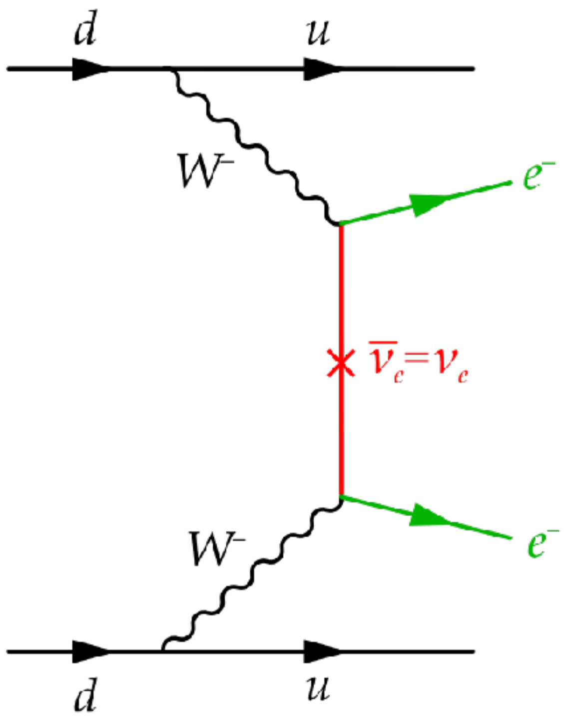
Double-beta decay searches with cryogenic detectors: R&Ds for CUPID and beyond

Zolotarova Anastasiia

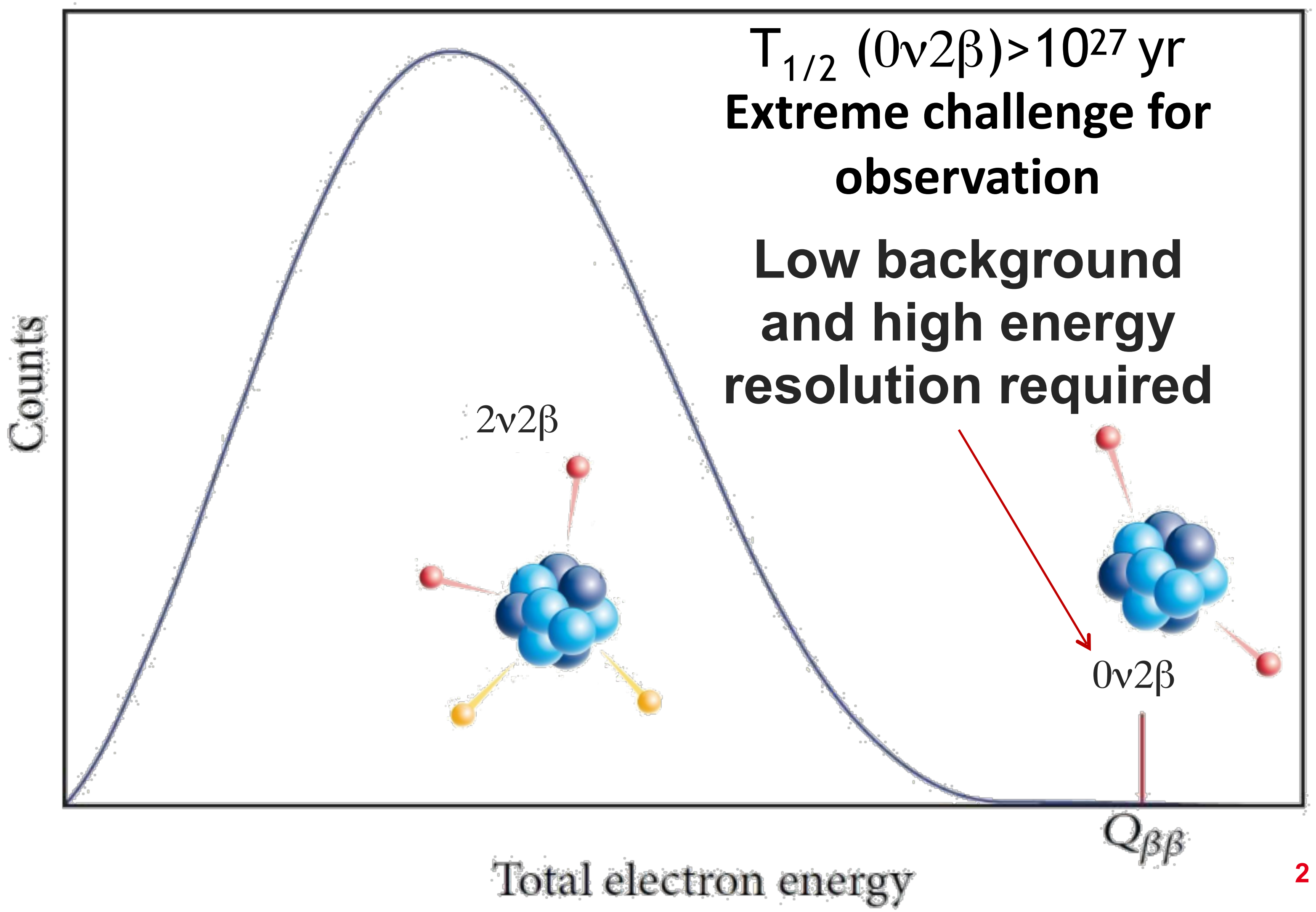
Neutrinoless double beta decay

$(A,Z) \rightarrow (A,Z+2) + 2e^-$



Total lepton number violation →
new physics beyond SM

Few isotopes can undergo this transition



0ν2β decay candidates

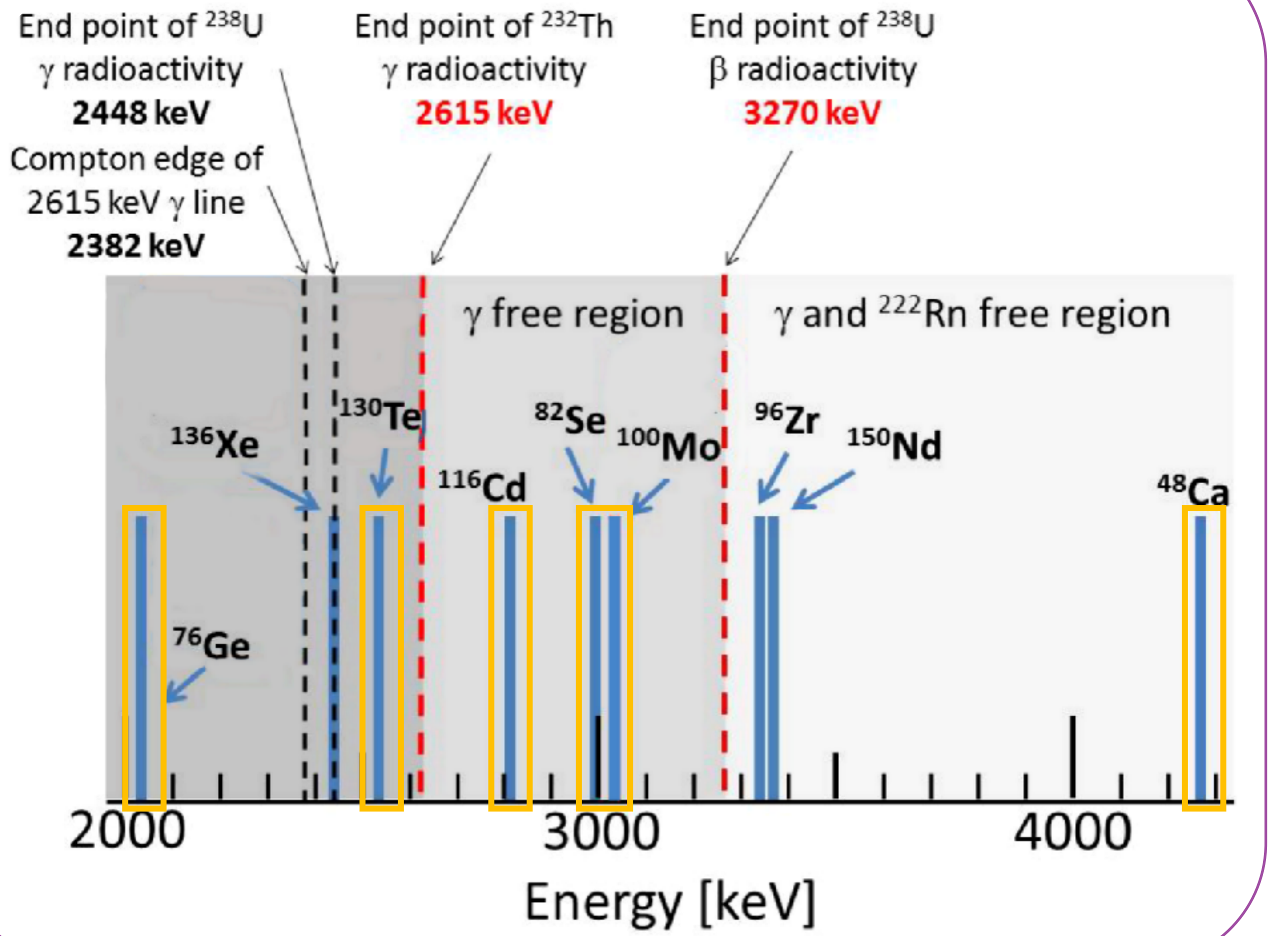
$$T_{1/2}^{0\nu2\beta} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

Experimental requirements:

Isotopic abundance and/or large scale enrichment

High $Q_{\beta\beta} \rightarrow$ lower background level in ROI and higher $0\nu2\beta$ decay rate

Minimum two isotopes should be measured: for observation and confirmation

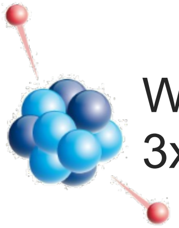


Bolometric detectors technology applicable for most of candidates!

Current picture on sensitivity

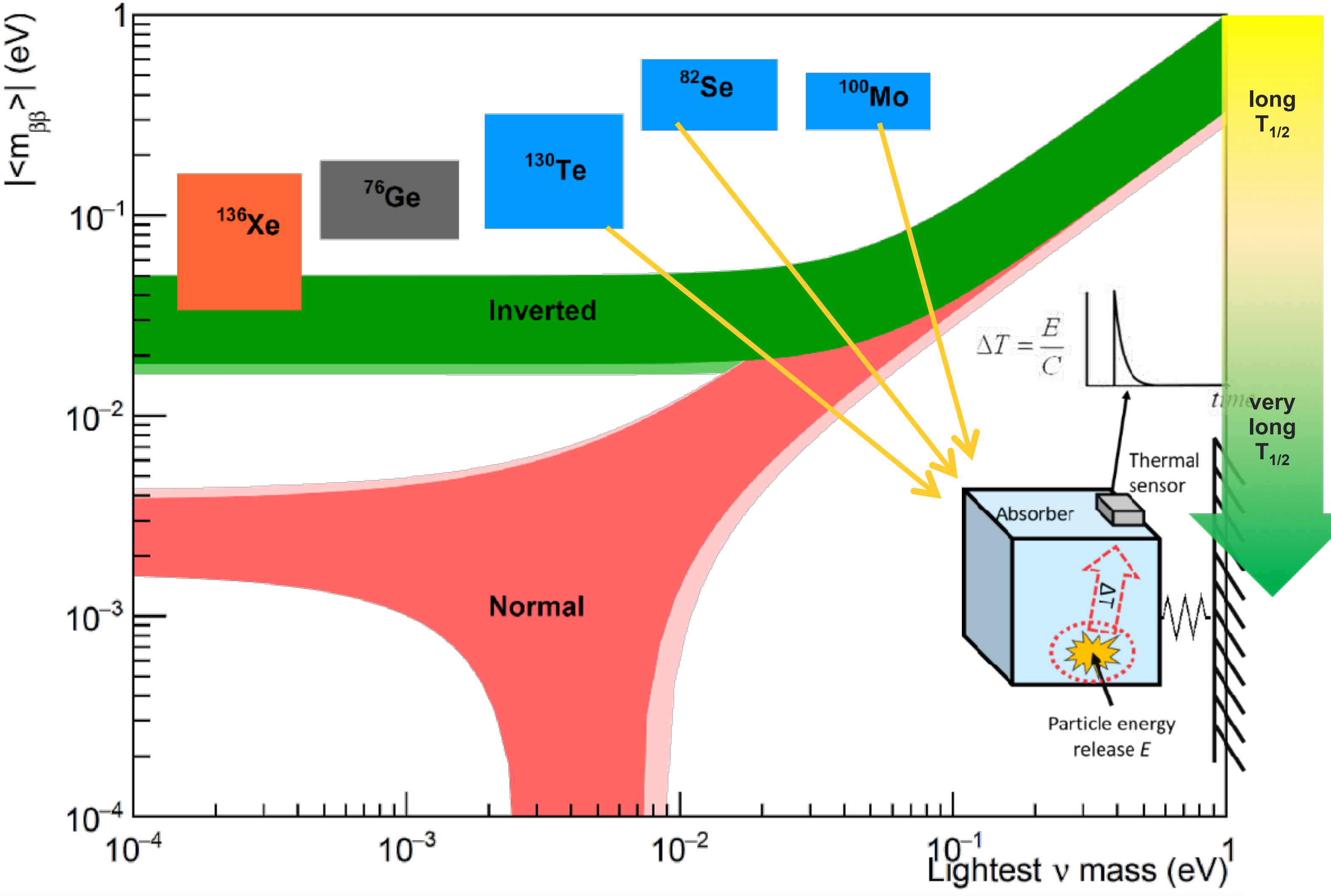
- Observation rate for future experiments:
  1 event per 1000 kg per year

This is around 0.1 Bq/g



We look for 3×10^{-14} Bq/g

- Worldwide efforts on improving technology:
  bolometers prove to be among the best detectors



Neutrino masses phase space

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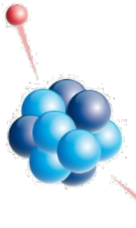

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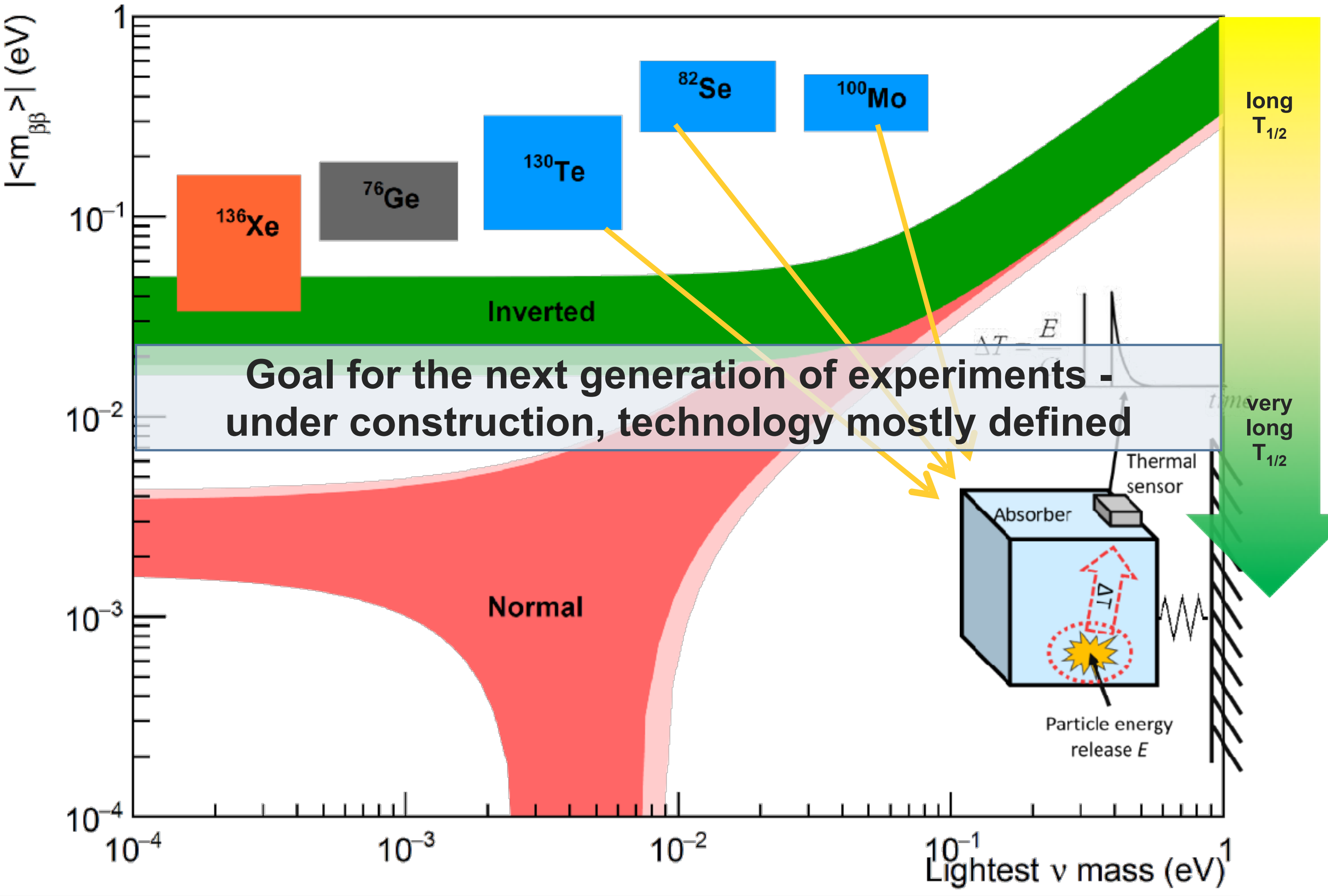

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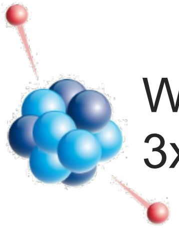

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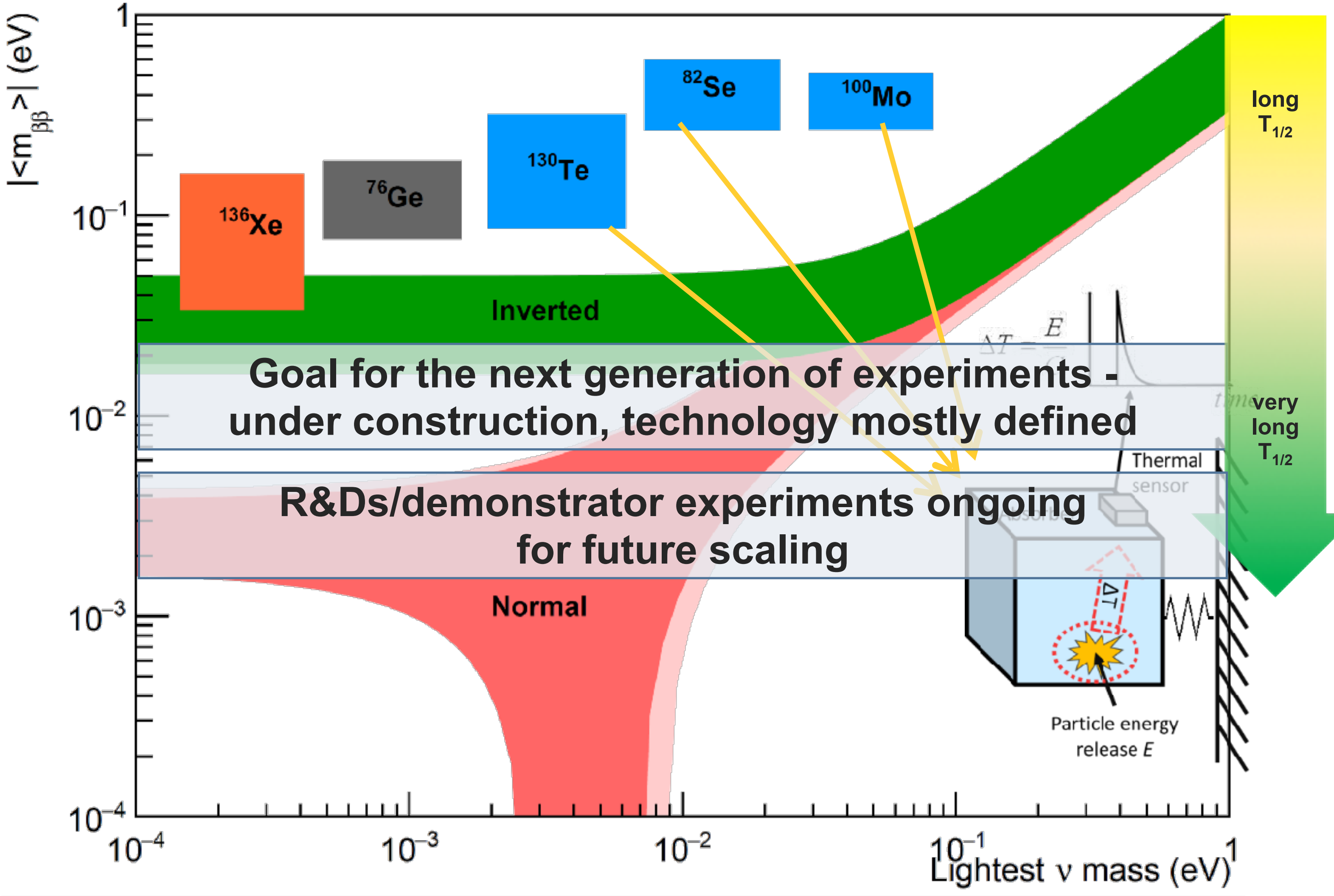
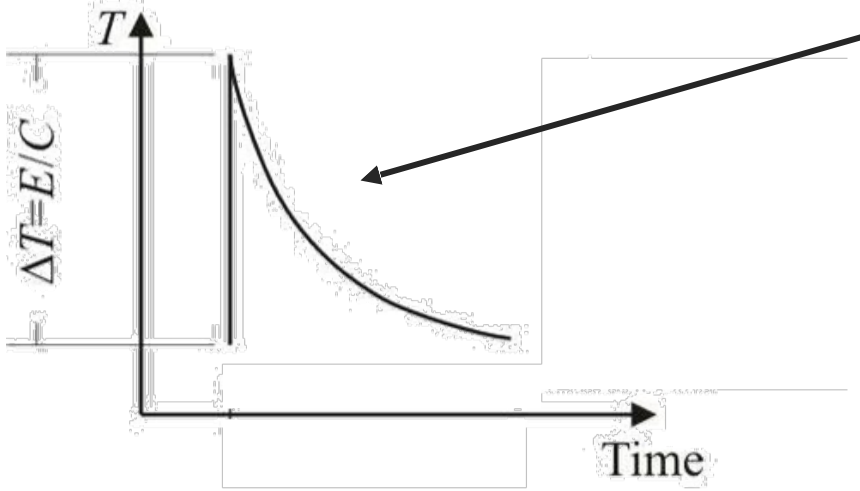
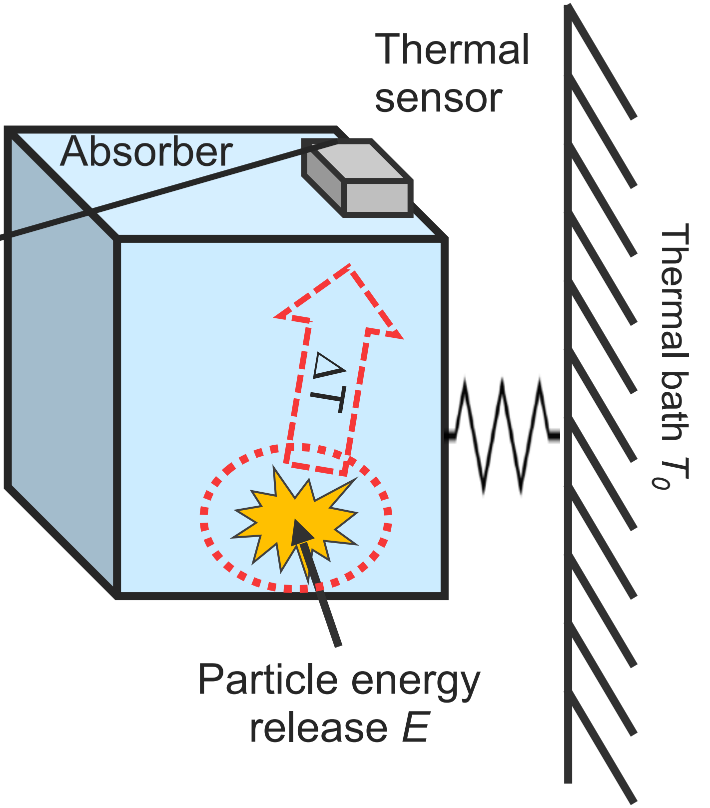


Neutrino masses phase space

Bolometers for particle detection

- Measurement of **particle interaction via temperature** change
- Requires very low temperatures of operation
  to detect this change (~10-100 mK)





- **Flexible material choice**: scintillating crystals can be used
- High energy resolution and efficiency solid state detectors

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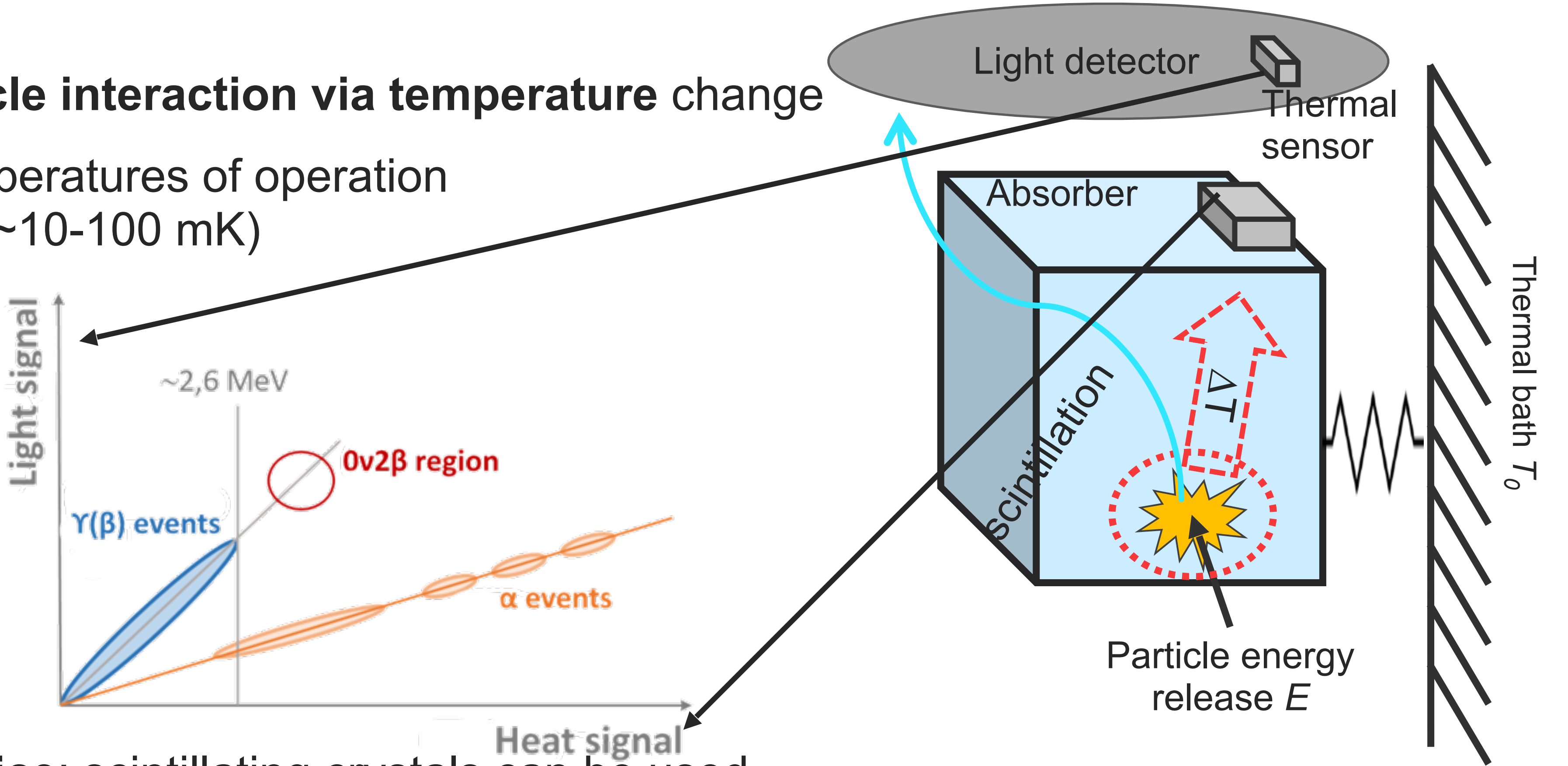
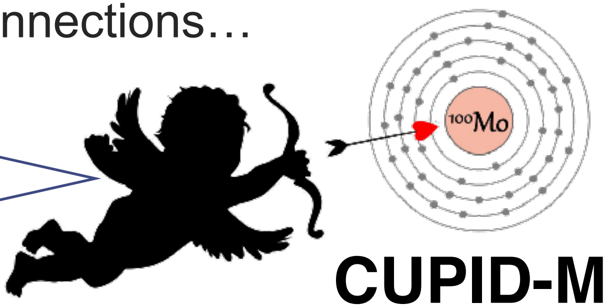


- **Flexible material choice**: scintillating crystals can be used
- High energy resolution and efficiency solid state detectors
- **Particle discrimination capability** via light ($\alpha/\gamma(\beta)$)

Family tree of European DBD research with bolometers

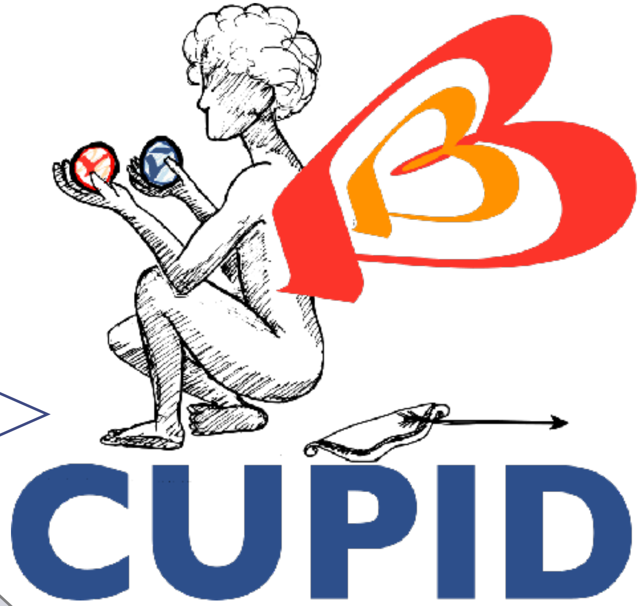
Long history and complex connections…



CUPID-Mo

CUPID-0

Crystals grown in Ukraine



BINGO

CROSS

CUORE: first ton-scale DBD experiment at 10 mK

No particle ID

Strongest limit for Te-130

CUPID demonstrators:

α rejection with light

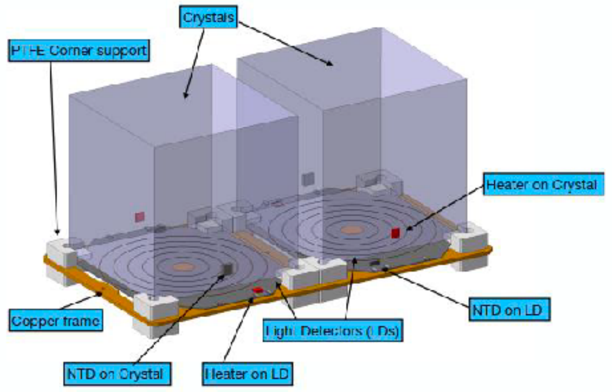
Best limits on ^{100}Mo and ^{82}Se $0\nu2\beta$

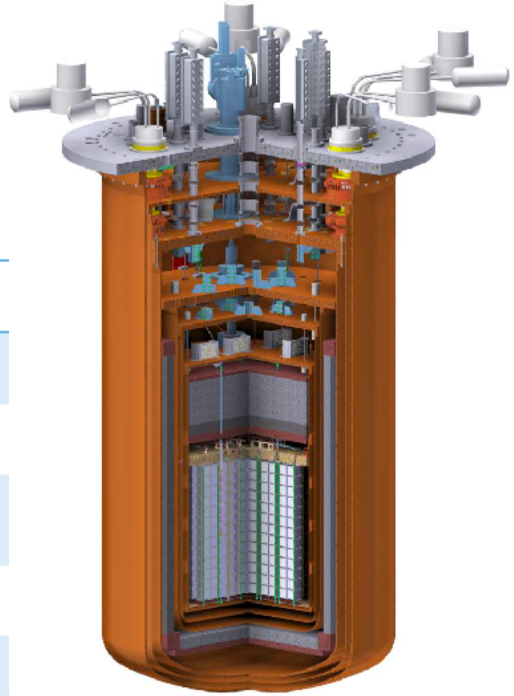
Inputs for ton-scale upgrade

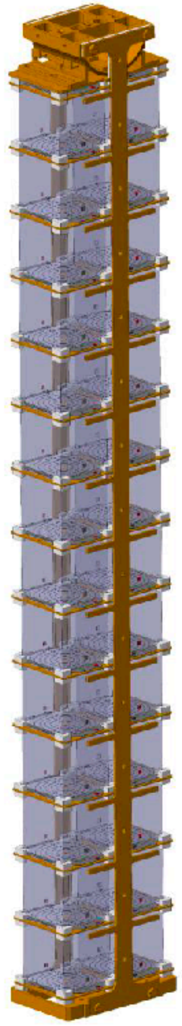
CUPID experiment: baseline

CUORE Upgrade with Particle IDentification

- Cryogenic infrastructure already exists: CUORE cryostat will be refurbished and reused
- 1596 Li_2MoO_4 crystals (45×45×45 mm)
- Arranged in 57 towers of 14 floors
- 1710 Ge wafer light detectors with SiO antireflective coating
- Enhanced LDs performance for pileup rejection with Neganov-Trofimov-Luke (Thanks to **BINGO and CROSS** R&Ds)
- 240 kg of ^{100}Mo (> 95% enrichment),total mass: 450 kg
- Pre-production in China (SICCAS) is ongoing



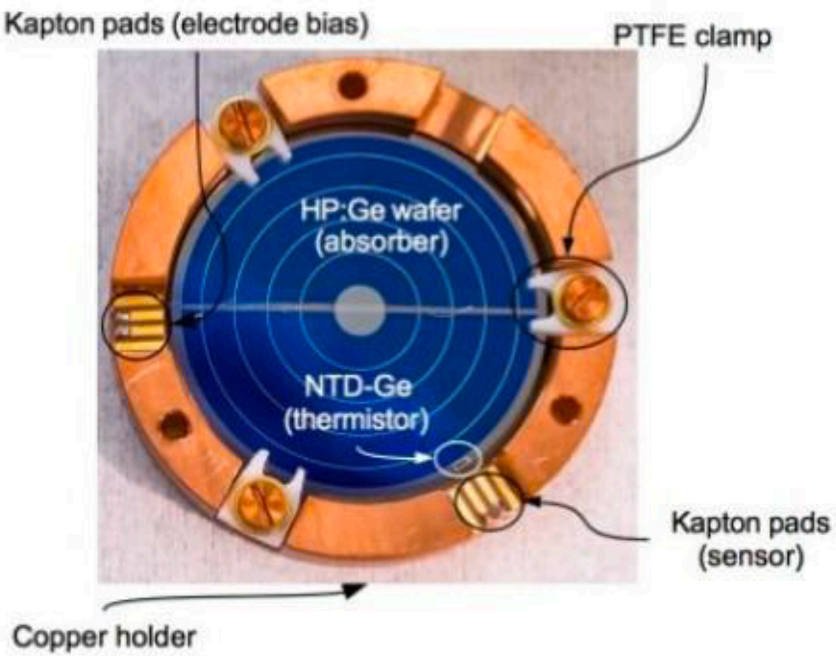


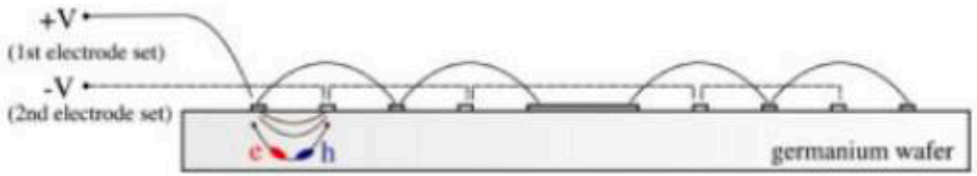


	CUPID-baseline performance aim
Energy resolution at $Q_{\beta\beta}$	5 keV FWHM
Background index	10^{-4} counts/(keV kg yr)
$T_{1/2}^{0\nu}$ exclusion sensitivity (90% C.L.)	1.4×10^{27} yr
LD baseline resolution	< 100 eV RMS
LY	0.3 (keV/MeV)

Neganov-Trofimov-Luke effect exploited with LDs

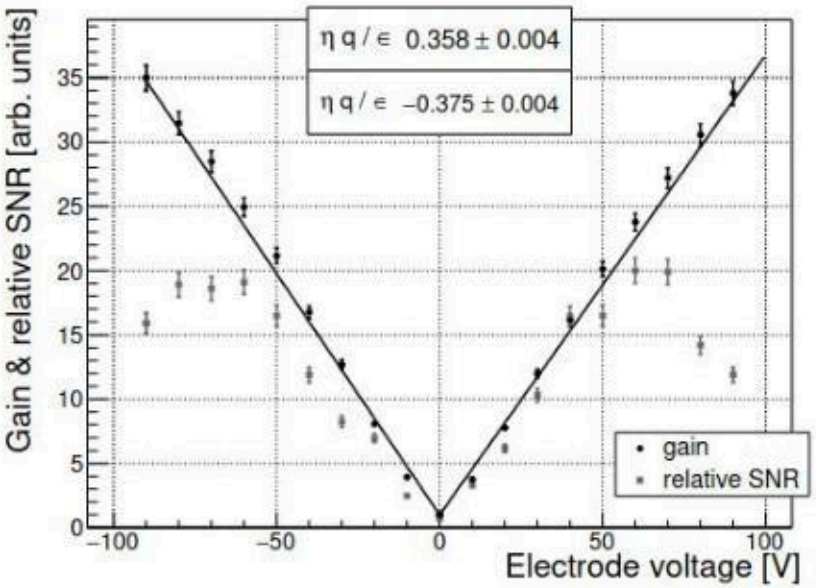
Enhanced light signal contributes to discrimination of background also via pile-up rejection





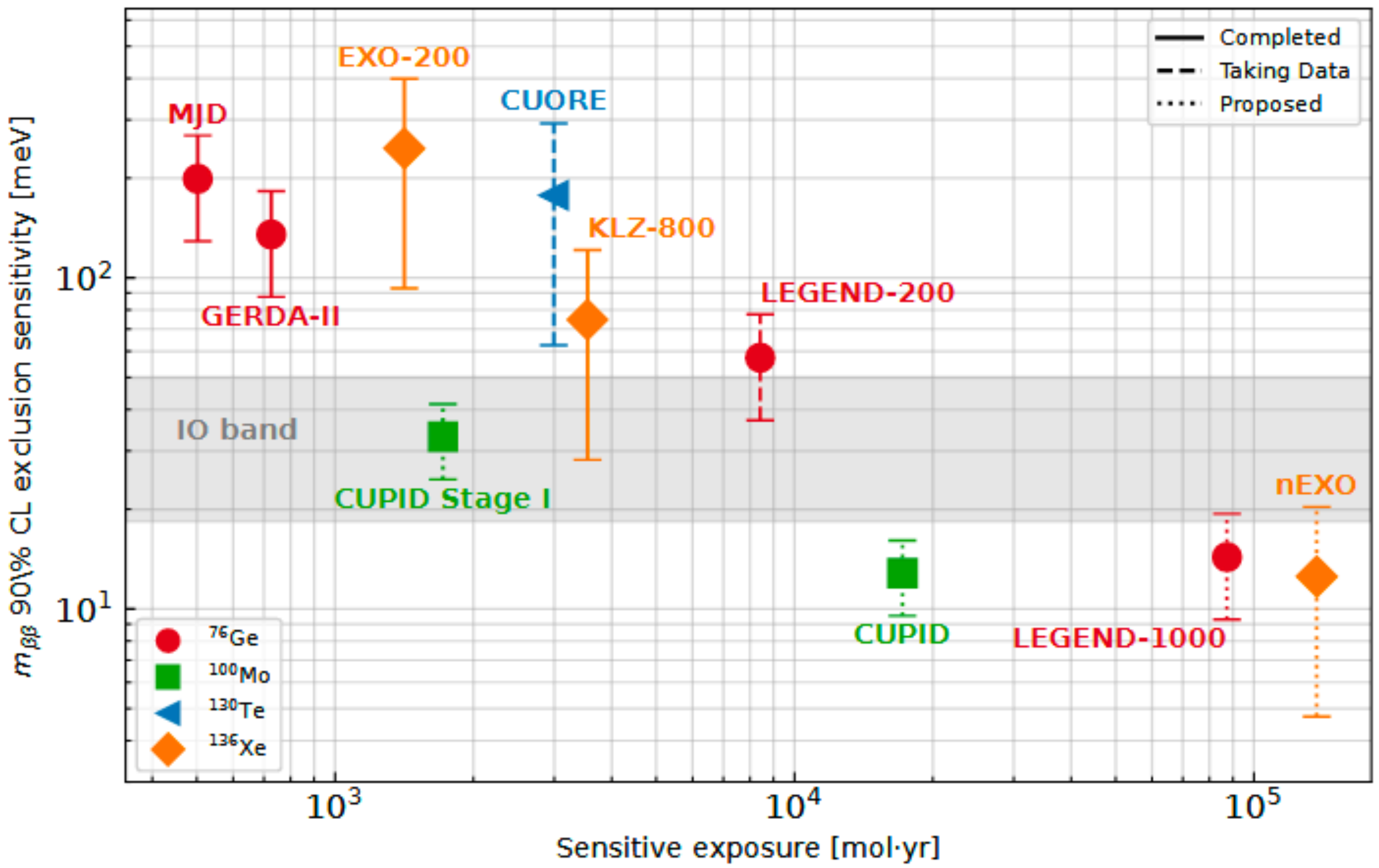
$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right) = E_0 \cdot G_{NTL}$$

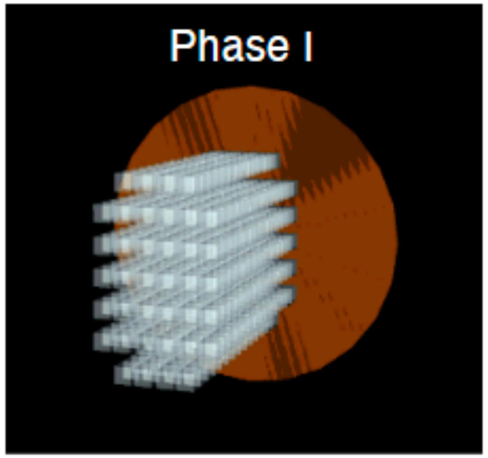
E_0: Energy of the ionizing particle
ε: Average energy required to generate an electron-hole pair
q: elementary charge
V_{el}: Potential between the electrodes
η: Amplification efficiency
G_{NTL}: Gain

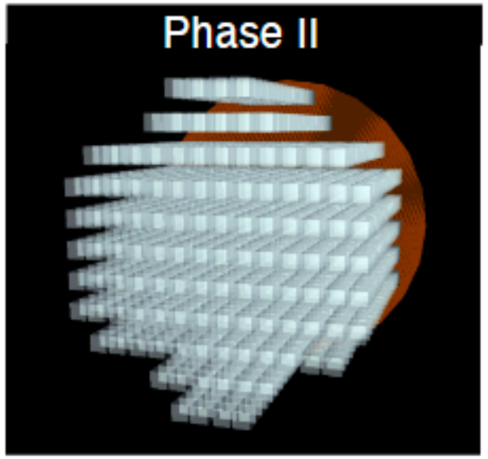


CUPID deployment

The most sensitive experiment worldwide at the beginning of the next decade



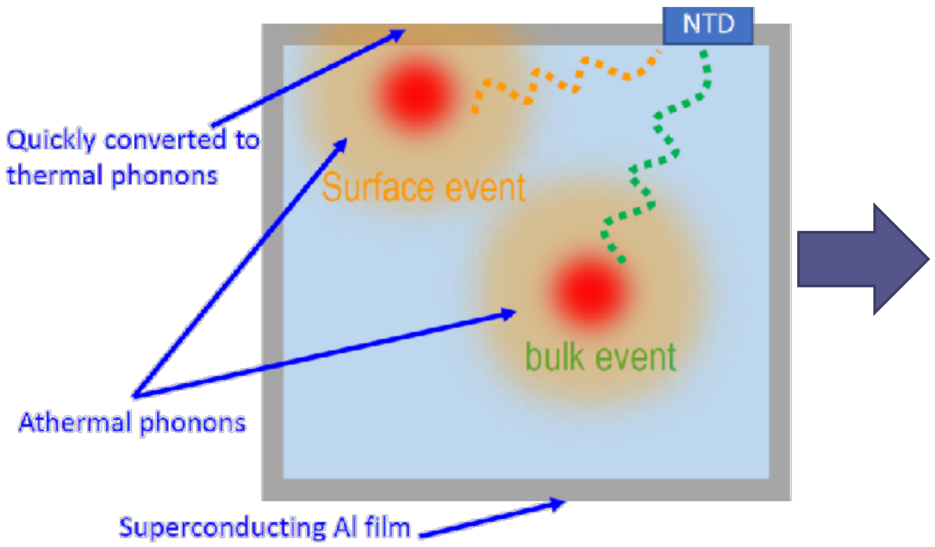


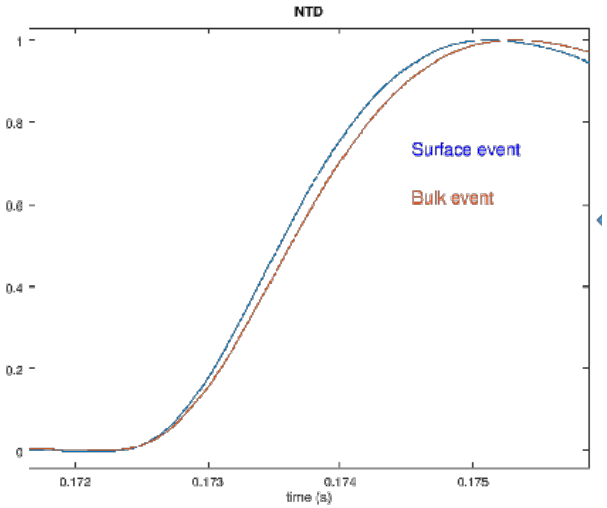


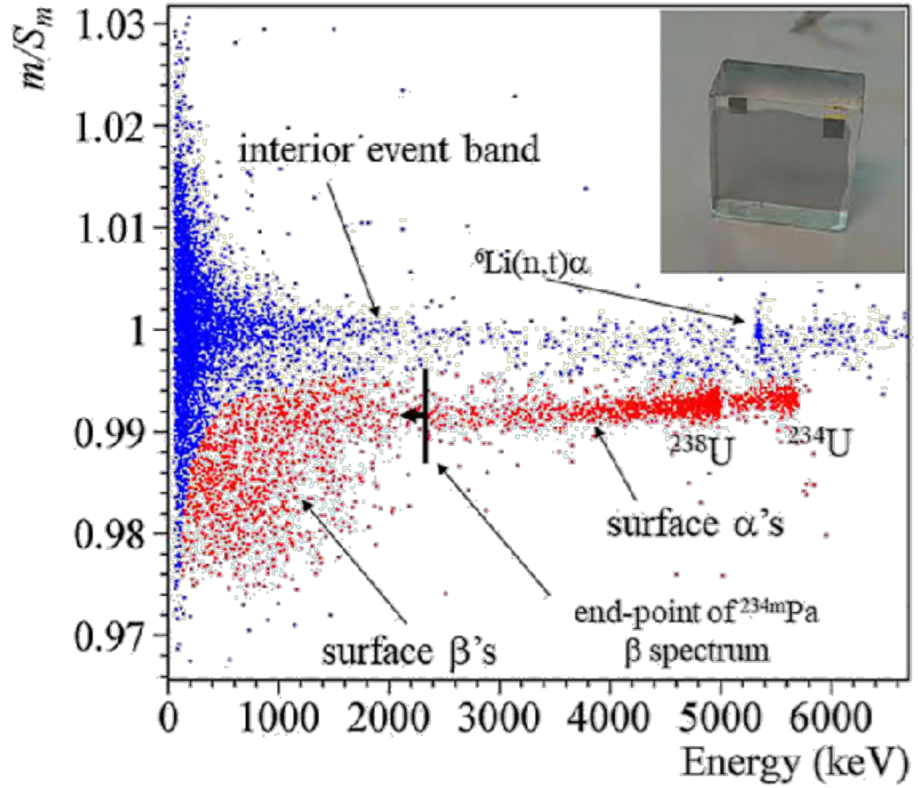
Demonstrators:CROSS experiment

CROSS: Cryogenic Rare-event Observatory with Surface Sensitivity

Proof-of-concept with small crystals
Difficulties with transferring this technology to larger samples
Technology is discarded from the final demonstrator but NTL LDs are exploited in synergy with CUPID







CROSS demonstrator

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:

$T_{1/2}^{0\nu\beta\beta}>9.36\cdot10^{24}$ yr, corresponding to **$m_{\beta\beta}<(126–213)$ meV**

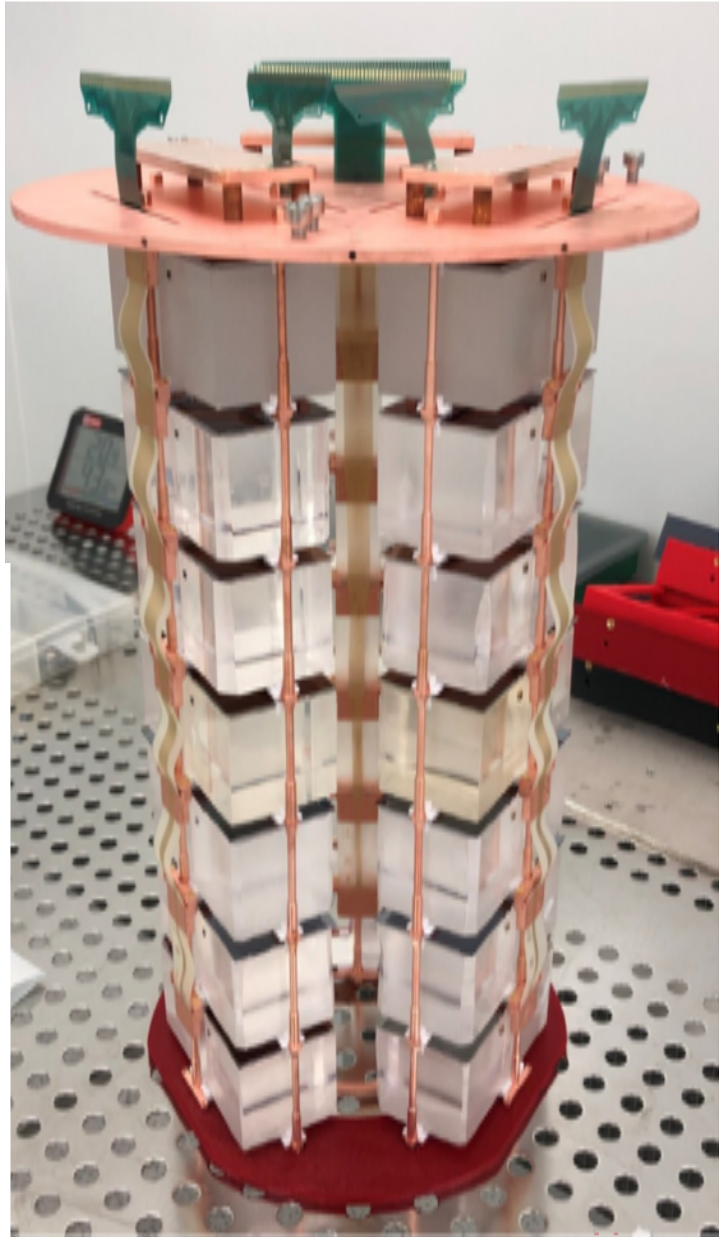
Location: Laboratorio Subterráneo de Canfranc (LSC), Spain (2450 m. w. e.)

Underground facility:

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

- 6 $^{130}TeO_2$ 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**

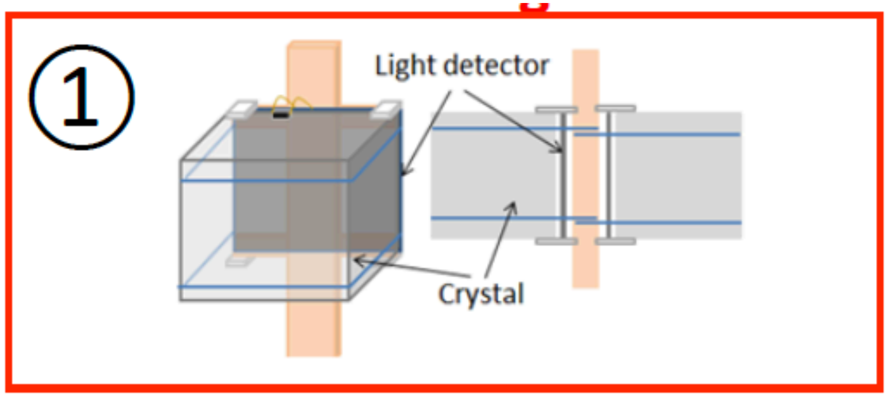


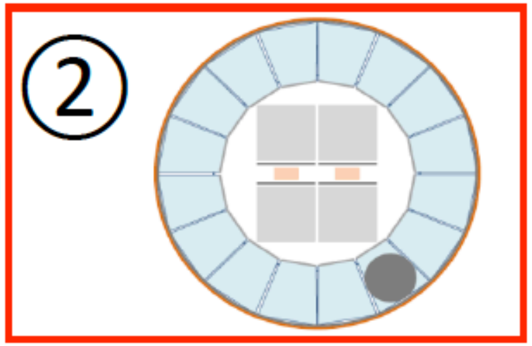
BINGO experiment

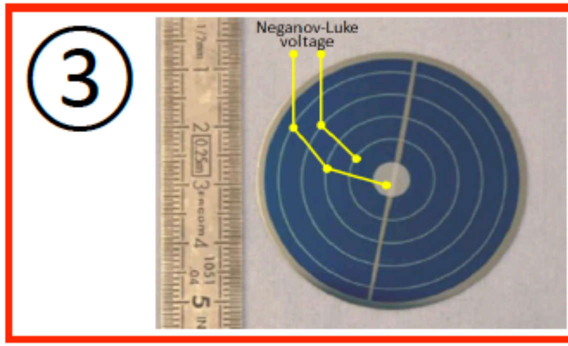
Three key upgrades for CUPID-like experiment:

- ✦ Surface events discrimination with innovative assembly: detectors will “see” only active elements
- ✦ Internal **active veto**: BGO scintillators, bolometric light read-out
- ✦ Light detectors with **Neganov-Luke technology** to reach 10 eV rms baseline both for veto and crystals

Tested with both Li_2MoO_4 and TeO_2 compounds



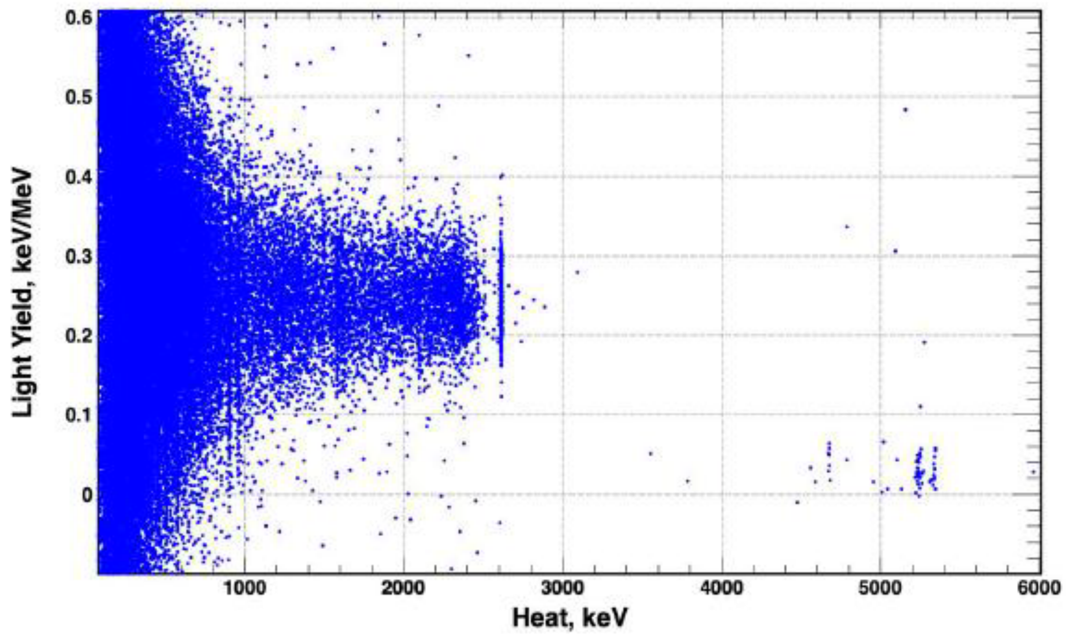


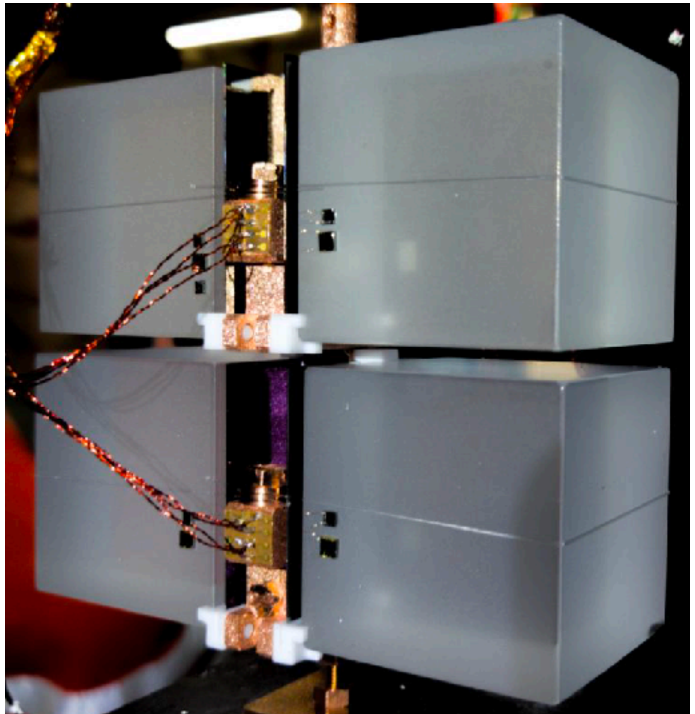


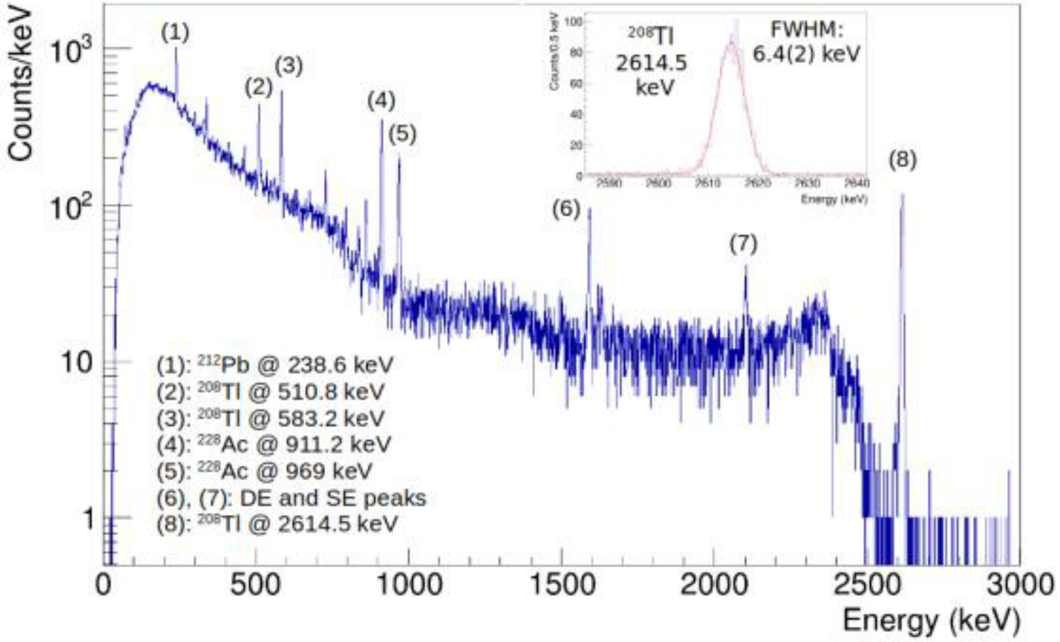
Goal for bkg index in ROI:
~10^{-5} cnts/keV/kg/yr for ton-scale experiment

BINGO assembly

- The average resolution at 2.6 MeV FWHM is ~6.3 keV for heat channels and baseline resolution RMS 92 eV for light channels
- No impact of nylon wire on noise or thermal coupling
- Good discrimination between α and g/b
- Structure is validated for demonstrator, simulations for ton-scale bkg index are ongoing







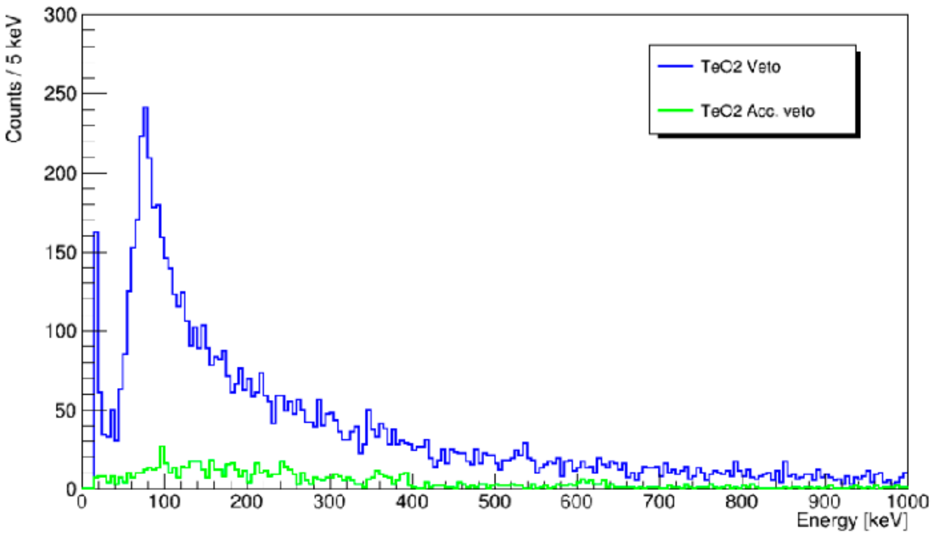
BINGO veto

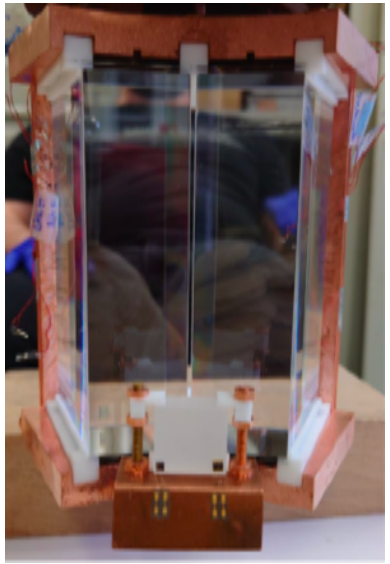
Background in ROI can appear for TeO2 if 2615 keV γ deposits a small amount of energy in the surrounding material (80 keV) and the rest in TeO_2

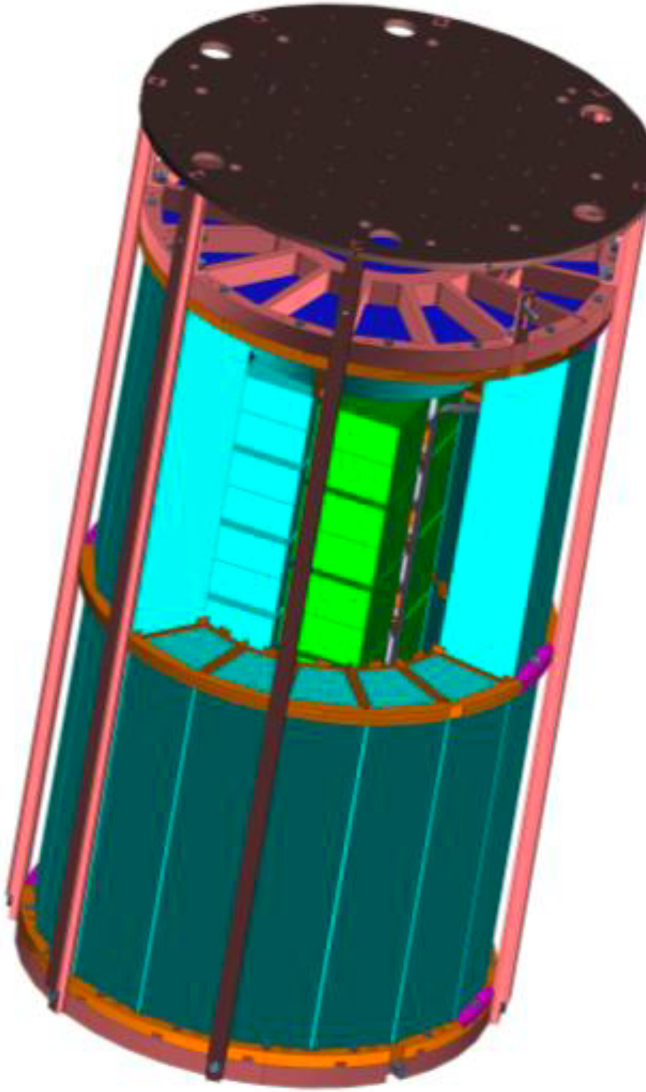
The energy deposition in the active veto will lead to scintillation light detected by the LD and these events can be rejected from TeO_2 Using anti-coincidence

Some surface contamination on the crystal can be dangerous if part of the energy escapes. This can also be rejected by anti-coincidence with the veto

Tests with prototypes were performed aboveground with promising results

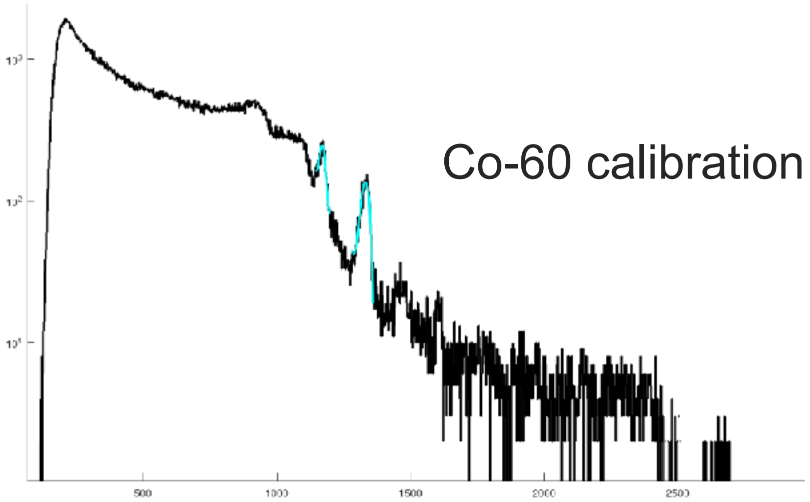






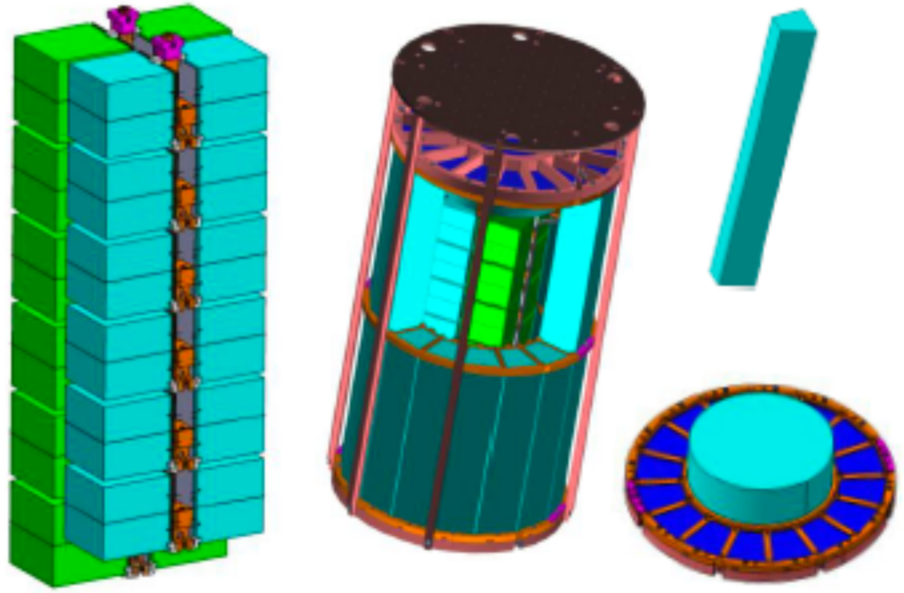
BINGO cryogenic facility

- ✦New cryostat @Cryoconcept with large experimental volume installed and validated last year
- ✦Measurements with bolometric detectors are ongoing: performance validation and electronics debugging
- ✦Lead shielding to be installed soon
- ✦Clean room will be built around the cryostat



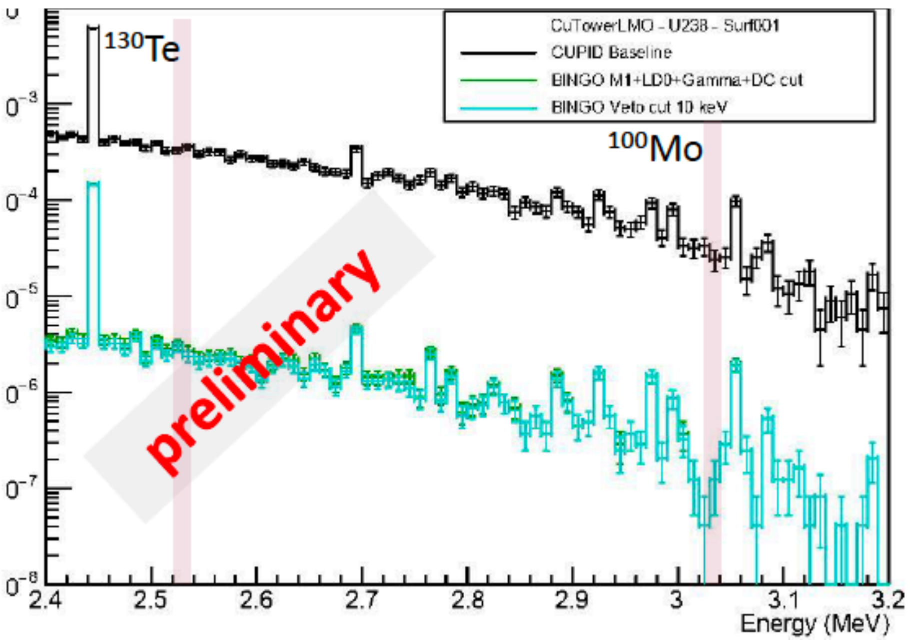
Co-60 calibration

MINI-Bingo demonstrator



- 12 cubic Li_2MoO_4 scintillating crystals (45x45x45 mm), each is coupled to an NTL light detector (45x45 mm)
- 12 cubic TeO_2 crystals (50x50x50 mm), each is coupled to an NTL
  light detector (50x50 mm)
- Cryogenic veto part surrounding the physics volume
- 16 trapezoidal cross-section + 2 disc scintillators (BGO) each coupled to LDs

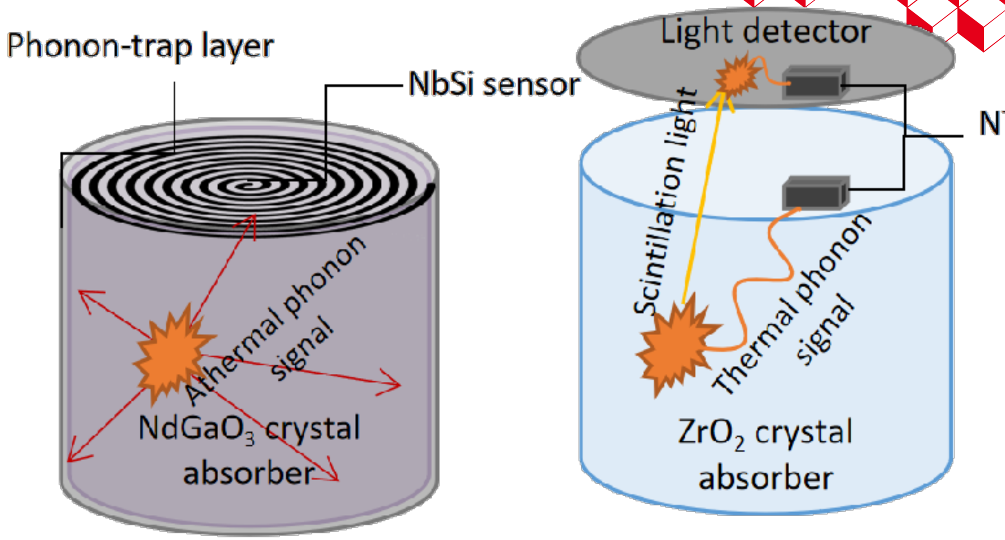
Scale high enough to demonstrate
$b \leq 10^{-3}$ cnts/keV/kg/yr
in 1 yr data taking
Simulations will confirm the scalability



TINY experiment

- Two Isotopes for Neutrinoless double beta decaY search
- Development of **easy to reproduce detector technology** for highly sensitive searches for $0\nu2\beta$ with **^{96}Zr and ^{150}Nd**
- Zero-background and “detector=source” concept
- R&D followed by an underground demonstrator on a small scale

TINY demonstrator proposal

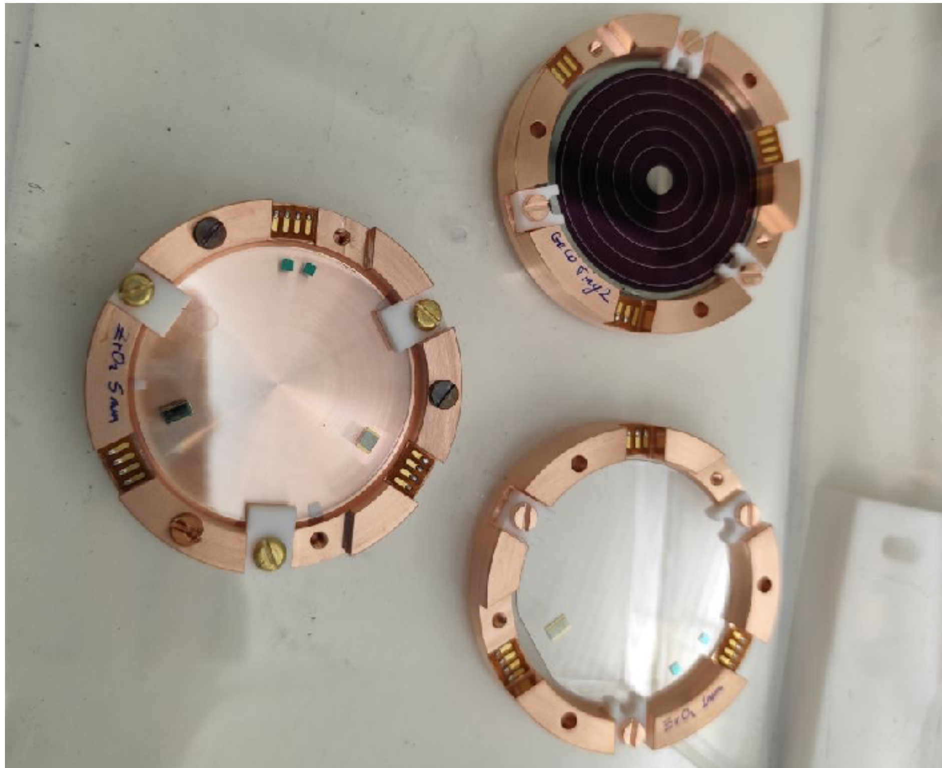


Baseline configuration: **array of 10 crystals**

- 5×400 g **ZrO_2 double read-out** scintillating bolometers: thermal sensors and NTL LDs
- 5×400 g natural **$NdGaO_3$ single read-out** magnetic bolometers: thermal phonon sensors

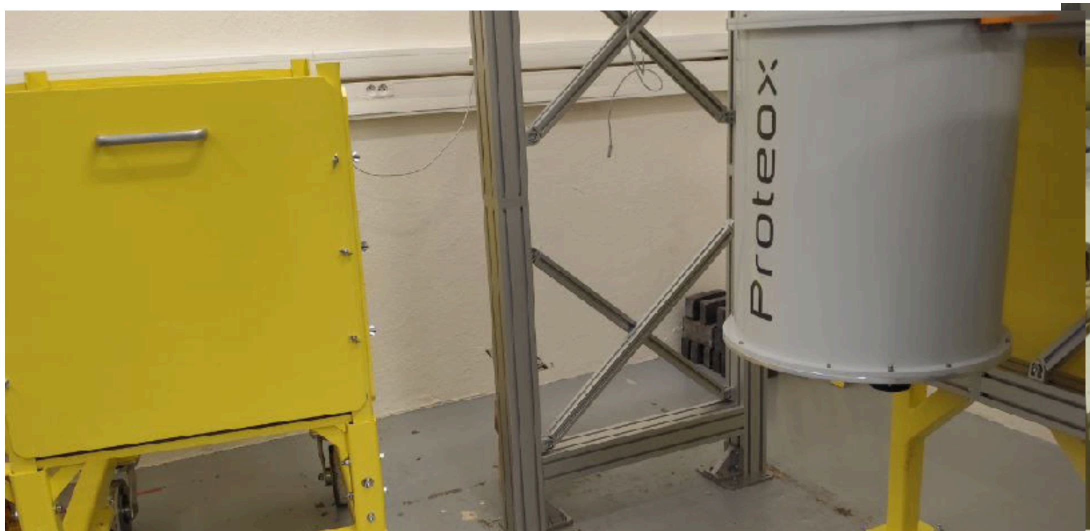
Precision measurement of $2\nu2\beta$ spectrums

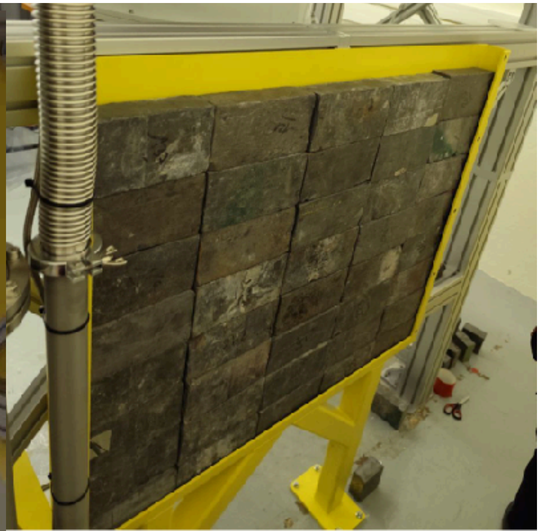
New limits in 1 year of measurements and background 10^{-3} cnts/keV/kg/yr for both if performance goal is reached



TINY cryogenic facility (CEA-Salcay)

- @Oxford ProteoMX cryostat, experimental volume 36x25 cm
- Installed at a shallow site @CEA-Saclay, muon rate reduction 66%
- Facility validated in terms of cryogenic performance: base temp 7,5 mK, 12 uW @20 mK, 450 mW @100 mK
- CUPID-like electronics to be installed
- First bolometric measurements are coming soon!





Summary

- **Bolometric technology** is one of the core approaches for next-generation DBD searches, thanks to high energy resolution and technology enhancements for background reduction

- Particle identification capability, materials flexibility, high energy resolution allow to reach unprecedented sensitivities

- Mo-based **CUPID Stage-I** can take data at the end of this decade and has **world leading science reach**

- Several demonstrator experiments are working on exploiting and exploring technological improvements with bolometric detectors for background reduction

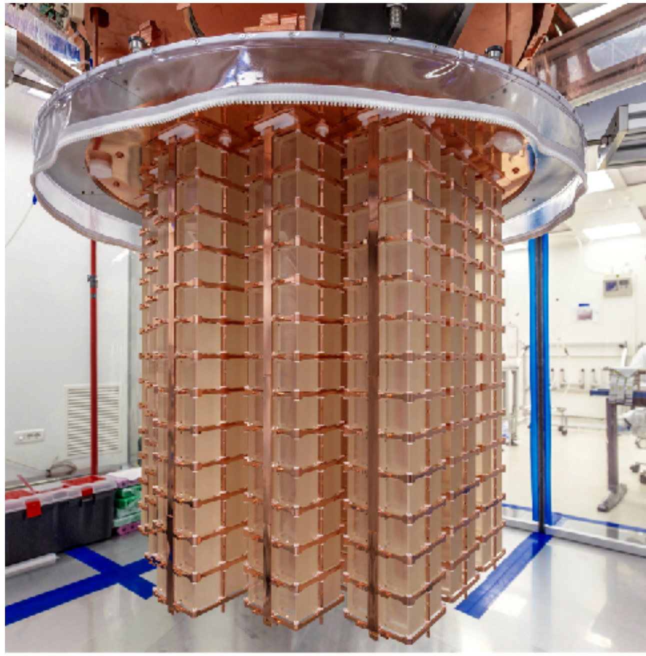
Backups

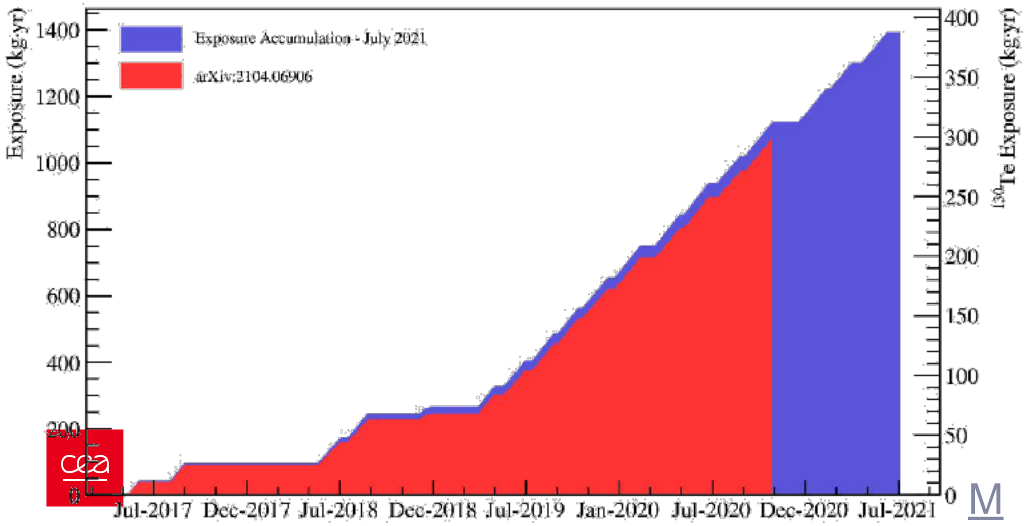
CUORE: the largest bolometric experiment

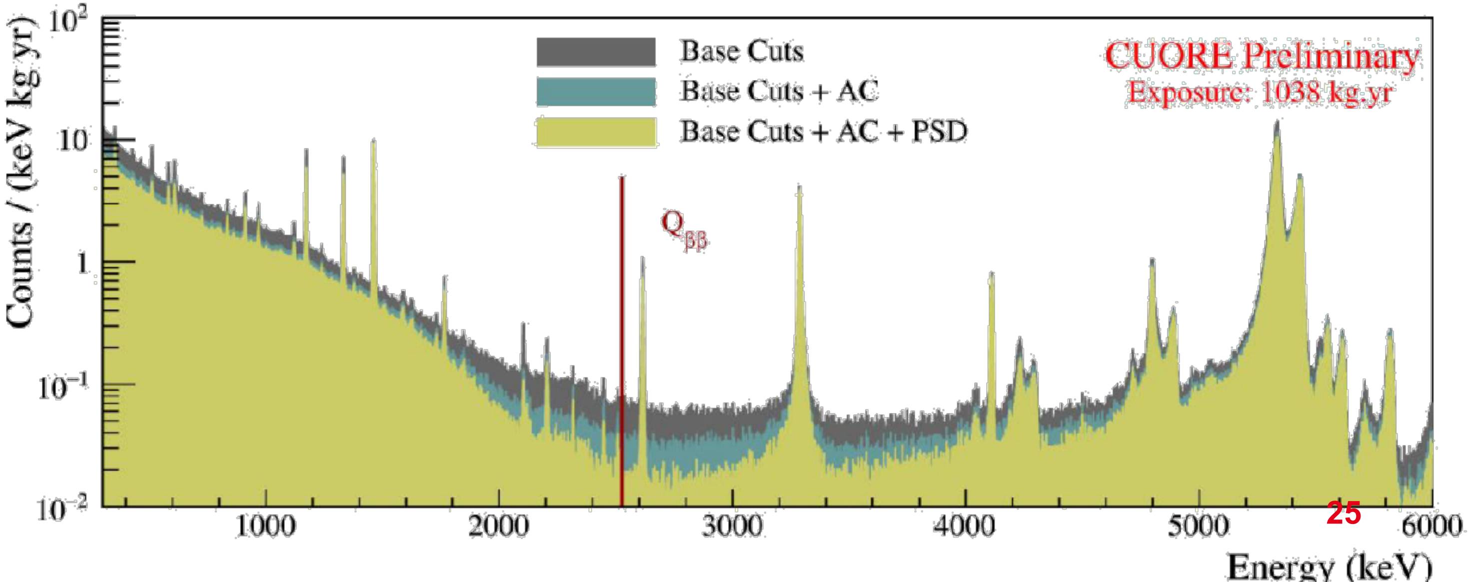
CUORE: the Cryogenic Underground Observatory for Rare Events

First ton scale array of cryogenic calorimeters: **988 TeO_2 crystals** (0.75 kg each)

CUORE cryogenic facility is an unprecendented techological challenge, which is now **taking data in steady and reliable conditions**

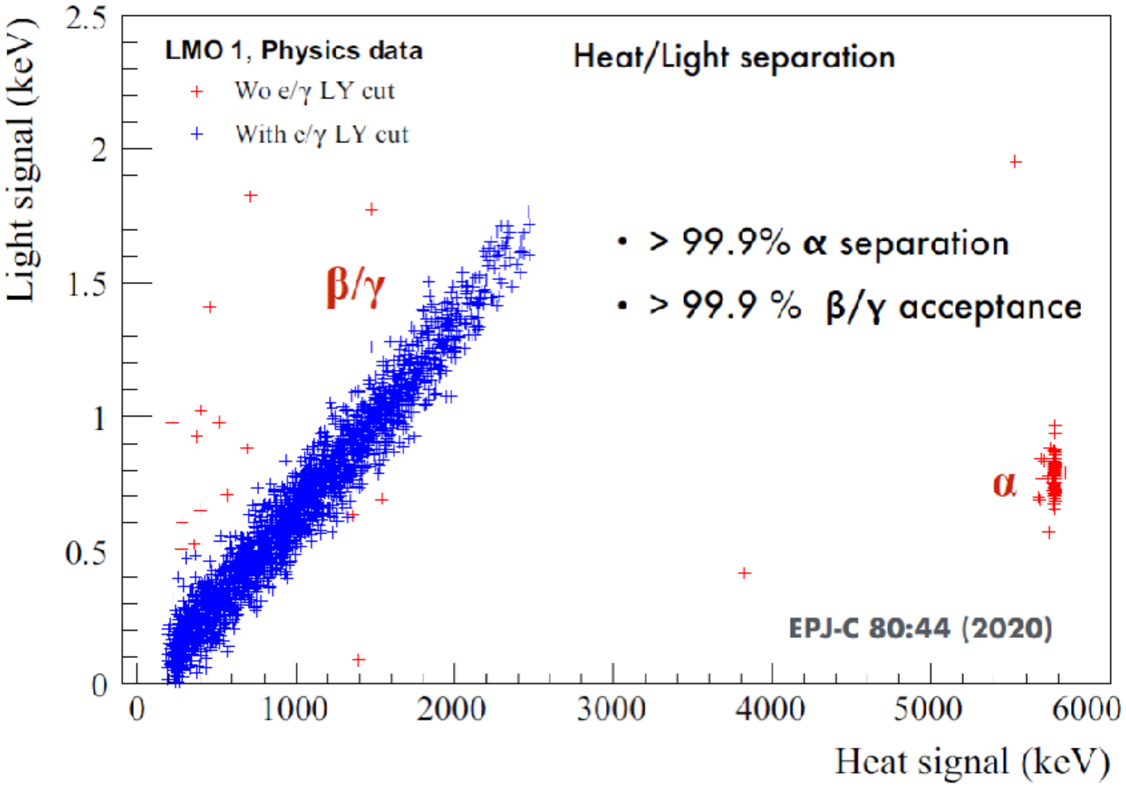


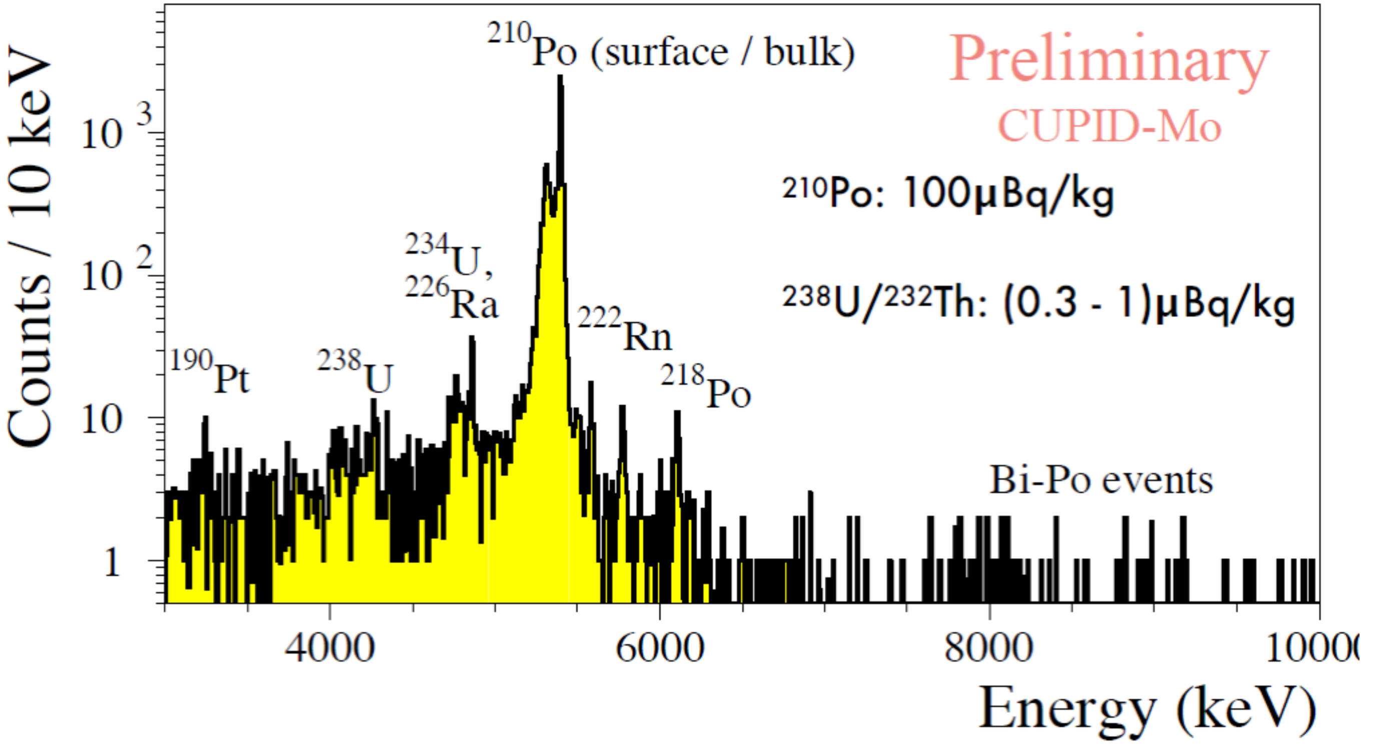




CUPID-Mo features

Excellent internal radiopurity of crystals: ^{210}Po and U/Th well within CUPID requirements

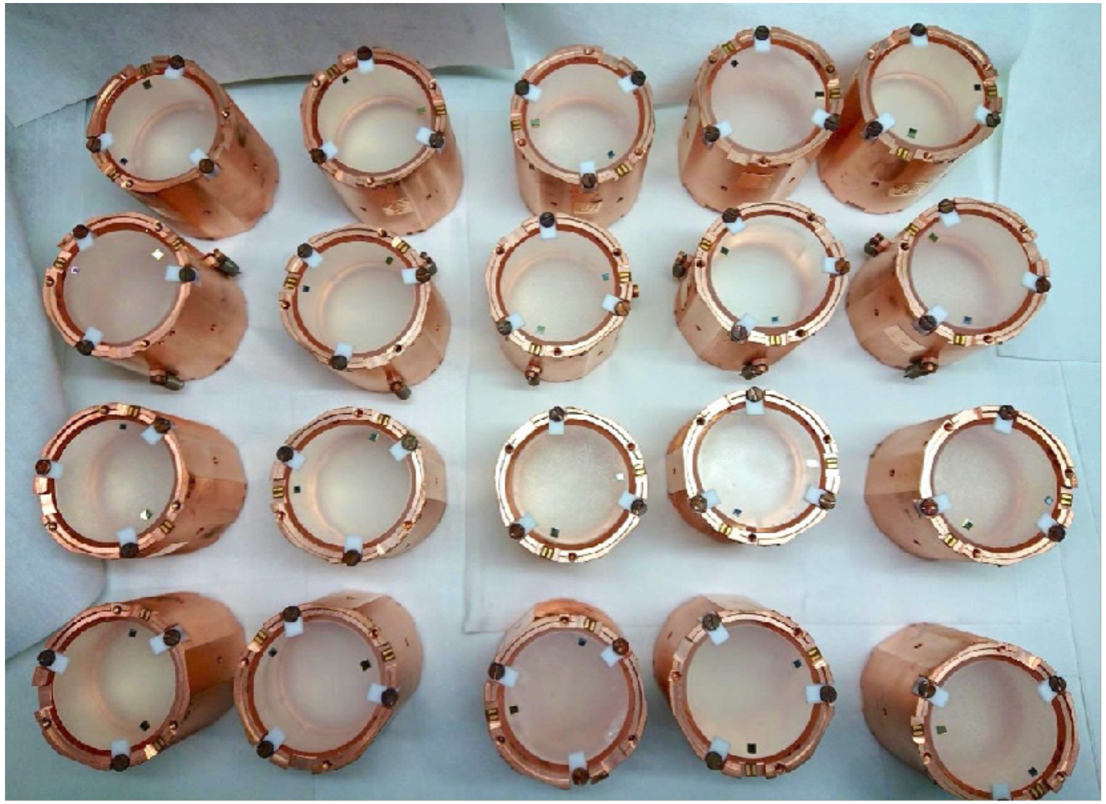


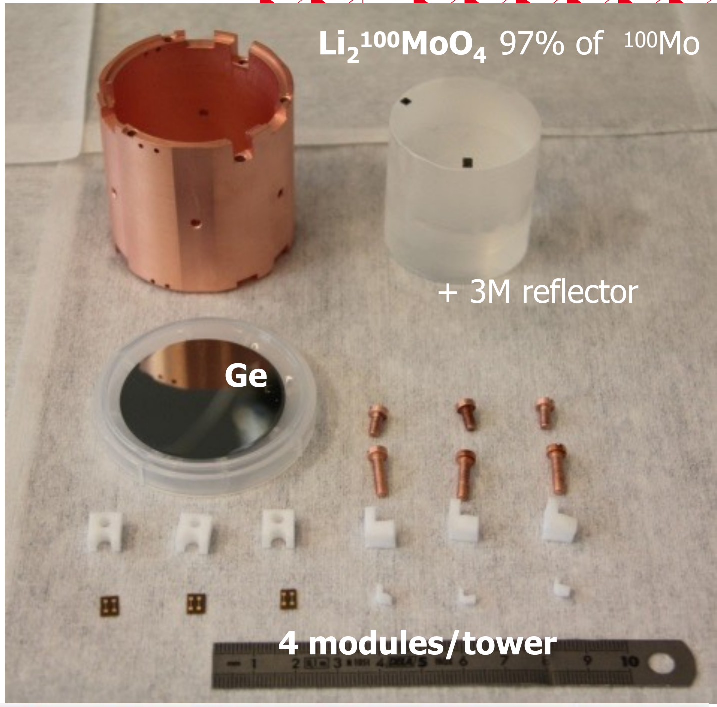


CUPID-Mo

$Li_2{}^{100}MoO_4$ scintillating crystals - high energy resolution and radiopurity, array of 20 modules at LSM

Total of 2.26 kg of ^{100}Mo, $Q_{\beta\beta}$ = 3034 keV





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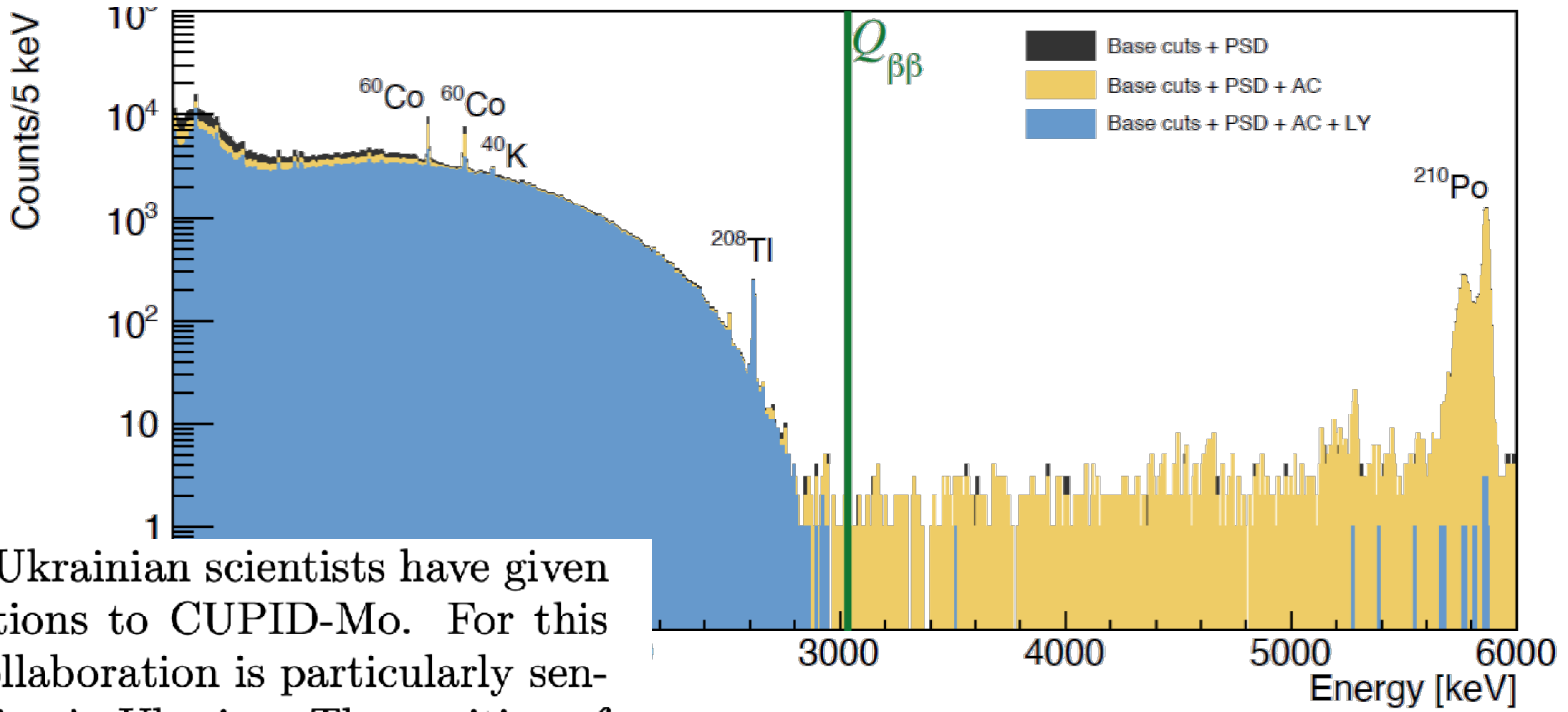
CUPID-Mo results

$$T^{0\upsilon}_{1/2} > 1.8 \times 10^{24} yr$$

(90% C. I. limit)

$m_{\beta\beta}$<280-490 meV

1.5 kg×yr



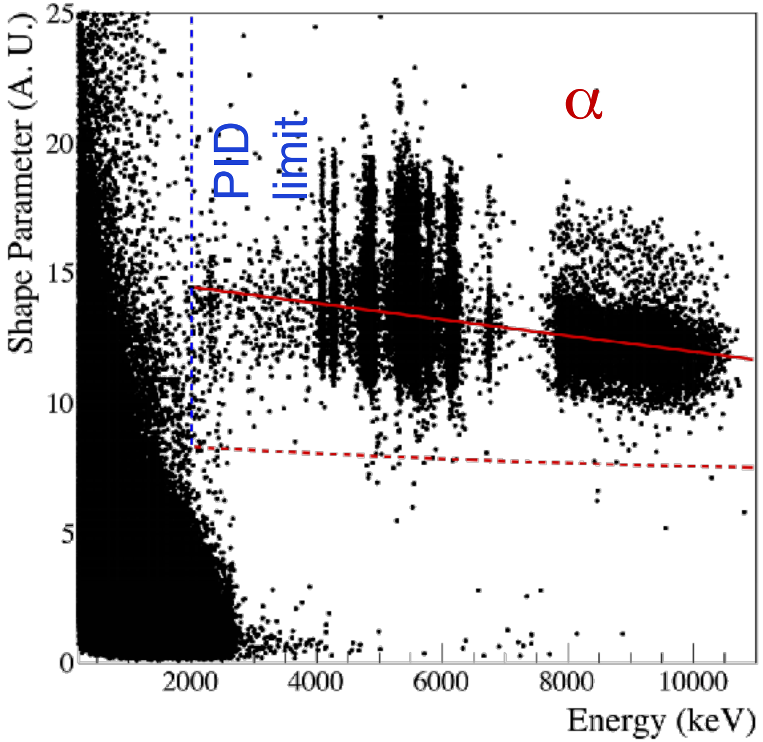
laborations. Russian and Ukrainian scientists have given and give crucial contributions to CUPID-Mo. For this reason, the CUPID-Mo collaboration is particularly sensitive to the current situation in Ukraine. The position of the collaboration leadership on this matter, approved by majority, is expressed at `https://cupid-mo.mit.edu/collaboration#statement` . Majority of the work described here was completed before February 24, 2022.

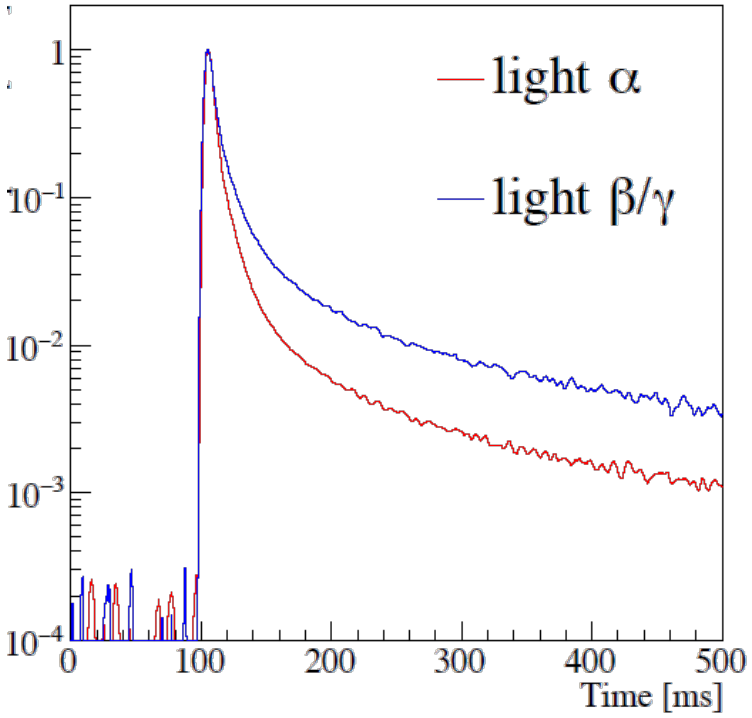
PRL 126, 181892 (2021)
JINST 16 (2021) P03032
EPJC 80, 44 (2020)
EPJC 80, 674 (2020)

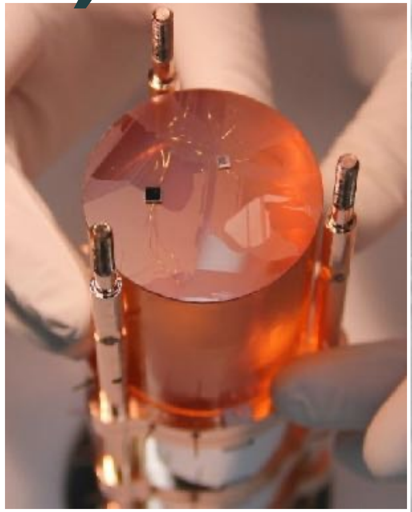
CUPID-0 demonstrator (^{82}Se)

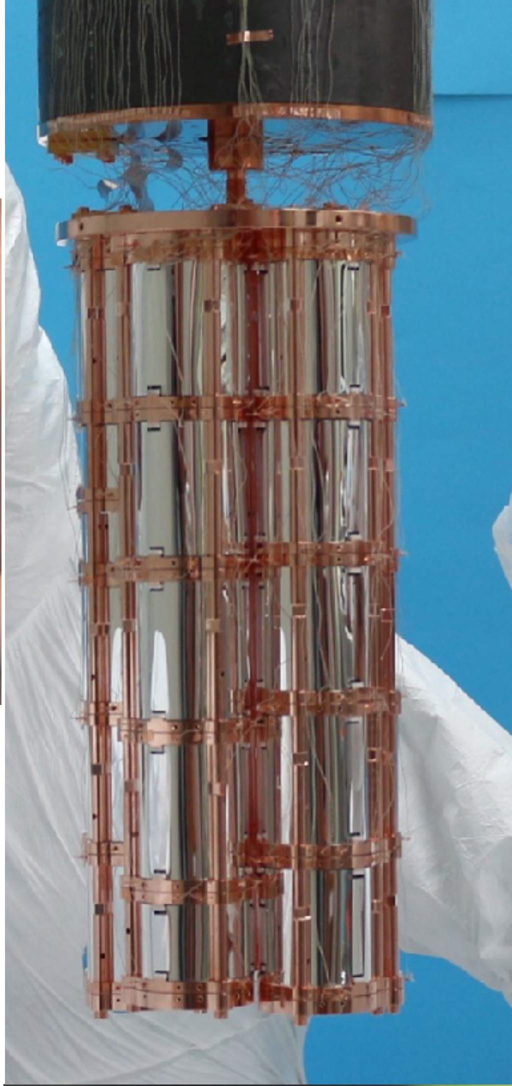
The first pilot experiment for CUPID with scintillating bolometers in LNGS

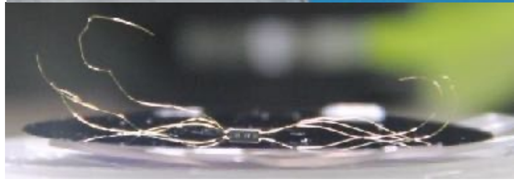
95% enriched Zn^{82}Se bolometers
(**5.17 kg of ^{82}Se, $Q_{\beta\beta}$=2998 keV**)











EPJC (2018) 78:428