The CUPID experiment

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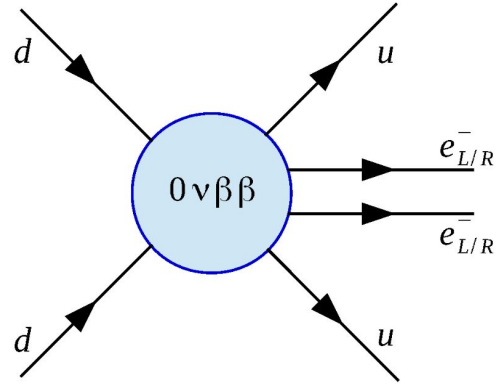
Neutrino-less double beta decay

Double beta decay: second order nuclear process, alternative to beta decay when forbidden by negative mass difference for some even-even nuclei

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

2nd order SM process, observed on nuclei with $T_{1/2} \sim 10^{18\text{-}24}$ years

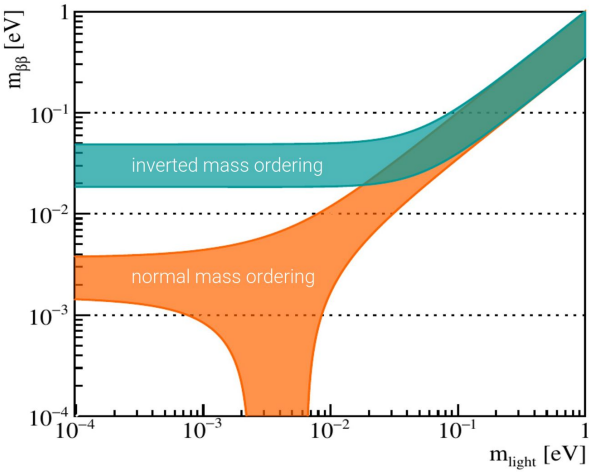
$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$



- SM forbidden, lepton number violation → **MATTER CREATION!**
- **if** observed, **then** neutrino is a Majorana particle
- underlying mechanism can give insight into BSM physics:
  - light neutrino mass scale and hierarchy
  - heavy, sterile neutrinos

Effective neutrino mass $m_{\beta\beta}$:

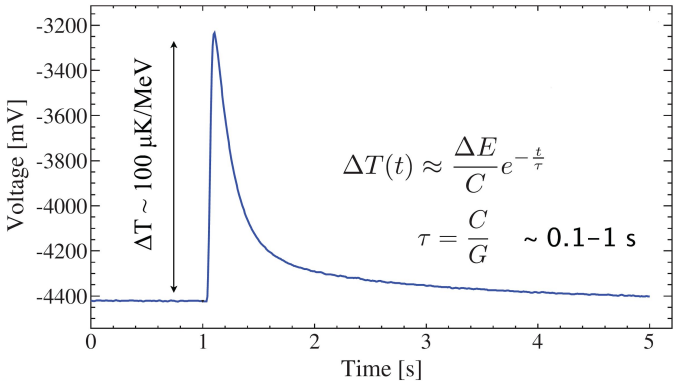
- measures the intensity of the new-physics involved in the process
- compares different isotopes

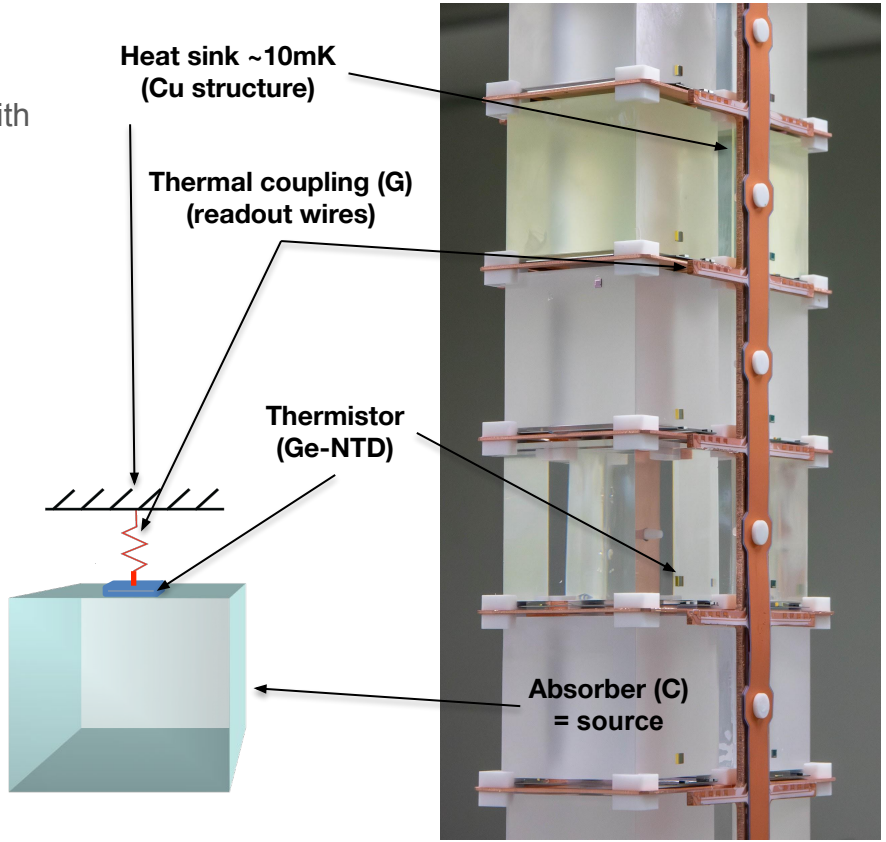


Experimental technique: low temperature detectors

Low temperature detectors:

- macroscopic (hundreds of grams) crystals instrumented with thermistors operated @10 mK → low thermal capacity
- energy deposition detected as temperature variation
- **large active mass** and **efficiency** per unit cost
- **high energy resolution, model-independent signature**





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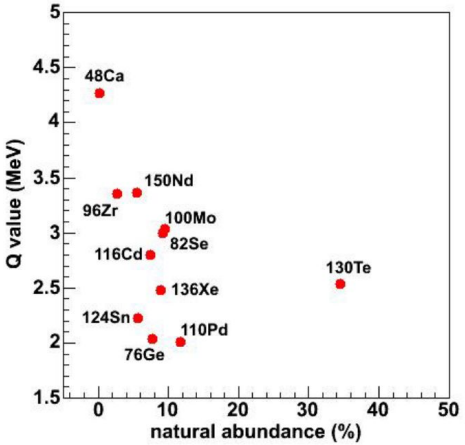
- **large active mass** and **efficiency** per unit cost
- fully active sensitive volume (= source), no dead-layer → simple response function → **high energy resolution, model-independent signature**



Intrinsically multi-isotope technique: many available compounds containing candidate nuclei

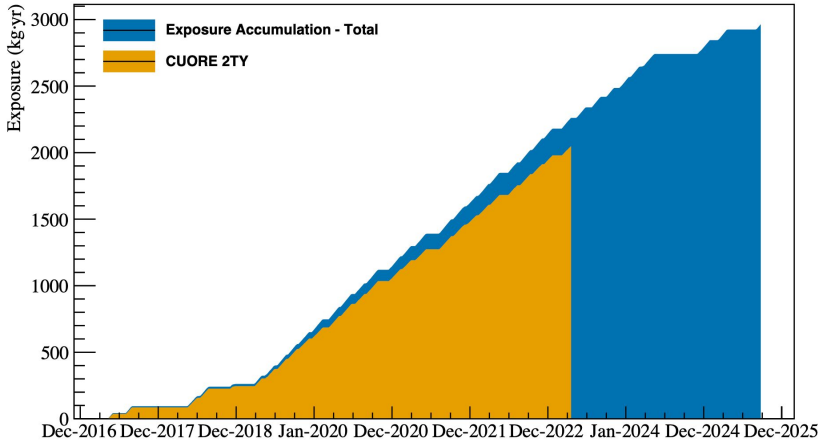
- $^{130}TeO_2$ (CUORE)
- $Li_2{}^{100}MoO_4$ (CUPID, AMoRE)
- $Zn^{82}Se$ (CUPID-0)
- $^{48depl}Ca^{100}MoO_4$
- $Na_2{}^{100}MoO_7$
- $^{48}CaF_2$
- $^{116}CdWO_4$

Unique feature: test simultaneously multiple candidates to **cross check discovery** and perform precision nuclear matrix measurements!

CUPID concept: Cuore Upgrade with Particle IDentification

Ton-scale array of high-resolution cryogenic calorimeters for the search for $0\nu\beta\beta$ and other other rare events

- replace CUORE (TeO_2) detector with new one based on $Li_2{}^{100}MoO_4$ crystals
- same mass scale as CUORE: **feasibility already demonstrated with 7 years of stable data-taking**
- existing cryogenic infrastructure: cost effective, low risk, highly reliable
- additional detector functionality:
  - particle identification
  - pile-up rejection with fast light-detectors
  - increased number of channels (x3)



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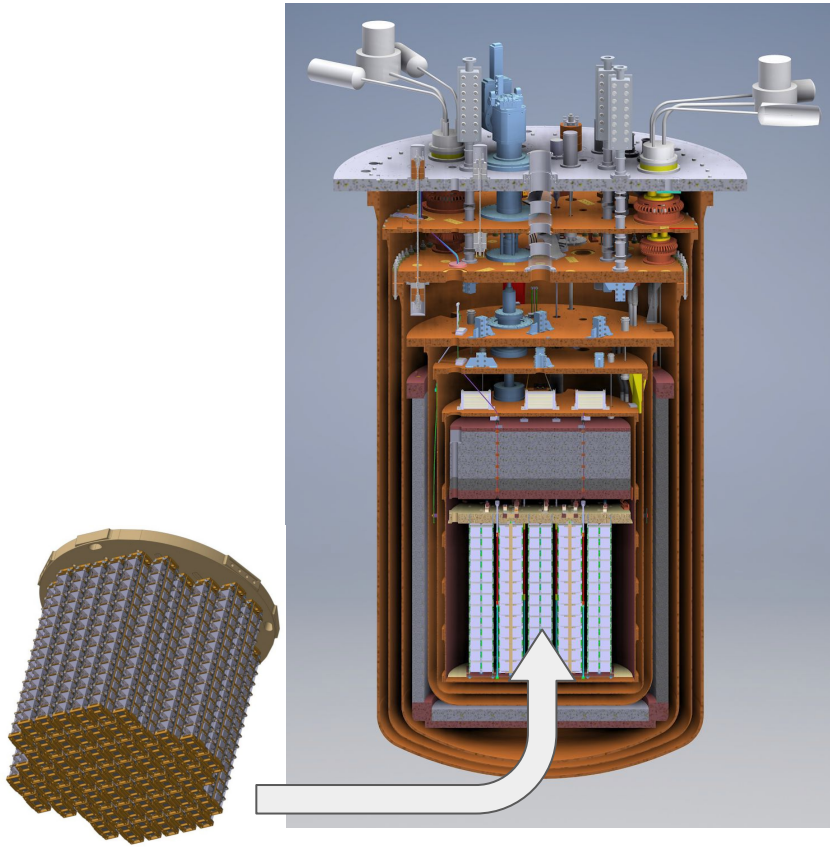
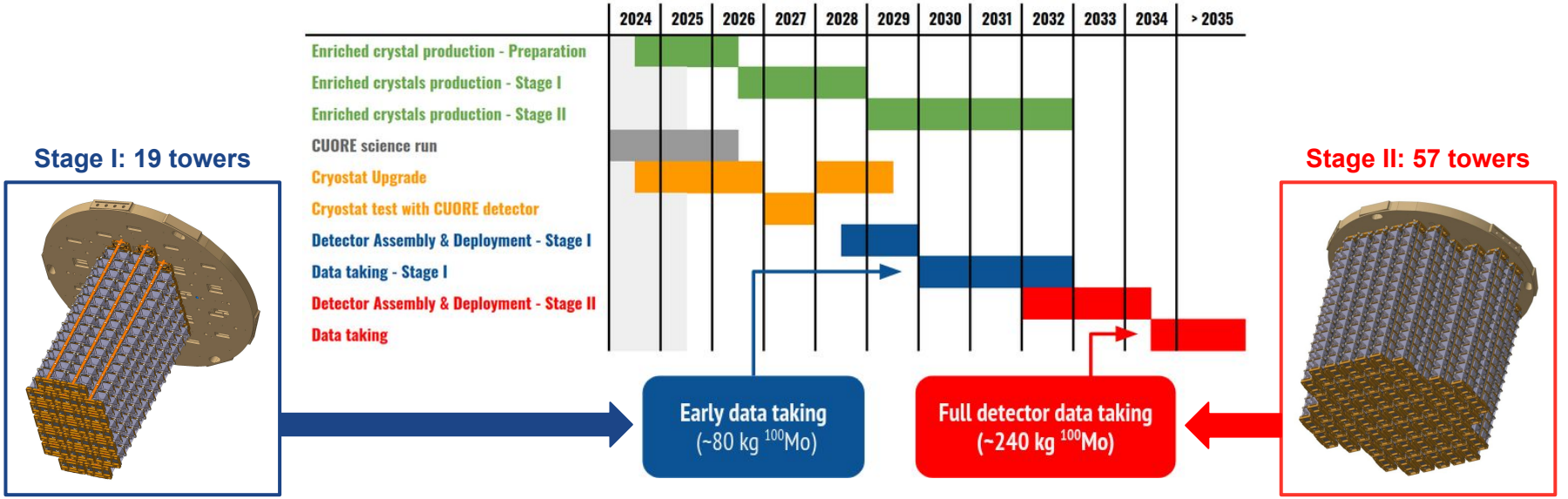


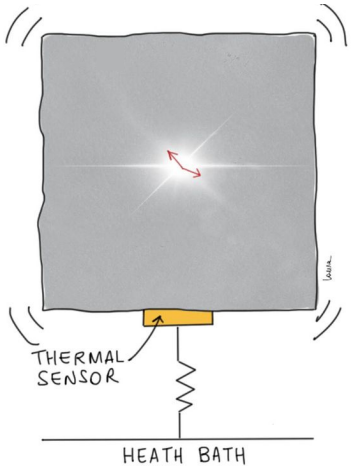
CUPID concept: staged deployment timeline

- Early delivery of science results, with world-leading sensitivity
- Technical risks mitigations
- Avoid long period without operation and scientific results → minimize risk of loss of expertise

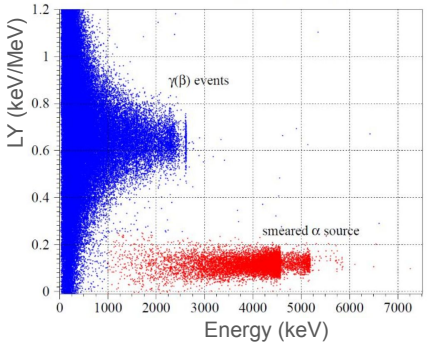


CUPID detector technology

CUORE: pure thermal detector



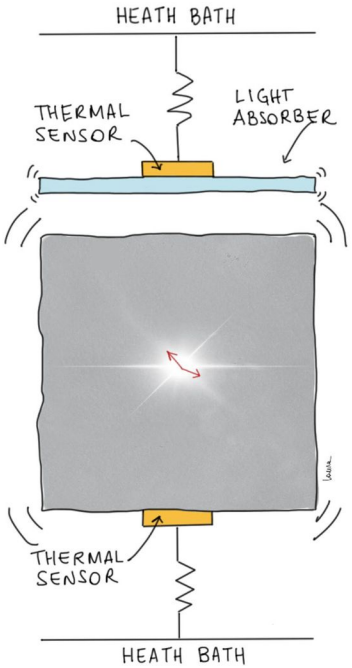
^{130}Te Q-value = 2527 keV



PID → remove α

higher Q → remove γ

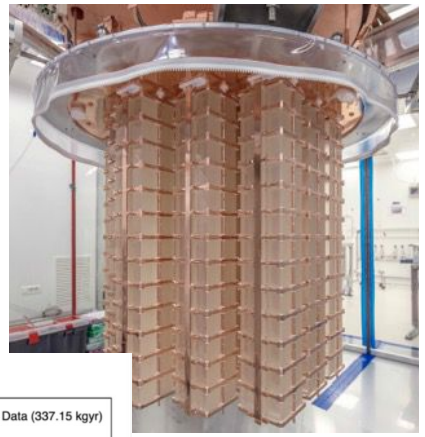
CUPID: combined heat/light thermal detector



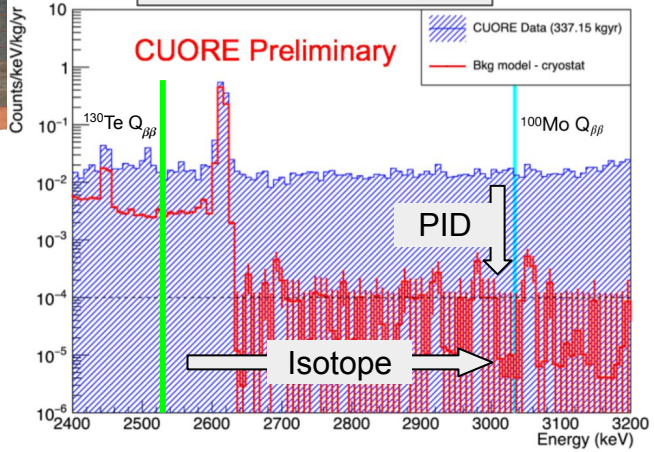
^{100}Mo Q-value: 3034 keV

CUPID background budget

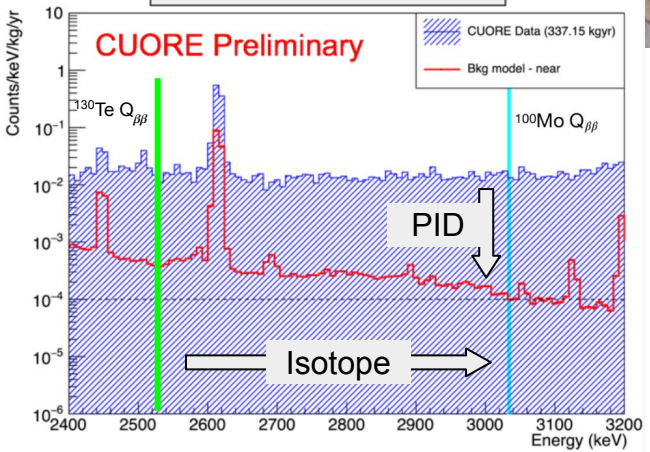
From CUORE to CUPID: **x100 reduction** of background in the ROI with **isotope choice** and **particle identification**



Far sources: cryostat, thermal and radiation shields, external environment



Near sources: crystals, detector structure, detector components inner copper shield



- total background (mainly α)
- background after α discrimination

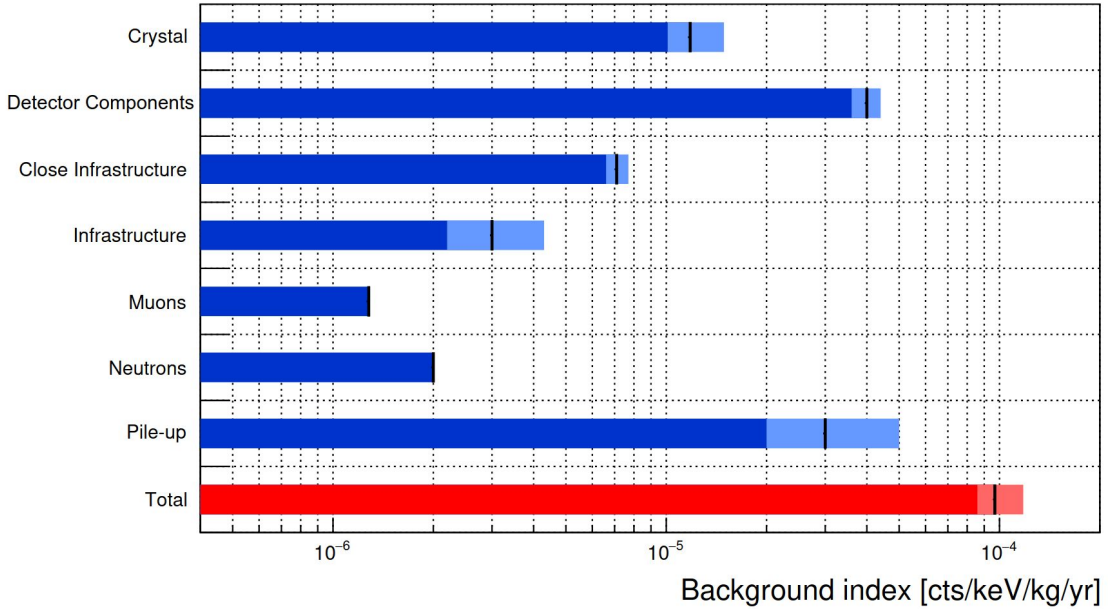
CUPID background budget

Data-driven background budget:

- CUORE, CUPID-0, CUPID-Mo background models
- measurements/limits already existing for all materials

Path to reach CUPID requirements = 10^{-4} ckky

- crystal purity quality control (required purity already demonstrated)
- cleaning of passive elements with CUORE protocols
- contamination in cryogenic infrastructure and shields well understood
- pile-up contribution well modeled and further reduction possible with current technology



The path to achieve CUPID background goal is well understood and conservative

CUPID physics reach - 0νββ

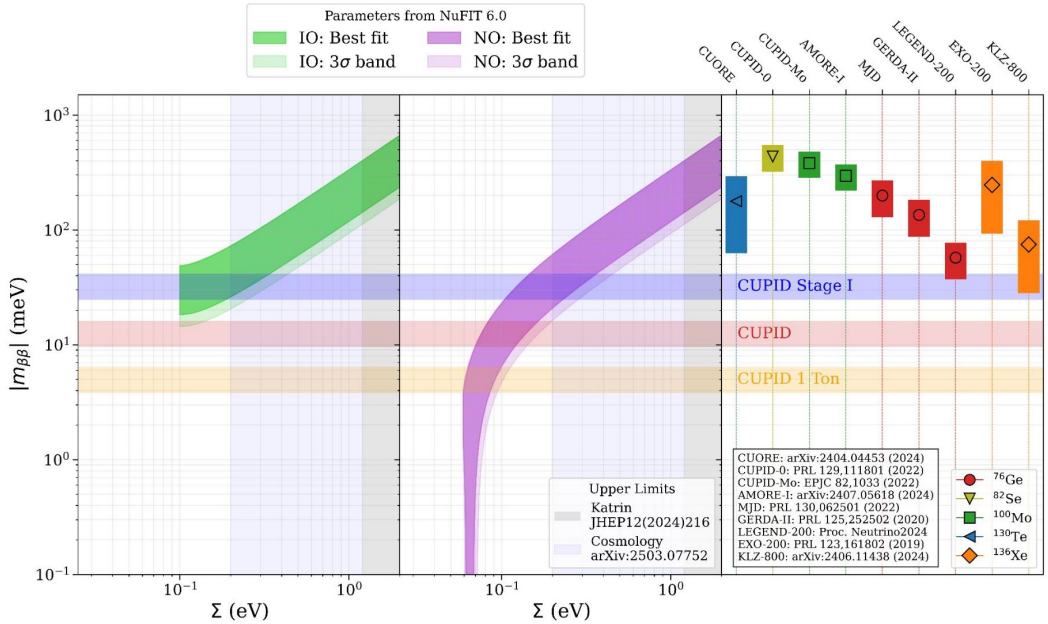
CUPID Baseline (Full deployment)

- Mass: ~450 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(**^{100}Mo**)
- **10** yr runtime
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr

Discovery Sensitivity

- $T_{1/2}$ > **1.1×10^{27} yrs**
- $m_{\beta\beta}$ ~ **9-15 meV @90% C.L.**

CUPID aims to cover the inverted hierarchy and a fraction of normal ordering



https://doi.org/10.48550/arXiv.1907.09376

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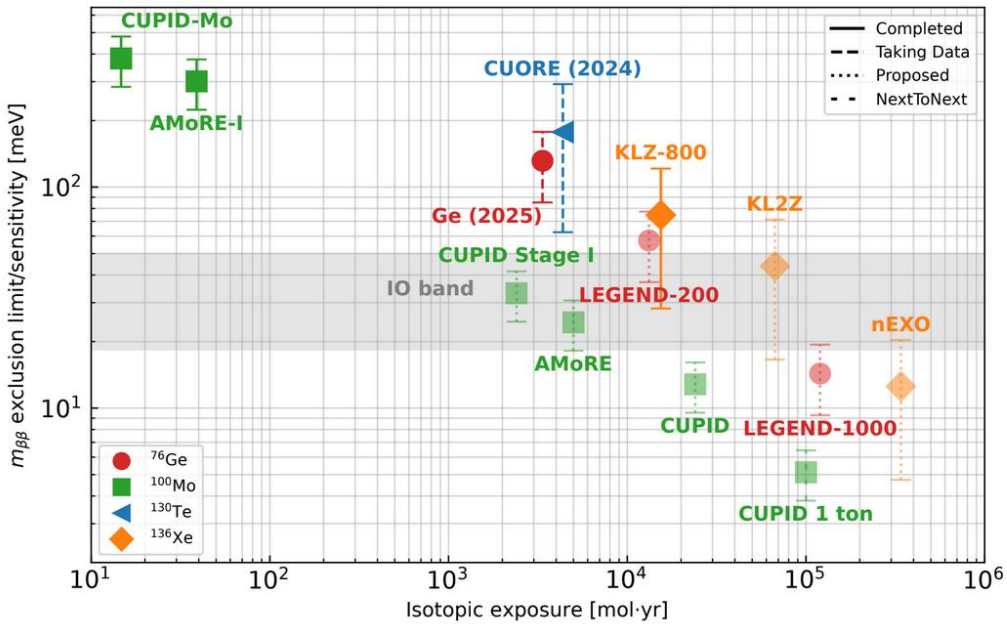

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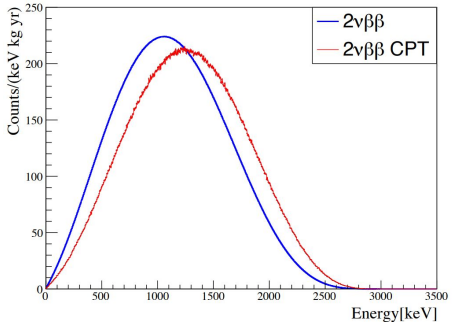
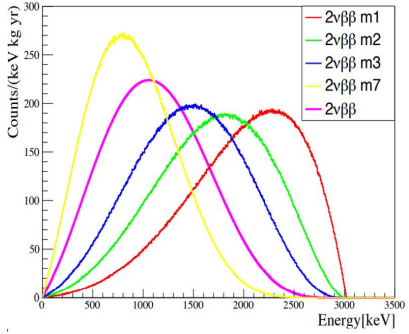
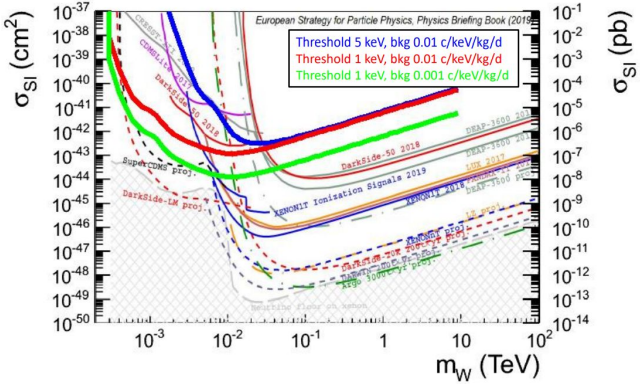
CUPID physics reach - other processes

- **Precision 2νββ spectral shape analysis:**
  - decays to excited states
  - Single State vs Higher State Dominance
  - CPT violation
  - Majoron emission
- **Topological analysis:**
  - electric charge conservation
  - Pauli exclusion principle
  - Tri-nucleon decay and baryon number conservation
- **Low energy searches:**
  - direct dark matter detection
  - supernova neutrinos via coherent scattering
  - solar axion searches

Rich physics program







CUPID Collaboration & Project

Leverage previous collaborative experience

CUORE

Built on the success of the CUORE Collaboration in deploying the only project of comparable scale

https://cupid-i.lngs.infn.it/doku.php?id=cupid_pub:start

Major participants: Italy (~60 authors), US (~40 authors), France (~25 authors)
Other participants: China, Ukraine, Spain

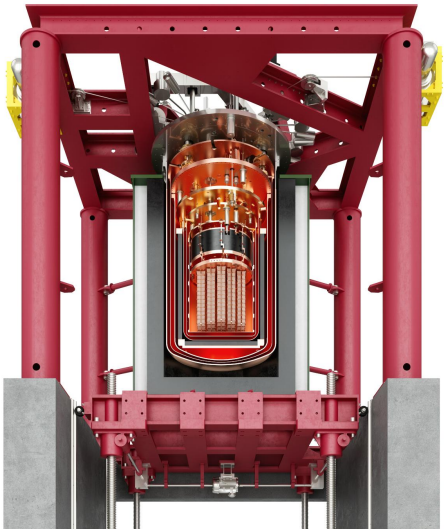
CUPID-0

Integrate the experience from CUPID-0 and CUPID-Mo in operating detectors with Particle Identification technology

CUPID-Mo

CUPID Collaboration & Project

Leverage previous technical experiences



Cost and time-effective reuse of the CUORE underground infrastructure

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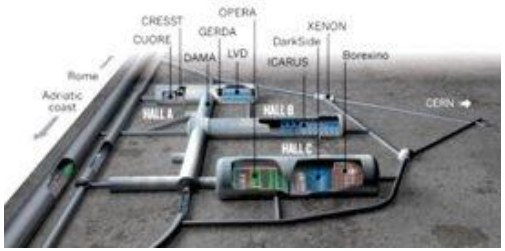
Long-lasting and well developed interaction with LNGS services and infrastructure



Fully leverages the CUORE cryogenic infrastructure, experience and expertise in its operation

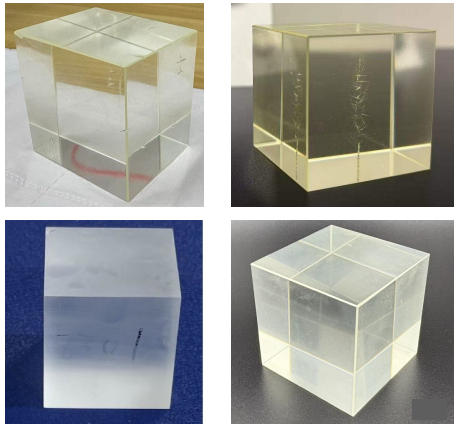
What’s new and challenging in CUPID?

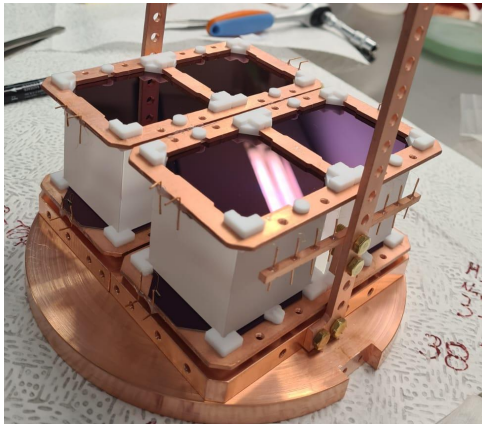
Crystals - supply chain

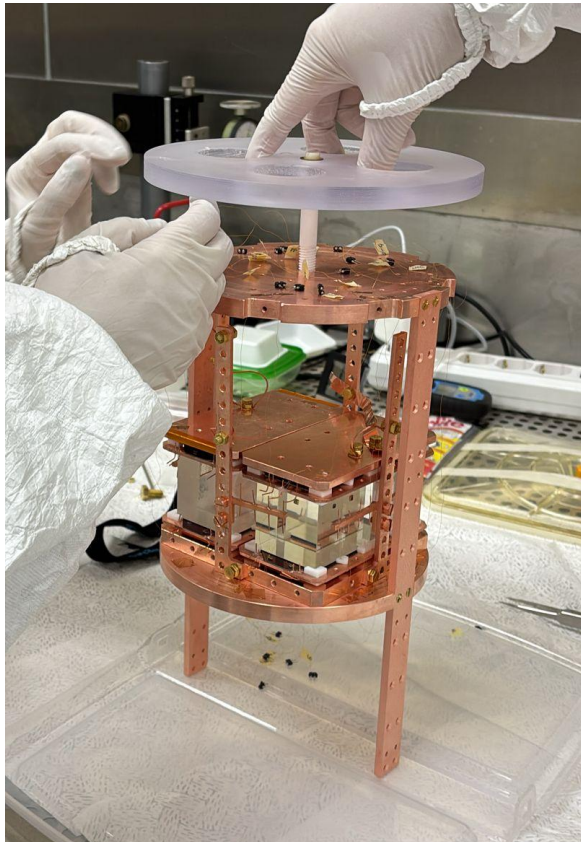
- SICCAS consolidated as the crystal producer with IPCE/CNNC taking care of the isotope enrichment
- Continuous interaction with INFN to establish requirements and procedures and monitor quality
- **Pre-production enriched crystals are being tested** to complete optimization phase and **start large scale production by end of 2026**

Crystals - CCVR

- **C**upid **C**rystal **V**alidation **R**un - bolometric test of crystals operated as detectors in LNGS HallC
- Most sensitive tool to validate production:
  - resolution and LY in realistic conditions
  - radio-purity assessment
- 4/8 crystals of **each batch** assembled in a 2x1 modules with 8/12 light detectors for light readout





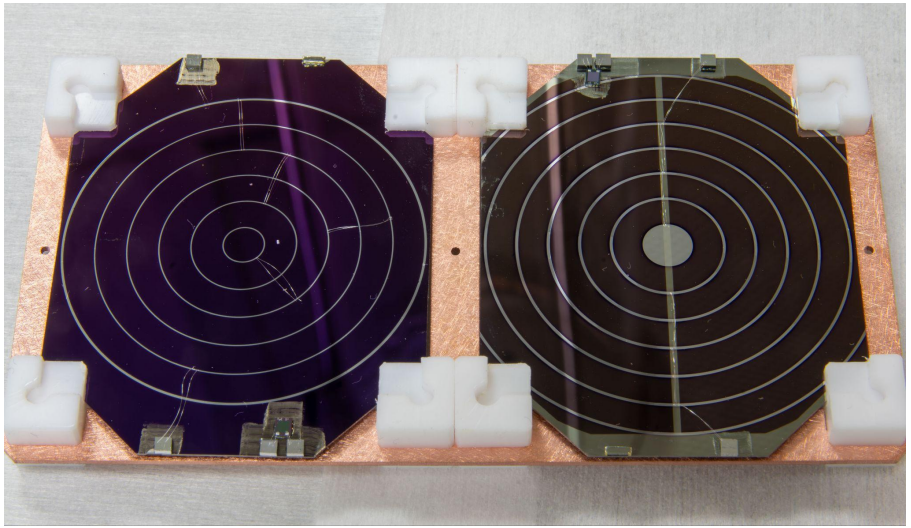


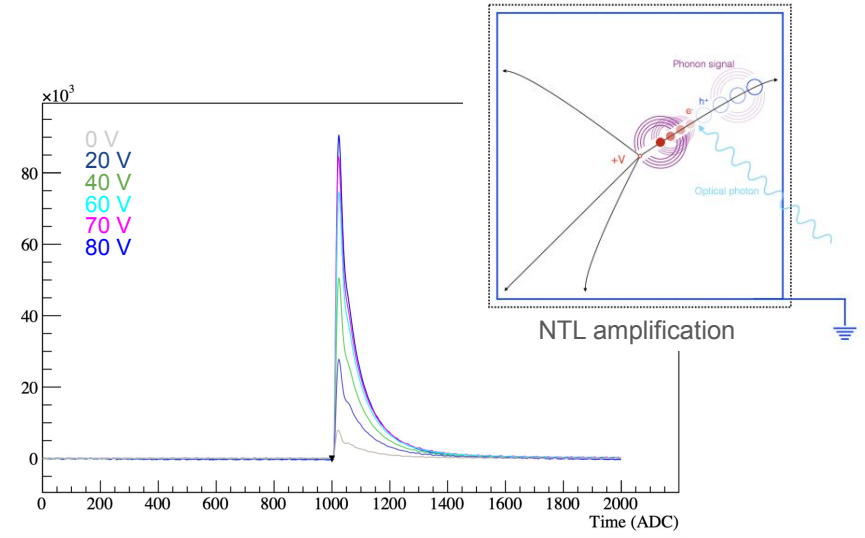
Light detectors

Key parameters:

- **particle discrimination** (<100 eV baseline RMS with 0.36 keV/MeV crystals sight yield - large safety margin)
- **pile-up rejection** (< 170 μs amplitude-averaged timing resolution required)

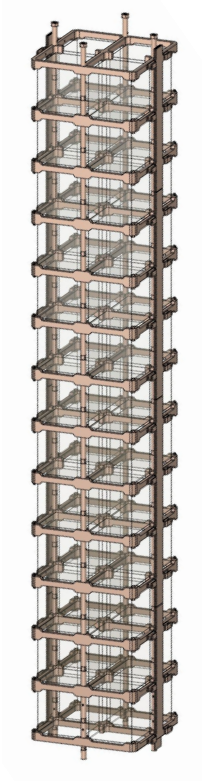
- **Implementation**: Ge absorber with NTD readout and NTL amplification



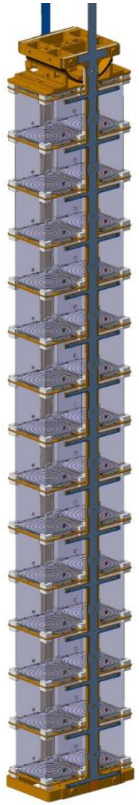


Detector Structure - from CUORE to CUPID

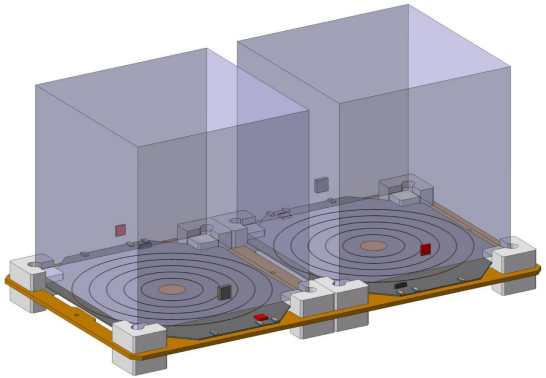
CUORE

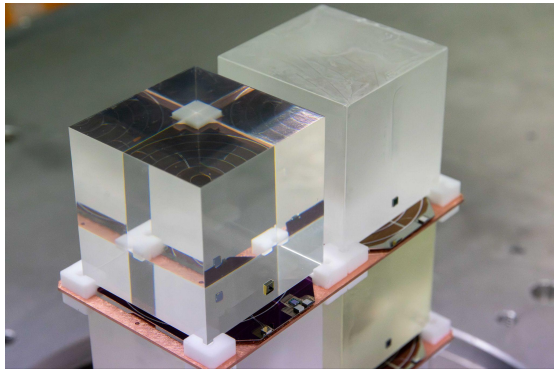


- **“gravity assisted”** - no vertical constraint, stack of crystals and light detectors sitting one on top of the other
- **easy and safe assembly** - no screws, self-aligning structure
- **loose tolerances** - cost effective, easy cleaning
- **laser cutting** - prevent copper surface recontamination



CUPID



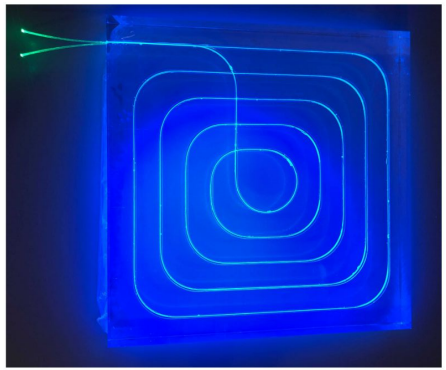


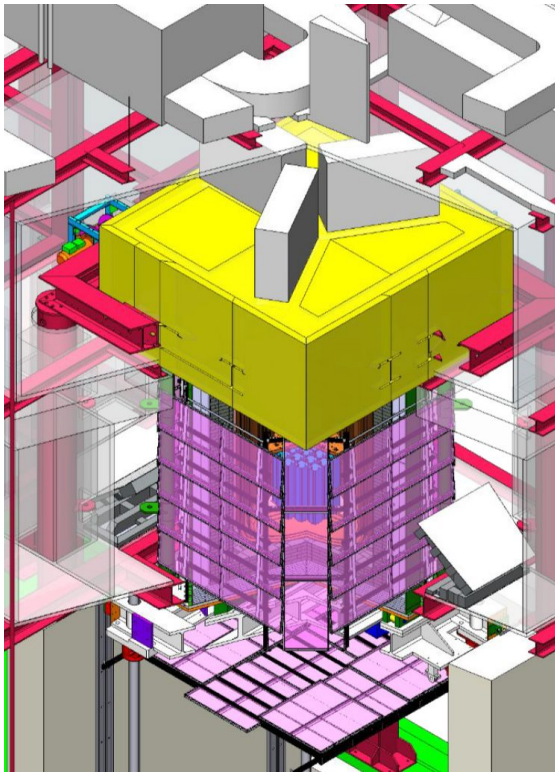
Muon Veto & Neutron Shield

- **Muons** and **neutrons** induced background is negligible in CUORE but expected to be relevant in CUPID → **increase in shielding and tagging required**
- Hybrid solution:
  - plastic scintillator tails around the existing shield
  - instrumented water tanks at the top of the cryostat for combined neutron shielding - muon tagging

Both contributions are measured in CUORE:

- high multiplicity events from muon tracks and showers to constraint contribution in M1
- high energy gamma cascades from neutron capture



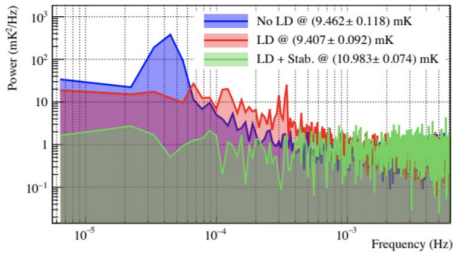


Cryostat Upgrades

Pulse Tubes system is an important source of **vibrational noise**
Three interlinked tactics to further reduce it

New linear drives for motor head control:

- improve current stability
- improve control on stepper motors
- enable new algorithms for PT phase scan and optimization

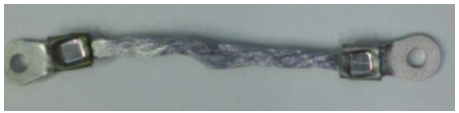


New Pulse Tubes:

- more cooling power
- less PTs required
- easier and more effective active noise cancellation

New termalizations

- high purity 6N Al
- increase thermal link while reducing mechanical coupling
- thermal switches to isolate unused PTs



Reduce input vibration power and improve active noise cancellation efficiency

Front End and DAQ

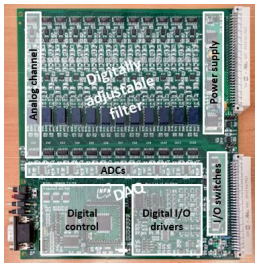
CUORE uses **custom-designed room-temperature front end electronics**. Raw data is stored for offline processing

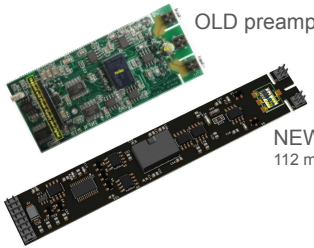
- Very stable and reliable operation for 7 years → Readout scheme proven on the field

CUPID adds several challenges

- More channels (x3), hence more power, more space, more data, etc.
- Faster signals on light detectors, required for pile-up rejection

New filter+DAQ board





OLD preamp

NEW preamp
112 mm x 17 mm

Main upgrades:

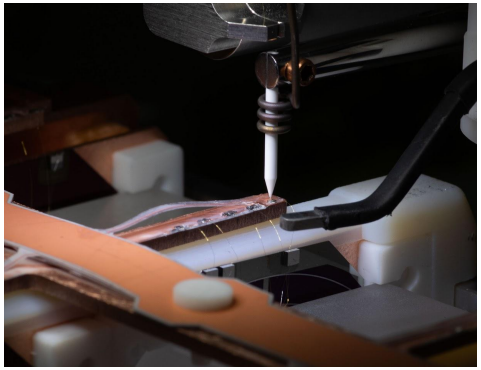
- The new frontend will save a factor of 2 in occupation space
- Keep the same power budget, optimizing preamps for light channels (same power, lower noise) and heat channels (lower power, same noise), and removing the PGA stage
- Reduce wiring capacitance to reduce input RC time constant
- Design a new board that merges anti-aliasing filters and DAQ, with tunable cut-off and 24-bit ADCs
- Update DAQ software and storage infrastructure to cope with the increased data rate

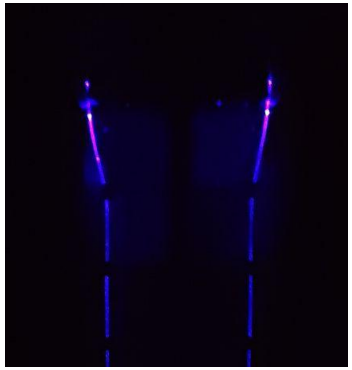
1-tower worth of channels already deployed and under testing

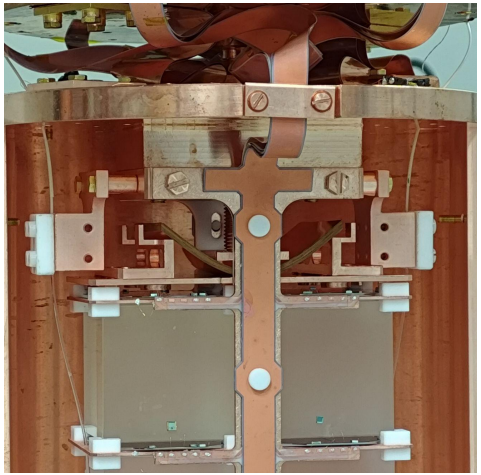
Detector integration test - VSTT

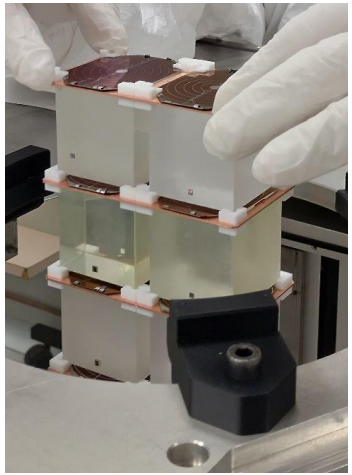
Vertical integration test of many subsystems:

- full scale mechanical structure assembly
- sensors gluing
- readout wiring
- NTL-assisted light detectors
- Optical Injection System
- Front-end and DAQ





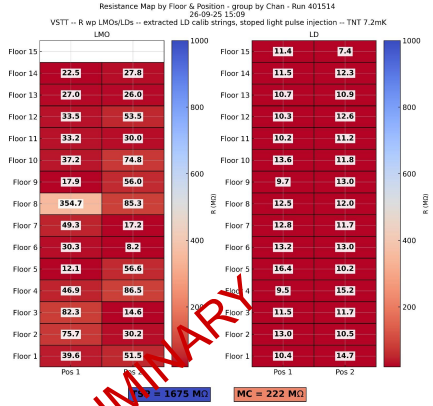


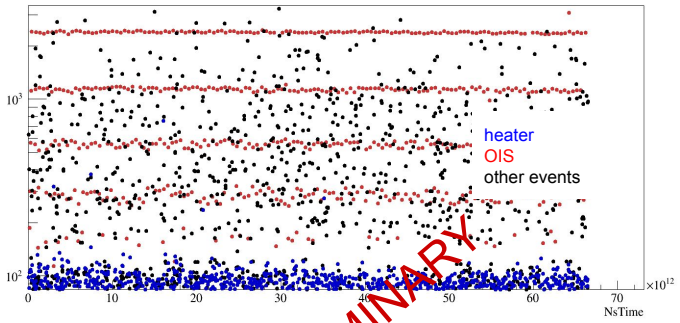


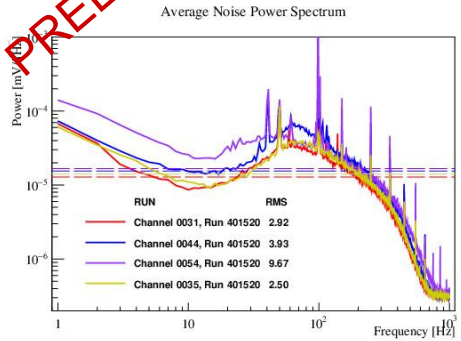
10.1140/epjc/s10052-022-10720-3

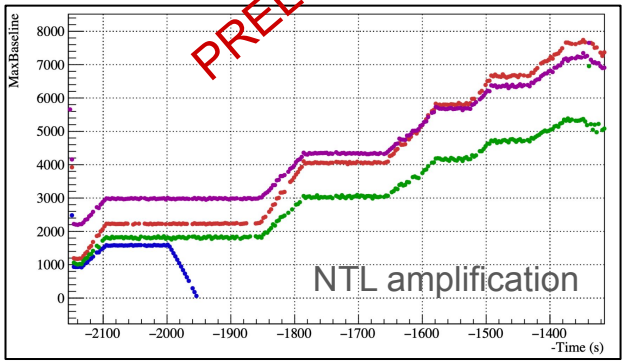
VSTT - preliminary results

- Extremely good **thermalization**, stable and uniform base and working temperatures
- **Detector noise** in line with expectations. Calibration ongoing
- **Optical Injection System** is able to illuminate all channels. Studies on photo-statistics ongoing
- **NTL bias** applied on a number of channels for preliminary test. Amplification confirmed





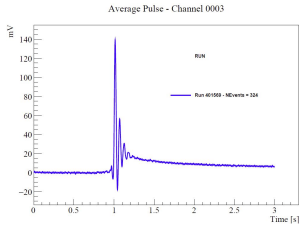


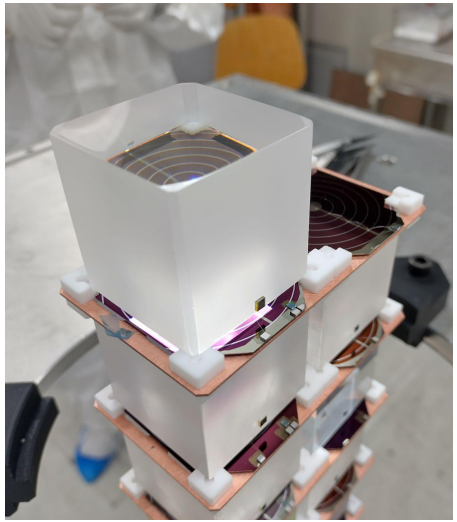


Detector integration test - AMoRE crystals

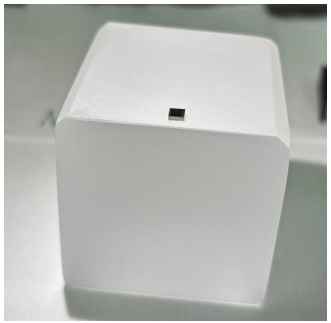
- Almost perfectly compatible with CUPID assembly
- Due to dimensional tolerances, 002 required manual gluing resulting in different working point
- Calibration ongoing

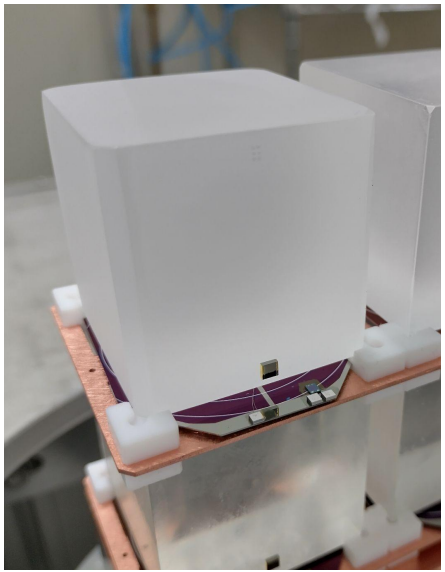
N LMO 002

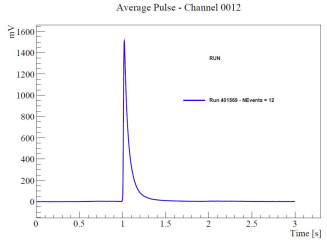




N LMO 001







Detector integration test - AMoRE crystals

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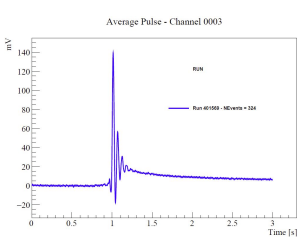
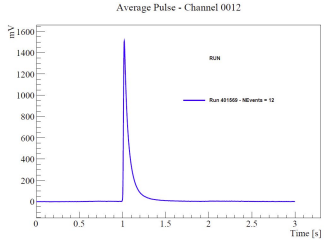
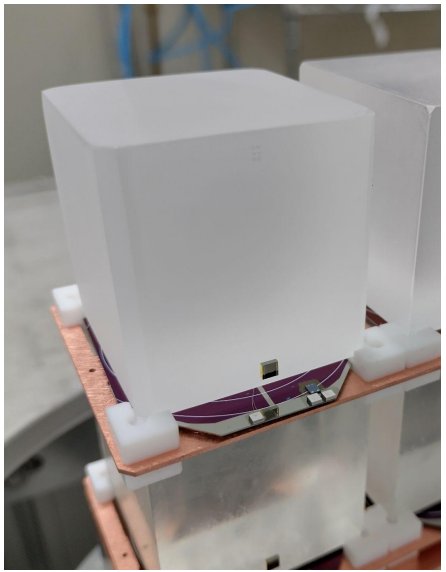
N LMO 002



GREAT COLLABORATION OPPORTUNITY

N LMO 001





Conclusions

- CUPID will **explore inverted ordering ($T_{1/2}$ > 10^{27}, $m_{\beta\beta}$ ~ 9-15 meV @90% C.L.)**
- **Builds on an existing and well-functioning international collaborations** and partnership between mainly Italy, Fr and US
- Collaboration has **operational experience at LNGS for ton-scale, bolometric experiment** and utilizes **existing infrastructure** (CUORE cryostat, experimental site).
- **CUPID is timely, highly leveraged, and cost-effective; an exceptional opportunity**
- Crystallization and enrichment at large scale are possible
- CUPID detector design is being extensively tested with **VSTT vertical integration test**
- **Data-driven background model** reaches baseline goal of B.I. ~ 10^{-4} counts/(keV kg y)

CUPID is proceeding towards construction

Complements international suite of ton-scale experiments in a world-wide program