# Recent results from CUORE and path towards CUPID

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On behalf the CUORE and CUPID collaborations

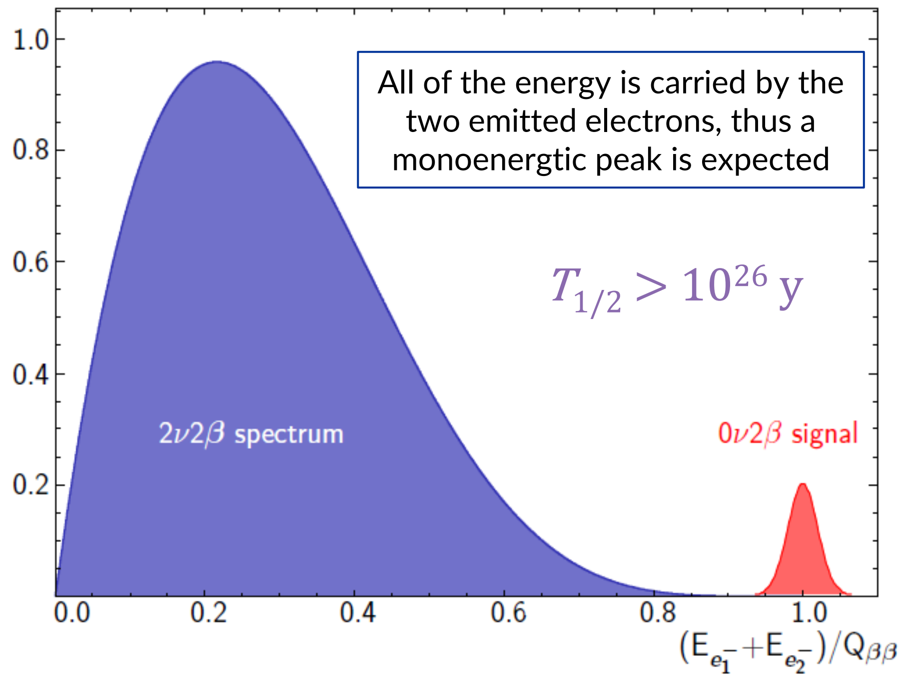
PASCOS (Durham, UK) – 24 July 2025

# Neutrinoless double beta decay

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

## Neutrinoless double beta decay observation will:

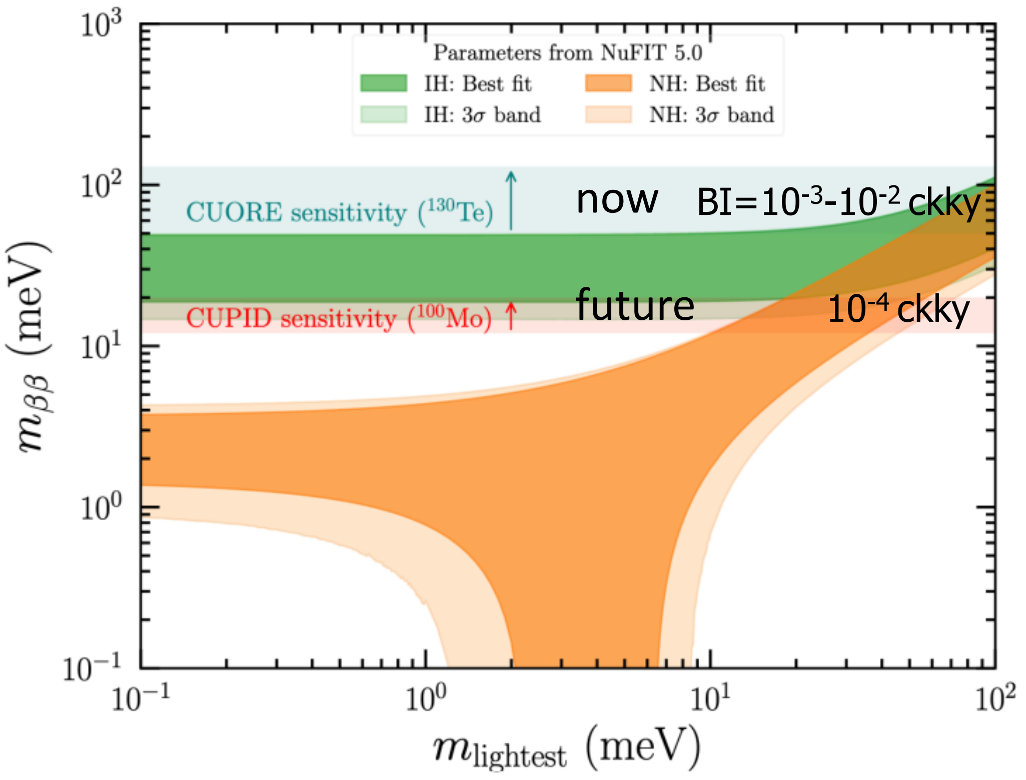
- **Ascertain the Majorana nature of neutrino** $(\nu = \overline{\nu})$
  - Provide information on neutrino mass scale and ordering
- **Confirm lepton number violation**
  - Not allowed in the SM → physics beyond the SM
  - Matter-antimatter asymmetry explanation (Leptogenesis)




Energetically possible for **35 nuclei**
Experimentally relevant: $^{82}$**Se**, $^{76}$**Ge**, $^{100}$**Mo**, $^{130}$**Te**, $^{136}$**Xe**

**Need to find single events in a ton of isotope × year(s) of exposure!**

# Enhancing the sensitivity to 0νββ

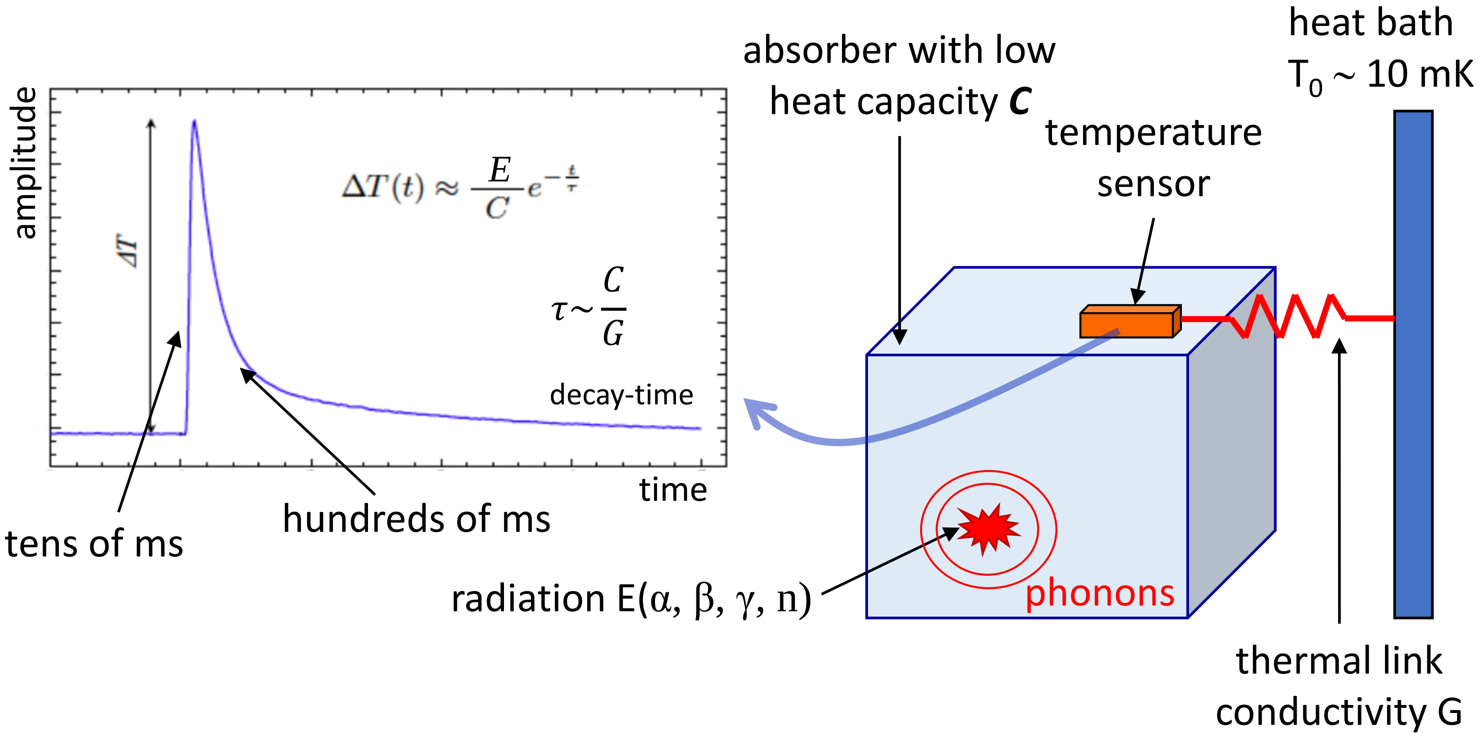



$$\boldsymbol{BI} = \frac{\text{number of background counts}}{\boldsymbol{M} \times \boldsymbol{t} \times \Delta \boldsymbol{E}}$$

Counts/(keV kg yr) → [ckky]

- High isotopic abundance of the ββ nuclide
  - enrichment of ββ source
- High detection efficiency
  - "detector = ββ source"
- Large detector mass
  - scalability of a technology to a tonne-scale
- Long term measurement
  - stable operation for ~ 5-10 yrs
- Extremely low background in the ROI
  - underground measurement → muon reduction
  - passive and active shields
  - high radio-purity of detector components
- High detector performance
  - high energy resolution
  - particle identification capability
  - fast time response

# Detection technique: bolometers




Particle releases energy in an absorber
↓
Energy is converted into lattice vibrations
↓
Generate temperature rise in the absorber
↓
Measured by a sensor

**The energy deposition is converted into an electrical signal**

**Temperature sensor:**
- Neutron Transmutation Doped (NTD) Germanium thermistor
- Temperature change leads to resistance change

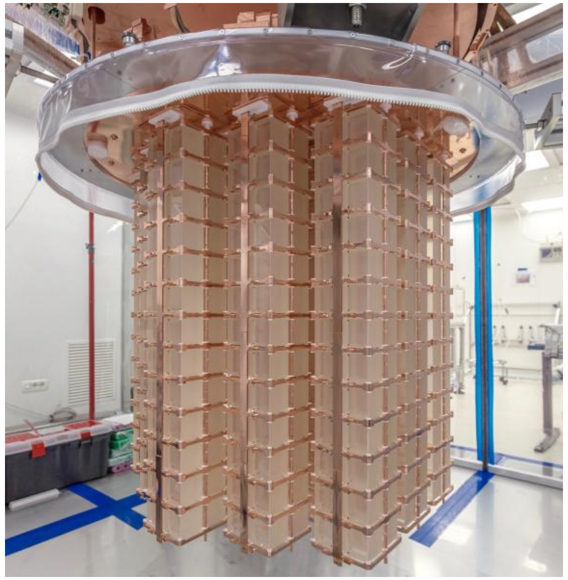
**Features**
- **High performance**
  - High energy resolution
  - Low threshold
- **Particle identification**
  - Active background rejection
- **Very low radioactive contamination**
- **Universality**
  - Wide choice of absorber materials

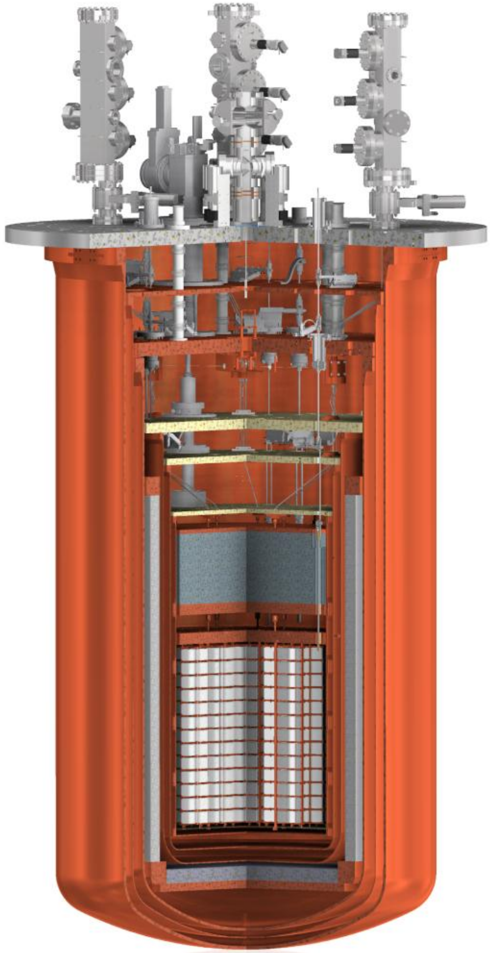
# CUORE in a nutshell

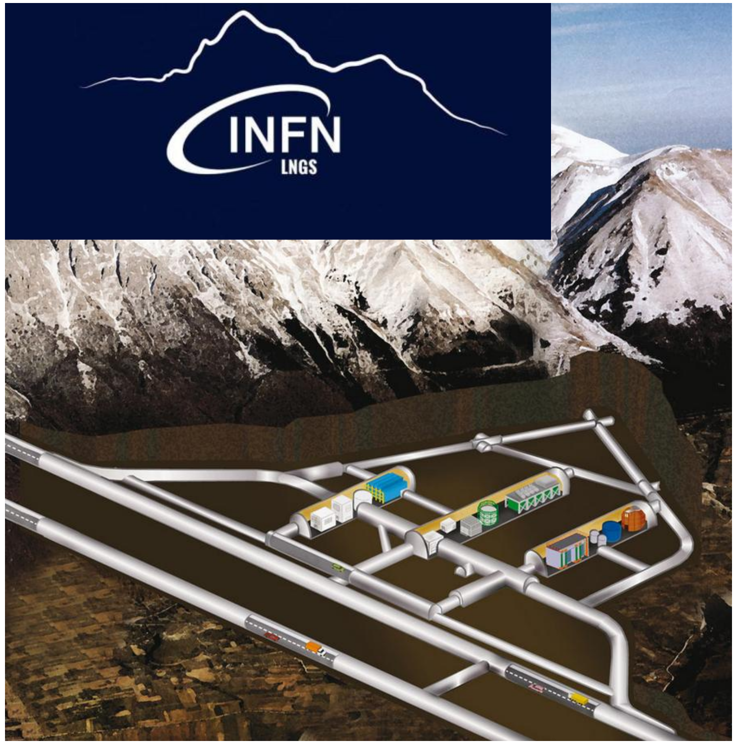
CUORE: Cryogenic Underground Observatory for Rare Events

Nature 604, 53–58 (2022)

The first tonne-scale bolometric experiment





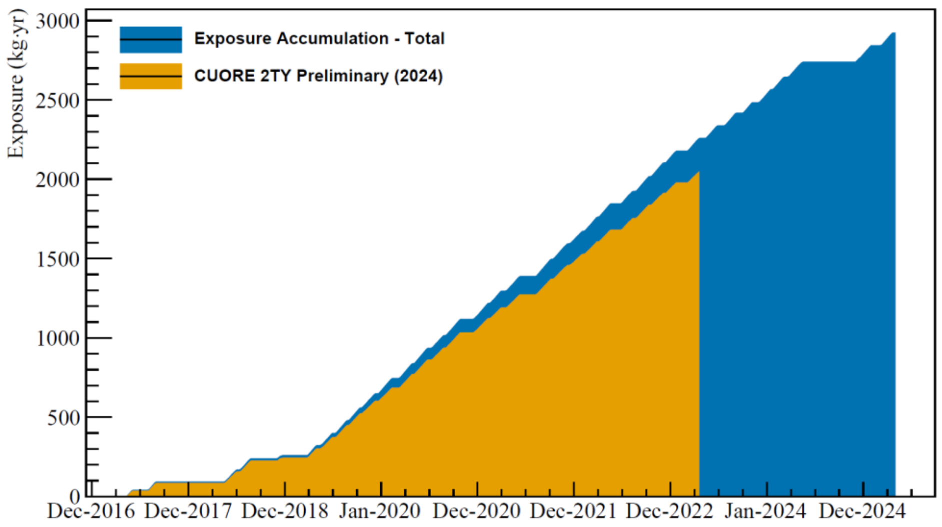


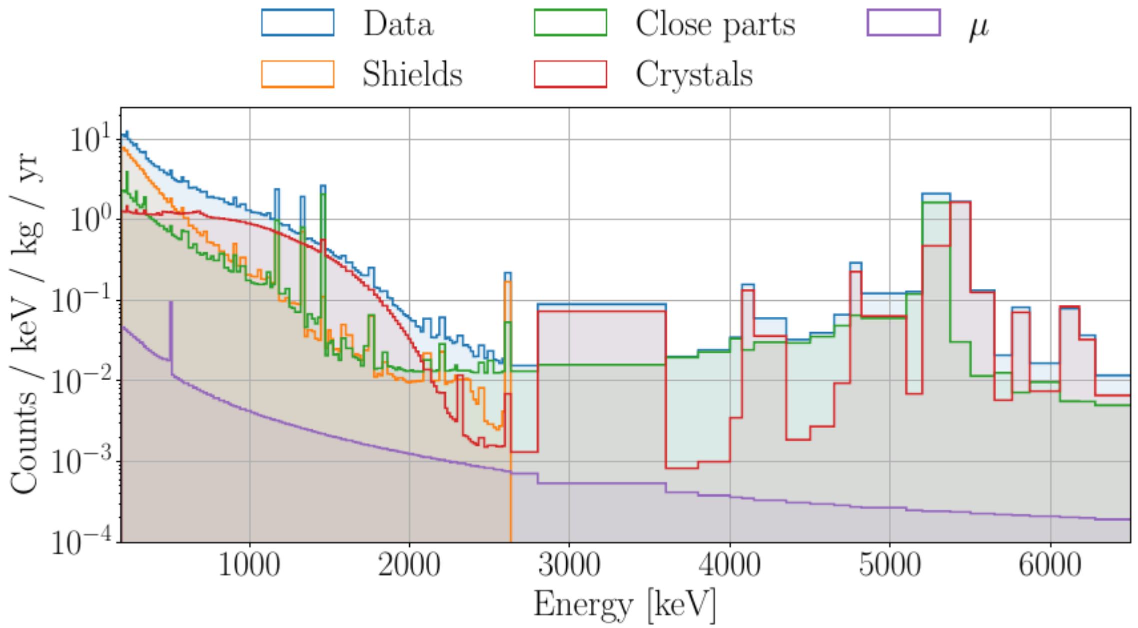

- $^{130}Te$ with a $Q_{\beta\beta}$ = 2527 keV
- Natural isotopic abundance: ~34%
- Embedded in $TeO_2$ crystal
- 988 crystals
- 19 towers with 13 floors each
- 206 kg of $^{130}Te$ (total: 742 kg)

Hosted in Gran Sasso underground laboratory

Shielding from cosmic rays

# CUORE results




- Taking data at LNGS (Italy) at ~ **12-15 mK** since 2017
- Currently > 2.9 ton·yr exposure (raw $TeO_2$)
- CUORE has analyzed 2 ton·yr of data ($TeO_2$ exposure)
- Energy resolution FWHM at $Q_{\beta\beta}$ is ~7.3 keV
- Bkg index in ROI ~$1.4\times10^{-2}$ ckky
- Best limit on $^{130}$Te 0νββ: $m_{\beta\beta}$ < (70-240) meV

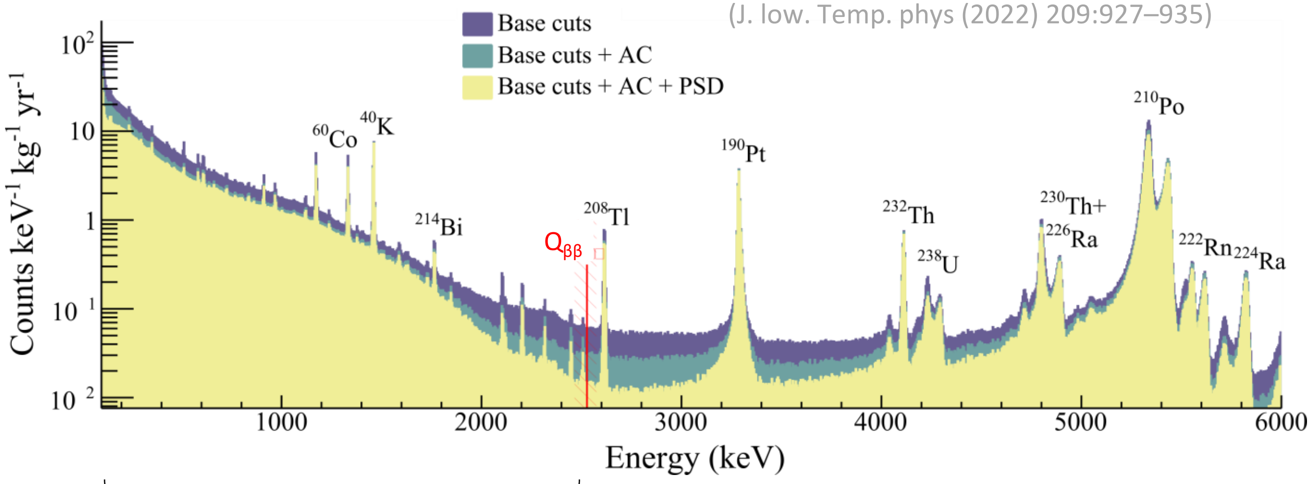
(arXiv:2404.04453)

Data reconstruction:

- Obtain background model, which will guide the design and optimization for future bolometric experiment (Phys. Rev. D 110, 052003)
- Study rare decays ($2\nu\beta\beta$ - $^{130}$Te): most precise measurement (arXiv:2503.24137)

$$T^{2\nu}_{1/2} = \left(9.32\,^{+0.05}_{-0.04}\,\text{stat.}\,^{+0.07}_{-0.07}\,\text{syst.}\right) \times 10^{20}\ \text{yr}$$

# CUORE lessons




β/γ due to radioactive contaminations and $^{130}$Te 2νββ

α events due to close contaminations

**CUORE is not background free**

**~ 50 cnts/yr in the ROI**, dominated by **surface α background (90%) from crystal, PTFE and copper**

## Improvements:

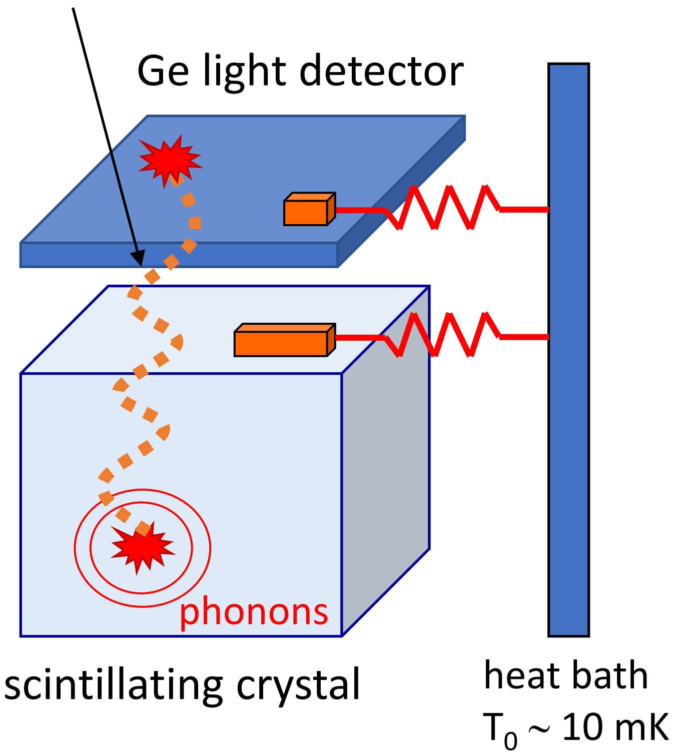
- Discrimination between α and β/γ or between surface and bulk is needed
- Isotope with a $Q_{\beta\beta}$ > 2615 keV
- a BI < $10^{-4}$ ckky is achievable with the CUORE infrastructure

## Three important messages from CUORE

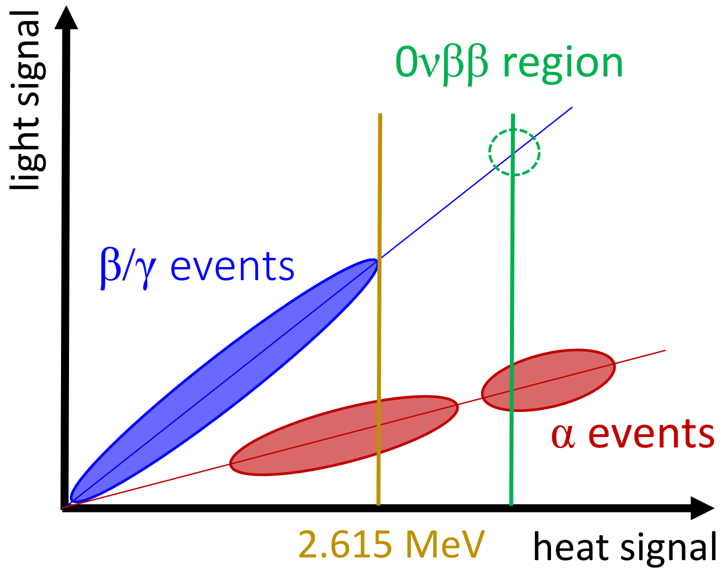
- A tonne-scale bolometric detector is technically feasable
- Analysis of ~1000 individual bolometers is handable
- An infrastructure to host a bolometric next-generation 0νββ experiment exists

# From CUORE to CUPID: scintillating bolometers

**CUPID: CUORE Upgrade with Particle IDentification**




**Dual heat-light readout**



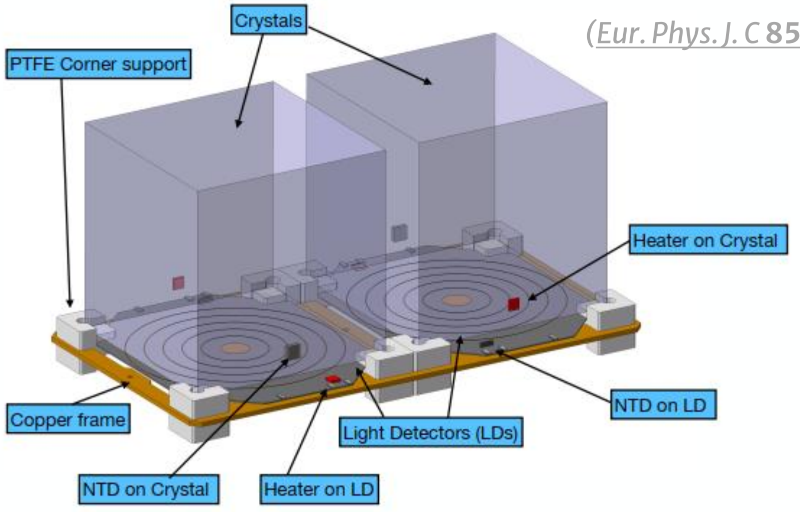

Scintillation at low temperature can be exploited for particle identification

**Light signal for α is quenched**
Amount of light produced in a scintillator by highly ionizing particles as **α** is lower than that for electrons of the same energy
↓
Full discrimination of α particles

# The CUPID experiment

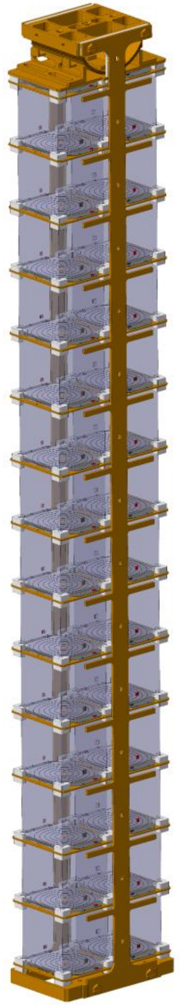
- $Li_2{}^{100}MoO_4$ scintillating crystal 95 % enrichment in $^{100}Mo$
- $Q_{\beta\beta}$ = 3034 keV
- CUPID-Mo demonstrated an excellent α rejection (> 99.9%) and energy resolution at $Q_{\beta\beta}$ (7.4 keV FWHM) (Eur. Phys. J. C **82**, 1033 (2022))

(Eur. Phys. J. C **85**, 737 (2025))



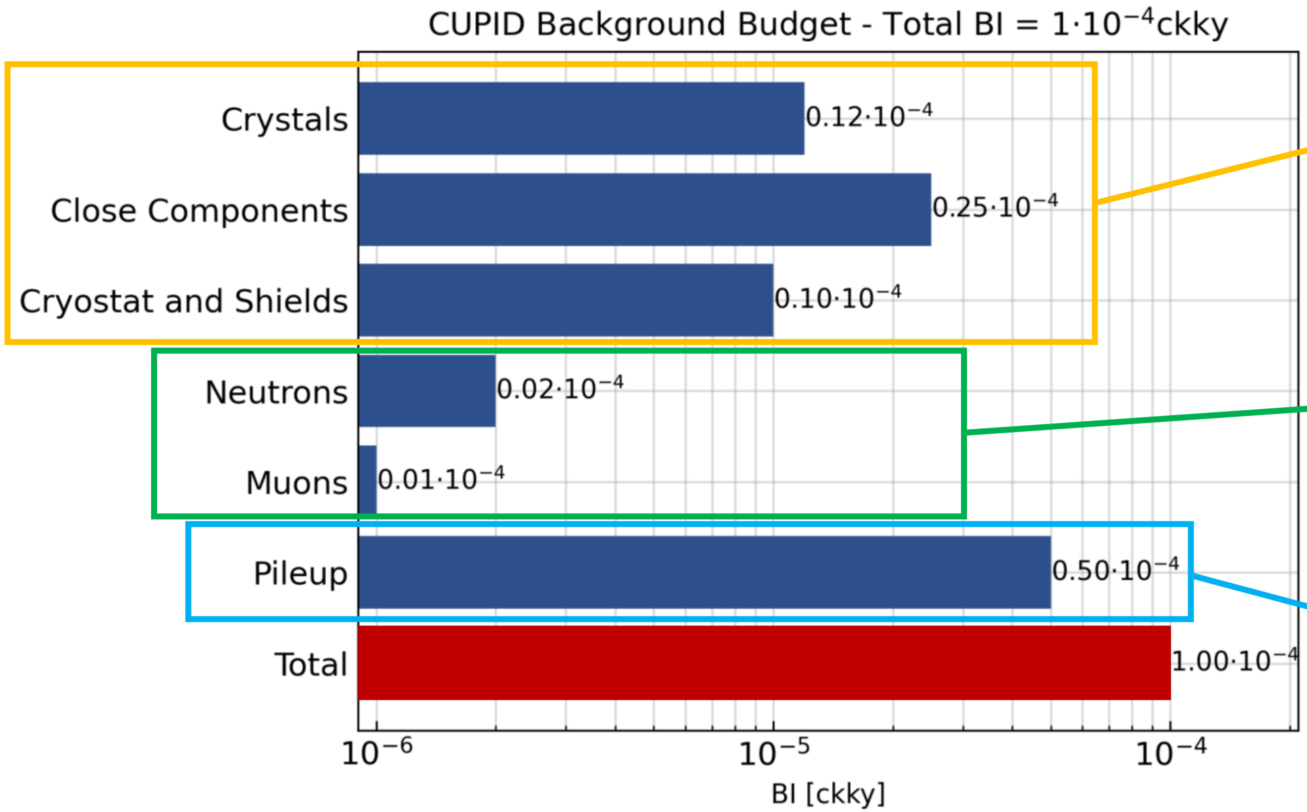

| | CUPID performance aim |
|---|---|
| Energy resolution at $Q_{\beta\beta}$ | 5 keV FWHM |
| Background index | $10^{-4}$ counts/(keV kg yr) |
| $T_{1/2}^{0\nu}$ exclusion sensitivity (90% C.L.) | $1.4\times10^{27}$ yr |
| LD baseline resolution | < 100 eV RMS |
| LY | 0.3 (keV/MeV) |

- 1596 $Li_2MoO_4$ crystals (45×45×45 mm)
- 1710 Ge wafer light detectors
  - With SiO antireflective coating
  - Neganov-Trofimov-Luke effect (NTL) for an enhanced thermal signal
- Arranged in 57 towers of 14 floors
- 240 kg of $^{100}Mo$ (> 95% enrichment)
- Total mass: 450 kg
- Pre-production in China (SICCAS) is ongoing



# CUPID projected background

What we learnt from CUORE, CUPID-Mo and CUPID-0 leads to an expected background index (BI) < $1\times10^{-4}$ counts/(kg keV yr)




$\beta/\gamma$ and $\alpha$ contamination:

- Careful selection of detector components, parts cleaning and handling, adding shielding
- Perform delayed coincidence cuts to remove background from U/Th chains
- > 99.9% of $\alpha$ background rejected by PID

- Shields
- Muon veto system with 99% geometric efficiency

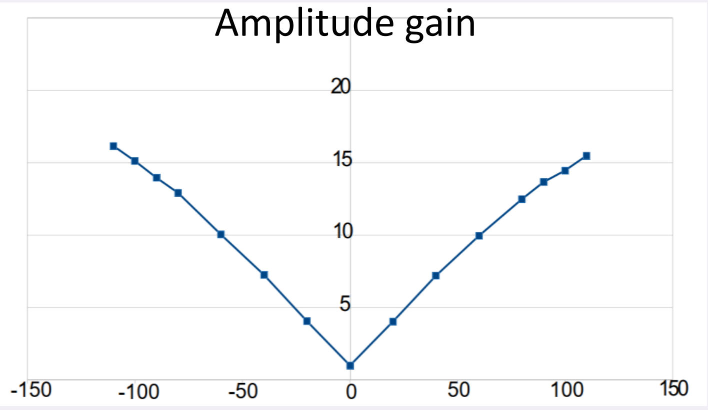
Relatively fast decay rate of $^{100}$Mo $(T_{1/2}^{2\nu} = 7.1\times10^{18}\,yr)$ + the slow pulses in heat channel $\rightarrow$ Random coincidences of $2\nu\beta\beta$ decay in ROI: Neganov-Trofimov-Luke LD

# Pile-up rejection

**Rely on NTL light channel (which is faster) to reject pileups though PSD**

**NTL effect**

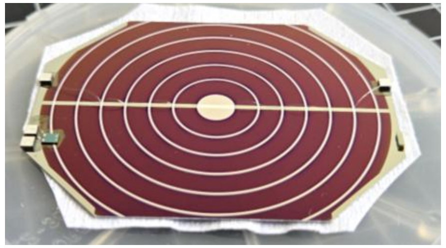
Voltage applied between electrodes
↓
Drifts e-h pair
↓
Generate additional heat
↓
Thermal signal amplification




Voltage bias

**Crucial parameters for pile-up events rejection**

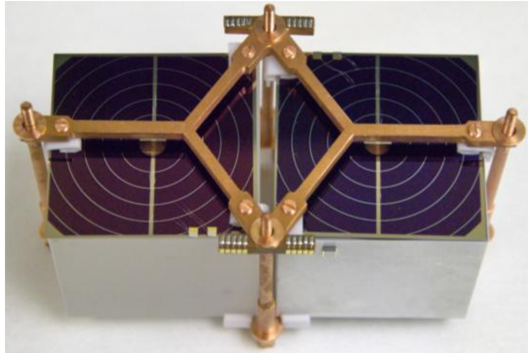
- Signal-to-noise ratio → Improved by **factor ~10** using NTL amplification
- Rise-time → Can be reduced to **0.5 ms** by choosing properly the working point + optimize sensor size to reduce heat capacity

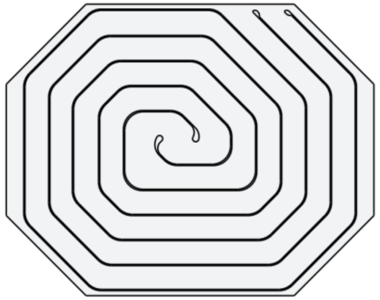


**NTL LDs test @ LSC, Spain** arXiv:2507.15732

8/9 can be biased > 80 V:

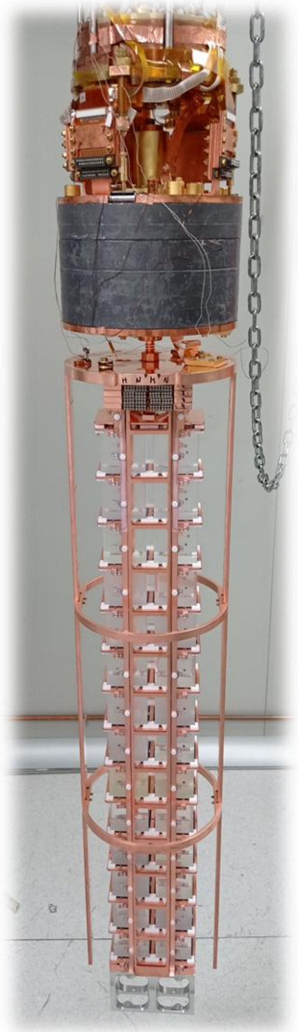
- Gain on S/N: 8.5 @ 80 V
- Fast signals: rise-time close to **0.54 ms**
- Pileup BI = 5.9e-5 ckky (projected to CUPID geometry), close to CUPID goal





Future test:
Optimized electrodes geometry

# Mechanical design test



**GDPT (gravity design prototype tower)**, is the first tower of CUPID-baseline tested at LNGS (Italy) (arXiv.2503.04481):

- 28 $Li_2MoO_4$ crystals arrange in 14 floors, 2 crystals each
- 30 Ge light detectors

## Main results

- Validation of the assembly procedure
- Innovative gravity based approach, copper/LMO ratio < 20%
- Good temperature stability (±0.5 mK at 10 mK)
- **(6.6 ± 2.2) keV** median FWHM @2615 keV (close to CUPID goal)
- **0.36 keV/MeV** light yield (LY) (fulfills CUPID goal)
- Some excess noise on the LD -> changes to the LD assembly structure for the next test

**Next test: VSTT (Vertical Slice Test Tower)**

- NTL LDs for pileup rejection
- Changes to the LD holding system to mitigate the noise

# CUPID: Staged deployment

The collaboration decided to move to a **staged deployment** for CUPID implementation

| | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Previous baseline** | | $Li_2{}^{100}MoO_4$ contract | $Li_2{}^{100}MoO_4$ production 355 xtls/year | | | | | construction and commissioning | | data | |
| **Stage I** 1/3 of the crystals | | $Li_2{}^{100}MoO_4$ contract | $Li_2{}^{100}MoO_4$ production 210 xtls/year | | | | data | | | | |
| **Stage II** Add 2/3 of the crystals | | | | | | $Li_2{}^{100}MoO_4$ production 270 xtls/year | | | | | data |

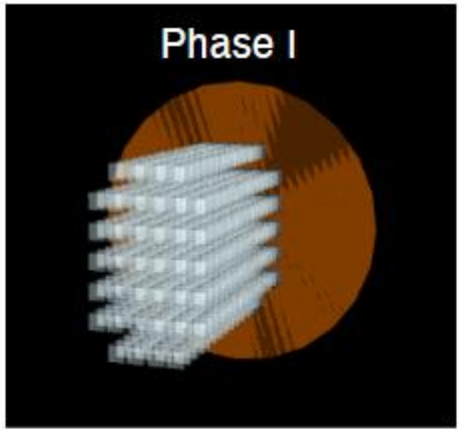
CUORE cryostat upgrade

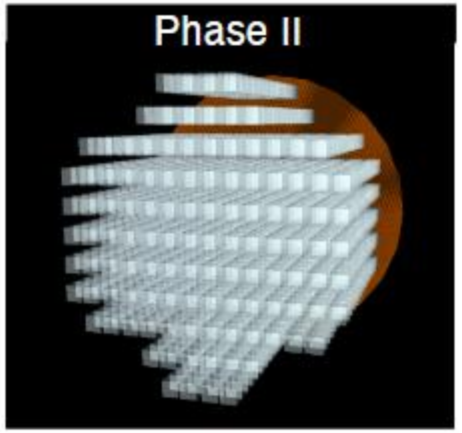
~2x10$^{26}$ y

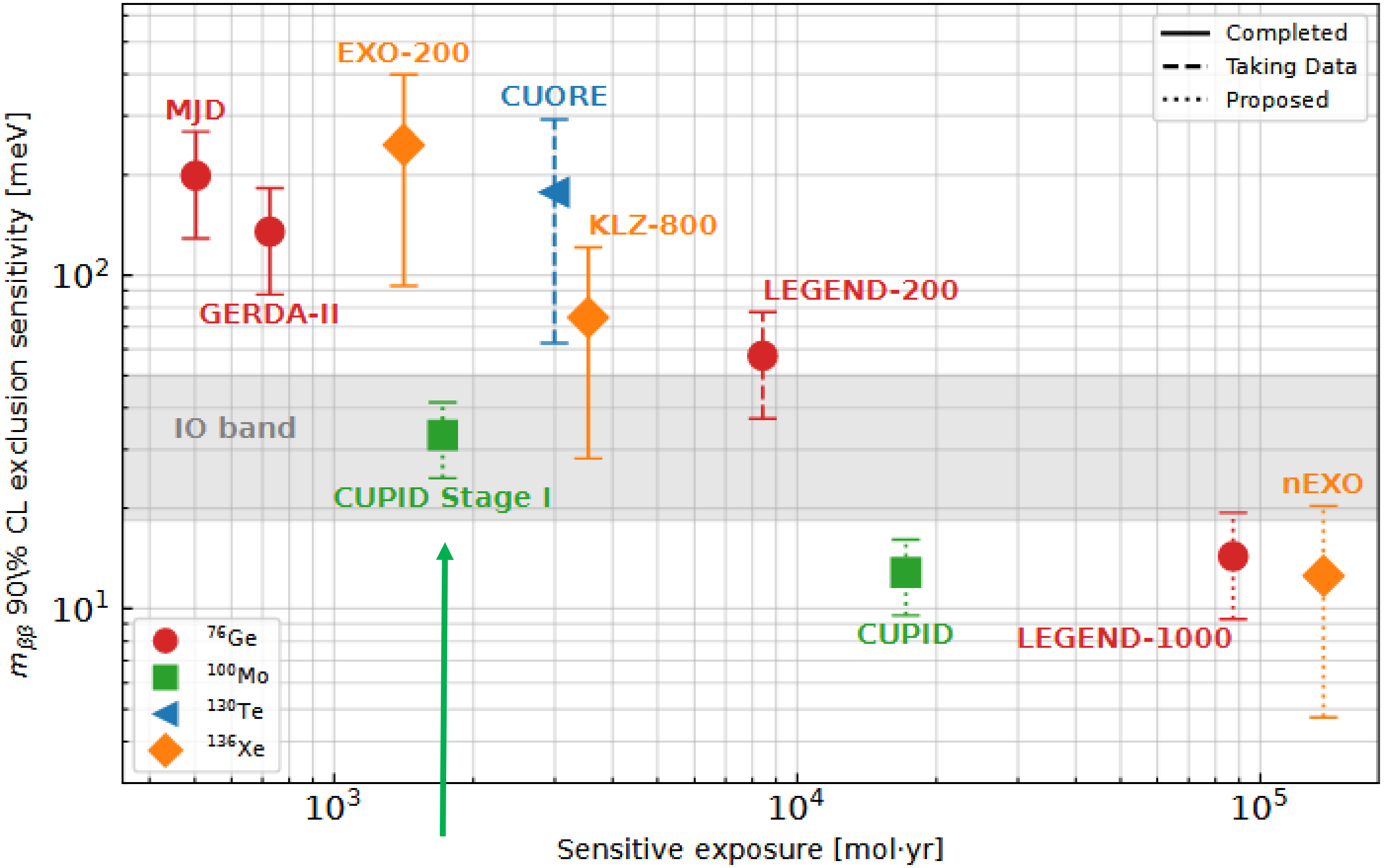
~4x10$^{26}$ y

CUORE cryostat upgrade

# Sensitivity: from stage I to full CUPID and beyond




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

# Conclusions

- CUORE is the first tonne-scale operating cryogenic $0\nu\beta\beta$ decay experiment with steady data taking
- CUORE has analyzed 2 ton·yr ($TeO_2$) of data, with the best limit on $^{130}Te$ $0\nu\beta\beta$
- CUORE opens the way for future bolometric experiment with an existing infrastructure and a known background model
- CUPID takes further steps to fully explore IH region
- CUPID technology is mature, leverages years of experience with CUORE
- Staged deployment: CUPID Stage-I can take data at the end of this decade and has world leading science reach
- CUPID approach is scalable to normal hierarchy region