Cryogenic Dark Matter Search – Present Results and Future Detectors

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Fermilab
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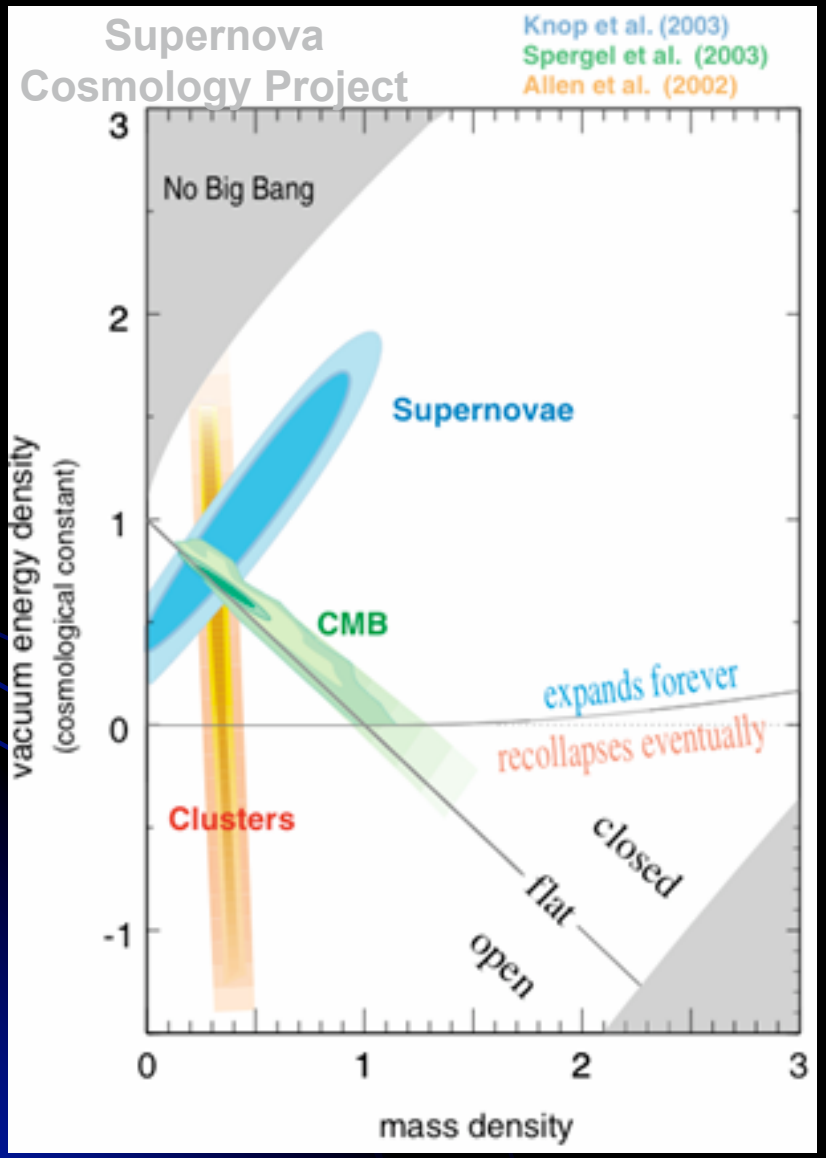
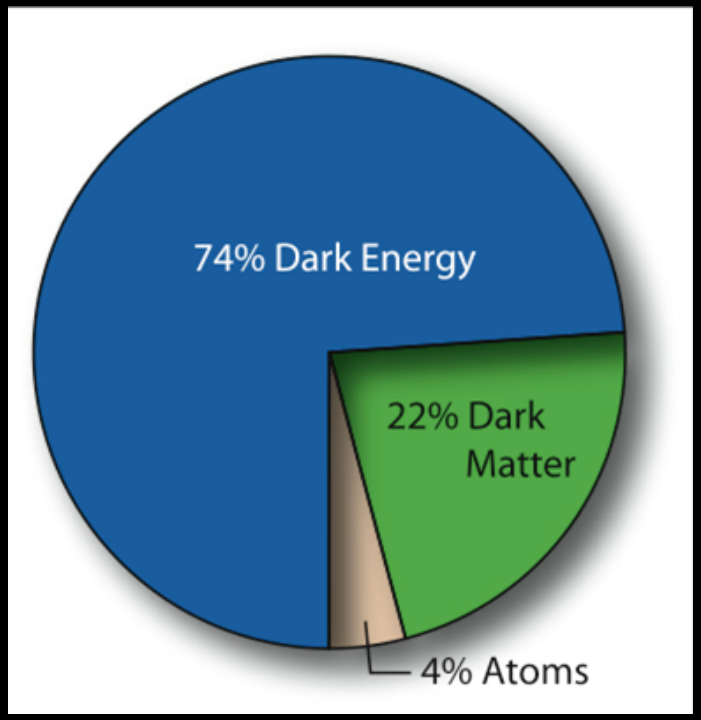
Outline

- Dark Matter and WIMPs
- CDMS
- 5-Tower Analysis and Results
- SuperCDMS and detector development

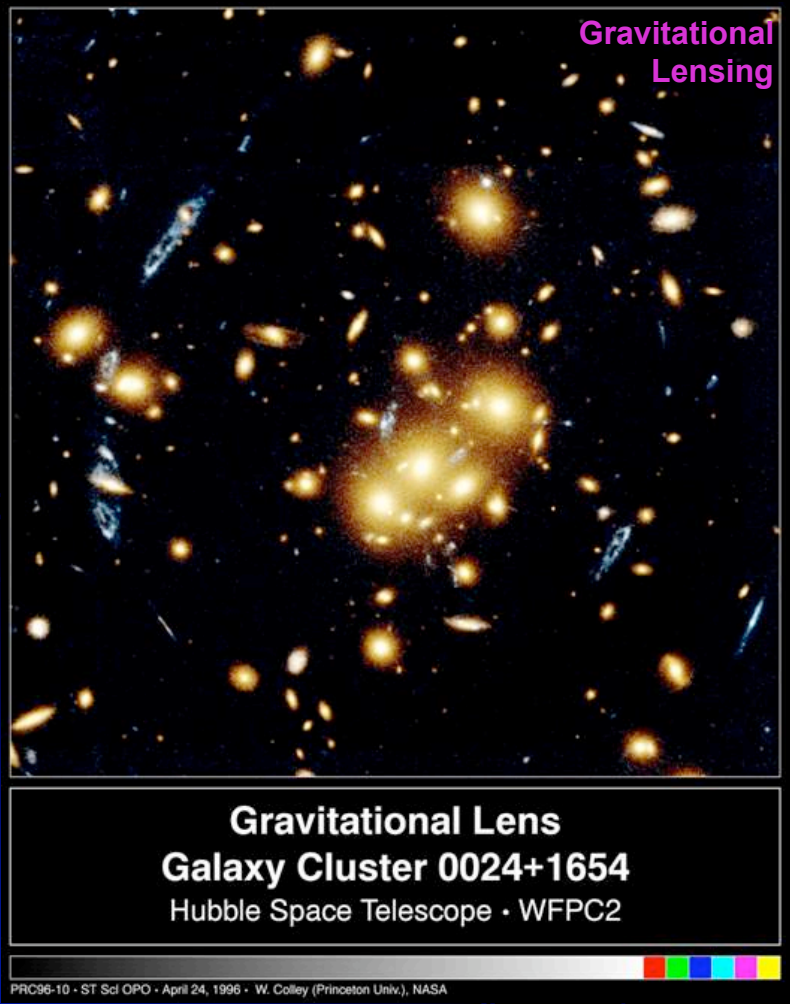
Standard Cosmology

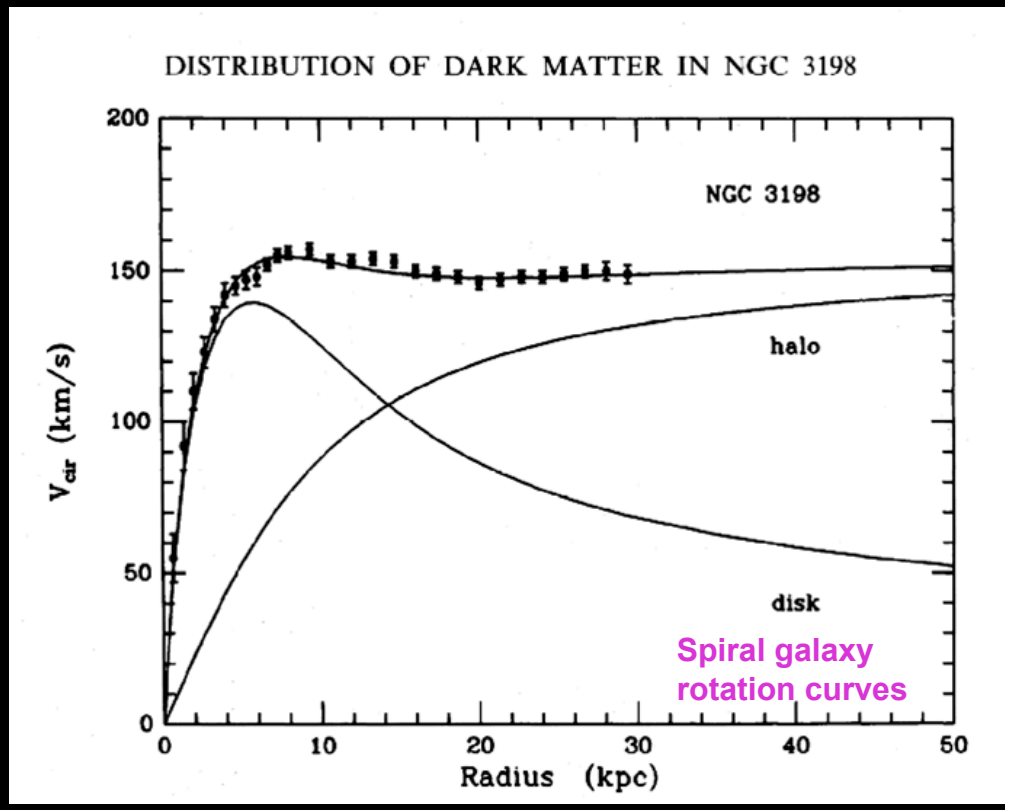




NASA/WMAP Science Team 2006

Evidence for Dark Matter

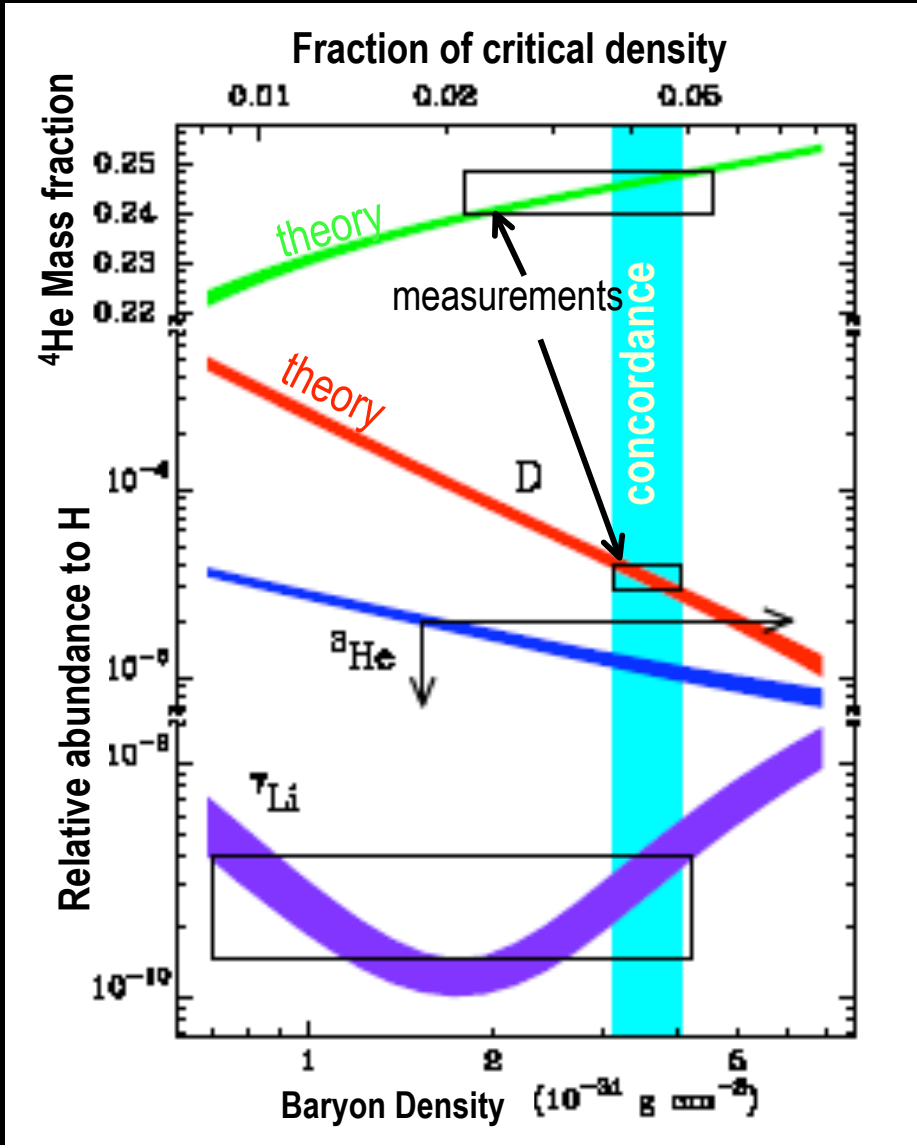




Big Bang Nucleosynthesis – non-baryonic dark matter

- Big Bang Nucleosynthesis
  - Constrain baryon density based on relative abundance of light elements from hot big bang
  - One-parameter model: baryon density
  - Best constraint: D/H in primordial gas clouds (Burles & Tytler) $\Omega_{Baryons} = 0.05 \pm 0.005$

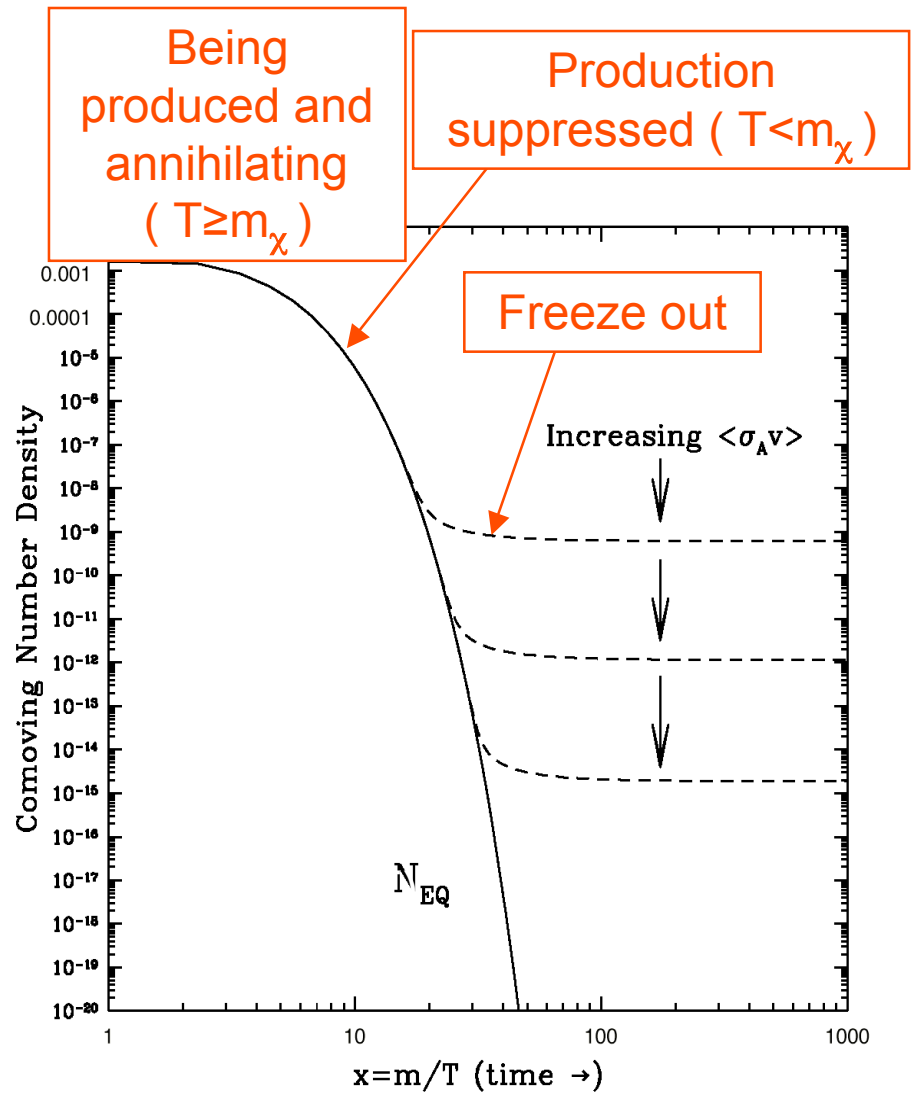
➡ 4% of atoms (in pie chart)



Weakly Interacting Massive Particles (WIMPs)

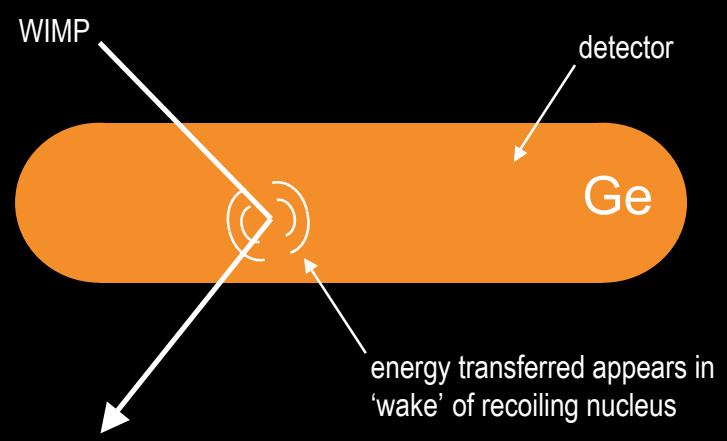
- Annihilation stops when number density drops to the point that annihilation too slow to keep up with Hubble expansion
- Leaves a relic abundance: $\Omega_\chi h^2 \approx 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1} / \langle \sigma_A v \rangle_{fr}$

if m_χ and σ_A determined by physics at electroweak scale, then $\Omega_\chi \sim 0.3$

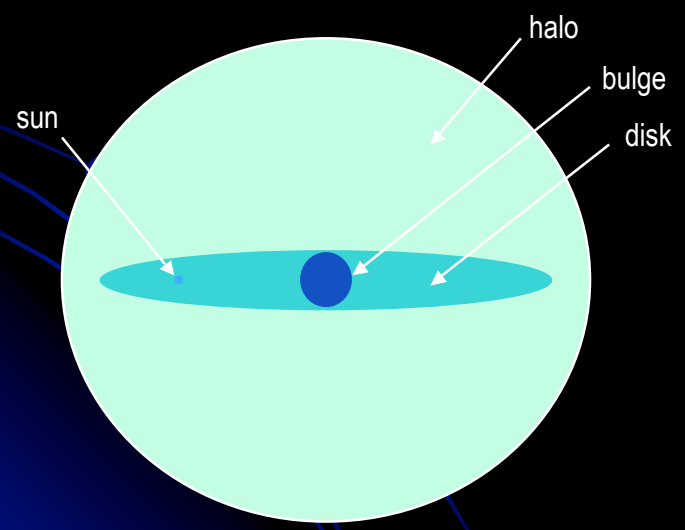


WIMPs in the Galactic Halo

WIMPs – the source of Mass in the Rotation Curves?



WIMP-Nucleus Scattering



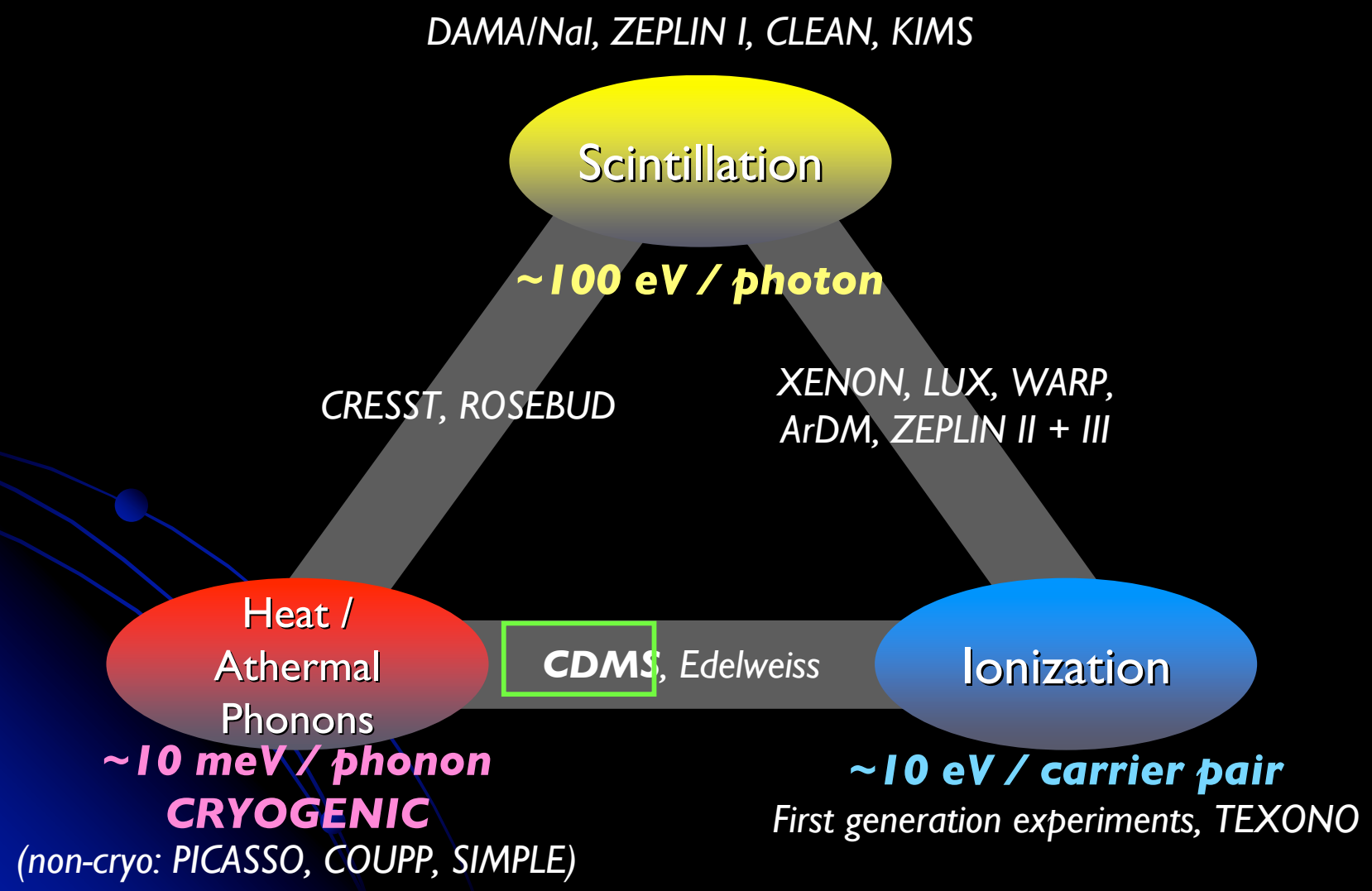
The Milky Way

Scatter from a Nucleus in a Terrestrial Particle Detector

WIMP Direct Detection Challenges

- Weakly interacting
- Low recoil energies ~ 10 keV
  - ➡ Low event energy thresholds
- Rates less than 0.01 events per day in a kilogram detector
  - ➡ Large masses
  - ➡ Long term stability
- Backgrounds much higher than event rate
  - ➡ Background control (cleanliness, shielding …)
  - ➡ Underground site (reduce muon induced neutrons)
  - ➡ Electron / Nuclear recoil event discrimination

WIMP Direct Detection Techniques

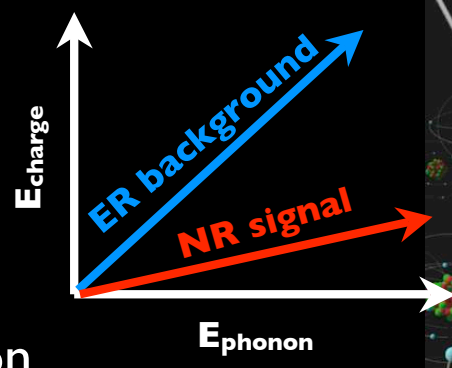


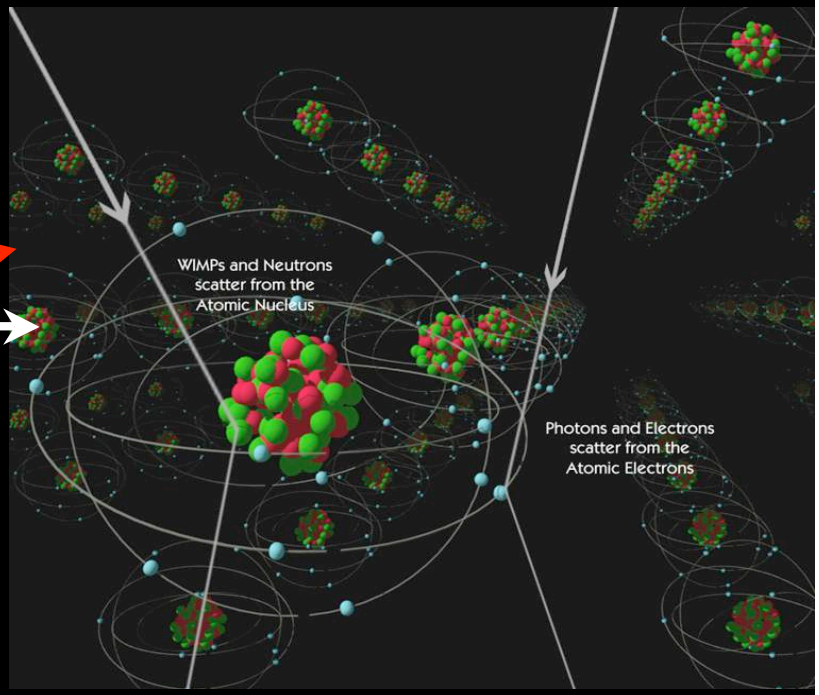
CDMS in a nutshell

Use a combination of **discrimination** and **shielding** to maintain a **"zero background"** experiment with **low temperature** semiconductor detectors

Discrimination

- Phonons
  - energy measure
  - pulse shape
- Ionization
  - dE/dx discrimination

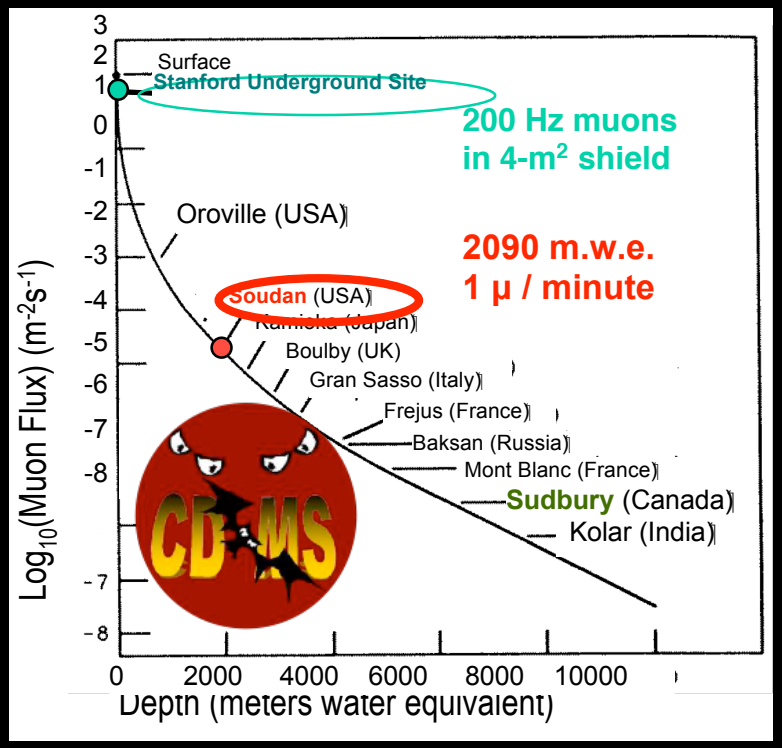




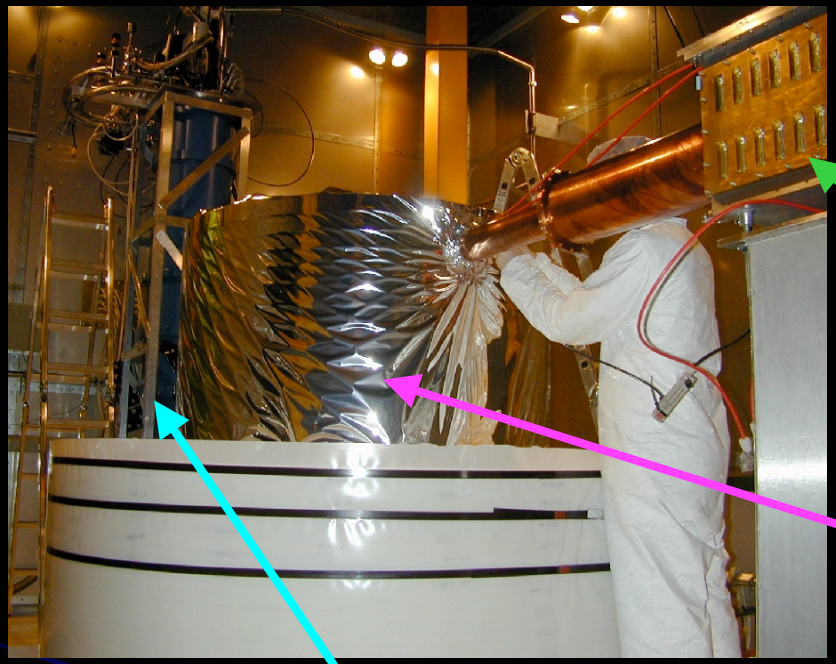
Shielding

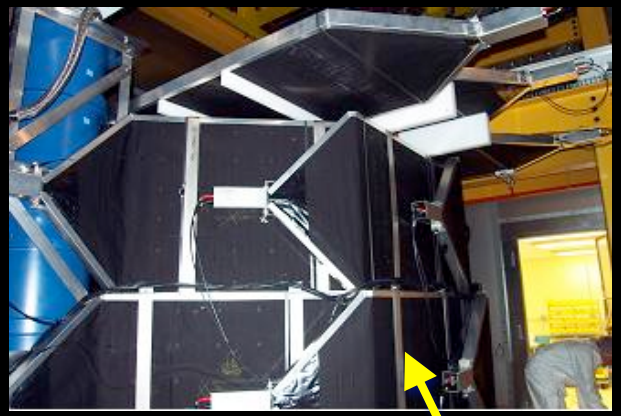
- Passive (Pb, poly, *depth*)
- Active (muon veto shield)

Soudan Underground Lab



Soudan Installation





vacuum-sealed electronic connector box ("E-box")

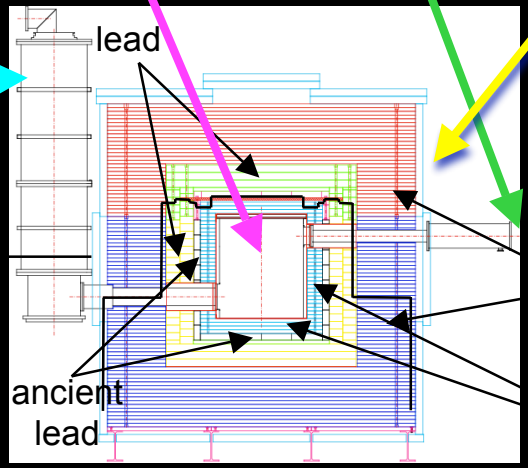
Plastic scintillator

detector cold volume ("icebox")

RF shielded class 10,000 clean room

Oxford Instruments 400μW dilution refrigerator

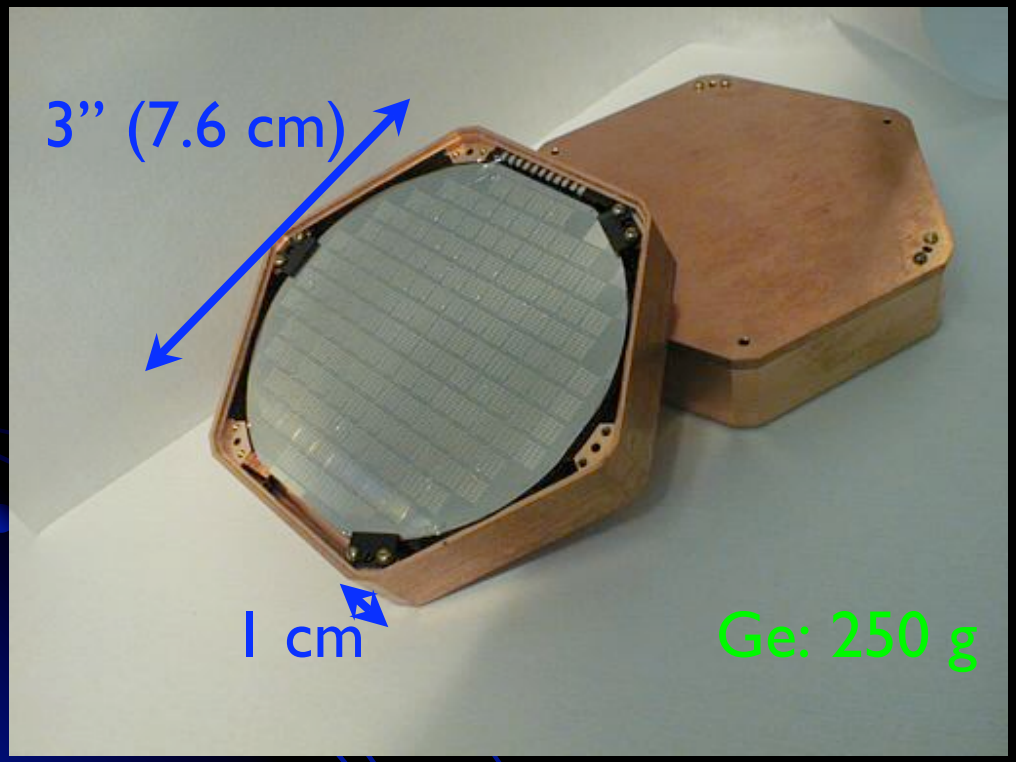
1 ft^3 @40 mK!



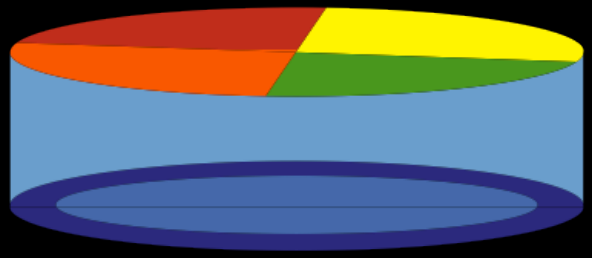
~0.05 unvetoed neutrons per kg-y (Monte Carlo)

ZIP Detectors

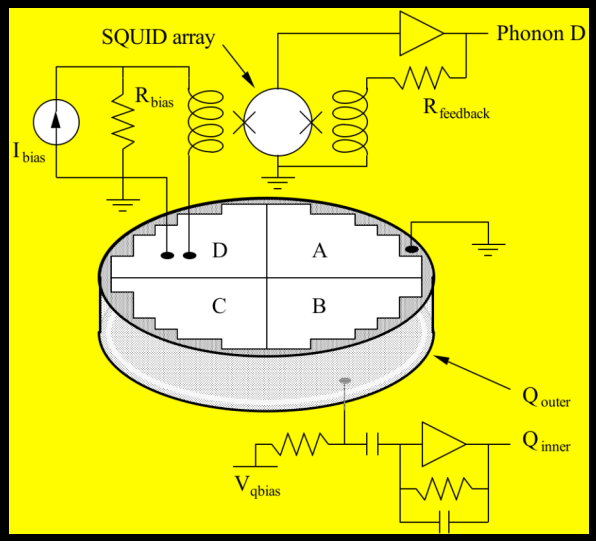
(Z-sensitive Ionization and Phonon)



Phonon side: 4 quadrants of athermal phonon sensors => ***energy measurement***

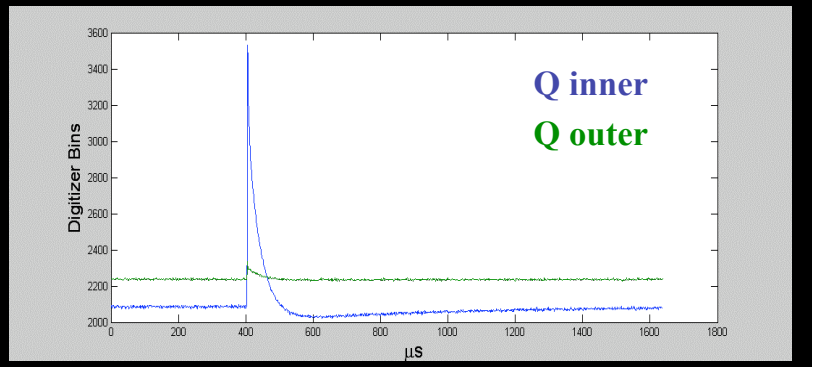


Charge side: 2 concentric electrodes



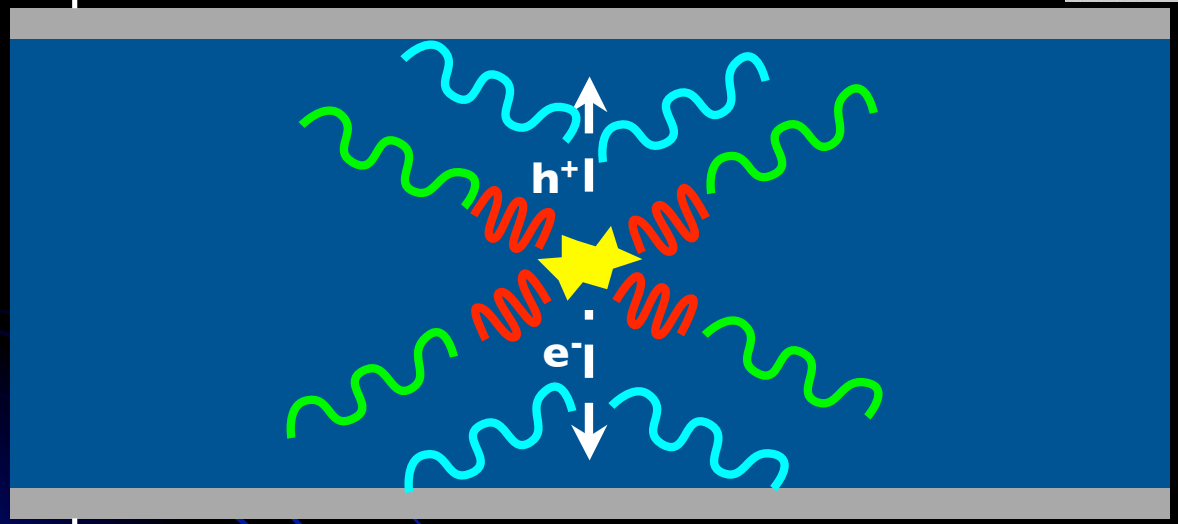
Operated at **~40 milliKelvin** for good phonon signal-to-noise

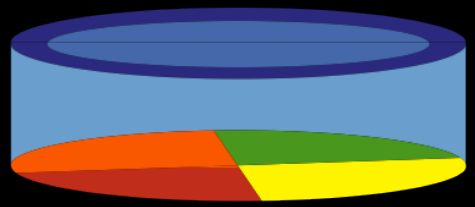
Anatomy of an event



-3V

Hot charge carriers (3eV/pair)



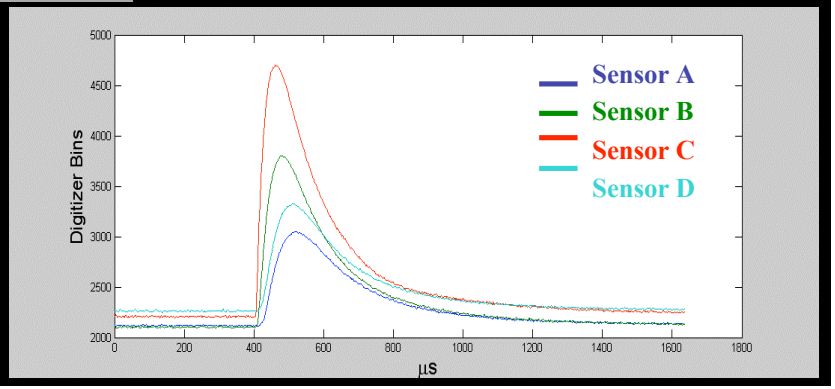


0V

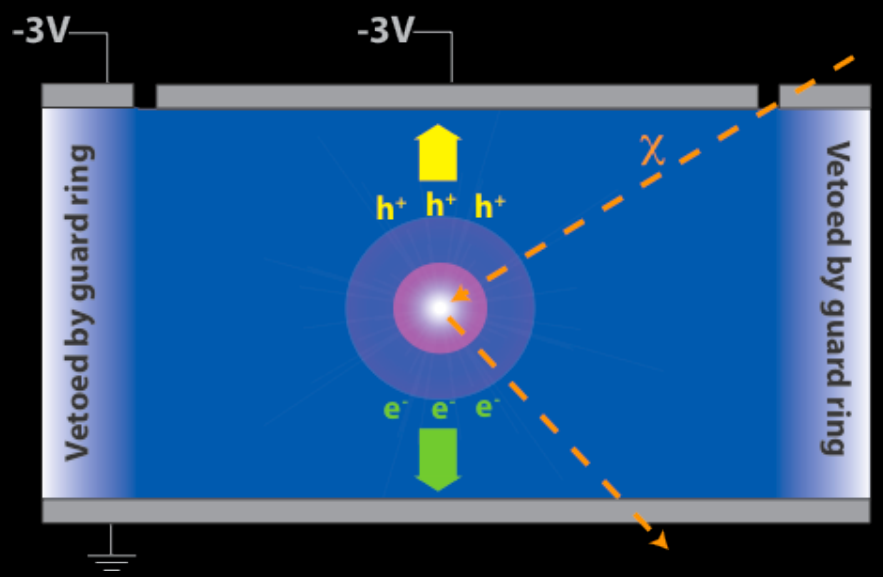
Quasi-diffusive THz phonons

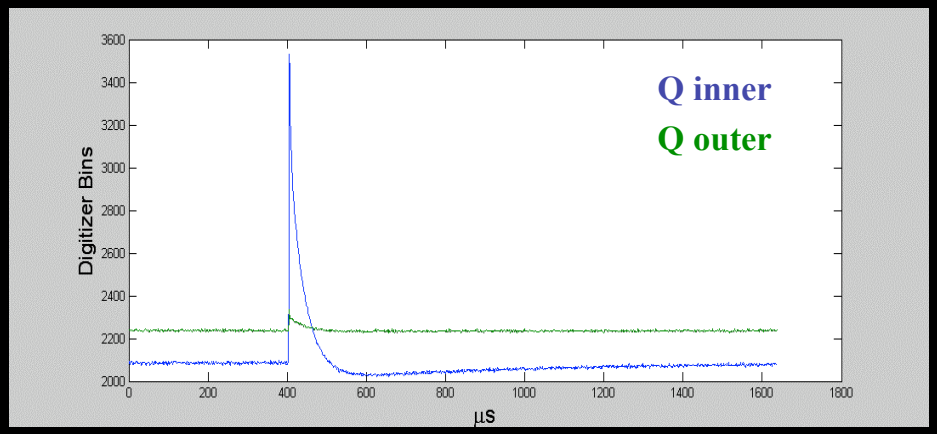
Ballistic Neganov-Luke phonons

Ballistic low-frequency phonons



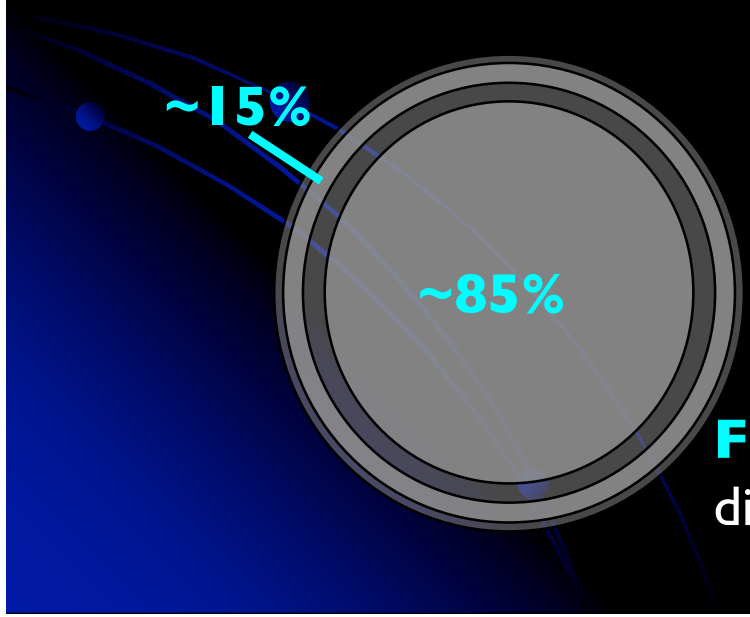
ZIP Detectors: Ionization





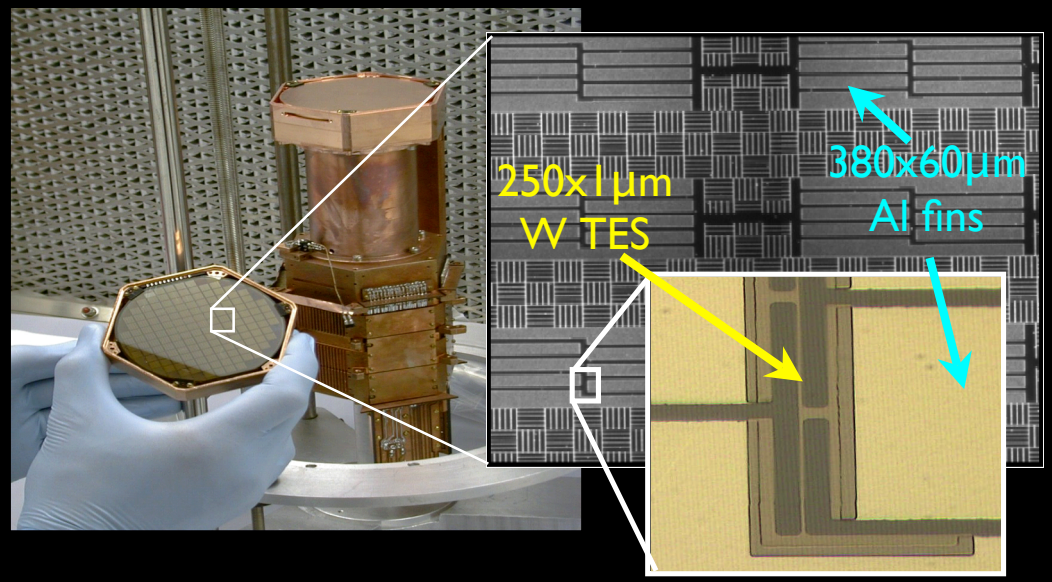
Essentially complete collection at **3V/cm** (after trap neutralization)

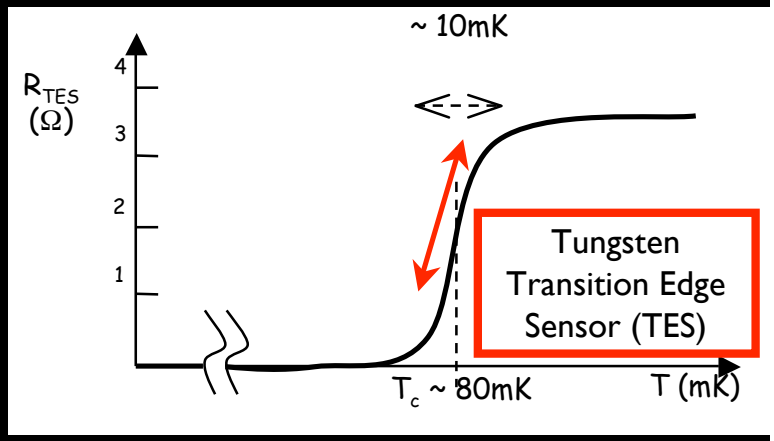
Low-noise JFET amp at 140 K: Zero-energy resolution **~250 eV**(~3 keV @ 511 keV)

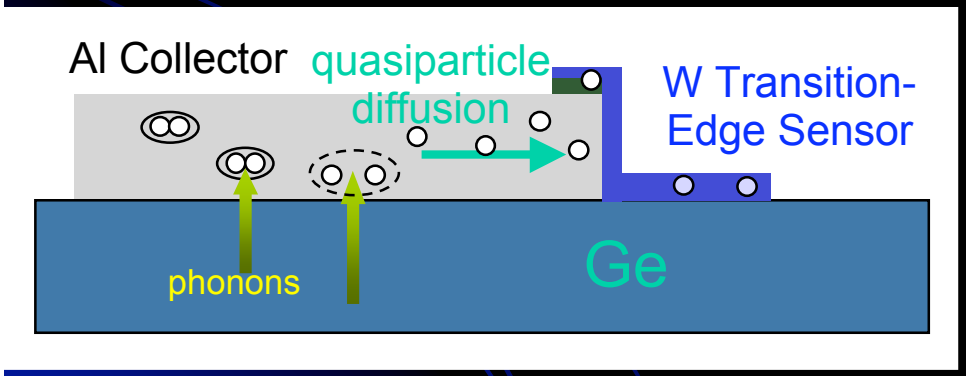


Fiducial volume cut from divided electrode ("**guard ring**")

ZIP Detectors: Phonons







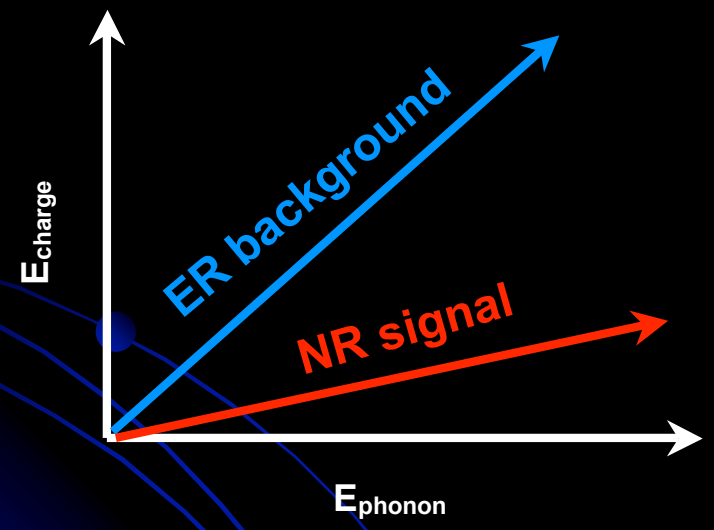
≈

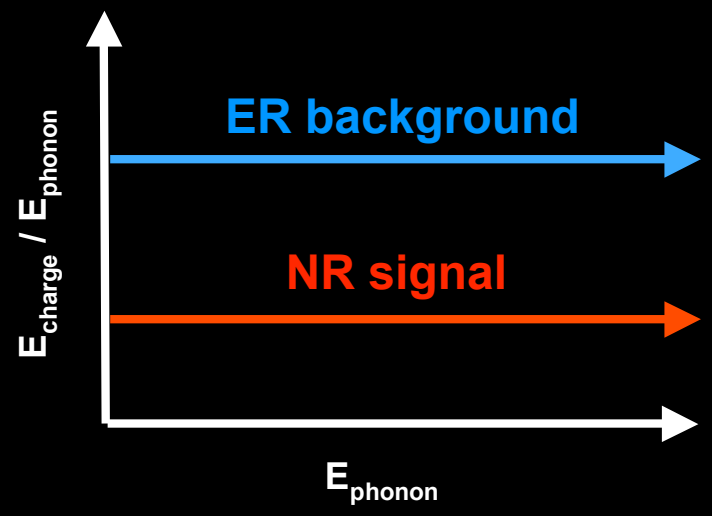
4 SQUID readout channels, each 1036 W TESs in parallel

Zero-energy resolution **~100 eV** in each channel, total **~5%** at higher energies (after position correction)

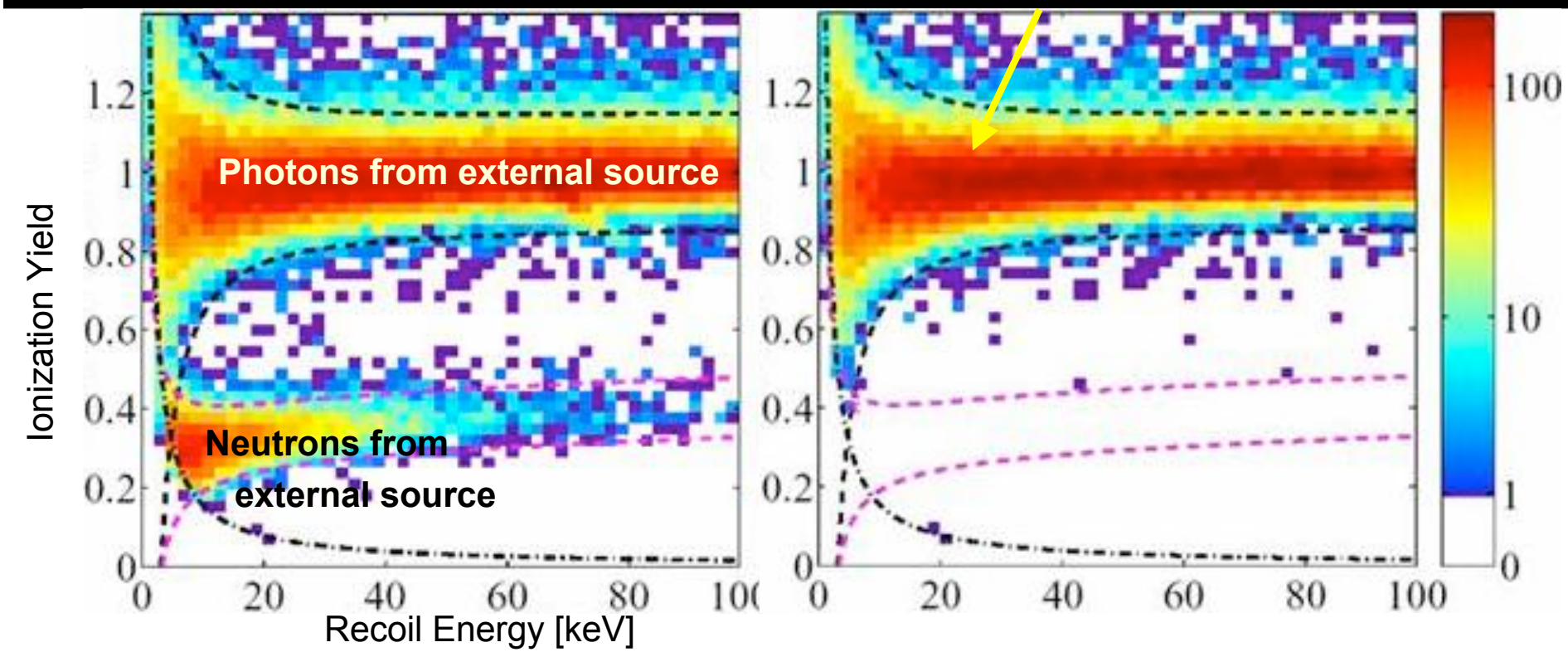
Fast response: ~5 µs risetime

Ionization Yield





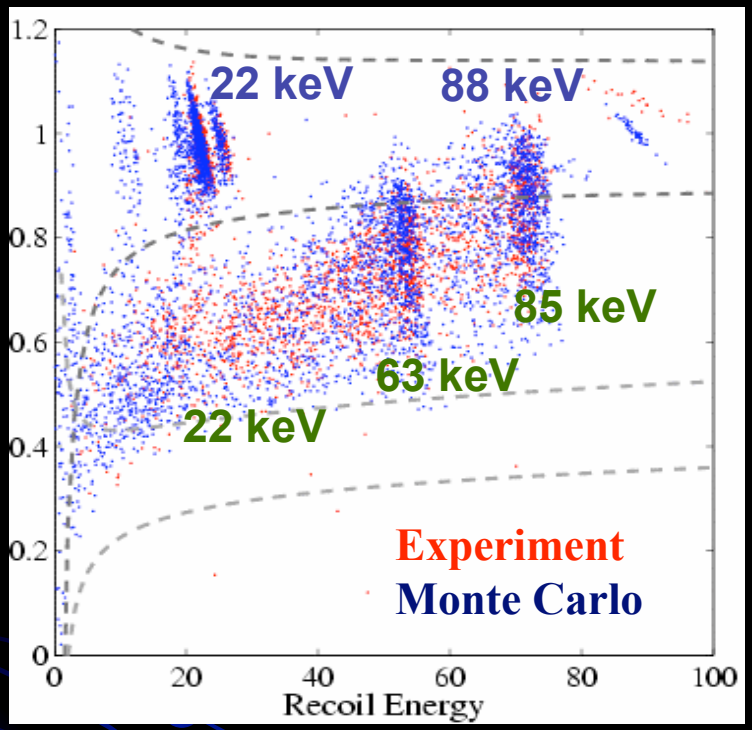
Ionization Yield



- Reject bulk electron recoils using ionization yield
- Better than 10,000:1 rejection

Ionization Yield ≡ Ionization / recoil energy

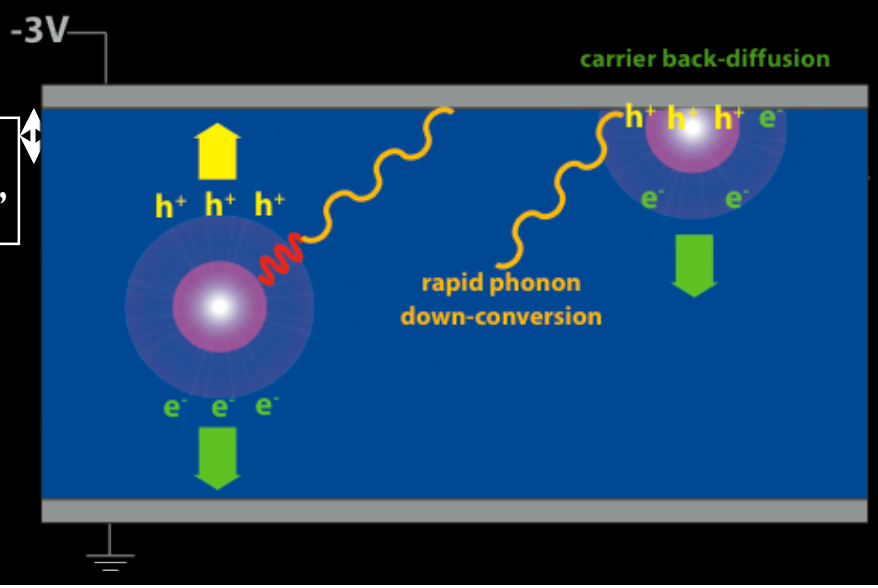
Near-Surface Events



Reduced charge yield from surface events (e.g. K-40, Rn chain) from carrier back-diffusion can mimic signal

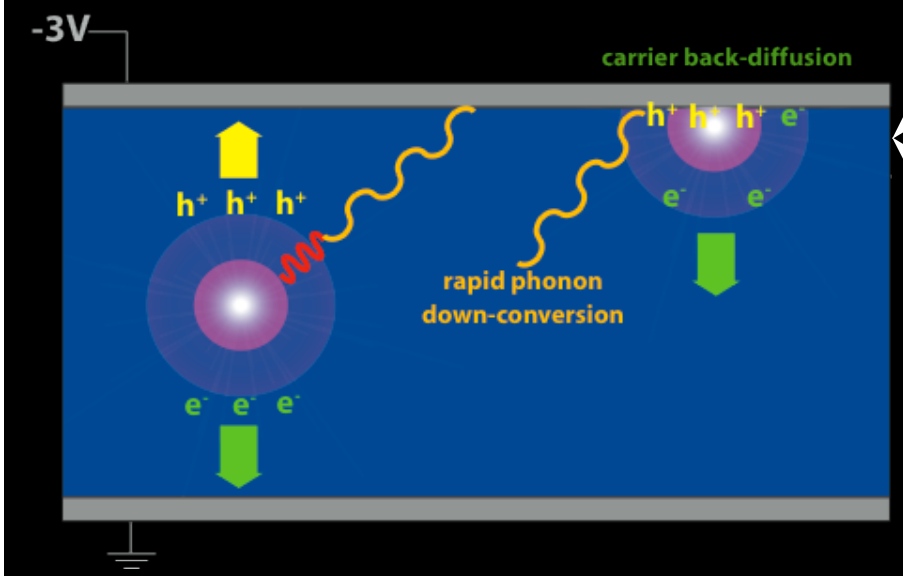
Greatly improved by aSi contact (Shutt et al.), still **dominant background** for CDMS

~10μm
"dead layer"

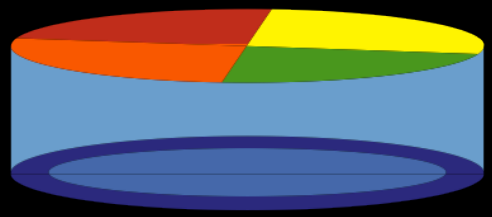


Data from UC Berkeley calibration of
T2Z5**, née **G31
*V. Mandic et al., NIM A **520**, 171 (2004)*

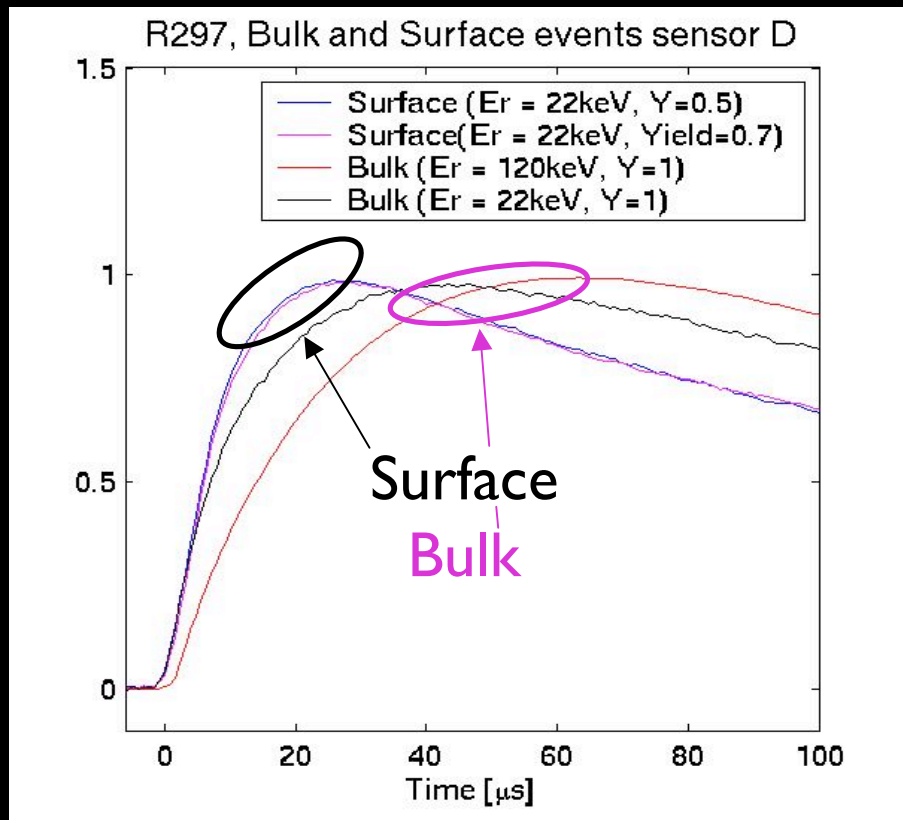
ZIP Detectors: Z-sensitivity



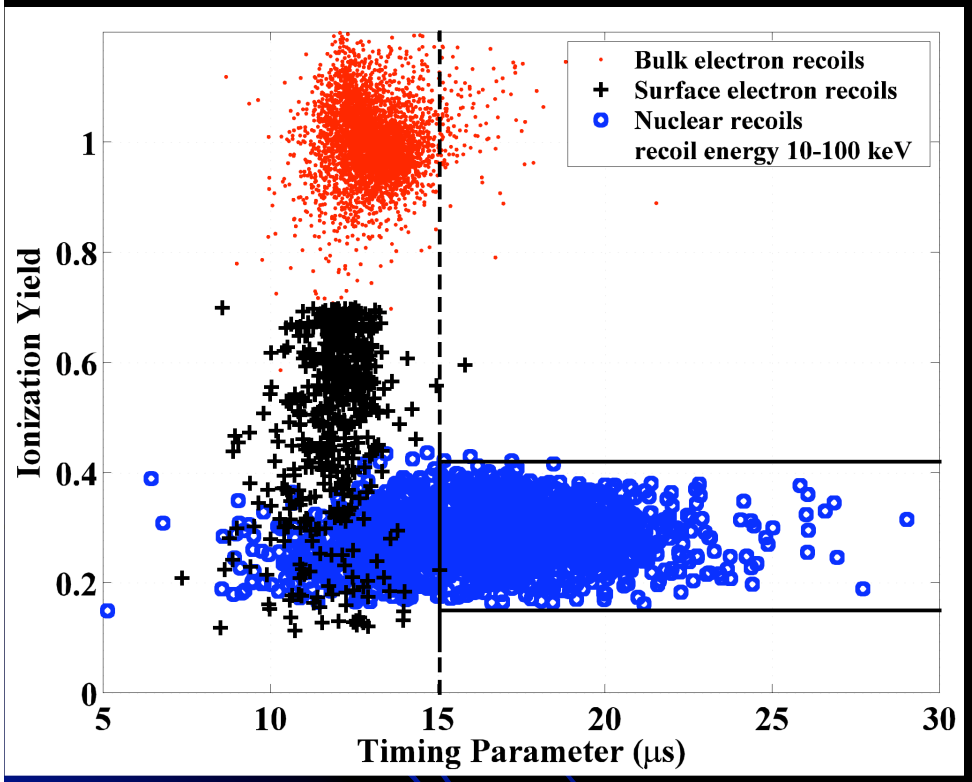
~10μm "dead layer"



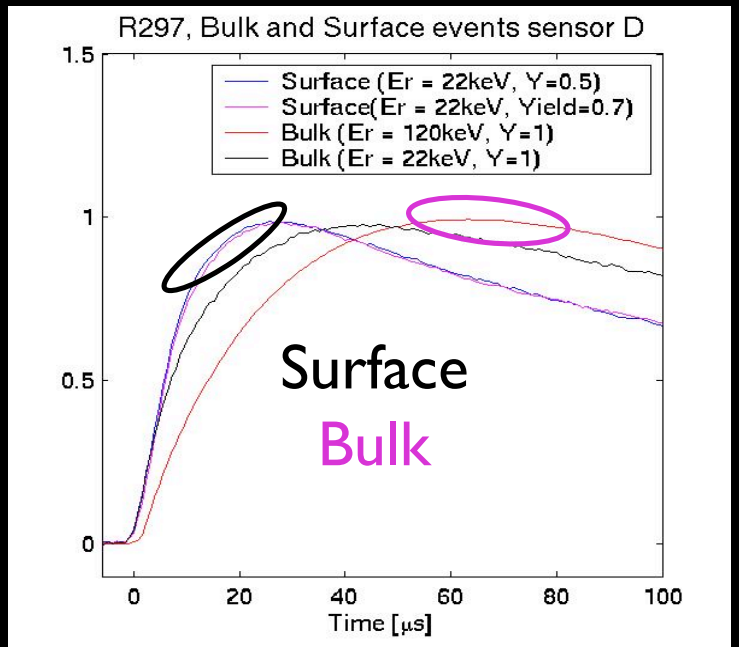
- Primary risetime
  (time from 10% - 40% in phonon amplitude for largest pulse)
- Primary delay
  (time from 20% charge amplitude to 20% phonon amplitude for largest pulse)



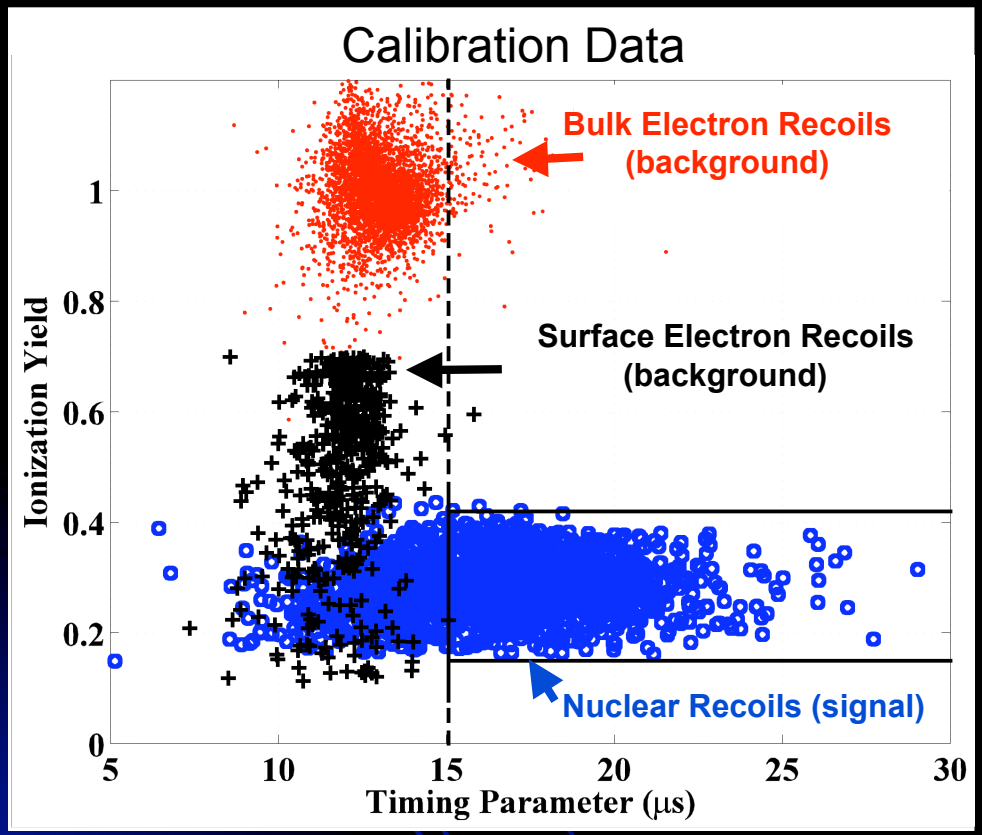
Phonon Timing



- Faster phonon signals from surface events (more ballistic phonons)
- Rejects surface electron recoils >200:1 using phonon timing

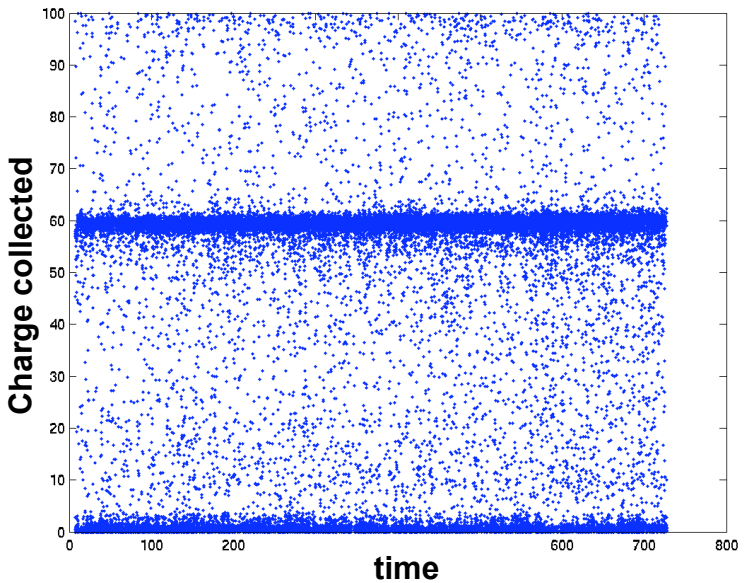


Discrimination: Ionization Yield & Phonon Timing



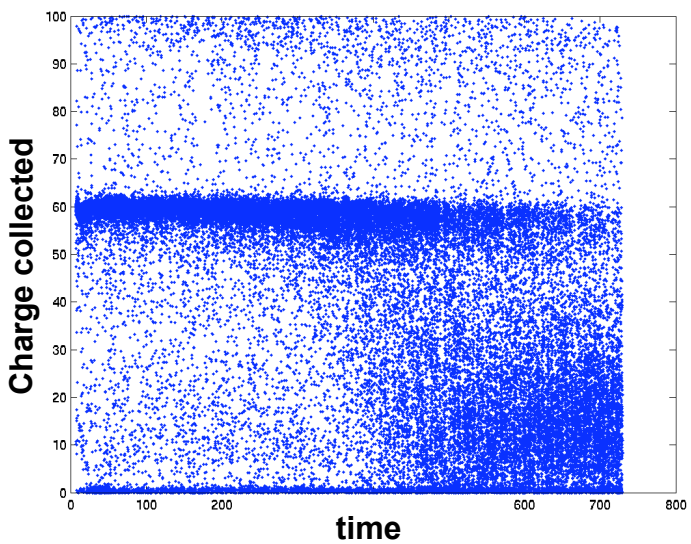
- Ionization Yield
  - Ionization / recoil energy
  - Reject bulk electron recoils
  - Better than 10,000:1 rejection
- Phonon Timing
  - Faster phonon signals from surface events (more ballistic phonons)
  - Rejects surface electron recoils >200:1

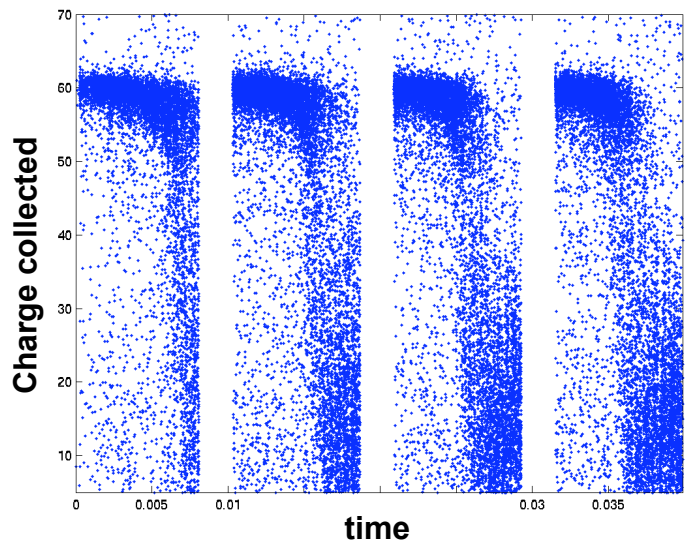
Neutralization



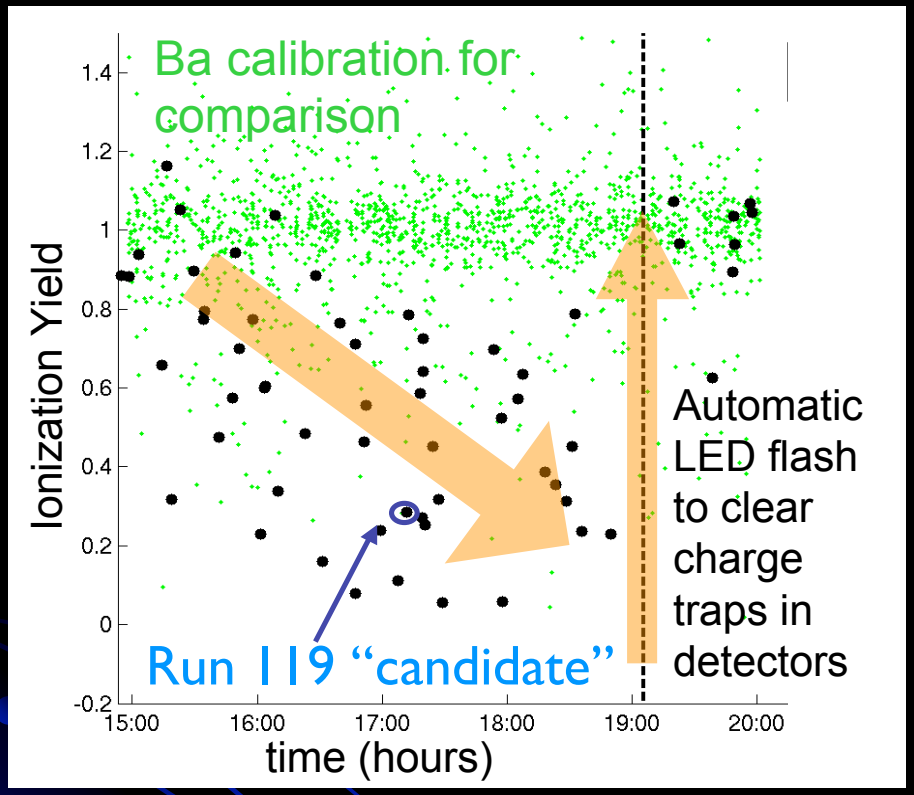
- "Neutralize" these impurities to maintain full charge collection
  - LED photons
  - Energetic particles (either from radioactive sources or surface backgrounds)

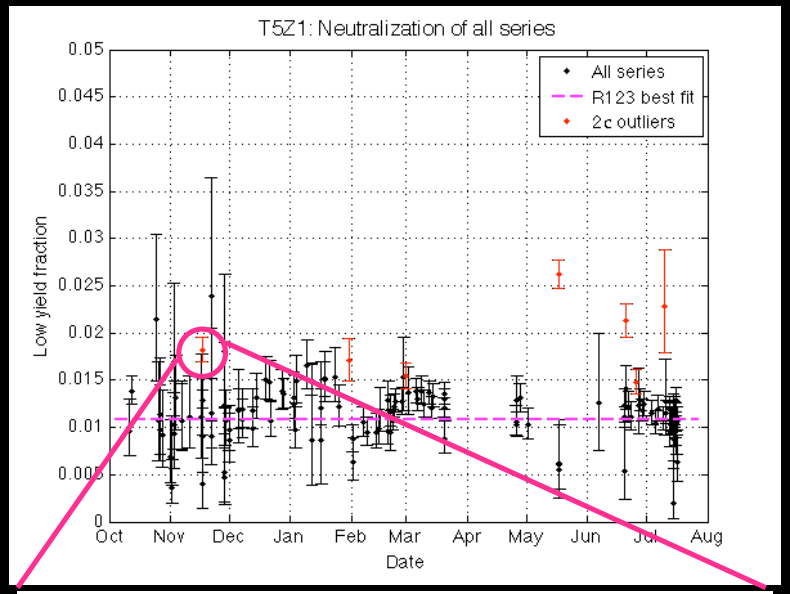
- Bulk charge trapping by lattice impurities

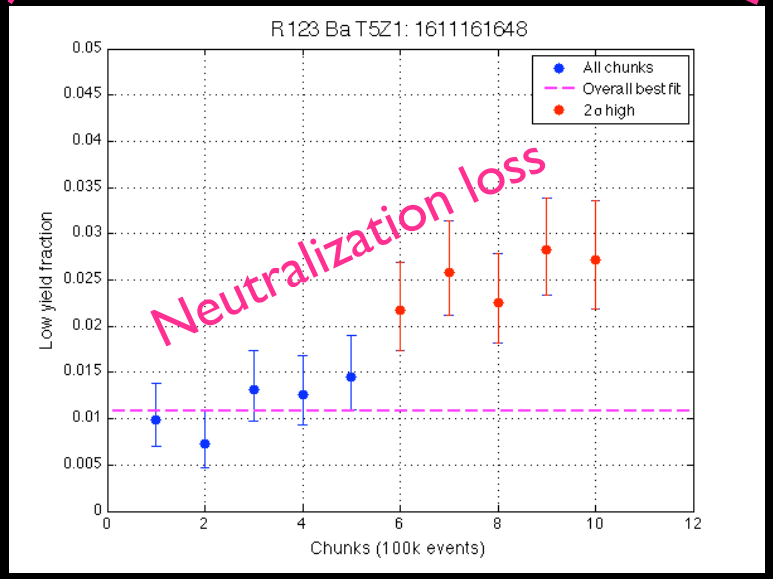




Neutralization



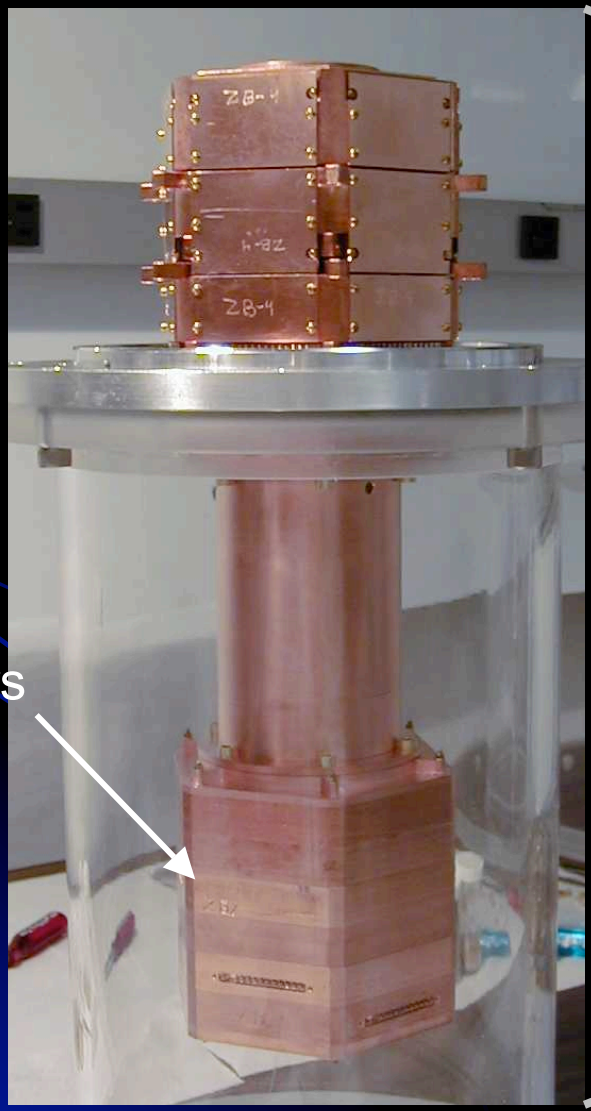




Quantitative neutralization monitoring based on R119 (2-Tower) experience

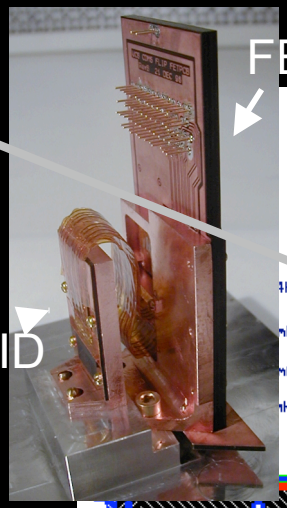
ZIP Tower

ZIP Tower



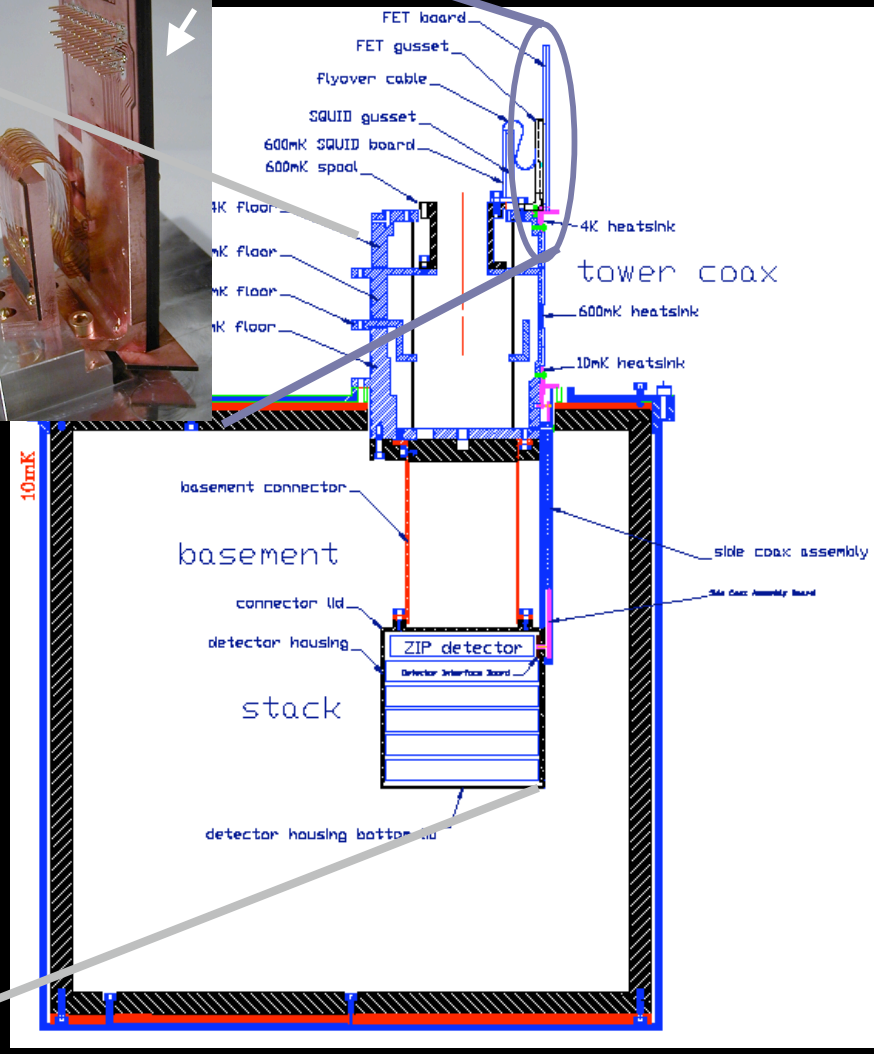
Detectors

SQUET card

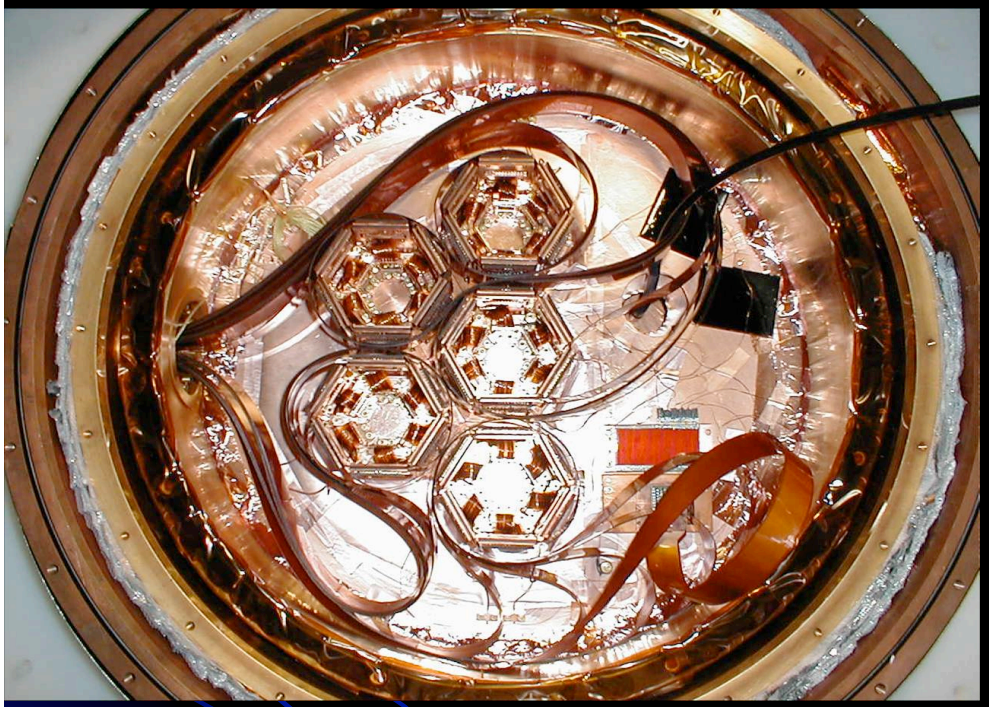


FET

SQUID



First Five Tower Runs (2006-7)



- 30 ZIPs (5 Towers) in Soudan icebox:

  4.75 kg Ge, 1.1 kg Si

First two runs analyzed:

- Run 123 (21Oct06 – 21Mar07):

~108 live days (430 kg-d Ge raw)

- Run 124 (20Apr07 – 16Jul07):

~56 live days (224 kg-d Ge raw)

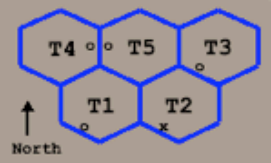
CDMS Event Display [5-Tower]

Fri Nov 2 23:45:38 2007

Per Trigger & WIMP Search

Series Number	=	1711022042
Event Number	=	230095
Time since Levt (ms)	=	16930
Live Time since Levt (ms)	=	16899

Tower & detector wiring



o : Z1 & clockwise

x : Z1 & c-clockwise

Ampl vs [us]

260 -------- Pd
240 -------- Pc
220 -------- Pb
200 -------- Pa

20 -------- Qo
0 -------- Qi

TrigInfo : Q P Q&P RANDOM

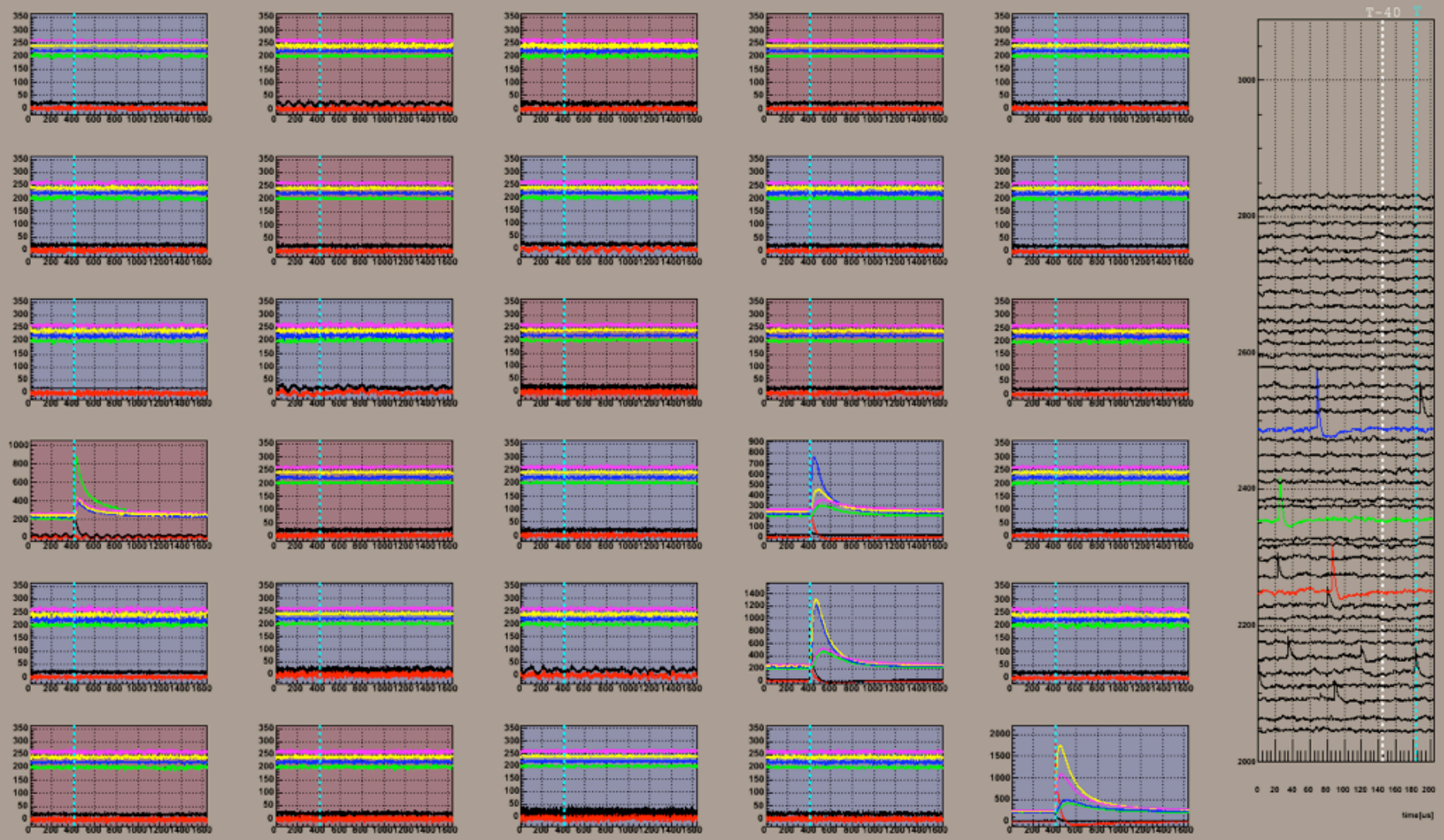
T1G1	T2S1	T3S1	T4S1	T5G1
T1G2	T2S2	T3G2	T4G2	T5G2
T1G3	T2G3	T3S3	T4S3	T5S3
T1S4	T2S4	T3G4	T4G4	T5G4
T1G5	T2G5	T3G5	T4G5	T5G5
T1S6	T2S6	T3G6	T4G6	T5G6

VETO Map (ColCode > 50 VADC)

Tne Te Tse
C-stem Tnw Tw Tsw E-stem

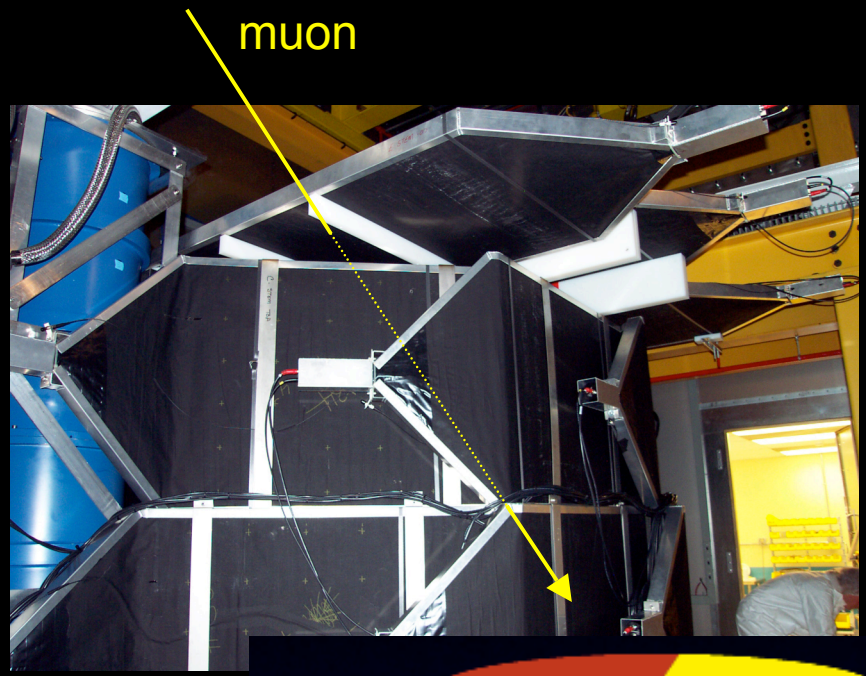
S3e S3ne S3n S3nw S3w S3sw S3s S3se
S2e S2ne S2n S2nw S2w S2sw S2s S2se
S1e S1ne S1n S1nw S1w S1sw S1s S1se

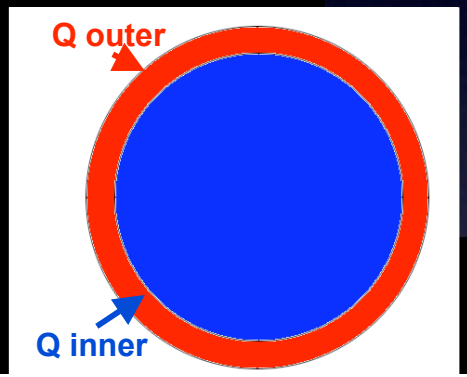
Bnw Bw Bsw
Bn Bne Be Bse Bs

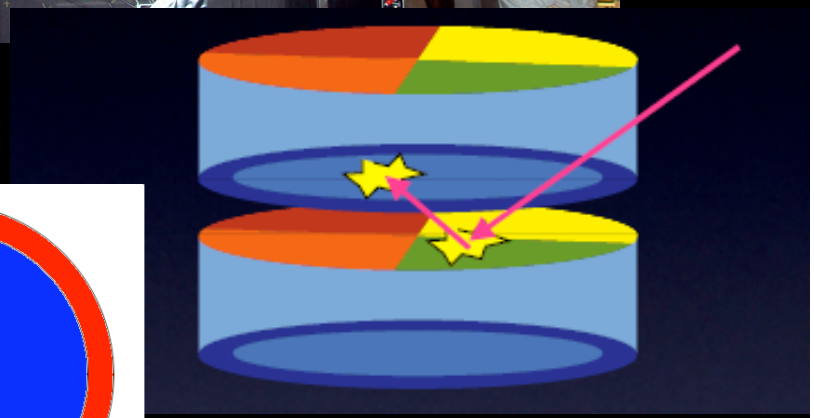


Analysis Cuts

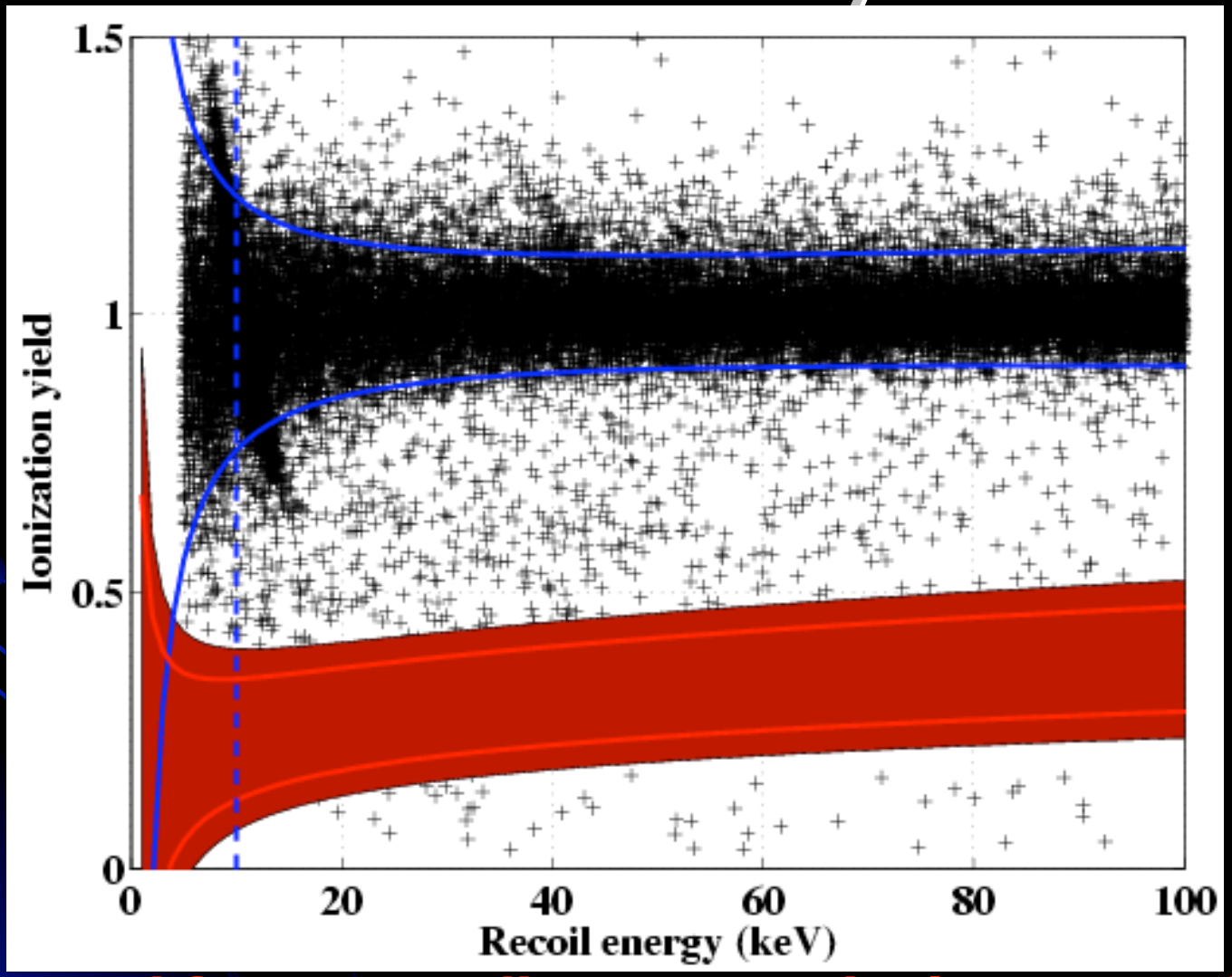
- Blind analysis
- Data Quality
- Physics
  - Veto-anticoincidence
  - Single-scatter
  - Qinner (fiducial volume)
  - Ionization yield
  - Phonon timing







The WIMP Search Data: Blind Ge Analysis

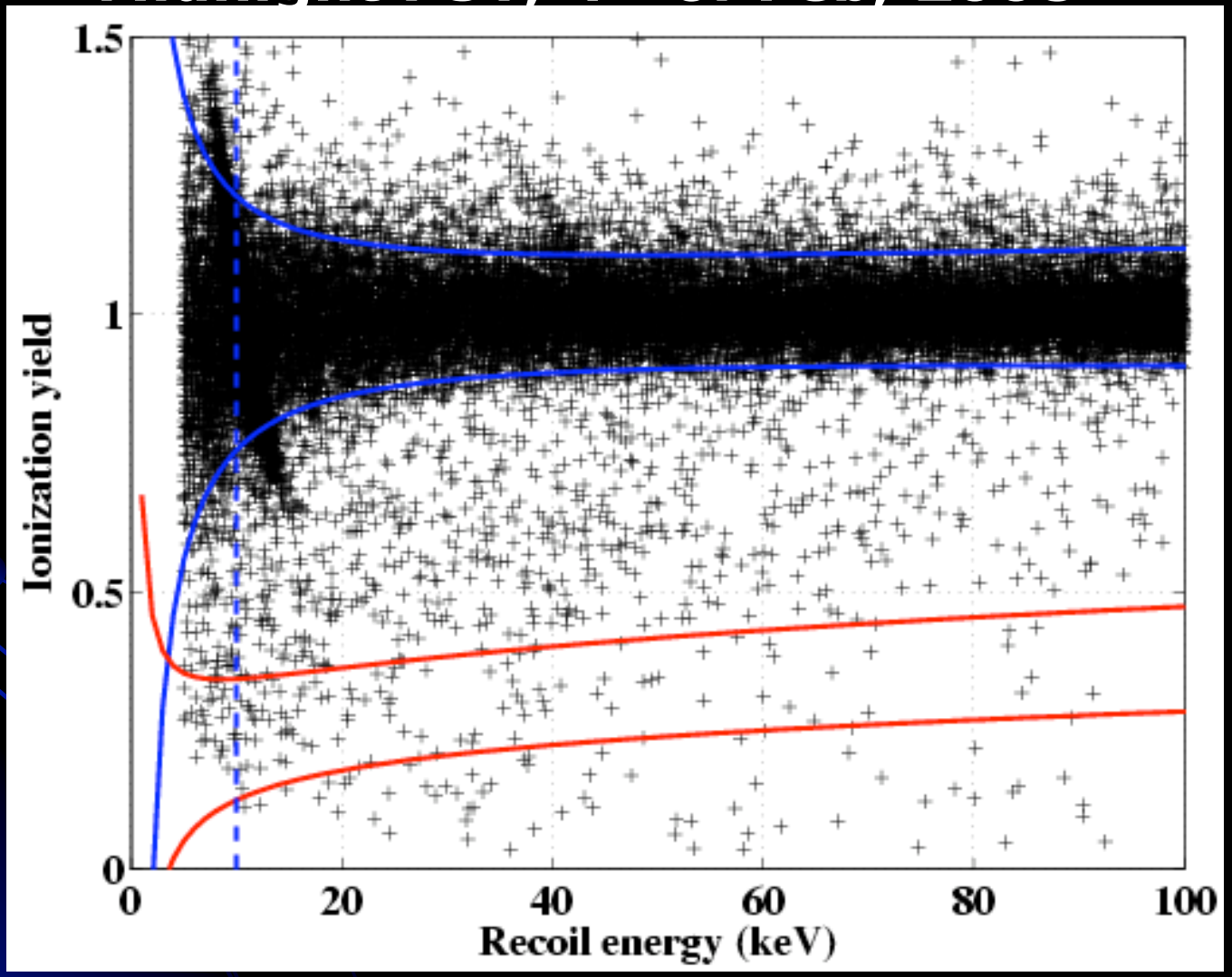


Prior to Phonon Timing Cut

All cuts set and frozen! Predict 77 ± 15 single scatters in NR

The WIMP Search Data

Midnight PST, 4th of Feb, 2008

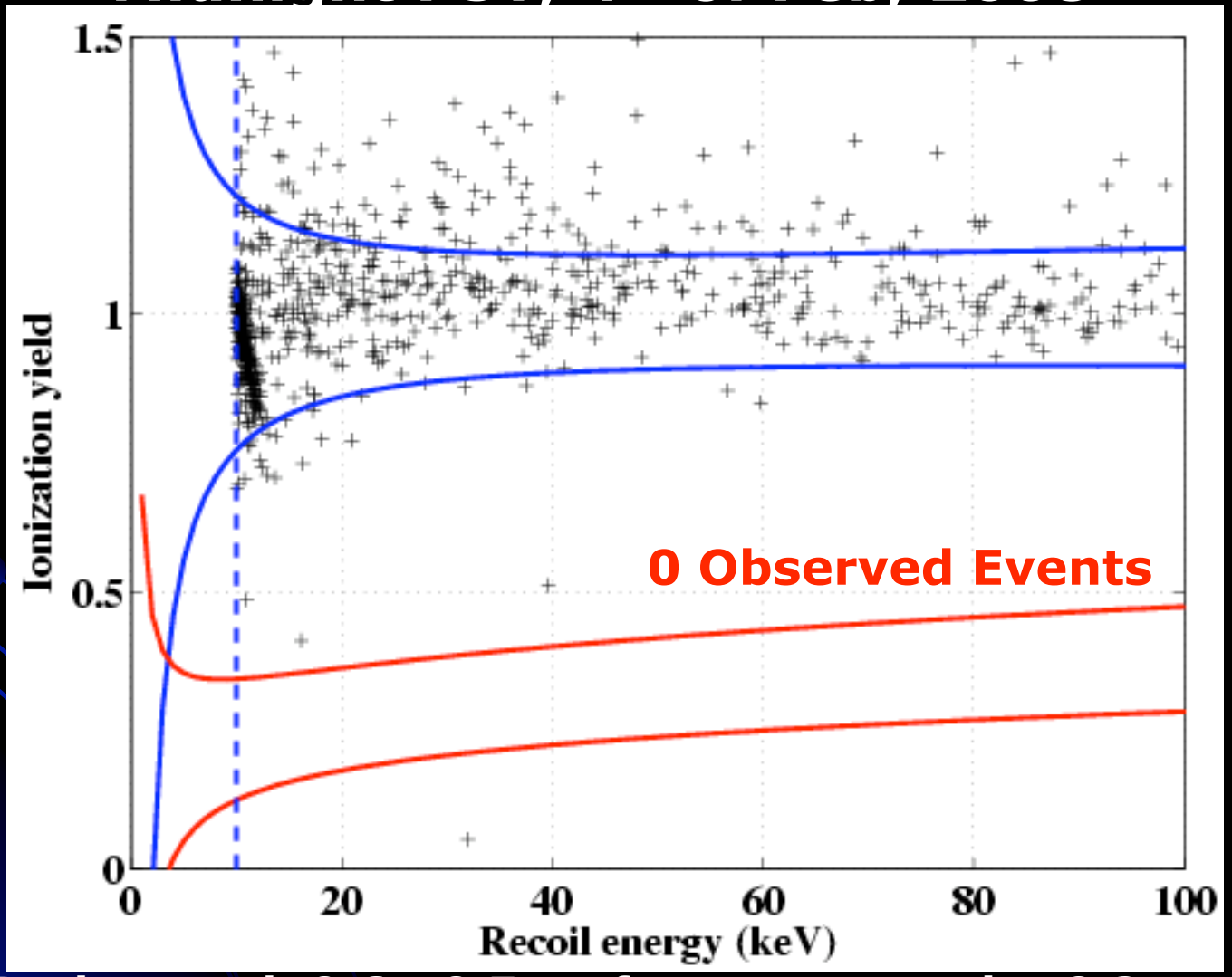


Prior to Phonon Timing Cut

97 Singles in Signal region rejected by Surface Event Cut

Open The Box

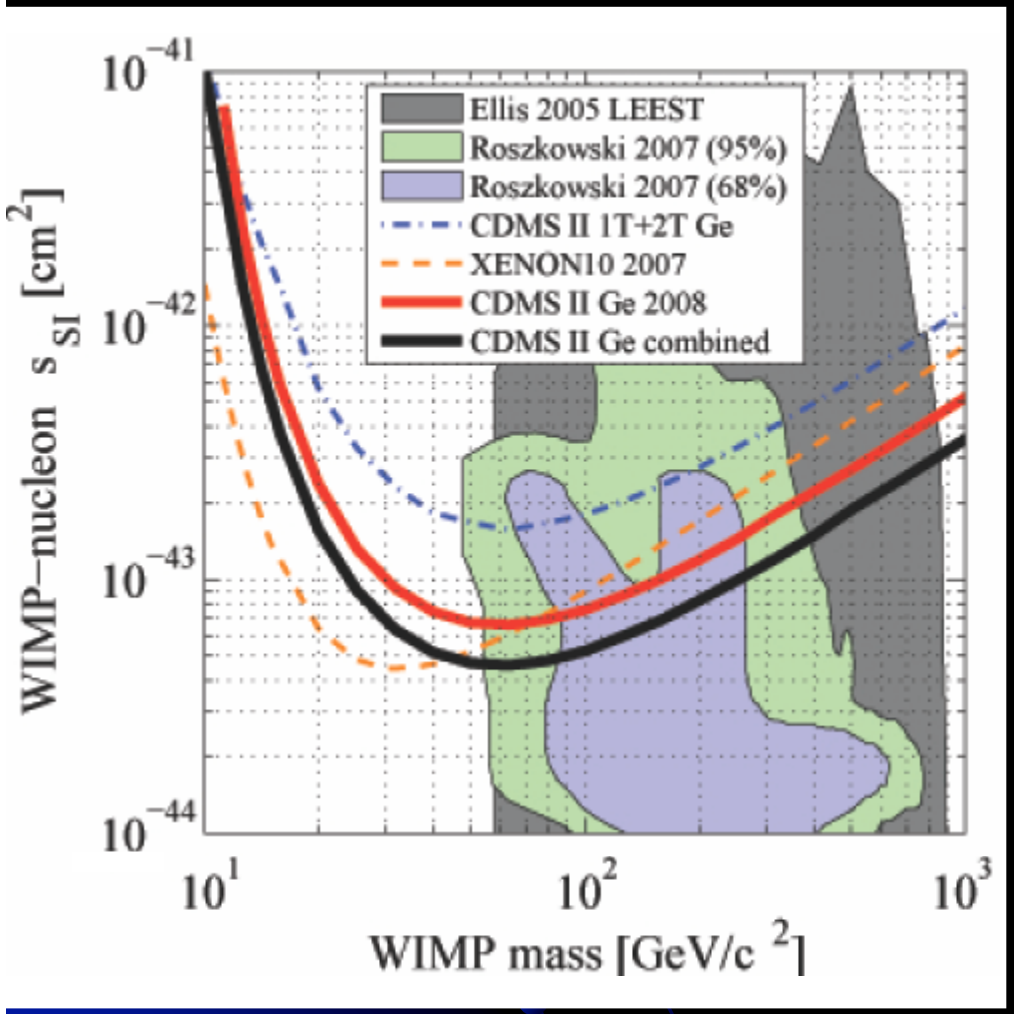
Midnight PST, 4th of Feb, 2008



After Phonon Timing Cut

Expected Background: 0.6 ± 0.5 surface events and < 0.2 neutrons

Results



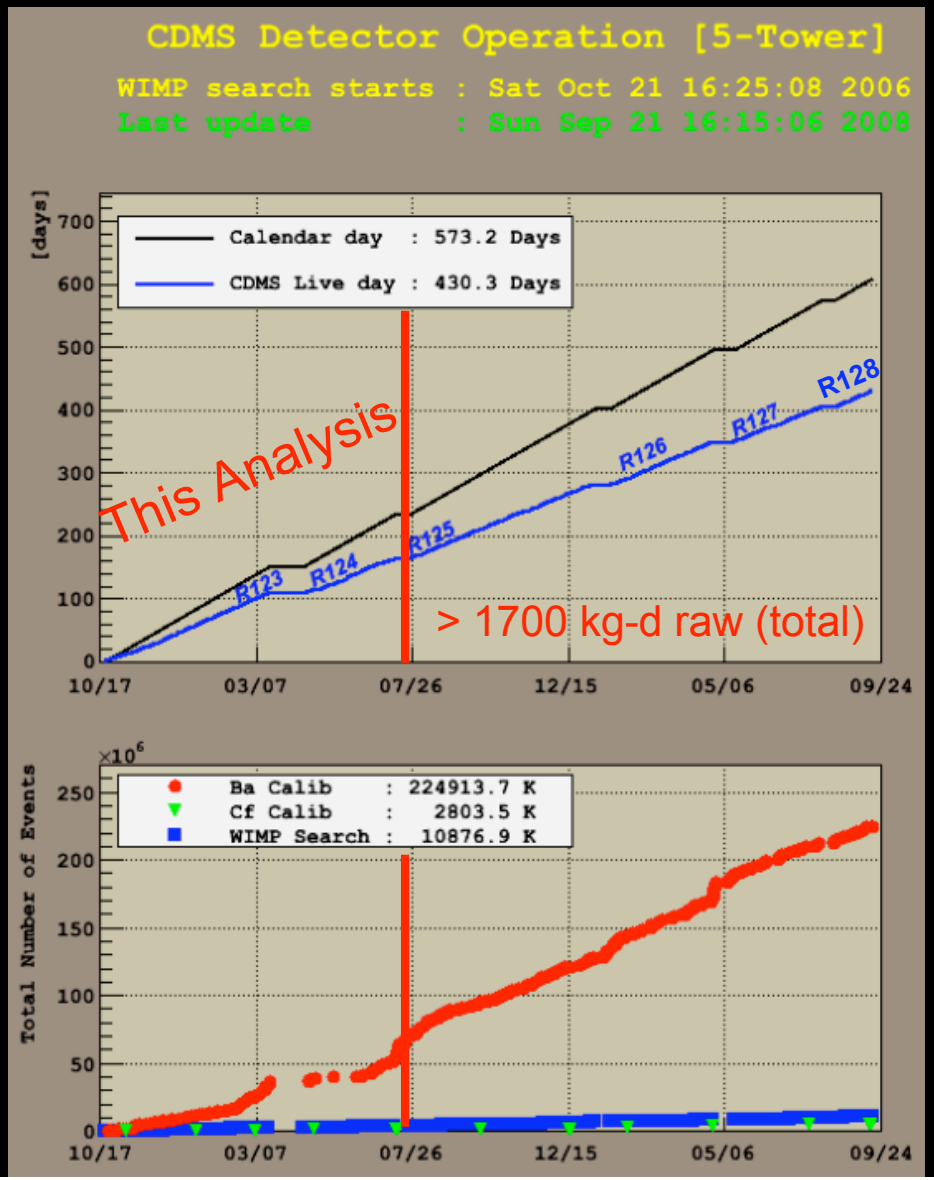
- Strongest SI limits above 44 GeV/c^2
- >2x data in hand and run continuing
- Ongoing detector characterization and analysis optimization

Preprint at:

- http://cdms.berkeley.edu
- arXiv:0802.3530 (accepted for publication in PRL)

CDMS II Future

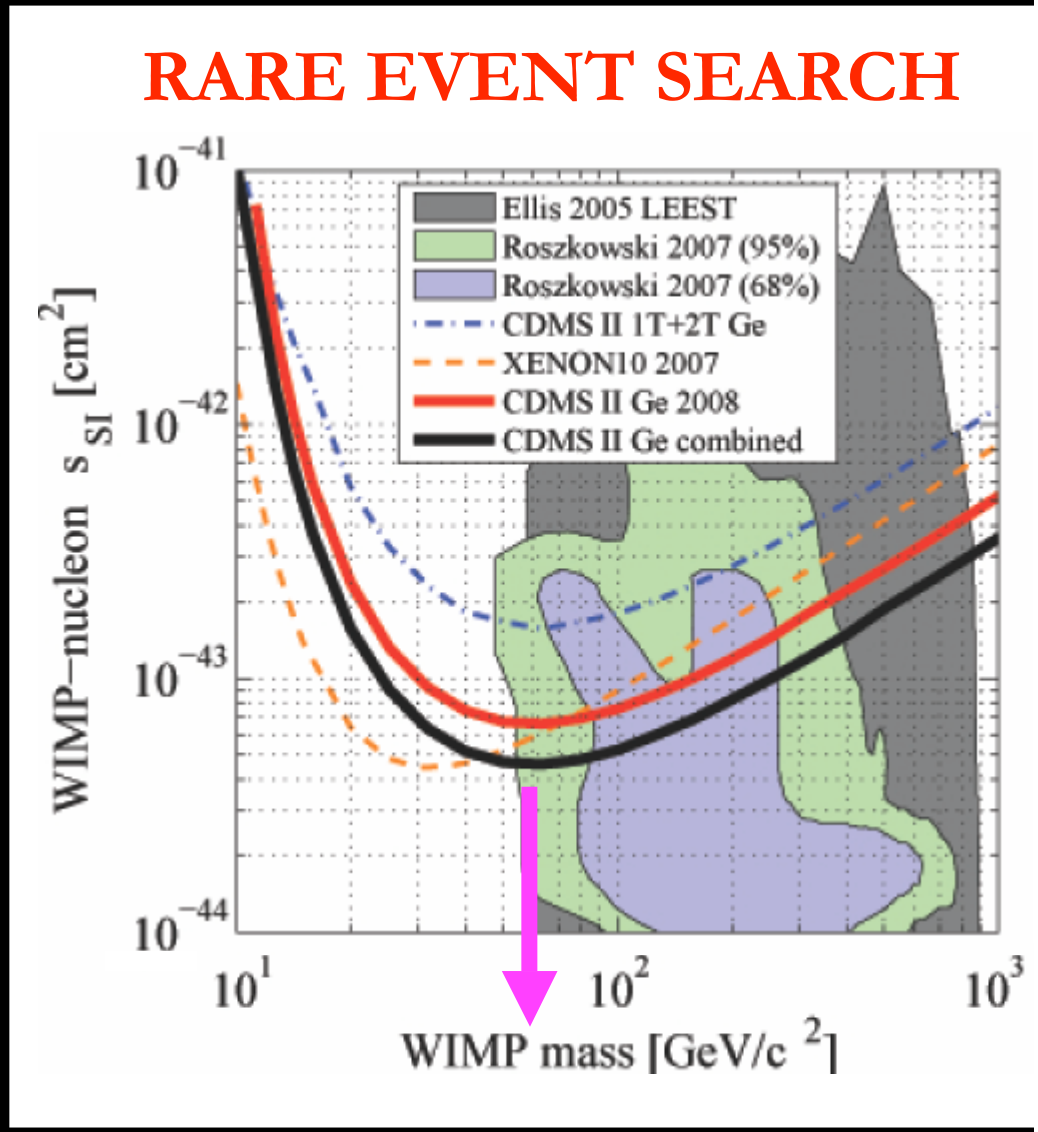
- Six successful data runs so far, first two analyzed *(all exposures before cuts)*
  - Run 123 (Oct06 – Mar07): 430kg-d Ge
  - Run 124 (Apr07 – Jul07): 224kg-d Ge
  - Run 125 (Jul07 – Jan08): 466kg-d Ge
  - Run 126 (Jan08 – Apr08): 273kg-d Ge
  - Run 127 (May08 – Aug08): 220kg-d Ge
  - Run 128 (Aug08 – Sep08): 108kg-d Ge
- **>2x the analyzed exposure, expect ~4x current reach by end of 2008 (~10^{-44} cm^2)**



SuperCDMS

- Increase Mass
- Decrease Background Leakage

As increase mass to explore more WIMP parameter space, need proportionate reduction in ability to reduce backgrounds

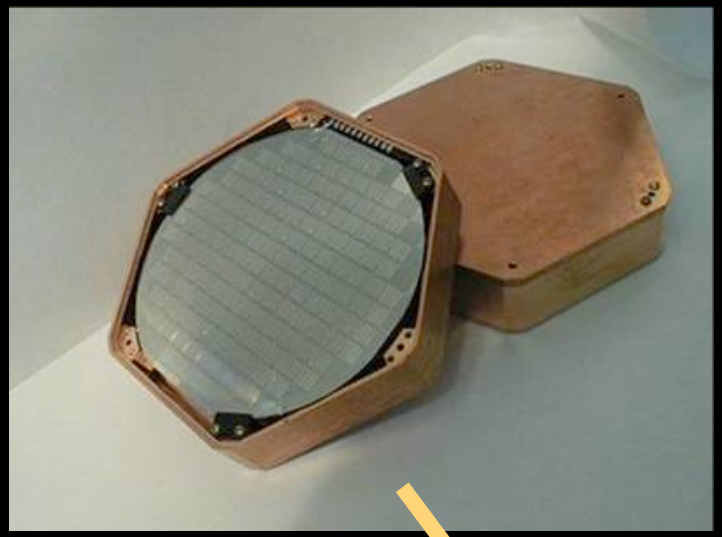


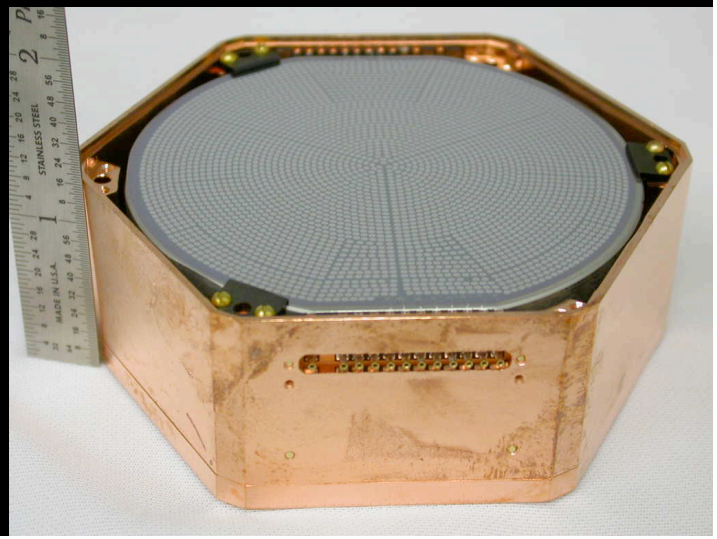
SuperCDMS

- New detectors for 2 new towers (12 detectors)
  - Improved background rejection (due to larger volume to surface ratio)
  - 2.5 times more mass per detector readout channel (1-inch thick instead of 1-cm thick)
  - Improved discrimination through phonon timing (due to new phonon collection system)

SuperCDMS Detector Design

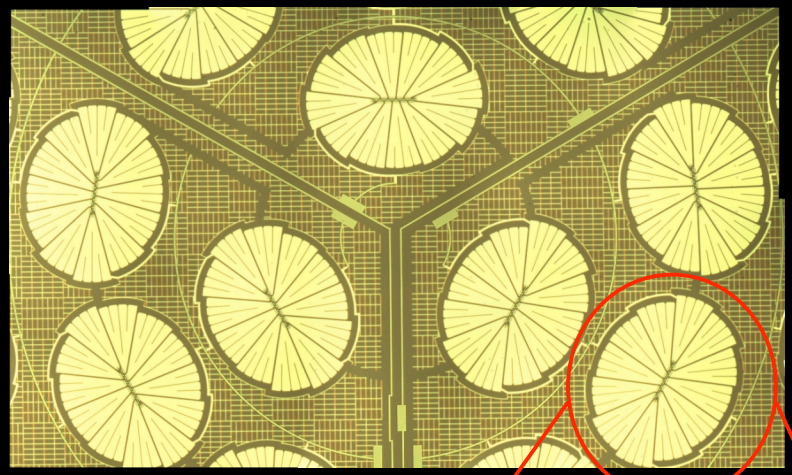
- 1 cm → 1 inch
  - Mass per channel
  - Surface / volume ratio

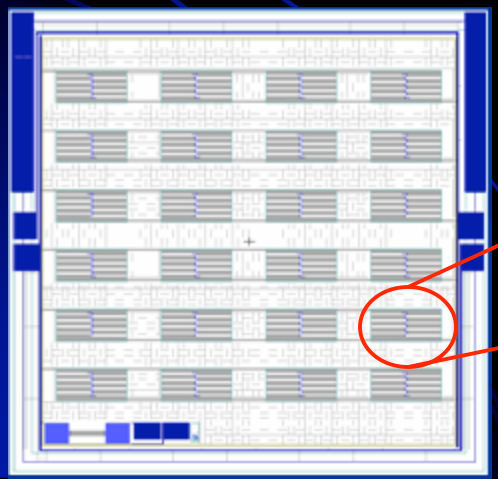


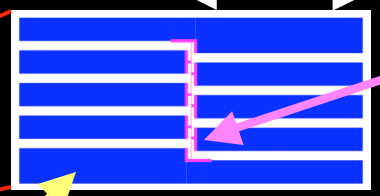


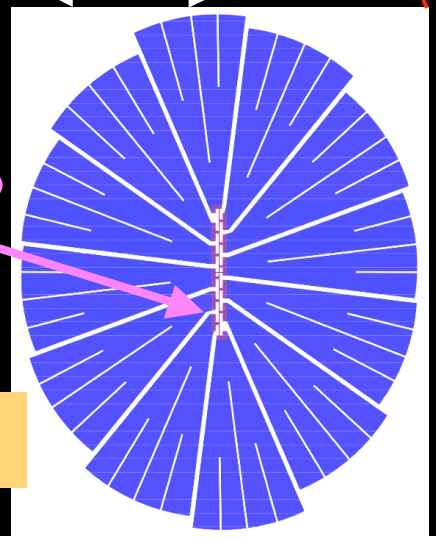
SuperCDMS Detector Design

- 1 cm → 1 inch
  - Mass per channel
  - Surface / volume ratio
- Phonon mask
  - Signal to noise (less passive Al)
  - Surface event discrimination



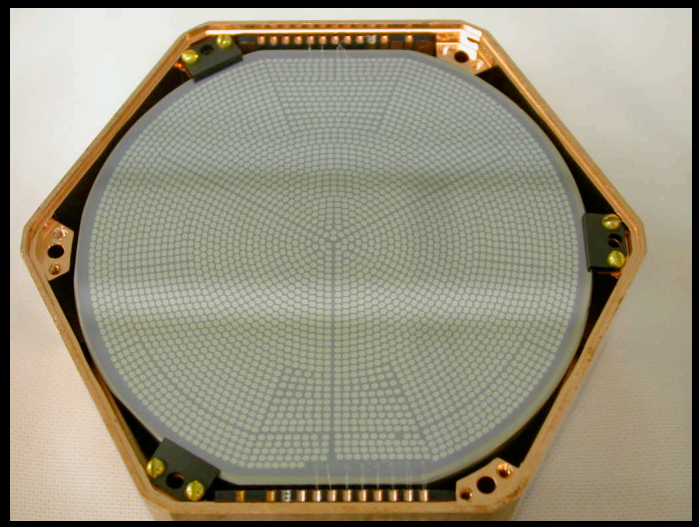




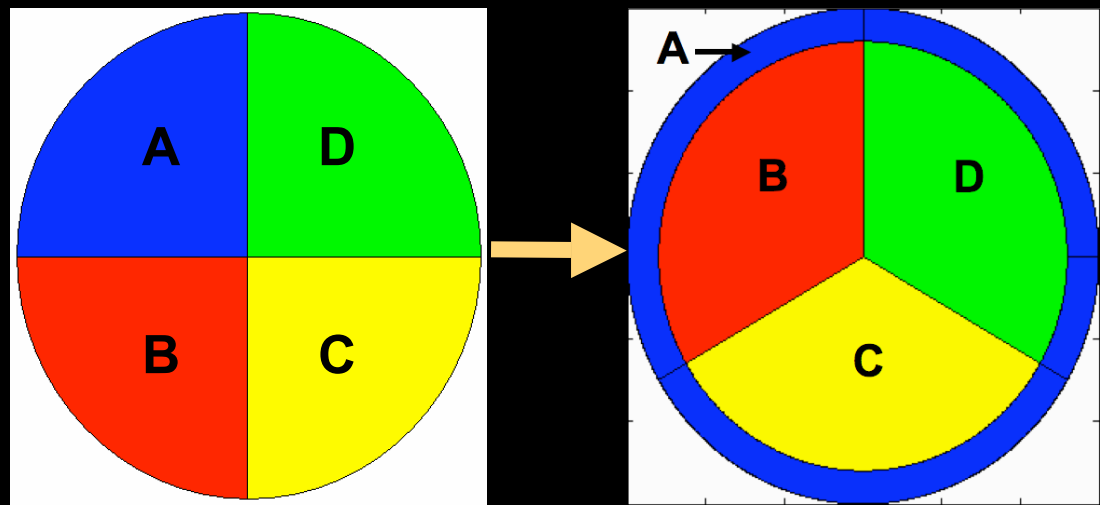


x2.5 Active Al

SuperCDMS Detector Design

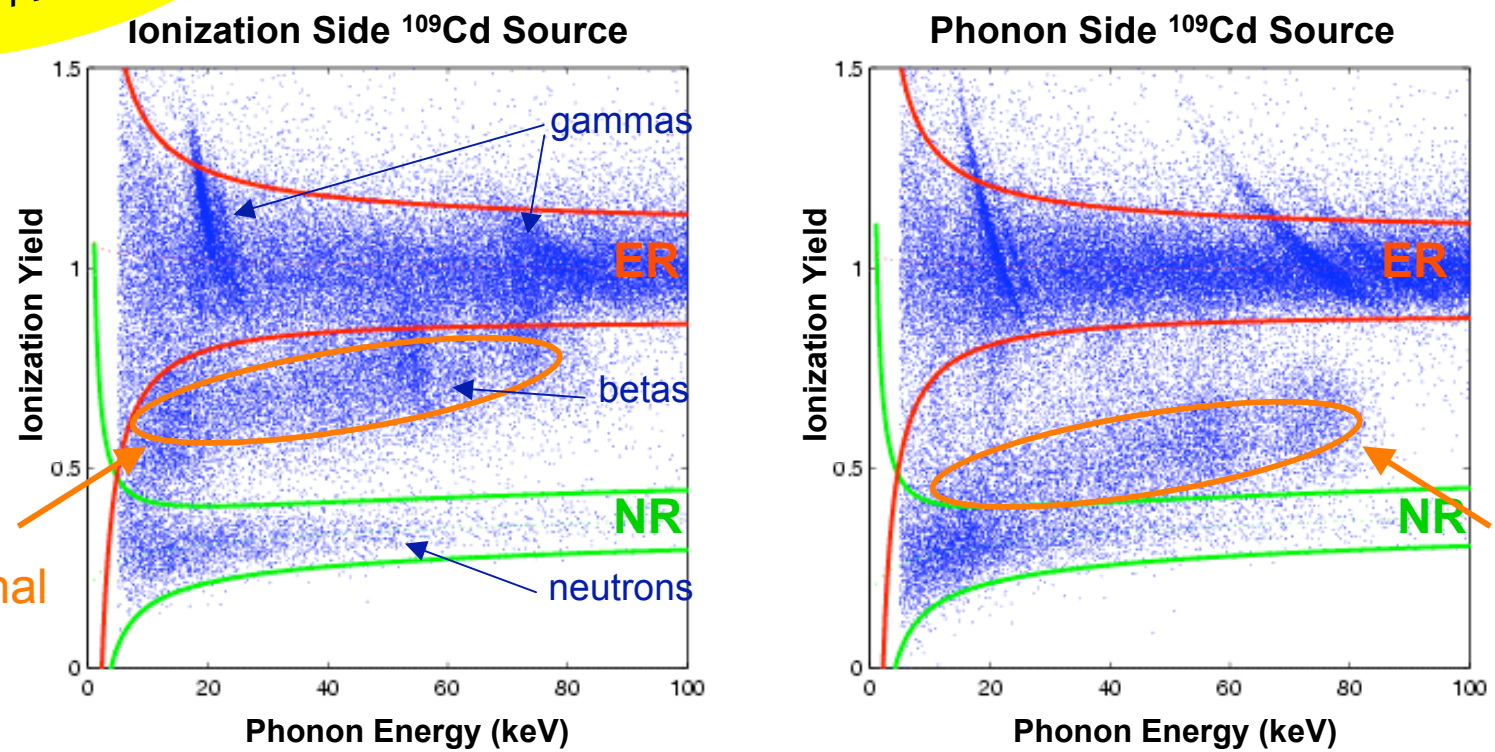


- 1 cm → 1 inch
  - Mass per channel
  - Surface / volume ratio
- Phonon mask
  - Signal to noise
  - Surface event discrimination
- Phonon sensor layout
  - Radial position information



CDMSII Yield Discrimination : Systematics

Ionization Yield = Ionization / recoil energy

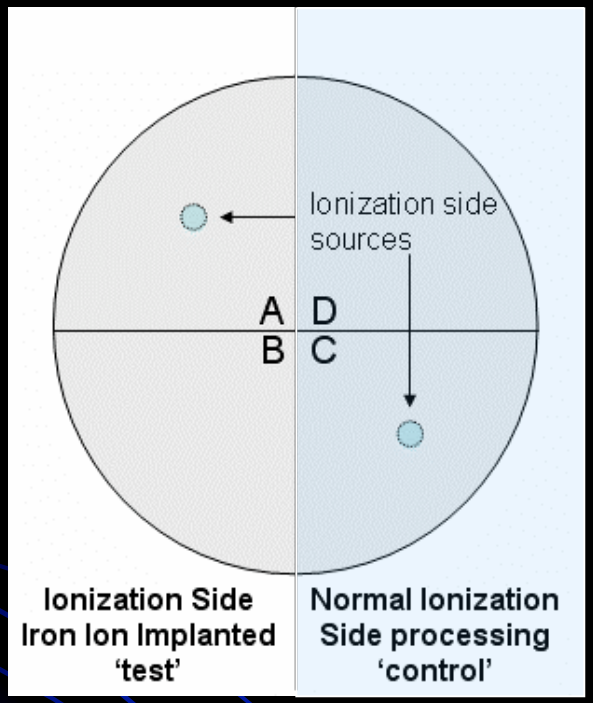


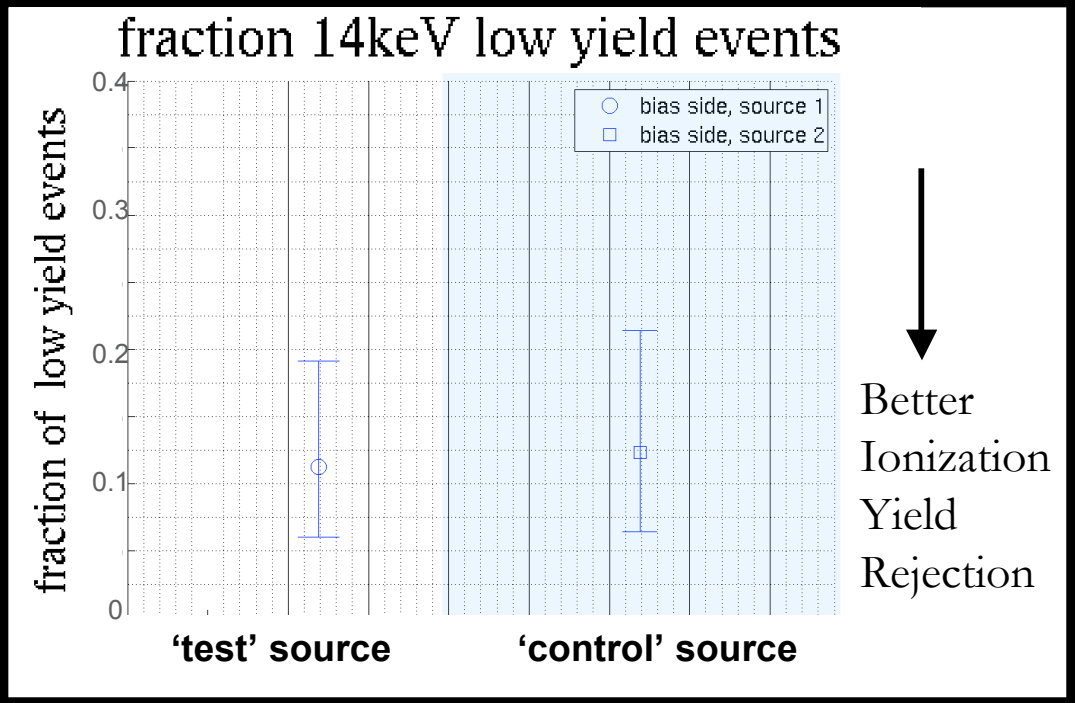
^{109}Cd surface events – separate from signal region

^{109}Cd surface events – leak into signal region

- Ionization Yield discrimination is worse for phonon side events than ionization side events
- Phonon timing provides rejection of phonon side events
- Goal : improve phonon side yield discrimination for SuperCDMS

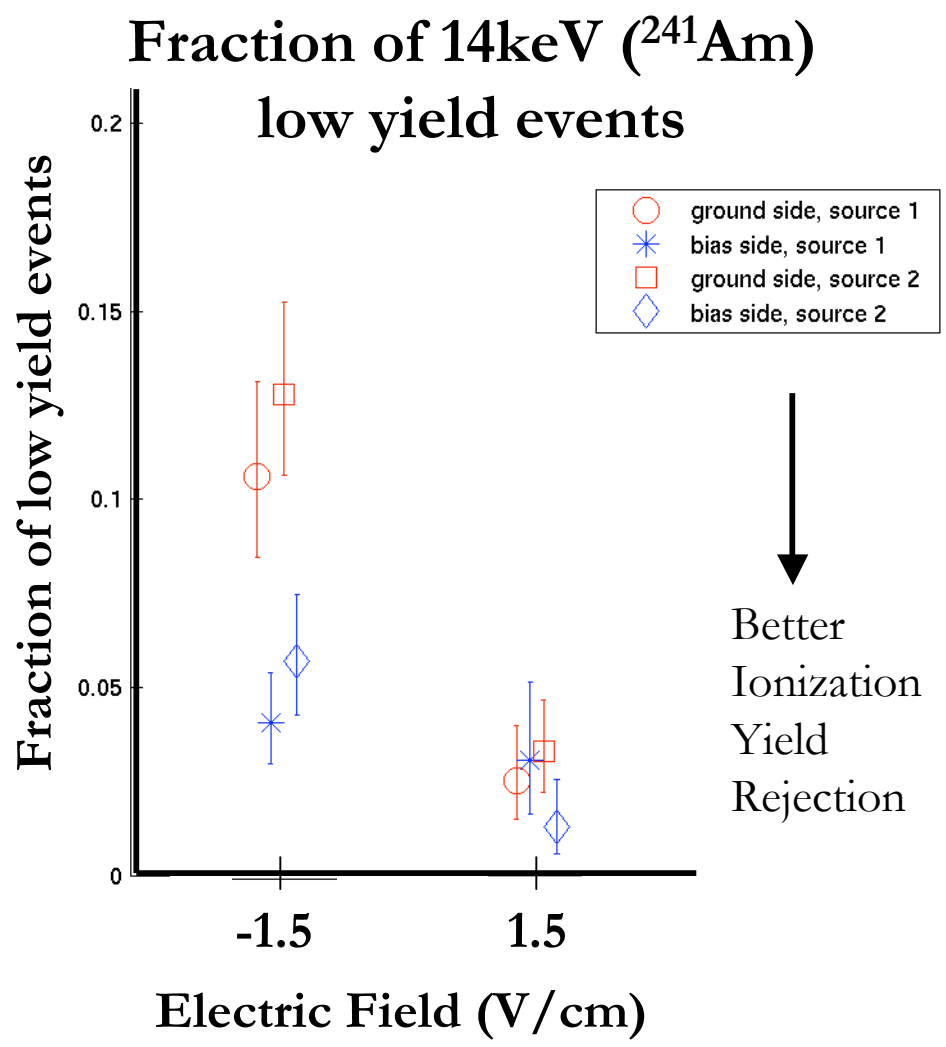
Yield Discrimination : finding the culprit?



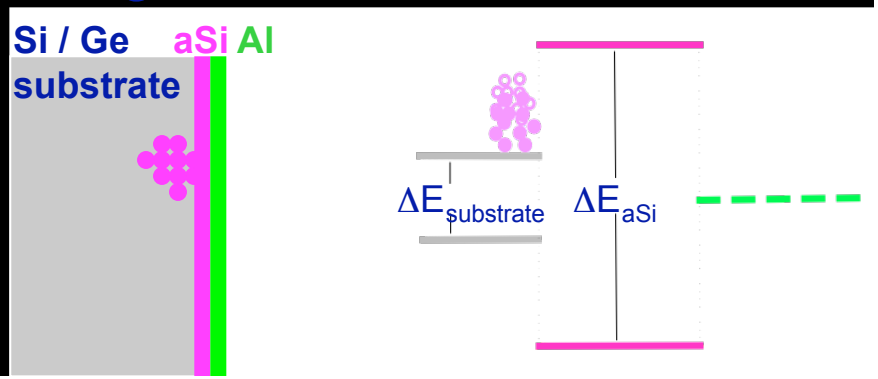


- Iron Ion Implantation used on phonon side of detector to create uniform W TES Tc across entire detector
- Induced lattice defects source of yield discrimination asymmetry? – No.

Yield Discrimination : Hydrogenation of aSi contacts

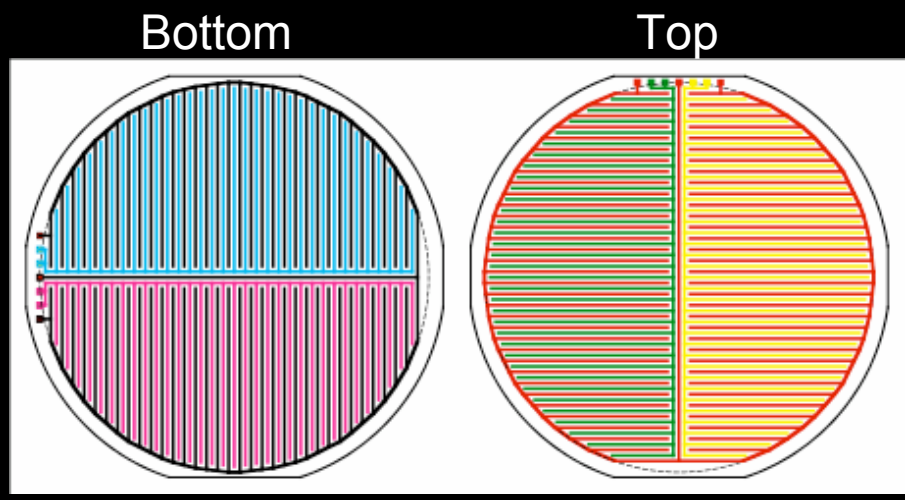


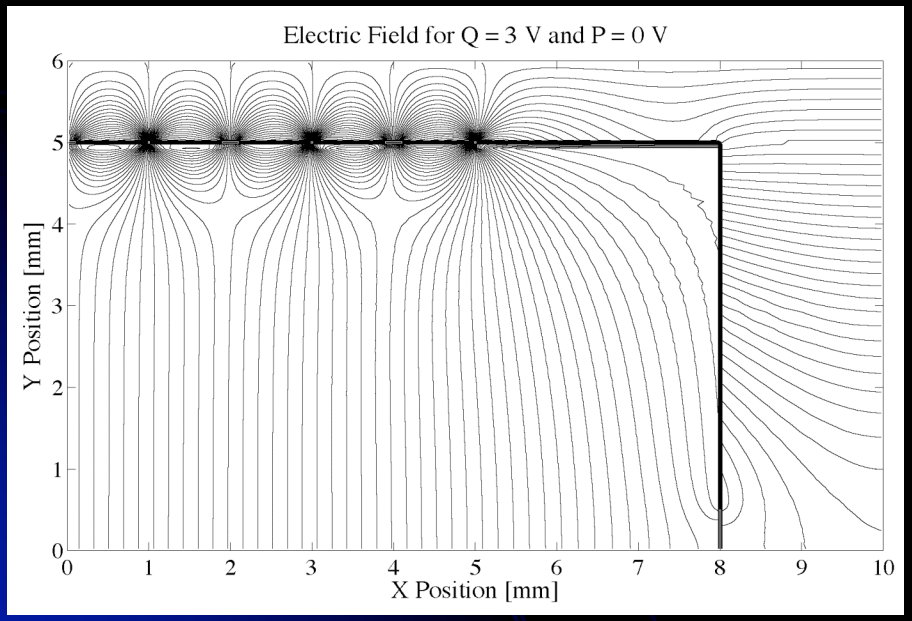
- Test on silicon substrate
- No phonon / charge side yield asymmetry seen for positive bias!
- Positive bias gives better yield rejection than negative bias
- Does this work with germanium substrates?

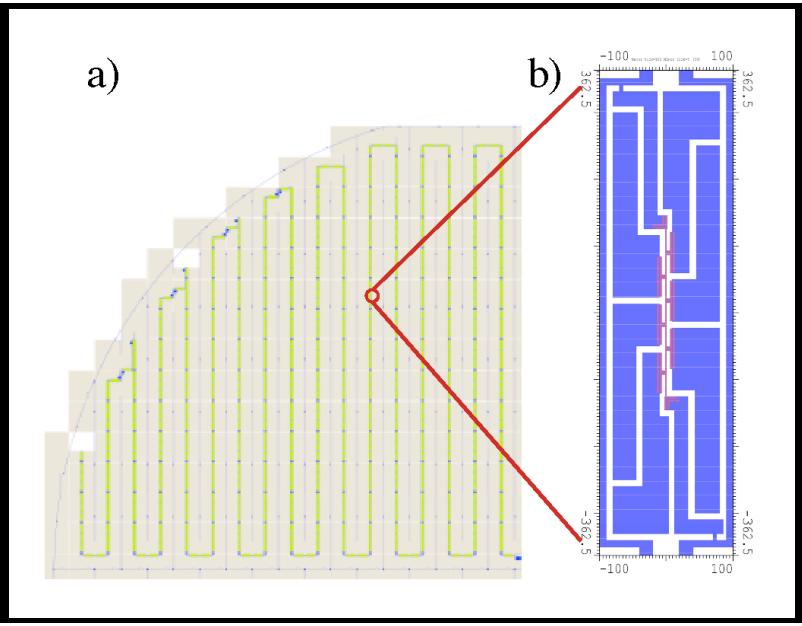


SuperCDMS – beyond 25kg interleaved ZIP (iZIP)

- Surface event discrimination through charge collection
- Phonon sensors and charge electrodes interleaved together

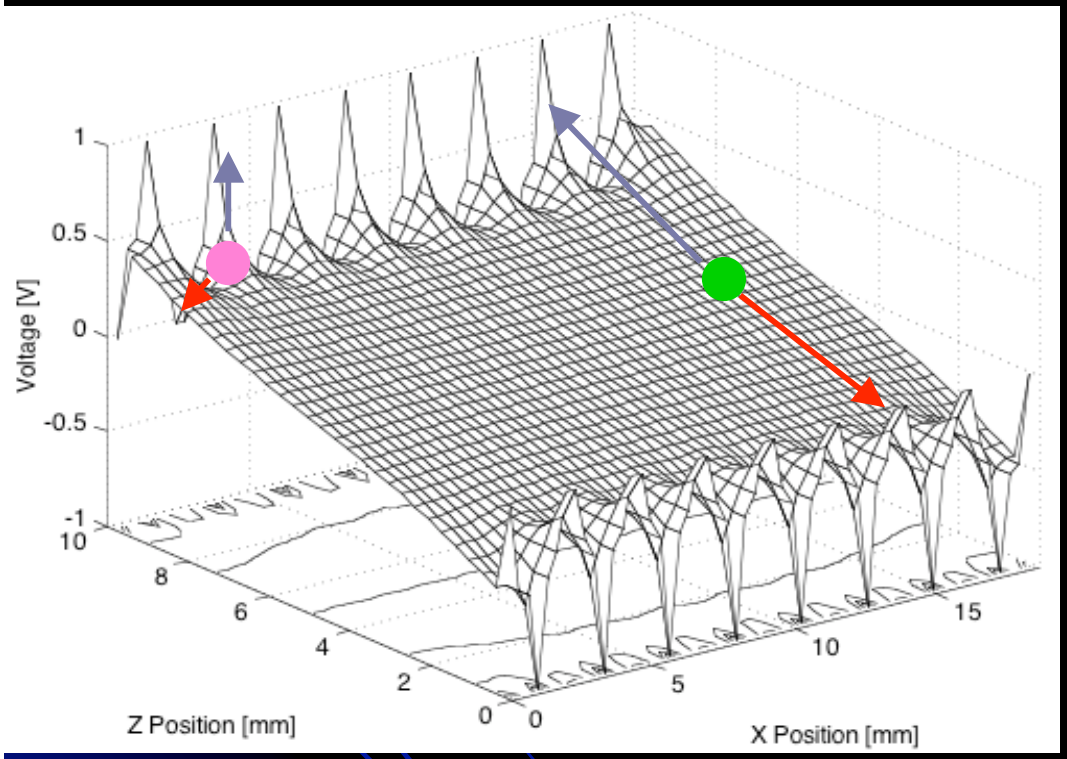


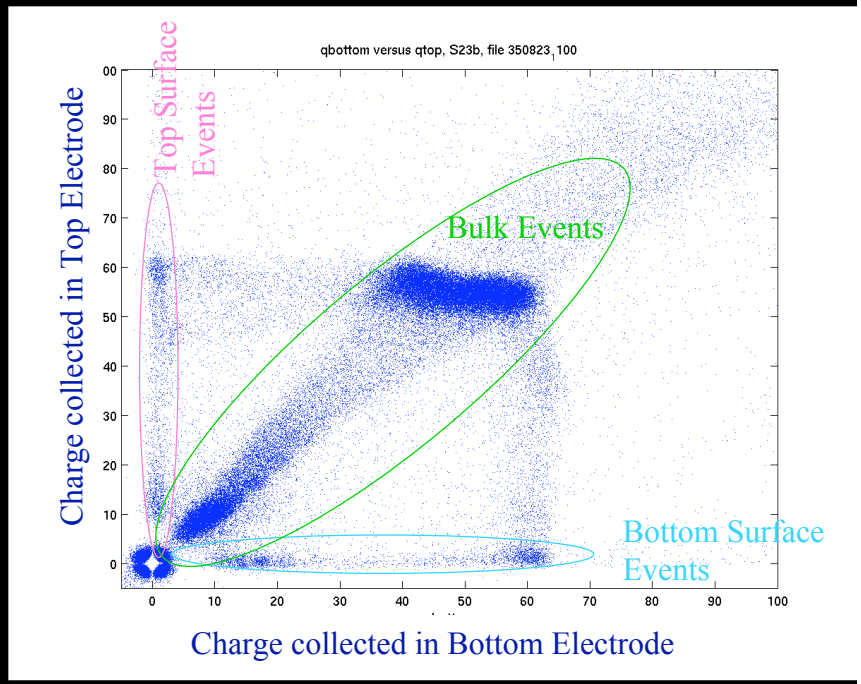


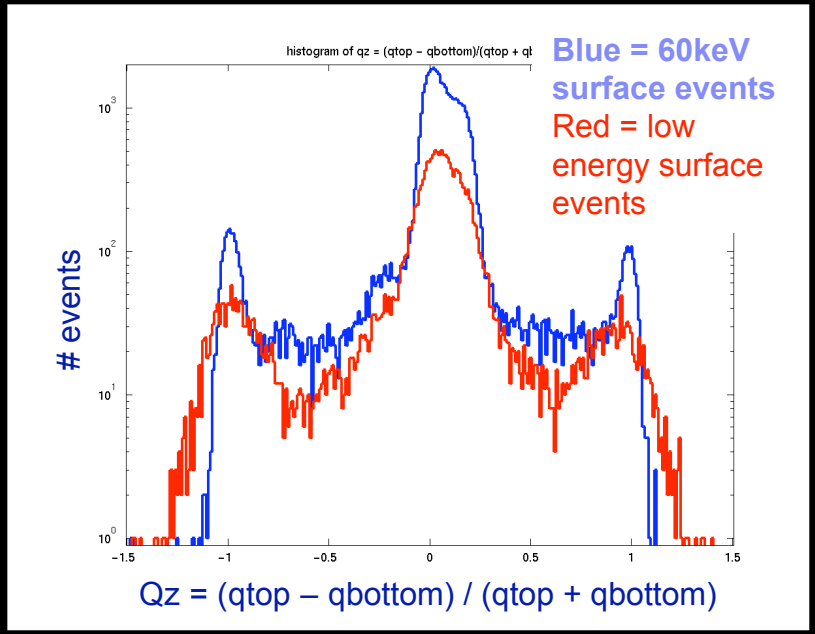


P. Luke

iZIP





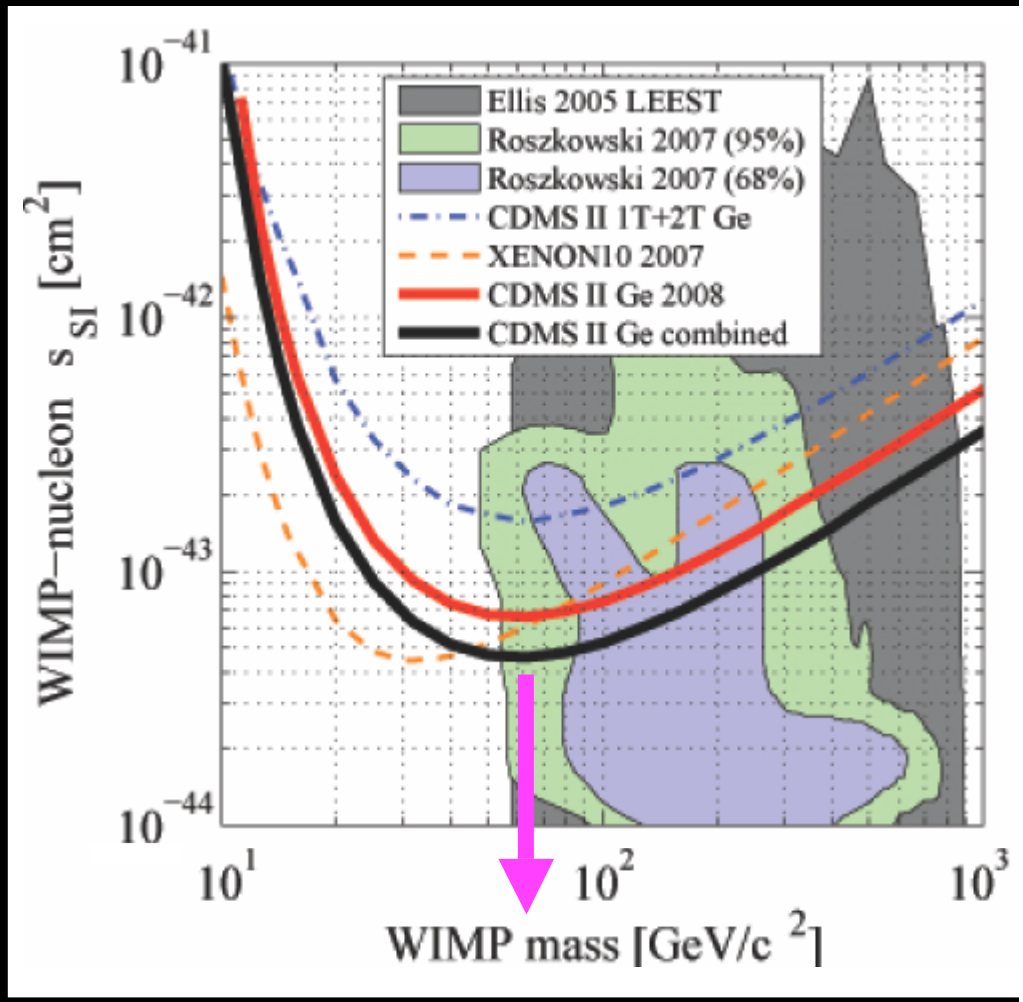


B. Cabrera

(Stanford University)

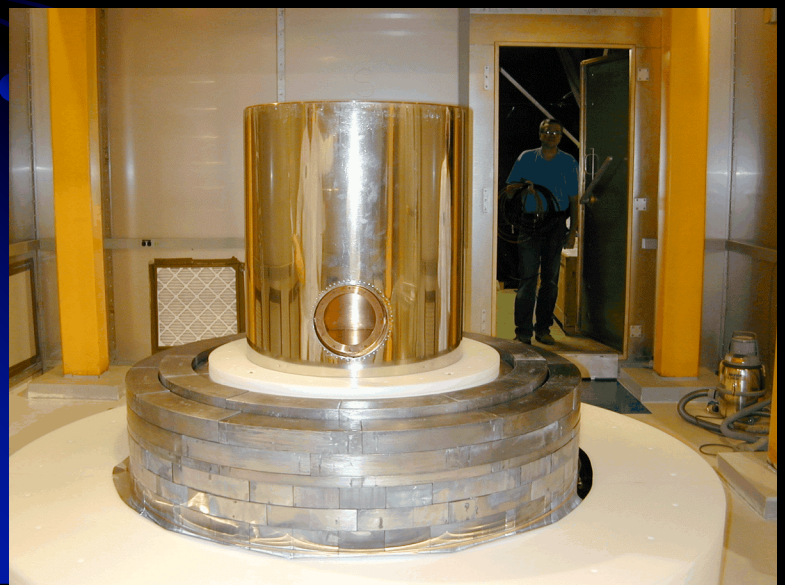
Conclusions

- World's best limits on WIMP dark matter properties above 44 GeV/c^2
- Data already taken and currently undergoing analysis to improve limits by ~4x
- Exciting detector modifications and R&D for the next generation of dark matter results



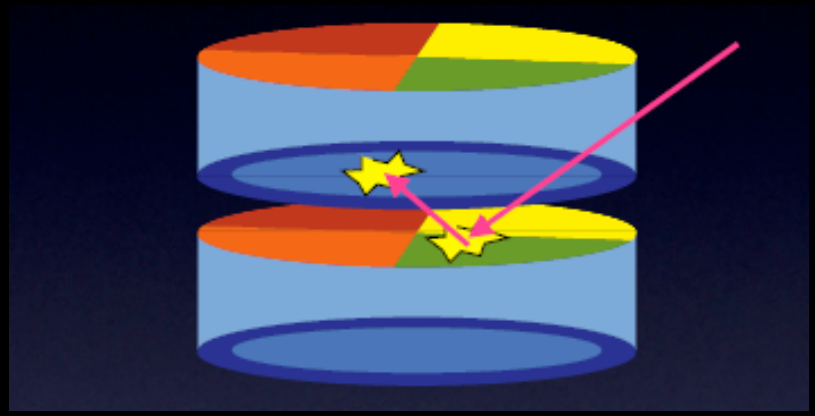
Rate Reduction

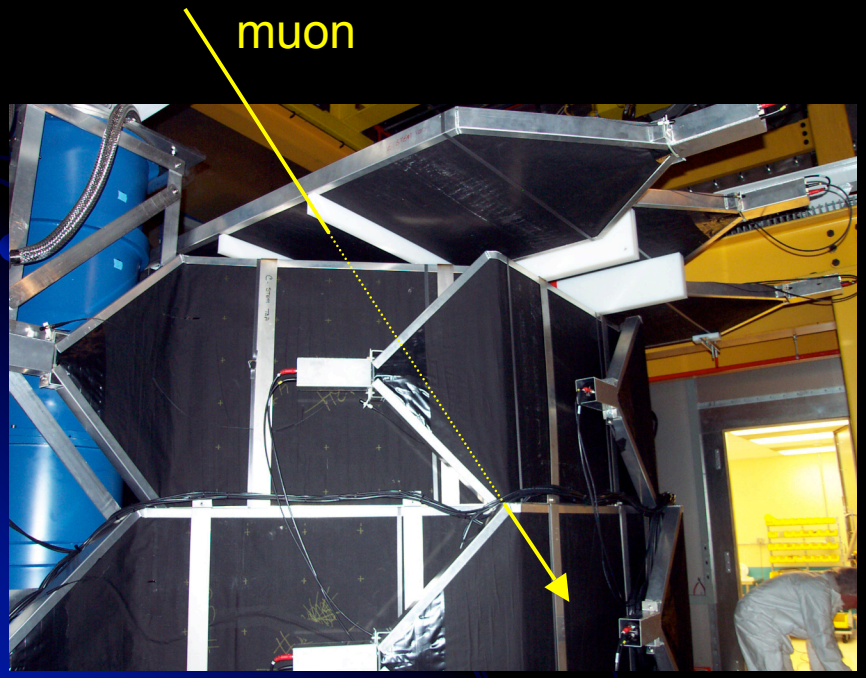
- 2700 mwe depth
- Passive Lead and polyethylene shielding
- Low-activity copper environment



Multiplicity

- Signal above 4σ noise in one and only one detector



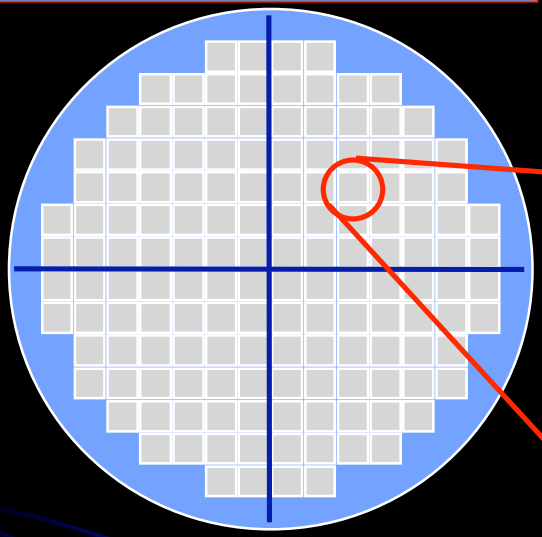


- No signal in surrounding scintillator shield

CDMS II ZIP Detectors : Z-coordinate Ionization & Phonon Detector

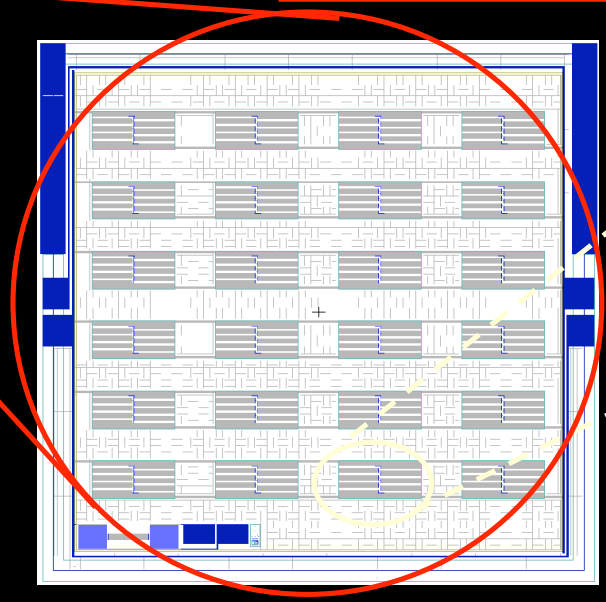
Detectors

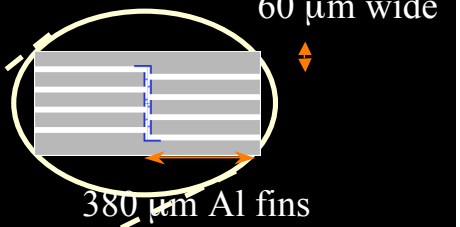
- 250 g Ge or 100 g Si crystal
- 1 cm thick x 7.5 cm diameter



Phonon Sensors

- Photolithographic patterning
- 4 quadrants
- 37 cells per quadrant
- 6x4 array of W transition-edge sensors per cell
- Each W sensor "fed" by 8 Al fins

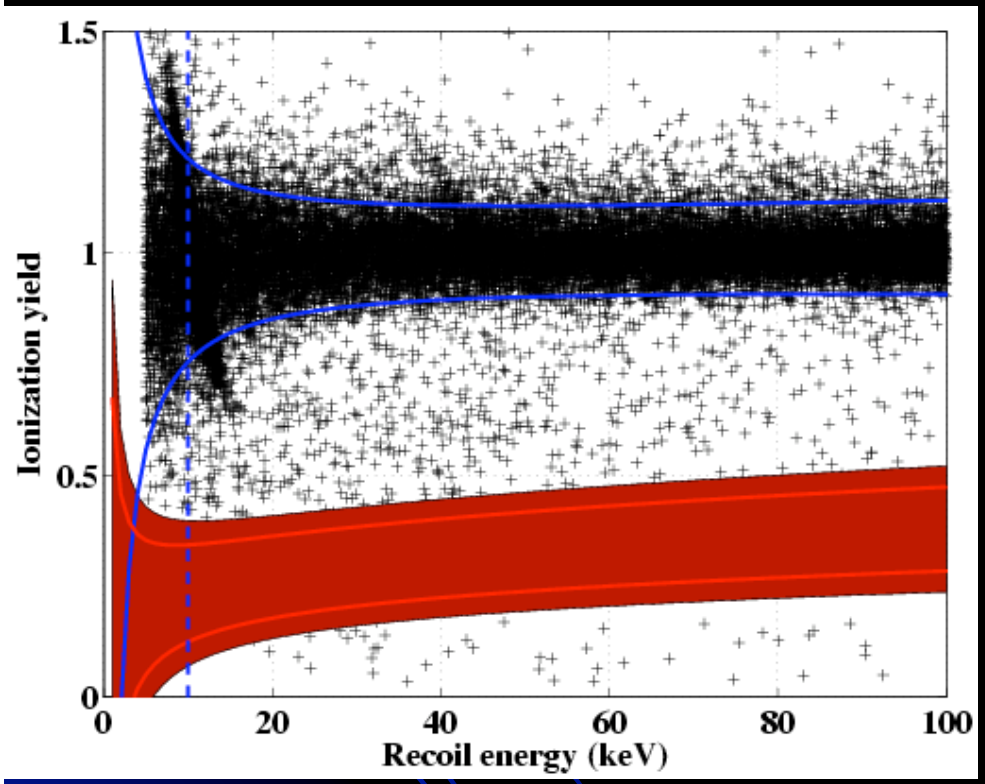




Charge Sensors

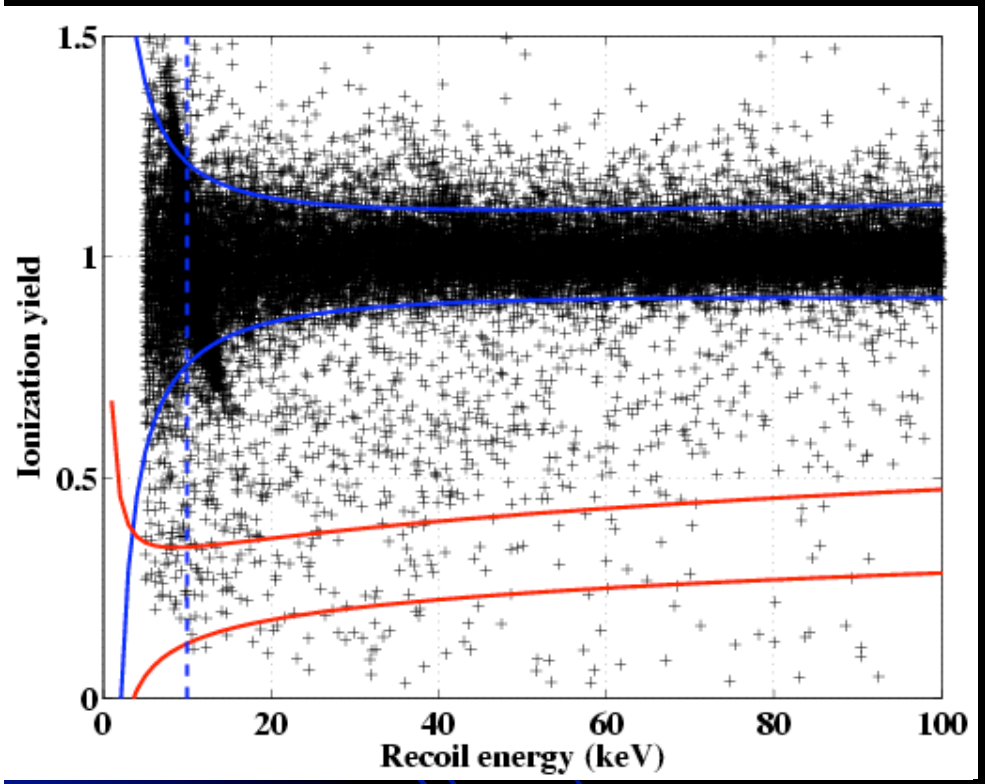
- 2 electrodes (+ ground)
- Allow rejection of events near outer edge

Leakage Estimation



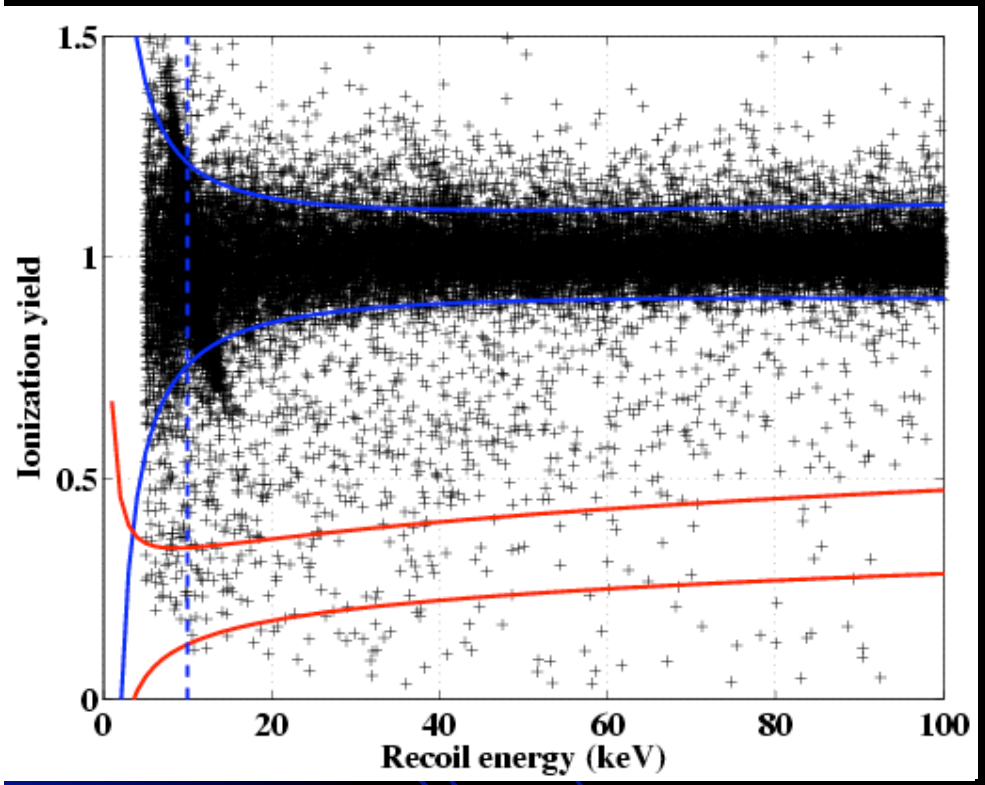
- Estimate using area around the masked WIMP search region
- Look at NR band in unblinded WIMP search data from previous runs
- Look at NR band in barium calibration data, taking systematics into account

Leakage Estimation



- Estimate using area around the masked WIMP search region
- **Look at NR band in unblinded WIMP search data from previous runs**
- Look at NR band in barium calibration data, taking systematics into account

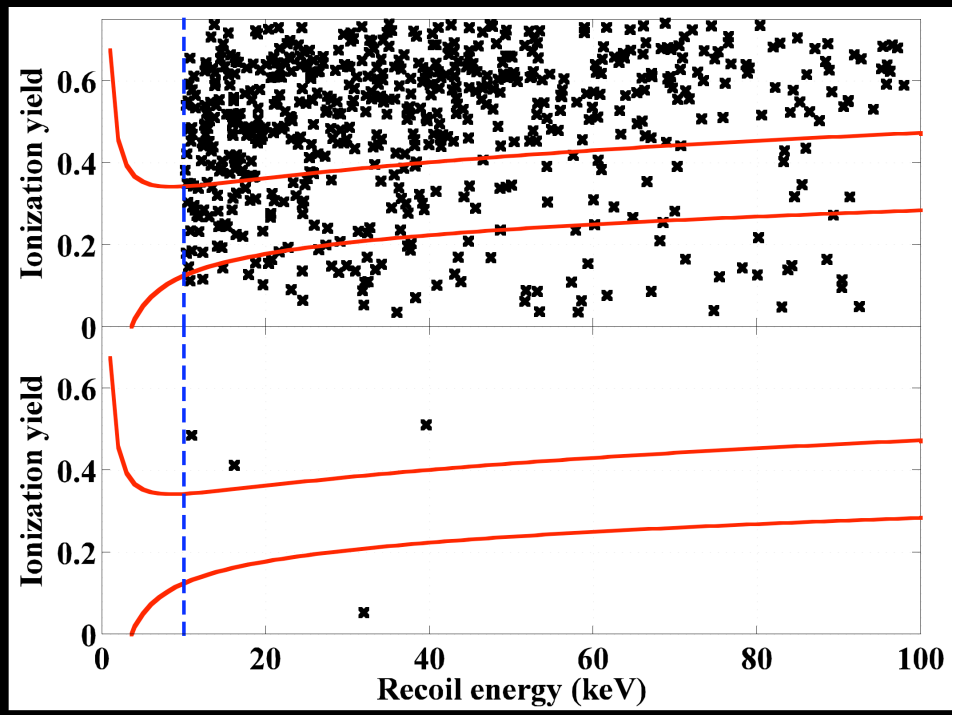
Leakage Estimation



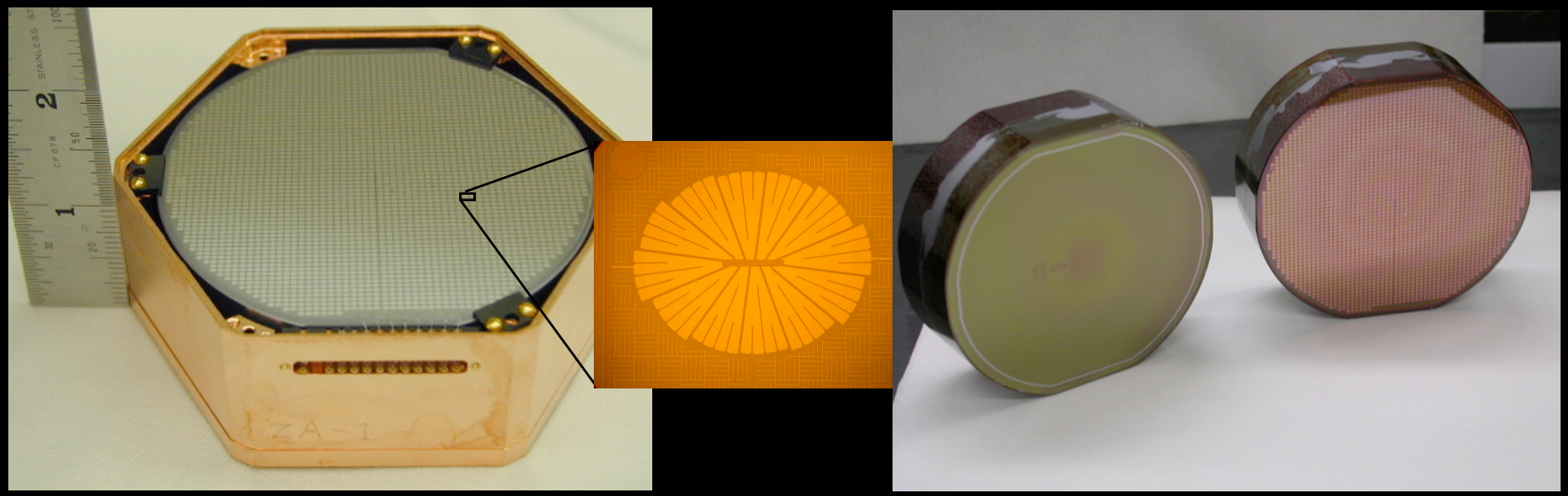
- Estimate using area around the masked WIMP search region
- Look at NR band in unblinded WIMP search data from previous runs
- Look at NR band in barium calibration data, taking systematics into account

Analysis

- Blind analysis
  - Reduction
    - Data processing
    - Position correction
    - Calibration
  - Data Quality
    - Periods of poor noise, incomplete neutralization
    - Bad detector regions
    - Reconstruction failures
  - Physics
    - Veto-anticoincidence
    - Single-scatter
    - Qinner (fiducial volume)
    - Ionization yield
    - Phonon timing



SuperCDMS ZIPs



- 2.5x detector mass (7.6 cm x **2.54 cm**, 600g)

=> *better volume/surface, faster manufacture*

- Single mask lithography

=> *more reliable manufacture, less testing time*

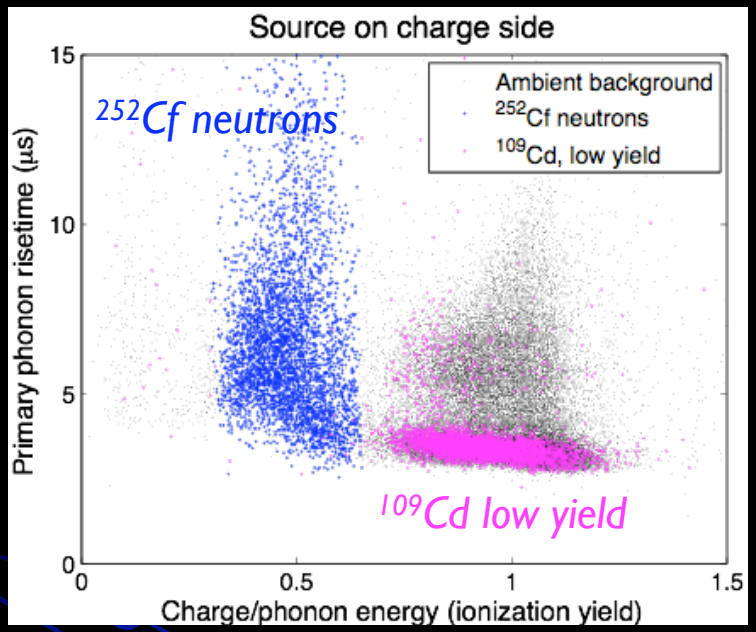
- Improved active Al coverage

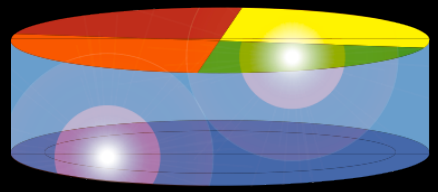
=> *better "antennas" for phonon collection*

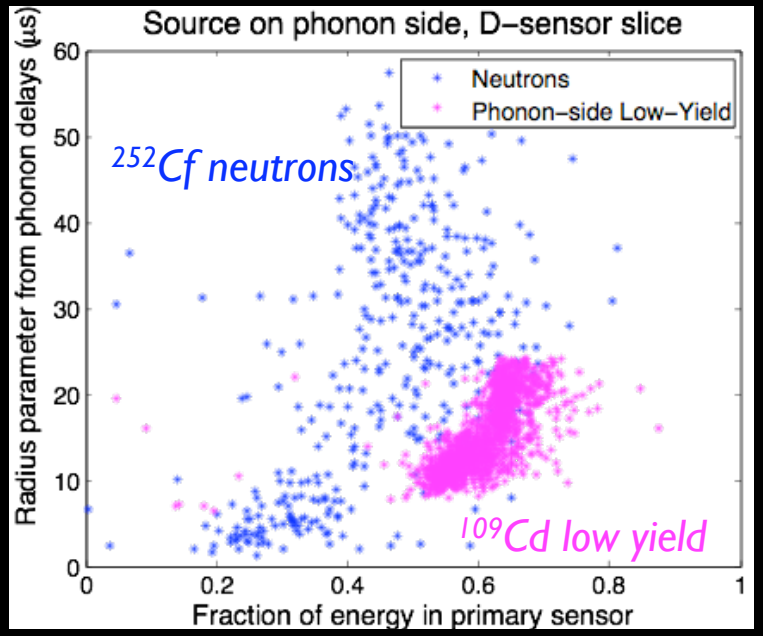
Also in development: new sensor configurations, double sided phonon sensors, electric field shaping, dislocation-free substrates, kinetic inductance technology, ...

First Characterizations

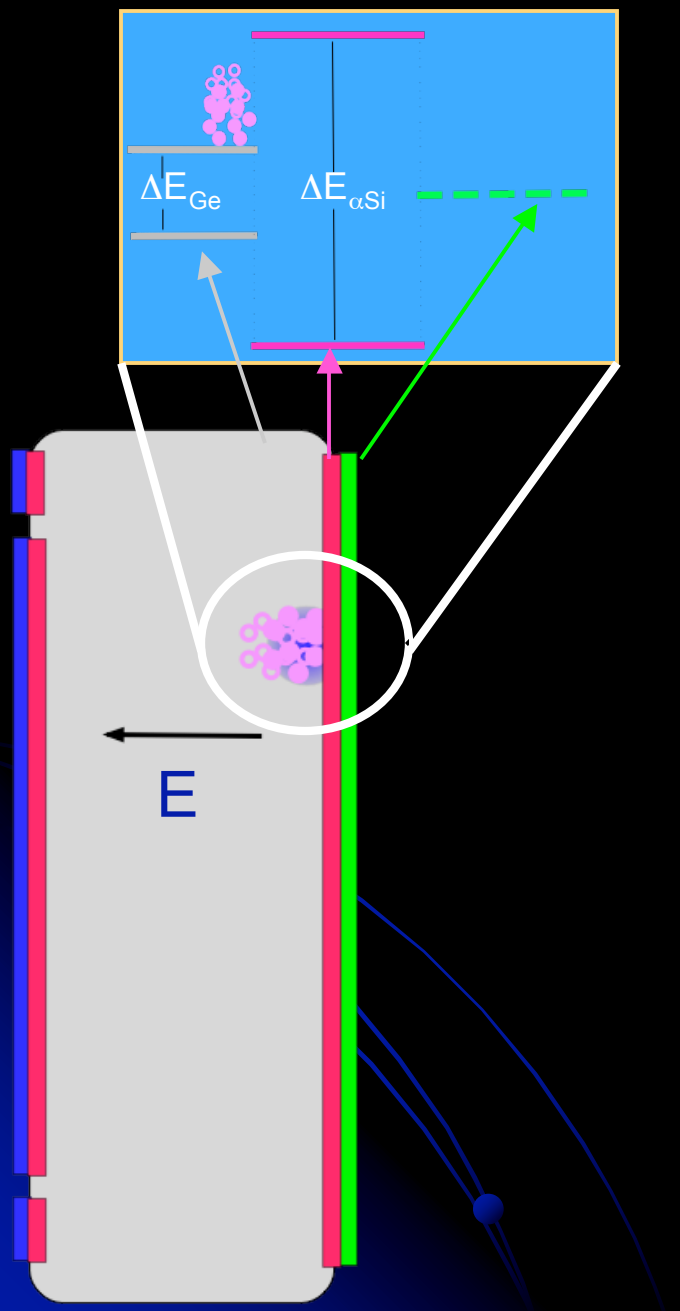
Cd-109 calibration of "G3D" at UC Berkeley (July 2007)







- Strong yield and timing discrimination on charge face
- Greatly enhanced phonon partition discrimination on phonon face

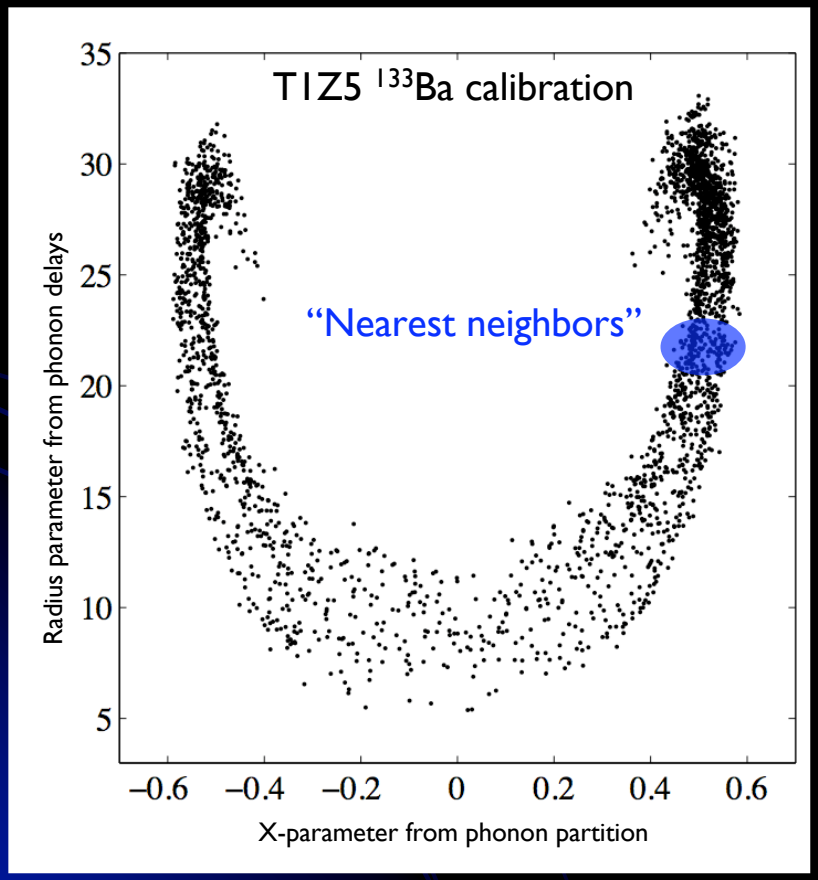


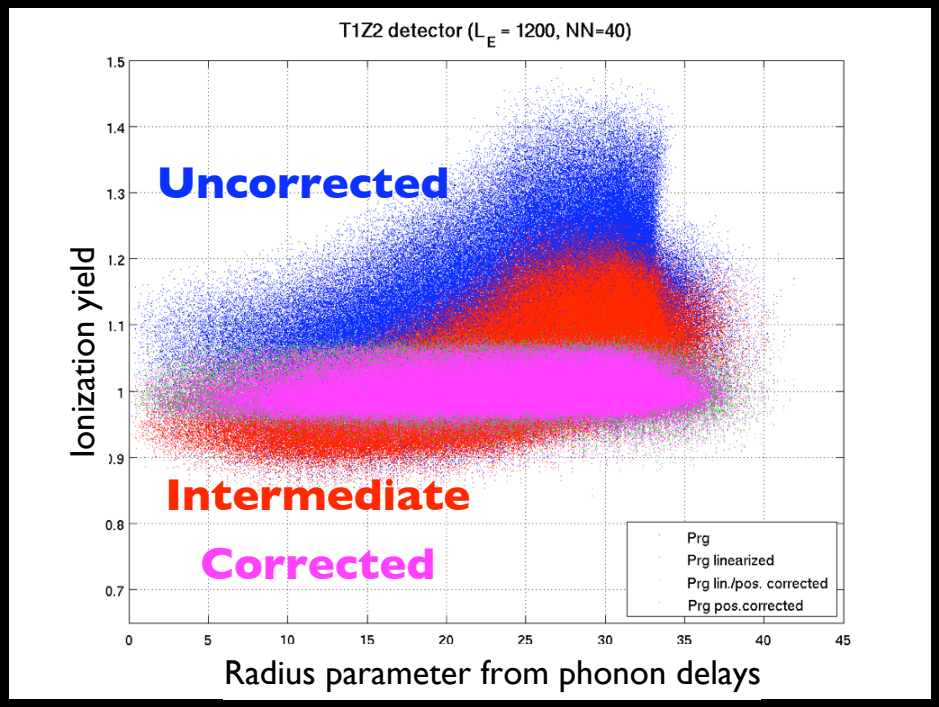
Hydrogenated aSi

- Previous experience suggests x2 better ionization yield based surface event rejection
- Previous CDMS detectors have a ~40nm aSi layer that was created in a 100% Ar environment.
- By sputtering aSi in a 20% H_2/ 80% Ar environment the aSi is passivated, increasing the barrier height for holes, reducing their back diffusion.

Parameter Correction

Correct "acoustics" by comparisons to neighbors in position parameters and energy





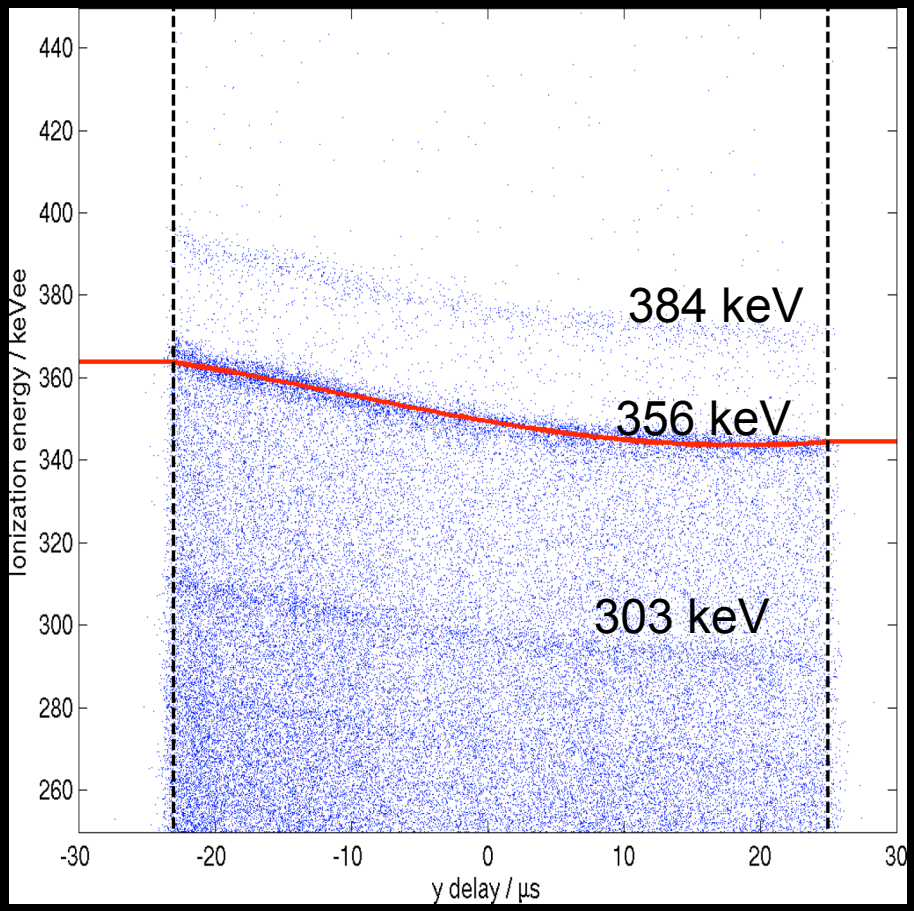
Why position matters: ionization

Ionization channels have weak position dependence (5%), as shown by 356-keV peak from ^{133}Ba.

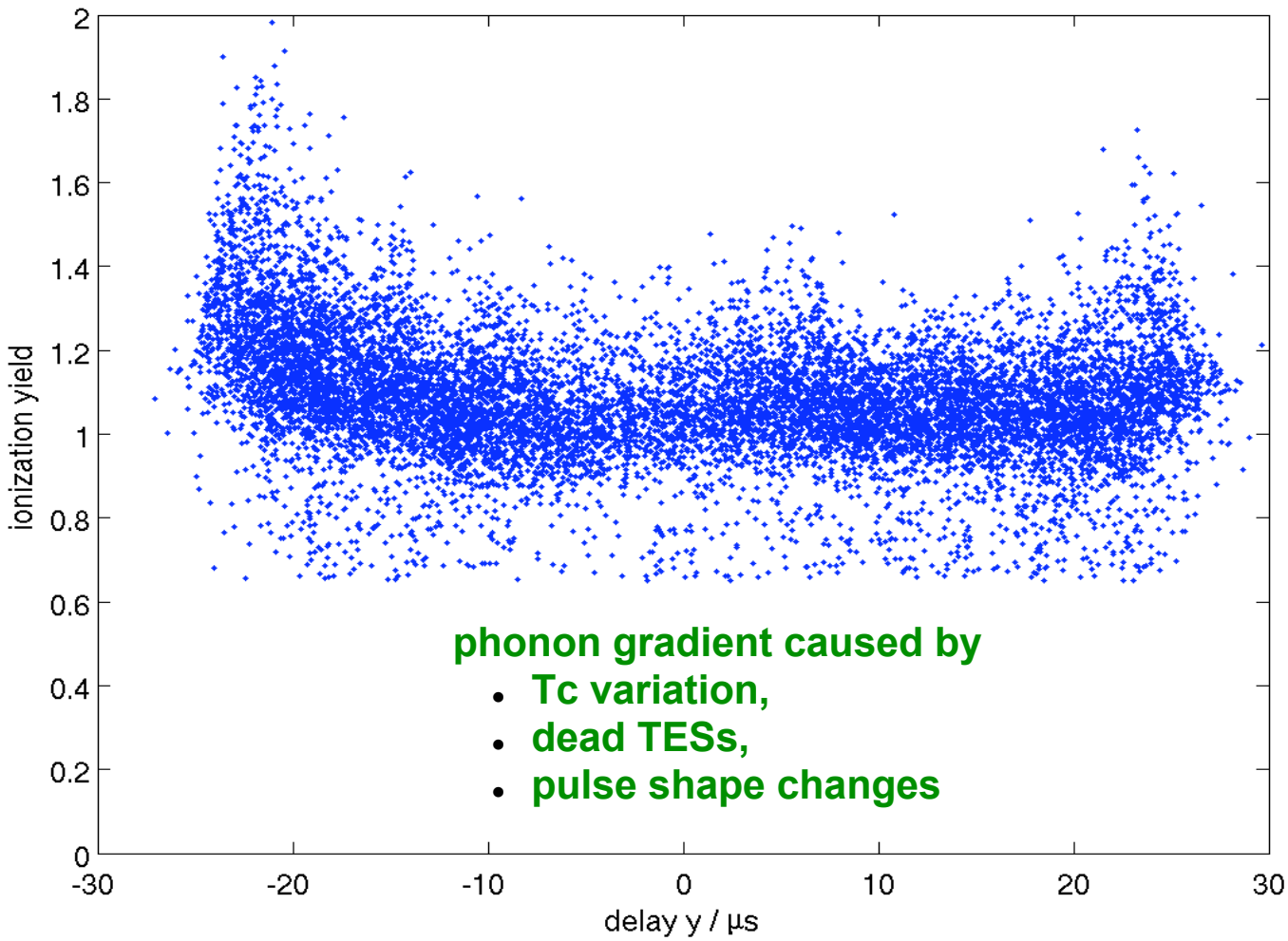
Dependence independent of energy, stable over time.

Origin: neutralization or metal films?

5% position dependence of ^{133}Ba peaks, germanium ZIP



Why position matters: phonons



phonon gradient caused by

- **Tc variation,**
- **dead TESs,**
- **pulse shape changes**

Lookup-table correction

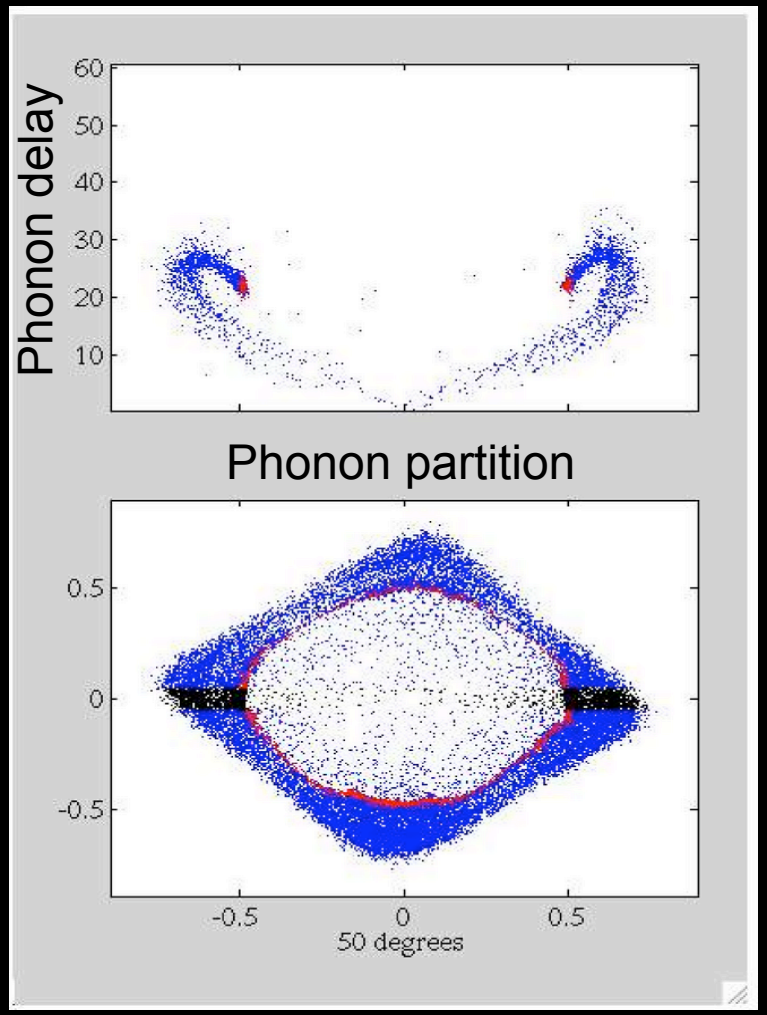
Make a manifold in 3D:
x and y from partition;
r from delay

This breaks degeneracy for good detectors

Events that are nearby in manifold space are also nearby in physical space

Use “neighborhoods” of gamma scatters from ^{133}Ba calibration as a lookup table

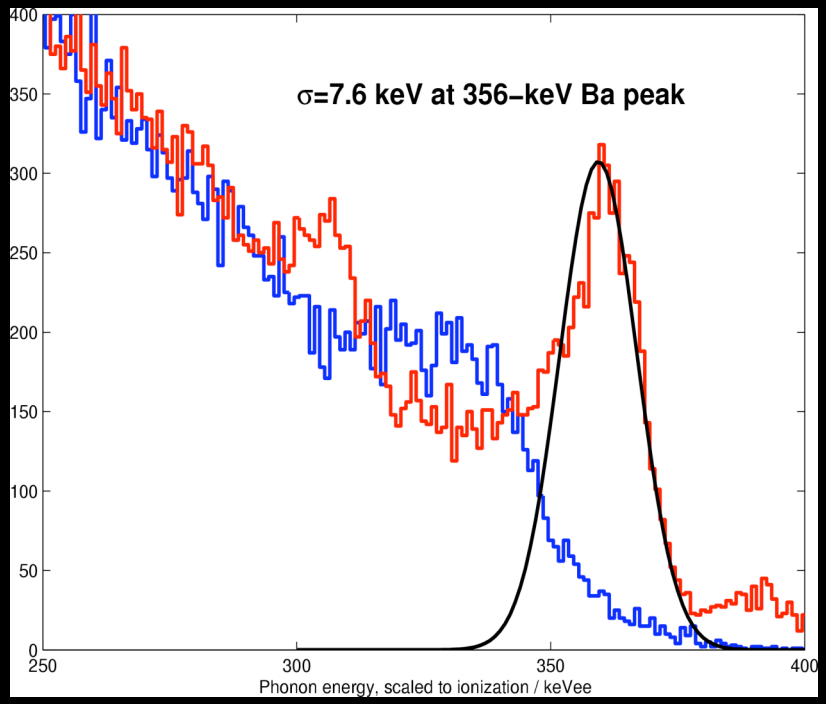
Apply scalings in every neighborhood to force phonon timing, yield to nominal values.

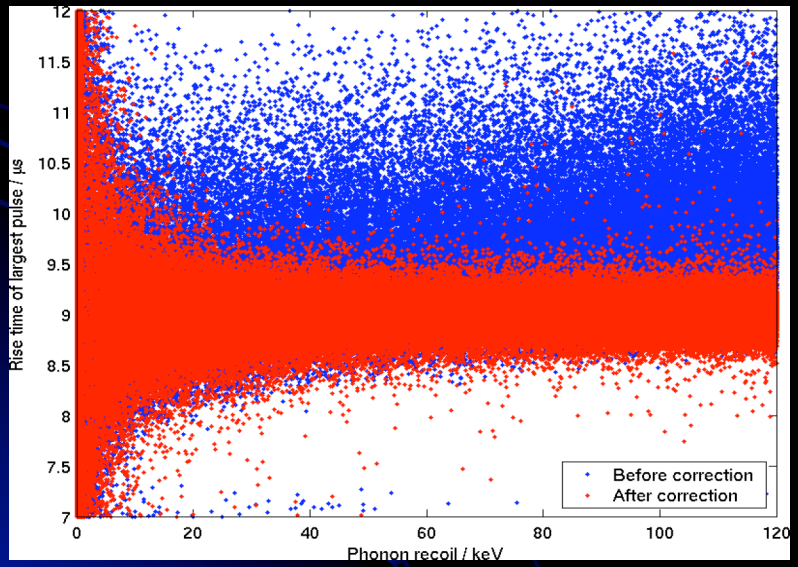


Lookup-table results

After position correction, resolution (Gaussian sigma) for best detectors is 8 keV (at 356 keV), 0.35 keV (at 10 keV).

Phonon timing parameters much more uniform after correction.

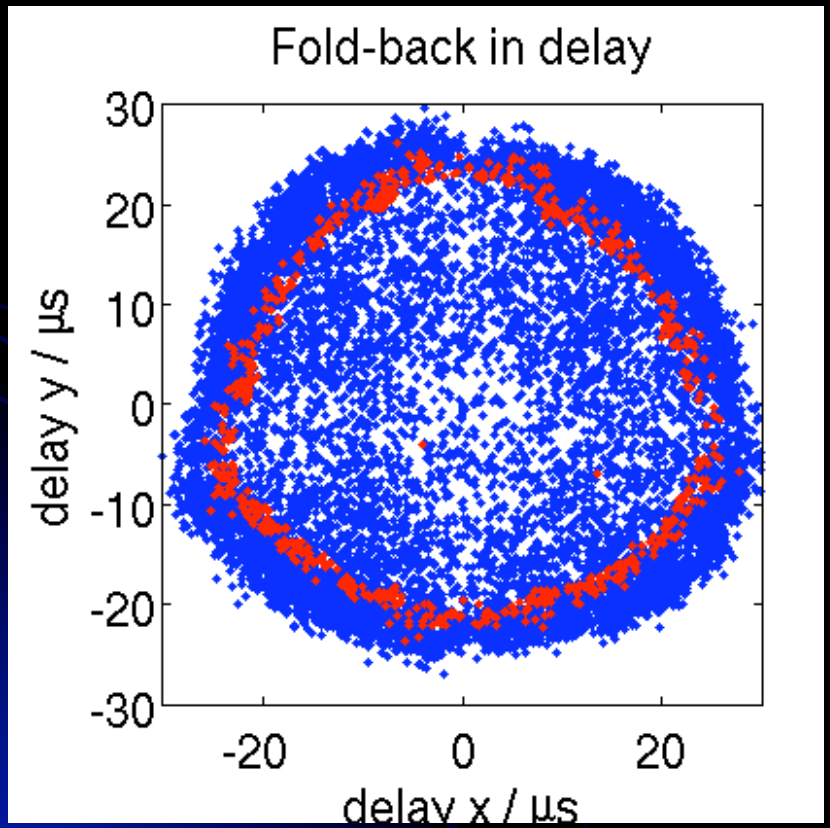


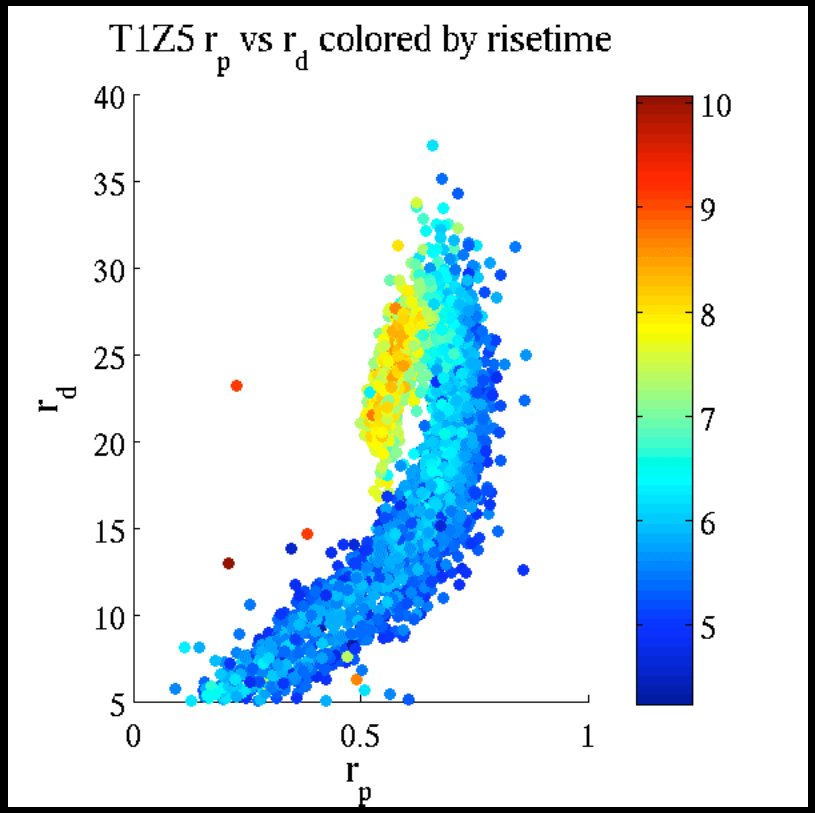


Position: not so easy!

blue = inner electrode (innermost 85% of area)
red = outer electrode (outer 15% of area)

Mis-identify nearest neighbor events
(low radius events used as a high radius neighbor event)



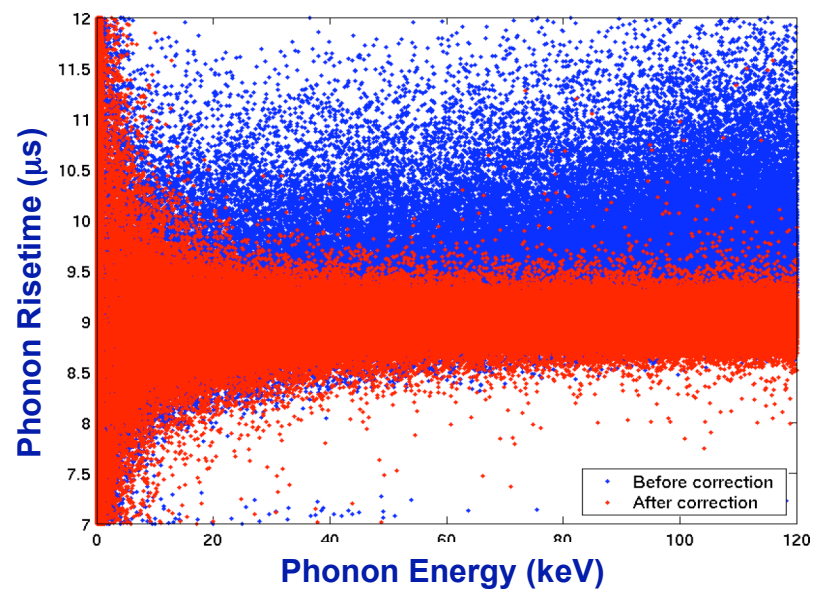


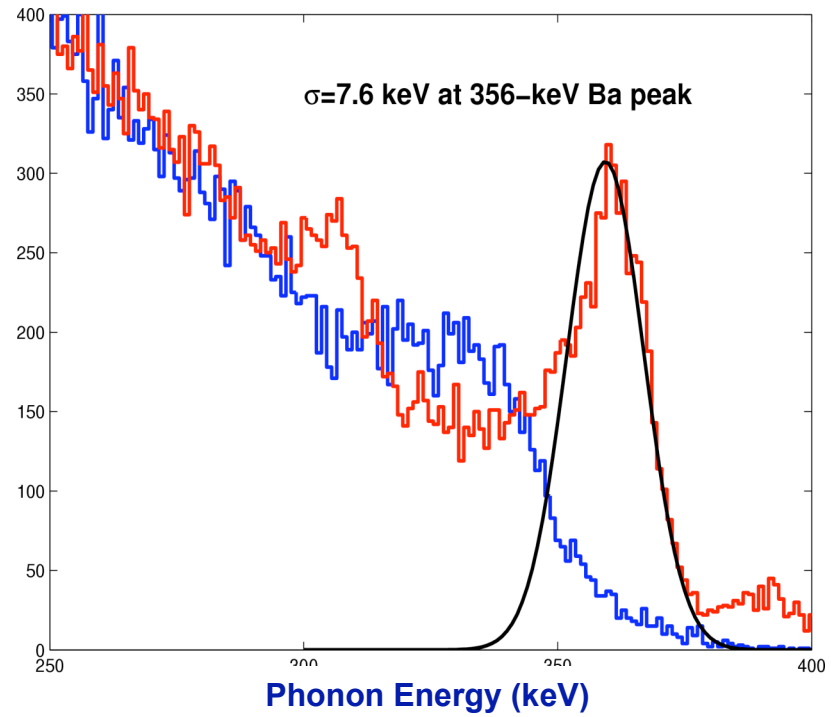
Parameter Position Correction

Correct "acoustics" by comparisons to neighbors in position parameters and energy

Blue = before correction

Red = after correction





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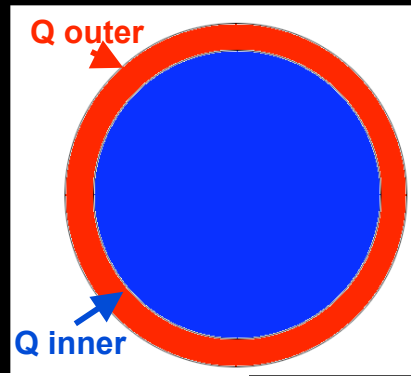

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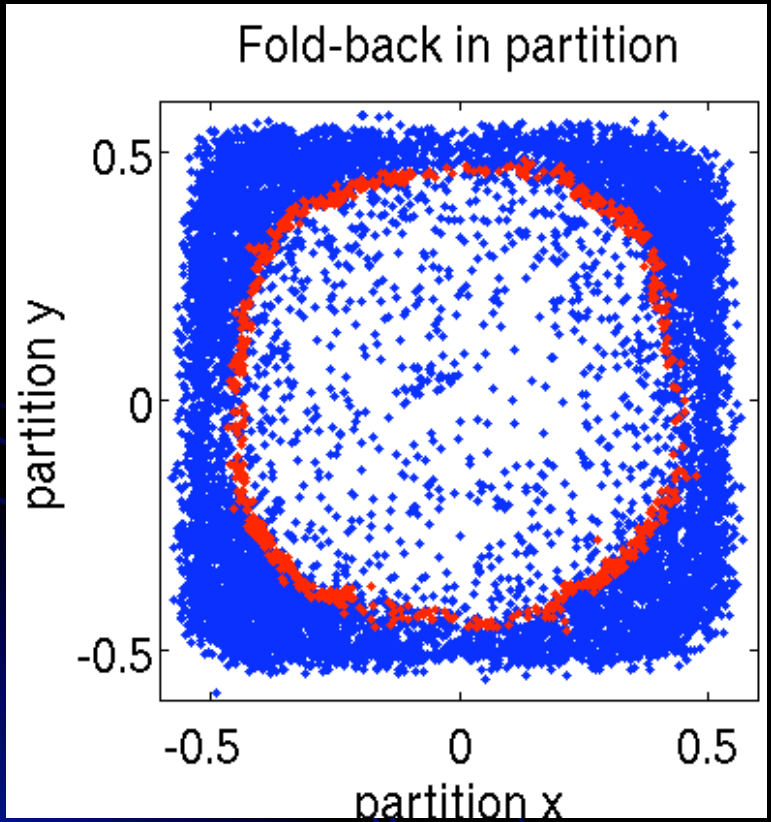

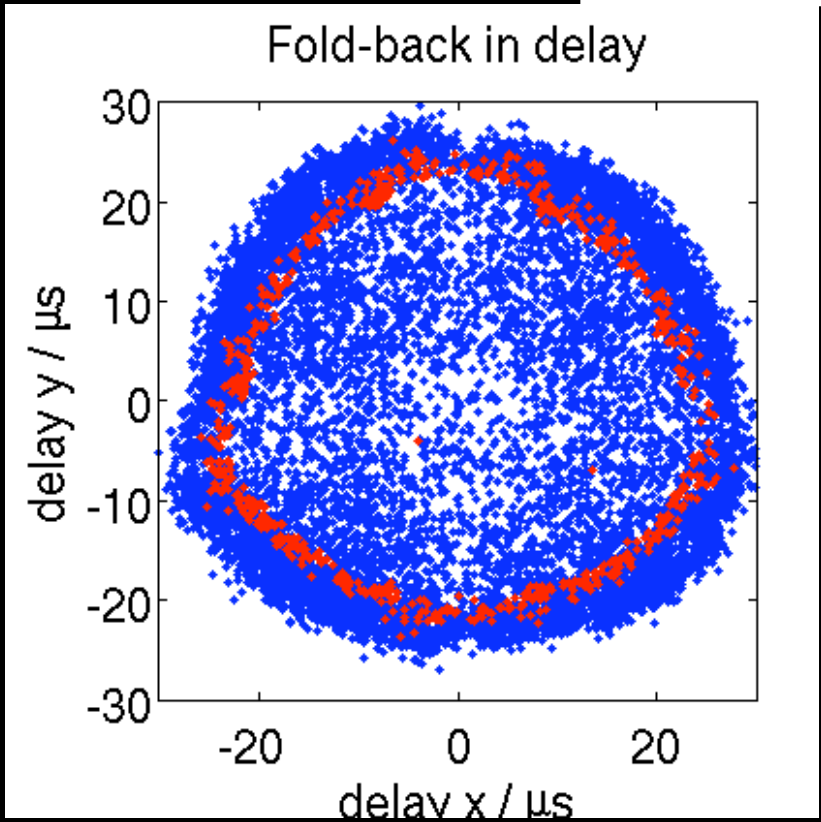

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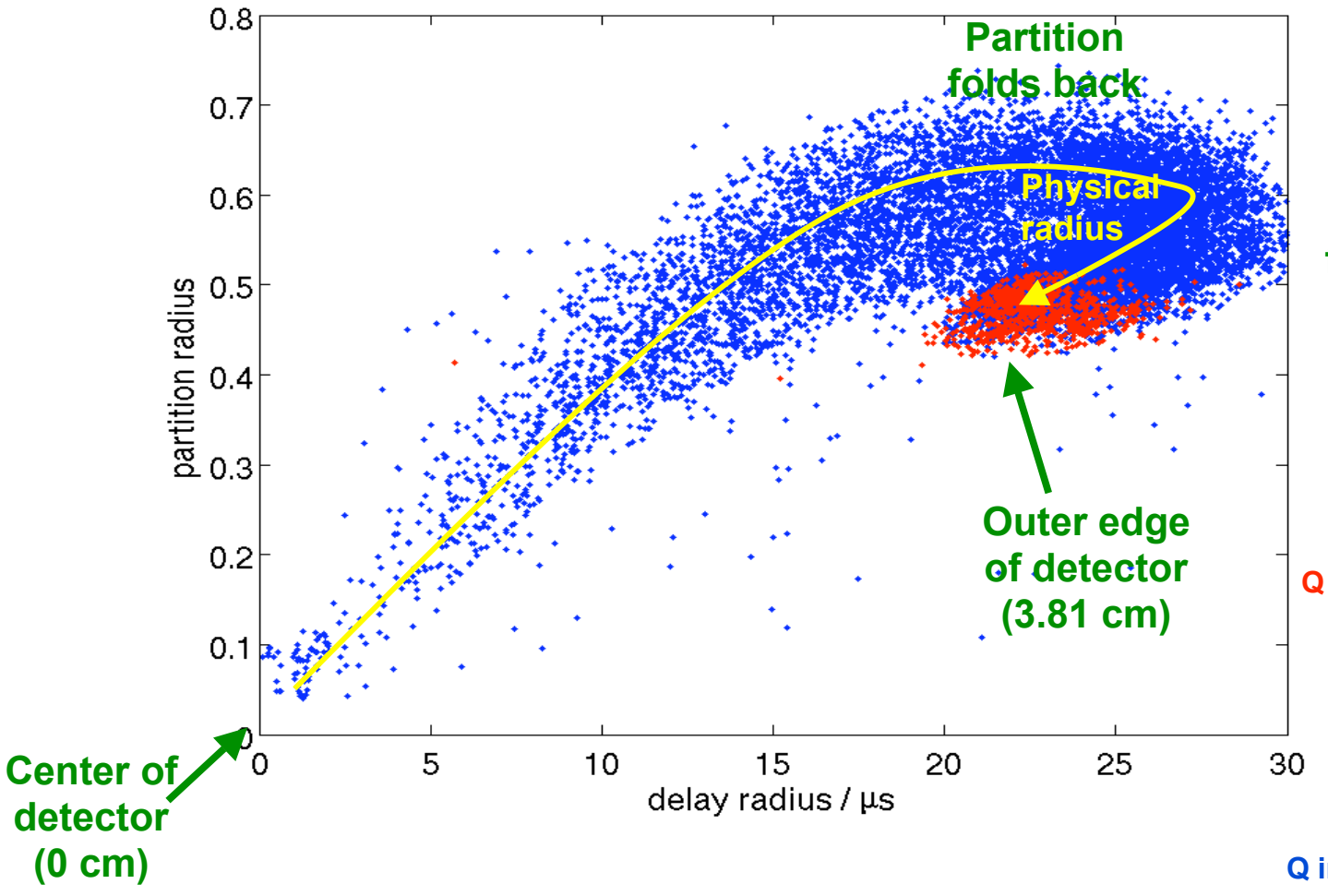
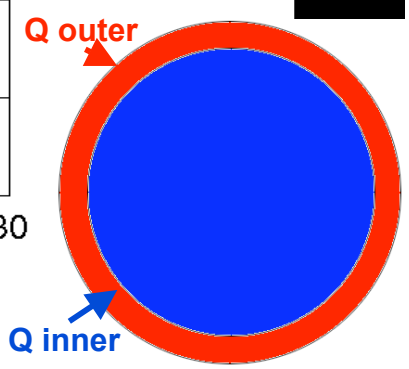
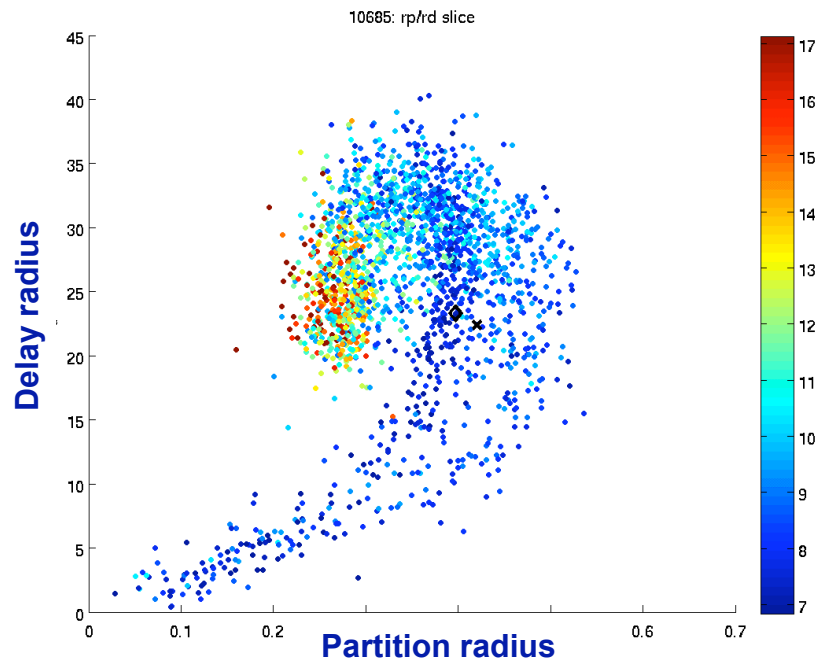
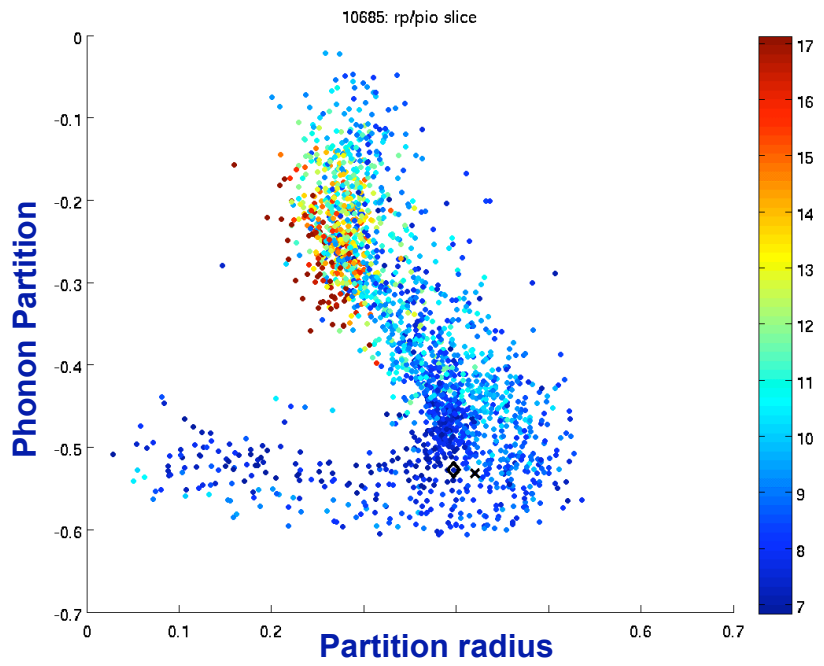




Position:
using new phonon sensor layout

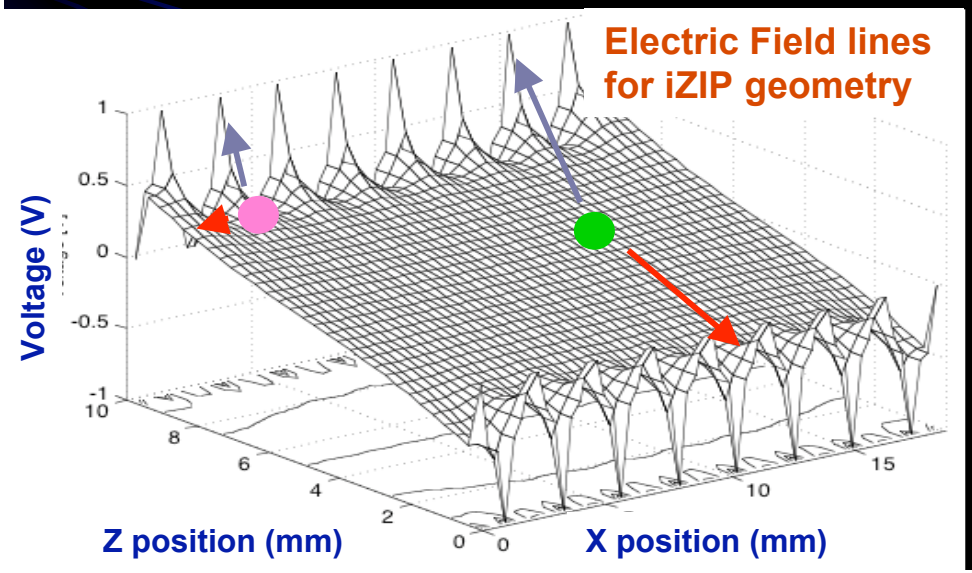


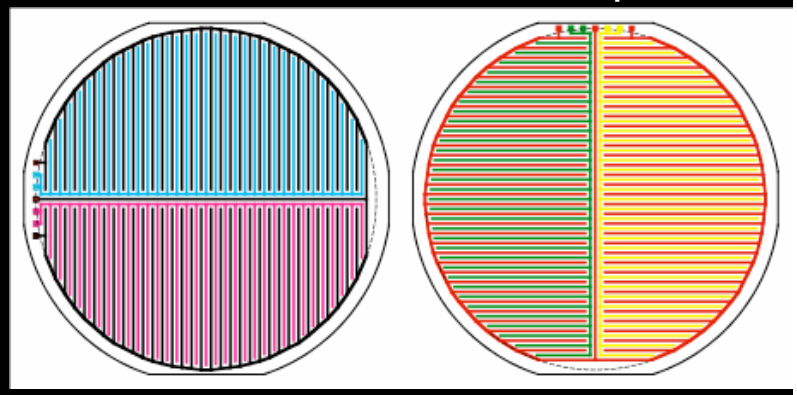


Multiple parameters to break position degeneracies!

Conclusion

- Improvements are showing promising results
- Future Work includes:
  - Returning to studies with hydrogen passivation of aSi contacts
  - Looking at other detector geometries (e.g. revisiting design which interleaves ionization and phonon readout)





P. Luke, B. Cabrera (Stanford University)

Ref: NIMA 559 (2006) 414-416