Non-Directional Direct Dark Matter Detection Experimental Techniques

Jodi Cooley
Southern Methodist University
Dallas, Texas

Outline

- Part 1: General Principles
    - Rates, backgrounds, signals, etc
- Part 2: Direct Detection Searches
    - Liquid Nobles
    - Cryogenic Detectors
    - Other Novel Technologies

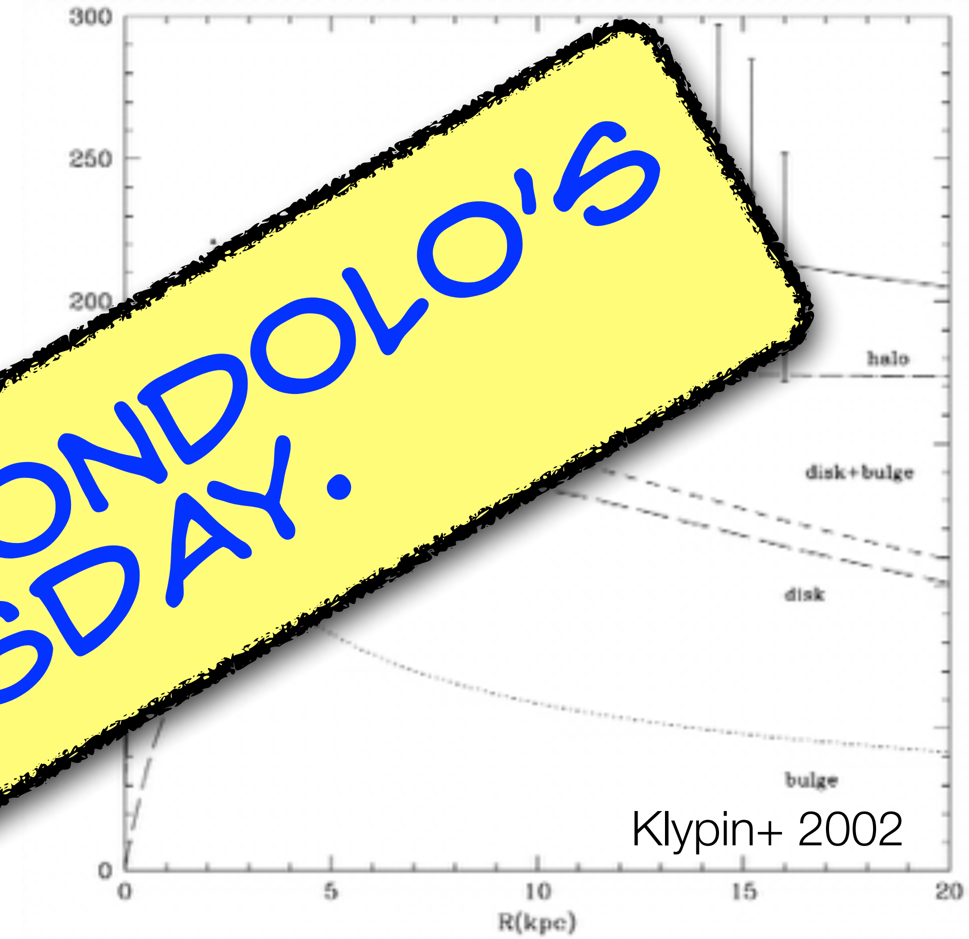
Further Reading

- 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/)

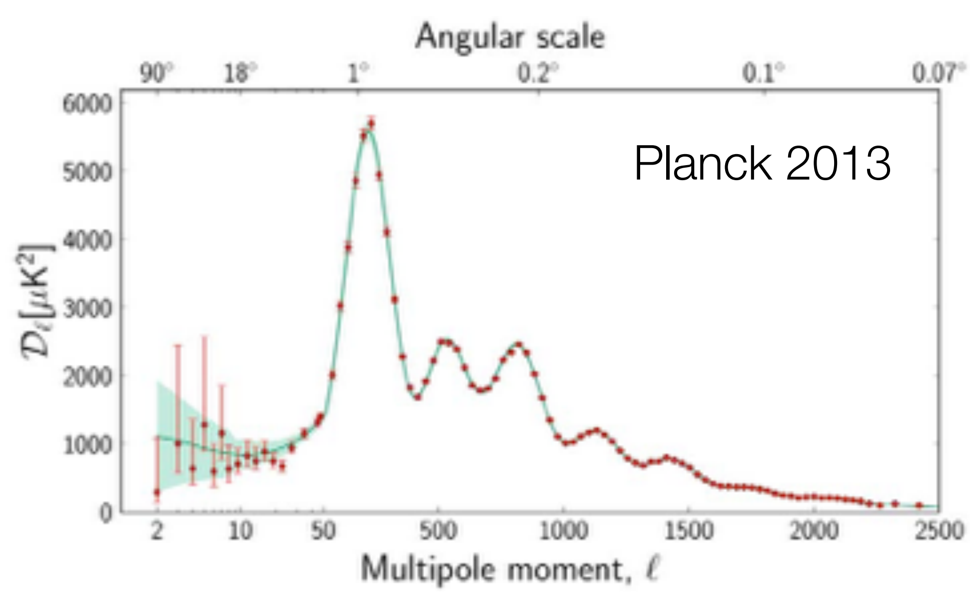
The Nature of Dark Matter

- **The Missing Mass Problem:**
  - Dynamics of stars, galaxies, and clusters
  - Rotation curves, gravitational lensing
  - Large Scale Structure formation
- **Wealth of evidence for a particle solutio**
  - Microlensing (MACHOs) mostly r
  - MOND has problems with B
- **Non-baryonic**
  - Height of acou … Ω_m)
  - Power s … tions (Ω_m)
  - P … s (Ω_b)
-
  - … l, non-relativistic
  - I … ts via gravity and (maybe) a weak force

DETAILS IN PAOLO GONDOLO'S TALK ON TUESDAY.



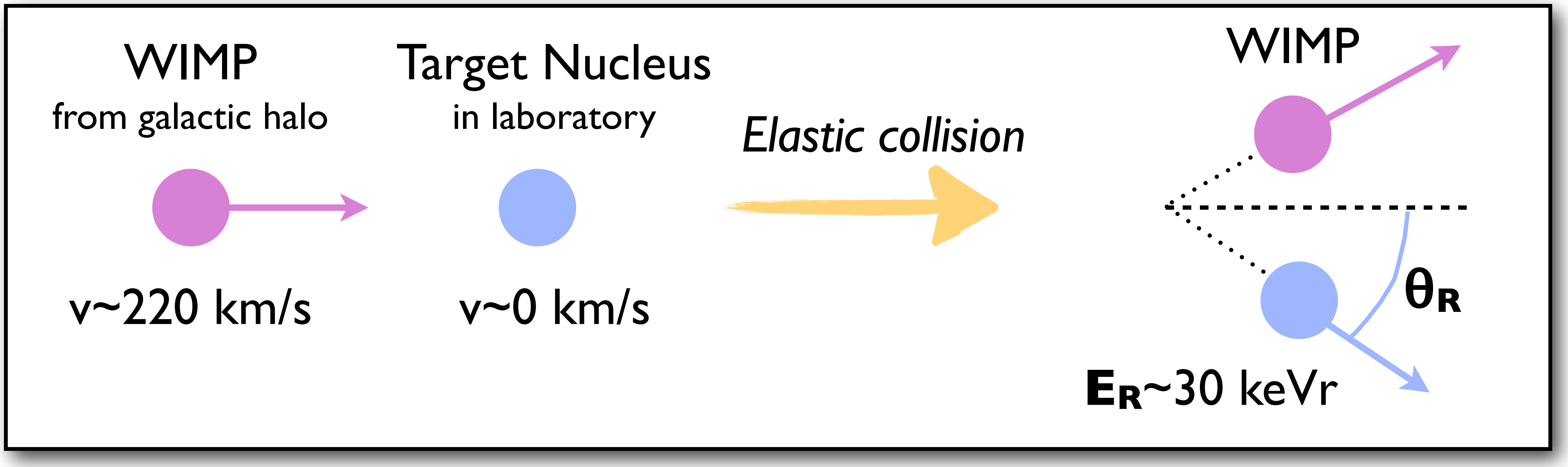
Klypin+ 2002



Planck 2013

Direct Detection Rates

Assume that the dark matter is not only gravitationally interacting (WIMP).



- Elastic scatter of a WIMP off a nucleus
  - Imparts a small amount of energy in a recoiling nucleus
  - Can occur via spin-dependent or spin-independent channels
  - Need to distinguish this event from the overwhelming number of background events

Event Rate

The differential event rate:

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

need input from astrophysics, particle physics and nuclear physics

local WIMP density

WIMP-nucleon scattering cross section

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

nucleus mass

WIMP mass

WIMP speed distribution in detector frame

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

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

Elastic scattering happens in the extreme non-relativistic case in the lab frame

$$E_R = \frac{\mu_N^2 v^2 (1 - \cos\theta^*)}{m_N}$$

where

$$\mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

reduced mass

WIMP-Nucleon Interaction

Event rate is found by integrating over all recoil:

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

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

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

The WIMP-nucleon cross section can be separated

$$\frac{d\sigma}{dE_R} = \left(\frac{d\sigma}{dE_R}\right)_{SI} + \left(\frac{d\sigma}{dE_R}\right)_{SD}$$

Spin-independent Spin-dependent

SI arise from scalar or vector couplings to quarks.

SD arise from axial vector couplings to quarks.

To calculate χ-N cross section, add coherently the spin and scalar components:

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\sigma_{SI} F_{SI}^2(E_R) + \sigma_{SD} F_{SD}^2(E_R)\right]$$

Spin-independent term Spin-dependent term

$F(E_R)$ = Form Factor encodes the dependence on the momentum transfer

WIMP-Nucleon Interaction

WIMP-nucleus cross sections:

$$\sigma_{SI} = \frac{4\mu^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2 \propto A^2$$

$$\sigma_{SD} = \frac{32\mu^2}{\pi} G_F^2 \frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

best sensitivity with high A

need a nucleus with spin

Nucleus	Z	Odd Nucleon	J	$\langle S_p\rangle$	$\langle S_n\rangle$	C^p_A/C_p	C^n_A/C_n
^{19}F	9	p	1/2	0.477	-0.004	9.10×10^{-1}	6.40×10^{-5}
^{23}Na	11	p	3/2	0.248	0.020	1.37×10^{-1}	8.89×10^{-4}
^{27}Al	13	p	5/2	-0.343	0.030	2.20×10^{-1}	1.68×10^{-3}
^{29}Si	14	n	1/2	-0.002	0.130	1.60×10^{-5}	6.76×10^{-2}
^{35}Cl	17	p	3/2	-0.083	0.004	1.53×10^{-2}	3.56×10^{-5}
^{39}K	19	p	3/2	-0.180	0.050	7.20×10^{-2}	5.56×10^{-3}
^{73}Ge	32	n	9/2	0.030	0.378	1.47×10^{-3}	2.33×10^{-1}
^{93}Nb	41	p	9/2	0.460	0.080	3.45×10^{-1}	1.04×10^{-2}
^{125}Te	52	n	1/2	0.001	0.287	4.00×10^{-6}	3.29×10^{-1}
^{127}I	53	p	5/2	0.309	0.075	1.78×10^{-1}	1.05×10^{-2}
^{129}Xe	54	n	1/2	0.028	0.359	3.14×10^{-3}	5.16×10^{-1}
^{131}Xe	54	n	3/2	-0.009	-0.227	1.80×10^{-4}	1.15×10^{-1}

Tovey et al., PLB488 17 (2000)

Standard Halo Model

- Energy spectrum and rate depend on details of WIMP distribution in the dark matter halo.

- Local Dark Matter Density

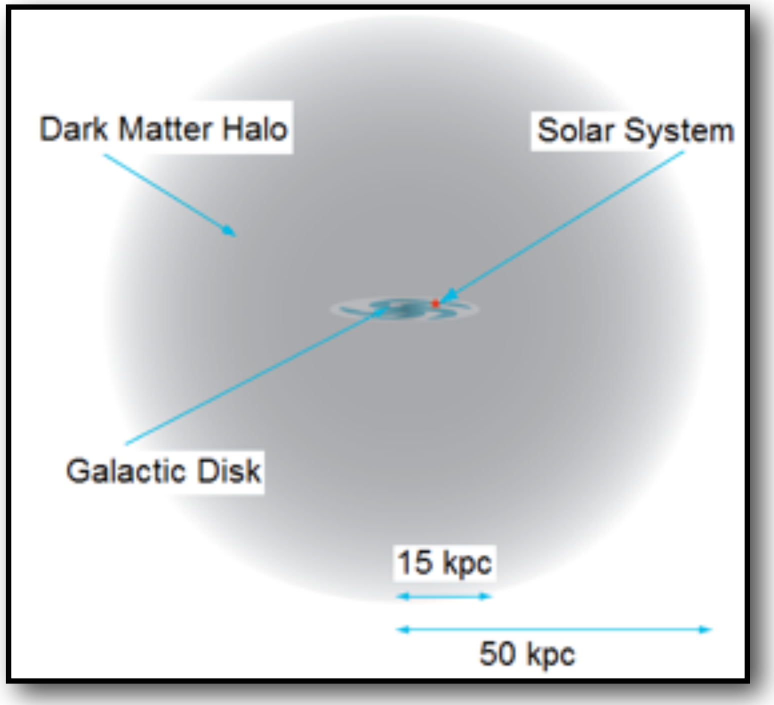
$$\rho_0 \equiv \rho(r = R_0) = 0.3 \;\; \mathrm{GeV/cm^3}$$

- Speed Distribution - isotropic, Maxwellian

$$f(\vec{v}) = \frac{1}{\sqrt{2\pi}\sigma} exp(-\frac{|\vec{v}|^2}{2\sigma^2})$$

where

$$\sigma = \sigma_{rms} = \sqrt{\frac{3}{2}} v_0 = 270 \,\mathrm{km/s} \quad \text{and} \quad v_0 = 220 \,\mathrm{km/s}$$



This corresponds to an isothermal sphere with density profile

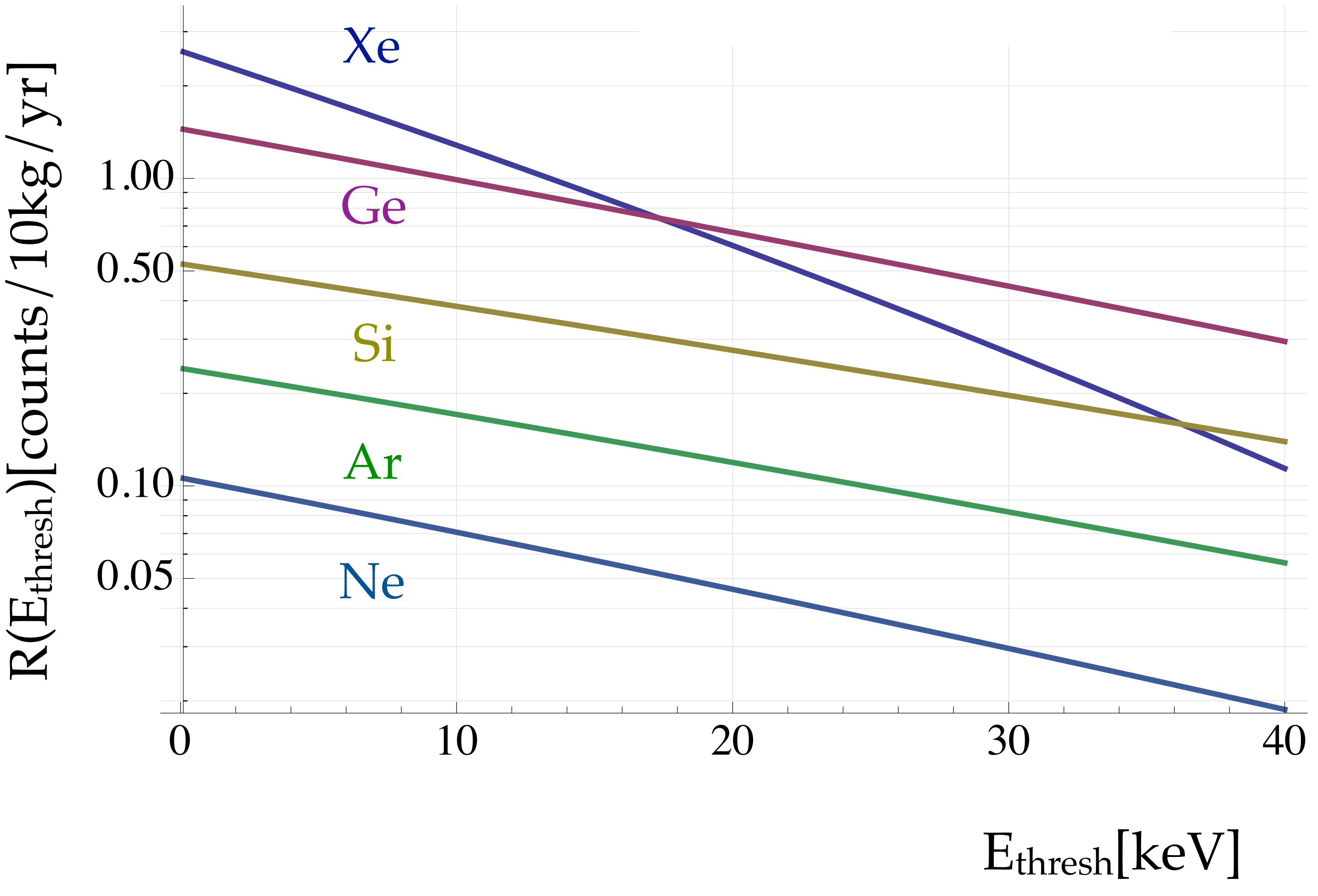
$$\rho \propto r^{-2}$$

- Note Particles with speed greater than the local escape speed are not gravitationally bound. The standard halo extends out to infinite radii and thus the speed distribution in this model must be truncated "by hand". We take v_{esc} = 650 km/s.

Event Rates

- Elastic scattering of WIMP deposits small amounts of energy into a recoiling nucleus (~few 10s of keV)
- Featureless exponential spectrum with no obvious peak, knee, break ...
- Event rate is very, very low.
- Radioactive background of mos materials is higher than the event rate.

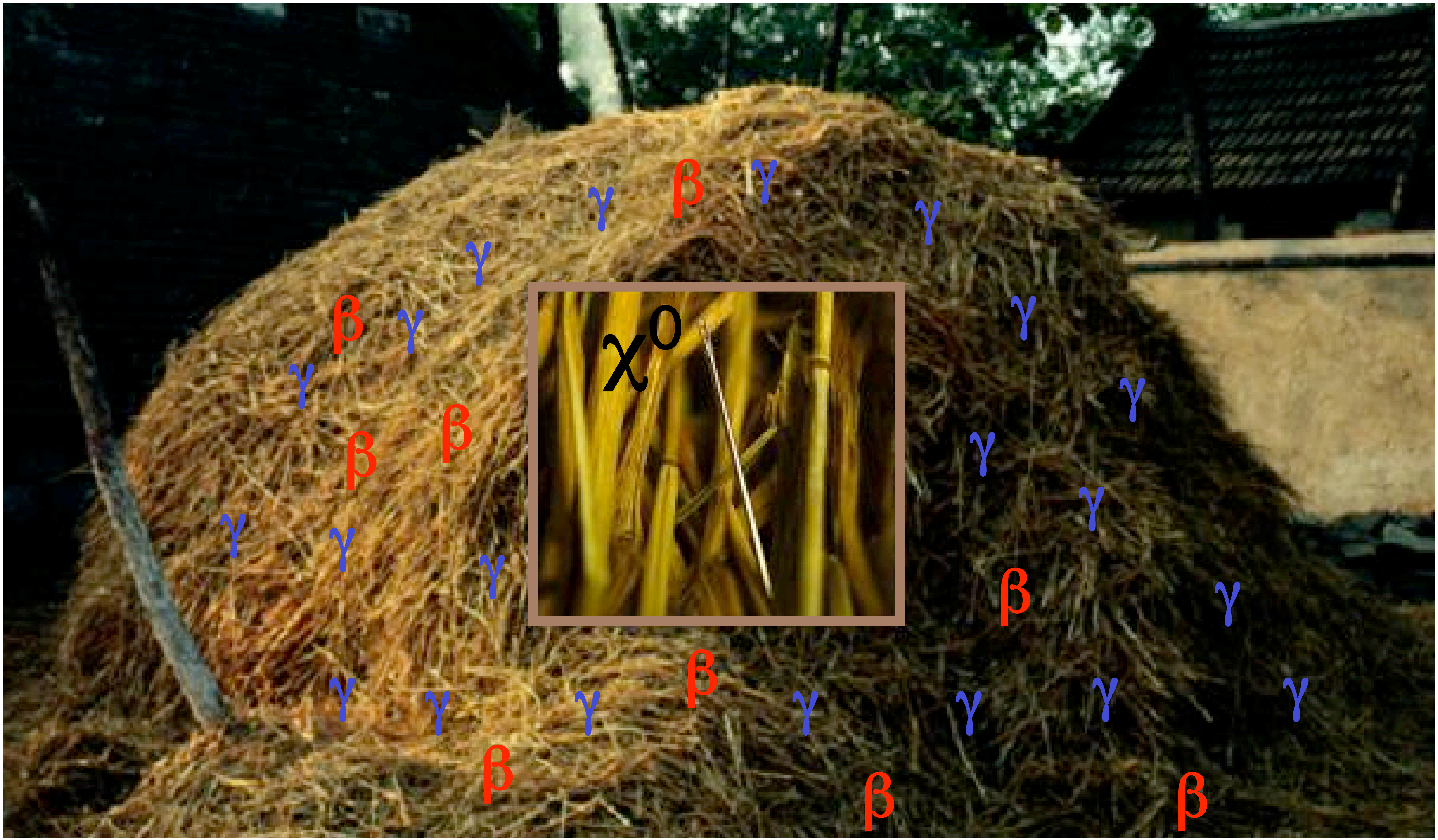
Total Event Rate
(m_χ = 100 GeV / c^2, $\sigma_{\chi\text{-}n} = 10^{-45}$ cm^2)



Detection Principles

- Various experimental methods exist for measuring such an energy deposition
    - Scintillation in crystals/liquids
    - Ionization in crystals/liquids
    - Thermal/athermal heating in crystals
    - Bubble formation in liquids/gels
- Easy in principle, hard in practice
    - Significant uncertainties/unknowns in estimating DM event rates and energy spectrum
    - Background rates overwhelm the most optimistic DM scattering rates.
    - And did I forget to mention - neutrons look just like the DM in our detectors.

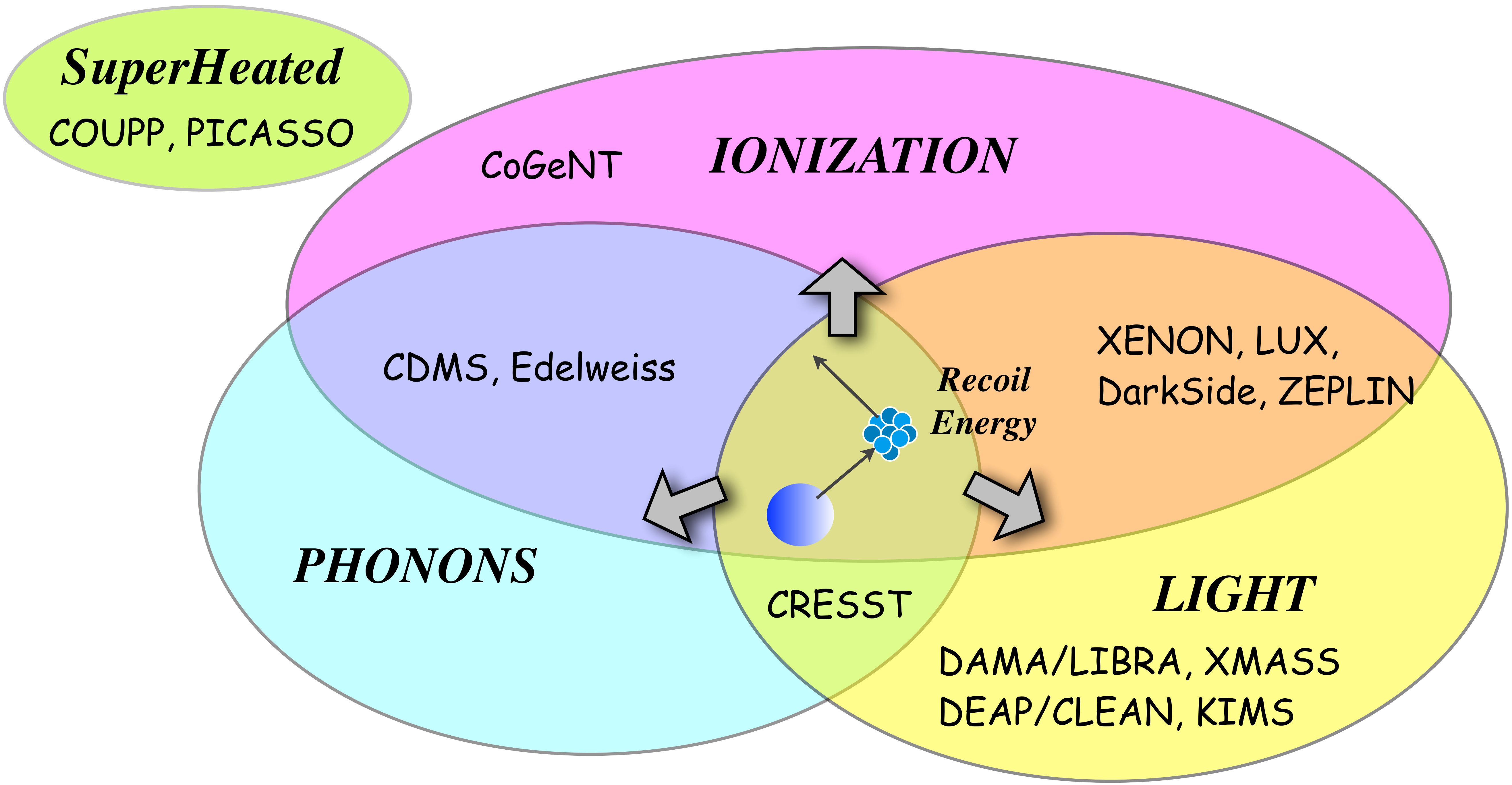
Looking for a Small Needle in a Very Large Haystack



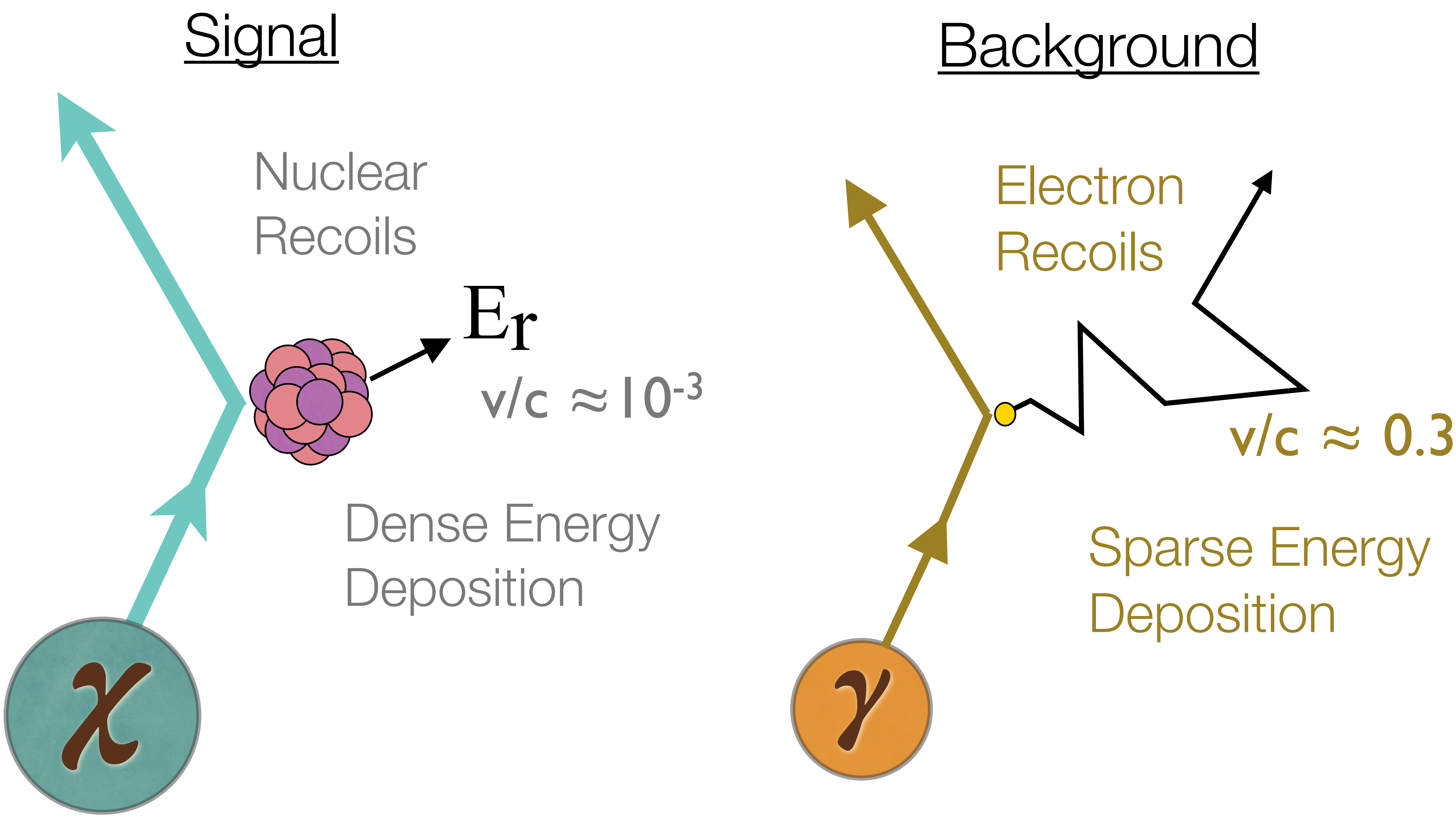
Looking for a Small Needle in a Very Large Haystack

Somewhere in the Midwest!

Direct Detection Principles



Detection Principles



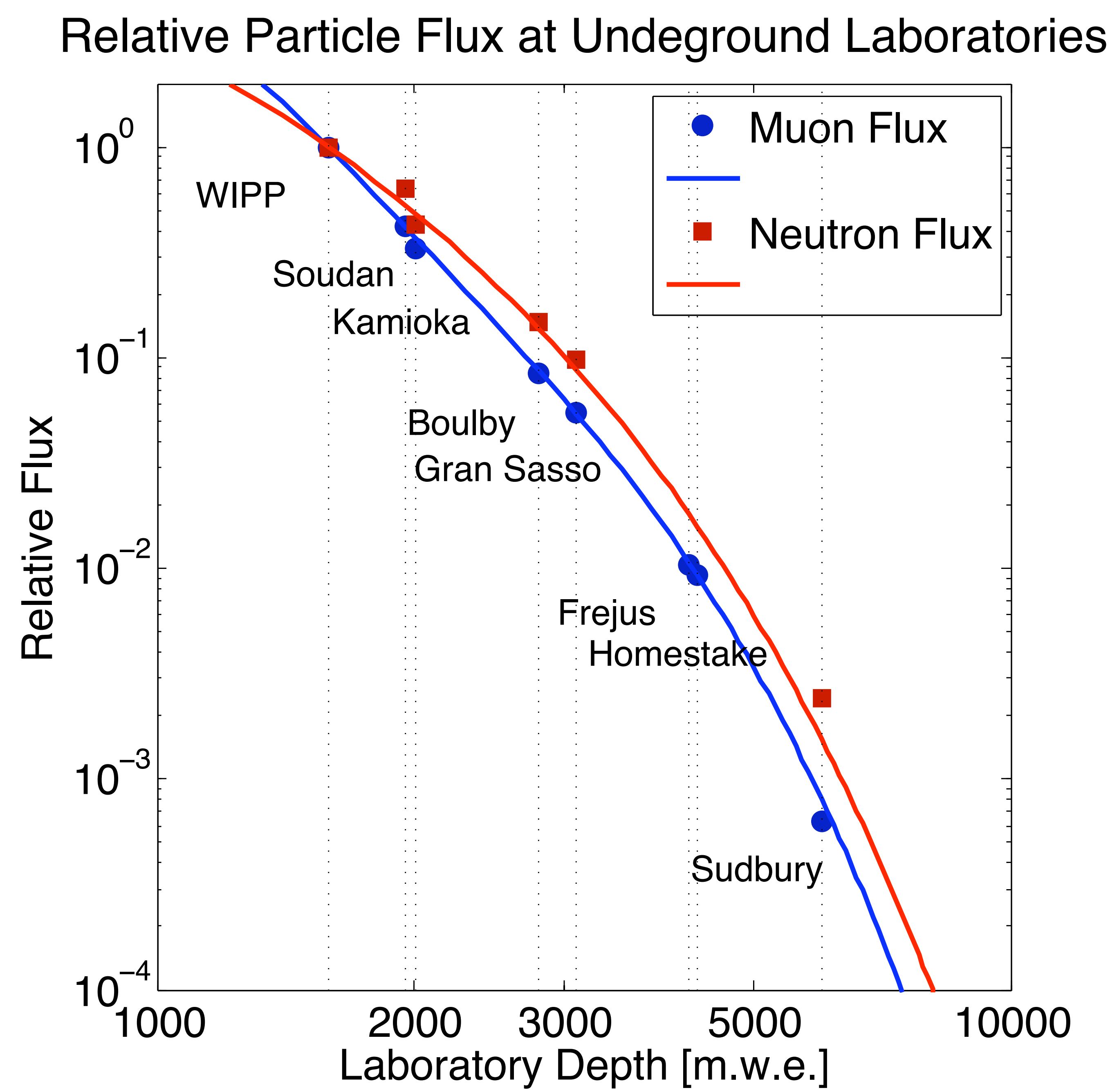
Particle Identification

- Scattering from an atomic nucleus leads to different physical effects than scattering from an electron in most materials.
- Sensitivity to this effect reduces background.
  - Dark Matter is expected to interact with the nucleus and backgrounds interact with electrons*.

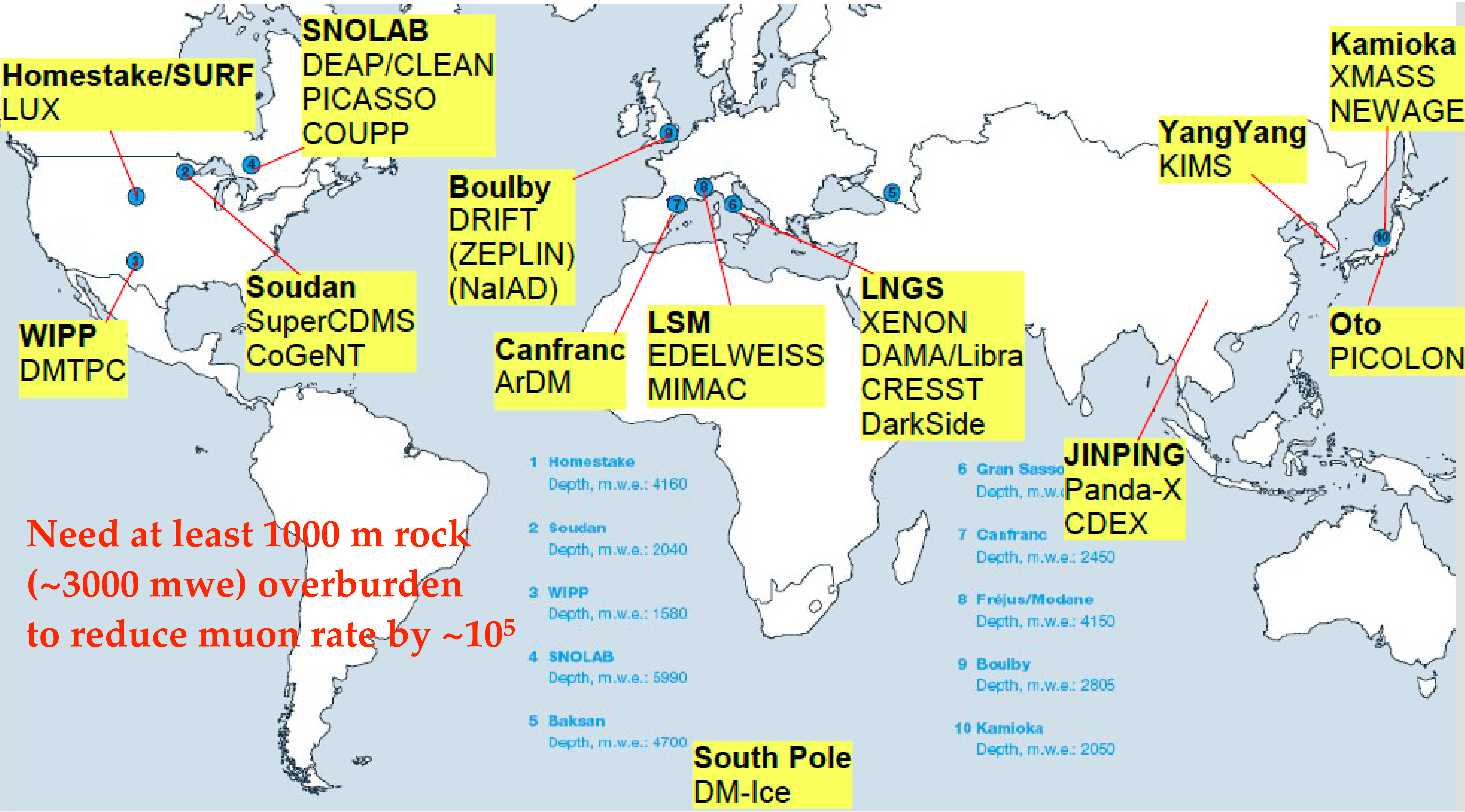
*CAVEAT: Neutrons interact with the nucleus.

Neutrons: Unrejected Background

- Neutrons recoil off atomic nuclei, thus appearing as WIMPs
- Neutrons come from
  - Environmental radioactivity
    - Slow/low energy
    - Can be addressed by shielding
  - Spallation due to cosmic muons
    - Fast/energetic = not shield-able
    - Must go deep underground to avoid



Minimize Backgrounds



Site experiments underground.

Minimize Backgrounds

Active Muon Veto:

rejects events from cosmic rays

- Scintillating panels
- Water Shield

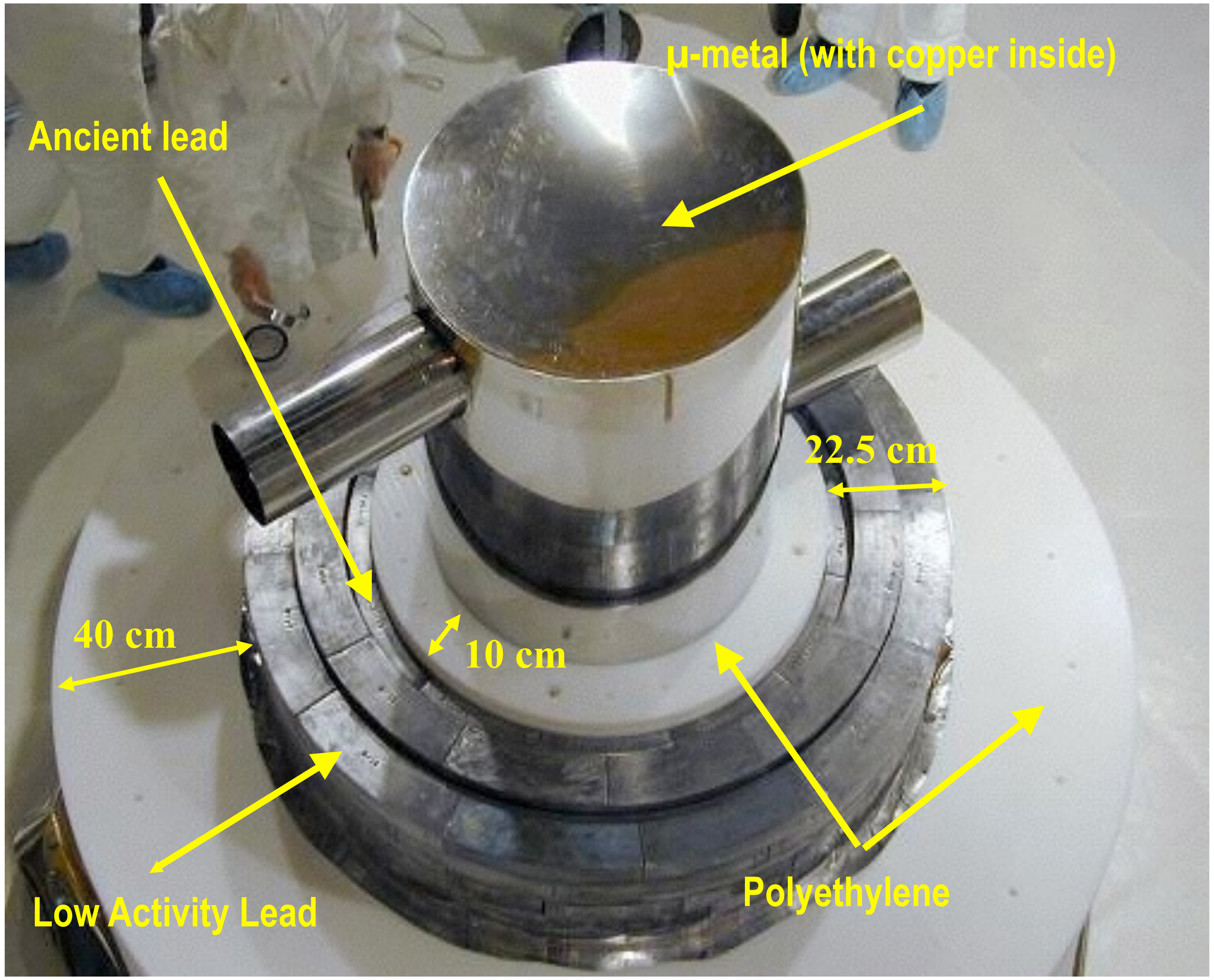
SCDMS active muon veto

LUX water shield

Minimize Backgrounds

Pb: shielding from gammas resulting from radioactivity

Polyethyene:
moderate neutrons produced from fission decays and from (α,n) interactions resulting from U/Th decays



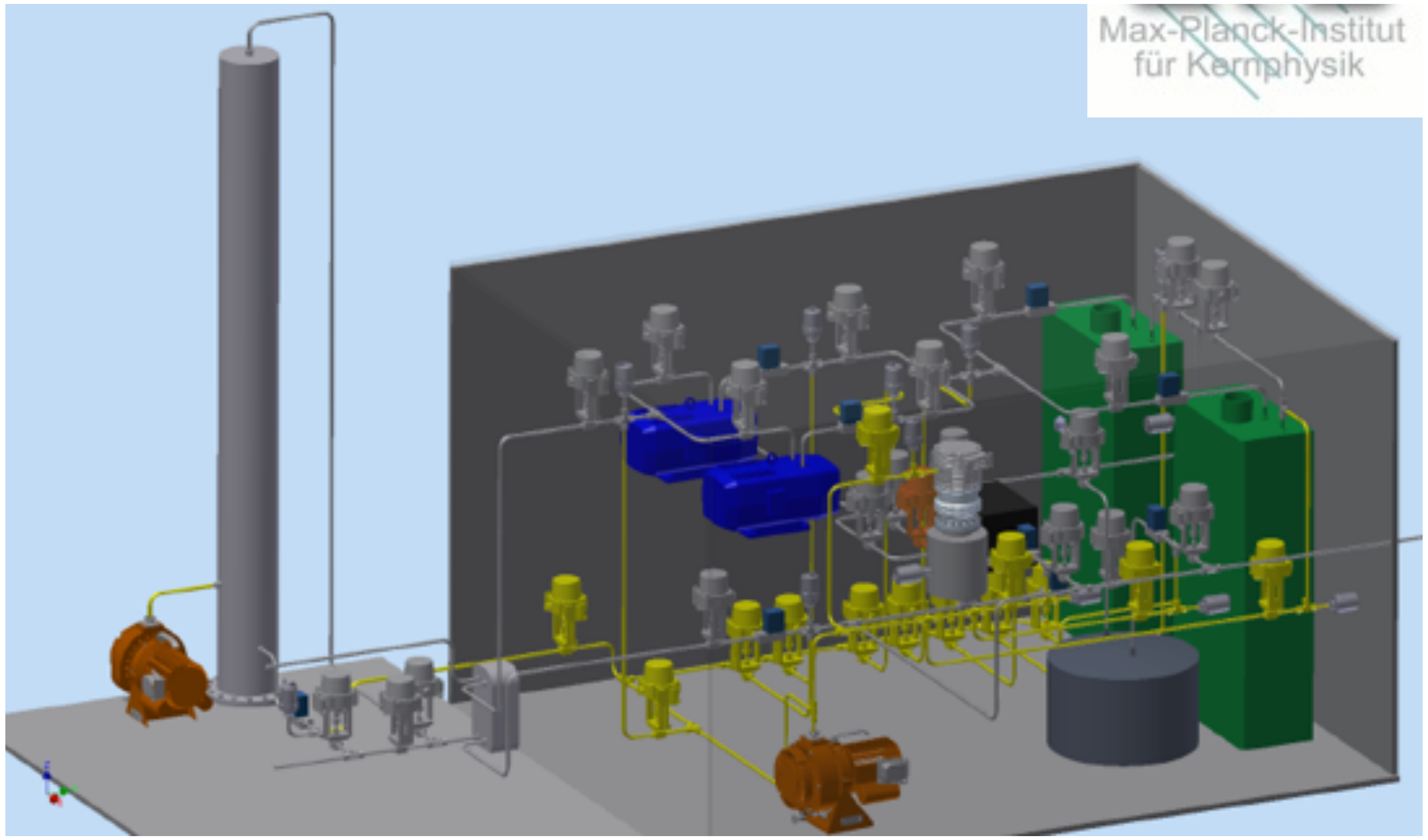
SCDMS - Layers of Polyethylene and Lead

Use Passive Shielding

Minimize Backgrounds

Krypton and Radon Mitigation

mobile radon extraction unit @ MPIK

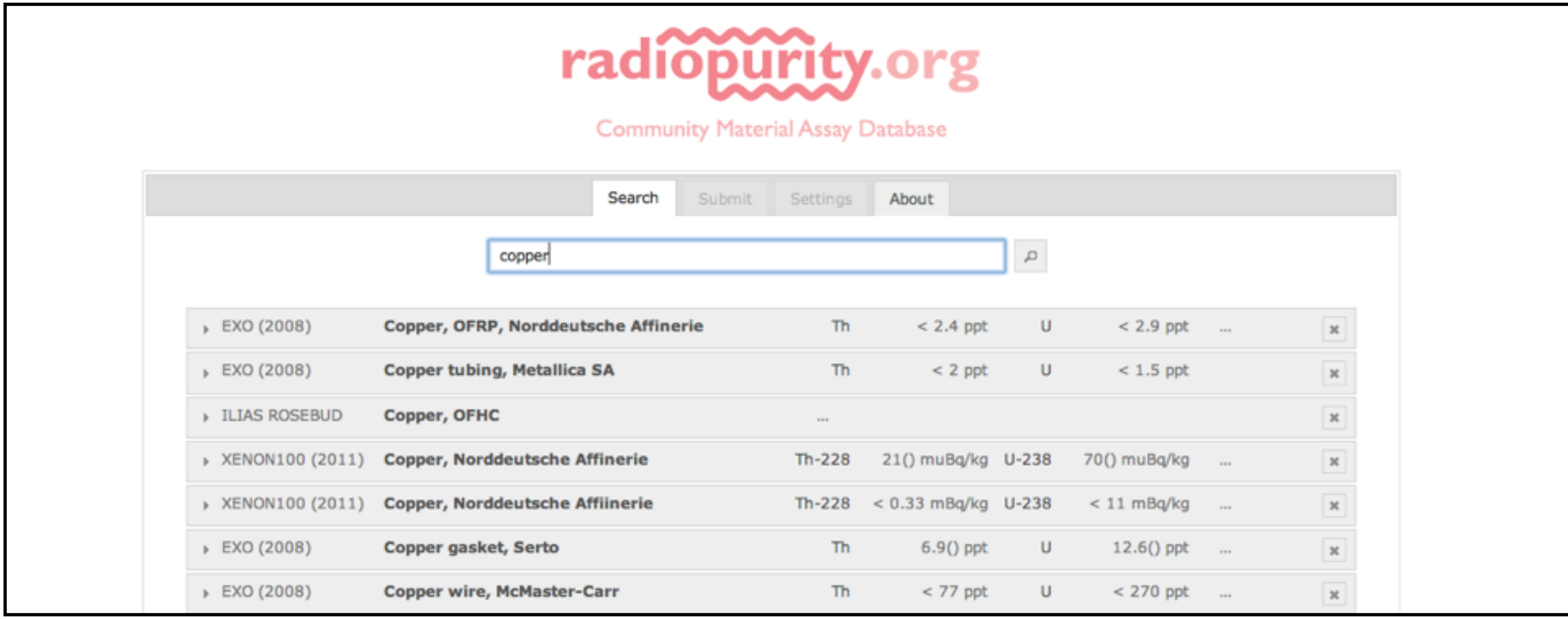


XENON1T purification loop with large charcoal tower.

- ^{39}Ar and ^{85}Kr are intrinsic backgrounds in LXe and LAr detectors.
  - Desired impurity levels of ~1ppt in natural krypton and ~ 1μBq/kg of radon for ton scale experiments.

Minimize Backgrounds

http://radiopurity.org



radiopurity.org

Community Material Assay Database

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copper

EXO (2008)	Copper, OFRP, Norddeutsche Affinerie	Th	< 2.4 ppt	U	< 2.9 ppt	...	×
EXO (2008)	Copper tubing, Metallica SA	Th	< 2 ppt	U	< 1.5 ppt		×
ILIAS ROSEBUD	Copper, OFHC	...					×
XENON100 (2011)	Copper, Norddeutsche Affinerie	Th-228	21() muBq/kg	U-238	70() muBq/kg	...	×
XENON100 (2011)	Copper, Norddeutsche Affiinerie	Th-228	< 0.33 mBq/kg	U-238	< 11 mBq/kg	...	×
EXO (2008)	Copper gasket, Serto	Th	6.9() ppt	U	12.6() ppt	...	×
EXO (2008)	Copper wire, McMaster-Carr	Th	< 77 ppt	U	< 270 ppt	...	×

Supported by AARM, LBNL, MAJORANA, SMU, SJTU & others

Use Clean Materials

All Hope is Not Loss

If Our Needle is VERY BIG!

Direct Detection Searches

Many Experiments

Phonon/Charge/Light:
- CDMS/SuperCDMS
- EDELWEISS
- CRESST

Charge Only:
- CoGeNT/C4
- MALBEK
- TEXONO
- CDEX
- CDMSlite

Other:
- DAMIC
- NEXT

Modulation:
- DAMA/LIBRA
- DM-ICE
- KIMS
- ANAIS
- SABRE
- KamLAND-PICO

Bubble Chambers/ Superheated:
- PICASSO
- COUPP
- PICO

Liquid Noble:
- XENON
- LUX
- Darkside
- DEAP
- CLEAN
- XMASS
- PandaX

Directional:
- DRIFT
- DM-TPC

General Detection Principles

- Many direct detection experiments have excellent discrimination between electron recoils (ER) and nuclear recoils (NR) from the simultaneous measurement of two types of energy in an event.
- Other experiments use pulse shape discrimination or other novel techniques.
- Most backgrounds will produce electron recoils.
- WIMPs and neutrons produce nuclear recoils.
    - Need to keep neutrons away from the detectors.
- Despite the excellent discrimination capability of these detectors, we still want to keep the backgrounds as small as possible.

Considerations Liquid Nobles

- In response to the passage of radiation we want an excellent scintillator and very good ionizer.
- High atomic number and high density to optimize detector size.
- We want to either have no intrinsic radioactive isotopes or isotopes that are easily removed.
- Boiling and melting point temperatures are considerations for detector handling.
- Abundance

Properties of Xe, Ar and Ne

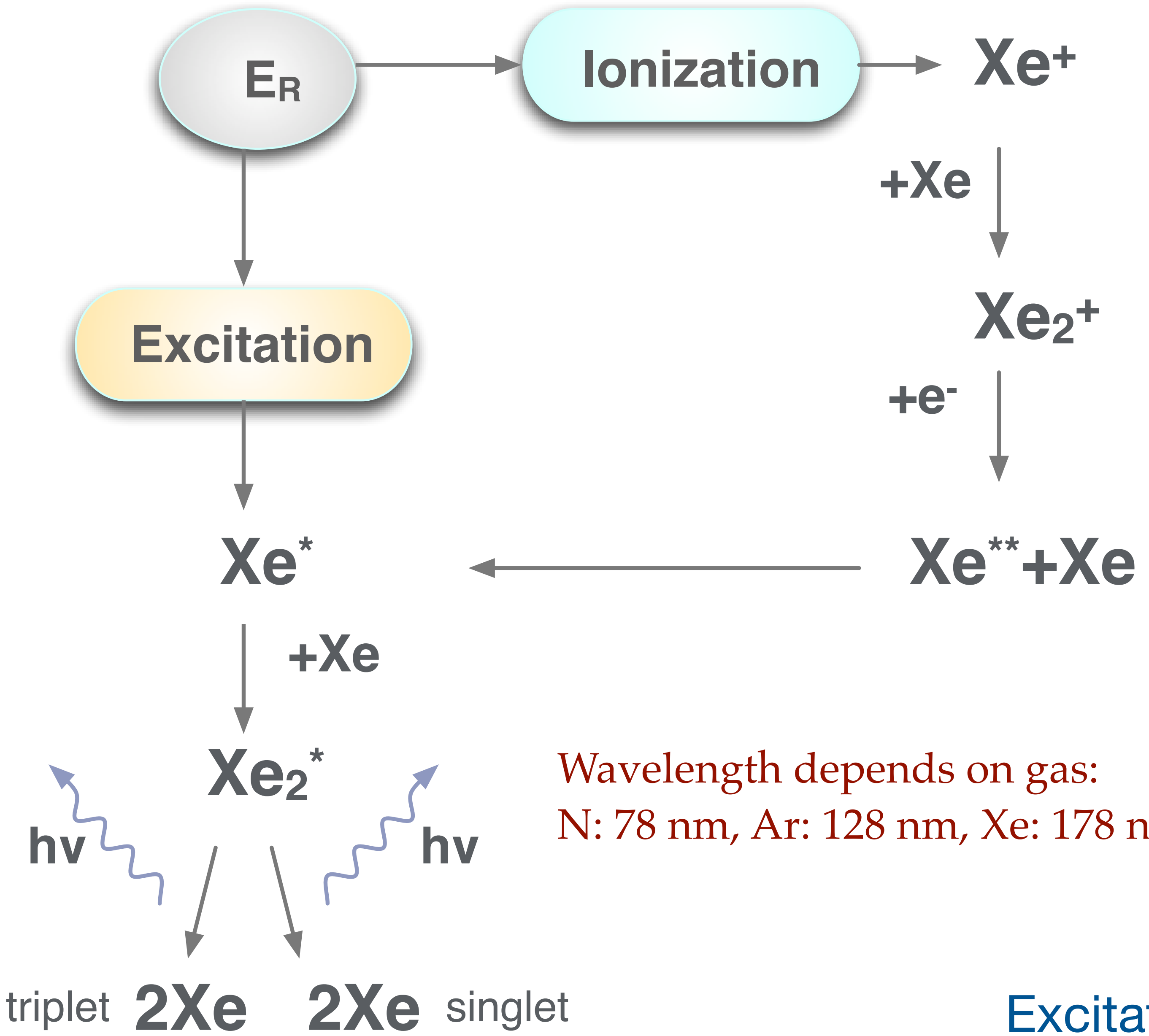
Table 21.1. *Physical properties of xenon, argon and neon.*

Properties [unit]	Xe	Ar	Ne
Atomic number	54	18	10
Mean relative atomic mass	131.3	40.0	20.2
Boiling point T_b at 1 atm [K]	165.0	87.3	27.1
Melting point T_m at 1 atm [K]	161.4	83.8	24.6
Gas density at 1 atm & 298 K [$g\,l^{-1}$]	5.40	1.63	0.82
Gas density at 1 atm & T_b [$g\,l^{-1}$]	9.99	5.77	9.56
Liquid density at T_b [$g\,cm^{-3}$]	2.94	1.40	1.21
Dielectric constant of liquid	1.95	1.51	1.53
Volume fraction in Earth's atmosphere [ppm]	0.09	9340	18.2

Particle Dark Matter, Cambridge University Press 2010, Bertone (editor)

*Atmospheric Ar contains radioactive ^{39}Ar, which must be depleted.

Liquid Nobles: Detection Mechanism



Wavelength depends on gas:
N: 78 nm, Ar: 128 nm, Xe: 178 nm

Time constants depend on gas:
(Ne & Ar few ns/µs, Xe 4/22 ns

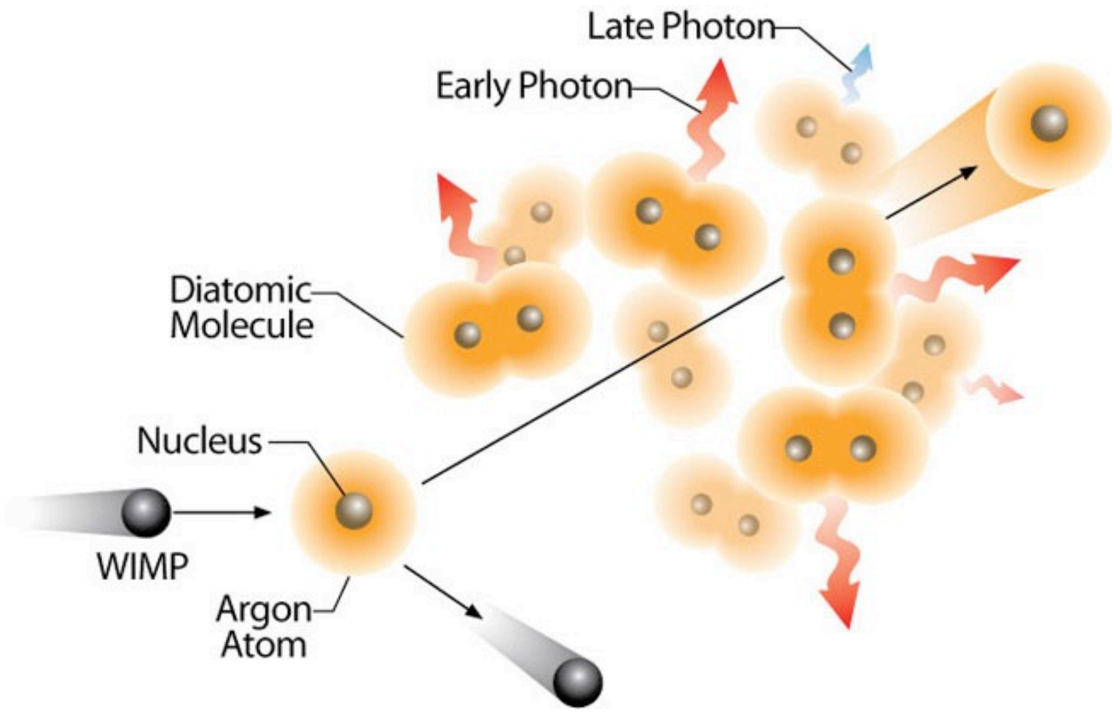
Excited Atoms*:

$$\mathrm{Xe}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^*$$
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu$$

Excited Ions+:

$$\mathrm{Xe}^+ + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^+$$
$$\mathrm{Xe}_2^+ + e^- \rightarrow \mathrm{Xe}^{**} + \mathrm{Xe}$$
$$\mathrm{Xe}^{**} \rightarrow \mathrm{Xe}^* + \mathrm{heat}$$
$$\mathrm{Xe}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}_2^*$$
$$\mathrm{Xe}_2^* \rightarrow 2\mathrm{Xe} + h\nu$$

Excitation/Ionization depends on dE/dx!
⟹ discrimination of signal (WIMPs → NR)
and (most of the) background (gammas → ER)!



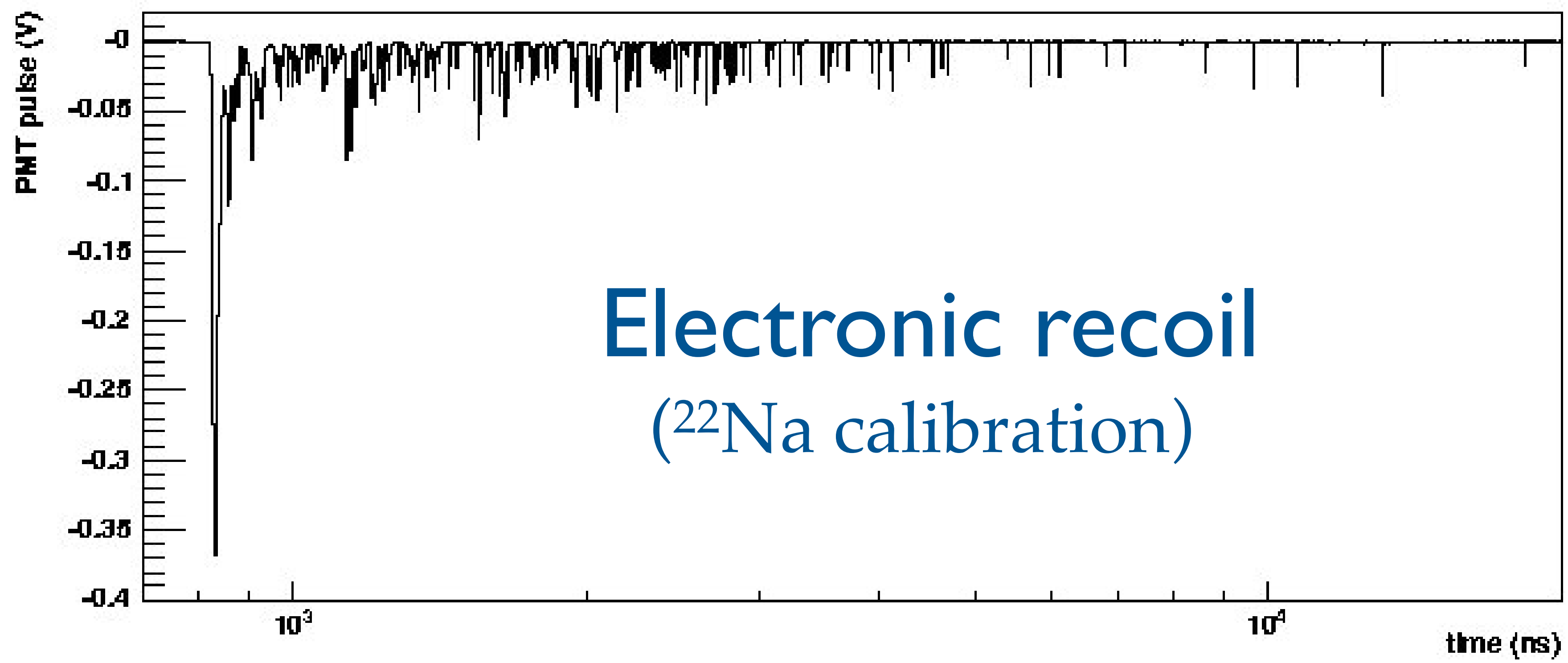
Single Phase Liquid Noble Experiments

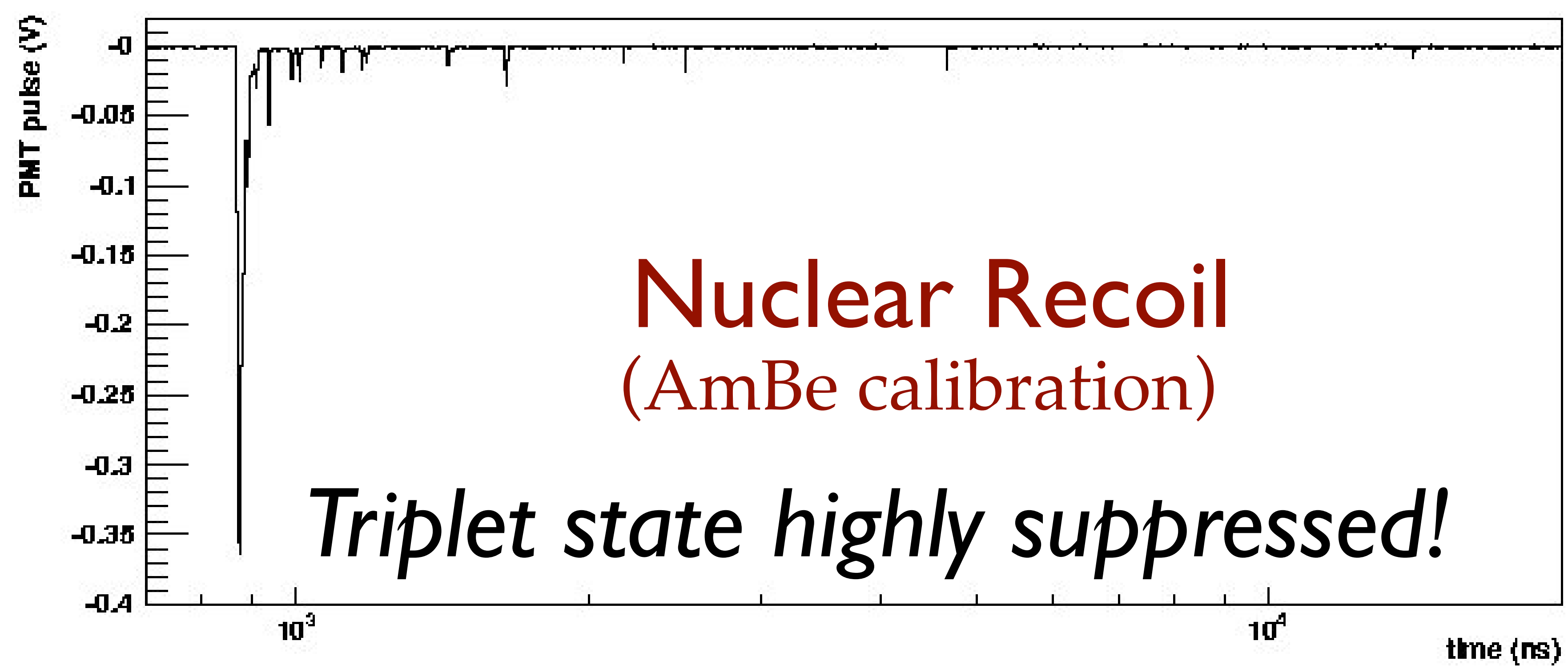
DEAP, MiniCLEAN, XMASS

Pulse Shape Analysis

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

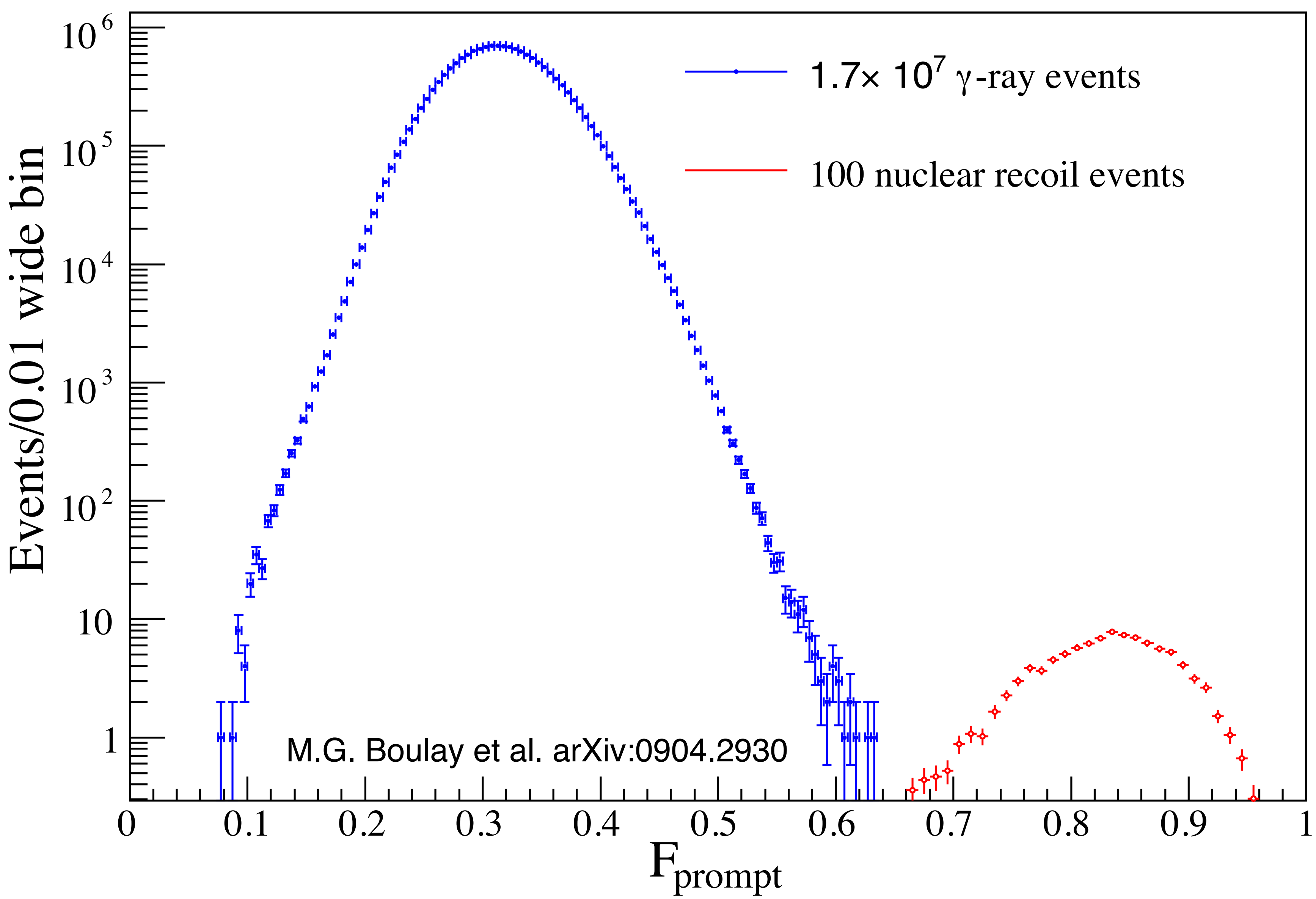
	Singlet	Triplet
Ne	< 18.2 ns	14900 ns
Ar	7ns	1600 ns
Xe	4.3 ns	22 ns





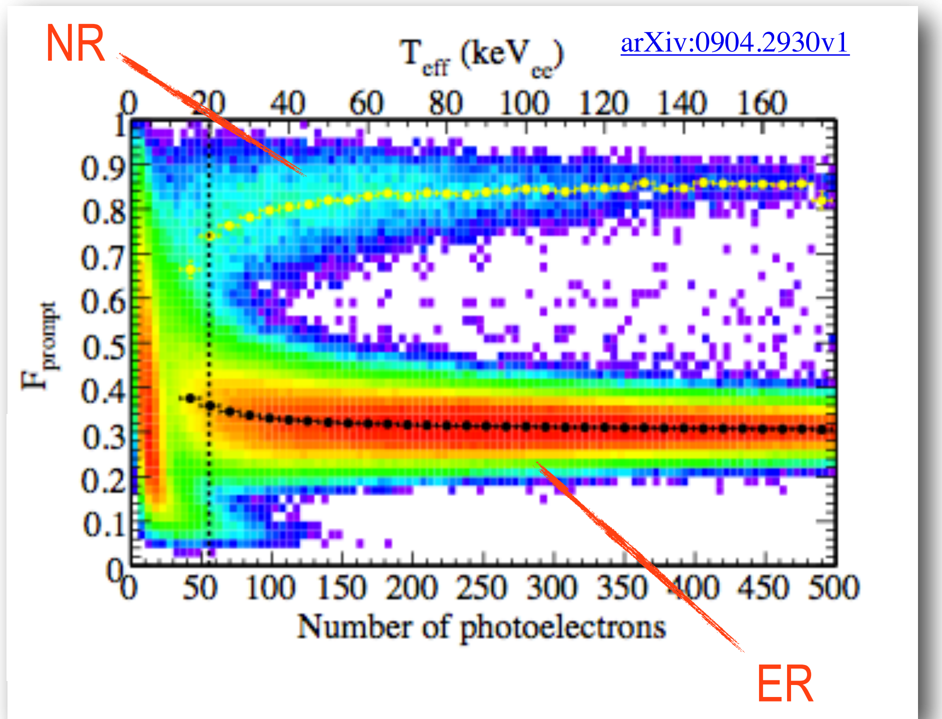
DEAP - Pulse Shape Discrimination

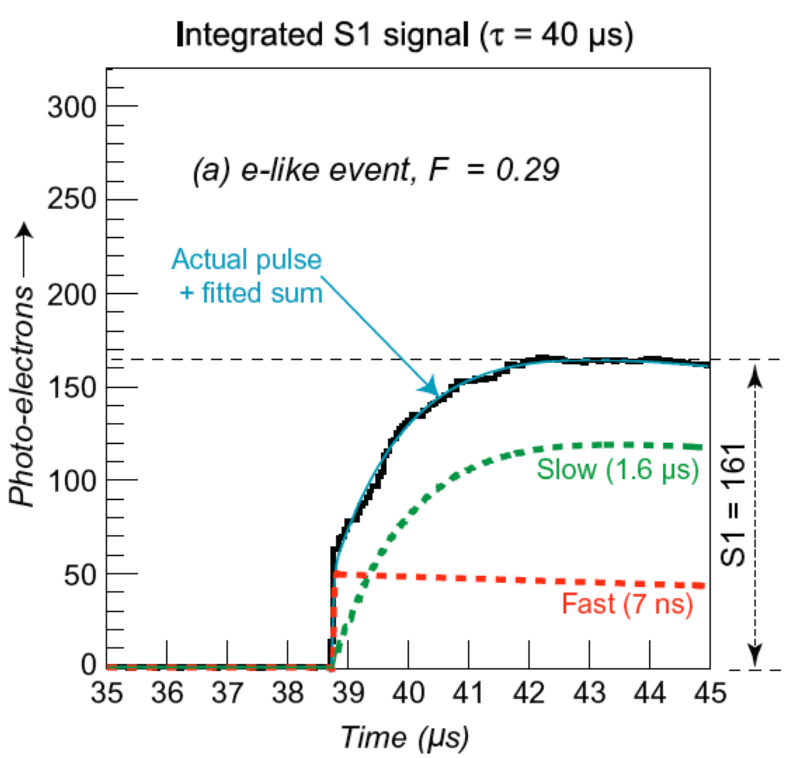
- Discriminate with ratio of prompt light (F_{prompt}) to total light.
- Reject beta and gamma backgrounds with less than 10^{-8} leakage.



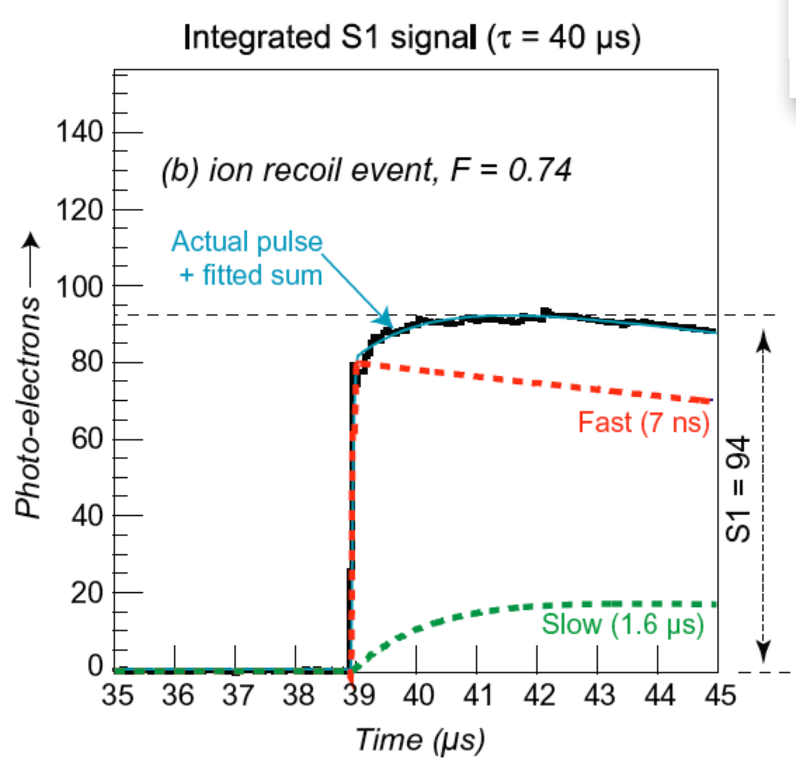
DEAP - Pulse Shape Discrimination

- Discrimination between background and signal comes from pulse shape.
- Excited atoms decay to ground state through formation of single or triplet excimer states which have different decay times.





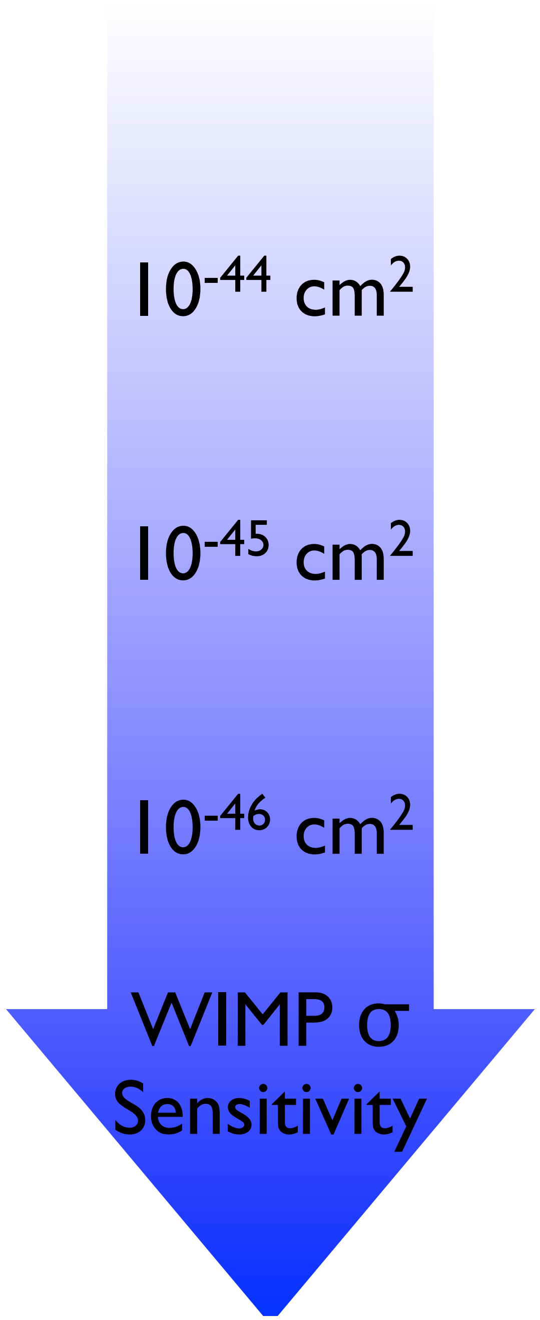
(a)



(b)

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

DEAP/CLEAN Program



DEAP-0:
Initial R&D detector

DEAP-1:
7 kg LAr
2 warm PMTs
At SNOLab since 2008

picoCLEAN:
Initial R&D detector

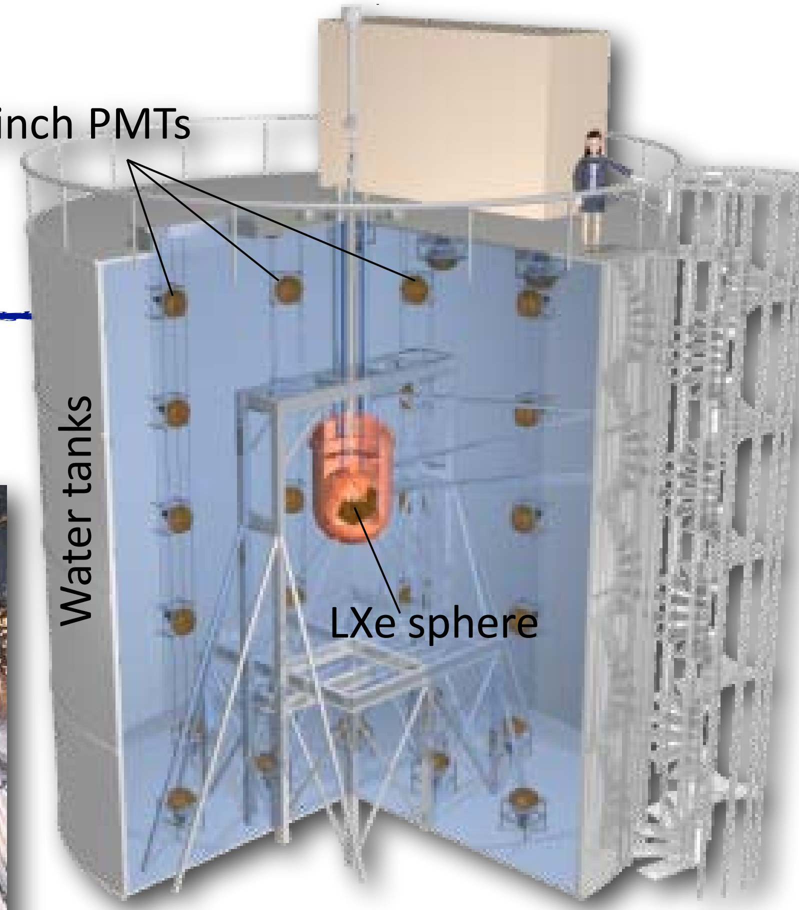
microCLEAN:
4 kg LAr or LNe
2 cold PMTs
surface tests at Yale

MiniCLEAN:
500 kg LAr or LNe (150 kg fiducial mass)
92 cold PMTs
SNOLAB 2013

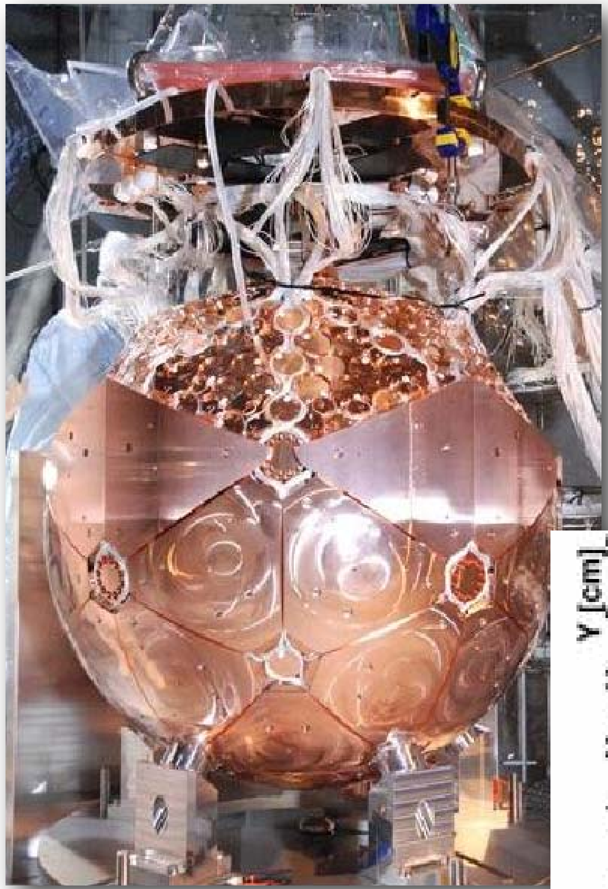
DEAP-3600:
3600 kg LAr (1000 kg fiducial mass)
266 warm PMTs
SNOLAB 2014

40-140 tonne LNe/LAr Detector:
pp-solar ν, supernova ν, dark matter <10^{-46} cm^2
~2018?

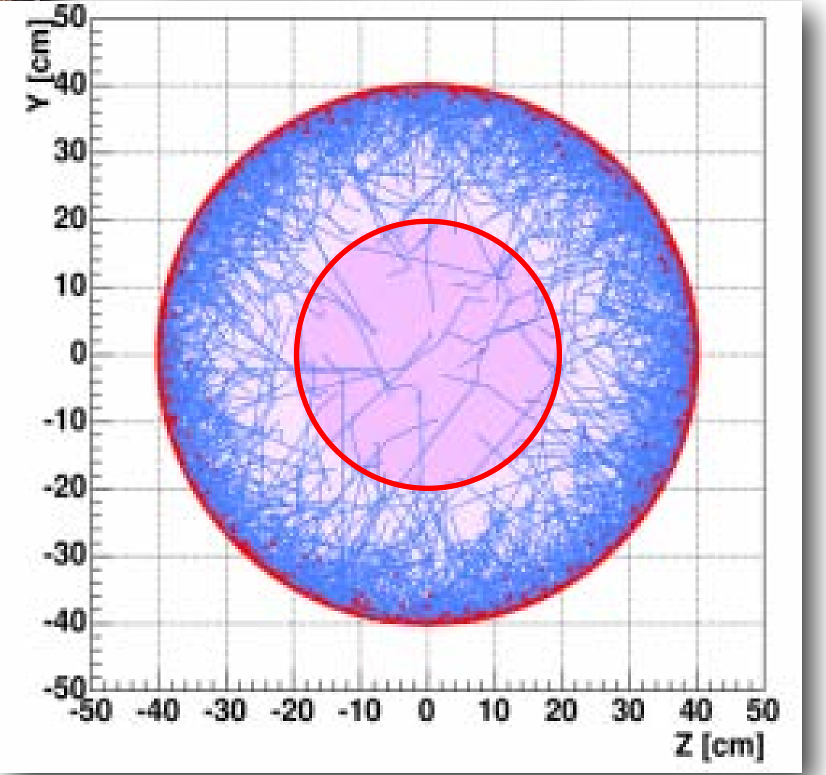
XMASS



- Single phase LXe detector located in the Kamioka Underground Observatory, Japan. Construction finished in late 2010.
- Water tank acts as an active muon veto.
- Key concept to background discrimination is “self-shielding”. Gamma particles are absorbed in the outer region of the liquid xenon.
- WIMPs and neutrons are evenly distributed thoughout volume.
- Recent science run revealed unexpected alpha background from materials used to support PMTs.



Simulation: γ into LXe

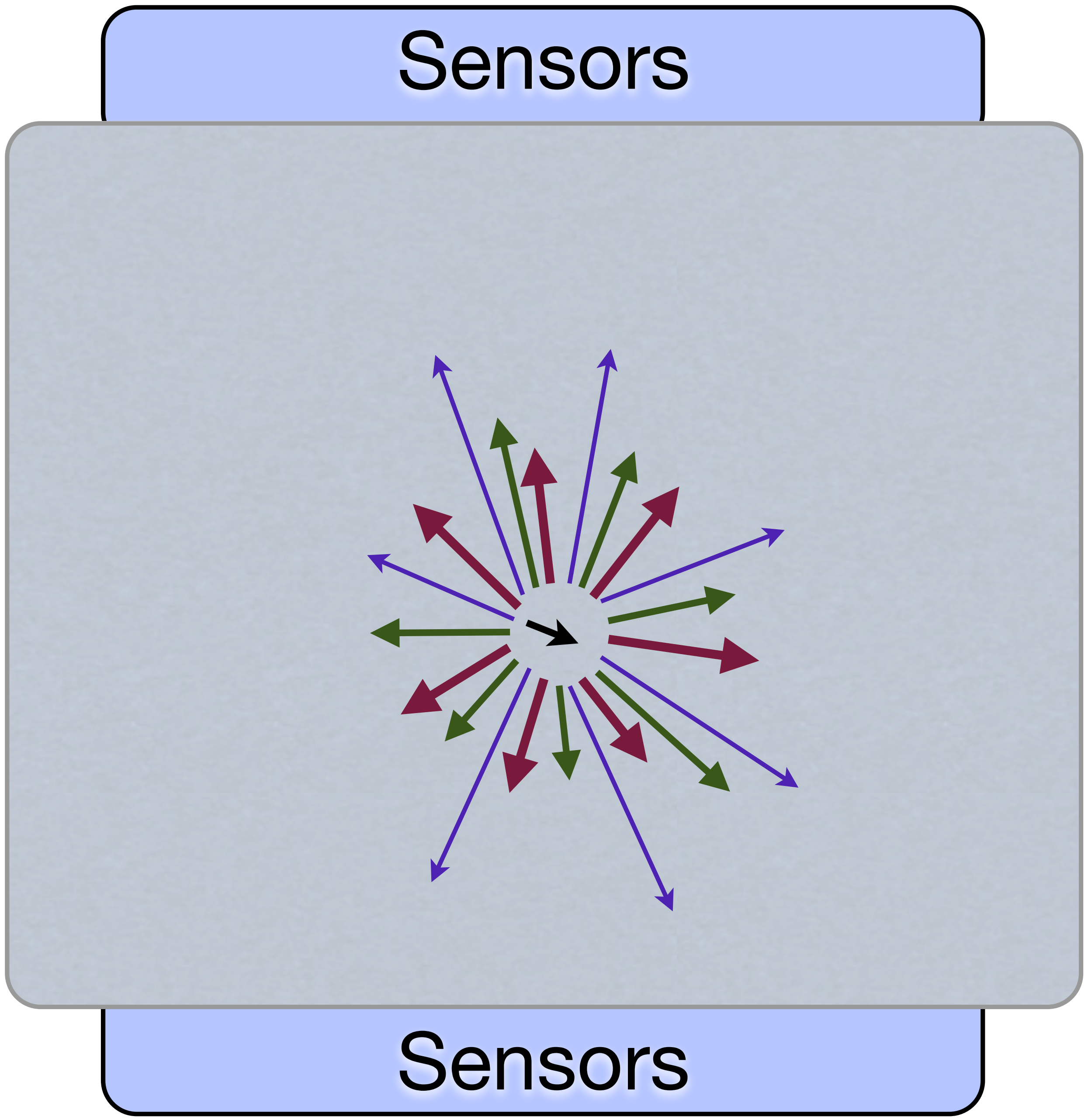


J. Liu TAUP 2011

Two Phase Experiments

CRESST, EDELWEISS, SuperCDMS,
DarkSide, LUX, PandaX, XENON,
and others.

Two Phase Detectors



Phonons
Charge Carriers
Photons

Relative fractions depend on dE/dx

Particle Dependent Response

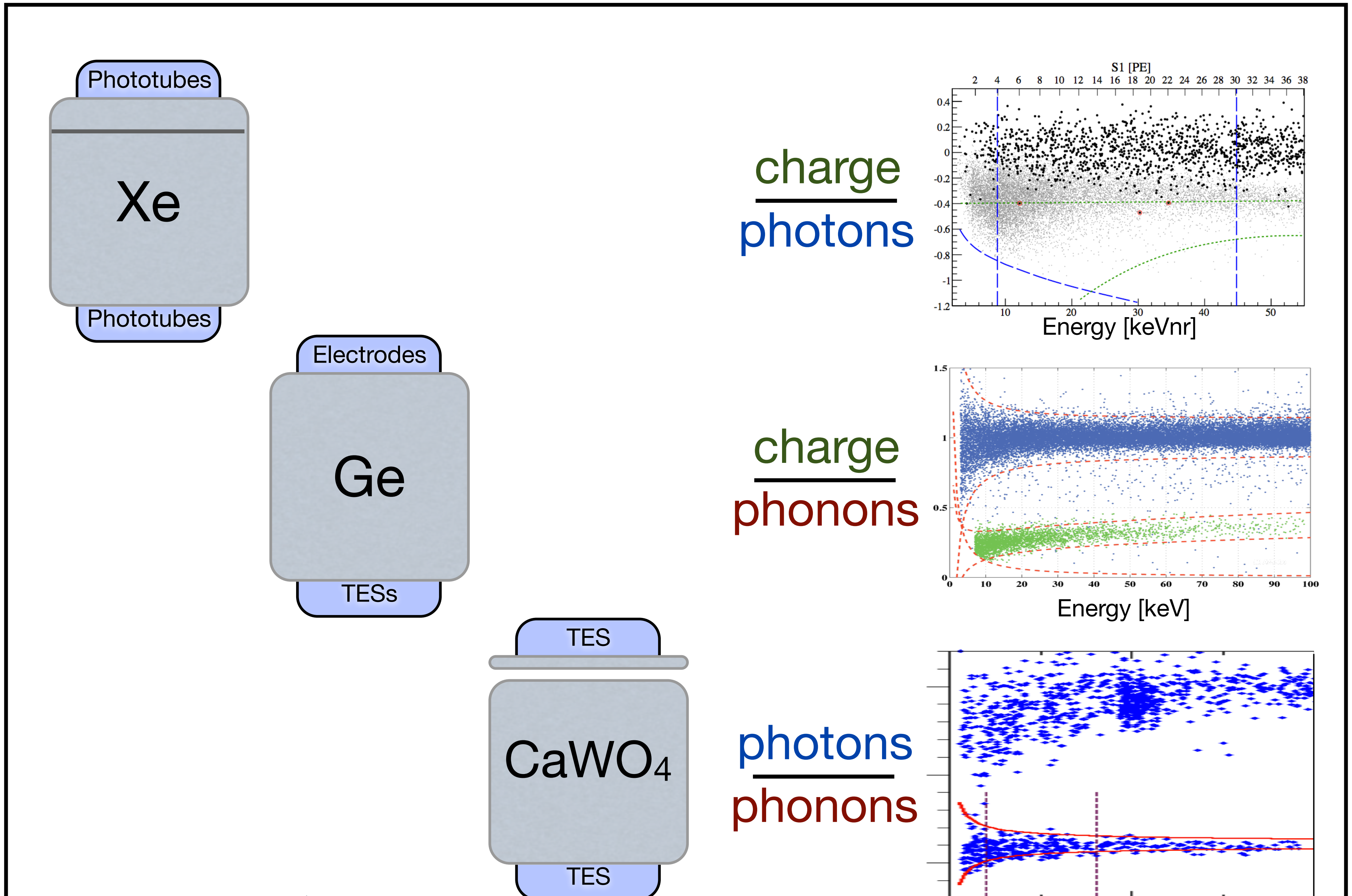
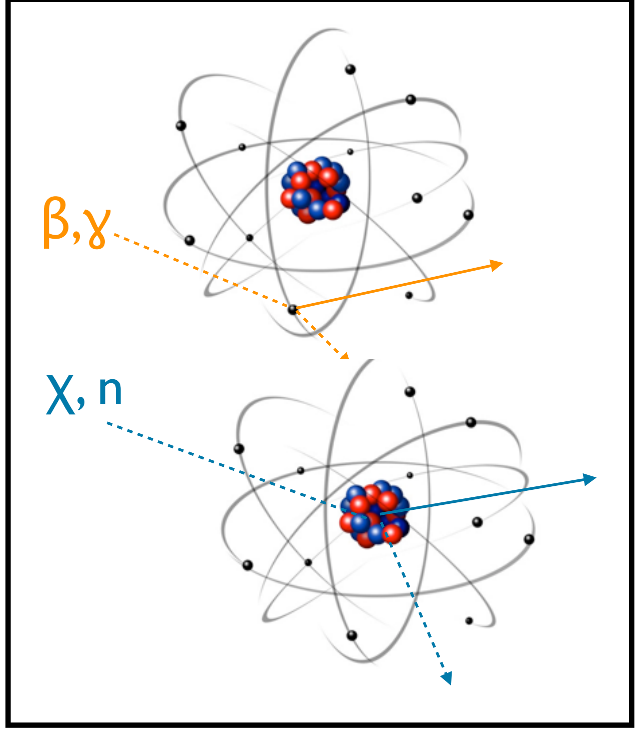
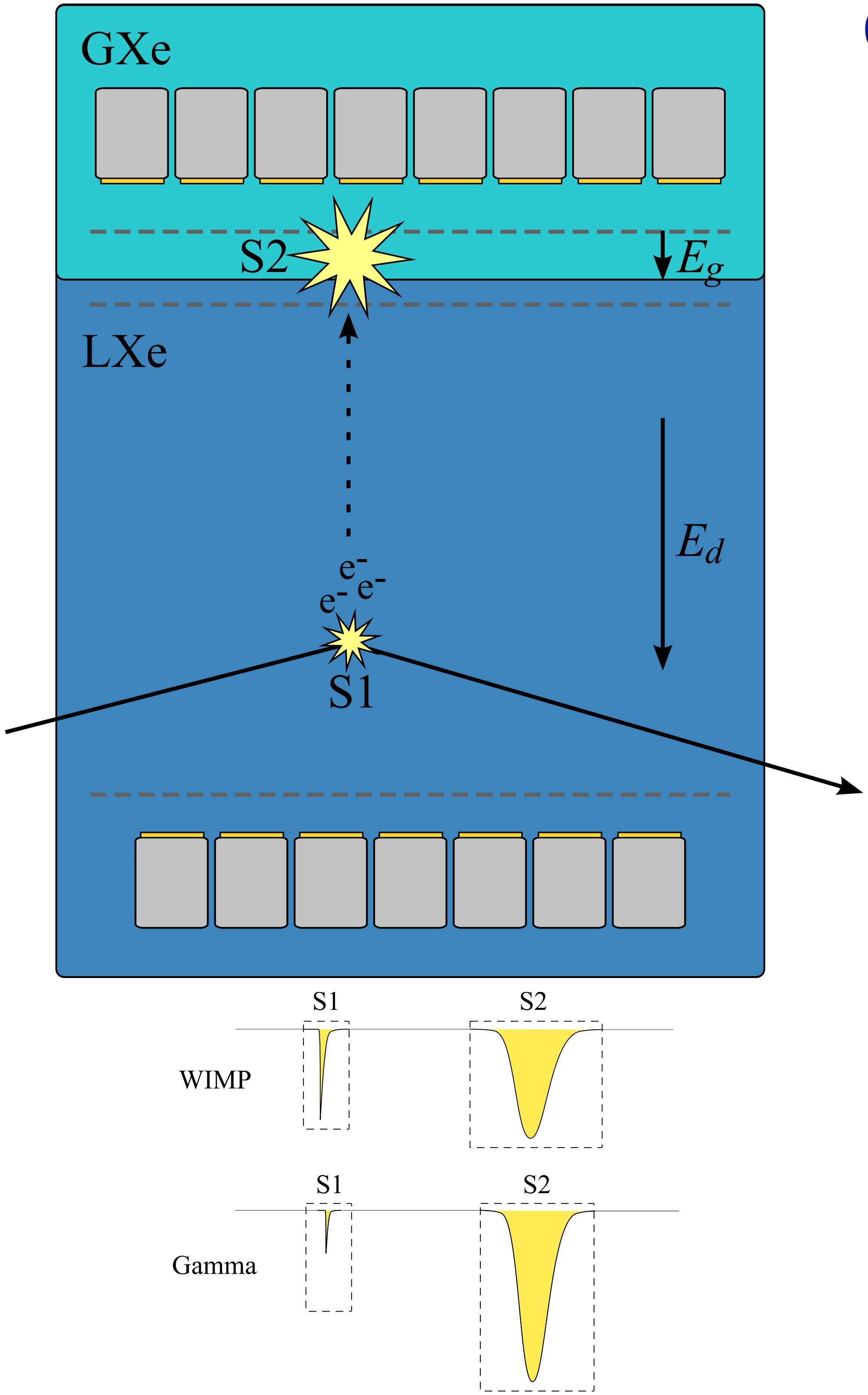


Image S. Hertel

CRESST, DarkSide, Edelweiss, LUX, SuperCDMS, XENON, etc.



Dual Phase Time Projection Chambers



(XENON, LUX, DarkSide, PandaX and others)

- Interactions in the liquid produce excitation and ionization.
- Excitation leads to scintillation light emission
- Ionization electrons are drifted with an applied electric field into the gas phase (S1).
- In the gas phase, electrons are further accelerated producing proportional scintillation (S2).
- PMTs on the bottom and top of the chamber record scintillation signals.
- Distribution of S2 give xy coordinates, drift time gives z coordinates
- Ratio of S2/S1 discriminates electron and nuclear recoils

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

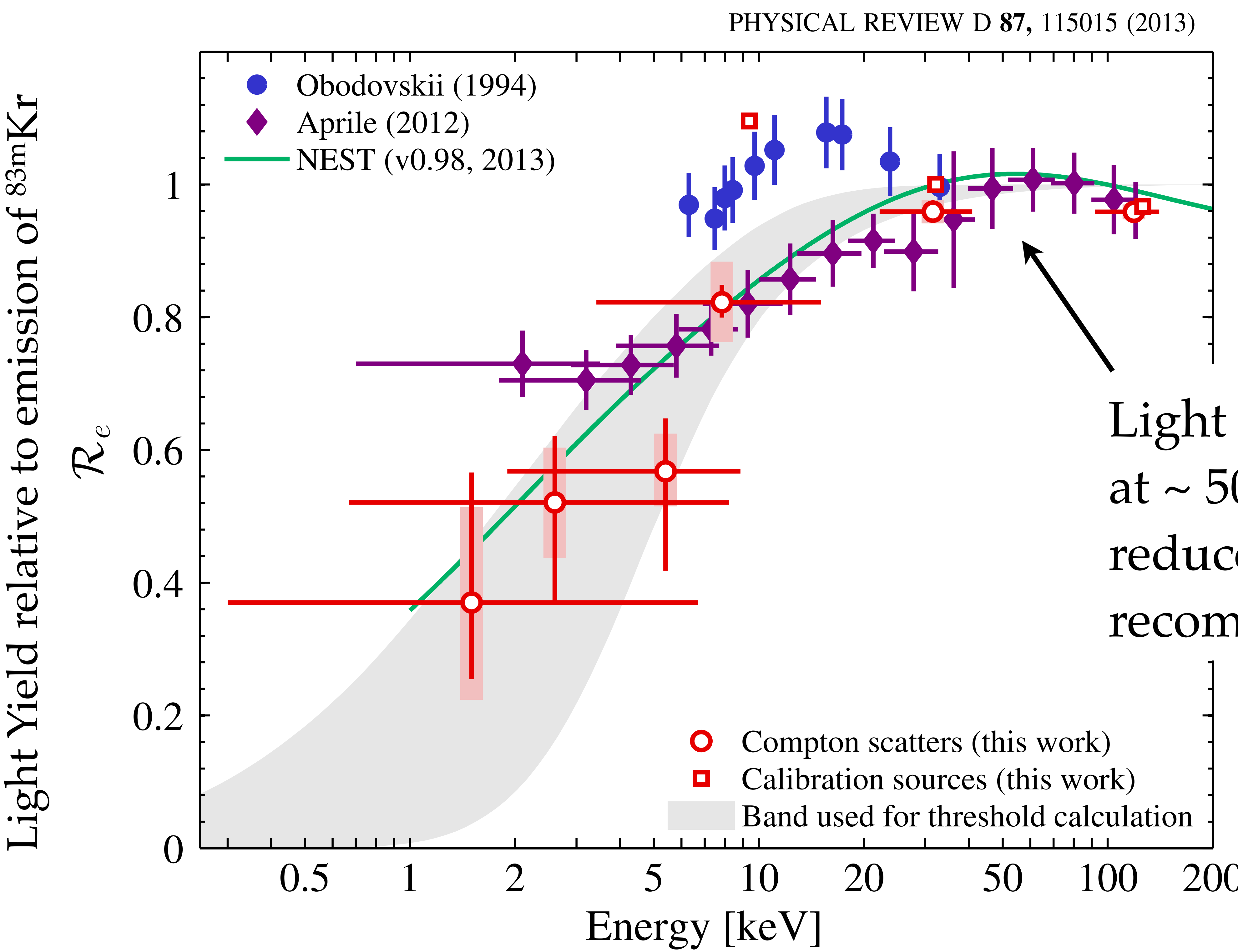
L_{eff} accounts for the quenching of the scintillation signal for a nuclear recoil.

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

122 keV γ line from ^{57}Co source

9.4 keV or 32.1 keV line2 from ^{83m}Kr (internal source)

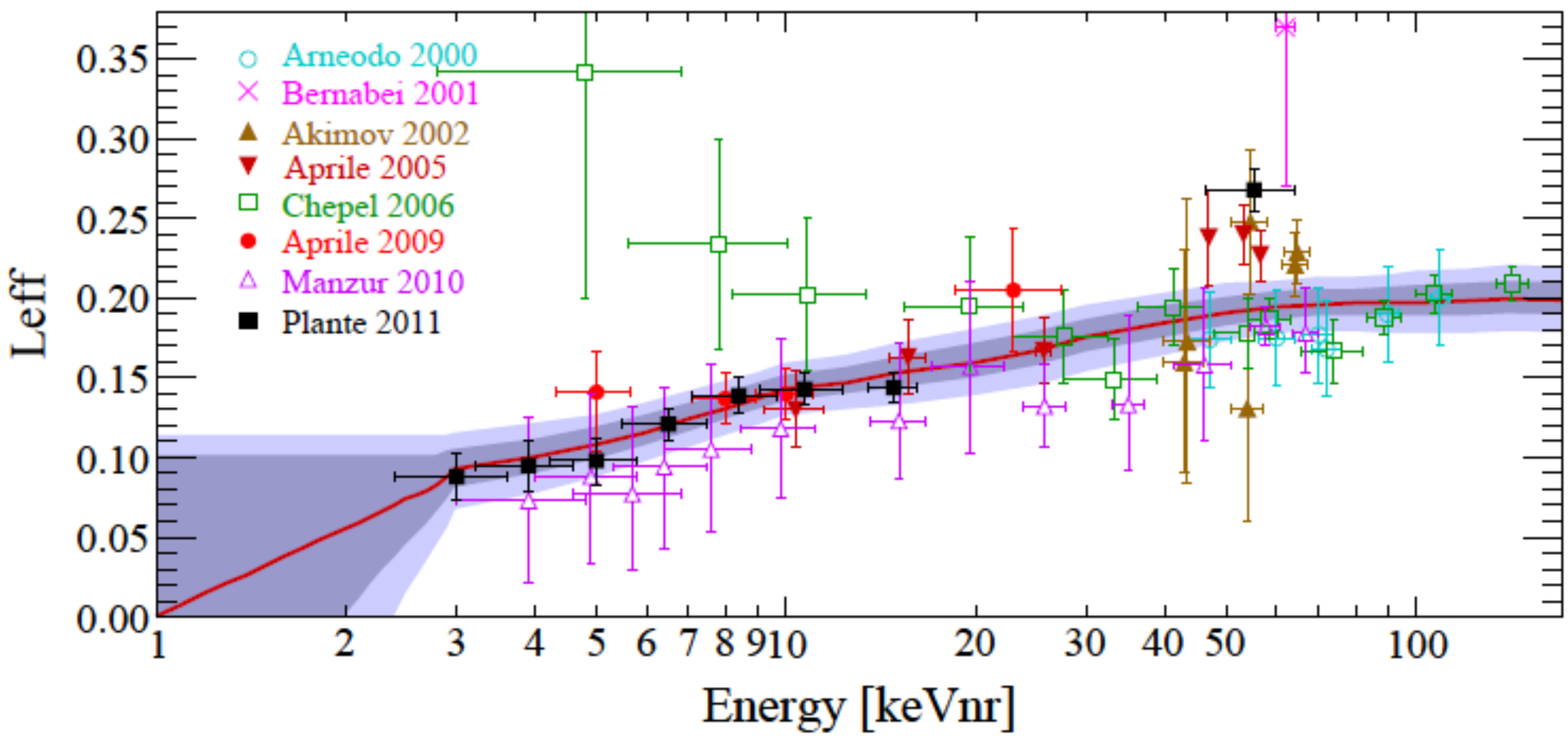
Light Yield - Zero Electric Field



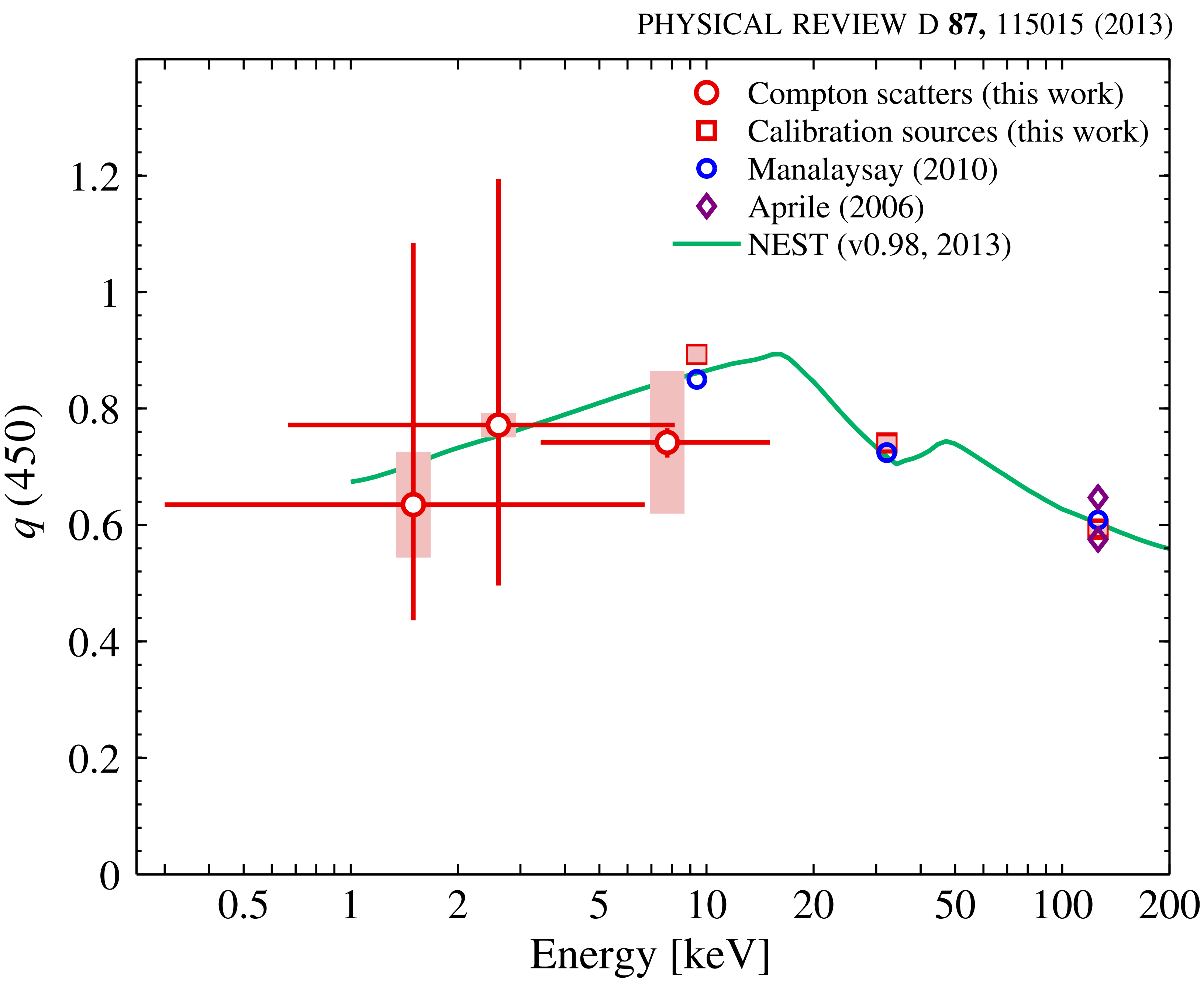
Light yield decreases at ~ 50 keV, due to reduced electron-ion recombination

L_{eff}: Scintillation Efficiency

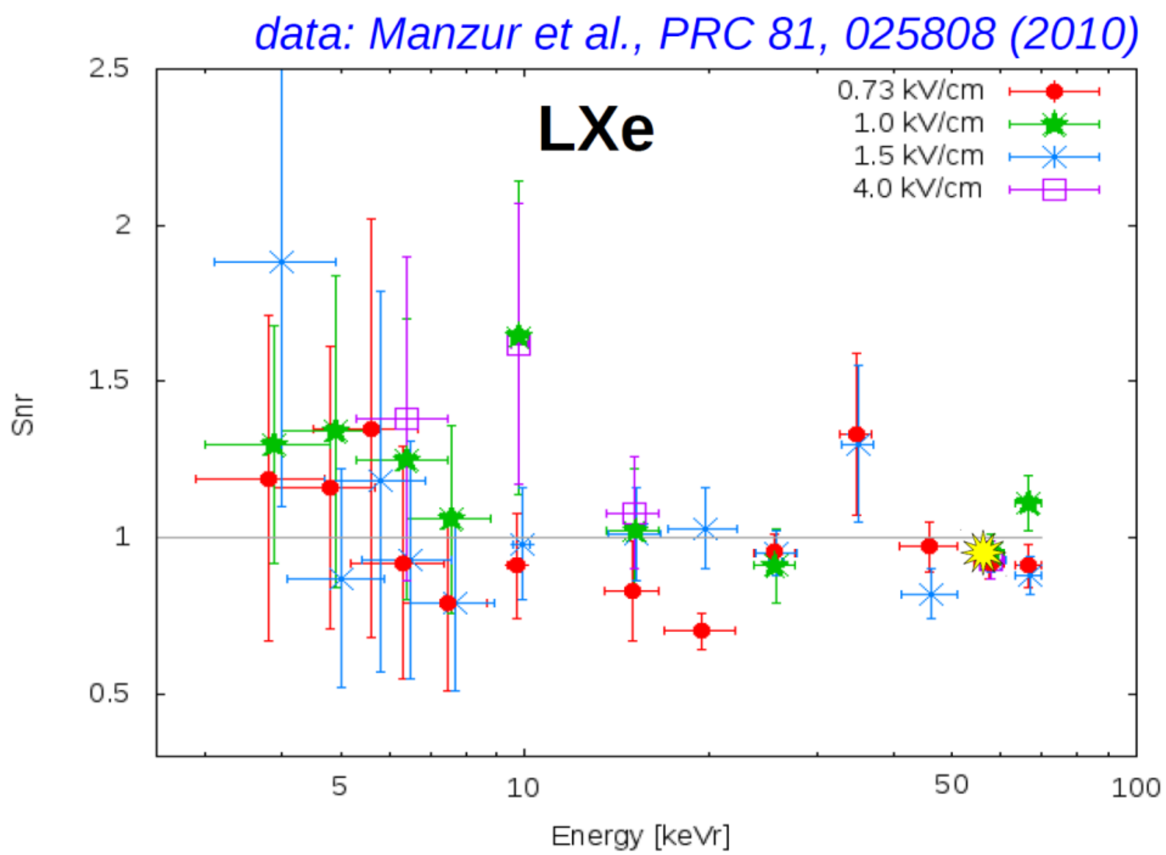
- Large experimental effort to determine L_{eff} as a function of NR energy.
- Best results so far are from direct neutron scattering experiments.

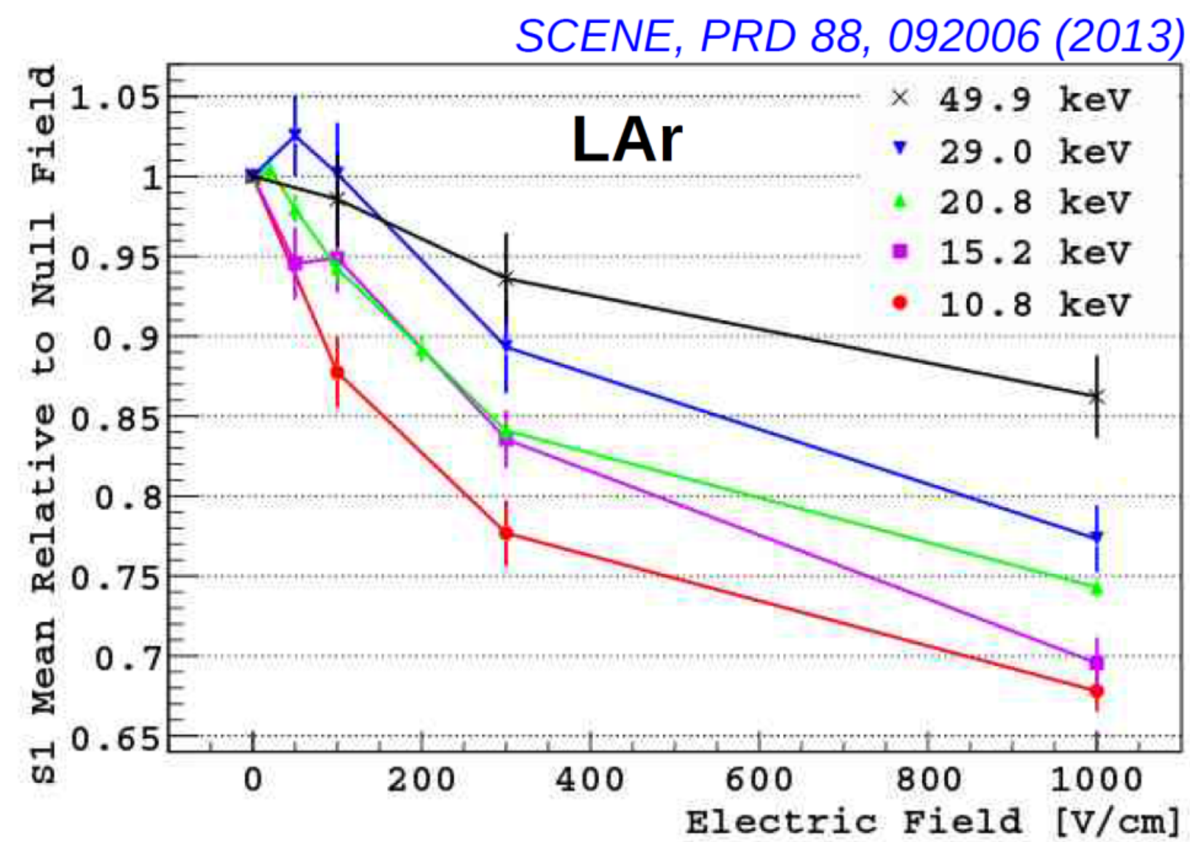


ER: Quenching Due to Electric Field



NR: Quenching Due to Electric Fields





- In LXe & LAr, the quenching factor is dependent on field strength.
- The quenching factor in LXe appears to not be dependent on energy. However, more precise measurements are needed to confirm.

Energy - Continued

The nuclear recoil energy is related to S2 by

observed
scintillation [PE]

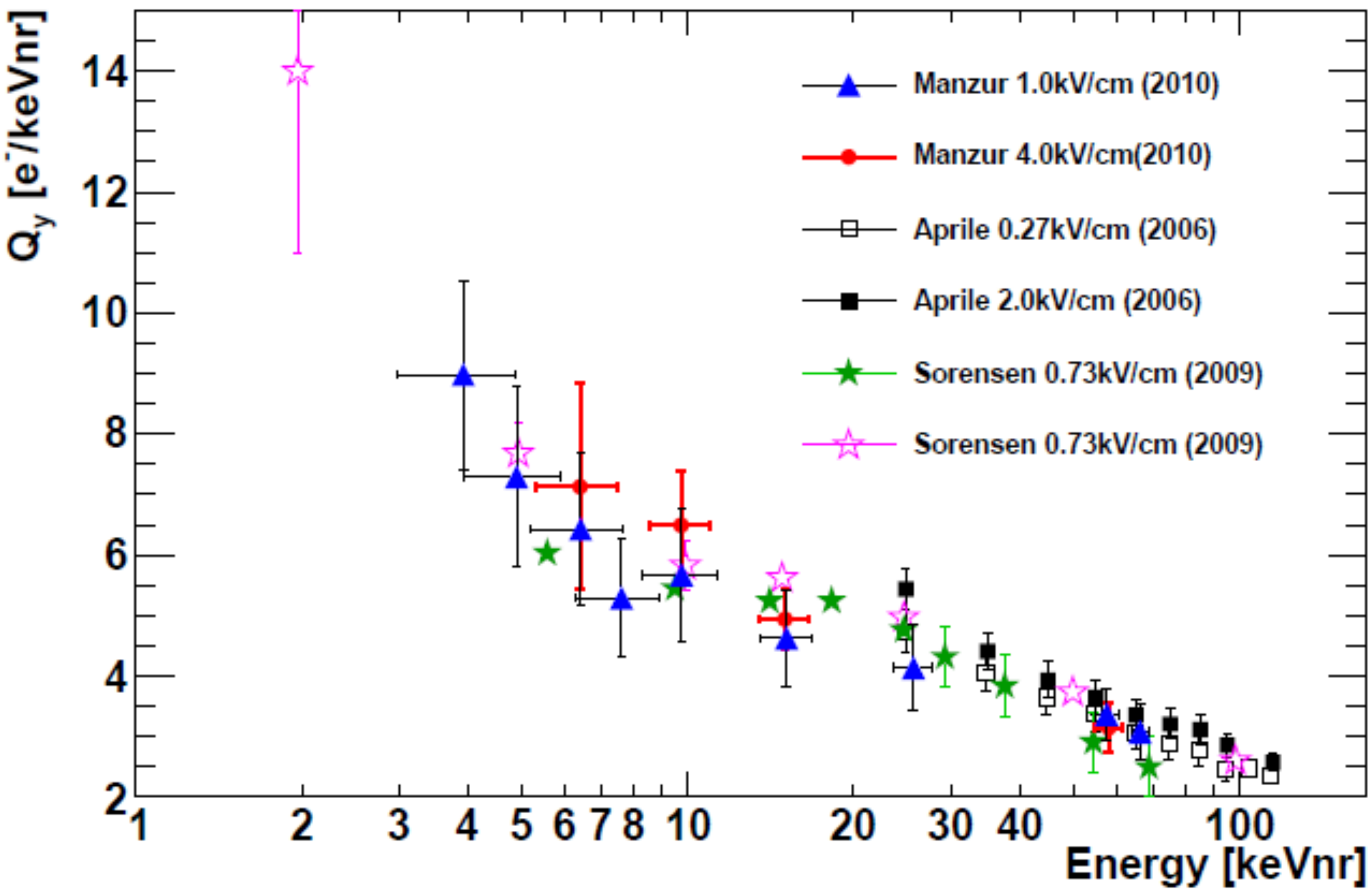
$$E = \frac{S2}{Y} \frac{1}{Q_y(E)}$$

[keV_{nr}]

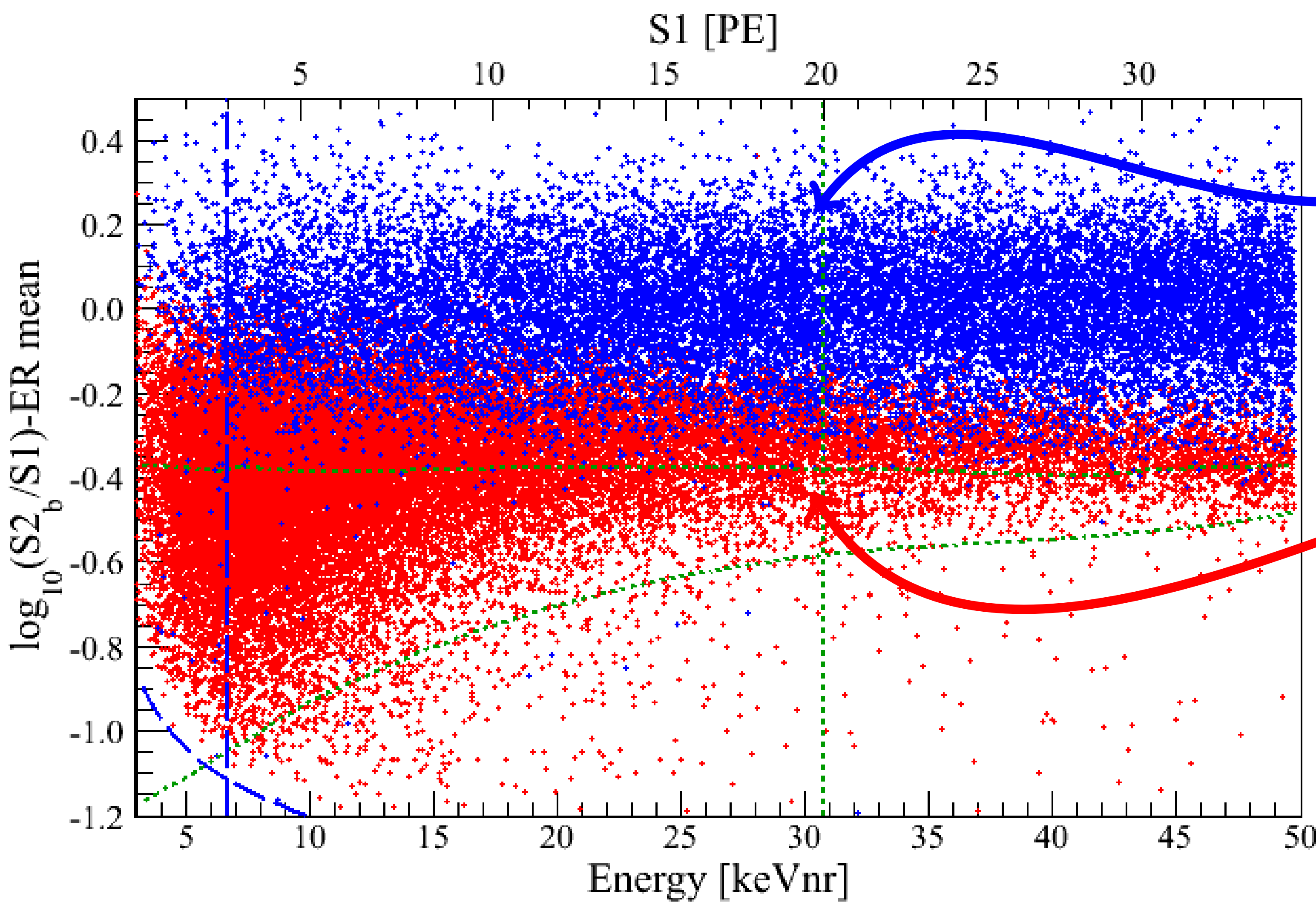
number of free electrons
per unit energy

secondary
amplification factor
[pe/e^-]

Q_y: Charge Yield



XENON Calibration Data



ER calibration data

^{60}Co and new ^{232} Th source

35× science data

NR calibration data

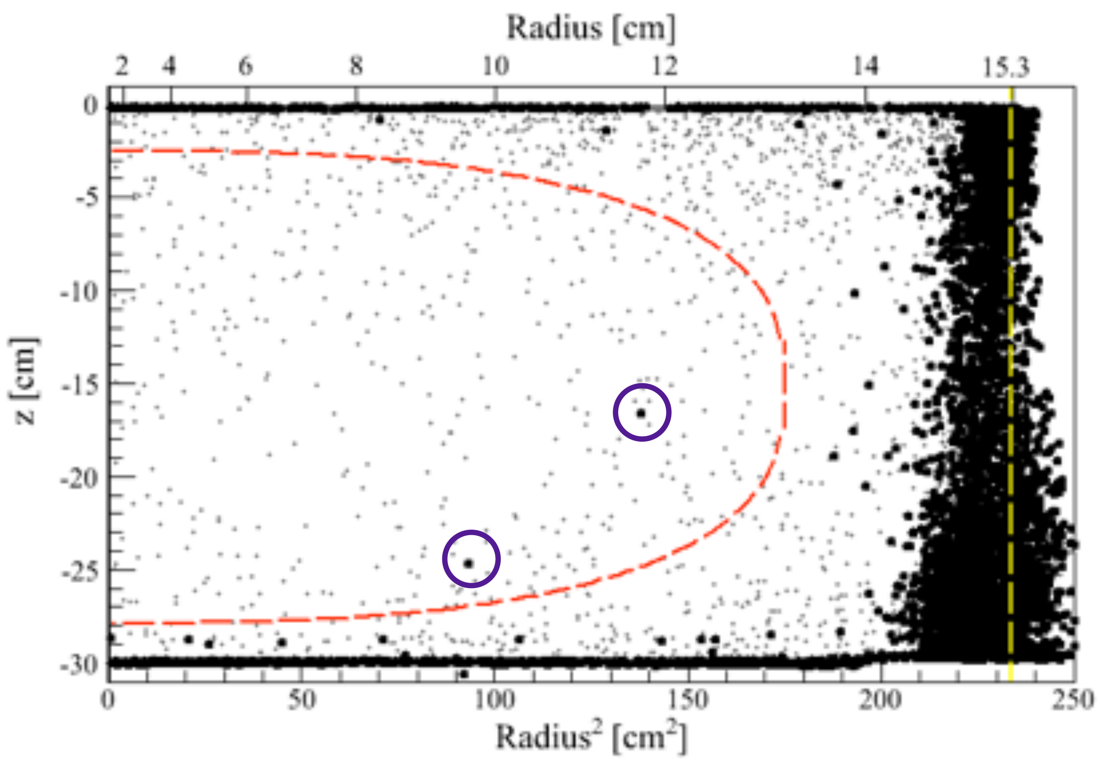
AmBe source

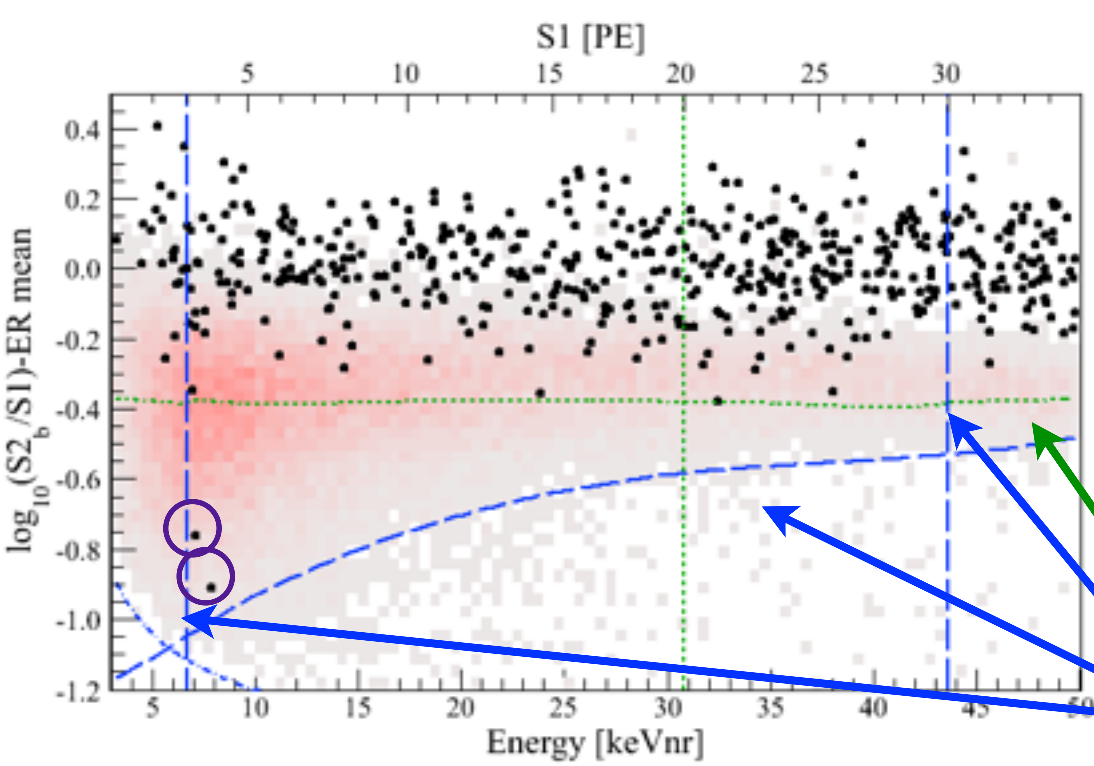
beginning and end of run

2013 Closing in on Dark Matter - E. Pantic

~99.5% ER rejection at 50% NR acceptance.

XENON 100 RESULTS



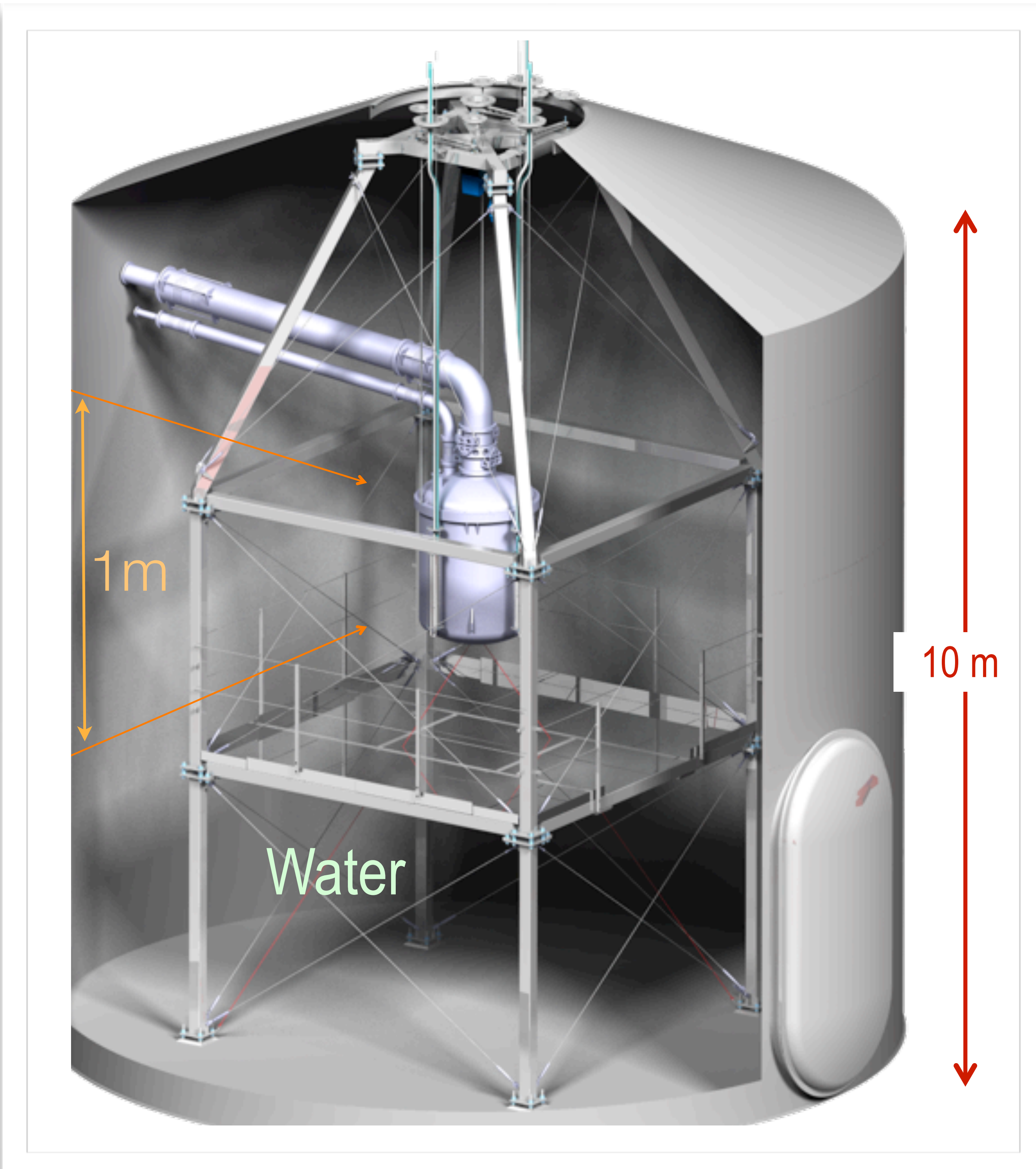


Phys. Rev. Lett. 109, 181391 (2012)

- 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

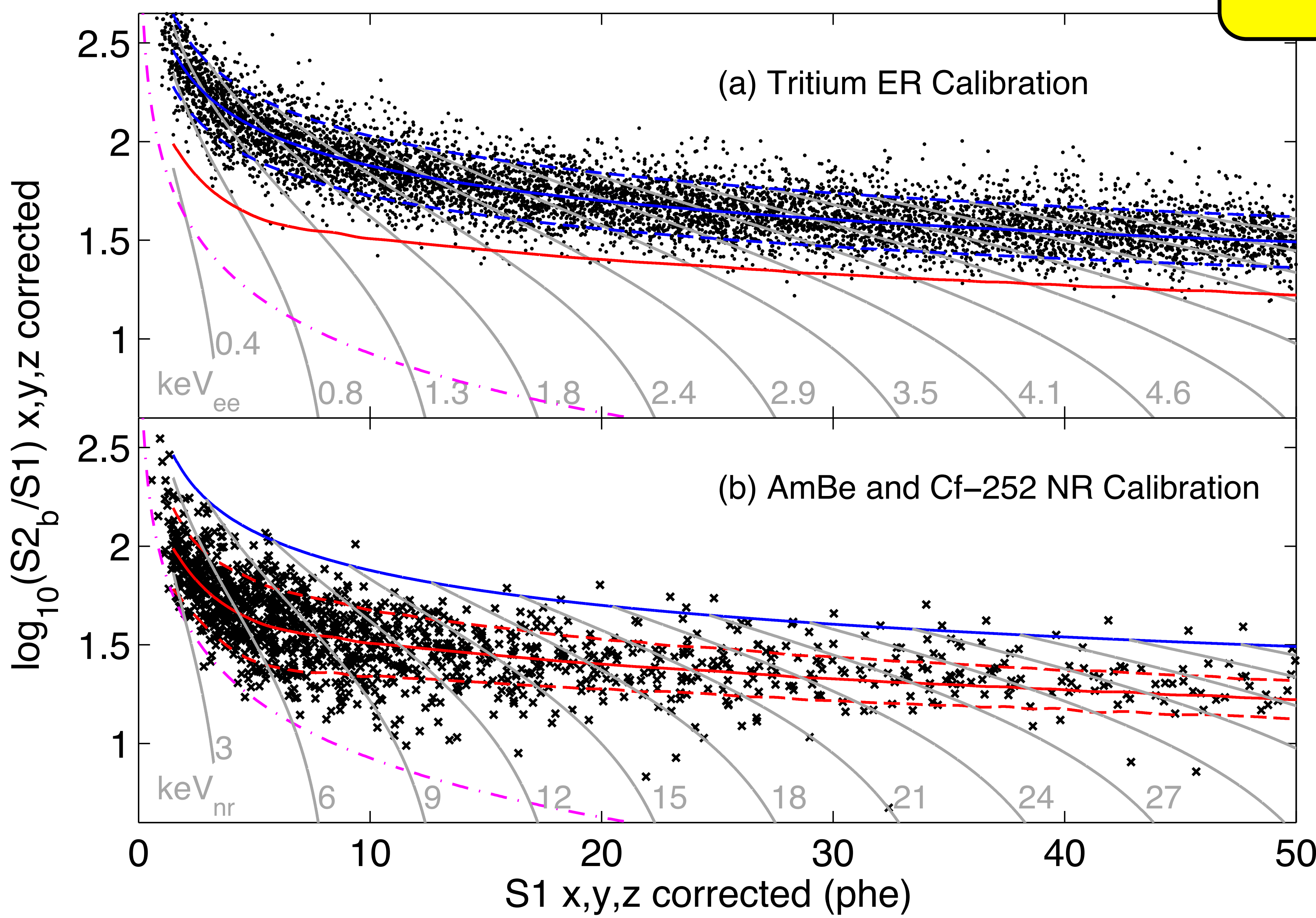
XENON 1T



- XENON 1T commissioning underground at LNGS starts in May 2014.
- First science run expected to start by mid 2015

LUX Calibration Data

arXiv: 1310:8214

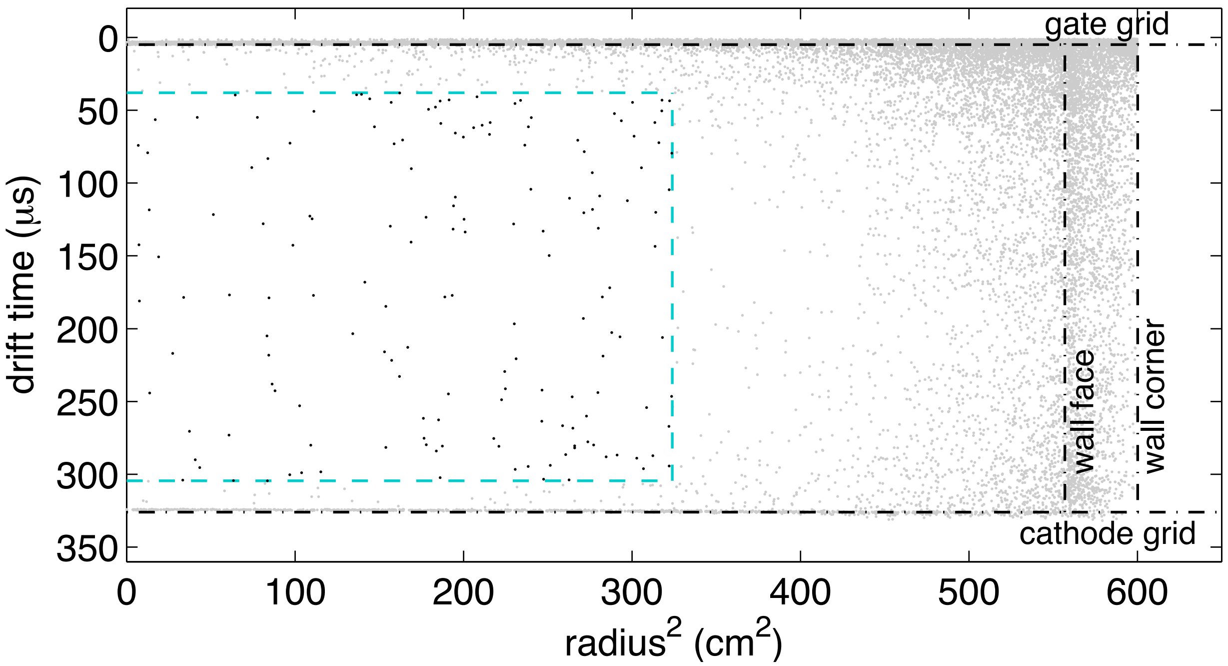


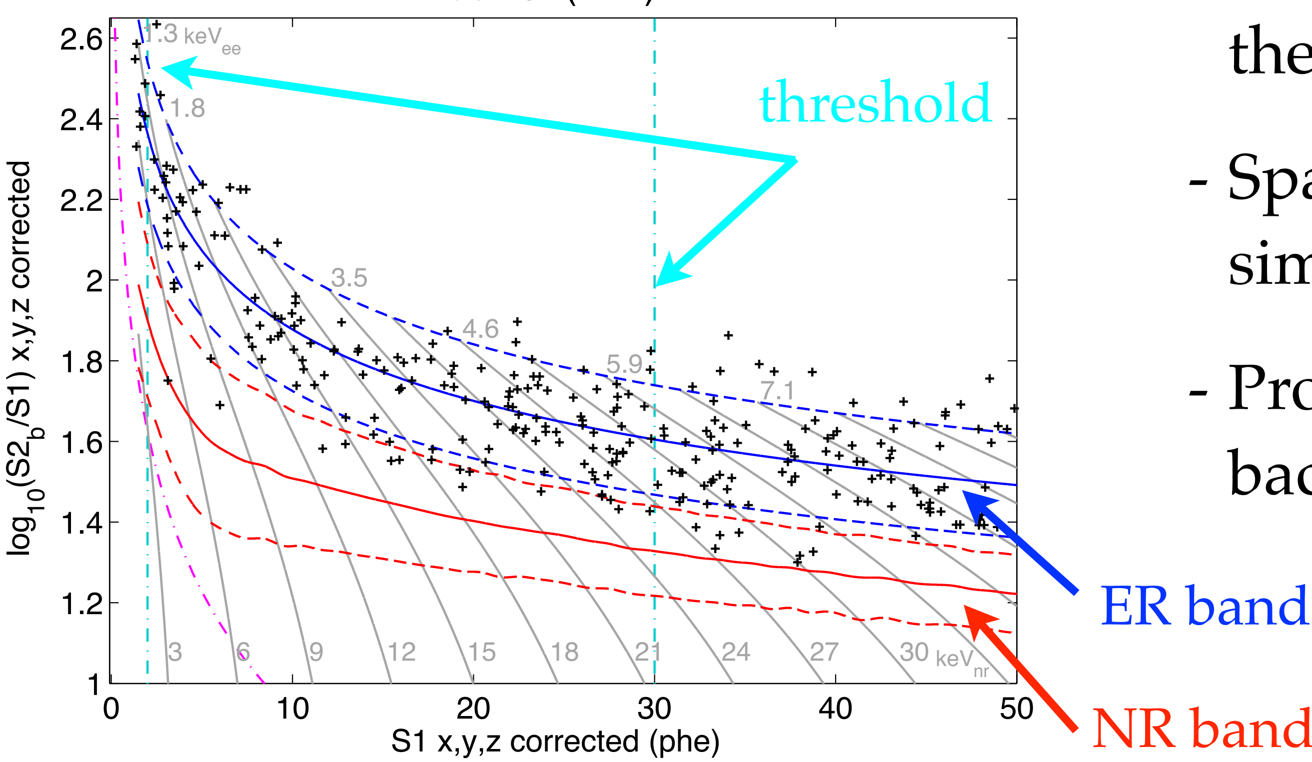
Data

Simulation + Data

LUX Results

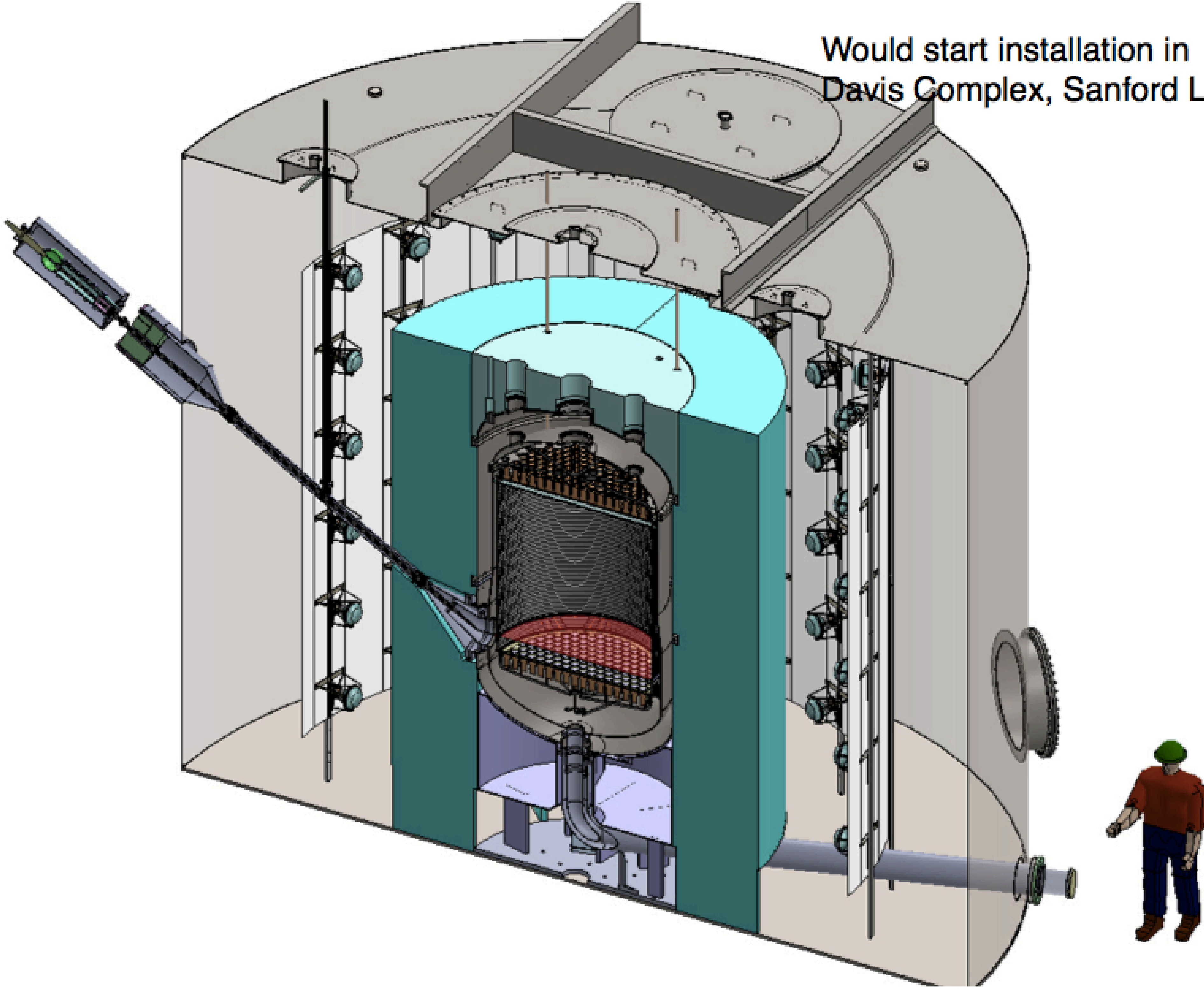
arXiv: 1310:8214





- 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)

LZ (LUX-ZEPLIN) 8T of Xe



Would start installation in
Davis Complex, Sanford Lab in 2016

Phonon and Heat Signals

(CRESST, EDELWEISS, SuperCDMS, ROSEBUD)

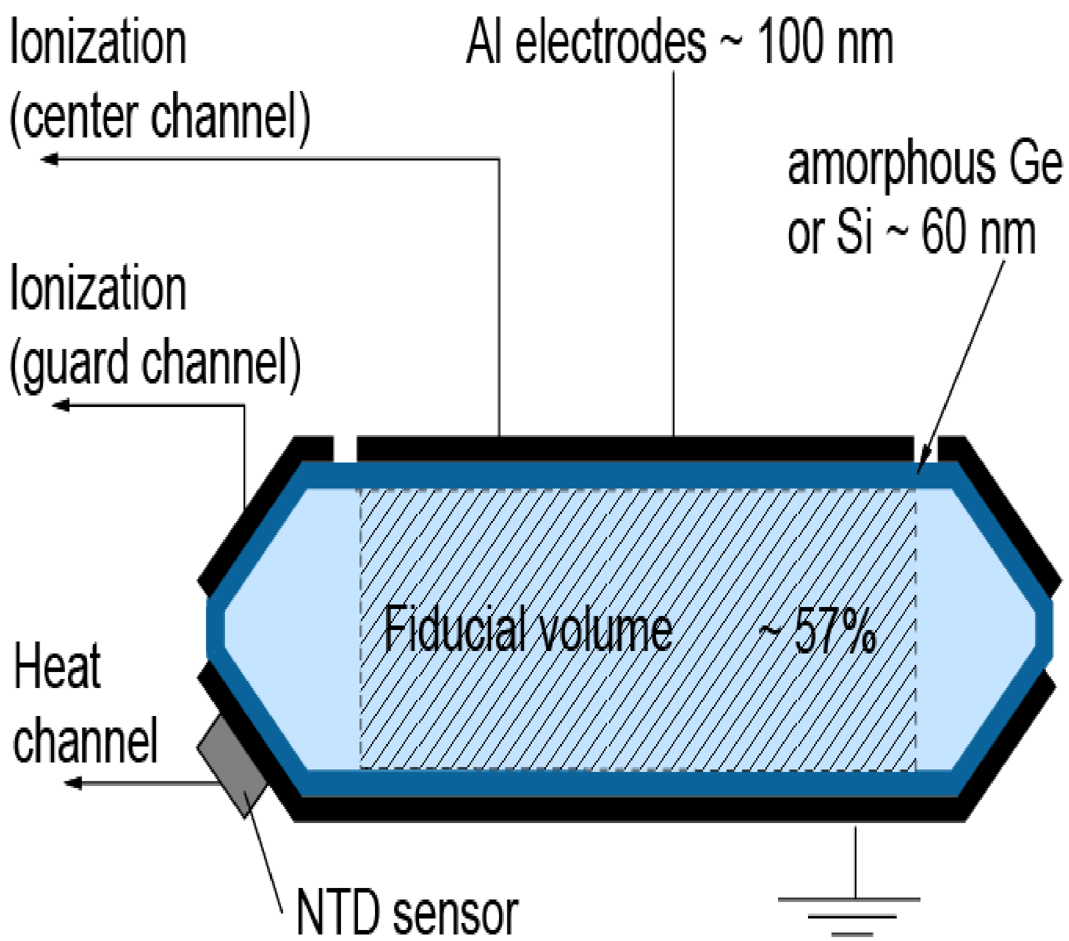
- Two families of sensors for phonon signal, themal and athermal
  - Thermal sensors - wait for the full thermalization of the phonons within the bulk of the detector and the sensor itself
  - Temperature increase is equal to the deposited energy over the heat capacity of the system.
- Two most widely 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 the superconducting to resistance regime with dependence of the resistance with temperature T

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



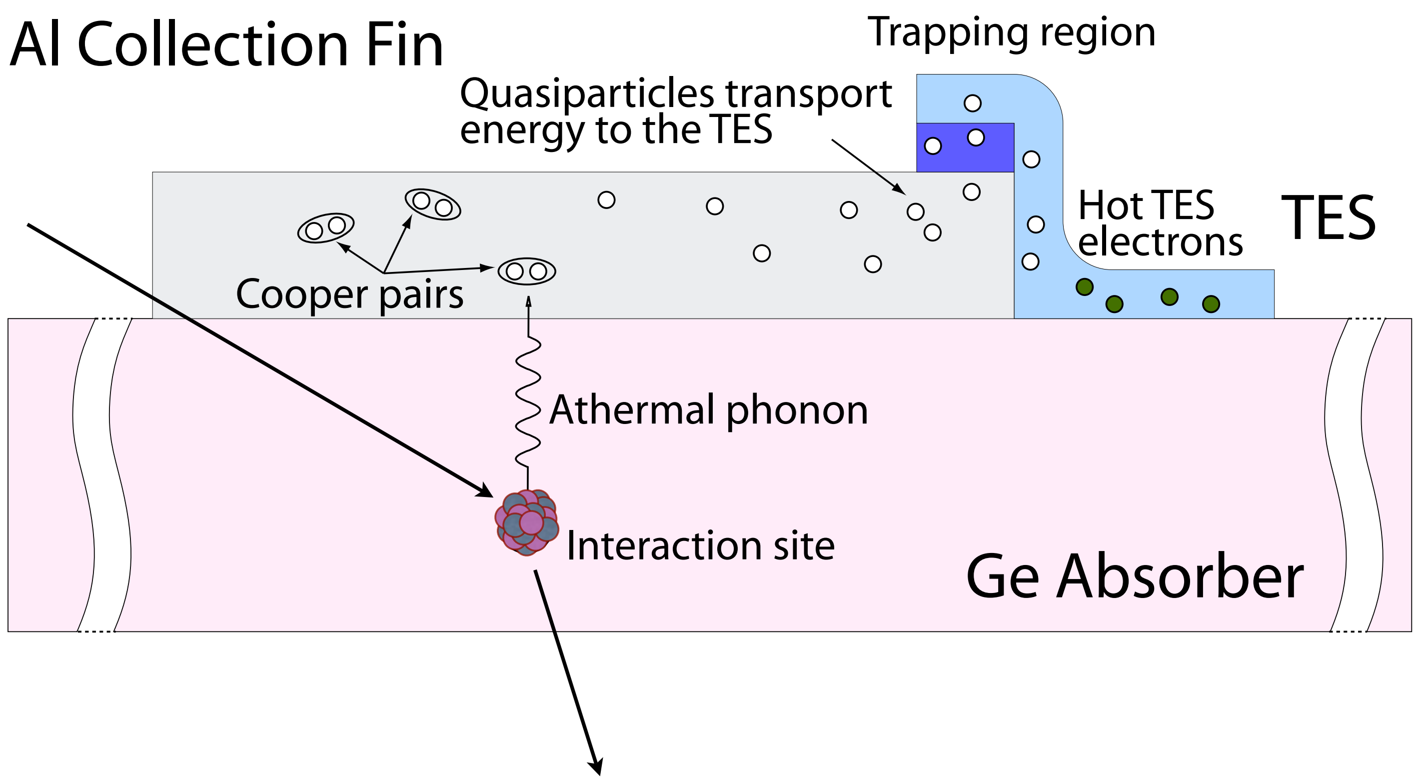
Schematic "Ge-NTD" EDELWEISS-II detector

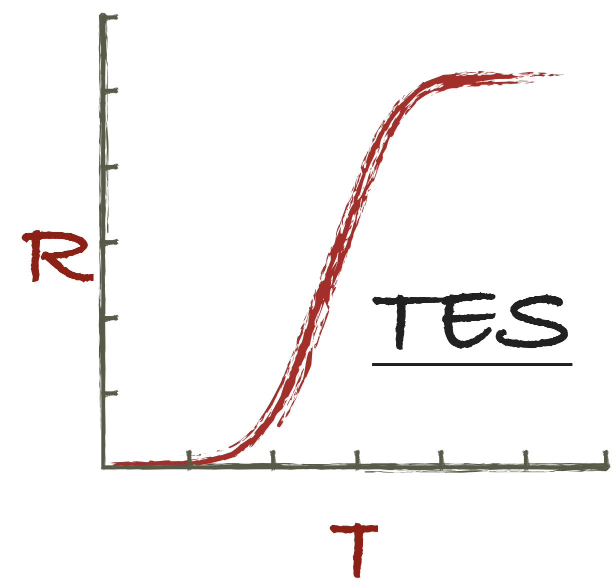
- Resistance is continuously measured by flowing current through it and measuring the resulting voltage.

- Sensors are glued onto detector.

TESs

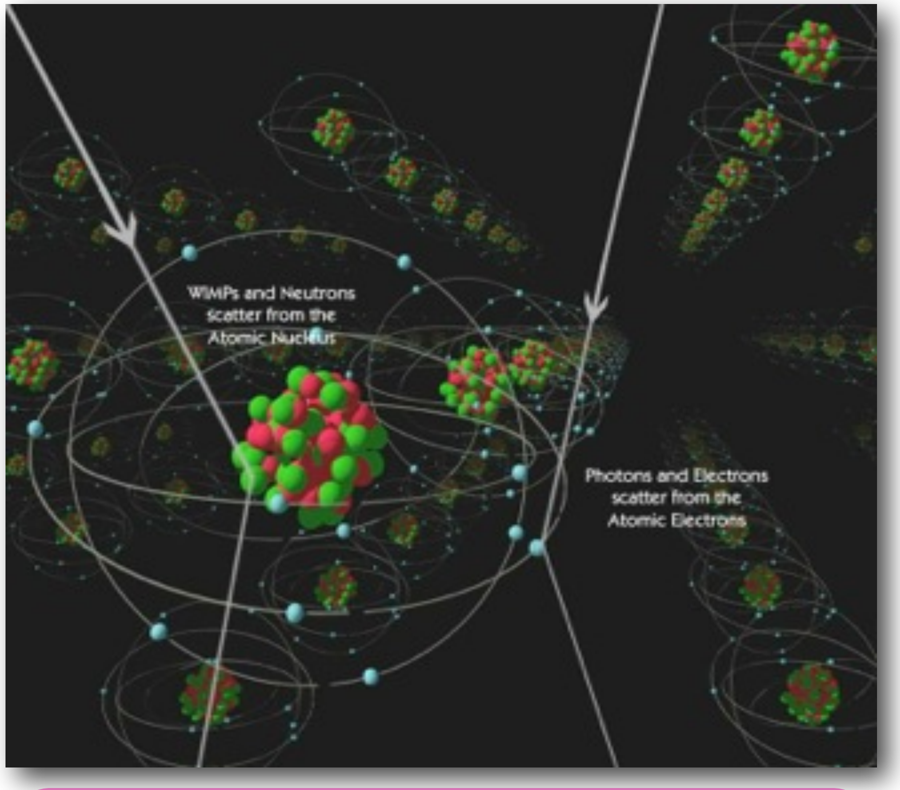
ZIP detector schematic from SuperCDMS



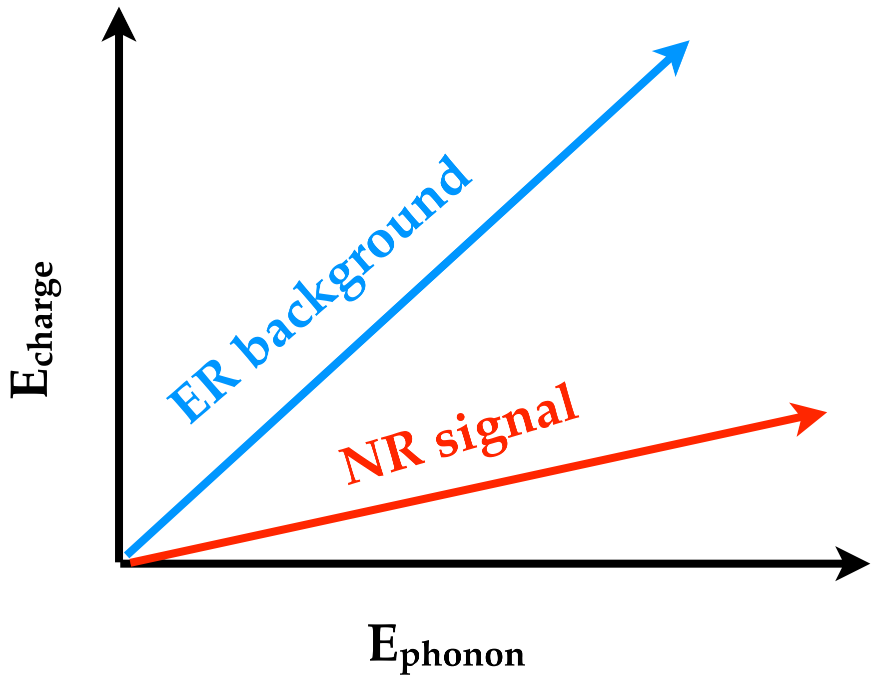


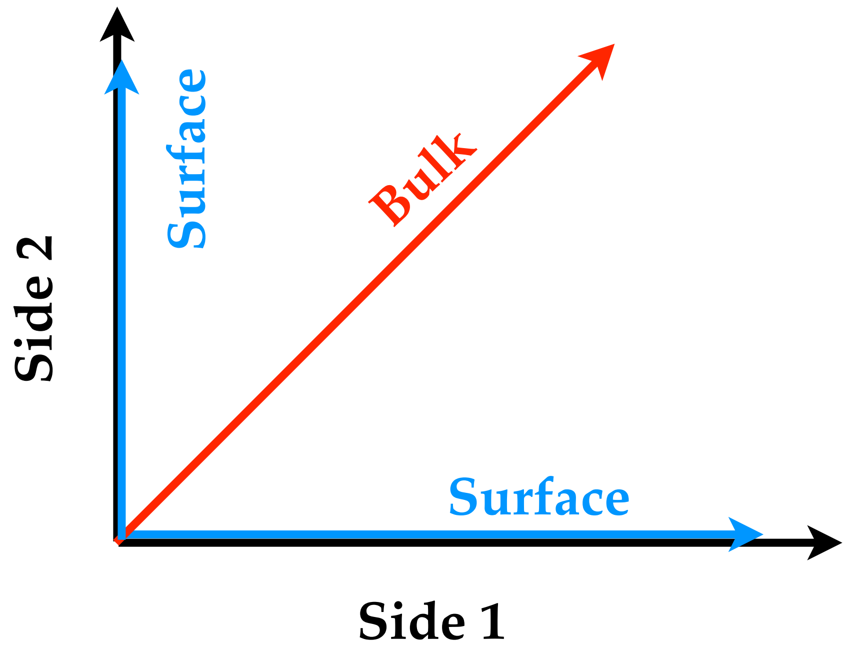
- TES is a thin superconducting film operated near its T_c.
- A heater with an electothermal feedback system maintains temperature at superconducting edge.
- Temperature changes are detected by a change in the feedback current, collected by a SQUID.

Discrimination - EDELWEISS AND SCMDS

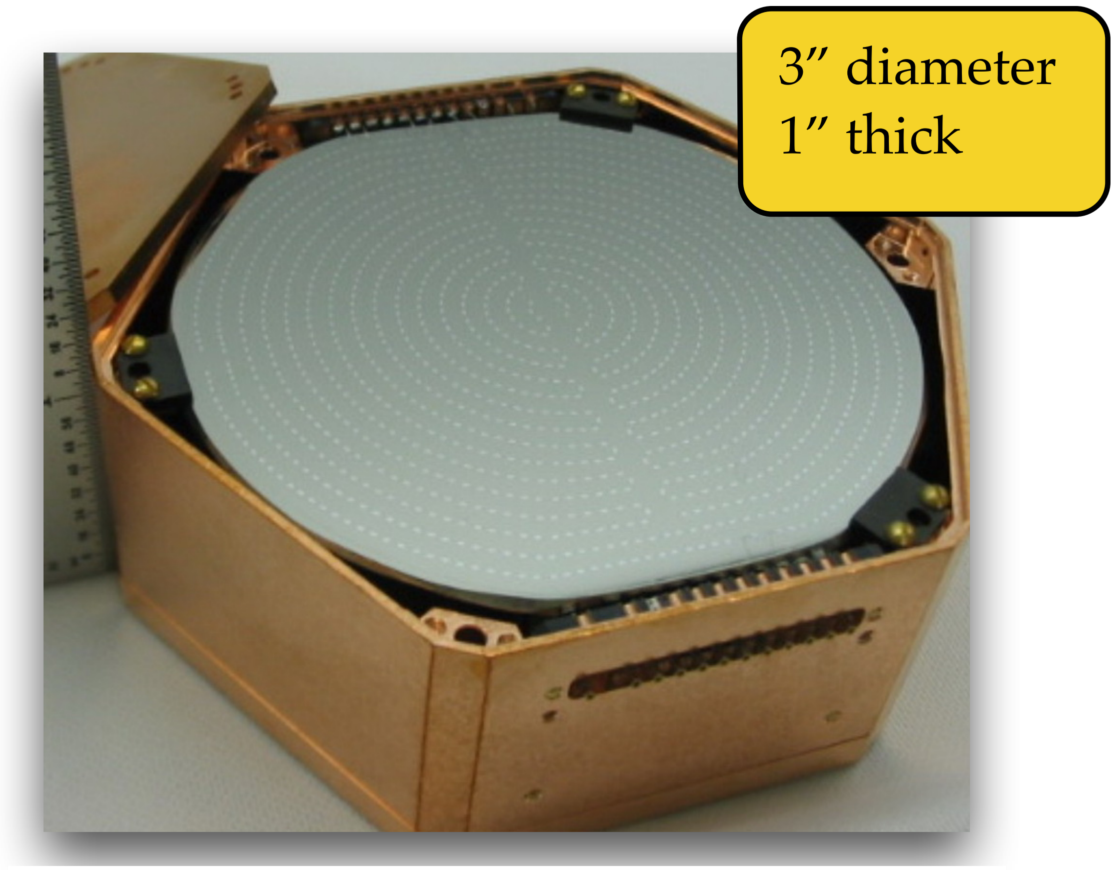


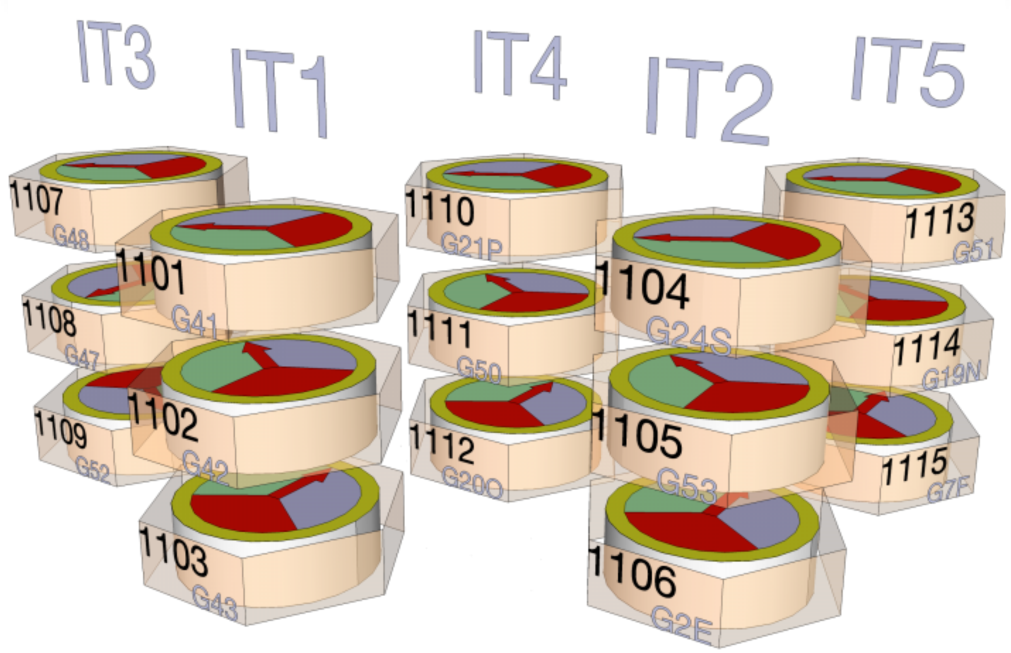
Discrimination from measurements of ionization and phonon energy **and** charge distributions





SuperCDMS iZIP Detectors





- Ge crystal (600 g) **i**nterleaved **Z**-sensitive **I**onization and **P**honon detectors (**iZIP**)

- Ionization lines (±2 V) are interleaved with phonon sensors

- Two charge channels on each face can be used to reject surface and sidewall events

- Phonon sensors and their layout are optimized to enhance phonon signal to noise ratio

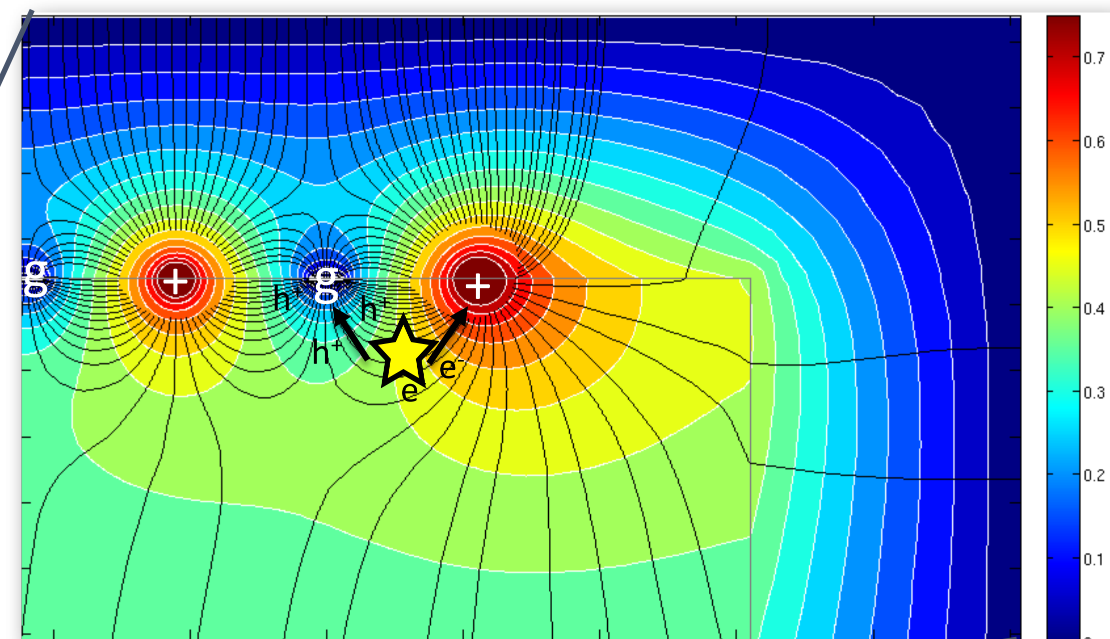
- Each side has one outer channel to reject zero charge events and 3 inner channels to reject surface and sidewall events.

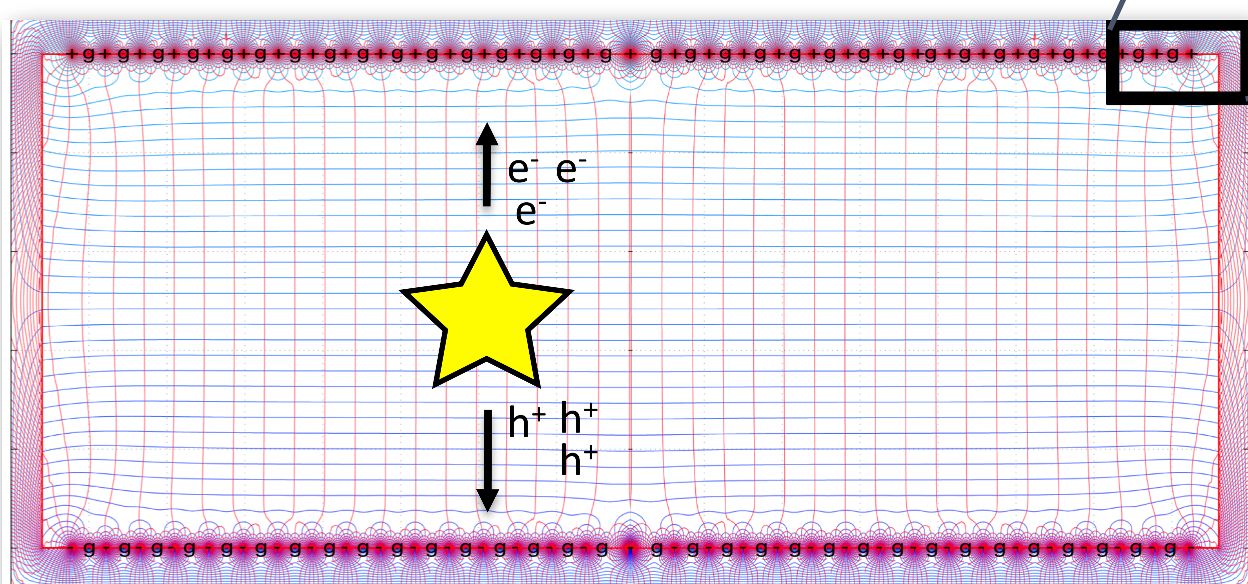
- 9 kg Ge (15 iZIP detectors, each with mass mass 600 g) stacked into 5 towers, located in the Soudan Underground Laboratory, USA

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

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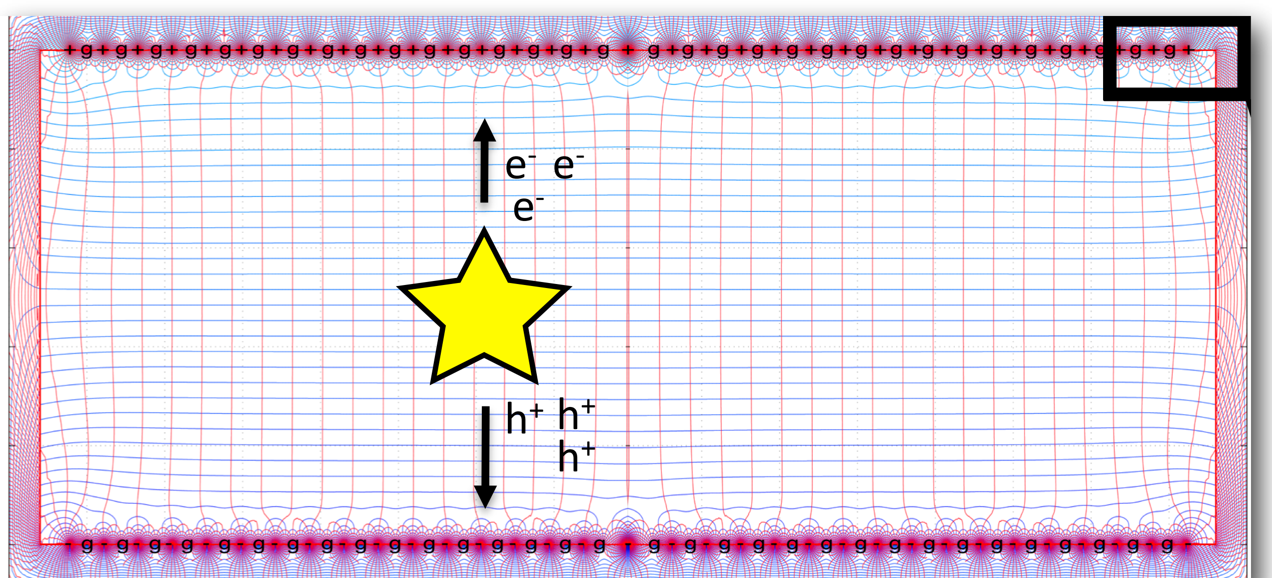
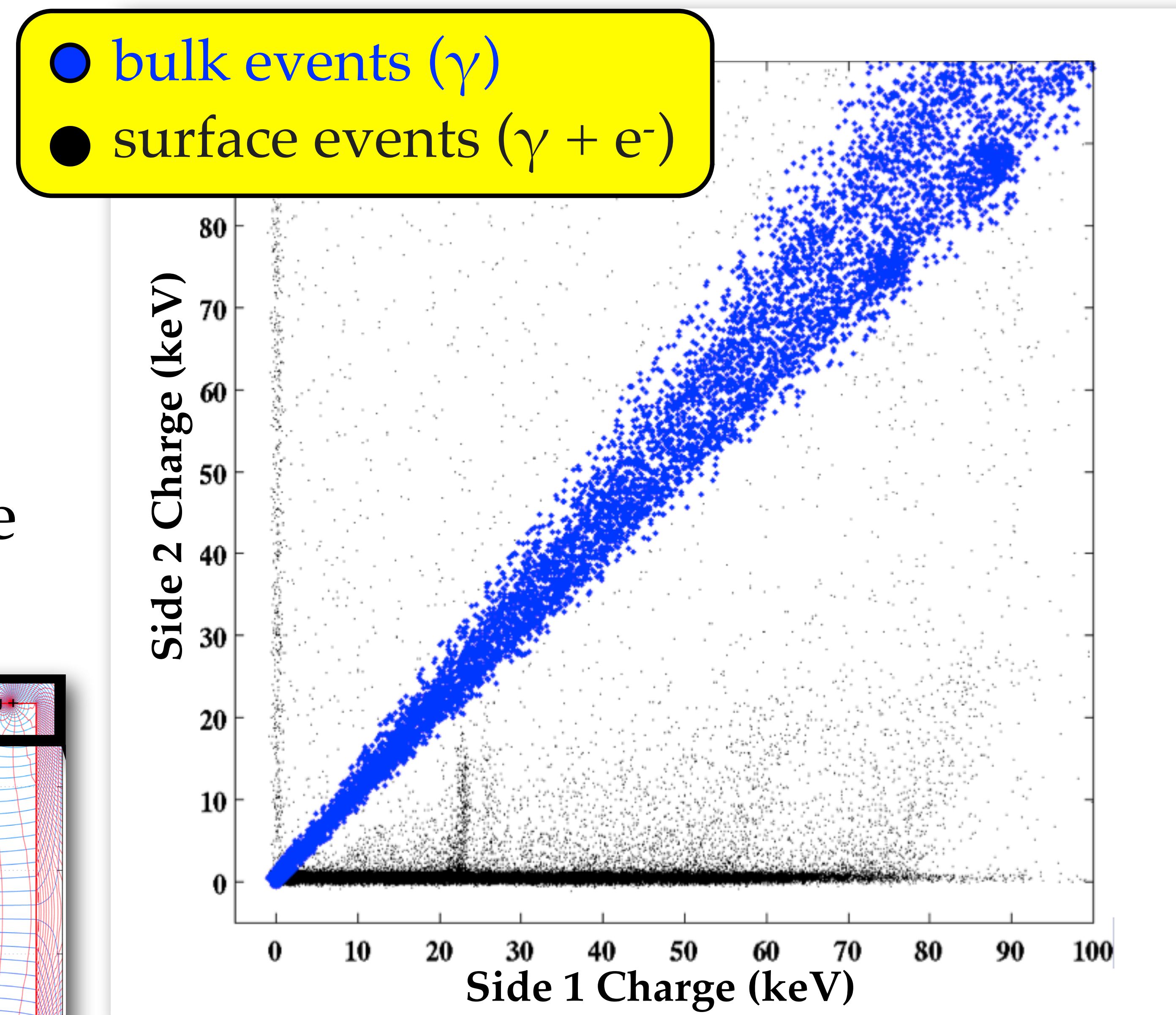
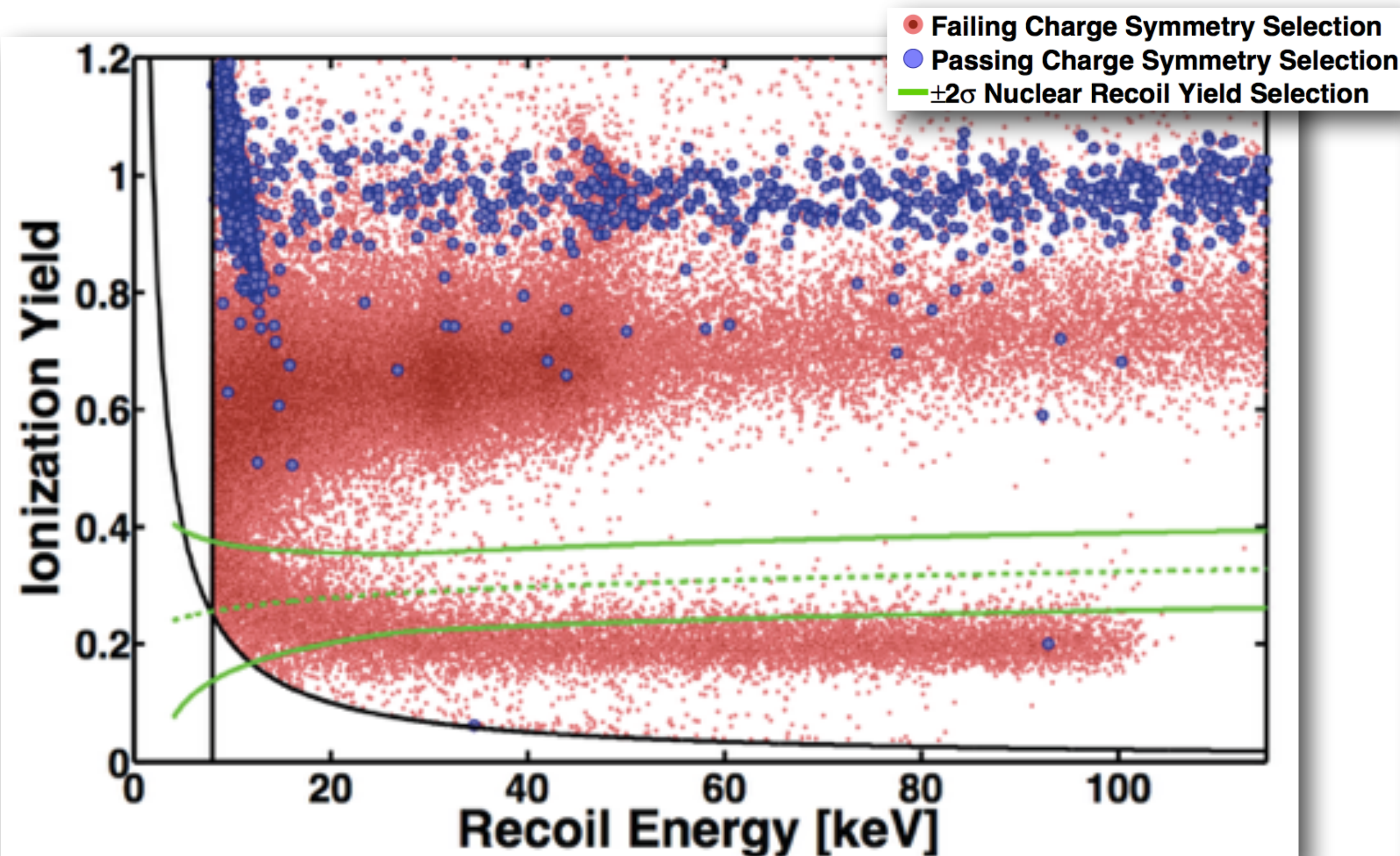
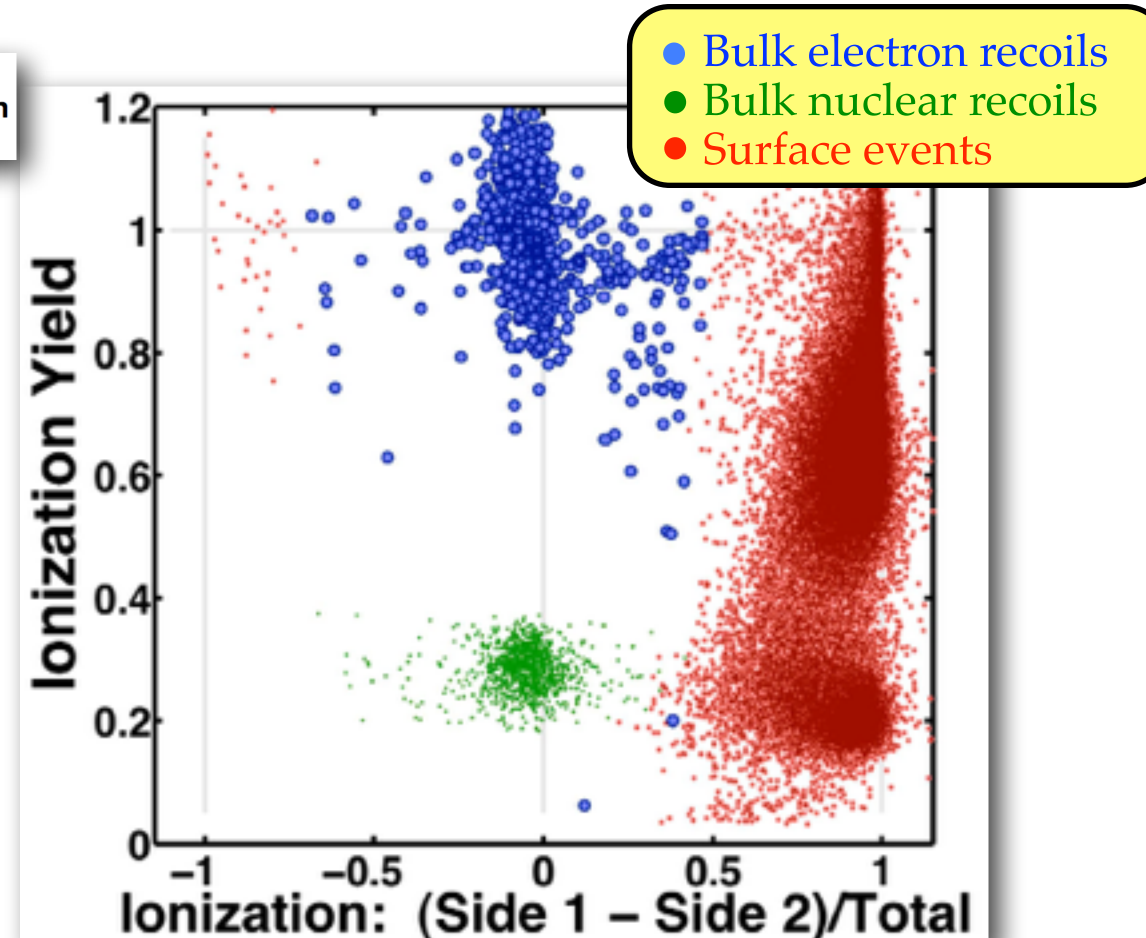




SuperCDMS: ^{210}Pb Test

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!

Energy

The total energy (phonon) is given by

recoil energy
[keV_{nr}]

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

total energy

Neganov-Luke
Phonons

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

where

V_b = bias Voltage

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 --

$$E_r(p_t) = p_t - eV_b N_Q = p_t - \frac{eV_b E_Q}{\epsilon} = p_t - E_Q$$

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

$$E_r = p_t - E_r \quad \Rightarrow \quad E_r = \frac{p_t}{2}$$

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

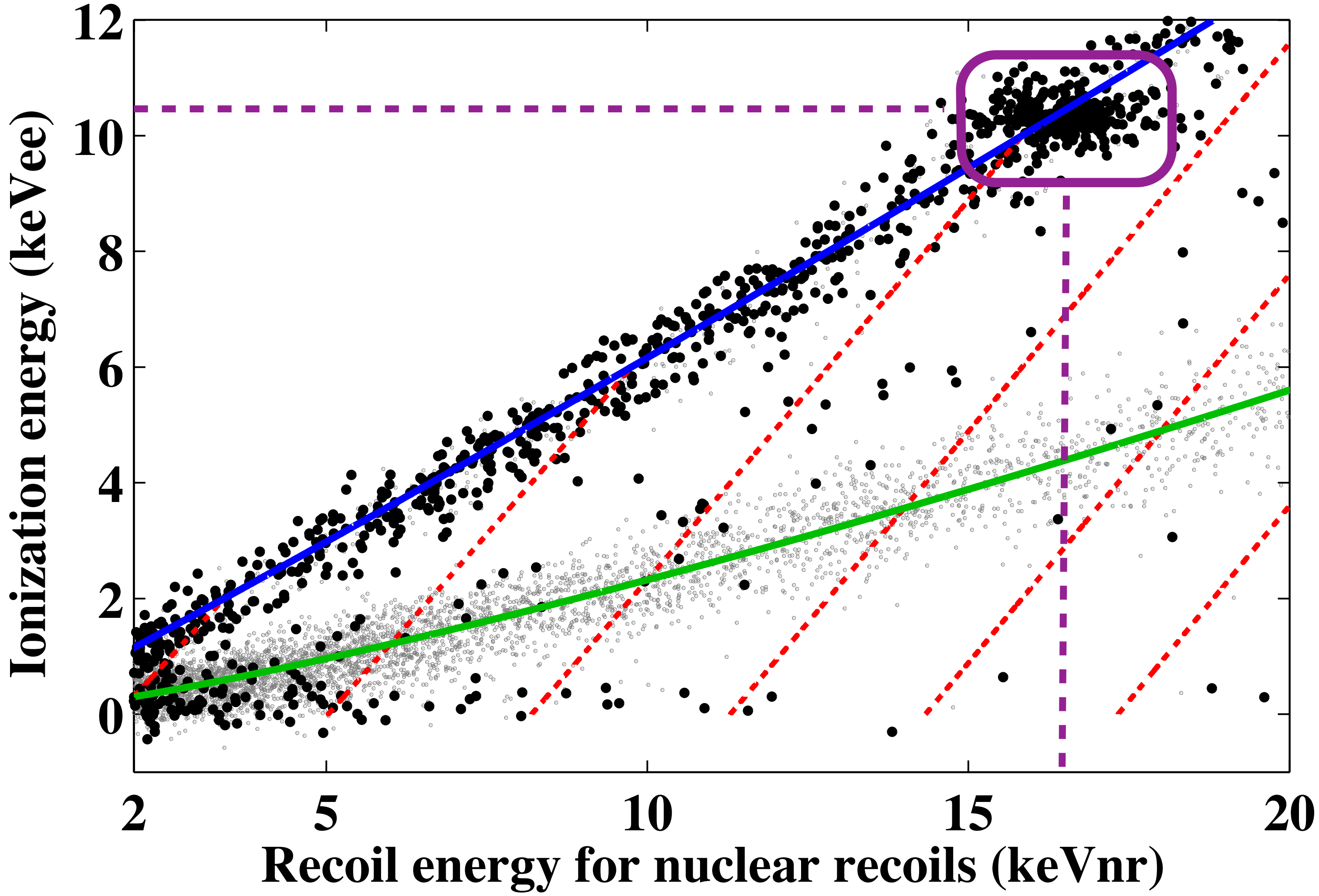
where

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

*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.



····· constant "true" energy
—— mean NR (^{252}Cf)
—— mean of ER (^{133}Ba)

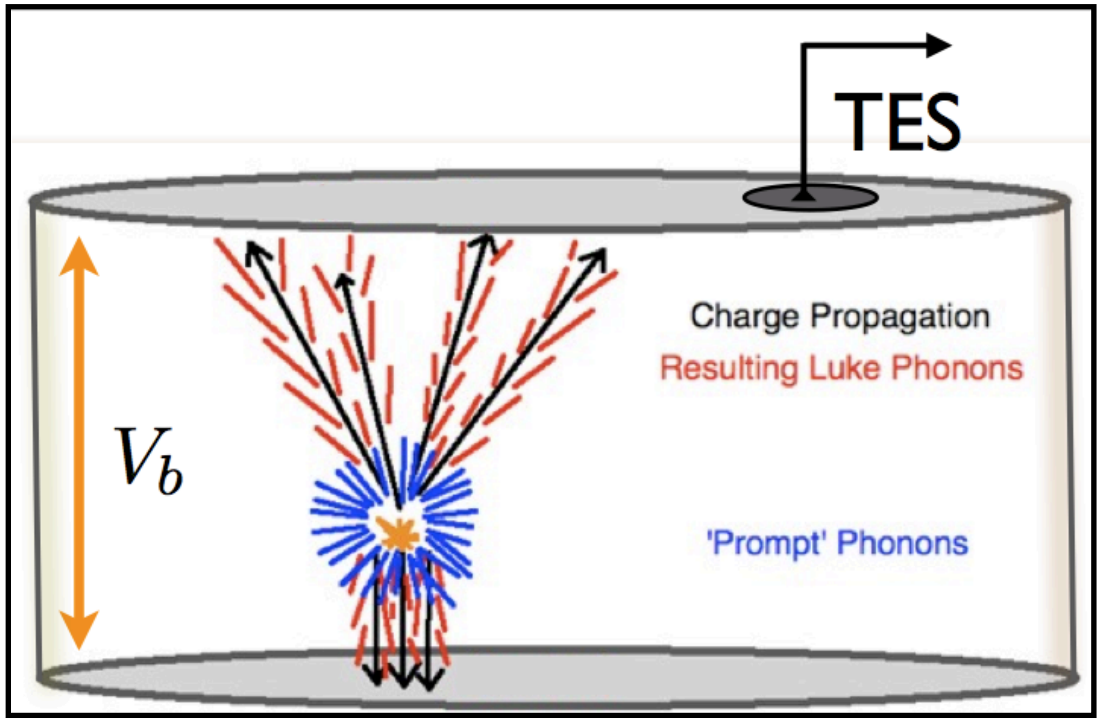
$$y = \frac{E_Q}{E_R}$$

- 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 be 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.

A Low Ionization Experiment



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

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

- 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

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

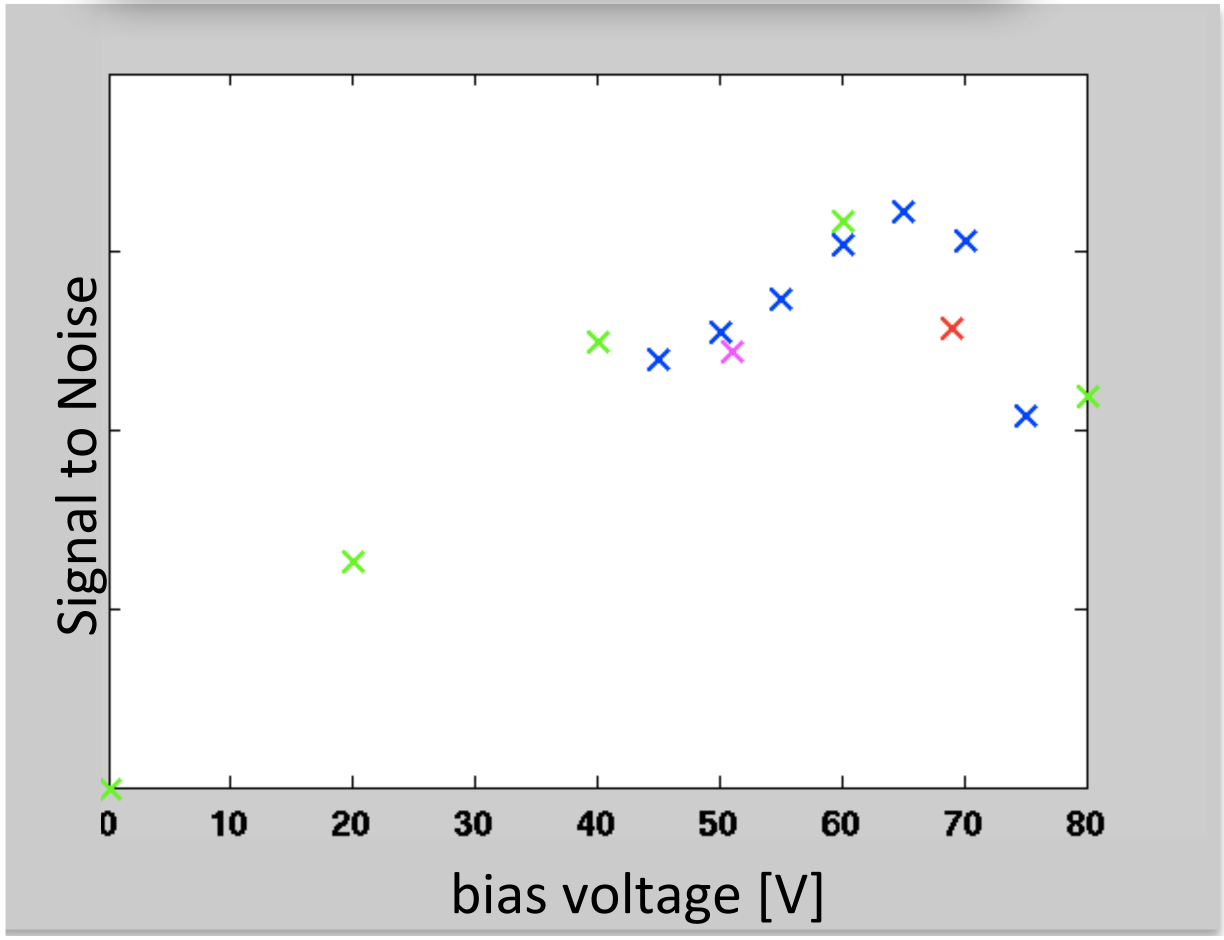
where $\epsilon = 3eV$ in Ge.

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

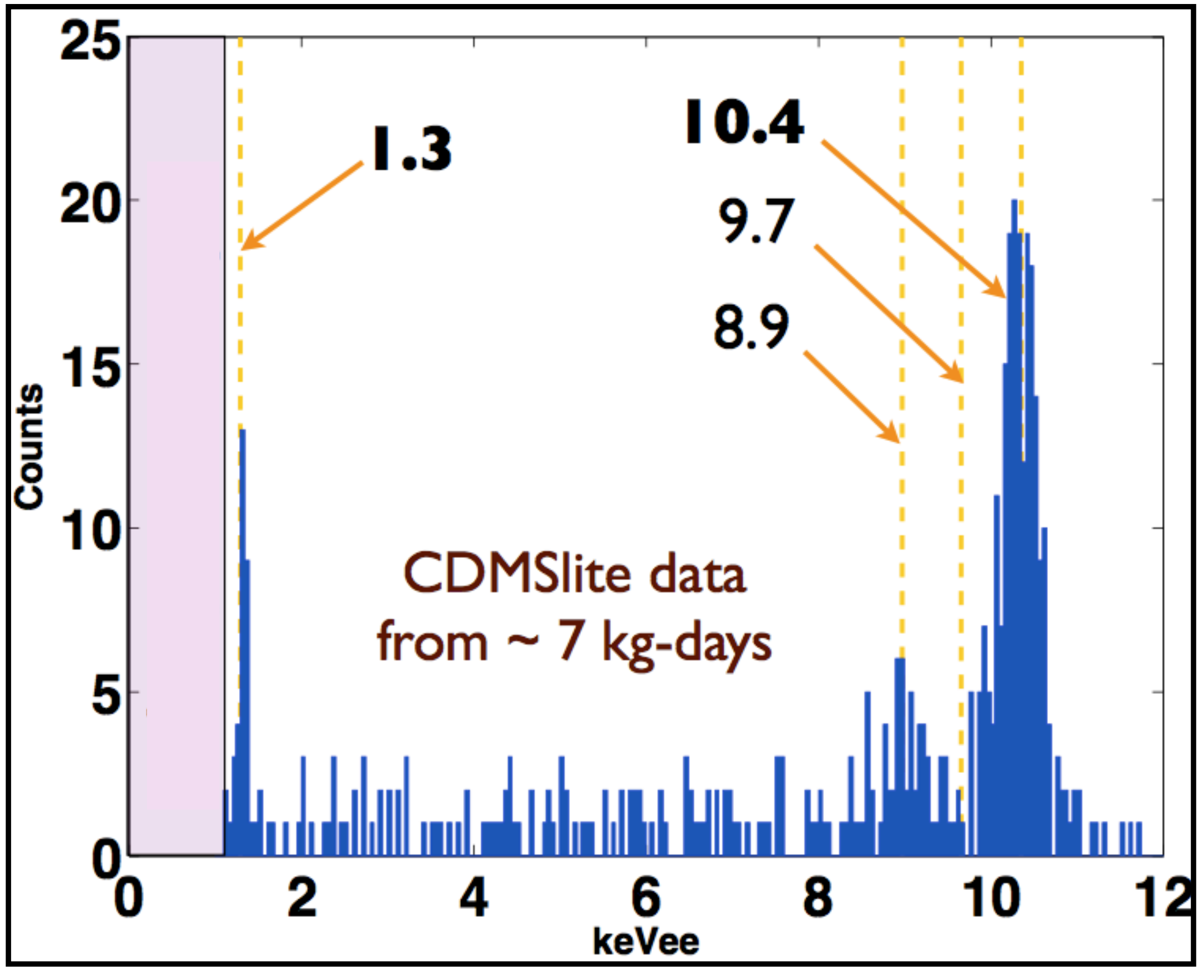
CDMSlite - The Detector

- 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 69 V 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 down to 170 eeV_{ee} in our detectors.
- Resolution of various Ge activation lines.

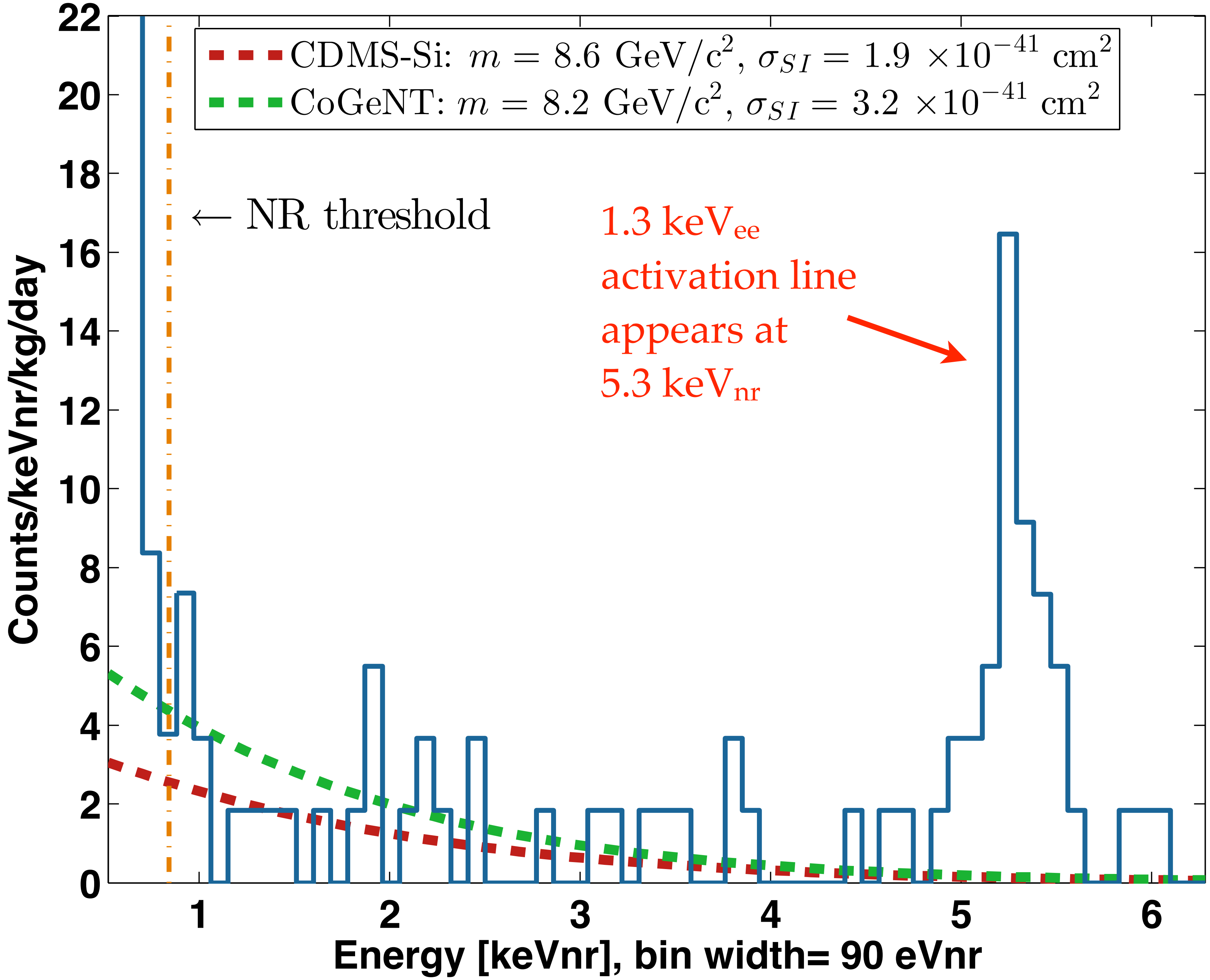
CDMSlite: The Data

- Data were taken during three periods in 2012
- One iZIP was used, IT5Z2 – 0.6 kg
  - Selected for its low trigger threshold and low leakage current
- There were two neutron exposures (^{252}Cf)
  - Activation of Ge (^{70}Ge + n --> ^{71}Ge) allowed determination of energy scale and monitoring of stability (10.36 keV_{ee} and 1.29 keV_{ee} lines).
- Raw exposure was 9.6 kg days (16 live days)

Run Period	Starting Date	Ending Date	Raw Livetime [h]
1	August 18	August 29	166.5
2	September 7	September 14	111.2
3	September 18	September 25	105.9

CDMSlite: Results

PRL 112, 041302, 2014



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.

SCDMS Low Threshold Strategy

Challenge:

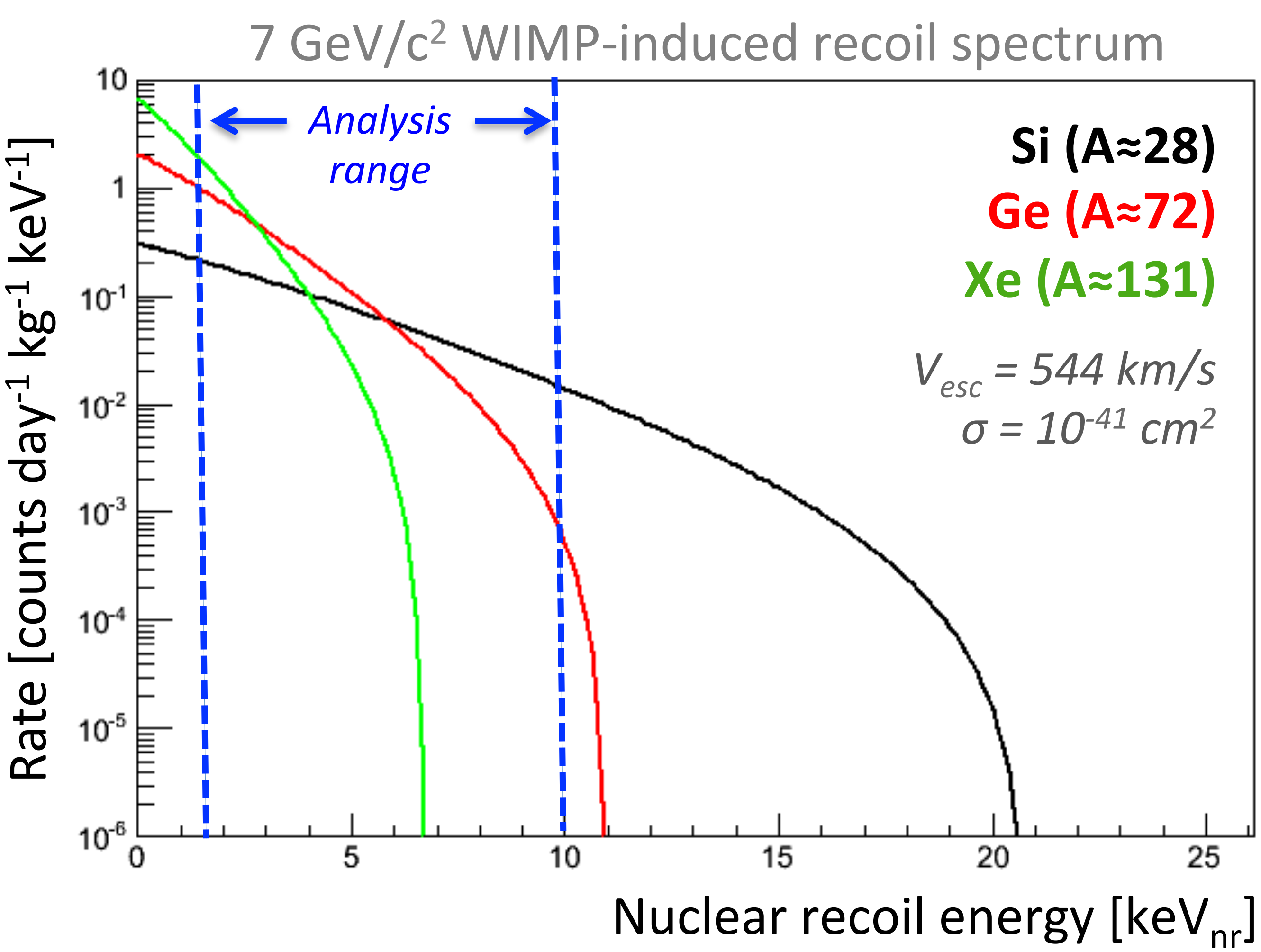
- Signal is at very low recoil energies where backgrounds are difficult to reject

Strategy:

- Use 7 detectors with lowest thresholds; lower the threshold as much as possible
    - 1.6 keV_{nr} trigger threshold
- 557 kg-days exposure taken from Mar 2012 - Jul 2013.

Trade-off:

- Background is difficult to reject below 10 keV_{nr}. Try to reject as much background as possible.



We expect background events in the signal region!

Background Estimates

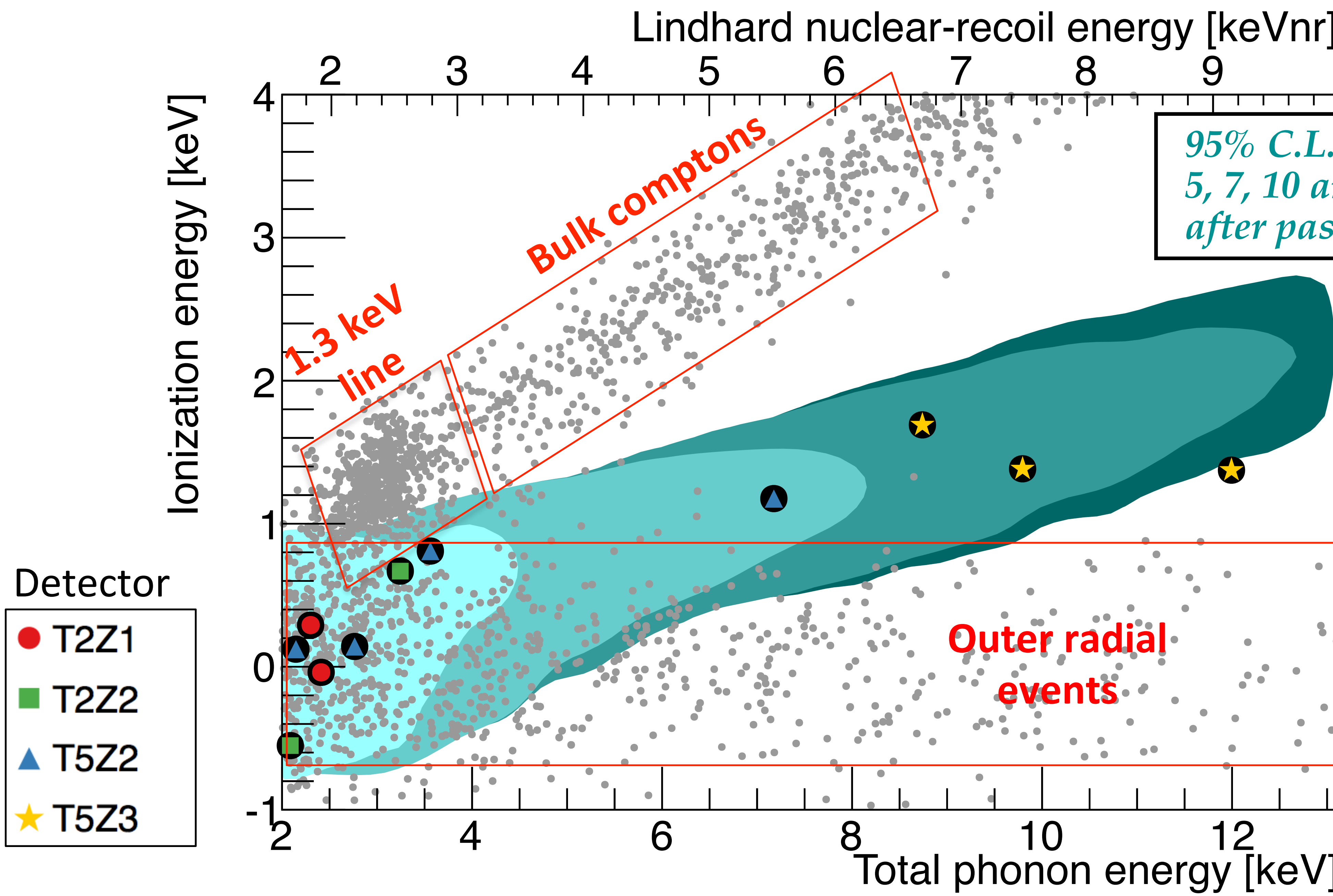
- Prior to unblinding, background estimates were finalized, including known systematic effects.
- The background model was used to tune selection criteria. Unknown systematics preclude background subtraction for this blind analysis.

  We decided prior to unblinding to only set an upper limit.
- 4 BDT cuts were optimized for 5, 7, 10 and 15 GeV/c^2 WIMPs. Accept events that pass any of the four cuts. Each cut was simultaneously tuned on all detectors, maximizing 90% C.L. poisson sensitivity for that mass.

Background model expectation: $6.1^{+1.1}_{-0.8}$ events

Neutron estimate: 0.1 ± 0.02 events

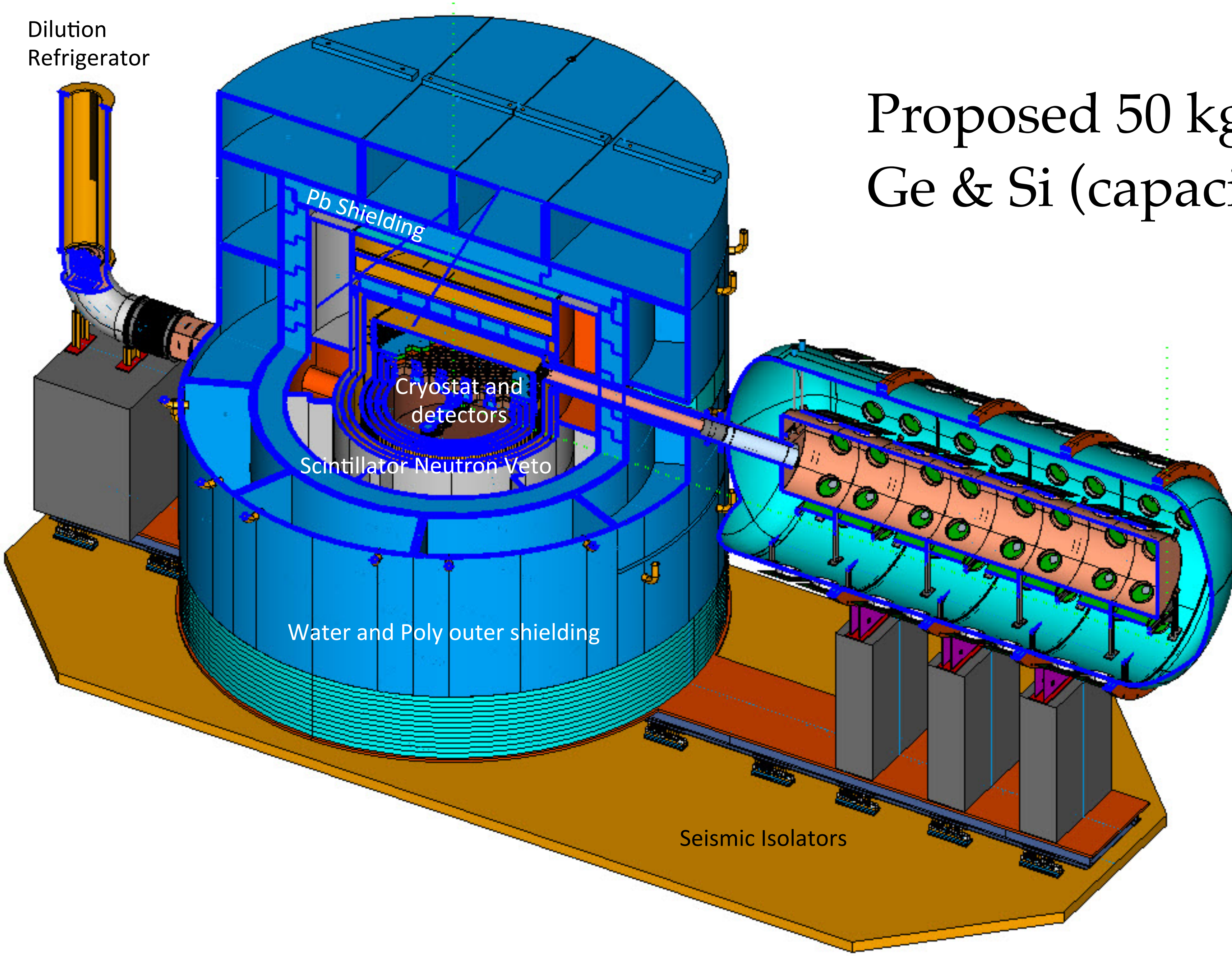
95% Confidence Intervals



95% C.L. interval for a 5, 7, 10 and 15 GeV/c² WIMP after passing BDT selection

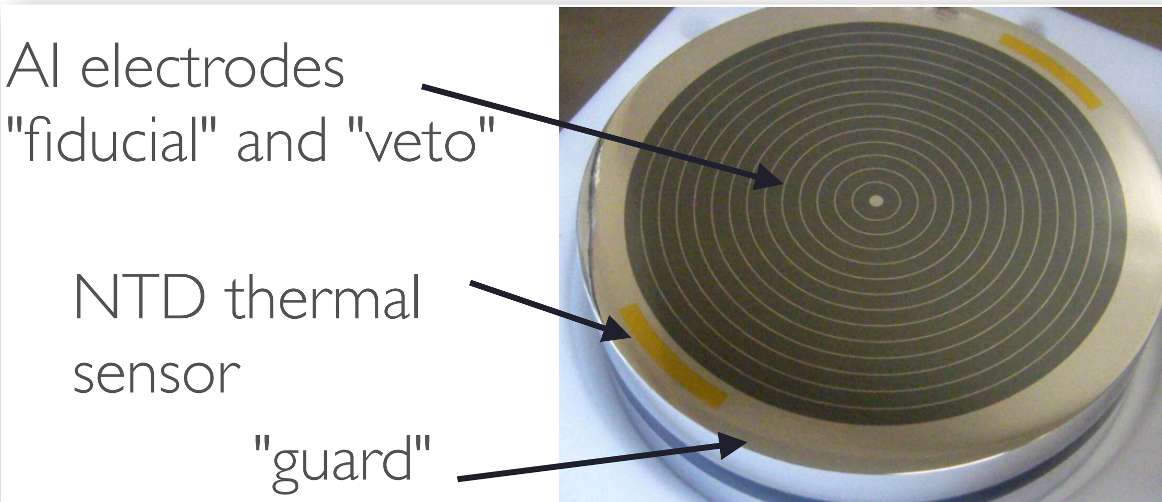
Detector	Energy [keVnr]	Bkgd	
T1Z1	—	0.03	+0.01 −0.01
T2Z1	1.8, 1.9	1.4	+0.2 −0.2
T2Z2	1.7, 2.6	1.8	+0.4 −0.3
T4Z2	—	0.04	+0.02 −0.02
T4Z3	—	1.7	+0.4 −0.3
T5Z2	5.8, 1.7, 2.8, 2.2	1.1	+0.3 −0.3
T5Z3	7.5, 9.2, 6.7	0.13	+0.06 −0.04

SuperCDMS @ SNOLAB

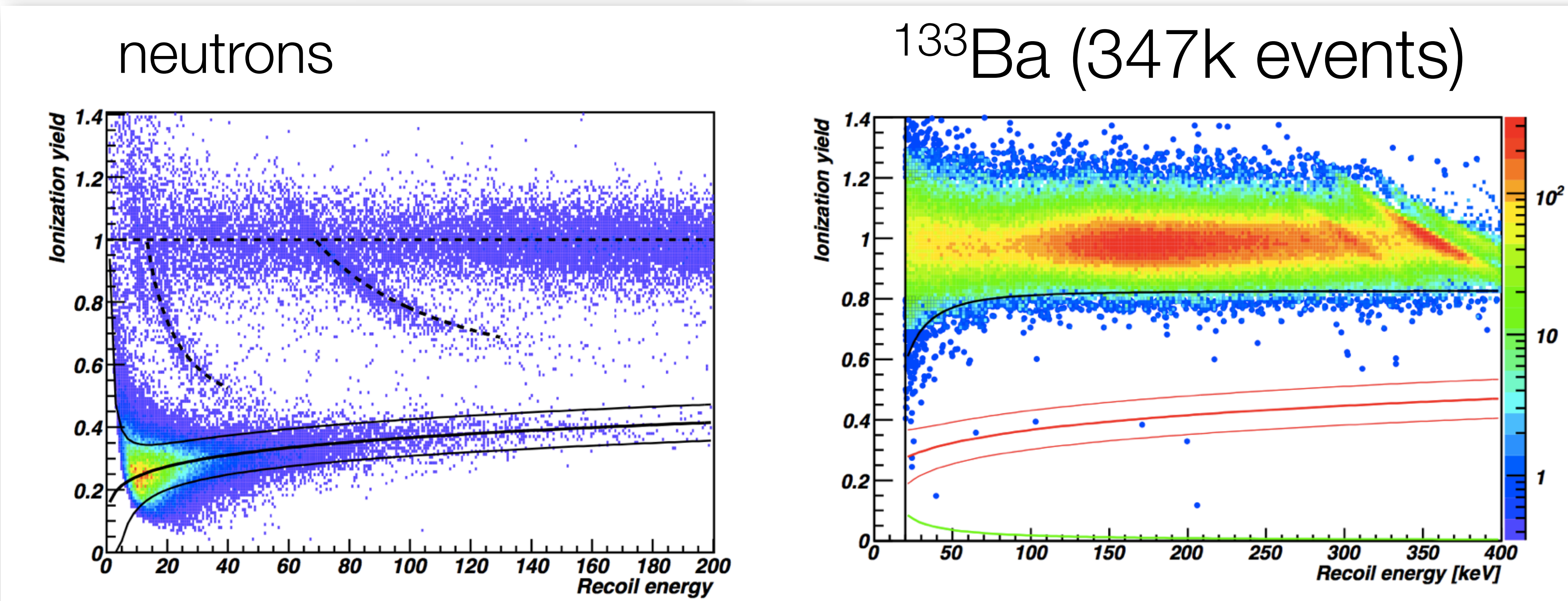


Proposed 50 kg payload of Ge & Si (capacity 400 kg Ge)

EDELWEISS

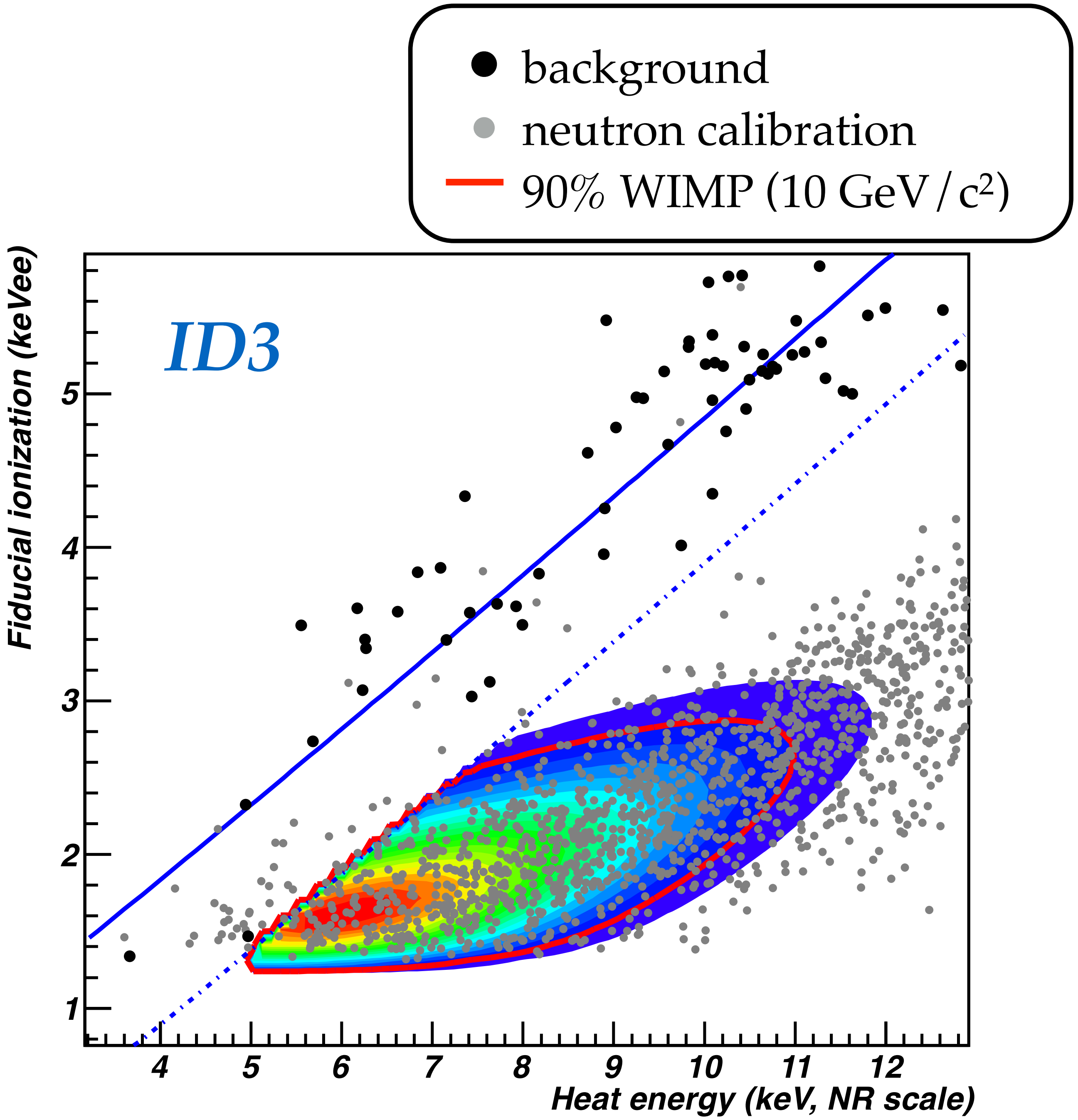


- Located in the Laboratoire Souterrain de Modane (LSM) between Italy and France.
- Detectors instrumented with electrodes (charge) and NTD thermal sensors (phonons)



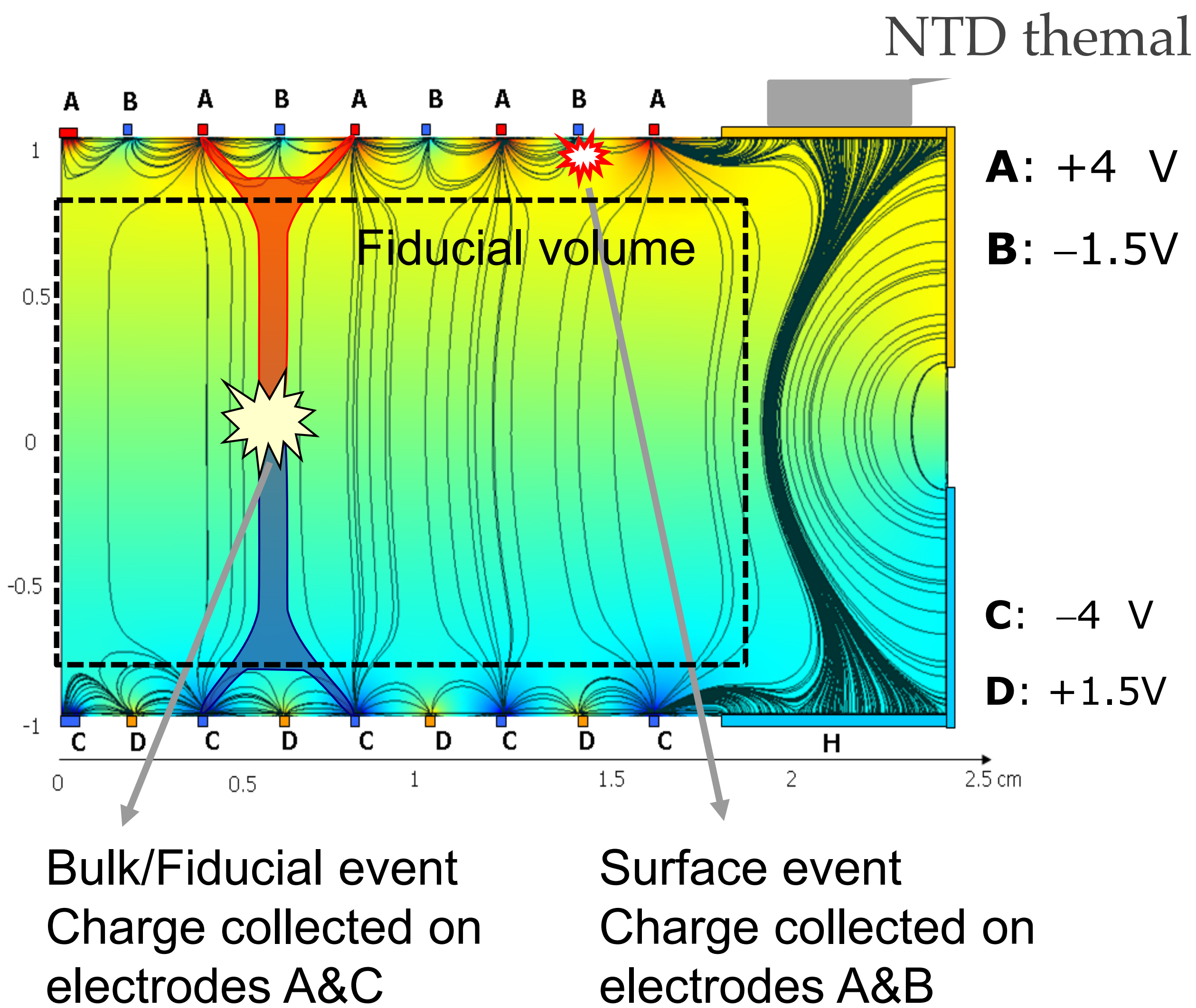
EDELWEISS II: Low Mass

- Search for low energy (E < 20 keV) WIMPs
- EDELWEISS II Exposure
    - Data obtained in 2009 - 2010 (14 months)
    - 113 kg-days in four ID Ge detectors
- Observed 1 (3) events consistent with background expectations for WIMP masses 10 GeV/c^2 (30 GeV/c^2).

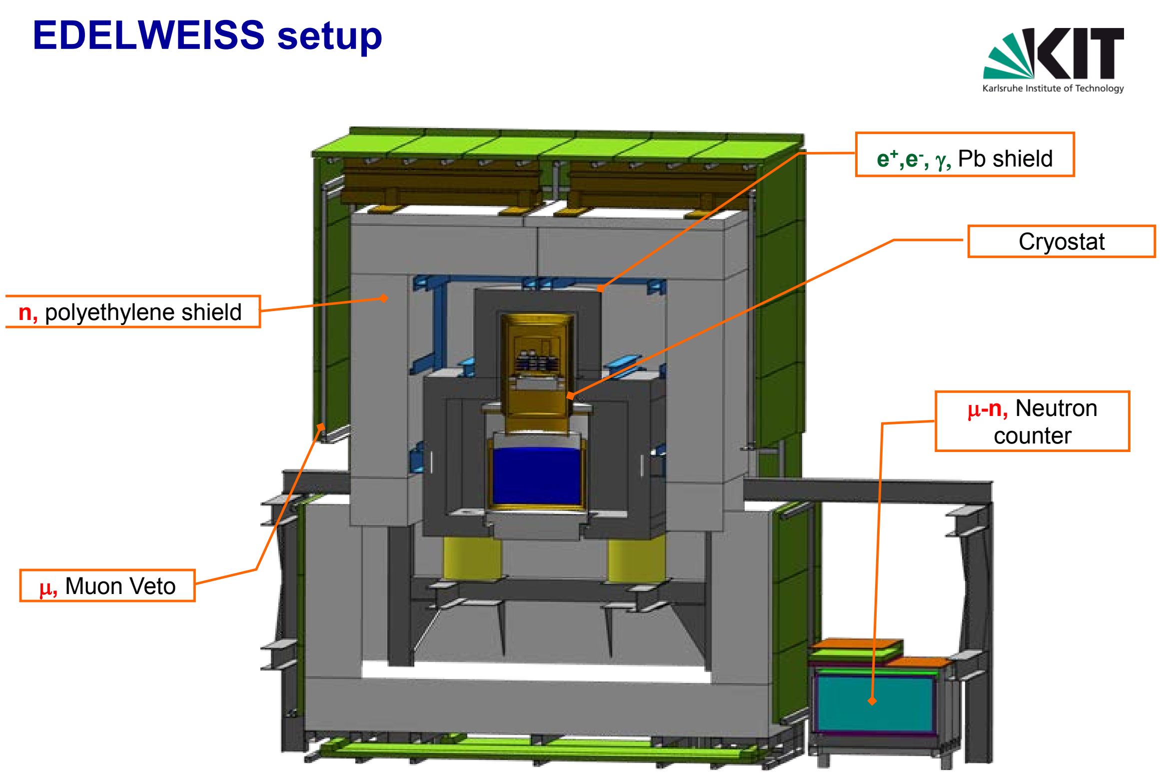


Phys. Rev. D 86, 051701(R) (2012)

EDELWEISS III



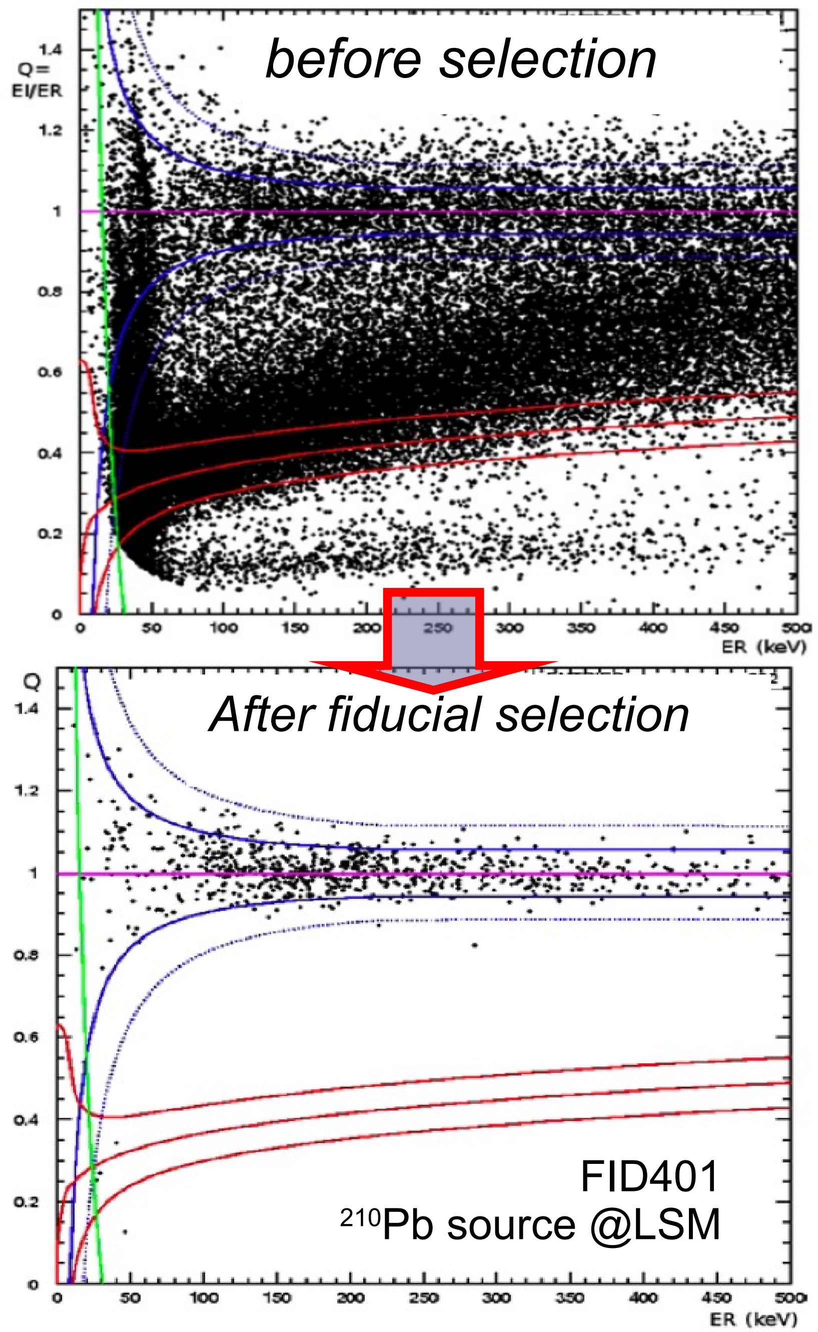
Detectors have been instrumented with interdigitated electrodes to measure charge and NTD thermal sensors to measure phonon signal.

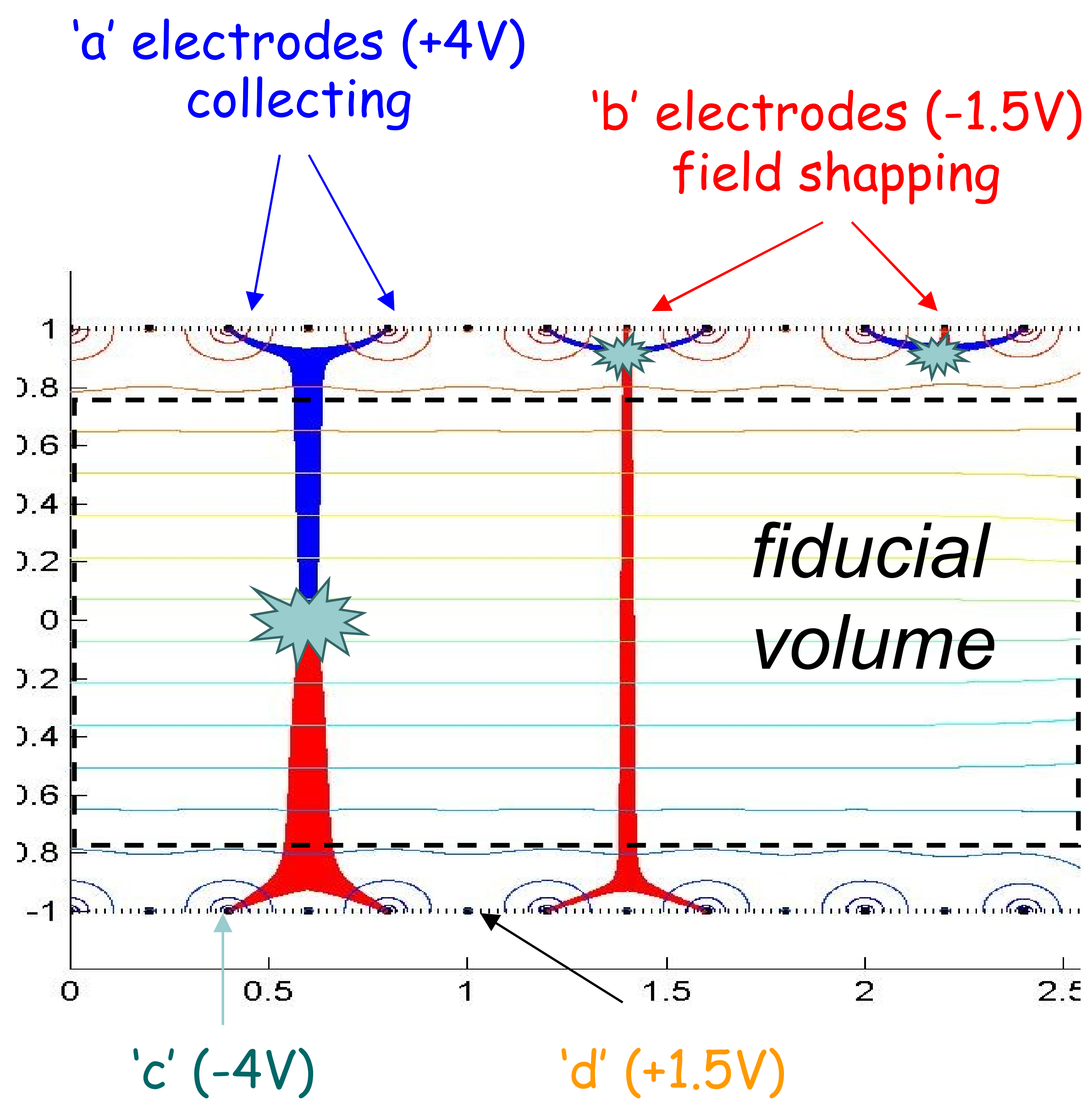


Discrimination from ionization yield and charge collection symmetry improvement yield surface event misID to:

< 4 x 10^{-5} misID events per kg-d (E_r > 15 keV)

EDELWEISS InterDigitized Detectors





FID beta rejection @ LSM 4/68000 for E > 25 keV

EDELWEISS III - Status

February 2014

- 36 FID detectors of mass 800g each installed
- upgraded cryostat, readout electronics and kapton cables to improve resolution (30%)
- New PE shield (10 x improvement in neutron backgrounds) and copper screens

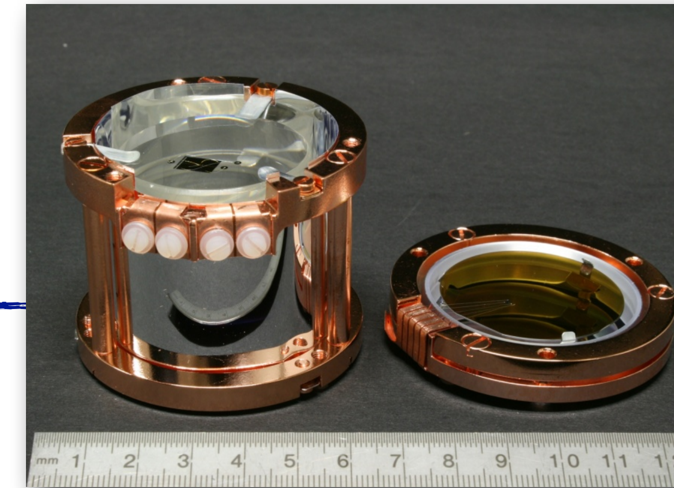
March 2014

- Began Cryogenic Run

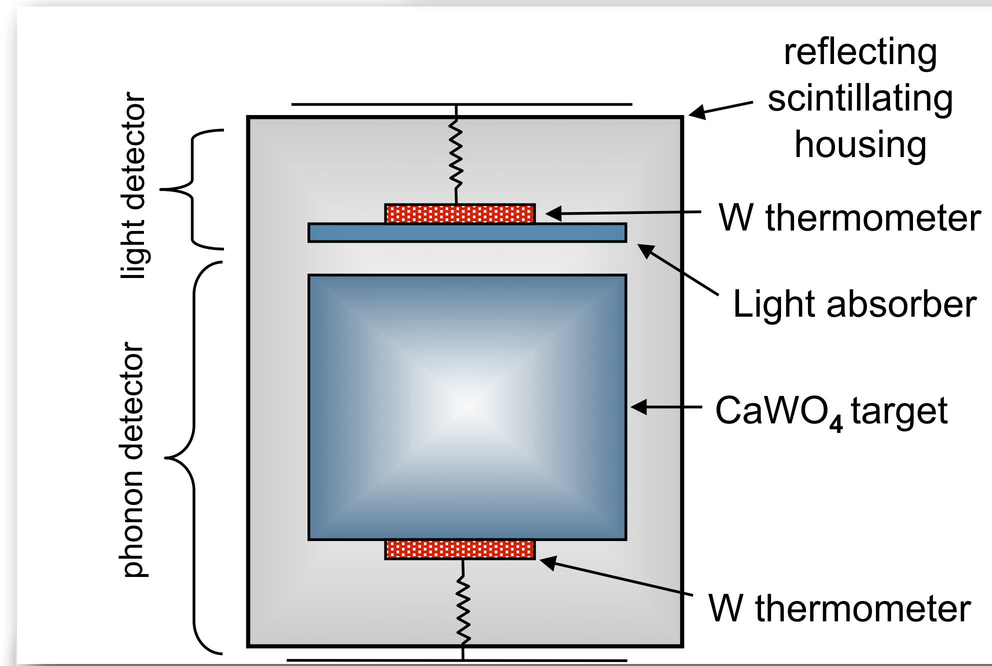
Future:

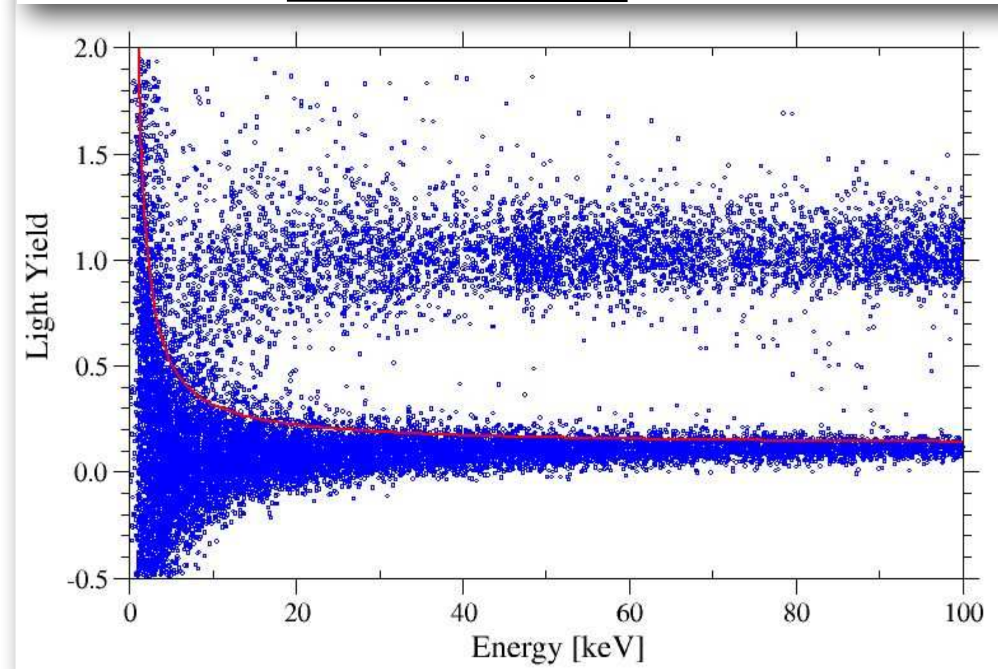
- Discussions of possibility to combine SuperCDMS and EURECA for larger experiment.

CRESST



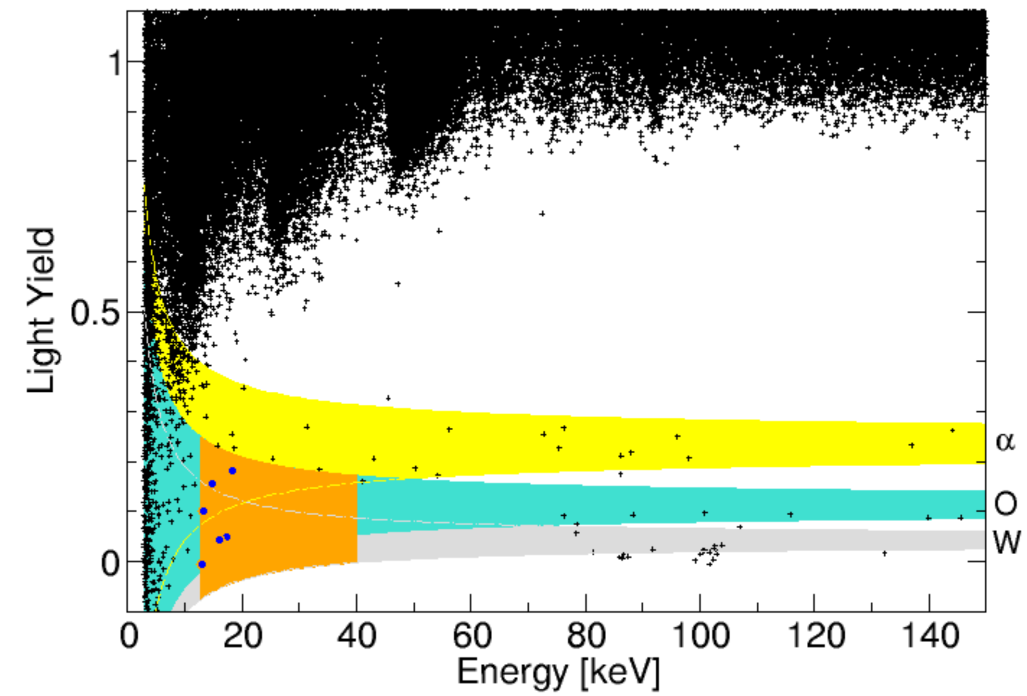
- Cryogenic $CaWO_4$ crystals are instrumented to readout phonon energy and scintillation.
    - operated at ~10 mK
    - each crystal ~ 300 g
- Located in Laboratori Nazionali del Gran Sasso, Italy
- Discrimination between ER and NR events via light yield (light/phonon energy)
- Signal expected to produce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





CRESST-II Data Analysis

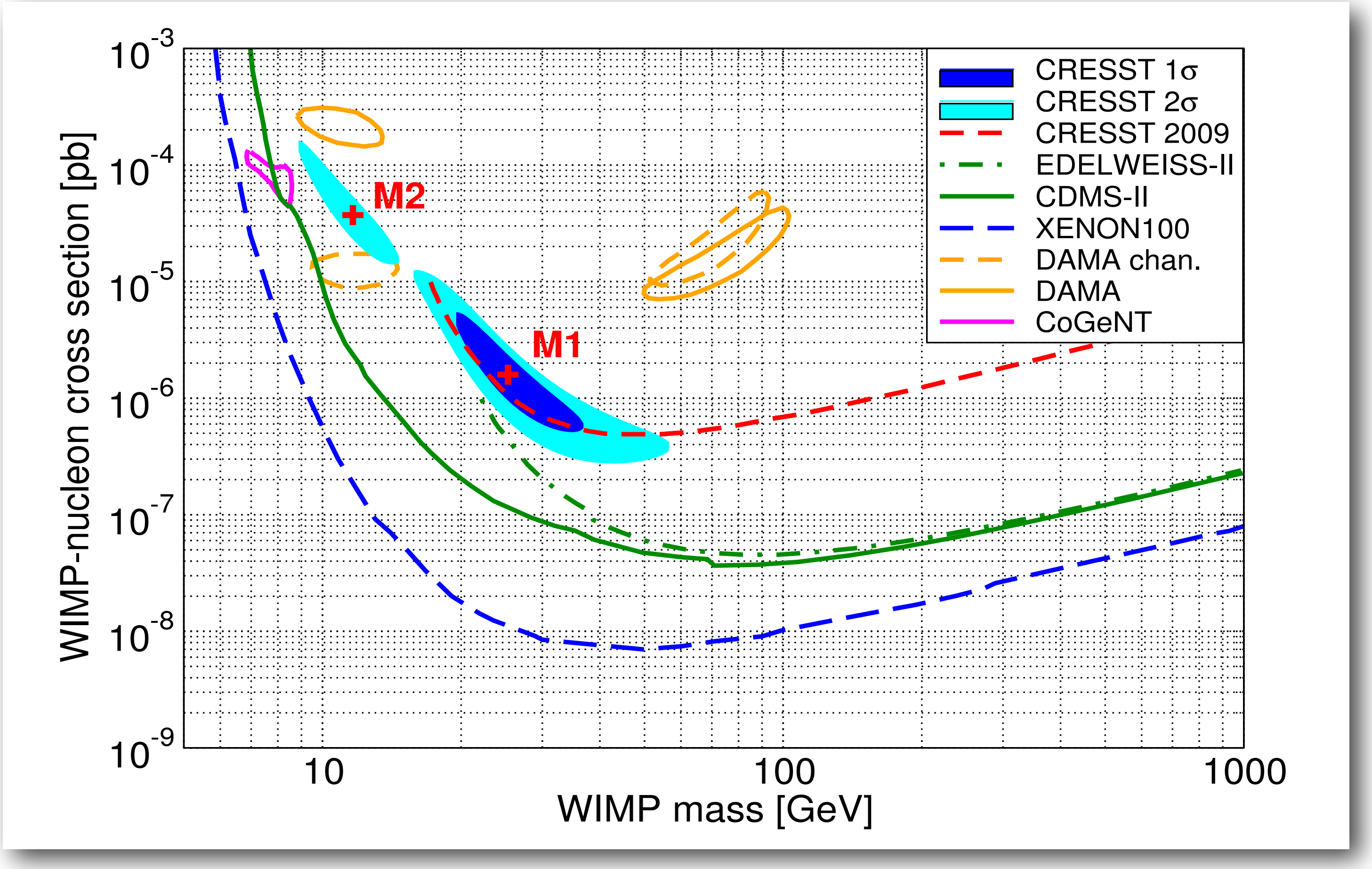
- Net exposure: 730 kg-day (July 2009 - March 2011) from 8 detector modules.
- Observed 67 events in acceptance region (orange).
- Analysis used a maximum likelihood in which 2 regions favored a WIMP signal in addition to predict background.
  - M1 is global best fit (4.7 σ)
  - M2 slightly disfavored (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



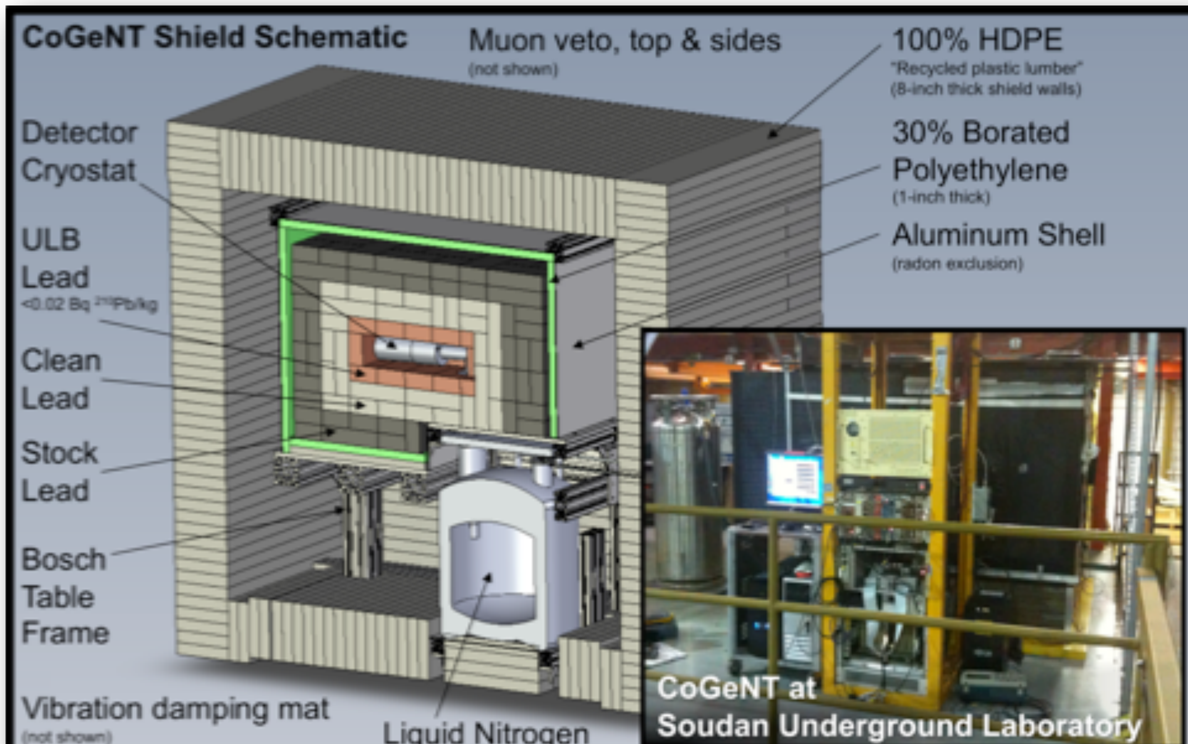
arXiv:1109.0702

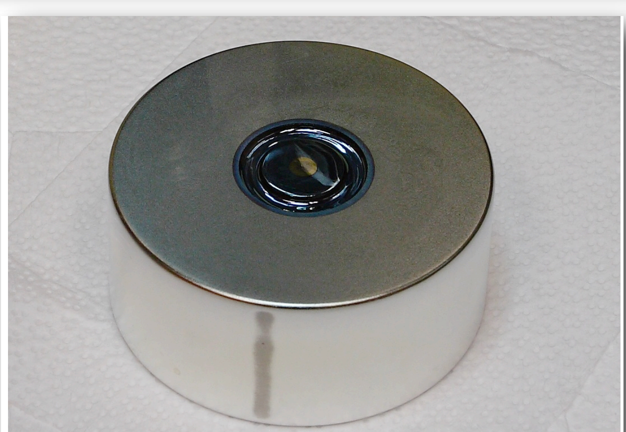
- June & July calibration runs with ^{57}Co source were successful.
- **July 30th, 2013 Science Runs Began!**

Ionization Only Experiments

CoGeNT, TEXANO, IGEX and others

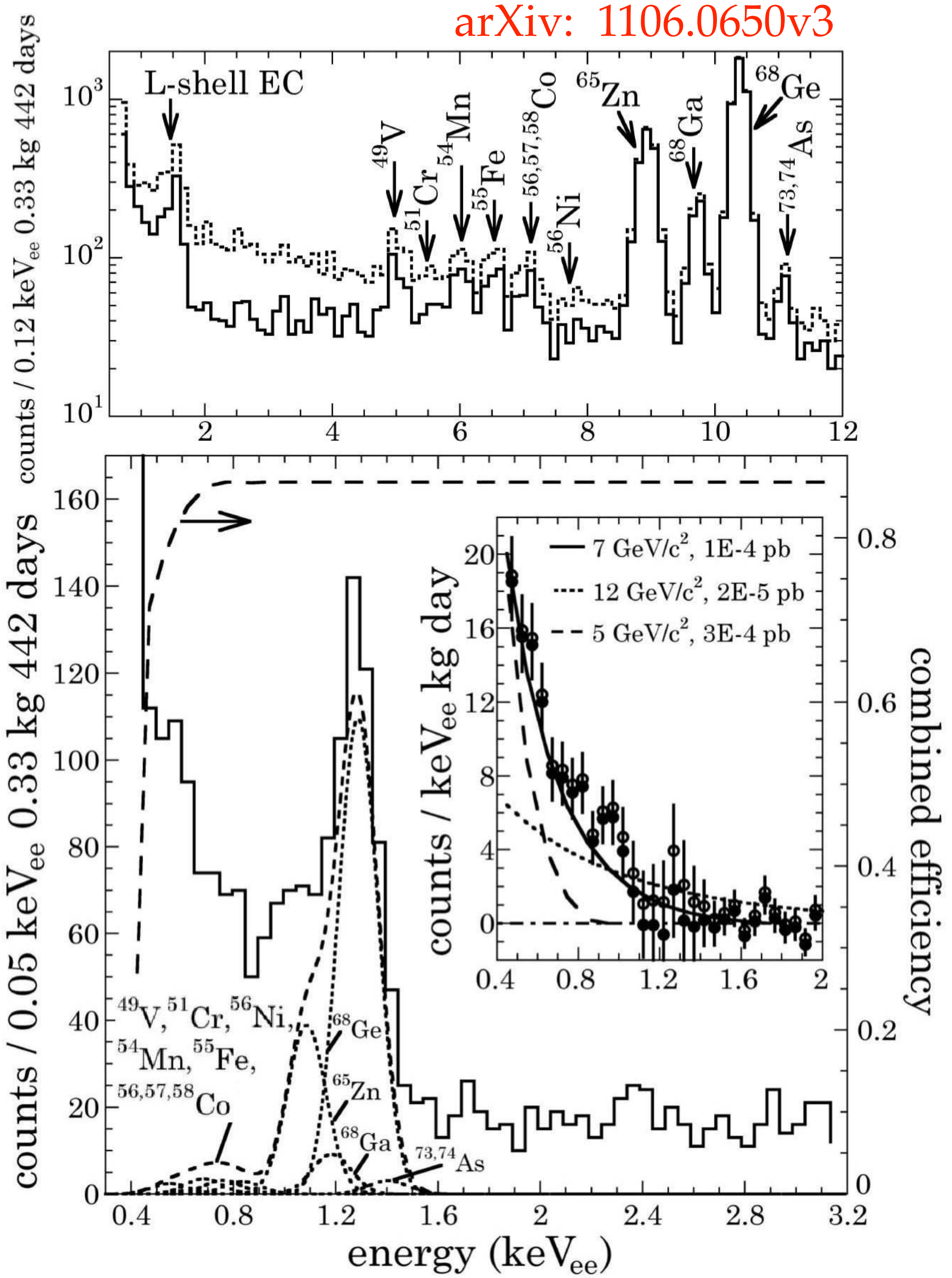
CoGeNT





- 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



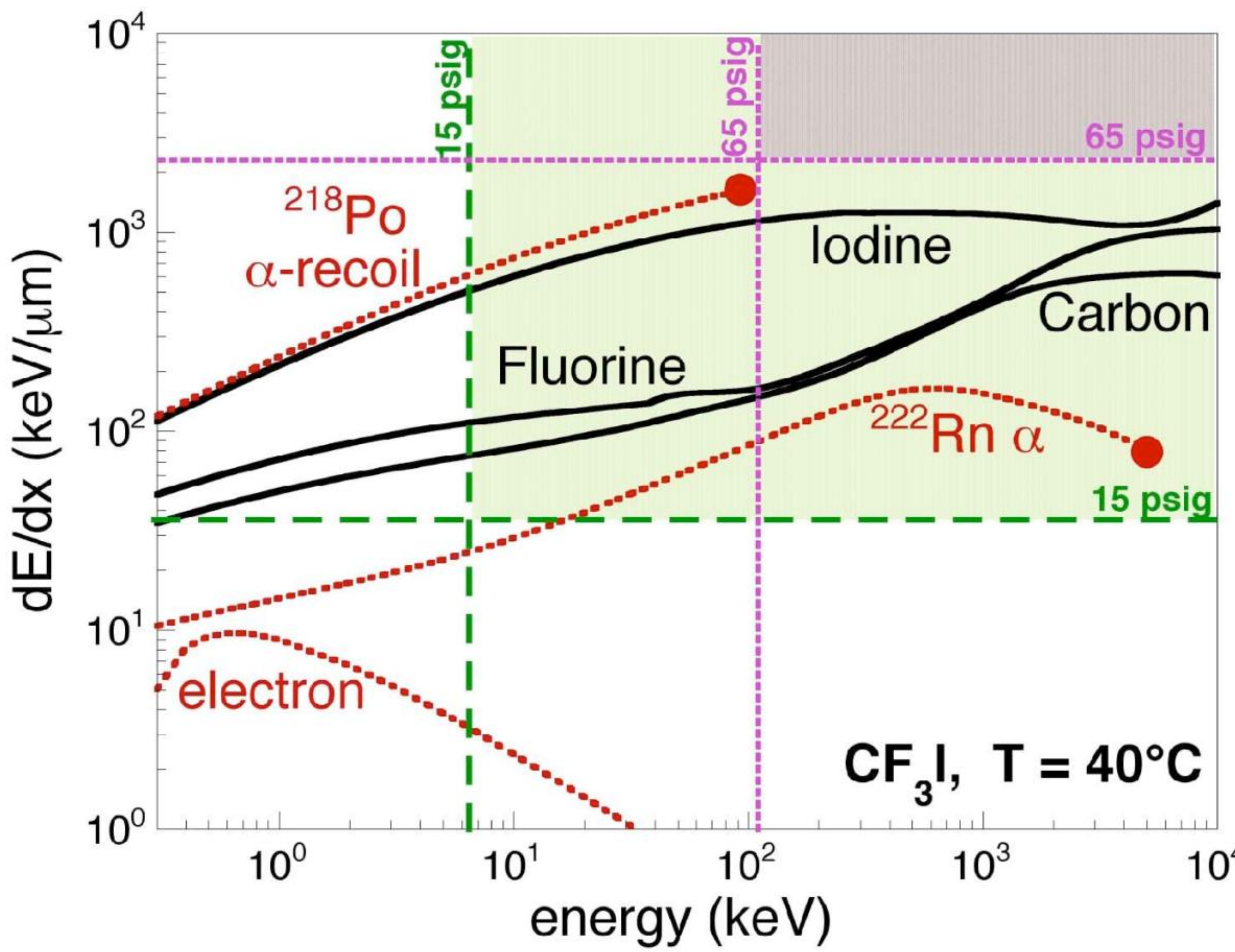
- First claim of excess in 2010.
- Reject surface events using risetime cut (2011).
- Peaks due to cosmogenic activation of Ge
- After subtraction of known background, an exponential excess of events remains
- Fits to a variety of light-WIMP masses and couplings shown in inset of lower figure.

SuperHeated Gas/Gel Experiments

COUPP, PICASSO, SIMPLE and others

Particle Detection in Bubble Chambers

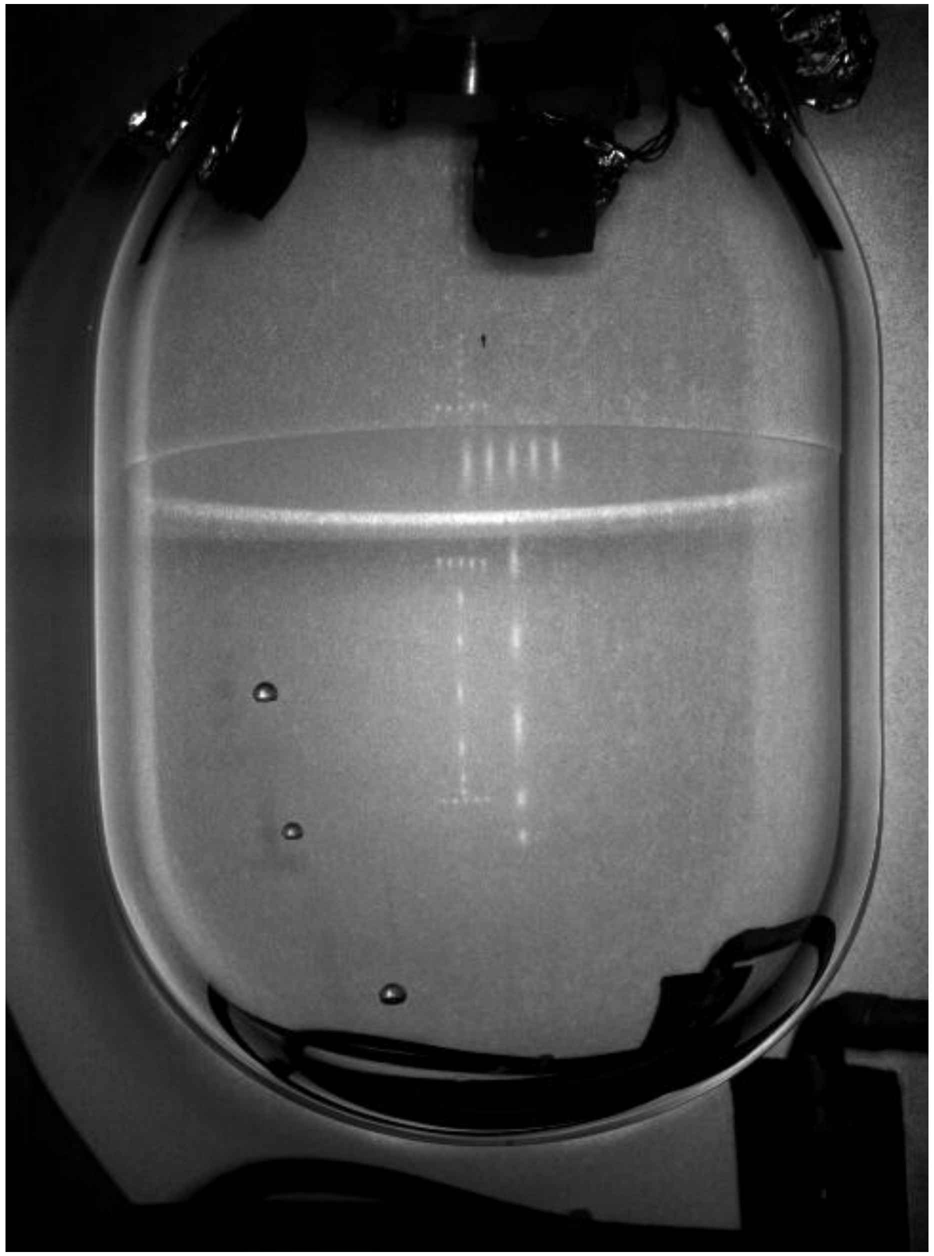
- A bubble chamber is filled with a superheated fluid in a metastable state.
- A particle interaction with energy deposition greater than E_{th} in a radius < r_c results in an expanding bubble.
- A smaller or more diffuse energy deposition will result in a bubble that immediately collapses.



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

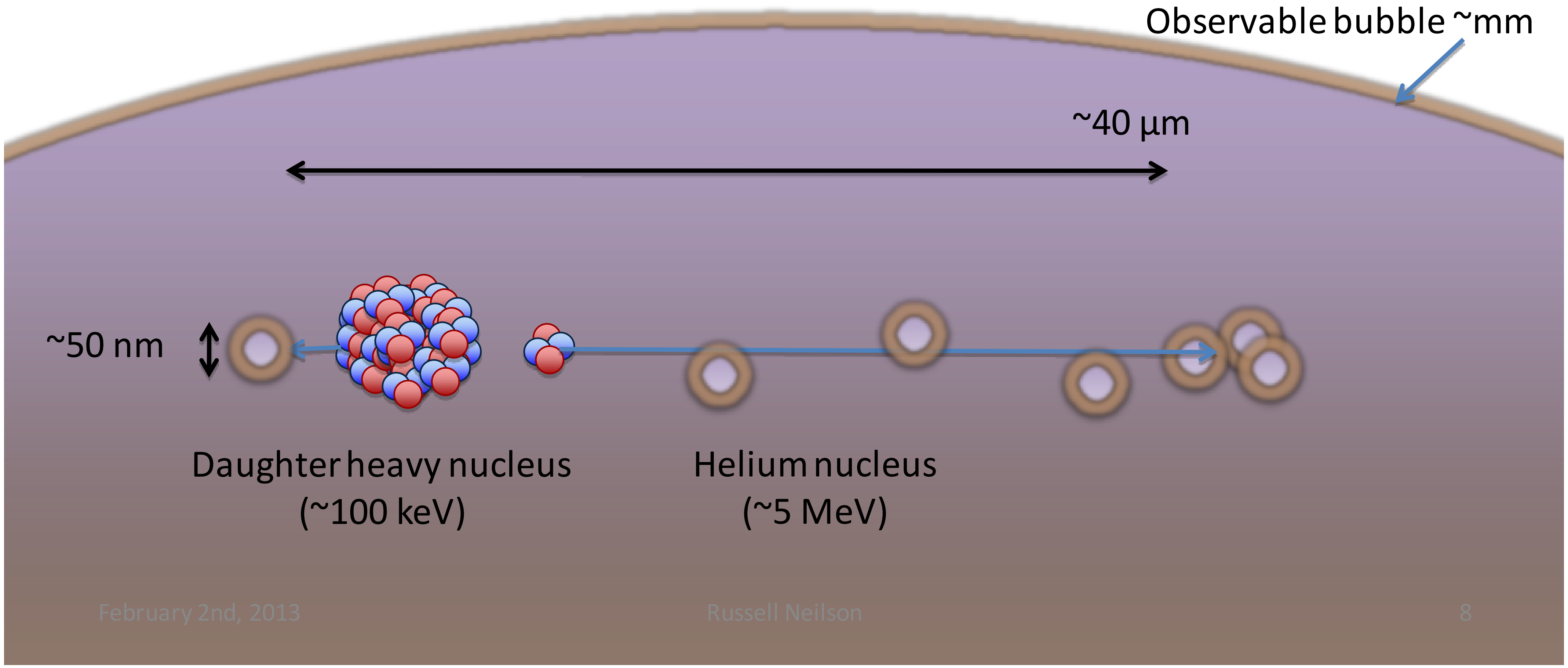
COUPP

- 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.



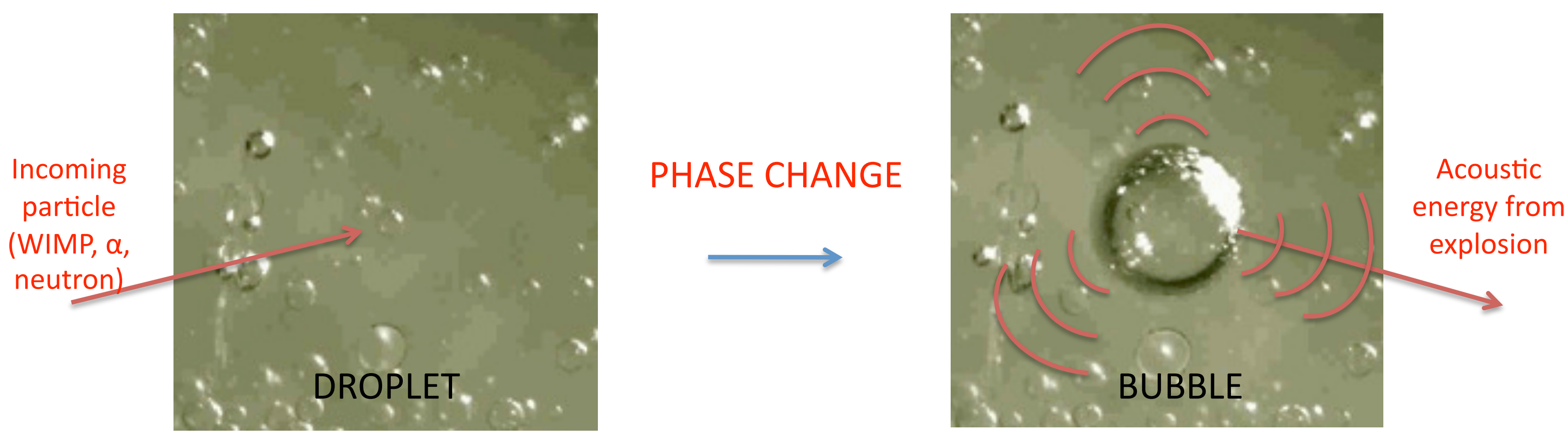
COUPP

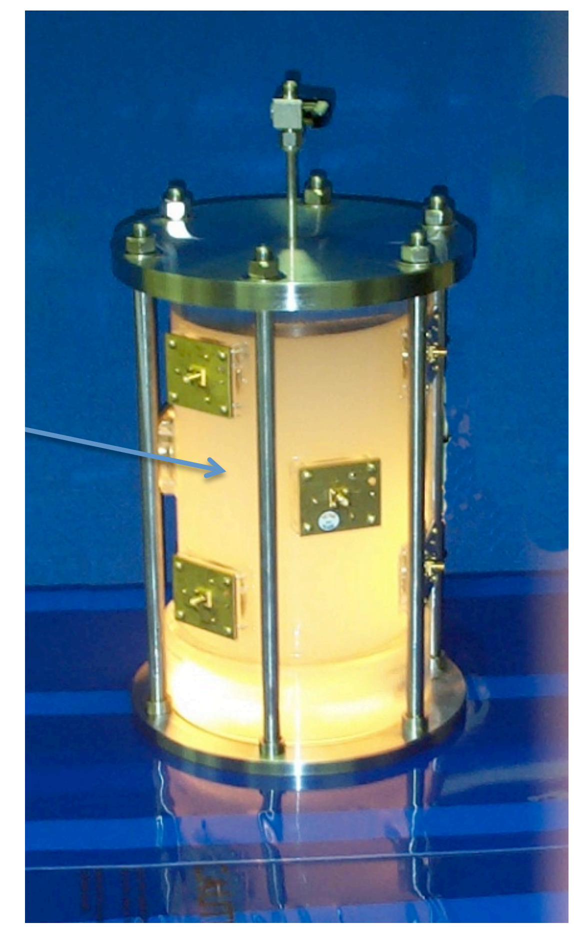
- Alphas deposit their energy over 10s of microns.
- Nuclear recoils deposit their energy over 10s of millimeters
- Alpha particles are louder than nuclear recoils. This can be measured by piezoelectric sensors.



PICASSO

- A superheated liquid detector using a C_4F_{10} target.
- Location: SNOLAB, Canada
- C_4F_{10} droplets are suspended in polymerized gel in a 4.5L acrylic vessel. Experiment contains 32 modular detectors.
- Acoustic energy deposition of incoming particles is measured by 9 piezoelectric sensors.
- New results are in preparation.
- Total exposure will be ~800 kg-d by end of 2013.

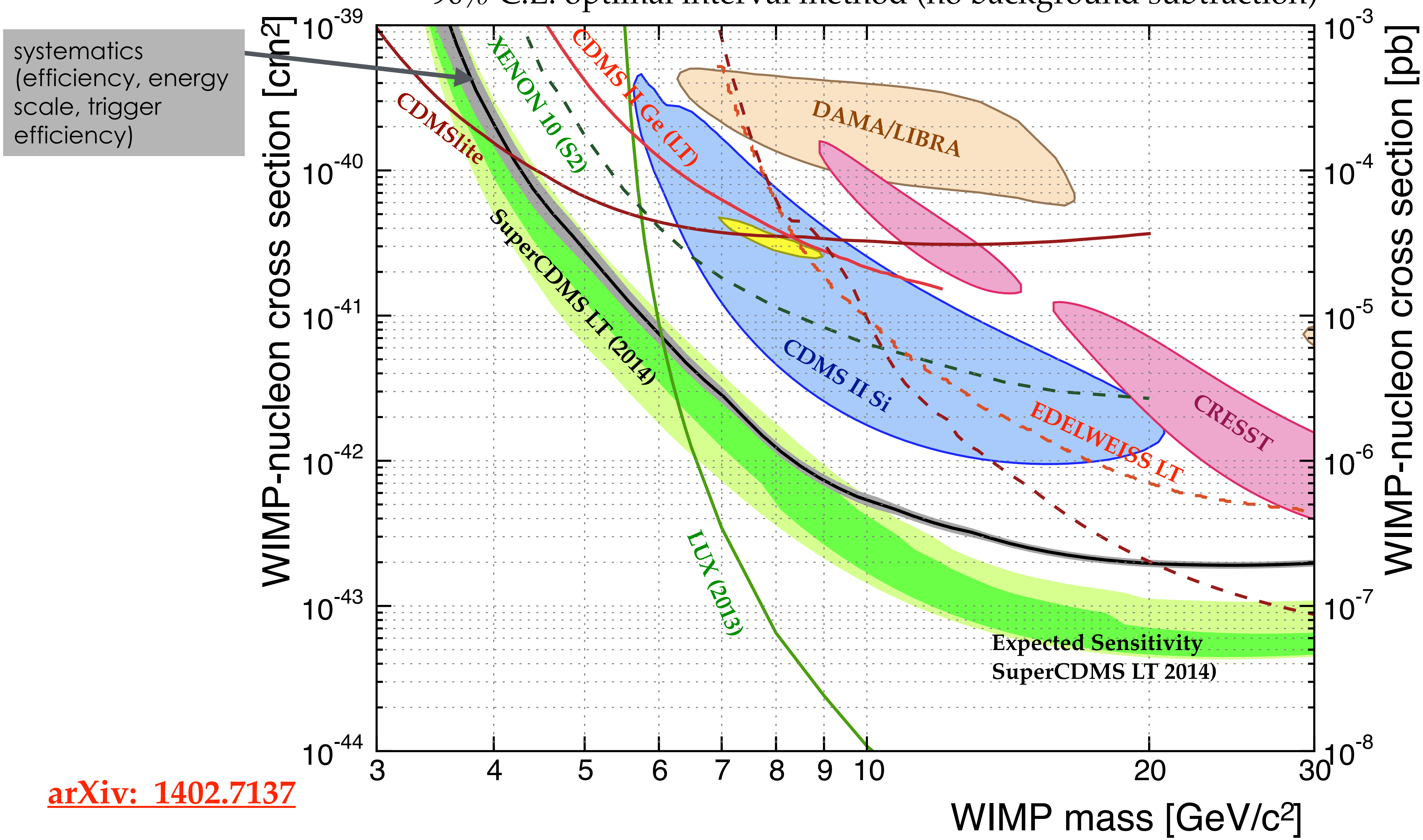




Where does that leave us?

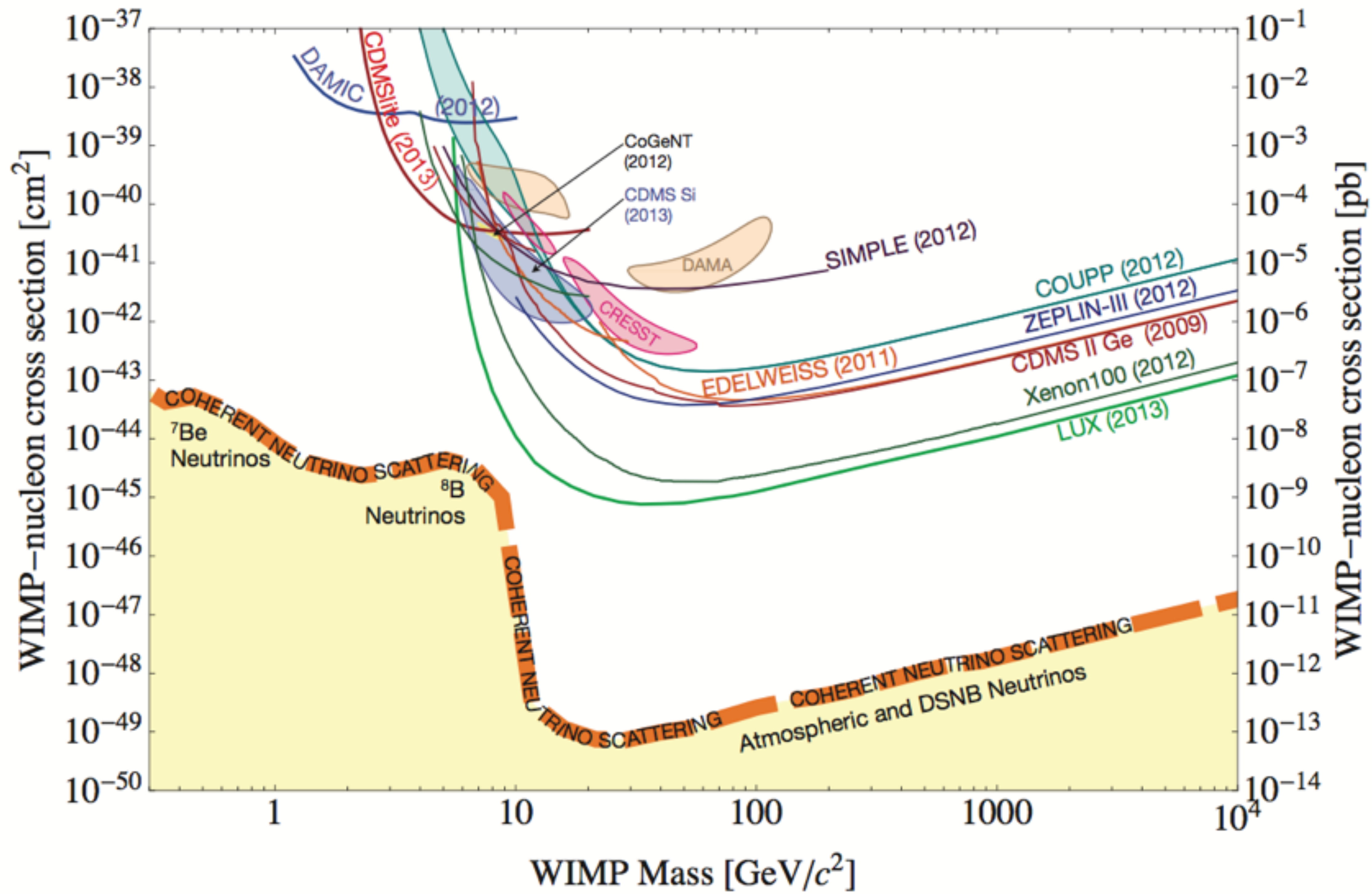
New Limits for Low Mass WIMPs

Note: Assumes SHM, Spin-Independent Couplings: This plot changes if we change assumptions!

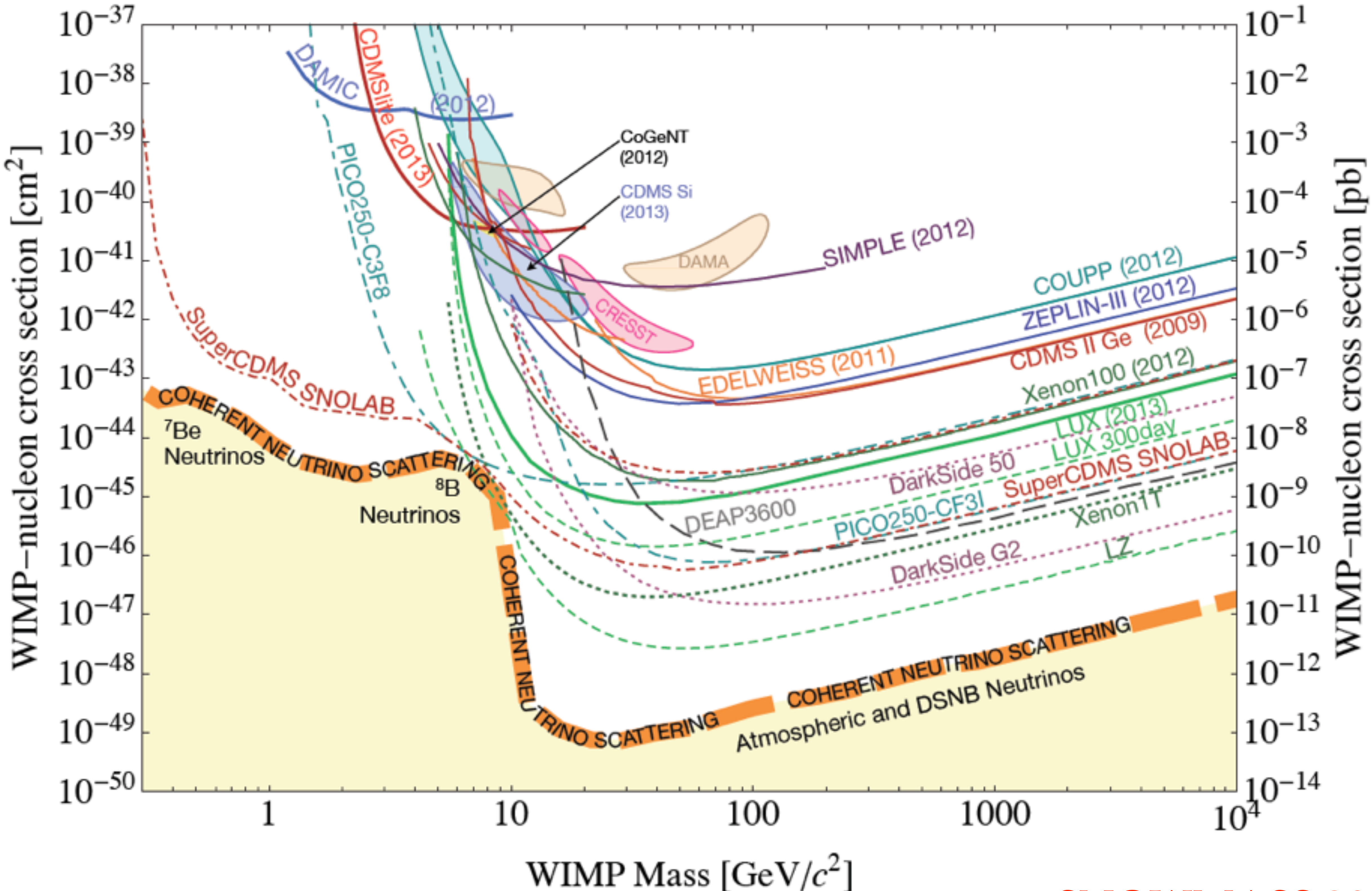


arXiv: 1402.7137

Results - High + Low Mass



The Future is Bright!



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/)