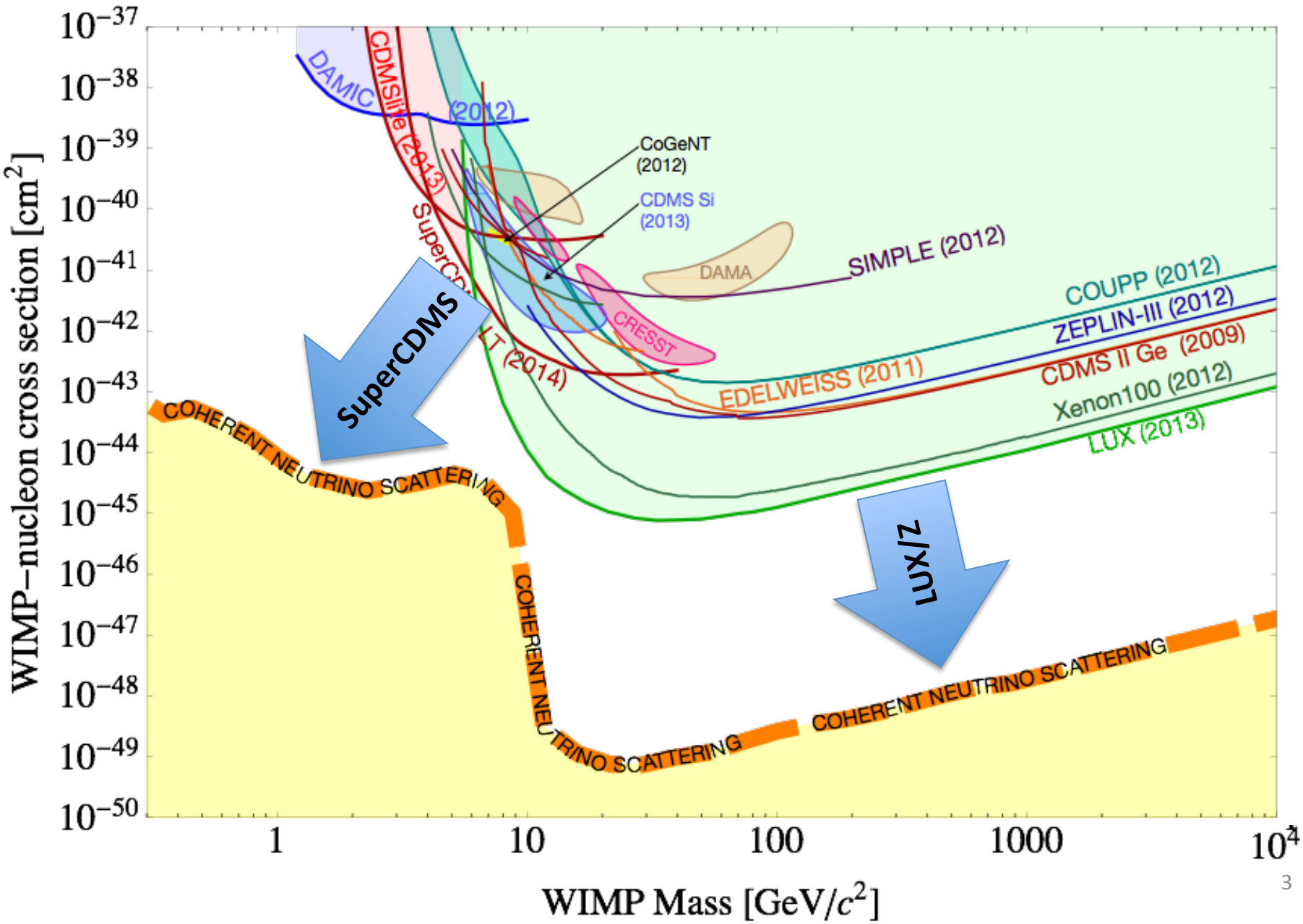
Toward Single Electron Resolution Large Mass Detectors for DM, CENNS…

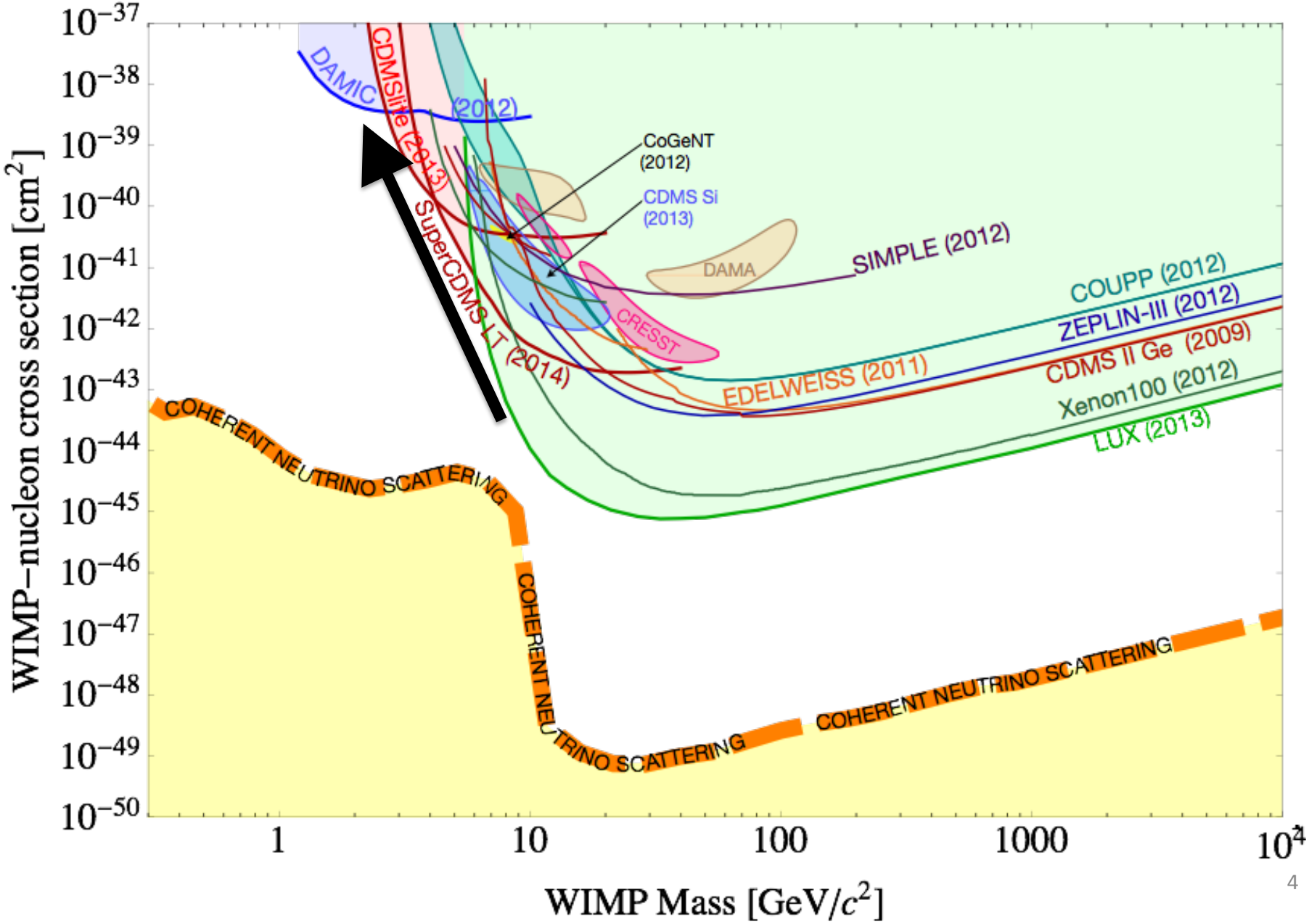
Nader Mirabolfathi
Texas A&M University
CPAD, Arlington Oct 2015

- Motivation
- DM and CDMS
- From CDMSlite to contact-free HV detectors
- MINER experiment
- Perspective

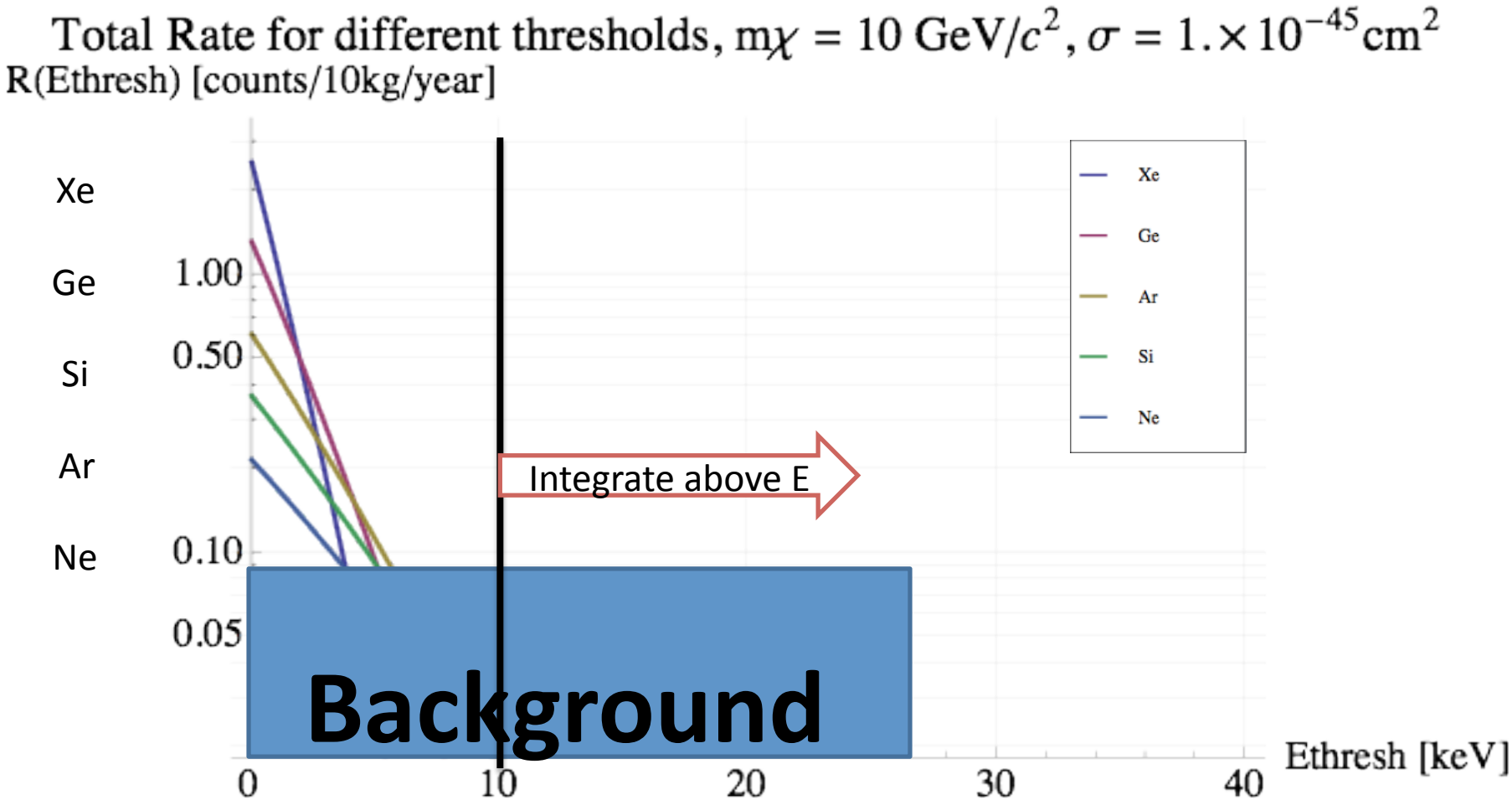
Dark Matter Direct Detection Current Status



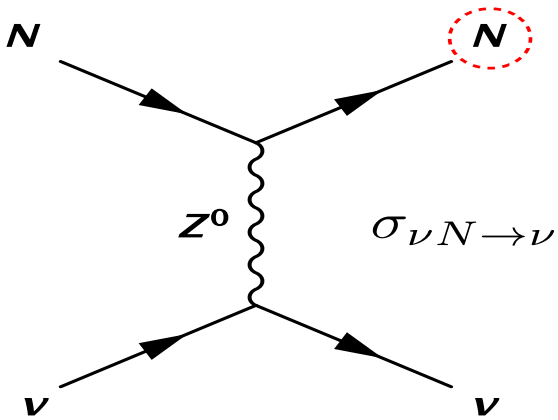
Low Mass Threshold Limited



Signal from a 10 GeV WIMP



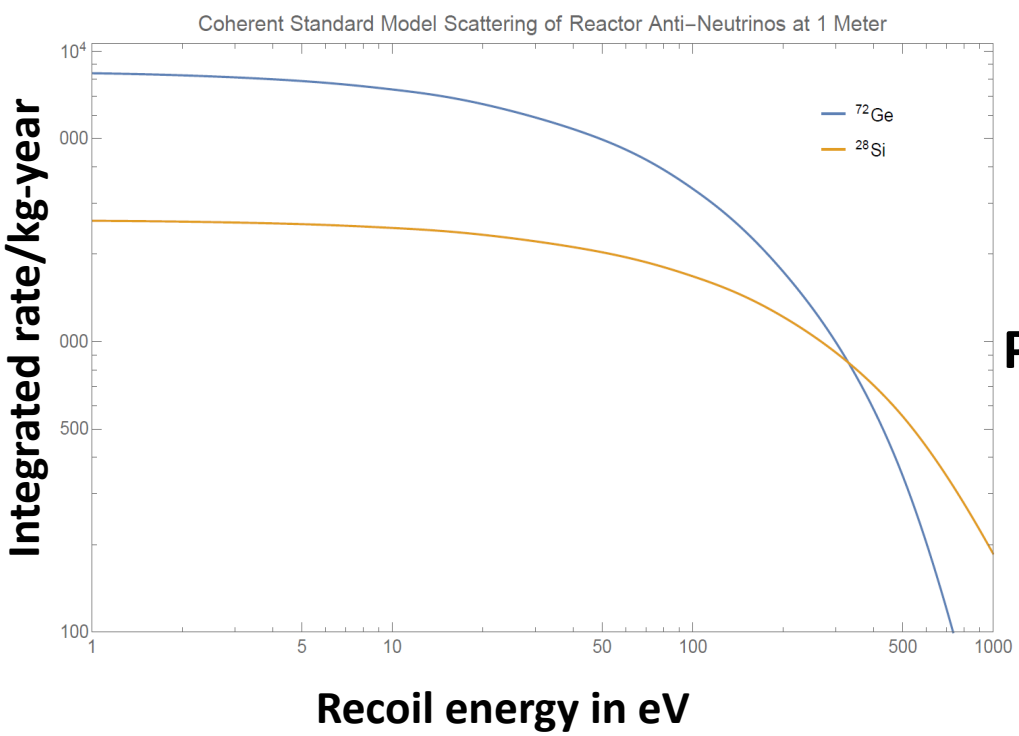
Coherent Neutrino-Nucleus Elastic Scattering



$$\sigma_{\nu N \to \nu N} \simeq \frac{G_F^2}{4\pi} N^2 E_\nu^2$$

Flavor-blind Standard Model process

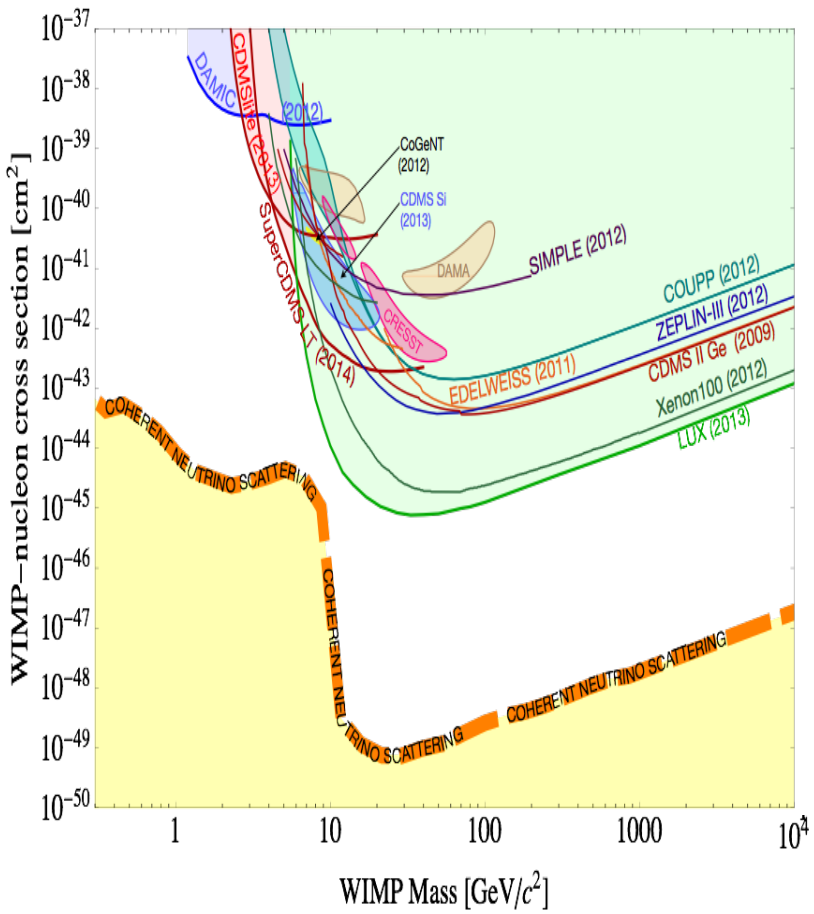
$\sigma_{\bar{\nu} N \to \bar{\nu} N}$	E_ν=3MeV
Ge	$6.0 \times 10^{-41} cm^2$
Ar	$1.8 \times 10^{-41} cm^2$
Si	$7.4 \times 10^{-42} cm^2$

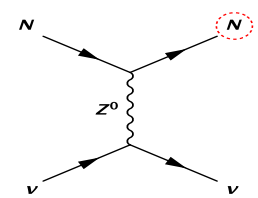


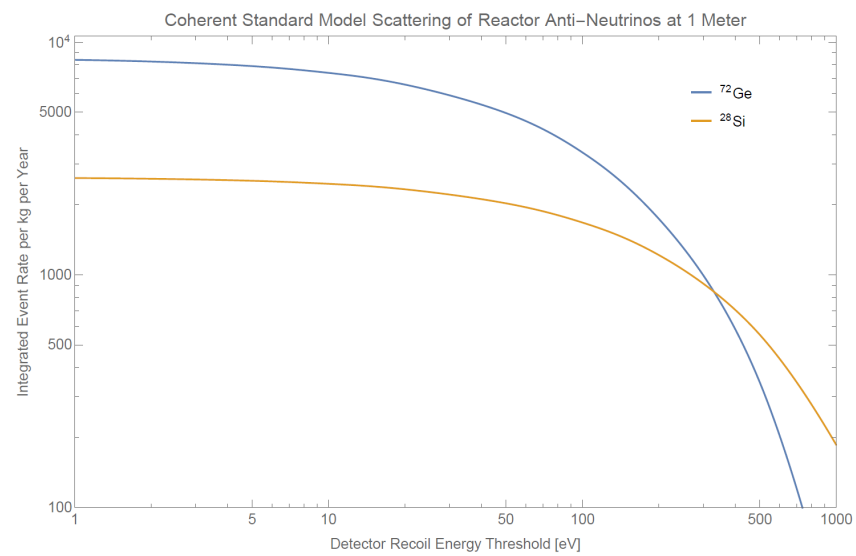
Excellent tool to probe BSM Physics, but never been utilized due to lack of low threshold detectors

Can detect CENNS in ~ 1month

Two big question one solution







Low Noise Phonon readout

- Phonons among the lowest quantum excitations in condense matter detectors.
- Tremendous progress in low noise phonon readout down to fraction of eV for small calorimeters.
- Almost mass independent for athermal phonon measurement.
- Various options to handle backgrounds: event-by-event discrimination.
- Measure phonons directly or use Neganov-Luke effect to indirectly measure ionization down to e-h resolution.

Luke-Neganov phonon amplification

- **Luke**-Neganov Gain

$$E_{tot} = E_r + E_{luke}$$
$$= E_r + n_{eh} e V_b$$
$$= E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right)$$

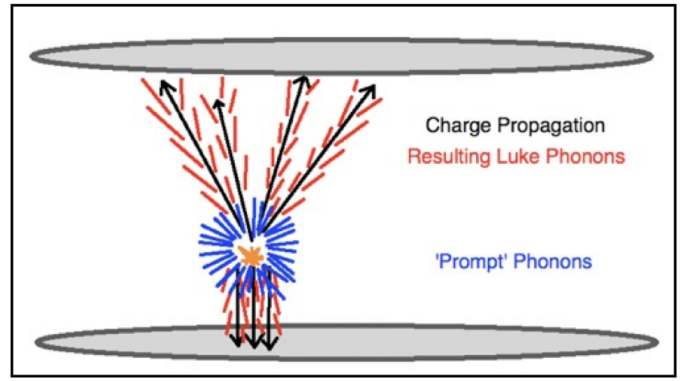
• Phonon noise doesn't scale with the ionization bias:

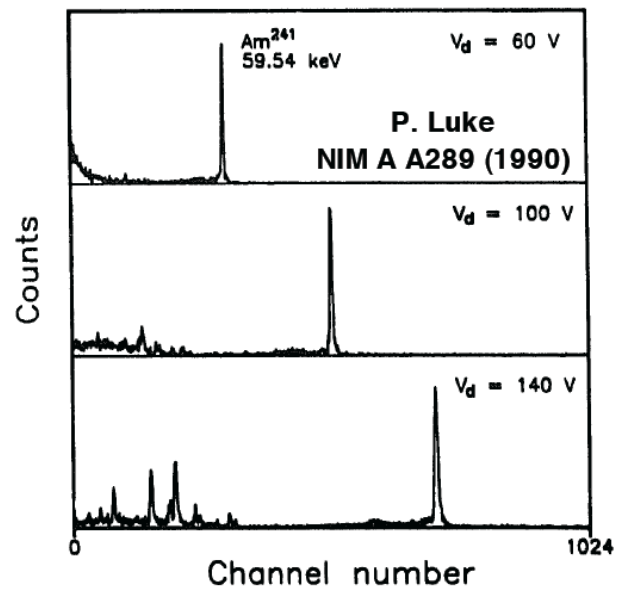
=> **S/N ⇧**

• In theory one can increase Bias to reach Poisson fluctuation limit:

$$\sqrt{F \varepsilon E}$$

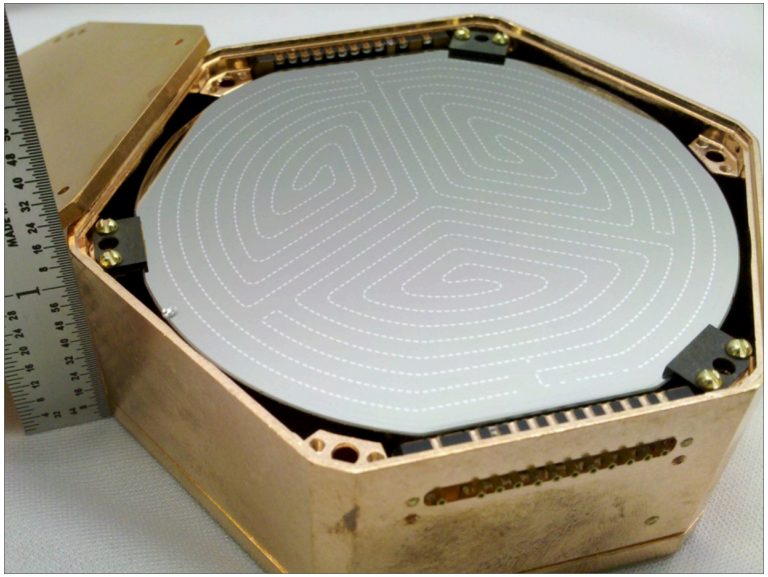
limitation: Ge Breakdown

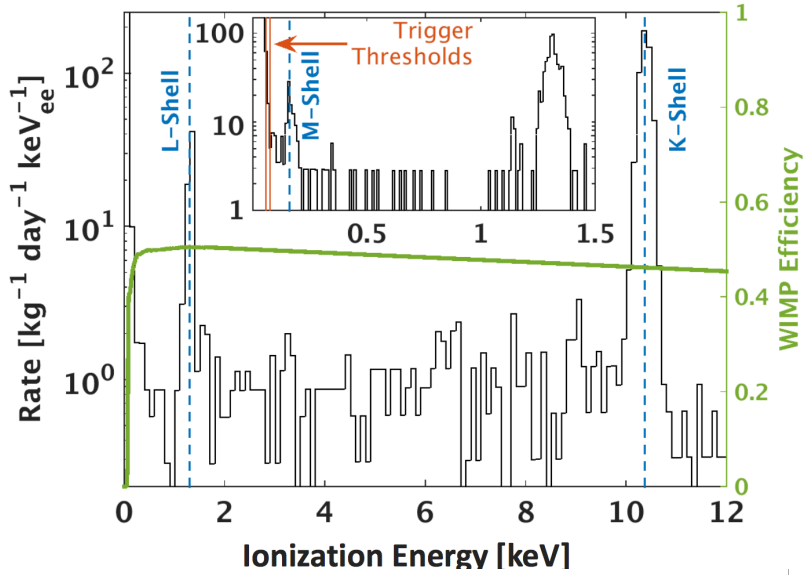


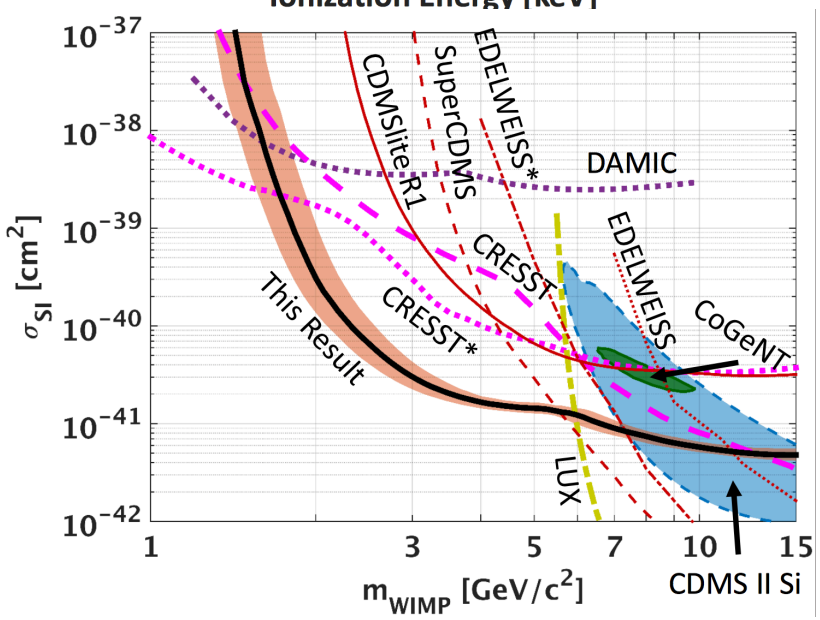


Luke et al., Nucl. Inst. Meth. Phys. Res.A 289, 406 (1990)

CDMSlite: CDMS with phonon gain





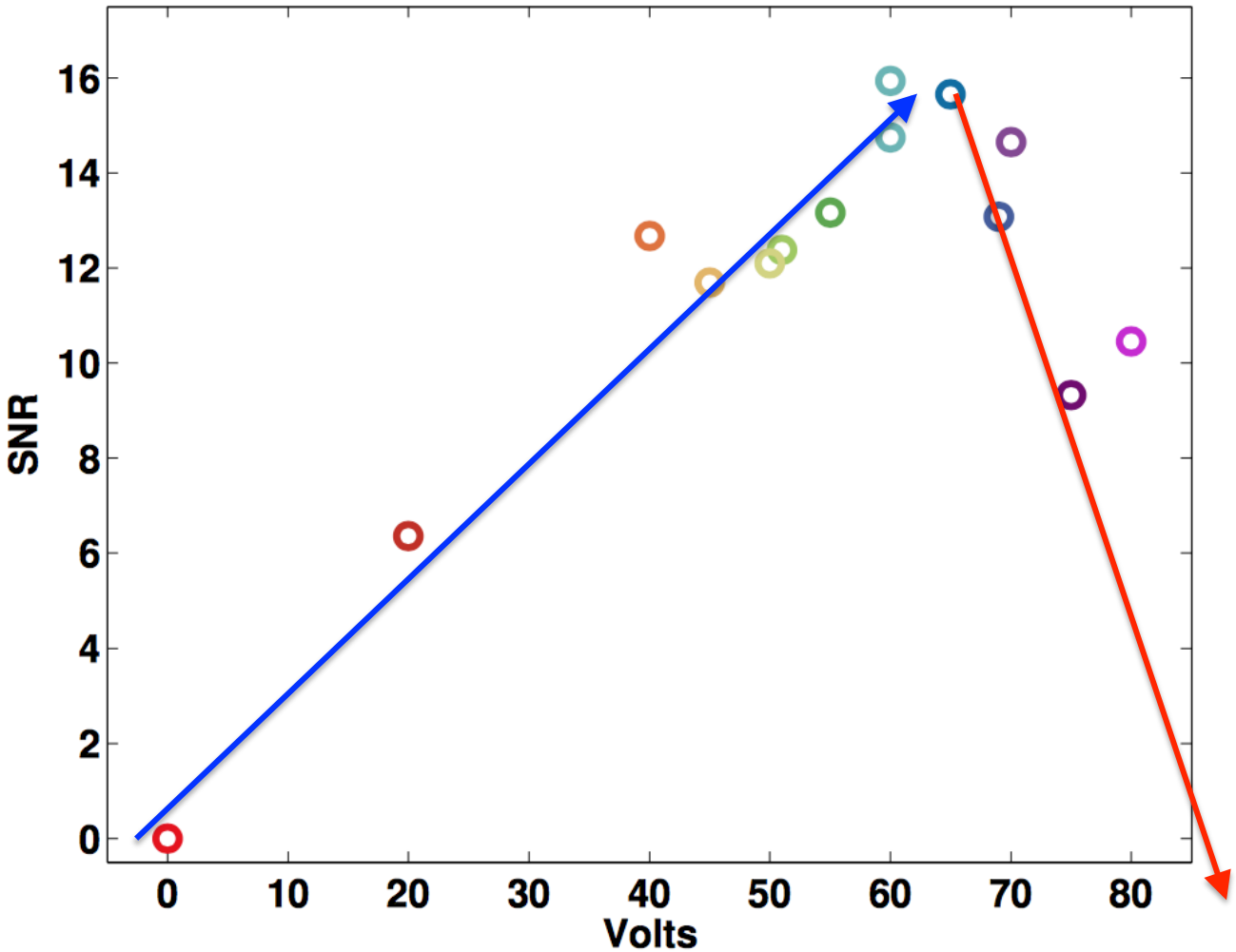


- Use the Luke phonon amplification to indirectly measure ionization using very good phonon resolution.
- One iZIP (0.625 kg) used for this data
- ~70 kg.day exposure
- Impressive 14 eVee resolution for Vbias=69 Volts.

Limited to current leakage for V>70 Volts
Or E> 24 Volts/cm

Very low compared to standard 77K Ge detectors

CDSMlite limitation: Breakdown?

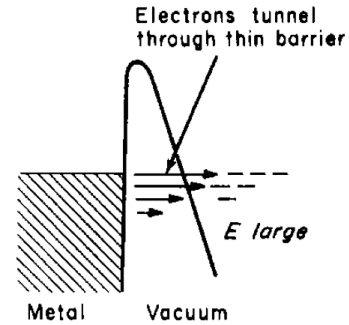


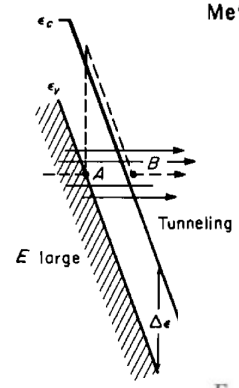
Ritoban Thakur Ph.D. thesis

Need to study breakdown!

- What causes the breakdown at such low fields?
- Impact ionization on impurities:
  - Ionized
  - Neutral
- Leakage through electrodes?
- Conduction over detector free surface:
  - Better surface treatment?
  - Common problem if surface damaged.

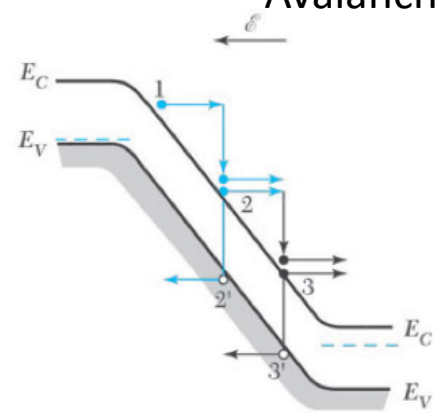
Injection through contact by tunneling





J.P. McKelvey, Solid-state and semiconductor physics, Harper & Row, 1966.S.M.
Sze, Semiconductor devices: physics and technology, 2nd Ed., Wiley, 2002.

Avalanche



Understanding Low Voltage Breakdown in CDMSlite

- High purity gamma spectroscopy 77K Ge detectors e.g. PPC at ~1000 V/cm
- A Collaborative effort formed between 3 institutions
- Proposal to UCOP INPAC-MRPI for R&D over 2 years in 2013

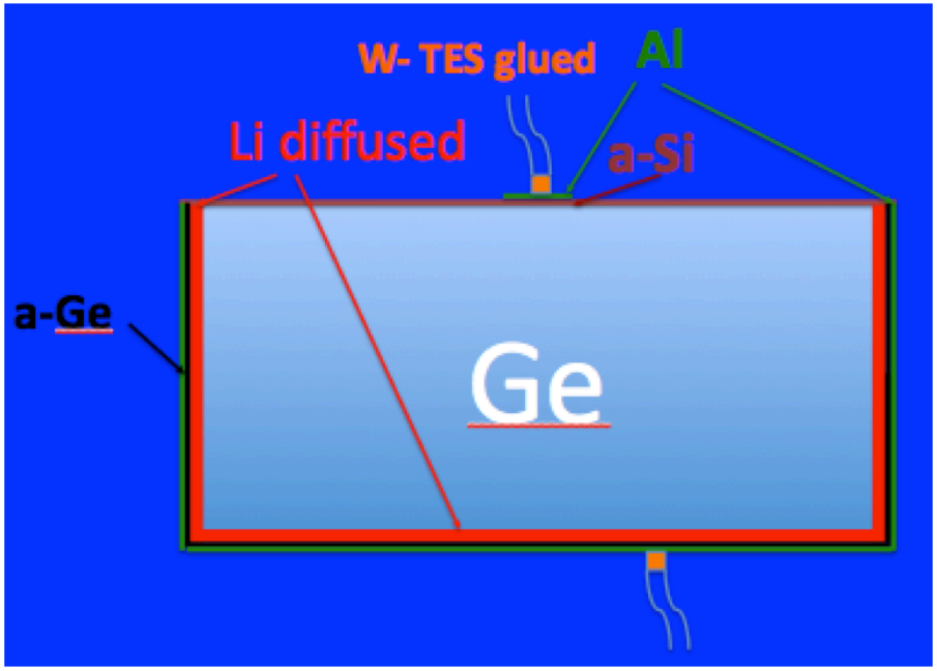
UC Berkeley
Nader Mirabolfathi, Kyle Sundqvist, Bruno Serfass, Arran Phips and Dana Faiez.

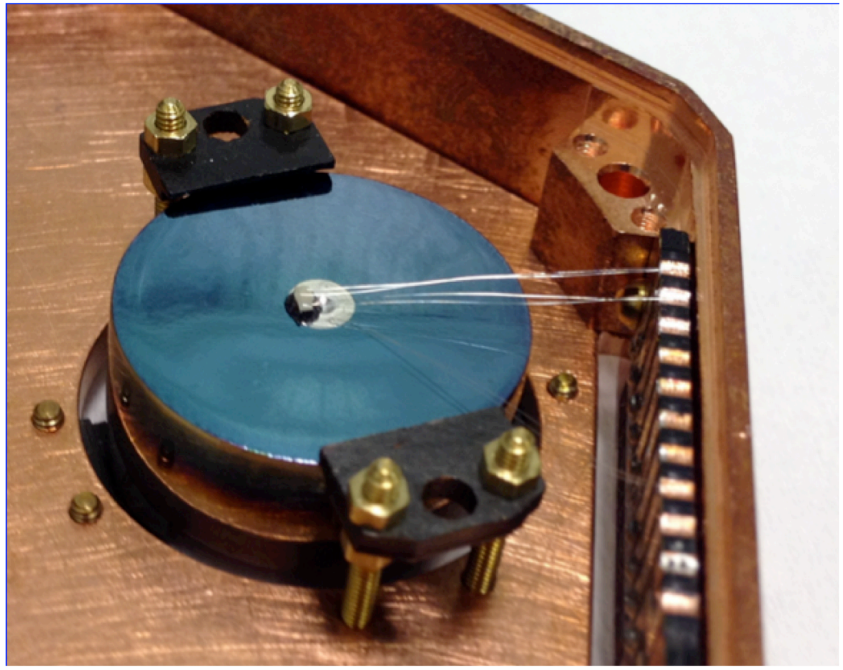
LBNL
Kai Vetter, Paul Luke, Ryan Martin and Mark Amman

TAMU
Rupak Mahapatra, Rusty Harris, Mark Platt, Andrew Jastram and James Phillips.

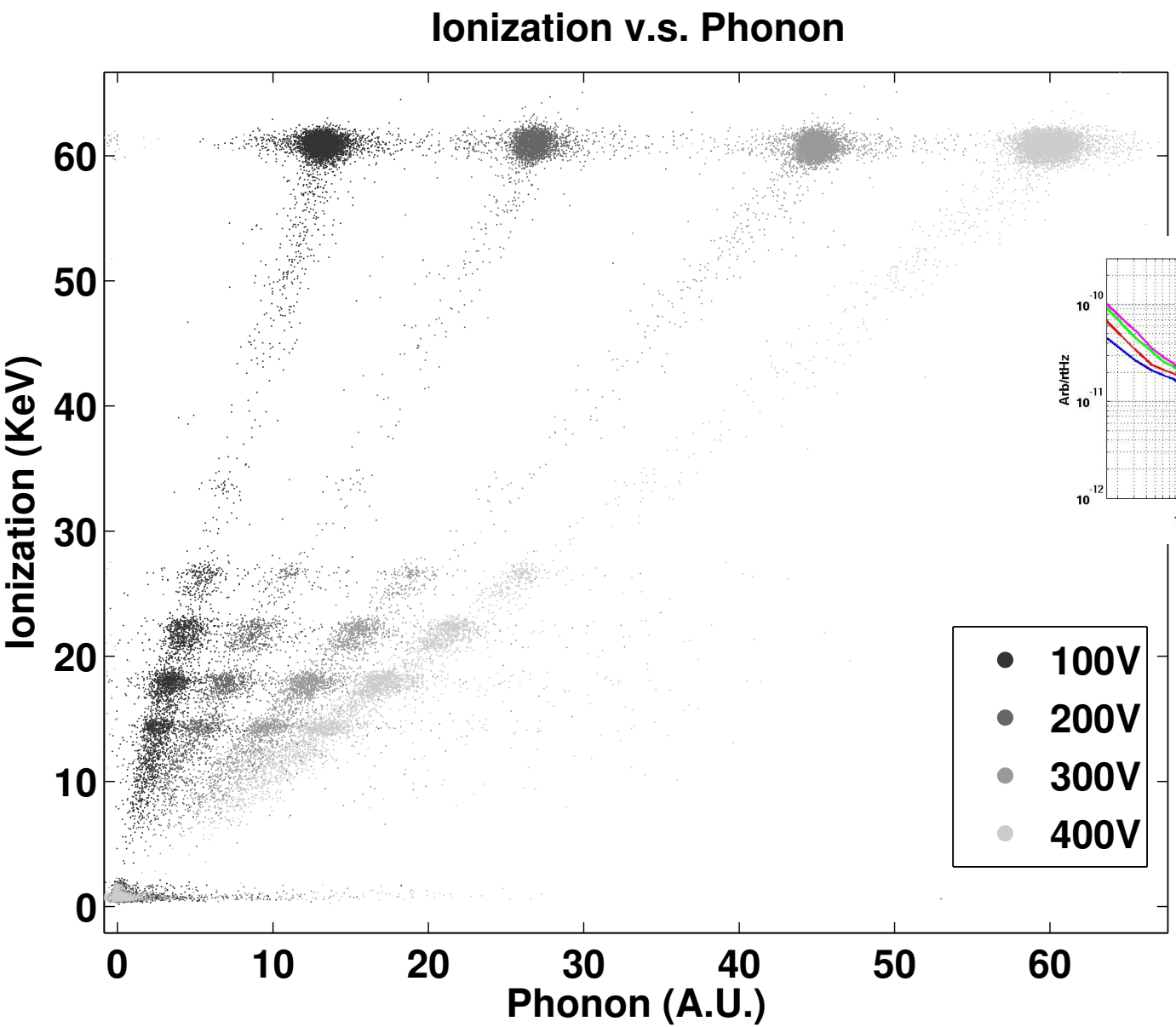
P-type Point Contact Ge at @T< 0.05 K

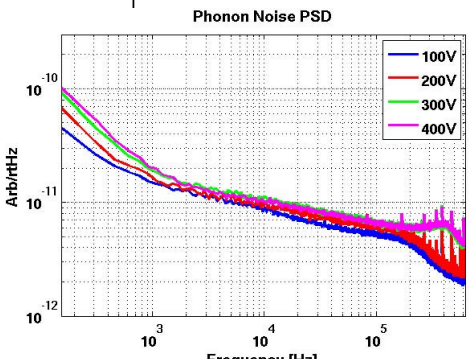
- PPC are common design for 77K Ge gamma spectrometers.
- Experiments using ultra pure Ge PPC: Majorana, CoGeNT,
- LBNL provided a prototype Majorana PPC.
- At UCB adhered a tungsten TES thermistor.

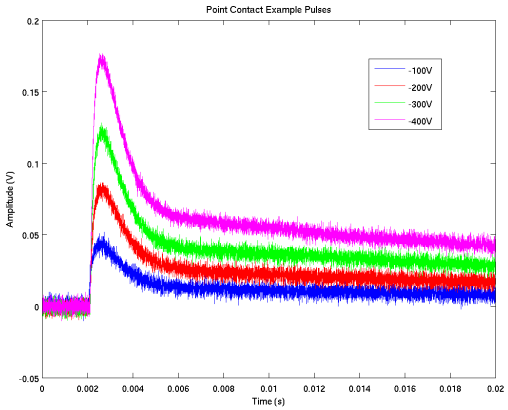




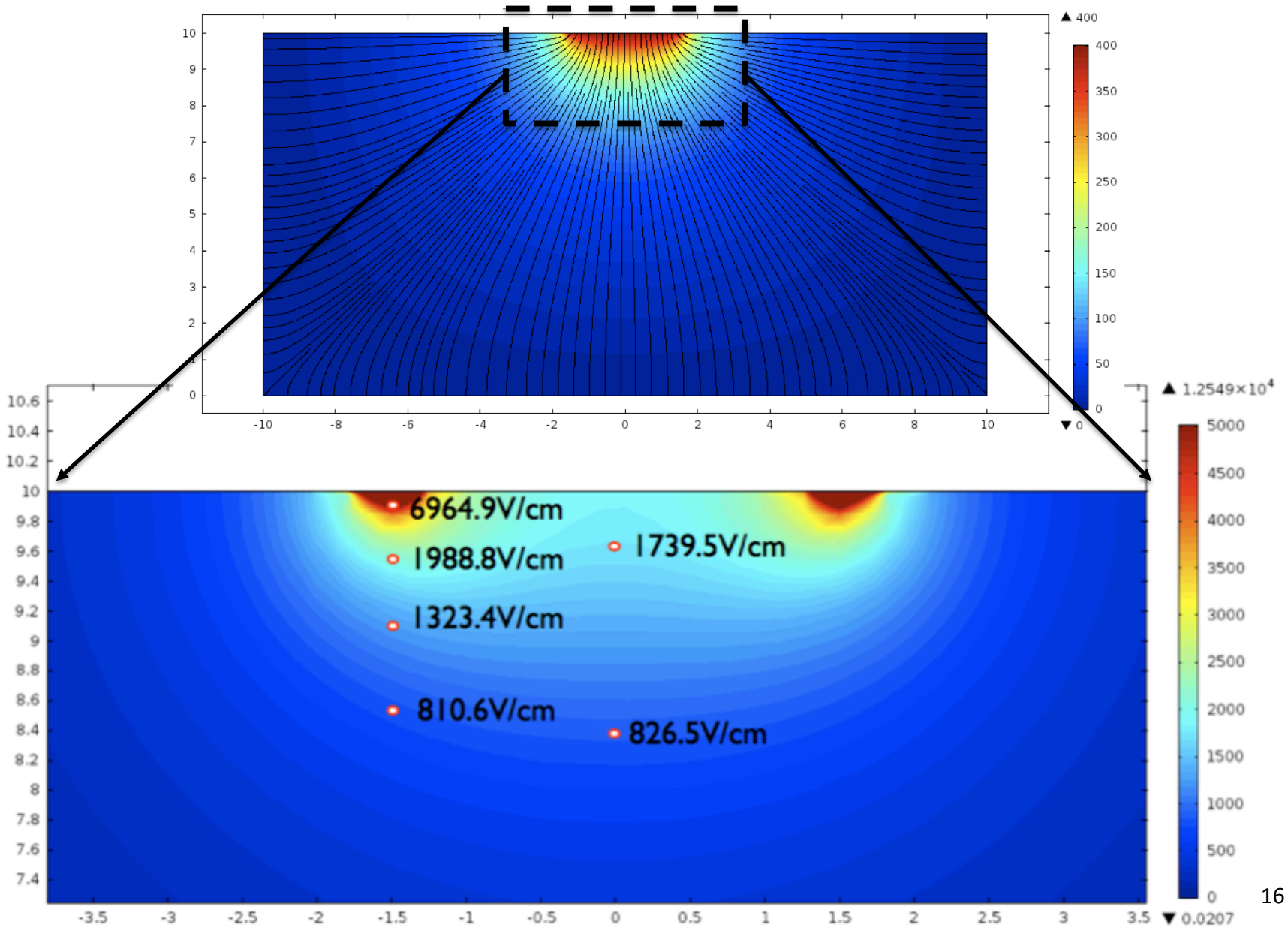
No Break down for V up to 400 Volts





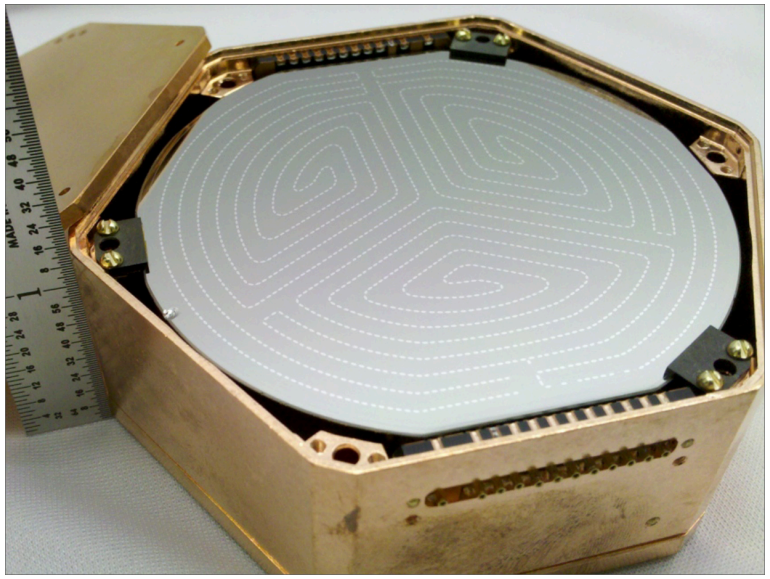


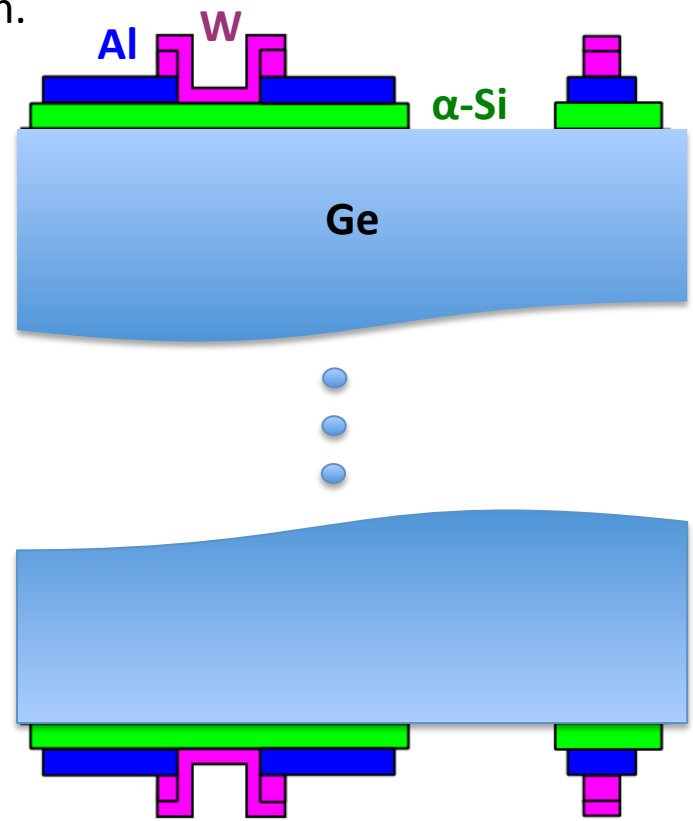
E Field in PPC for V_{bias}=400Volts



CDMS symmetric contact geometry

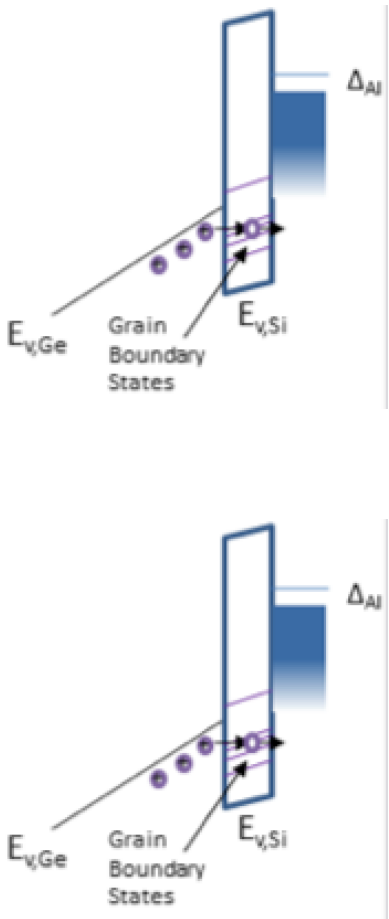
- Use W TES (T_C~75 mK) phonon sensors
- Both faces of the detector uniformly covered with sensors.
- Simultaneously measures athermal phonons and ionization.
- Design tailored for excellent background rejection.

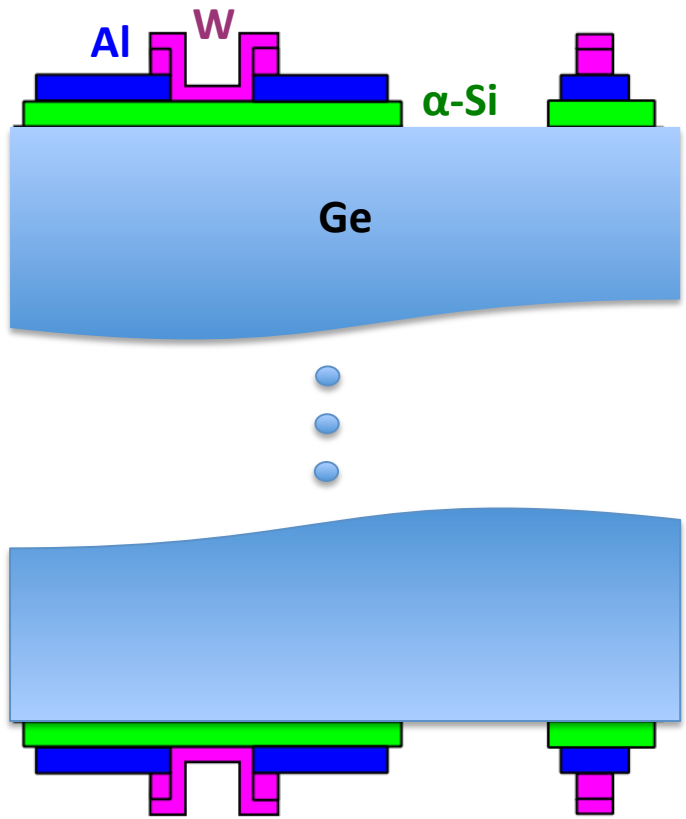




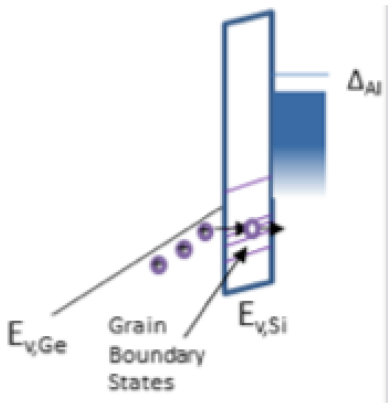
In CDMSlite mode only readout one face phonon sensors. The other face used for biasing.

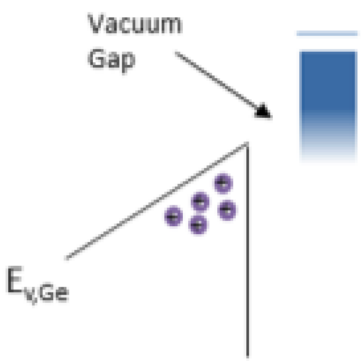
CDMSlite symmetric contact geometry

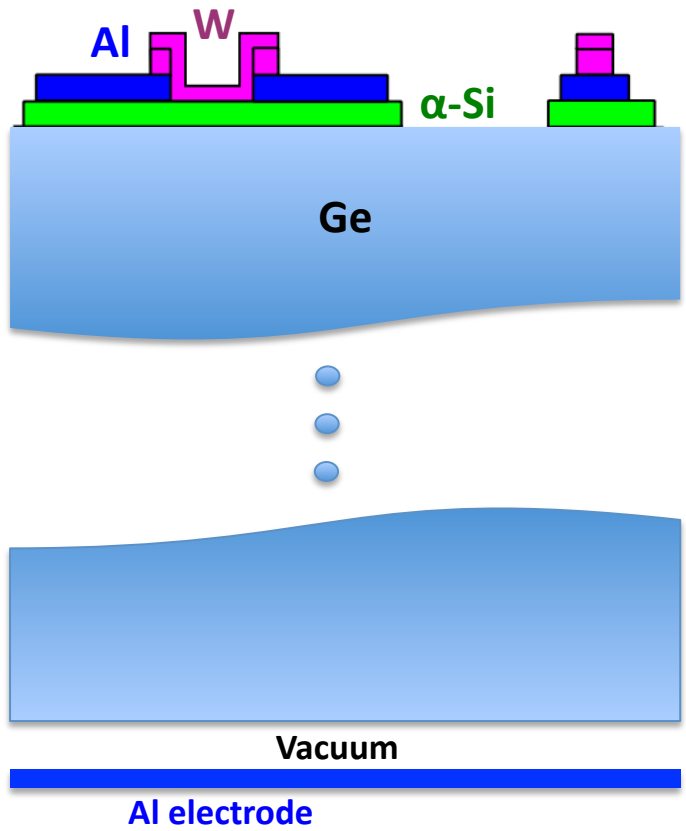




CDMSlite symmetric contact geometry

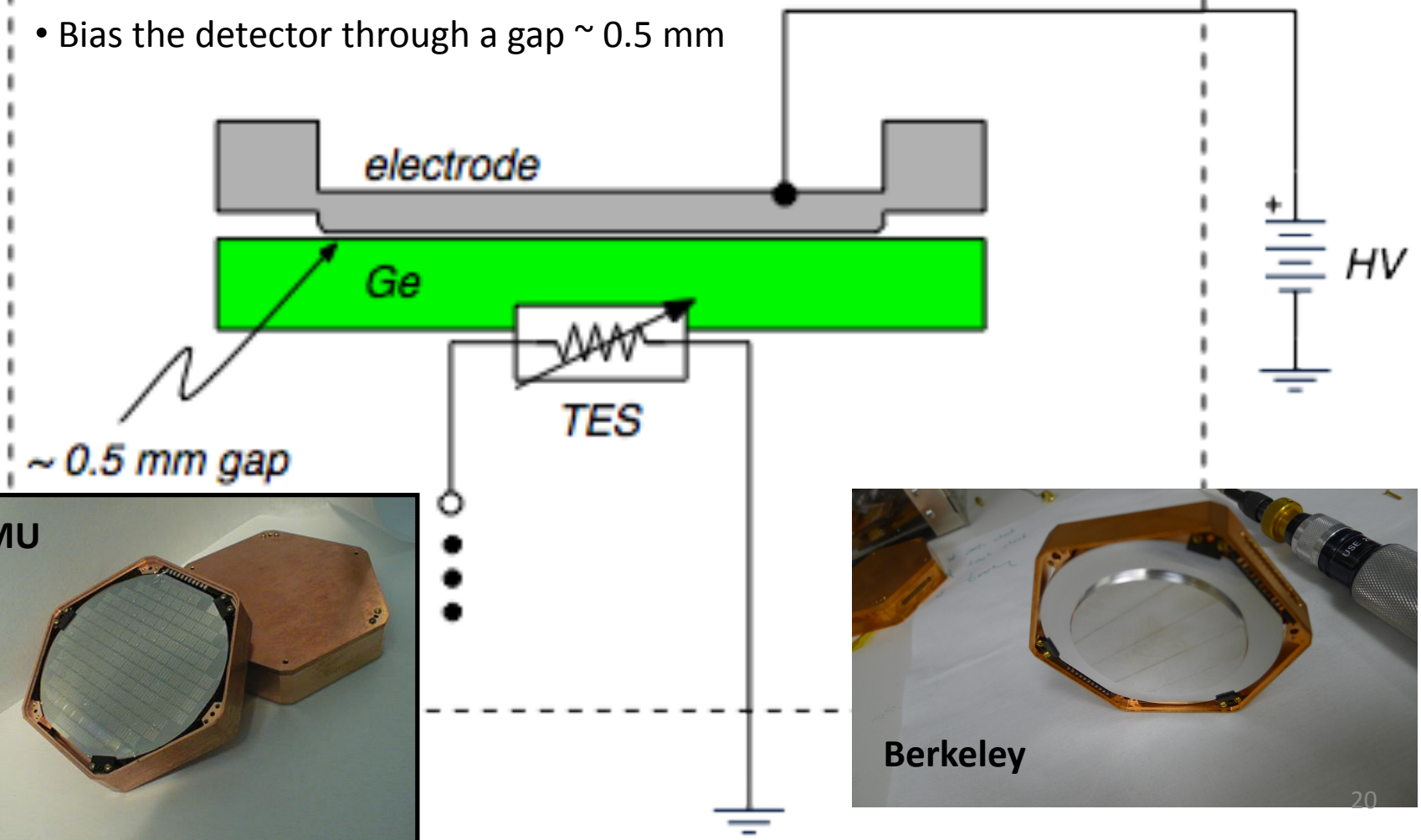


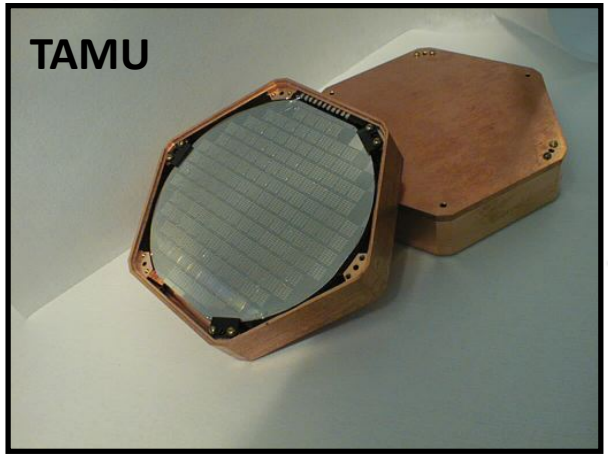




High Voltage athermal phonon readout: contact free biasing

- One face of the detector processed similar to a CDMS II detector:
  - fully covered by Four W based athermal phonon readouts.
- The other face of the detector left free
- Bias the detector through a gap ~ 0.5 mm



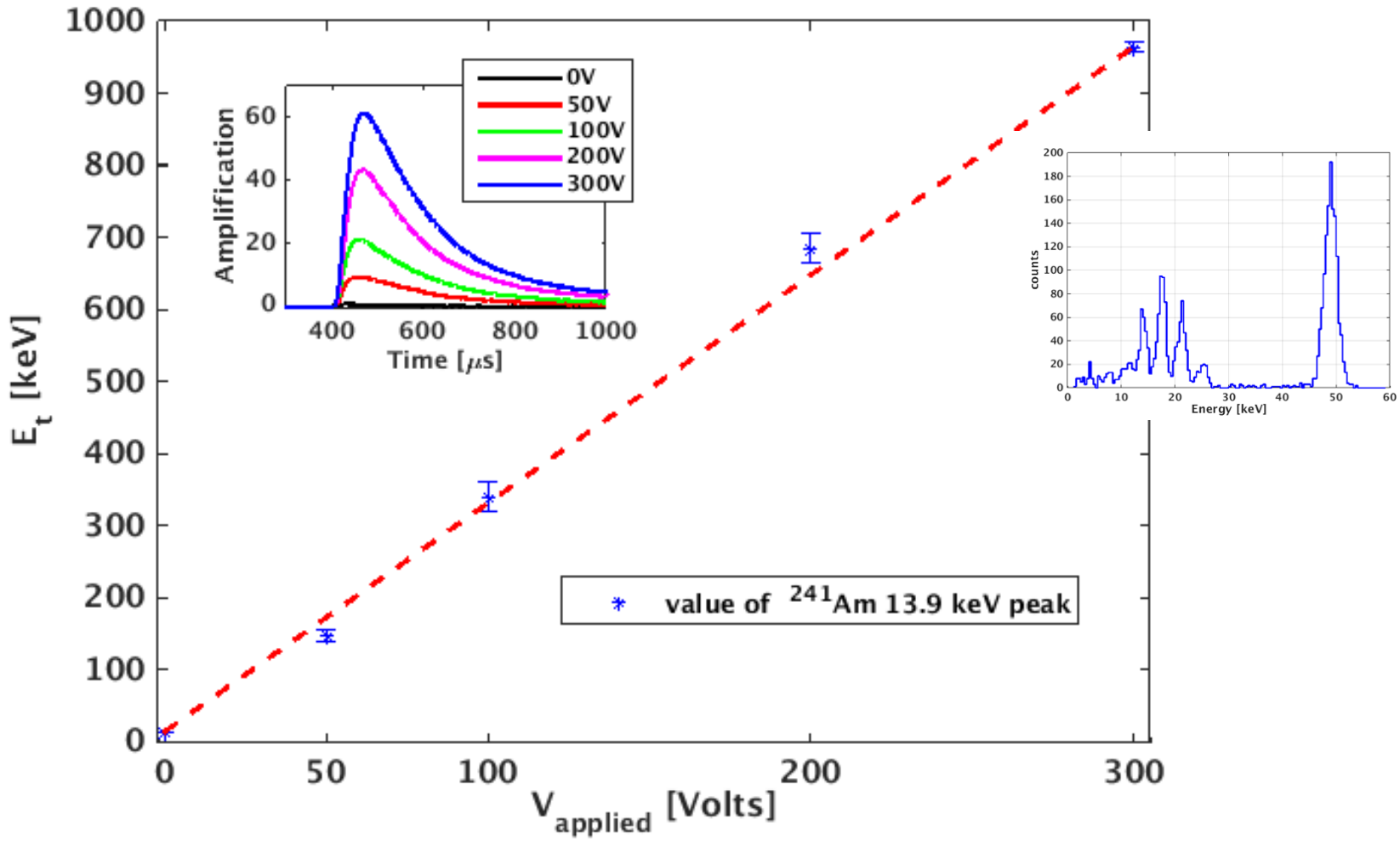


Contact free asymmetric results

- The phonon sensor always at ground potential.
- Observed a strong leakage polarity dependence.
- Significant leakage when biased negative.

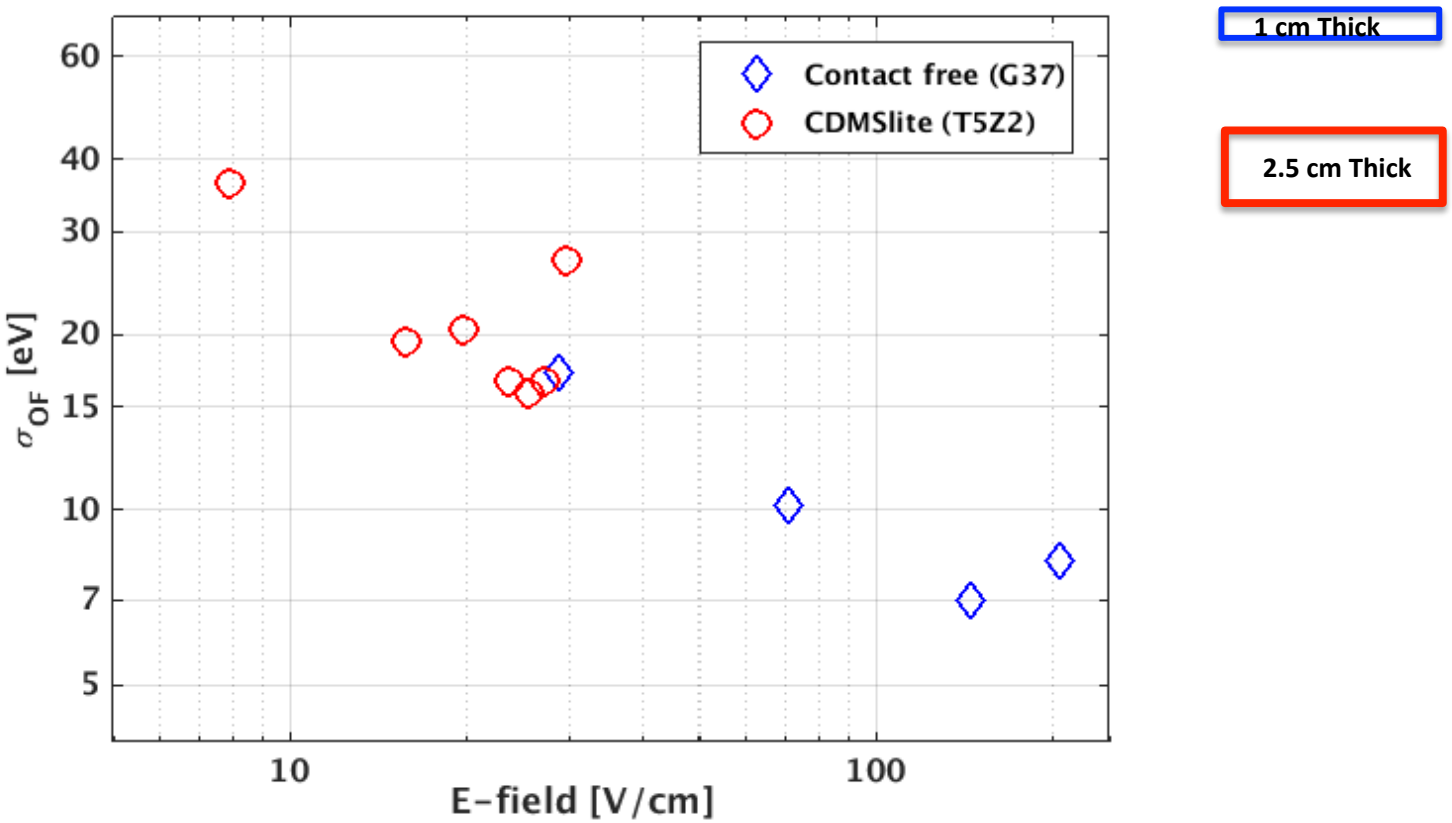
  => Holes leak through the interface
- Requires further studies on contact properties.

Contact Free performance



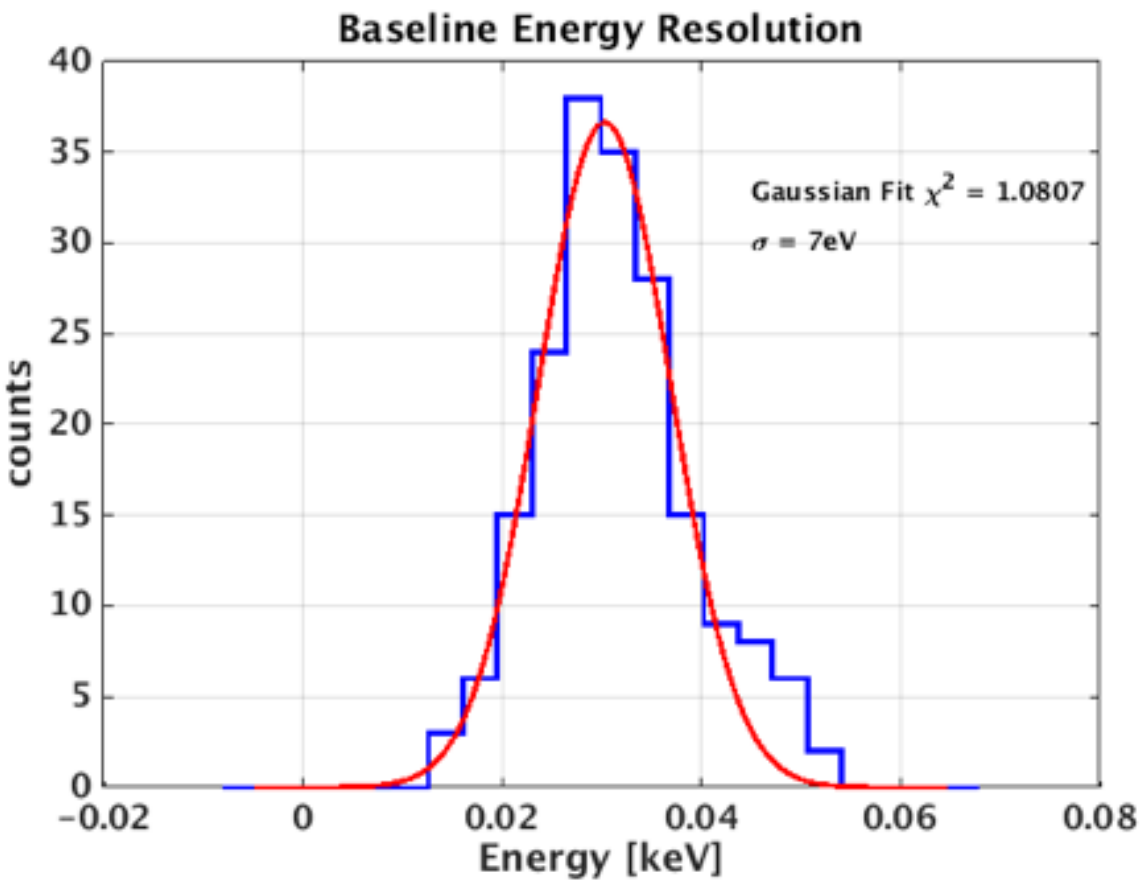
N.Mirabolfathi et al. arXiv:1510.00999

Comparing Contact free and CDMSlite



N.Mirabolfathi et al. arXiv:1510.00999

Baseline Resolution



N.Mirabolfathi et al. arXiv:1510.00999

Given a fixed $E_{critical}$

1 cm Thick

↓

2.5 cm Thick

=>

× 2.5 V_{max}

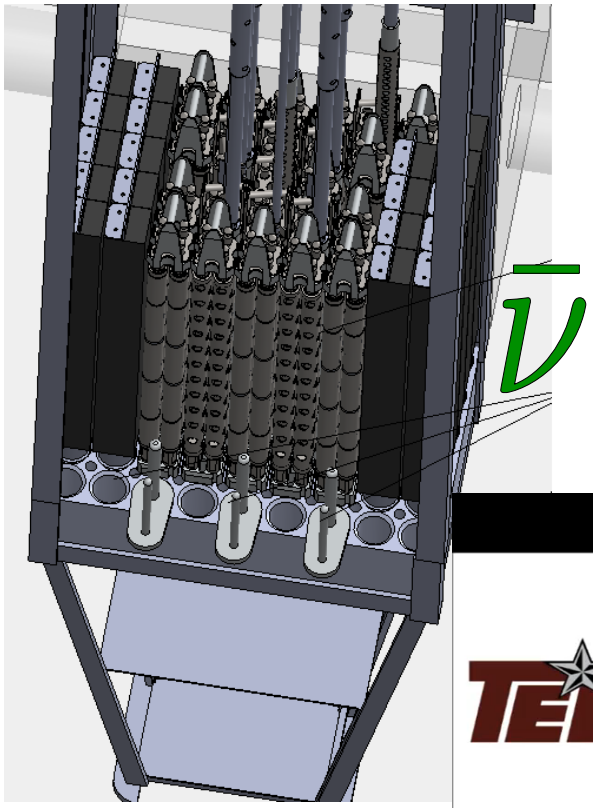
=>

× 2.5 Phonon gain

Using this concept in CDMSlite iZIP absorber geometry, we expect to achieve:

$\sigma < 2.8\ eV_{ee}$

Mitchell Institute Neutrino Experiment at Reactor (MINER)



Mining the "Invisible" at the TAMU Nuclear Reactor

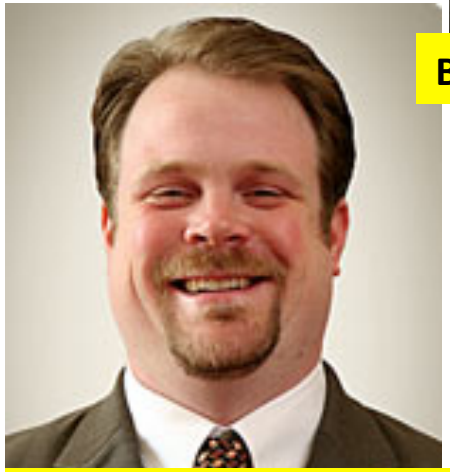
Rupak Mahapatra , TAMU

Nader Mirabolfathi , TAMU

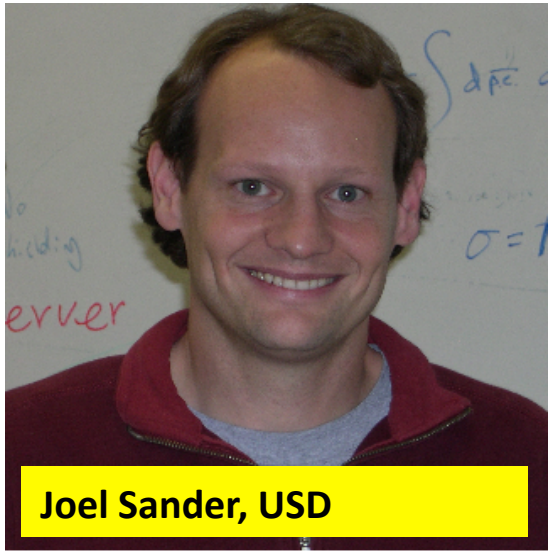
Bob Webb , TAMU

Rusty Harris, TAMU

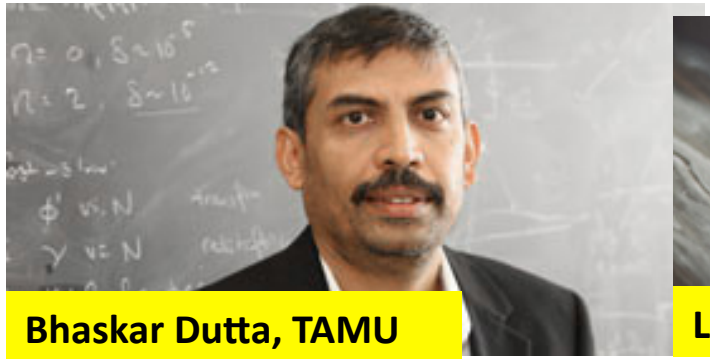
Sean McDeavitt, Nucl Engg Director, TAMU NSC



Joel Walker, SHSU



Joel Sander, USD



Bhaskar Dutta, TAMU

Louis Strigari, TAMU

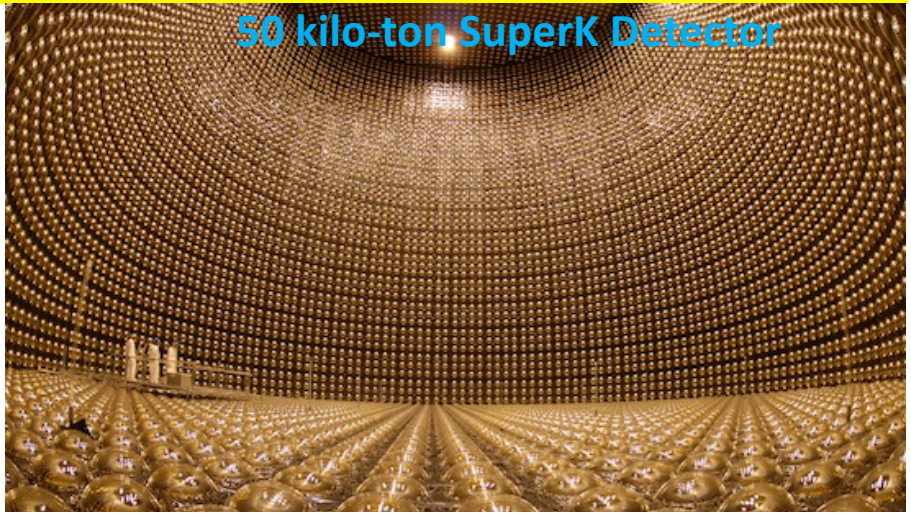
How Neutrinos Are Produced and Detected

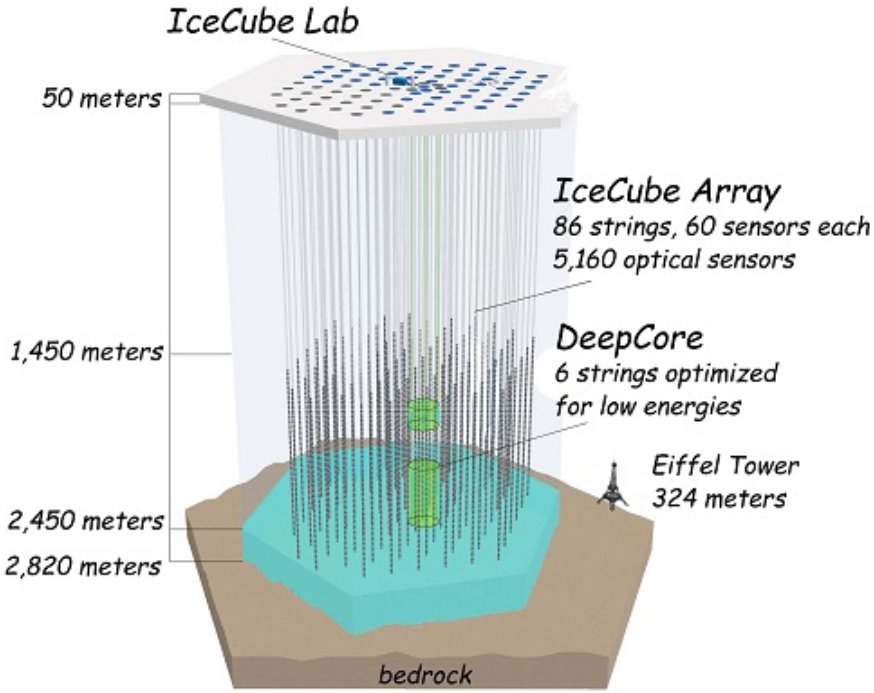
- High energy neutrinos produced in cosmos and accelerator based sources (> GeV to PetaeV as in recent news)
- Typically detected by k-ton detectors
  - Charged current or Inv. β-decay $\nu_e + p \rightarrow n + e^+$
  - Neutral current or scattering $\nu + e \rightarrow \nu + e$

- Huge rate enhancement (10^4)possible from lower energy neutrinos (MeV) from reactor through Coherent Scattering on Nucleus $\nu_e + N \rightarrow \nu_e + N$

- This neutrino energy is mostly below inverse beta decay threshold, thus not easily detected through standard detection techniques.

- However, we can detect CNS and with only few kg payload due to coherence!

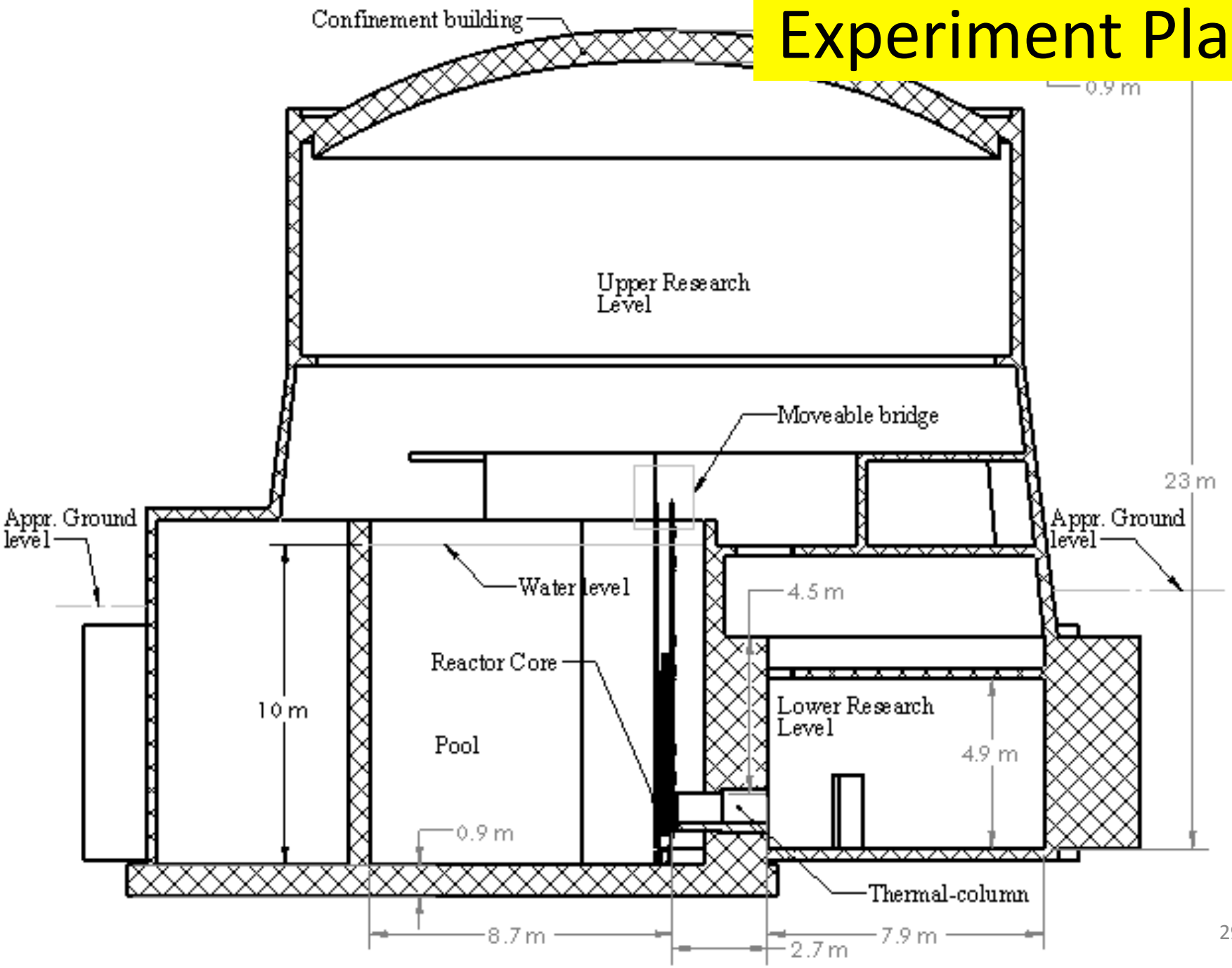




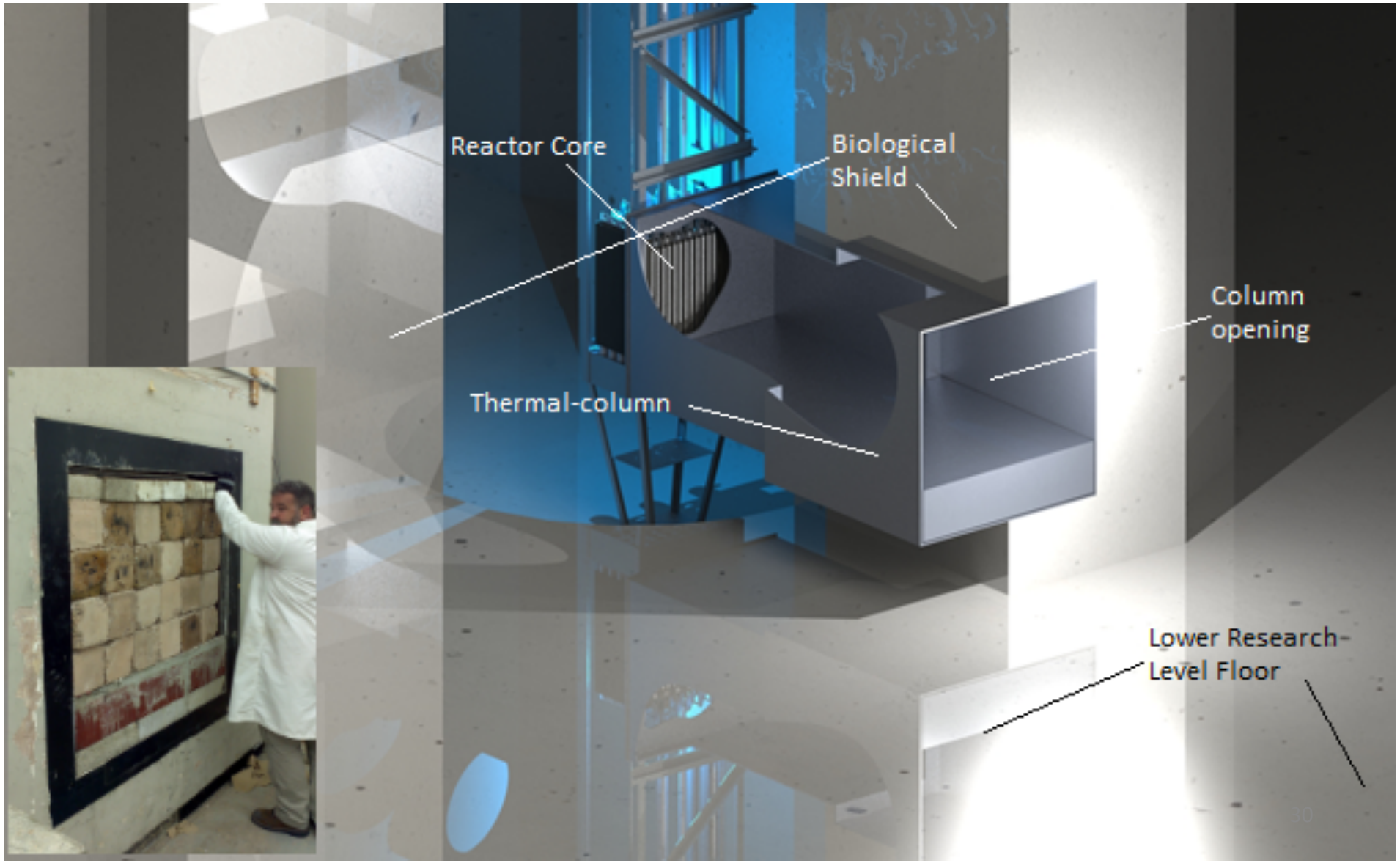
How Do our Rates Compare with GW Power Reactors?

- Many experiments proposed around the world, to perform this experiment at GW power reactors
- Most promising experiment ~30 m from GW reactor
- Just by being @1 meter from MW reactor gives same rate
  - Our 10 kg detectors provide equivalent rate to a 10 ton experiment 30 m away (best alternative is TEXONO) or a 10 kiloton detector 1 km away (typical short baseline experiments), for similar starting flux
- Biggest uncertainty is from knowing the reactor power

Experiment Plans

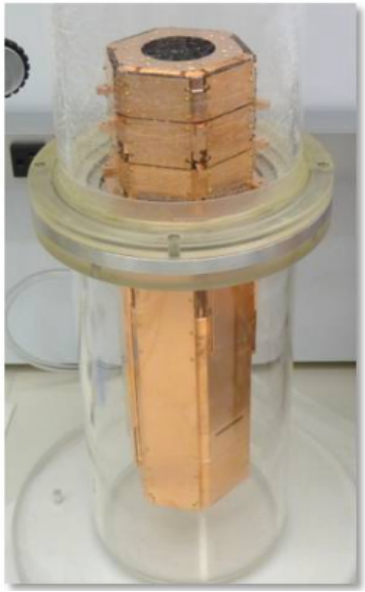


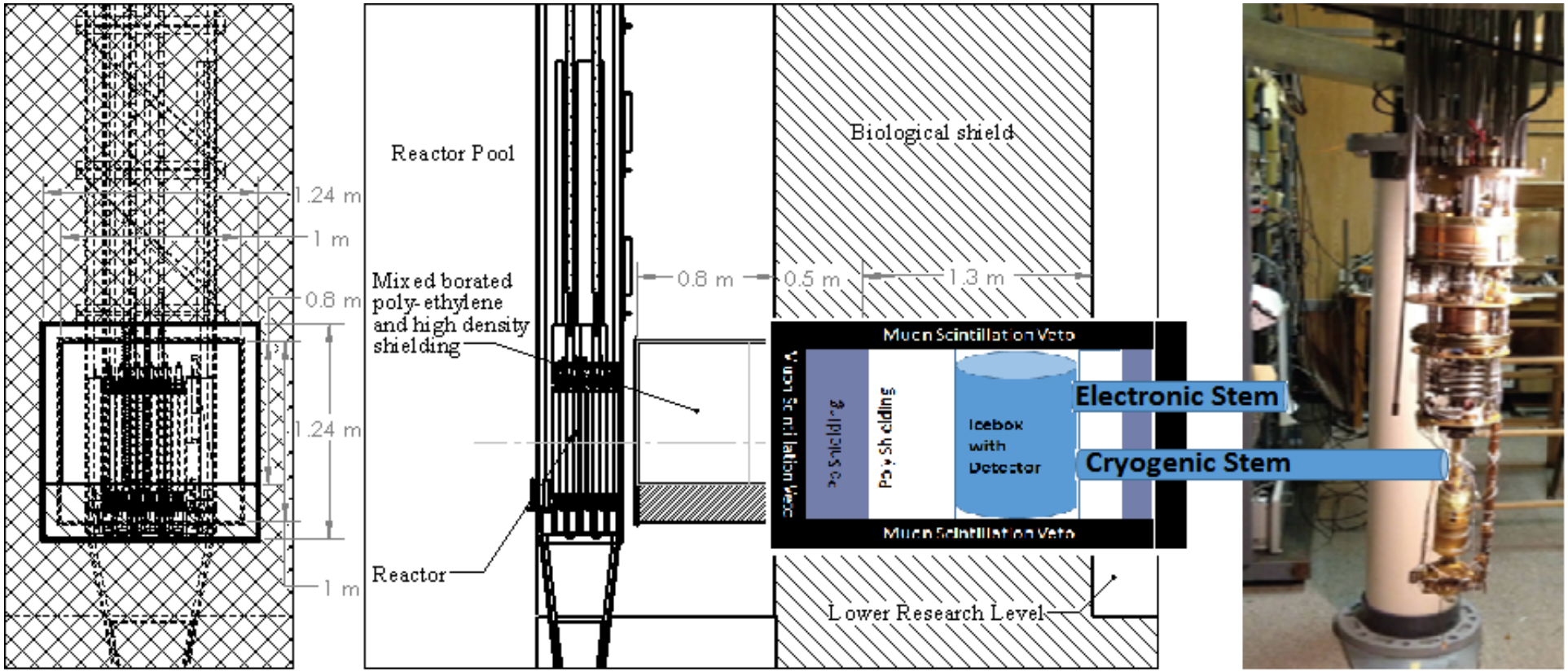
Experiment Plans



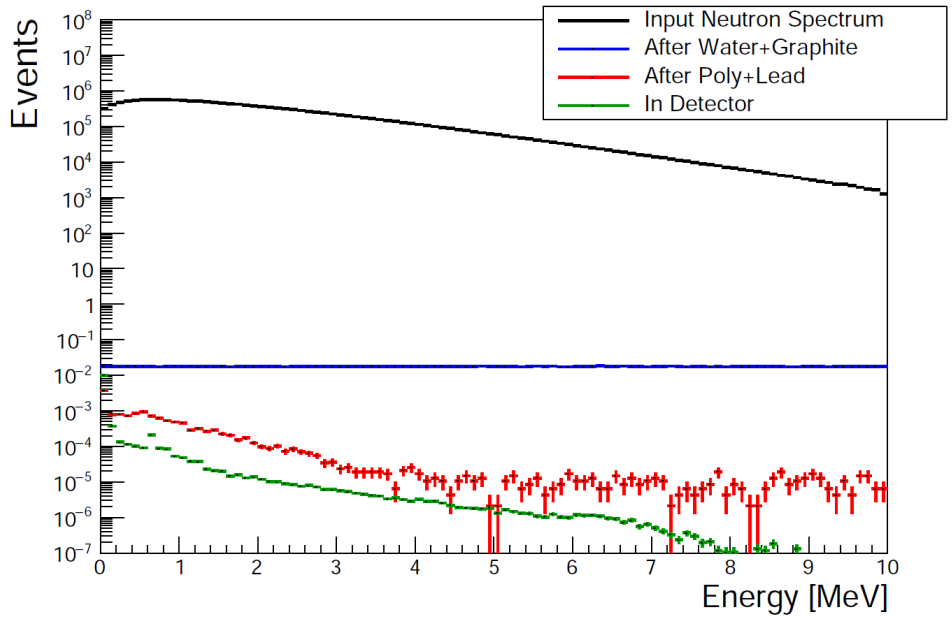
Layout of the MINER Experiment

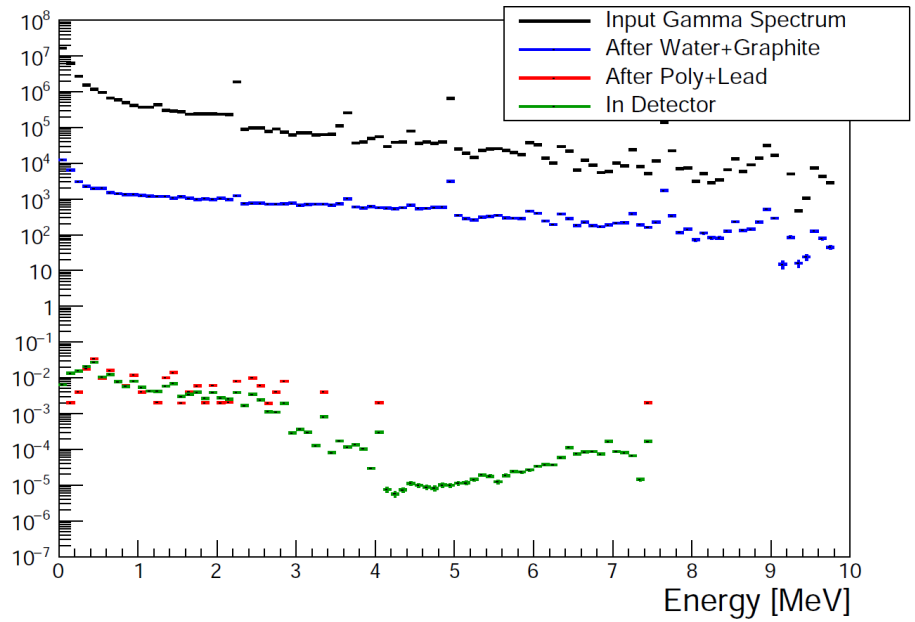
1 Tower of 4 Ge and 4 Si detectors, similar to what we develop for SuperCDMS. Total mass 12 kg.





Neutron and Gamma Background Reduction



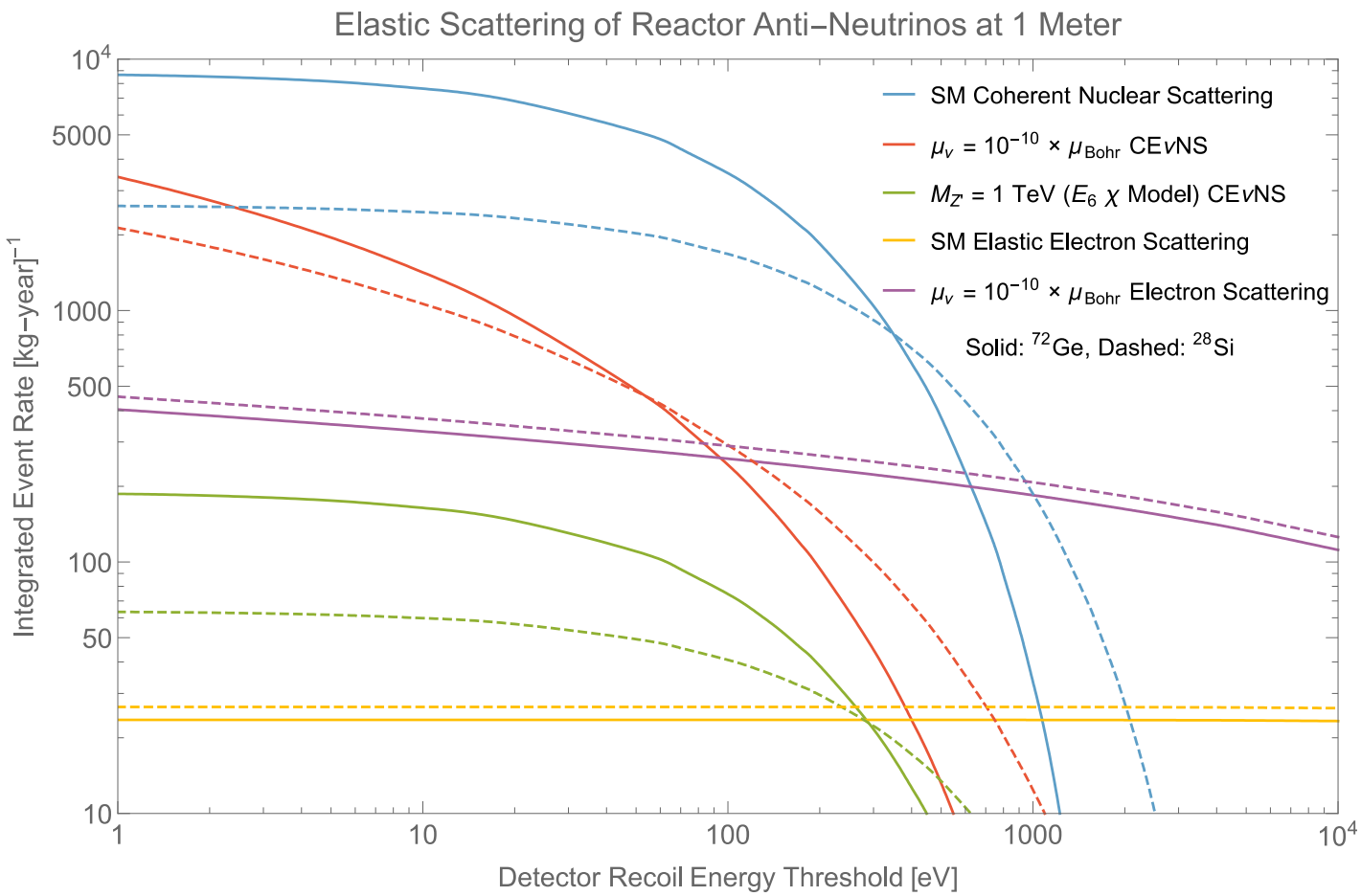


MCNP+GEANT4 Monte Carlo shows acceptable background

Expected event rate ~40/detector/day
Will design shielding to keep rate < 1/det/day in the ROI .01 – 1 keV

Most dominant background at the low energies are Compton scatters. Actual expected trigger rate would be <1000/day, from all energies and sources

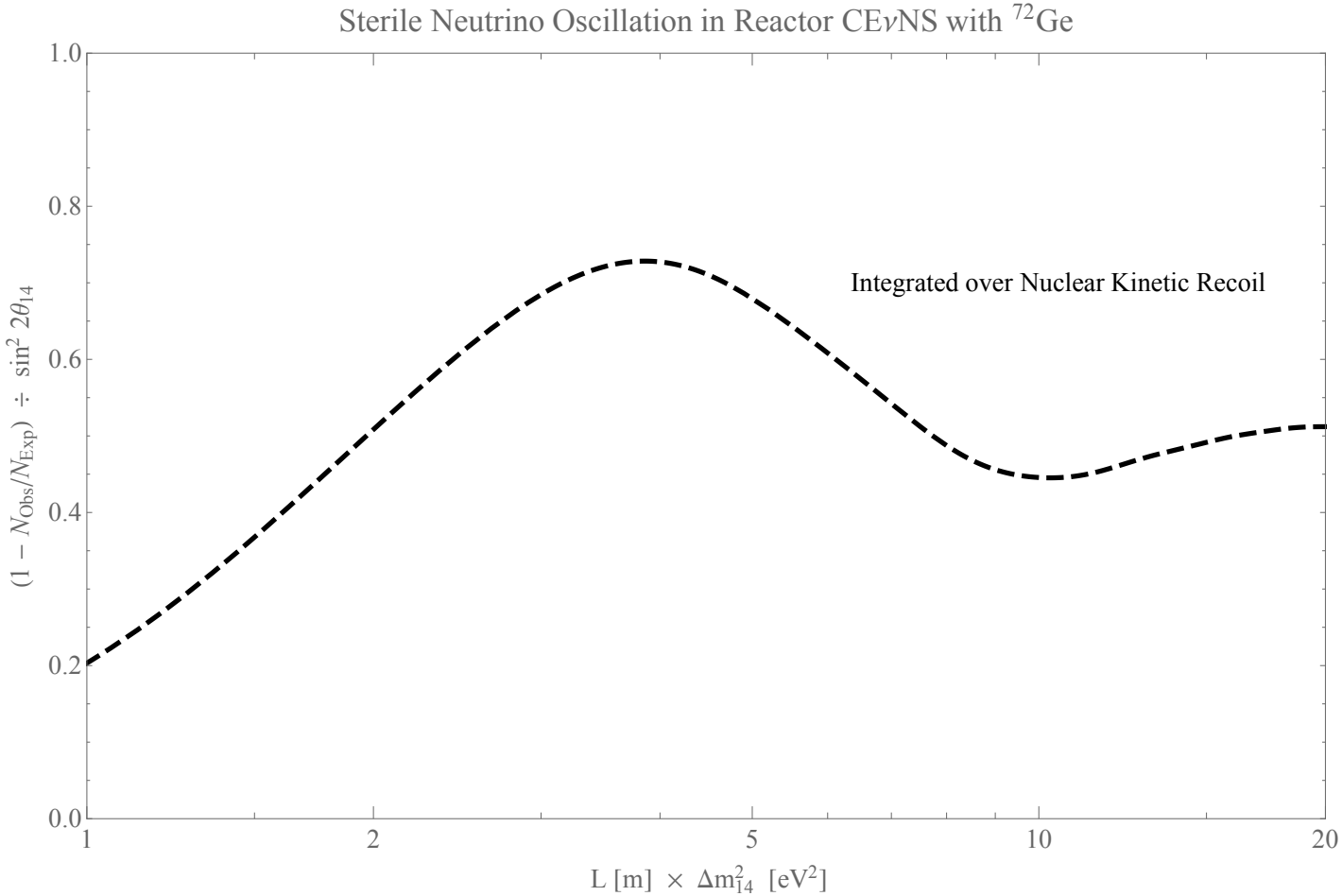
Components of Elastic Scattering



- Coherency boosts nuclear cross section, but large mass implies low recoil thresholds
- Nucleus - neutrino magnetic moment scattering (red) benefits most at low thresholds

Dutta, Mahapatra, Strigari, Walker. "Sensitivity to Z' and Non-Standard Interactions from ultra-low threshold neutrino-nucleus coherent scattering. arXiv 1508.07981

Sterile Neutrino Search through Short (1-10 m) Baseline Oscillations



Long-Term, High-Mass Detector Reach

kg-years	$M_{Z'}(E_6, \chi)$	$M_{Z'}(B-L, g'=0.4)$	$\mu_\nu/\mu_{\rm Bohr}$
12	$(1.9, 1.9, 1.6)$	$(3.5, 3.4, 2.8)$	$(1.1, 1.7, 3.1) \times 10^{-11}$
5×10^3	$(8.7, 8.5, 7.1)$	$(16, 15, 13)$	$(2.5, 3.7, 7.0) \times 10^{-12}$
1×10^5	$(18, 18, 15)$	$(33, 32, 27)$	$(1.2, 1.8, 3.3) \times 10^{-12}$

- Statistical projections are for (1 year, 12 kg), or (5 year, 1,000 kg), or (10 year, 10,000 kg)
- Systematics are comparable to statistical errors in first phase, but dominate in latter
- Parenthesis compare (1,10,100) eV detector recoil thresholds
- Ultra-low eV-scale thresholds present greatest benefit to magnetic moment searches
- Z-prime masses are in TeV units

Conclusion

- Both low mass dark matter searches (e.g. CDMS) and coherent neutrino scattering experiments (e.g. MINERS) are striving for very low threshold detectors.
- CDMSlite already achieved unprecedented sensitivity for low mass WIMPs and is using the Neganov-Luke phonon amplification as detector principle.
- CDMSlite limitation of leakage current seems to originate form the particular electrode/absorber interface.
- Electrically insulating electrodes from the absorber can be a solution to reach very low threshold.
- For the very first step using vacuum as a perfect insulation, we achieved Luke amplification of ×50 and reached an RMS resolution of $\sigma < 7\ eV_{ee}$ in a 0.25 kg Ge detector. With thicker CDMSlite geometry expect $\sigma < 2.8\ eV_{ee}$.
- We believe single electron resolution phonon mediated detectors are just couple devices away with exciting physics that they can deliver.