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

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CUPID Concept

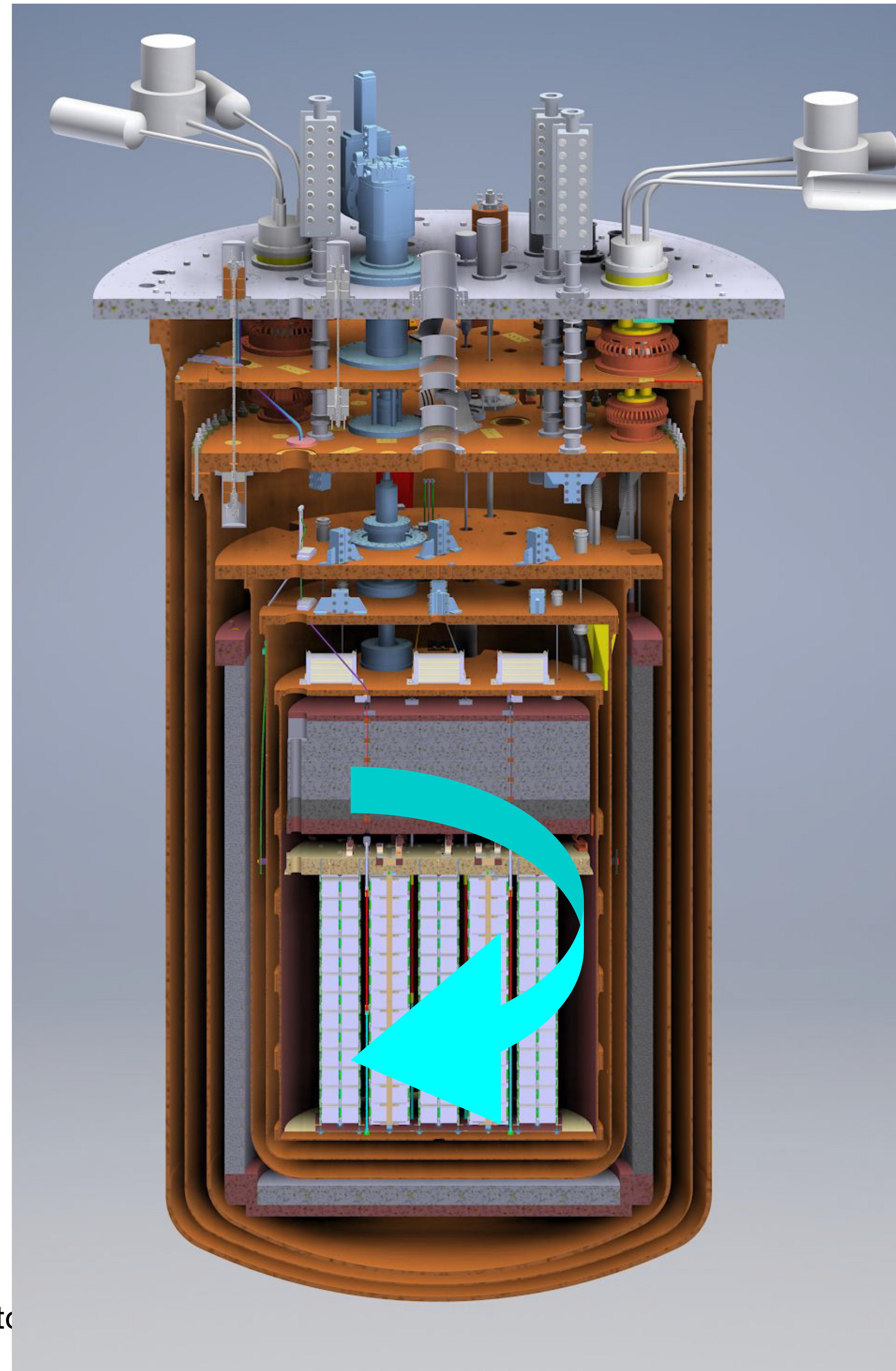
A ton-scale high-resolution bolometer array for the search of 0νββ and other rare events

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.

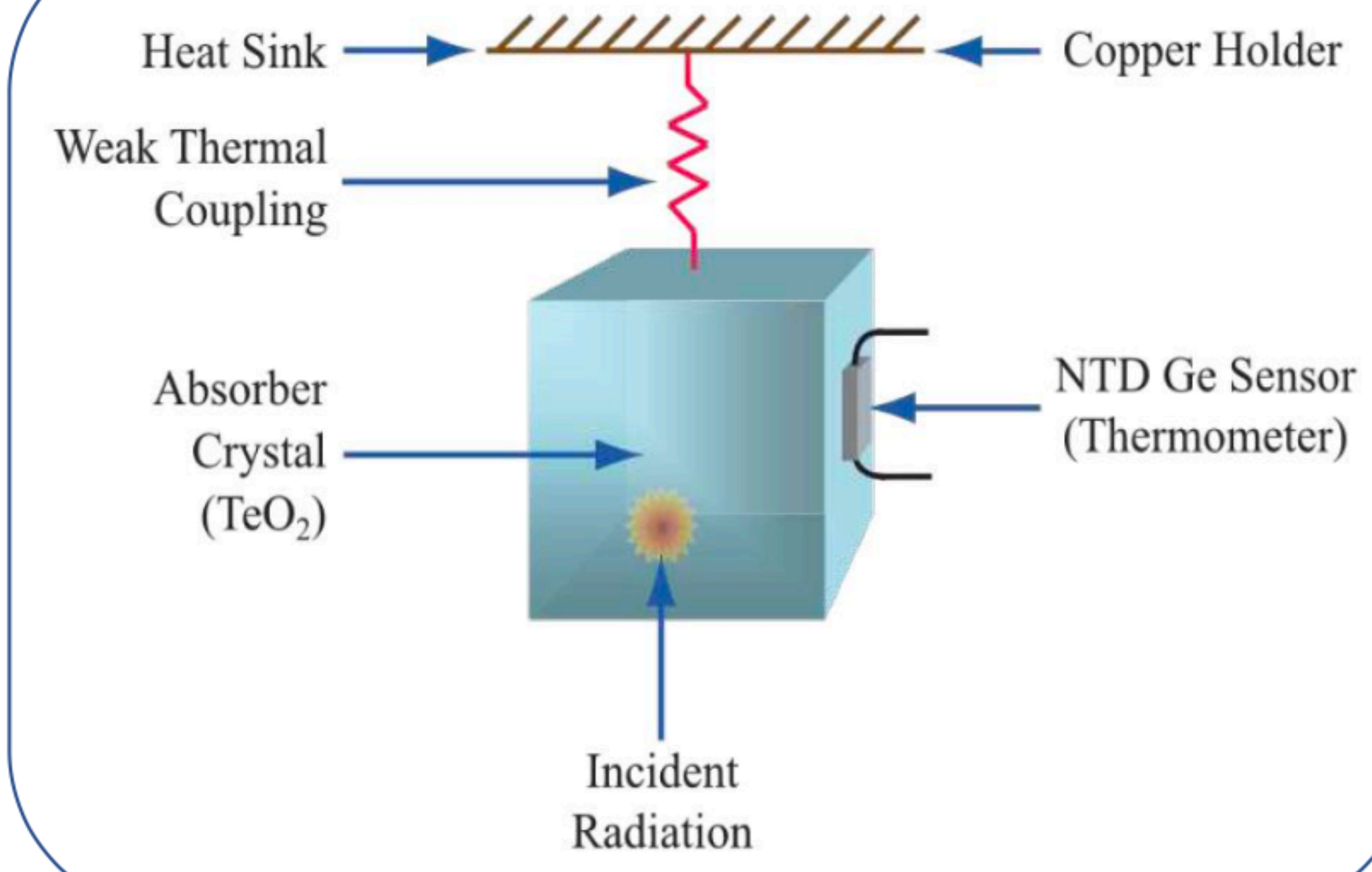
Existing cryogenic infrastructure: Was challenging for CUORE, now an established technology.

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



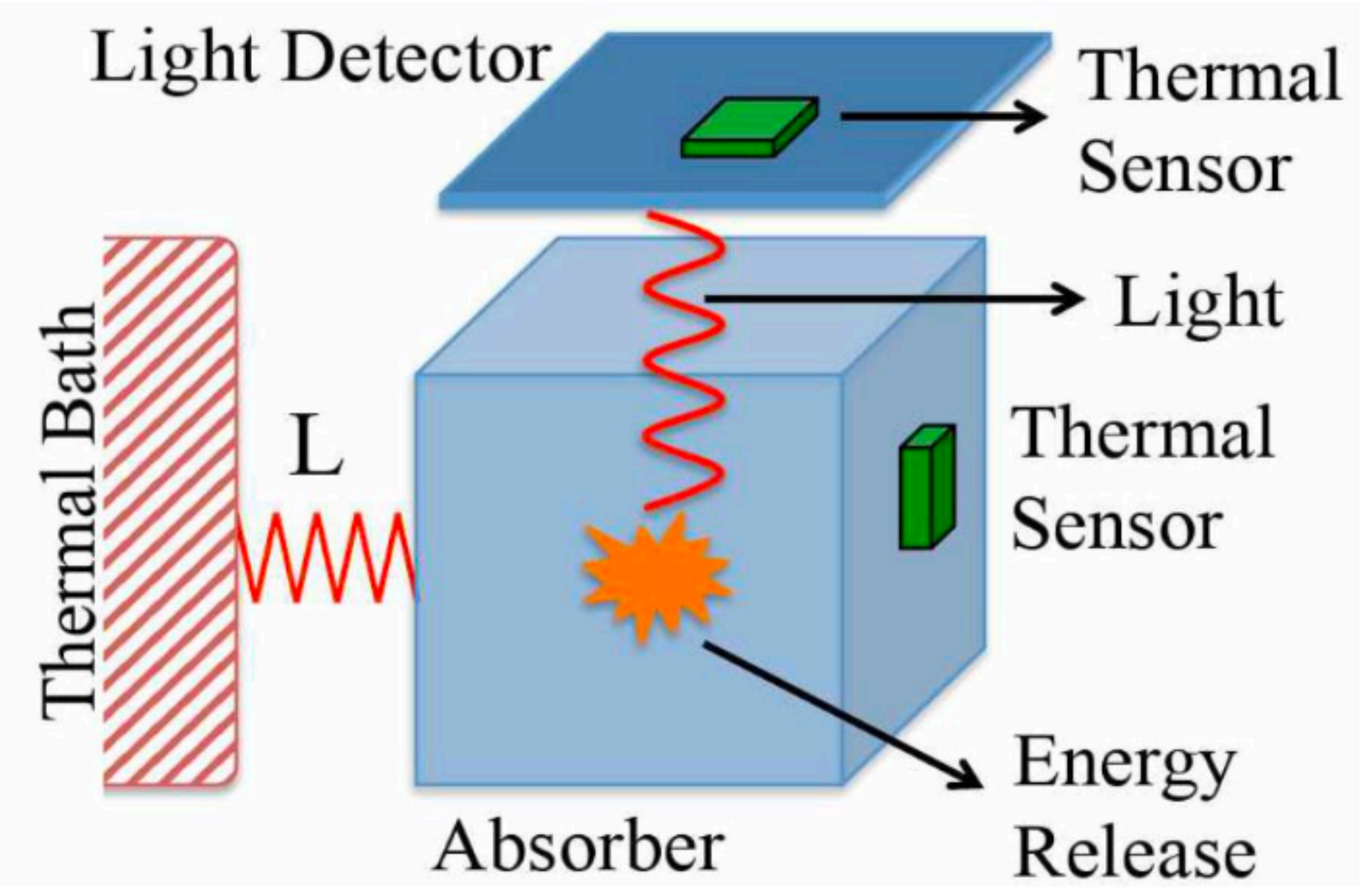
CUPID Technology

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



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

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



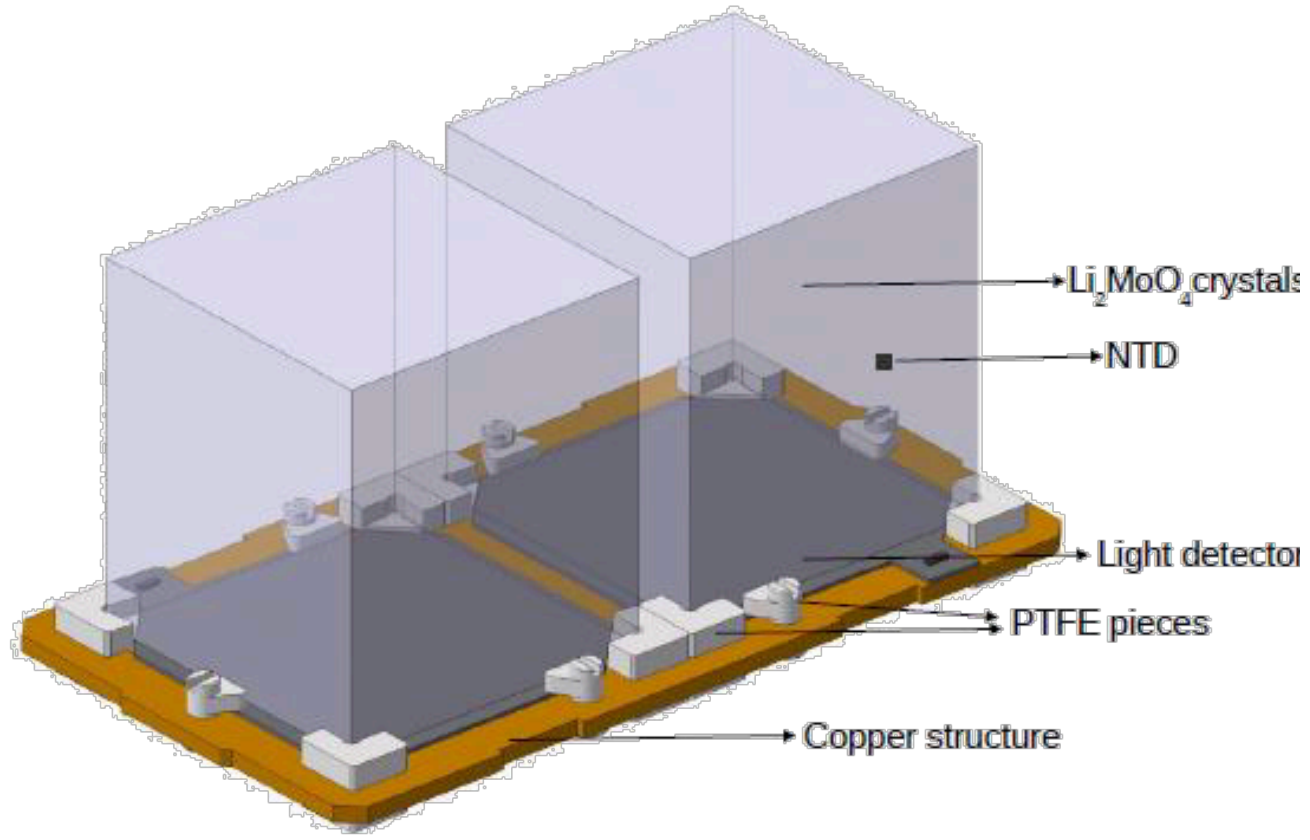
^{100}Mo **Q-value: 3034 keV**: β/γ background significantly reduced

CUPID Detector

Single Detector

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

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



Gravity stacked structure
Crystals thermally interconnected

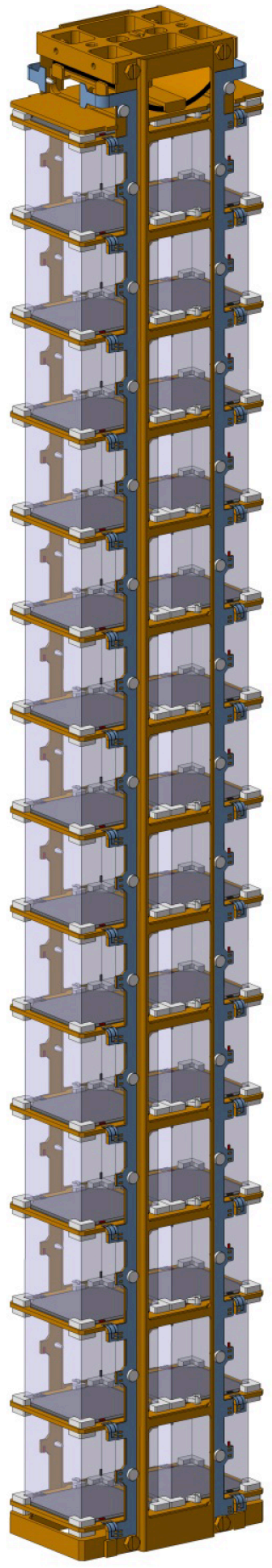
Detector Array

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

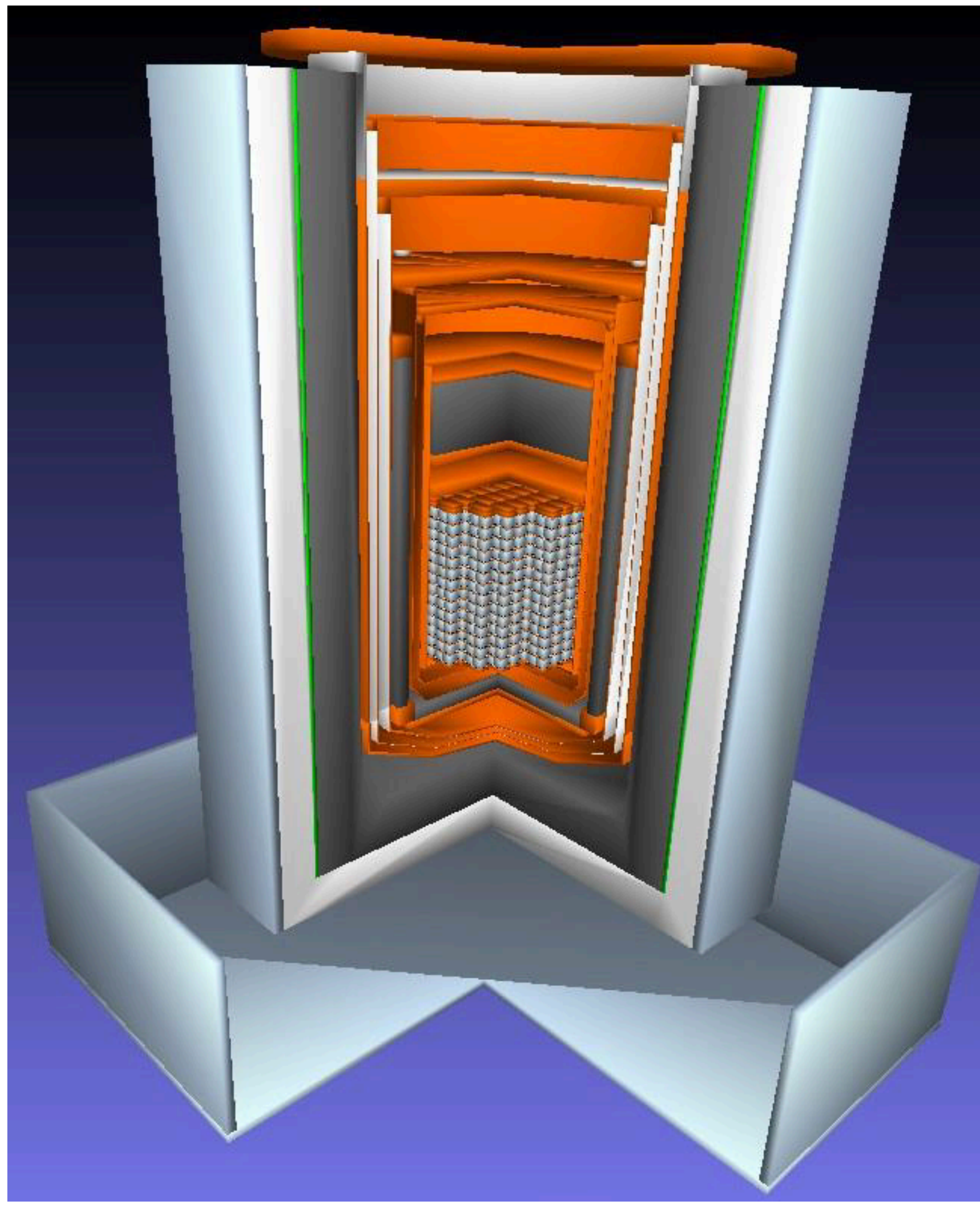
~1.6.10^{27} ^{100}Mo atoms

57 towers of 14 floors with 2 crystals each,

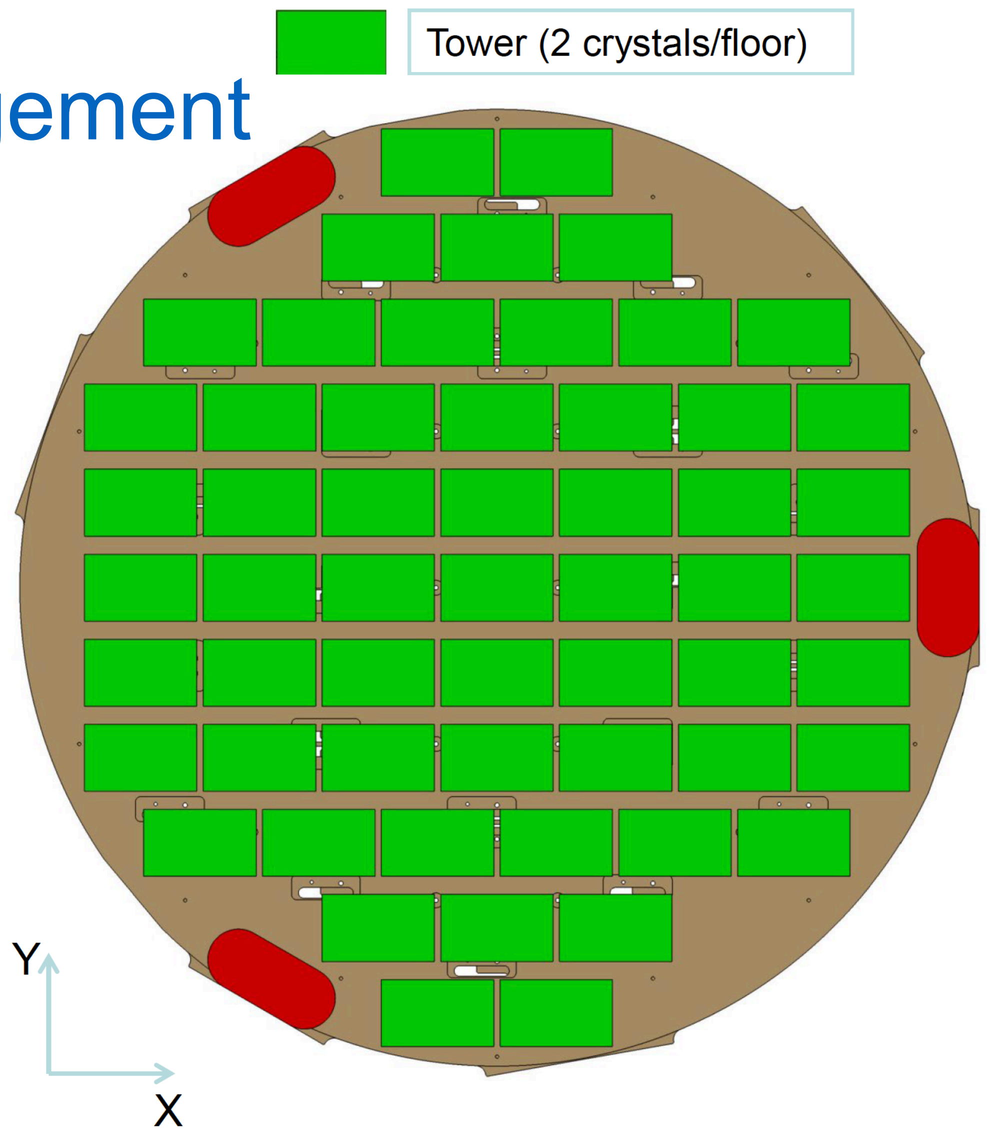
1596 crystals



Tower



Tower Arrangement



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**:

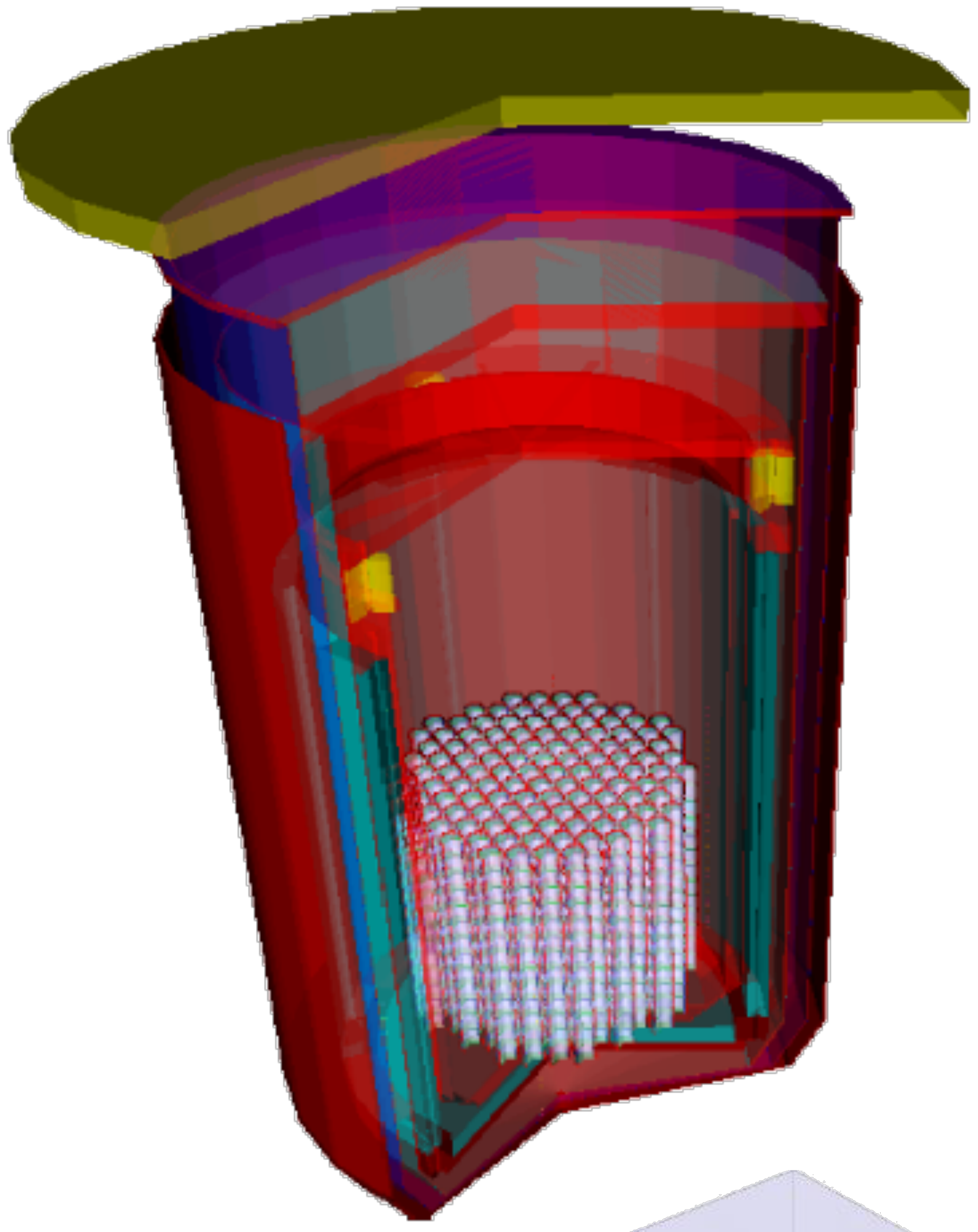
- β/γ background significantly reduced
- favorable NME

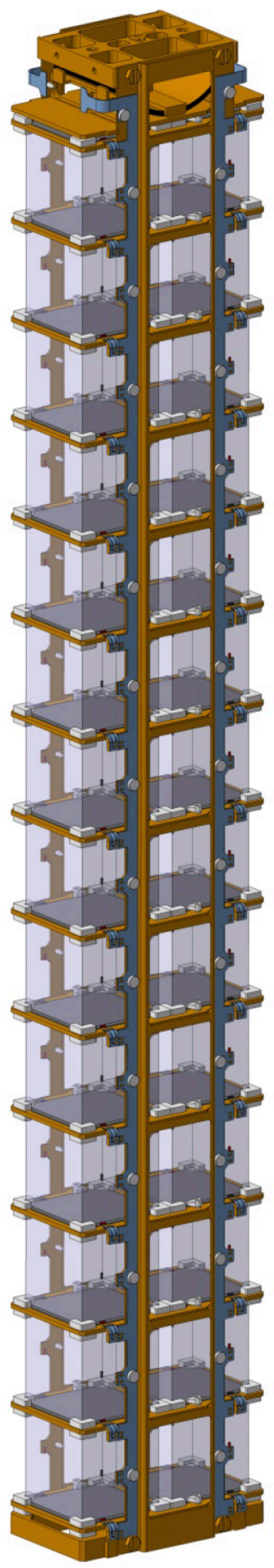
Exploit Particle ID using scintillation bolometer technique
Technique robustly demonstrated by CUPID-0 and CUPID-Mo

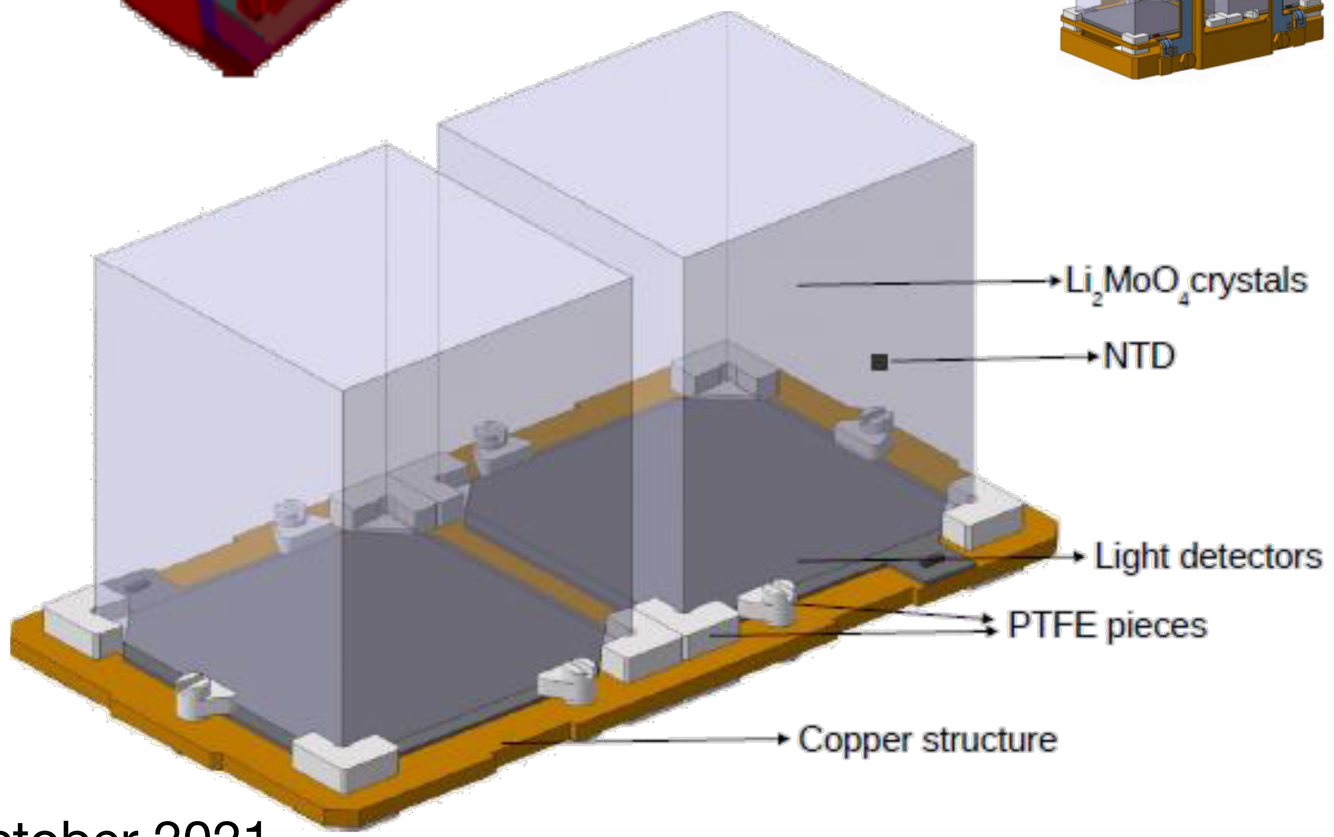
Reuse **proven CUORE cryogenic infrastructure** at LNGS for a cost-effective deployment

Add external muon veto, improved neutron shield

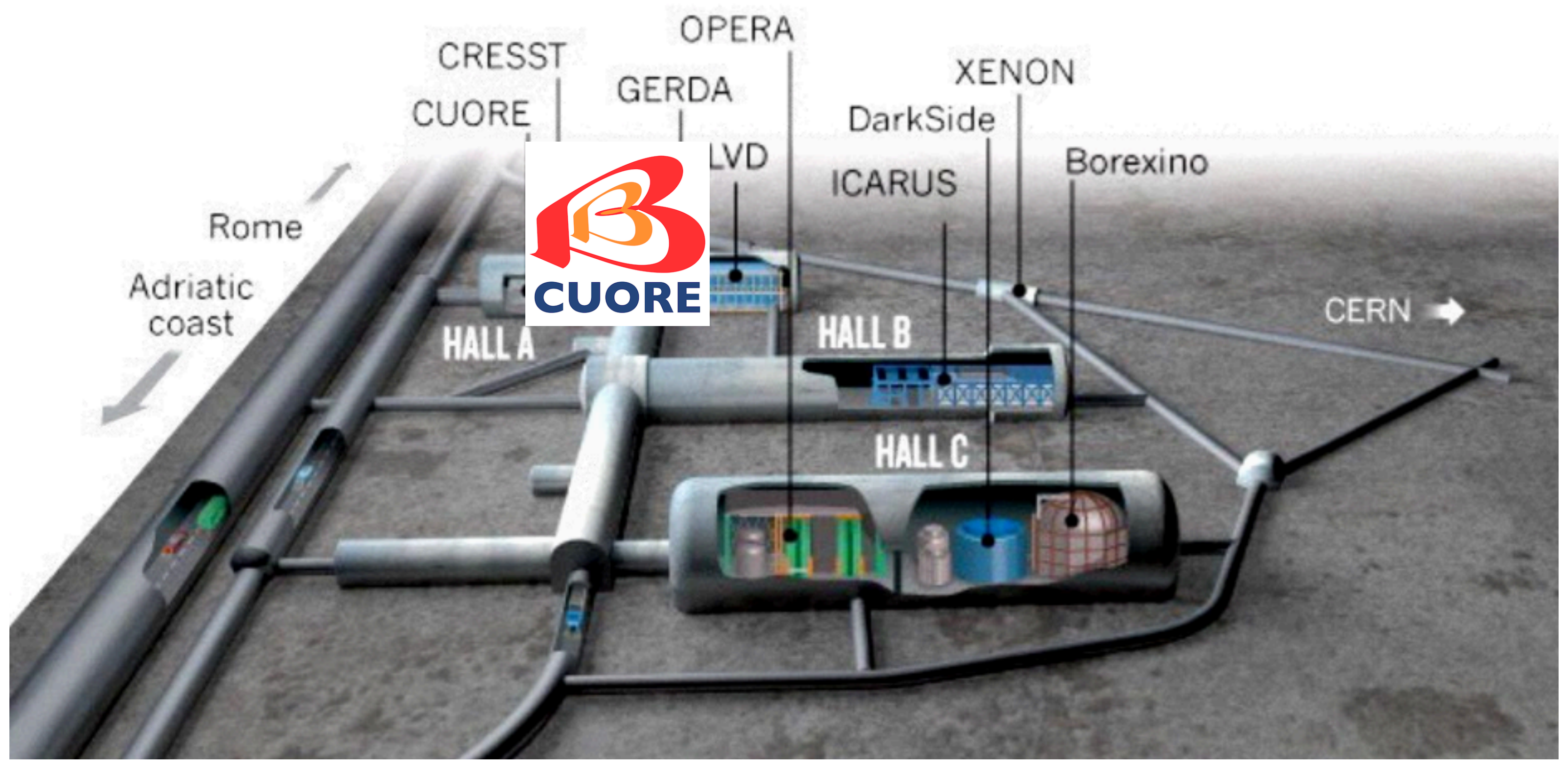
Scalable to 1-ton scale (CUPID-1T) technically possible

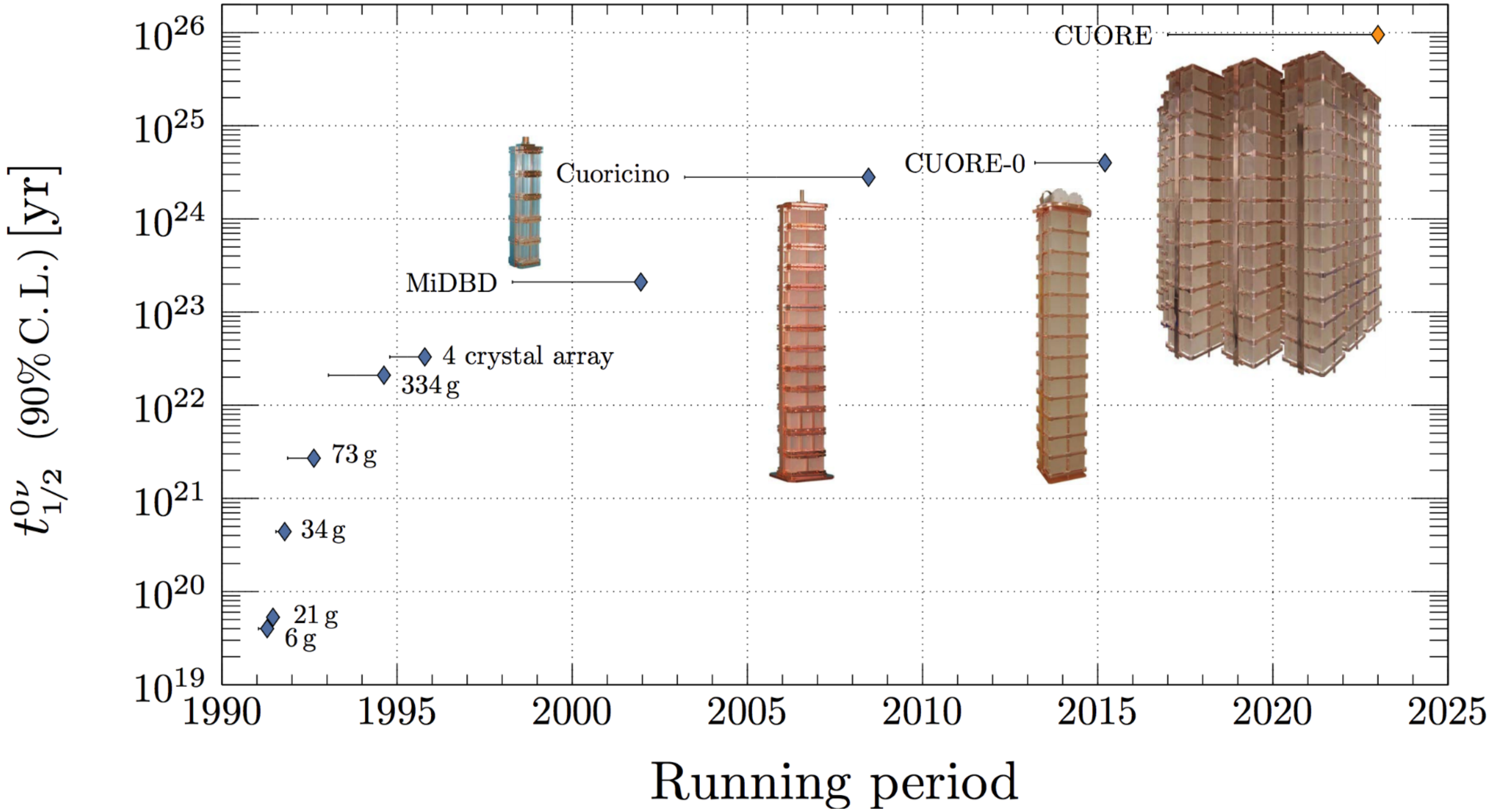






Collaboration at LNGS



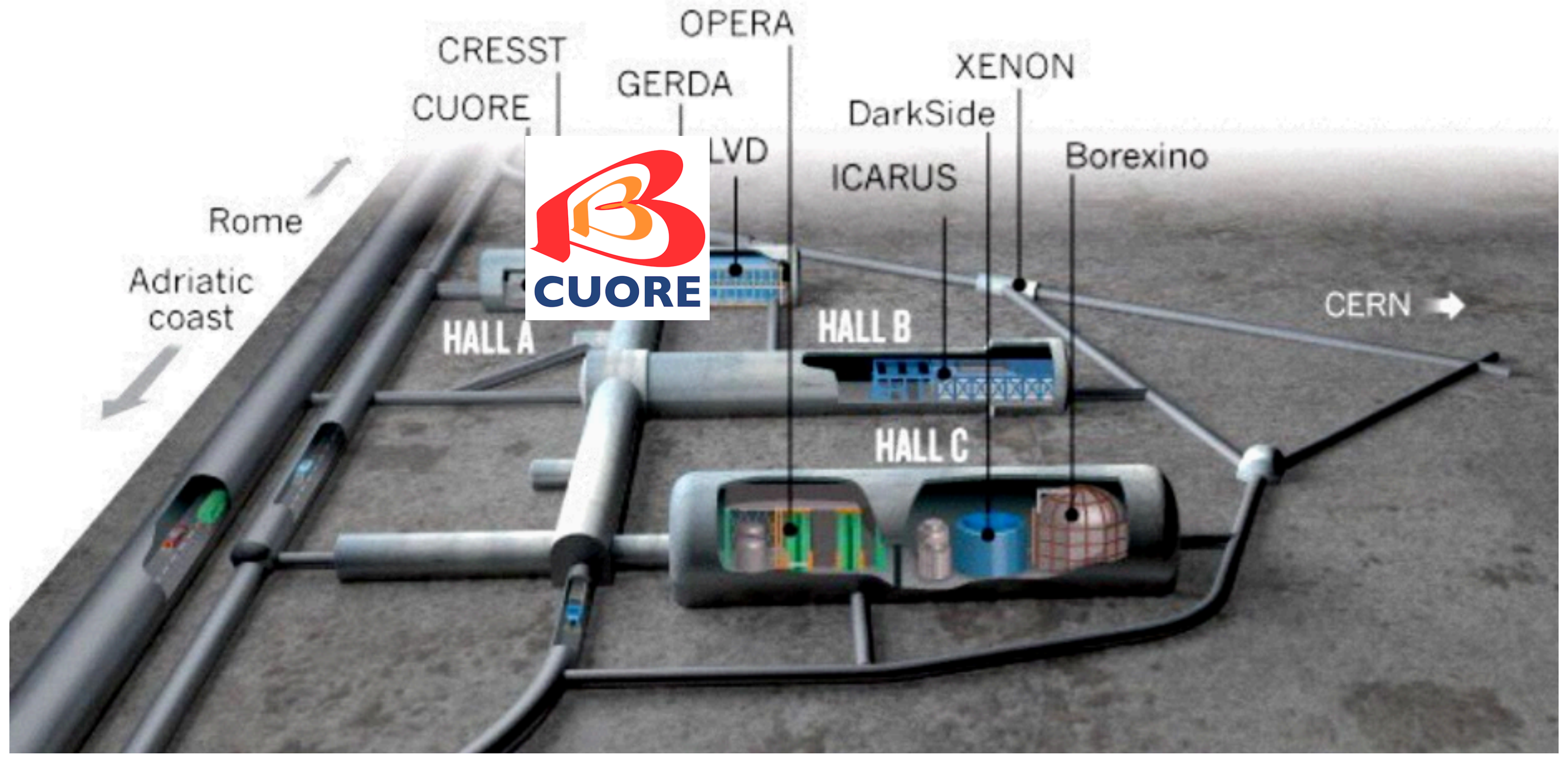


CUPID is next step in a series of bolometric experiments at LNGS:
Cuoricino, CUORE, CUPID-0, CUPID

Collaboration has worked at LNGS for many years.

Established Italian-US partnership.

LNGS as Host Lab

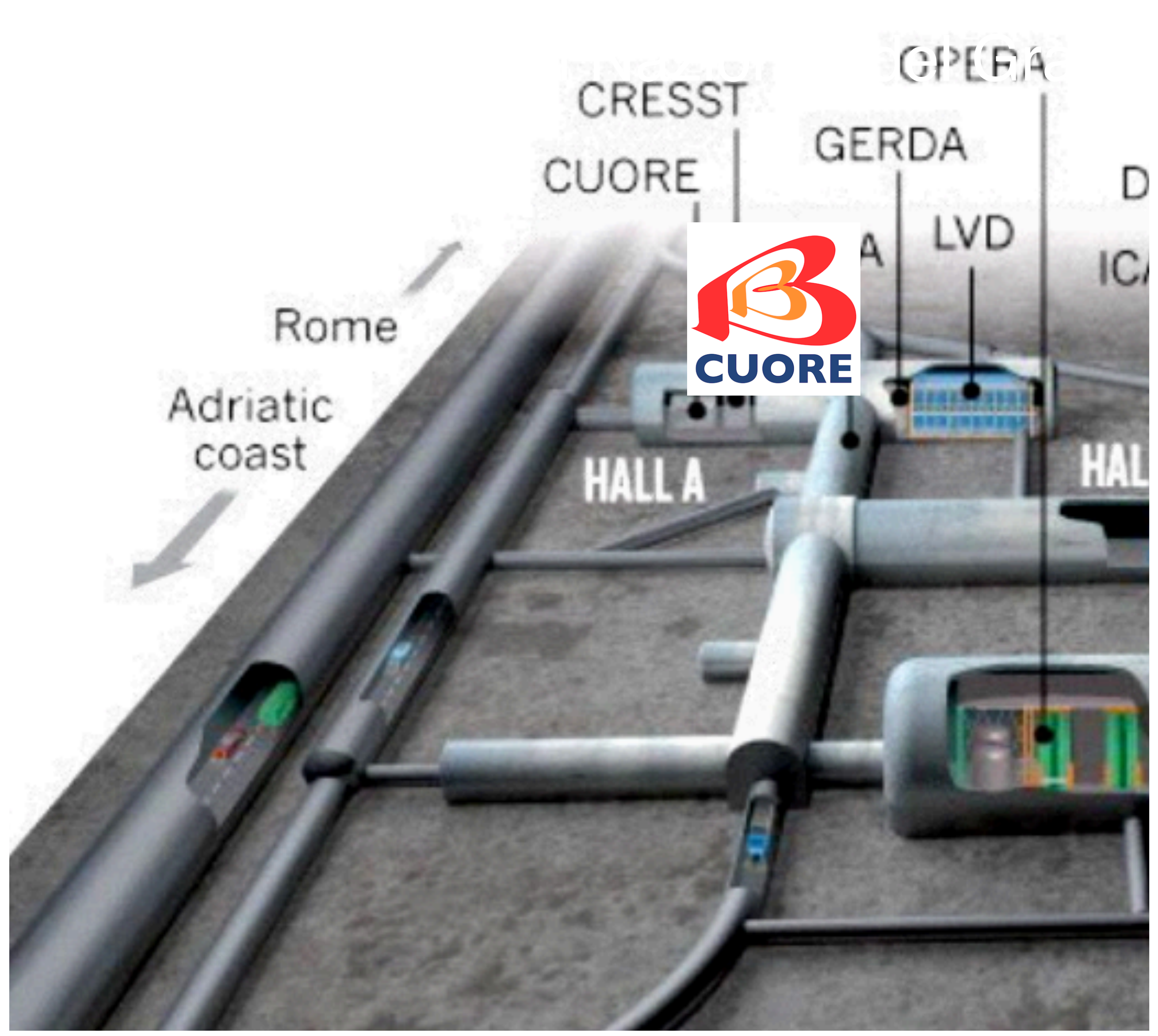


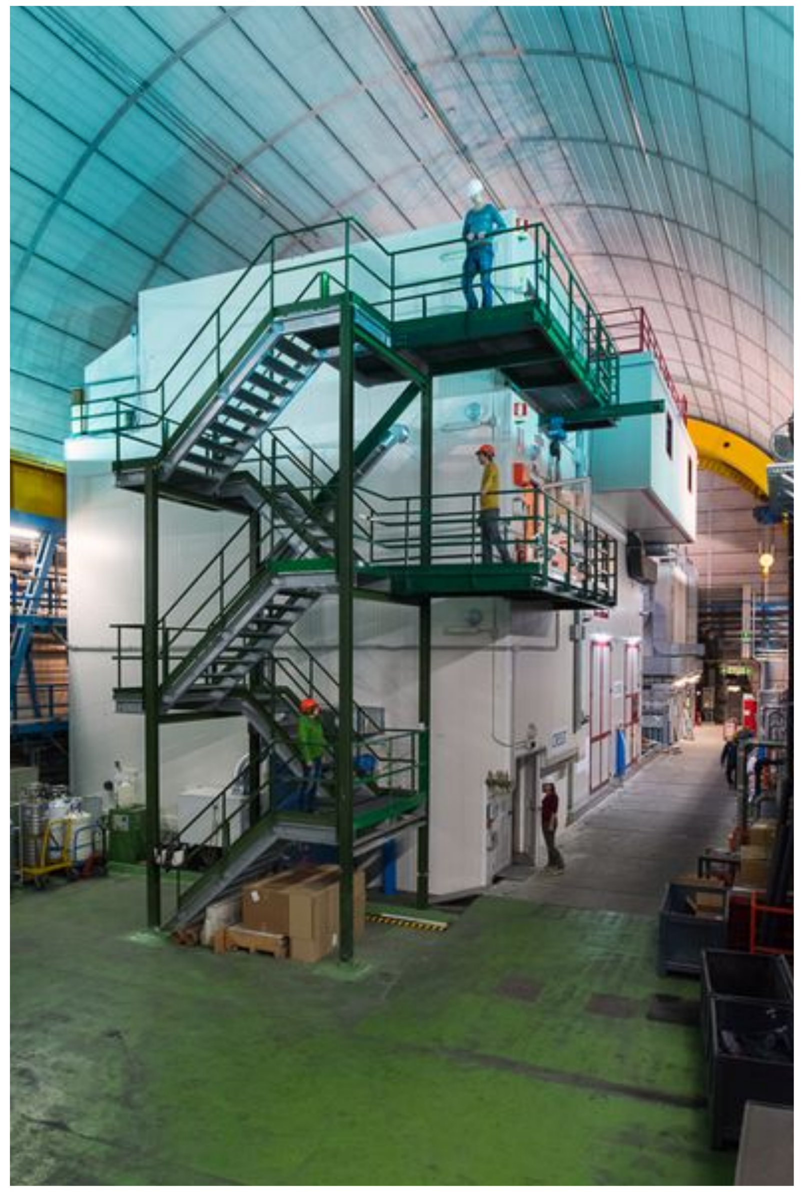
Strong support from the Lab in terms of services like ICP-MS, γ-spectroscopy, electronics, cryogenics, clean rooms, etc

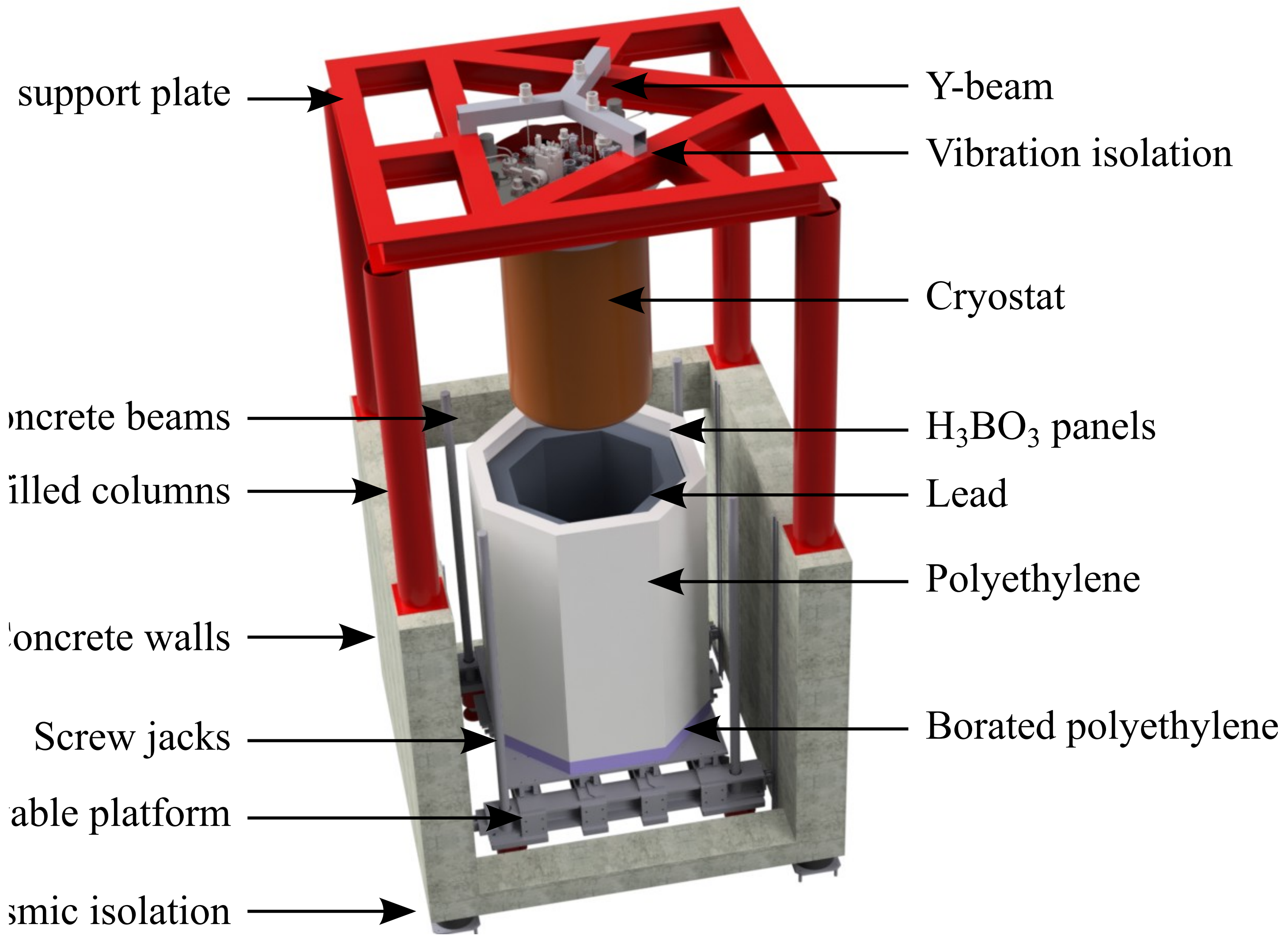
LNGS Scientific Committee gave its **scientific approval in September 2020.**

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

Established Site and Infrastructure







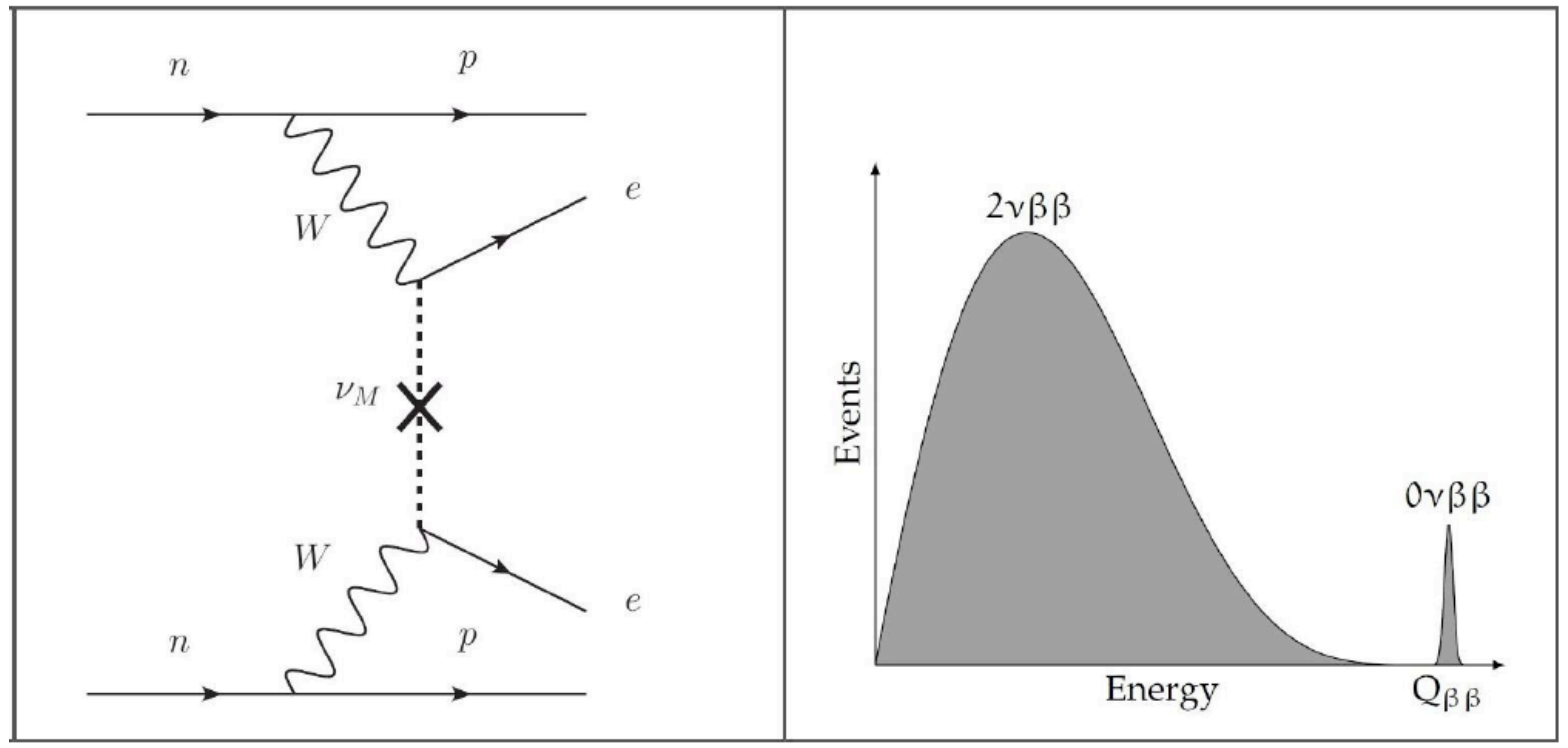
CUPID is extremely well-leveraged and cost-effective:

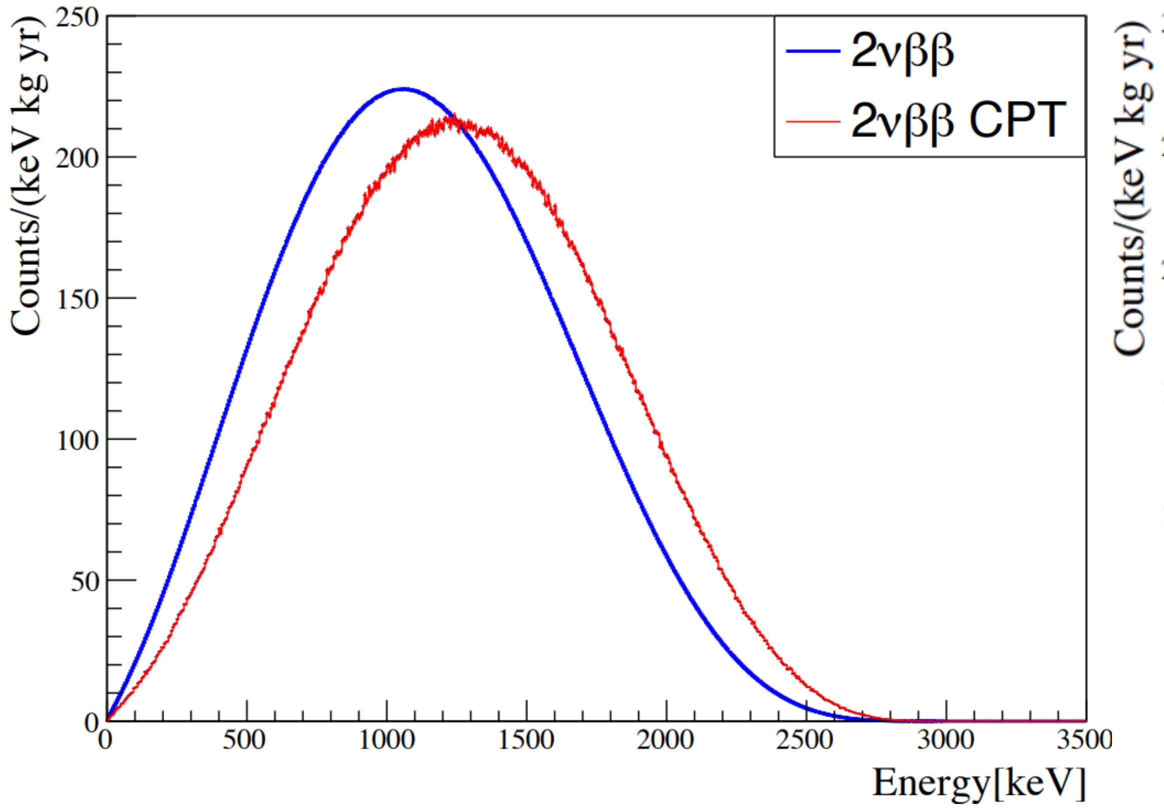
Existing experimental site, unique cryogenic infrastructure.

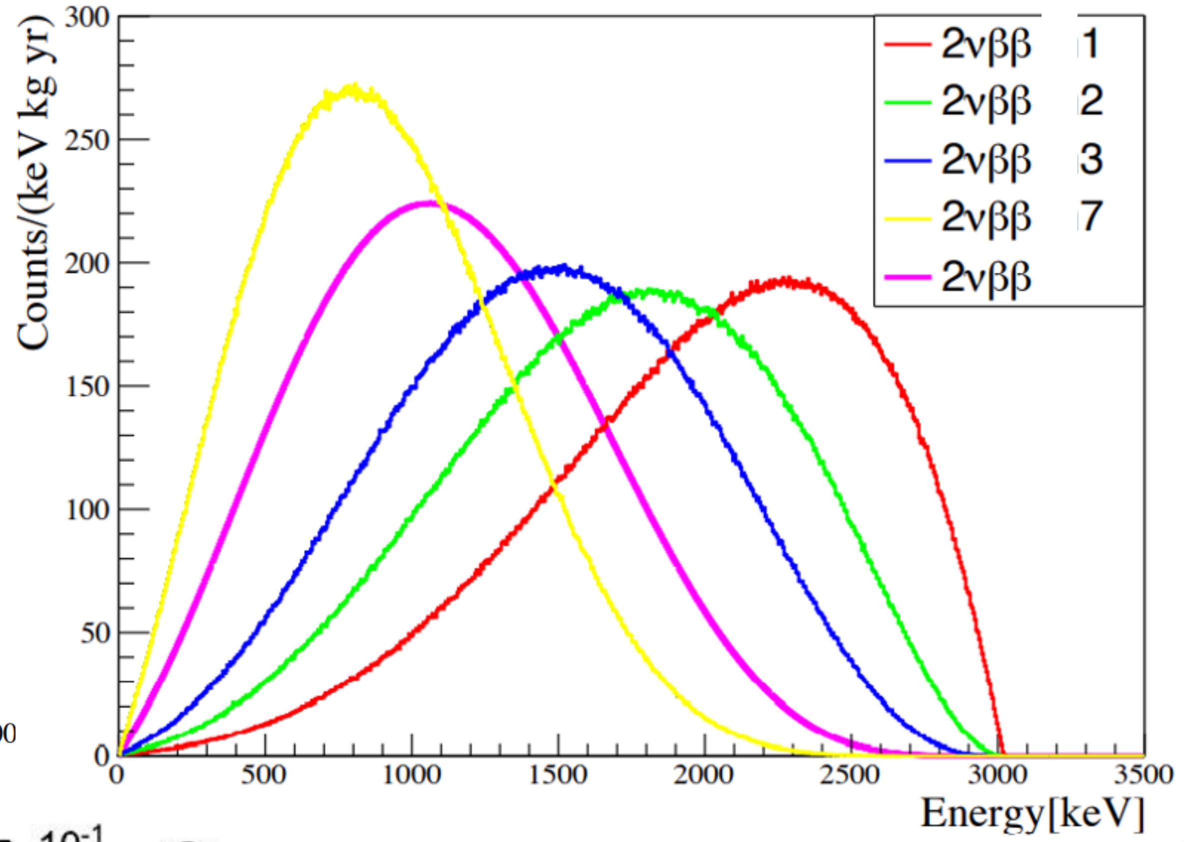
LNGS provides technical and user support.

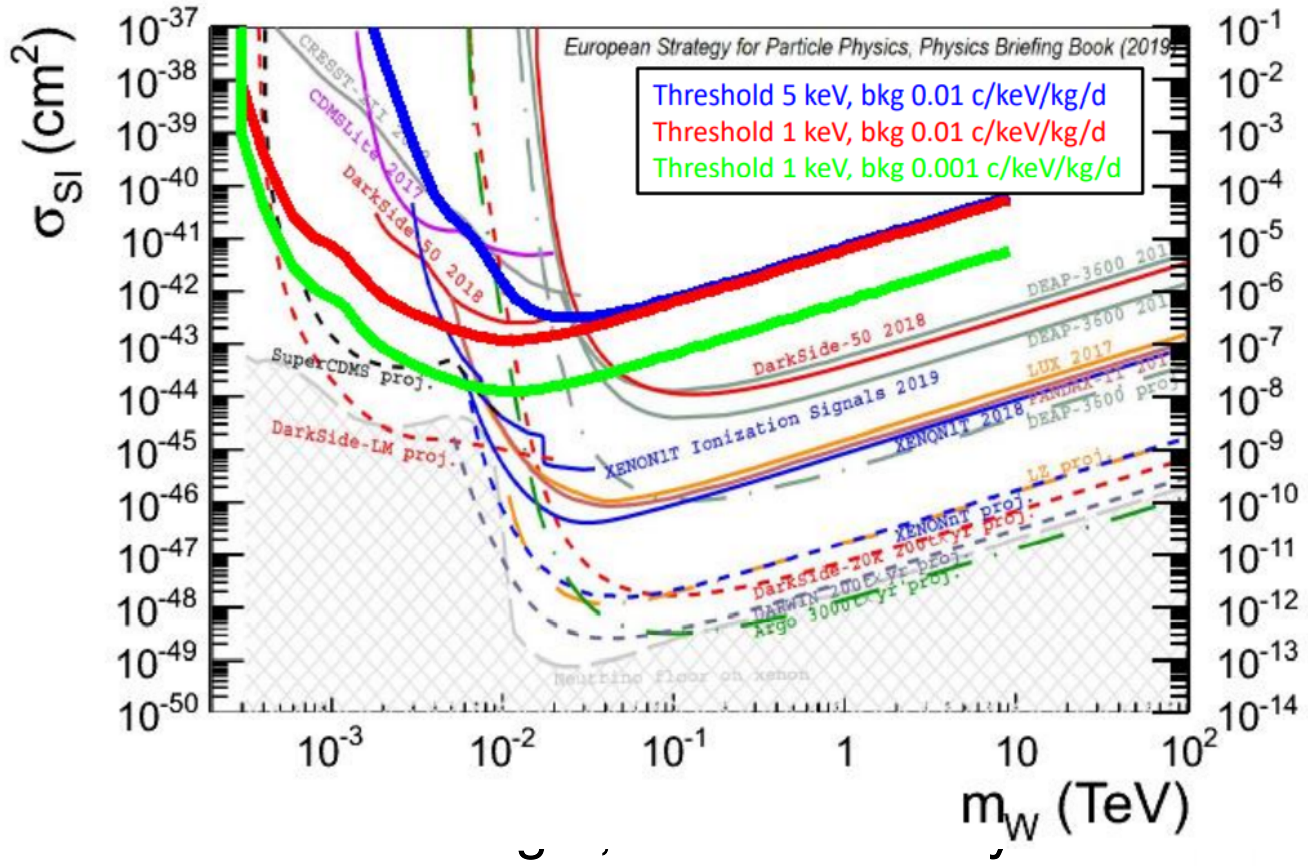
CUPID leverages on many years of work and investment from INFN and LNGS

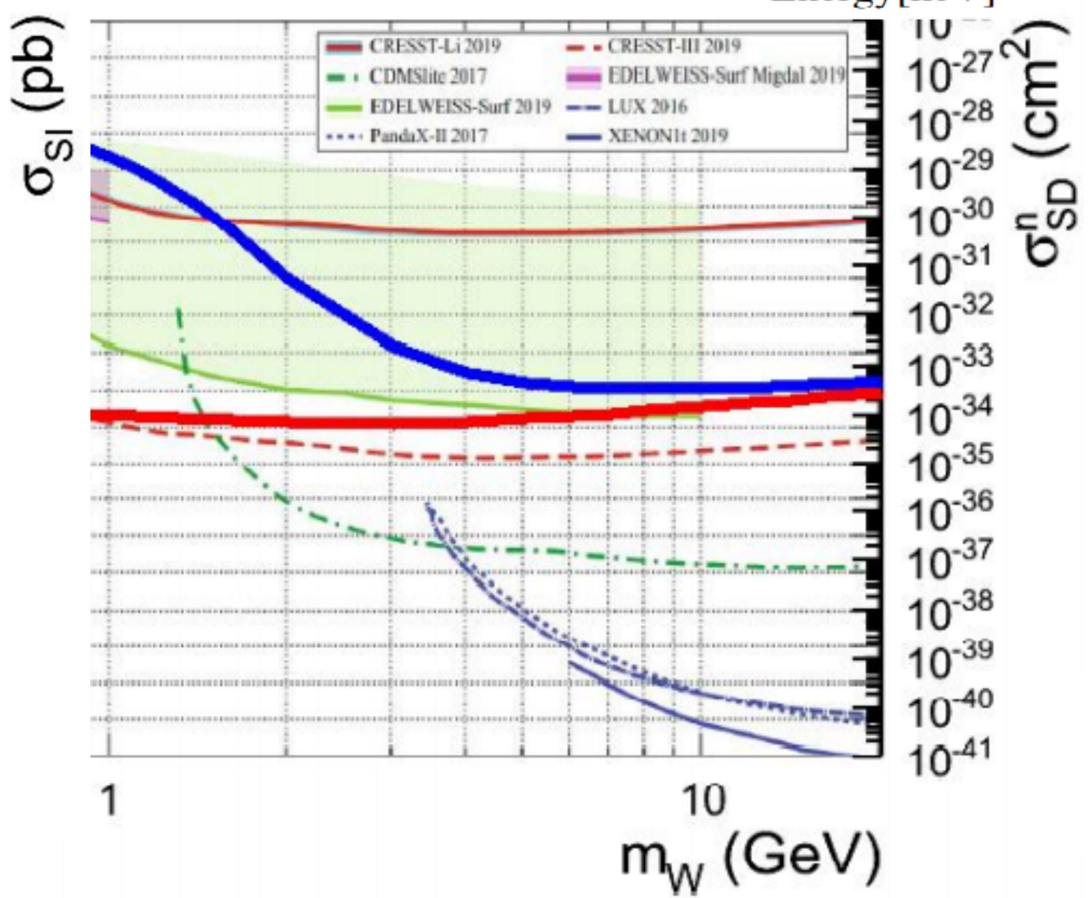
CUPID Science Program











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

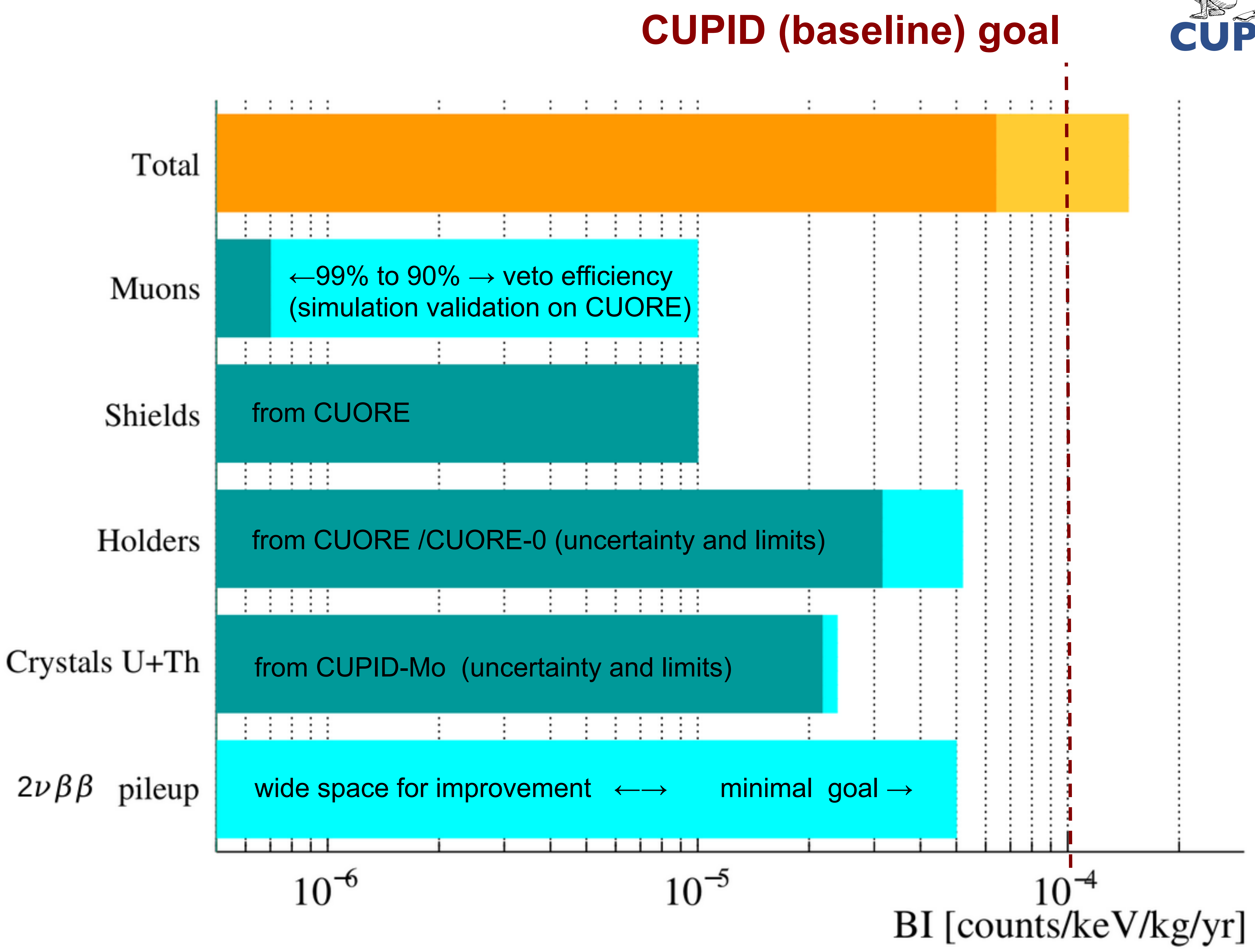
Background Budget

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



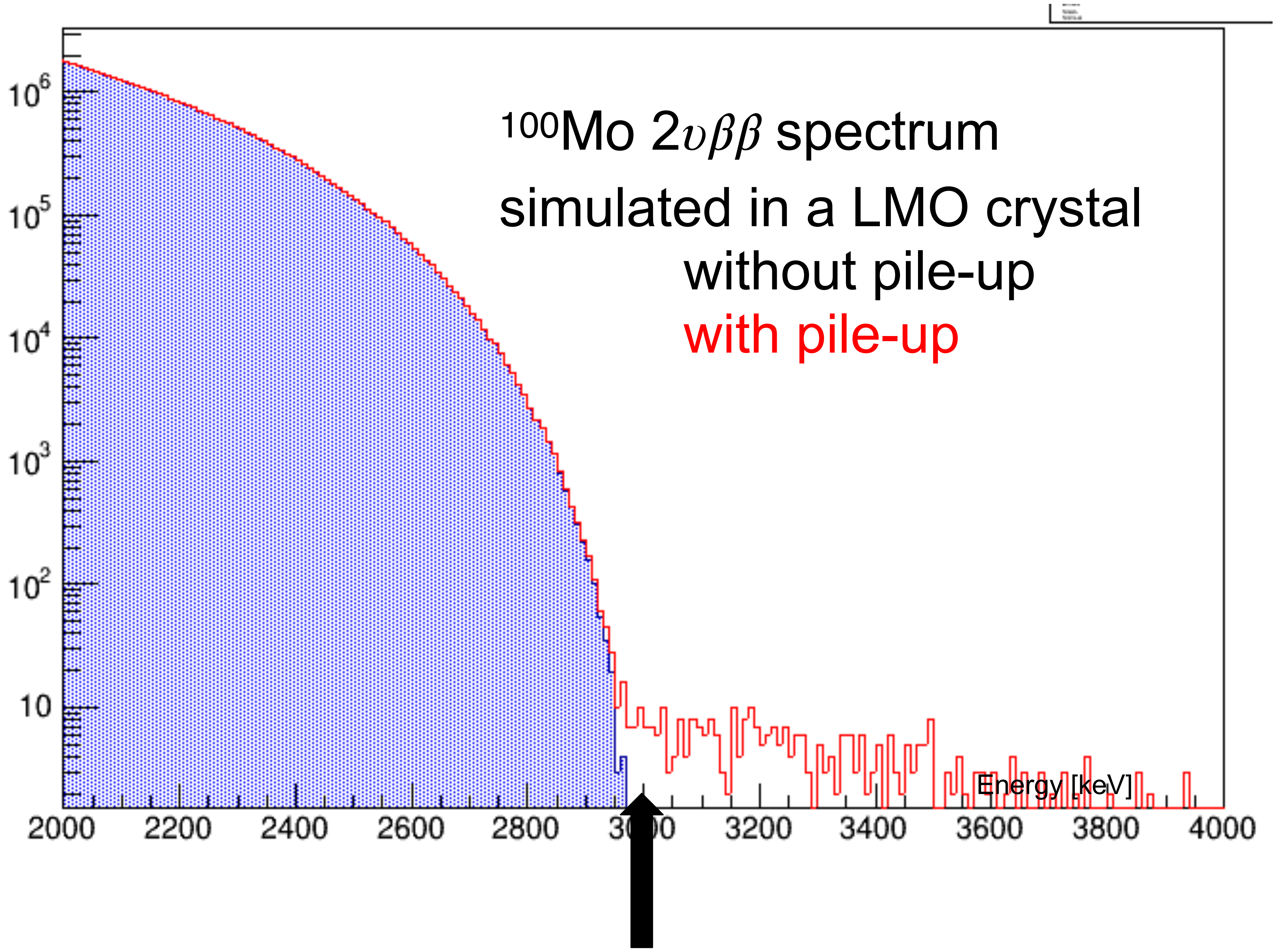
The path to achieve the CUPID background goal is well understood and conservative

Background from ^{100}Mo 2νββ Pileup

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

rate ~ 3 mHz/crystal

pile-up events may populate the 0νββ 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)

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CUPID Sensitivity to 0νββ

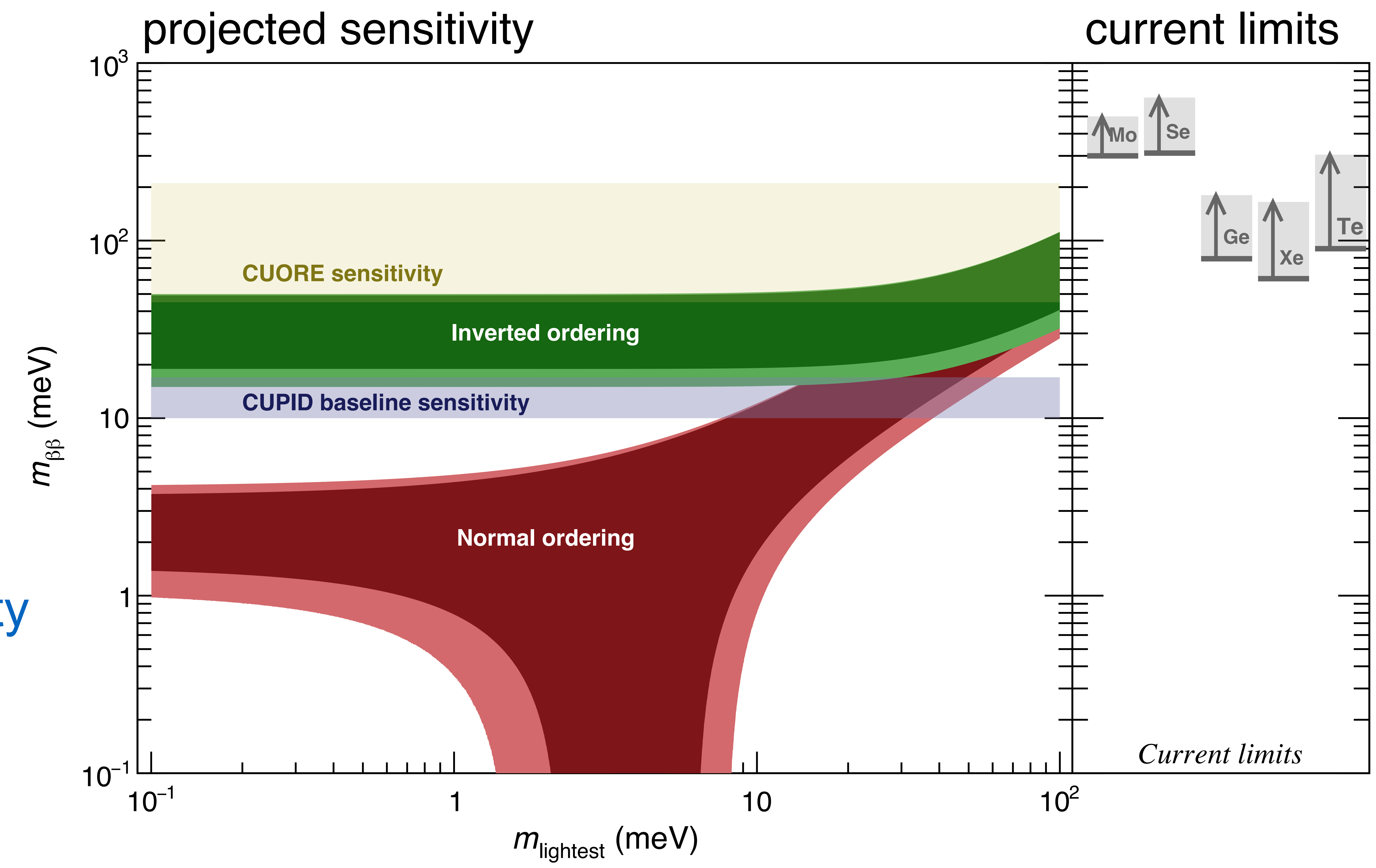
CUPID Baseline

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

CUPID Baseline Discovery Sensitivity

$T_{1/2}$ > **1.1x10^{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

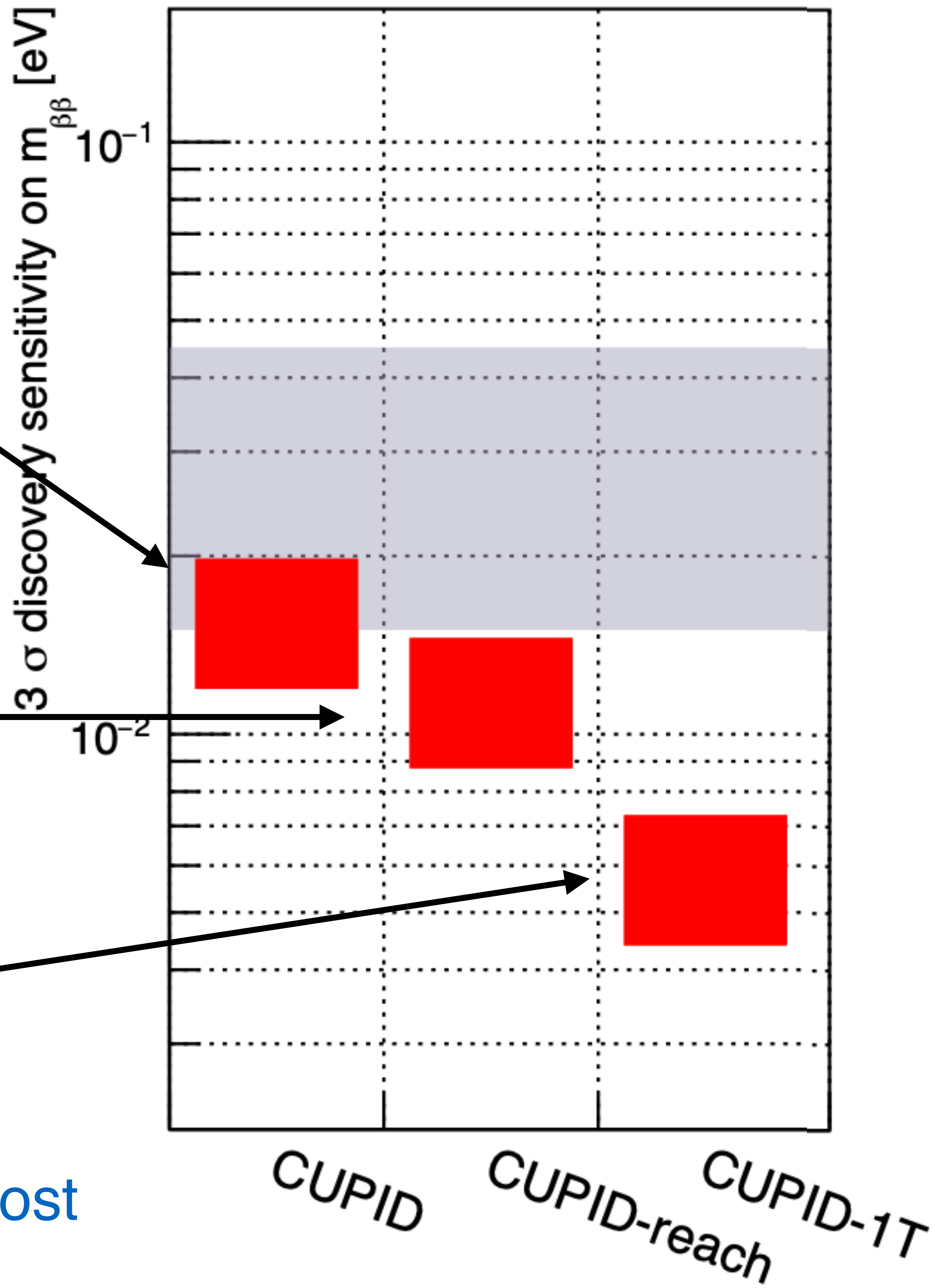
- Mass: 450 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$ (^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr
- Discovery sensitivity **$T_{1/2}$ > 1.1×10^{27} yr (3σ)**
- Conservative, limited R&D

Reach

- R&D for further background reduction by radio purity and reduce pileup background
- Discovery sensitivity **$T_{1/2}$ > 2×10^{27} yr (3σ)**

1-Ton

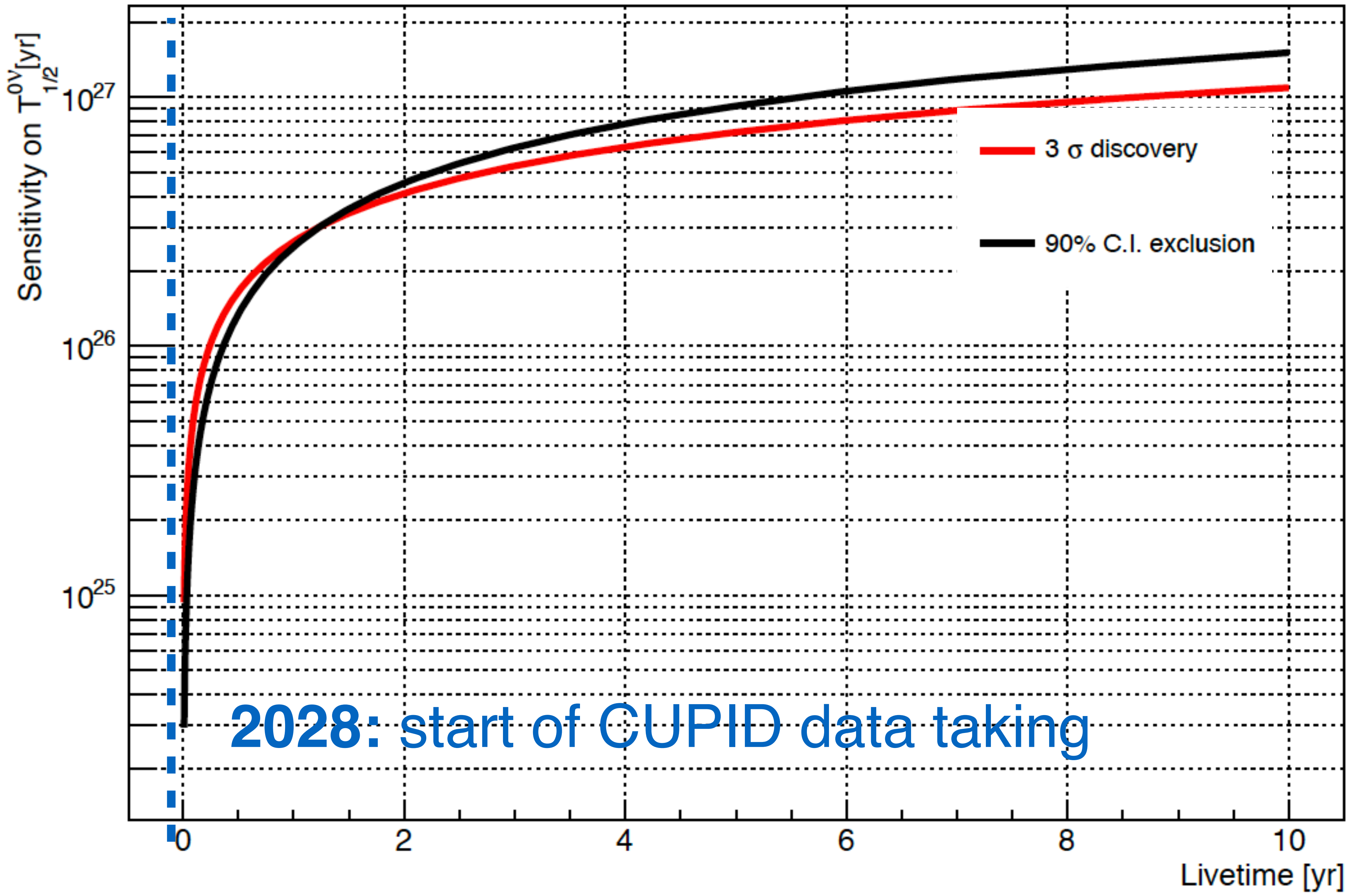
- 1000 kg of ^{100}Mo
- Discovery sensitivity **$T_{1/2}$ > 8×10^{27} yr (3σ)**



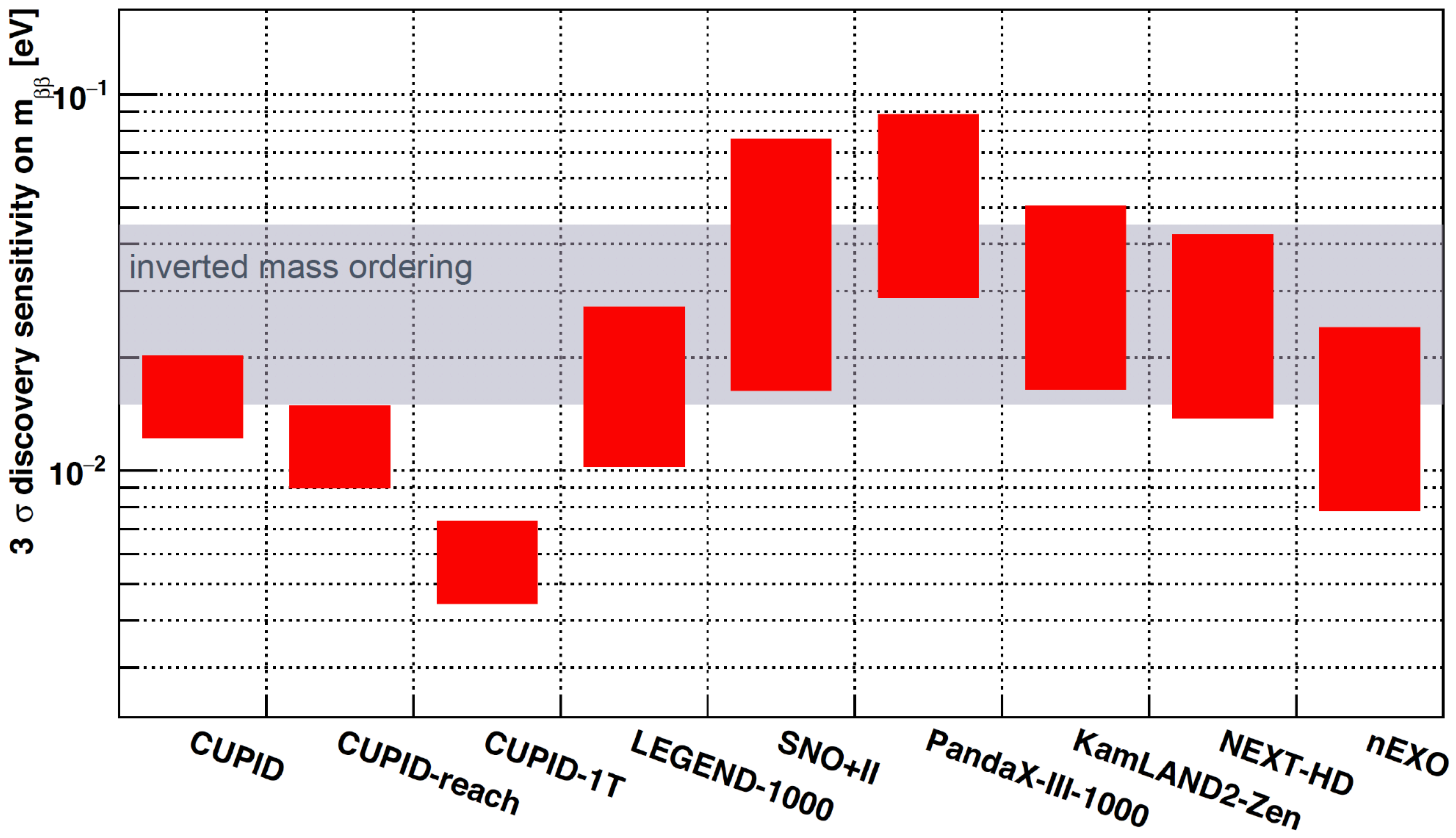
CUPID-1T is within technical reach, limited by timeline and cost

Timeline and Discovery Sensitivity

Discovery Sensitivity and Lifetime



Worldwide context



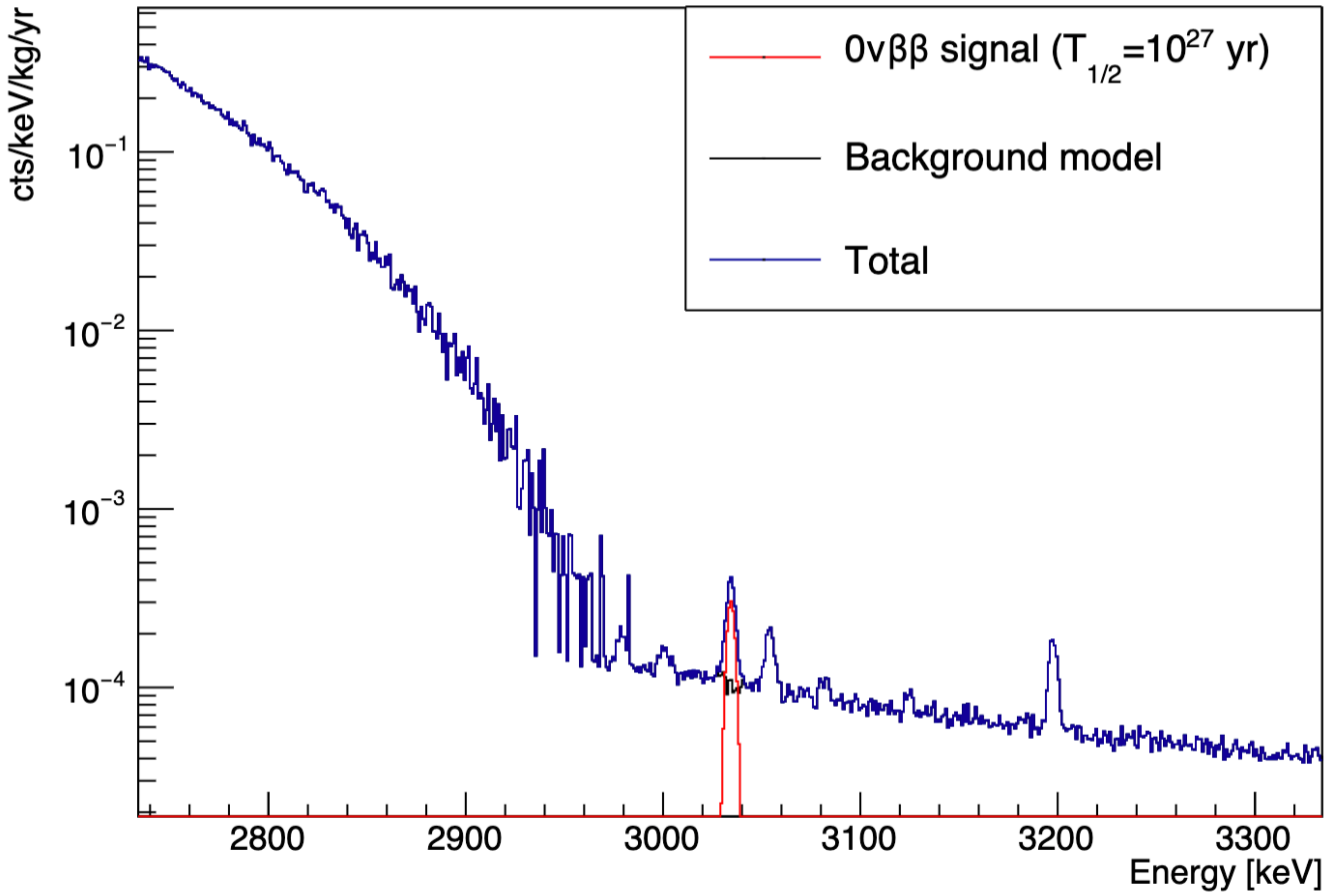
2024: completion of CUORE data taking

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

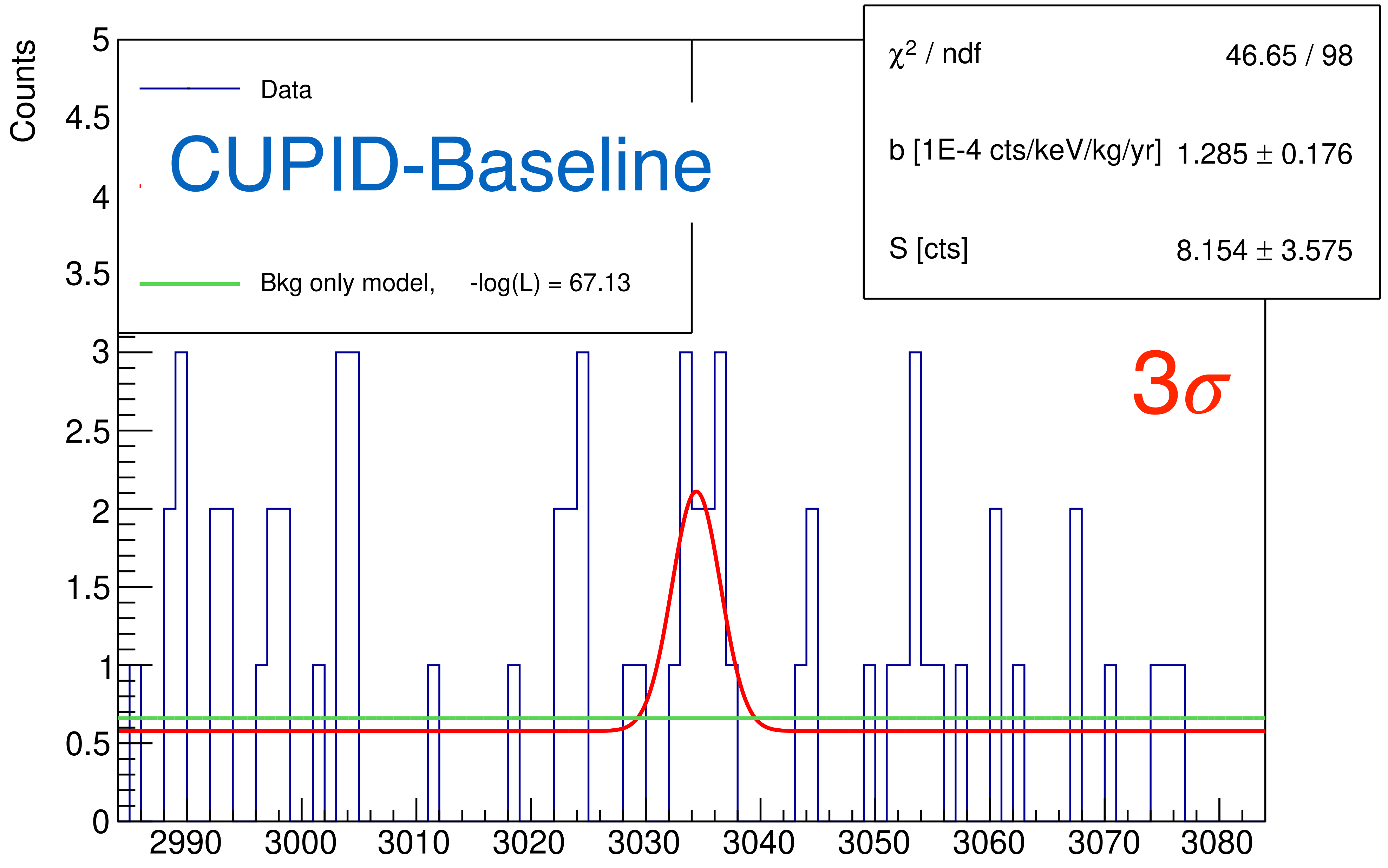


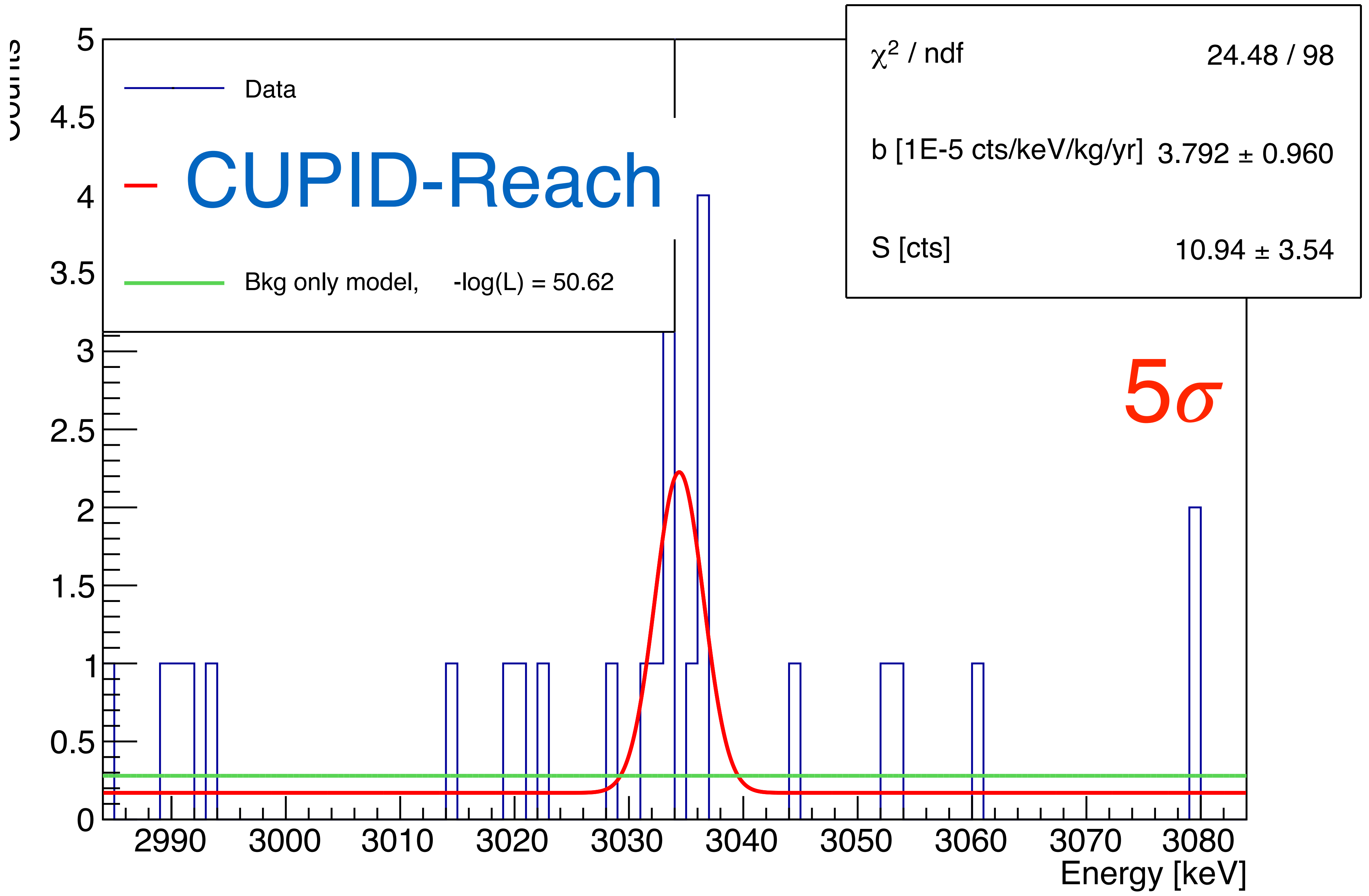
Example of toy experiments simulated for 10-year exposure and $T_{1/2}(^{100}Mo)=10^{27}$ years.

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.

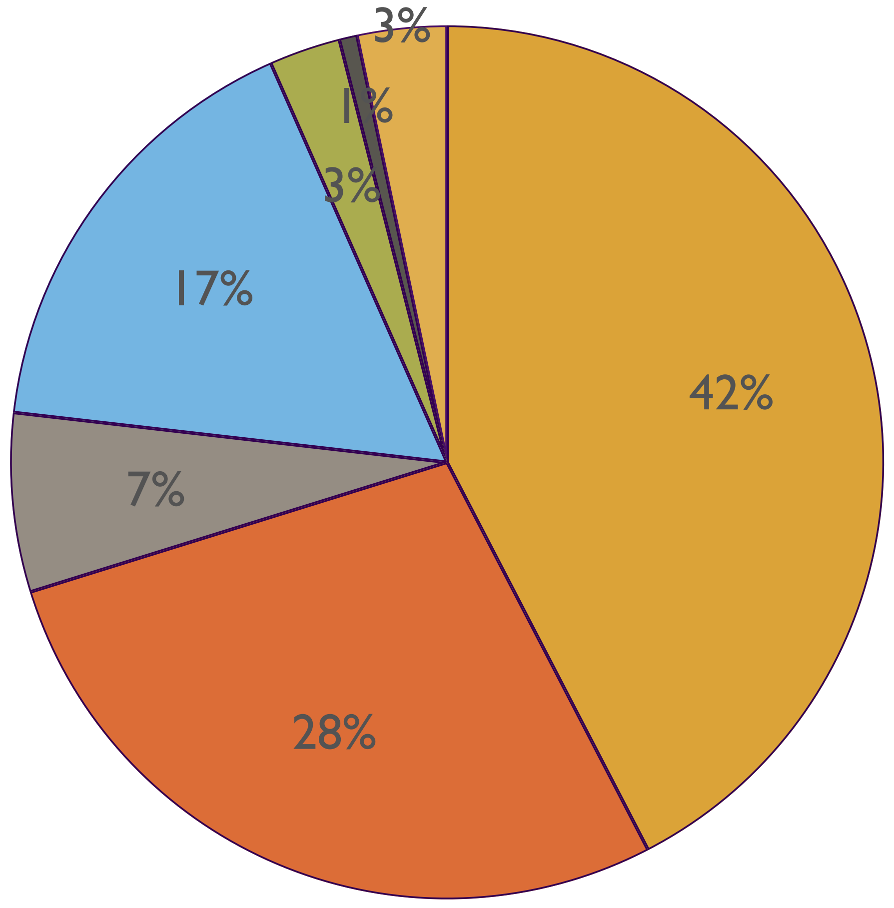




Collaboration

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



Italy
USA
China
France
Russia
Spain
Ukraine

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 Univers
Yale University

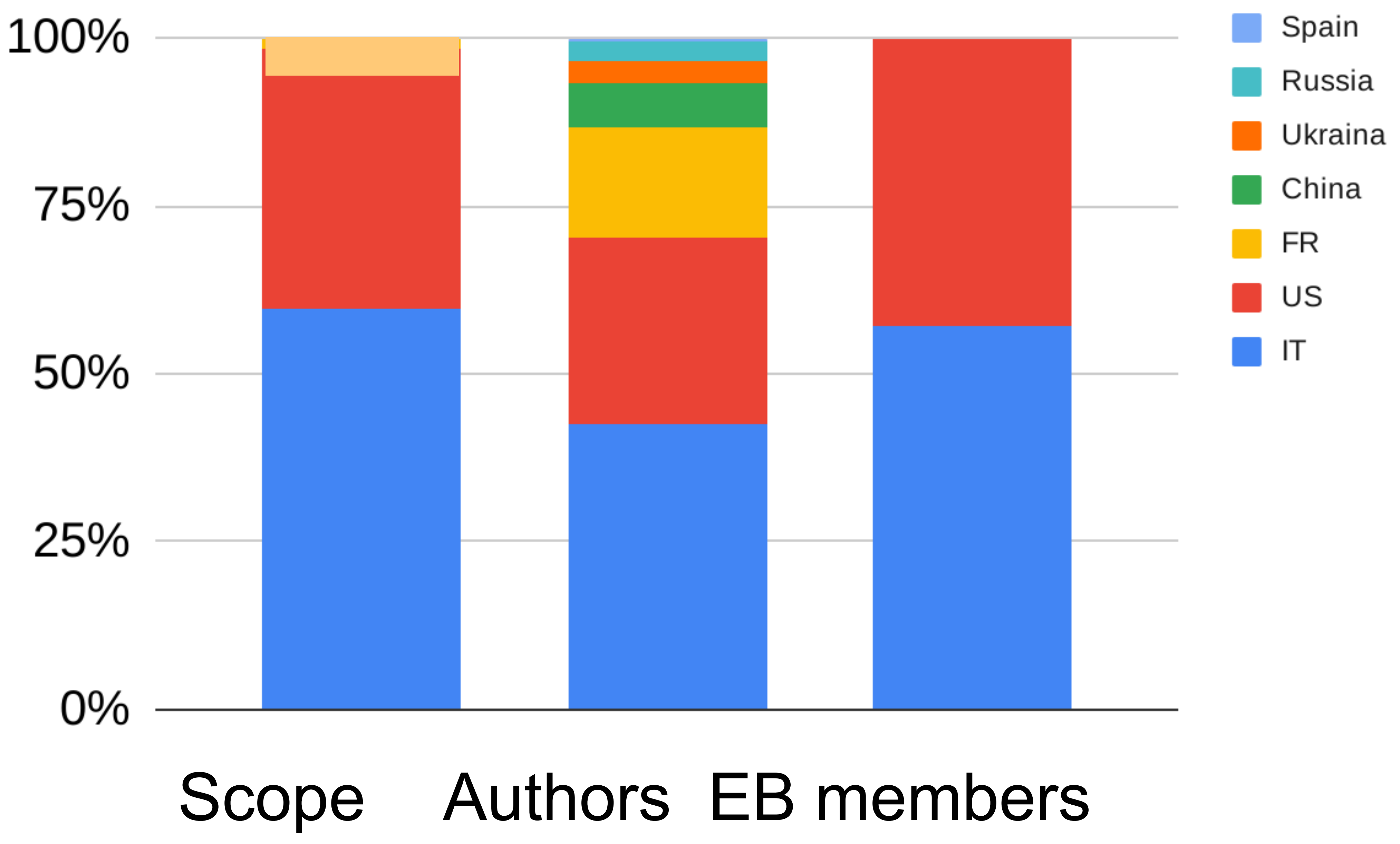
https://cupid.lngs.infn.it/

Collaboration

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

Project management has line responsibility for country's scope.

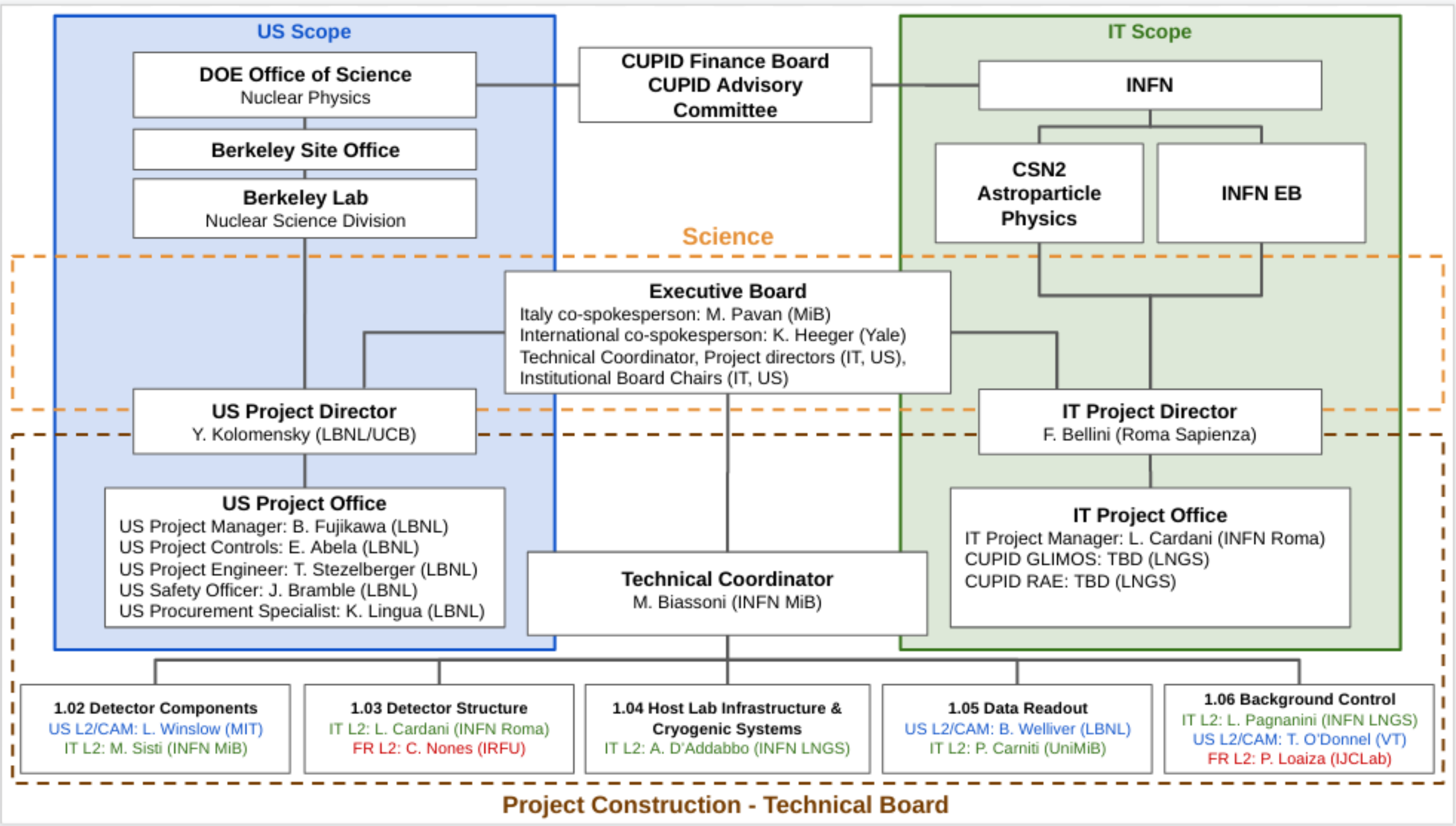
Inclusive collaboration, leverages international expertise, moderately correlated to funding.



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

Other participants: Russia, Ukraine, China, Spain

Project Structure



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Project structure reflects Italian-US scope.

Project & WBS

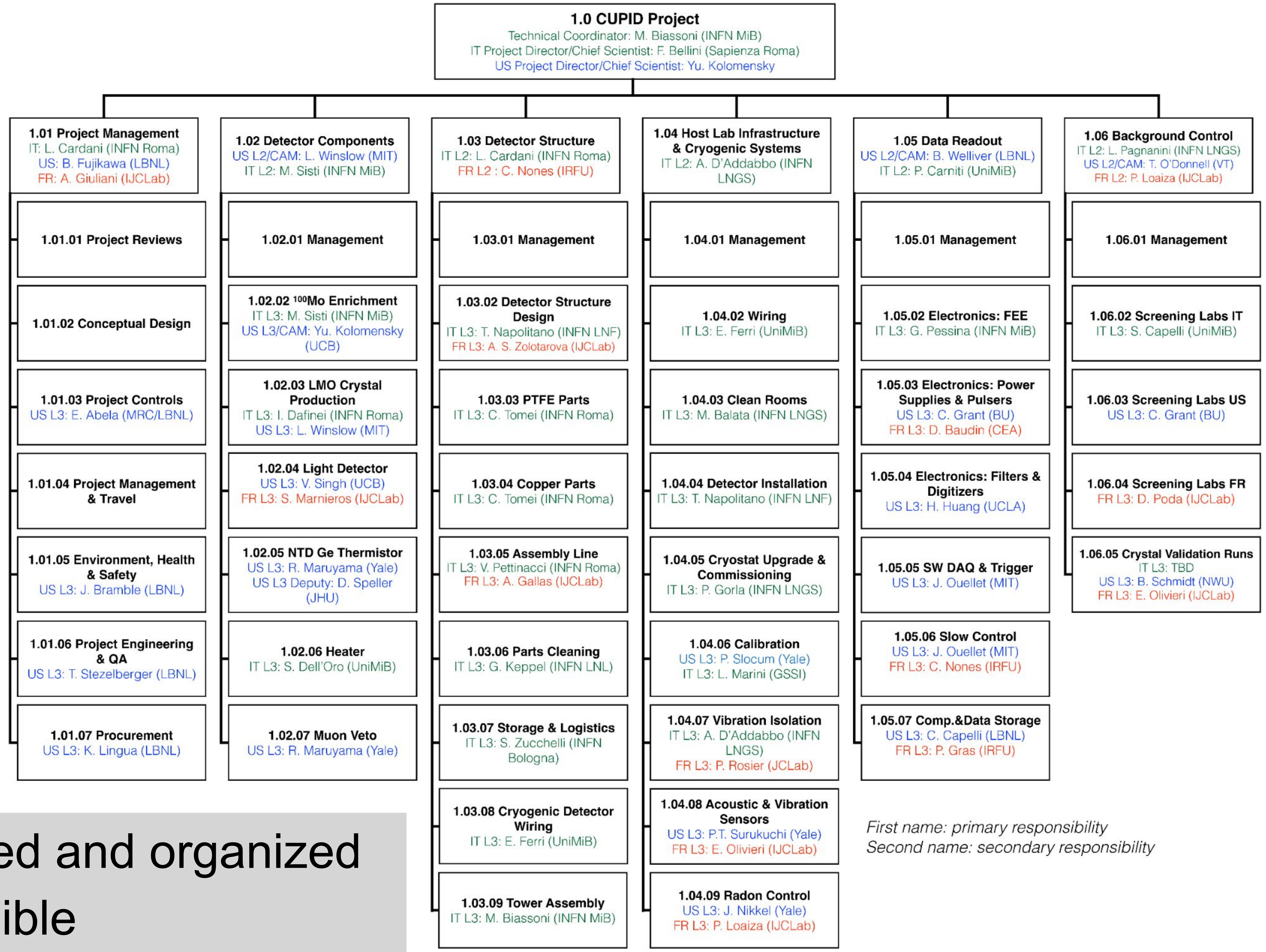
WBS 1.1 management	WBS 1.2 detector components	WBS 1.3 detector structure	WBS 1.4 host infrastructure	WBS 1.5 data readout	WBS 1.6 background contro

what we have to do:

- array of 1596 LMO scintillating bolometers
- upgrade the cryogenic infrastructure
- install a muon veto + improve neutron veto

all these activities are organized in a **WBS**

a *human readable version* in backup slides

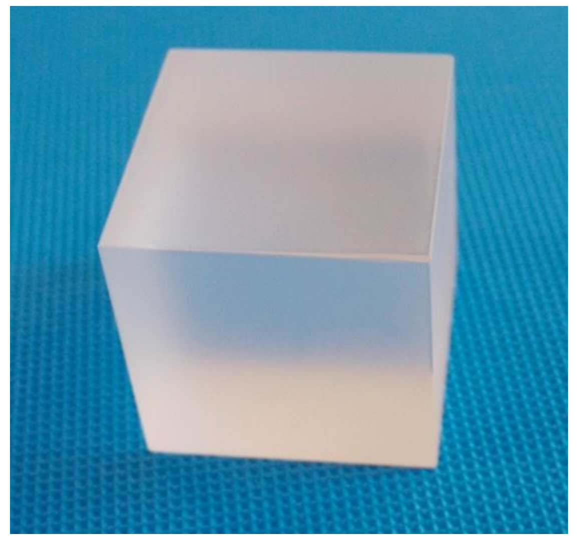


here the message is:

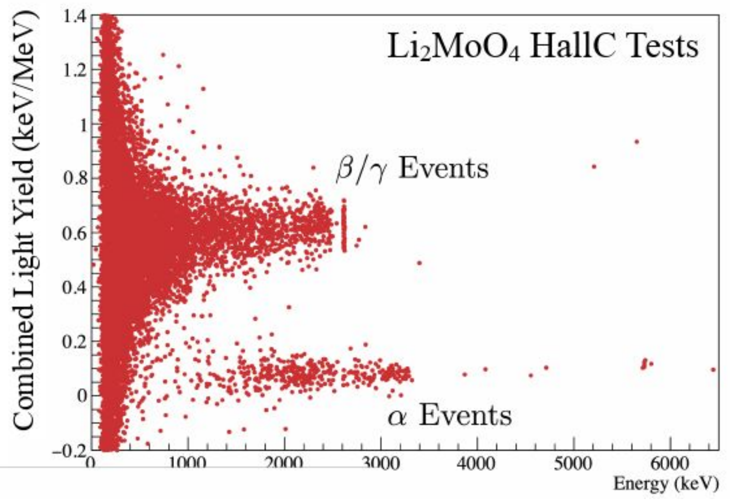
- all the needed activities are identified, described and organized
- for each activity we have one or more responsible
- the needed budget is known and detailed

Design Parameters

LMO crystals mass & i.a.



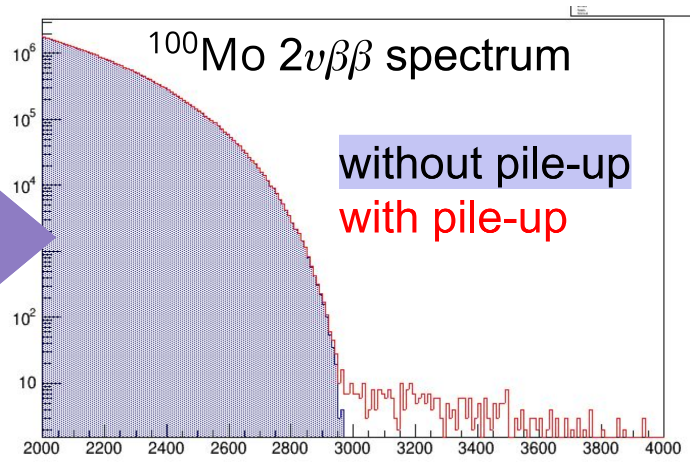
LMO performances



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)
α discrimination	99.9%

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 perform. pile-up rejection



Radiopurity

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Project Breakdown Structure

hierarchical oganization of project deliverables, it is organized in 4 systems each corresponding to a WBS system (two ways of looking to the organization: WBS-how PBS-what. PBS is a collection of data-sheet.

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Project Breakdown Structure

CUPID

next slides discuss PBS considering

- **validation of the adopted technological solutions**
- **priorities**
- **readiness & critical issue**

Readiness Evaluation Table			
Technology /Design	Design & Prototyping	Optimization	Engineering & Executive Drawings
Large Scale Production	To be organized	Plan ready	Ready to start
Radioactivity	Material assay to be done	Selection on-going	Requirements fulfilled

T
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- **risks**

Risk	Severity	Probability	Mitigation
description risk #1	high	low	...
description risk #2	medium	low	...

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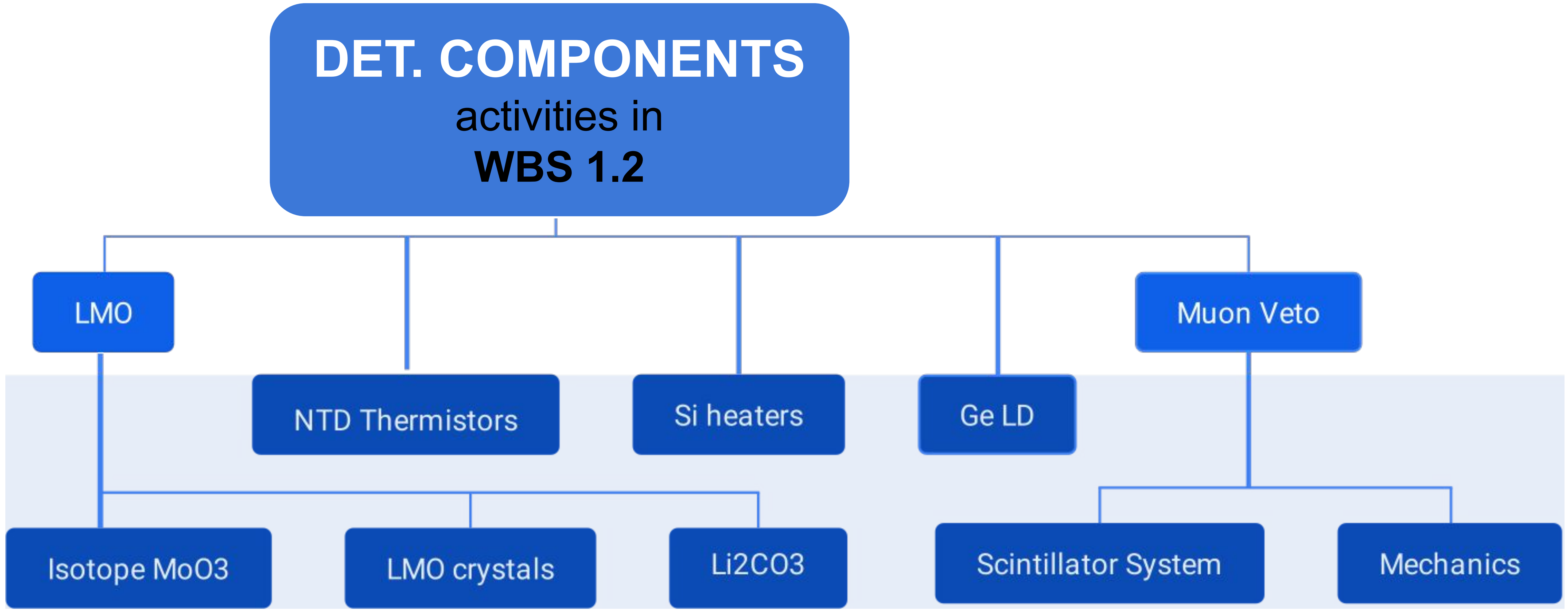
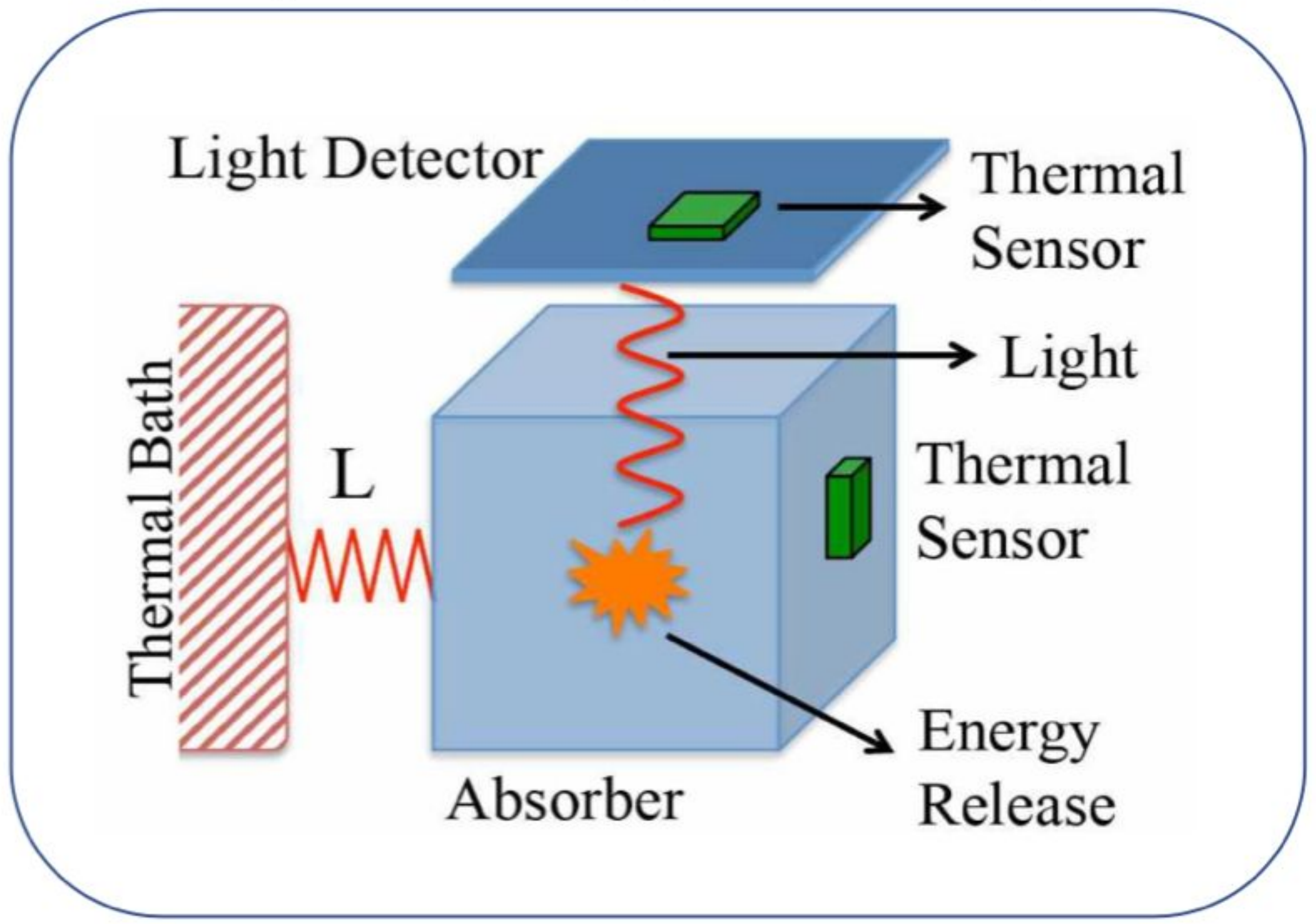
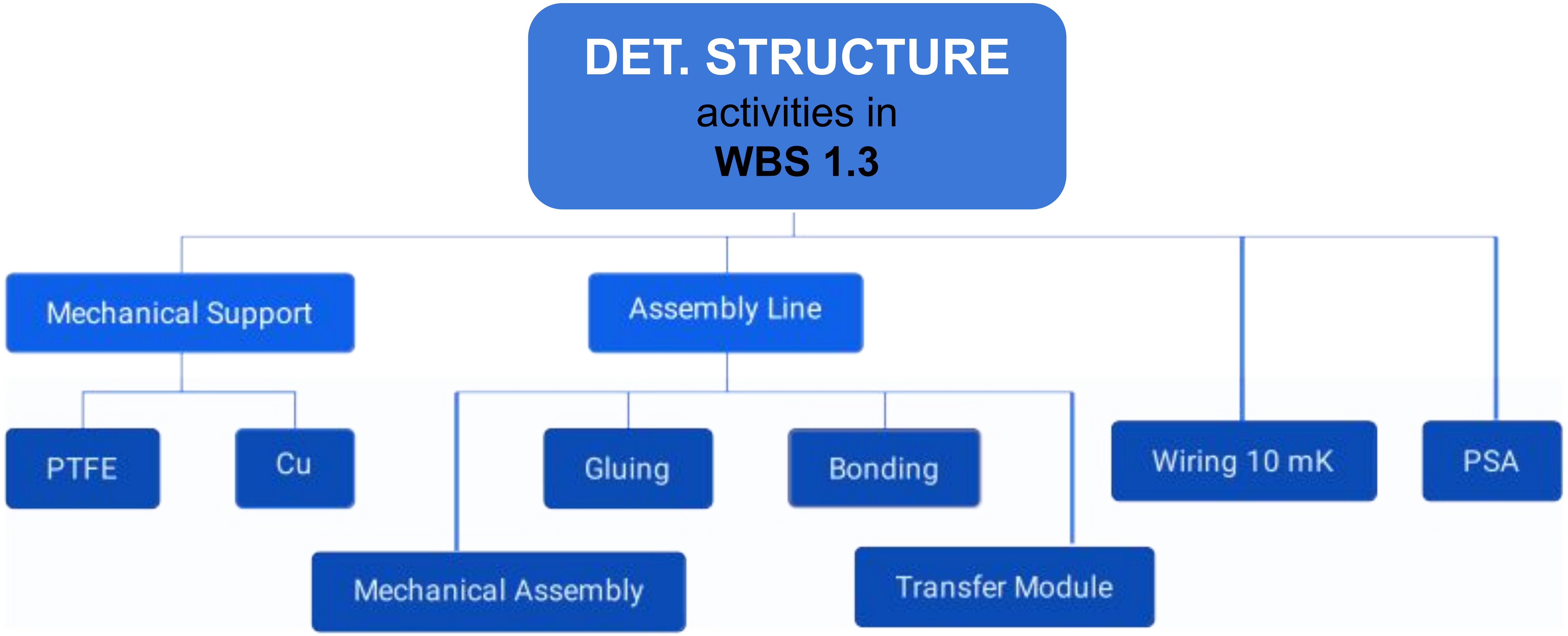




- **validation of the adopted technological solutions and critical issues**
  - CUPID-0 and CUPID-Mo have extensively proved scintillation bolometer technology & a particle rejection
  - CUPID-Mo proved LMO performances and radiopurity
  - Hall-C measurements proved CUPID-like LMO-crystal performances

- **priorities**
  - **1st priority is choice of isotope purity (critical path) two purity levels (two prices) Italy and France have purchased crystals grown with the two types and will soon measure them**
  - **2nd priority is optimization of pile-rejection (multi front approach, involves more WS)**

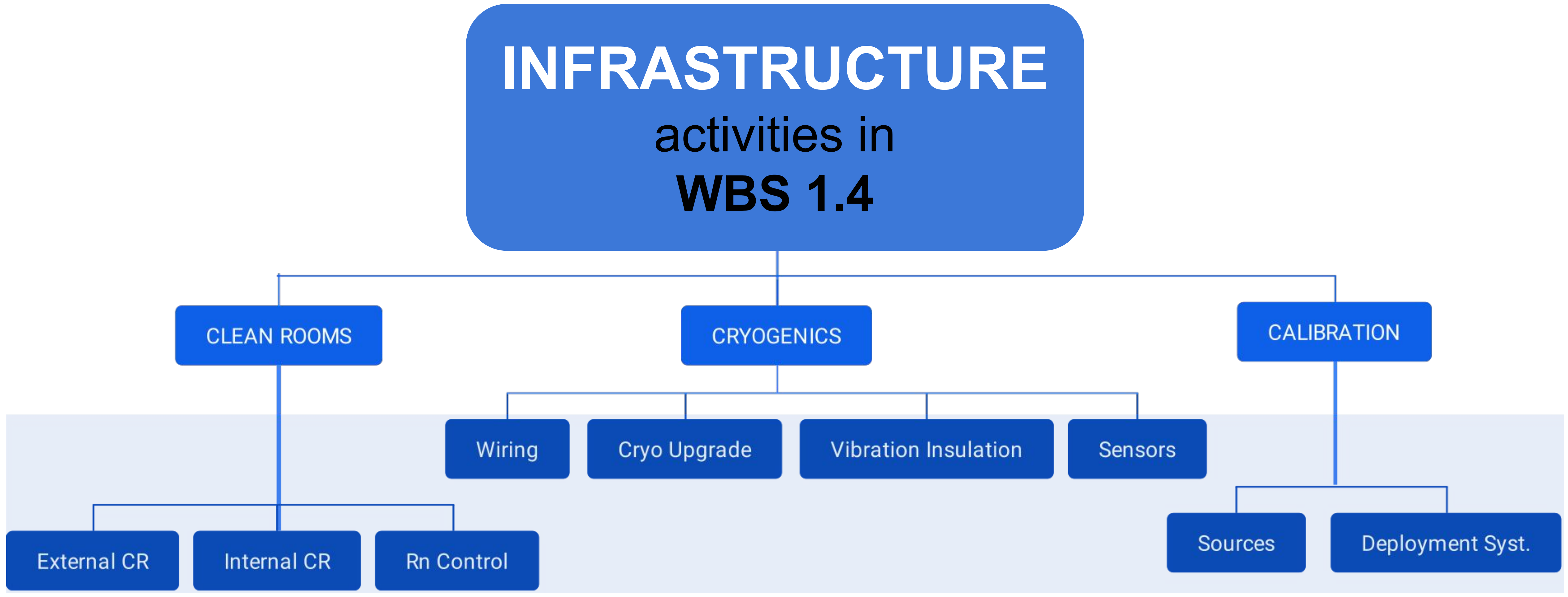
- **readiness & risk** backup slides

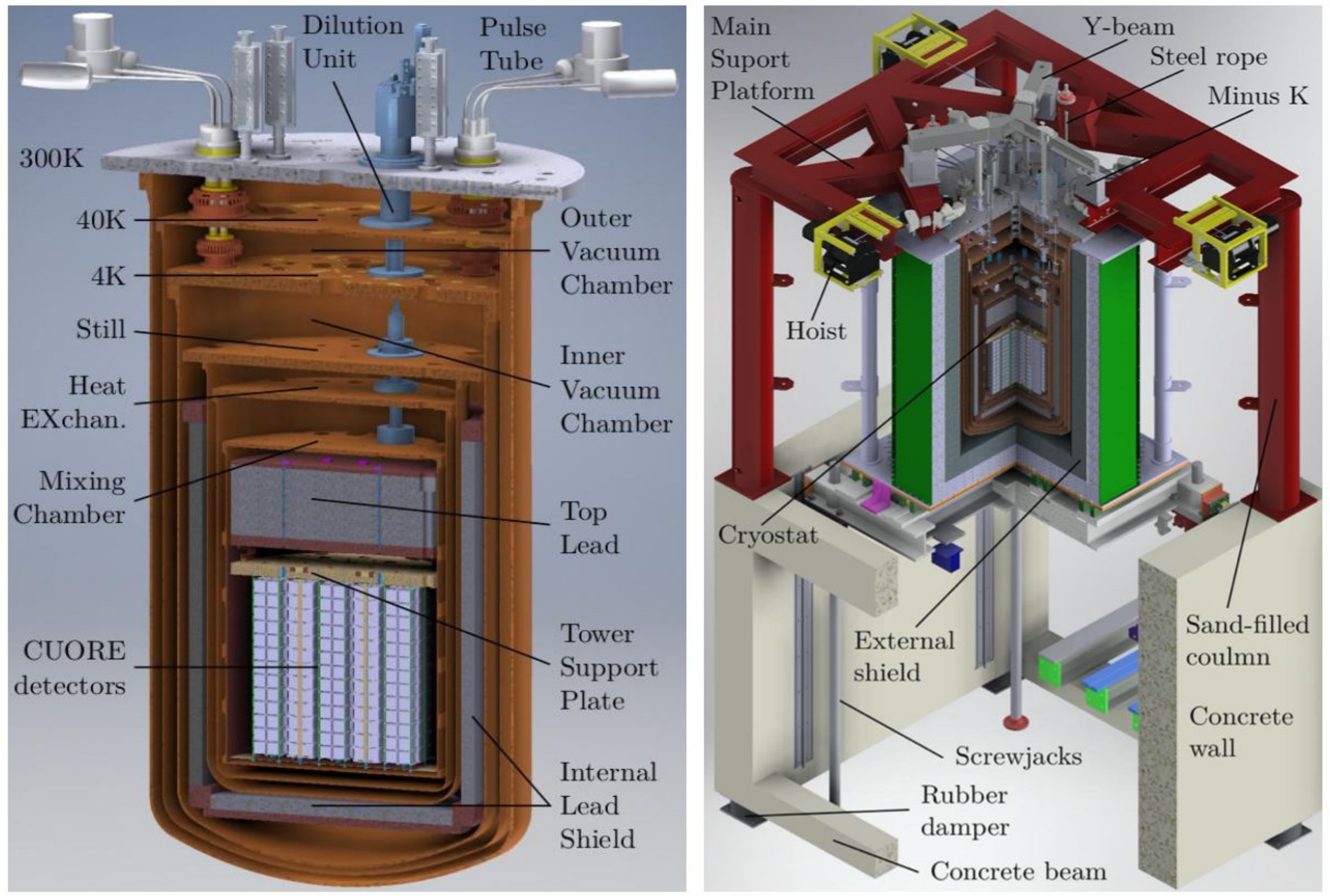


- **validation of the adopted technological solutions & critical issues**
  - **innovative mechanical design, it is based on the lessons learned in CUORE, small prototype tested, a CUPID-like tower operated by the end of the year (equivalent to CUORE-0)**
  - assembly line is designed on the basis of the CUORE one (988 detectors):
    - no crystals was damaged during assembly
    - 4 channels over 988 are disconnected (0.4% channel failure)

- **priorities**
  - freezing the **mechanical design of the detector array** (critical path)

- **readiness & risk** backup slides





- **validation of the adopted technological solutions, risks & critical issues**
  - CUORE cryostat is working with a 90% cryogenic livetime at 10 mK
  - additional heat load (3 times more wires) fully sustainable by the meas. cooling power of 4 μW @ 10 mK
  - lot of space to improvement in vibrational noise

- **priorities**

- **readiness & risk** backup slides

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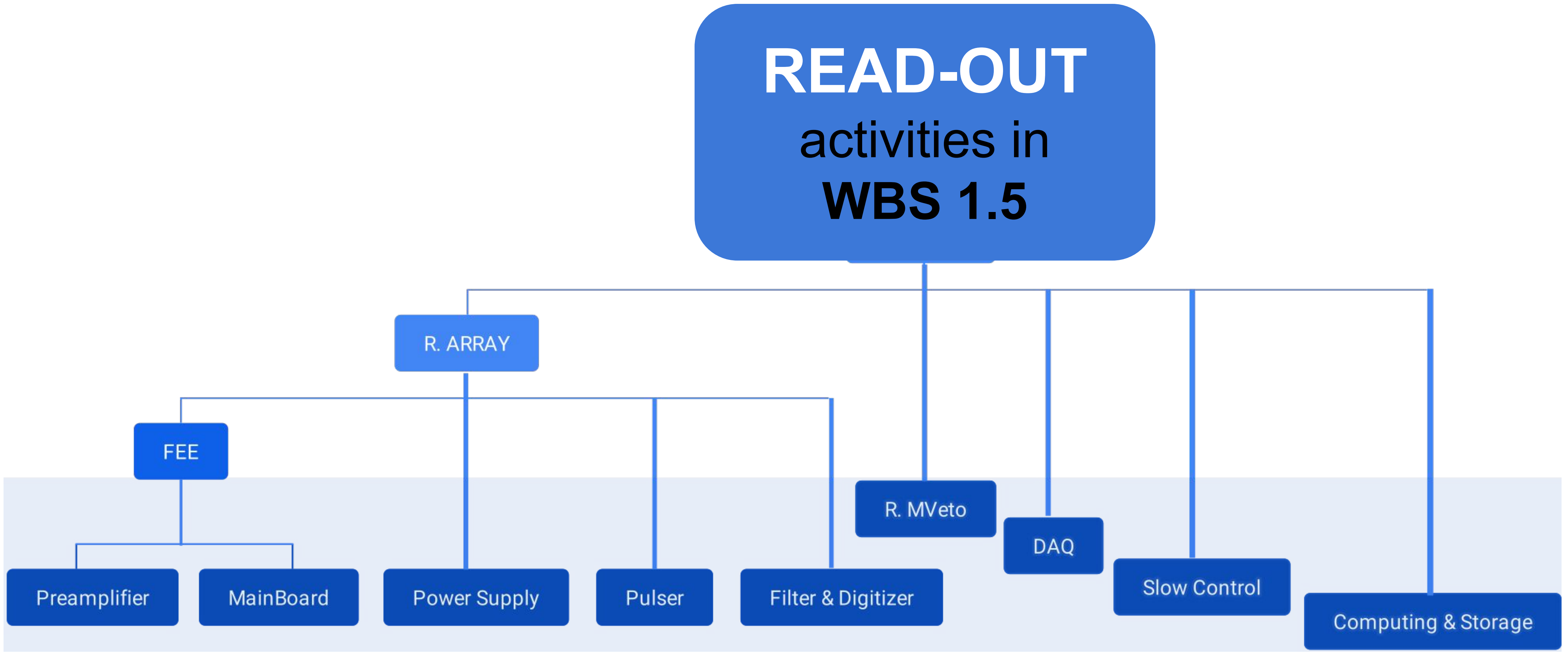
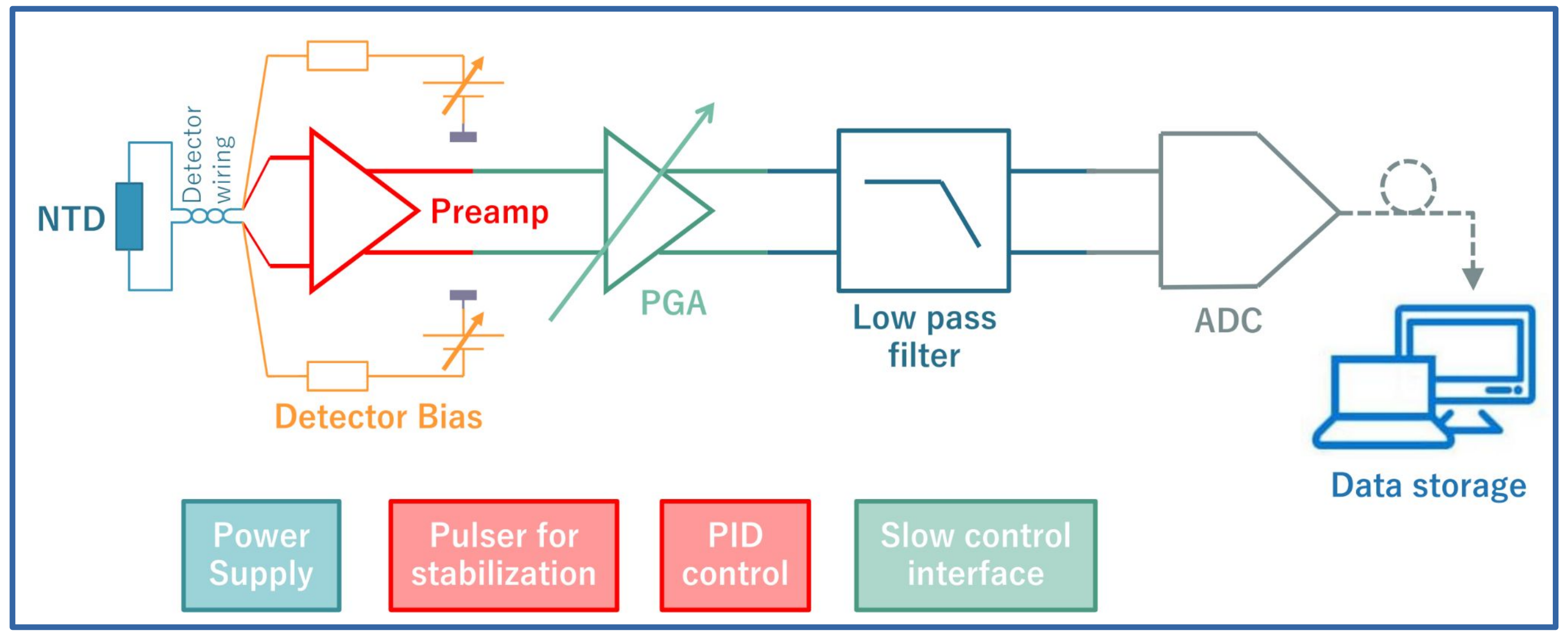
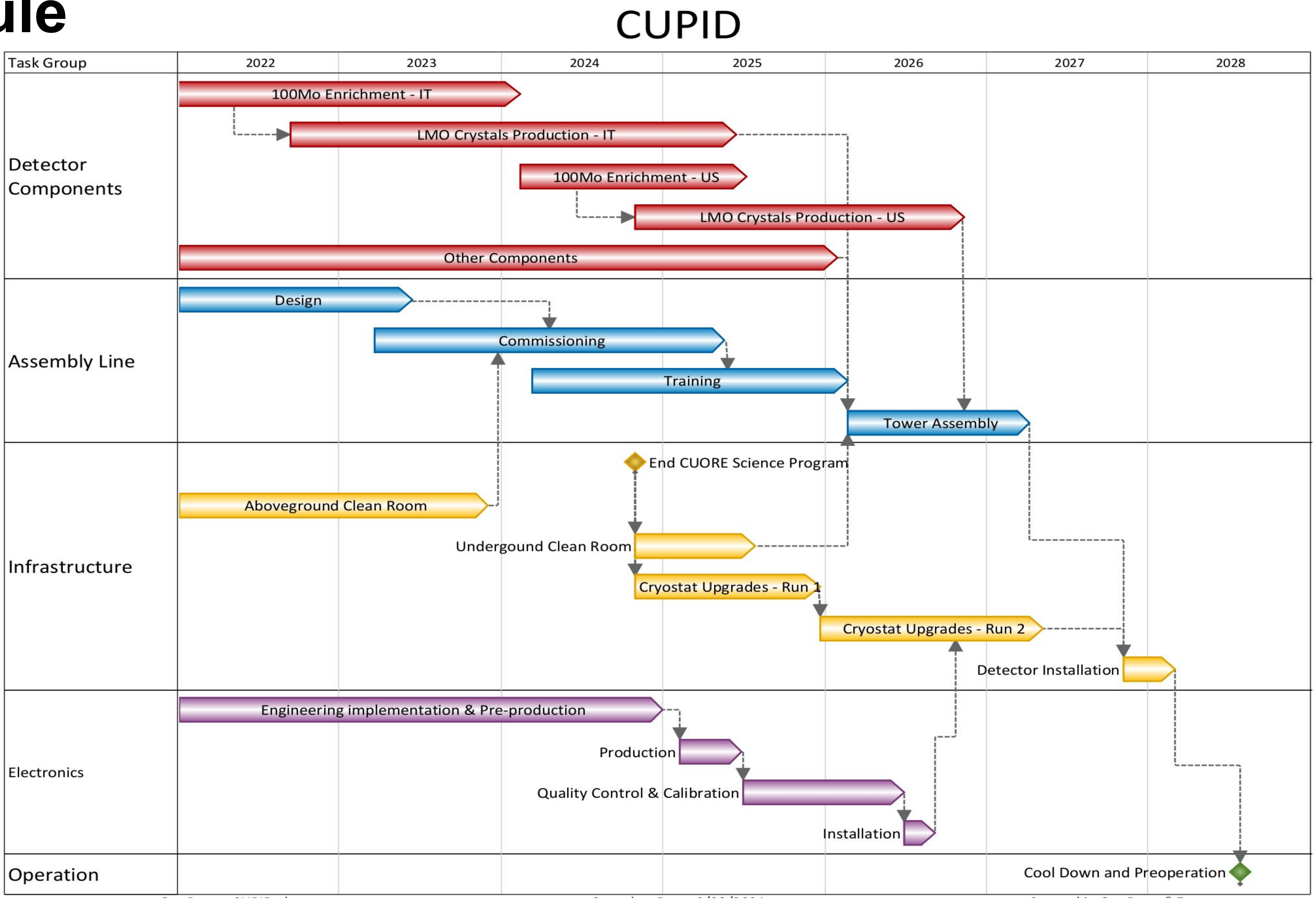




- **validation of the adopted technological solutions**
  - the read-out chain is an optimized version of the CUORE one already tested and matching CUPID requirements (main difference is in the integration of the digitized on the Bessel filter board and a design of the preamplifier that allows it to match requirements of both LMO and LD sensors.)
  -
- **priorities**

Schedule



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Budget

CUPID

due to different accounting rules in each country we compare the **Material & Service budget**

- no personnel
- no contingency

indirect costs, depending on the country, account for overhead, escalation, specific services of the Host lab (e.g. clean room for exclusive CUPID use …)

few changes with respect to July:

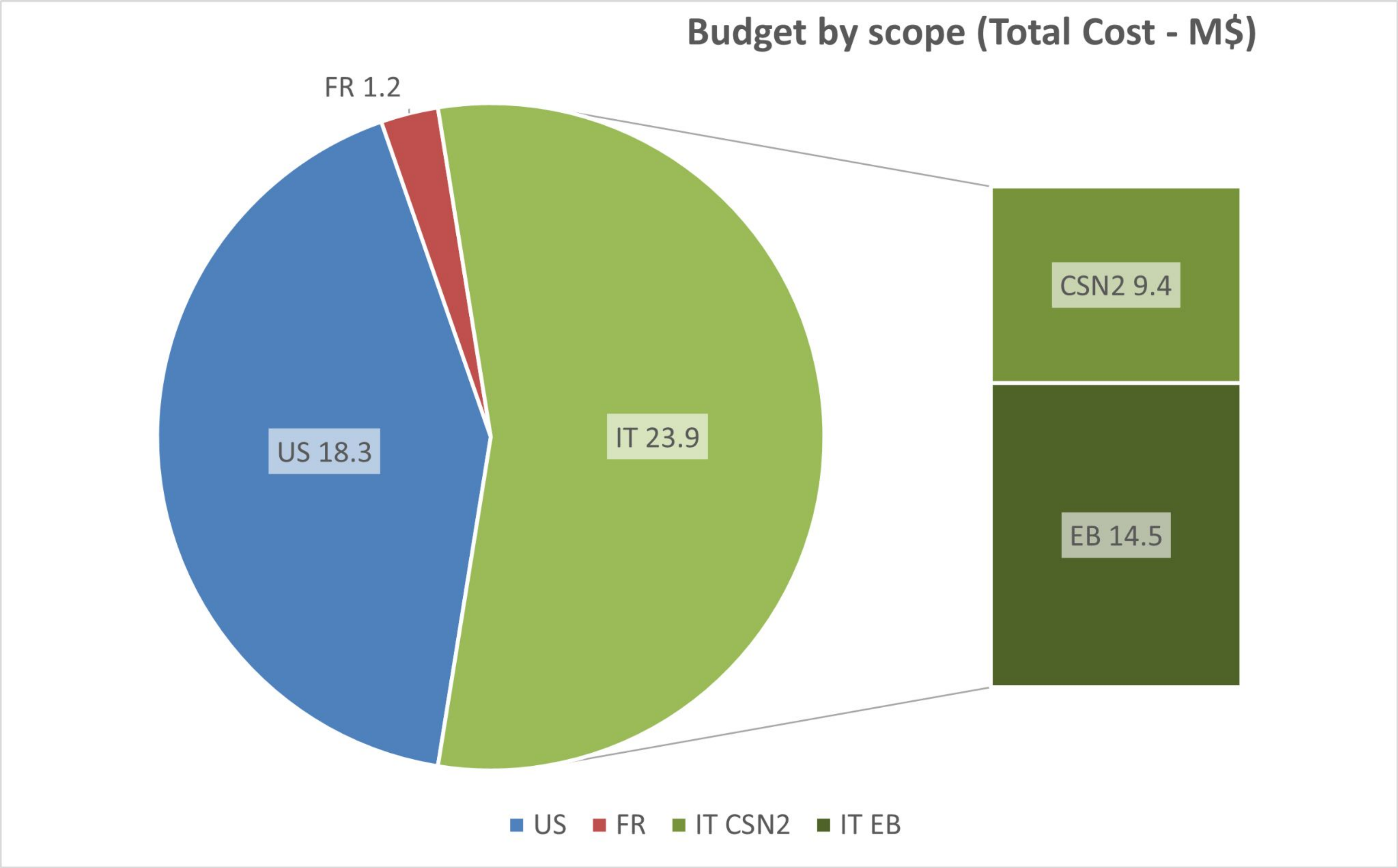
- Italy finalization of the budget
- France scope expanded (items previously in Italian scope), 1.2 M$ commitment (extra ~0.5 M$ under discussion)
- US budget & scope unchanged

Country	M&S base k$	M&S contingency k$	In-kind k$	Total equipment k$
Italy	22,781	5,867	7,479	36,126
USA	18,257	4,740	494	23,491
France	442	0	590	1,032
Total	**41,480**	**10,607**	**8,563**	**60,650**

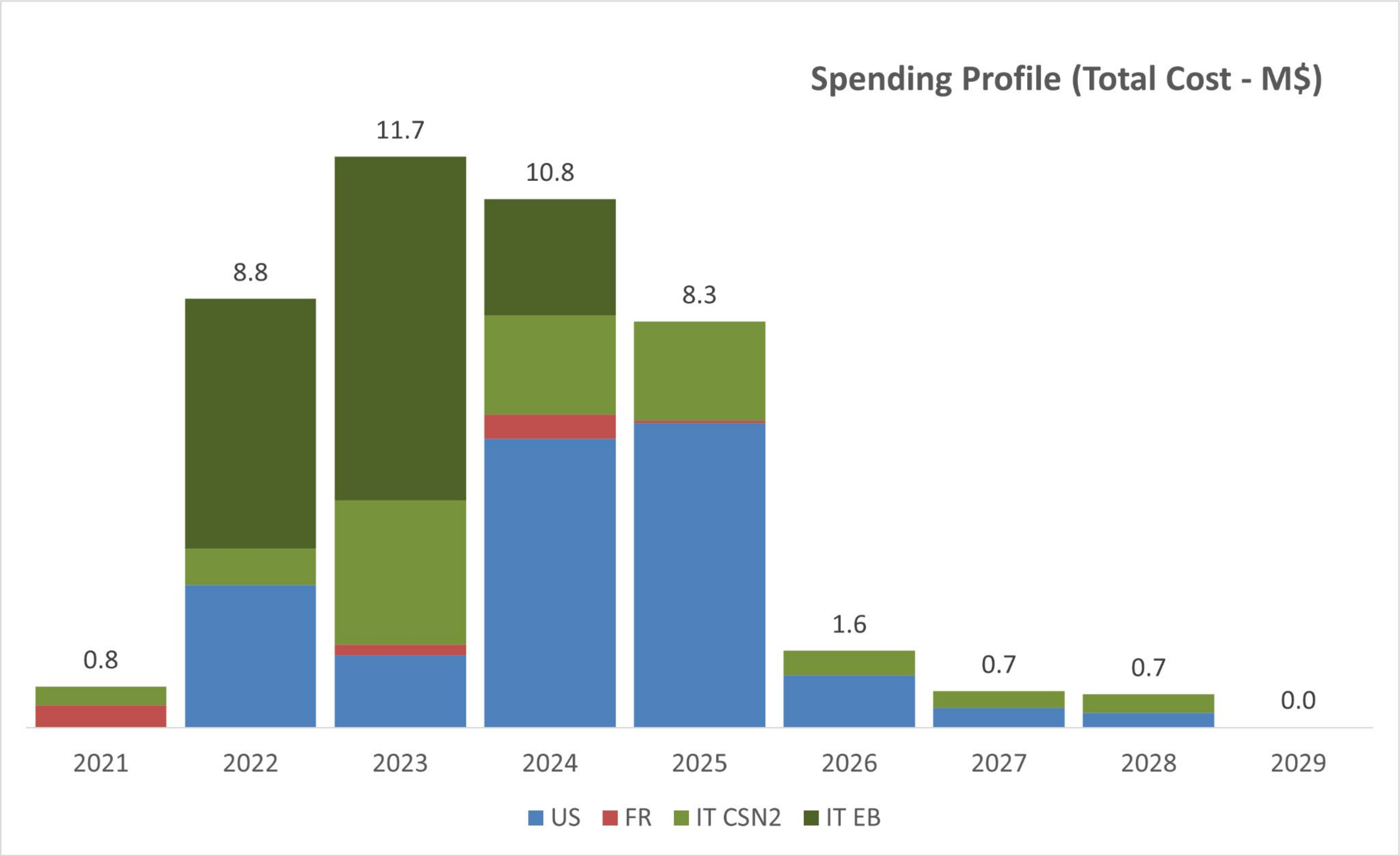
unaccounted: LNGS infrastructure (safety, power supply, water)

Country	direct k$	indirect k$	anticipated	M&S base k$	+ in-kind
Italy (INFN)	**22.2**	**1.3**	**0.4**	**23.9**	**7.5**
USA (DOE)	**16.4**	**1.9**		**18.3**	**0.5**
France (CEA+IN2P3)	**0.8**		**0.4**	**1.2**	**0.6**
Total				**43.5**	**8.5**

M&S Base k$



Budget by scope (Total Cost - M$)
FR 1.2
US 18.3
IT 23.9
CSN2 9.4
EB 14.5
US
FR
IT CSN2
IT EB



Spending Profile (Total Cost - M$)
0.8
8.8
11.7
10.8
8.3
1.6
0.7
0.7
0.0
2021
2022
2023
2024
2025
2026
2027
2028
2029
US
FR
IT CSN2
IT EB

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,** $m_{\beta\beta} \sim$ **12-20 meV)**
- **Builds on an existing and well-functioning international collaboration** and 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 mode**l 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