Perspective of neutrino physics with CUPID

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La Thuile 2023 - Les Rencontres de Physique de la Vallée d'Aoste

March 5-11th, 2023

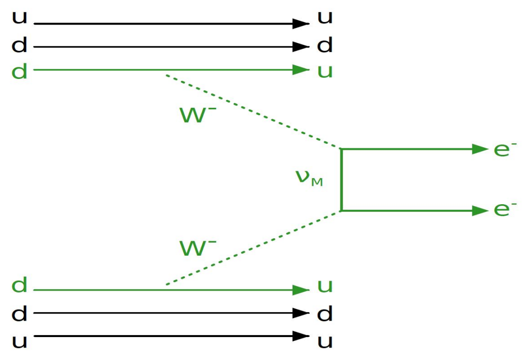
Neutrino-less double beta decay

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 $T_{1/2}$ ~ $10^{18\text{-}24}$ years

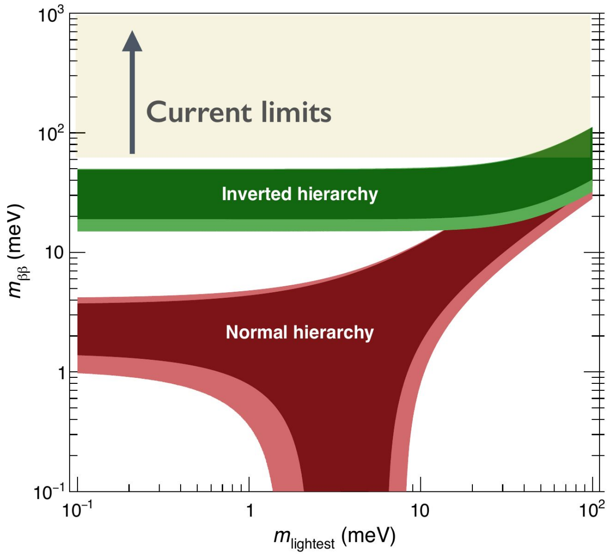
$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$



- 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 $m_{\beta\beta}$:

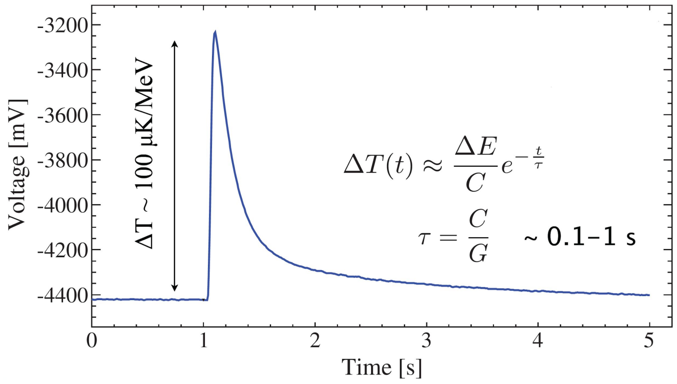
- measures the intensity of the new-physics involved in the process
- compares different isotopes



Experimental technique: low temperature detectors

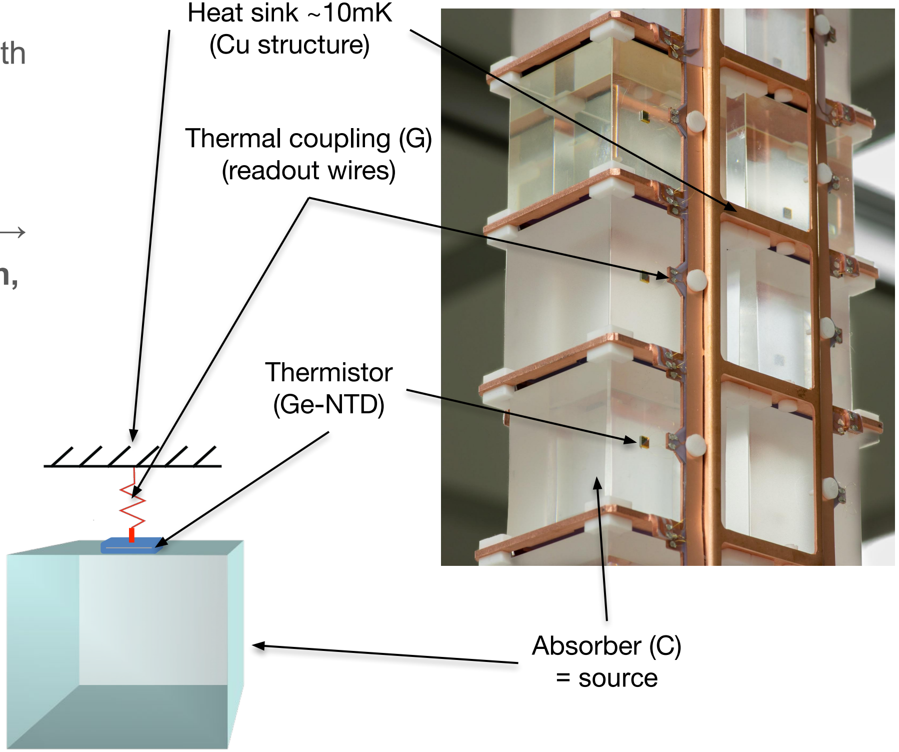
Low temperature detectors:

- 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
- fully active sensitive volume (= source), no dead-layer → simple response function → **high energy resolution, model-independent signature**



$$\Delta T(t) \approx \frac{\Delta E}{C} e^{-\frac{t}{\tau}}$$

$$\tau = \frac{C}{G} \sim 0.1\text{–}1 \text{ s}$$



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CUPID

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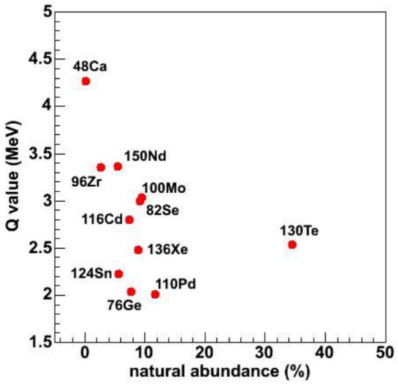


Intrinsically multi-isotope technique: many available compounds containing candidate nuclei

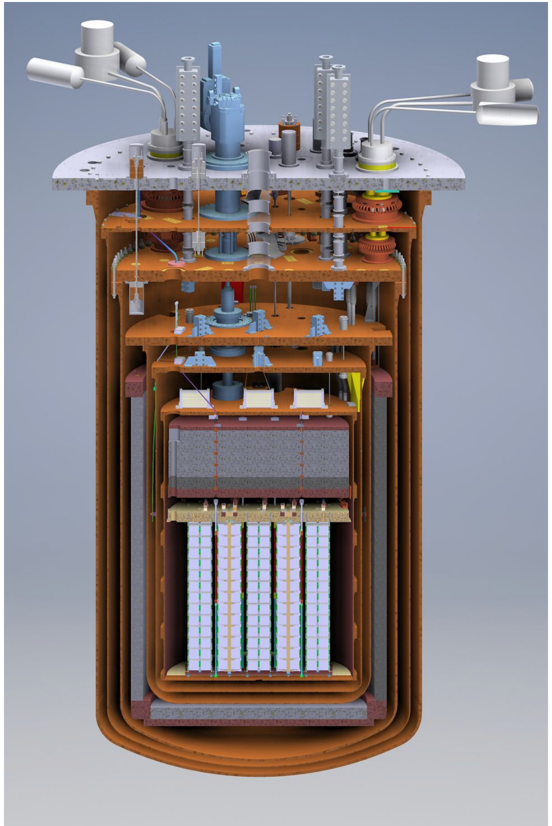
- $^{130}TeO_2$ (CUORE)
- $Li_2{}^{100}MoO_4$ (CUPID, AMORE)
- $Zn^{82}Se$ (CUPID-0)
- $^{48depl}Ca^{100}MoO_4$
- $Na_2{}^{100}MoO_7$
- $^{48}CaF_2$
- $^{116}CdWO_4$

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

CUPID concept: Cuore Upgrade with Particle IDentification

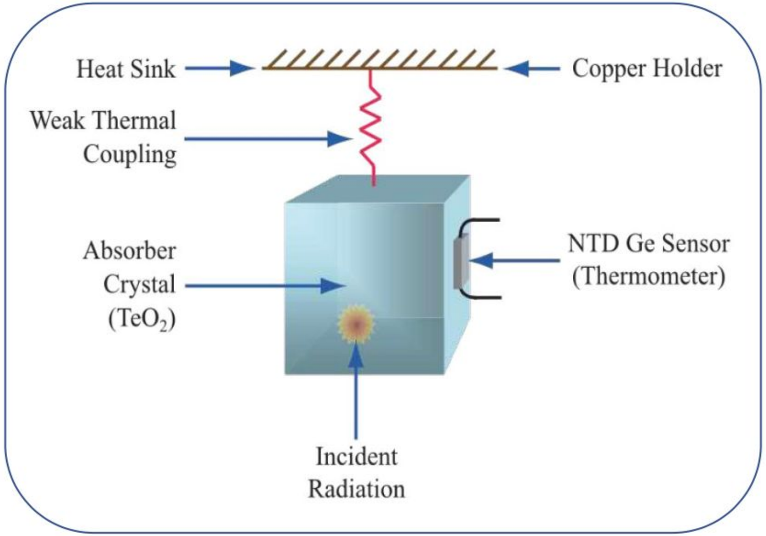
Ton-scale array of high-resolution cryogenic calorimeters for the search for 0νββ and other other rare events

- 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 3 years of stable data-taking
- existing cryogenic infrastructure: cost effective, low risk
- additional detector functionality:
  - particle identification
  - pile-up rejection with fast light-detectors
  - increased number of channels (x3)

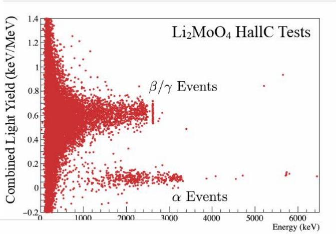


CUPID detector technology

CUORE ^{130}Te
pure thermal detector
(bolometer)



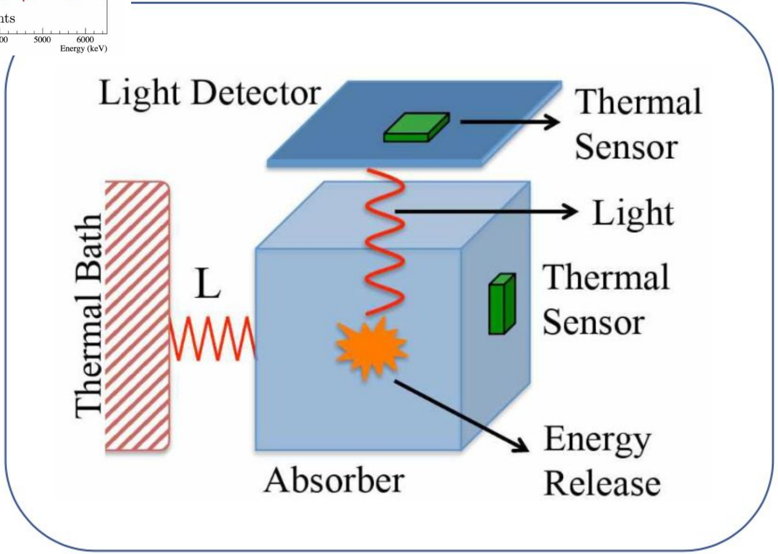
No PID
Q = 2527 keV **< 2615 keV**



PID → remove α

higher Q → remove γ

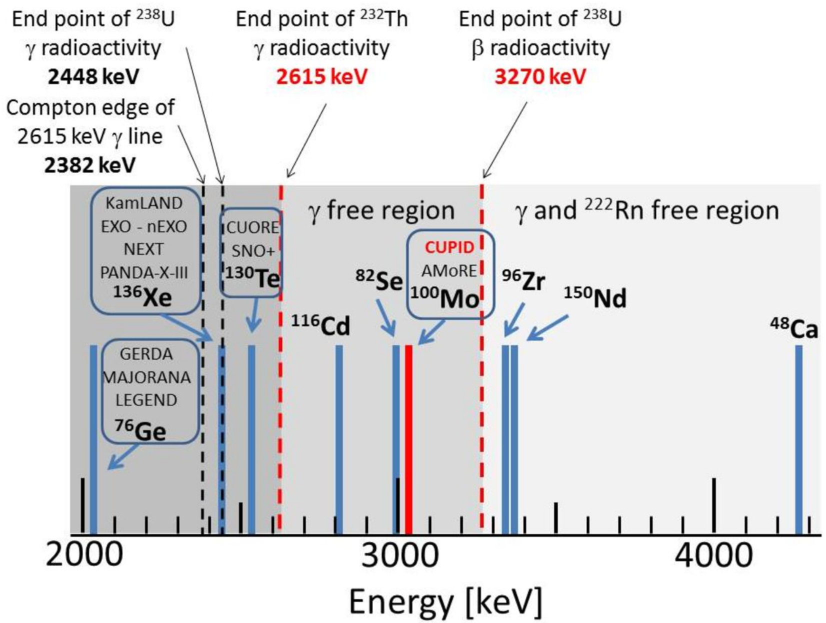
CUPID ^{100}Mo
heat + light
(scintillating bolometer)



^{100}Mo **Q-value: 3034 keV**: β/γ background significantly reduced

Isotope choice

Balance between **performance** (background reduction, NME, detector performance) and **cost** (isotope enrichment, crystal growth). **Higher Q-value translates into smaller background**



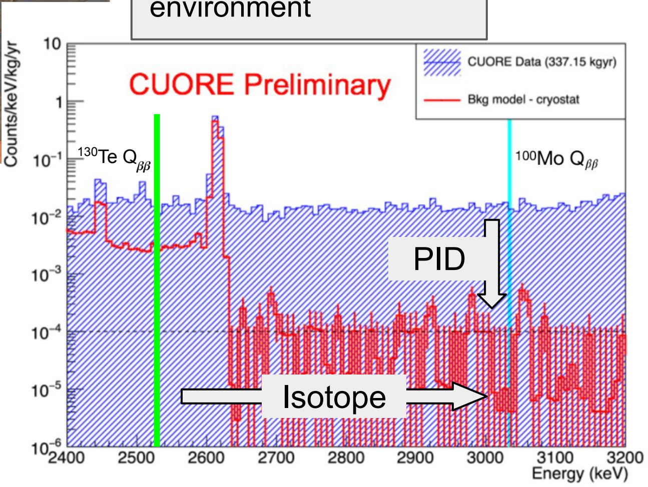
^{100}Mo

- Q-value above most of natural radioactivity
- good quality scintillating crystals for α-β discrimination
- existing enrichment technology and interest for medical applications
- relatively expensive enrichment

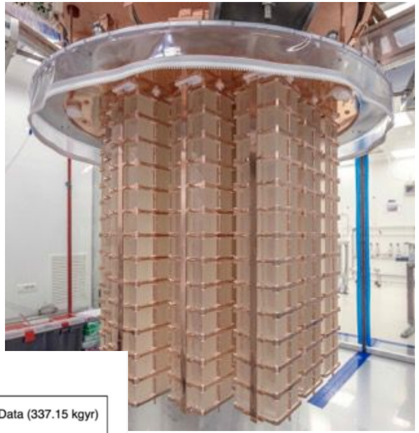
Isotope choice + Particle Identification

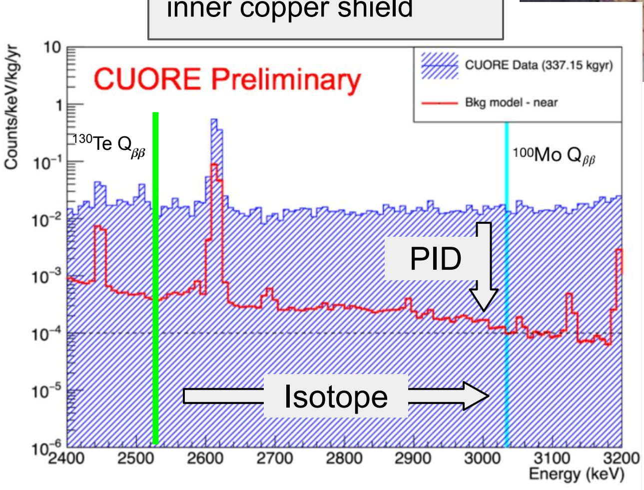
From CUORE to CUPID: x100 reduction of background in the ROI

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

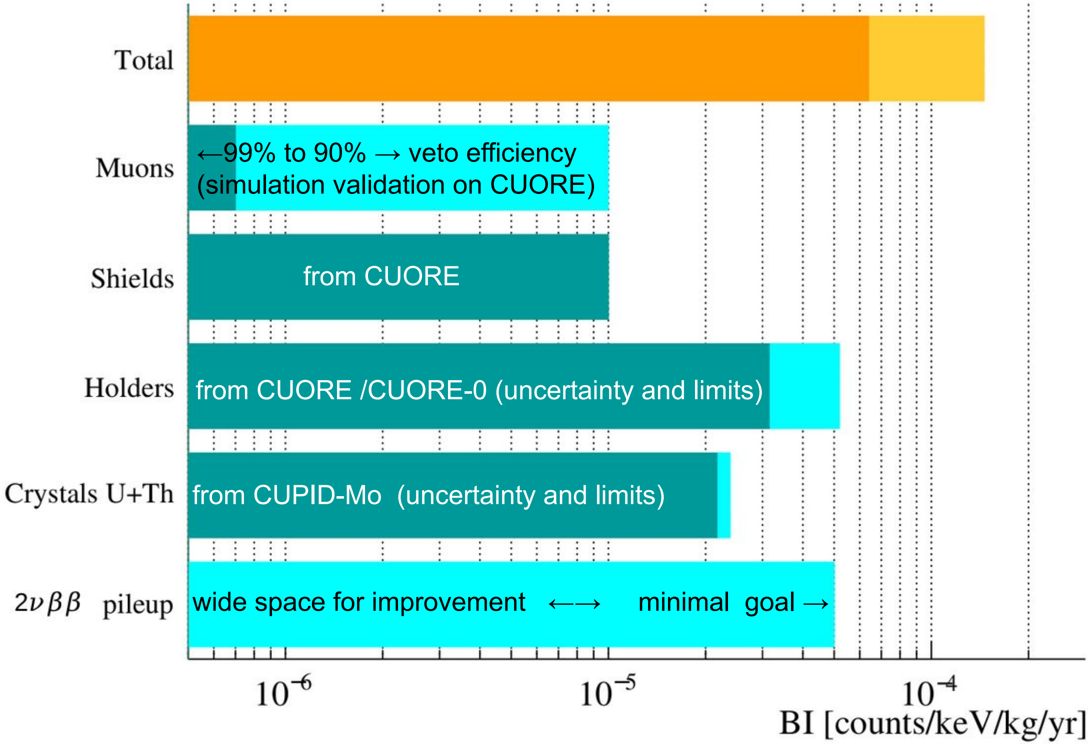
CUPID physics reach - background budget

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 reduction possible with current technology



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

CUPID physics reach - 0νββ

CUPID Baseline

- 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

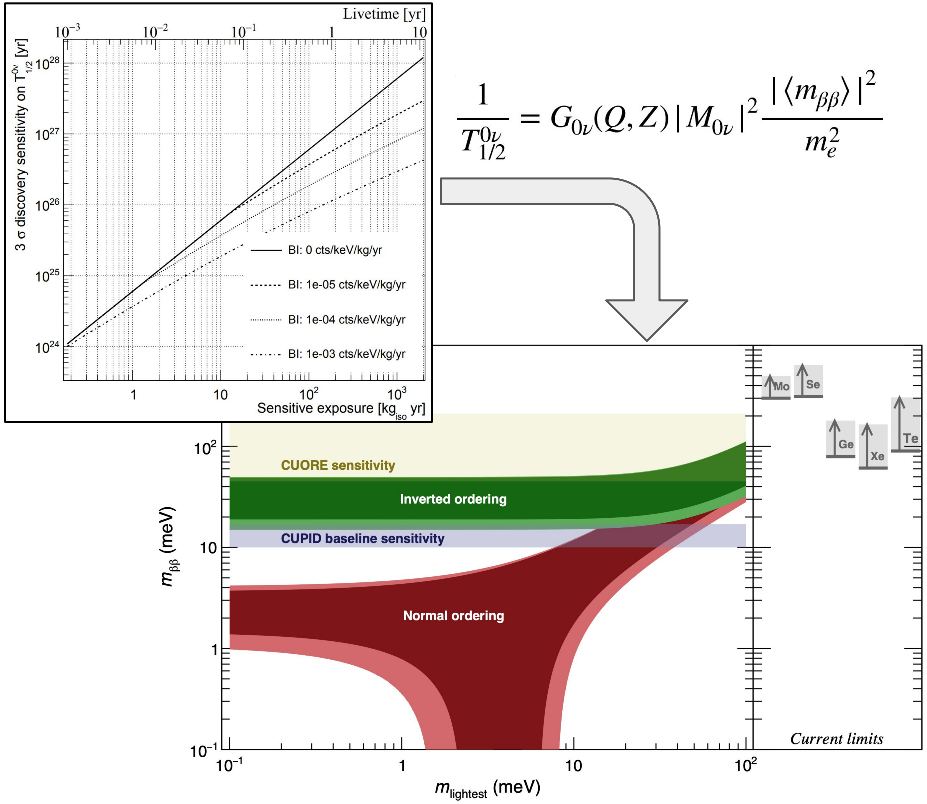
CUPID Baseline Discovery Sensitivity

- $T_{1/2}$ > **1.1×10^{27} yrs (3σ)**
- $m_{\beta\beta}$ ~ **12-20 meV**

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

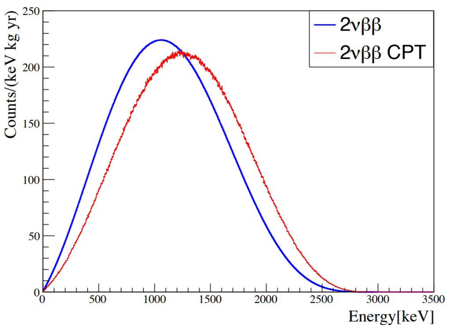
https://doi.org/10.48550/arXiv.1907.09376

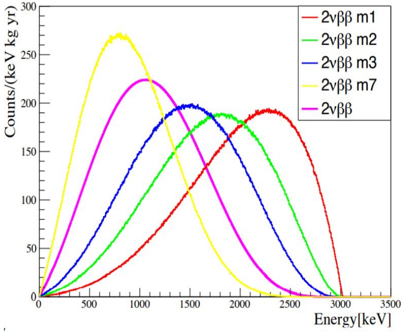
$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

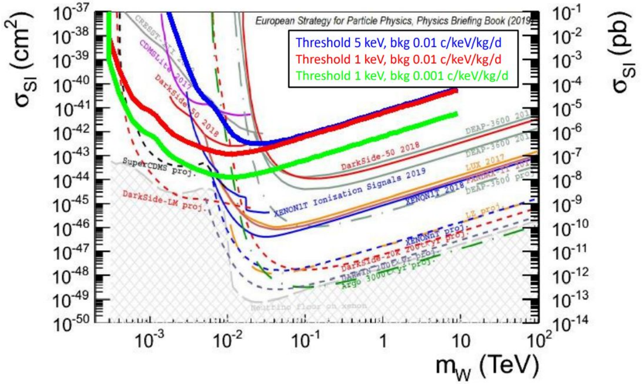


CUPID physics reach - other processes

- Precision $2\nu\beta\beta$ 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

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

CUORE

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

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

CUPID-0

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

CUPID-Mo

CUPID Collaboration & Project

Collaboration formally created in May 2021

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

Major participants: Italy (~60 authors), US (~40 authors), France (~25 authors)
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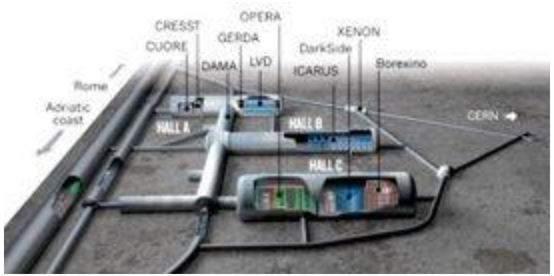
CUPID Collaboration & Project

Leverage previous technical experiences

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

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



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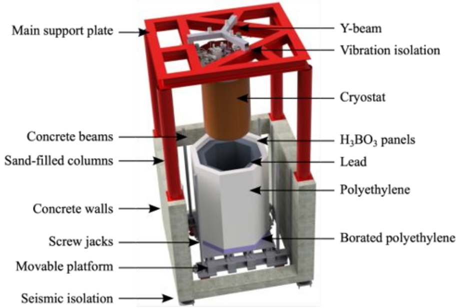


Cost and time-effective reuse of the CUORE underground infrastructure

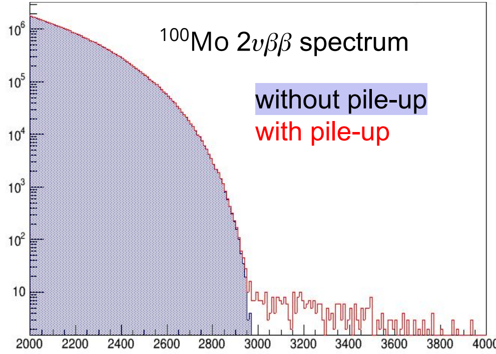
Fully leverages the CUORE cryogenic infrastructure, experience and expertise in its operation

CUPID project parameters (DOE Portfolio Review)

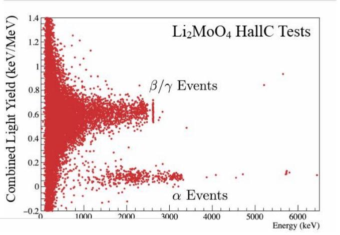
Parameter	Value
Crystal	$Li_2{}^{100}MoO_4$
Size	45×45×45 mm^3
Number of crystals	1596
Number of light detectors	1710
Detector mass	450 kg
Enrichment	95%
^{100}Mo mass	240 kg
Energy resolution	5 keV
Light yield (β)	0.3 keV/MeV
Background index	10^{-4} counts/(kg*keV*year)
Selection Efficiency	90%

Parameter	Value
LD light absorption	>90%
LD energy resolution	<100 eV RMS
LD pileup resolution	<0.17 ms
LD risetime*resolution	<1 msec*80 eV-FWHM
Muon detector efficiency	>90%
Crystal radiopurity	CUPID-Mo
Surface radiopurity	CUORE
Cu, PTFE radiopurity	CUORE
DAQ bandwidth, storage	~10×CUORE
Calibration system	External (CUORE)
Cryogenics	CUORE

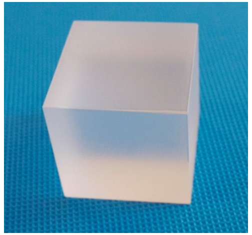
LD performance - pilup rejection



LMO performance



LMO crystals mass & i.a.



Background control and reduction

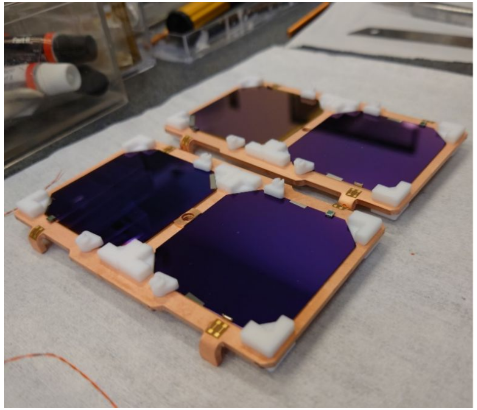
Detector Components - Isotope & Crystals

- Isotope procurement and lithium molybdate crystals growth are currently defining the critical path of the project
- CUPID is working with several potential vendors to explore isotope production*
  - this includes established vendors and new production facilities
  - all options that are viable for Italy and the US are being explored
- The Collaboration has experience with crystal production from CUORE, CUPID-0, and CUPID-Mo
- Crystals from multiple vendors are being tested and a baseline and alternative vendors are expected to be defined by DOE CD-1 review in late 2023

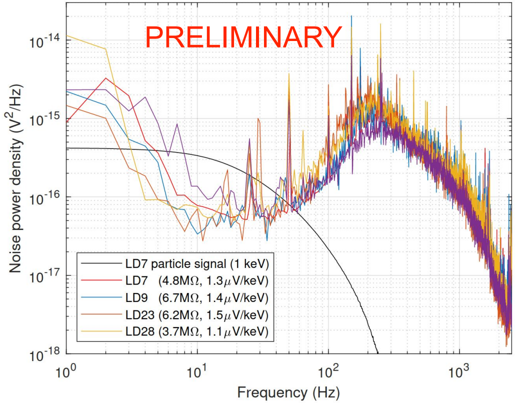
* Some of the discussions are covered by non-disclosure agreements (NDA)

Detector Components - NTDs, Heaters and LDs

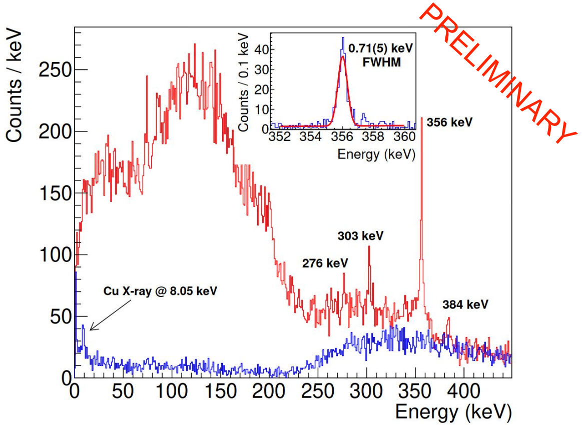
- Si-heaters and NTD thermistors are a robust technology from predecessors, both for crystals and light detectors readout
- optimization of size, geometry and absorber coupling to further improve LDs timing and S/N
- baseline choice for light detectors: Ge wafers with AR coating and NTD readout



Assembled light detectors for test in Pulse Tube cryostat



Noise validation studies



Energy calibration and energy resolution within specs

Detector Components - NTDs, Heaters and LDs

- Baseline Light Detectors: Ge wafers with AR coating and NTD readout:
  - particle discrimination (<100 eV RMS and >90% absorption efficiency required - large safety margin)
  - **pile-up rejection** (< 170 μs amplitude-averaged timing resolution required) is the **key parameter**

Extensive situation assessment program completed in 2022
Program of performance optimisation started in 2023

Detector response model to identify speed-limiting factors

High rate external sources on LiMO crystals for realistic light emission

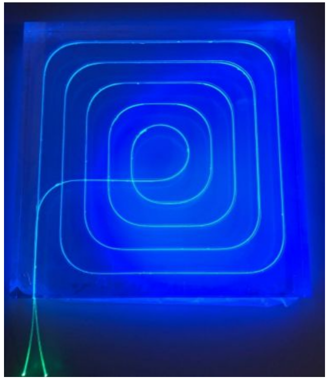
LED + optical-fibers to explore timing resolution with direct approach

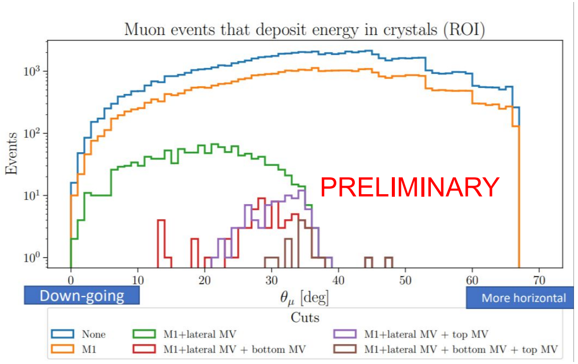
Synthetic data to extrapolate from measured performance (noise and pulse shape) to expected B.I.

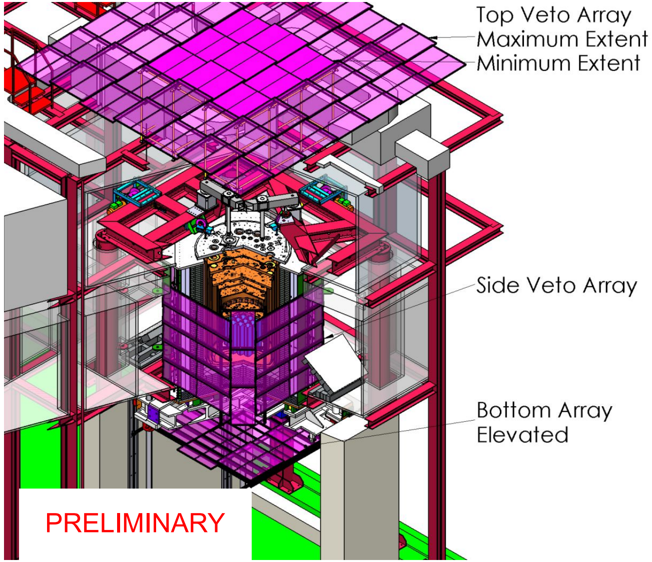
Detector Components - Muon Veto & Neutron Shield

- **Muons** and **neutrons** induced background is negligible in CUORE but expected to be relevant in CUPID → **increase in shielding and tagging required**
- 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

Muon veto scintillating tiles to intercept >90% muons → 99% reduction of M1 background when combined with detector granularity







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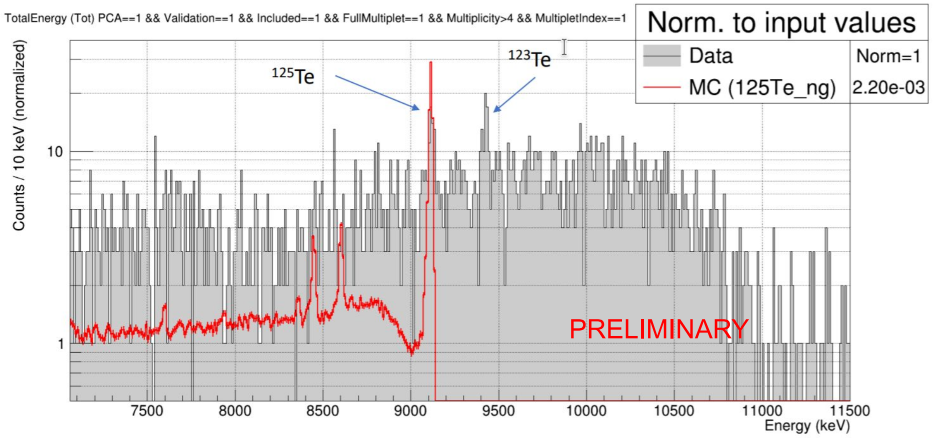
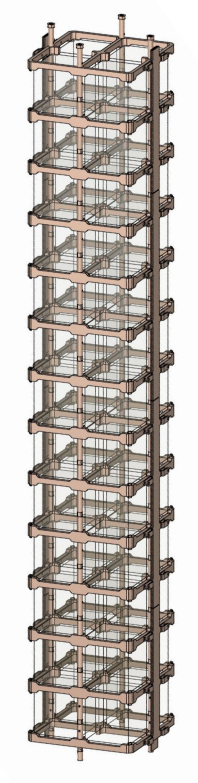
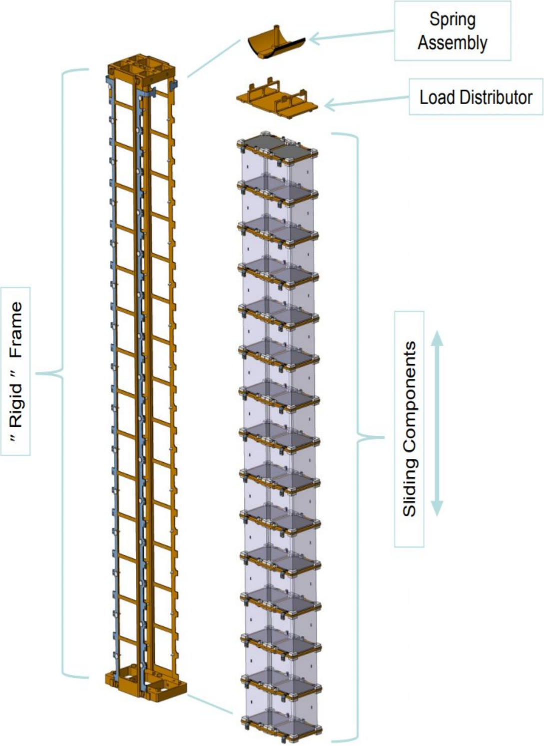


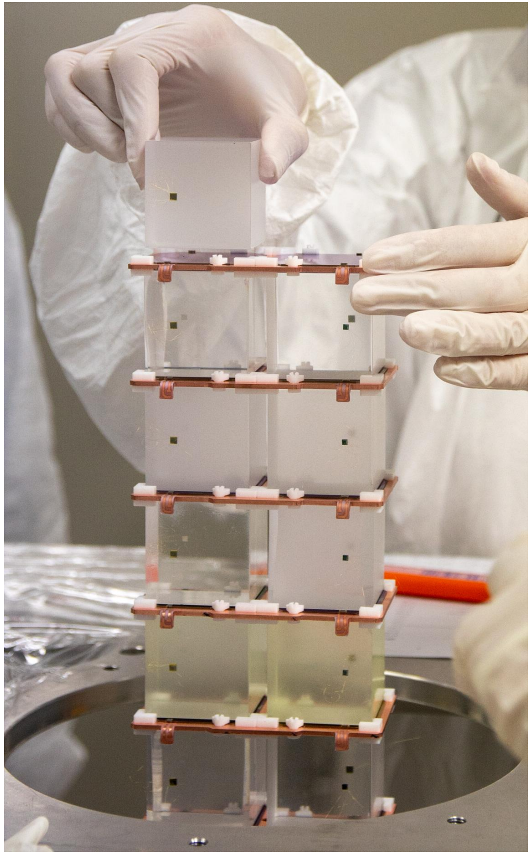
Improve tightness and thickness of existing neutron shield with water tanks surrounding the muon veto layer

Detector Structure - from CUORE to CUPID



- “gravity assisted” - no vertical constraint, stack of crystals and light detectors sitting one on top of the other (vs. rigid, fixed height structure in CUORE)
- tunable spring at the top for vibration damping and extra rigidity during transport
- easy and safe assembly - no screws, self-aligning structure
- loose tolerances - cost effective, easy cleaning

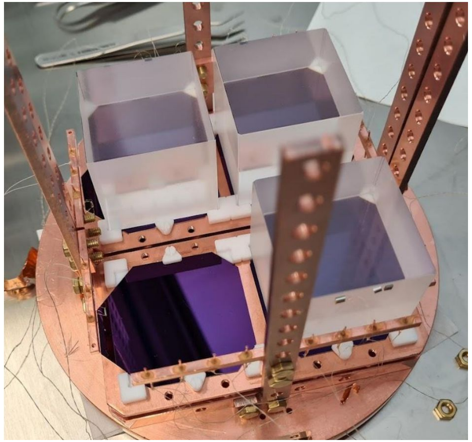


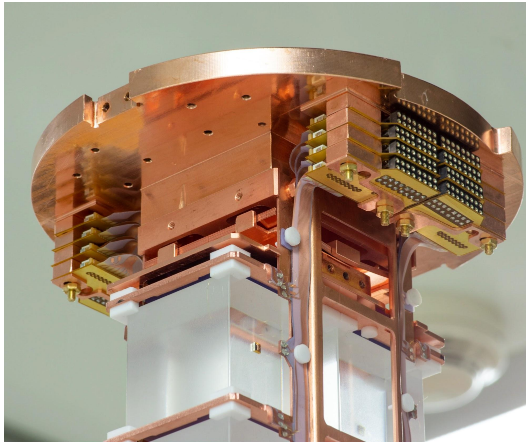


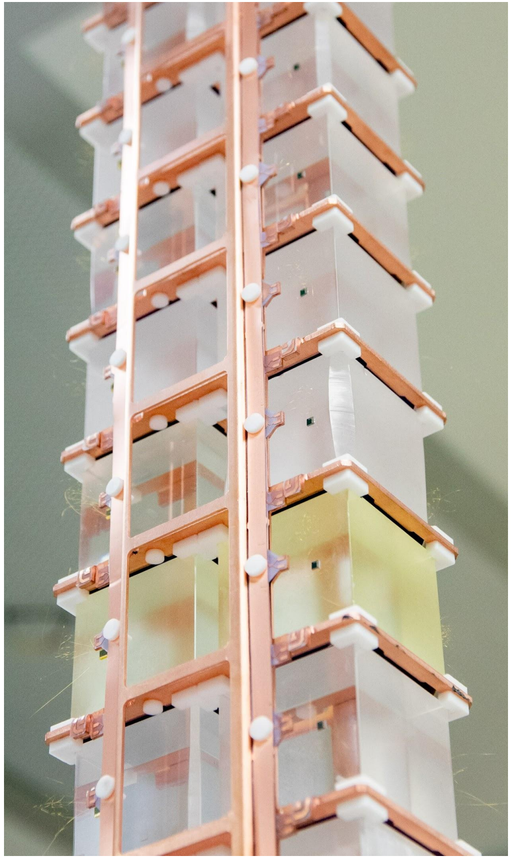
Detector Structure - BDPT

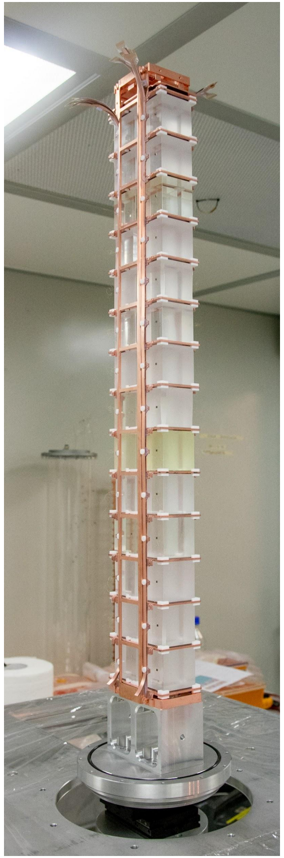
Validation of the detector design: **BDPT (Baseline Design Prototype Tower)**

- preliminary proof-of-principle on small scale (2 floors) successfully deployed
- validation of assembly procedures completed on full scale (14 floors)









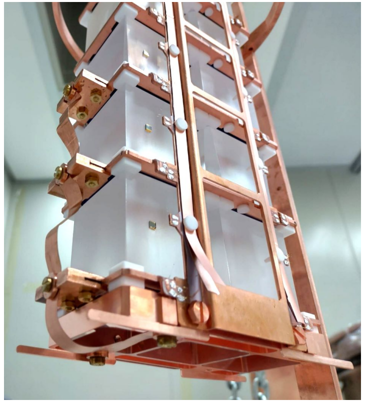
10.1140/epjc/s10052-022-10720-3

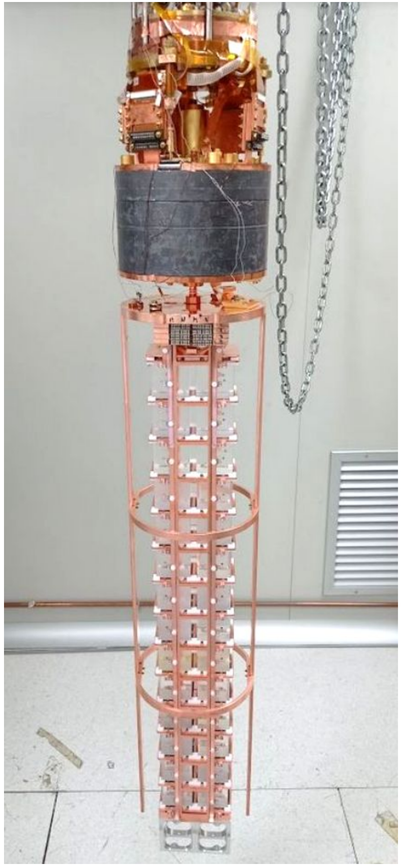
Detector Structure - BDPT

CUPID

Validation of the detector design: **BDPT (Baseline Design Prototype Tower)**

- program of validation of thermal and vibrational characteristics ongoing
- fast iterative process (build → run → analyze → modify) for design optimization ongoing





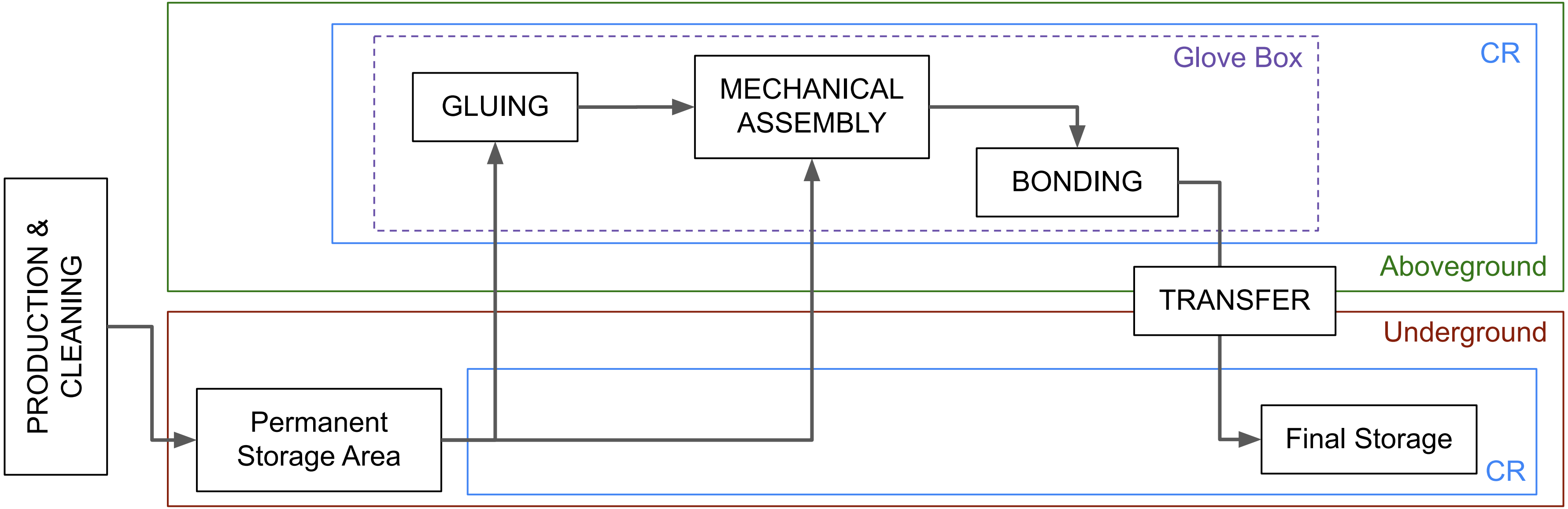
Run 1 (spring loaded) July - Aug 22 → assess thermalization, assess LMO performance, study LD performance and excess noise w.r.t previous setups

Run 2 (spring unloaded) Sep - Oct 22 → test effect of the spring, study floor-to-floor noise correlation

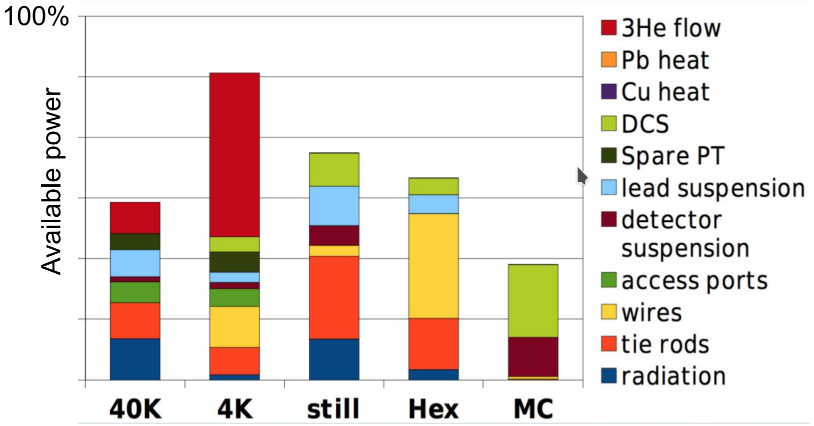
Run 3 (loose omegas, bottom floors thermalization) ongoing → test hypothesis on LD excess noise origin

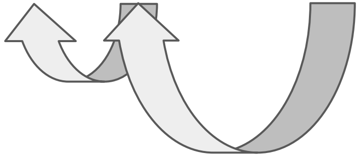
CUPID Assembly Organization

- Learn from CUORE experience → simplify and optimize procedures
- assembly line located in above ground Clean Room
- assembled towers are stored underground in CUORE Clean Room before installation
- assembly above ground → simple organization of working shifts and logistics



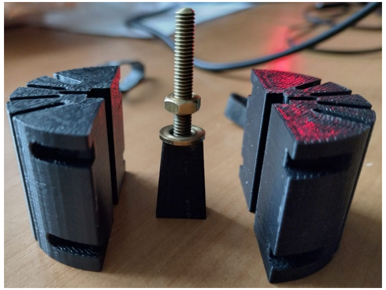
Cryogenic Systems - Cryostat Upgrades

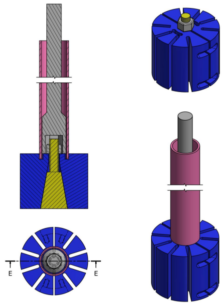


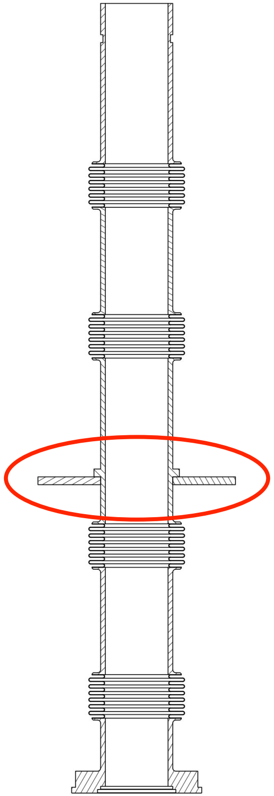


- CUORE Cryostat thermal budget extremely well known and understood
- Relevant contribution on colder stages comes from wiring
- Wiring will increase by a factor 3

Improve the thermalization at 40K where extra cooling power is available





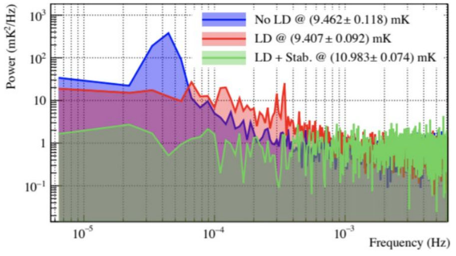


Host Lab & Cryogenic System - Cryostat Upgrades

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

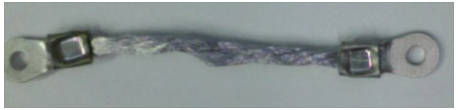


New Pulse Tubes:

- 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

Data Readout - 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 5 years → Readout scheme proven on the field

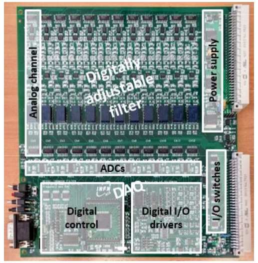
CUPID will add several challenges

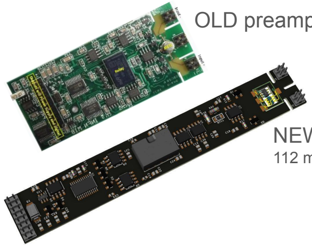
- More channels (x3), hence more power, more space, more data, etc.
- Faster signals on light detectors, required for pile-up rejection

Main upgrades (collaboration between ITA, USA, FRA)

- 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

New filter+DAQ board





OLD preamp

NEW preamp
112 mm x 17 mm

Small scale prototypes already deployed in multiple facilities for R&D

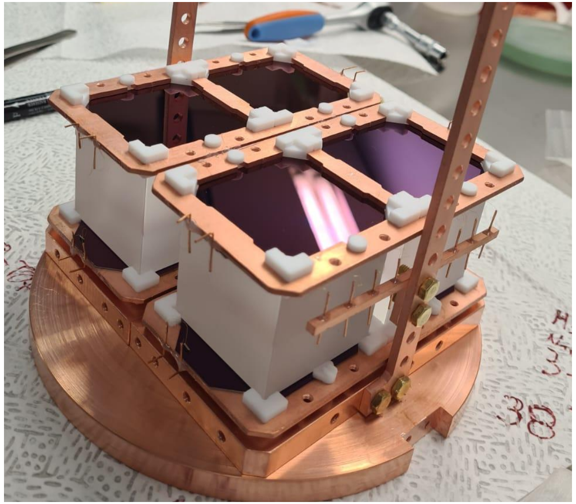
Background Control - Screening Labs

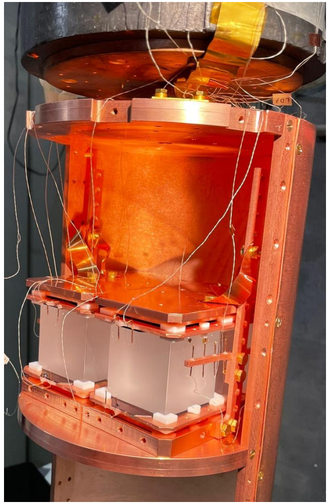
- High sensitivity radio-purity screening infrastructures available in Italy, US and France:
  - HPGe
  - ICP-MS
  - NAA
  - Surface barrier Si alpha counters
  - Cryogenic infrastructures for bolometric measurements (CCVR, large surface cryogenic Si detectors)
- Main screening activities:
  - MoO_3, Li_2CO_3 crystal growth precursors: certify vendors
  - materials used by CUORE: improve limits and/or re-certify vendors (e.g. CuPEN for cryogenic wiring, Roman lead)

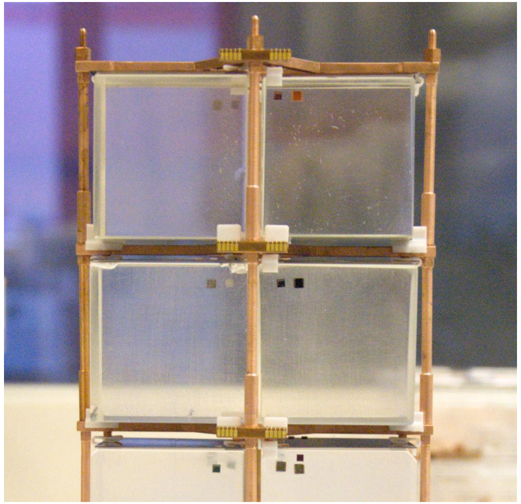
Background Control - CCVR

- Bolometric test of crystals operated as detectors in two cryogenic facilities
- Most sensitive tool to certify vendors
- Certify compliance of precursors radio-purity and crystal growth process with our specs
- Typically 4 crystals of each type/producer assembled in a 2x2 array with 8 light detectors for light readout and particle discrimination
- Run-time ~ 4 weeks to reach required sensitivity on U, Th and ^{40}K bulk and surface contaminations

HallC @LNGS







CROSS cryostat @LSC

Conclusions

- CUPID will **explore inverted ordering ($T_{1/2}$ > 10^{27} years at 3σ,** $m_{\beta\beta}$ ~ **12-20 meV)**
- **Builds on an existing and well-functioning international collaborations** and partnership between mainly Italy 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
- **Limited technology verification remaining** for CUPID baseline.
- **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