CUPID:
CUORE **U**pgrade with **P**article **ID**

Lindley Winslow
CUPID Institutional Board Chair
L2 Manager - Detector Components
MIT

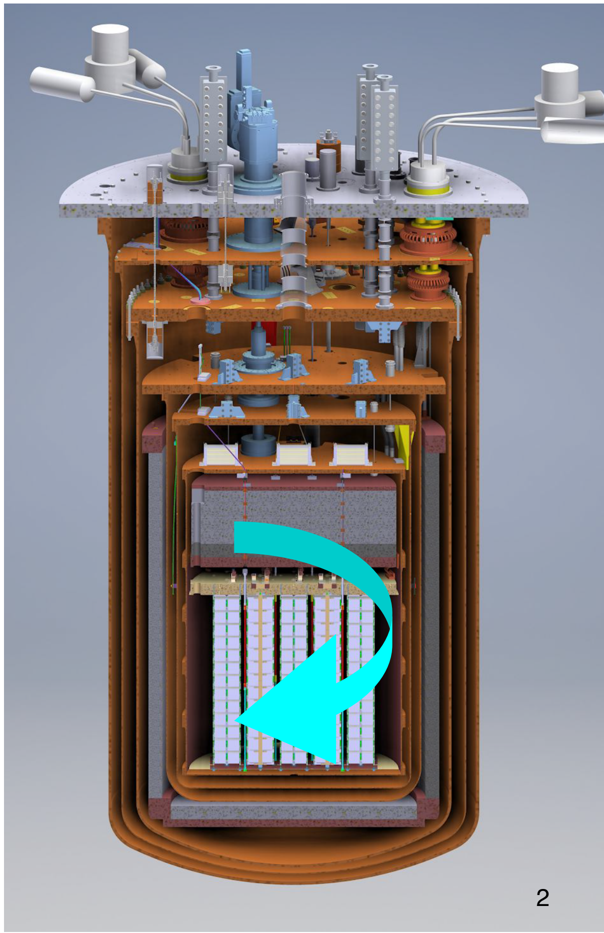
CUPID Concept

Replace CUORE detector array of TeO_2 with new one, based on Li_2MoO_4

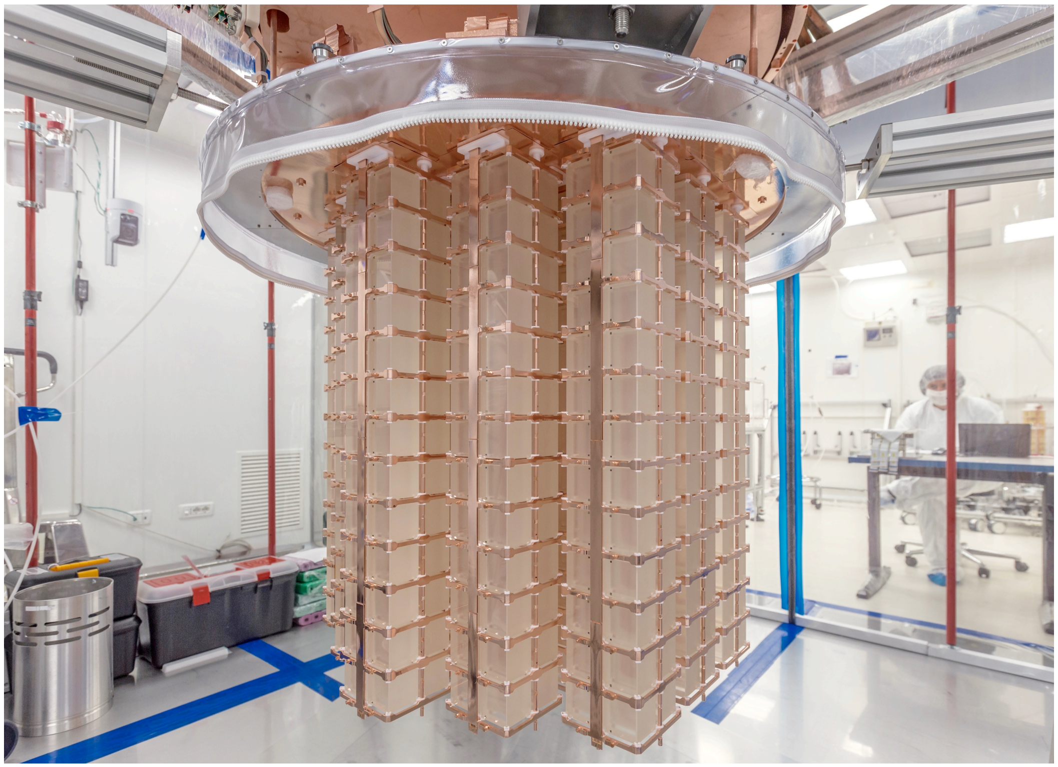
Same mass scale as CUORE: Build on experience in existing cryostat, with improved technology

Existing cryogenic infrastructure: Was challenging for CUORE, now an established technology.

Additional detector functionality: particle identification through light read-out, 3 times higher # of channels.



CUORE in Person



The construction and now stable operation (>90% livetime) of the largest 10 mK refrigerator in the world is huge accomplishment.

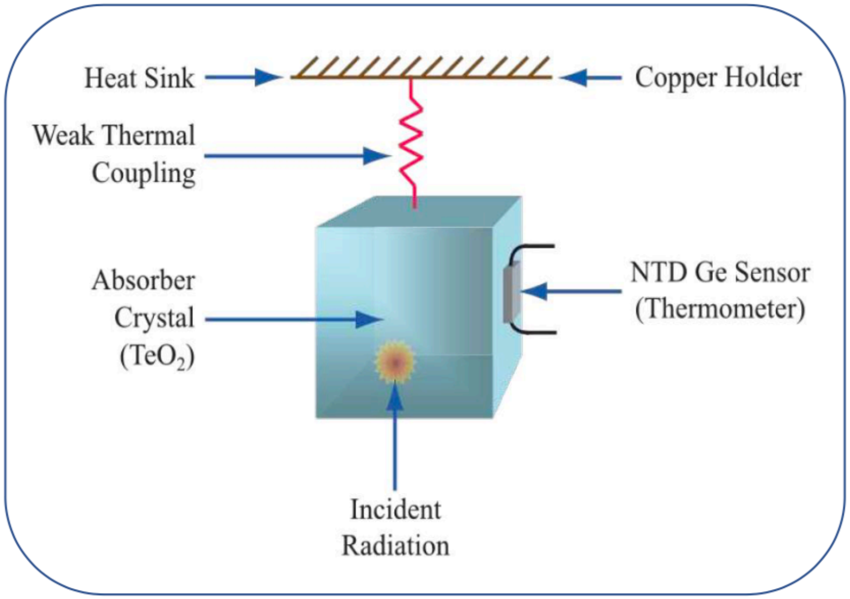
CUORE in Person

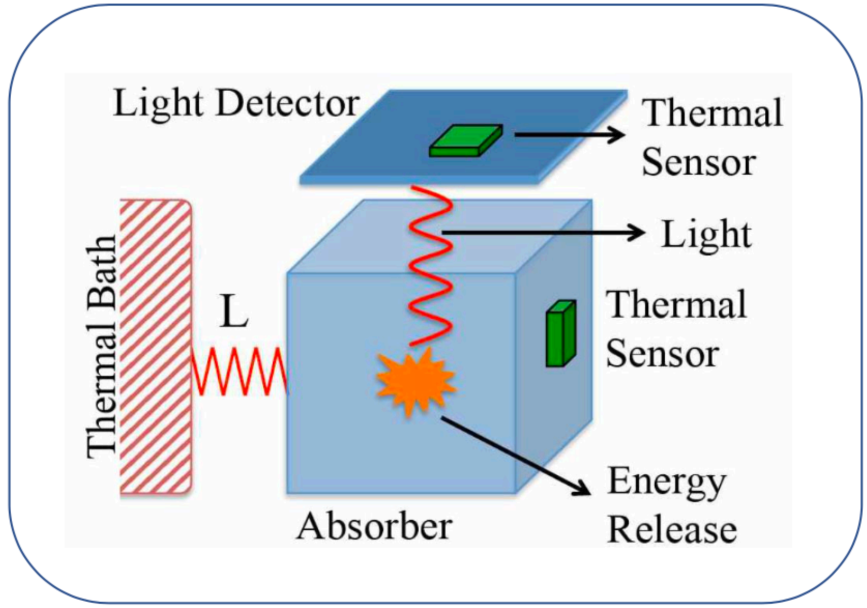
The CUPID team and CUORE teams are highly overlapping and excited to realize the next generation experiment

CUPID Technology

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

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





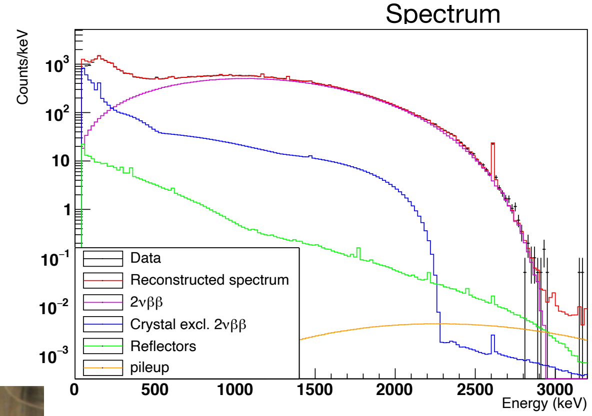
No PID
Q = 2527 keV **< 2615 keV**

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

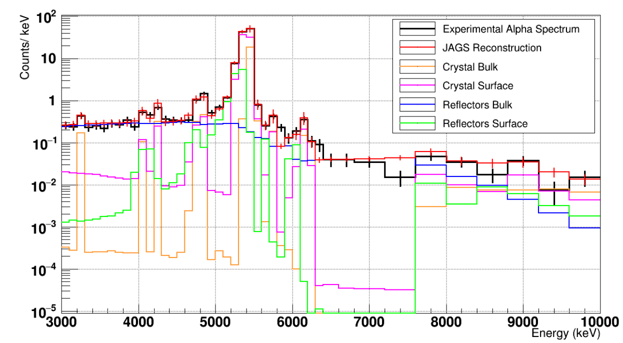
Highlight: CUPID-Mo Demonstrator

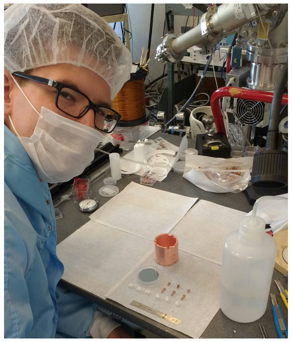
- French-led Demonstrator operating in LSM
- 20 200g $Li_2{}^{100}MoO_4$ scintillating bolometers (97% enriched)
- PID allows separation of α events from β/γ events

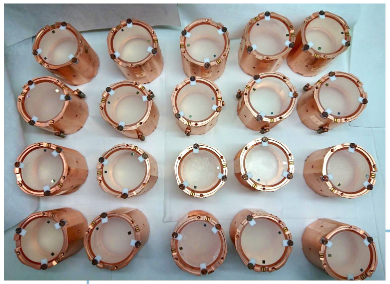
CUPID-Mo β/γ Spectrum

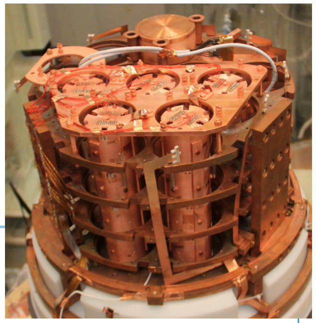


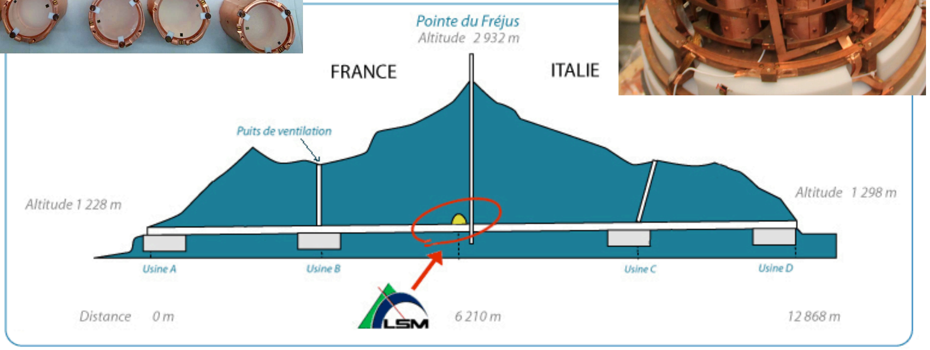
CUPID-Mo α









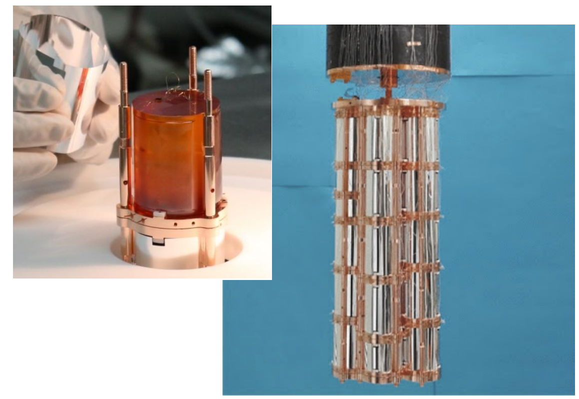


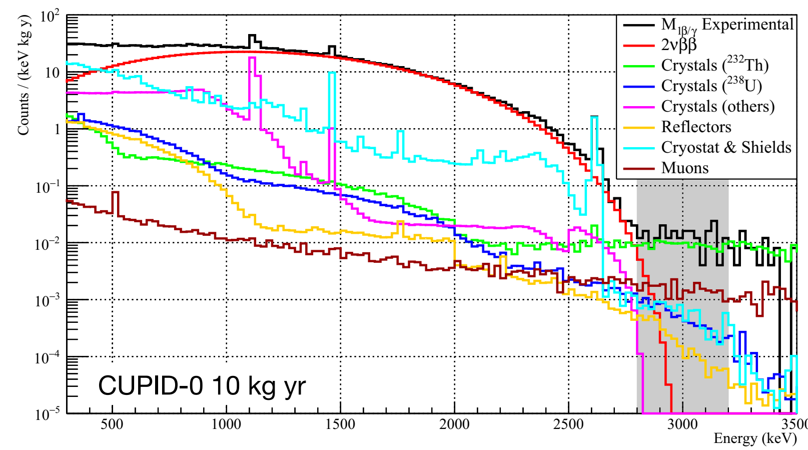
MIT Grad Student:
Joe Johnston

Highlight: CUPID-0 Demonstrator

- Italian-led Demonstrator Operating in LNGS
- 26 400g $Zn^{82}Se$ scintillating bolometers (97% enriched)
- PID allows separation of α events from β/γ events
- Observed significant background in the ROI
  - Mostly due to crystal contaminations
  - Indicates issues with ZnSe purification and growth

➡ CUPID-0 background model is a demonstration of the background model reconstruction technique, but not relevant for extrapolating to CUPID
  - CUPID is not using ZnSe bolometers
  - CUPID-Mo is the relevant comparison



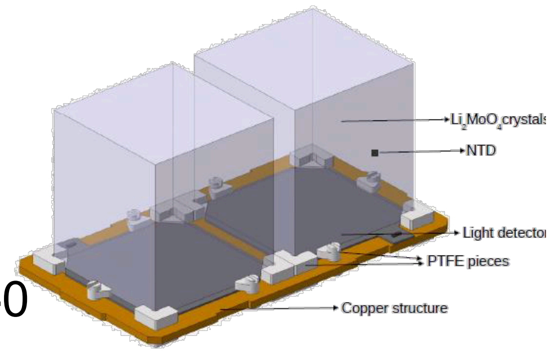


CUPID Detector

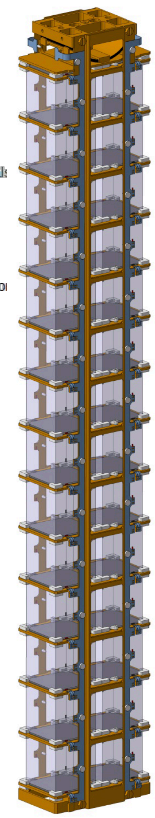
Single Detector

$Li_2{}^{100}$MoO4, 45x45x45 mm, 280 g

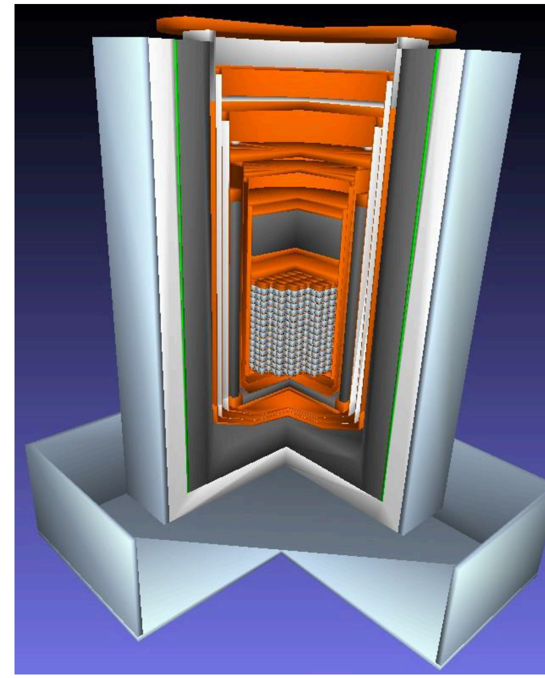
Ge light detector as in the demonstrators, CUPID-Mo, CUPID-0

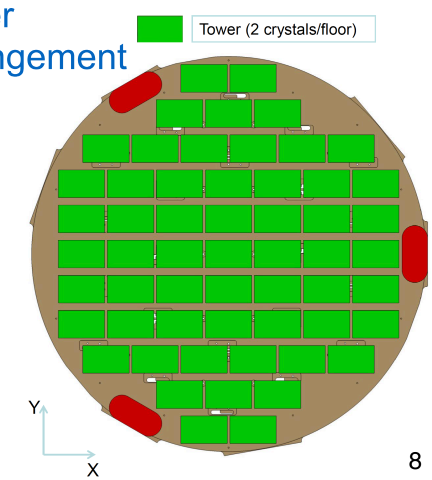


Gravity stacked structure
Crystals thermally interconnected



Tower





Tower Arrangement

Detector Array

~240 kg of ^{100}Mo with >95% enrichment

~1.6.10^{27} ^{100}Mo atoms

57 towers of 14 floors with 2 crystals each, 1596 crystals

Opportunity to deploy multiple isotopes, phased deployment

CUPID (CUORE Upgrade with Particle Identification)

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

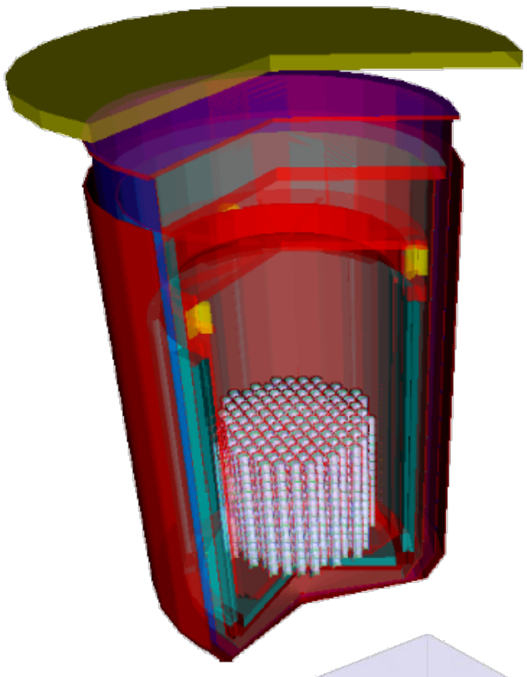
favorable NME

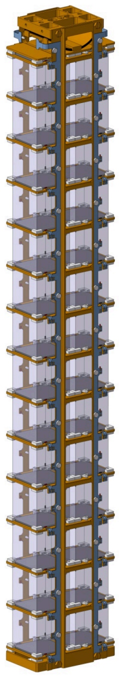
Exploit Particle ID using scintillation bolometer technique
Technique robustly demonstrated by CUPID-0 and CUPID-Mo

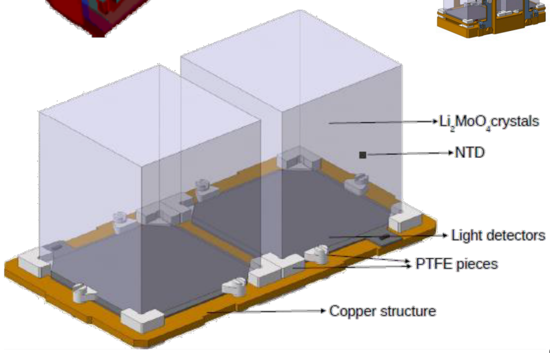
Reuse **proven CUORE cryogenic infrastructure** at LNGS for a cost-effective deployment

Add external muon veto, improved neutron shield

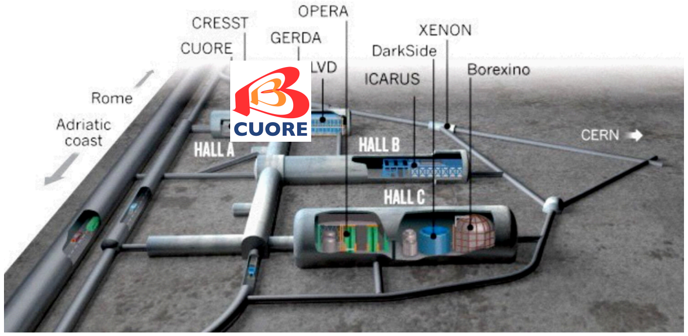
Scalable to 1-ton scale (CUPID-1T) technically possible

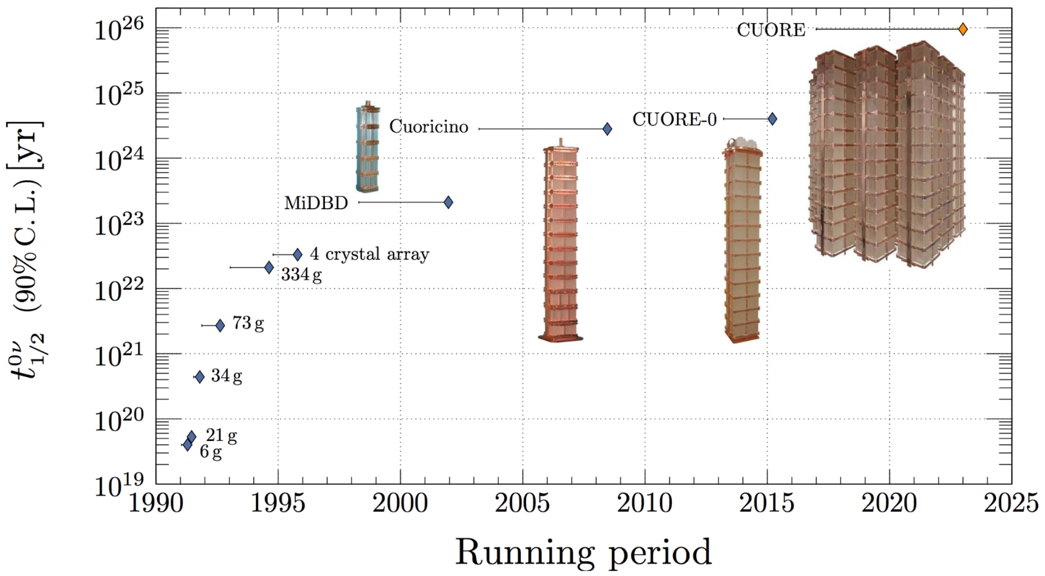






Collaboration at LNGS



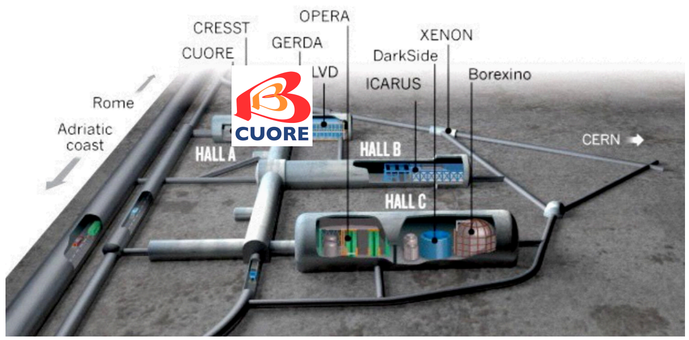


CUPID is next step in a series of bolometric experiments at LNGS: Cuoricino, CUORE, CUPID

Collaboration has worked at LNGS for many years.

Based on Established Italian-US partnership.

LNGS as Host Lab

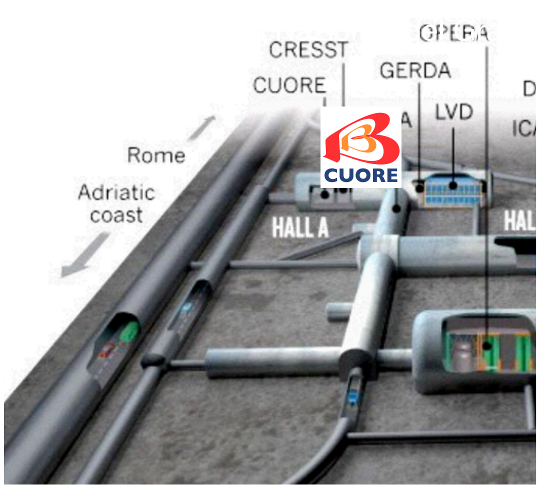


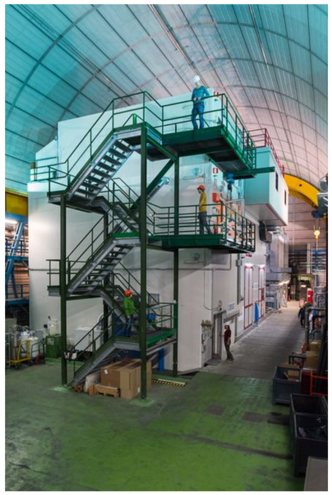
Strong support from the Lab in terms of services like ICP-MS, γ-spectroscopy, electronics, cryogenics, clean rooms, etc

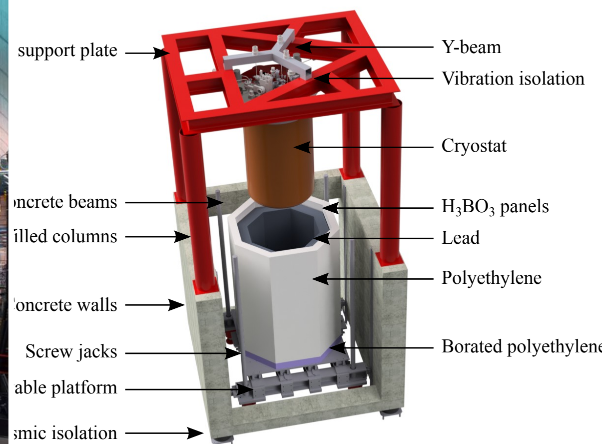
LNGS Scientific Committee gave its **scientific approval in September 2020.**

CUPID is allowed to use **underground space and the CUORE infrastructure.**

Established Site and Infrastructure





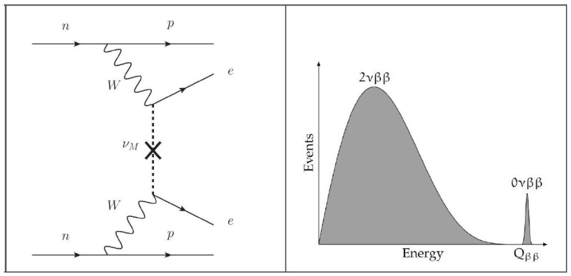


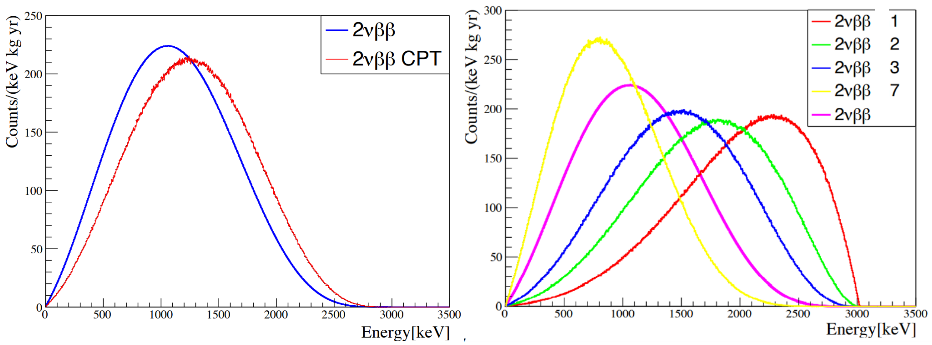
CUPID is extremely well-leveraged and cost-effective:

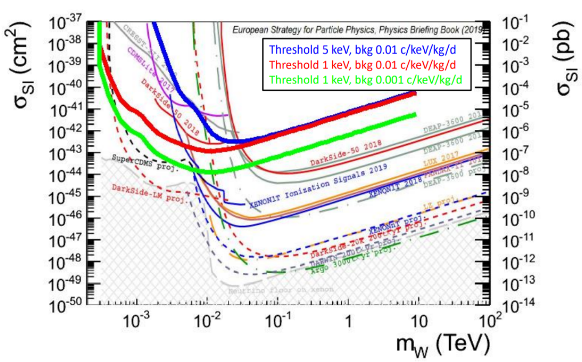
Existing experimental site, unique cryogenic infrastructure.

LNGS provides technical and user support.

CUPID Science Program







Search for 0νββ decay

Precision two-neutrino double beta decay

$2\nu\beta\beta$ and $0\nu\beta\beta$ decays to excited states

Majoron-emitting decays

Tests of Lorentz invariance and CPT violation

Tests of fundamental principles

- Electric charge conservation
- Verification of the Pauli exclusion principles

Tri-nucleon decay and baryon number conservation

Light dark matter searches

Supernova neutrino searches

Solar axion searches

Millicharged particles

All topics potential papers and student theses

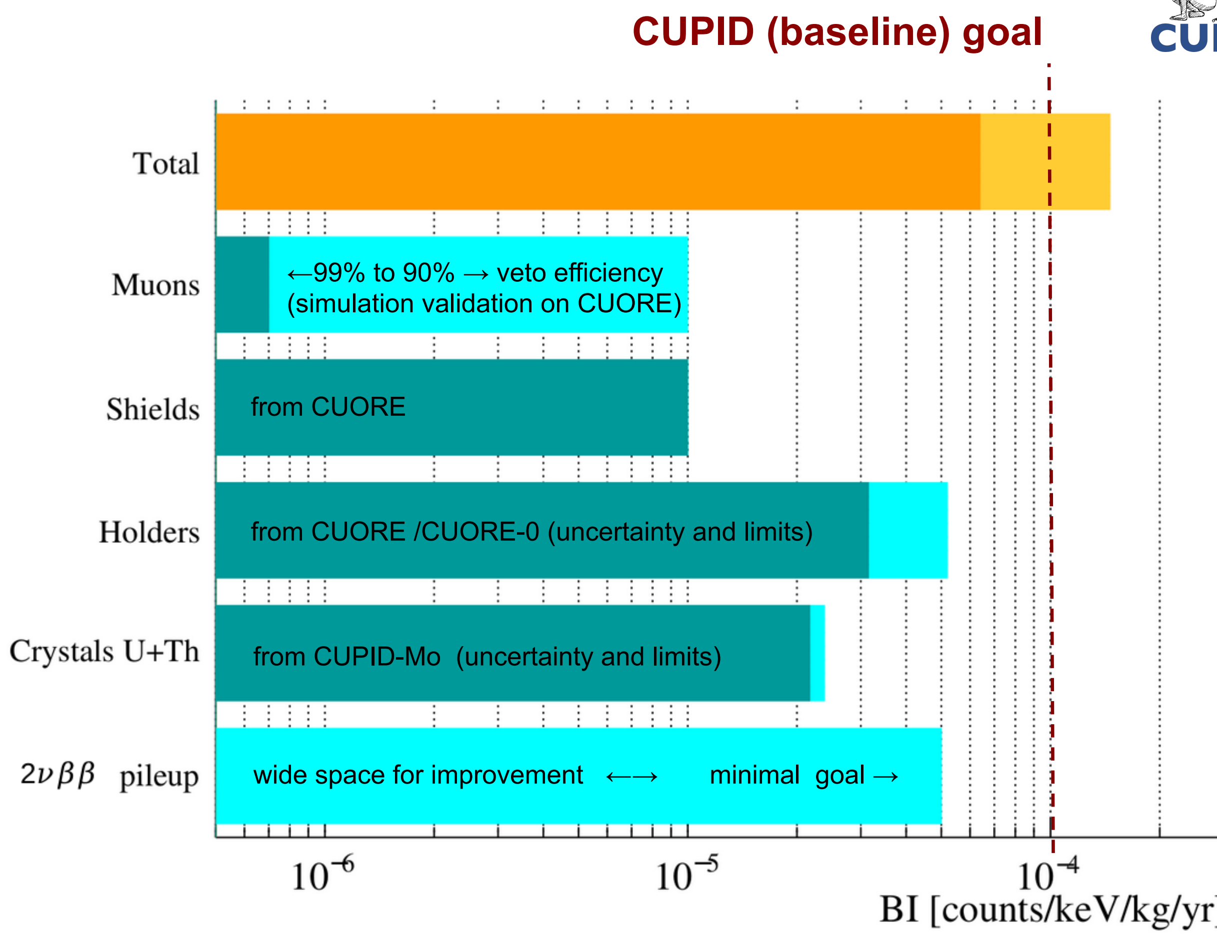
Background Budget

Data-driven background model

- validated in multiple experiments
- measurements/limits for all materials to be used in CUPID

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

- demonstrated required crystal purity levels
- holders U/Th contamination levels achieved in CUORE are sufficient for CUPID
- contamination in cryogenic shields is well understood
- pileup background is well understood and we have several well defined paths to achieve this



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

Background from ^{100}Mo 2vββ Pileup

^{100}Mo $2\upsilon\beta\beta$ half-life ~ 7 x 10^{18} yr

rate ~ 3 mHz/crystal

pile-up events may populate the 0vββ ROI

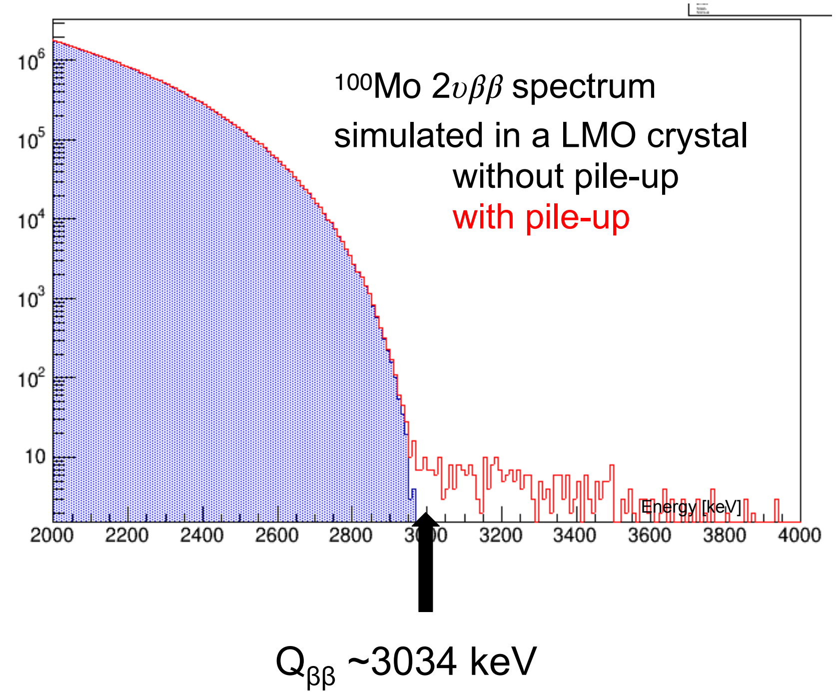
Pile-up discrimination depends

LMO and light detector risetime and S/N

read-out & DAQ band-width

noise (vibration reduction)

analysis algorithms



demonstrated	**< 1×10^{-4} counts/(keV·kg·yr)**
goal (test on-going)	< 0.5×10^{-4} counts/(keV·kg·yr)

CUPID Sensitivity to 0νββ

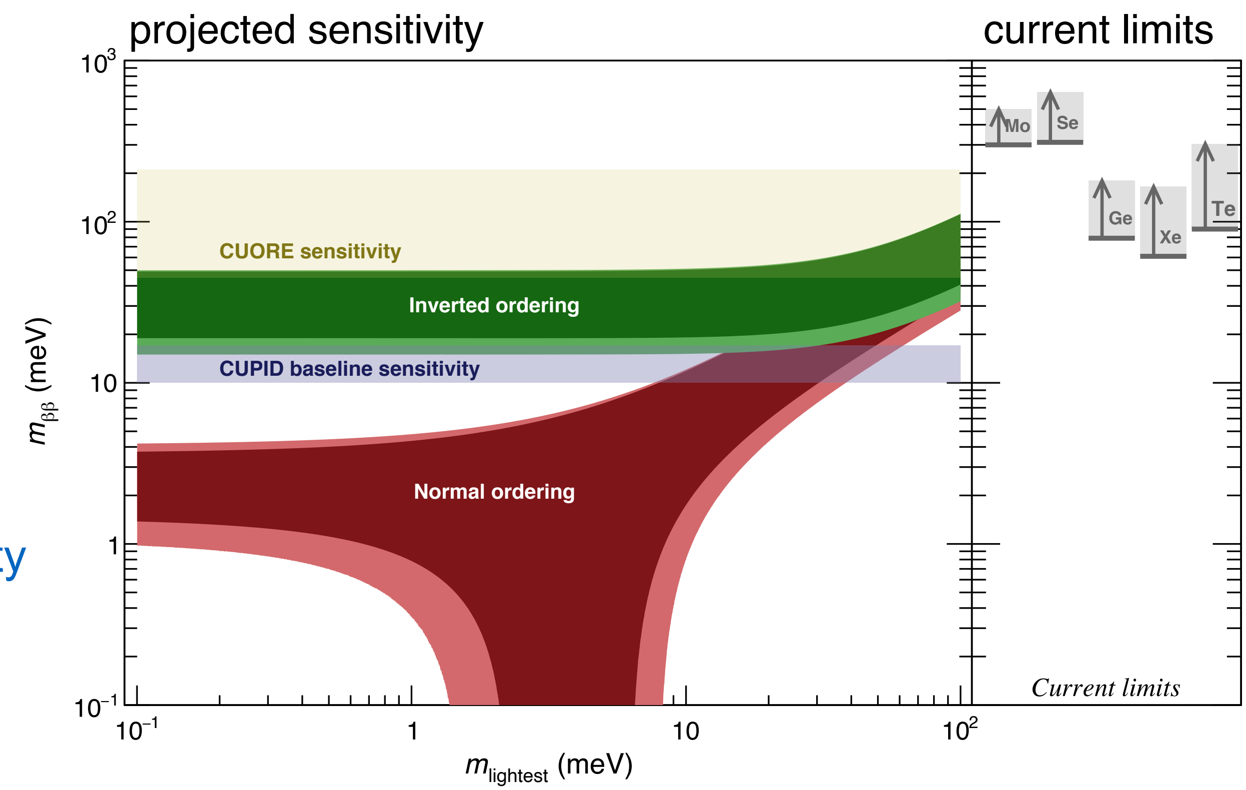
CUPID Baseline

- Mass: 472 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo)
- **10** yr runtime
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr

CUPID Baseline Discovery Sensitivity

$T_{1/2}$ > **1.1×10^{27} yrs (3σ)**

$m_{\beta\beta}$ ~ **12-20 meV**



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

CUPID Sensitivity to 0νββ

Baseline - Ready to Go

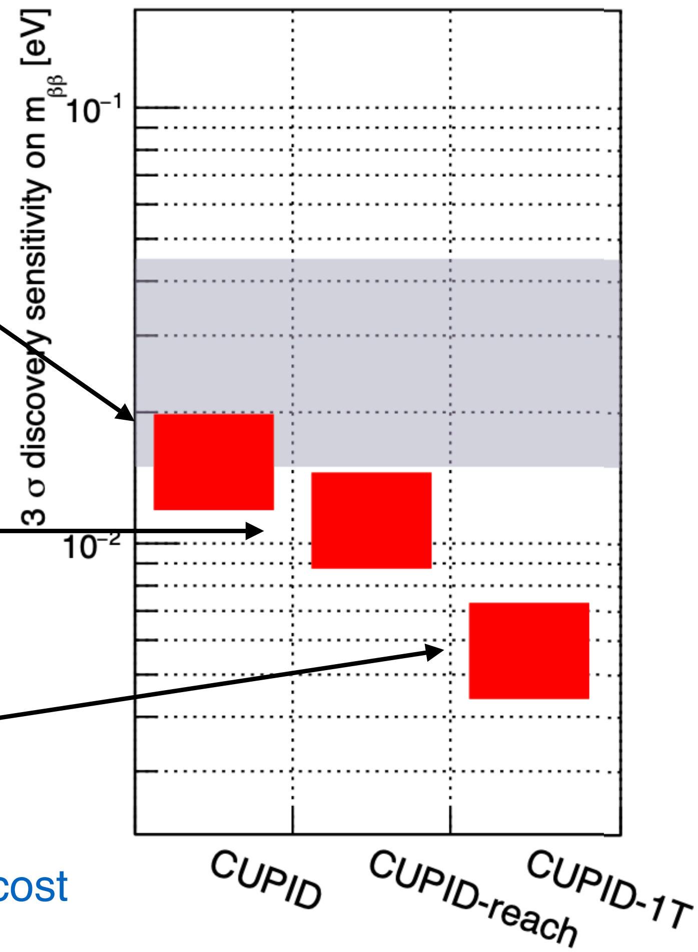
- Mass: 450 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$ (^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr
- Discovery sensitivity **$T_{1/2} > 1.1\times10^{27}$ yr (3σ)**
- Conservative, limited R&D

Reach

- R&D for further background reduction by radio purity and reduce pileup background
- Discovery sensitivity **$T_{1/2} > 2\times10^{27}$ yr (3σ)**

1-Ton - Quantum Enabled, Normal Hierarchy

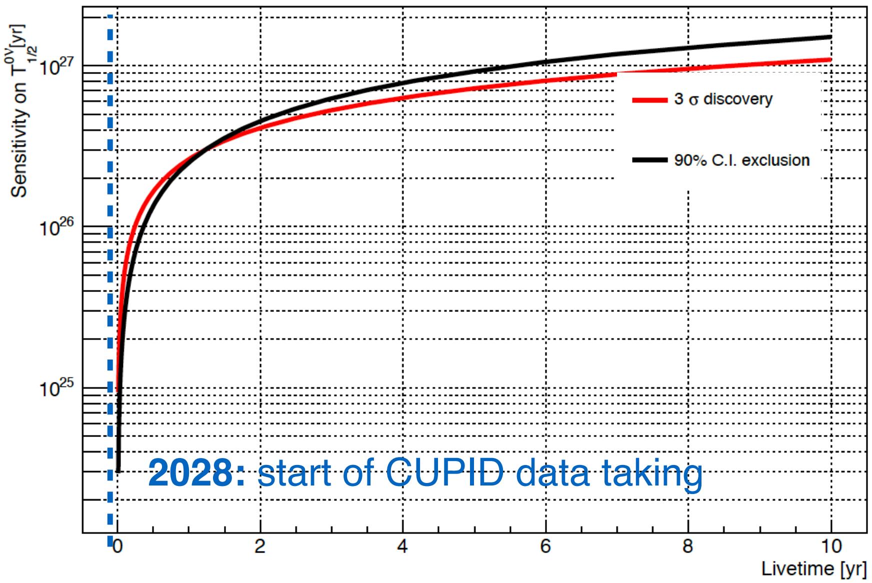
- 1000 kg of ^{100}Mo
- Discovery sensitivity **$T_{1/2} > 8\times10^{27}$ yr (3σ)**



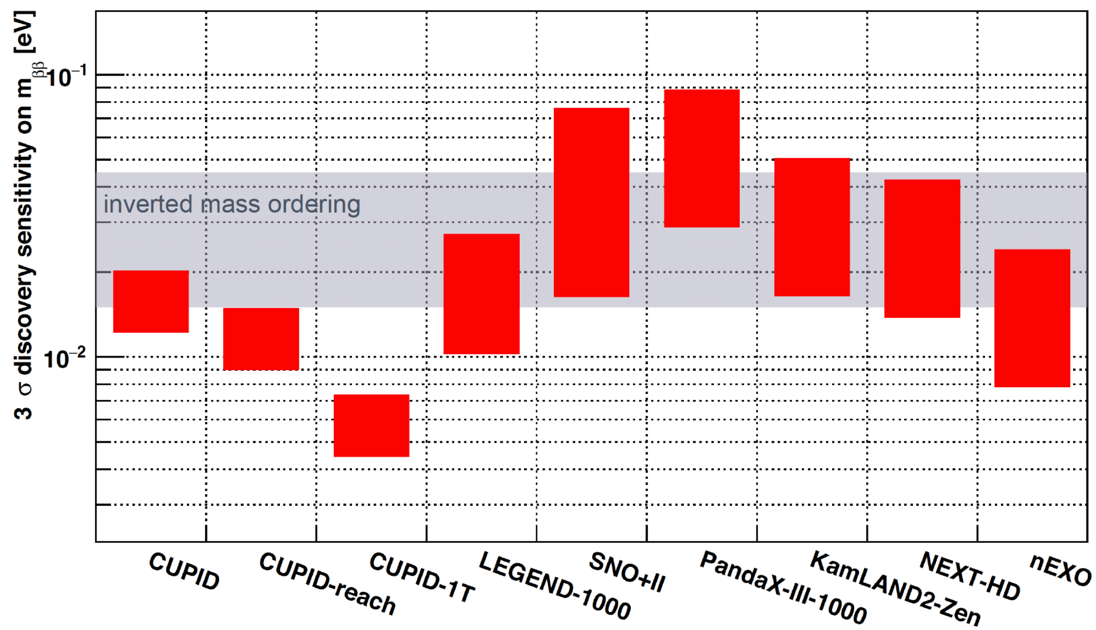
CUPID-1T is within technical reach, limited by timeline and cost

Timeline and Discovery Sensitivity

Discovery Sensitivity and Lifetime



Worldwide context



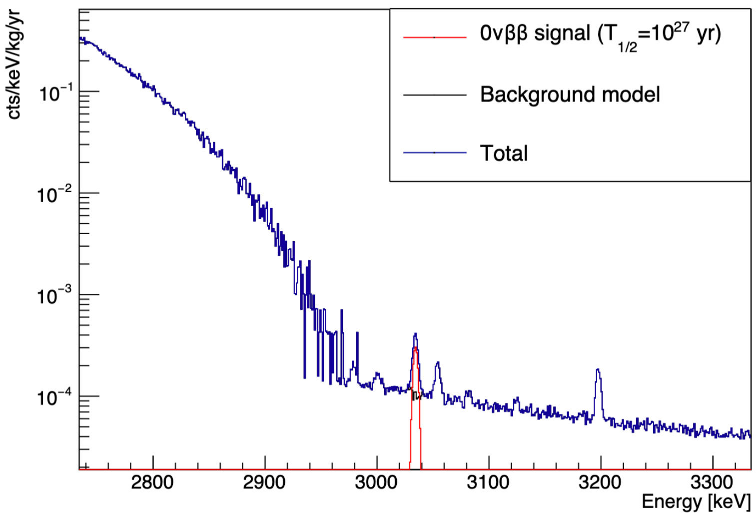
2024: completion of CUORE data taking

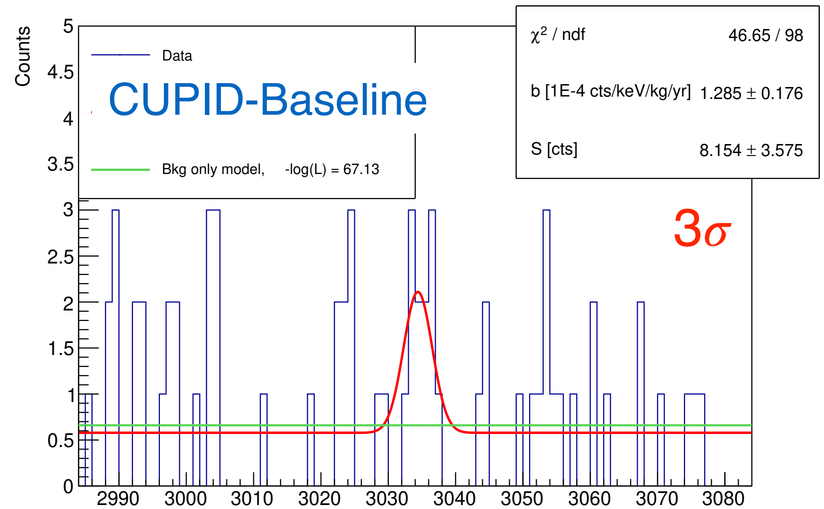
2025: start preparing cryostat for CUPID, modest modifications

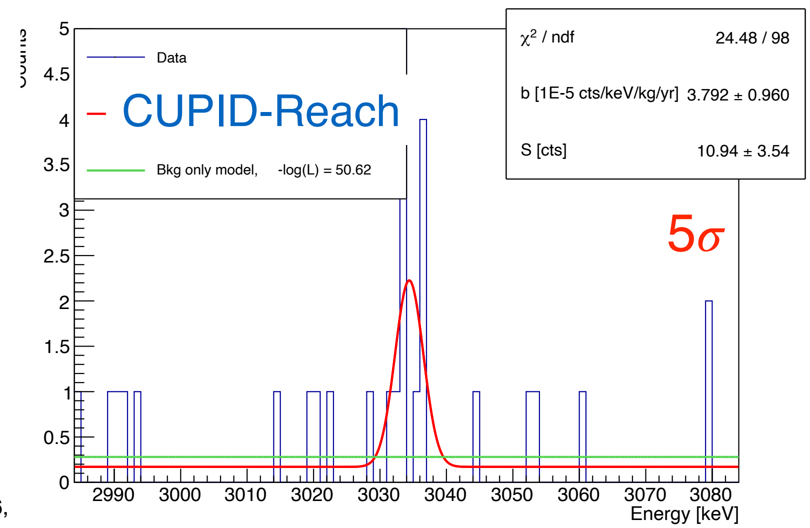
2028: start of CUPID data taking

2030: **n**ew data and scientific results before the end of the decade in technically-driven schedule

CUPID Signal: Preparing for Discovery







Example of toy experiments simulated for 10-year exposure and $T_{1/2}(^{100}Mo)=10^{27}$ years.

If signal is seen, modular detector allows data taking with different isotopes.

Envision CUPID to be part of a world-wide suite of experiments to discover 0νββ.

Multiple experiments will be needed to establish discovery.

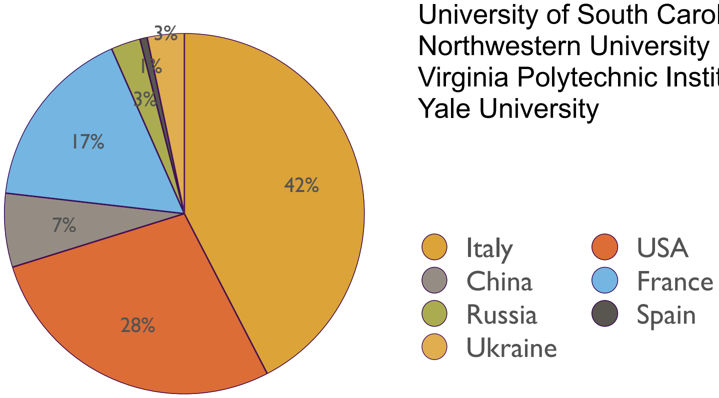
Collaboration

A strong, international collaboration builds on Italian-US partnership

Countries	Authors
Italy	64
USA	42
France	25
China	10
Ukraine	5
Russia	4
Spain	1

US Institutions

Argonne National Laboratory
Boston University
California Polytechnic State University
University of California, Los Angeles
University of California, Berkeley
Drexel University
Johns Hopkins University
Lawrence Berkeley National Laboratory
Massachusetts Institute of Technology
University of South Carolina
Northwestern University
Virginia Polytechnic Institute and State University
Yale University



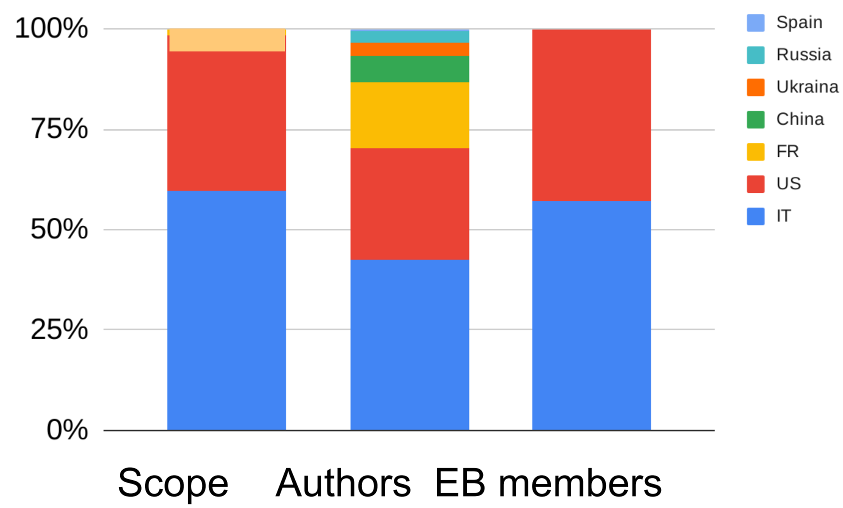
https://cupid.lngs.infn.it/

Collaboration

Collaboration structure and agreement reflect (expected) resources and financial commitment of countries

Project management has line responsibility for country's scope.

Inclusive collaboration, leverages international expertise, moderately correlated to funding.

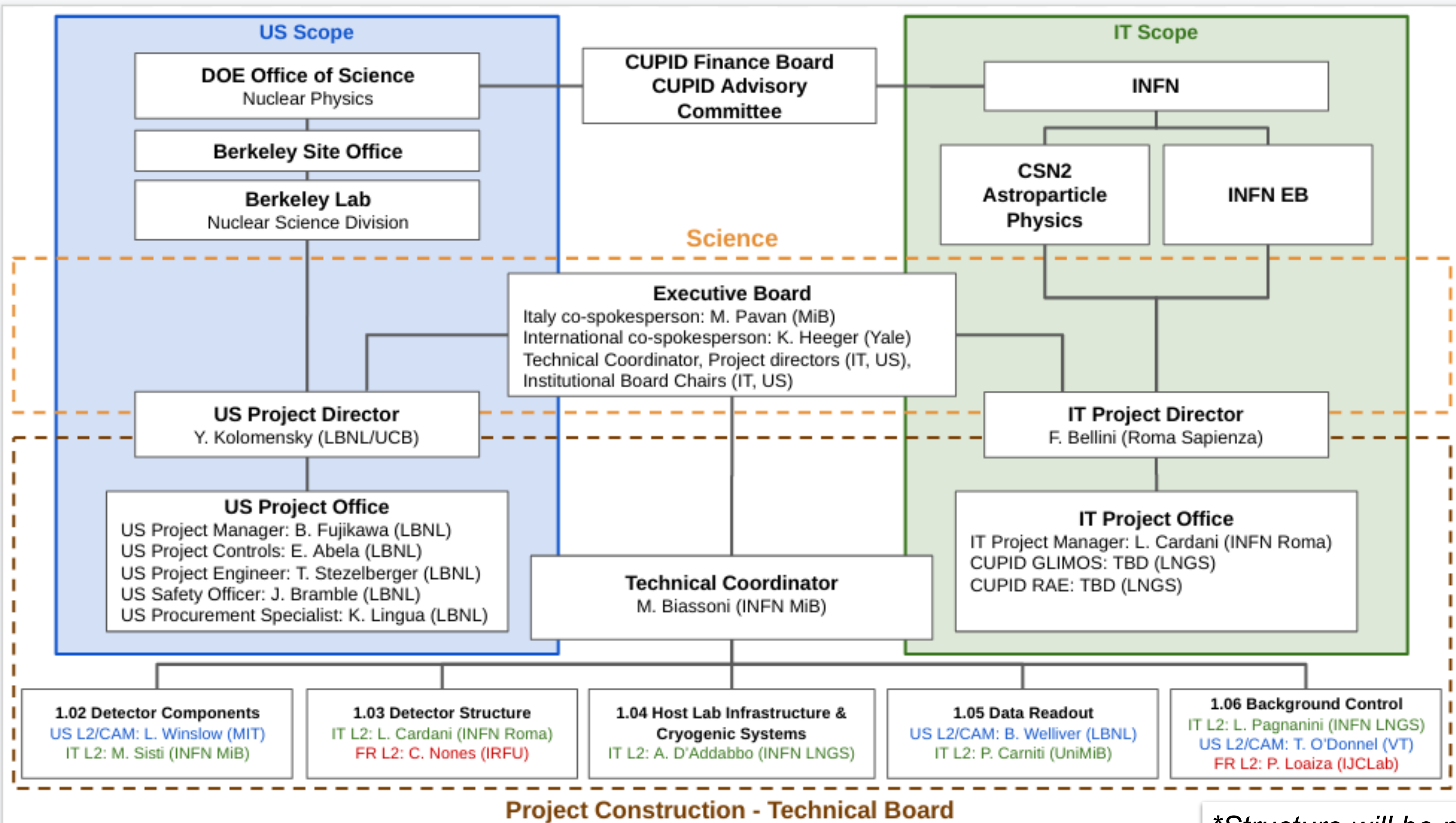


Major participants: Italy (~60 authors), US (~40 authors), France (~25 authors)

Other participants: Russia, Ukraine, China, Spain

Project Structure

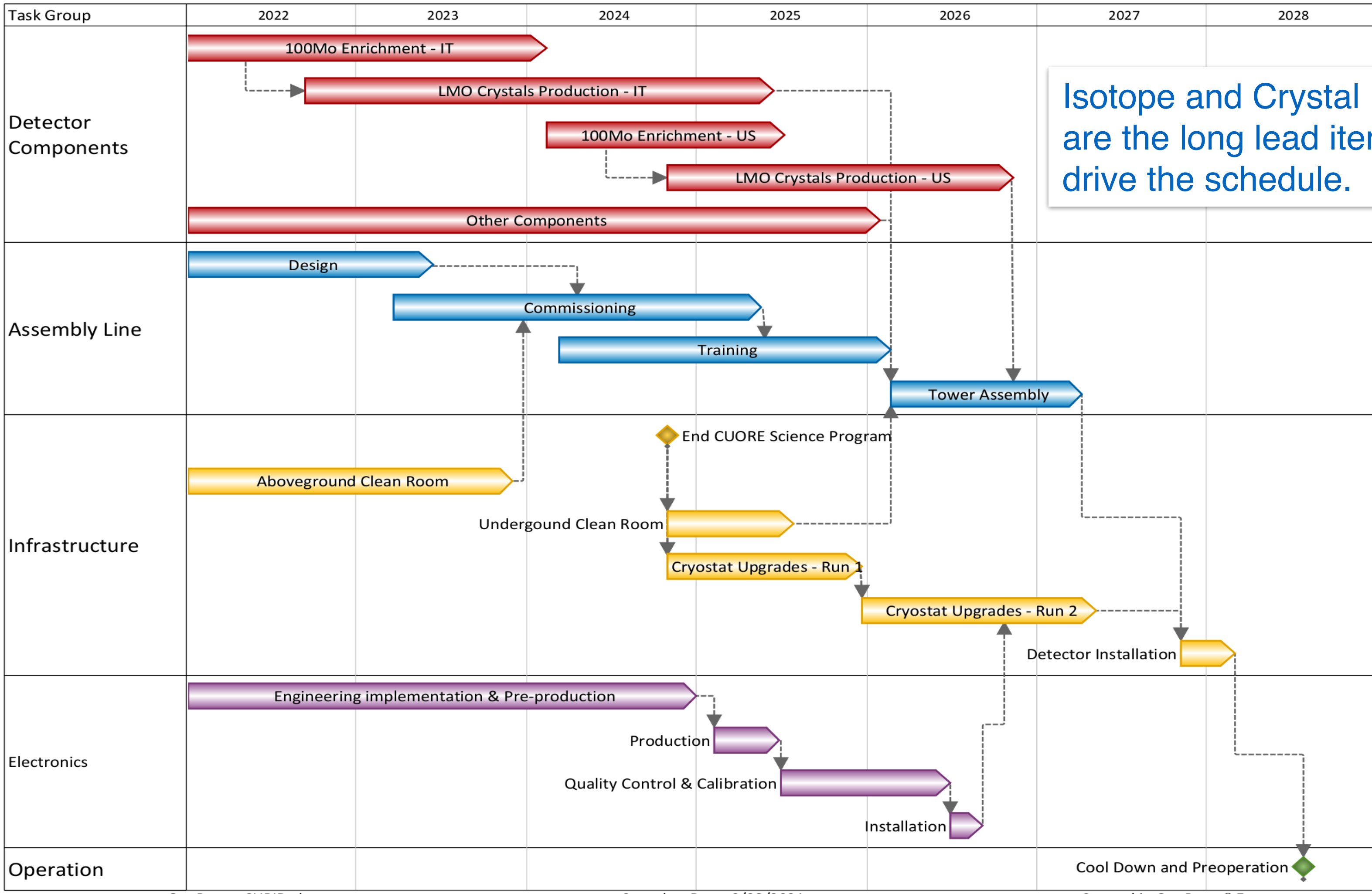
CUPID



**Structure will be mirrored for France and other countries as additional contributions are finalized.*

Project structure reflects Italian-US scope*

CUPID Schedule - Details



Isotope and Crystal Production are the long lead items that drive the schedule.

Budget summary

US Project Cost

Resource Type	Resource group	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	Total FTE-year	Base cost in FY k$	Base cost in FY22 k$	Escalation k$	Contingency k$	Total k$
Labor FTE	Technical	0.7	3.4	4.5	3.2	3.8	1.8	0.3	0.0	17.6					
	Engineering	5.0	5.0	5.9	5.4	5.6	2.0	0.5	0.0	29.4					
	Program Management	1.2	1.2	1.2	1.2	1.2	1.2	0.5	0.0	7.7					
	Uncosted	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	63.6					
	Total	**14.8**	**17.5**	**19.5**	**17.7**	**18.5**	**13.0**	**9.3**	**8.0**	**118.2**					
Labor Cost	Technical	50	283	112	176	122	50	8	0		802	778	24	200	1,002
	Engineering	914	844	925	838	1,179	597	109	0		5,407	5,244	162	1,153	6,560
	Program Management	483	494	514	535	554	573	259	20		3,431	3,328	103	515	3,946
	Total	1,447	1,621	1,552	1,549	1,856	1,220	376	20		9,640	9,350	289	1,868	11,508
Non-Labor	Procurement	2566	1695	4446	7088	1775	80	607	0		18257	17874	383	4740	22997
	Travel	23	36	43	17	13	7	20	0		158	155	3	40	198
US total		**4,035**	**3,352**	**6,041**	**8,654**	**3,643**	**1,306**	**1,003**	**20**		**28,055**	**27,379**	**676**	**6,648**	**34,703**

Total Project Cost

Cost		FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	Base cost in FY k$	Base cost in FY22 k$	Escalation	Contingency	Total
US	1.01 Project Management		604	594	626	651	674	698	244		4,091	3,968	123	614	4,704
	1.02 Detector Components		2,475	1,882	3,635	6,284	1,278		21		15,575	15,229	346	4,070	19,644
	1.03 Detector Structure						245	201	8		455	441	14	0	455
	1.04 Host Lab Infrastructure & Cryogenic Systems		397	17	0	18	215				647	631	16	162	809
	1.05 Data Readout Hardware & Software			418	1,314	1,439	626	84	673	20	4,573	4,468	105	1,131	5,704
	1.06 Background Control		559	442	466	262	605	323	57	0	2,715	2,643	72	672	3,387
US Total			**4,035**	**3,352**	**6,041**	**8,654**	**3,643**	**1,306**	**1,003**	**20**	**28,055**	**27,379**	**676**	**6,648**	**34,703**
FRANCE	1.06 Background Control	442									442	442			442
FR Total		**442**									**442**	**442**			**442**
	1.02 Detector Components		3,602	6,877	3,880	158					14,517	14,517		3,861	18,378
ITALY	1.03 Detector Structure		389	2,061	1,015	262	210	147	58	26	4,169	4,169		982	5,151
	1.04 Host Lab Infrastructure & Cryogenic Systems		1,150	227	76	61	271	32	121		1,938	1,938		484	2,422
	1.05 Data Readout Hardware & Software		416			1,133	121	121			1,791	1,791		448	2,239
	1.06 Background Control	366									366	366		91	457
IT Total		**366**	**5,558**	**9,166**	**4,970**	**1,614**	**602**	**300**	**179**	**26**	**22,781**	**22,781**		**5,867**	**28,647**
Total		**808**	**9,593**	**12,518**	**11,011**	**10,268**	**4,246**	**1,606**	**1,182**	**46**	**51,278**	**50,602**	**676**	**12,515**	**63,792**

US total $34.7M ($31.2-$39.9, includes scope contingency)

Timeline & Approval Steps - Proposed

Integrated planning between Italy and US

INFN

Sept '21	Oct '21	Dec '21	June-Dec '22	
Astroparticle Committee: CY2022 funds	North America-Europe DBD Workshop	Astroparticle Committee & INFN EB	Isotope and crystal contract signed, production started	Construction

DOE (technically-driven)

July '21	Oct '21	Dec '21	June-Dec '22	FY23, Q2	
NLDBD Portfolio Review	North America-Europe DBD Workshop	CD-1/3A	Isotope and crystal contract negotiations	CD2/3B, start of construction	Major procurements

Summary

- CUPID will **explore inverted ordering ($T_{1/2}$ > 10^{27} years at 3σ,** $m_{\beta\beta}$ ~ **12-20 meV)**
- **Builds on an existing and well-functioning international collaboration** and long partnership between Italy and US
- Collaboration has **operational experience at LNGS for ton-scale, bolometric experiment** and utilizes **existing infrastructure** (CUORE cryostat, experimental site).
- **CUPID is timely, highly leveraged, and cost-effective; an exceptional opportunity.**
- Crystallization and enrichment at large scale are possible
- **Limited technology verification remaining** for CUPID baseline.
- **Data-driven background model** reaches baseline goal of b~10^{-4}counts/(keV kg y).

CUPID is ready to proceed

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