CUPID:

CUORE Upgrade with Particle Identification

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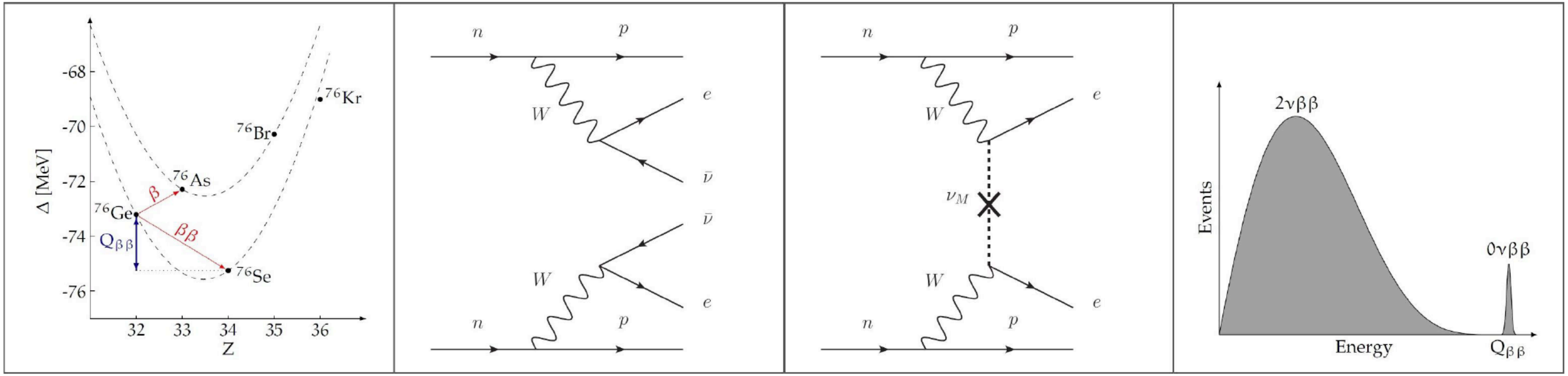
US Project Director
UC Berkeley/LBNL

CUPID LBNL Project Review
December 16-17, 2024

Search for Neutrinoless Double Beta Decay



$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot |f|^2 / m_e^{\,2}$$

$T^{1/2}_{0\nu}$ = 0νββ decay half-life
$G_{0\nu}$ = phase space (known)
$M_{0\nu}$ = nuclear matrix element (NME)
f = new physics term, e.g. effective neutrino mass $m_{\beta\beta}$

0νββ Decay Signature

Distinguishing peak at $Q_{\beta\beta}$ for 0νββ decay from continuum for 2νββ decay

Energy peak is necessary and sufficient signature to claim a discovery

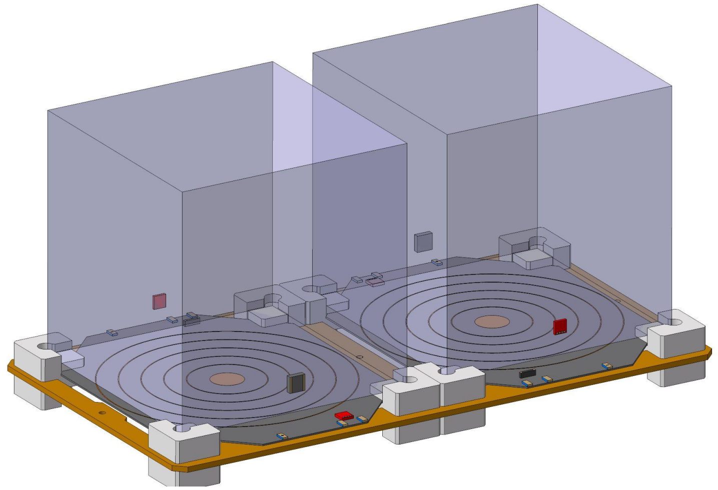
Additional signatures from signal topology, pulse shape discrimination, multiple channel readout, …

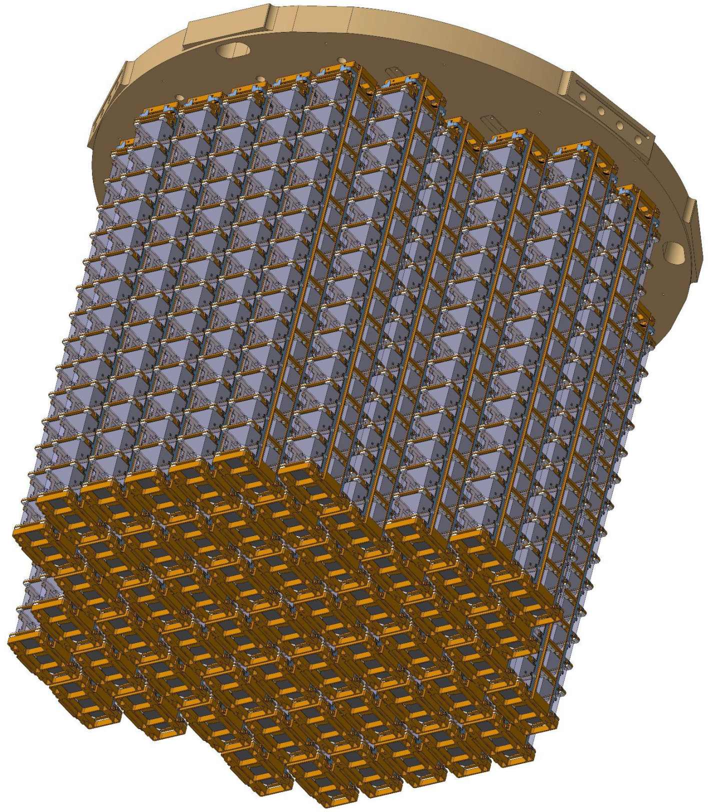
CUPID is optimized to achieve this goal

CUPID: CUORE Upgrade with Particle Identification

In summary

- Array of 1596 $Li_2{}^{100}MoO_4$ **scintillating** bolometers
- Enriched to >95% in ^{100}Mo (240 kg of ^{100}Mo)
- Isotope: **^{100}Mo** with **Q-value: 3034 keV**:
    - β/γ background significantly reduced
    - favorable NME
- Exploit Particle ID using scintillation bolometer technique
    - Technique robustly demonstrated by CUPID-0 and CUPID-Mo
- Reuse **proven CUORE cryogenic infrastructure** at LNGS with modest upgrades for a cost-effective deployment





CUPID baseline goals are conservative and can be implemented within the existing detector technology and infrastructure.

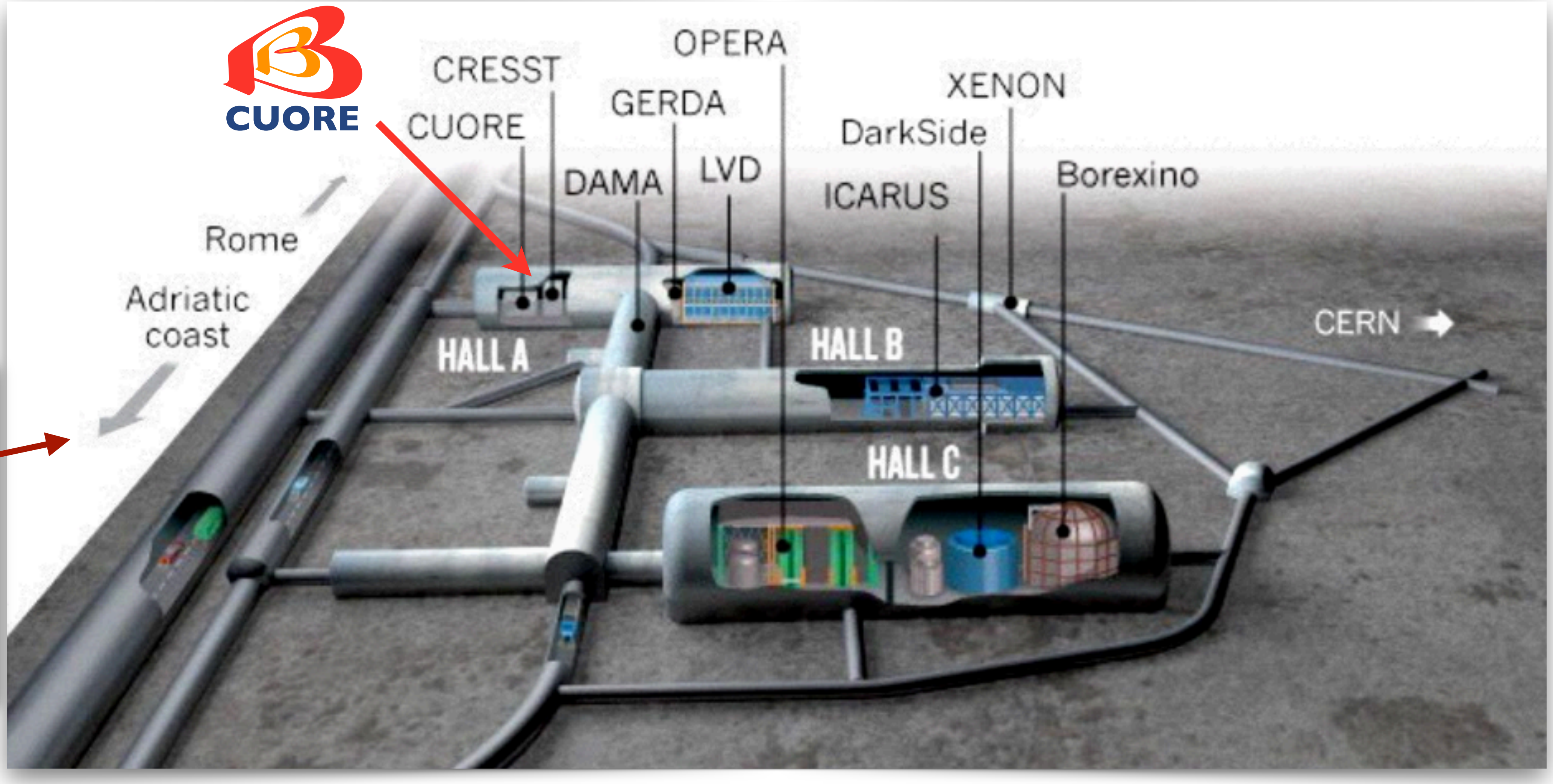
LNGS: Laboratori Nazionali del Gran Sasso

Natural shielding from cosmic rays by the mountain of Gran Sasso

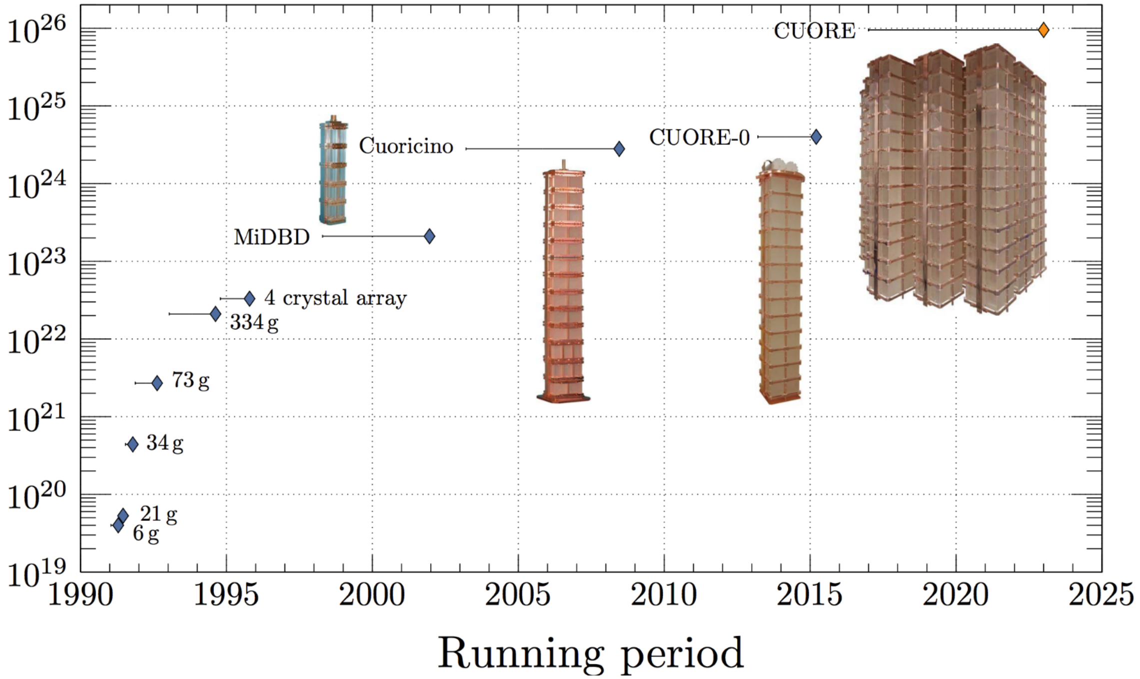
3600 meter water equivalent overburden

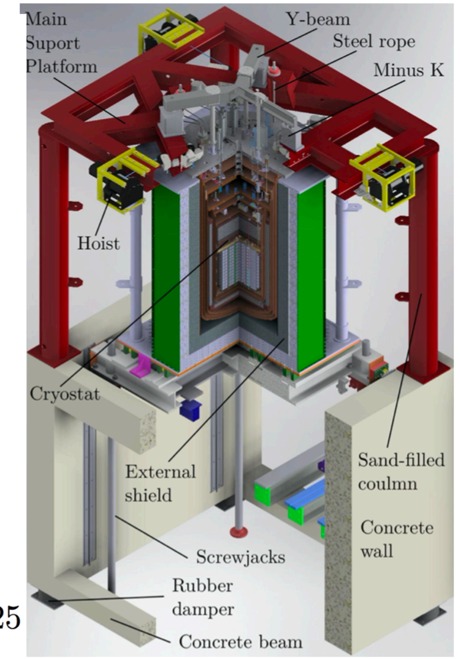
Well-established support for experiments and user access

Also site for a proposed LEGEND NLDBD experiment



Established Site and Collaboration





CUPID is extremely well-leveraged and cost-effective:

- Based on decades of bolometric experiments, including Cuoricino, CUORE, CUPID-Mo, CUPID-0
- Established US-Italy-France partnership with experience to execute complex international projects
- Existing underground laboratory and experimental site
- LNGS provides technical and user support
- **Unique cryogenic infrastructure**

CUORE Infrastructure

CUPID will utilize existing infrastructure (CUORE cryostat, experimental site)

CUORE cryostat

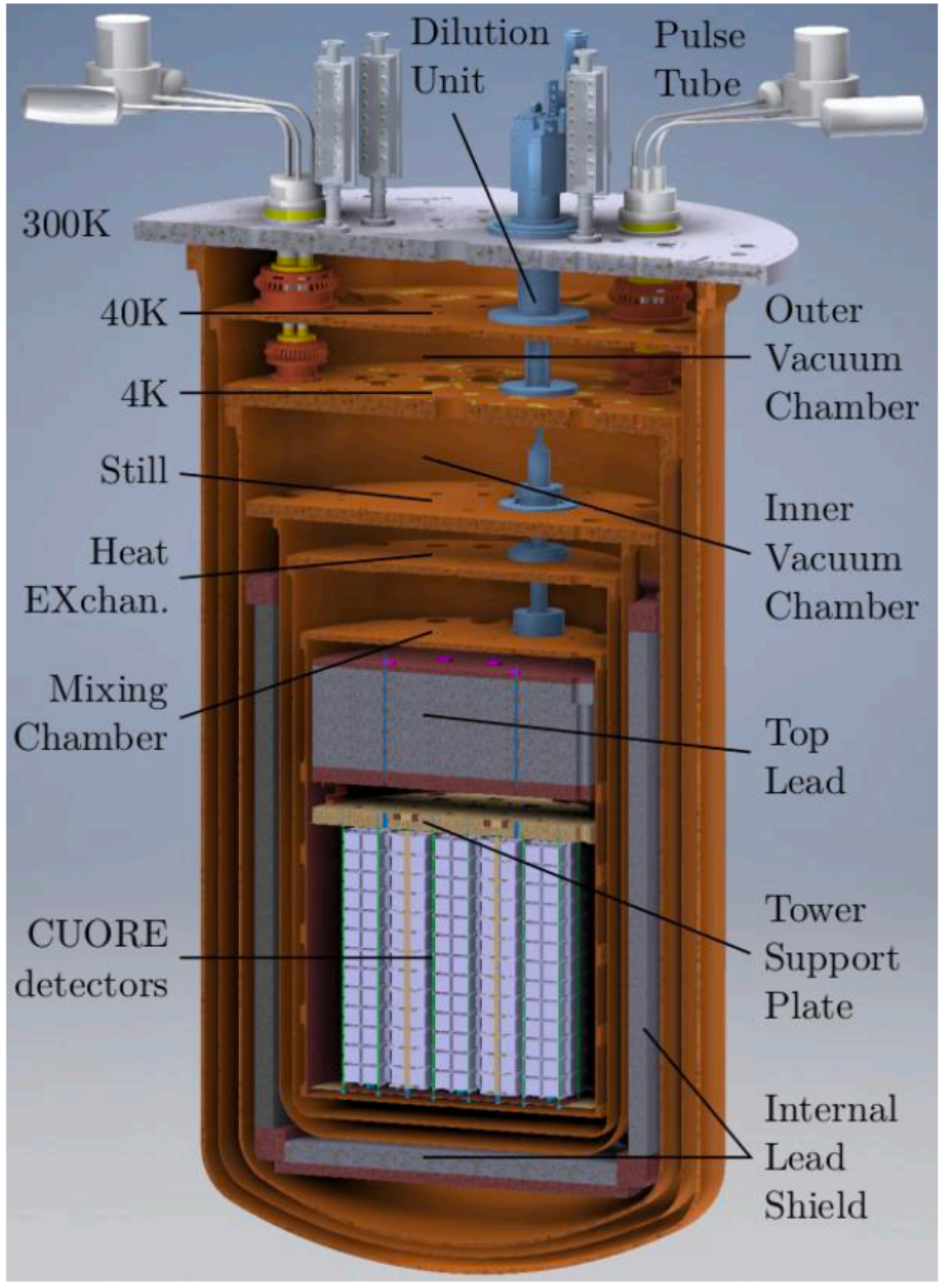
- Multistage cryogen-free cryostat
- Cooling systems: fast cooling system, Pulse Tubes (PTs), and
- Dilution Unit (DU)

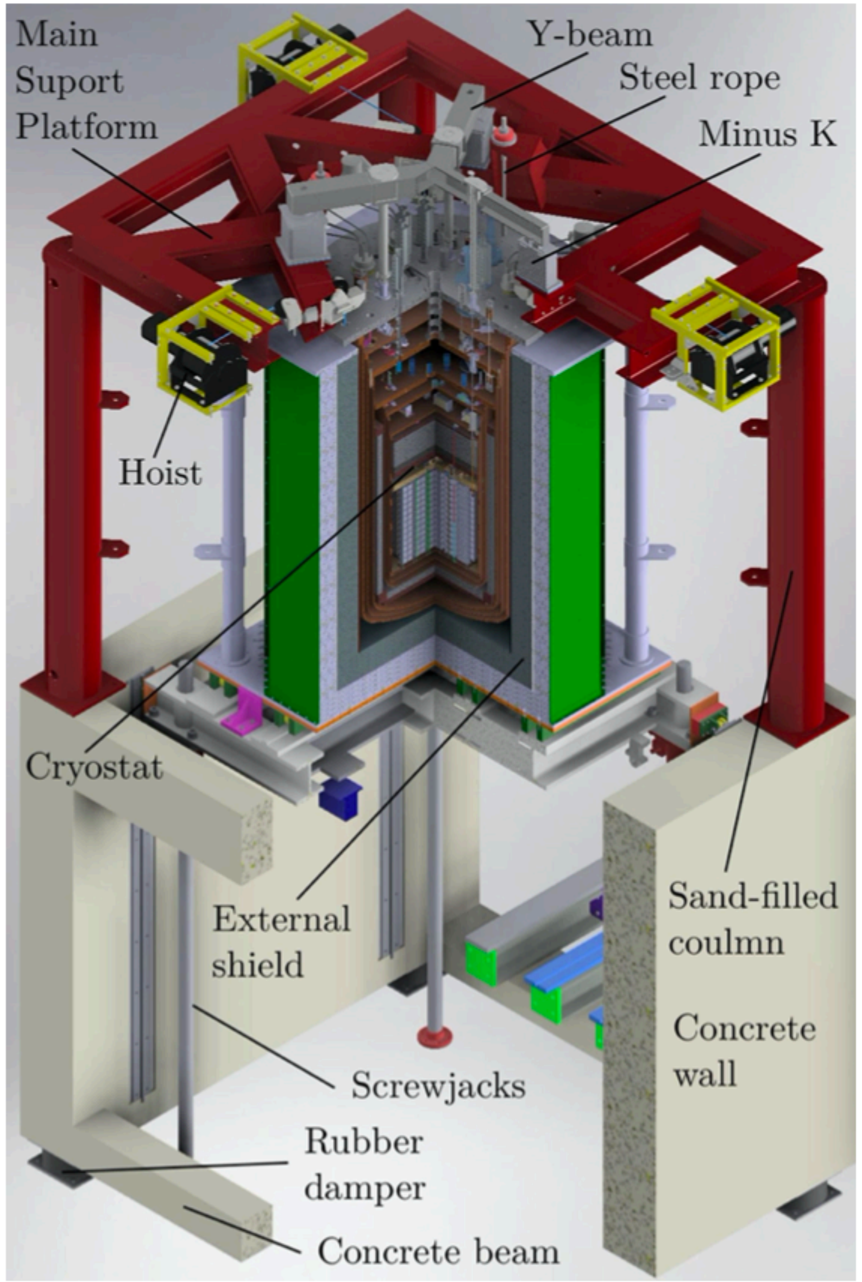
  ~15 tons @ < 4 K

  ~ 3 tons @ < 50 mK
- Mechanical vibration isolation
- Active noise cancellation

CUORE (passive) shielding

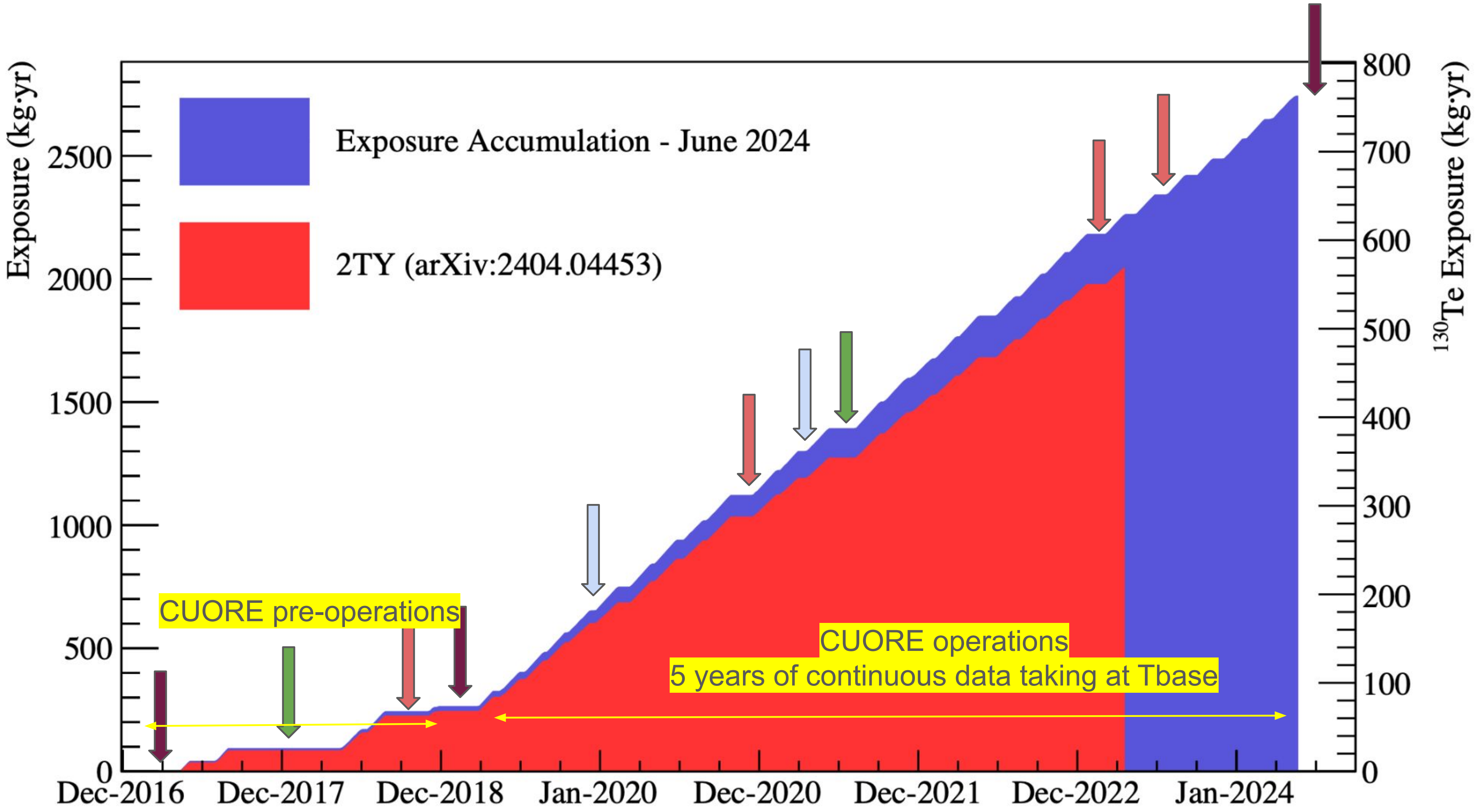
- Ancient Roman Pb shielding in cryostat
- External Pb shielding
- H_3BO_3 panels + polyethylene





CUORE Infrastructure

CUPID will utilize existing infrastructure and CUORE operational experience



- optimization campaigns
- standard maintenance between dss
- longer (and more invasive) maintenances between dss
- warm-up to 90K / cryogenic interventions / cooldown

Isotope Choice

^{100}Mo

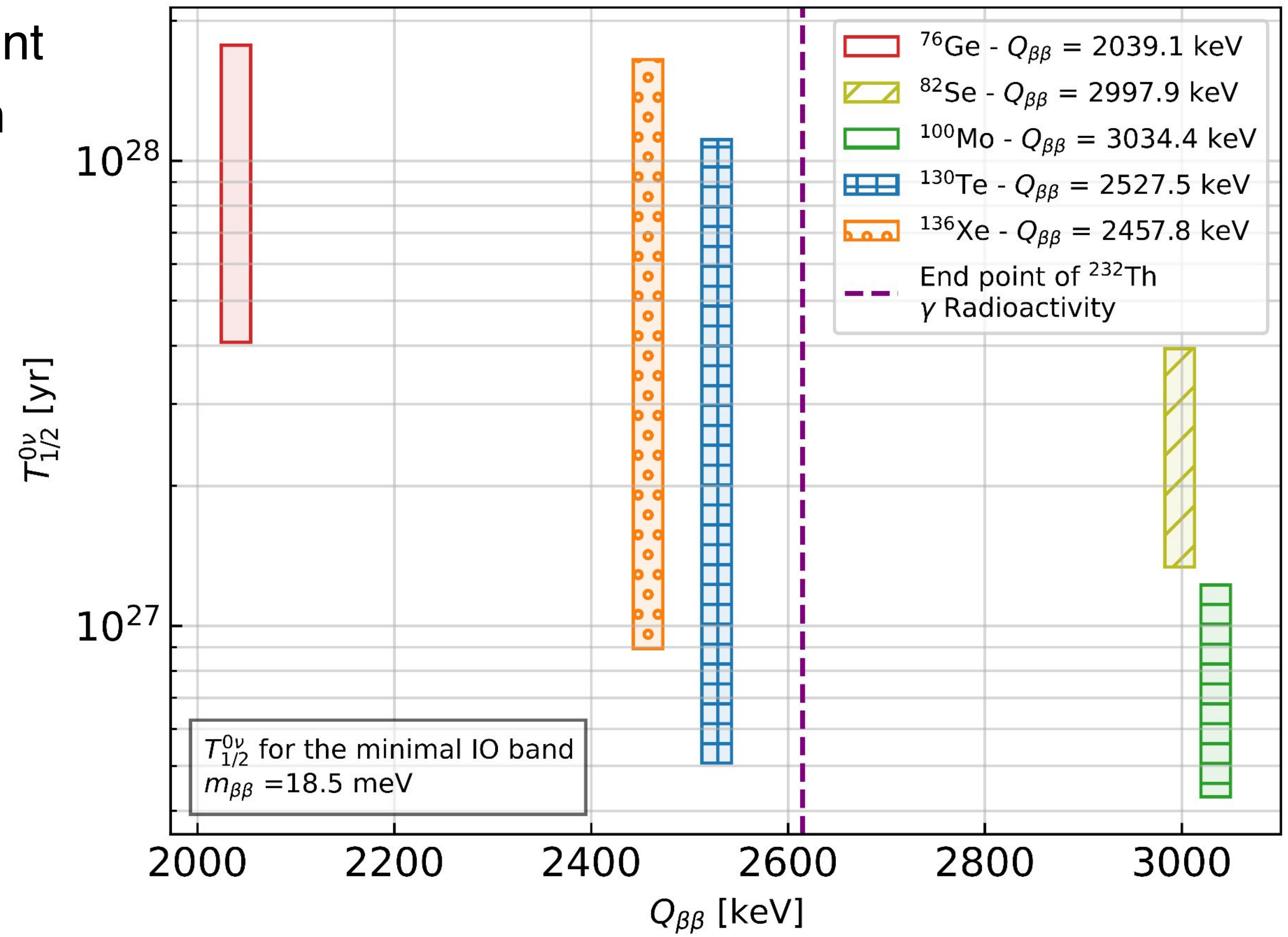
- High isotopic abundance, feasible enrichment
- $Q_{\beta\beta}$ above end point of most β or γ radiation
- Favorable phase space and nuclear matrix elements
- Scintillating crystals available
- Large scale crystal production possible

Advantages of Bolometric Approach

Detectors and infrastructure are decoupled.

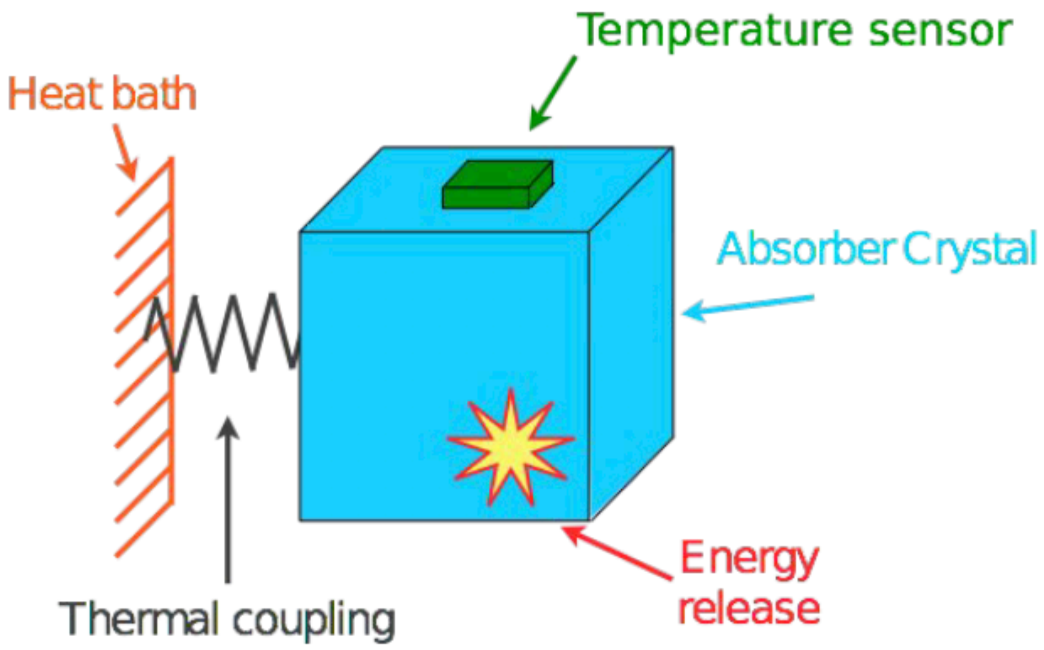
Same cryogenic infrastructure reusable with different isotopes and/or crystals

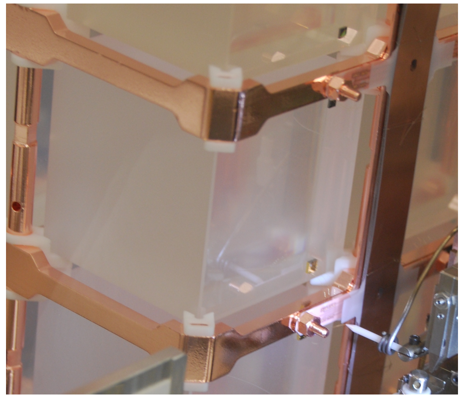
Perfect for test of discovery or precision measurements

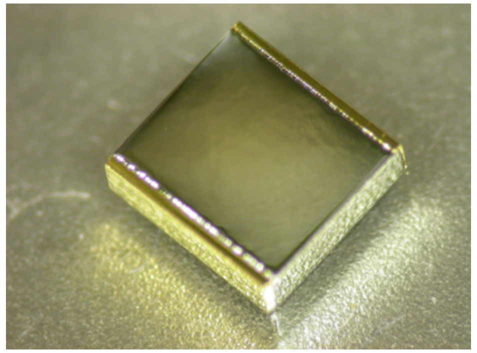


$T_{1/2}$ sensitivity required to cover Inverted Ordering region of $m_{\beta\beta}$ parameter space

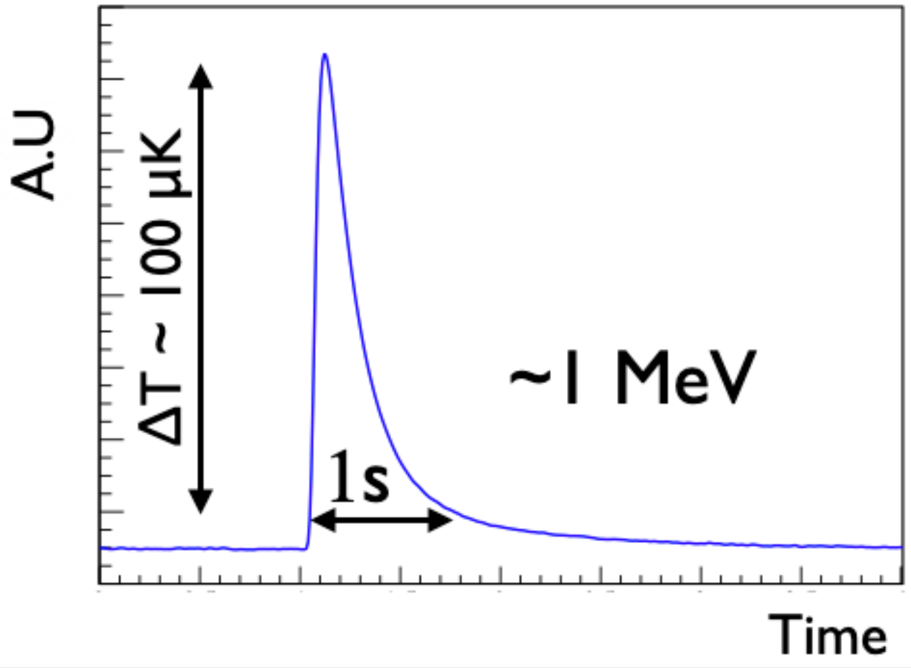
Bolometric Detectors







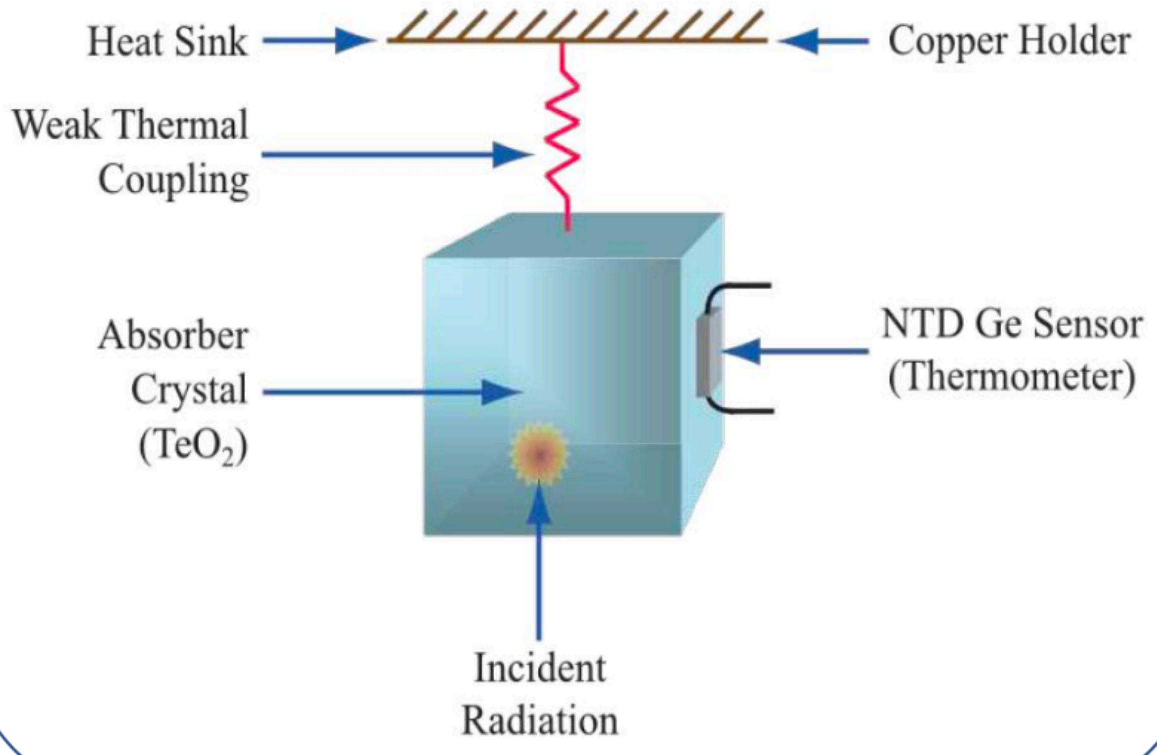
- Low heat capacity @ T ~ 10 mK
- **Excellent energy resolution** (~0.2% FWHM)
- Detector response independent of particle types
- **Flexibility in 0νββ candidate choice**
- Detector response of O(1) sec if readout with e.g. Neutron Transmutation Doped (NTD) Ge sensors



- Crystal heat capacity: C
- Conductivity of coupling to thermal bath: G
- Signal amplitude $\propto \Delta T = E_{dep} / C$
- Decay constant: $\tau = G / C$

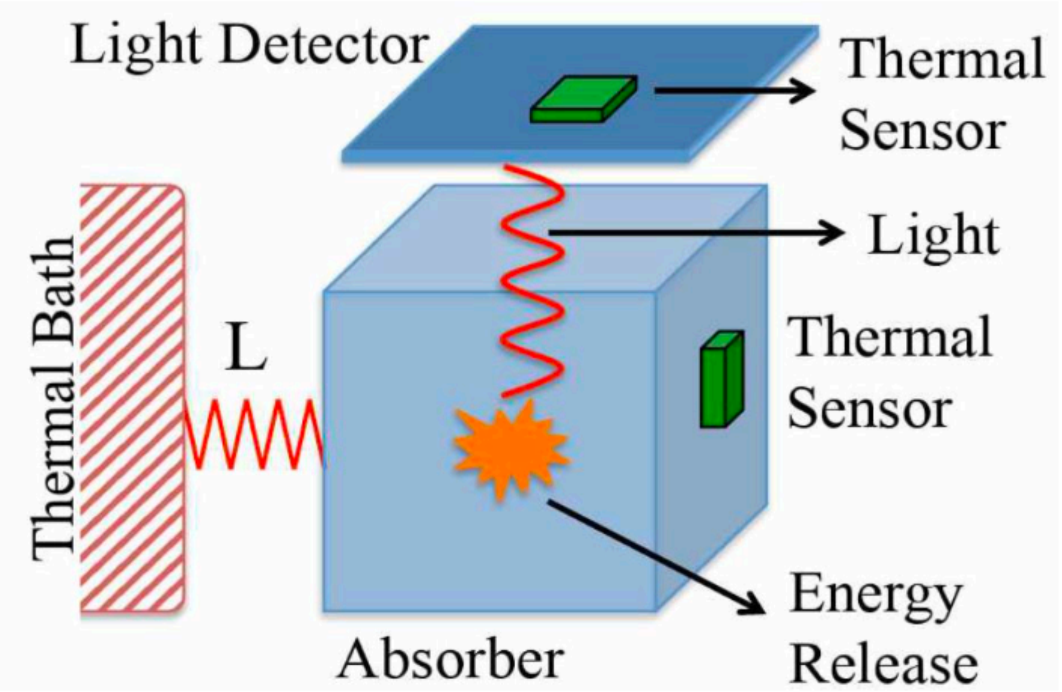
CUPID Concept

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



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

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



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

CUPID Concept

CUPID ^{100}Mo
heat + light
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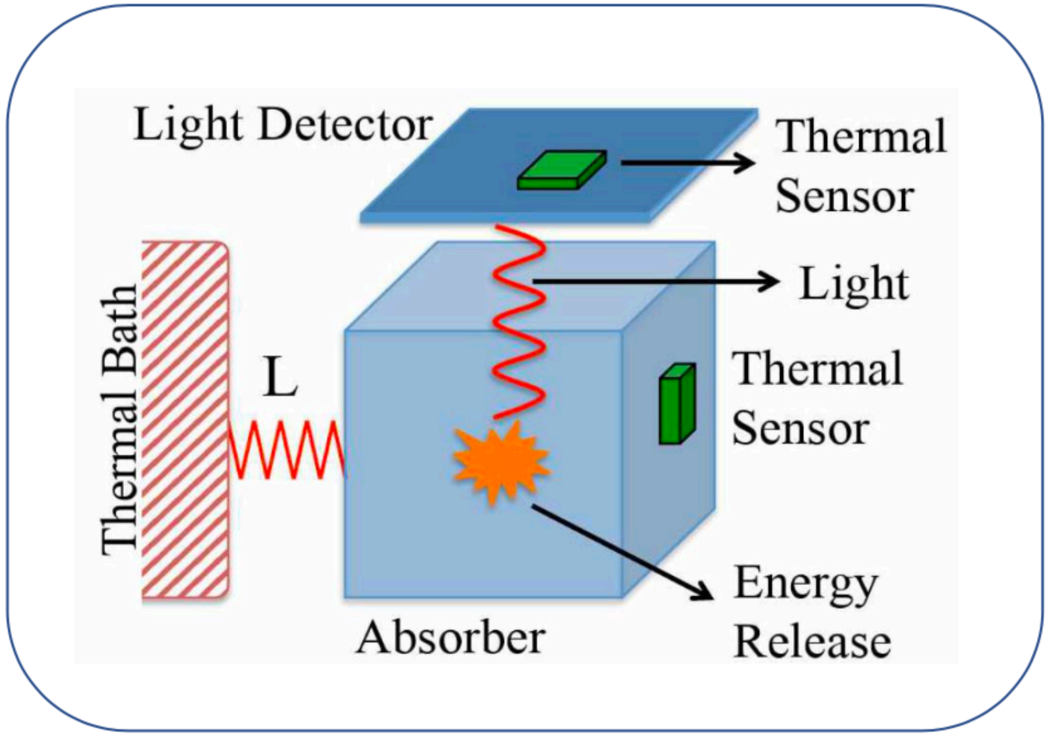
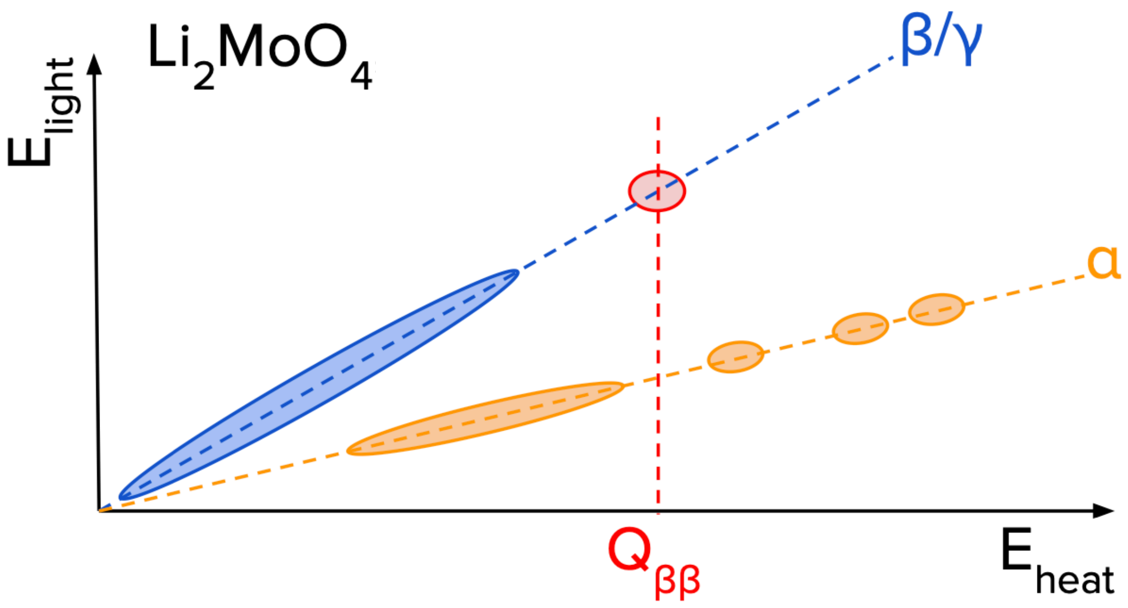
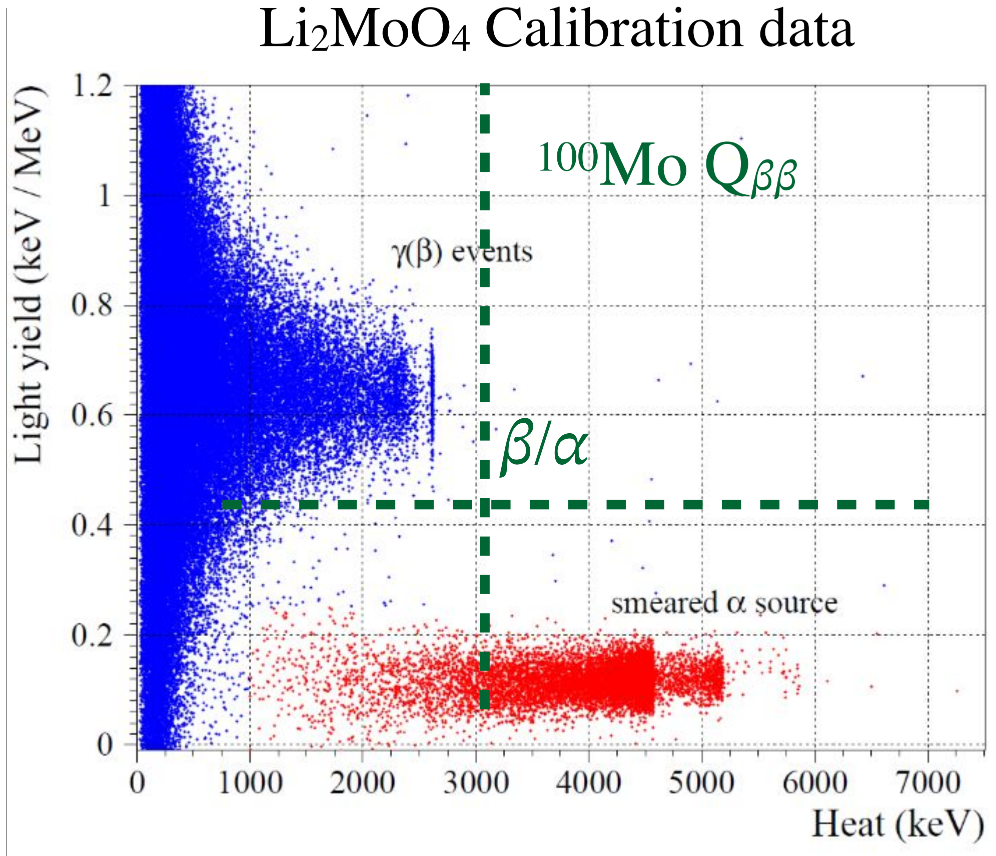






Measure heat and light from energy deposition

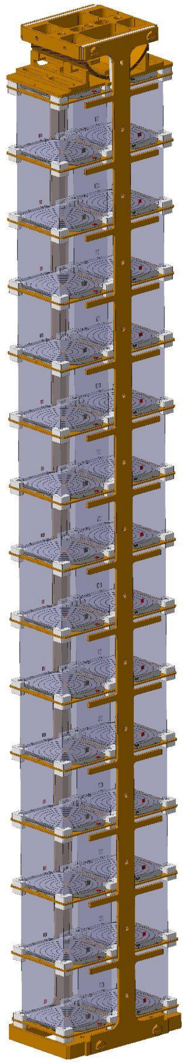
Heat is particle independent, but light yield depends on particle type

Actively discriminate α using measured light yield

CUPID Detector

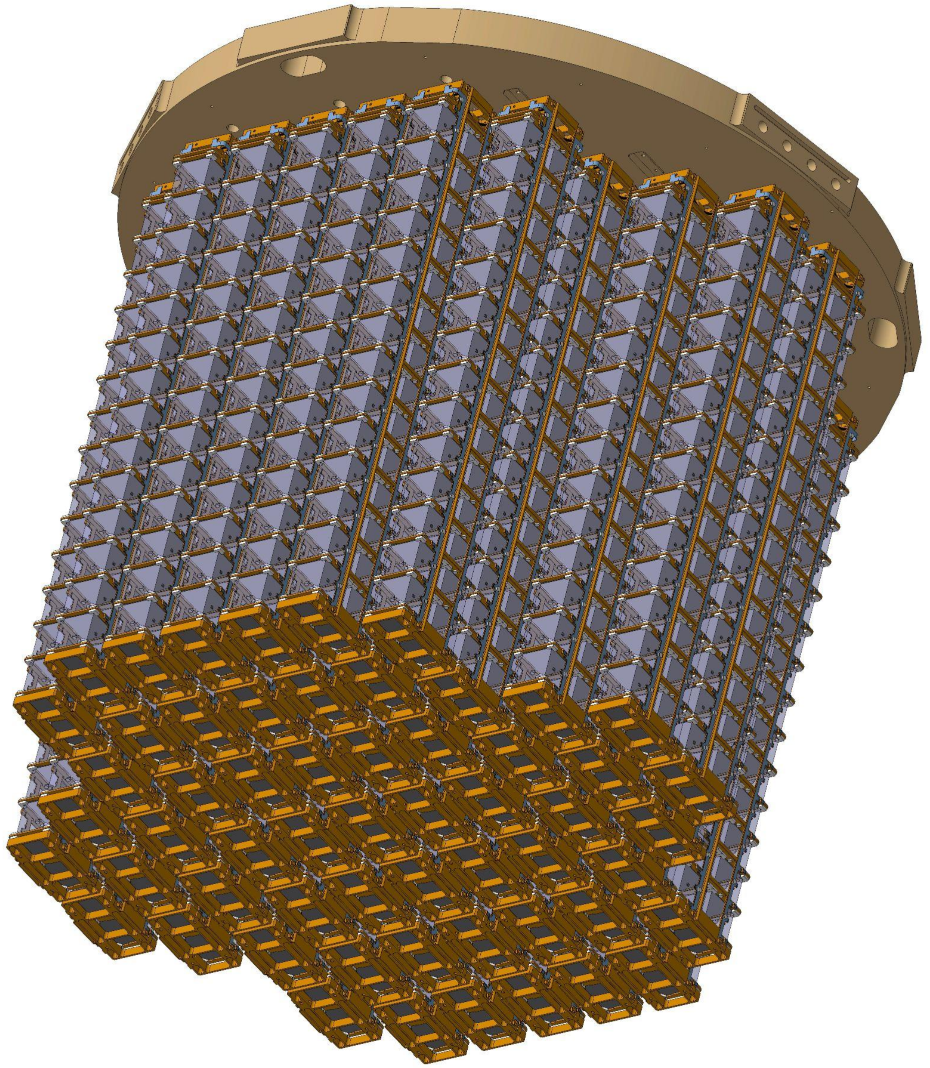
Single module: Li$_2$^{100}MoO4, 45x45x45 mm^3, 280 g
Detector: 57 towers of 14 floors with 2 crystals each, 1596 crystals
~240 kg of ^{100}Mo with >95% enrichment
~1.6.10^{27} ^{100}Mo atoms
1710 Ge light detectors with NTL amplification

Tower



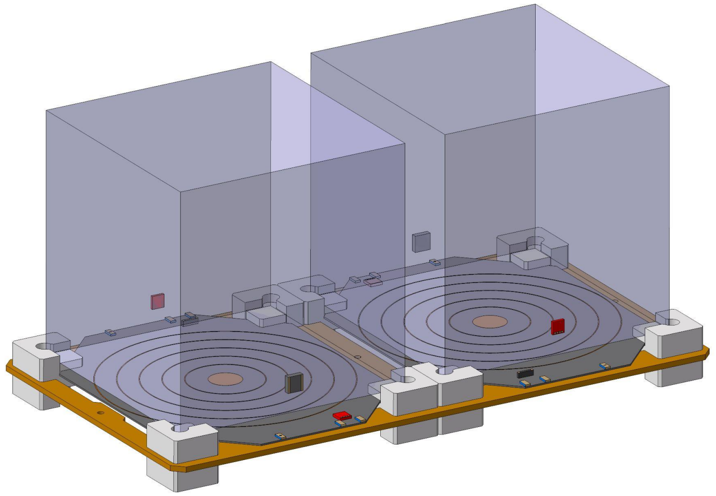
Gravity stacked structure
Crystals thermally interconnected

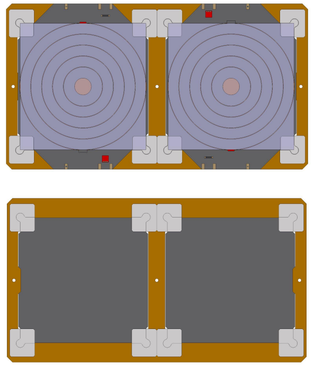
Full CUPID detector



Towers connected suspended from the 10 mK plate

Detector Module





Modular construction enables staged deployment and early science

CUPID Sensitivity

CUPID Baseline

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

CUPID Discovery Sensitivity

$T_{1/2}$ > **1×10^{27} yrs (3σ)**

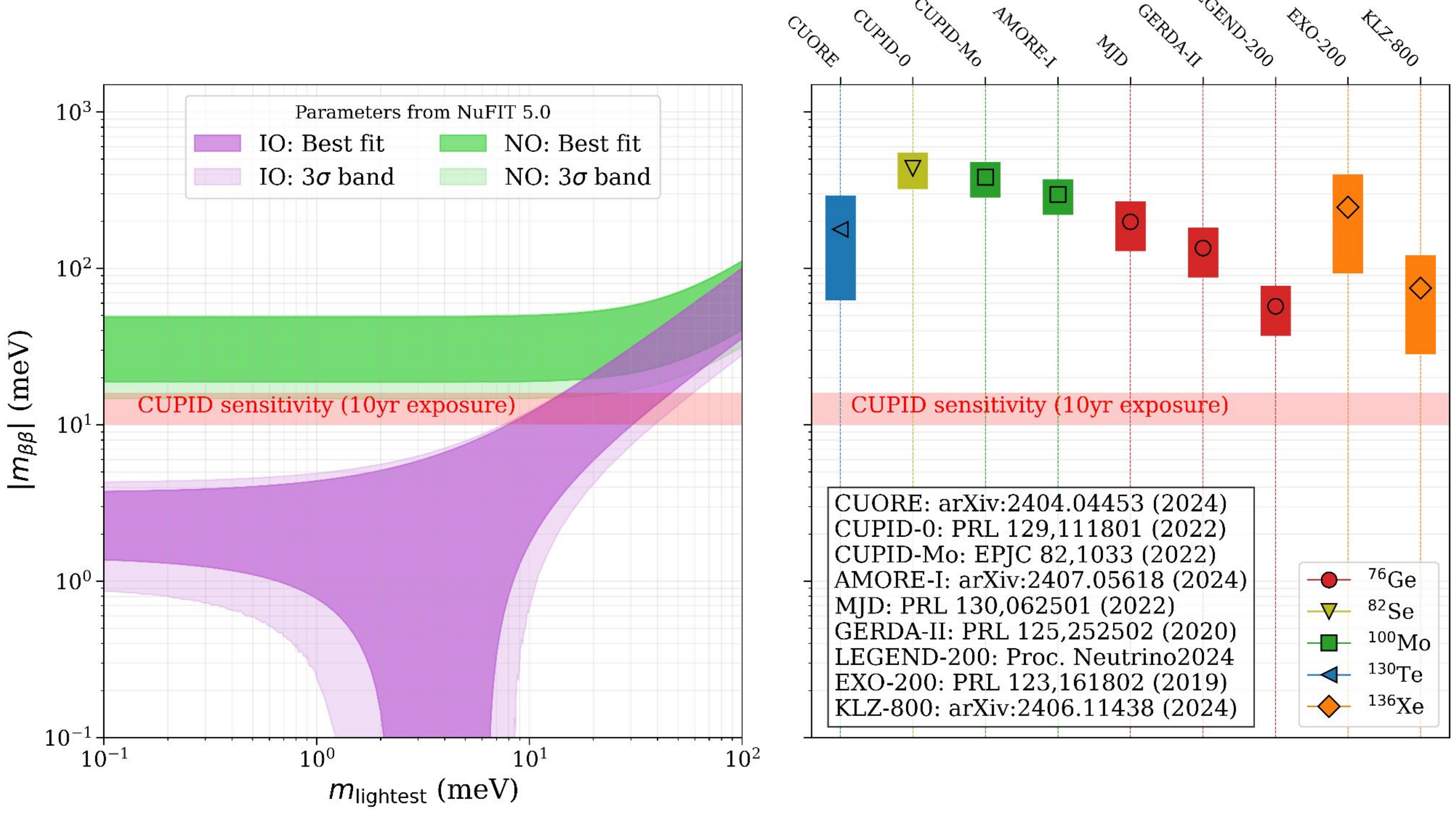
$m_{\beta\beta}$ < 13-21 meV

CUPID Exclusion Sensitivity

$T_{1/2}$ > 1.8 x 10^{27} yrs (90% C.I.)

$m_{\beta\beta}$ ~ 9-15 meV

Projected exclusion sensitivity



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

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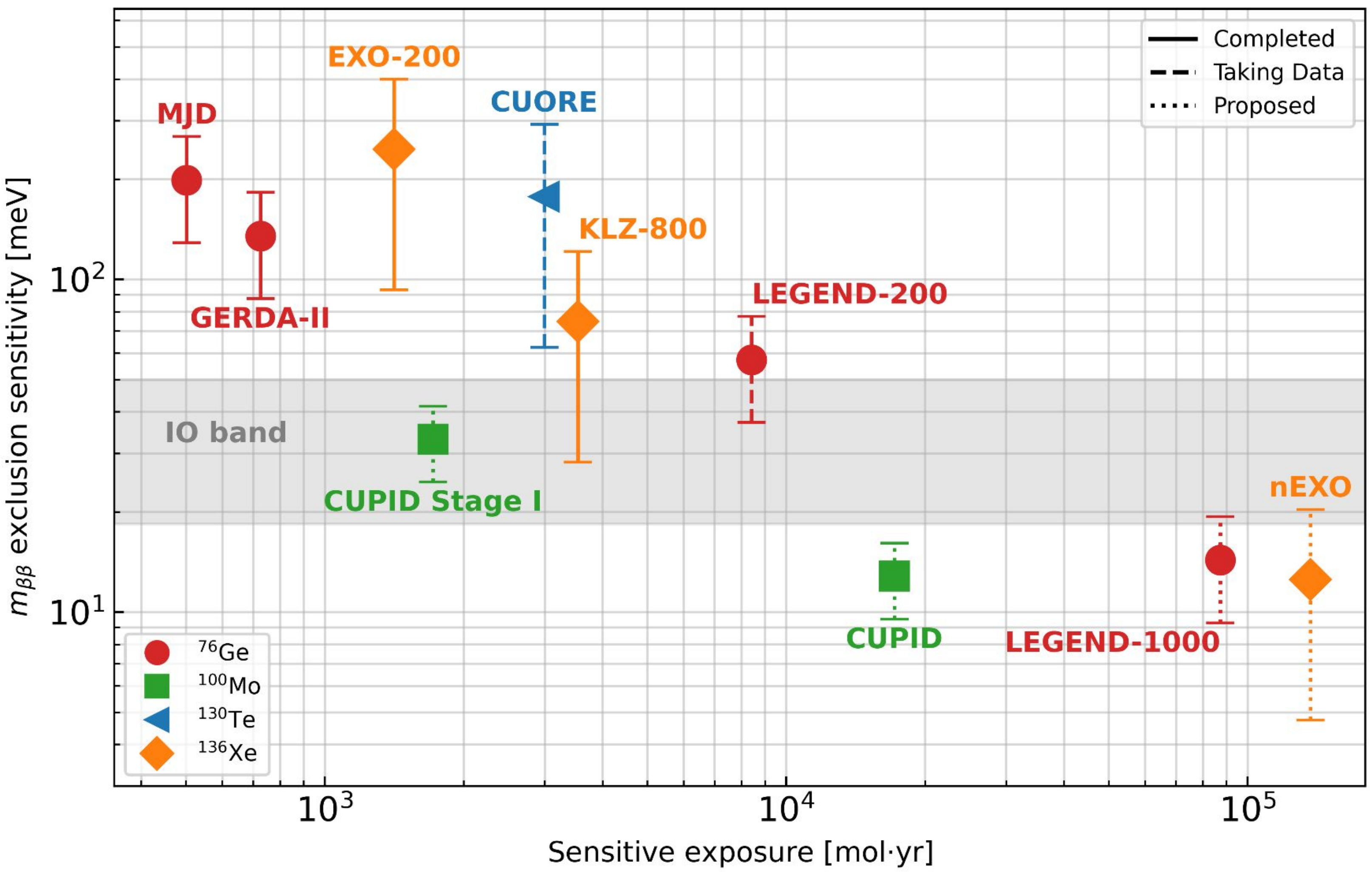
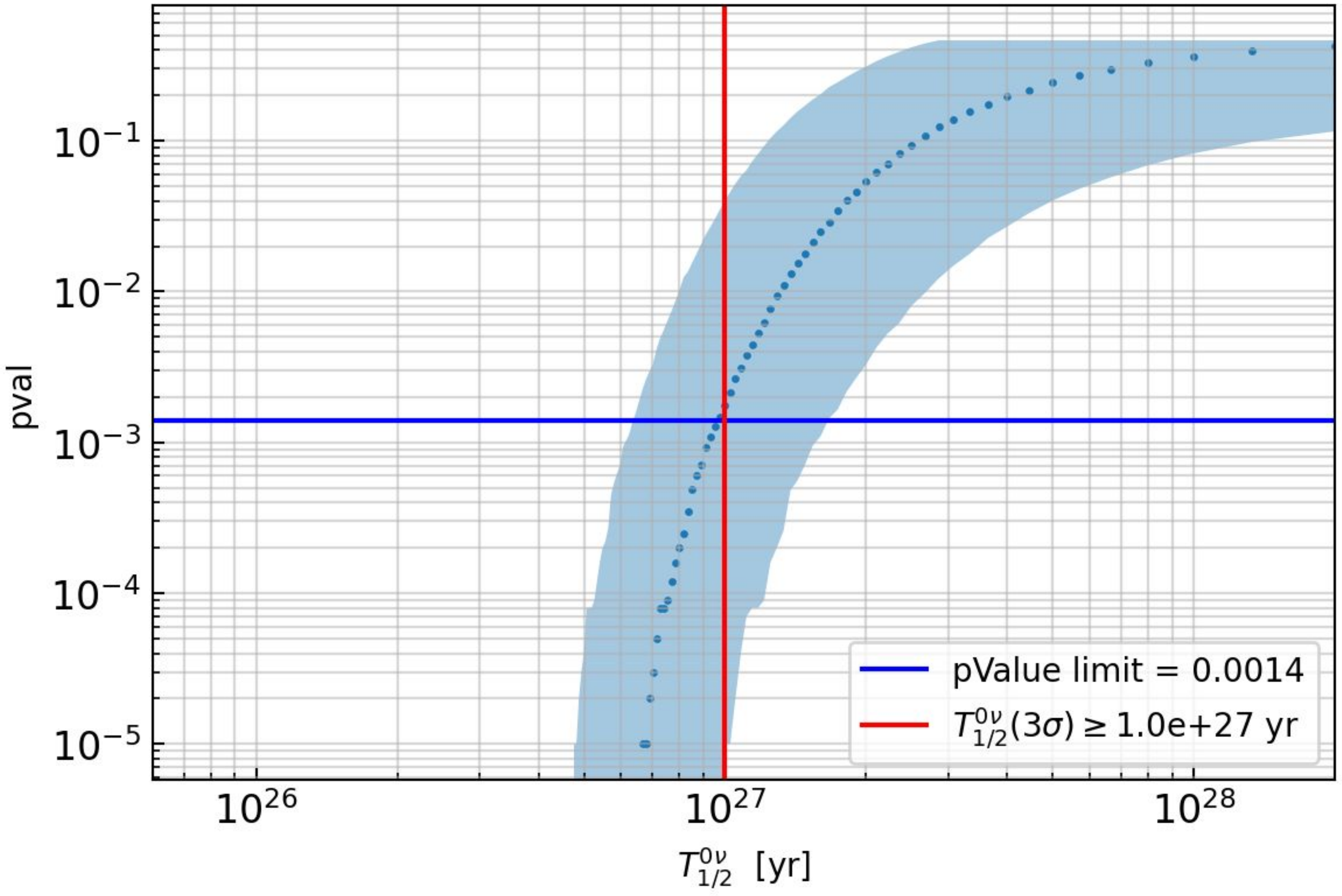


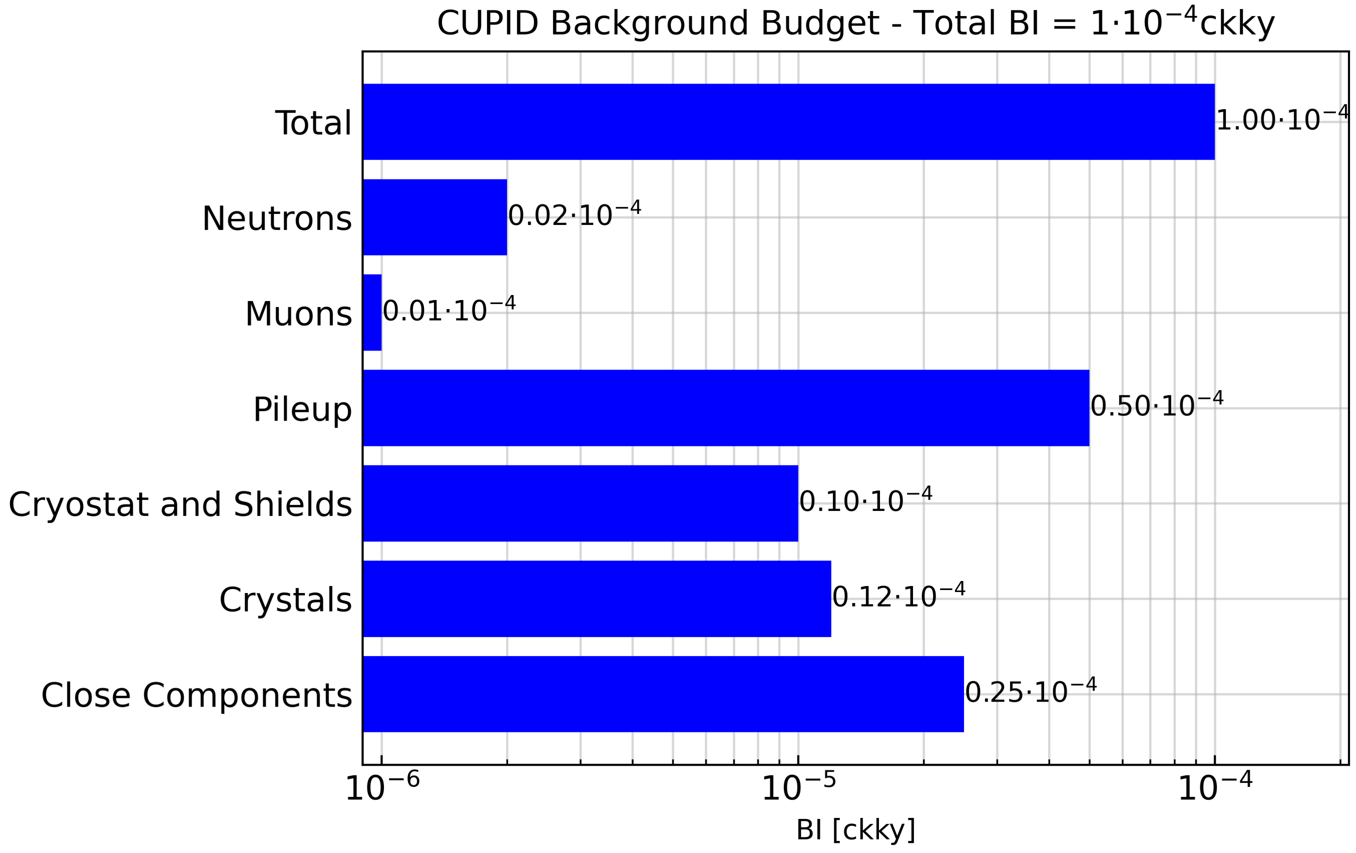
CUPID aims to cover the inverted hierarchy and a fraction of normal ordering

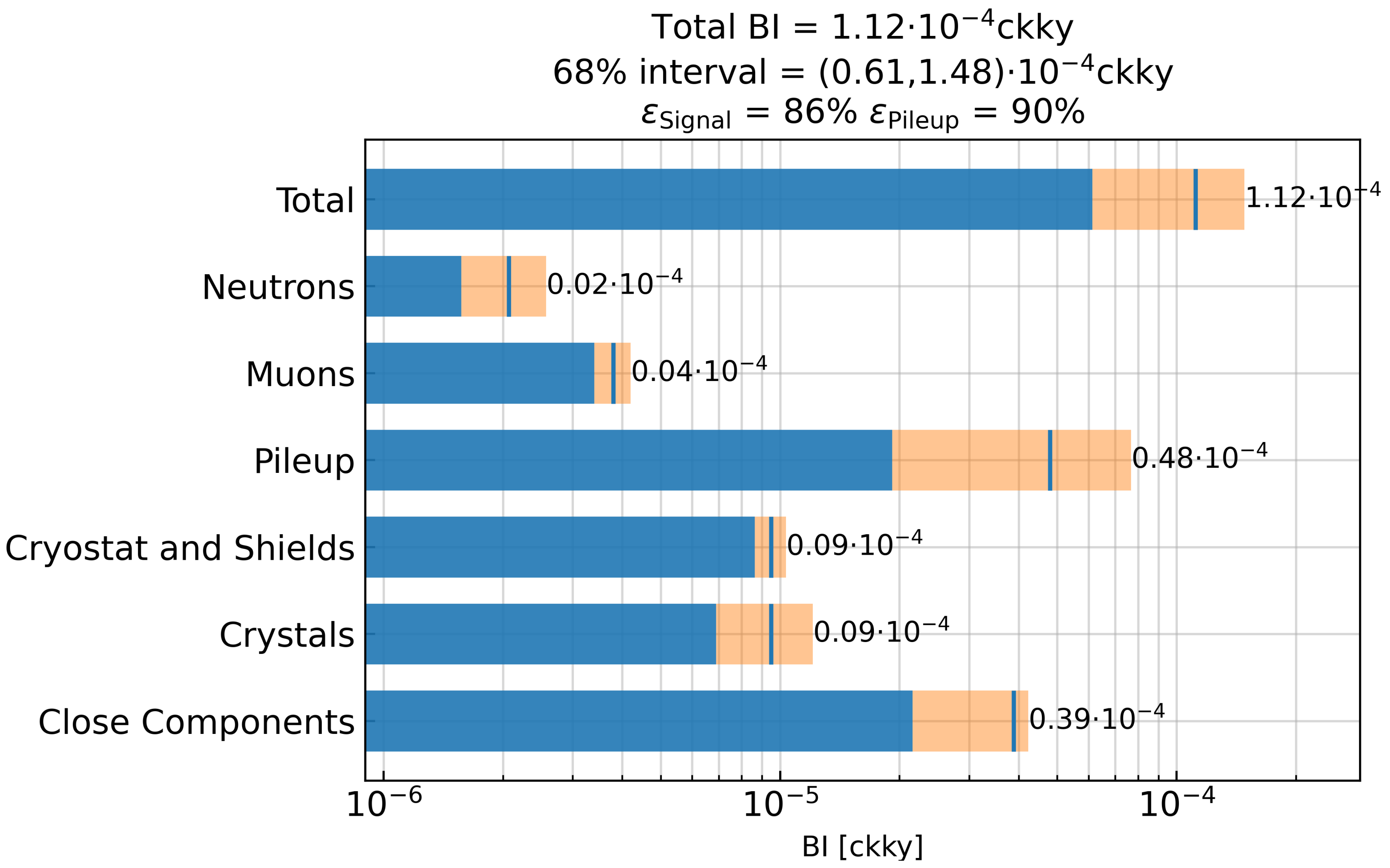
CUPID: High-level Requirements



Parameter	Value
Crystal	$Li_2{}^{100}MoO_4$
Detector mass	450 kg
^{100}Mo mass	240 kg
Energy resolution (FWHM)	5 keV
Background index	10^{-4} counts/(kg*keV*year)
Total $0\nu\beta\beta$ Efficiency (containment × selection)	66%
Livetime	10 years

Background budget and current evaluation



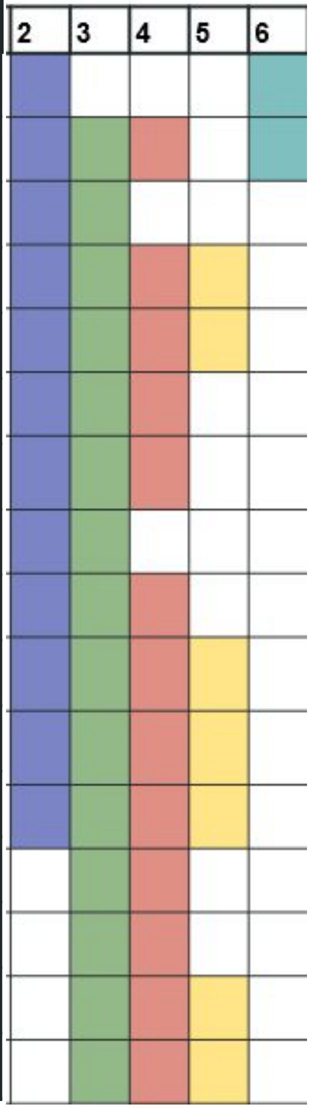


Background budget shows the goals for the experiment and drives requirements
Background evaluation demonstrates the current, data-driven evaluation of the backgrounds and uncertainties for the conceptual design of the experiment

Subsystem Requirements

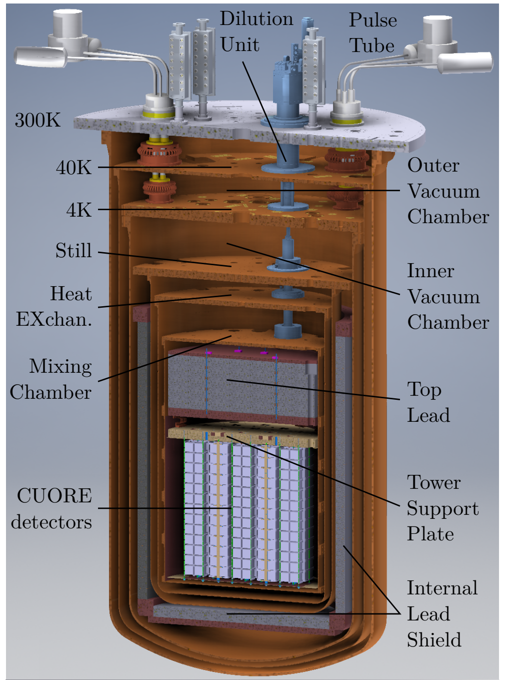
WBS

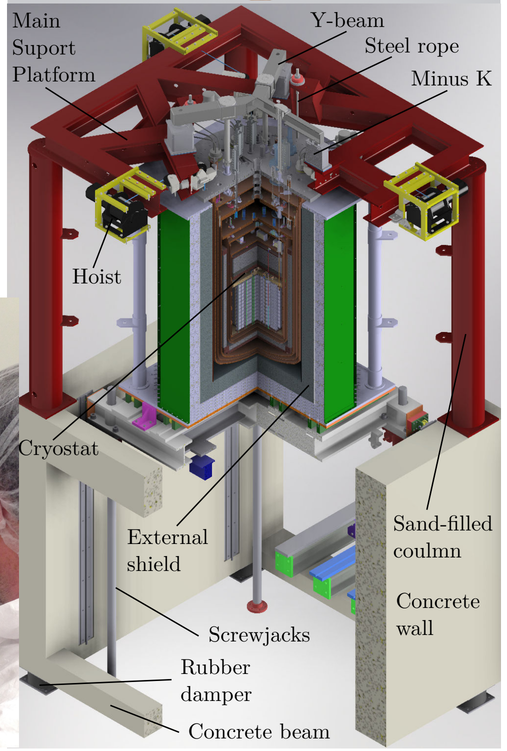
Requirement	Value
Pileup BI (ckky)	5,00E-05
Radioactive BI (ckky)	5,00E-05
Alpha/beta discrimination efficiency	0,996
Light detector rise time [ms]	0,5
Light detector S/N after NTL	60
Detector cooling time (weeks)	6
Minimum achievable operating temperature (mK)	10
Light collection (keV/MeV)	0,36
Combined signal selection efficiency	0,86
Fraction of working LD at the beginning of operation	0,98
Fraction of working HD at the beginning of operation	0,995
Overall detector time resolution @3MeV	0.1 ms
Radon recontamination (nBq/cm^2)	BKG < 1e-5ckky
Dust contamination (particles/m^3)	BKG < 1e-5ckky
Readout total capacitance (pF)	500
Total cross-talk (dB)	-65

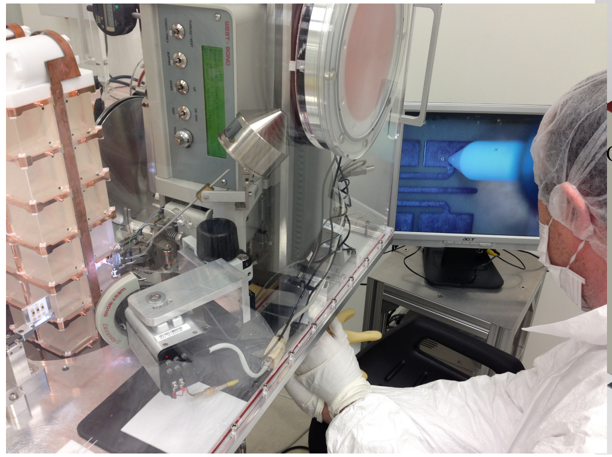


CUPID: technically mature baseline design

- Conservative design, with many parts directly designed, tested, and/or inherited from CUORE
  - CUORE “hut”, Faraday cage
  - Cryogenic infrastructure
  - Detector suspension, vibration isolation
  - Cleanrooms, anti-radon system
  - Detector parts, fabrication, cleaning
  - Sensors (NTD), temperature stabilization (Si heaters)
  - Assembly, storage, installation
  - Slow controls
  - Calibration system (external)
  - Decade of experience

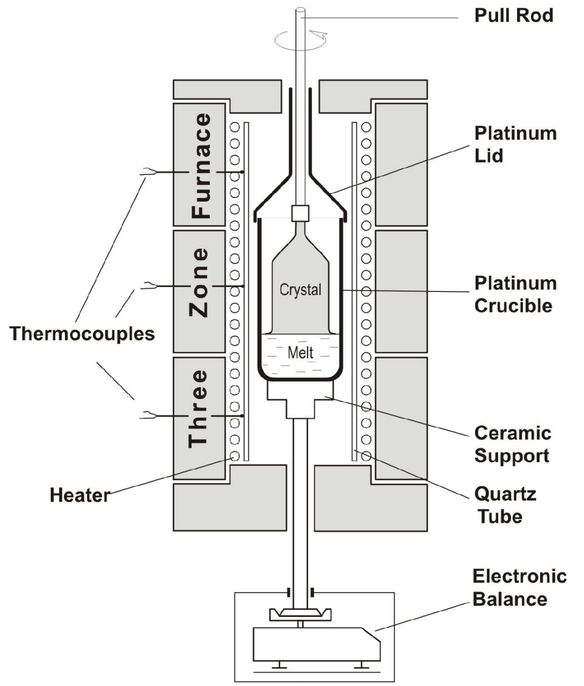


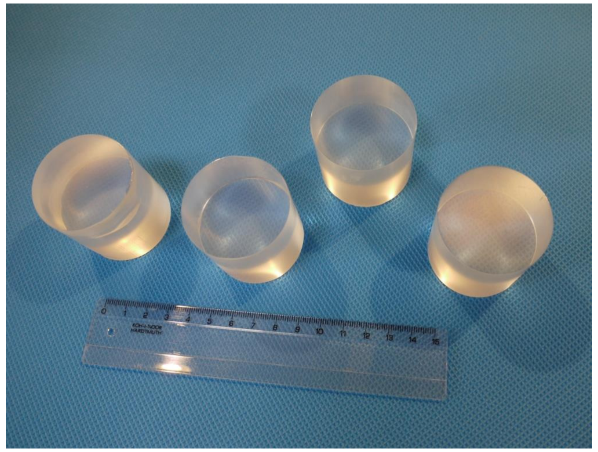


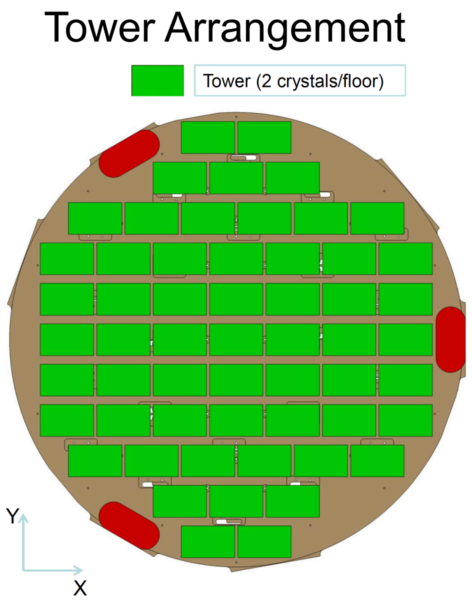


CUPID: technically mature baseline design

- Straightforward scaling from CUORE and CUPID-Mo:
  - – Upgraded cryocoolers (PTs)
  - – Upgraded internal thermalization (reduce vibrations)
  - – Baseline Li_2MoO_4 crystal vendor
  - – Light detector design
  - – Detector wiring
  - – Denser detector packing
  - – Readout electronics, DAQ, trigger
  - – Computing, analysis, simulation tools
  - – QA/QC procedures and protocols
  - – Background mitigation and control





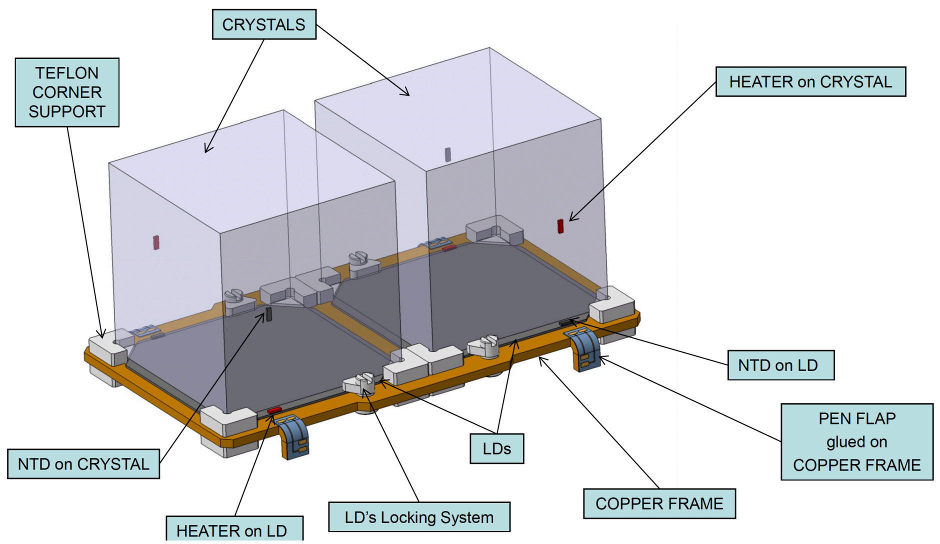


More details in Technical Readiness session

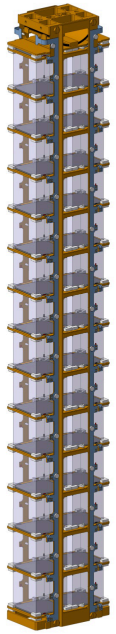
CUPID: technically mature baseline design

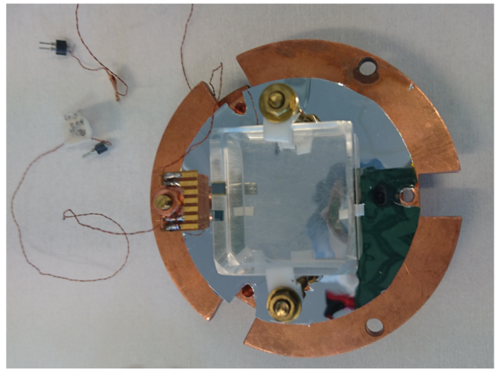
- New components/developments
  - ^{100}Mo isotope, Li_2CO_3 source
  - Streamlined tower design
  - “Bare” crystals without reflective foil
    - Still excellent α rejection, lower backgrounds
  - Light detectors with NTL amplification
  - Muon veto
- Possible alternatives to mitigate risks
  - Conventional tower design
  - Light detector technology
  - Scope of muon veto system

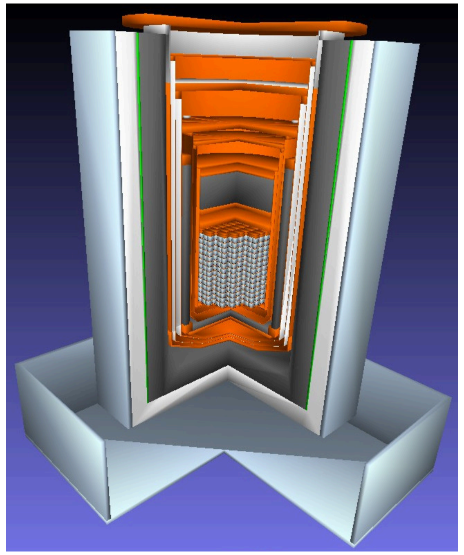
Detector Module



Tower







WBS Structure

CUPID

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

- **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** — US L3: B. Fujikawa (LBNL)
  - **1.01.03 Project Controls** — US L3: G. Zehnder (LBNL)
  - **1.01.04 Project Management & Travel** — US L3: B. Fujikawa (LBNL)
  - **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)
  - **1.01.08 Risk Management** — US L3: E. Imani (LBNL)
  - **1.01.09 Pre-Operation** — IT L3: M. Biassoni (INFN MiB); US L3: B. Fujikawa (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)
  - **1.02.03 LMO Crystal Production** — IT L3: C.Tomei (INFN Roma)
  - **1.02.04 Light Detector** — US L3: V. Singh (UCB); FR L3: K. H. Khalife (IRFU)
  - **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); FR L3: A. Zolotarova (IRFU)
  - **1.02.07 Muon Veto** — US L3: K. Heeger (Yale); US L3 Deputy: J. Torres (Yale)
  - **1.02.08 Neutron Shield** — IT L3: G. Mazzitelli (LNF)
- **1.03 Detector Structure**
  IT L2: L. Cardani (INFN Roma)
  FR L2 : C. Nones (IRFU)
  US CAM: B. Fujikawa (LBNL)
  - **1.03.01 Management**
  - **1.03.02 Detector Structure Design** — IT L3: T. Napolitano (INFN LNF)
  - **1.03.03 PTFE & Copper Parts** — IT L3: C. Tomei (INFN Roma)
  - **1.03.04 Assembly Line** — IT L3: V. Pettinacci (INFN Roma); FR L3: A. Gallas (IJCLab)
  - **1.03.05 Tower Bonding** — IT L3: I. Colantoni (CNR Roma)
  - **1.03.06 Gluing** — FR L3: P. Mas (IRFU)
  - **1.03.07 Parts Cleaning** — IT L3: G. Keppel (INFN LNL)
  - **1.03.08 Storage & Logistics** — IT L3: S. Dell'Oro (UniMiB)
  - **1.03.09 Cryogenic Detector Wiring** — IT L3: E. Ferri (UniMiB)
  - **1.03.10 Tower Assembly** — IT L3: M. Biassoni (INFN MiB)
- **1.04 Host Lab Infrastructure & Cryogenic Systems**
  IT L2: A. D'Addabbo (INFN LNGS)
  US CAM: B. Fujikawa (LBNL)
  - **1.04.01 Management**
  - **1.04.02 Wiring** — IT L3: E. Ferri (INFN MiB)
  - **1.04.03 Clean Rooms** — IT L3: V. Pettinacci (INFN Roma)
  - **1.04.04 Detector Installation** — IT L3: T. Napolitano (INFN LNF)
  - **1.04.05 Cryostat Upgrade & Commissioning** — IT L3: A. D'Addabbo (INFN LNGS)
  - **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 (Pitt)
  - **1.04.08 Ambient Control** — US L3: J. Wilhelmi (Yale); FR L3: P. Loaiza (IJCLab)
  - **1.04.09 CUPID/CUORE Joint Operation** — IT L3: P. Gorla (INFN LNGS)
  - **1.04.10 Optical Injection System** — IT L3: S. Copello (INFN Pavia)
- **1.05 Data Readout**
  US L2: B. Welliver (UCB)
  US CAM: T. Stezelberger (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** — FR L3: D. Baudin (CEA)
  - **1.05.04 Electronics: Filters & Digitizers** — US L3: H. Huang (UCLA)
  - **1.05.05 SW DAQ & Trigger** — US L3: B. Welliver (UCB)
  - **1.05.06 Slow Control & Monitoring** — US L3: P.T. Surukuchi (Pitt)
  - **1.05.07 Comp.& Data Storage** — US L3: B. Welliver (UCB)
  - **1.05.08 Data Readout Integration** — IT L3: P. Carniti (UniMiB); US L3: T. Stezelberger (LBNL)
- **1.06 Background Control**
  IT L2: L. Pagnanini (GSSI)
  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: L. Marini (INFN LNGS); US L3: K. Alfonso (VT); FR L3: E. Olivieri (IJCLab)

US Scope

US responsibility
Italy responsibility
France responsibility

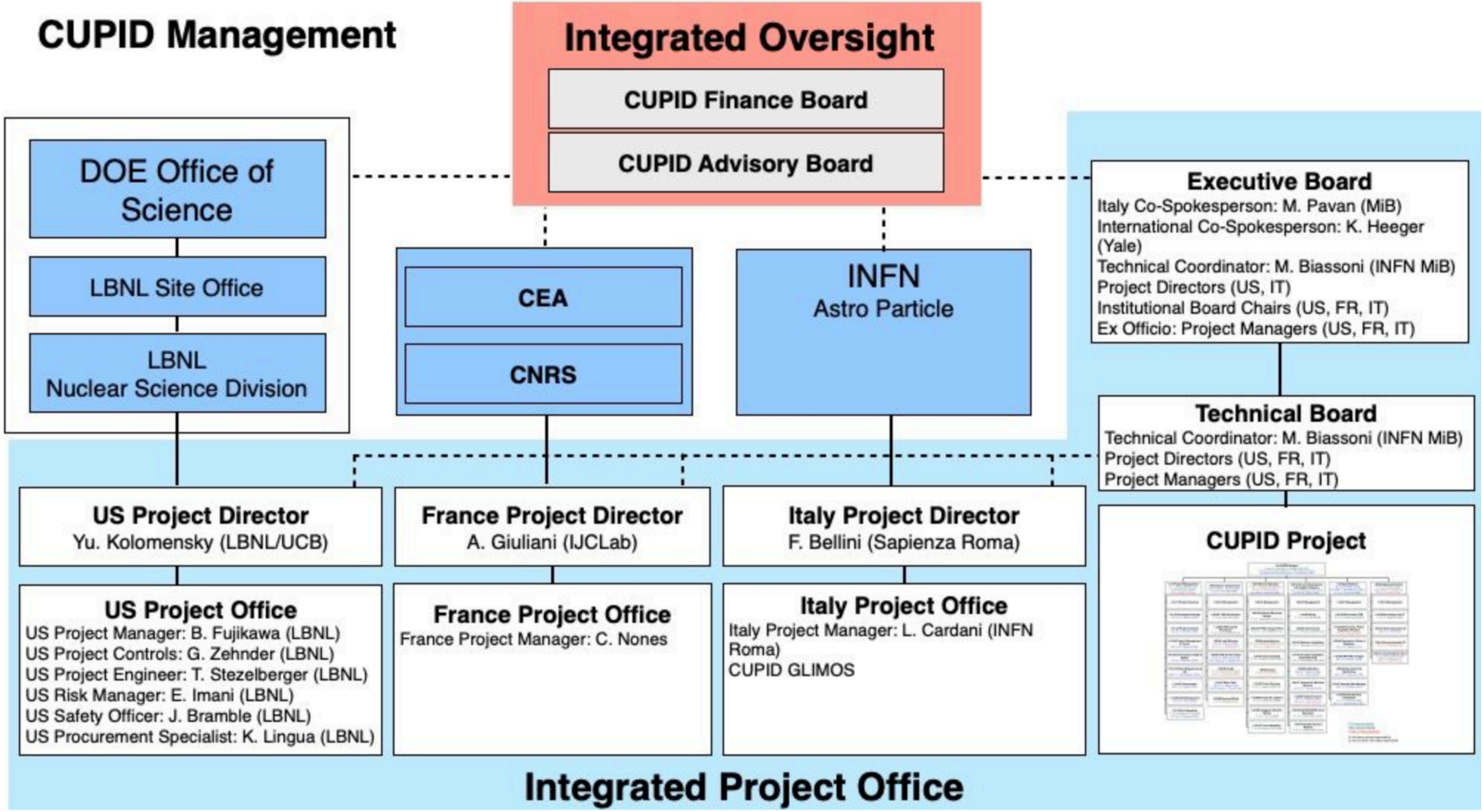
L3 first name: primary responsibility
L3 second name: secondary responsibility

Experienced team (CUORE+CUPID-Mo)
CUORE experience as international project
Clean separation of scope between US and EU

Scope Division

- Guiding principles:
  - Leverage scientific and technical strength of each participant
  - ~40:60 split of US:Italy contributions to M&S budget driven by the expected ratio of scientific personnel
  - Respect boundary conditions within each country
  - Cost-effective, technically conservative, fiscally responsible design
- The scope of the project has evolved since CDR review, reflecting the re-assignment of responsibilities for the isotope/crystal purchase
  - INFN assumes responsibility for the entirety of the enriched crystal procurement
  - US assumes limited financial responsibility for the remaining CUPID scope and operations, up to the 40:60 split of M&S expenses
- What this means in practice:
  - US agrees to provide financial support of some part of the CUPID scope where INFN leads technical developments
  - US assumes a large fraction of operational support, to make up the difference in 40:60 split
  - US exposure is limited by the overall cost of the isotope/crystals, to be finalized when INFN contract is signed. US exposure will be documented by the MOUs between DOE/INFN and LBNL/LNGS

Organizational structure



Organizational principles

- Fully integrated project management structure
  - TCB for coordination of technical decisions, management of construction
  - EB for coordination of strategic decisions
  - Integrated project controls (operated at LBNL)
- Separate budget management and reporting responsibilities
  - Direct reports to individual funding agencies
  - Separate management of scope and contingency within each country
- Coordination between funding agencies, joint technical reviews (Finance Board, CUPID Advisory Board)
  - Will eventually need to be formalized by MOUs (DOE-INFN and LBNL-LNGS)

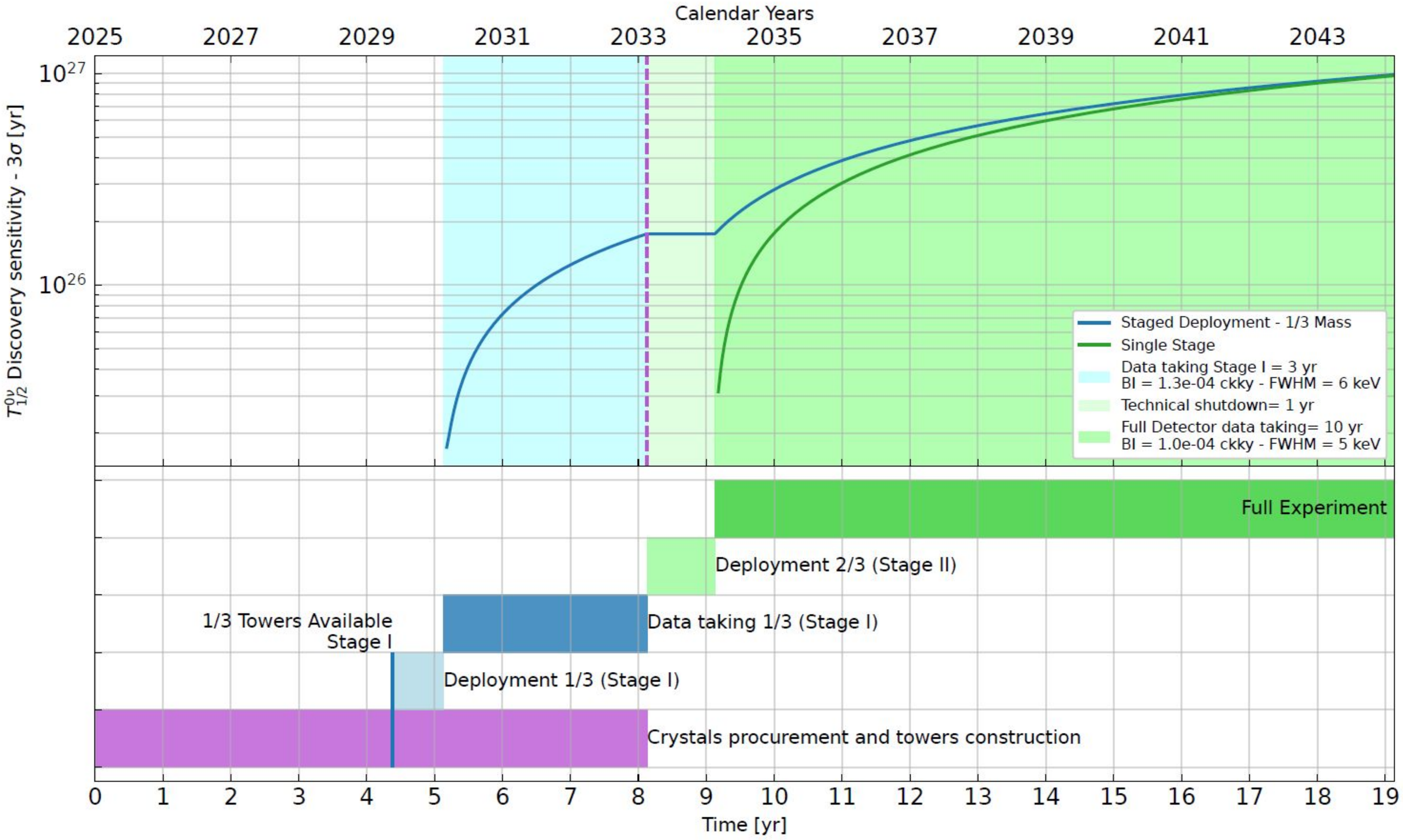
Experienced Project Office

US Project Office	NP project experience
US Project Director: Yu. Kolomensky (LBNL/UCB)	CUORE, E158
US Project Manager: B. Fujikawa (LBNL)	CUORE, KamLAND
US Project Controls: K. Minor, G. Zehnder (LBNL)	ALS-U
US Project Engineer: T. Stezelberger (LBNL)	GRETA, IceCube
US Safety Officer: J. Bramble (LBNL)	NSD Safety Coordinator
US Procurement Specialist: K. Lingua (LBNL)	Extensive experience

Most of L2 and L3 managers have CUORE experience. Healthy mix of senior (L2) and junior (some L3) collaborators in line management positions.

Logistical support from Export Controls, Shipping/Receiving, Travel office
Advice and oversight by LBNL Project Management Office (John Corlett)
Support by NSD leadership and PSA ALD

Schedule with Staged Deployment



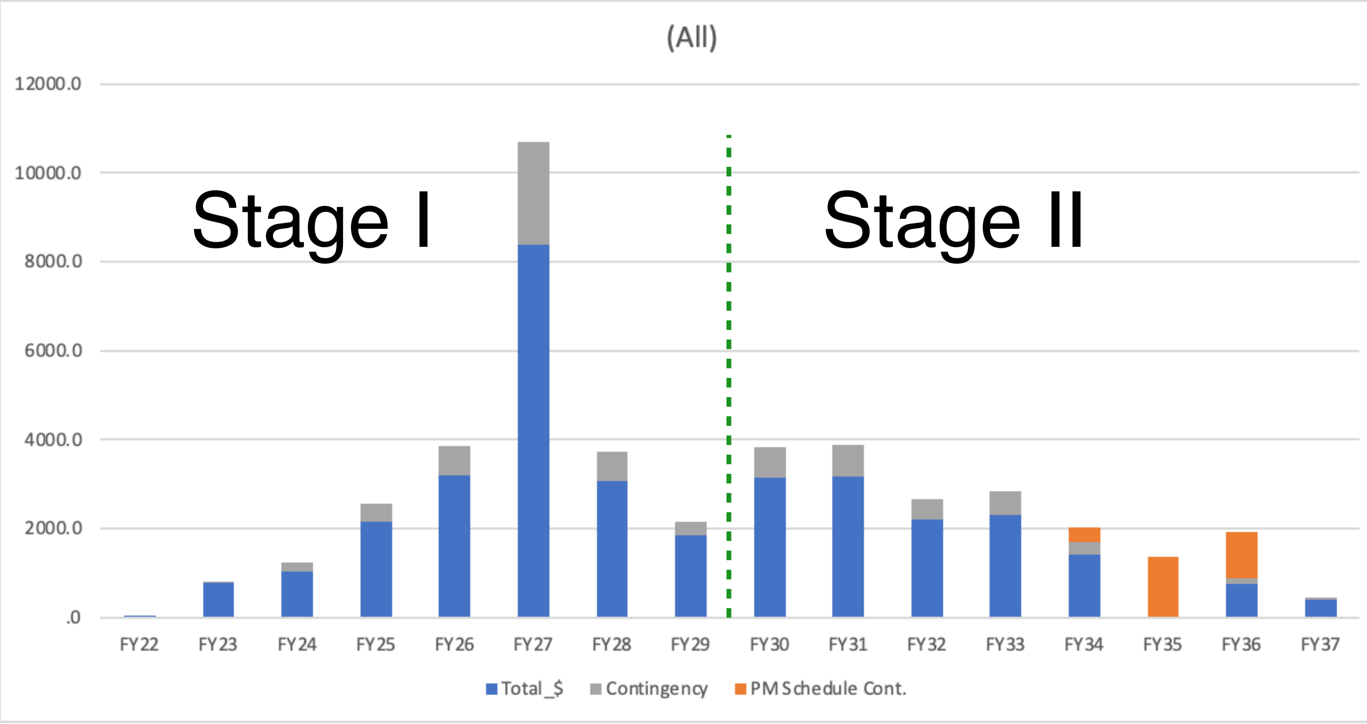
Technically limited schedule

Early deployment of ~1/3 of the detector:

- Progress towards LRP-23 goals before the end of the decade
- Mitigates risks
- Helps maintain collaboration expertise and workforce training

Budget summary, cost range

- Point estimate: $44.1M
  - Includes bottoms-up contingency, risk-based schedule contingency
- Cost range: $39M-$49M
  - Low end: reduced scope (e.g. NSF contributions)
  - High end: full project outside of 413.3B (increased burdens)



Row Labels	Total k$	W. Contingency
US	33885.4	41314.6
Stage I	20487.0	25086.4
Stage II	13398.4	16228.2
Grand Total	33885.4	41314.6

Summary

- CUPID aims to discover (or rule out) neutrinoless double beta decay in the parameter space consistent with the Inverted Ordering of neutrino masses
- CUPID project is technically conservative and mature
- Collaboration and the project team are experienced and capable

Charge

1. Is the project's scope sufficiently well-defined and technically mature to support the preliminary cost and schedule estimates?
   - YGK, BKF, KM talks, drill-down tomorrow
2. Is there sufficient detailed information available and documented to support the current TPC Point Estimate and range?
   - KM talk, BOEs, drill-down tomorrow
3. Are the estimates accurate, credible, and realistic for this stage of the project?
   - KM talk, BOEs, drill-down tomorrow
4. Is the basis for the proposed low and high cost range reasonable? Is the proposed schedule contingency between early finish and late finish reasonable for this stage of the project?
   - YGK, BKF, KM talks, drill-down tomorrow
5. Are the project risks identified, reasonable, and is cost contingency adequate for this stage of the project?
   - BKF talk, Risk registry
6. Is the schedule reasonable, does it identify a critical path, and include sufficient detail for this stage of the project?
   - KM talk
7. Have Lessons Learned from similar projects (i.e. CUORE, LZ, and others) been considered?
   - BKF talk