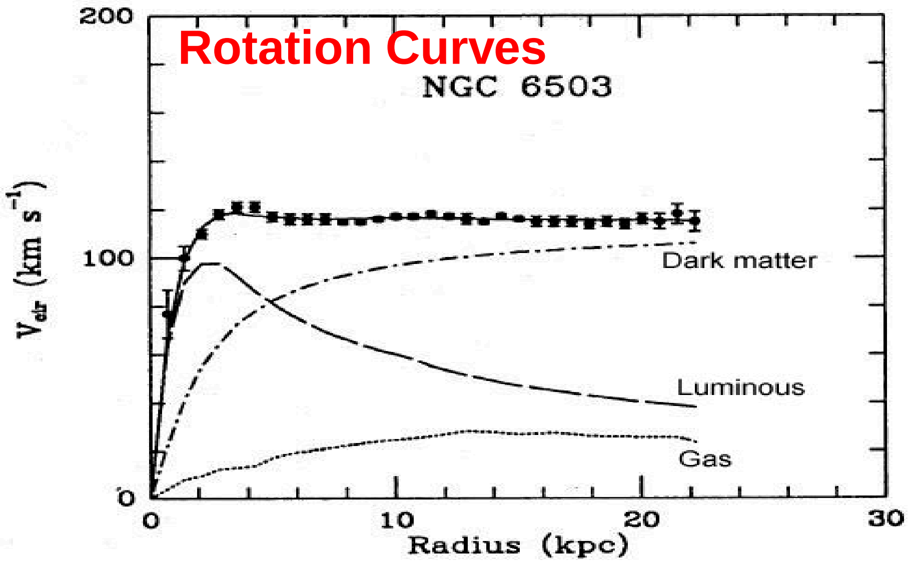
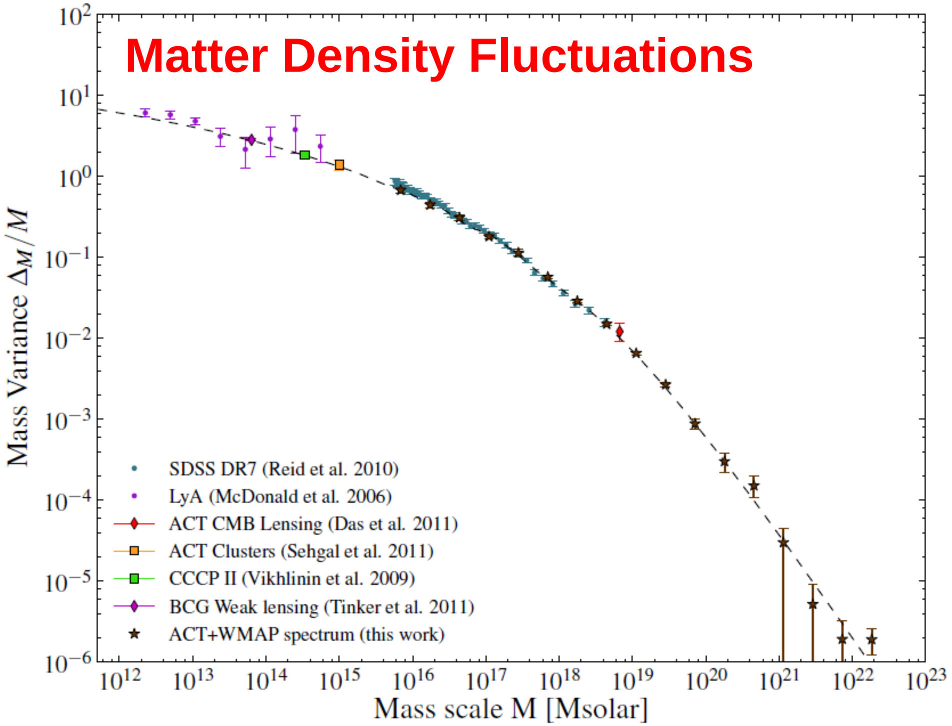
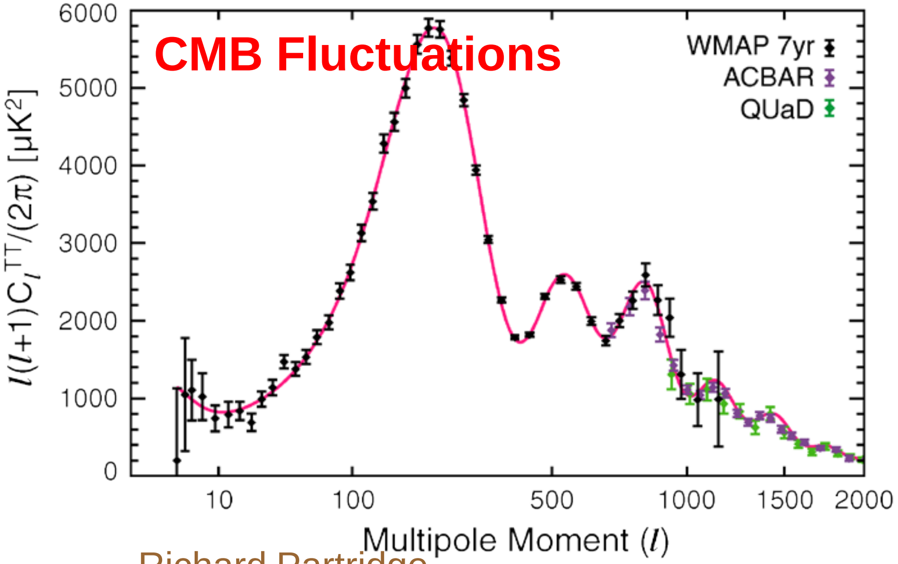
The Search for Dark Matter by the CDMS Collaboration

Richard Partridge
(for the CDMS Collaboration)
SLAC Experimental Seminar
15 November 2012

Abundant Evidence for Dark Matter

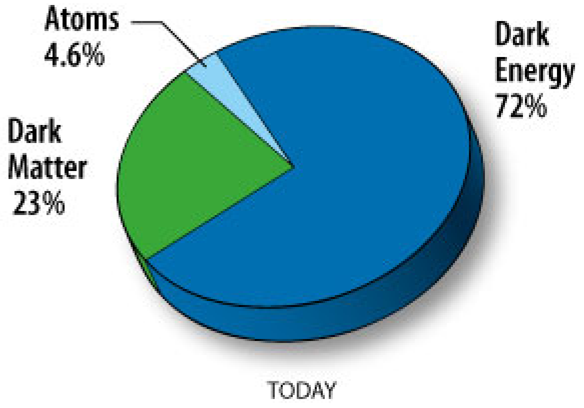


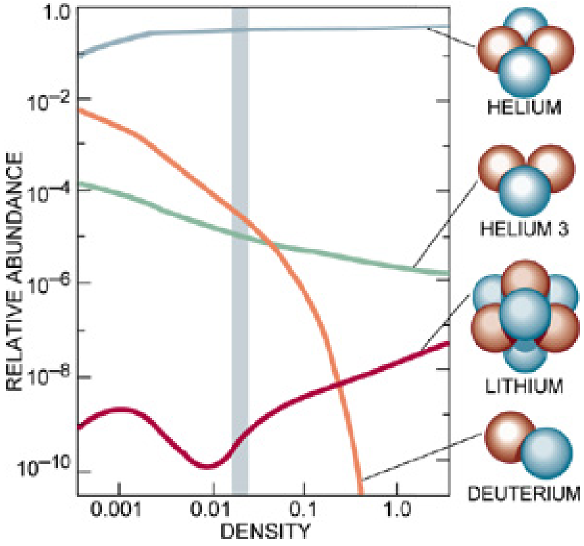


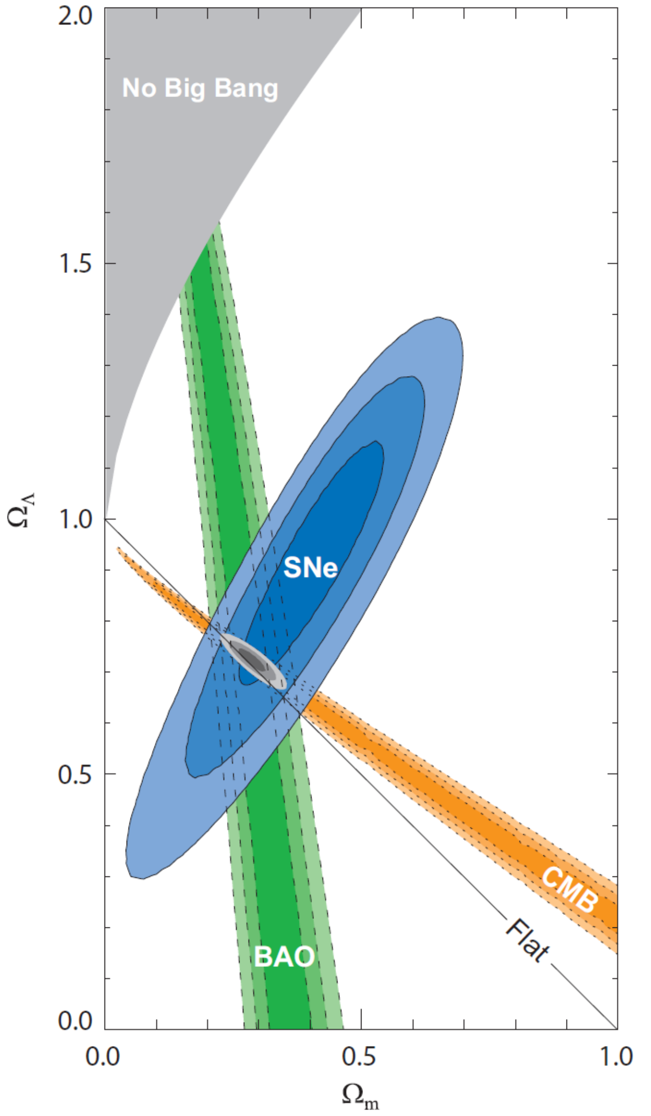


A Consistent Picture Has Emerged

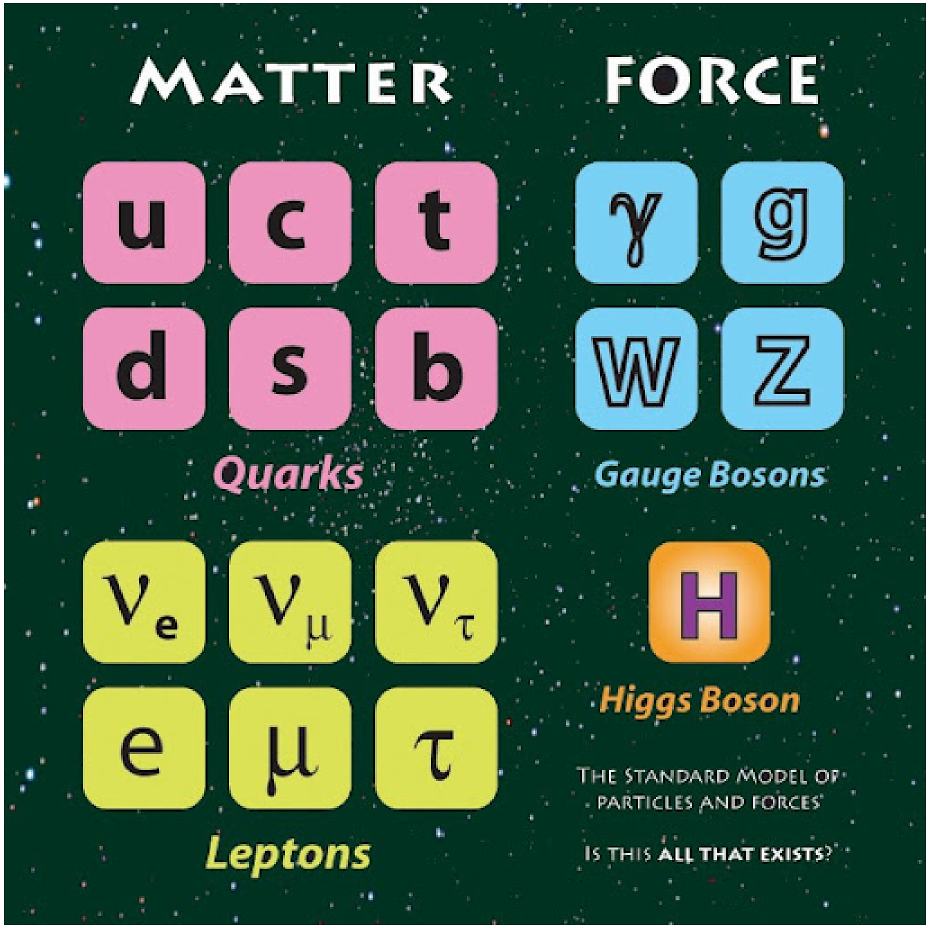
- 4.6% of universe is ordinary matter
- 23% of universe is dark matter
  - Non-baryonic
  - Non-relativistic (cold)
  - Non-luminous, non-absorbing (dark)
  - Non-decaying, non-charged
- 72% of universe is dark energy







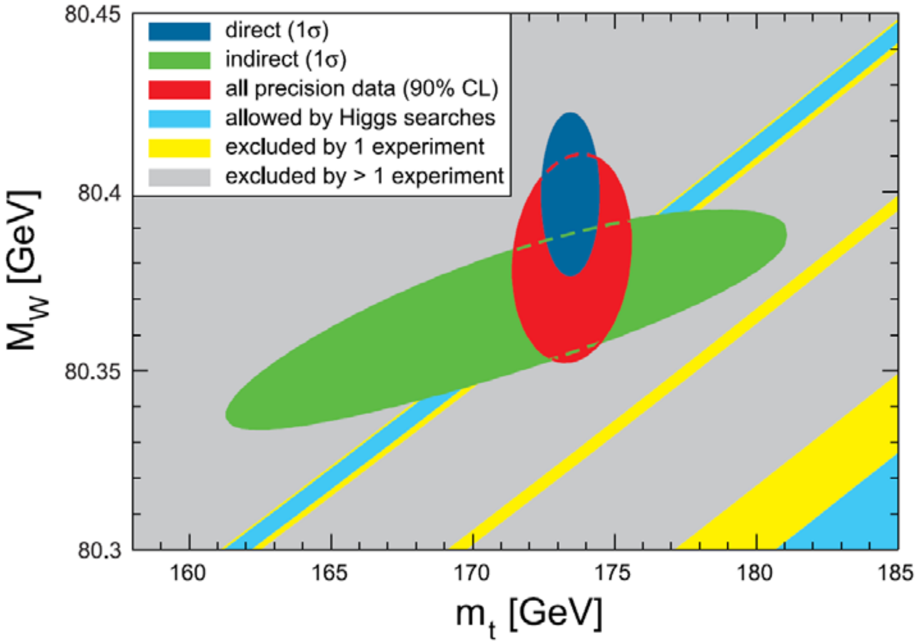
Dark Matter and the Standard Model



No sign of dark matter in this neighborhood!

New Physics Beyond the SM?

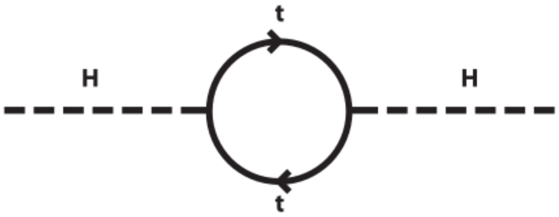
- One of the great successes of the SM is the ability to make accurate calculations and predictions
  - Example: consistent results for radiative corrections to the W mass



- Problem: radiative corrections to the Higgs mass have a quadratic divergence

Supersymmetry to the Rescue?

- Supersymmetry (SUSY) elegantly solves the problem of divergent radiative corrections
  - Each SM fermion has a supersymmetric boson partner
  - Each SM boson has a supersymmetric fermion partner
  - Cancellation of loop divergences due to Fermi-Dirac statistics



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{UV}^2 + ...].$$

$$\Delta m_H^2 = 2 * \frac{\lambda_S}{16\pi^2}[\Lambda_{UV}^2 + ...].$$

- If SUSY conserves “R Parity”, supersymmetric particles can only be created/annihilated in pairs
  - Lightest supersymmetric particle (LSP) is stable - strong DM candidate

CDMS Focus: WIMP Dark Matter

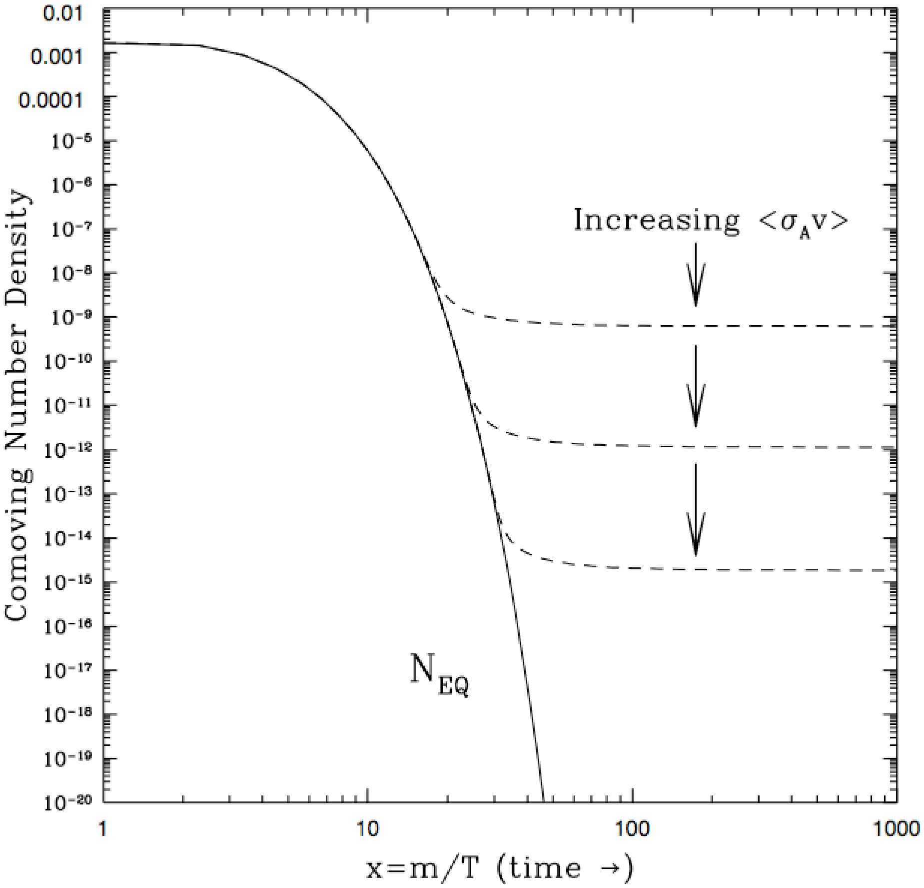
WIMP = Weakly Interacting Massive Particle

In thermal relic models, Ω_{DM} related to DM annihilation cross section

$$\Omega_{DM} \sim \langle \sigma_A v \rangle^{-1}$$

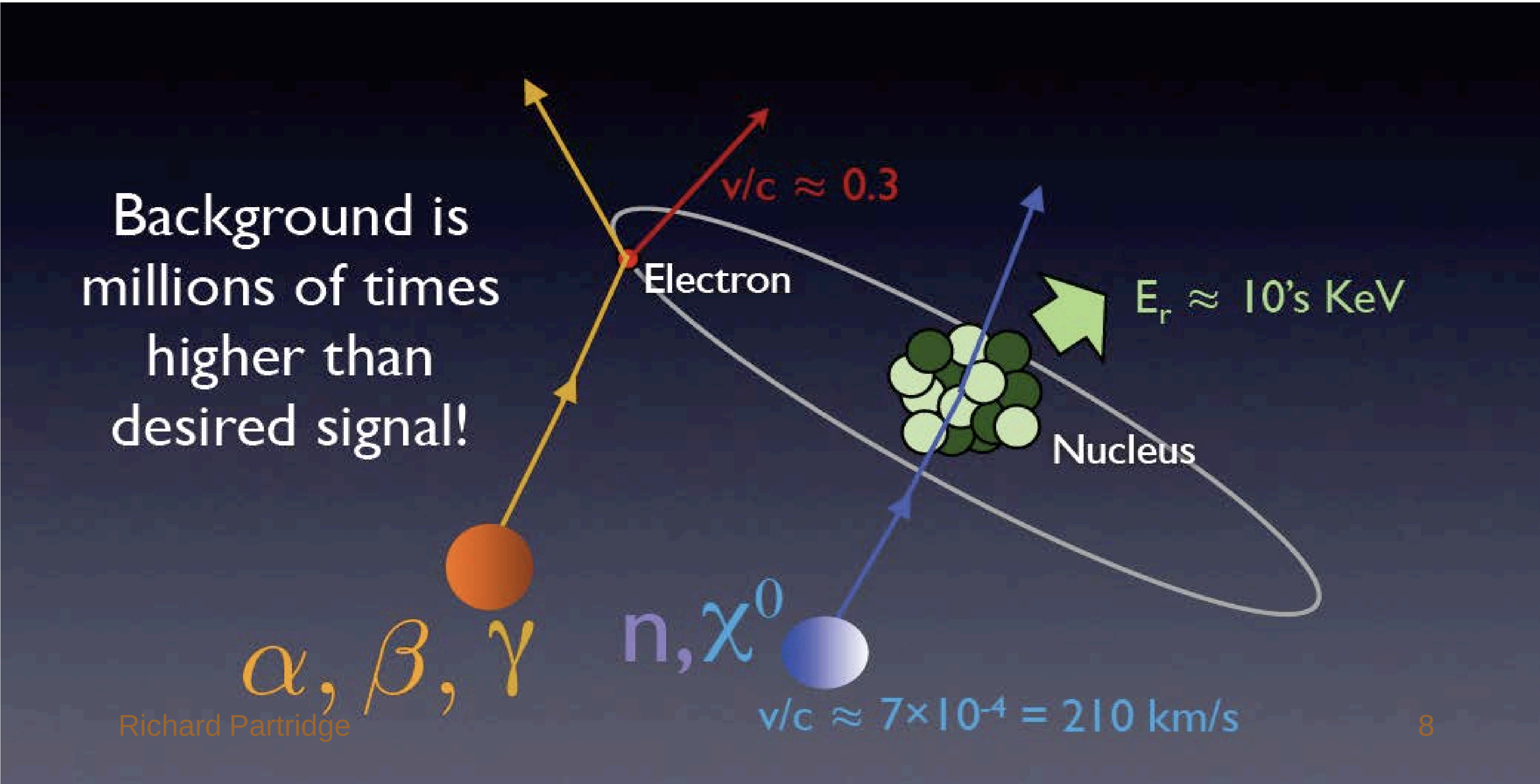
Consistent with weak scale dark matter (m ~0.1–1 TeV) and SM weak interactions

SUSY models: neutralino χ^0 can have properties expected for WIMP dark matter



Direct Detection of Dark Matter

- Look for rare collisions of dark matter and a nucleus
  - Signal is a nuclear recoil with 10’s of keV of kinetic energy
  - Need to suppress electron recoil backgrounds from ionizing radiation



Direct Detection Kinematics

- Simplest assumption: non-relativistic elastic scattering
  - Recoil energy depends on WIMP velocity, scattering angle

$$E_r = \frac{m_N v_\chi^2}{\left(1 + m_N / m_\chi\right)^2}\left(1 - \cos\theta^*\right)$$

$$v_r^{\max} = 2v_\chi \text{ for } m_\chi >> m_N$$

$$v_r^{\max} = 2\frac{m_\chi}{m_N} v_\chi \text{ for } m_\chi << m_N$$

- Dark matter velocity distribution is a key input

Dark Matter Halo Velocity

- Simplest velocity model is Maxwellian distribution in galactic rest frame

$$f(v_G) \propto e^{-v_G{}^2/v_0^2} \quad \text{for} \quad \mathrm{v}_\mathrm{G} < v_{esc}$$

  - Mean DM velocity expected to be similar to that of stars

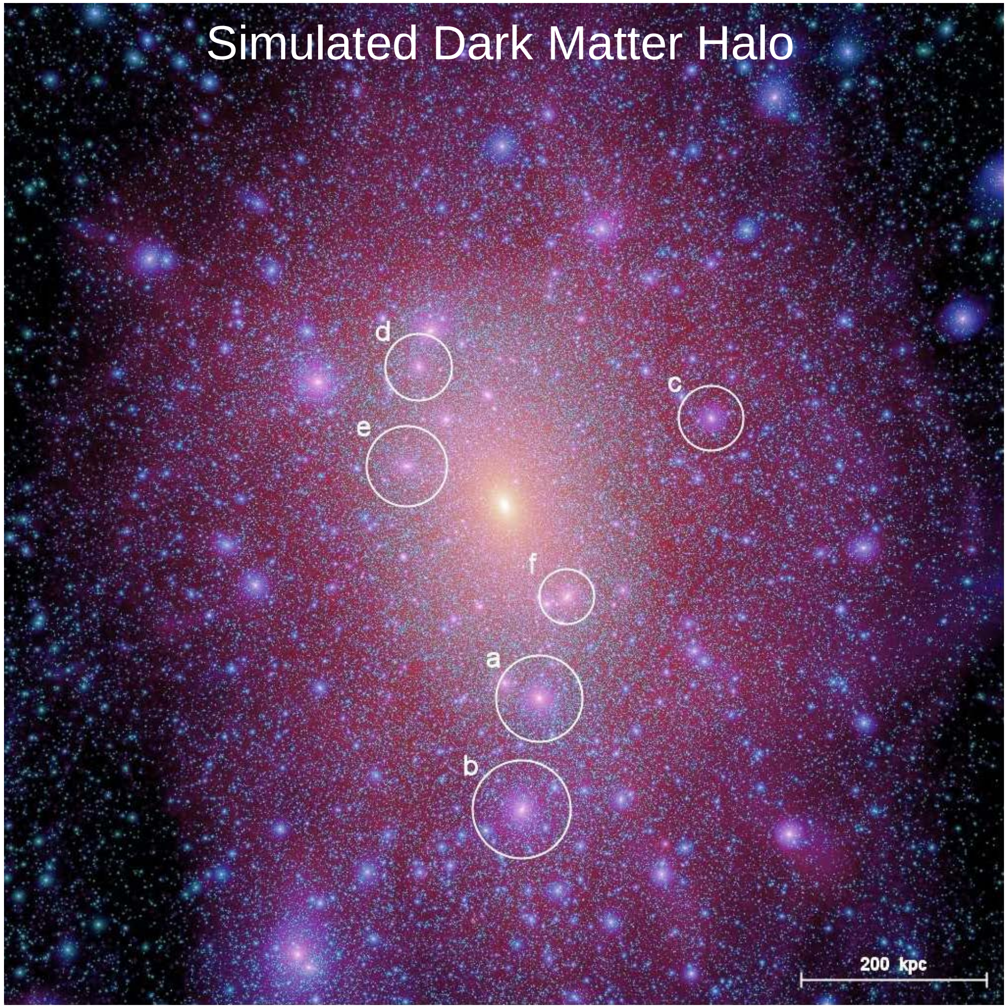
$$v_0 \sim 220\ \text{km/s}$$

$$v_{esc} \sim 540\ \text{km/s}$$

  - Local velocity must take into account earth's motion

$$\vec{v}_L = \vec{v}_G - \vec{v}_{earth}$$

  - Maxwellian distribution will at best approximate true velocity distribution – dark matter halo is more complex!



Simulated Dark Matter Halo

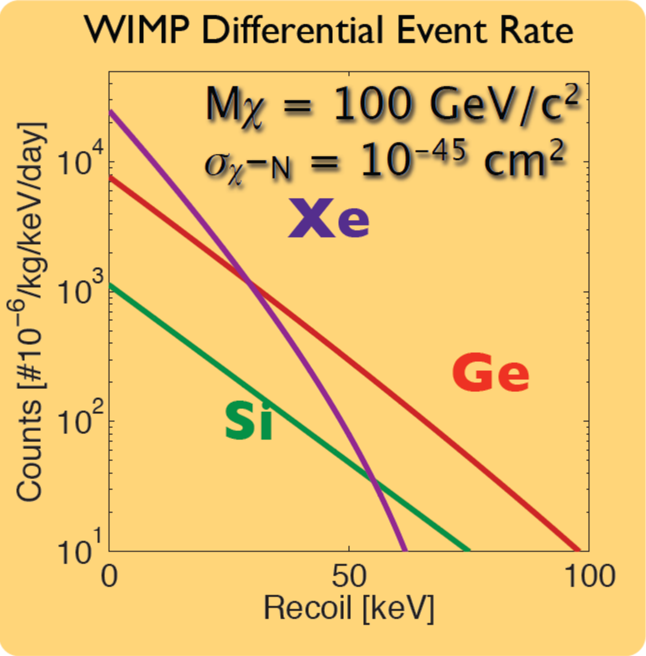
Springel et al, arXiv:0809.0898

Recoil Energy Distribution

- Recoil energy is the sole kinematic variable measured in direct detection experiments

$$\frac{dR}{dE_r} = \frac{\rho_0}{m_N m_\chi} \int v_L \, f(v_L) \frac{d\sigma}{dE_r} \, dv_L$$

Local DM density: $\rho_0 = 0.39\ \mathrm{GeV/cm^3}$



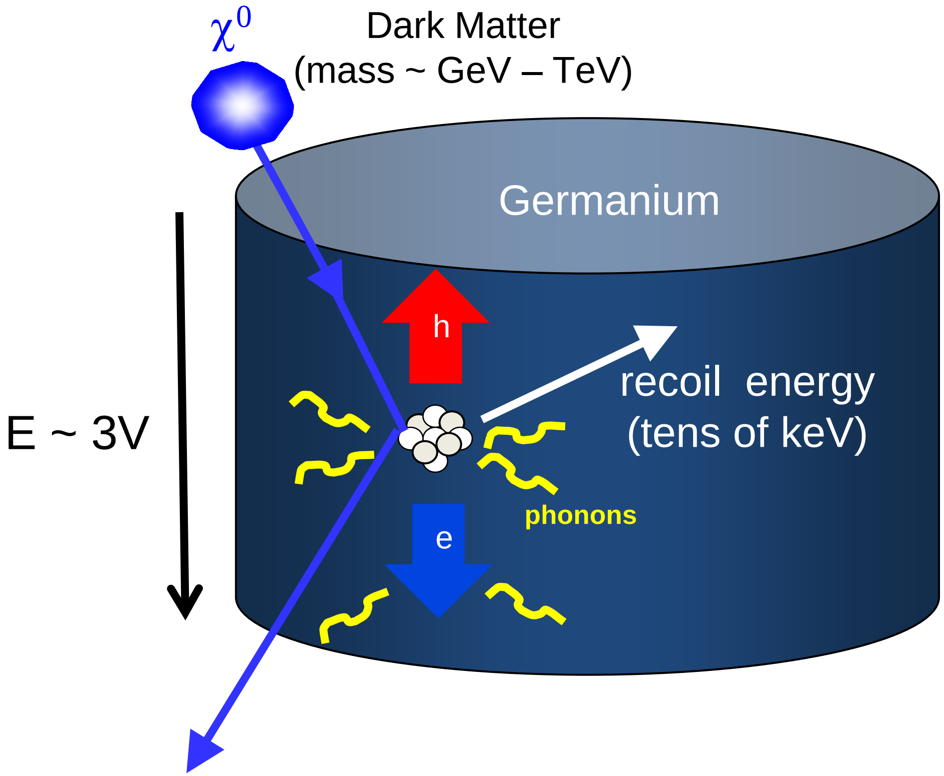
- Example:
  - Spin-independent coherent scattering

$$\sigma \approx \sigma_0 A^2 F^2(q) \quad q = \sqrt{2 m_N E_r}$$

  - Recoil energy distributions are ~ exponential and ~ featureless
  - Comparing “DM signals” in different target nuclei provides an important test of WIMP hypothesis if a signal is observed
  - With sufficient statistics in multiple experiments, can measure WIMP mass and test velocity model / cross section assumptions

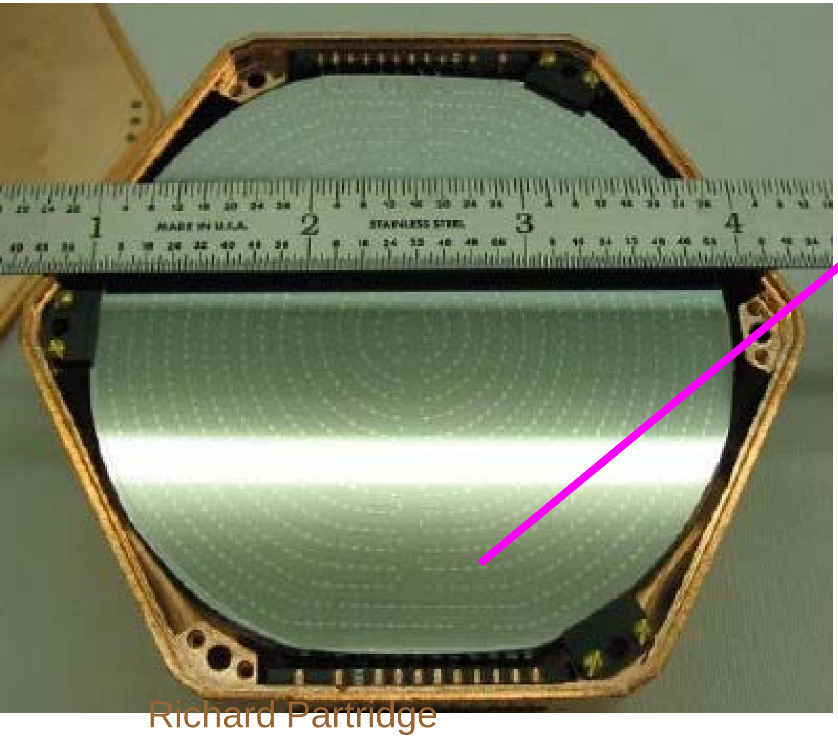
Searching for Dark Matter with CDMS

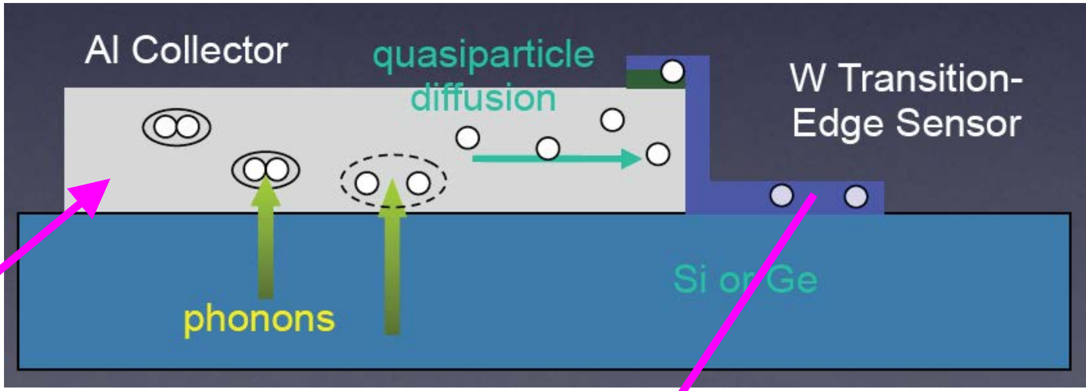
- CDMS has pioneered the technique of searching for dark matter in cryogenic Ge crystals that detect both ionization and phonon signals to achieve nearly "0-background" sensitivity

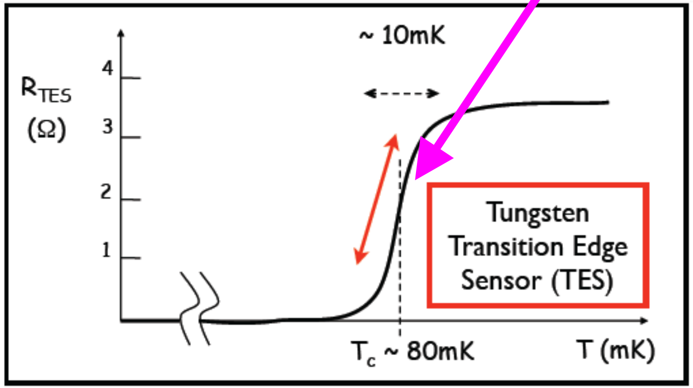


SuperCDMS Technology

- Phonon and ionization electrodes are fabricated directly onto Ge crystal faces using photolithography
    - Phonons heat tungsten strips kept at transition between normal and superconducting state, producing change in resistance
    - Ionization signal helps distinguish electron recoils (highly ionizing - largely background) from nuclear recoils (dark matter signal)



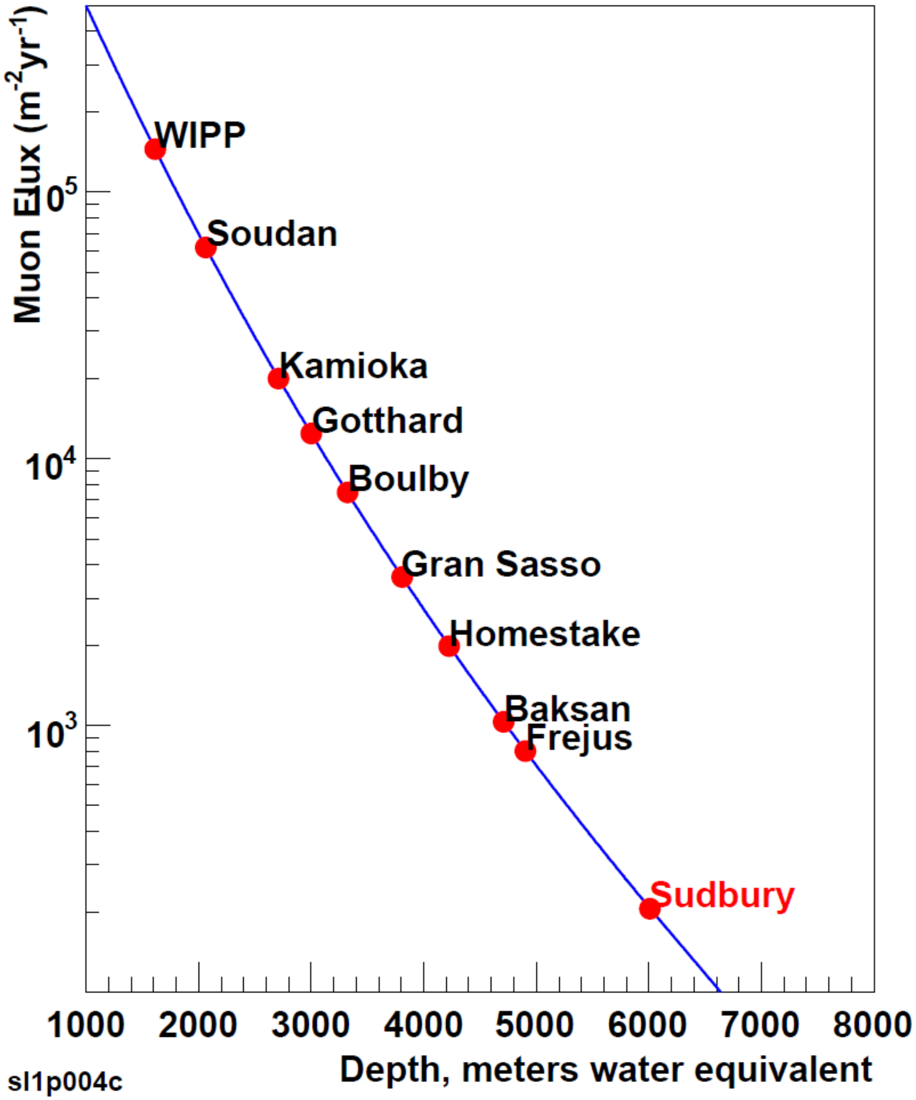




Low Background ⇒ Go Underground

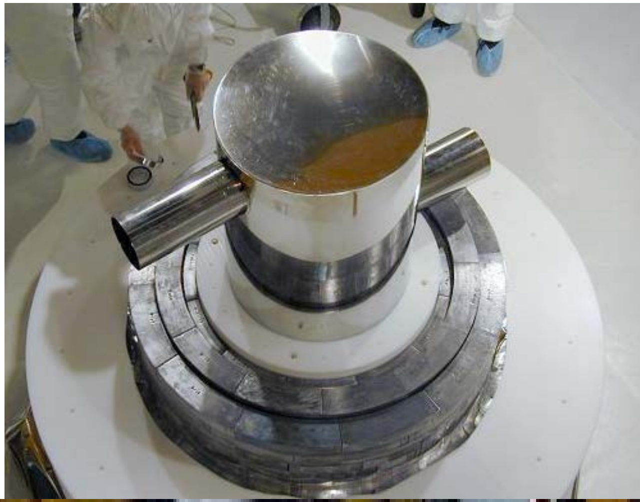
Soudan (now):
CDMS II
SuperCDMS Soudan

SNOLAB (future):
SuperCDMS SNOLAB



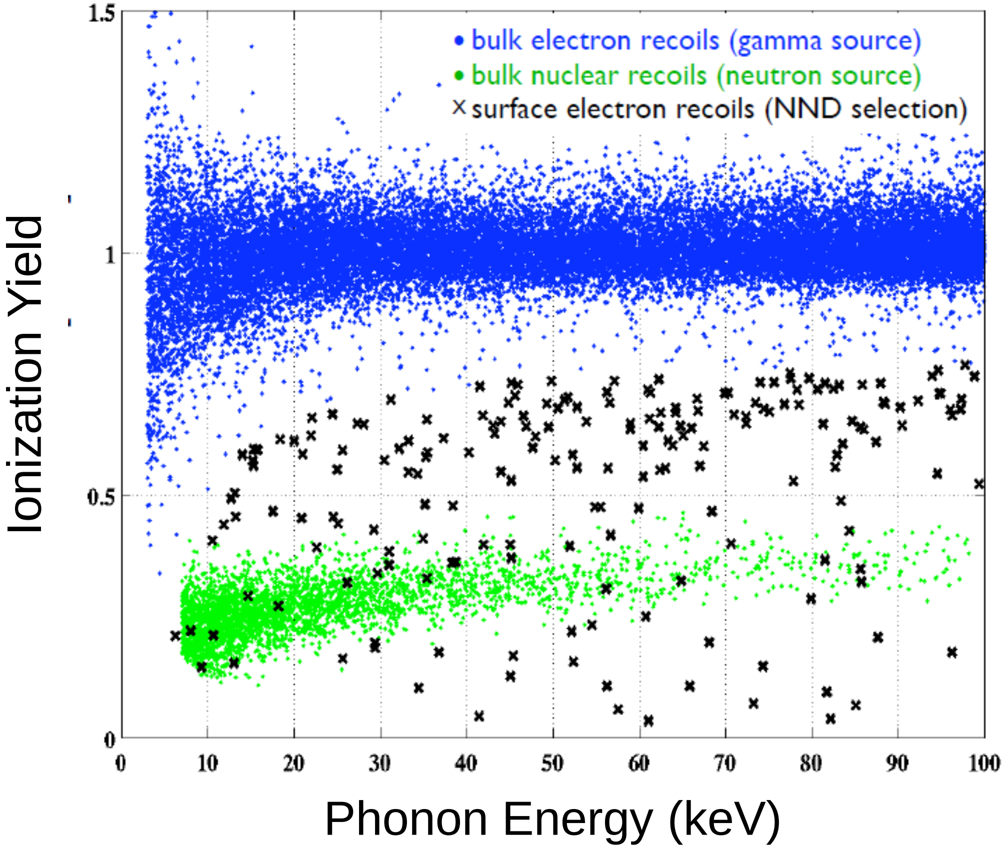
Passive Shielding / Muon Veto

- Lead: shielding for γ's from radioactive decay
- Poly: moderate fission and (α,n) neutrons from U/Th decay chain
- Muon veto: reject residual cosmics



CDMS II Rejection of Electron Recoils

- Ionization yield provides powerful rejection of electron recoils
- Discrimination compromised by surface events where energy is deposited near the surface with phonon electrodes



$$Ionization\ Yield = \frac{Ionization\ (keV)}{Phonon\ Energy\ (keV)}$$

~ 1 for bulk electron recoils (γ source)

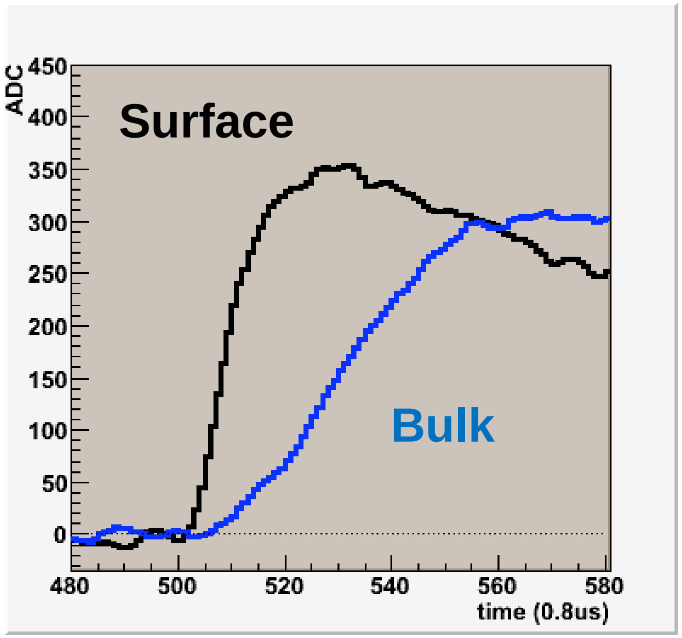
.1 – 1 for surface events (β source)

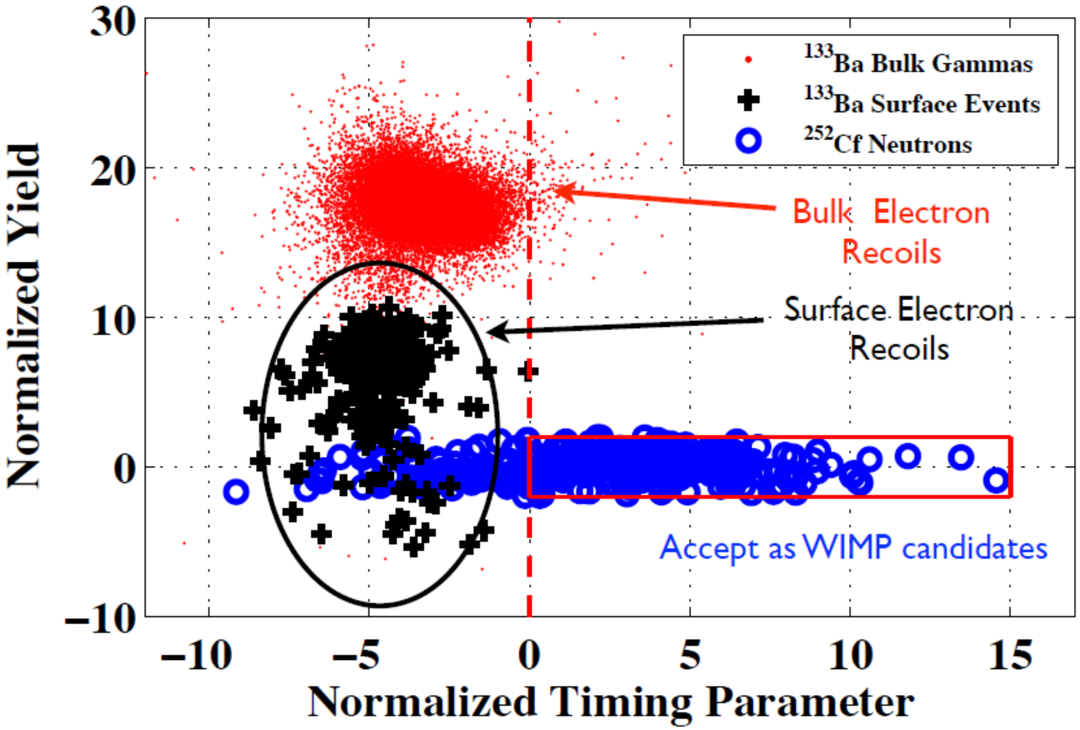
~0.3 for nuclear recoils (n source)

CDMS II Timing Discrimination

- Fully digitized waveforms for phonon and charge signals provide additional handles for rejecting surface events
- Cut on timing parameter removes most of the surface event background

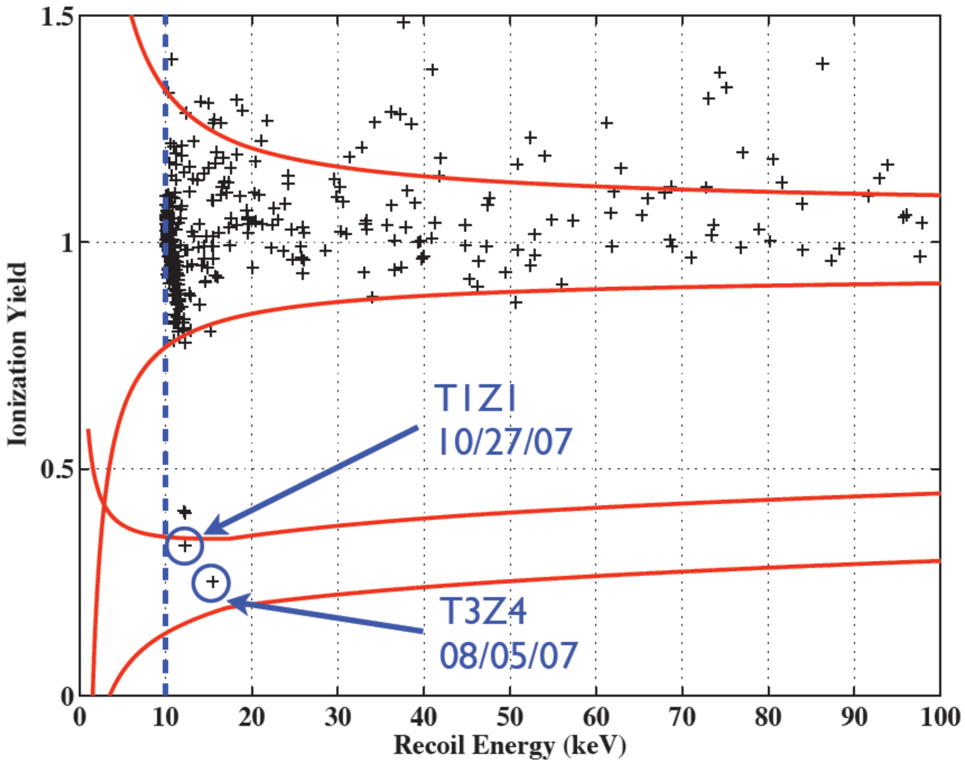
Sample Phonon Waveforms



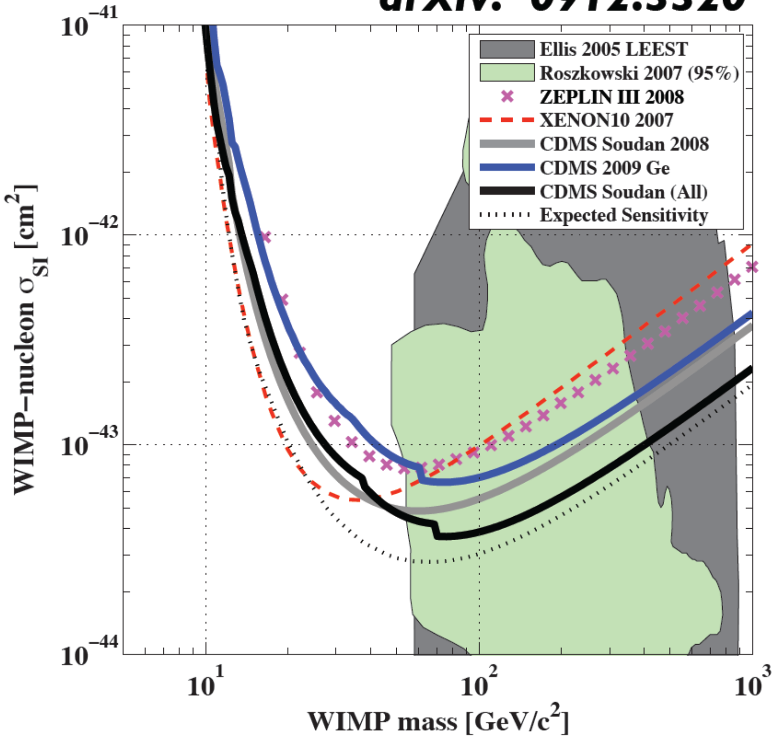


CDMS II Final Results

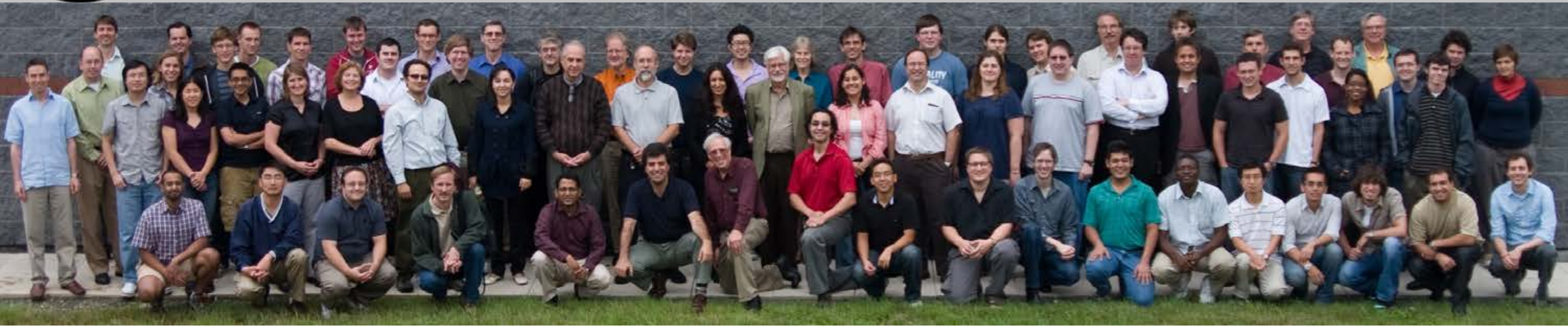
- World leading result at the time of publication
- Residual surface event background limited prospects for dramatically improving sensitivity of CDMS II detectors
  - A new idea was needed!



arXiv: 0912.3320



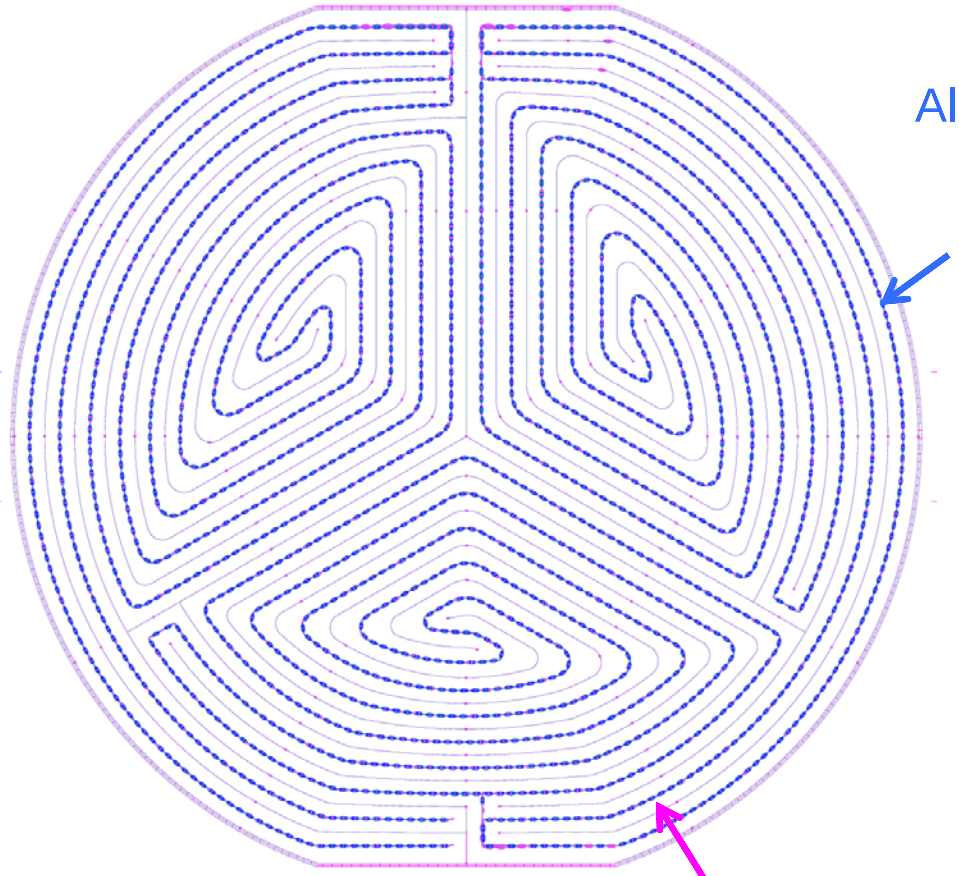
The SuperCDMS Collaboration

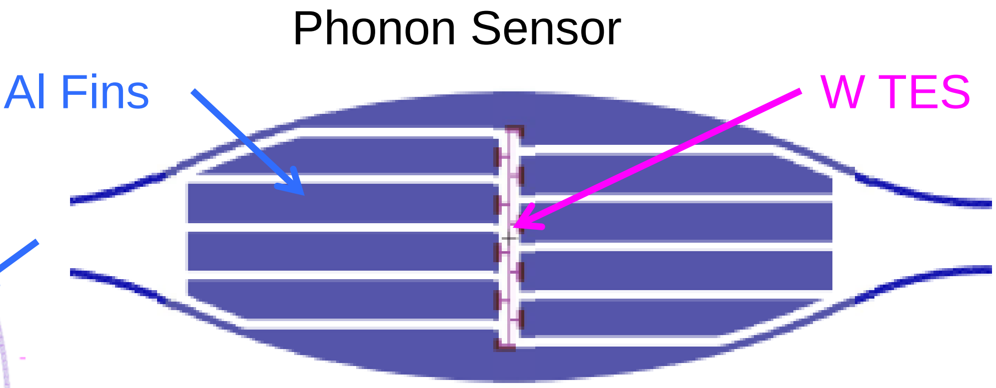


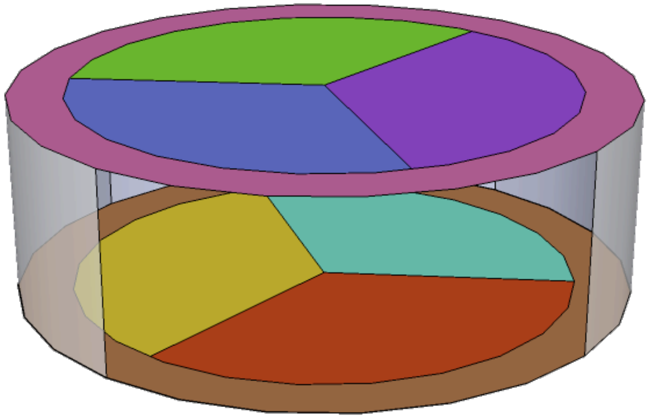
California Institute of Technology	Fermi National Accelerator Laboratory	Massachusetts Institute of Technology
Queen's University	Santa Clara University	SLAC / Kavli Institute for Particle Astrophysics and Cosmology
Southern Methodist University	Stanford University	Syracuse University
Texas A&M University	Universidad Autónoma de Madrid	University of British Columbia
University of California, Berkeley	University of California, Santa Barbara	University of Colorado, Denver
University of Evansville	University of Florida	University of Minnesota

SuperCDMS uses New iZIP Detectors

- Interleaved charge and phonon readout electrodes on both sides of detector are designed to greatly reduce surface event background
  - CDMS II had phonon electrodes on one side, charge electrodes on the other side

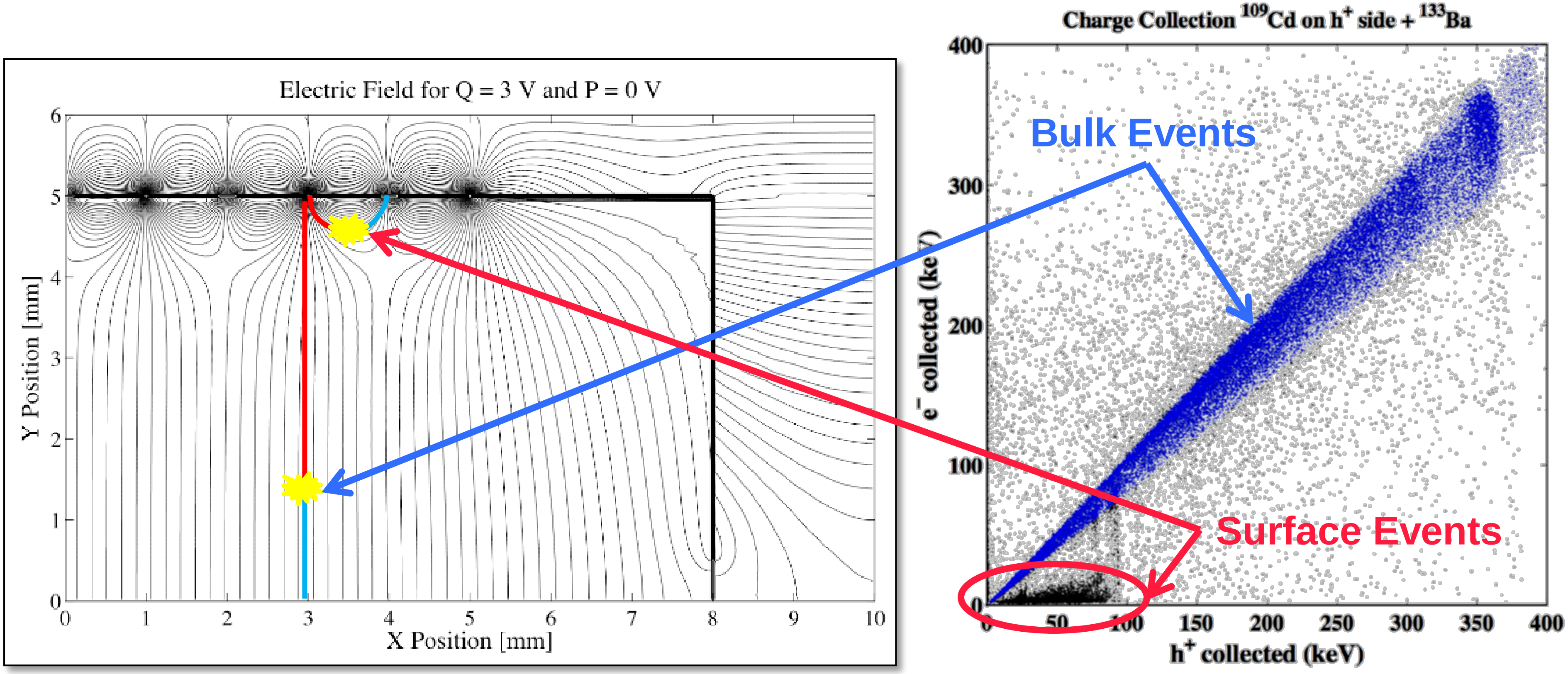






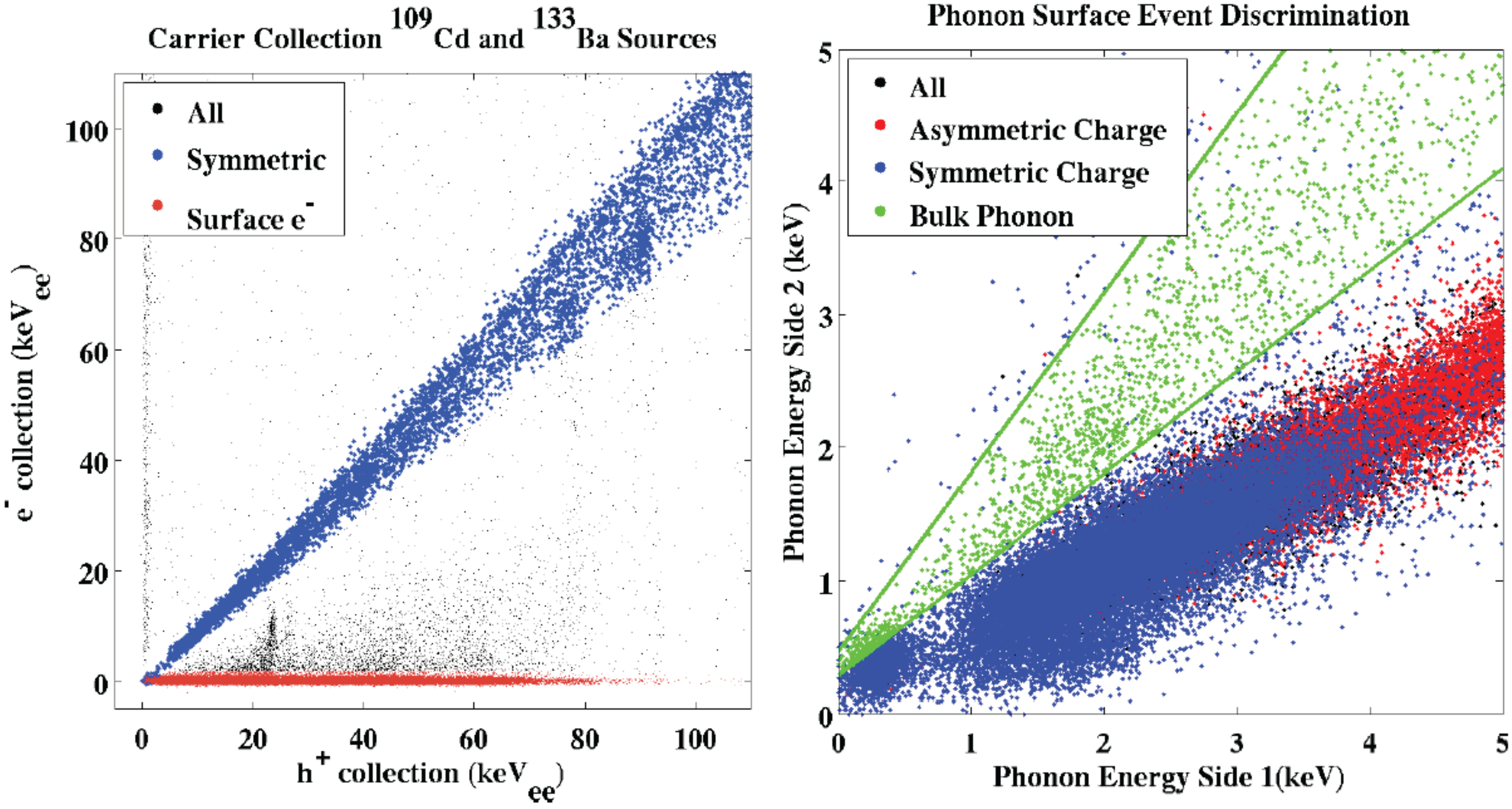
iZIP Electric Field Configuration

- Transverse surface field in addition to bulk drift field
  - Typical charge electrode bias is +2V (side 1) and -2V (side 2)
  - Phonon rails are set to ground potential on both sides
  - Surface events can be identified through their charge asymmetry



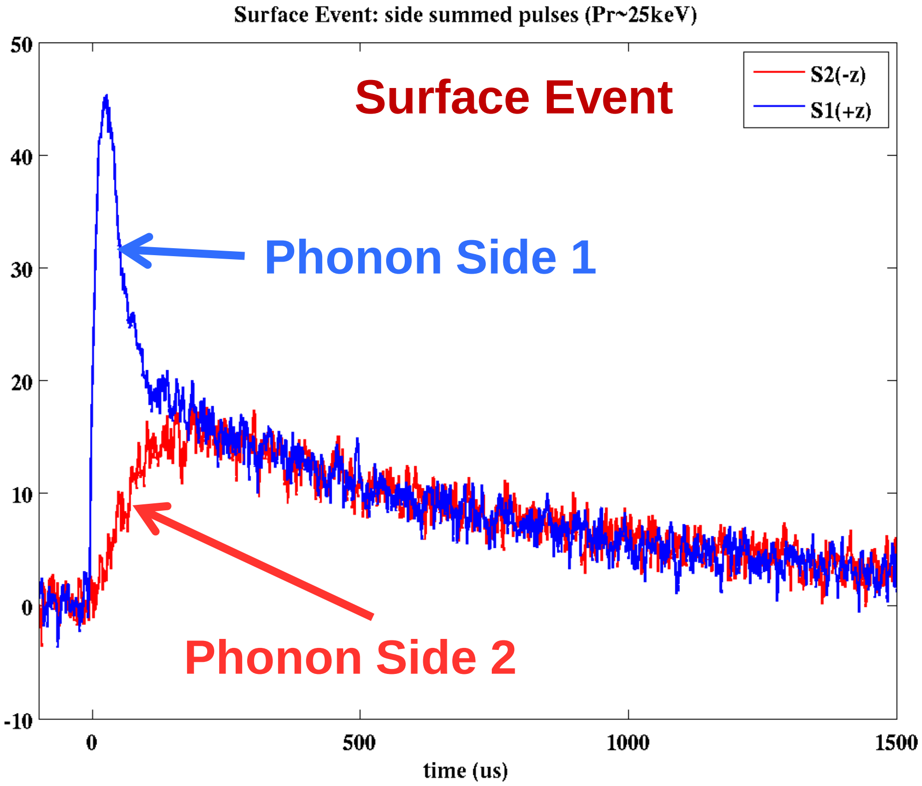
Surface Event Identification

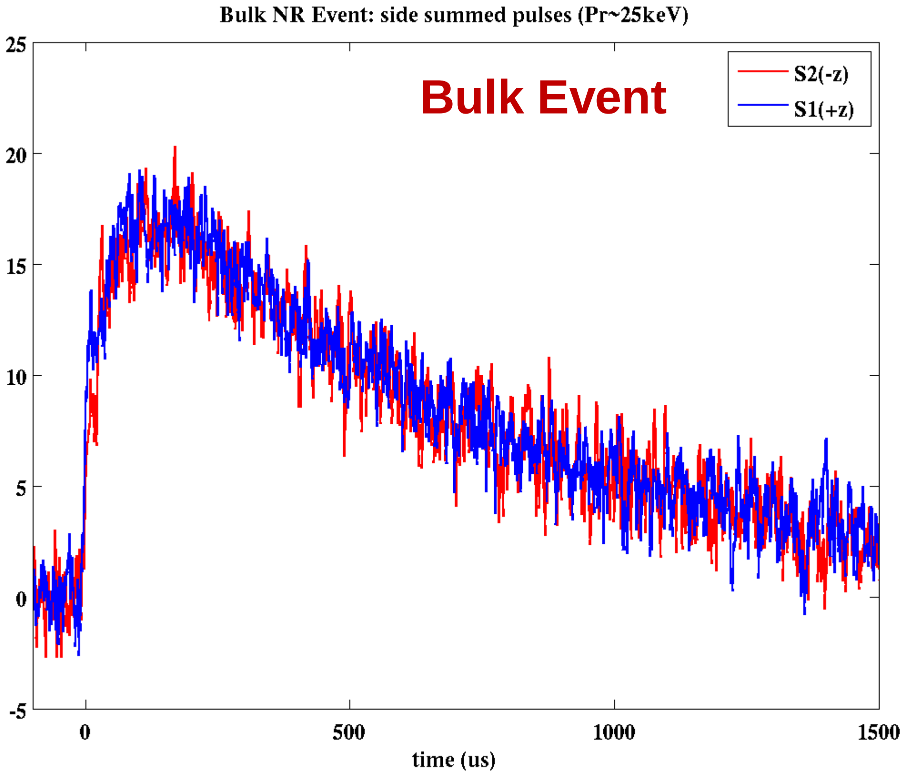
- Surface events exhibit top/bottom asymmetry in both charge and phonon measurements



iZIP Pulse Shape Discrimination

- Phonon waveforms provide further BG discrimination
  - Position dependence can help identify surface events
  - Prompt Luke-Neganov phonon contribution from accelerated e/h pairs may allow independent estimate of ionization charge

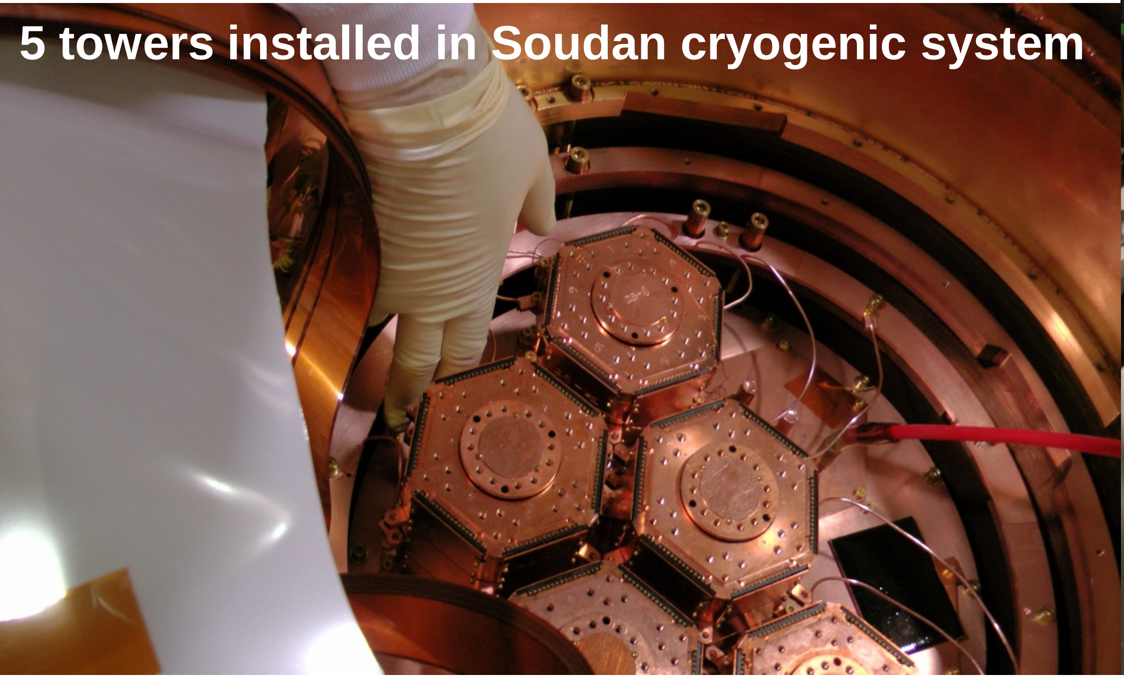

Surface Event: side summed pulses (Pr~25keV)


Bulk NR Event: side summed pulses (Pr~25keV)

15 iZIP Detectors Deployed at Soudan

- 5 Towers, each with 3 iZIPs
- ~9 kg of Ge target mass
- Cool down began late 2011
- Taking data since March 2012

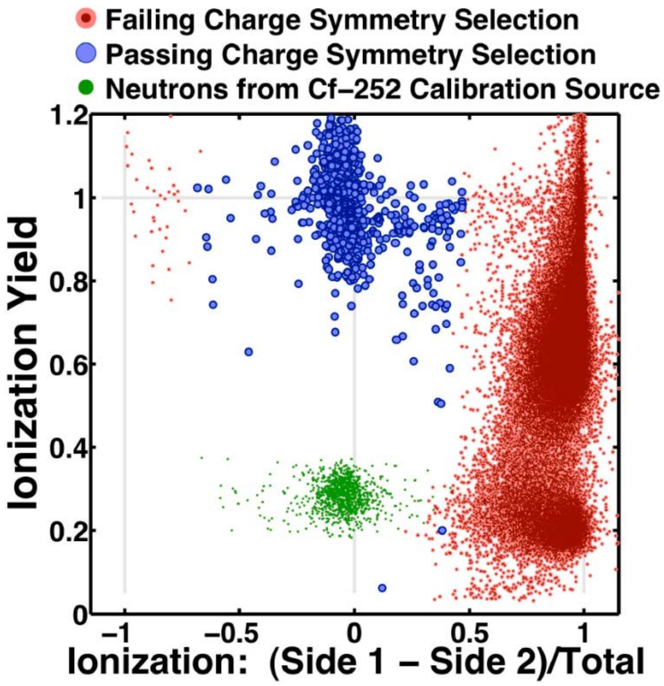
Unpacking the first iZIP tower at Soudan

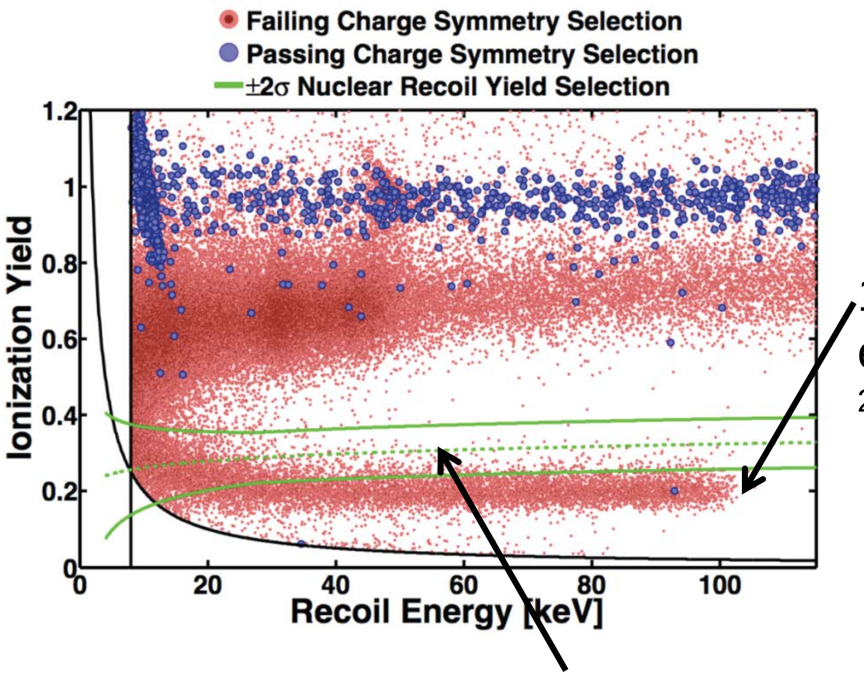


5 towers installed in Soudan cryogenic system

Testing iZIP Surface Event Rejection

- Radioactive sources on two Soudan iZIPs demonstrate rejection of surface events is sufficient for “0-background” performance in full payload for SuperCDMS SNOLAB



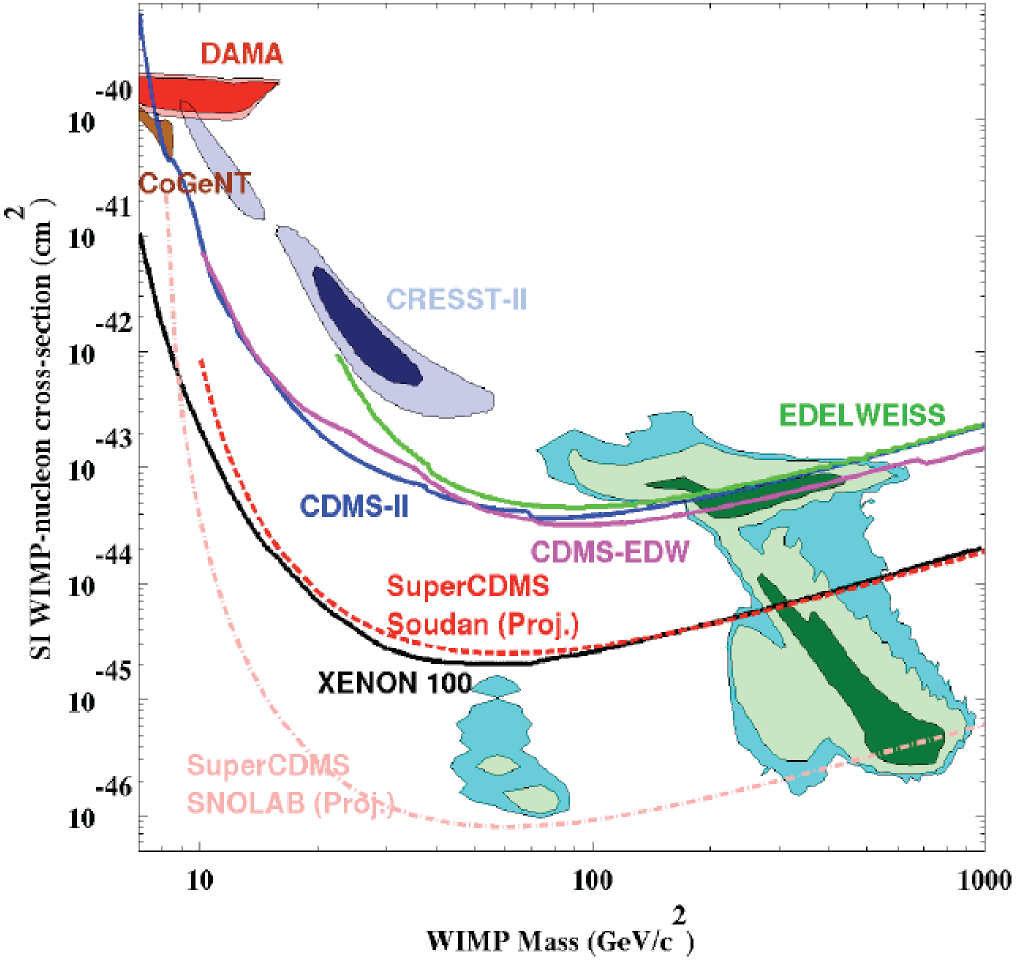


104 keV endpoint for ^{206}Po recoils

No symmetric (blue) events in nuclear recoil band for exposure equivalent to full SuperCDMS SNOLAB expt

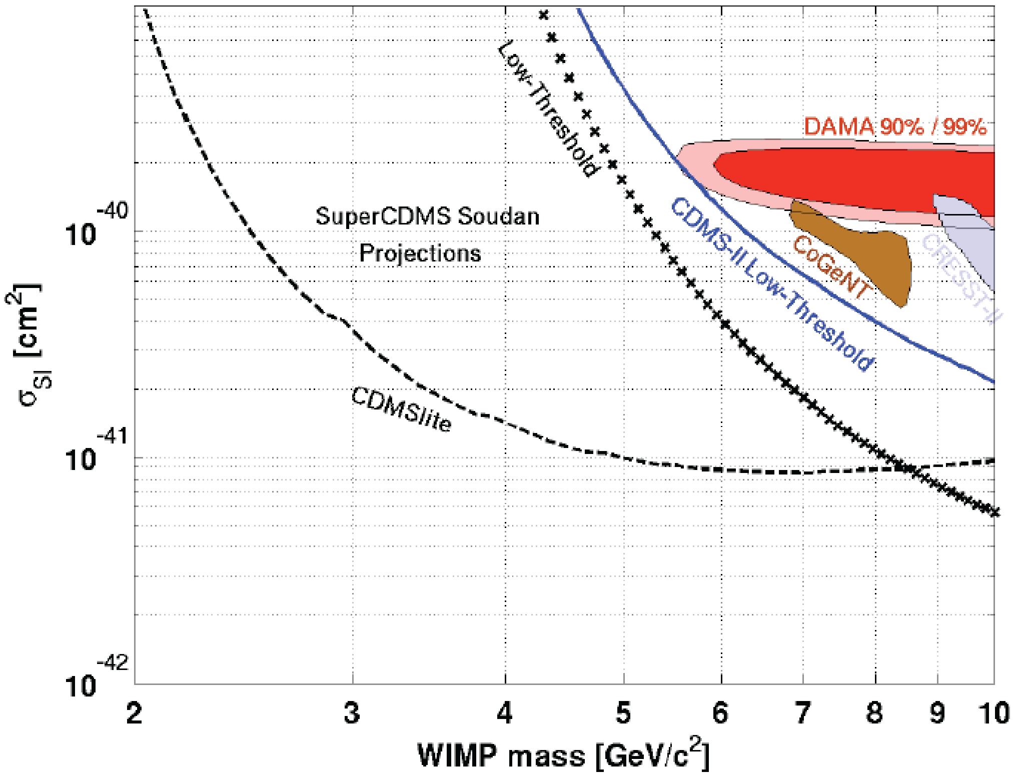
Projected Sensitivity @ Soudan

- Expect factor of ~15 improvement in sensitivity over CDMS II
- Comparable sensitivity to Xenon 100 for spin independent cross section



Low Mass WIMP Search

- Standard approach:
  - Lower thresholds, tolerate some background
- CDMS-Lite approach:
  - Apply ~70 V bias voltage
  - Ionization charge *q* produces $q\Delta V$ of "Luke Phonons", amplifying the phonon signal proportional to the ionization charge
  - Lose ionization yield rejection, but flat Compton background is stretched out / reduced in amplitude
  - Unique sensitivity to very low WIMP masses

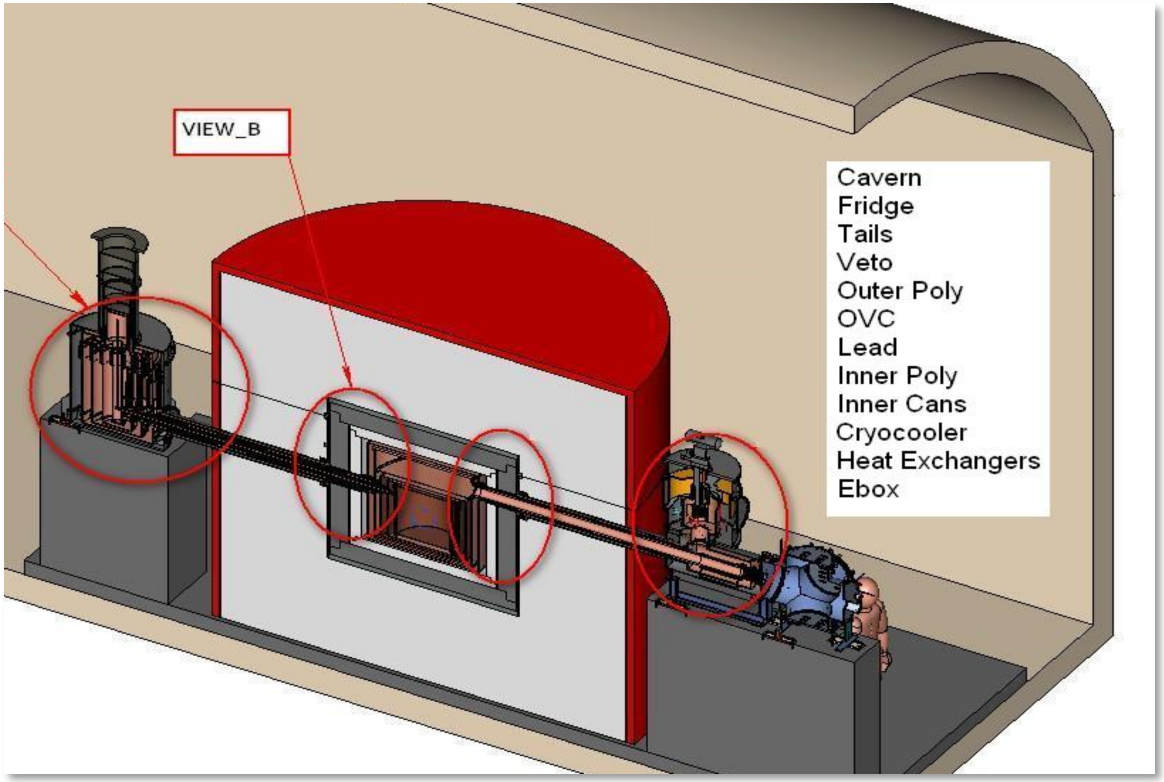


CDMS-Lite:

$$E_{phonon} = E_{recoil}*(1+\text{Yield}*\Delta V/3\text{eV})$$

SuperCDMS SNOLAB

- R&D underway for a G2 experiment at SNOLAB
  - Scale up Ge iZIP technology to larger target mass
  - Initial target mass of 200 kg, with cryostat capacity for 400 kg
  - Deep underground site required to eliminate cosmic backgrounds



SLAC Role in SuperCDMS SNOLAB

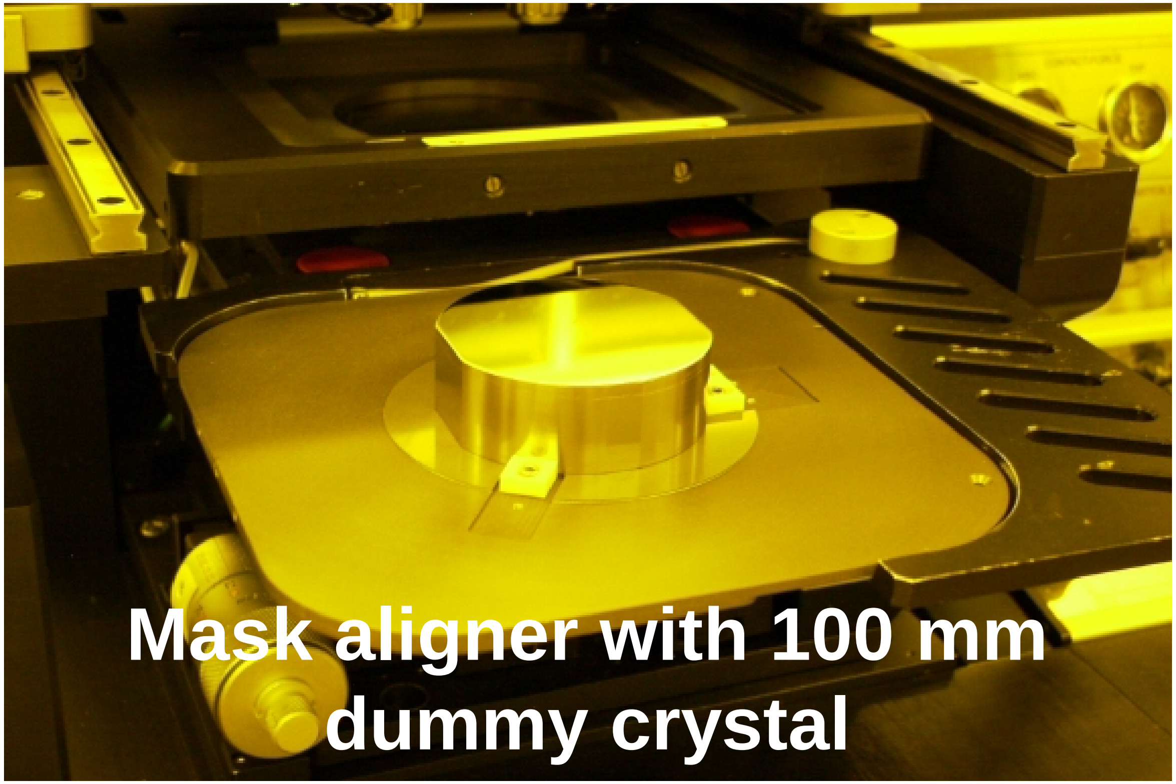
- SLAC is responsible for the Ge Tower System that provides the detector payload for SuperCDMS SNOLAB
- Broad program of R&D underway with efforts in:
  - Detector fabrication
  - Cold electronics
  - Cold mechanics
  - GEANT simulations
  - SNOLAB test facility
- Many interesting problems and new challenges
  - Strong SLAC team working closely with Stanford / CDMS collaborators
    - Makoto Asai, Anders Borgland, Daniel Brandt, Paul Brink, Wes Craddock, Brian Duda, Ken Fouts, Gary Godfrey, Jasmine Hasi, Mike Kelsey, Chris Kenney, Maria-Elena Monzani, Dave Nelson, Marco Oriunno, Richard Partridge, Mike Racine, Rudy Resch, Kristi Schneck, Astrid Tomada, Dennis Wright
- A brief tour of this effort follows

100 mm iZIP Detectors

- Plan to use 100 mm diameter, 33 mm thick Ge crystals
  - ~2.3 more mass per crystal than for 76 mm Soudan iZIP detectors
  - 1.4 kg per detector, plan to fabricate ~140 iZIP detectors @ ~8 / month
  - Crystals shaped into cylinders and polished by Stanford & Texas A&M

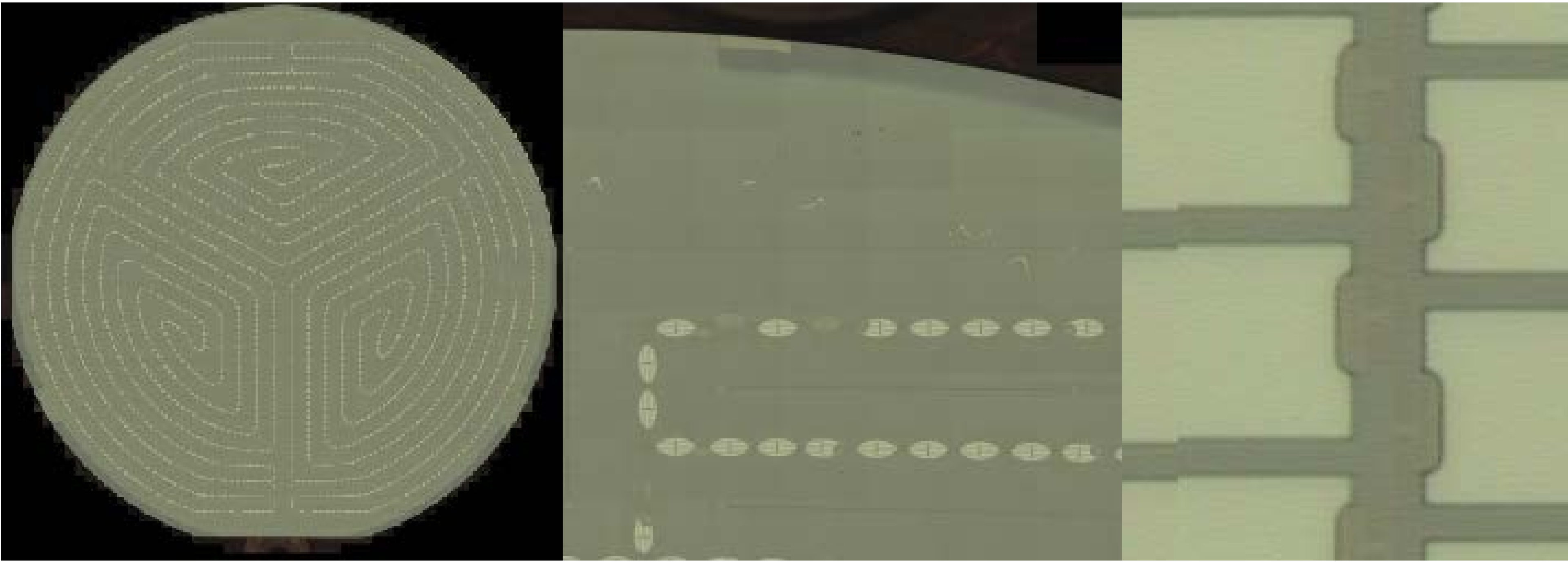
100 mm Fabrication Tooling

- CDMS uses customized semiconductor fabrication equipment for detector photolithography
  - Commercial equipment designed for thin wafers
  - Custom fixturing developed for 100 mm work

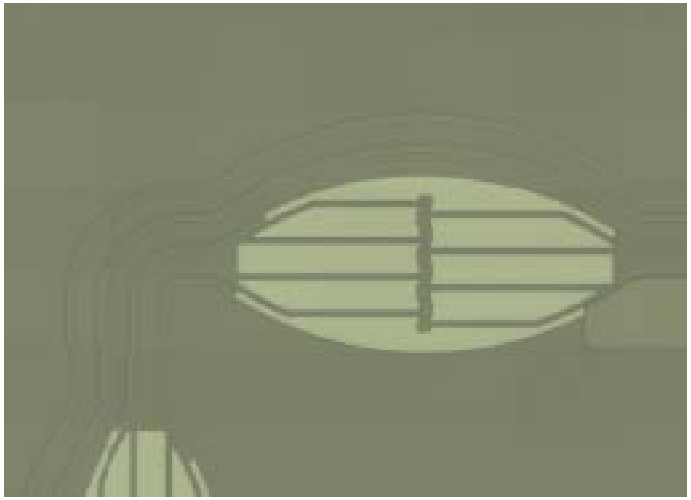


Mask aligner with 100 mm dummy crystal

Detecting Photolithography Defects



Optical CMM used to image entire detector surface (~20K images, 0.6μm pixel size)

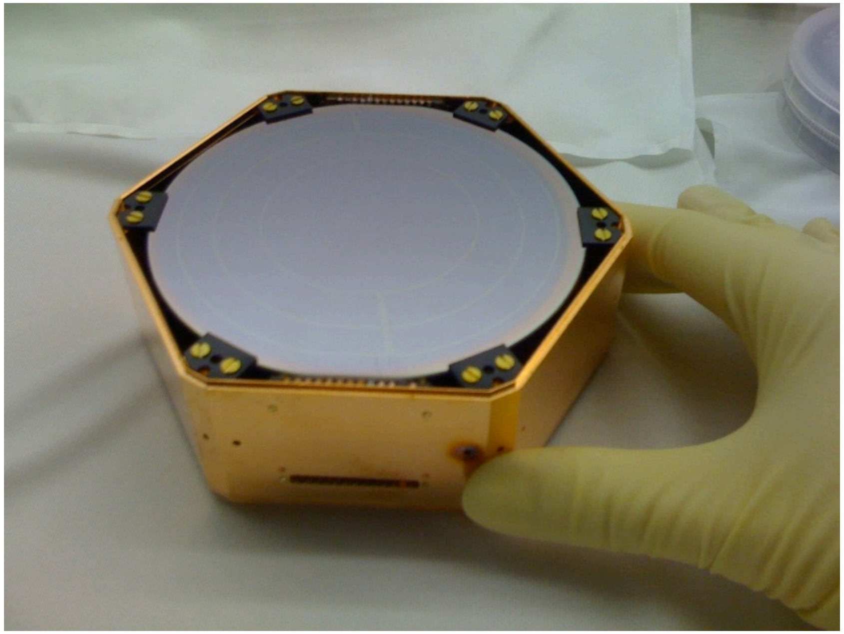


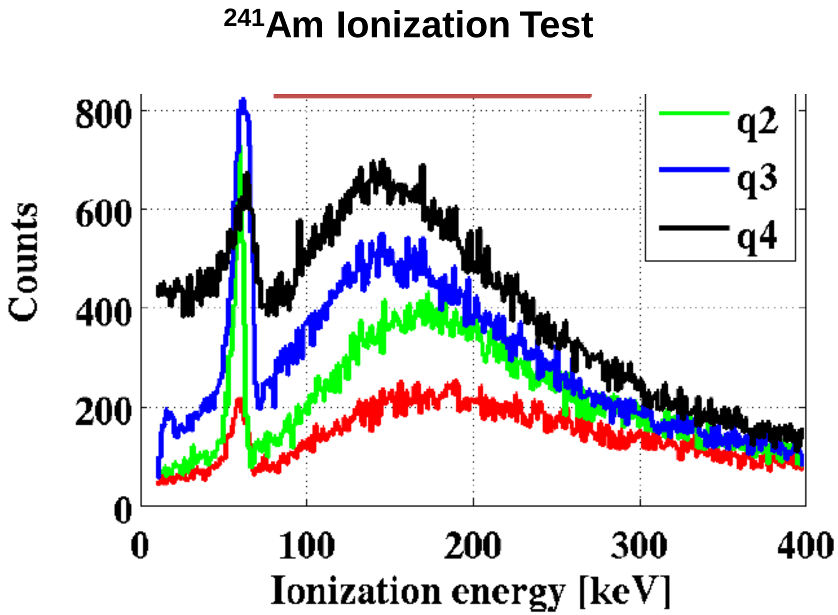
Images tiled using Google Maps API for easy navigation

Working on automated inspection software

100 mm Ionization Test

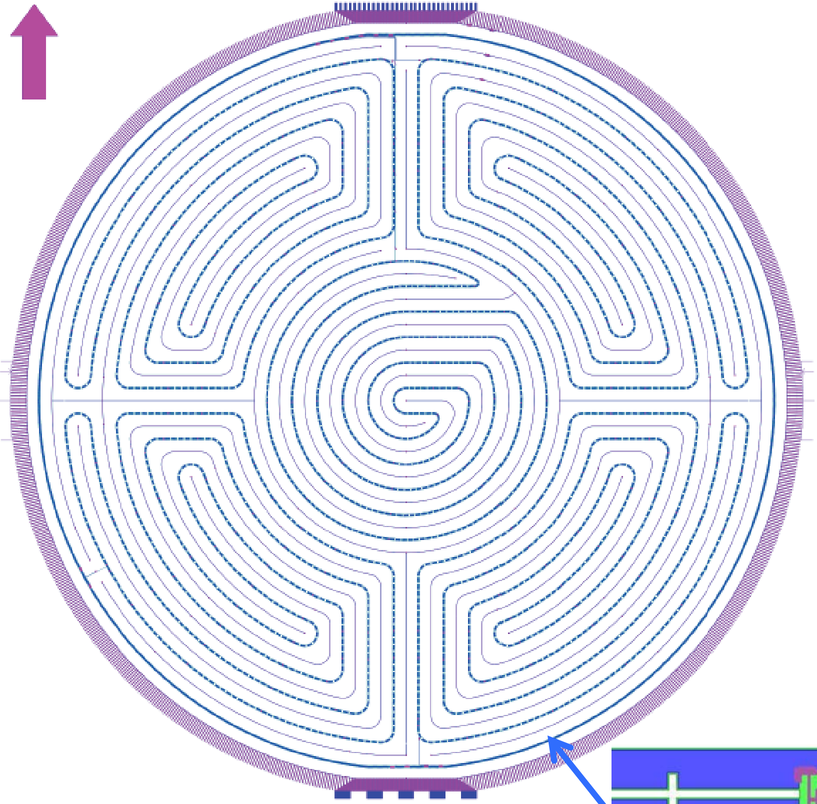
- 100 mm detector fabricated with ionization electrodes to verify good charge collection in 33 mm thick Ge crystal
  - See 60 keV gamma line from ^{241}Am source

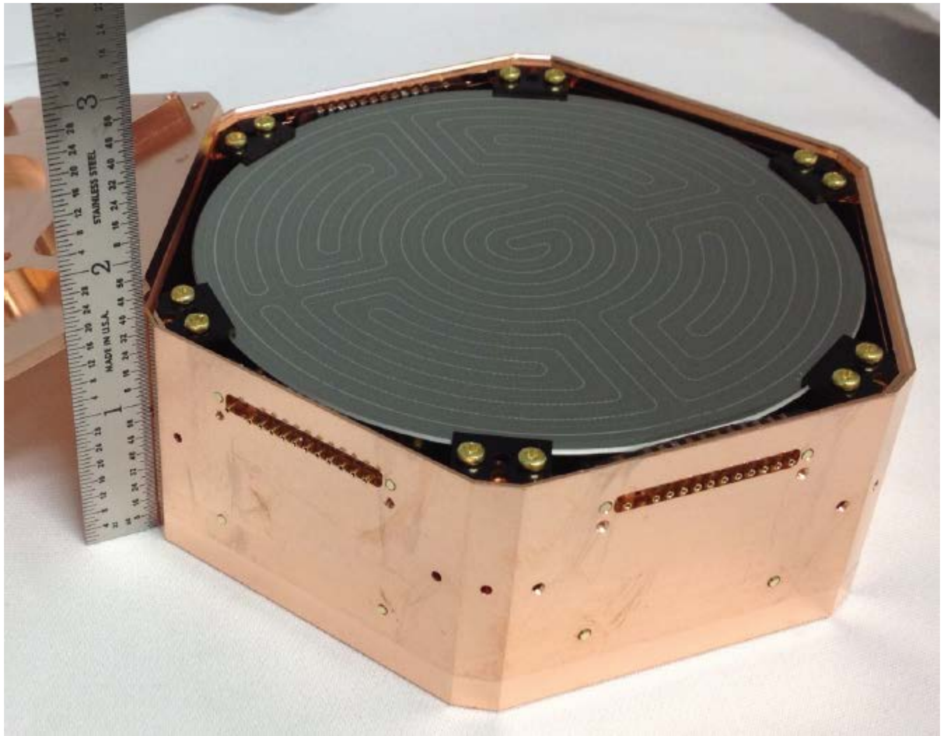


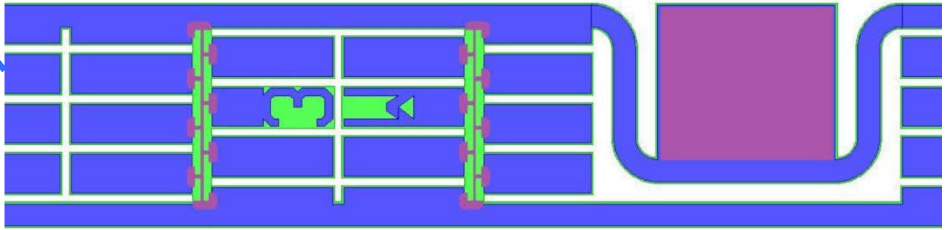


iZIP Design

- First iZIPs consistent with SNOLAB requirements
  - 6 phonon channels / side, 2 ionization channels per side
  - Fiducial region can be defined using ionization or phonon measurements



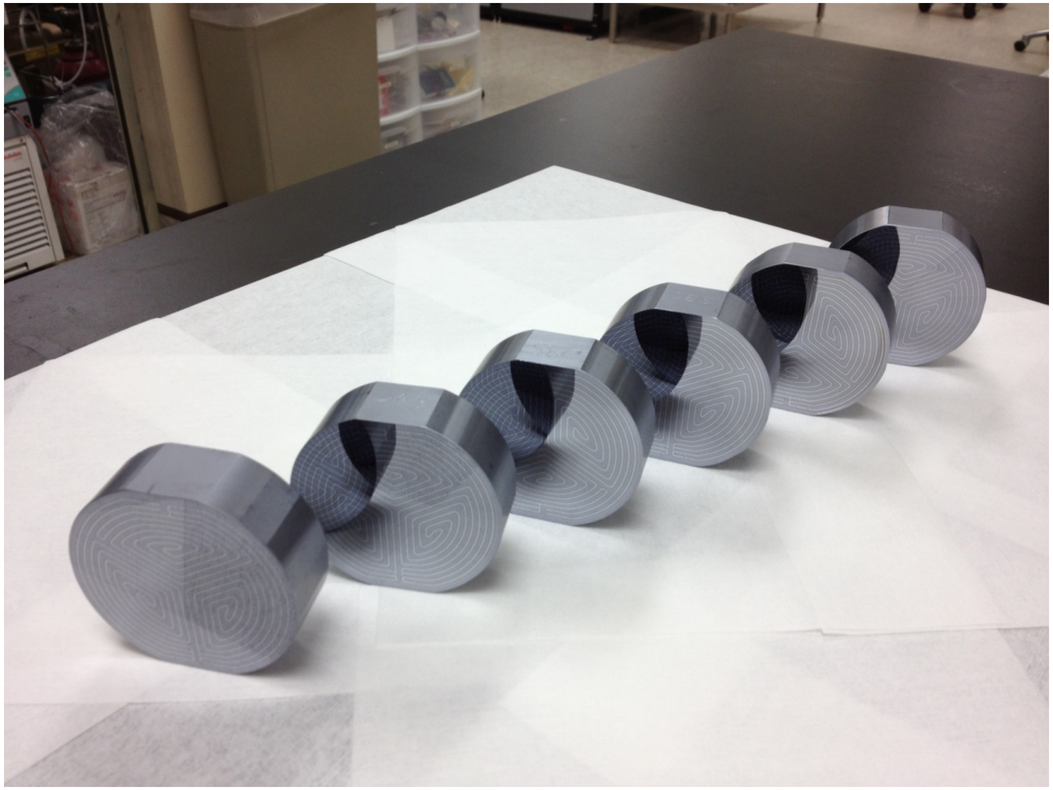




Detector Fabrication Throughput

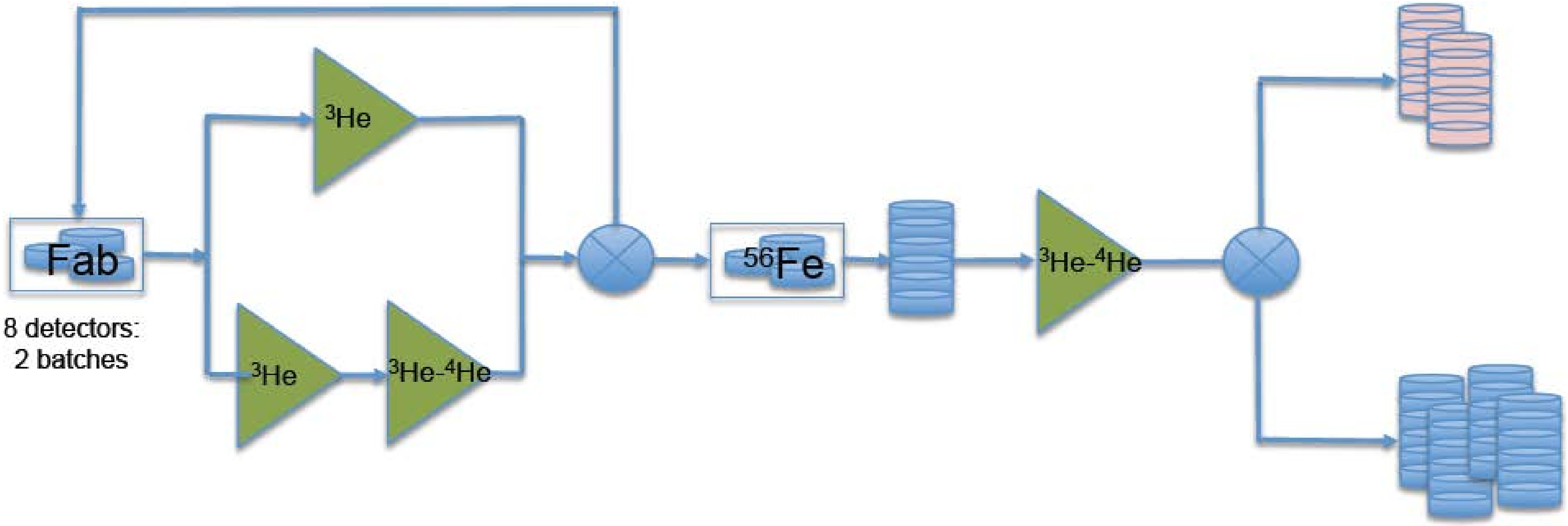
- SNOLAB goal is to fabricate 8 detectors / month
- Performed throughput test using 76 mm Si crystals
  - Fabricated 6 detectors in ~3 weeks at Stanford Nanofabrication Facility
  - New sputtering system expected to boost rate to >8 detectors / month
  - Additional capacity available at TAMU

Detector fabrication should not be a bottleneck



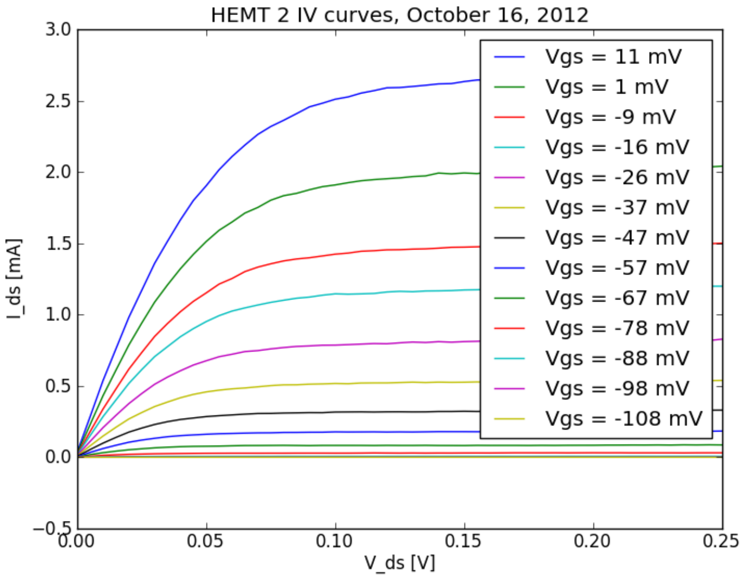
Testing Throughput

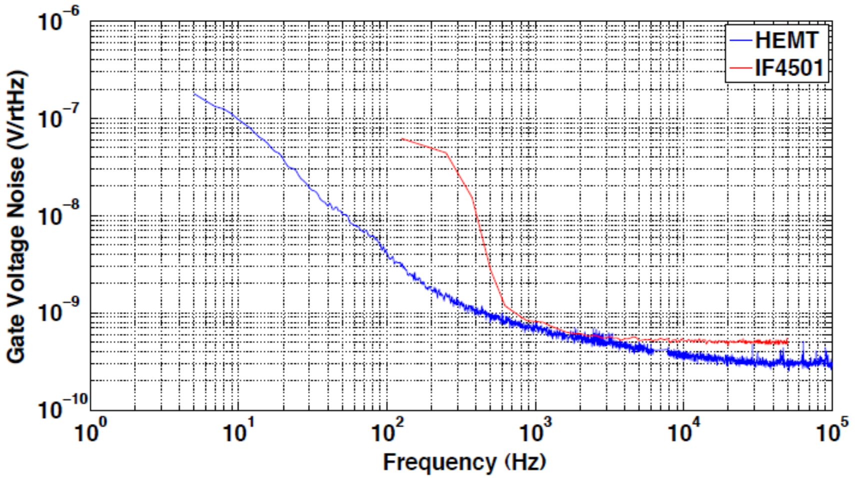
- Testing needs to keep up detector fabrication pipeline
  - All detectors tested in ^{3}He fridge (shorts, opens, ionization tests?)
  - 1 detector per batch tested in dilution fridge to determine TES T_C
  - If necessary, implant with ^{56}Fe to adjust T_C of batch to ~70-80 mK
  - Assembled towers tested in dilution fridge (6 detectors / tower)
  - Parallel testing program for cold hardware (typically at 4K)



Cold Readout Electronics

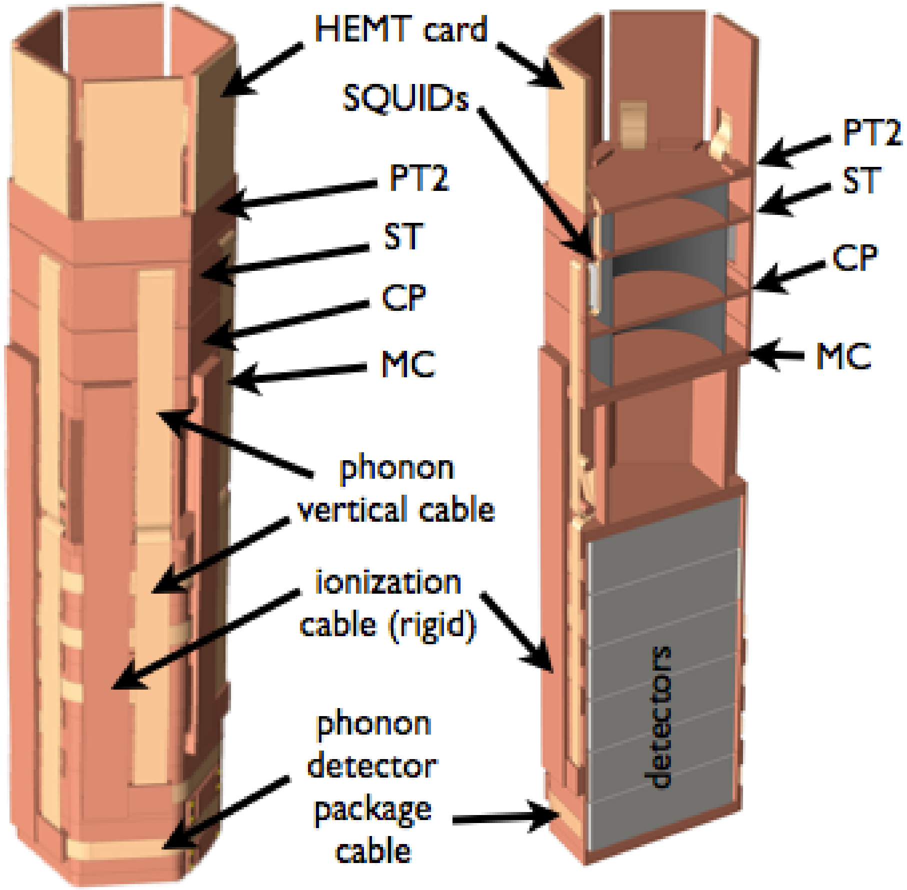
- SQUID phonon readout
  - SQUID arrays are extremely sensitive to changes in current
  - Transition edge sensors biased at constant voltage, so small change in in TES resistance produces a change in current through the SQUIDs
- High Electron Mobility Transistor (HEMT) charge readout
  - Traditional FET front end freezes out below ~100° K
  - HEMT based on 2D electron gas – works fine at 4° K
  - ~50 μW per channel (x100 reduction from current JFET), lower noise





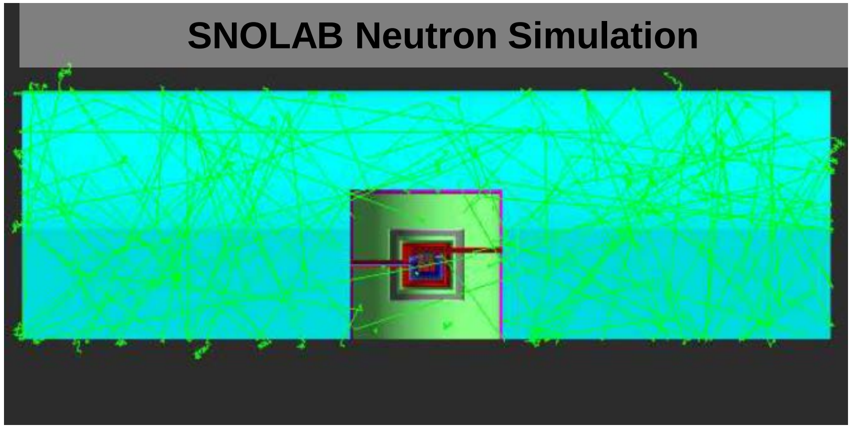
100 mm Tower Design

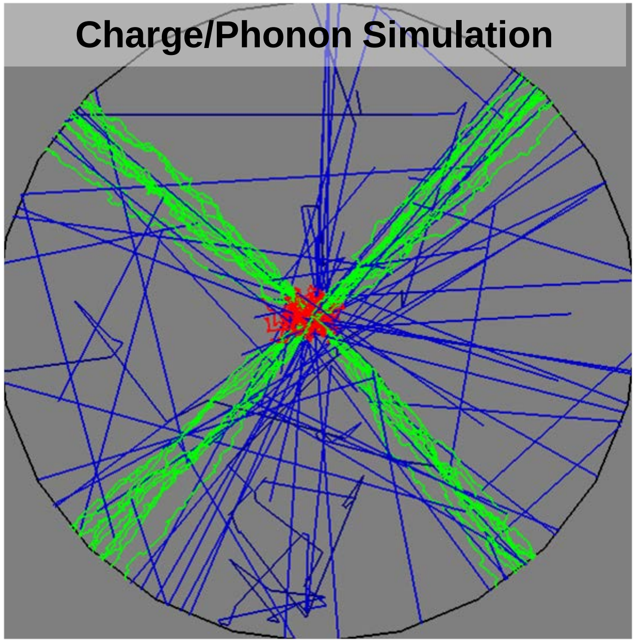
- Tower provides a tightly integrated set of components and functions
  - Mechanical support
  - Thermal management
  - Wiring from 50 mK to 4K
  - Cold electronics (SQUIDs, HEMTs)
  - IR blocking
  - Interface to wiring assembly for 4K → 300K (~14000 wires)
- Thermal issues are huge
  - Very limited cooling capacity from dilution refrigerator

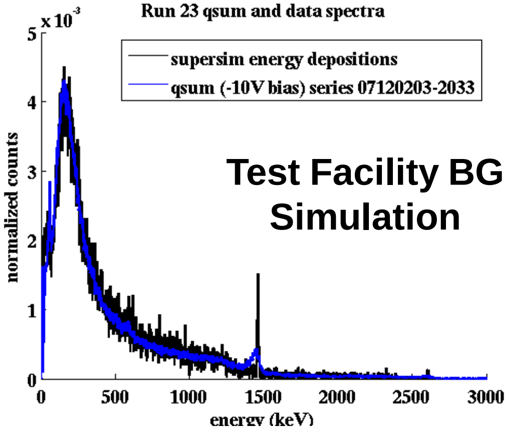


MC Simulations

- SLAC has developed G4-based background simulation framework (supersim) and implemented cryogenic electron/hole/phonon transport in G4


SNOLAB Neutron Simulation


Charge/Phonon Simulation



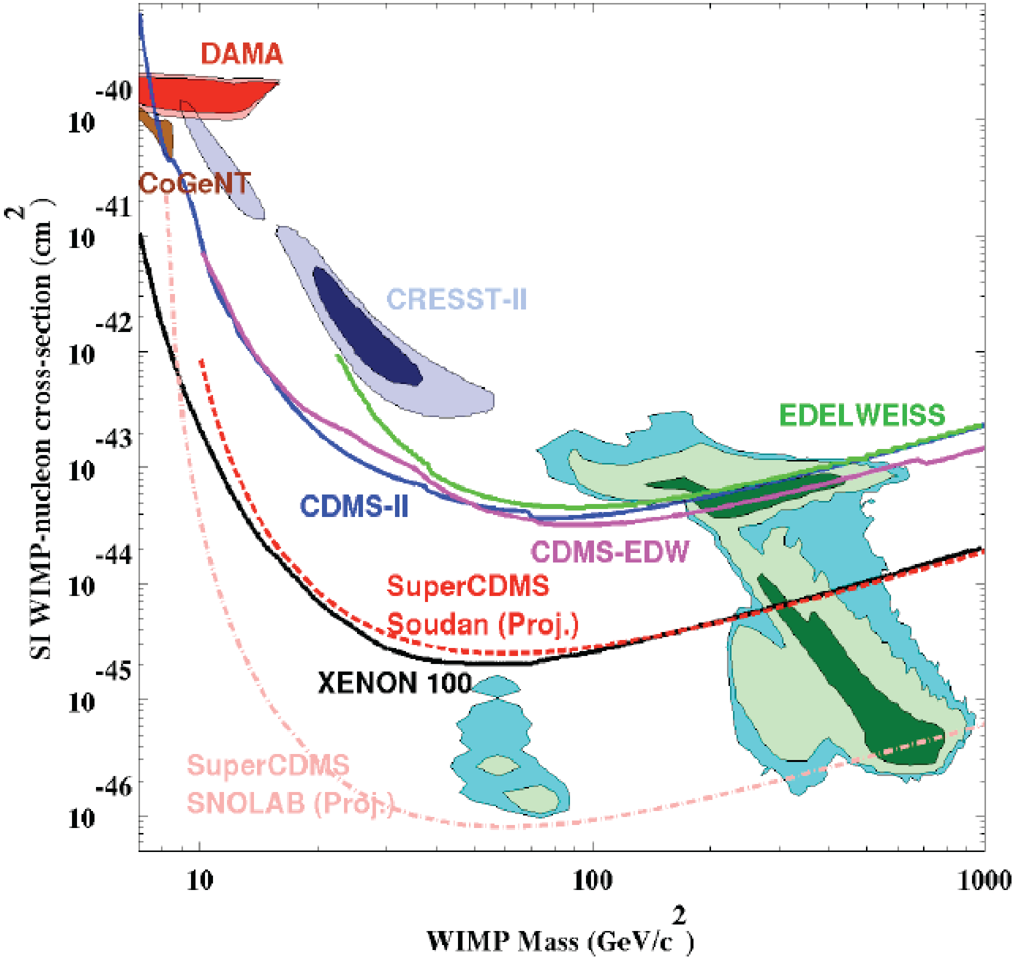
Test Facility BG Simulation

SNOLAB Test Facility (STF)

- SLAC is refurbishing the dilution refrigerator from CDMS-1 for use in STF
- STF will be located in the Ladder Lab, adjacent to the planned location for SuperCDMS-SNOLAB
- STF will allow low background, deep underground testing of CDMS detectors
  - Ability to test individual detectors allows performance to be verified before construction of full detector

Projected Sensitivity @ SNOLAB

- Expect to achieve G2 sensitivity of 80 yoctobarn (8×10^{-47} cm^2) for spin independent WIMP scattering
- Factor of ~30 improvement over SuperCDMS Soudan
- Capability for background rejection at this level of sensitivity has already been demonstrated



Richard Partridge

Summary

- SuperCDMS has been running at Soudan for past 9 months with 9 kg of 76 mm diameter iZIP detectors
    - Expect factor of ~15 improvement in sensitivity over CDMS II
    - Unique ability to achieve low thresholds for low mass WIMP search
- Broad program of R&D underway to develop 100 mm Ge Tower system that comprises the payload for SupCDMS SNOLAB
    - Many interesting challenges in scaling up original CDMS 76 mm design
    - SLAC is managing and strongly contributing to this effort
- Working towards a 200 kg experiment at SNOLAB
    - Expect factor of ~30 improvement in sensitivity over SuperCDMS Soudan that will cover a significant region of SUSY parameter space
    - Have already demonstrated required surface event rejection using sources at Soudan
    - Cryostat sized for 400 kg payload for future initiatives