RICOCHET

Probing Reactor Neutrinos Through Coherence

Joseph A. Formaggio

Massachusetts Institute of Technology

RICOCHET

Science

Detectors

Location

RICOCHET

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Detectors

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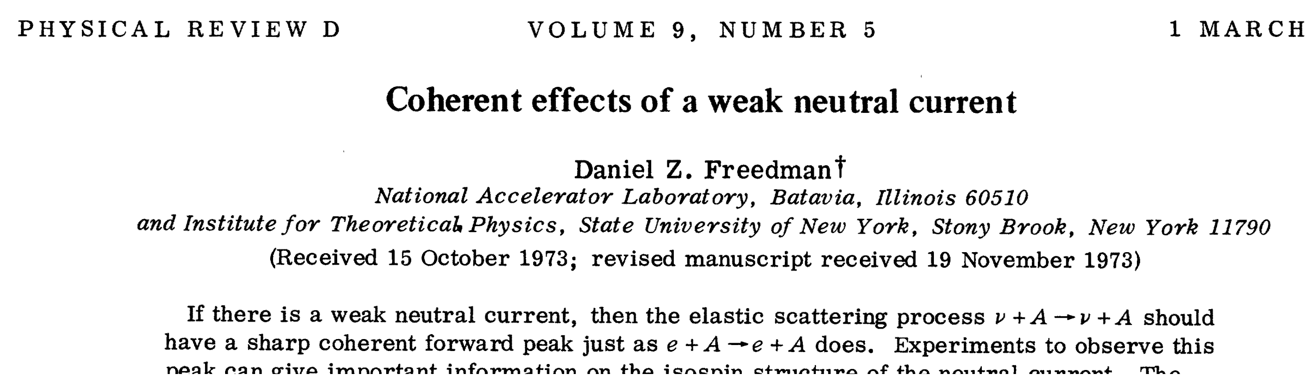
Coherent Neutrino Scattering

- Idea originally proposed in 1974 by Daniel Freedman, predicting that for sufficiently small momentum transfers, the neutrino can interact *coherently* with a nucleus.



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH

Coherent effects of a weak neutral current

Daniel Z. Freedman†
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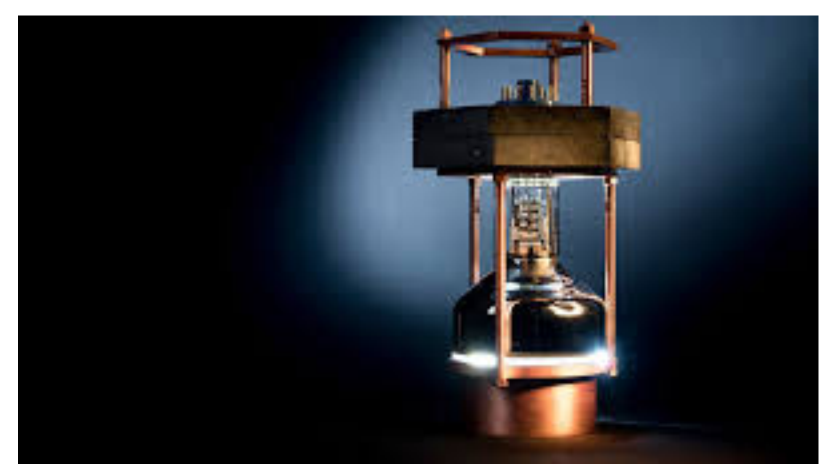
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this

- A process known as **C**oherent **E**lastic Neutrino(**v**)-**N**ucleus **S**cattering, or **CEvNS** is now experimentally realized.

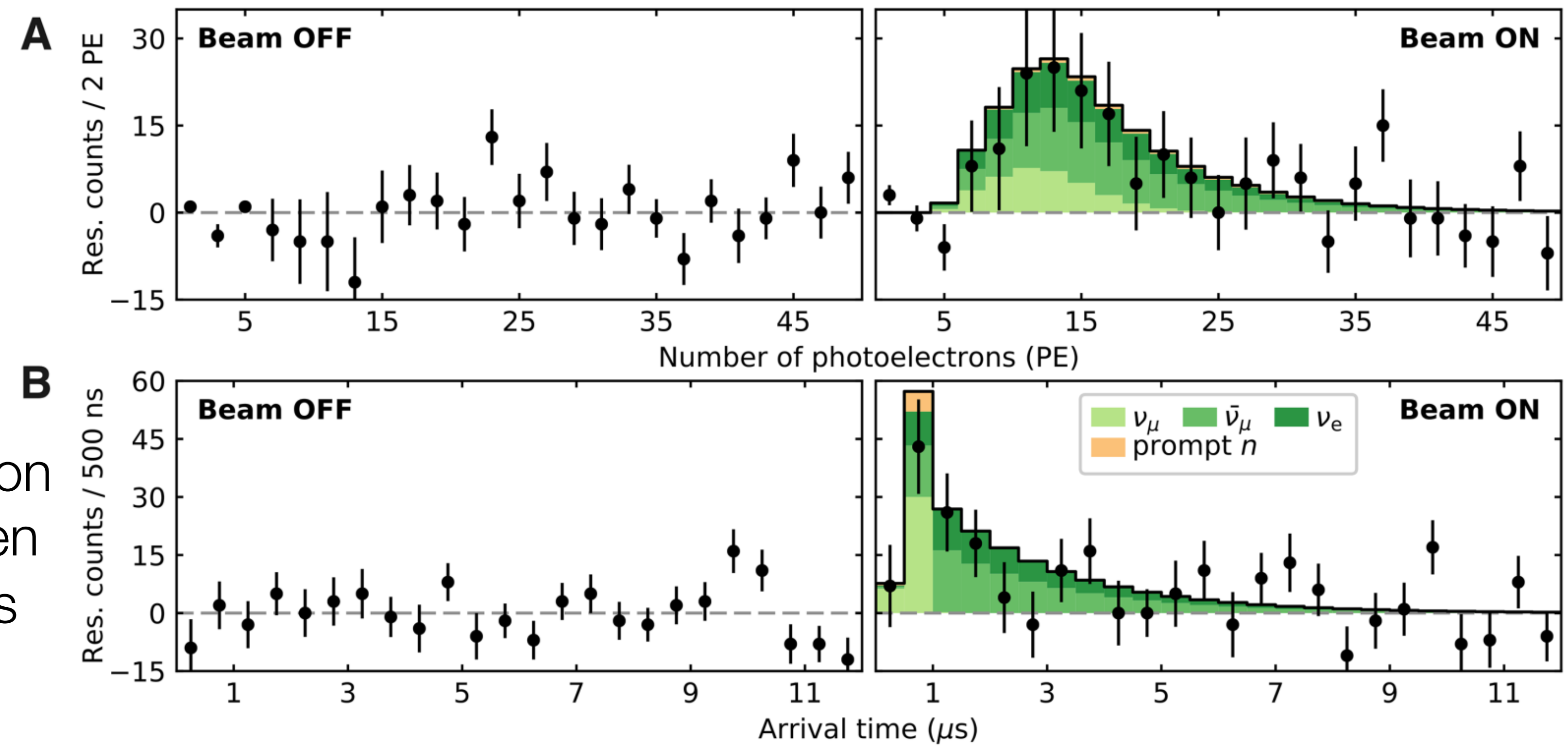
- Such a process would significantly enhance the cross-section, allowing it to scale with the number of neutrons *squared*.

- This is now an ***observed*** neutrino reaction.



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

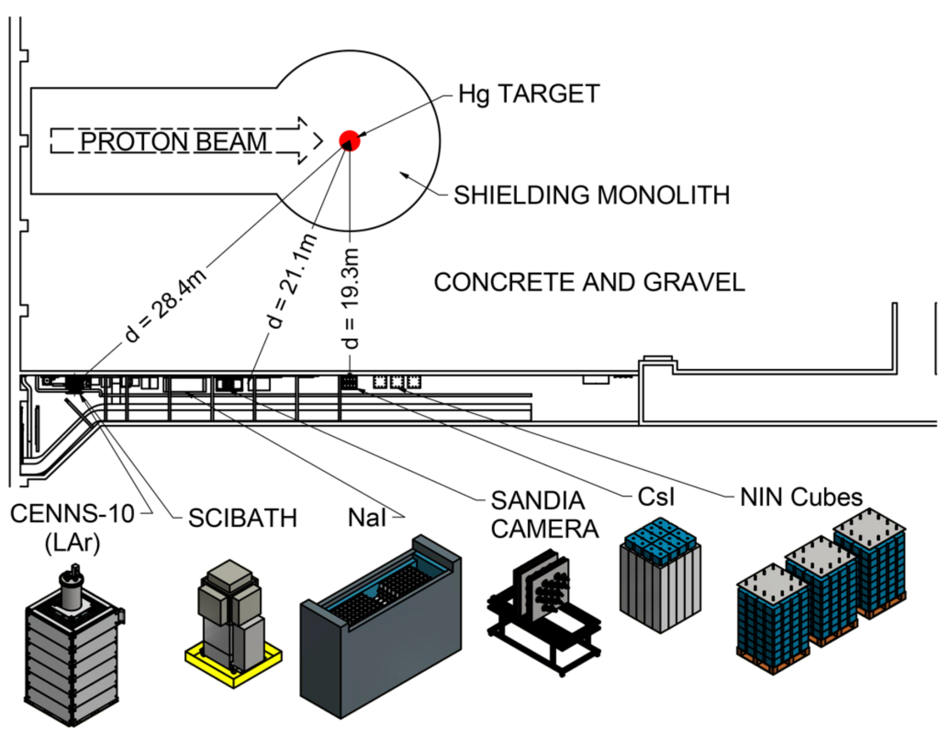
Discovery!



As of **August 3rd, 2017**, a first detection of coherent neutrino scattering has been reported by **COHERENT**! The process does indeed take place.

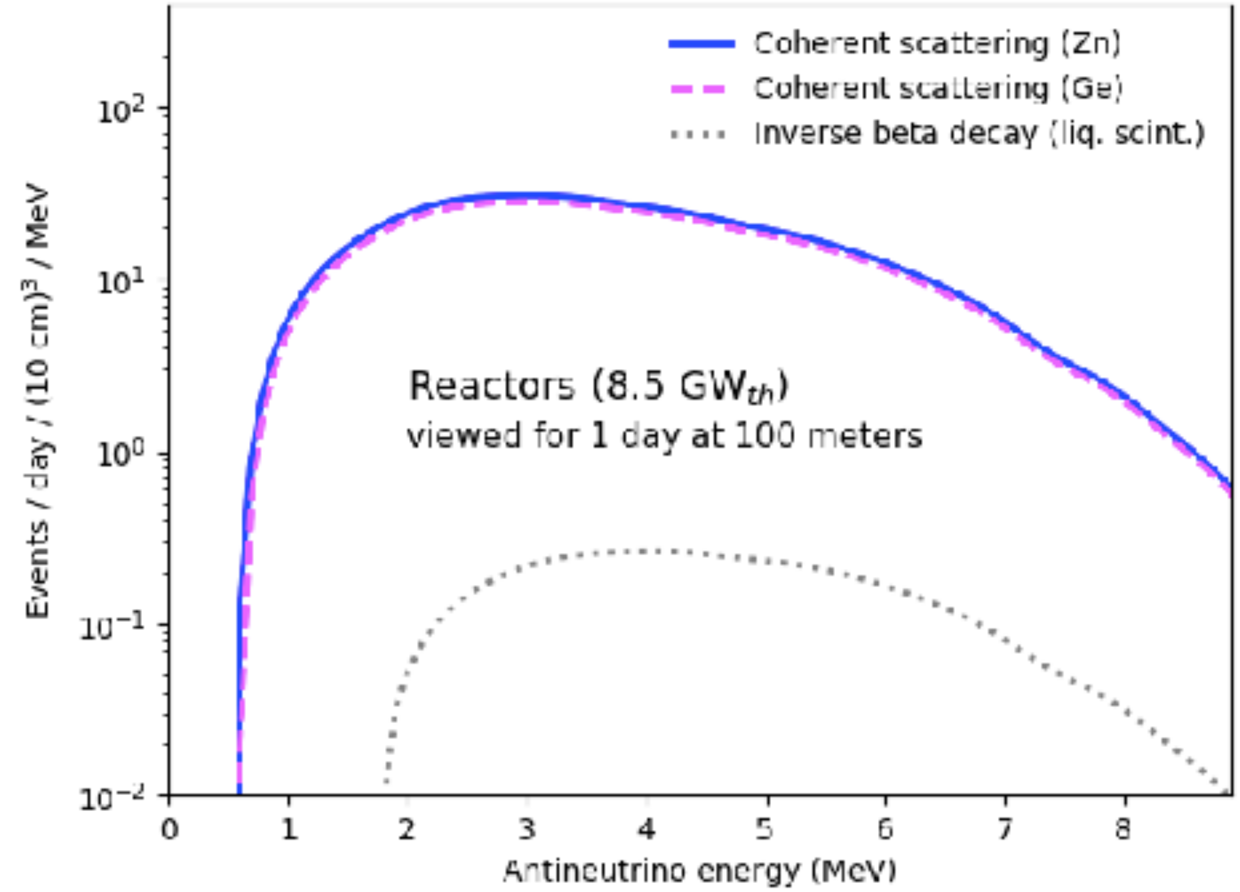
Only 16 kg-years to get ~7 sigma!

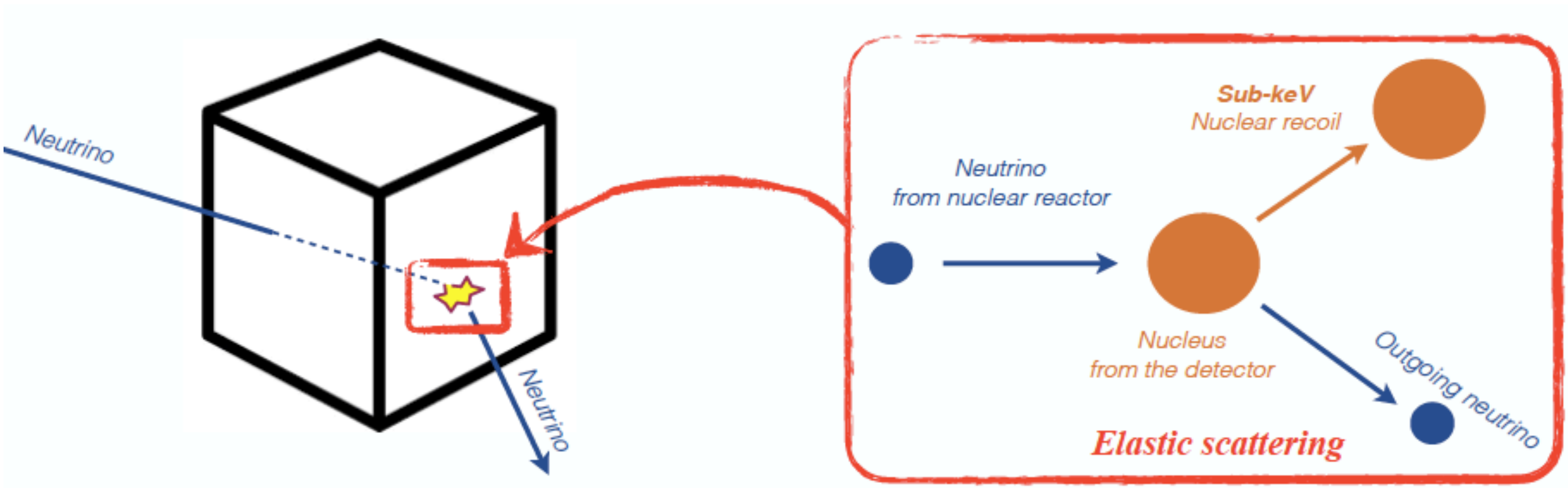
Coherent neutrino detection from reactors remains a goal for future experiments.



The CEvNS Portal

- CEvNS has huge cross-section compared to conventional neutrino interactions, allowing for **kg-scale** detectors as opposed to **ton-scale** detectors.
- The catch?? The signature entails a very small recoil energy.
- Current technology —particularly with quantum sensors— has opened up this new detection channel.





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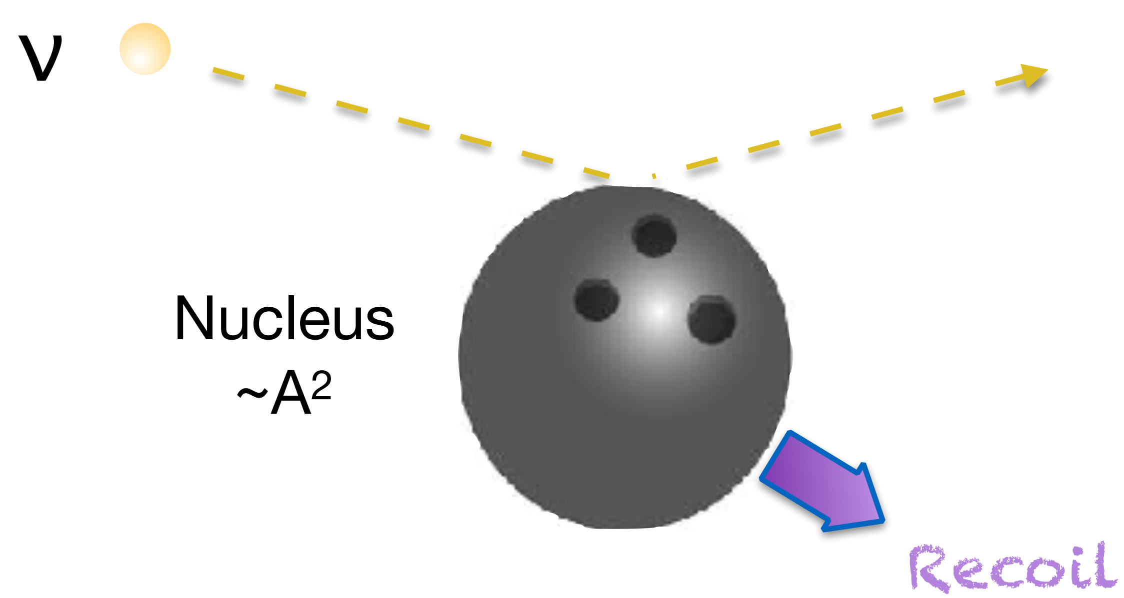
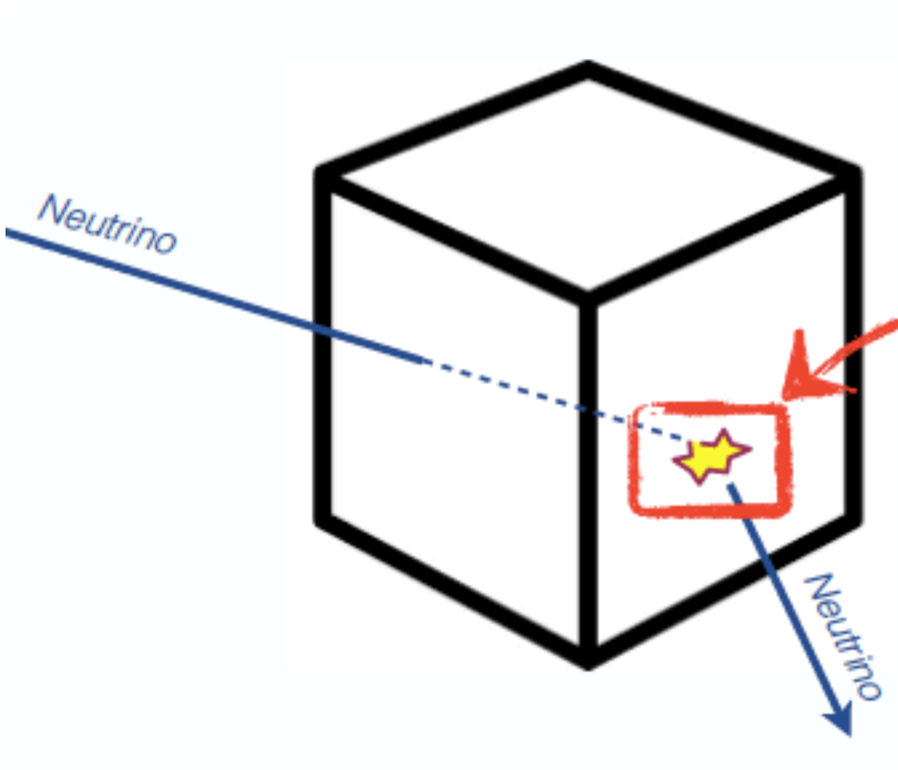
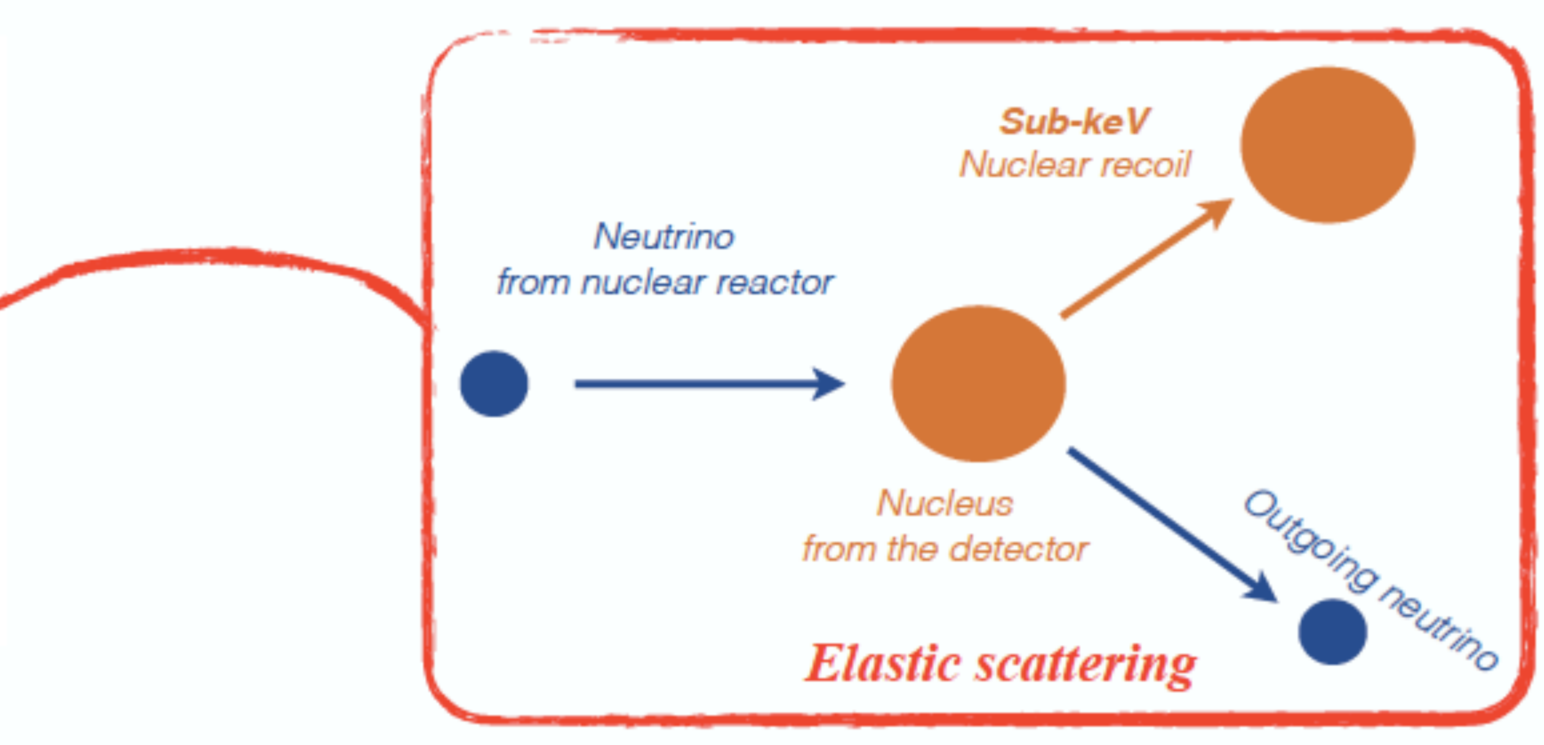


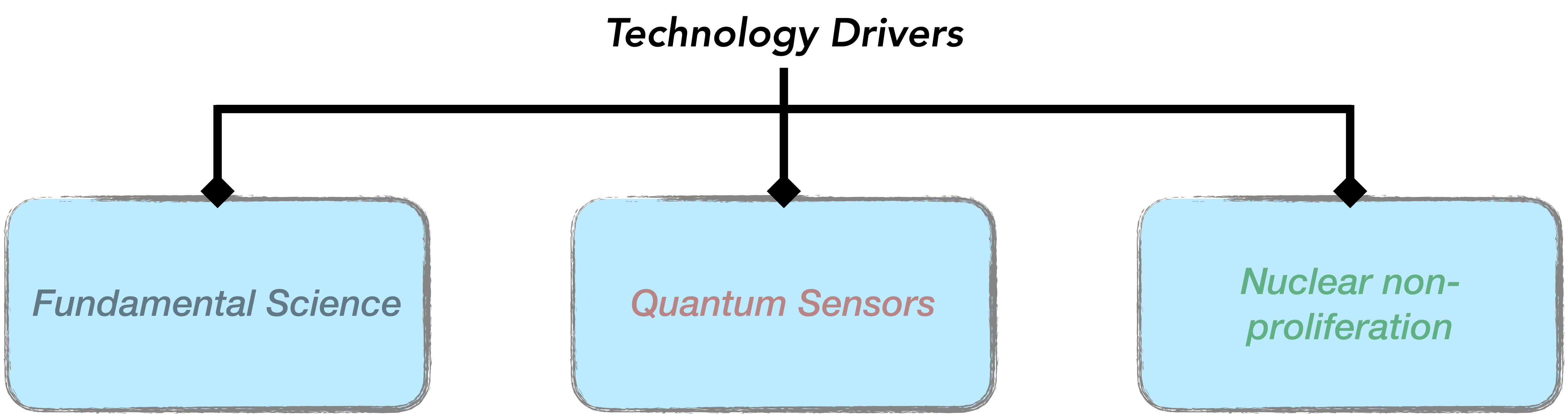




Drivers for Science

- Coherent neutrino scattering opens a new door for science and applications that were previously not available.
- The program impacts three distinct areas of science and technology.
- Driven by the ability of constructing low threshold recoil detectors which can be scaled to 100s or 1000s of units.

Leverages superconducting quantum sensors to scale number and sensitivity of detectors.



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

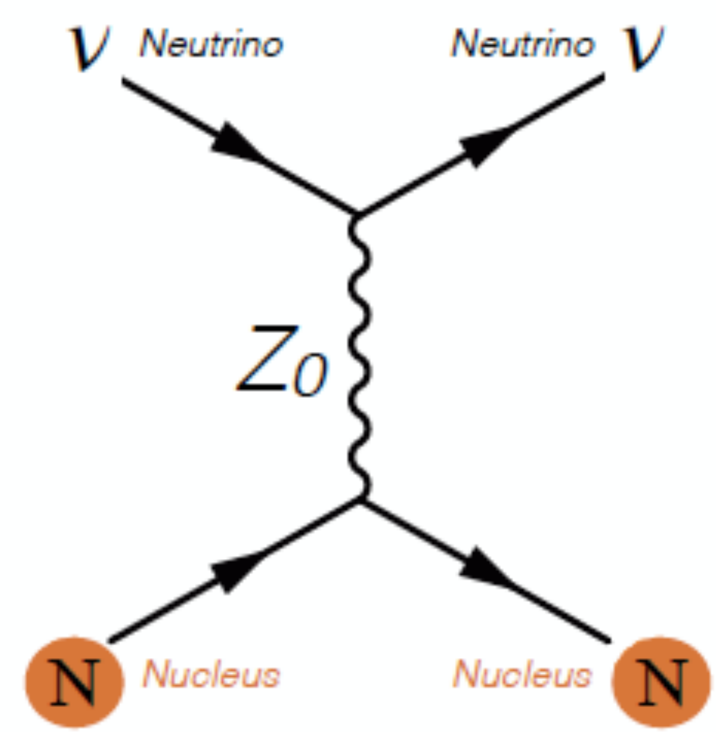
—> Cross section proportional to N^2

Initial and final states must be identical

—> Neutral Current elastic scattering

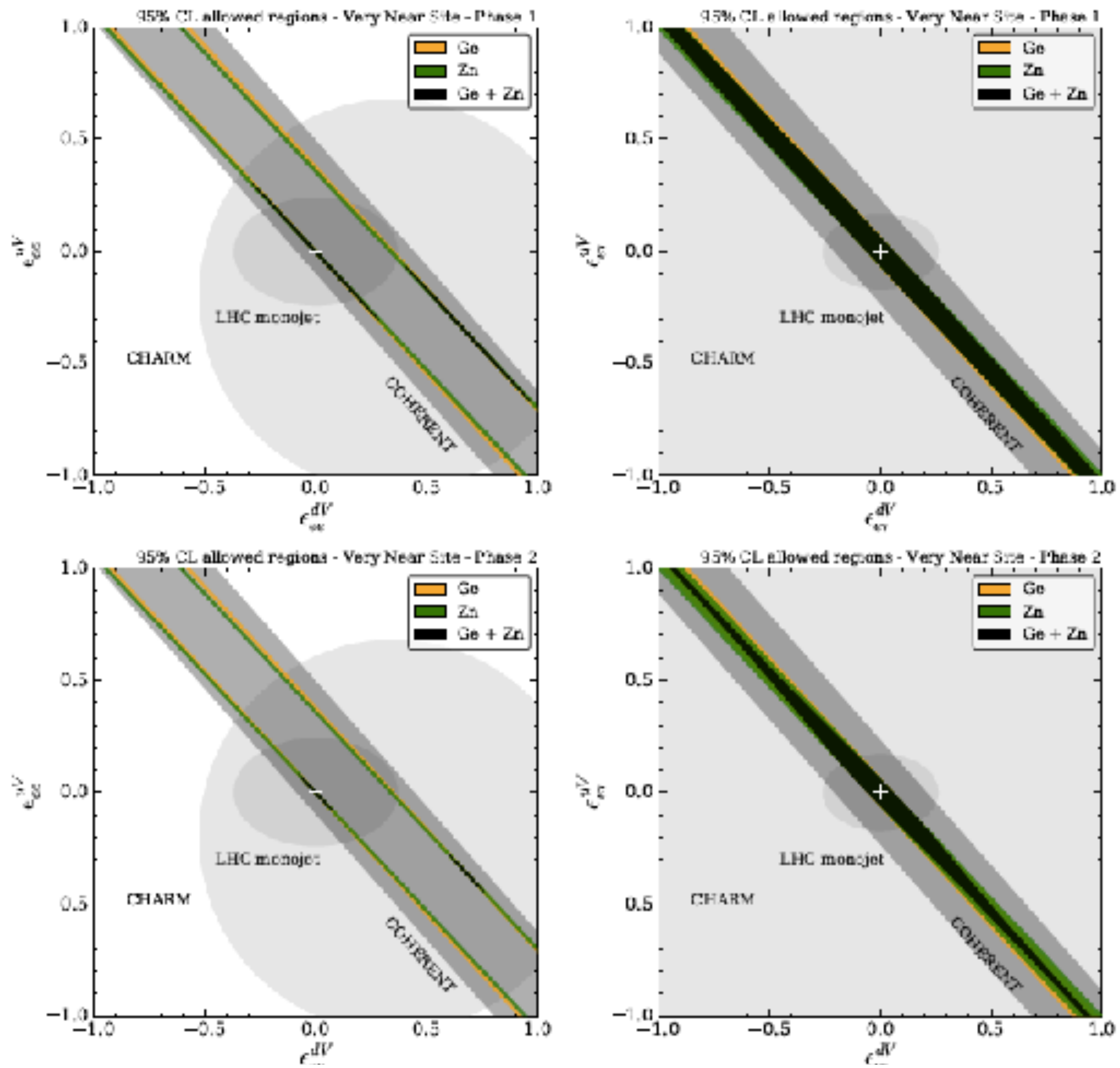
Nucleons must recoil in phase

—> Low momentum transfer (qR<1)



New Forces

- The program also broadens the science reach for non-standard interactions.
- This includes anomalous couplings, as well as general deviations from Standard Model predictions.
- Can also compare directly to electron-PV scattering.



J. Billard, J. Johnston, B. J. Kavanagh, arXiv:1805.01798

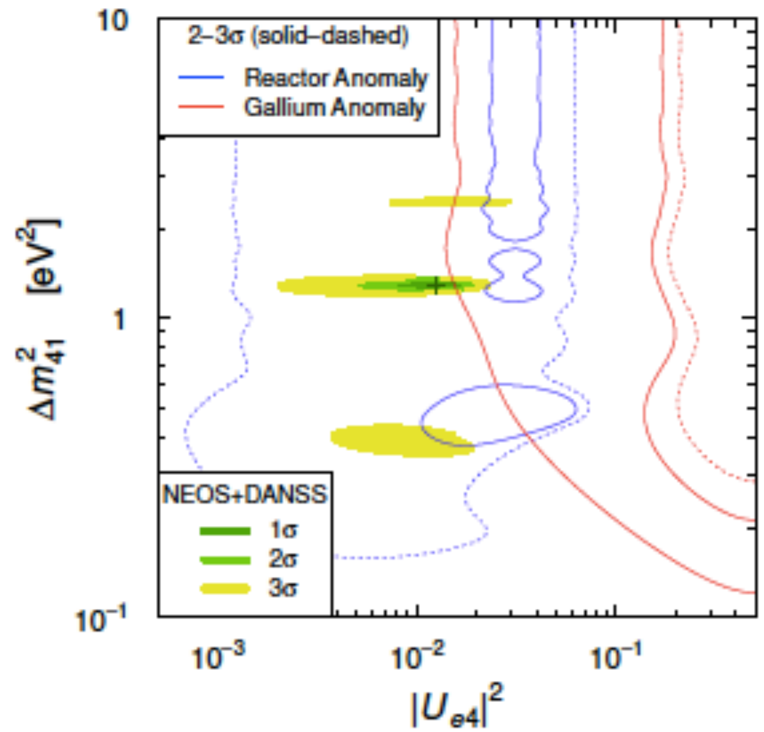
$$\mathcal{A}_{(e,e)} = \frac{\left(\frac{d\sigma}{d\Omega}\right)^{h=+1} - \left(\frac{d\sigma}{d\Omega}\right)^{h=-1}}{\left(\frac{d\sigma}{d\Omega}\right)^{h=+1} + \left(\frac{d\sigma}{d\Omega}\right)^{h=-1}}$$

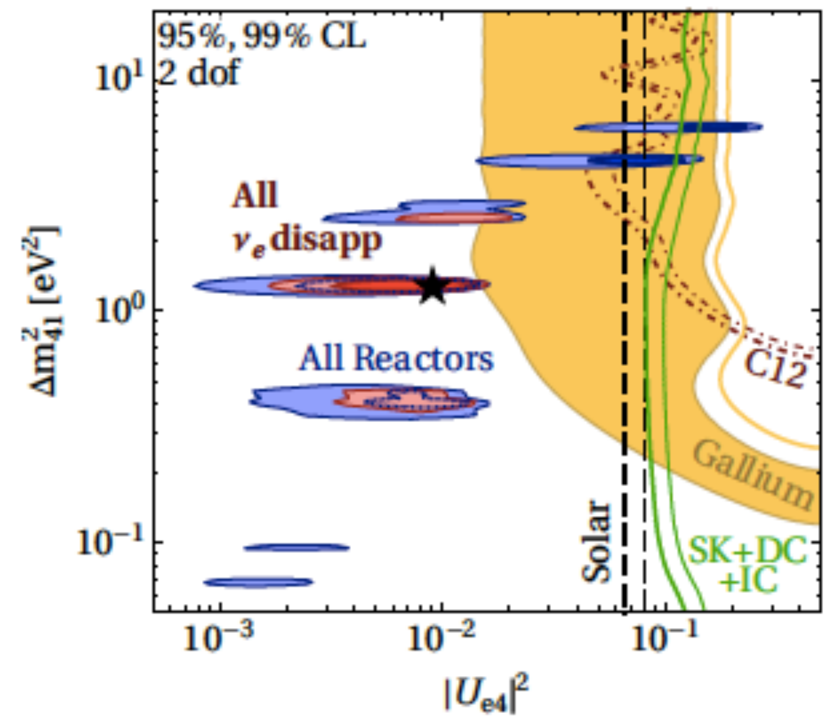
$$\left(\frac{d\sigma}{d\Omega}\right)_{(\nu,\nu)} = \mathcal{A}^2_{(e,e)} \left(\frac{d\sigma}{d\Omega}\right)_{(e,e)}$$

Parity violating asymmetry

ν-e Correspondence

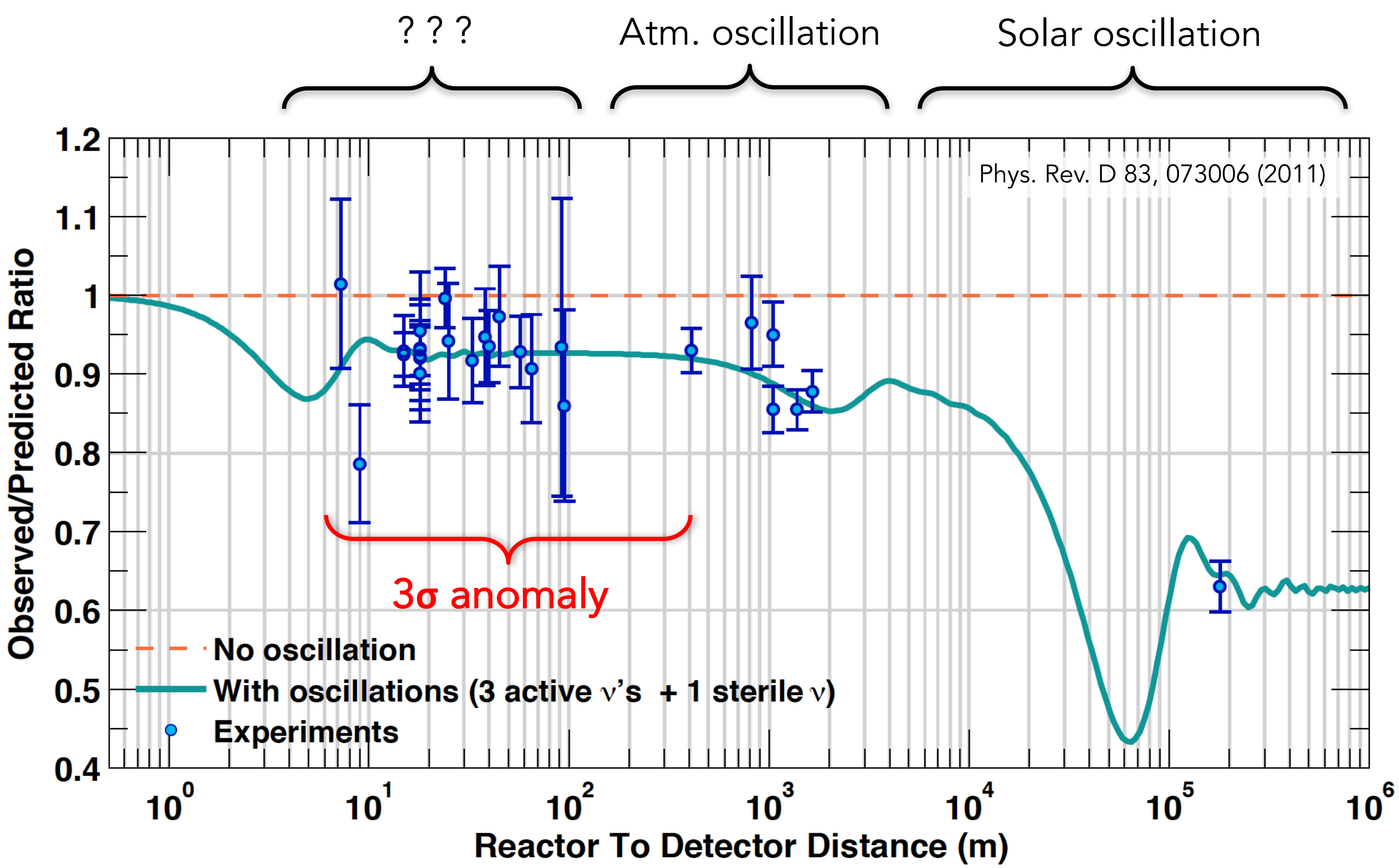
New Types of Neutrinos





A number of recent (and not so recent) results seem to indicate the possibility of sterile neutrinos.

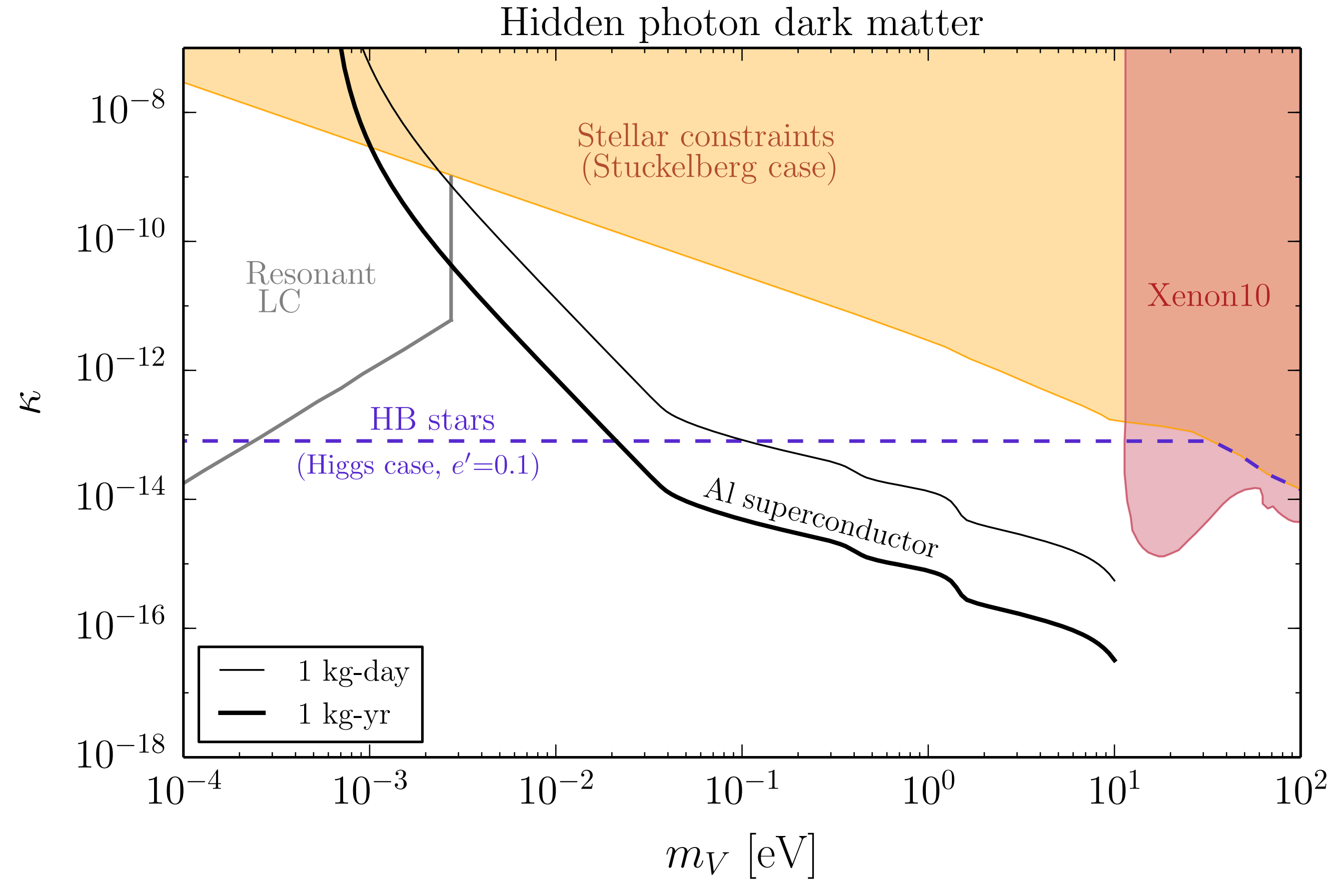
All suggestive, but no "smoking gun" accepted by the community at the moment.



CEvNS would strongly settle the question of whether sterile neutrinos are responsible (unique channel to this physics).

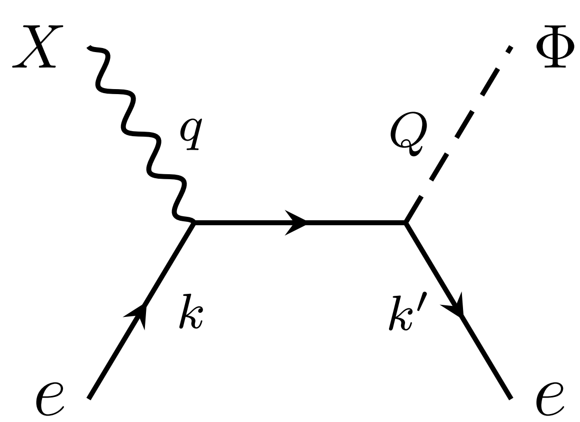
Reactor Anomaly

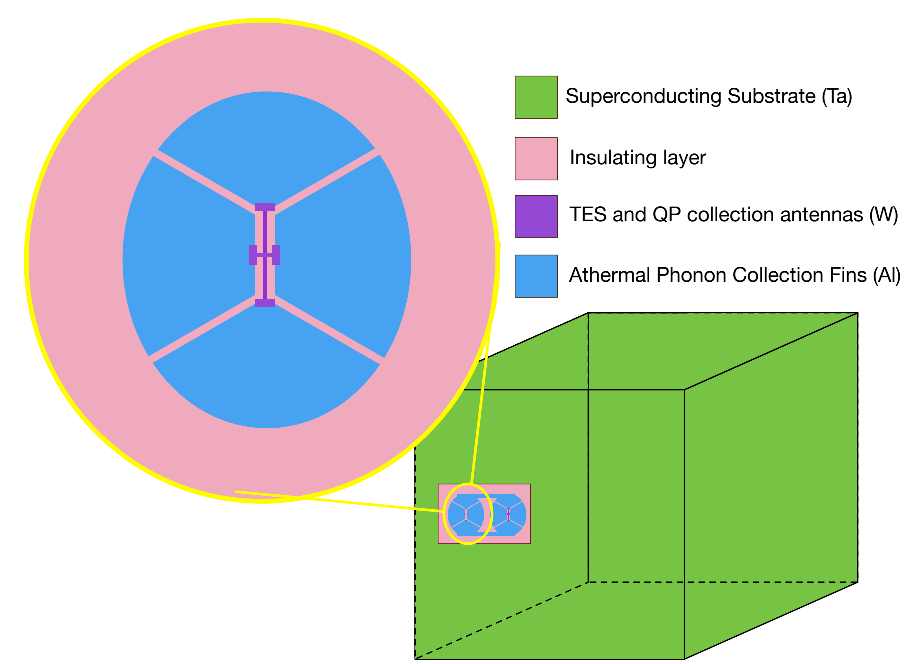
New Particles



R.Hochberg et al arXiv:1604.06800v1 [hep-ph]

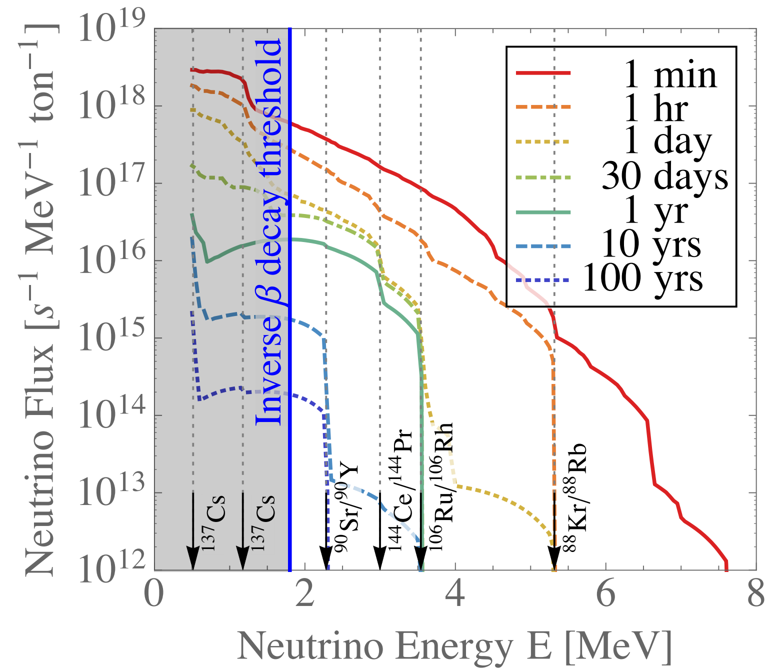
Metallic superconductors can be used to probe bosonic dark matter at very low mass scales.





Takes advantage of long quasi-particle lifetimes and thermal phonon emissions (and very small superconducting gap energies) to see low energy interactions.

Neutrinos as Applied Technology?



Monitoring of Spent Fuel
arXiv:1606.06309v1

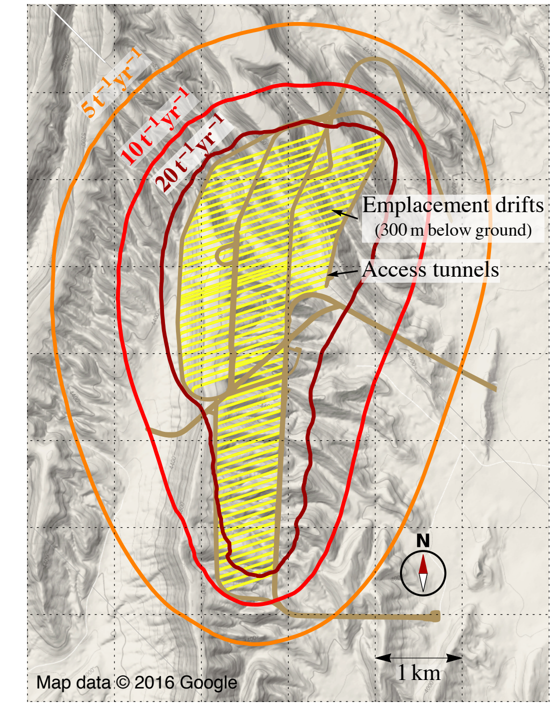


FIG. 3. The planned long term storage facility at Yucca mountain. The yellow grid indicates the drifts holding the radioactive material at a depth of 300 m below the surface, while red and orange contours show the expected antineutrino count rates for a detector at the surface.

- Inverse beta decay is by far the most developed technology, already used to measure reactor neutrinos.
- Technology often requires **large-scale** detectors to have sufficient rate for determining change in fuel composition. Also, neutrino energies below 1.8 MeV **cannot be detected**.
- Coherent scattering does not suffer from this limitation. Advantages:
    - Smaller footprint for detecting neutrinos from reactors.
    - Has the possibility to detect neutrinos below 2 MeV, such as from **breeder blankets** or **spent fuel** sites.

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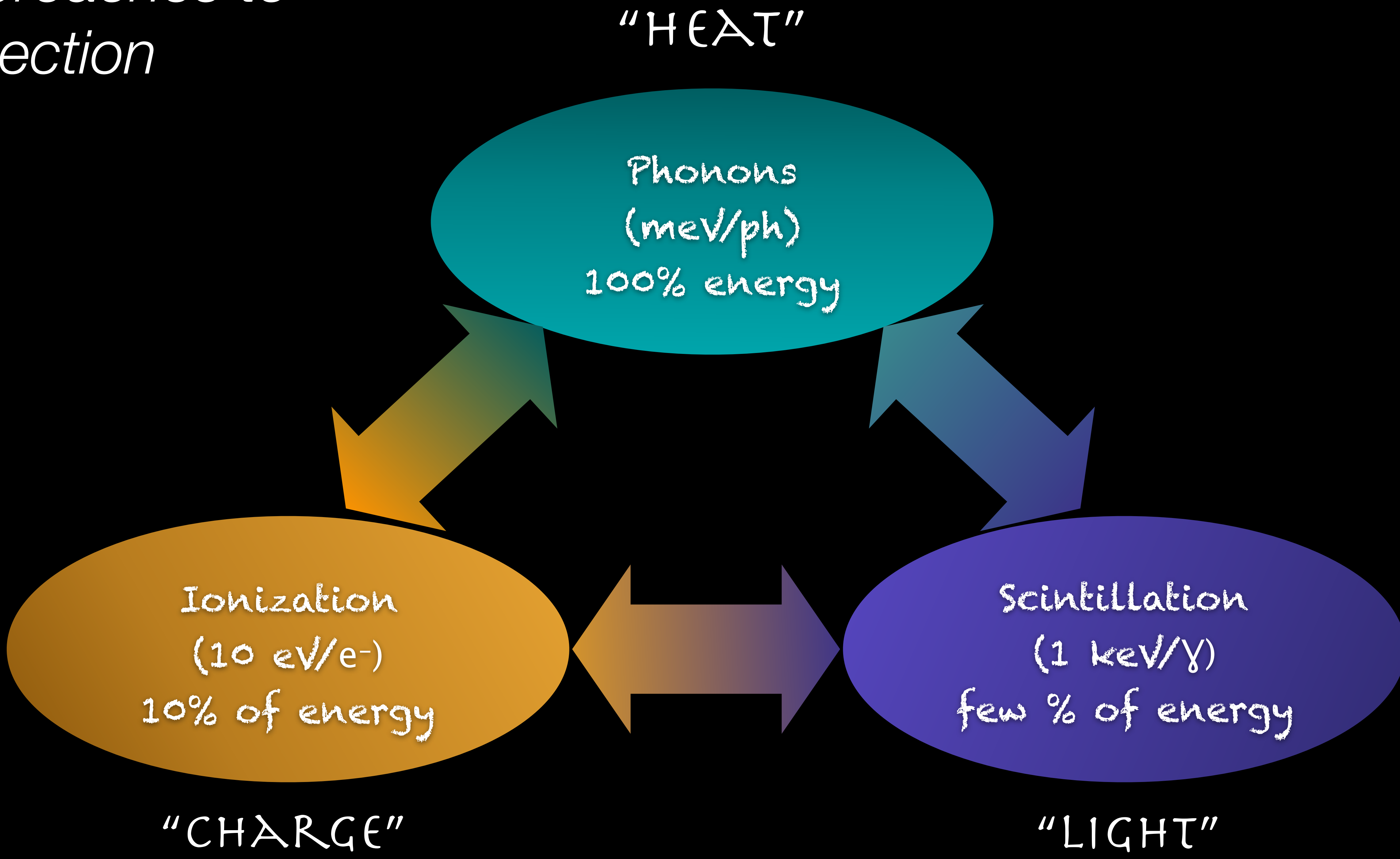
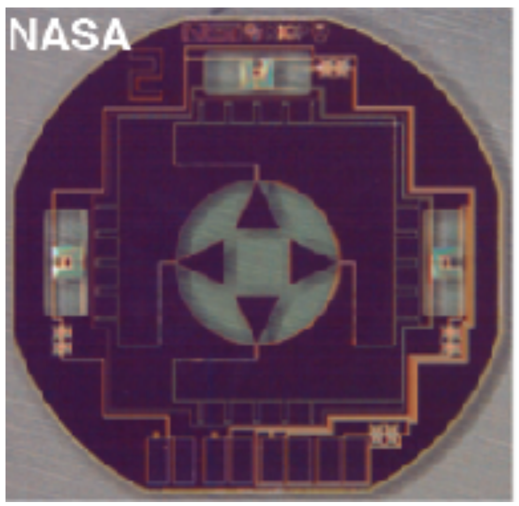
A new experiment is being assembled to demonstrate the technology.

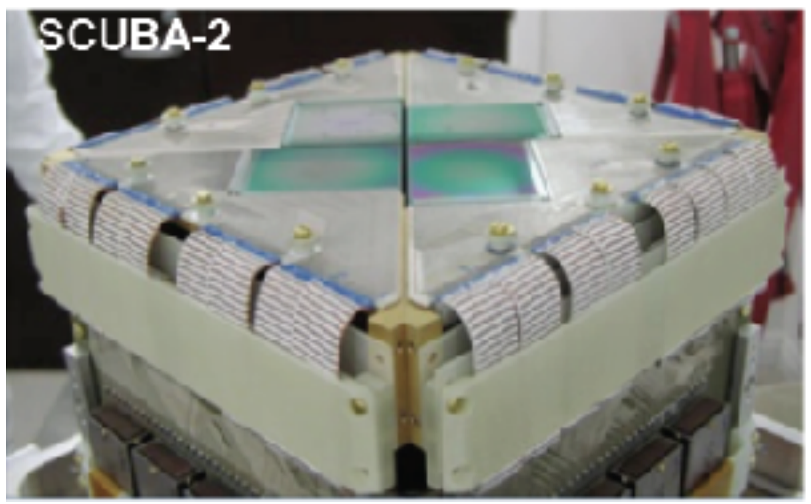
Partnership between US and France to study neutrinos from nuclear reactors.

Different Approaches to Detection

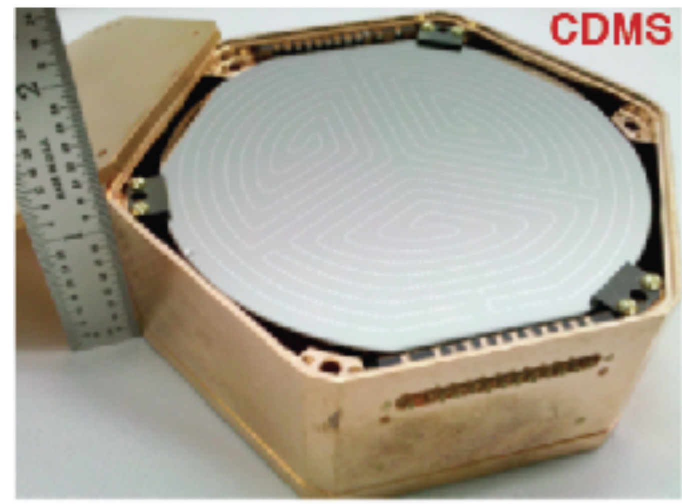


Where Phonon Technology is Used

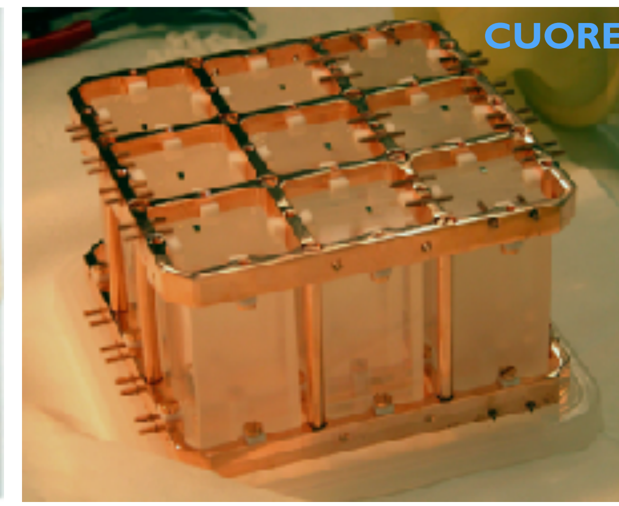




CMB, Infrared detection



Dark matter

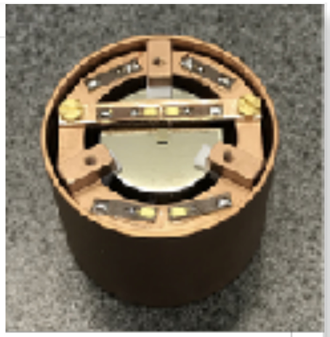


$0\nu\beta\beta$

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 **10 eV** recoil threshold.

A Detector Wish List…

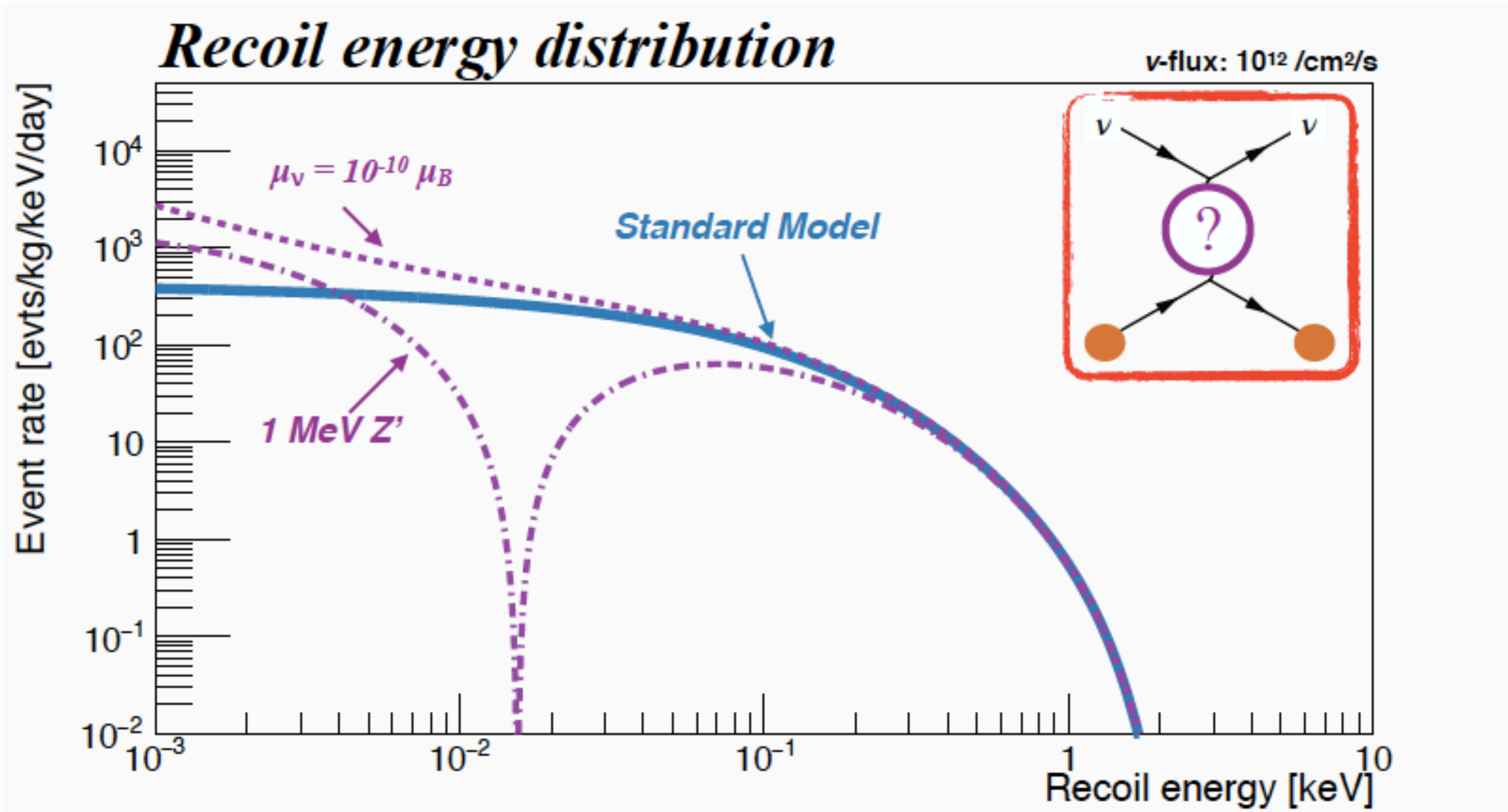


(1) VERY LOW ENERGY THRESHOLDS:	O(~10 eV)
(2) ELECTROMAGNETIC BACKGROUND REJECTION:	> 10^3
(3) SIGNIFICANT TARGET MASS:	~ 1 Kg (AND SCALABLE)
(4) TARGET COMPLEMENTARITY:	Ge (SEMI-) AND Zn (SUPER-) CONDUCTORS

…and a Source Wish List

(1) HIGH FLUX	~ FEW GW POWER
(2) ON/OFF CYCLES	~10-30% DOWNTIME OF FLUX
(3) OVERBURDEN	UNDERGROUND (~150 MWE) OR SHIELDED

Requirement for Low Thresholds



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- ***Calls for low threshold ~O(10 eV) detectors.***

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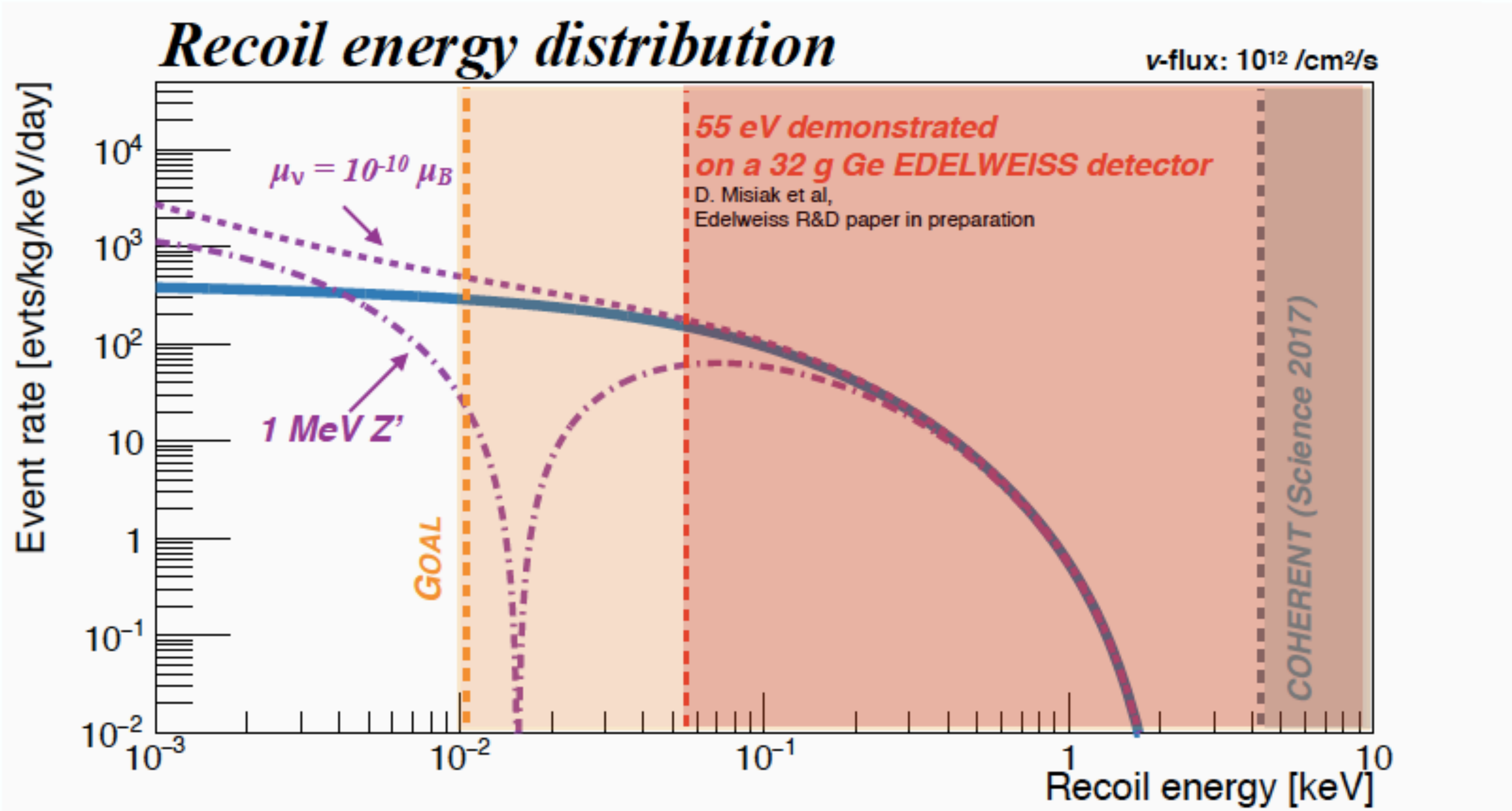

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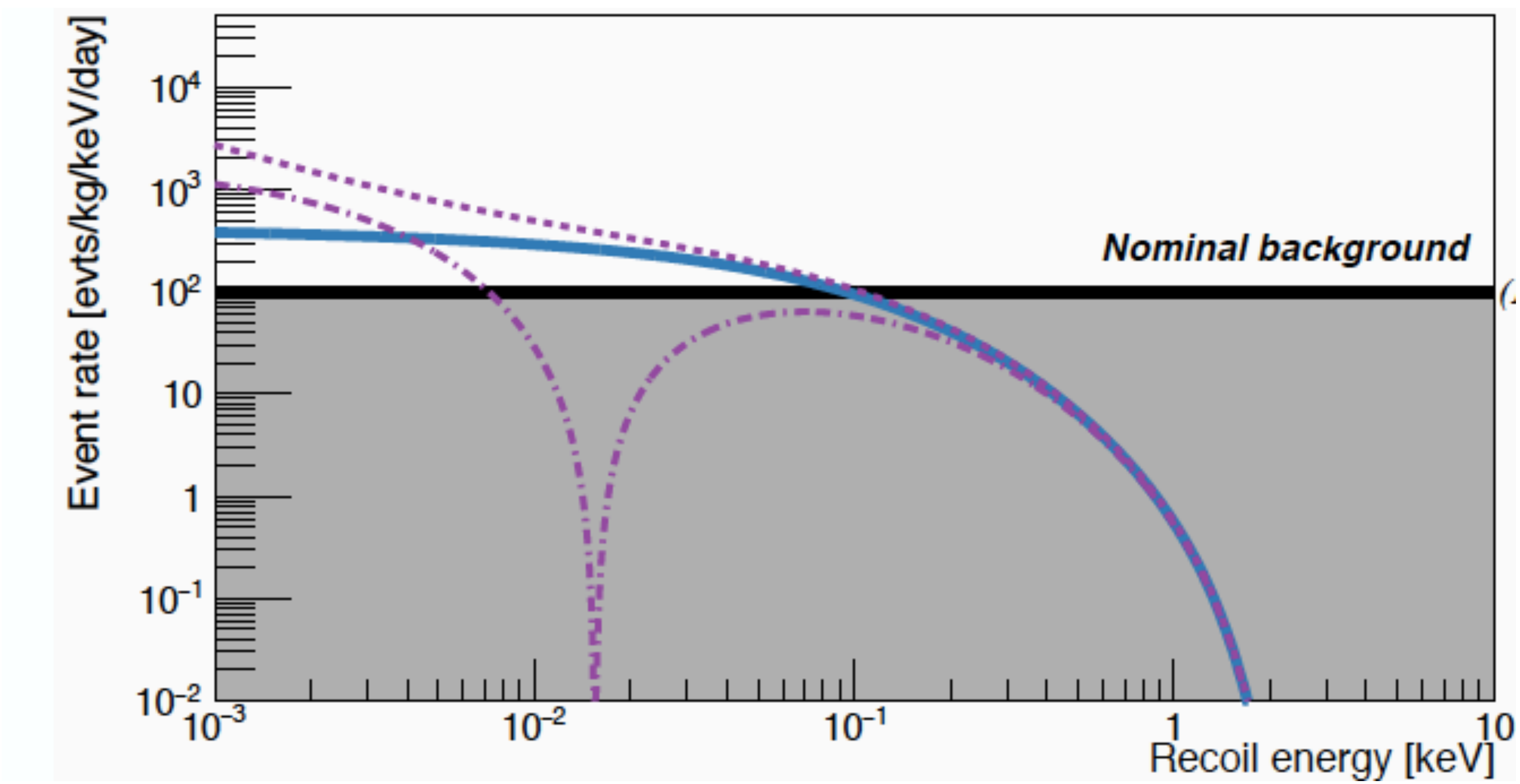

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- ***For factor of x1000 rejection, signal greatly enhanced for discovery potential.***

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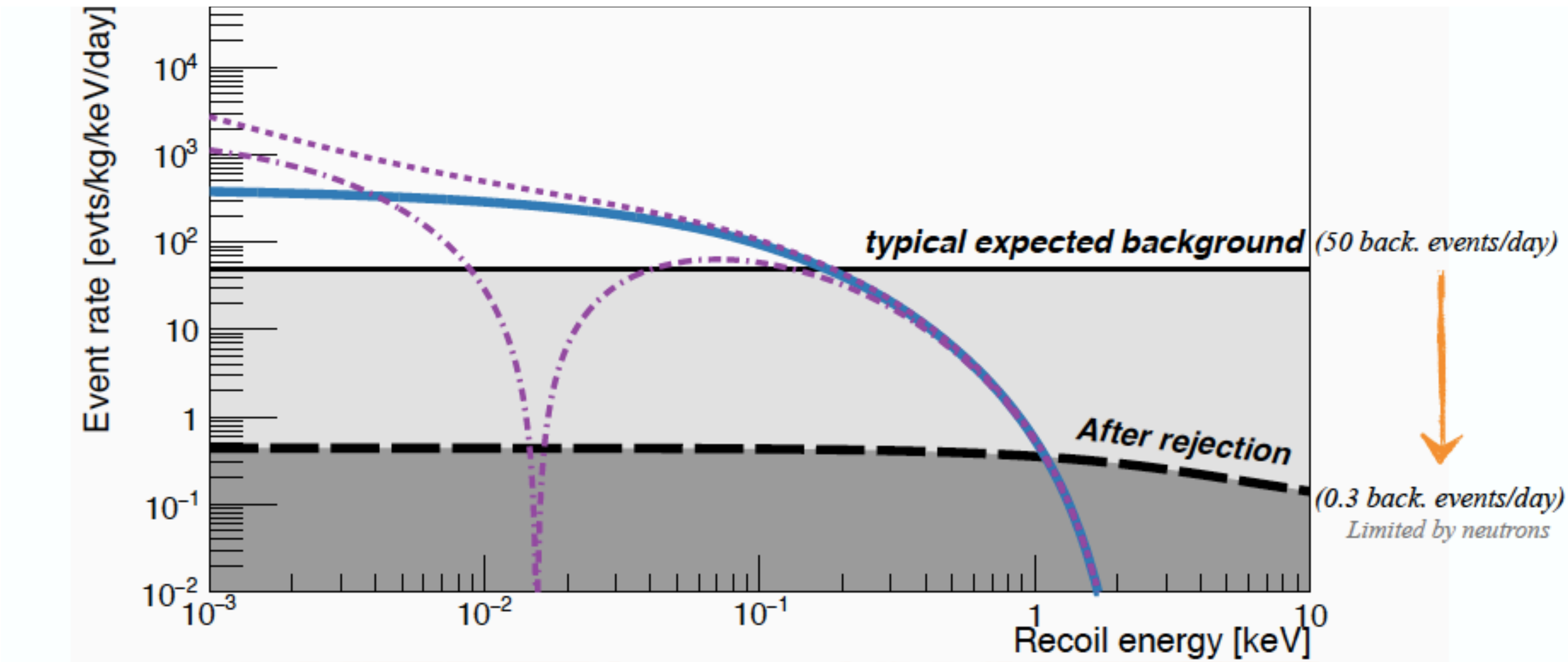

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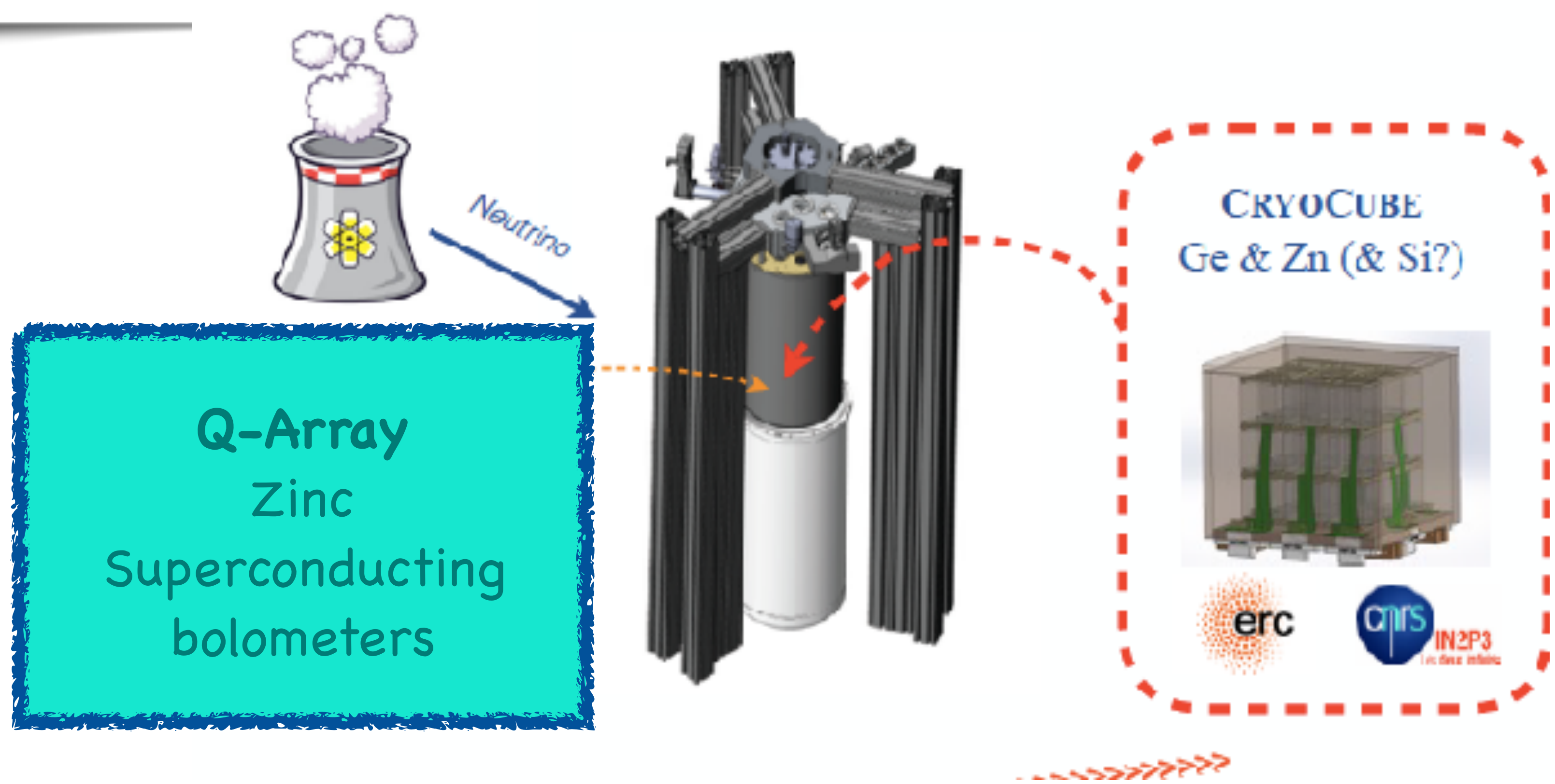
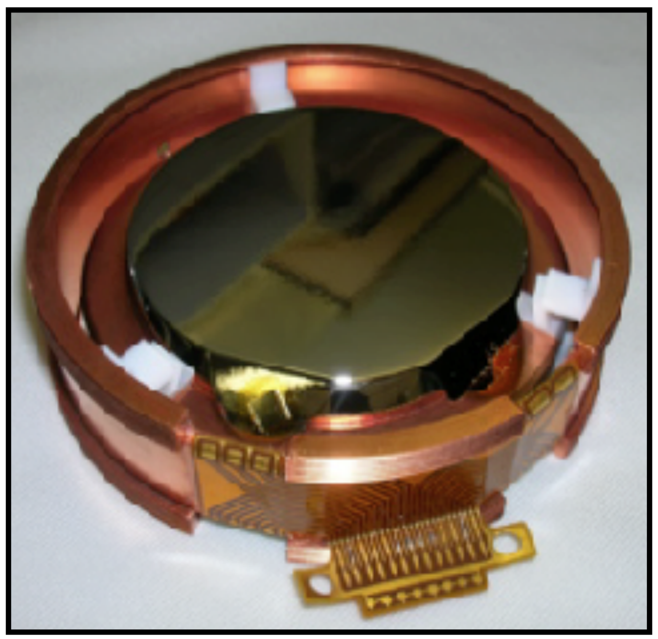


``The first low energy kg-scale CEνNS neutrino observatory combining different targets and different bolometric technologies"

What Kind of Detectors to Use?

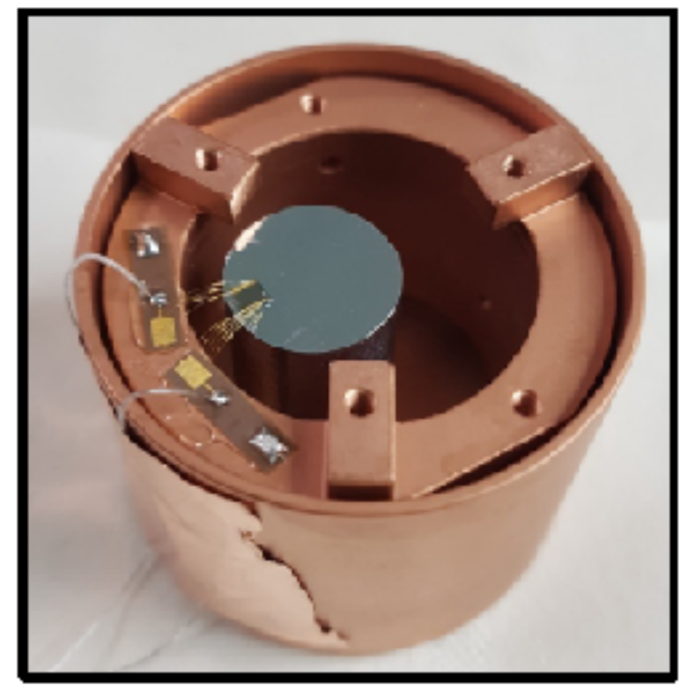
Leverage two technologies that are used by both the US and French groups.

This amplifies the science reach (complementary detectors) and reduces the science risk.



Germanium
Detectors

(based on EDELWEISS technology)



Superconducting Metals
(Zinc)

(new R&D effort**)

****Not really. Superconductors were also studied by Oxford, Milan and Genoa groups.**

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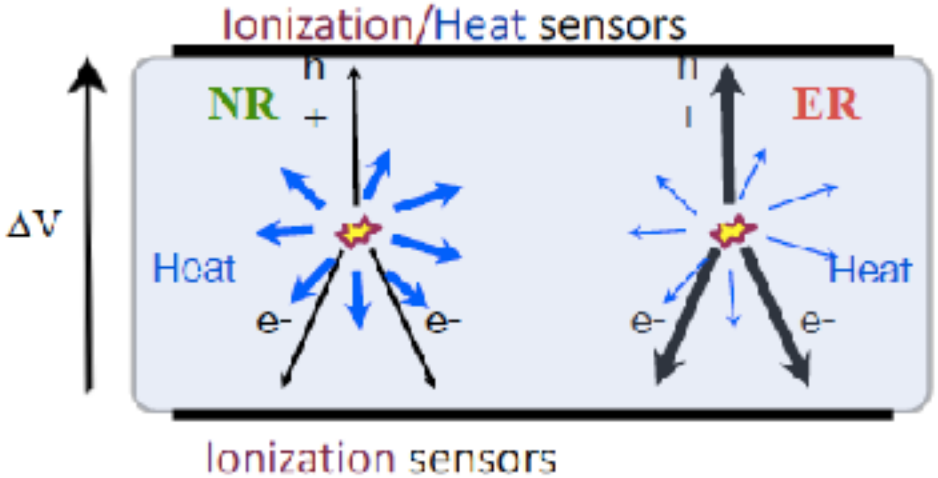

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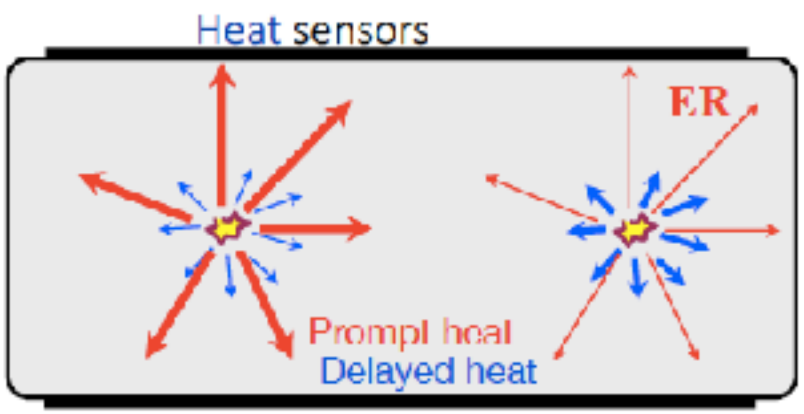

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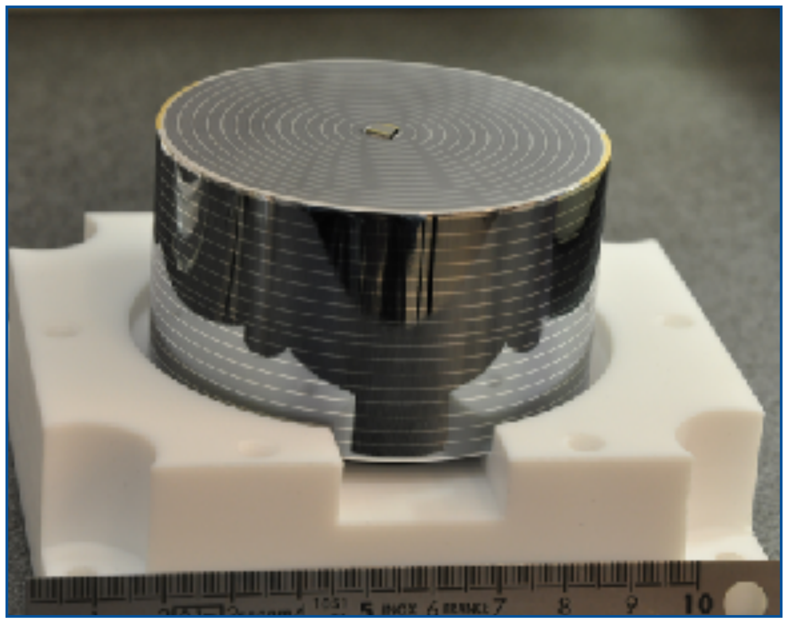
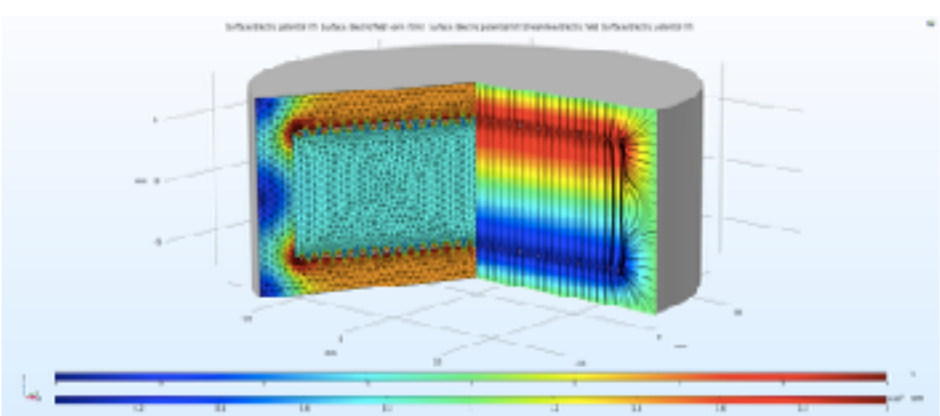
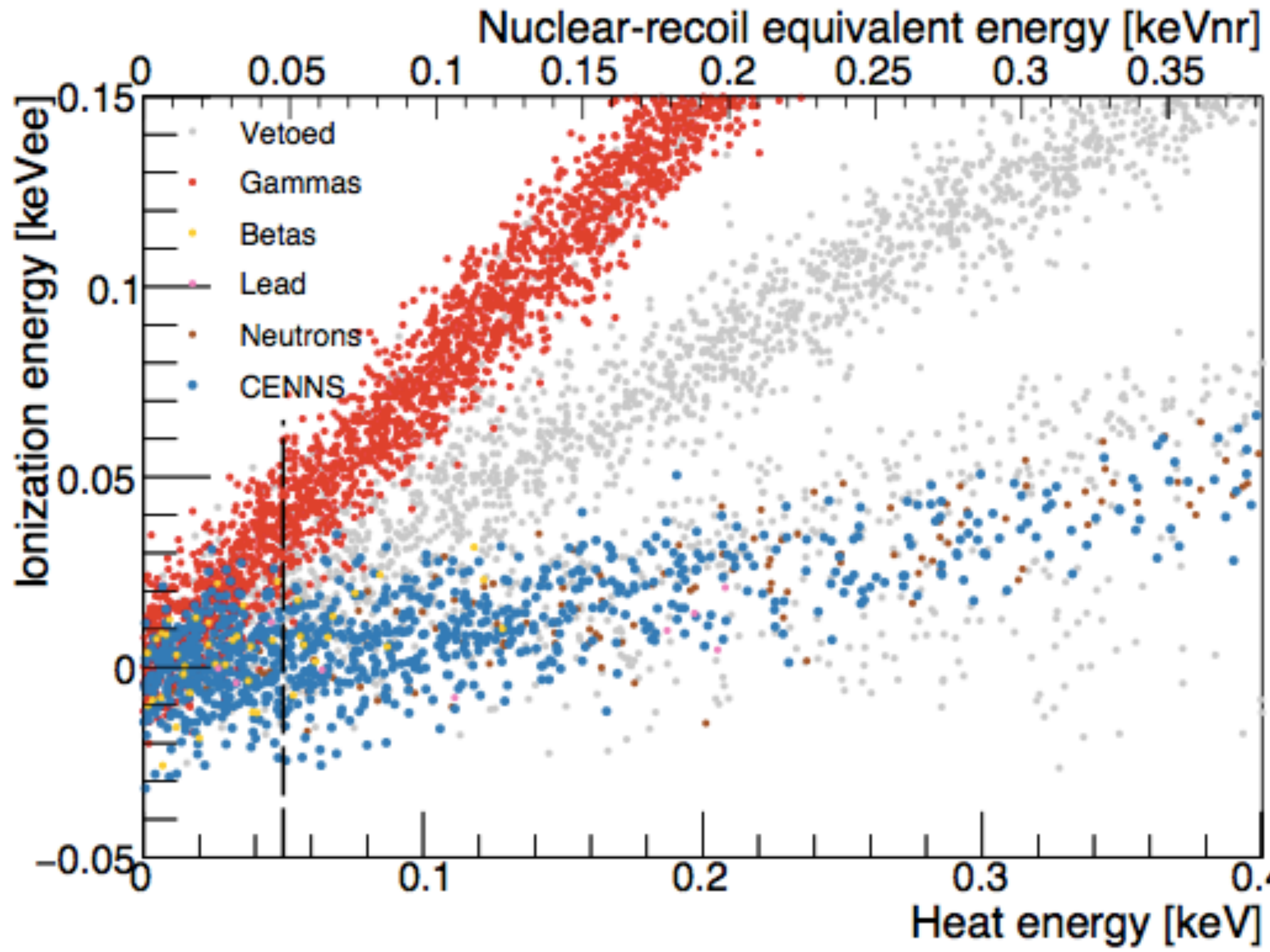
Germanium Approach



EDELWEISS-Based Ge-Detector



EM Field Model

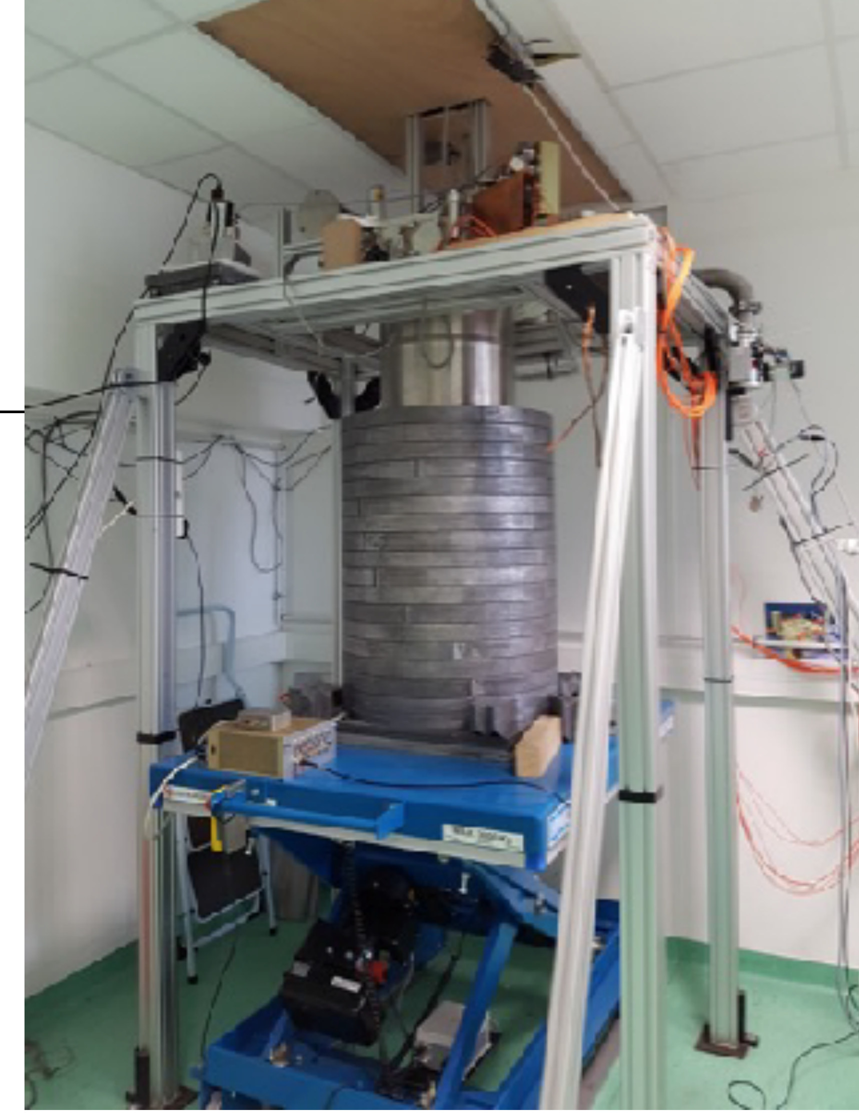


<u>Germanium Detectors:</u>

Separation of recoil from electromagnetic events using **heat** and **charge** signatures.

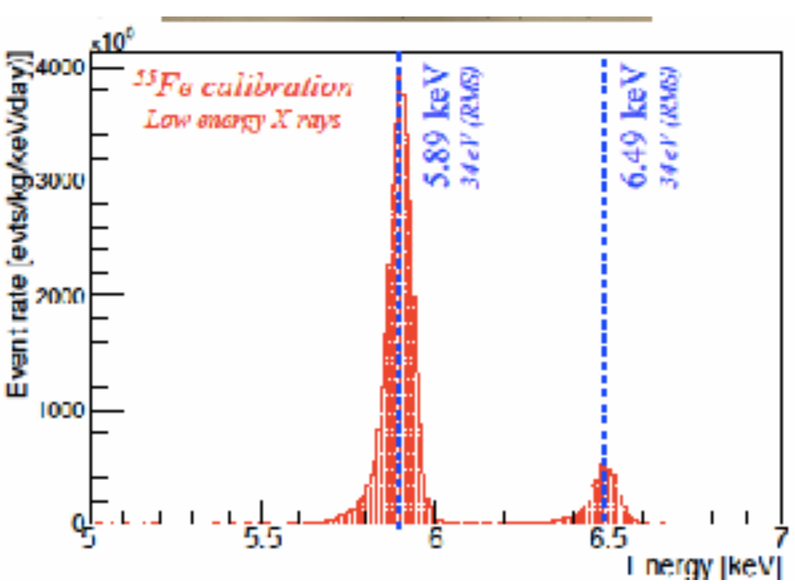
Ionization versus thermal phonon readout allows for recoil signal separation down to 50-150 eV thresholds.

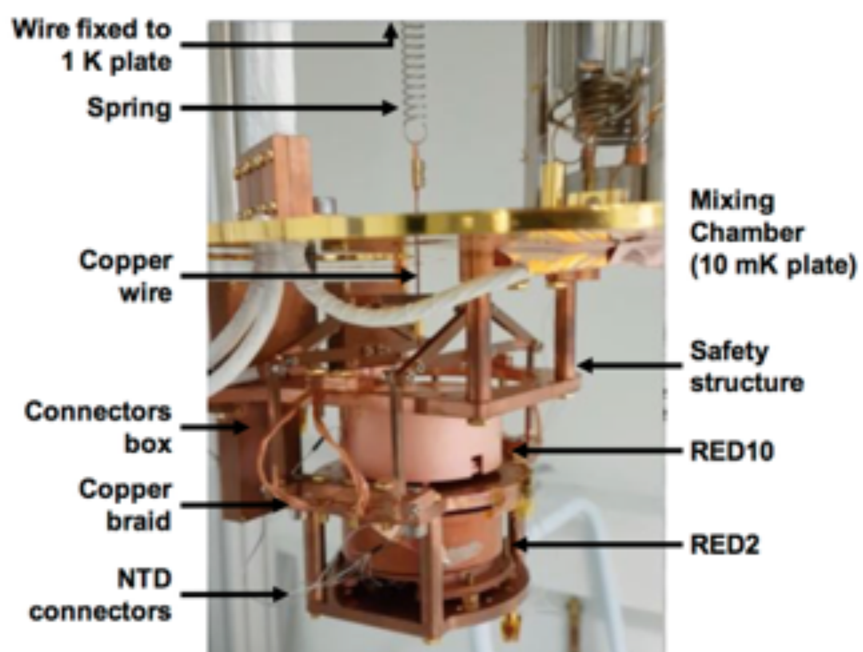
Prototype Detectors

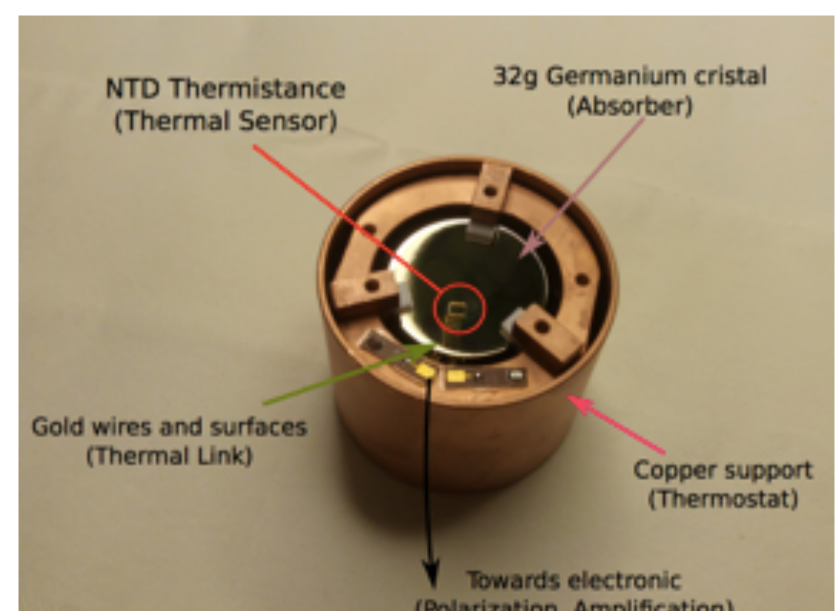


- A 32 g Ge-detector (RED-20) — built at Lyon— serves as a prototype for demonstrating the semi-conductor technology.

18 eV energy resolution (RMS)
55 eV energy threshold with a 32 g detector (Ge)
stability at few ~% level

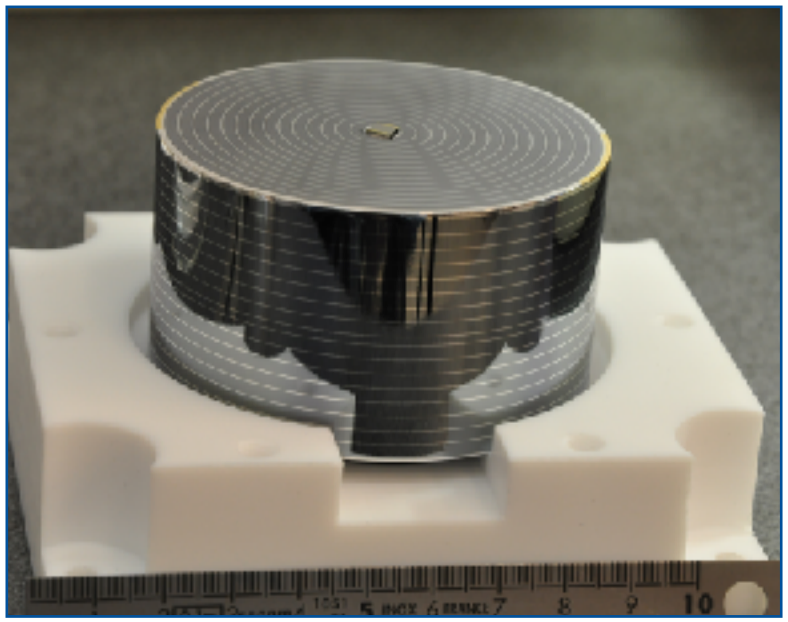






E. Armengaud et al., arXiv:1901.03588

Germanium Approach



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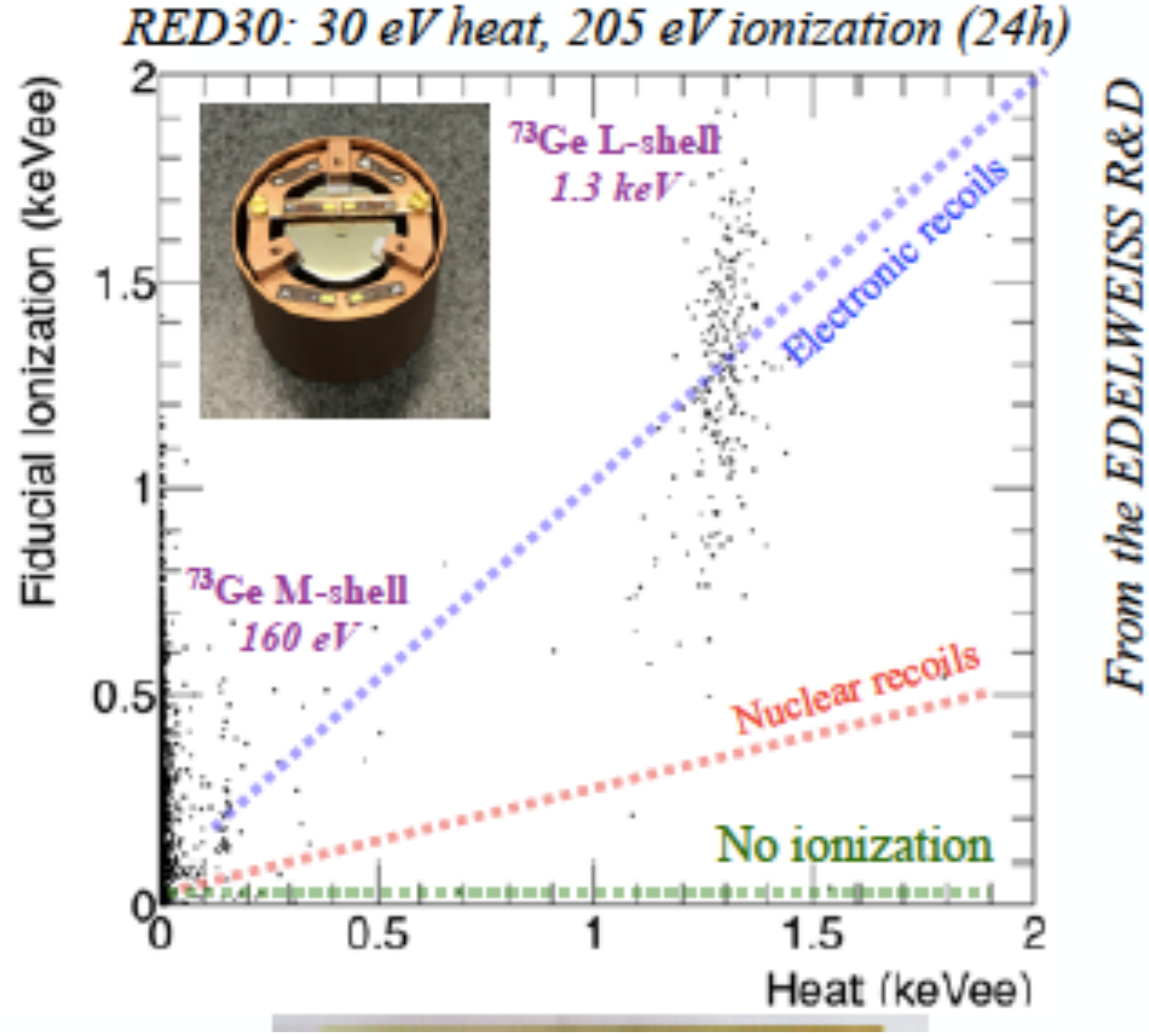
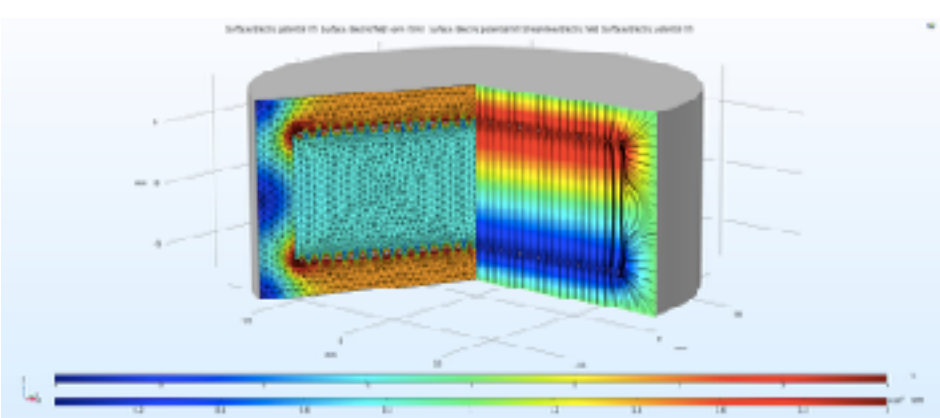




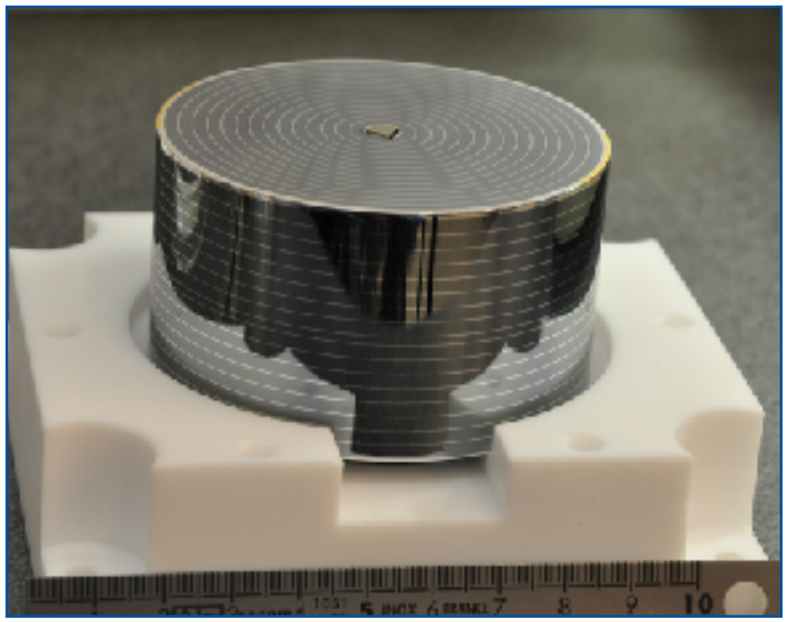
EM Field Model

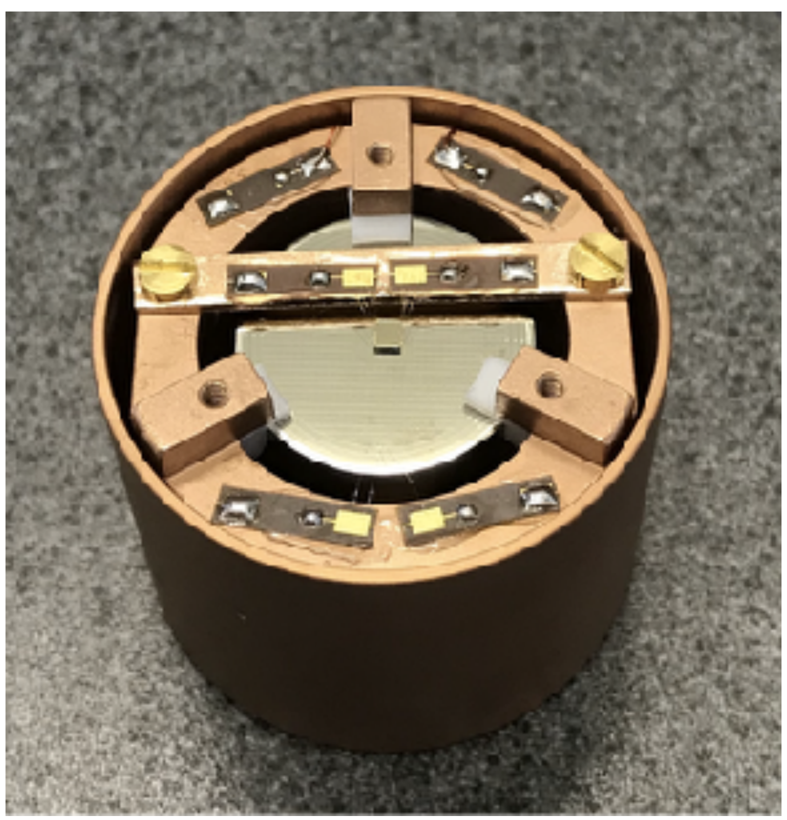
Germanium Detectors:

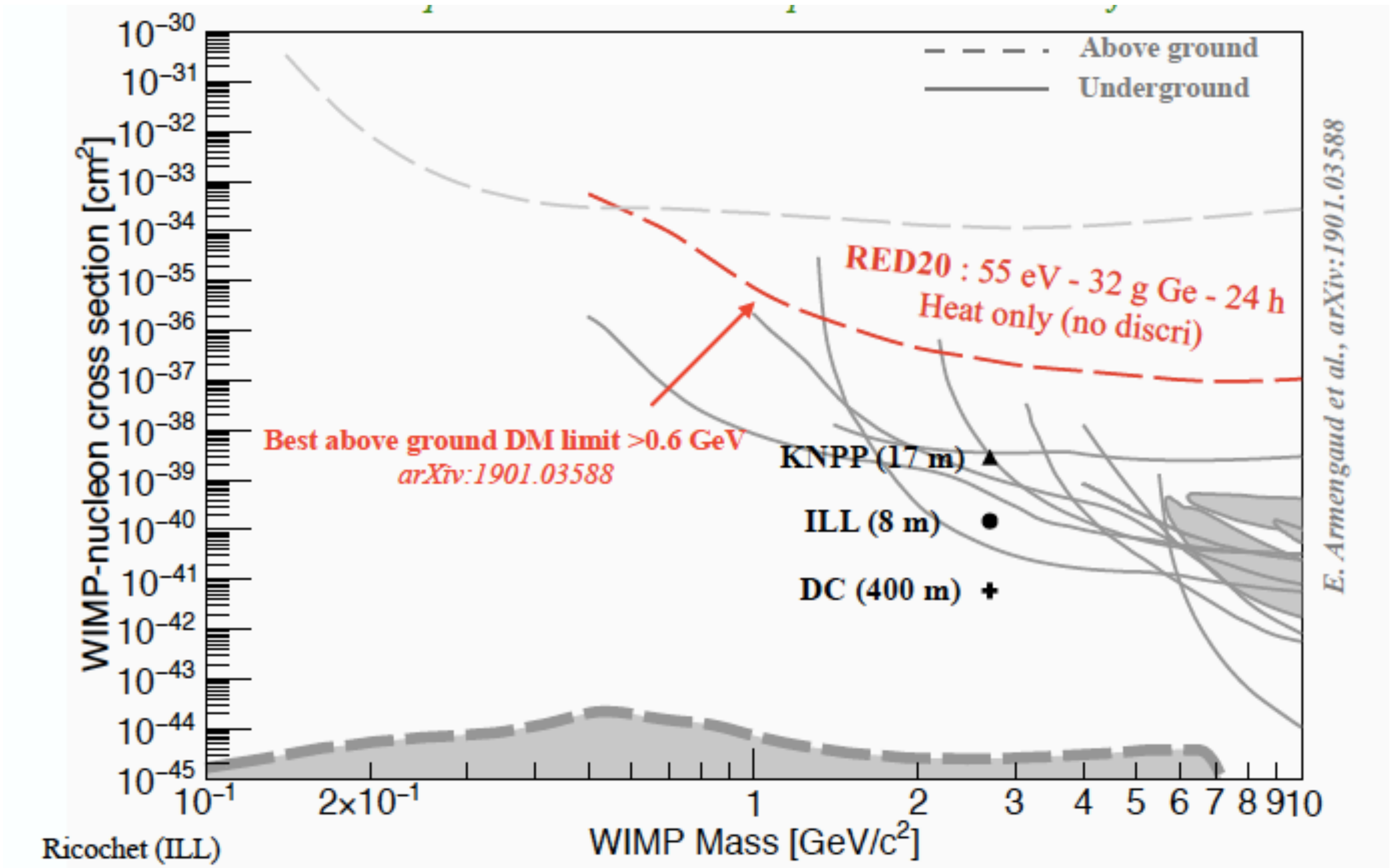
ER/NR discrimination limited only by ionization resolution (200 eV). Need to reach 20 eV (best achieved 90 eV (arXiv:1611.09712)).

- HEMT have lower intrinsic noise than JFET
- O(10) eV resolution achievable with 10 pF input
- First Cryo HEMT preamp being tested in Lyon

Dark Matter Limits on Surface







- Neutrino-WIMP equivalent model independent of target material
- CEvNS signal from reactor neutrino is similar to a 2.7 GeV WIMP
- The equivalent cross section depends on the neutrino flux

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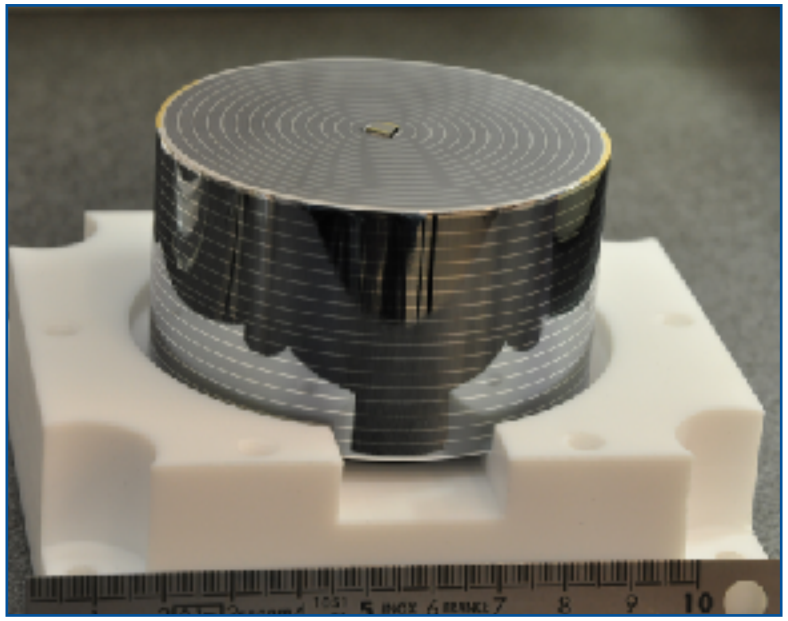

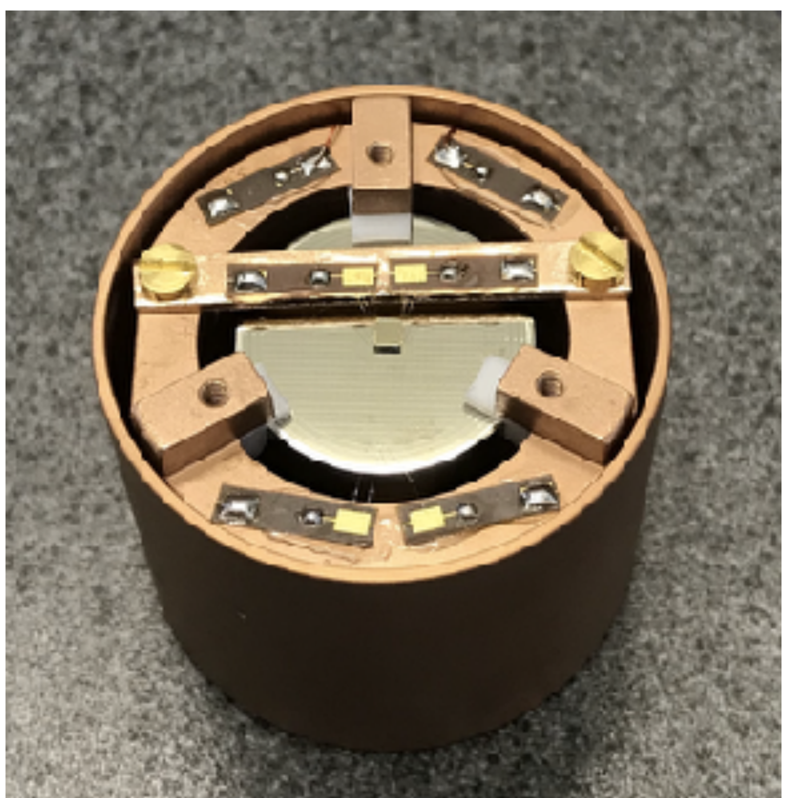

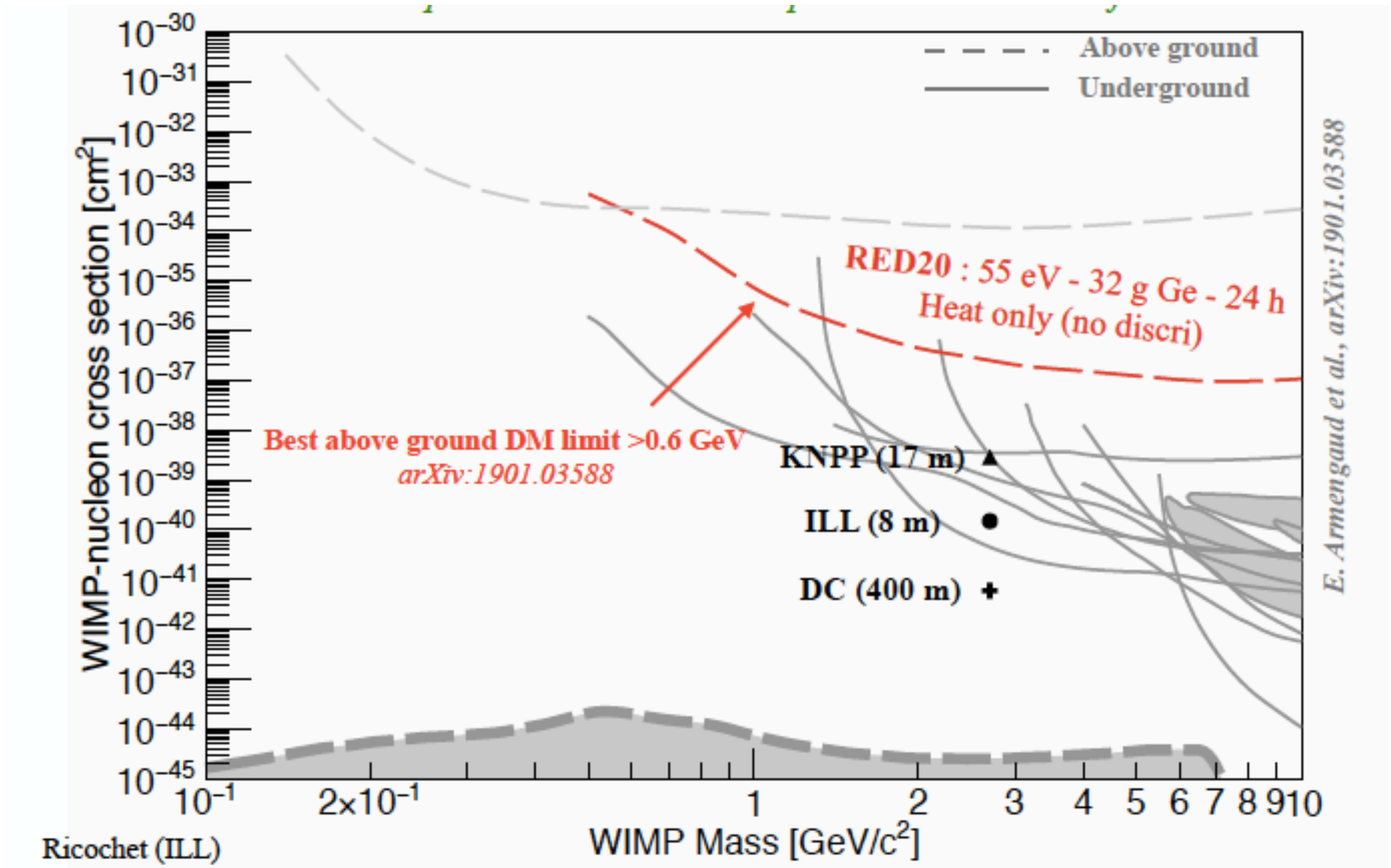

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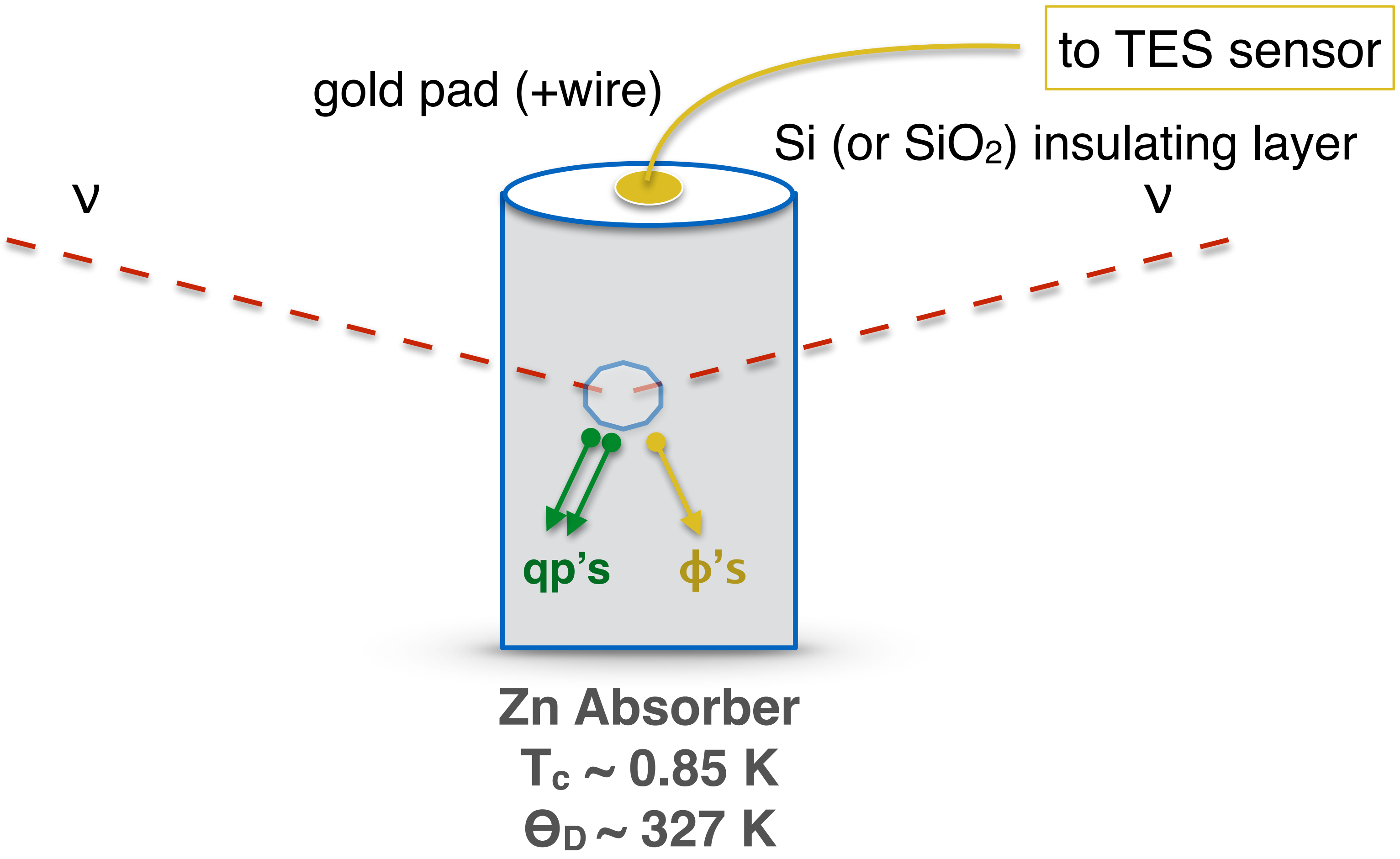
- The equivalent cross section depends on the neutrino flux

Much of the risk reduced through demonstration!

Why Superconducting Metals?



Metallic Superconductors as Detectors:

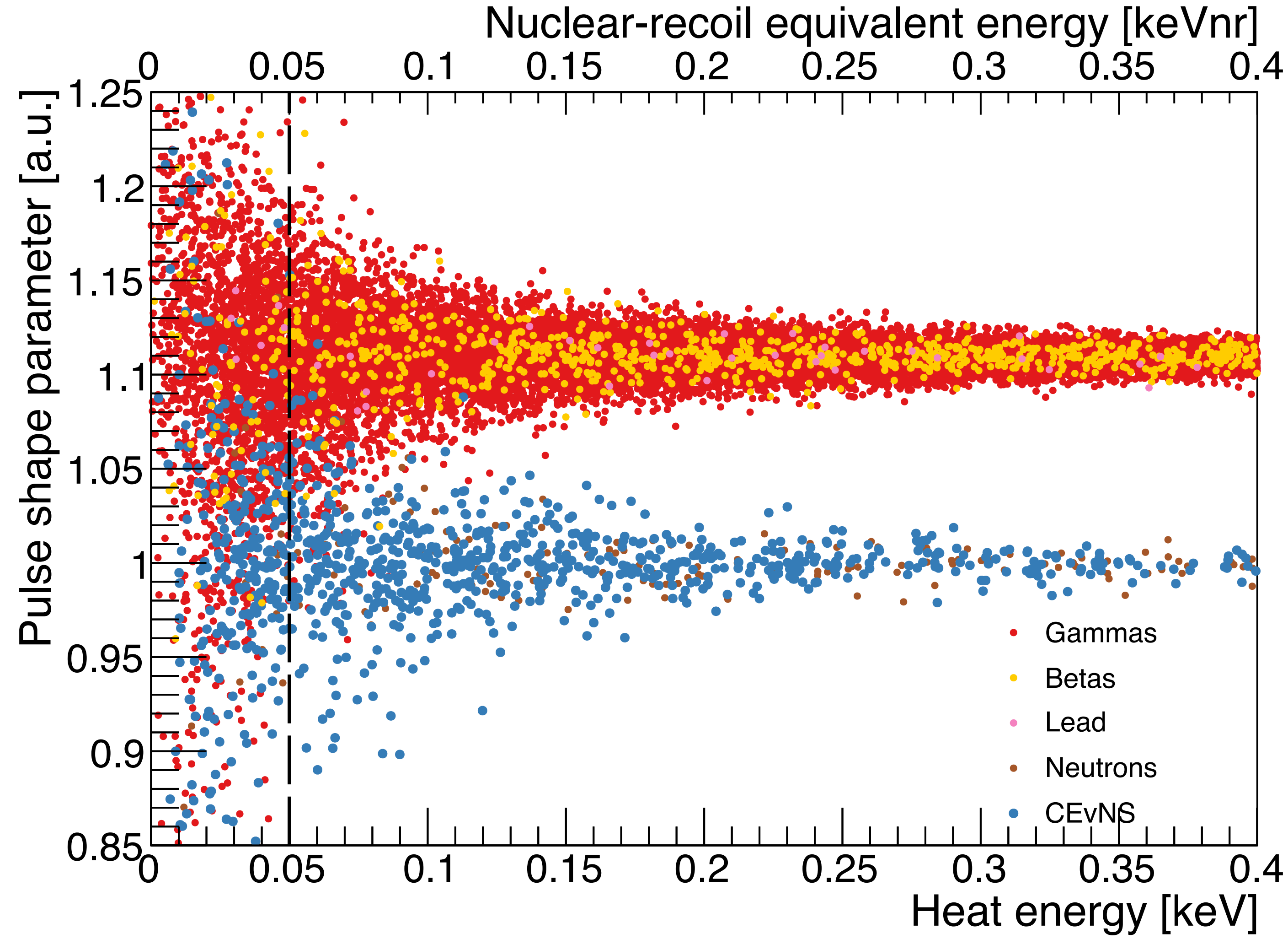
Zinc crystals become superconducting below 850 mK. If operating at 15 mK, this is well below Tc. Implies that capacitance dominated by lattice contributions (scale as T^3).

High Debye temperature implies low capacitance.

Target atomic number very similar to germanium.

Energy breaks Cooper pairs; turning into either **quasi-particles** or **phonons**.

Why Superconducting Metals?



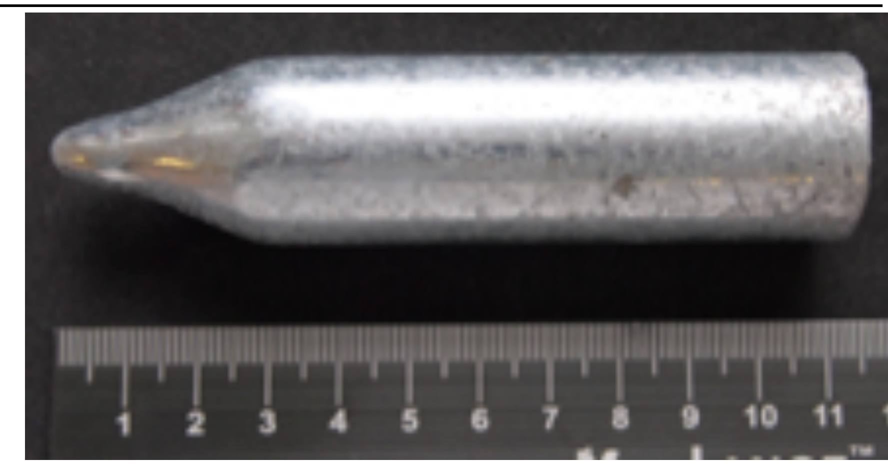
Metallic Superconductors as Detectors:

However, quasi-particles and phonons do not evolve in the same way.

Recombination times for quasi-particles become extremely long at low temperatures (~ seconds), while (a)thermal phonons operate at much different (faster) time scales.

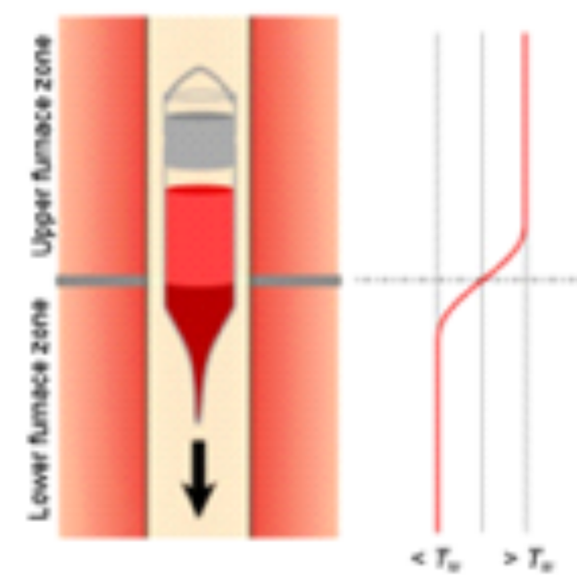
Separation of recoil from electromagnetic events using **quasi-particle** versus **athermal phonon** timing signatures should be explored.

Zinc Detectors

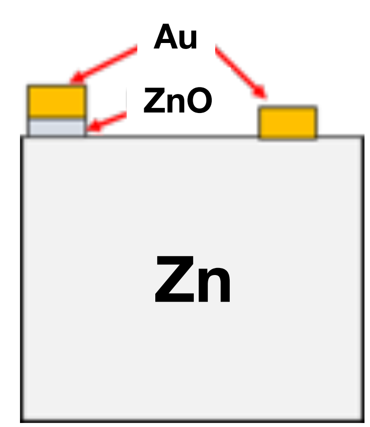


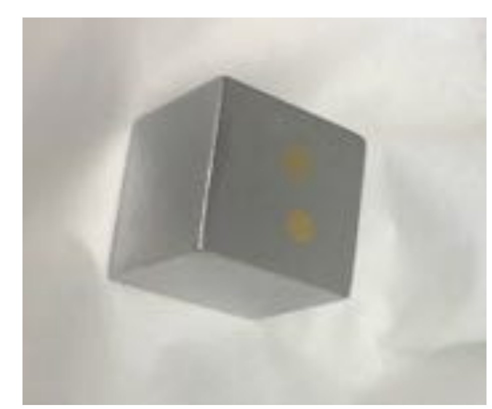
- Prototype single crystals are now being made thanks to a contract with RMD, Inc. (specializes in low background detector crystals).

- Crystals grown from zinc and aluminum ampules now readily made, without much difficulty (Bridgman method).



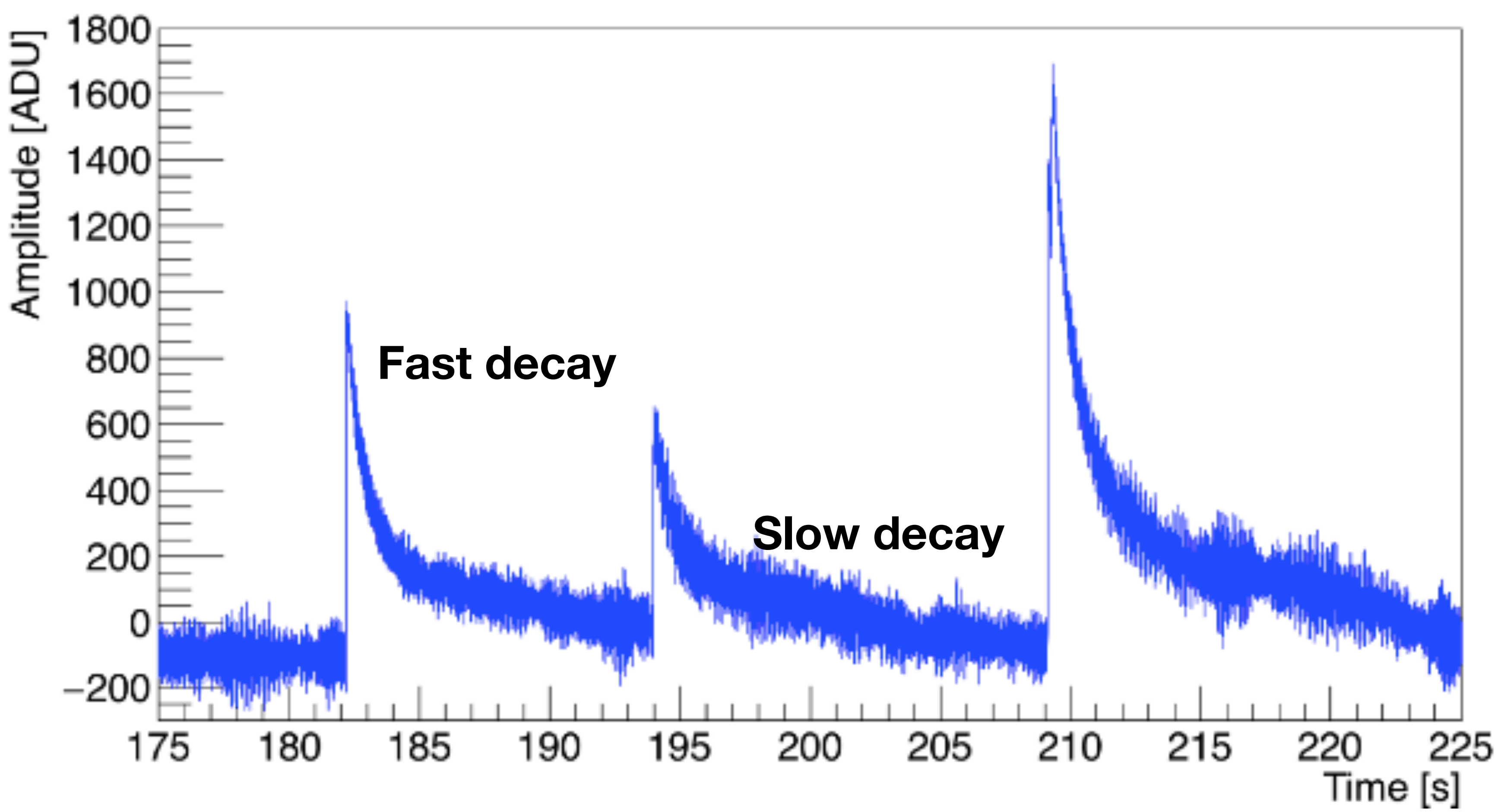
- Have in hand several 25-40 gram zinc crystals, small Al crystals also produced.





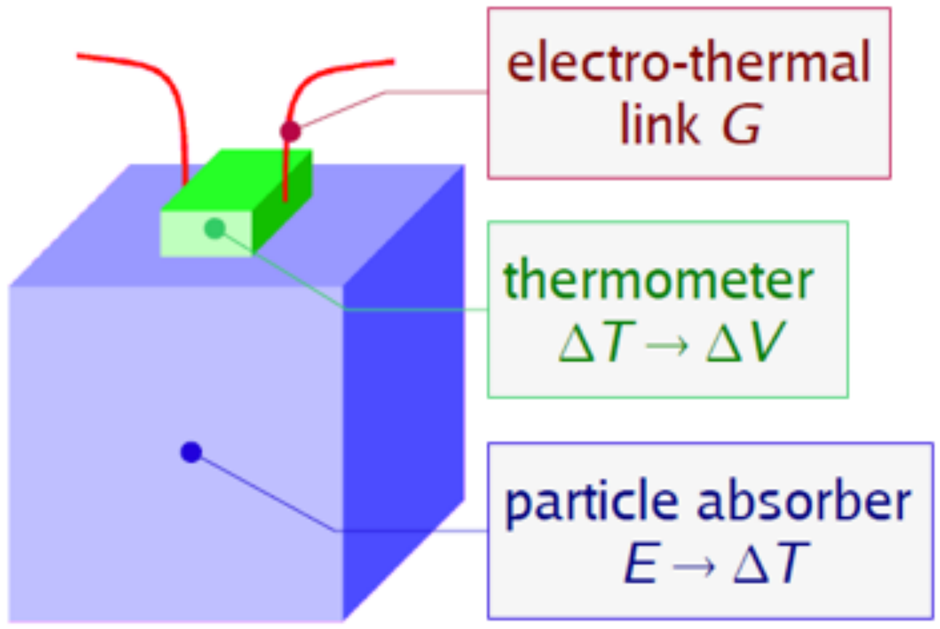
- Switched to cubes, to allow better polishing on all surfaces.

First (and Second) Pulses!

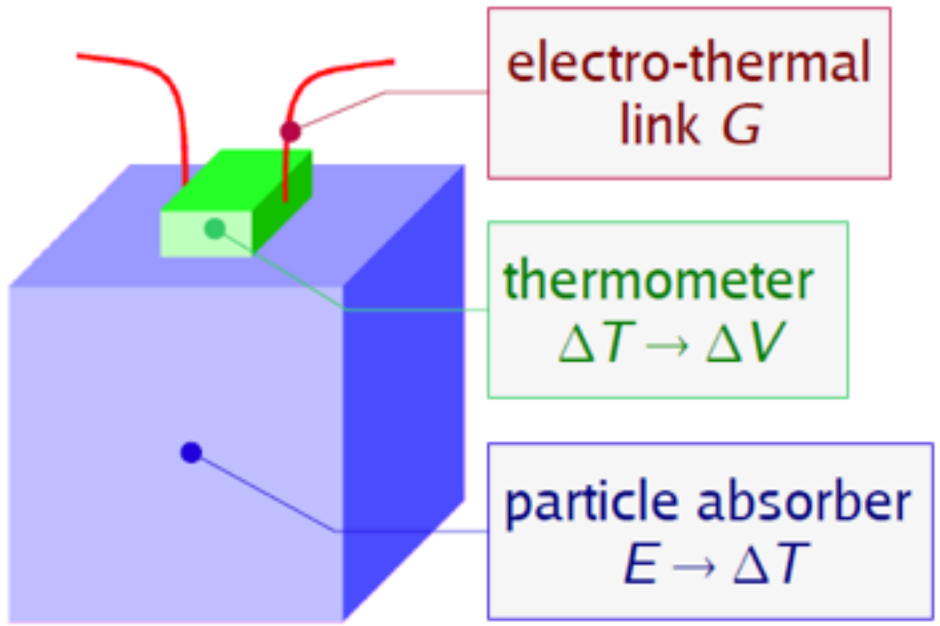


- First zinc crystals cooled to 15 mK and tested. First pulses seen!
- New zinc crystals also tested at cryogenic temperatures. Extremely long pulses with different decay times observed.
- Analysis underway to characterize pulses, energy resolution and particle identification.
- Note: This is thermal (not athermal) readout of pulses.

Readout Scheme



Readout Scheme

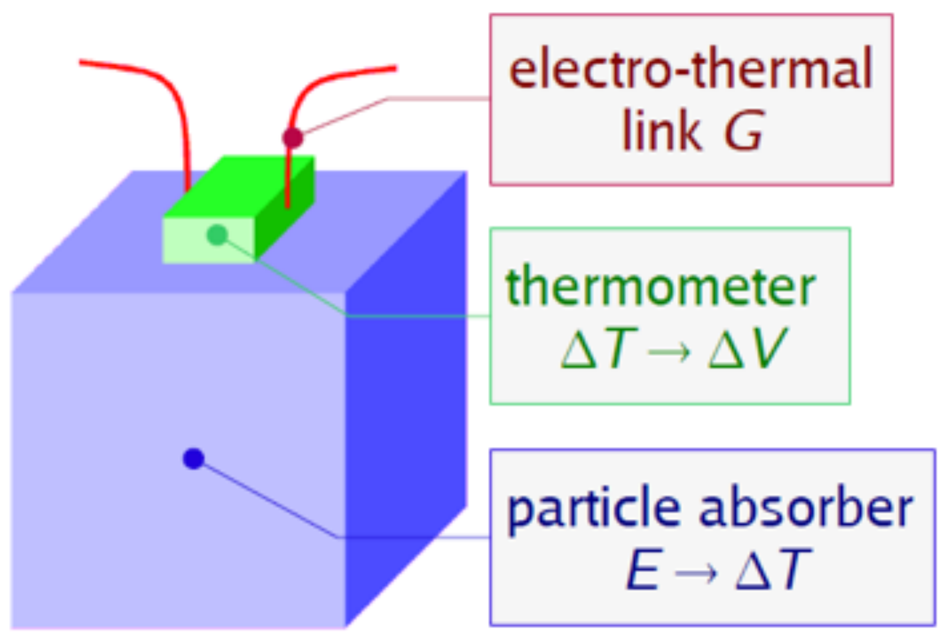


The **absorber** allows conversion from energy to heat (phonons)

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

Small detectors & low temperatures
=
lower thresholds

Readout Scheme



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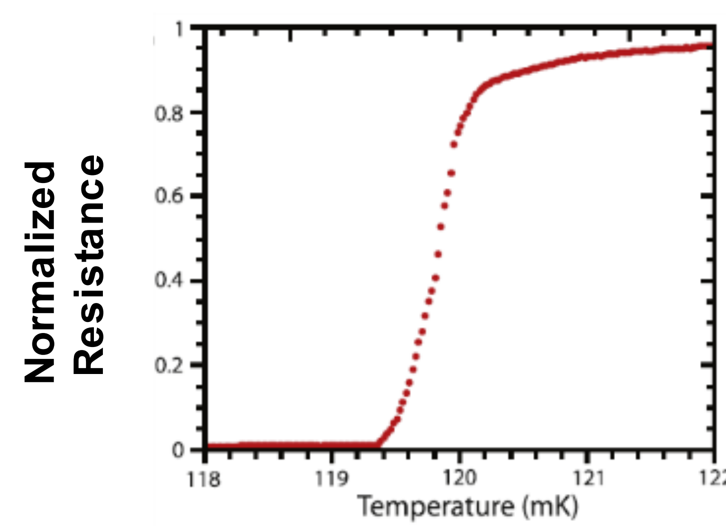
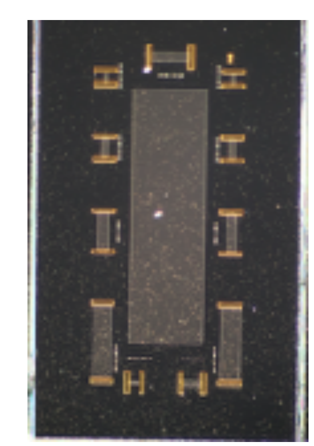
Small changes in temperature can be captured by **Transition Edge Sensors** (TES), which allow great sensitivity to small temperature depositions.

TES Resistance @ Tc





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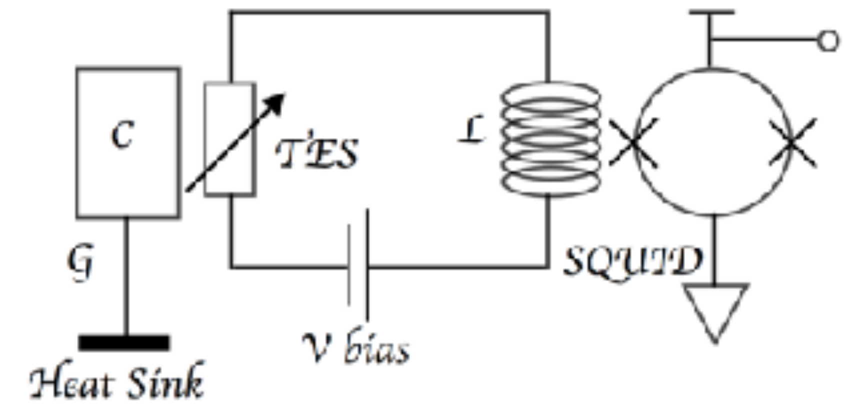

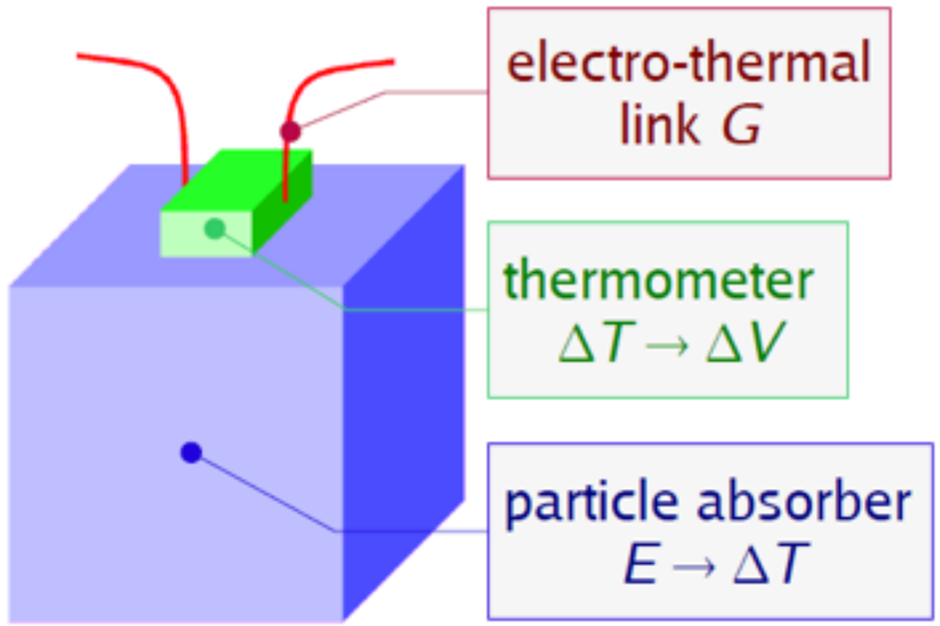

Readout of TES done using **SQUID** amplifiers, quantum-limited magnetometers, ideal for small currents.

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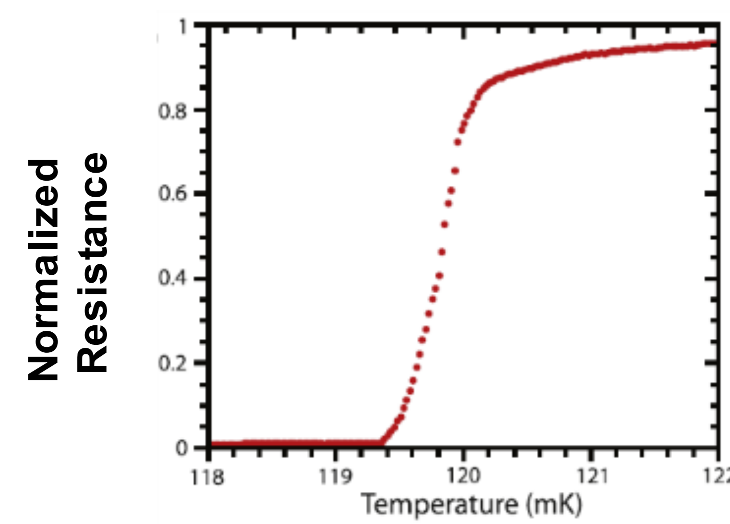
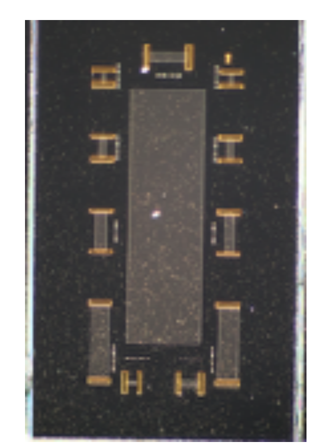
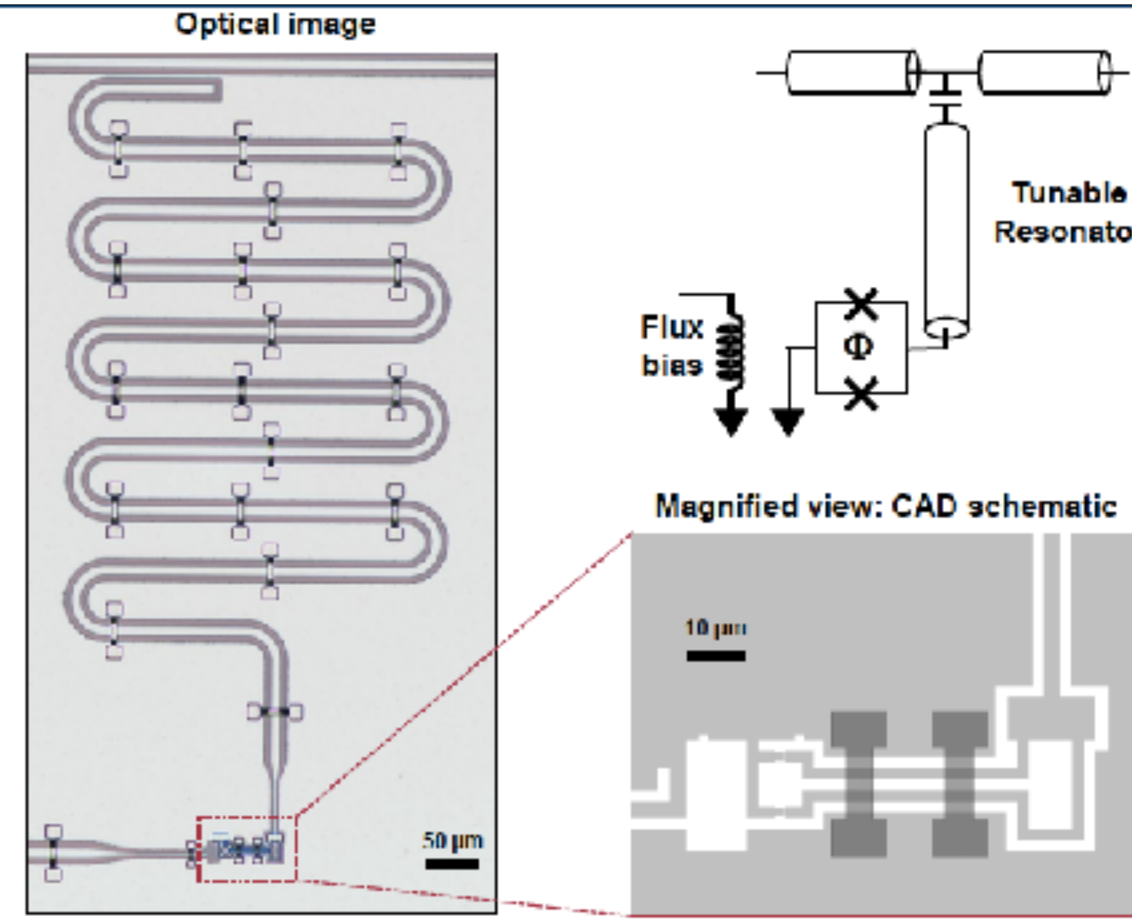


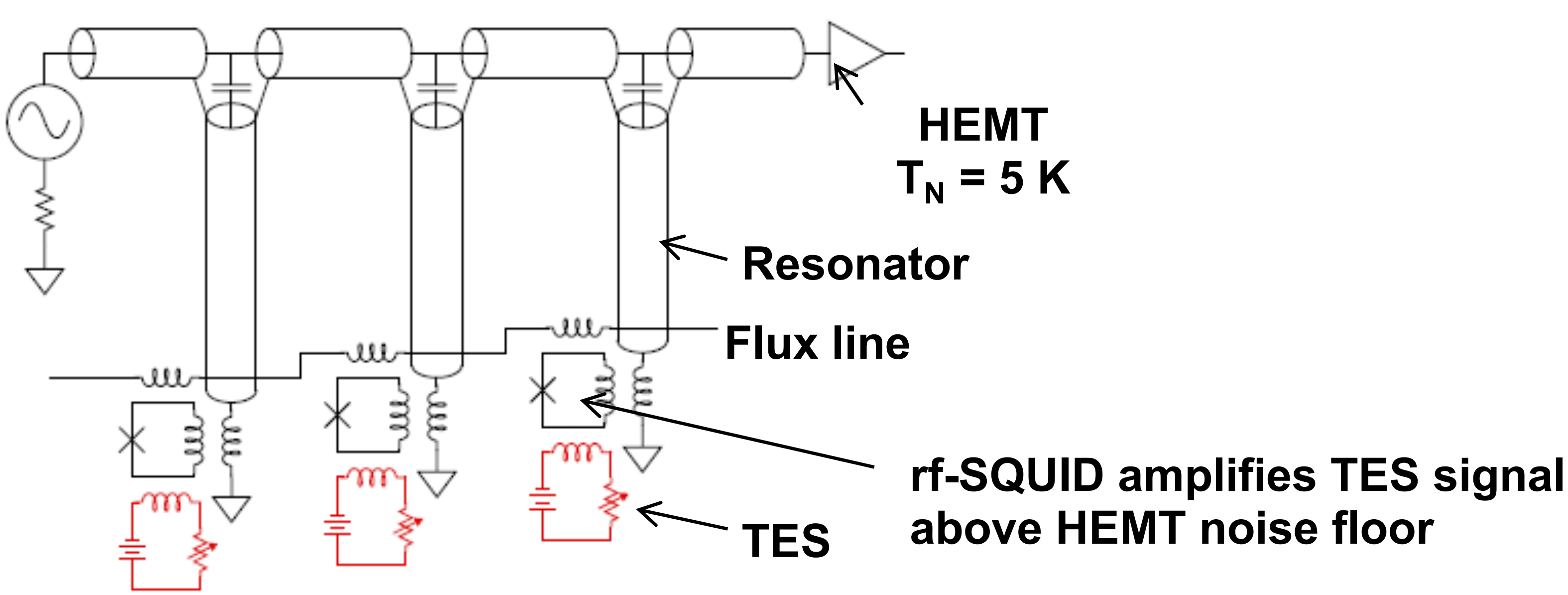


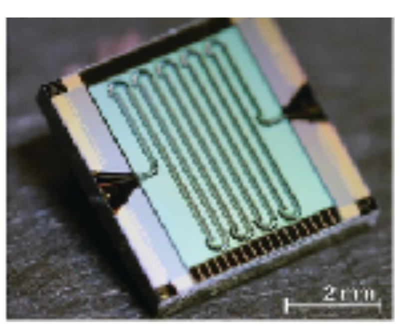
SQUID Readout

- Successfully secured ACC grant with **Lincoln Laboratories** to work on multiplexing SQUID array.
- Leverage large fabrication infrastructure for development of **quantum readout devices**.
- 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 (around 7 GHz).



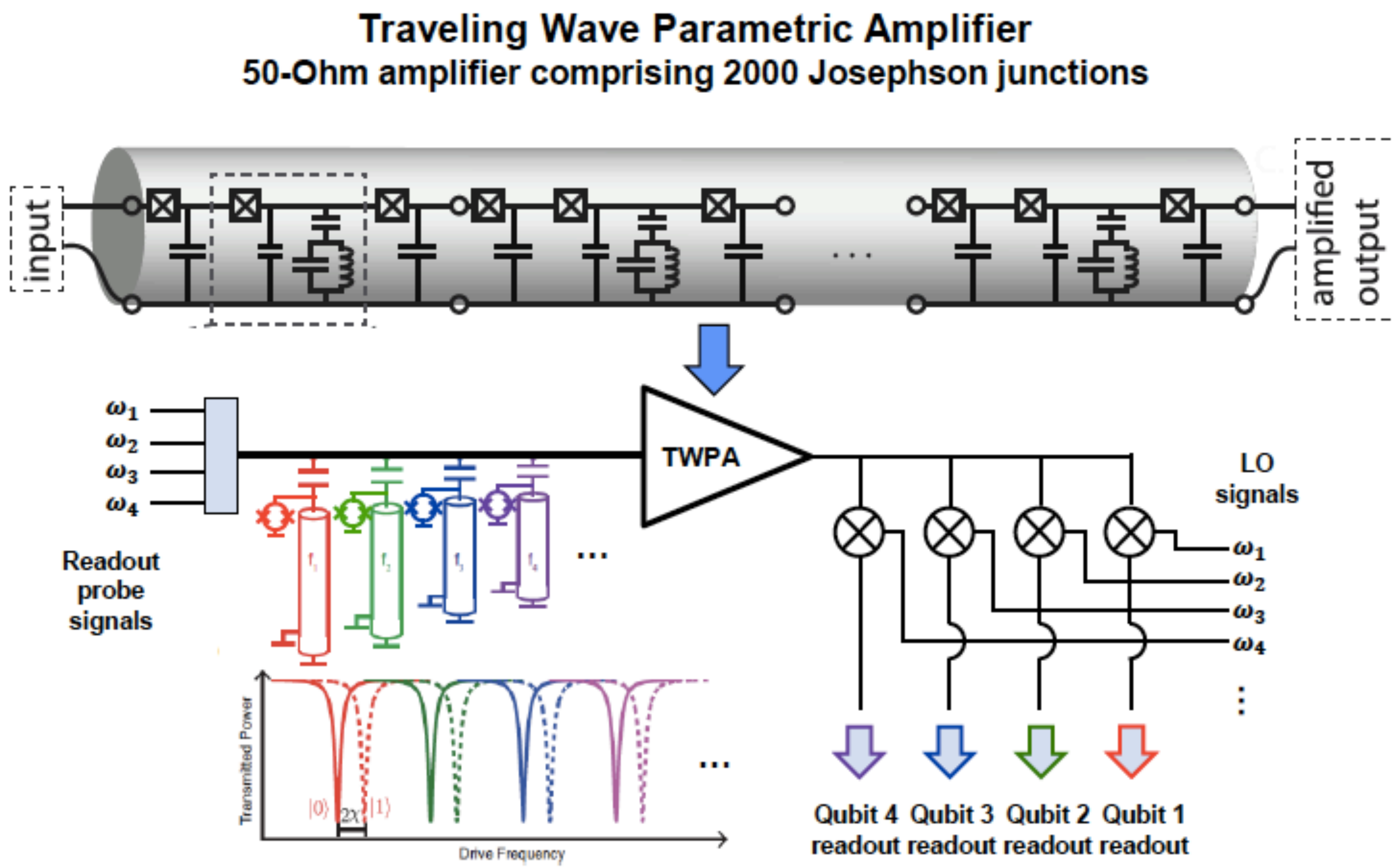
uMux Schematic





Traveling Wave Parametric Amplifiers

Traveling Wave Parametric Amplifiers



TWPA has sufficient dynamic range to read out 20+ qubits using standard frequency multiplexing and mod/demod techniques

C. Macklin et al., Science 350, 307 (2015)

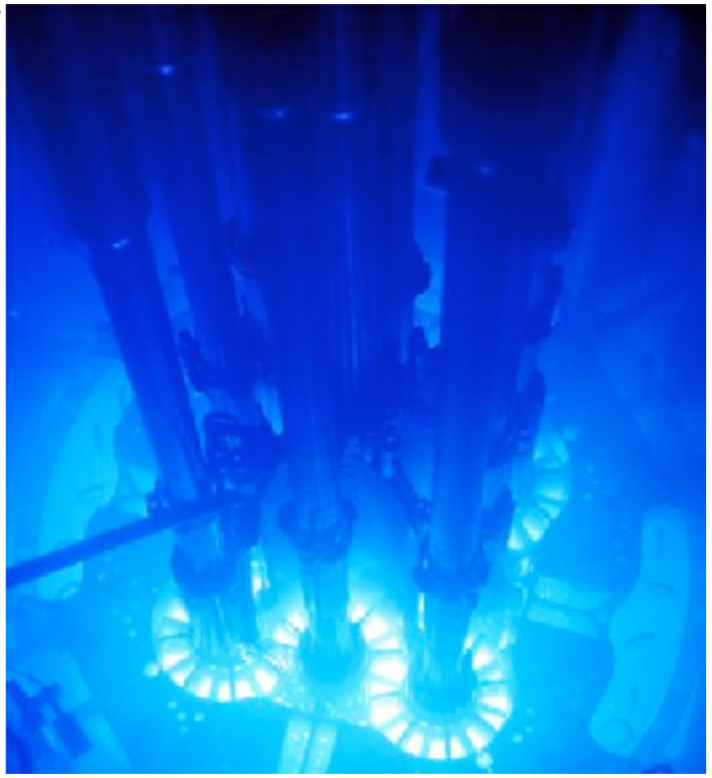
RICOCHET

Science

Detectors

Location

Neutrino Sources

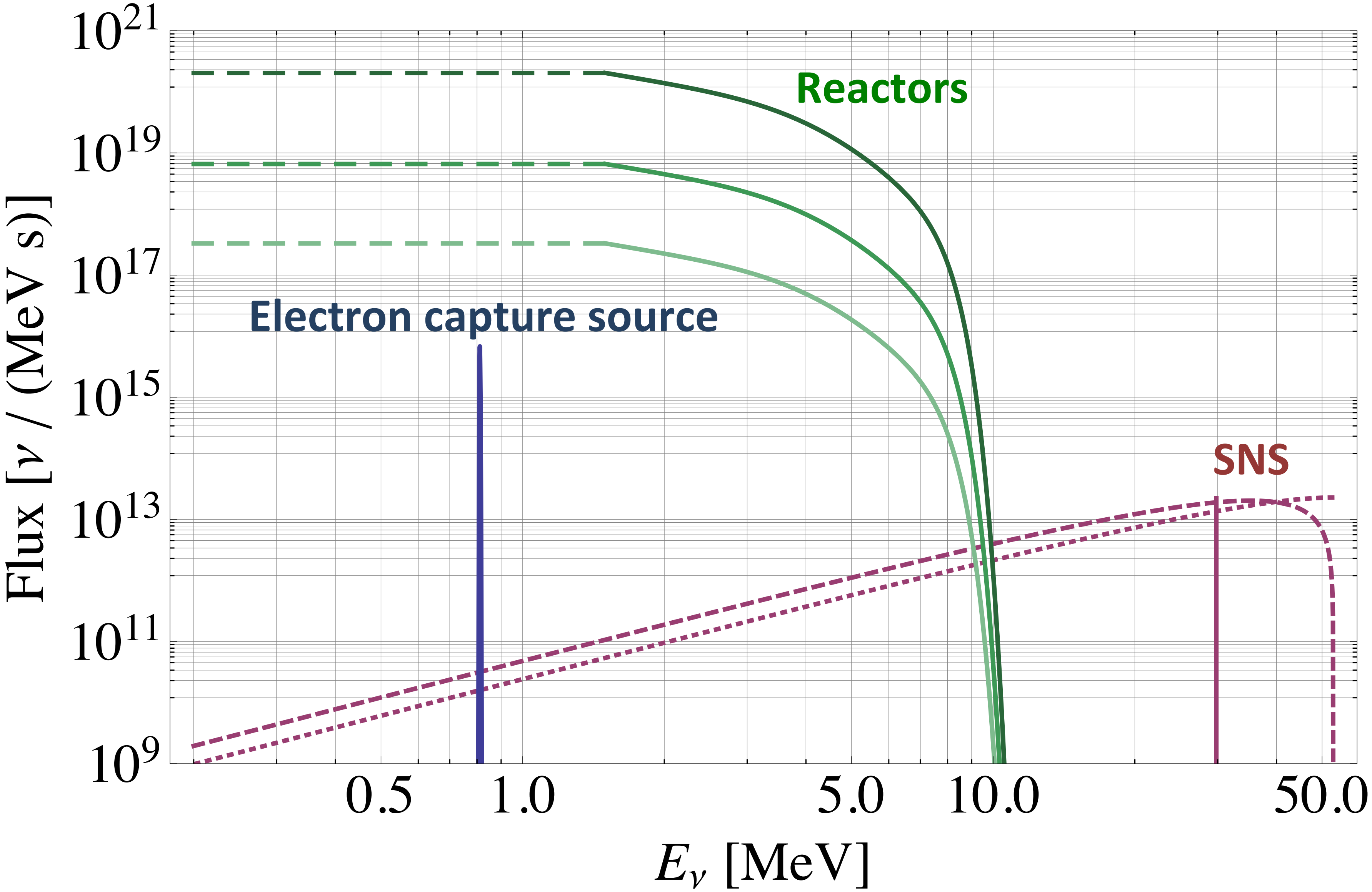


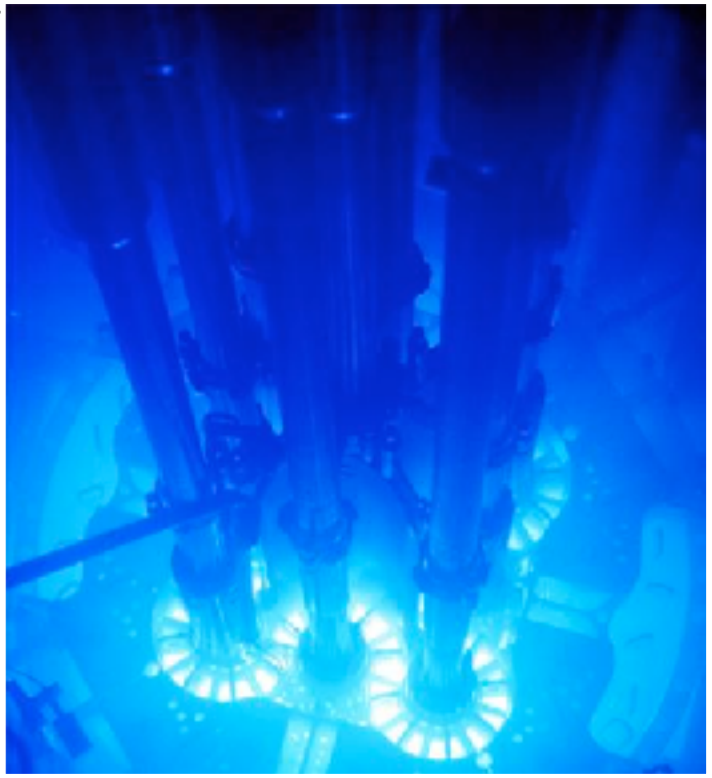
- The variety of sources trade off flux, energy and knowledge of spectrum.

Sources	Pros	Cons
Radioactive Sources (Electron Capture)	Mono-energetic, can place detector < 1m from source, ideal for sterile neutrino search	< 1 MeV energies require very low (~10 eVnr) thresholds, limited half-life, costly
Nuclear Reactors	Free*, highest flux	Spectrum not well known below 1.8 MeV, site access can be difficult, potential neutron background
Spallation/Decay at Rest	Higher energies can use higher detector thresholds, timing can cut down backgrounds significantly	Prompt neutron flux; large shielding or distances needed

Neutrino Sources

- The variety of sources trade off flux, energy and knowledge of spectrum.





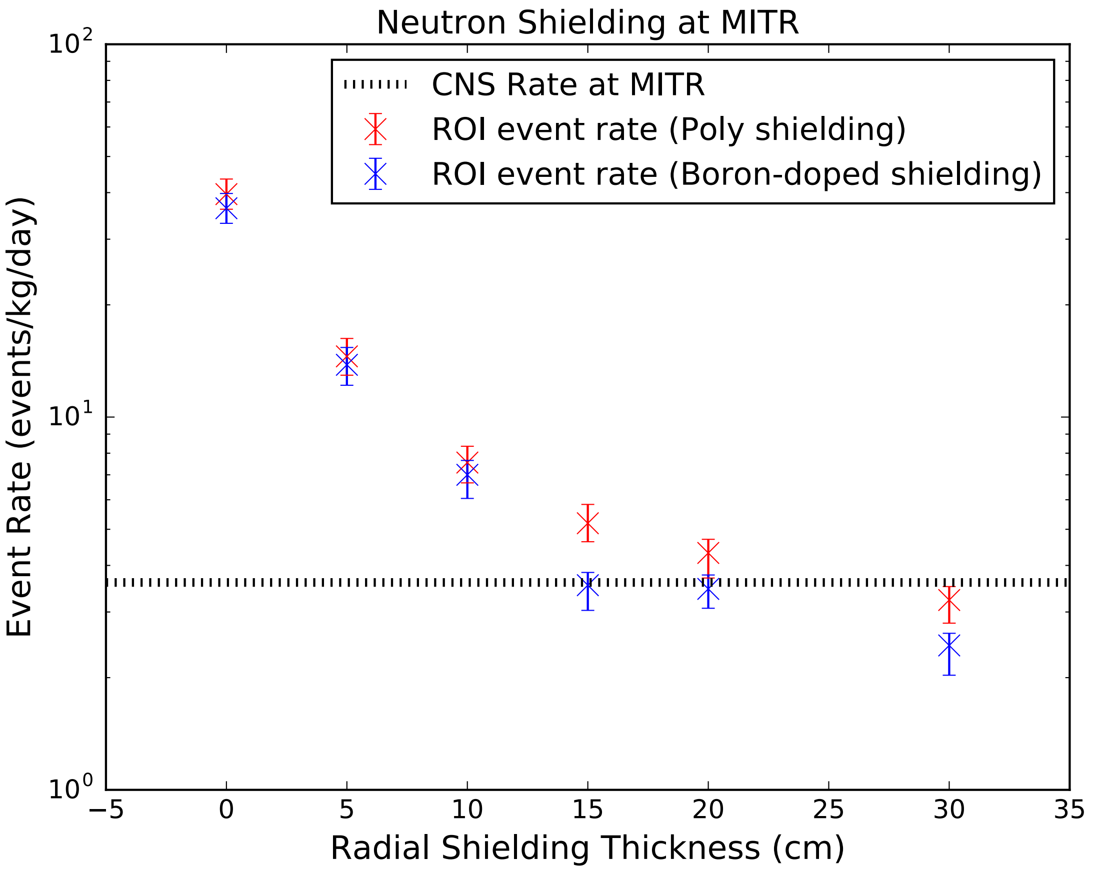
Range of Detection

- The following table lists the potential detection and rate capability assuming a 1 kg target detector and a 50 eV energy threshold. This is the reach from current technology.
- Megawatt reactors can yield rates at meter-scale distances; Gigawatt reactors at hundreds of meters distances.

	Power (Megawatts)	Distance (meters)	Neutrino Flux	Detected Events (per day)
Double Chooz (France)	4250	400	5×10^{10} ν/cm²/s	0.6
MITR (USA)	5.5	4	6×10^{11} ν/cm²/s	7.4
ILL (France)	58.3	10	1×10^{12} ν/cm²/s	12.5
Double Chooz (France)	4250	80	1.2×10^{12} ν/cm²/s	14.3
Brokdorf (Germany)	3900	17	2.4×10^{13} ν/cm²/s	290
Kalinin (Russia)	3000	10	5×10^{13} ν/cm²/s	645

The Early Ricochet Program

- Early potential location, the MIT research reactor in Cambridge, MA
- Details:
  - 5.5 MW thermal tower
  - 4.5×10^{11} ν/cm²/s @ 4 meters from core
  - 4 weeks on, 1 week off operating cycle
- PROs:
  - Ideal for sterile neutrino searches
- CONs:
  - practically no overburden,
  - reactogenic background is very large



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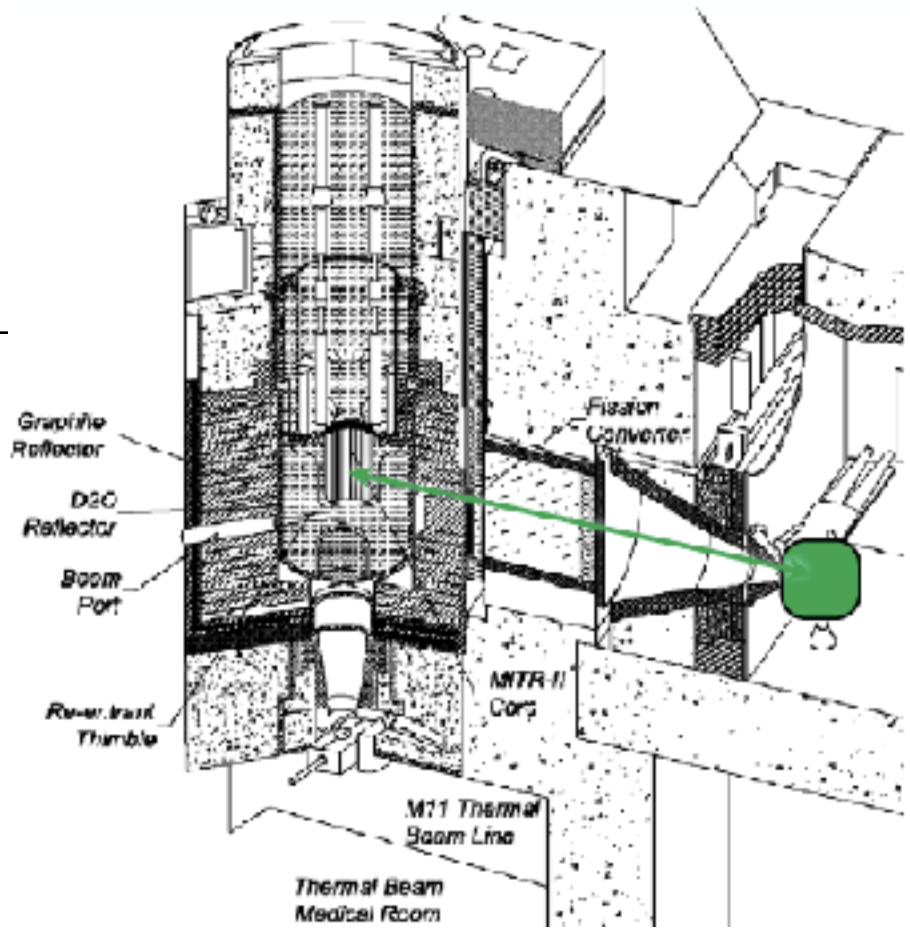
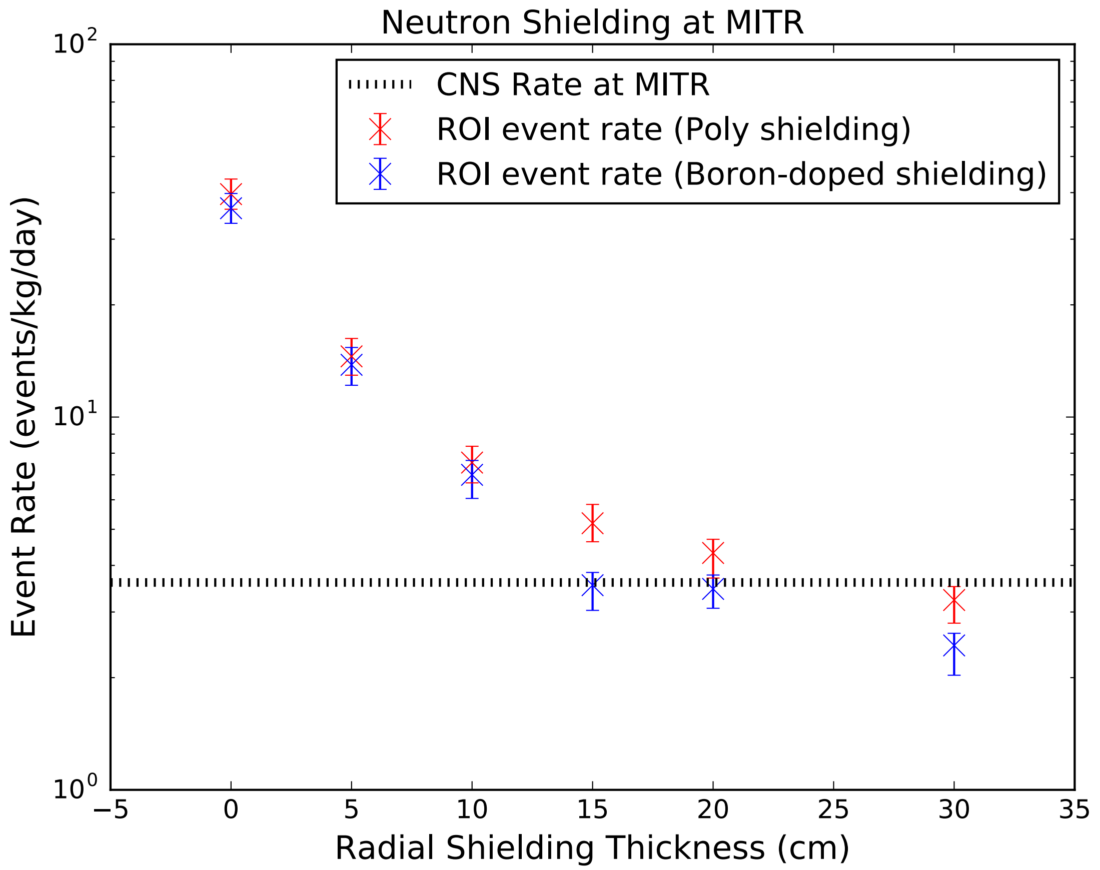


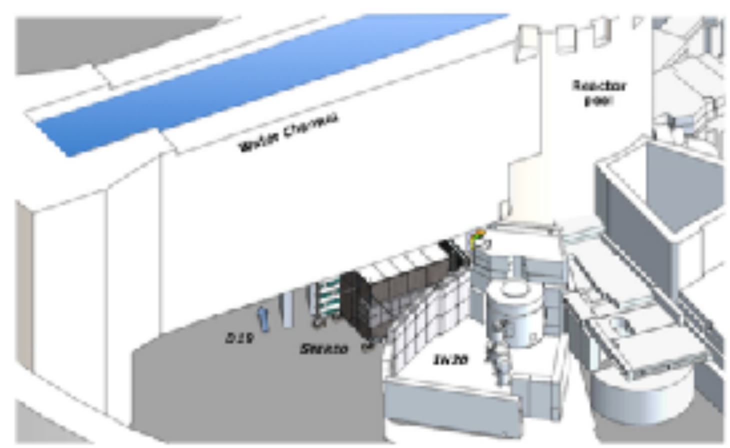


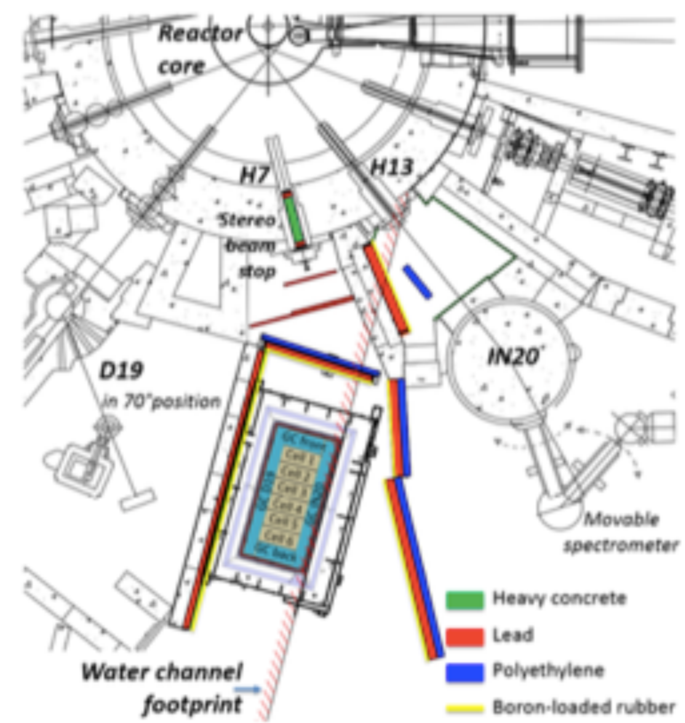
Ricochet @ Chooz

- ***The Chooz Near Site***
  - Chooz two core reactors (~8.5 GW power combined).
  - About 400 meters from the cores with 150 m.w.e. overburden.
  - Thermal power changes over the course of the year (40% with one reactor off).
- **PROs:**
  - Almost zero neutron background from reactor. Infrastructure already exists.
  - 120 m.w.e. overburden allows for significant reduction of cosmogenic background.
- **CONs:**
  - Low CEvNS rate
  - Not optimal for sterile searches

Ricochet @ ILL

- ***The ILL Grenoble Site***
  - 58 MW thermal power.
  - Over 20 events/day/kg at 7 m from the core.
- **PROs:**
  - 3-4 cycles per year, ideal for ON/OFF background studies
  - Significant (15 m.w.e) overburden for background reduction.
  - Benefit from STEREO experience
- **CONs:**
  - Presence of active neutrino beam lines.





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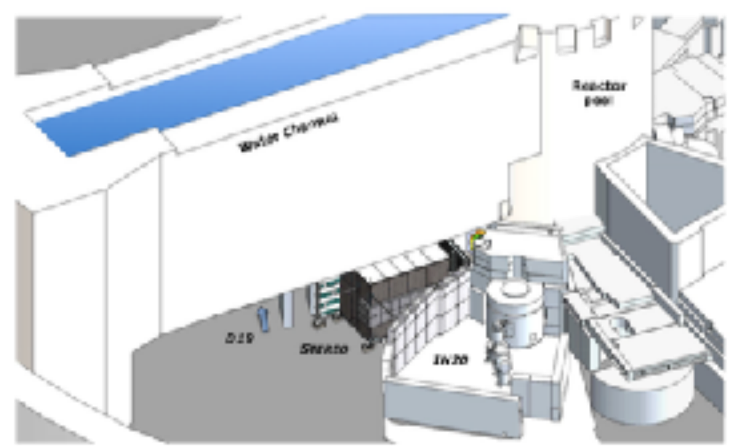
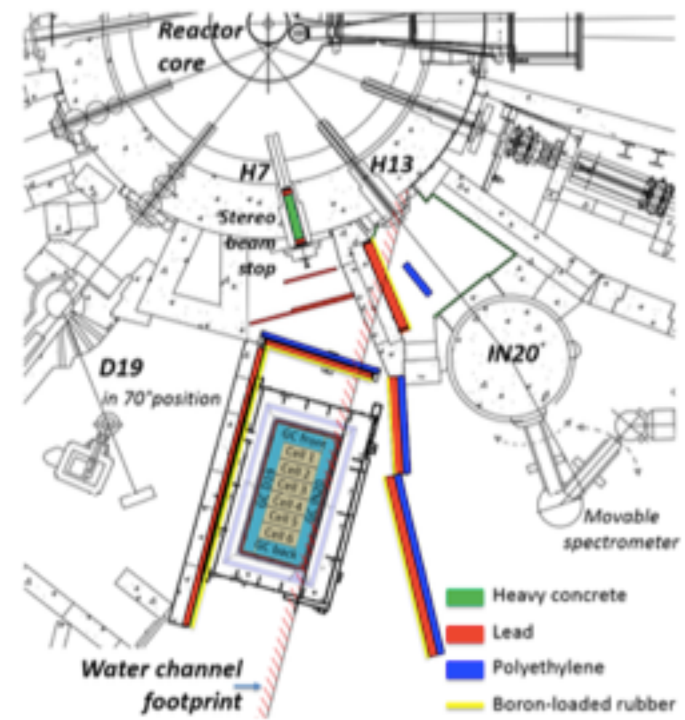
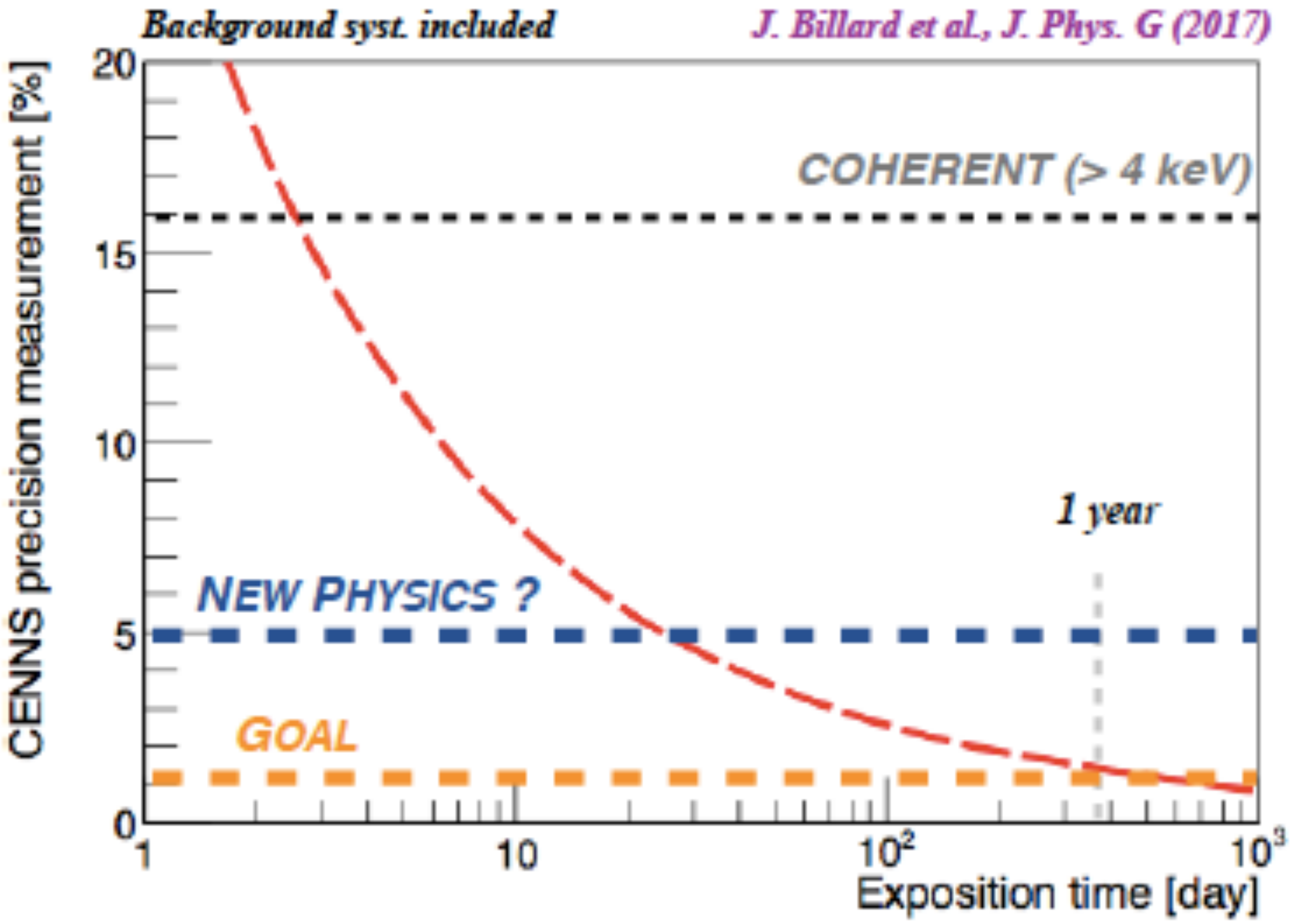




Letter of Intent submitted to ILL for consideration

Summary



After forty years, we are finally at the point where coherent neutrino scattering is detectable. This opens a myriad of doors in the ability to explore new physics and even in applications.

Ricochet is quickly building as an experiment with fast sensitivity to first CEvNS detection using promising and proven bolometric technologies.

Could open the the door for a wide range of physics beyond the Standard Model.

Summary

RICOCHET

THANKS FOR YOUR ATTENTION

MIT iPNL Northwestern University WISCONSIN CSNSM LPSC Grenoble