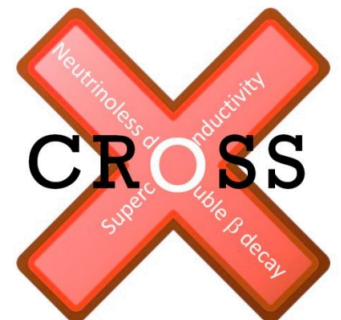


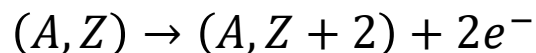
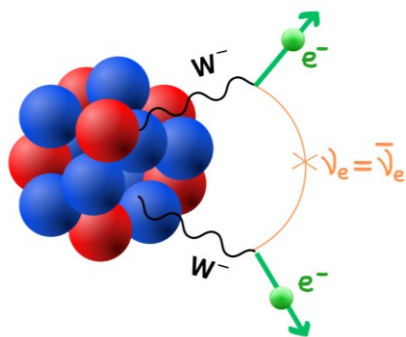


The CROSS experiment on ^{100}Mo $0\nu\beta\beta$ decay: status and physics reach

Mariia Buchynska on behalf of the CROSS collaboration



$0\nu\beta\beta$ decay



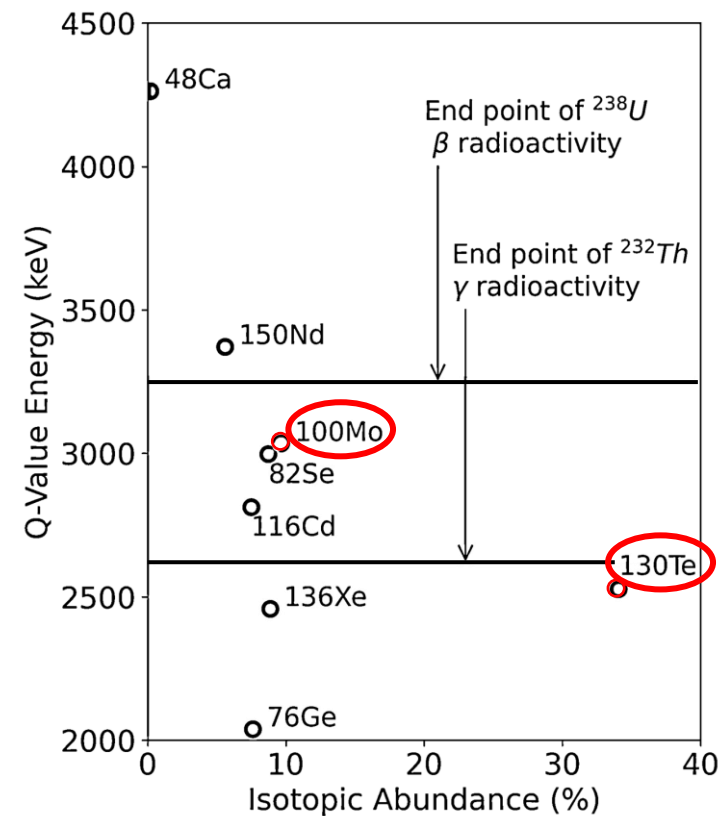
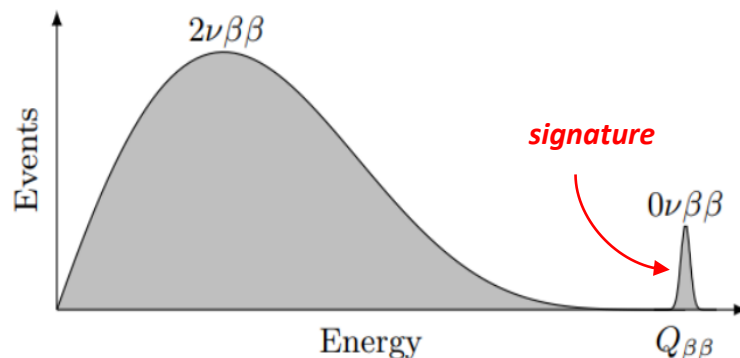
Observation would imply:

- Lepton number violation ($\Delta L = 2$)
- Majorana nature of neutrinos => provide information of the neutrino mass scale and ordering
- Explanation of matter-antimatter asymmetry

Sensitivity of the experiment:

$$T_{1/2} \propto \begin{cases} \delta \times \varepsilon \times \sqrt{\frac{M \times t}{b \times \Delta E}} \rightarrow \text{with background} \\ \delta \times \varepsilon \times M \times t \rightarrow \text{background free } (b \times \Delta E \times M \times t \ll 1) \end{cases} \quad \Rightarrow$$

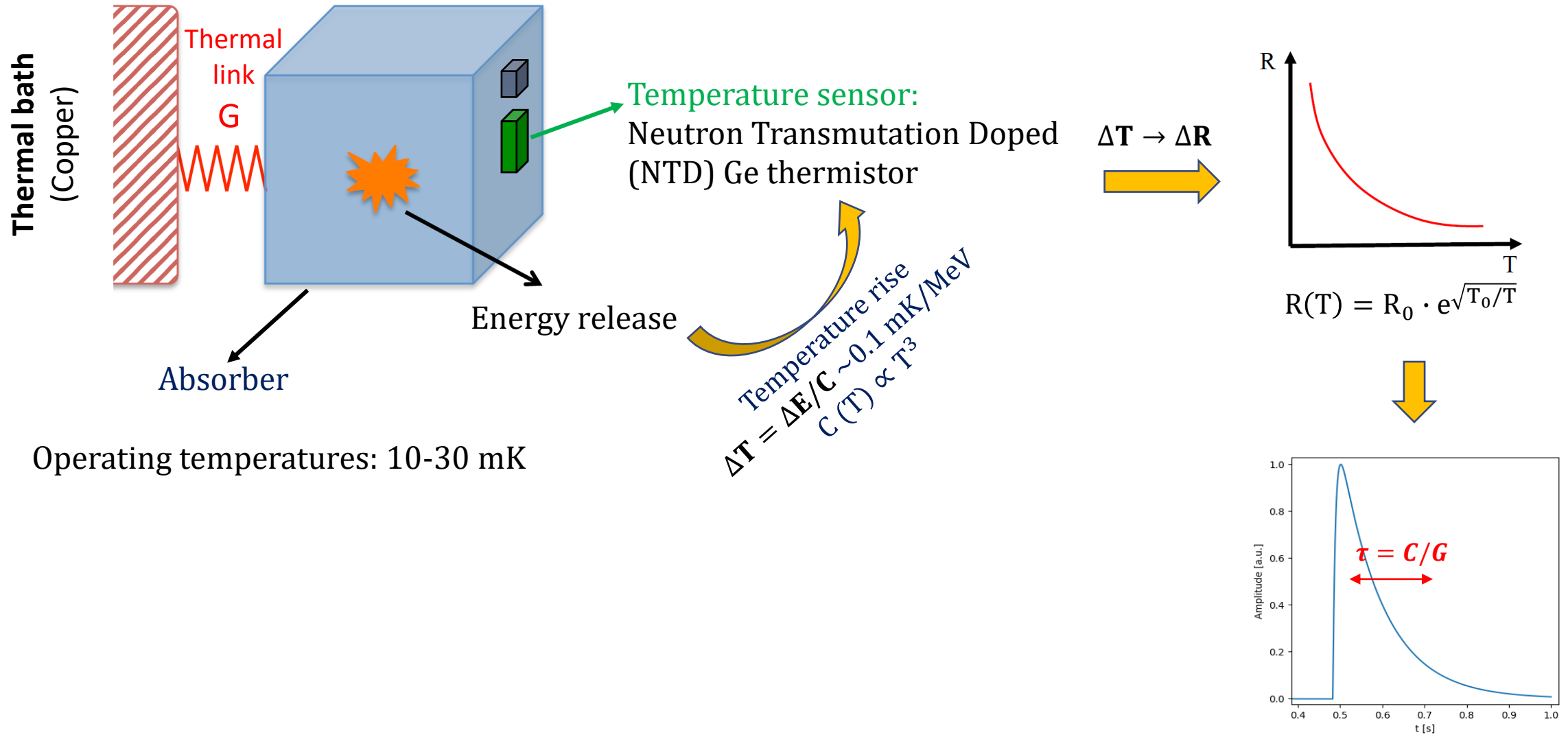
δ - isotopic abundance; b - background index in the ROI;
 ΔE - energy resolution; ε - detection efficiency; $M \times t$ - exposure



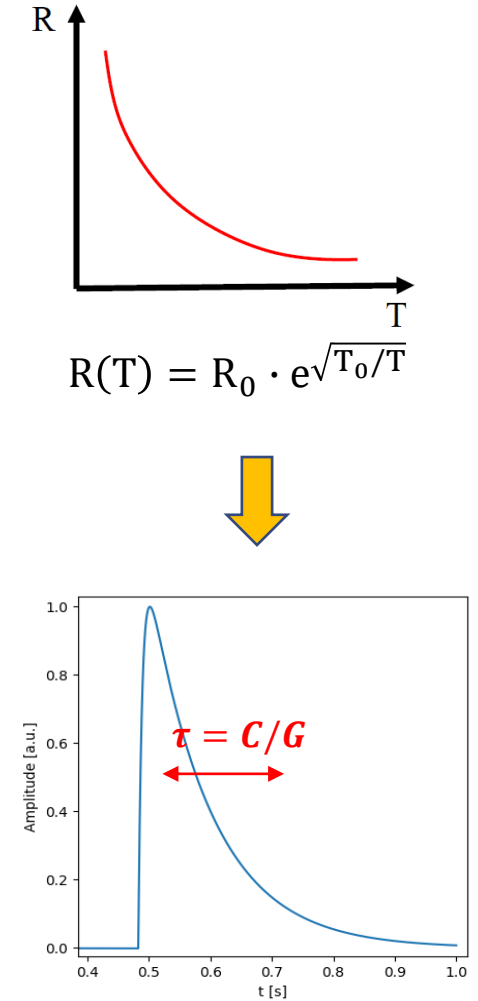
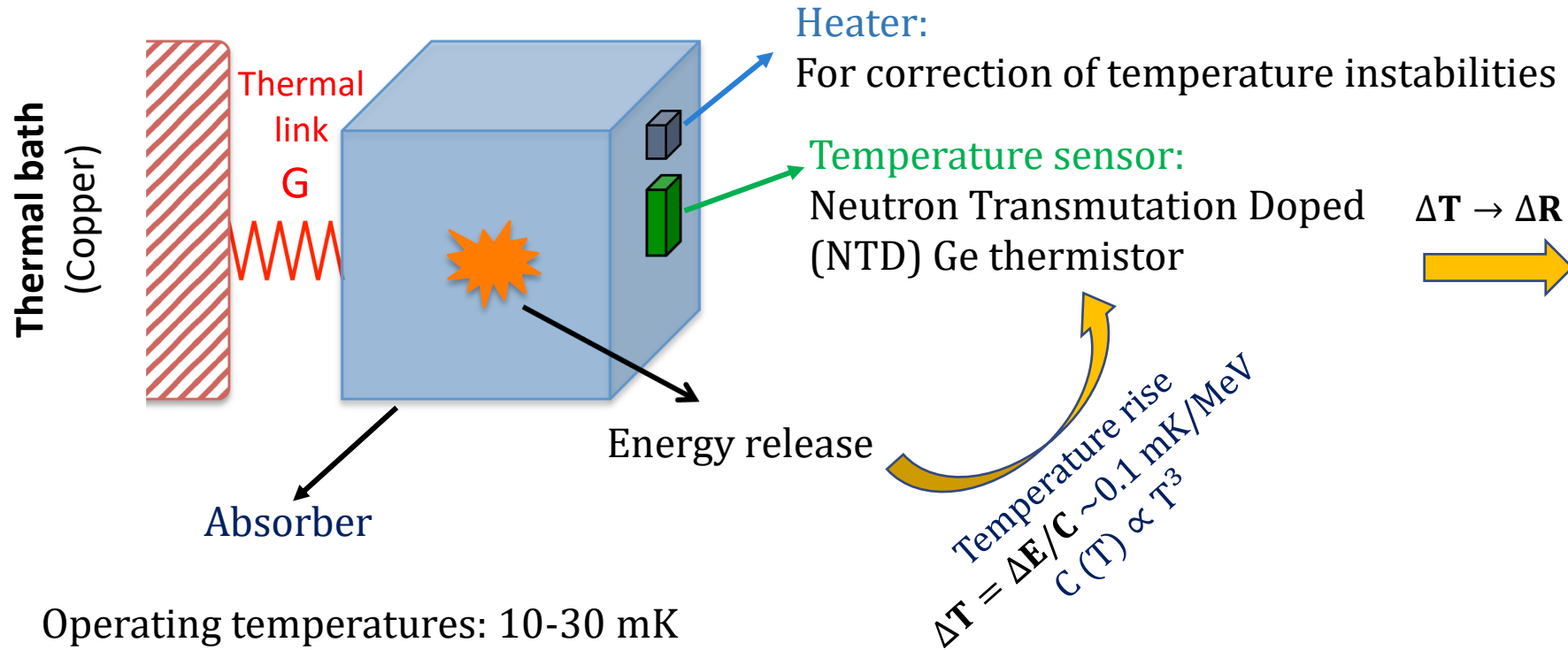
Requirements for the experiment:

- Low background
- Good energy resolution
- High detection efficiency

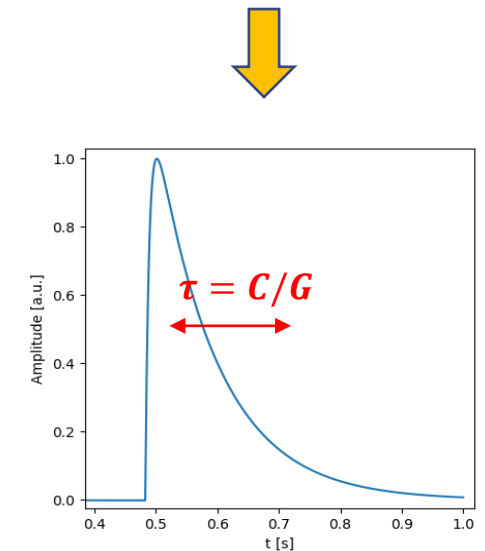
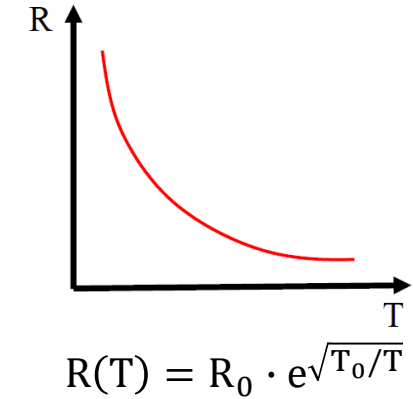
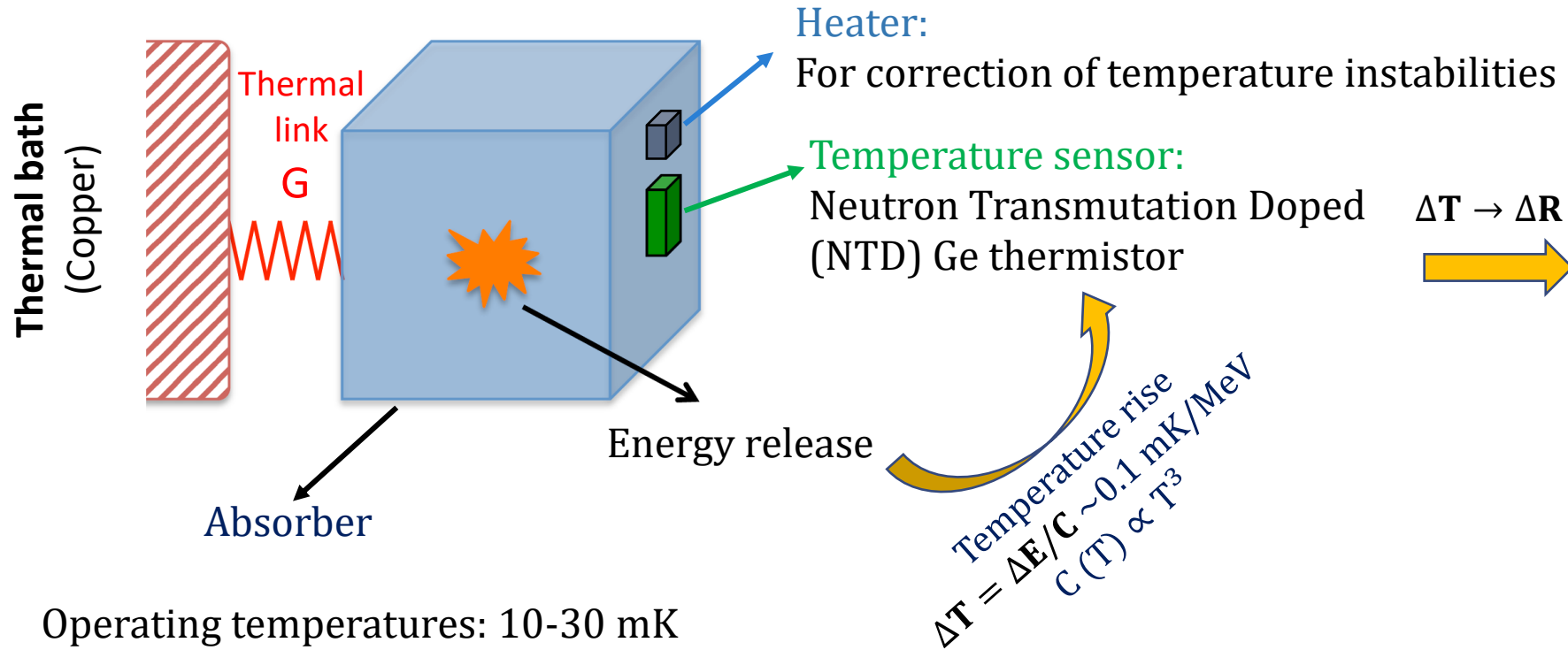
Bolometric technique



Bolometric technique



Bolometric technique

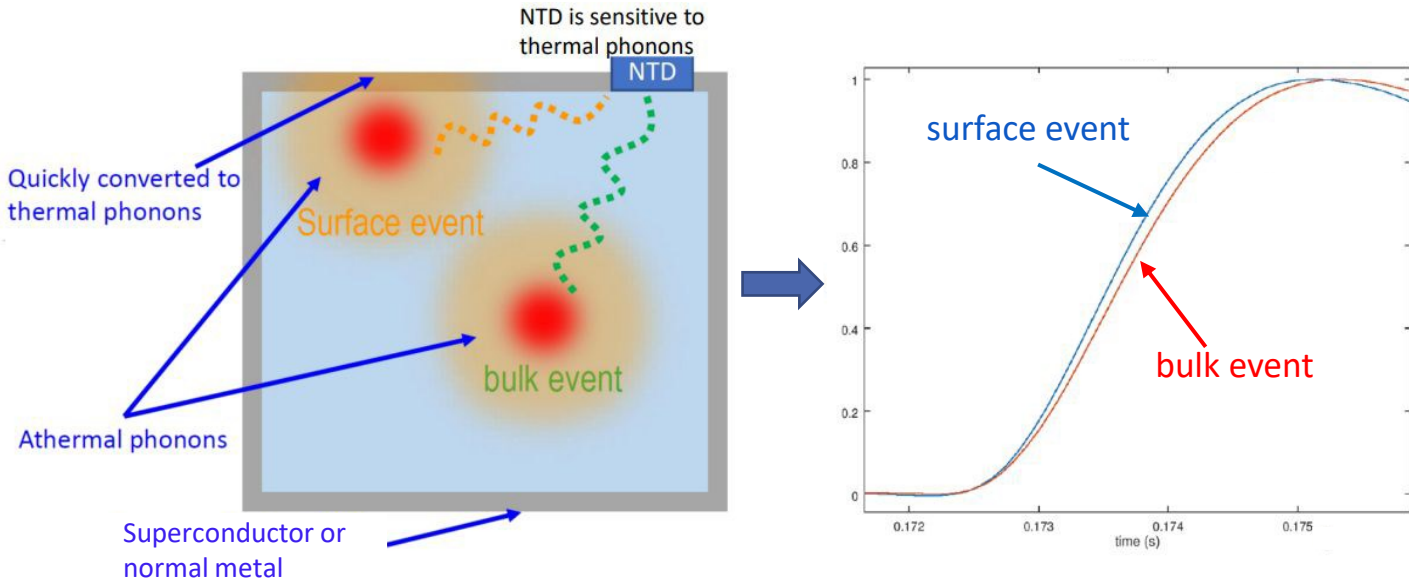


Operating temperatures: 10-30 mK

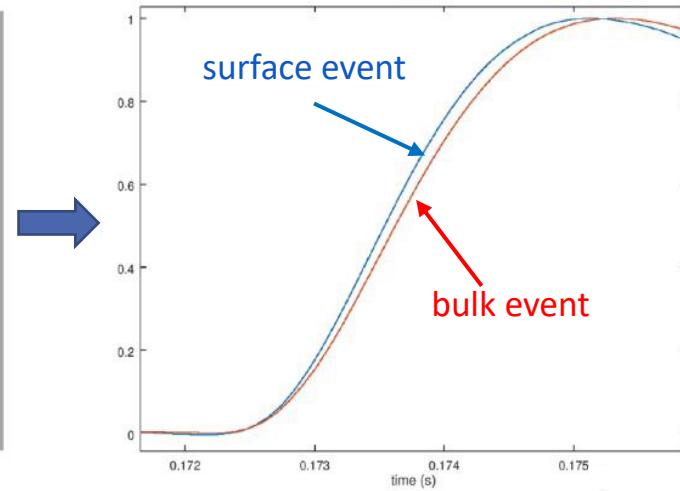
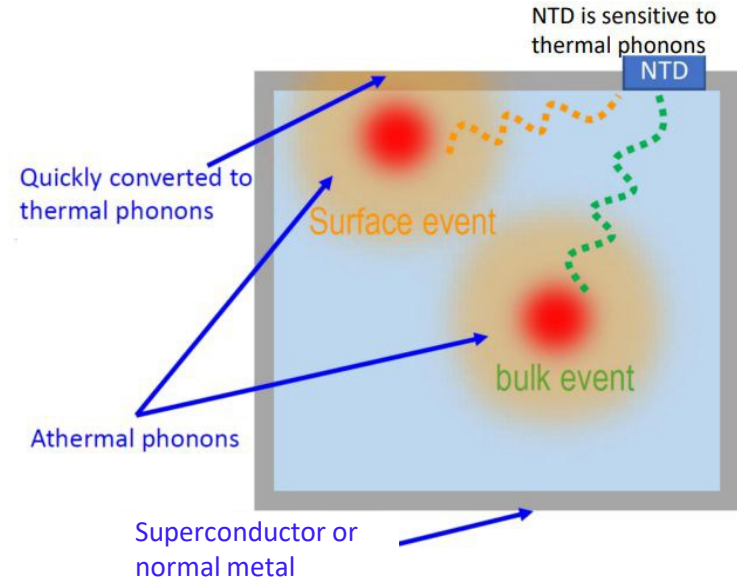
Cryogenic detectors properties:

- Good energy resolution $\sim 5\text{-}10 \text{ keV}$ at Q-value (3 MeV)
- Source = detector: high efficiency

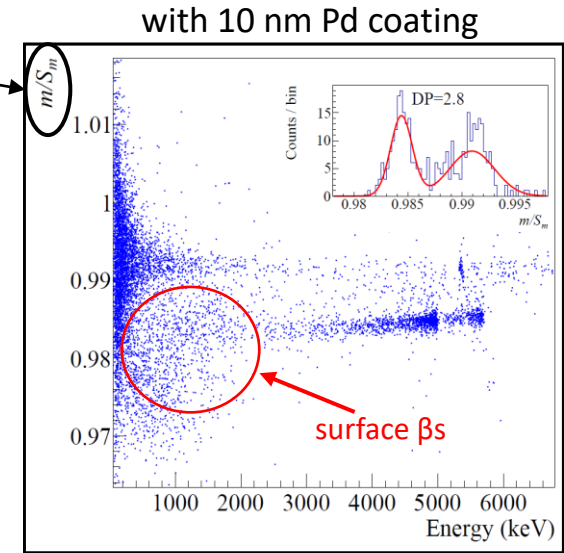
Cryogenic Rare-event Observatory with Surface Sensitivity



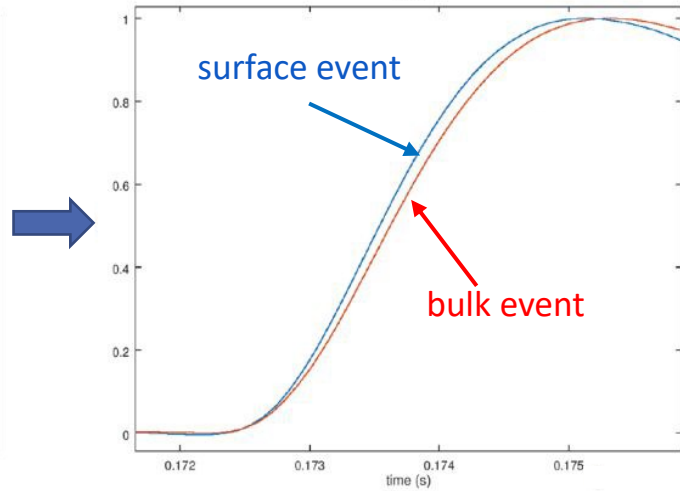
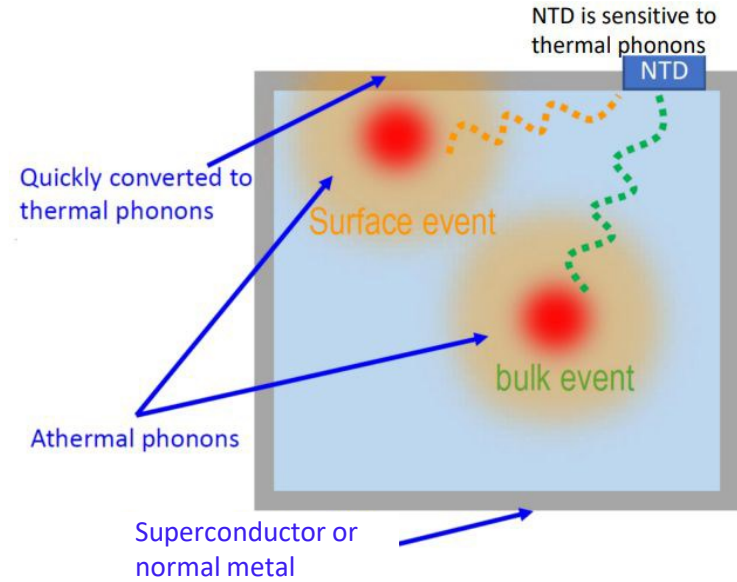
Cryogenic Rare-event Observatory with Surface Sensitivity



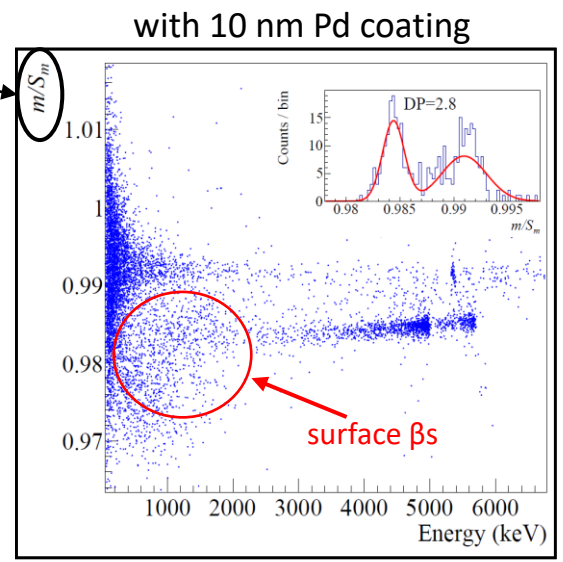
Pulse-shape discrimination parameter



Cryogenic Rare-event Observatory with Surface Sensitivity



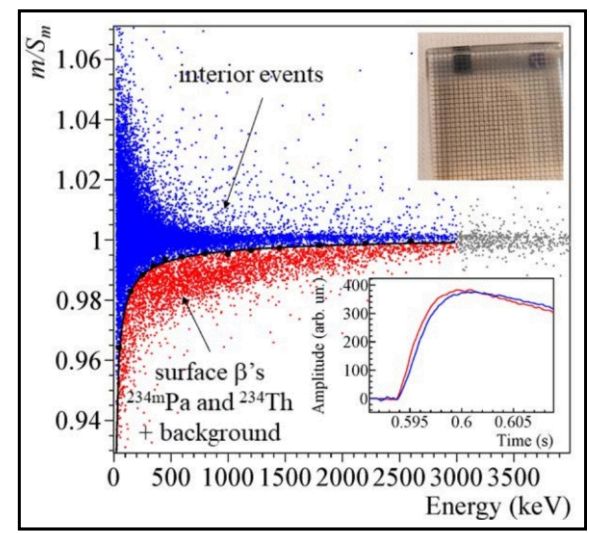
Pulse-shape discrimination parameter



Results obtained with small ($2 \times 2 \times 1 \text{ cm}^3$) Li_2MoO_4 crystals coated with Al-Pd grid:

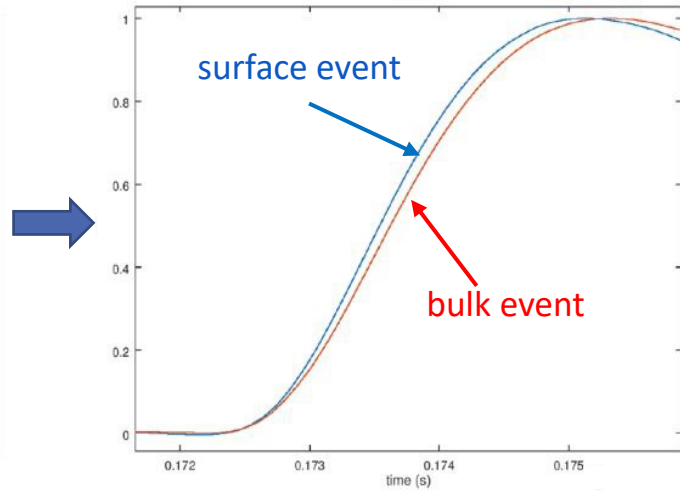
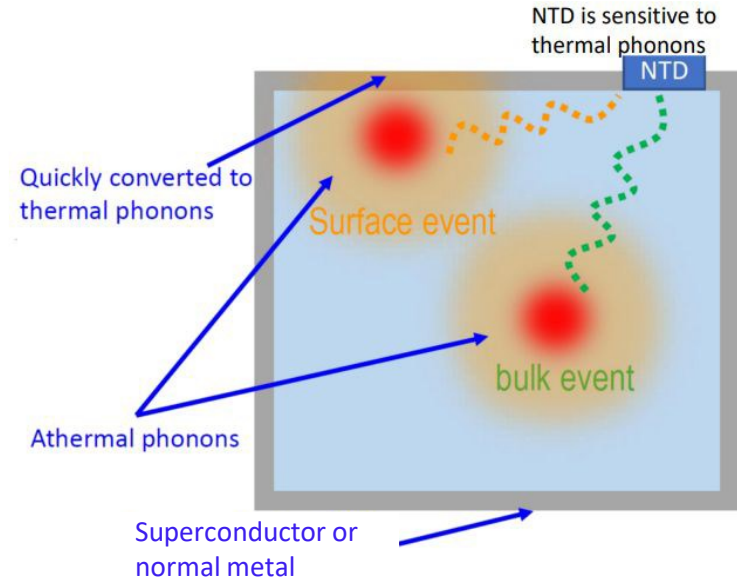
- Discrimination power (DP) of surface α 's $\geq 4.5\sigma$
- β surface events selection efficiency $\sim 93\%$
- Baseline resolution is not affected

$$DP = \frac{\mu_{\beta/\gamma} - \mu_{\alpha}}{\sqrt{\sigma_{\beta/\gamma}^2 + \sigma_{\alpha}^2}}$$

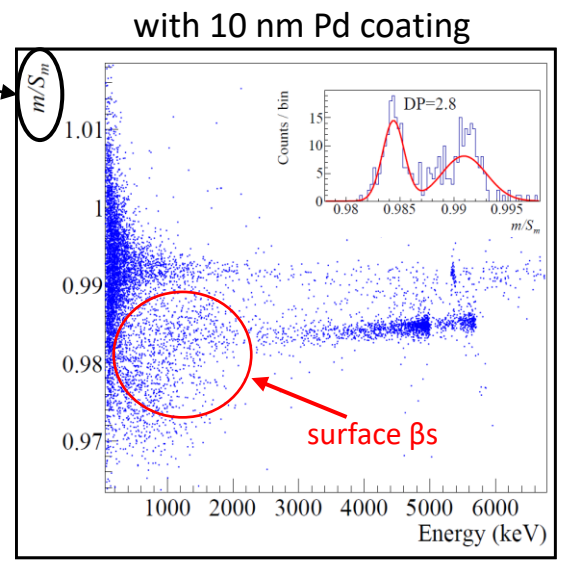


[Appl. Phys. Lett. 118, 184105 \(2021\)](#)

Cryogenic Rare-event Observatory with Surface Sensitivity



Pulse-shape discrimination parameter

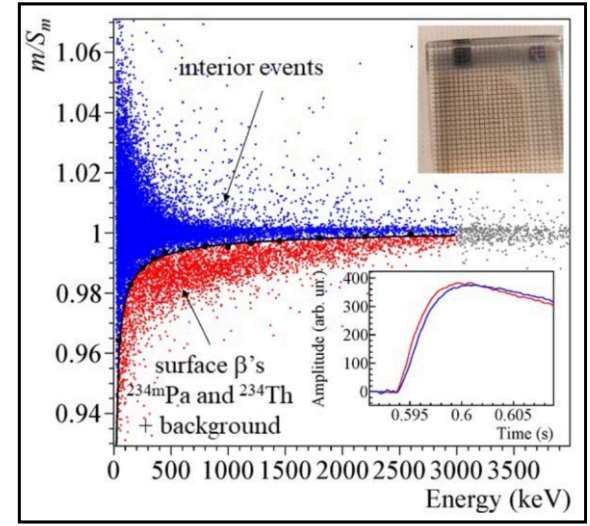


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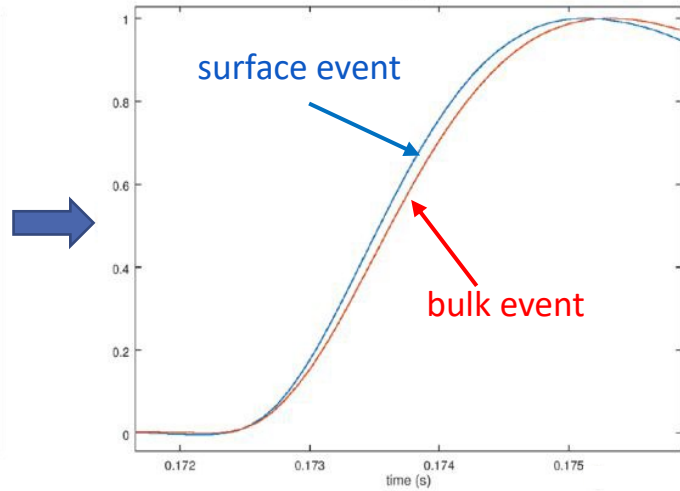
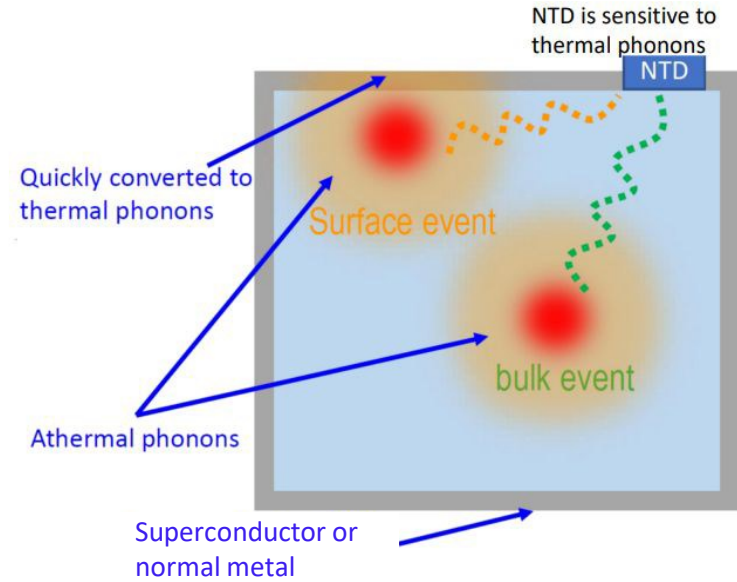
$$DP = \frac{\mu_{\beta/\gamma} - \mu_{\alpha}}{\sqrt{\sigma_{\beta/\gamma}^2 + \sigma_{\alpha}^2}}$$

Difficulties with transferring this technology to larger samples ($4.5 \times 4.5 \times 4.5 \text{ cm}^3$)

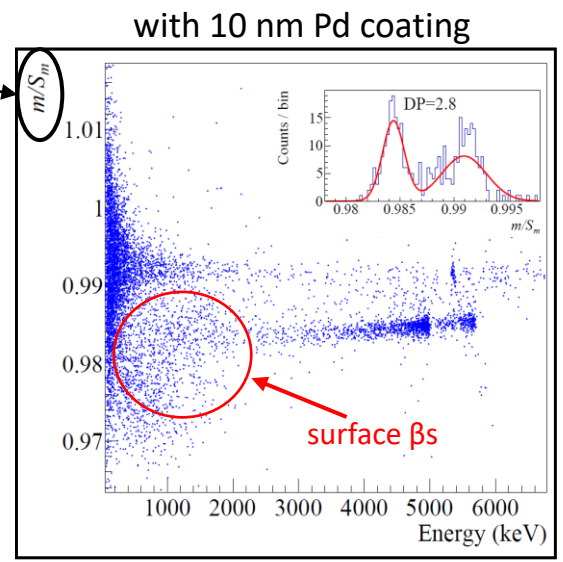


[Appl. Phys. Lett. 118, 184105 \(2021\)](#)

Cryogenic Rare-event Observatory with Surface Sensitivity



Pulse-shape discrimination parameter



Results obtained with small ($2 \times 2 \times 1 \text{ cm}^3$) Li_2MoO_4 crystals coated with Al-Pd grid:

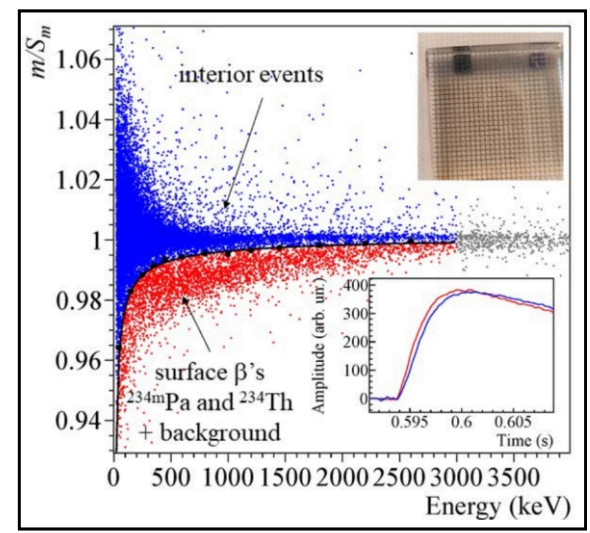
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Difficulties with transferring this technology to larger samples ($4.5 \times 4.5 \times 4.5 \text{ cm}^3$)

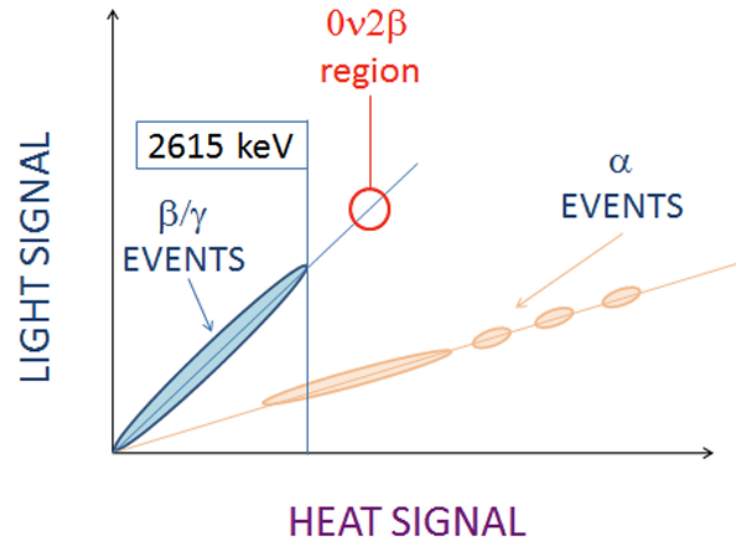
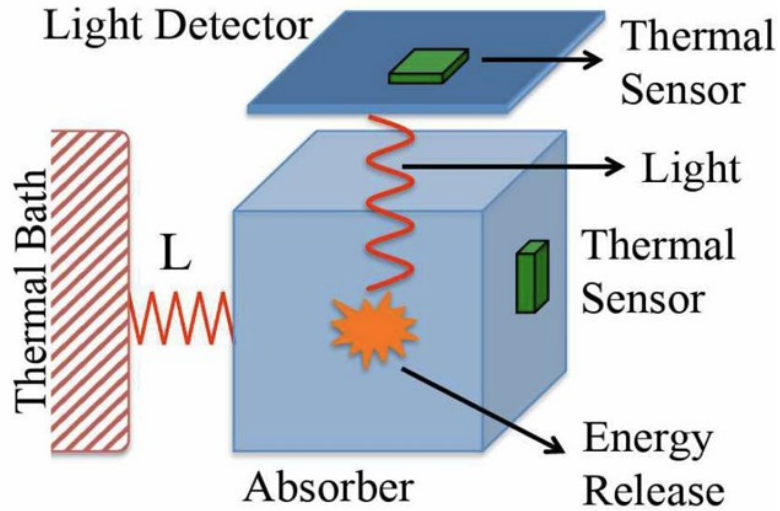
Technology is discarded from the final demonstrator **BUT** this will not affect its $0\nu\beta\beta$ sensitivity, because

- we are not limited by surface β 's background
- for α -s rejection -> **scintillating bolometers technique**



[Appl. Phys. Lett. 118, 184105 \(2021\)](#)

Scintillating bolometers technique



Technology proven in CUPID-0
and CUPID-Mo demonstrators

Rejection efficiency > 99.9%

[Eur.Phys.J.C 76 \(2016\) 364](#)

[Eur.Phys.J.C 80 \(2020\) 44](#)



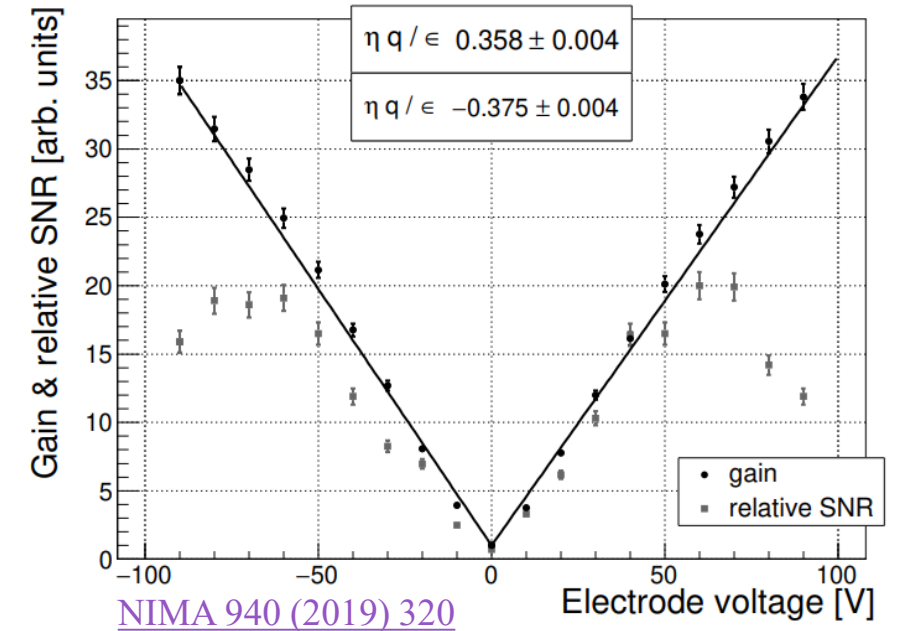
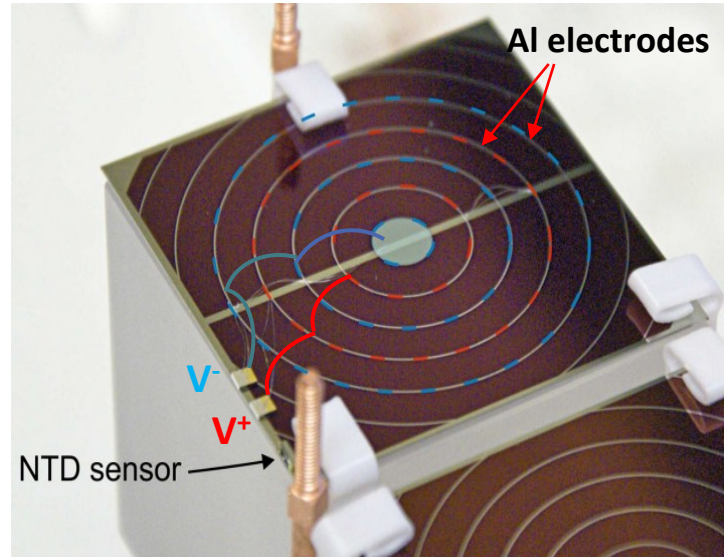
Rejection of α 's due to their lower
light yield compared to β/γ 's

Neganov-Trofimov-Luke (NTL) light detectors

Signal enhancement due to the extra heat produced by the drift of e-h pairs in the electric field (NTL effect)

$$\text{Total heat: } \mathbf{E}_{\text{tot}} = \mathbf{E}_0 \cdot \text{Gain}_{\text{NTL}}$$

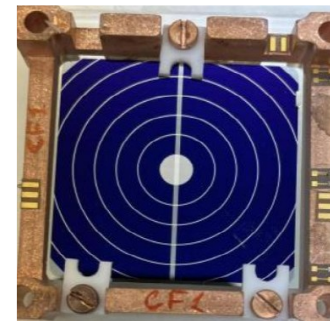
$$\text{Gain}_{\text{NTL}} \propto V_{\text{bias}} = V^+ - V^-$$



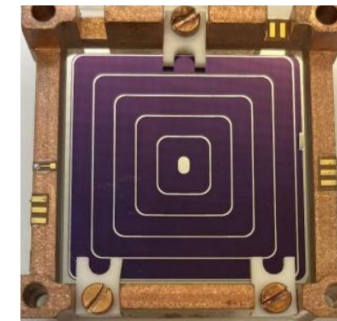
Material

- Si wafers
- Ge wafers with SiO coating to enhance light collection

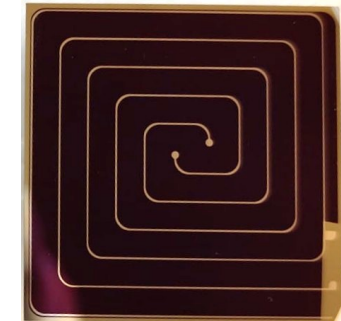
Electrodes geometry



circular

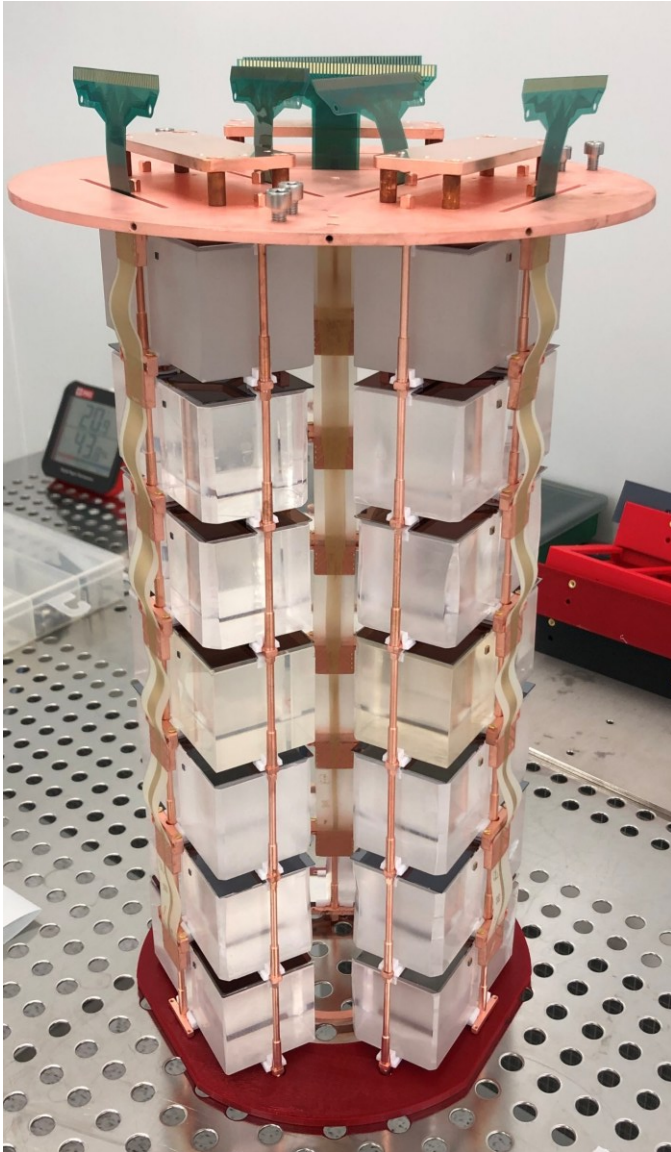


square



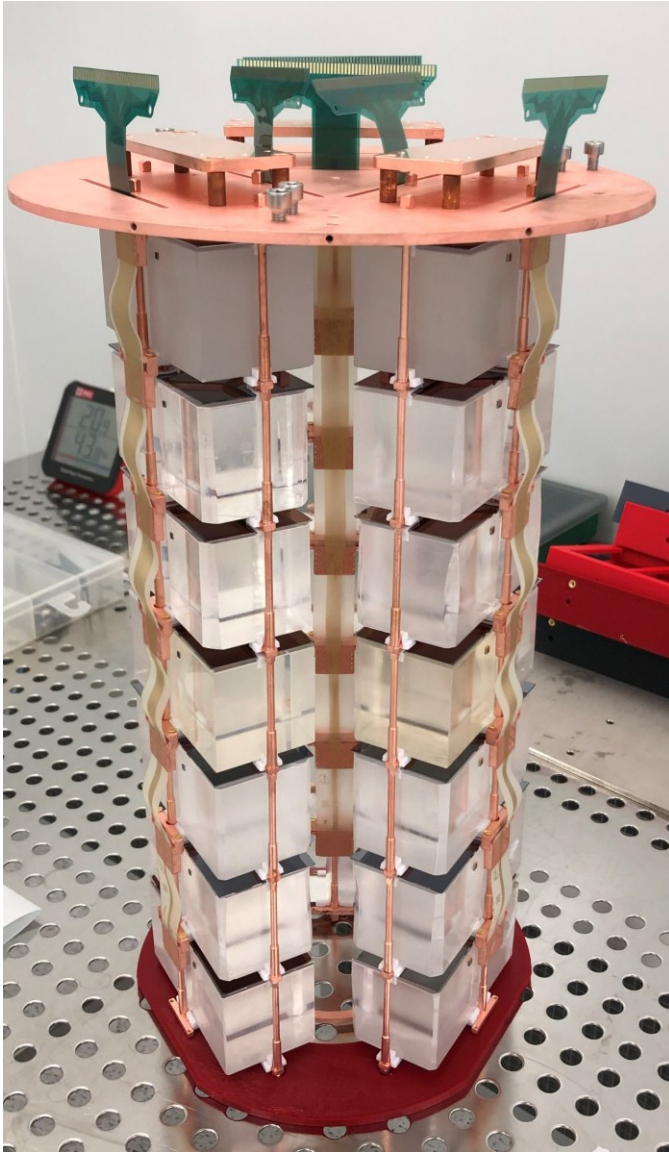
spiral

CROSS demonstrator



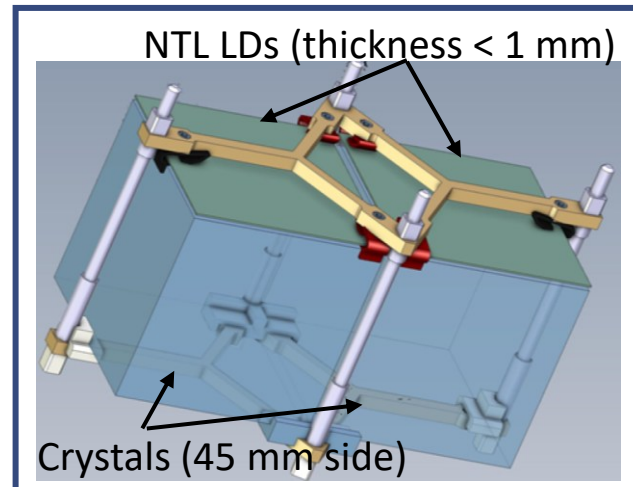
3 towers,
each with 14 crystals (7 floors)

CROSS demonstrator

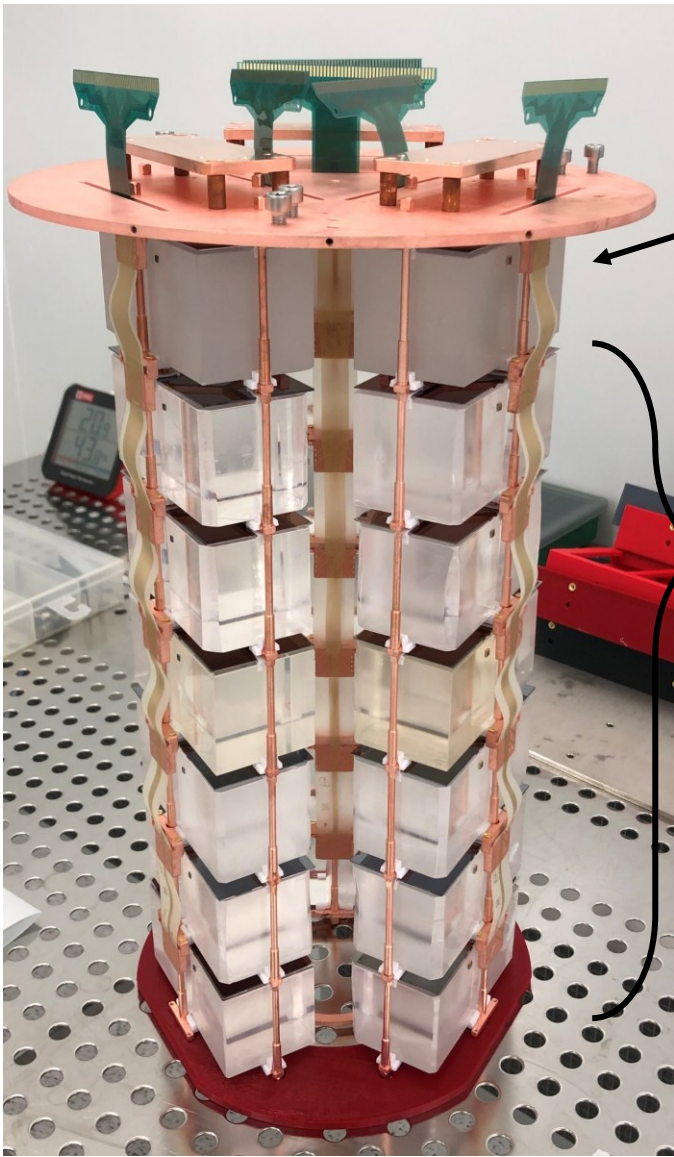


3 towers,
each with 14 crystals (7 floors)

Structure of the floor



CROSS demonstrator



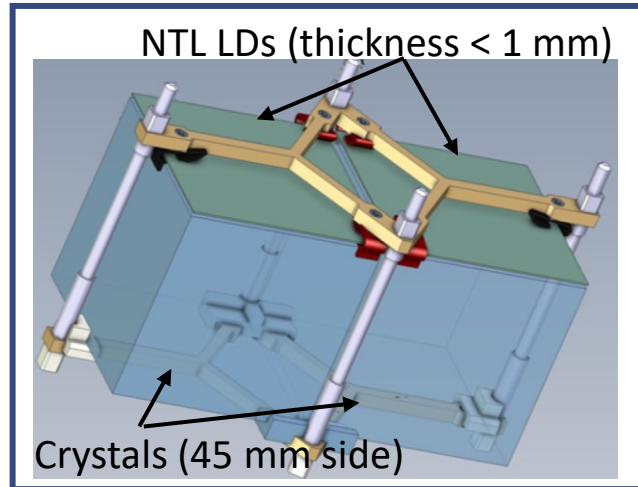
3 towers,
each with 14 crystals (7 floors)

2 $^{130}\text{TeO}_2$

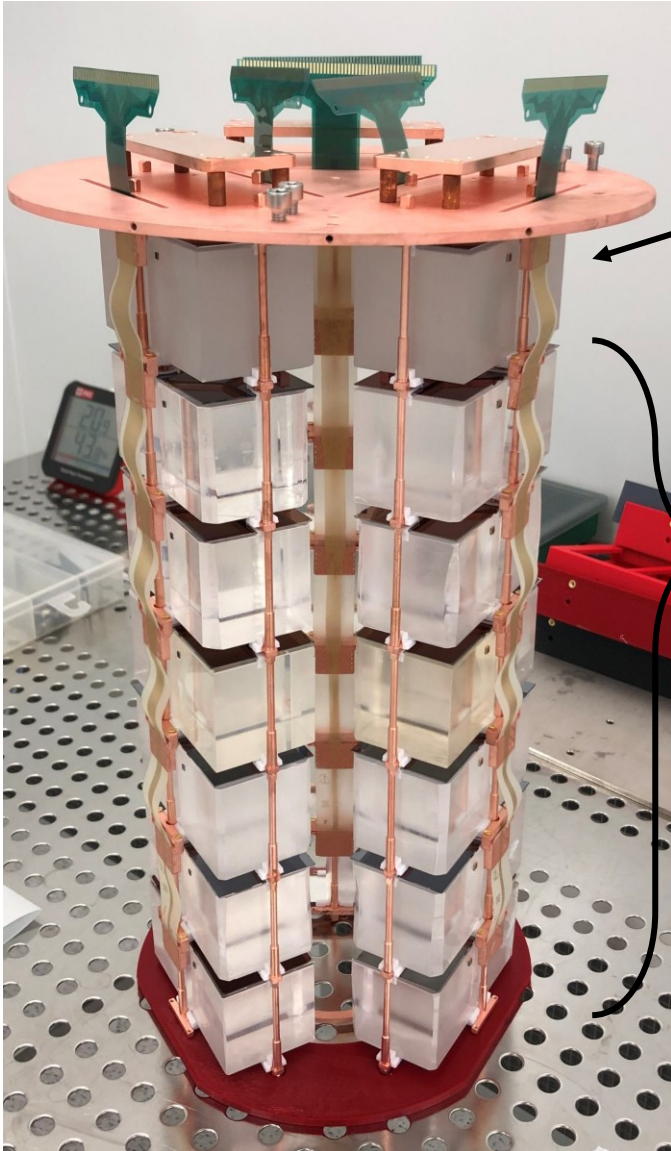
Work also as shielding due to
twice higher density compared
to Li_2MoO_4

12 Li_2MoO_4

Structure of the floor



CROSS demonstrator



3 towers,
each with 14 crystals (7 floors)

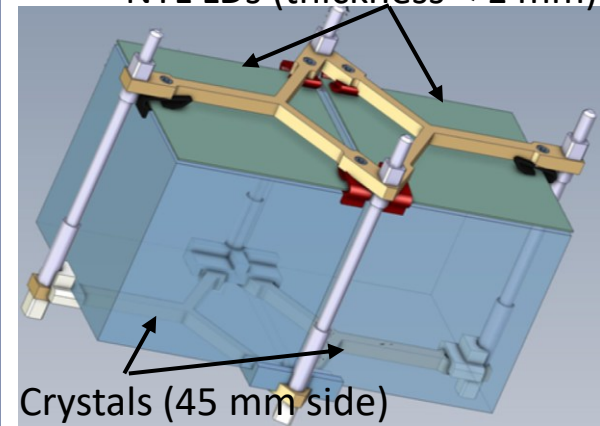
2 $^{130}\text{TeO}_2$

Work also as shielding due to
twice higher density compared
to Li_2MoO_4

12 Li_2MoO_4

Structure of the floor

NTL LDs (thickness < 1 mm)

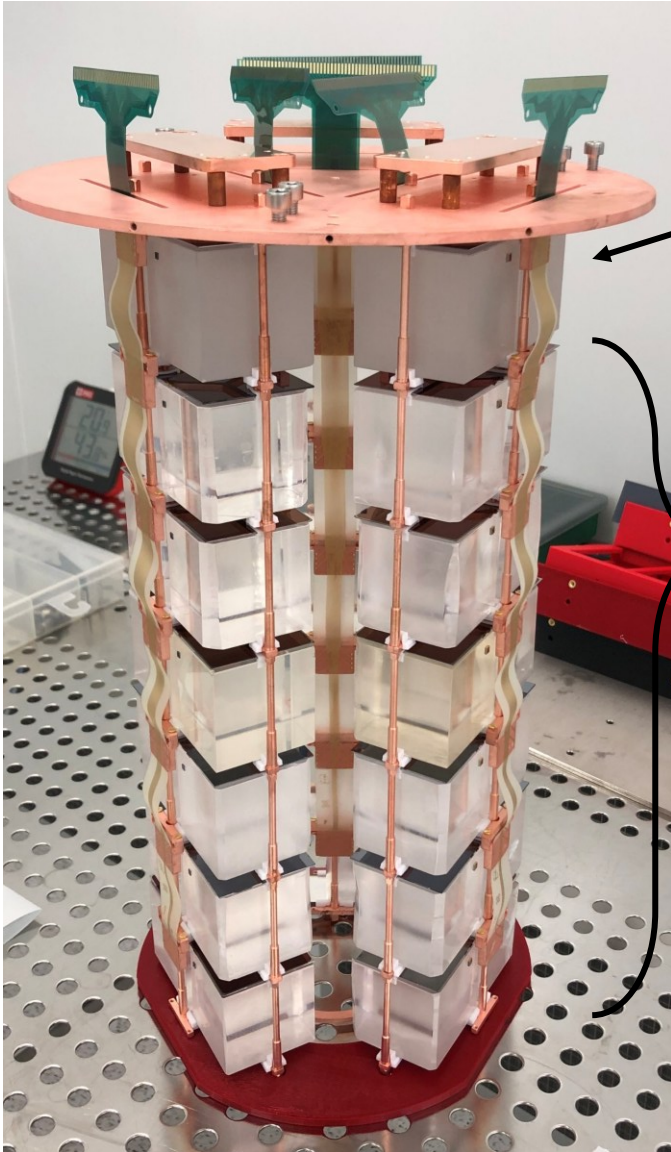


Crystals (45 mm side)

In total:

- 6 $^{130}\text{TeO}_2$ crystals (enrichment level >90%)
- 36 Li_2MoO_4
- 42 NTL LDs

CROSS demonstrator



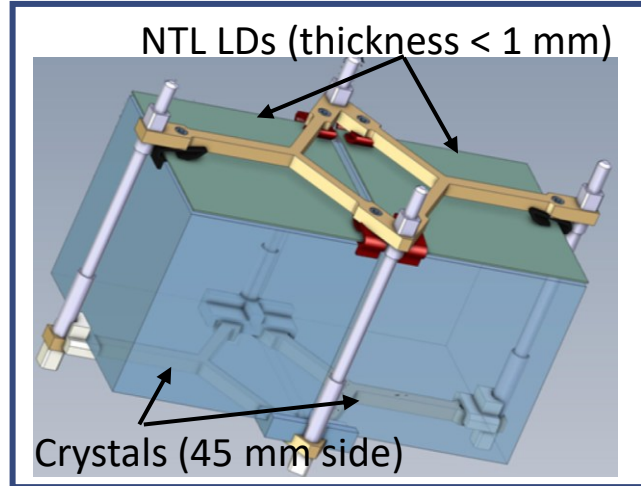
3 towers,
each with 14 crystals (7 floors)

2 $^{130}\text{TeO}_2$

Work also as shielding due to
twice higher density compared
to Li_2MoO_4

12 Li_2MoO_4

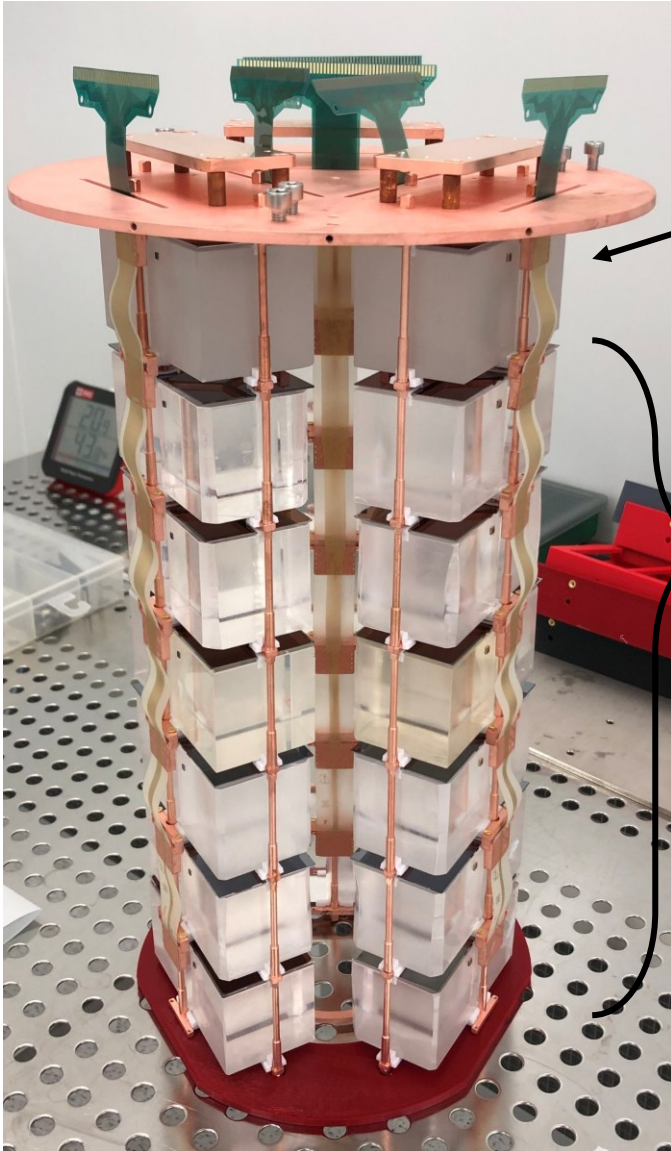
Structure of the floor



In total:

- 6 $^{130}\text{TeO}_2$ crystals (enrichment level >90%)
 - 32 enriched in ^{100}Mo (enrichment level >95%)
 - 2 natural Mo
 - 2 depleted in ^{100}Mo (for background studies)
- 42 NTL LDs

CROSS demonstrator



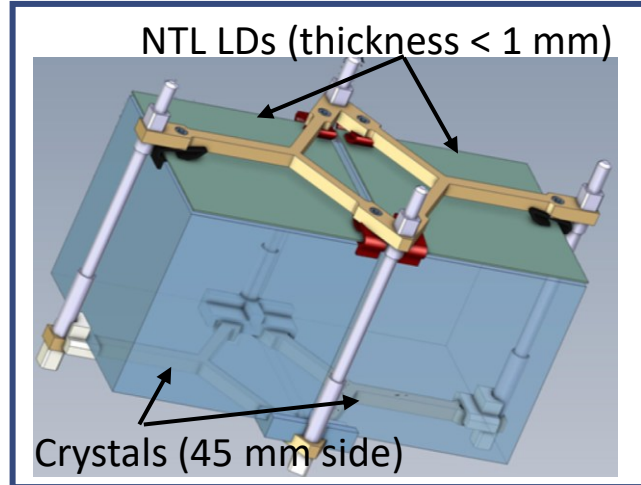
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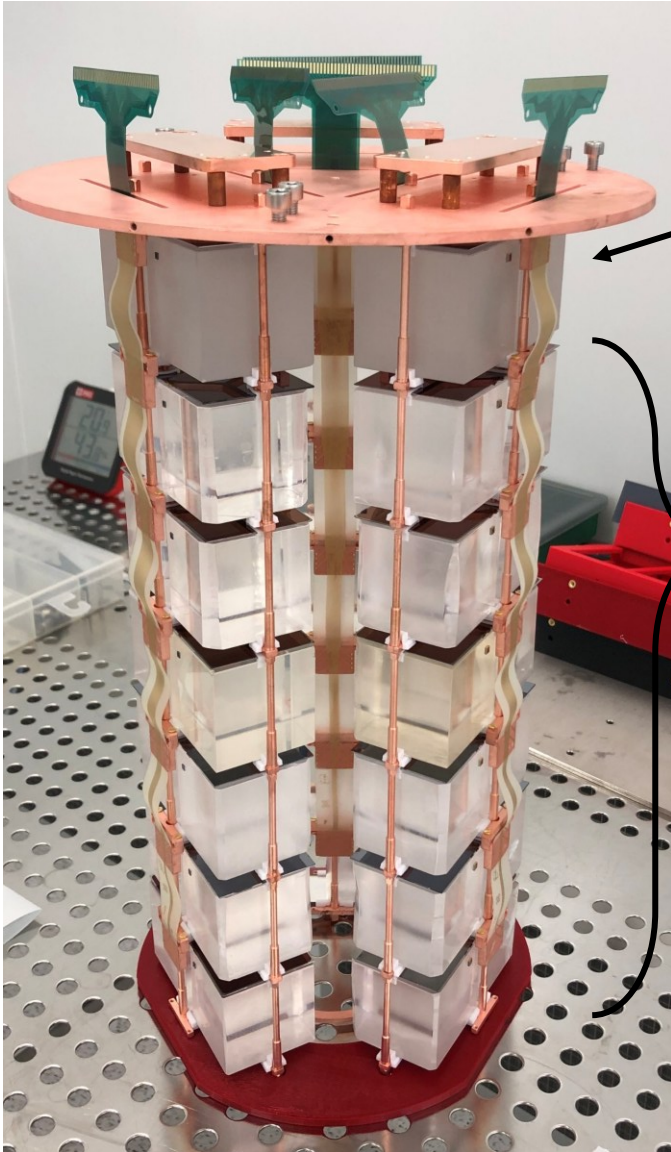
Structure of the floor



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 - 2 natural Mo
 - 2 depleted in ^{100}Mo (for background studies)
- 42 NTL LDs
 - 26 Germanium
 - 16 Silicon

CROSS demonstrator



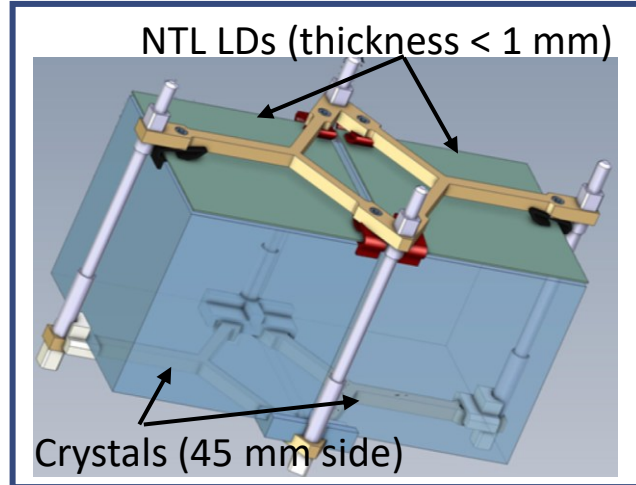
3 towers,
each with 14 crystals (7 floors)

2 $^{130}\text{TeO}_2$

Work also as shielding due to
twice higher density compared
to Li_2MoO_4

12 Li_2MoO_4

Structure of the floor



In total:

➤ 6 $^{130}\text{TeO}_2$ crystals (enrichment level >90%)

➤ 36 Li_2MoO_4

32 enriched in ^{100}Mo
(enrichment level >95%)

2 natural Mo

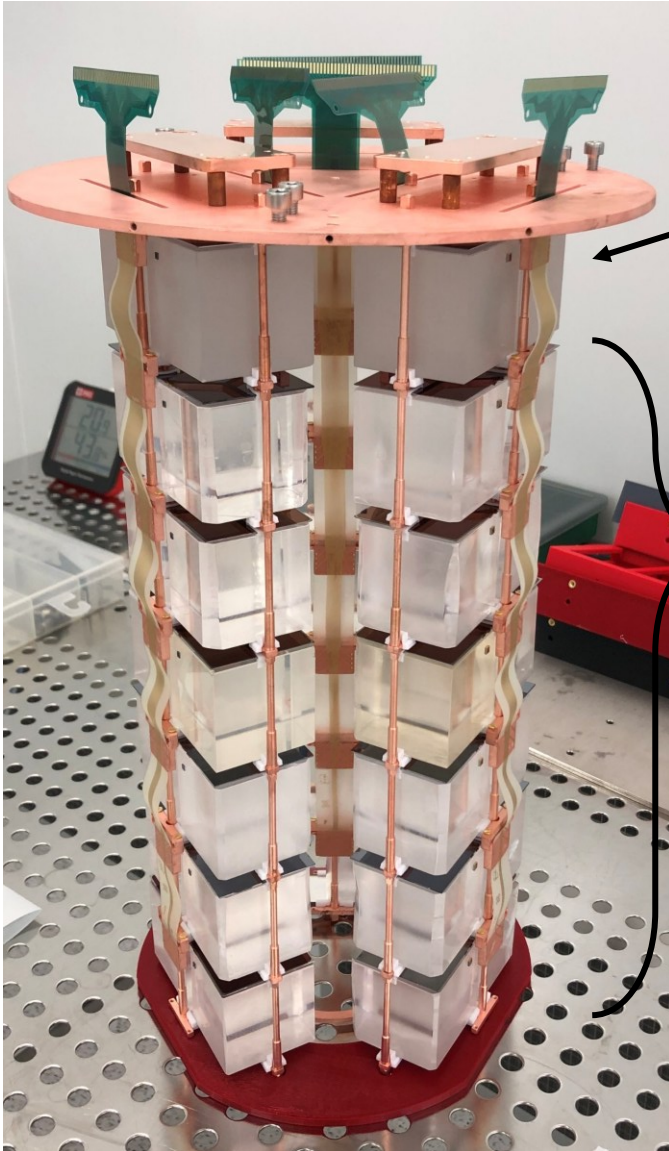
2 depleted in ^{100}Mo
(for background studies)

➤ 42 NTL LDs ➤ 26 Germanium
➤ 16 Silicon

Mass of ^{100}Mo : 4.9 kg

Mass of ^{130}Te : 3.0 kg

CROSS demonstrator



3 towers,
each with 14 crystals (7 floors)

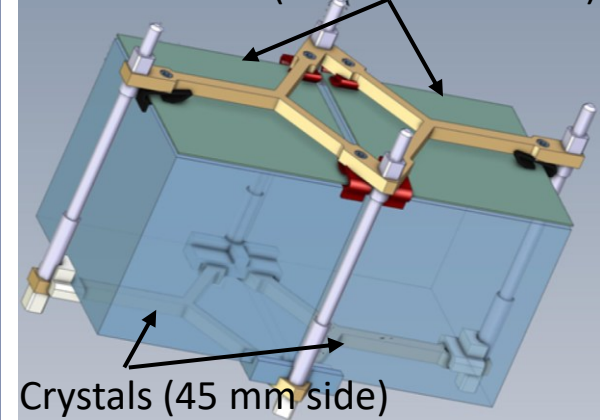
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12 Li_2MoO_4

Structure of the floor

NTL LDs (thickness < 1 mm)



Crystals (45 mm side)

In total:

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2 natural Mo

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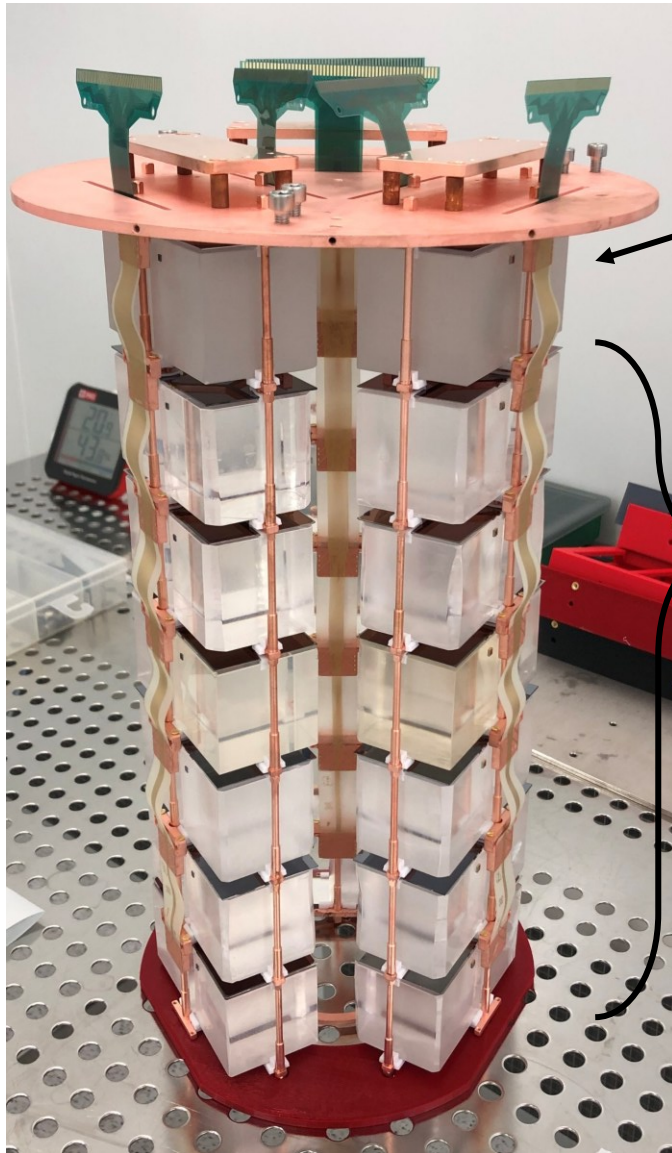
➤ 42 NTL LDs ➤ 26 Germanium
➤ 16 Silicon

Mass of ^{100}Mo : 4.9 kg

Mass of ^{130}Te : 3.0 kg

Location: Laboratorio Subterráneo de Canfranc
(LSC), Spain (2450 m. w. e.)

CROSS demonstrator



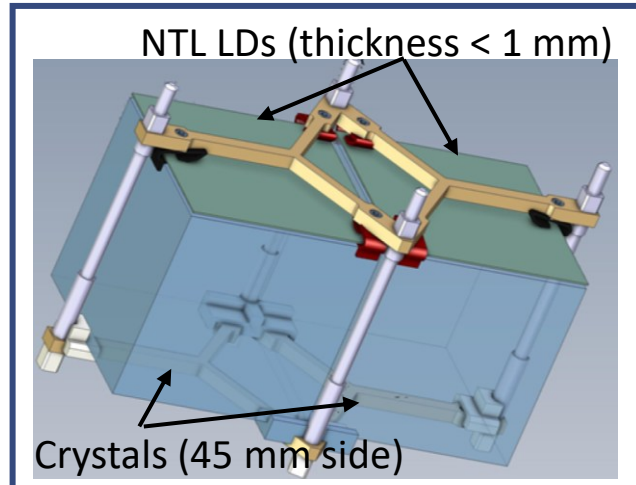
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each with 14 crystals (7 floors)

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Work also as shielding due to
twice higher density compared
to Li_2MoO_4

12 Li_2MoO_4

Structure of the floor



In total:

➤ 6 $^{130}\text{TeO}_2$ crystals (enrichment level >90%)

➤ 36 Li_2MoO_4

32 enriched in ^{100}Mo
(enrichment level >95%)

2 natural Mo

2 depleted in ^{100}Mo
(for background studies)

➤ 42 NTL LDs

26 Germanium

16 Silicon

Mass of ^{100}Mo : 4.9 kg

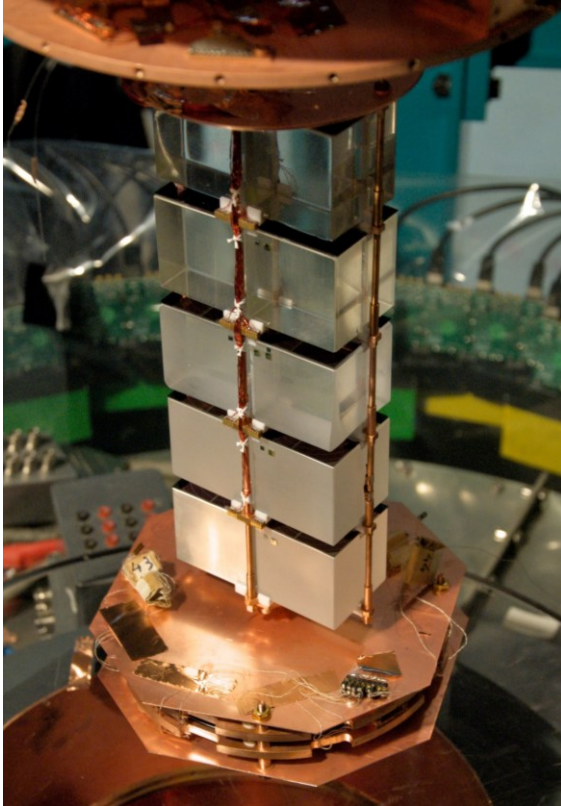
Mass of ^{130}Te : 3.0 kg

Location: Laboratorio Subterráneo de Canfranc (LSC), Spain (2450 m. w. e.)

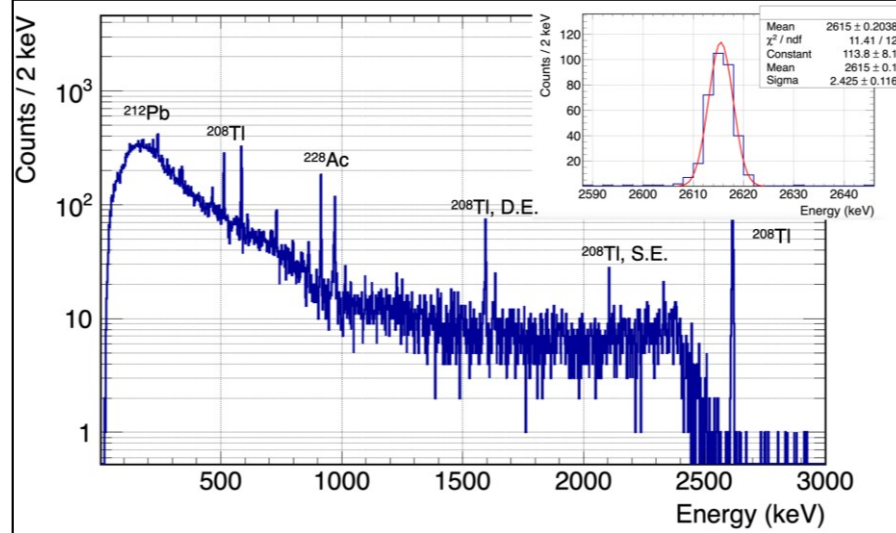
Underground facility:

- Pulse-tube based dilution refrigerator
- External and internal lead shielding
- Anti-radon system
- Muon veto

Recent results. Crystals performance

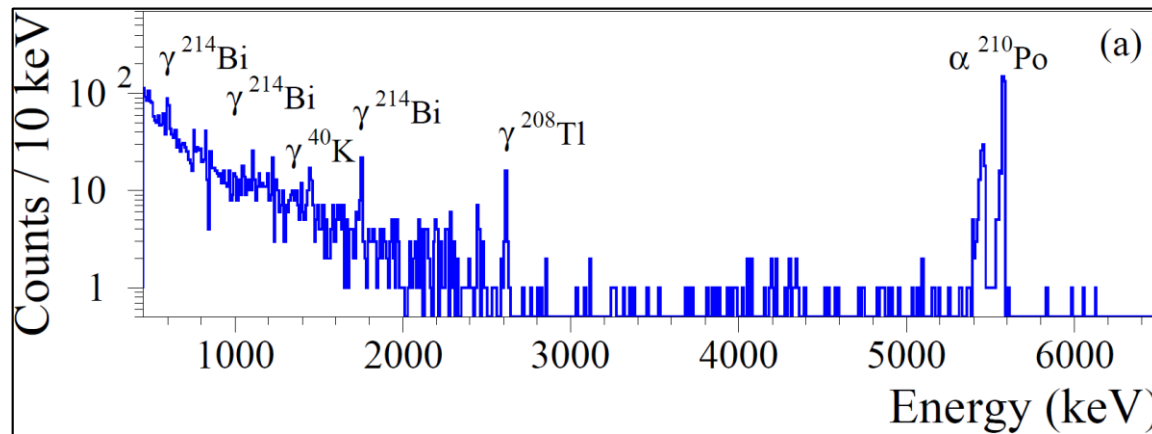


- $6 \text{ Li}_2\text{MoO}_4 + 4 \text{ }^{130}\text{TeO}_2$
- 10 NTL LD



Energy spectrum of the reference $\text{Li}_2^{100}\text{MoO}_4$ crystal

Energy resolution @ 2615 keV ^{208}Tl line is (5.7 ± 0.3) keV



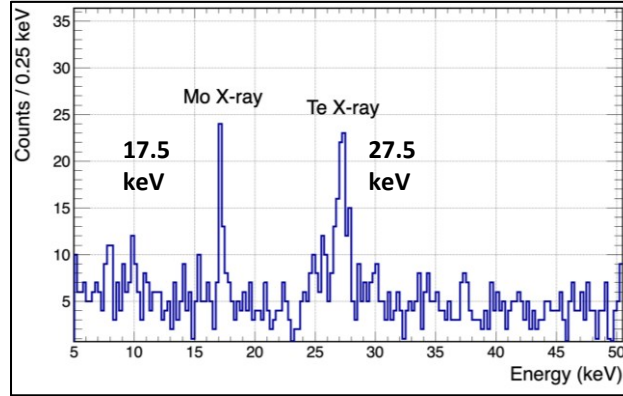
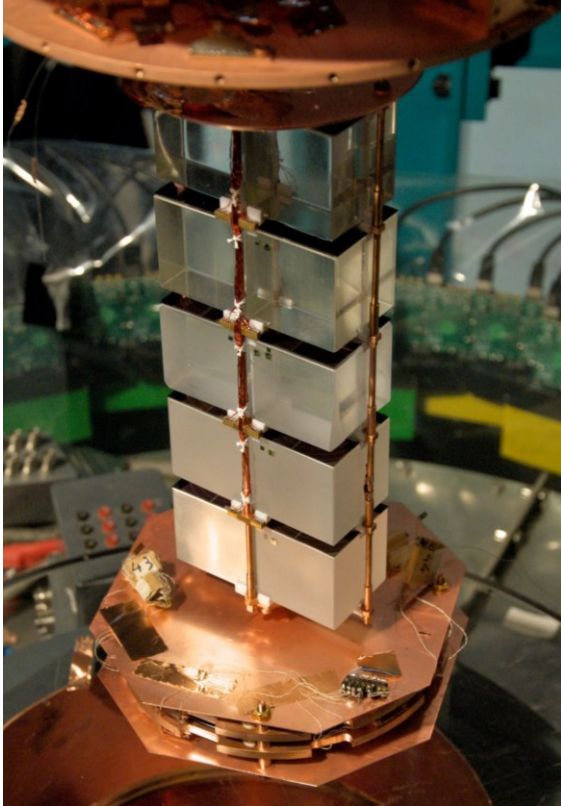
Background spectrum measured by a 0.55 kg $^{130}\text{TeO}_2$ bolometer (116 h at 27 mK) [JINST 19 \(2024\) 09, P09013](#)

Confirmation of the radiopurity of the $^{130}\text{TeO}_2$ crystals (~1 mBq/kg activity of ^{210}Po)

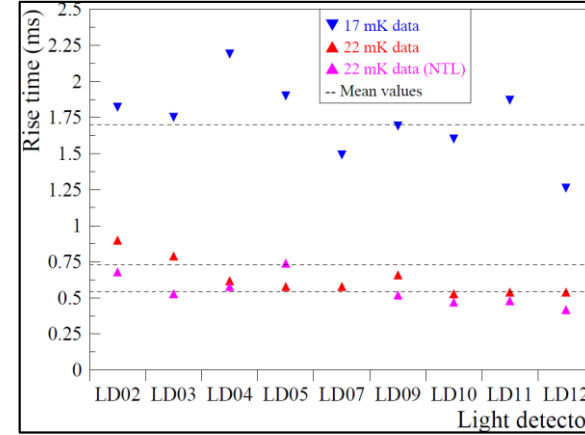
and

excellent energy resolution

Recent results. LDs performance



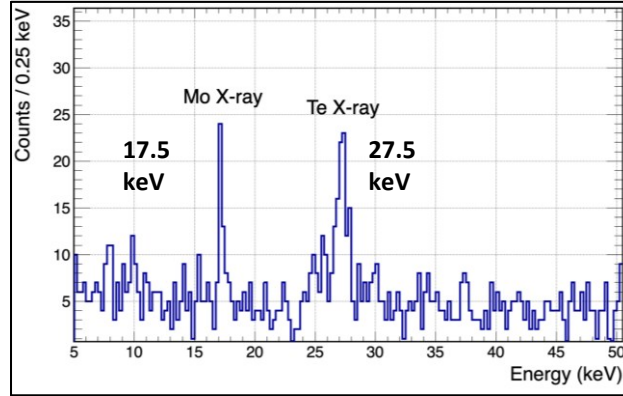
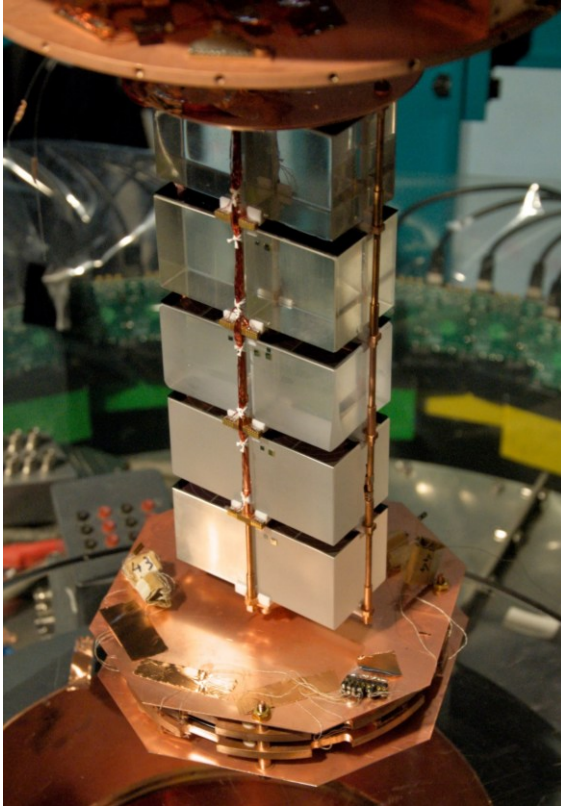
Energy spectrum accumulated by NTL LD after 83 h of calibrations with a Th source at 17 mK



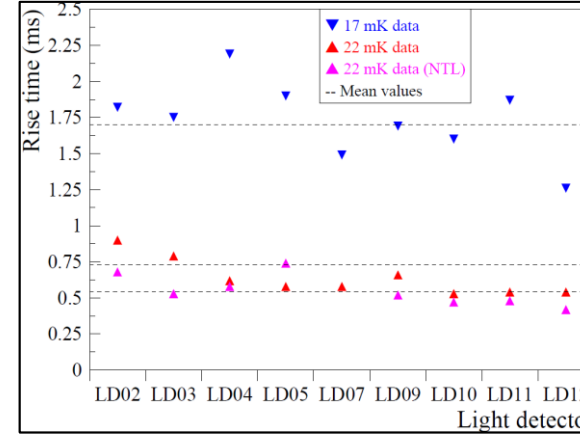
Mean value of
the risetime: **0.54 ms**
baseline resolution: $\sigma_{\text{bsl}} = 10 \text{ eV}$
(for measurements at 22 mK)

- $6 \text{ Li}_2\text{MoO}_4 + 4 \text{ }^{130}\text{TeO}_2$
- 10 NTL LD

Recent results. LDs performance

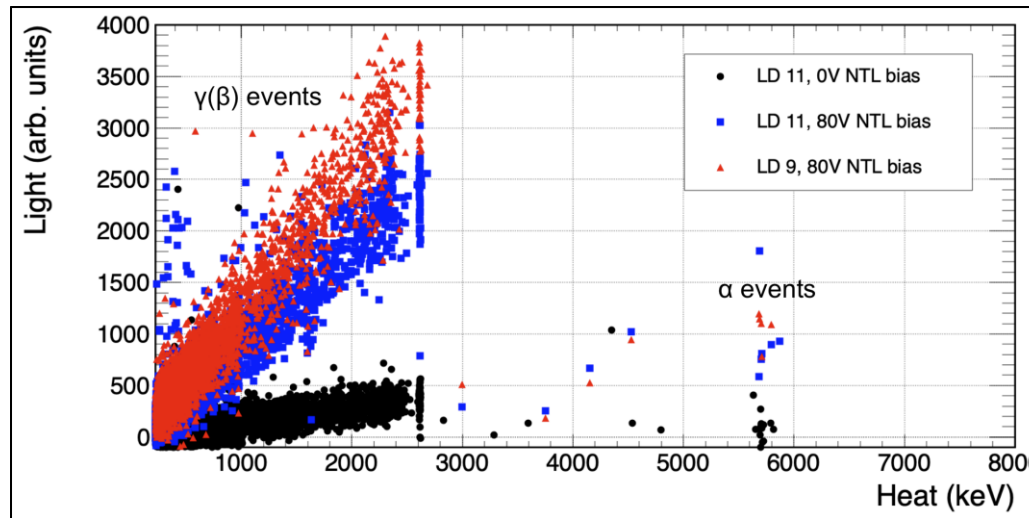


Energy spectrum accumulated by NTL LD after 83 h of calibrations with a Th source at 17 mK

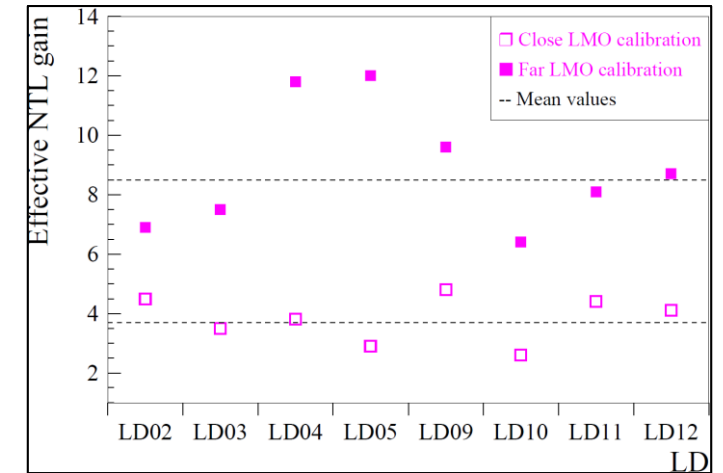


Mean value of
the risetime: **0.54 ms**
baseline resolution: $\sigma_{\text{bsl}} = 10 \text{ eV}$
(for measurements at 22 mK)

Good α 's rejection (>99.9%) and signal amplification



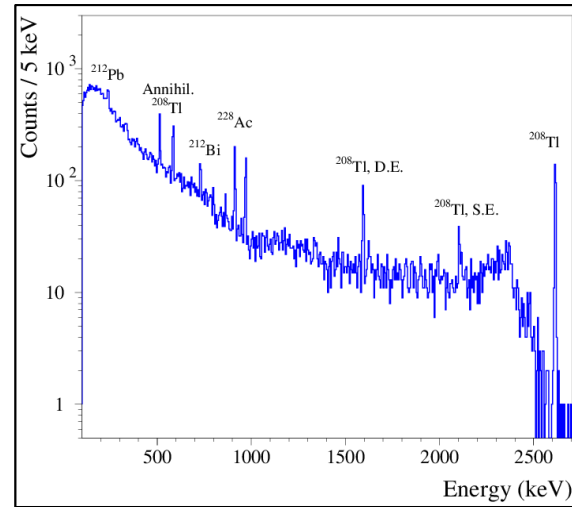
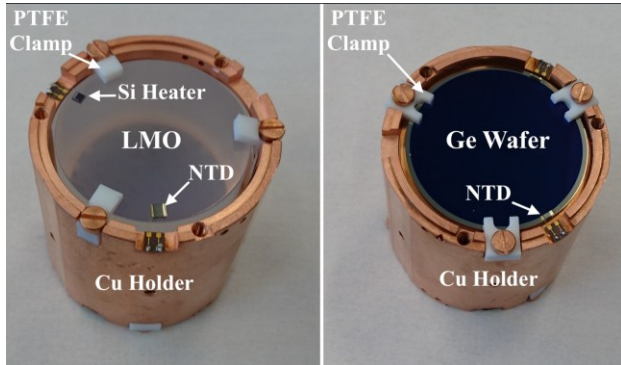
Energy detected in the top and bottom LDs facing the LMO crystal vs energy detected in the LMO (T = 22 mK)



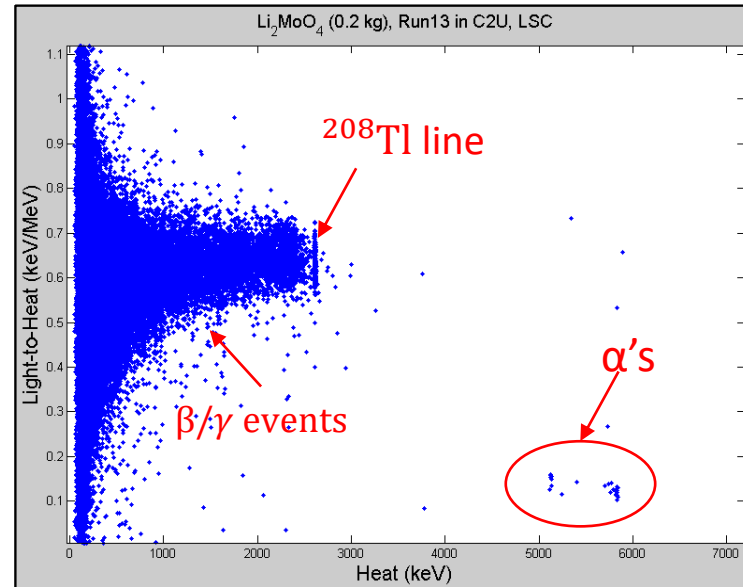
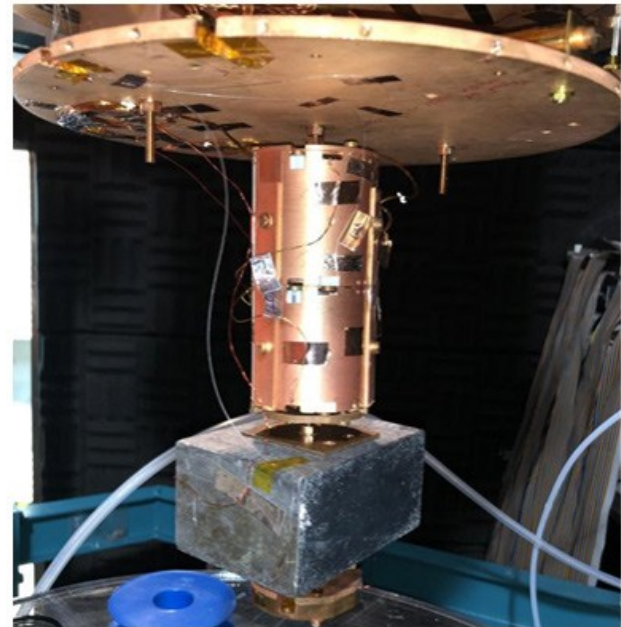
Mean value of the effective gain:
G = 8.5 when light impinges on the electrode side

- $6 \text{ Li}_2\text{MoO}_4 + 4 \text{ }^{130}\text{TeO}_2$
- 10 NTL LD

Validation of cryogenic setup: test with 2 CUPID-Mo modules



Energy spectrum from calibration run (78h)



Light to heat ratio vs heat

Crystal performance

| | Detector | FWHM @2615 keV (keV) |
|----------|---------------------|----------------------|
| CROSS | LMO-5 | 5.7(13) |
| | LMO-12 | 5.2(11) |
| CUPID-Mo | mean: 6.6 ± 0.1 | |

[Eur.Phys.J.C 82 \(2022\) 11, 1033](#)

LDs performance

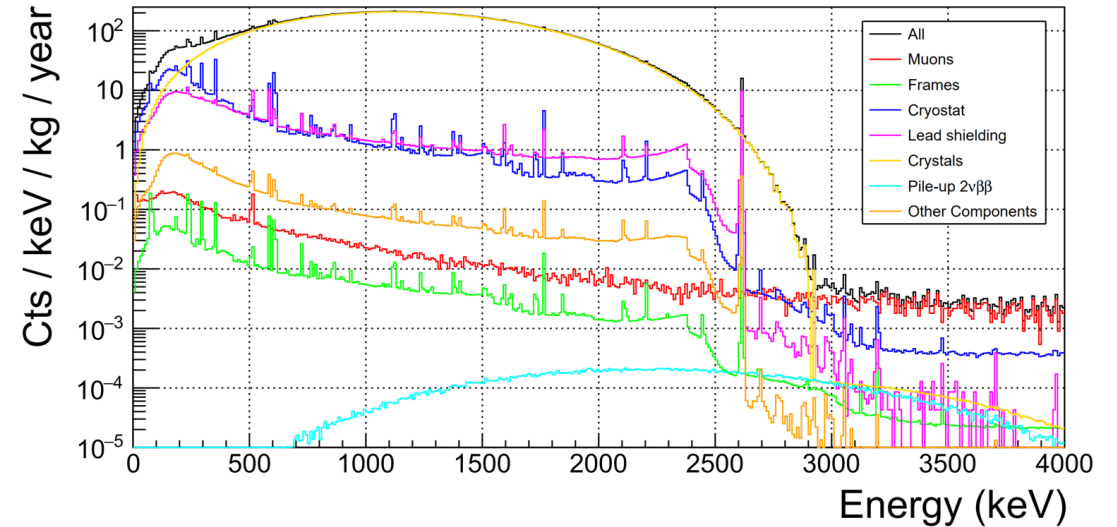
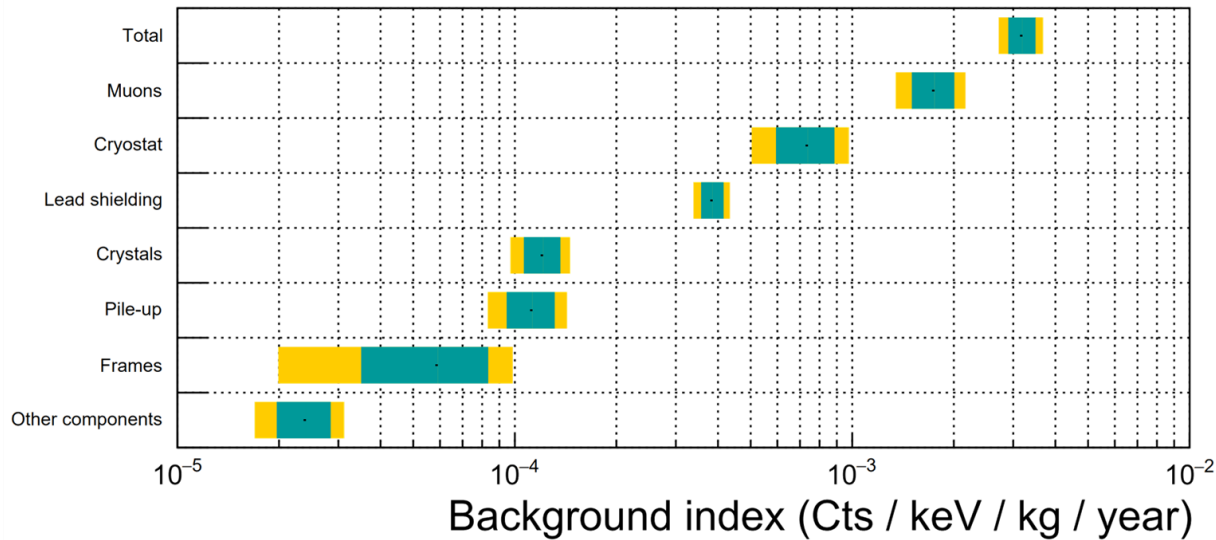
| | Detector | $\sigma_{baseline}$ [keV] |
|----------|----------|---------------------------|
| CROSS | LD-5 | 64 |
| | LD-12 | 72 |
| CUPID-Mo | LD-5 | 66 |
| | LD-12 | 69 |

[Eur.Phys.J.C 80 \(2020\) 44](#)

Background index and sensitivity



Total BI: $(3.2 \pm 0.5) \cdot 10^{-3}$ counts/keV/kg/year



Sensitivity:

Assuming 2 years live time, the CROSS experiment will be able to set a limit (at 90% C.L.) on the ^{100}Mo $0\nu\beta\beta$ decay:
 $T_{1/2}^{0\nu\beta\beta} > 9.36 \cdot 10^{24}$ yr, corresponding to $m_{\beta\beta} < (126 - 213)$ meV

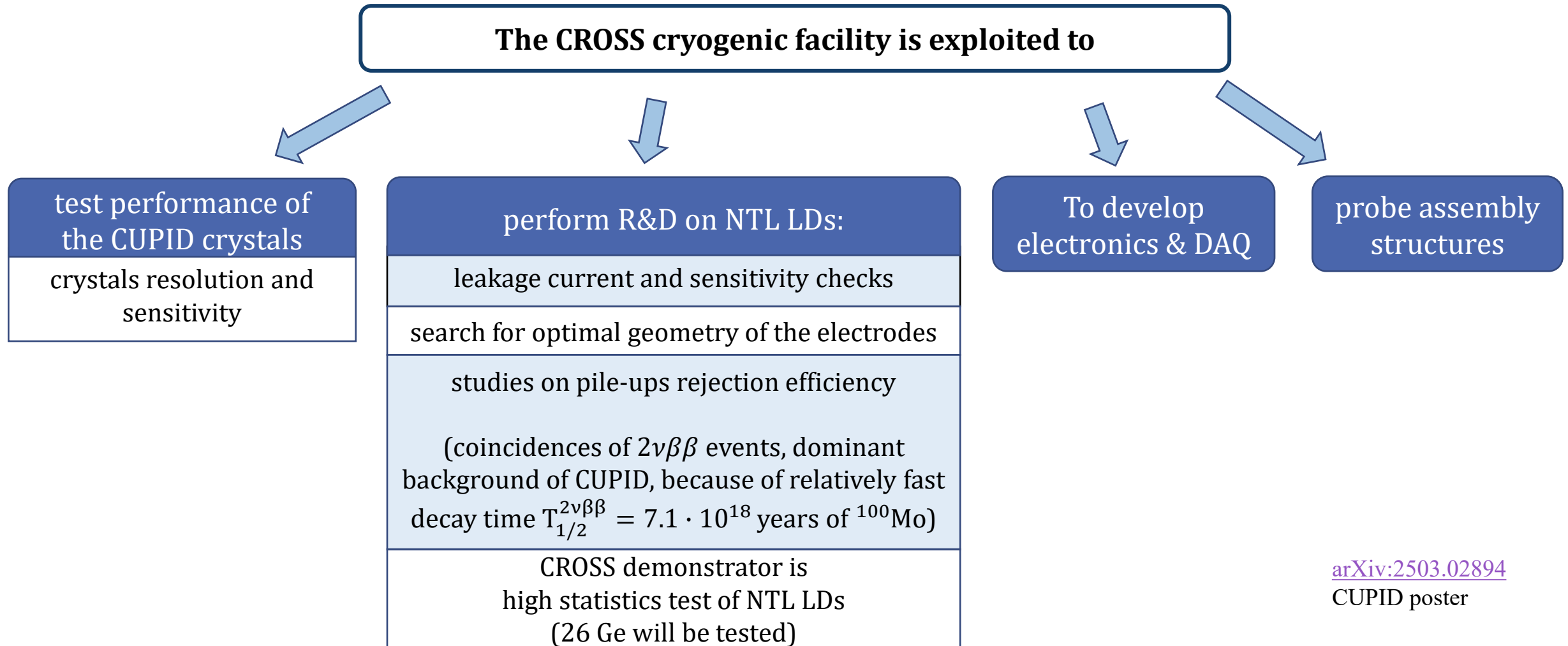
Current limits on ^{100}Mo $0\nu\beta\beta$:

- CUPID-Mo: half-life $T_{1/2}^{0\nu} > 1.8 \cdot 10^{24}$ yr
- AMORE-I: half-life $T_{1/2}^{0\nu} > 2.9 \cdot 10^{24}$ yr

CUPID and CROSS interplay



CUPID (CUORE upgrade with Particle Identification) is a future ton-scale experiment to search for $0\nu\beta\beta$ decay in ^{100}Mo , using scintillating bolometers technique.



[arXiv:2503.02894](https://arxiv.org/abs/2503.02894)
CUPID poster

CROSS is developing new technologies to reduce background noise in $0\nu 2\beta$ decay detection using bolometers and advanced NTL light detectors

NTL LDs

- demonstrate excellent energy resolution: $\sigma_{\text{bsl}} = 10$ eV
- good discrimination of α 's
- signals with the rise time ~ 0.5 ms were achieved, that together with high SNR due to NTL effect and geometry improvement allows to better reject pile-up events

Crystals

- LMOs show excellent energy resolution (FWHM ~ 5 -6 keV at 2615 keV)
- high radiopurity of $^{130}\text{TeO}_2$ crystals together with good energy resolution is confirmed

Preparation for the CROSS demonstrator is ongoing. Test with CUPID-Mo modules validated that cryogenic setup is ready for the final demonstrator.

CROSS demonstrator is a competitive experiment on the ^{100}Mo $0\nu\beta\beta$

CROSS underground facility at LSC

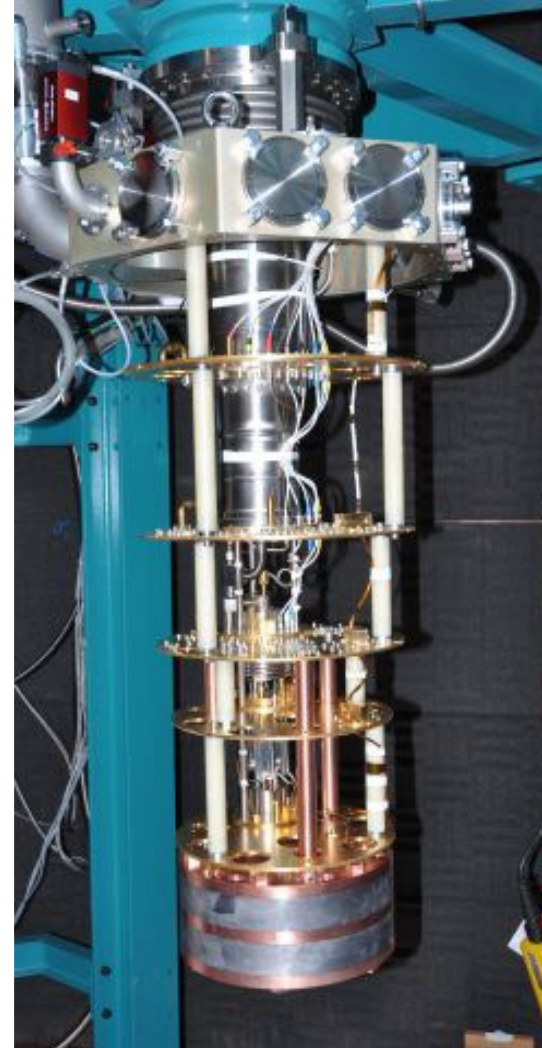


Cryostat installed and commissioned in April 2019

Passive shields:

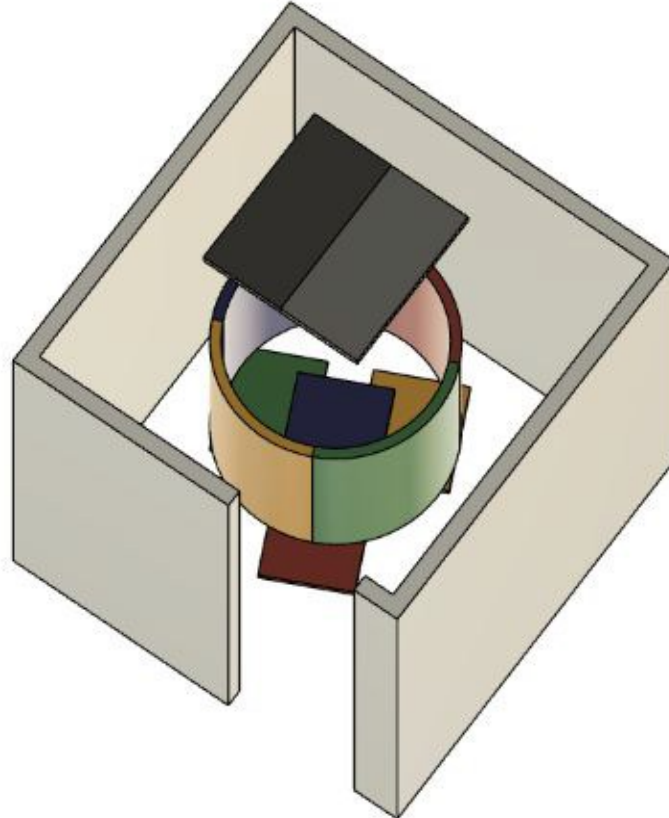
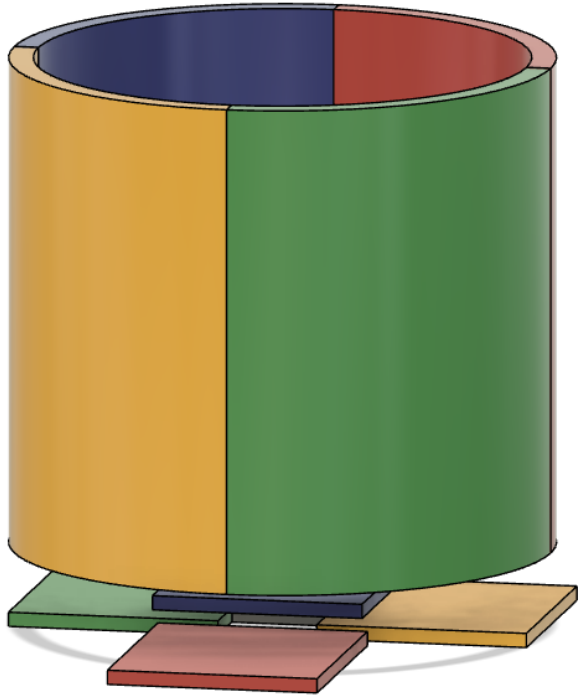
- antiradon shield
- external lead shielding
- internal lead shielding

Active: muon veto system

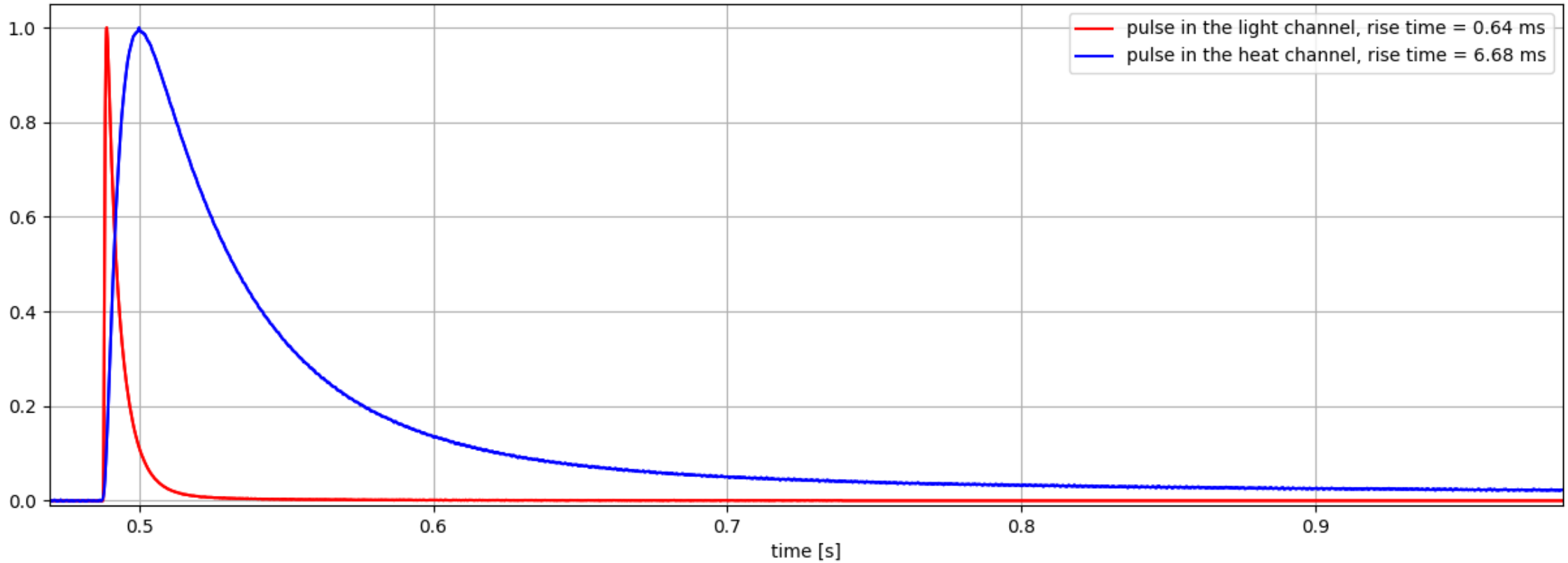


CROSS muon veto system

- Made of plastic scintillators
- SiPMs as light detectors
- 9 sectors (4 lateral + 4 bottom + 1 top)



Example of the pulses in light and heat channels

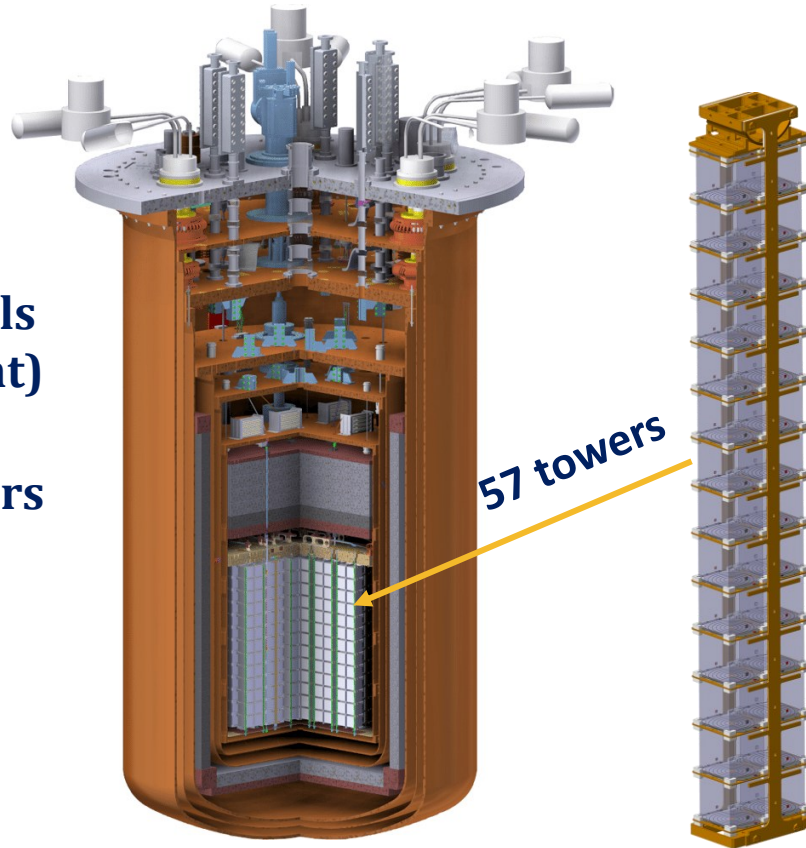


CUPID structure

1596 enriched $\text{Li}_2^{100}\text{MoO}_4$ crystals
(>95% enrichment)

1710 light detectors

240 kg of ^{100}Mo



CUORE cryostat and shielding

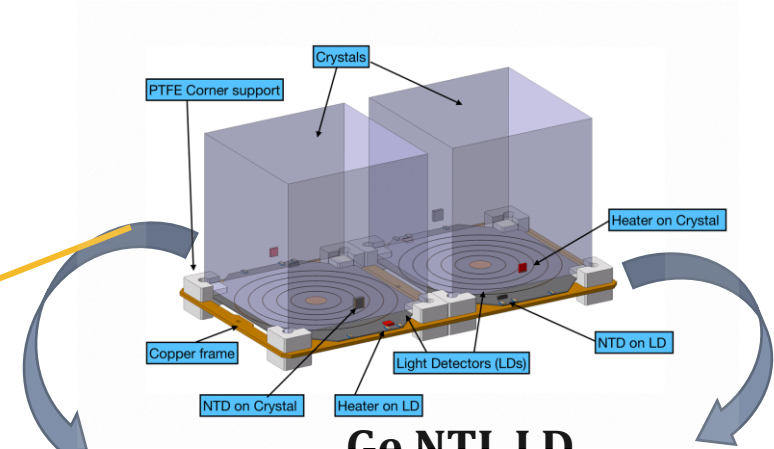
+ muon-veto system
& neutron shields

14 floors
each with
2 crystals

57 towers

$\text{Li}_2^{100}\text{MoO}_4$ crystal

- $45 \times 45 \times 45 \text{ mm}^3$
- Thermal sensor:
NTD Ge thermistor



Ge NTL LD

- Thin Ge wafer (<1 mm thickness)
- Thermal sensor: NTD Ge thermistor
- SiO antireflective coating
(enhances light collection by ~ 30 %)
- Exploiting Neganov-Trofimov-Luke
effect for signal amplification