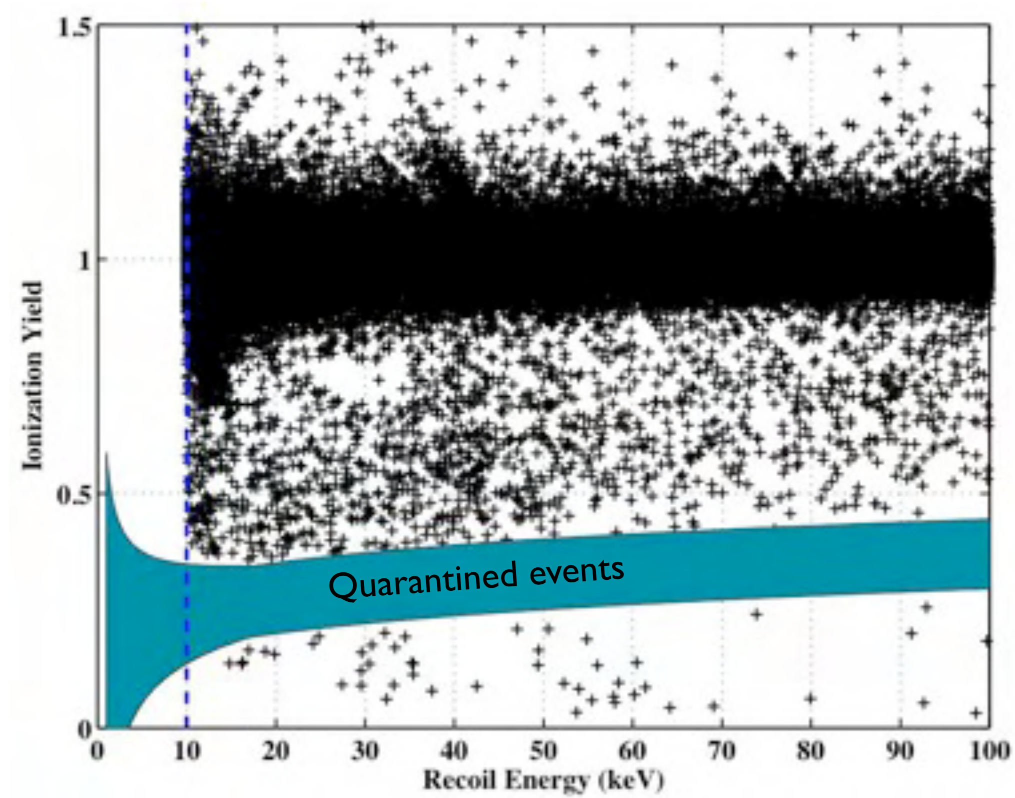
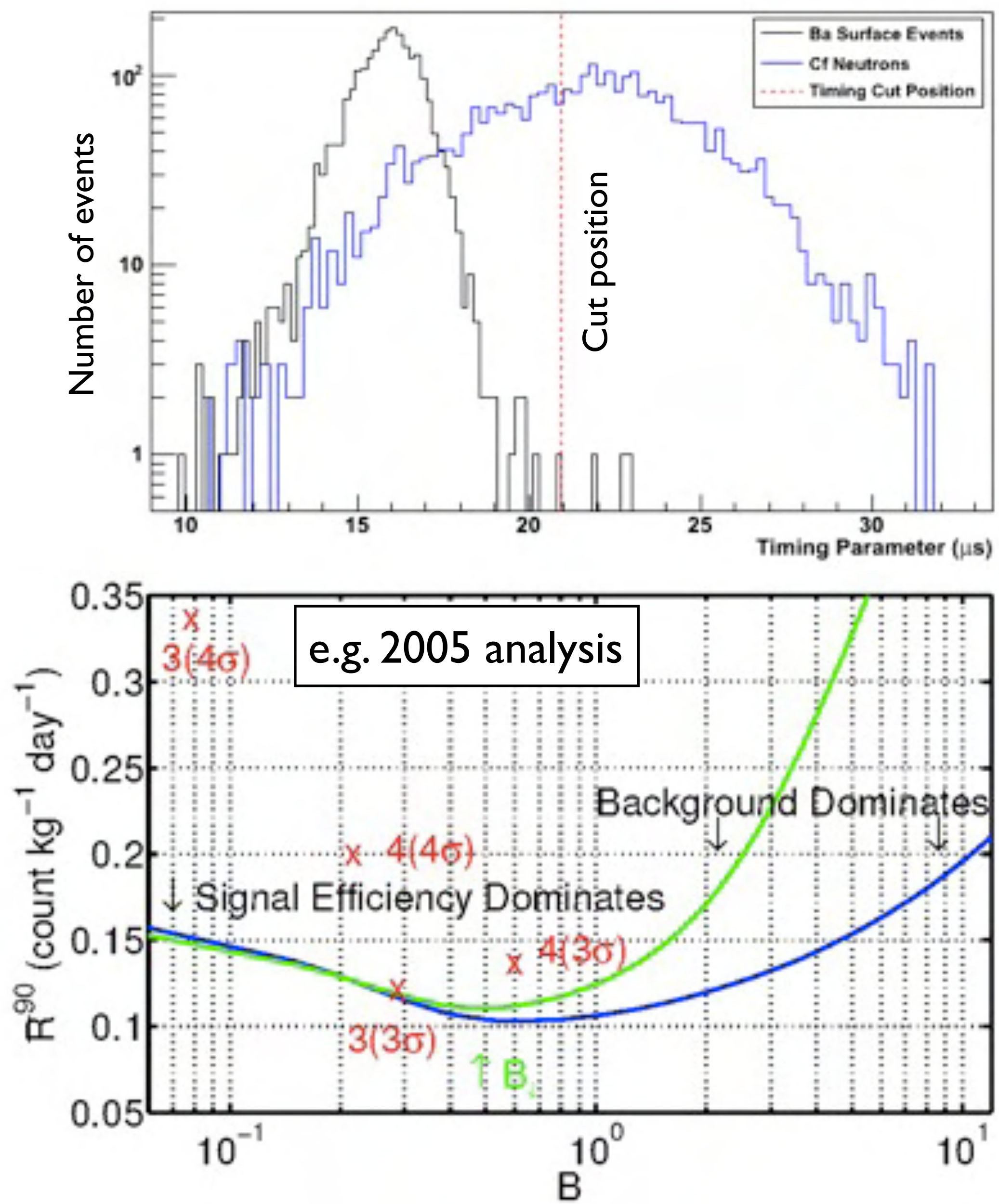
Blind Analysis

- Quarantined signal-like events during data reduction
  - Single-scatter
  - No activity in veto shield
  - Ionization yield near nuclear recoil band
- These events have no effect on the definition of our signal criteria
- Quarantine broken only when all cuts are finalized: "unblinding"
- Avoids statistical bias: cut on independent event distributions, not observed candidate events



Choosing our Misidentified Background

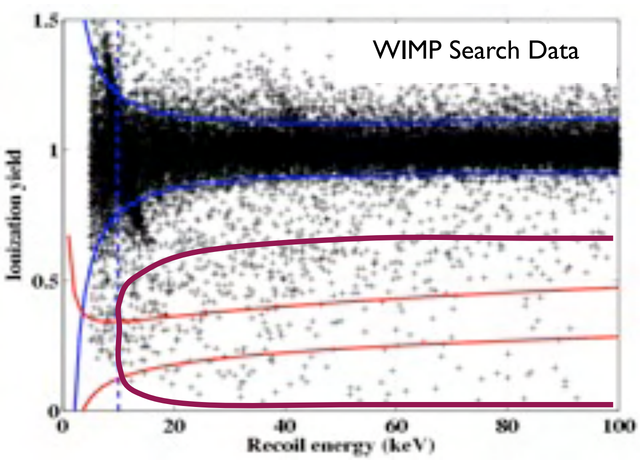
- Goal: Select surface event cut position to maximize expected sensitivity / discovery potential
  - Strongest expected upper limit
  - Greatest significance of a few observed events
- Usually a broad optimum near ~0.5 expected events
  - Each analysis employs tighter cuts
  - Improved analysis limits loss in signal acceptance
- Choose cut based on surface event background model

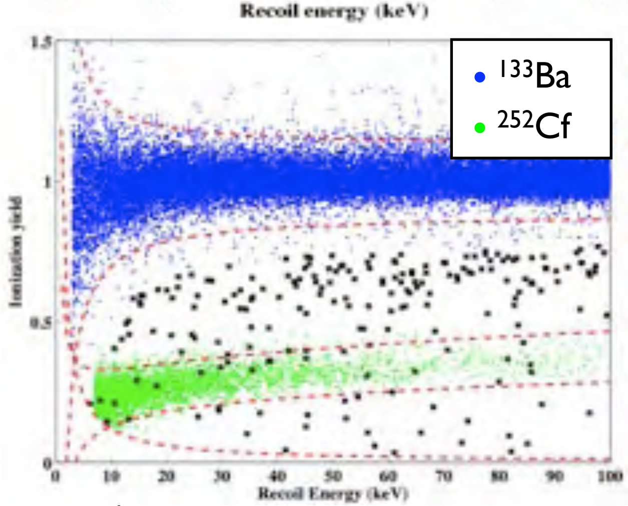


Surface Event Misidentified Background

$$\text{Expected surface leakage} = \frac{N^{\text{sideband}}_{\text{passing cut}}}{N^{\text{sideband}}_{\text{failing cut}}} \times N^{\text{data}}_{\text{failing cut}}$$

3 independent sidebands for estimating the passing/failing ratio





	Multiple-scatter	Single-scatter	^{133}Ba
Nearby NR band	#2	#2	#3
Inside NR band	#1	?	#3
	WIMP-Search		Calibration

Correct #2, #3 (best statistics) for systematic differences in energy and detector face distributions

All three consistent:
0.6 ± 0.1 (stat.)
(... plus systematic error)

Neutron Background

Radiogenics

Estimate U/Th content of nearby materials with HPGe and fit to observed gammas

Simulate fission/α-n, propagate in GEANT

0.03 - 0.06 events expected

	U/Th (ppb)	Mass (kg)
Electronics	1.2	15
Cu	0.4	260
Poly	0.24	120
Pb	<0.05	14000

Cosmogenics

$$\frac{N^{MC}_{\text{unvetoed, single NR}}}{N^{MC}_{\text{vetoed, single NR}}} \times N^{data}_{\text{vetoed, single NR}} \times \varepsilon_{\text{neutron}}$$

$= 0.04^{+0.04}_{-0.03}$ (stat.) events expected

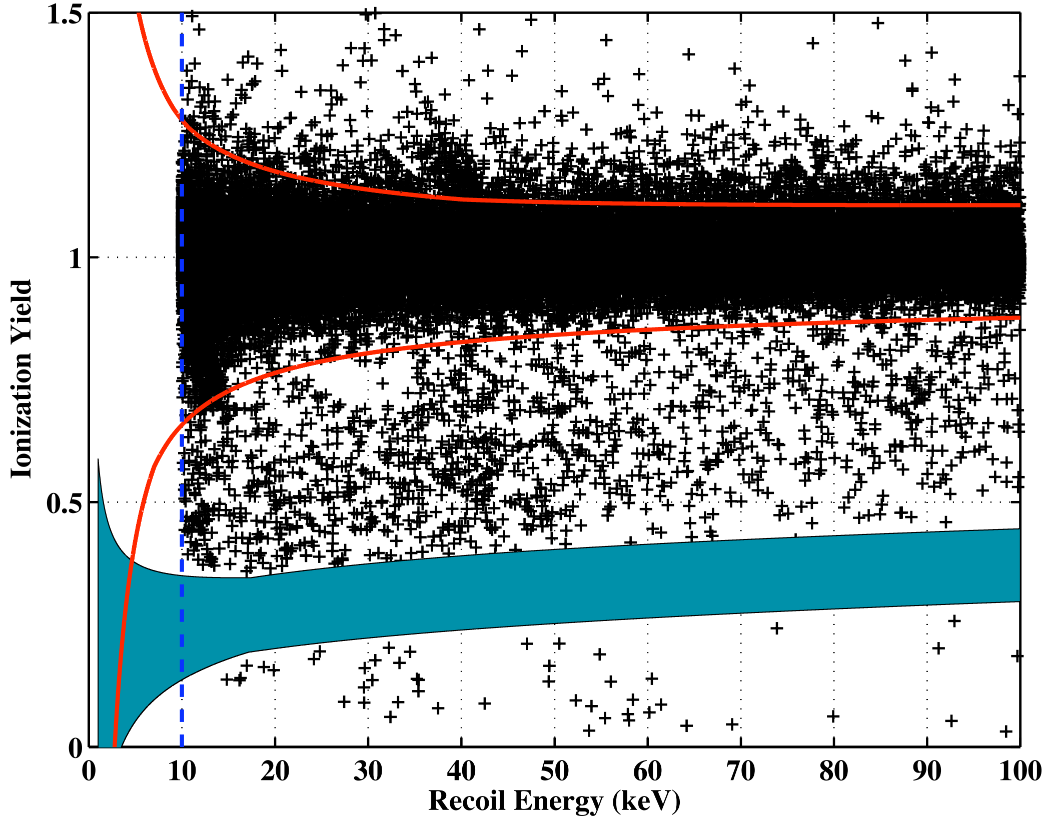
From GEANT4 and FLUKA simulations

3 vetoed, single NRs observed

Correct for efficiency, exposure

WIMP-Search Data Set

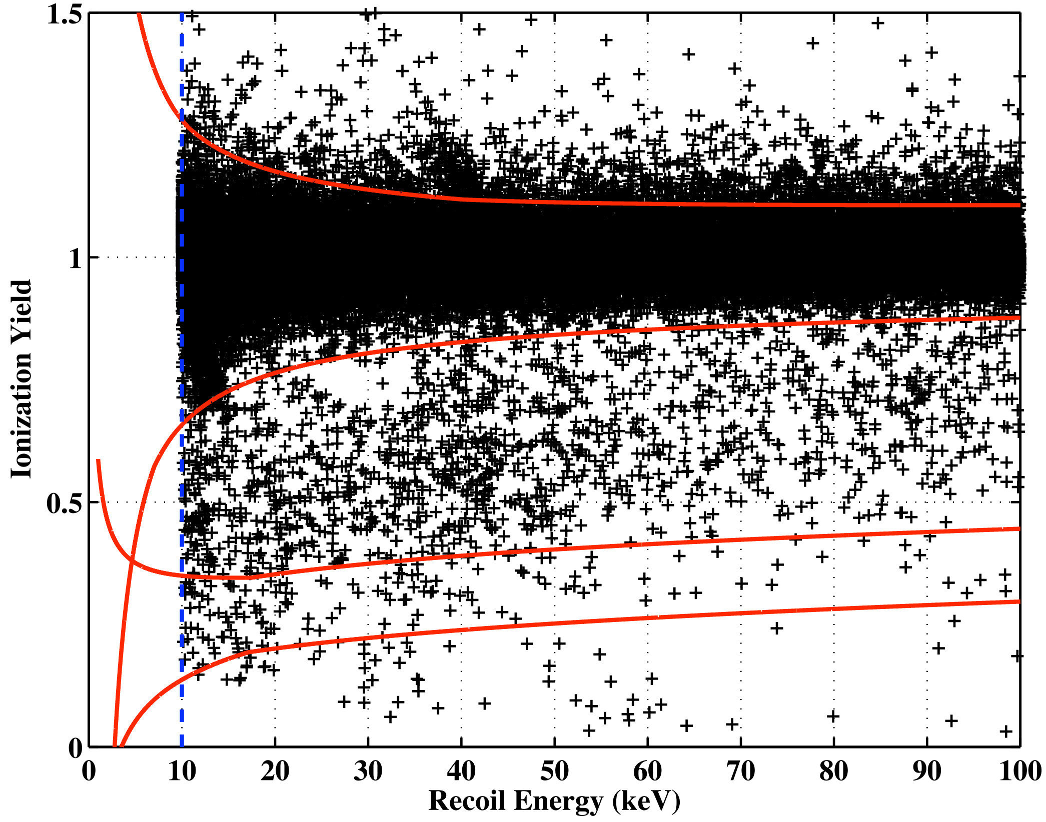
3σ region masked
→ Hide unvetoed singles



WIMP-Search Data Set

3σ region masked
→ Hide unvetoed singles

Lift the mask, see 150 singles *failing* timing cut

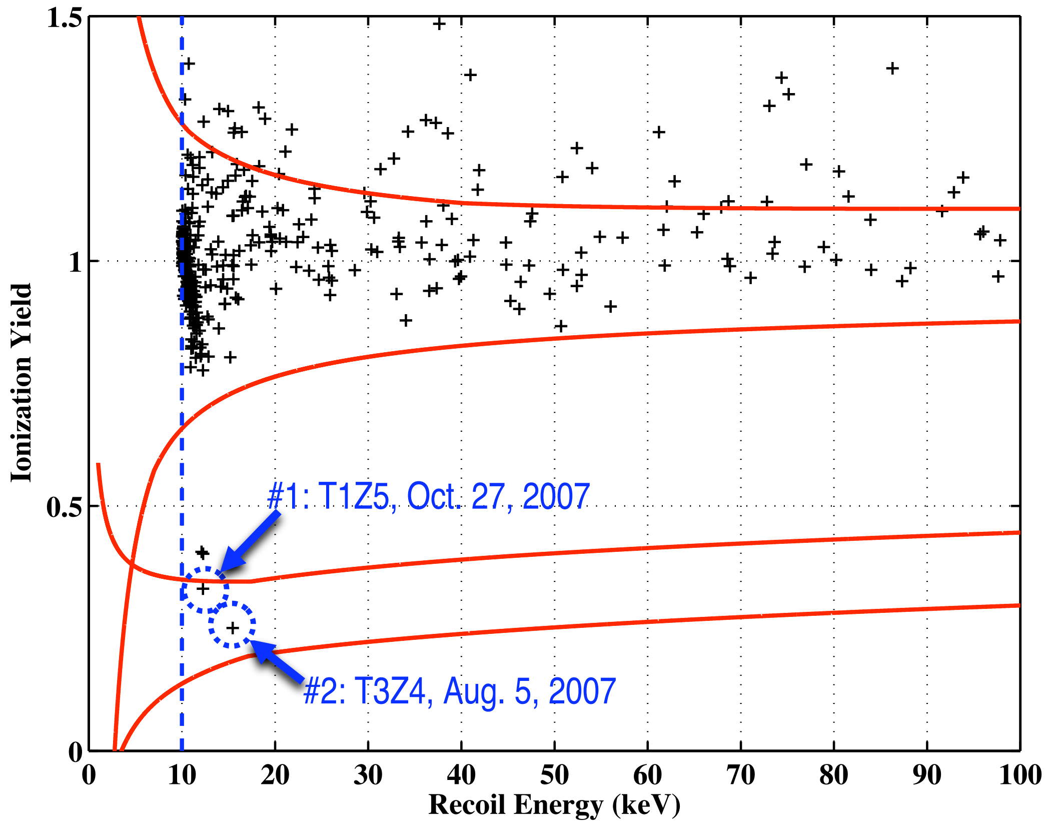


WIMP-Search Data Set

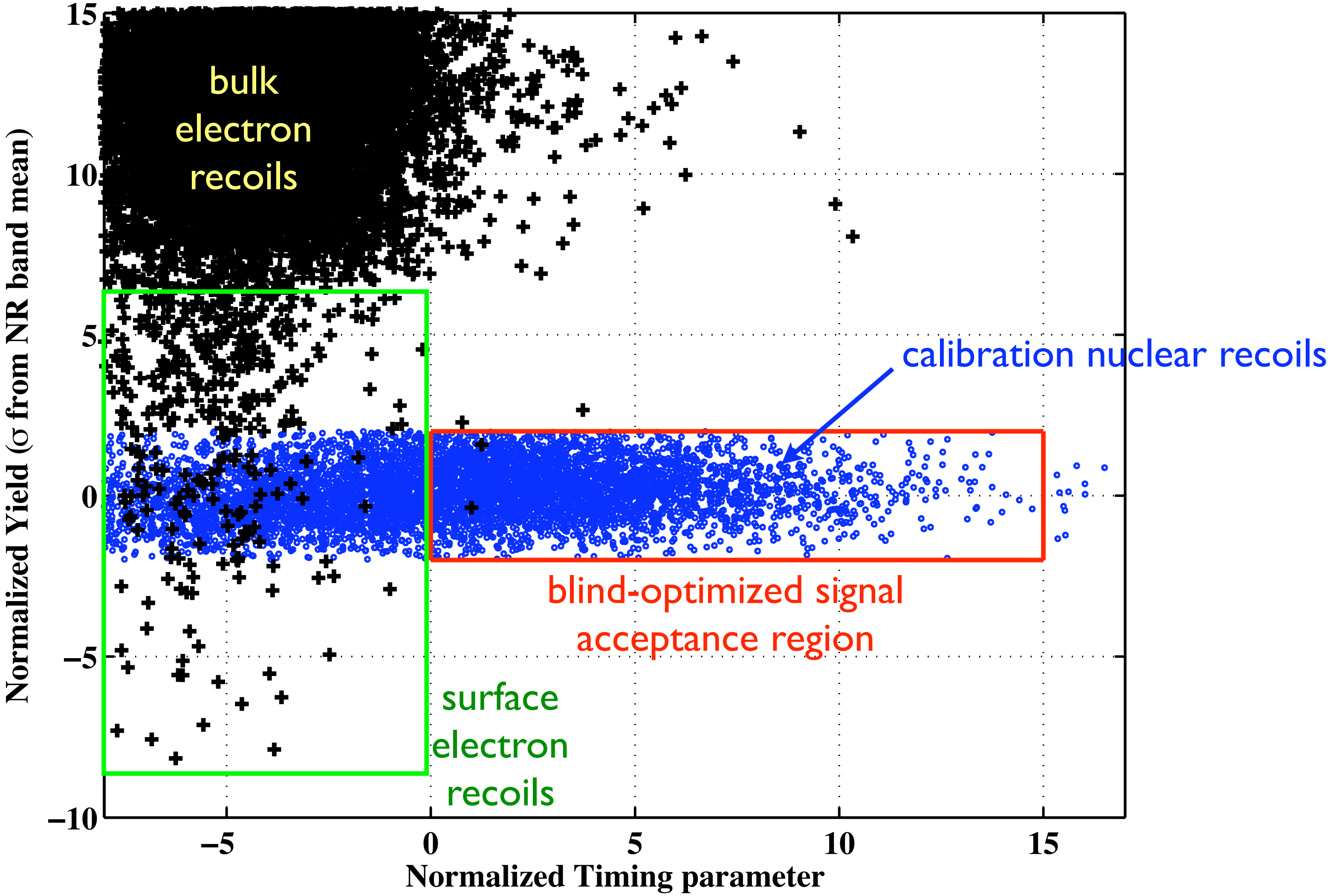
3σ region masked
→ Hide unvetoed singles

Lift the mask, see 150 singles *failing* timing cut

Apply the timing cut, count the candidates: two events observed



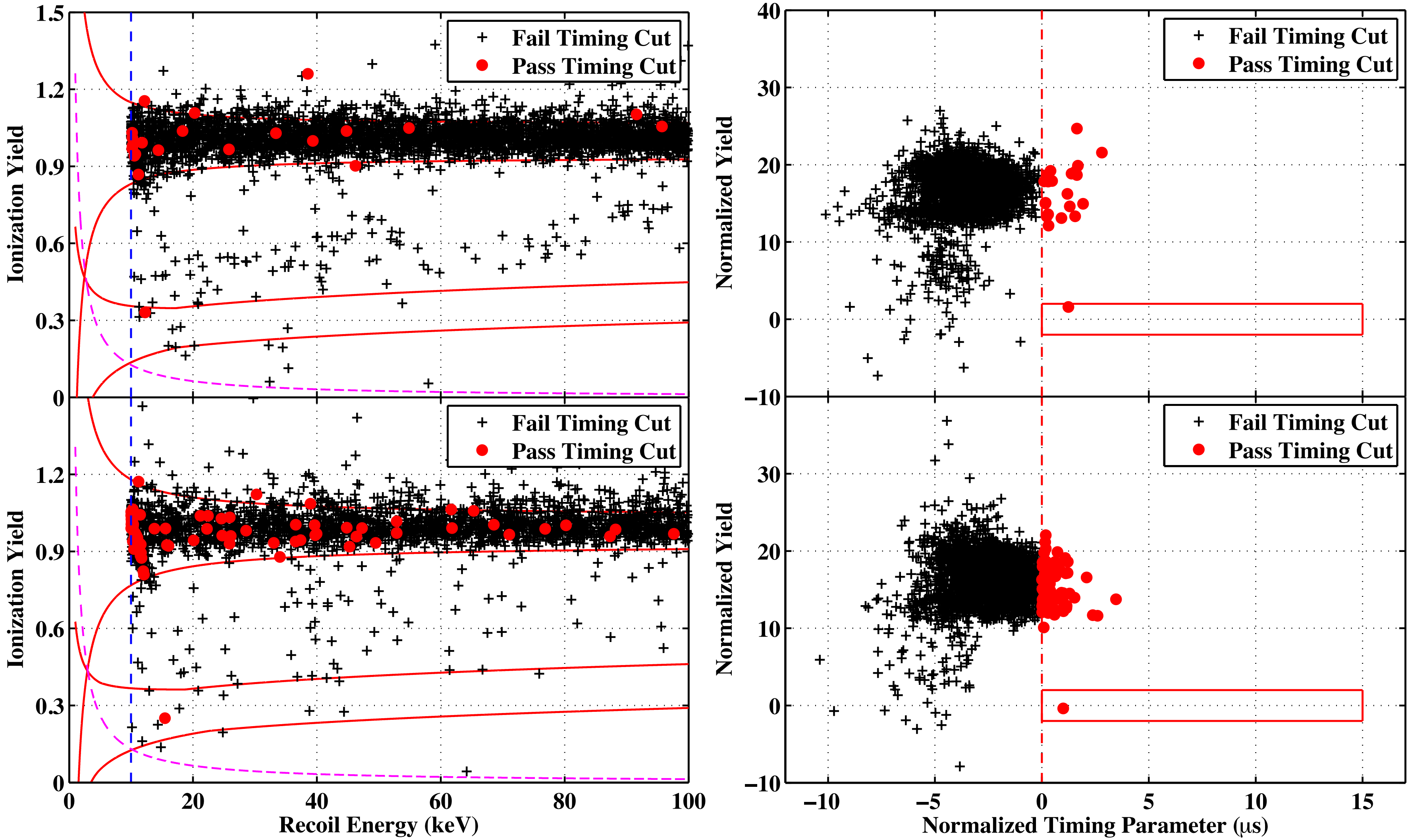
Another View



The Two Candidates

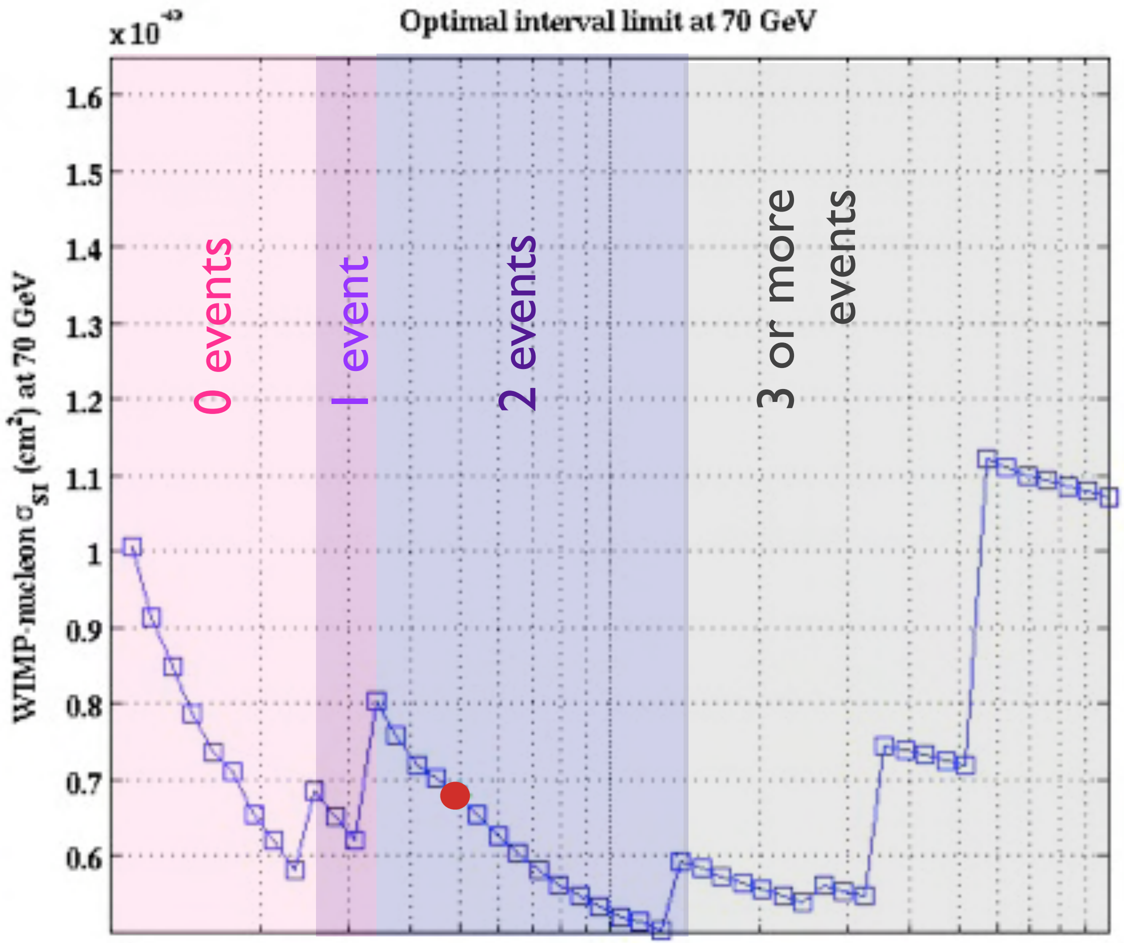
#1: T1Z5
2007/10/27
12.3 keV

#2: T3Z4
2007/08/05
15.5 keV



Candidates were observed during ideal running conditions, several months apart, in different interior detectors

Varying the Surface-Event Cut

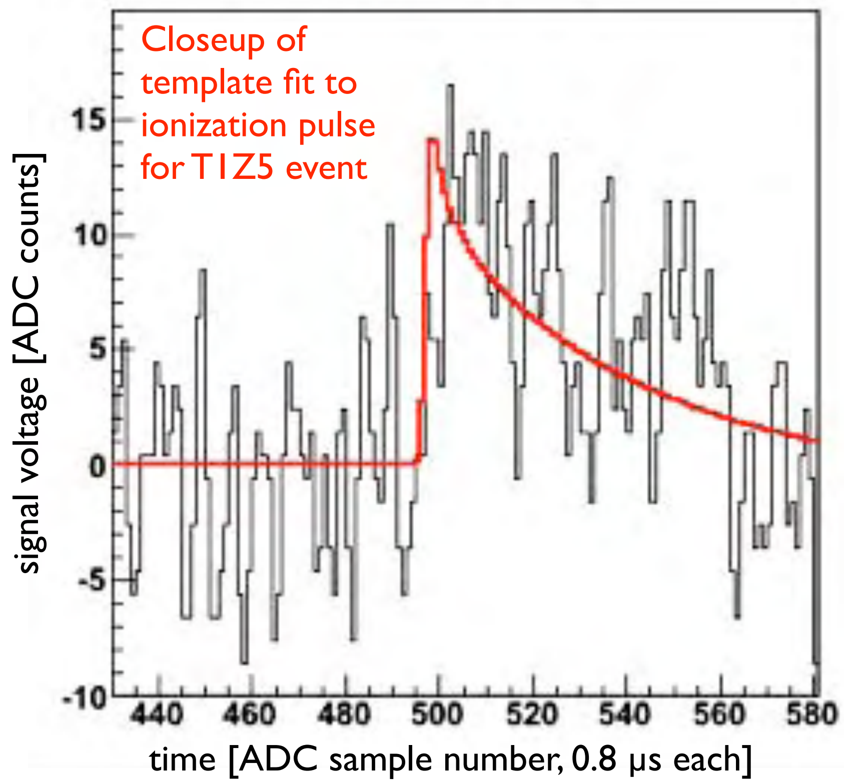


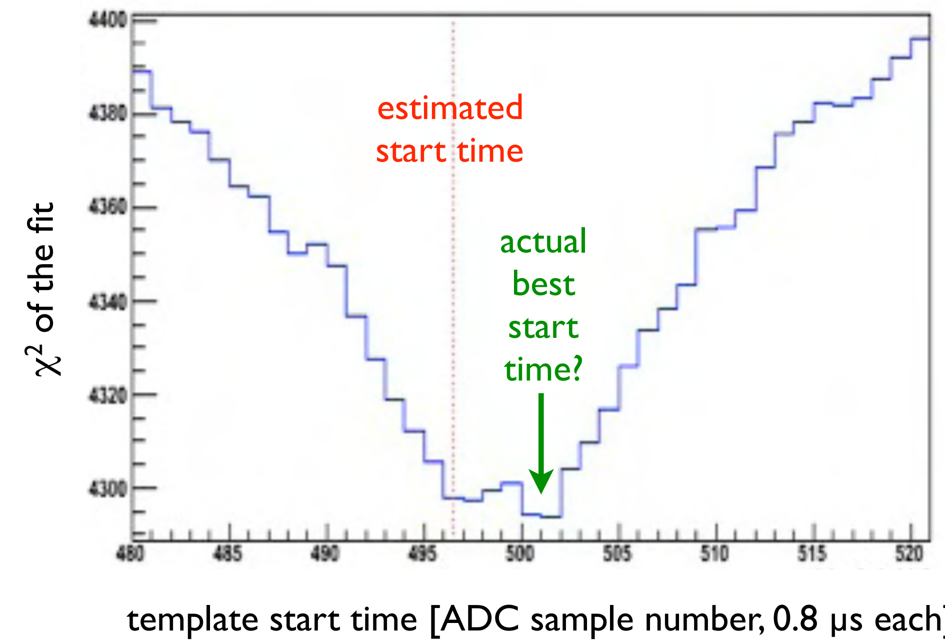
To *exclude both candidates*, we must reduce the expected background by ~1/2 and the exposure by 28%

To *admit a third candidate*, we must increase the expected background to 1.7 events.

Our result is not overly sensitive to the cut position

Pulse Reconstruction





Our reconstruction technique misestimates the ionization start time for a small fraction of events with <6 keV of ionization energy.

This issue does not affect the T1Z5 candidate.

With a better estimator, the T3Z4 candidate may fail the timing cut (and/or other candidates might appear)

Event #1 (T1Z5) shows no reconstruction issues

Event #2 (T3Z4) has a misreconstructed start time

A full reprocessing is needed to study this definitively

Background Estimate Redux

A refined estimate of the surface background accounting for this effect yields

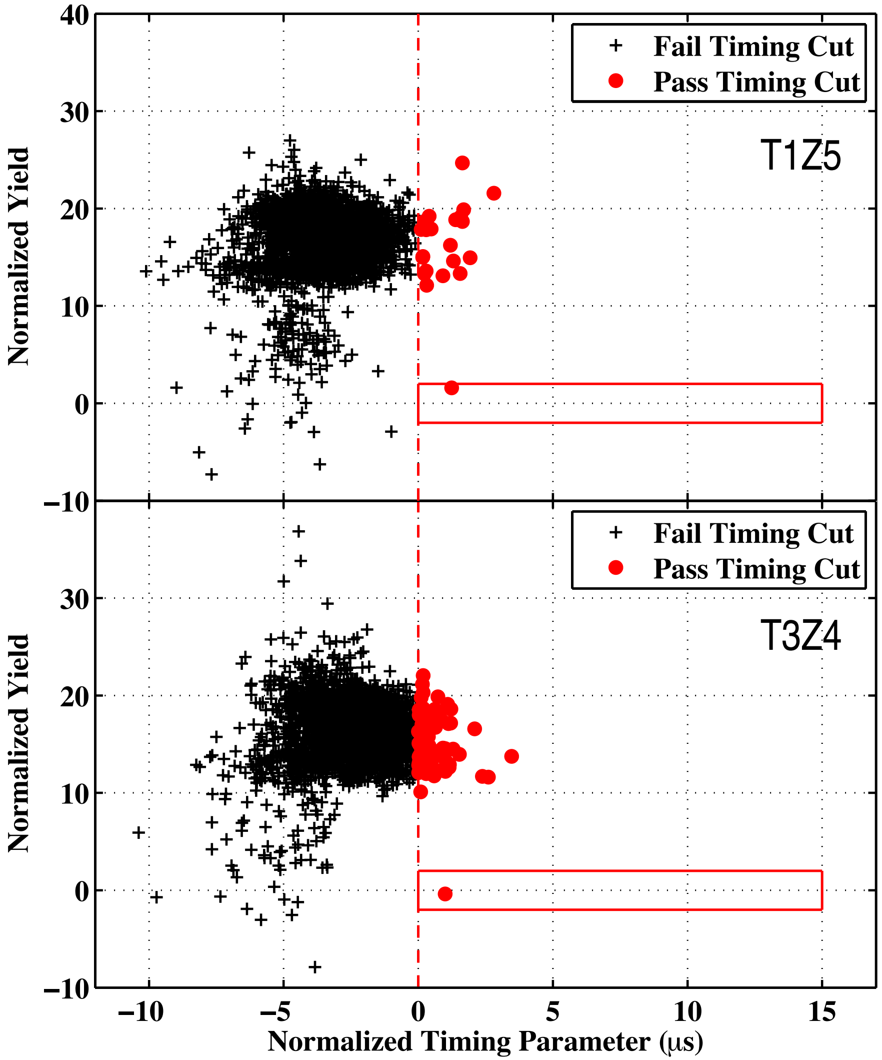
Surface background
0.8 ± 0.1 (stat.) ± 0.2 (syst.)

With this revised estimate (and including neutron backgrounds),
the probability for observing at least 2 events is ~23%.

Likelihood Analysis

- Go beyond Poisson counting analysis: given dist'n of bgnds and signal in timing, yield, and energy, can we estimate how likely/unlikely the observed two events are?
- The challenge: estimating the distributions given limited statistics in cal data and differences between cal and WIMP-search data.
  3 techniques:
  - Non-parametric: kernel-density estimation to smooth cal data dist'n (E, y, t_{sum})
  - parametric: fit lambda distributions to cal data dist'n (2 variants: y, t_{sum}, t_{diff} or y, t_{sum} and side separation)
  - Use "factorization assumption"
- Use

$$R_{ne}(t,p,y) \equiv log\left(\frac{f_n(t,p,y)}{f_e(t,p,y)}\right)$$



Likelihood Analysis

- Q: what fraction of the time would *any* of the surface events in this detector had R_{ne} that is more NR-like?

event	Non-parametric E, y, t_{sum}	Parametric y, t_{sum}, t_{diff}	Parametric y, t_{sum} side-sep
T1Z5	24%	12%	12%
T3Z4	4%	5%	5%

- Q: what fraction of the time would an *accepted* NR have R_{ne} that is more ER-like?

event	Non-parametric E, y, t_{sum}	Parametric y, t_{sum}, t_{diff}	Parametric y, t_{sum} side-sep
T1Z5	1%	3%	
T3Z4	12%	2%	

- Q: what fraction of the time would an *accepted* ER have R_{ne} that is more NR-like?

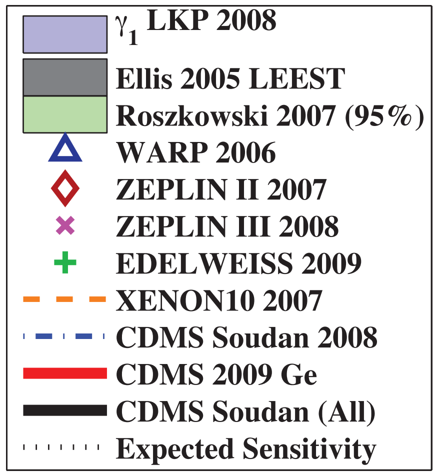
event	Non-parametric E, y, t_{sum}	Parametric y, t_{sum}, t_{diff}	Parametric y, t_{sum} side-sep
T1Z5	83%	28%	
T3Z4	55%	34%	

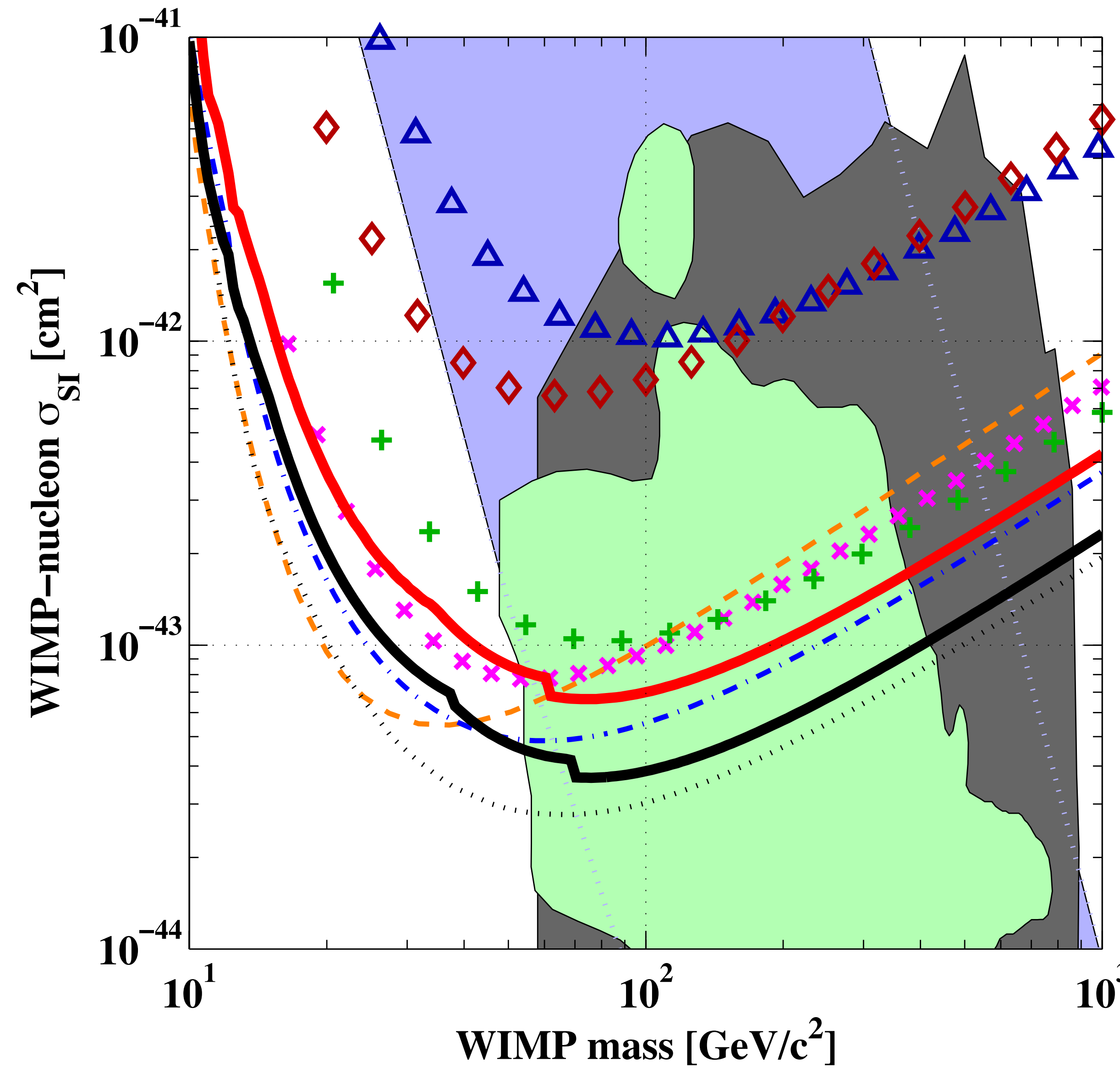
Spin-Independent Limits

KK/SUSY theory

Other searches

CDMS II results





Combined CDMS II data:

- Yellin's Optimum Interval method (*no background subtraction*)
- **σ_{SI} > 3.8 x 10^{-44} cm^2** (>38 zeptobarn) at 90% C.L. for M_{WIMP} = 70 GeV/c^2.
- World-leading result above ~$M_Z/2$

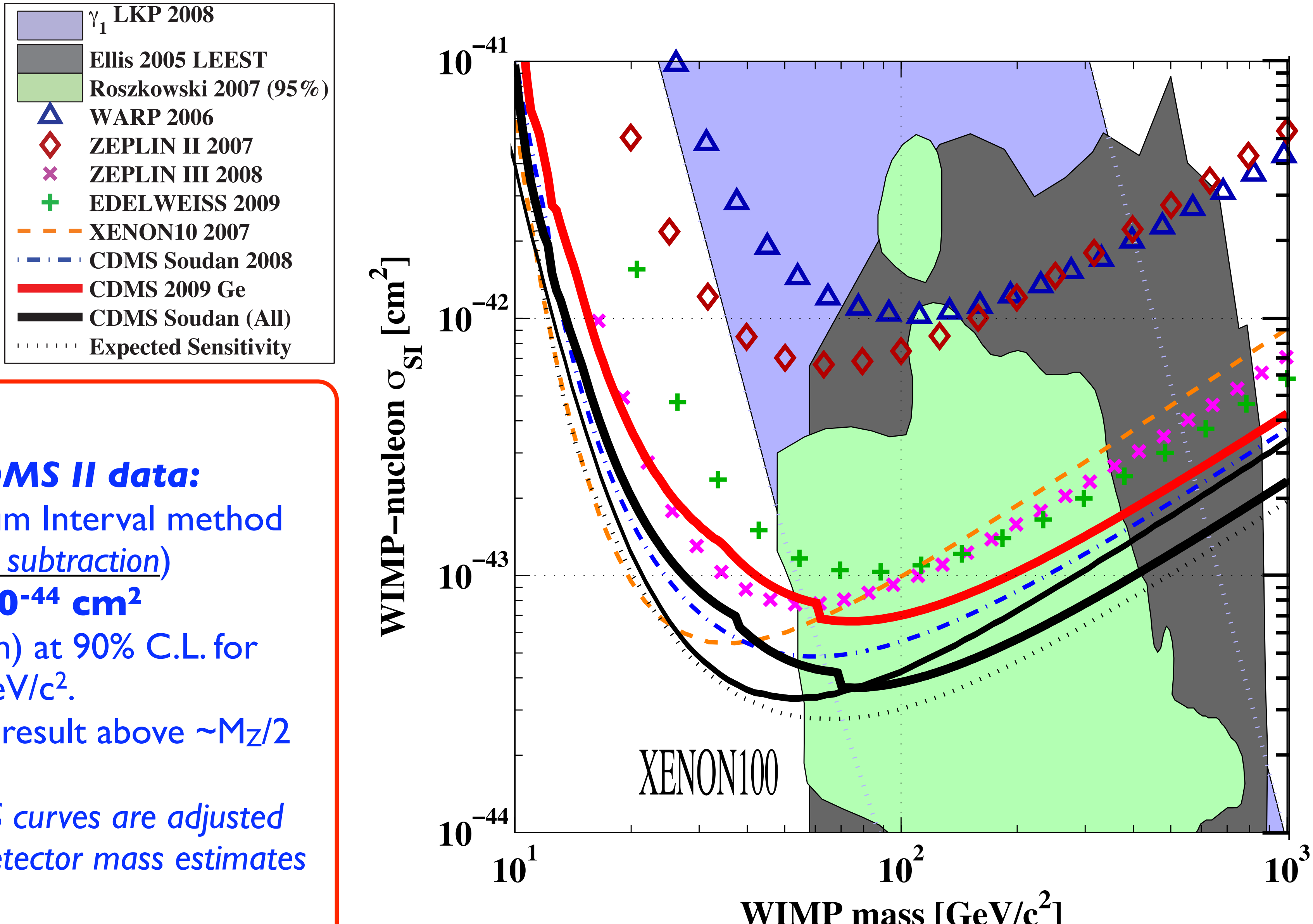
Note: *All CDMS curves are adjusted for ~9% lower detector mass estimates*

Spin-Independent Limits

KK/SUSY theory

Other searches

CDMS II results



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- World-leading result above ~$M_Z/2$

Note: *All CDMS curves are adjusted for ~9% lower detector mass estimates*

From CDMS II to SuperCDMS and GEODM

CDMS II

⌀7.5cm x 1cm ZIP
0.25 kg/detector

16 detectors = 4 kg
2 yr, 1700 kg-d

SuperCDMS Soudan

⌀7.5cm x 2.5cm iZIP
0.64 kg/detector

15 dets = 10 kg **x 2***
2 yr, 4000 kg-d

SuperCDMS SNOLAB

⌀10cm x 3.5cm iZIP
1.5 kg/detector

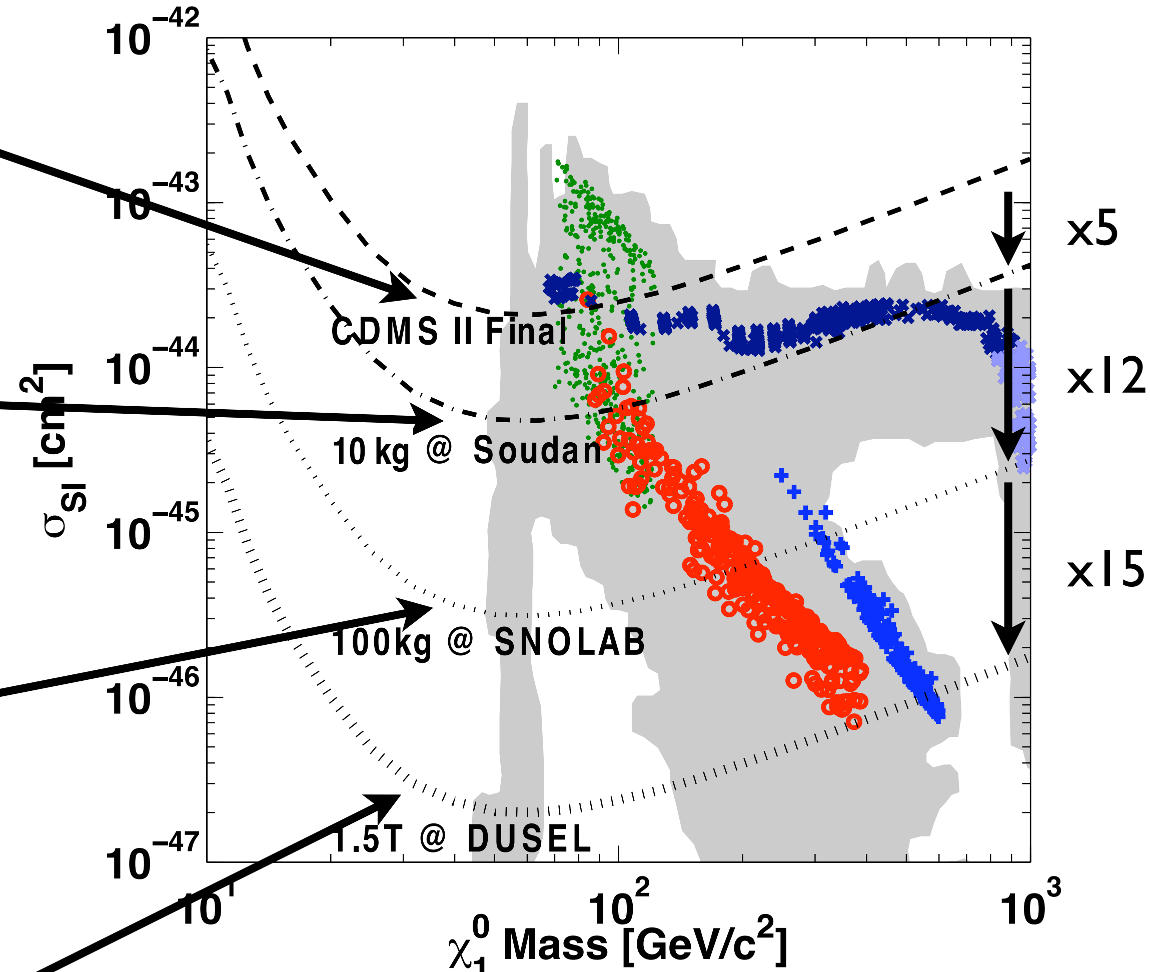
70 detectors = 105 kg
3 yr = 100,000 kg-d

GEODM DUSEL

⌀15cm x 5cm iZIP
5.1 kg/detector

300 detectors = 1.5 T
2 yr, 1.5 M kg-d

*new iZIP design has x 2 better efficiency



Staged three-prong program to explore MSSM or study a signal:

- decreased backgrounds
- improved background rejection
- increase in mass/detector and decrease in cost/detector

< 1 event misid'd bgnd at each stage

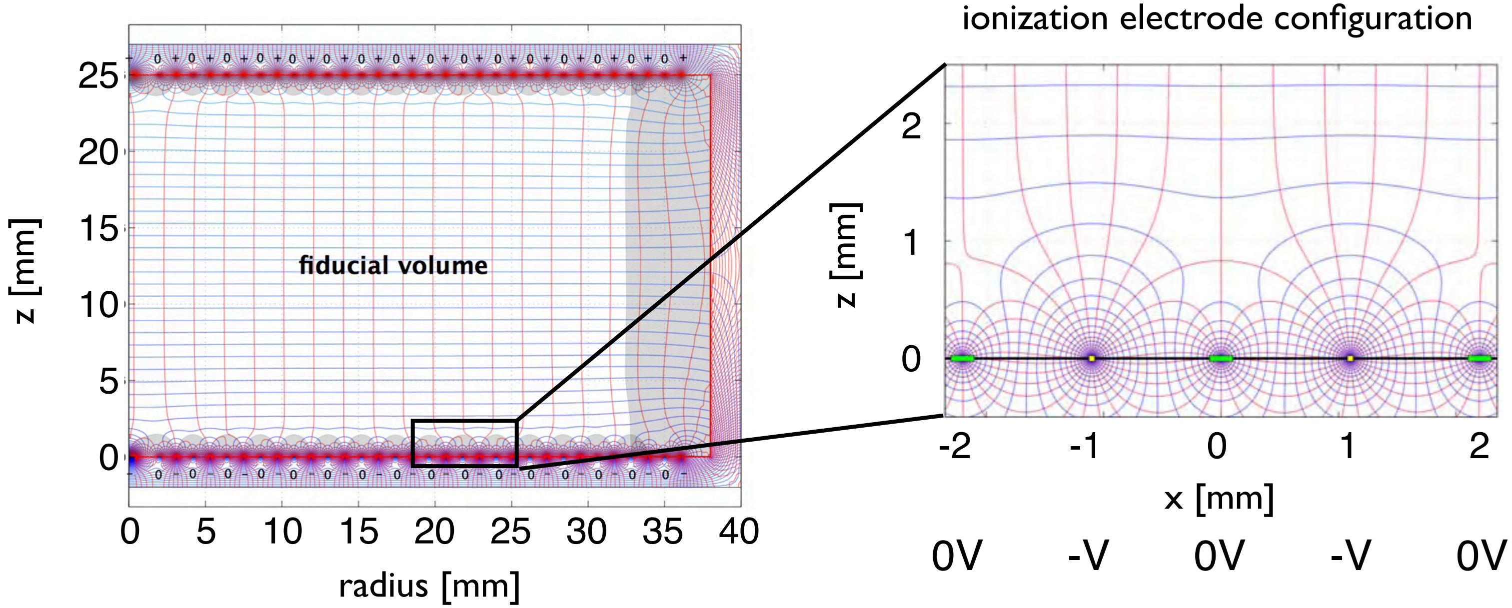
Project(s) Status

- SuperCDMS Soudan
  - Fully approved Aug 2009, iZIP revision approved July 2010: 3 to 5 iZIP towers
  - 2 mZIP towers + 1 iZIP tower driving across country right now for installation!
  - ~2 year run beginning mid-2011
- SuperCDMS SNOLAB
  - iZIP + 100 kg total mass received substantial endorsement from PASAG
  - SLAC has joined experiment
  - requesting R&D funds this year, project proposal next year, hope for FY14 construction start
  - SNOLAB test facility being assembled to demo iZIP rejection underground ASAP
- GEODM DUSEL
  - iZIP + 15 cm x 5 cm to provide 1.5 T detector mass
  - "S4" DUSEL engineering study proposal funded
  - Working on production of large crystals and automation of fab using evolution of current detector design
  - Caltech working on simplified phonon sensors using MKIDs
  - SNOLAB test facility will provide underground demonstration of rejection

Physics Approach: Detector Design

- Interleaved ZIP (iZIP) design appears to meet needs of GEODM

ionization electrode configuration

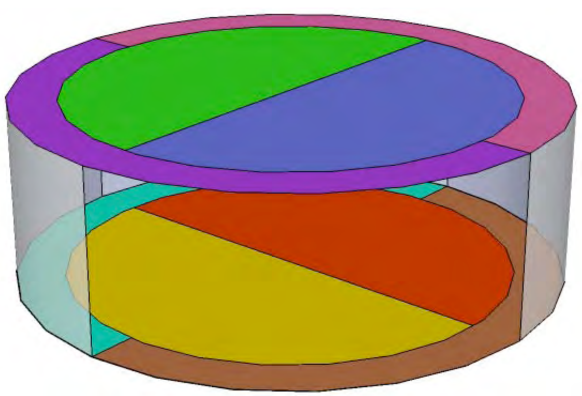


negative version on other face

M. Pyle

- Interleaved ionization electrodes causes different distribution of ionization signals among electrodes for surface and bulk events
- High field near surface increases ionization yield for surface events
- Top/bottom phonon sensors (ground rails) provide simpler, more direct z information

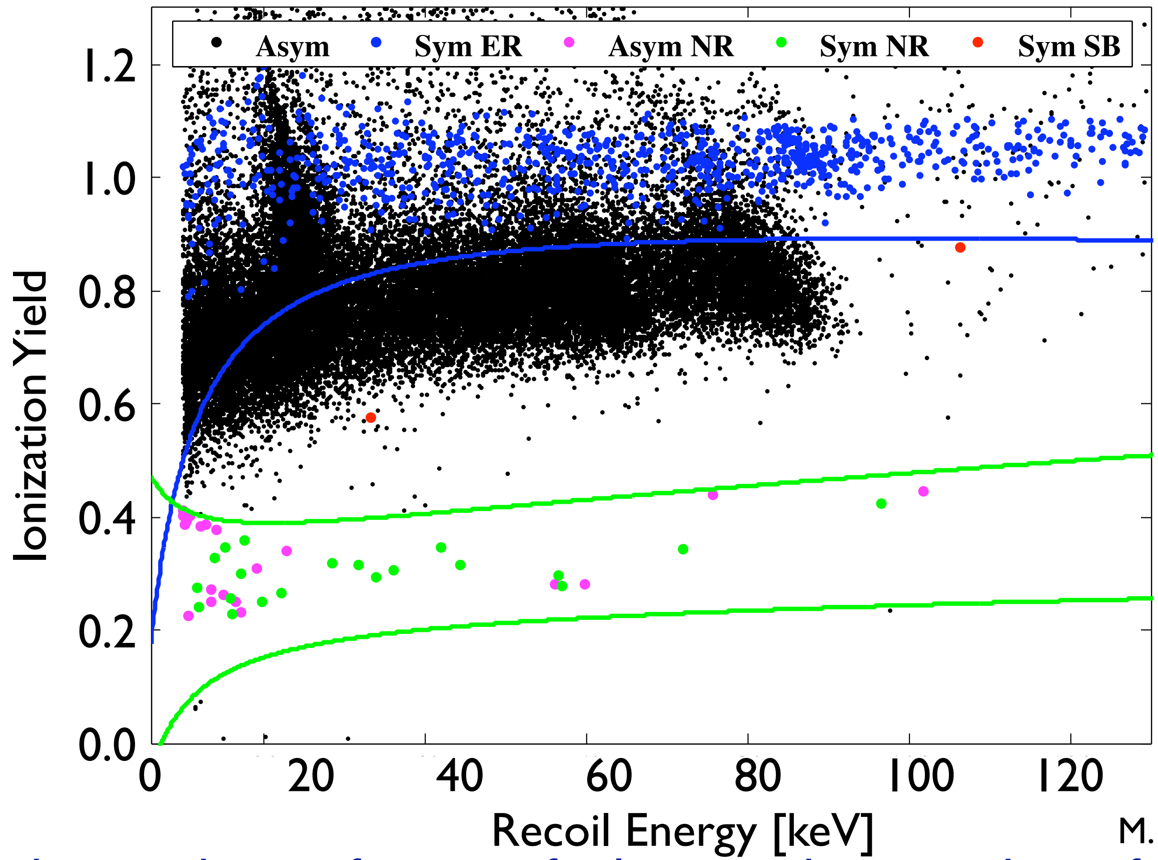
phonon sensor configuration



Physics Approach: Detector Design

- Interleaved ZIP (iZIP) design appears to meet needs of GEODM
  - High field at surfaces increases ionization yield: 0.2 misid → < 10^{-3} misid
  - Surface events share charge asymmetrically: < 10^{-3} misid
  - Phonon energy sharing and timing z position: < 10^{-3} misid
  - All measurements limited by neutron background in surface test facilities; underground test facility at SNOLAB under construction to obtain better limits
  - Ionization yield and Q/P asymmetry likely uncorrelated; if true, then overall misid 10^{-3} → < 10^{-6}, far better than needed for GEODM

^{109}Cd e^{-} source ^{133}Ba photon source



M. Pyle, B. Serfass

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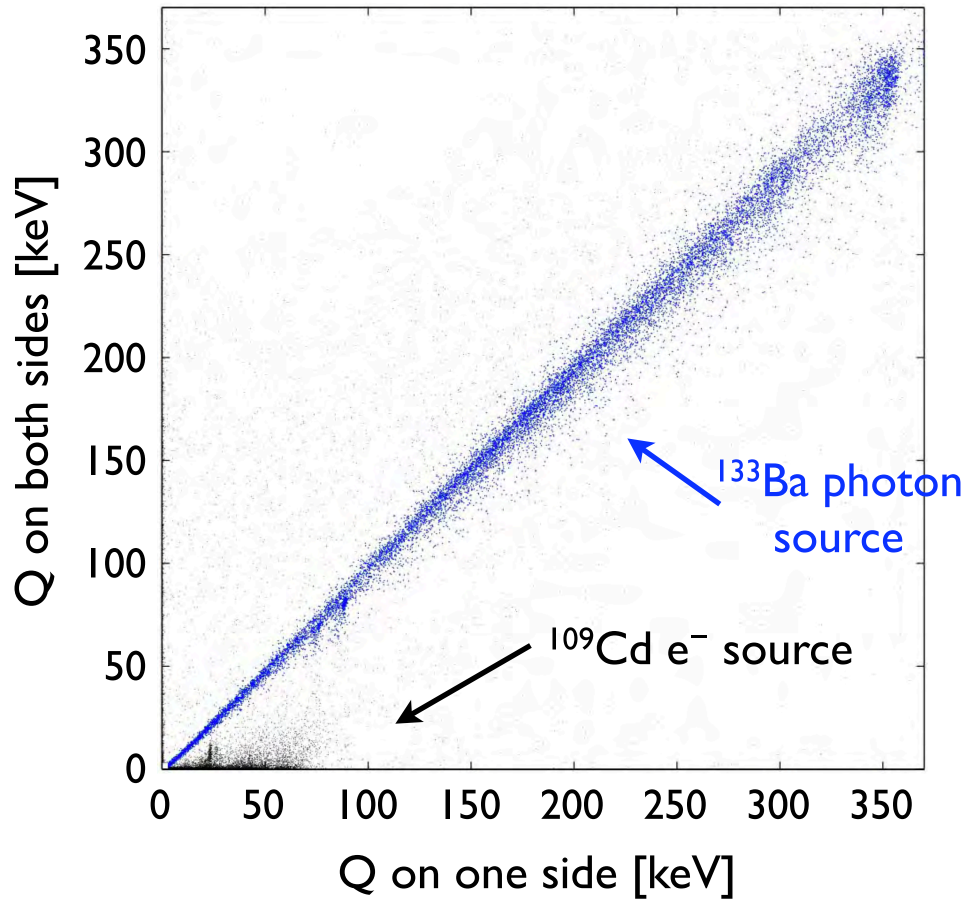

M. Pyle, B. Serfass

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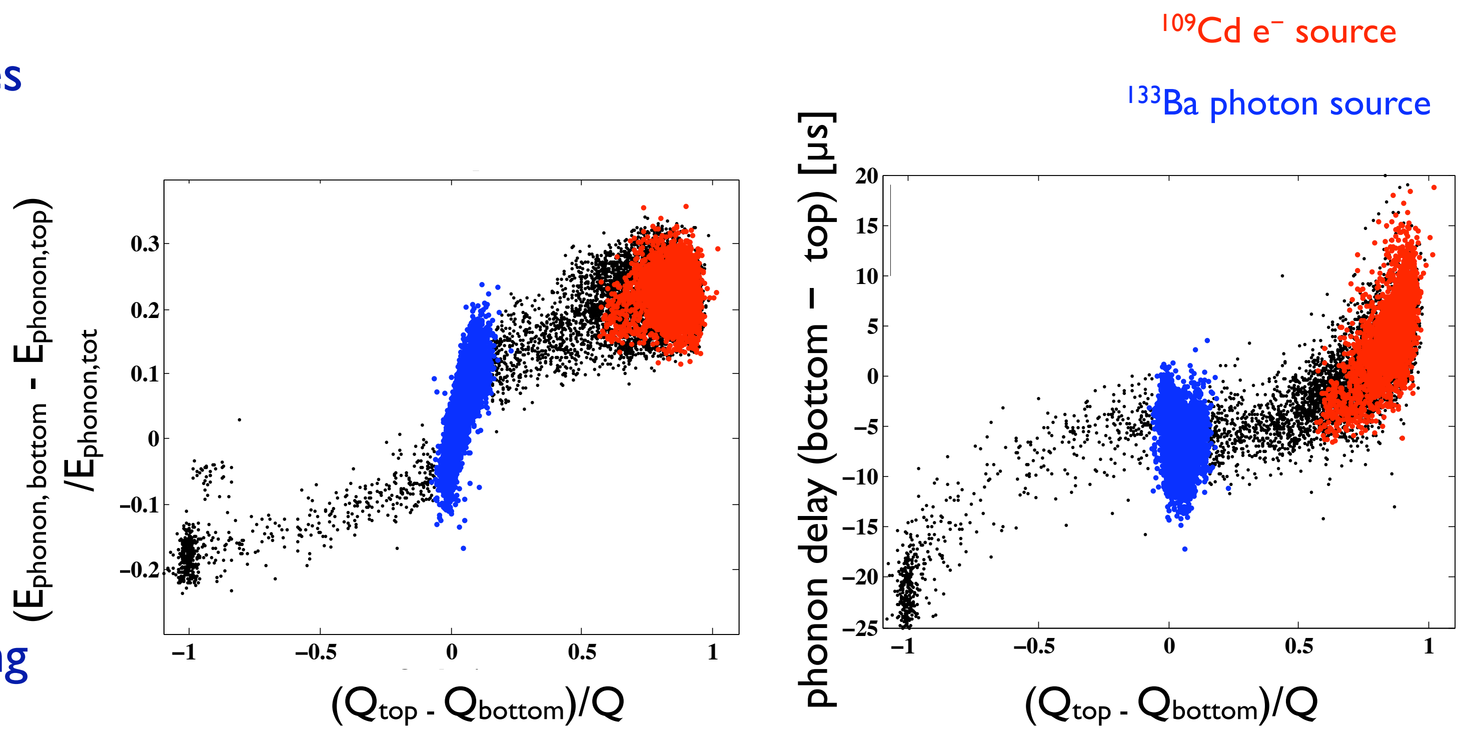

M. Pyle, B. Serfass

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Larger Substrates

- Larger substrates provide gains in bgnds and in cost/time per kg
- Step 1: 10-cm HPGe substrates
- Step 2: Dislocation-free Ge
  - deep (E_v + 0.080 eV) V_2H impurity ruins 77K HPGe γ spectrometers; inhibited via dislocations at 10^{2-4} cm^{-3} created by thermal gradients during crystal pulling
  - impurity no problem for CDMS: impurities are neutralized
  - dislocation-free xtals available up to 30 cm diameter!

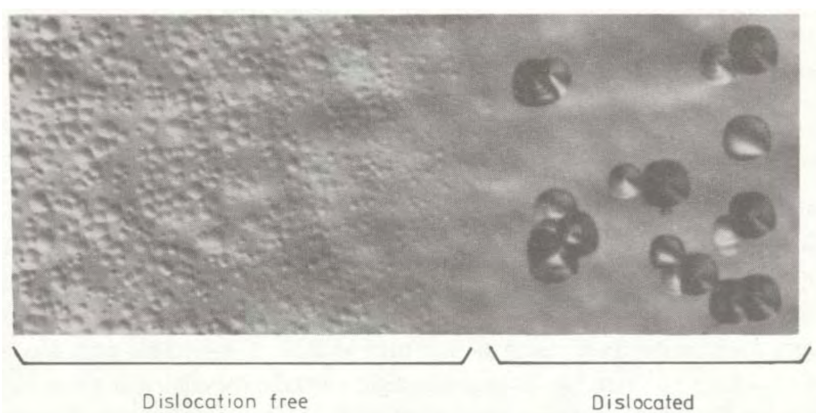

Figure 2. Photograph of a partially dislocated (100) surface of a hydrogen-grown Ge crystal. The large etch pits with four-fold symmetry in the right half of the picture are due to dislocations. The hemispherical pits in the left half of the picture are attributed to vacancy and hydrogen complexes.

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Divacancy–hydrogen complexes in dislocation-free high-purity germanium †

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‡ Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA
§ Max-Planck-Institut für Metallforschung, Stuttgart, Germany

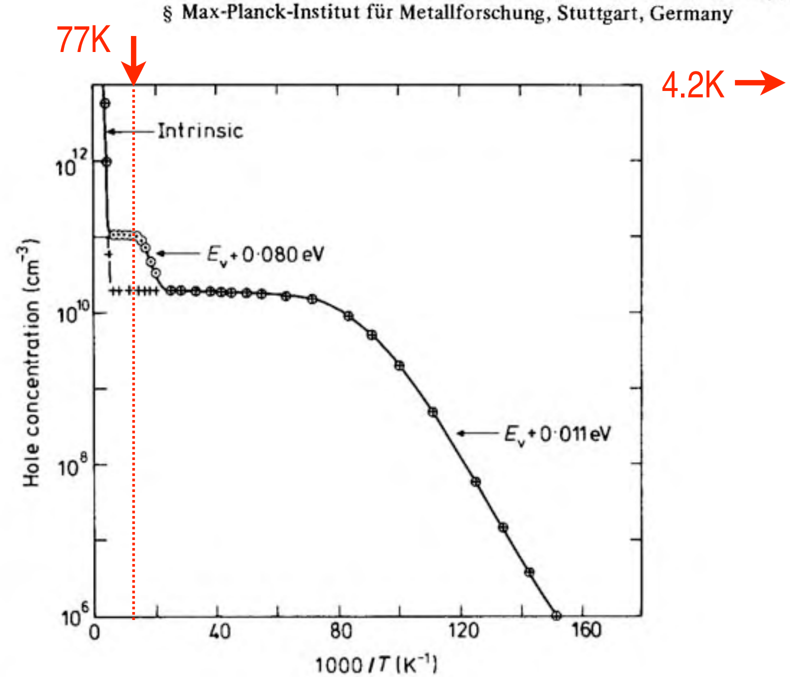
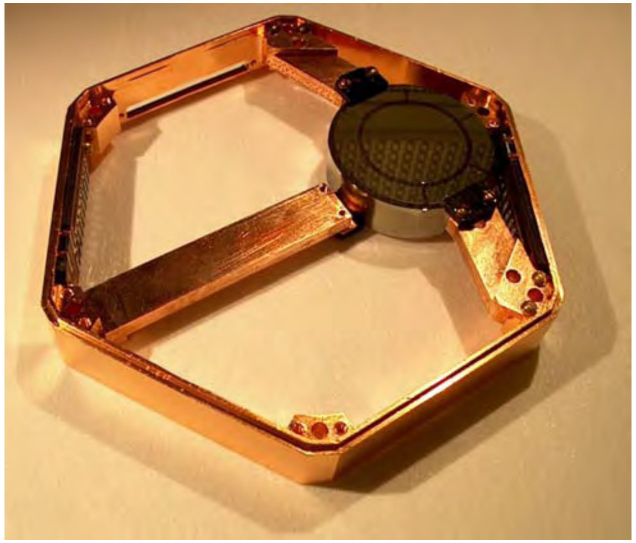
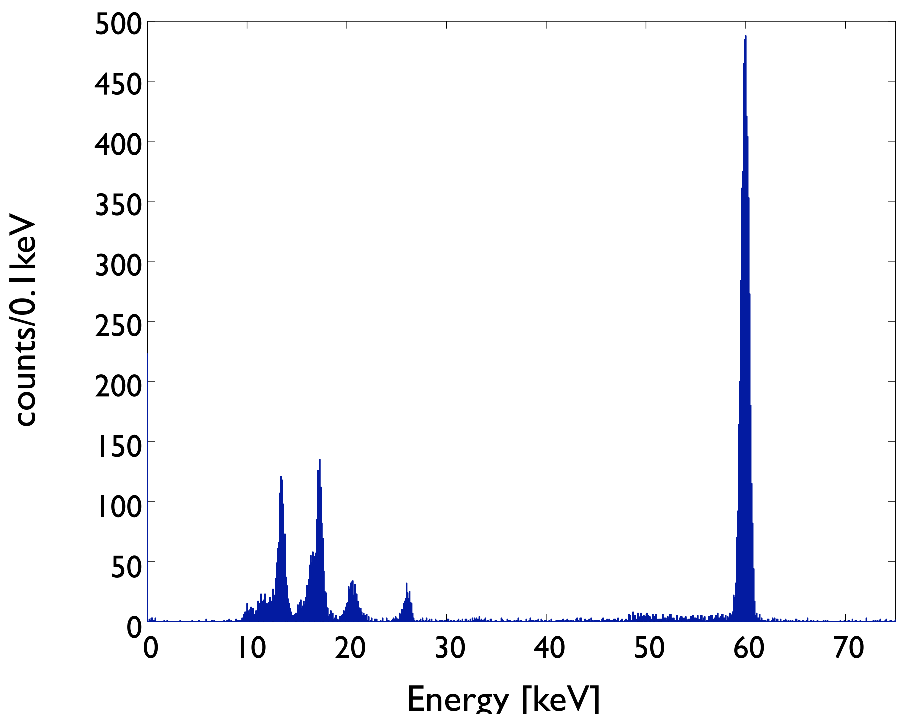


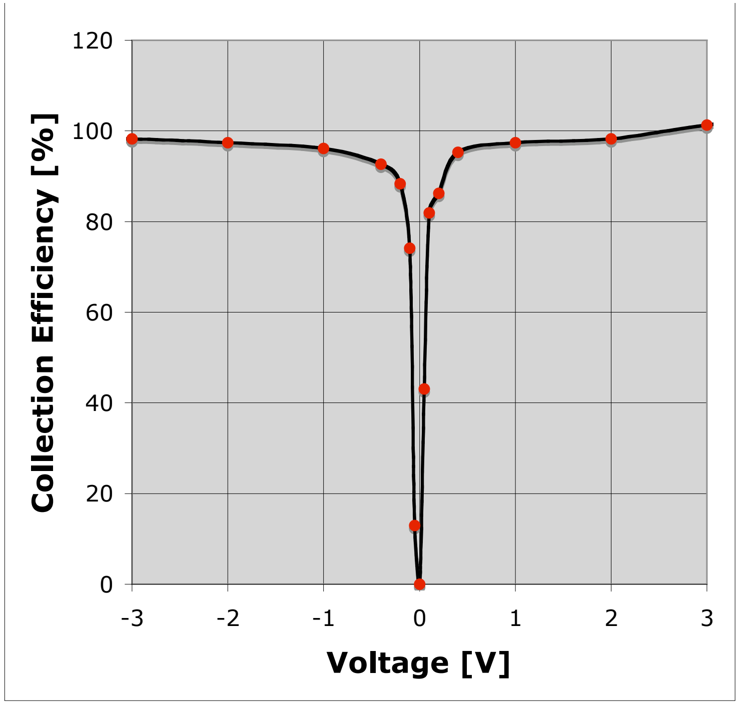
Figure 1. Hole concentration against reciprocal temperature 1/T of a dislocated and an undislocated Ge sample cut from the same crystal slice. The net impurity concentration o shallow acceptors and donors is equal for both samples. The E_v + 0·08 eV acceptor only appears in the dislocation-free piece; its concentration depends on the annealing temperature. ⊙ dislocation free; + dislocated.

Larger Substrates

- Proof-of-principle from Haller sample of dislocation-free Ge (3 cm x 1 cm)
  - Good collection at 1 V/cm (reasonable field)
- Working on obtaining crystals from assorted vendors
  - Umicore
  - Dick Pehl (LBNL ret'd, SBIR)
  - Dongming Mei/CUBED







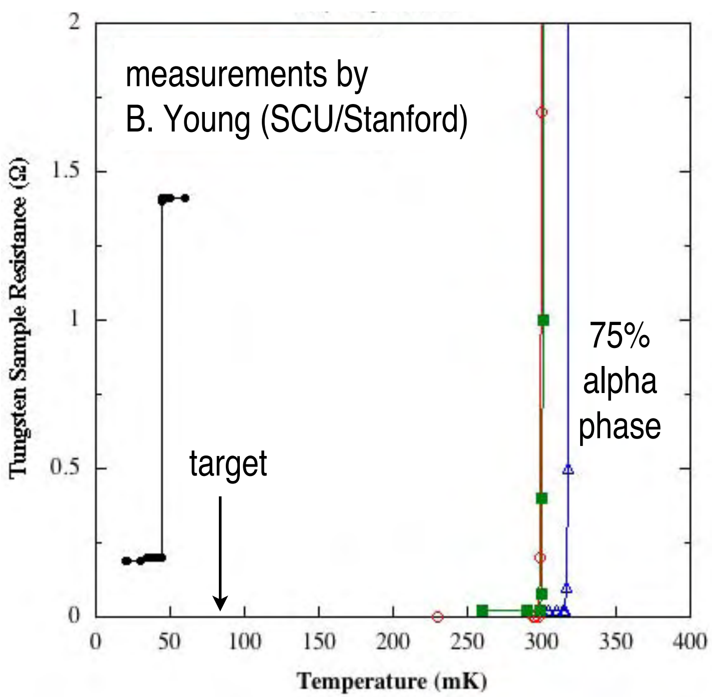
Detector Fabrication

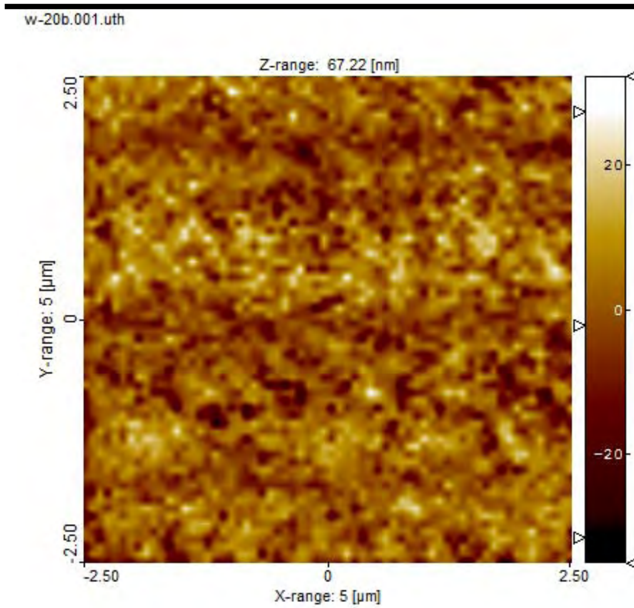
- Tools to fabricate on large substrates
  - 15-cm is no problem: industry standard
  - 5-cm is the problem
- Automation
  - Most time-consuming step is photoresist baking; slow process, must be carefully timed, substrates need to be exposed and etched soon after baking
- Strategy
  - Stanford produced CDMS detectors at Stanford Nanofabrication Facility (SNF)
  - Some pieces of equipment can be adapted to 15-cm x 5-cm, some cannot
  - With SLAC group, moving to 10-cm x 3.3-cm for SuperCDMS SNOLAB at SNF; undertaking simultaneous upgrade to 15-cm x 5-cm at SNF would be difficult
  - Instead, new TAMU faculty Mahapatra has dedicated effort on 15-cm x 5-cm
    - Substantial startup package and department/HEP group support & resources
    - Donations from Maxim/Dallas and other semiconductor/high-tech contacts
    - S4 funds + DOE CAREER award
  - Substantial expertise and assistance from EE/Physics faculty Rusty Harris

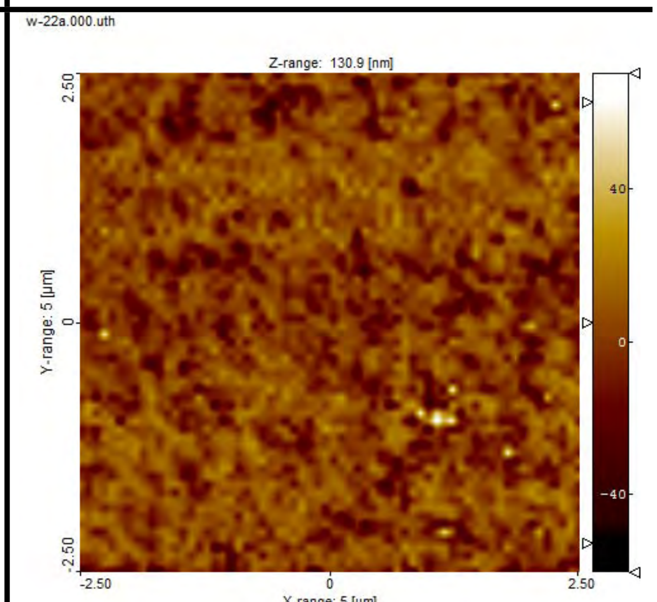
TAMU Fabrication Status

- W films deposited on thin wafers, initial T_c tests promising
  - Have used AFM to tune alpha-phase/beta-phase percentage to 75%/25%; gives T_c = 350 mK. Samples with Tc < goal obtained, too, so homing in.
  - Sharp transitions!
  - Will repeat with patterned films; changes in film stress affect T_c

110 nm thick	310 nm thick
Roughness: (Sa) 7.3nm	Roughness: (Sa) 11.6nm
Rms (Sq) 9.4nm	Rms (Sq) 15nm

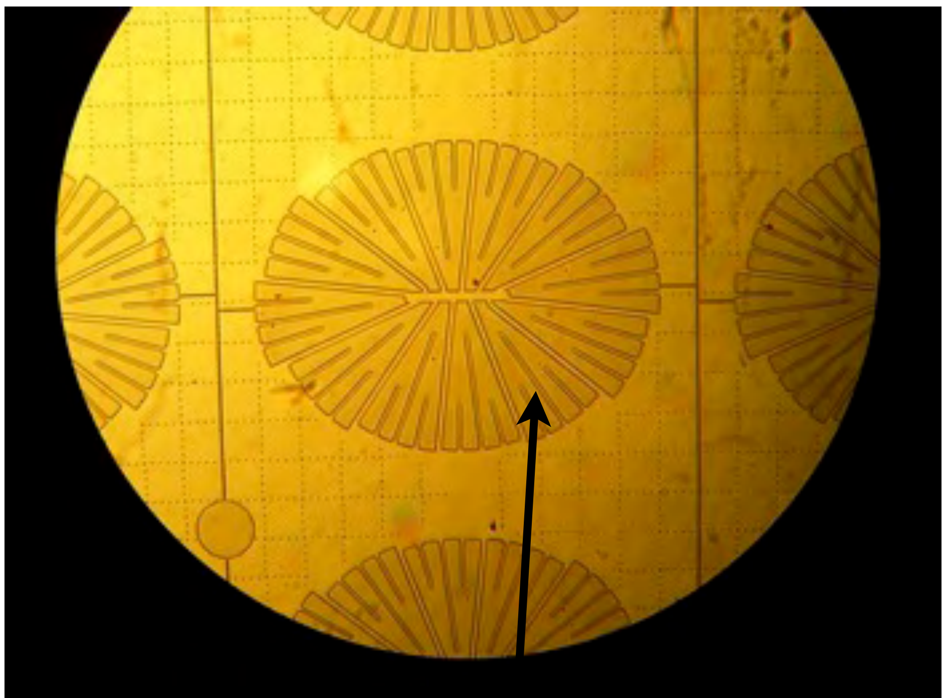




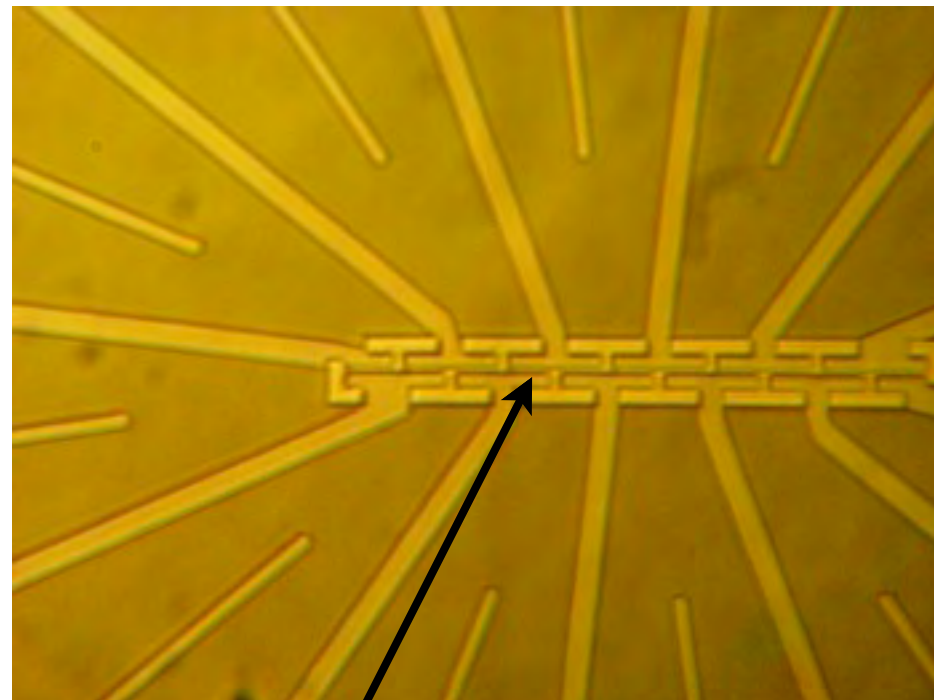


TAMU Fabrication Status

- Photolithography carried through to completion on Al films
  - Demonstrated etching of SuperCDMS Al structures
  - Good alignment of tungsten mask with Al mask
  - Expecting full sensor deposition by end of 2010



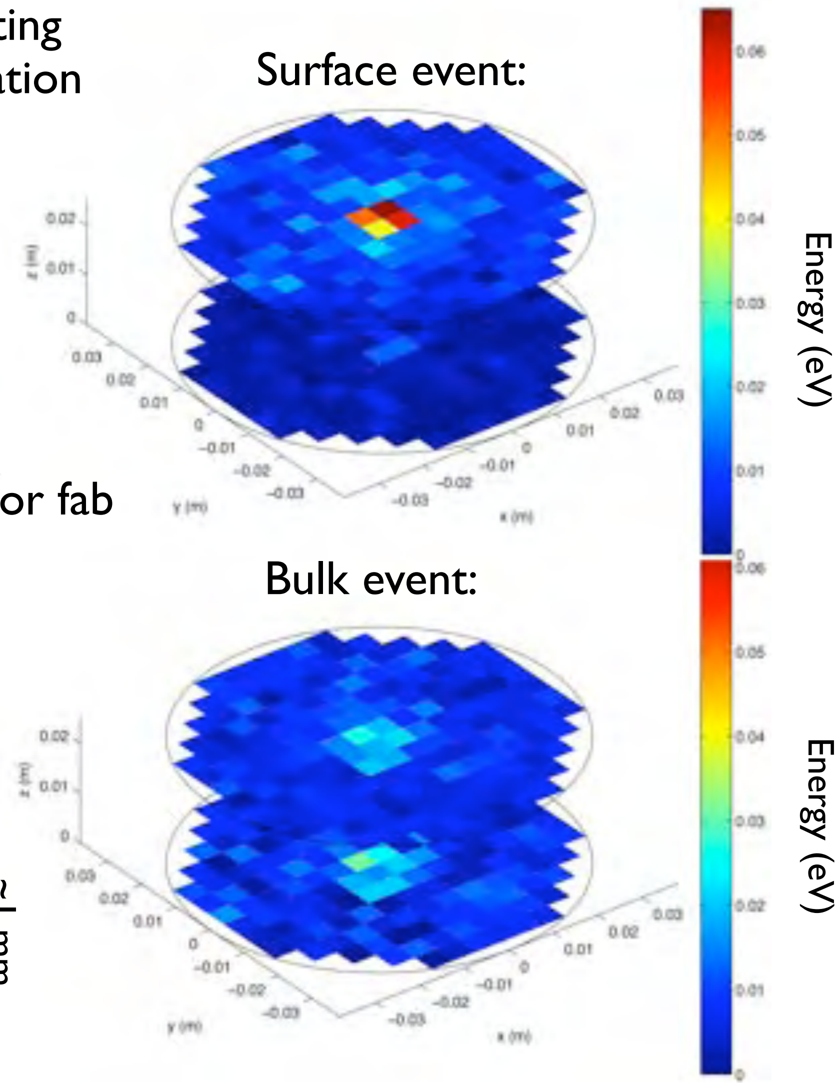
aluminum phonon absorber

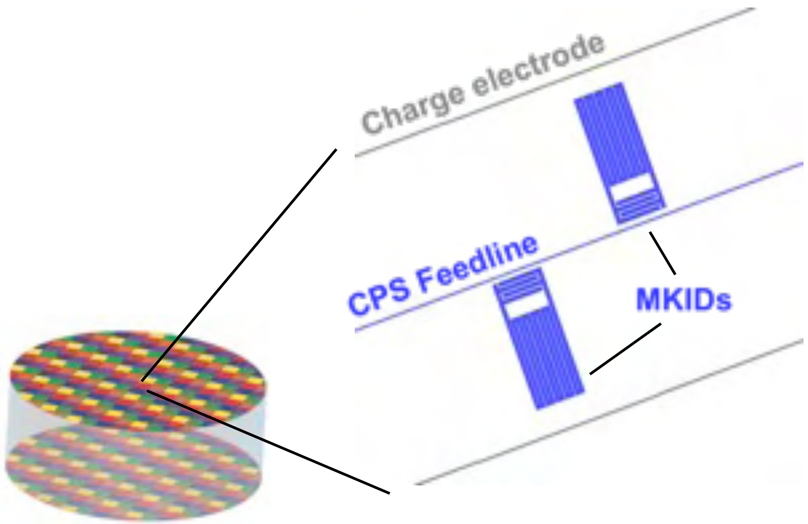


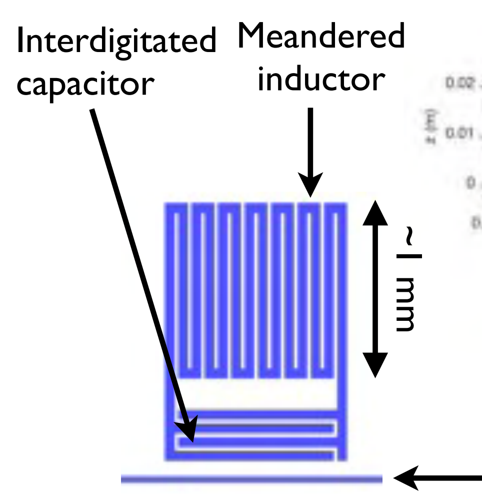
tungsten TES structure on mask
(TES mask aligned to patterned Al film)

Phonon Detection Using MKIDs

- Microwave kinetic inductance detectors (MKIDs, Zmuidzinas et al) can detect phonon energy: meV phonons break Cooper pairs, change L of superconductor
- Multiplexable: Form LC resonator w/single superconducting film. Readout like FM/AM radio with digital signal generation and demodulation.
- Recent development of lumped-element designs having low susceptibility to dielectric constant fluctuation noise and using large penetration depth materials enables large-area resonators for phonon sensing (Day, Gao, LeDuc, Noroozian, Zmuidzinas)
- Single film, 5 μm features would simplify GEODM detector fab
- Finer pixellization of phonon sensor provides additional surface event rejection



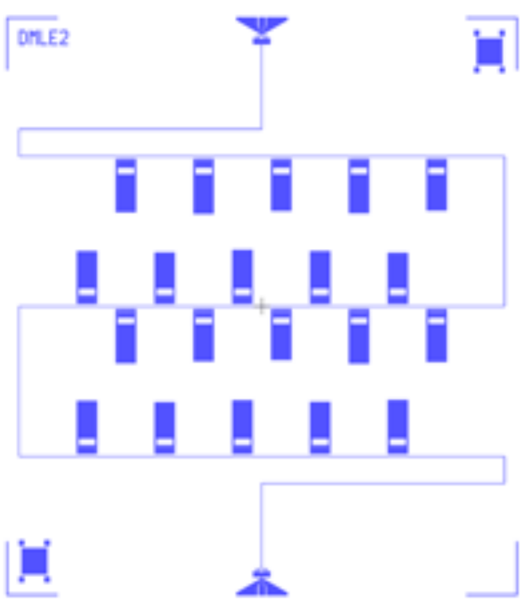


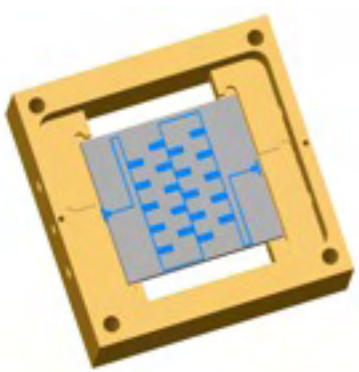


Figures by D. Moore

Progress to Date

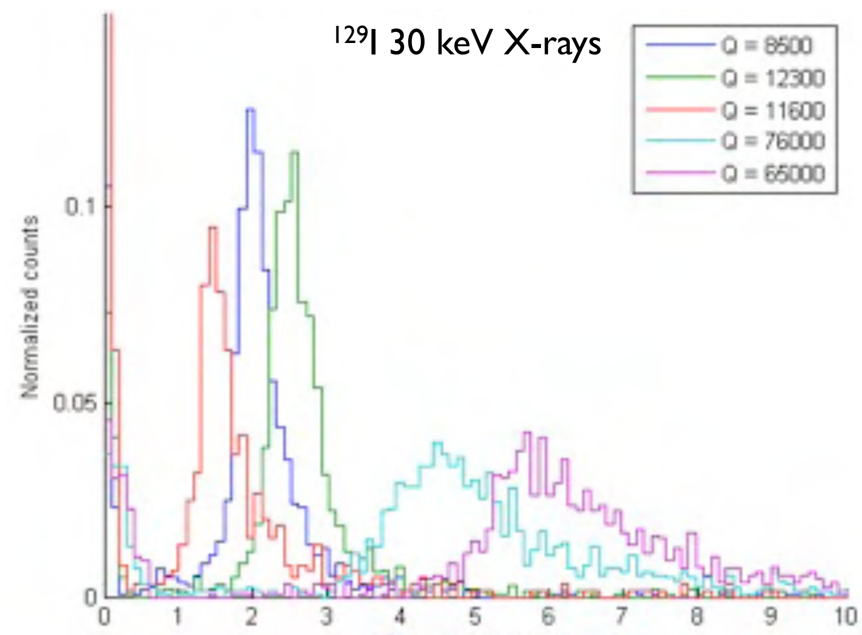
- Using measured noise and responsivities, calculate a noise-equivalent power (NEP)
- Converting to an energy resolution gives: σ_E = 46 eV for A = 1.5 mm^2 and σ_E = 14 eV for A = 0.64 mm^2 (single-resonator resolution)
- An MKID-based detector with 500 one mm^2 resonators would have similar energy resolution as current designs, but would be much easier to fabricate and read out
- 12 mm x 16 mm array of 20 resonators being tested now with collimated source to demonstrate position reconstruction. Pulses seen in all resonators! Tuning up biasing and analysis to get data on all resonators at once and reconstruct position.





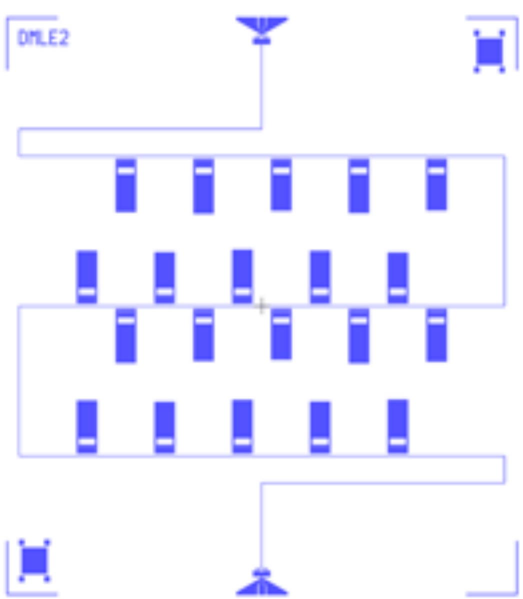
collimated source incident on bottom side of silicon wafer

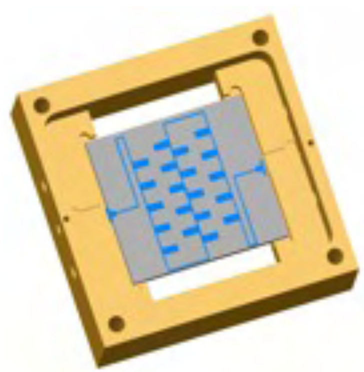
Single Resonator Spectra



Progress to Date

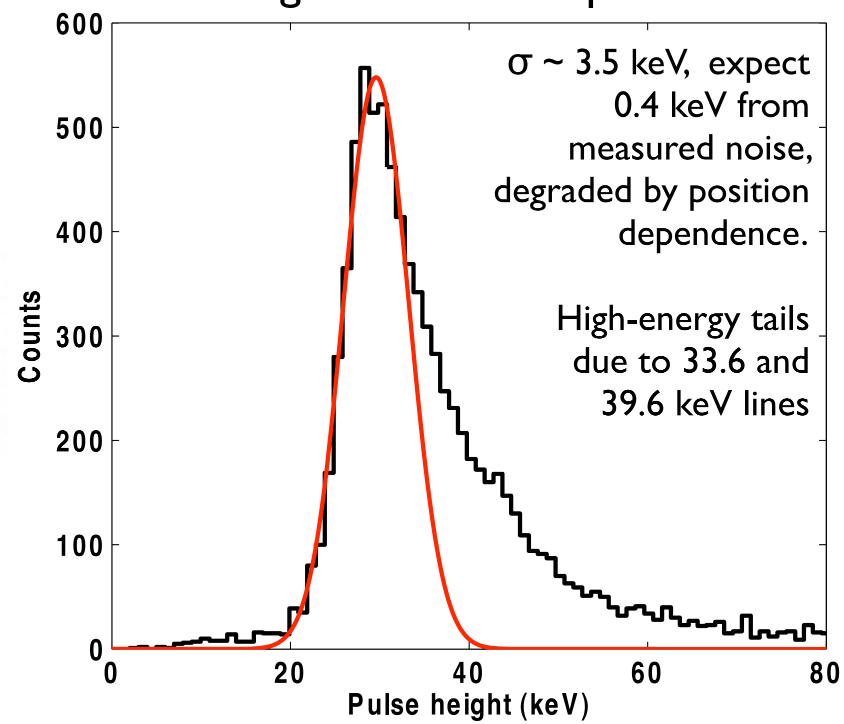
- Using measured noise and responsivities, calculate a noise-equivalent power (NEP)
- Converting to an energy resolution gives: σ_E = 46 eV for A = 1.5 mm^2 and σ_E = 14 eV for A = 0.64 mm^2 (single-resonator resolution)
- An MKID-based detector with 500 one mm^2 resonators would have similar energy resolution as current designs, but would be much easier to fabricate and read out
- 12 mm x 16 mm array of 20 resonators being tested now with collimated source to demonstrate position reconstruction. Pulses seen in all resonators! Tuning up biasing and analysis to get data on all resonators at once and reconstruct position.





collimated source incident on bottom side of silicon wafer

Single Resonator Spectra



Conclusions

- CDMS II has completed its data set, providing the best sensitivity to spin-independent scattering of WIMPs for M > $M_Z/2$; unfortunately, no significant detection of WIMPs.

- SuperCDMS and GEODM will provide sensitivity gains of up to 1000; MKIDs are a promising avenue for simplifying detector production.