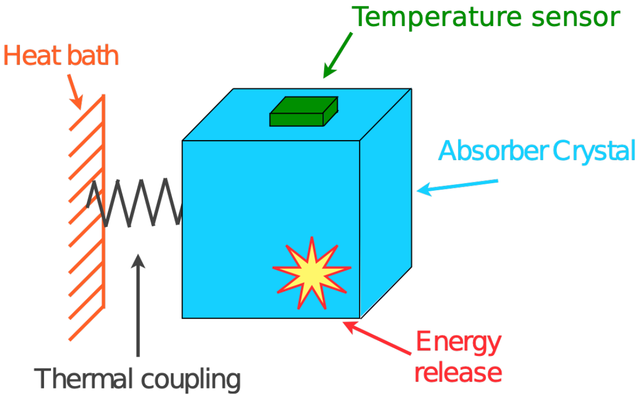
The CUPID neutrinoless double-beta decay experiment

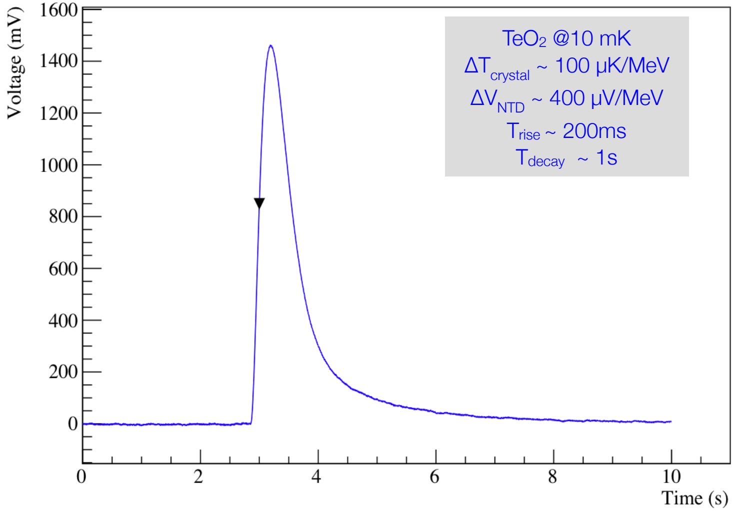
I.Nutini (INFN Milano Bicocca)
on behalf of the CUPID collaboration

August 25th, 2025

0νββ searches with cryogenic calorimeters: how

Cryogenic calorimeters
Conversion of energy deposit into phonons, measuring the heating of the crystal/absorber, which has to be operated at ~10 mK.



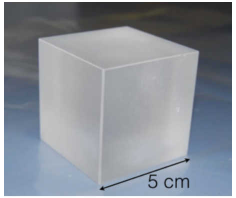


Crystals with masses of ~ tens-hundreds g read by high impedance thermistors are slow detectors (~1ms-1s), still suitable for rare event physics searches

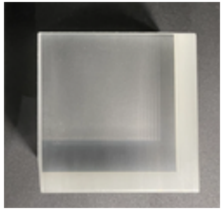
0νββ searches with cryogenic calorimeters: why

- ββ source embedded into the detector: high detection efficiency, ε~1
- Wide choice of absorber materials: possibility to exploit many ββ candidates
- Crystals of masses ~ 0.5kg with reproducible radio purity levels and detector performance: large active mass, up to ton-scale
- High energy resolution detectors (FWHM/E ~ 0.1-0.3% at $Q_{\beta\beta}$): measurement of the sum energy of the two emitted electrons
- Particle ID possibile for scintillating crystals: α background rejection
- Large dynamics: from keV to MeV

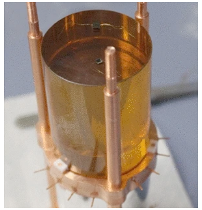
TeO_2 - ^{130}Te

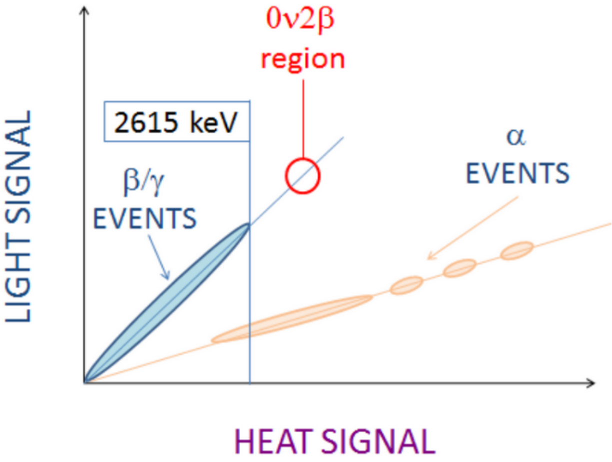


Li_2MoO_4 - ^{100}Mo



ZnSe - ^{82}Se



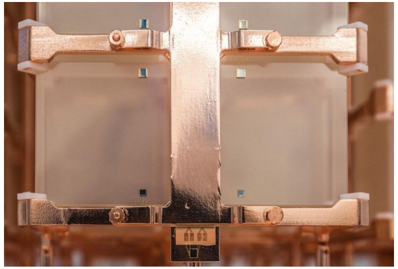


0νββ searches with cryogenic calorimeters: where are we?

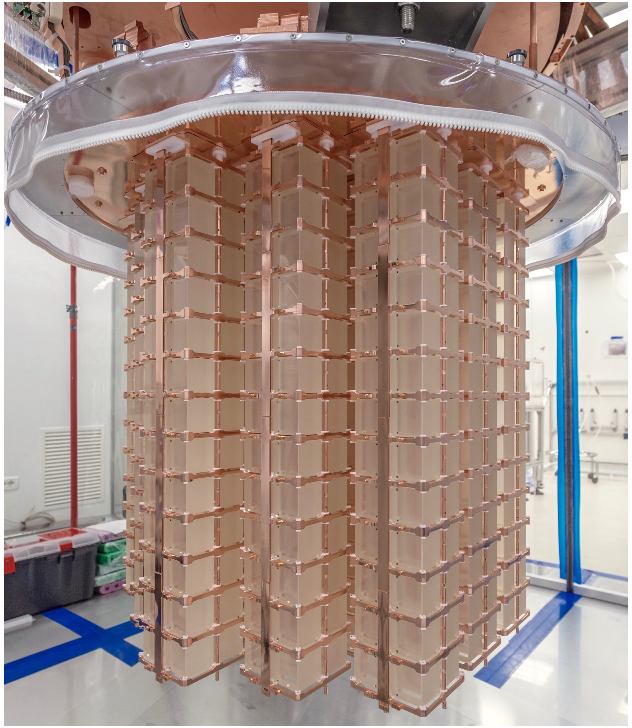
CUORE (2017-ongoing) @LNGS

CUORE 1TY - Nature (2022)

CUORE



TeO_2

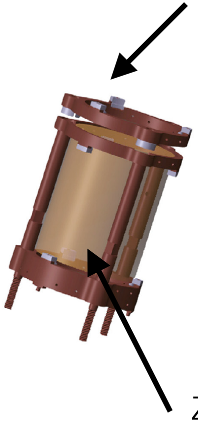


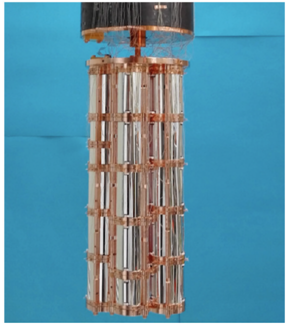
CUORE demonstrated the feasibility of a **tonne-scale experiment** employing cryogenic calorimeters, for the search of the 0νββ decay and rare events

Talk CUORE results (A.Campani) - 25/8

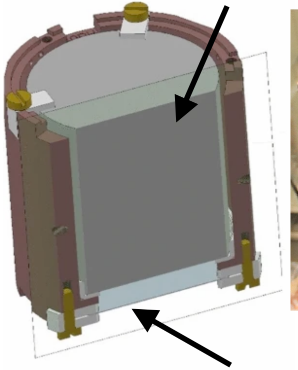
0νββ searches with cryogenic calorimeters: where are we?

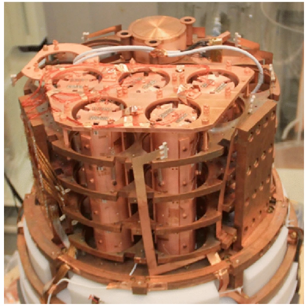
CUPID-0 (2017-2020)
@LNGS

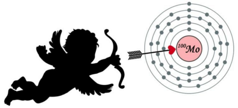




CUPID-Mo (2019-2021)
@Modane







CUPID-0 and CUPID-Mo demonstrated that the **technology of scintillating calorimeters** is mature to be implemented on large scale

Talk Cupid-Mo Li2MoO4 detectors (B.Schmidt) - 26/8

The path towards CUPID

CUPID: CUORE Upgrade with Particle Identification

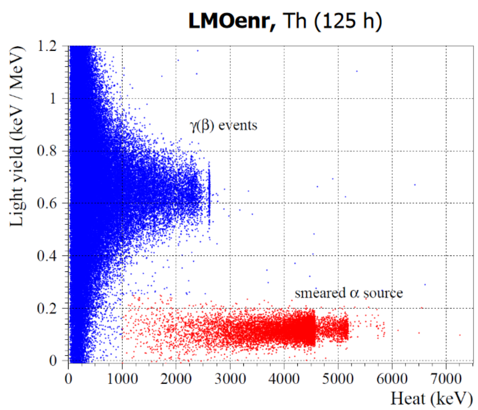
Exploit ^{100}Mo as ββ candidate

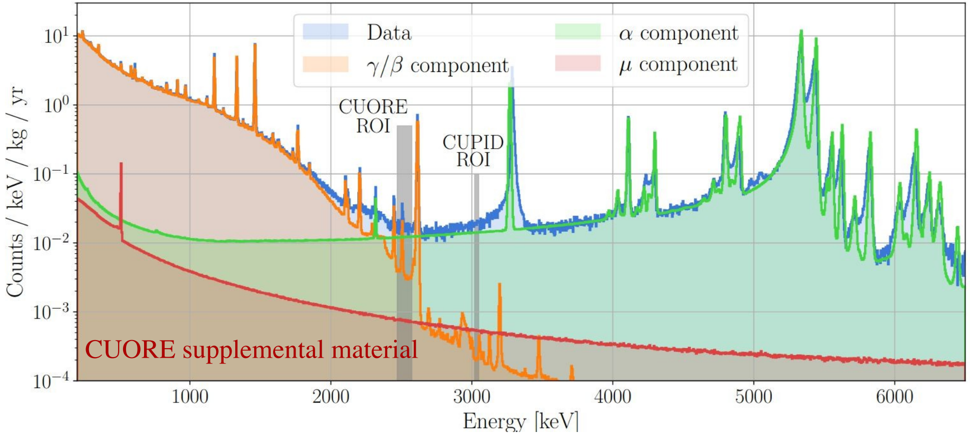
→ Utilise Li_2MoO_4 **scintillating crystals** for particle ID: high reduction of α background

→ Higher Q-value ($Q_{\beta\beta}$ = 3034 keV), most β/γ backgrounds reduced

→ Better phase space ad NME compared to ^{130}Te

CUORE background in the ^{100}Mo region, once α and μ are removed, is close to 10^{-4} cts/(keV kg yr)





CUORE Bkg Model - PRD (2024)

The CUPID project goals

Probe the full IH region for $m_{\beta\beta}$

Active mass:
450 kg (240 kg) $Li_2{}^{100}MoO_4$ (^{100}Mo)

Livetime:
10 yr

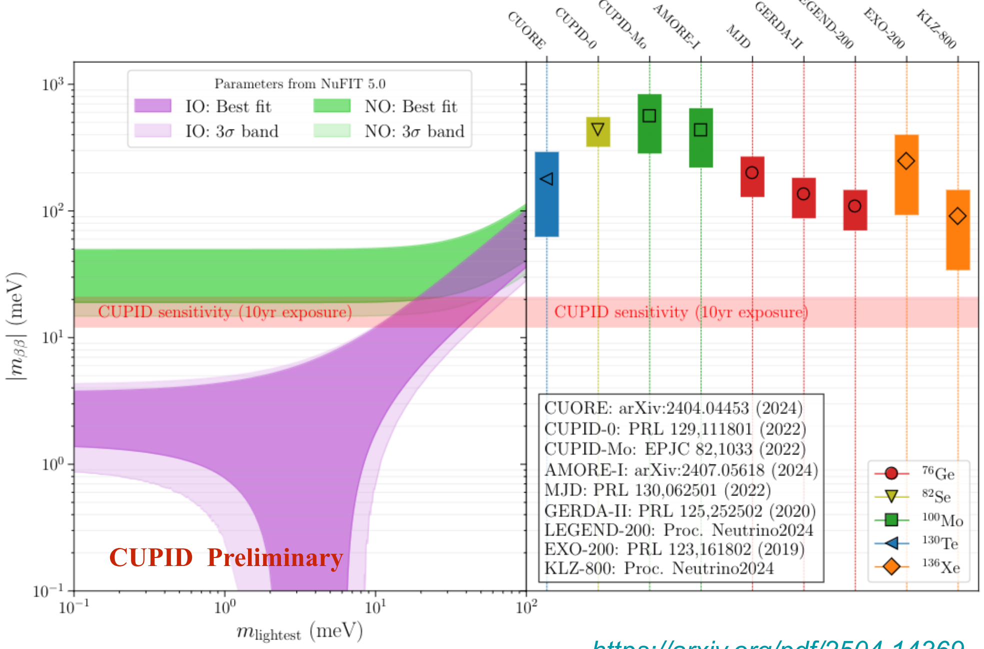
Energy resolution:
5 keV FWHM at $Q_{\beta\beta}$

Background index:
BI < 10^{-4} cts/(keV kg yr)

Sensitivity goal:
$T^{0\nu}_{1/2}$ = 1 x 10^{27} yr
$m_{\beta\beta}$ = 12-20 meV

Talk Sensitivity CUPID (P.Loaiza) - 26/8

CUPID



https://arxiv.org/pdf/2504.14369

The CUPID Experiment

Replace CUORE TeO_2 detector with an array of $Li_2{}^{100}MoO_4$ scintillating crystals

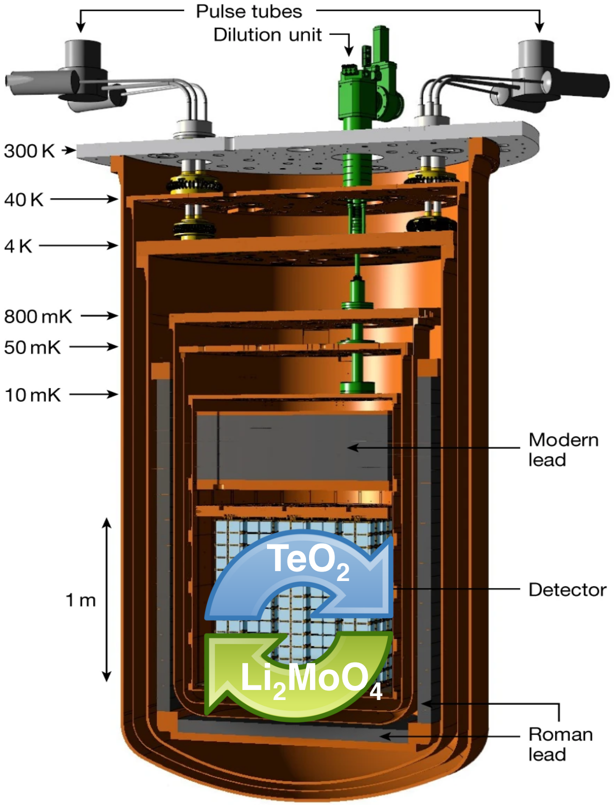
New detector array:

- 1596 Li_2MoO_4 scintillating crystals (280 g each)
- 1700 light detectors → scintillation signal read-out
- Mo enrichment > 95% in ^{100}Mo

Additional needs:

- Upgrade the CUORE cryostat for a ~1600 double read-out array
- Improve external n-shield & add a μ-veto

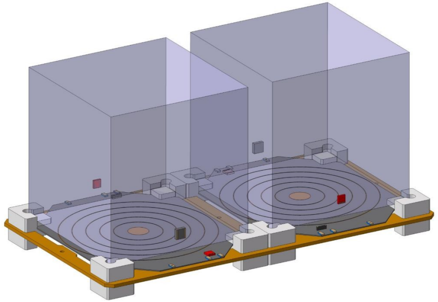
https://arxiv.org/pdf/2503.02894 (Accepted for publication by EPJC)

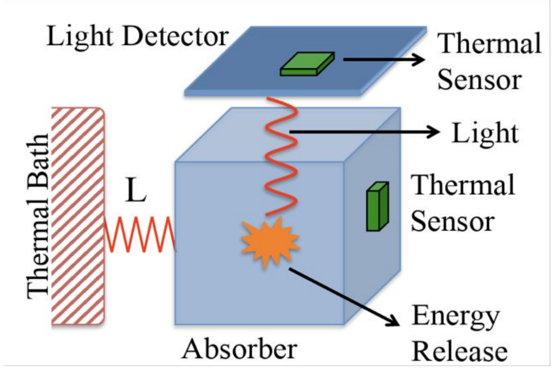


The CUPID detectors

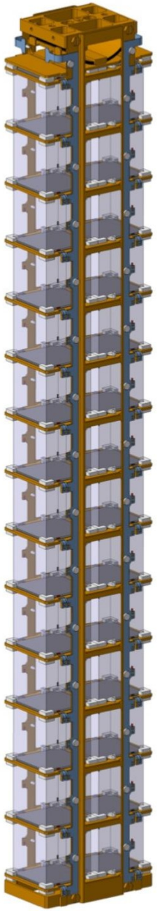
The detector is the major change in CUPID:

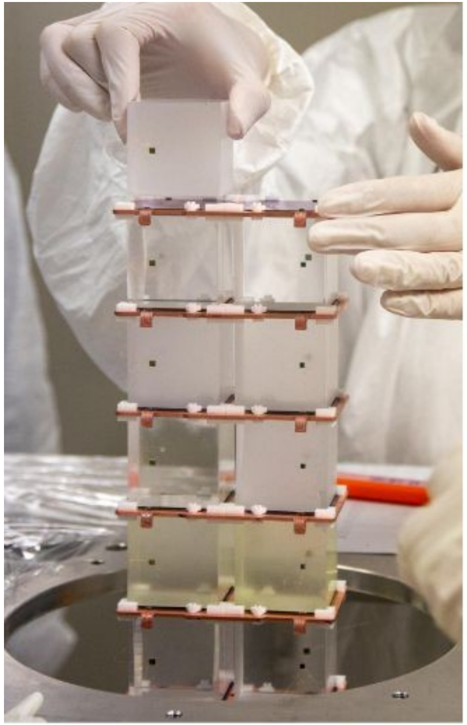
- enriched Li_2MoO_4 (LMO) crystals
- light detectors (LD)
- mechanical assembly





- Crystals and light detectors are both read with Ge-NTD sensors
- Each crystal has top and bottom light detectors



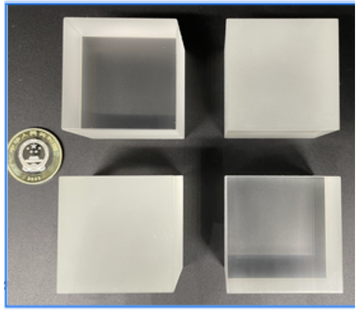


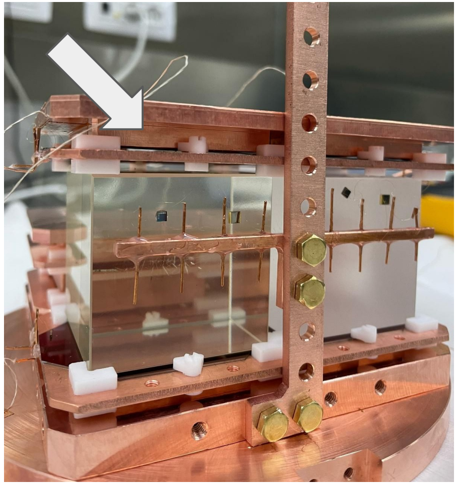
The CUPID detectors

Talk CUPID CCVR (M.Girola) - 27/8

$Li_2{}^{100}MoO_4$ crystals:

- Procurement of ^{100}Mo isotope (IPCE) compliant with requirements
- Controlled $Li_2{}^{100}MoO_4$ crystals production chain: detector performance, optical properties (light yield, transmission), radiopurity, minimal loss of isotopes (SICCAS)
- Sequential crystal tests at LNGS CUPID HallC facility (CCVR runs) to assess crystals performances at 10mK and analyse residual radioactivity *(ongoing)*





Background of enriched LMO crystals operated at 10mK (slow detectors) will be dominated by $2\nu\beta\beta$ rate ~ 2.6 mHz/crystal

The CUPID detectors

Light detectors:

Poster NTL LDs #77 (H.Khalife) - 27/8

NTL Light Detector technology now well established:

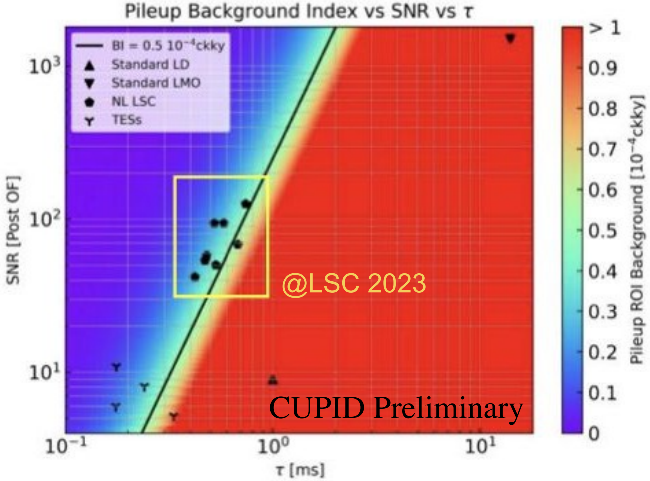
Ge wafer + NTD Ge thermistor + a set of electrodes: Exploit Neganov-Trofimov-Luke effect

Signal amplification allows the use of light detectors for efficient $2\nu\beta\beta$ pile-up rejection

NTL LD - France

NTL LD - US

https://arxiv.org/pdf/2507.15732



- Still room for optimization and improvements
- Large scale test of NTL detectors in CUPID demonstrators
- Ready for mass production

Progress on CUPID prototype towers

GDPT (Gravity Detector Prototype Tower)

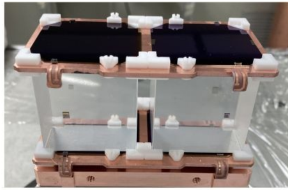
Innovative assembly design, compared to all the precursors (CUORE/CUPID-0/CUPID-Mo), that has advantages in production/cleaning/detector construction ease and time

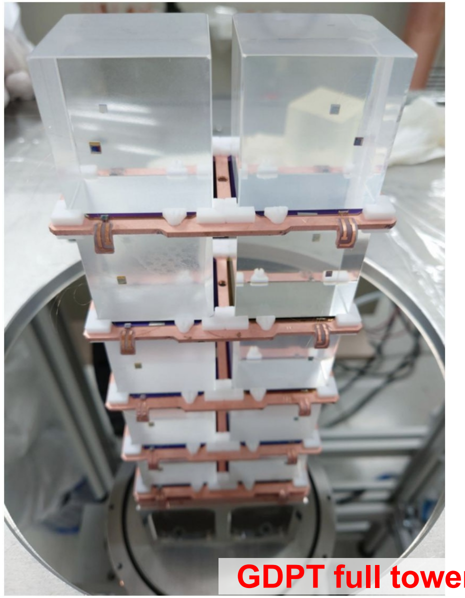
Conceptual test of the new mechanical assembly of the tower (GDPT). Run in CUPID HallA facility @LNGS (2022)

The first full tower test was successful, but LDs experienced limited SNR and correlated noise

https://arxiv.org/pdf/2503.04481 (Accepted for publication by EPJC)

GDPT single module





GDPT full tower

Progress on CUPID prototype towers

CUPID

VSTT (Vertical Slice Test Tower)

Poster VSTT #154 (I.Nutini) - 27/8

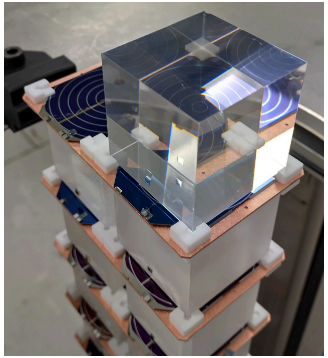
Full integrated test in CUPID HallA facility @LNGS (2025)

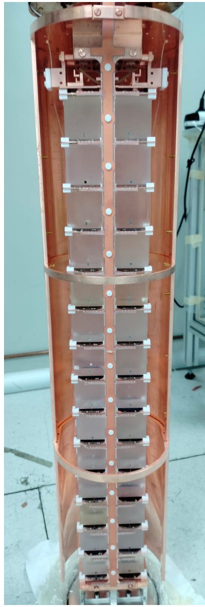
- Mechanical assembly with upgraded tower design
- Test of the assembly-line (glueing, mounting, bonding,…)
- NTL light detectors
- Optical fibers along the tower
- New electronics and DAQ

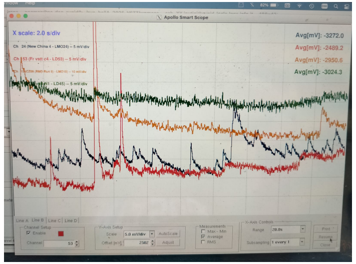
VSTT cooled down in **early August 2025**, at Tbase 7mK. Currently taking data for characterising the detectors response!

VSTT will prove the overall readiness to CUPID detector construction

VSTT: tower assembly and installation



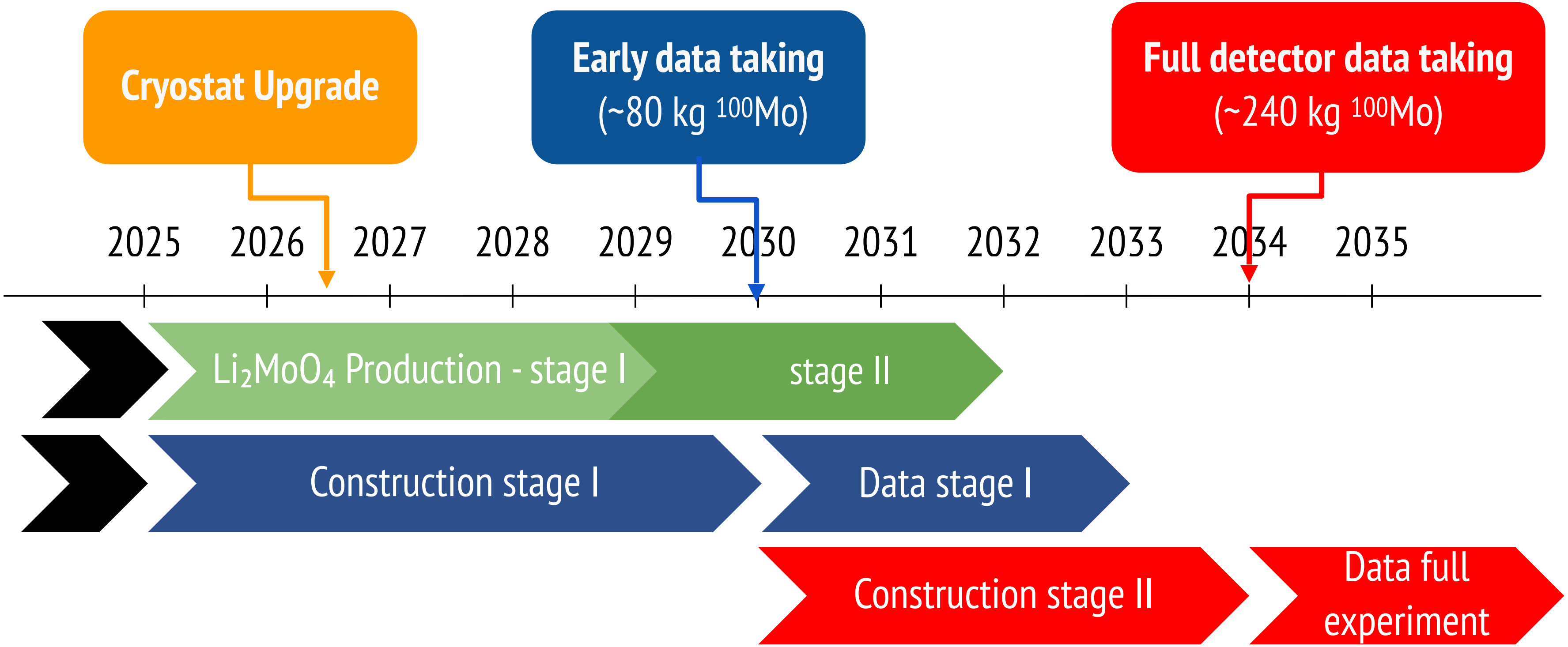




VSTT first pulses at ~7 mK

CUPID timeline

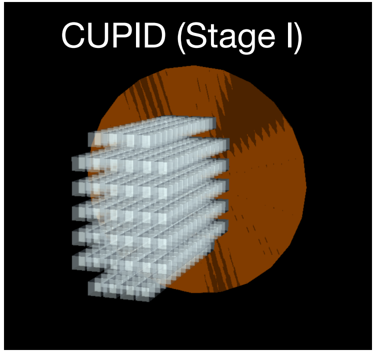
CUPID staged deployment

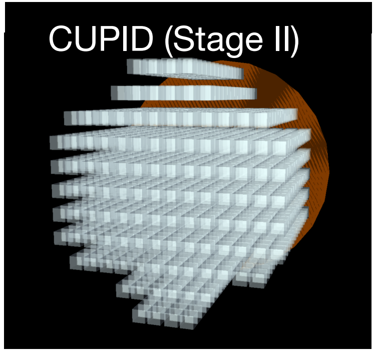


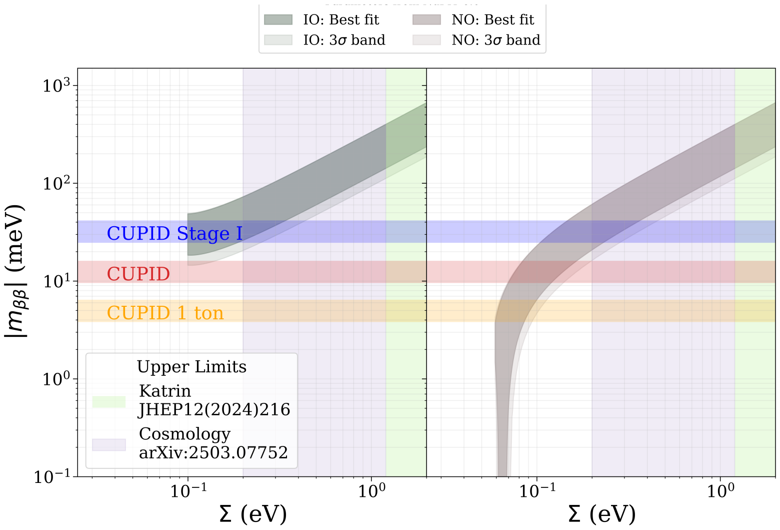
CUPID timeline

CUPID staged deployment

- Cryogenic upgrade [2026-2029]
  - Test of upgraded cryostat with CUORE detector in place (CUORE-phase II) [2027]
- CUPID Stage-I: 1/3 of the crystals & 3 year data-taking [2028-2033]
  - Early data from CUPID
  - Risk mitigation
- CUPID full array: Add the remaining 2/3 of the crystals [2029 - 2034] & full data-taking [> 2034]
- R&D towards CUPID 1ton, with further background reduction







CUPID summary and outlook

Next-generation 0νββ experiments aim to probe lepton number violation and to extend sensitivity to fully cover the inverted hierarchy region of neutrino mass.
A multi-isotope approach is essential to ensure robust discovery potential.

CUPID builds directly on CUORE, the world's largest cryogenic calorimeter array for rare event searches.

- CUPID has a path for isotope enrichment, procurement and crystal growth
- Final technical integration tests are underway at LNGS
- CUPID is ready to start construction
- Preparations for cryostat upgrade are underway at LNGS
- CUPID will pursue a staged deployment

CUPID will play a central role in the 0νββ search and discovery program at LNGS in the next years

Thank you on behalf of the CUPID Collaboration

CUPID

CNRS IN2P3
NRC KI-ITEP
Università degli Studi di Milano Bicocca
iP2i
Beijing Normal University
University of California
University of South Carolina
IMM Bologna Unit
cea
Fudan University
VirginiaTech Invent the Future
UCLA
IJCLab Irène Joliot-Curie
Johns Hopkins University
Argonne National Laboratory
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Massachusetts Institute of Technology
Northwestern
araid
Yale
CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza
Boston University
Drexel University
GSSI

CUPID and related contributions at TAUP

- *Sensitivity of the CUPID experiment to 0nubb decay of 100Mo* (P. Loaiza), 26/08
- *Detector response study of cryogenic scintillating Li2MoO4 detectors for next generation 0νββ search* (B.Schmidt), 26/08
- *CUPID-CJPL: a cryogenic bolometer testbed* (H.Chen), 26/08

- *Validation of LMO crystals for the CUPID Experiment* (M.Girola), 27/08

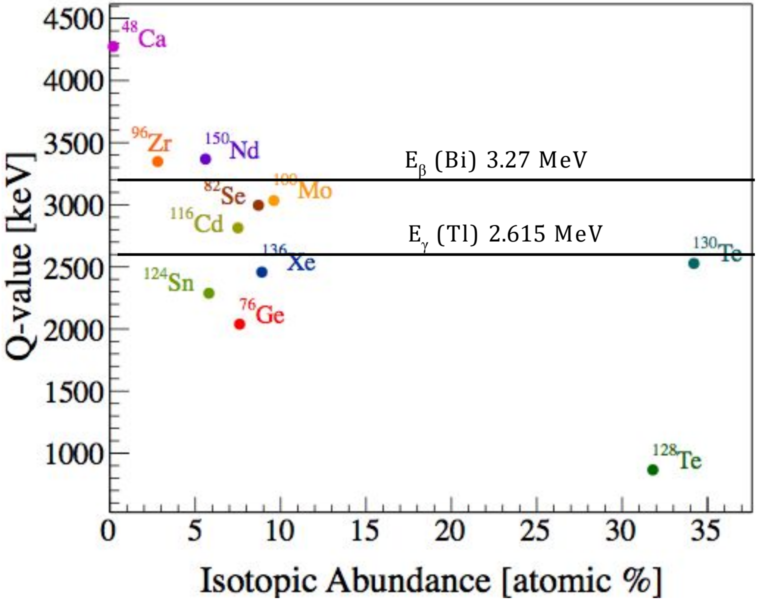
- *Performance Validation of the VSTT: An Upgraded CUPID Prototype Tower with Neganov-Luke Enhanced Light Detectors* (I.Nutini) [poster]
- *Neganov-Trofimov-Luke light detectors in 0vbb experiments* (H.Khalife) [poster]

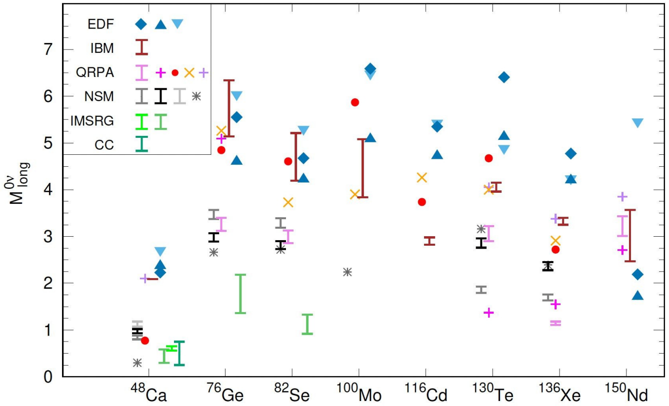
- *The CUORE experiment: current status and road ahead* (A.Campani), 25/08
- *Toward a background-free ton-scale 0νββ bolometric experiment: Status and Prospects of BINGO* (C.Nones), 25/08
- *High-precision study of 2νββ of 130Te from the CUORE experiment* (S.Dell'Oro), 26/8
- *The CROSS demonstrator: structure, performance and physics reach* (A.Giuliani), 27/8

CUPID

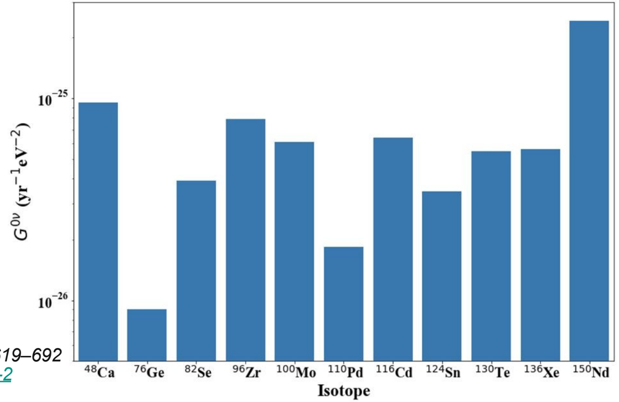
Backup

0νββ searches: candidate isotopes



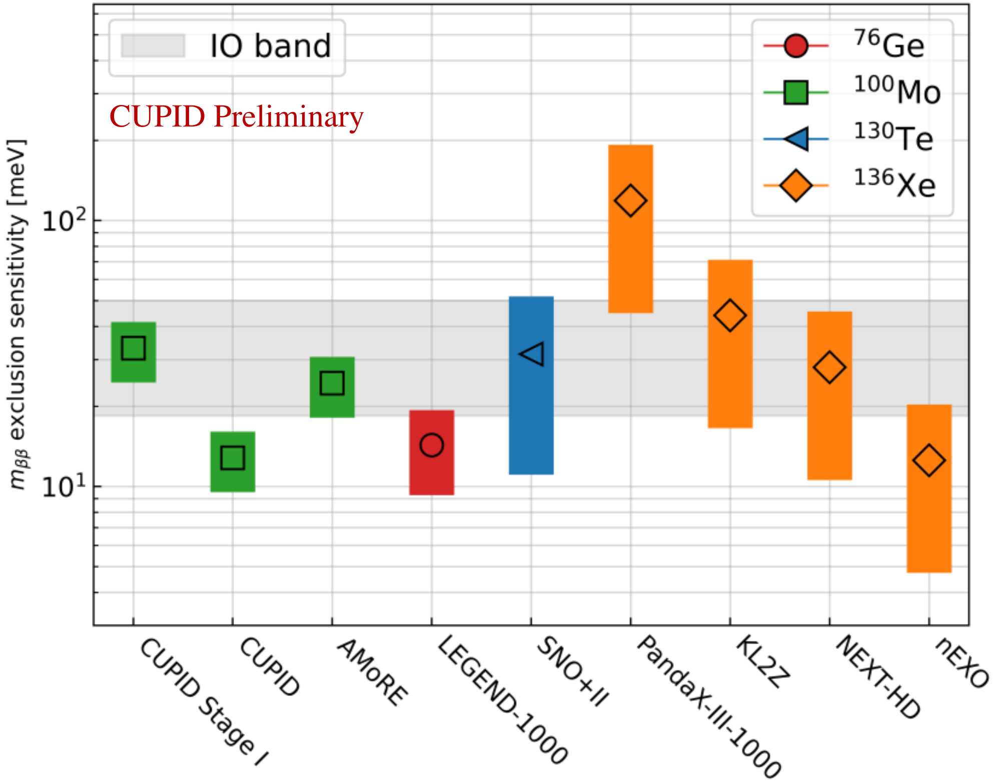


Rev. Mod. Phys. **95**, *025002; https://doi.org/10.1103/RevModPhys.95.025002*



La Rivista del Nuovo Cimento (2023) 46:619–692
https://doi.org/10.1007/s40766-023-00049-2

CUPID sensitivity vs other experiments

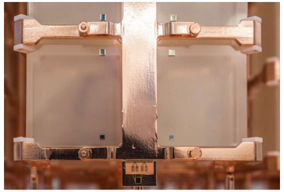


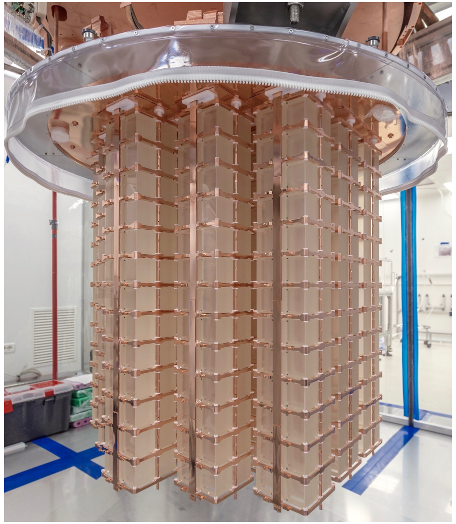
0νββ searches with cryogenic calorimeters: where are we?

CUORE

CUORE (2017-ongoing) @LNGS

TeO2





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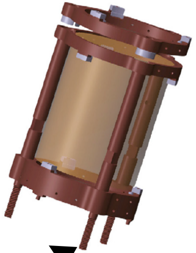
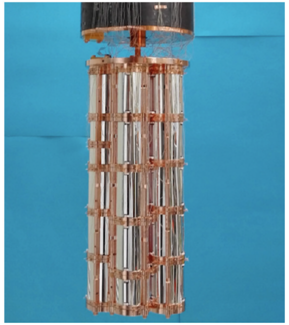
CUPID-0 (2017-2020) @LNGS

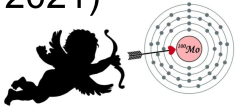
Ge LD



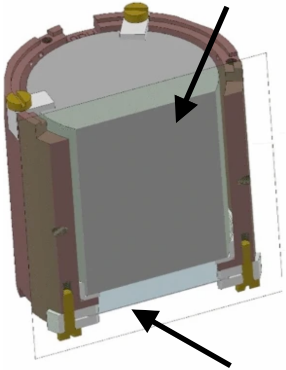
ZnSe



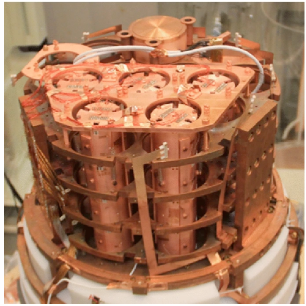
CUPID-Mo (2019-2021) @Modane



Li_2MoO_4



Ge LD

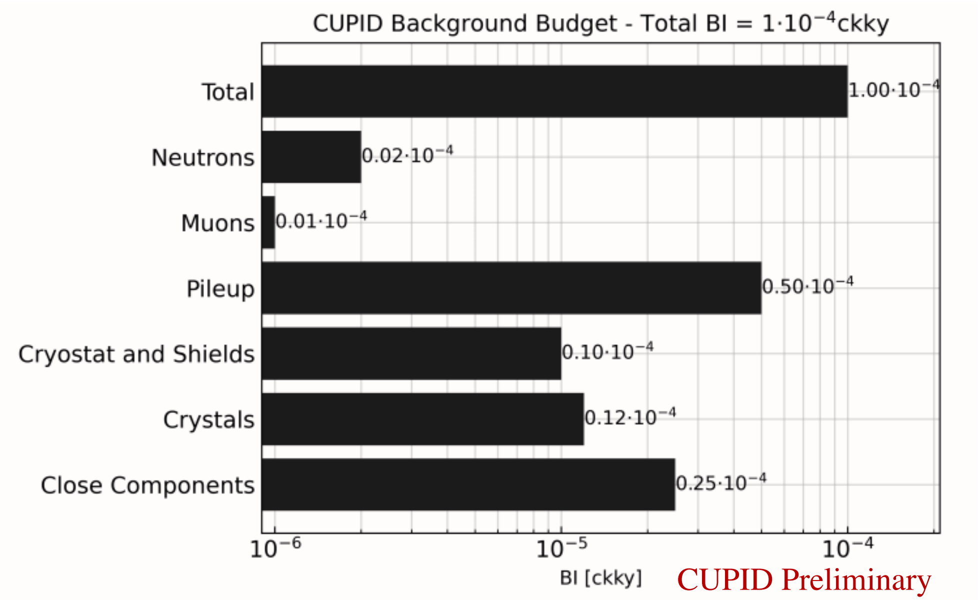


CUPID-0 and CUPID-Mo demonstrated that the **technology of scintillating calorimeters** is mature to be implemented on large scale

CUPID background

Background Index (BI) goal for the counting rate in ROI < 1 x 10-4 ckky

In order to achieve this BI:
- α rejection with scintillation light readout, 99.7 %
- 2νββ pileup rejection (90%) with 0.1ms time resolution of the LDs
- Addition of a μ-veto
- Improved external n-shield

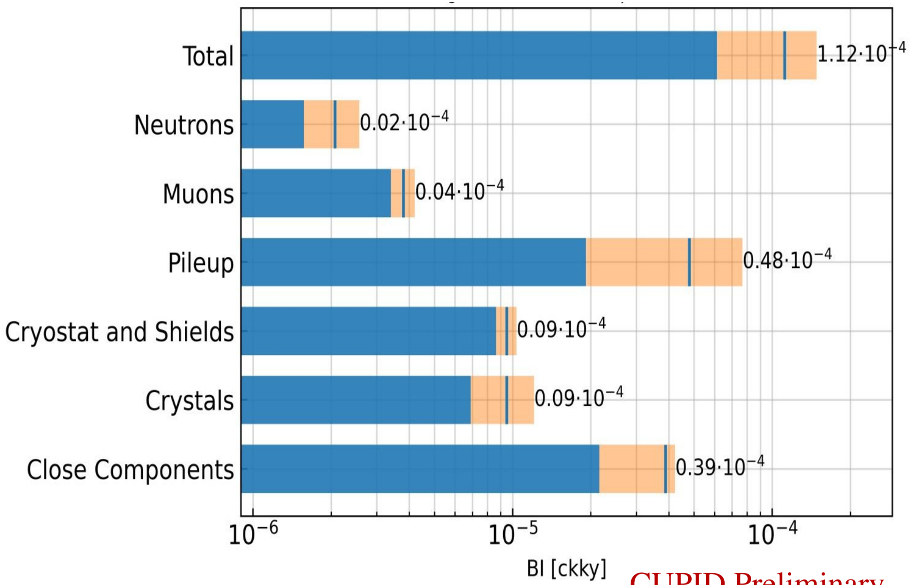


CUPID background

Current background projections based on currently available data* = **1.1 x 10^{-4} ckky**

68% interval = (0.6, 1.5) x 10^{-4} ckky

* CUORE background model, CUPID-Mo background model, material assay



CUPID Preliminary

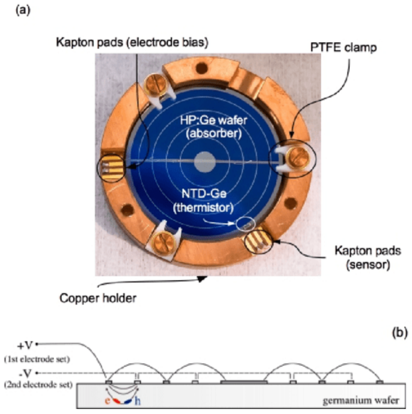
The CUPID detectors

Poster NTL LDs (H.Khalife) - 27/8

Light detectors:

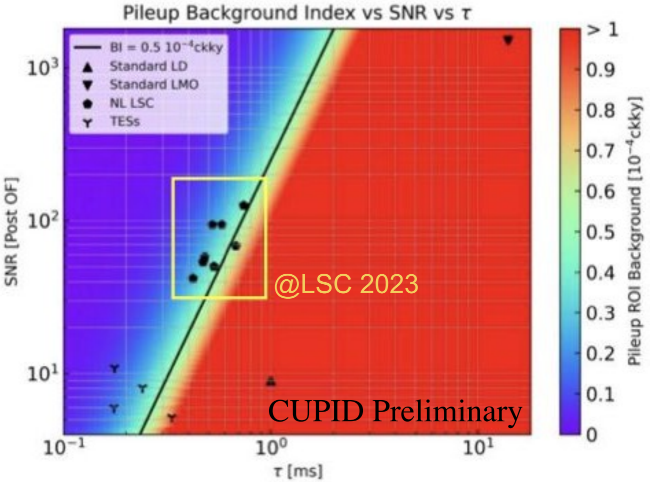
Standard Light Detector = Ge wafer + NTD Ge thermistor

NTL Light Detector = + a set of electrodes. Exploit Neganov-Trofimov-Luke effect. Charge to heat transduction. an electric field applied to the Ge substrate drifts e-hole pairs produced by scintillation light, while drifting they generate more phonon excitations; the result is signal amplification with constant noise, improved SNR for LDs.



https://doi.org/10.1016/j.nima.2019.06.044

Signal amplification allows the use of light detectors for efficient $2\nu\beta\beta$ pile-up rejection



Progress on CUPID prototype towers

GDPT (Gravity Detector Prototype Tower)

Conceptual test of the new mechanical assembly.
Run in CUPID HallA facility @LNGS (2022)

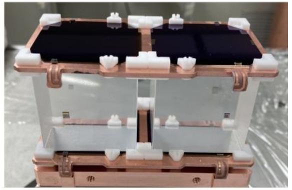
- Uniform thermalization along the tower ✅
- Stability of detector performance over 1-2 months of data taking ✅
- Good energy resolution of LMOs ✅

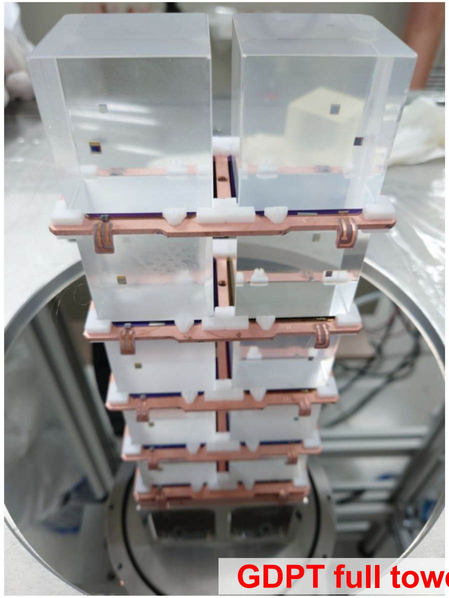
But

- Limited SNR of LDs
- Residual correlated noise on LDs

https://arxiv.org/abs/2503.04481

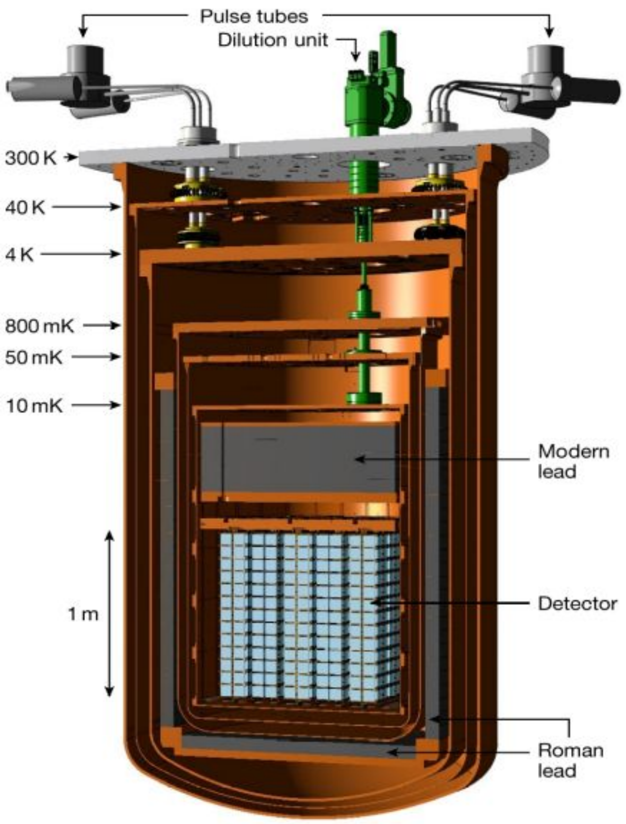
GDPT single module





GDPT full tower

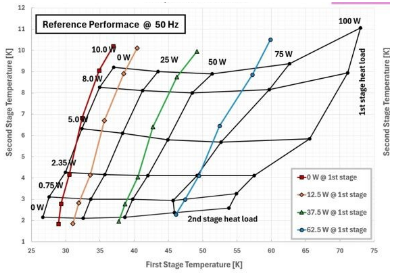
CUPID cryogenic infrastructure upgrades

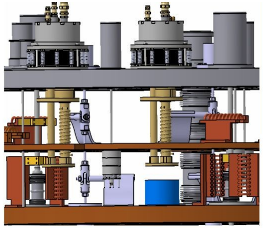


Leveraging the CUORE experience with the cryogenic infrastructure
- Long term cryostat performances
- Temperature stability
- Vibrational decoupling: stable and high energy resolution

Upgrades:

- 3 more efficient PTs (PT-425 RM: Base T ~ 1.9K) with improved thermal link (Al6N)
- Noise reduction: anti vibration collars for the PTs, dynamical and vibrational structural analysis, new vibrational sensors





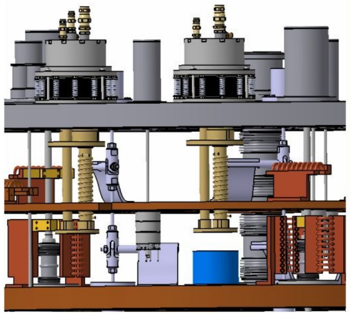
CUPID timeline

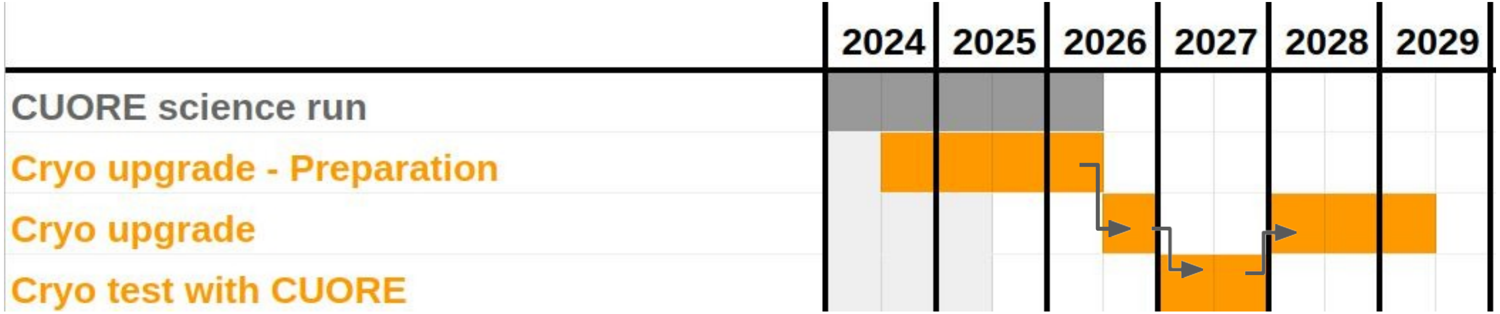
Joint CUORE+CUPID activity

Cryostat upgrade and CUORE-phase II (low energy run)

Leveraging the CUORE experience with the cryogenic infrastructure and running detectors inside.

Cryogenic upgrades: new more efficient pulse tubes (PTs), new PT mechanical insulation system and thermalizations, new vibrational sensors for noise characterization and decorrelation

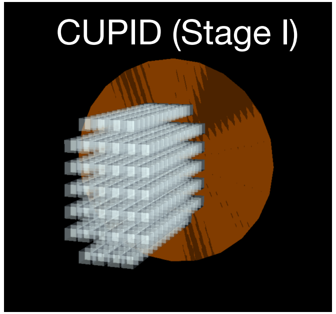


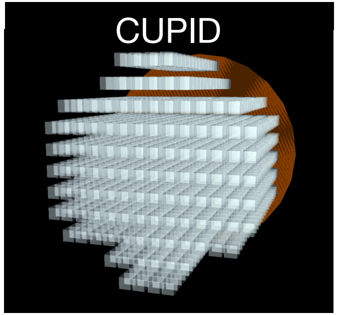


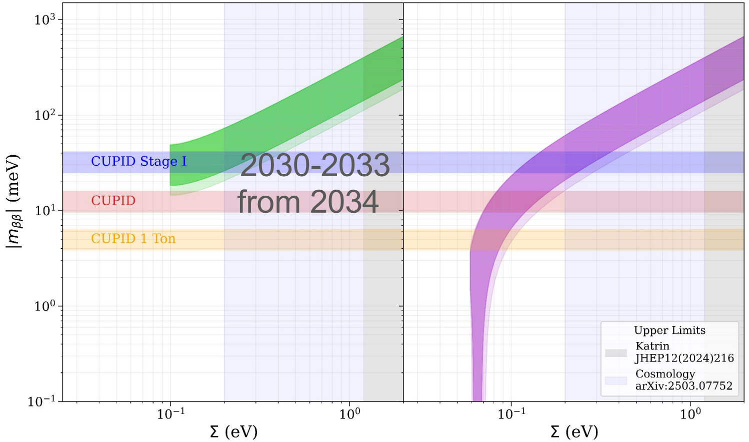
CUPID timeline

CUPID staged deployment

- CUPID Stage-I: 1/3 of the crystals & 3 year data-taking [2028-2033]
  - Early data [2030] (small gap between CUORE-phase II shut down in 2027 and first CUPID data)
  - Risk mitigation (early identification of issues)
- CUPID full array: Add the remaining 2/3 of the crystals [2029 - 2034] & full data-taking [> 2034]
  - Enrichment and crystal growth will proceed in parallel with Stage-I data-taking







Interplay with other mass measurements:
- Katrin
- cosmology
- ordering from oscillations