15th Pisa Meeting on Advanced Detectors

La Biodola, Isola d'Elba, May 22-28, 2022

Bolometers: powerful tools to search for rare events

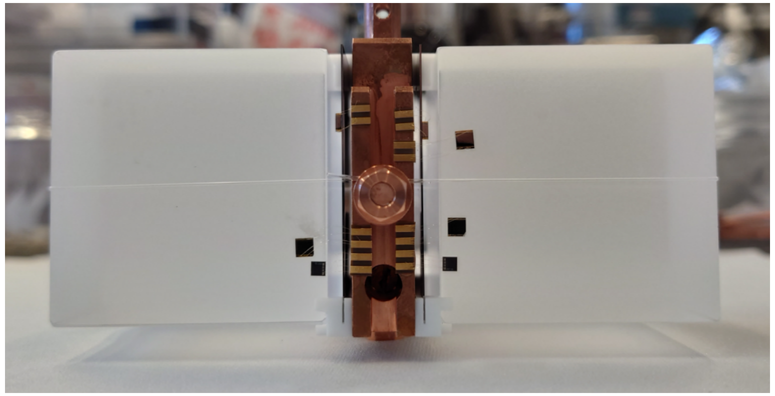
Claudia Nones

DE LA RECHERCHE À L'INDUSTRIE

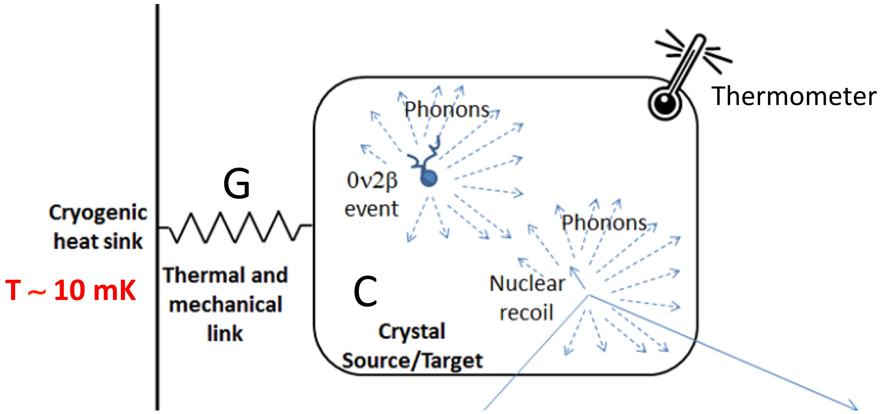
ICFA Instrumentation Early Career Award

Outline

- A pure bolometer, a phonon-mediated particle detector: how it works
- And what about if we read out other excitations besides phonons?
- Bolometers and their attractive features for rare event experiments
- Three emblematic cases of bolometer applications to the search for double beta decay – at different development stages – CUPID-Mo, CROSS and BINGO

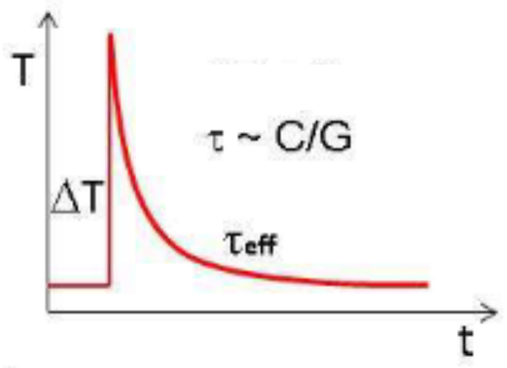


A pure bolometer: how it works



The **energy** deposited by an event into an energy absorber weakly connected to a heat sink determines an **increase** of its **temperature**

$$\Delta T = \frac{E}{C}$$



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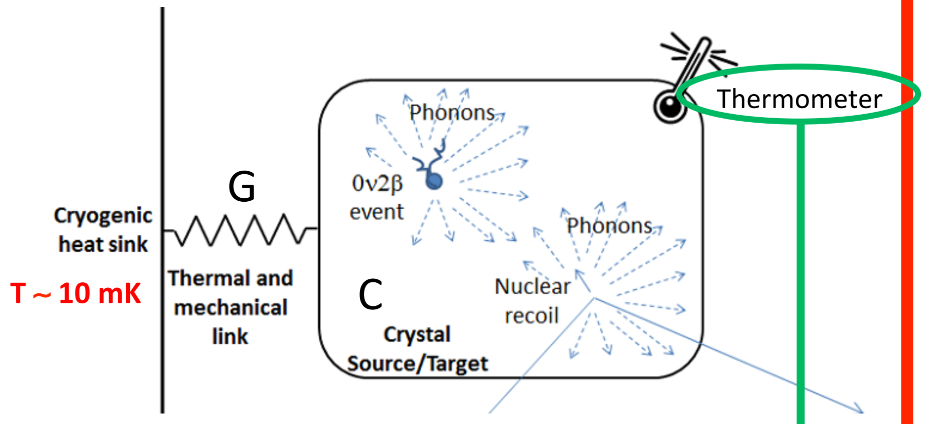

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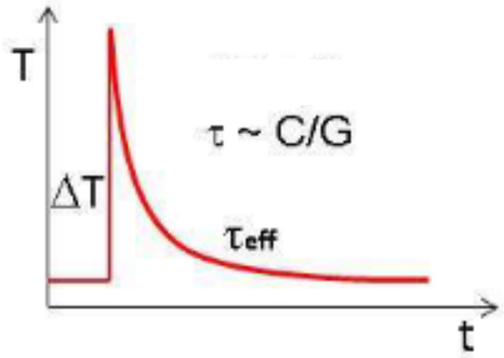


Initial phonons are **athermal** (1-10 meV)

An energy-down conversion cascade leads them to the **thermal regime** (~ μeV)

Athermal phonon sensors

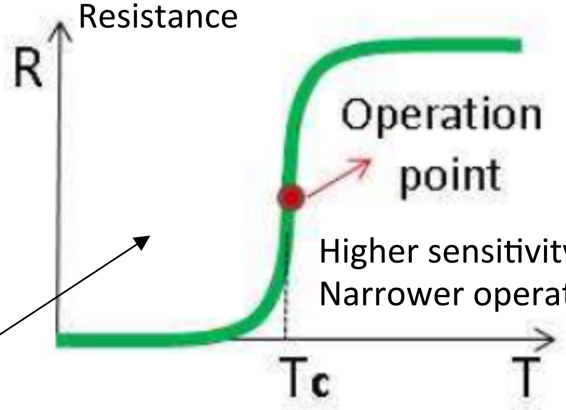
Thermometer

TES – readout: SQUID or JFET

CRESST
SuperCDMS
NuCLEUS
EDELWEISS/CRYOSEL

Mainly athermal phonons

Fast
< 1ms



$$\Delta T \rightarrow \Delta R, \Delta M$$

NTD – readout: JFET

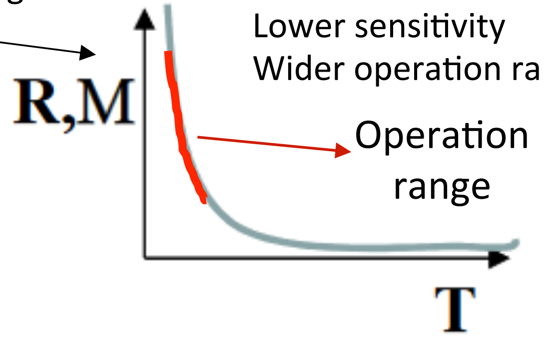
CUORE
CUPID
CROSS
BINGO
EDELWEISS
RICOCHET

High impedance

Slow
1-100 ms

Mainly thermal phonons (thermometers)

Resistance
Magnetization

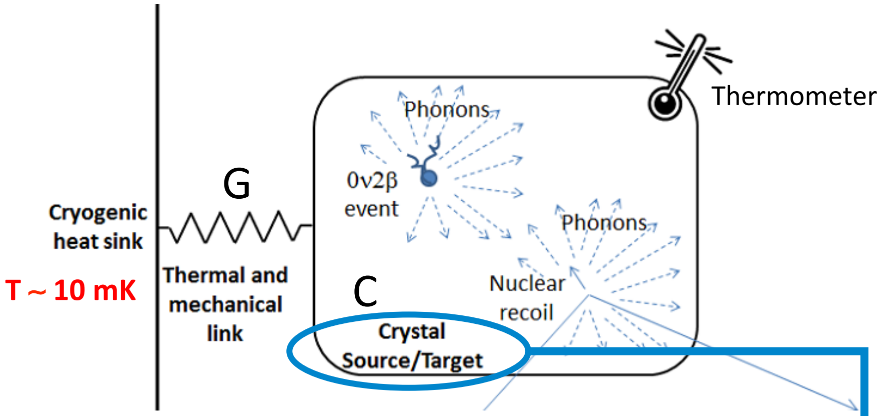


MMC – readout: SQUID

AMoRE

Fast
< 1ms

A pure bolometer: how it works



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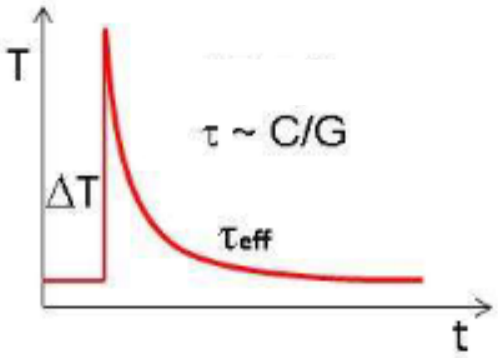


Absorber

- **Dielectric diamagnetic** single crystal
- **Superconducting** absorber (with some caveats)

→ Only lattice contribution to C

In macrobolometers for astroparticle physics, the **typical mass range** for the absorber is **several 10 – 100 g**

Typical **signal amplitudes**:

- ΔT/ΔE ~ 0.1 mK/MeV
- ΔV/ΔE ~ 0.1 mV/MeV

for NTD readout (constant bias current)

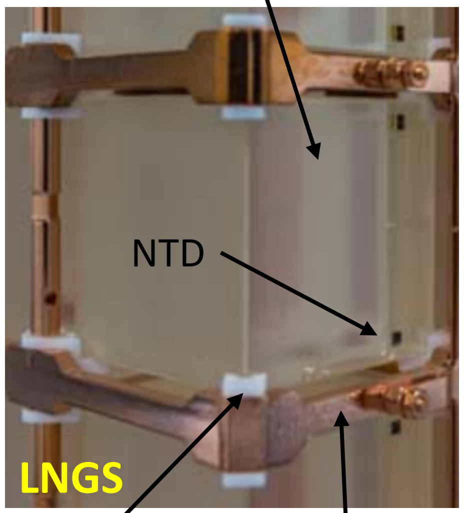
Main advantages

- High energy resolution (0.1% - 1%)
- Low energy thresholds
- High efficiency
- Versatility in the choice of materials

An actual implementation
CUORE single module

Search for **neutrinoless double beta decay**

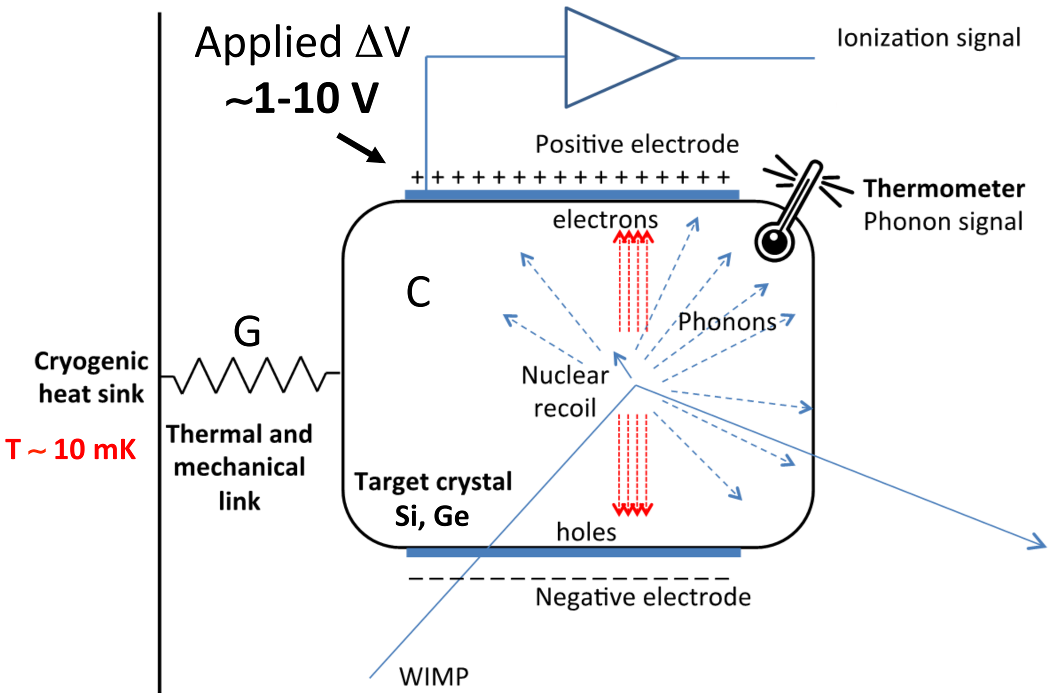
Absorber – TeO_2 crystal (750 g)



Cryogenic heat sink

Weak thermal link

Hybrid bolometers: phonons + charge



Add a **charge readout** to the phonon readout

Excellent method to discriminate **nuclear recoils** from **electron recoils**

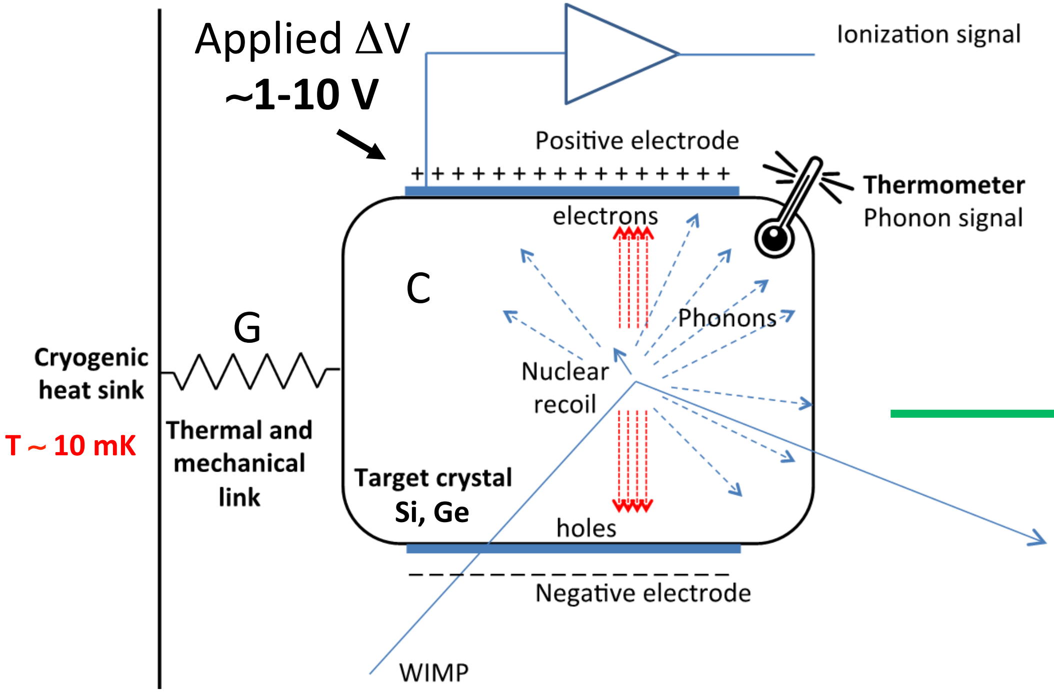
Applications

- **Dark matter** search → WIMP scattering
- Coherent elastic **neutrino-nucleus scattering**

EDELWEISS
SuperCDMS

RICOCHET
MINER

Hybrid bolometers: phonons + charge



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Applications

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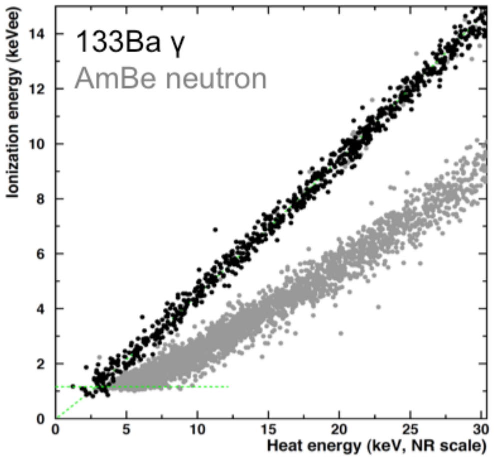
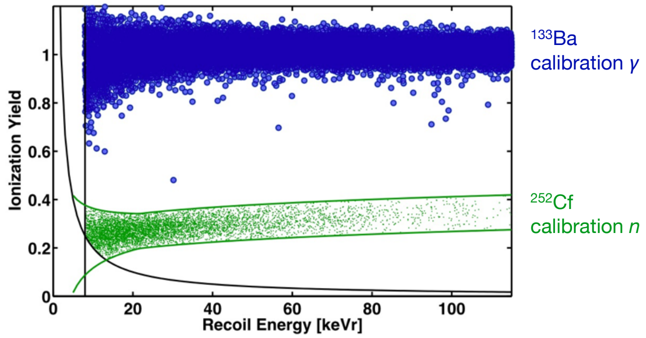
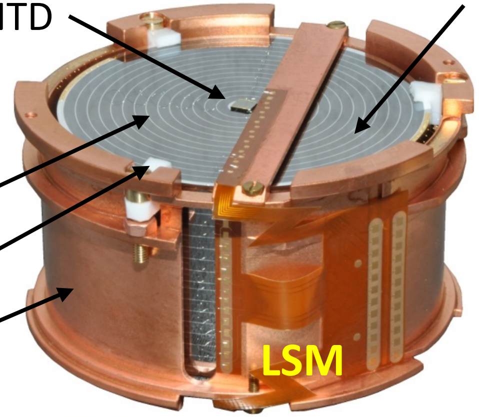
Nuclear recoils produce less charge with respect to same-energy electron recoils induced by beta/gamma.

A **scatter plot charge vs. heat** or a **plot ionisation-yield vs. heat)** separates nuclear recoils from betas / gammas

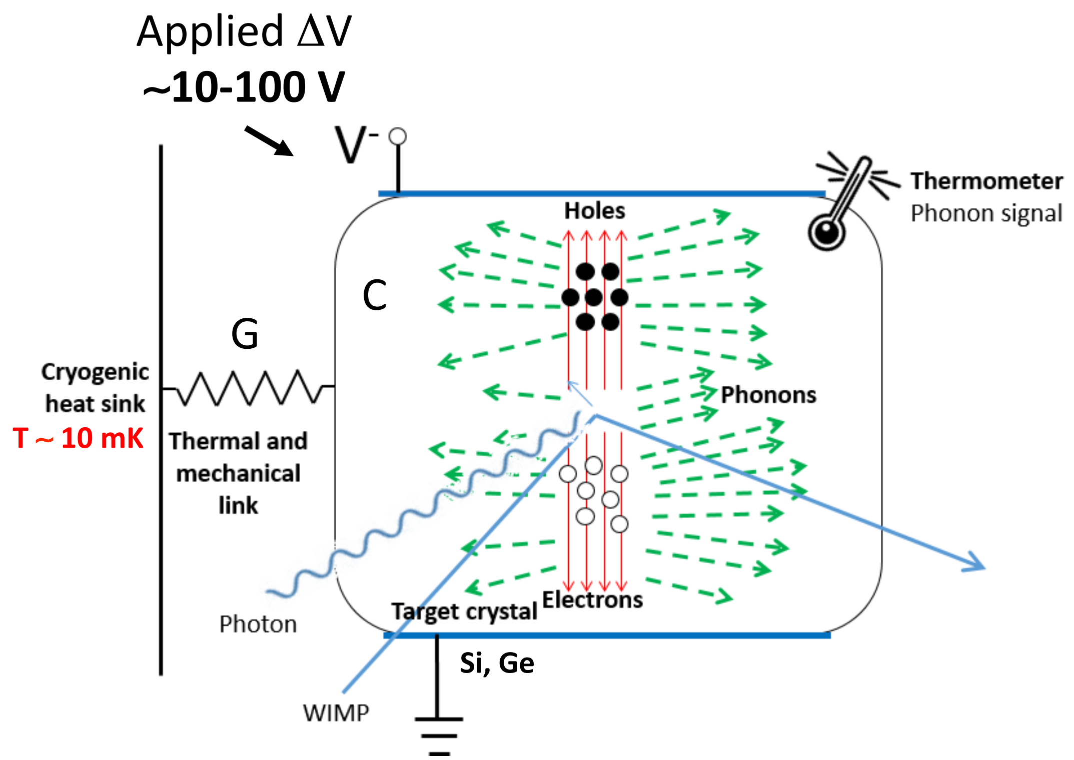




An actual implementation
EDELWEISS-III single module



Luke effect: measure charge via phonons



Charges drifting in the electric field produce heating

Joule effect in a bolometric context:

Neganov-Trofimov-Luke (NTL) effect

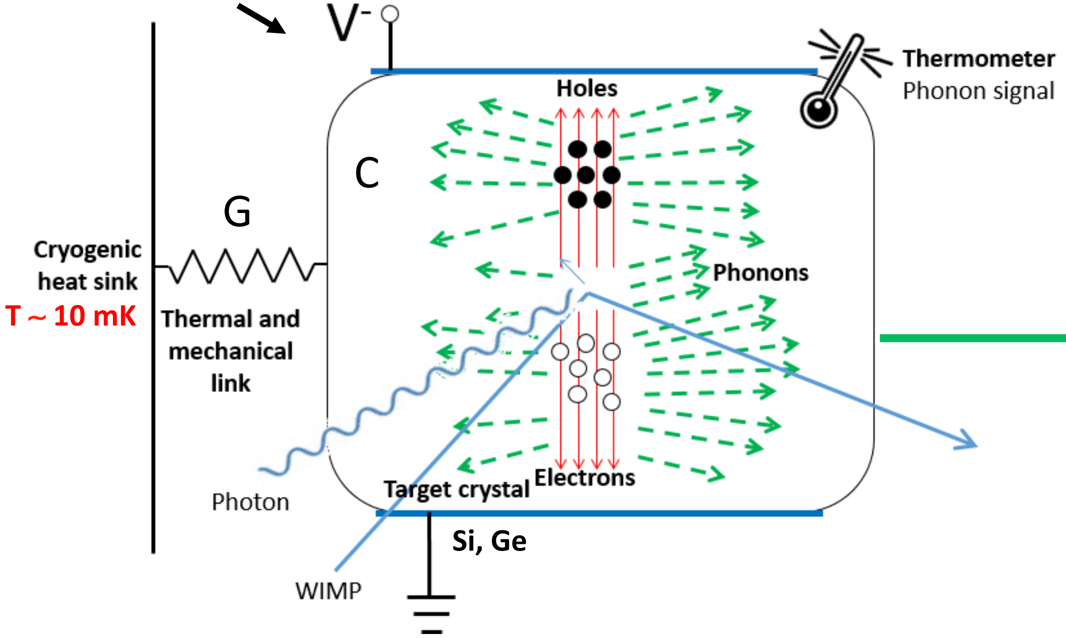
⬇

Phonon-mediated voltage-assisted **measurement of the charge**

Nuclear/electron recoil separation is lost

Luke effect: measure charge via phonons

Applied ΔV
~10-100 V



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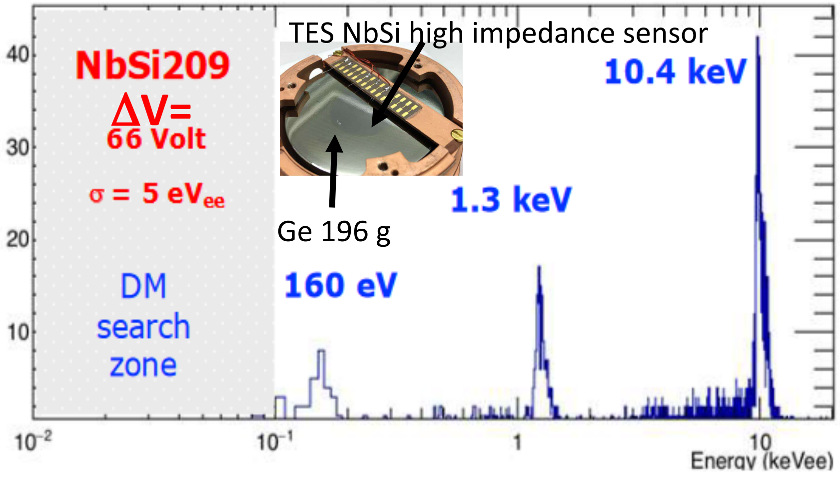
Phonon-mediated voltage-assisted **measurement of the charge**

Nuclear/electron recoil separation is lost

$$Q_{\Delta V} = Q_0\left(1+\frac{e\Delta V}{\varepsilon}\frac{l_T}{d}\right)$$

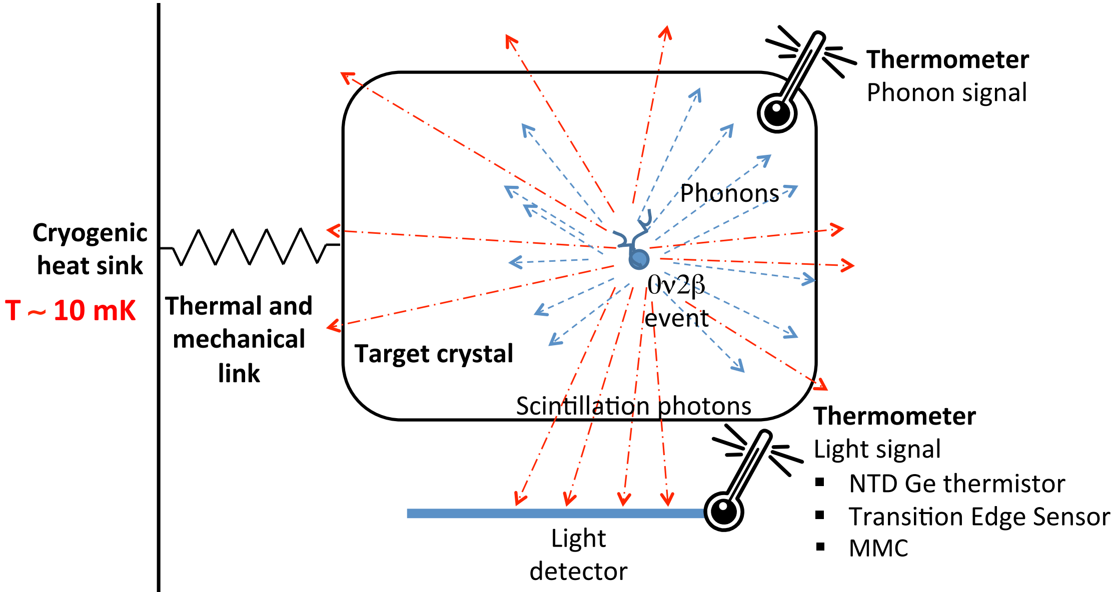
- $Q_{\Delta V}$: Heat under NTL bias
- Q_0: Pure heat without NTL effect
- l_T: Average distance before trapping or collection
- ε: Energy to create an e-h pair
- d: Inter-electrode distance

An actual implementation
EDELWEISS low-mass single module



Single e-h pair sensitivity achieved in Si detectors by SuperCDMS-like detectors (TES readout)

Hybrid bolometers: phonons + light



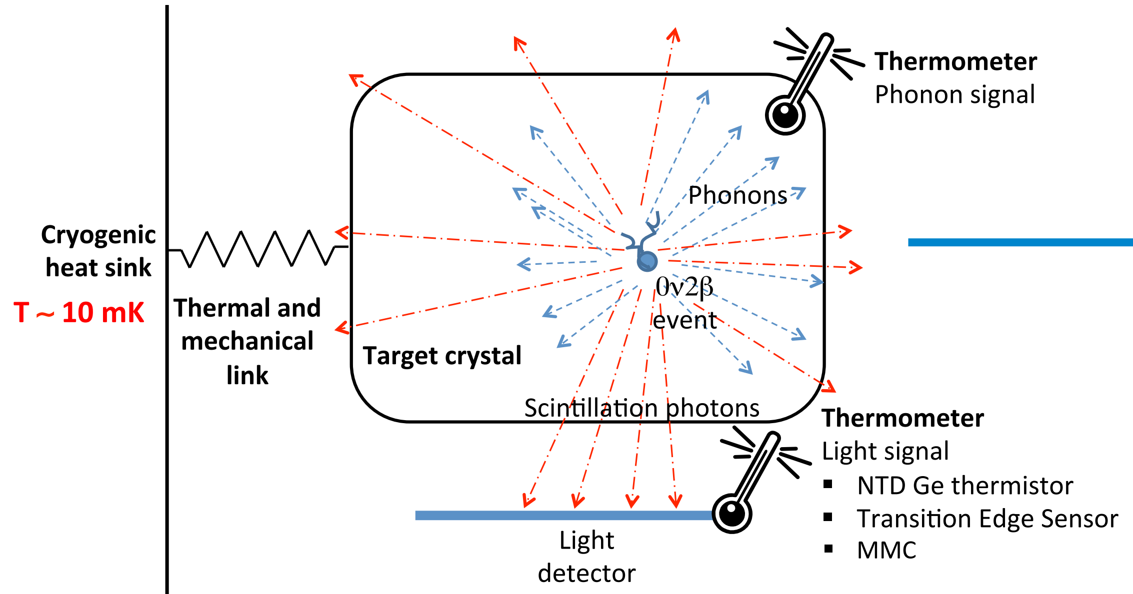
- The absorber, operated as a bolometer, is a **scintillator** (emission in visible light - typically 500-600 nm) and/or a **Cherenkov radiator** (ex. TeO_2) if scintillation is weak
- The emitted light is read in coincidence with the help of an **auxiliary bolometer** which works as **light detector**

→ **Scintillating bolometer**

Applications

- **Dark matter** search → WIMP scattering → CRESST
- **Neutrinoless double beta decay** → CUPID, AMoRE

Hybrid bolometers: phonons + light



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Applications

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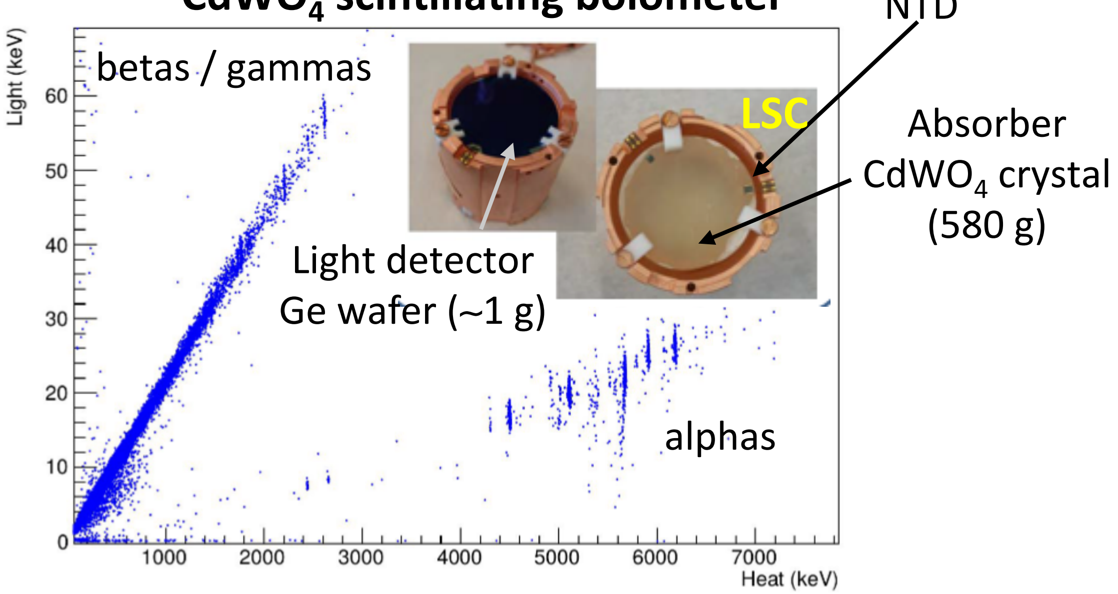
- Alphas and nuclear recoils emit in general a different amount of light with respect to beta/gamma of the same energy
- A **scatter plot light vs. heat** or a **plot light-yield vs. heat** separates alphas and nuclear recoils from betas / gammas
- **PSD** can work as well
- Separation of nuclear recoils in the keV region (Dark Matter search) requires high scintillation yield and outstanding light detectors

An actual implementation

$^{116}CdWO_4$ scintillating bolometer



Bolometers for astroparticle and rare events

Bolometers are well suited for experiments in **astroparticle** and **neutrino physics**, implying often the search for **very rare events** in extreme **low radioactivity** and **low background** conditions → heavily-shielded **cryogenic infrastuctures** in **underground laboratories**

- Low threshold
- High energy resolution
- Radiopurity
- Material flexibility
- High efficiency
- Detector technology and microphysics for background control

→

Low-mass Dark Matter candidates, axions

Coherent elastic neutrino-nucleus scattering

Neutrinoless double beta decay

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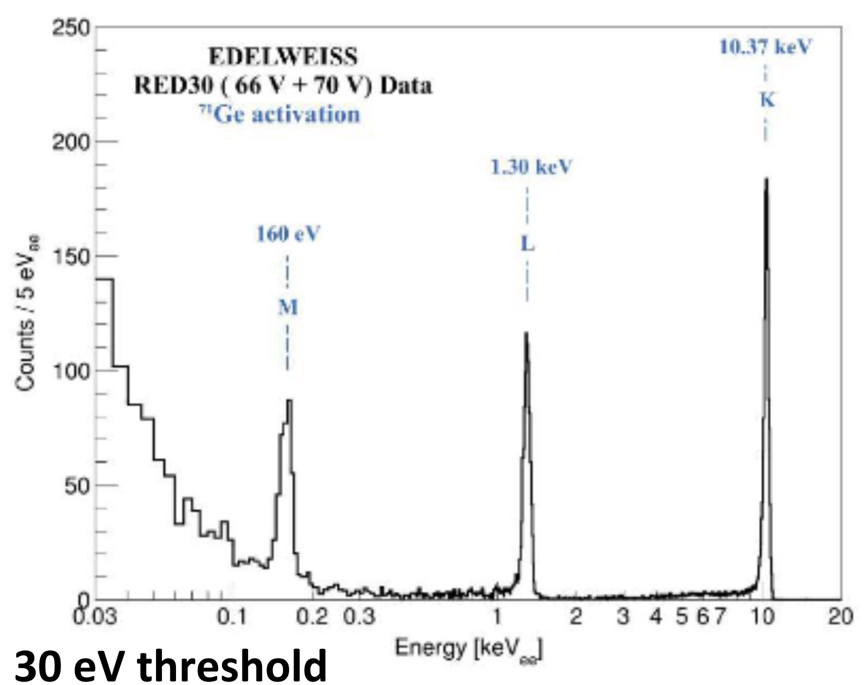
...s for background control



30 eV threshold
30 g Ge absorber
NTL assisted

J. Gascon, EXCESS workshop, 2021

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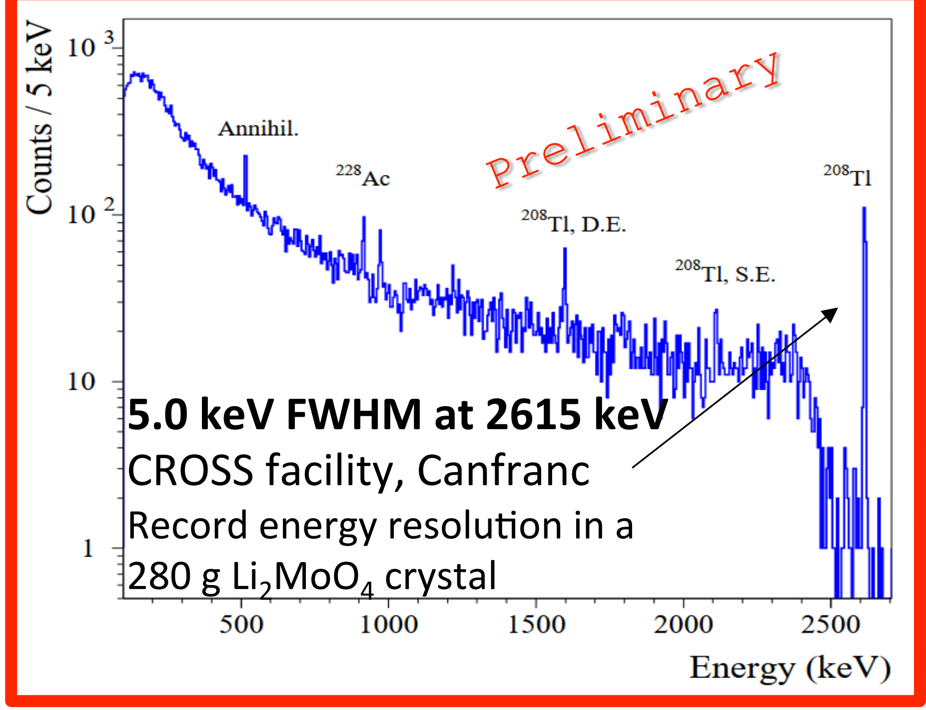

Bolometers for astroparticle and rare events

Large enriched $Li_2{}^{100}MoO_4$ crystal

Crystallization → by-itself purification
Dominant use of **copper** in cryogenics
→ Intrinsically pure metal

…r experiments in **astroparticle** and **neutrino physics**, implying …e **events** in extreme **low radioactivity** and **low background** … **cryogenic infrastuctures** in **underground laboratories**

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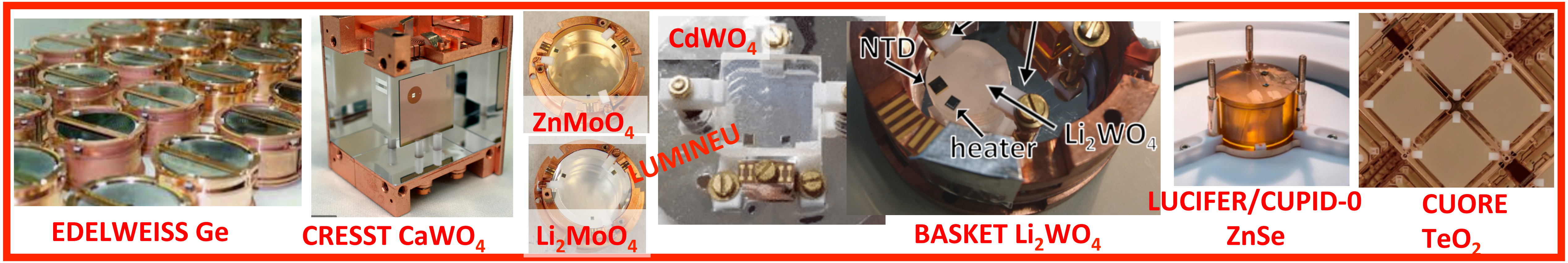

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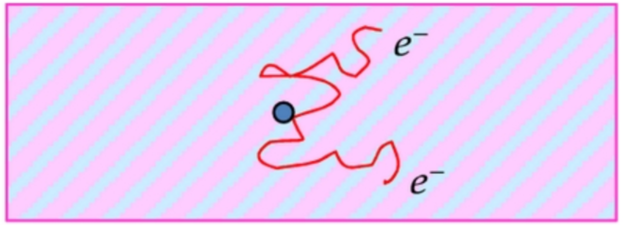
Almost full event containment



Source ≡ detector

(Calorimetric technique)

- Material flexibility
- High efficiency
- Detector technology and microphysics for background control

Low-mass Dark Matter candidates, axions

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Bolometers for astroparticle and rare events

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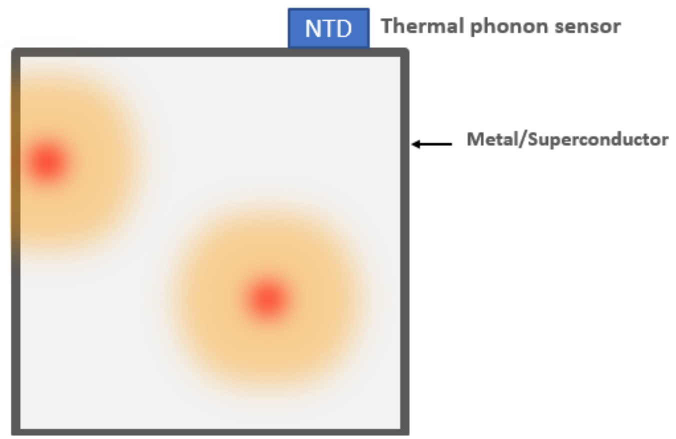


CROSS
Phonon physics
Surface events are faster than bulk events

Low-mass Dark Matter candidates, axions

Coherent elastic neutrino-nucleus scattering

Neutrinoless double beta decay

- Detector technology and microphysics for background control

The key issue: background control

Sources

Cosmic muons, neutrons

Environmental γ α β

Underground
Radiopurity
Shielding

Electron recoils (for Dark Matter)

$2\nu2\beta$ **decay** (for $0\nu2\beta$)

The key issue: background control

Sources

Underground
Radiopurity
Shielding

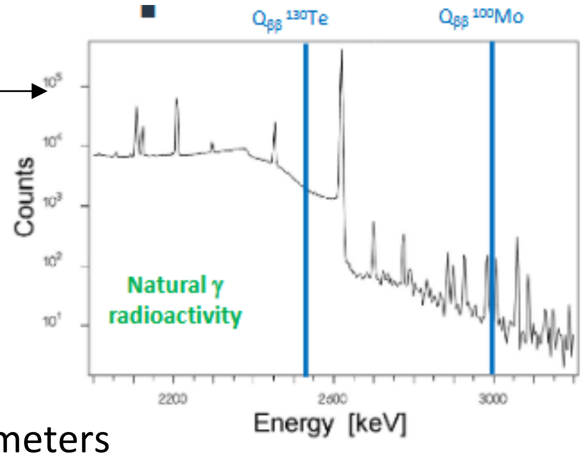
Cosmic muons, neutrons

Environmental γ α

Electron recoils
(for Dark Matter)

$2\nu2\beta$ decay (for $0\nu2\beta$)

High Q-value candidates for $0\nu2\beta$ decay: peak expected at high energy
CUPID-0 CUPID-Mo CUPID AMoRE



Internal active shield
BINGO NuCLEUS

Scintillating bolometers
CUPID-0 CUPID-Mo CUPID AMoRE CRESST

Charge+heat bolometers
EDELWEISS SuperCDMS RICOCHET

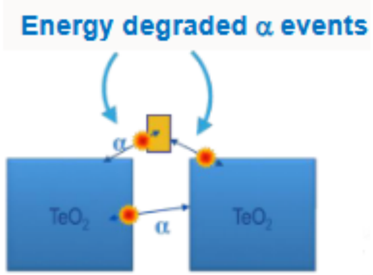
High energy resolution
CUPID-0 CUPID-Mo CUPID AMoRE

High time resolution
AMoRE

High S/N ratio for optimal PSD
BINGO

α, β surface radioactivity

- High level of contamination
- Difficult purification
- Partial absorption → energy continuum



Rejection based on phonon physics
CROSS SuperCDMS

Rejection based on anticoincidence (detector construction and geometry)
BINGO

Rejection exploiting charge readout
EDELWEISS SuperCDMS

Focus on three projects

CUPID-Mo → A successful story

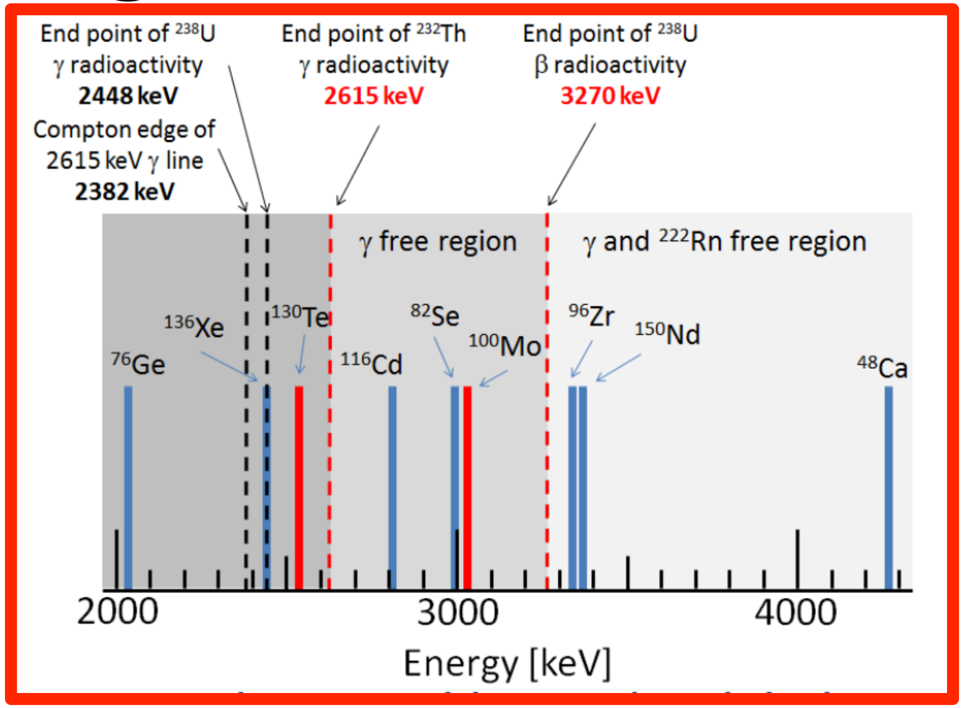
CROSS erc → A promising R&D

BINGO erc → Challenges for the future

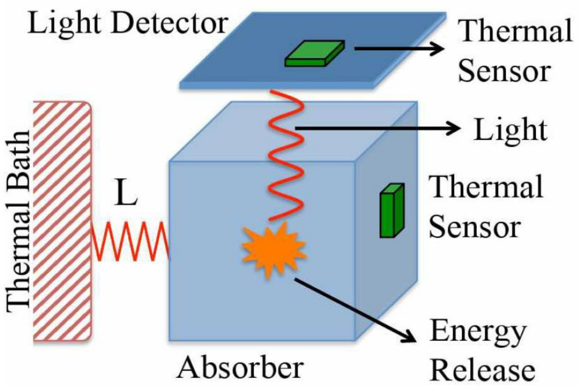
Common denominator
neutrinoless double beta decay in ^{100}Mo and ^{130}Te
$(A,Z) \rightarrow (A,Z+2) + e^- + e^-$

Source=detector approach → Li_2MoO_4 and TeO_2 crystals

Look for a peak at 2.5 MeV and 3.0 MeV
in extremely low background conditions



CUPID-Mo single module



LUMINEU has succesfully developed the $Li_2{}^{100}MoO_4$ technology
Multiple tests with natural and enriched crystals (2014-2017) in LSM and LNGS

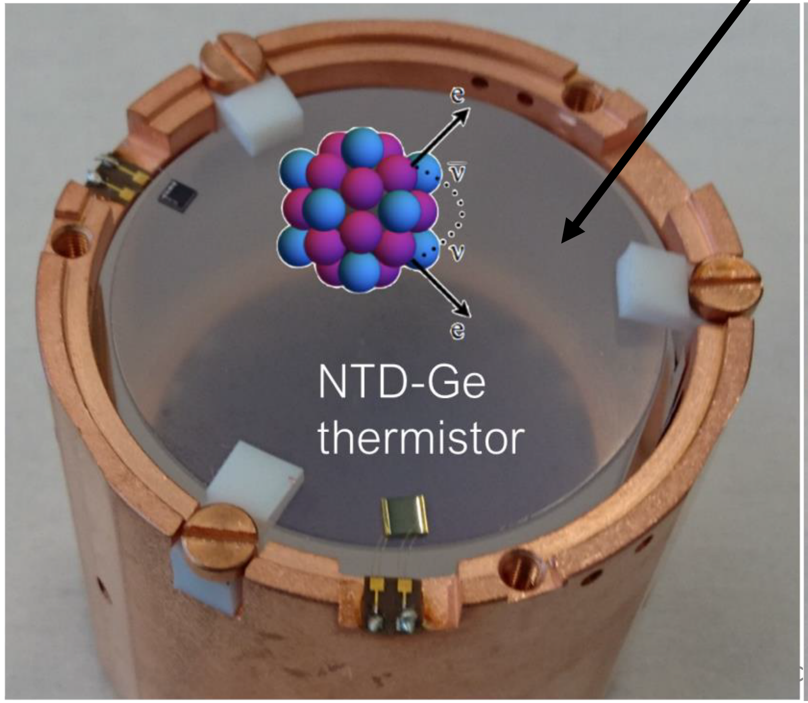
NTD $\rightarrow$ $R(T) = R_0 e^{\sqrt{T_0/T}}$

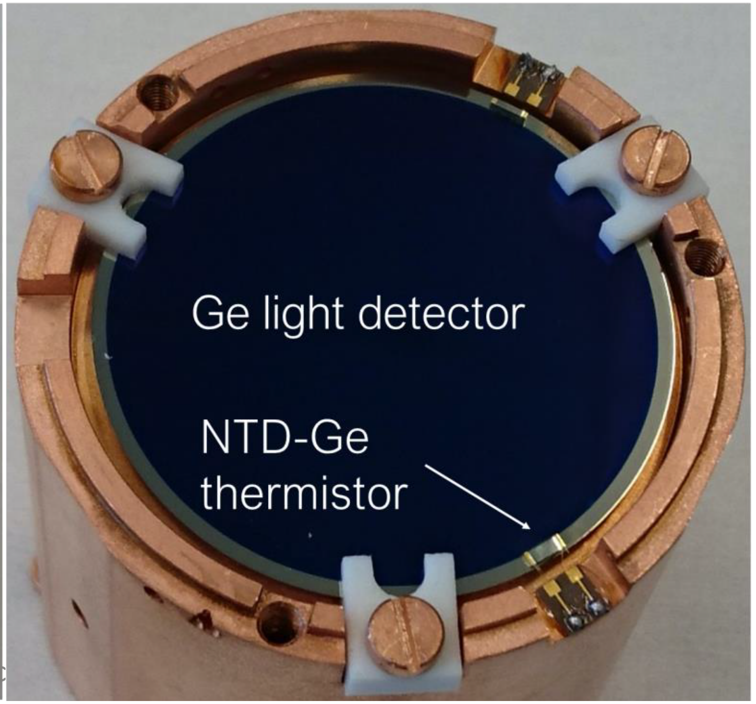
Source [^{100}Mo] = Detector [Li_2MoO_4]
97% enrichment in ^{100}Mo
High efficiency

Li_2MoO_4 single crystal
210 g

Teflon: weak thermal link

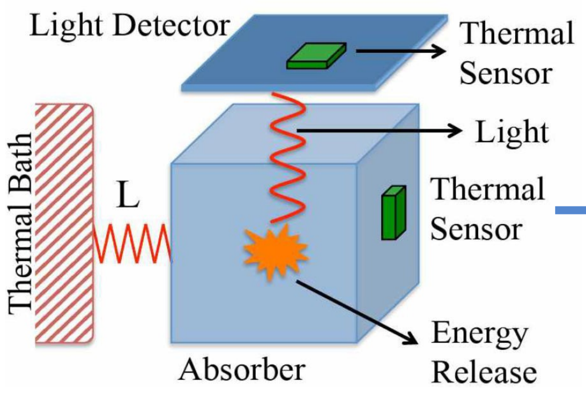
Copper: Thermal Bath

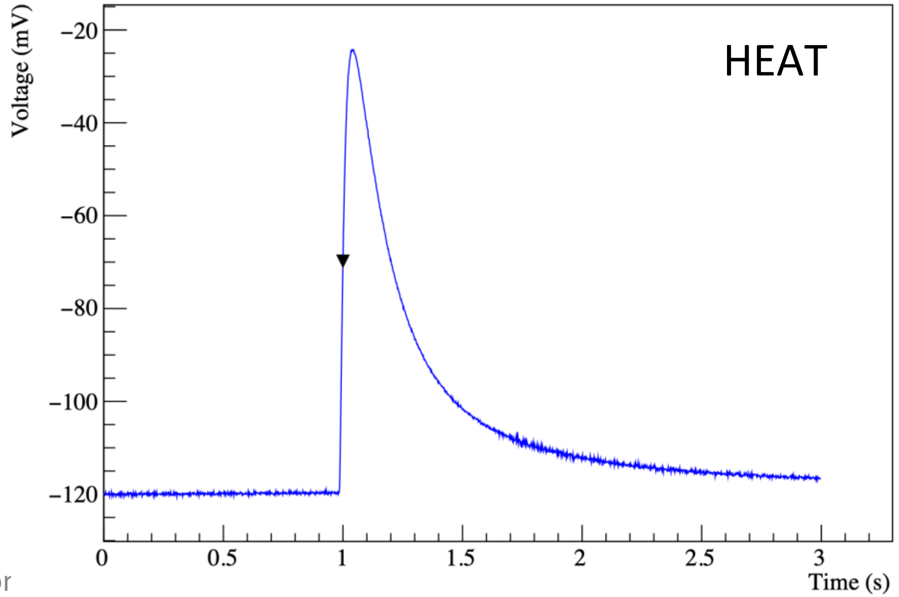


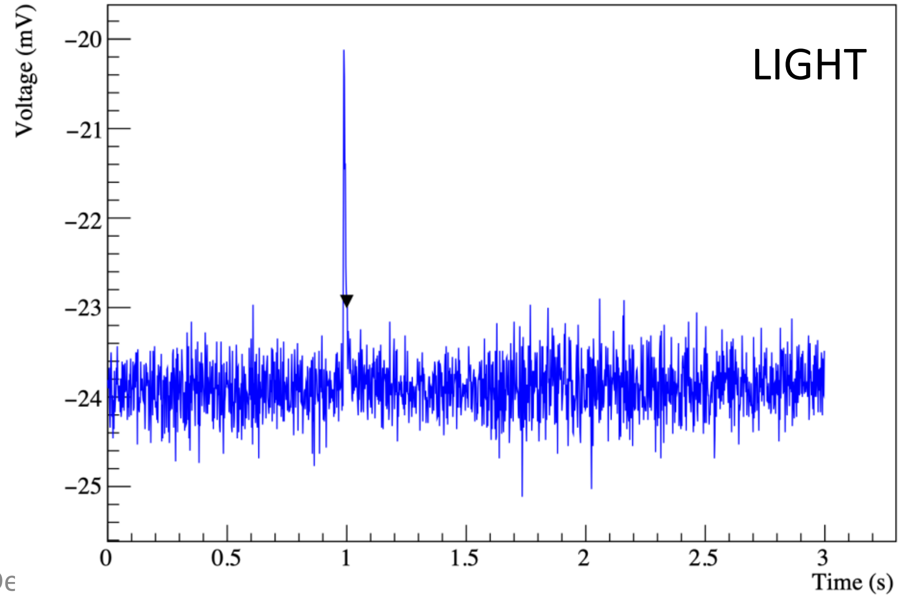


Copper: Thermal Bath

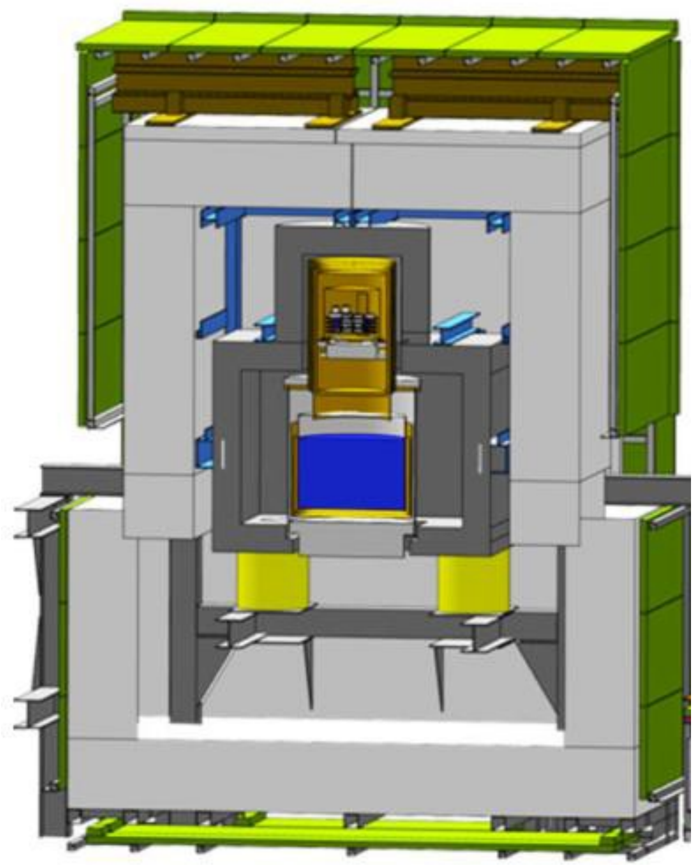
CUPID-Mo detector response







CUPID-Mo configuration at Modane



4800 m.w.e. rock overburden

shared EDELWEISS cryogenic infrastructure operated at **@ 20 - 22 mK**

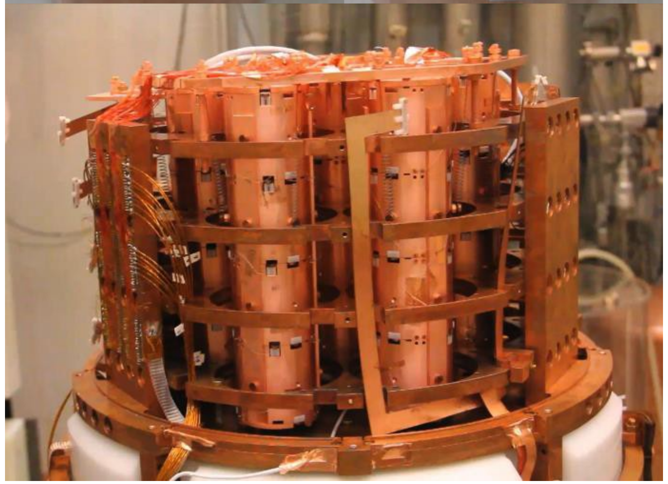
20 $Li_2{}^{100}MoO_4$ detectors of ~210 g, ~97% enriched (**2.26 kg ^{100}Mo**)

Ge light detectors

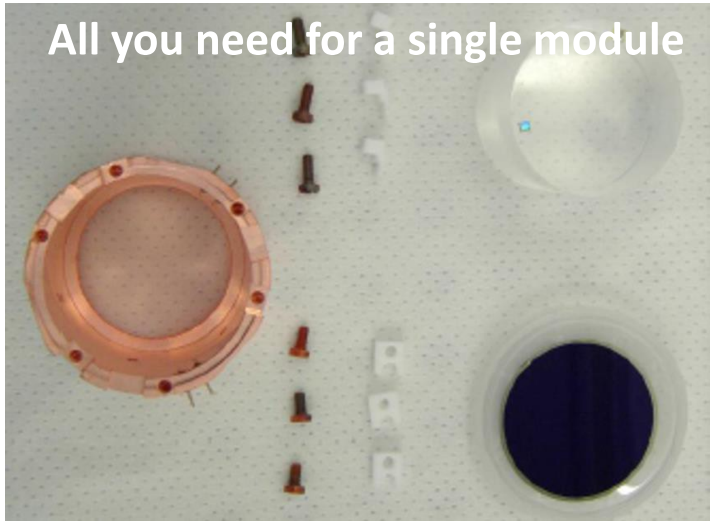
Ge-NTD based sensor readout

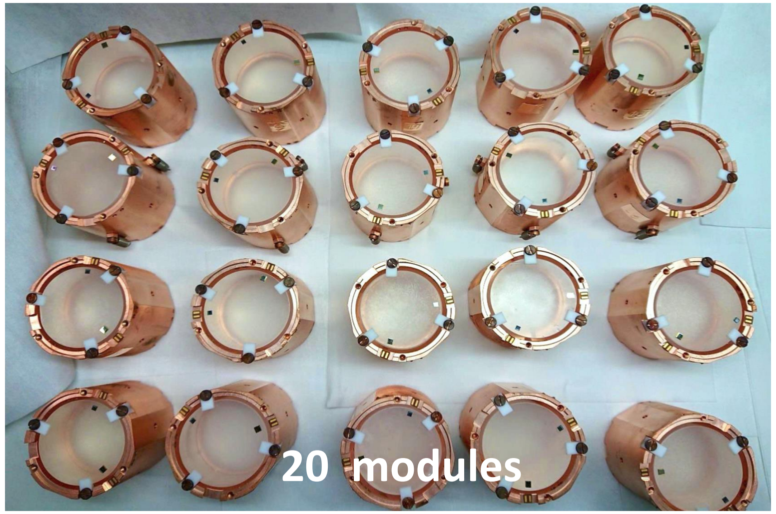
19x $Li_2{}^{100}MoO_4$ scintillating bolometers operational

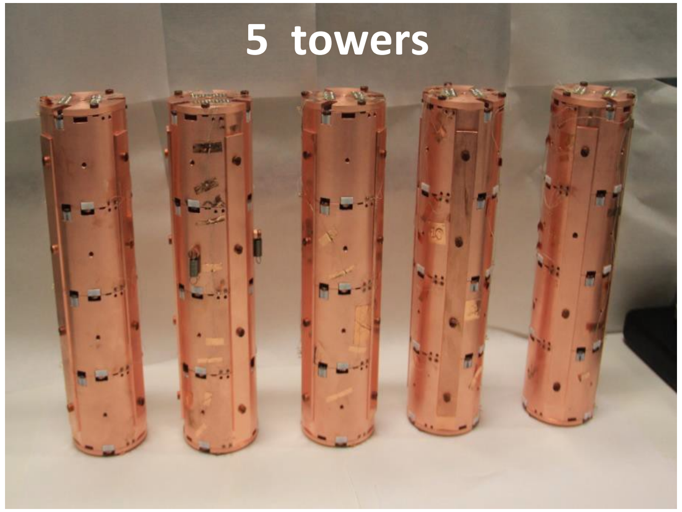
physics data taking March 2019 - June 2020

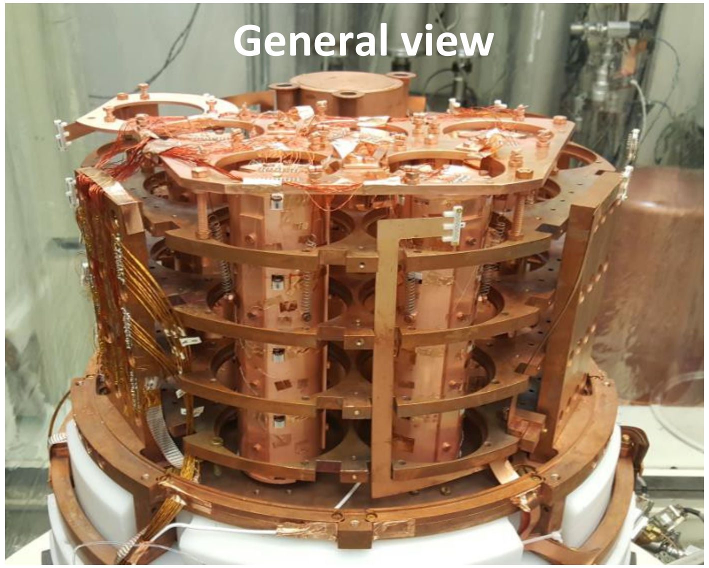


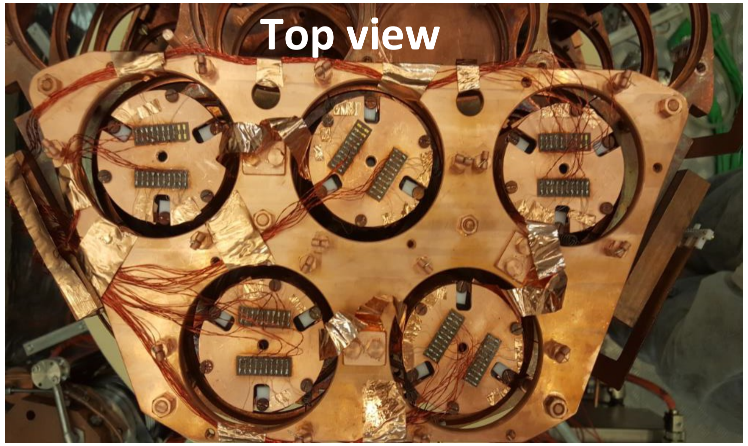
CUPID-Mo picture gallery



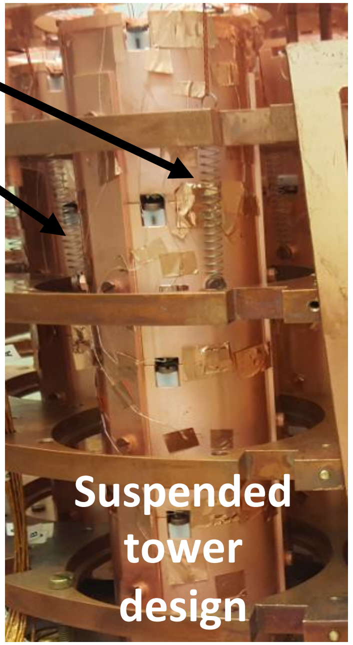






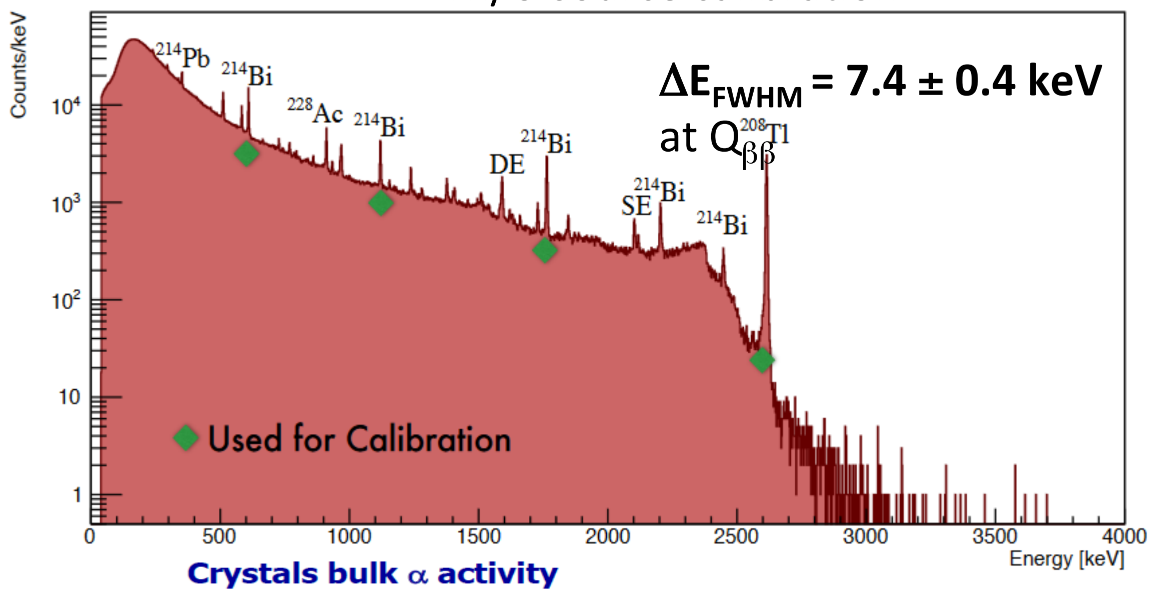


Springs



CUPID-Mo performance

Th/U source calibration

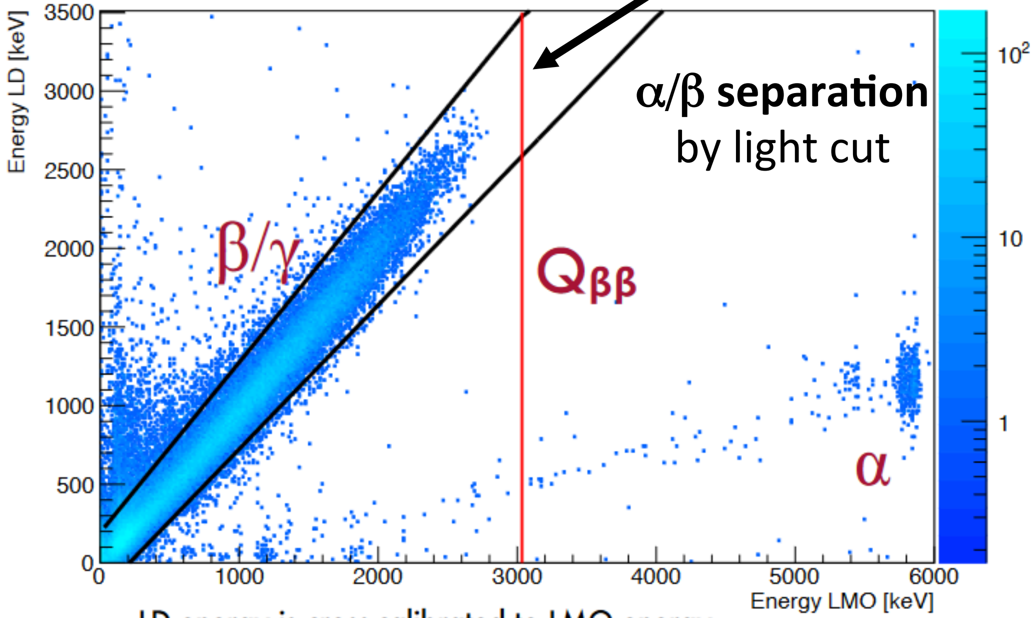


Crystals bulk α activity
(19/20 $Li_2{}^{100}MoO_4$, 2.17 kg×yr)

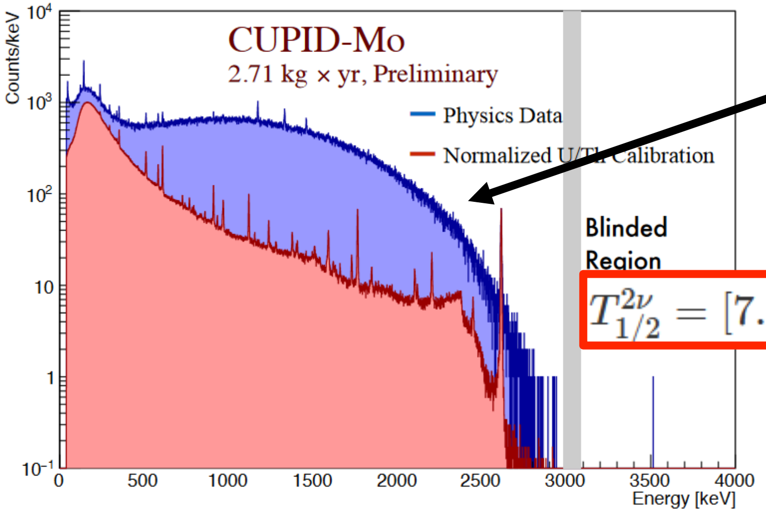
Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{232}Th	0.22(9)
	^{228}Th	0.38(9)
	^{224}Ra	0.34(9)
	^{212}Bi	0.22(7)
^{238}U	^{238}U	0.35(10)
	^{234}U+^{226}Ra	1.22(17)
	^{230}Th	0.48(12)
	^{222}Rn	0.47(10)
	^{218}Po	0.35(9)
	^{210}Po	95(6)
	^{190}Pt	0.19(8)

Excellent crystal radiopurity
U,Th ≤ 1 μBq/kg

Zero background



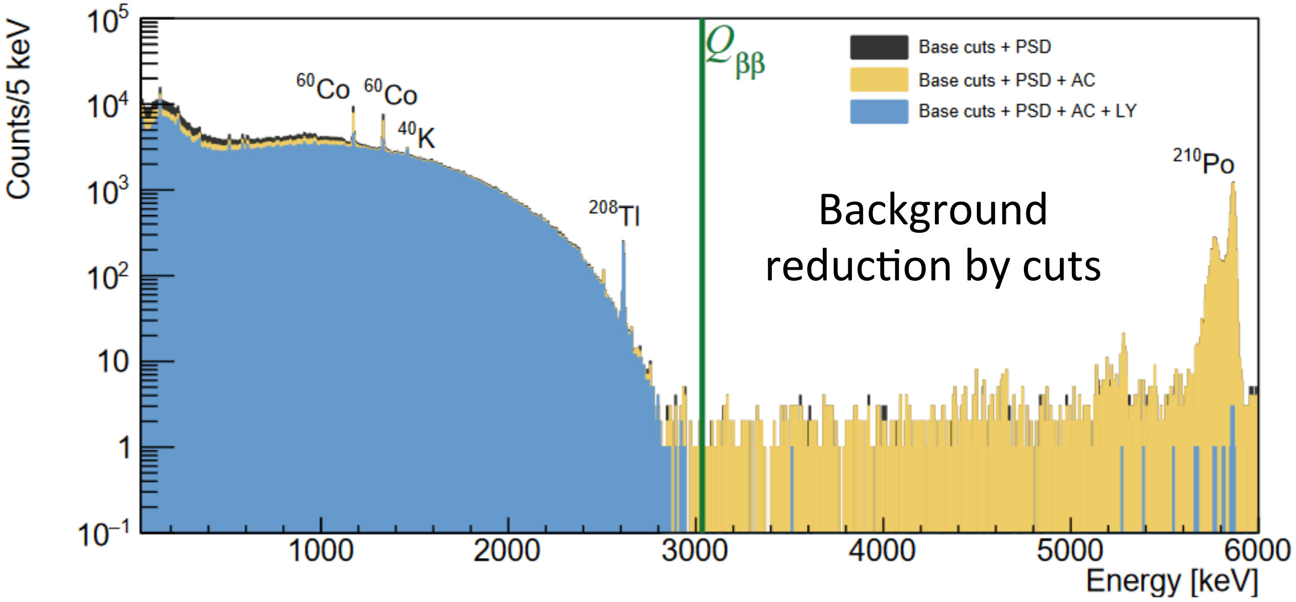
LD energy is cross-calibrated to LMO energy

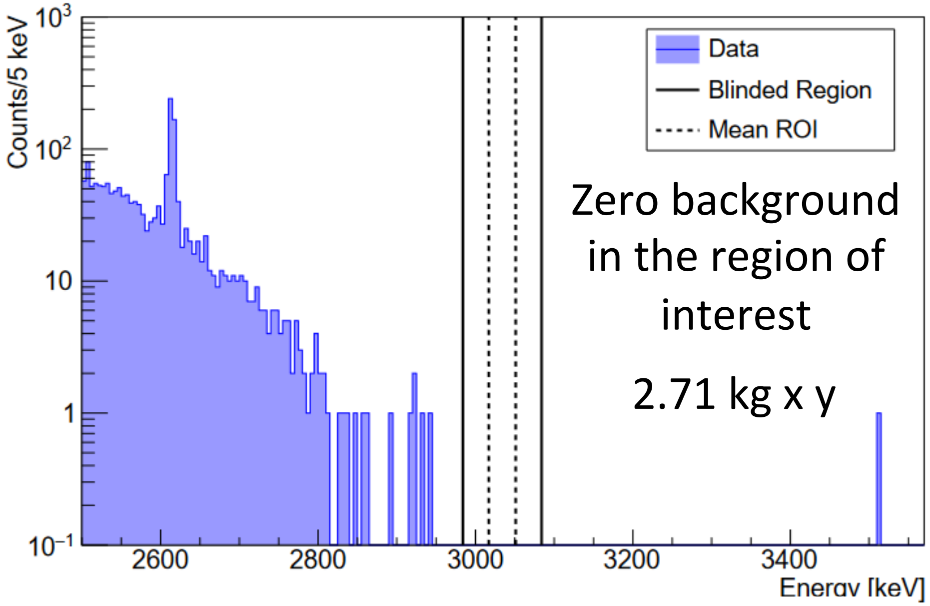


In single-tower precursor, most precise ever 2ν2β measurement of ^{100}Mo

$$T^{2\nu}_{1/2} = [7.12^{+0.18}_{-0.14}\,(\text{stat.}) \pm 0.10\,(\text{syst.})] \times 10^{18}\ \text{years}$$

CUPID-Mo results

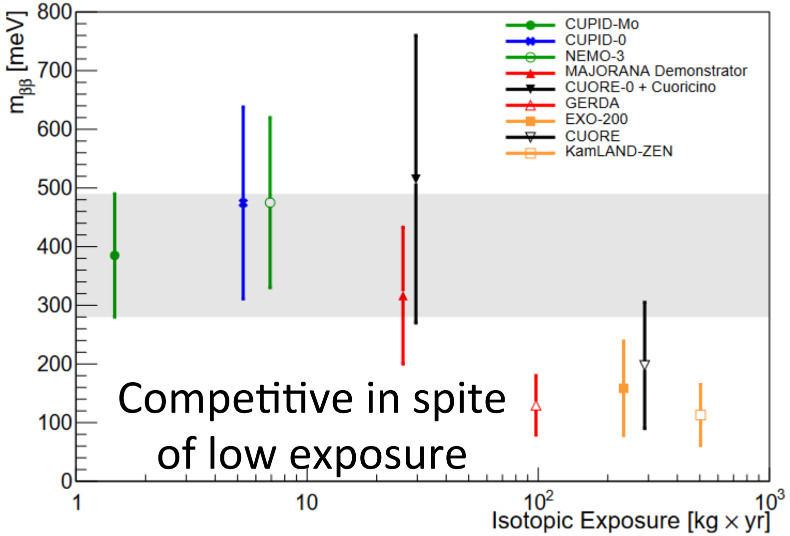




$$T^{0\nu}_{1/2} > 1.8 \times 10^{24}\ \mathrm{yr}\ (90\,\%\ \mathrm{C.I.})$$

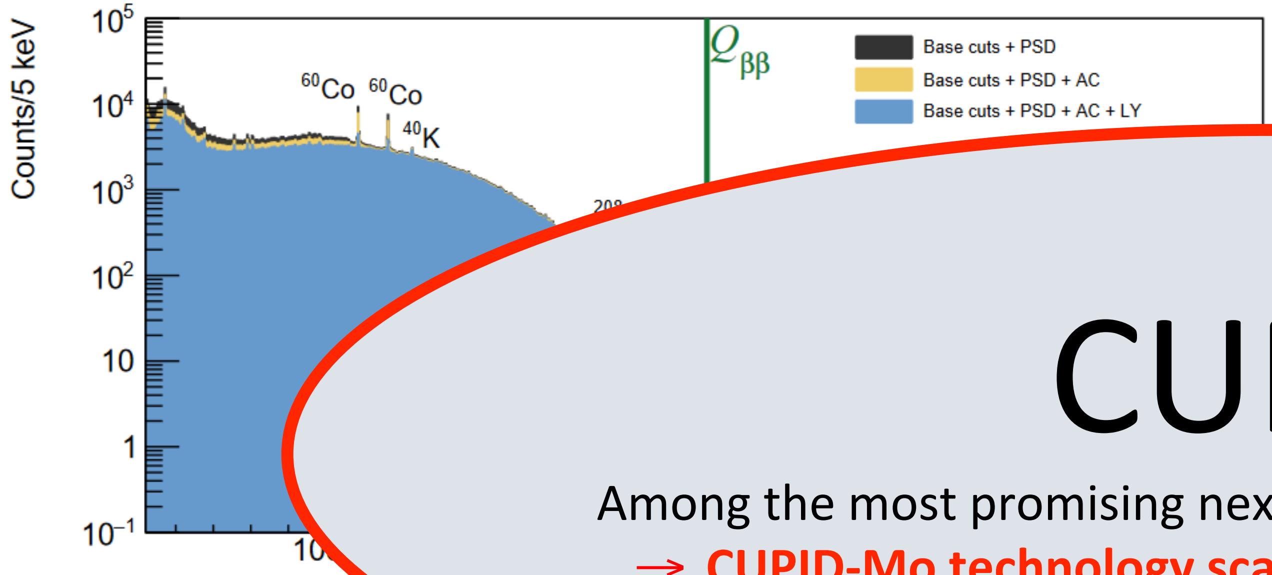
$$m_{\beta\beta} < 0.28 - 0.49\ \mathrm{eV}\ (90\,\%\ \mathrm{C.I.})$$

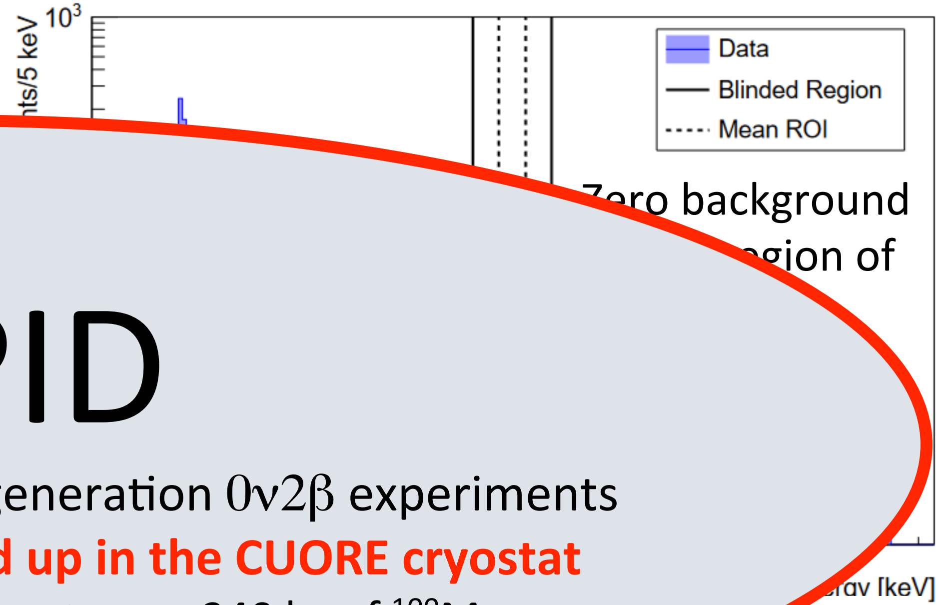
Most stringent worldwide limit on $0\nu2\beta$ of ^{100}Mo



Several physics papers in preparation

CUPID-Mo results





CUPID

Among the most promising next-generation $0\nu2\beta$ experiments

→ **CUPID-Mo technology scaled up in the CUORE cryostat**

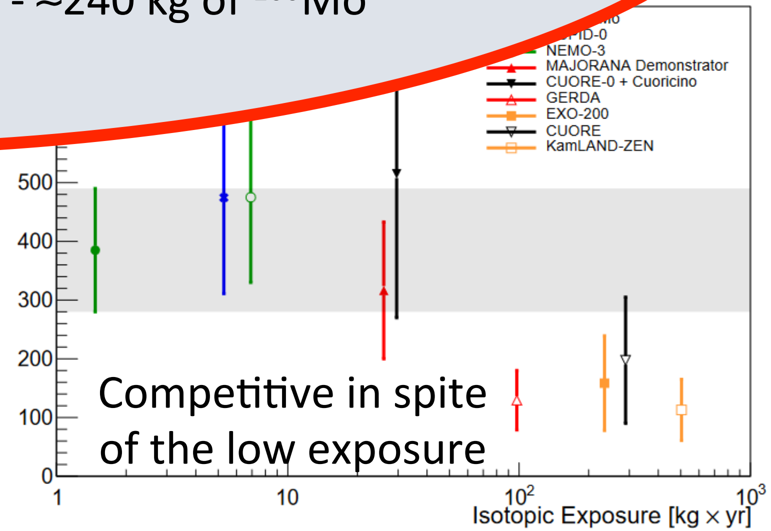
~1600 Li_2MoO_4 scintillating bolometers - ~240 kg of ^{100}Mo

$T^{0\nu}_{1/2} > 1.8$

$m_{\beta\beta} < 0.28 - 0.49$ eV (90

Most stringent worldwide limit on $0\nu2\beta$ of ^{100}Mo

Several other physics papers in preparation



The CROSS technology: rationale

CROSS is a demonstrator to be installed in the Canfranc underground laboratory (Spain) for a new double beta decay technology with detectors capable of **rejecting surface events (both α and β) → superior to scintillating bolometers**

Main compound: **Li_2MoO_4** (as CUPID-Mo) – a small section with **TeO_2** is foreseen

Surface vs bulk events

High energy phonons are generated

↓

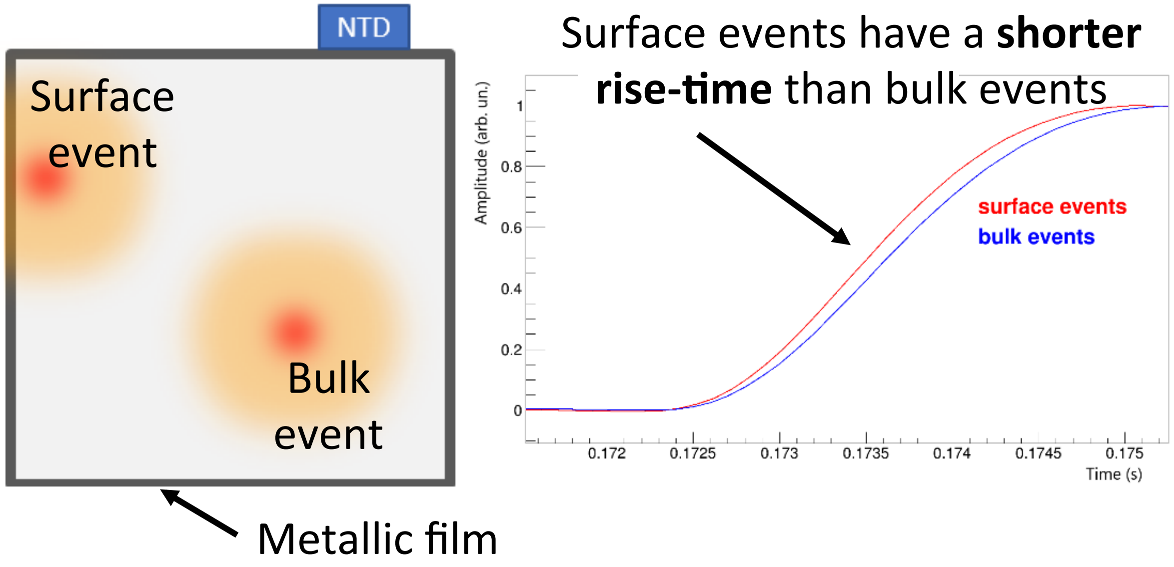
More efficient trapping of out-of-equilibrium phonons for surface events by a metal (normal or superconductor)

↓

Fast energy degradation of out-of-equilibrium phonon in a metal

↓

Acceleration of thermalization for surface events



Film works as a **pulse-shape modifier** of surface events

The CROSS technology: results

After a long R&D with small samples to fix the best coating material, **AlPd bi-layer** was selected

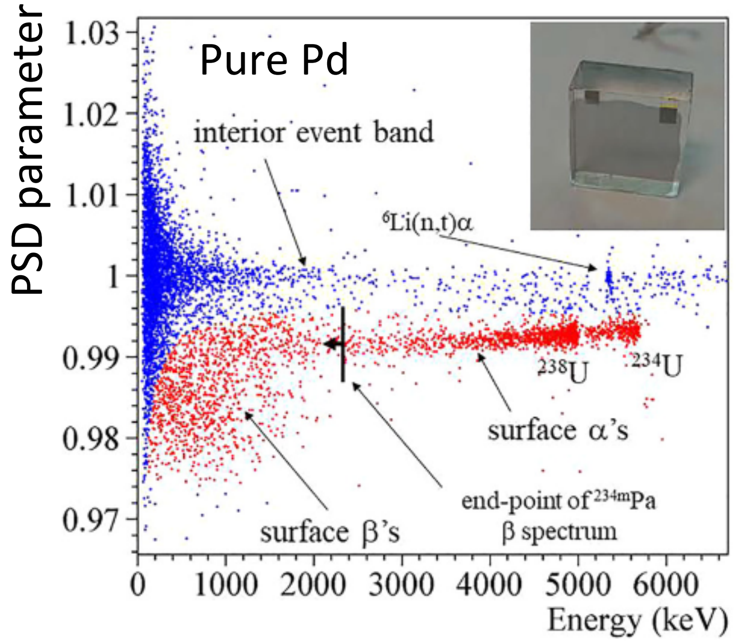
- Al is superconductive with T_C=1.2 K – Pd is a normal metal
- **Pd(10 nm) on the crystal – Al(100 nm) on top of Pd** → $T_C \sim 0.7$ K (proximity effect)

Best compromise between

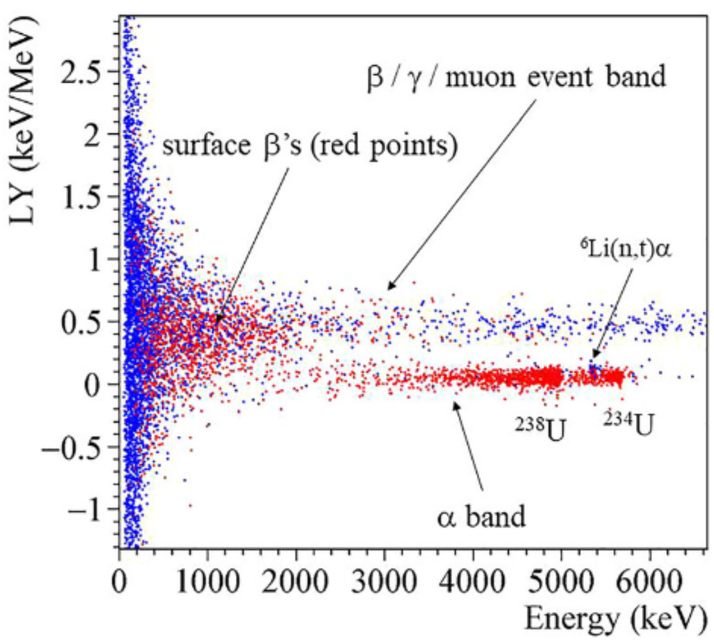
- Efficient thermalization of surface events
- Low specific heat
- Easy deposition by evaporation

Sample are irradiated with an U source providing both α (4.2 and 4.7 MeV) and β (end-point at 2.2 MeV)

For redundancy, also scintillation light is detected



Both surface α's and β's are discriminated by the metallic film



Only surface α's are discriminated by a light-yield cut

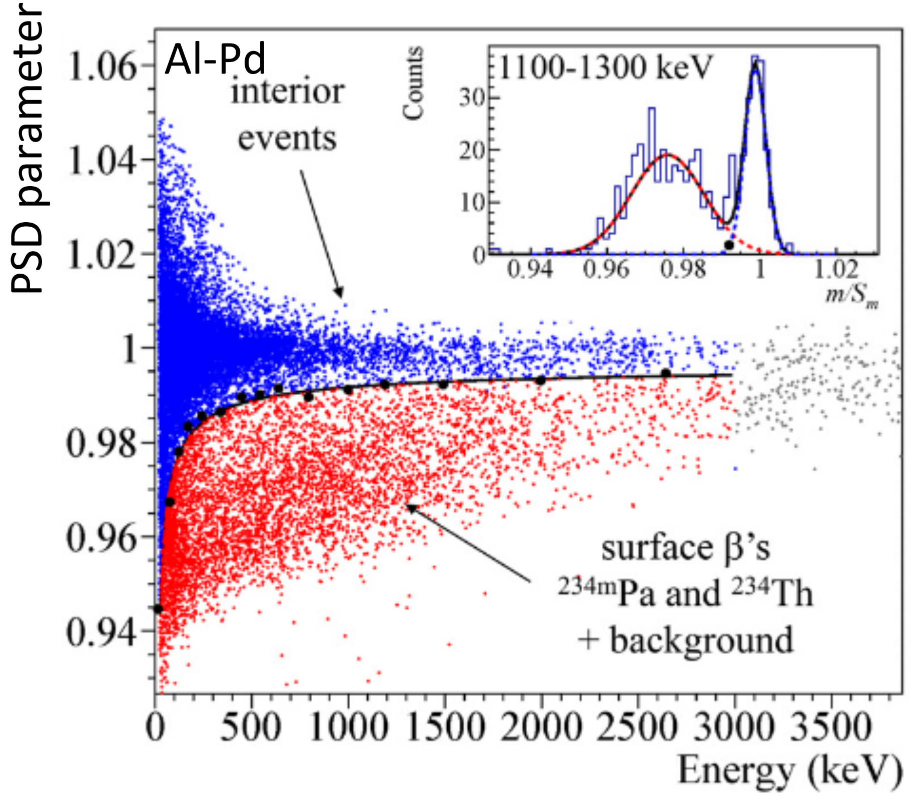
The CROSS technology: results

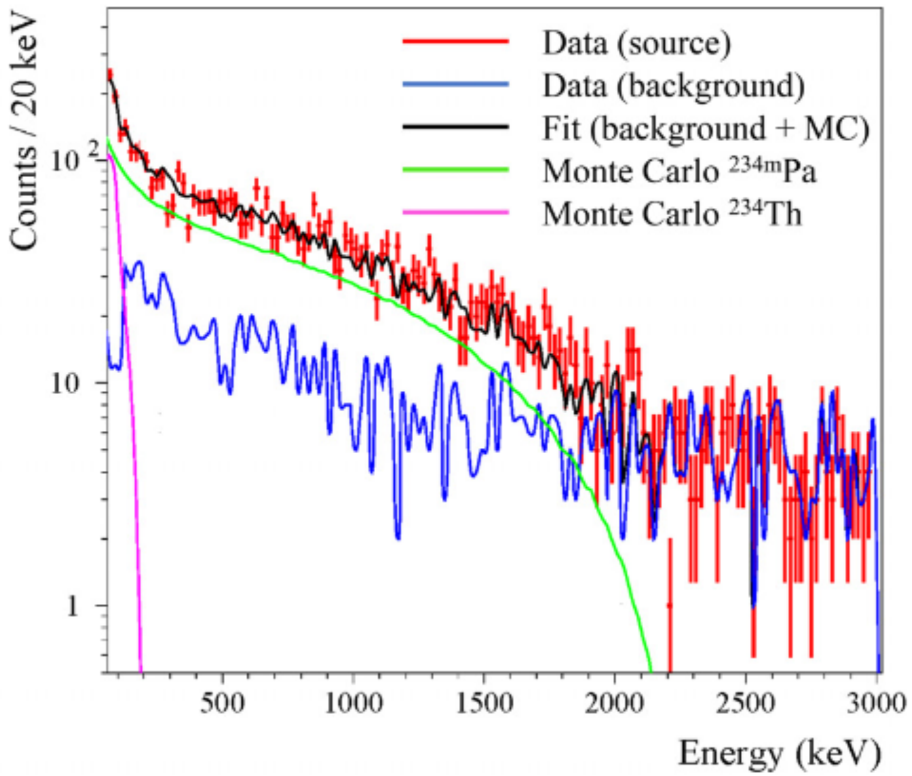
Deep insight into surface β rejection – α's are rejected by a light cut

- A measurement **with and without source** is performed (background subtraction)
- Comparison with **Monte Carlo simulations**
- **β surface rejection efficiency** is compatible with **100%**

Breakthrough in bolometric double beta decay search

Transfer to large crystals is in progress





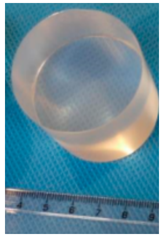
Looking to the future: BINGO

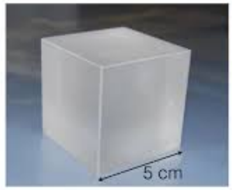
Isotopes

^{100}Mo	Q = 3034 keV > 2615 keV – AI: 9.7%
^{130}Te	Q = 2527 keV < 2615 keV – AI: 34%

Crystals

Li_2MoO_4
TeO_2





Excellent bolometric properties
High radiopurity → CUPID-Mo, CUORE
Extensively tested

α rejection — **heat-light double readout**

Li_2MO_4: scintillator
TeO_2: only Cherenkov light → Feeble light yield: **Outstanding light detector required**

NTD readout / Electronics → Keep successful CUORE / CUPID-Mo solutions

Bi-Isotope approach

- more options for next-to-next generation searches
- observation in 2 candidates → discovery + confirmation

Innovative elements in BINGO

Aim: to reduce by **a further order of magnitude** the background level of CUPID in two isotopes

CUPID-1T

① Revolutionary assembly of the detectors

The crystal will be surrounded only by active elements

→ **Kill surface radioactivity**

② Full active shield inside the experimental space,

for the first time in bolometric technology. The shields will consist of $BGO/ZnWO_4$ radiopure scintillators with bolometric light read-out

→ **Kill external γ background**

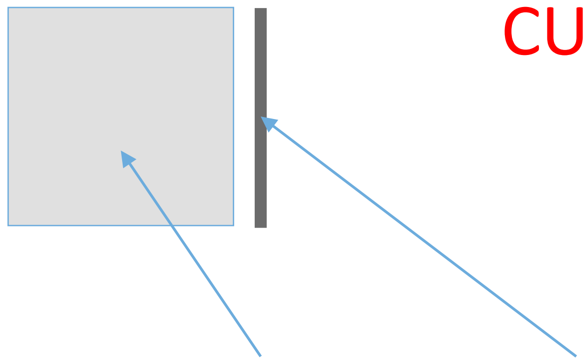
③ Innovative light detector based on the Neganov-Luke effect

Increase by a factor 10 current sensitivity

reach < 10 eV rms baseline width – Multipurpose :

→ **α/β discrimination in TeO_2 by Cherenkov light**

→ **read-out scintillator light of the active shield**



Crystal + light detector (Ge)

(Li_2MoO_4 or TeO_2)

Innovative elements in BINGO

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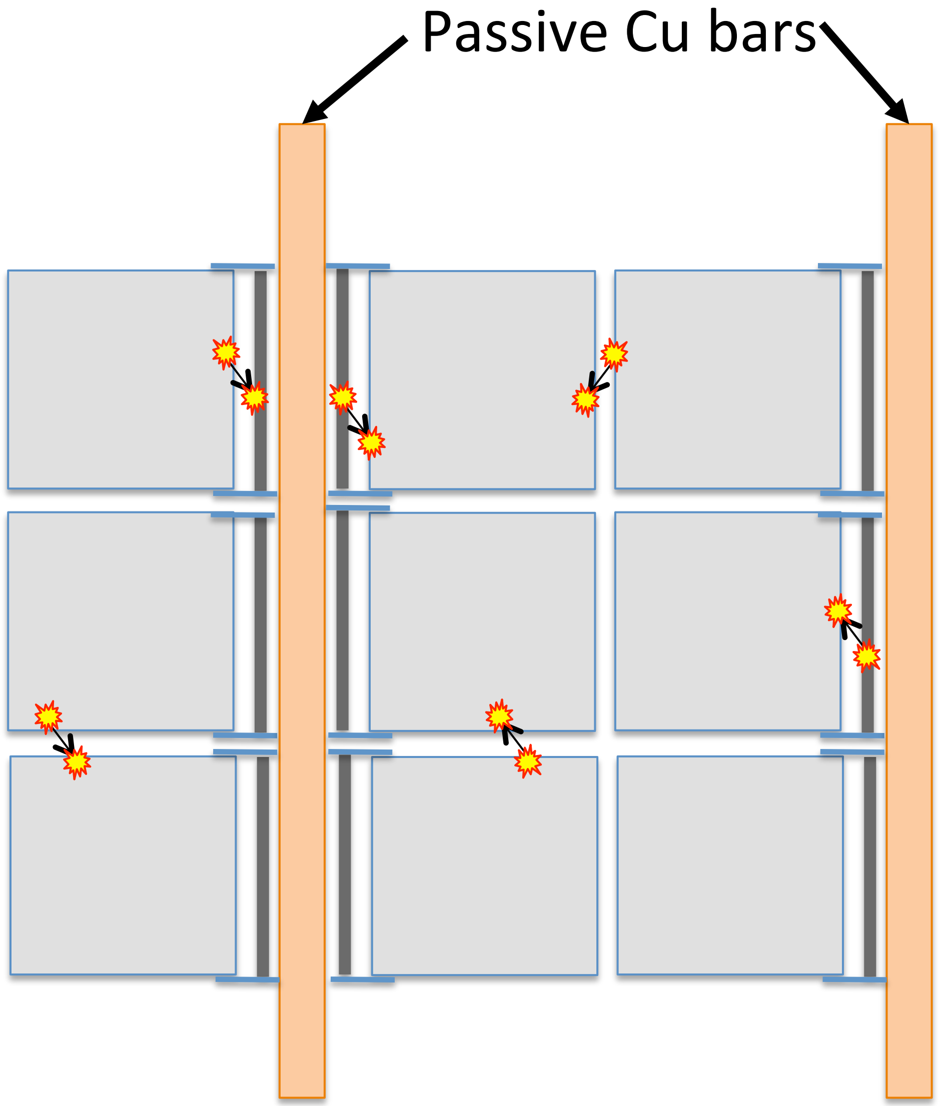
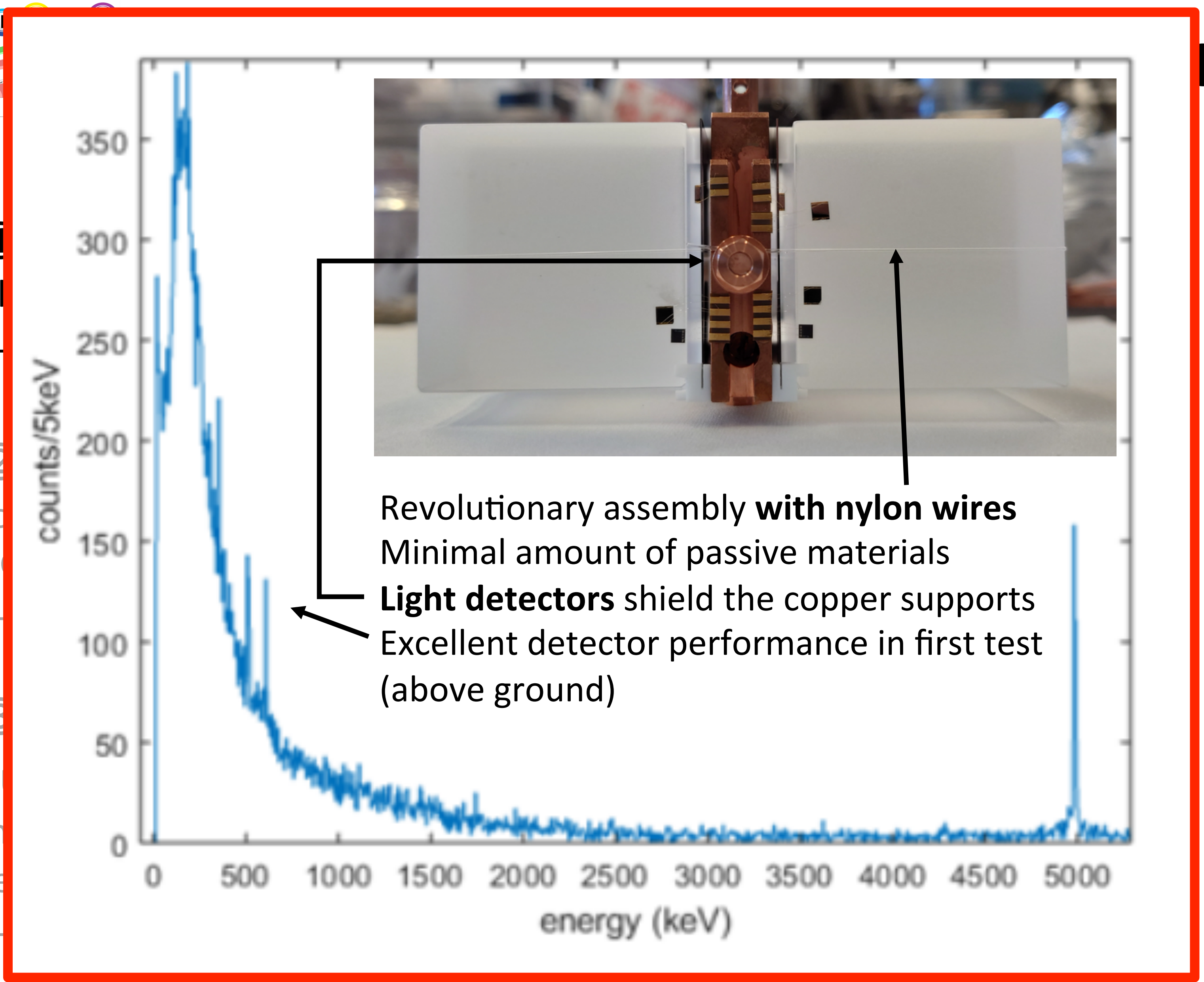
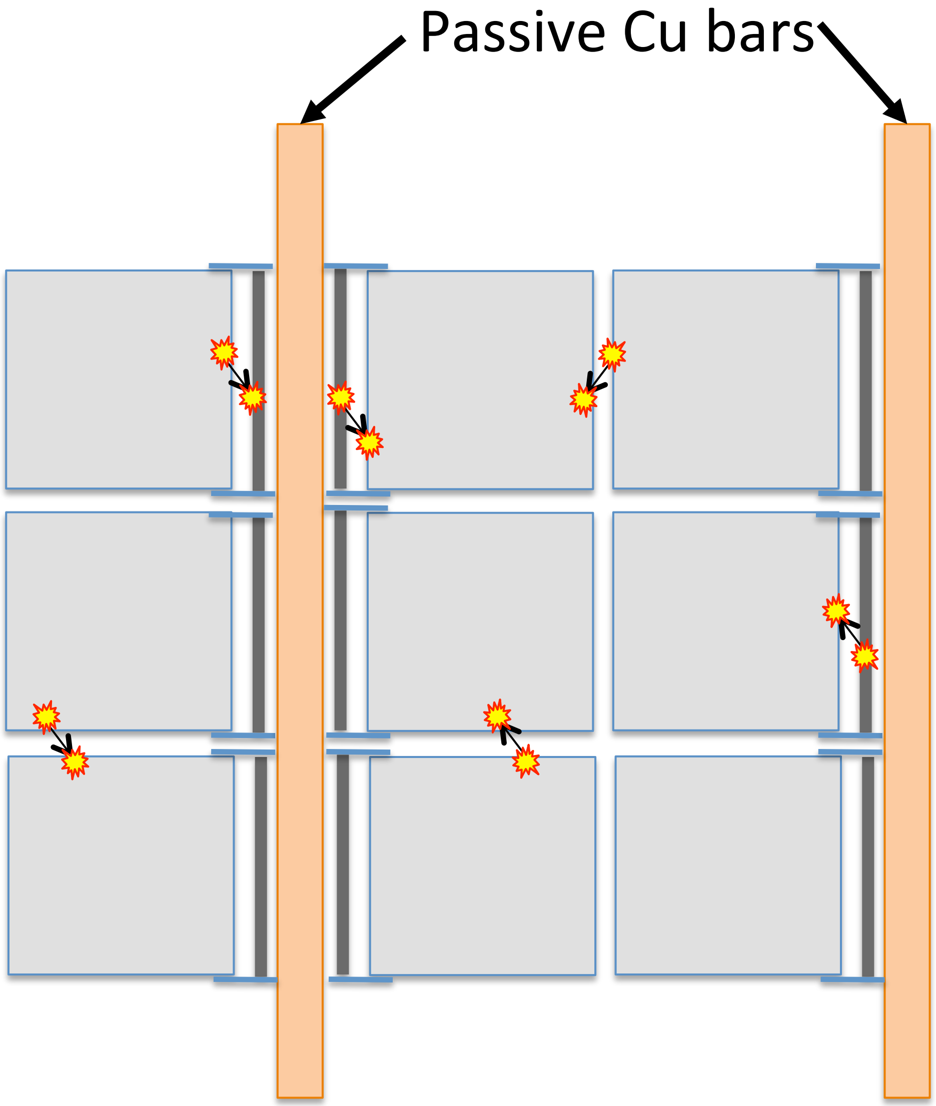


n BINGO





→ read-out scintillator light of the active shield

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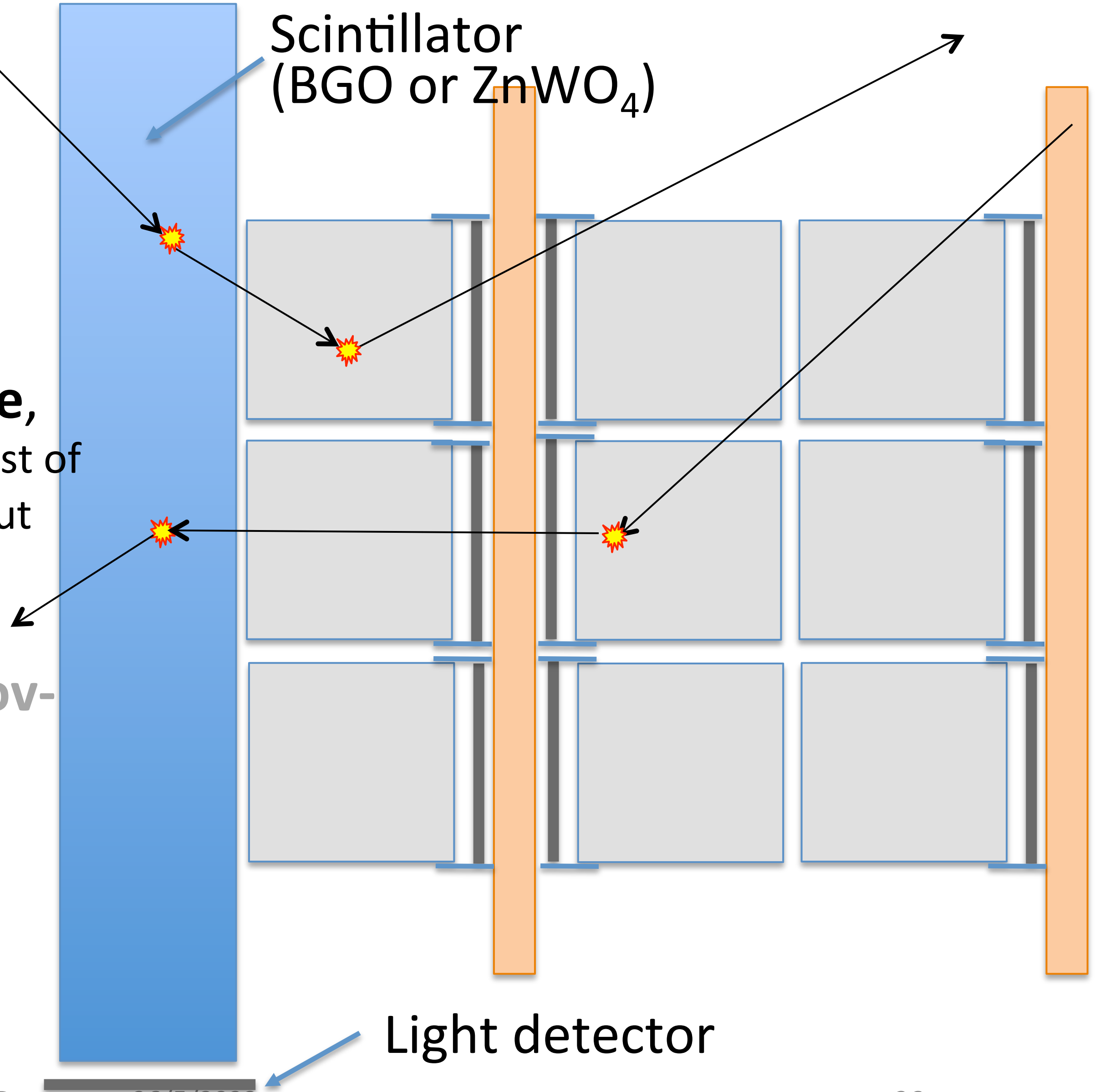
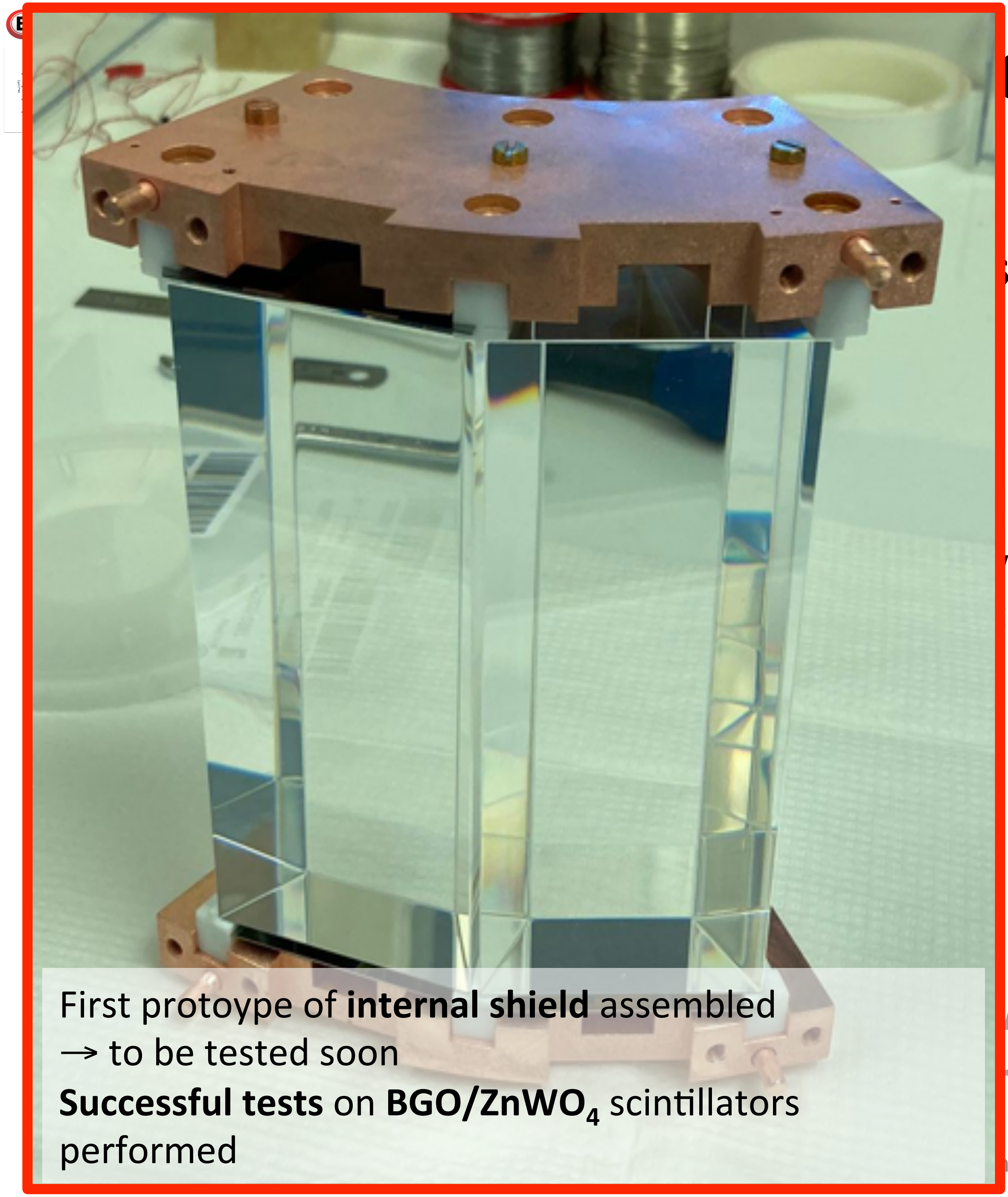


ements in BINGO



First protoype of **internal shield** assembled
→ to be tested soon
Successful tests on **BGO/$ZnWO_4$** scintillators performed

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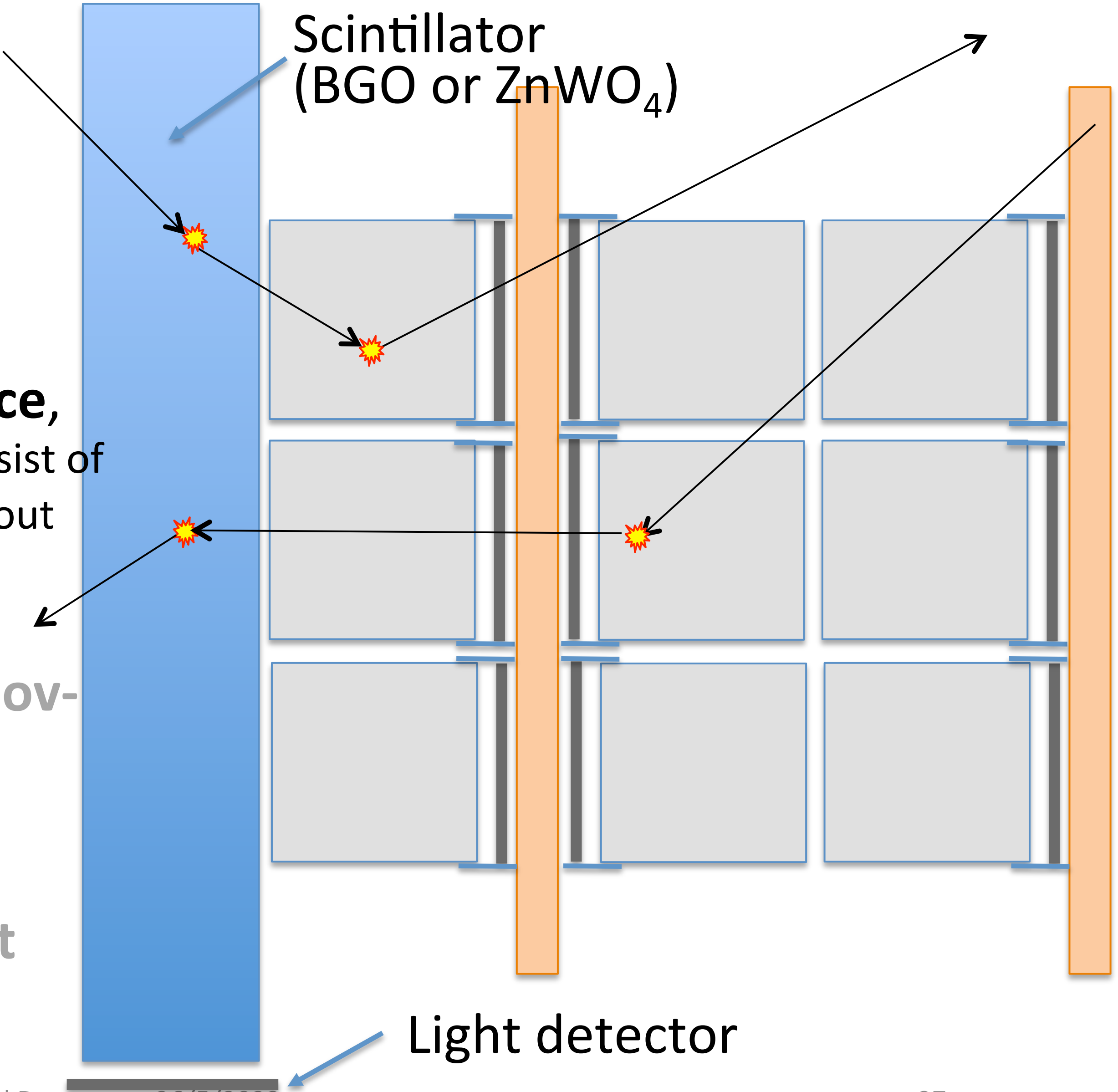

Innovative elements in BINGO

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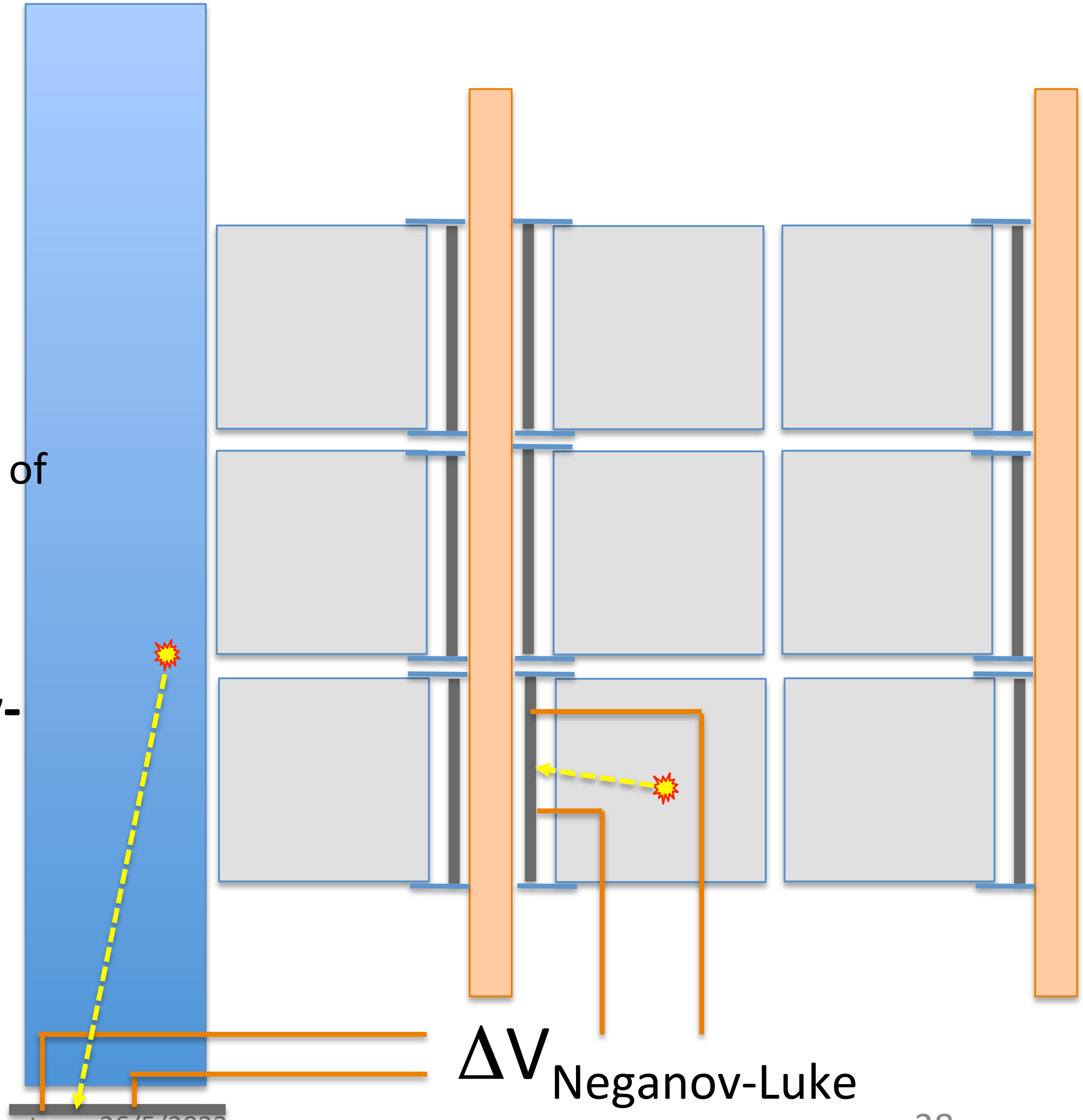
→ **Increase S/N to perform pile-up rejection**



Innovative elements in BINGO

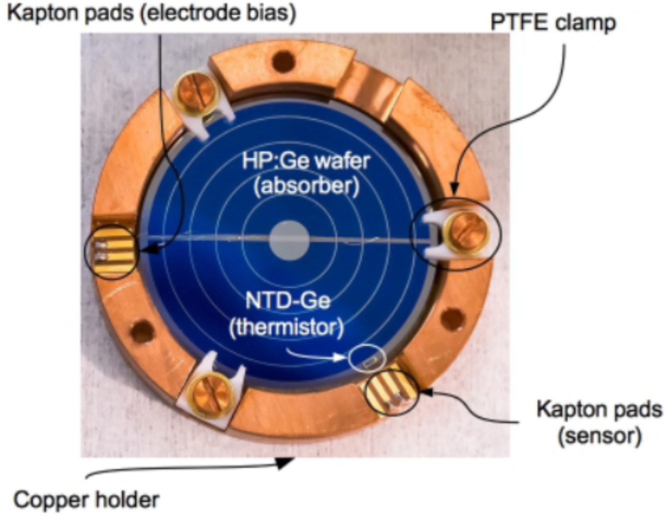
Well established technology capable of detecting **Cherenkov light** in CUORE-like TeO_2 crystal [succesfull test in Modane]

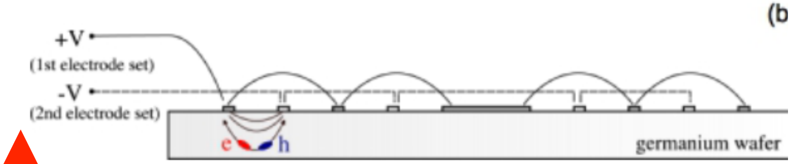
Ge light detectors with sensitivity enhanced by NTL effect

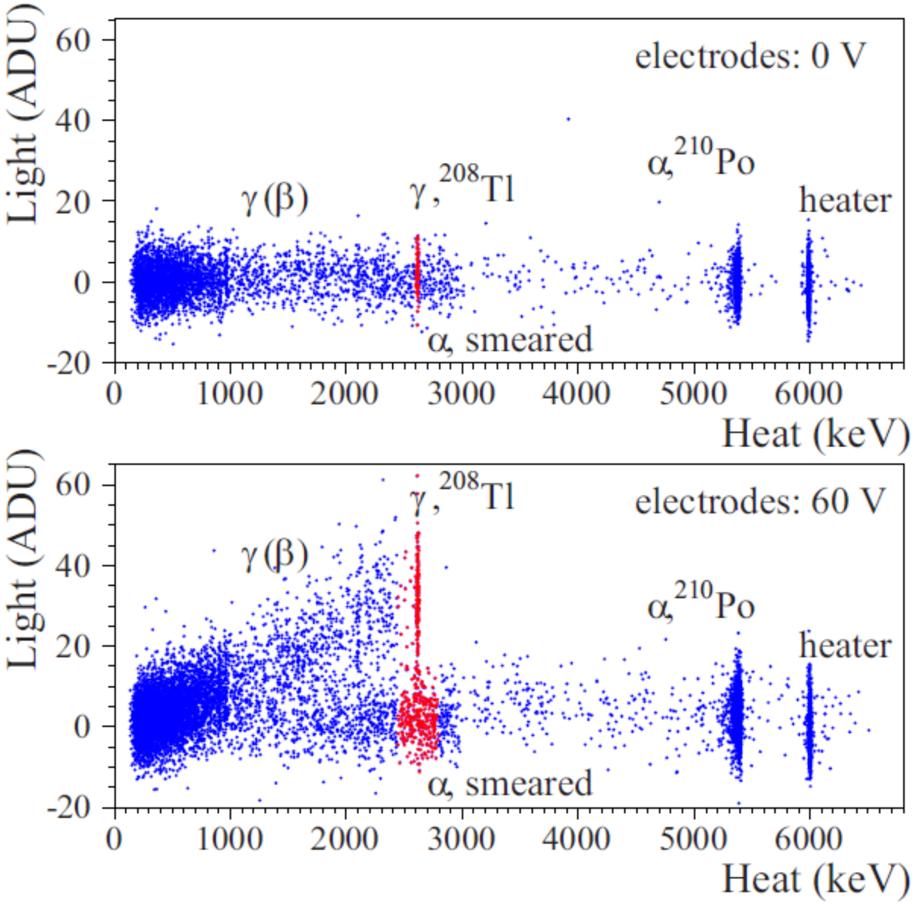
x12 gain – ~10 eV RMS noise

Objetives in BINGO

- Reach the theoretical gain (improve x2)
- Make NTD readout faster (act on size and coupling)







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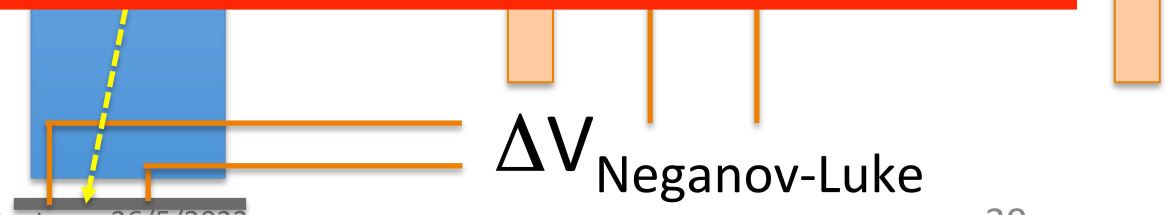

Conclusions

- Bolometers are nowadays a well established particle detection technique with different types of phonon sensors, selectable on the basis of the experimental needs
- In addition to phonons, other excitations can be measured, like charge or scintillation light, providing a more complete description of the events
- Pure charge can be measured through the mediation of phonon in the Luke-effect devices, enabling for extremely low thresholds in large-size semiconductors
- Bolometers have attractive features for rare event experiments, as the search for low-mass dark matter candidates and neutrinoless double beta decay
- The bolometric technology is compatible with low radioactive background thanks to material radiopurity and particle / impact-point identification methods