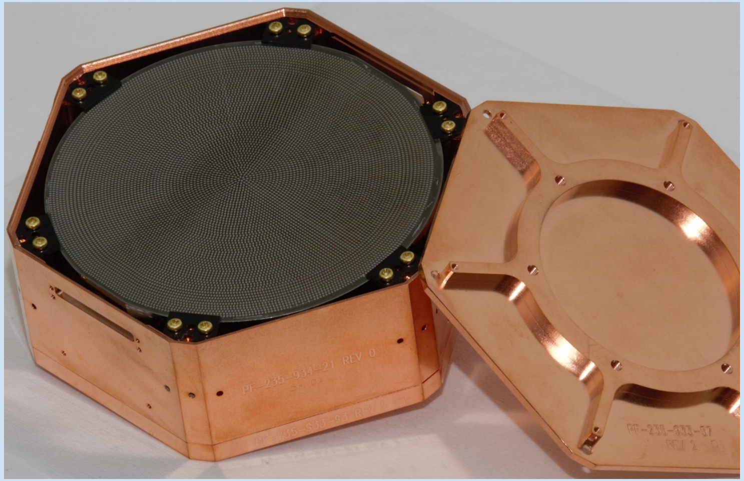
50 mK base temperature, 6-stage fridge

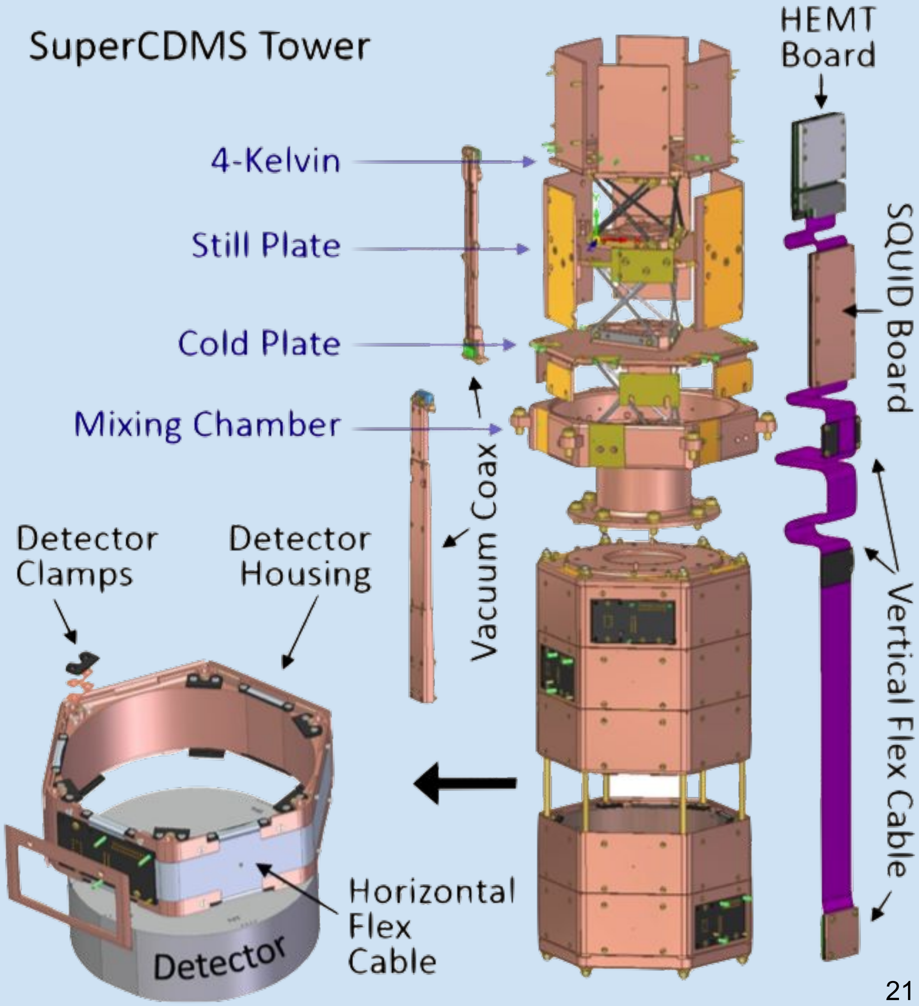
4 towers, 6 detectors each

Germanium, silicon detectors

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

Charge and phonon sensors





SuperCDMS Detectors

SuperCDMS Detectors

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

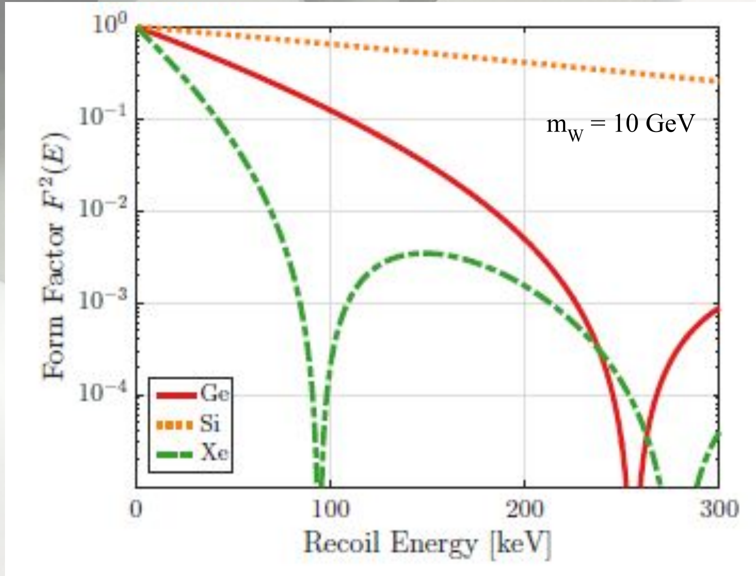
Precise crystal orientation, machined and polished dimensions

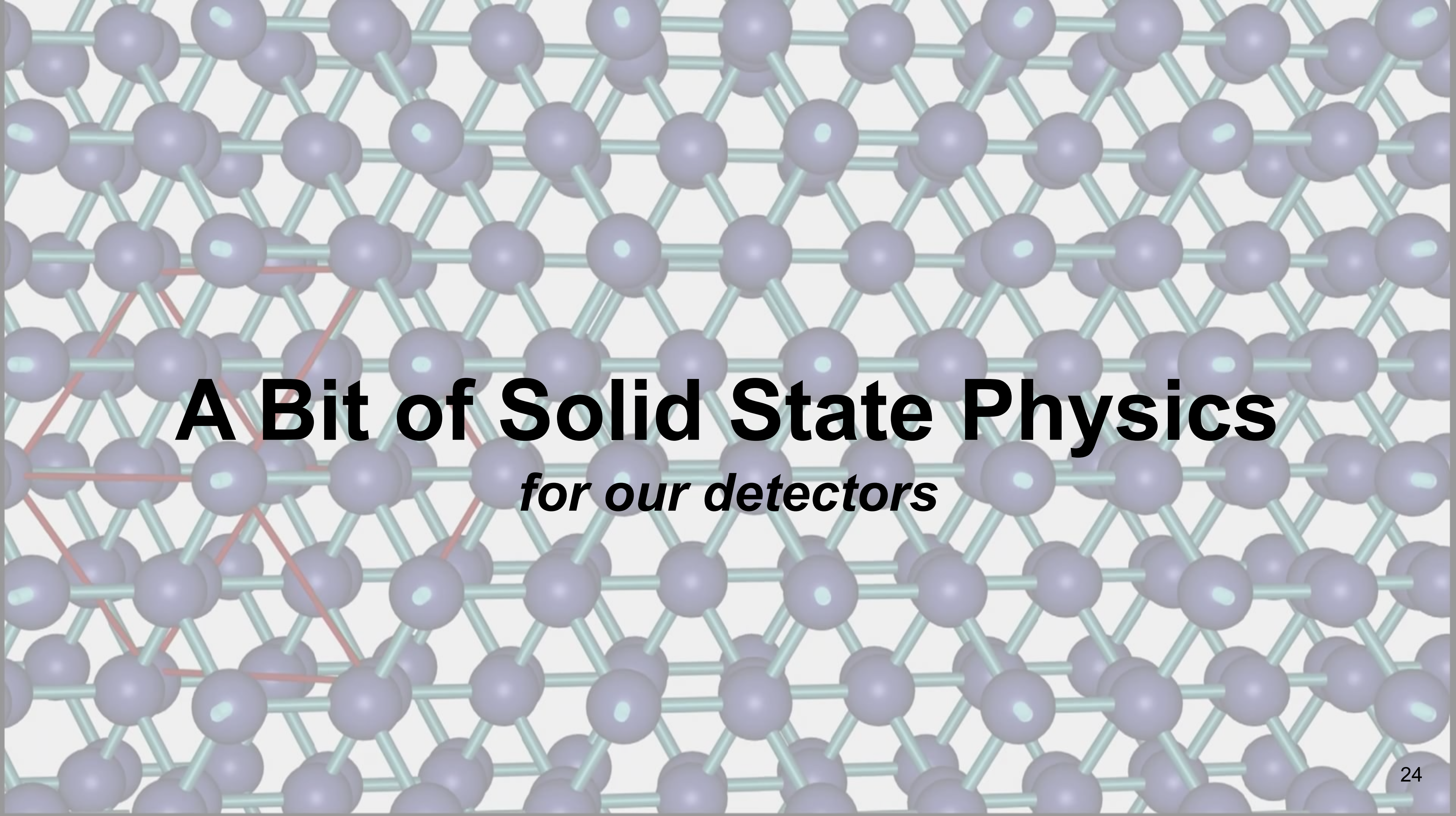
Some germanium, some silicon

- 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



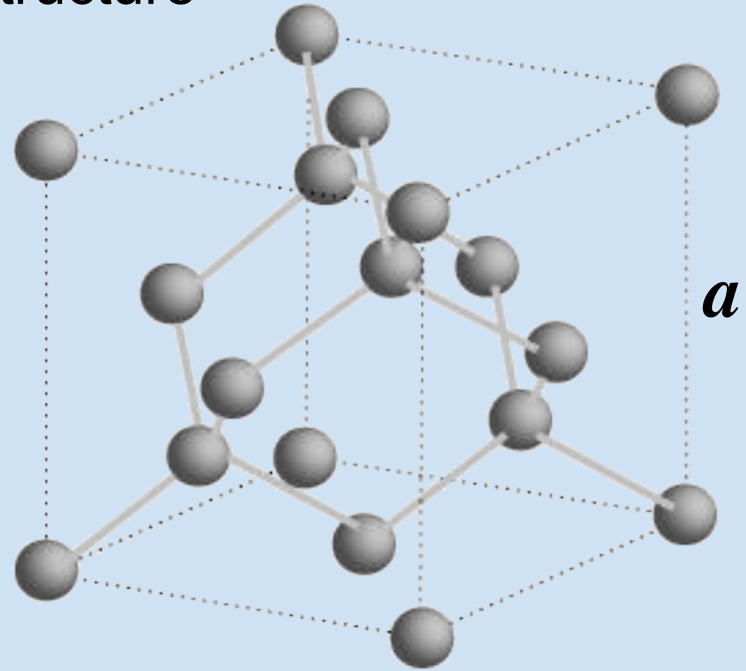


A Bit of Solid State Physics

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_{sound} (L)	5.3 km/s	9.0 km/s
V_{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

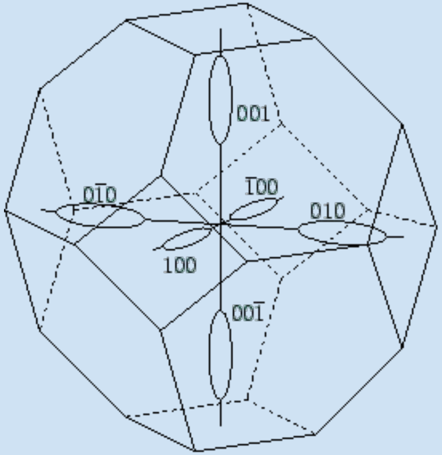
Charge Transport, Scattering and Valleys

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

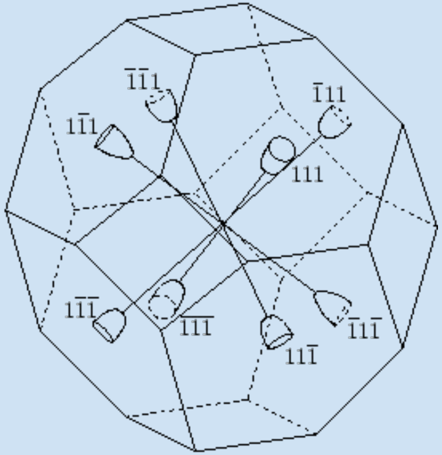
Lowest energy bands have particular orientations, “valleys”

Electrons travel along these directions, with some scattering

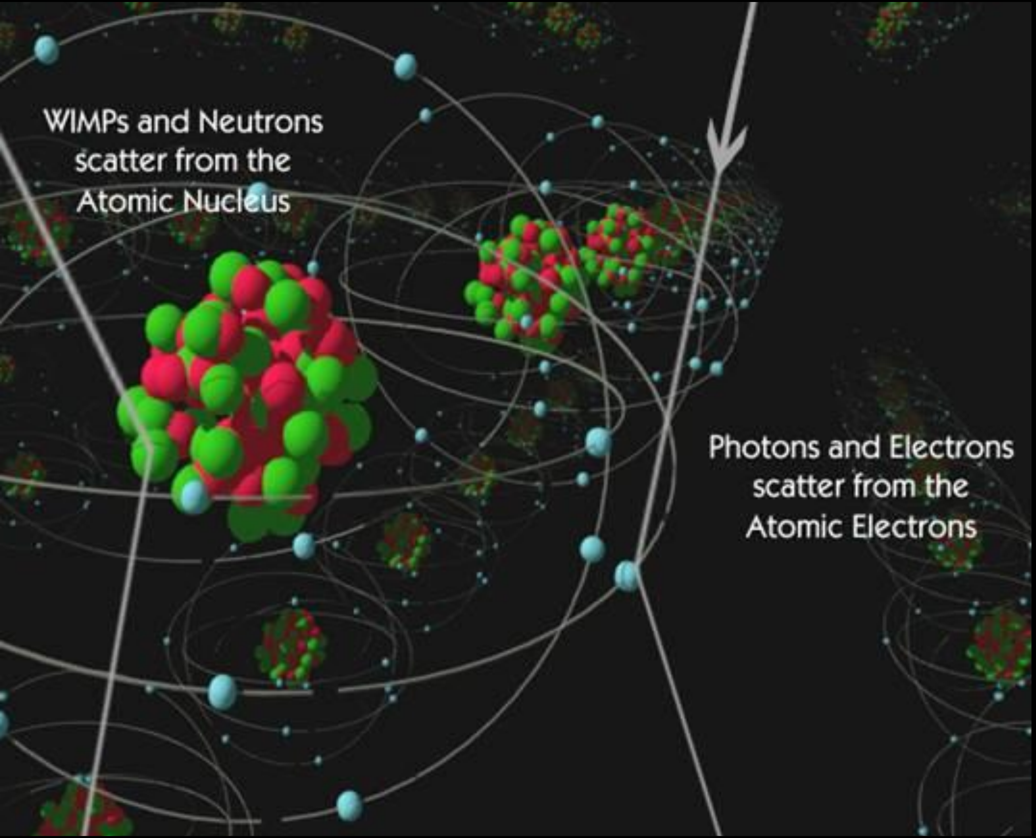
Charges accelerated in electric field radiate phonons



Silicon



Germanium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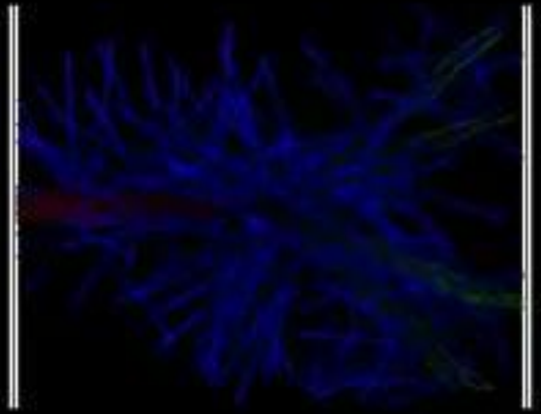


1.824 mus

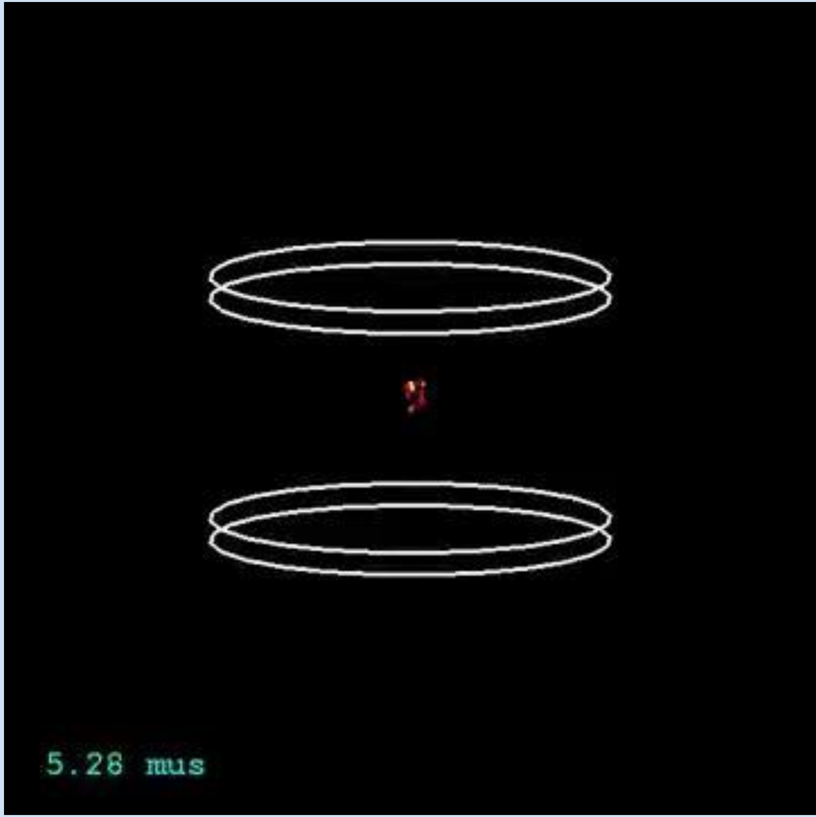
Phonons: Scattering and Equipartition

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

Scatter and transform from one mode to another, rate ~ E^4

Some split into two lower energy phonons, rate ~ E^5

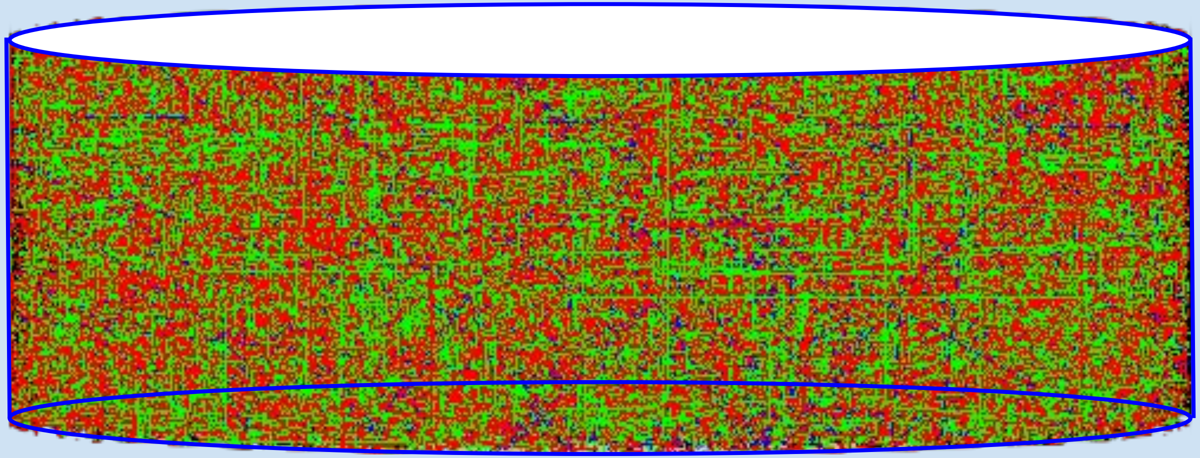
Low energy phonons rarely scatter



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

Q*uasiparticle trap assisted* ***E****lectrothermal feedback*
T*ransition edge sensor*

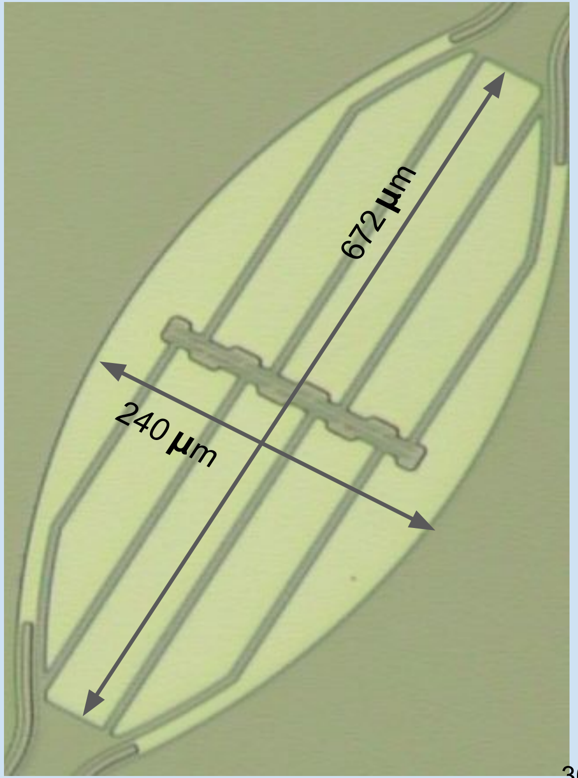
Absorbs phonons, produces change in current

Thin tungsten TES connected to readout lines

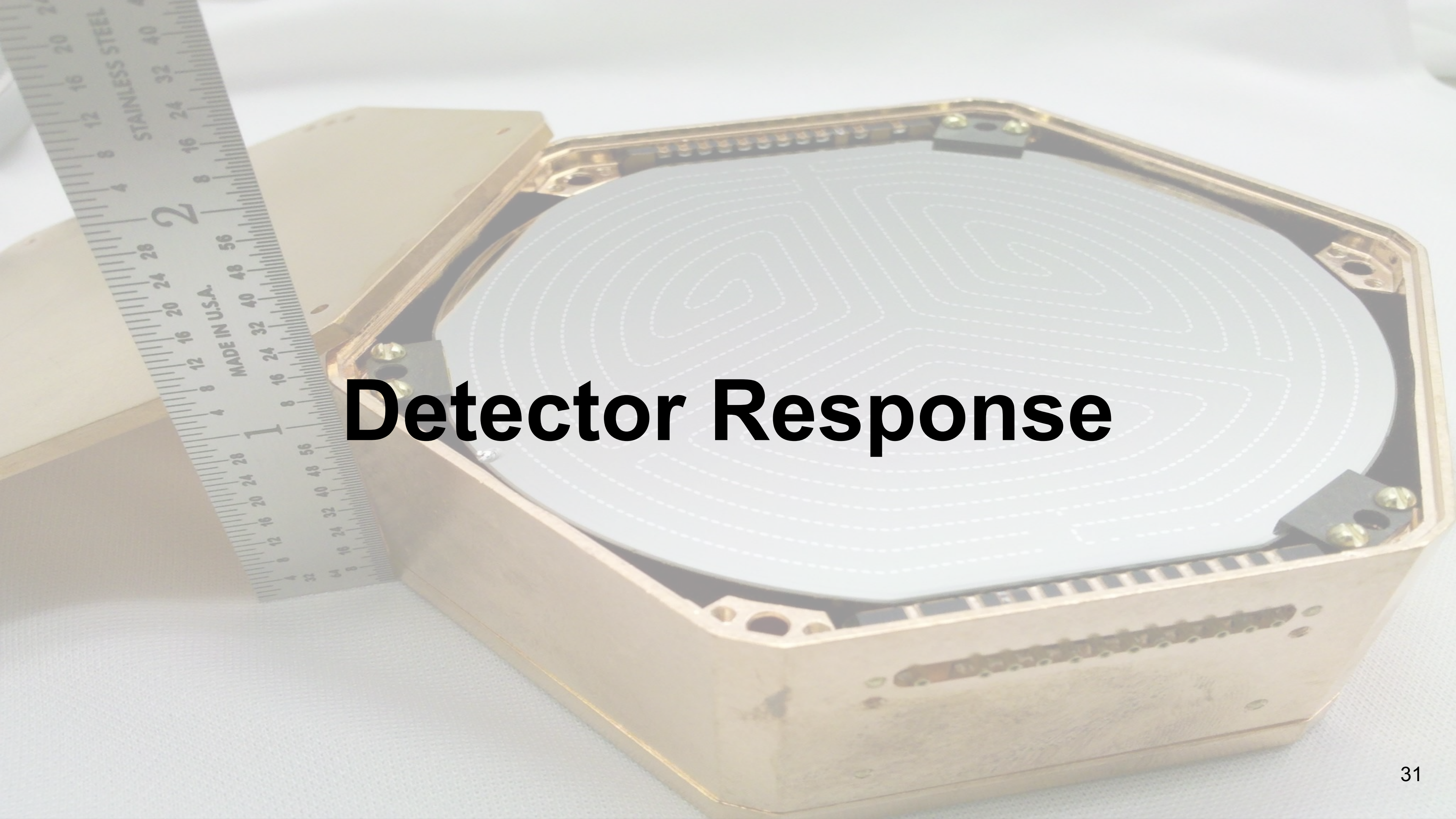
- On edge of superconducting transition
- Small δT ⇒ large δR ⇒ measurable δI

Attached to superconducting aluminum fins

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



Detector Response

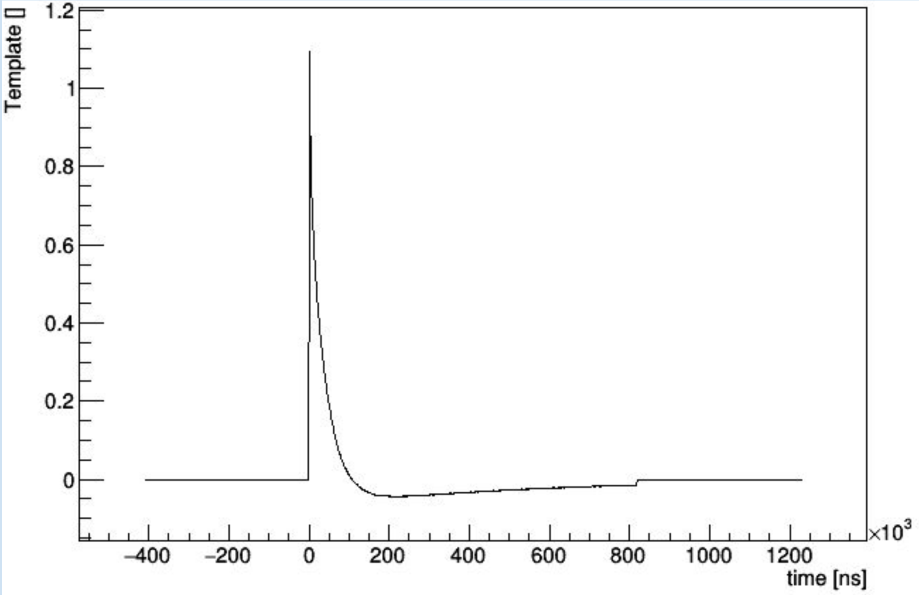


Charge Signals

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

Voltage bias carries charges to electrodes on opposite sides

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



Phonon Signals

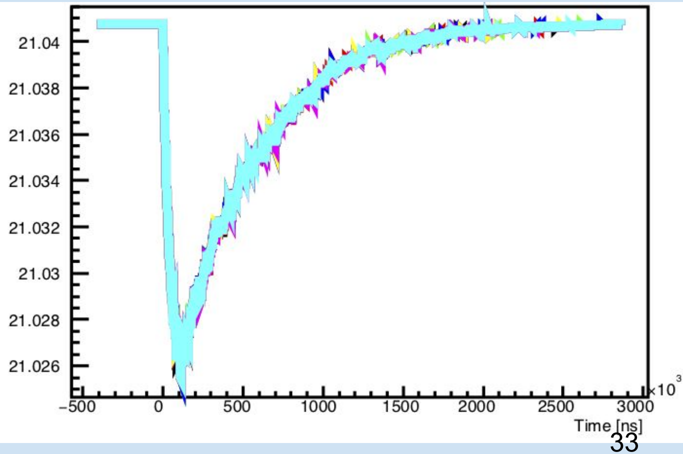
Charges gain energy in voltage, radiate phonons as they move

Phonons near surfaces arrive quickly, maxium 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

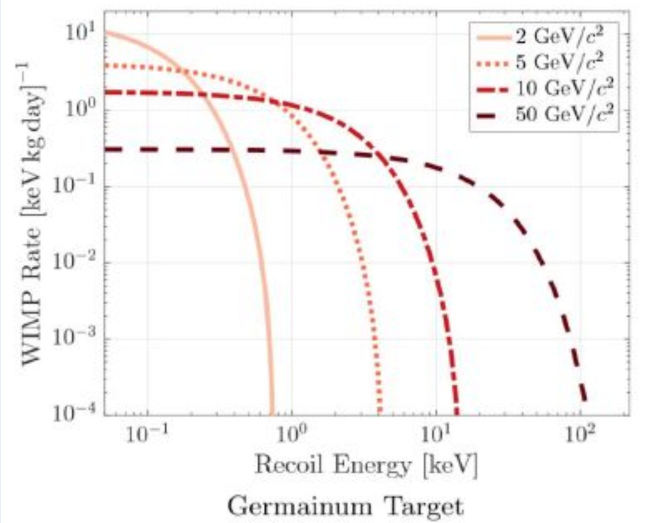
Background rate of few per second

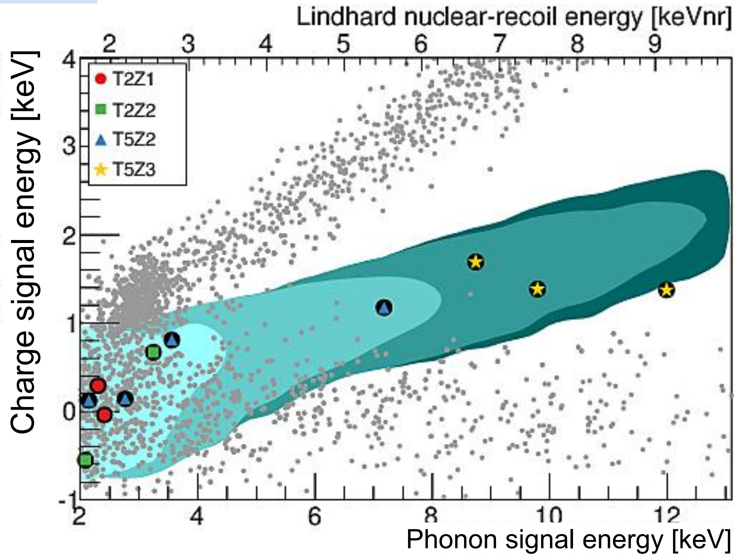
- Physical shielding, low-activity materials

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}Si, 172 y; ^{3}H, 12.3 y) part of mix
- Neutron calibrations can induce radioactivity (^{71}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}Pb in shield; U, Th in cavern walls; neutrons from cosmic rays

Calibration: Properly Interpreting Signals

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

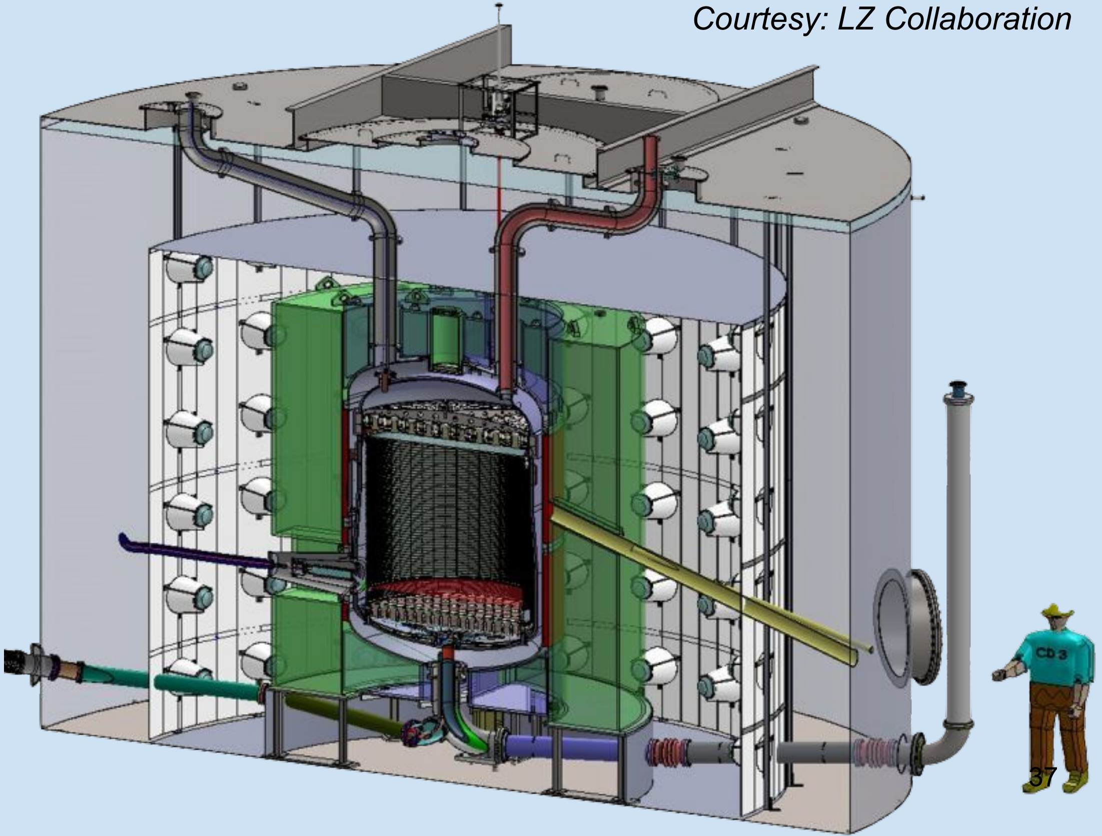
Want events with known energy to convert units into physical values

Radioactive sources, exposing single detectors or whole experiment

^{55}Fe	5.9 keV gamma
^{133}Ba	356 keV gamma, other gammas at known energies
^{71}Ge	10.37 keV gamma, from activating natural Ge in detector
^{252}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

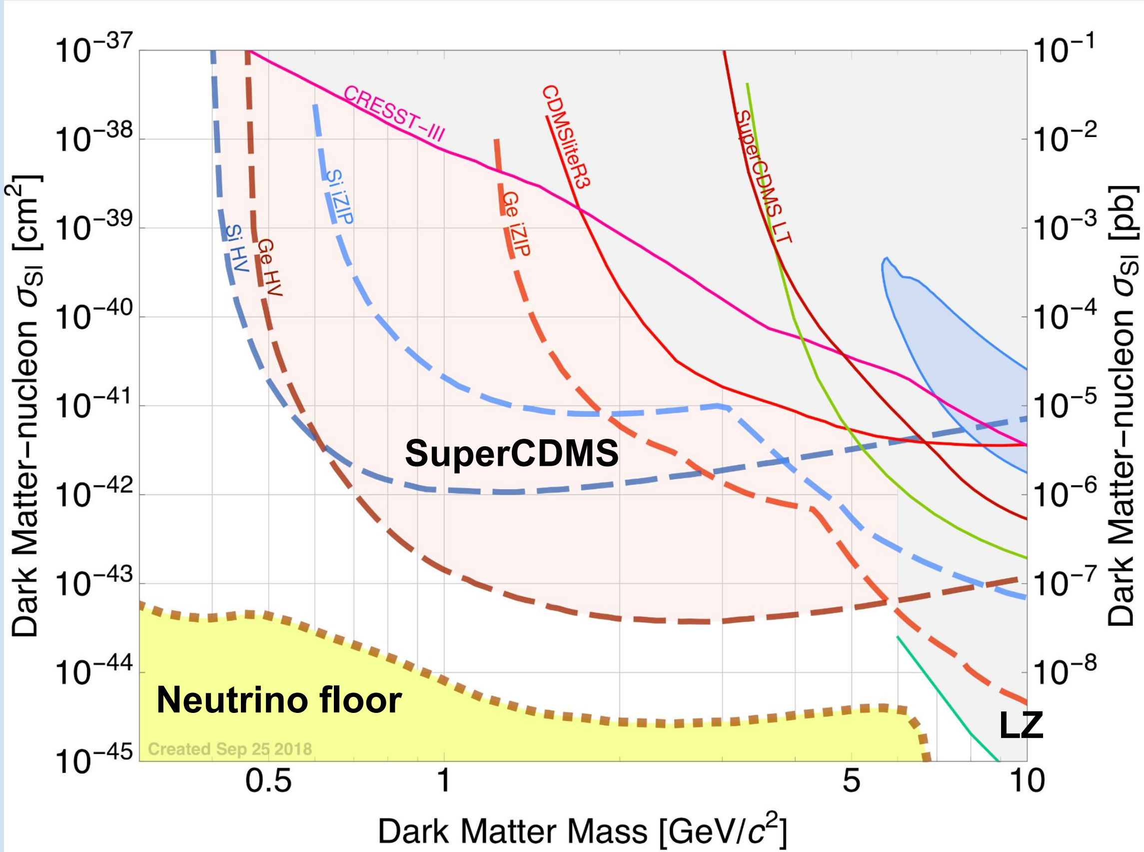
Dark Matter Search Limits

Sensitivity depends on both DM mass and cross-section

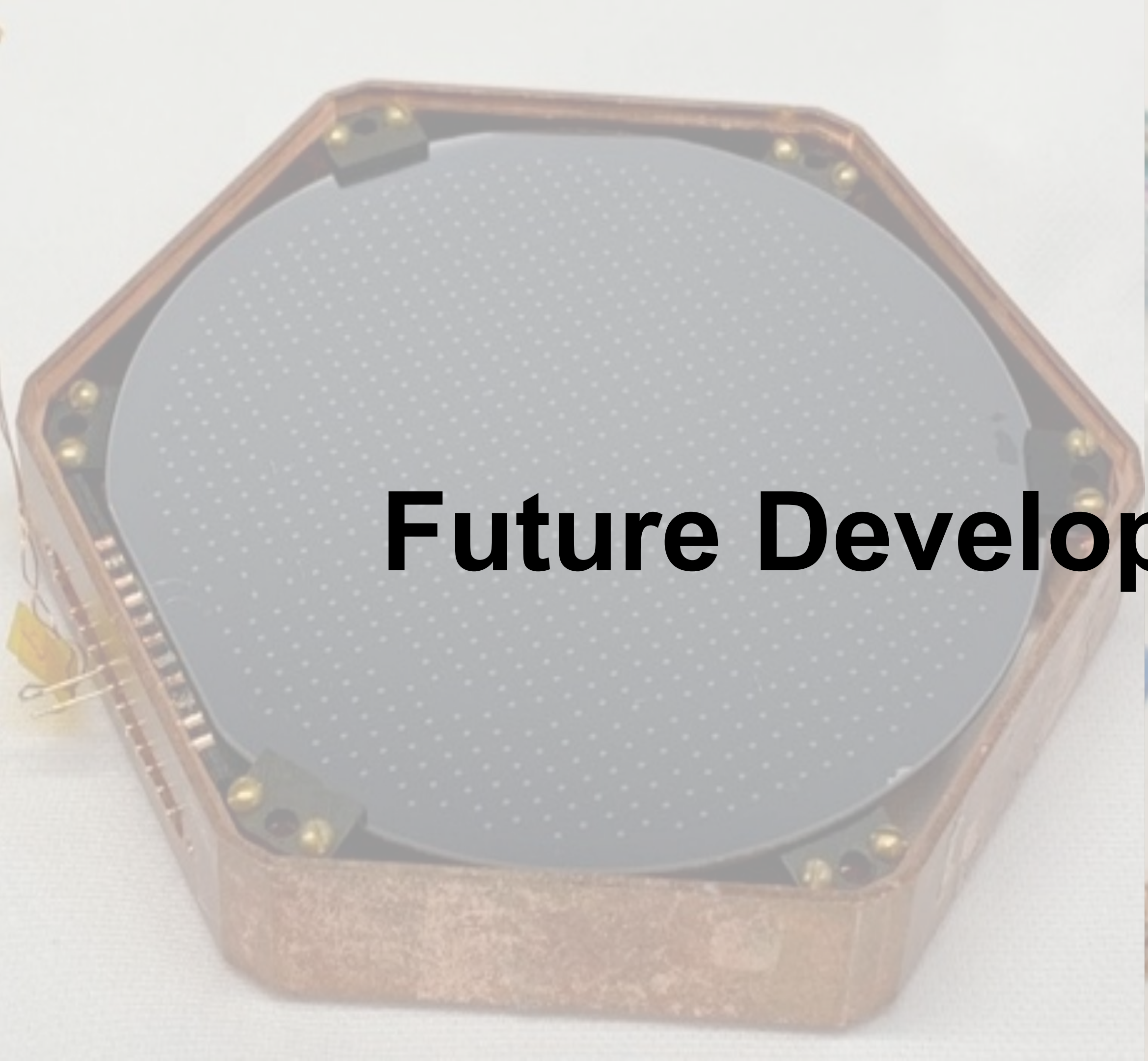
SuperCDMS can push to lower masses (~500 MeV)

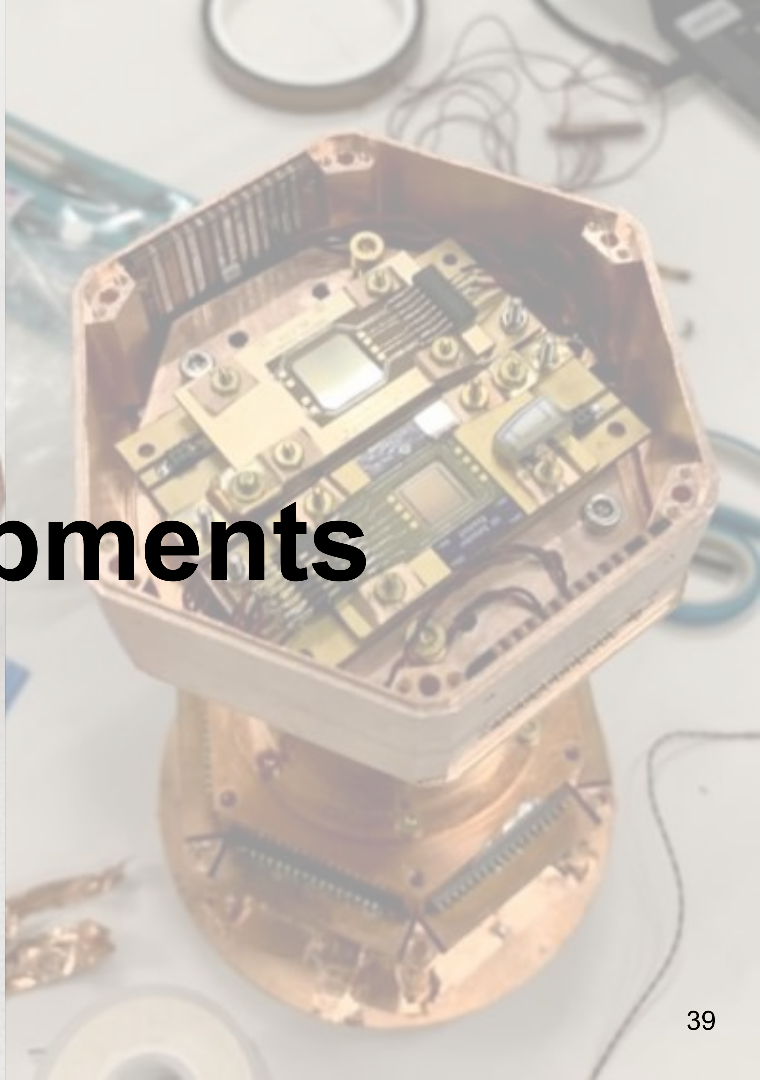
- Different detector types have different strengths

LZ sensitive to higher masses, much lower cross-sections

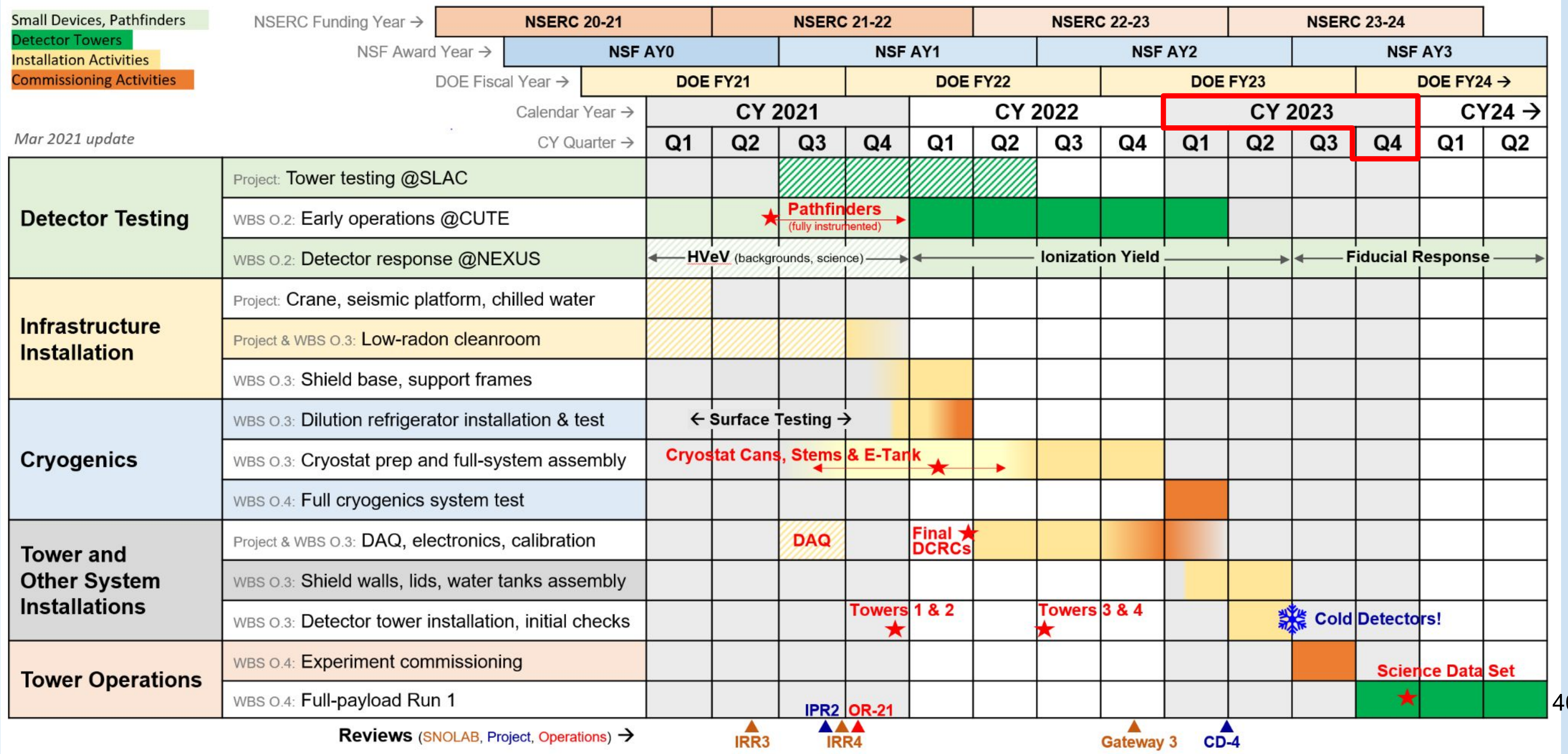


Future Developments





SuperCDMS Installation and Startup



LAPD : Large Area Photon Detector

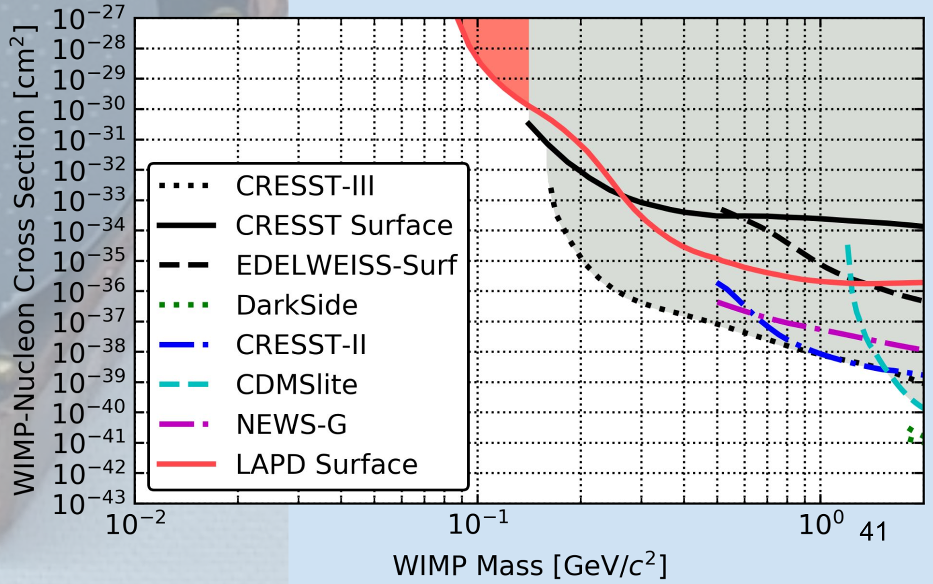
Thin Si wafer, 75×1 mm, 11 g (vs. CDMS 0.6 kg)

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

Science run ~10 g · day exposure

- Limits on m_{DM} 93−140 MeV/c^2

I.Alkhatib *et al.*, arXiv:2007.14289
(submitted to PRL, in review)



HVeV : High Voltage, eV resolution

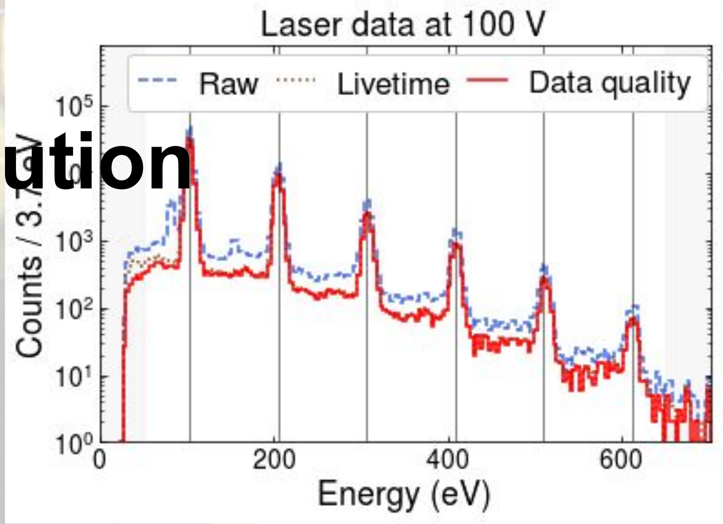
Si chip, 10×10×4 mm, 0.93 g

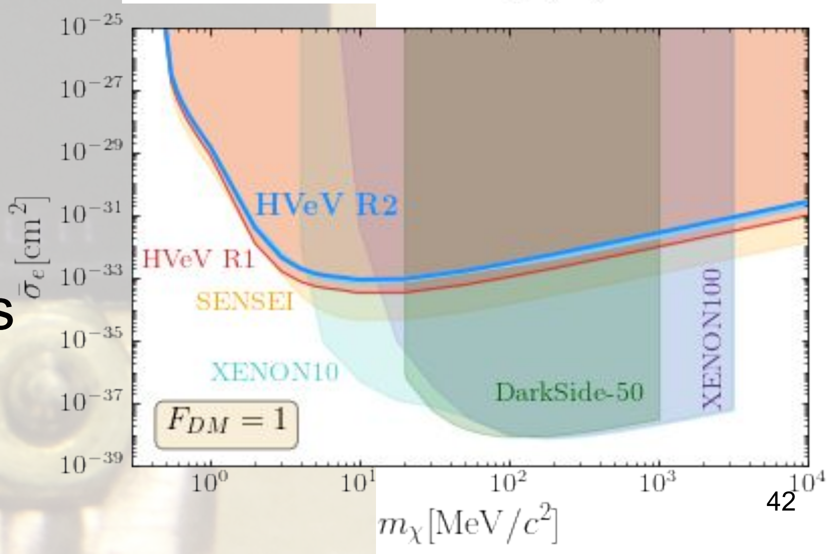
- Dense array of QETs, two channels
- 100V bias for phonon amplification
- Sensitive to individual charges

Science run just 1.2 g·day exposure

- Limits on $m_{DM} \gtrsim 50$ 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

Evidence for Dark Matter

Galaxy Clusters

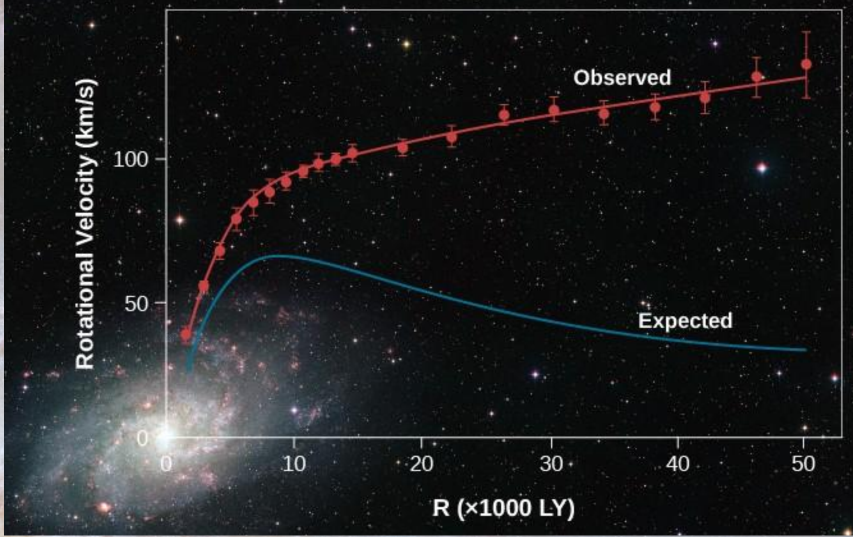
Large collection of galaxies, bound together by gravity

- 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

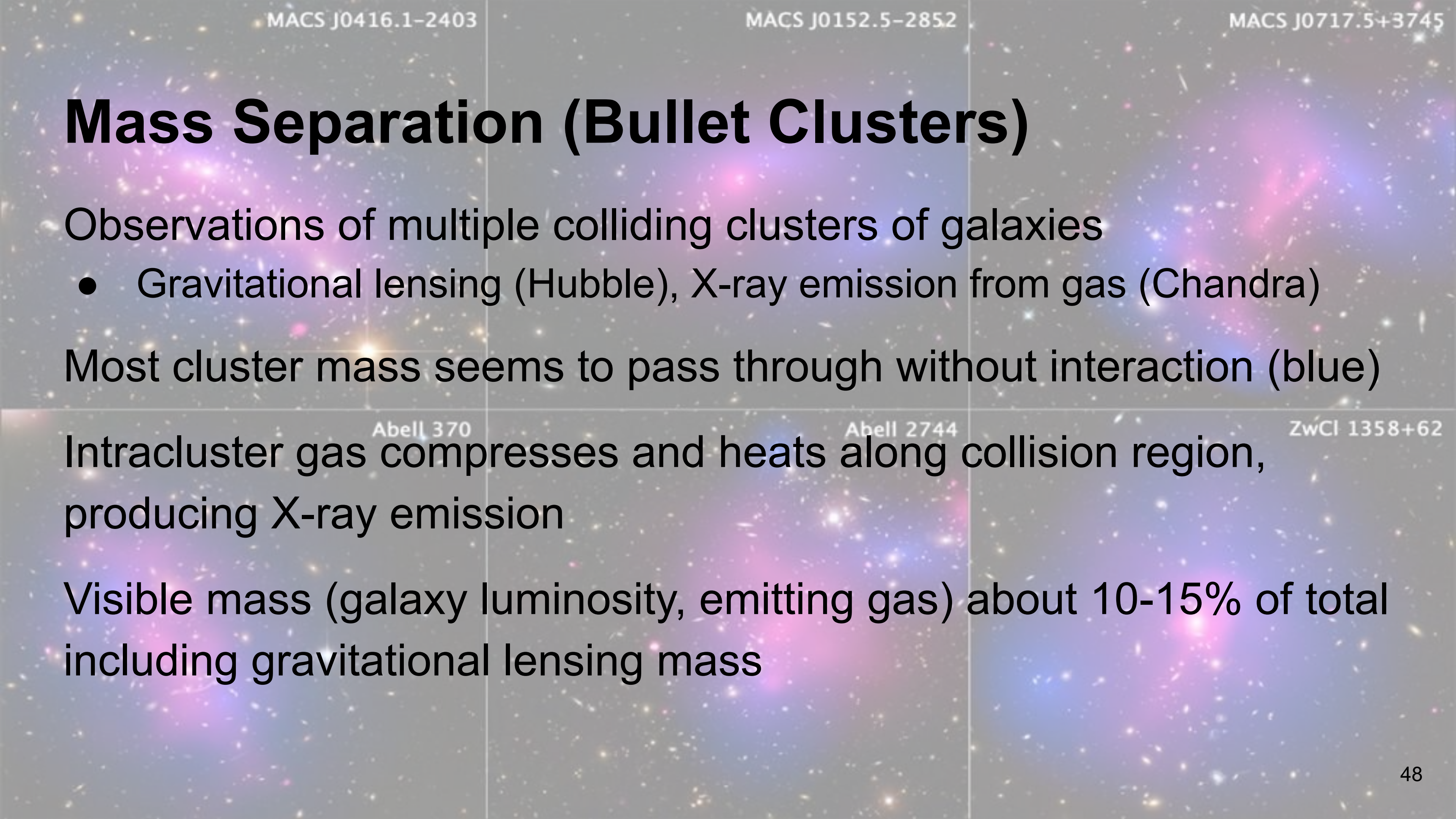


Measure speed of stars at distances from galaxy center, hydrogen gas in halo around luminous galaxy

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)

Intracluster 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

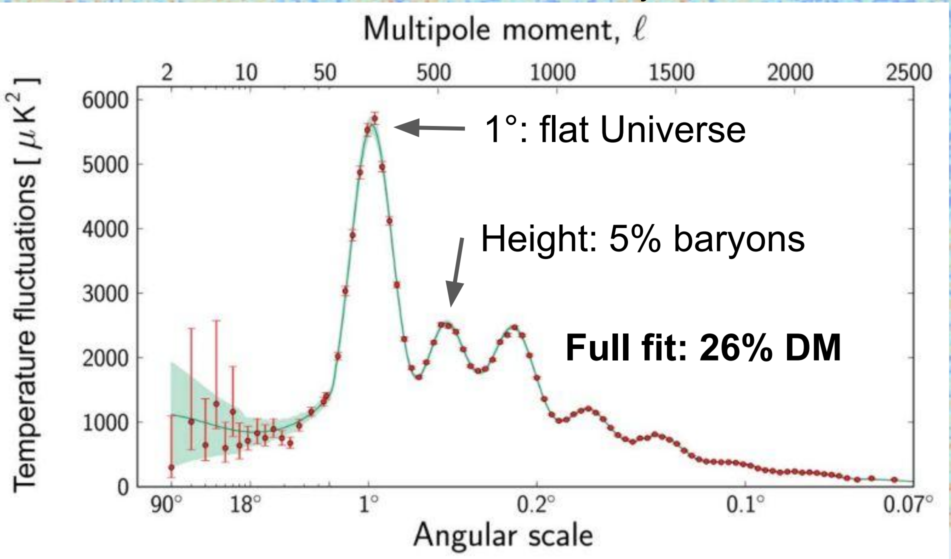
CMB and Nucleosynthesis

Planck measured cosmic microwave background on small scales

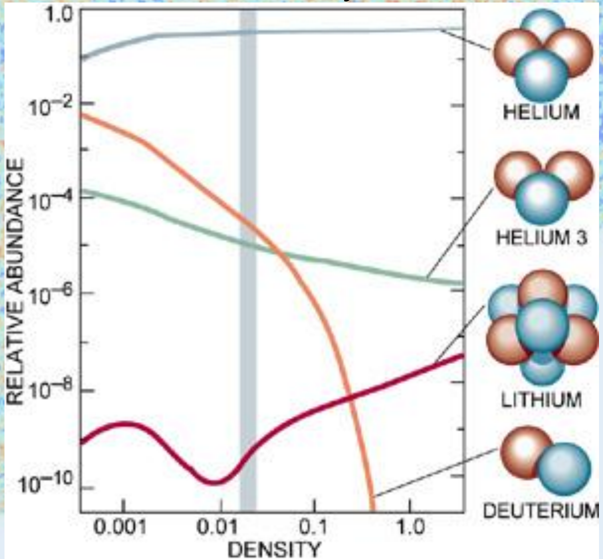
- Fit to angular power spectrum says 5% baryons, 26% non-baryonic matter

Primordial abundances consistent with baryons 3~5% of total

Courtesy: K.Freese, Caltech



Courtesy: M.White, UCB



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

Courtesy: CERN/ATLAS

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

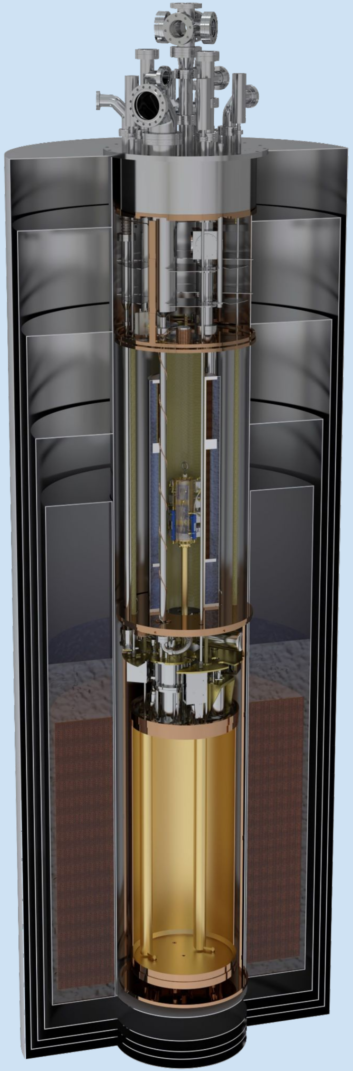
Tune cavity (frequency scan) to match axion mass

- Look for signal above baseline noise

Results exclude axions with mass 2.66 to 3.33 μeV

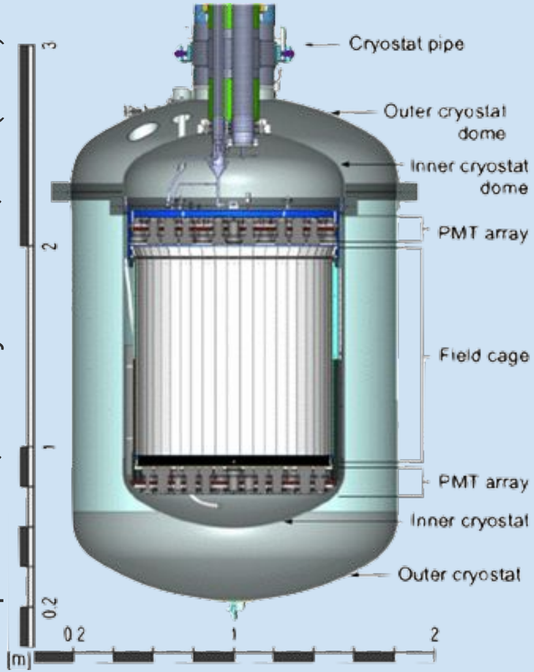
N.Du *et al.*, Phys. Rev. Lett. 120, 151301 (2018)

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



Courtesy: ADMX Collaboration/FNAL

Liquid Xenon Detectors: XENON1T



E.Aprile *et al.*, *Eur. Phys. J. C* 77, 890 (2017)

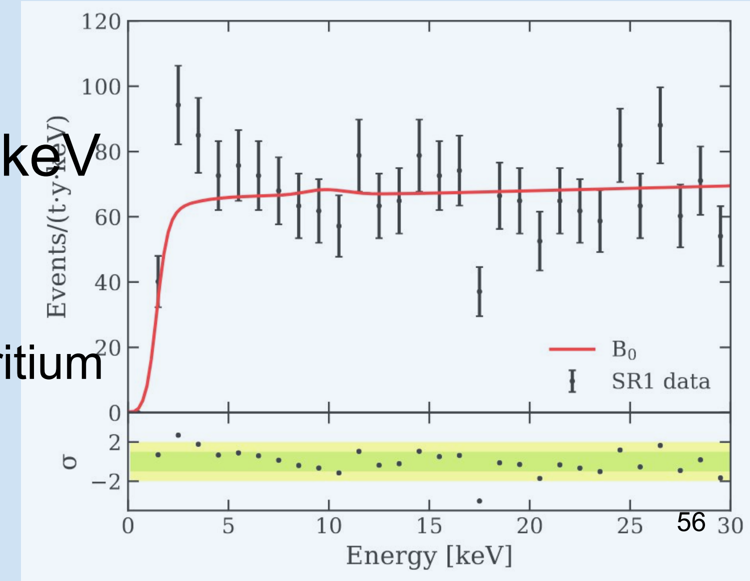
3500 kg liquid xenon

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

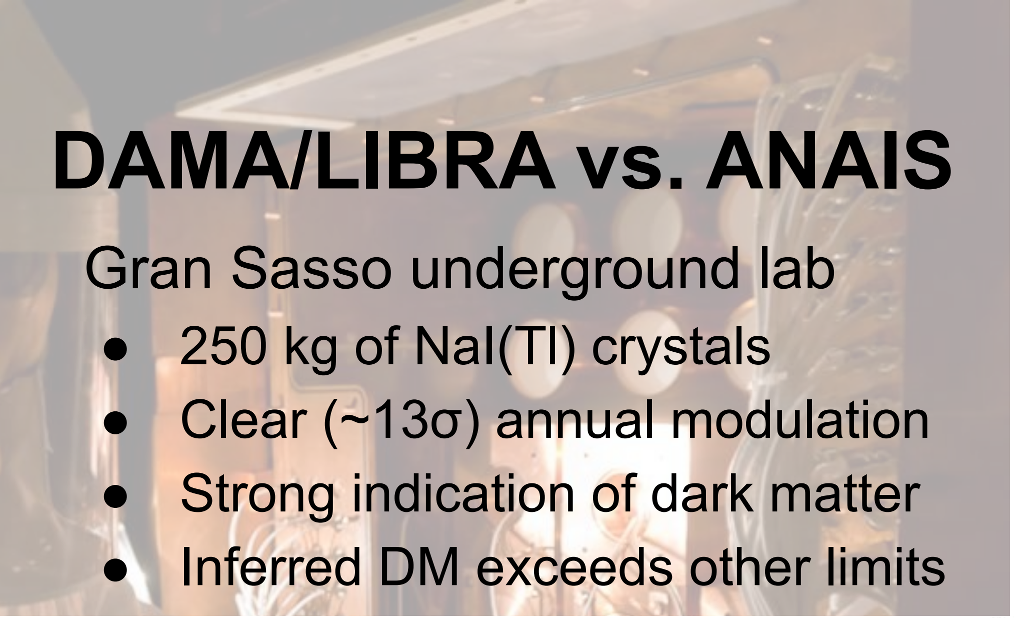
Sensitive to WIMPs

Excess events in 1-7 keV

- Close to threshold
- Only 3.5σ signficance
- Also consistent with tritium



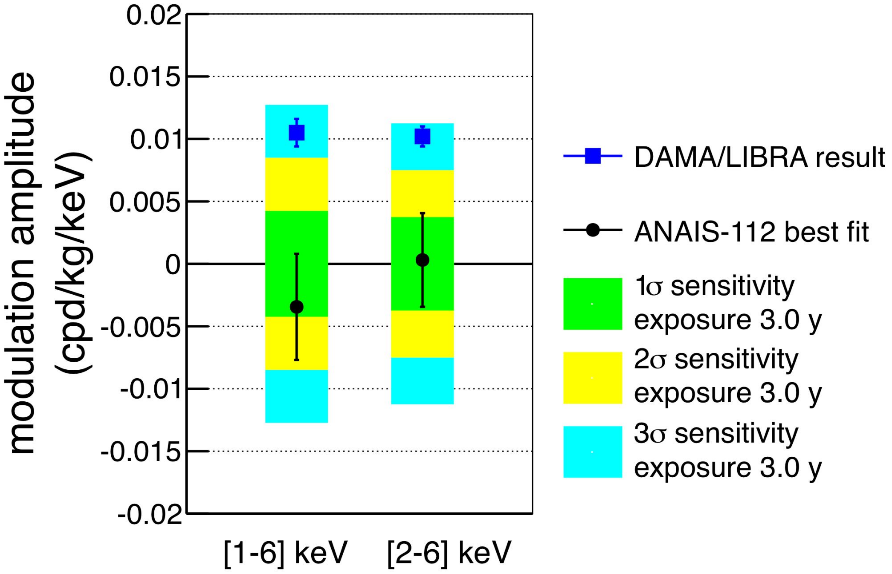
E.Aprile *et al.*, *Phys. Rev.* **D102**, 072004 (2020)

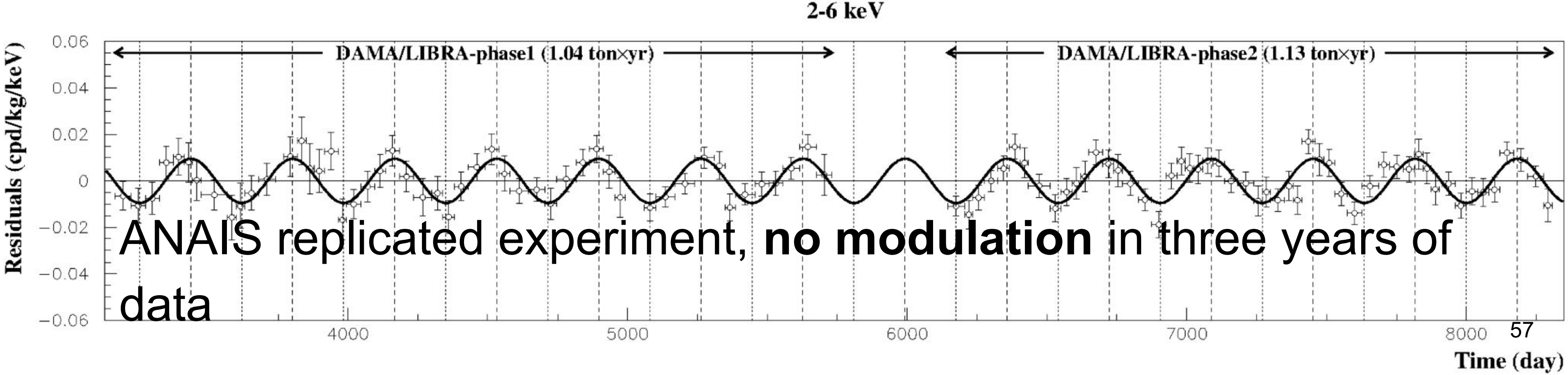


DAMA/LIBRA vs. ANAIS

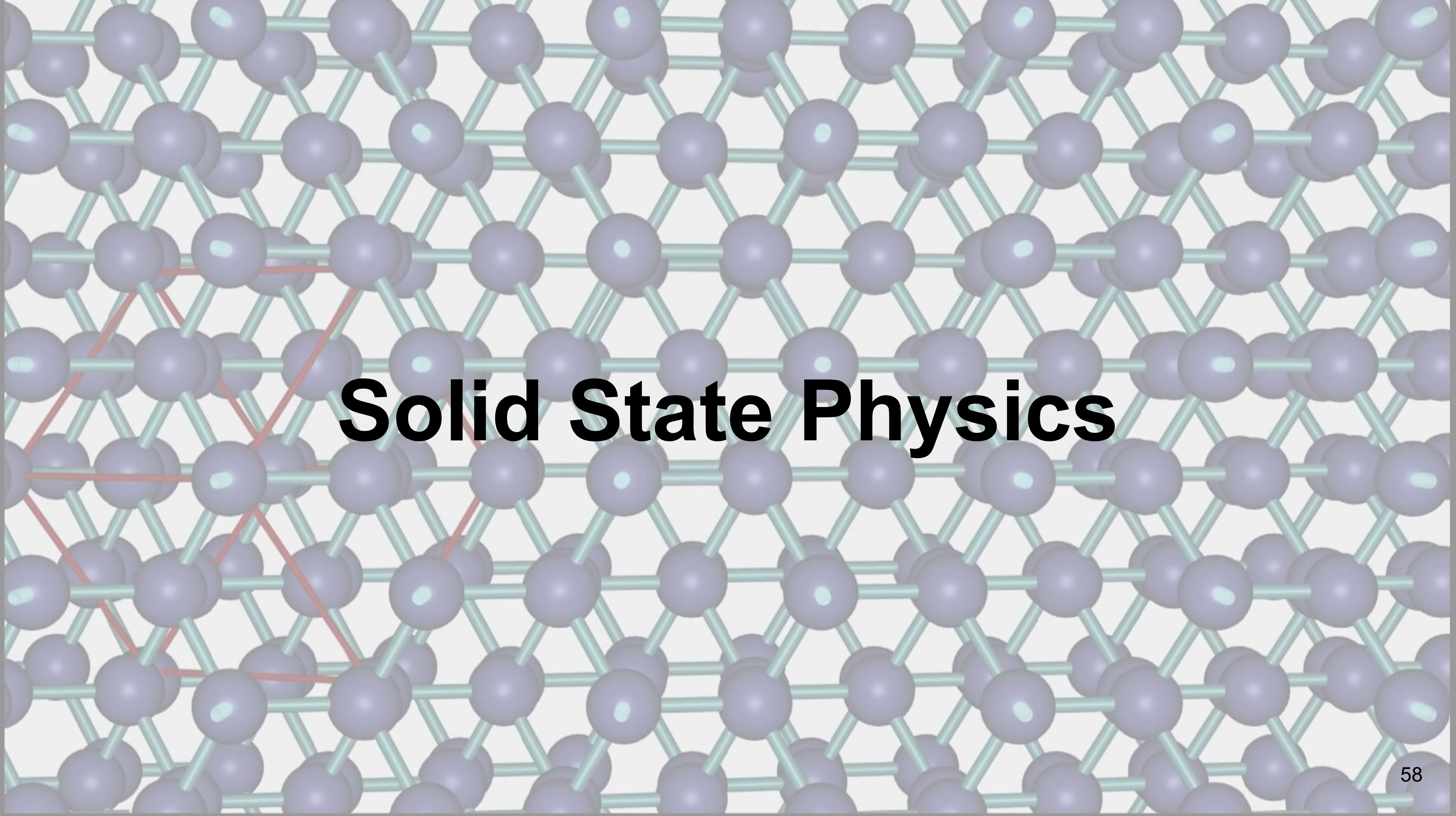
Gran Sasso underground lab

- 250 kg of NaI(Tl) crystals
- Clear (~13σ) annual modulation
- Strong indication of dark matter
- Inferred DM exceeds other limits





ANAIS replicated experiment, **no modulation** in three years of data

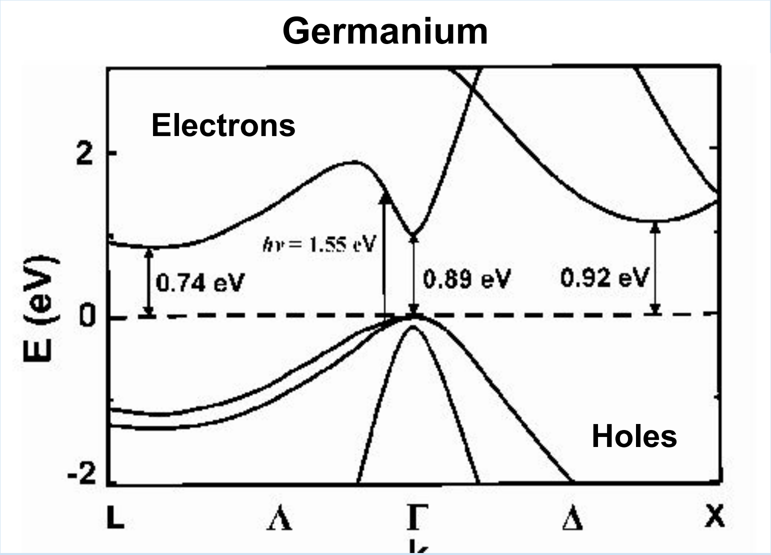


Solid State Physics

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)

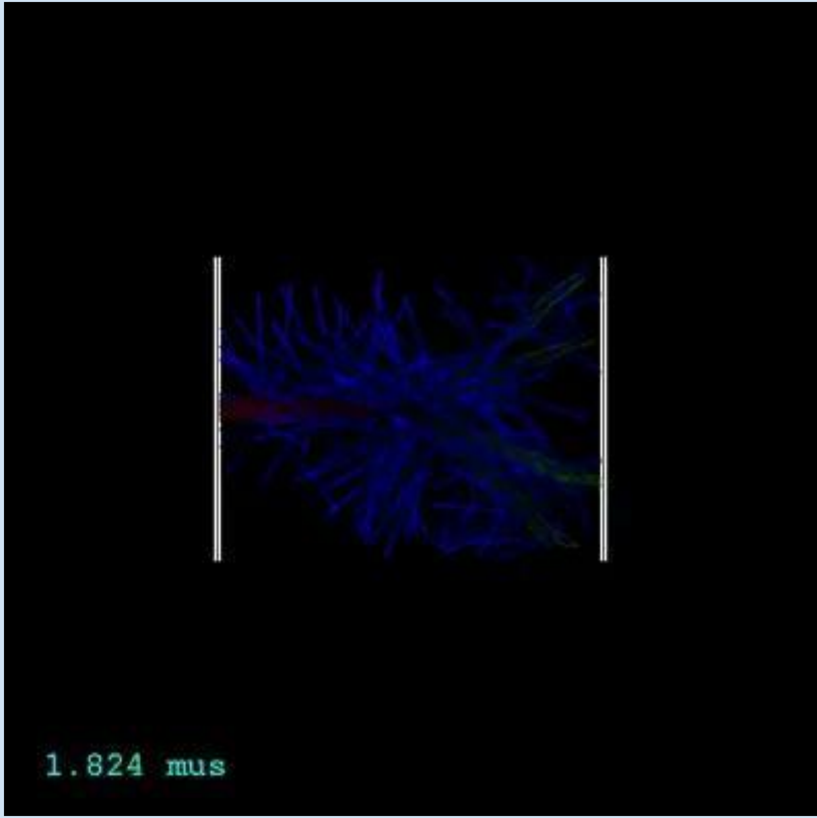


Charge Transport, Scattering and Valleys

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

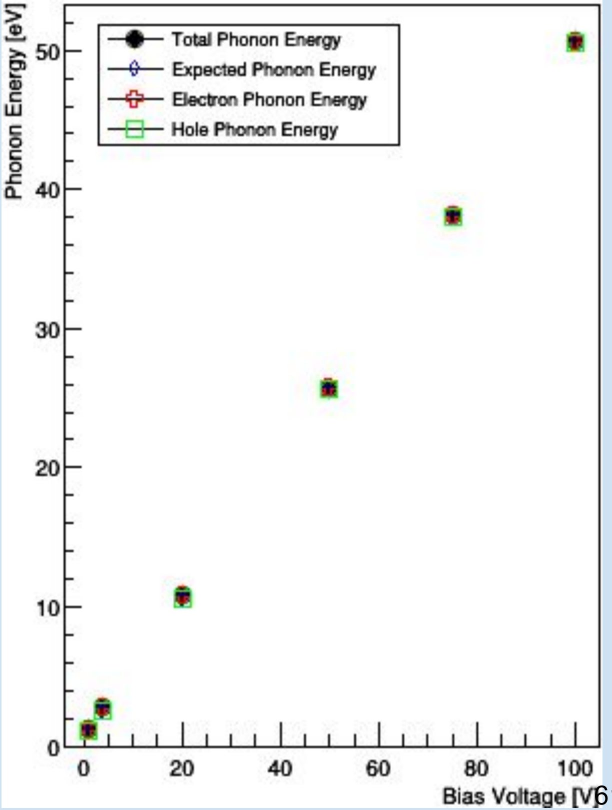
- Charges scatter, have steady “drift speed”
- Typically 20~30 km/s

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

Phonon emission scales with voltage

Total signal can exceed energy deposit

➪ Amplifies low-energy signals



Lattice Vibrations (Heat and Sound)

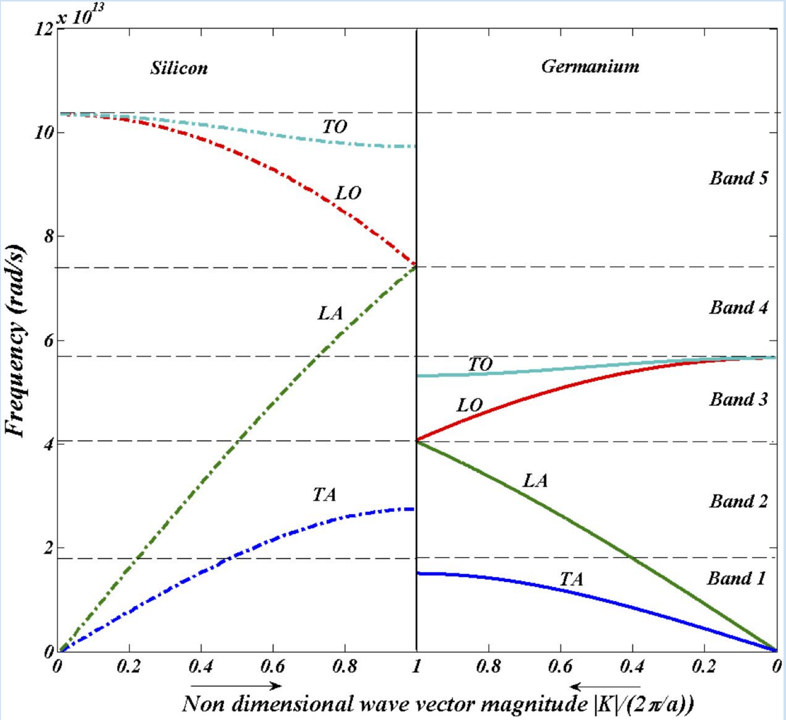
Crystal has strong, covalent bonds

High speed of sound (like metals)

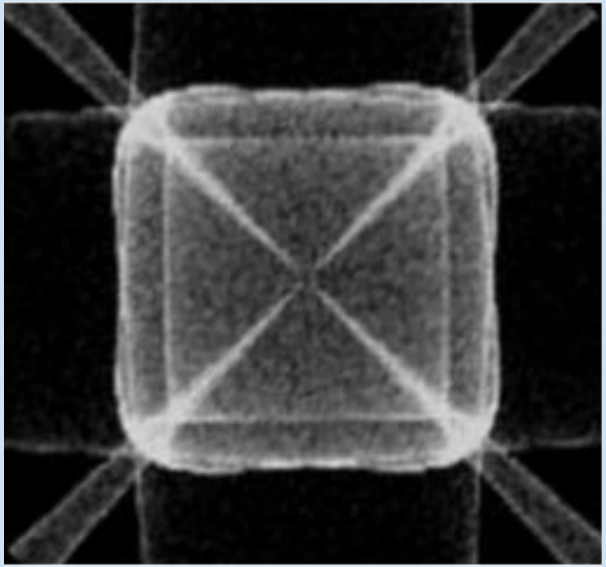
Longitudinal or transverse vibrations

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

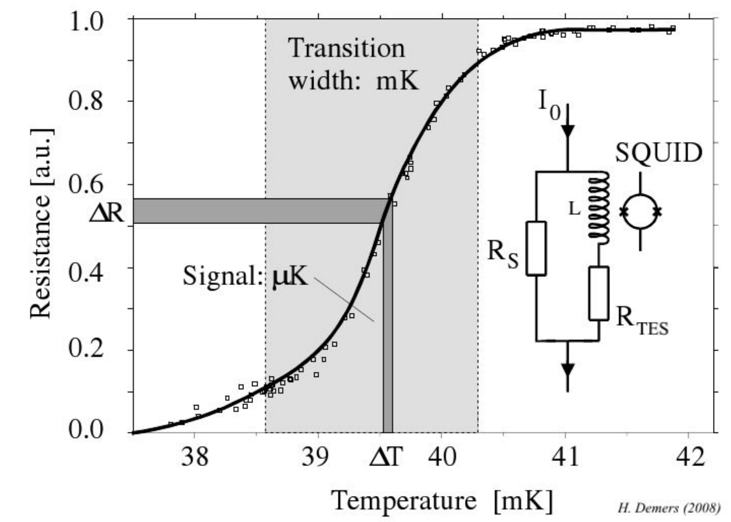
Transition Edge Sensors

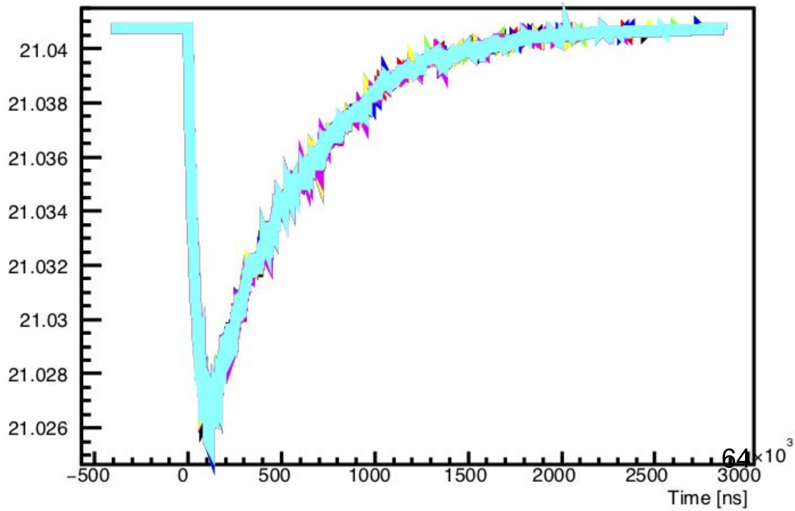
Superconducting films have finite width δT for transition from normal to superconducting state

Operate within transition region

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

Fast (< 1 μs) response, fast readout



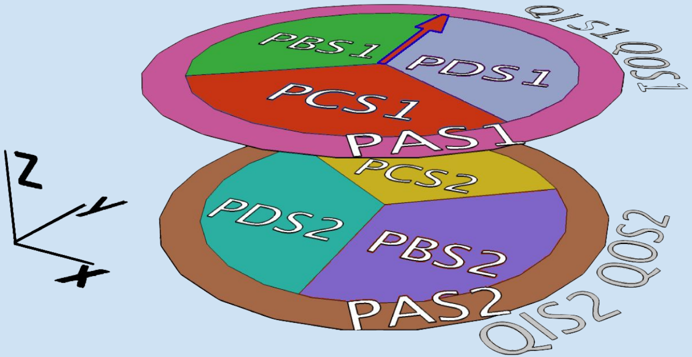


Understanding the Detectors

Readout Channels (Multiple Designs)

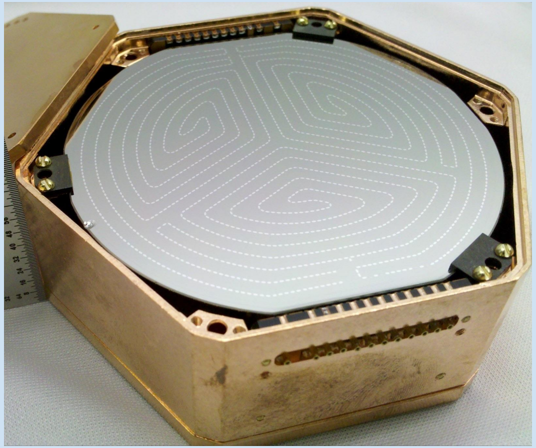
Sensor patterns on top and bottom faces

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

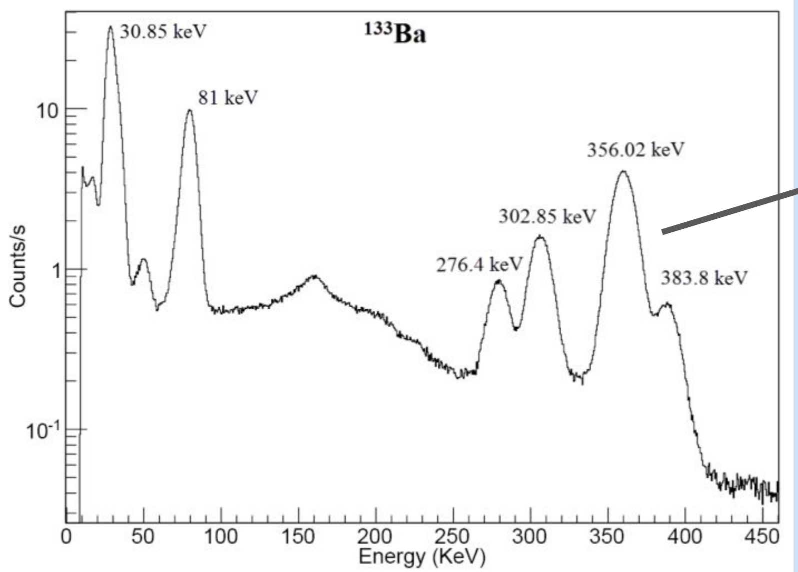


Soudan: eight phonon channels, four charge channels

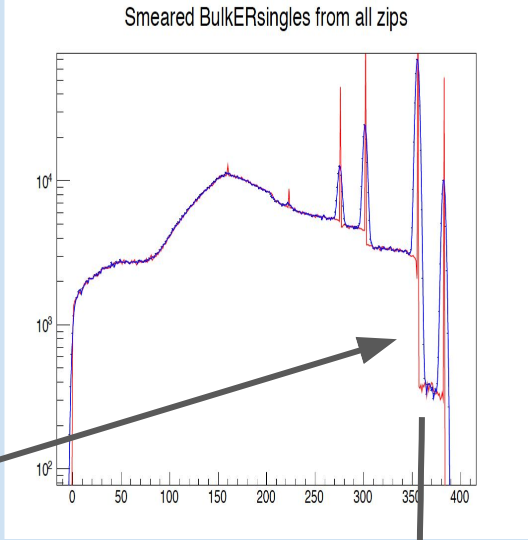
SNOLAB: twelve phonon channels (four middle, two rings), four charge channels



Example: ^{133}Ba

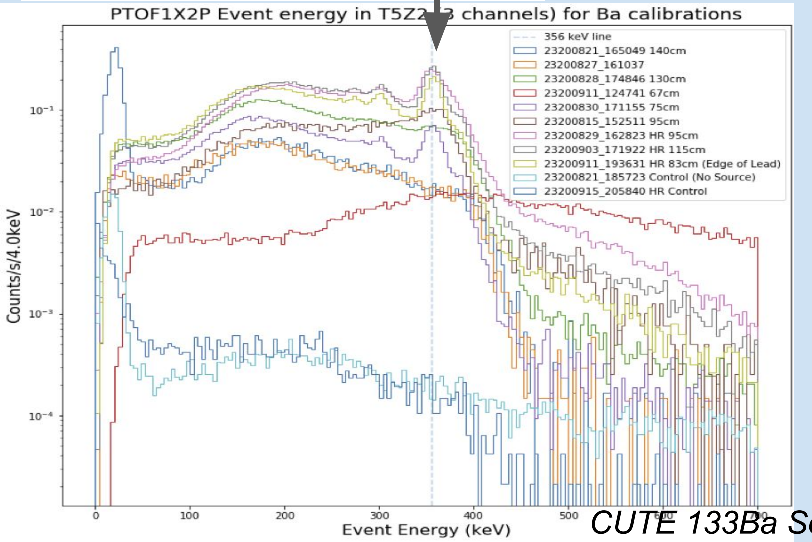


Courtesy: D-L.Zhang/ResearchGate

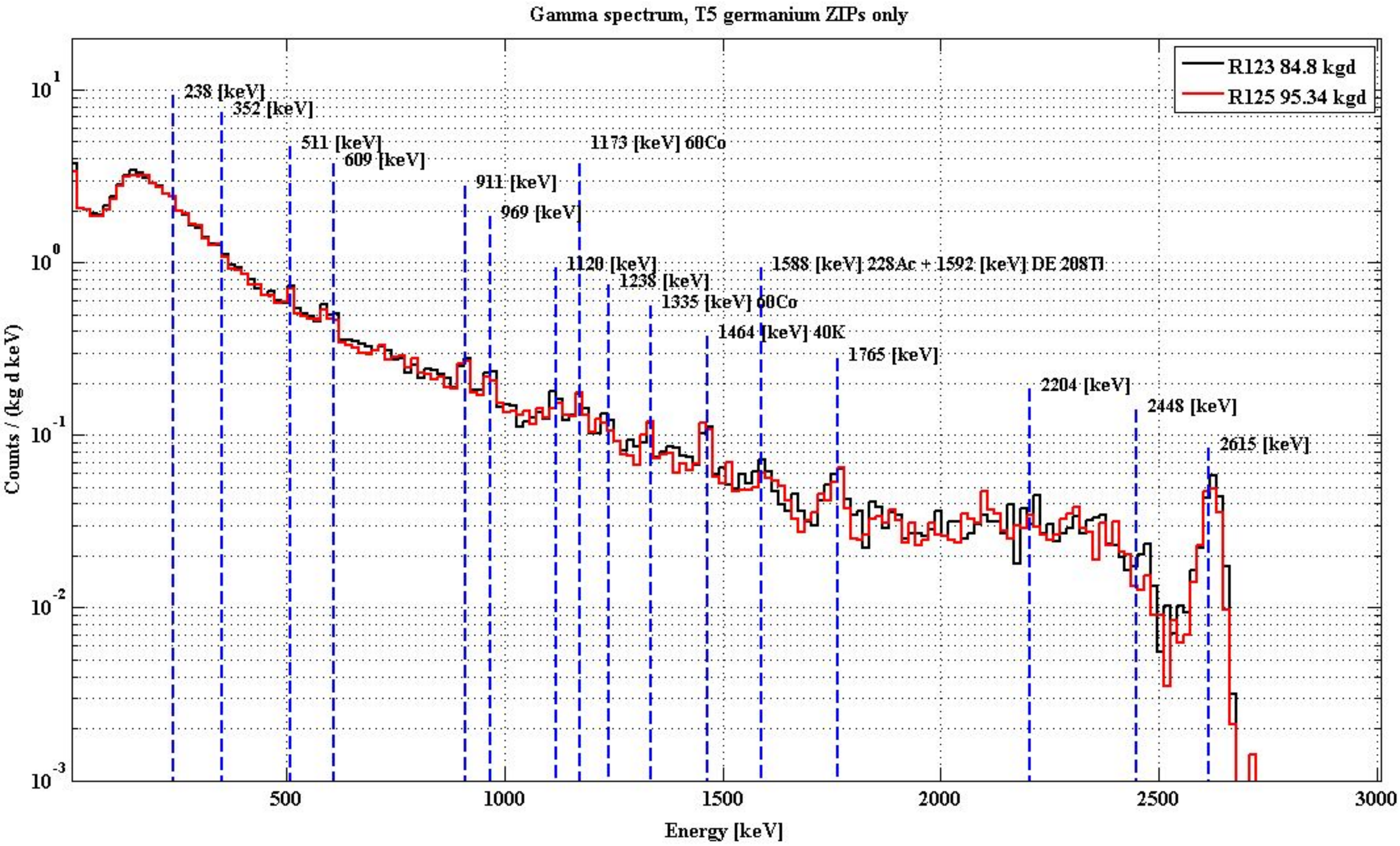


Simulation of detector with “perfect” ^{133}Ba source

Real detector, source in different locations



CUTE 133Ba Source Study


Gamma spectrum, T5 germanium ZIPs only
R123 84.8 kgd
R125 95.34 kgd
238 [keV]
352 [keV]
511 [keV]
609 [keV]
911 [keV]
969 [keV]
1173 [keV] 60Co
1120 [keV]
1238 [keV]
1335 [keV] 60Co
1464 [keV] 40K
1588 [keV] 228Ac + 1592 [keV] DE 208Tl
1765 [keV]
2204 [keV]
2448 [keV]
2615 [keV]
Counts / (kg d keV)
Energy [keV]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
500
1000
1500
2000
2500
3000

How Do We Interpret Signal or Set Limit?

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

v_{vir} = 220 km/s, ϱ_{DM} ~ 0.35 GeV/c^2 / cm^3, m_{nuc} = 28 (Si), 72.64 (Ge)

Exposure (mass × 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}-σ_{DM} plane