Northwestern

RICOCHET

Search for Coherent Elastic Neutrino-Nucleus Scattering with the Ricochet Experiment

Ran Chen

ranchen2025@u.northwestern.edu

Northwestern

Abstract:

The RICOCHET experiment, located at the Institut Laue Langevin (ILL) in Grenoble, France, is a Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) observatory that aims to detect reactor-neutrinos through sub-keV nuclear recoils. This low-energy frontier presents itself as an opportunity to probe neutrino physics beyond the Standard Model as the coherent interaction amplifies the cross section, reducing the total exposure required to reach new sensitivity limits or discovery. RICOCHET has been commissioned at ILL and has been operating since early 2024 with an array of Ge detectors utilizing heat and ionization readouts. Although in this talk, I will focus on the development of the complementary detector array (Q-Array), which uses superconducting crystals (e.g. Al, and Sn) of around 30 ~50 grams as the recoil target and Mn-doped Al transition-edge-sensors (TESes) for heat readout.

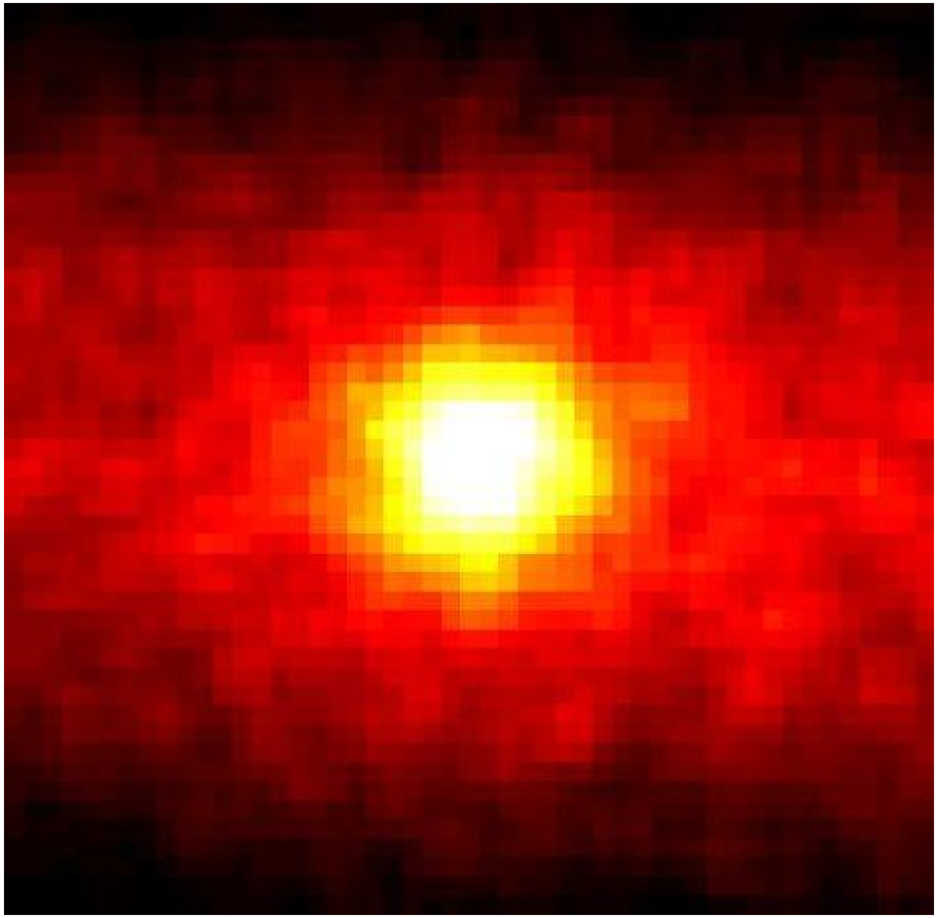
OUTLINE

1. Coherent elastic neutrino-nucleus scattering (CEvNS)
2. Why measure it? What is the physics motivation?
3. How to measure CEvNS
4. The Ricochet experiment at ILL nuclear reactor
5. The R&D of Ricochet experiment

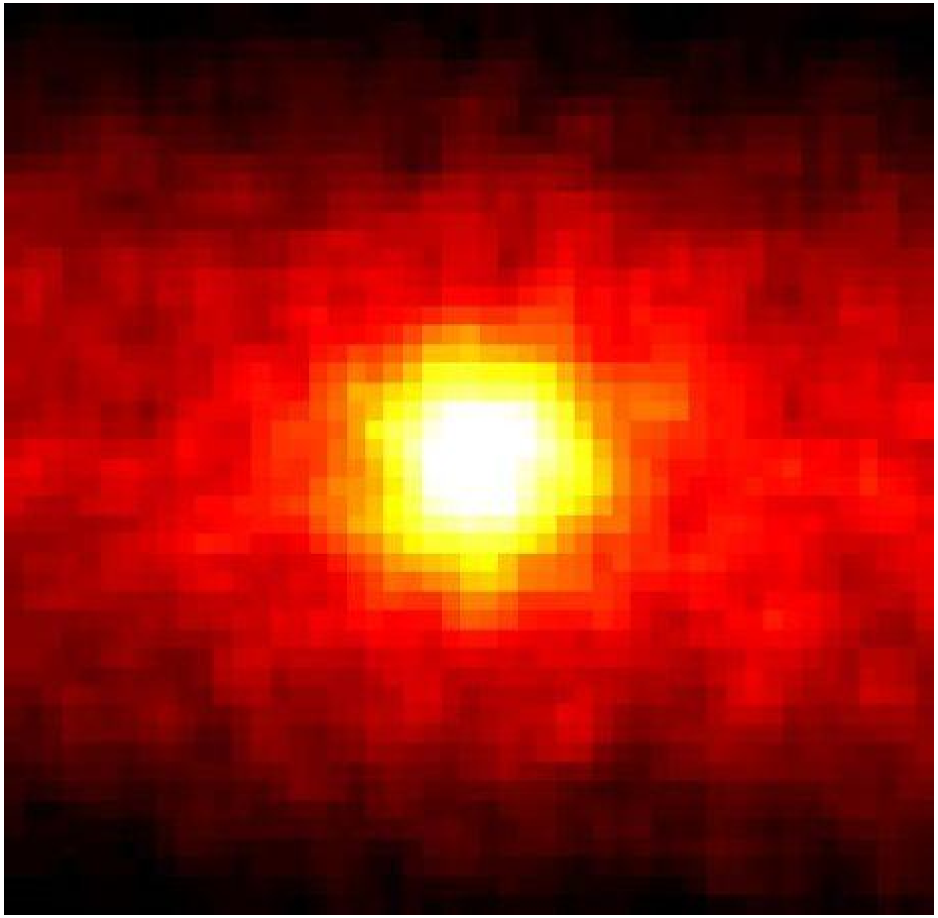
OUTLINE

1. Coherent elastic neutrino-nucleus scattering (CEvNS)
2. Why measure it? What is the physics motivation?
3. How to measure CEvNS
4. The Ricochet experiment at ILL nuclear reactor
5. The R&D of Ricochet experiment

What is neutrino?

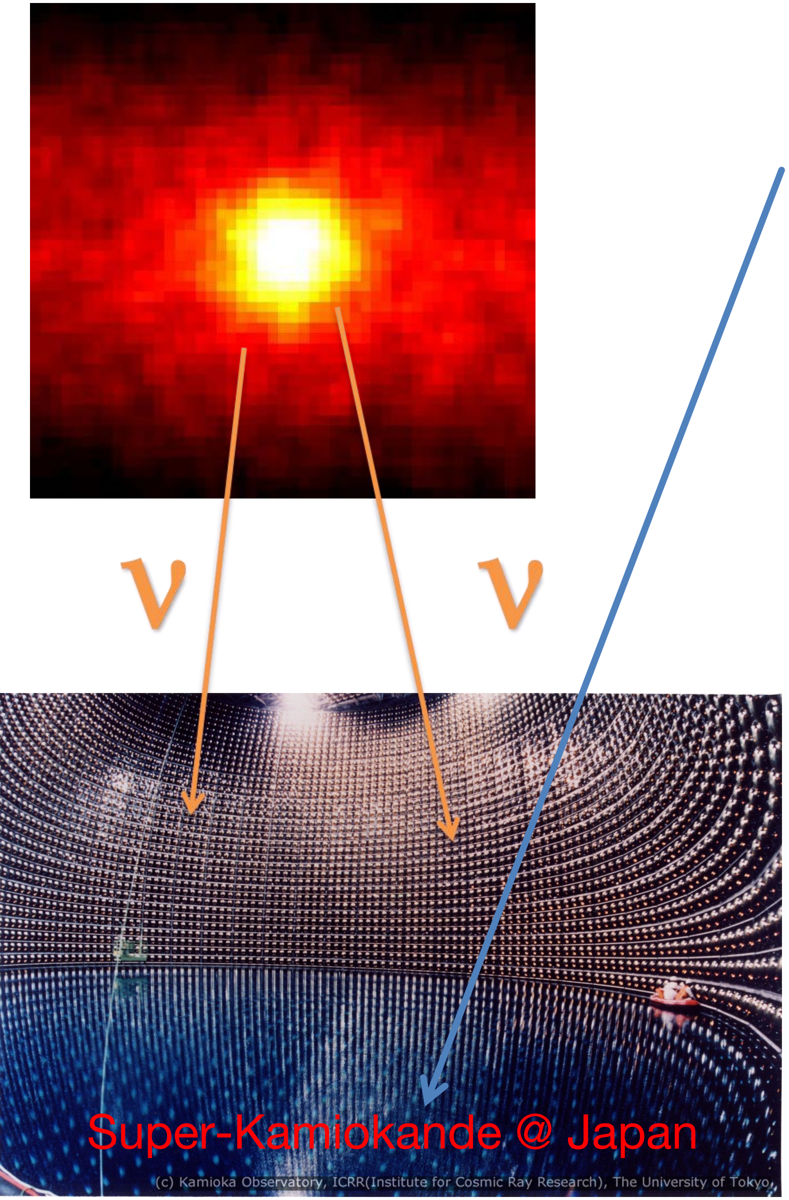


What is neutrino?



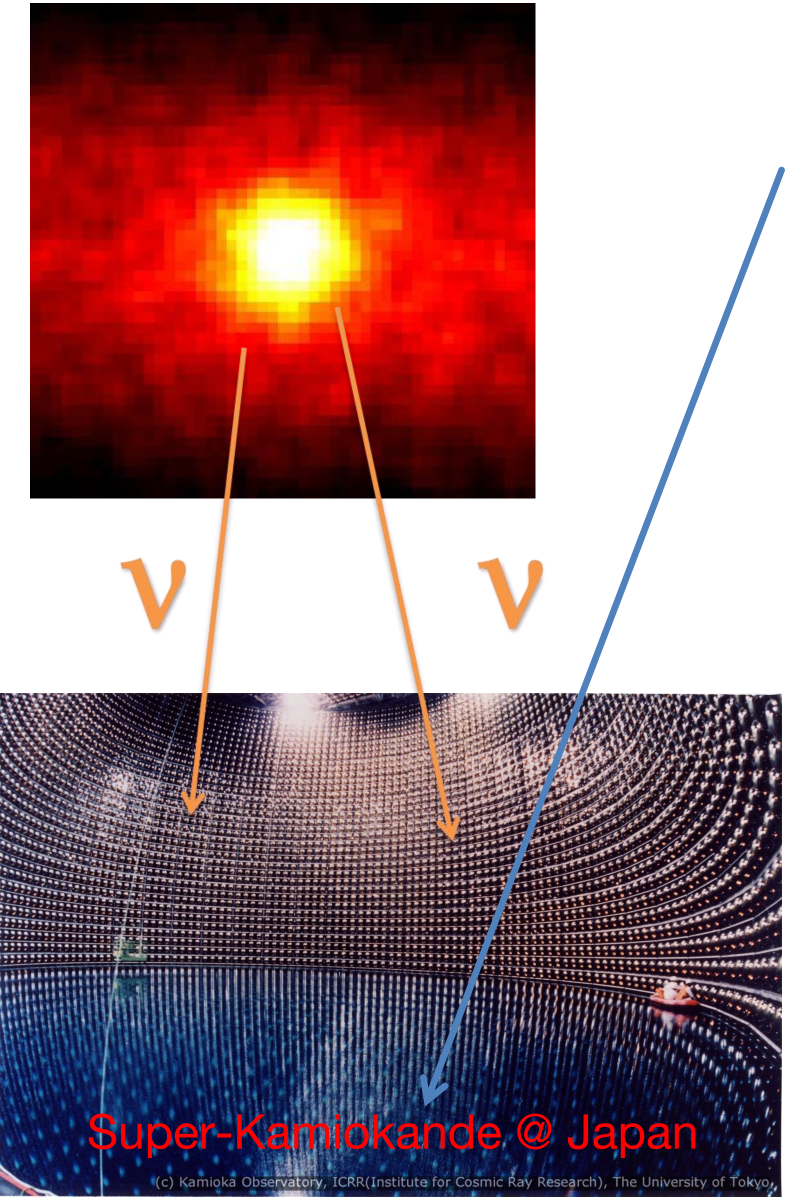
It is the Sun!

What is neutrino?



- The sun under a "Neutrino Telescope"!
  - 50,220 tons of pure water
  - 11,146 PMTs, a kind of photon sensor
  - 1,000 meter underground
  - Detect the electrons accelerated by neutrinos.

What is neutrino?

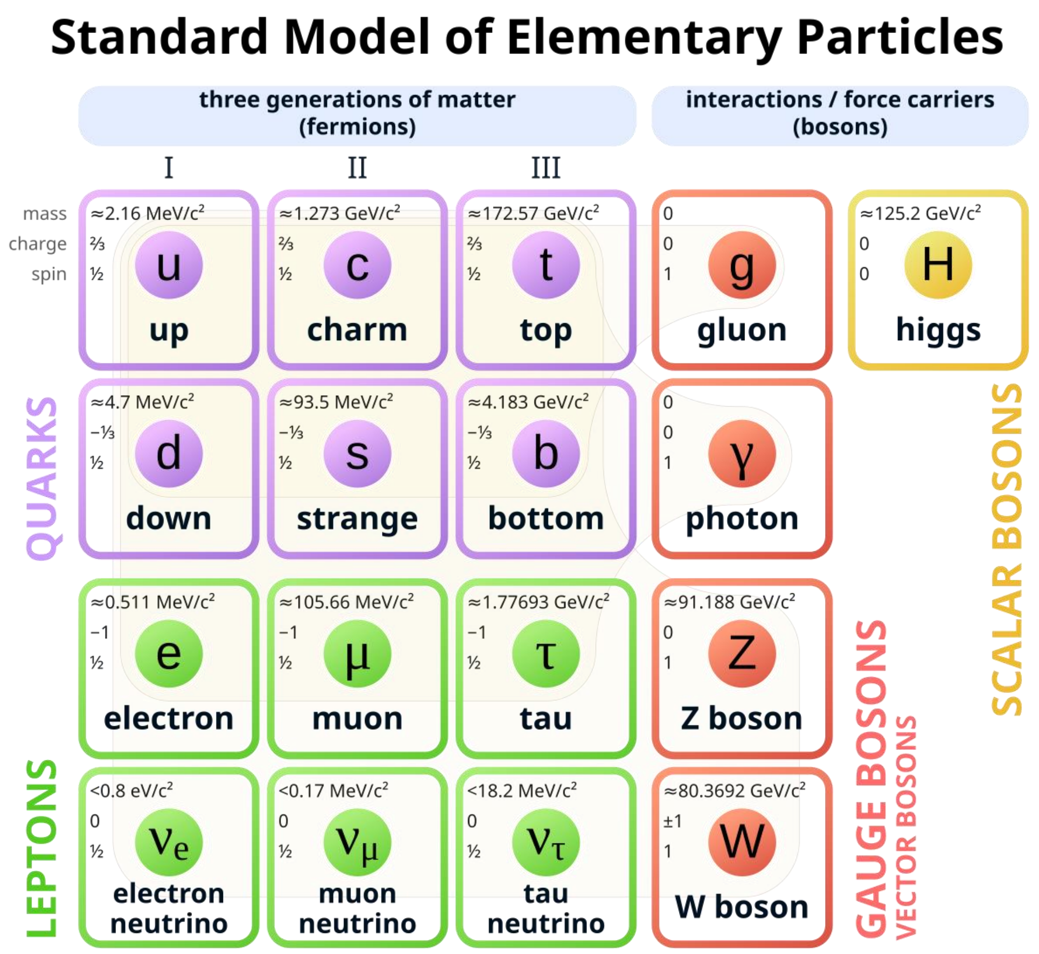


- The sun under a "Neutrino Telescope"!
  - 50,220 tons of pure water
  - 11,146 PMTs, a kind of photon sensor
  - 1,000 meter underground
  - Detect the electrons accelerated by neutrinos.

- 7×10^{10} solar neutrinos per second per square centimeter pass through the earth.
- 7000 solar neutrino detected over 504 days of live time by this detector

- **Extremely hard to catch!**

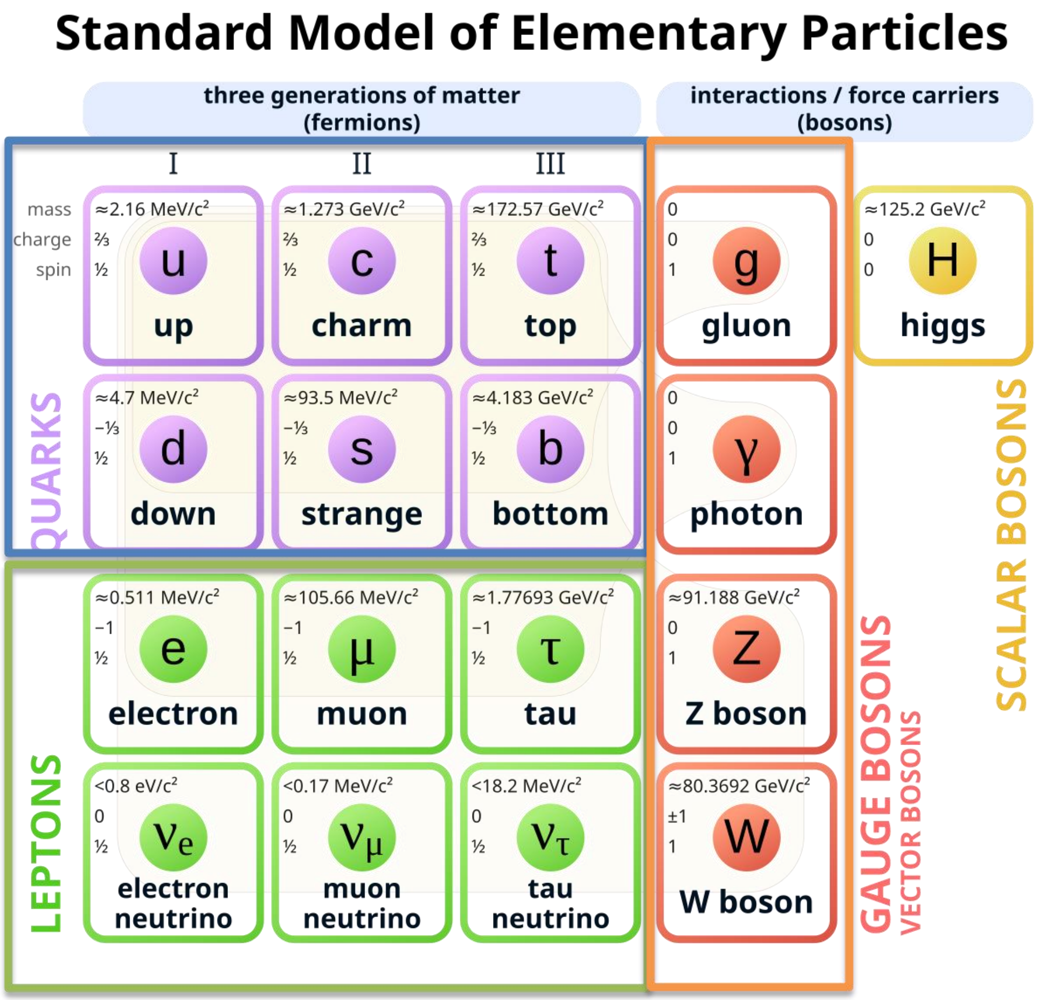
Neutrino: One of Fundamental Particle



Neutrino: One of Fundamental Particle

Quarks make up hardrons, like proton and neutron.

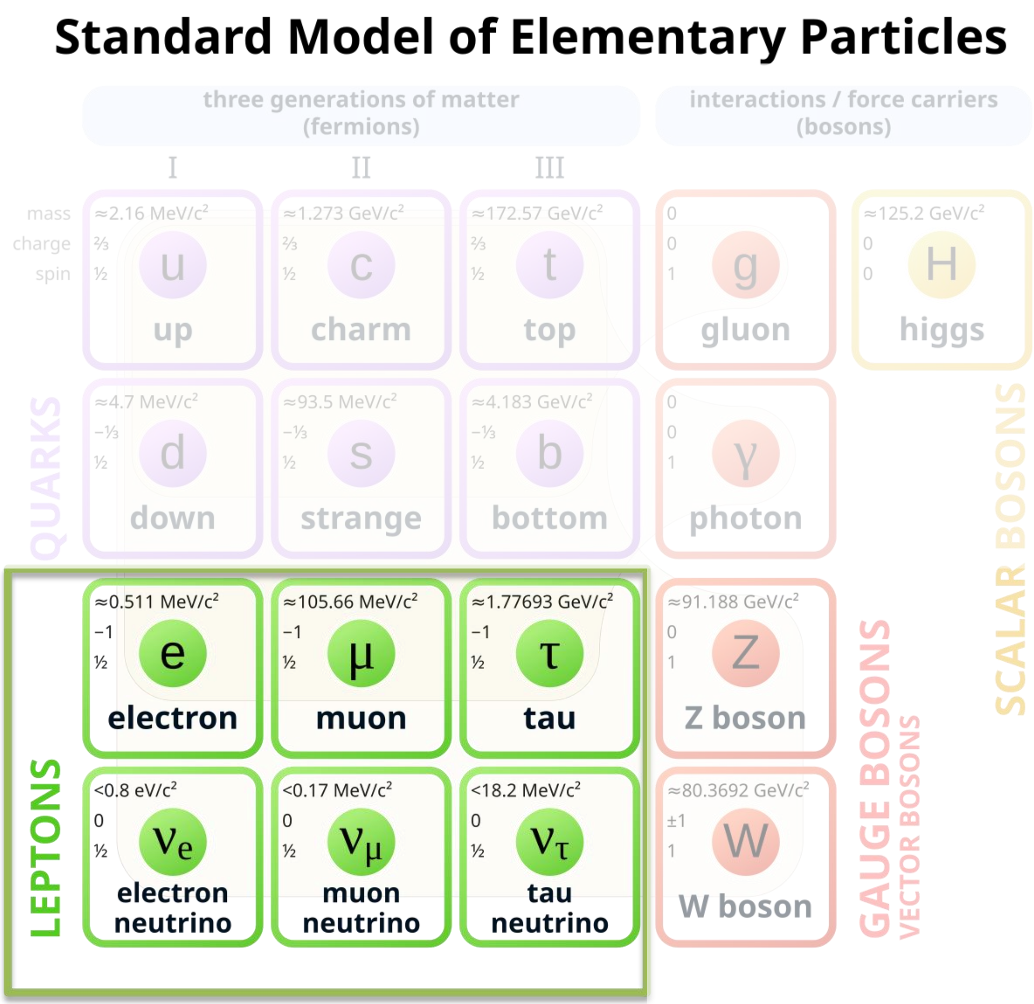
Leptons include charged leptons and neutrinos.



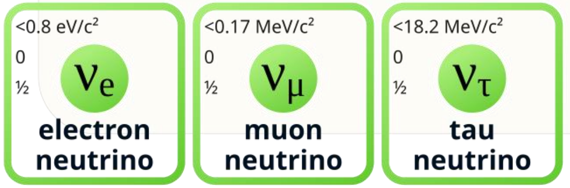
Gauge Bosons carry forces

Neutrino: One of Fundamental Particle

Leptons include charged leptons and neutrinos.

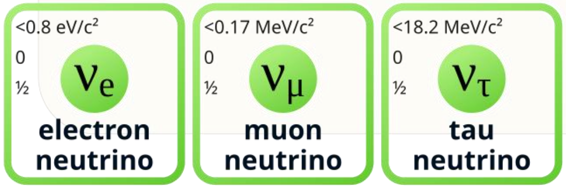


Why we study Neutrinos?



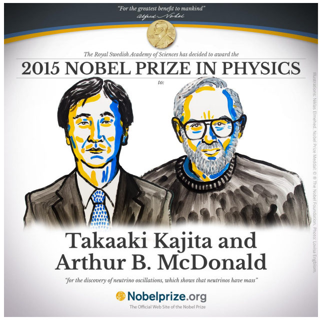
- Known Property:
  - Leptons
  - No electrical charge
  - "No mass"
  - 3 flavors, each is a "sister" of the charged lepton

Why we study Neutrinos?

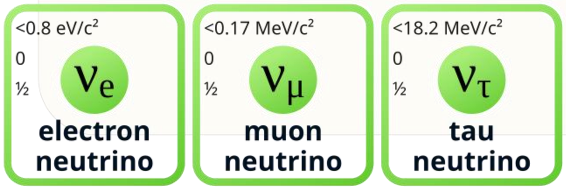


- Known Property:
  - Leptons
  - No electrical charge
  - "No mass"
  - 3 flavors, each is a "sister" of the charged lepton

- Why we are interested in it?
  - One of the most abundant particles in the Universe
    - Remember the amount of solar neutrino
  - Yet also one of the least well understood
    - Even the mass is unknown
  - Properties that confirm the existence of physics Beyond the Standard Model!!!
    - Like the neutrino oscillations: 3 flavors change to others when propogating.



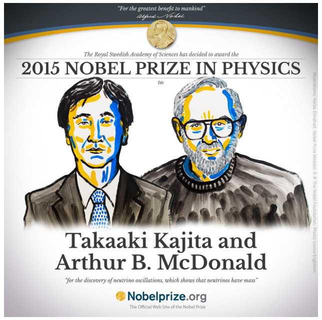
Why we study Neutrinos?



- Known Property:
  - Leptons
  - No electrical charge
  - "No mass"
  - 3 flavors, each is a "sister" of the charged lepton

- Why we are interested in it?
  - One of the most abundant particles in the Universe
    - Remember the amount of solar neutrino
  - Yet also one of the least well understood
    - Even the mass is unknown
  - Properties that confirm the existence of physics Beyond the Standard Model!!!
    - Like the neutrino oscillations: 3 flavors change to others when propogating.

- Physicists are eagering to study on Neutrinos!

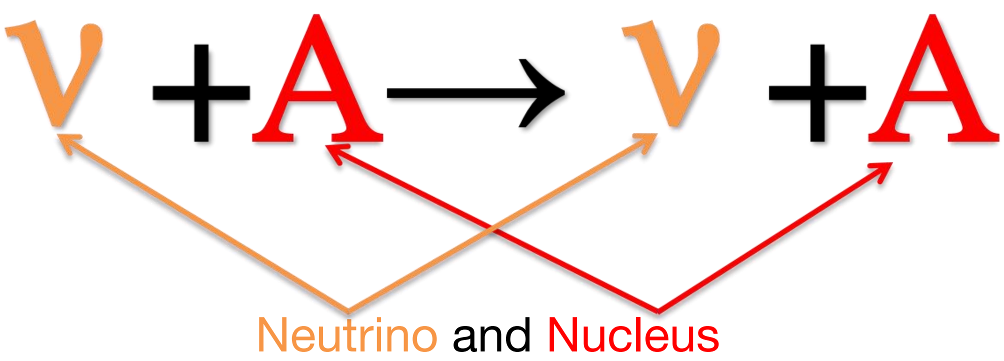


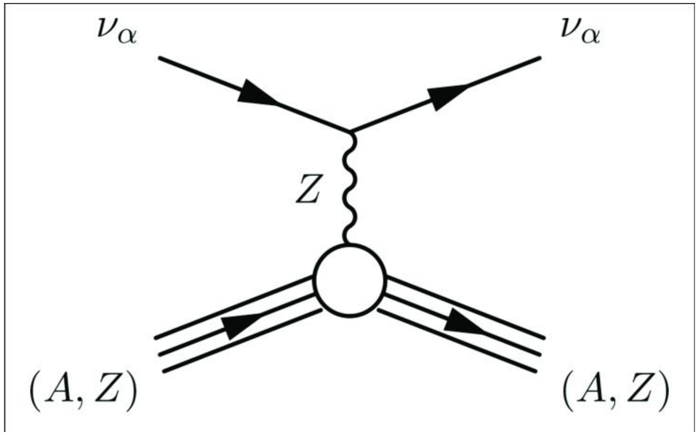
Coherent elastic neutrino-nucleus scattering

In short “CEvNS”, pronounced as 7’s

Coherent elastic neutrino-nucleus scattering

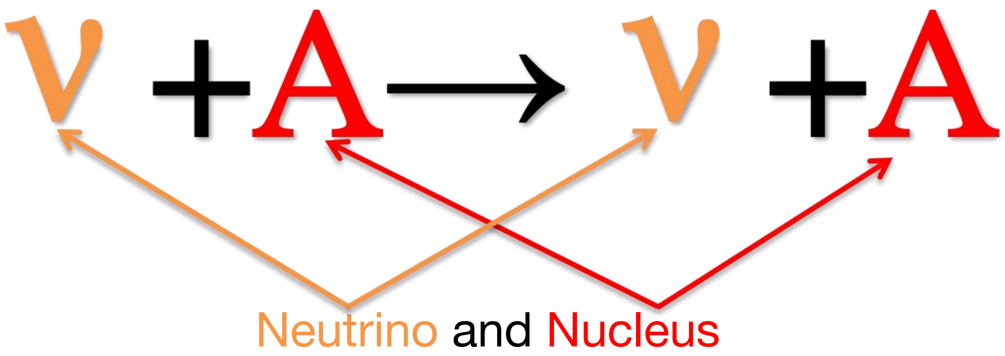
Elastic means the nucleus does not change after the interaction.
Only momentum exchange happens.

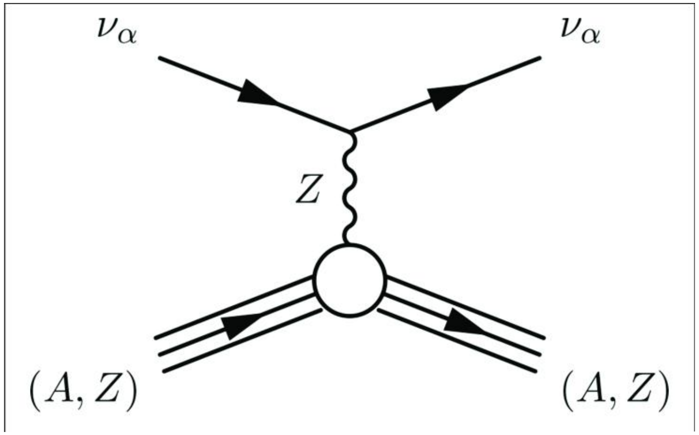




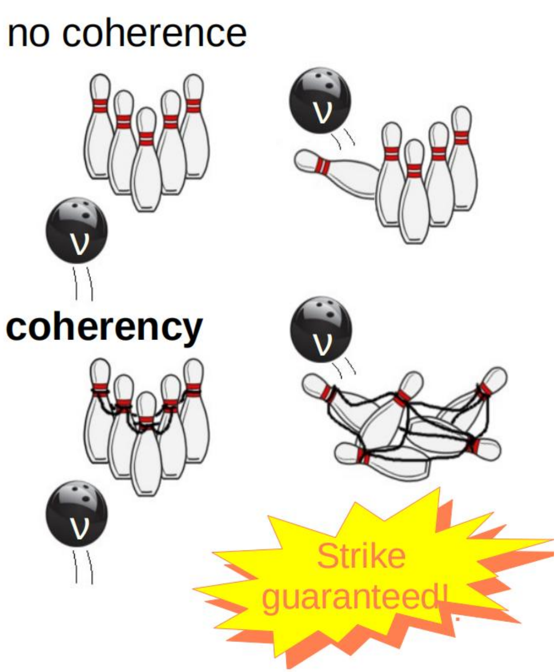
Coherent elastic neutrino-nucleus scattering

Elastic means the nucleus does not change after the interaction.
Only momentum exchange happens.



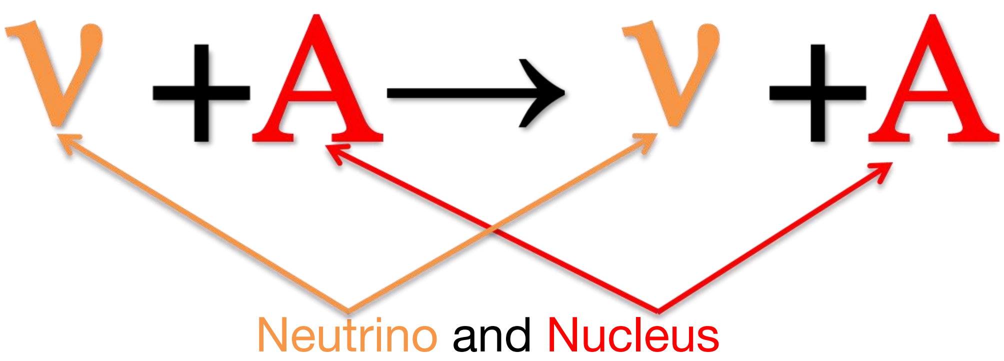


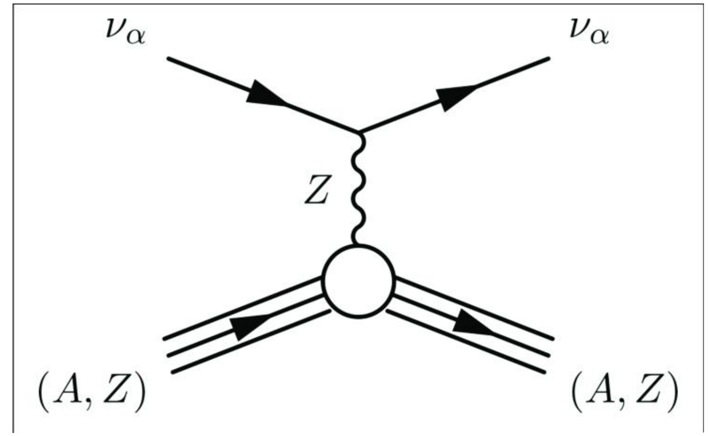
Coherent means the neutrino scatters with the entire nucleus, not single nucleon.
Due to this feature, the cross section is enhanced.



Coherent elastic neutrino-nucleus scattering

Elastic means the nucleus does not change after the interaction.
Only momentum exchange happens.



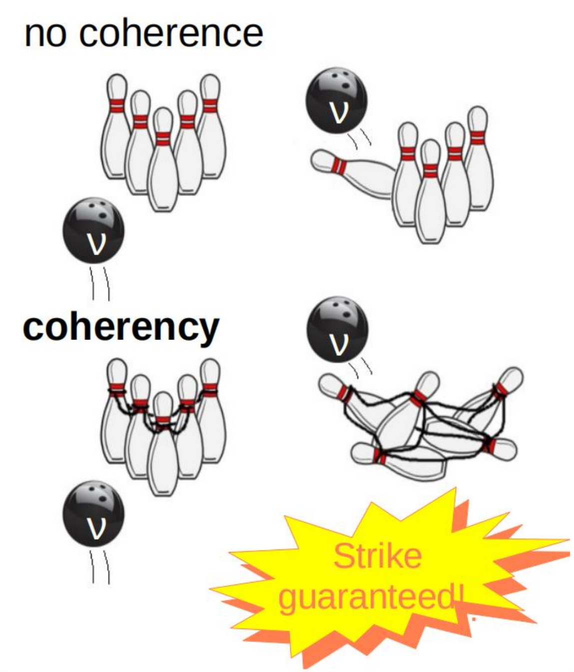


Coherent means the neutrino scatters with the entire nucleus, not single nucleon.
Due to this feature, the cross section is enhanced.

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q)\left(2 - \frac{MT}{E_\nu^2}\right)$$

σ: cross-section
T: Recoil energy
G_F: Fermi constant
M: nuclues mass

F: Nuclear form factor
E_ν: Neutrino Energy
Q_W: Nuclear weak charge



Coherent elastic neutrino-nucleus scattering

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q)(2 - \frac{MT}{E_\nu^2})$$

σ: cross-section
T: Recoil energy
G_F: Fermi constant
M: nuclues mass
F: Nuclear form factor
E_ν: Neutrino Energy
Q_{W}: Nuclear weak charge

$$Q_{\mathrm{W}} = \mathrm{N} - (1 - 4sin^2\theta_w)\mathrm{Z}$$

$$sin^2\theta_w = 0.231$$

so protons unimportant

Coherent elastic neutrino-nucleus scattering

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4} F^2(Q)(2 - \frac{MT}{E_\nu^2})$$

σ: cross-section
T: Recoil energy
G_F: Fermi constant
M: nuclues mass

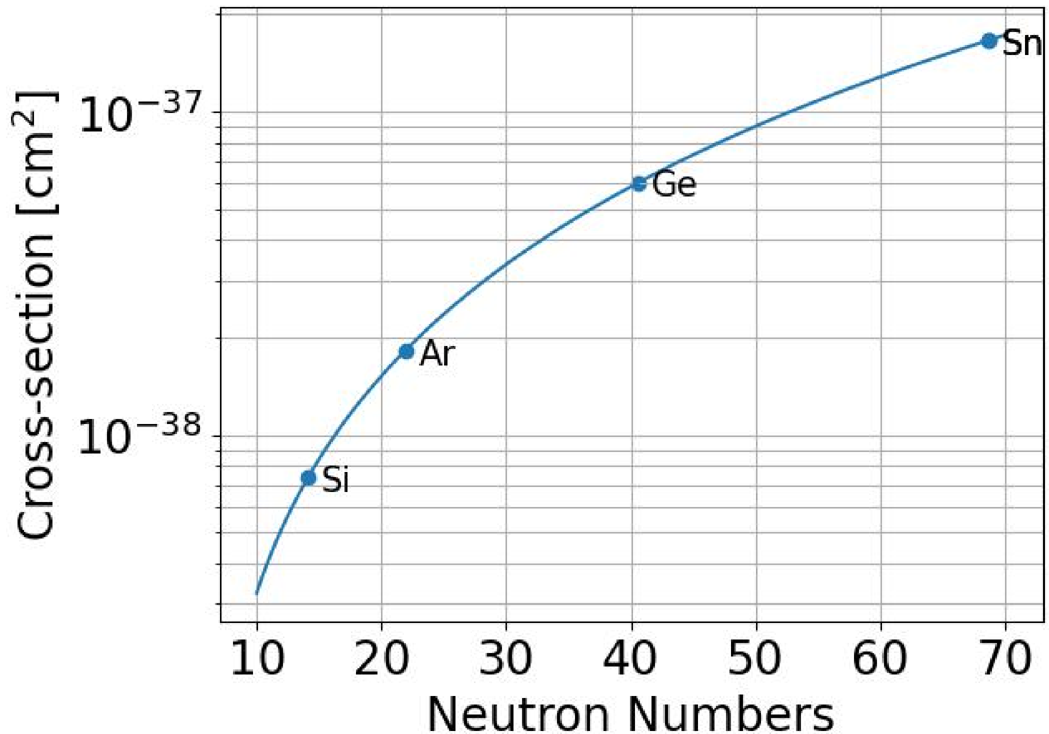
F: Nuclear form factor
E_ν: Neutrino Energy
Q_W: Nuclear weak charge

$$Q_W = N - (1 - 4\sin^2\theta_w)Z$$

$\sin^2\theta_w = 0.231$
so protons unimportant

$$\frac{d\sigma}{dT} \propto N^2$$

Due to this feature, the cross-section is enhanced.



OUTLINE

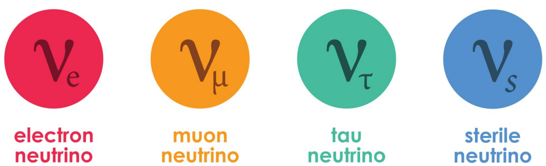
1. Coherent elastic neutrino-nucleus scattering (CEvNS)
2. Why measure it? What is the physics motivation?
3. How to measure CEvNS
4. The Ricochet experiment at ILL nuclear reactor
5. The R&D of Ricochet experiment

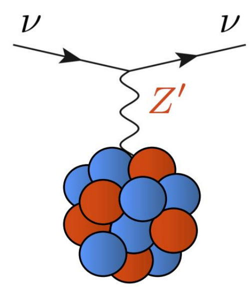
Why we measure it?

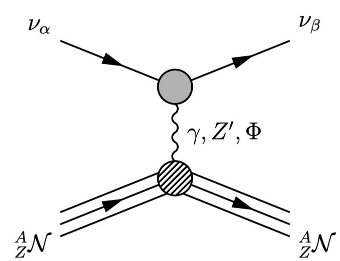
- CEvNS as a test for "known" physics

$\theta_w, F(Q),$ quenching factor……

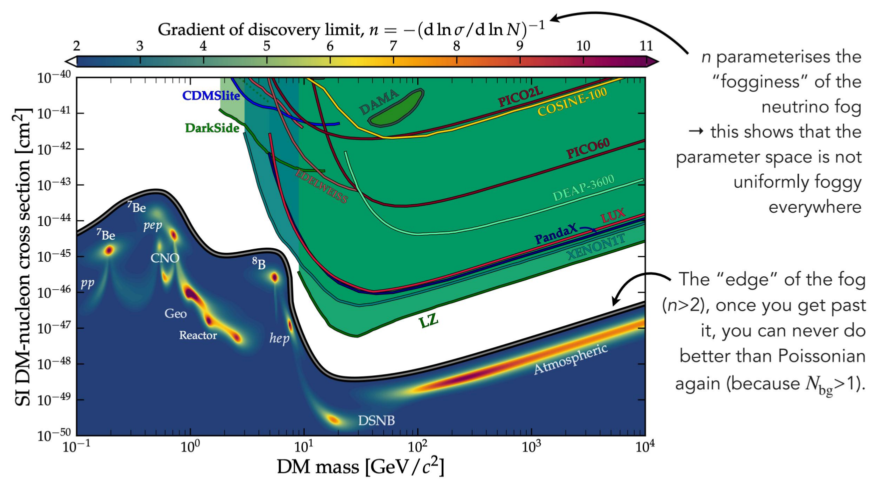
- CEvNS as a window for Beyond Standard Model Physics



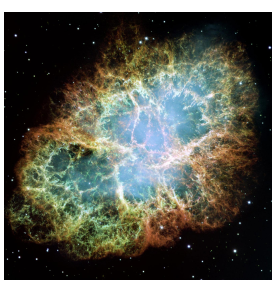




- CEvNS as a background for new physics



- CEvNS as a messager for astrophysics

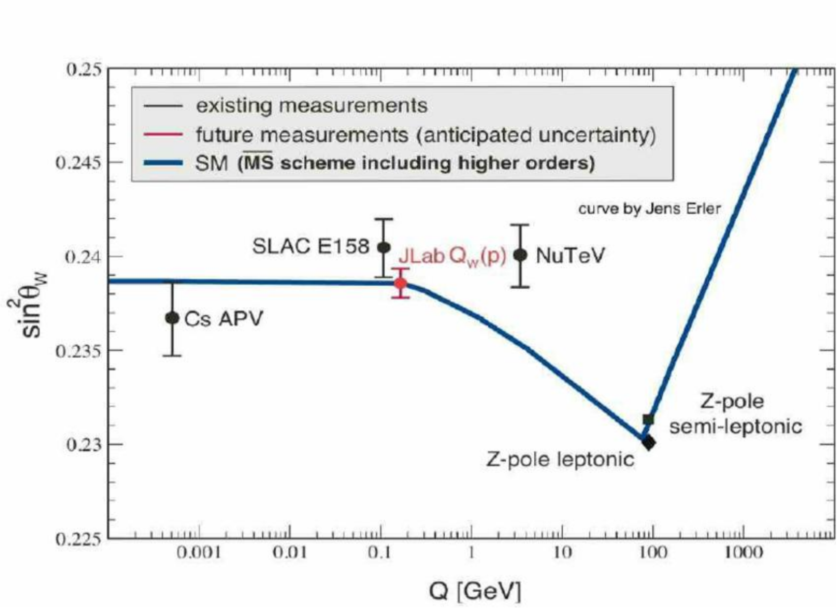


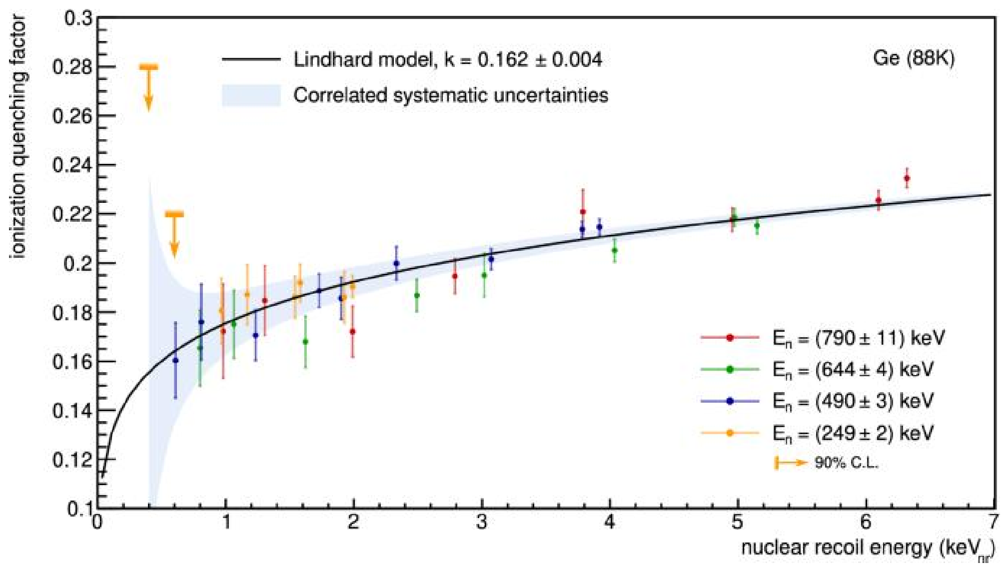
CEvNS as a test for "known" physics

- CEvNS is predicted by the Standard Model.
  - Test for the Weinberg Angle

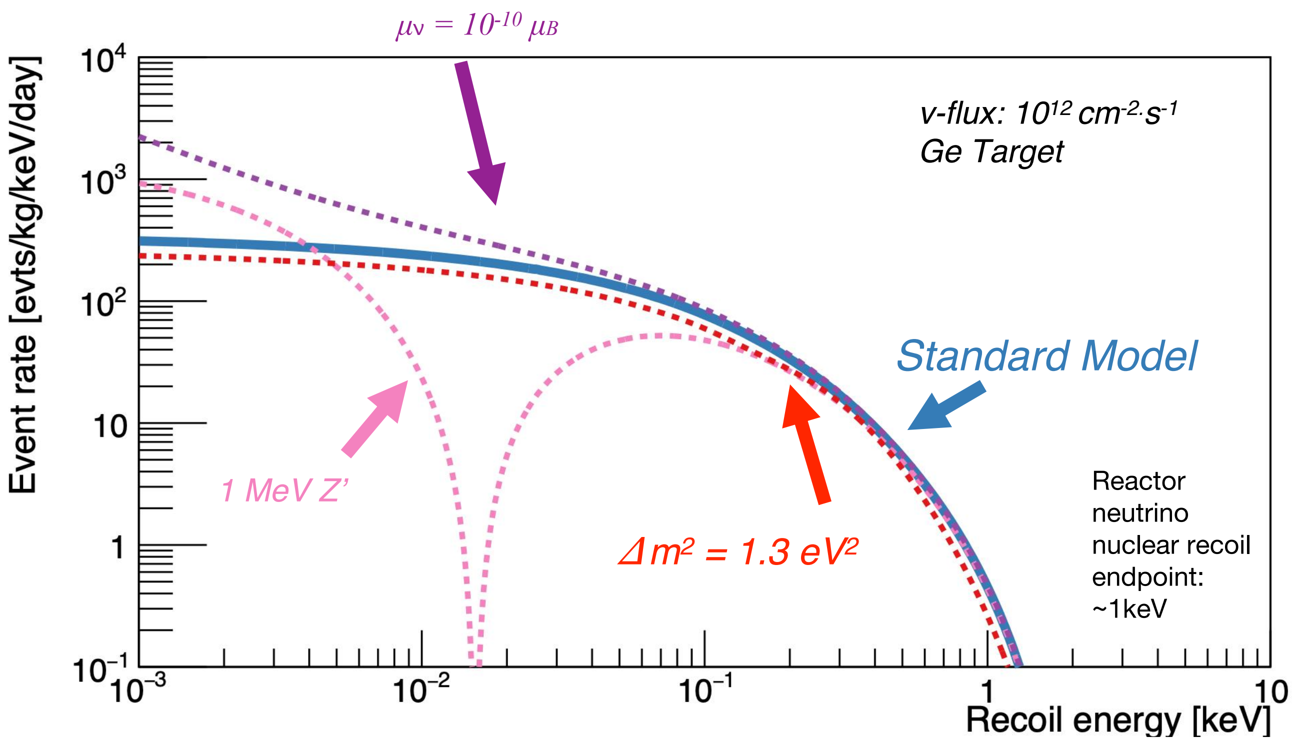
$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q)(2 - \frac{MT}{E_\nu^2})$$

- Interplay between electron weak and nuclear physics
  - Test for the nuclear form factor $F^2(Q)$
  - Measurment for quenching factor



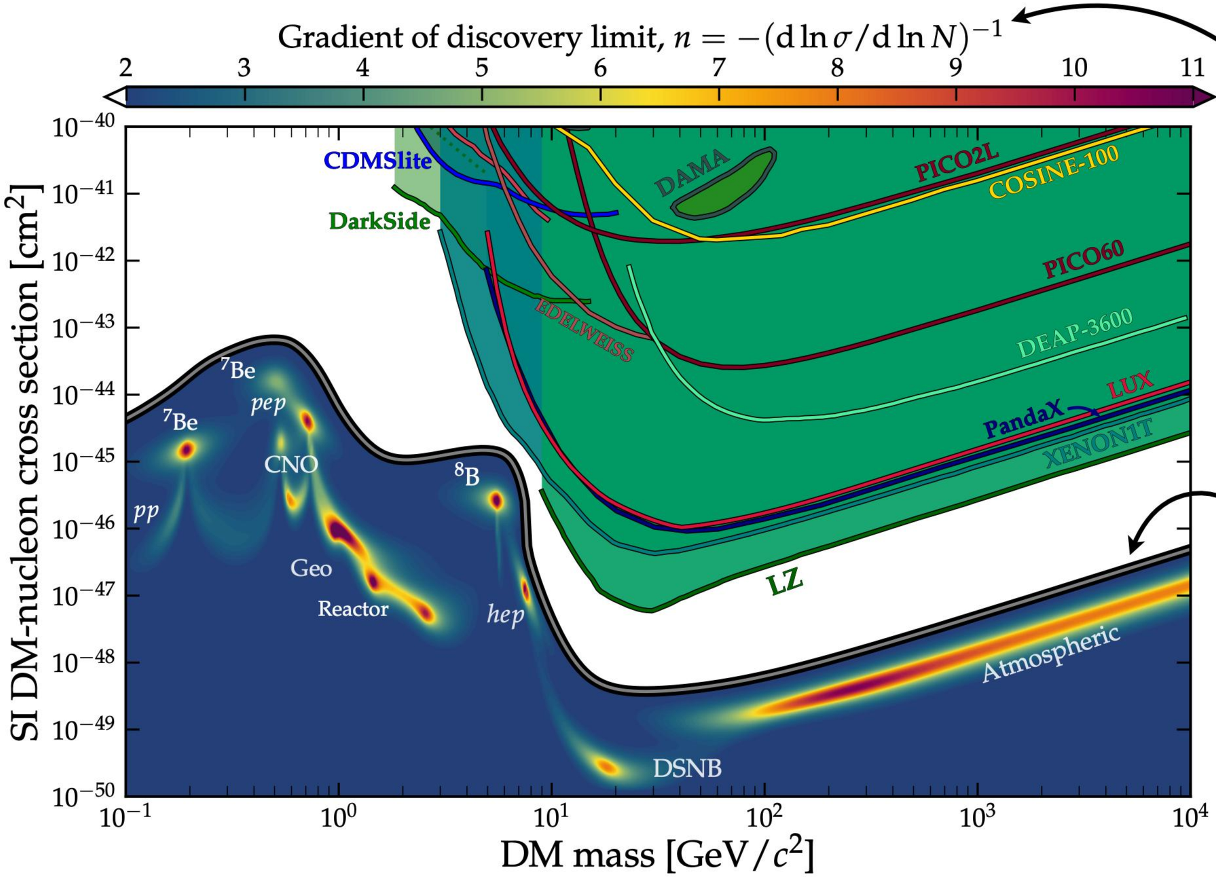


- Beyond Standard Model Physics will modify the spectrum
  - neutrino magnetic moment
  - sterile neutrinos
  - new force mediators



CEvNS as a background for new physics

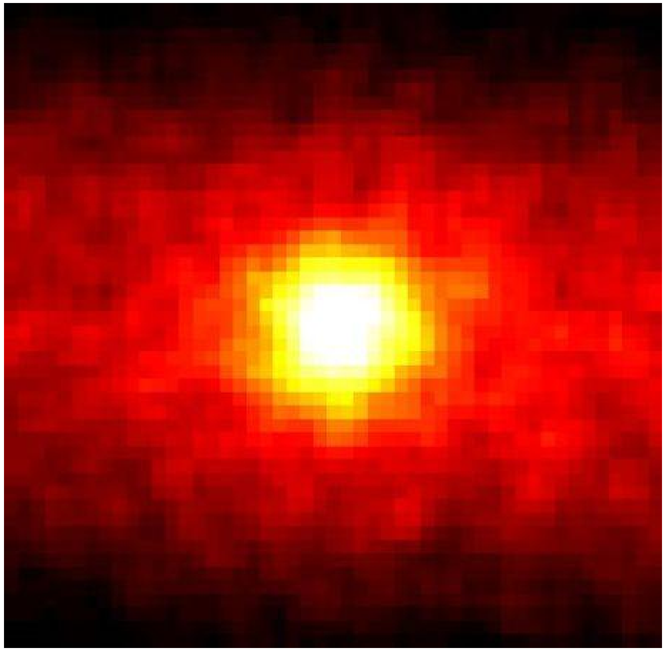
- CEvNS is known as the "Neutrino Fog" for dark matter direct detection.

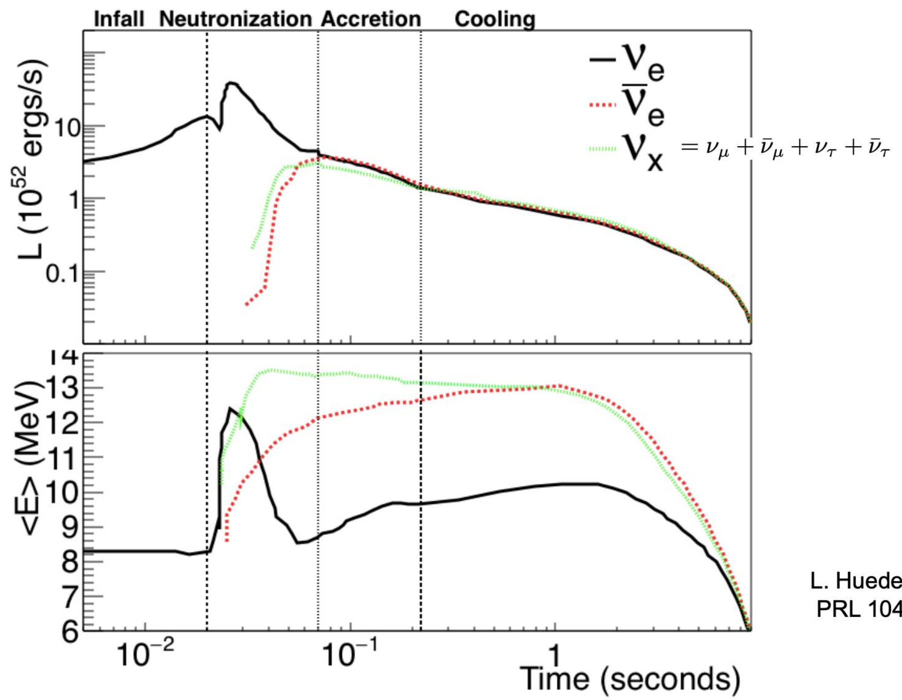


n parameterises the "fogginess" of the neutrino fog → this shows that the parameter space is not uniformly foggy everywhere

The "edge" of the fog (n>2), once you get past it, you can never do better than Poissonian again (because N_{bg}>1).

- Neutrinos carry information from the deep universe.
  - Solar neutrino detected by the CEvNS process
  - Supernova: 99% of core-collapse energy goes into all flavor neutrinos of 10s of MeV.



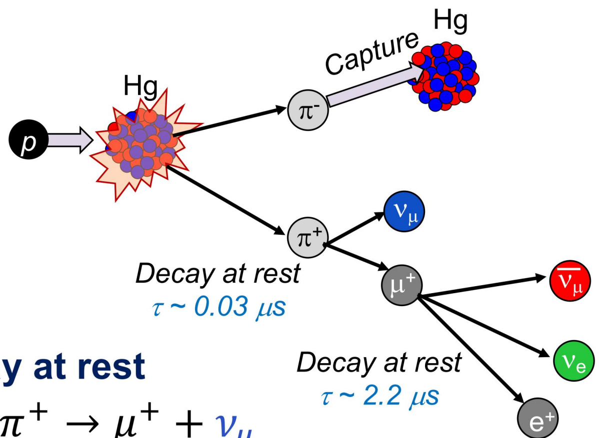


L. Huedepohl et al., PRL 104 251101

OUTLINE

1. Coherent elastic neutrino-nucleus scattering (CEvNS)
2. Why measure it? What is the physics motivation?
3. How to measure CEvNS
4. The Ricochet experiment at ILL nuclear reactor
5. The R&D of Ricochet experiment

First measurement on CEvNS



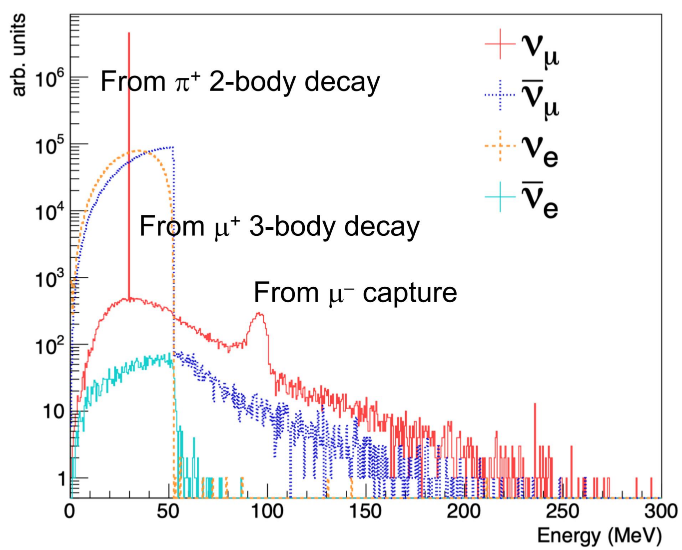
Pion decay at rest

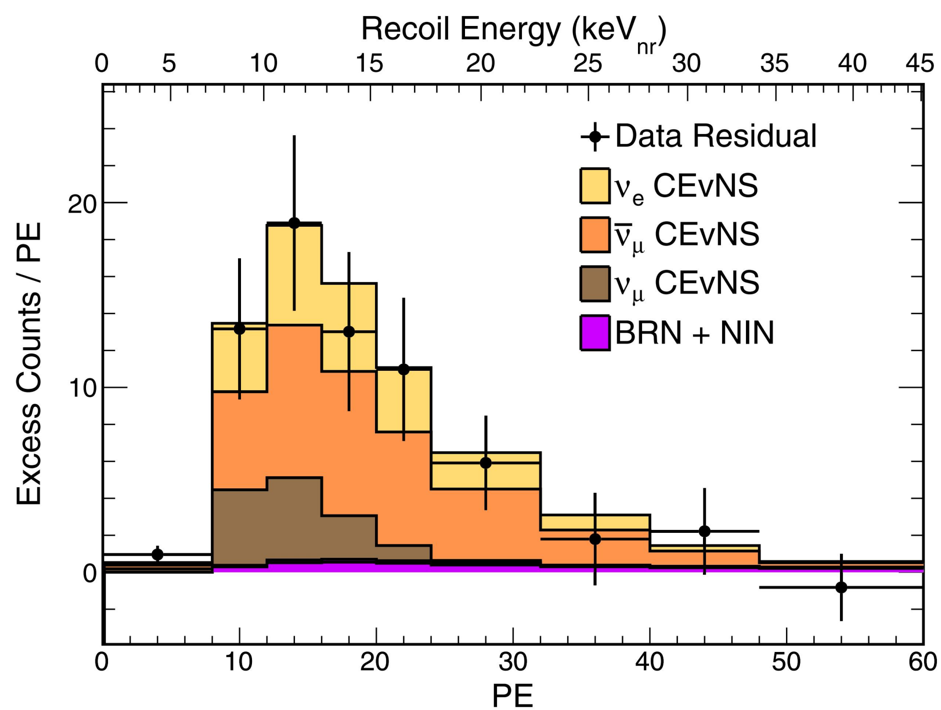
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Neutrino source: the Spllation Neutron Source at Oak Ridge National Lab
- Done by the COHERENT Collaboration with CsI scintillator detectors

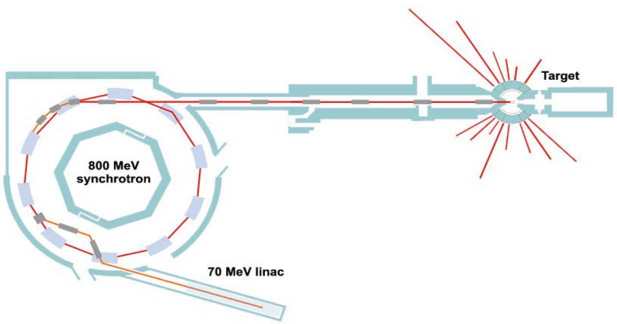
Energy



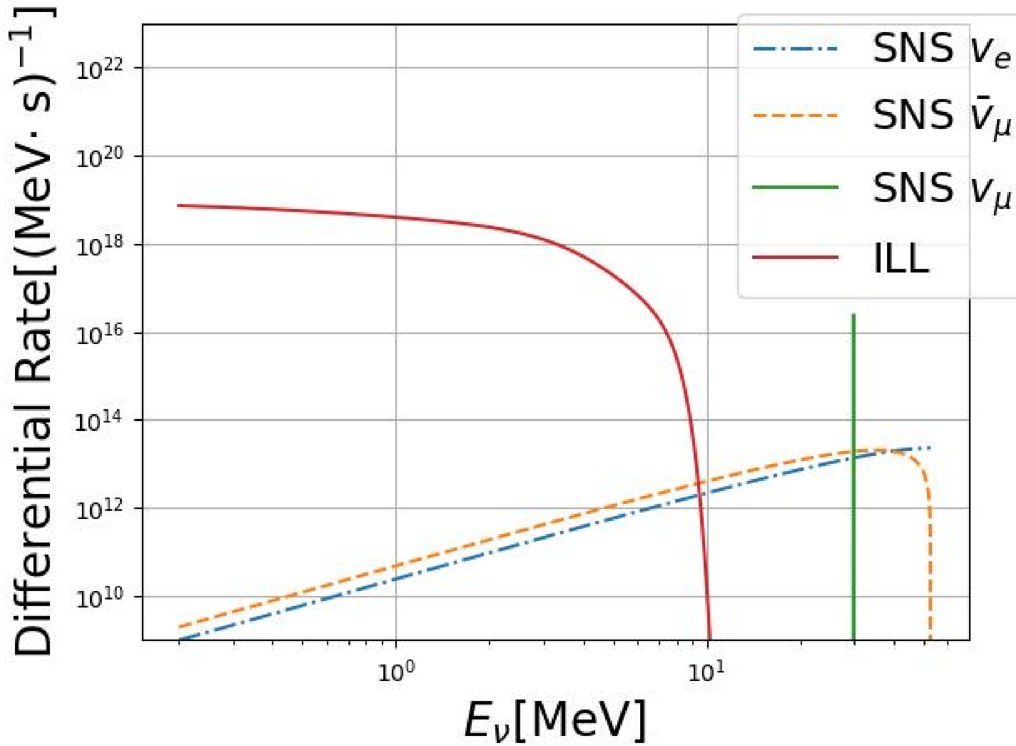


- Source
  - Nuclear Reactor

  - Spallation neutron source



  - Solar neutrino, supernova...



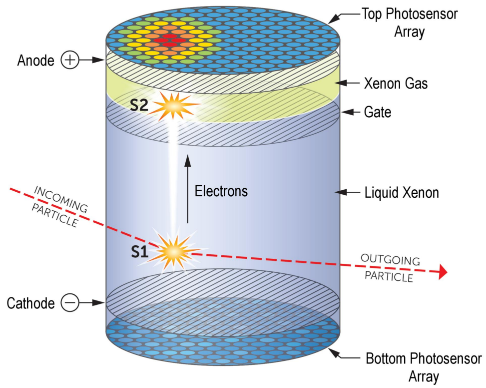
How we measure it?

Ionization
Charge

Scintillation
Light

Phonons
Heat

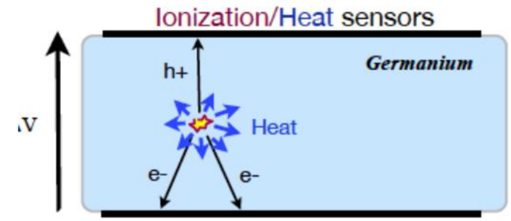
How we measure it?



Liquid Noble-Gas Dual-Phase Time Projection Chamber

Germanium Detector

Ionization Charge



Cryogenic Bolometer with Charge Readout

Scintillation Light

Scintillating Cryogenic Bolometers

Phonons Heat

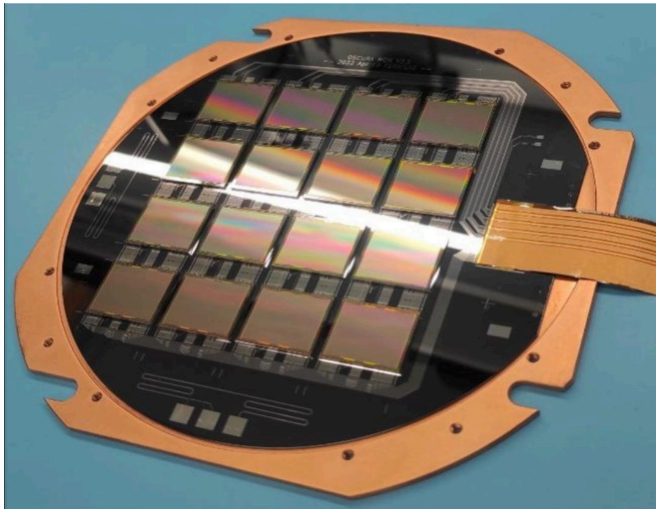
Scintillating Crystal
Liquid Noble-Gas Detector

Cryogenic Bolometer
Superheated Liquid

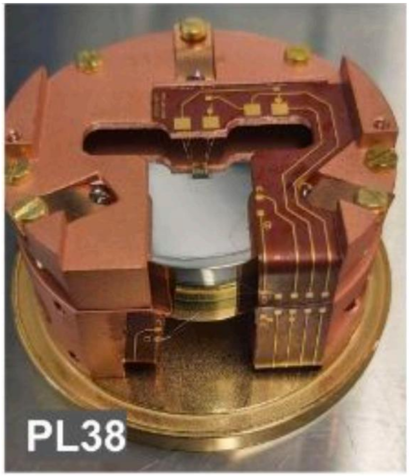
How we measure it?

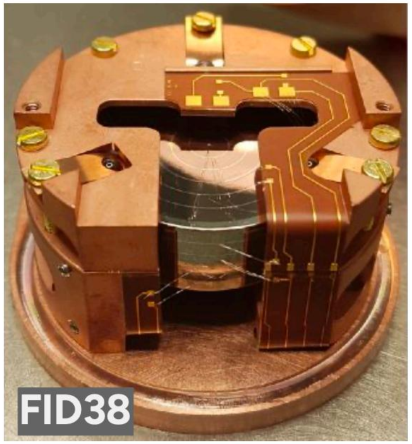
- **Detector**
  - Solid state detector: Ge+NTD, CaWO4+TES, Si+TES, Skipper CCD...
  - Liquid detector: LAr Bubble Chamber, LXe scintillator...

Skipper CCD Array

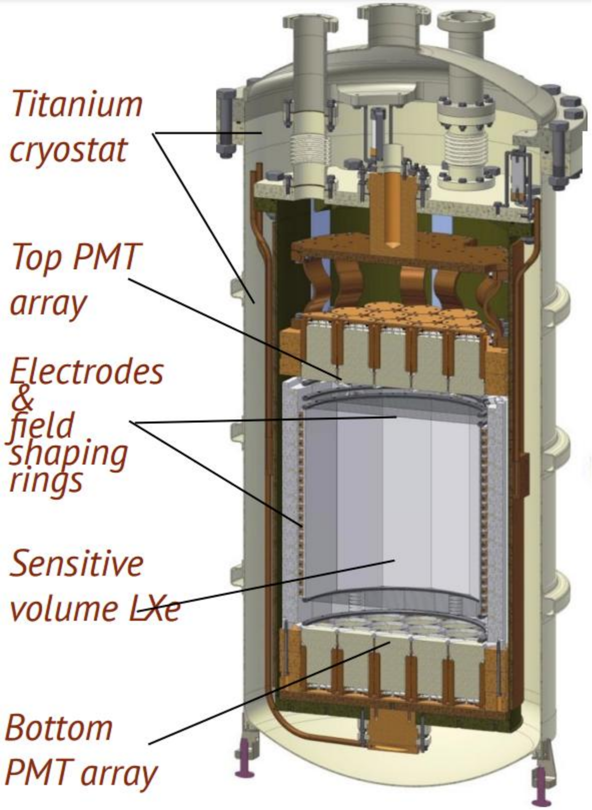


Ricochet Ge Detector

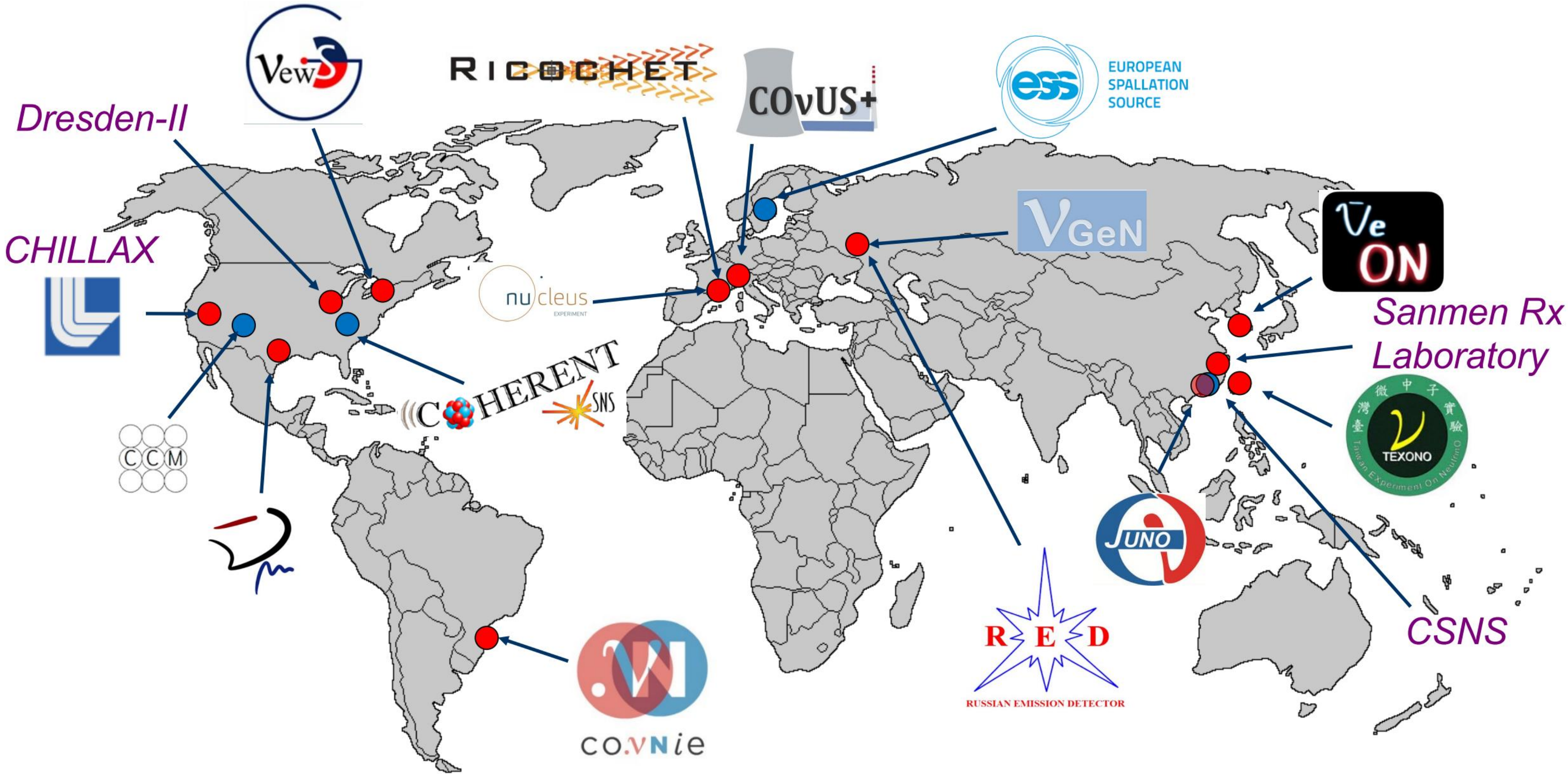




RED-100 LXe Detector



Worldwide CEvNS Race is coming!



OUTLINE

1. Coherent elastic neutrino-nucleus scattering (CEvNS)

2. Why measure it? What is the physics motivation?

3. How to measure CEvNS

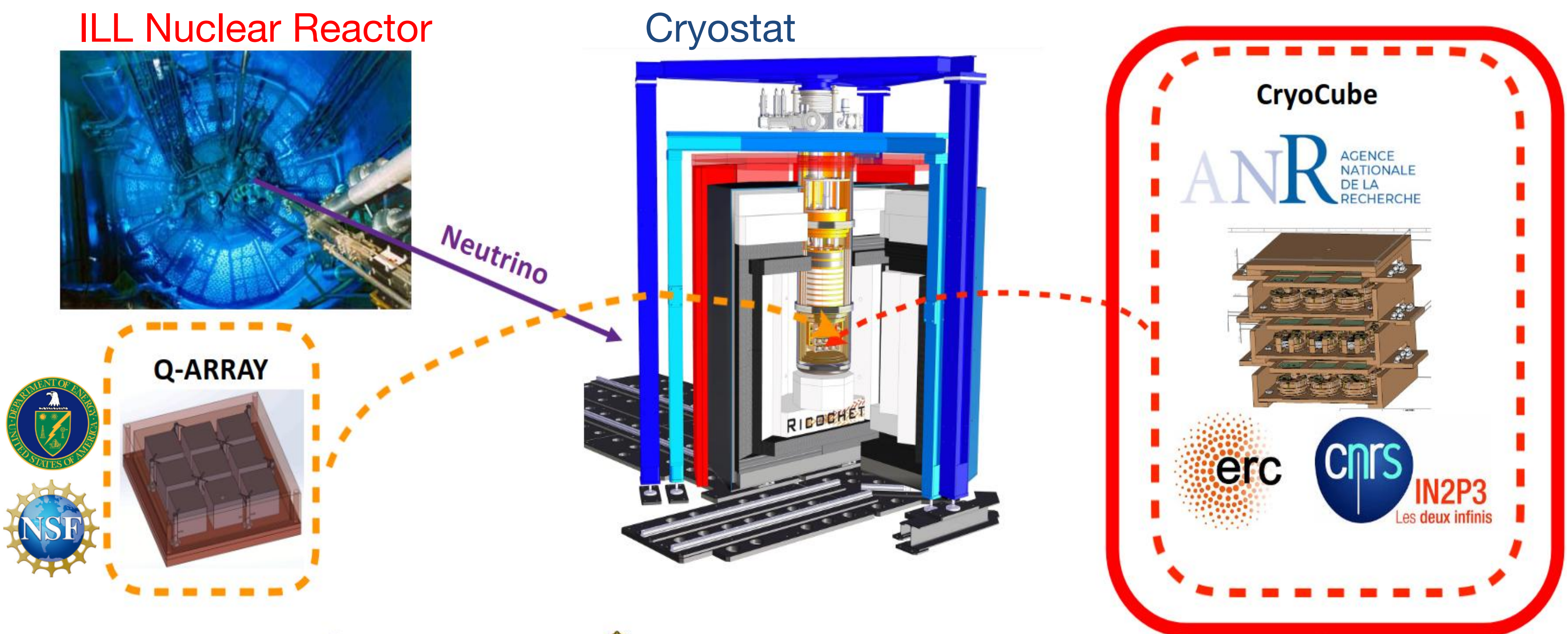
4. The Ricochet experiment at ILL nuclear reactor

5. The R&D of Ricochet experiment

The Ricochet Experiment

RICOCHET

Ricochet is a **France, US, Canada and Russia** collaboration accounting for about 60 physicists, engineers, and technicians, aiming at building a low-energy neutrino observatory.



MIT · UMASS AMHERST · UNIVERSITY OF TORONTO · THE UNIVERSITY of WISCONSIN MADISON · Northwestern University · ill · IJCLab Irène Joliot-Curie · NÉEL · iP2i · LPSC Grenoble

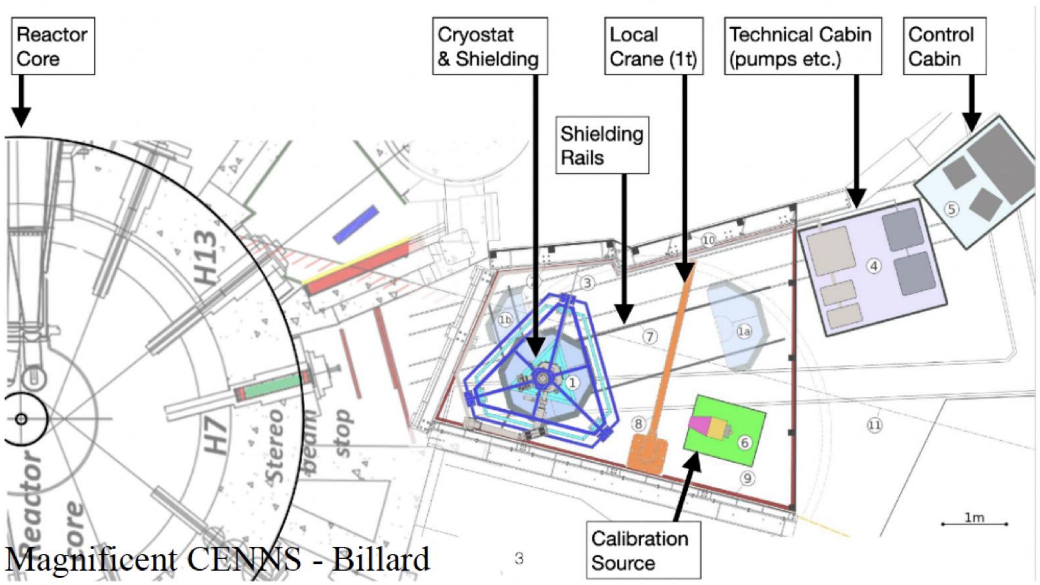
Argonne NATIONAL LABORATORY · LINCOLN LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY · UNIVERSITY OF OXFORD · C2N

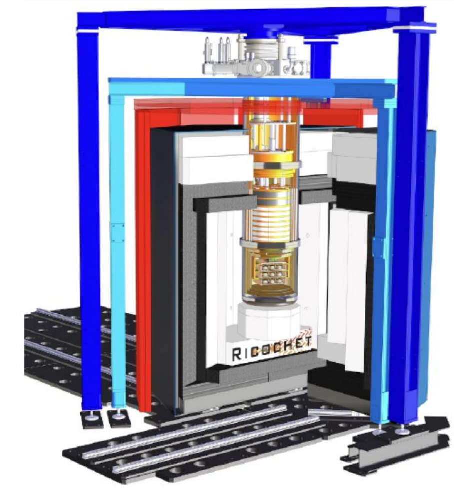
The Ricochet Experiment

- Ricochet @ ILL installation finished!
- 58 MW power: ~11 evts/day/kg (50 eV threshold)
- Ability to turn ON/OFF: subtract uncorrelated backgrounds!
- Significant overburden (~15 m.w.e) to reduce cosmics
- Fast and thermal neutron flux characterized
  - Eur. Phys. J. C 83, 20 (2023).
- Test run with 3 Ge detectors finished
  - Commission paper will come out soon!

Inner shielding:
- PE/Cu: 30 cm
- Pb/Cu: 15 cm
- Cryogenic Muon Veto
- Mu-Metal

Outer shielding:
- PE: 35 cm
- Pb: 20 cm
- Muon veto
- Soft iron



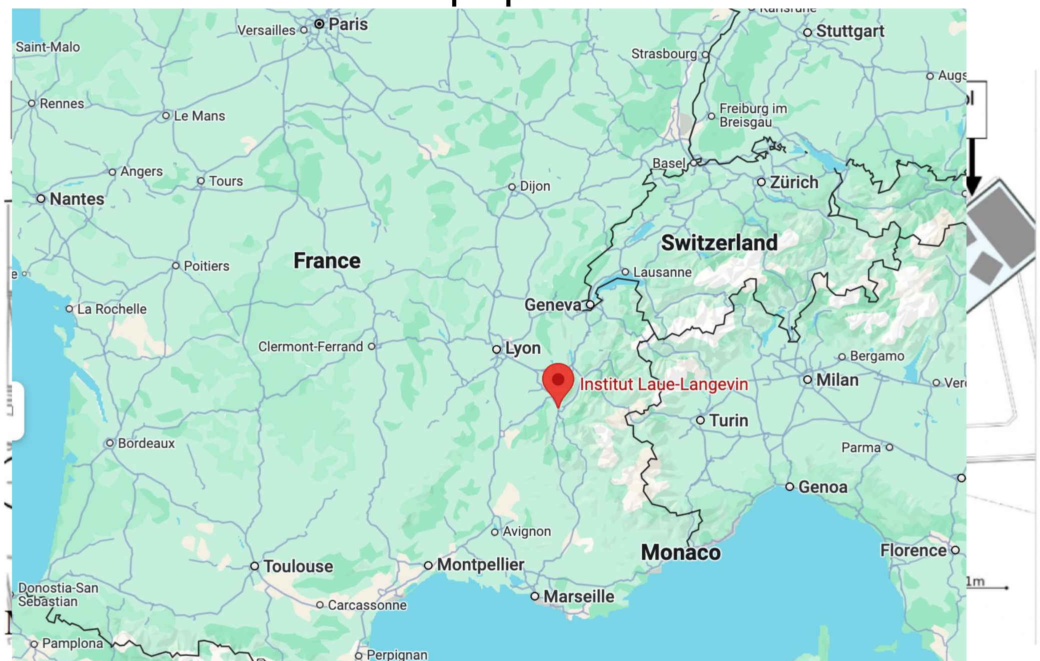


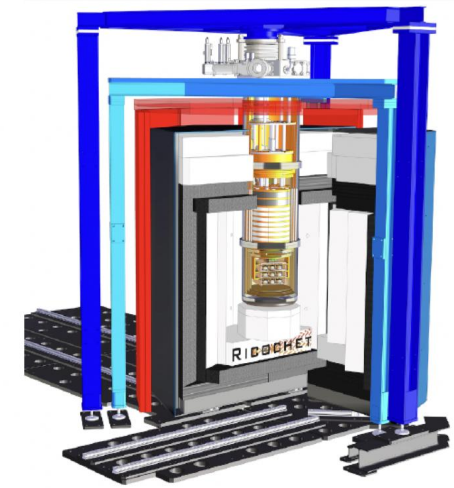
The Ricochet Experiment

- Ricochet @ ILL installation finished!
- 58 MW power: ~11 evts/day/kg (50 eV threshold)
- Ability to turn ON/OFF: subtract uncorrelated backgrounds!
- Significant overburden (~15 m.w.e) to reduce cosmics
- Fast and thermal neutron flux characterized
  - Eur. Phys. J. C 83, 20 (2023).
- Test run with 3 Ge detectors finished
  - Commission paper will come out soon!

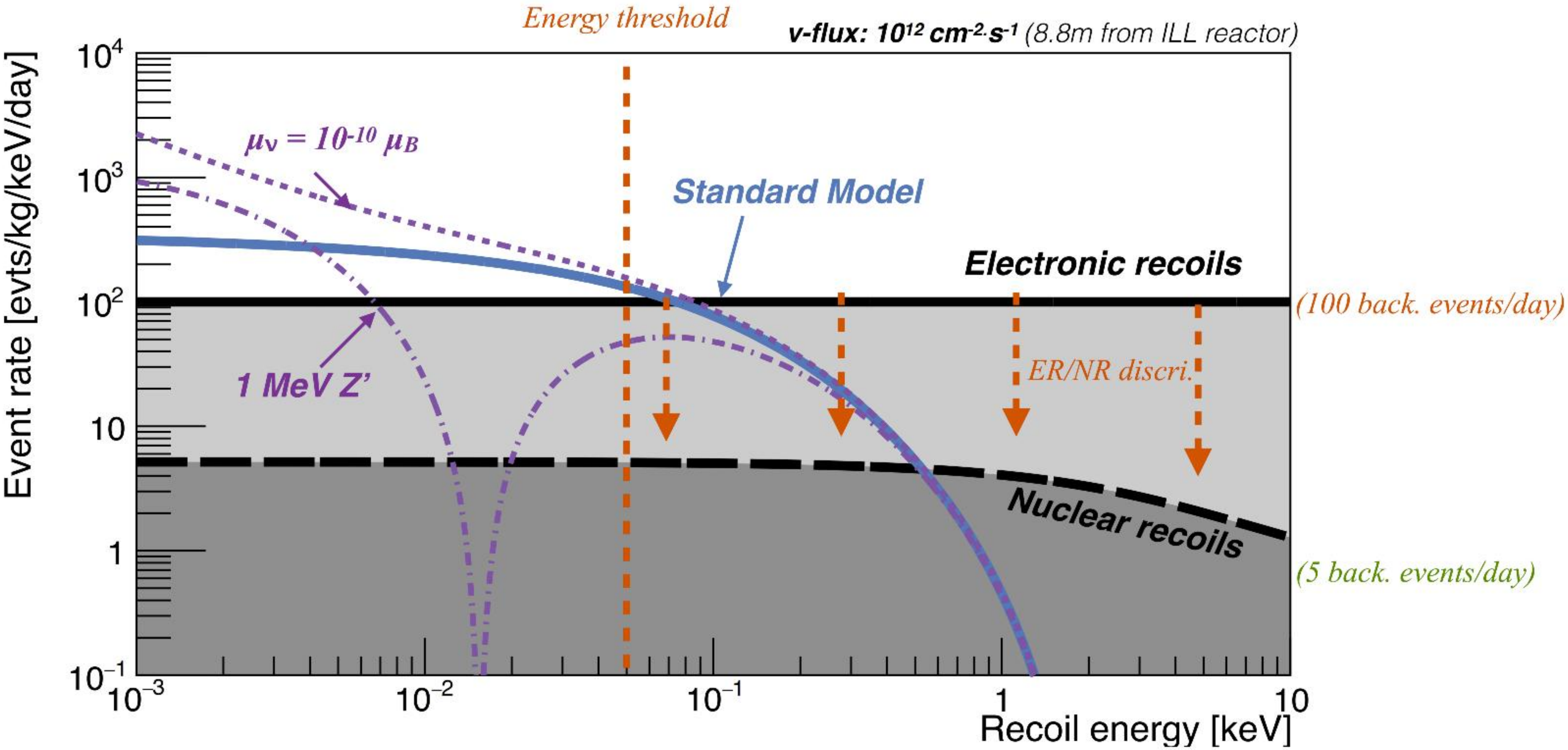
Inner shielding:
- PE/Cu: 30 cm
- Pb/Cu: 15 cm
- Cryogenic Muon Veto
- Mu-Metal

Outer shielding:
- PE: 35 cm
- Pb: 20 cm
- Muon veto
- Soft iron

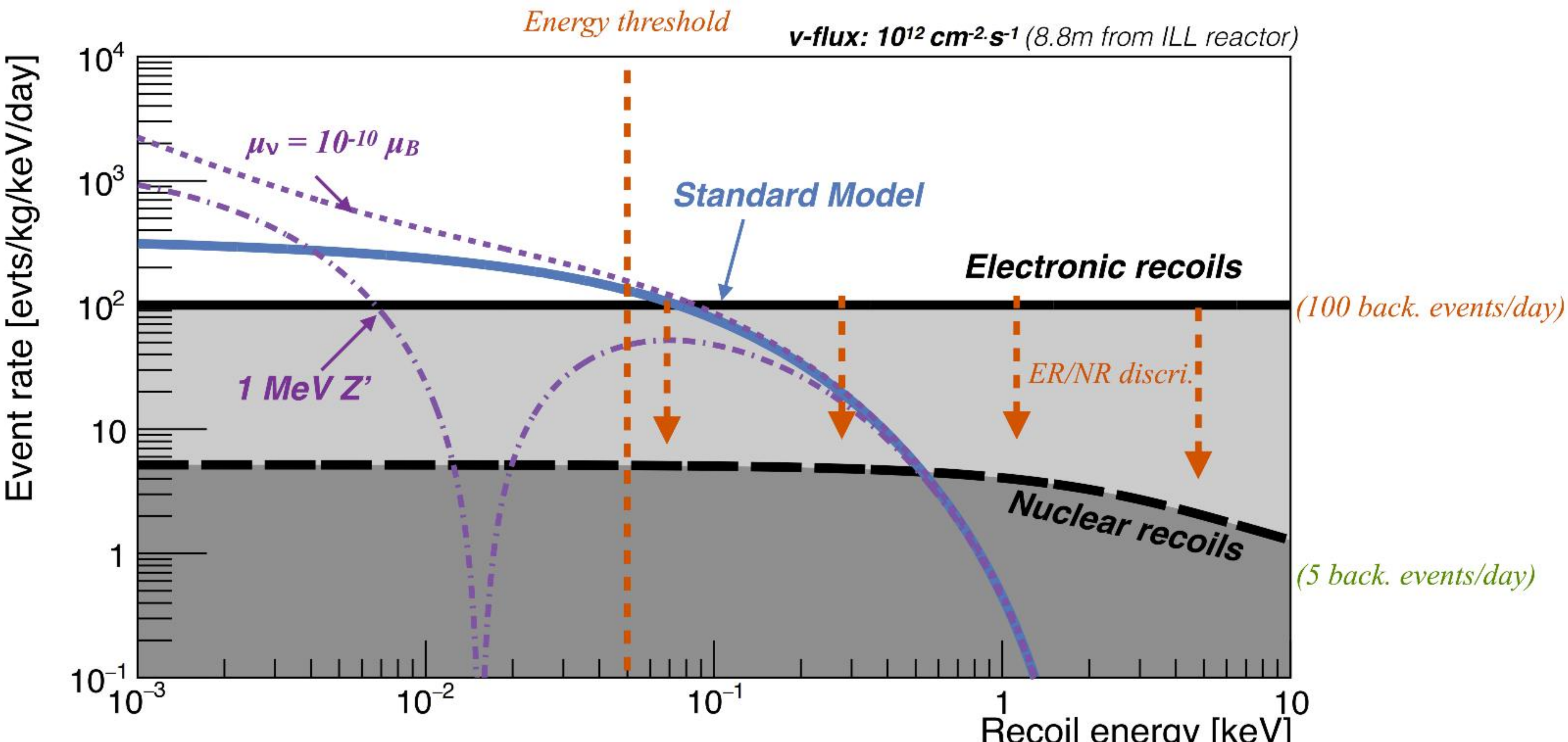




Searching for New Physics



Searching for New Physics



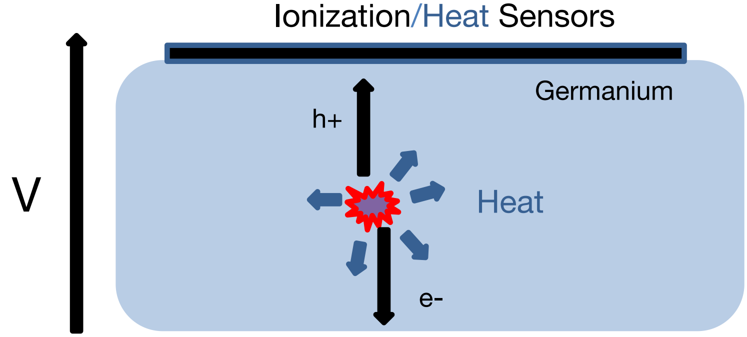
Requirements for detectors:

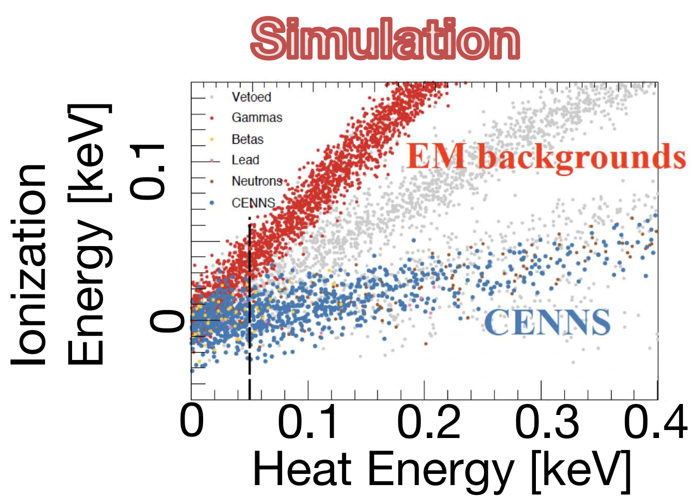
- Energy threshold below 50 eV
- Target mass ~ 1 kg
- Discrimination ability between nuclear recoil and electron recoil

Ricochet Detector Technologies

"Cryocube"

Ionization+Heat in Ge
Sensors: NTDs and HEMTs

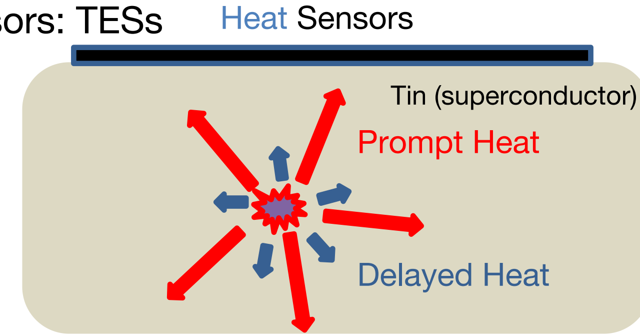


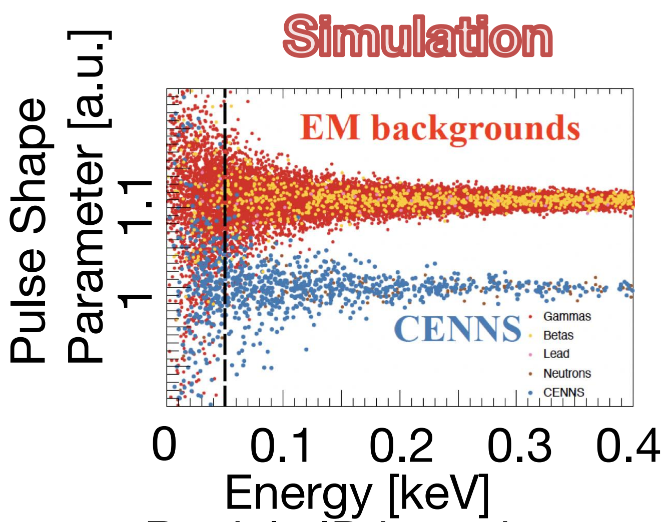


Particle ID based on Heat/Ion ratio

"Q-Array"

Heat Pulse Timing in Superconductor
Sensors: TESs



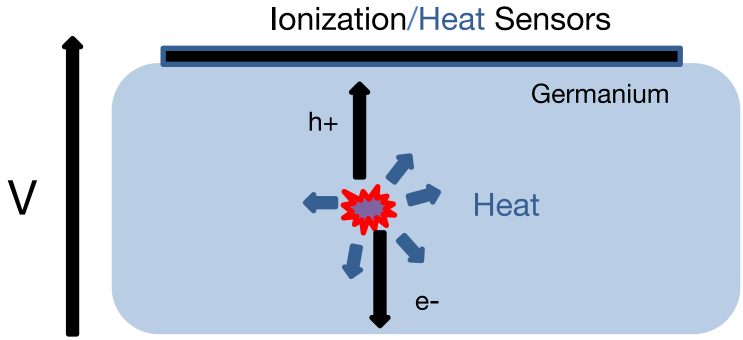


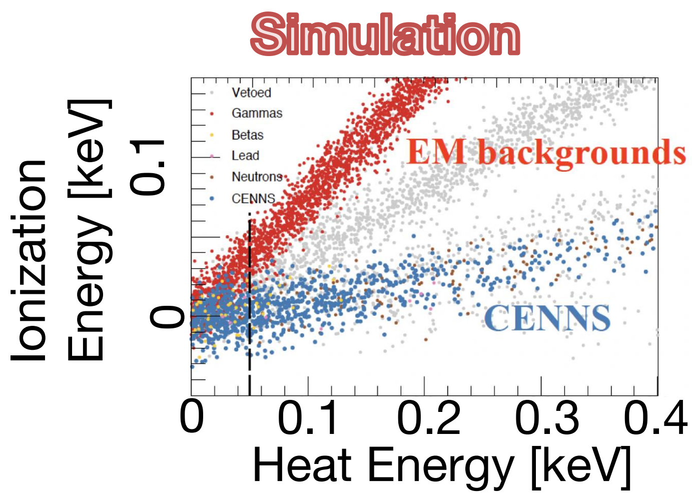
Particle ID based on
Prompt/Delayed heat Signal

Ricochet Detector Technologies

“Cryocube”

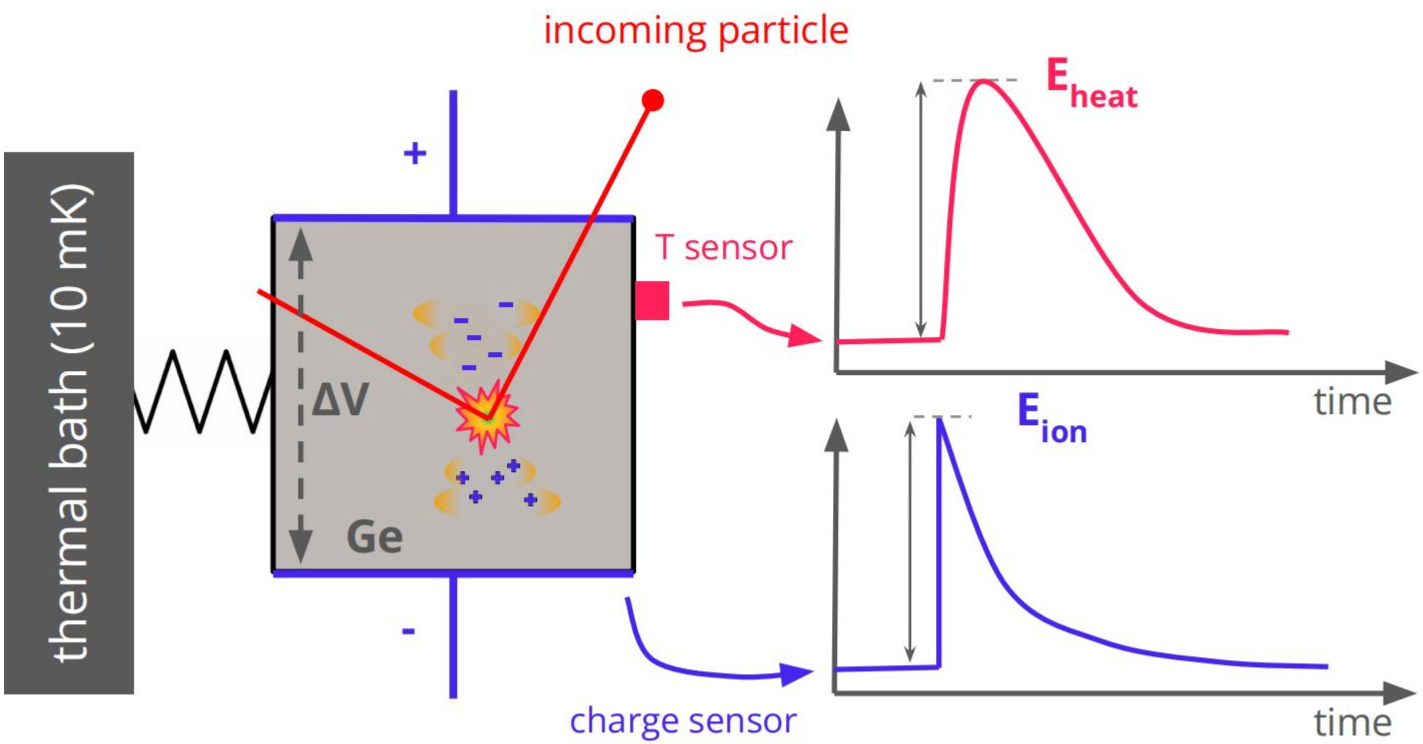
Ionization+Heat in Ge
Sensors: NTDs and HEMTs





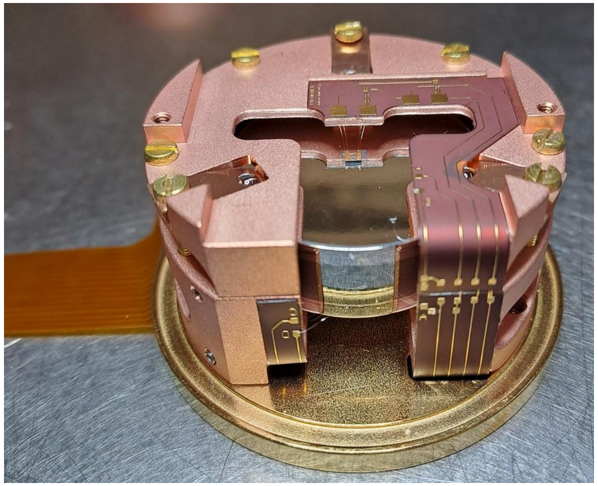
Particle ID based on Heat/Ion ratio

Cryocube Technology

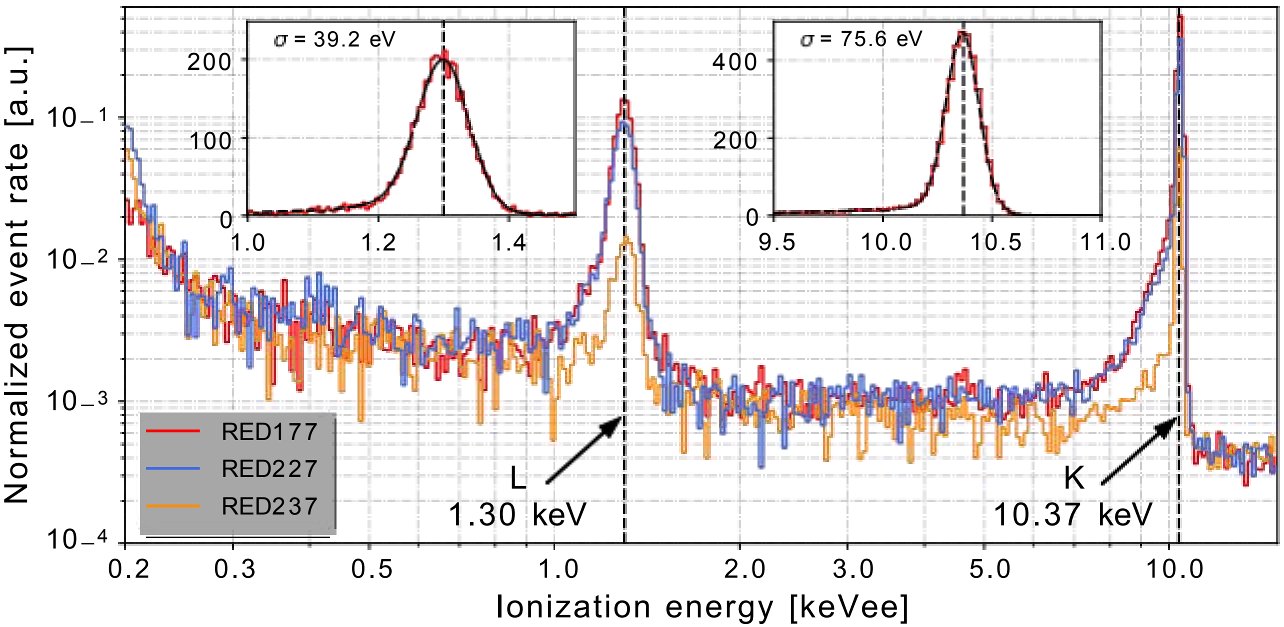


- apply ΔV to collect electron-holes pair (10's e-h sensitivity)
- measure heat elevation (μK sensitivity)

Cryocube: Demonstration

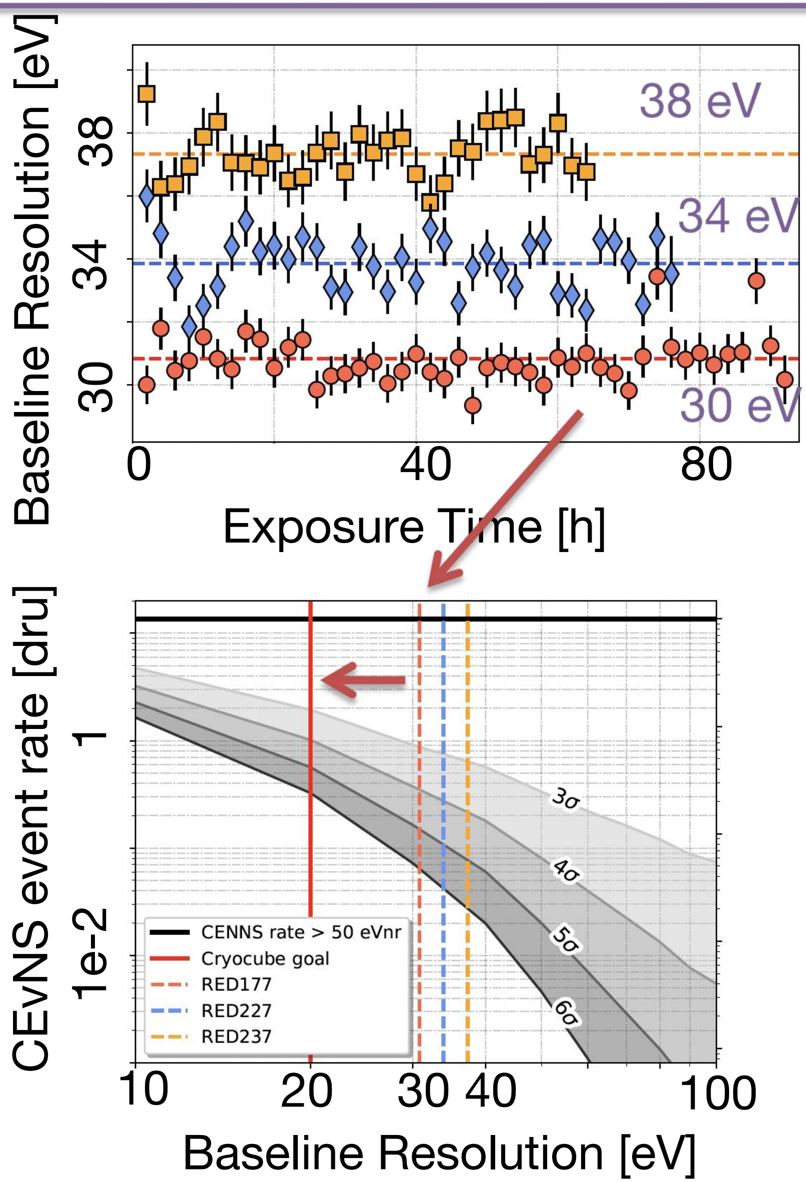


- Ge-based NTD detector.
- A mini-cryocube with three detectors was tested. Mass: 3*18 gram

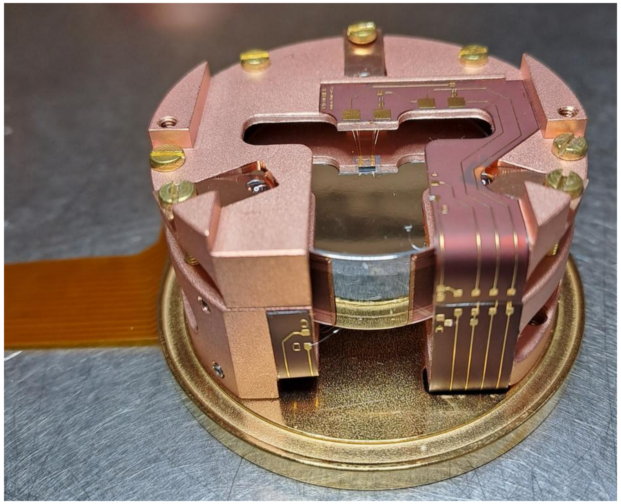


Reference:
First demonstration of 30 eVee ionization energy resolution with Ricochet germanium cryogenic bolometers.
Eur. Phys. J. C 84, 186 (2024).

Cryocube: Demonstration



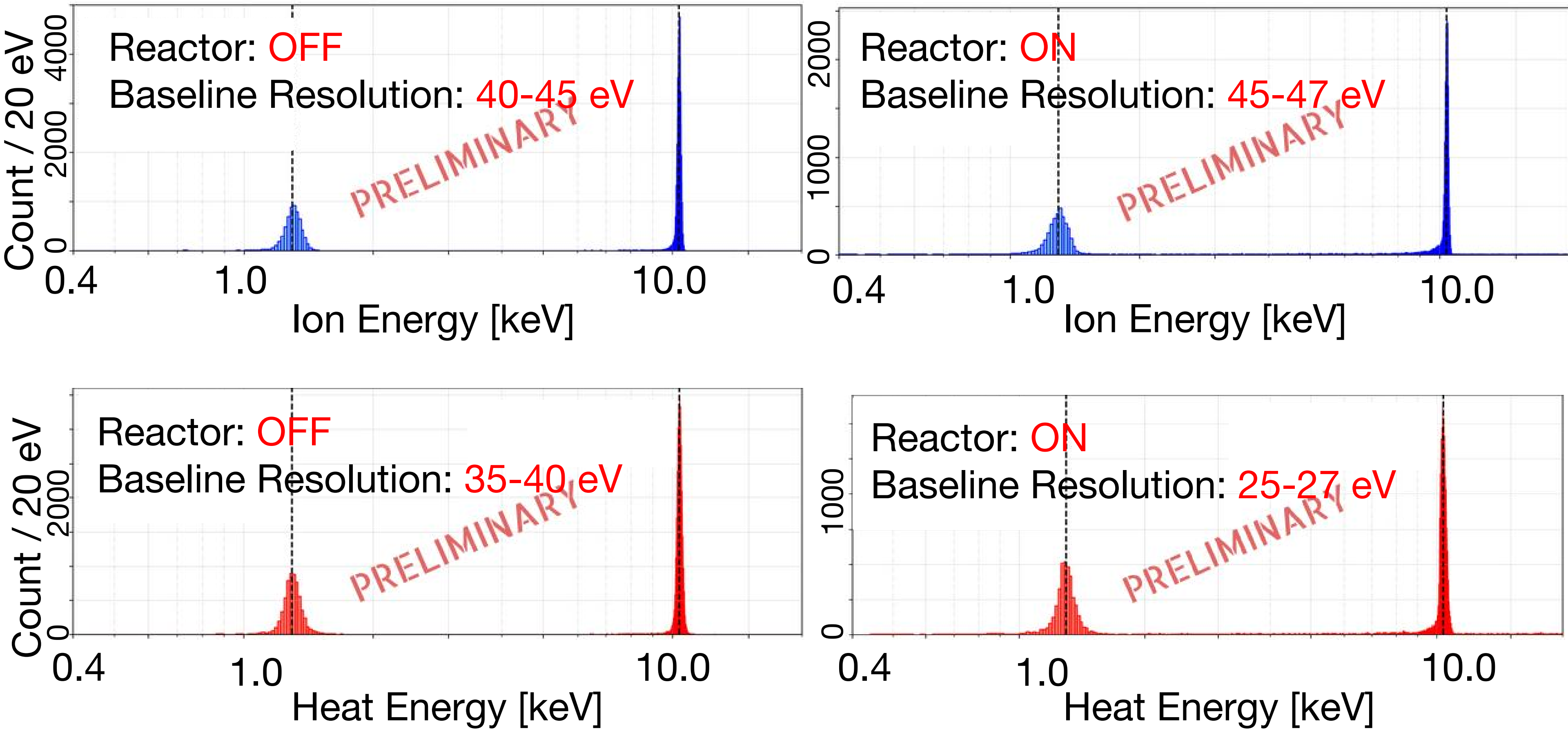
- The baseline resolution ~ 34 eV @ IP2I in Lyon.
- With optimized HEMT-based preamplifier, shoot for 20 eV.
  - Leading resolution on CEvNS!



Reference:
First demonstration of 30 eVee ionization energy resolution with Ricochet germanium cryogenic bolometers.
Eur. Phys. J. C 84, 186 (2024).

ILL Commissioning Result

RICOCHET



- First in-situ detector performance assessment Reactor ON/OFF data.
- Calibrated by the 71Ge L-Shell EC(1.30 keV) and K-Shell EC(10.37 keV).

OUTLINE

1. Coherent elastic neutrino-nucleus scattering (CEvNS)

2. Why measure it? What is the physics motivation?

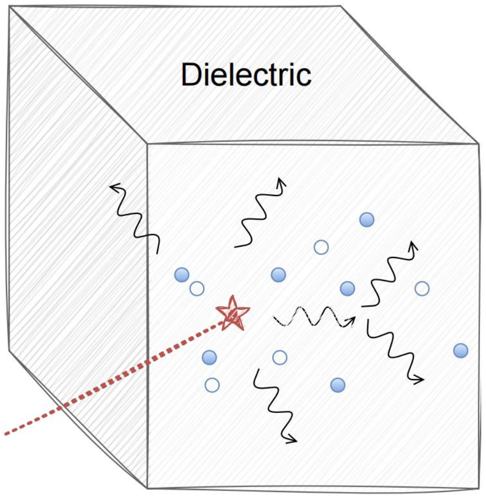
3. How to measure CEvNS

4. The Ricochet experiment at ILL nuclear reactor

5. The R&D of Ricochet experiment

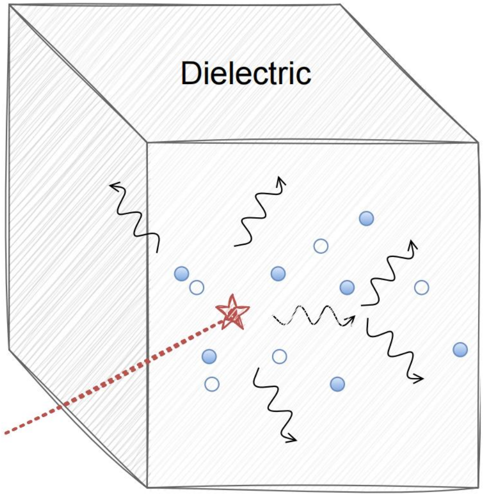
Limit on Ge Detector

- Dielectric Detectors
  - Ionisation above energy gap ~ 1 eV
  - When Recoil Energy > ~10 eV: Heat and Charge
    - Discrimination between electron recoil and nuclear recoil
  - When Recoil Energy < ~10 eV: Only Heat
    - Cannot do discrimination

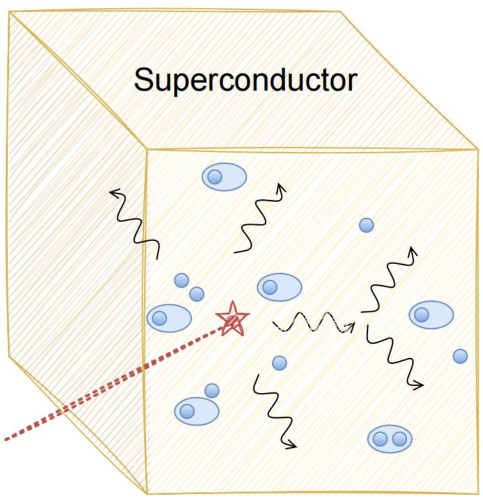


Limit on Ge Detector

- Dielectric Detectors
  - Ionisation above energy gap ~ 1 eV
  - When Recoil Energy > ~10 eV: Heat and Charge
    - Discrimination between electron recoil and nuclear recoil
  - When Recoil Energy < ~10 eV: Only Heat
    - Cannot do discrimination



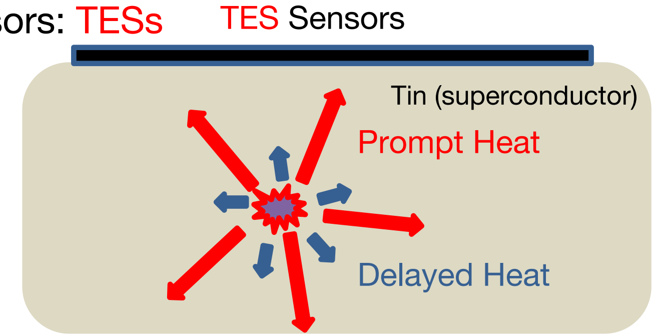
- Superconductors
  - Energy gap ~ 1-10 meV
  - 2 path of thermal transportation:
    - Phonon -> Thermal Sensor
    - Phonons above the gap -> Break Cooper Pairs -> Quasiparticles -> Recombine as Cooper Pairs and release phonon -> Sensor
  - All energy goes into heat eventually
  - Electron recoil and nuclear recoil might have different thermal response!

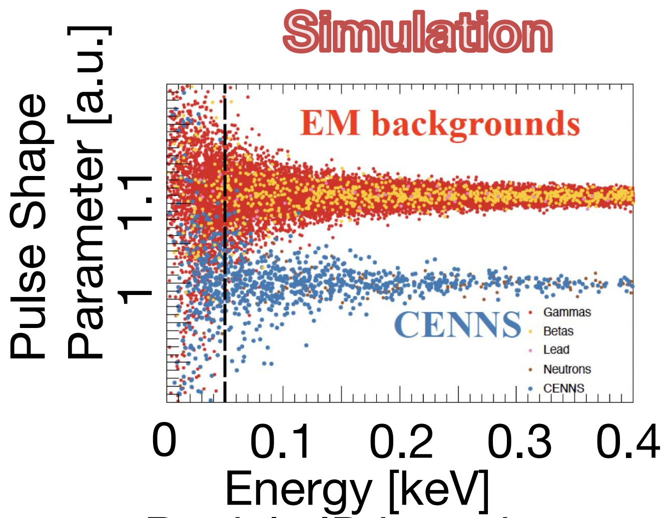


Ricochet Detector Technologies

"Q-Array"

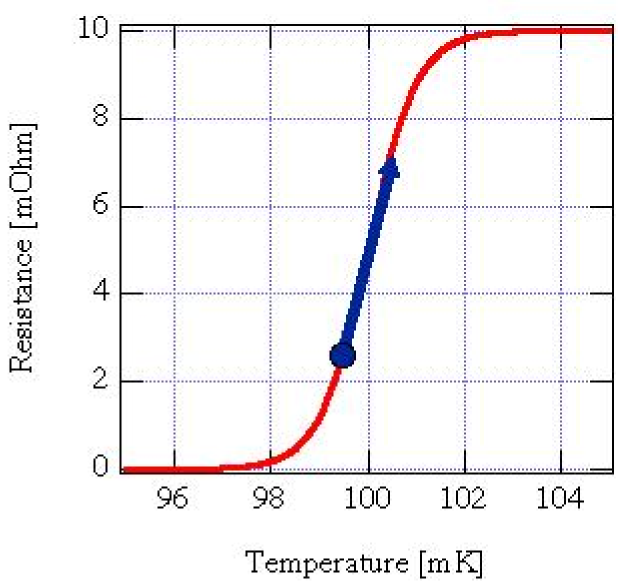
Heat Pulse Timing in Superconductor Sensors: TESs

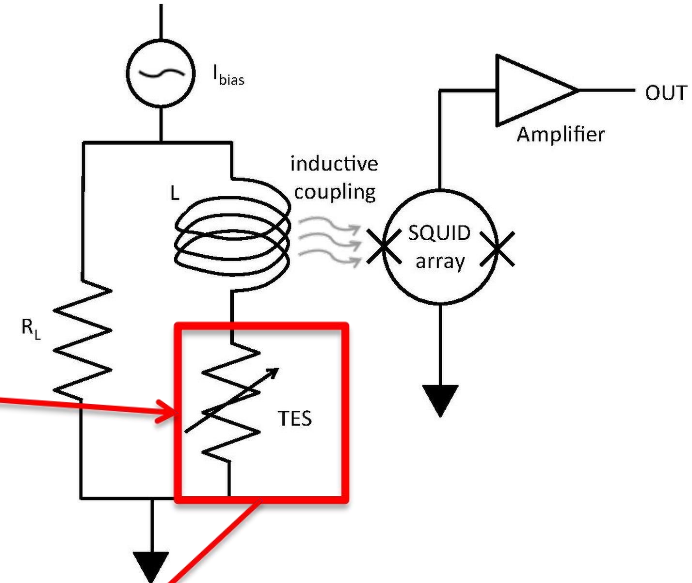


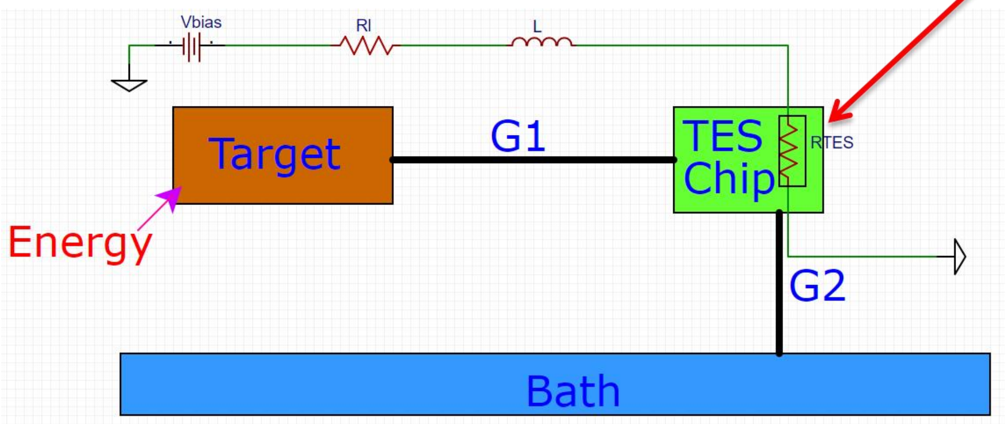


Particle ID based on Prompt/Delayed heat Signal

Transition Edge Sensor





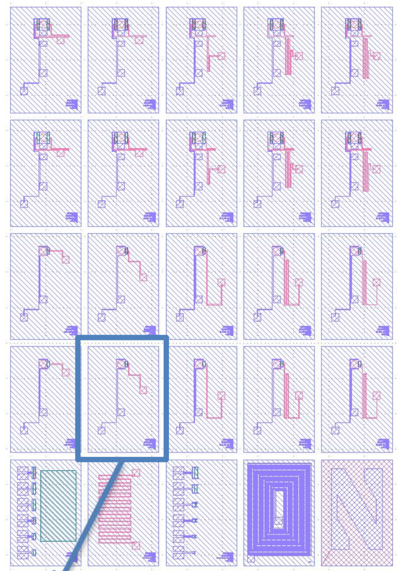


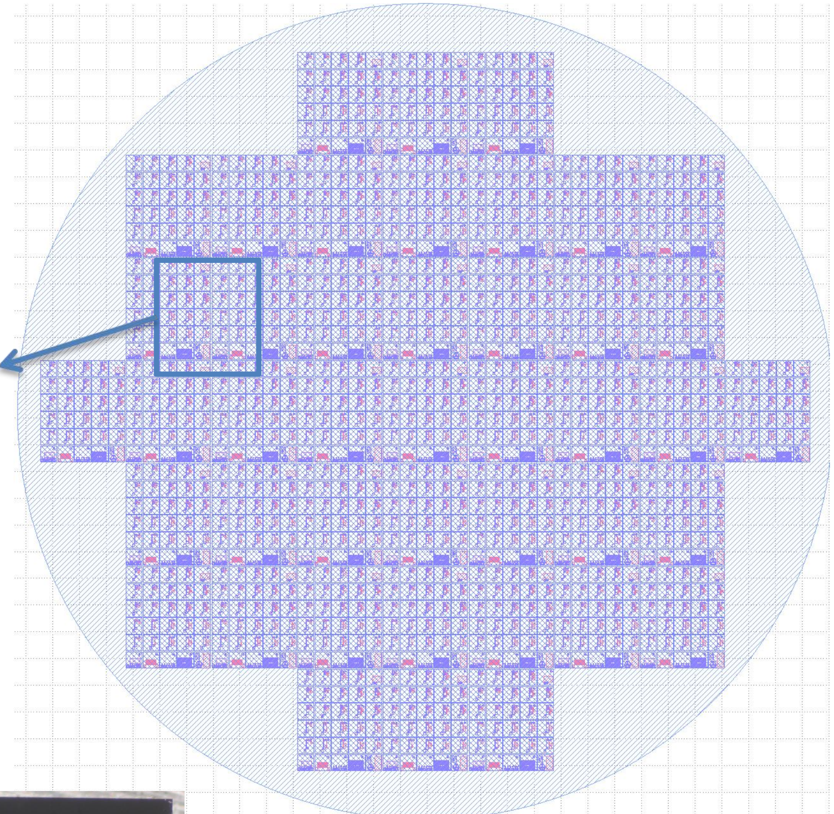
Energy Deposition ->
Temperature ↑ ->
TES Resistance ↑ ->
Current ↓ ->
Jules Heat ↓ ->
Temperature ↓

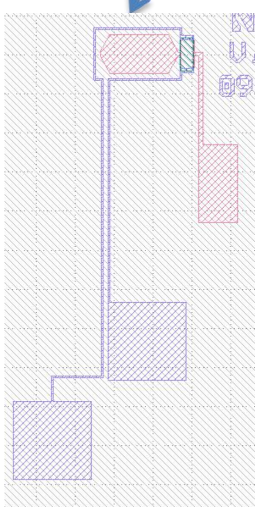
Ricochet Modular Sensor Design

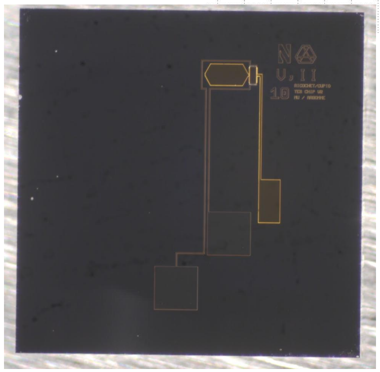
RICOCHET

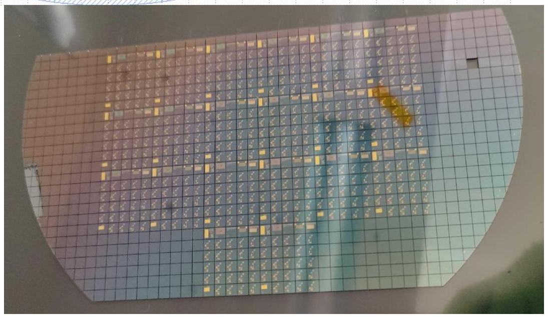
- Al/Mn TES with tunable Tc fabricated at Argonne National Laboratory
- More than 1000 chips from a single wafer
- Easy to change design and re-fabrication







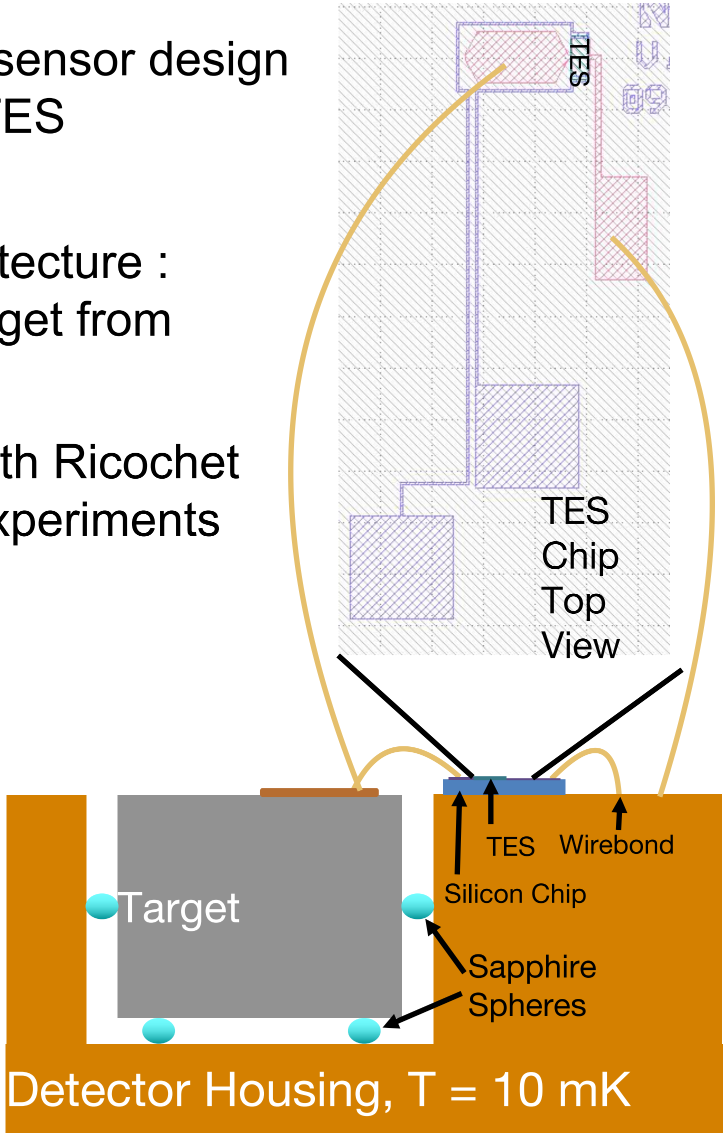


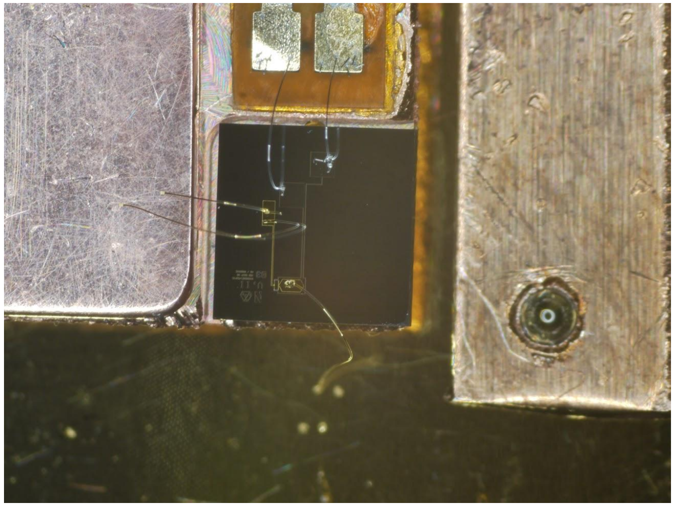


A 6-inch test wafer

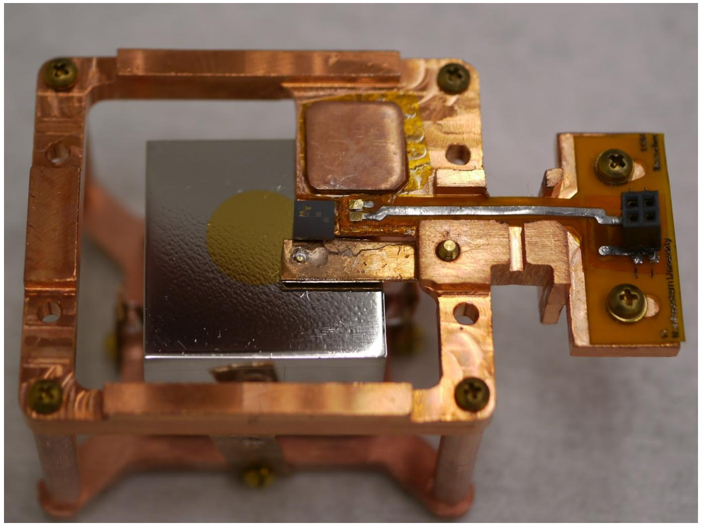
Q-array and Modular TES Sensor Readout

- New modular sensor design using Al/ Mn TES
- Scalable architecture : decoupling target from thermometer
- Designs for both Ricochet and CUPID experiments underway

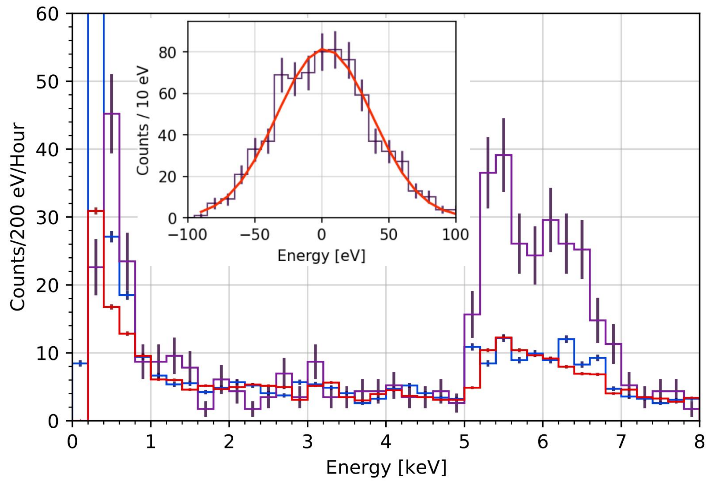


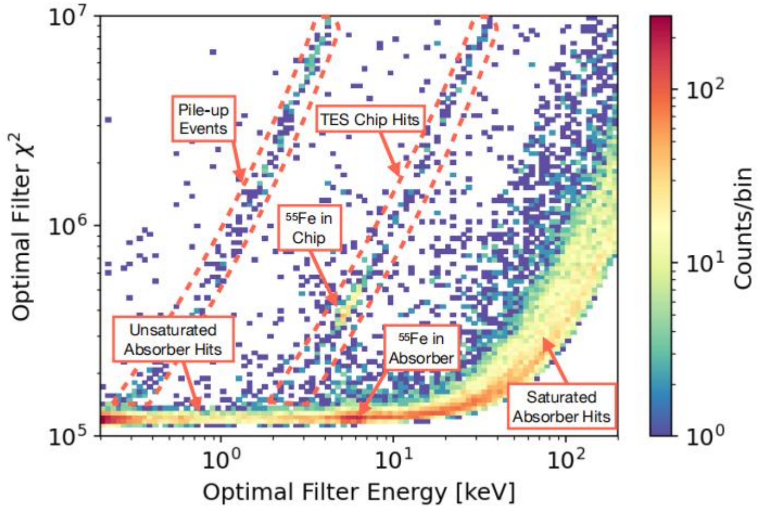


Sn Detector



Prototype Q-Array Detector



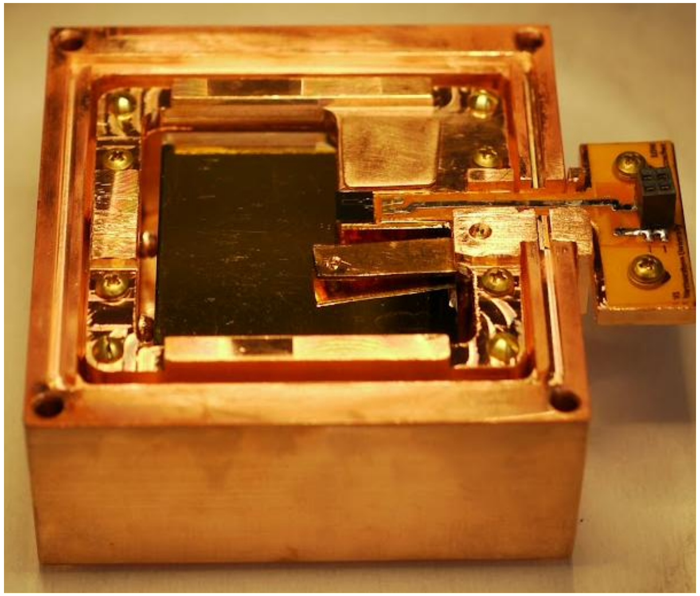


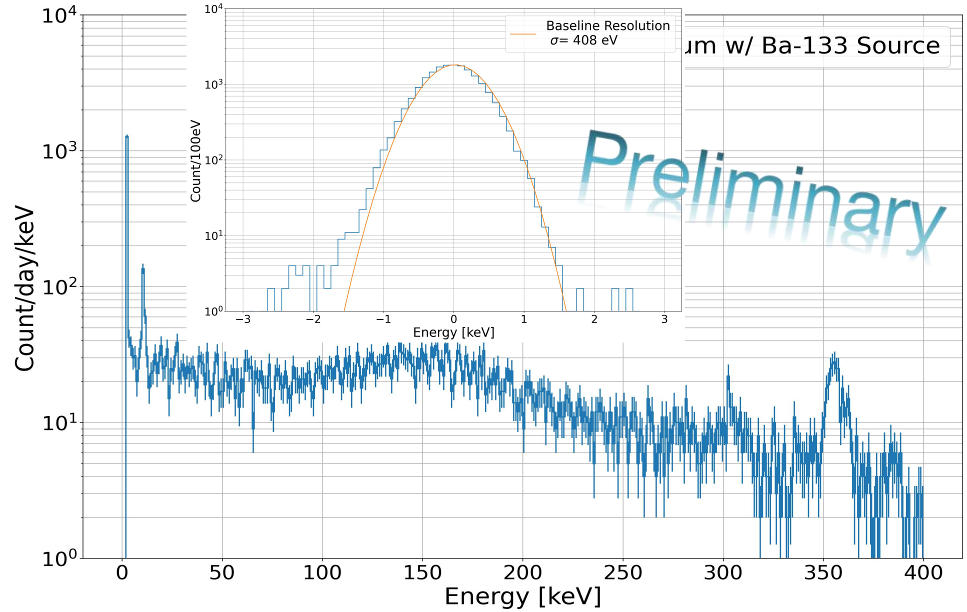
- First Q-Array style detector @ UMass
  - 1 gram of Si target
  - Al/Mn bi-layer TES with Tc of 20 mK
  - Baseline Resolution is about 30 eV.

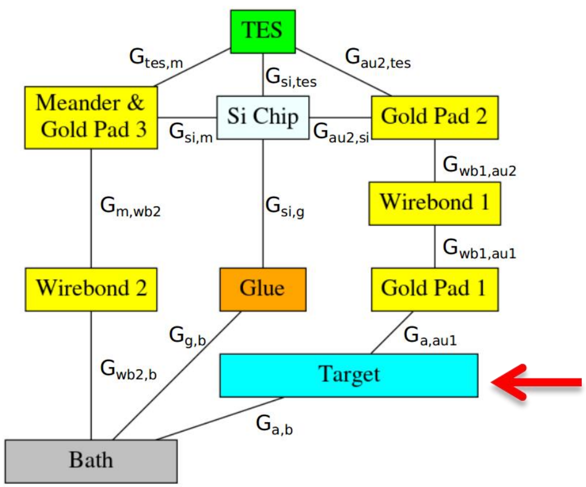
Reference:
Augier, C., & others (2023). Results from a prototype TES detector for the Ricochet experiment. Nucl. Instrum. Meth. A, 1057, 168765.

Prototype Q-Array Detector

RICOCHET

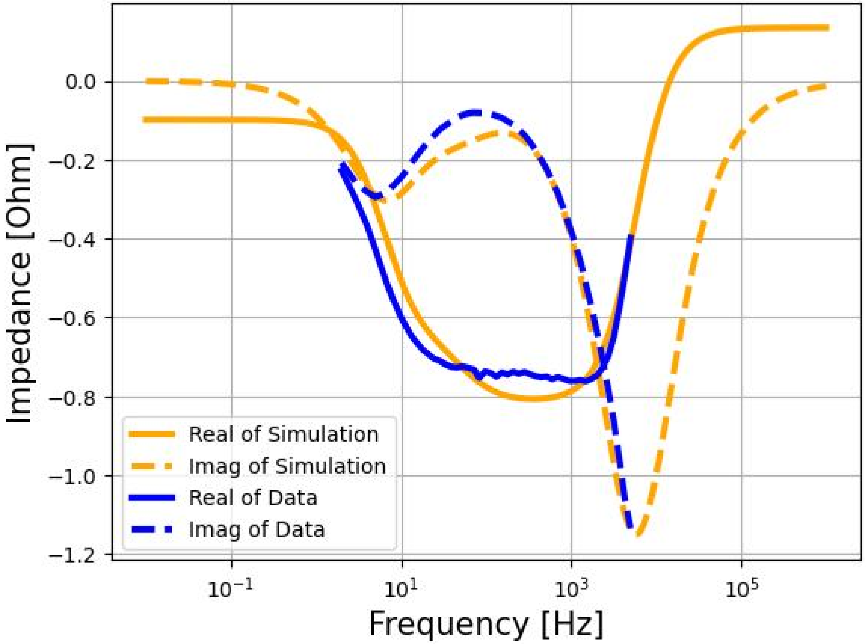


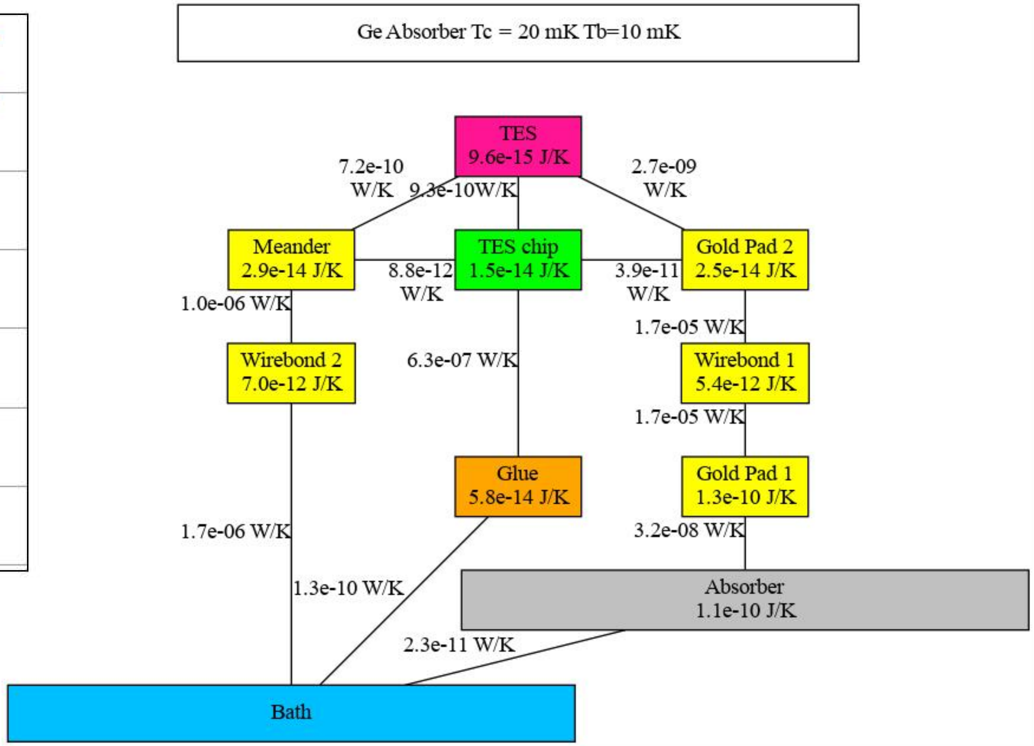




- Larger Q-Array style prototype with 30 gram Ge crystal
- The baseline resolution is ~400 eV.
- Why baseline resolution is not good?
- A model was build to understand the detector.

Complex Impedance of Ge detector





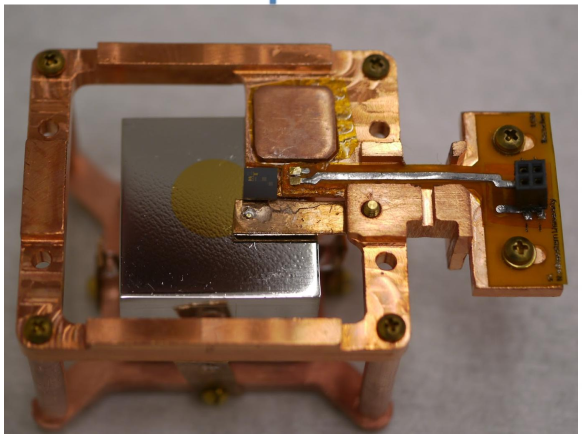
- Information from complex impedance
- Tune the model parameters to reproduce
- Test different parameter to improve baseline resolution
- Predicted energy resolution ~ 400 eV which matched the measurement!

Reference:
Chen, R., Figueroa-Feliciano, E., Bratrud, G. et al. Modeling and Characterization of TES-Based Detectors for the Ricochet Experiment. J Low Temp Phys 215, 217–224 (2024).

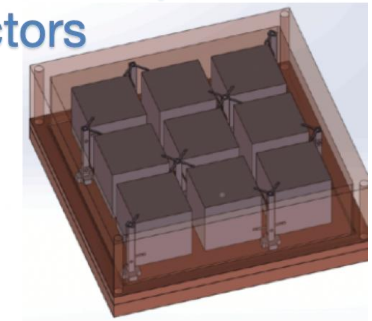
Q-Array Detector: Superconductor

RICOCHET

Superconductor crystal



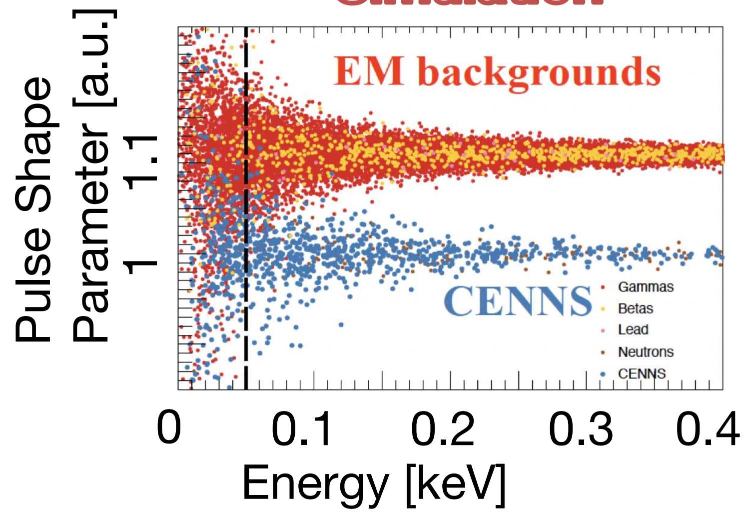
Array of 9 superconductor detectors



Ultimately using superconductors as the target is the goal of the Q-Array

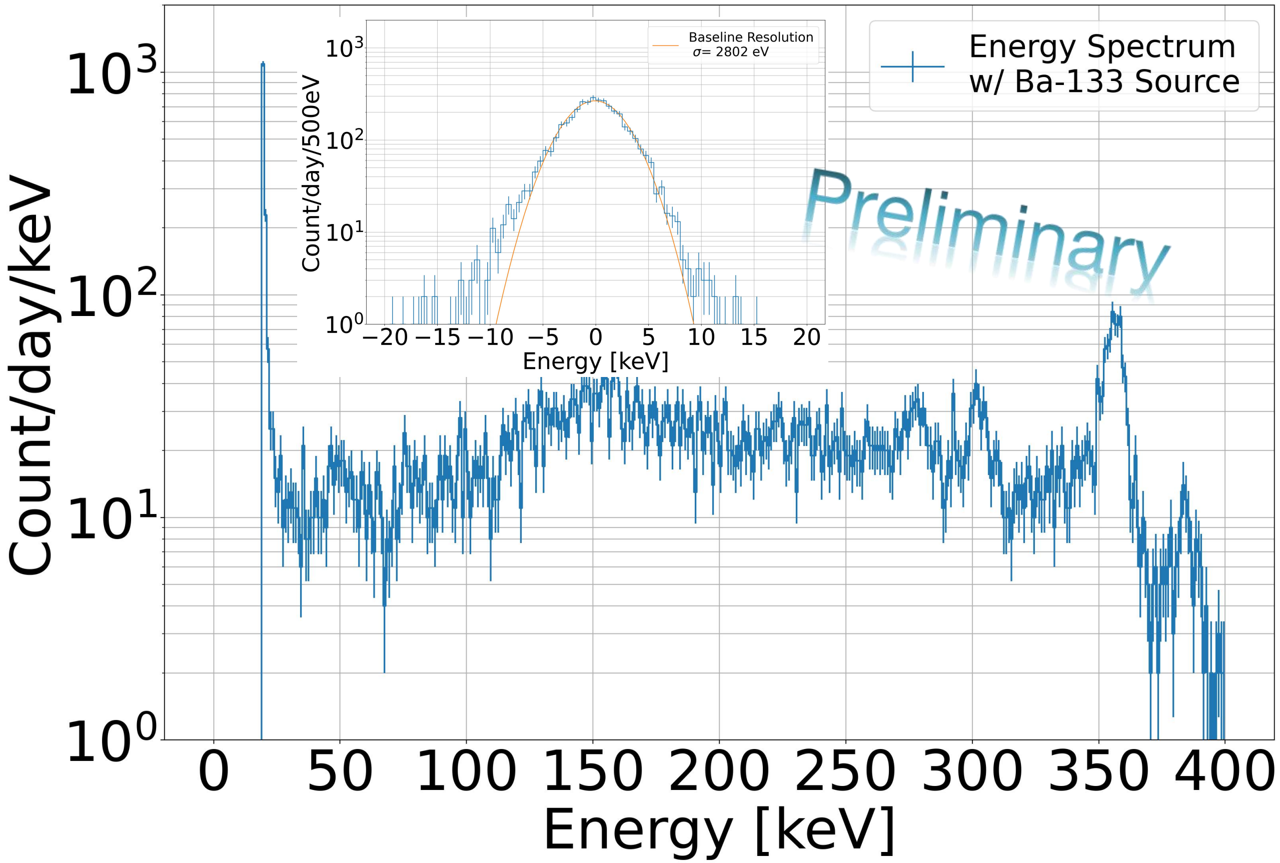
- Discrimination between NR and ER

Simulation



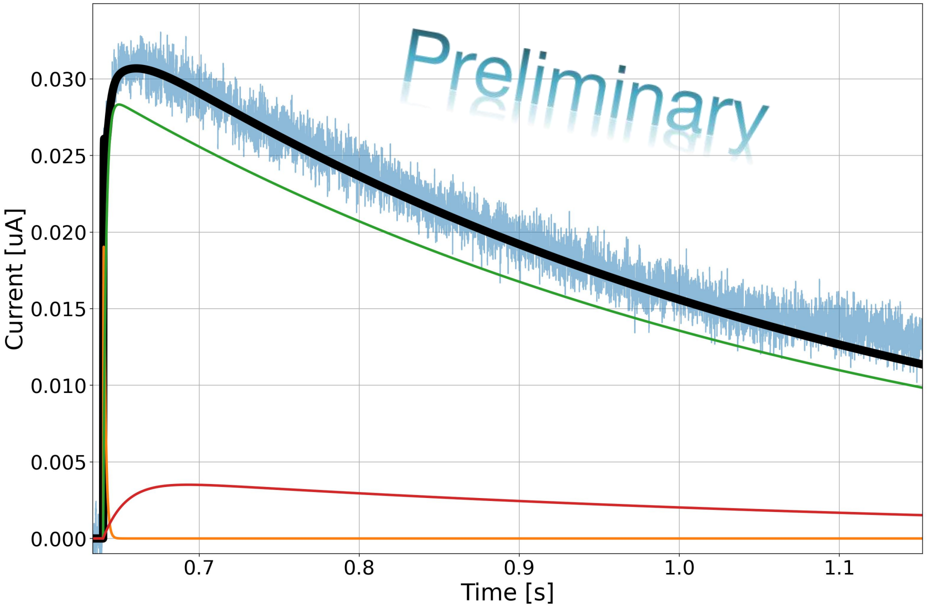
Particle ID based on Prompt/Delayed heat Signal

Q-Array Technology



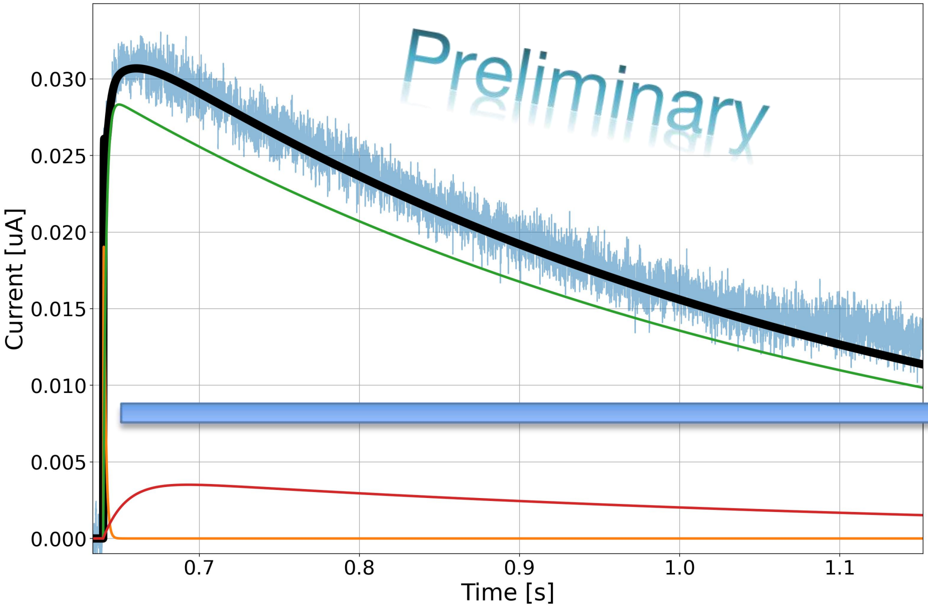
- Preliminary result from Sn crystal detector
- Baseline Resolution ~ 2.8 keV

Q-Array Technology

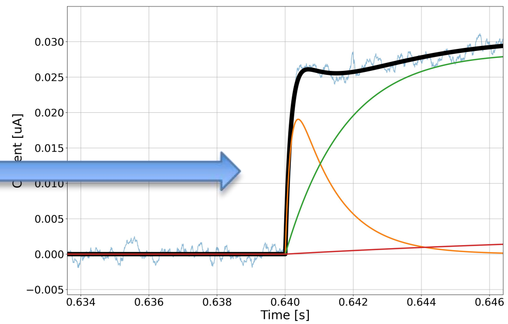


- Blue: Raw Pulse
- Black: Main Fit
- Orange, Green, Red:
  3 components of fit

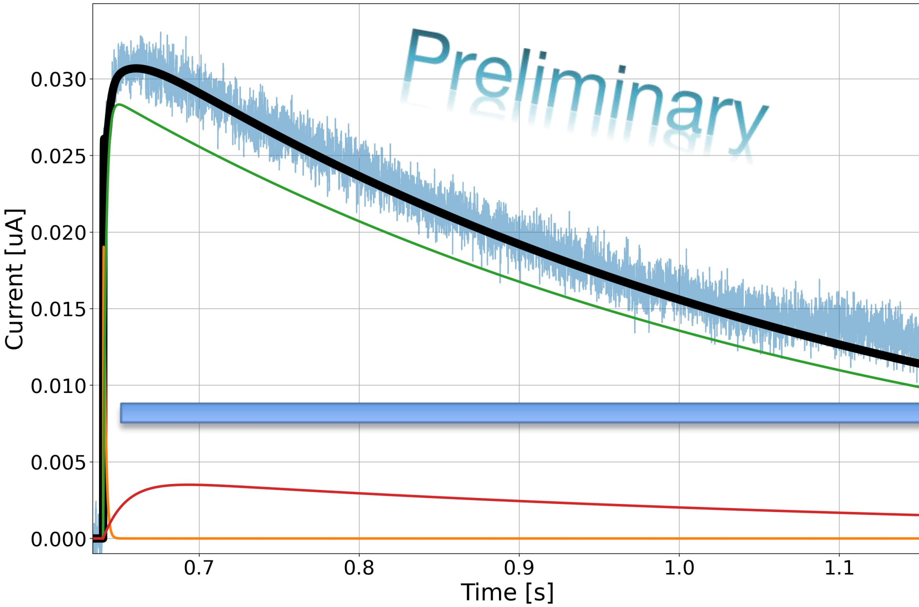
Q-Array Technology



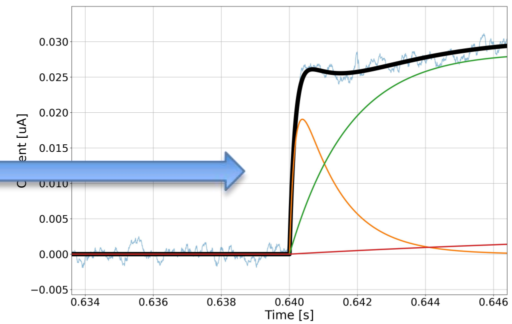
- Blue: Raw Pulse
- Black: Main Fit
- Orange, Green, Red:
  3 components of fit



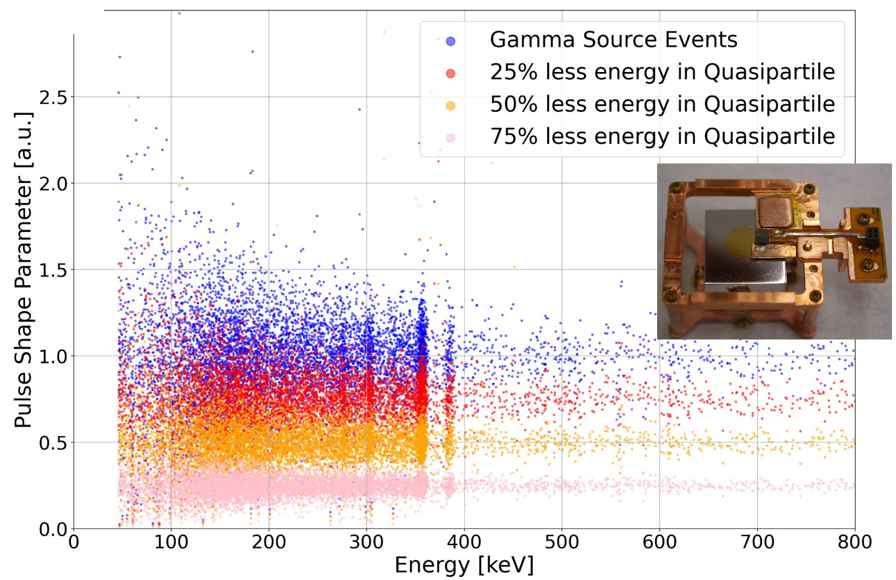
Q-Array Technology



- Blue: Raw Pulse
- Black: Main Fit
- Orange, Green, Red:
  3 components of fit

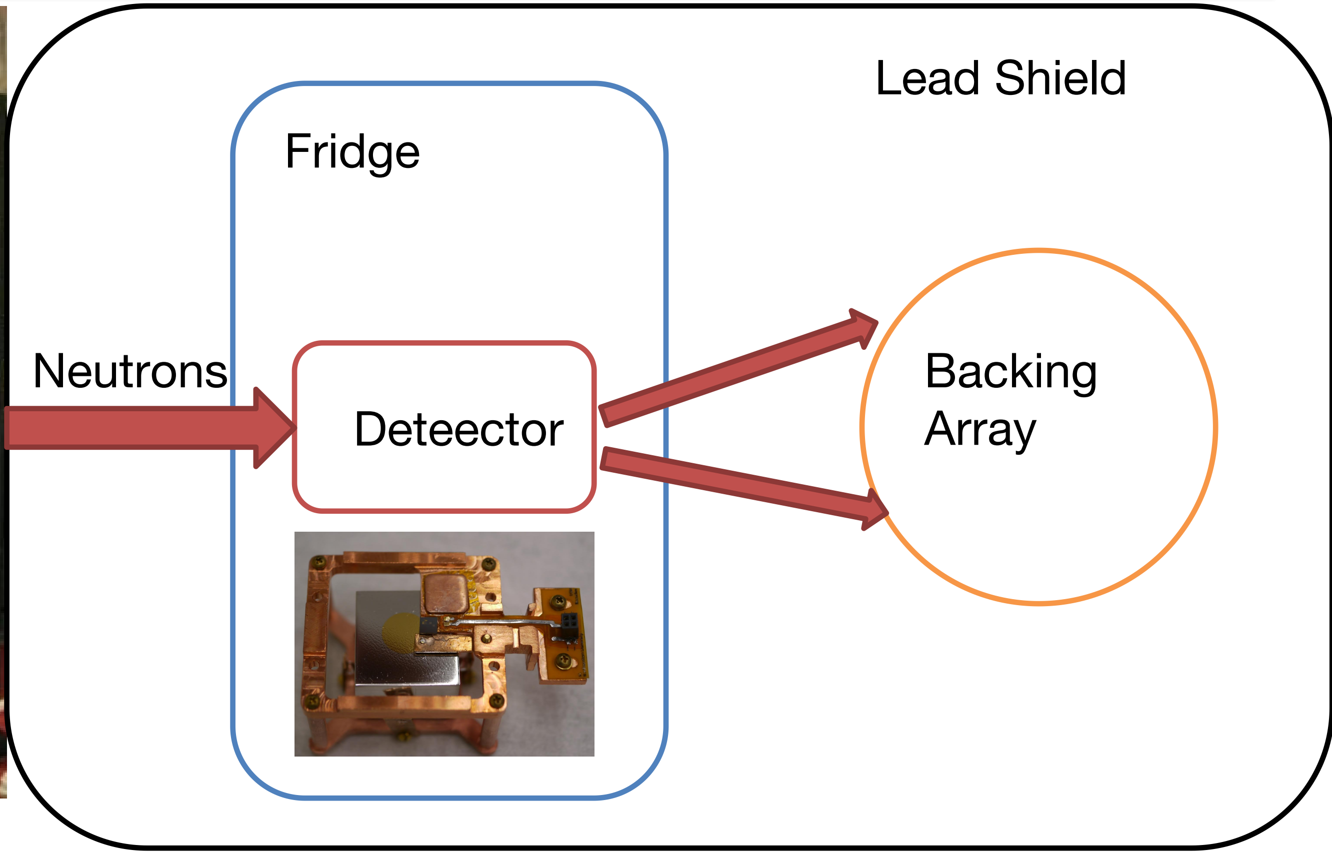


- Preliminary result from Sn crystal detector
- Pulses always contain a 2 fast and a slow component. Potentially Quasiparticle effect.
- Model work is underway!
- Simulation with lower Red component amplitude



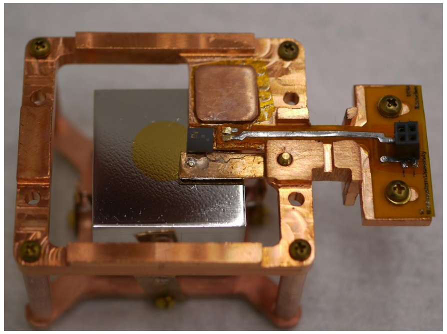
Test with Neutron Generator

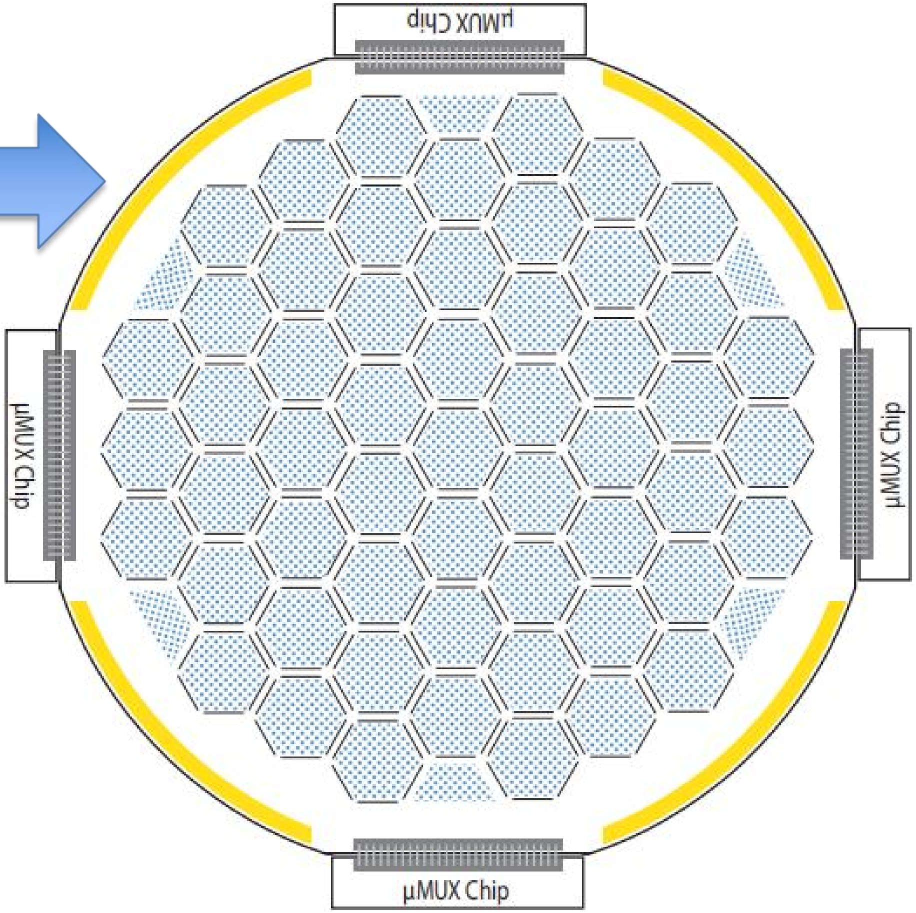
DD Generator



- Mono-energy neutron beam of 2.5 MeV
- Plan to start in a few weeks!

Future of Q-Array Technology



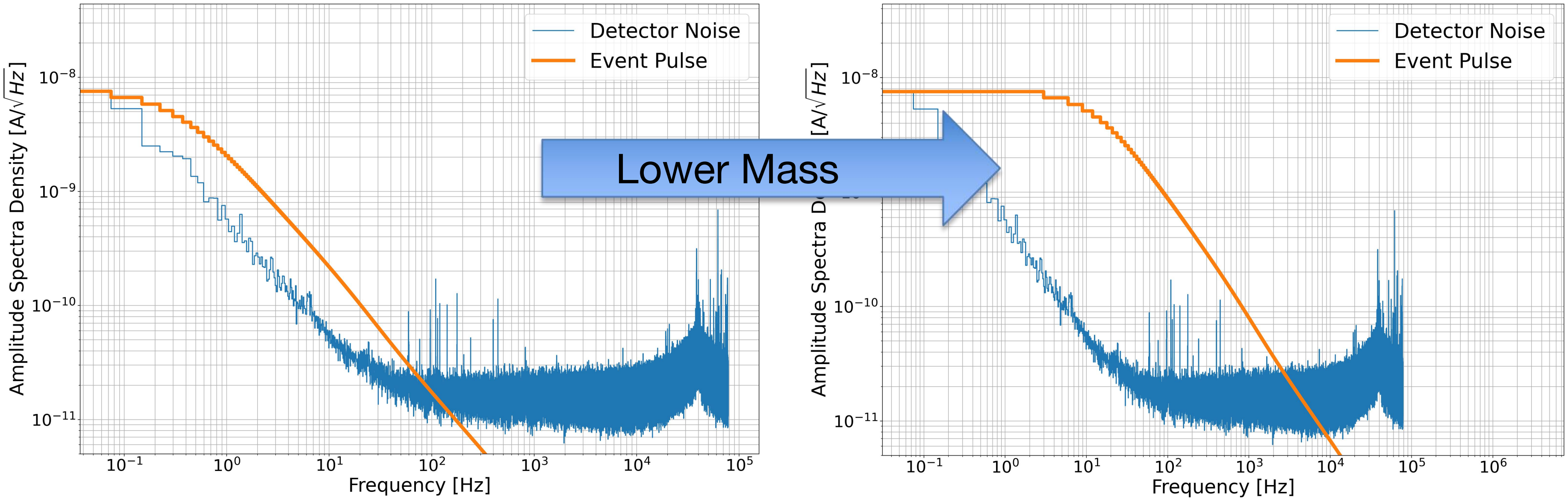


- Goal: Improve the baseline resolution

- 40 gram target crystal
  -> Hexegon thin wafer of 2 gram

- Resolution ∝ $\sqrt{C}$

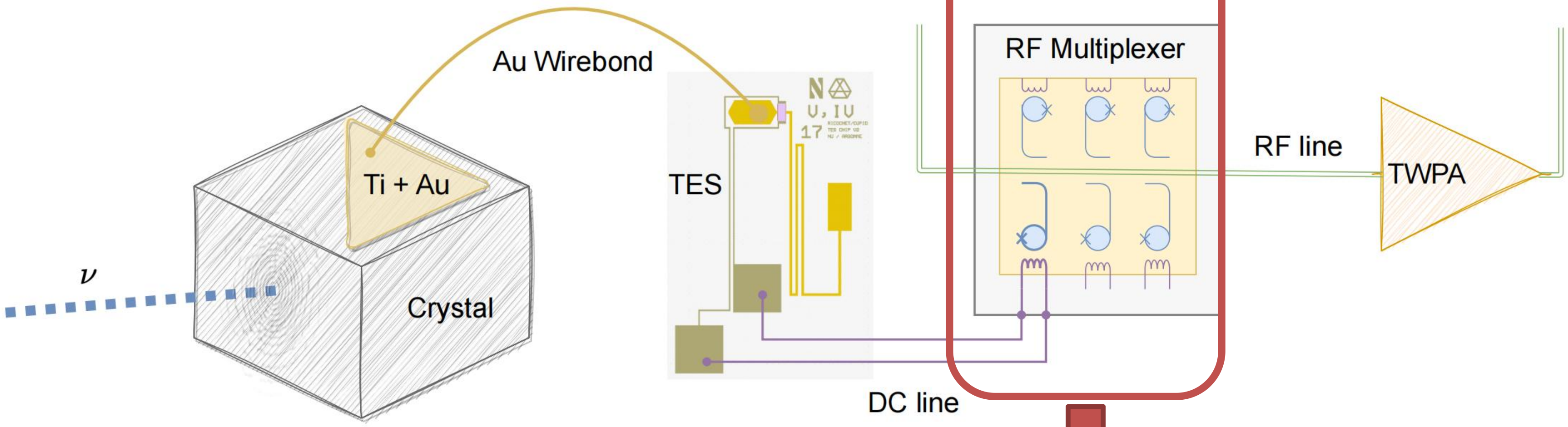
Future of Q-Array Technology

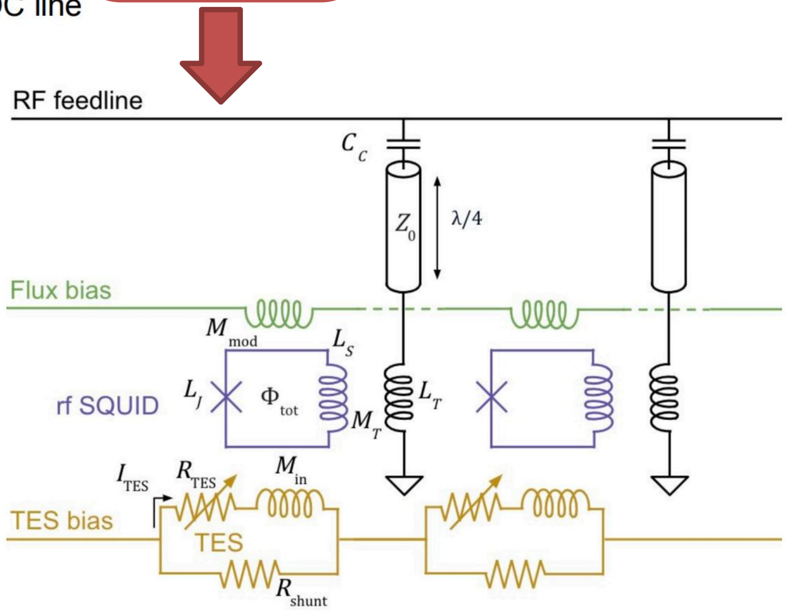


- Lower target mass will speed up pulses

- Move the signal away from the 1/f Electronic Noise
  -> Increase Signal Noise Ratio

Multi-Plexing





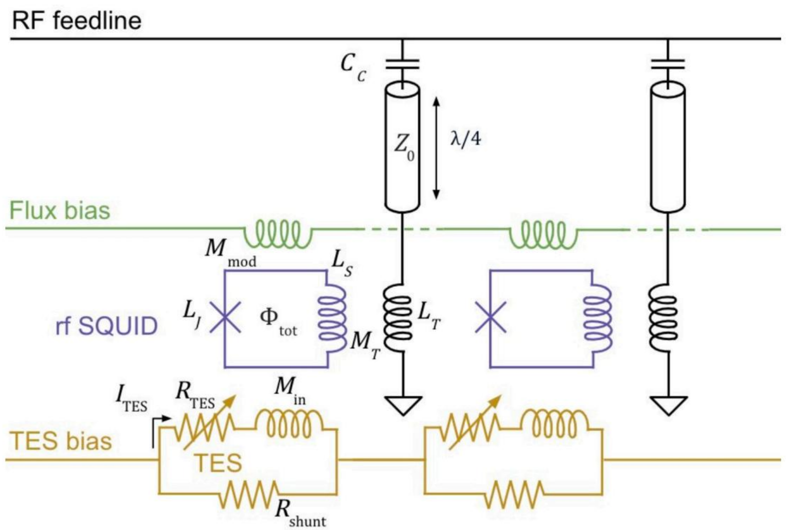
- Encode low frequency TES signals into microwave resonators.
- Readout multiple detectors with a single RF feedline.

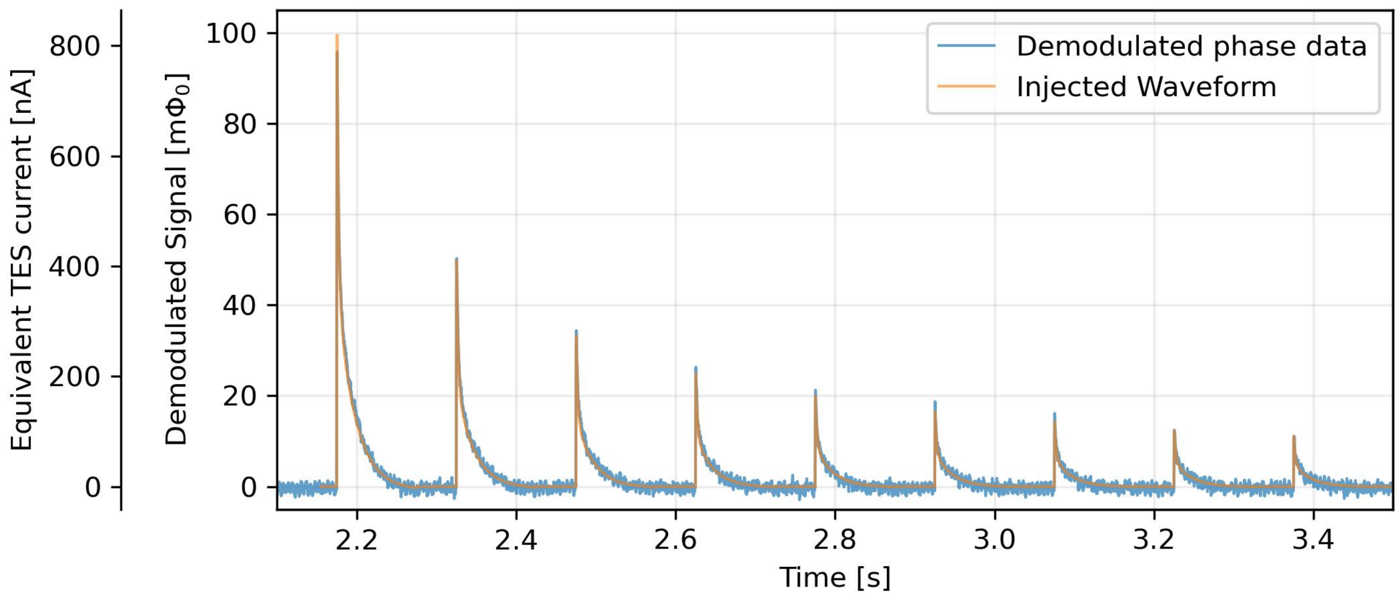
Multi-Plexing

1. Raw pulse in eact TES

2. RF SQUID + Resonator encode into RF line

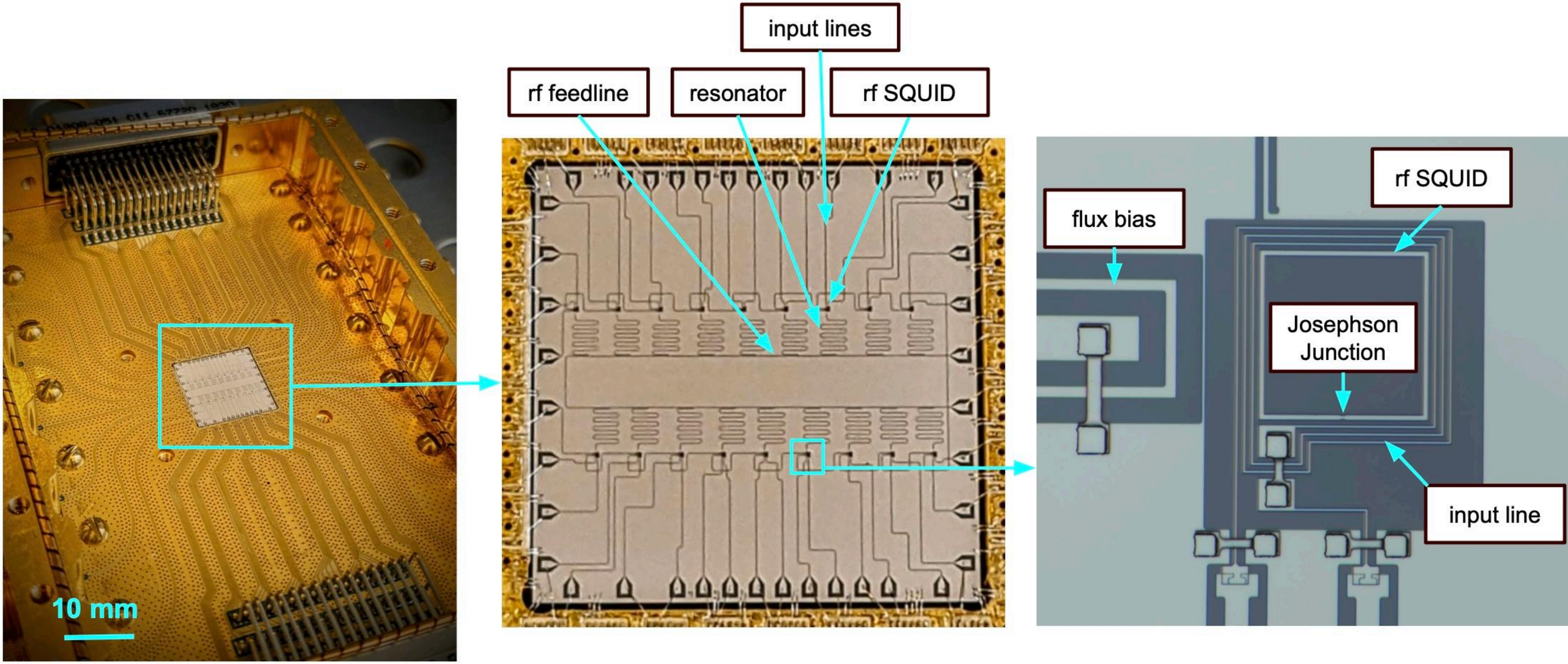
3. Decode RF to get raw pulses





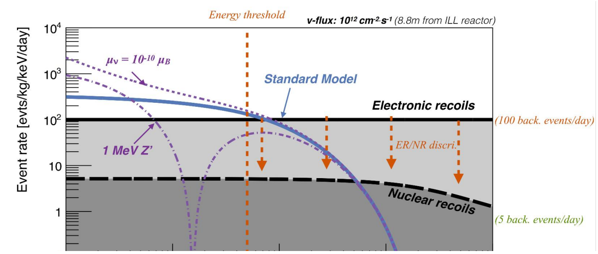
Multi-Plexing

RICOCHET

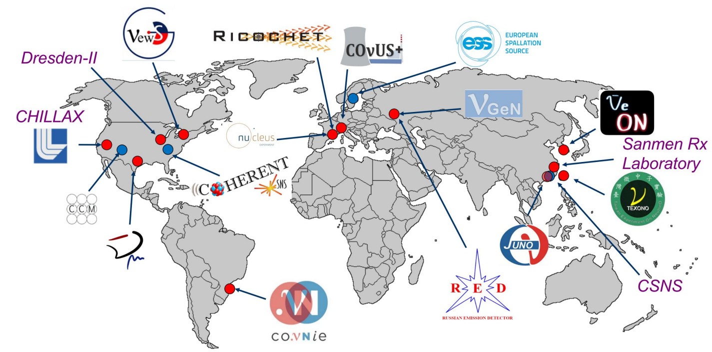


Summary

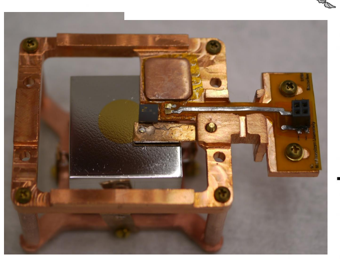
1. CEvNS measurement is a key to exciting physics.
   - Test old and search new physics
   - Contribute to other precision measurement
   - New messager for astrophysics

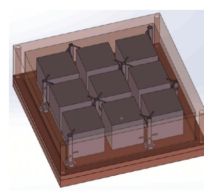


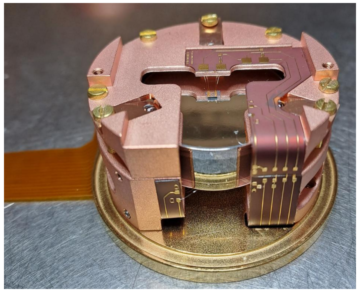
2. A worldwide race is ongoing!
   - ~ 20 collaborations all over the world.

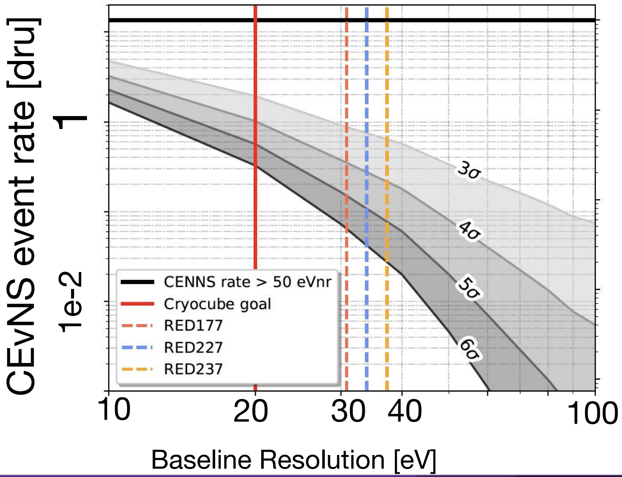


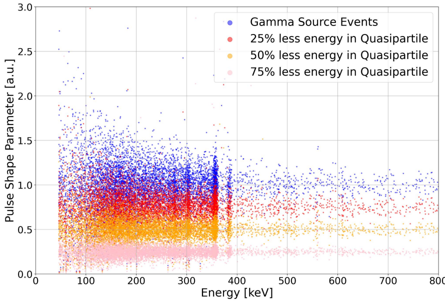
3. Ricochet is shooting for a world-leading result
   - High neutrino flux from ILL research reactor
   - Multiple technologies employed

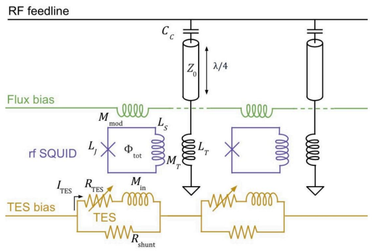












Backup

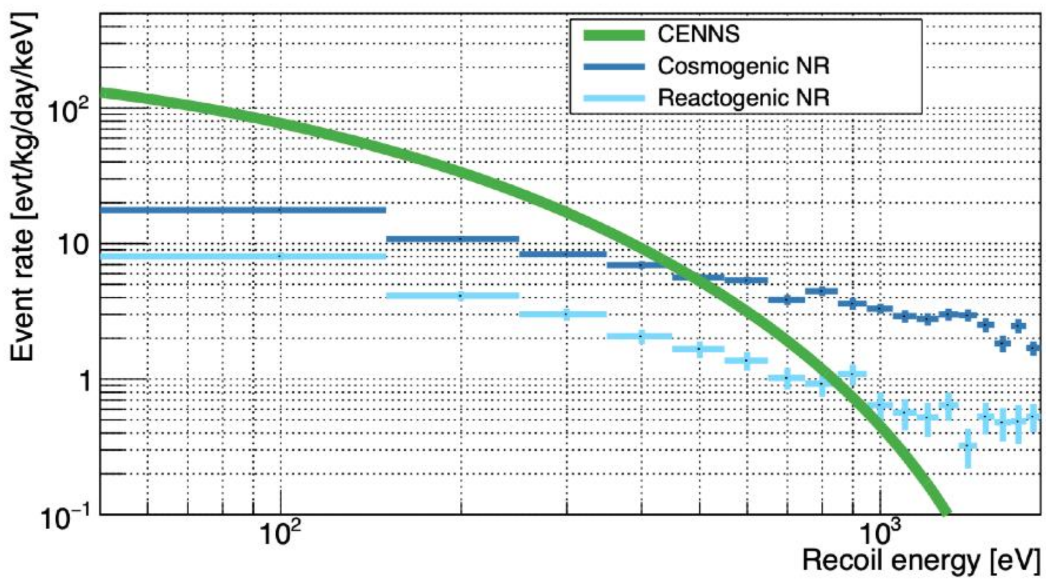
Background and Shielding

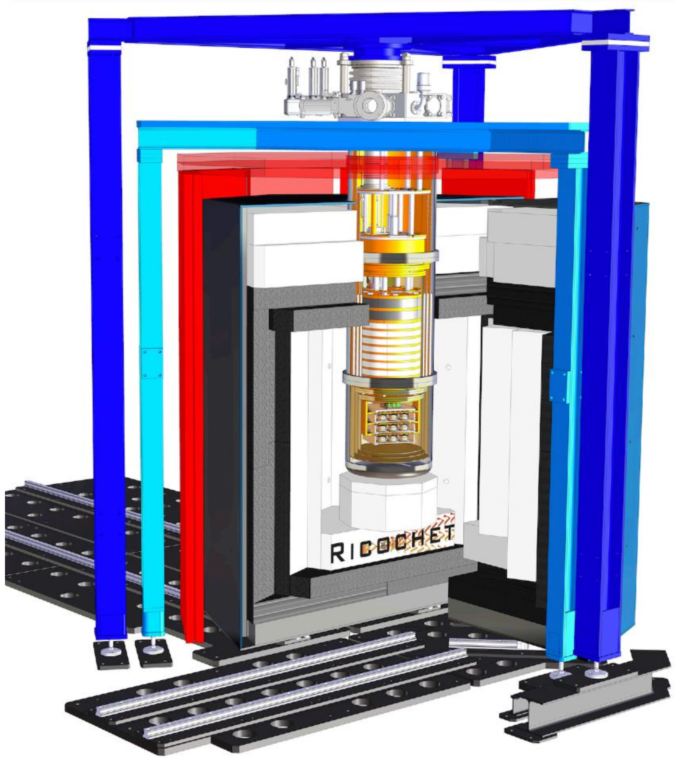
Main Baground
- Neutrons and gammas from reactor
- Neutron induced gammas
- Cosmic muon

Outer shielding:
- PE: 35 cm
- Pb: 20 cm
- Muon Veto
- Soft Iron

Inner Shielding:
- PE/Cu: 30 cm
- Pb/Cu: 15 cm
- Cryogenic Muon Veto
- Mu-Metal

		Cosmogenic	Reactogenic	Total (MC)	**CENNS (Ge/Zn)**
Nuclear recoils	No Shielding (I)	1554 ± 12	53853 ± 544	55407 ± 545	–
[50 eV, 1 keV]	Passive Shielding (II)	42 ± 3	2.4 ± 0.3	44 ± 3	–
(evts/day/kg)	Passive + μ-veto (III)	7 ± 2		9 ± 2	**12.8 / 11.2**





Complex Impedance

- Complex impedance measurement is a standard method to characterize electronic and thermal properties of microcalorimeters.
- The complex impedance of a TES-only devices could be written as: $Z_{\mathrm{tes}}(f) = R_0 \frac{(1+\beta)(1+i2\pi f\tau)+\mathcal{L}}{1-\mathcal{L}+2i\pi f\tau}$ [1]
  - where R_o is the resistance of TES, β is the current sensitivity of TES, $\mathcal{L}$ is the loop gain which ∝ temperature sensitivity α, τ is the time constant of the TES.
- Following is an example with following parameters:
  - R_o=69 mOhm
  - β = 1 and $\mathcal{L}$=14
  - τ = 0.1 ms