An Overview of Cryogenic Experiments

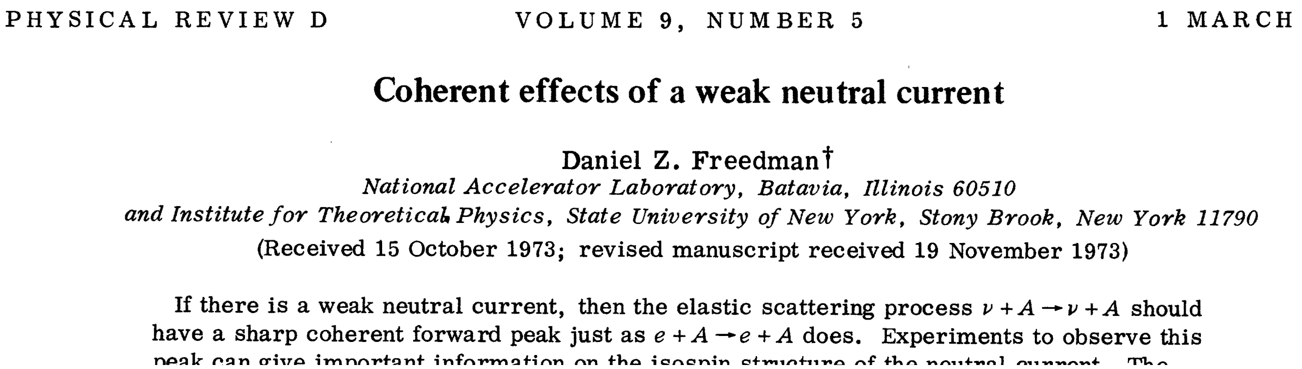
Joseph A. Formaggio

Magnificent CEvNS

October 7th, 2021

Massachusetts
Institute of
Technology

Coherent Neutrino Scattering



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH

Coherent effects of a weak neutral current

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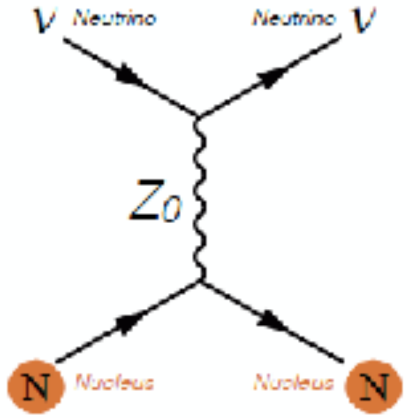
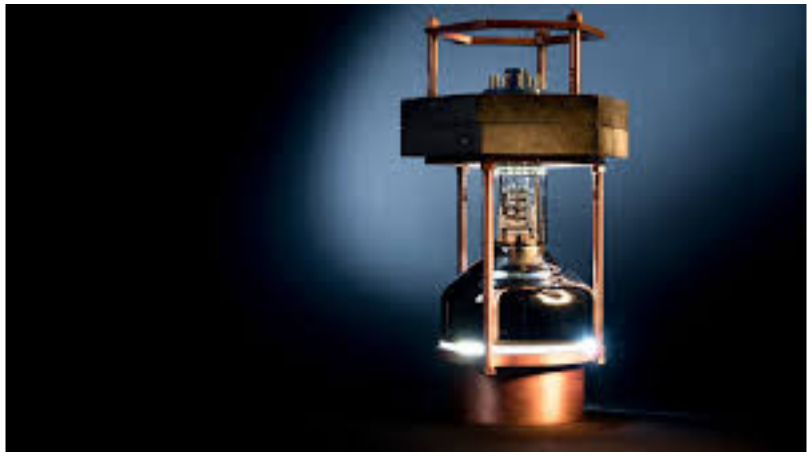
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The





Target detector of the ***COHERENT*** *experiment, first to observe the CEvNS process.*

- Idea originally proposed in 1974 by Daniel Freedman, predicting that for sufficiently small momentum transfers, the neutrino can interact *coherently* with a nucleus.
- After 40 years, the process is now an ***observed*** neutrino reaction, opening a new door for new physics.
- So far seen at MeV energy scale. Rich physics belies at **lower** momentum exchange.

Fundamental Coherent Interactions

Coupling term
(tiny)

Cross-section
(probability of interacting)

Coherence effect

$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$

Neutrino energy

Neutrino scatters coherently off all Nucleons

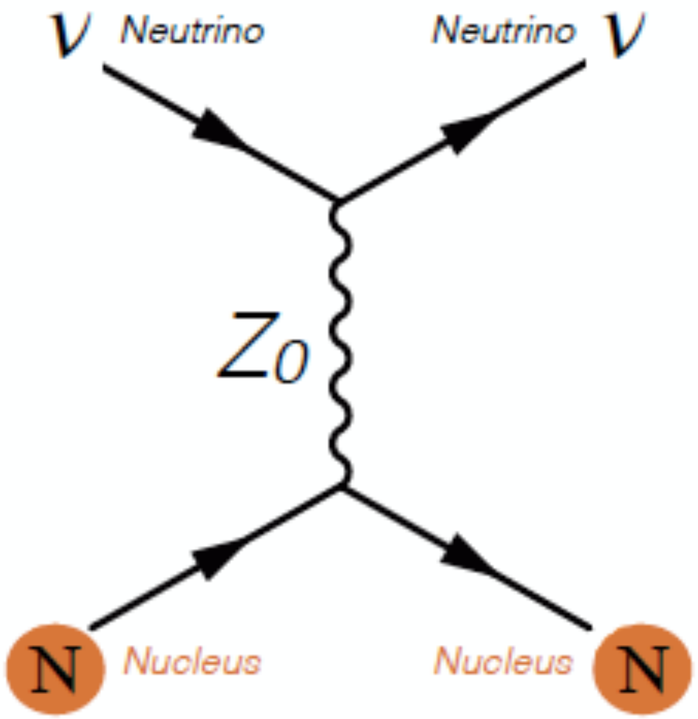
—> Cross section proportional to N^2

Initial and final states must be identical

—> Neutral Current elastic scattering

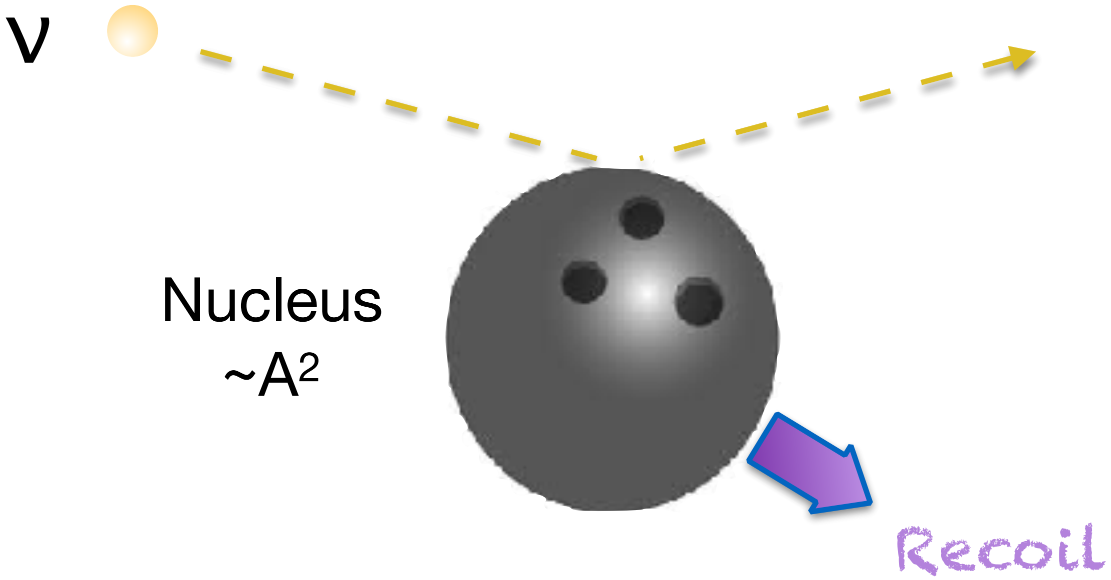
Nucleons must recoil in phase

—> Low momentum transfer (qR<1)

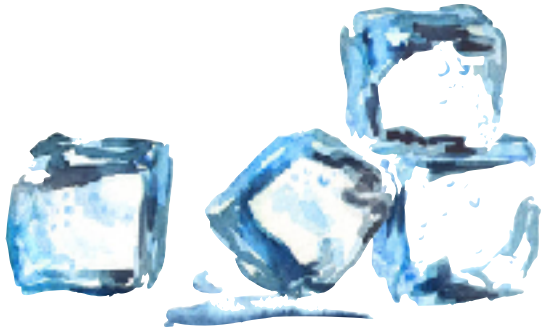


The CEvNS Portal

- CEvNS allows probing new physics using **kg-scale** detectors as opposed to **ton-scale** detectors.
- So far, only MeV scales have been probed. Why not at lower energies?
  - **Cross-sections decrease with energy**
  - **Recoils harder to detect**

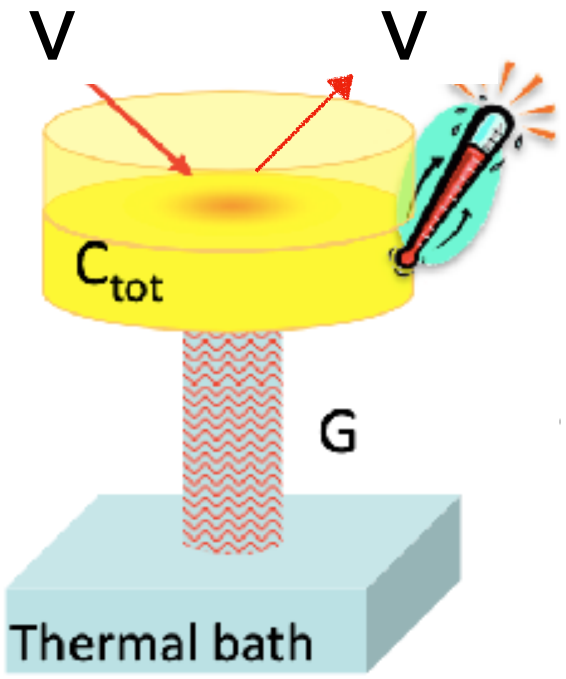


Use Nuclear Reactors as Source

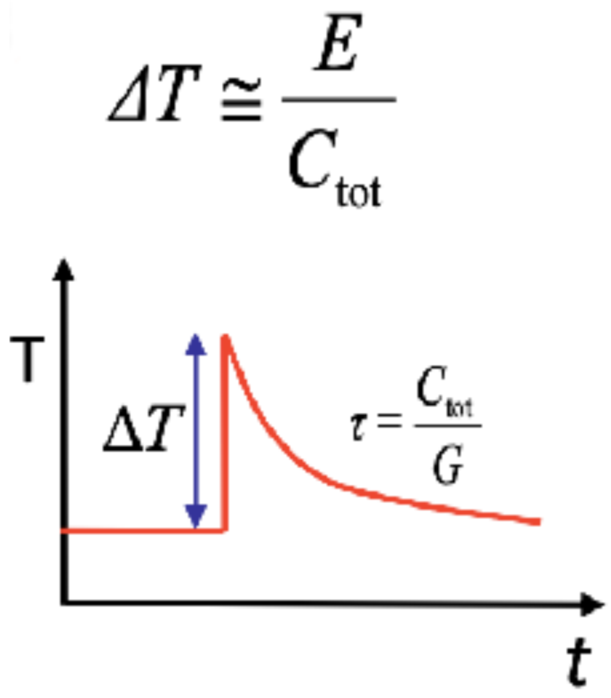


Use Cryogenic Bolometers

What Kind of Detectors to Use?



Sensitivity of the detectors governed by the total heat capacitance (C_{tot}) of the detector and the thermal coupling (G) to the thermal bath.

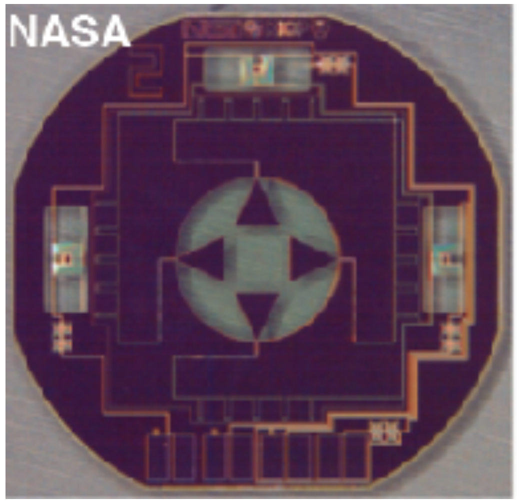


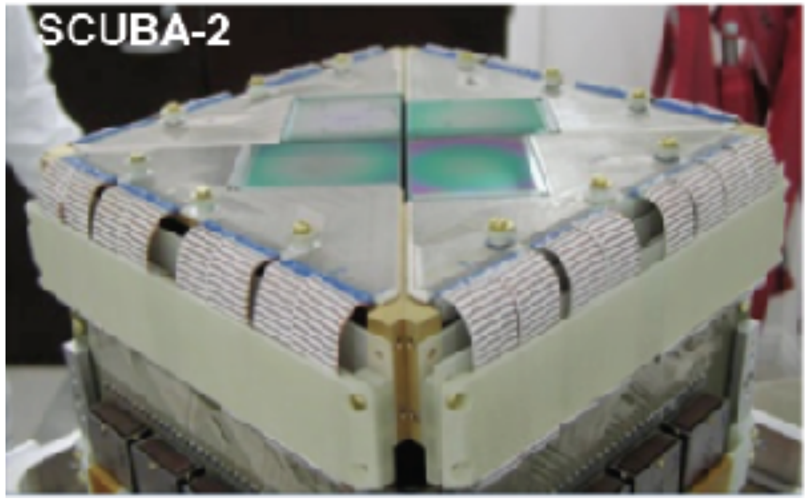
$$\Delta T \cong \frac{E}{C_{tot}}$$

Superconductors and semi-conductors	**Metals**
$C(T) \propto T^3$	$C(T) \propto T$

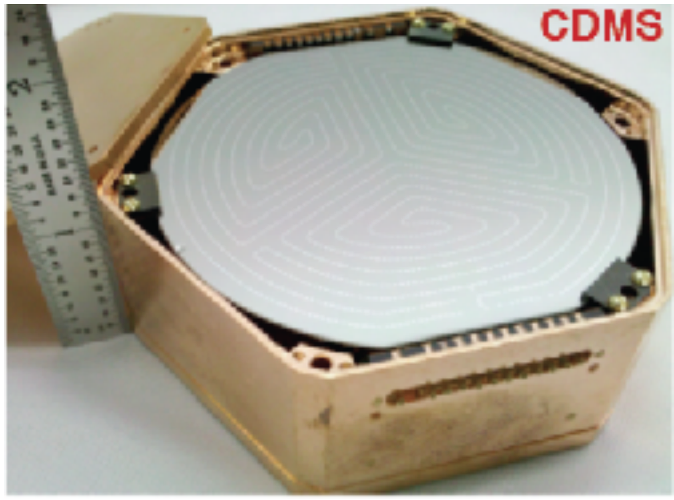
Since the noise scales as the capacitance, these detectors are optimized for **smaller volumes/masses** and **colder** temperatures.

Where Phonon Technology is Used

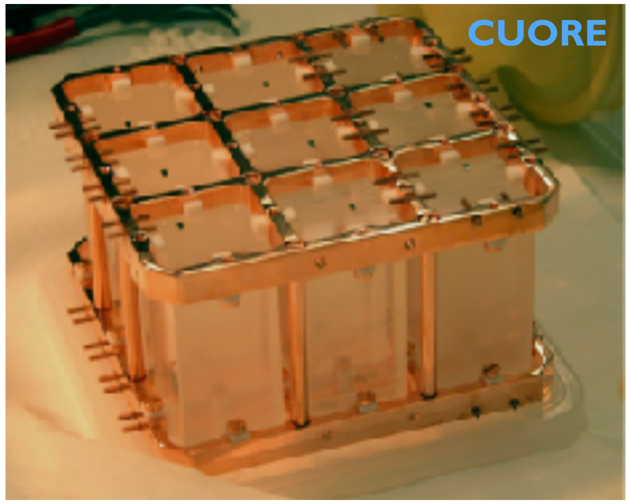




CMB, Infrared detection



Dark matter

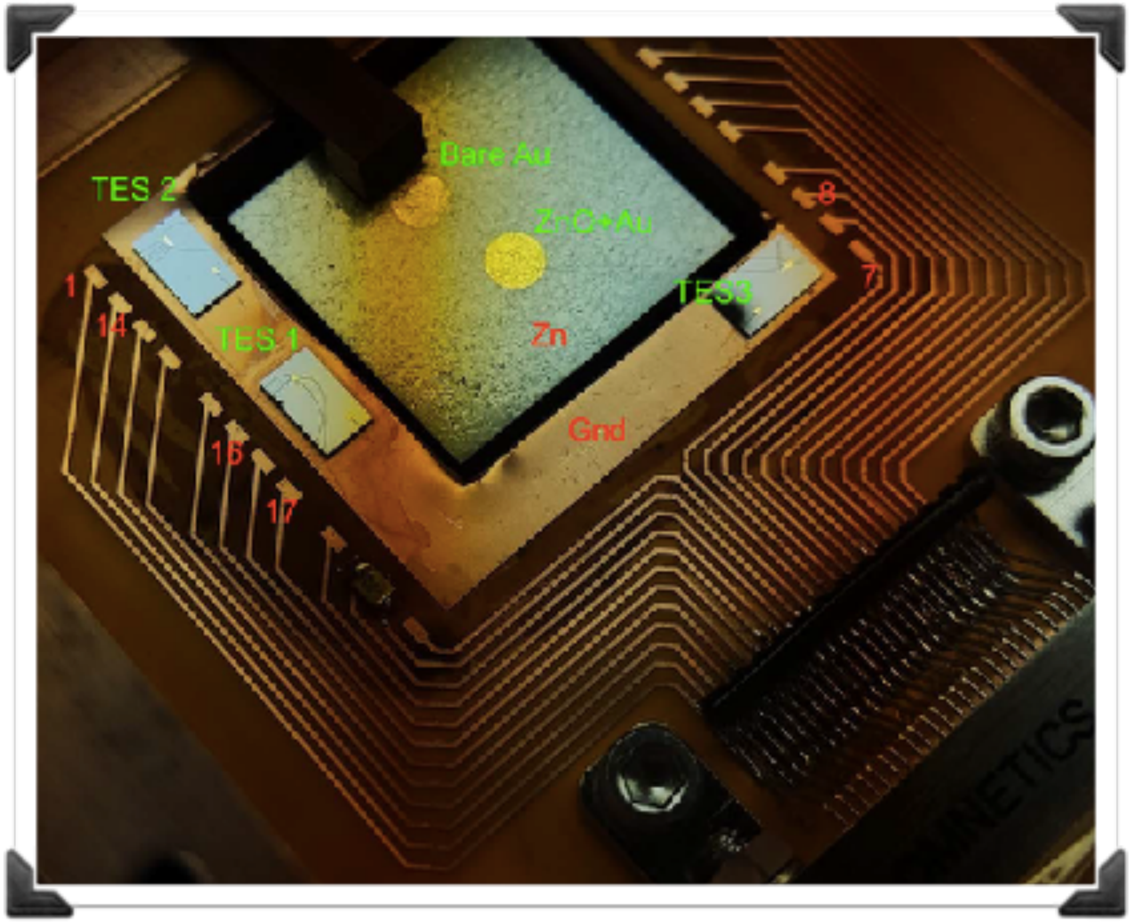


$0\nu\beta\beta$

To go to lower neutrino energies, lower threshold are required. Phonon readout is a promising technology already used in many other experiments.

Ricochet uses *phonons* readout to reach low threshold, with eventual goal of reaching **eV-scale** recoil thresholds.

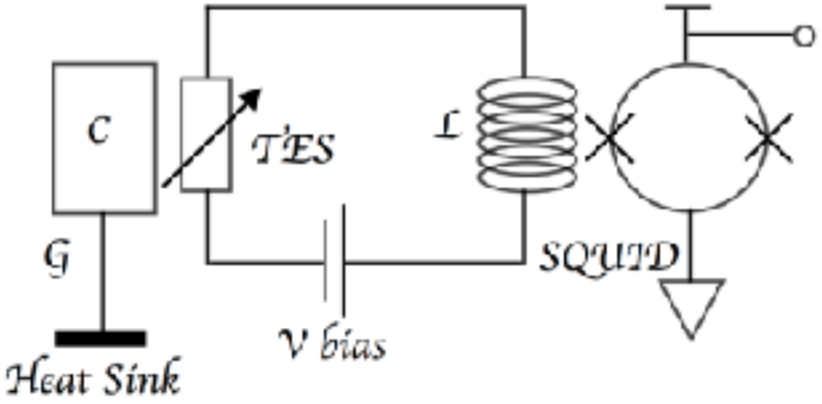
Readout Scheme



The **absorber** allows conversion from energy to heat (phonons)

For semi-conductors and superconductors, only lattice vibrations contribute to thermal capacitance (C ~ T^3)

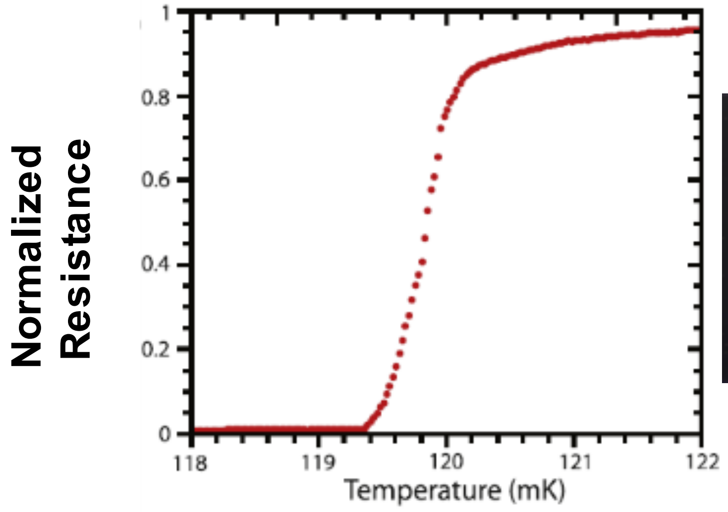
Small detectors & low temperatures
=
lower thresholds

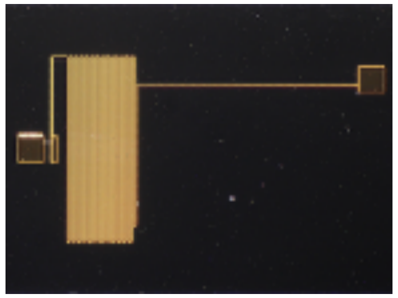


Readout of TES done using **SQUID** amplifiers, quantum-limited magnetometers, ideal for small currents.

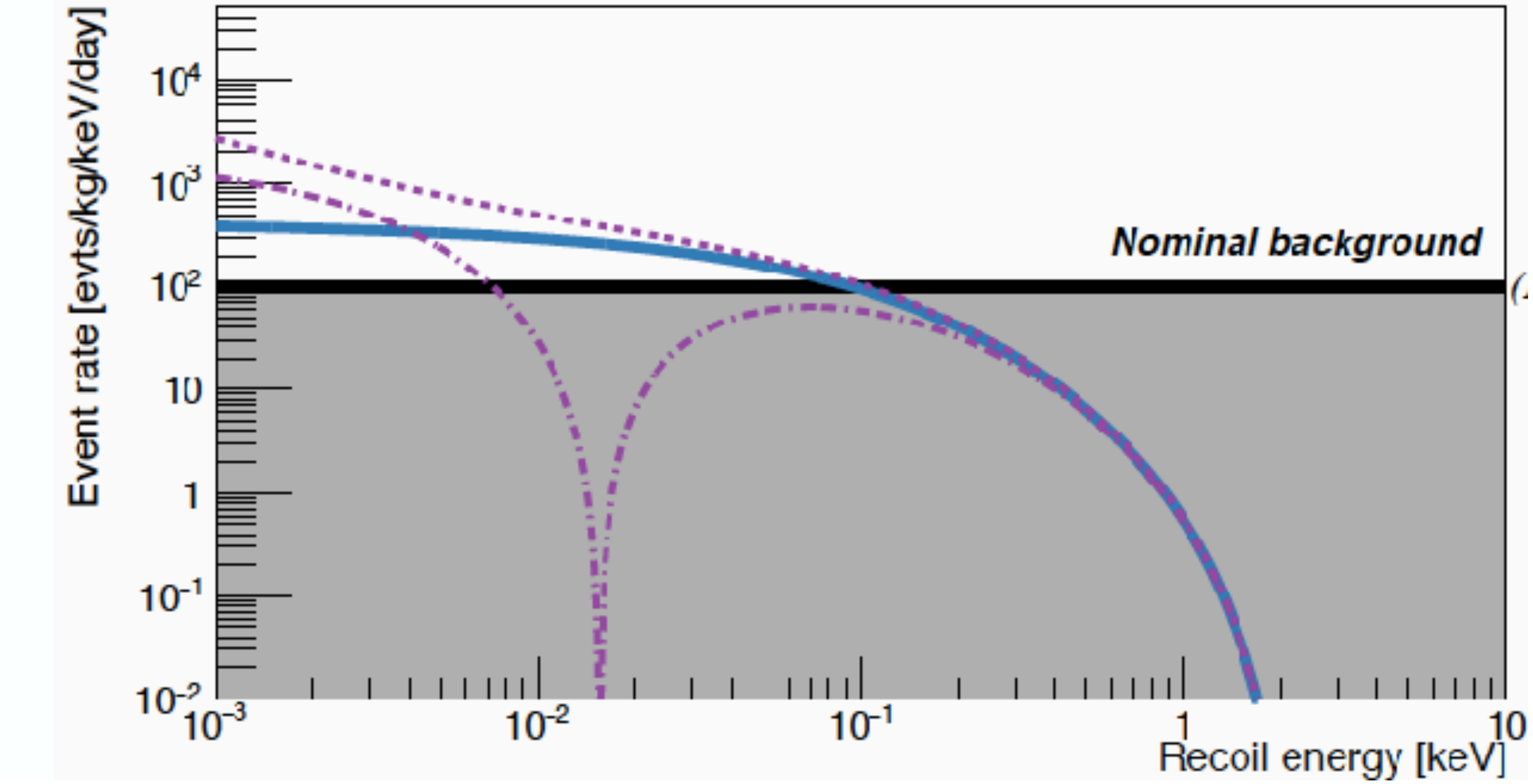
Small changes in temperature can be captured by **Transition Edge Sensors** (TES), which allow great sensitivity to small temperature depositions.

TES Resistance @ Tc



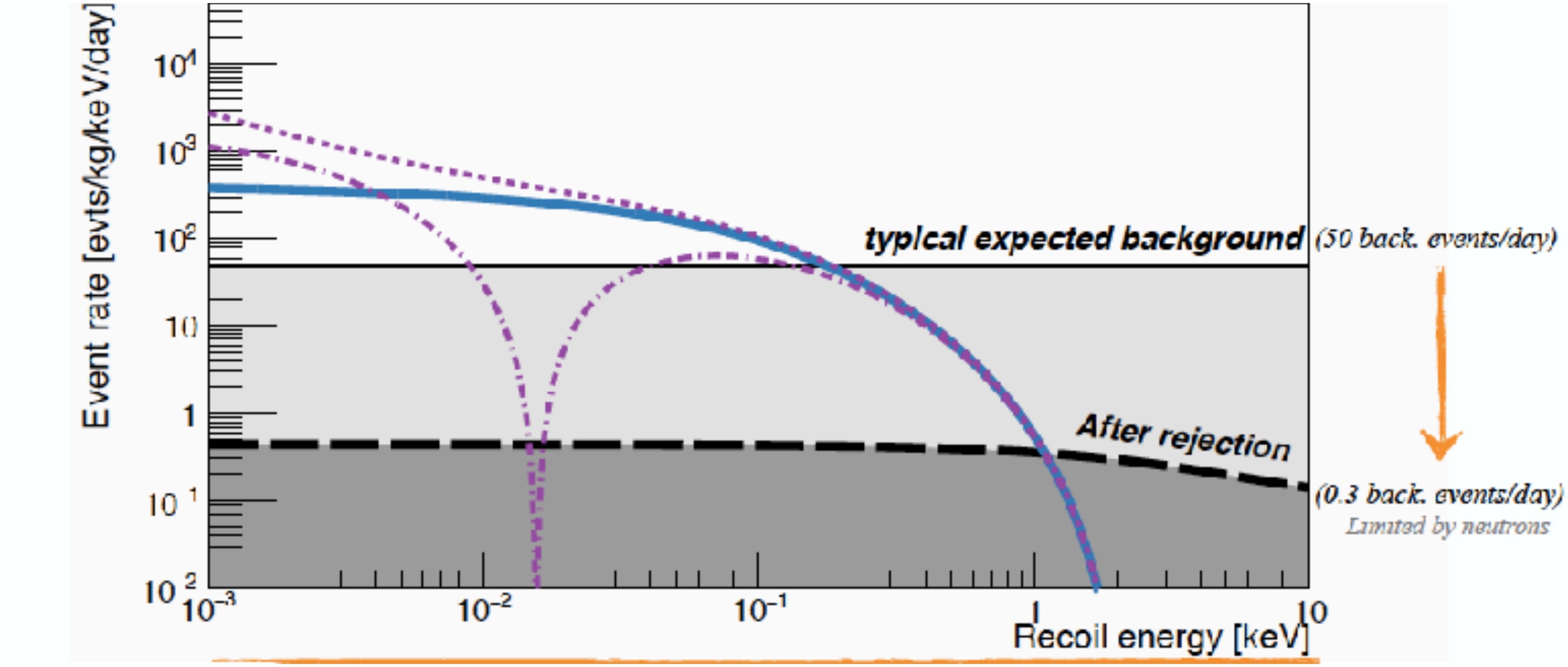


Requirement for Low Backgrounds



- For no background rejection, thresholds below 100 eV necessary.
- ***For factor of x1000 rejection, signal greatly enhanced for discovery potential.***

Requirement for Low Backgrounds



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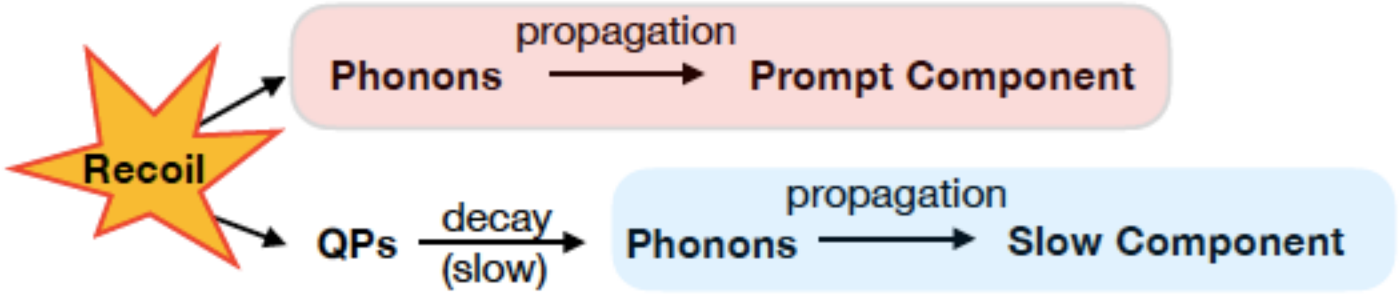
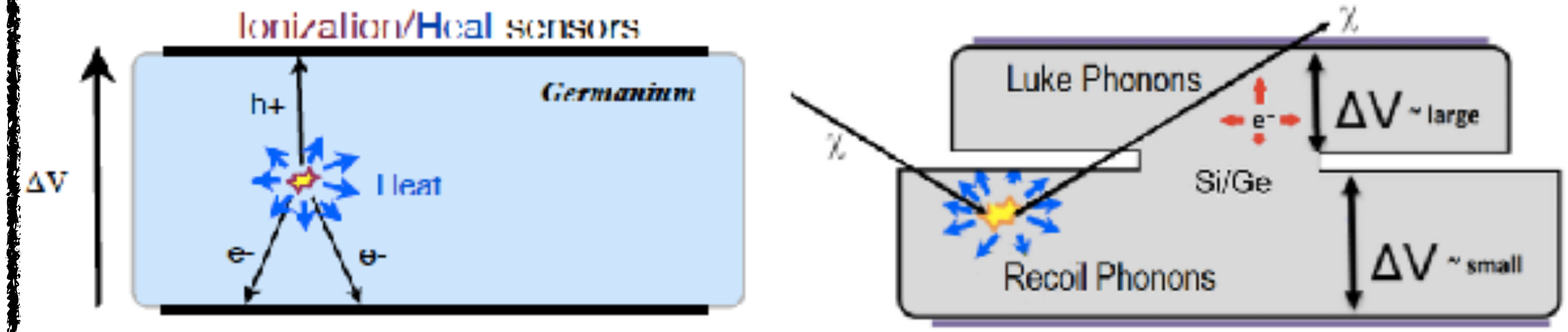
Methods for Background Rejection

Phonon/Quasi-Particle Timing



Phonons $\xrightarrow{\text{propagation}}$ Prompt Component

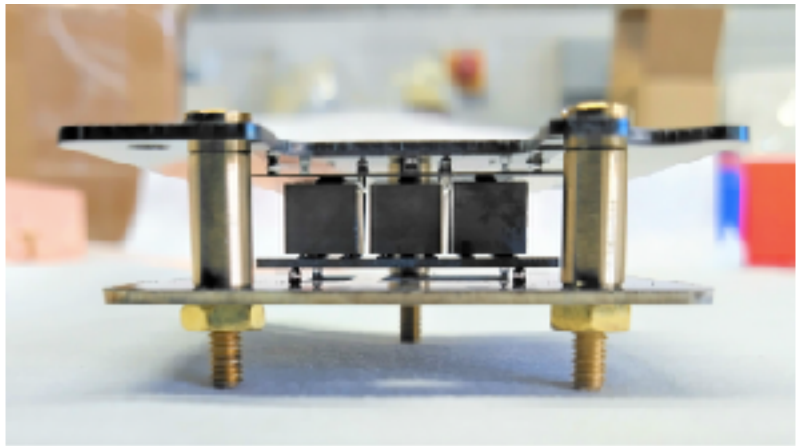
QPs $\xrightarrow[\text{(slow)}]{\text{decay}}$ Phonons $\xrightarrow{\text{propagation}}$ Slow Component



$$\underbrace{E_t}_{\text{Total phonon energy}} = \underbrace{E_r}_{\text{Recoil energy}} + \underbrace{\frac{qV_b}{\varepsilon_\gamma}E_Q}_{\text{NTL gain}}$$

Neganov–Luke Effect

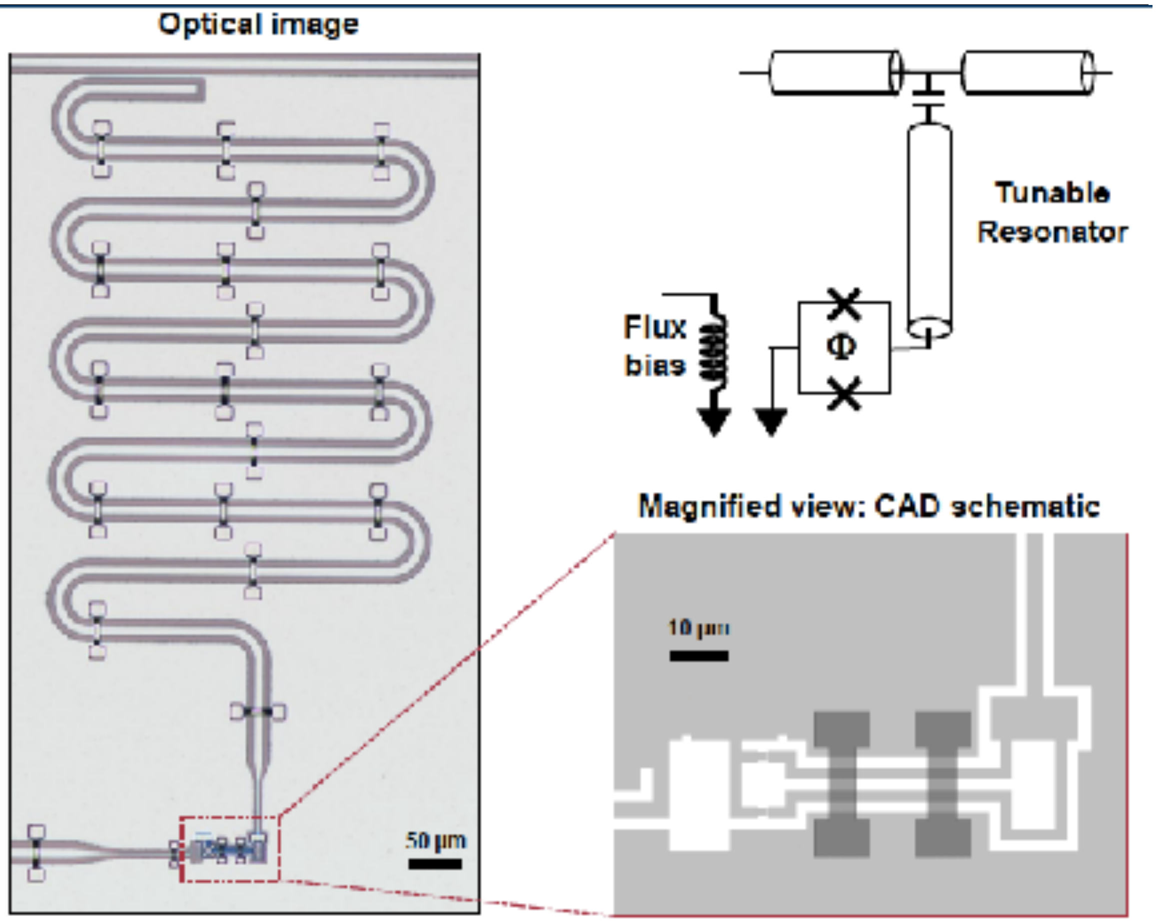
Cryogenic Veto



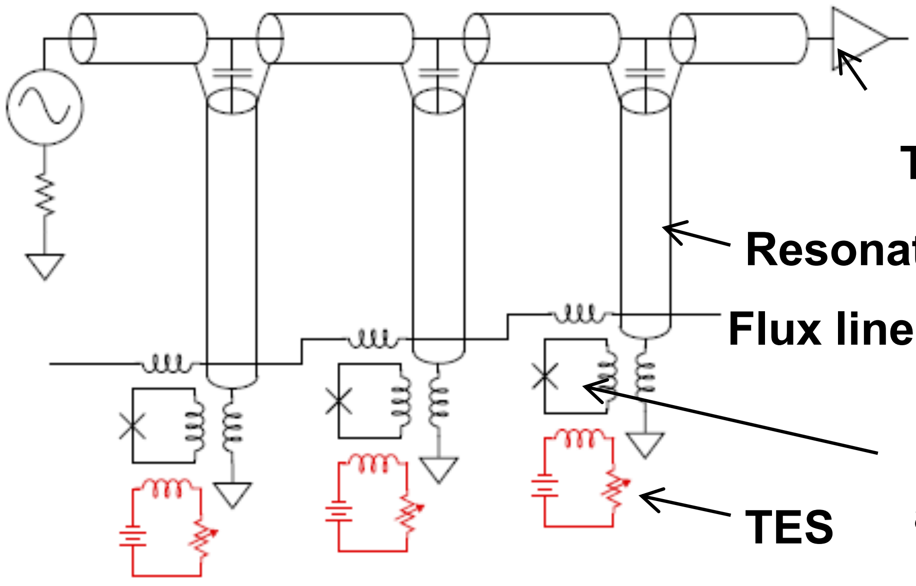
Different experiments use various methods to suppress electromagnetic backgrounds.

Future Channel Readout

- Eventually will need to readout many, many channels for > 1 kg scale experiments (exception, CDMS-style detectors)
- Developing RF-SQUIDs (micro-resonators) to read multiple channels with one system.
- Tuned resonators based on transmission line impedance. Each resonator is tuned to a specific frequency.



uMux Schematic



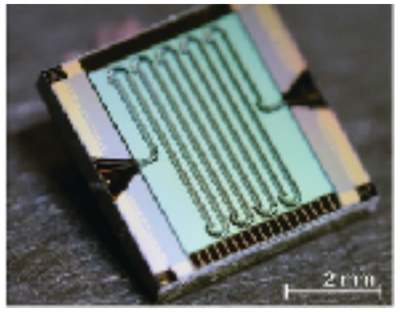
HEMT
T_N = 5 K

Resonator

Flux line

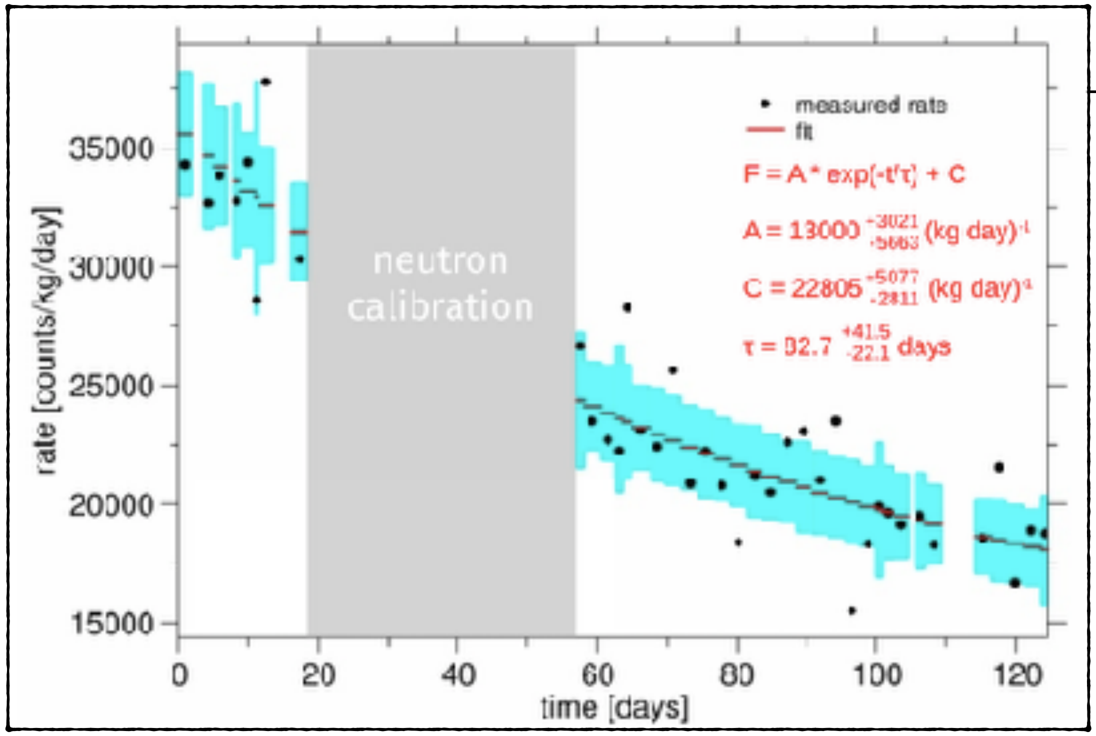
rf-SQUID amplifies TES signal above HEMT noise floor

TES

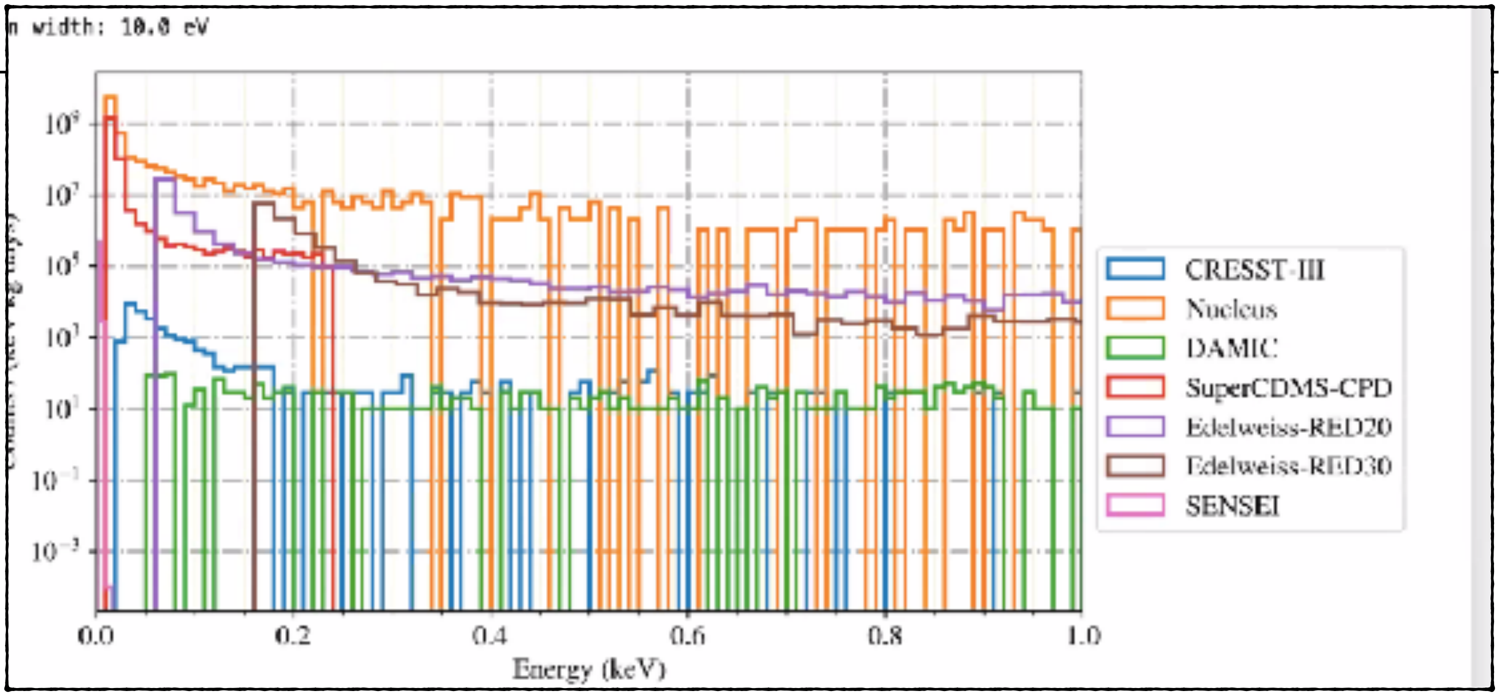


Traveling Wave Parametric Amplifiers

New (?) Backgrounds



From CRESST



A common background is being seeing across a variety of recoil detectors (cryogenic and others) at low recoil energies.

- Excess background observed in all low-E detectors/experiment
- 10^6 DRU @100eV (CRESST, CCDs(?) lower)
- Excess is strongly varying between detectors/materials/ technology in rate and slope
- Excess has particle event signature, but not electron-recoil-like!
- Seems to decrease with time.

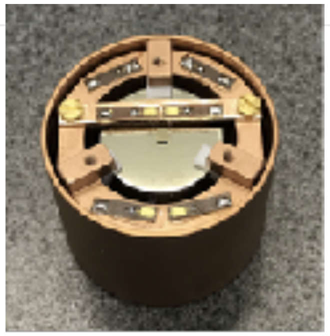
What to Do?

Study anti-coincidence detectors

Study muon veto data (including secondaries)

Study different detector configurations, electronics, etc.

Your Detector Wishlist…



(1) LOW ENERGY THRESHOLDS: $O(\sim 10\ \mathrm{eV})$

(2) BACKGROUND REJECTION: $> 10^3 - 10^5$

(3) SIGNIFICANT TARGET MASS: ~ 10-1000 grams (AND SCALABLE)

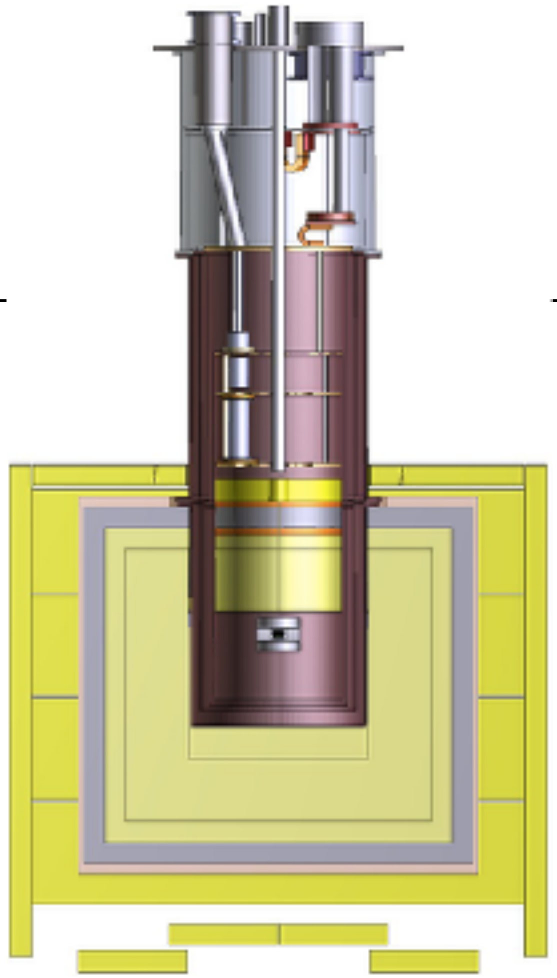
…and your Source Wish List

(1) HIGH FLUX ~ HIGH POWER OR CLOSE DISTANCE

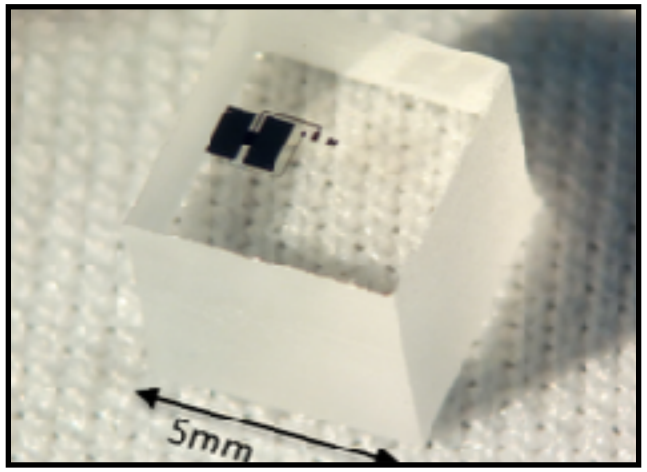
(2) BACKGROUND MEASUREMENT ~DOWNTIME OF REACTOR

(3) BACKGROUND REMOVAL - UNDERGROUND, SHIELDED, OR TAGGED

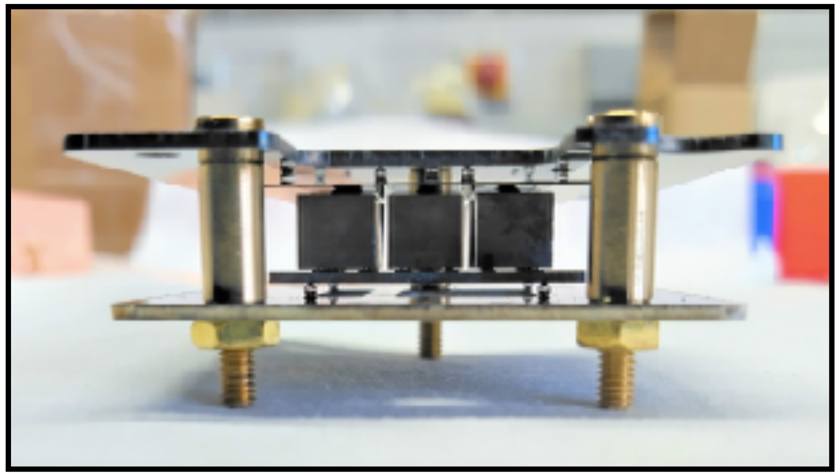
nucleus EXPERIMENT



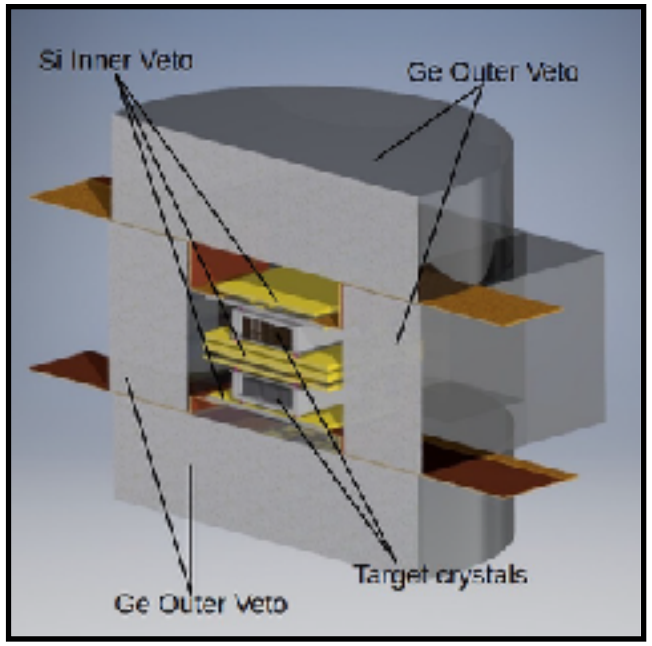
DETECTORS	$CaWO_4$ & Al_2O_3
(1) LOW ENERGY THRESHOLDS:	**19.7 ± 0.8 eV (Threshold)**
(2) BACKGROUND REJECTION:	Cryogenic Inner and Outer Veto
(3) SIGNIFICANT TARGET MASS:	10 grams: 3x3 arrays of $CaWO_4$ & Al_2O_3
(4) TARGET COMPLEMENTARITY:	$CaWO_4$ & Al_2O_3



Target Crystal

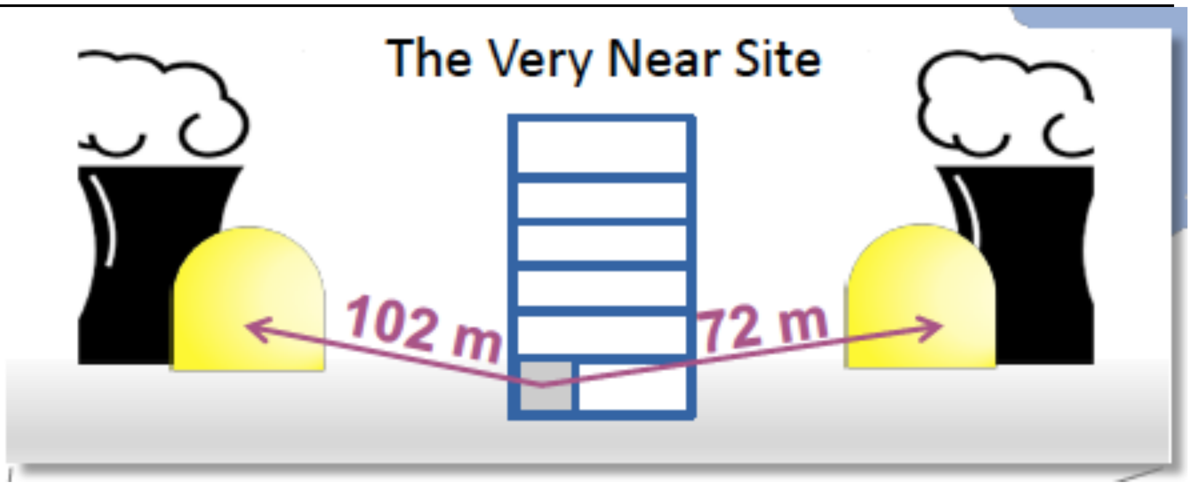


Inner veto: TES-instrumented holder



Germanium Outer Veto

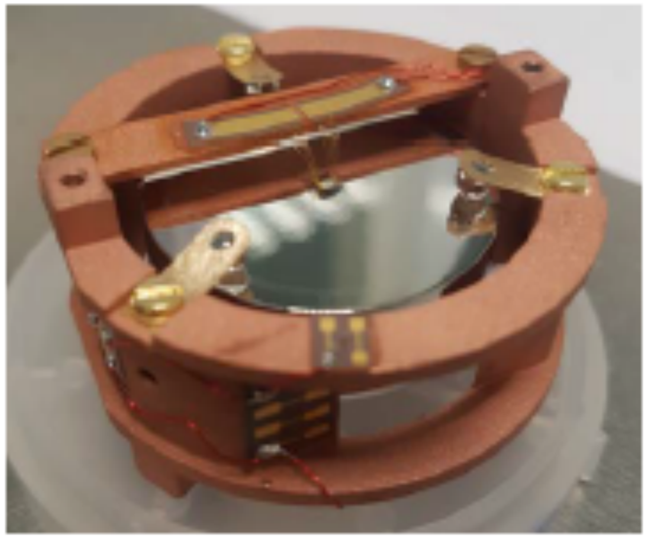
nucleus
EXPERIMENT



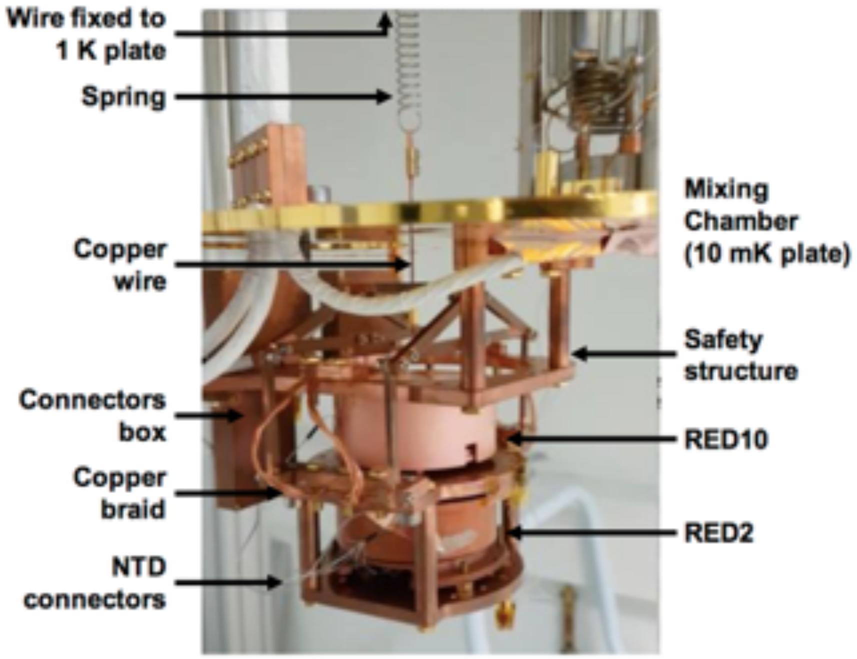
REACTORS:	CHOOZ Reactor Complex (Very Near Site)
(1) HIGH OUTPUT	2 X 4.25 GW power
(2) HIGH FLUX	1.7×10^{12} v/cm^2/s
(3) BACKGROUND REDUCTION:	Almost 100 meters from reactor cores

RICOCHET

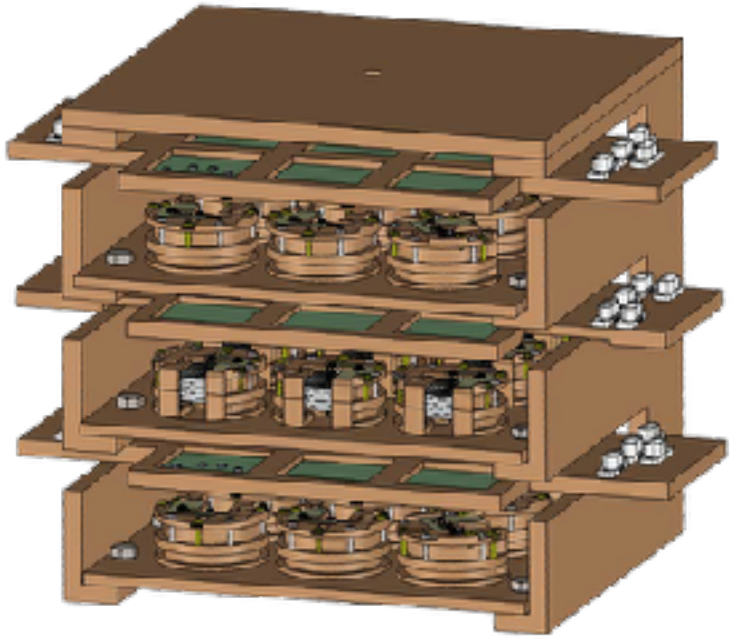
DETECTORS	Ge (semi-conductor) & Zn (super-conductor)
(1) LOW ENERGY THRESHOLDS:	**Ge: 22 eV RMS (heat). Target 10 eV heat, 20 eV charge**
(2) BACKGROUND REJECTION:	Gamma/recoil discrimination
(3) SIGNIFICANT TARGET MASS:	1000 grams: 3x3x3 arrays of Ge & 3 x 3 Zn



Target Crystal



Demonstrator Holder



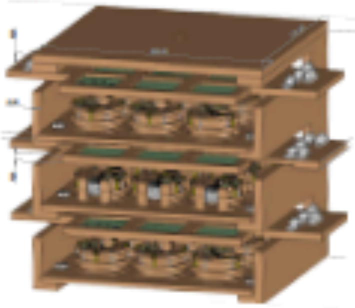
Cryocube

RICOCHET

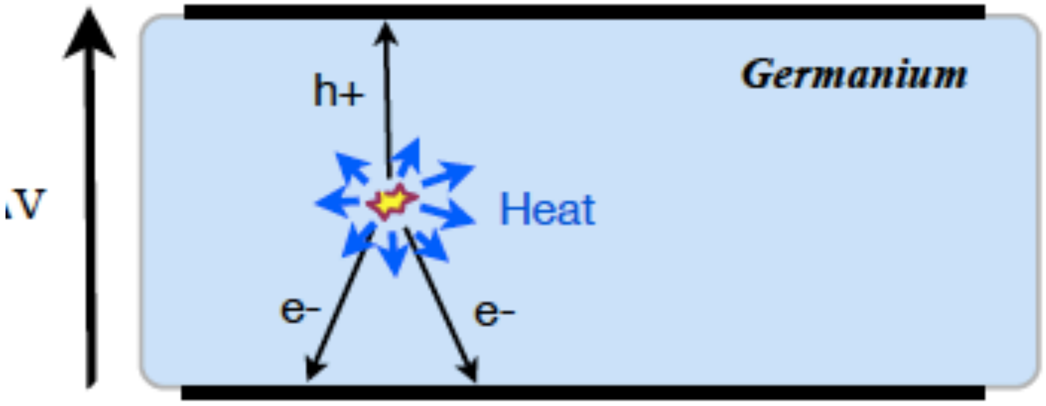
"CryoCube" (See poster P4-4)

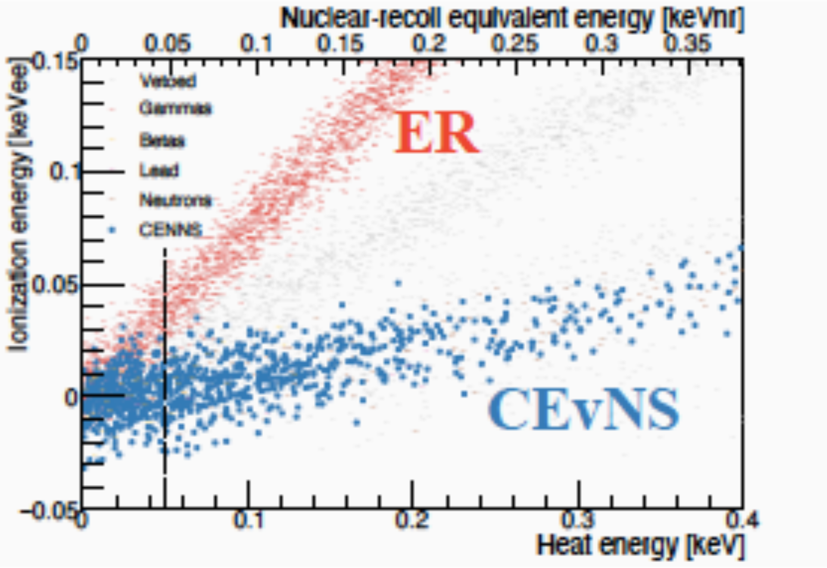
Ionization+Heat in Ge

Sensors: NTDs and HEMTs



Ionization/Heat sensors

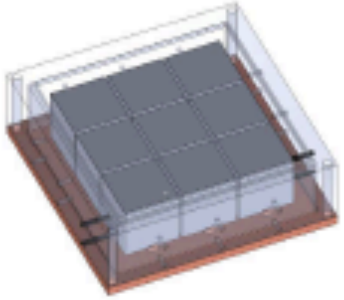




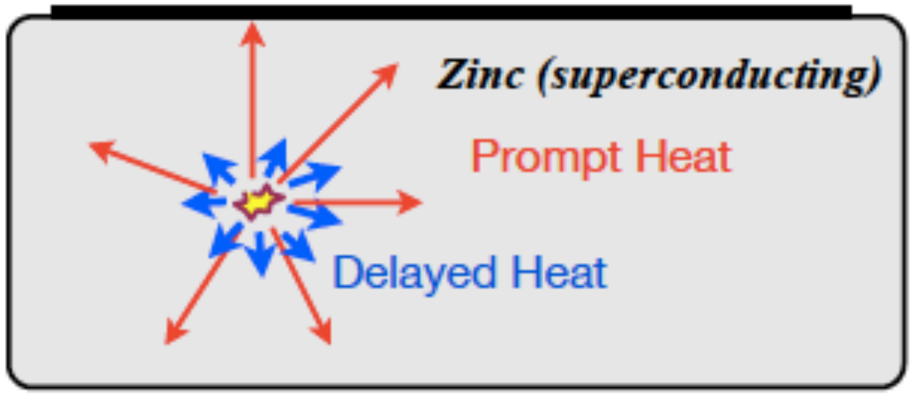
"Q-Array"

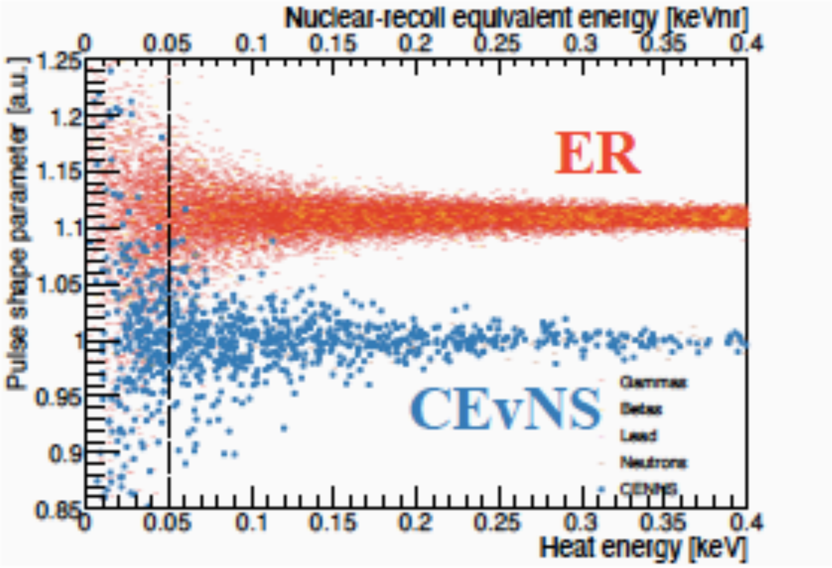
Heat Pulse Timing in Zn

Sensors: TESs



Heat sensors





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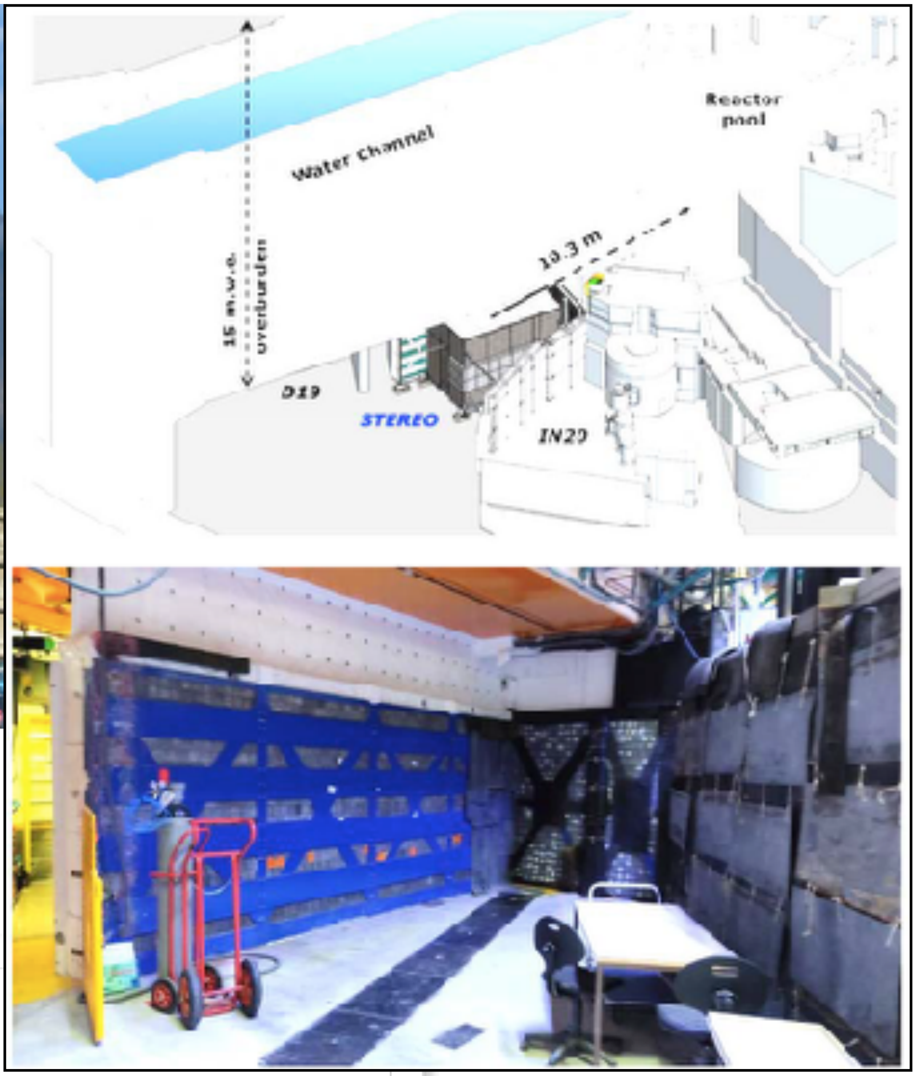
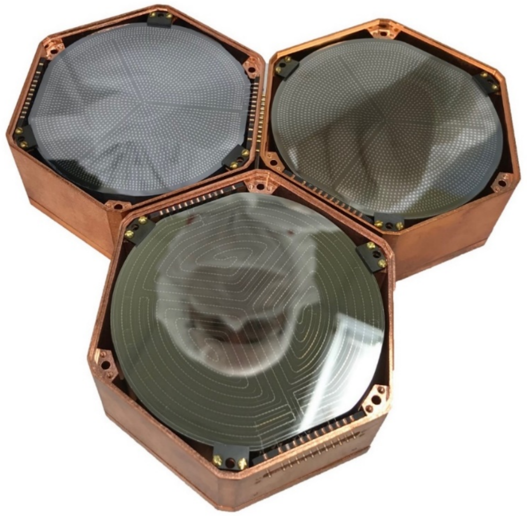


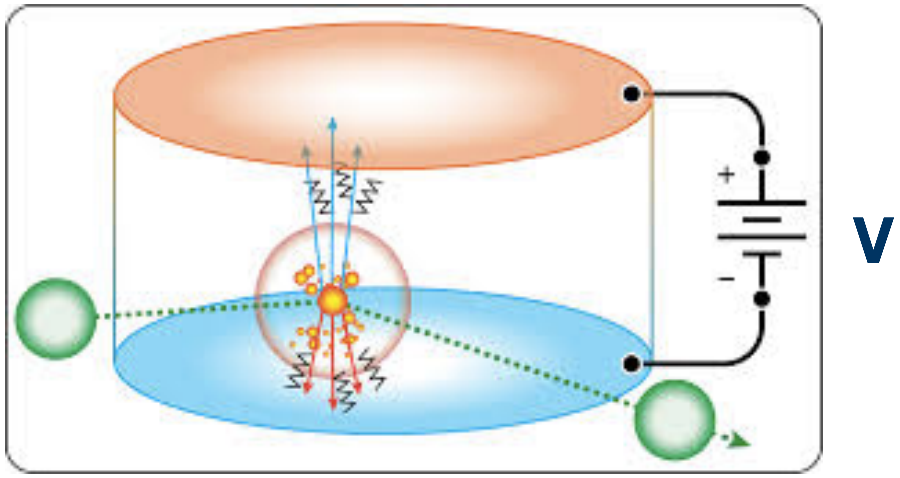
REACTORS:	ILL Grenoble Reactor
(1) *HIGH OUTPUT*	58 MW power
(2) *HIGH FLUX*	~ 1.2 x 10^{12} ν/cm²/s
(3) *BACKGROUND REDUCTION:*	15 m.w.e overburden; heavy shielding

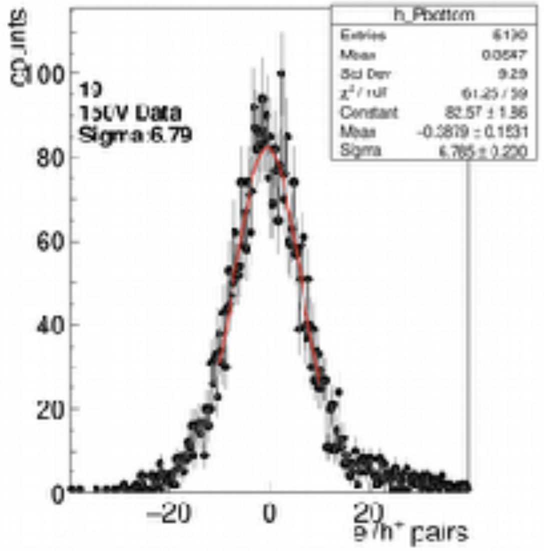
MIÑER

DETECTORS	Si, Ge and Sapphire
(1) LOW ENERGY THRESHOLDS:	**250 gm Ge with σ = 7 eV**
(2) BACKGROUND REJECTION:	Gamma/recoil discrimination
(3) SIGNIFICANT TARGET MASS:	100 grams - 1 kg detectors



Silicon HV Detectors





MIÑER

DETECTORS	Si, Ge and Sapphire
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Hybrid HV Detectors

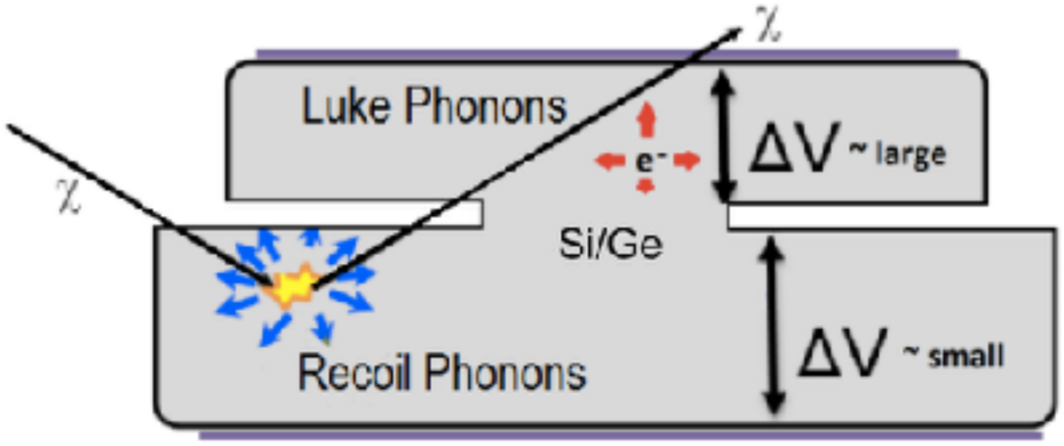
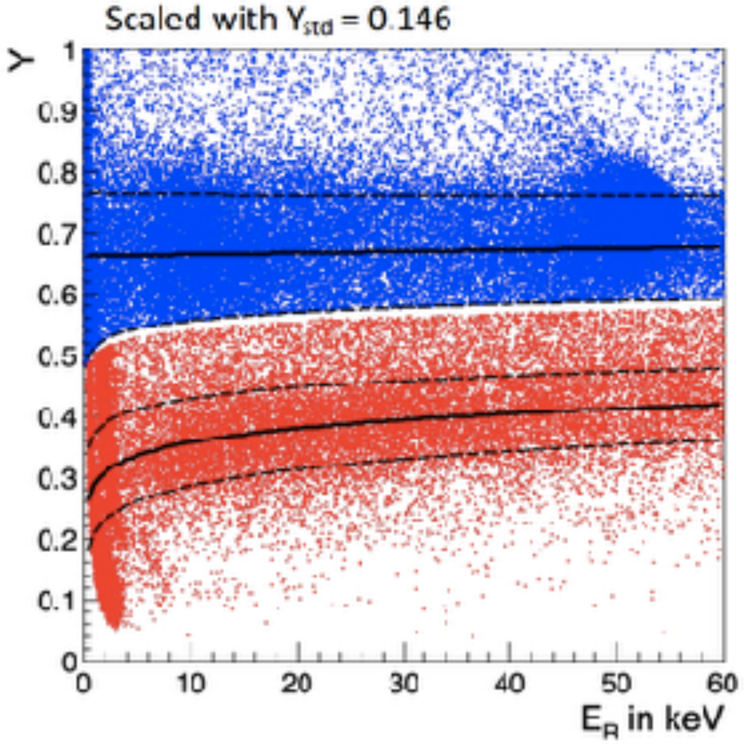


Fig. Schematic Diagram of a hybrid two-stage detector



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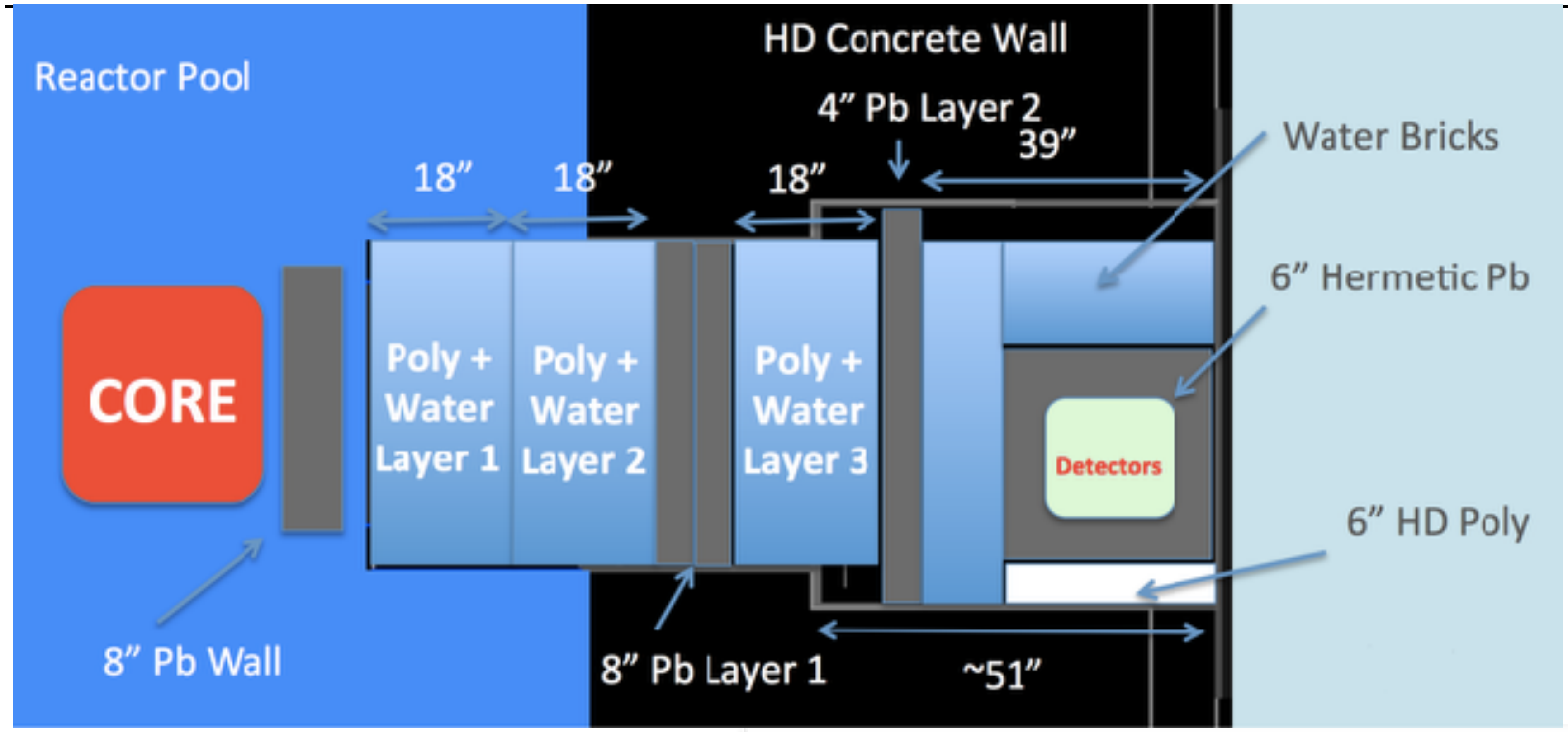
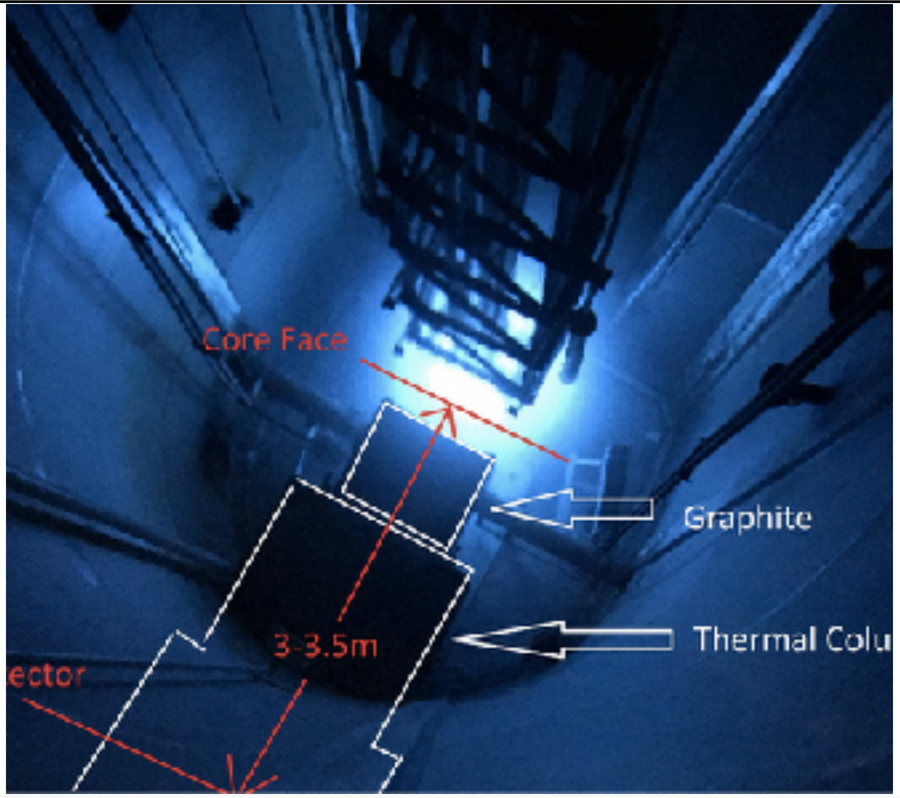
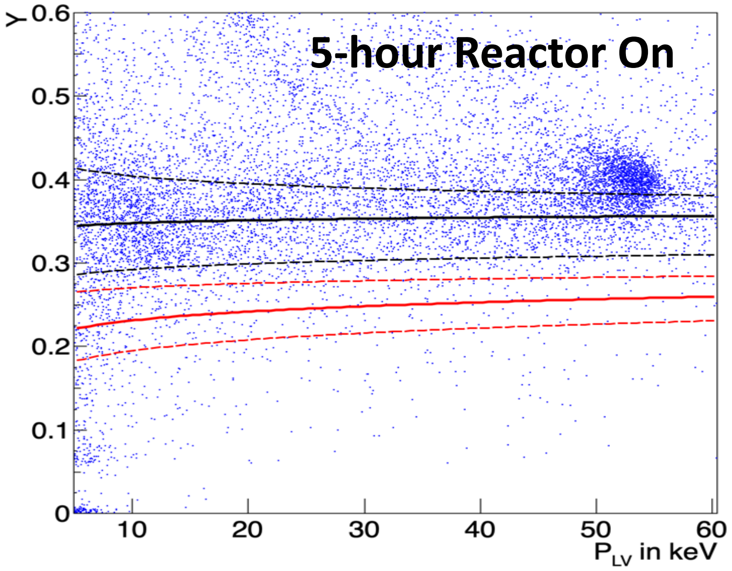






Core On: Raw count (ER+NR) ~3000 DRU.

NR band with single scatter cut <100 DRU above keV

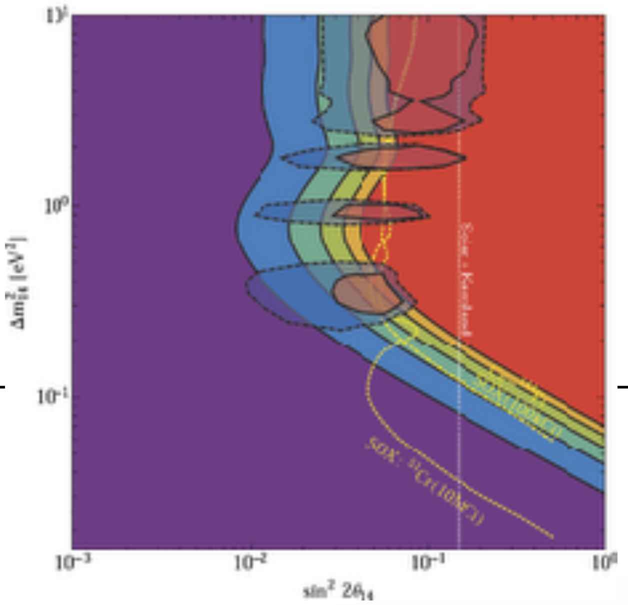
REACTORS: Texas A&M	Nuclear Science Center at
(1) HIGH OUTPUT	1 MW power
(2) HIGH FLUX	~ $1 \times 10^{12}\ \nu/cm^2/s$
(3) BACKGROUND REDUCTION:	Movable core (2-10 meters)

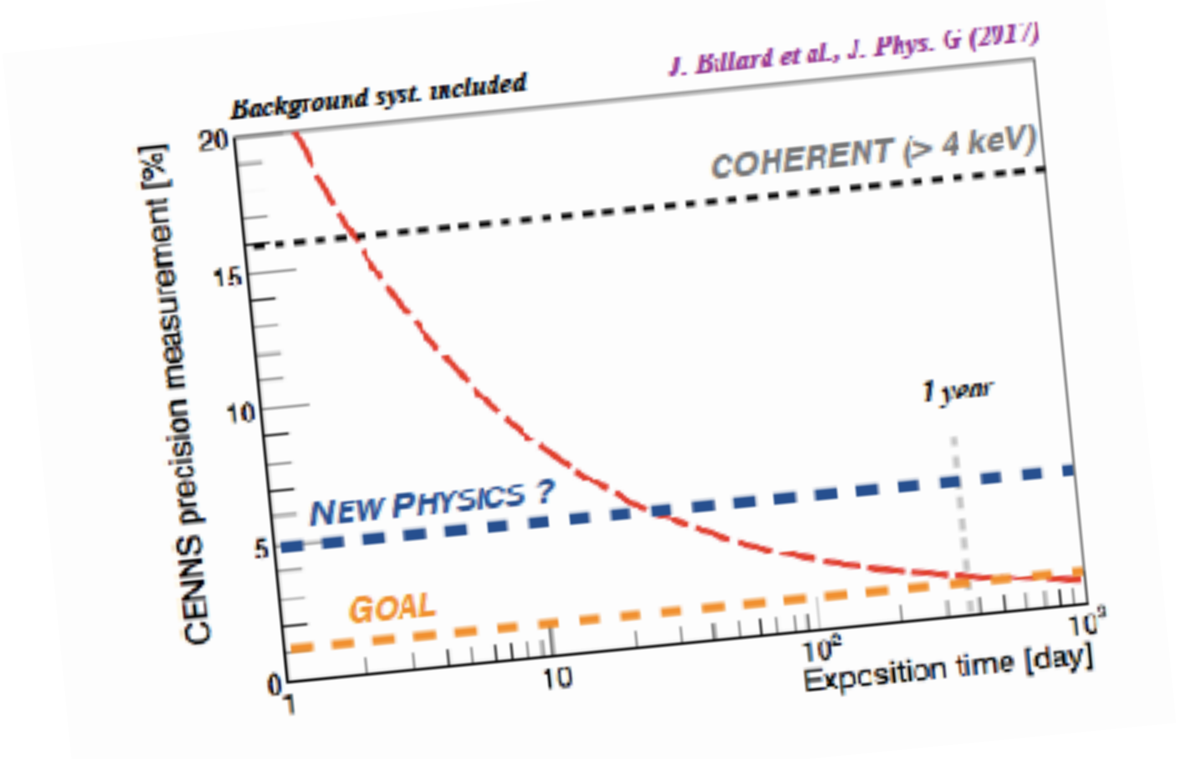
Summary

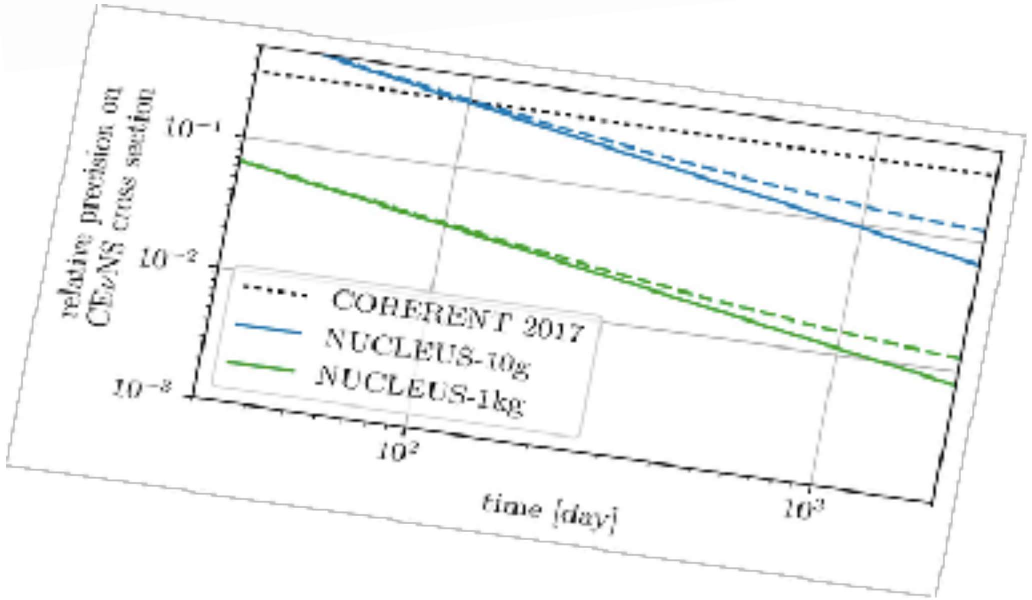
After forty years, we are finally at the point where coherent neutrino scattering is a usable channel for exploring new physics.

Ricochet, **MINER** and **NuCLEUS** are quickly commissioning detectors to provide detection of the CEvNS process from reactor neutrinos using cryogenic bolometers.

Expect to see first data within the next few years from each of these efforts.







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and thank *you* for your attention.