Searches for Low-Mass WIMPs with CDMS II and SuperCDMS

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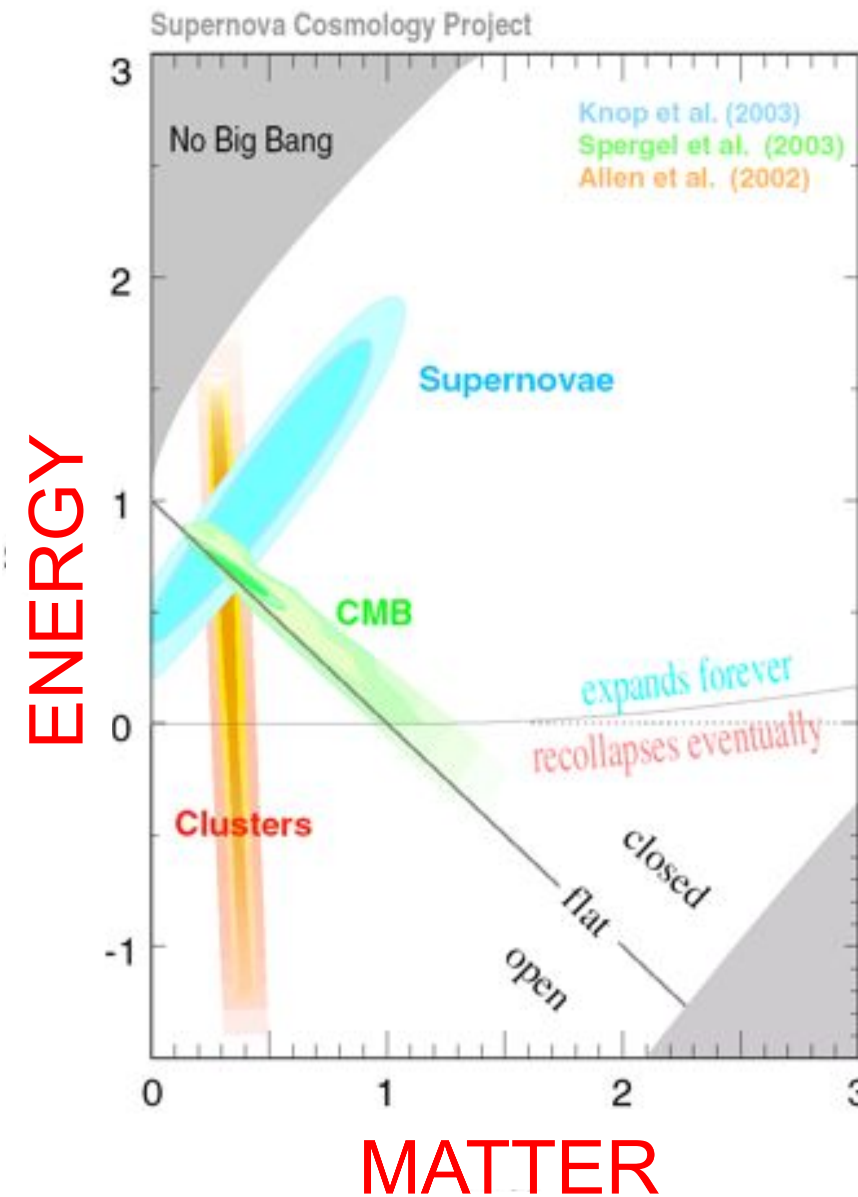
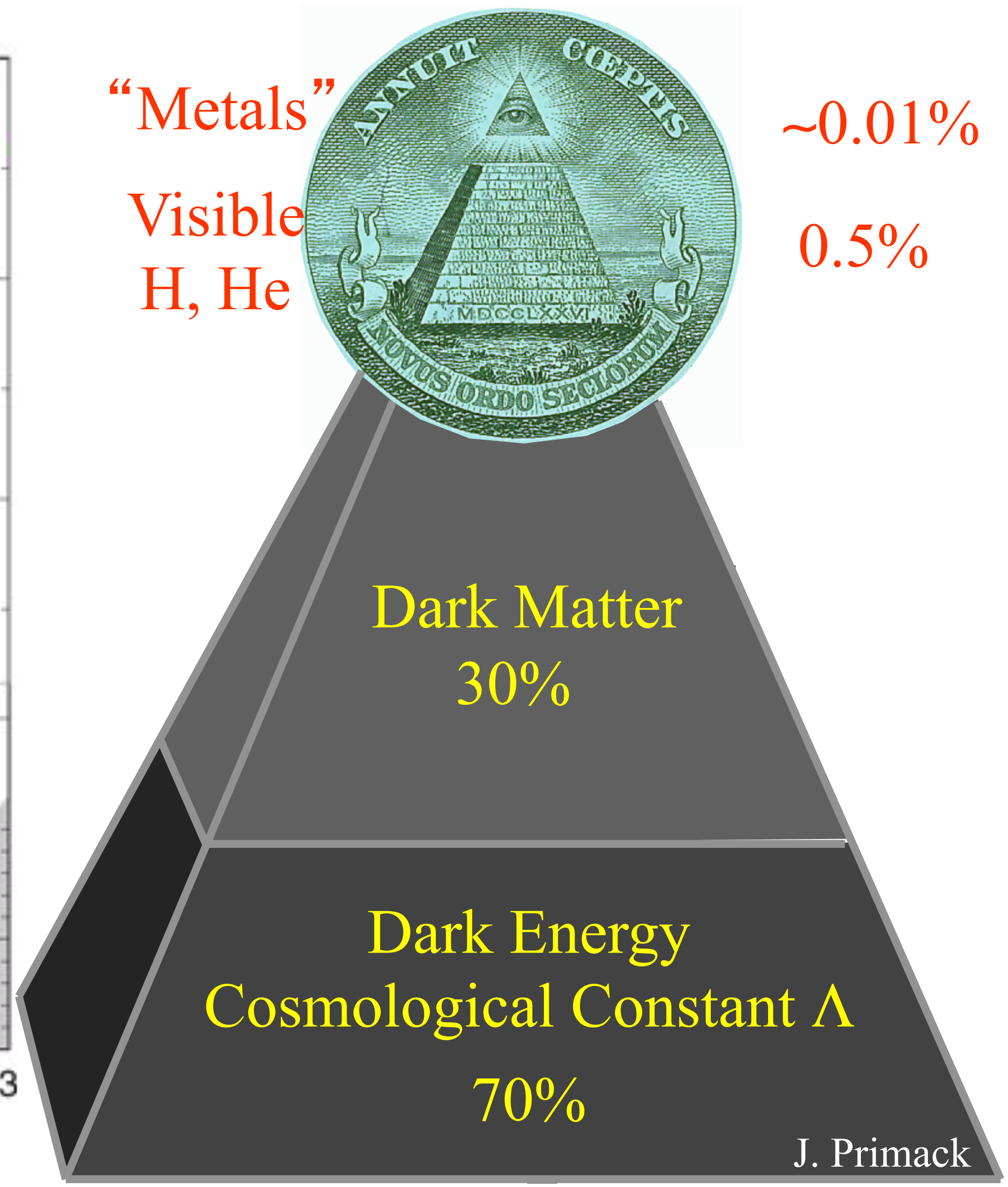
SuperCDMS Science Coordinator
Syracuse University

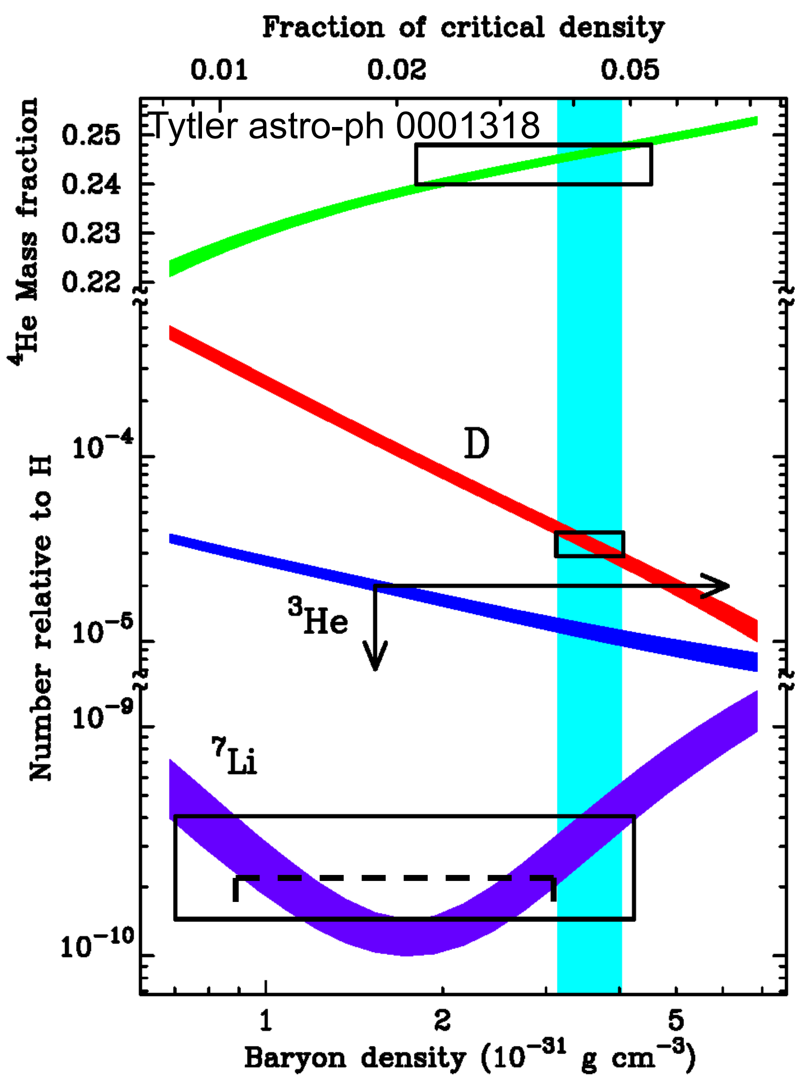
arXiv:
1304.4279
1304.3706
1203.1309

A New Order

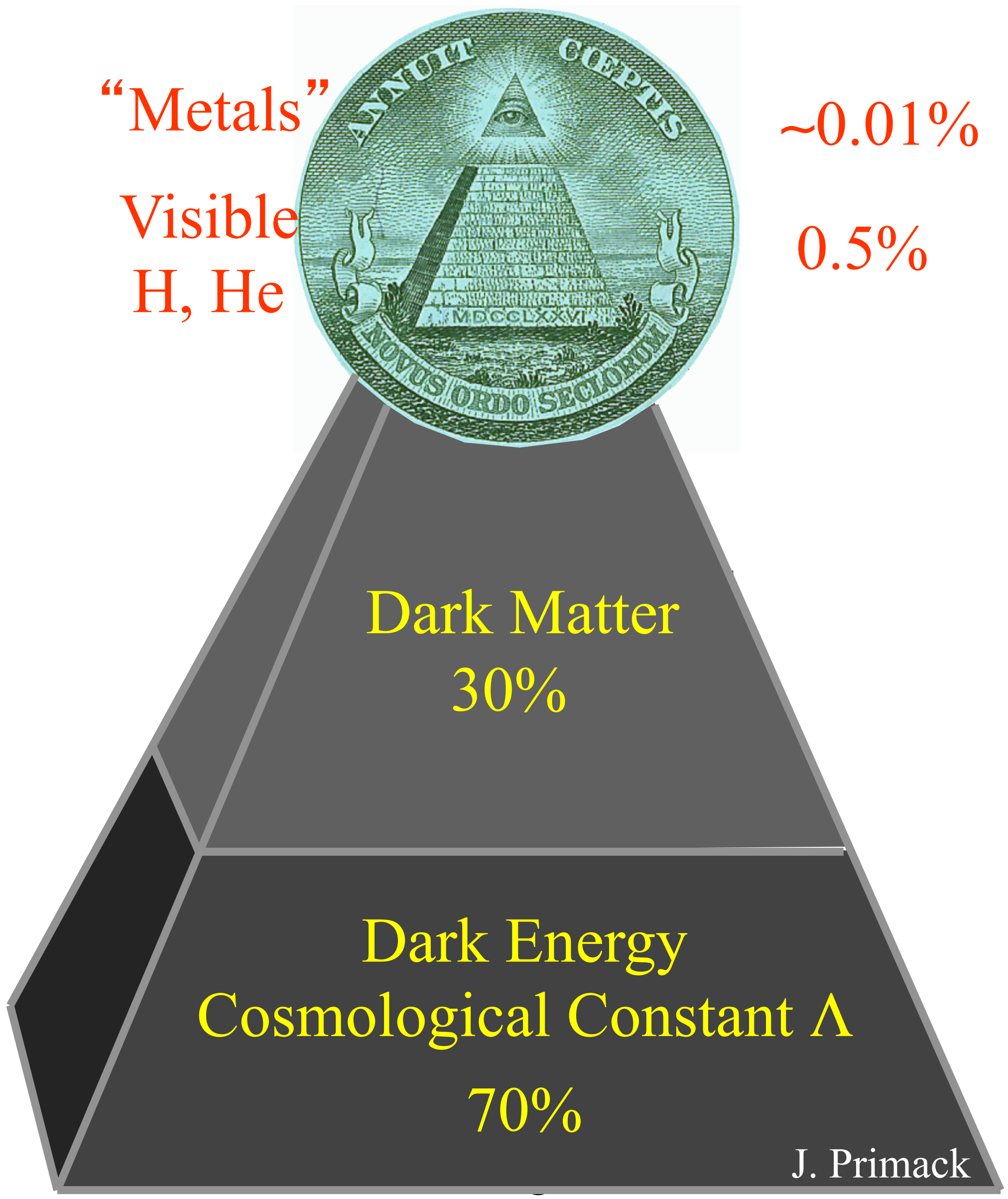

Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
expands forever
recollapses eventually
Clusters
closed
flat
open
ENERGY
MATTER


"Metals"
~0.01%
Visible
H, He
0.5%
Dark Matter
30%
Dark Energy
Cosmological Constant Λ
70%
J. Primack

A New Order



Fraction of critical density
0.01
0.02
0.05
Tytler astro-ph 0001318
4He Mass fraction
0.25
0.24
0.23
0.22
Number relative to H
10−4
10−5
10−9
10−10
D
3He
7Li
1
2
5
Baryon density (10−31 g cm−3)



"Metals"
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Visible
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ANNUIT COEPTIS
MDCCLXXVI
NOVUS ORDO SECLORUM
Dark Matter
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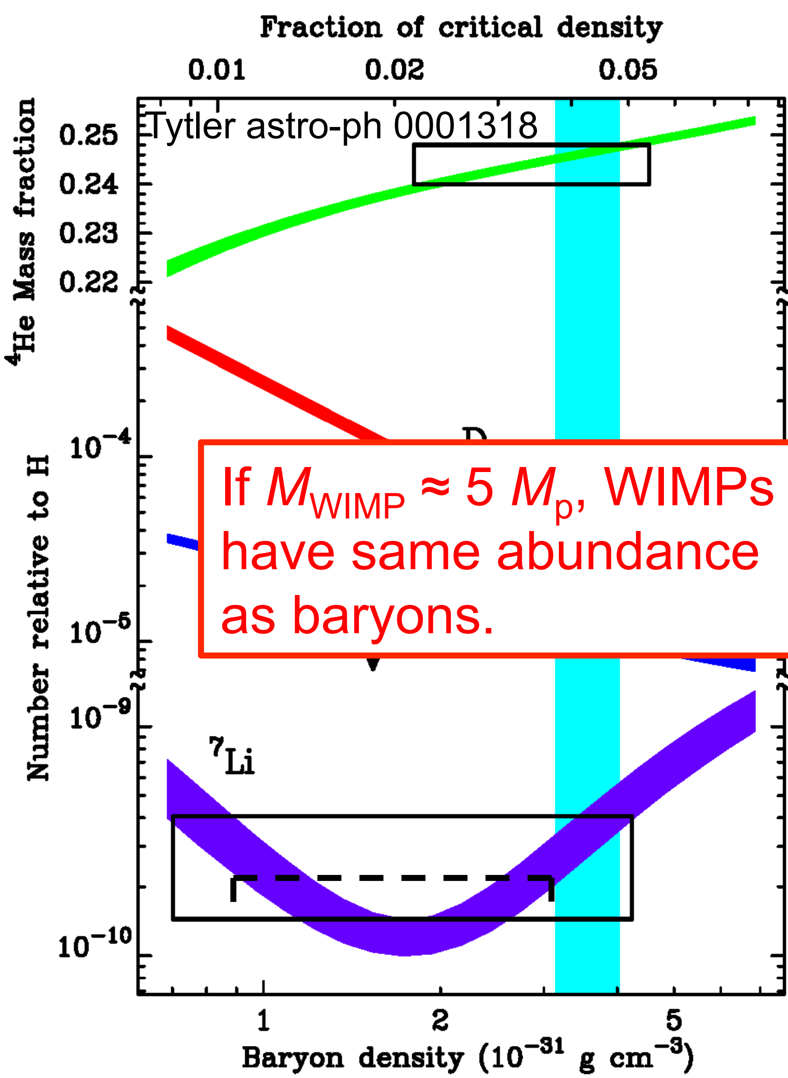
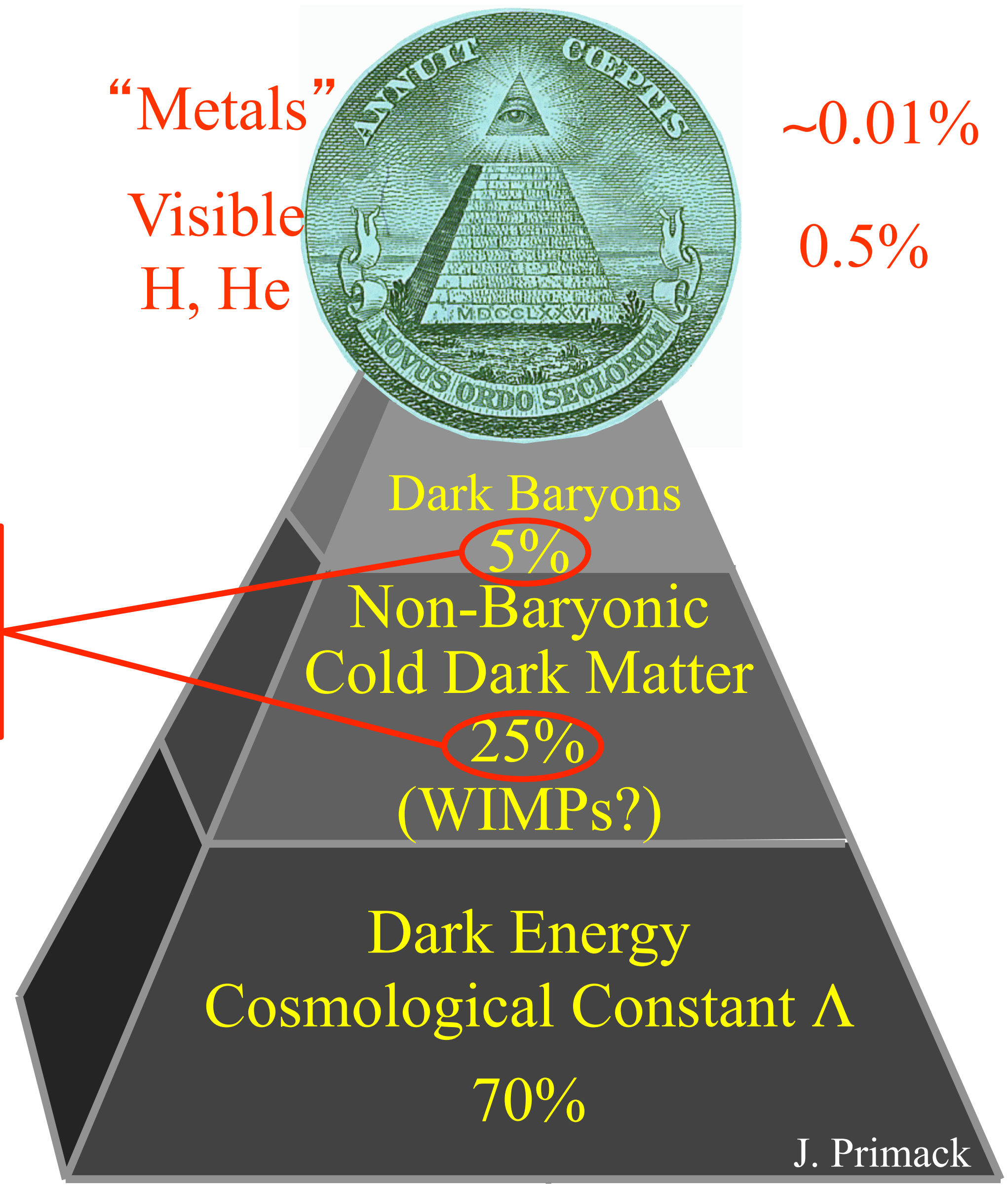
A New Order

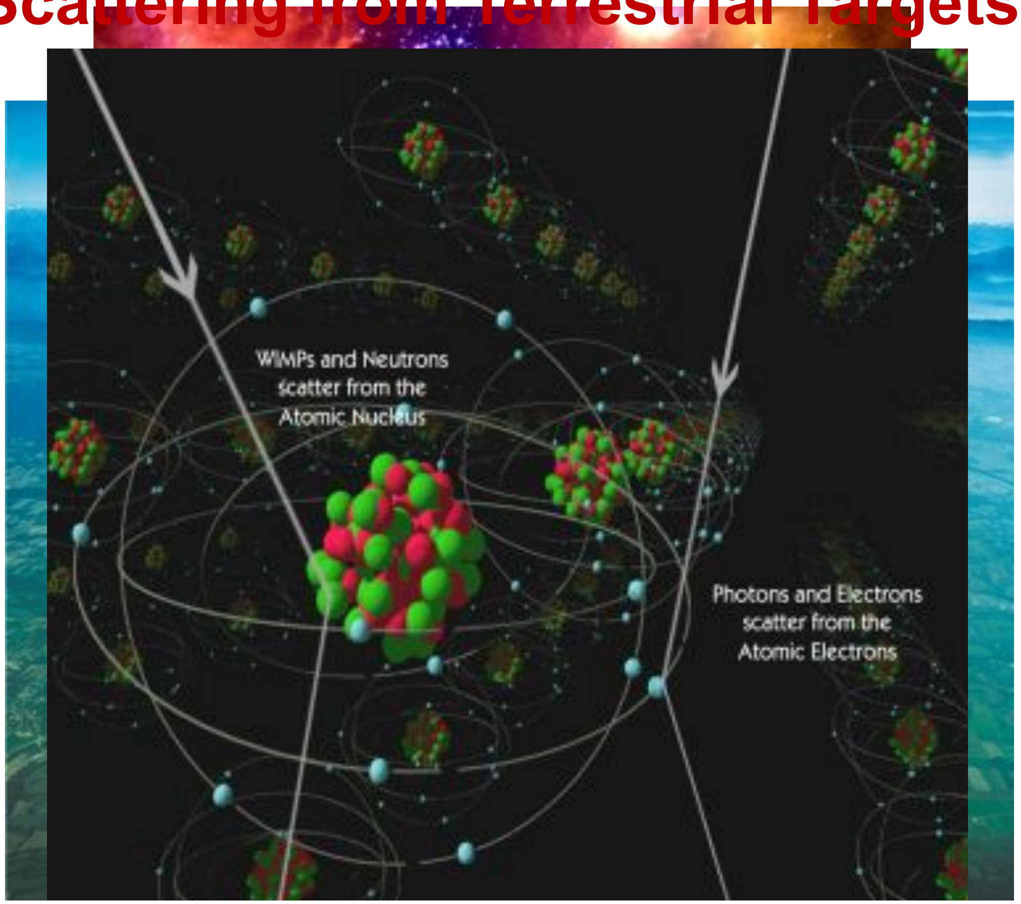


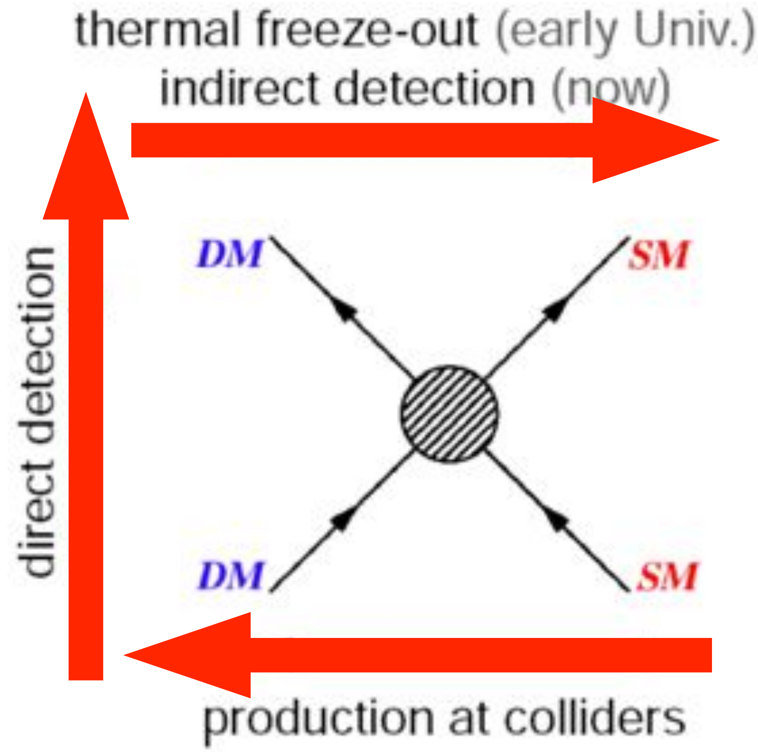
If $M_{\mathrm{WIMP}} \approx 5\ M_p$, WIMPs have same abundance as baryons.



WIMP Detection

Solar-neighborhood WIMPs
The Fermi-LAT γ-ray Observatory
Scattering from Terrestrial Targets



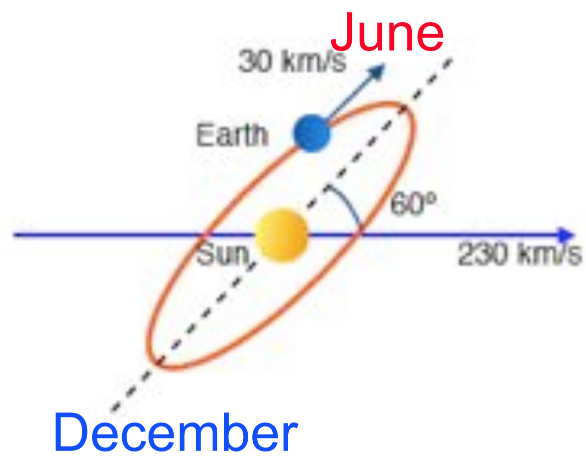


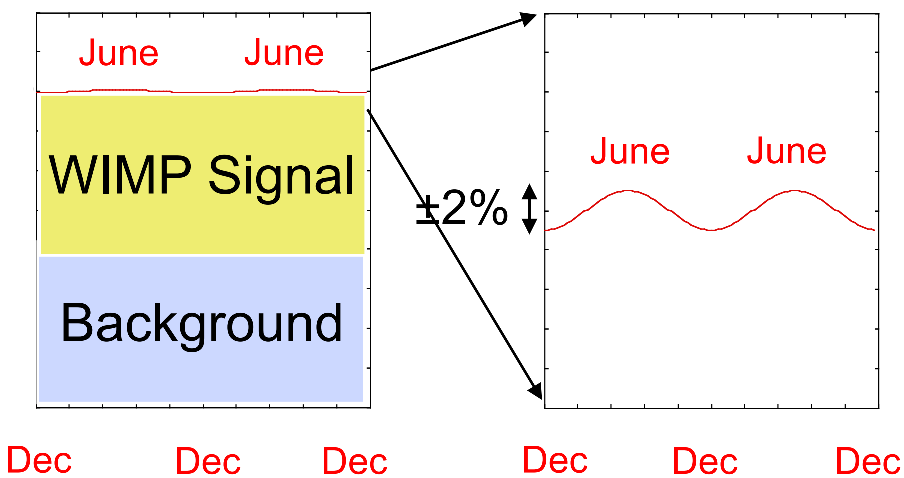
Use radiopure apparatus, shielded underground, preferably with discrimination against backgrounds from natural radioactivity

Current WIMP Detection? DAMA/LIBRA

•If WIMPs exist, expect annual modulation (Drukier/Freese/Spergel 1986)

•DAMA/LIBRA do not distinguish between WIMPs and backgrounds directly, but infer WIMPs from annual modulation in lowest-energy single-scatter interactions, assuming backgrounds don’t modulate:



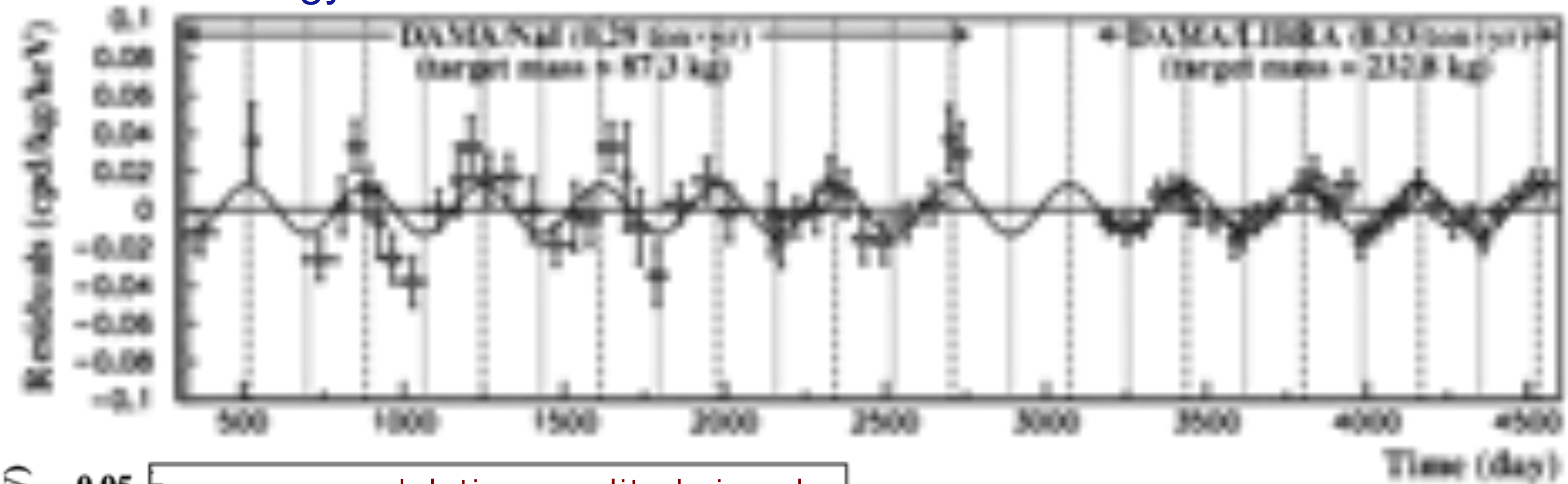


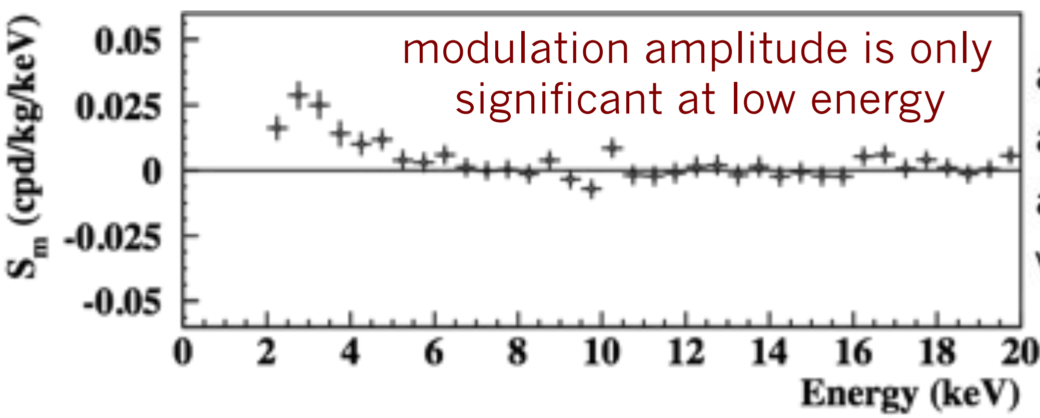
•Use 250-kg array of 25 ultraclean NaI scintillators

DAMA/LIBRA Annual Rate Variation

Sum of residuals after subtracting time-averaged rates in each energy bin in each detector

arXiv:0804.2738
arXiv:0804.2741





an amplitude	$A_m = 0.0131 \pm 0.0016$
a period of	$\omega = 0.998 \pm 0.003$ years
a phase max at	$t_0 = 144 \pm 8$ days
with significance	C.L. = 8.2σ

Consistent with a variety of models (fewer when DC rate spectrum also considered)

Could Background be Modulating?

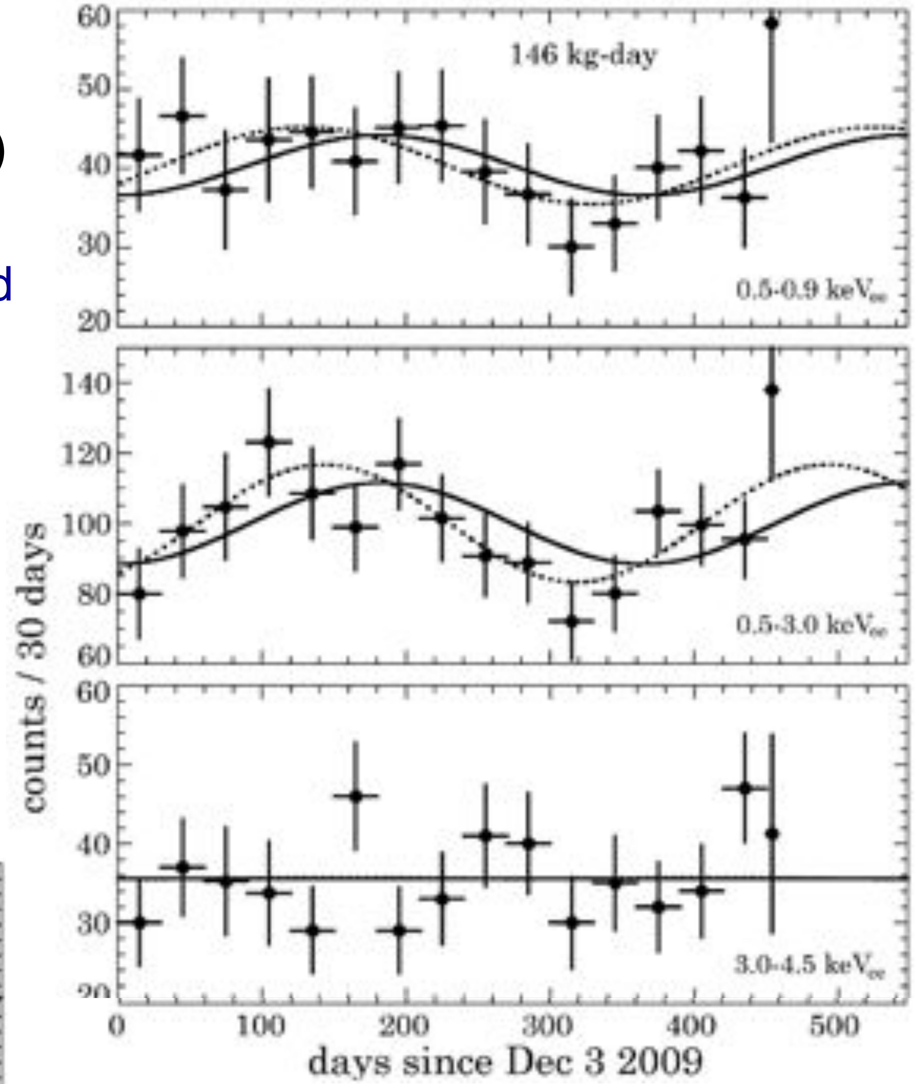
- Such a background would have to fulfill the annual modulation characteristics of a standard WIMP:
  - Rate = cos(t)
  - 1 year period
  - Known phase

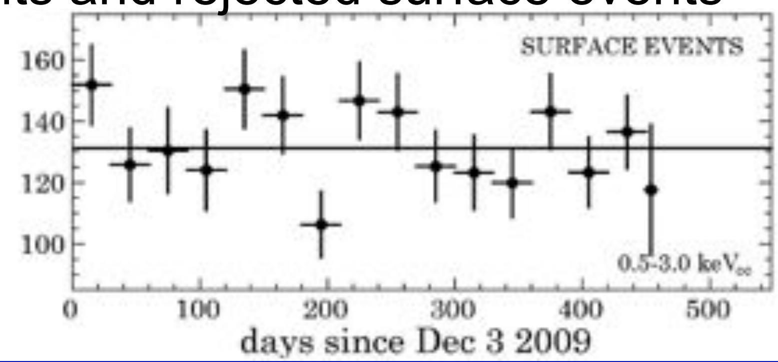
  } Many differences between summer/winter

  - Low energies only — Most likely to be affected by systematic effect
  - Single hits only — Not very powerful test
  - Consistent signal between NaI/LIBRA and different detectors — 2.5σ, borderline pass
- Nothing suggested seems likely
  - Modulation in rejection efficiency of noise pulses near threshold?
  - Modulation of muon flux causing phosphorescence (D. Nygren, 1102.0815) or exciting unknown 3 keV nuclear line? (S. Klein)
  - 3.2 keV line from ^{40}K contamination? (requires bad MC by DAMA)
  - Modulating neutrons activating ^{128}I to decay by 3.1 keV Auger electrons (J. Ralston, 1006.5255)

CoGeNT Annual Modulation

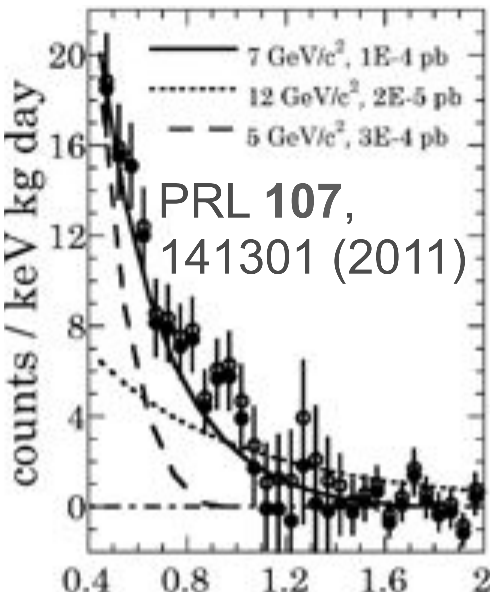
- Nearly continuous data from December 4, 2009 - March 6 2011 (plus ~650 days since, not yet public)
- Modest significance
  - Flat rate with time gives fit allowed at 16% CL
  - Likelihood ratio test prefers modulation at 2.8σ
- Compatible with WIMP hypothesis
  - Period = 347 ± 29 days
  - Min. Oct 16 ± 12 days (little early)
  - Amplitude 12.8% (big) or bigger!
- Modulation absent for high-energy events and rejected surface events



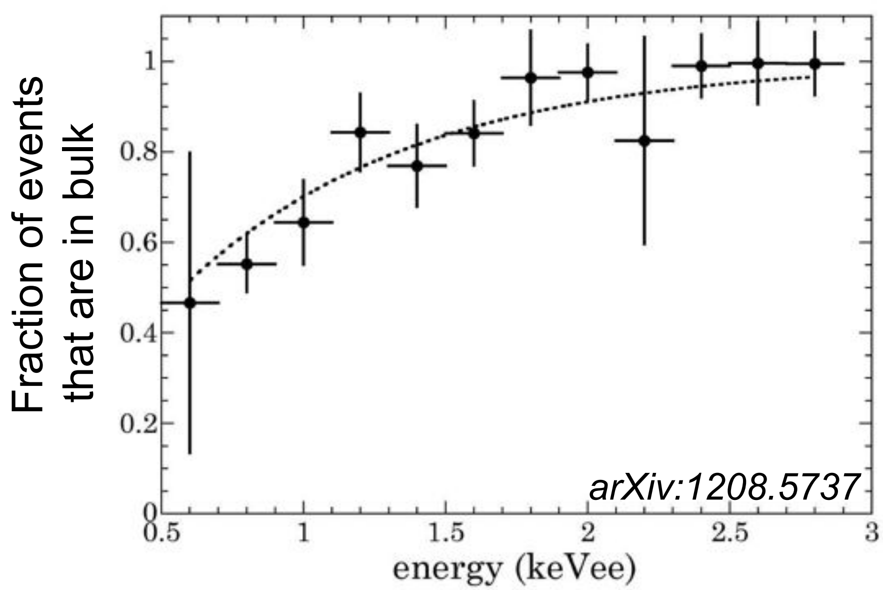


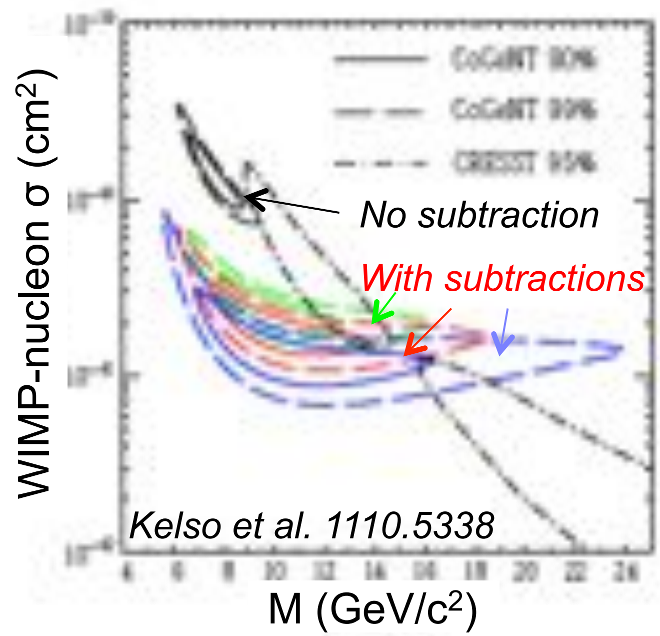
PRL **107**,141301 (2011)

CoGeNT Event Spectrum & ROI



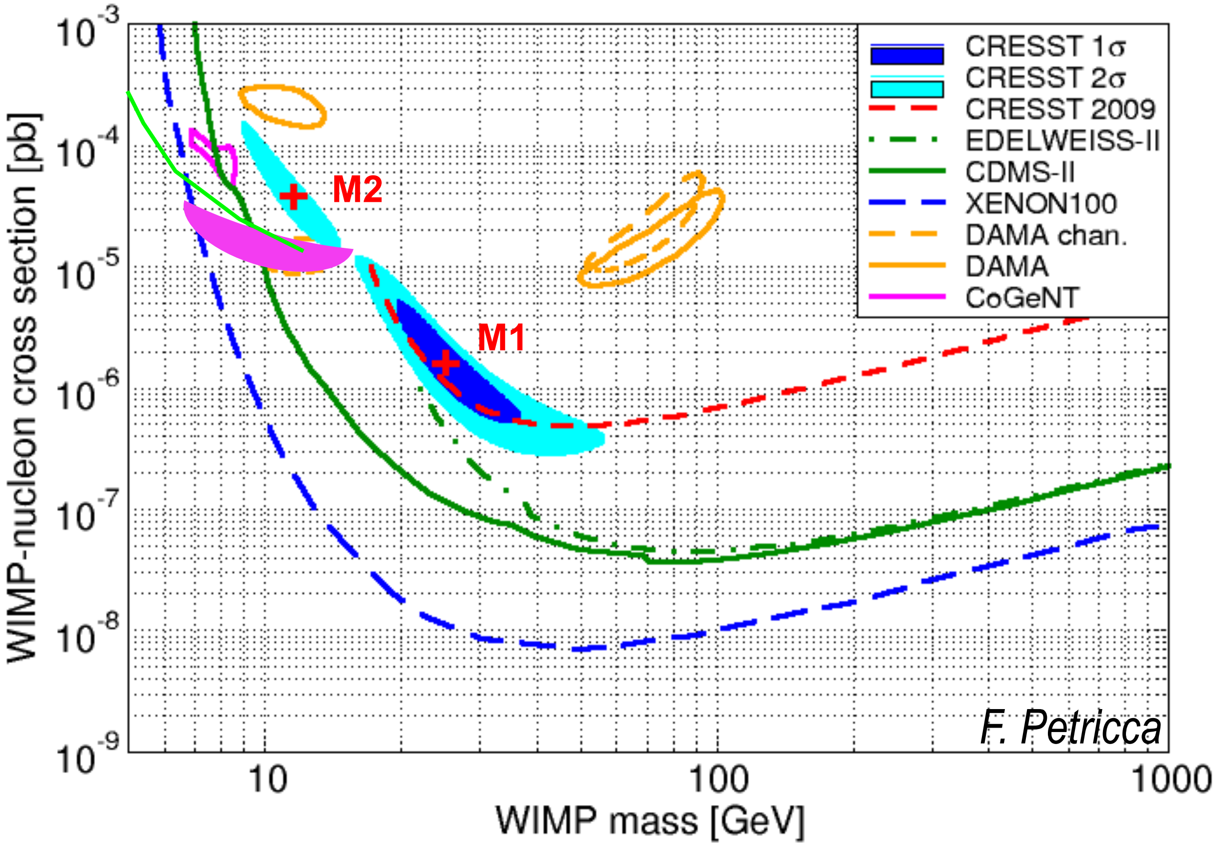
- See exponentially increasing rate above known backgrounds for energies < 1.5 keVee
- Some determined to be misidentified surface events
- Kelso et. al infer WIMP allowed region based on subtracting these events off, pushing allowed region to lower cross section & larger mass





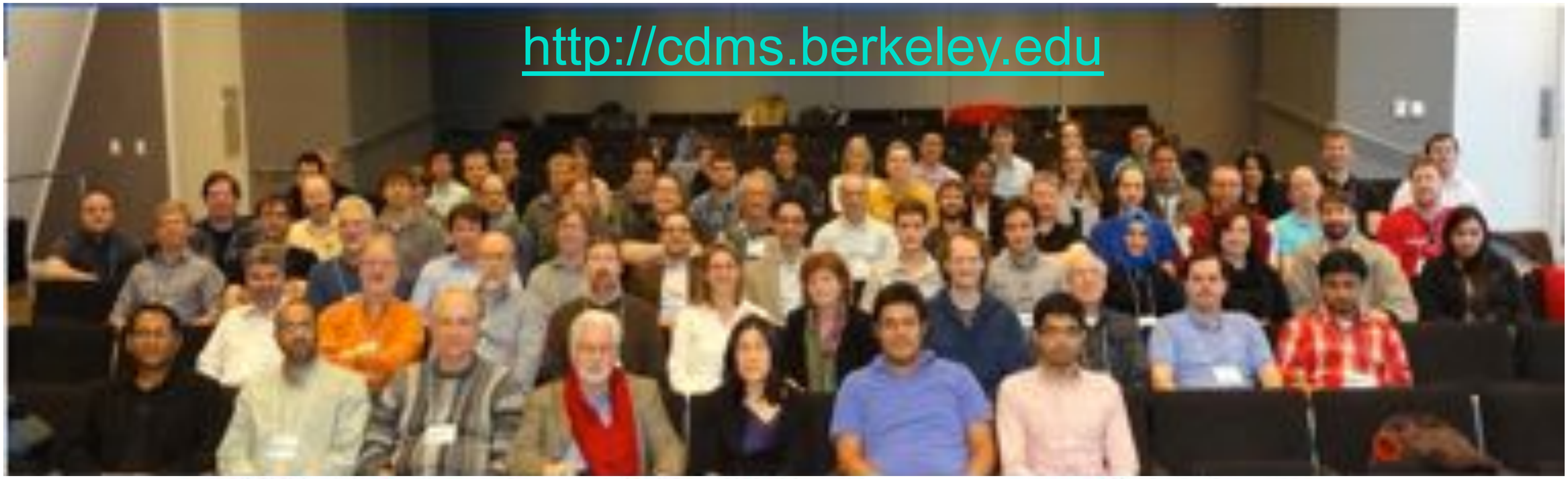
Hints of Low-Mass WIMPs, Circa 2011-12

- DAMA, CoGeNT, and CRESST with hints, large backgrounds
- CRESST obtained good fit by adding light WIMPs, but extrapolation of backgrounds to low energy worrisome
  - α / Pb-recoils backgrounds (Astropart. Phys. **36**, 1, 77–82)



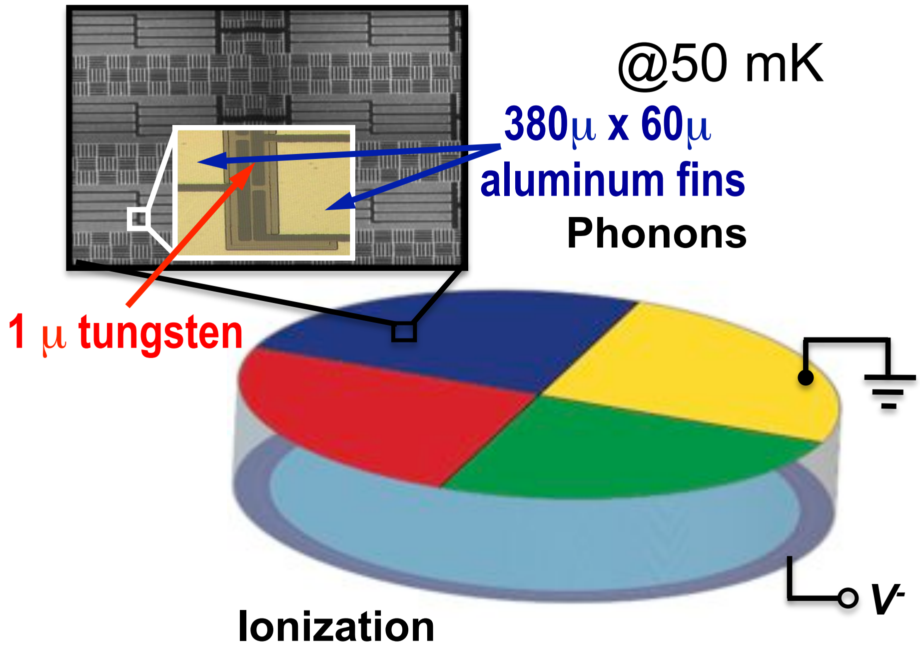
- In strong tension with XENON100 limits
  - Imaginable to sidestep via systematic or theory (e.g. different interaction on Xe) but not easy

The SuperCDMS Collaboration



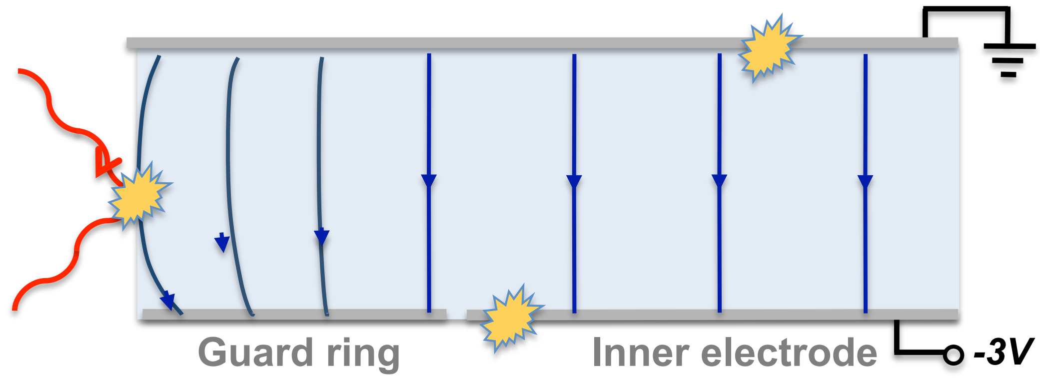
- California Institute of Technology
- Queen's University
- Southern Methodist University
- Texas A&M University
- University of California, Berkeley
- University of Evansville
- Fermi National Accelerator Laboratory
- Santa Clara University
- Stanford University
- Universidad Autónoma de Madrid
- Pacific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

CDMS: Ionization and Athermal Phonons



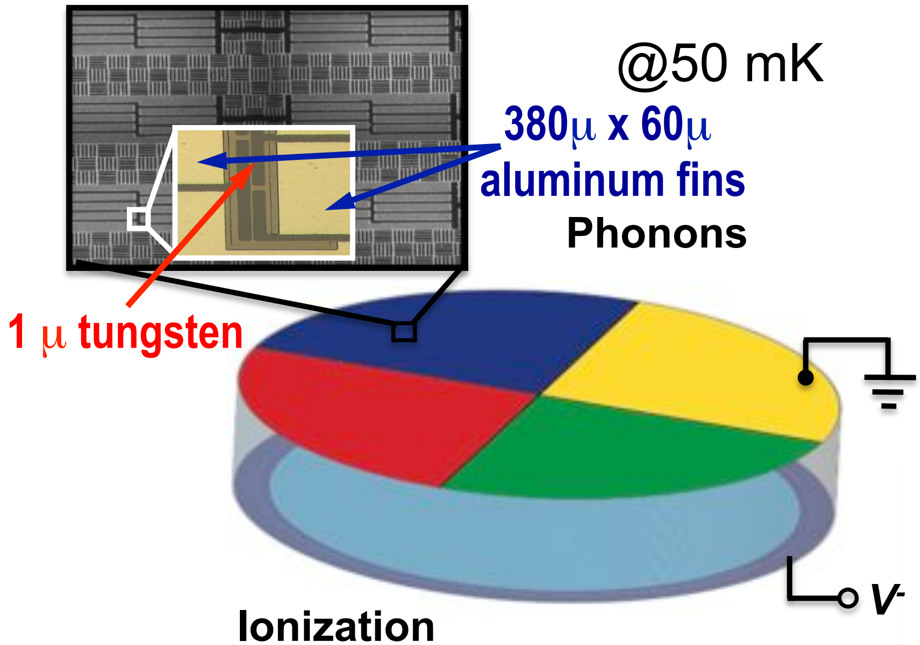
- 240 g Ge or 106 g Si crystals
- 1 cm thick x 7.5 cm diameter
- Collect athermal phonons

- Measure ionization in low field (~volts/cm) with segmented contacts to allow rejection of events near outer sidewall

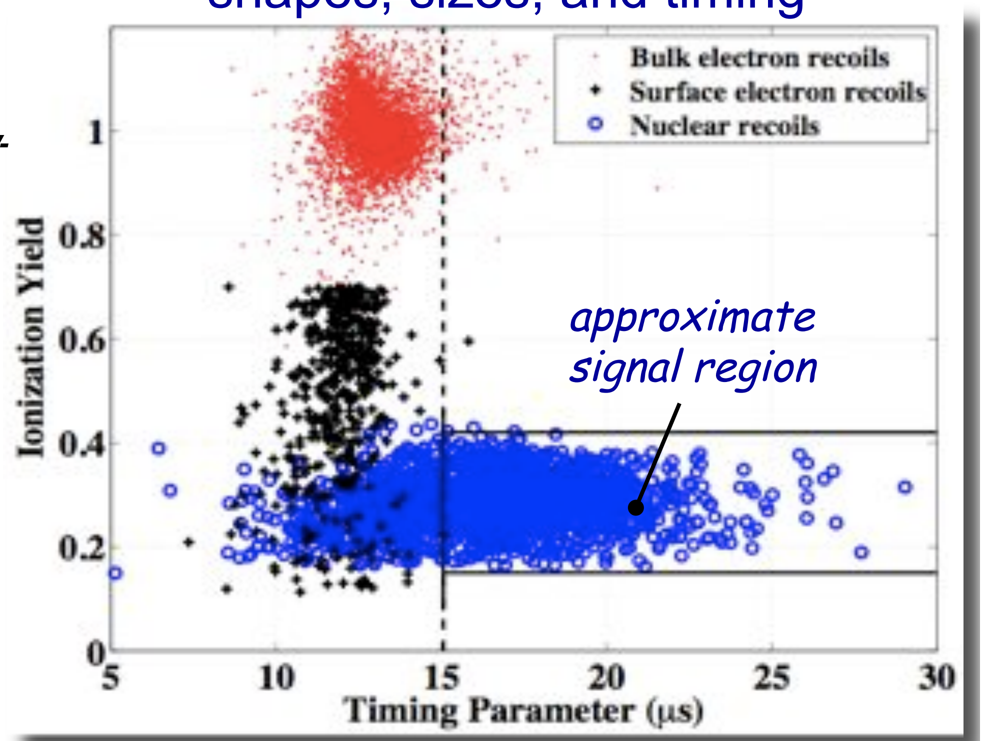


Electric field lines near cylindrical wall

CDMS: Ionization and Athermal Phonons



- 240 g Ge or 106 g Si crystals
- 1 cm thick x 7.5 cm diameter
- Collect athermal phonons:
  - 3D position information, top/bottom surface event veto based on sensor pulse shapes, sizes, and timing



- Measure ionization in low field (~volts/cm) with segmented contacts to allow rejection of events near outer sidewall
  - Ionization yield (ionization energy per recoil energy) ~3x larger for electron recoils than nuclear recoils

CDMS II Experimental Setup

Reduce backgrounds, especially nuclear recoils due to neutrons

1. Go Deep:

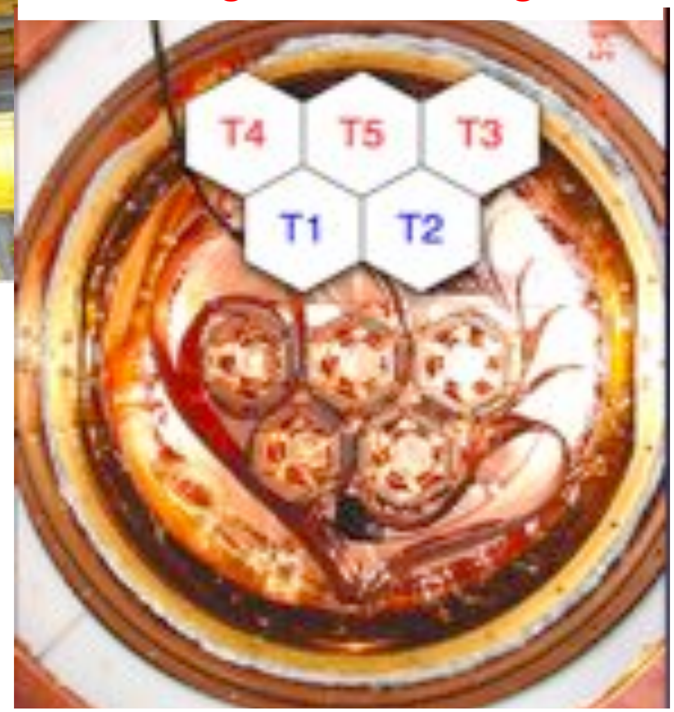
Soudan Mine: 2090 mwe
(muon rate reduced by >10^4)

2. Use Active Shielding:

muon veto ~98% efficient

30 ZIPs (5 Towers)

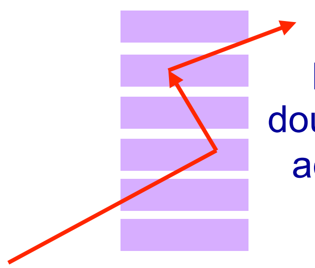
~4.4 kg Ge, ~1.1 kg Si



3. Use Passive Shielding:

2 layers polyethylene - shields from cosmogenic and radiogenic neutrons

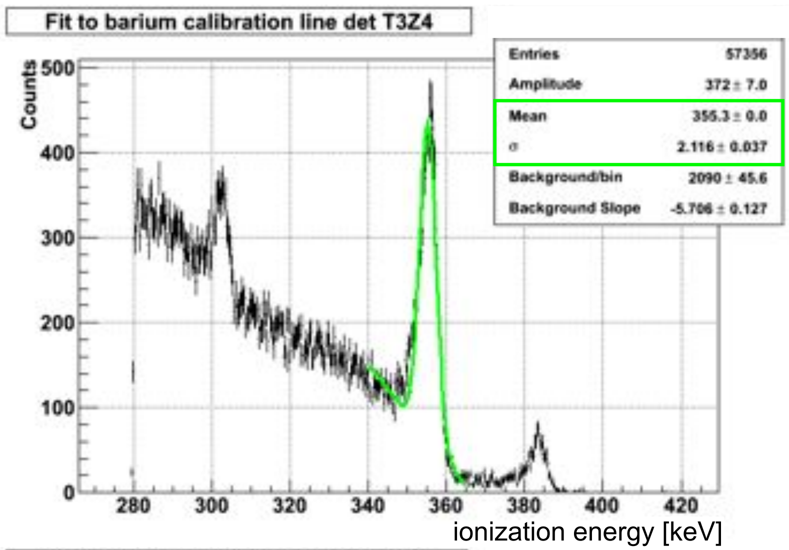
4. Use Event Topology

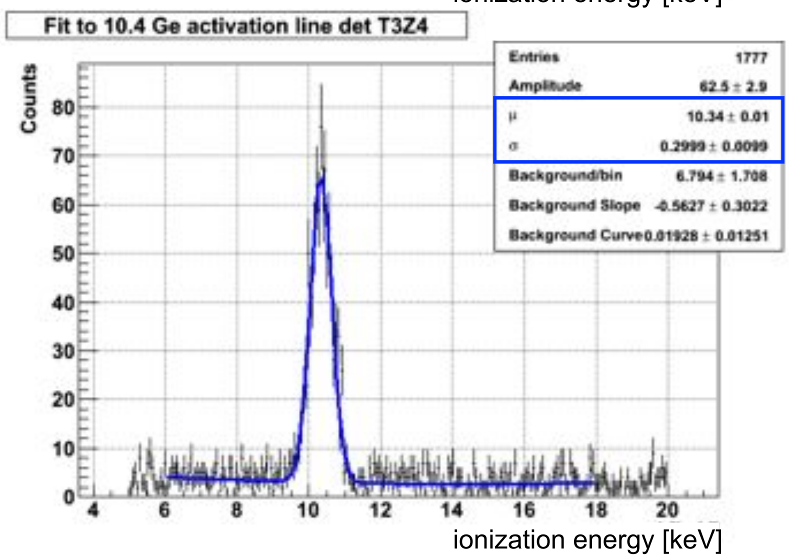


Neutrons may double scatter or be accompanied by EM shower

Extensive simulations (FLUKA/GEANT/MUSIC) indicate << 1 unvetoed single scatter neutron/ kg year

Calibration Data





L. Hsu, FNAL

Two Sources:

^{133}Ba: γ-lines at 303, 356 & 384 keV, lower-energy Compton-scatter continuum, tagable surface events

^{252}Cf: neutrons ~few MeV, neutron activation of Ge → 10.4 keV γ-line

Many Uses:

In-situ measurement of energy scale

resolution and linearity

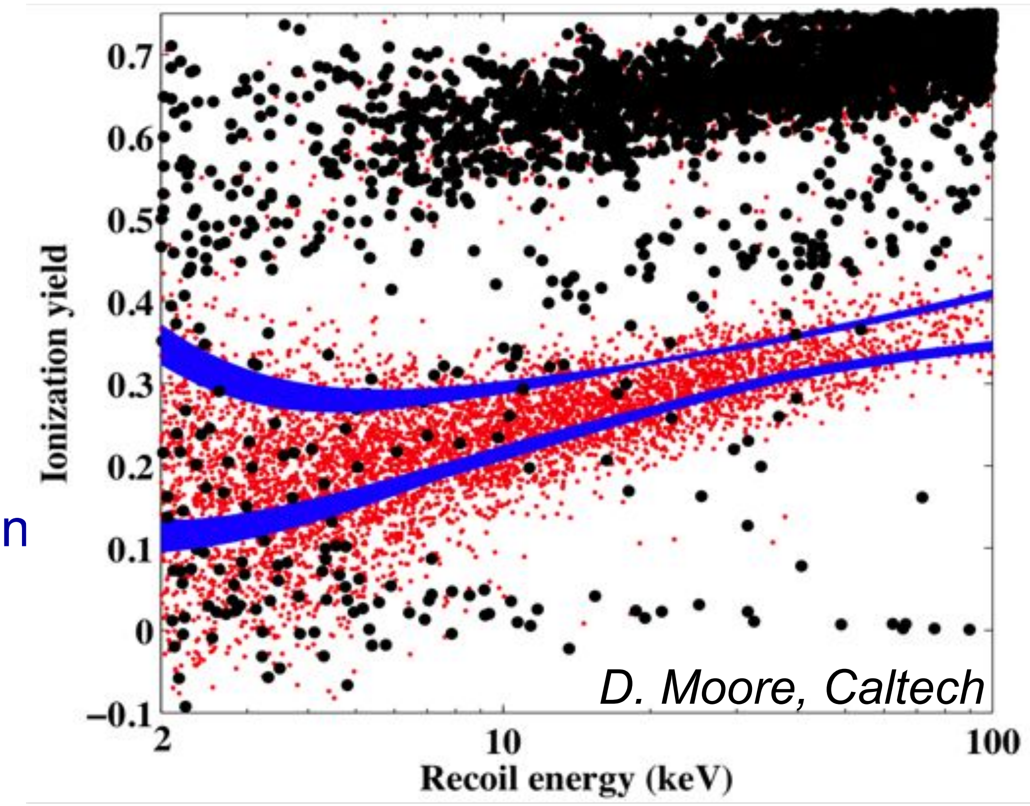
position correction

set cuts & measure selection efficiencies

develop surface-event rejection (^{133}Ba ~40X the number of WIMP-search events)

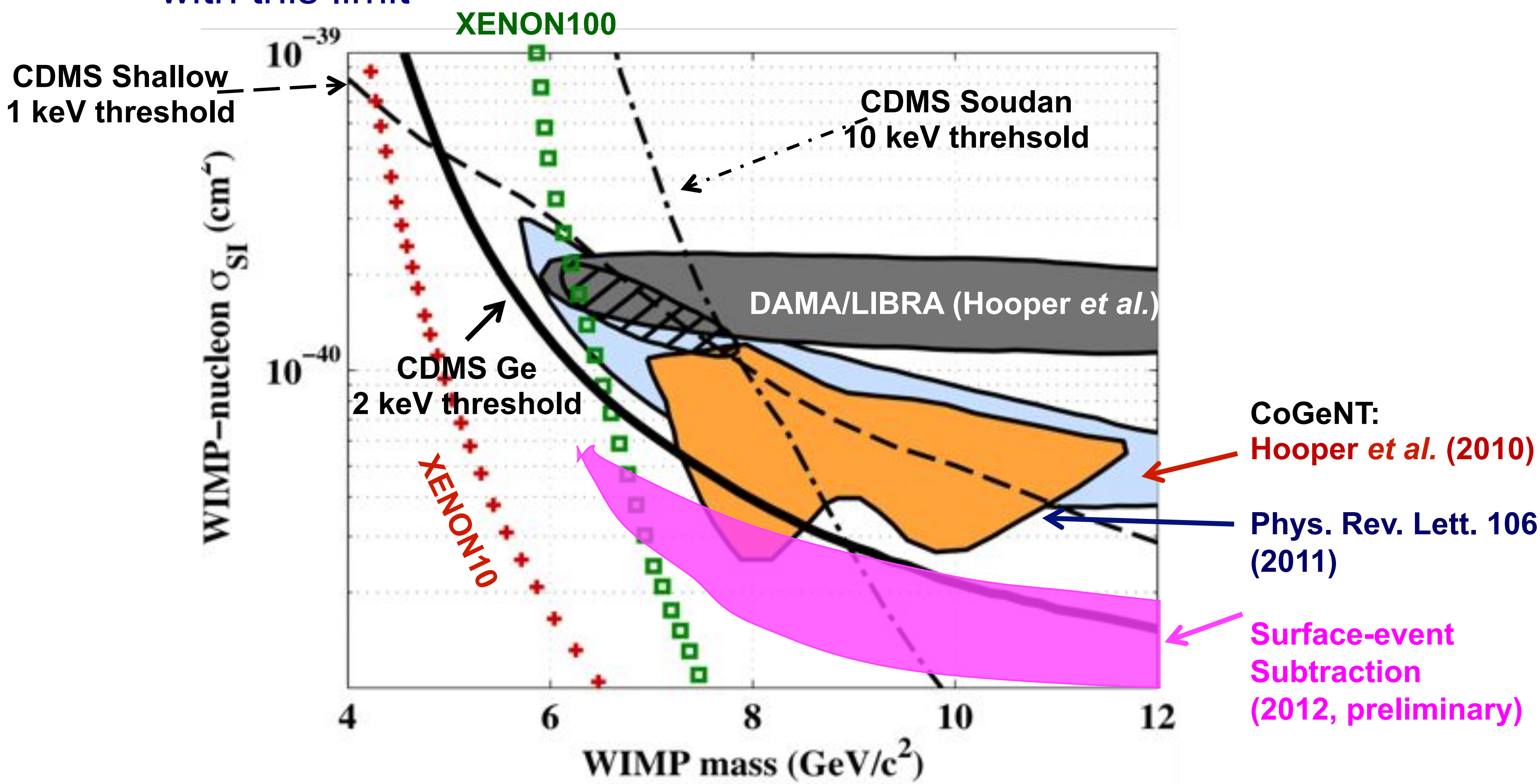
CDMS II Ge Low-threshold Analysis

- Analyzed with 2 keVr threshold to probe low-mass region
- No phonon-timing cut since ineffective below ~5 keV
  - Expect to be background-limited
- Used 8 Ge detectors with lowest trigger thresholds
  - Ideal for comparison to CoGeNT since Ge
  - Oct. 2006 – Sep. 2008
- 1/4 of data used to study backgrounds at low energy
  - Limits calculated from remaining 241 kg-day raw exposure
    - No background subtraction



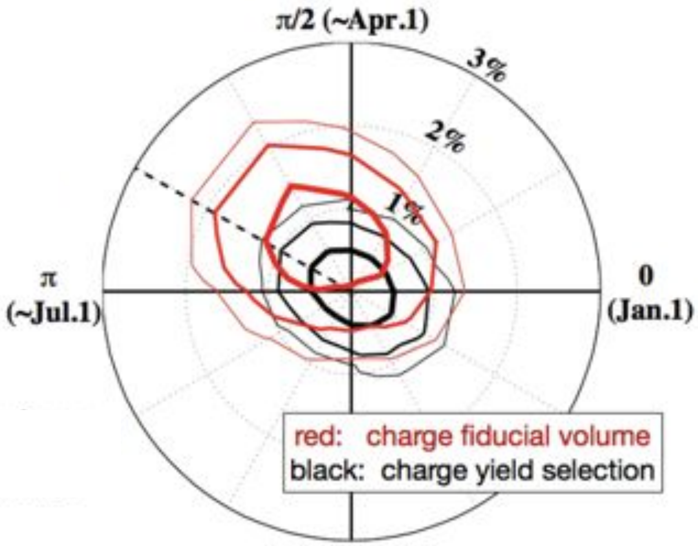
CDMS II Ge Low-threshold Results

- Resulting spectrum ruled out possibility that all or most of CoGeNT's events were WIMPs
  - CoGeNT region after subtracting their surface events is consistent with this limit

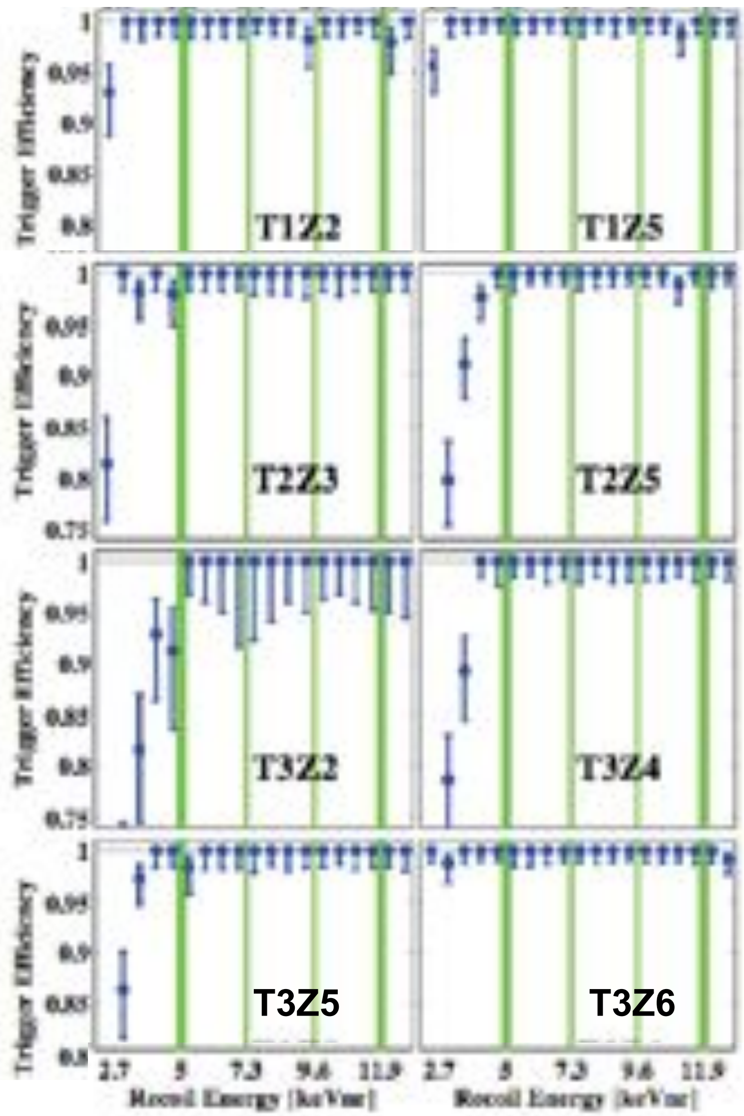


CDMS II Ge Search for Annual Modulation

- Same 8 Ge detectors used
- 5 keV threshold to ensure constant trigger efficiencies
  - ~ 1.2 keVee (CoGeNT energy)
  - Will extend to lower threshold later this year for 3 lowest-threshold detectors
- No modulation in efficiencies of cuts



courtesy S. Hertel

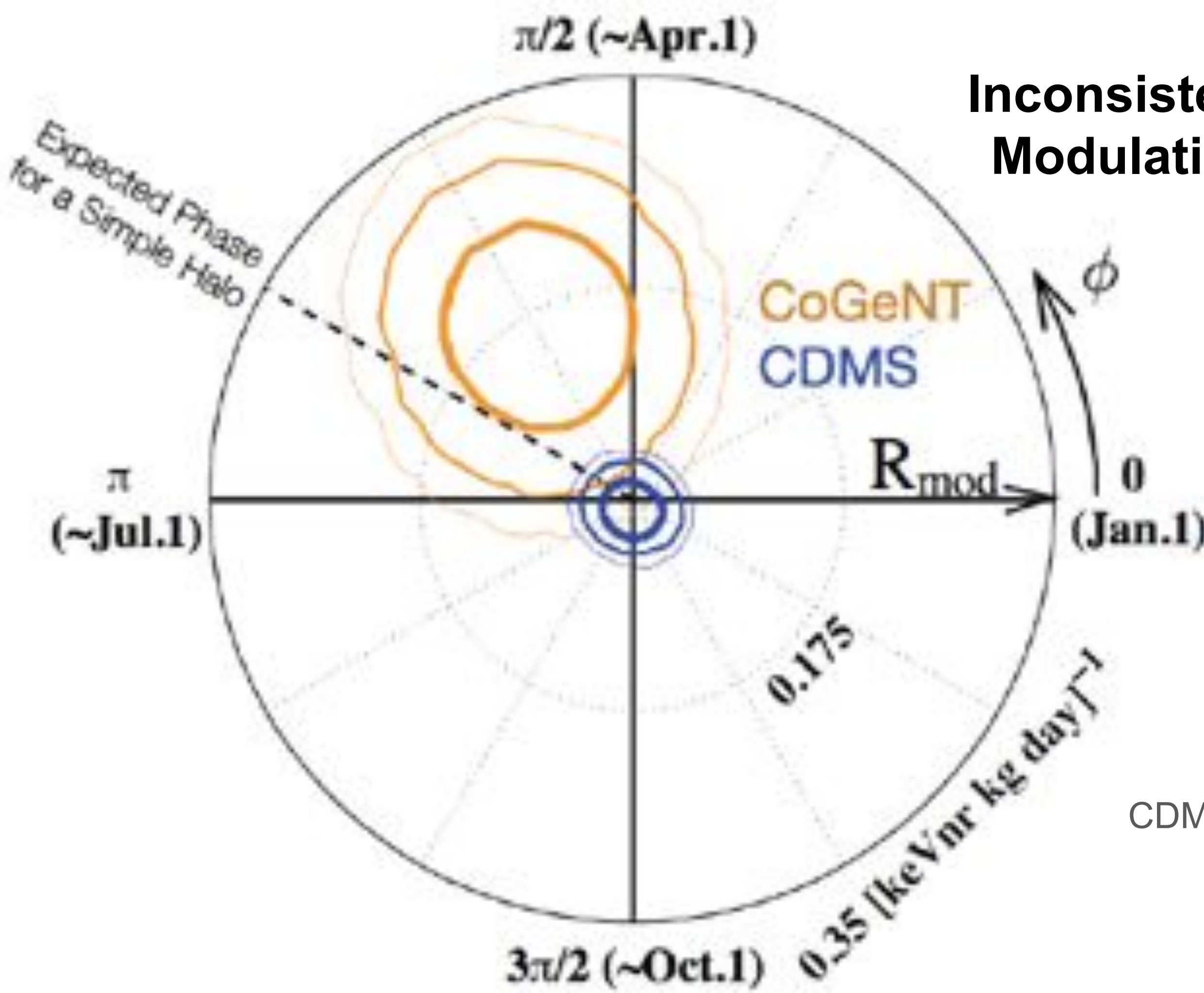


- Recently completed additional checks:
  - No modulation of background rates, acceptance of backgrounds

CDMS II Ge Modulation Results

CDMS II Modulation Amplitude
< 0.06 [keVnr kg day]$^{-1}$ at 99% C.L.

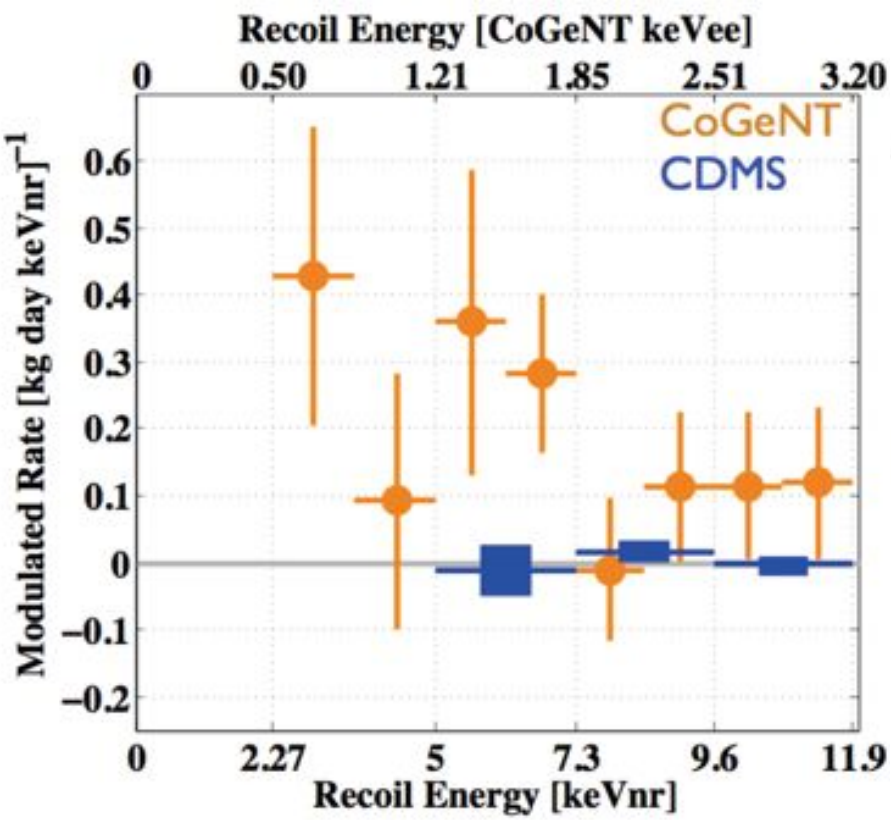
Inconsistent with CoGeNT
Modulation at >98% C.L.



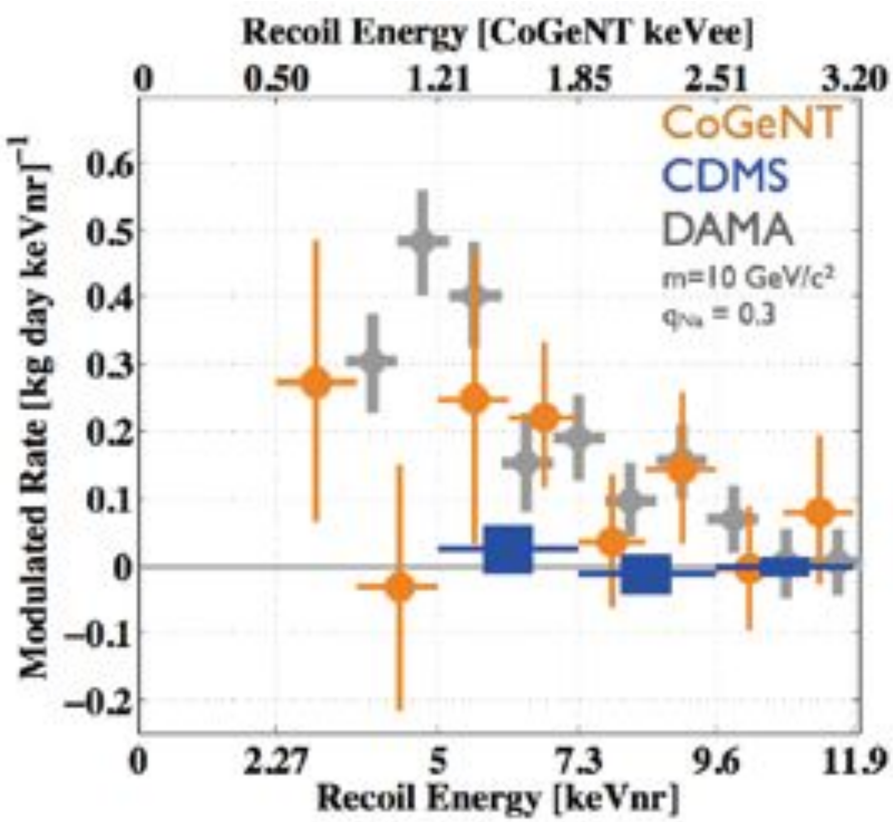
CDMS Collaboration, arXiv:1203.1309

CDMS II Ge Modulation Results

106-day Phase CoGeNT Best Fit



152.5-day Phase Standard Halo Model

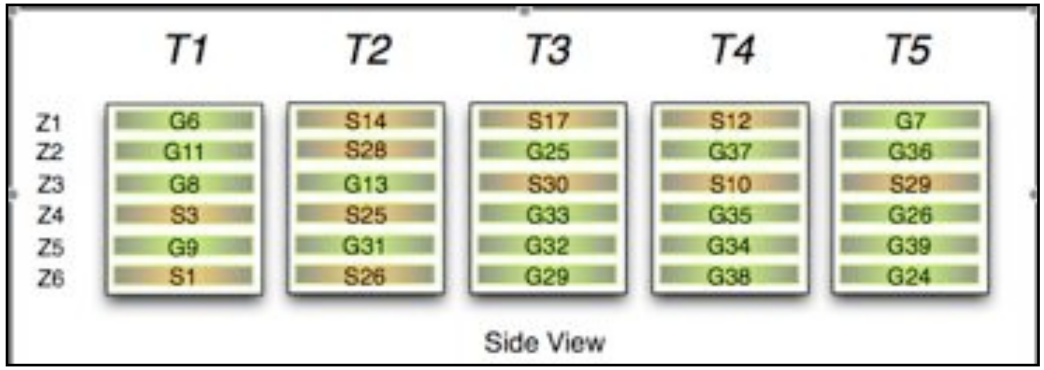


- Will probe CoGeNT's low-energy modulation (the part that corresponds to observed excess in raw spectrum) with analysis to be completed later this year (aiming for TAUP).

CDMS II Si Analysis

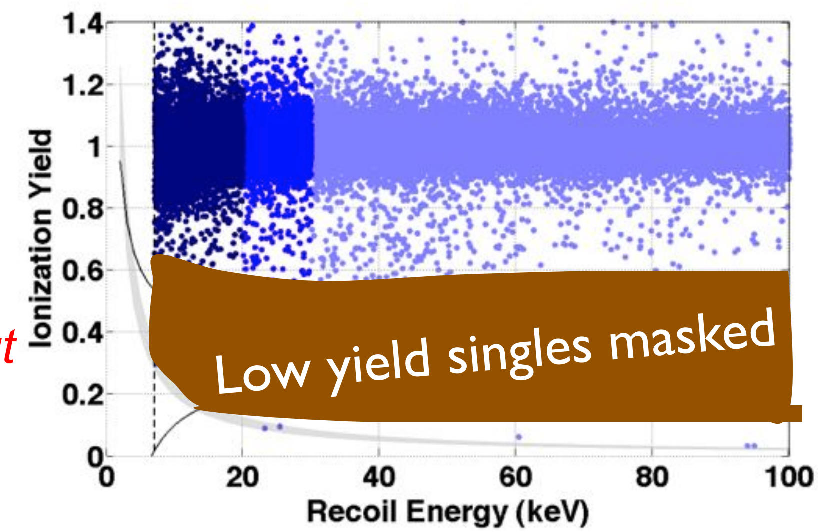
CDMS-II Exposure

- Oct. 2003 - Aug. 2004
  - 42.7 kg-days in 4 Si detectors
- Oct. 2006 - July 2007
  - 55.9 kg-days in 6 Si detectors
- July 2007 - Sep. 2008
  - 140.23 kg-days in 8 Si detectors



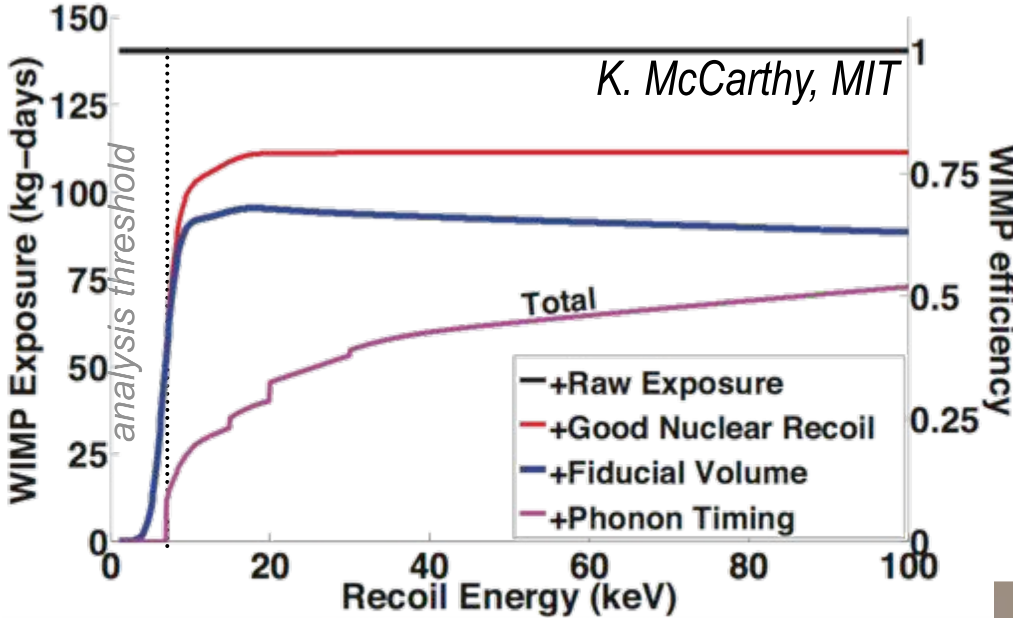
All cuts established before unblinding!

(sidebands and calibration data are used for cut development)



K. McCarthy, MIT

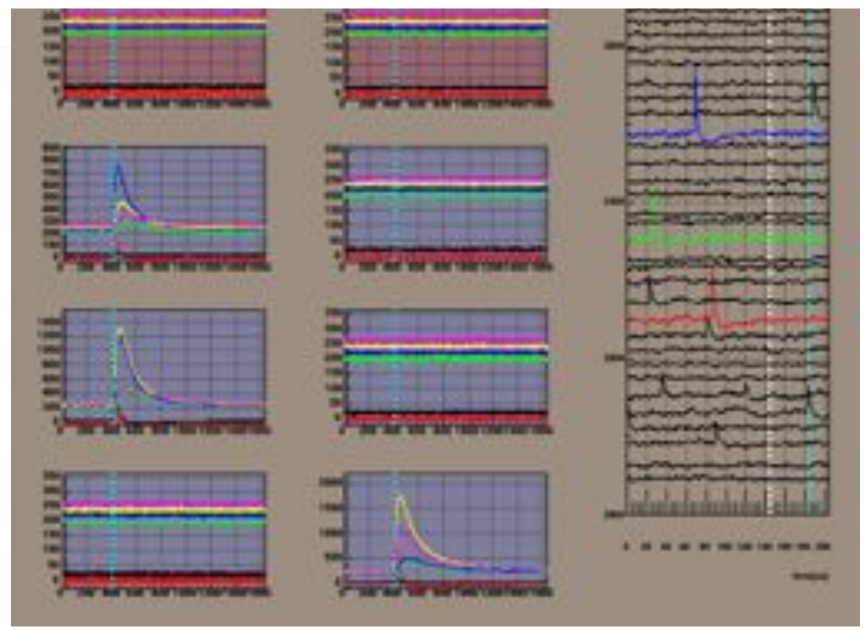
CDMS II Si Analysis Overview



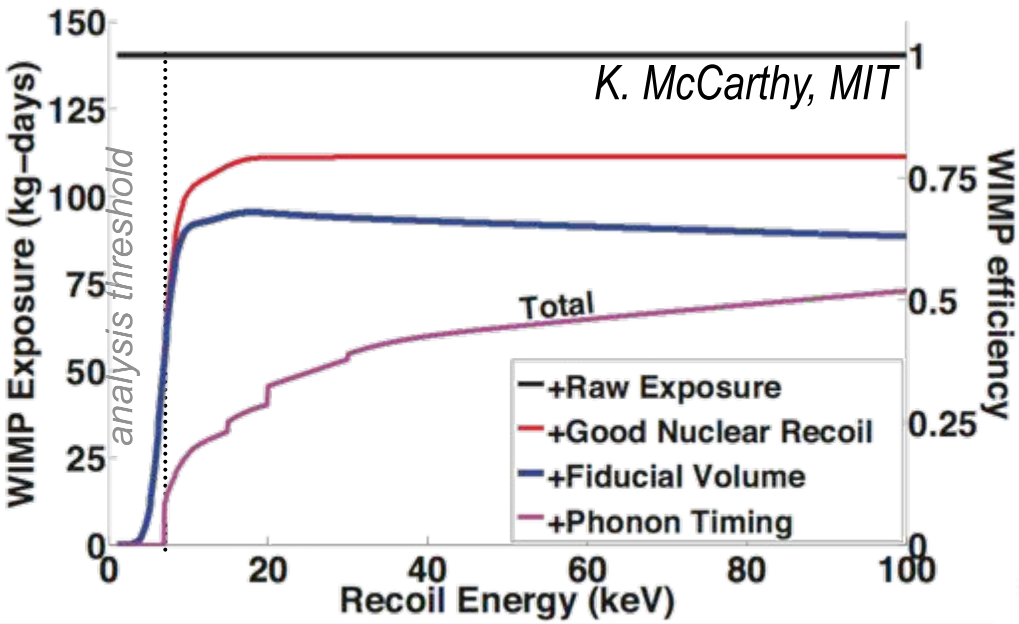
Candidate Criteria:

- Data Quality + Single Scatter
  - only 1 detector w/ signal, no muon-veto signal,
- Ionization yield within +1.2σ/-1.8σ nuclear recoil band, signal above noise in QI
- Fiducial Volume cut (no signal in QO)
- Phonon "timing" cut

- Single Scatter cut



CDMS II Si Analysis Overview



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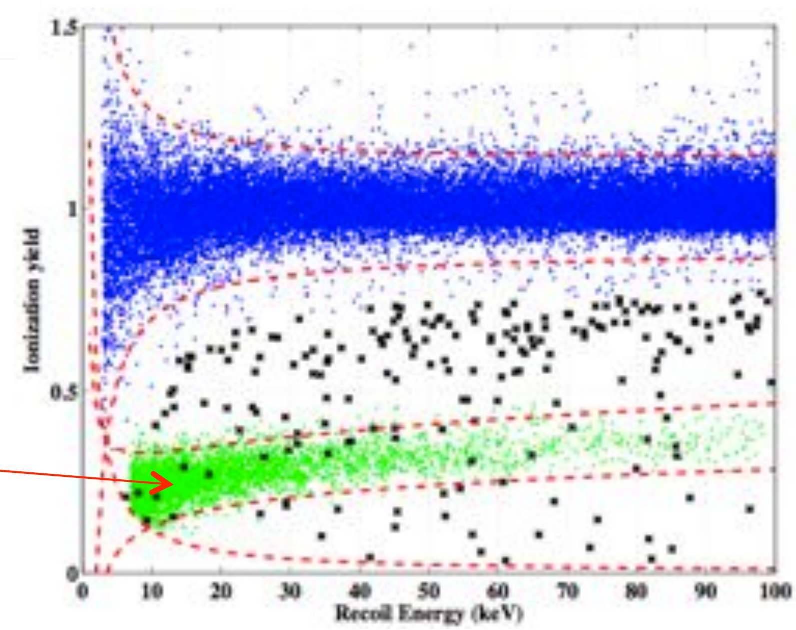
- Phonon "timing" cut

- Low ionization yield consistent with nuclear recoils



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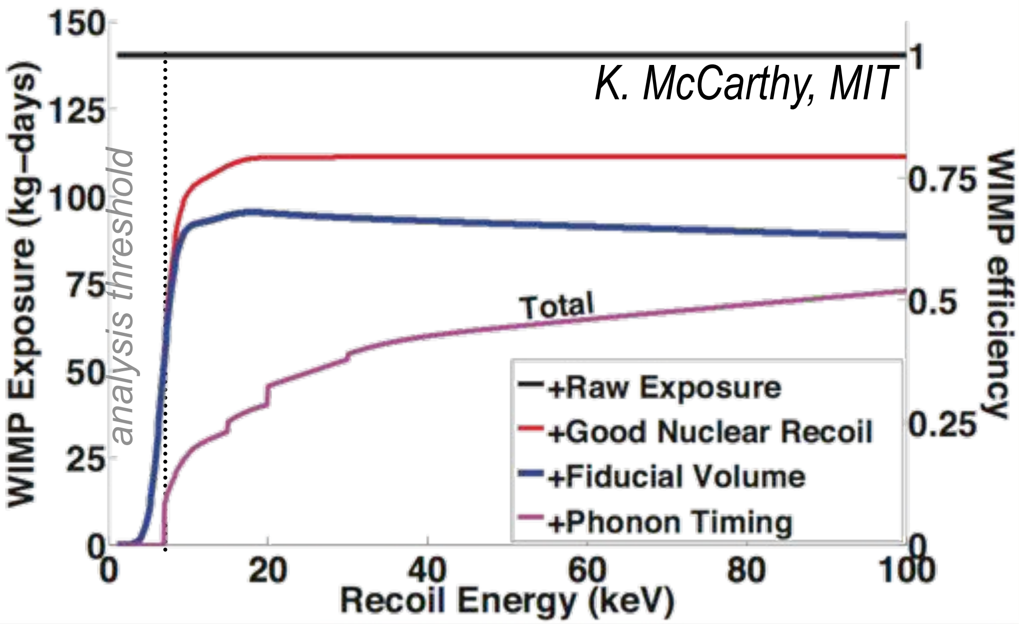

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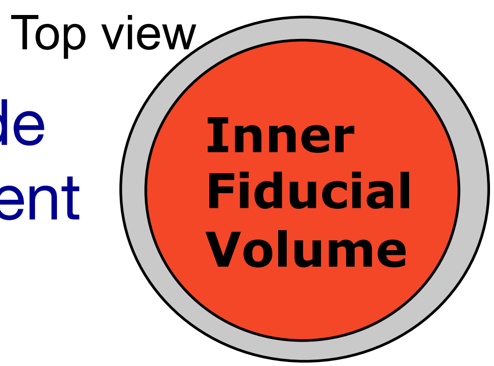
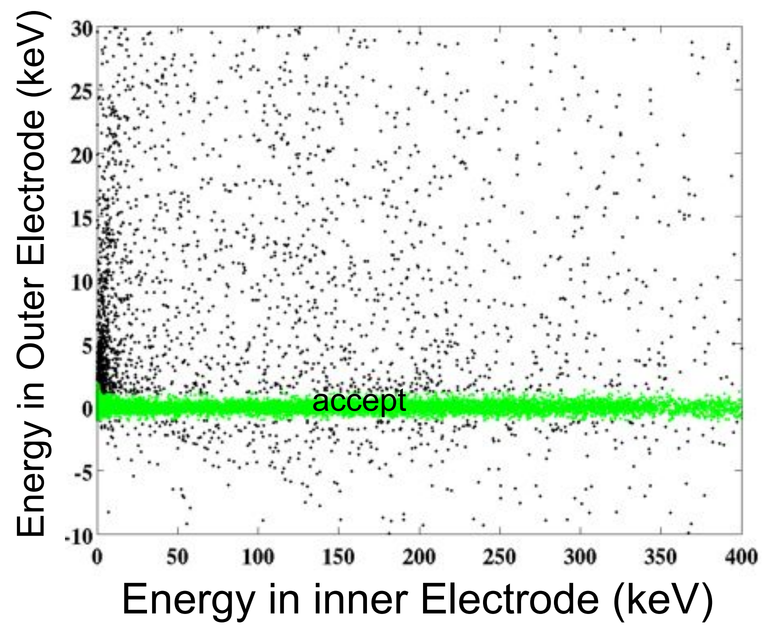
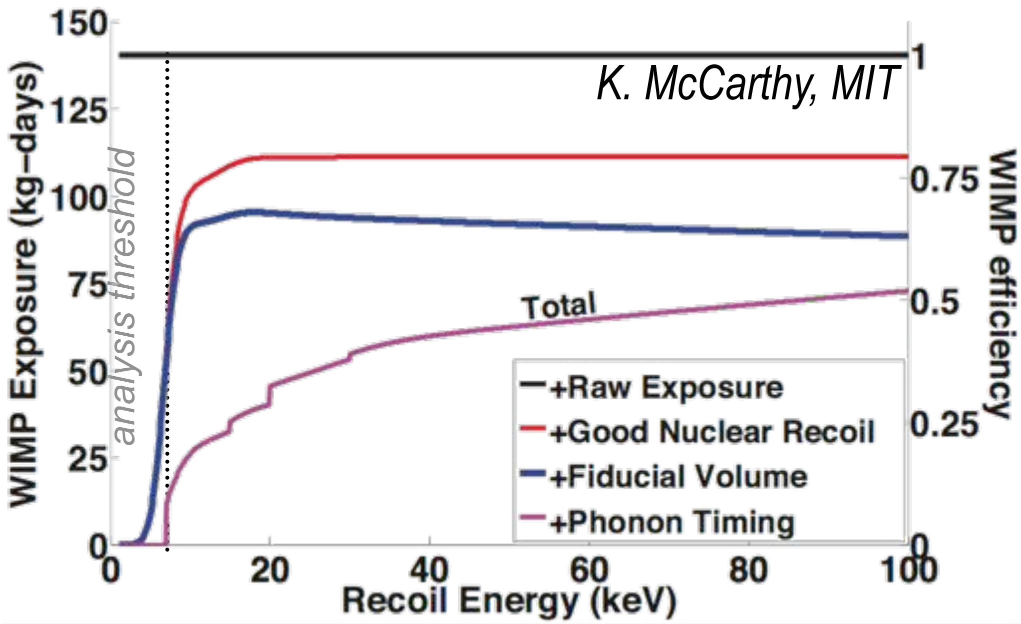
- Phonon “timing” cut

- Outer electrode signal consistent with noise





CDMS II Si Analysis Overview



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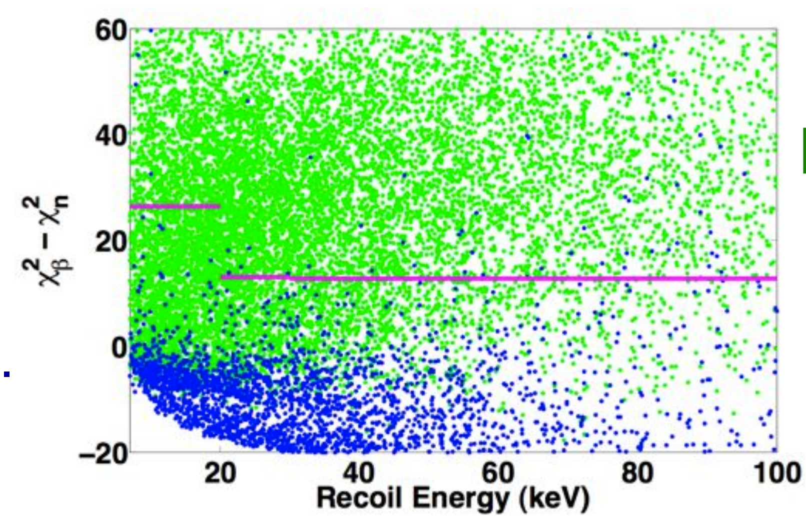
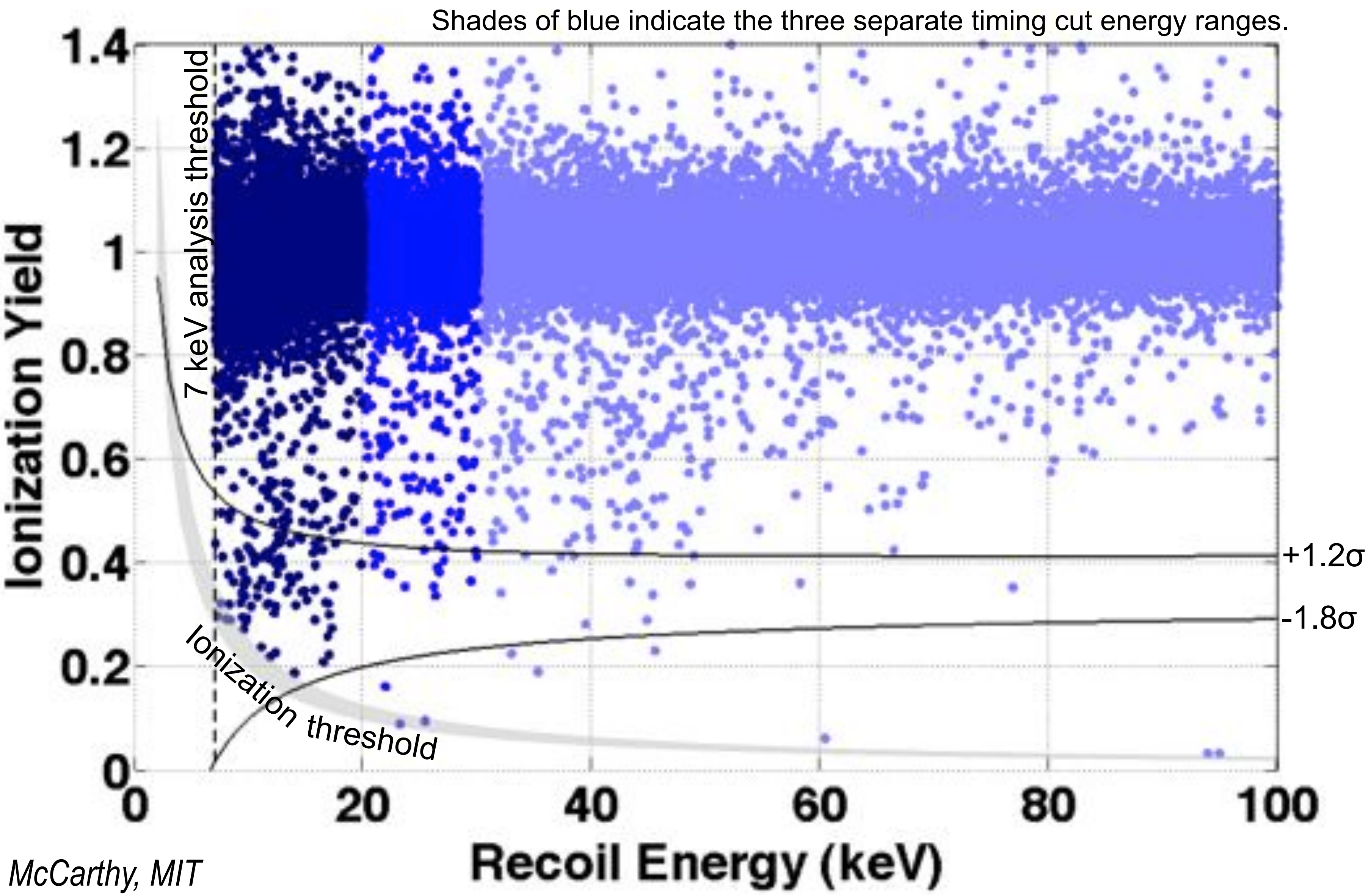
- Fiducial Volume cut (no signal in QO)
- Phonon "timing" cut

- Phonon timing cut to reject surface events
  - Optimize in 3 energy bins
    - 7-20, 20-30, 30-100 keV
  - 0.47 expected events estimated before unblinding.
- < 0.13 Neutrons expected



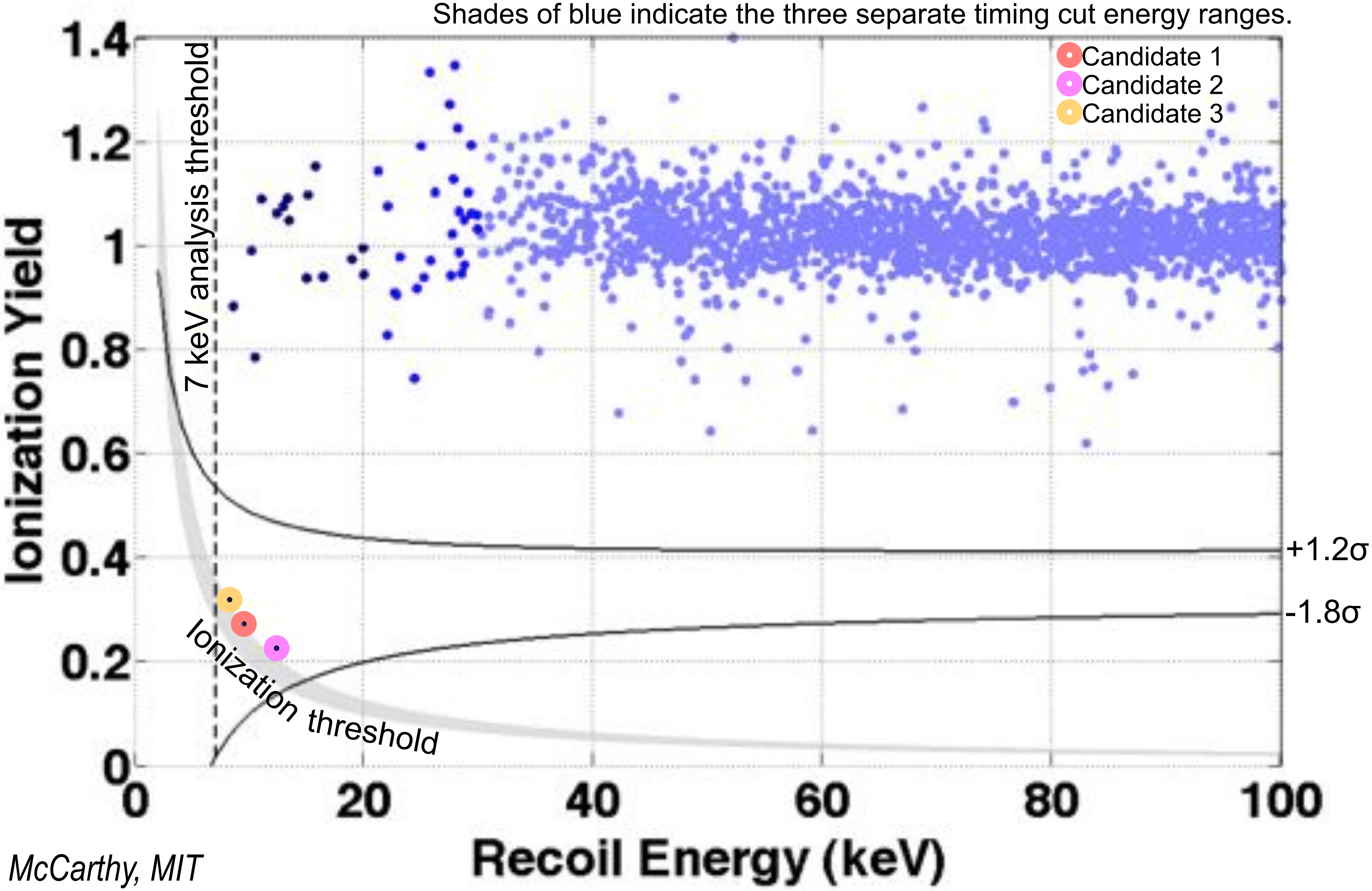
Unblinding Results - before timing cut



K. McCarthy, MIT

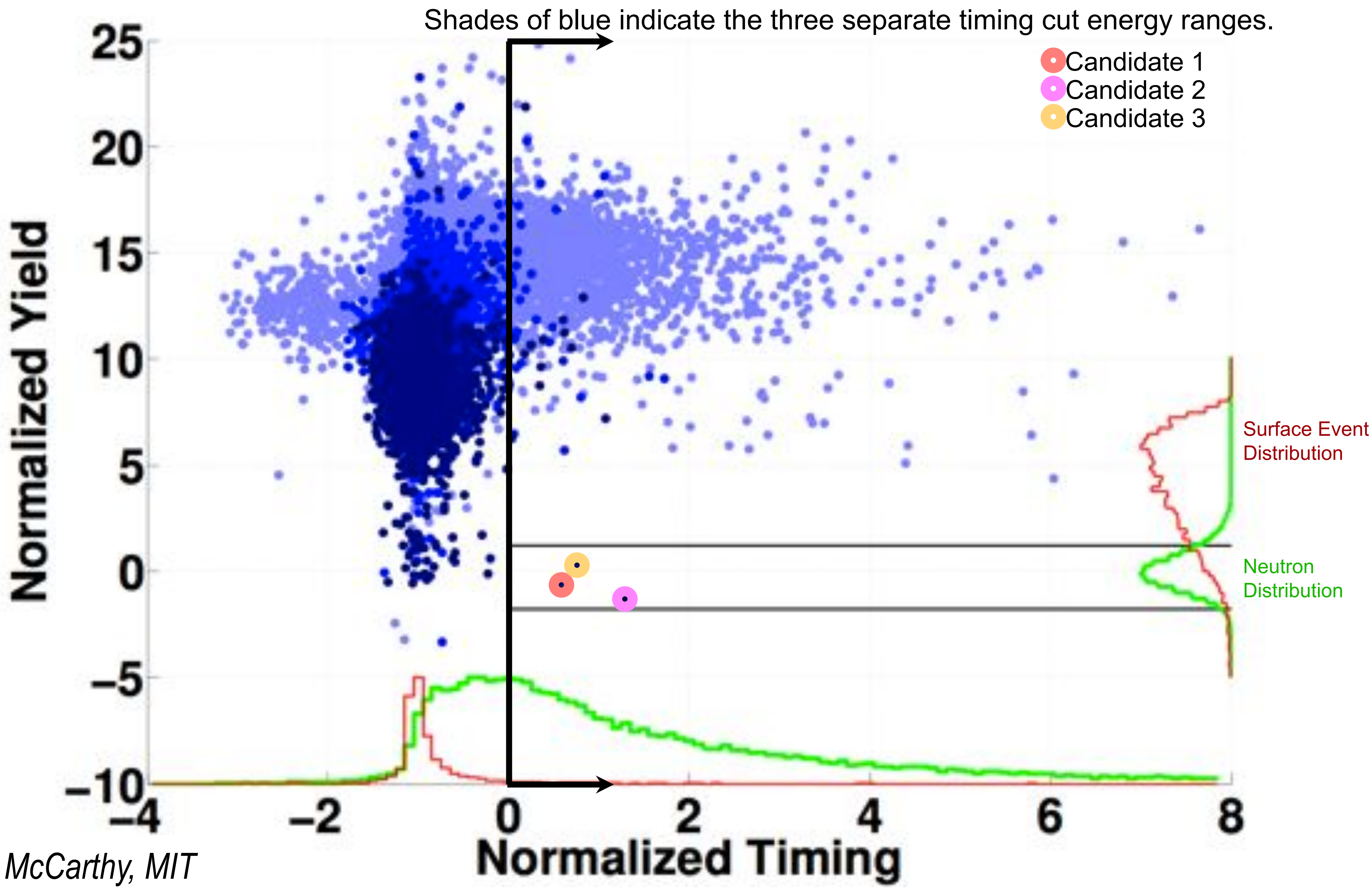
Unblinding Results - after timing cut

Shades of blue indicate the three separate timing cut energy ranges.



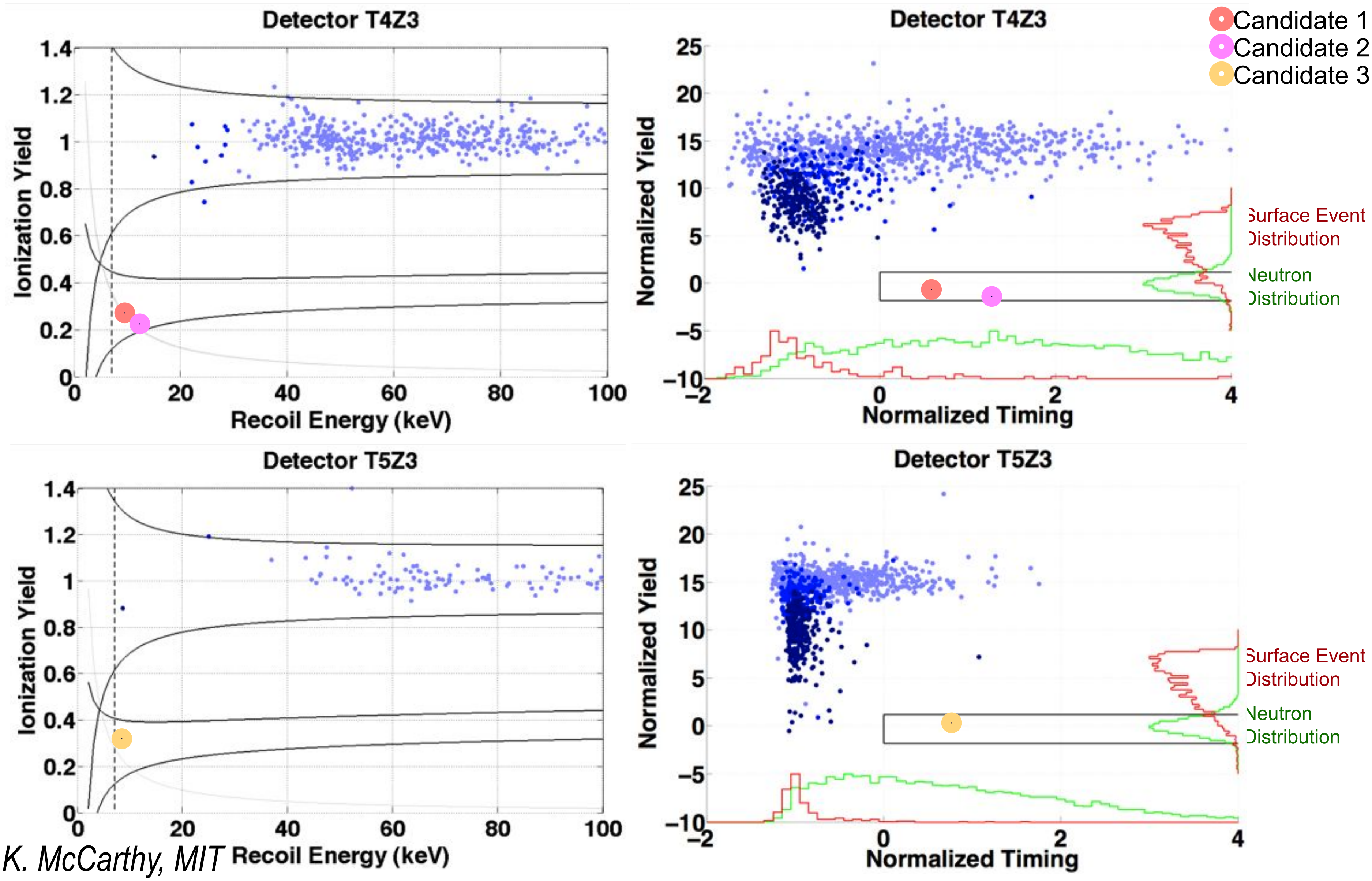
K. McCarthy, MIT

Unblinding Results - Yield vs Timing



K. McCarthy, MIT

Three Events!

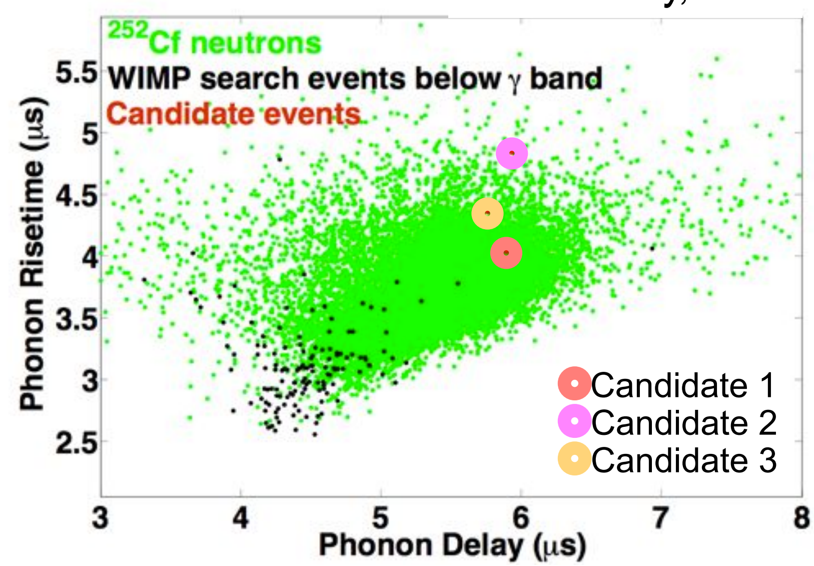


K. McCarthy, MIT

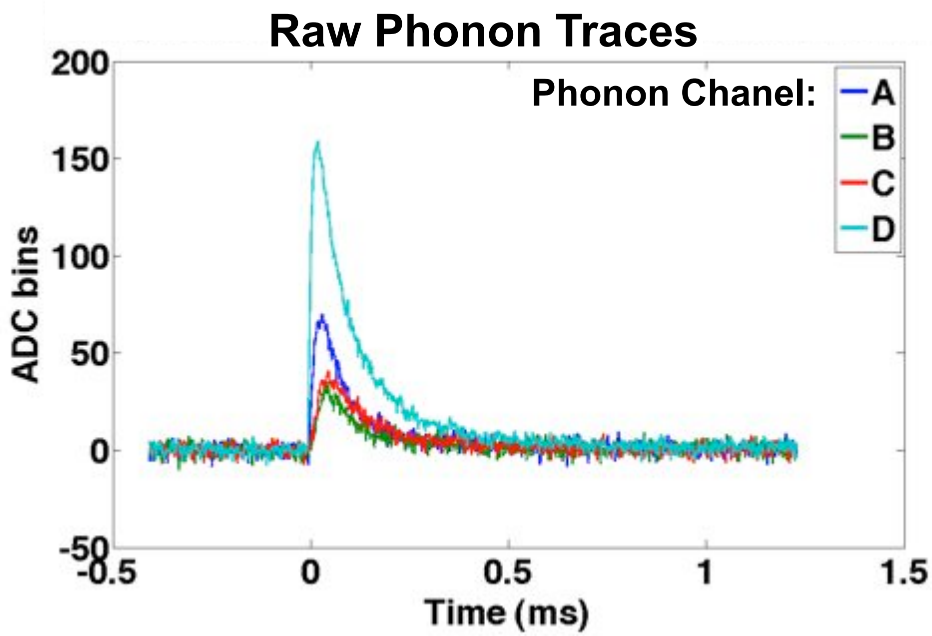
Post-Unblinding Checks

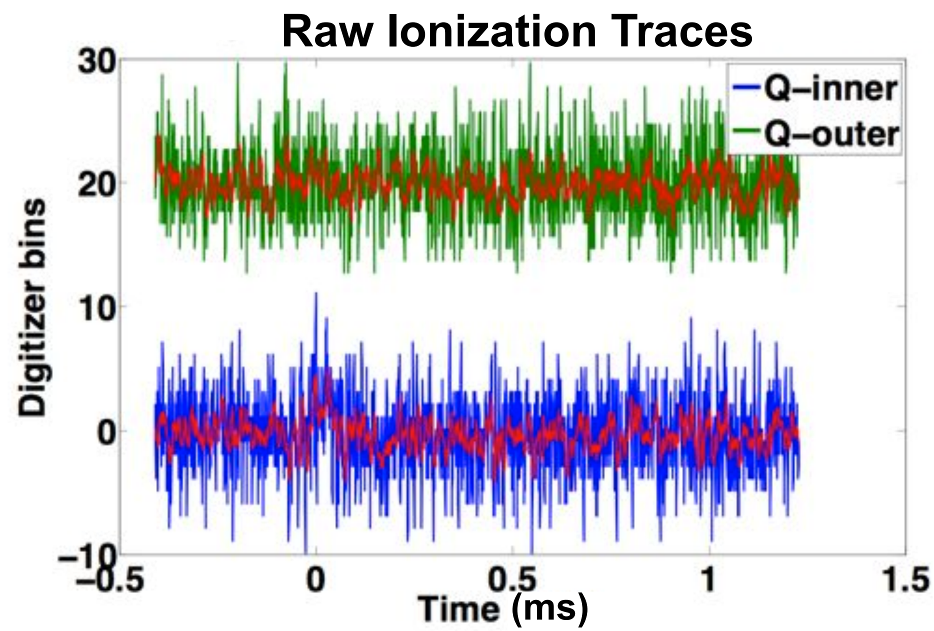
- After unblinding, the data quality was re-checked.
  - Events occurred during high-quality data series
    - Detectors well neutralized
    - Good baseline noise
    - Normal overall event rates
    - Normal KS tests for all data-quality measures
  - Events were well-reconstructed
    - Good fits
    - Normal values of individual timing parameters
  - Checked energy in other detectors to verify events were single scatters
    - No veto activity
    - Candidate one is almost a multiple (but energy in other detector is more likely a noise fluctuation than a real multiple)

K. McCarthy, MIT



Candidate 1

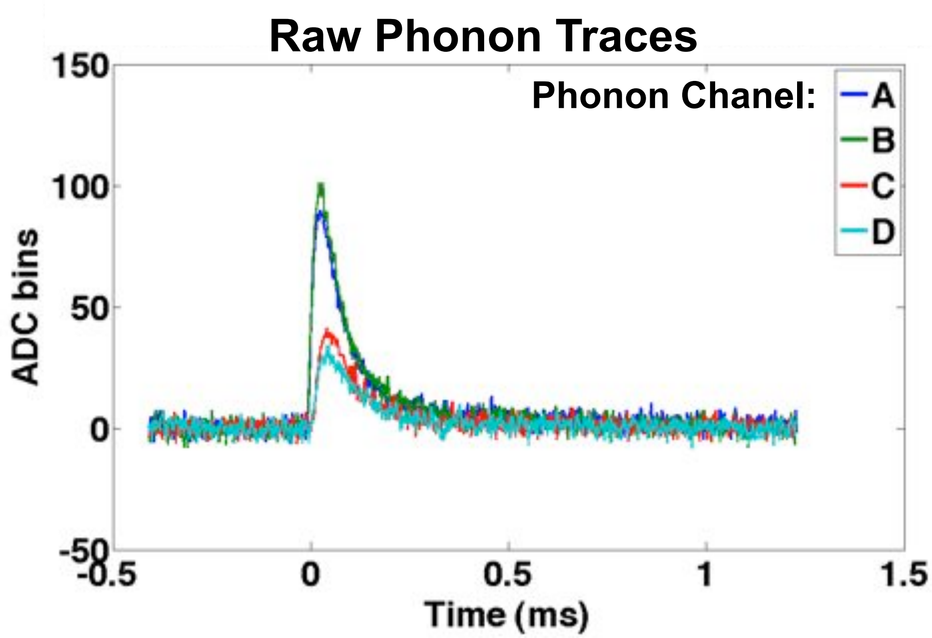


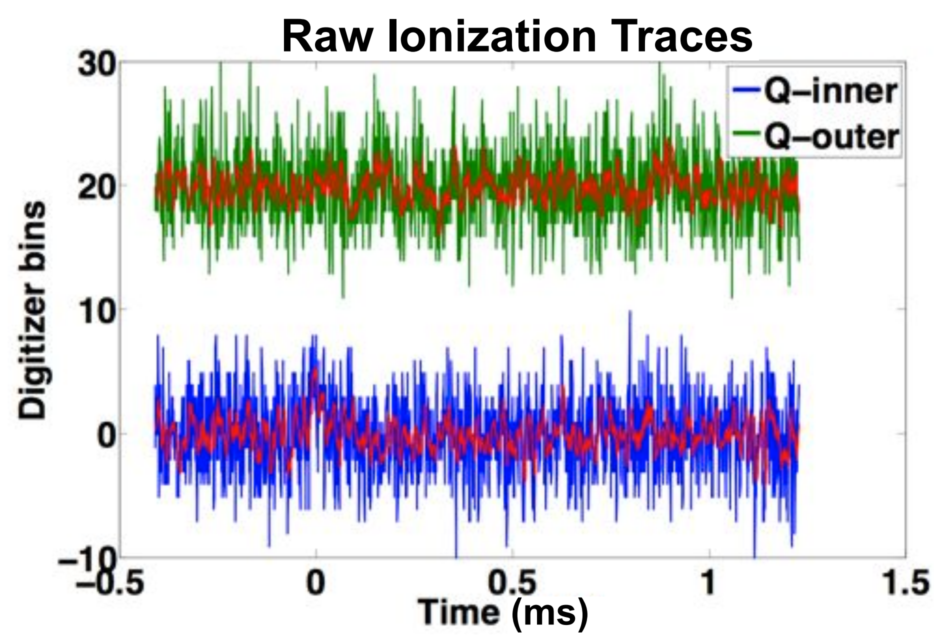


Detector	Recoil Energy	Yield	Charge Signal to Noise	Single Scatter Probability	Date
T4Z3	9.51 keV	0.27	4.87 σ	96.1%	July 1, 2008

K. McCarthy, MIT

Candidate 2

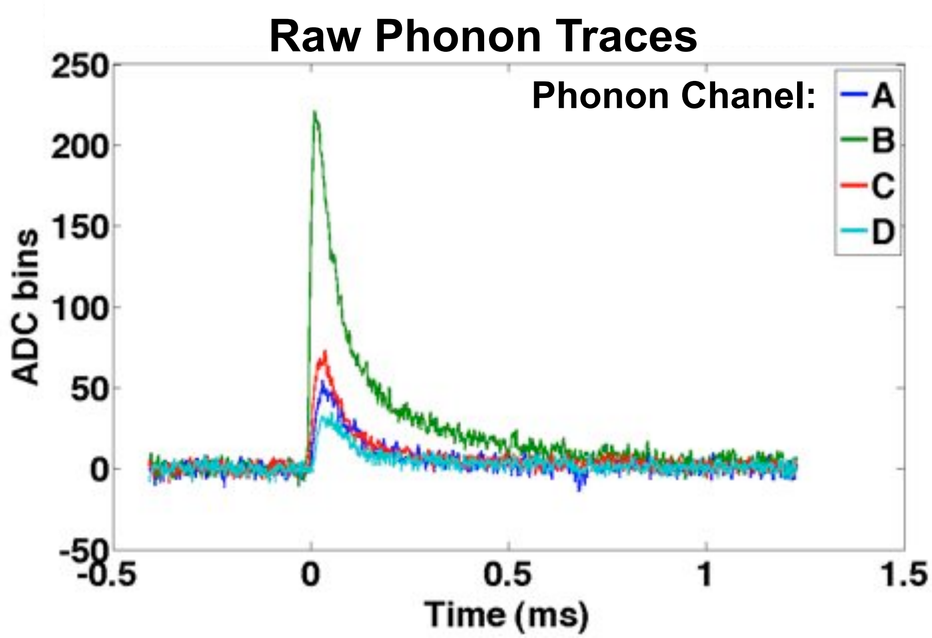


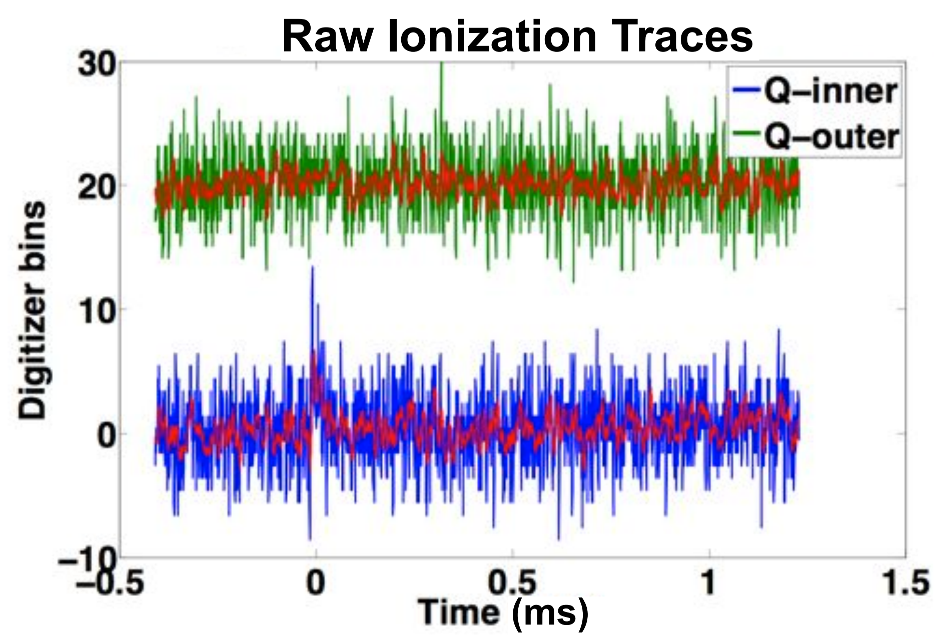


Detector	Recoil Energy	Yield	Charge Signal to Noise	Single Scatter Probability	Date
T4Z3	12.29 keV	0.23	5.11 σ	99.7%	Sep 6, 2008

K. McCarthy, MIT

Candidate 3



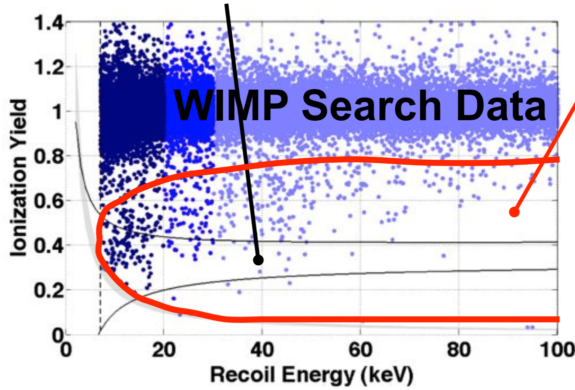


Detector	Recoil Energy	Yield	Charge Signal to Noise	Single Scatter Probability	Date
T5Z3	8.20 keV	0.32	6.66 σ	99.7%	March 14, 2008

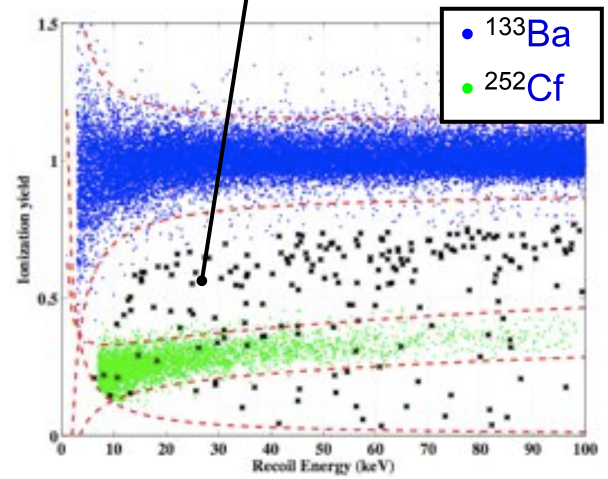
K. McCarthy, MIT

Post-Unblinding Background Estimate

SIDEBAND 1	SIDEBAND 2	SIDEBAND 3
Use multiple-scatters in NR band	Use multiples just outside NR band	Use multiples from Ba calibration in wide region



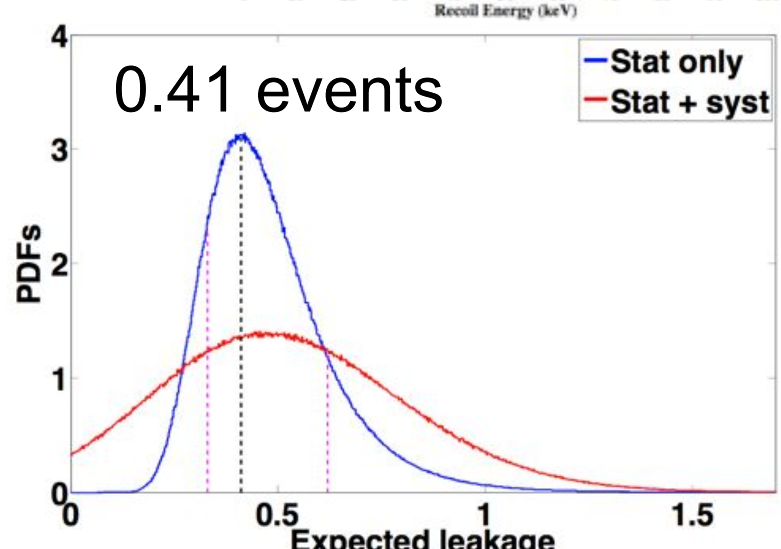
Correct for systematic effects due to different distributions in energy and yield, singles vs. multiples



- Surface event background estimated from the tails of three different NR sideband distributions to be

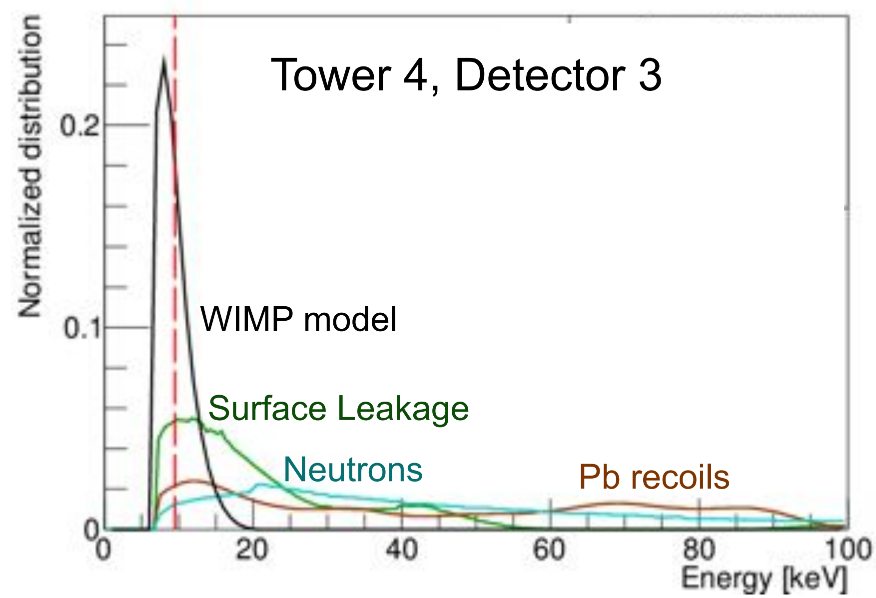
$$0.41^{+0.20}_{-0.08}(stat.)^{+0.28}_{-0.24}(syst.)$$

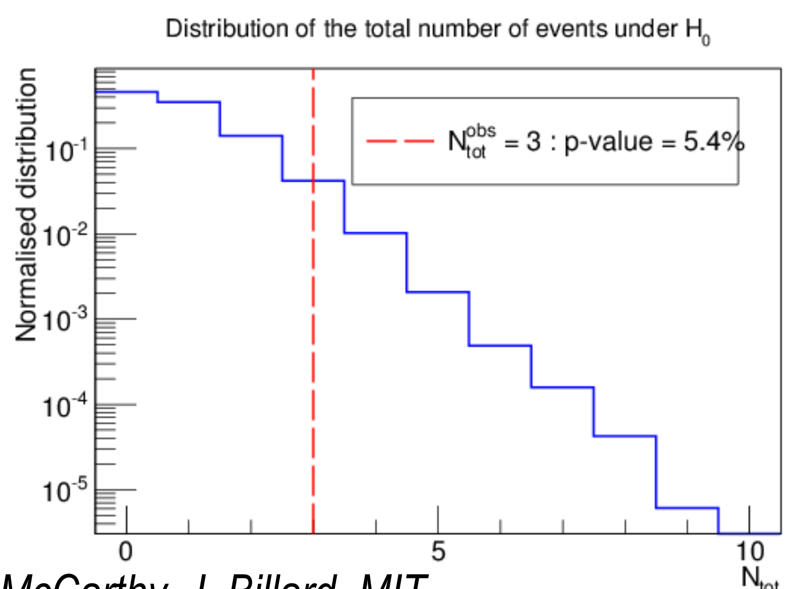
- Checked for the possibility of ^{206}Pb recoils from ^{210}Po decay, limited this to be <0.08 events.

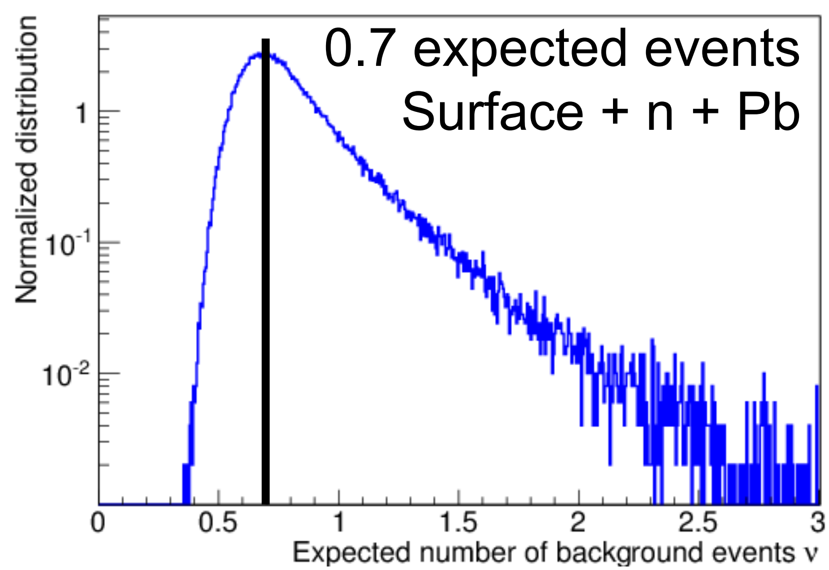


Profile Likelihood Analysis

- Incorporated data-driven background models into a WIMP +background likelihood analysis.
- Monte Carlo simulations of the background-only model indicate the probability of a statistical fluctuation producing three or more events anywhere in our signal region is 5.4%.







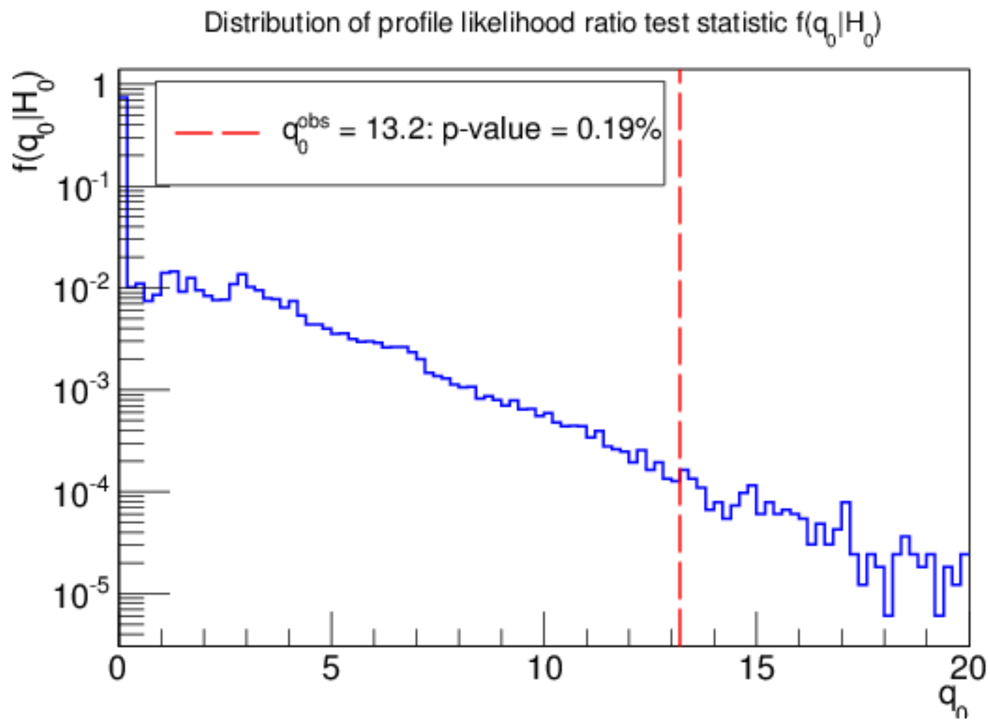
K. McCarthy, J. Billard, MIT

Profile Likelihood Analysis - cont.

Testing our known background estimate against a WIMP+background hypothesis

$$q_0 = -2\log\left\{\frac{\mathscr{L}(m_\chi, \sigma_{\chi-n}=0, \hat{\hat{\vec{\nu}}})}{\mathscr{L}(\hat{m}_\chi, \hat{\sigma}_{\chi-n}, \hat{\vec{\nu}})}\right\} \equiv 2\log\left\{\frac{\mathscr{L}(H_1)}{\mathscr{L}(H_0)}\right\}$$

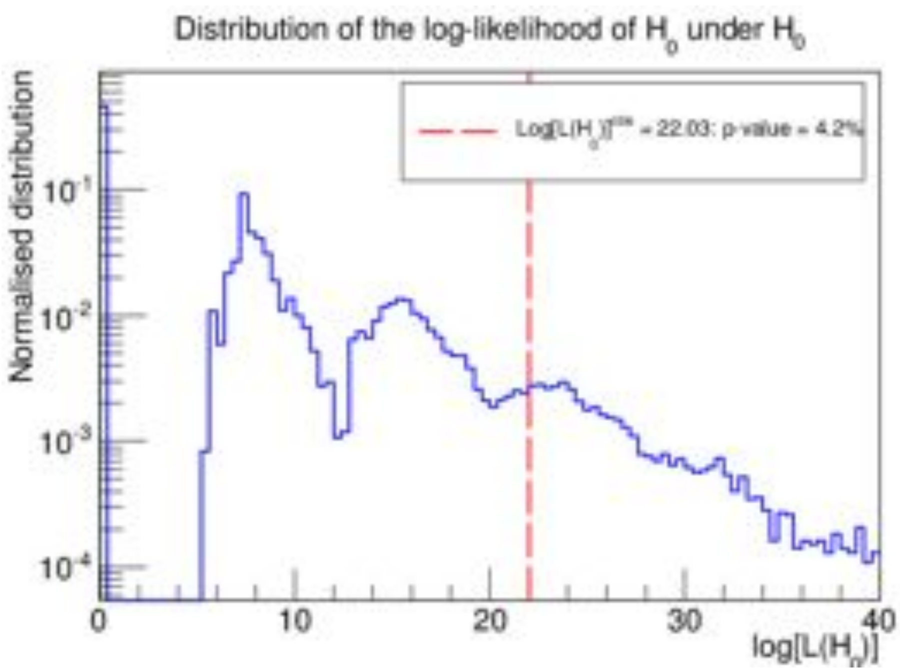
- A likelihood ratio test favors a WIMP +background hypothesis over the known background estimate as the source of our signal at the 99.81% confidence level (p-value:0.19%, ~3σ).
- The maximum likelihood occurs at a WIMP mass of 8.6 GeV/c^2 and WIMP-nucleon cross section of 1.9x10^{-41} cm^2.

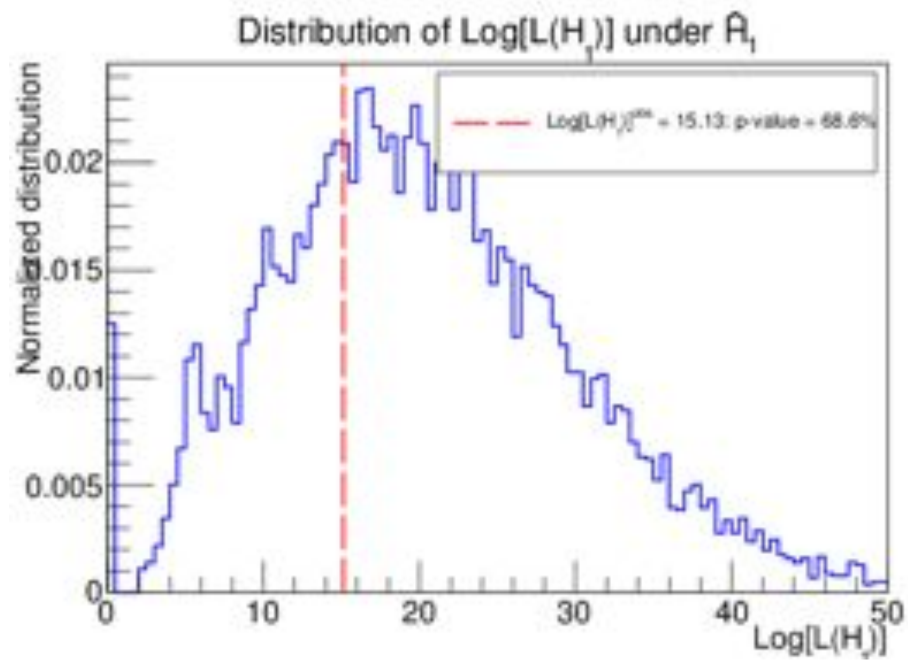


J. Billard, MIT

Profile Likelihood Goodness of Fit

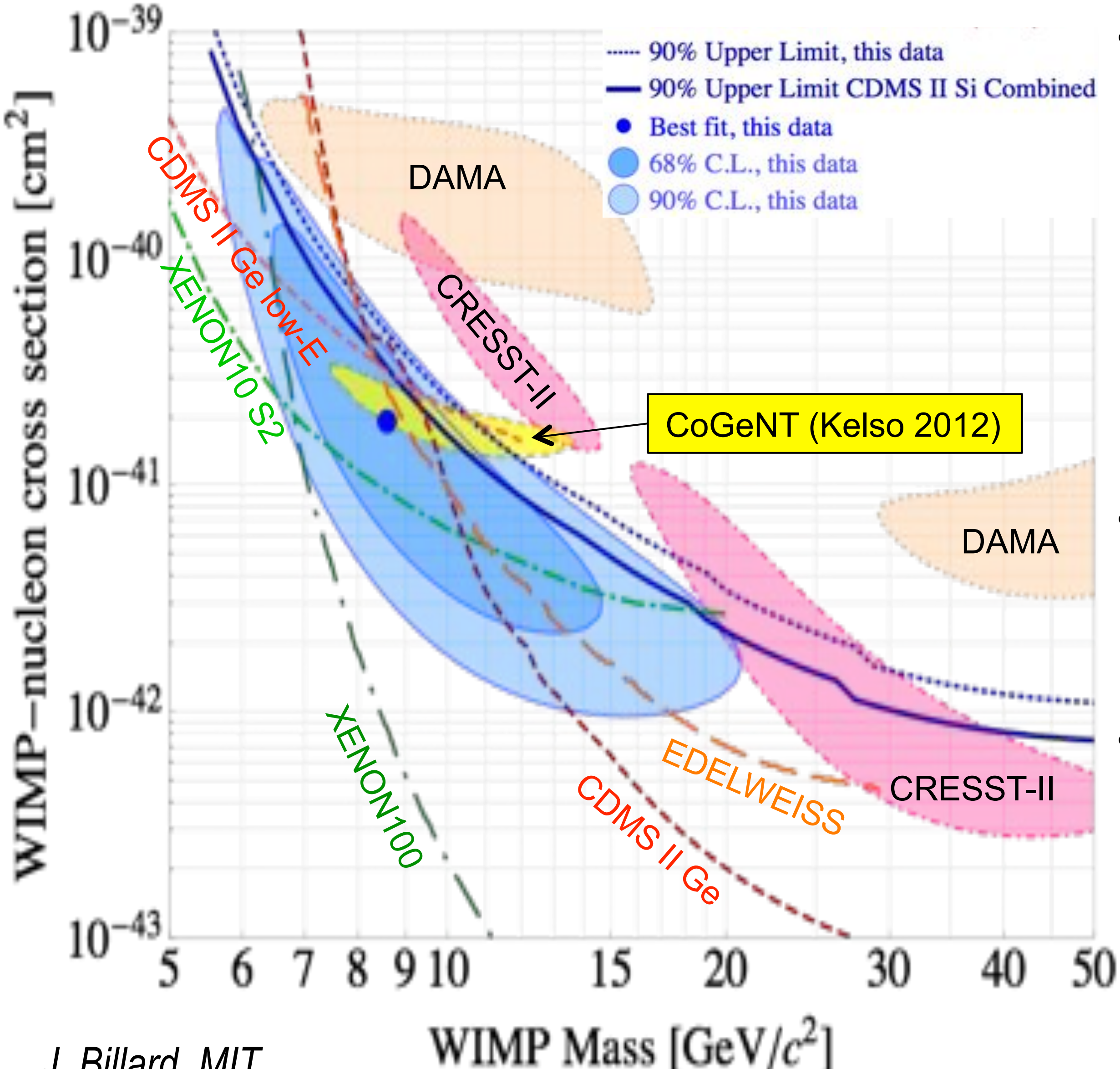
- Its very important to check if the WIMP+background actually fits the data well.
- The goodness of fit of the known-background-only hypothesis is 4.2%
- The goodness of fit of the WIMP+background hypothesis is 68.6%





J. Billard, MIT

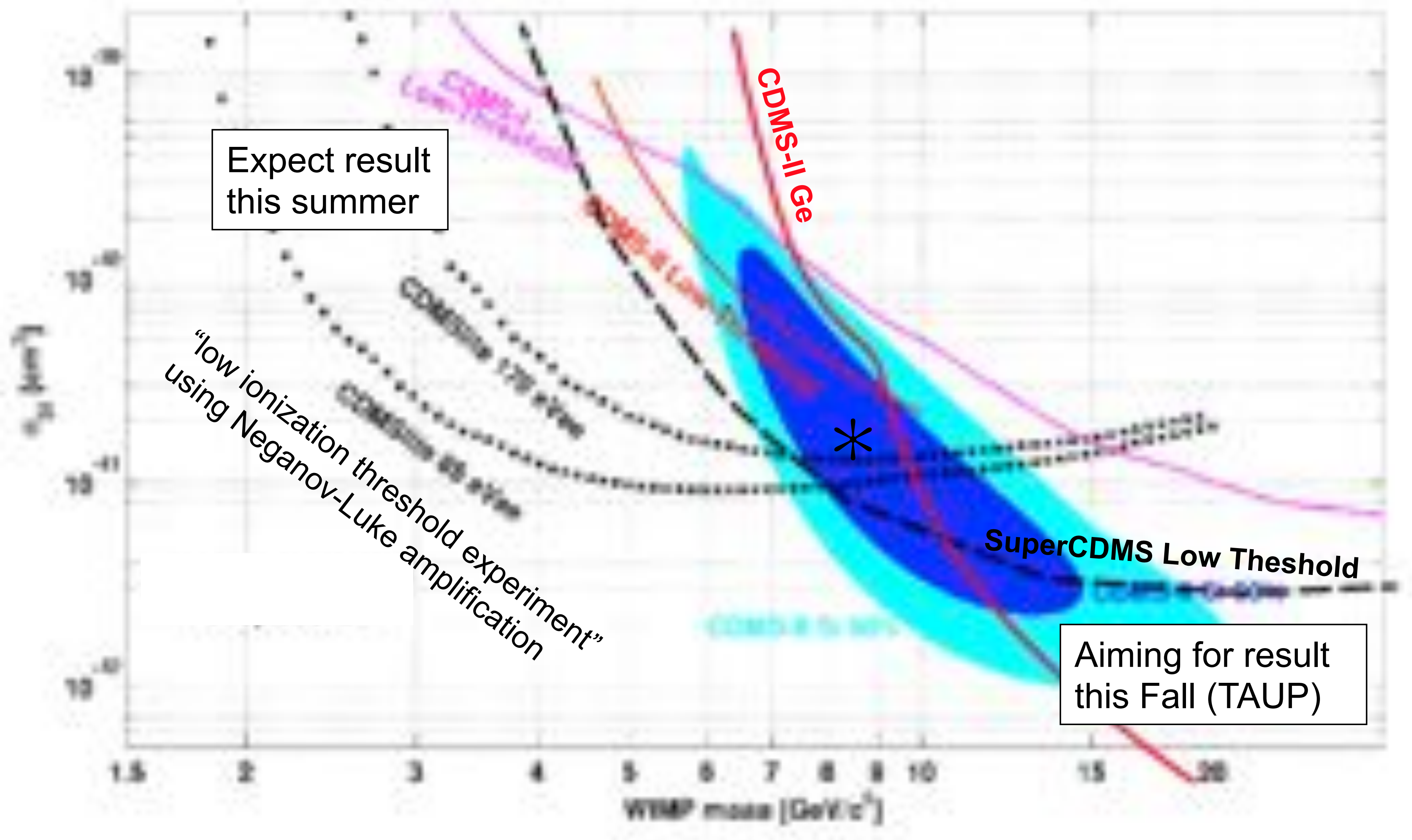
Profile Likelihood Confidence Intervals



J. Billard, MIT

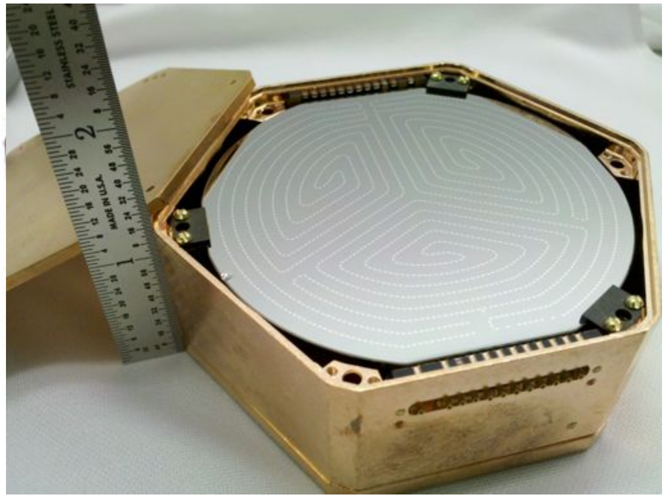
- A profile likelihood analysis favors a WIMP +background hypothesis over the known background estimate as the source of our signal at the 99.81% confidence level (~3σ, p-value: 0.19%).
- We do not believe this result rises to the level of a discovery, but does call for further investigation.
- An optimal gap analysis sets a limit for the spin-independent WIMP-nucleon cross section of 2.4×10^{-41} cm^2 for a WIMP mass of 10 GeV/c^2.

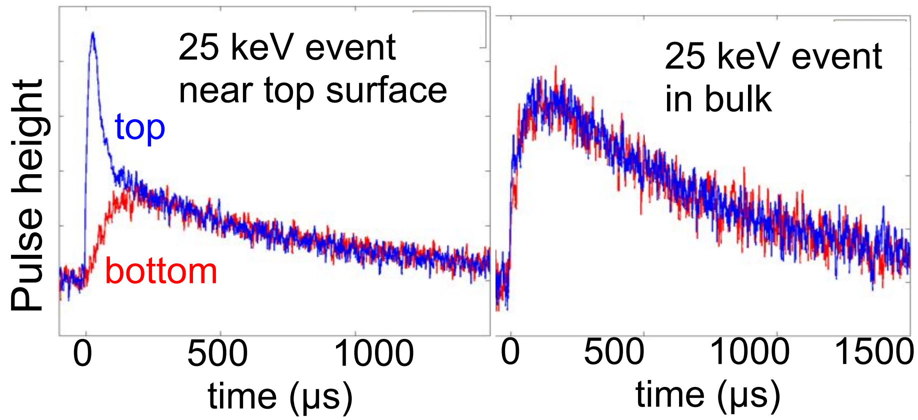
Next Steps: SuperCDMS Soudan!

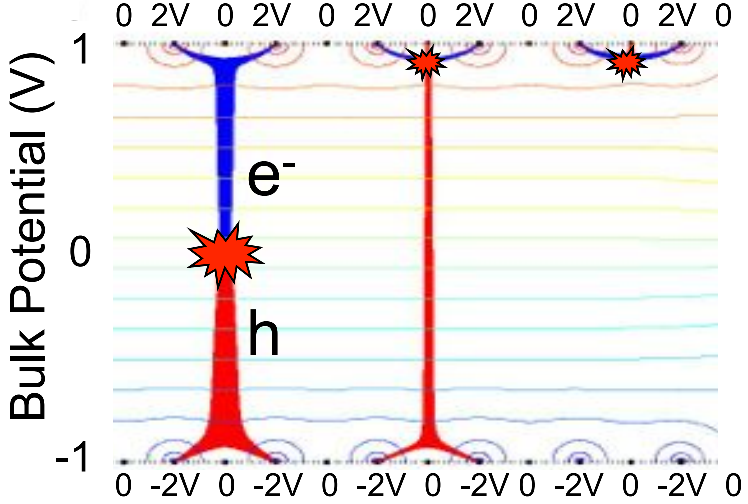


SuperCDMS Soudan

- WIMP-search run with 15 new "iZIP" detectors (thicker, better rejection, 9 kg total) since March 2012
- Interdigitated electrodes improve rejection of surface events using symmetry, yield
- Additional info from phonon sensors
  - xyz from energy partition, timing
    - Phonon guard ring rejects high-radius "zero-charge" events that dominated background at low energy in CDMS III
  - Help test potential signals







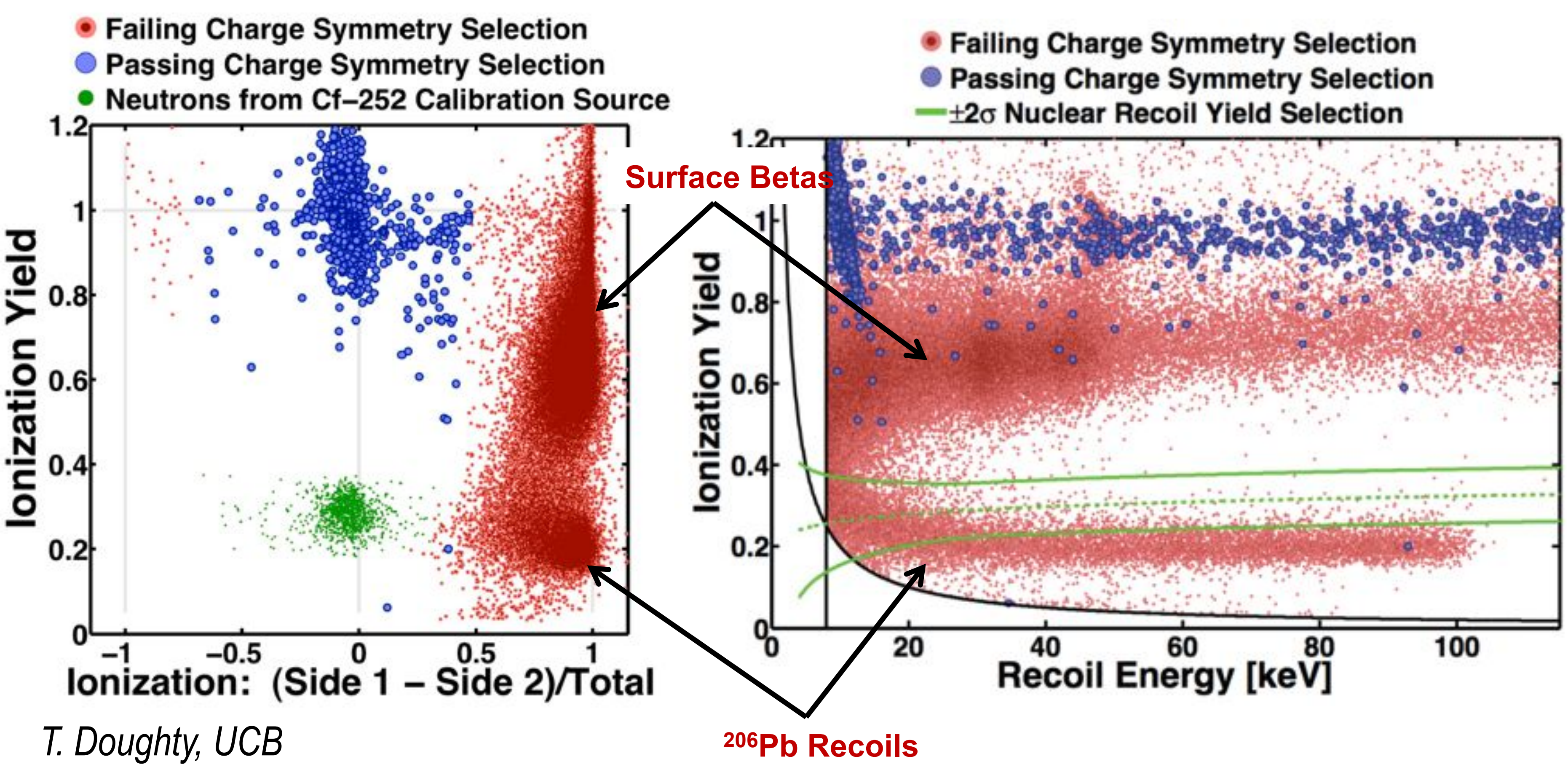
In situ Demonstration of Surface-Event Rejection

Surface-event sources placed above and below super-tower 3

20 live days → 0 of 80,000 leaked SE in (symmetric) NR signal region

→ Good enough rejection for SuperCDMS SNOLAB

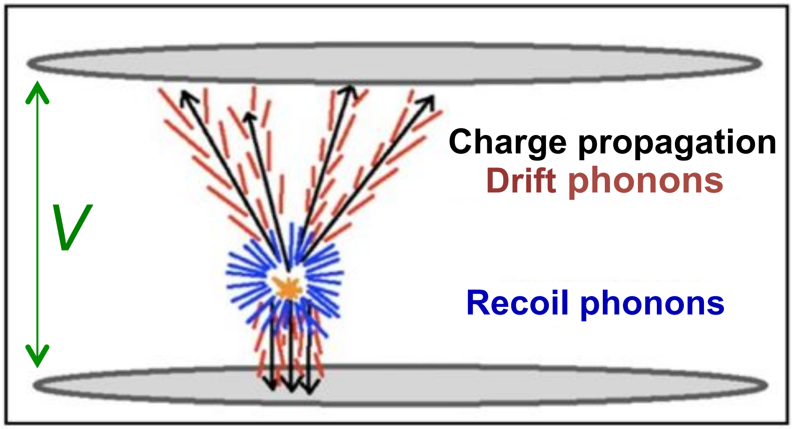
(200 kg, < 8 x 10^{-47} cm^2 for 60 GeV/c^2 WIMP)



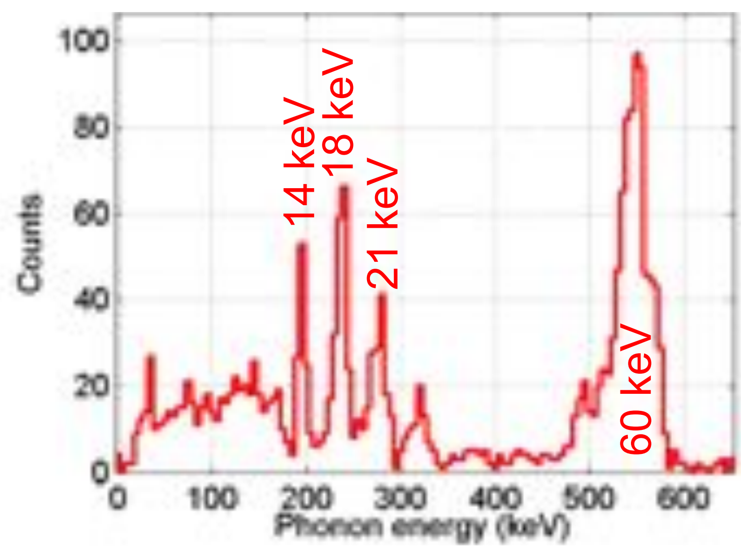
T. Doughty, UCB

Lowering Thresholds with Phonon Amplification

- Drifting N_e electron–hole pairs across a potential V generates $N_e V$ electron volts of phonons
- Noise approximately independent of bias
- Preliminary tests demonstrated ~100 eVee thresholds
  - Expect to do better with PPCs
    - Mirabolfathi et al. in progress
- Ionization measurement only, so no event-by-event electron/ nuclear recoil discrimination
  - But can subtract ERs statistically by running at multiple biases (arXiv:1201.3685)



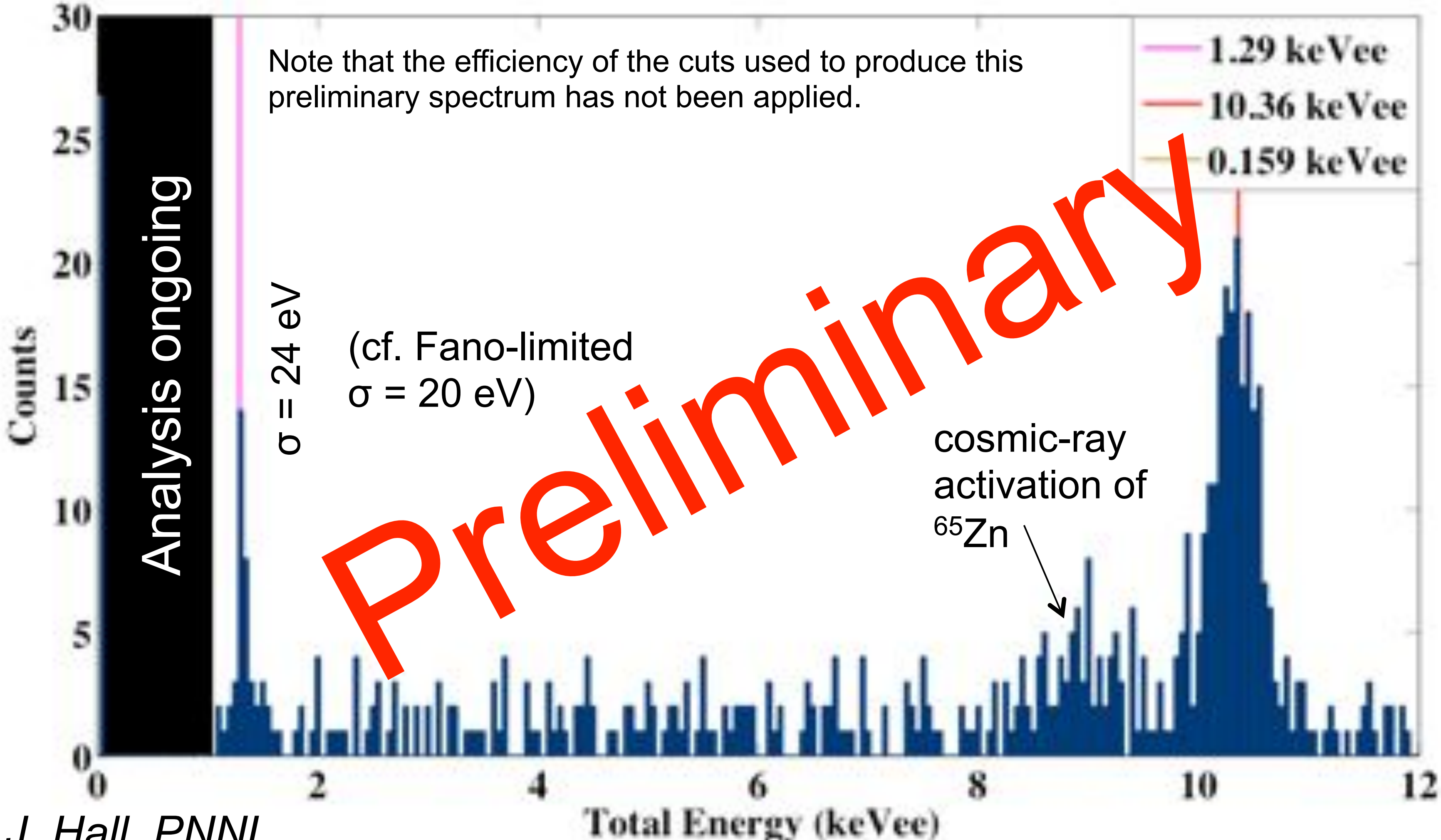
Neganov and Trofimov, Otkryt. Izobret., ***146***, *215 (1985)*
Luke, J. Appl. Phys., 64, 6858 (1988), Luke et al., Nucl. Inst. Meth. Phys. Res. A, ***289***, *406 (1990)*



Akeriib et al., NIM A, ***520***, *163 (2004)*

CDMS low ionization threshold experiment

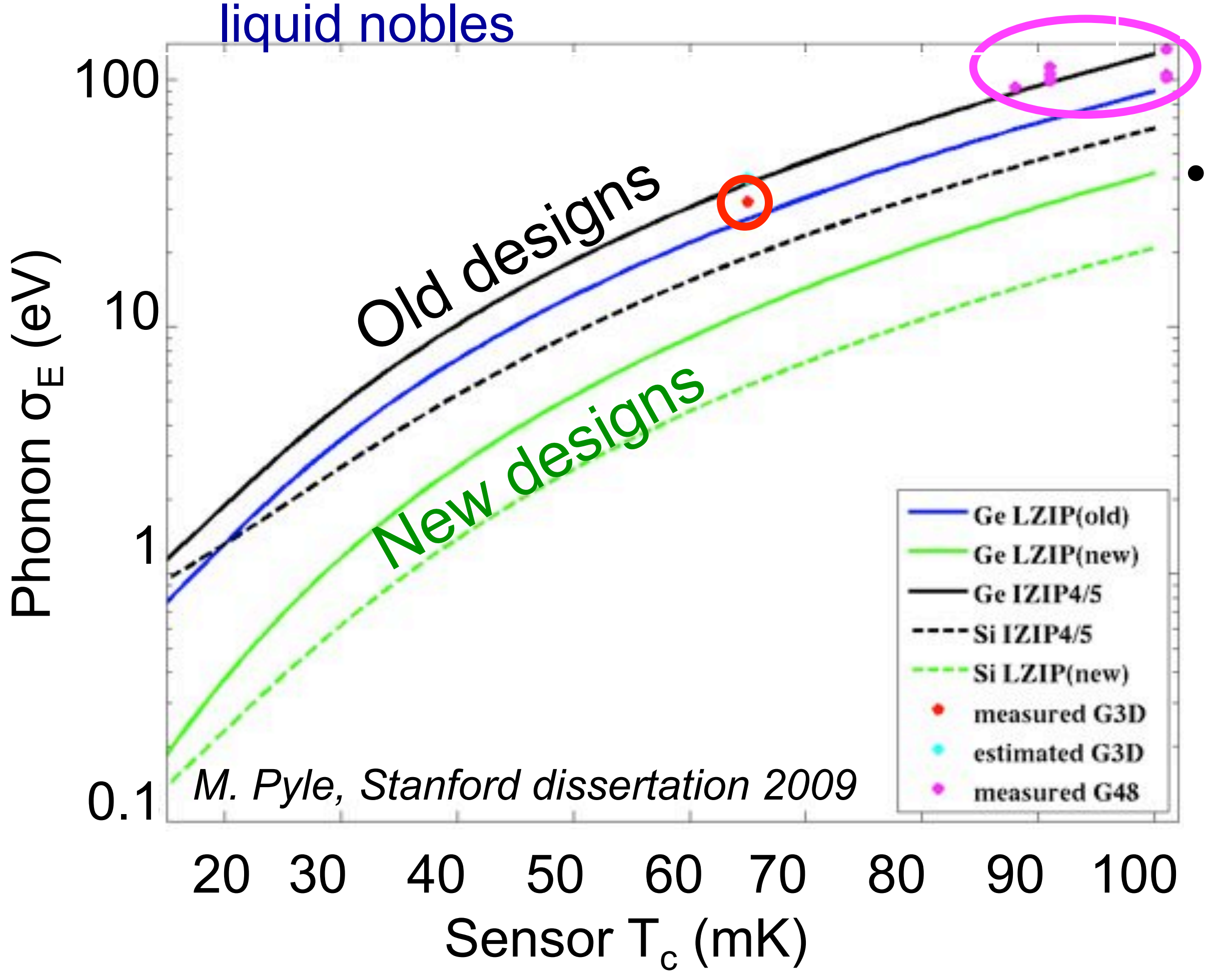
- WIMP-search data taken Fall 2012 with 69 V bias.
- First results expected May 2013



J. Hall, PNNL

CDMS for low-mass WIMPs longterm

- Highest number of quanta
  - 10^5 phonons, 300 e-h pairs per keV
  - vs. <100 photons (or e's) per keV for liquid nobles



- Better exploitation in future
  - Recently realized

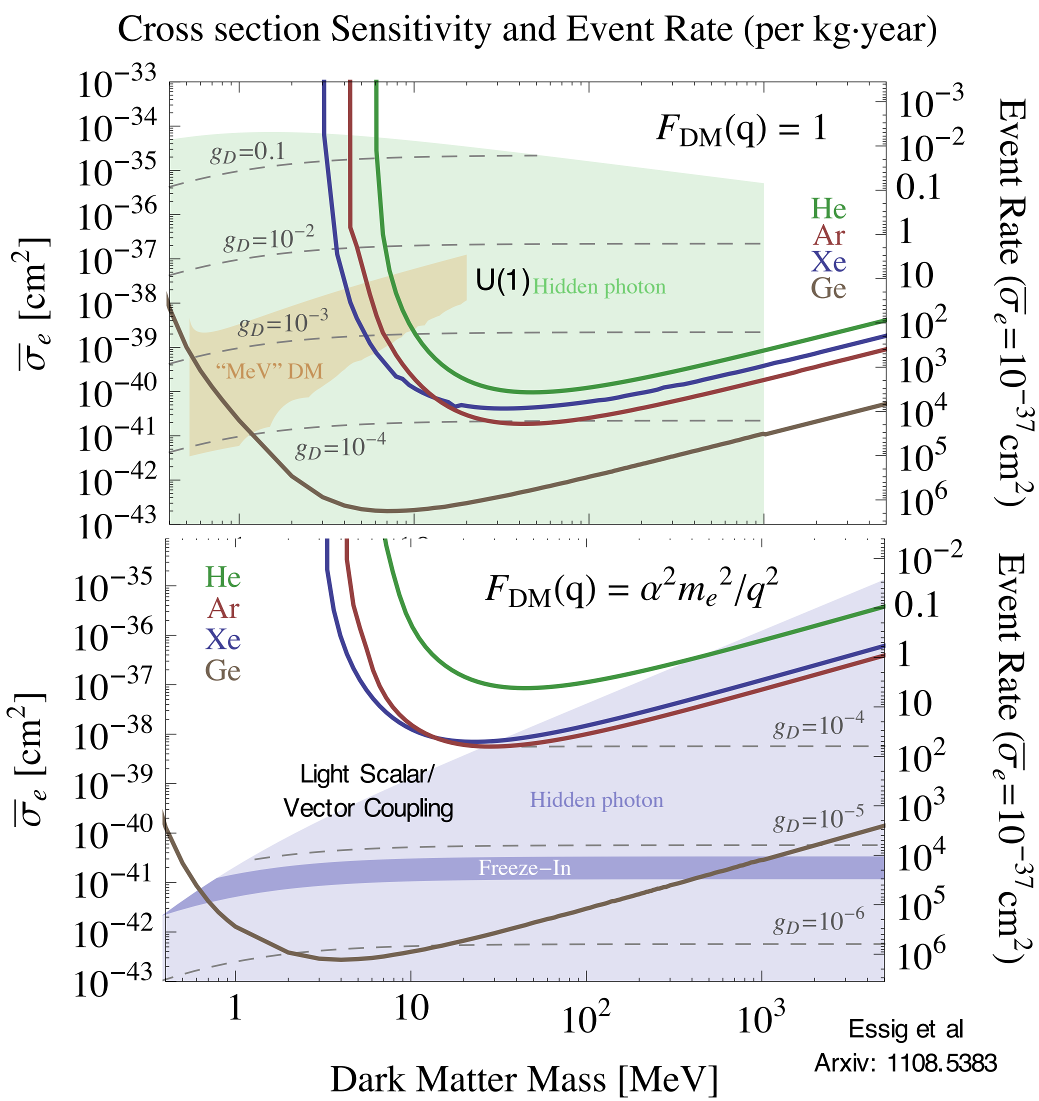
$$\sigma_E \propto T_c^3$$

- For T_c= 20 mK: x125 better E resolution than CDMS!
  - ~100 eV ➔ < 1 eV
  - Harder cryogenics, new recipe for T_c

Single excitation sensitivity should be possible, greatly improving sensitivity to low-mass dark matter!

Sensitivity to sub-GeV Dark Matter

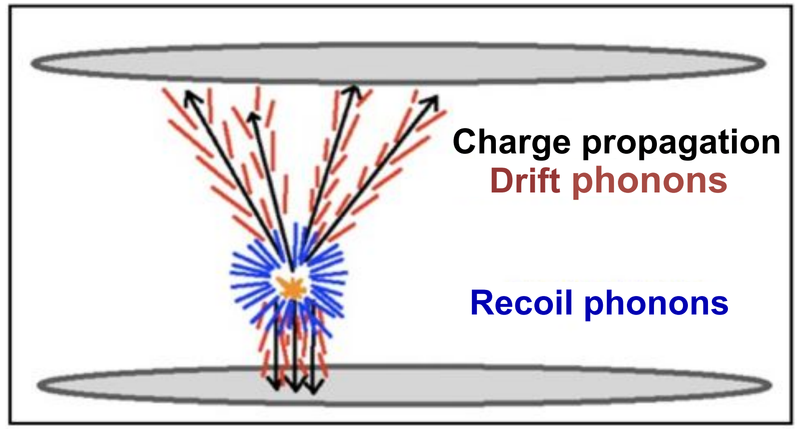
- Sub-GeV nuclear recoils may not have enough energy
- May detect
  $$DM + e^- \rightarrow DM + e^-$$
- Ideally requires single e^-/h^+ pair sensitivity
- Ge & Si much more sensitive than Ar, Xe, & He because of small bandgap
- (Essig et al. arXiv:1108.5383)



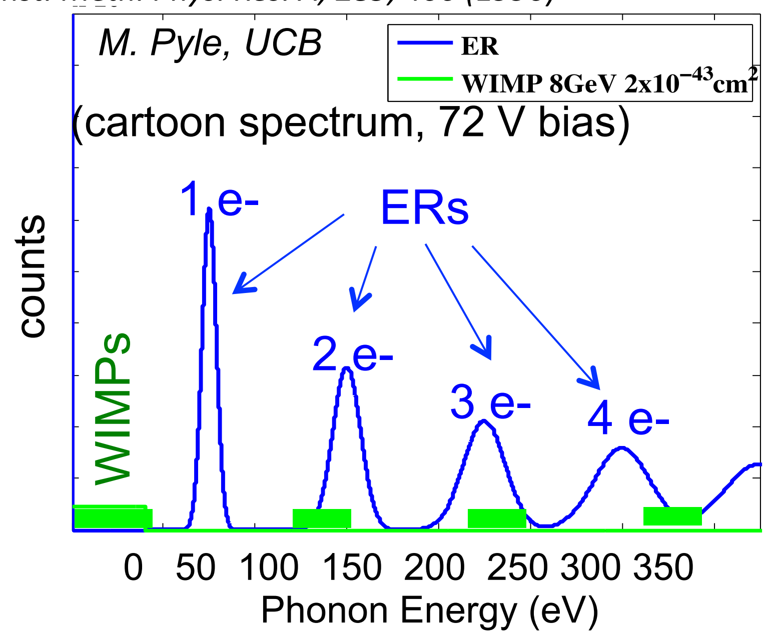
Essig et al
Arxiv: 1108.5383

Recoil Discrimination at Very Low Energy

- By combining high-voltage Neganov-Luke amplification with higher-resolution phonon sensors, the electron recoil spectrum should resolve into a 'forest' of charge peaks
  - 6 eV recoil energy yields 2 e/h pairs on average, 150 eV phonon energy for an ER, but yields only 6 eV phonon energy for an NR since no ionization
- Nuclear recoils should be the only events between the electron recoil peaks

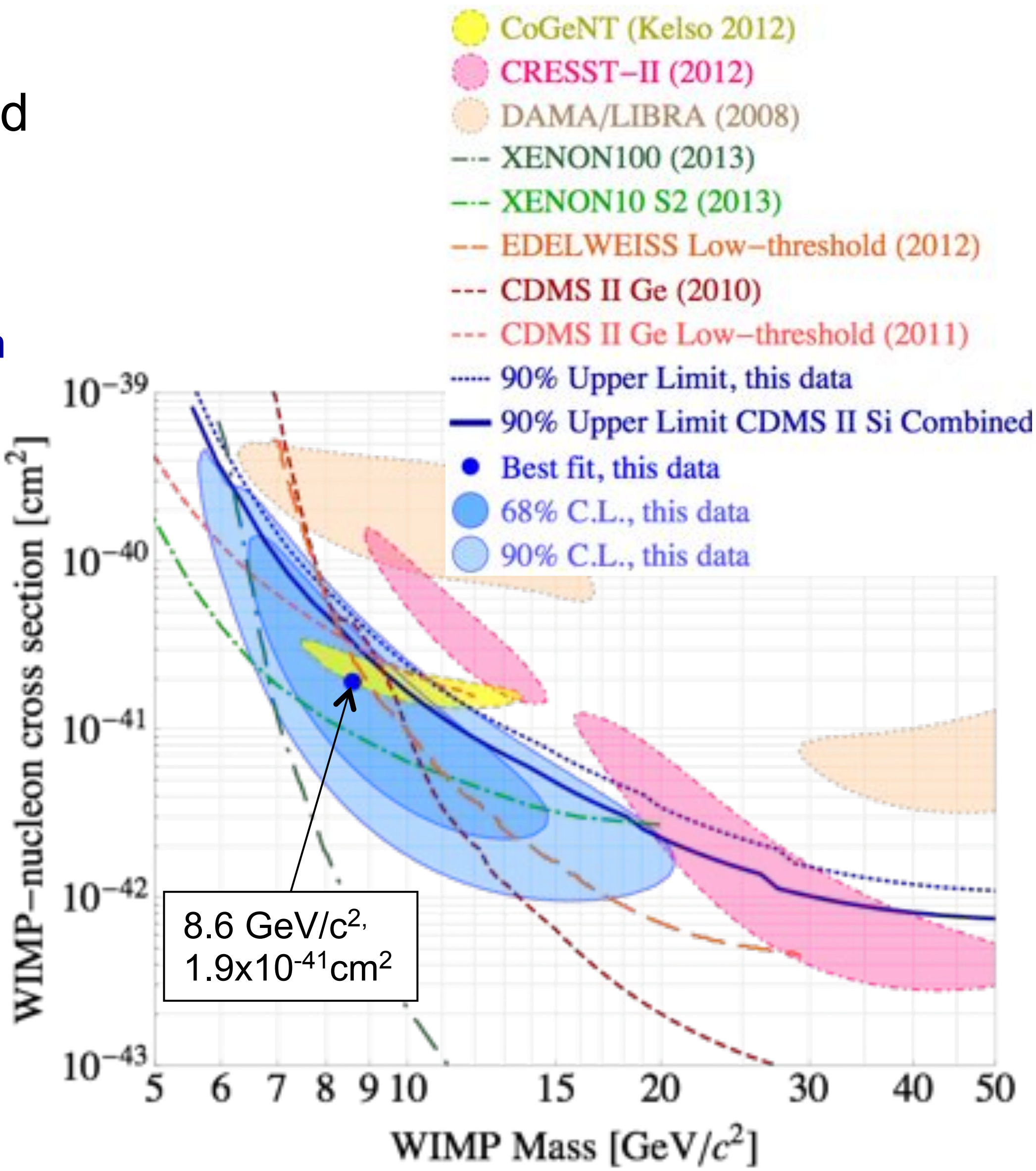


Neganov and Trofimov, Otkryt. Izobret., ***146***, *215 (1985) Luke, J. Appl. Phys., 64, 6858 (1988), Luke et al., Nucl. Inst. Meth. Phys. Res. A,* ***289***, *406 (1990)*



Conclusions

- Three events in the CDMS II Si signal region with a total expected background of <0.7 events.
  - The probability of a statistical fluctuation producing three or more events anywhere in our signal region is 5.4%.
  - WIMP+background hypothesis favored over known backgrounds at the 99.81% confidence level (not a discovery).
- SuperCDMS will test and constrain low-mass WIMP hypothesis this year by annual-modulation, low-threshold, and CDMSlite analyses
- In long run, CDMS technology provides great path to discovery for low-mass WIMPs



Backup Slides