Direct Dark Matter Detection

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Outline for Today

- Part 2: Direct Detection Searches
    - Liquid Nobles
    - Cryogenic Detectors
    - Other Novel Technologies
    - Current and Future Landscape

Last Time:

EVENT RATES:

The differential event rate:

[counts kg^{-1} day^{-1}] $\longrightarrow$ (dru = differential rate unit)

local WIMP density

WIMP-nucleon scattering cross section

$$\boxed{\frac{dR}{dE_R} = \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma}{dE_R}(v, E_R) dv}$$

nucleus mass

WIMP mass

WIMP speed distribution in detector frame

need input from astrophysics, particle physics and nuclear physics

Minimum WIMP velocity which can cause a recoil of energy E_R.

$$\boxed{v_{min} = \sqrt{\frac{E_R m_N}{2\mu^2}}}$$

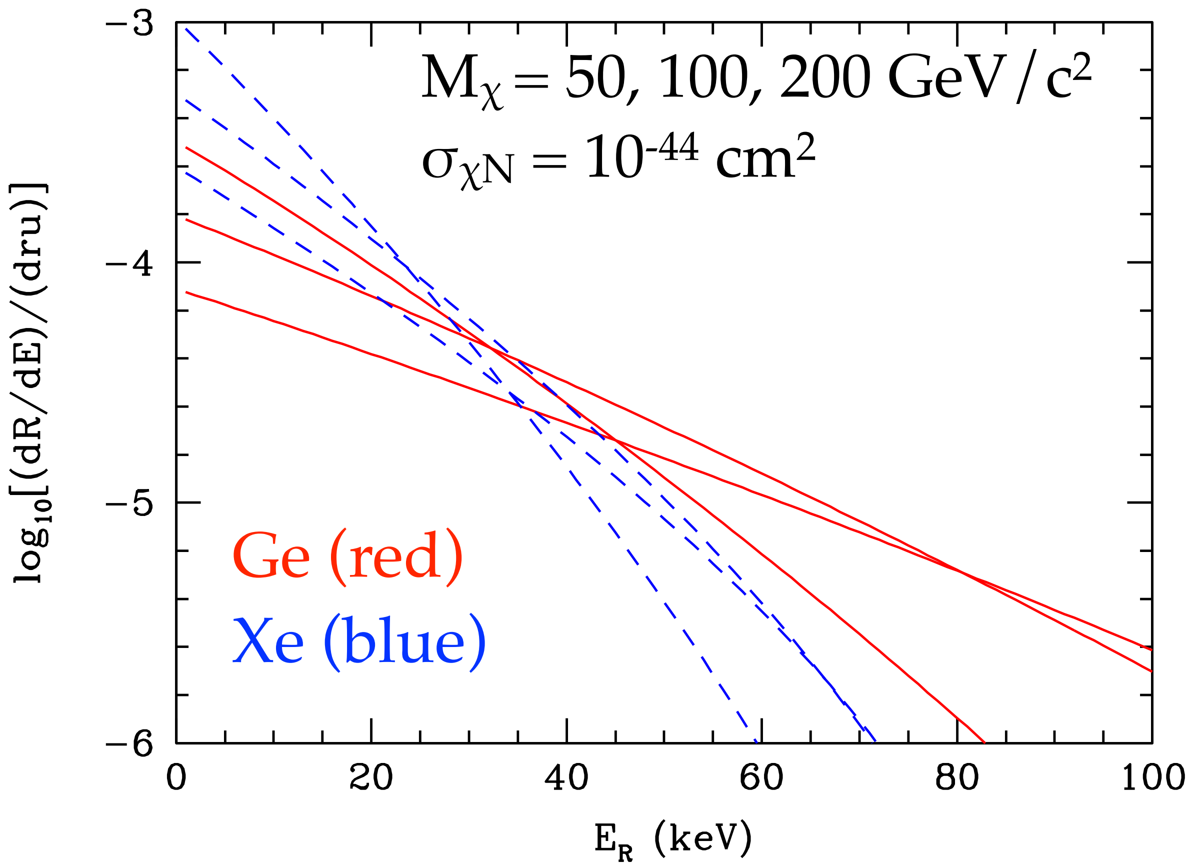
BACKGROUND MITIGATION:

- Active vetoes, passive shielding, purification, material selection
- Discrimination between ER and NR events

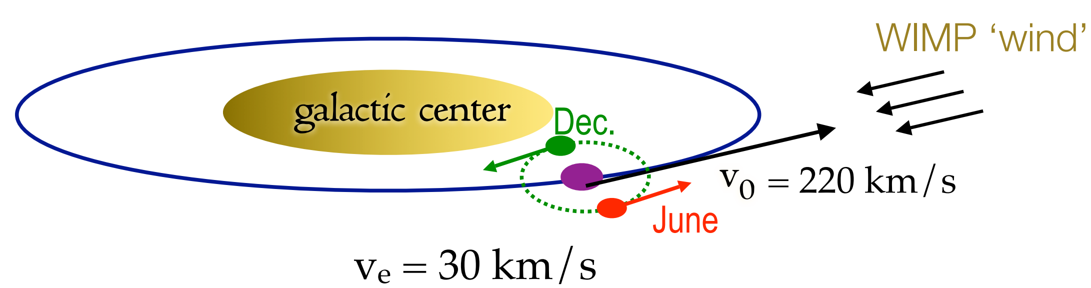
Last Time:

CHARACTERISTICS OF SIGNAL:

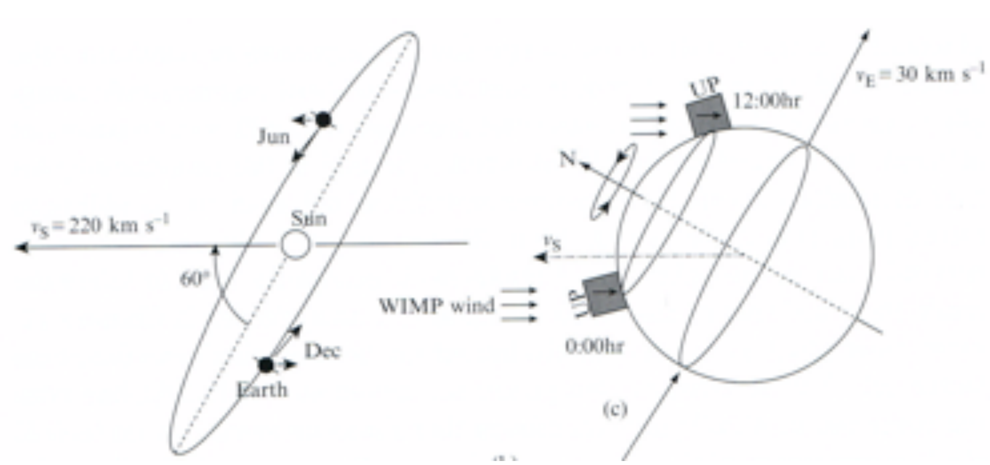
Energy:



Modulation:



Direction:

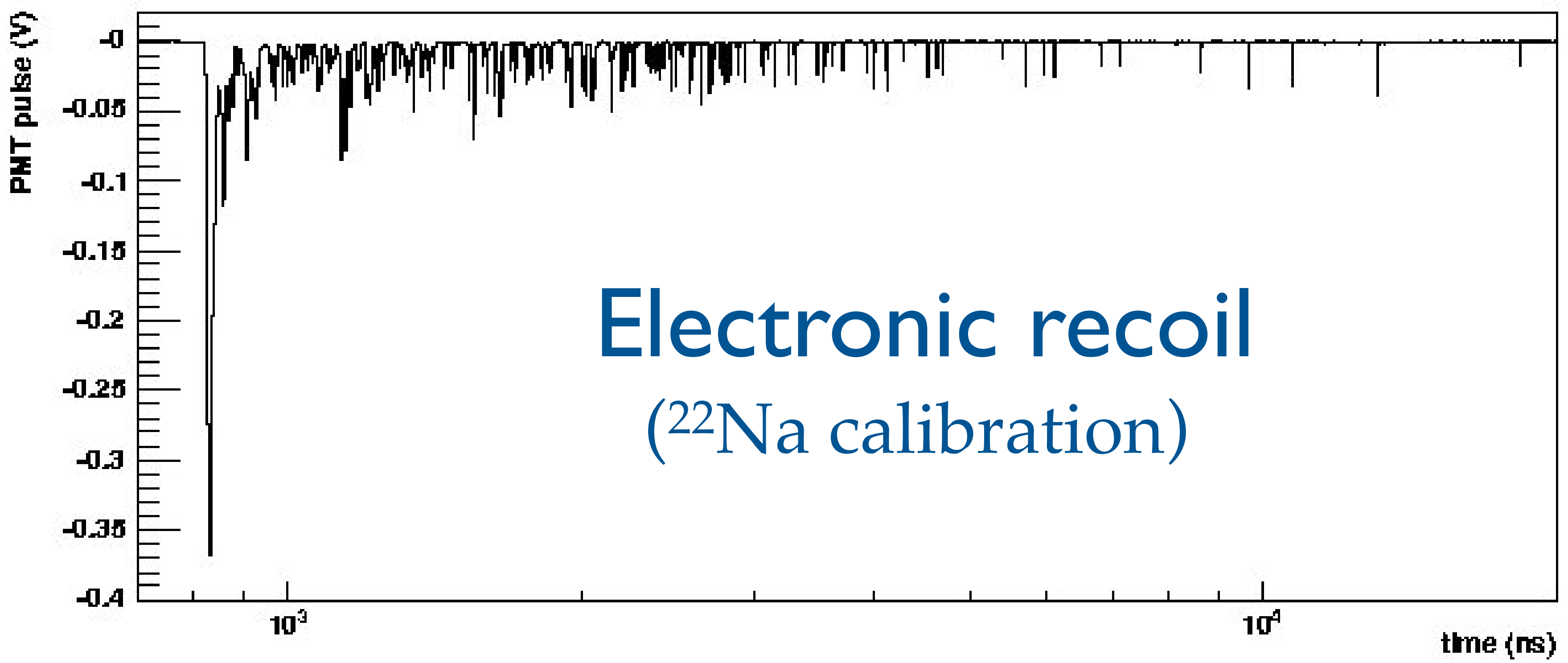


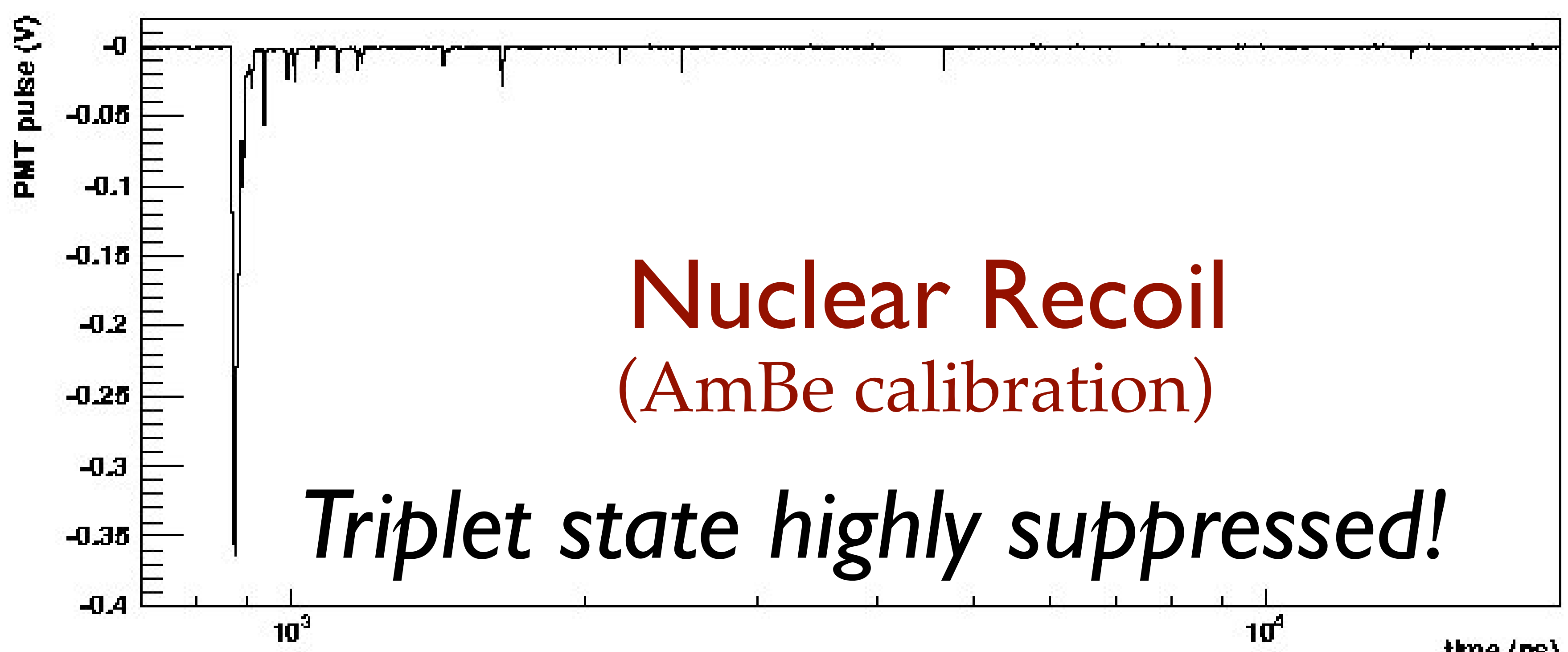
Last Time:

SINGLE PHASE:

- Early singlet state and delayed triplet state.
- The triplet state is highly suppressed for nuclear recoils.

	Singlet	Triplet
Ne	< 18.2 ns	14.9 μs
Ar	7ns	1.6 μs
Xe	4.3 ns	22 ns





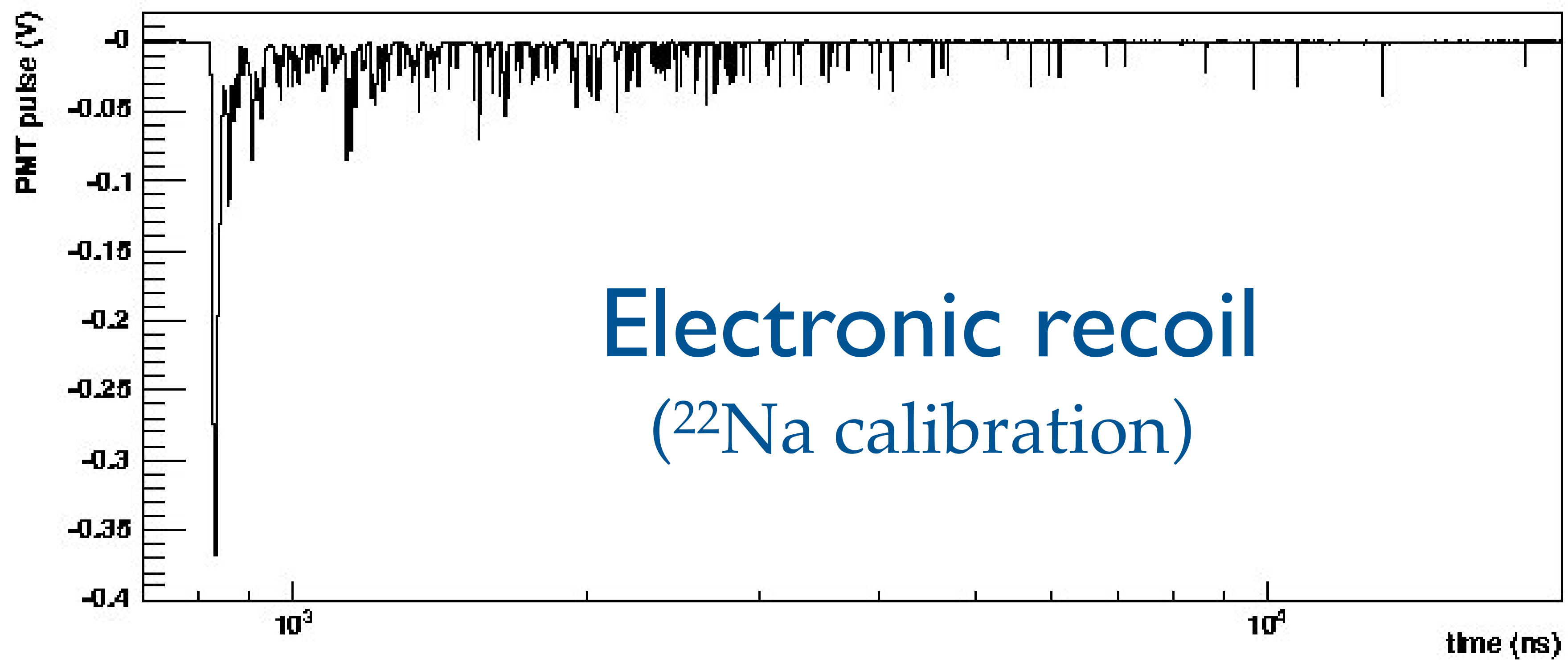
Triplet state highly suppressed!

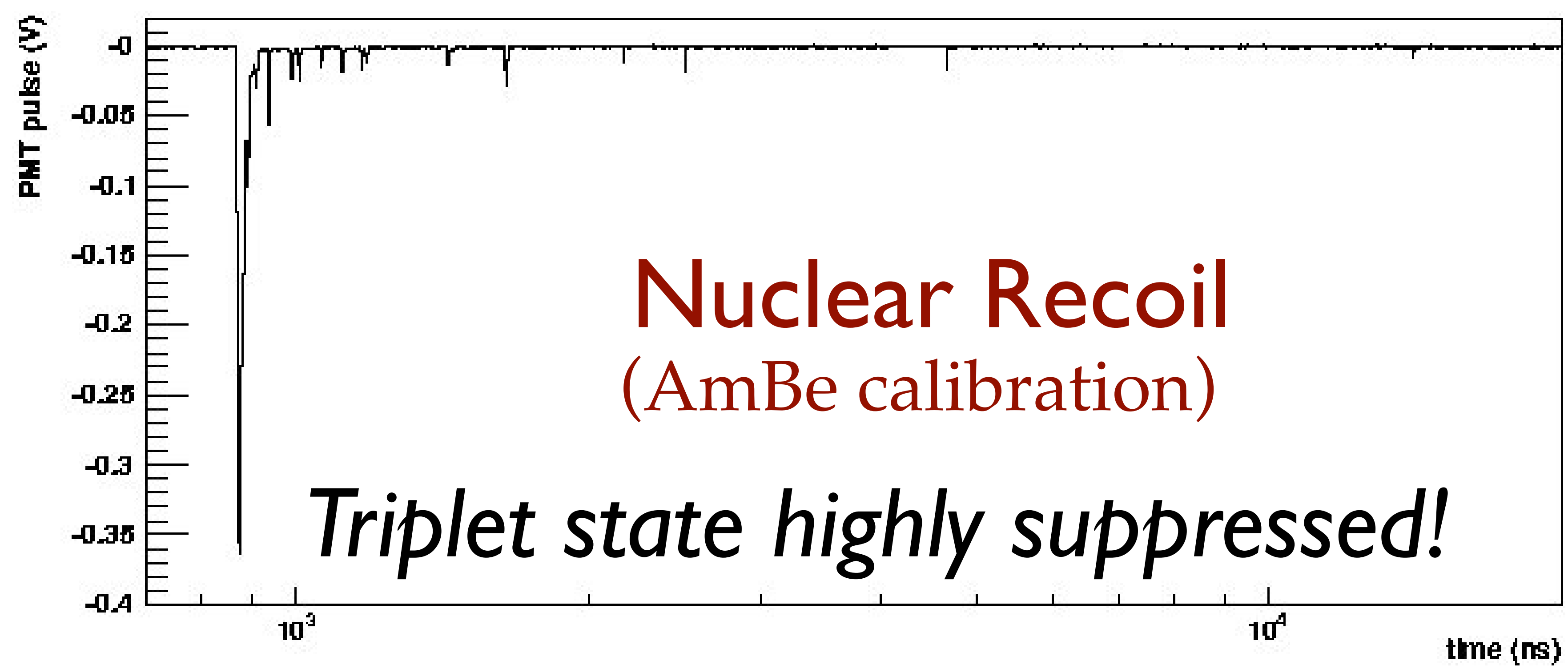
Last Time:

SINGLE PHASE:

- Early singlet state and delayed triplet state.
- The triplet state is highly suppressed for nuclear recoils.

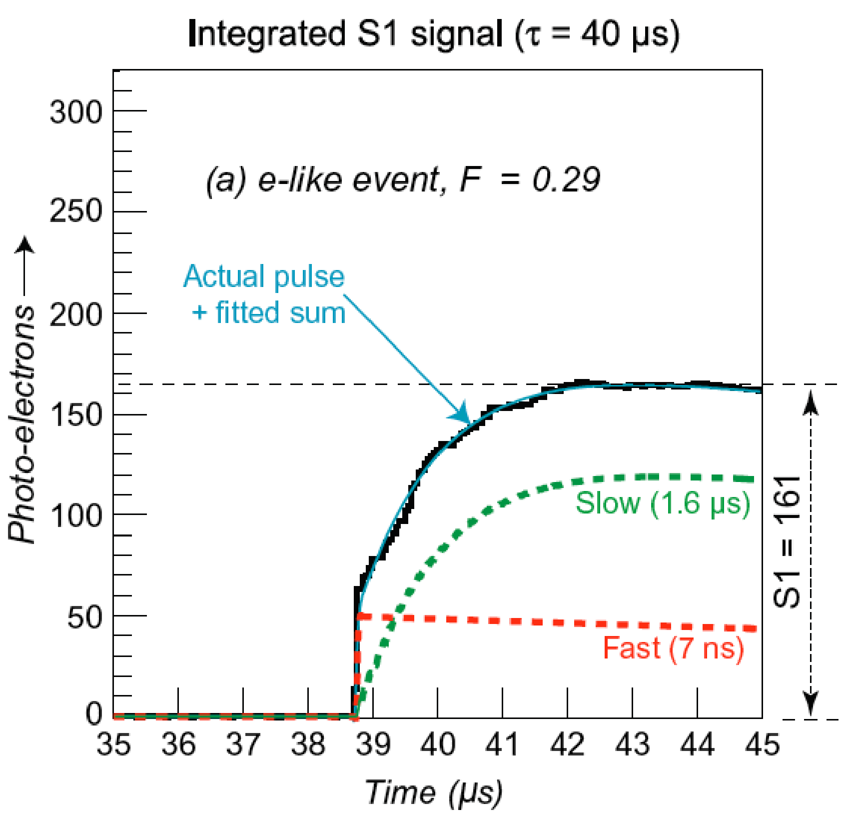
	Singlet	Triplet
Ne	< 18.2 ns	14900 ns
Ar	7ns	1600 ns
Xe	4.3 ns	22 ns



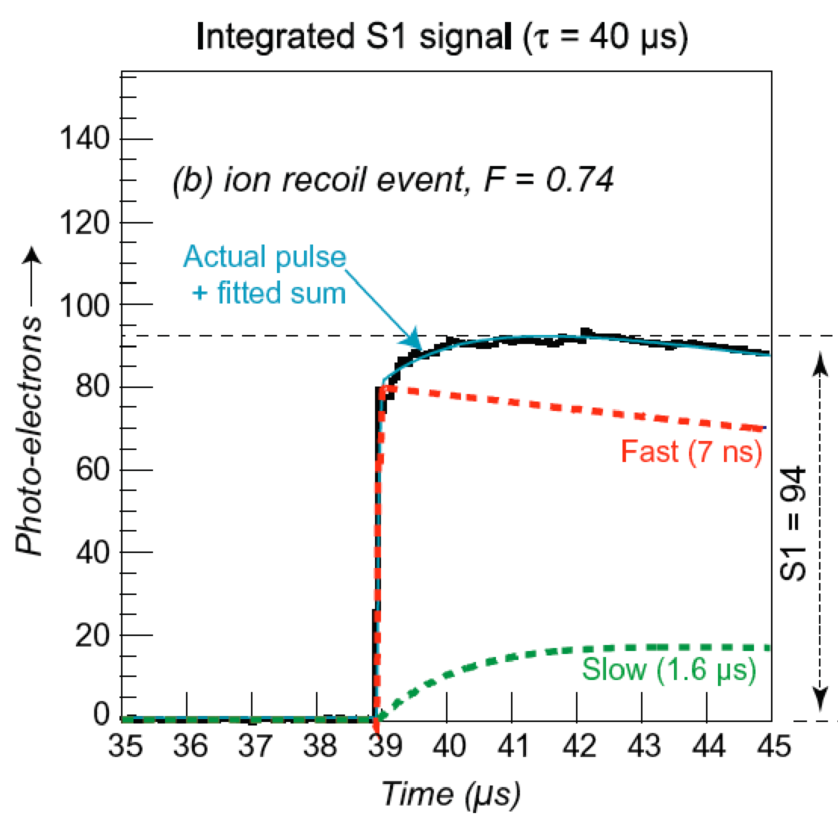


Last Time:

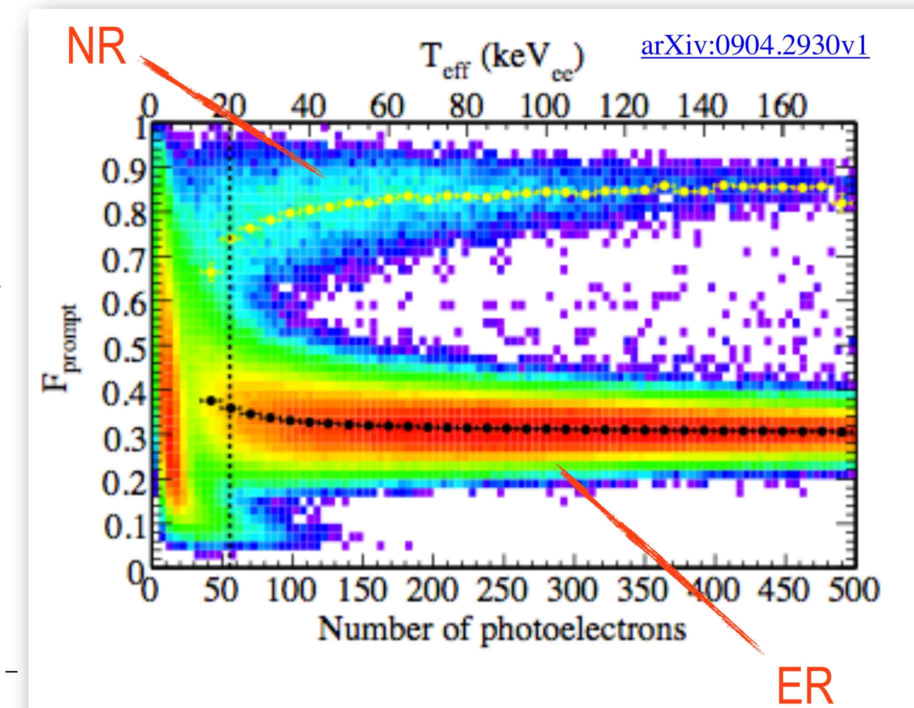
PULSE SHAPE DISCRIMATION:



(a)



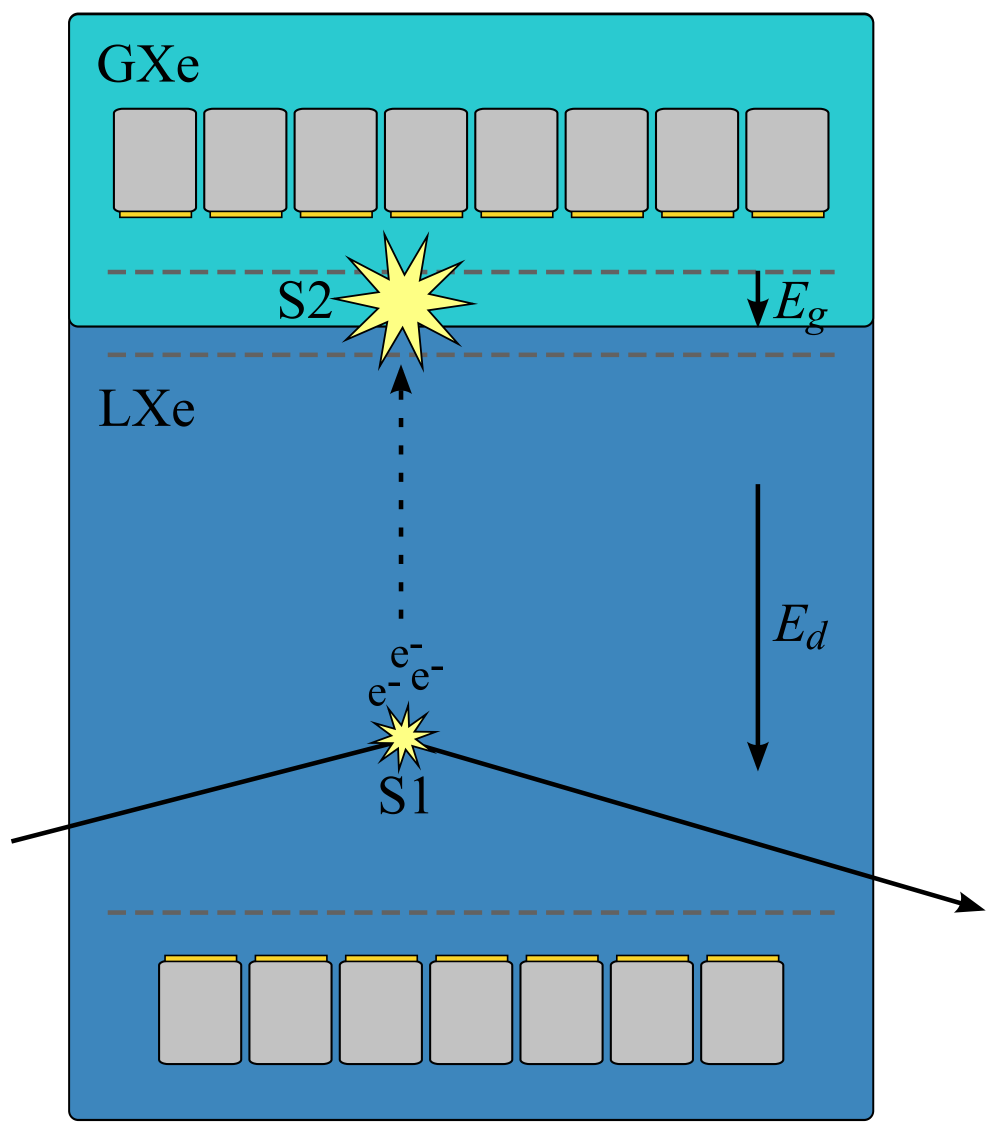
(b)

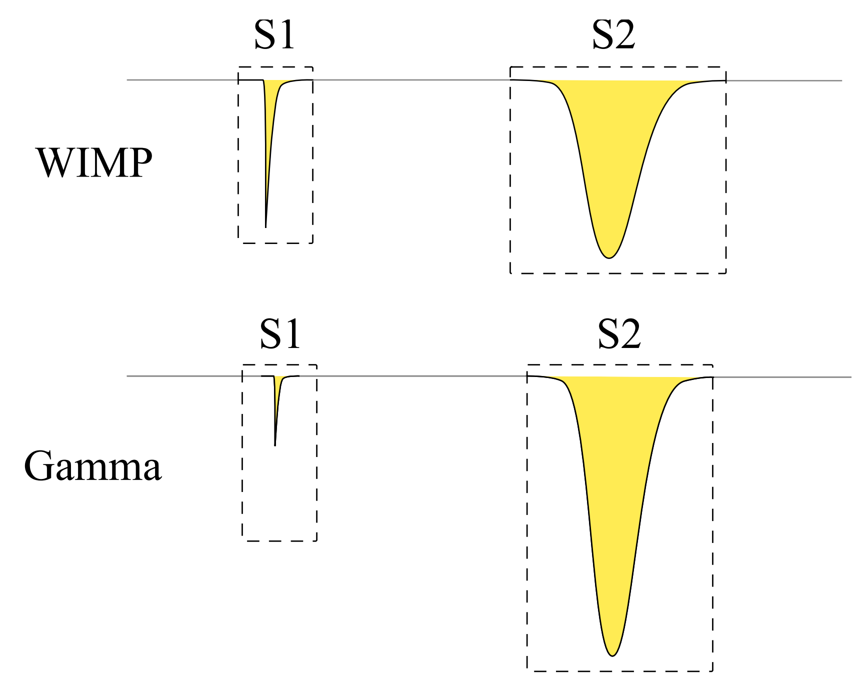


- 70% of excimer states created by nuclear recoils are singlets
- 30% of excimer states created by electron recoils are triplets

Last Time:

DUAL PHASE LIQUID NOBLES:





Energy

Nuclear recoils are measured through a combination of scintillation light and ionization. The nuclear recoil energy is related to S1 by

observed scintillation [PE]

[keV_{nr}]

$$E_{nr} = \frac{S1}{L_y L_{eff}} \times \frac{S_e}{S_r}$$

suppression of scintillation signal from electric field for ER and NR events

light yield [PE/keVee]

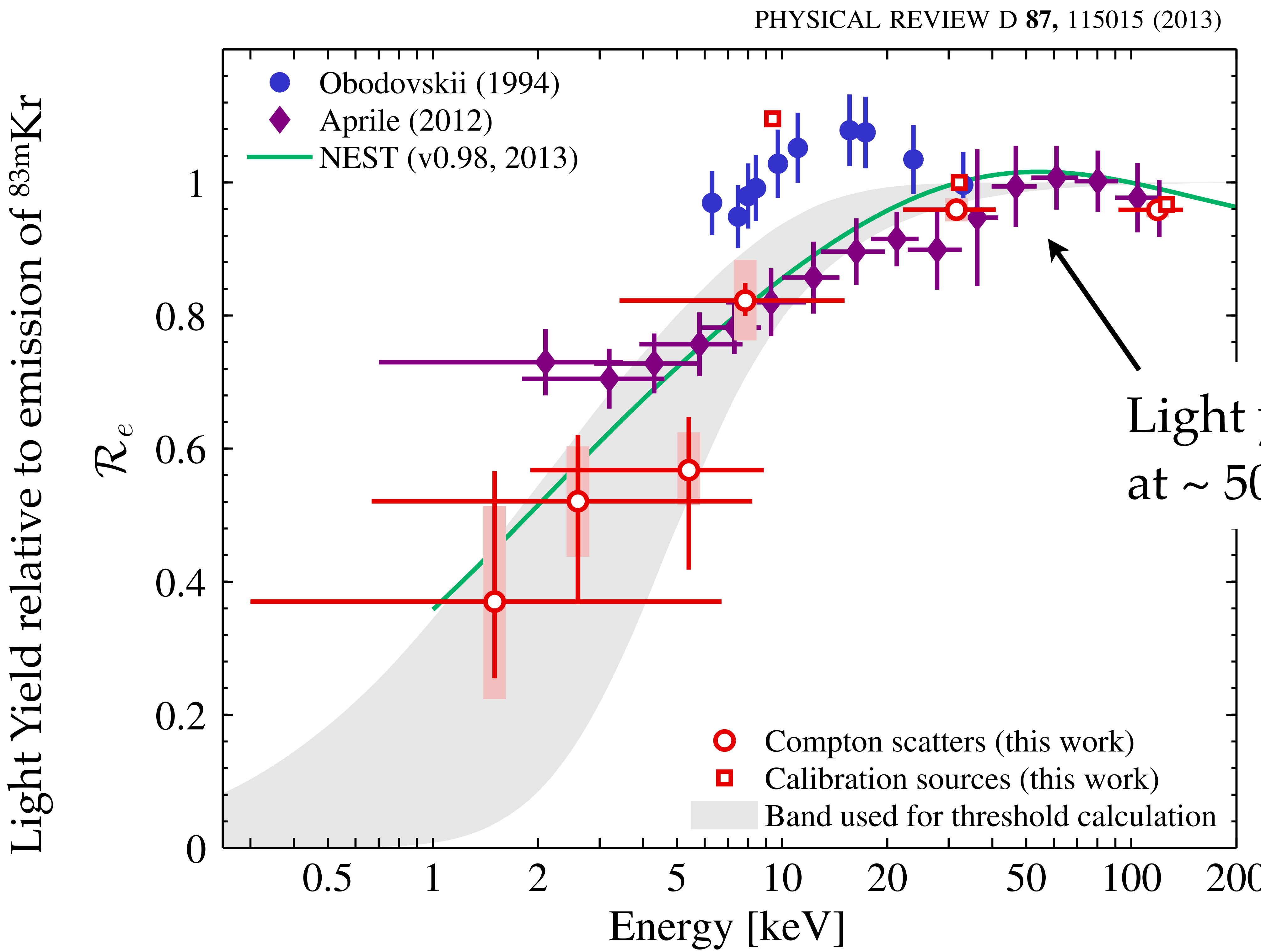
scintillation efficiency of NR in LXe

L_{eff} accounts for the quenching of the scintillation signal for a nuclear recoil.

$$L_{eff} \equiv \frac{S1(E_{nr})/E_{nr}}{S1(122keV_{ee})/122keV_{ee}}$$

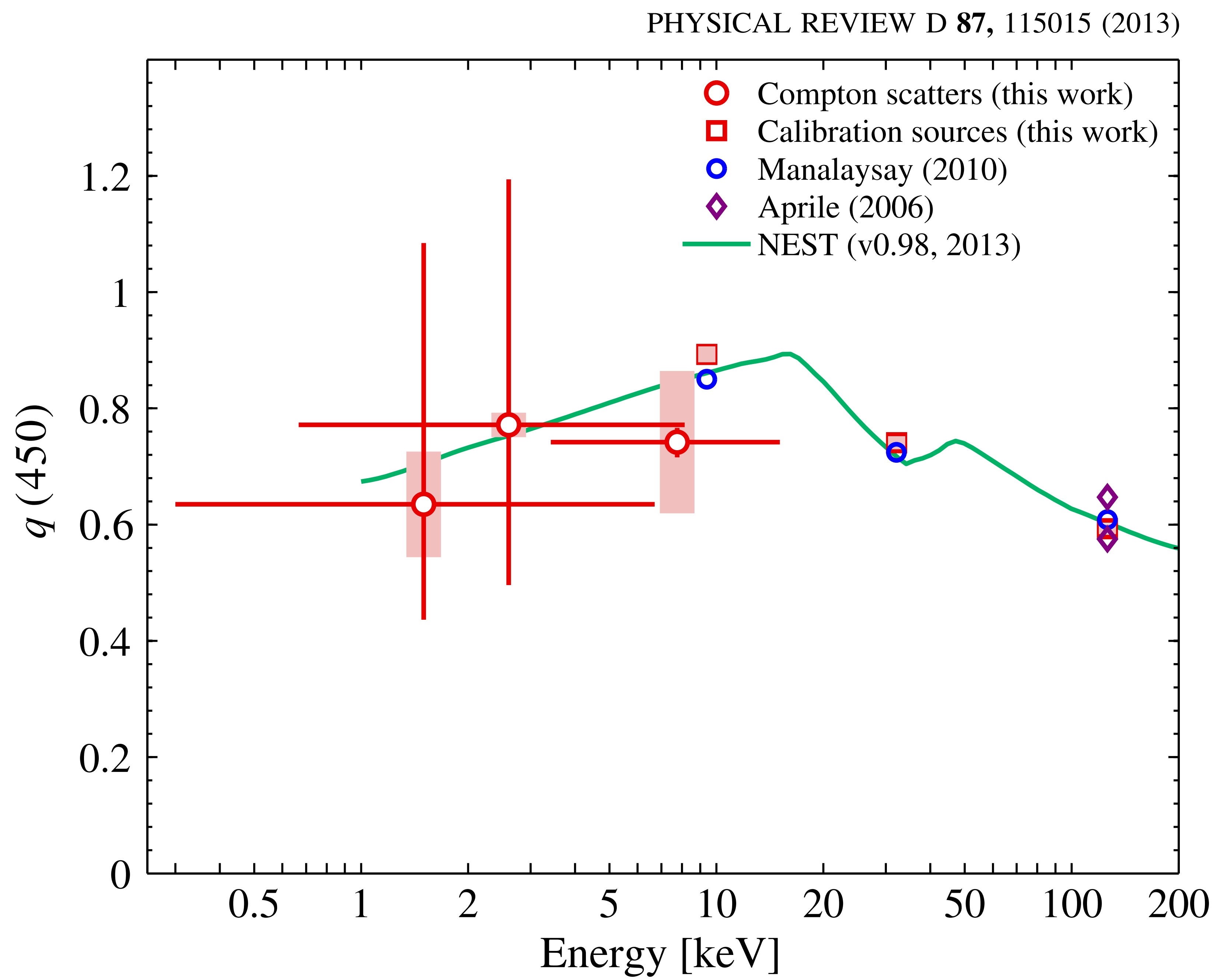
122 γ line from ^{57}Co source

Light Yield - Zero Electric Field



Light yield decreases at ~ 50 keV

Quenching Due to Electric Field



Energy - Continued

The nuclear recoil energy is related to S2 by

observed
scintillation [PE]

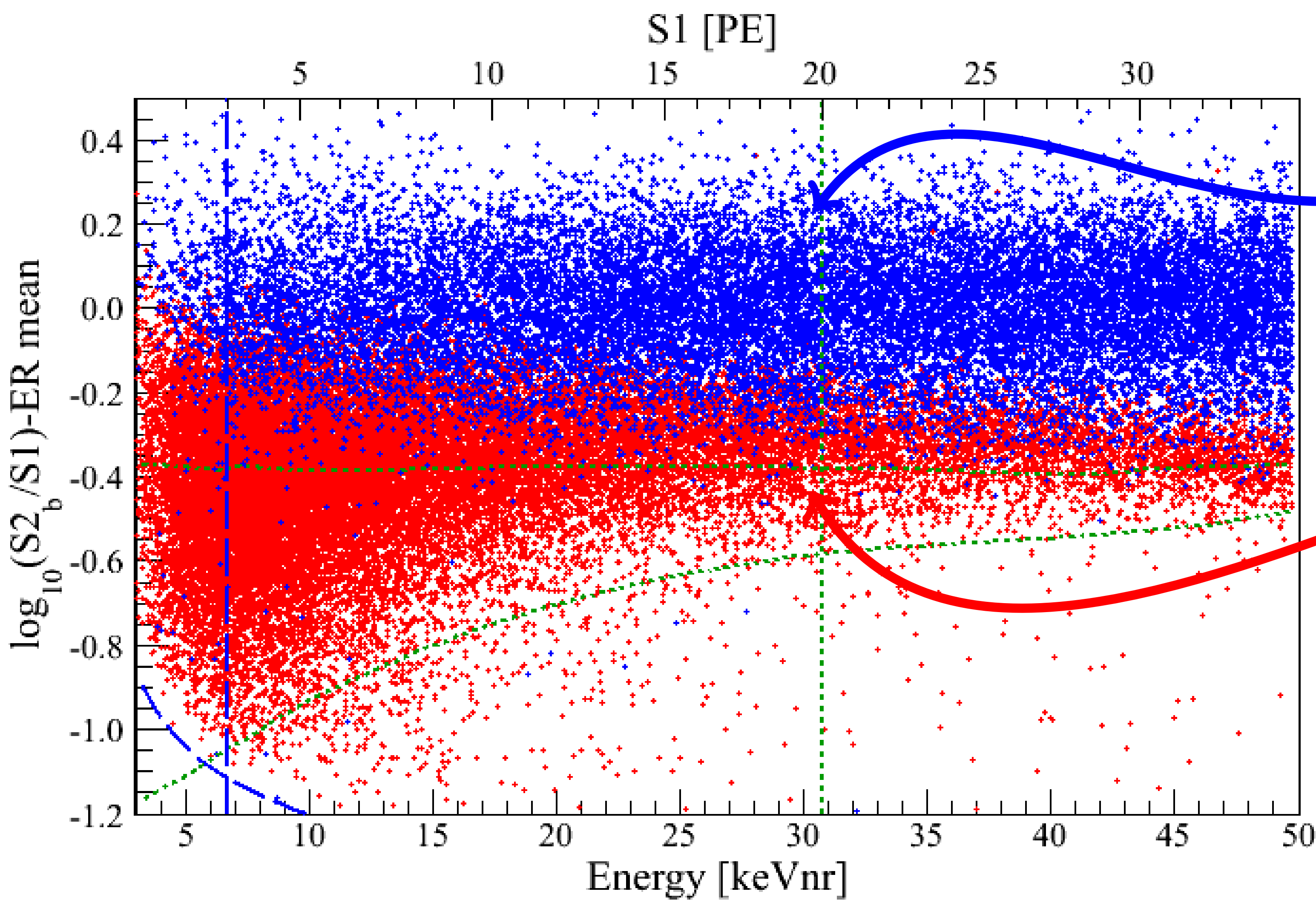
$$E = \frac{S2}{Y}\frac{1}{Q_y(E)}$$

$[\mathrm{keV_{nr}}]$

number of free electrons
per unit energy

secondary
amplification factor
$[\mathrm{pe}/e^-]$

XENON Calibration Data



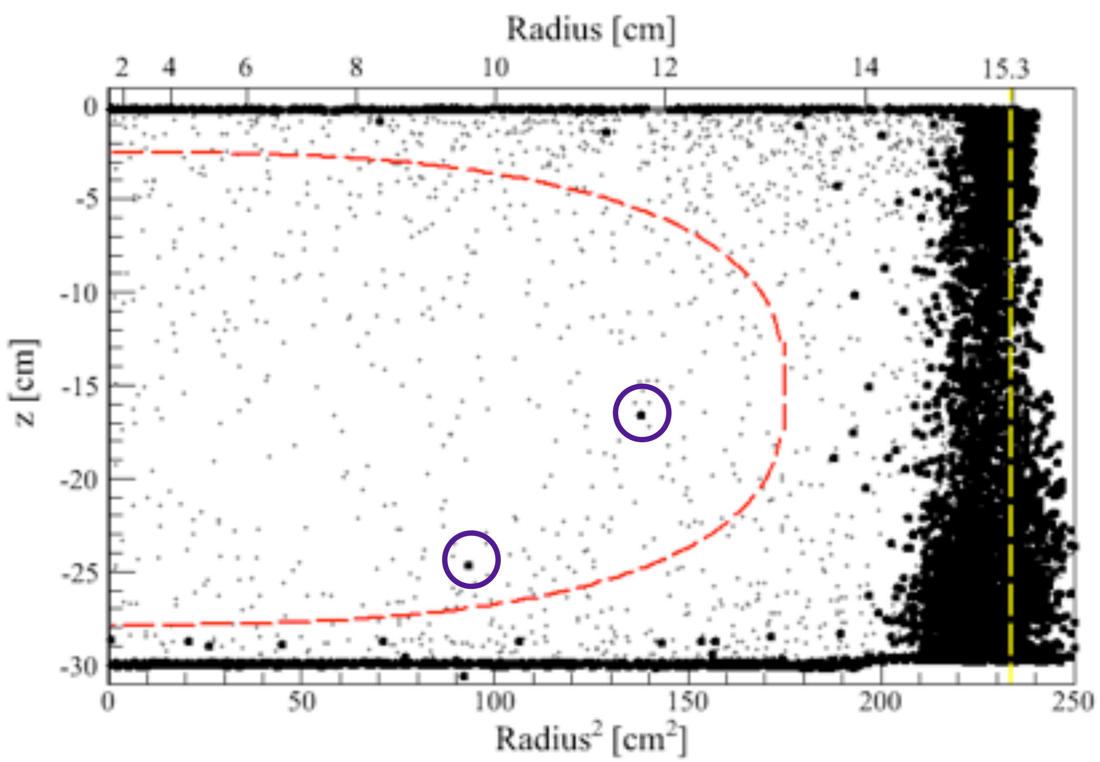
ER calibration data
^{60}Co and new ^{232} Th source
35× science data

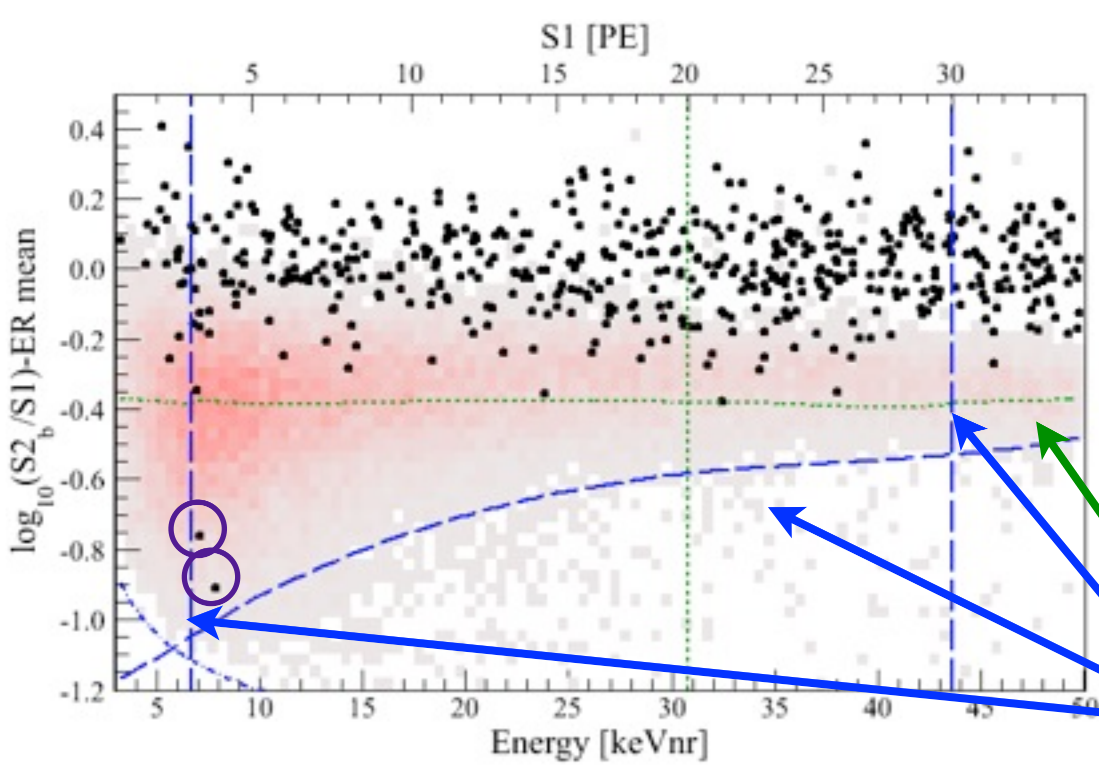
NR calibration data
AmBe source
beginning and end of run

2013 Closing in on Dark Matter - E. Pantic

~99.5% ER rejection at 50% NR acceptance.

XENON 100 RESULTS





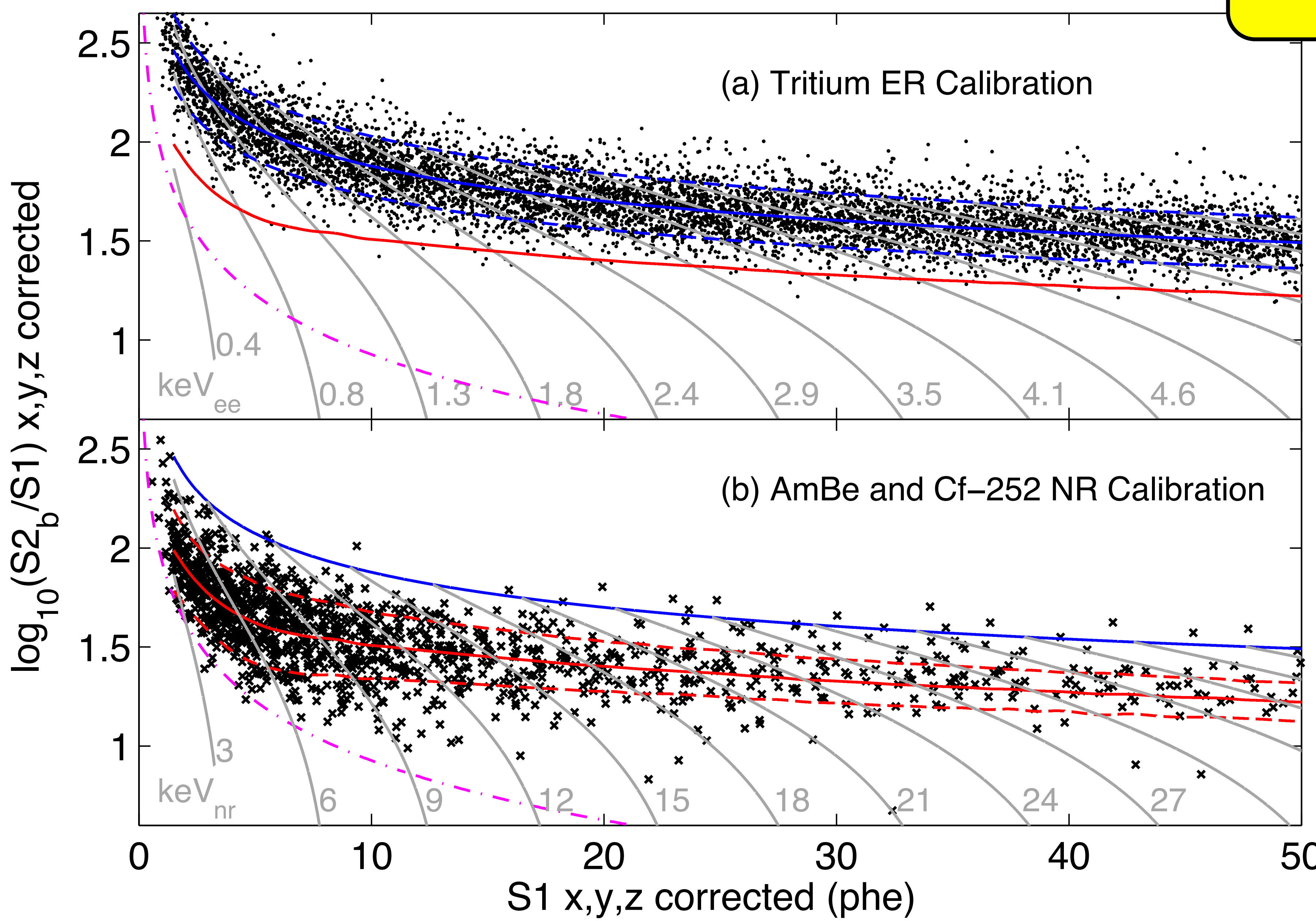
Phys. Rev. Lett. 109, 181391 (2012)

- 224.6 live days acquired from Feb. 2011 to Mar. 2012 in fiducial mass 34 kg liquid Xe.
- 2 events observed on a predicted background of 1.0 ± 0.2 background events (NR and ER 0.79 ± 0.16)
- Red shading (below) indicate nuclear recoil region measured by neutrons from ^{241}AmBe source.
- Grey dots (above) are events above the 99.75% ER rejection line.
- WIMP search region is restricted to 3 - 20 PE in S1.

99.75% ER Rejection Line
Profile Likelihood Analysis Threshold

LUX Calibration Data

arXiv: 1310:8214

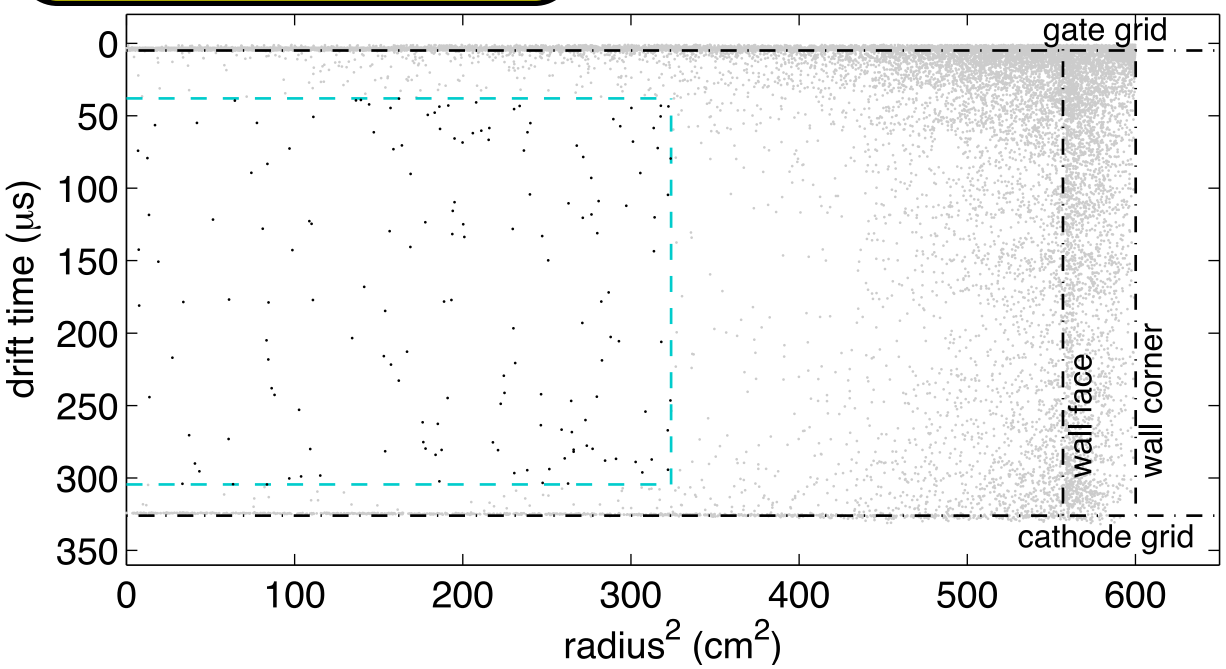


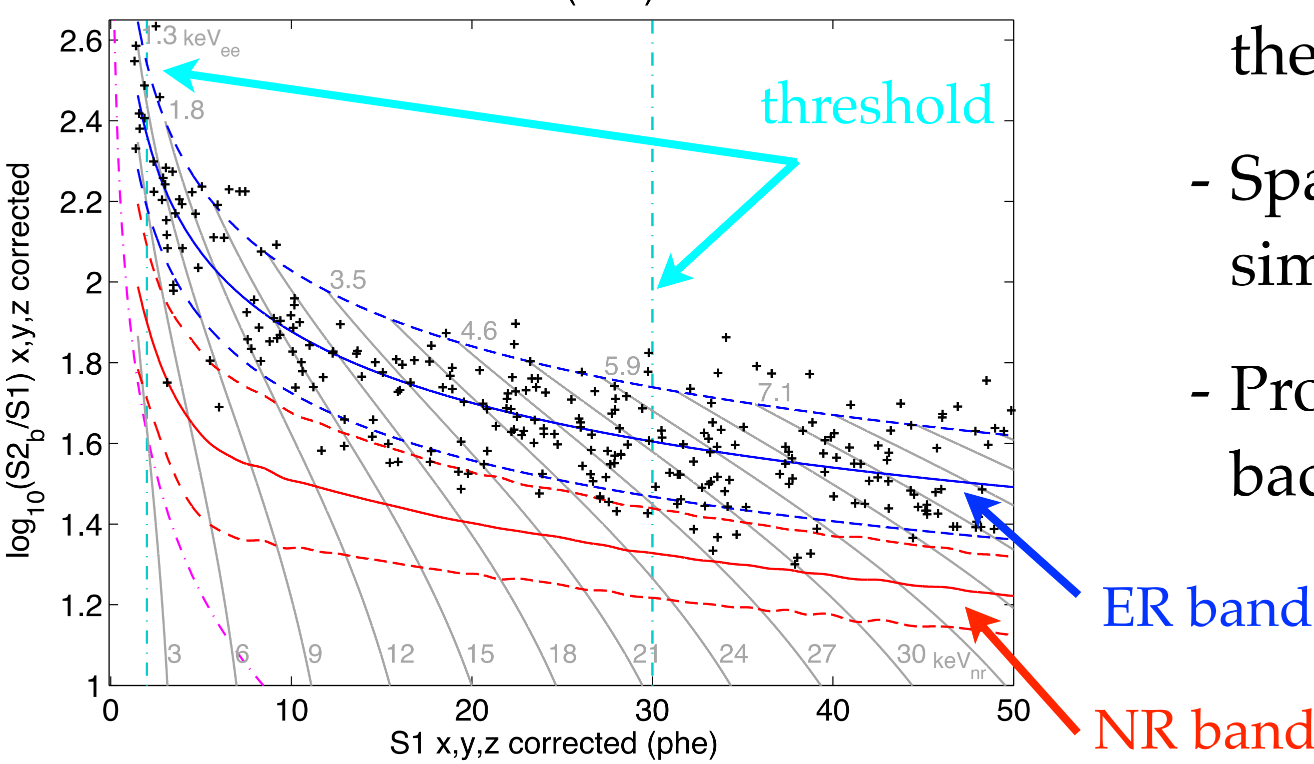
Data

Simulation + Data

LUX Results

arXiv: 1310:8214





- 85.3 live days acquired from April to Aug. 2013 in fiducial mass 118 kg liquid Xe.
- 160 events were observed between 2 and 30 PE (S1) in the fiducial volume.
- 99.6% rejection of ER events with 50% NR acceptance.
- No events are observed below the mean of the NR band (0.64 ± 0.16 expected).
- Spacial distribution is consistent with MC simulations of ER events.
- Profile likelihood analysis favors background only hypothesis (p-value: 0.35)

Phonon and Heat Signals

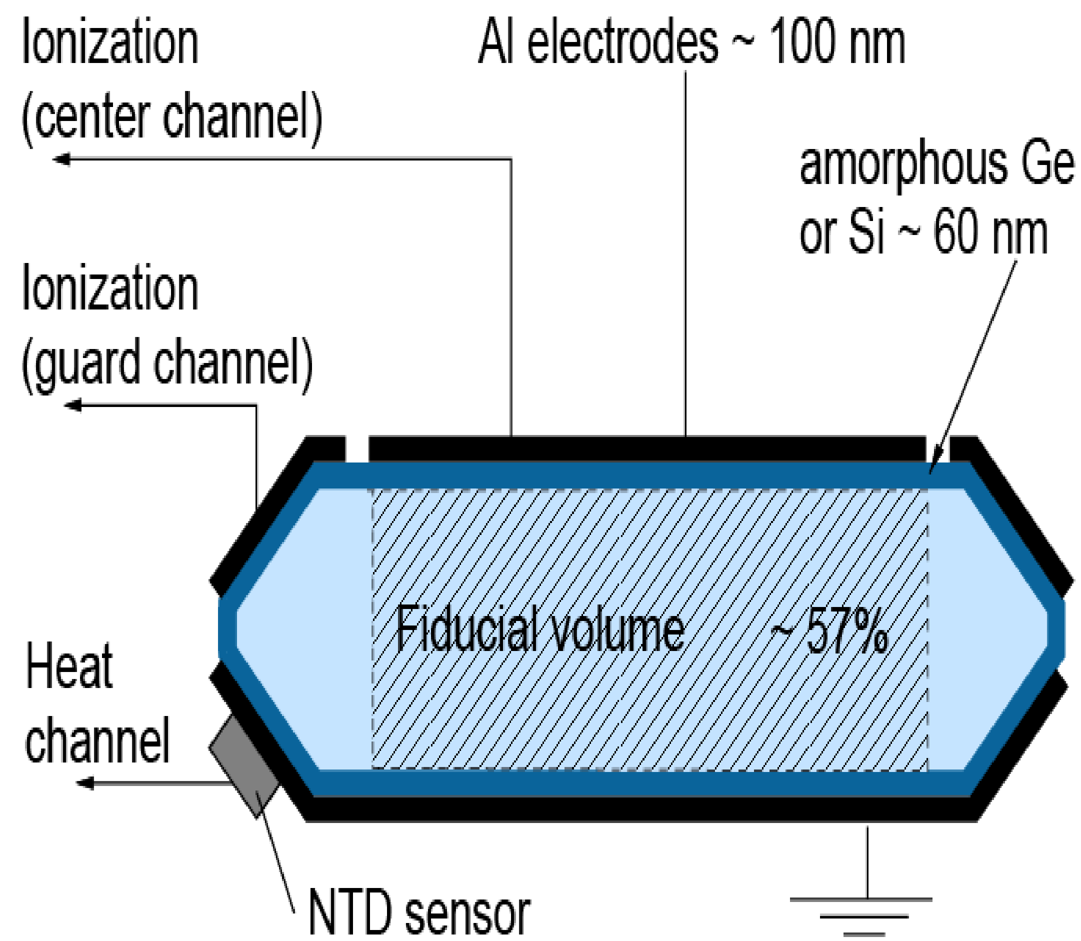
(CRESST, EDELWEISS, SuperCDMS, ROSEBUD)

- Two families of sensors for phonon signal, themal and athermal
  - Thermal sensors - wait for the full thermalization of the phonons within the bulk of the detector and the sensor itself
  - Temperature increase is equal to the deposited energy over the heat capacity of the system.
- Two most widely used technologies to measure these signals are neutron doped germanium sensors (NTD) and transition edge sensors (TES)

NTDs

- NTDs are small Ge semiconductor crystals that have been exposed to a neutron flux to make a large, controlled density of impurity.
- NTD measures small temperature variations relative to T_0 which is set to be on the transition from superconducting and resistance regime with dependence of the resistance with temperature T

$$\exp\left(-\sqrt{\frac{T}{T_0}}\right)$$

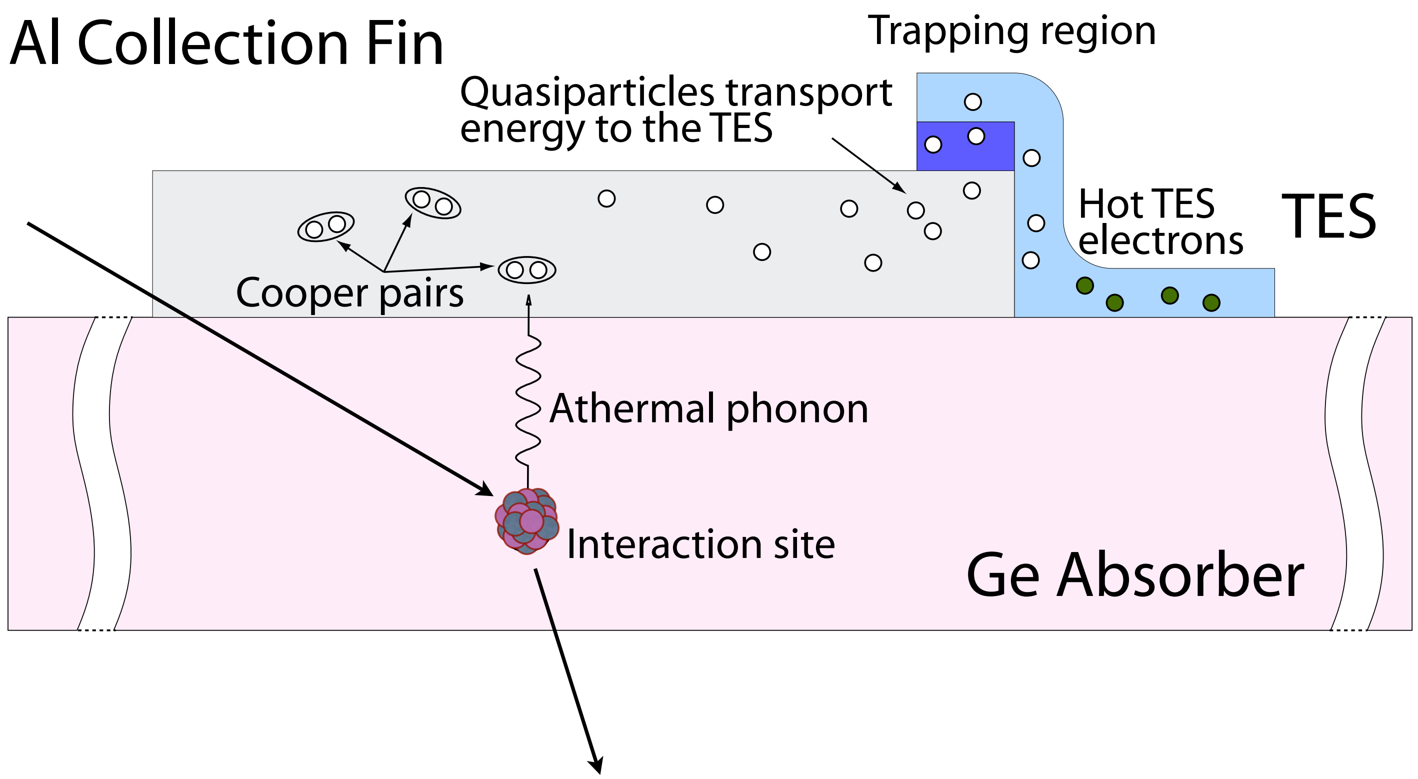


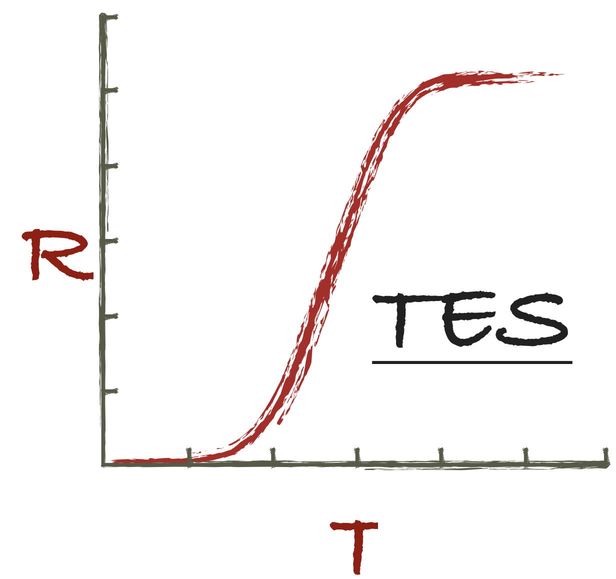
Schematic "Ge-NTD" EDELWEISS-II detector

- Resistance is continuously measured by flowing current through it and measuring the resulting voltage.
- Sensors are glued onto detector.

TESs

ZIP detector schematic from CDMS II

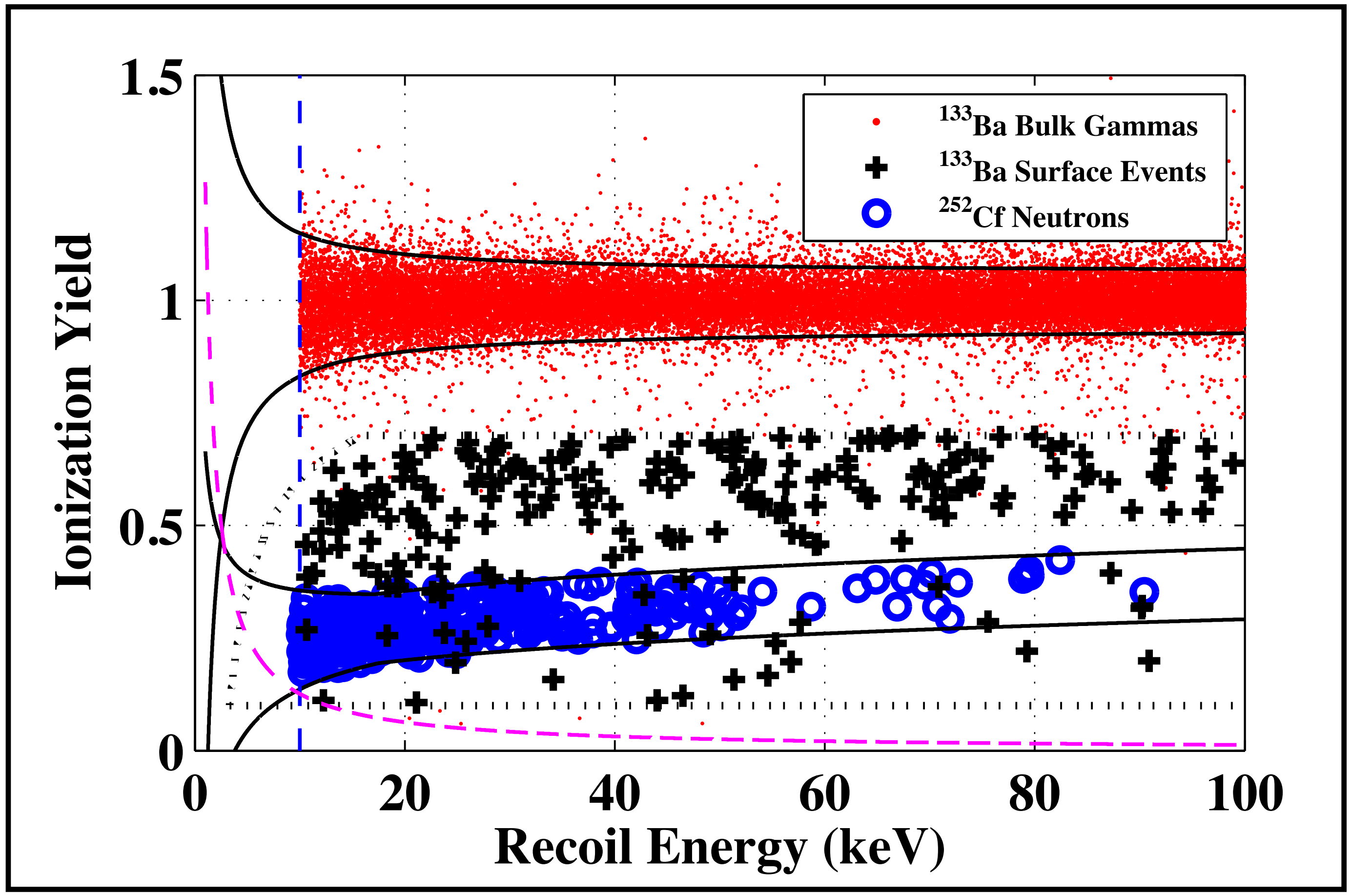




- TES is a thin superconducting film operated near its T_c.
- A heater with an electothermal feedback system maintains temperature at superconducting edge.
- Temperature changes are detected by a change in the feedback current, collected by a SQUID.

CDMS II

- Ionization yield (ionization energy per unit phonon energy) depends strongly on particle type.
- Most backgrounds produce electron recoils
- WIMPs and neutrons produce nuclear recoils



- Excellent yield-based discrimination for electron recoils: $< 10^{-4}$ mis-id probability
- Surface events suffer reduced ionization yield

Aside: Energy

The total energy (phonon) is given by

recoil energy
[$\mathrm{keV_{nr}}$]

$$E_{tot} = E_r + \underline{eV_b N_Q}$$

total energy

Neganov-Luke
Phonons

"Luke" phonons are created when charge carriers are drifted across the crystal.

where V_b = bias Voltage (= 3.0 V for CDMS Ge detectors)

and the average number of electron hole pairs produced by an interaction

$$N_Q = \frac{E_R}{\epsilon}$$

epsilon = average energy to create an e^-/hole pair (3.0 eV in Ge)

Energy - Electron Recoil

Assuming that an event is an ER, the recoil energy in [keVee] can be expresses as --

$$E_r(p_t) = p_t - eV_bN_Q = p_t - \frac{eV_bE_Q}{\epsilon} = p_t - E_Q$$

total phonon energy - Luke energy

$\epsilon_{Ge} = 3.0$ eV, $V_b = 3$ V

Recall, that ionization yield is defined as

$$y = \frac{E_Q}{E_R}$$

($E_Q = E_r$ for ER events)

Thus, we can write

$$E_r = p_t - E_r \quad \Longrightarrow \quad \boxed{E_r = \frac{p_t}{2}}$$

recoil energy [keVee]

*A good reference is David Moore's thesis, Chapters 3 and 4 http://thesis.library.caltech.edu/7043/

Energy - Nuclear Recoil

Assuming that an event is a NR, a smaller correction for the Luke phonons is applied.

The mean ionization energy for nuclear recoils ($\mu_{Q,NR}(p_t)$) is determined using calibration data from a ^{252}Cf source.

$$E_r(p_t) = p_t - \mu_{Q,NR}(p_t)$$

[keV$_{nr}$]

total phonon energy - Luke energy

where

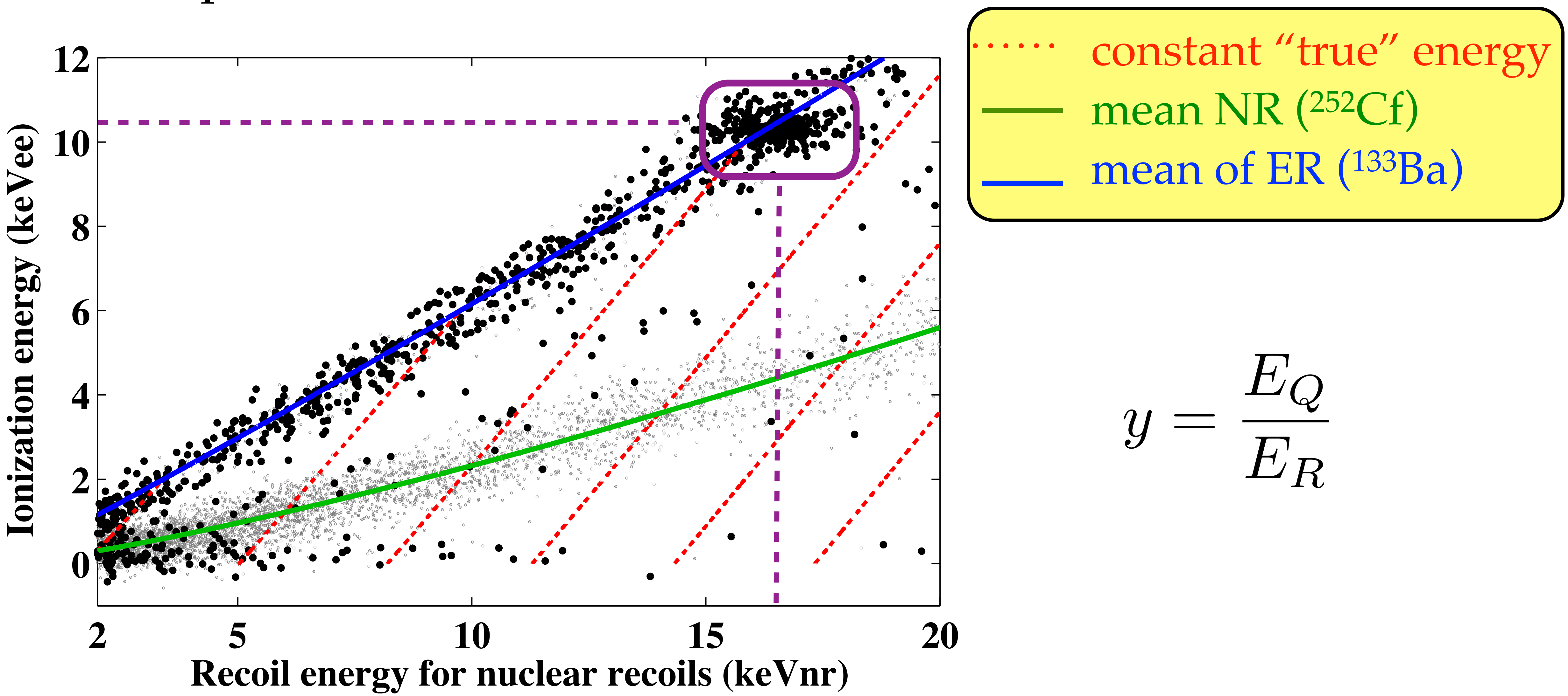
$$\mu_{Q,NR} = AE_r^B$$

Note: Due to the low ionization yield for low energy NR (~15% of total energy), any error due to uncertainties in the measurement of ionization yield is reduced by the same factor.

*A good reference is David Moore's thesis, Chapters 3 and 4 http://thesis.library.caltech.edu/7043/

keVee vs keVnr

Ionization energy vs recoil energy assuming NR scale consistent with Luke phonon contributions for NR.



$$y = \frac{E_Q}{E_R}$$

- ER recoils are pushed to higher energies using the NR scale.
  - Example - 10.4 keV_{ee} ER line appears at ~16 keV_{nr}

Aside: Summary

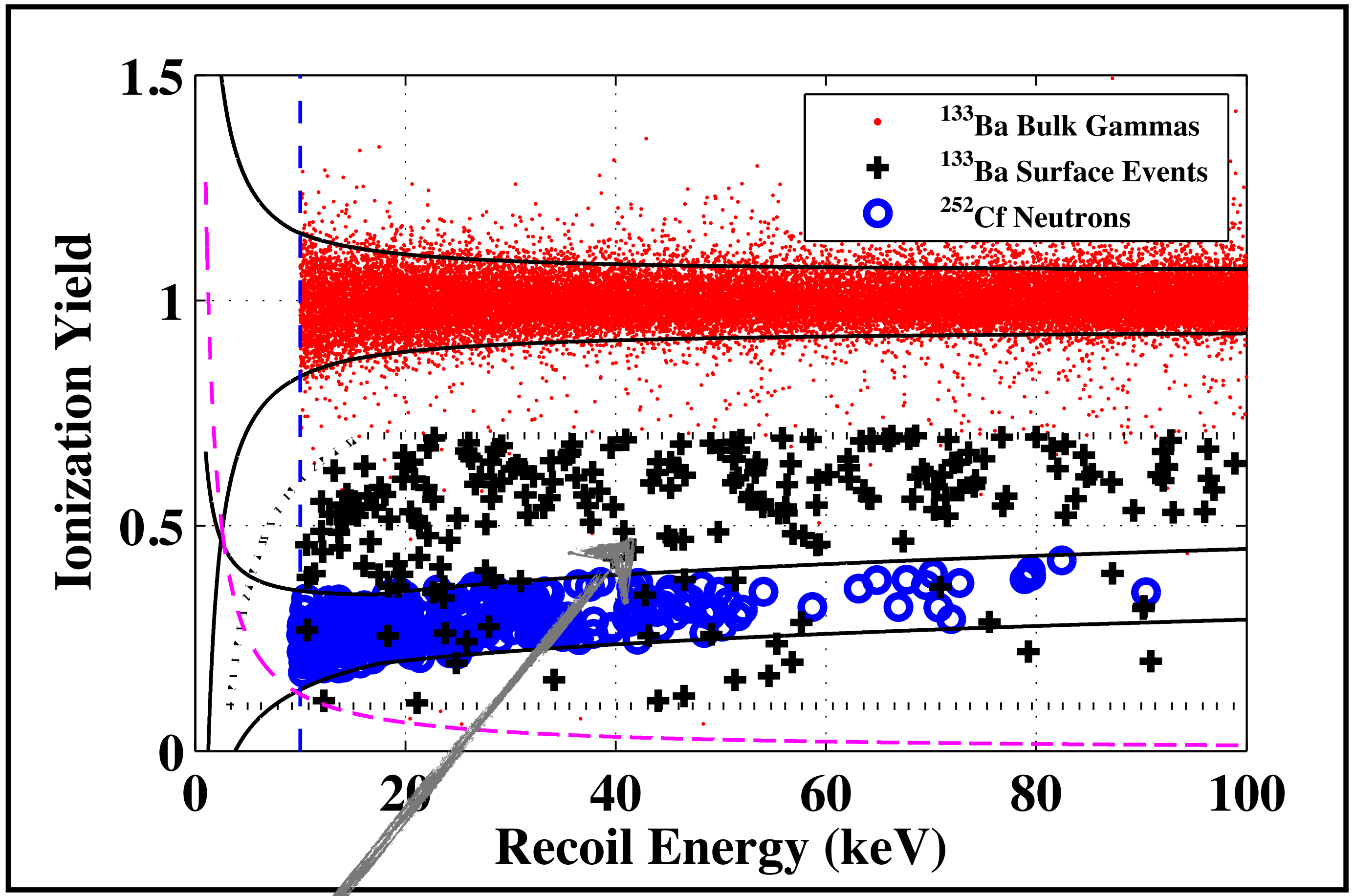
- The Luke correction for ER is larger than for NR.
- This effect results in the ionization yield difference between ER and NR events.
- The ionization yield of a 50 keV nuclear recoil will lower than that of a 50 keV electron recoil by a factor of ~3.
- The energy dependence of ionization yield is described well by the Lindhard theory for stopping power of ions in matter.

CDMS II

- Ionization yield (ionization energy per unit phonon energy) depends strongly on particle type.

- Most backgrounds produce electron recoils

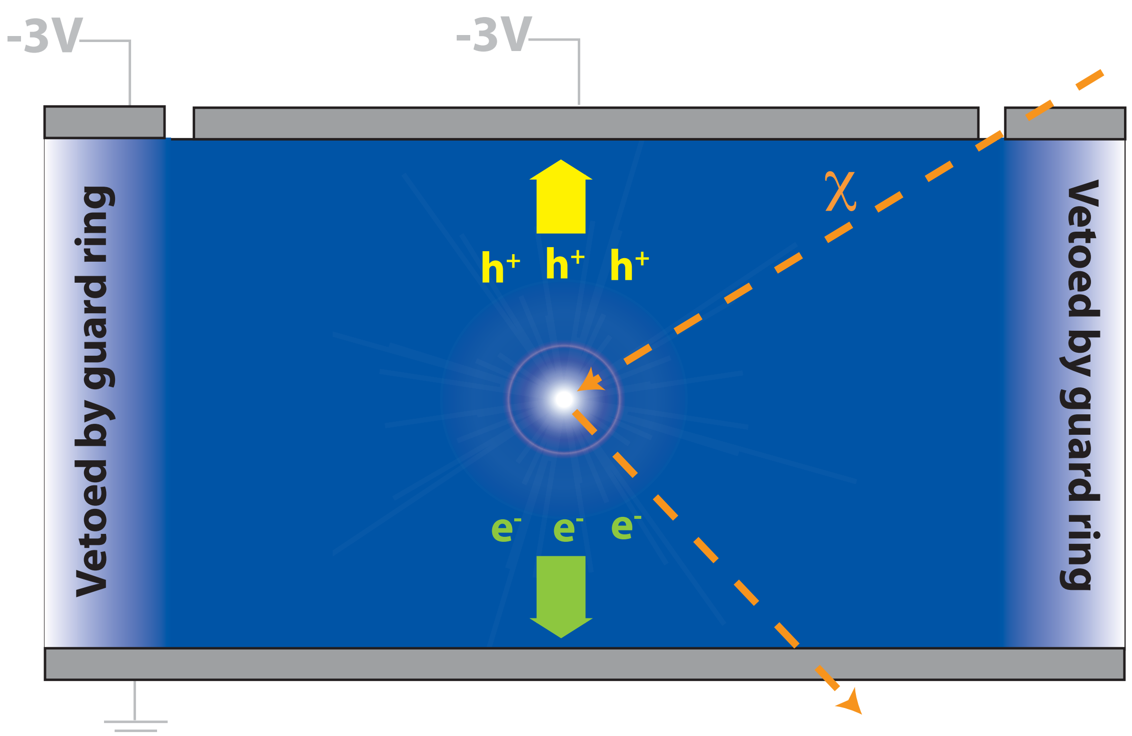
- WIMPs and neutrons produce nuclear recoils

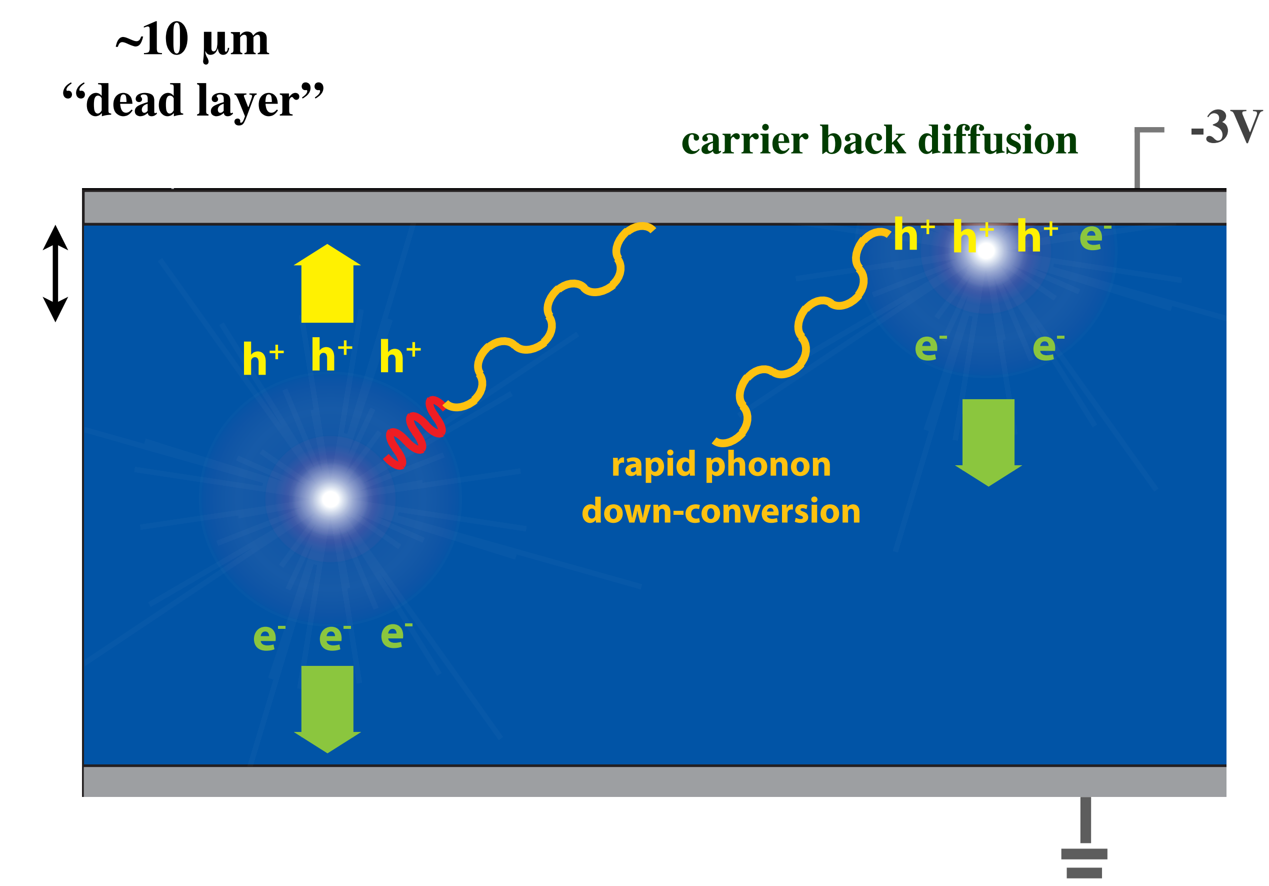


- Excellent yield-based discrimination for electron recoils: < 10^{-4} mis-id probability

- Surface events suffer reduced ionization yield

Charge Carrier Back Diffusion

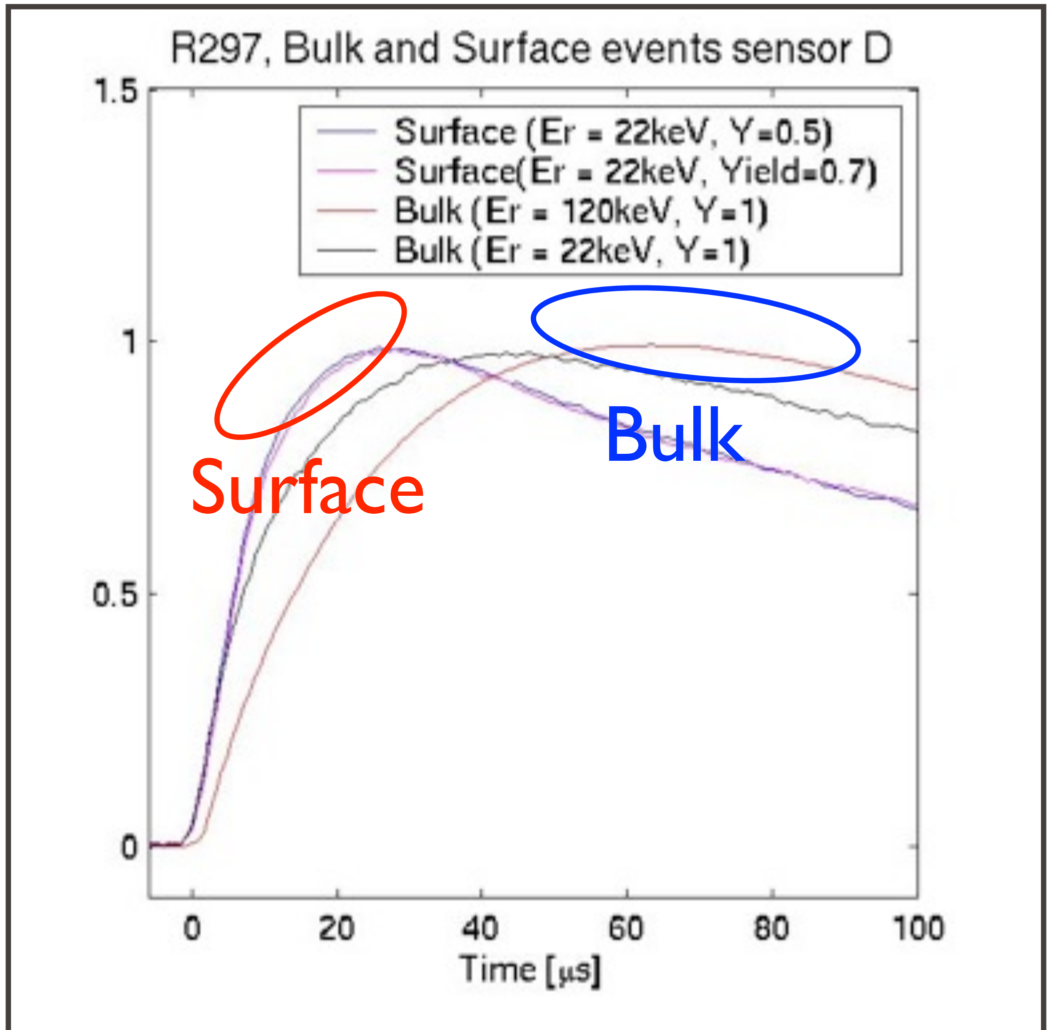


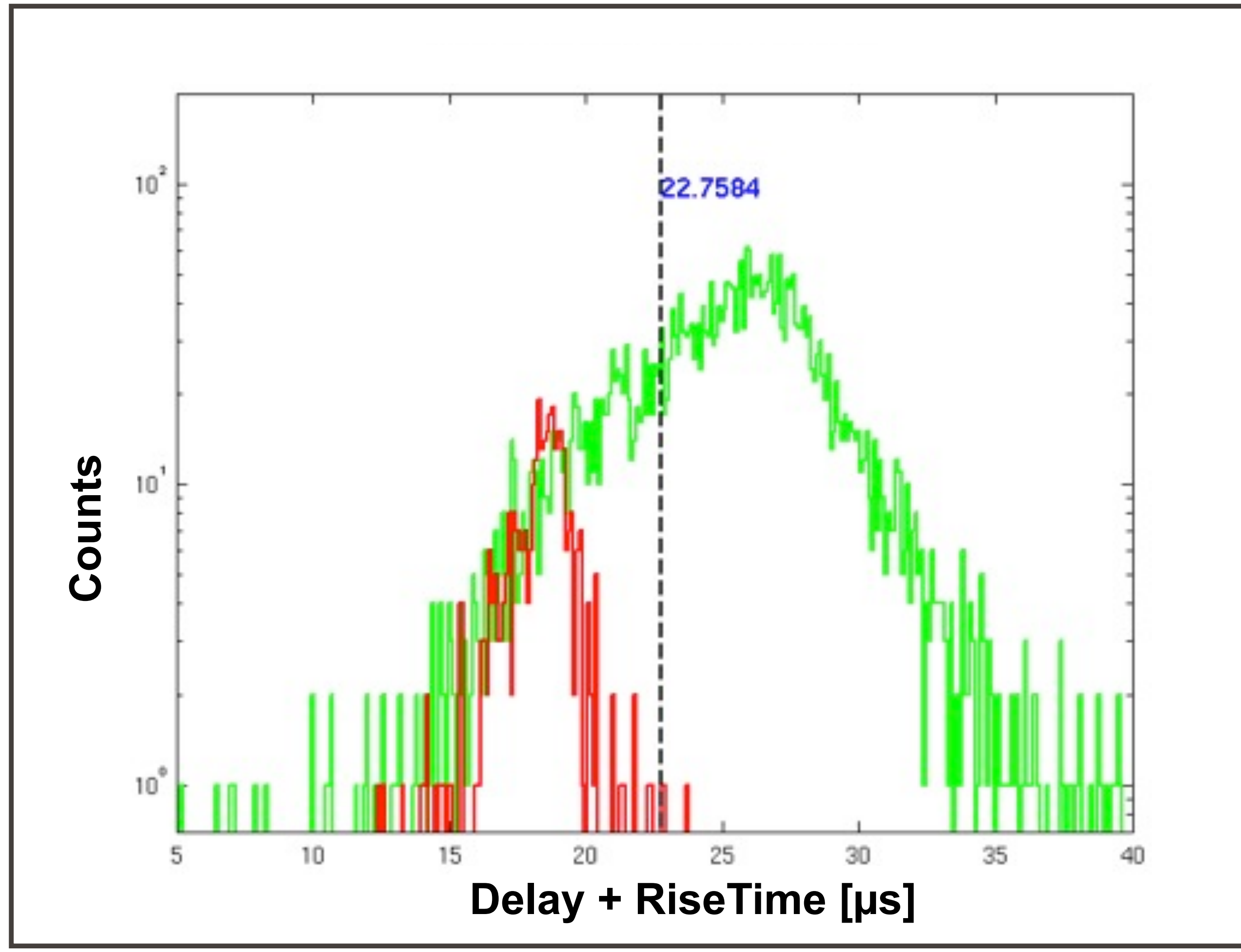


- Reduced charge yield is due to carrier back diffusion in surface events.
- "Dead layer" is within ~10µm of the surface.

Background Discrimination: Pulse Shape

☑ **Surface events rejected based on pulse shape**

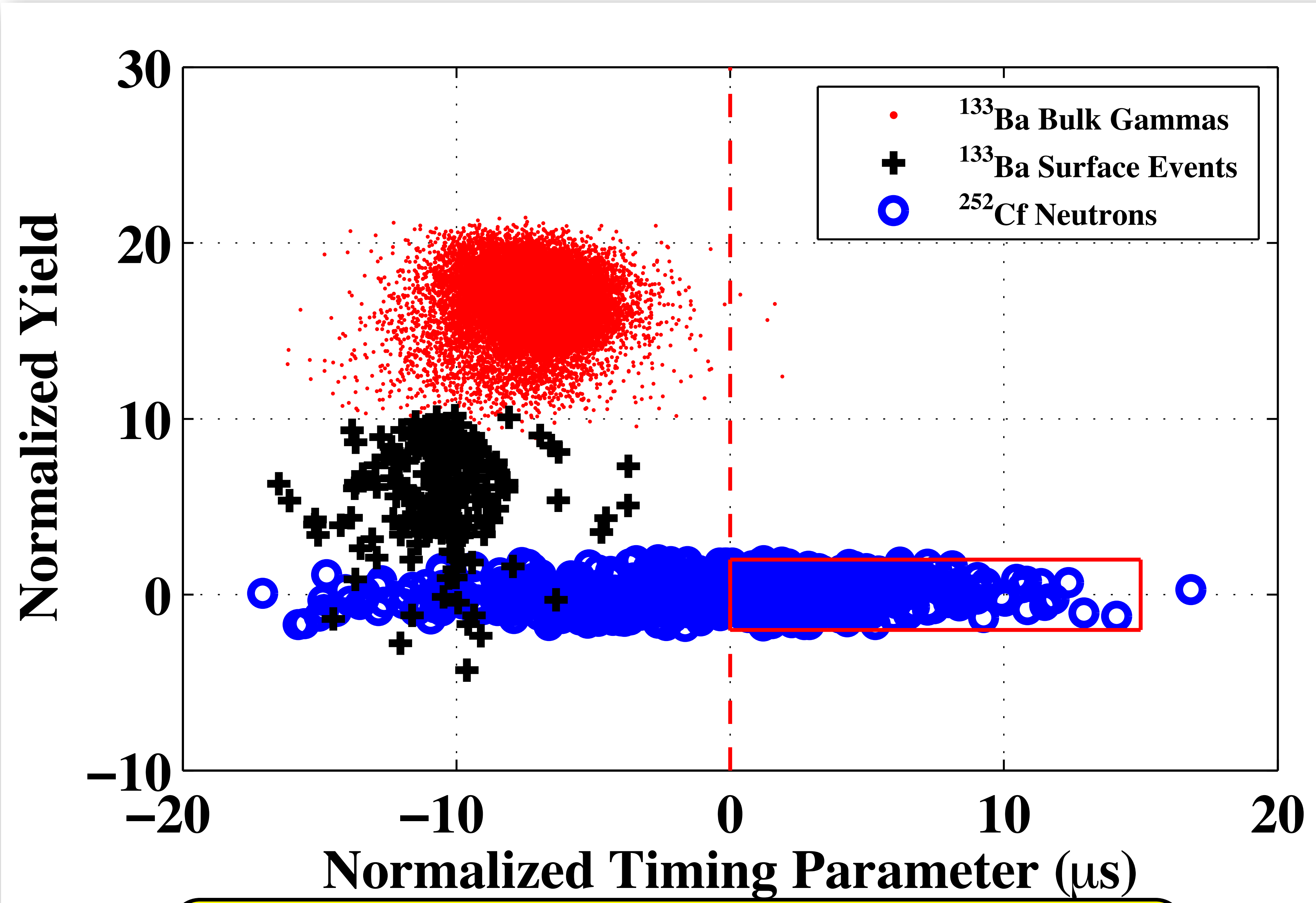




Phonons near surface travel faster, resulting in shorter risetimes of phonon pulse.

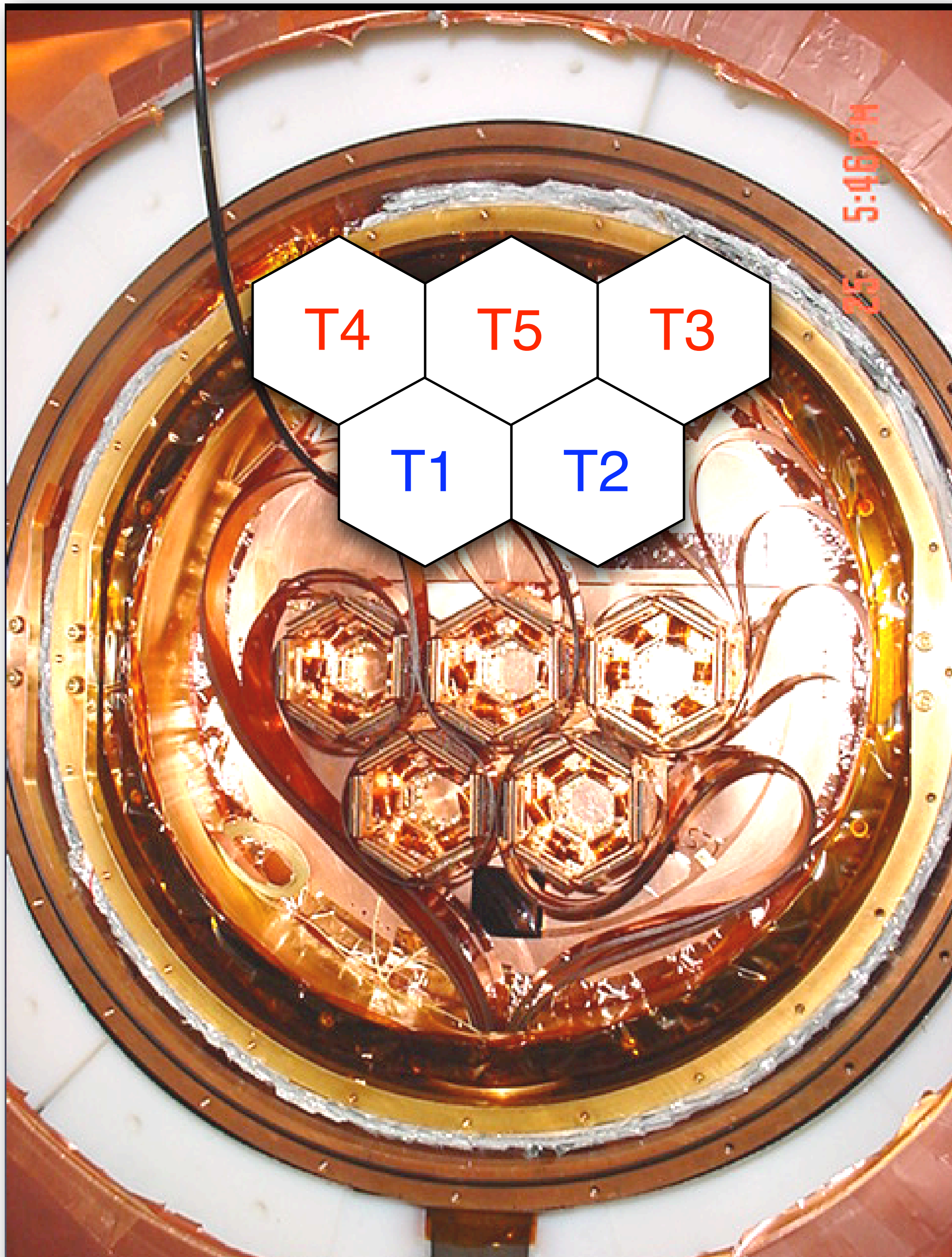
Selection criteria set to accept ~0.5 background events.

CDMS II

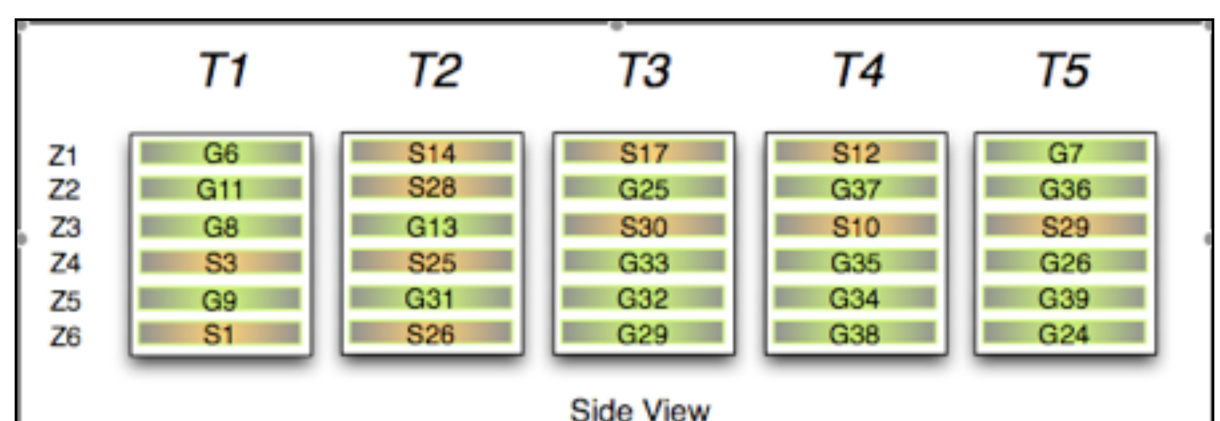


COMBINED ELECTRON RECOIL MIS-ID PROBABILITY: < 10^{-6}

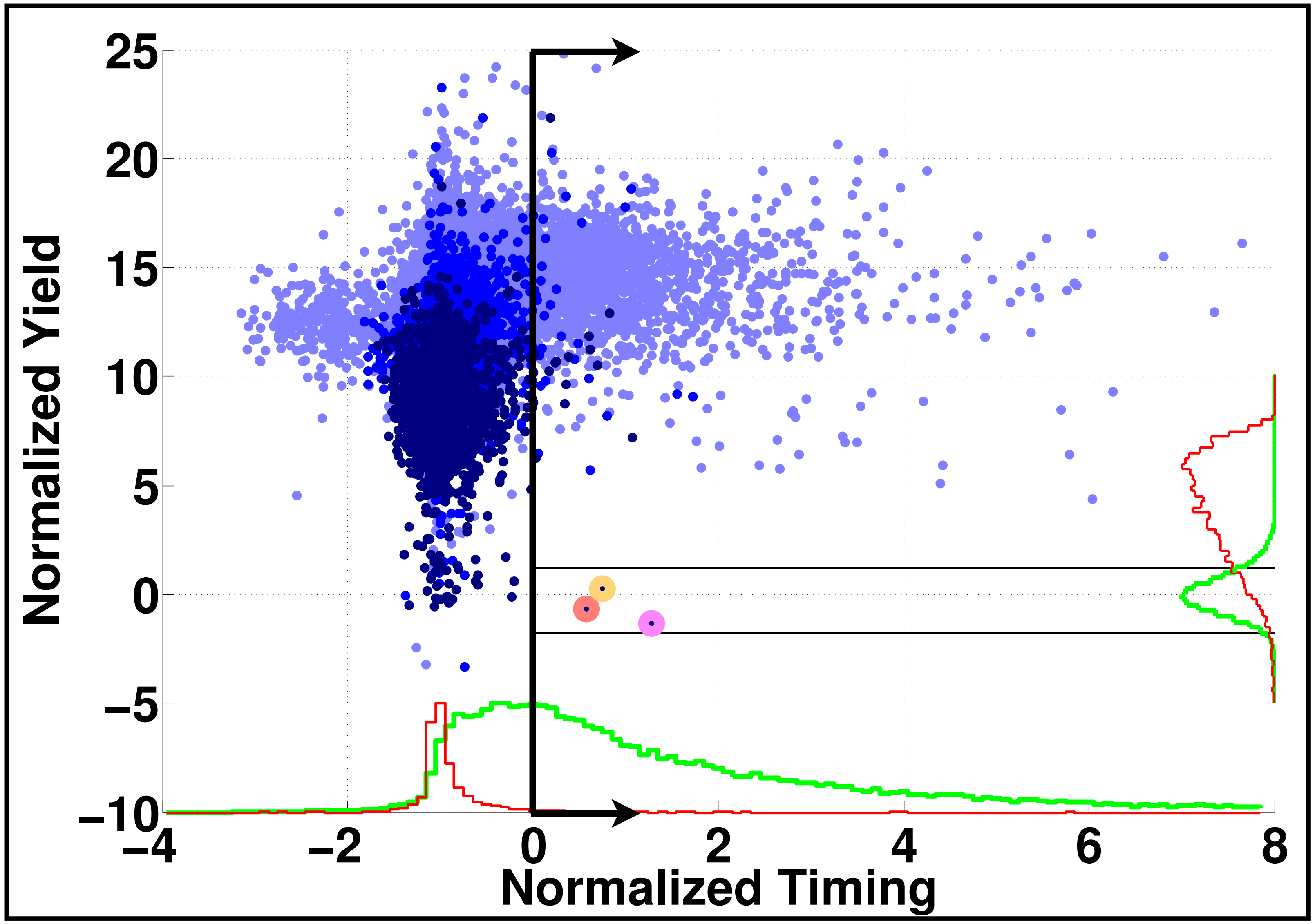
CDMS II - Recent Analysis



- 30 detectors installed and operated in Soudan from June 2006 - March 2009.
  - ~4.75 kg Ge, ~1.1 kg Si
- Seven Total Data Runs
  - R123- R124 (Oct. 2006 - July 2007)
    - 55.9 kg-days in 6 Si detectors
  - **R125 - R128 (July 2007 - Sep. 2008)**
    - **140.23 kg-days in 8 Si detectors**
  - R129 (Nov. 2008 - Mar. 2009)



Results: CDMS II Silicon Detectors



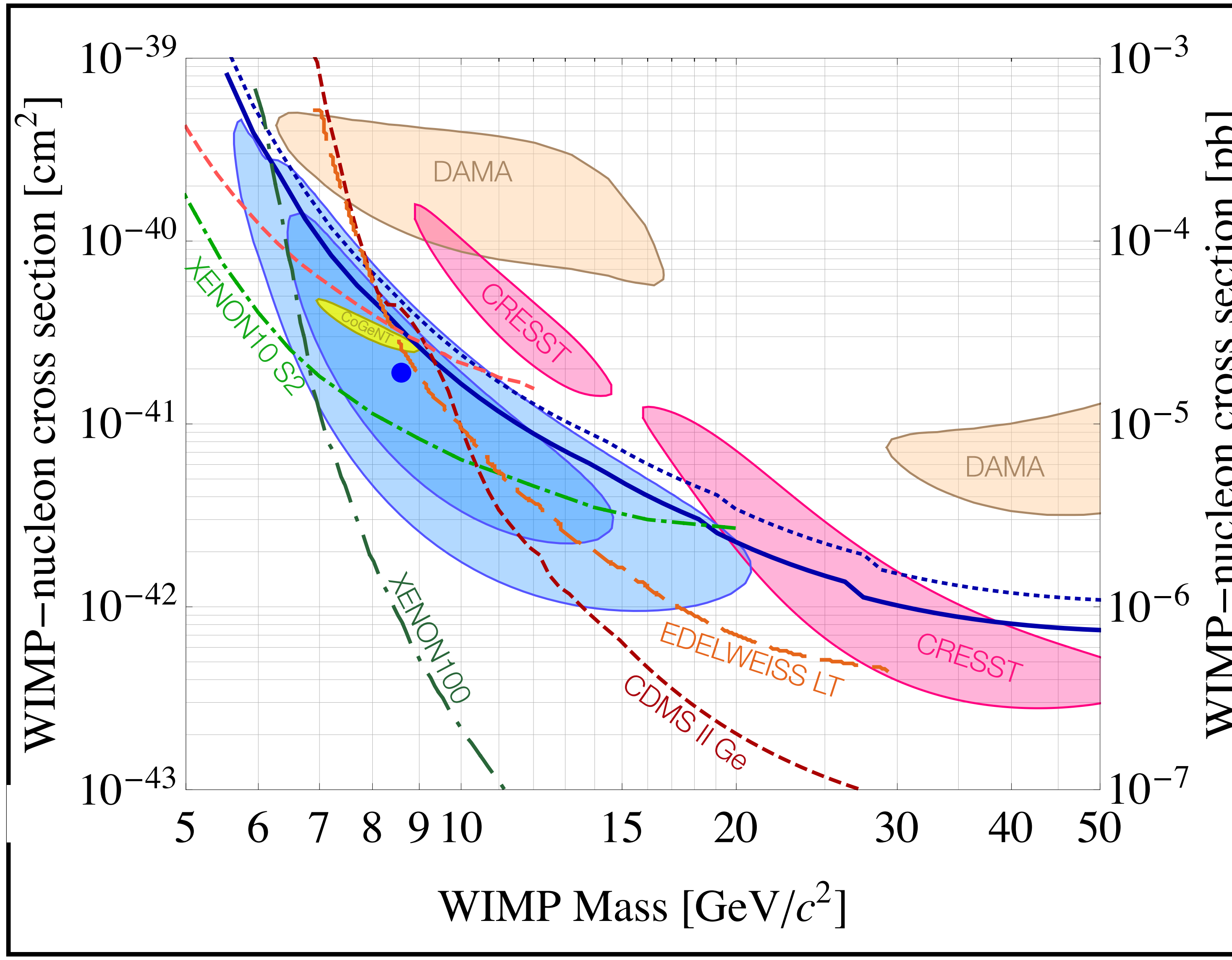
Observed 3 events.

- Shades of blue indicate three separate timing cut energy ranges.
  - 7- 20 keV
  - 20 - 30 keV
  - 30 - 100 keV
- Background Estimate
  - < 0.13 neutrons from Cosmogenics & Radiogenics
  - $0.41^{+0.20}_{-0.08}(stat.)^{+0.28}_{-0.24}(syst.)$
  - < 0.08 ^{206}Pb recoils from ^{210}Pb decays

CDMS II Results

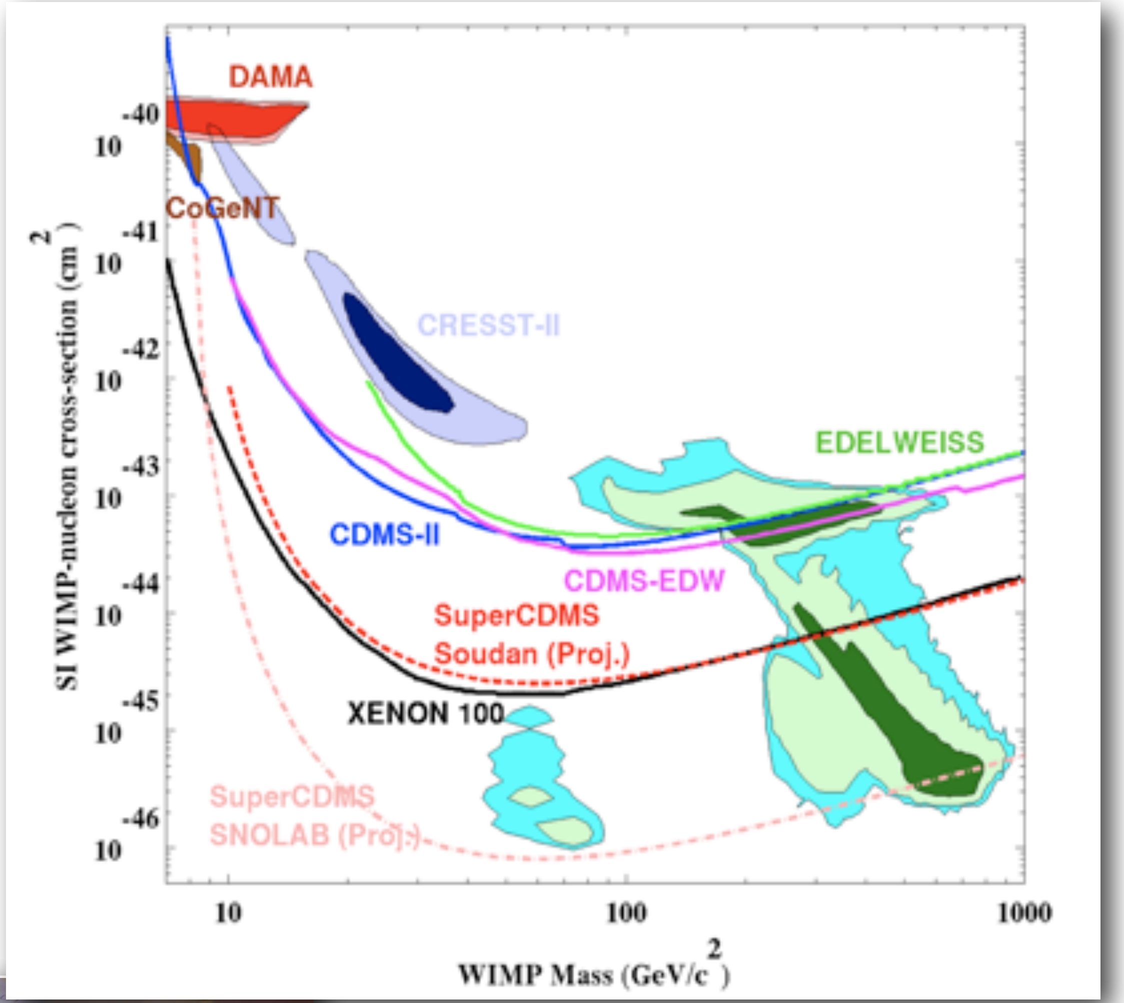
- A profile likelihood analysis favors a WIMP+background hypothesis over the known background estimate as the source of our signal at the 99.81% C.L. (~3σ, p-value: 0.19%)
- Does not rise to level of discovery, but does call for further investigation.
- The maximum likelihood occurs at a WIMP mass of 8.6 GeV / c² and WIMP-nucleon cross section of 1.9 x 10^{-41}.

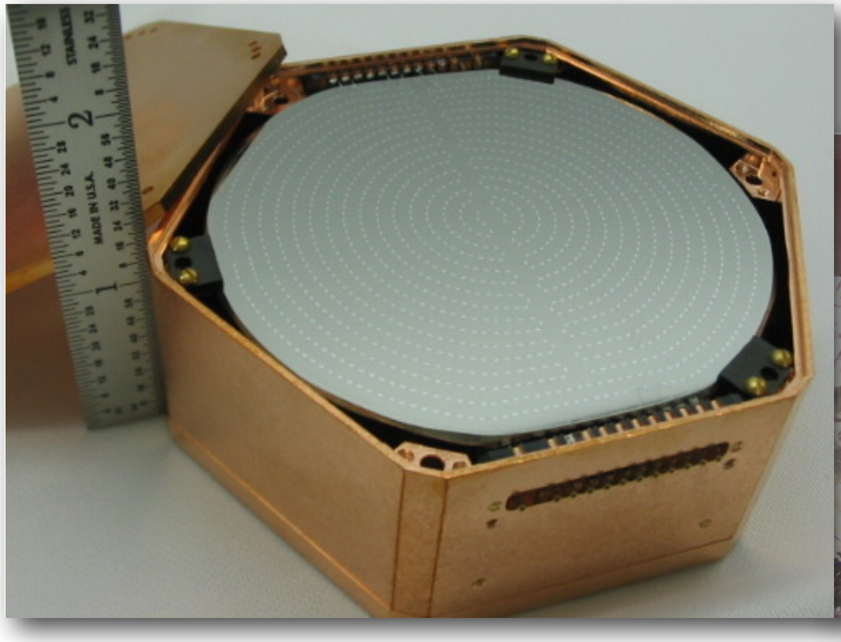
CoGeNT (2013)
CRESST−II (2012)
DAMA/LIBRA (2008)
XENON100 (2012)
XENON10 S2 (2013)
EDELWEISS Low−threshold (2012)
CDMS II Ge (2010)
CDMS II Ge Low−threshold (2011)
90% Upper Limit
90% Upper Limit CDMS II Si Combined
Best fit,
68% C.L.,
90% C.L.,

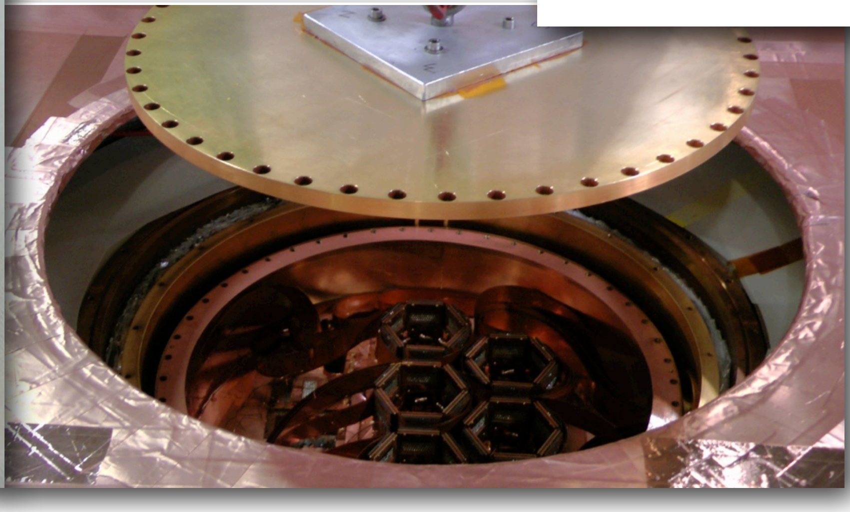


SuperCDMS at Soudan

- Currently operating 5 towers of of advanced iZIP detectors (~9 kg Ge) in the existing cryostat at the Soudan Underground Laboratory.
- After 3 years of operation, expected to improve sensitivity to spin-independent WIMP-nucleon interactions by a factor of ~10 over existing CDMS II results.







Installation complete Nov. 8, 2011. Operating with final detector settings since Mar. 2012.

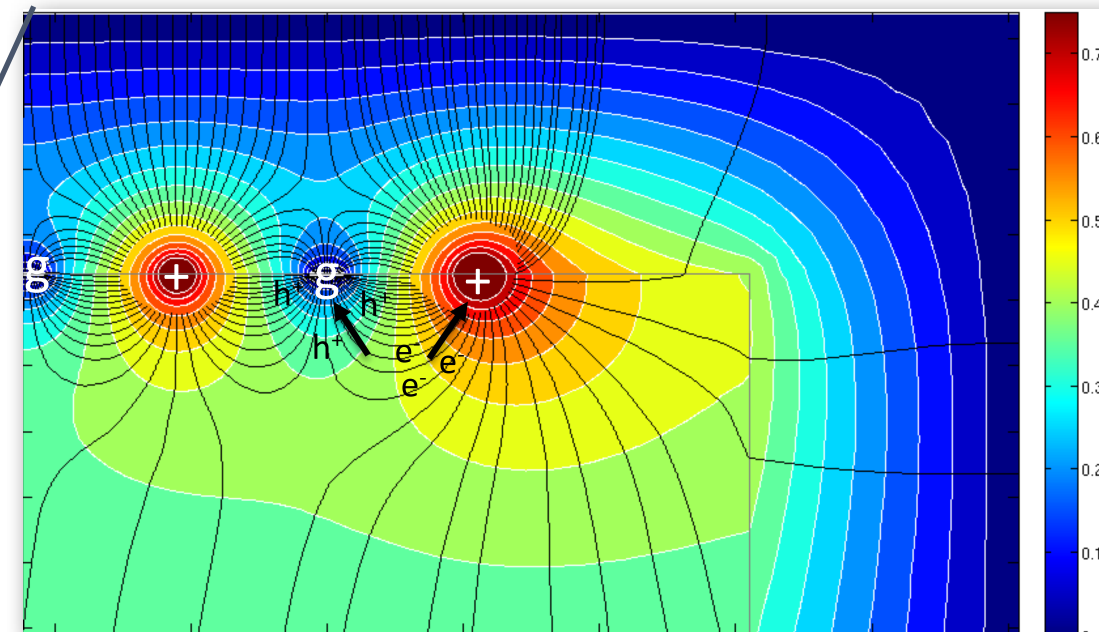
SCDMS iZIPs: Charge Signal

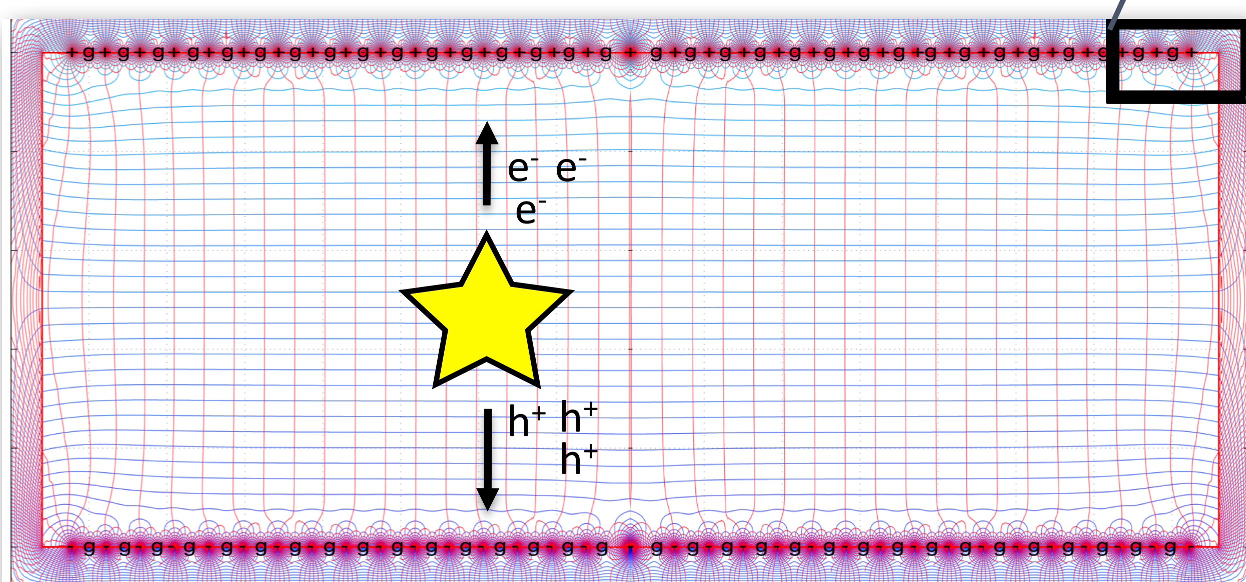
Bulk Events:

Equal but opposite ionization signal appears on both sides of detector (symmetric)

Surface Events:

Ionization signal appears on one detector side (asymmetric)





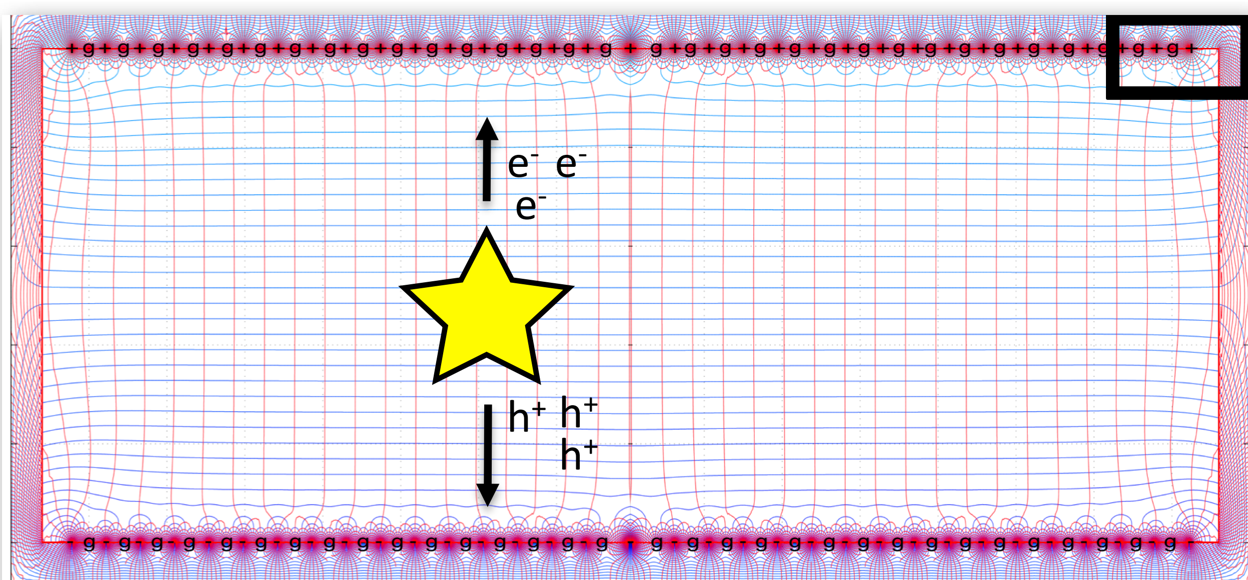
SCDMS iZIPs: Charge Signal

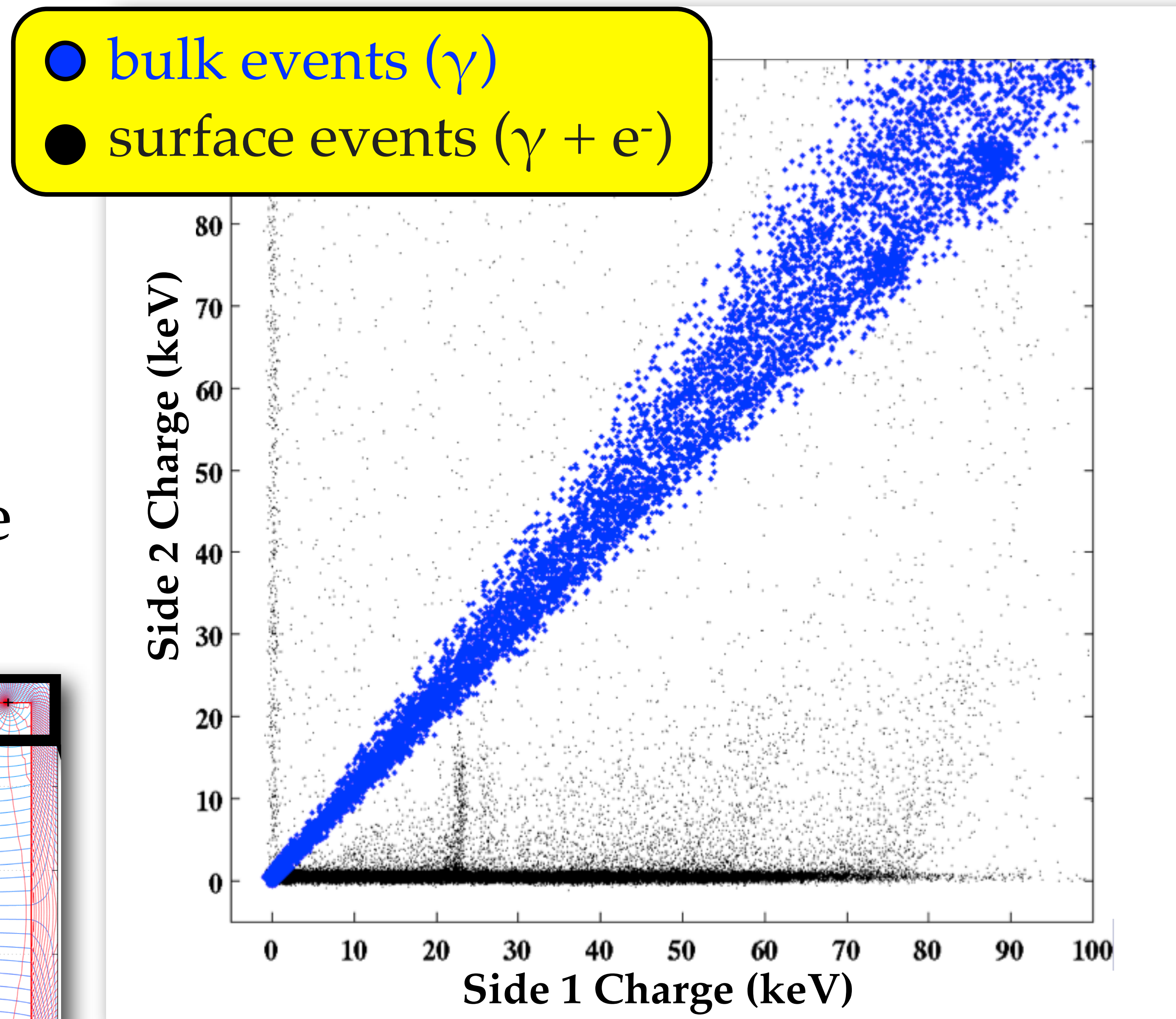
Bulk Events:

Equal but opposite ionization signal appears on both sides of detector (symmetric)

Surface Events:

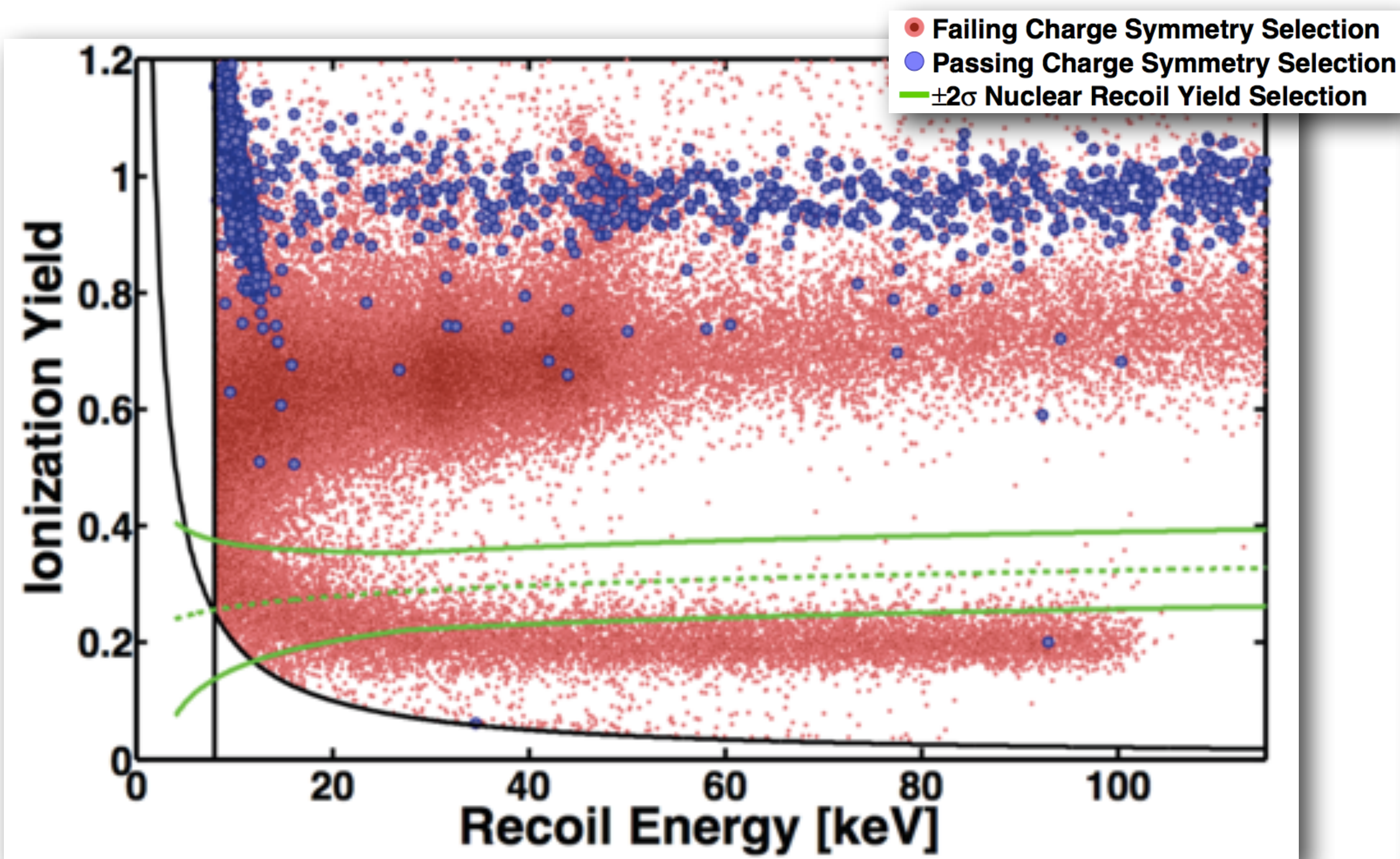
Ionization signal appears on one detector side (asymmetric)

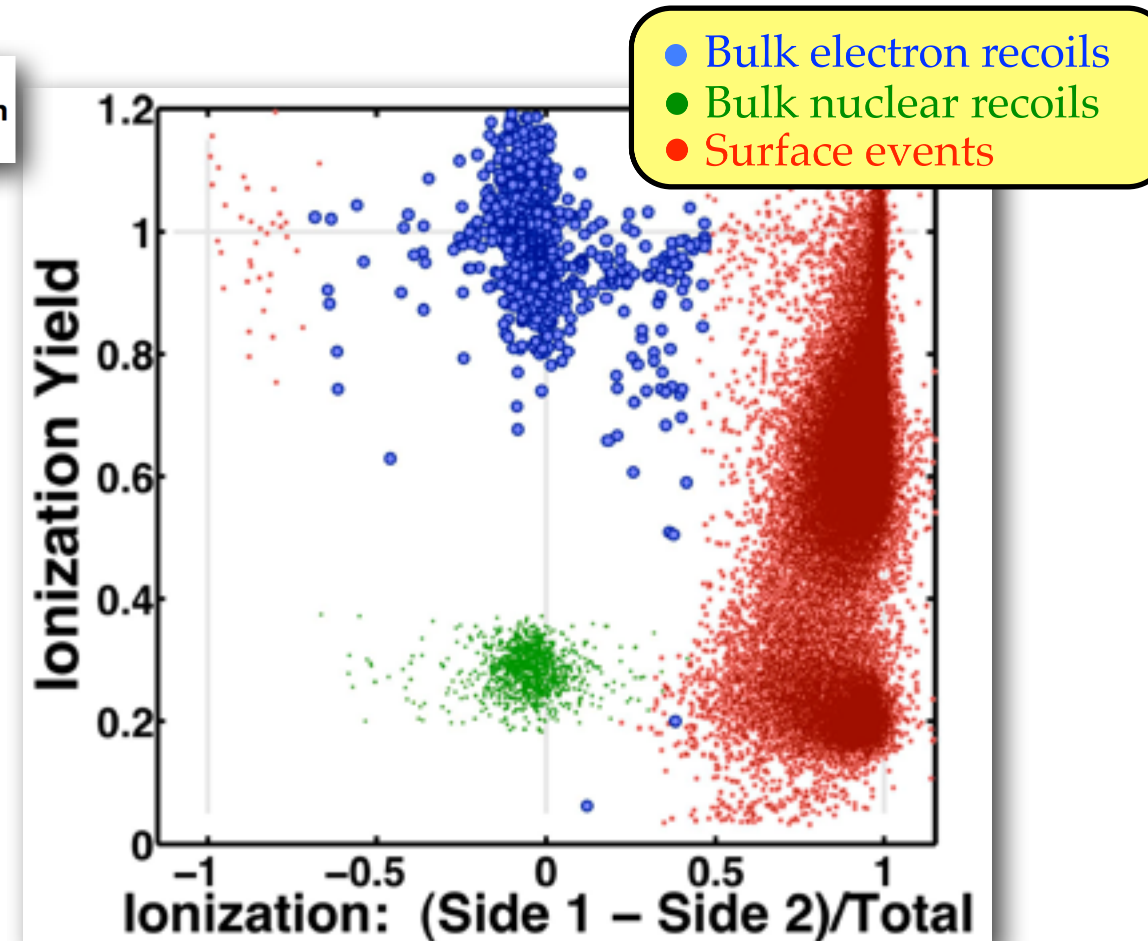




SuperCDMS: ^{210}Pb Test

Two ^{210}Pb sources were deployed with the detectors to test surface rejection capabilities of the new iZIP detectors.

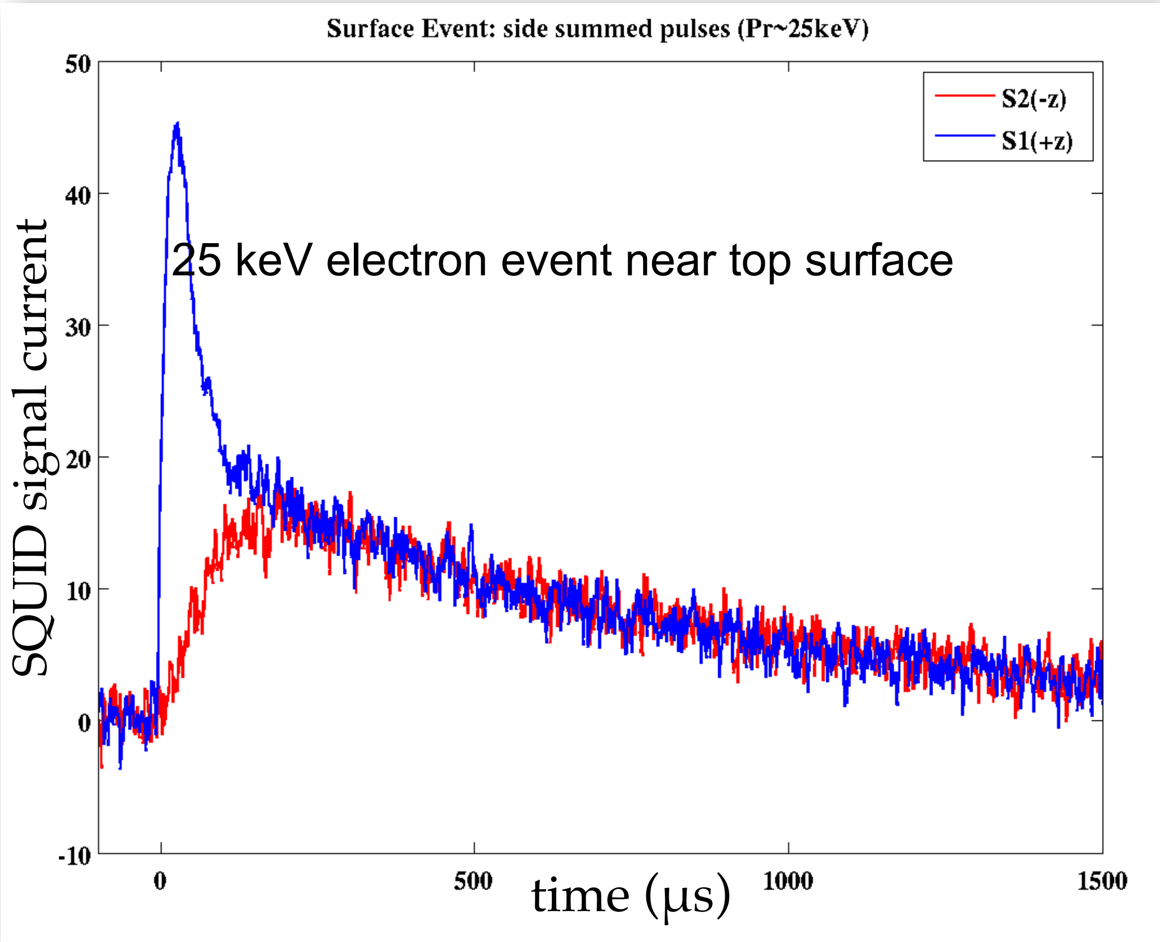


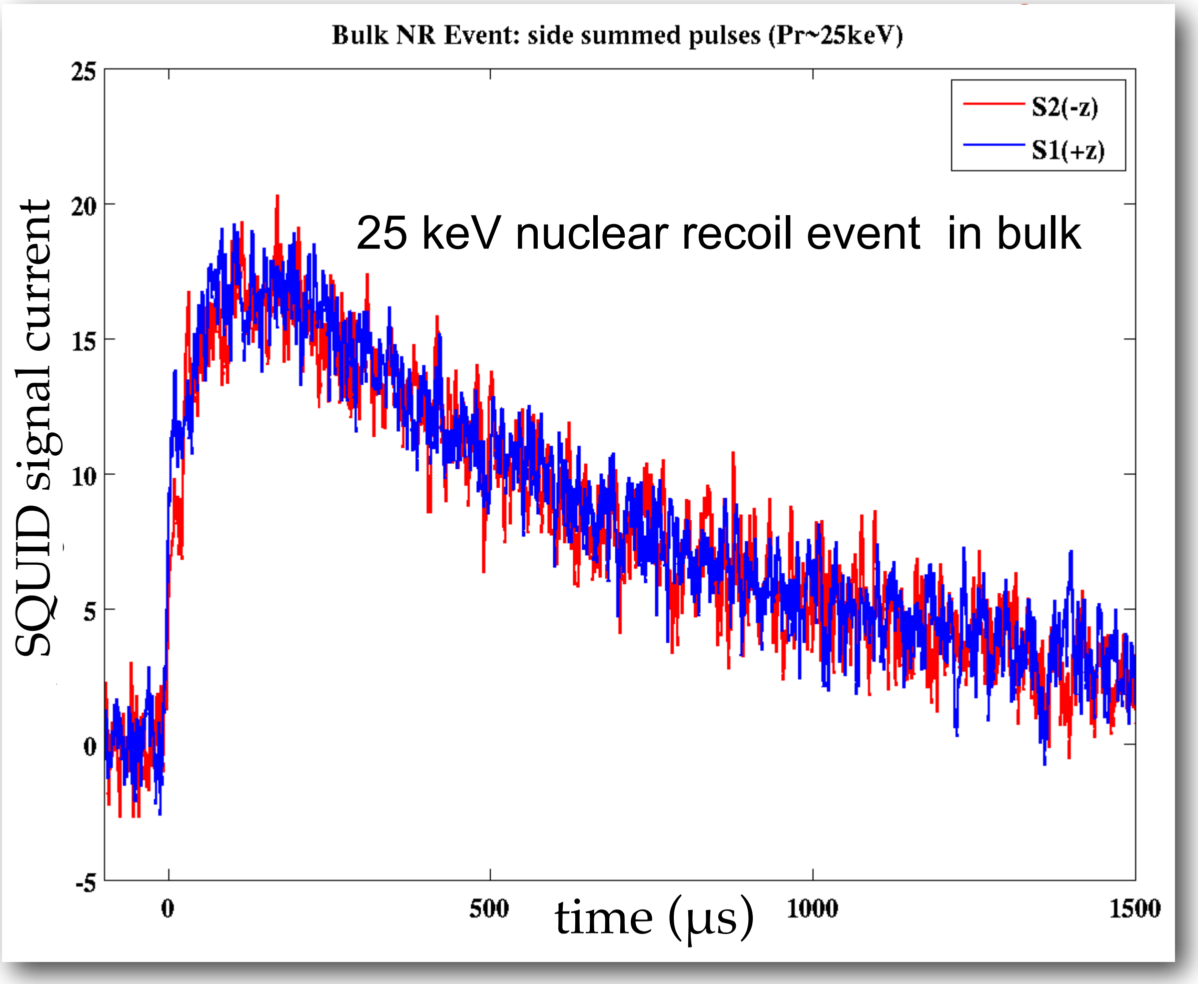


- 71,525 (38,178) electrons and 16,258 (7,007) ^{206}Pb recoil surface event collected from ^{210}Pb source in 905.5 (683.8) live hours
- In ~800 live hours 0 events leaking into the signal region (< 1.7 x 10^{-5} @90% C.L. misID)

- ~50% fiducial volume (8-115 keVr)
- <0.6 events in 0.3 ton-years
- Good enough for a 200 kg experiment run for 4 years at SNOLAB!

SuperCDMS: Phonon Signal





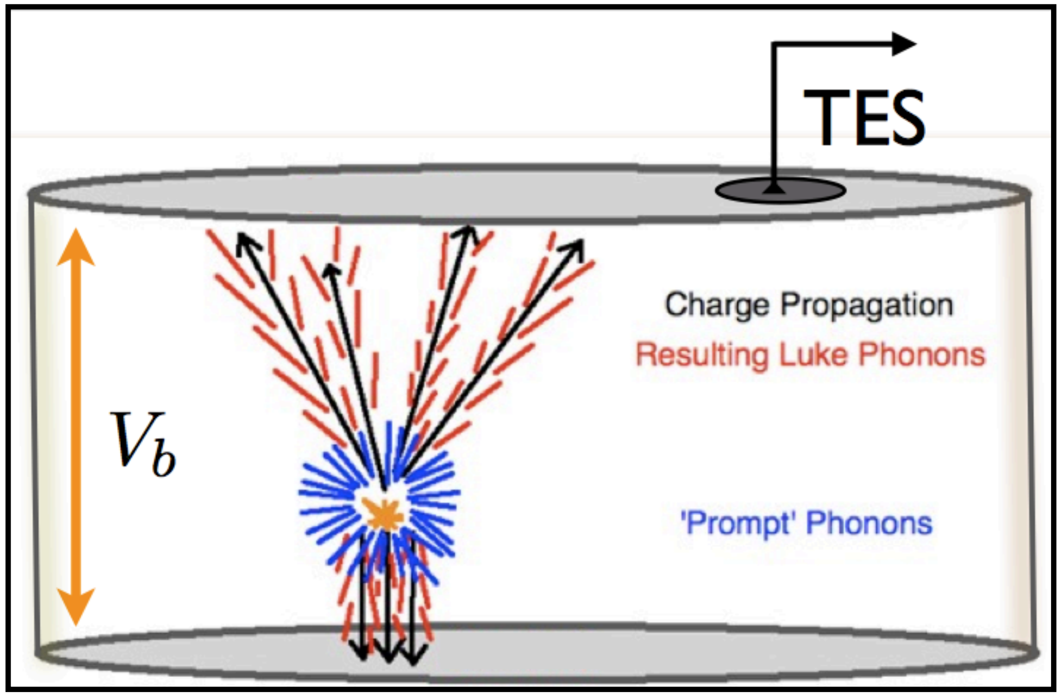
- Phonon timing pulse information still possible.
  - Surface electron vs bulk nuclear recoil event discrimination
- PULSE SHAPE HAS NOT YET BEEN USED! (It's not needed.)

A Low Ionization Experiment

- CDMSlite strategy leverages Neganov-Luke amplification to obtain low thresholds with high-resolution
  - Ionization only, uses phonon instrumentation to measure ionization
  - no event-by- event discrimination of nuclear recoils
- Drifting N_e electrons across a potential, V, generates qN_eV electron volts of heat

$$N_e = \frac{E_i}{\epsilon}$$

where $\epsilon = 3eV$ in Ge.



- The work done drifting the charges can be detected as heat.

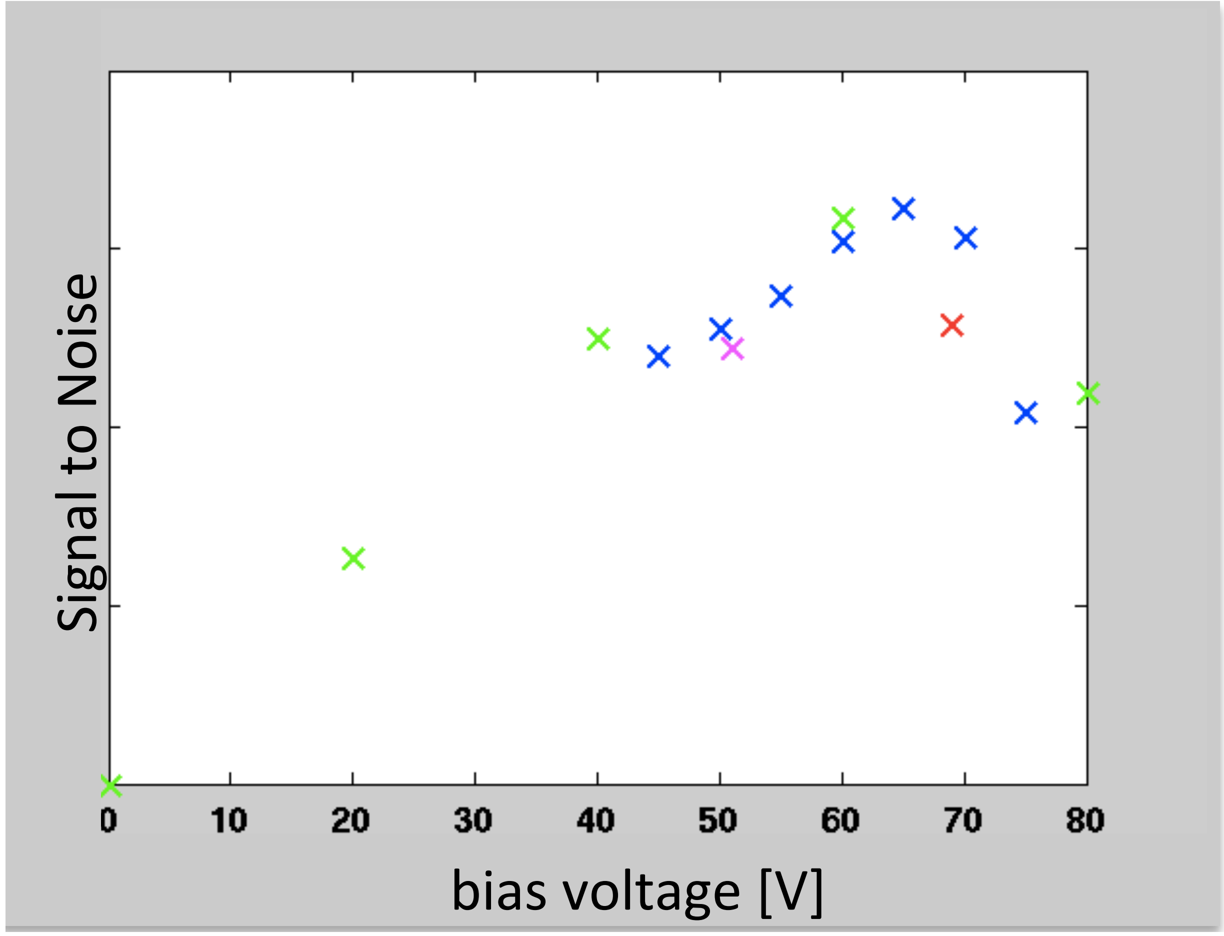
$$E_{luke} = N_{e/h} \times eV_b$$

- Luke energy scales as bias voltage and noise remains constant until breakdown

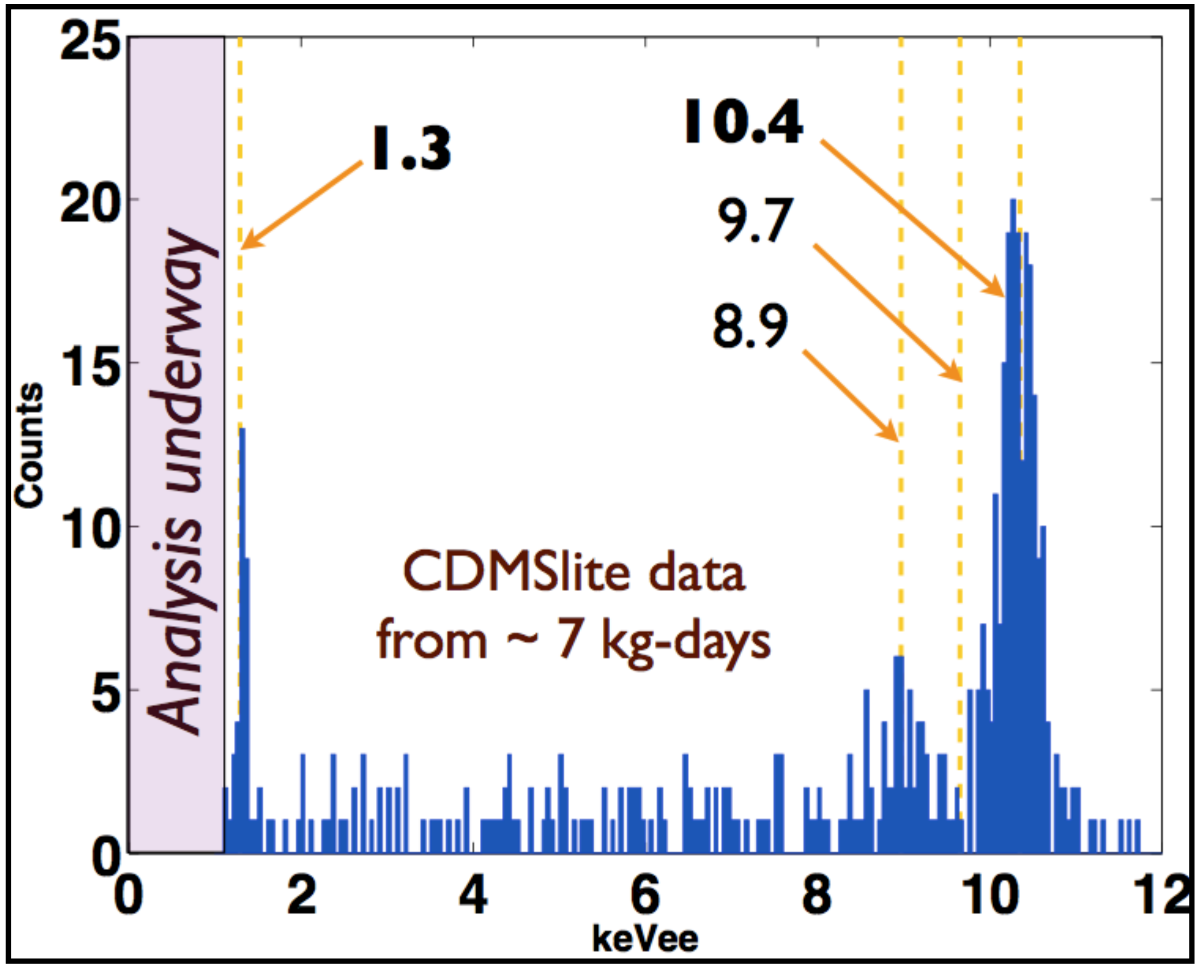
CDMSlite - The detector

- Custom electronics were installed to allow biases above 10V
  - Disable one side of iZIP and raising that entire side to the bias voltage.
- A voltage scan indicated 69 V was the optimal operating voltage.
  - At low voltage, the signal increases linearly with no charge noise.
  - At high voltage onset of leakage current increases the phonon noise.
- The signal gain at 69V is substantial.

$$G^* = \frac{E_t(V = 69)}{E_t(V = 0)} = \frac{1 + qN_eV}{1} = 24$$



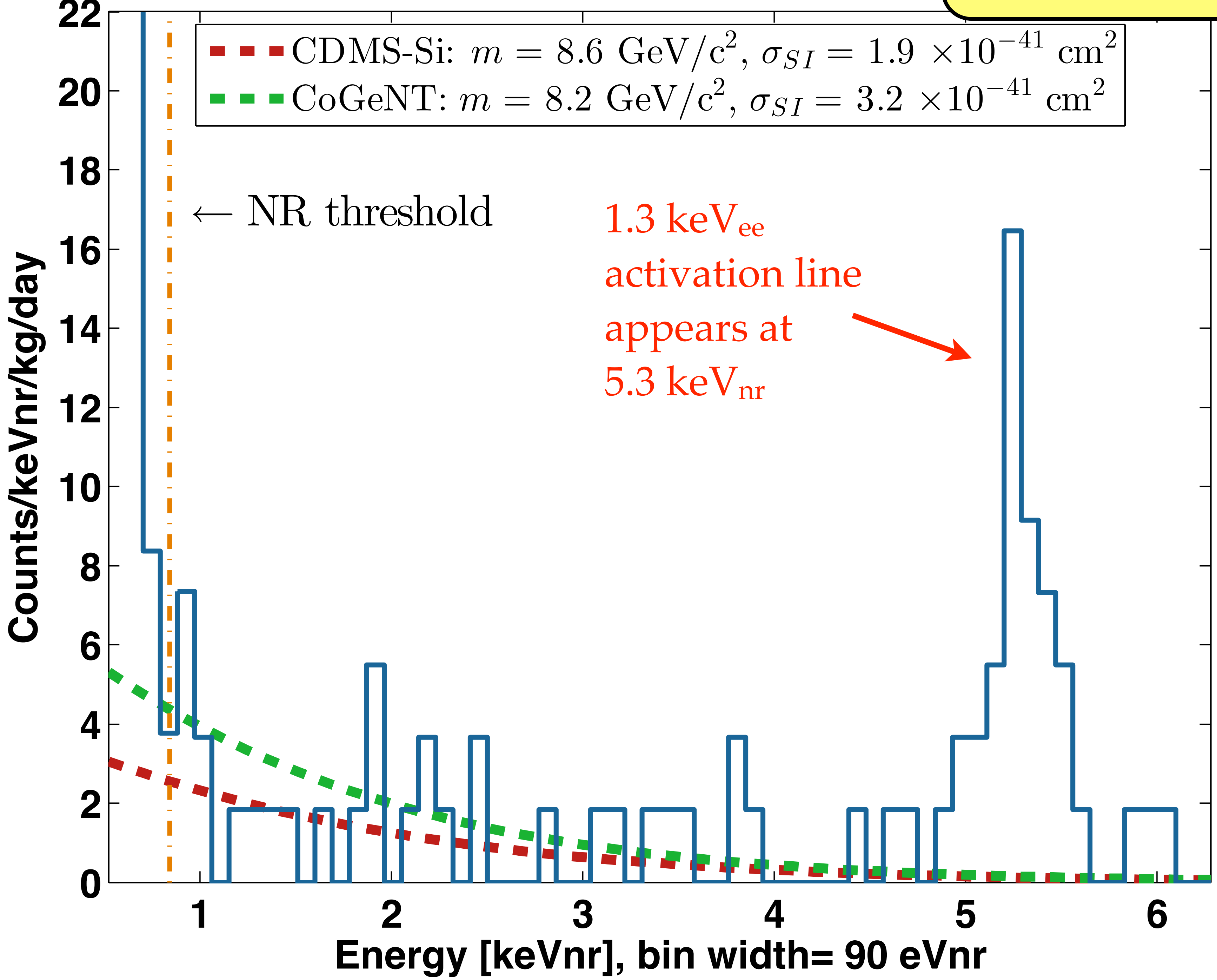
CDMSlite



- Voltage assisted calorimetric ionization detection can improve energy resolution and threshold of bolometric devices.
- Resulting Luke amplification has excellent energy resolution potentially down to 14 eeV_{ee}.
- Resolution of various Ge activation lines.

CDMSlite: Results

Accepted PRL.
arXiv: 1309.3259



Nuclear recoils create fewer charges than electron recoils.

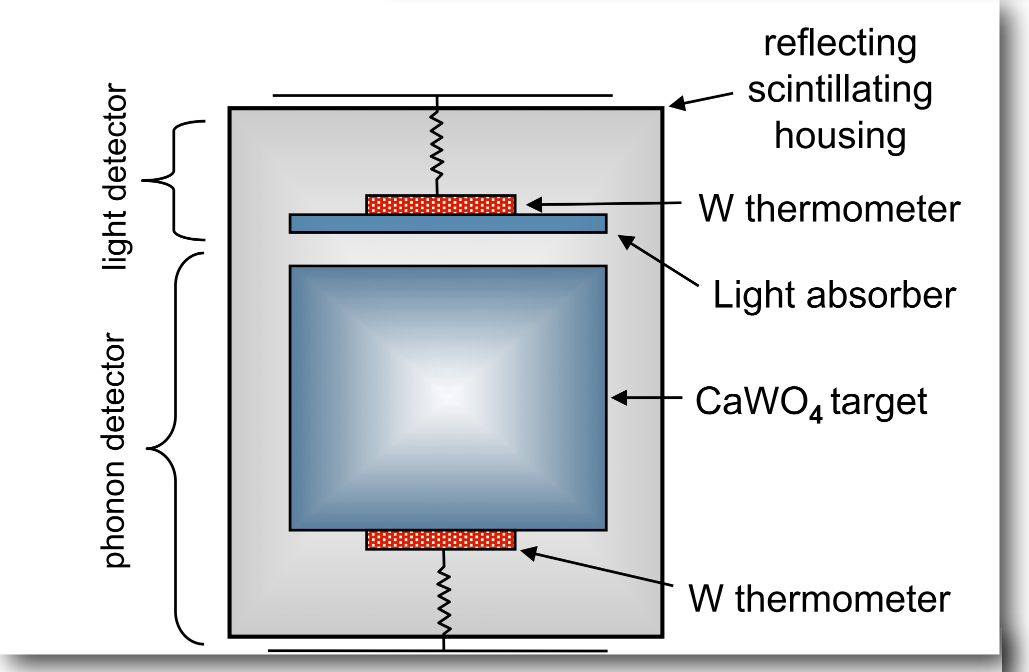
Conversion keVee to keVnr

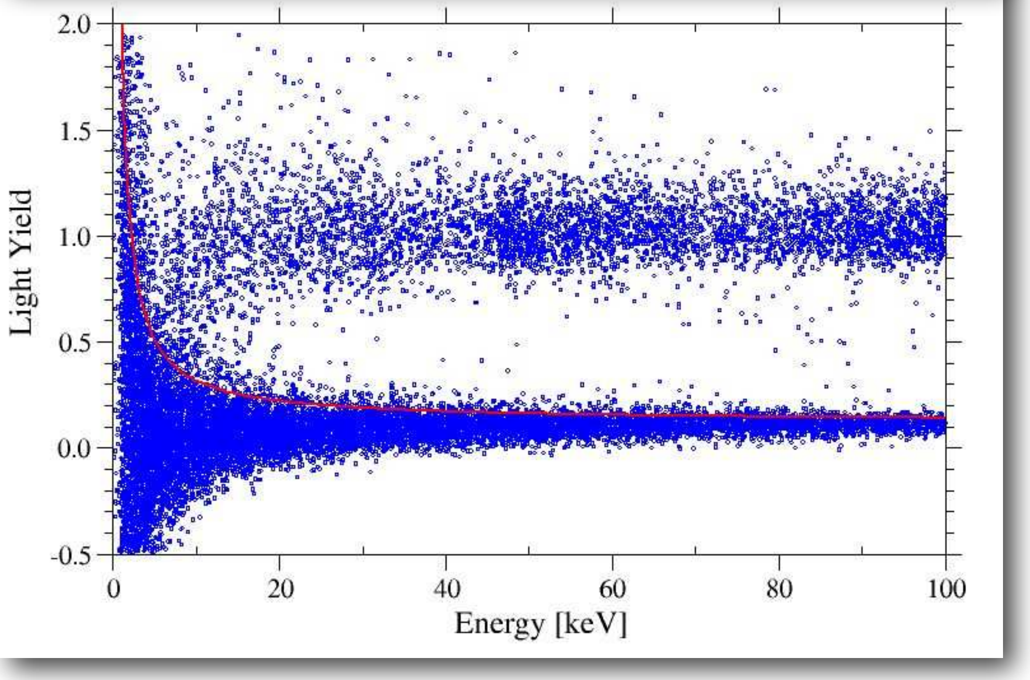
$$E_{nr} = E_{ee} \frac{1 + \frac{eV_b}{\epsilon}}{1 + \frac{eV_b}{\epsilon} Y(E_{nr})}$$

where Y is the ionization yield, defined to be unity for electron recoils.

CRESST

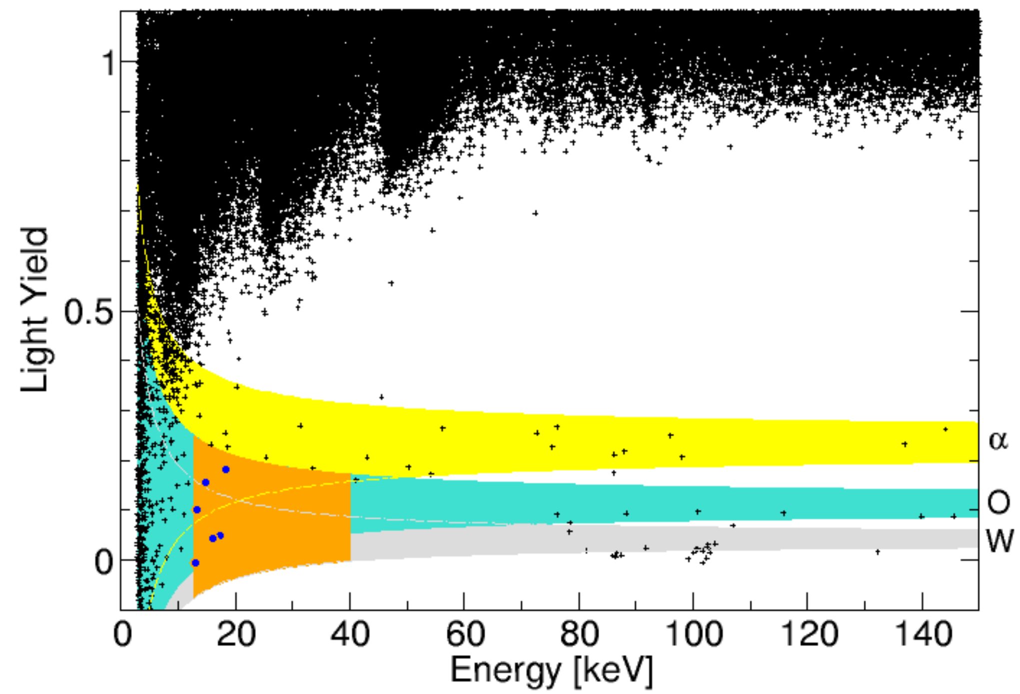
- Cryogenic $CaWO_4$ crystals are instrumented to readout phonon energy and scintillation.
  - operated at ~10 mK
  - each crystal ~ 300 g
- Located in Laboratori Nazionali del Gran Sasso, Italy
- Discrimination between ER and NR events via light yield (light/phonon energy)
- Signal expected to produce nuclear recoils
- Dominant background from radioactivity produces electron recoils.





CRESST-II Data Analysis

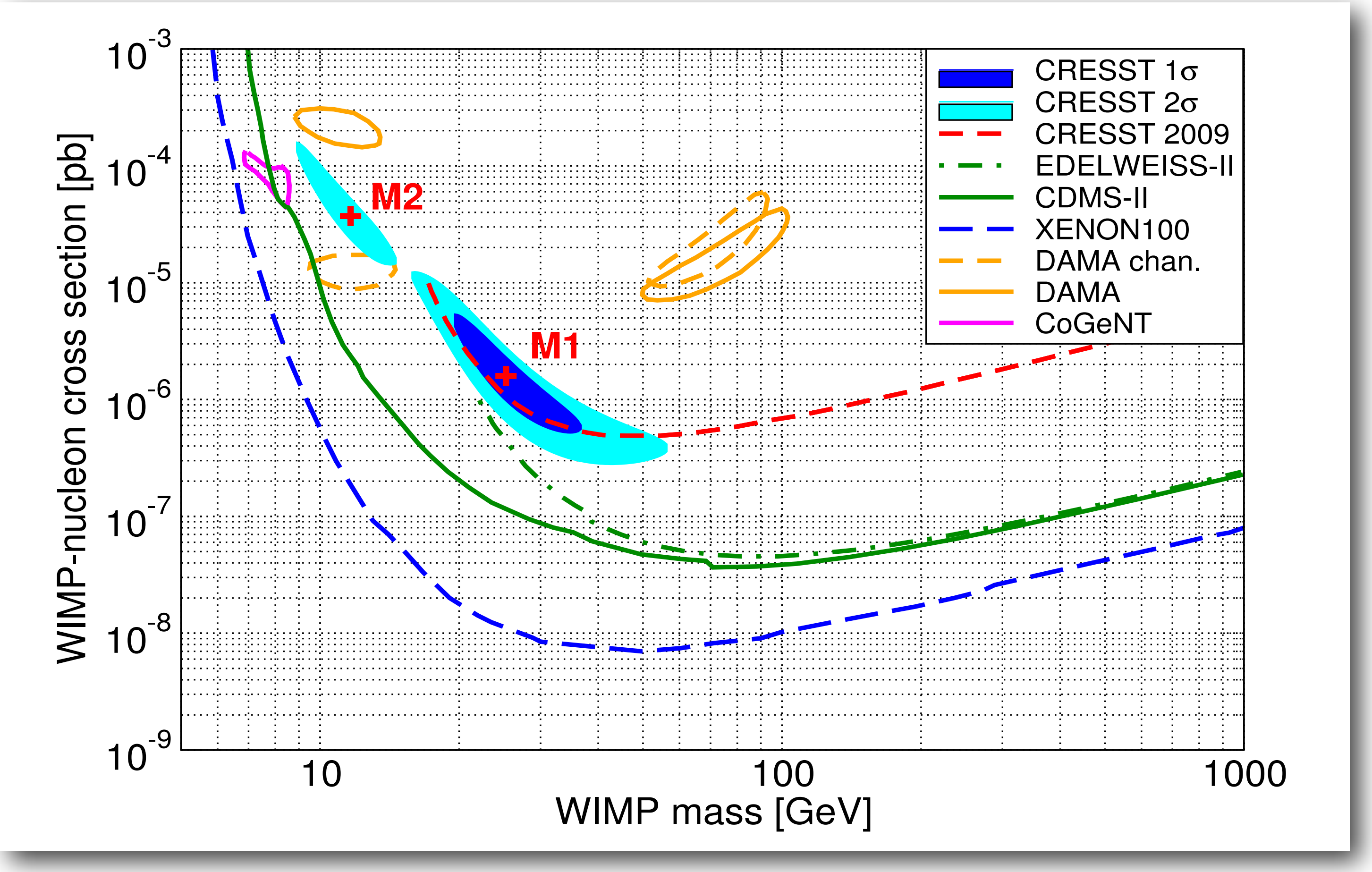
- Net exposure: 730 kg-day (July 2009 - March 2011) from 8 detector modules.
- Observed 67 events in acceptance region (orange).
- Analysis used a maximum likelihood in which 2 regions favored a WIMP signal in addition to predict background.
    - M1 is global best fit (4.7 σ)
    - M2 slightly disfavored (4.2 σ)
- Excess events can not be explained by known backgrounds
- Large background contribution



	M1	M2
e/γ events	8.00 ± 0.05	8.00 ± 0.05
α events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

CRESST Plans

- Current data run aims to reduce background, increase detector mass.
  - Alphas - new clamping design and material
  - Detector assembly in a radon free environment
  - New detector design to discriminate ^{206}Po recoils
  - Add additional shielding to reduce neutron background



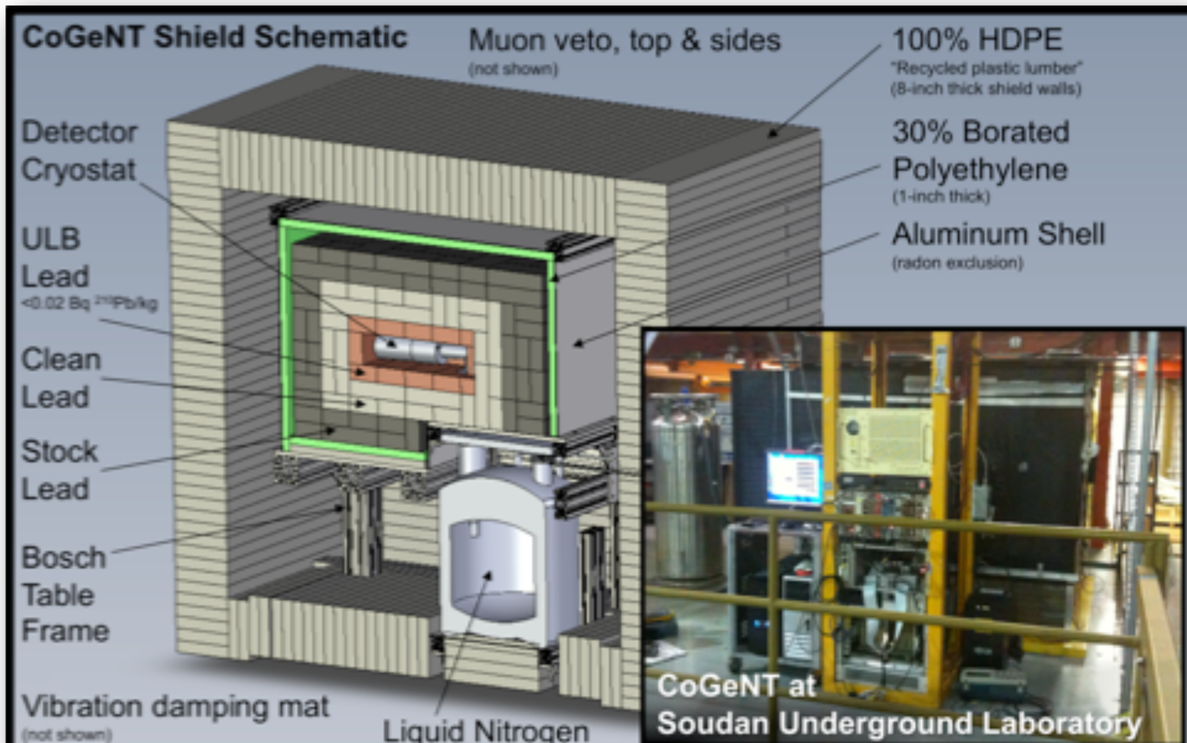
arXiv:1109.0702

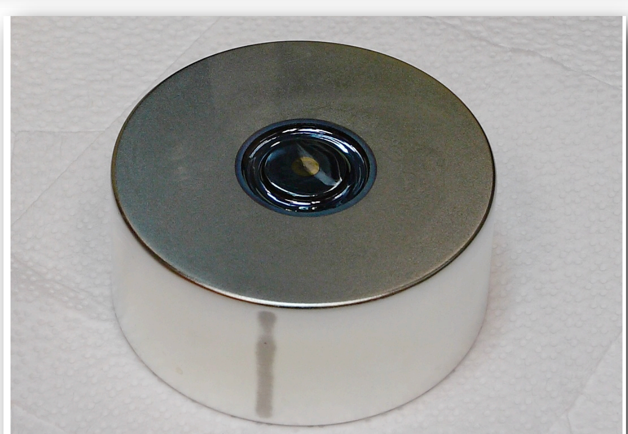
- June & July calibration runs with ^{57}Co source were successful.
- **July 30th, 2013 Science Runs Begin!**

Ionization Only Experiments

CoGeNT, TEXANO, IGEX and others

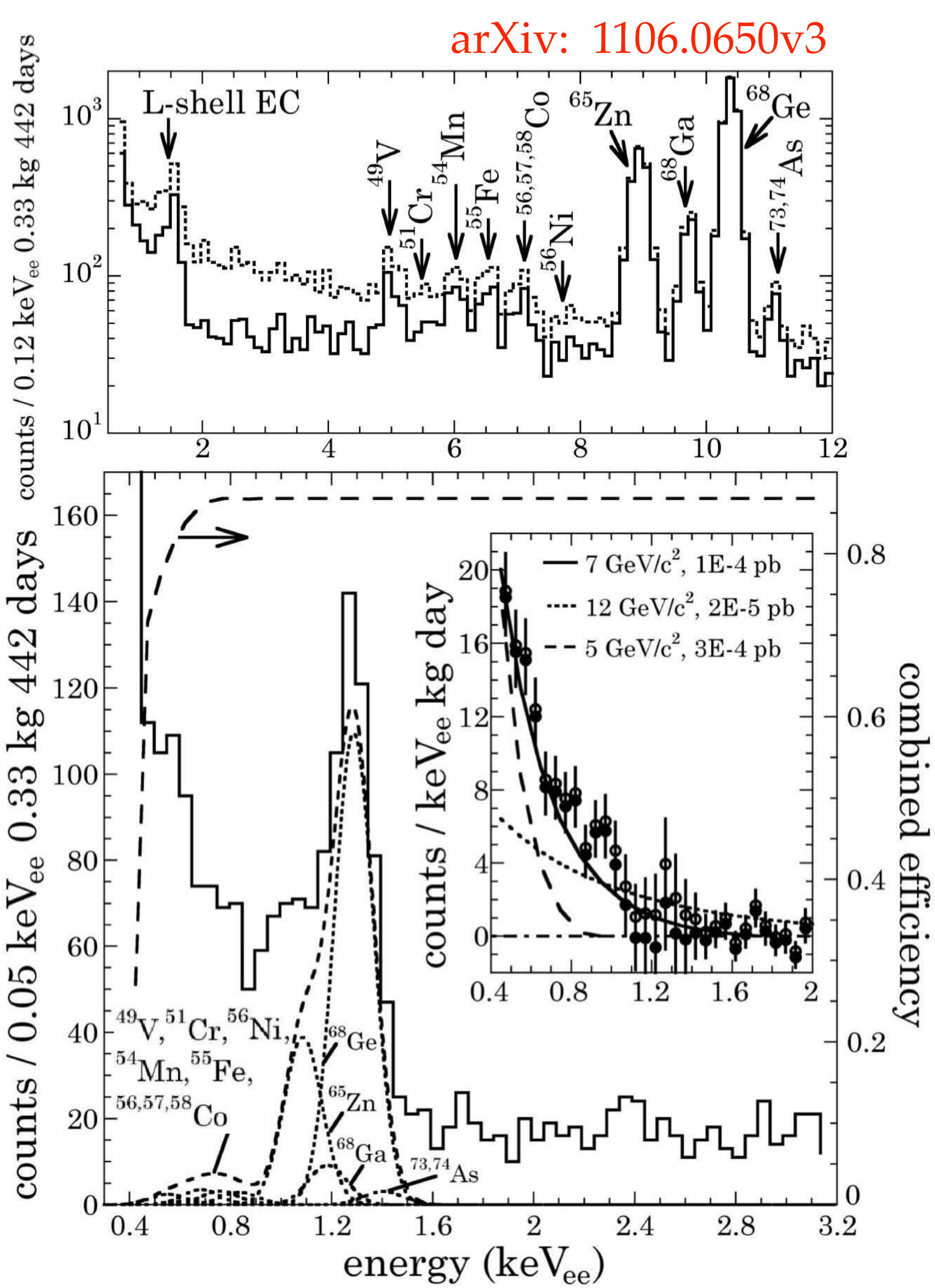
CoGeNT





- Location: Soudan Underground Laboratory, Minnesota, USA
- 440 g HPGe ionization spectrometer
- Data collection from Dec. 4, 2009 - Mar. 6, 2011 (442 live days)
- Data collection interrupted due to fire.
- Data collection resumed July 2011.

CoGeNT

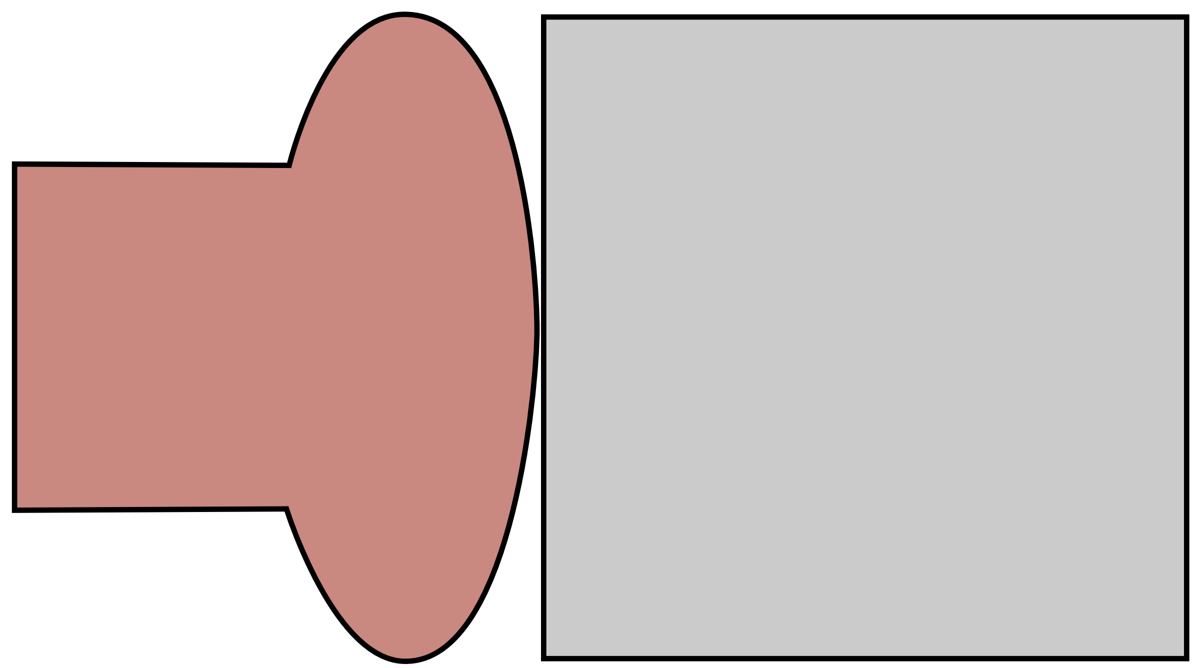


- First claim of excess in 2010.
- Reject surface events using risetime cut (2011).
- Peaks due to cosmogenic activation of Ge
- After subtraction of known background, an exponential excess of events remains
- Fits to a variety of light-WIMP masses and couplings shown in inset of lower figure.

Annual Modulation Experiments

DAMA, KIMS, DM-ICE
and others (CoGeNT, CDMS II, etc.)

NaI and CsI Scintillator

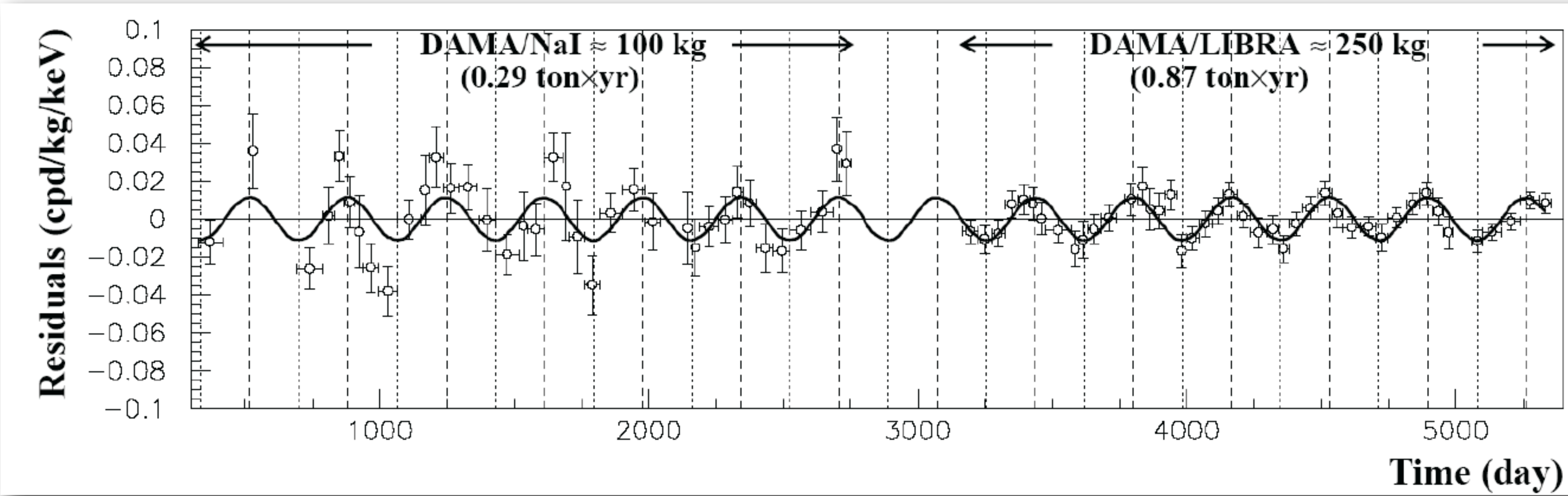


DAMA/LIBRA

- DAMA
  - 100 kg NaI array operated from 1996 - 2002 in Laboratori Nazionali del Gran Sasso.
  - Measures scintillation from particle interactions in detectors.

  - No discrimination between nuclear and electron recoils
  - Positive results reported in 1998.
- LIBRA
  - 250 kg array operating since 2003 with first results in 2008.

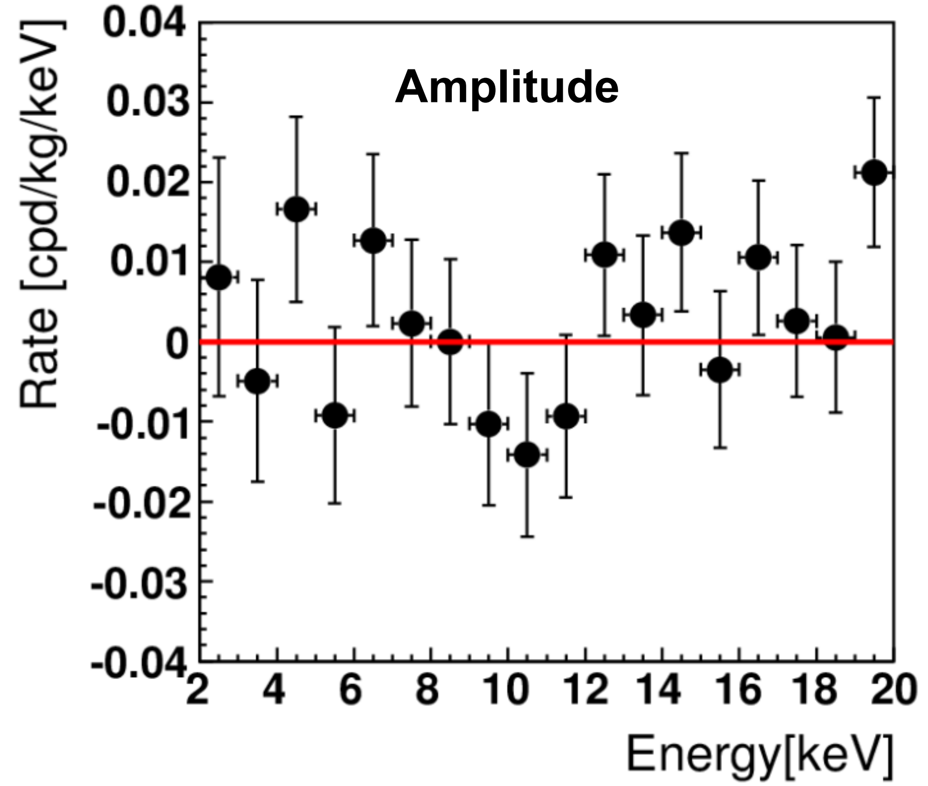
DAMA/LIBRA

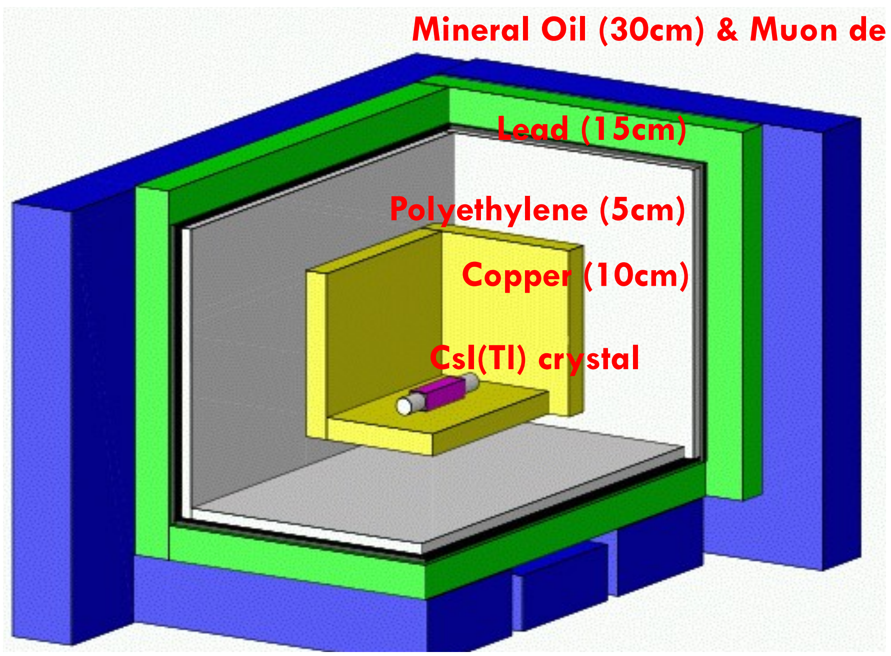


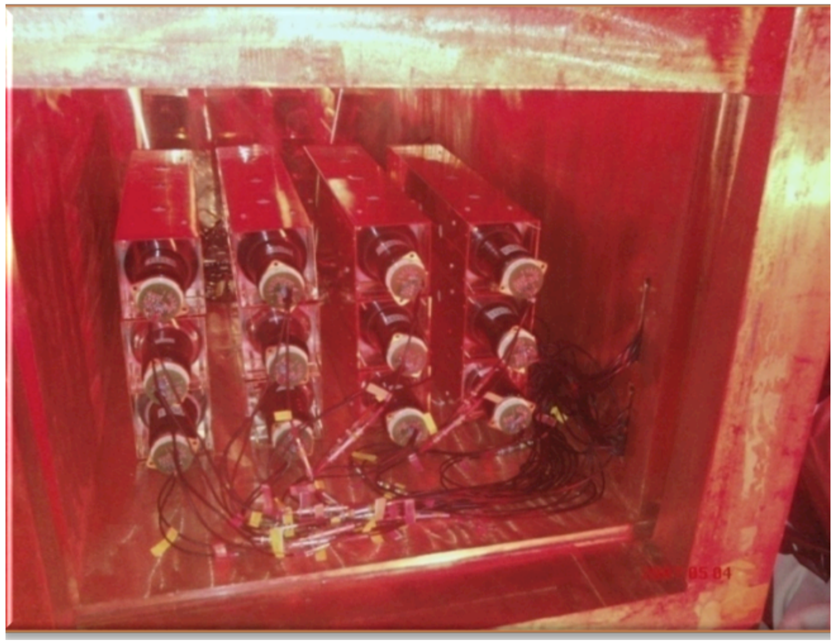
- Modulation has been observed over 13 cycles.
- Significance is 8.9σ.
- Signal is observed only in lowest energy bin.

KIMS

- Direct comparison to DAMA annual modulation signal using CsI(Tl) crystals
    - Pulse shape discrimination also possible
- 12 crystals (104.4 kg) installed
- Data taking from Sept 2009 - Feb. 2012
- Pulse shape discrimination excludes DAMA/LIBRA - PRL 108, 181301 (2012)
- No annual modulation is observed.





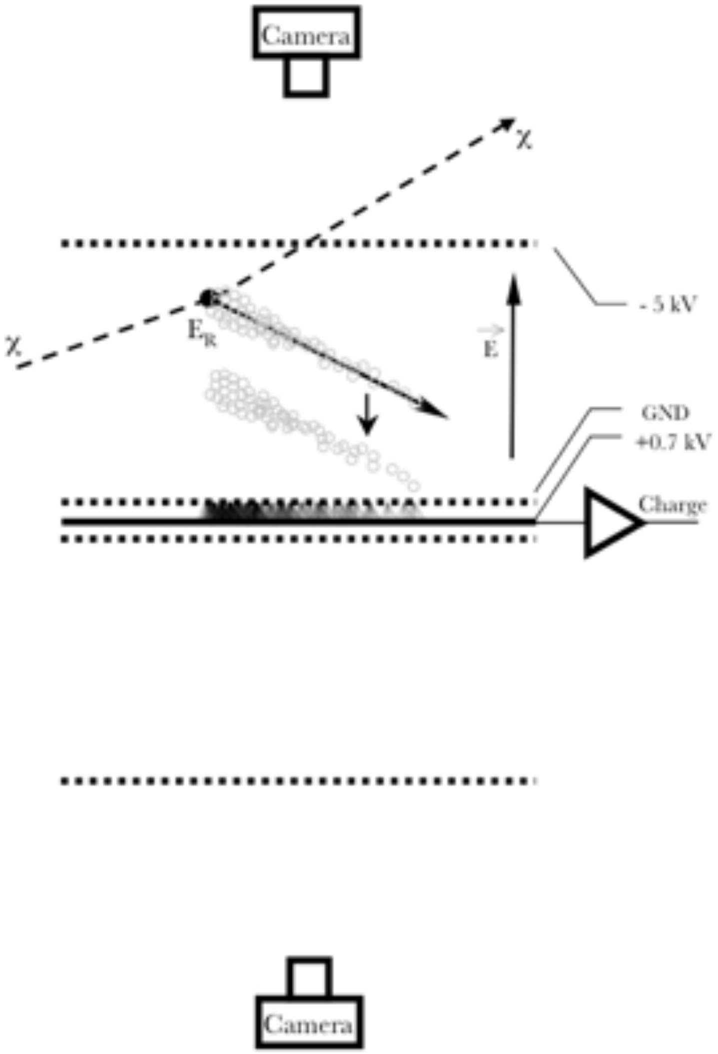


Directional Experiments

DMTPC, DRIFT, MIMAC, NEWAGE,
and others

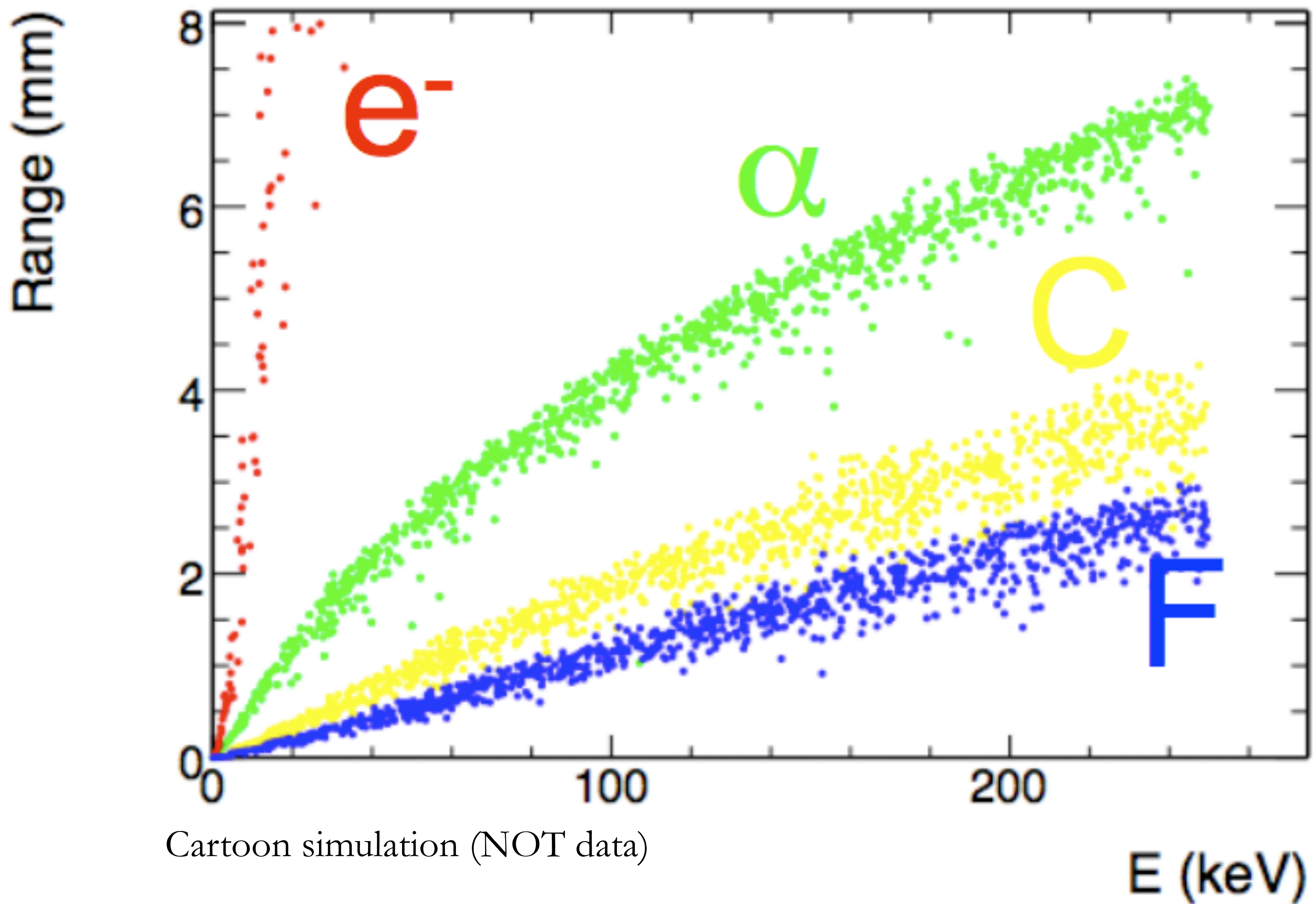
DMTPC

- 10 L prototype underground at WIPP in Carlsbad, NM, USA
- Filled with CF_4 gas to probe the WIMP-^{19}F spin-dependent cross-section
- Dark matter is identified by directional signal.
- In additional, electron recoils can be identified by their low ionization density (i.e. stopping power).



DM-TPC

PID with Range vs. Energy



Cartoon simulation (NOT data)

DMTPC

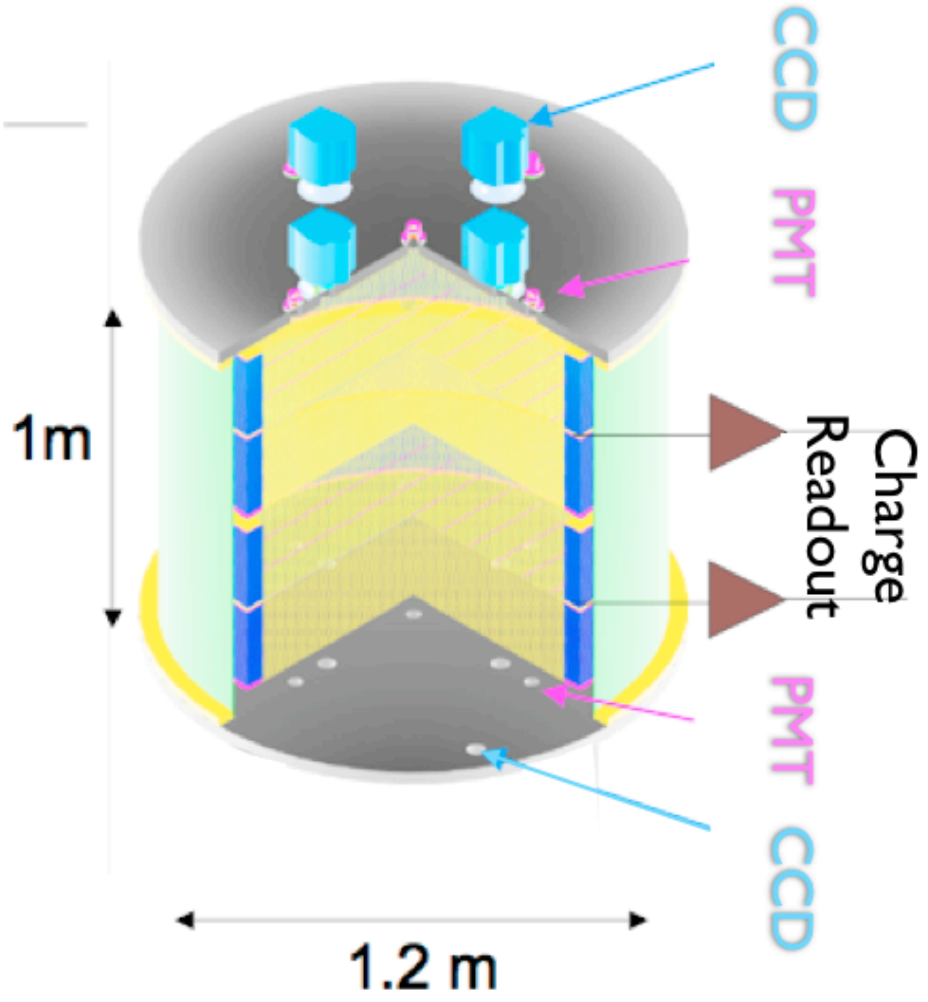
10L

Underground at WIPP

4Shooter (20L)

At MIT

DMTPCino (1 m^3)



Funded by NSF+DoE

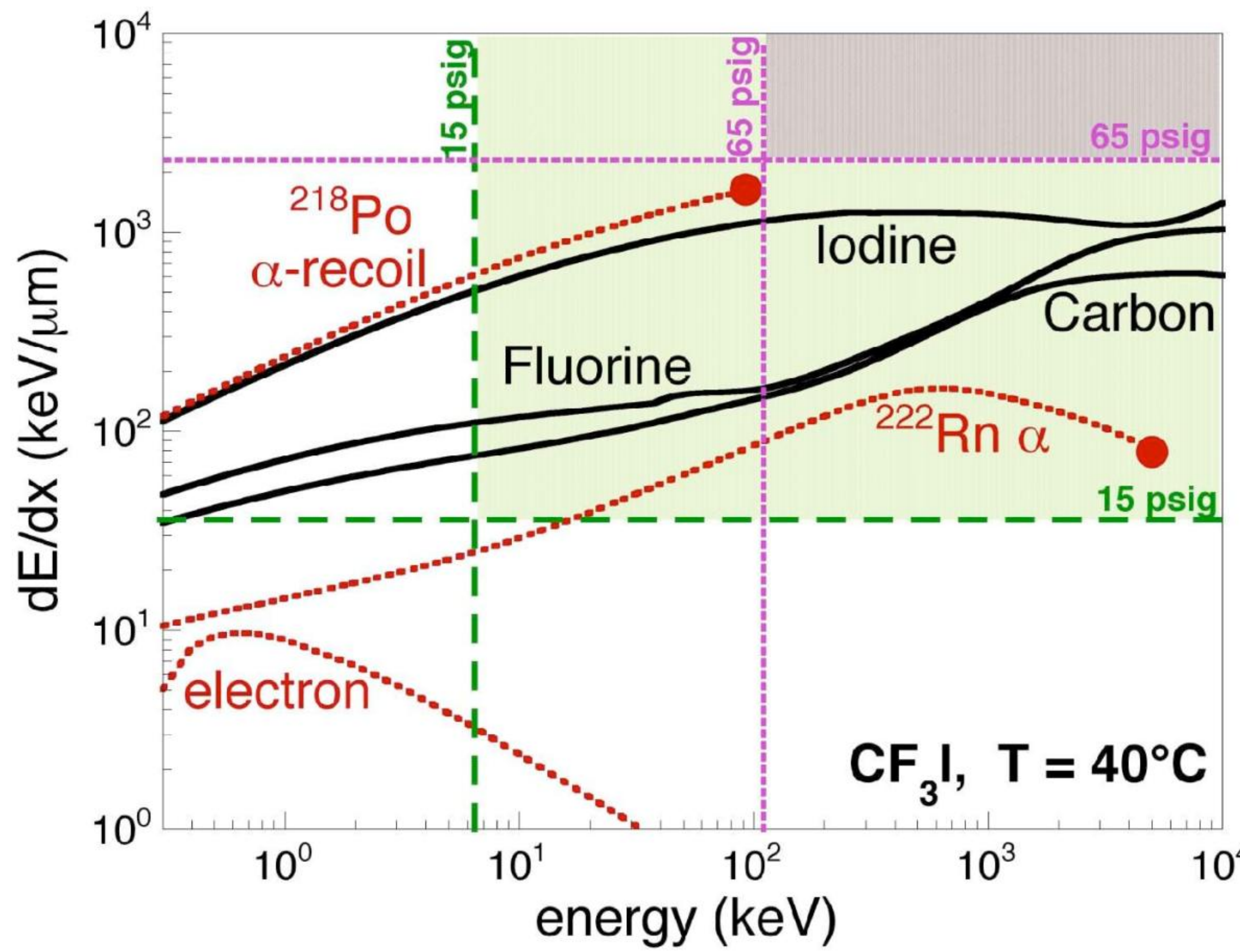
James Battat Bryn Mawr College

SuperHeated Gas/Gel Experiments

COUPP, PICASSO, SIMPLE and others

Particle Detection in Bubble Chambers

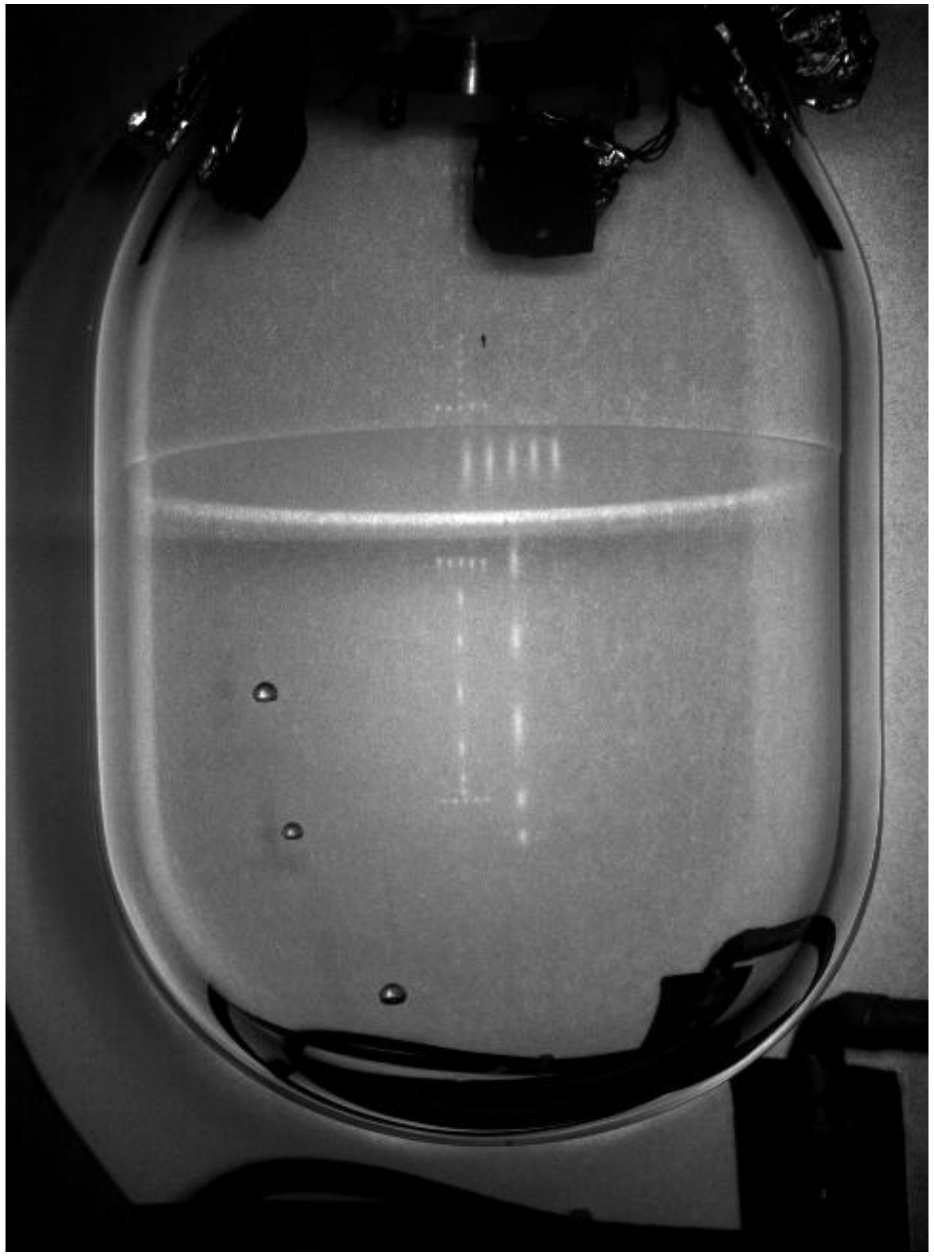
- A bubble chamber is filled with a superheated fluid in a metastable state.
- A particle interaction with energy deposition greater than E_{th} in a radius < r_c results in an expanding bubble.
- A smaller or more diffuse energy deposition will result in a bubble that immediately collapses.



- You can "tune" the chamber to make bubbles for nuclear recoils and not for electron interactions.

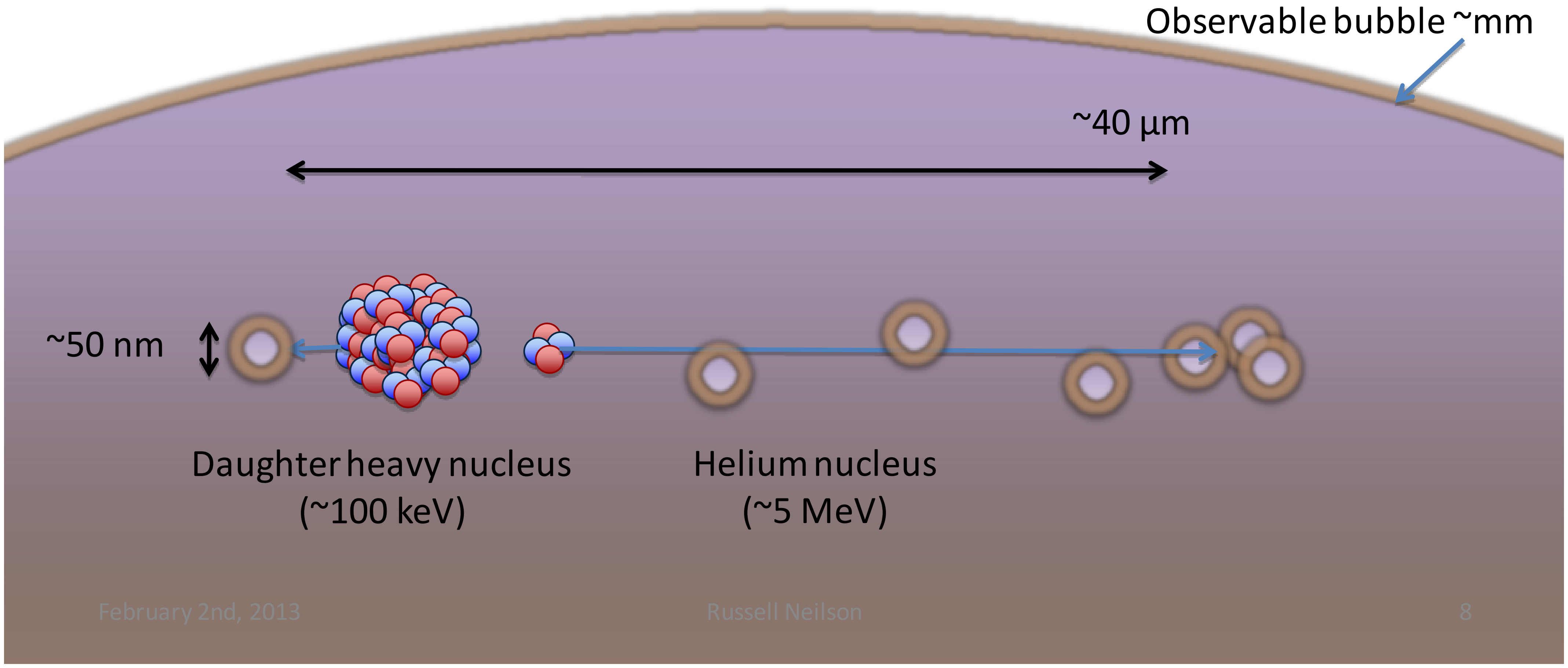
COUPP

- Superheated fluid CF_3I
  - F for spin-dependent interactions
  - I for spin-independent interactions
  - Target can be swapped out
- Bubbles are observed by two cameras and piezo-acoustic sensors
- Better than 10^{-10} rejection of electron recoils
- Alphas can be a concern. However, they can be rejected by acoustic discrimination.

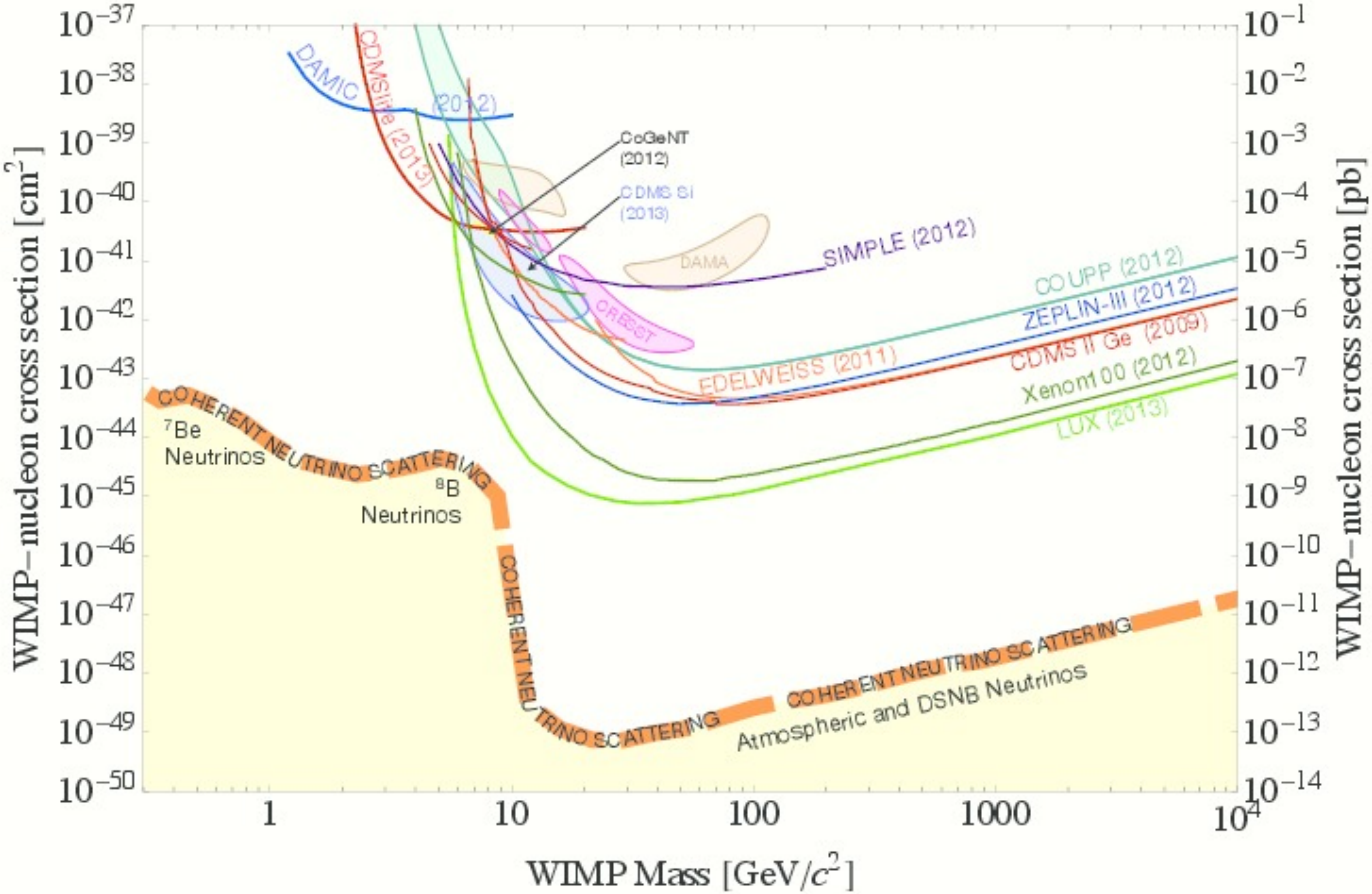


COUPP

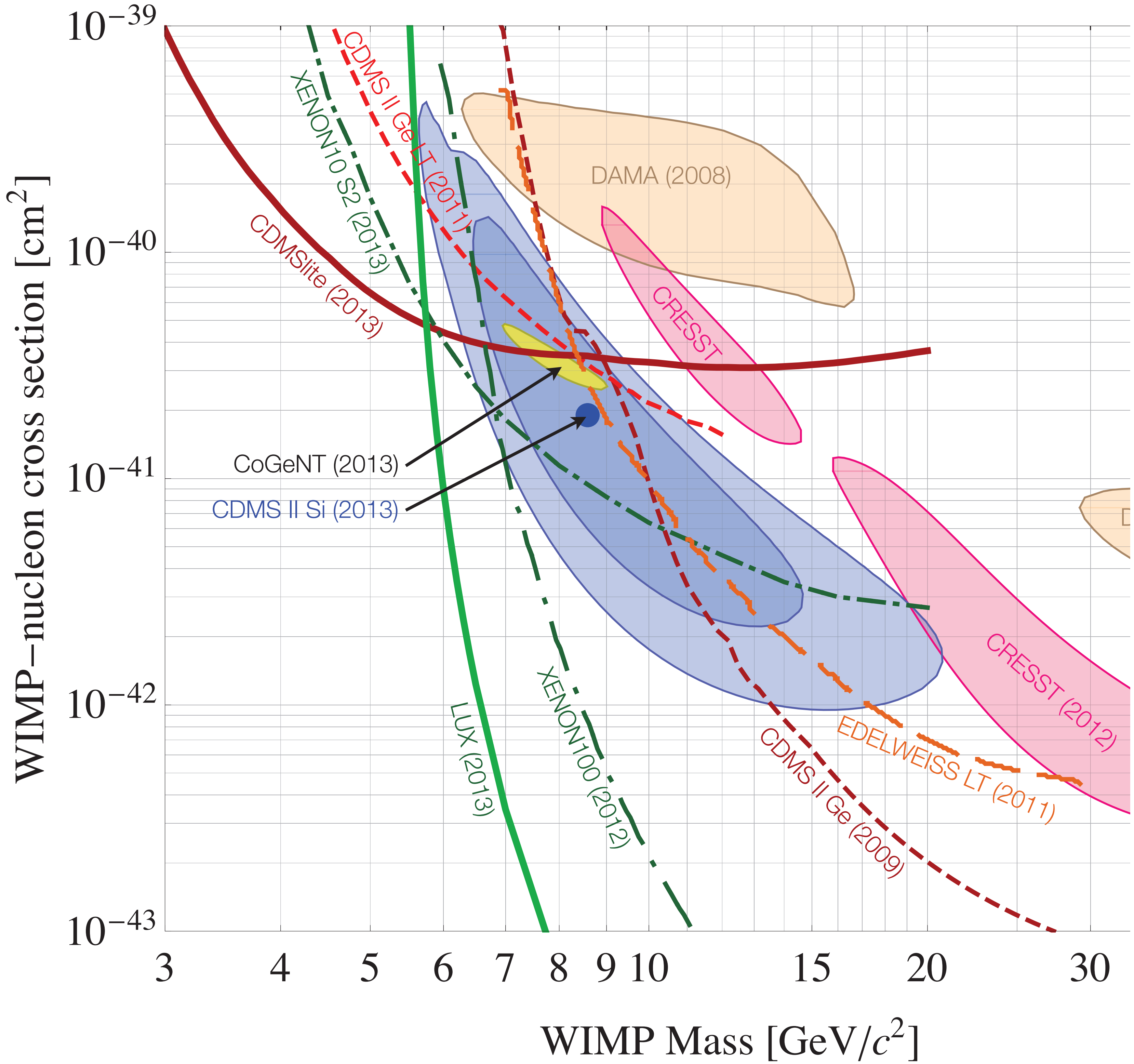
- Alphas deposit their energy over 10s of microns.
- Nuclear recoils deposit their energy over 10s of millimeters
- Alpha particles are louder than nuclear recoils. This can be measured by piezoelectric sensors.



Where does that leave us?

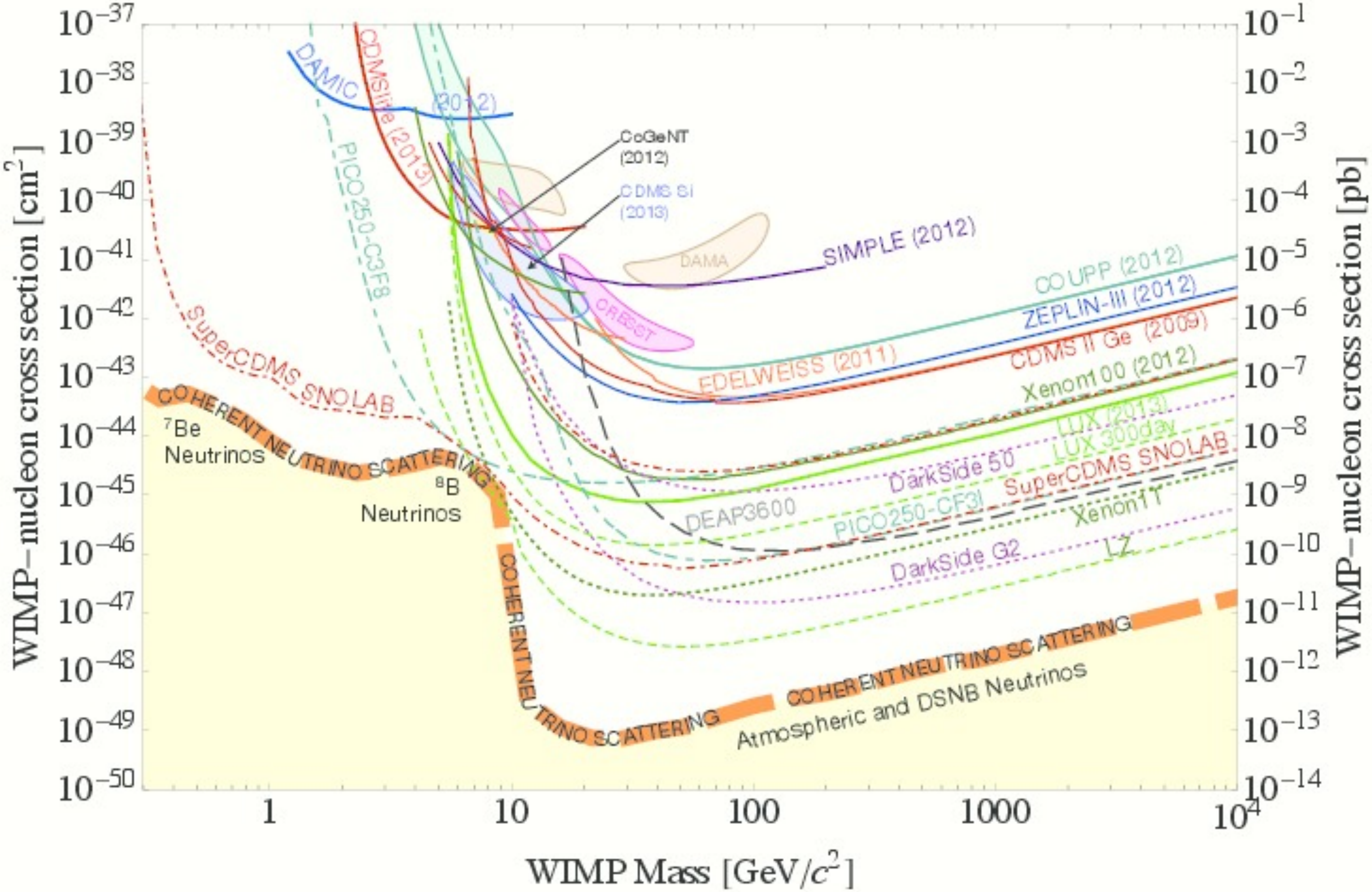


WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
DAMIC
CDMSlite (2013)
(2012)
CoGeNT
(2012)
CDMS Si
(2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
Xenon100 (2012)
LUX (2013)
EDELWEISS (2011)
CRESST
COHERENT NEUTRINO SCATTERING
^{7}Be
Neutrinos
^{8}B
Neutrinos
Atmospheric and DSNB Neutrinos


WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
3
4
5
6
7
8
9
10
15
20
30
DAMA (2008)
CRESST
CRESST (2012)
CDMS II Ge LT (2011)
XENON10 S2 (2013)
CDMSlite (2013)
CoGeNT (2013)
CDMS II Si (2013)
LUX (2013)
XENON100 (2012)
CDMS II Ge (2009)
EDELWEISS LT (2011)

Where are we going?

SNOWMASS 2013



Further Reading

- Classic Papers on specific calculations
  - Lewin, Smith, Astroparticle Physics 6 (1996) 87-112
  - Kurylov and Kamionkowski, Physical Review D 69, 063503 (2004)
  - G. Jungman, M. Kamionkowski, K. Griest, Phys. Rep. 267 (1996) 195-373, arXiv:hep-ph/9506380
- Books/Special Editions that Overview the Topic of Dark Matter
  - Bertone, Particle Dark Matter Observations, Models and Searches, Cambridge University Press, 2010. ISBN 978-0-521-76368-4
  - Physics of the Dark Universe, vol 1, issues 1-2, Nov. 2012 (http://www.journals.elsevier.com/physics-of-the-dark-universe/)