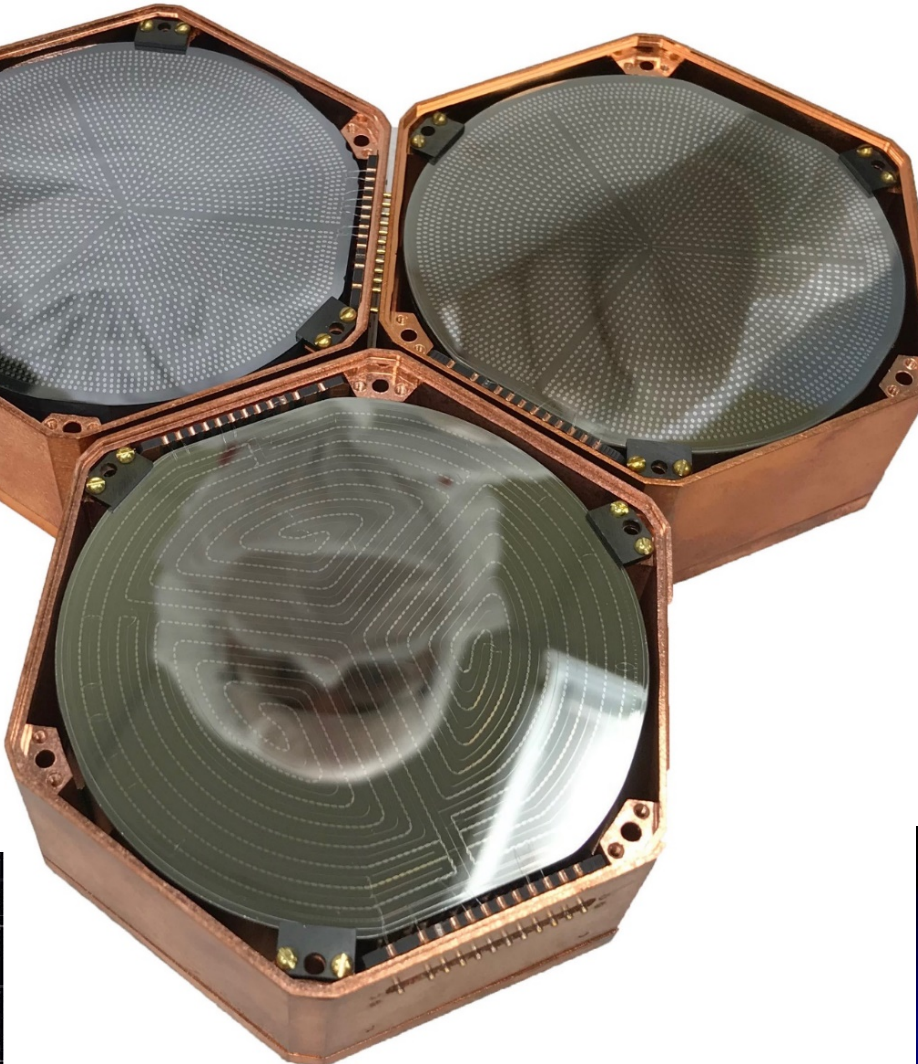
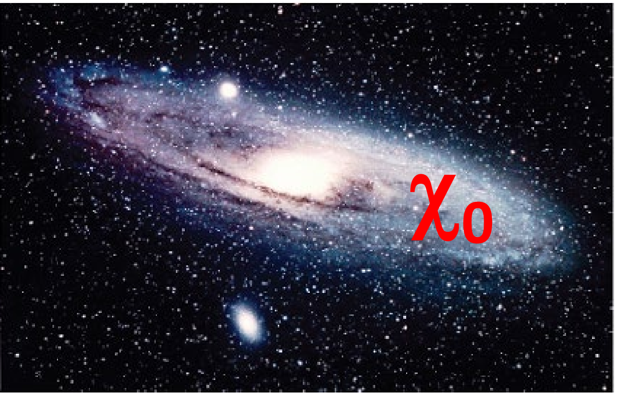
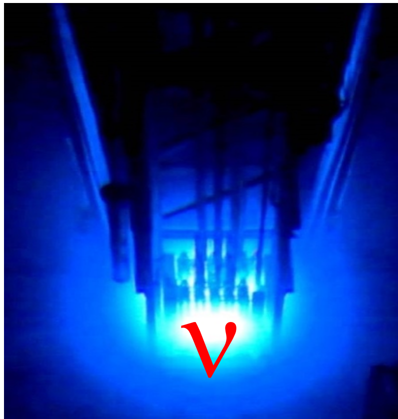
Reactor CEνNS Detection using Low-threshold Detector Technology Developed for Dark Matter Searches

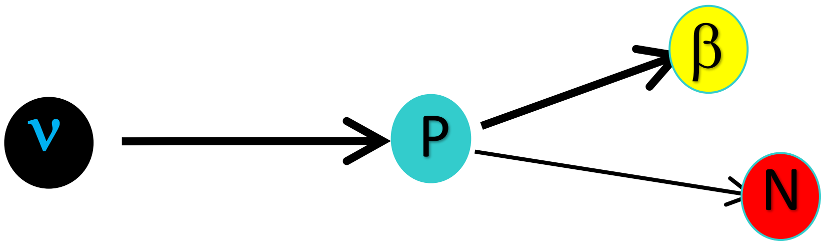




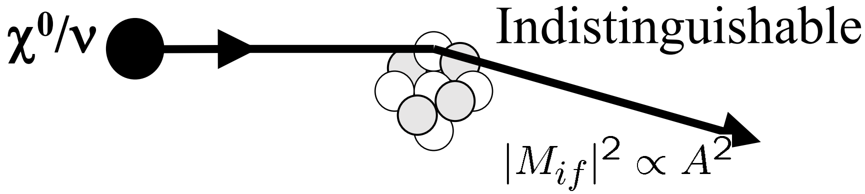
Rupak Mahapatra,
Texas A&M



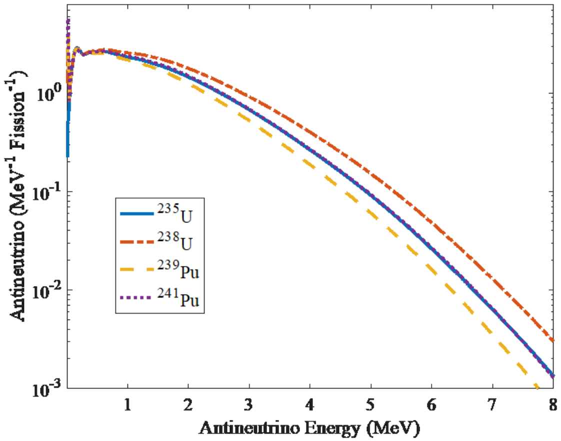
IBD vs CEνNS: Rate, Threshold, and Background



Prompt β^+, delayed neutron for full reconstruction.
Very good background rejection. Need E_ν>1.8 MeV



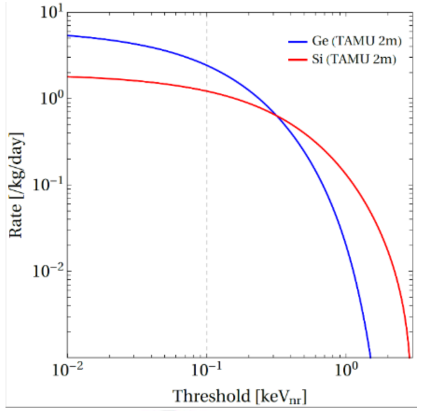
$E_R \approx m^2 v^2/m_{Ge} \approx$ 0-few keV recoil energy
Detected through ionization/phonon/light
Recoil spectra is used to infer the mass/energy



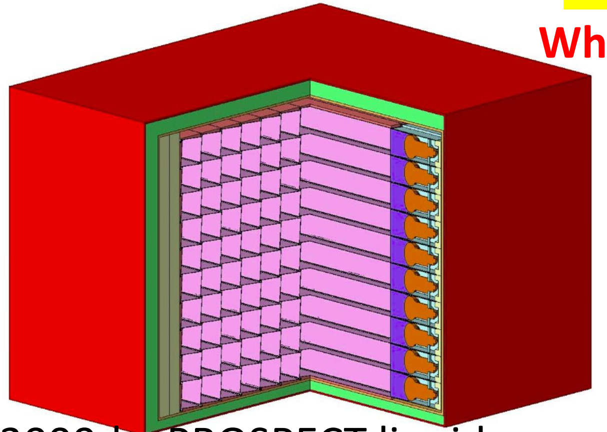
Both Weak Interaction Processes, but
Coherent ν-N Scattering $\Rightarrow$ A^2 enhancement

This provides the ~1000x higher rate
Also, allows access to sub-IBD ν spectrum

Determine reactor ON/OFF. Also, fuel type if measured with high statistical significance



Why is Reactor CEνNS not discovered yet?

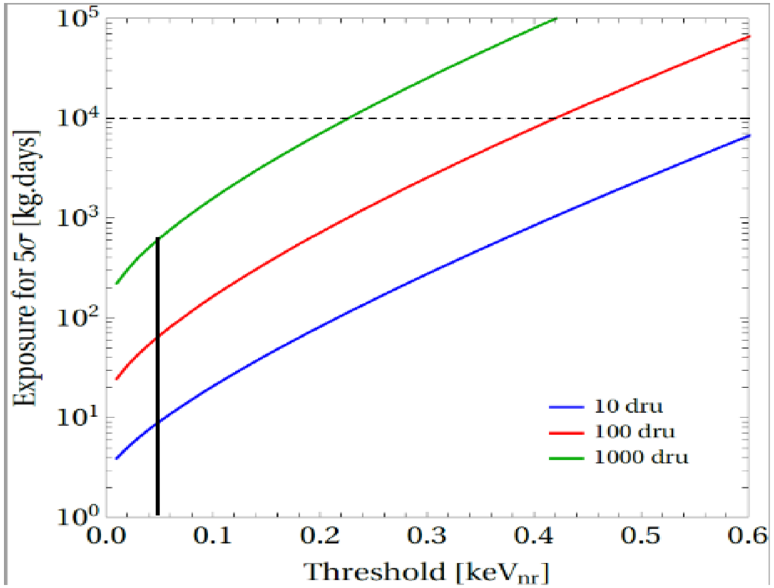


3000-kg PROSPECT liquid scintillation detector with PSD

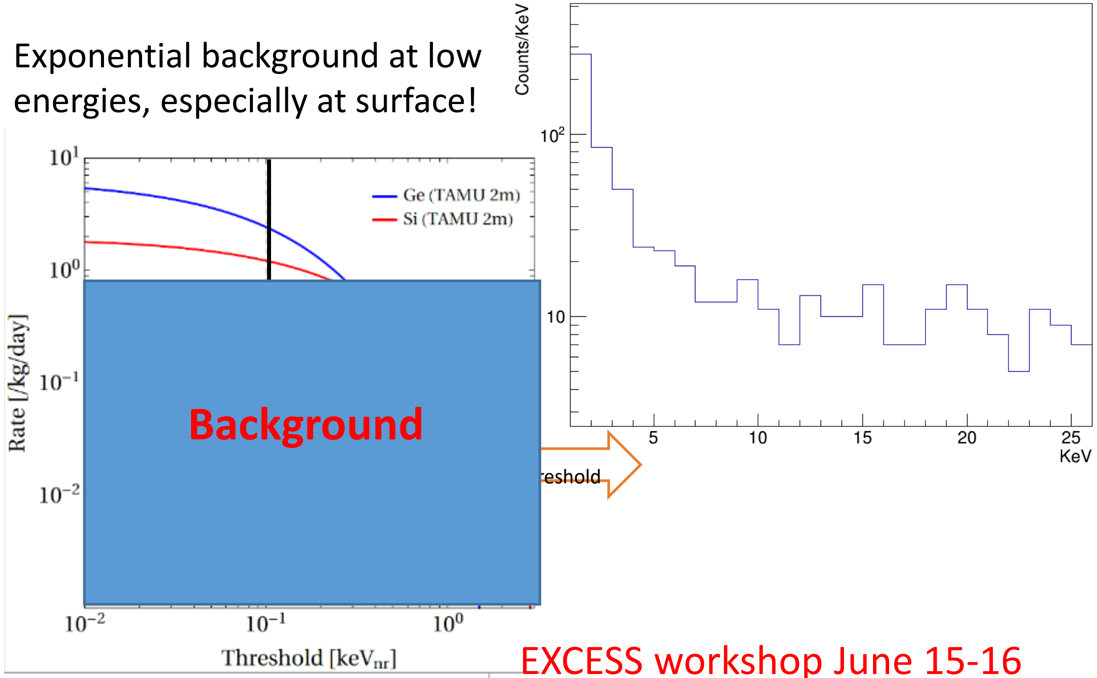
Kg-scale MINER germanium/silicon cryogenic detector ER/NR discrimination

The Interplay Between Threshold and Background

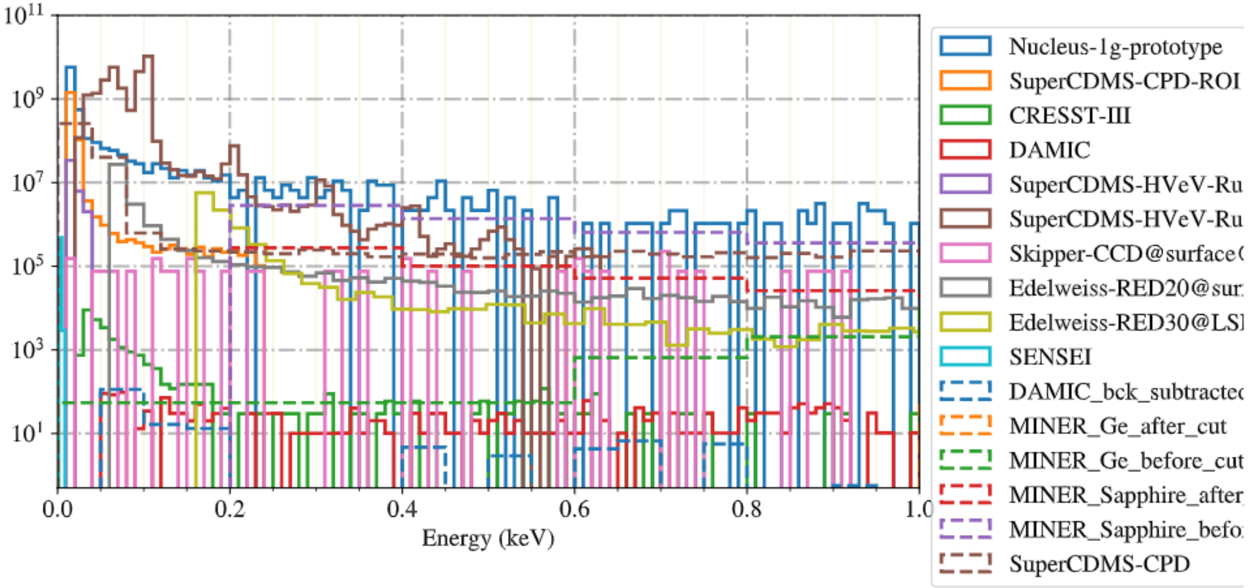
MW Reactor at 2m - Scale for Power and $1/r^2$



Exponential background at low energies, especially at surface!



EXCESS workshop June 15-16



The Dark Matter/CEνNS community had a workshop to put all expts. on the same scale to initiate a program to understand background sources

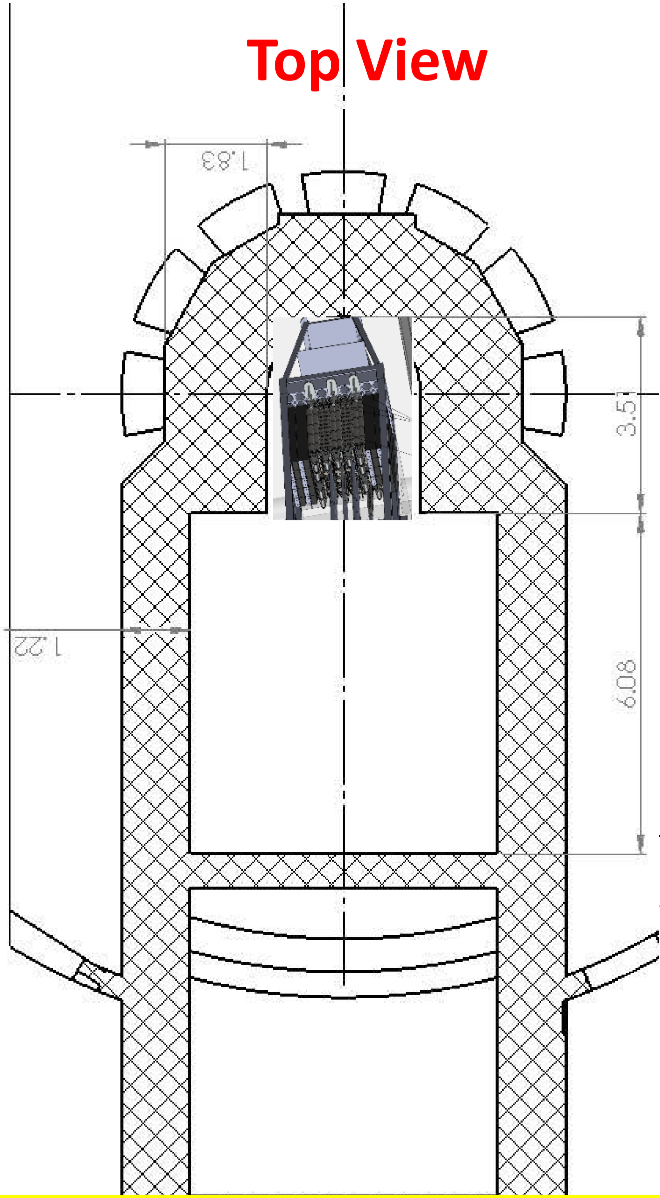
The biggest remaining hurdle for CEνNS to be used as a practical tool for reactor monitoring and nuclear safeguards is the background

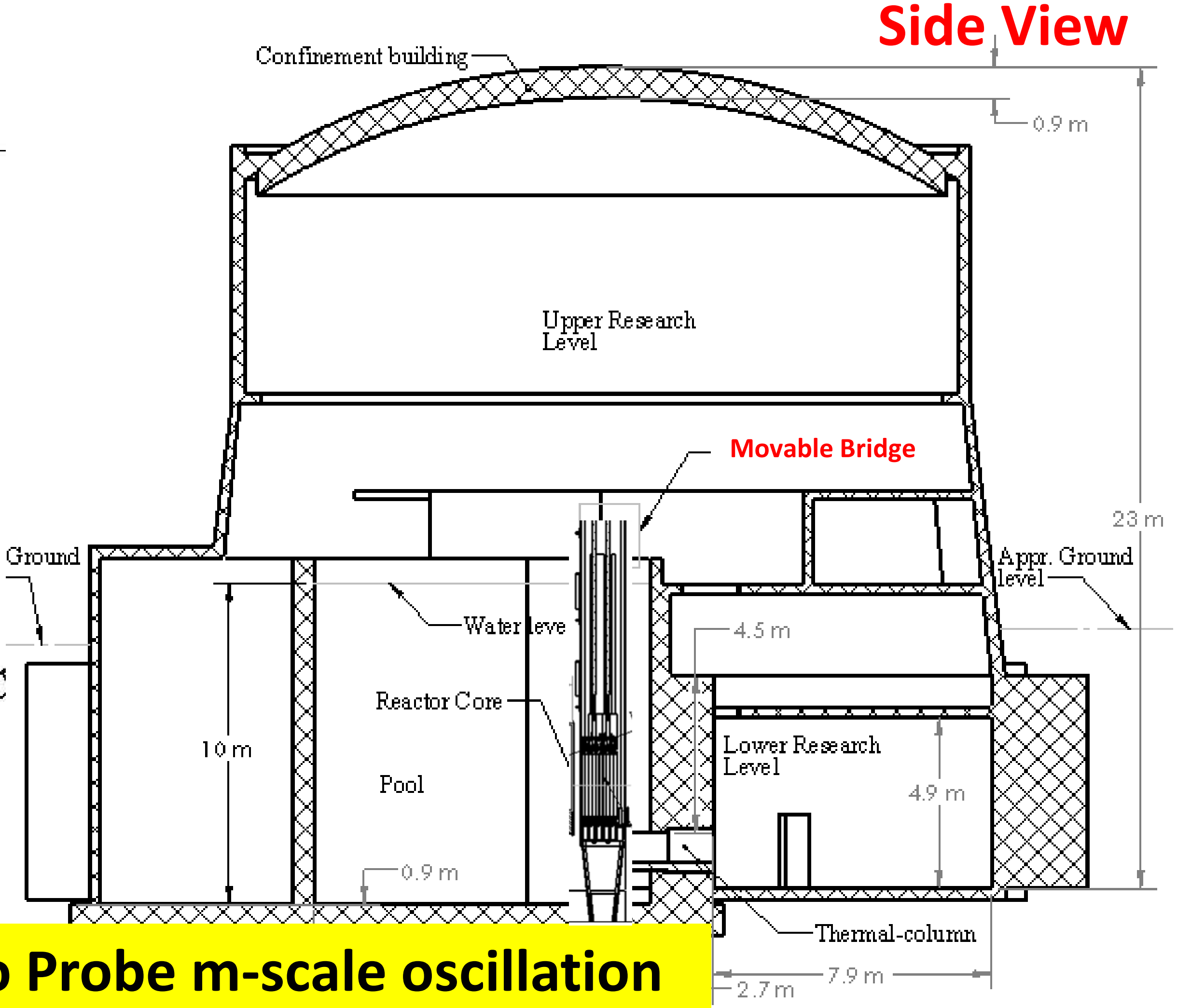
However, the synergy with DarkMatter is helping us reduce background and improve ER/NR rejection for discovery

MIνER Experiment - Generic to most expts

Key Features

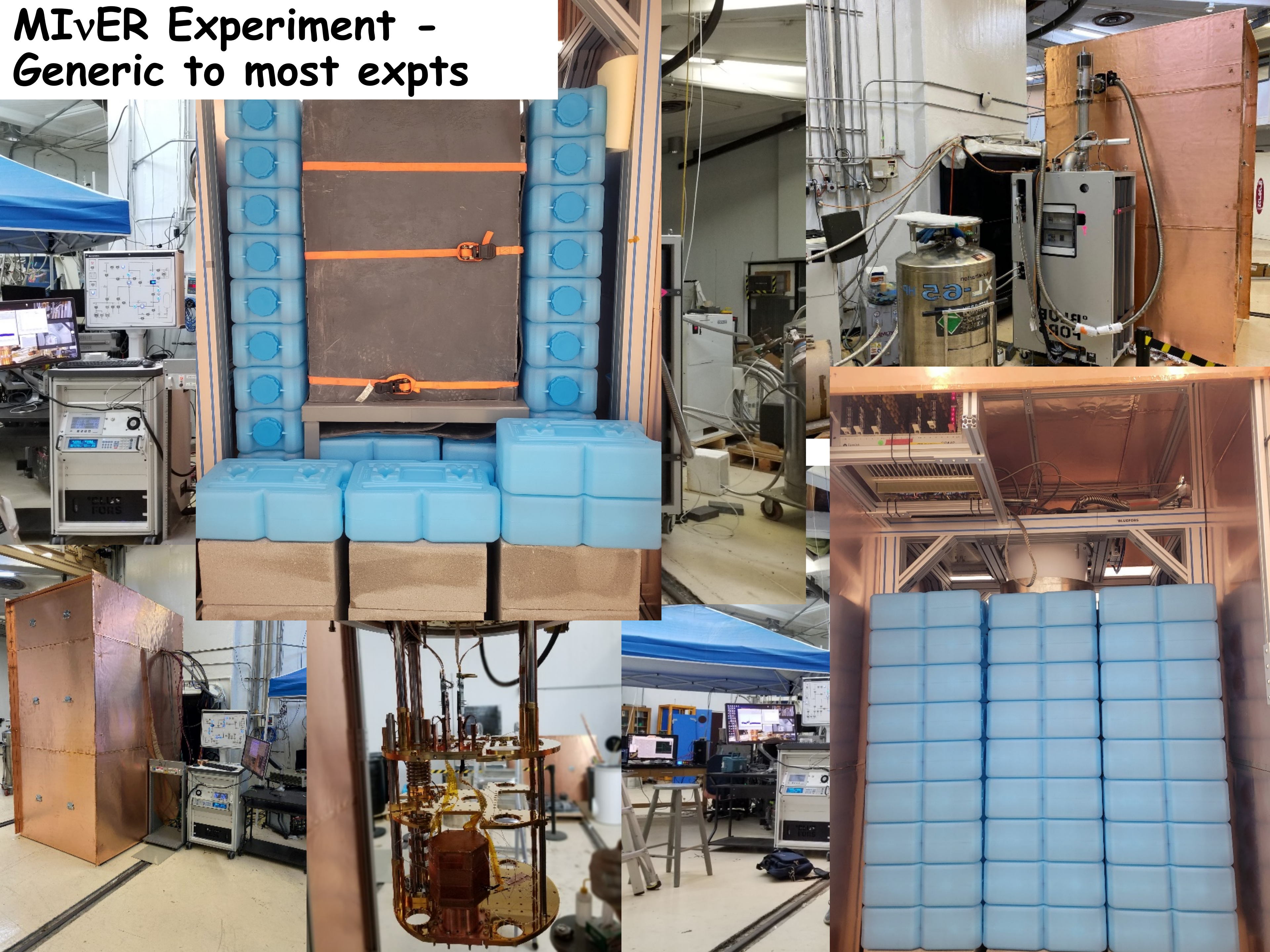
1. Low-threshold (<100 eV) with sensitivity to CEνNS
2. Proximity to core (rate enhancement)
3. Once detected, physics program involves precision measurement for new physics – sterile-ν, NSI, etc
4. Moveable Core tests short baseline oscillation


Top View


Side View

Precisely Movable Core to Probe m-scale oscillation

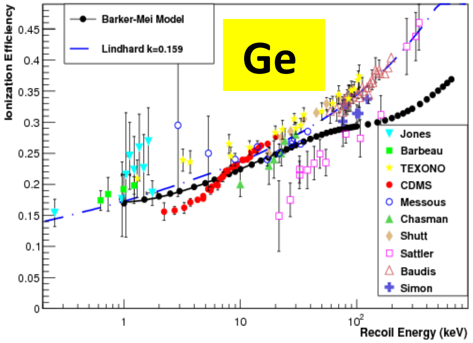
MIνER Experiment - Generic to most expts

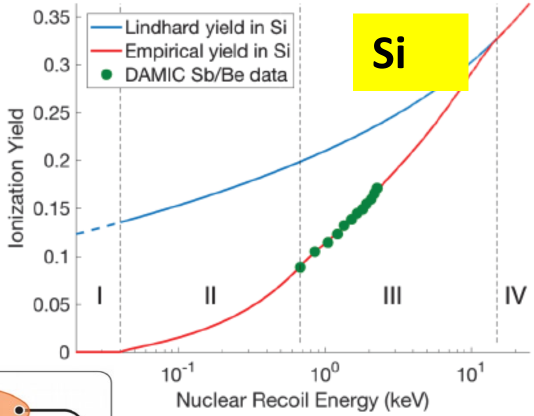


CEνNS Detector Technologies

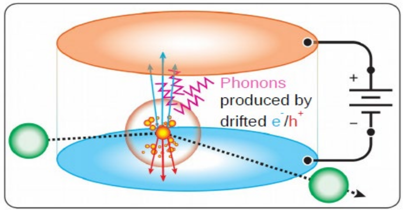
- Most Dark Matter detectorss now in use for CEνNS – synergy in low threshold and background reduction techniques
- Fundamentally, phonon detectors (with SQUIDs) can access lower recoil thresholds due to lower noise and no Lindhard
- CCDs have shown very low noise and low-threshold too
- Any detector (PPC, CCD) using charge will suffer from Lindhard

Light (quenched)	Ionization (quenched)	Phonon(no quenching)
Lindhard=.1-.2	.15 (Ge), .05 (Si)	No Quenching!
Req E_{th} =20 eV	30eV(Ge),10(Si)	200 eV
Resol. σ=4 eV	5 eV (Ge), 2 (Si)	40 eV
CRESST (10 gm)	CDMS(kg), CONNIE(gm)	CRESST, CDMS



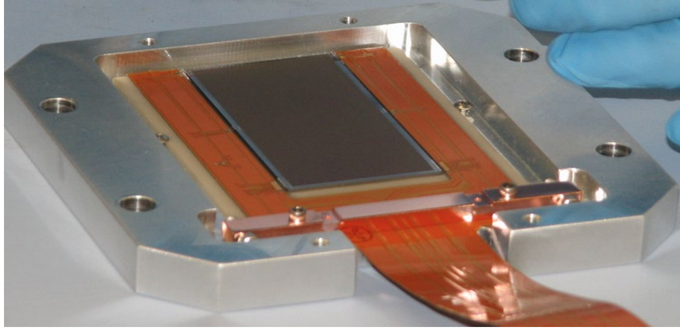


Trick to overcome Lindhard: convert ionization to phonon

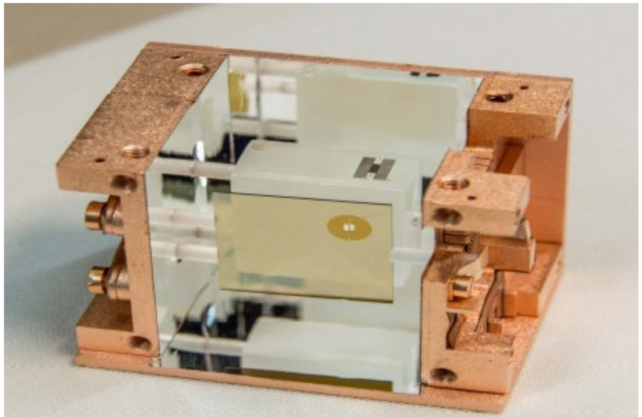


- **Luke-Neganov Gain**

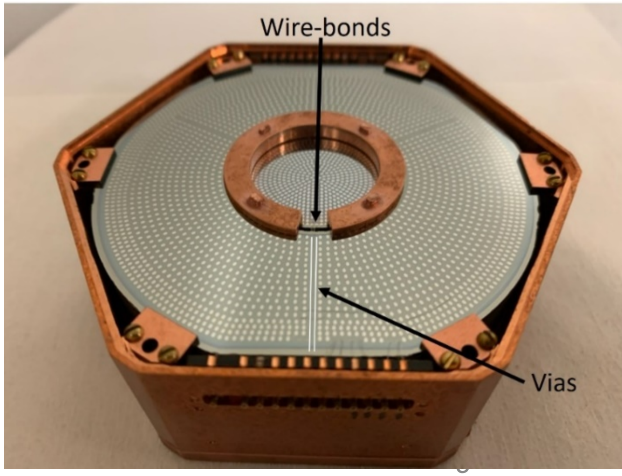
$$\begin{aligned} E_{tot} &= E_r + E_{luke} \\ &= E_r + n_{eh} eV_b \\ &= E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right) \end{aligned}$$



CONNIE CCD: ~gm mass with eVee sensitivity

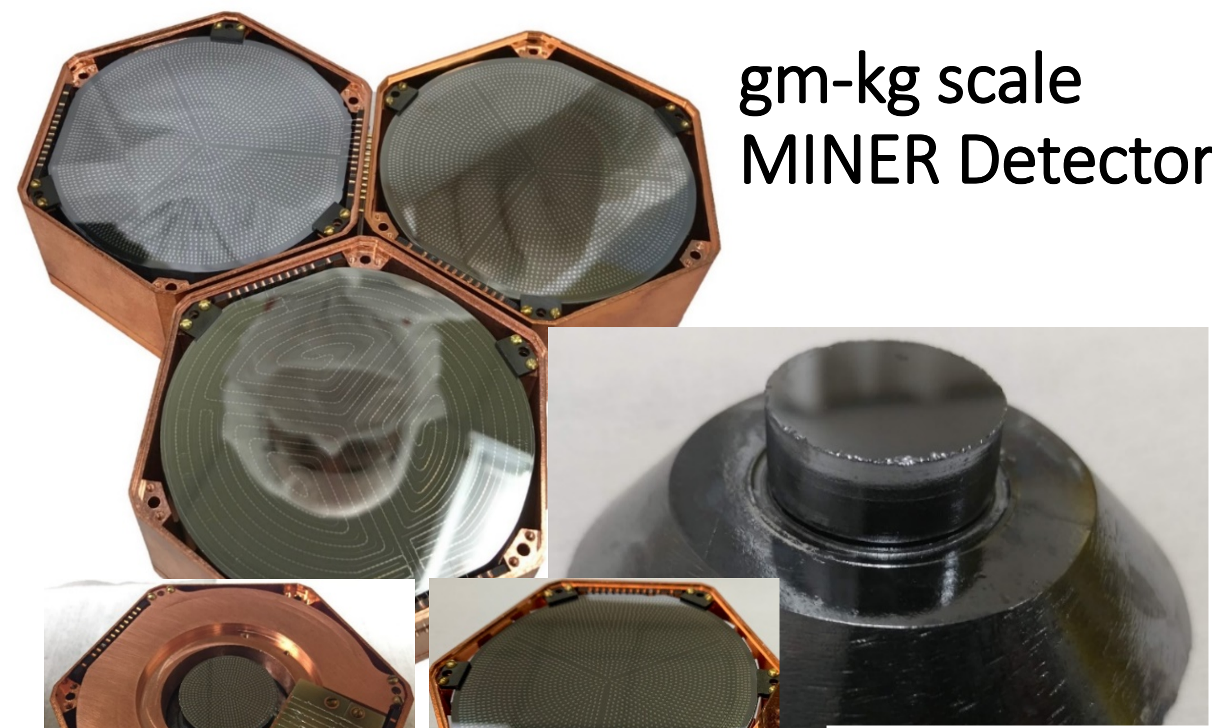


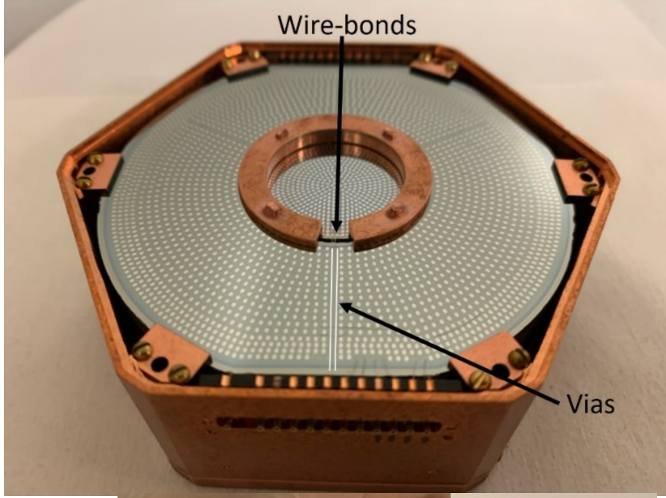
CRESST/NUCLEUS: ~gm mass with few eVnr sensitivit

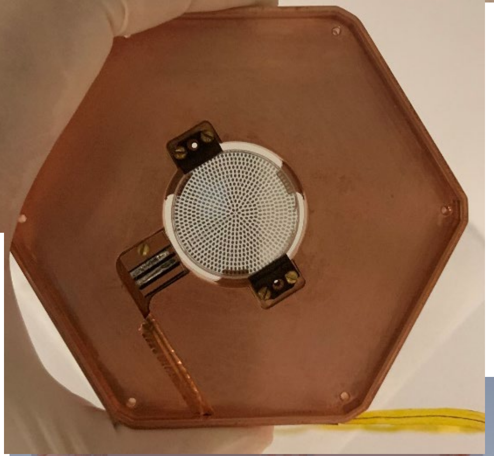


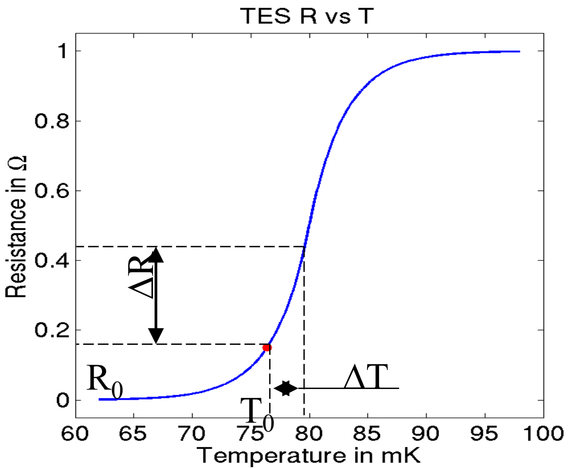
MINER: ~gm-kg mass with 50 eVnr sensitivity

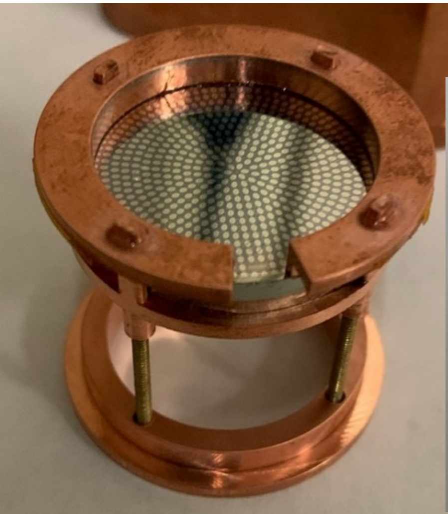
gm-kg scale MINER Detectors

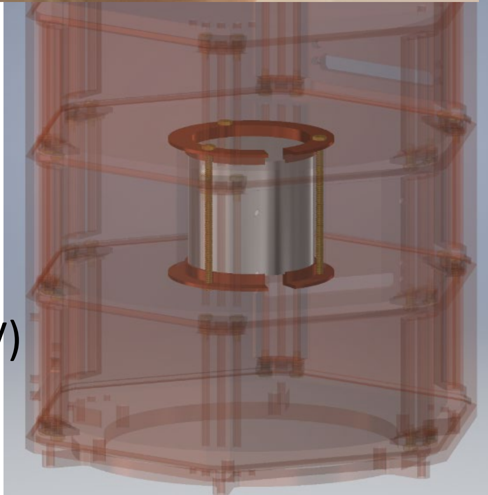












Ge, Si, Al2O3

0V, LV (few V), HV (up to 400V)

Smallest – 10 gm Si

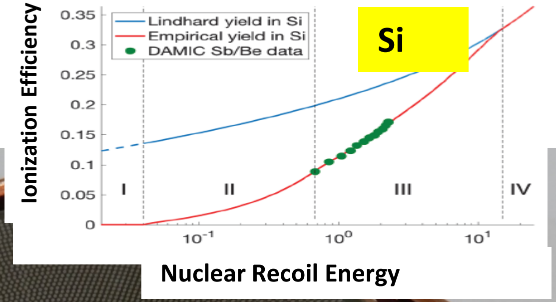
Largest – 1.5 kg Ge (SNOLAB)

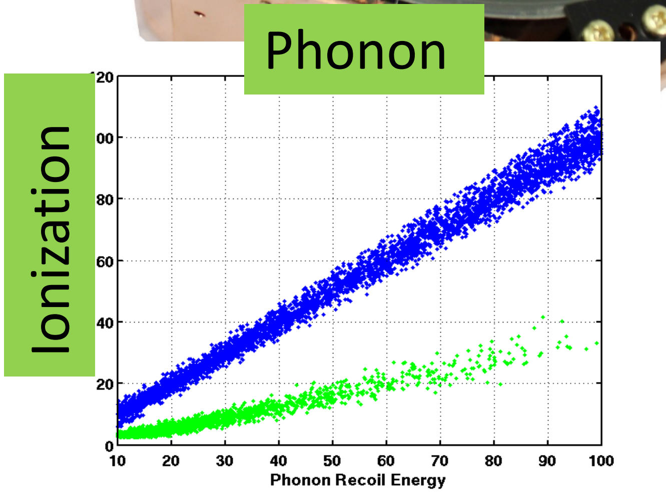
Detector Technology Developed for SuperCDMS

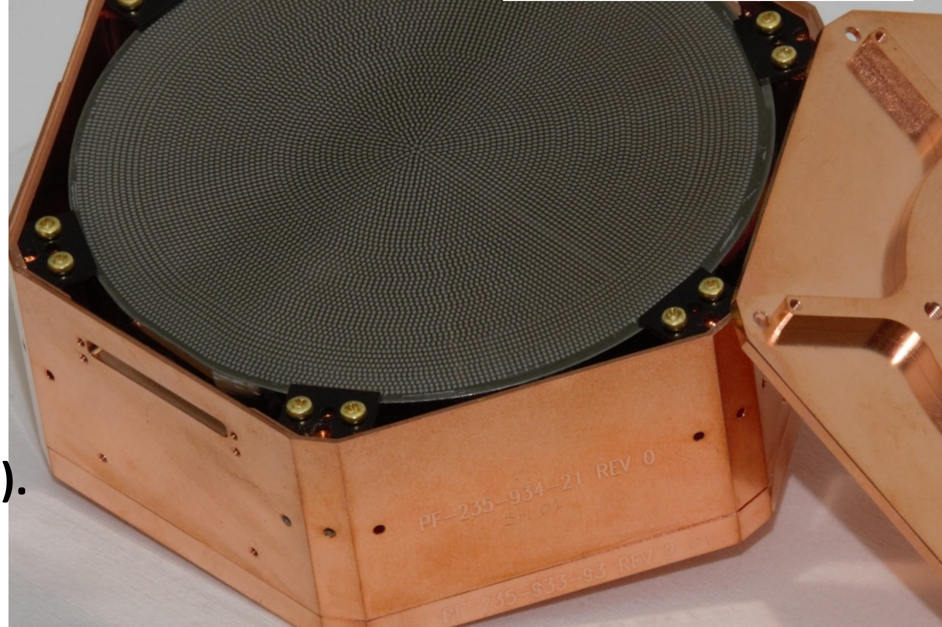
iZIP Detector with ionization and phonon sensors for ER/NR discrimination (>keV)

First SNOLAB Ge iZIP (fabricated at TAMU)

https://arxiv.org/pdf/1610.00006.pdf



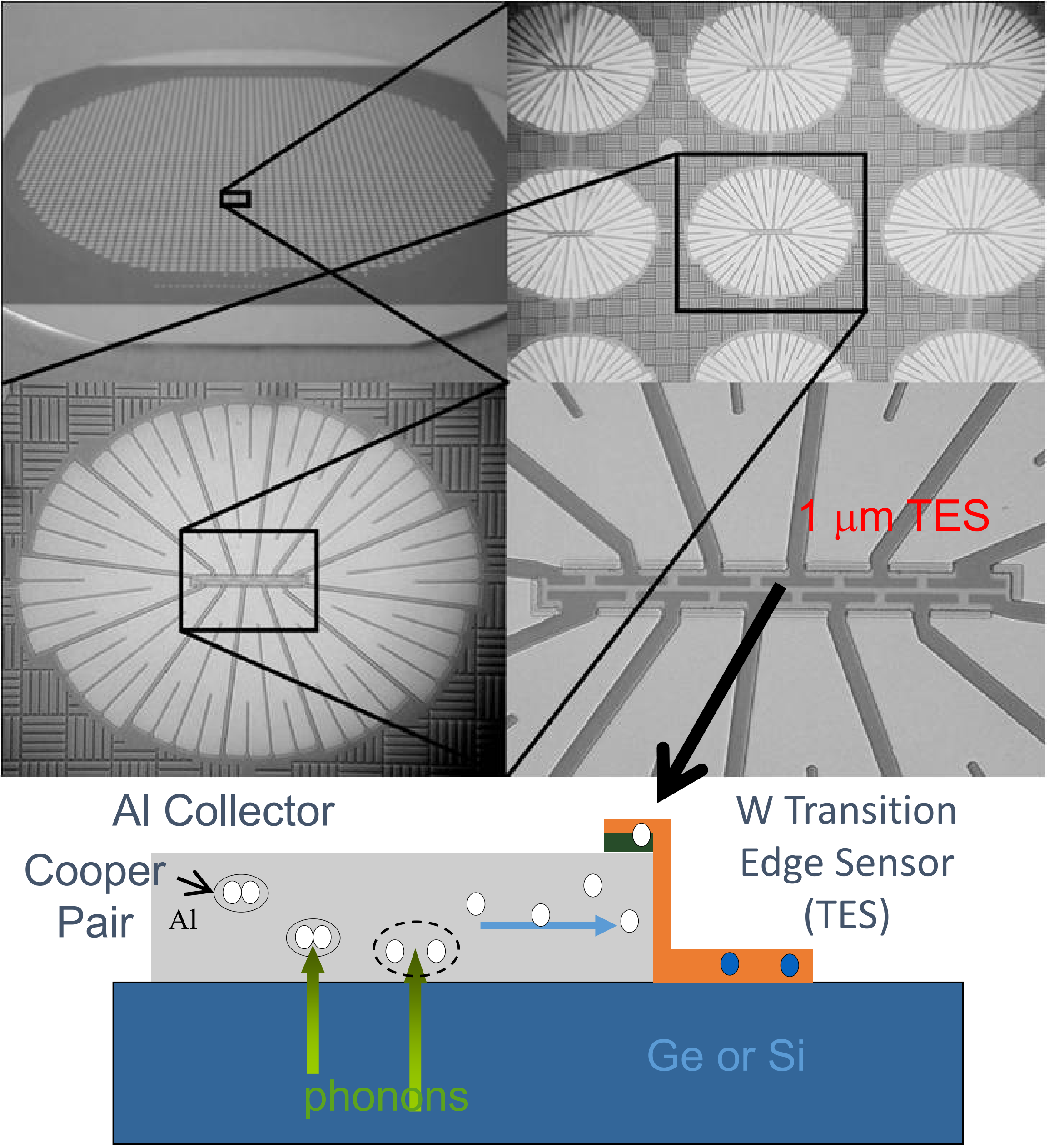


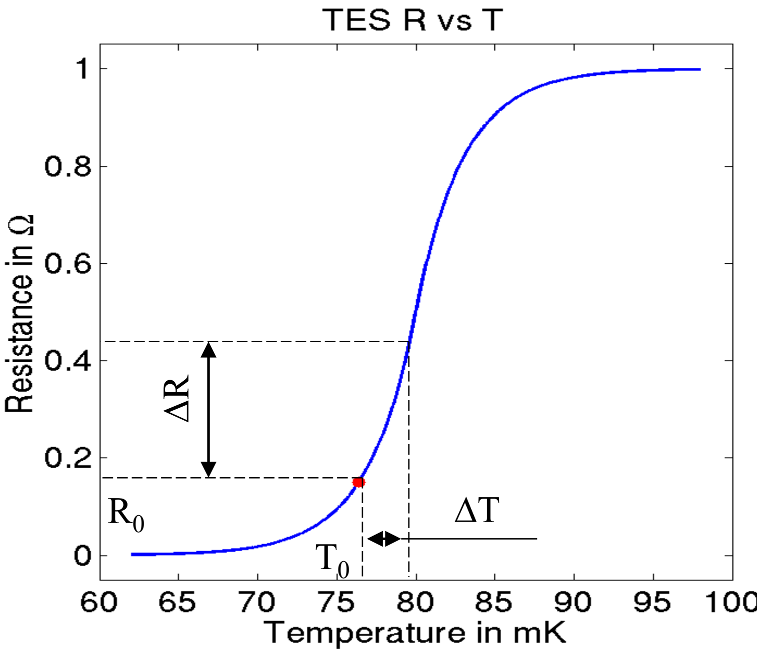


High Voltage Detector with NTL gain. Give up discrimination in favor of low threshold (~100eV).

First SNOLAB Si HV (fabricated at TAMU)

Phonon Sensors

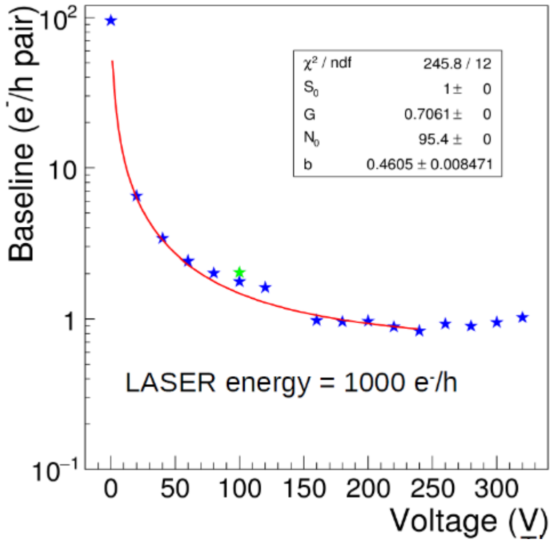


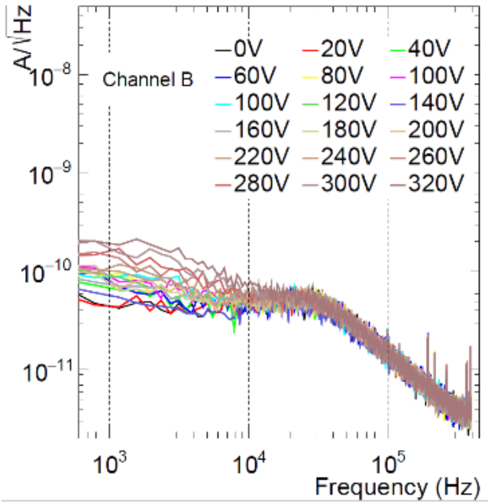


Phonons are collected by superconducting Al fins (Δ=~meV), creating quasi particles that are then trapped by the W Transition Edge Sensors (TES), held in equilibrium between Normal and Super Conducting temp. SQUIDs measure small change in current through sharp ΔR/ΔT

Contact-Free High Voltage Detectors

100-gm single-e sensitive Contact Free Si HV Detector. Signal amplification observed without increase in leakage up to 300 V. Laser calibration done.

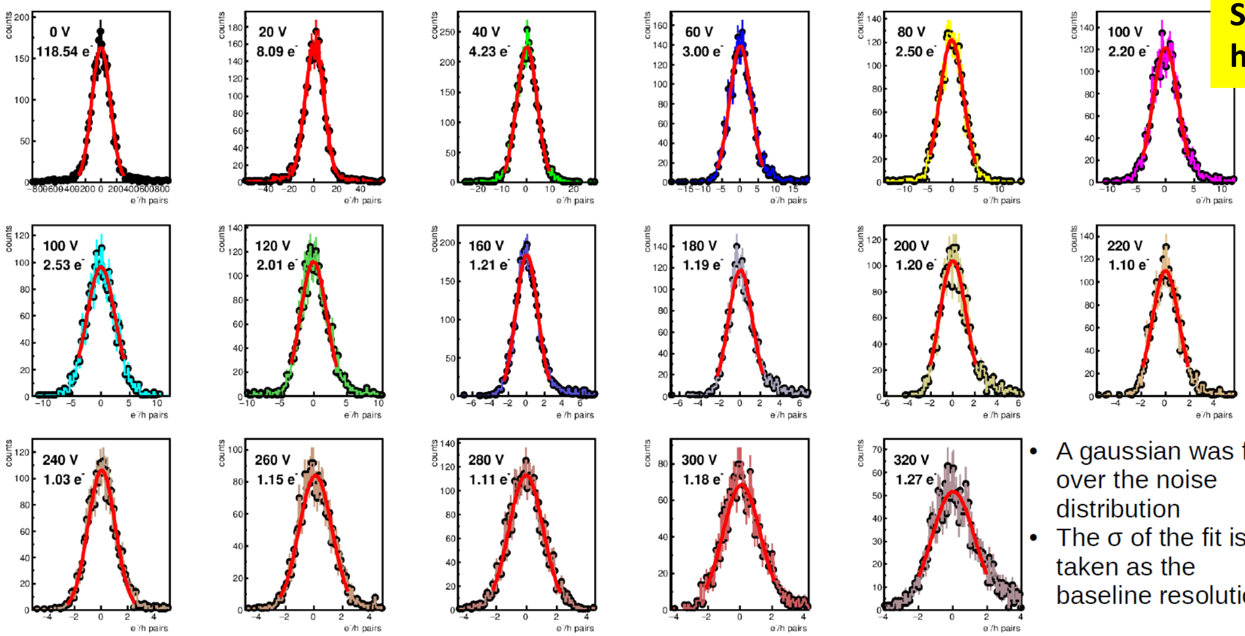




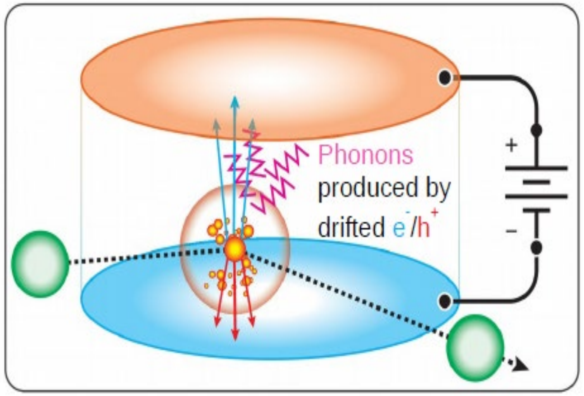
Initial demo with 250 gm Ge with σ=7 eV
https://doi.org/10.1016/j.nima.2017.02.032

Single-e/h pair 100 gm Si :
https://inspirehep.net/literature/1828158

Baseline Resolution for all voltages in e⁻/h pair units

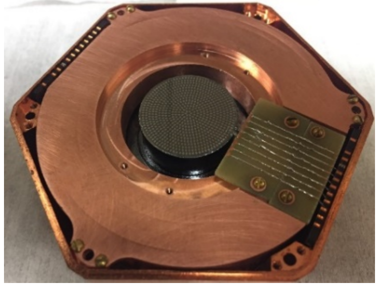


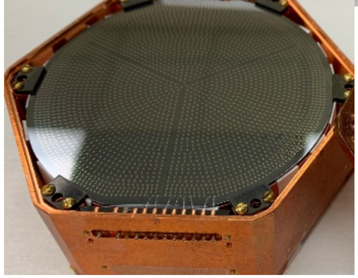
- A gaussian was fit over the noise distribution
- The σ of the fit is taken as the baseline resolution

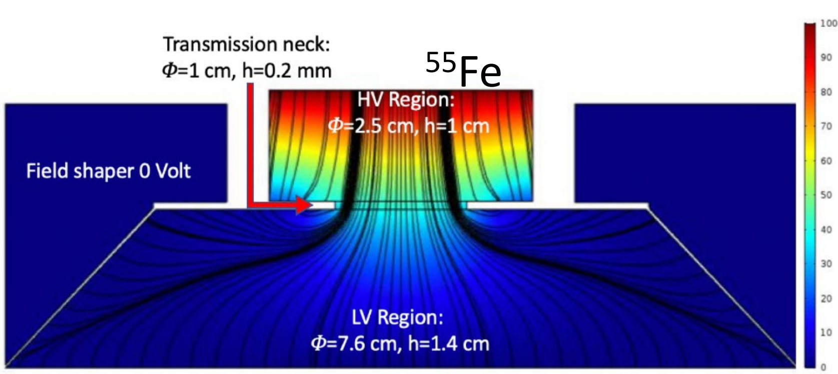


Hybrid HV Detector

Main idea: Monolithic detector with a LV and a HV side – LV to measure primary phonons like iZIP and HV to measure NTL phonons. Do it without significant NTL pollution from HV to LV. **~100gm**







^{241}Am

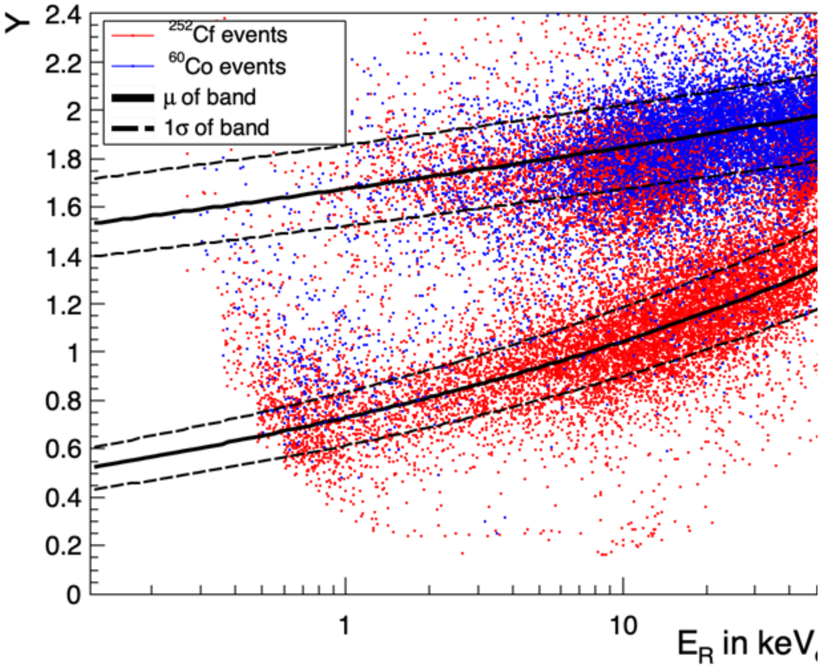
Charge transport from LV region to HV almost 100%

$$P_{HV} = \alpha[(1-\eta_{HL})E_R LV_{HV}/4 + \eta_{LH}E_R(1+LV_{LV}/4)]$$

$$P_{LV} = \beta[\eta_{HL}E_R LV_{HV}/4 + (1-\eta_{LH})E_R(1+LV_{LV}/4)]$$

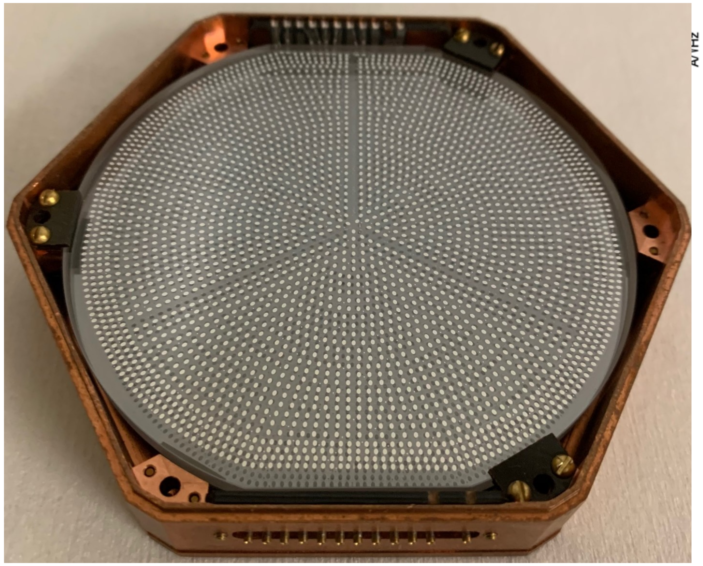
$$\text{Discrimination}: D = \frac{P_{HV}}{P_{LV}}$$

Discrimination improves at low energies. Funded by DOE to push the DM and CEνNS discovery potential – background is key to discovery

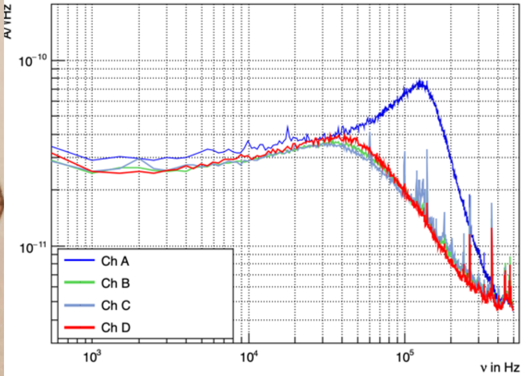


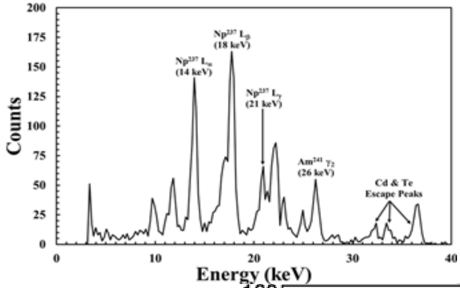
Phonon-mediated High-voltage Detector with Background Rejection for Low-mass Dark Matter and Reactor Coherent Neutrino Scattering Experiments: https://inspirehep.net/literature/1802528

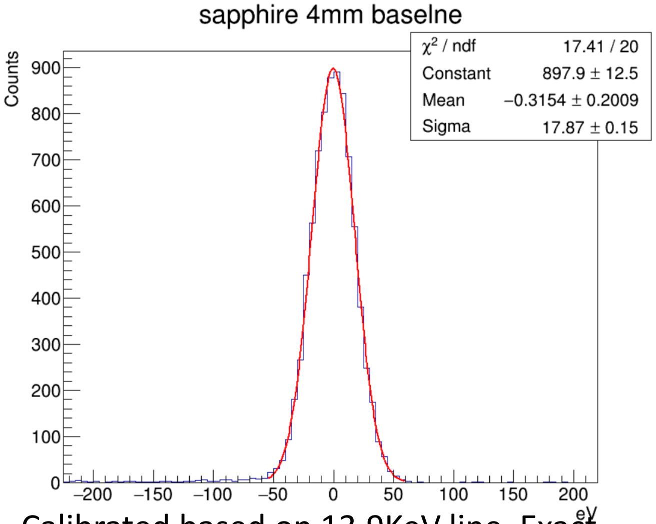
~100gm sapphire detector with ~15 eV σ baseline resolution



~100 gm 3”x 4mm sapphire detector

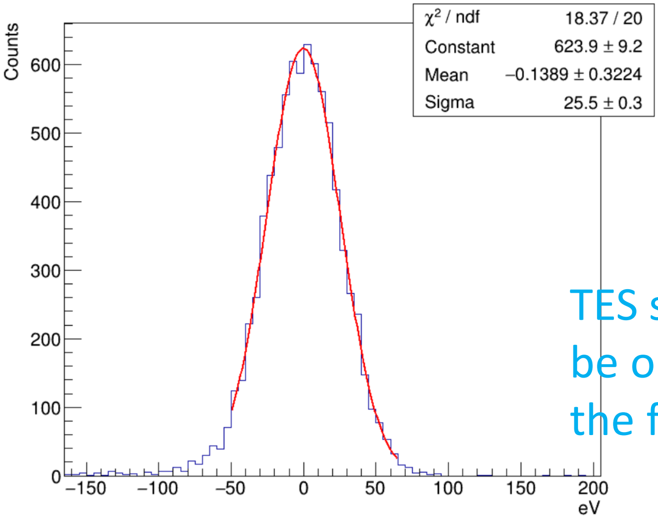




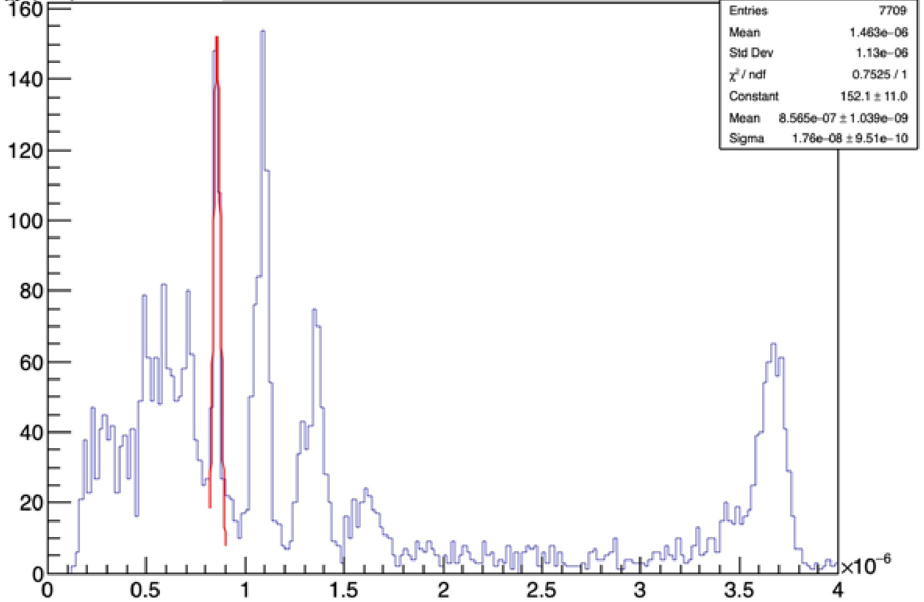


Calibrated based on 13.9KeV line. Exact value is within 15-18 eV, based on peak

(ampOFD)

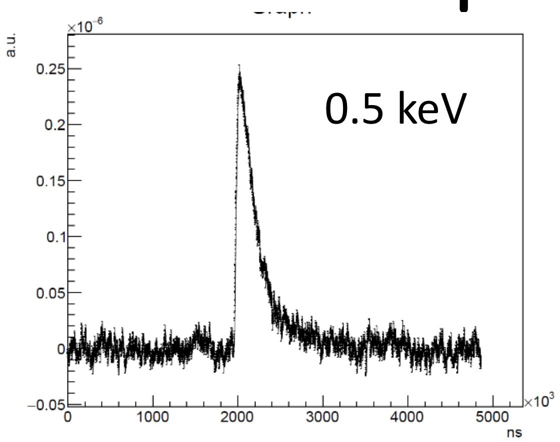


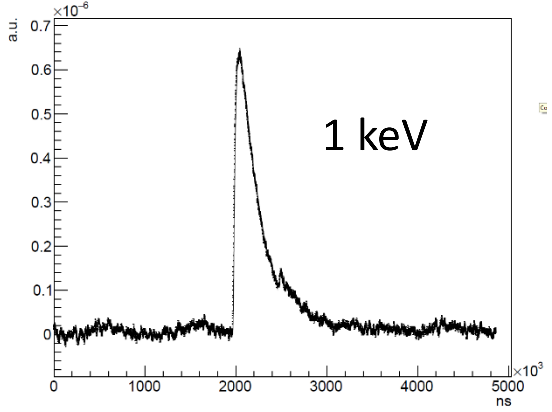
TES sensors will be optimized for the faster timing

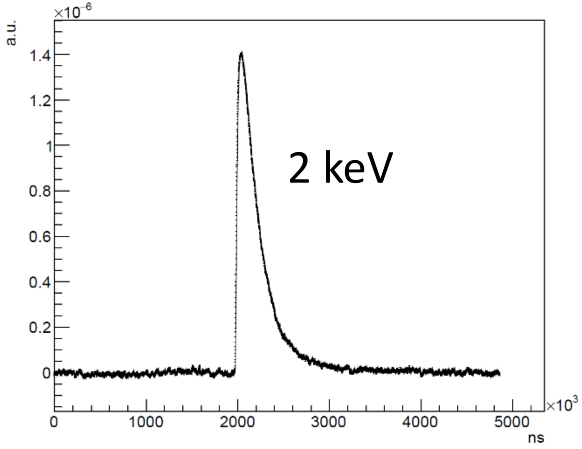


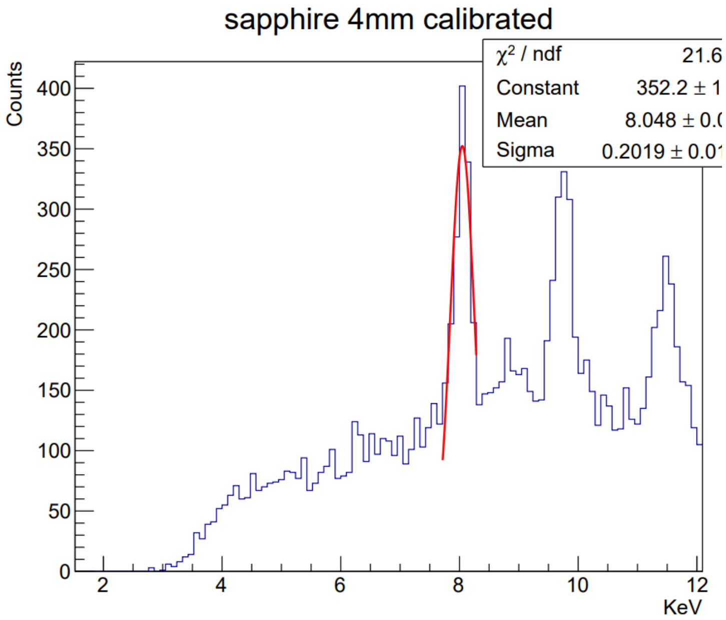
~5 times better (A+B+C+D) resolution than Si detector with same mask (~120eV in Si HV at 0V)

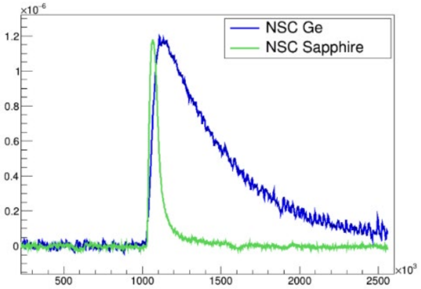
Pulse examples and Copper fluorescence

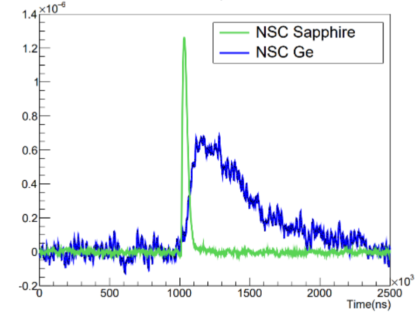


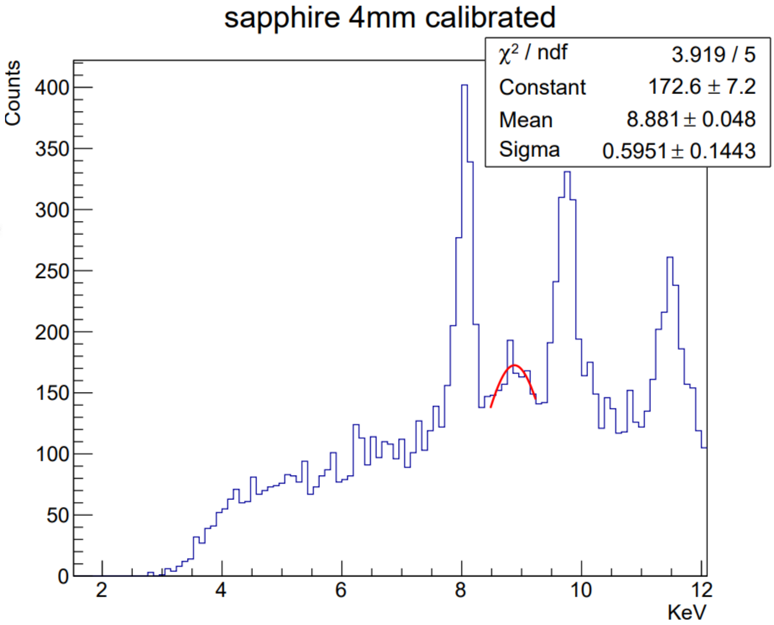






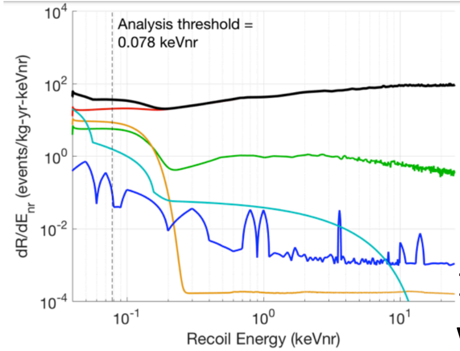


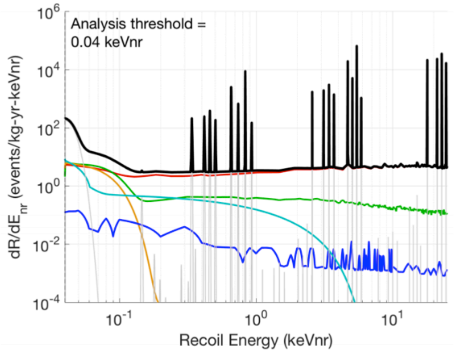




- Much faster timing from sapphire for position reconstruction and possible ER/NR discrimination
- 8.05 and 8.91 keV copper fluorescence lines for new way of calibrating in-situ

Low-Threshold Ge Detector inside Fully Hermetic Ge Shielding





3He + 32Si (β-decay in bulk)

Ge Activation

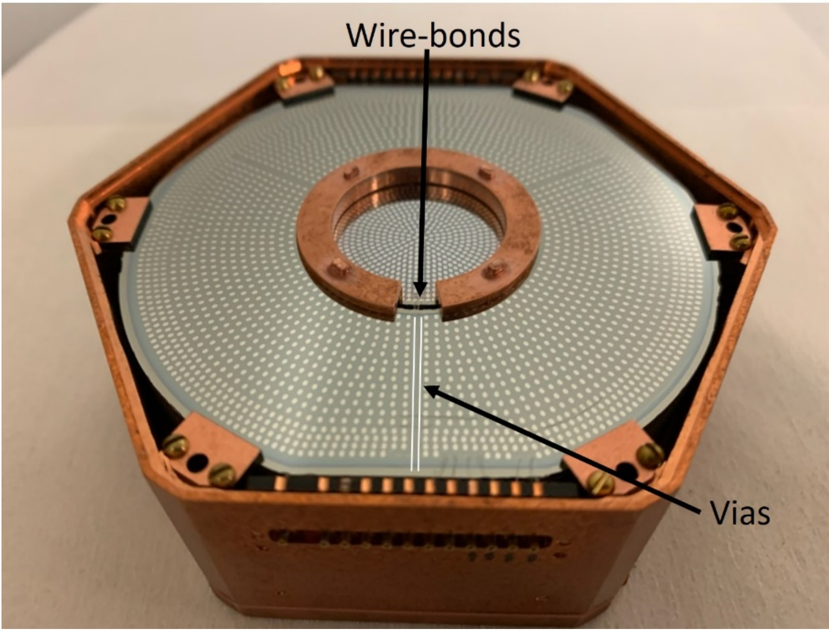
Surface Betas

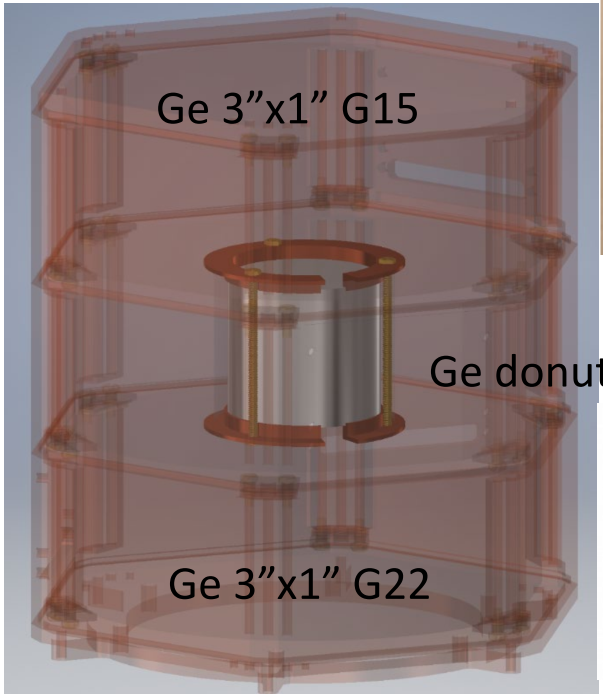
Surface 206Pb

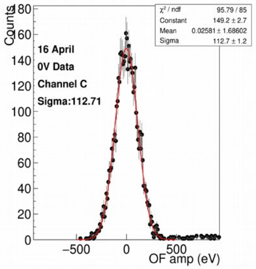
Neutrons

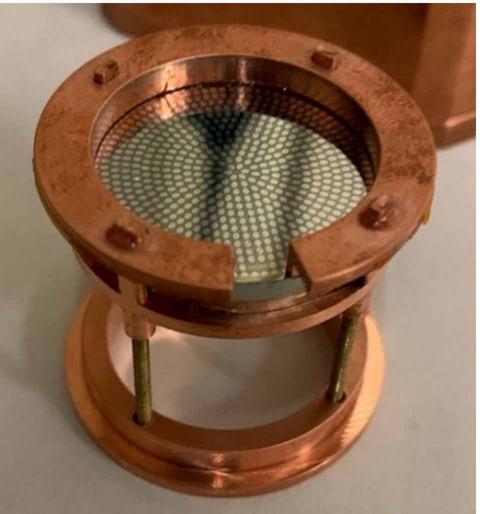
CNS

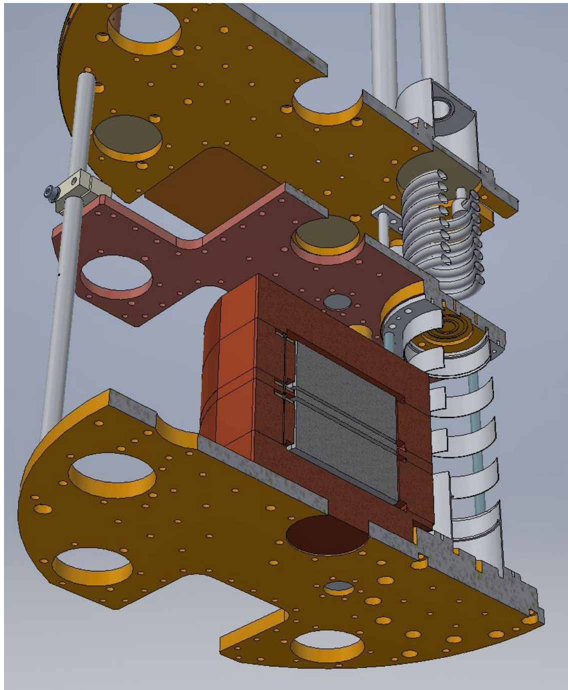
12 Ge coin was run. Next runs with~30-75 gm Ge coin run planned.





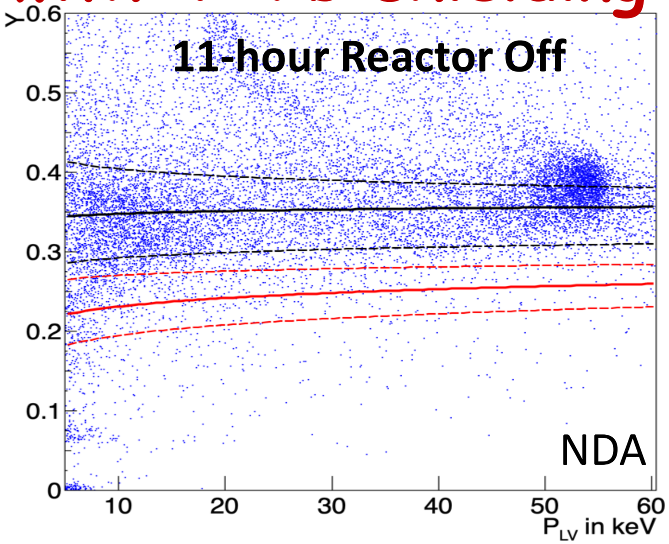






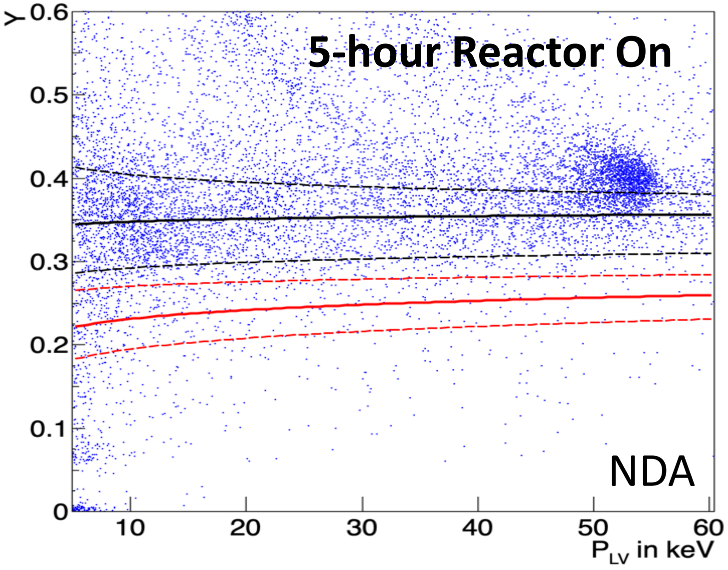
Inner copper shielding to for additional hermetic shielding being designed. Capable of hosting gm-kg scale detector

MIνER Background with 4" Pb shielding



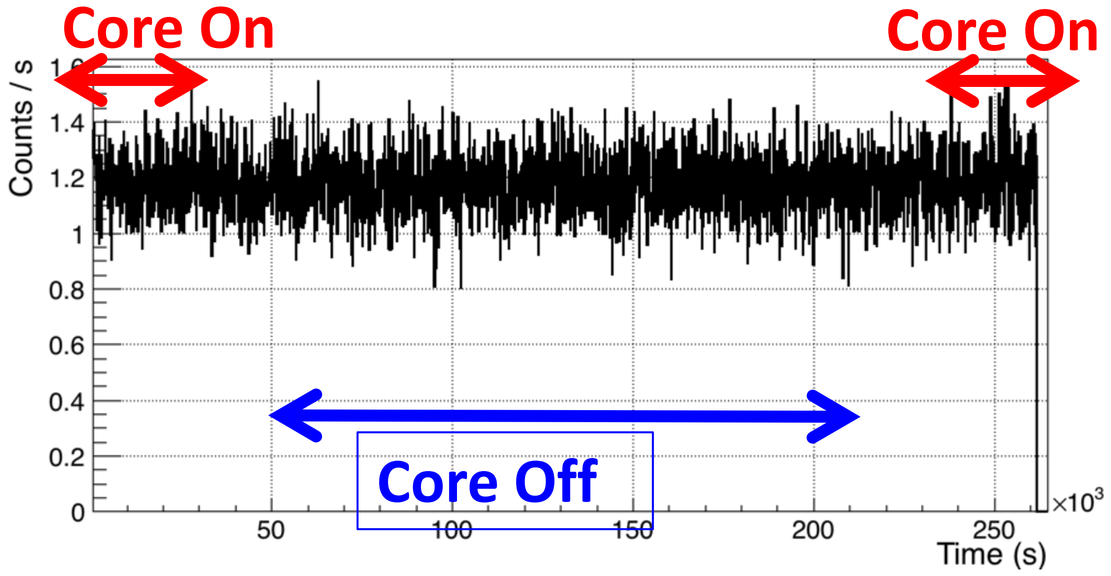
Core off: Raw count (20-45 keV ER+NR) ~2000 DRU.

NR band with single-scatter cut <100 DRU above keV.

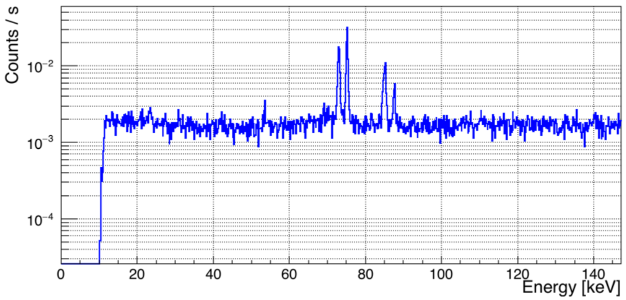


Core On: Raw count (ER+NR) ~3000 DRU.

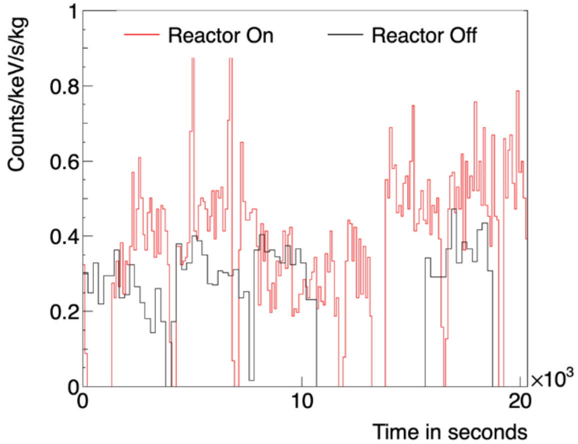
NR band with single scatter cut <100 DRU above keV

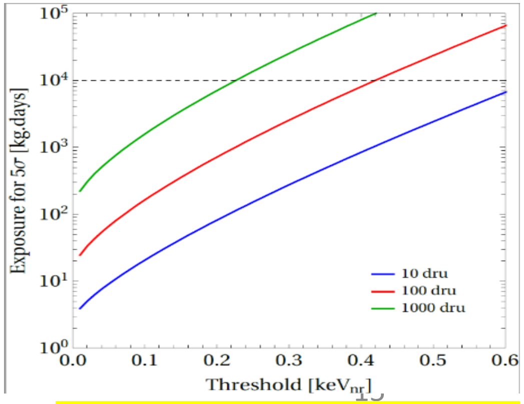


- NaI (~1kg) Rate v. Time (integrated: 30 keV – 2.1 MeV)
- Raw count (ER+NR) ~40 DRU inside **both γ and N shielding**



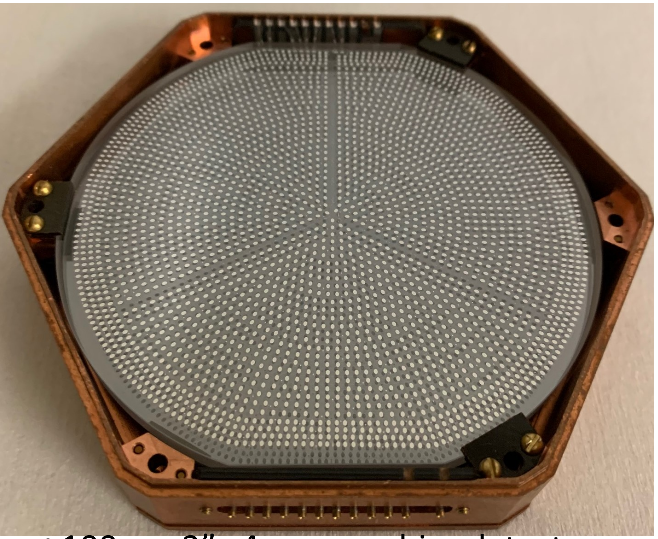
Low Energy Scan using BeGe (77K) detector shows flat Compton background. Raw count (ER+NR) ~85 DRU inside **both γ and N shielding**





MIνER has breakthroughs in both

Our Non-blind Region Excess



~100 gm 3”x 4mm sapphire detector

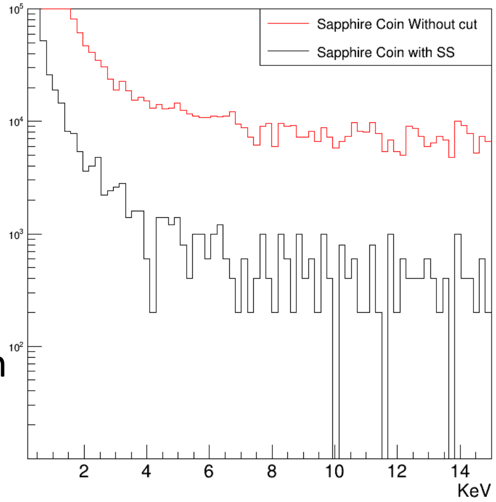
All configurations sandwiched between two 3”x1” detectors, except the Ge coin has additional active Ge donut veto

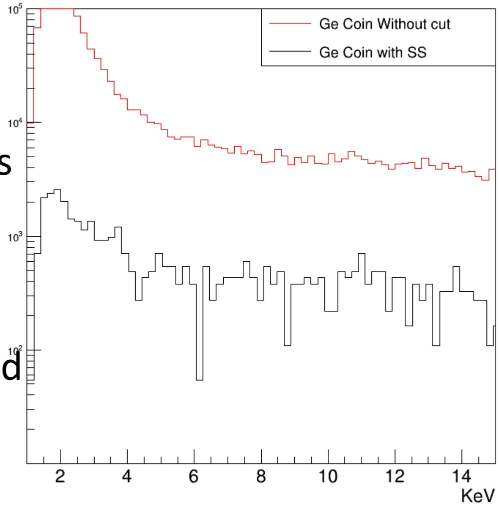
Passive and active inner shielding/veto payoff. Single-scatter events in bulk!

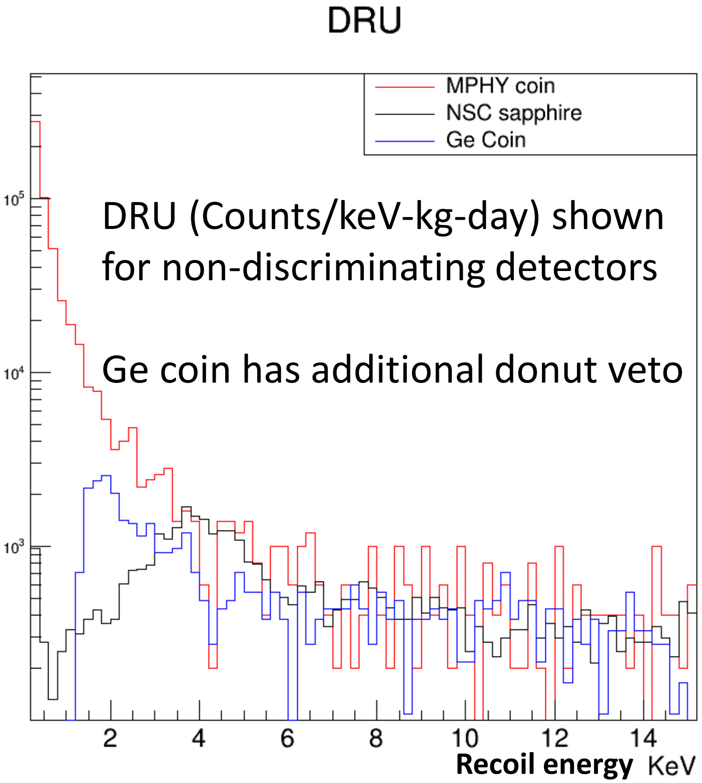
ER/NR discrimination, even if ~500eV, is highly desirable for discovery potential in CEνNS and DM

On MINER, we attempt to use Ge, Si and sapphire detectors of same size in the same configuration to understand BG.

~10 gm 1”x4mm sapphire coin

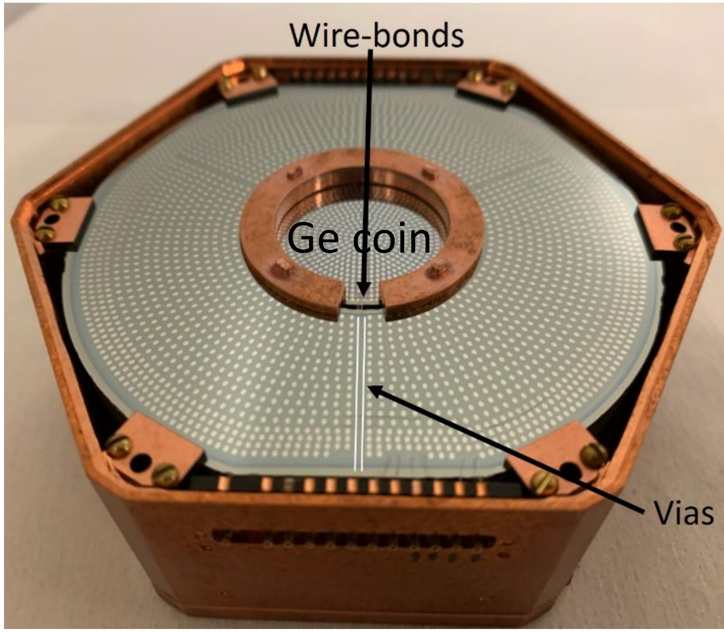




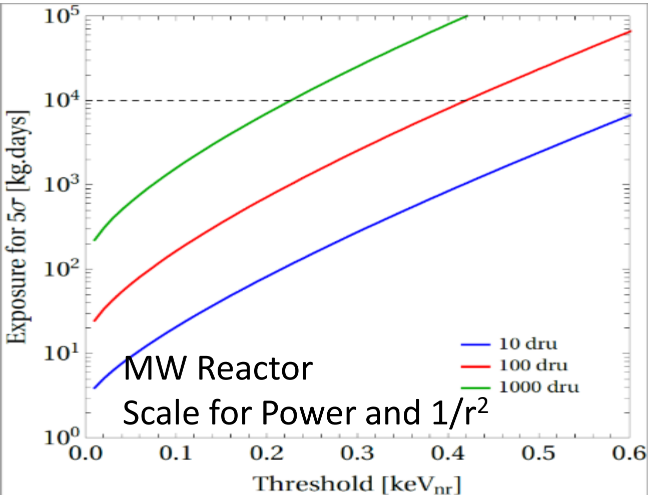


DRU (Counts/keV-kg-day) shown for non-discriminating detectors

Ge coin has additional donut veto



CEνNS for Monitoring – Game Changing Technologies in Hand!



MW Reactor
Scale for Power and $1/r^2$

Exposure in kg-days

10-kg 100-ev NR Ge Hybrid
(discrimination gives 10-DRU)

1 day for 5-σ detection

10-kg 100-ev NR Si Hybrid
(discrimination gives 10-DRU

10 days for 5-σ detection

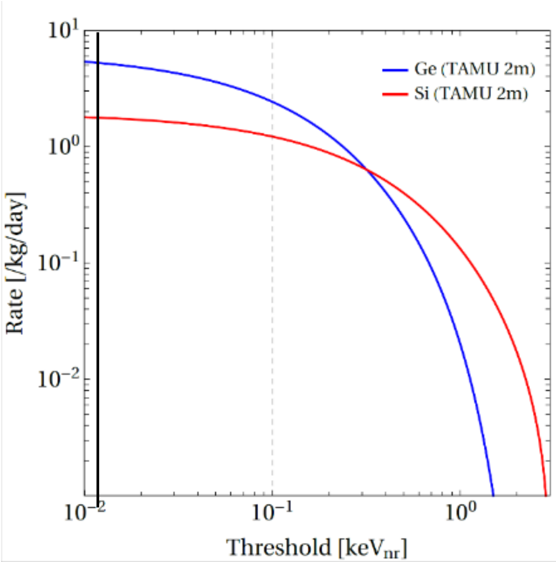
10-kg 100-ev NR Si HV
(without discrim. 100-DRU)

100 days for 5-σ detection

Safeguards needs quick (<100 days) Detection!

10-kg Non-Phonon (Lindhard) detector (1000-DRU without discrimination and without background modeling) – Integrate on tails

1000-10000 days for 5-σ detection

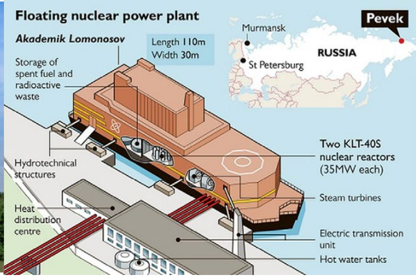


Reactor CEνNS experiments will not only help us understand fundamental new physics, but also fundamentally change how we use the unstoppable neutrinos to detect threat!

Possible Near Field Applications

- Expectations: provide reactor operation/history
  - Reactor power and fuel cycle changes, such as fuel composition U/Pu/Th and fuel burnup
  - Identify covert reactors/Pu diversion
- Compact MIνER setup ideal for deployment
  - Monitor age and cooling time at spent fuel storage
  - Breeding and proliferation activities in the case of advanced and molten salt rectors

Phase-2 at South Texas Project (STP) ~3 GW next year.

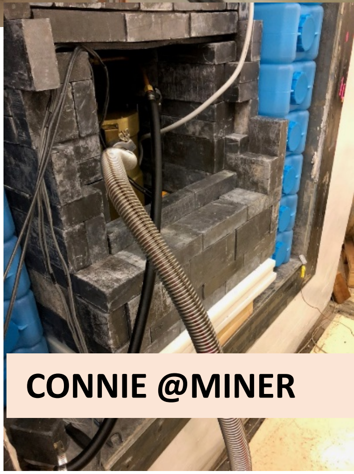


MIνER Compact Installation with Bluefors closed-cycle fridge in RF cage and shielding

Proposed site
40 and 110 m

Beneficial to collaborate at a common site for quicker application of technology

We invite you to bring your technology to STP and collaborate on a common state of art shielding, active veto, analysis, and applications.



CONNIE @MINER

Reactor CENNS Program is very active

- Dark Matter detector technologies with stricter threshold and background requirements have allowed CENNS programs to flourish.
- Background at surface (not underground like Dark Matter experiment) still an issue
- Rapid progress in achieving sub-1000 DRU and sub-100eVnr requirements
- Within the next couple of years CENNS will open up new frontiers in fundamental physics research and applied nuclear safeguards