Low Temperature Detectors

RES-NOVA & COSINUS EXPERIMENTS

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GRAN SASSO hands-on
PhD autumn school on experimental astroparticle physics
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GSSI

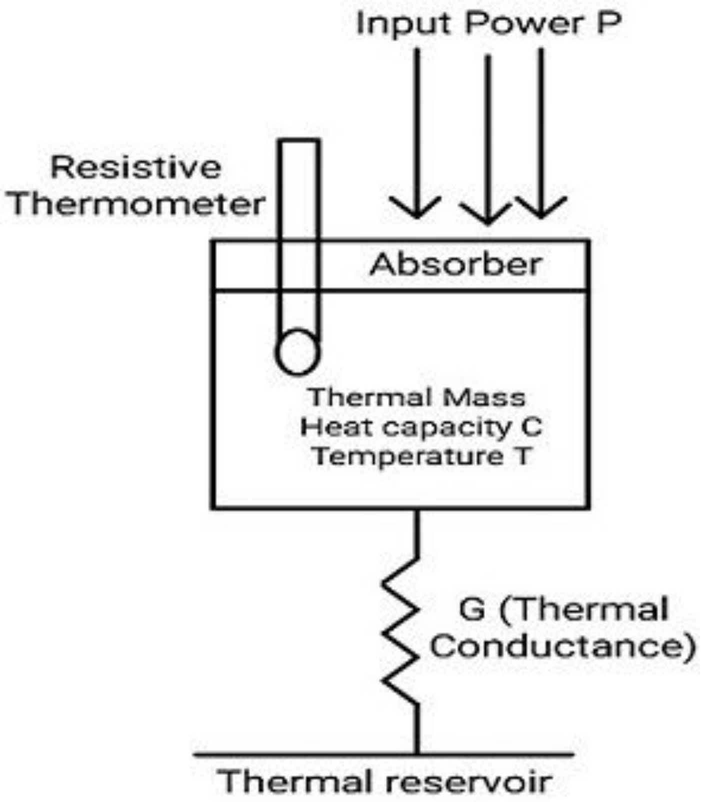
SFB 1258 Neutrinos Dark Matter Messengers

Outline

1. Low temperature calorimetry
2. Why use crystals as detectors?
3. Crystals characterization
4. Low temperature sensors
5. Cryostat assembly and leak search
6. Experimental Applications

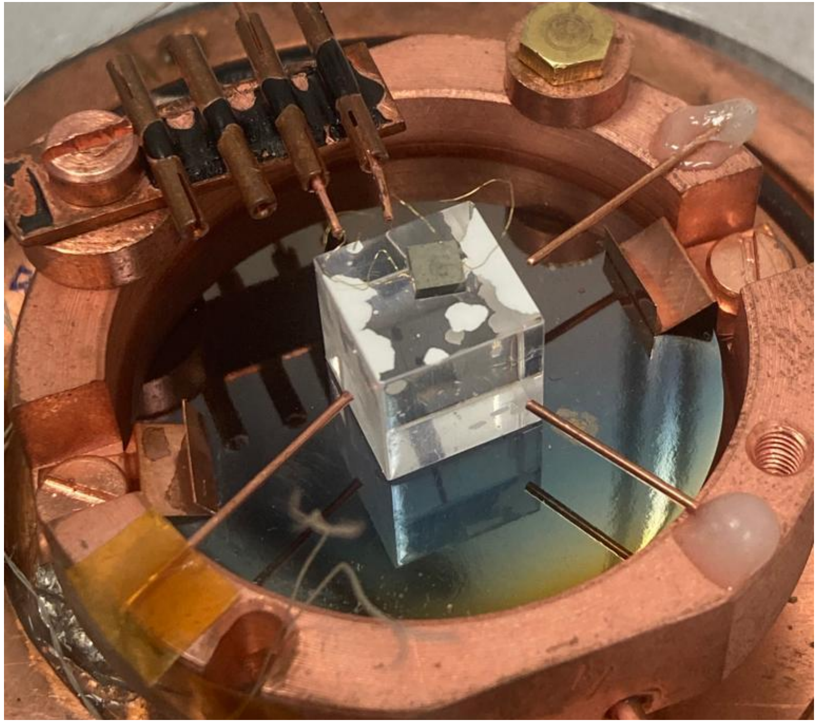
Bolometers

- The **low calorimeter working principle** is to measure the temperature increase in an absorber with a thermal sensor. One of the detection methods relies on a change in resistance in the sensor to temperature variations in the absorber.
- In our activity, we used low calorimeter detectors at mK temperature which will be employed in rare events searches, such as WIMPs interactions.



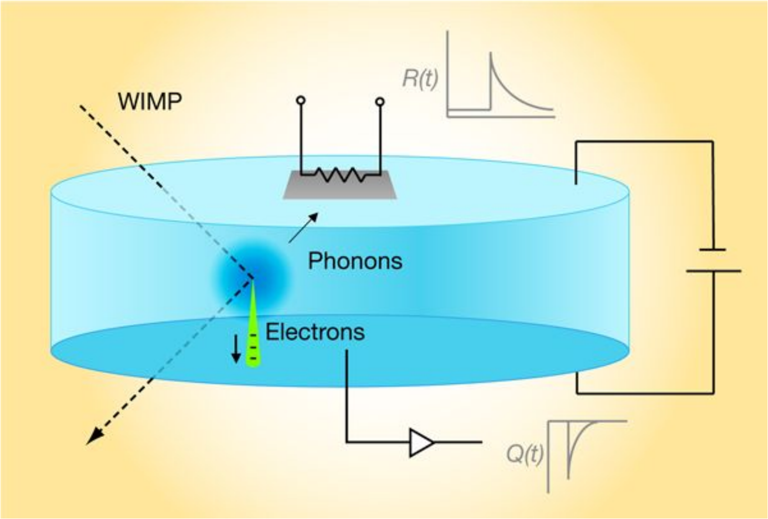
Crystal-Based Detectors

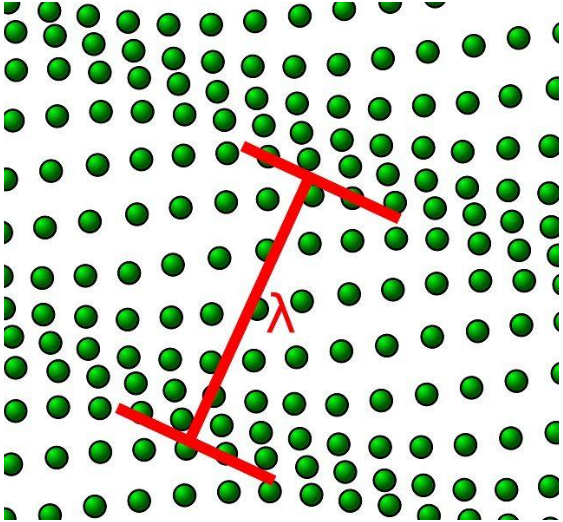
- 2 detection channels:
  phonon (90%) and **scintillation** (10%) signals after each interaction. This allows for background discrimination
- Spatial identification (we wish)
- High detection efficiency (~90%)
- High energy resolution in the phonon channel



Crystal-Based Detectors

- 2 detection channels
  1) Phonons: large energy fraction is quenched in the target crystal in the phonon channel; lattice vibrations propagate through the crystal and hit the thermal detector - a Transition Edge Sensor (TES) for example

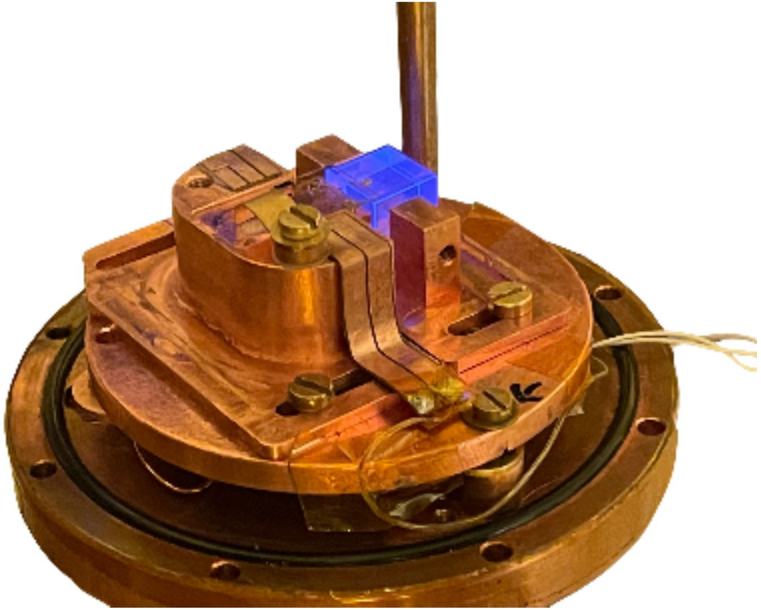




Crystal-Based Detectors

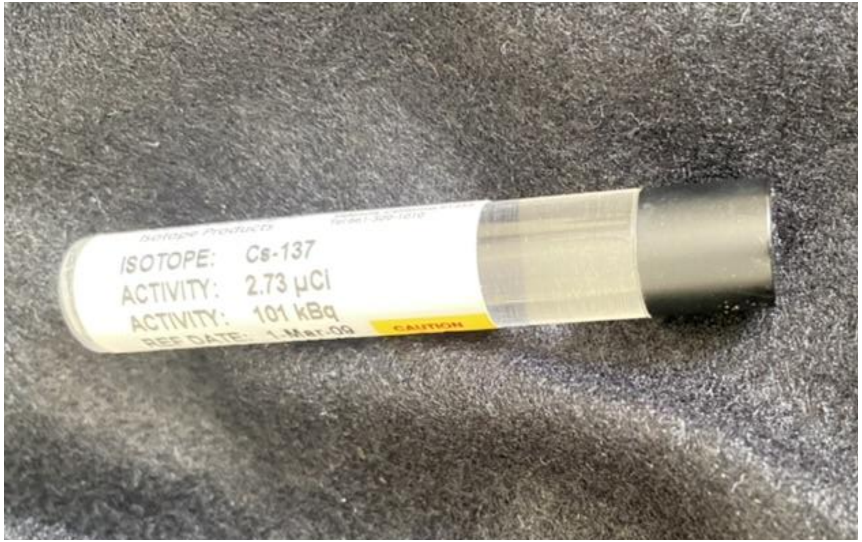
- 2 detection channels

  2) Scintillation light: part of the deposited energy is quenched in the scintillation channel instead.
  Upon de-excitation or recombination, electrons or nucleons return to low-energy states emitting photons, whic propagate through the crystal and are ultimately measured with a light detecting calorimeter facing the crystal.

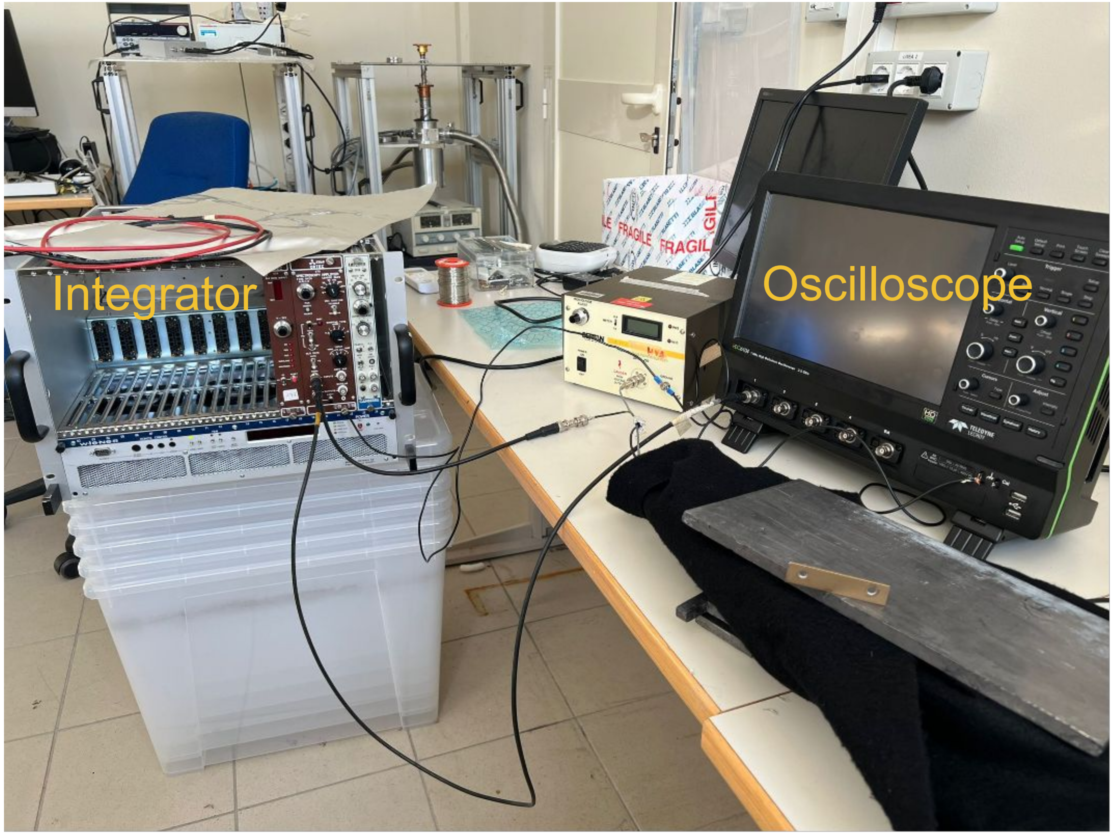


Crystal Characterization at Room Temperature

- We measured the response of 3 different crystals
- Cs 137 as calibration source
- It emits a monochromatic gamma ray at 662 keV after beta decay.



Crystal Characterization



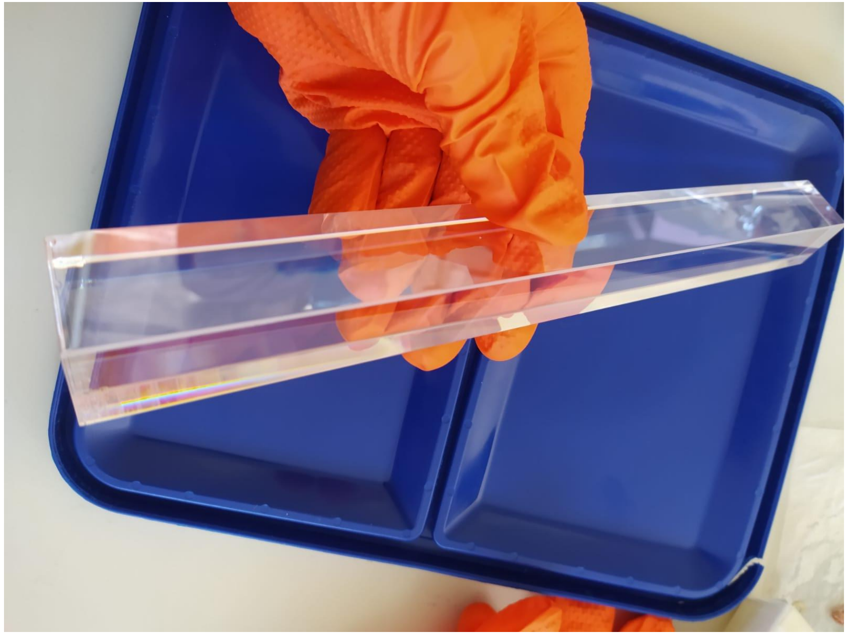
Crystal Characterization

1) Lithium Tantalate ($LiTaO_3$)

- Scintillation energy below the threshold of our system…

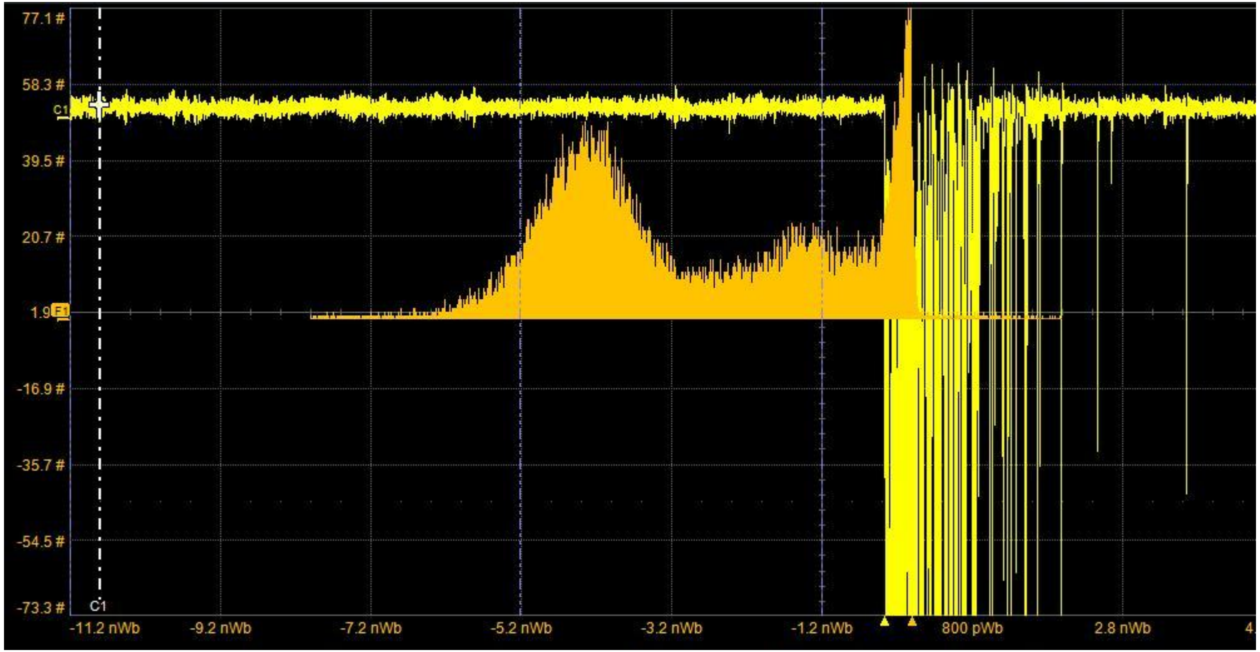
Crystal Characterization

2) Bismuth Germanate (BGO)



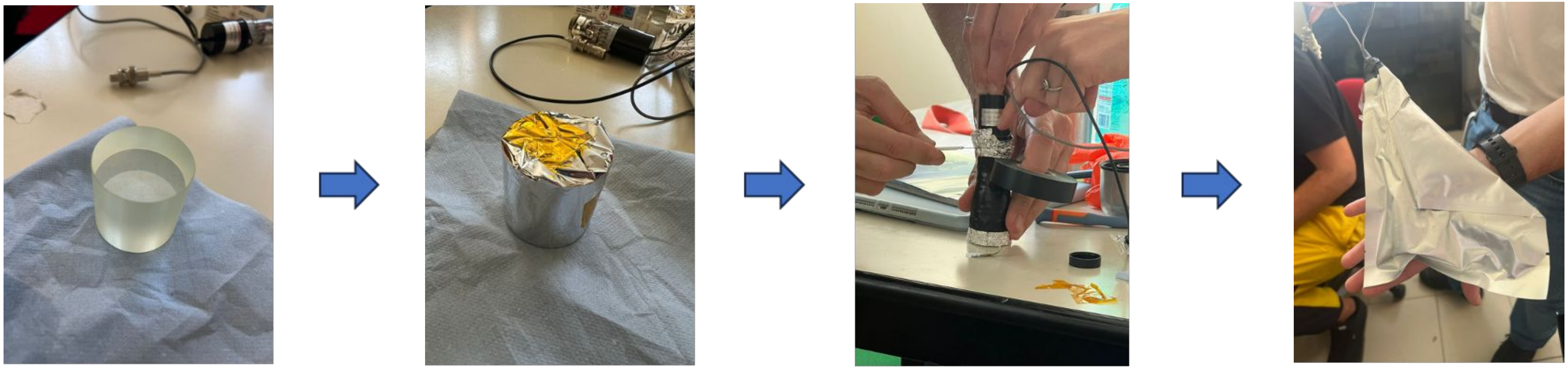
Crystal Characterization

2) Bismuth Germanate (BGO)



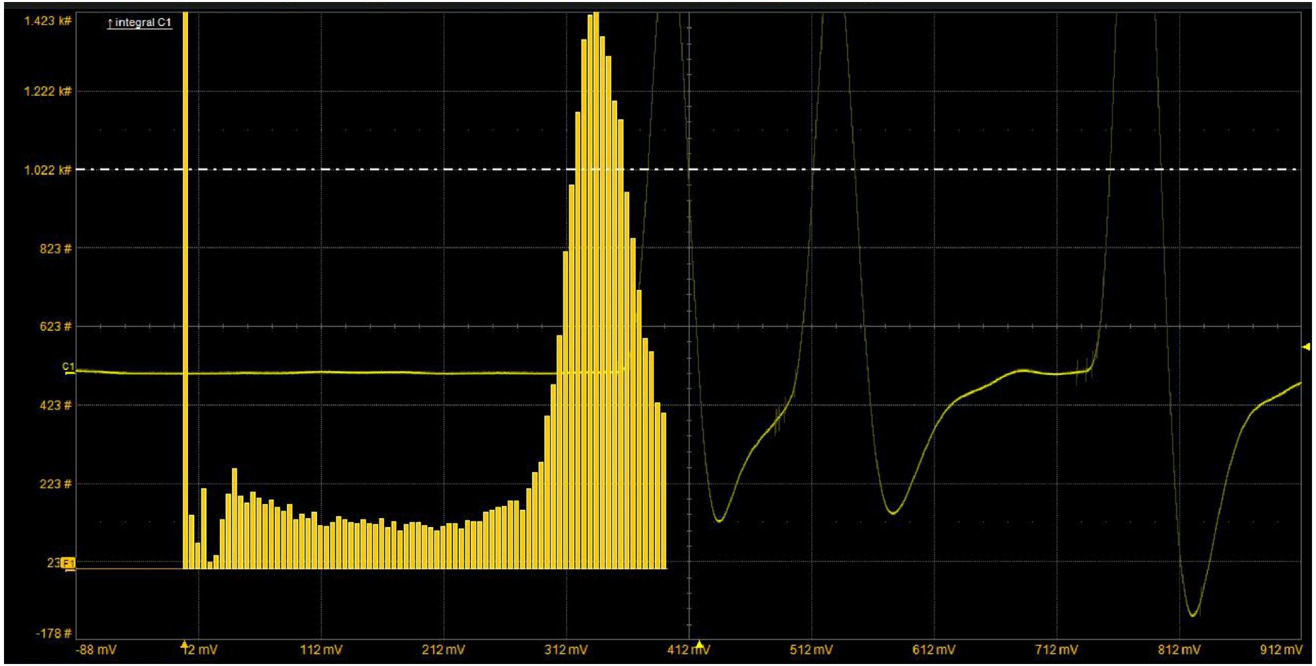
Crystal Characterization

3) Cadmium Tungstate ($CdWO_4$)



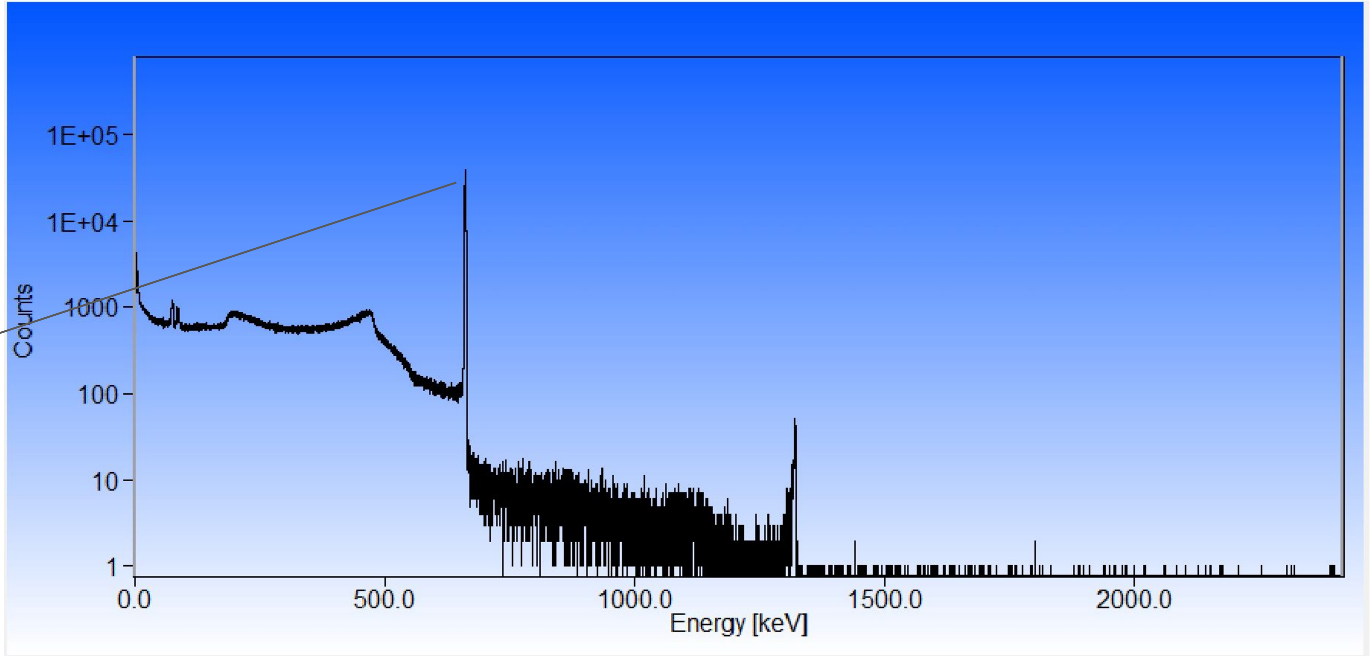
Crystal Characterization

3) Cadmium Tungstate ($CdWO_4$)



Crystal Characterization

- Comparison to Germanium semiconductor detector

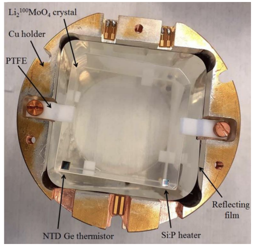


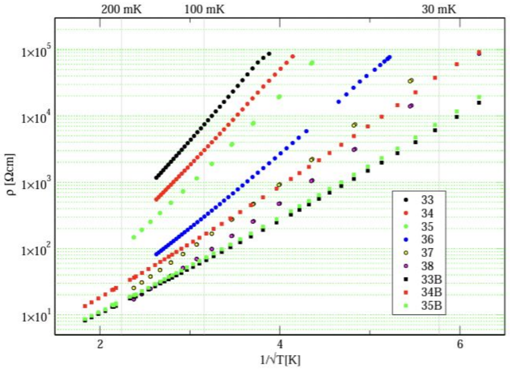
Cs-137 662 keV
gamma peak

Low Temperature Sensors

- Neutron Transmutation Doped Ge thermistor (NTD)

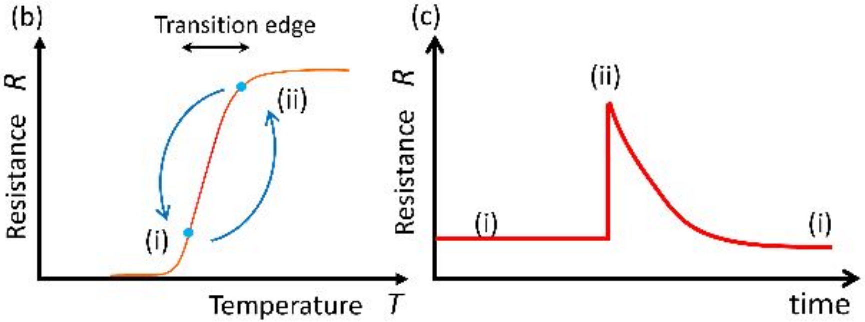
  phonons transmitted from the crystal to the NTD produce a resistance change in the NTD itself, which is then measured with dedicated bias circuit



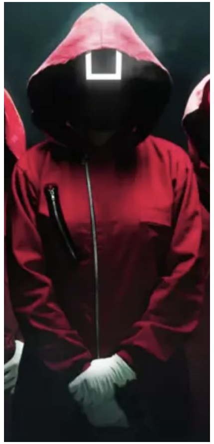


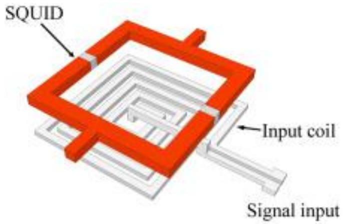
- Transition-Edge Sensor (TES)

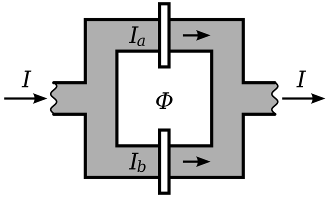
  Incident energy increases the resistance of the voltage-biased sensor within its transition region. The resistance is measured from the current change with a sensitive SQUID (Superconducting QUantum Interference Device)



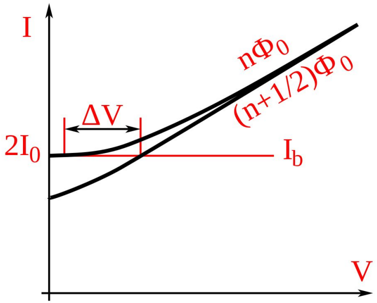
SQUID

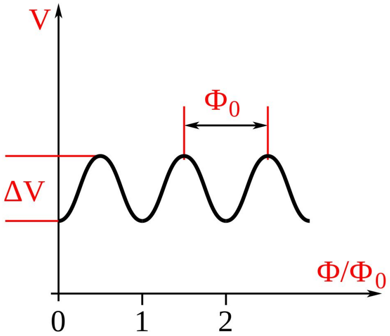


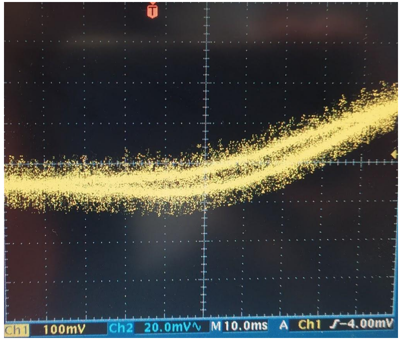


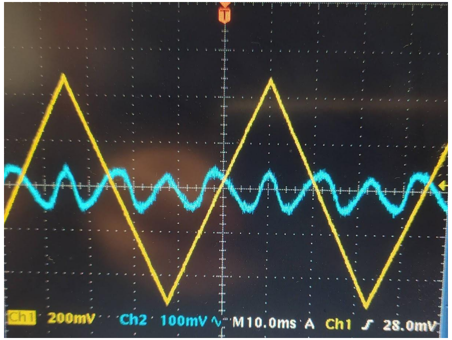


- Superconducting loop interrupted by two Josephson junctions
- highly sensitive to magnetic fields
- when $I > I_c$ a voltage ΔV builds up across the junction
- since magnetic field is quantised (unit ϕ_0), when $\phi > \phi_0/2$ to reach a more stable configuration the circuit tends to increase the magnetic field up to ϕ_0.
- The total current then **decreases**, creating a hysteresis loop.



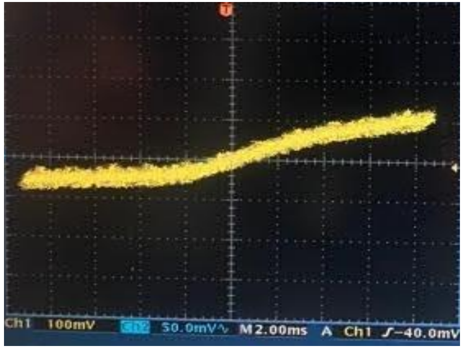


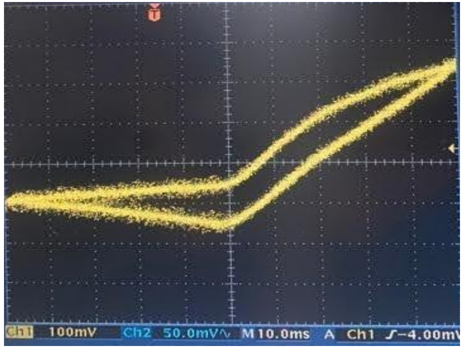




SQUID - Parameter Setup

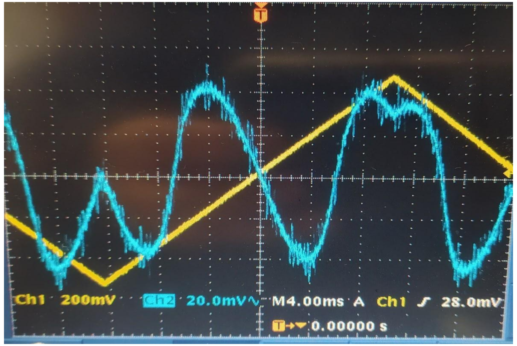
bias current

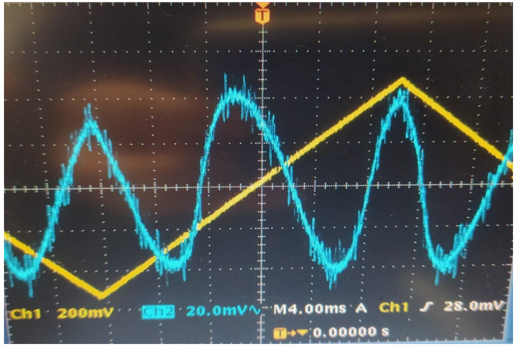




try to maximize the loop width (ΔV)

phase

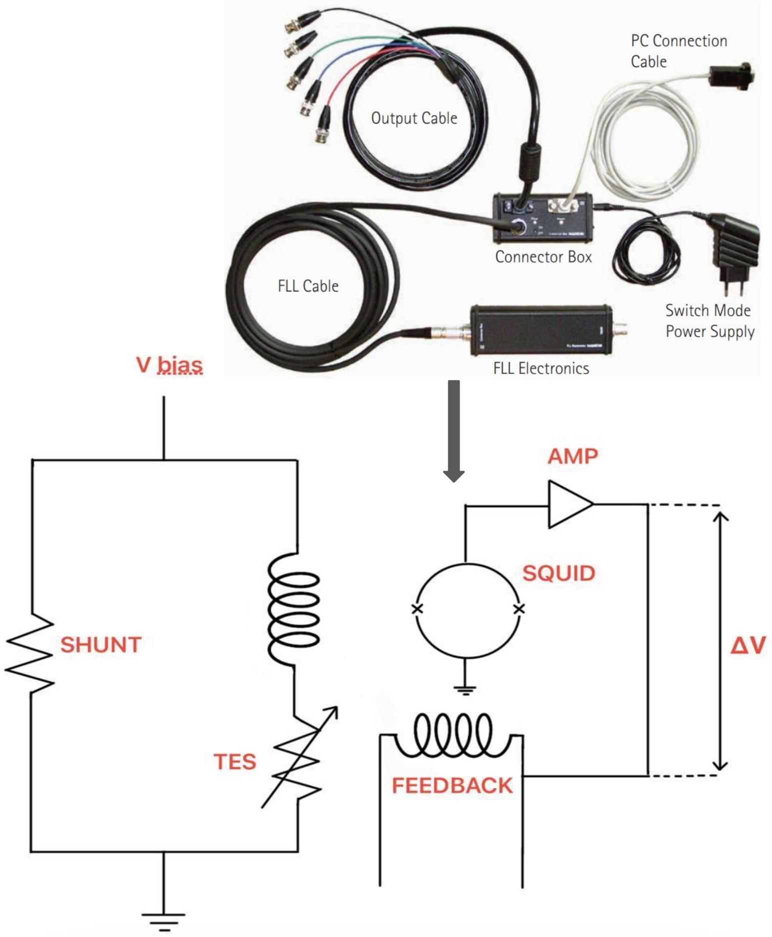


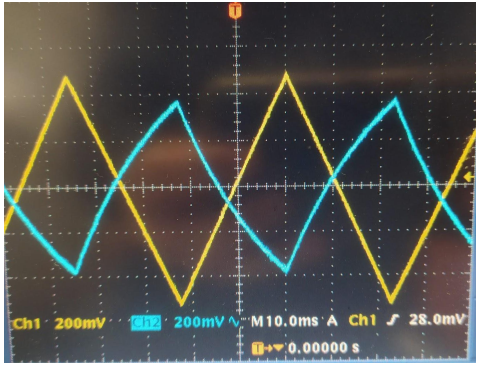


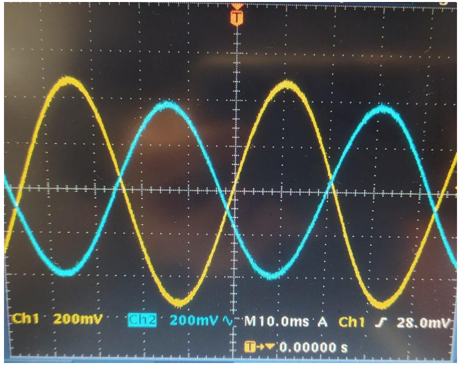
try make the oscillations as uniform as possible

SQUID Readout for TES

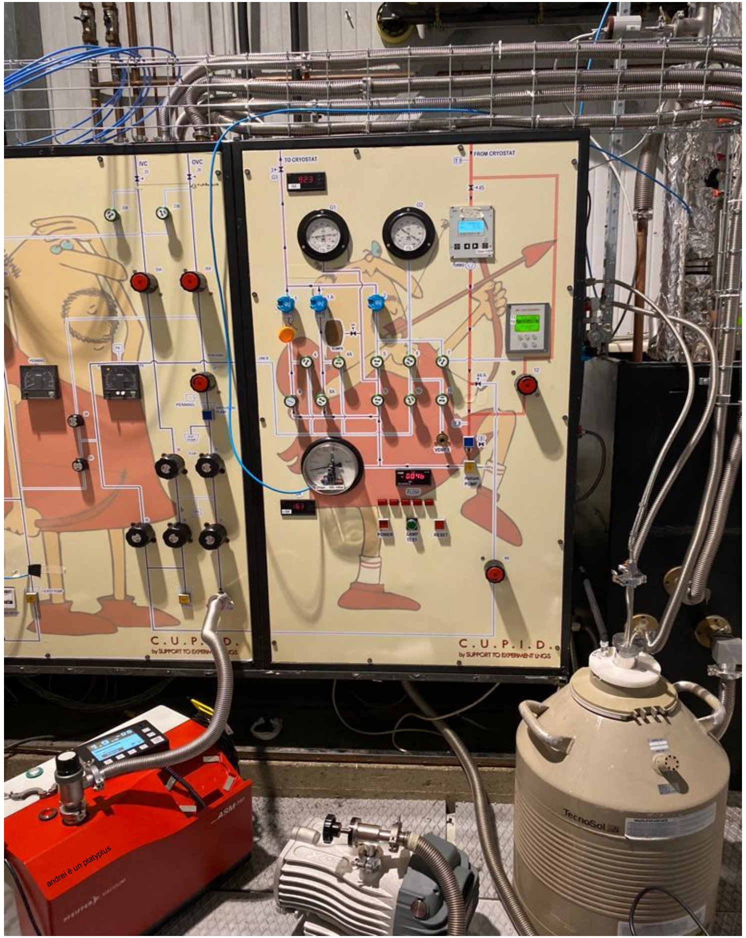
- TES acts like a variable resistance
- A **shunt resistor** in parallel to the TES keeps the voltage **constant** across the sensor
- To bypass the periodicity of the SQUID voltage response to flux variation, a target voltage is set for a **feedback circuit**. The feedback responds to voltage variations in the SQUID and produces the actual signal.



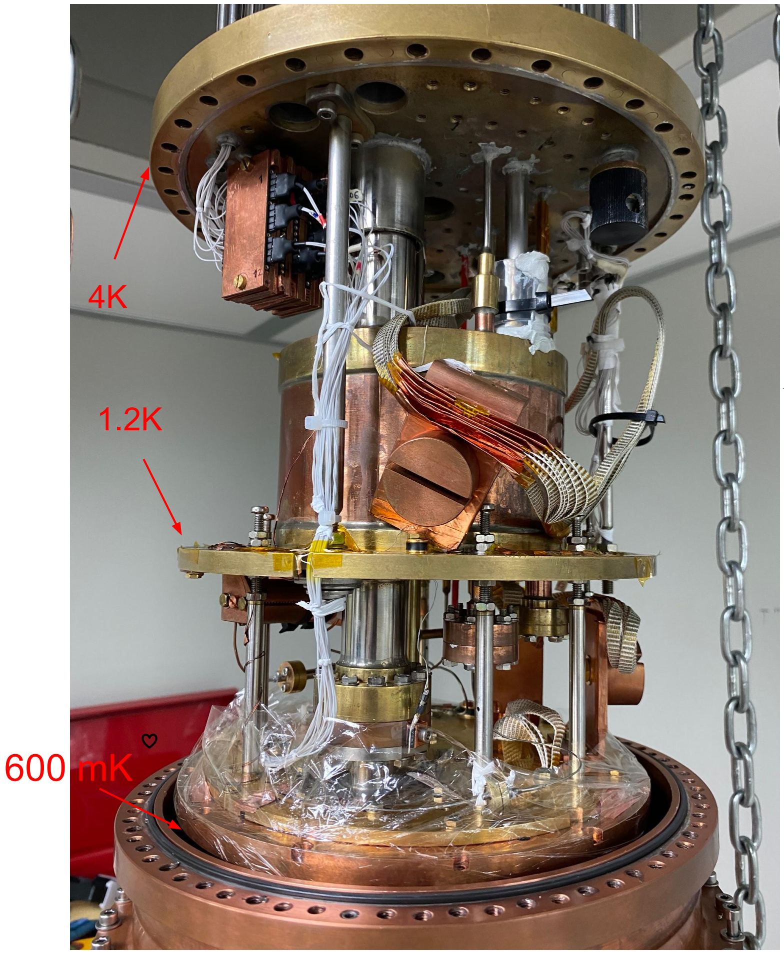




Dilution Refrigerator Hall A: old but gold

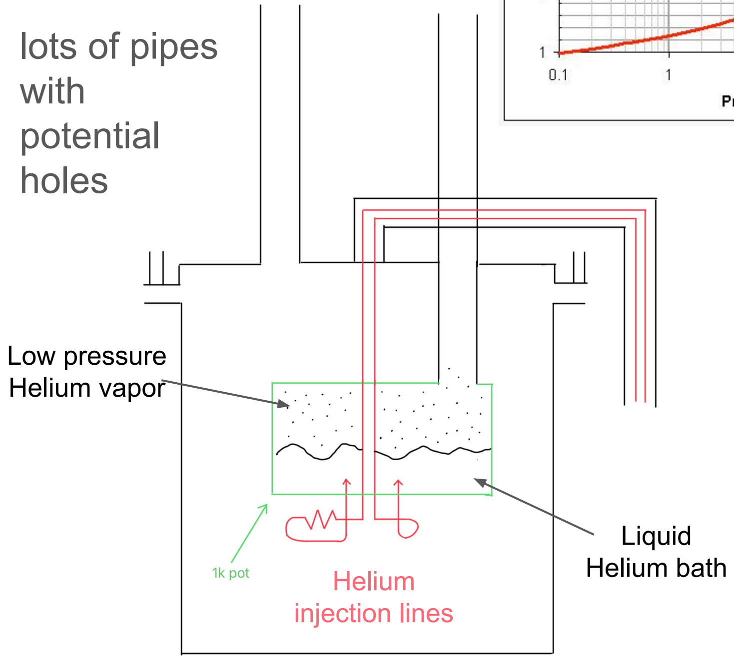


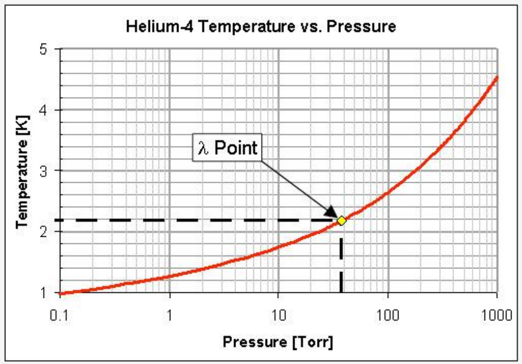
CRYOSTAT - WORKING PRINCIPLES - (below 4 K, which is rather trivial)



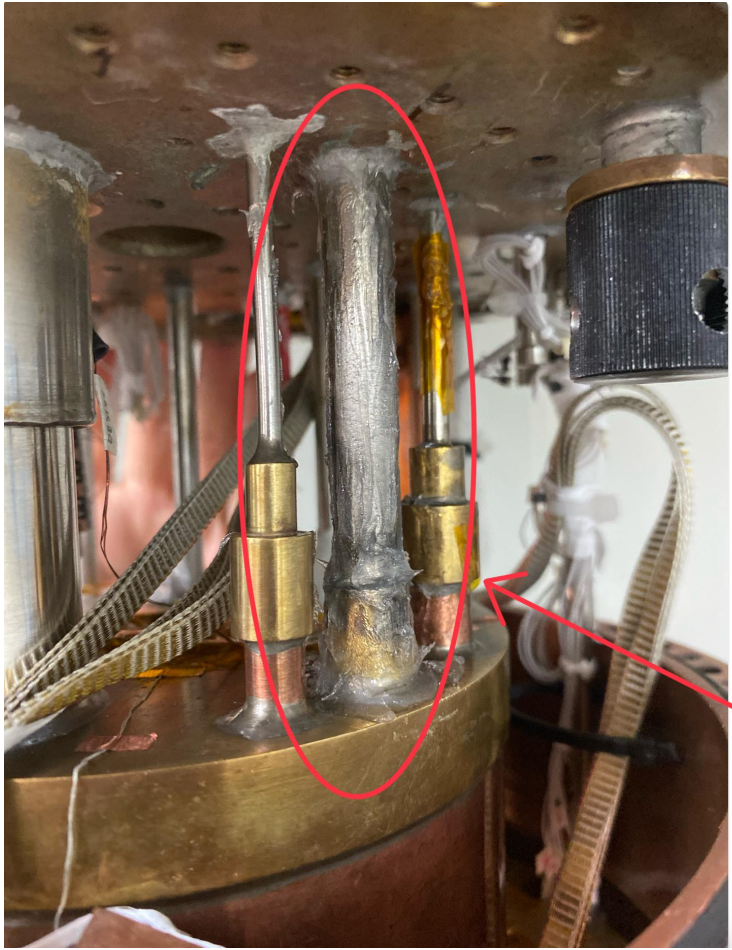
GOAL: to cool down a 3He/4He mixture below 2 K

lots of pipes with potential holes



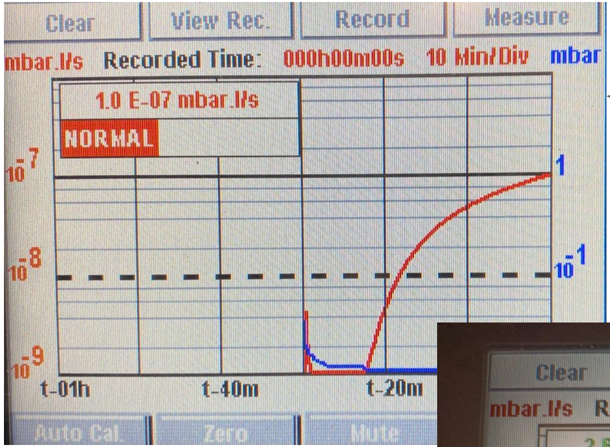


Leaky 1K-Pot : how to find a um-scale hole -> needle in the hay



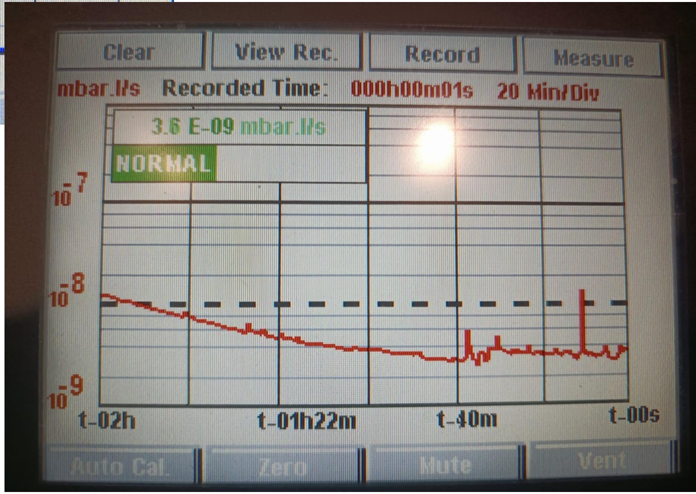
isolate one pipe at the time, close, vacuum and inject helium in the 1K-Pot hoping it will not diffuse in the vacuum chamber

HELIUM - 4 FLUX



before sealing: helium flux increases

after sealing with vacuum grease

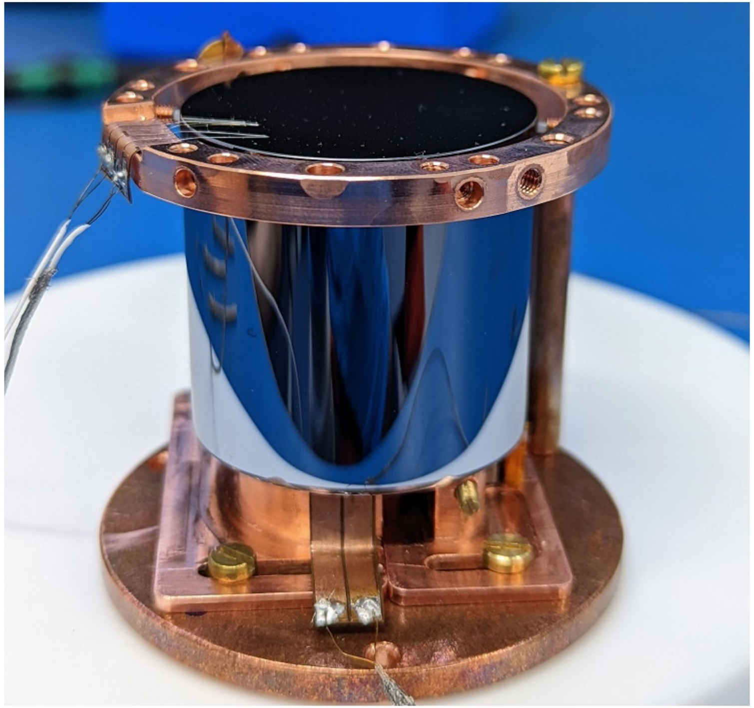


WE FOUND THE LEAK!

Experimental Application

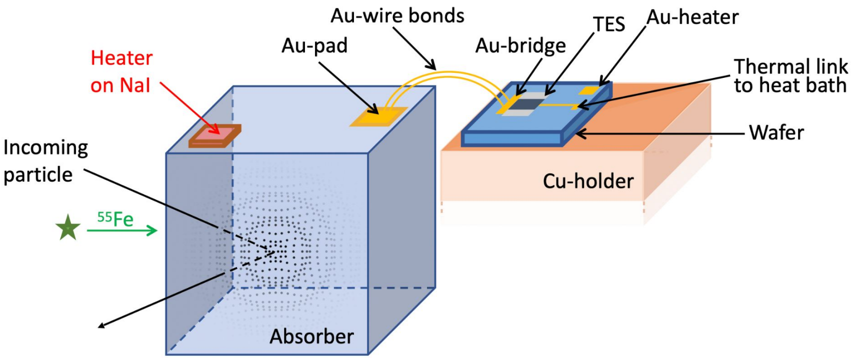
COSINUS

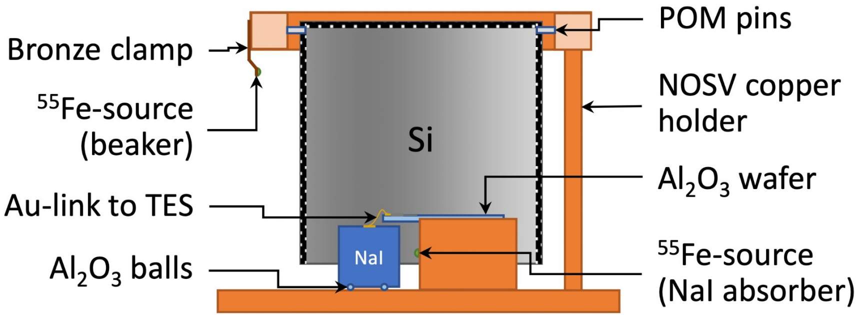
- Cryogenic scintillating calorimeter used in the search for WIMPs
- COSINUS detectors have a significantly lower nuclear recoil threshold tagging. Low threshold and particle discrimination are unique features in the realm of NaI-based dark matter searches.



2 types of signal:

- phonon signal (heat signal) used to measure the energy deposited in the crystal by the incoming particle
- scintillation light signal provides discrimination of the particle type: the amount of scintillation light produced strongly depends on the particle type.





RES-NOVA

Archaeological Pb-based cryogenic detectors.
RES-NOVA wants to investigate the neutrinos coming from the supernova explosions ⟶ Coherent elastic neutrino-nucleus scattering, the single channel sensitive to ALL neutrino flavours.

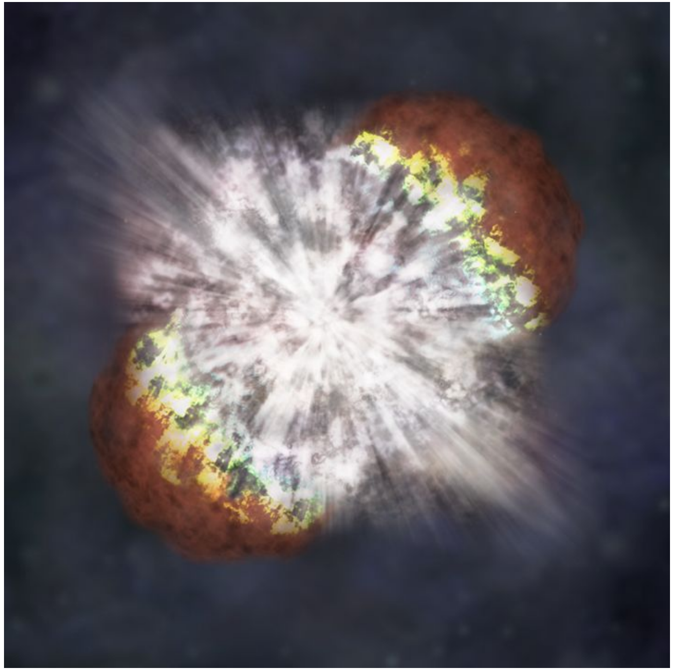
Form factor

$$\sigma_{\mathrm{CE}\nu\mathrm{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2$$

Neutrino energy

Electroweak-charge

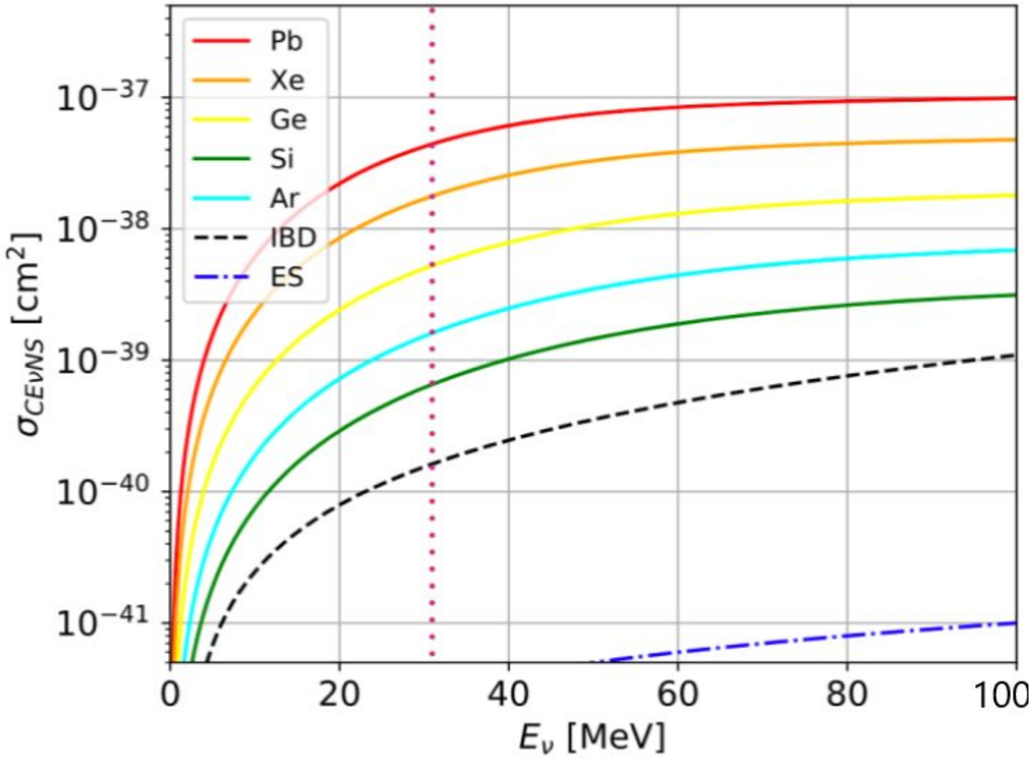
$$Q_W = N - Z(1 - 4\sin^2\theta_W)$$

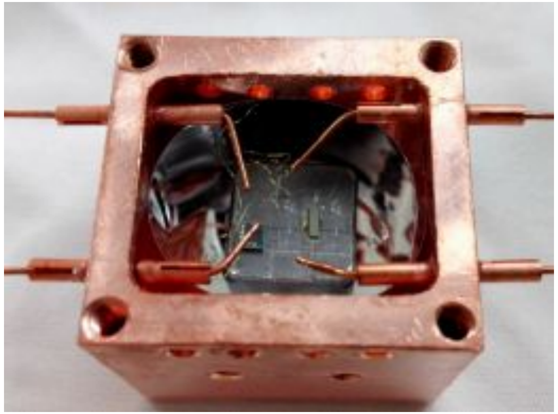


supernova explosion (NASA)

Archaeological Pb

Pb allows us to have the largest known cross-section for neutrino-nucleon scattering -> higher statistics with smaller volume detectors





L. Pattavina et al., Eur. Phys. J. A (2019) 55: 127

Conclusion

From this experience we learned:

- the working principle of crystal detectors and how to use them;
- we saw how a crystal detector behaves at room temperature and at very low temperature;
- how to characterize a crystal detector;
- how a cryogenic experimental setup works;
- more practical skills and how to face off problems that could take place in a laboratory

thank you for your attention

WINE so serious?
Stay tuned

References

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- ❖ Scintillation Bolometers, arXiv:2011.13806v1 [physics.ins-det] 27 Nov 2020
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- ❖ Transition-edge sensor arrays for UV-optical-IR astrophysics, J. Burney, T.J. Bay, J. Barral, P.L. Brink, B. Cabrera, J.P. Castle, A.J. Miller, S. Nam, D. Rosenberg, R.W. Romani, A. Tomada, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 559, Issue 2, 2006,

BACKUP SLIDES