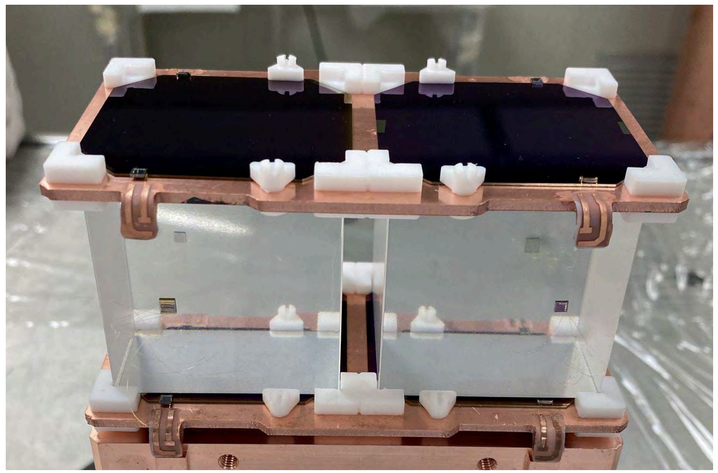
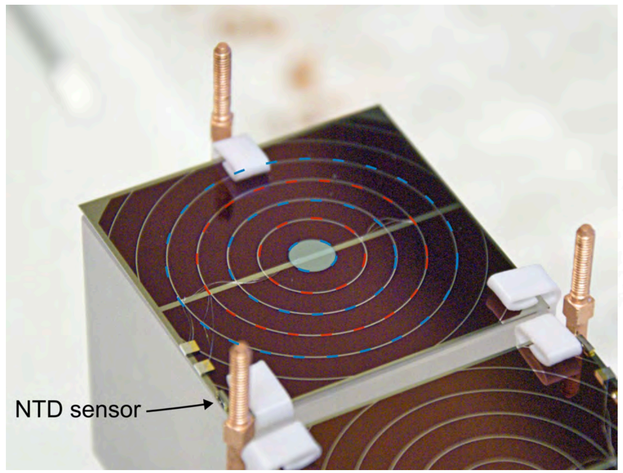
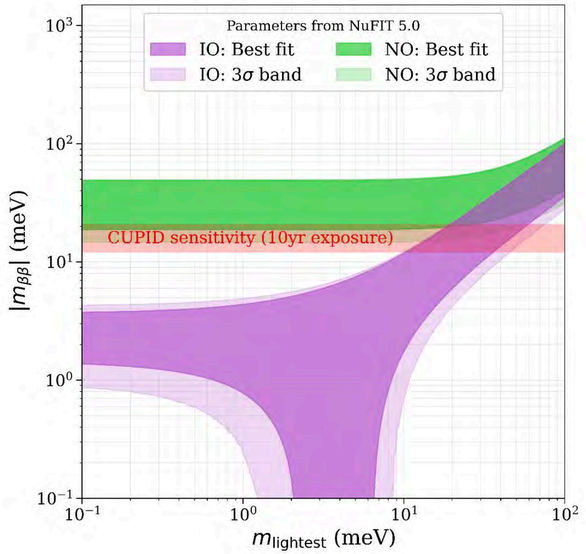
# CUPID
# CUORE Upgrade with Particle Identification






Karsten Heeger and Maura Pavan

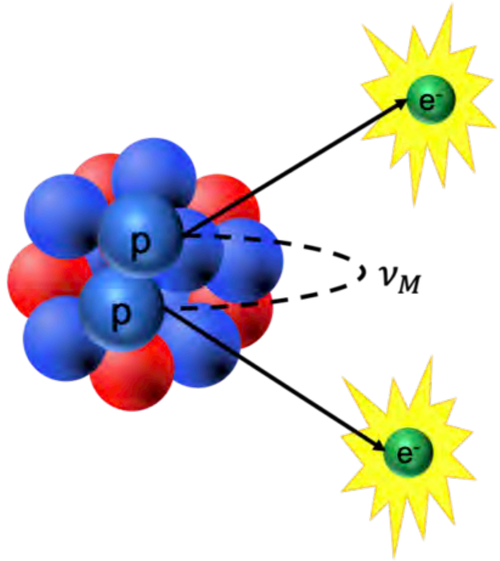
*co-spokespersons on behalf of the CUPID Collaboration*

October 3, 2024

# A 0νββ Discovery Program

The observation of 0νββ would reveal the quantum nature of the neutrino and revise our understanding of physics

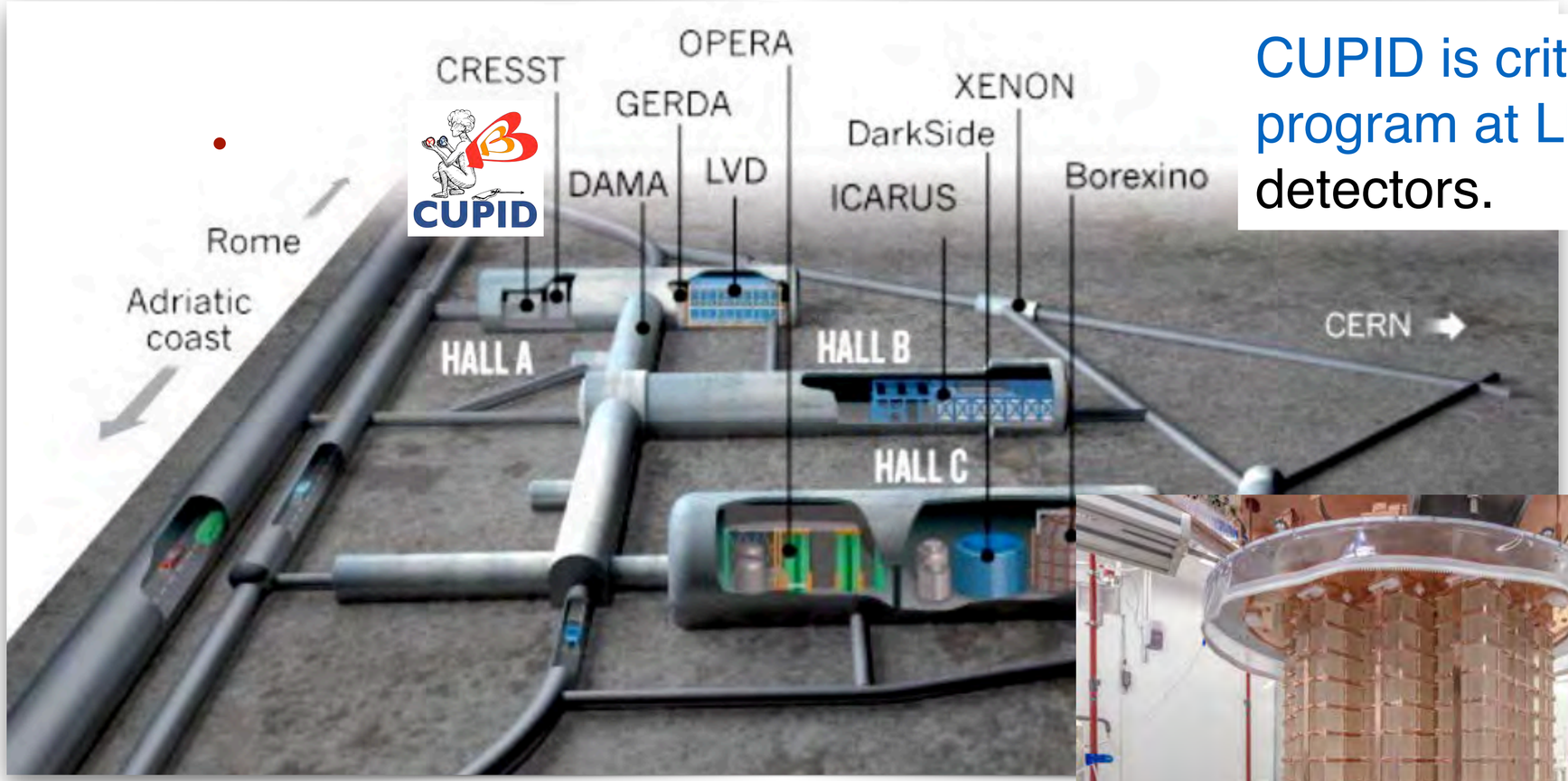
- Matter creation (Lepton number is not conserved)
- The neutrino is its own anti-particle  (Majorana particle)
- Provide a mechanism for generating the predominance of matter to antimatter in the cosmos (the matter - antimatter asymmetry).
- Demonstrate a new means for the generation of mass



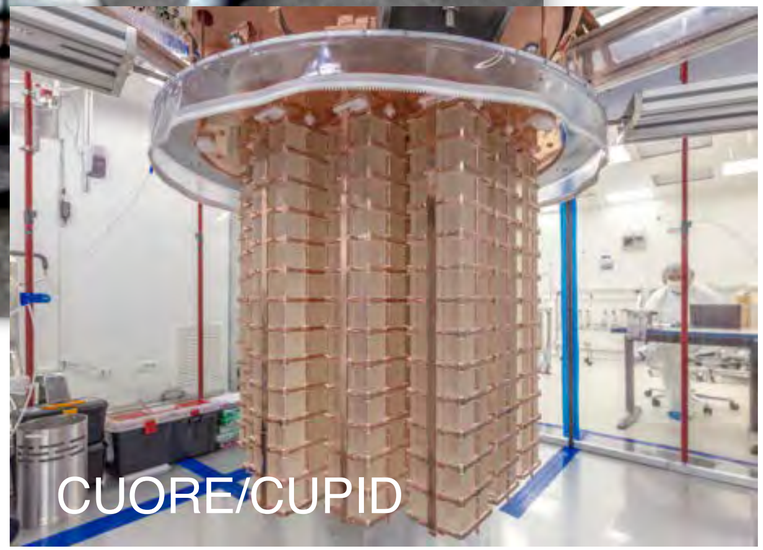

Requires a discovery program with high-resolution detectors and multiple isotopes.

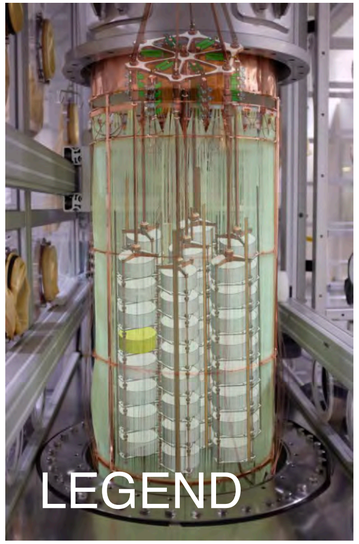
**CUPID is critical to the discovery program at LNGS.**

# A 0νββ Discovery Program at LNGS




CUPID is critical to the discovery program at LNGS with high resolution detectors.




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

# CUPID: CUORE Upgrade with Particle Identification

## Single Detector

$Li_2{}^{100}MoO_4$, 45x45x45 mm, 280 g

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

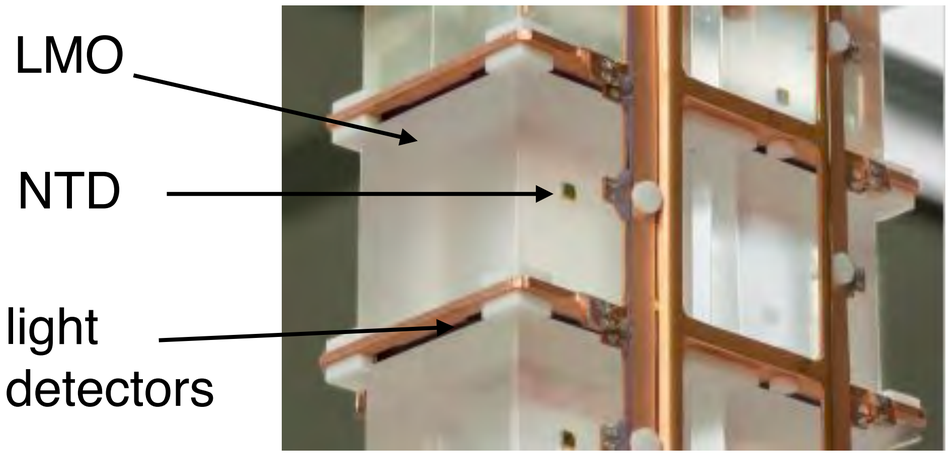
## Detector Array

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

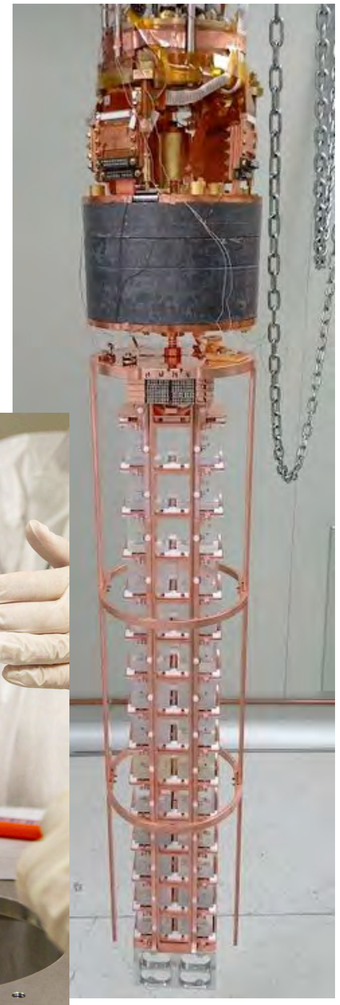
~$1.6.10^{27}$ $^{100}Mo$ atoms

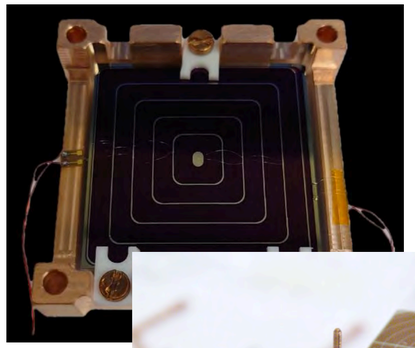
57 towers of 14 floors with 2 crystals each, 1596 crystals

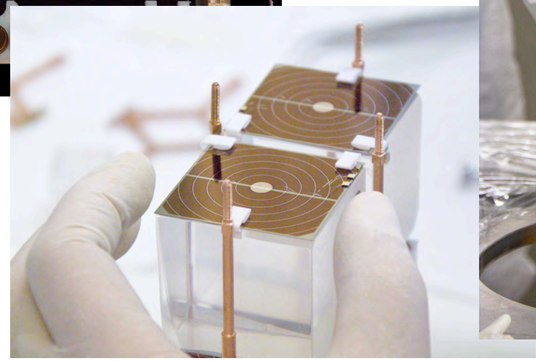
Opportunity for staged deployment

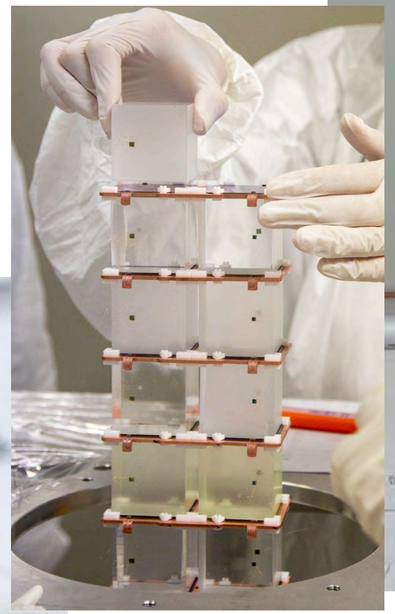



single tower









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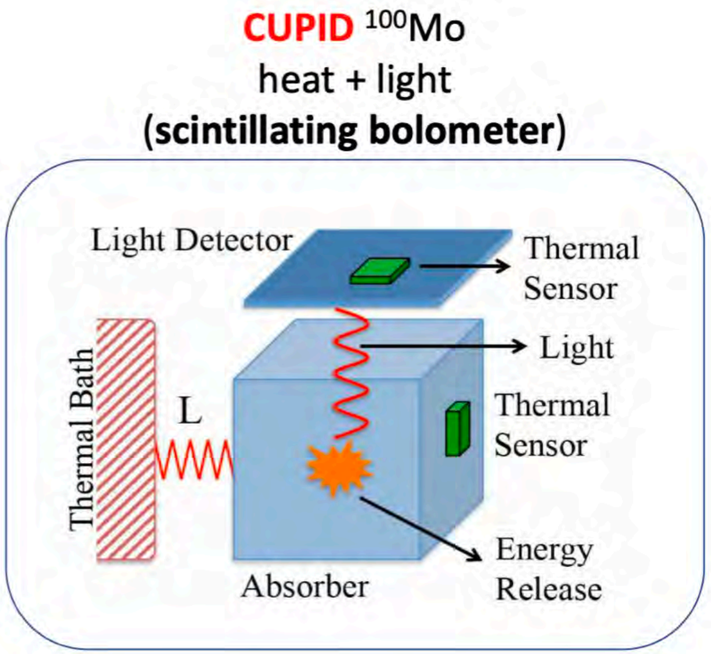
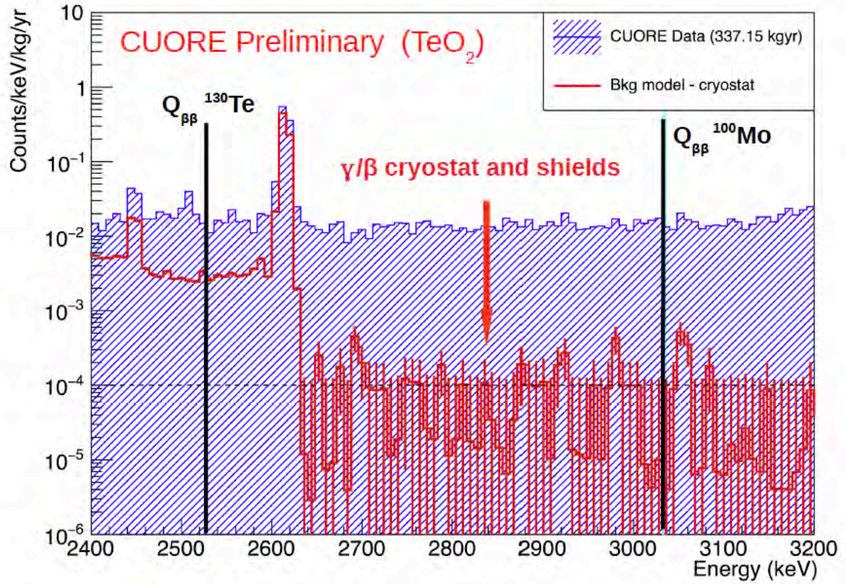
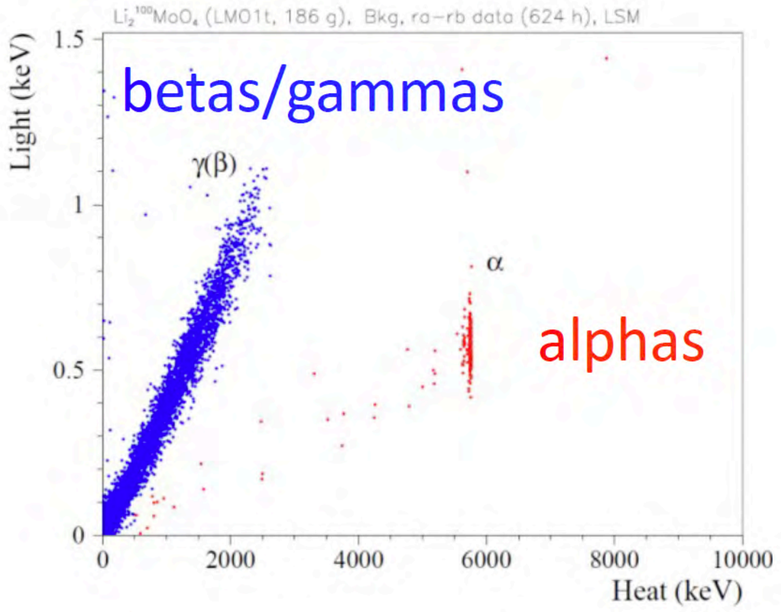
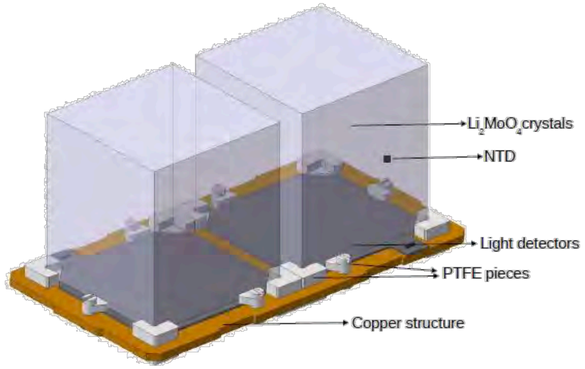


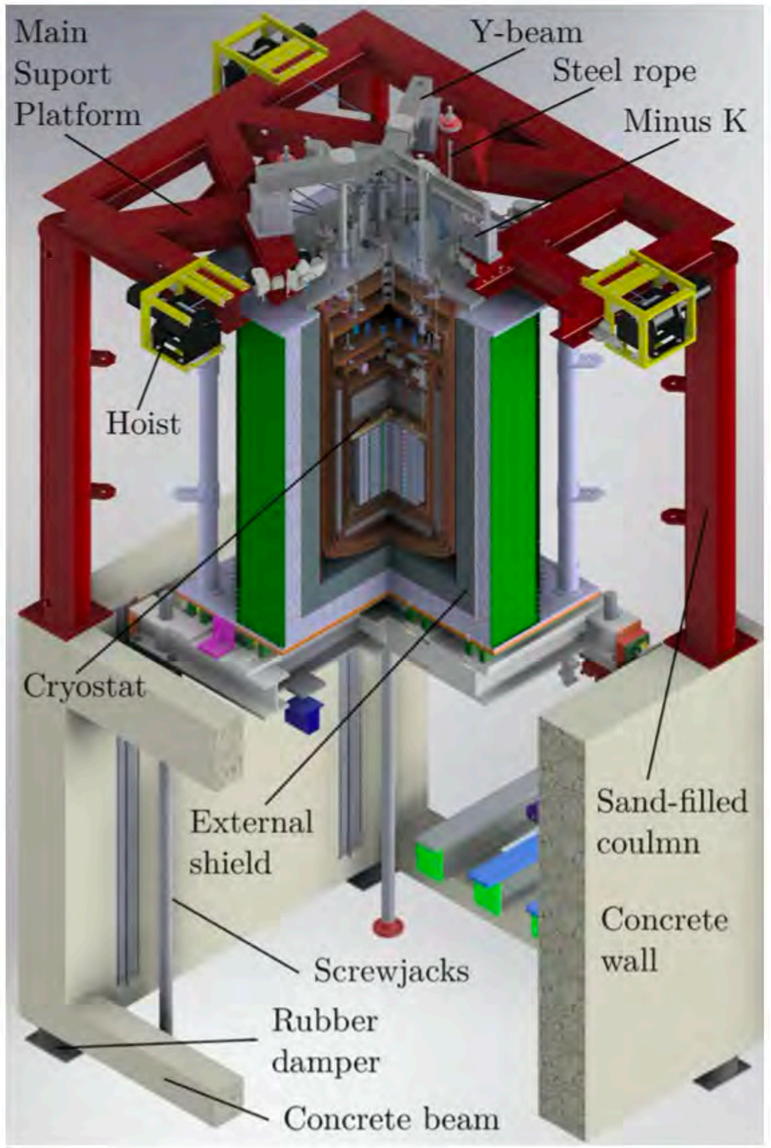




$Q_{\beta\beta}$ ($^{100}$Mo) = 3034 keV, above γ background from natural radioactivity

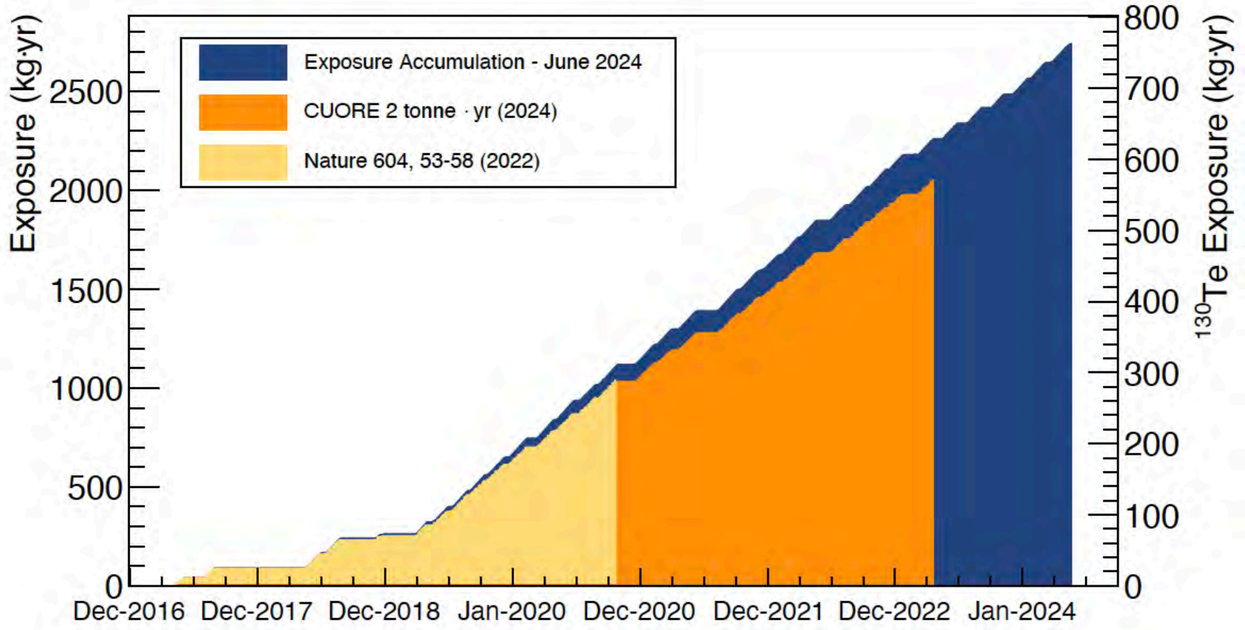
Heat and light detection allows α rejection

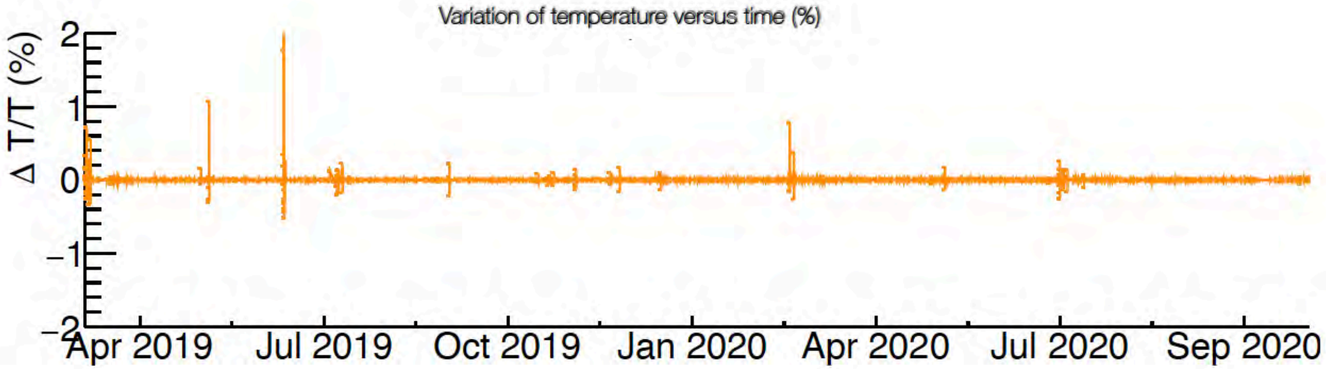
# CUPID builds on existing cryogenic infrastructure

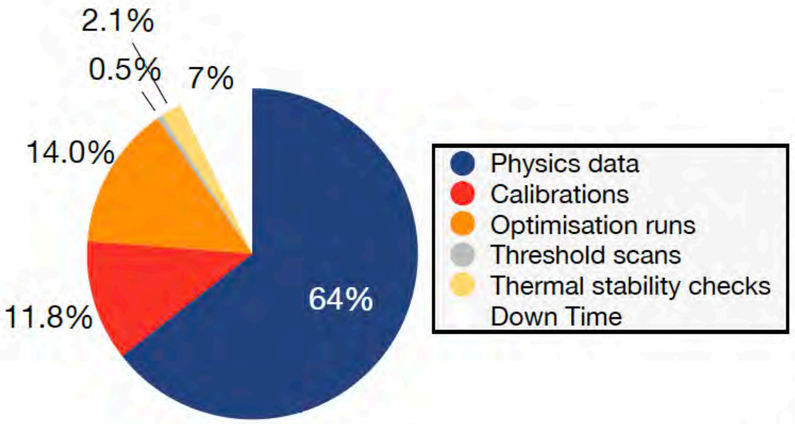



# CUORE Data Taking

- Data taking started in Spring 2017
  - In the first two years we learned how to operate the cryogenic system at its best and optimised the performances
  - Datasets (~ 2 months long) interleaved by routine maintenances
- Continuous physics data taking at mK temperature since March 2019
  - Uptime > 90%
  - Data taking rate ~ 50 kg·yr/month



# CUPID builds on experience from CUORE

# CUPID builds on experience from CUORE

## CUORE has been a great success

- One of the most sensitive operating $0\nu\beta\beta$ experiments
- Technology demonstrator for CUPID at ton scale
- Validated CUPID background model: all components verified with data
- Train the next generation of scientists who will build CUPID

## Collaborations envision “adiabatic” transitions from CUORE to CUPID

- Complete and analyze 3 ton-year $0\nu\beta\beta$ dataset
- Additional scientific opportunities will be open by cryogenic upgrades
- Retain expert knowledge in the collaboration
- Most importantly, additional data taking campaign with CUORE important for career development of our young scientific personnel

# CUORE Cryostat Upgrade for CUPID

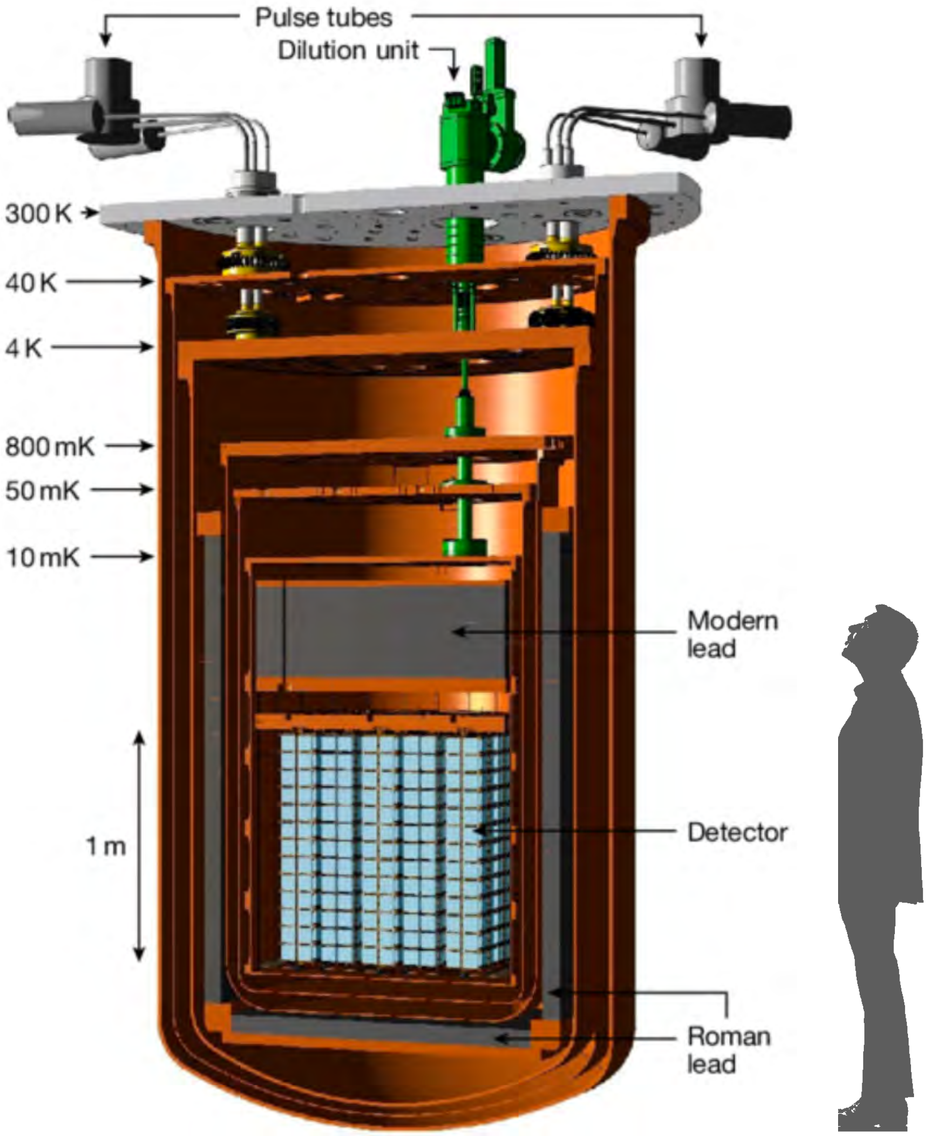
## Largest and most powerful dilution cryostat worldwide: base temperature 10 mK

From CUORE to CUPID:

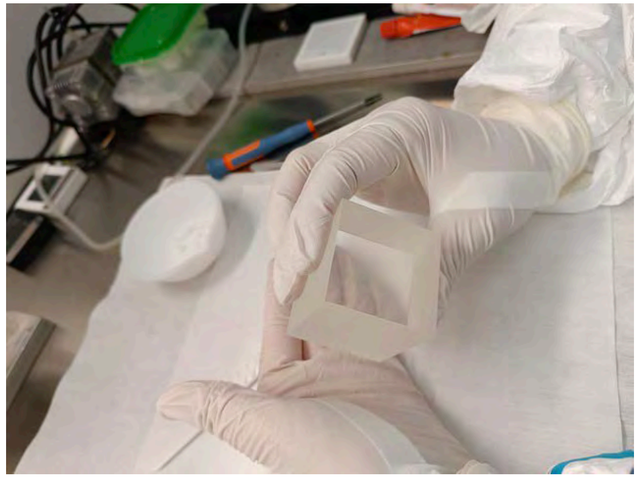
- detector mass is similar
- wiring changes from 2000 to 7000 wires, the heat load especially at 4.2 K is much higher
- light detectors more sensitive to vibrations

## Upgrade with a new system of pulse tubes and a better mechanical decoupling of pulse tubes from cryostat

- 4 new PT425-RM by Cryomech, shipped to LNGS in July 2024
- performance validation ongoing @LNGS (base T ~2 K demonstrated)
- new thermalization system, tests on-going at LNGS
- installation in CUORE cryostat planned for early 2026



# Isotope Production and Crystal



## $Li_2MoO_4$ crystals

- 1596 crystals
- 4.5x4.5x4.5 $cm^3$ (tolerance ~ 200 μm, no bevel)
- 240 g $^{100}Mo$ in mass
- grown with Czochralski (seed) + Bridgman
- 95% in $^{100}Mo$

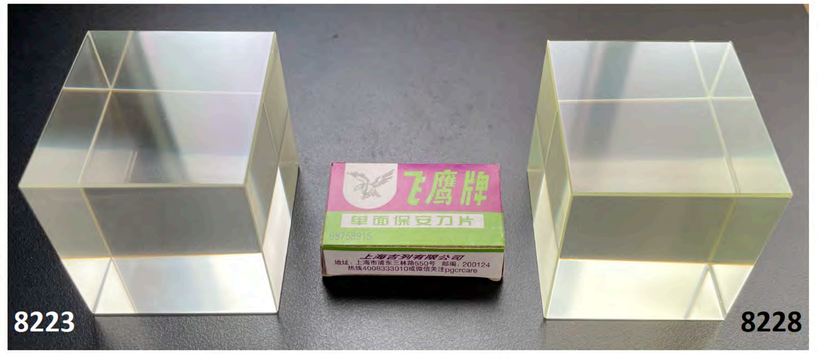
## $Li_2MoO_4$ crystal producer: SICCAS (Shanghai, China)

- Pre-production contract for > 12 enriched crystals in progress. Optimize crystal production and material (isotope) recovery efficiency, technical specification are the same as for the full production
- SICCAS has demonstrated ability to produce high-quality crystals at adequate production rate and cost. Natural crystals produced by SICCAS, and already tested

SICCAS is ready to commit to full production

SICCAS Since 1928 — 中国科学院上海硅酸盐研究所 Shanghai Institute of Ceramics Chinese Academy of Sciences

**1. Two Natural LMO for CNRS**




Delivered to Orsay at the end of July 2024: cryogenic measurement ongoing

Light yield of SICCAS crystals consistent with expectations

Energy resolution is also consistent but was affected by noise conditions in run

# Isotope Production and Crystal

## LMO Crystal Production

Starting from Molybdenum Oxide (MoO3) powder, enriched in $^{100}$Mo, and Lithium Carbonate (Li2CO3) powder.

Full production will require setting up a dedicated chain for crystal growth, material recovery and purification, crystal cut and polishing similar to CUORE

China National Nuclear Corporation

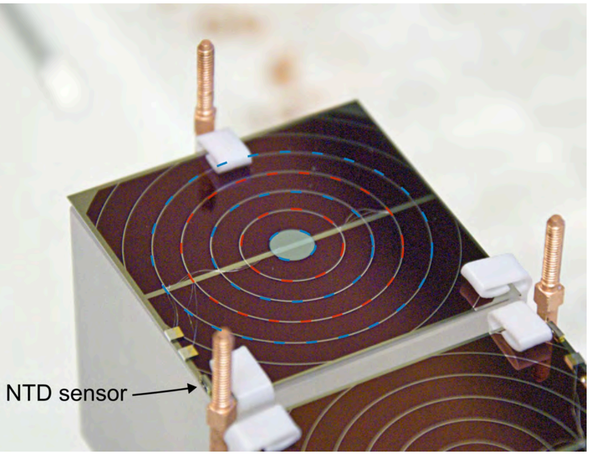

## Enriched $^{100}MoO_3$ from IPCE company (Tianjin, China)

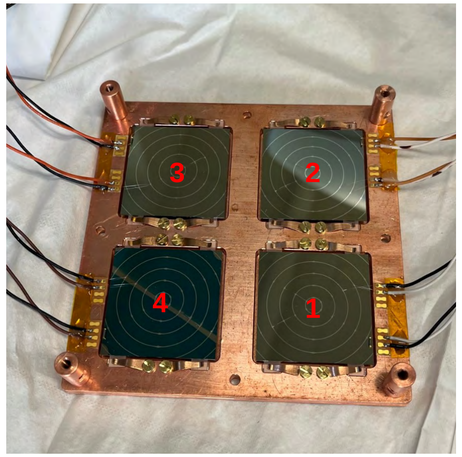
Converted an existing enrichment cascade into a $^{100}$Mo one.
In 2023-2024 produced 4 kg of $^{100}$Mo (all the quantity needed for the pre-production)

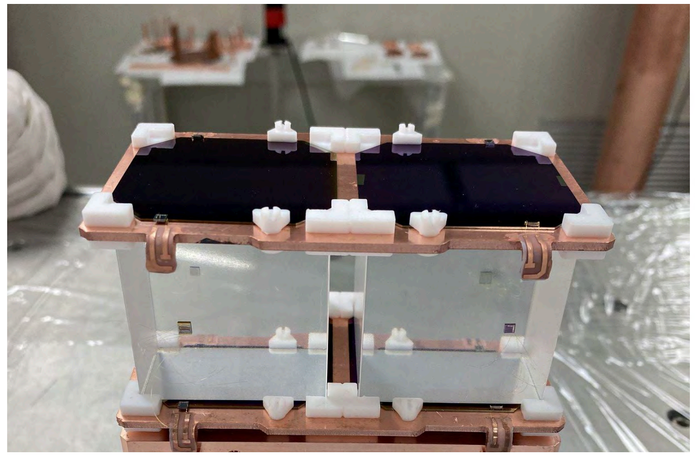
Space for building the $^{100}$Mo mass production enrichment cascade for CUPID available at the new IPCE plant

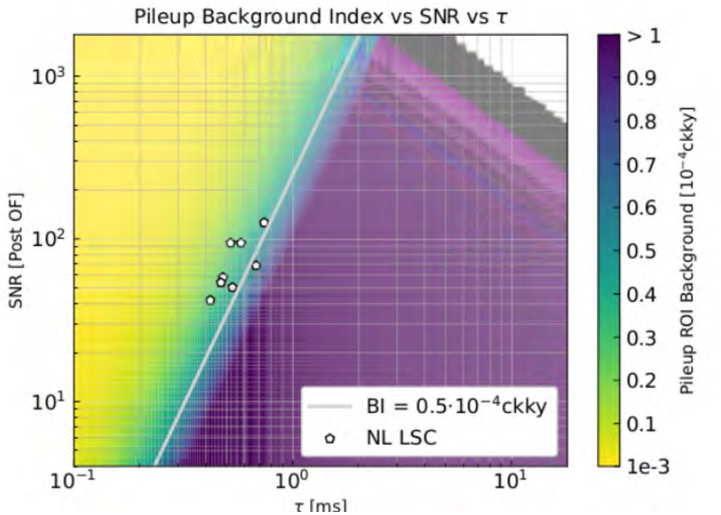
Next: Demonstration of production with enriched $^{100}$Mo
Optimization of the production process (purity, polishing, recycling)

# Light Detectors






## Technology Development

Neganov-Trofimov-Luke-amplified detectors with NTD readout is baseline for CUPID

NTL technology was developed at IJCLab, France

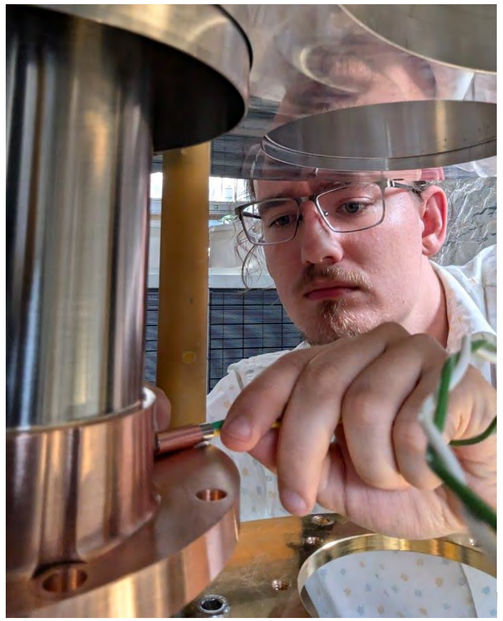
Pile-up rejection capability was validated with ten prototypes at Canfranc in the CROSS facility

## Fabrication

Light detector manufacturing is divided between France and US

Fabrication technologies shared with US, first devices already produced in the US, ANL iterating on production recipe (photolithography vs sputtering vs e-beam evaporation)

# CUPID On-Site Tests



CUPID Crystal Validation Run (CCVR) in Hall C test facility

Vertical Slice Test Tower (VSTT) assembled in 2024, cooldown in Q1 2025

Received natural crystals from SICCAS,

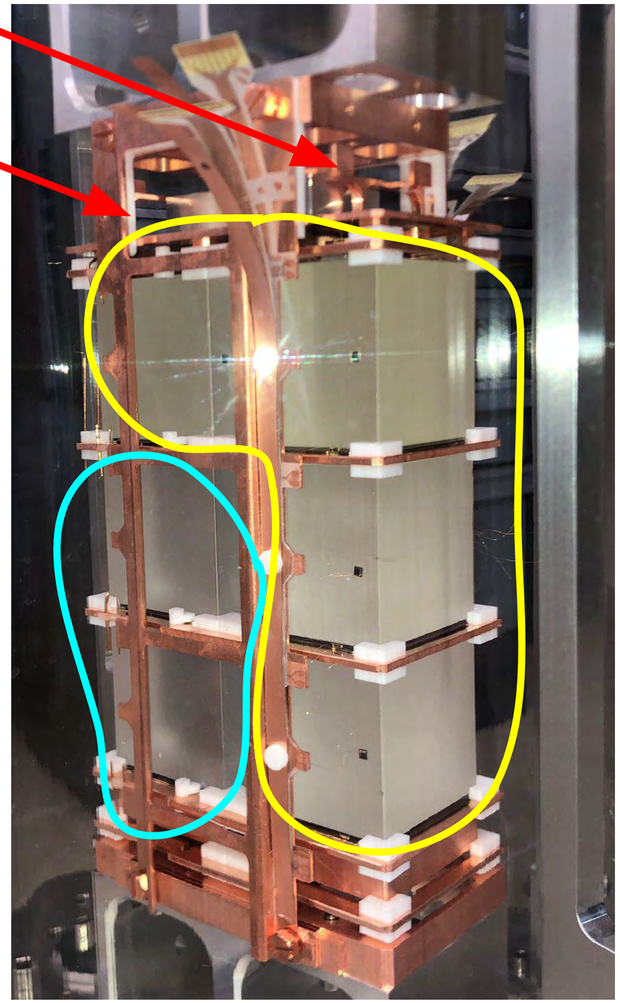
Delivery of >12 enriched crystals from SICCAS in early 2025

Continuous presence of CUPID collaborators at LNGS for on-site tests

# CUPID On-Site Tests in LNGS (Hall C)

Cu-PEN

Cu-pins + constantan wirea



4 chinese LMOs

2 reference crystals

6-crystal tower in Hall C of LNGS

- Validate crystal vendor and optimize requirements
- Optimize of tower design (detector thermalization, grounding, noise)
- Optimize NTD parameters
- One tower with two different wiring schemes
- Multiple runs with different thermalization techniques
- Characterize and mitigate LD noise

Bolometric run ongoing

# CUPID Crystals and Light Detectors

## Validation of crystal procurement chain, crystal quality (Italy/France)

- First batch of crystals delivered
- Production quality of natural crystals from SICCAS validated
- First batch of enriched crystals expected before end of 2024 (thanks to IN2P3)

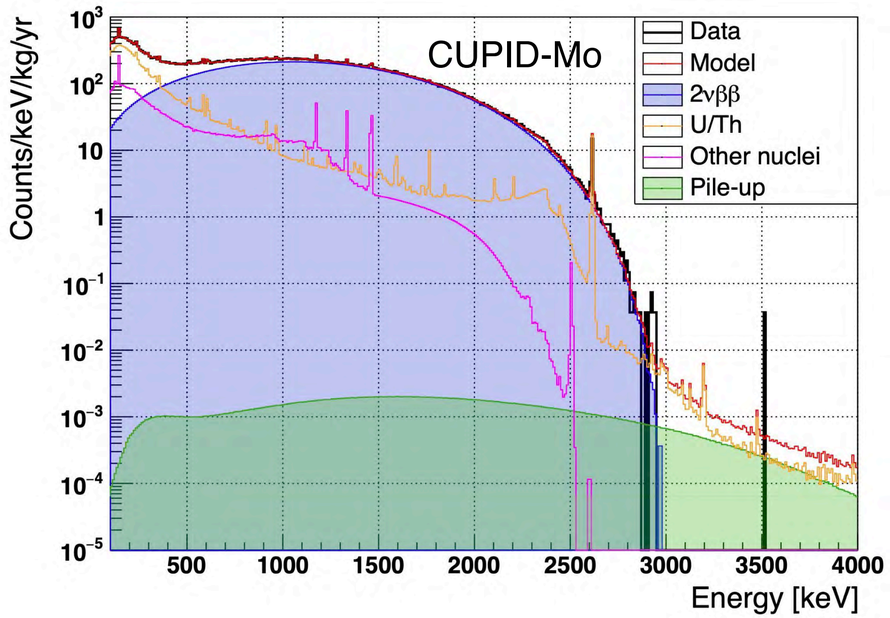
## Validation of light detector performance, US/France fabrication capability

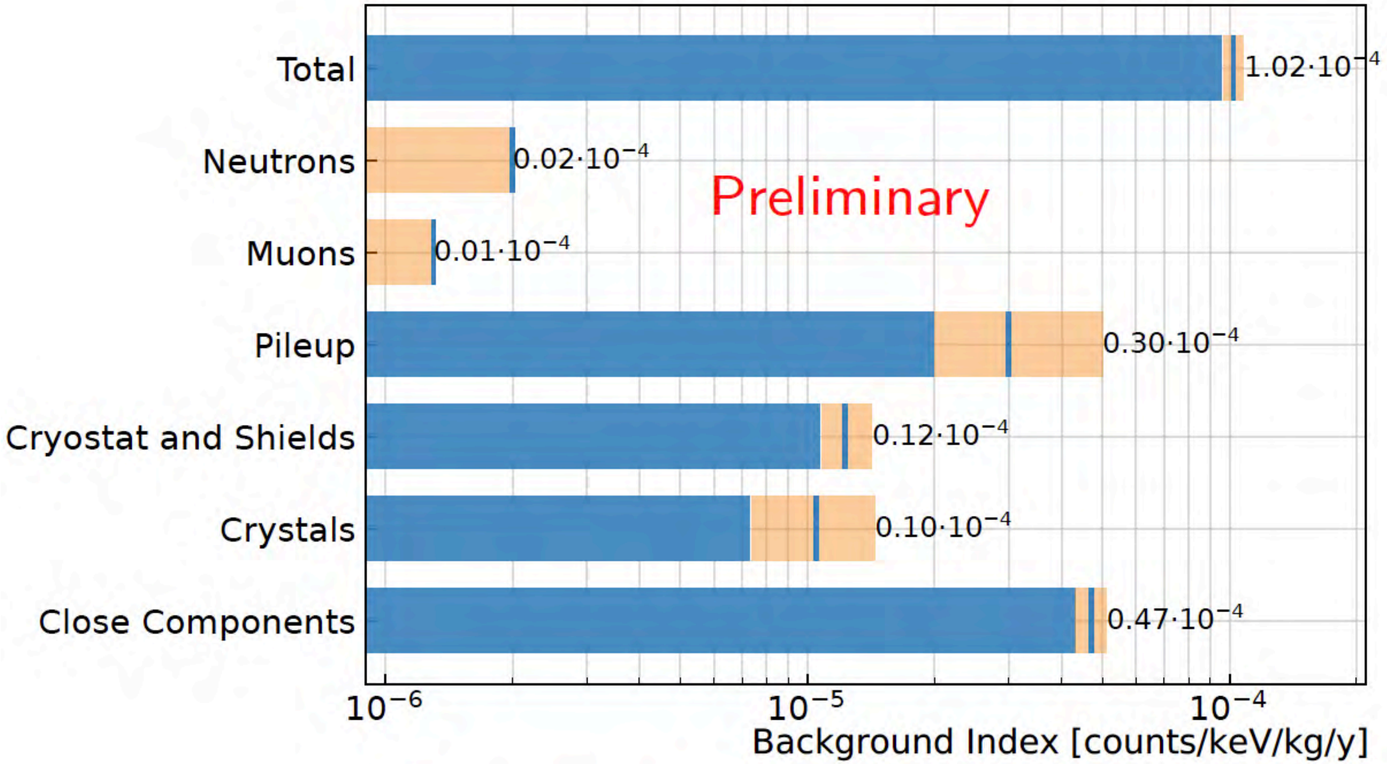
- Established production and testing facilities in the US, prototype development ongoing
- Produced 30 wafers for VSTT run at LNGS
- Electrodes for the VSTT light detectors will be produced at IJCLab

## Validation of NTD production capability

- Established production and testing facilities in the US, prototype development ongoing

# Background Budget




Vertical blue bar: mode of the pdf distribution.
Orange band: $\pm 1\sigma$ uncertainty

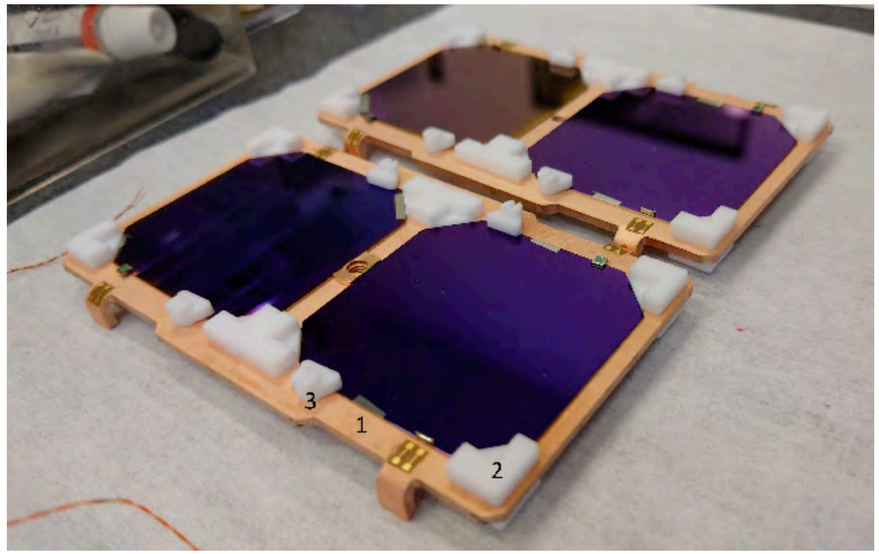
Predictions based on results from precusor experiments, CUORE and CUPID-MO and improved new. Simulations with realistic light yield and NTL on light and ionization.

Reaches background goal of project
1.0 x $10^{-4}$ cts/(keV*kg*y)

Full prototype-tower tests at LNGS
$Li_2{}^{100}MoO_4$ crystals pre-production ongoing

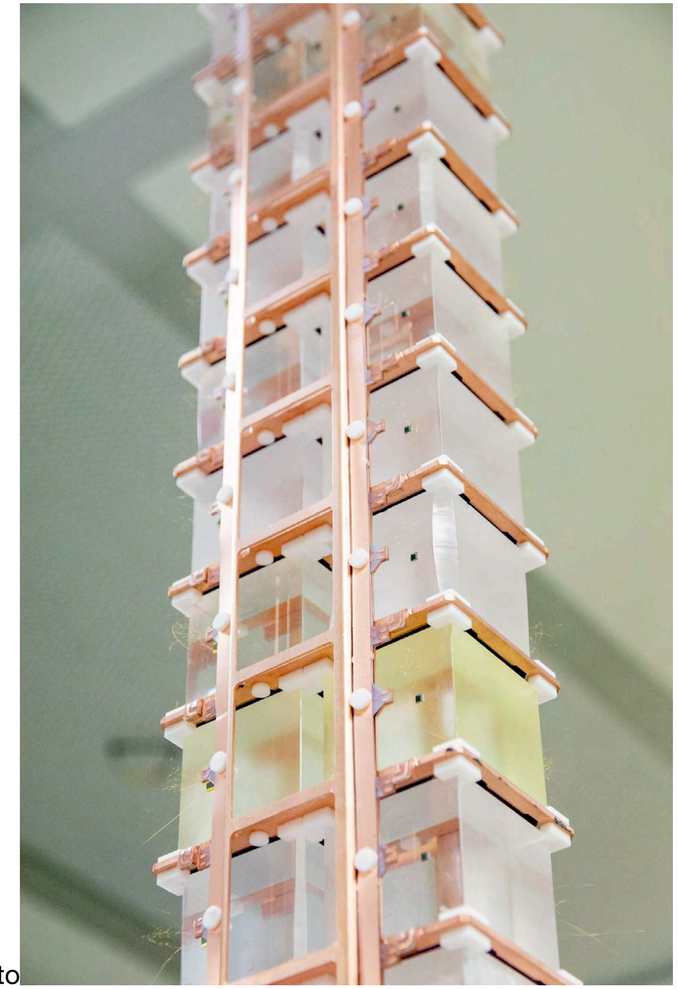
Room for background reduction on close components by improvements on surface contaminations

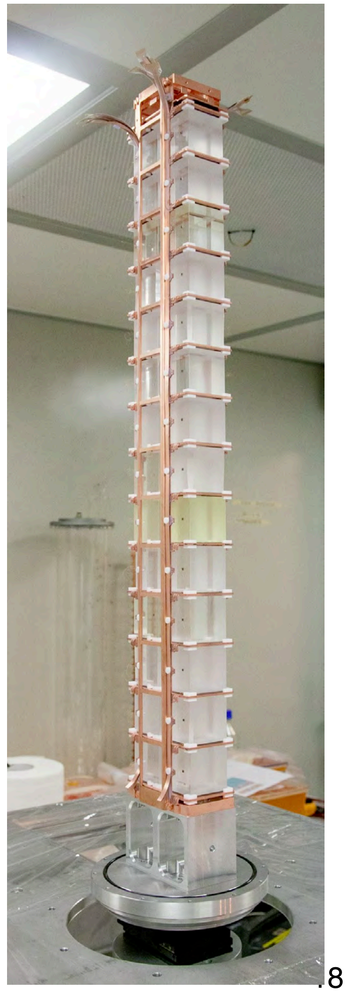
# Background Budget - Close Components




NOSV copper + PTFE spacers + readout wires

| $^{226}$Ra | $^{228}$Th |
|---|---|
| $<0.5$ $\mu$Bq/kg | $<0.4$ $\mu$Bq/kg |
| $8.4 \pm 0.7$ nBq/cm$^2$ | $11.5 \pm 0.5$ nBq/cm$^2$ |





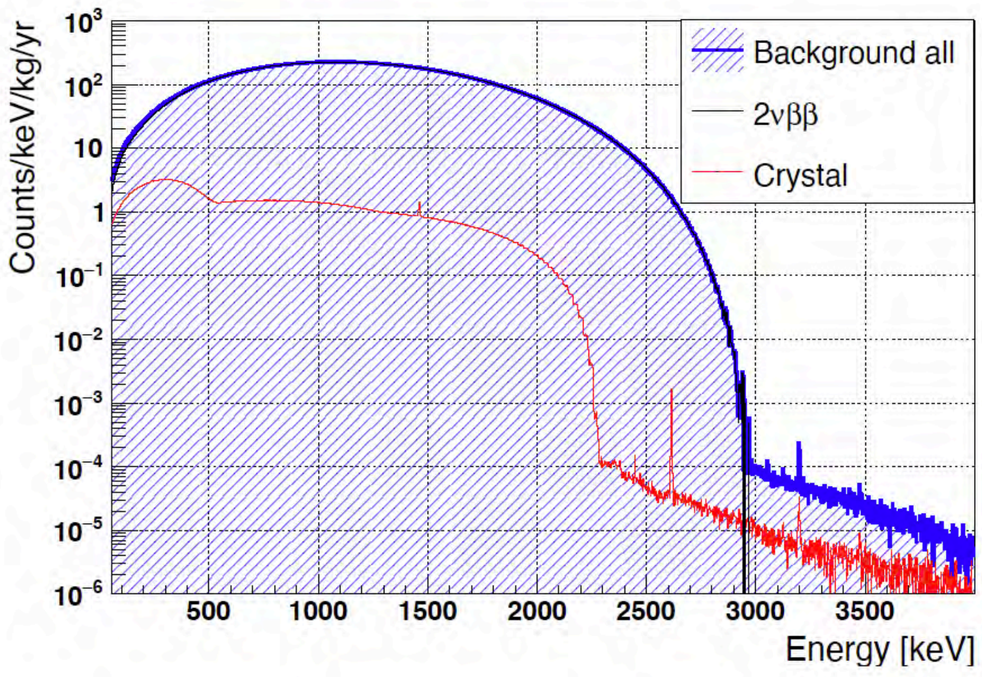
Room for background reduction on close components by improvements on surface contaminations

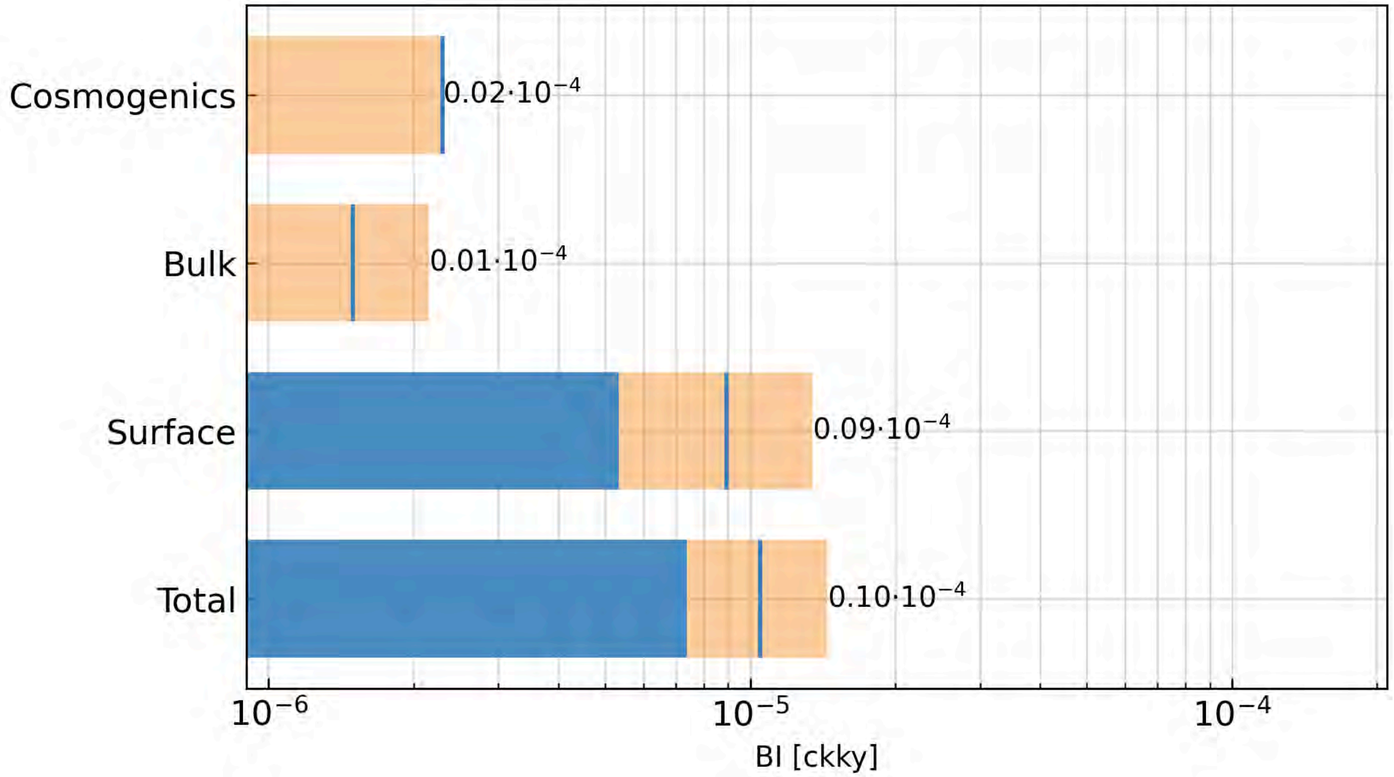
# Background Budget - $Li_2{}^{100}Mo$ Crystals

**$^{226}Ra/^{228}Th$**

Bulk → 1.5±0.7 x 10–6 cts/(keV*kg*y)

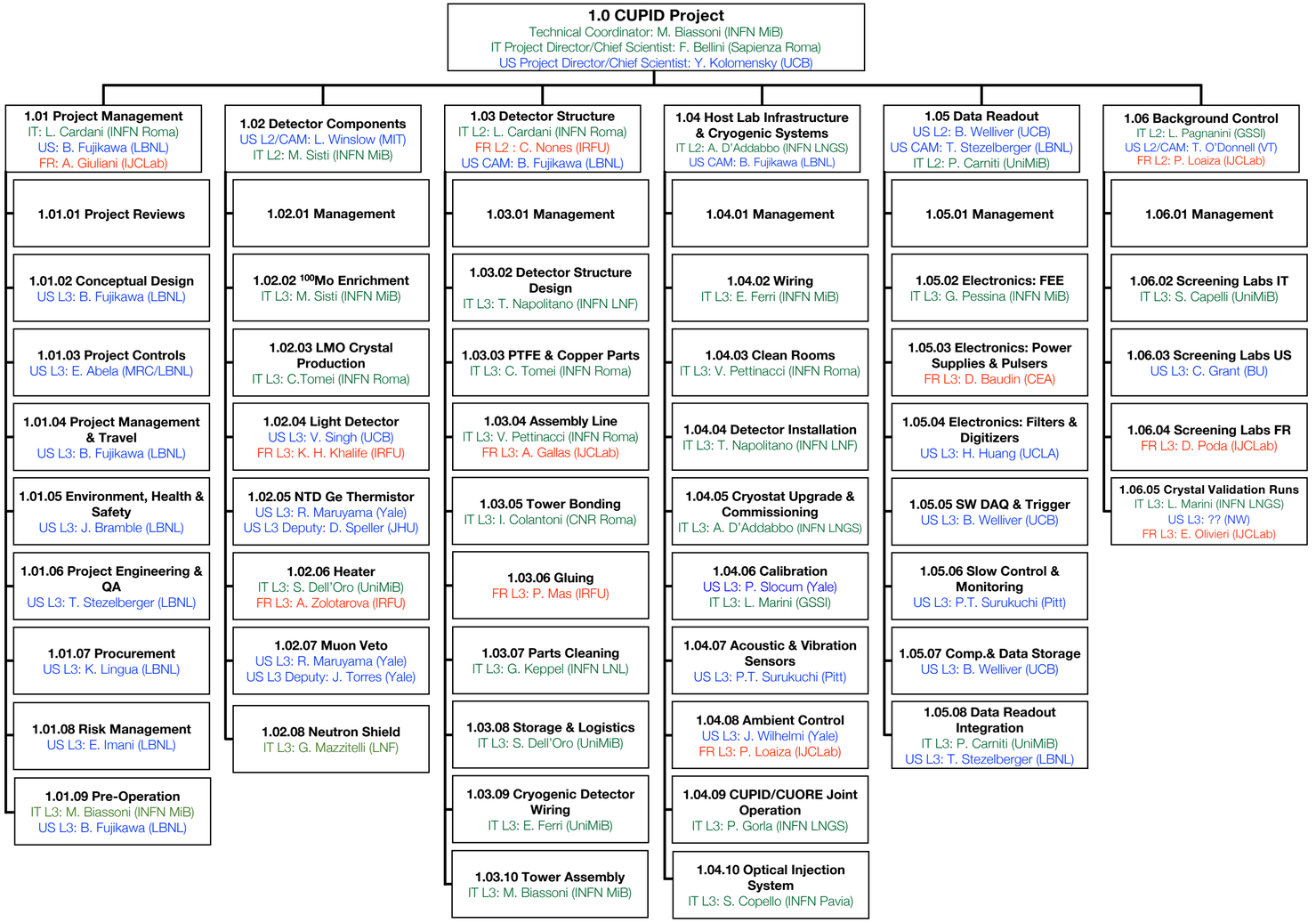
Surface → 9.0±4 x 10–6 cts/(keV*kg*y)




**Cosmogenics**
90 days at sea level and
1 y cooling-down (ACTIVIA). $^{42}K$, $^{82}Rb$,
$^{88}Y$, $^{56}Co$ → 2.3 x $10^{-6}$ cts/(keV*kg*y)

# CUPID Project




Complete team of L2s and L3 managers

Project controls team

Regular technical board and project meetings

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

# CUPID Project Planning

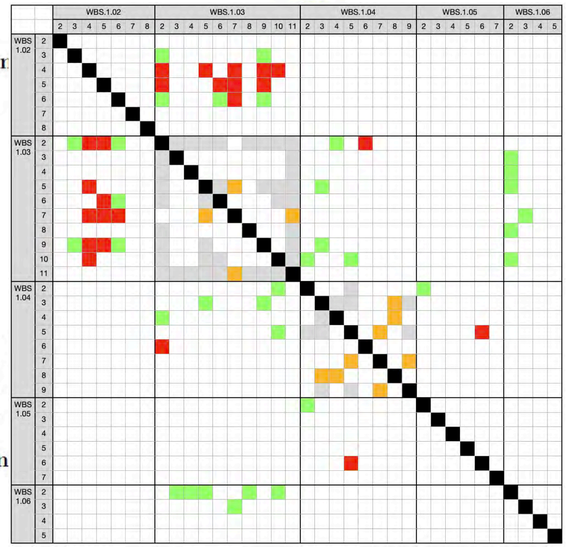
- Developing technical reference document for reviews, will contain updated and detailed informations on the experiment and project
- Defined science requirements and technical requirements
- Preparing for upcoming reviews in US and Italy (proposed: LBNL-led review in Dec 2024, INFN review in early 2025)



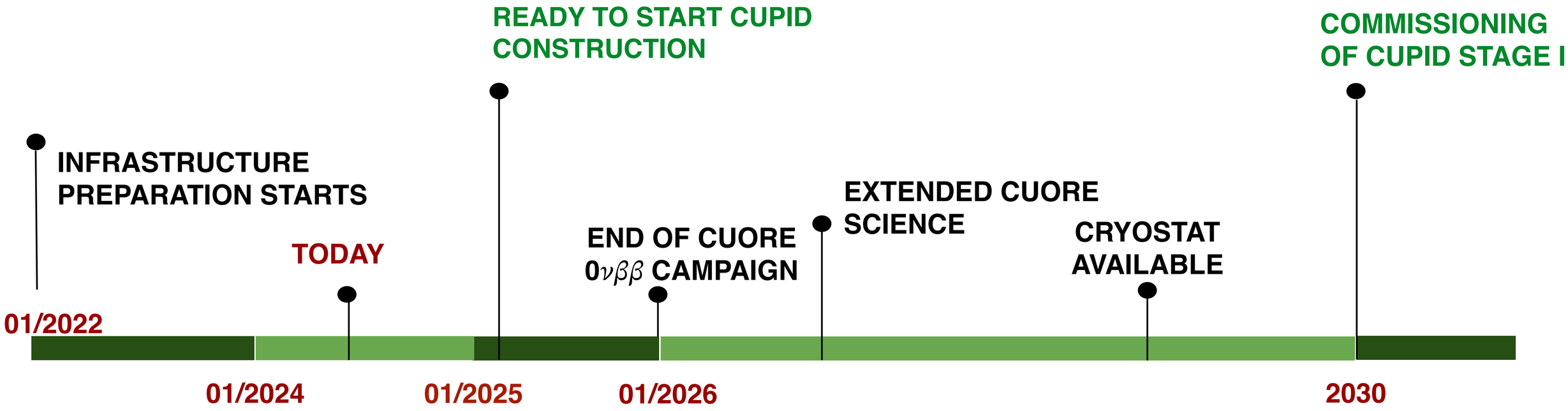
## Requirements

| | | |
|---|---|---|
| **Global requirement** | | |
| Half-life discovery sensitivity ($3\sigma$) | | $1 \cdot 10^{27}$ yr |
| $m_{\beta\beta}$ discovery sensitivity ($3\sigma$) | | (12-21) meV |
| **Isotope** | Isotope | $^{100}$Mo |
| | Q-value ($Q_{\beta\beta}$) | 3034 keV |
| **Scintillating crystal** | Scintillating Crystal | $Li_2MoO_4$ |
| | $^{100}$Mo enrichment | 95% |
| | Crystal size | $(4.5 \times 4.5 \times 4.5)$ cm$^3$ |
| | Crystal mass | 280 g |
| **Number of detectors** | Detector mass | 450 kg |
| | Number of crystals | 1596 |
| | Number of LDs | 1710 |
| | $^{100}$Mo mass | 253.5 kg |
| **Detector performances** | FWHM Heat Energy resolution | 5 keV UNDER REVIEW |
| | $\beta/\gamma$-$\alpha$ discrimination | 99.7 % |
| **Efficiencies** | Containment efficiency | 79% |
| | Selection efficiency | 90% |
| **Background Index (BI)** | Background index | $1{\cdot}10^{-4}$ counts/(keV·kg·yr) |
| | $2\nu\beta\beta$ pile-up rate in the ROI | $0.5{\cdot}10^{-4}$counts/(keV·kg·yr) |
| **Run Time** | Livetime | 10 yr |

## Interfaces



# Transitioning from CUORE to CUPID

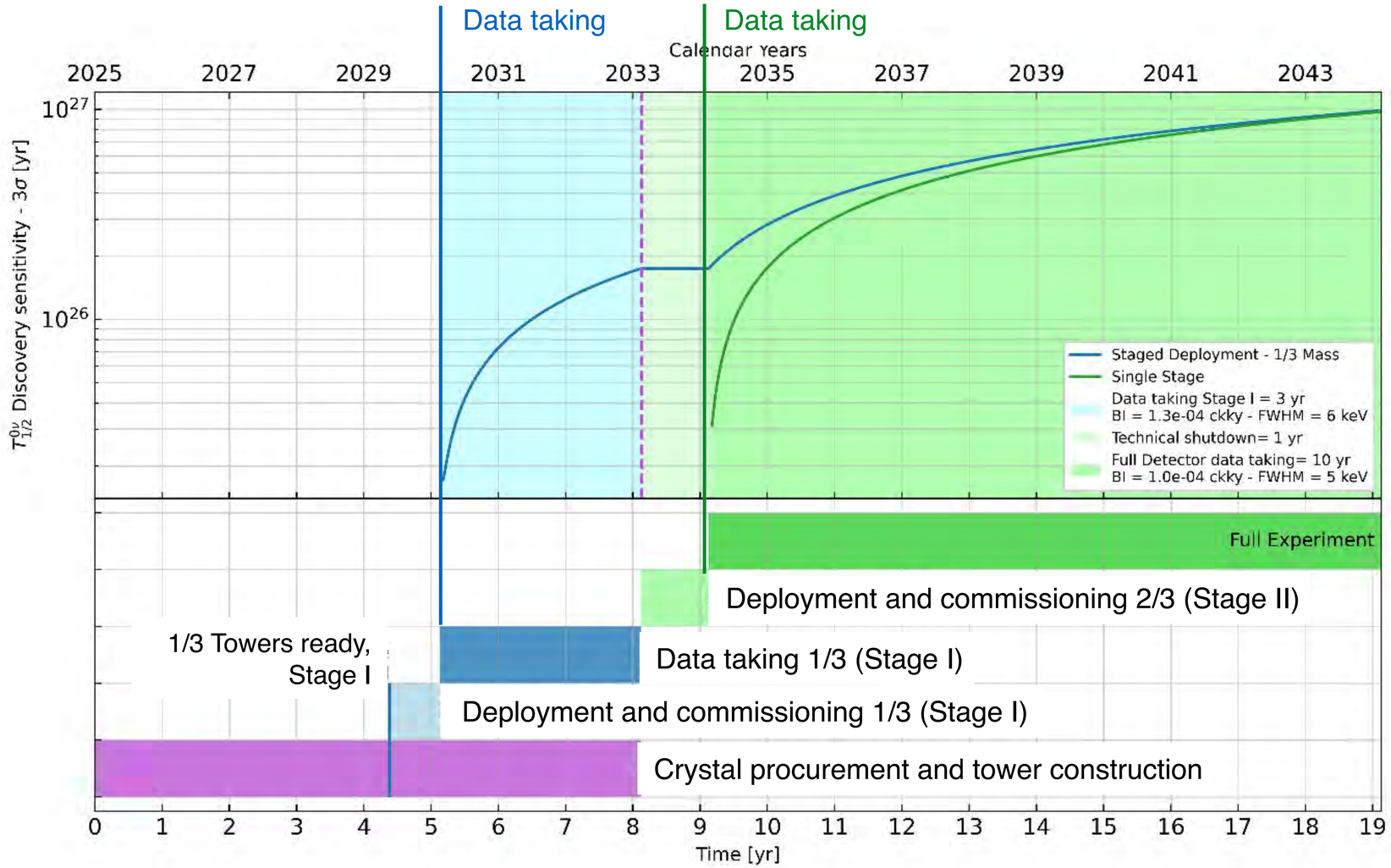


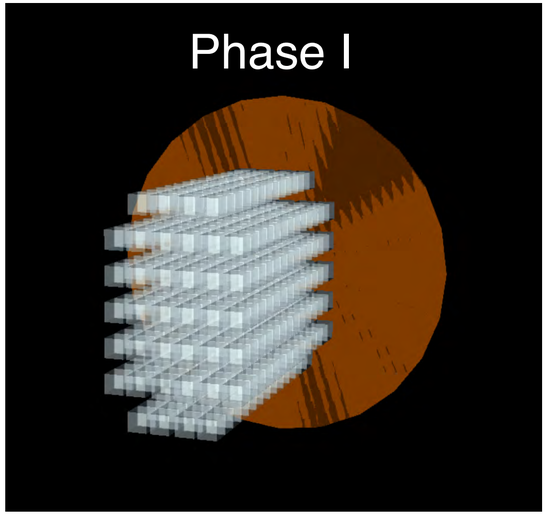

Seamless transition between CUORE and CUPID possible.

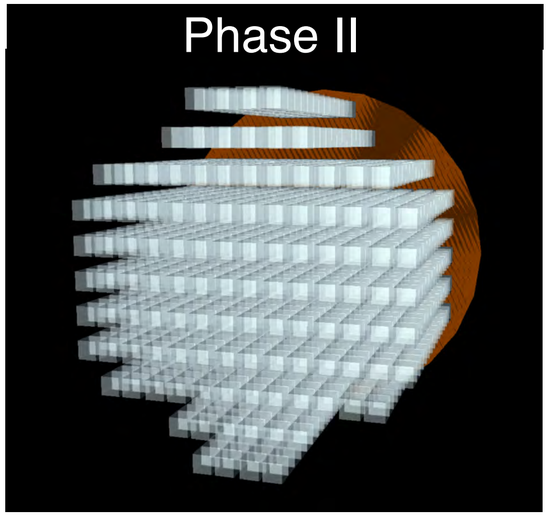
Collaborations are coordinating proposed CUORE operations plan and CUPID construction.

Aim to retain specialized knowledge in collaboration

# Staged Deployment of CUPID

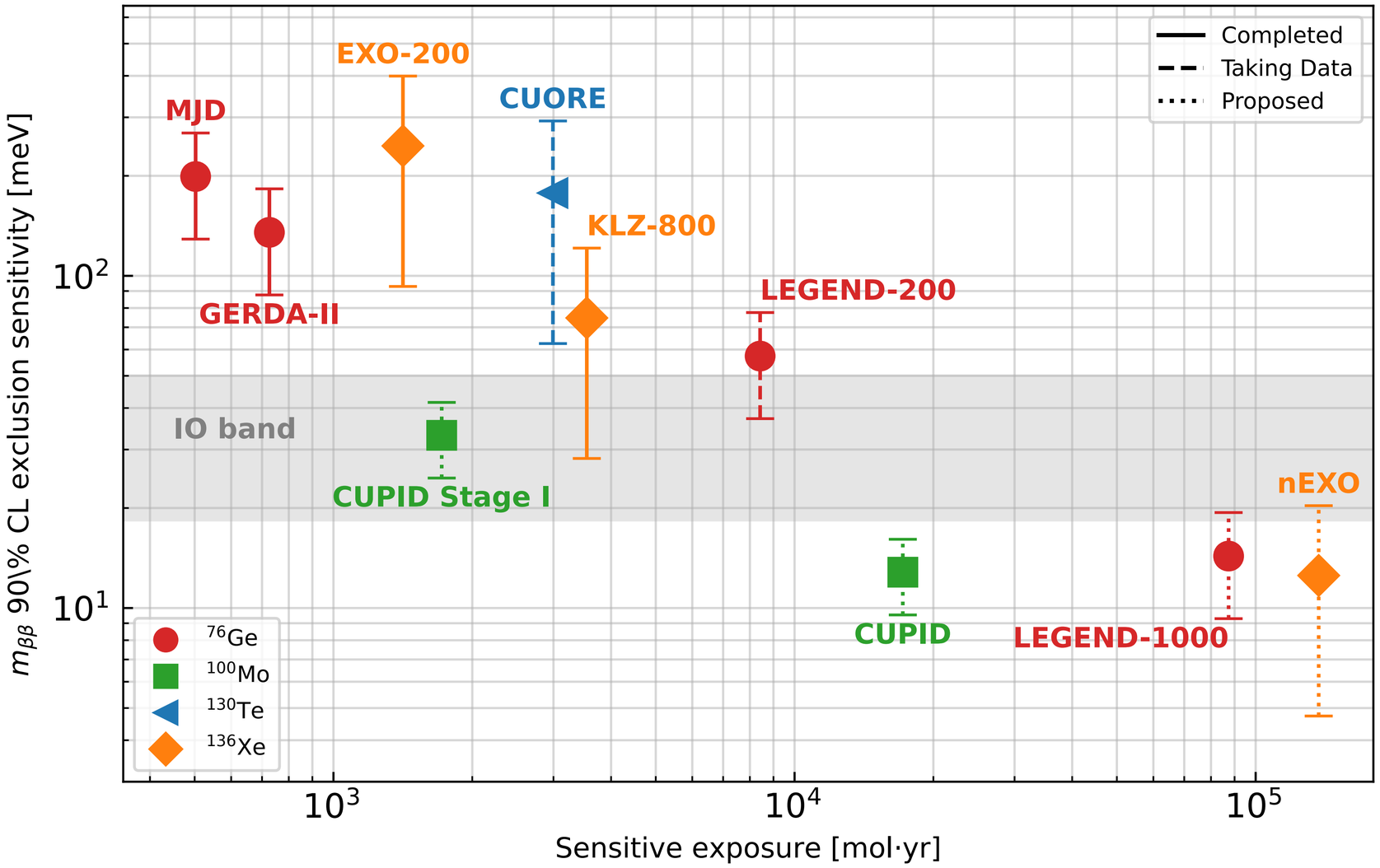



Detector configuration inside cryostat

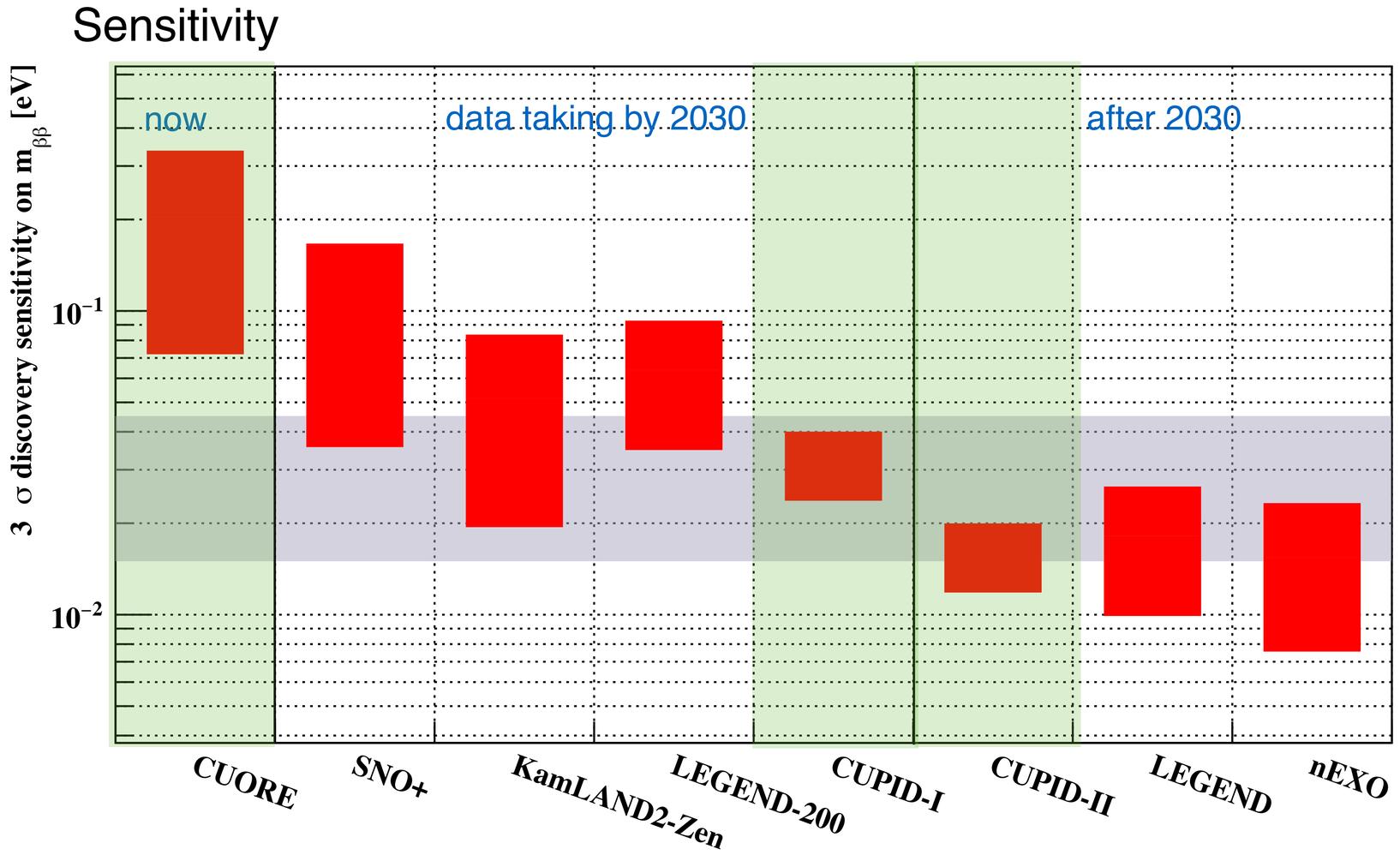
# CUPID Sensitivity




CUPID Stage I has world-leading science reach

CUPID is ton-scale experiment with competitive sensitivity

# CUPID Discovery Sensitivity




CUPID is critical to the discovery program at LNGS.

Staged deployment enables first science data by 2030 with CUPID-I

Ton-scale experiment with competitive sensitivity

On-site test are underway
Technically ready for construction