CUPID: CUORE Upgrade with Particle ID

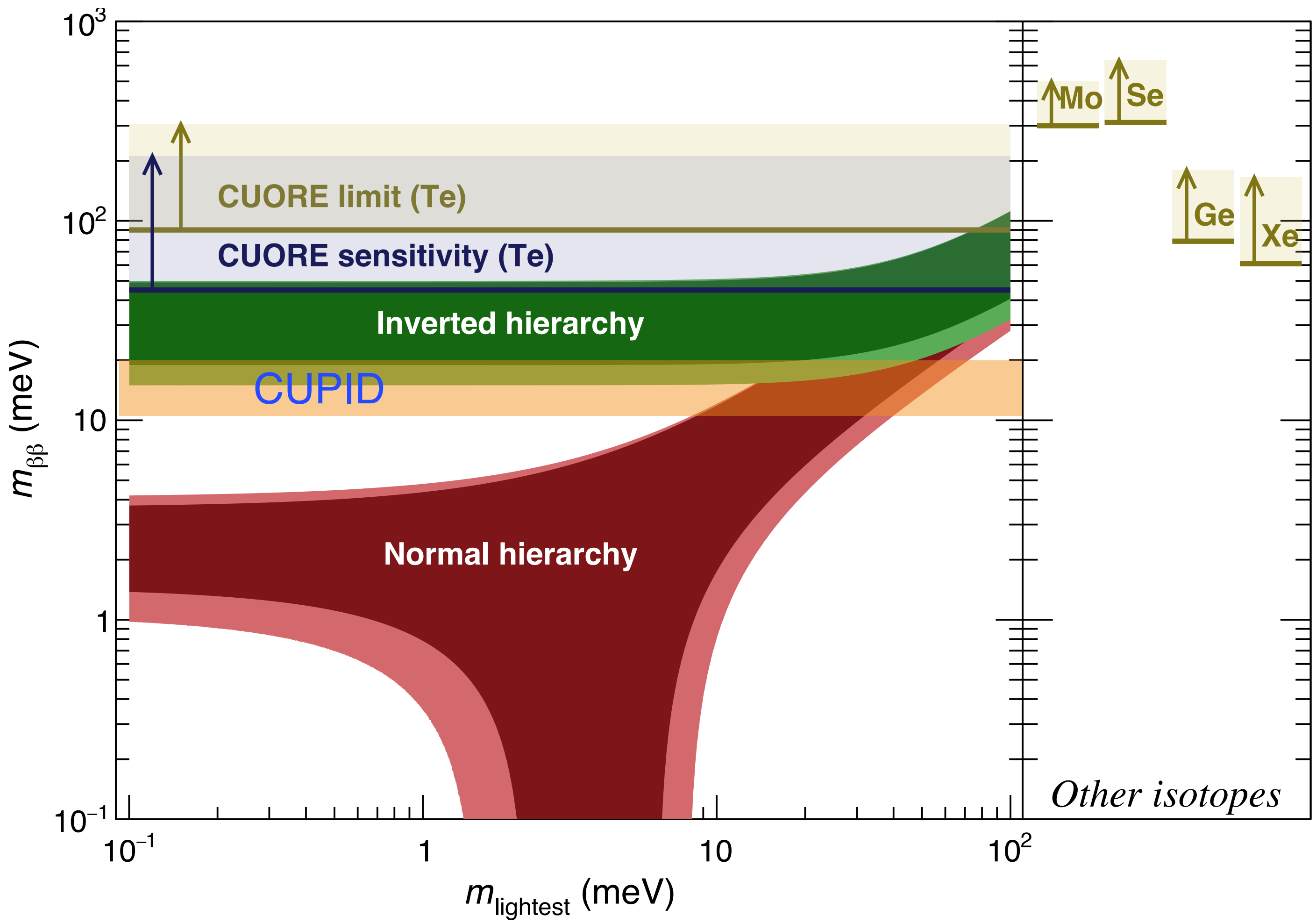
F.Bellini, Sapienza University & INFN

DBD workshop: the road to normal hierarchy *Lisboa, June 6 2022*

CUPID Baseline Sensitivity

Goal: cover the Inverted Hierarchy region and a fraction of normal one

- 3σ $m_{\beta\beta}$ discovery sensitivity in the 12-20 meV range
- 3σ discovery sensitivity $T_{1/2} > 1.1\text{x}10^{27}$ yrs

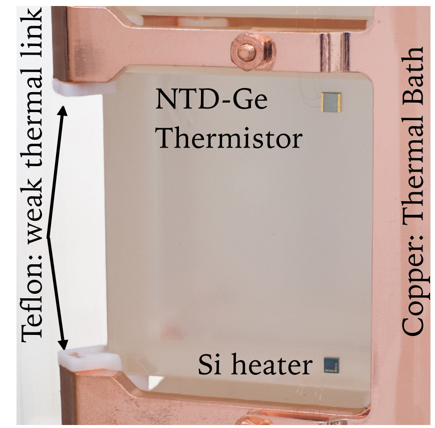


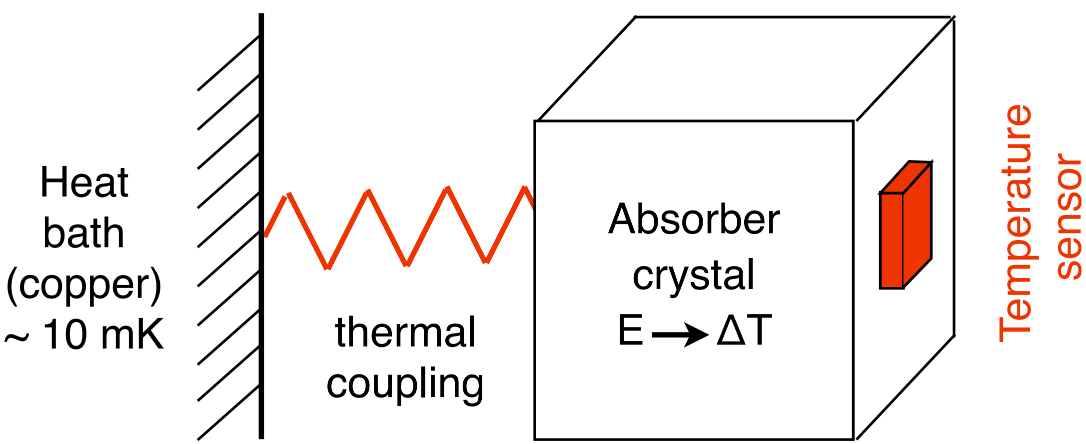
Cryogenic calorimeters

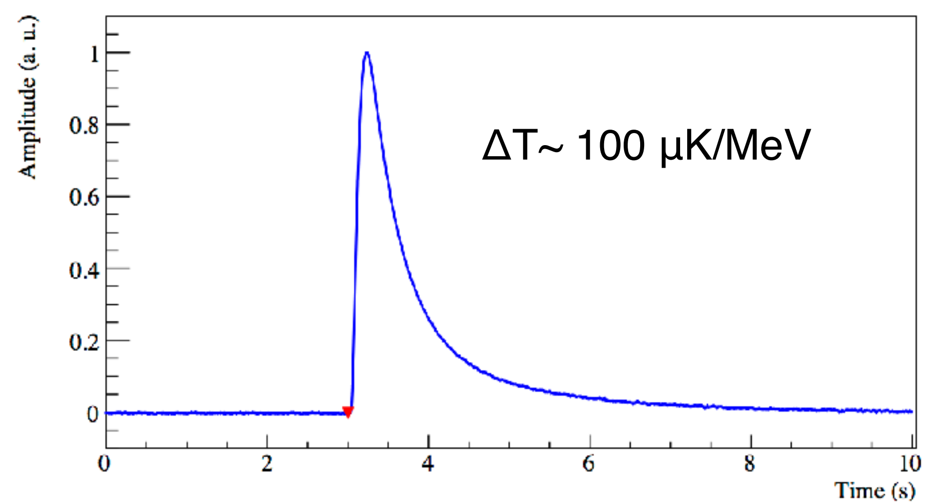
- Solid state detectors operating at low temperatures ~10 mK
- Readout with sensitive semiconductor NTD-Ge thermistor

$$R(T) \simeq 1\,\Omega \cdot \exp\left(\frac{3\,\mathrm{K}}{T}\right)^{\frac{1}{2}}$$

- Isotope of interest embedded in the source
    - Flexible choice of isotopes (Mo,Cd,Se,Te)
- Resolution @$0\nu\beta\beta$ energy: ~0.2% FWHM
- Detector response independent of particle types

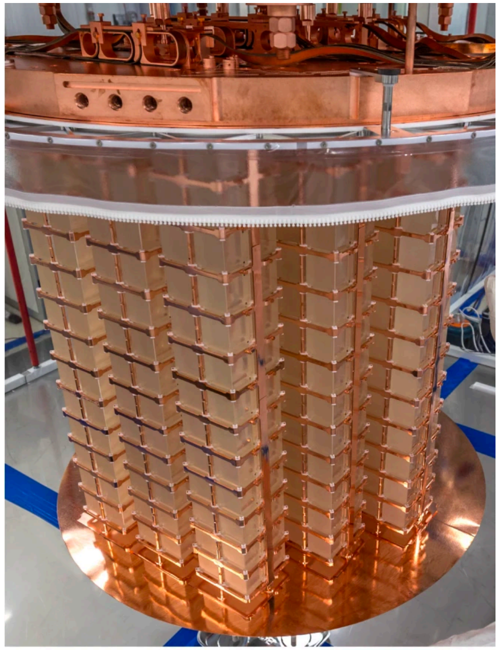


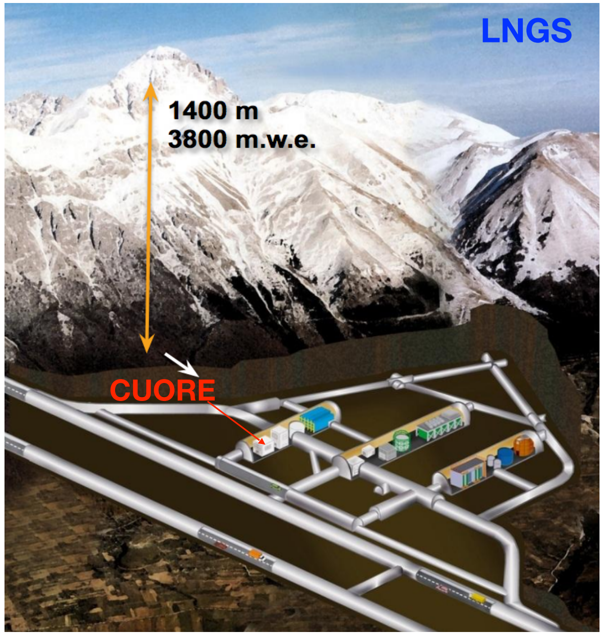


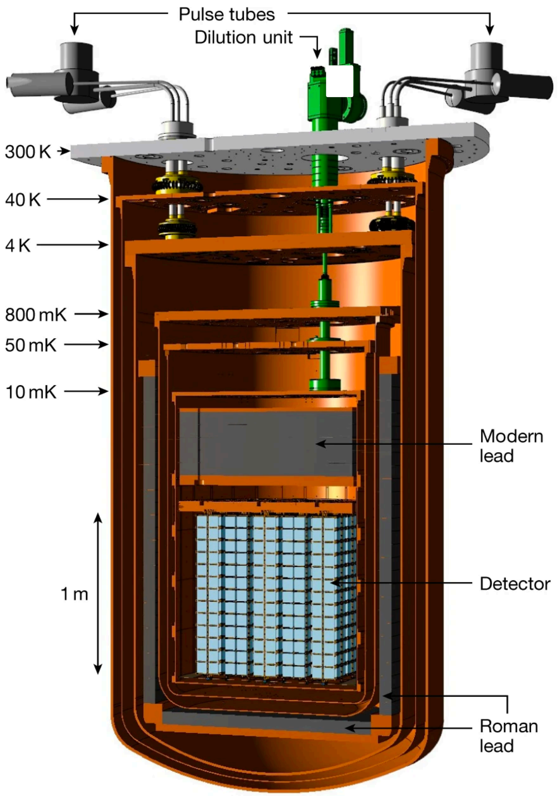


State of the art: CUORE

- Larger bolometric detector ever built
  - 988 $^{nat}TeO_2$ crystals
  - 742 kg of TeO2, 206 kg ^{130}Te.







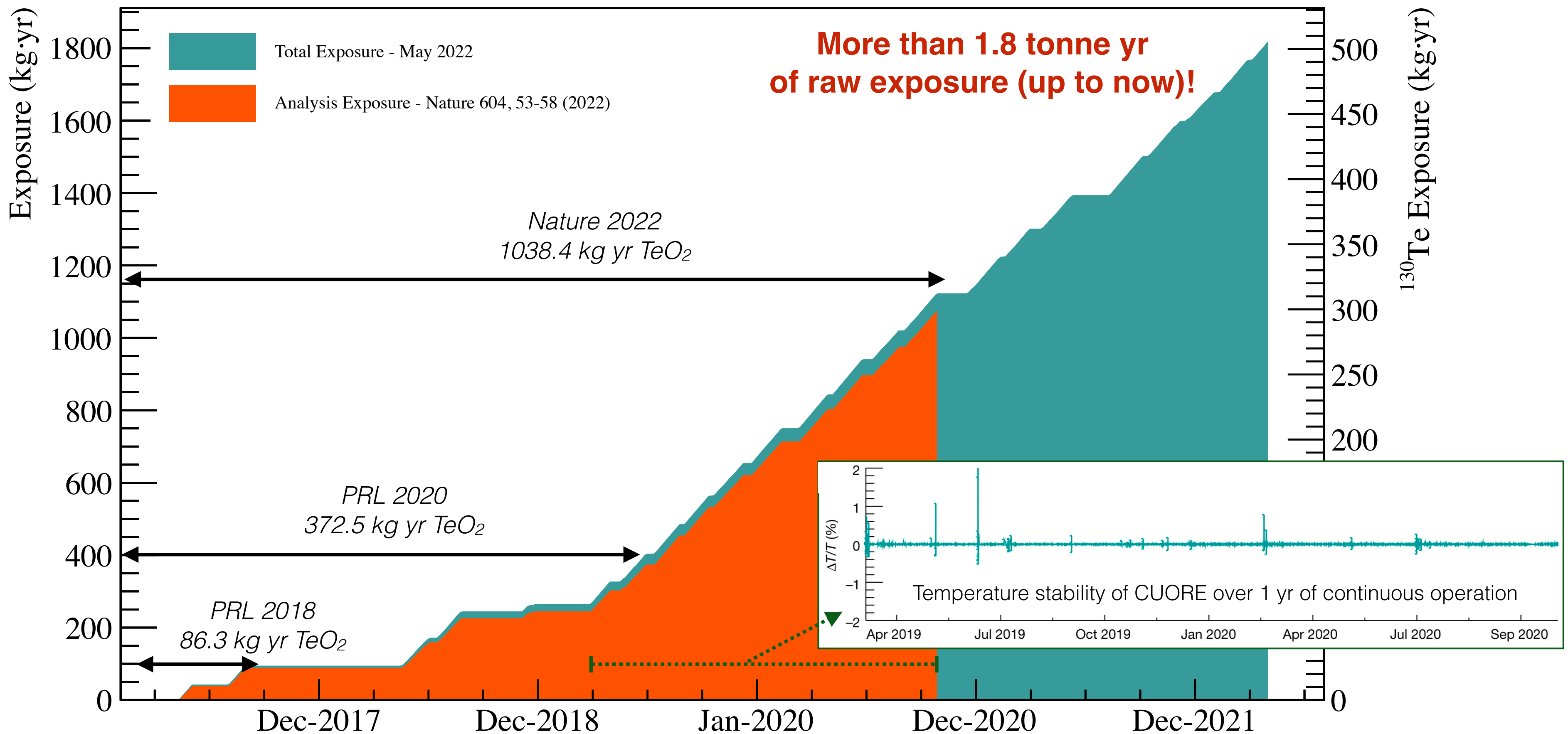
- Operating in a custom cryostat + cooling system

  5 Pulse Tube Cryocoolers 40W @ 40K, 1.2W @ 4K
  Custom 3He/4He DU 2mW @ 100mK, 4μW @ 10mK

  - Cryostat total mass ~30 tons. ~15 tons @ 4K, ~3 tons @50 mK (Pb, Cu, TeO_2).
  - Large duty cycle and long term stability. Low bkgd (material constraints) & low noise environment ->detector mechanically decoupled from cryostat
  - Challenge at the time of CUORE, established technology

CUORE successes

- Since 2019: 90% uptime (70 % physics data). Stable data taking: 50 kg/month



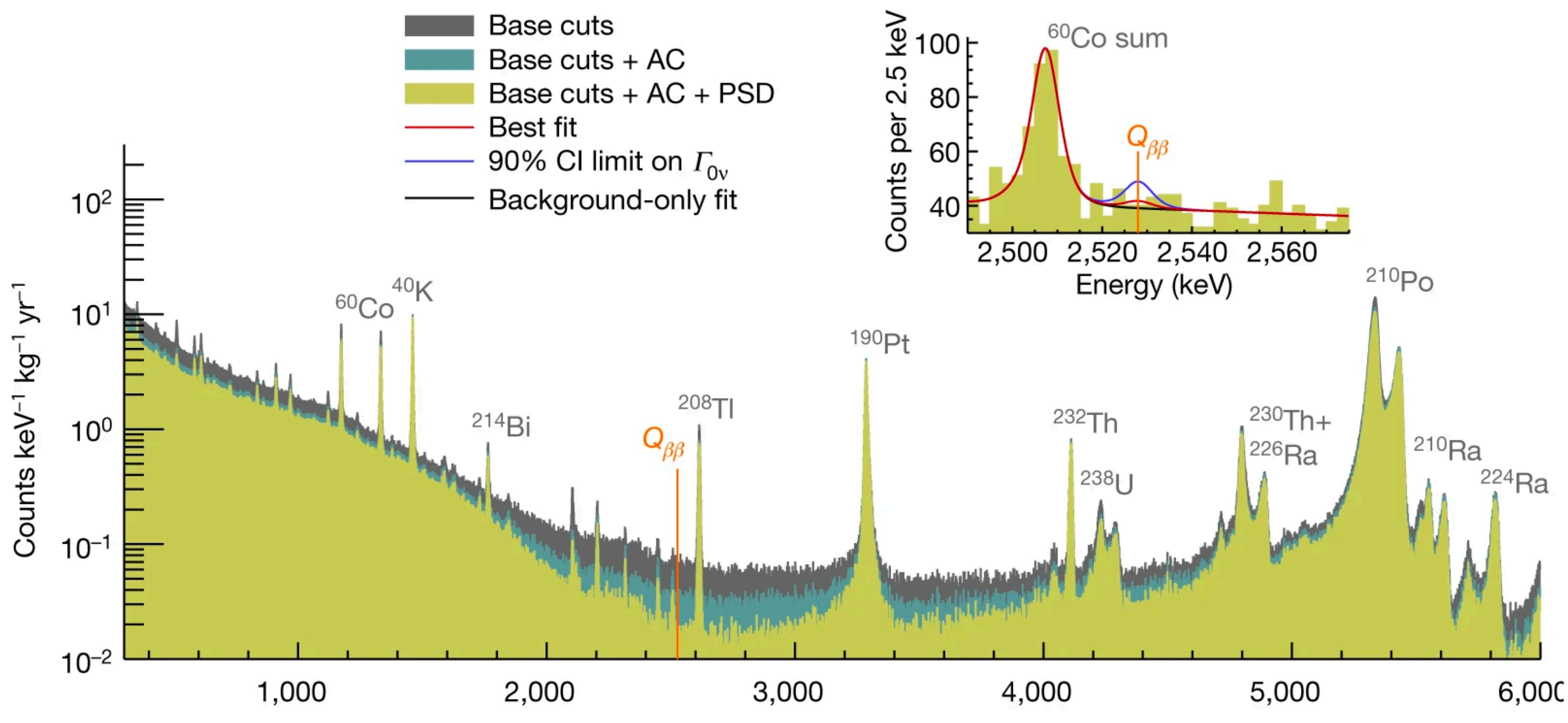
CUORE successes

Total exposure:
1038.4 kg yr TeO_2, 288 kg yr ^{130}Te

ROI background index (B)
~ $1.49(4) \times 10^{-2}$ c/(keV·kg·yr)

Half-life limit for 0νββ in ^{130}Te (90%C.I. including syst.)
$T_{0\nu}^{1/2}$ (^{130}Te) > 2.2×10^{25} yr

$m_{\beta\beta}$ < 90 - 305 meV



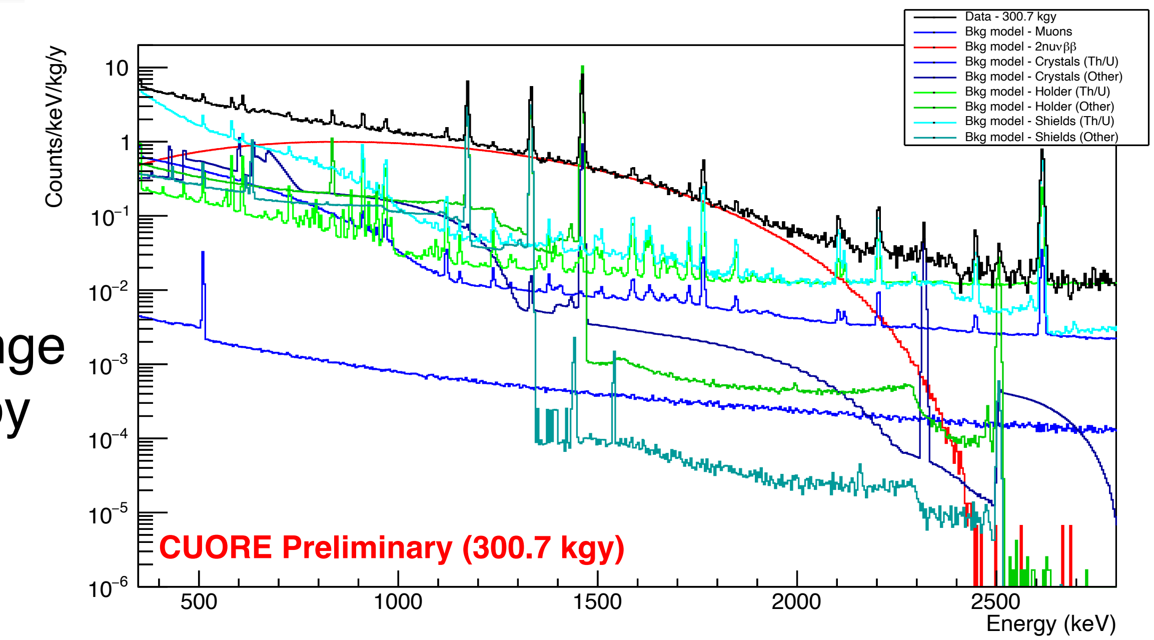
Nature 604 (2022) 7904, 53-58

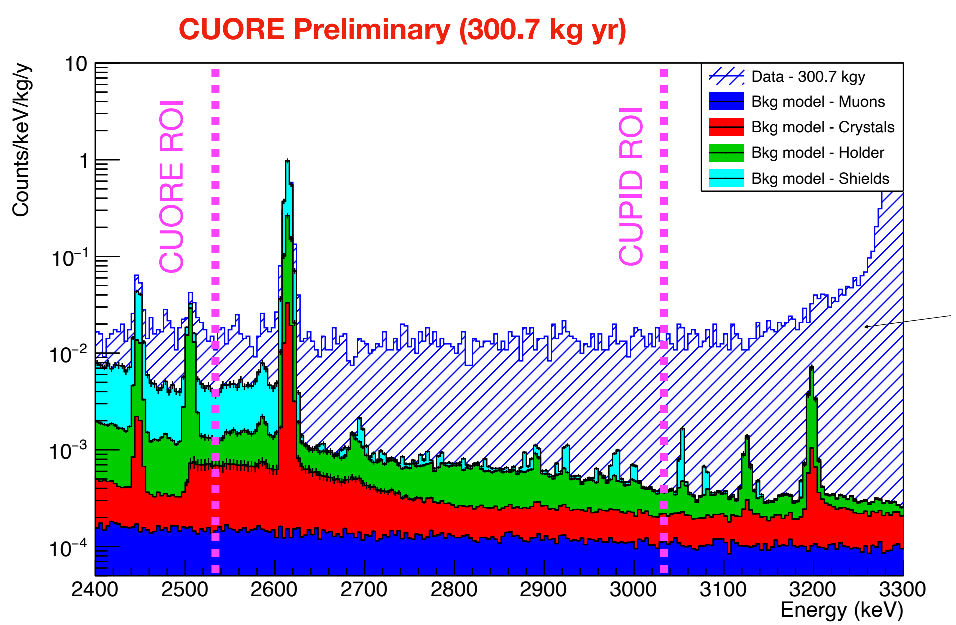
^{130}Te 2νββ decay measurement
^{130}Te ββ decay to excited states

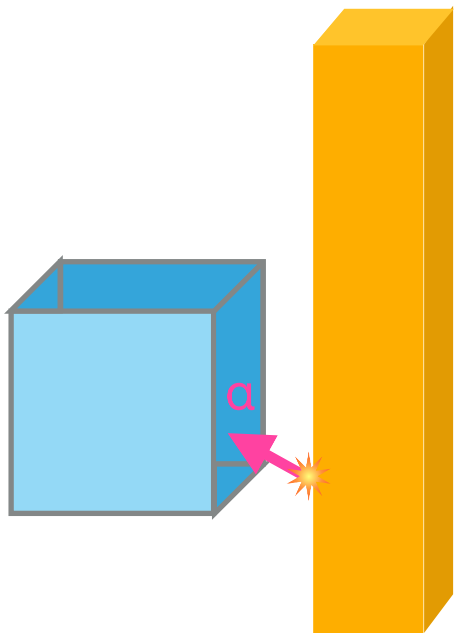
^{120}Te 0νβ$^+$EC decay search
^{128}Te 0νββ decay search

CUORE limits: α bkgd

- Fit to the observed spectra to extract origin and level of contaminants
- 90% degraded α background
  - decays with Q-value in 4-8 MeV range that lose part of the energy in nearby passive materials
- 10% γ , muons <1%



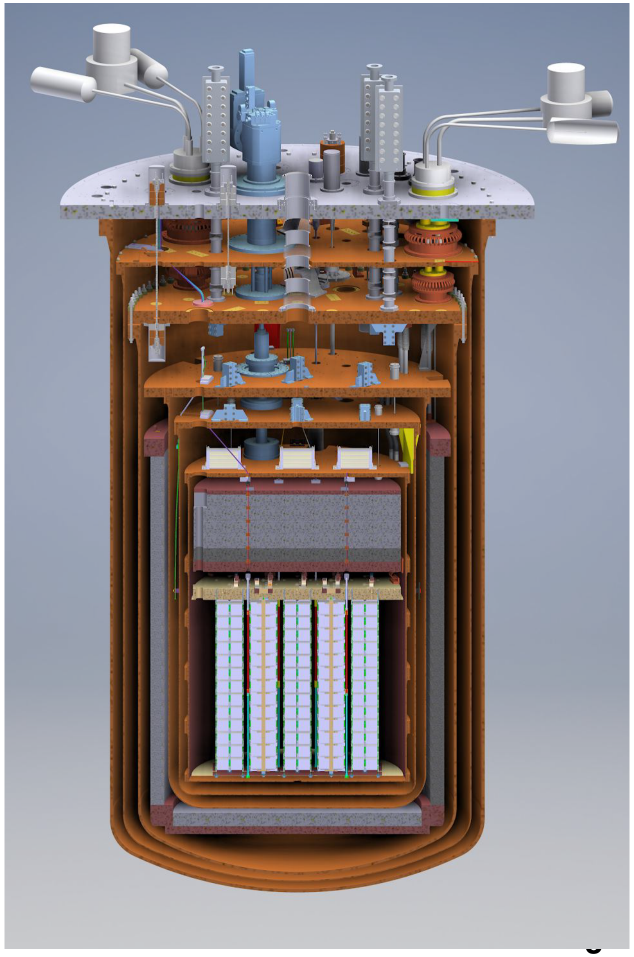




CUPID Strategy

A ton scale high-resolution detector array for the search of $0\nu\beta\beta$ in the inverted hierarchy

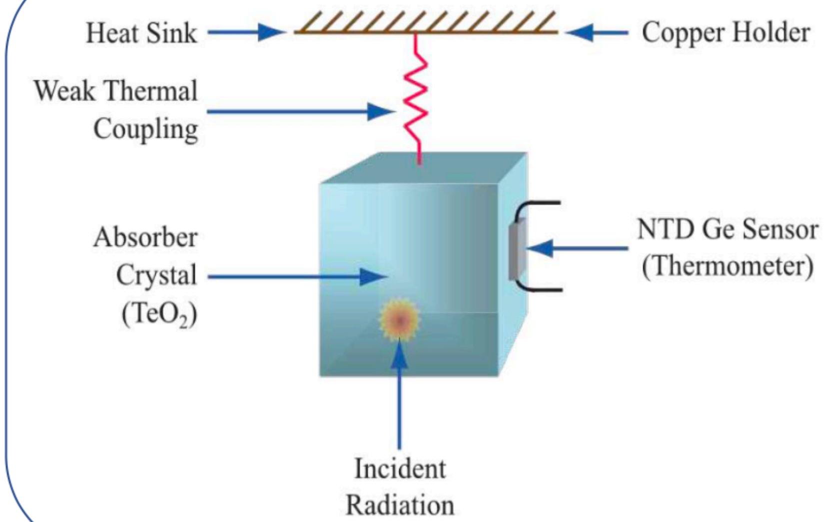
- Re-use CUORE Infrastructure
- Replace CUORE $^{nat}TeO_2$ detectors with an array of 95% enriched $Li_2{}^{100}MoO_4$



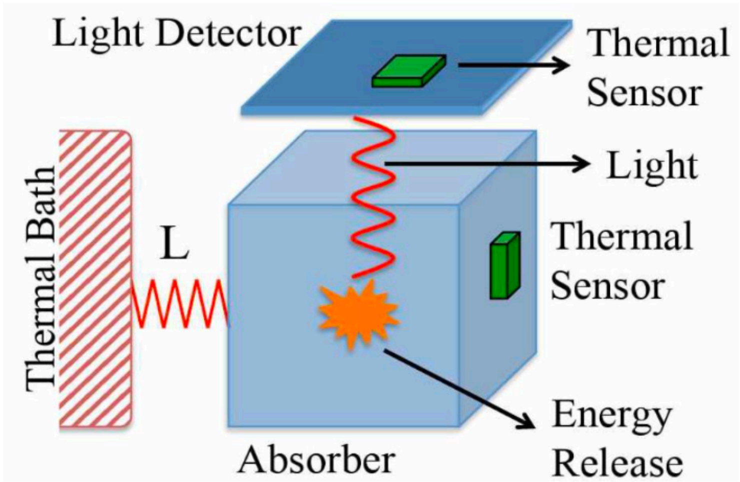
- Enough to take a leap forward in sensitivity because we reduce dramatically (~150) the background
  - ^{100}Mo has higher $Q_{\beta\beta}$ (3037 keV) than ^{130}Te(2.5 MeV): less γ-induced background in ROI, more favourable phase space and matrix element
  - new detector with very efficient α particle rejection: remove the dominant background in CUORE

Concept

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



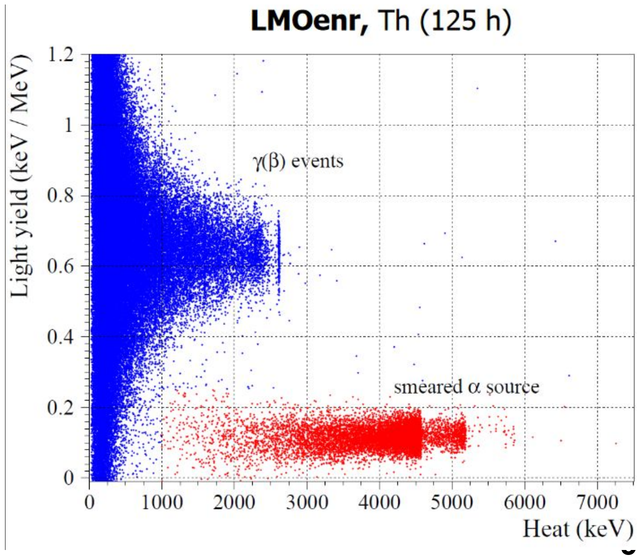
CUPID ^{100}Mo
heat + light
(scintillating bolometer)



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

~~α background~~
~~γ background~~
PID

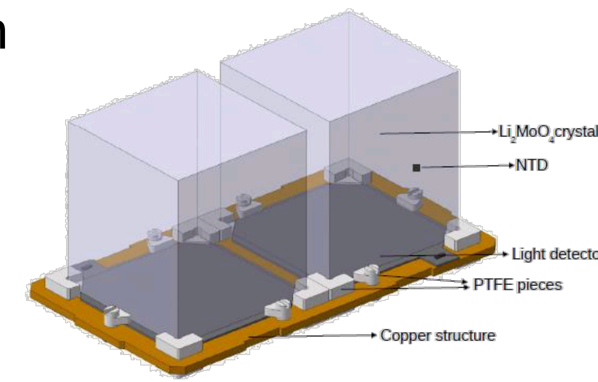
Q = 3034 keV **> 2615 keV**



CUPID

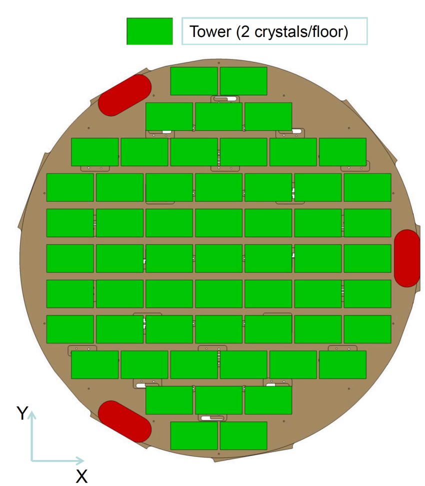
- Single module: $Li_2{}^{100}MoO_4$, 45x45x45 mm, 280 g
- Detector: 1596 crystals in 57 towers,14 floors 2 crystals each
  - ~240 kg of ^{100}Mo ~$1.6.10^{27}$ ^{100}Mo atoms
- Ge light detector (LD) with SiO antireflective coating
  - NTD readout for both LD and $Li_2{}^{100}MoO_4$

Detector Module

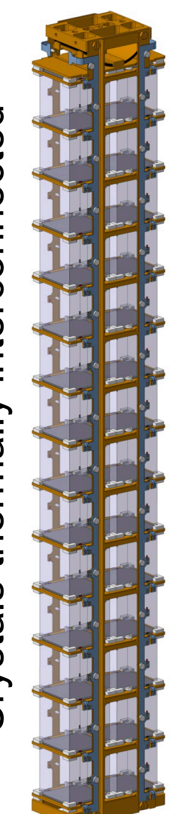


- Physics reach
  - 10 yrs run time
  - Energy resolution: **5 keV** FWHM
  - Background: **10^{-4} cts/(keV kg yr)**
  - Discovery sensitivity **$T_{1/2} > 1.1\times10^{27}$ yr (3σ)**
  - Discovery sensitivity **$M_{\beta\beta}$: [12-20] meV (3σ)**

Tower Arrangement



Gravity stacked structure
Crystals thermally interconnected



Tower

Collaboration

International collaboration: ~140 collaborators across 7 countries

Leverage previous collaborative experiences

https://cupid.lngs.infn.it

CUORE

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

CUPID-0

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

CUPID-Mo

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

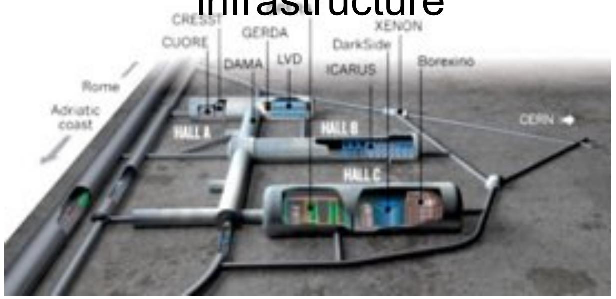
Collaboration

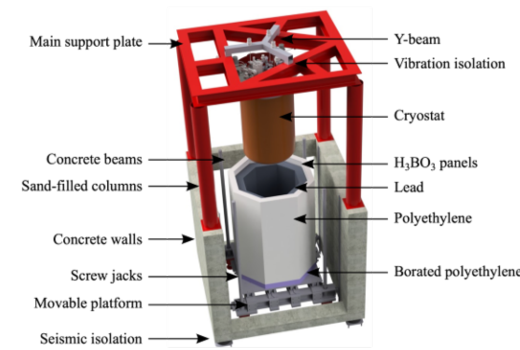
International collaboration: ~140 collaborators across 7 countries

https://cupid.lngs.infn.it/

Leverage previous technical experiences

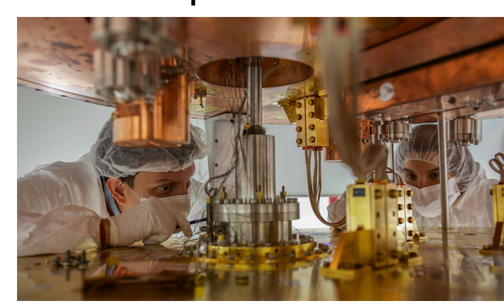
Long-lasting and well developed interaction with LNGS services and infrastructure





Cost and time-effective reuse of the CUORE underground infrastructure

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



Re-use a unique existing infrastructure

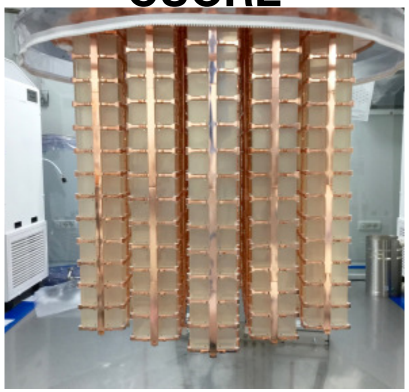
CUPID leverages many years of work and investment

CUPID Background model

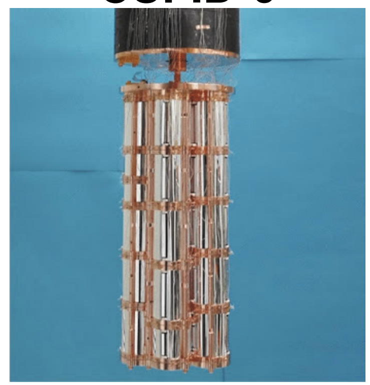
Our background model reconstruction approach is well validated in multiple experiments.

All the materials for CUPID have been directly measured in bolometric setups.

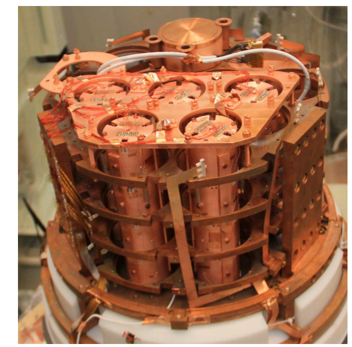
CUORE

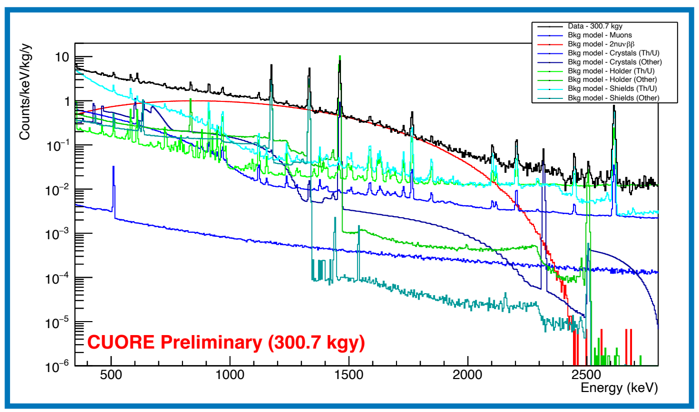


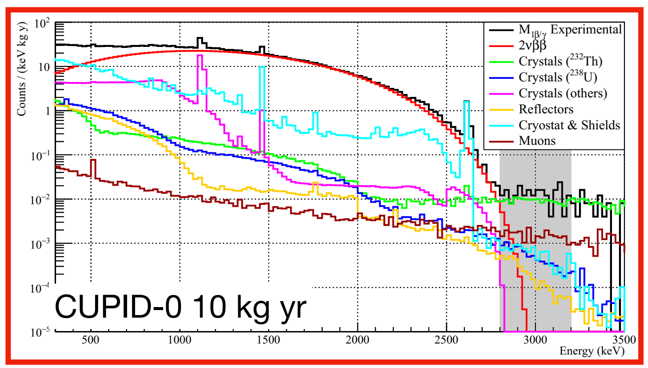
CUPID-0

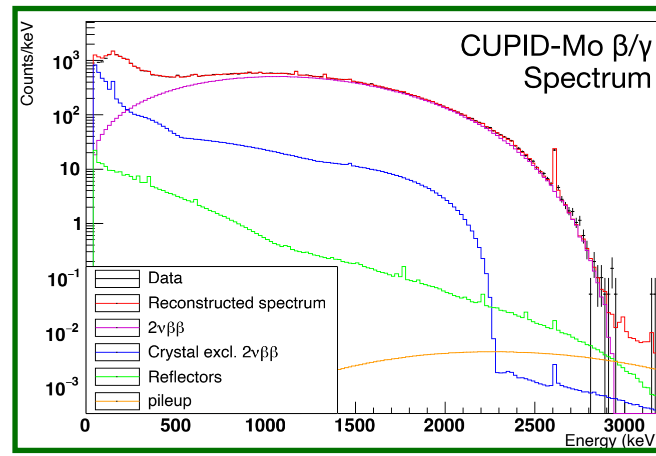


CUPID-Mo









Characterize β/γ background from cryogenic system and detector holders in the ^{100}Mo ROI ($Q_{\beta\beta}$= 3034 keV)

α-rejection
Confirms the β/γ background from detector holders in 3 MeV ROI

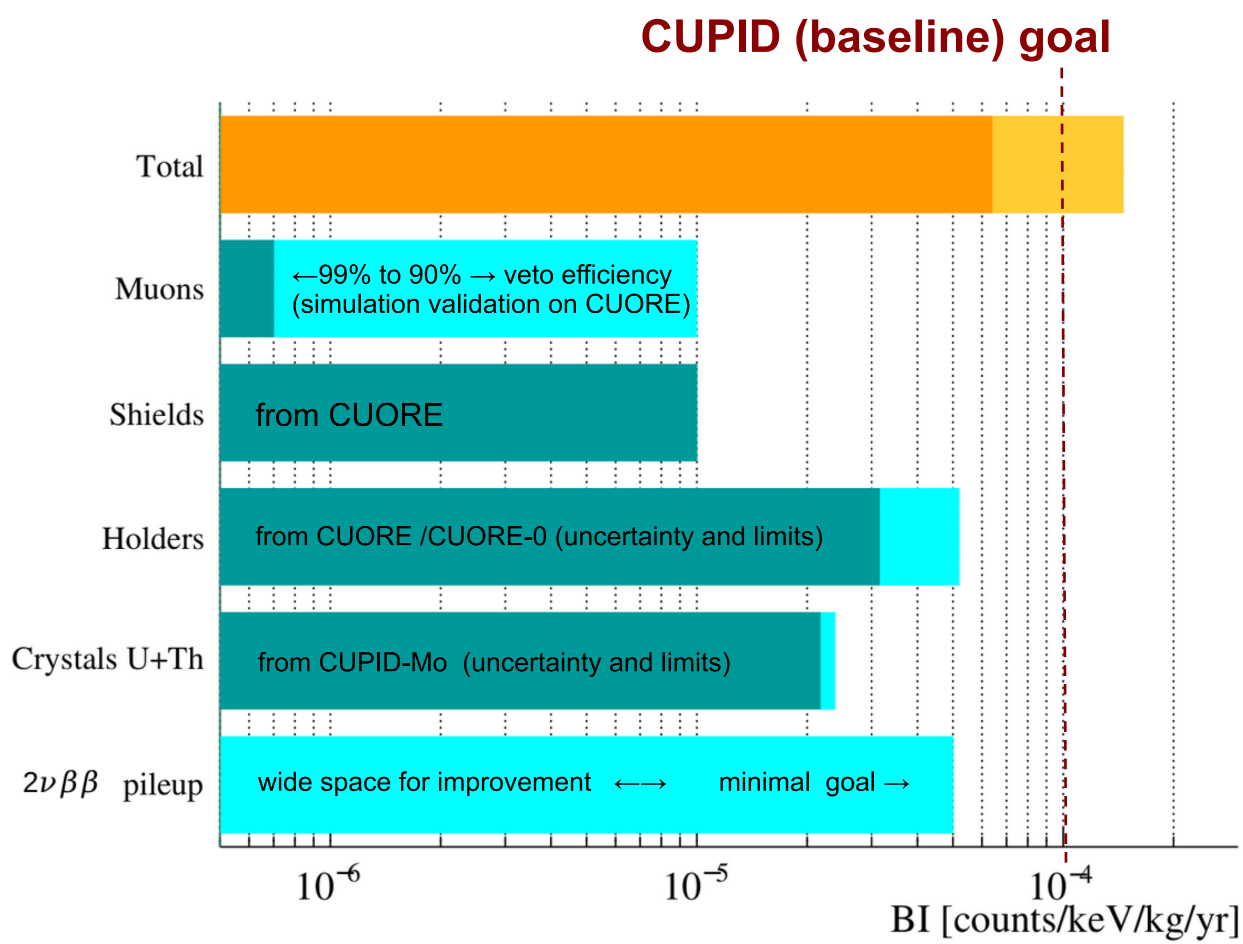
Data confirms:
- α tagging performance
- Radiopurity of crystals
- Energy resolution

Background budget

Our background model reconstruction approach is well validated in multiple experiments.

All the materials for CUPID have been directly measured in bolometric setups.

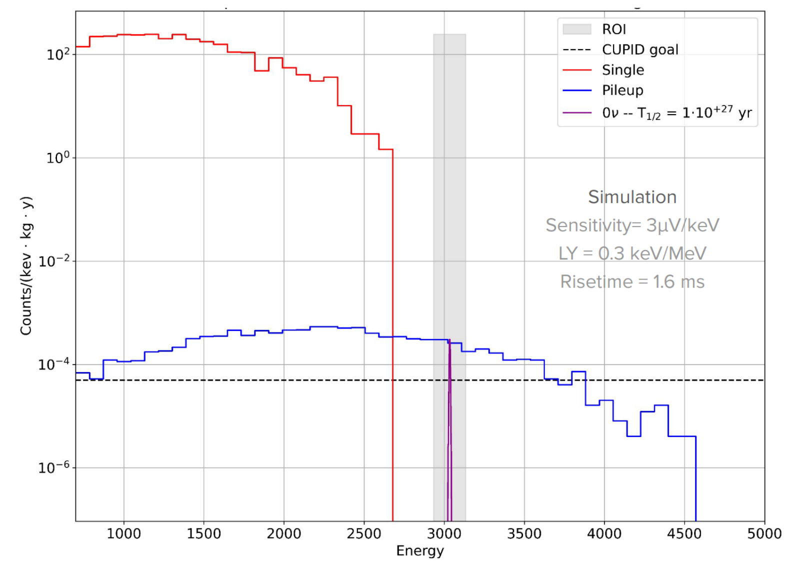
- demonstrated required crystal purity levels
- holders U/Th contamination levels achieved in CUORE are sufficient for CUPID (CUORE protocols for passive elements cleaning)
- contamination in cryogenic shields is well understood
- pileup background is well modelled and reduction possible with current technology

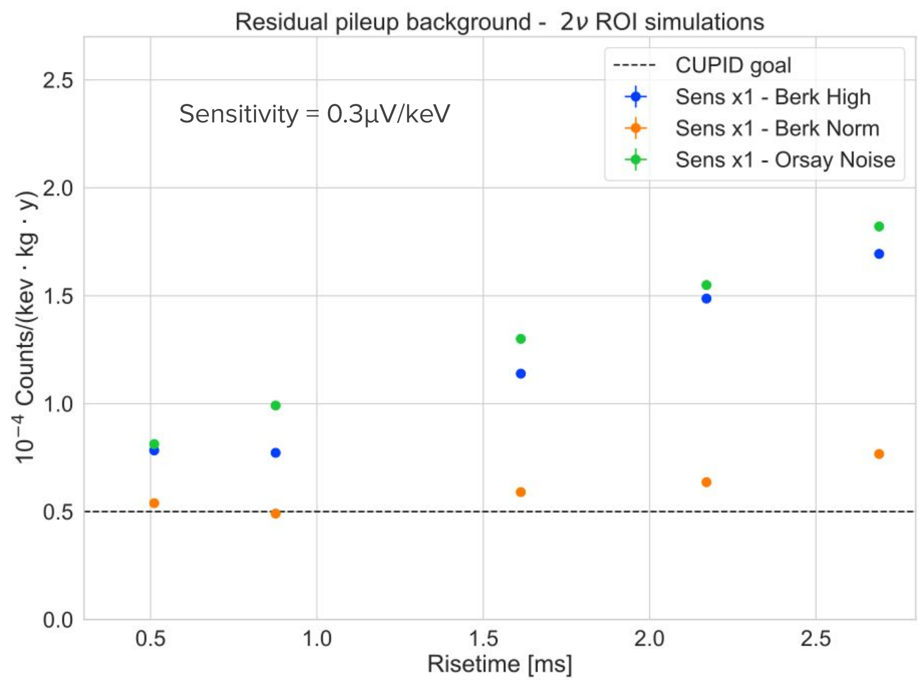


Well-defined path to reduce the CUORE backgrounds to the levels required for CUPID

Pile up

- Relatively fast decay rate of ^{100}Mo
  $T_{1/2\ 2\nu} = 7.1\times10^{18}$ yrs
  leads to possibility of two 2νββ decays events piling up & reconstructing in ROI
- Rejection depends on: signal amplitude & rise time, Bessel frequency, sampling rate, NPS and algorithms
- Validated nock data to explore rise time, noise, and bandwidth configurations and noise condition
- Use both LD and Li_2MoO_4
- 0.5 10^{-4} ckky in the reach with modest improvement and higher SF and Bessel cutoff
- Confirm performances with optical fibers or intense sources



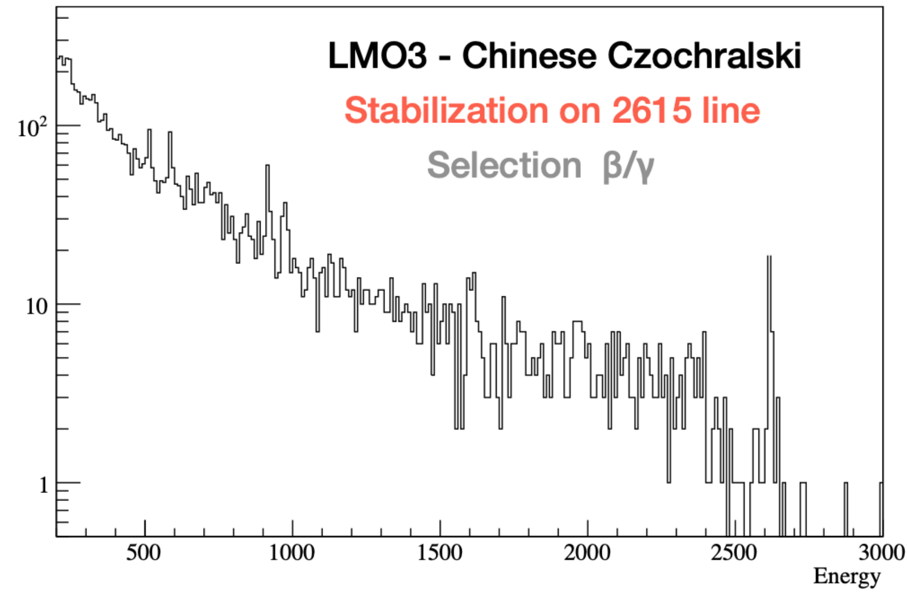


Isotope & crystal procurement

- CUPID Baseline : ^{100}Mo (Isotope JSC) and crystal grower (NIIC) are Russian
  - both activities are currently suspended due to current geopolitical situation

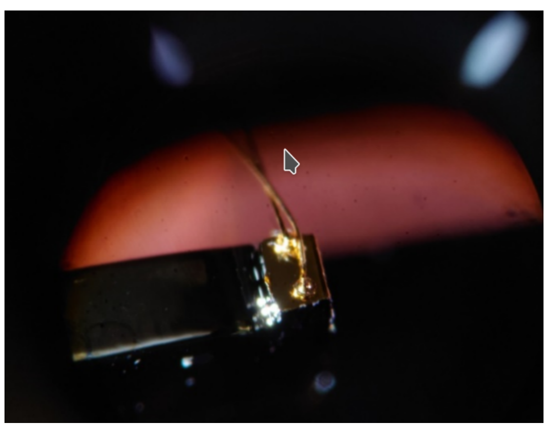
- Isotope alternative vendor: **Urenco** (Netherland), producer of stable isotopes in Eu
  - test facility for ^{100}Mo production on a commercial scale in progress independently from our needs (medical applications)

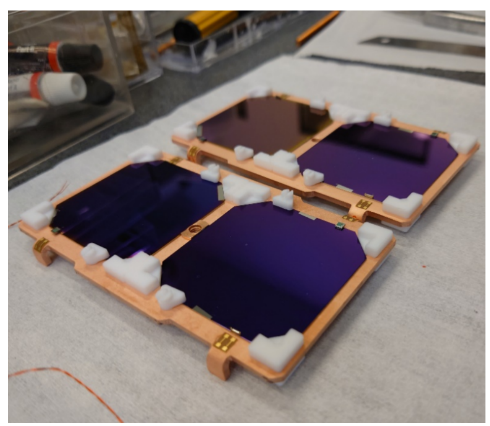
- Crystals alternatives vendor:
  - Under test: 6 Li_2MoO_4 natural crystals grown by Ningbo University (China) + 2 by SICCAS (China).
  - 2 crystals tested in a short run in 2021 compliant with our requirements
  - Need certification of capability to produce radio-clean crystals
  - Alternative vendors in US (RMD) and France

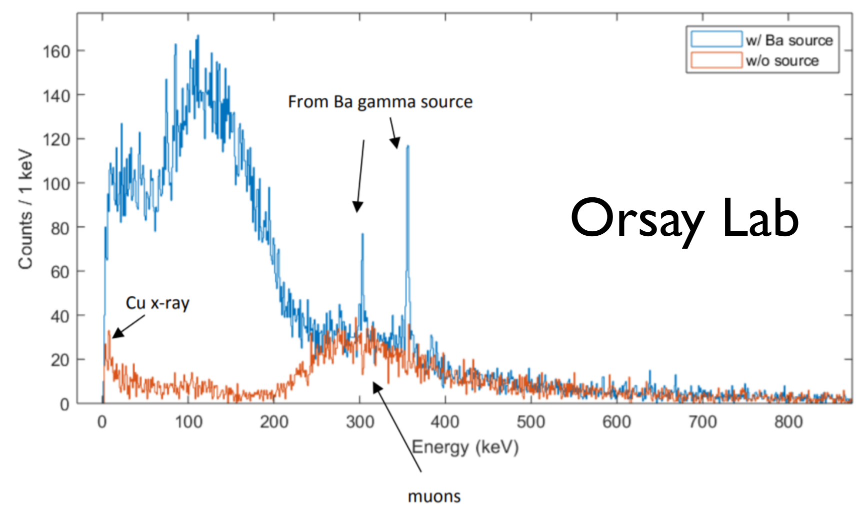


NTD, heaters, LDs

- 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
- Light Detectors: Ge wavers with SiO Anti-Reflective coating
    - particle discrimination (<100 eV RMS & >90% absorption efficiency required - large safety margin)







NTD, heaters, 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
- Light Detectors: Ge wavers with SiO Anti-Reflective coating
  - pile-up rejection (< 170 μs amplitude-averaged timing resolution required)

Extensive validation program to be completed in 2022

Detector response model to identify speed-limiting factors

High rate external sources on LiMO crystals for realistic light emission

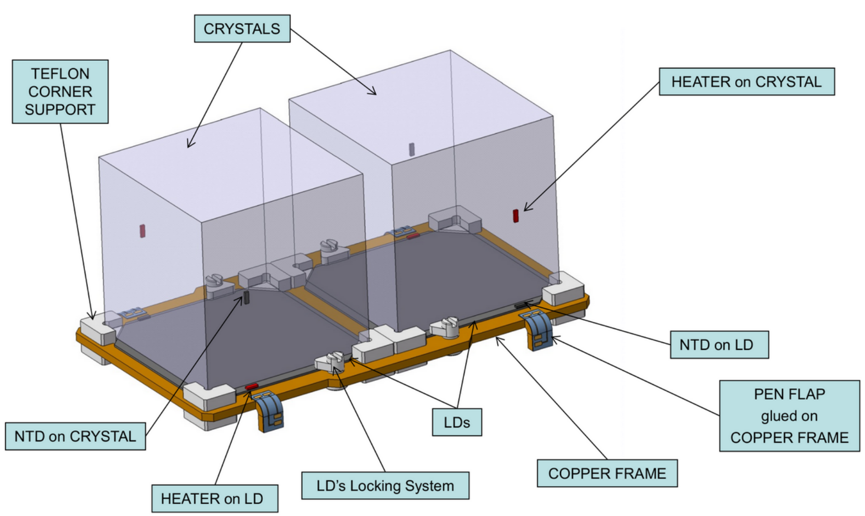
LED + optical-fibers to explore timing resolution with direct approach

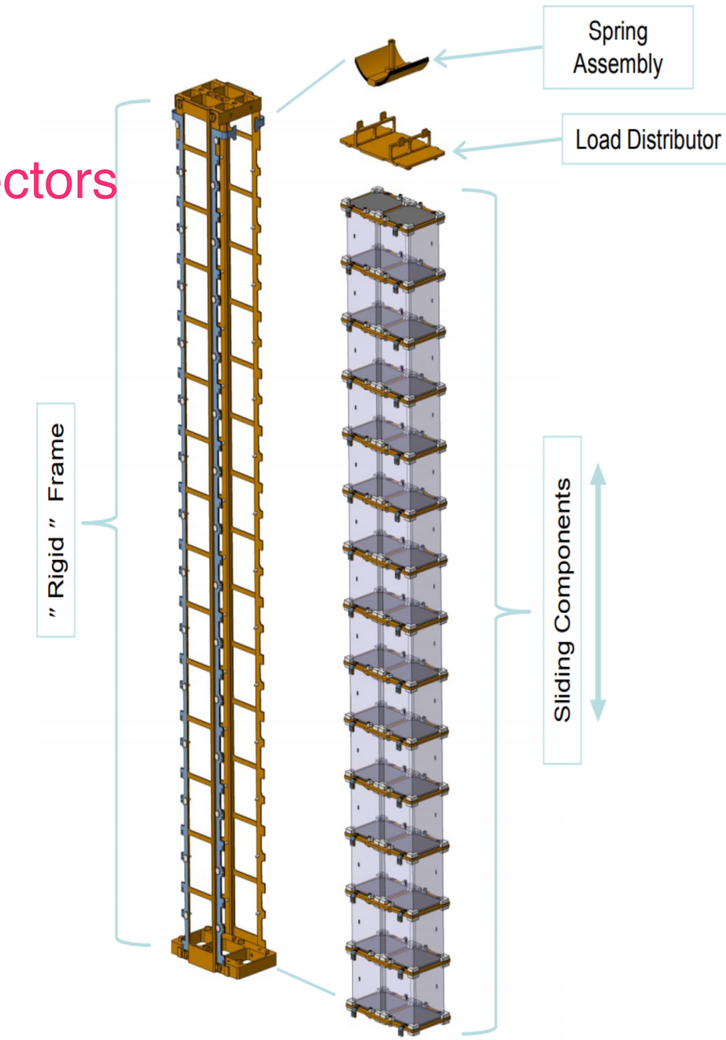
Synthetic data to extrapolate from measured performance (noise and pulse shape) to expected B.I.

Detector Structure

- The challenge:
  - integrate LD without adding complexity
  - address weak points in CUORE design (e.g. reduce time needed for assembly despite higher number of detectors, cleaning of parts,.)

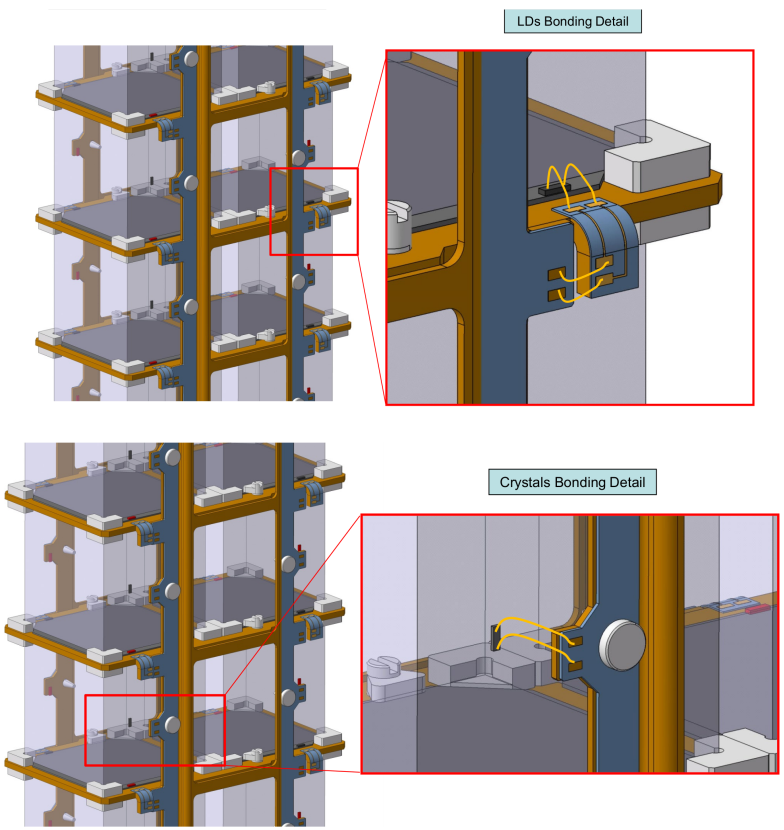
- The solution: "gravity assisted" tower
  - no vertical constraint, stack of crystals and light detectors sitting one on top of the other (vs. rigid, fixed height structure in CUORE)
  - tunable spring at the top for vibration damping and extra rigidity during transport

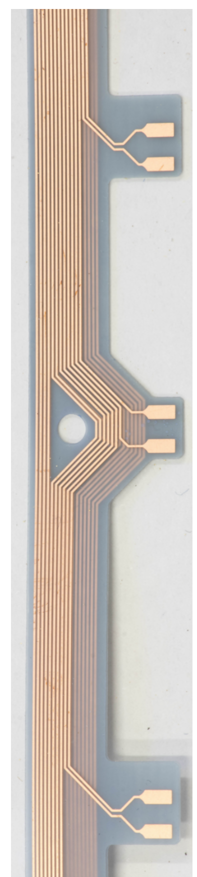


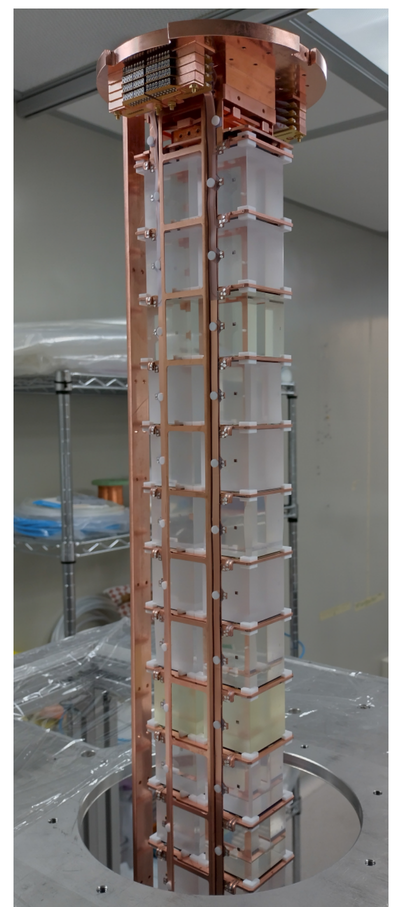


Detector structure

- Same materials used in CUORE(CU, PTFE, Cu-PEN wiring)
  - easy & fast assembly - no screws, self-aligning structure
  - loose tolerances - easy to produce (laser cut of Cu sheets), easy to clean (with no special care for threads and abutment surfaces)
  - better wiring integration







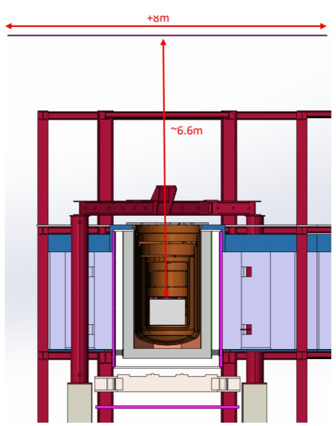
Thermal & vibrational validation ongoing

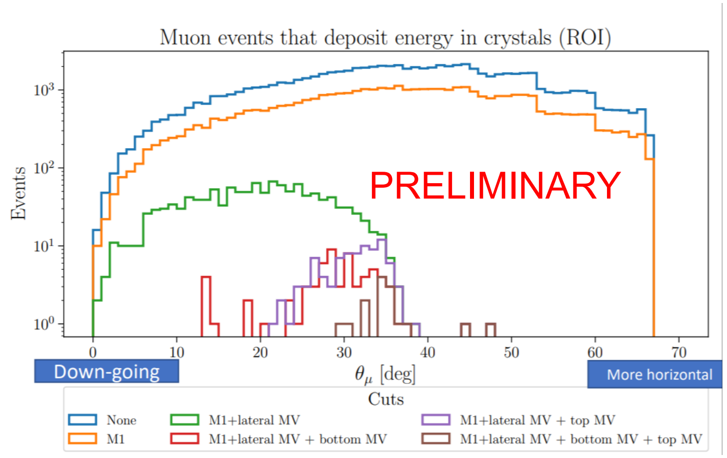
Crystal from BINGO, CROSS, INFN, China

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 & showers constraints contribution in M1
  - high energy gamma cascades from neutron capture

Muon veto on top/side of the cryostat to intercept >90% muons → 99% reduction of M1 background when combined with detector granularity



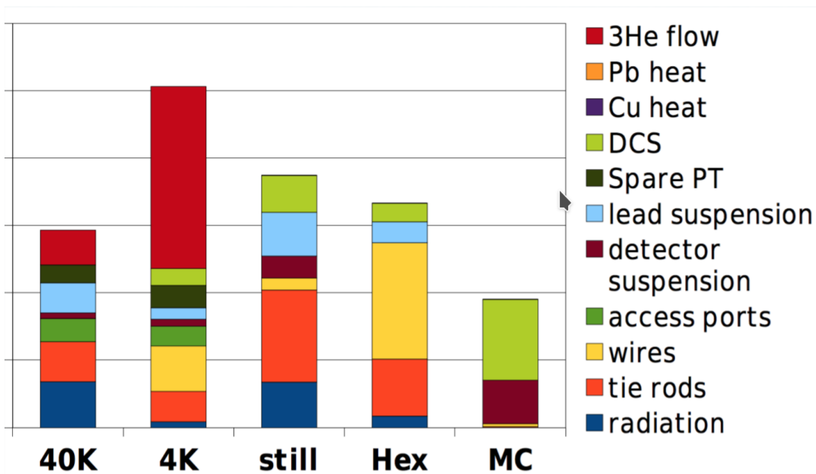


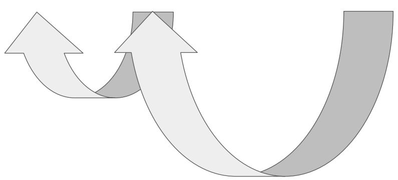
Operate as a stand-alone subsystem and integrated offline into main event at event building level.

CUORE shield: 20 cm PE(moderator) + 3 cm H_2BoO_3 (absorber) +25 cm Pb
Add (10-20 cm) of moderator under study

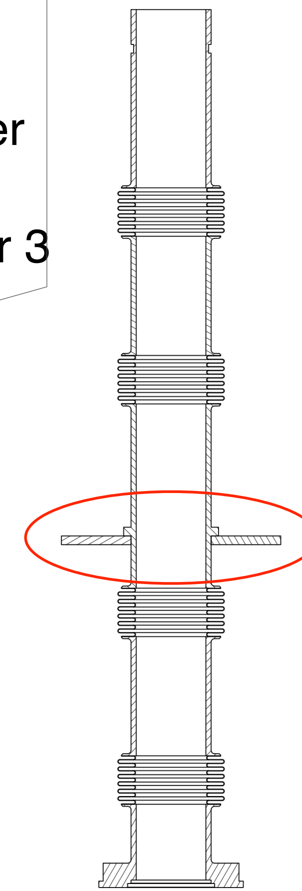
Cryostat upgrade

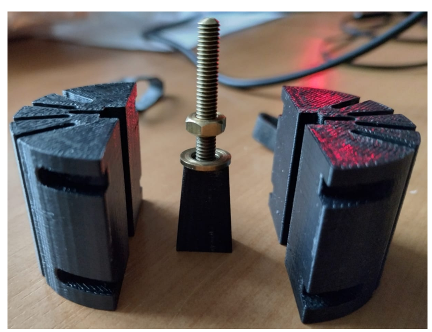
- CUORE Cryostat thermal budget extremely well known and understood
- Relevant contribution on colder stages comes from wiring
- Wiring will increase by a factor 3

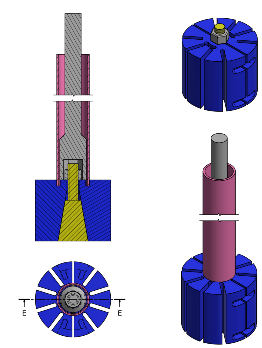




Improve the thermalization at 40K where extra cooling power is available







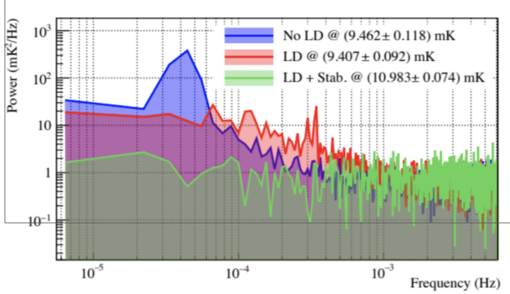
Cryostat upgrade

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

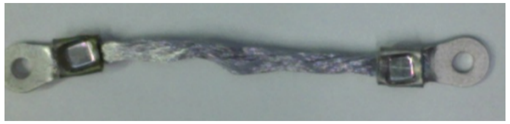


New Pulse Tubes:

- 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: FEE and DAQ

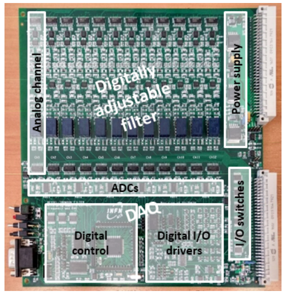
CUORE: custom-designed room-temperature front end electronics. Raw data is stored for offline processing

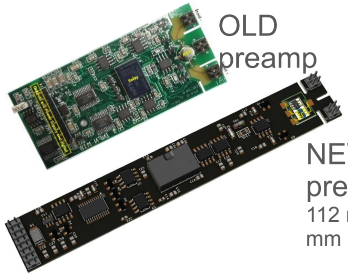
- Very stable and reliable operation for 5 years → Readout scheme proven on the field

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

New filter+DAQ board





OLD preamp

NEW preamp 112 mm x 17 mm

Main upgrades

- New frontend will save a factor of 2 in space
- Keep same power budget, optimizing preamps for light channels (same power, lower noise) & heat channels (lower power, same noise)
- Reduce wiring capacitance to reduce input RC time constant
- New board merges DAQ (24-bit ADCs, 25ksps sampling rate for channels) + anti-aliasing filters (with 10-bit tunable cut-off up to 2.5 kHz)
- Update DAQ software and storage infrastructure to cope with increased data rate

24

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

Bkgd control: Li_2CO_3

- High sensitivity radio-purity screening infrastructures in Italy, US,France:
  - HPGe,ICP-MS, NAA, Surface barrier Si alpha counters
  - Cryogenic infrastructures for bolometric measurements

- Measurements ongoing: Li_2CO_3 crystal growth precursors: certify vendors

Old USSR stock -reference

```
sample:          Li2CO3, MiB, CUPID, September 2021
weight:          0.10006 kg
live time:       1683000 s
detector:        GeMPI2

radionuclide concentrations:

Th-232:
Ra-228:          < 4.0 mBq/kg              <==>     < 9.9 E-10 g/g
Th-228:          (5 +- 1) mBq/kg           <==>     (1.2 +- 0.3) E-9 g/g

U-238:
Ra-226           (4 +- 1) mBq/kg           <==>     (3.1 +- 0.8) E-10 g/g
Th-234           < 14 mBq/kg               <==>     < 1.2 E-9 g/g
Pa-234m          < 75 mBq/kg               <==>     < 6.1 E-9 g/g

U-235:           < 3.9 mBq/kg              <==>     < 6.8 E-9 g/g

K-40:            < 15 mBq/kg               <==>     < 4.9 E-7 g/g

Cs-137:          < 0.51 mBq/kg

upper limits with k=1.645,
uncertainties are given with k=1 (approx. 68% CL);

Ra-228 from Ac-228;
Th-228 from Pb-212 & Bi-212 & Tl-208;
Ra-226 from Pb-214 & Bi-214;
U-235 from U-235 & Ra-226/Pb-214/Bi-214;
```

China new vendor

```
=====================================================================

sample:          lithium carbonate, Li2CO3, Cina, CUPID
weight:          0.60632 kg
live time:       2863381 s
detector:        GeMPI2

radionuclide concentrations:

Th-232:
Ra-228:          (0.8 +- 0.3) mBq/kg       <==>     (1.9 +- 0.8) E-10 g/g
Th-228:          (0.4 +- 0.2) mBq/kg       <==>     (1.1 +- 0.5) E-11 g/g

U-238:
Ra-226           (3.8 +- 0.3) mBq/kg       <==>     (3.1 +- 0.3) E-10 g/g
Th-234           < 16 mBq/kg               <==>     < 1.3 E-9 g/g
Pa-234m          < 17 mBq/kg               <==>     < 1.4 E-9 g/g

U-235:           < 0.5 mBq/kg              <==>     < 9 E-10 g/g

K-40:            (38 +- 5) mBq/kg          <==>     (1.2 +- 0.2) E-6 g/g

Cs-137:          (0.3 +- 0.1) mBq/kg

upper limits with k=1.645,
uncertainties are given with k=1 (approx. 68% CL);

Ra-228 from Ac-228;
Th-228 from Pb-212 & Bi-212 & Tl-208;
Ra-226 from Pb-214 & Bi-214;
U-235 from U-235;
```

- Multiple vendors are being validated and compared to old USSR sample as reference
- U and Th chains are all compliant with our requests
- 40K is higher by a factor 3-5 in Chinese Li_2CO_3 w.r.t. USSR sample

Bkgd control: MoO_3

MoO_3 powder: Isotopic enrichment

Type 1 powder

Table 7. Isotopic res

Sample ID	^{92}Mo *	^{94}Mo *	^{95}Mo *	^{96}Mo *	^{97}Mo *	^{98}Mo *	^{100}Mo **
	[%]						
MoO_3_1	0,11	0,08	0,14	0,16	0,13	3,08	96,30
MoO_3_2	0,11	0,07	0,13	0,16	0,13	3,07	96,33
MoO_3_3	0,11	0,07	0,13	0,16	0,13	3,08	96,31
MoO_3_4	0,11	0,08	0,13	0,17	0,13	3,10	96,28

*The uncertainty is about 5% of the given results
**The uncertainty is about 1% of the given results

Type 2 powder

Table 6. Isotopic results

Sample ID	^{92}Mo *	^{94}Mo *	^{95}Mo *	^{96}Mo *	^{97}Mo *	^{98}Mo *	^{100}Mo **
	[%]						
MoO_3_1	0,02	0,01	0,02	0,02	0,07	3,7	96,2
MoO_3_2a	0,02	0,01	0,03	0,03	0,07	3,8	96,1
MoO_3_3a	0,02	0,01	0,02	0,03	0,07	3,7	96,1
MoO_3_4	0,02	0,01	0,02	0,03	0,07	3,8	96,1

*The uncertainty is about 5% of the given results
**The uncertainty is about 1% of the given results

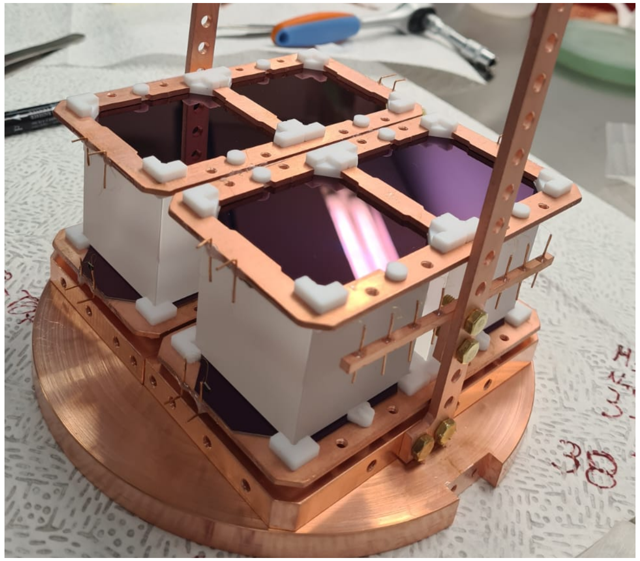
	^{232}Th [pg/g]	^{238}U [pg/g]	K [ng/g]
Type 1 (2-step centrifugation)	25	50	8000
Type 2 (1-step centrifugation)	<25	<10	27000

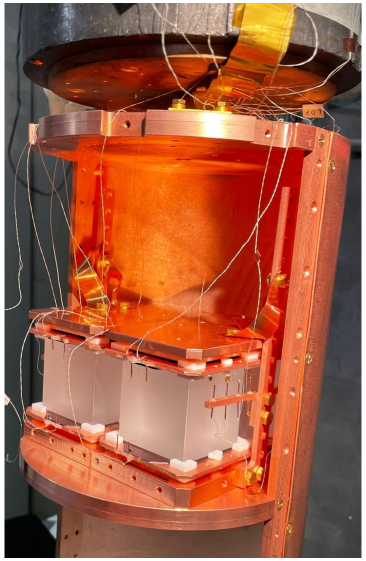
- All numbers have large systematics, basically compatible
- U and Th chains are all compliant with our requests
- 40K is very high but very effectively removed by segregation during crystal growth → CCVR test will provide final number on purification efficiency

Bkgd CCVR

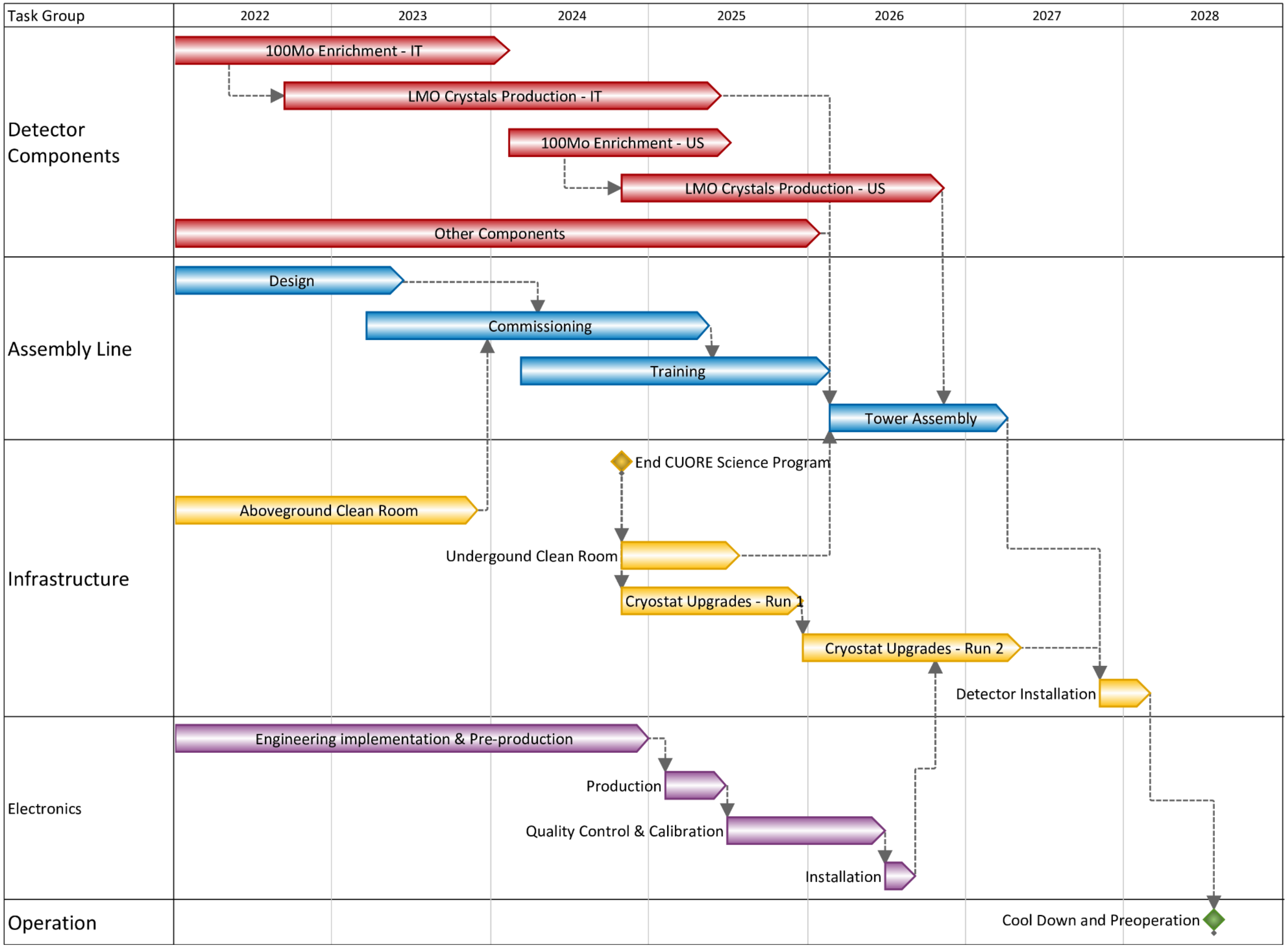
- Bolometric test of crystals produced starting with different types of MoO_3 powder
- Most sensitive tool to certify compliance of precursors radio-purity and crystal growth process with our specs
- 4 crystals of each type (currently only Type 1 available) assembled in a 2x2 array with 8 light detectors for light readout and particle discrimination
- Run-time ~ 4 weeks to reach required sensitivity on U, Th and ^{40}K bulk and surface contaminations, cool down in progress

	Required sensitivity	Live time [days]
Th surf	4.2 nBq/cm^2	20
Th bulk	1.2 μBq/kg	20
U surf	4.5 nBq/cm^2	18
U bulk	3.7 μBq/kg	6
^{40}K	1mBq/kg	-



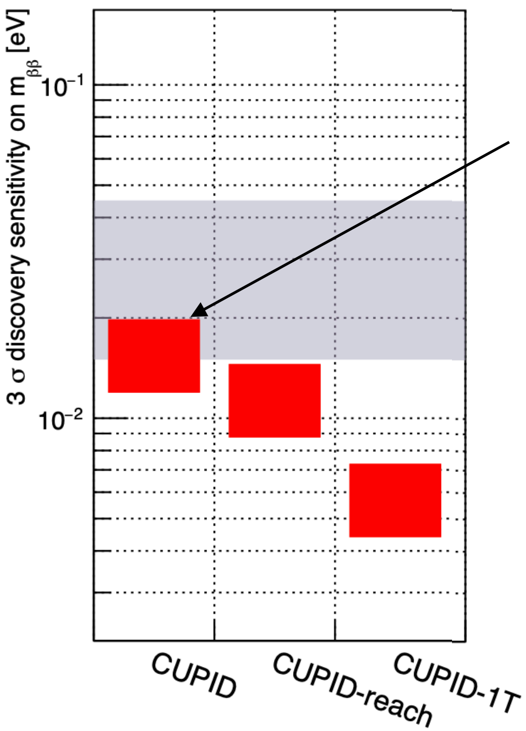


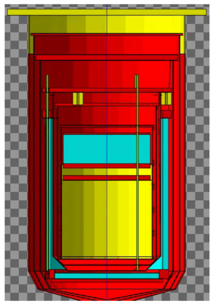
Timeline



Task Group
2022
2023
2024
2025
2026
2027
2028
Detector Components
100Mo Enrichment - IT
LMO Crystals Production - IT
100Mo Enrichment - US
LMO Crystals Production - US
Other Components
Assembly Line
Design
Commissioning
Training
Tower Assembly
Infrastructure
End CUORE Science Program
Aboveground Clean Room
Undergound Clean Room
Cryostat Upgrades - Run 1
Cryostat Upgrades - Run 2
Detector Installation
Electronics
Engineering implementation & Pre-production
Production
Quality Control & Calibration
Installation
Operation
Cool Down and Preoperation

CUPID scenarios

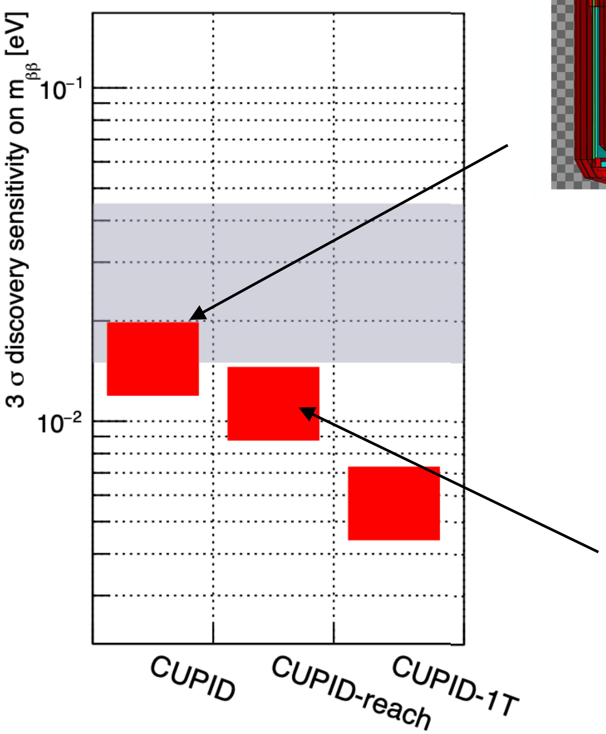




CUPID Baseline

- Mass: 450 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/(keV kg yr)
- Discovery sensitivity **$T_{1/2}$ > 1.1×10^{27} yr (3σ)**
- Discovery sensitivity **$M_{\beta\beta}$ > [12-20] meV (3σ)**
- Conservative, limited technology verification remaining

CUPID scenarios



CUPID Baseline

- Mass: 450 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/(keV kg yr)
- Discovery sensitivity **$T_{1/2}$ > 1.1×10^{27} yr (3σ)**
- Discovery sensitivity **$M_{\beta\beta}$ > [12-20] meV (3σ)**
- Conservative, limited technology verification remaining

CUPID-reach can be realized within existing cryogenic setup

- Same payload as CUPID baseline
- Background: **2 10^{-5}** cts/(keV kg yr)
- Discovery sensitivity **$T_{1/2}$ > 2×10^{27} yr (3σ)**
- Discovery sensitivity **$M_{\beta\beta}$ > [9-15] meV (3σ)**

Pileup background below ~1×10^{-5} cnts/(keV kg yr).

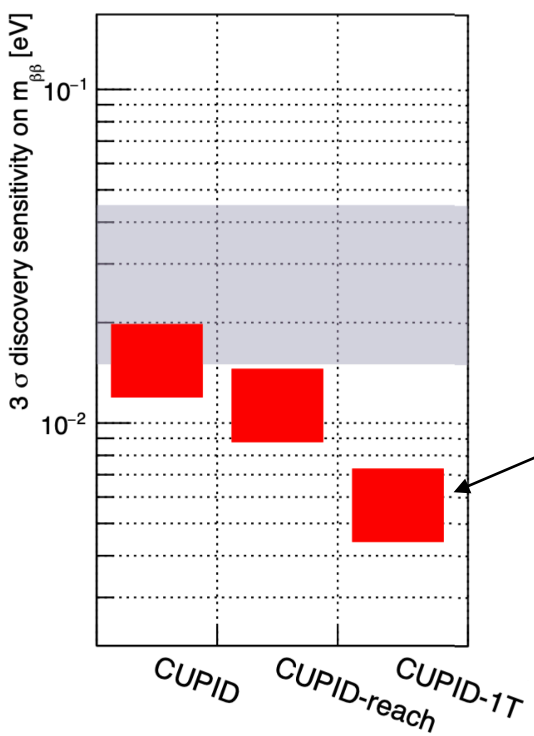
- achieved e.g. with faster sensor: NL-NTD, KID, TES based light detectors.

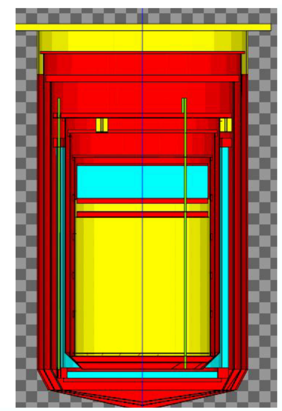
Surface backgrounds from the holders reduced by a factor of ~3.

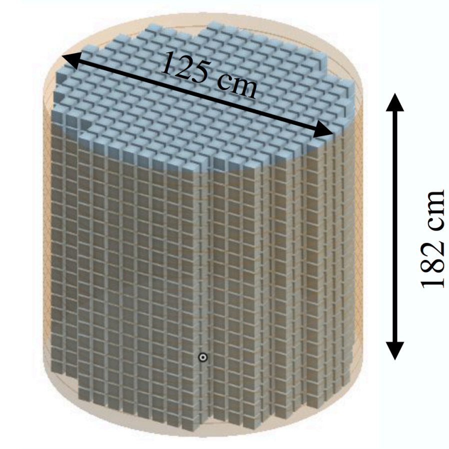
- Baseline background budget from crystals and holders amounts to 3.6×10^{-5} cnts/(keV kg yr).
- Could be reduced e.g. through the use of the laser machining

CUPID 1 Ton

An Inverted Hierarchy Precision measurement device across multiple isotopes or a Normal Hierarchy Explorer







- Mass: 1000 kg of ^{100}Mo
- Energy resolution: **5 keV** FWHM
- Background: **5x10^{-6}** cts/(keV kg yr)
- Discovery sensitivity **$T_{1/2}$ > 8×10^{27} yr (3σ)**
- Discovery sensitivity **$M_{\beta\beta}$ > [4-7] meV (3σ)**

– Multi-cryostat setup or large-scale dilution refrigerator (cooling power comparable to CUORE) , technologically achievable (increasingly common interest in Quantum Computing)

– require full implementation of next-generation (TES or mKID) low-noise, high-bandwidth multiplexed quantum sensors (DM,QIS)

– Need to consider/verify subdominant backgrounds active gamma veto and event topology (synergy with low mass DM experiments)

Conclusions

- CUPID **builds on existing and well-functioning international collaborations**
  - **Operational experience at LNGS for ton-scale bolometric experiment** and re-use of **existing infrastructure (CUORE cryostat and experimental site)**
- **Cost effective, timely,** and **leverages international investments: exceptional opportunity**
- **Limited technology verification remaining** for CUPID baseline.
- **Data-driven background model** reaches baseline goal of bkgd~10^{-4} ckky.
- CUPID will **explore inverted ordering ($T_{1/2}$ > 10^{27} years at 3σ,** $m_{\beta\beta}$ ~ **12-20 meV)**
- Possibility of phased deployment and us of different isotopes in case of discovery
- Plans for CUPID-1T experiment are feasible and within technical reach of bolometer technology. CUPID baseline/reach will help understand backgrounds for CUPID-1T.

Backup

Project organisation

All construction activities up to detector commissioning are organized in the project WBS coordinated by the Technical Coordination Board

1.0 CUPID Project
Technical Coordinator: M. Biassoni (INFN MiB)
IT Project Director/Chief Scientist: F. Bellini (Sapienza Roma)
US Project Director/Chief Scientist: Yu. Kolomensky

- **1.01 Project Management** — IT: L. Cardani (INFN Roma); US: B. Fujikawa (LBNL); FR: A. Giuliani (IJCLab)
  - **1.01.01 Project Reviews**
  - **1.01.02 Conceptual Design**
  - **1.01.03 Project Controls** — US L3: E. Abela (MRC/LBNL)
  - **1.01.04 Project Management & Travel**
  - **1.01.05 Environment, Health & Safety** — US L3: J. Bramble (LBNL)
  - **1.01.06 Project Engineering & QA** — US L3: T. Stezelberger (LBNL)
  - **1.01.07 Procurement** — US L3: K. Lingua (LBNL)
- **1.02 Detector Components** — US L2/CAM: L. Winslow (MIT); IT L2: M. Sisti (INFN MiB)
  - **1.02.01 Management**
  - **1.02.02 ^{100}Mo Enrichment** — IT L3: M. Sisti (INFN MiB); US L3/CAM: Yu. Kolomensky (UCB)
  - **1.02.03 LMO Crystal Production** — IT L3: C.Tomei (INFN Roma); US L3: L. Winslow (MIT)
  - **1.02.04 Light Detector** — US L3: V. Singh (UCB); FR L3: S. Marnieros (IJCLab)
  - **1.02.05 NTD Ge Thermistor** — US L3: R. Maruyama (Yale); US L3 Deputy: D. Speller (JHU)
  - **1.02.06 Heater** — IT L3: S. Dell'Oro (UniMiB)
  - **1.02.07 Muon Veto and Neutron Shield** — US L3: R. Maruyama (Yale)
- **1.03 Detector Structure** — IT L2: L. Cardani (INFN Roma); FR L2 : C. Nones (IRFU)
  - **1.03.01 Management**
  - **1.03.02 Detector Structure Design** — IT L3: T. Napolitano (INFN LNF); FR L3: A. S. Zolotarova (IJCLab)
  - **1.03.03 PTFE Parts** — IT L3: C. Tomei (INFN Roma)
  - **1.03.04 Copper Parts** — IT L3: C. Tomei (INFN Roma)
  - **1.03.05 Assembly Line** — IT L3: V. Pettinacci (INFN Roma); FR L3: A. Gallas (IJCLab)
  - **1.03.06 Parts Cleaning** — IT L3: G. Keppel (INFN LNL)
  - **1.03.07 Storage & Logistics** — IT L3: S. Dell'Oro (UniMiB)
  - **1.03.08 Cryogenic Detector Wiring** — IT L3: E. Ferri (UniMiB)
  - **1.03.09 Tower Assembly** — IT L3: M. Biassoni (INFN MiB)
- **1.04 Host Lab Infrastructure & Cryogenic Systems** — IT L2: A. D'Addabbo (INFN LNGS)
  - **1.04.01 Management**
  - **1.04.02 Wiring** — IT L3: E. Ferri (INFN MiB)
  - **1.04.03 Clean Rooms** — IT L3: M. Balata (INFN LNGS)
  - **1.04.04 Detector Installation** — IT L3: T. Napolitano (INFN LNF)
  - **1.04.05 Cryostat Upgrade & Commissioning** — IT L3: P. Gorla (INFN LNGS); FR L3: P. Rosier (IJCLab)
  - **1.04.06 Calibration** — US L3: P. Slocum (Yale); IT L3: L. Marini (GSSI)
  - **1.04.07 Acoustic & Vibration Sensors** — US L3: P.T. Surukuchi (Yale); FR L3: E. Olivieri (IJCLab)
  - **1.04.08 Ambient Control** — US L3: J. Nikkel (Yale); FR L3: P. Loaiza (IJCLab)
- **1.05 Data Readout** — US L2/CAM: B. Welliver (LBNL); IT L2: P. Carniti (UniMiB)
  - **1.05.01 Management**
  - **1.05.02 Electronics: FEE** — IT L3: G. Pessina (INFN MiB)
  - **1.05.03 Electronics: Power Supplies & Pulsers** — US L3: C. Grant (BU); FR L3: D. Baudin (CEA)
  - **1.05.04 Electronics: Filters & Digitizers** — US L3: H. Huang (UCLA)
  - **1.05.05 SW DAQ & Trigger** — US L3: J. Ouellet (MIT)
  - **1.05.06 Slow Control** — US L3: J. Ouellet (MIT); FR L3: C. Nones (IRFU)
  - **1.05.07 Comp.&Data Storage** — US L3: C. Capelli (LBNL); FR L3: P. Gras (IRFU)
- **1.06 Background Control** — IT L2: L. Pagnanini (INFN LNGS); US L2/CAM: T. O'Donnell (VT); FR L2: P. Loaiza (IJCLab)
  - **1.06.01 Management**
  - **1.06.02 Screening Labs IT** — IT L3: S. Capelli (UniMiB)
  - **1.06.03 Screening Labs US** — US L3: C. Grant (BU)
  - **1.06.04 Screening Labs FR** — FR L3: D. Poda (IJCLab)
  - **1.06.05 Crystal Validation Runs** — IT L3: V. Dompè (UniRoma1); US L3: B. Schmidt (NWU); FR L3: E. Olivieri (IJCLab)

IT, US, FR

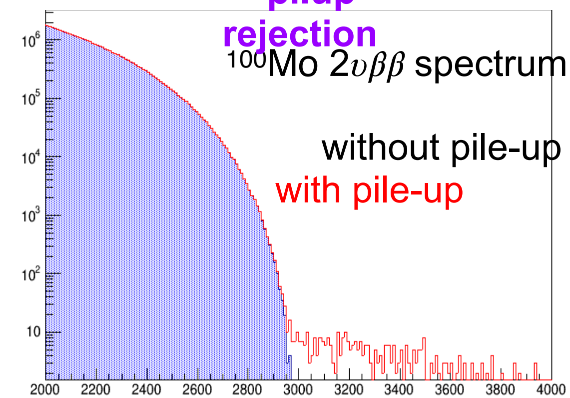
First name: primary responsibility
Second name: secondary responsibility

Project paramaters

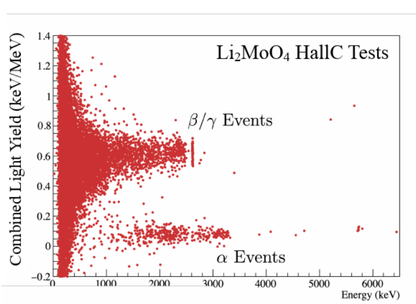
Parameter	Value
Crystal	$Li_2{}^{100}MoO_4$
Size	45×45×45 mm^3
Number of crystals	1596
Number of light detectors	1710
Detector mass	450 kg
Enrichment	95%
^{100}Mo mass	240 kg
Energy resolution	5 keV
Light yield (β)	0.3 keV/MeV
Background index	10^{-4} counts/(kg*keV*year)
Selection Efficiency	90%

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

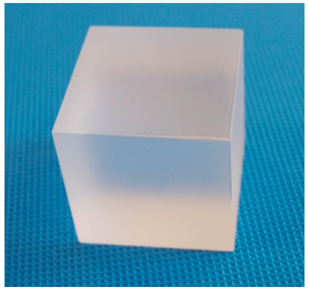
LD performance - pilup rejection



LMO performance



LMO crystals mass & i.a.

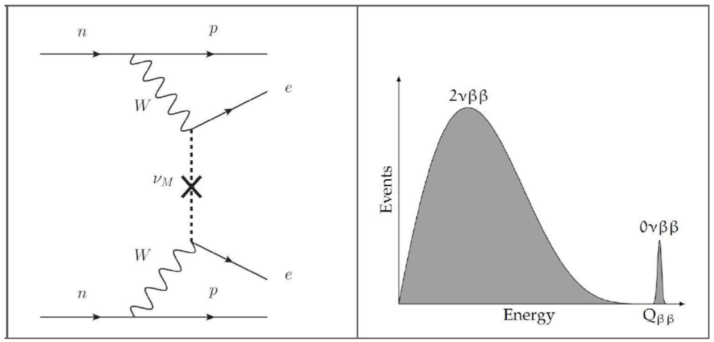


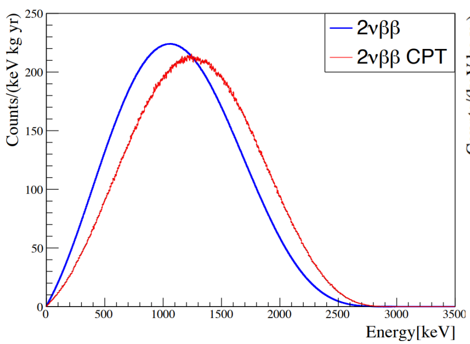
Background control and reduction

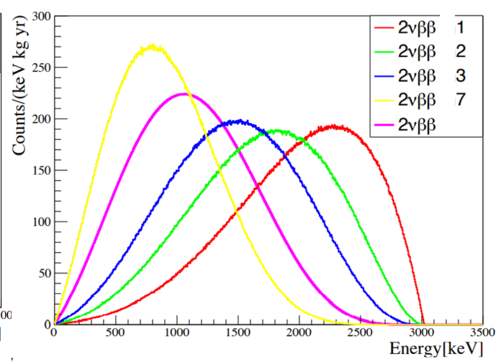
CUPID Sensitivity

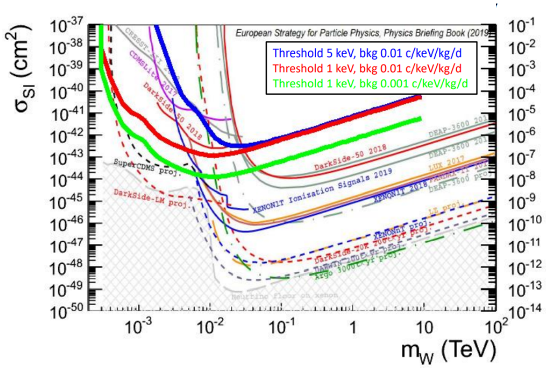
Parameter	CUPID baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	450	450	1871
^{100}Mo mass (kg)	240	240	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	78%	78%	78%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.4×10^{27} y	2.2×10^{27} y	9.1×10^{27} y
Half-life discovery sensitivity (3σ)	1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.4–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	9–15 meV	4.4–7.3 meV

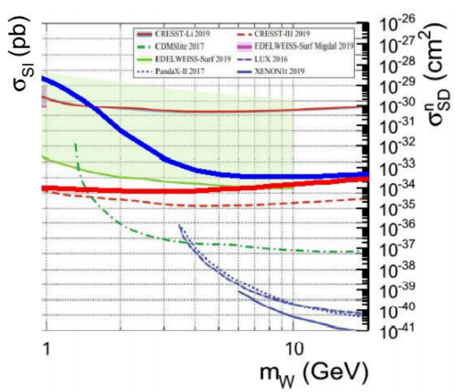
CUPID Science Program











- Search for 0νββ decay
- 2νββ spectral shape analysis:
  - decays to excited states
  - Single State vs Higher State Dominance
  - CPT violation and Lorentz invariance
  - 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

Organisational structure

Executive Board
Italy co-spokesperson: M. Pavan (MiB)
International co-spokesperson: K. Heeger (Yale)
Technical Coordinator
IT Project director
US Project director
IT Institutional Board Chair
US Institutional Board Chair

Technical Coordinator
M. Biassoni (INFN MiB)

US Project Director
Y. Kolomensky (LBNL/UCB)

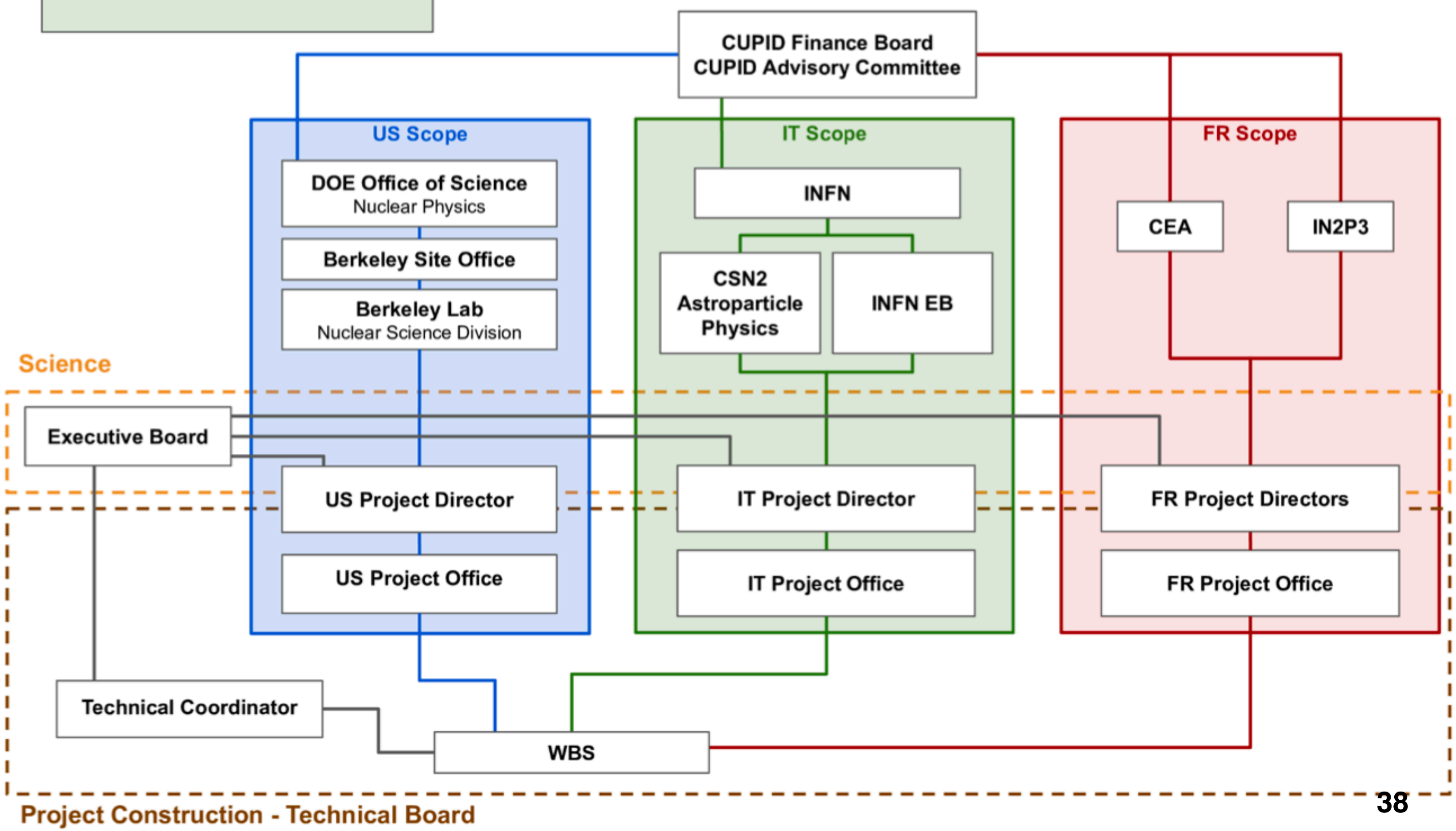
IT Project Director
F. Bellini (Roma Sapienza)

US Project Office
US Project Manager: B. Fujikawa (LBNL)
US Project Controls: E. Abela (LBNL)
US Project Engineer: T. Stezelberger (LBNL)
US Safety Officer: J. Bramble (LBNL)
US Procurement Specialist: K. Lingua (LBNL)

IT Project Office
IT Project Manager: L. Cardani (INFN Roma)
CUPID GLIMOS: TBD (LNGS)
CUPID RAE: TBD (LNGS)

- Project mainly driven by Italy, US and France efforts
- Collaboration structure and agreement reflects “expected” resources and financial commitments of countries

Scope is clearly divided among countries with corresponding line responsibility in the project management



LNGS Laboratory

120 km from Rome

~ 3600 m.w.e. deep

μ flux: ~ 3×10^{-8}/(s cm^2)

γ flux: ~ 0.73/(s cm^2)

neutrons: 4×10^{-6} n/(s cm^2) below 10 MeV