CUPID Experiment

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For the CUPID collaboration

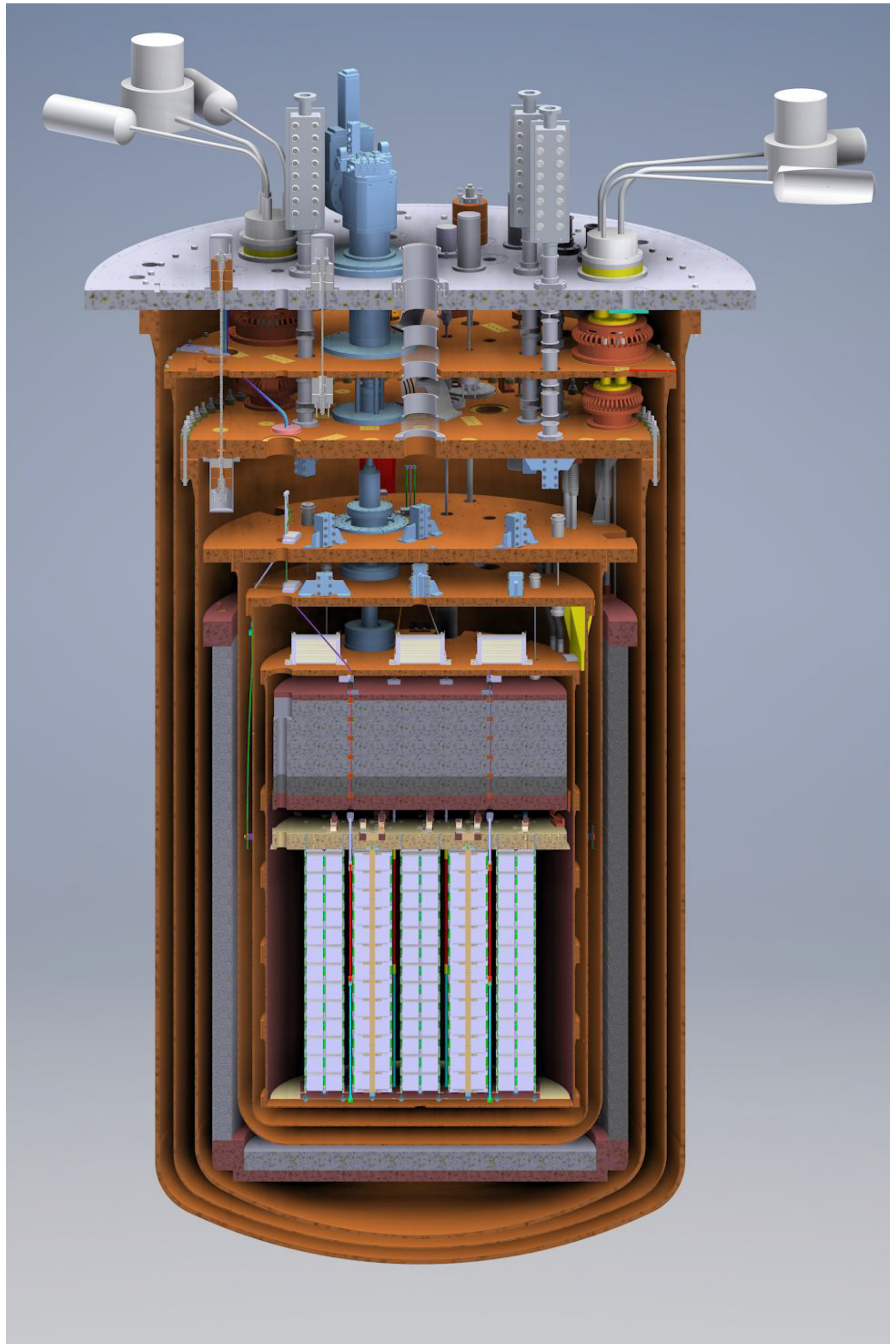
Second International Summit on the Future of Double Beta Decay

SNOLAB 27-28 April 2023

CUPID concept

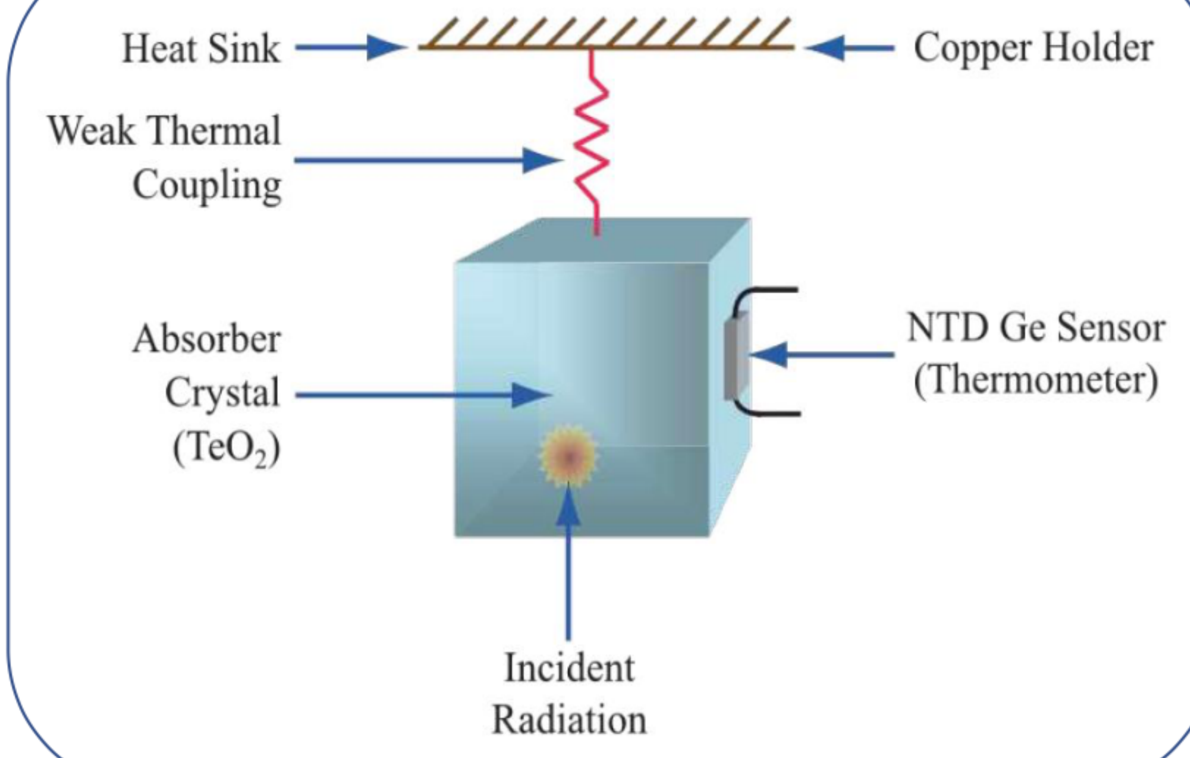
Ton-scale array of high-resolution cryogenic calorimeters for the search for $0\nu\beta\beta$ and other other rare events

- Replace the CUORE detector with a new detector array based on Li_2MoO_4 scintillating bolometer crystals
- Similar mass as CUORE: feasibility already demonstrated with > 2 ton-years of data
- Existing cryogenic infrastructure: cost effective, low risk
- Additional detector functionality:
  - particle identification (light yield vs energy)
  - pile-up rejection with fast light detectors
  - increased number of channels (x3 compared to CUORE)



CUPID detector technology

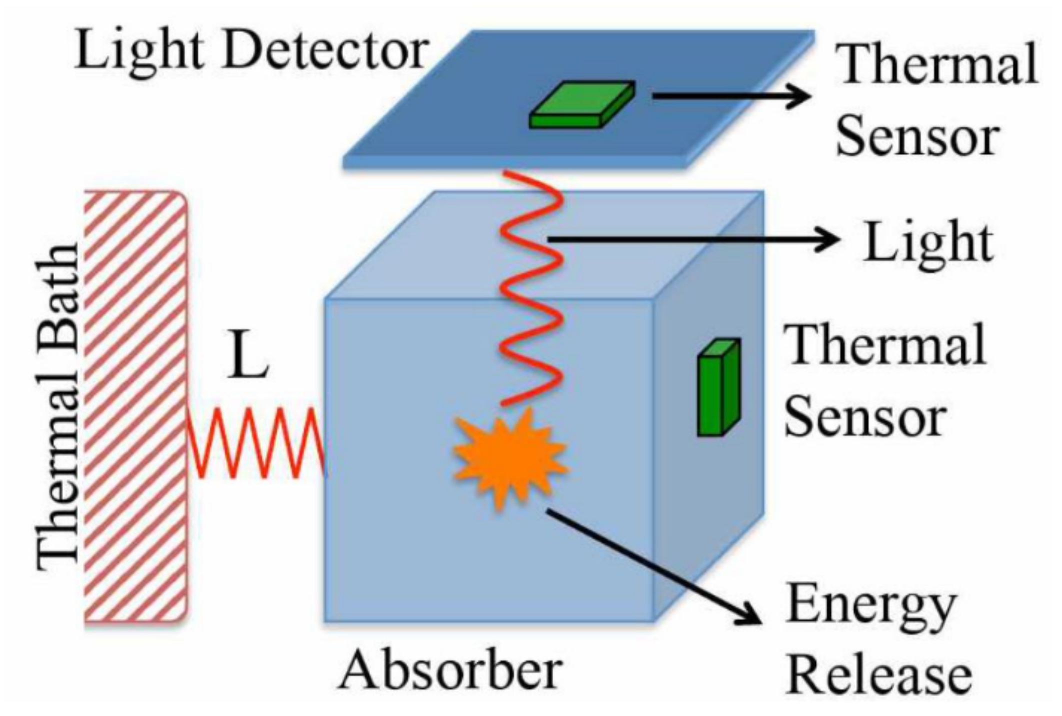
CUORE ^{130}Te
pure thermal detector
(bolometer)



PID → remove α

high Q → remove ɣ

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

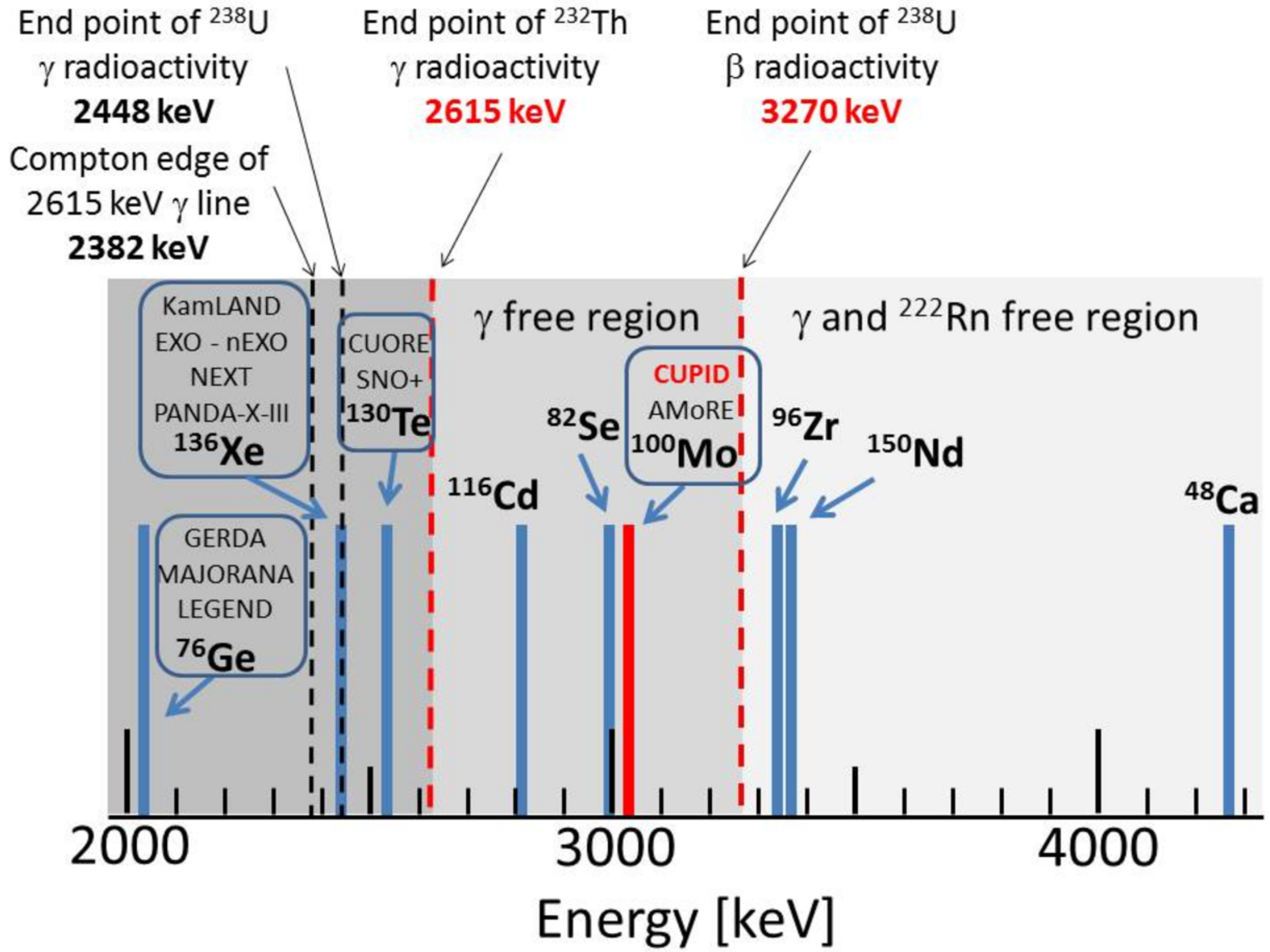


No PID
Q = 2527 keV **< 2615 keV**

^{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**



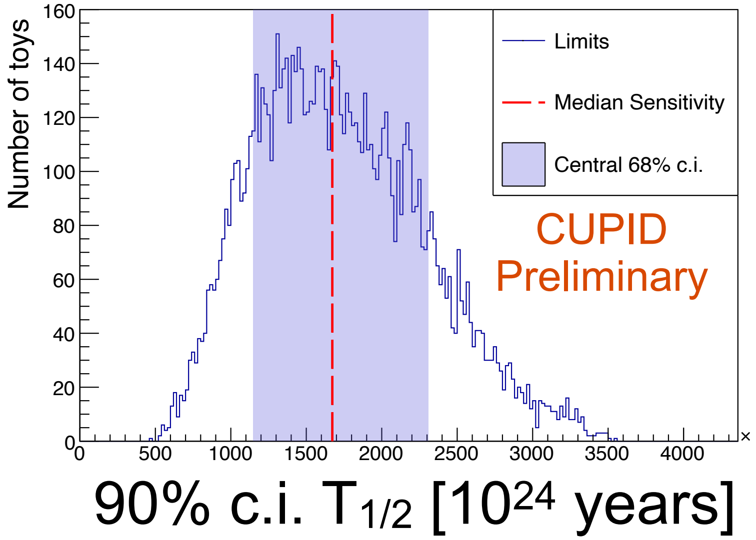
^{100}**Mo**

- Q-value above most of natural radioactivity
- good quality scintillating crystals for α-β discrimination
- existing enrichment technology and interest for medical applications
- CUPID requires producing ~280 kg of ^{100}Mo

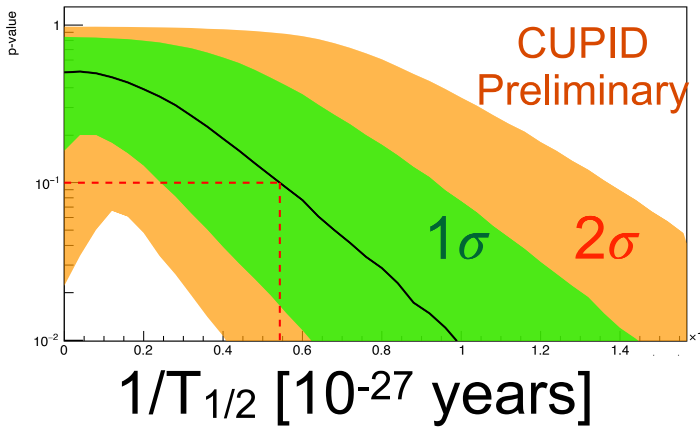
CUPID Parameters and Sensitivity - $0\nu\beta\beta$

Parameter	Baseline
Isotope	^{100}Mo
Q-value	$Q_{\beta\beta}$=3034 keV
Crystal	Li_2MoO_4
Crystal size	$45 \times 45 \times 45$ mm^3
Crystal mass (g)	280
Number of crystals	1596
Number of light detectors	1710
Detector mass (kg)	450
^{100}Mo mass (kg)	240
Energy resolution FWHM (keV)	5
Background index (counts/(keV·kg·yr))	10^{-4}
Containment efficiency	78%
Selection efficiency	90%
Livetime	10 years
Half-life exclusion sensitivity (Bayesian 90% C.I.)	1.7×10^{27} y
Half-life exclusion sensitivity (Frequentist 90% C.L.)	2.1×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.I.)	9.6–16 meV
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	8.4–14 meV
Half-life discovery sensitivity (3σ)	1×10^{27} y
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV

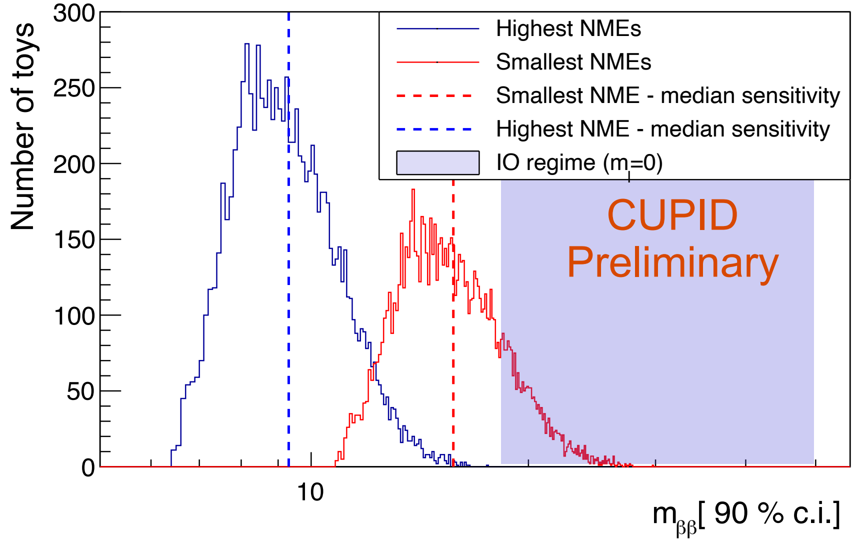
Bayesian $T_{1/2}$ limits



Frequentist $T_{1/2}$ limits



Bayesian mass limits



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

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

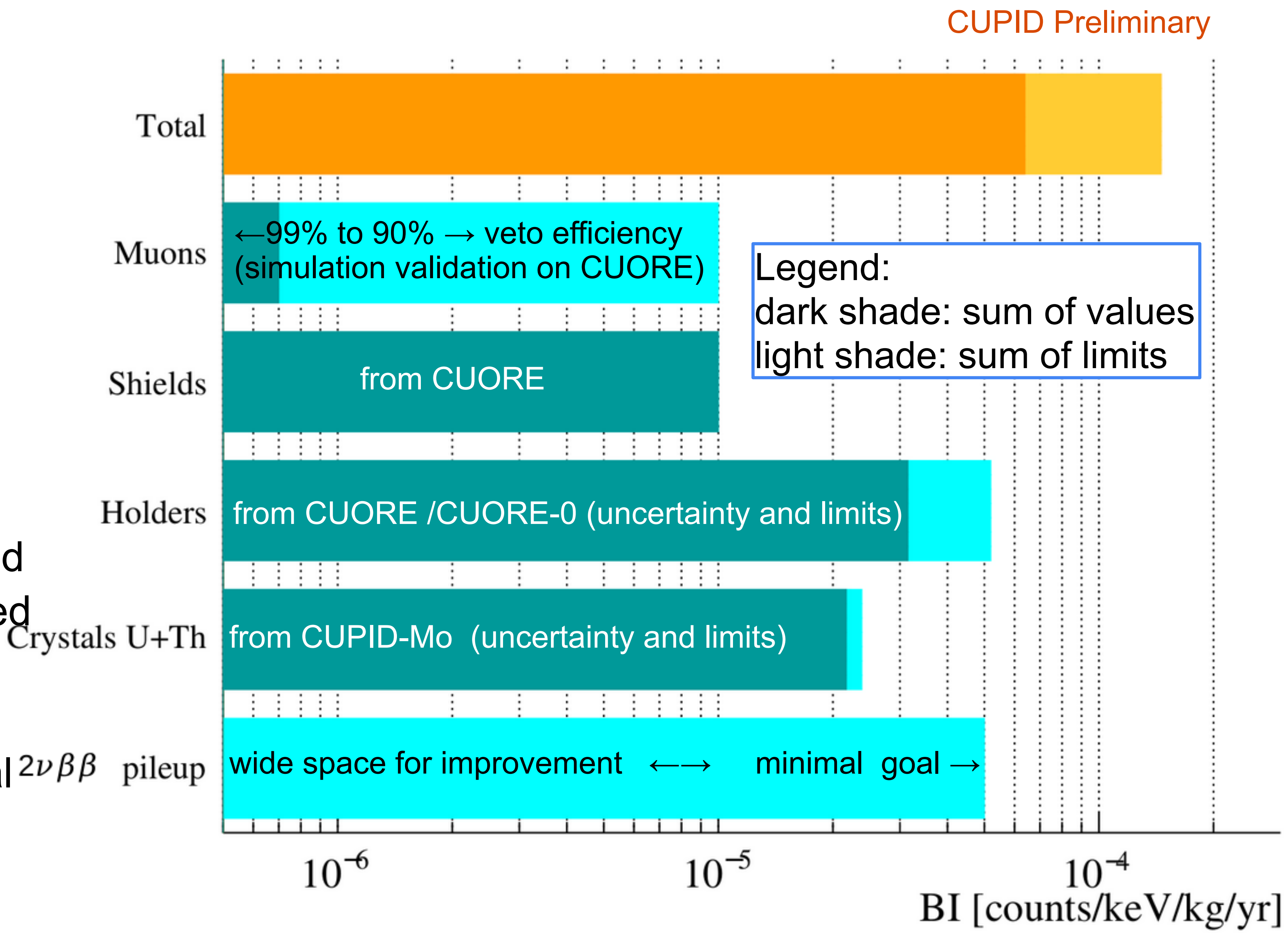
CUPID physics reach - background budget

Data-driven background budget:

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

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

- crystal purity quality control (already demonstrated)
- cleaning of passive elements with CUORE protocols
- backgrounds from cryogenic infrastructure and shields well understood and could be improved
- pile-up contribution minimized with current technology
- backgrounds lower than the conservative goal are achievable



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

CUPID Collaboration & Project

Leverage previous collaborative experience

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

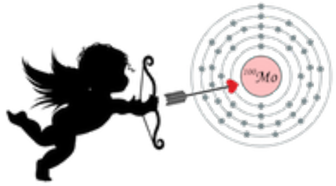
CUORE

Based 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



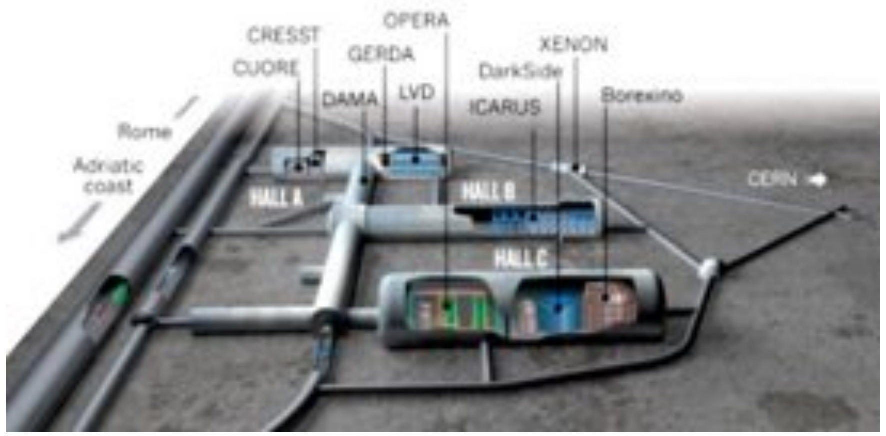
CUPID-Mo

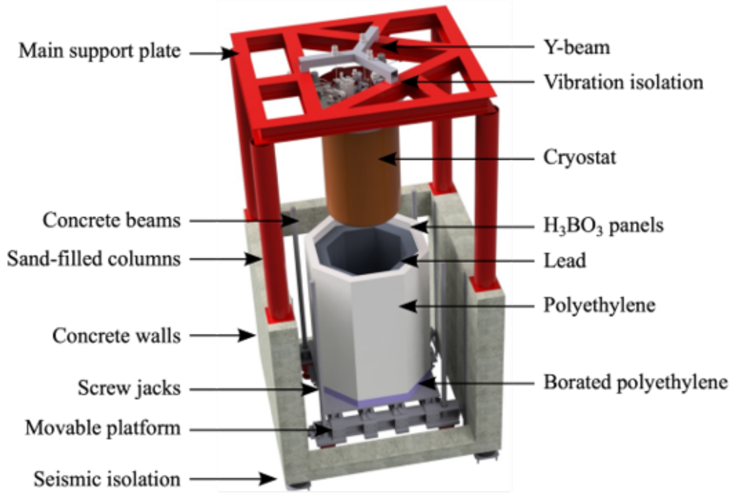
CUPID Collaboration & Project

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



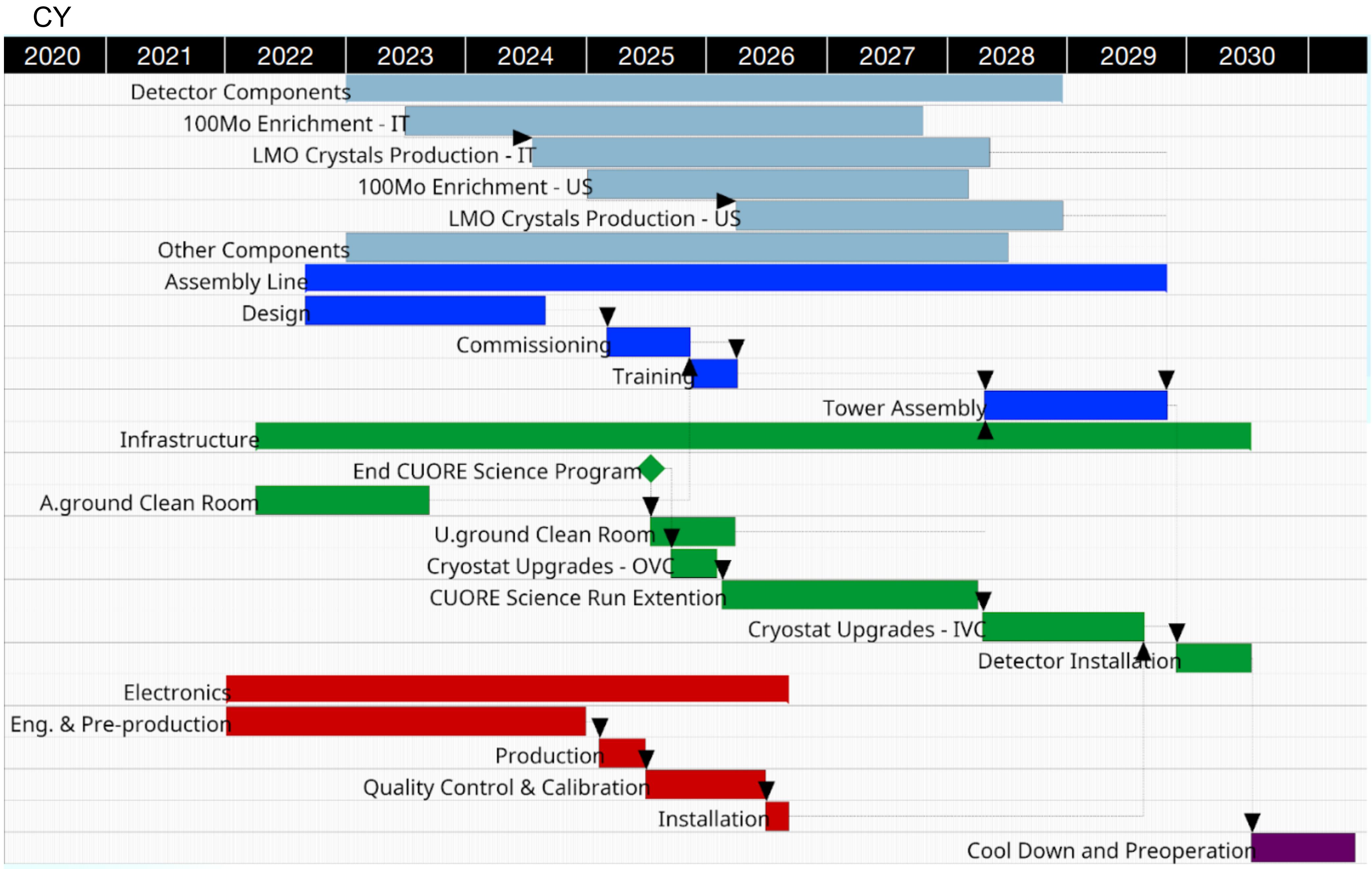


Cost and time-effective reuse of the CUORE underground infrastructure

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

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

CUPID Schedule (technically limited)



Critical Decision	Quarter and FY
CD-0	Q1FY19
CD-1	Q1FY24
CD-2	Q1FY25
CD-3	Q1FY25
CD-4	Q4FY33

Projected costs and contributions

CUPID

Country	M&S base k$	M&S Contingency k$	Total Equipment k$	Labor+Contingency k$	In-kind k$	2022-23 Commitments k$
Italy	27,000	3,000	30,000	research	8,250	853
US	20,235	6,137	26,372	18,387	550	850
France	1,800		1,800	research	500	605
Total	49,035	9,137	58,172		9,300	2,308

Not included: underground and lab infrastructure, services (LNGS, LSC, NEXUS)
Also not included: significant investments by Italy, US, France into pre-project R&D, pre-project demonstrators, and project preparation
Funded separately: EU personnel costs, travel, and other research commitments

Integrated, fully-loaded schedule in Primavera P6 (LBNL). Mature cost estimates. Independent reviews and drill-downs in run-up to CD-1 planned.

Assumes project start in the US in FY24 and technically-limited schedule. Costs may continue to escalate with prolonged duration of the project.

US Pre-CD1 (OPC) Budget

CUPID

Sum of Value	Column Labels		
	Total_$		
Row Labels	FY22	FY23	FY24
1.10	**28,631.28**	**1,055,297.27**	**543,260.44**
1.10.01.03 Project Management and Travel OPC		253,280.11	138,158.25
1.10.01.04 Project Controls OPC	28,631.28	304,585.62	181,301.03
1.10.01.06 Project Engineering and QA OPC		95,841.18	62,412.01
1.10.01.08 Risk Management OPC		81,470.06	53,694.32
1.10.02.01 Detector Components Management OPC		46,168.19	5,344.51
1.10.02.05 NTD Ge Thermistor OPC		43,830.29	
1.10.05.01 Data Readout Hardware & Software Management OPC		188,635.69	80,492.63
1.10.06.01 Background Control Management OPC		22,122.76	5,344.51
1.10.01.09 Senior Advisor OPC		19,363.37	16,513.19

Assumes CD-1 IPR in Q1FY24, ESAAB approval Q2FY24

Cost and Schedule Drivers, Risks

- Isotope procurement
- Crystal production
- Project start and profile: expect ~6% escalation per year

Mo-100 Isotope Vendors

- **July 2021 pre-CDR and Italian pre-TDR:**
  - **baseline** = purchase ^{100}Mo from JSC Isotope (Russia) through US vendor IsoFLEX USA
  - **risk mitigation strategy** = ^{100}Mo from URENCO (Netherlands)

- **Developments since 2021**
  - At least four potential new vendors with headquarters in US, Europe, Asia
    - Interest in ramping up Mo-100 production driven by medical market (Mo-99/Tc-99m)
    - Maintain close contact and discussion of production capability, costs, schedule
    - NDAs signed
  - While Russian suppliers maintain the largest production capacity and relatively low costs, prospects are good for developing alternatives on the timescale of the US CD-2/3
  - Crucial to explore these alternatives to mitigate risks
  - Demonstrating viability of alternative vendors for CUPID would require project resources in FY24 and beyond

Li_2MoO_4 Crystals

CUPID

- **July 2021 pre-CDR and Italian pre-TDR:**
  - **baseline** = purchase 4.5x4.5x4.5 cm^3 LMO crystals from NIIC (Russia)
  - **risk mitigation strategy** = multiple vendors contacted: RMD and Gooch&Housego (US), Ningbo University and SICCAS (China)
- **Significant progress in establishing alternative vendors**
  - RMD (US): 4 crystals delivered to France for bolometric tests (currently operating at Canfranc)
  - SICCAS (China): 6 unenriched crystals validated in Hall A baseline tower test
  - Excellent prospects for validating alternative vendors by US CD-2/3

	crystal quality & bolometric performances	**radiopurity** (bulk & surfaces)	enriched material **purification** & **recovery** during production	**mass production**
NIIC	✅	✅	✅	✅
SICCAS	✅	in progress	in progress	✅
RMD	✅	in progress	SBIR 2023	✅

Status of the CUPID Project

- We appreciate continuing support for the CUPID project from the funding agencies
- Italy:
  - INFN Astroparticle committee committed to the CUPID budget outside of the isotope+crystals. Funds allocated for CY22-23.
  - INFN Executive Committee provisionally approved isotope+crystal budget.
- France:
  - CEA and IN2P3 have committed to their scope.
- US:
  - Preparations for CD-1 OPA review in Q1FY24. Committed OPC funding. Enthusiastic support from the lead lab (LBNL).

CUPID Experiment - Technical

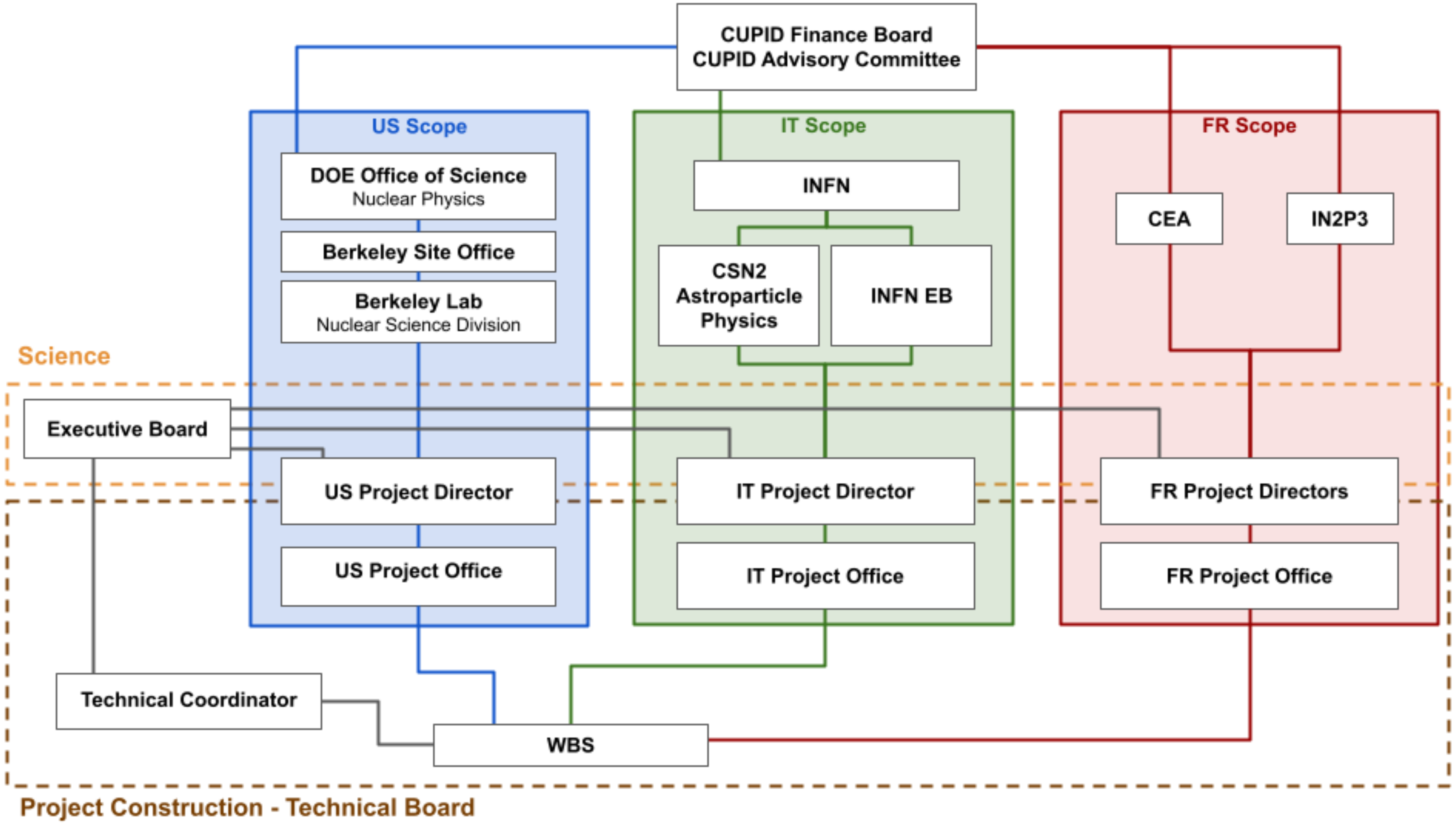
Matteo Biassoni for the CUPID collaboration

Second International Summit on the Future of Double Beta Decay

SNOLAB 27-28 April 2023

CUPID: integrated project organization

- Project mainly driven by Italy, US, and France efforts
- Collaboration structure and agreements reflect (expected) resources and financial commitment of each country
- Scope is clearly divided among countries with the corresponding line responsibility in the project management
- Each country manages its own contingency and risks
- Schedule is managed jointly through Primavera P6 (at LBNL)
- Coordination through Technical Coordination Board, Executive Board, and oversight committees

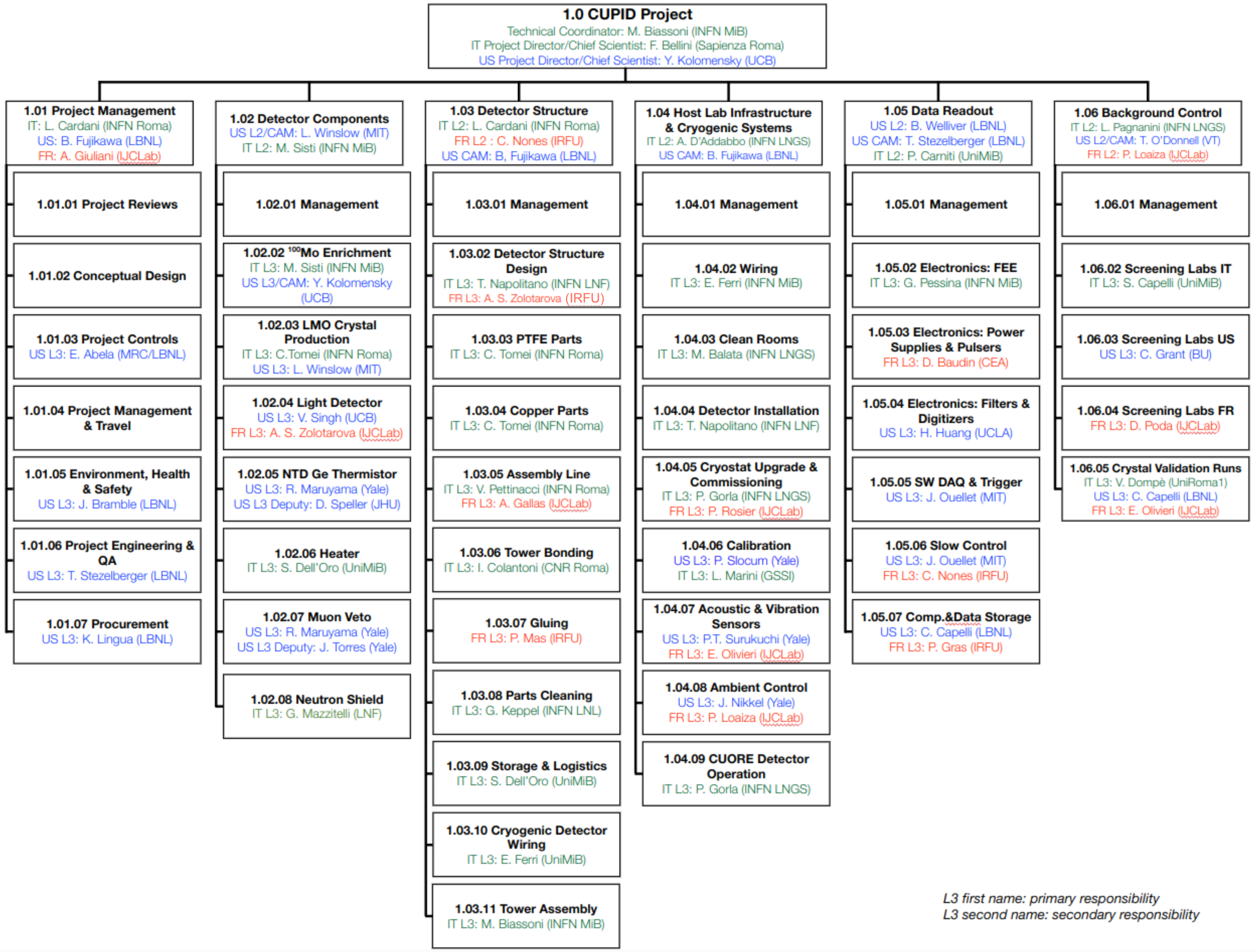


CUPID project organization

- All construction activities up to detector commissioning are organized in the project WBS and coordinated by the Technical Coordination Board
- The TCB is responsible for the construction of the experiment according to specific parameters defined for each component or subsystem

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



CUPID project organization

- Activity already ongoing across all the WBS in preparation for construction
- Focus on most critical items

1.02.02 ^{100}Mo Enrichment
IT L3: M. Sisti (INFN MiB)
US L3/CAM: Y. Kolomensky (UCB)

1.02.03 LMO Crystal Production
IT L3: C.Tomei (INFN Roma)
US L3: L. Winslow (MIT)

Covered by Yury's slides

More details in this part of the talk

1.02.04 Light Detector
US L3: V. Singh (UCB)
FR L3: A. S. Zolotarova (IRFU)

1.03.02 Detector Structure Design
IT L3: T. Napolitano (INFN LNF)
FR L3: A. S. Zolotarova (IRFU)

1.02.07 Muon Veto
US L3: R. Maruyama (Yale)
US L3 Deputy: J. Torres (Yale)

1.02.08 Neutron Shield
IT L3: G. Mazzitelli (LNF)

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)

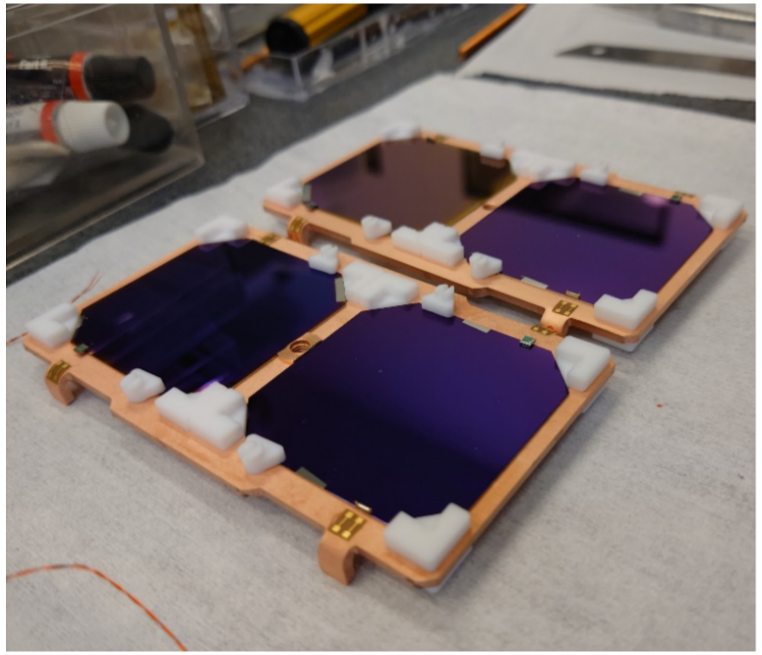
1.06.03 Screening Labs US
US L3: C. Grant (BU)

1.06.04 Screening Labs FR
FR L3: D. Poda (IJCLab)

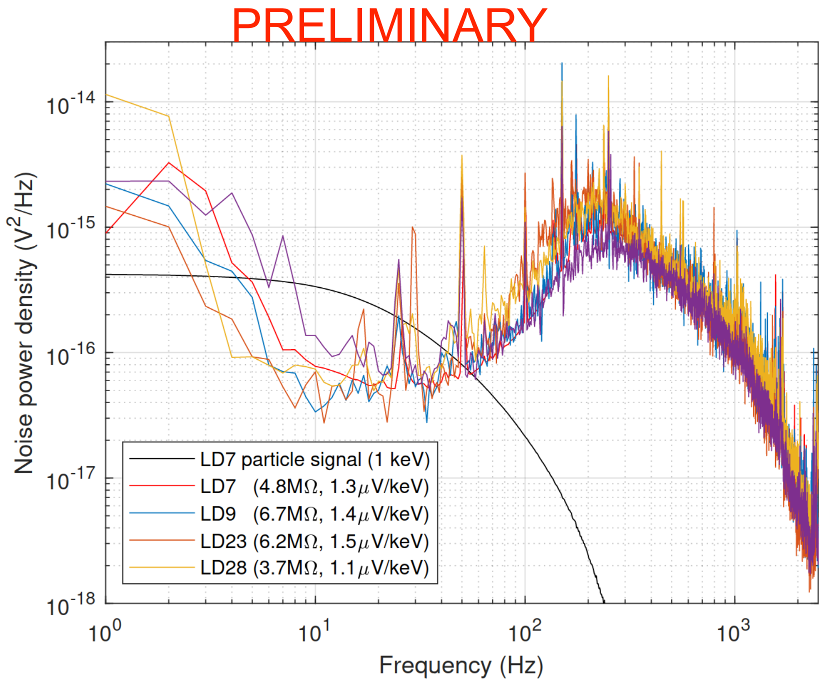
1.06.05 Crystal Validation Runs
IT L3: V. Dompè (UniRoma1)
US L3: C. Capelli (LBNL)
FR L3: E. Olivieri (IJCLab)

Detector Components - LDs

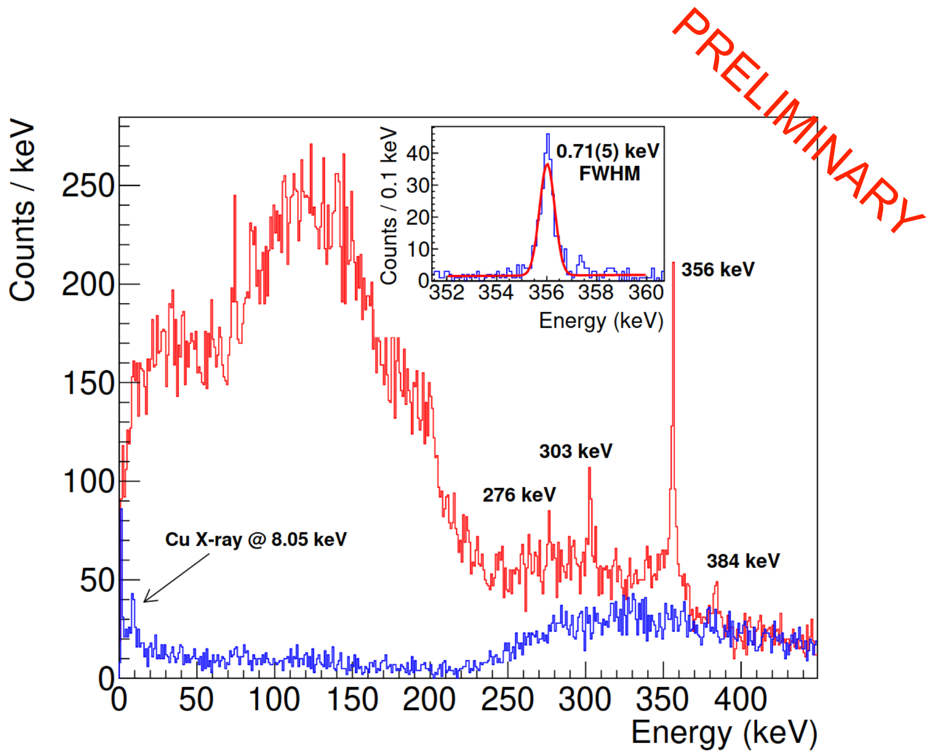
- NTD thermistors are a robust technology from predecessors, both for crystals and light detectors readout
- **current baseline choice for light detectors**: Ge wafers with AR coating and NTD readout
  - detector performance extensively studied in 2022
  - optimization of size, geometry and absorber coupling to further improve timing and S/N in 2023



Assembled light detectors for test in Pulse Tube cryostat



Noise validation studies
arXiv:2304.04674



Energy calibration and energy resolution within specs

Detector Components - LDs

CUPID

Situation assessment:

- Technology of current baseline has **little engineering margin** to guarantee the requirement performance for all detectors
- Unlikely to improve background beyond the ~ 5×10^{-5} c/keV/kg/y

Adaptive strategy

- Exploit delays in project startup to select an alternative with better performance and larger risk mitigation margin

Neganov-Trofimov-Luke (NTL) amplification

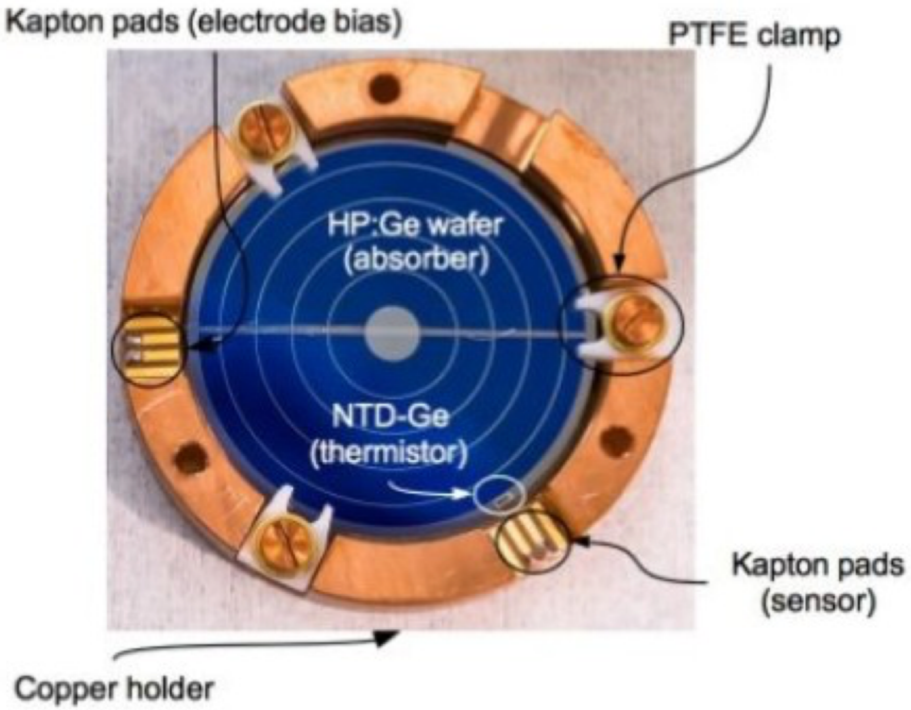
- add an electrode on the Ge wafer (~x10 SNR)
- signal read-out still NTD-based

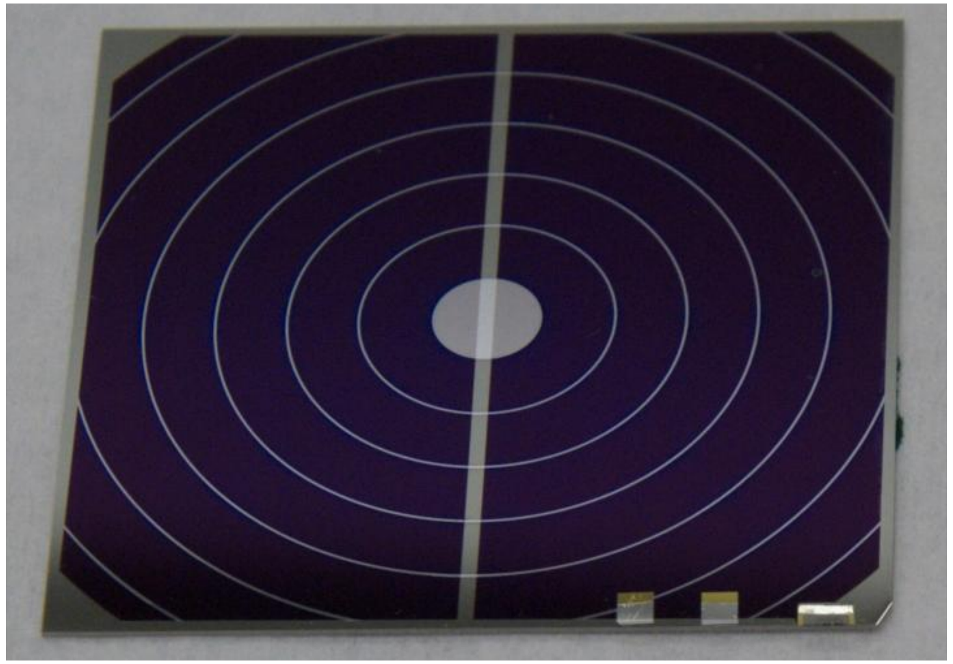
Transition Edge Sensors

- NTD replaced by TES (~x10 faster RT)
- new read-out system: SQUID based with multiplexing: spinoff from CMB

Detector Components - LDs with NTL amplification

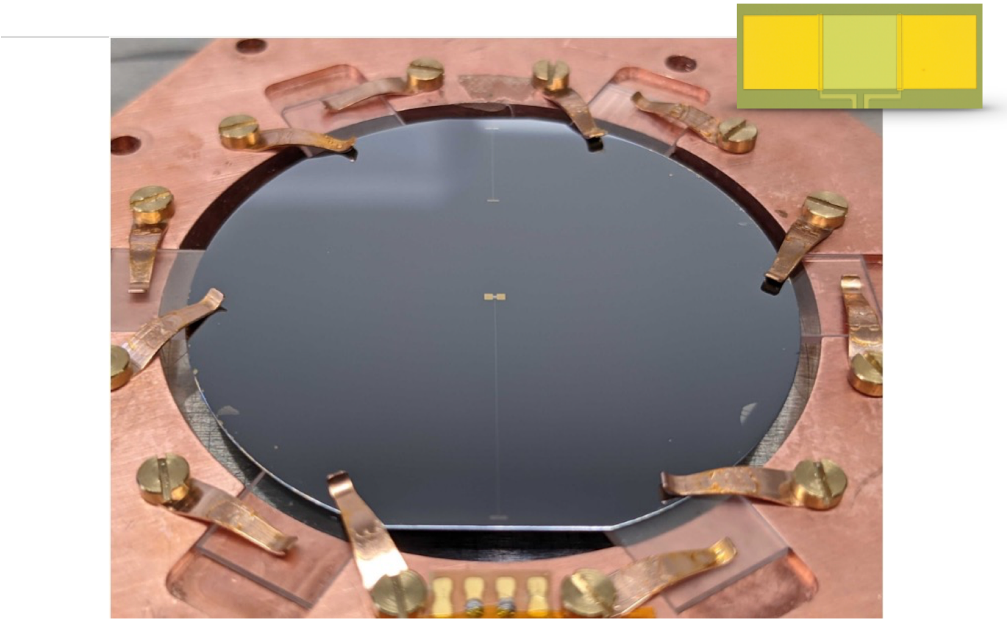
- NTL technology already exploited by other experiments (EDELWEISS, SuperCDMS, Ricochet) - adaptation to CUPID geometry ongoing
- Same readout technology but add electrodes to apply electric field
- Major improvement in SNR with signal amplification
- Minor impact on other subsystems, no changes in DAQ and analysis



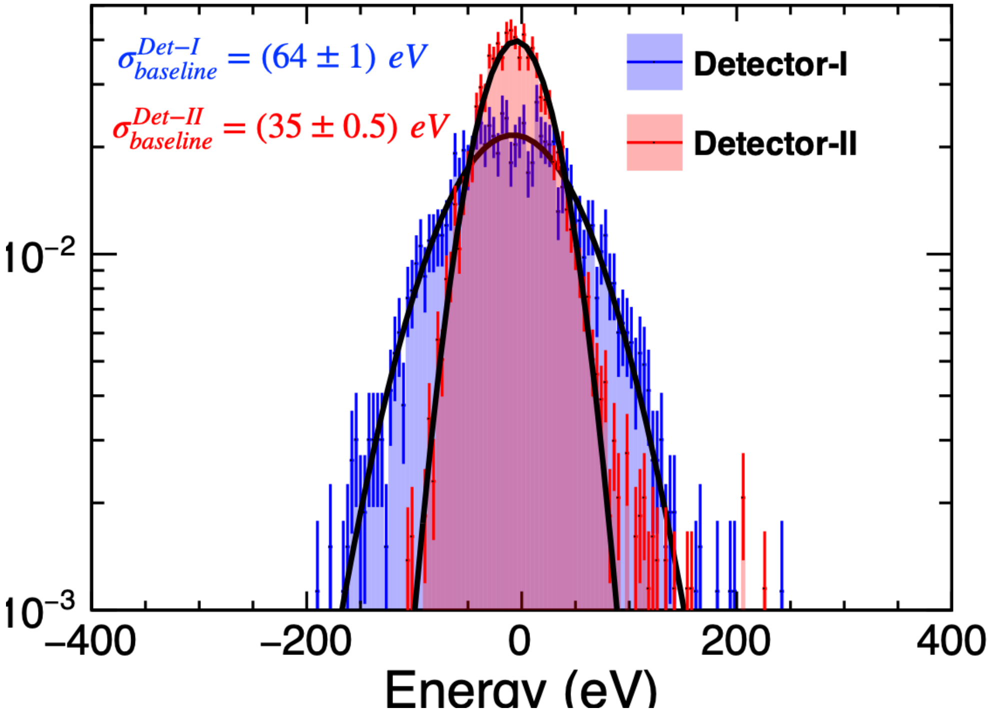


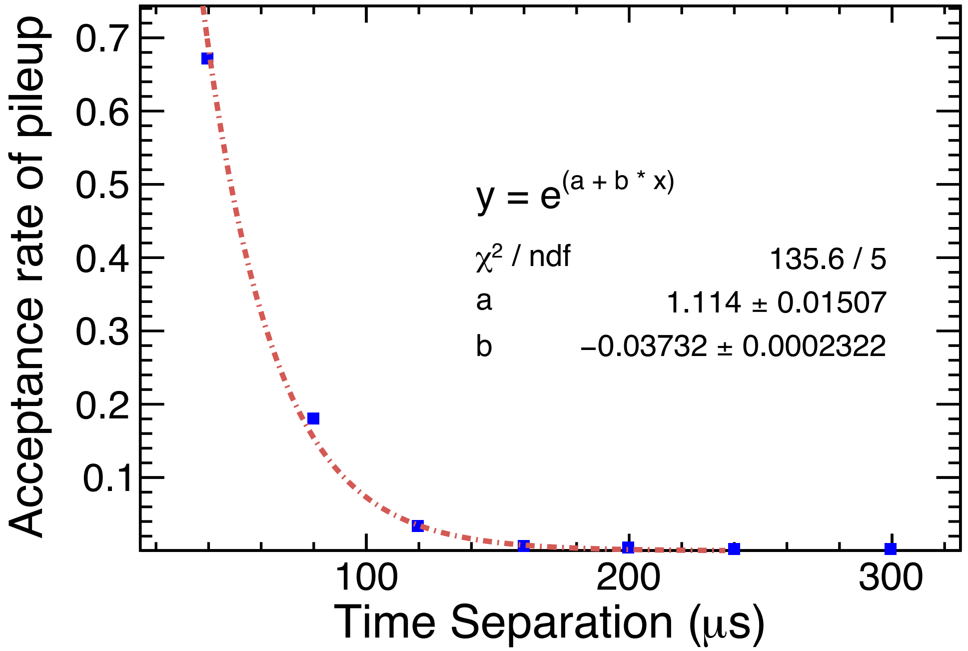
Detector Components - LDs with TES readout

- Technology already exploited by other experiments (CRESST, SuperCDMS, x-ray micro-calorimeters, CMB, …)
- Off-project R&D by the CUPID collaborators
- Significant improvement both in SNR and timing
- Relevant impact on several subsystems, including electronics and DAQ



- 2″ Silicon wafer as optical photon absorber
- Ir/Pt (45 nm/20 nm) bilayer with Nb traces as electrical leads.



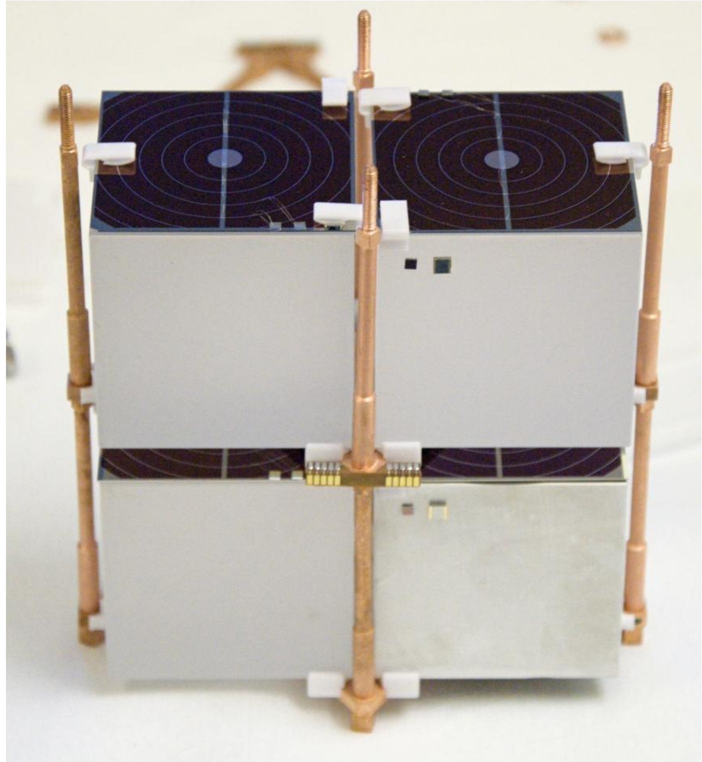


e-Print: 2210.15619 [physics.ins-det]

Detector Components - LDs

CUPID

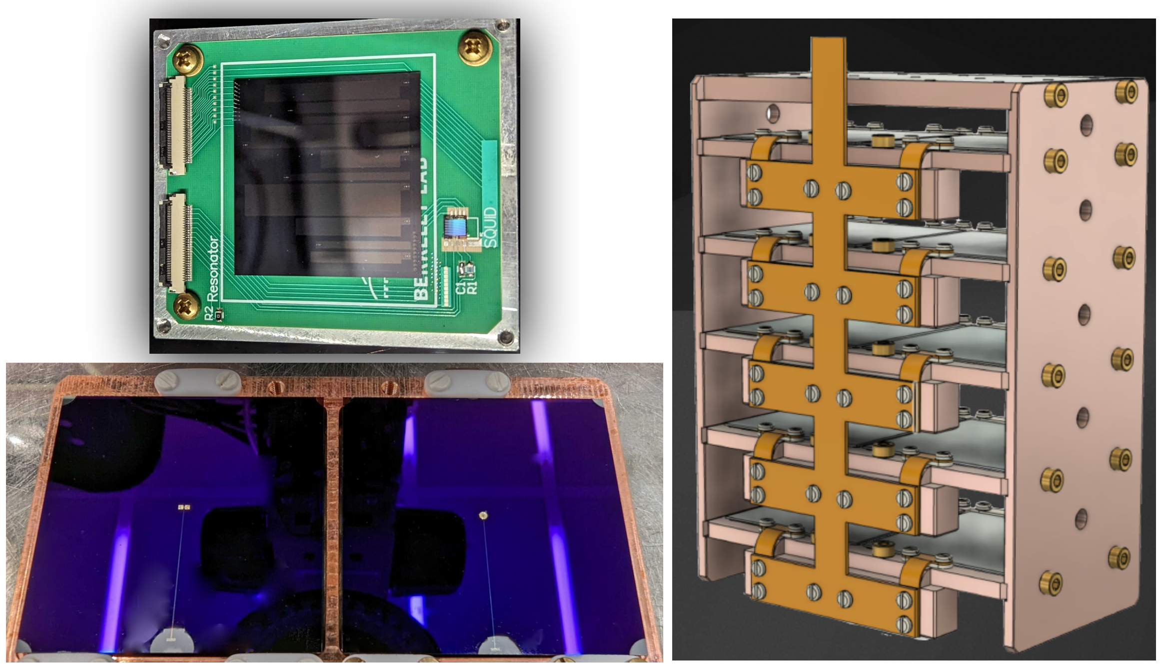
- New baseline selection through formal baseline change procedure
- Comparative large-scale test:
  - 10 detectors for each technology
  - operated in a mechanical and thermal environment similar to CUPID design
  - same calibration and performance assessment procedures



NTL test tower in France

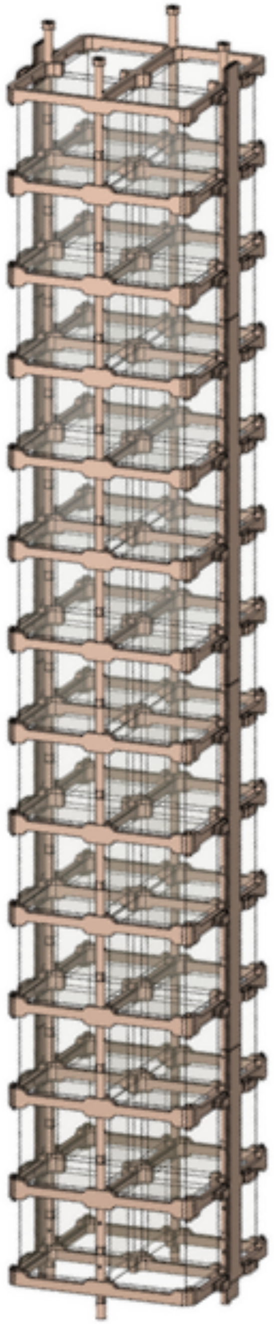
Tests ongoing

Relevant data for decision making available by end of May

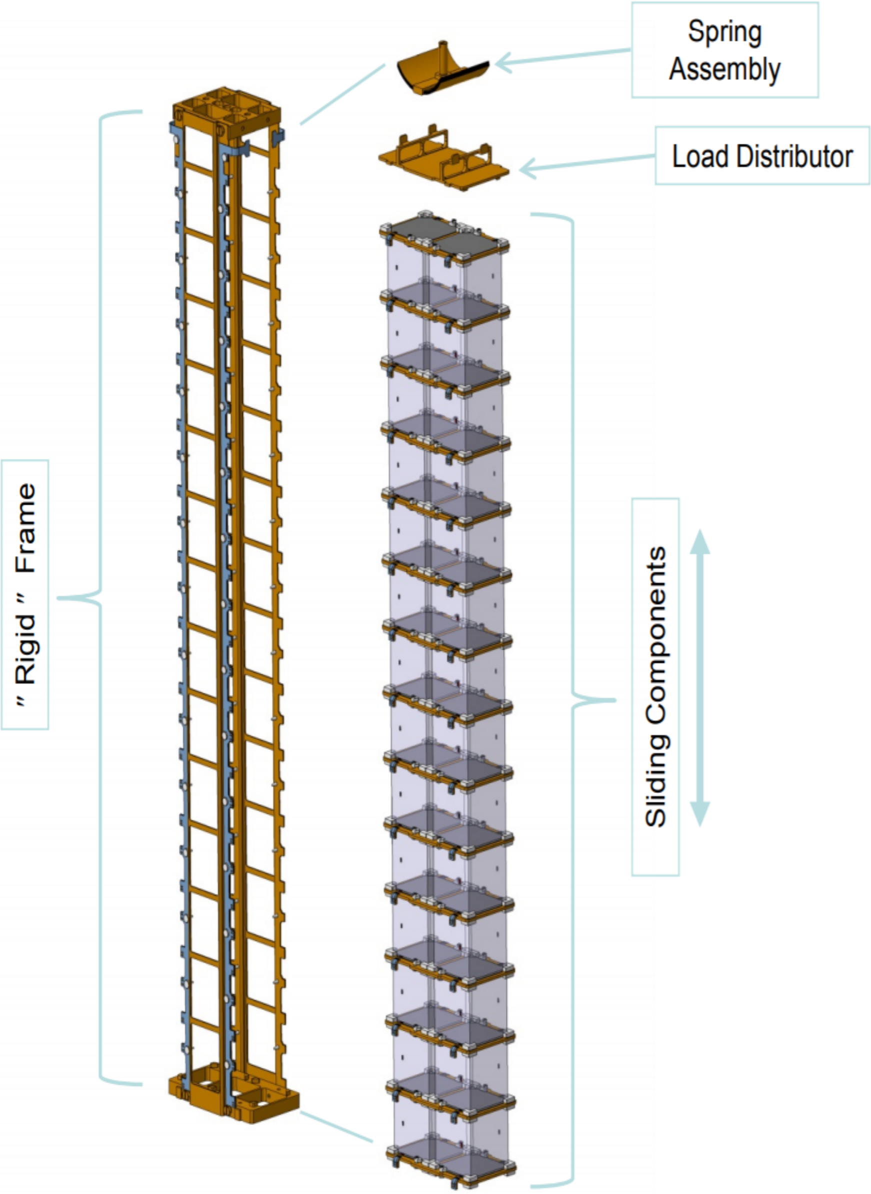


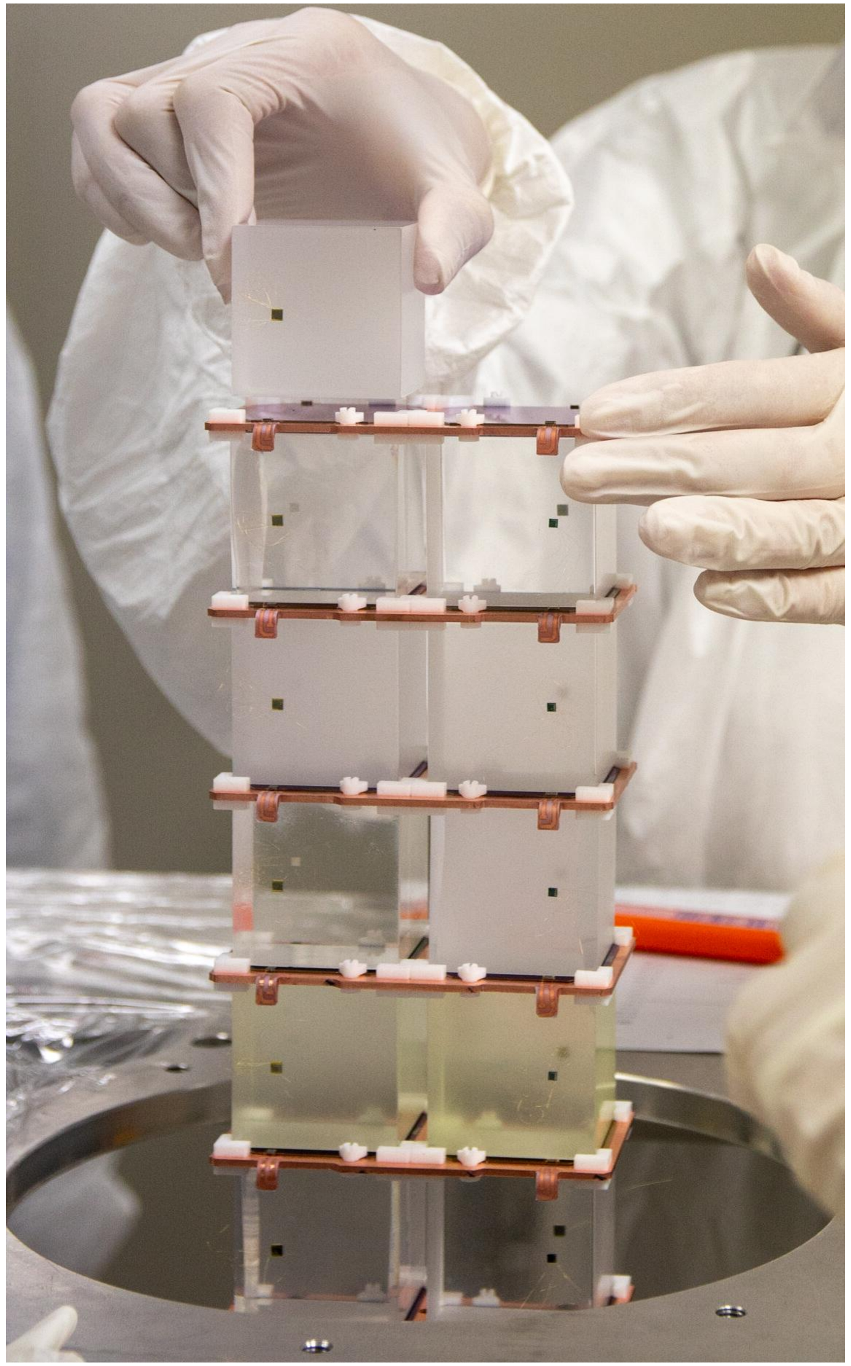
TES test tower in the US

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

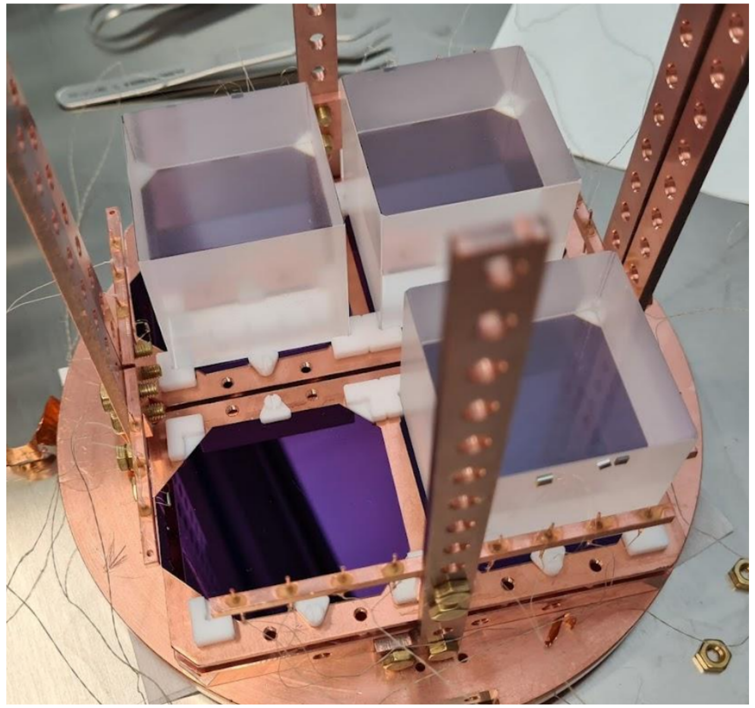
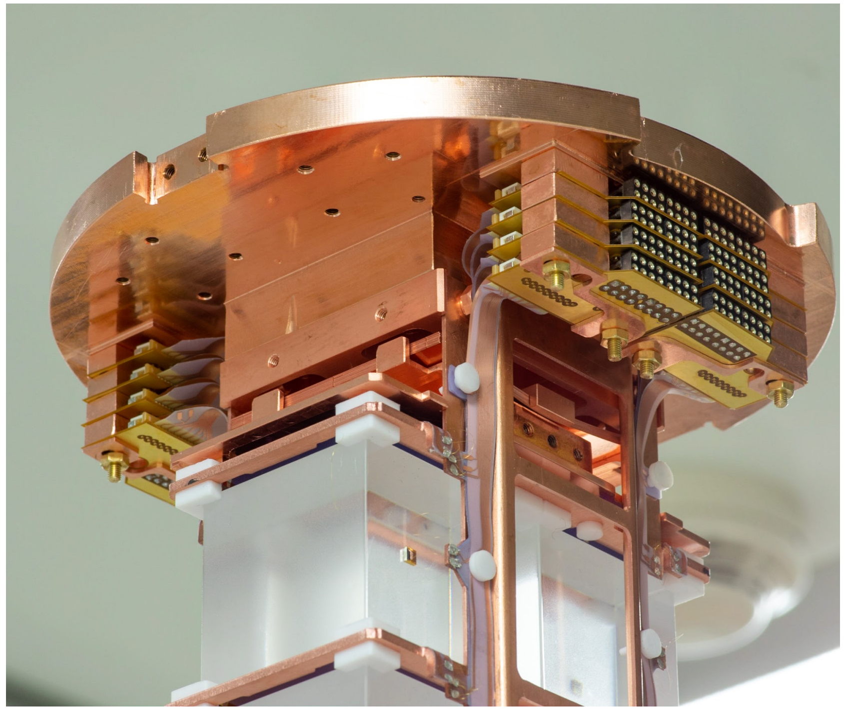
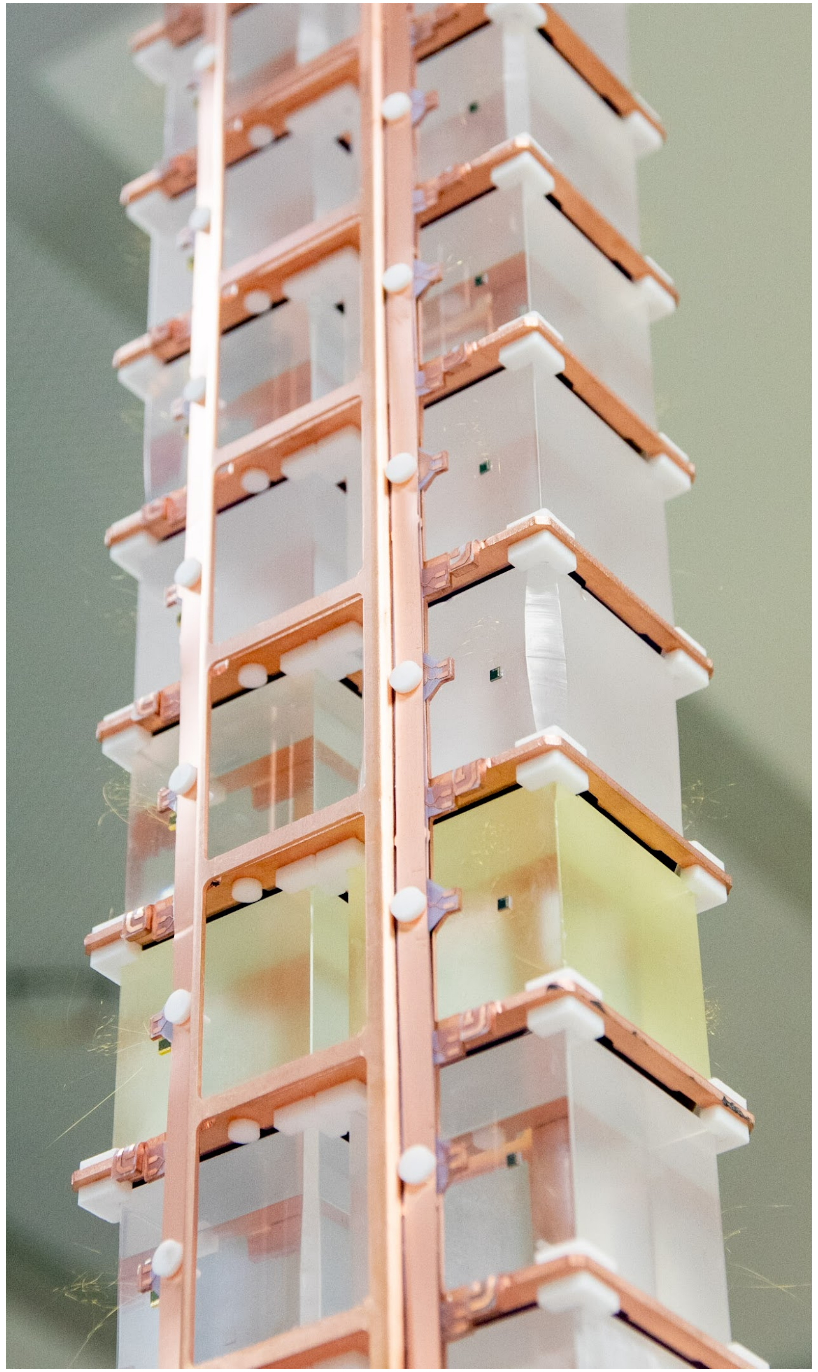
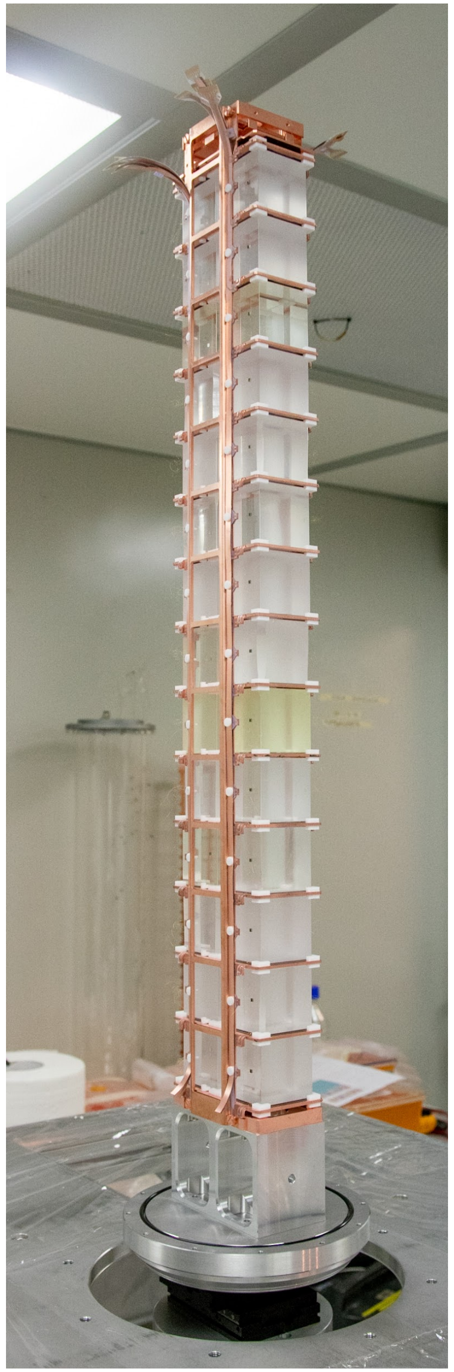




Detector Structure - BDPT

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)

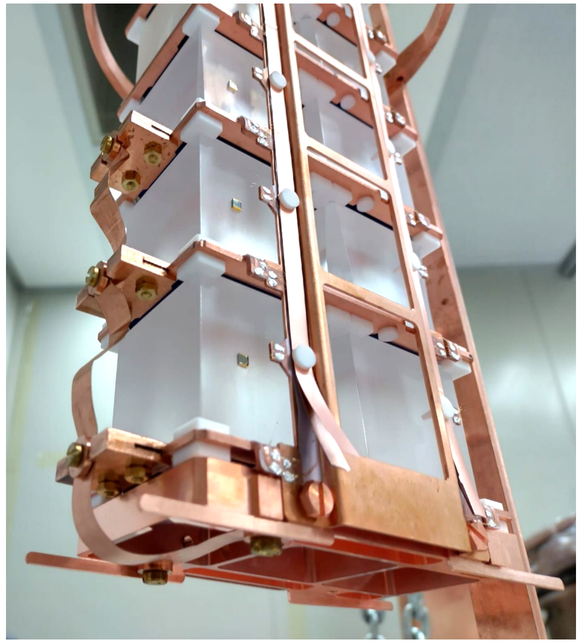





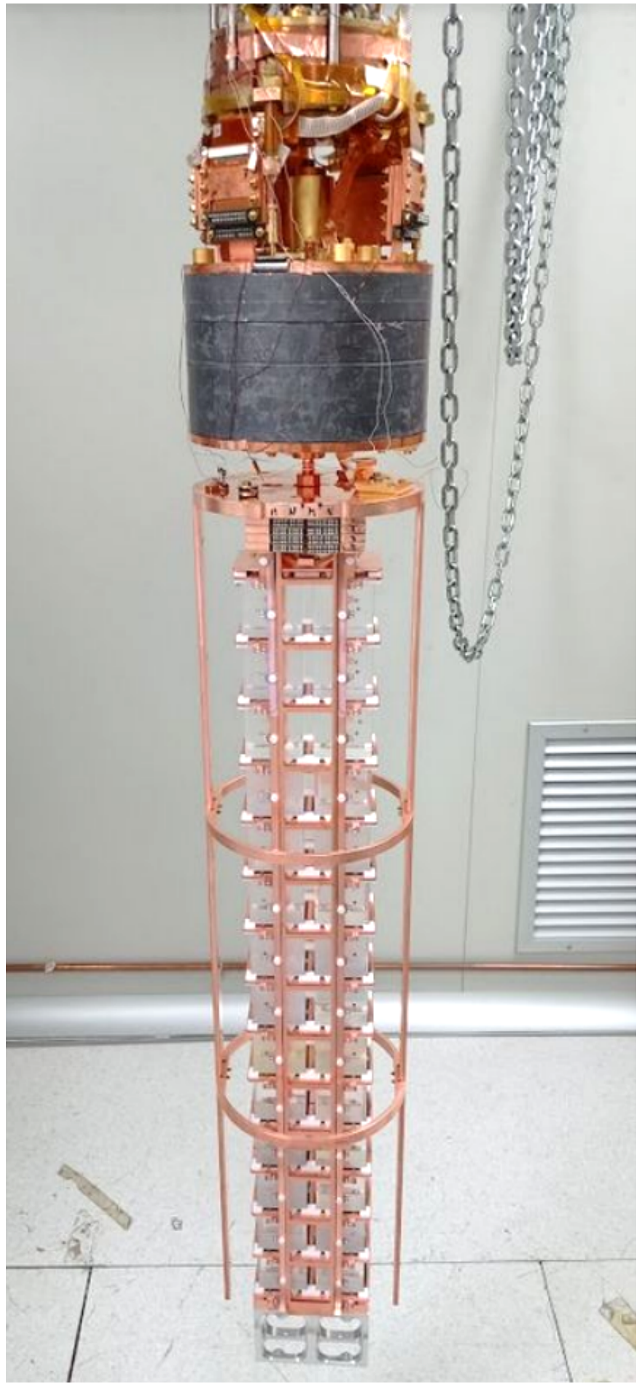
10.1140/epjc/s10052-022-10720-3

Detector Structure - BDPT

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

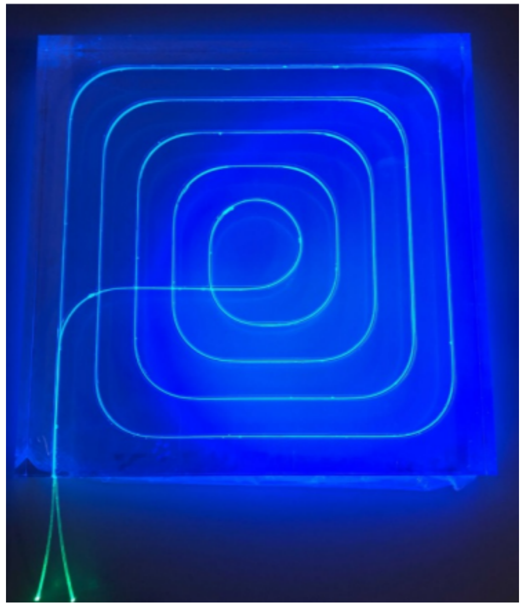
Run 2 (spring unloaded) Sep - Oct 22 → test effect of the spring, study floor-to-floor noise correlation

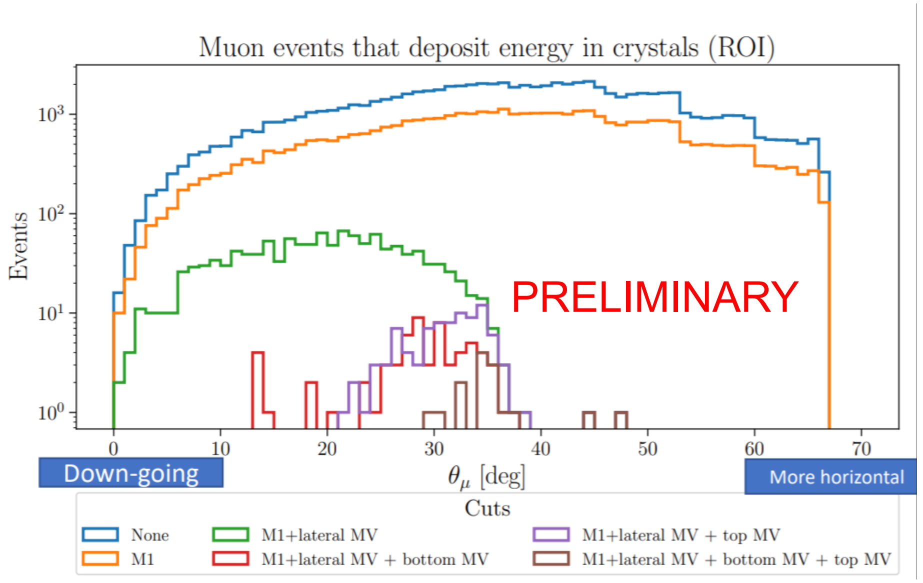
Run 3 (loose omegas, bottom floors thermalization) ongoing → test hypothesis on LD excess noise origin

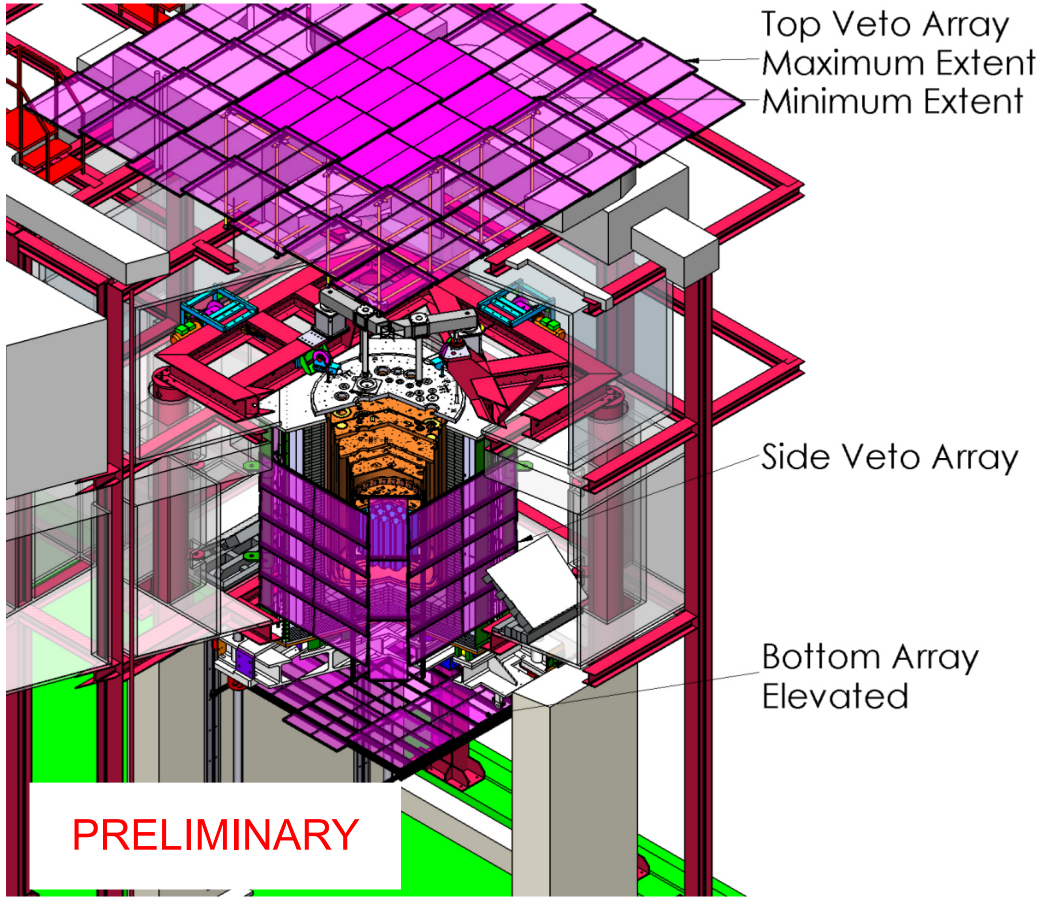
Detector Components - Muon Veto & Neutron Shield

- **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 → >x10 reduction of ROI background when combined with detector granularity

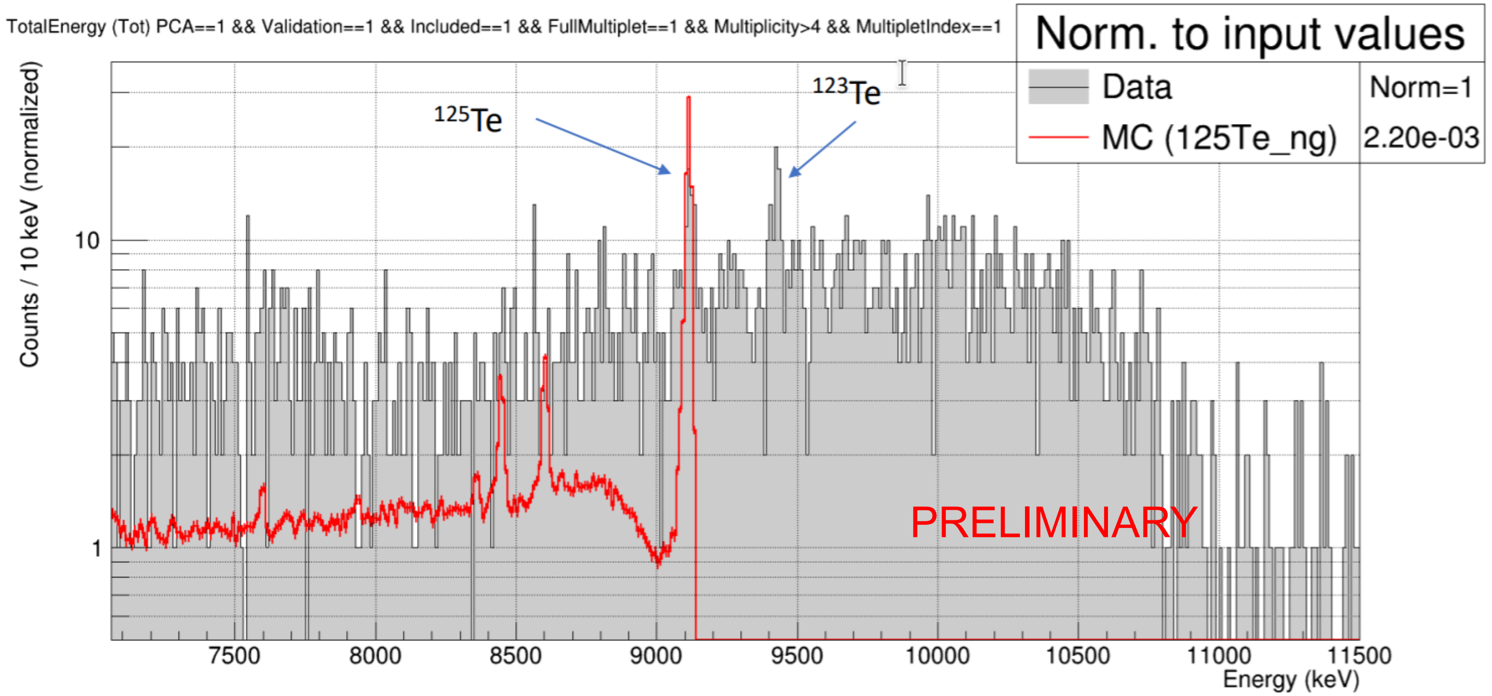






Detector Components - Muon Veto & Neutron Shield

- **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 constrain $0\nu\beta\beta$ backgrounds
  - high energy gamma cascades from neutron capture



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

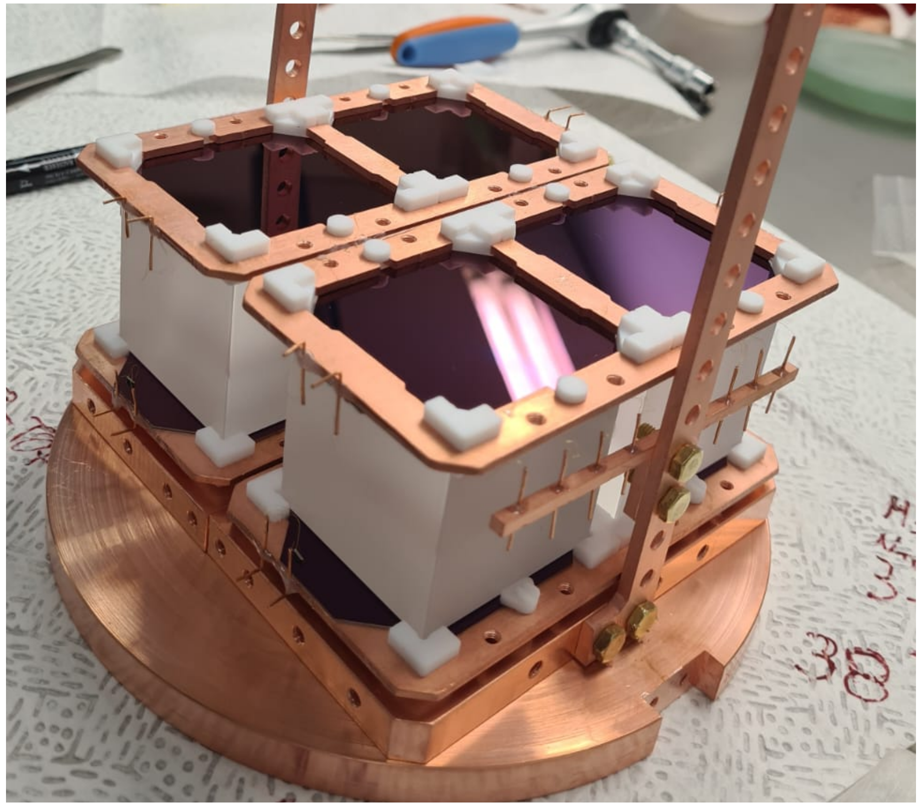
Background Control - Screening Labs

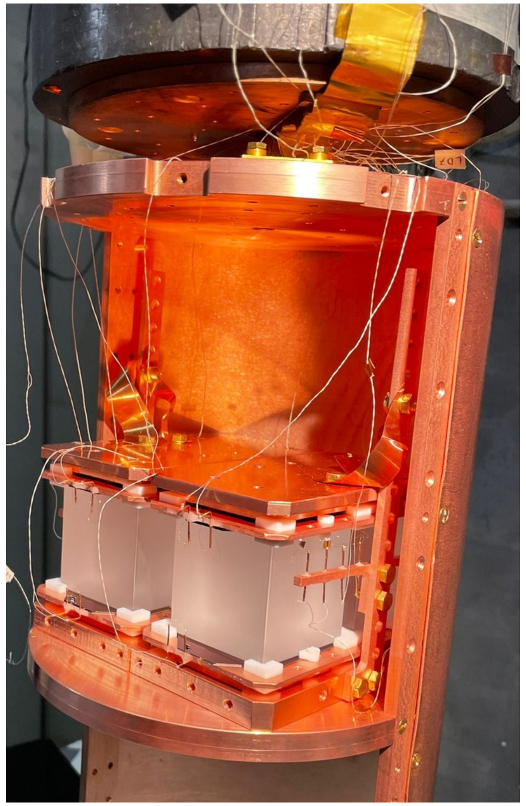
- High sensitivity radio-purity screening infrastructures available in Italy, US and France:
  - HPGe
  - ICP-MS
  - NAA
  - Surface barrier Si alpha counters
  - Cryogenic infrastructures for bolometric measurements (CCVR, large surface cryogenic Si detectors)
- Main screening activities:
  - MoO_3, 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)

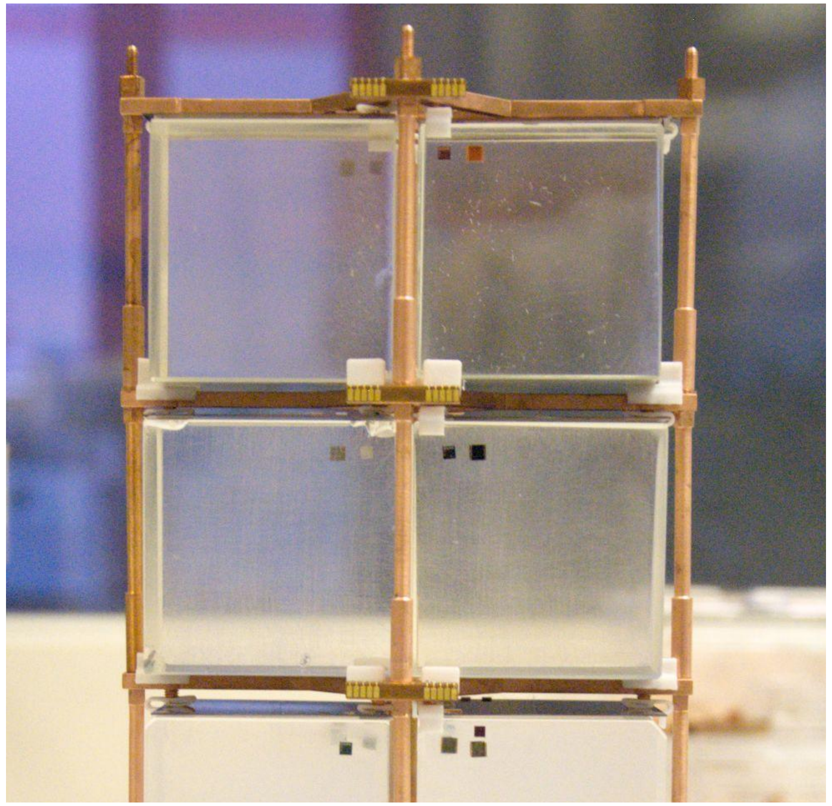
Background Control - CCVR

- 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 contamination

HallC @LNGS

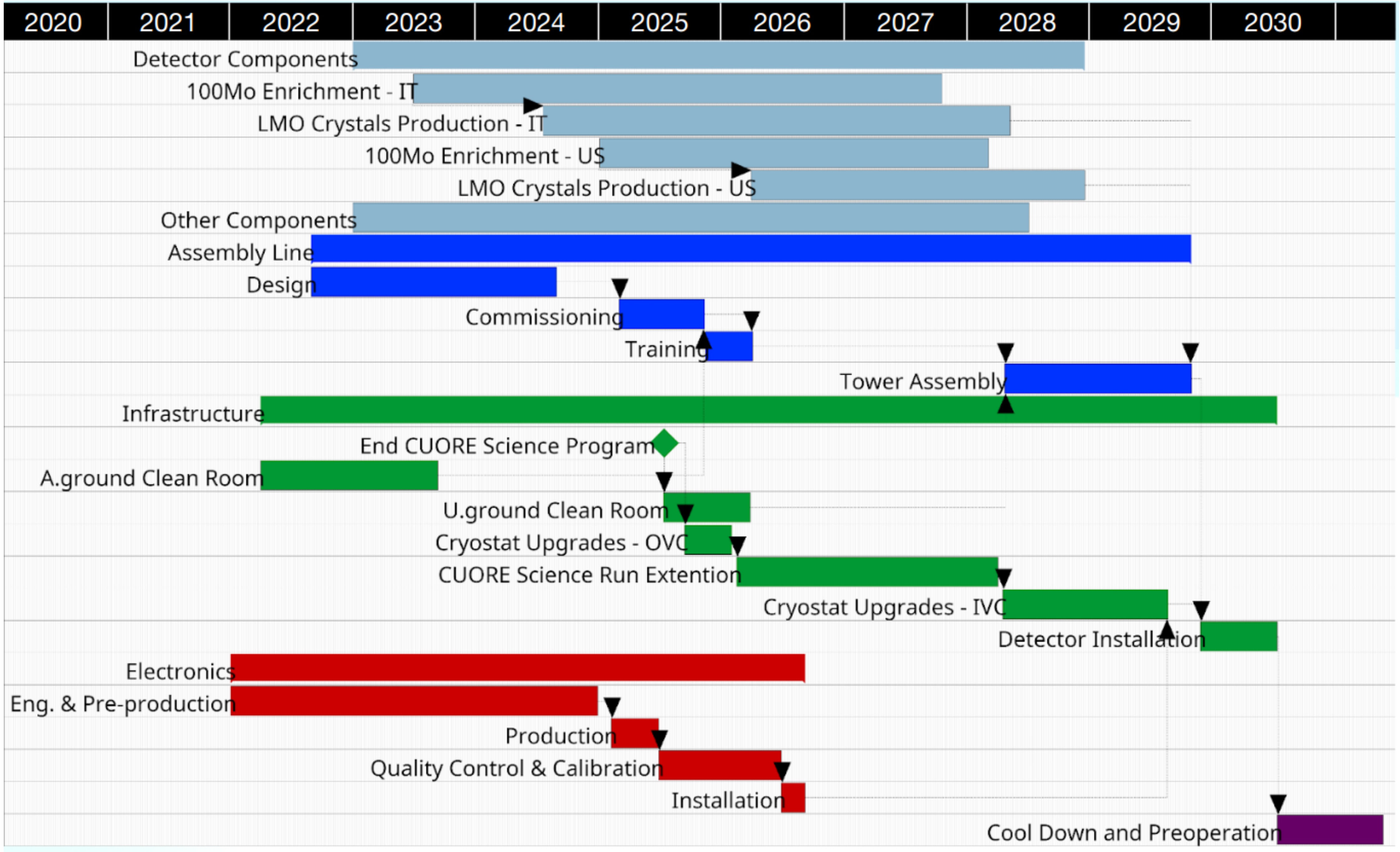






CROSS cryostat @LSC

Timeline



2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
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
A.ground Clean Room
U.ground Clean Room
Cryostat Upgrades - OVC
CUORE Science Run Extention
Cryostat Upgrades - IVC
Detector Installation
Electronics
Eng. & Pre-production
Production
Quality Control & Calibration
Installation
Cool Down and Preoperation

Conclusions

- CUPID will **explore inverted ordering ($T_{1/2}$ > 10^{27} years at 3σ,** $m_{\beta\beta}$ ~ **12-20 meV)**
- **Builds on existing and well-functioning international collaborations** and partnerships
- 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 mode**l reaches baseline goal of B.I. ~ 10^{-4} counts/(keV kg y)

CUPID is proceeding towards construction phase.
Complements international suite of ton-scale experiments in a world-wide program

Thank you !