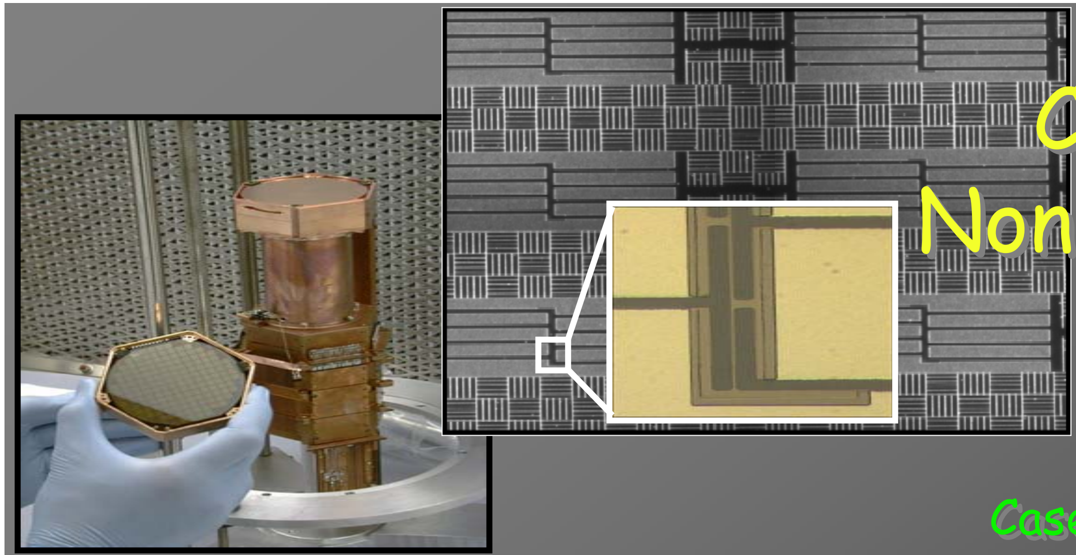


Calorimetry with Nonequilibrium Phonon Detectors

Michael Dragowsky

Case Western Reserve University

For the Cryogenic Dark Matter Search Collaboration

Outline

-What is Dark Matter?
-Detection Strategy
-NE Phonon Detectors
-BOD: Complementarity
-Room for Improvement

CALOR06 - Chicago
6/6/06

Dark Matter Evidence

- Dark Matter (non-luminous) only sensed through Gravity
- Compelling Evidence from:
  - Astronomy/Astrophysics
    - Large-Scale Structure
    - Galaxy clusters
    - Galaxy rotation curves
    - Dwarf galaxies
  - Cosmology
    - Cosmic Microwave Background
    - SN-Ia
    - Big-Bang Nucleosynthesis
- Nonbaryonic and Nonrelativistic Dark Matter dominates the Matter Budget

Dark Matter and Particle Theory

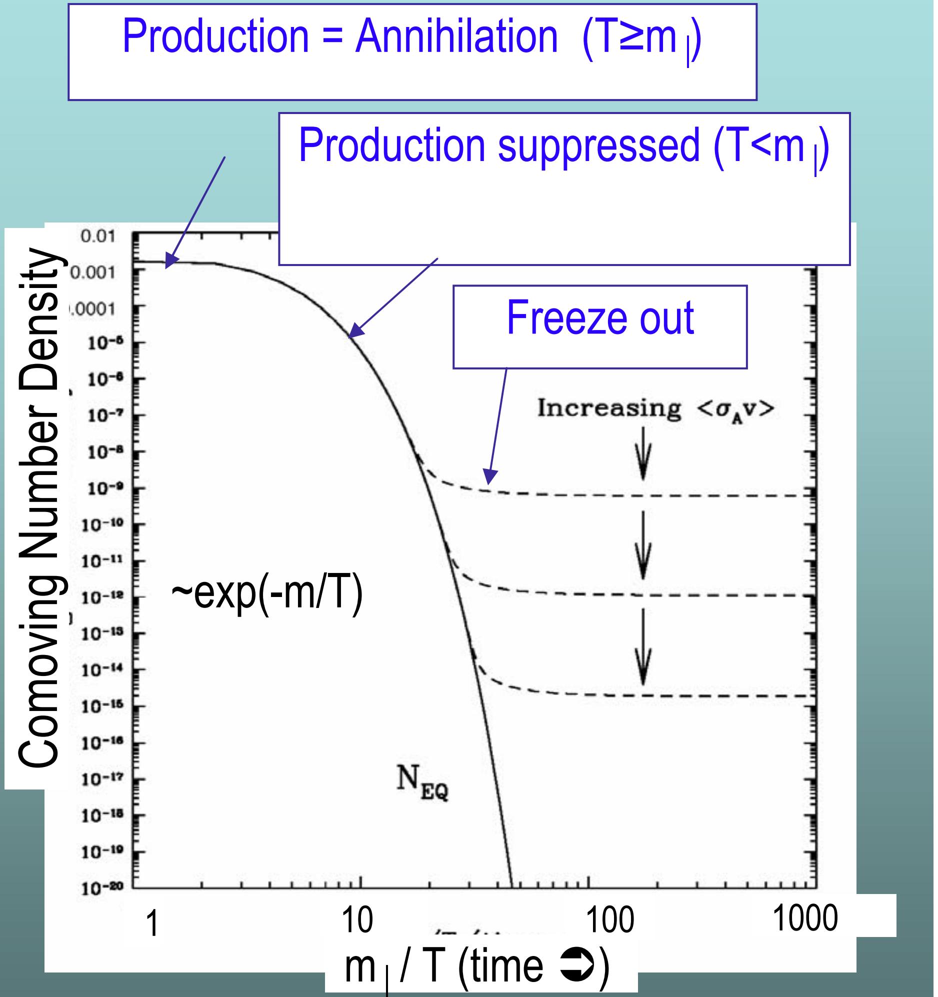
- Why is $m_{EW} \ll m_{Planck}$? (Hierarchy Problem)
  - Supersymmetry
    - Each boson, a fermion superpartner, and vice versa
    - With R-parity conserved, predicts a stable, neutral, particle [illegible]
  - Ext[illegible]
    - Kaluza-Klein dark matter
    - Universal extra dimensions

WIMPS

- QCD Strong-CP Problem
  - Axions
    - ultra-light particles associated with Pecci-Quinn symmetry to preserve CP with the strong interaction
    - Strong **B** induces conversion to photon (microwave)

Big Bang Relic Particles

- Early: equilibrium with 'soup'
- Freeze-out: |, | no longer meet
- Late: stable particles persist
- <u>Particle mass and cross section well-matched to deduced DM mass density, and very likely accessible with accelerators</u>
- Potential observables: Co-moving N, m$_|$ and ⌠$_A$


Production = Annihilation (T≥m$_|$)

Production suppressed (T<m$_|$)

Freeze out

$$\frac{dN}{dE_r} = \frac{\sigma_0 \rho_\chi}{2\mu^2 m_\chi} F^2(q) \int_{v_{min}}^{v_{esc}} \frac{f(v)}{v} dv$$

- DM density 0.3 GeV/c^2/cm^3
- *f(v)* Maxwell-Boltzmann 220km/s

Kamionkowski, hep-ph/0210370

Cryogenic Dark Matter Search

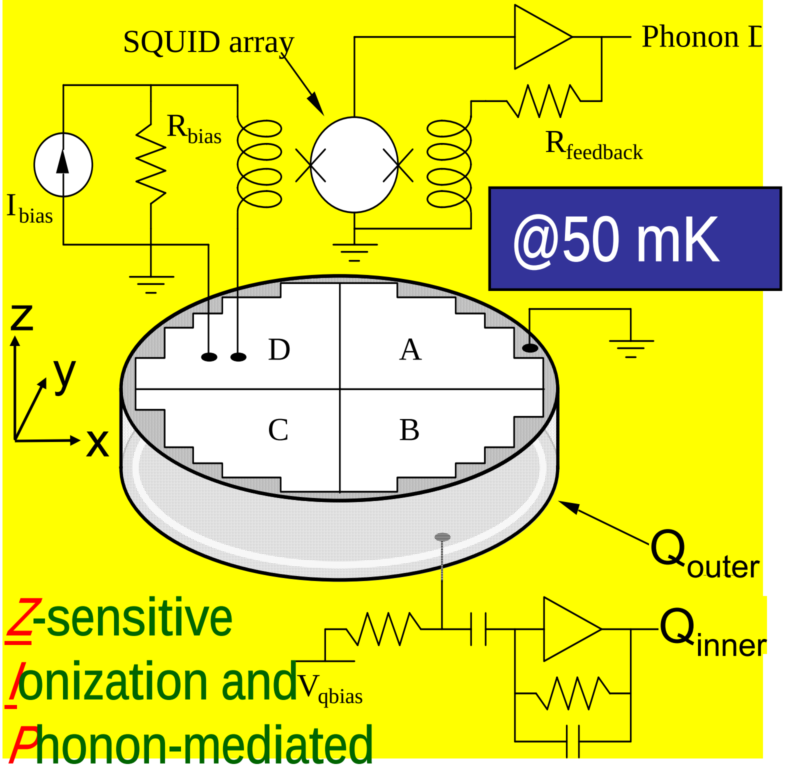
WIMP dark matter:

- Big-Bang relics that are neutral, non-relativistic, and massive
- experimental signature: low-E nuclear recoils

Few-MeV neutrons constitute a non-rejectable background.
Electron recoils from radioactive backgrounds will be far more common.

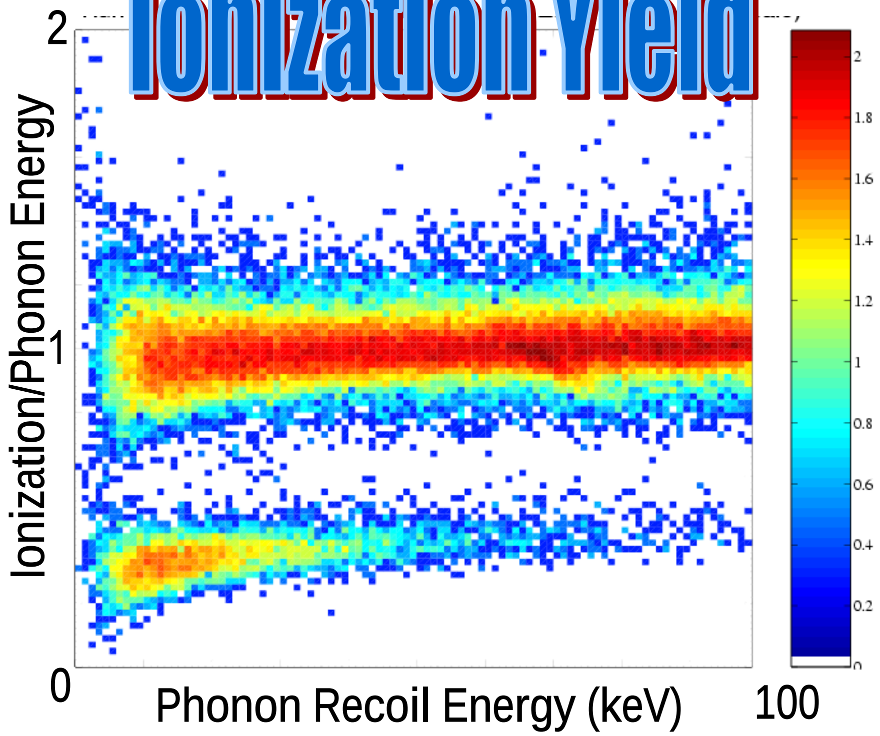
Reduce backgrounds
(Shielding, site location and materials selection and handling)
Event-by-event nuclear and electron recoil discrimination with…

Really Cool Detectors: ZIPs



Z-sensitive
Ionization and
Phonon-mediated

Ionization Yield



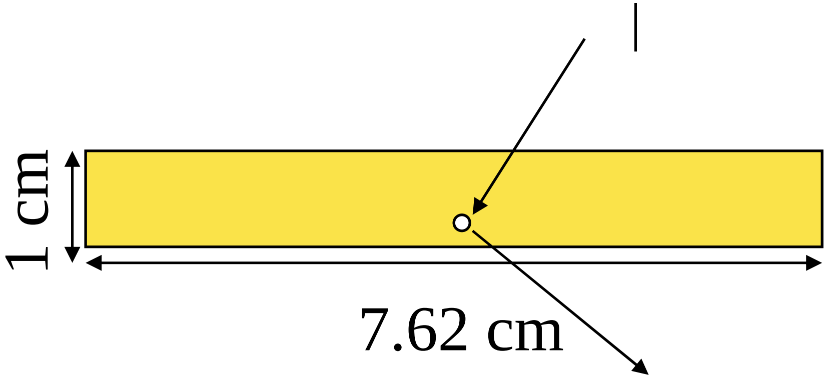
- Measure ionization
  - low-field (~volts/cm)
  - Segmented contacts define fiducial volume.
- QET* collect athermal phonons
  - Type-ind. recoil energy
  - µs leading-edge timing

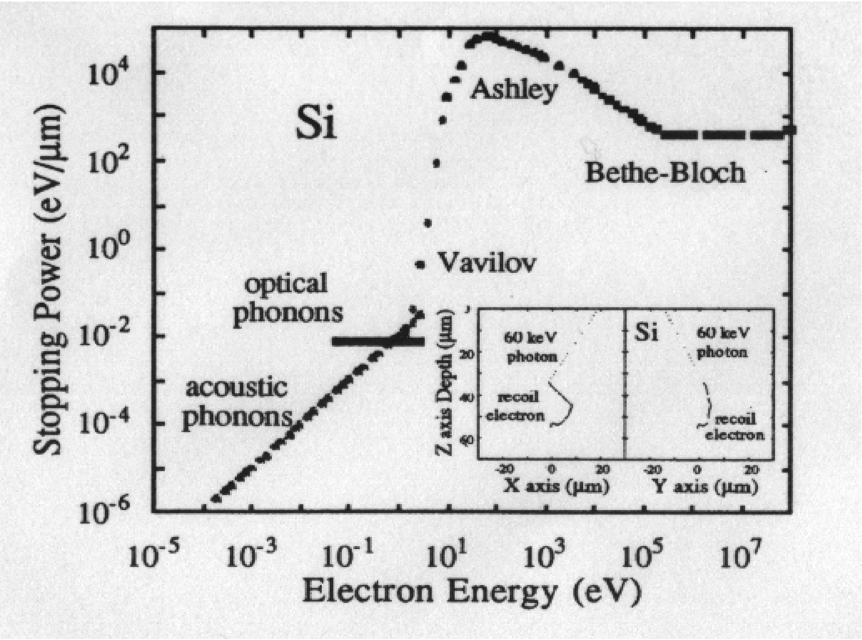
- Ionization/phonon energy distinguishes electron- and nuclear-recoil events

* Quasiparticle Trap-assisted Electrothermal Feedback Transition Edge Sensor

Low-Energy Electron Stopping Power

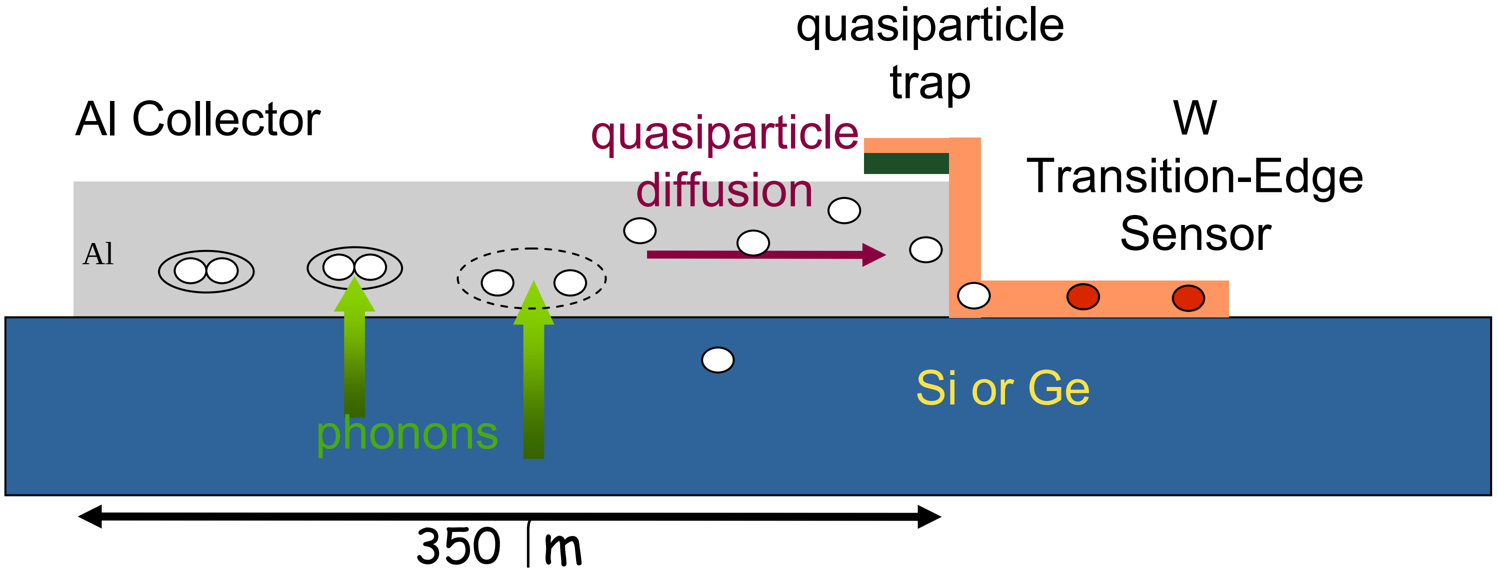
- Sub-MeV energy deposition in Si/Ge
  - free carrier pairs (e-h)
  - optical phonons (~4Thz)
  - Lattice damage (NRs)
- Optical phonons relax diffusively to acoustic phonons ~ 1 mm
- Acoustic phonons travel ballistically, and timing info aids in ER v. NR evaluation





Phonon Energy Collection

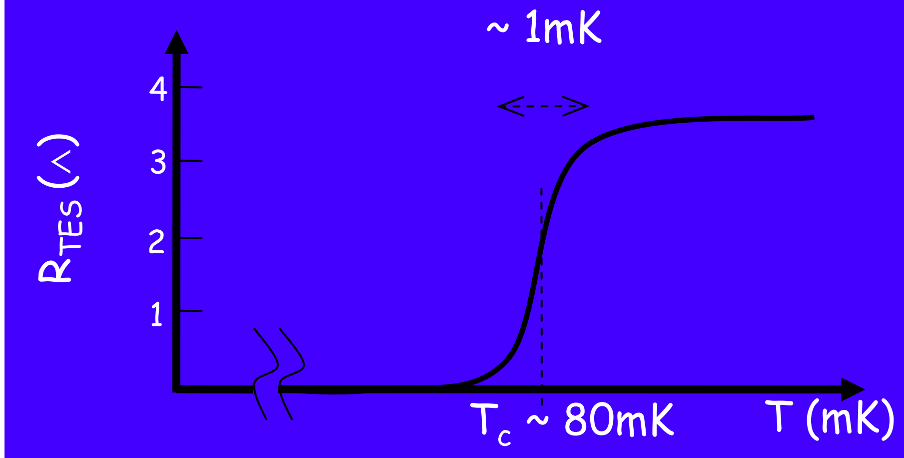
The Quasi-Particle Assisted Trap Electrothermal Feedback Transition-Edge Sensor



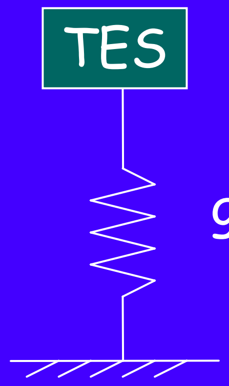
- Energy transport
  1. Non-equilibrium phonons dissociate Cooper pairs (2Δ = 0.3 meV)
  2. Quasiparticles in Al diffuse (some losses)
  3. Quasiparticles enter W, raise local temperature and resistance

Transition Edge Sensor

Obtaining Pulses



Weak thermal link to substrate needed for ™T --> ™R.



Electron-phonon decoupling

Consider small heat pulse ⊗T, expand heat balance equation to 1st order:

$$C\frac{d\Delta T}{dt} = -\frac{P_0\alpha}{T_0}\Delta T - g\Delta T$$

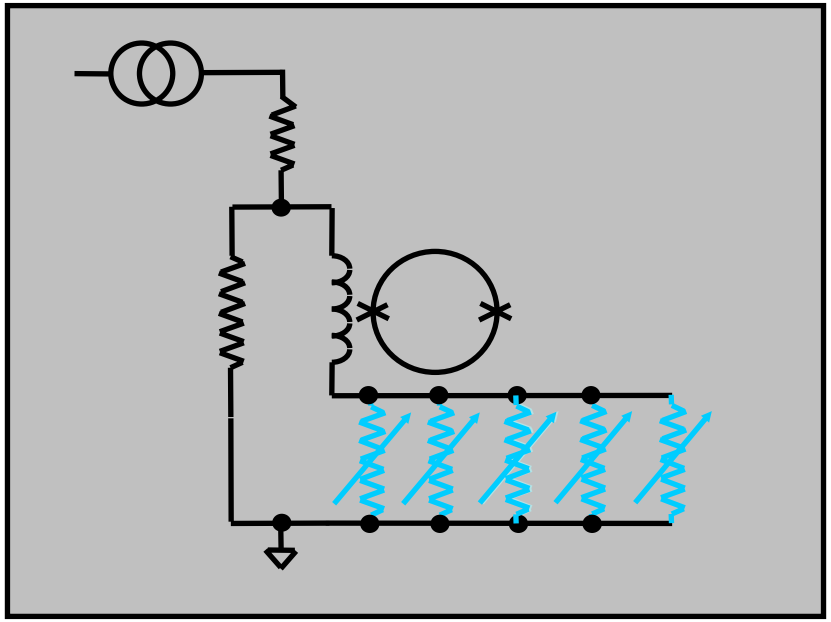
⋮

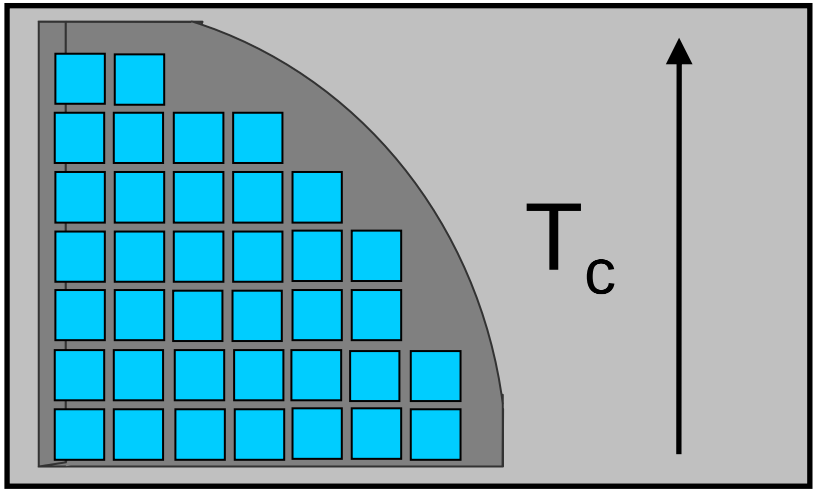
$$\tau = \frac{C}{g}\frac{1}{1+\frac{\alpha}{n}(1-\frac{T_s^n}{T_0^n})}$$

Extreme electrothermal feedback for $T_s \ll T_0$

Electrothermal Feedback TES Circuit

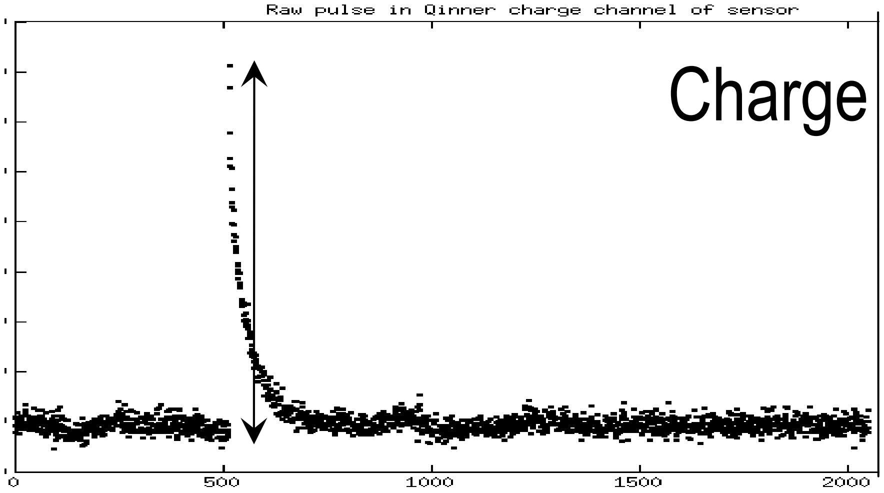
- Large area coverage 1036 TES in parallel
- Voltage bias achieves dynamic stability (ETF)
- Readout via 1-stage SQUID array at 600 mK
  - Minimize noise
  - L/R affects pulse duration

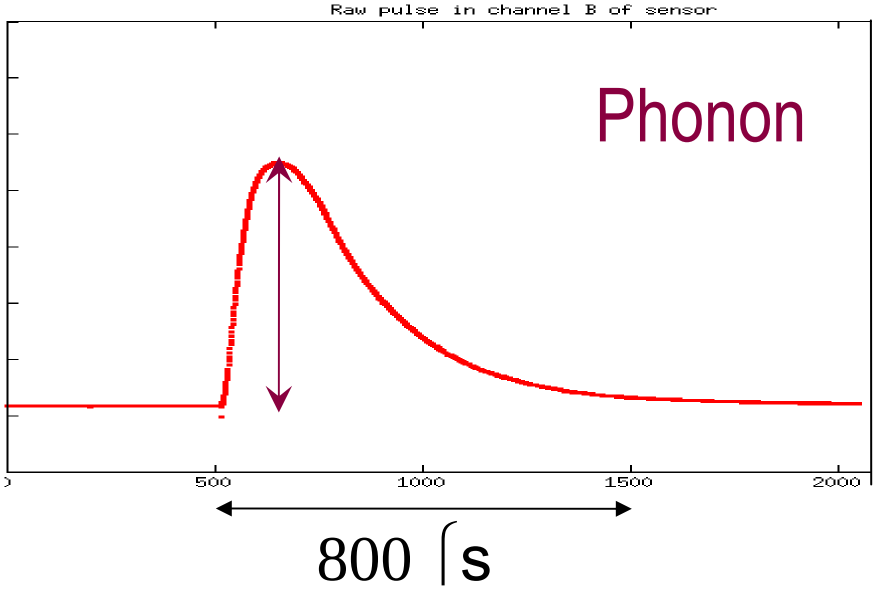




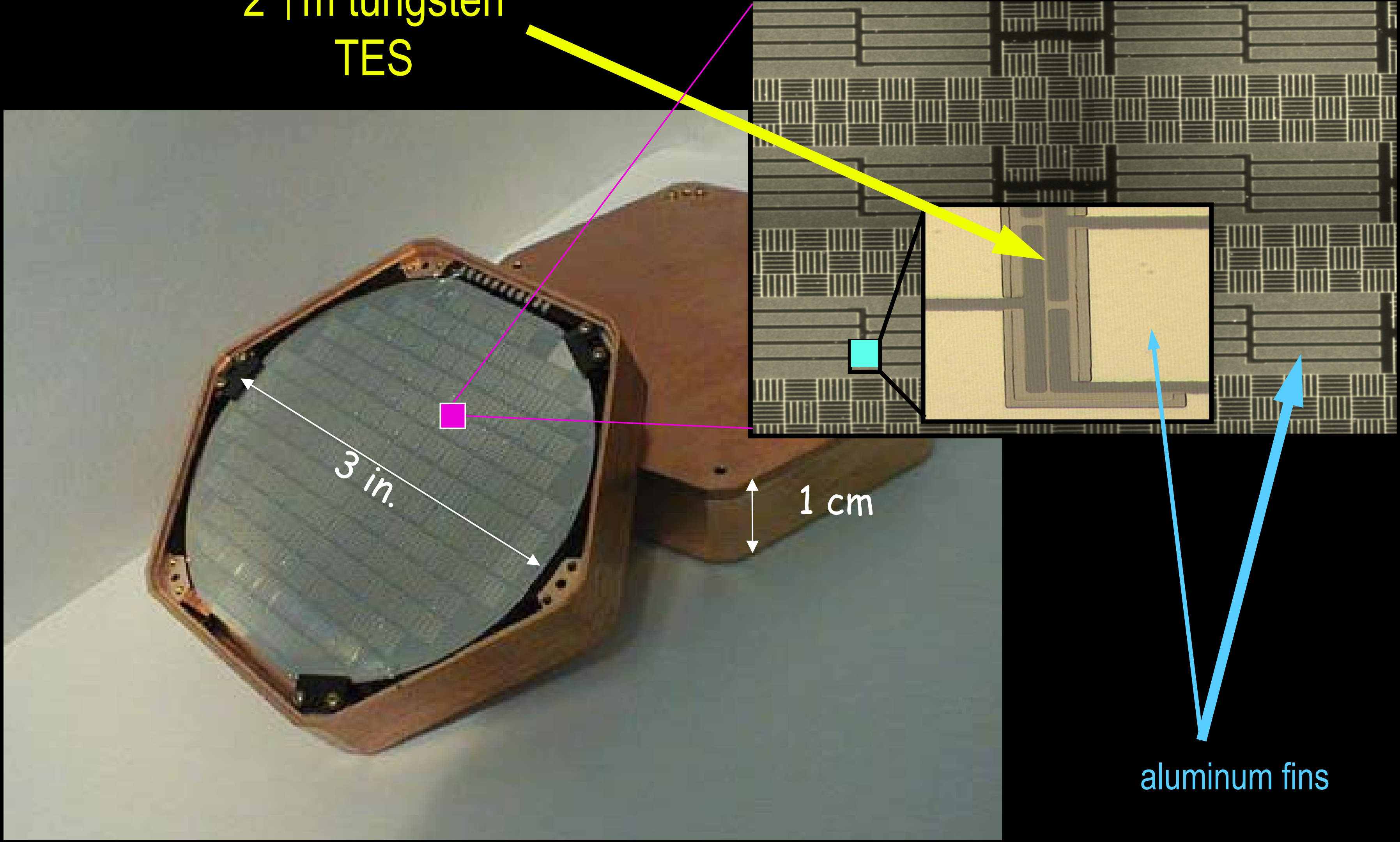
Pulse Shape Observables

- Pulse height, integral, start times and rise times amongst observables
- Ionization readout serves as event start time
- Phonon rise times vary by event position
  - Leading edge timing is ~⌠s
  - Full development involves reflected phonons, q.p. diffusion time and TES thermal time constant
  - equilibrium phonons can’t promote q.p. in Al





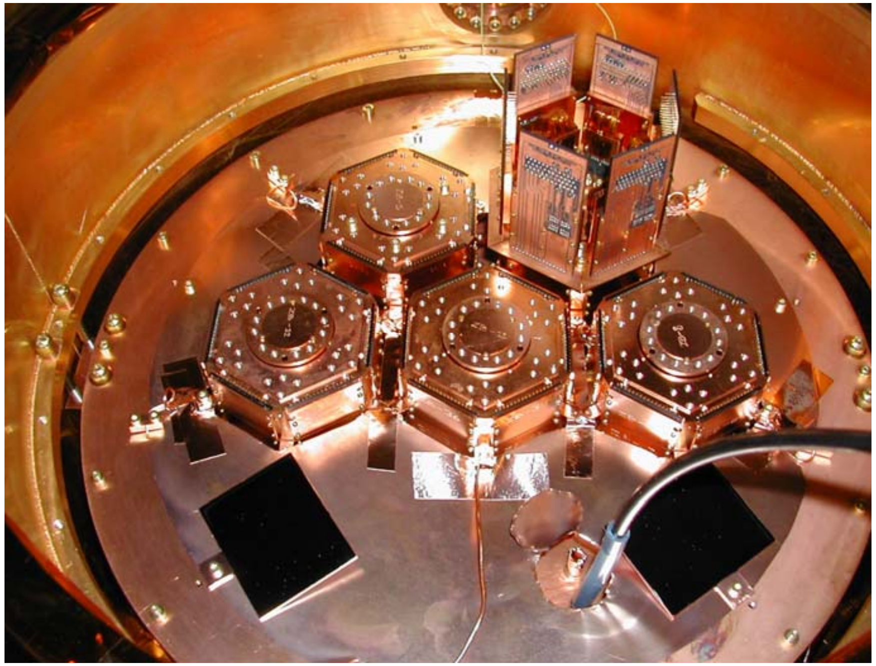
ZIP Glamour Shot

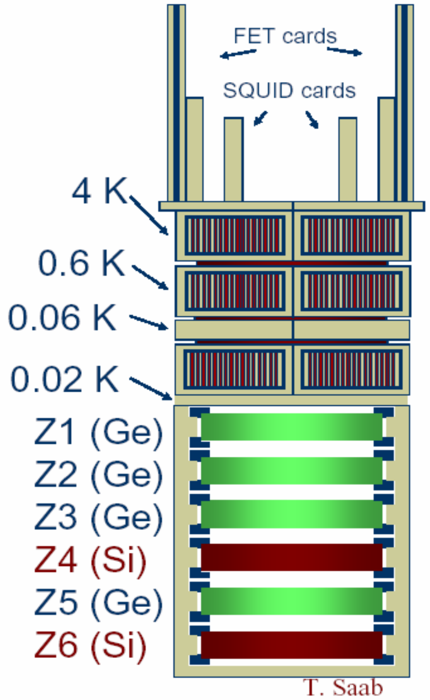


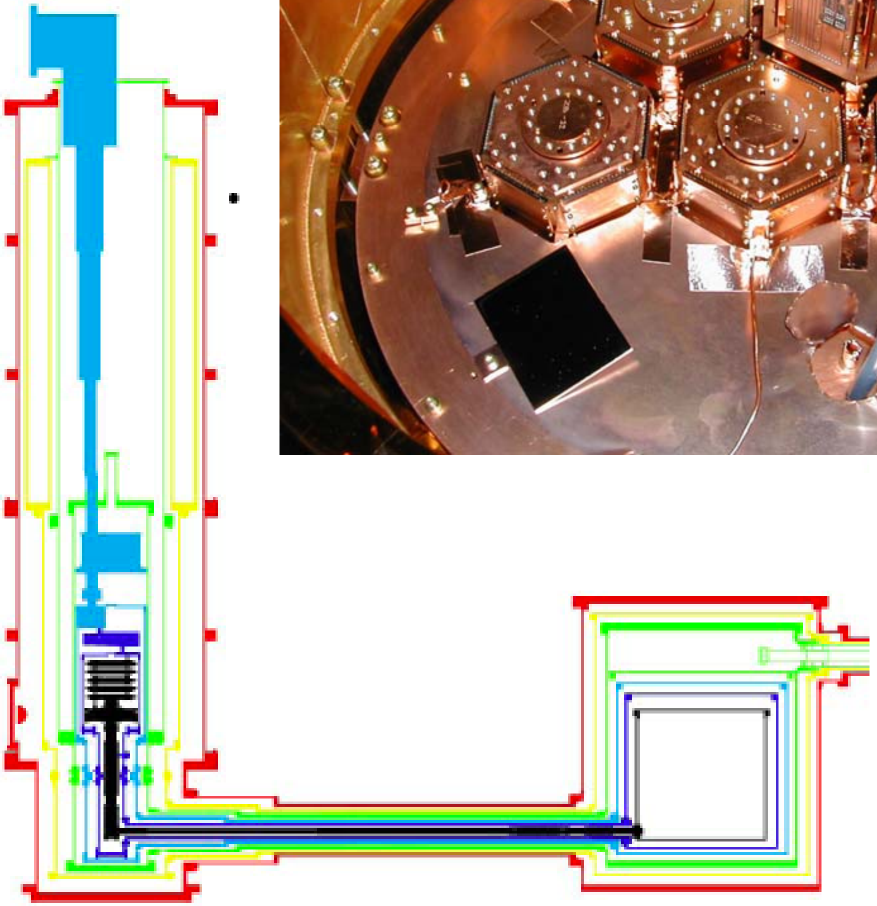
2 ∫m tungsten TES

aluminum fins

CDMS Instrumentation



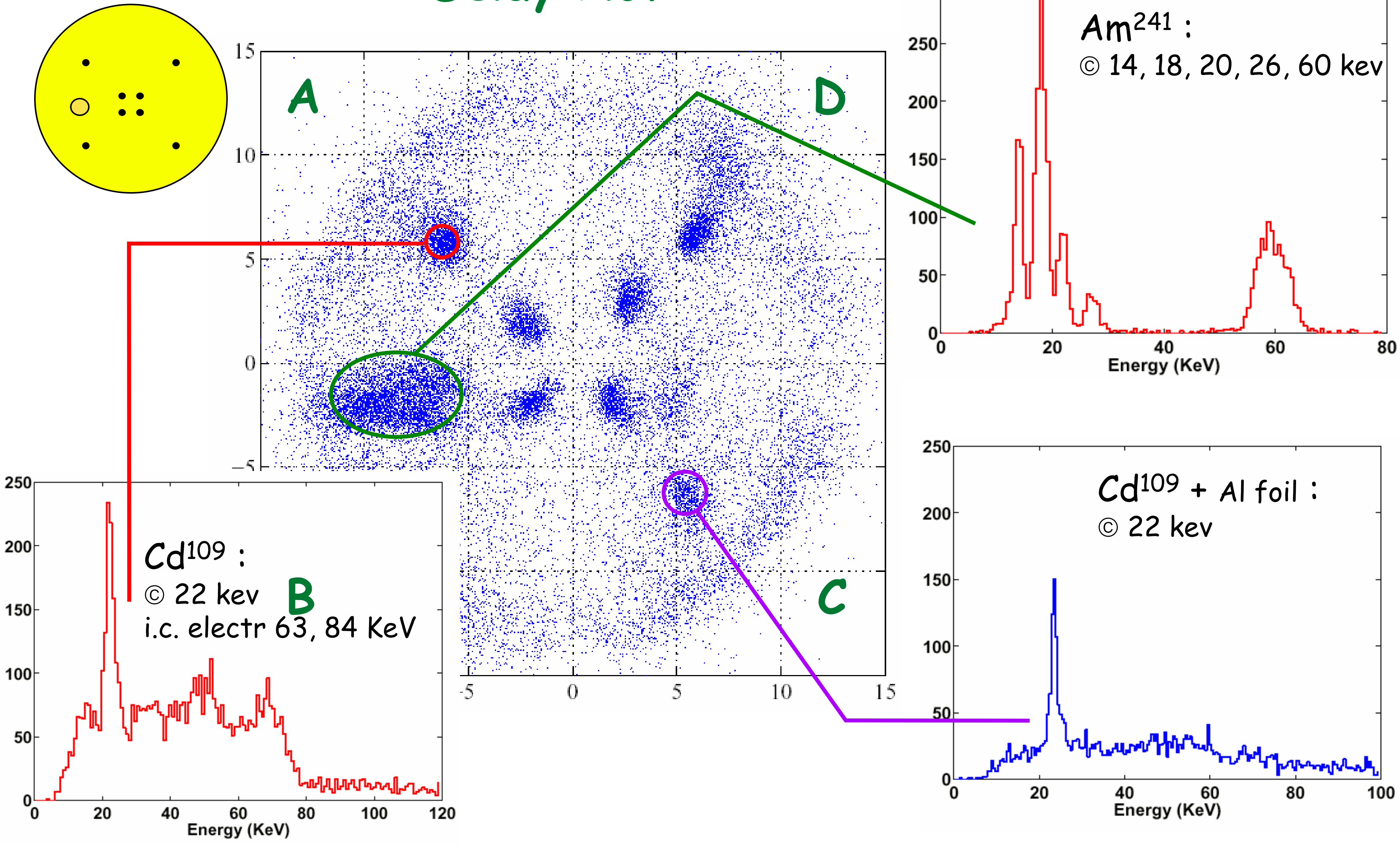




Dilution Fridge: $T_{min} < 10$ mK
Phonons: SQUIDs at 0.6 K
Ionization: FETs at 4K

Position and Energy

Delay Plot



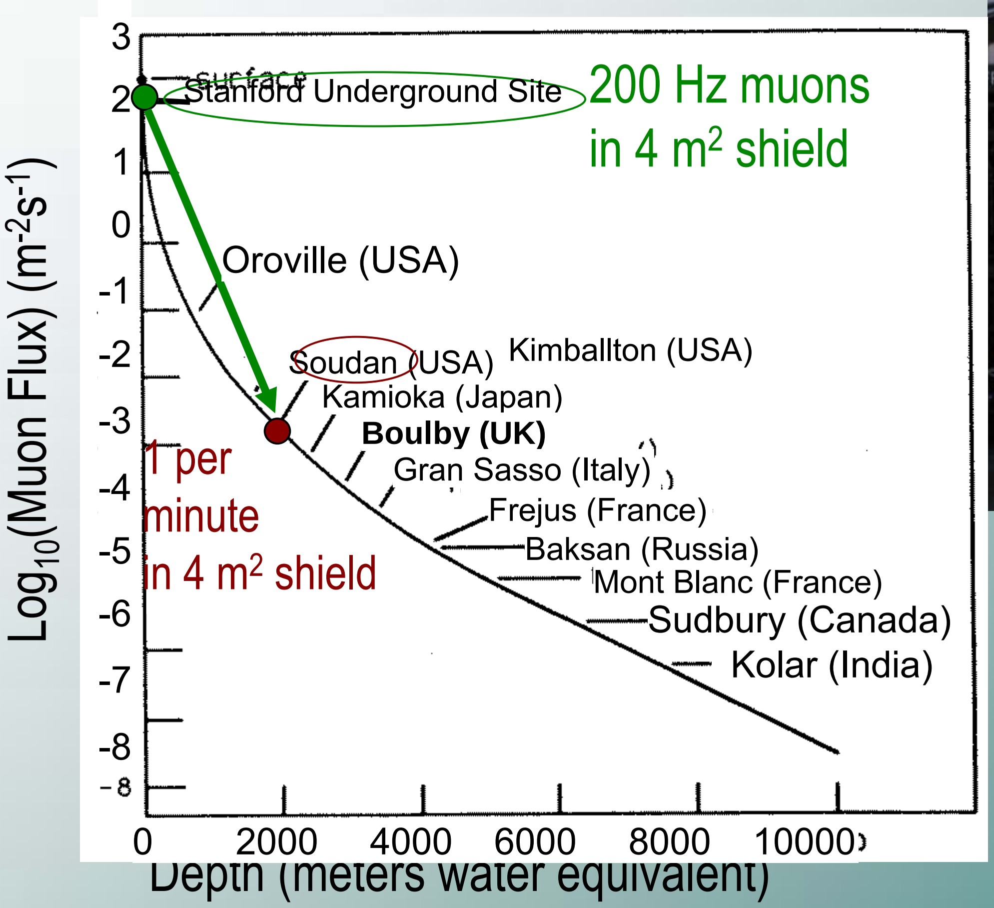
Am^{241} :
© 14, 18, 20, 26, 60 kev

Cd^{109} :
© 22 kev
i.c. electr 63, 84 KeV

Cd^{109} + Al foil :
© 22 kev

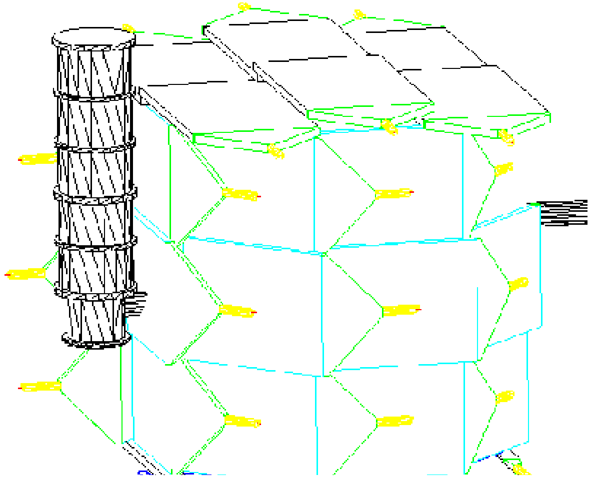
Soudan Underground Laboratory

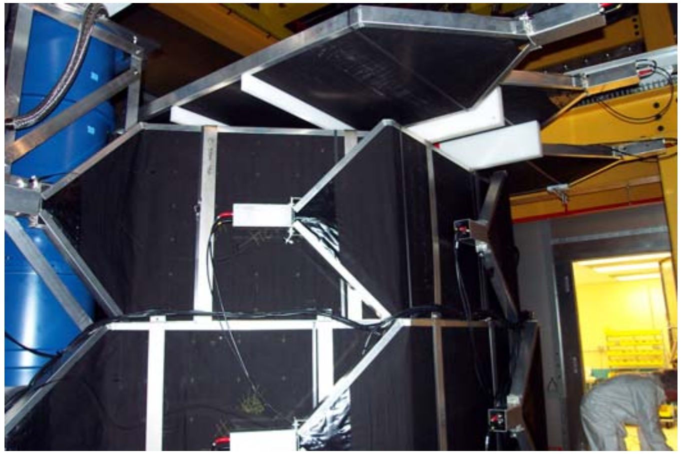
- Background-free experiment maximizes sensitivity =>
  Exposure ~ mass x time

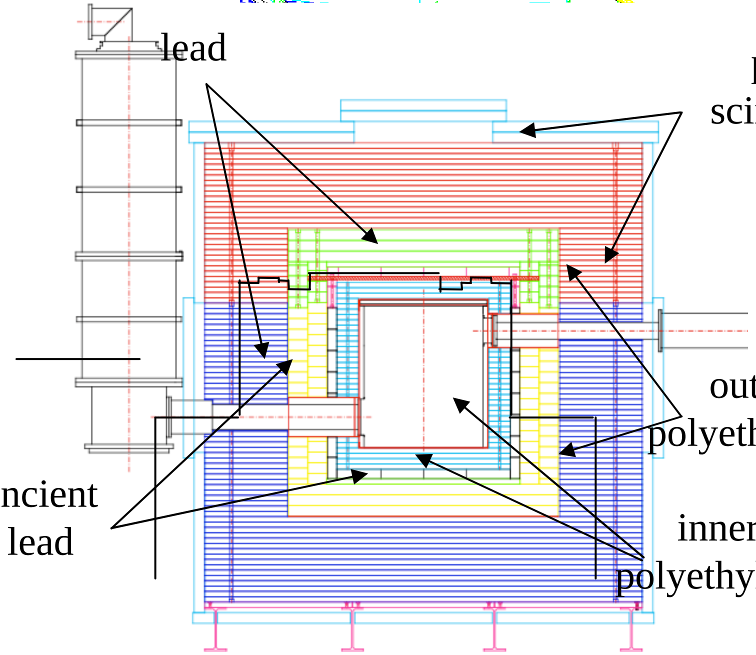

200 Hz muons in 4 m^2 shield

1 per minute in 4 m^2 shield

CDMS-II Soudan facility







lead

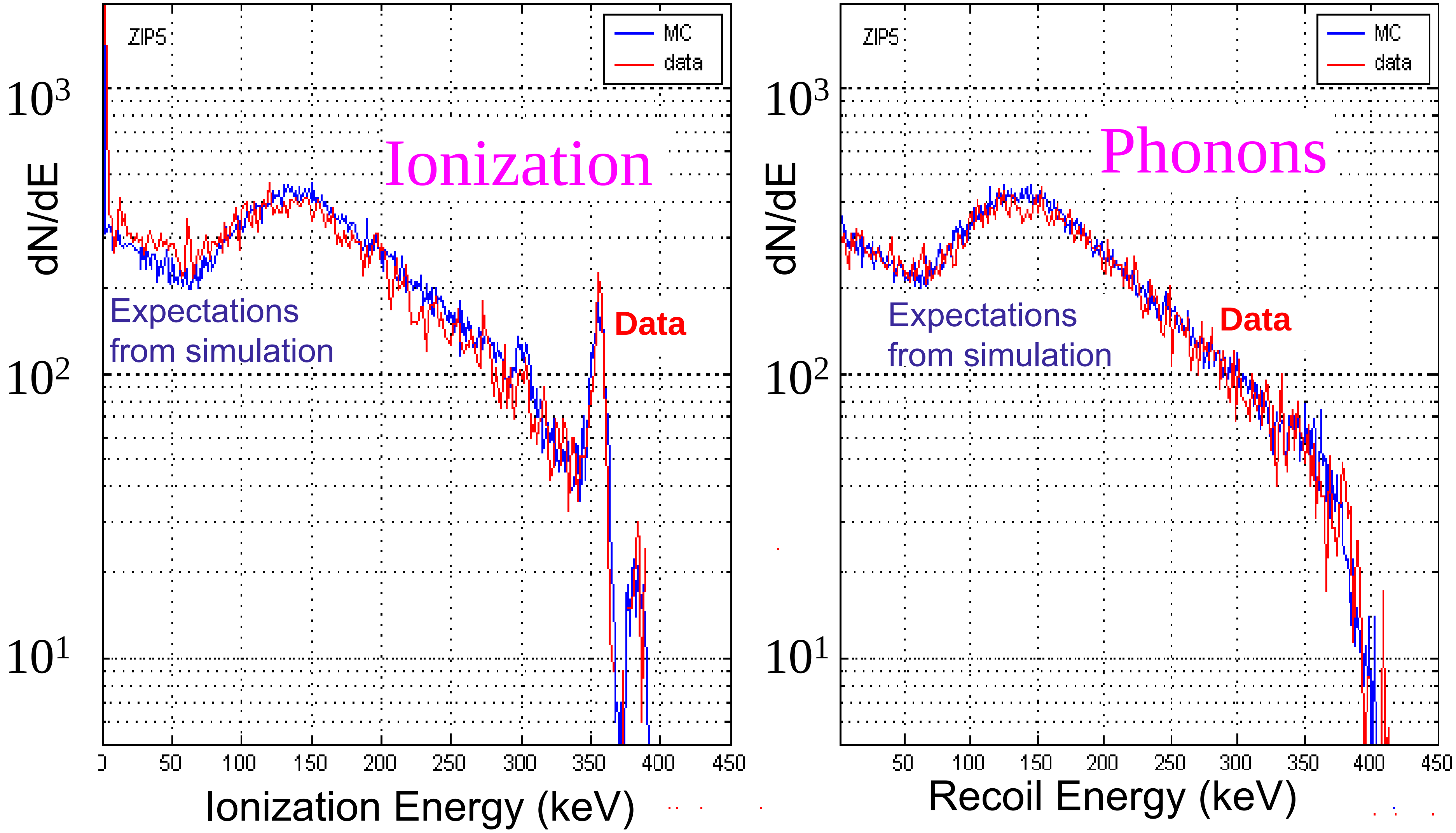
plastic scintillators

outer polyethylene

inner polyethylene

ancient lead

^{133}Ba *In situ* Photon Calibration



Ionization

Expectations from simulation

Data

Phonons

Expectations from simulation

Data

L. Baudis

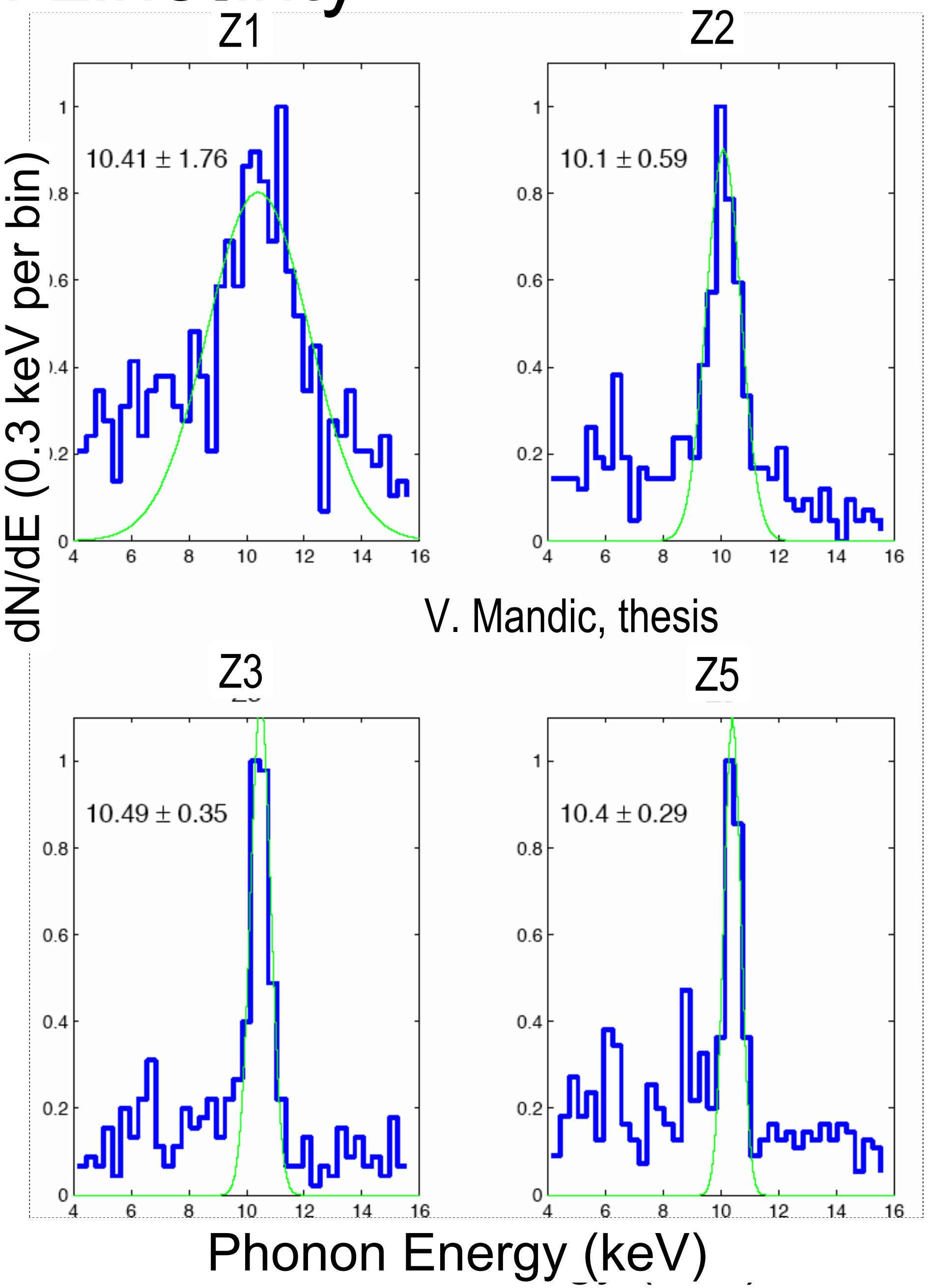
Calibration Linearity

WIMP search data

- Ionization linearity is checked from ^{68}Ga in detectors
  - cosmogenic origin
  - 10.36 keV photon

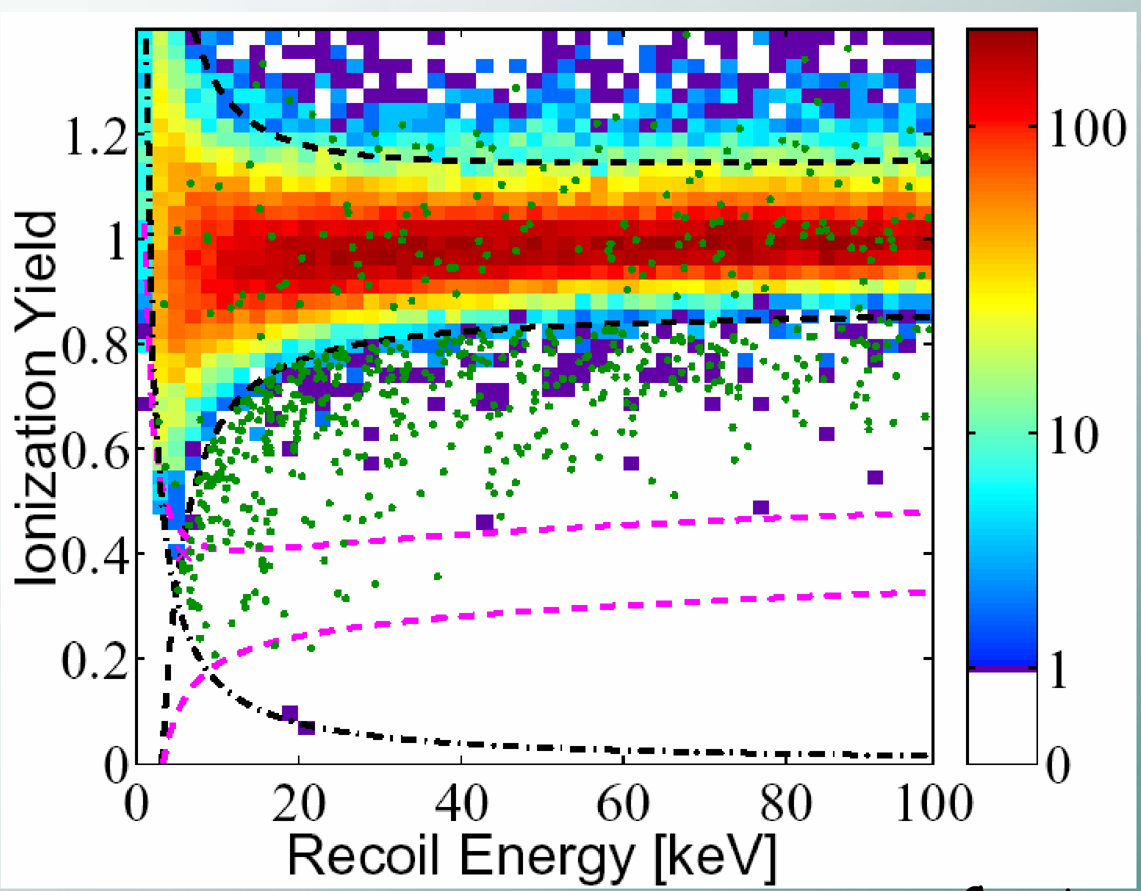
- Peak width is measure on stability as well as resolution

- Resolution ~5% in both Q and P, quite satisfactory for defining NR 10-100 keV acceptance window



V. Mandic, thesis

Surface "Dead Layer"



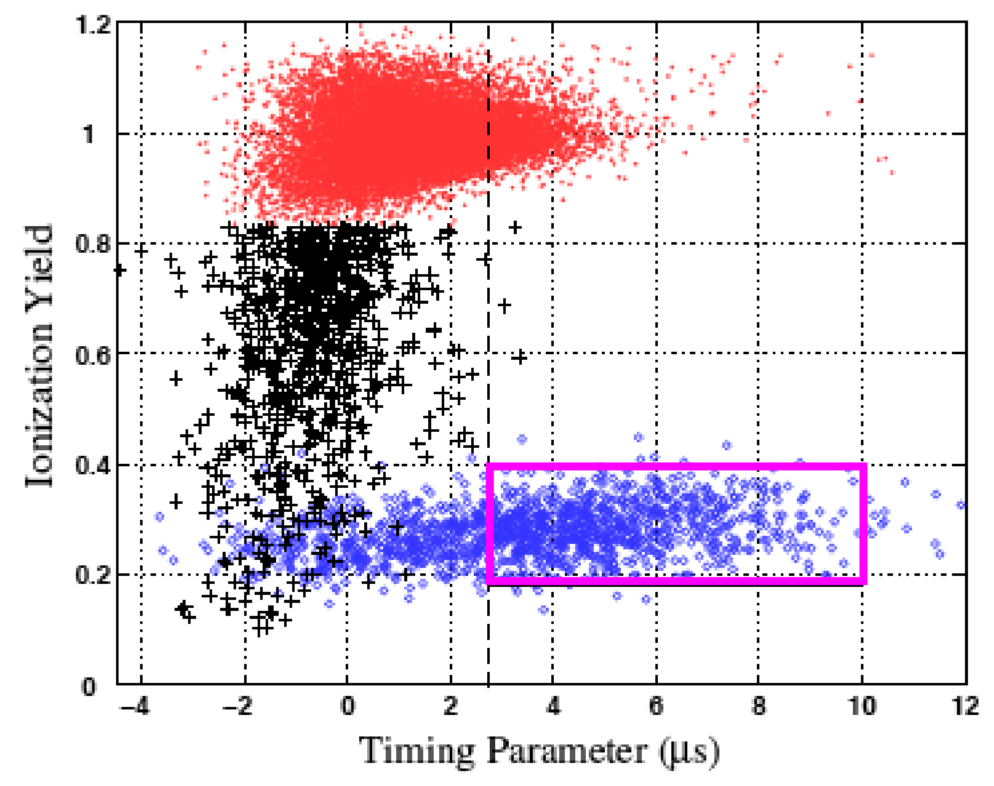
Courtesy R. Schnee

Incomplete collection of charge suppresses ionization, thus also Ionization Yield

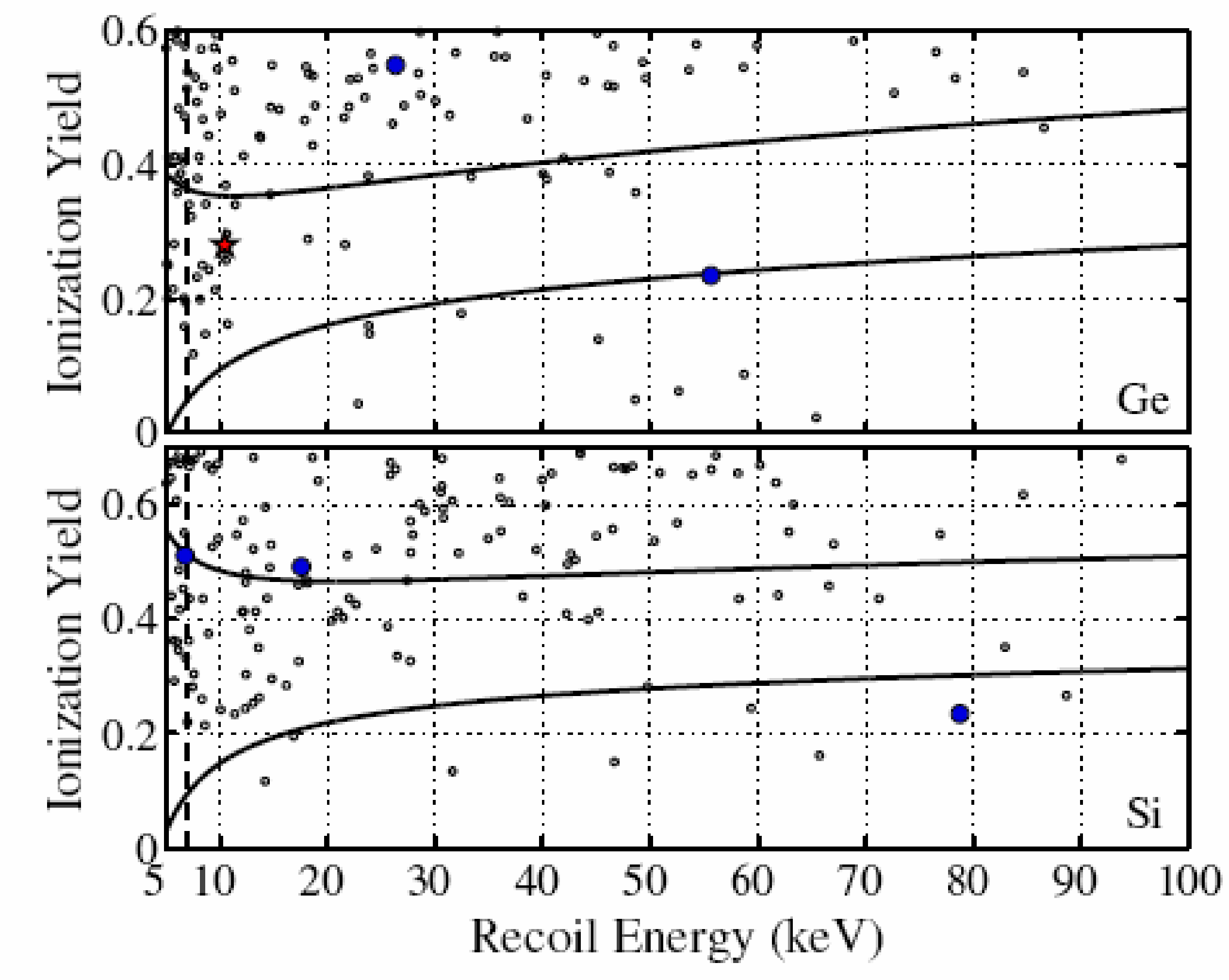
Need to enhance analysis

Understanding Surface Events

- Within ~10 microns of surface, reduced ionization signal
- Fortunately, phonon generation and transport differs as well
- Timing Parameters
  - Ionization-Phonon start time
  - Phonon risetime
- Data from in-situ calibrations
  - Red & Black: ^{133}Ba gammas
  - Blue: ^{252}Cf neutrons
  - Excellent rejection
  - Modest efficiency reduction



WIMP search data (2004)

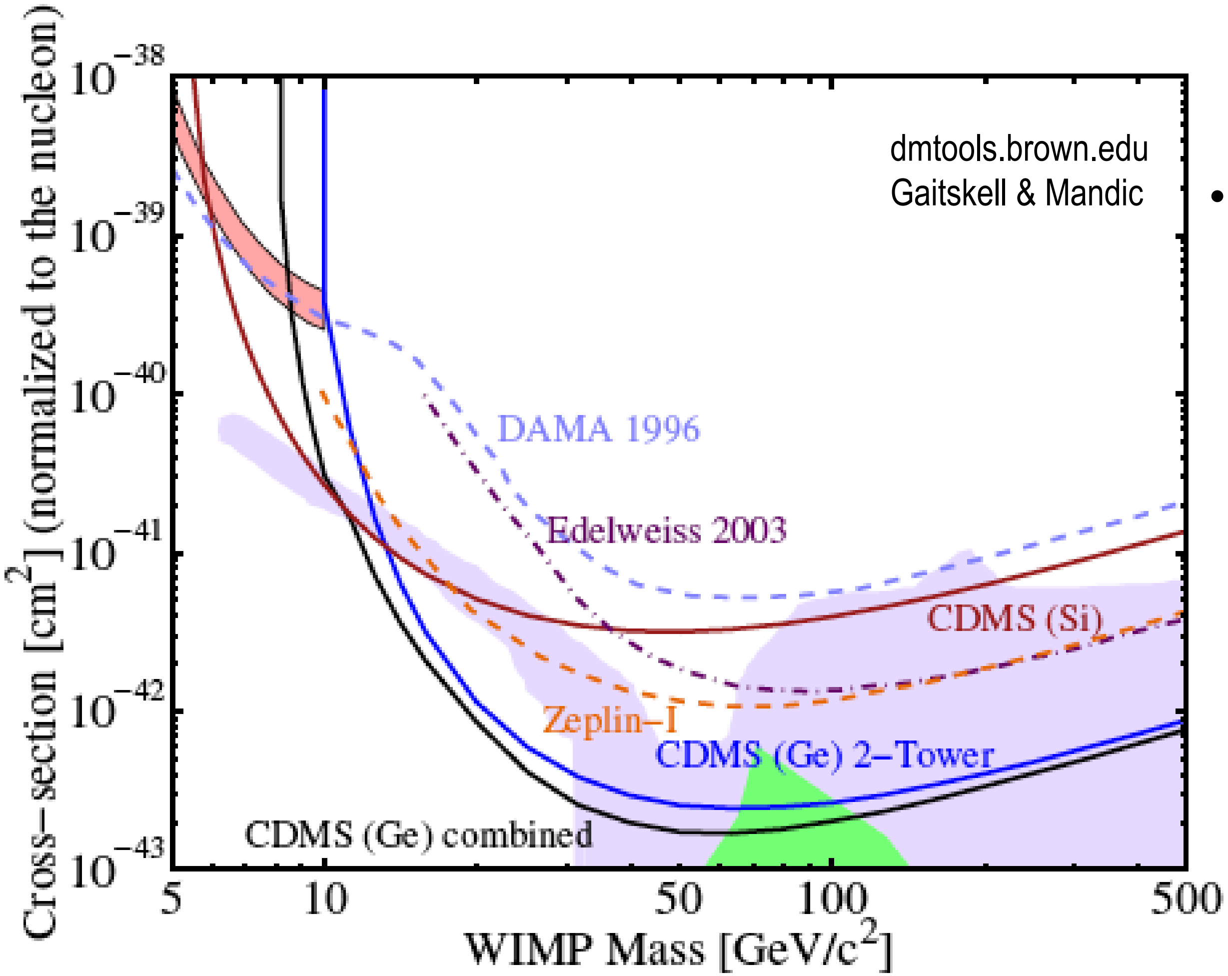


- ○ Events passing all data selection, except timing
- ☆ Event passes timing inside signal region
- ● Event passes timing, but outside signal region

Experimental Upper Limits

Scalar interactions 90% CL upper limits assuming standard halo, A^2 scaling

PRL **96** 011302 (2006), astro-ph/0509259



- Live Time Period:
  25 Mar - 8 Aug 2004
- Exposure after cuts
  - 34-kg/d Ge
  - 14-kg/d Si
- Excludes significant regions of SUSY parameter space under some frameworks, e.g.
  some models with nonuniversal Higgs, squark, and slepton masses and neutralino masses <~700 GeV
  Ellis et al PRD 71/095007

Spin-dependent analysis:
PRD **73**, 011102 (2006)
astro-ph/0509269

Final CDMS-II Run Configuration

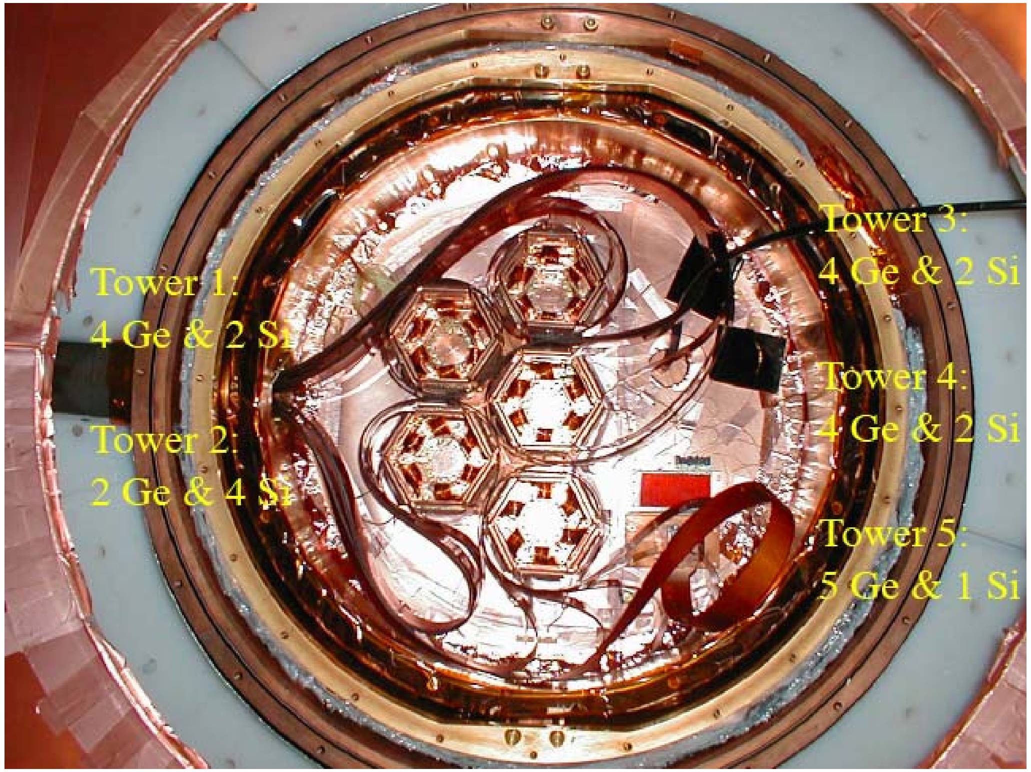
Running CY 2006-7

~1 kg Si

~4.5 kg Ge

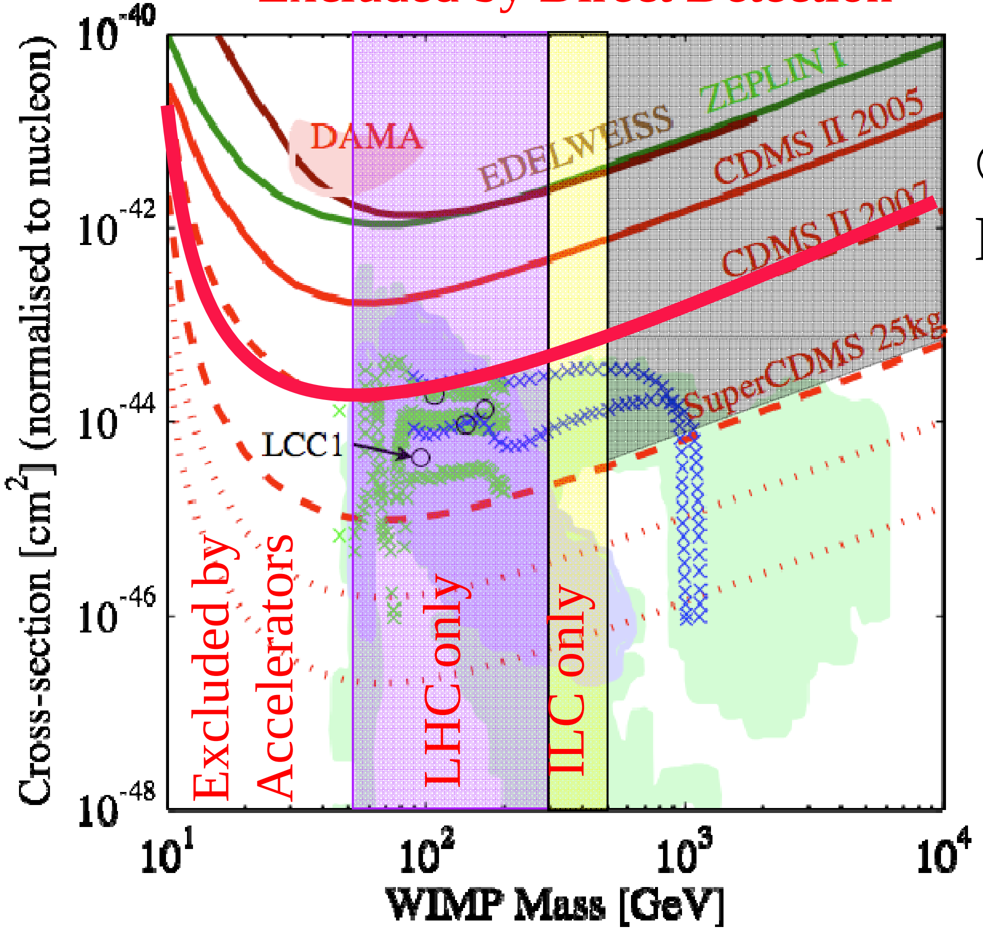
TOWER 1	TOWER 2	TOWER 3	TOWER 4	TOWER 5
G 06	S 14	S 17	S 12	G 07
G 11	S 28	G 25	G 37	G 36
G 08	G 13	S 30	S 10	S 29
S 03	S 25	G 33	G 35	G 26
G 09	G 31	G 32	G 34	G 39
S 01	S 26	G 29	G 38	G 24

OPERATED IN SOUDAN



Cooldown to begin
mid-June 2006

Accelerator/Nonaccelerator Complementarity



Excluded by Direct Detection

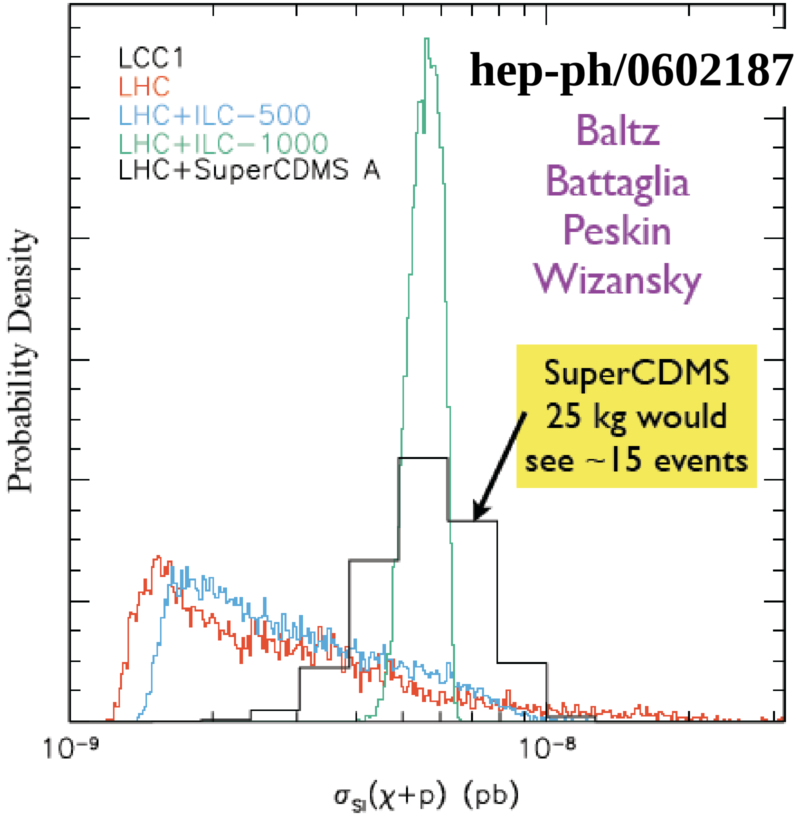
Excluded by Accelerators

LHC only

ILC only

Accelerators are *mass-limited*

® spectral info, but often can’t see LSP or deduce its relic density



hep-ph/0602187

Baltz
Battaglia
Peskin
Wizansky

SuperCDMS 25 kg would see ~15 events

CDMS is *cross section-limited*

® TeV WIMPs detectable, direct connection to cosmology

LHC data taking in ~1 year

Preferred Collisions

- Detection of dark matter via collisions with nuclei
  - most extensive discovery potential to high mass
  - observe the signal in multiple materials to study
  - providing annual modulations
- Indirect detection to map the galactic DM distribution
- DM at colliders
  - measure detailed properties
  - determine relic abundance

In Closing…

…Dark matter direct detection relies on distinguishing low-energy nuclear- and electron-recoil events

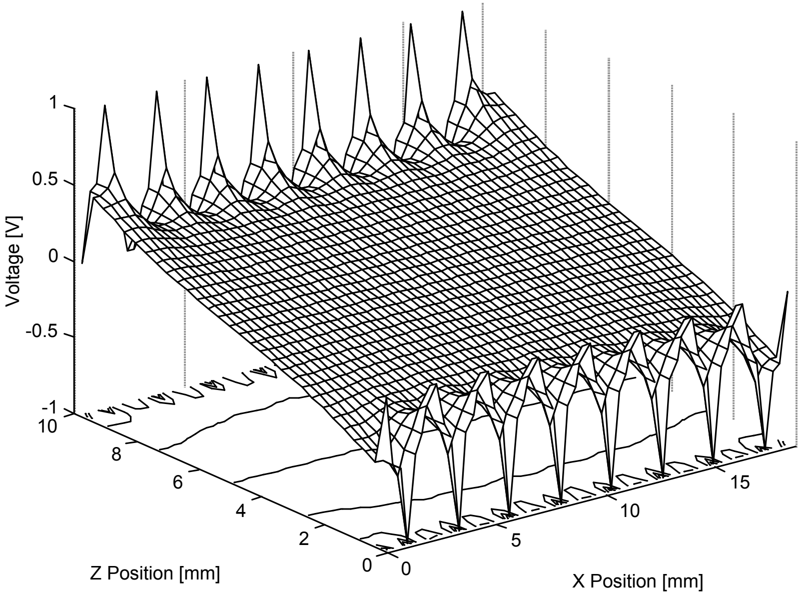
…Cryogenic nonequilibrium phonon sensors have demonstrated high sensitivity rejection of electron-recoil with high efficiency to detect nuclear-recoils

…Understanding the nature of dark matter requires direct detection and accelerators

…CDMS detectors are coming online for a ~5 kg-y exposure; SuperCDMS is ready to build new 25 kg; We welcome new collaborators!

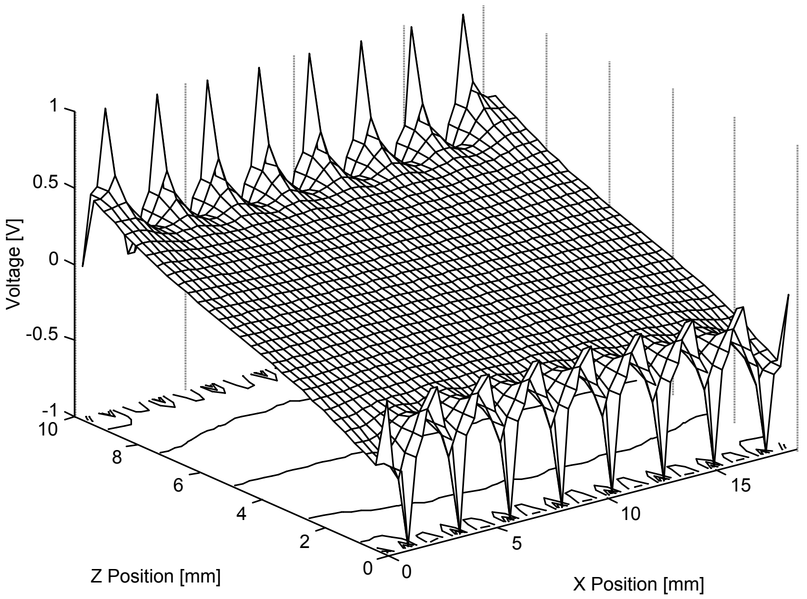
Enhancing Background Rejection

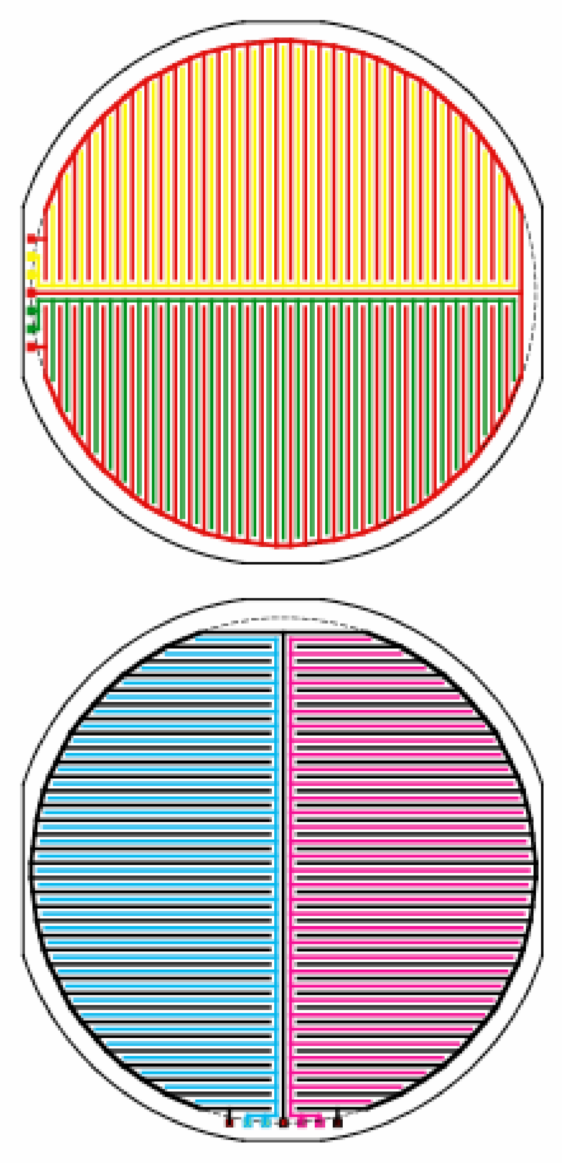
- Baseline (25-kg)
  - Increase detector thickness
  - Hydrogenate the a-Si blocking layer
  - Full-wafer mask
- Next-generation Scaling
  - New electrode/sensor arrangements
    - Interdigitate ionization and phonons
    - Increase quasi-particle trapping efficiency



Interdigitated Ionization electrodes

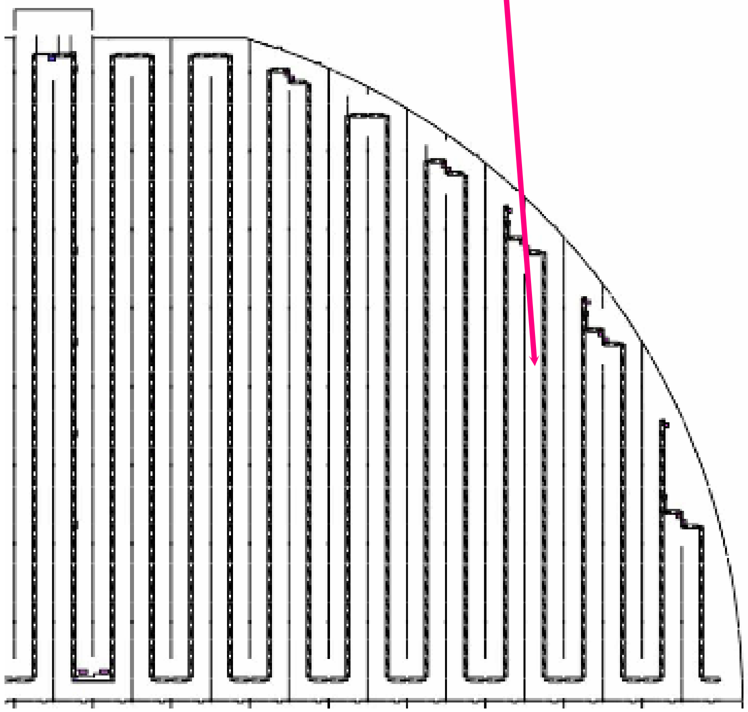
- Alternative method to identify near-surface events
  - Ionization electrodes on opposing surfaces
  - Bias rails on bottom surface connected to other Qamp
  - Phonon sensors on both sides are virtual ground reference.

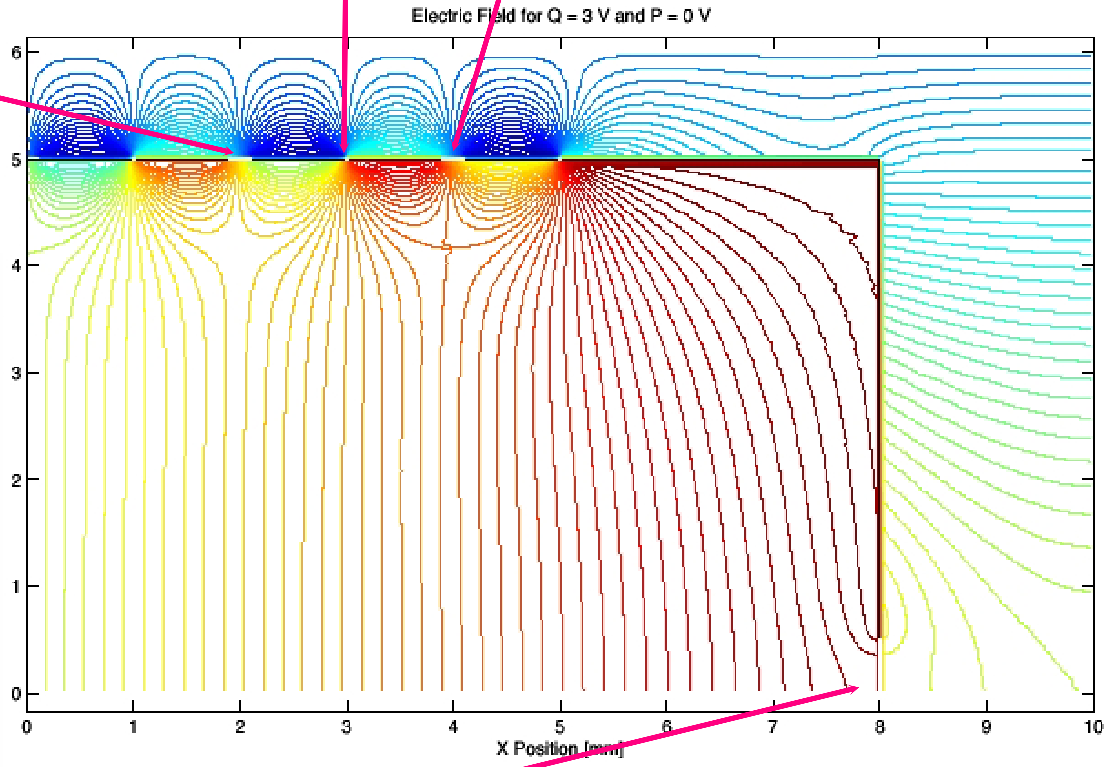




Electric field configuration

- Design details
  - To maintain ~60 pF of capacitance requires keeping bias and ground rails ~ 1 mm apart.
  - Phonon sensors ‘contained’
  - within the (200 μm wide)
  - ground rails.

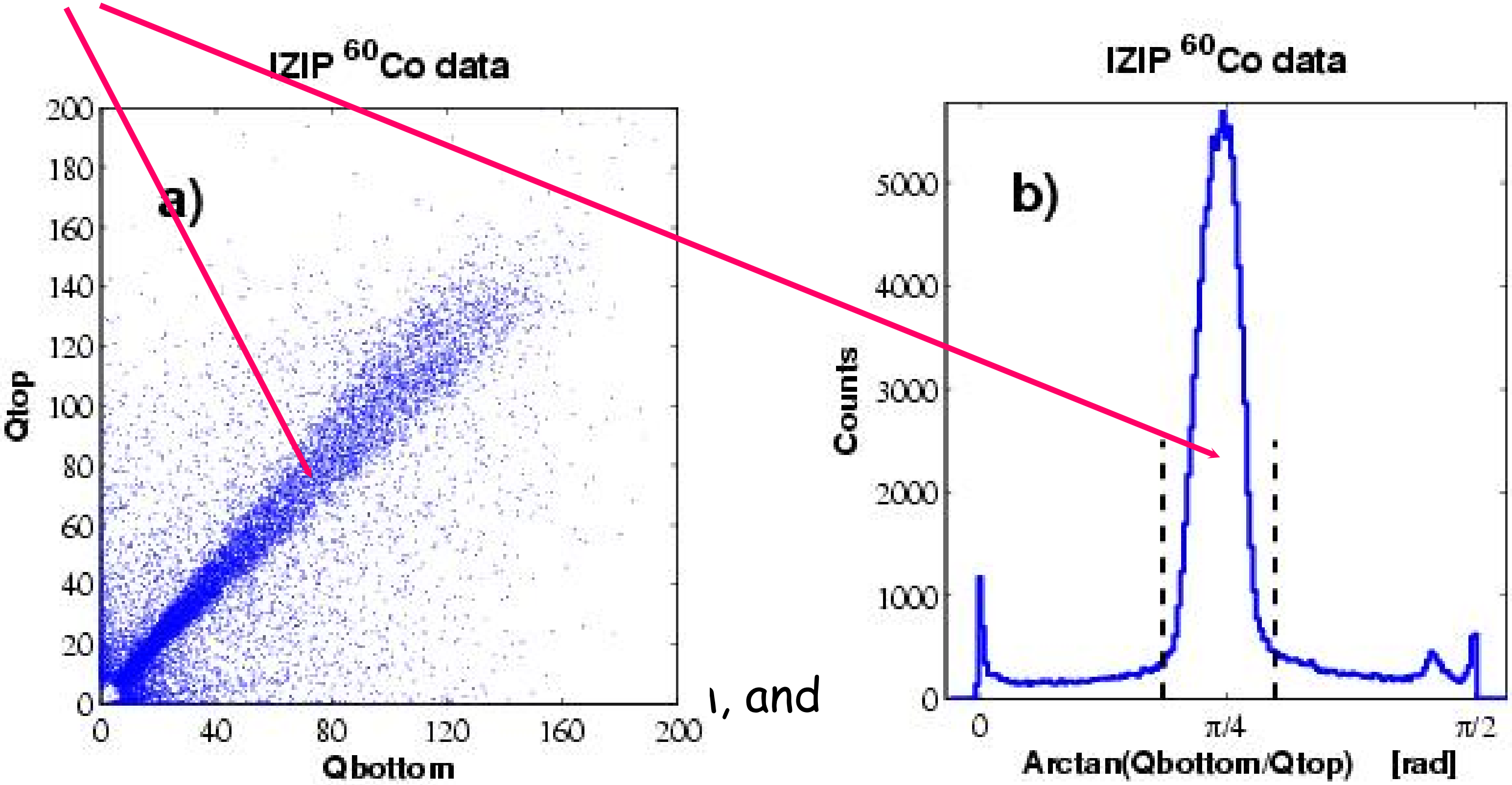




Equatorial ring around perimeter of crystal keeps electric field distribution well defined - a Q ‘outer’ volume exists, as well as the top and bottom volumes.

Surface event identification

- Bulk events are coincident, equal in magnitude in the charge channels.

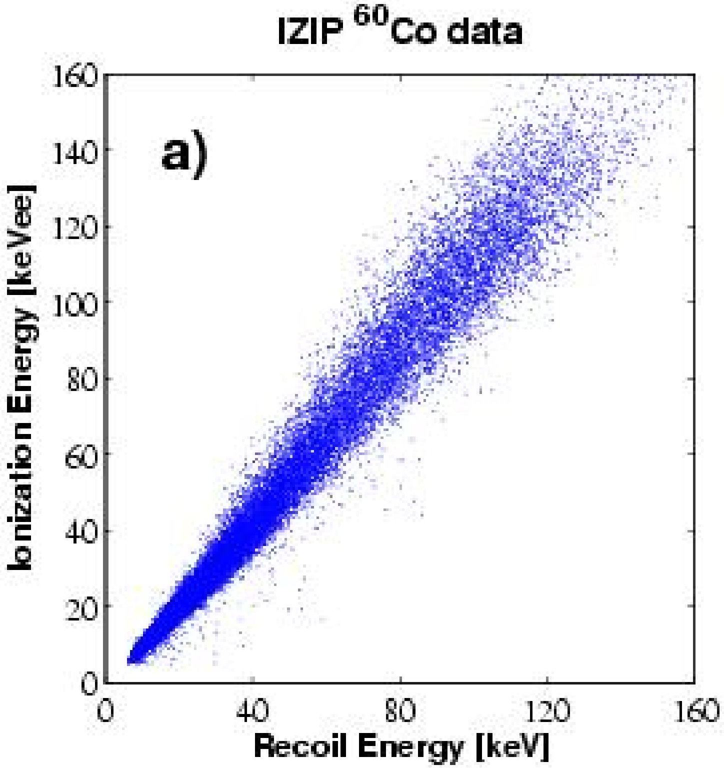


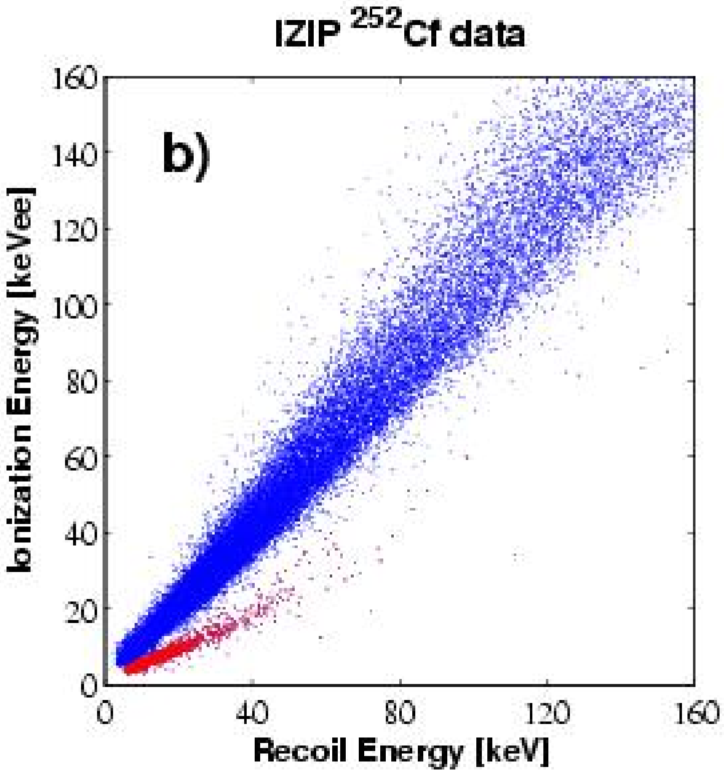
ı, and for

  - The charge pulse shapes for surface events are also slightly different from bulk events, so a Chi2 cut identifies surface events.
- Si 1cm substrate, -2 V bias bottom electrode, +2 V top electode.

Electron vs nuclear recoil discrimination

- Pre-ion-implanted Si detector, one phonon channel not working, but …
- Went ahead and performed Co-60 and Cf-252 external source calibrations.

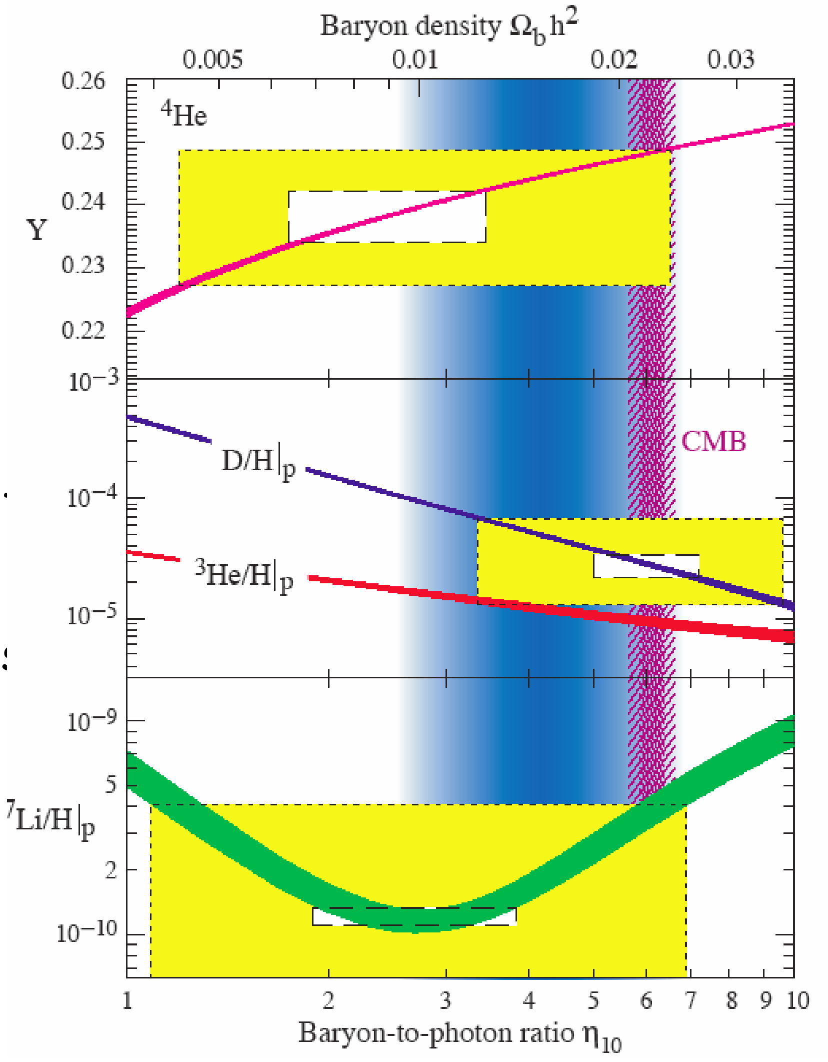




  - Expected nuclear recoil band events (red) clearly visible.
  - Calibrations shown are only approximate.

Big Bang Nucleosynthesis

- Abundances calculable from b/γ
- Observational Findings
  - Unprocessed d, ^{4}He and ^{7}Li
  - Primordial d:
    - from high-z hydrogen clouds backli
      by Quasars
    - Lyman-α absorption line freq differ
      for d and h
  - $\wedge_b h^2 = 0.018 \pm .006$

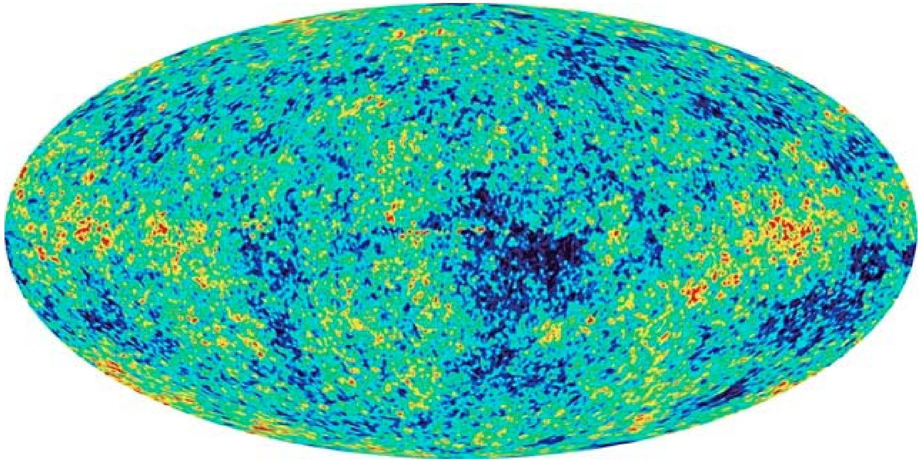


Fields and Sarkar
"in The Review of Particle Properties" 2004
astro-ph/0406663

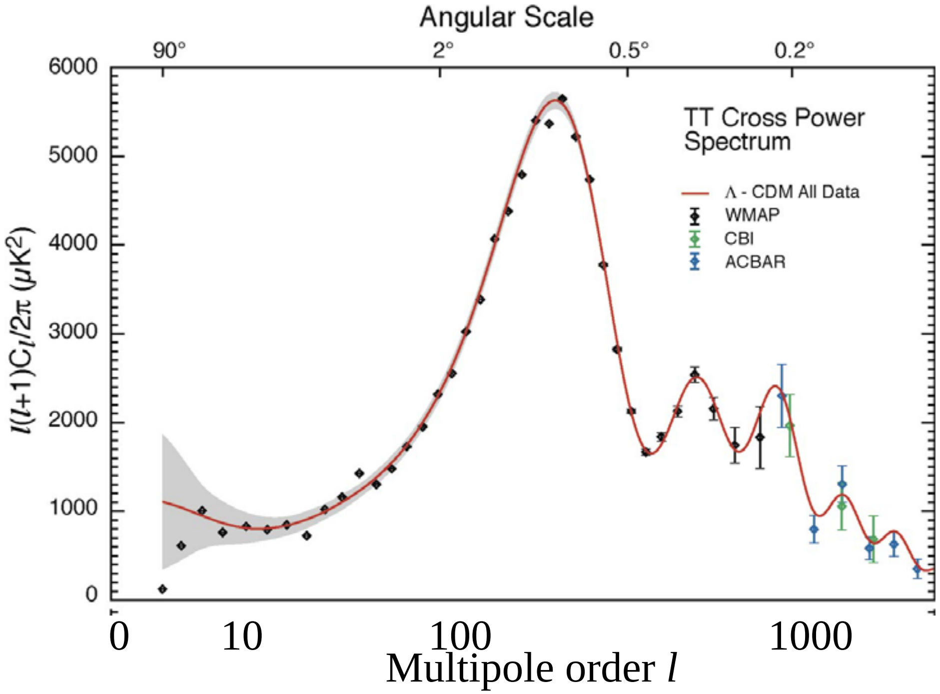
Cosmic Microwave Background

http://lambda.gsfc.nasa.gov

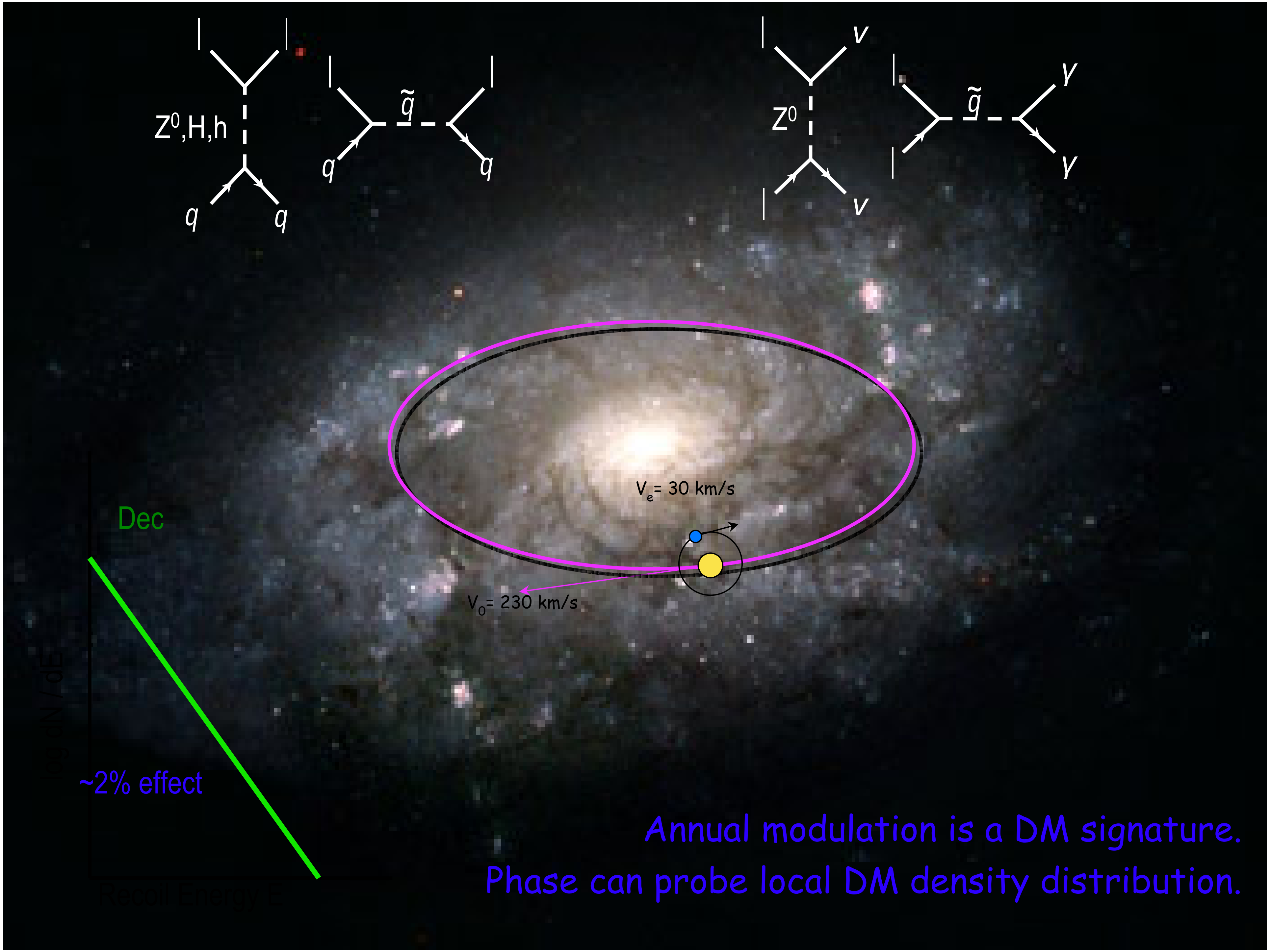
- Observational foundation of the Big Bang: Relic photons from neutral atom formation ("radiation decoupling epoch")



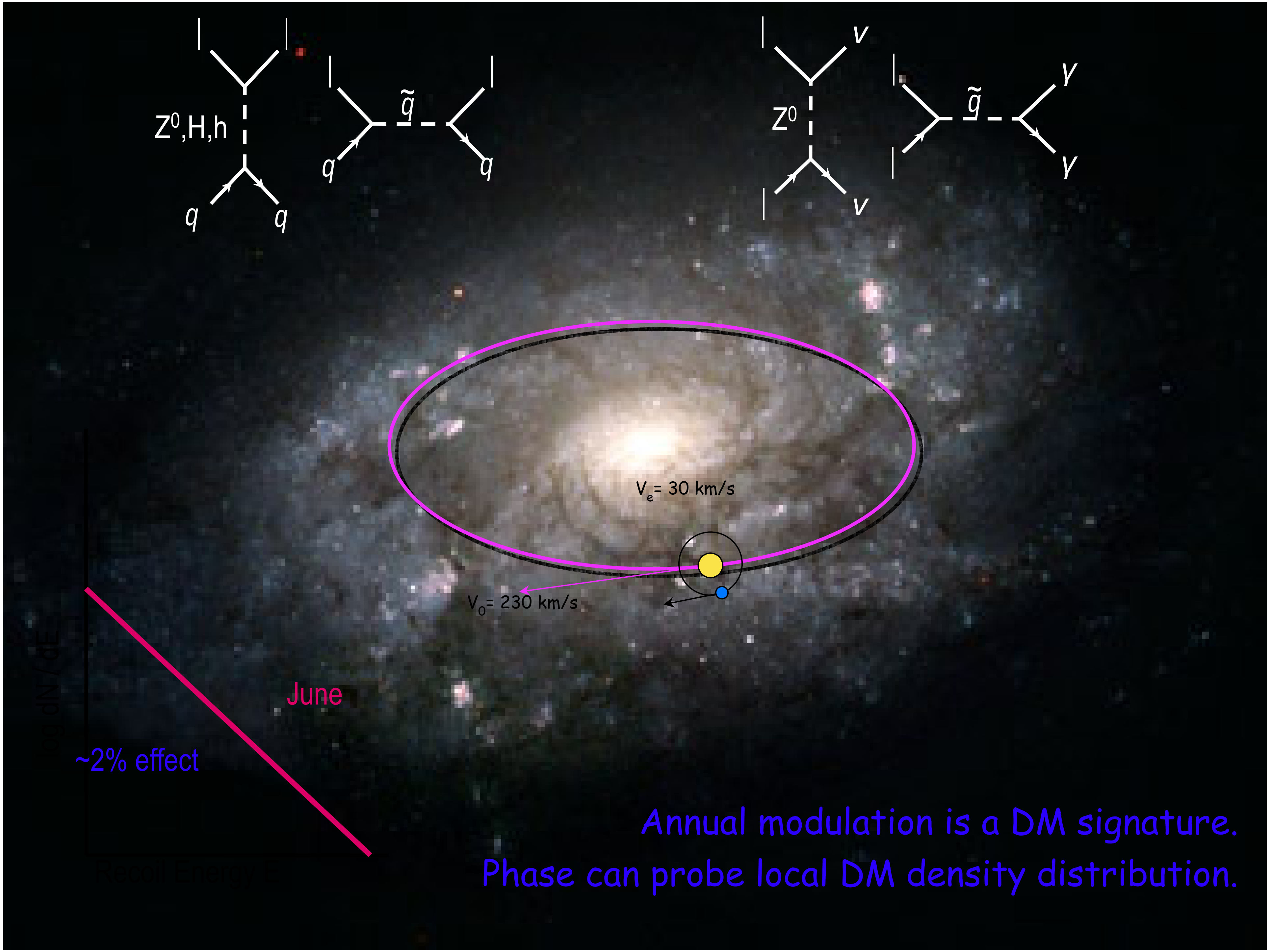
- WMAP temp. anisotropy map
  - Interpret power spectrum data by fit to cosmology parameters
  - accoustic peaks 1 & 2 inform:
    - $\wedge_m h^2 = 0.135$ (30%)
    - $\wedge_b h^2 = 0.0224$ (5%)



Spergel et. al..
ApJS, **148**, 175 (2003)



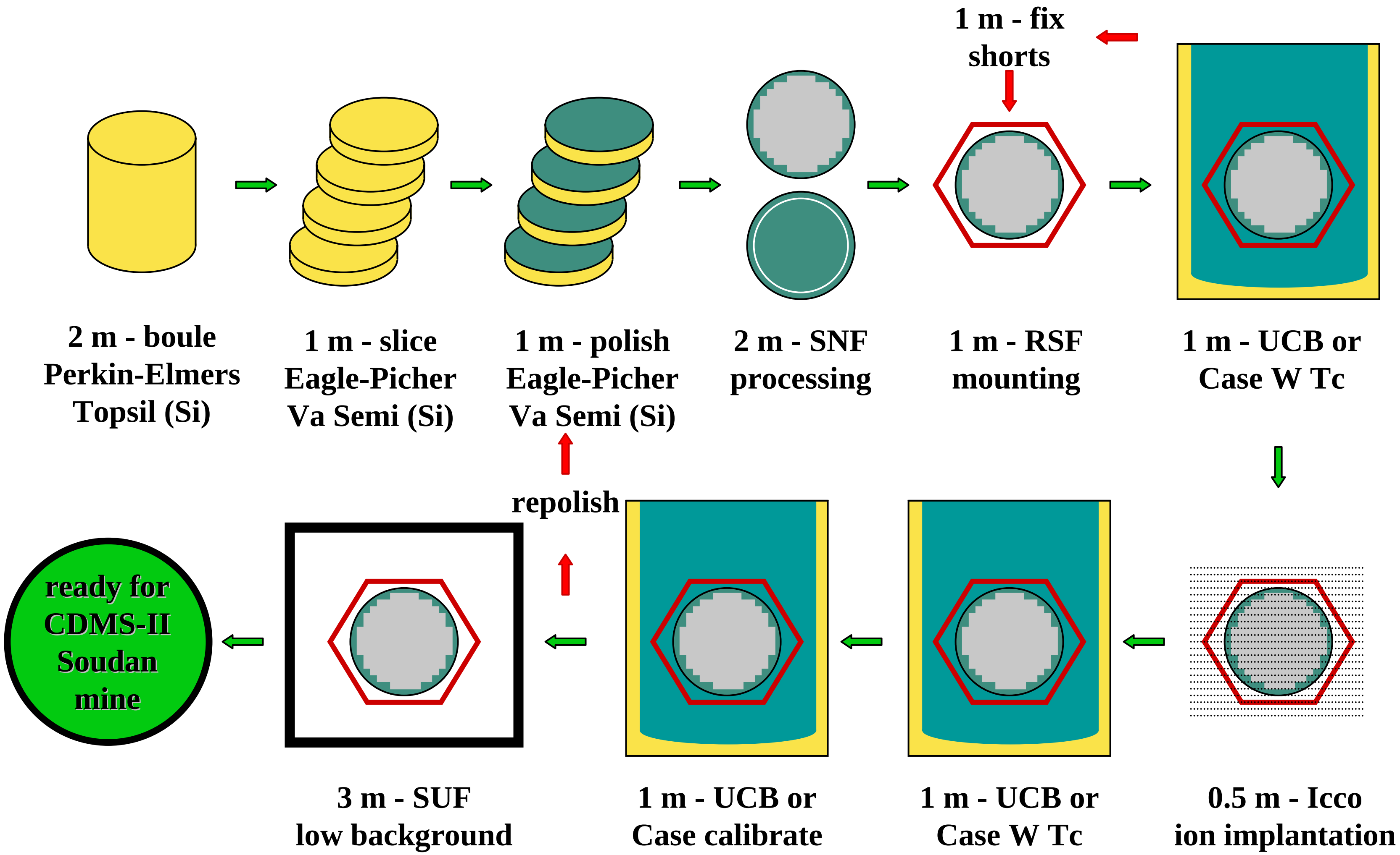
Annual modulation is a DM signature.
Phase can probe local DM density distribution.



Annual modulation is a DM signature.

Phase can probe local DM density distribution.

ZIP Detector Lifecycle



2 m - boule
Perkin-Elmers
Topsil (Si)

1 m - slice
Eagle-Picher
Va Semi (Si)

1 m - polish
Eagle-Picher
Va Semi (Si)

2 m - SNF
processing

1 m - fix
shorts

1 m - RSF
mounting

1 m - UCB or
Case W Tc

0.5 m - Icco
ion implantation

1 m - UCB or
Case W Tc

1 m - UCB or
Case calibrate

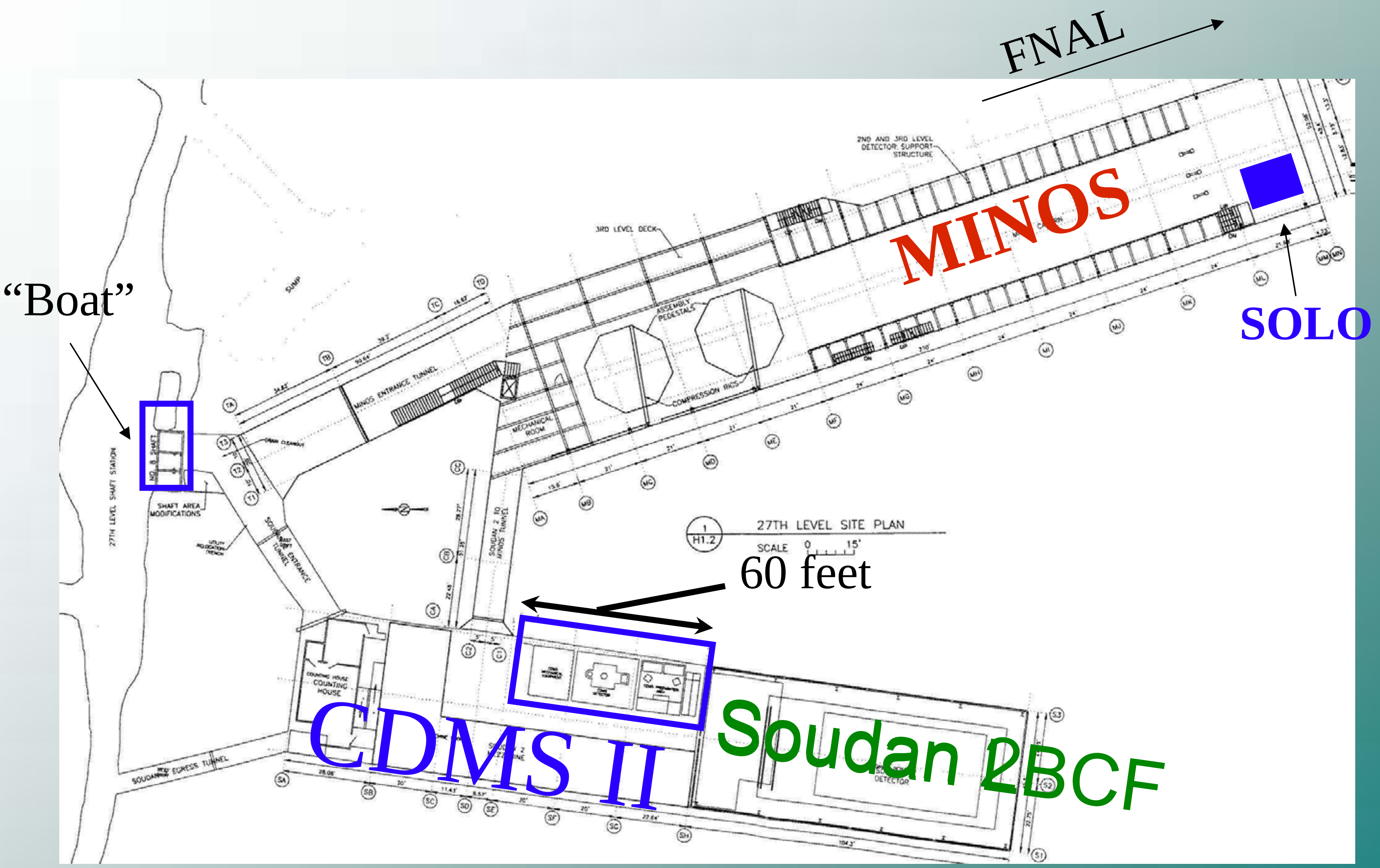
repolish

3 m - SUF
low background

ready for
CDMS-II
Soudan
mine

From Paul Brink

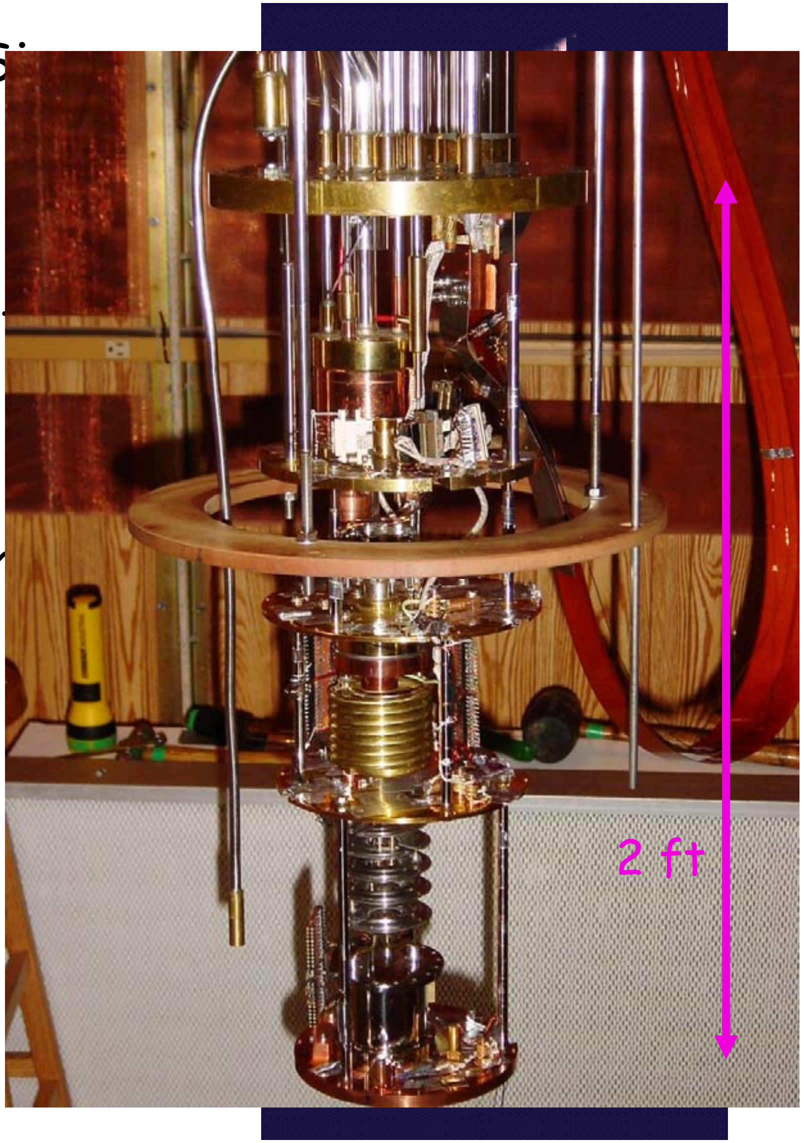
Soudan Particle Physics Facilities



^{3}He/^{4}He Dilution Refrigerator

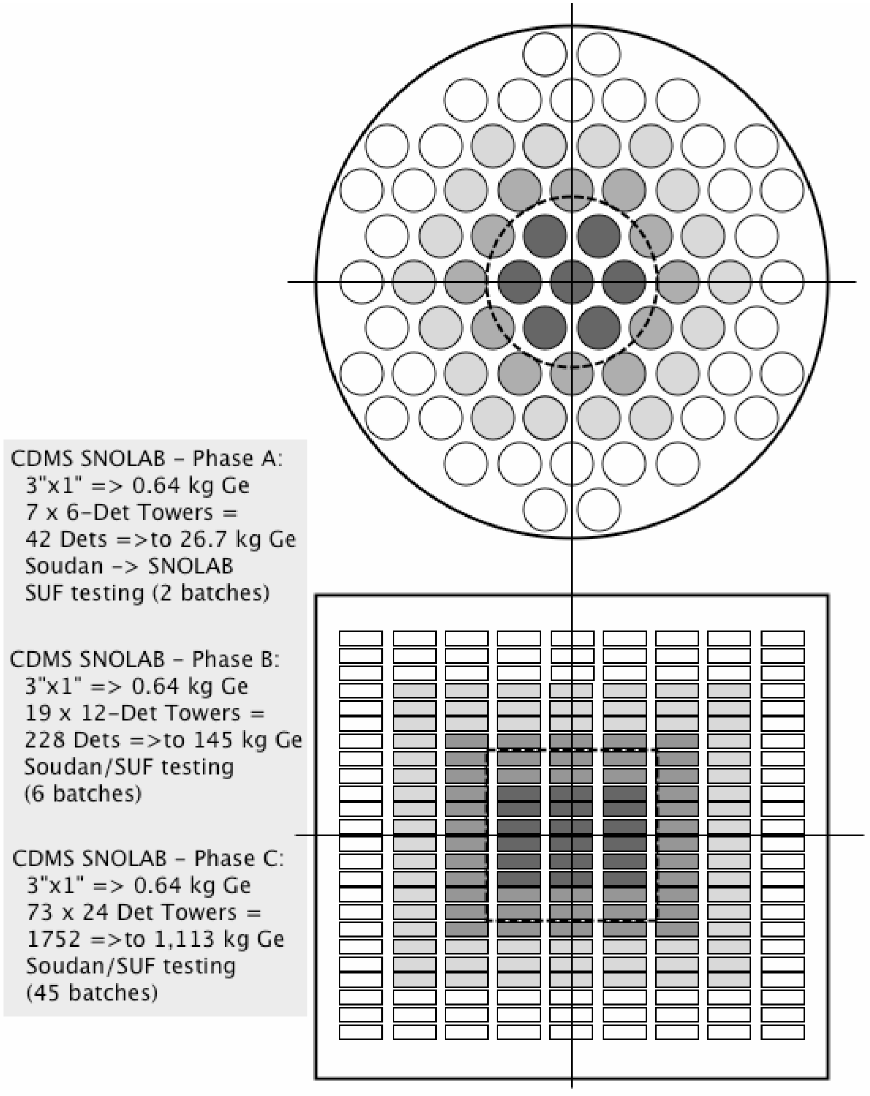
5 mK by Perspiration

- CDMS TES tuned to 80 mK, Ge/S absorber colder (50 mK)
- Evaporative Cooling
  - ^{3}He/^{4}He mixture separates into concentrated and dilute phases tha stratify below 1K.
  - Cooling by ^{3}He evaporation from concentrated to dilute phase
  - Continuous cooling below 10 mK fro ^{3}He circulated through superfluid ^{4}He
- A little help required
  - Radiation shields externally cooled
  - Vacuum to prevent convection
  - Very efficient heat exchangers to recondense the ^{3}He.



The CDMS Challenge of Scaling Up

- Enhanced background reduction
  - "Clean" handling
  - Enhanced analysis
- Production
  - TES thin-film non-uniformity
  - Photolithography by stitches
- Heat Load
  - Replace the FETs
  - Improve cryogenic operations
- Readout Instrumentation
  - Multiplexing
  - Reduce noise
- Mundane Logistics
  - Packaging
  - Calibration with external sources



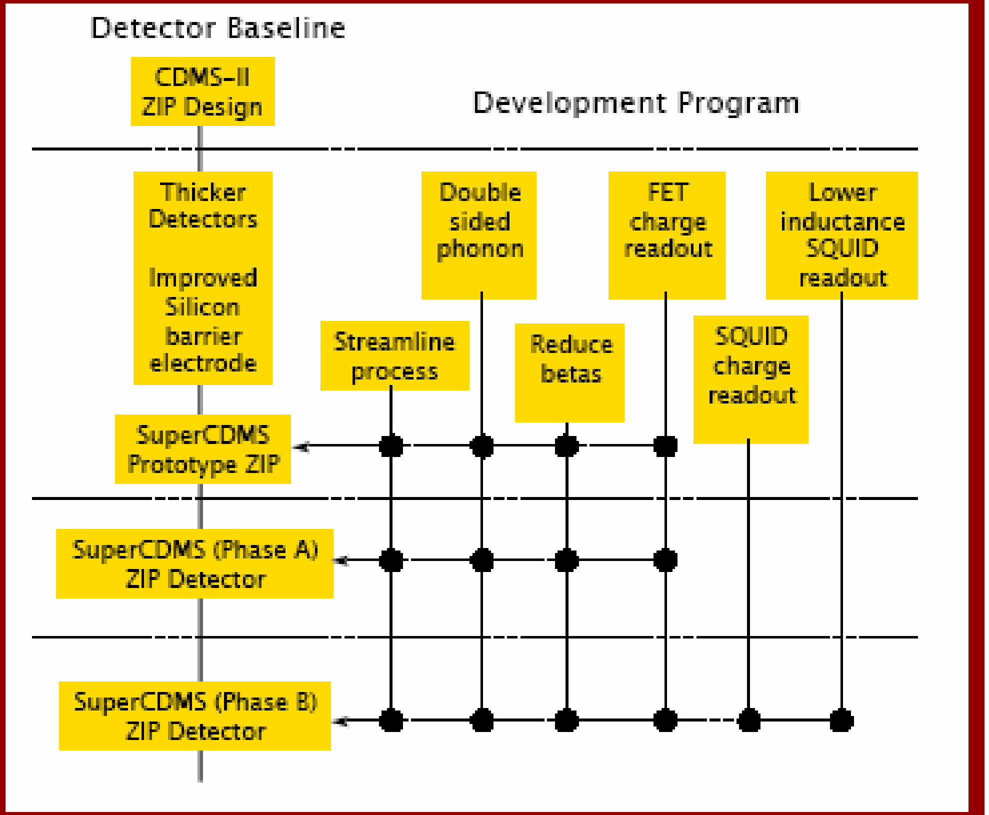
CDMS SNOLAB - Phase A:
3"x1" => 0.64 kg Ge
7 x 6-Det Towers =
42 Dets =>to 26.7 kg Ge
Soudan -> SNOLAB
SUF testing (2 batches)

CDMS SNOLAB - Phase B:
3"x1" => 0.64 kg Ge
19 x 12-Det Towers =
228 Dets =>to 145 kg Ge
Soudan/SUF testing
(6 batches)

CDMS SNOLAB - Phase C:
3"x1" => 0.64 kg Ge
73 x 24 Det Towers =
1752 =>to 1,113 kg Ge
Soudan/SUF testing
(45 batches)

SuperCDMS Development

- Scale-up CDMS ZIP mass
  - More mass per ZIP
  - No cryo-testing for fab
- ZIP refinements in parallel, leading to even better bkg rejection
- 25 kg expt (Phase A)
- 150 kg expt (Phase B)
- Future -> 1 ton



Detector Baseline

CDMS-II ZIP Design

Development Program

Thicker Detectors

Improved Silicon barrier electrode

Double sided phonon

FET charge readout

Lower inductance SQUID readout

Streamline process

Reduce betas

SQUID charge readout

SuperCDMS Prototype ZIP

SuperCDMS (Phase A) ZIP Detector

SuperCDMS (Phase B) ZIP Detector

Development to preceed experiment at each stage, leveraging on low-risk "baseline", and evaluating multiple options to enhance background rejection.