Dark Matter Search Results Using the Silicon Detectors of CDMS II

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On behalf of the SuperCDMS Collaboration

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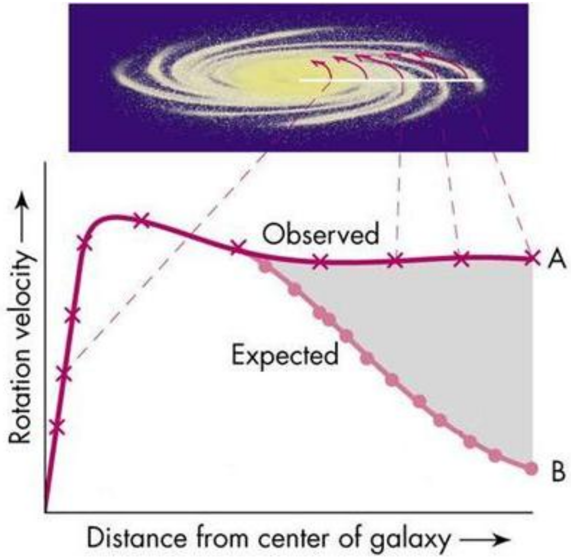
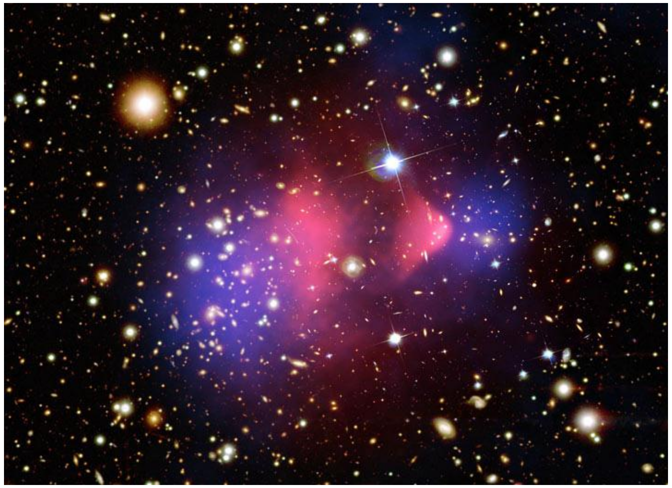
Outline

- Dark matter basics
- The CDMS approach to dark matter
- Overview of previous CDMS results
- The recent CDMS-II silicon analysis
- Reach of current and future CDMS efforts to the silicon region of interest

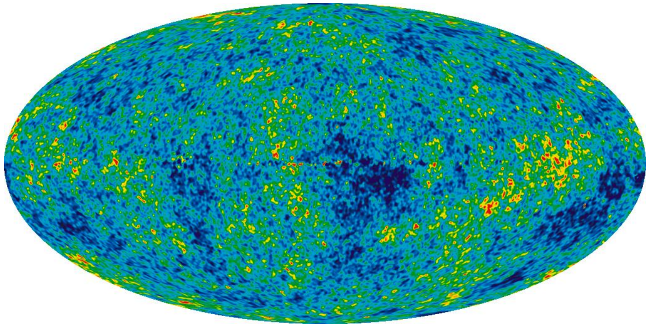
Evidence for dark matter: Compelling at all scales

Single galaxies

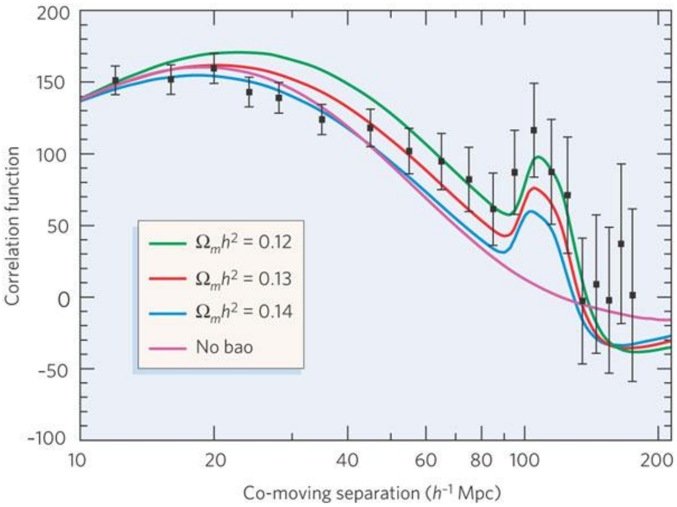




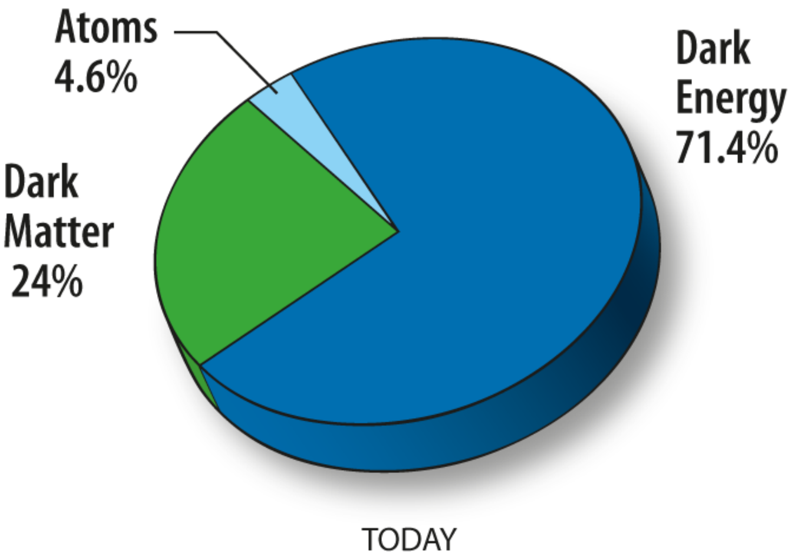
Galaxy clusters

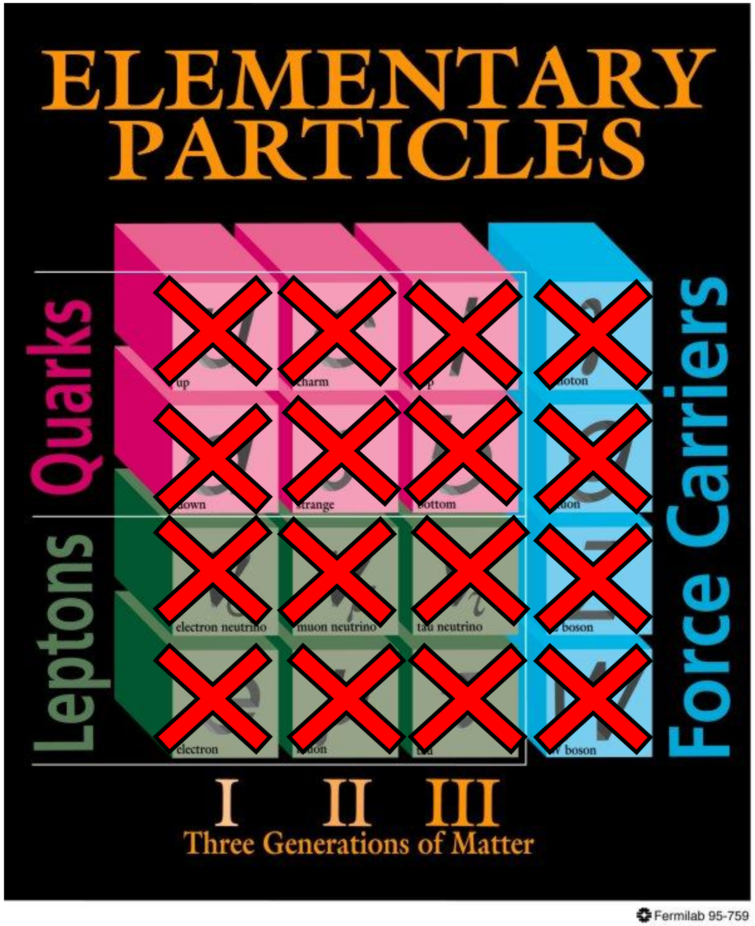


The whole observable universe



Survey says:

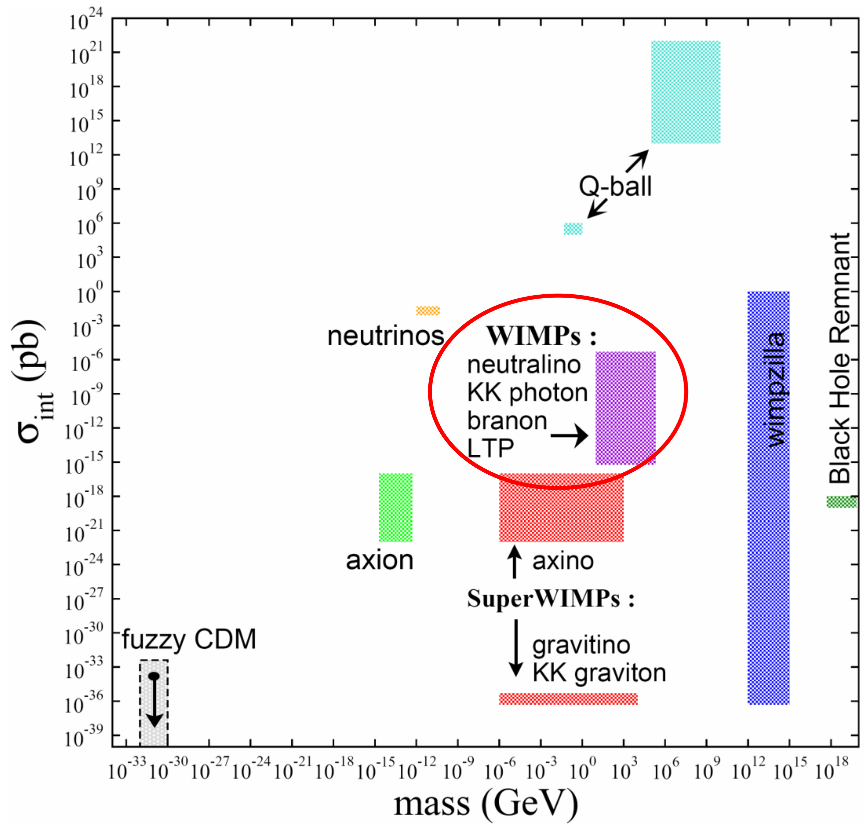




- 84% of the matter in the universe is not something in the standard model
- Then what is it?

Lots of possible candidates

- Most experimental focus on WIMP: Weakly Interacting Massive Particle
- Cosmological relic density naturally leads to ~GeV—TeV particle with weak-scale annihilation cross-sec
- Bonus: matches neutralino in many SUSY models



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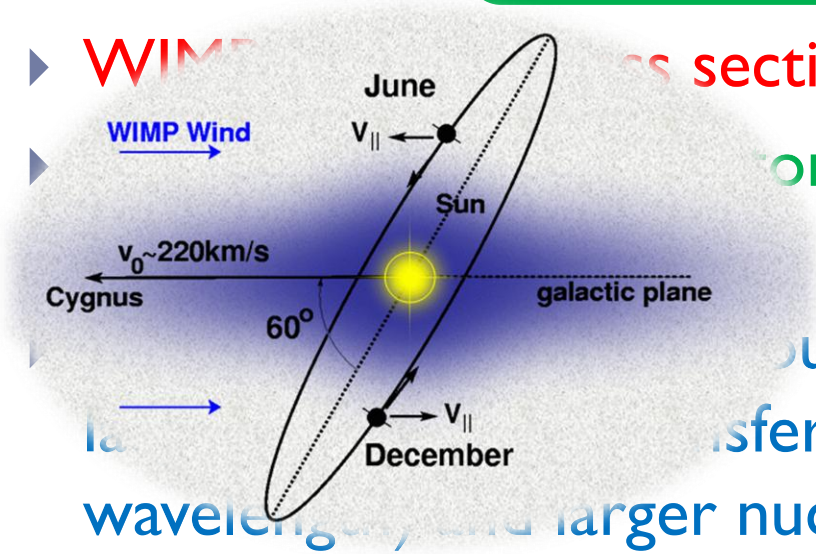
WIMP Dark Matter Basics

- WIMPs act like heavy neutrino with only neutral-current interactions
- Standard assumptions:
  - WIMPs are a non-interacting gas on average at rest w.r.t. the galaxy
  - Energies follow Maxwellian velocity distribution with average velocity ~250 km/s with cutoff at galactic escape velocity
  - Local density ~0.3 GeV/cm^3; per-particle mass is a free parameter. For 100 GeV wimp, flux would be ~10^5 $/cm^2/s$
- With large mass and low velocity, WIMPs are very non-relativistic. Interaction details don't matter to first order: it's billiard ball physics

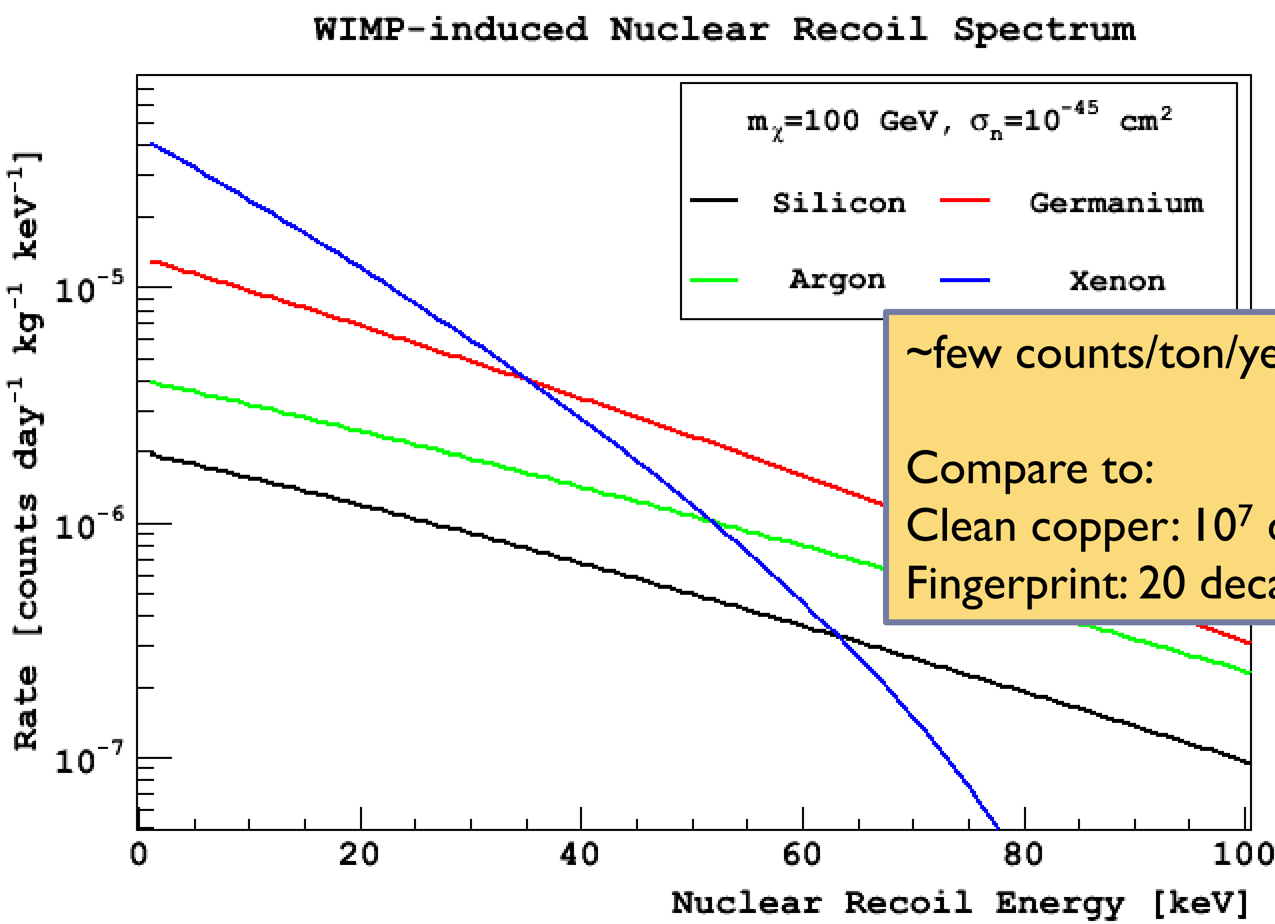
Expected spin-independent detector response to WIMPs

$$\frac{dR}{dE_R} = \frac{N_0 \sigma_n \rho_D M_T}{2A\mu_n^2 M_D}\left(Z\frac{f_p}{f_n}+(A-Z)\right)^2 F^2(q)\int_{v_{min}}^{\infty}\frac{f(v_D,v_E,v_{esc})}{v_D}\,dv_D$$



- WIM... ...s section and local WIMP density
- ...or. If fp=fn (isospin symmetry),
- ...unts for imperfect coherence at la... ...sfer (i.e. smaller propagator wavele... ...larger nucleus
- Velocity distribution function. v_E term introduces seasonal modulation. Only upper tail of velocity distribution above v_{min} can cause recoil of energy E_R

Dark Matter Signal



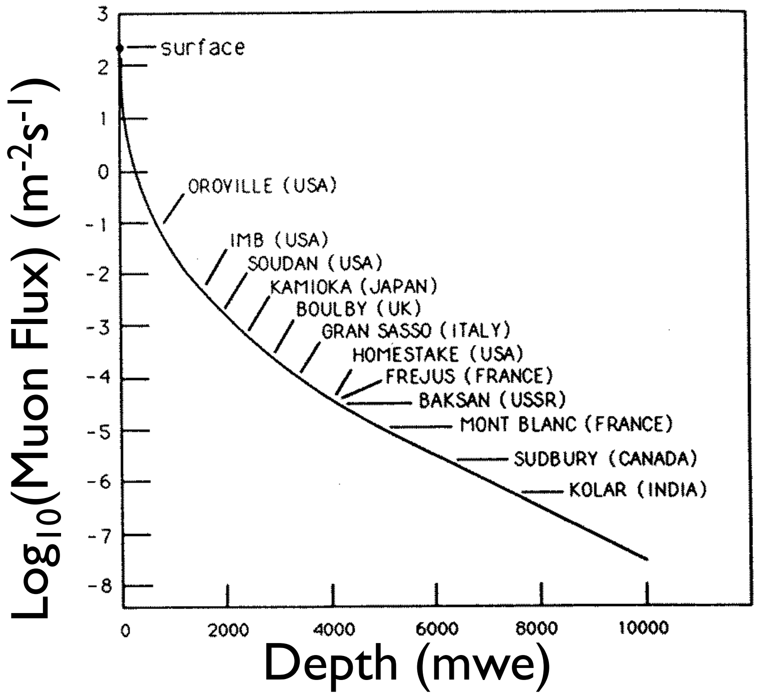
~few counts/ton/year

Compare to:
Clean copper: 10^7 decays/ton/year
Fingerprint: 20 decays/year

Heavier elements win at higher WIMP mass and low threshold due to A^2 coherence effect

Identifying dark matter signals: Overcoming three classes of background

- Cosmogenic neutrons
  - High energy neutrons from cosmic ray spallation
  - Solution: Go deep! Earth overburden attenuates cosmic ray muon flux
  - Use a veto to tag events by the parent muon or shower



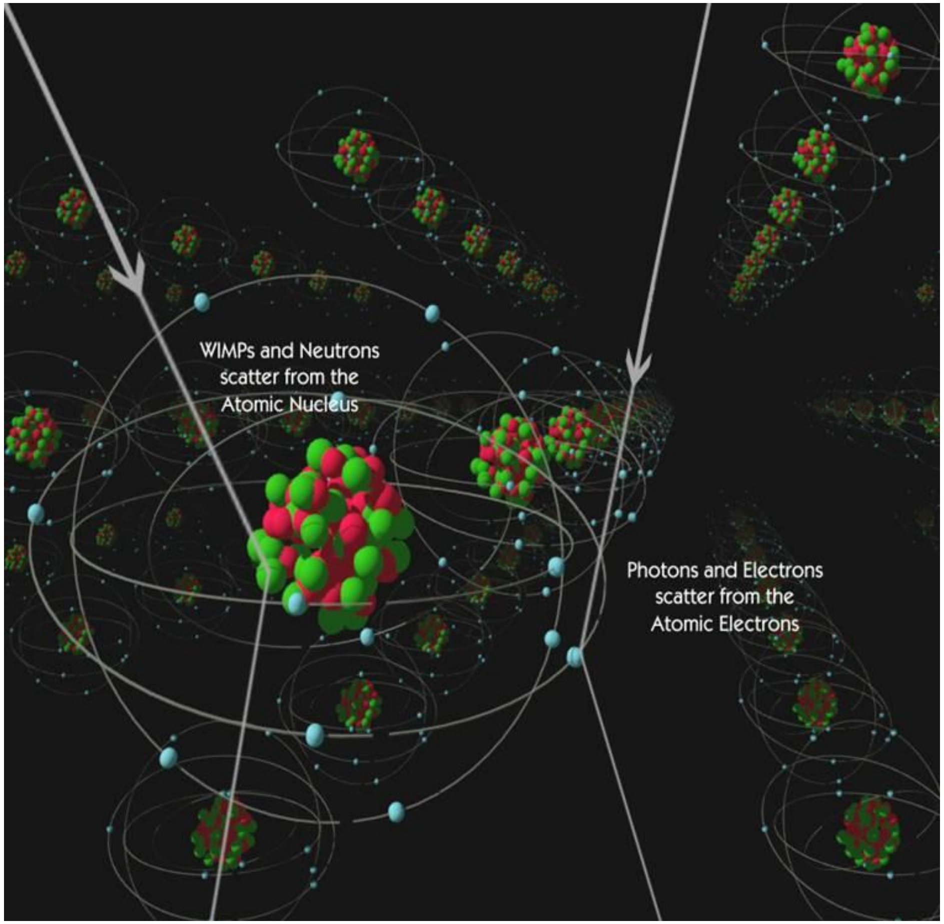
Identifying dark matter signals: Overcoming three classes of background

- Cosmogenic neutrons
- Radiogenic neutrons
  - ~MeV energies, from spontaneous fission and alpha,n reactions from U,Th in cavern and detector materials
  - Solution: Build detector with ultra-clean screened materials + lots of passive shielding

SuperCDMS Shielding installation

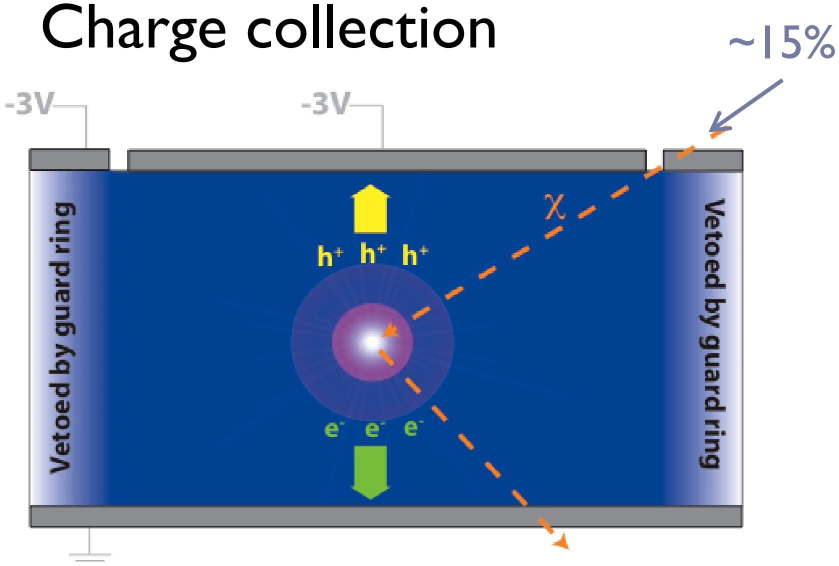
Identifying dark matter signals: Overcoming three classes of background

- Cosmogenic neutrons
- Radiogenic neutrons
- Environmental gammas
  - From same U, Th (+K, Co,…) as radiogenic neutrons, but ~million times higher rate!
  - Solution: design detectors that can separate nuclear recoils (from WIMPs, neutrons) from electron recoils (from gammas, betas)



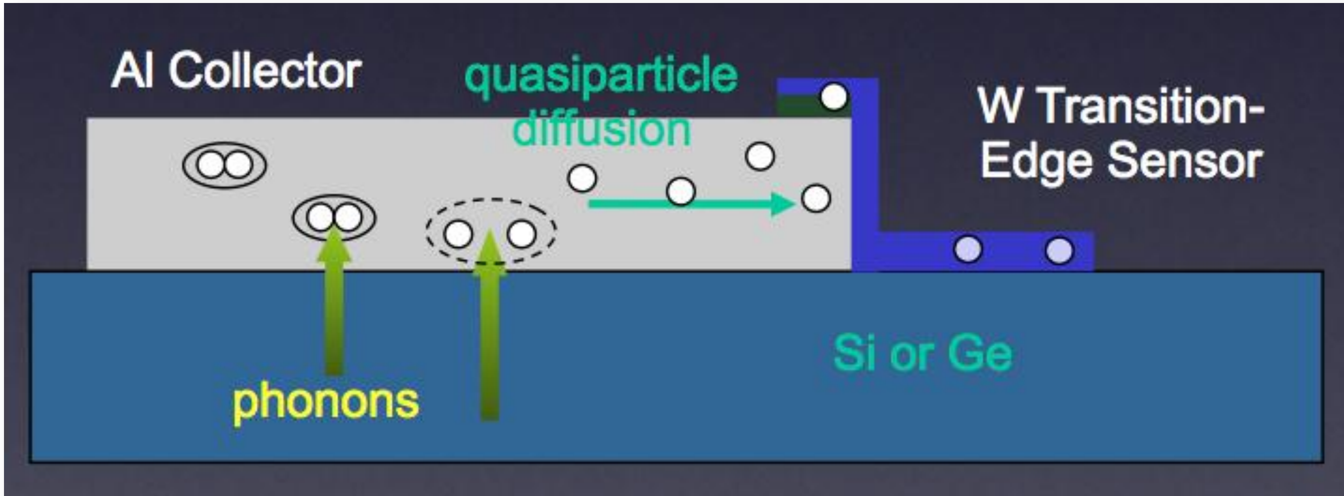
ZIPs: Z-sensitive Ionization and Phonon Detectors

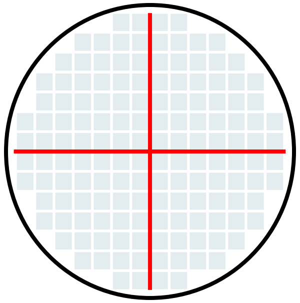
Charge collection



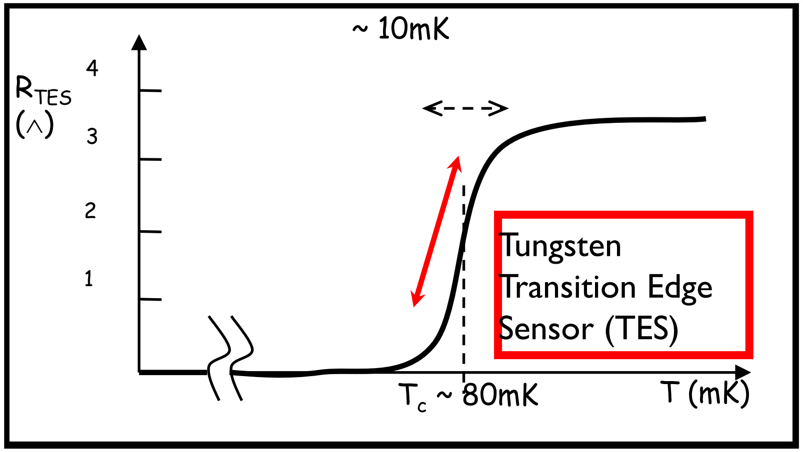
- Outer ring allows fiducial volume, to remove partial collection due to field edge effects
- Nuclear recoils with high dE/dx produce fewer electron/hole pairs per unit energy than minimum ionizing particles

ZIP Detectors: Phonons



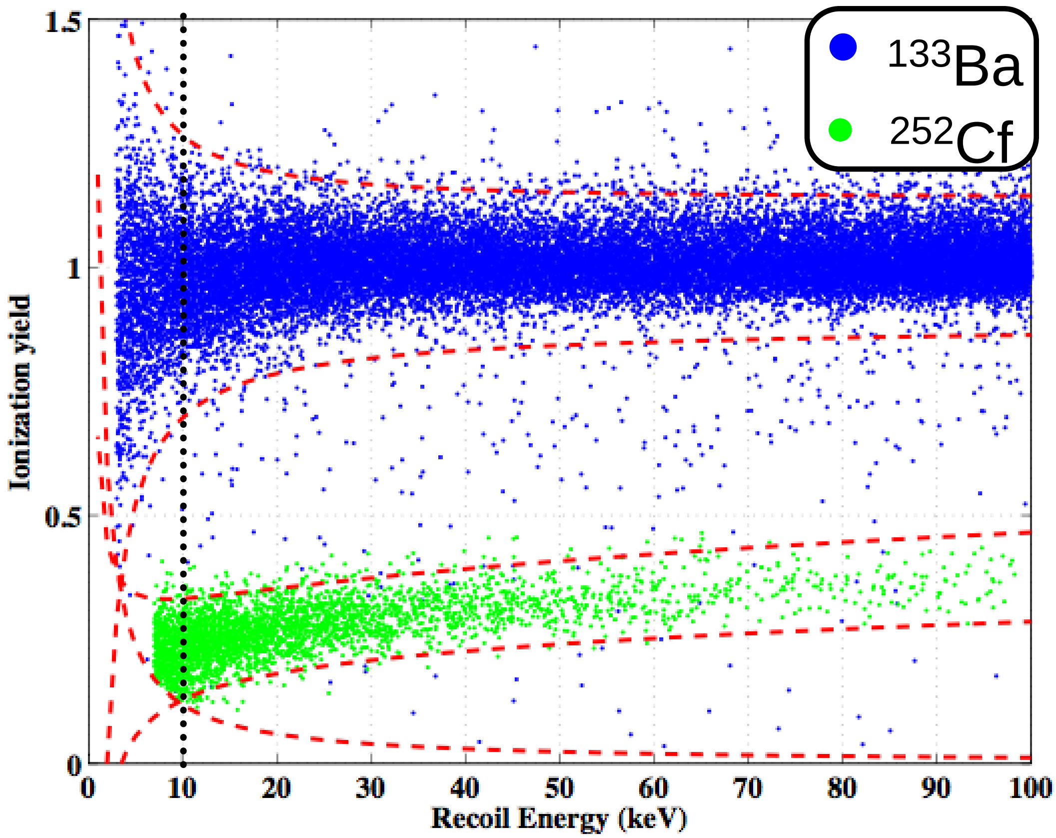


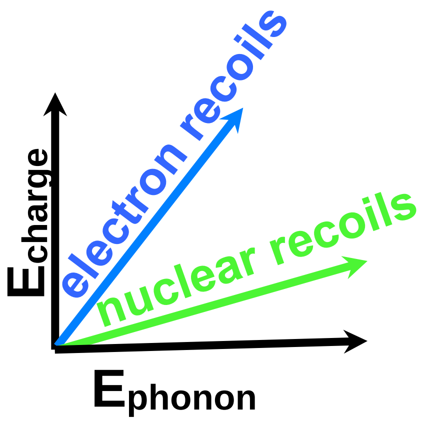
4 SQUID readout channels, each reads out 1036 TESs patterned on the bottom face of the Ge crystal



Phonons are crystal lattice vibrations (very high frequency sound), but we measure them with very sensitive thermometers.

Gamma Rejection

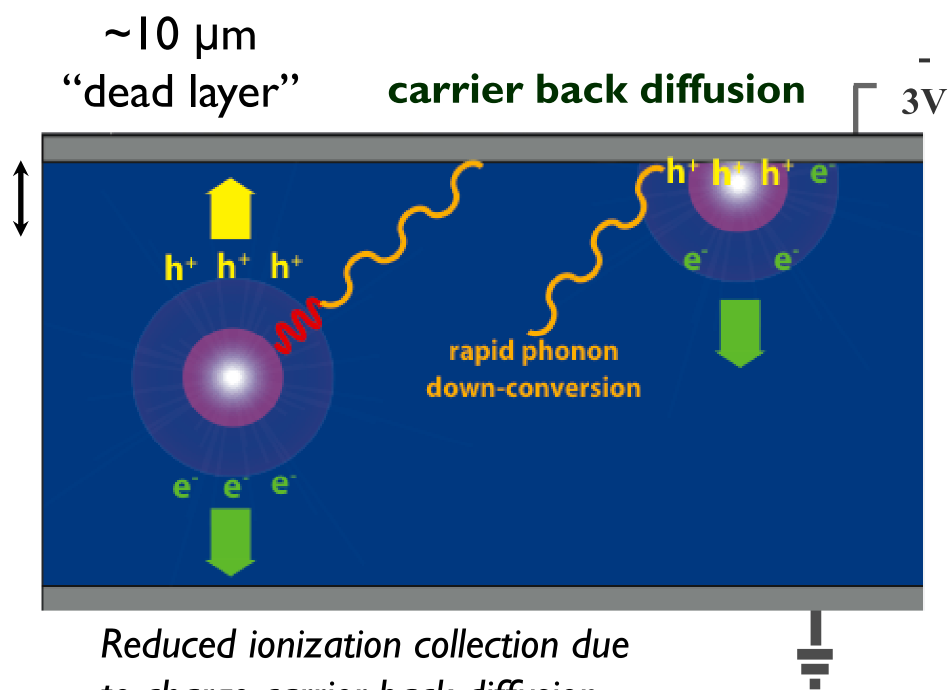




$$\text{ionization yield} = \frac{E_{charge}}{E_{phonon}}$$

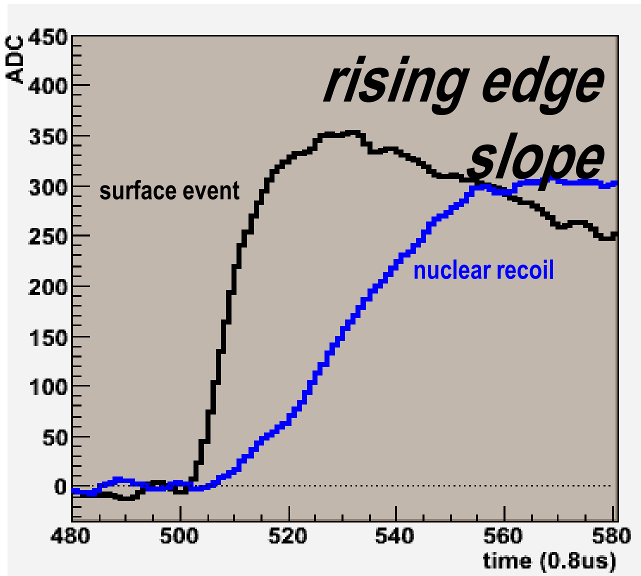
Better than 1:10^4 rejection of gammas based on ionization yield alone

Main Problem: Surface Events



Reduced ionization collection due to charge carrier back-diffusion in surface events.

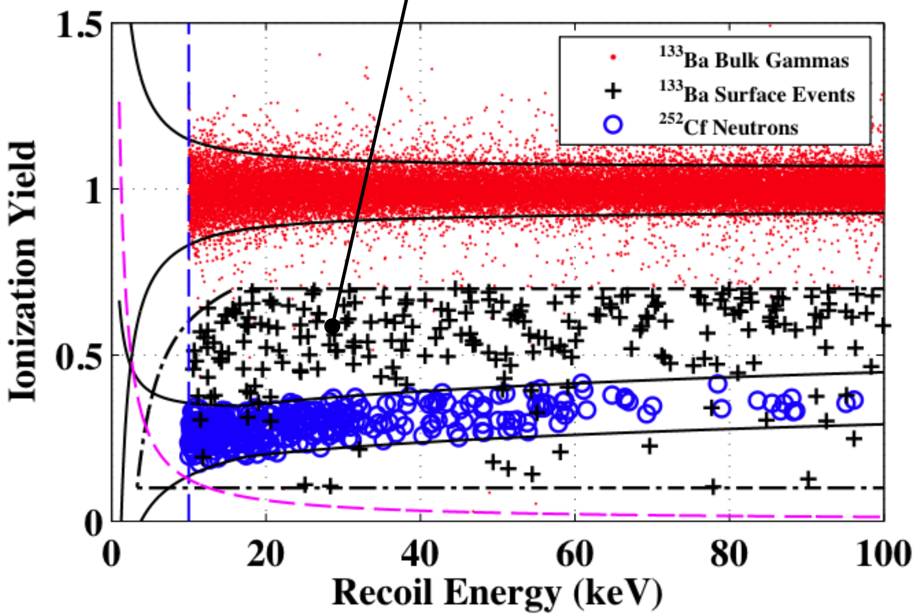
Phonon pulse shape (timing) distinguishes surface events

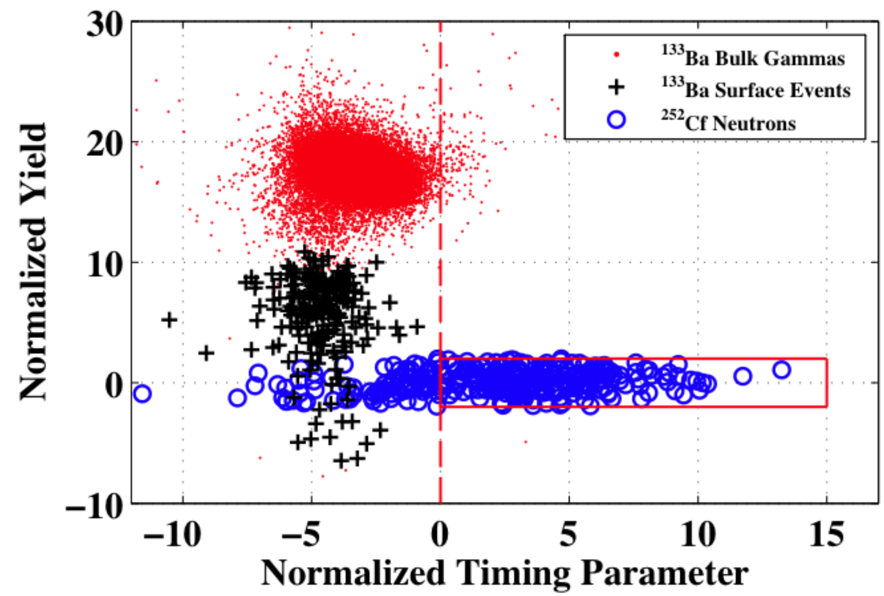


These events are primarily electrons and soft x-rays originating from surfaces of the detectors and surrounding materials

Surface Event Rejection

10 μm “dead layer” results in reduced ionization collection

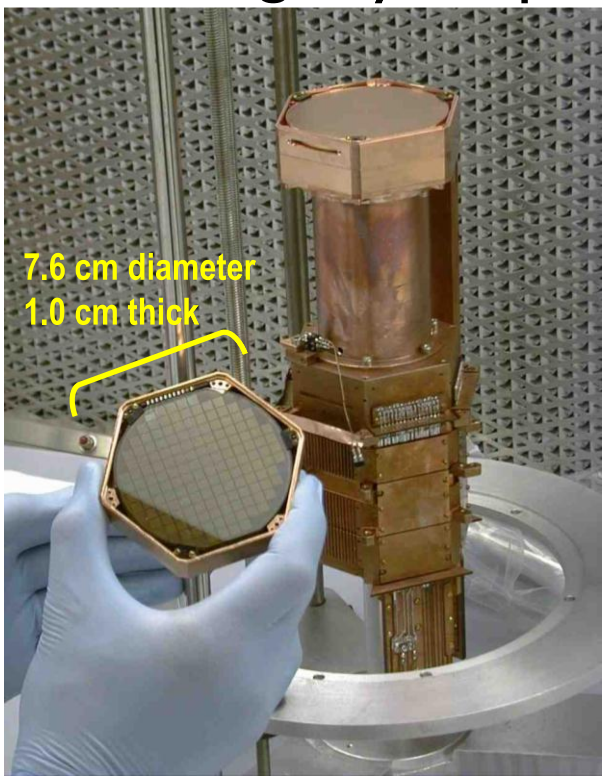




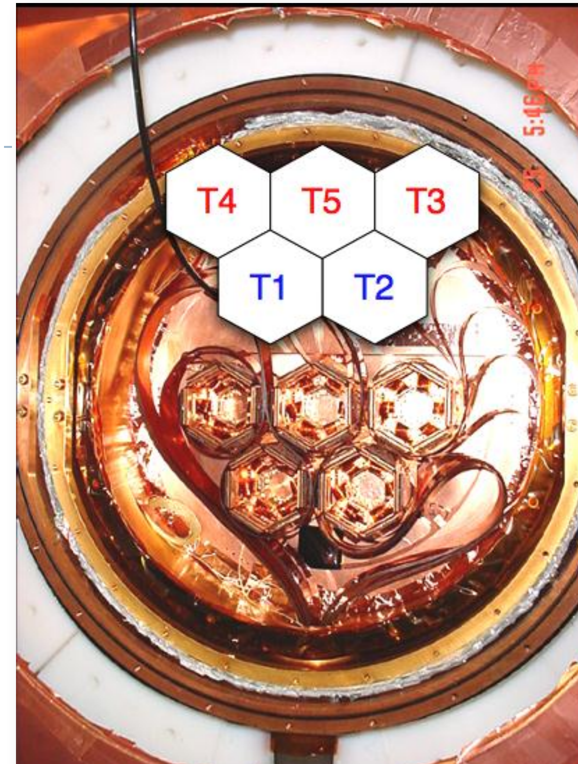
Combination of yield and “timing” cuts needed to reject these events

CDMS-II

- 19 Ge and 11 Si ZIPs in 5 “towers”
- Various runs since 2003
- 612 kg-days exposure “final” Ge analysis

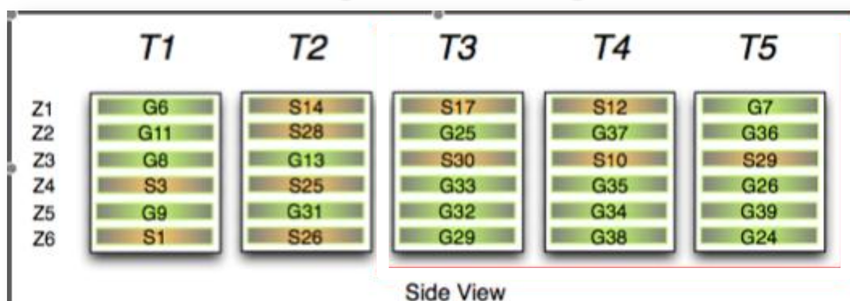


Six detectors
stacked in each tower



Five towers arranged in cold volume

4.75 kg of Ge, 1.1 kg of Si

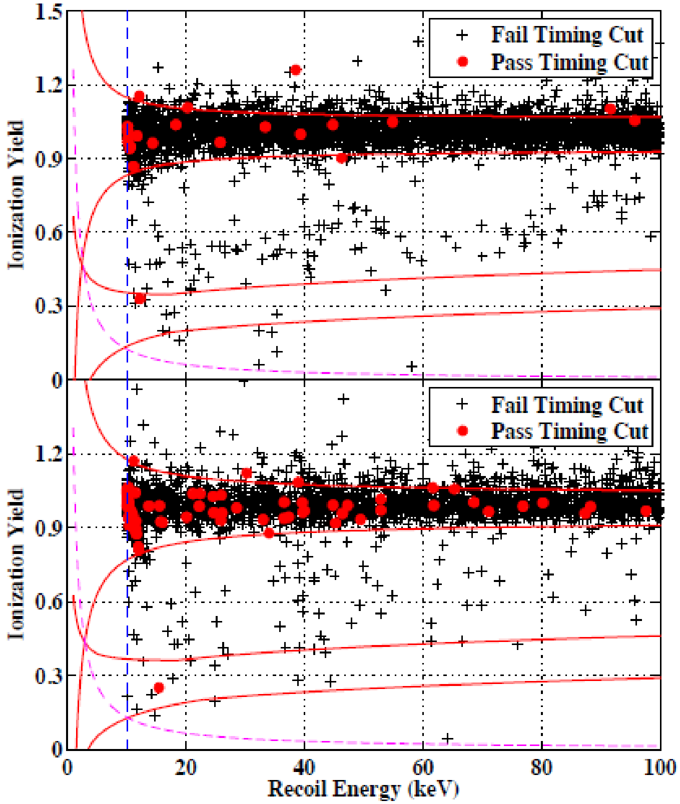


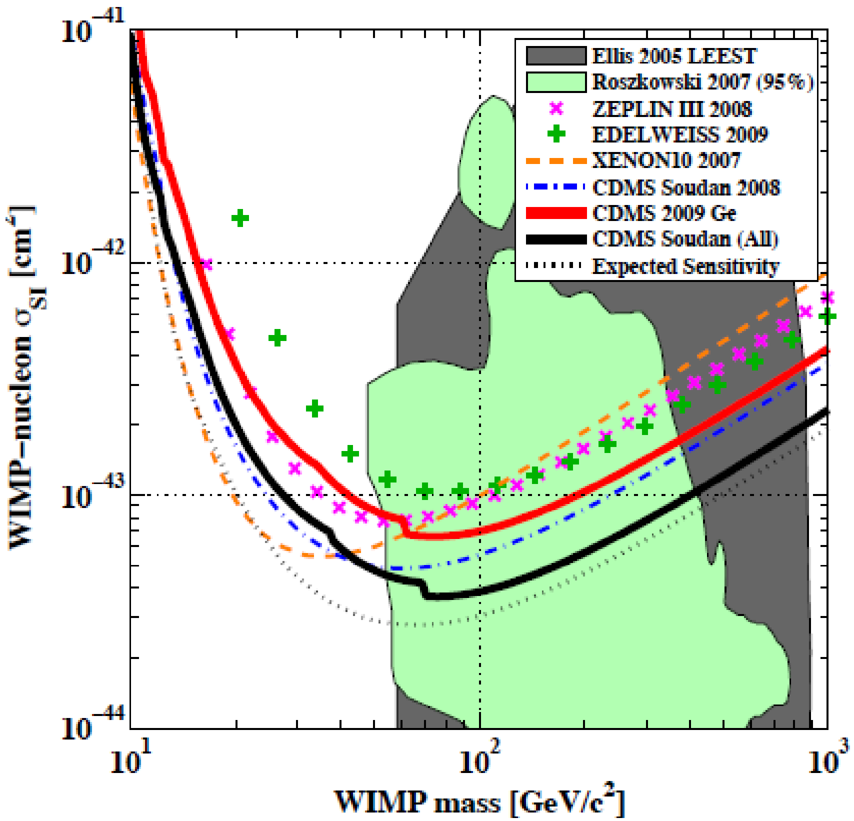
	T1	T2	T3	T4	T5
Z1	G6	S14	S17	S12	G7
Z2	G11	S28	G25	G37	G36
Z3	G8	G13	S30	S10	S29
Z4	S3	S25	G33	G35	G26
Z5	G9	G31	G32	G34	G39
Z6	S1	S26	G29	G38	G24

Side View

CDMS-II Germanium results

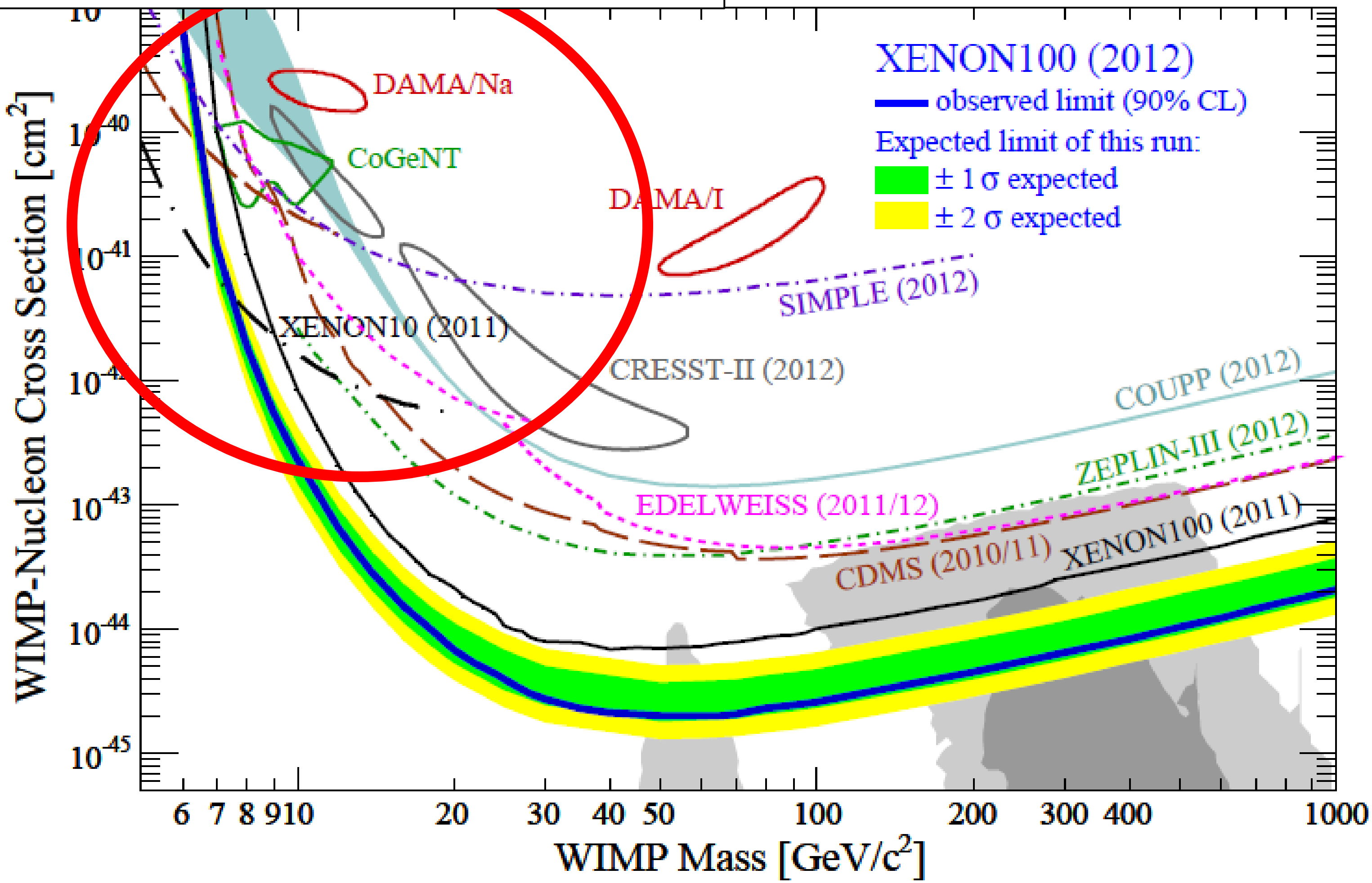
- Observed 2 events with 0.8 ± 0.1(stat) ± 0.2(sys) expected background





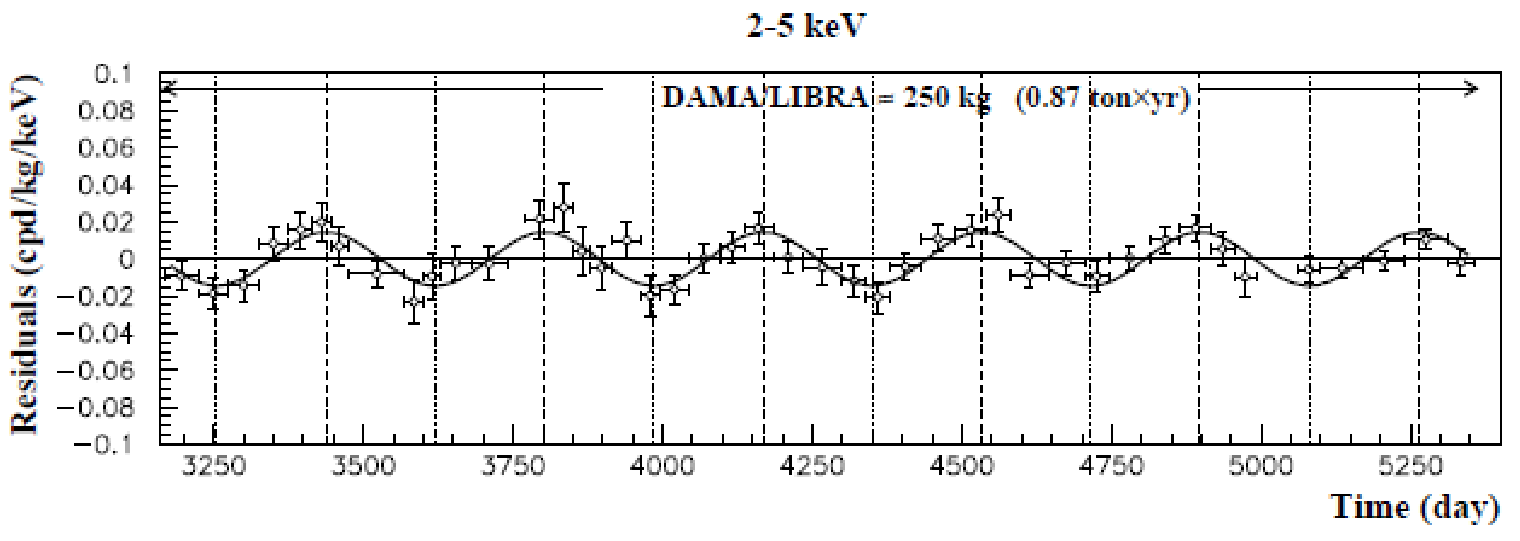
2 years later, where are we?

Growing interest in low-mass region



Have we been seeing signals for a long time already?

- Starting in 1997, DAMA/LIBRA observes annual modulation with correct phase, now at >9σ



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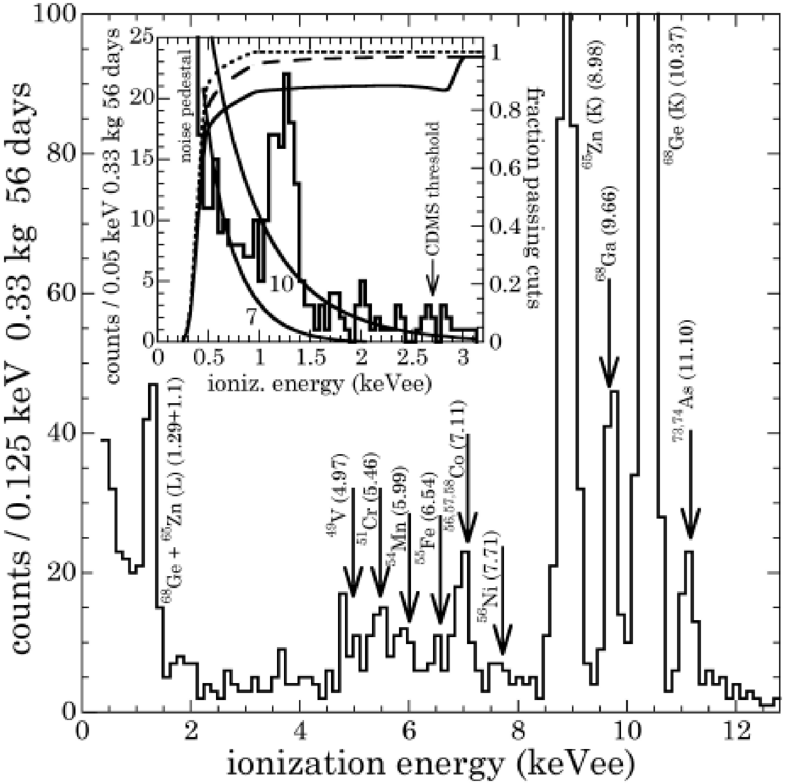
- 2010: CoGeNT observes low energy rate excess



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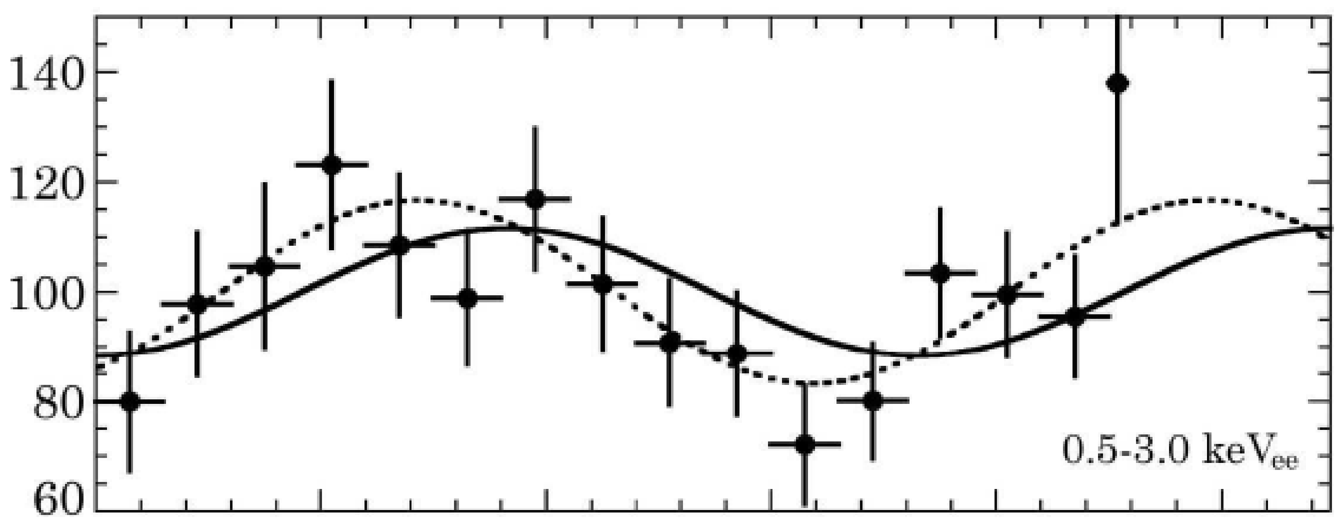
- 2011: CoGeNT sees 2.8 σ annual modulation



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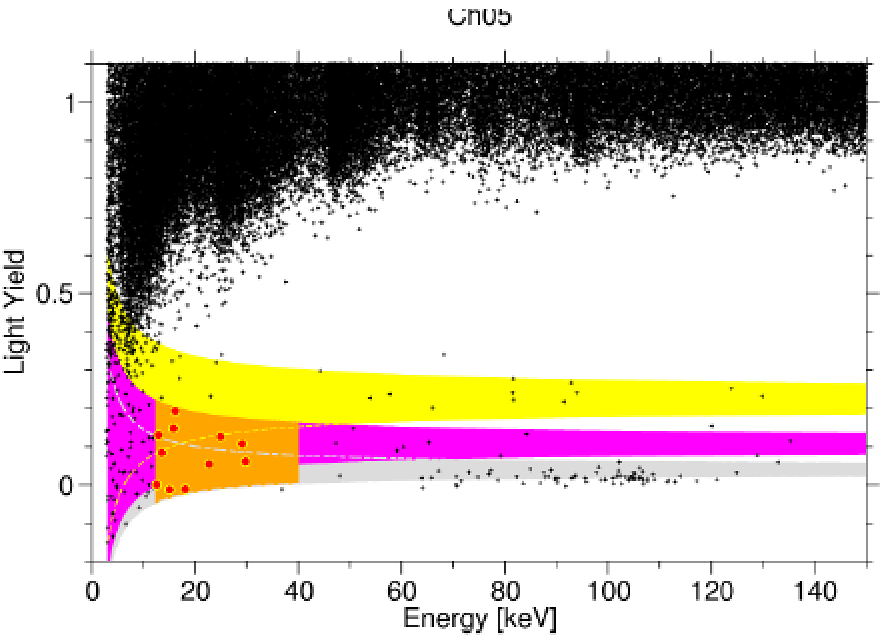
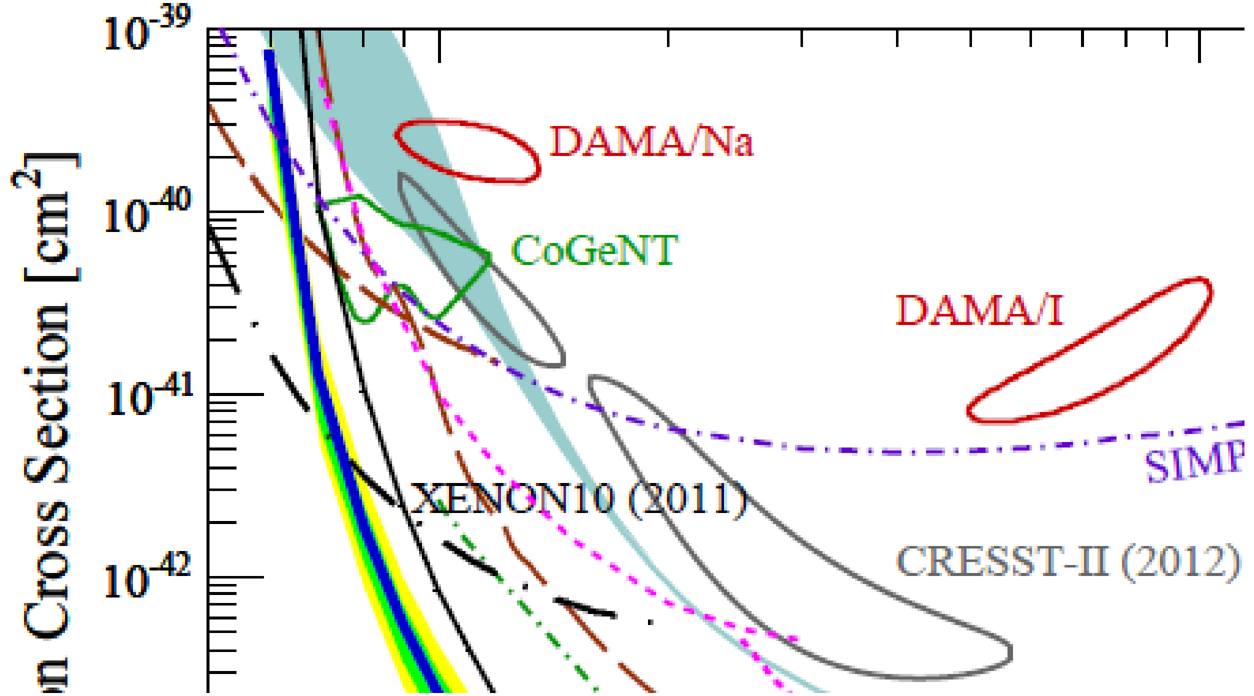
- Starting in 1997, DAMA/LIBRA observes annual modulation with correct phase, now at >9σ
- 2010: CoGeNT observes low energy rate excess
- 2011: CoGeNT sees 2.8 σ annual modulation
- 2011: CRESST sees excess in nuclear recoil band, disfavored as background at 4 σ



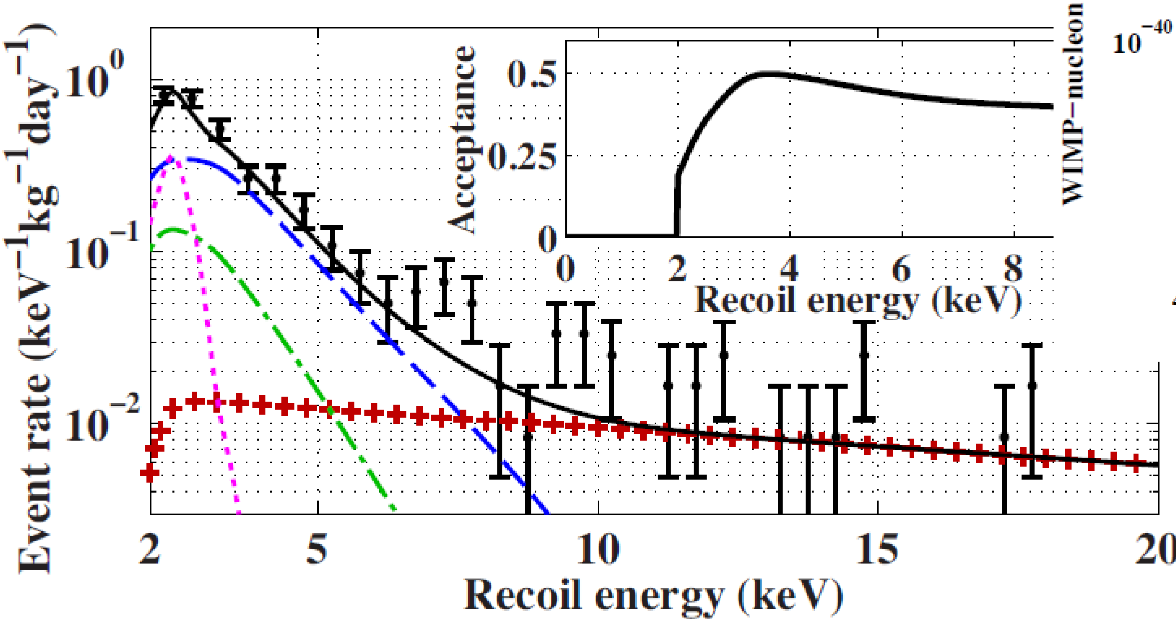
Have we been seeing signals for a long time already?

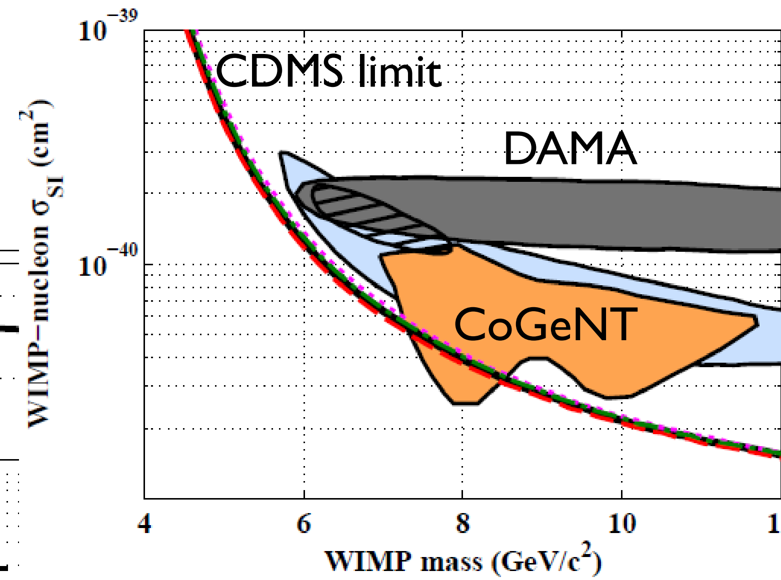
- All seem to hint at light, relatively high cross section WIMPs
- All are in tension with results from other experiments
- Only CRESST has NR/ER discrimination capability



CDMS Low threshold analysis

- 2011: Analysis of 8 best germanium ZIPs down to 2 keV shows no evidence of signal above expected background in 241 kg-days of exposure





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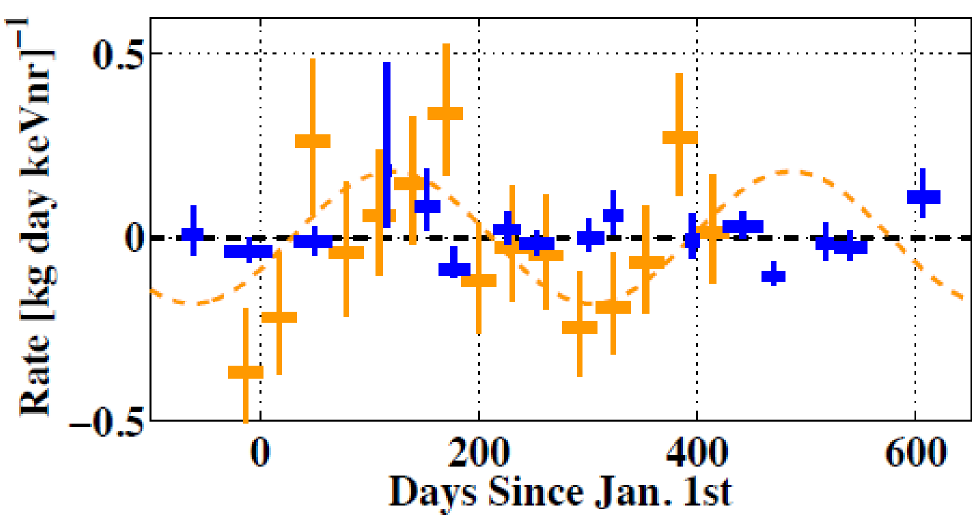
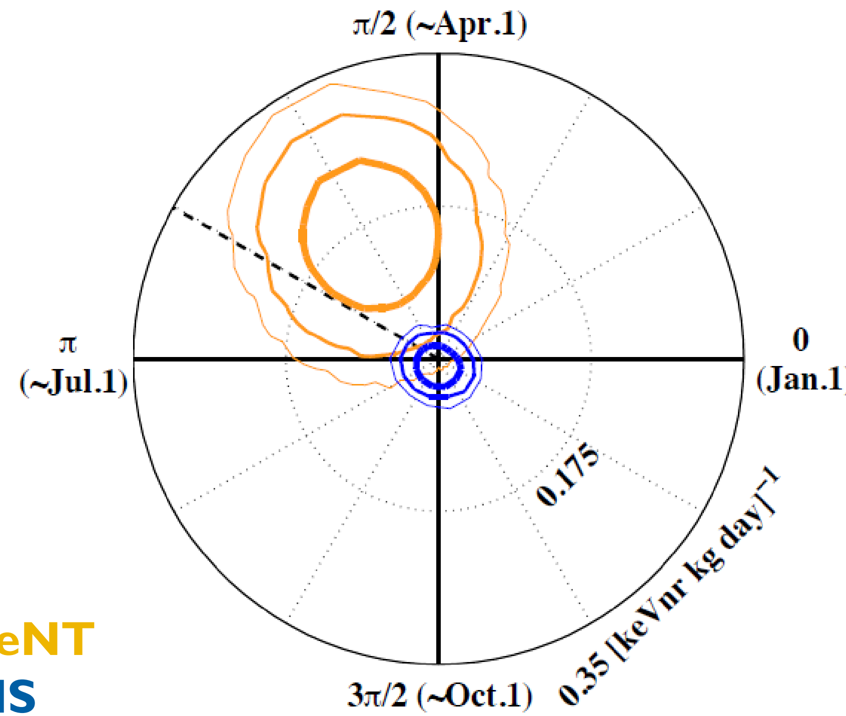
Annual modulation analysis

- No annual modulation of low energy events observed over 2 year period in 8 best Ge ZIPs





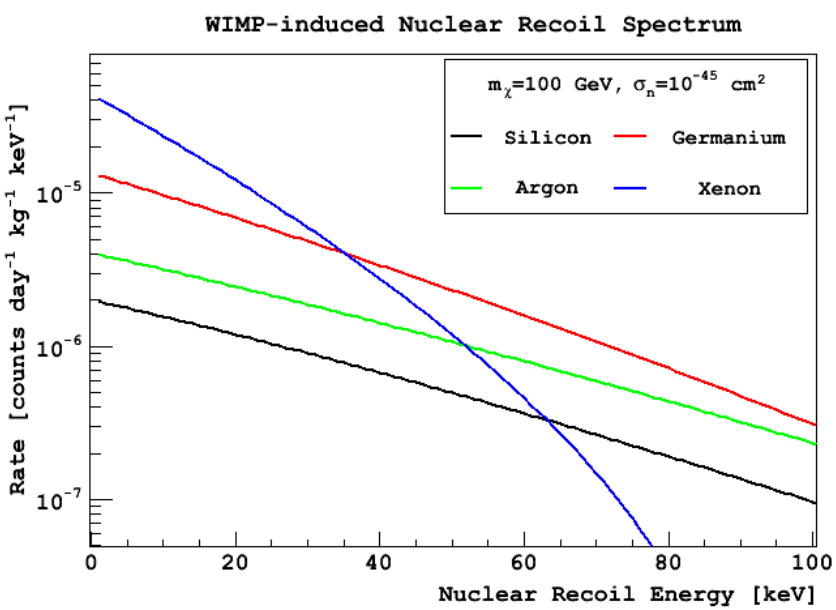
CoGeNT
CDMS

CDMS: Ruining everyone else's fun

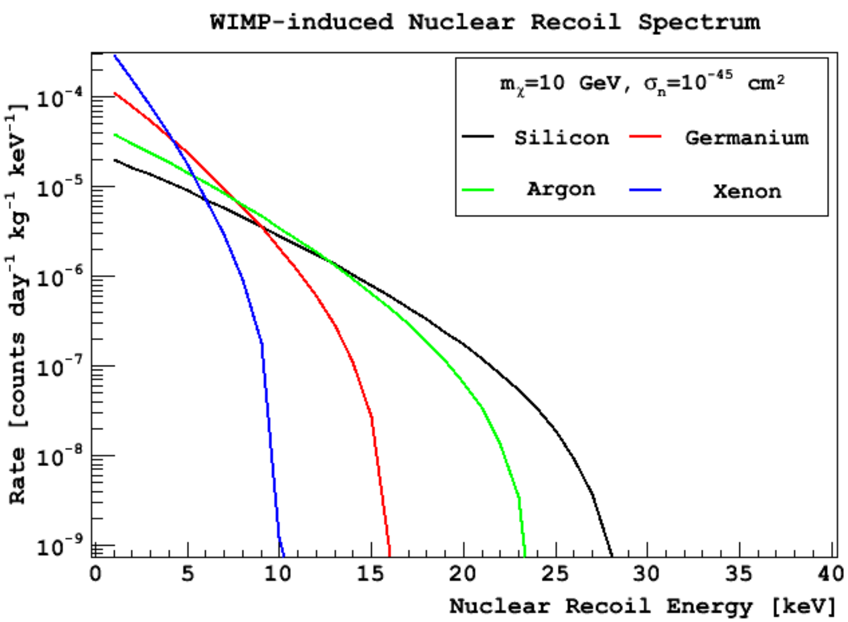
But wait…haven't yet looked at data from silicon ZIPs

Silicon is more effective at low WIMP mass

100 GeV WIMP



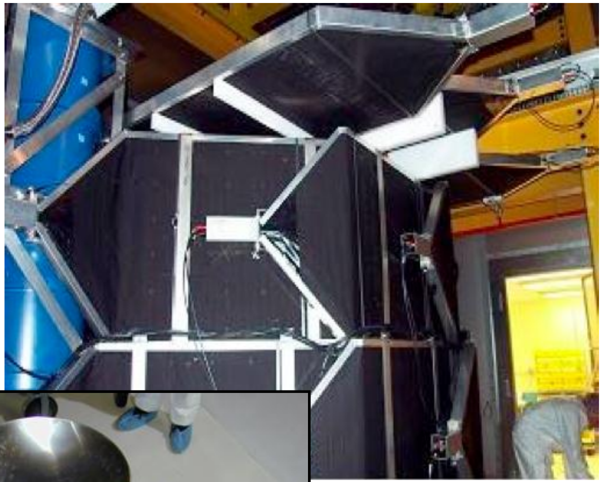
10 GeV WIMP

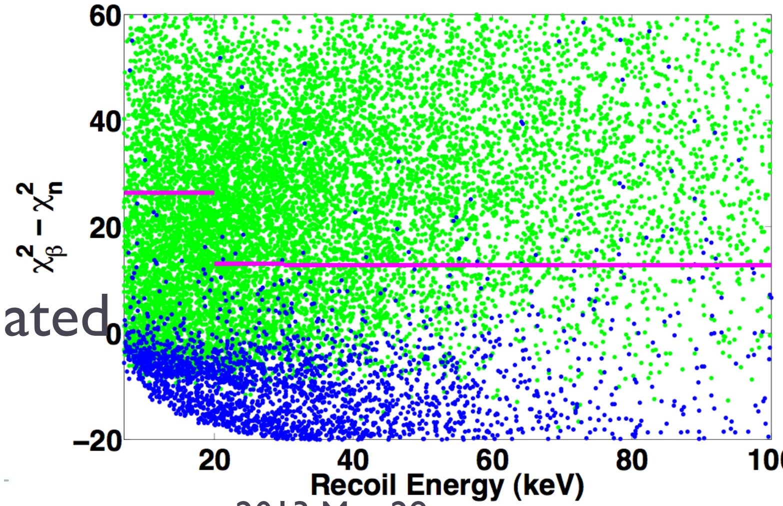


For lighter WIMPs, lighter nuclei win due to more efficient energy transfer

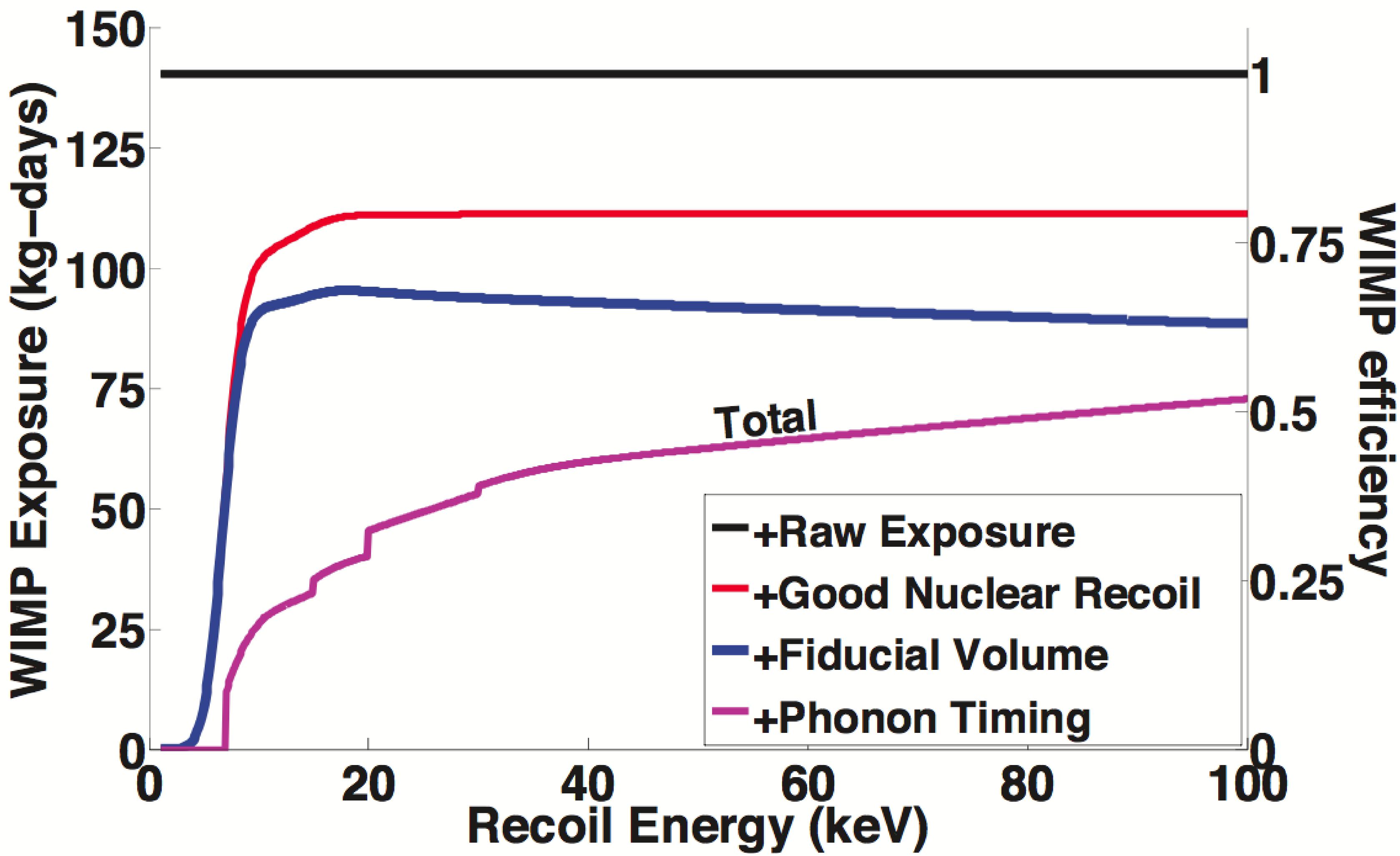
Background Estimate

- Neutrons
  - Indistinguishable from WIMPs!
  - Cosmogenic: active veto
  - Radiogenic: passive shielding & materials screening
  - <0.13 expected events
- Surface events
  - Discriminate using phonon timing
  - Optimize in 3 energy bins
  - 0.47 expected events estimated before unblinding.



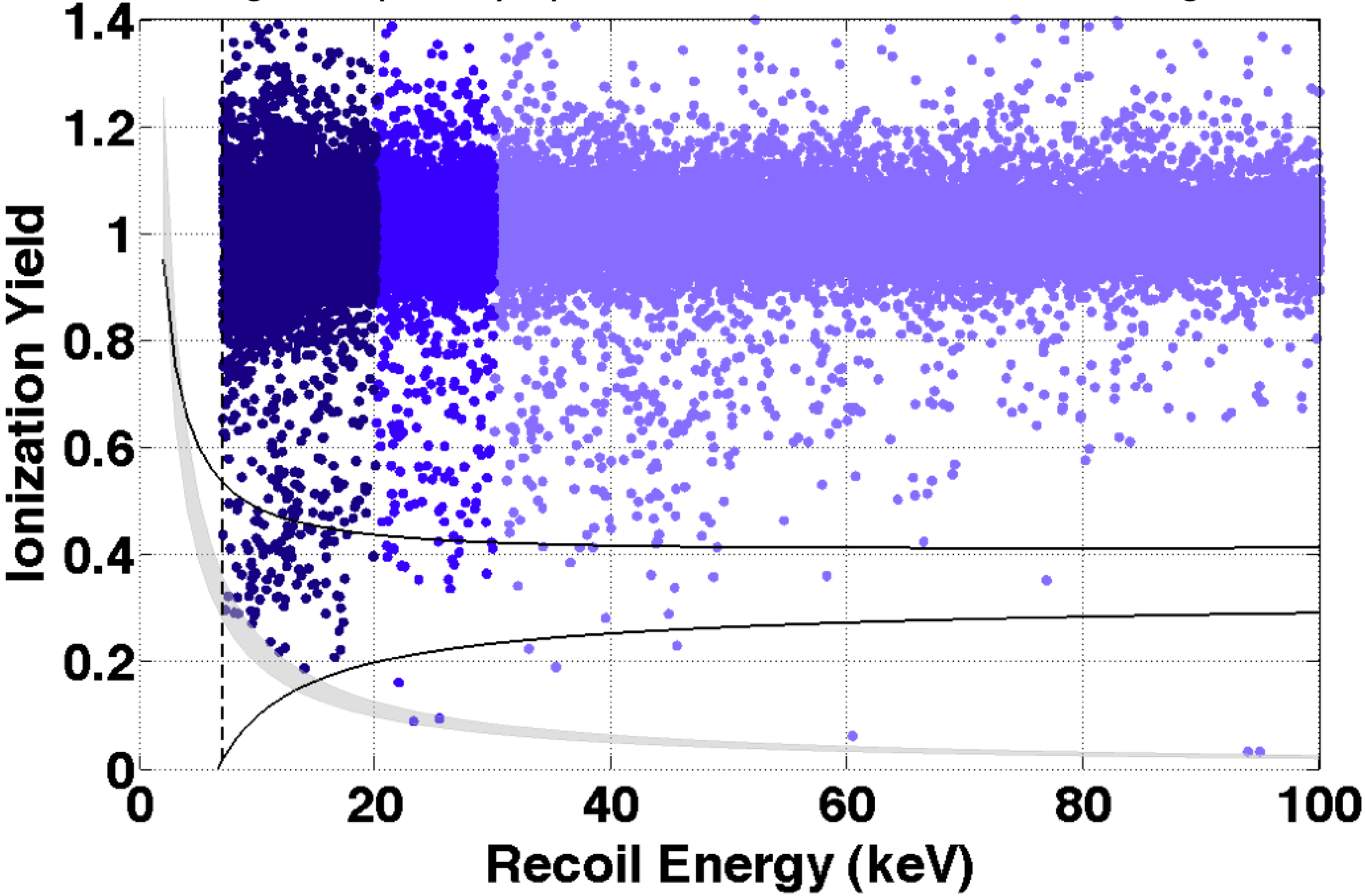


Exposure vs. Recoil Energy



Unblinding Results - before timing cut

Timing cut separately optimized in 10-20,20-30,>30 keV ranges



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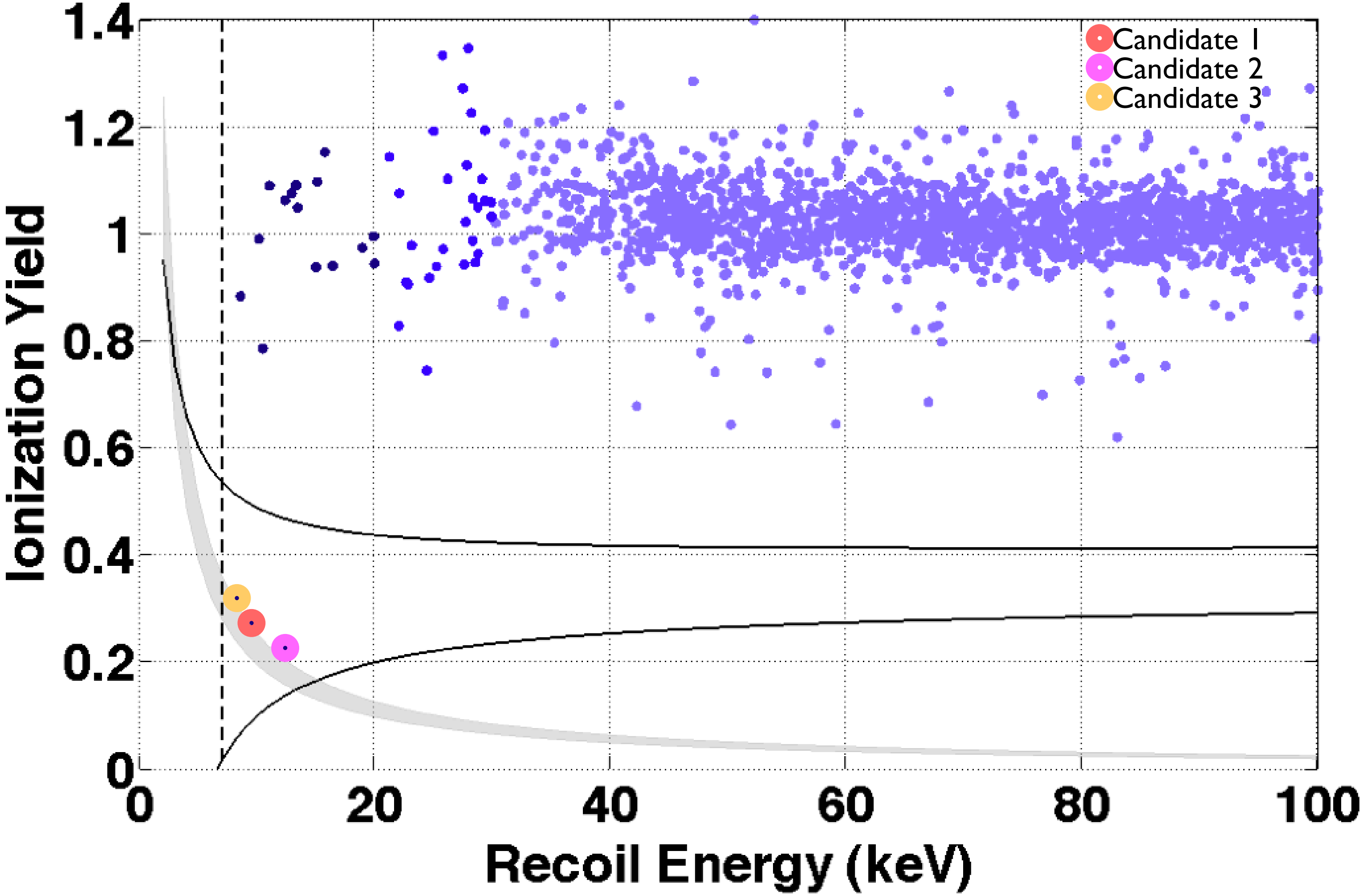
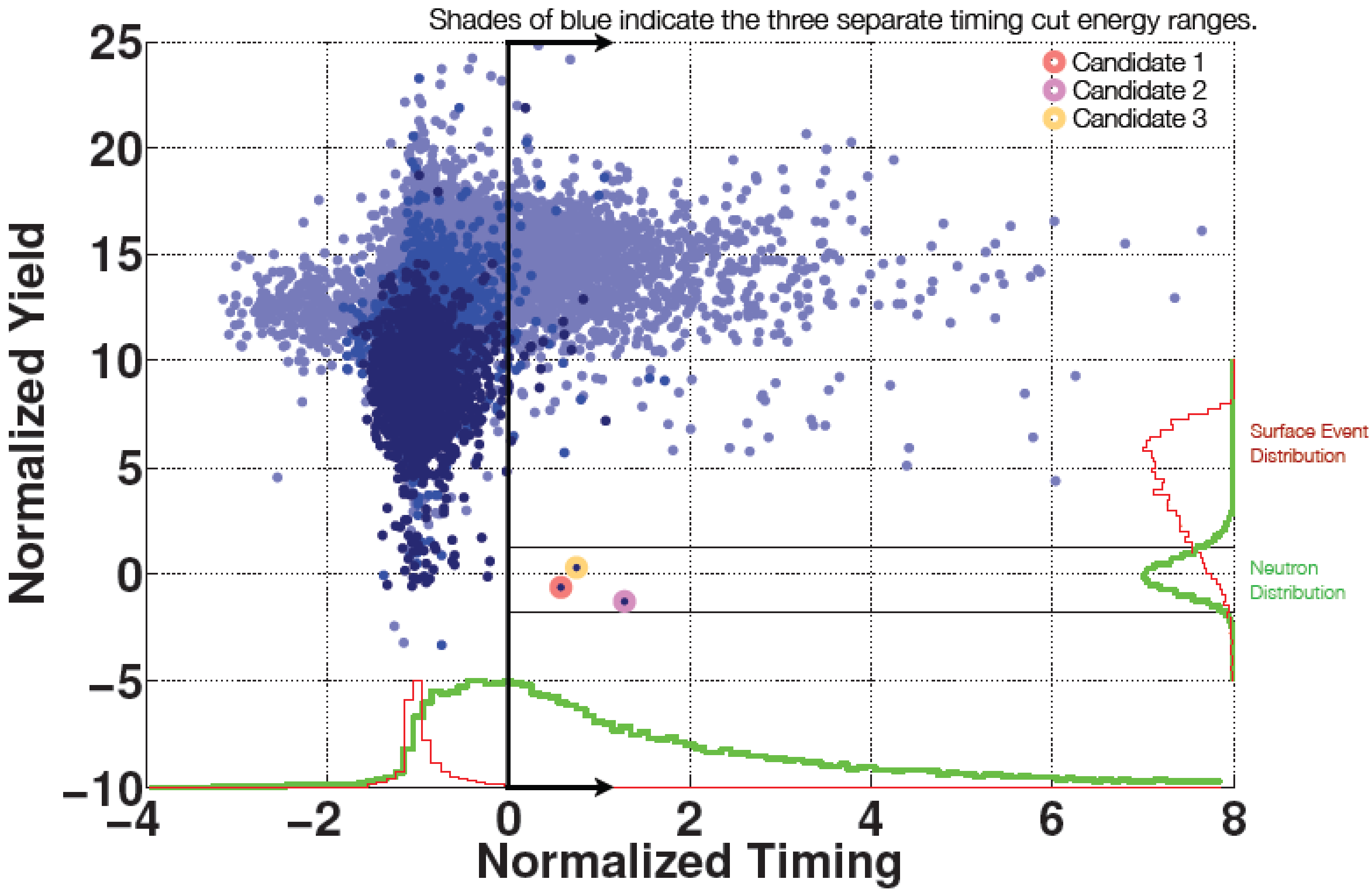
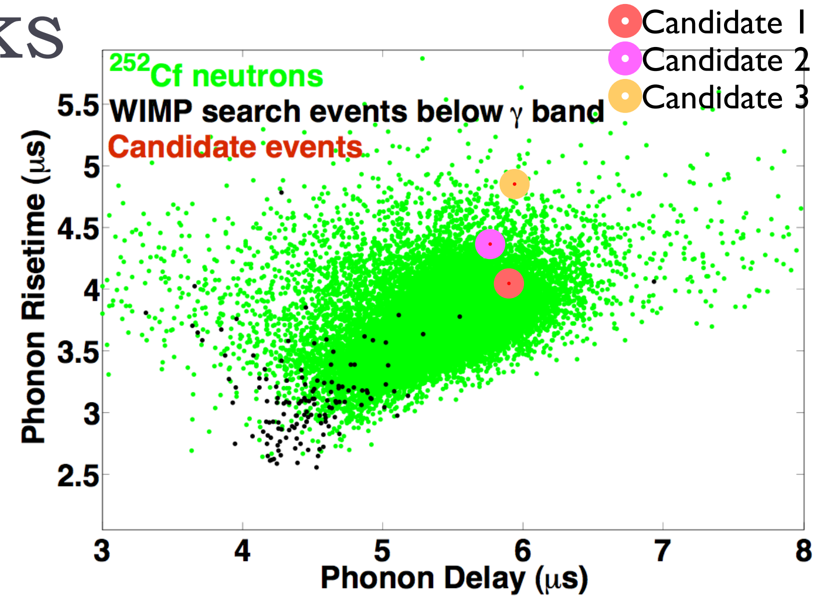


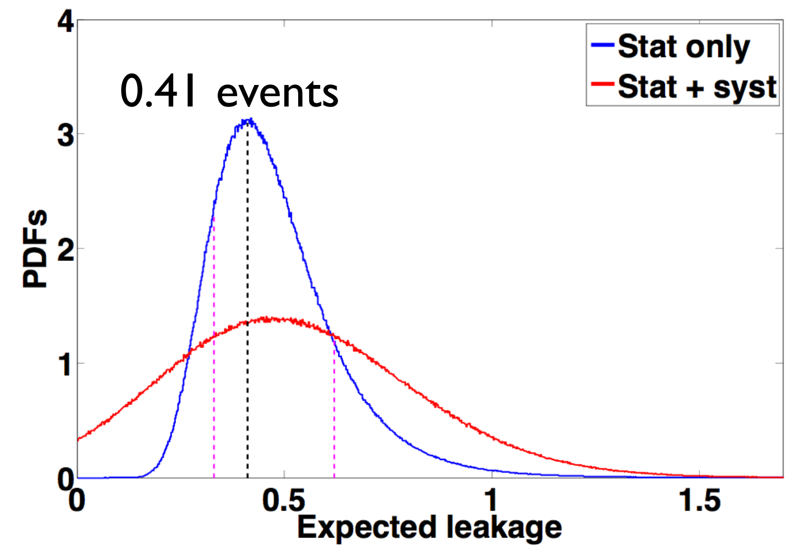
Three events!



Post-Unblinding Checks

- After unblinding, the data quality was re-checked.
  - Events occurred during high-quality data series
  - Events were well-reconstructed
  - Checked energy in other detectors to verify events were single scatters
- Surface event background fully estimated from the tails of three different NR sideband distributions
  - 0.41 (-.08 +.20 stat.) (-.24 +.28 syst.)
- Checked for the possibility of ^{206}Pb recoils from ^{210}Po decay, and limited this to be <0.08 events.





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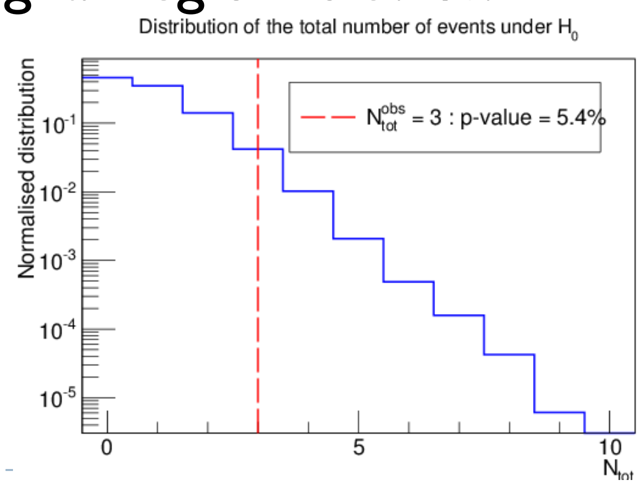
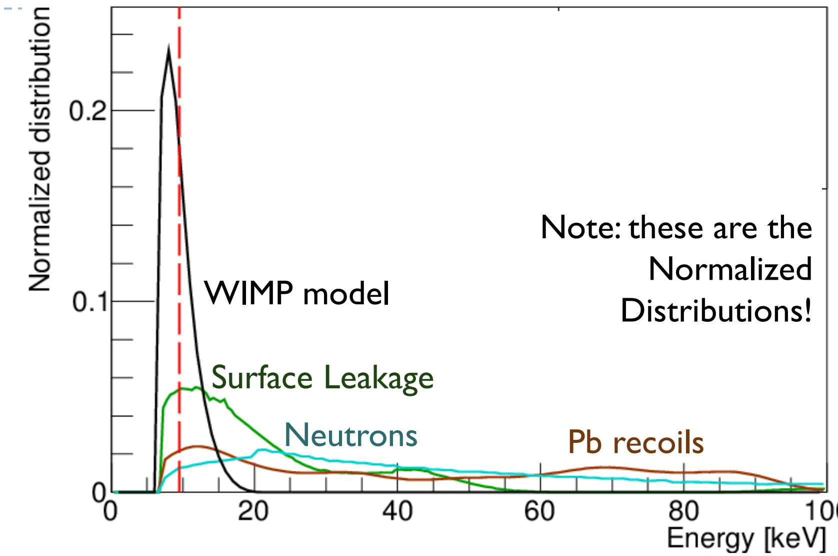
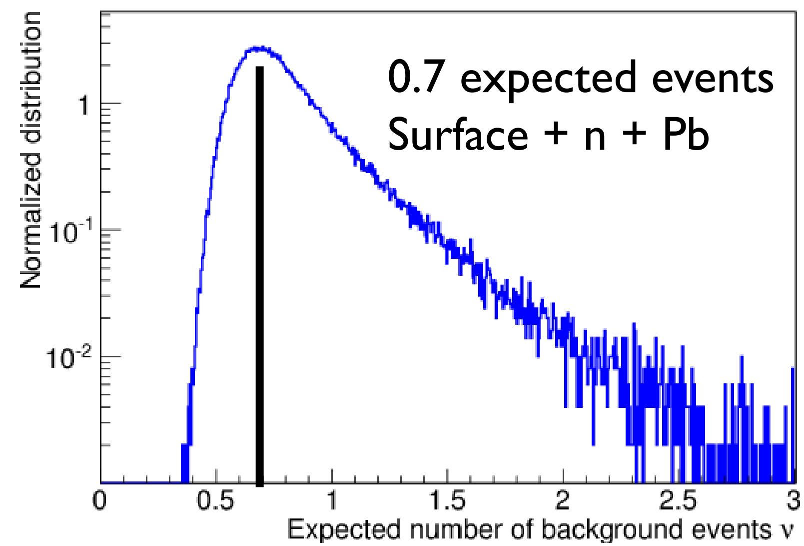
Profile Likelihood Analysis

- 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%.



Tower 4, Detector 3



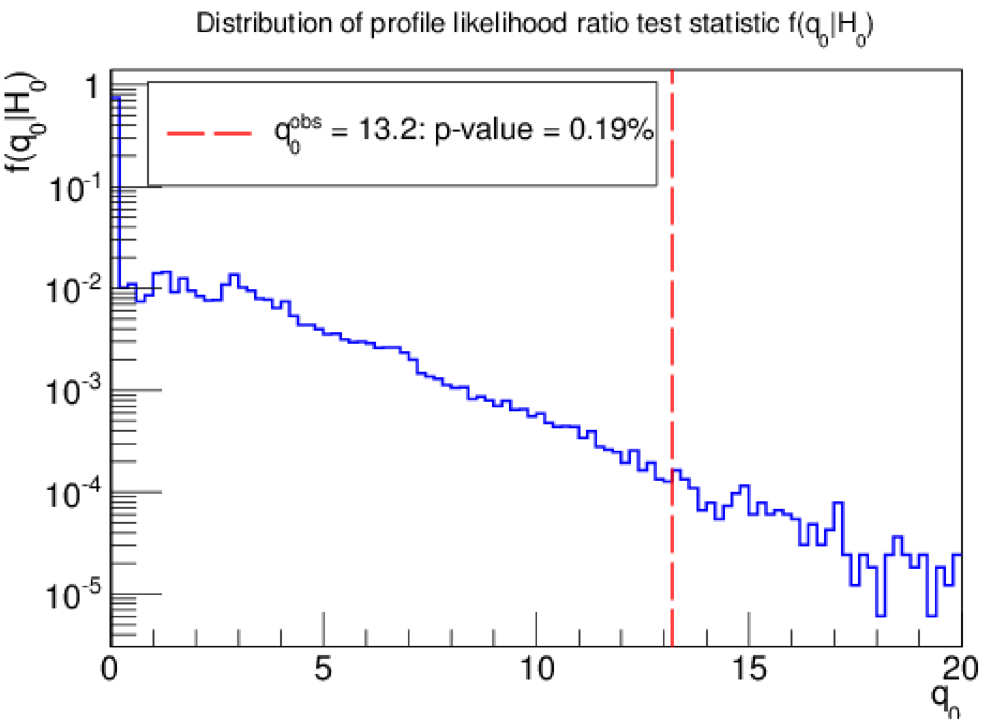


Profile Likelihood Analysis - cont.

Testing our known background estimate against a WIMP+background hypothesis

- 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 (~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.

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



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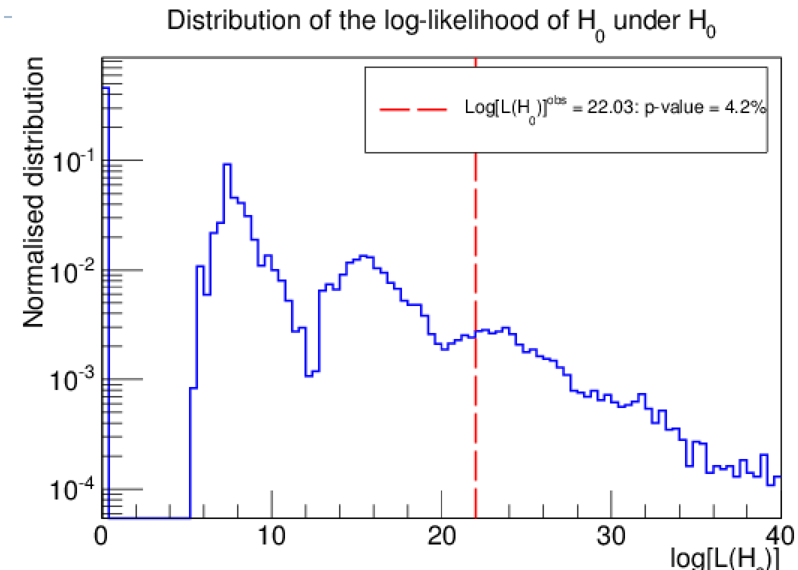
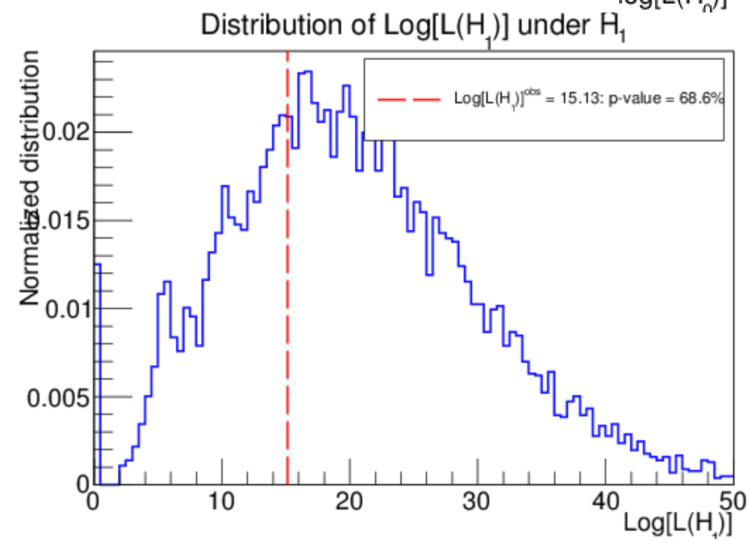
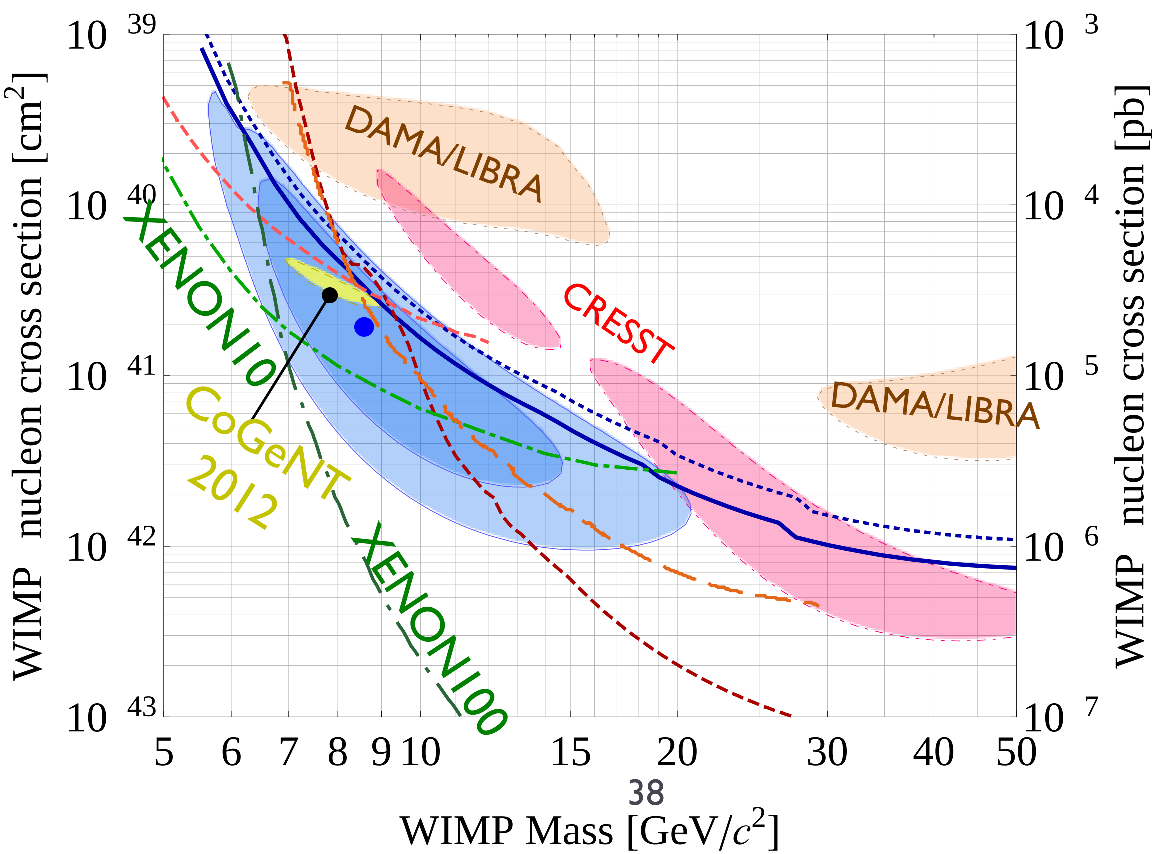
Profile likelihood goodness of fit

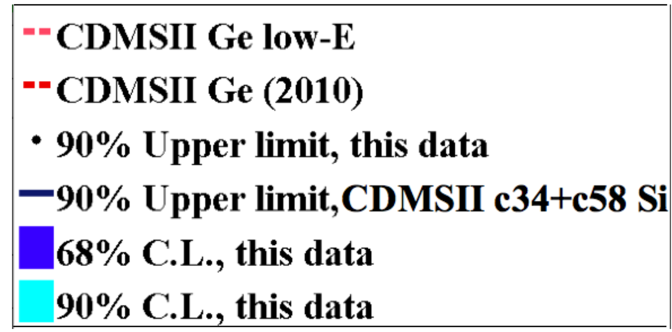
- WIMP+background is preferred over background alone to high significance, but is it a good fit?
- Goodness of fit for known-background-only hypothesis is 4.2%
- Goodness of fit for WIMP+background hypothesis is 68.6%





Confidence intervals



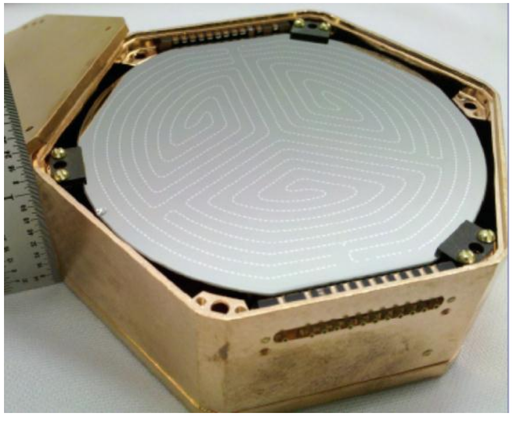


- ~3σ significance does not meet significance for discovery
- But it does merit more investigation!

What's next? SuperCDMS

- iZIP: interleaved phonon and charge sensors on both sides

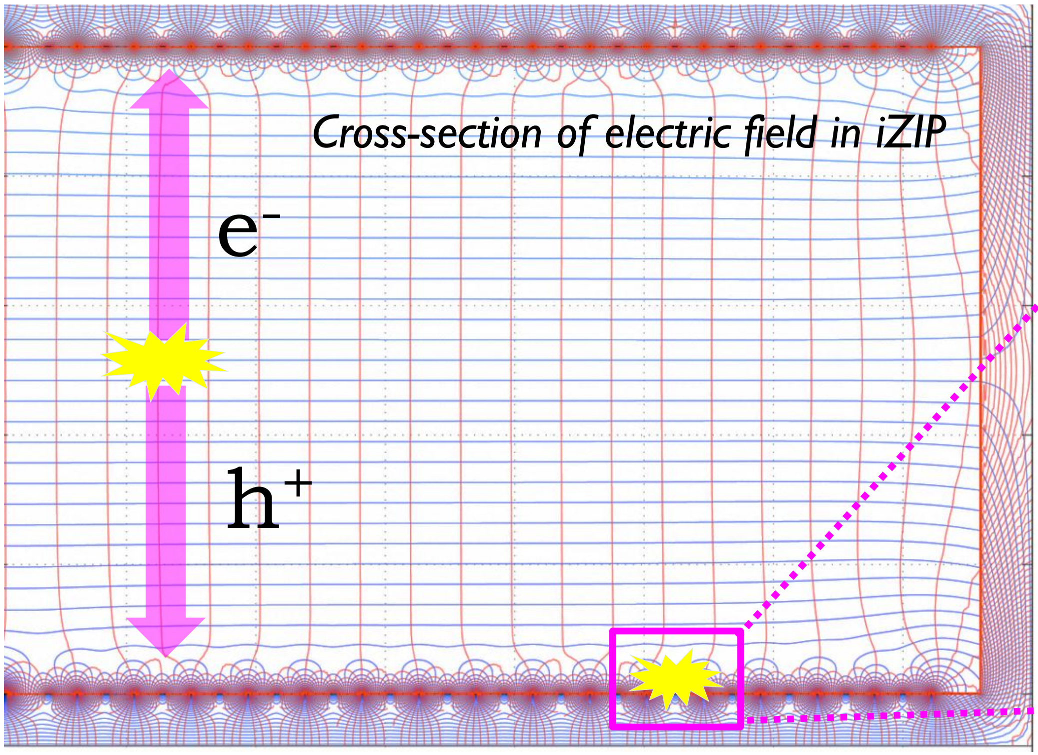
7.6cm X 1cm
CDMSII ZIP
~2000 – '09



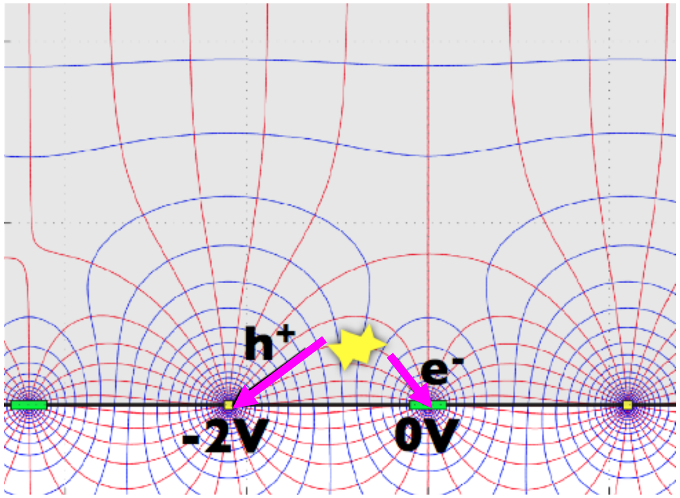
7.6cm X 2.5cm
SuperCDMS iZIP
~2011 – '13

10cm X 3.8cm SNOLAB
prototype iZIP
starting ~2015?

Surface events a thing of the past?



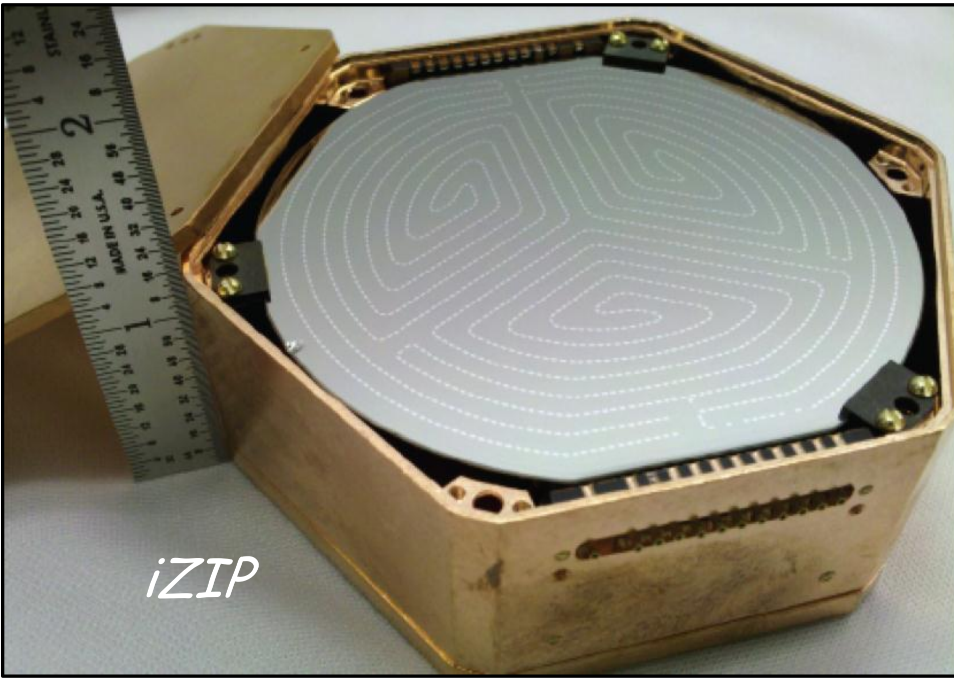
iZIPs have > 30X better surface event rejection w/ 50% better efficiency to WIMPs

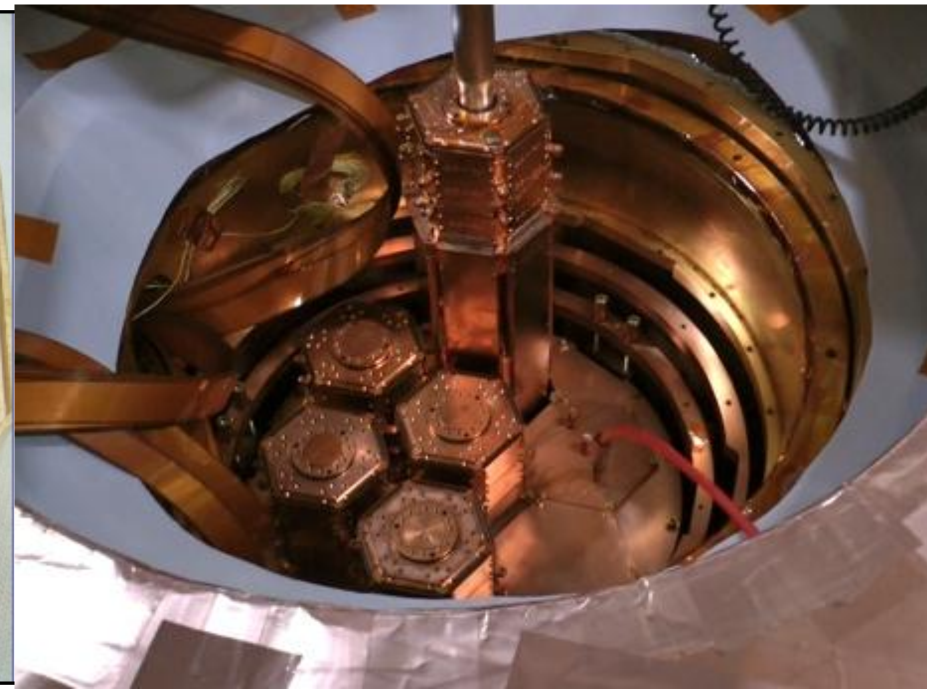


SuperCDMS Soudan

9 kg of Ge arranged in 5 towers (15 iZIPs)

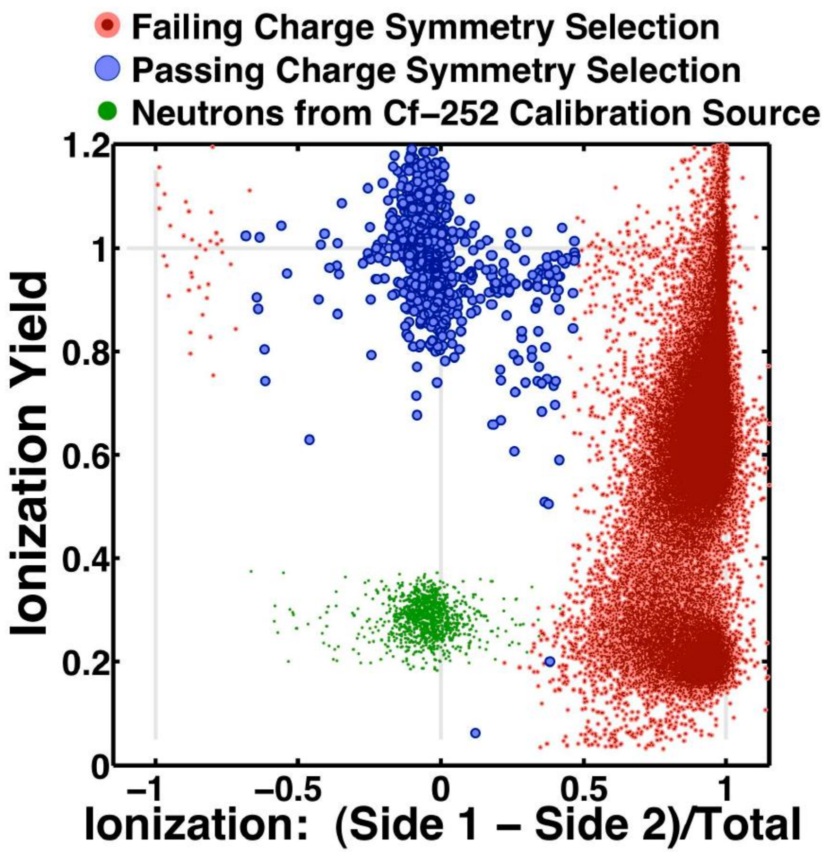
running time of ~2 years - data collection since March 2012

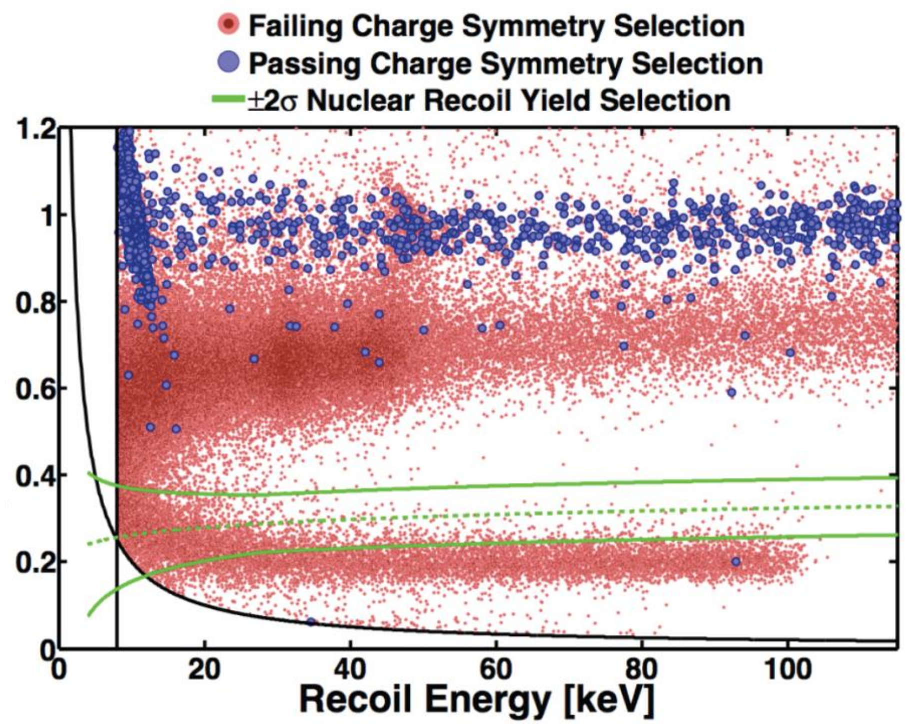




2 iZIPs outfitted with ^{210}Pb source to study surface event rejection with high statistics

Surface events a thing of the past?

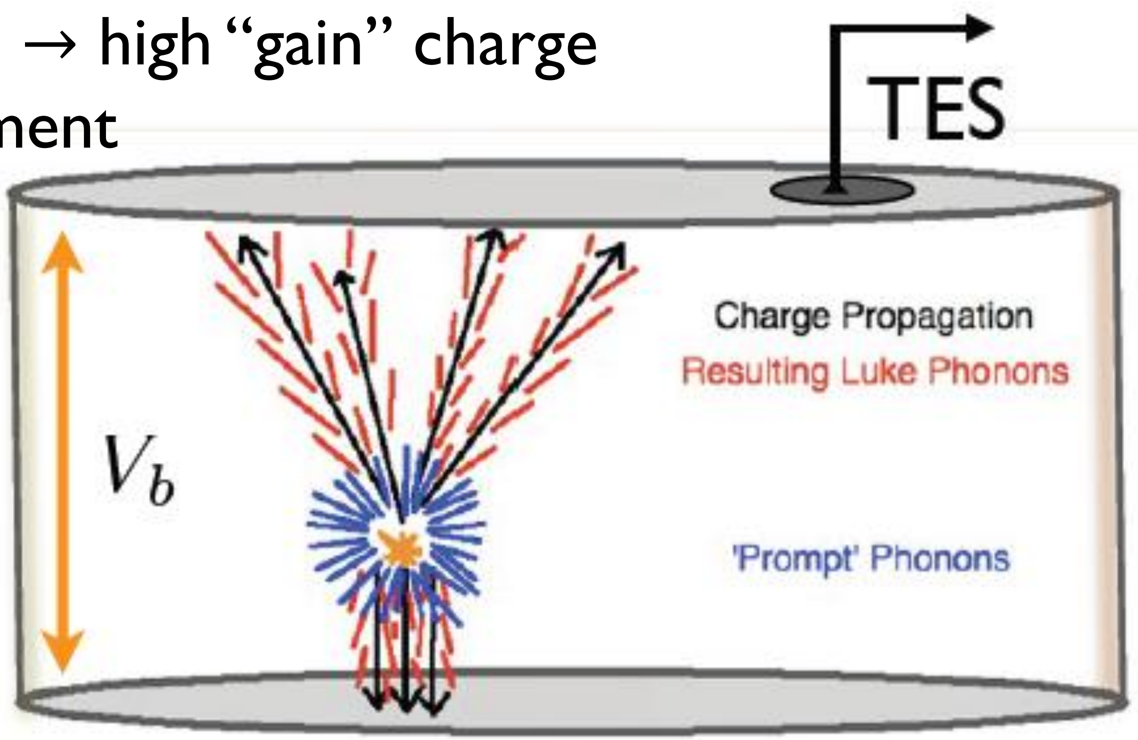




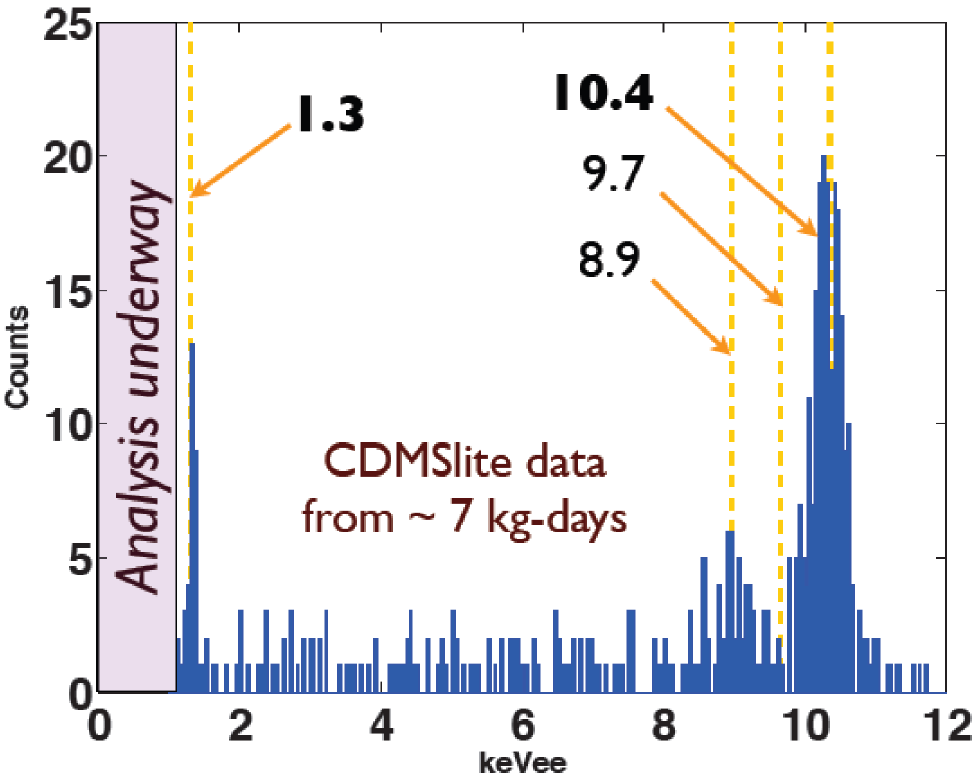
Data from Pb-210 surface source shows 0 leaked events with 80,000 surface events ($<2.5\times10^{-5}$ 90% CL) with 60% nuclear recoil acceptance

CDMSlite
low ionization threshold experiment

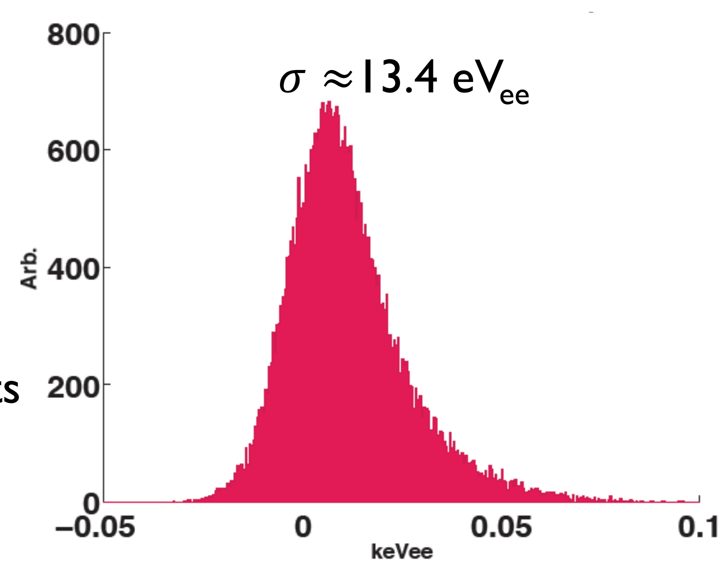
- Electrons/holes propagating in crystal reach "terminal velocity"
- Excess energy from bias field transferred to lattice as Luke phonons
- High field → high "gain" charge measurement



CDMSlite: extend WIMP search to sub-keV

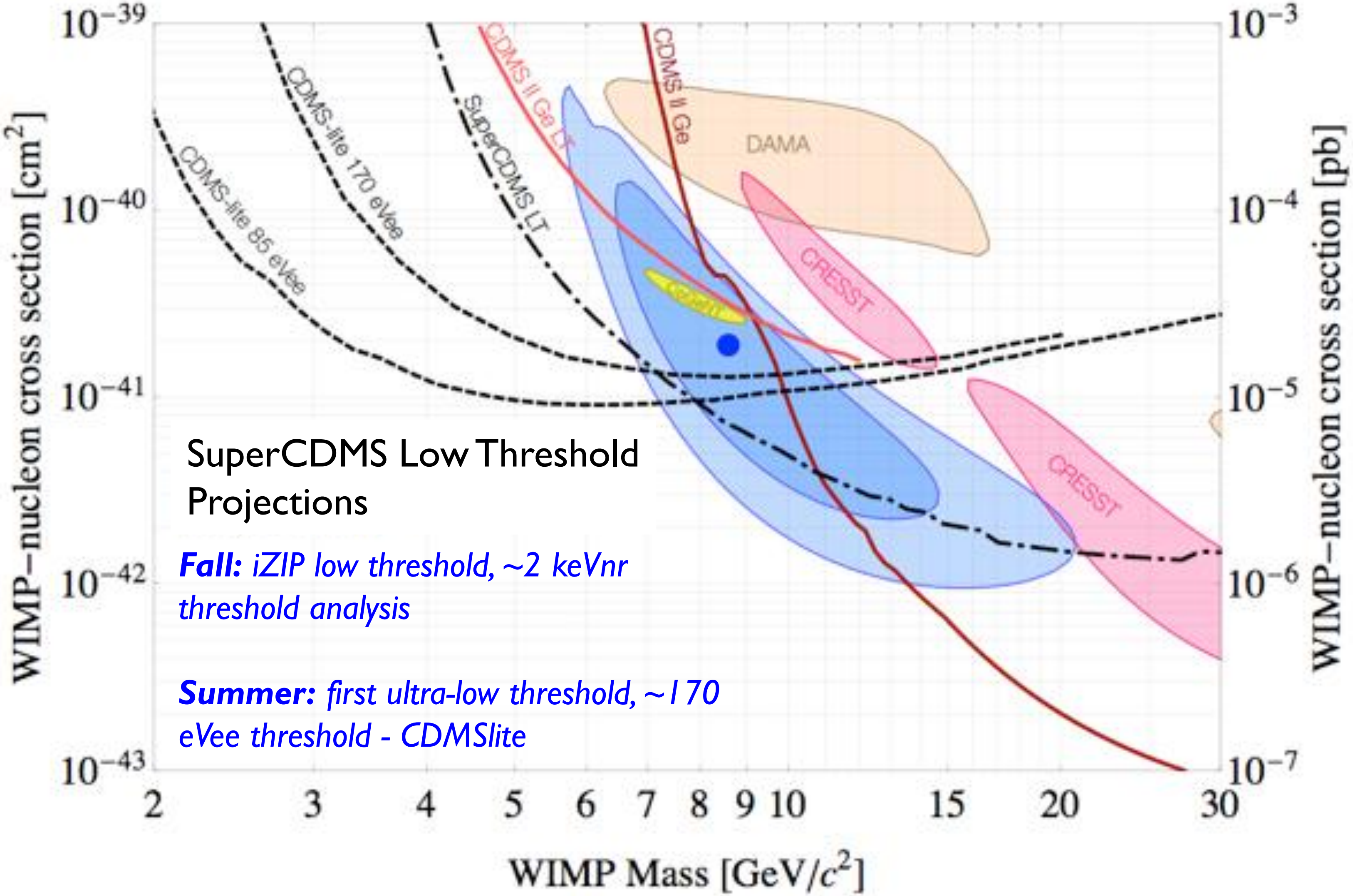


Sharp peaks from neutron capture lines (3.3% for 1.3 keV line) show gain functioning



Minimal increase in noise with increasing bias.
RMS of baseline noise indicates smallest possible events
Hope to achieve ~170 eV_{ee} threshold

Future prospects

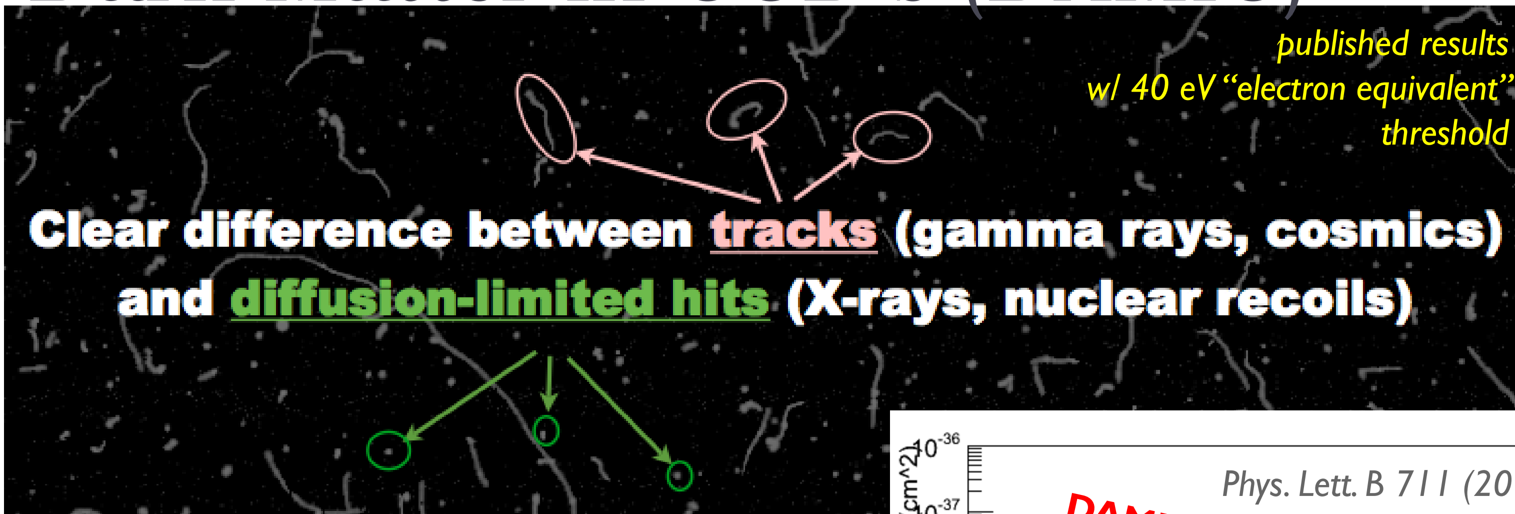


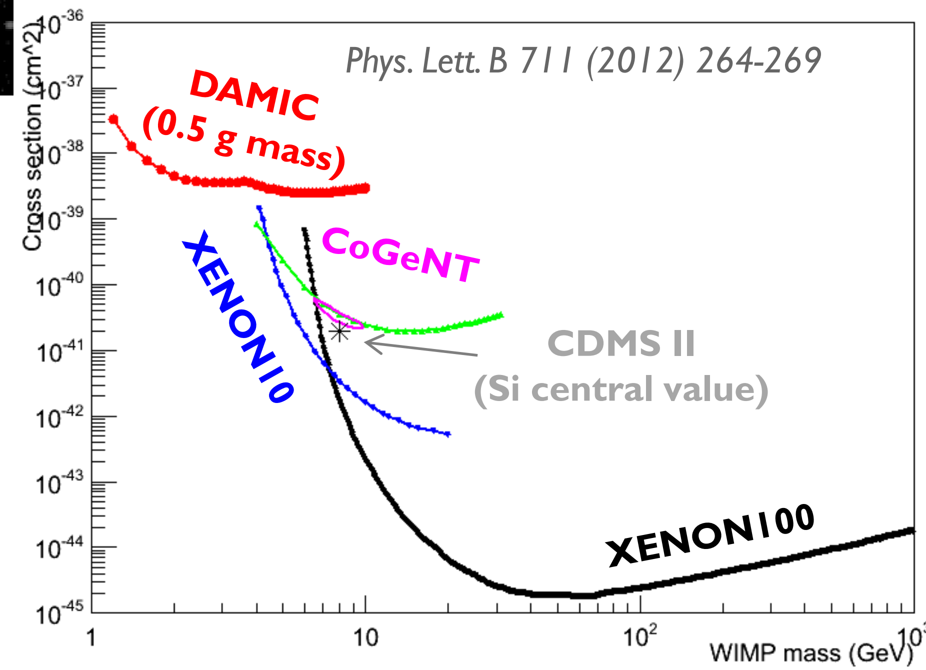
SuperCDMS Low Threshold Projections

Fall: *iZIP low threshold, ~2 keVnr threshold analysis*

Summer: *first ultra-low threshold, ~170 eVee threshold - CDMSlite*

Dark Matter in CCD's (DAMIC)



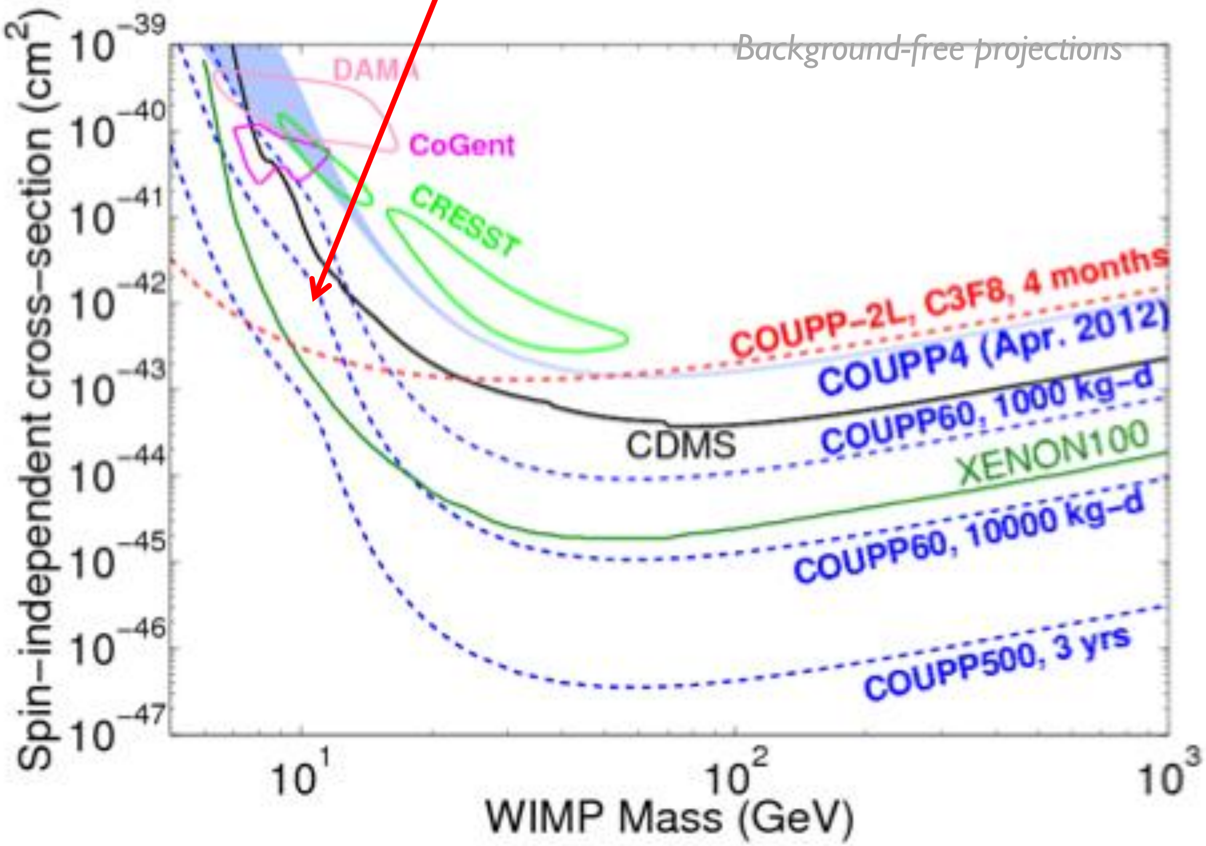


Aside from CDMS, the only other direct detection experiment with a Si target, but with significantly different technology!

DAMIC100 will have 100g of target and could see O(100) events per year for 8.6 GeV/c^2 WIMP and $\sigma = 2\times10^{-41}$cm^2

"COUPP-4lite" (official name still under debate)

will replace target CF_3I fluid with C_4F_{10} to yield impressive sensitivity at low masses (and significant gains in spin-dependent sensitivities)

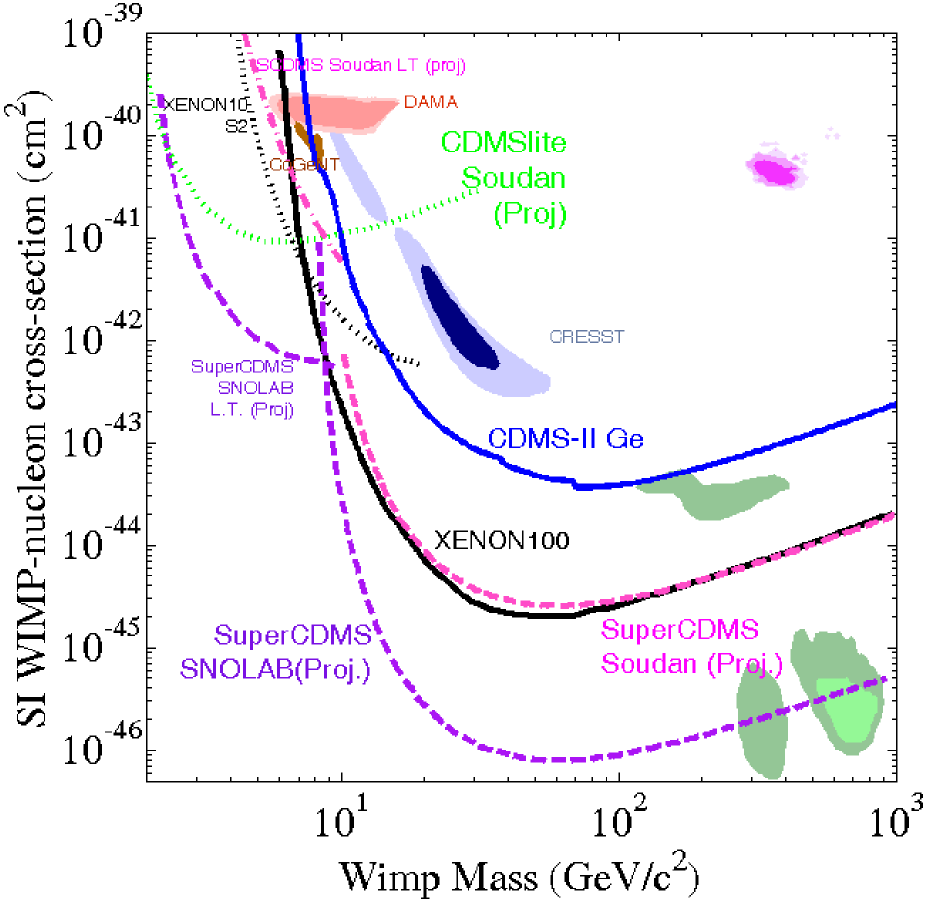


Operation beginning as soon as this summer?

Coming up next: SuperCDMS SNOLAB

Move to North America's deepest underground lab for >100X reduction in cosmogenic neutron backgrounds; deploy 200 kg of advanced Ge iZIPs

Now seriously considering including silicon iZIPs



Conclusions

- In 140.2 kg-days of silicon ZIP data, observed 3 events with an expected background of ~0.5 events
- P-value of likelihood for best fit known-backgrounds-only hypothesis is 4.2%
- A likelihood ratio test favors a background+WIMP hypothesis over background-only hypothesis at 99.81% confidence
- If interpreted as a WIMP, the best fit gives a mass of 8.6 GeV/c^2 and a spin-independent WIMP-nucleon scattering cross section of 1.9×10^{-41} cm^2
- Though not significant enough to be a "discovery", it's certainly an interesting region that needs further exploration, which we hope to do soon with SuperCDMS Soudan data

Thank you!

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