Search for neutrinoless double-beta decays

lundi 6 oct. 2025, 09:00 → 18:00 Europe/Paris

Auditorium Marie Curie, CNRS, rue Michel-Ange, Paris

Joint IN2P3-Irfu session scoping

CUORE Upgrade with Particle IDentification

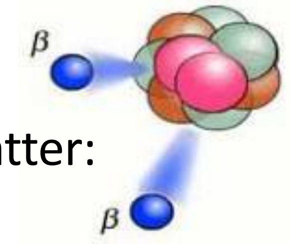
Andrea Giuliani, **Benjamin Schmidt**, **Claudia Nones**

On behalf of CUPID-France

$0\nu2\beta$ and CUPID reach in a nutshell

$0\nu2\beta$ is an inclusive test for the « creation of leptons »:

$2n \rightarrow 2p + 2e^-$ $\Rightarrow$ LNV



This test is implemented in the nuclear matter:

$(A,Z) \rightarrow (A,Z+2) + 2e^-$

Very rare (**> 10^{26} yr**) - Energetically possible for **35 nuclei**

Experimentally relevant: **^{76}Ge**, **^{82}Se**, **^{100}Mo**, **^{130}Te, ^{136}Xe**

Enrichment is mandatory, with the exception of ^{130}Te

Signal: **a peak** in the sum-energy spectrum of $2e^-$ **at $Q_{2\beta}$**

$0\nu2\beta$

Standard mechanism: neutrino physics

$0\nu2\beta$ is mediated by

light massive Majorana neutrinos

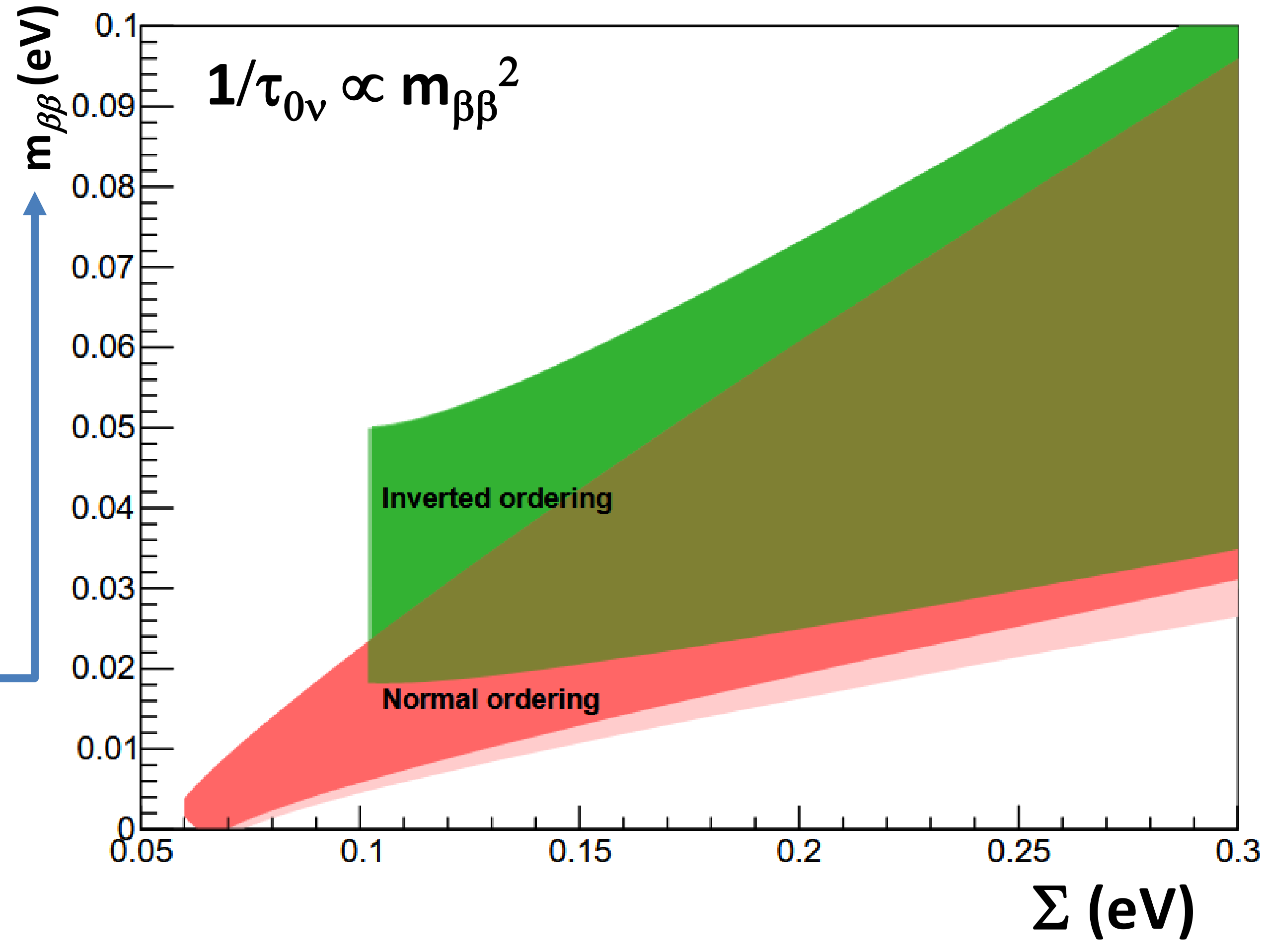
(exactly those which oscillate)

BSM non-standard mechanisms

Not necessarily neutrino physics

$\Sigma = m_1 + m_2 + m_3$ $\rightarrow$ Cosmology

$m_{\beta\beta} = \left| |U_{e1}|^2 m_1 + e^{i\alpha 1} |U_{e2}|^2 m_2 + e^{i\alpha 2} |U_{e3}|^2 m_3 \right|$ $\rightarrow$ $0\nu2\beta$



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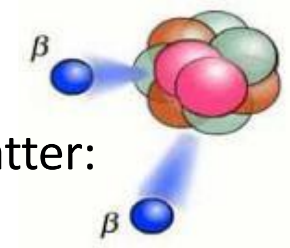

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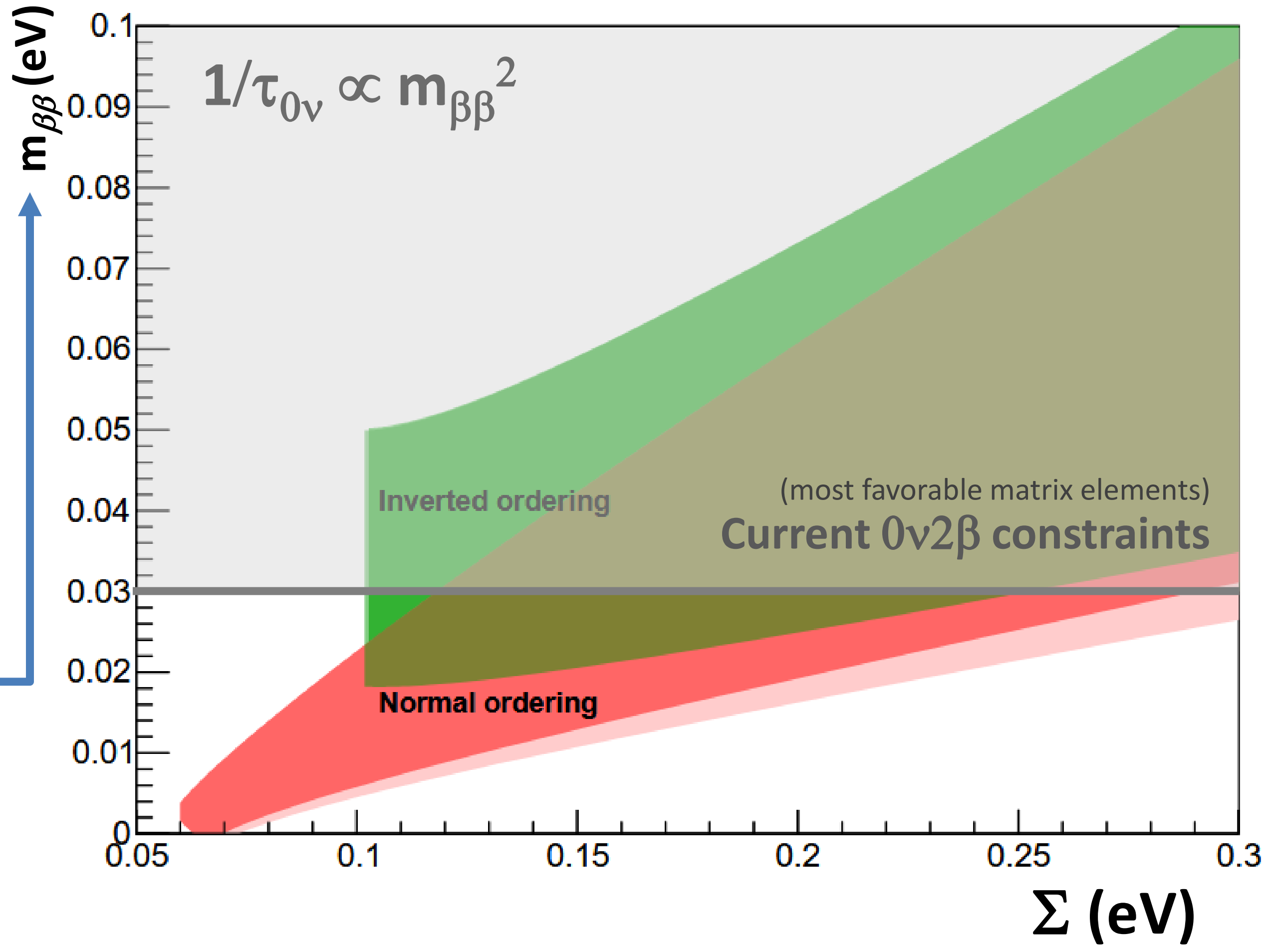

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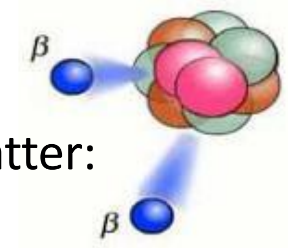

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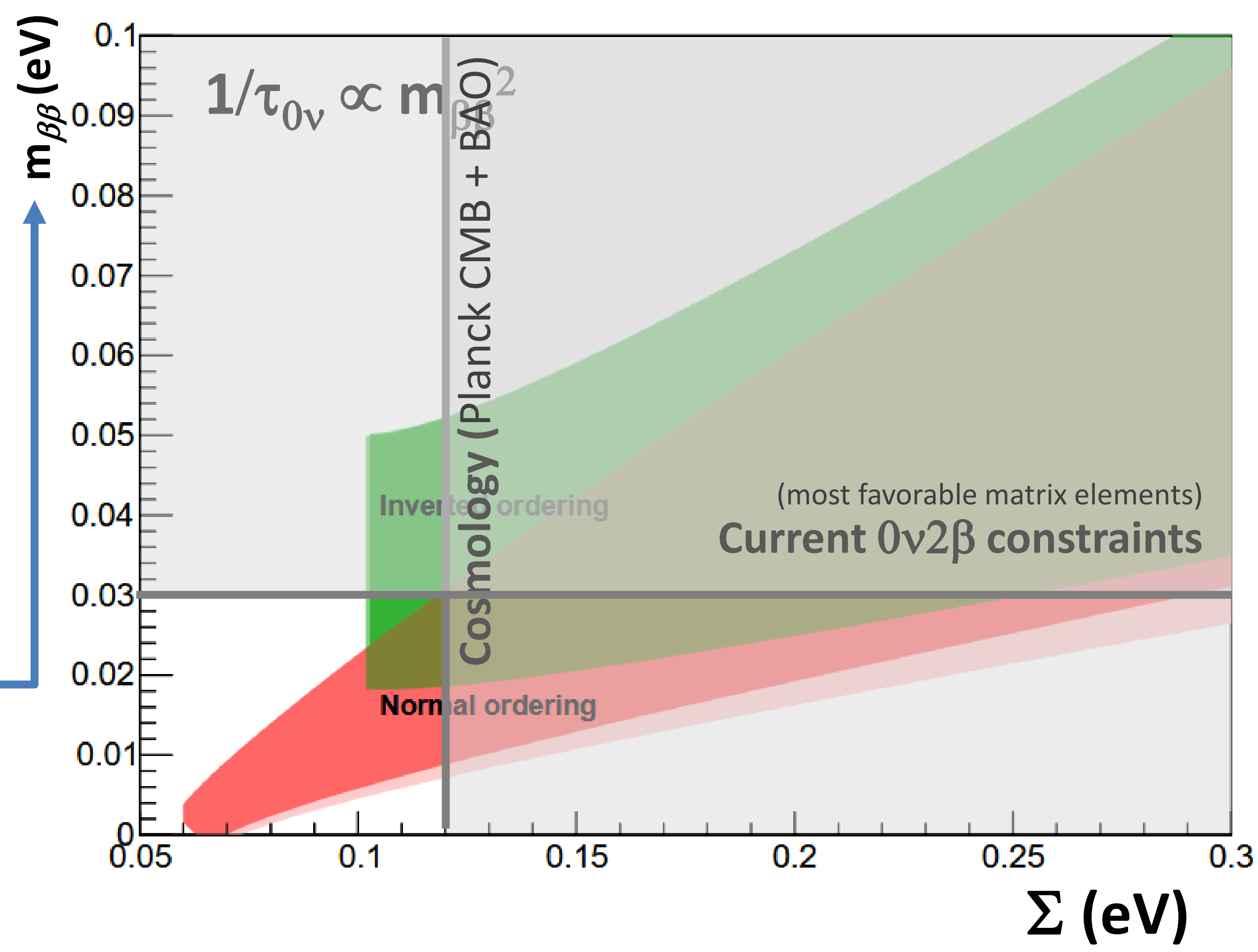

0ν2β and CUPID reach in a nutshell

$\Sigma = m_1 + m_2 + m_3$ → Cosmology

$m_{\beta\beta} = | |U_{e1}|^2 m_1 + e^{i\alpha 1} |U_{e2}|^2 m_2 + e^{i\alpha 2} |U_{e3}|^2 m_3 |$ → 0ν2β

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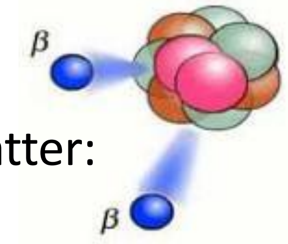

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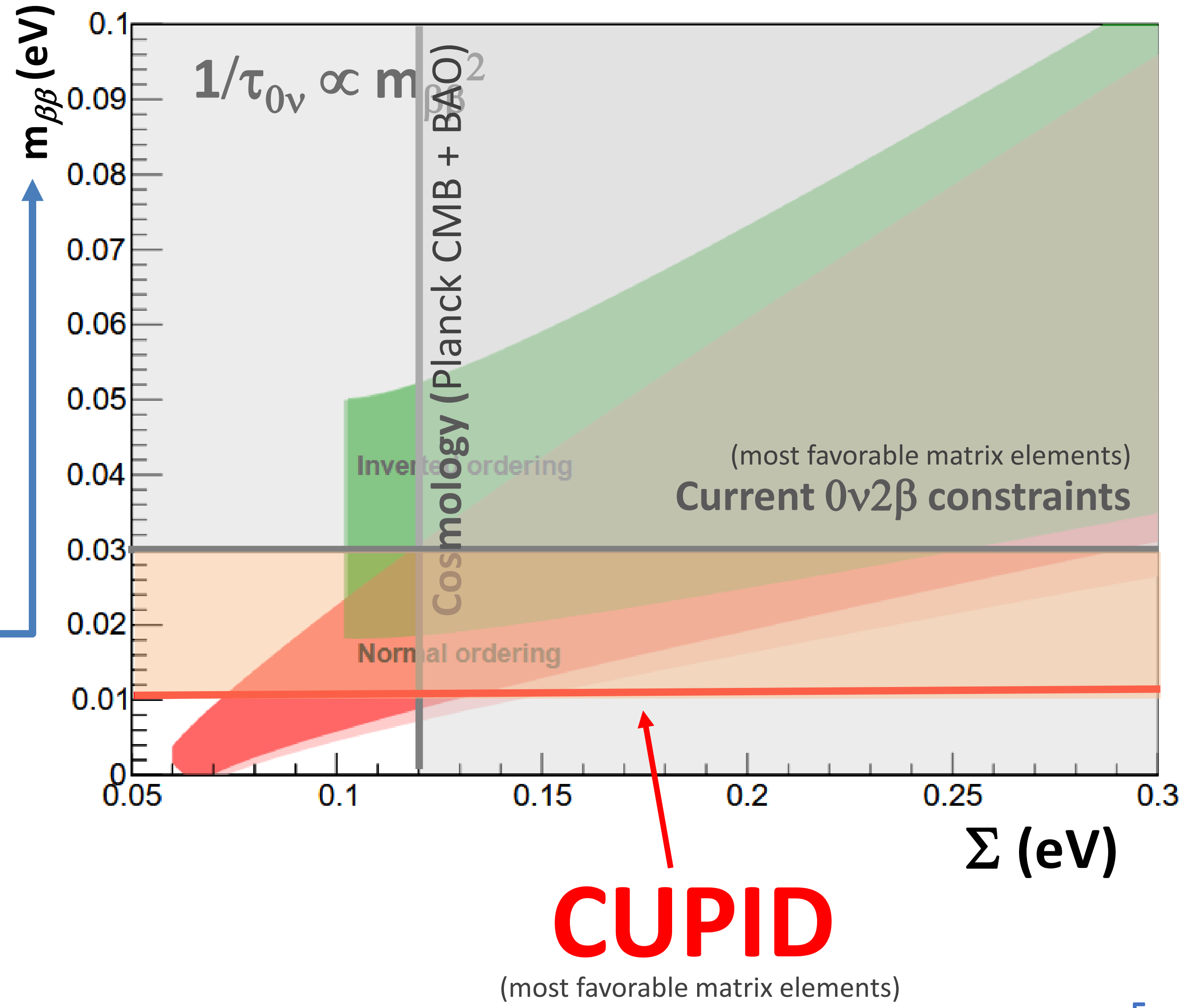
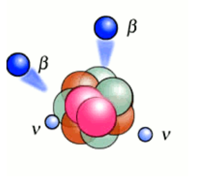


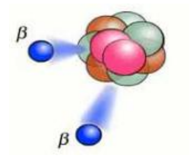
Searching for 0ν2β

Standard and new-physics channels:

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$ ➡ **2ν Double Beta Decay** (2ν2β)
allowed by the Standard Model
already observed – τ **~10^{19} – 10^{24} y**



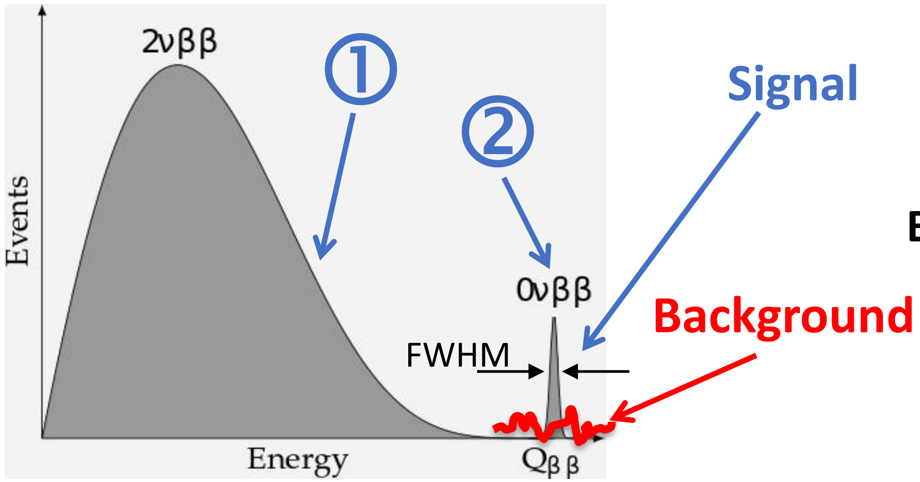
② $(A,Z) \rightarrow (A,Z+2) + 2e^-$ ➡ **Neutrinoless**
Double Beta Decay (0ν2β)
never observed τ **> 10^{26} y**



Experimental signatures based on the

Sum-energy spectrum of the two electrons

$Q_{\beta\beta}$ **~ 2-3 MeV**
for the most promising candidates



Energy resolution
FWHM
[keV]

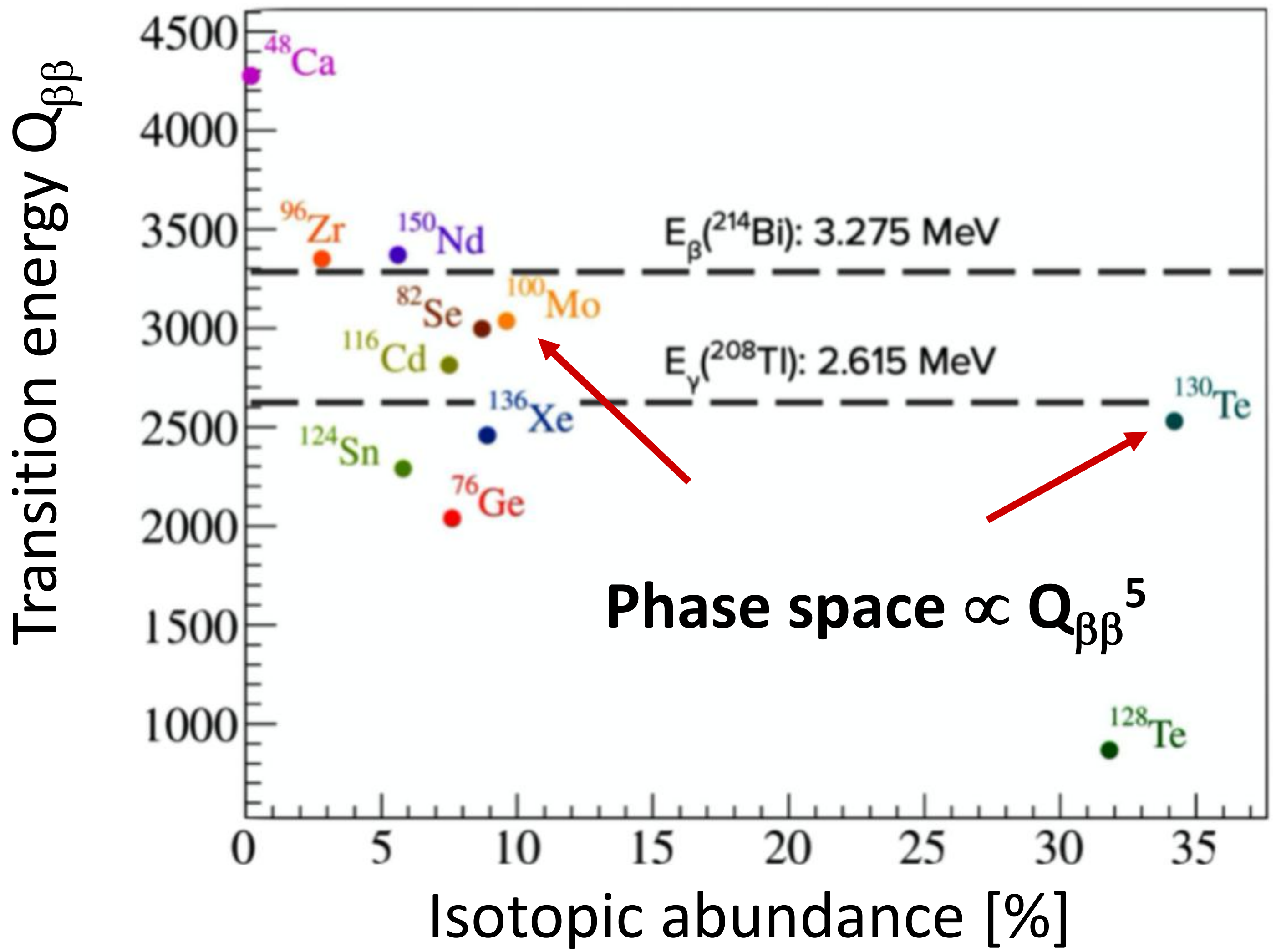
Background index b:

$$\frac{\text{Counts}}{M \cdot T \cdot \Delta E}$$

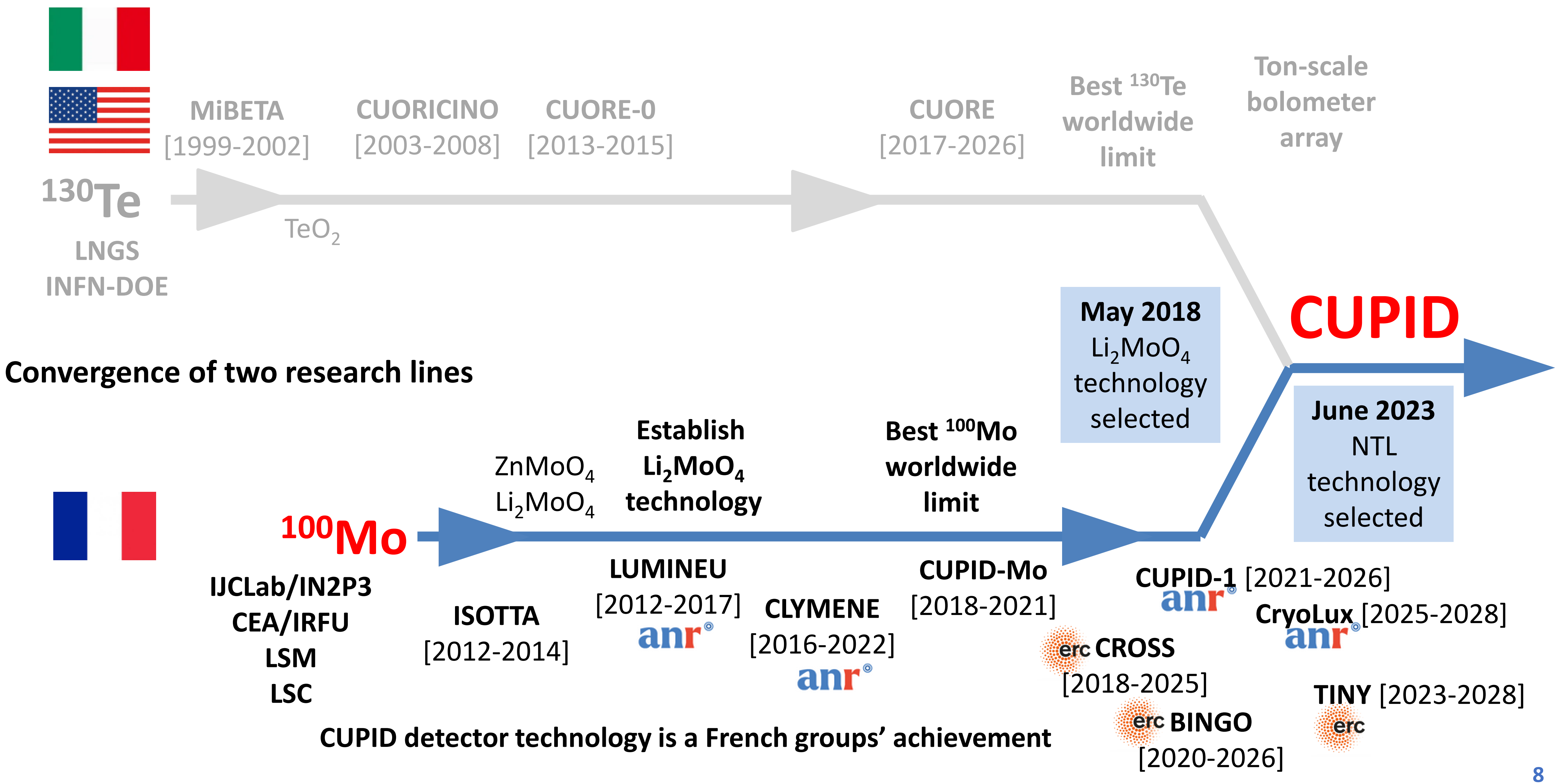
[counts/(keV·kg·y)]

Searching for $0\nu2\beta$

35 candidates → Only ~**10 experimentally relevant** ← **Importance of $Q_{\beta\beta}$**



CUPID's history and origin



CUORE in a nutshell

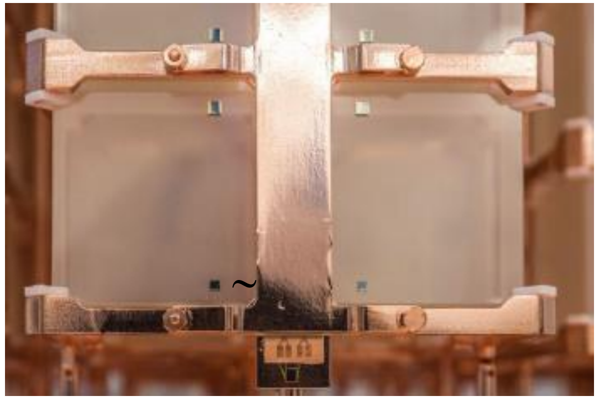
CUORE is an array of **TeO_2 bolometers** searching for $0\nu2\beta$ decay of the **isotope ^{130}Te** and taking data in LNGS (Italy) at **~12-15 mK**

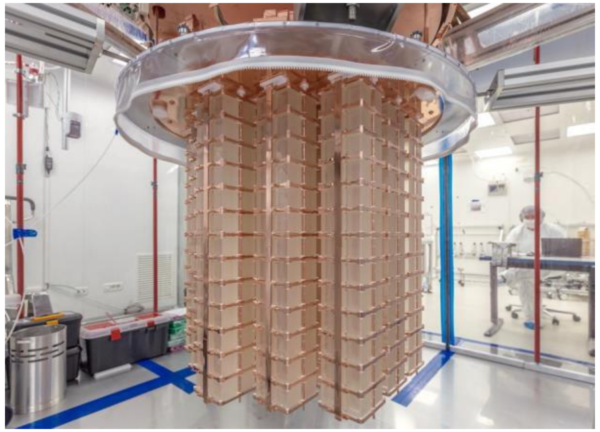
3 people in CUPID-France are members of CUORE

The largest bolometric experiment ever

- 988 crystals 5x5x5 cm, closely packed arranged in 19 towers of 13 floors each
- 742 kg (**206 kg** of **^{130}Te**)
- Start data taking: 2017
  Stable data taking: from **2019**
- Background at $Q_{\beta\beta}$ (2527 keV)
  1.42×10^{-2} counts/(keV·kg·y)
- Energy resolution at $Q_{\beta\beta}$
  7.3 keV FHWM

Nature 604 (2022) 53-58





One of the most sensitive $0\nu2\beta$ experiments of the current generation

- Exposure for the current limit: **2039 kg·y** (**> 2.8 tonne·y collected**)
- Current limit (^{130}Te $T_{1/2}^{0\nu2\beta}$) : **> 3.5×10^{25} y**
  → **$m_{\beta\beta}$< 70 – 250 meV** Preliminary
- Continue data taking until final goal:
  3 tonne·yr TeO_2 exposure
  → **mid 2026**

A. Campani, TAUP 2025

CUORE is not background free

→ **~70 counts/y in a ROI size FWHM energy resolution**, dominated by **surface α background**

CUORE → CUPID

Three important messages from CUORE

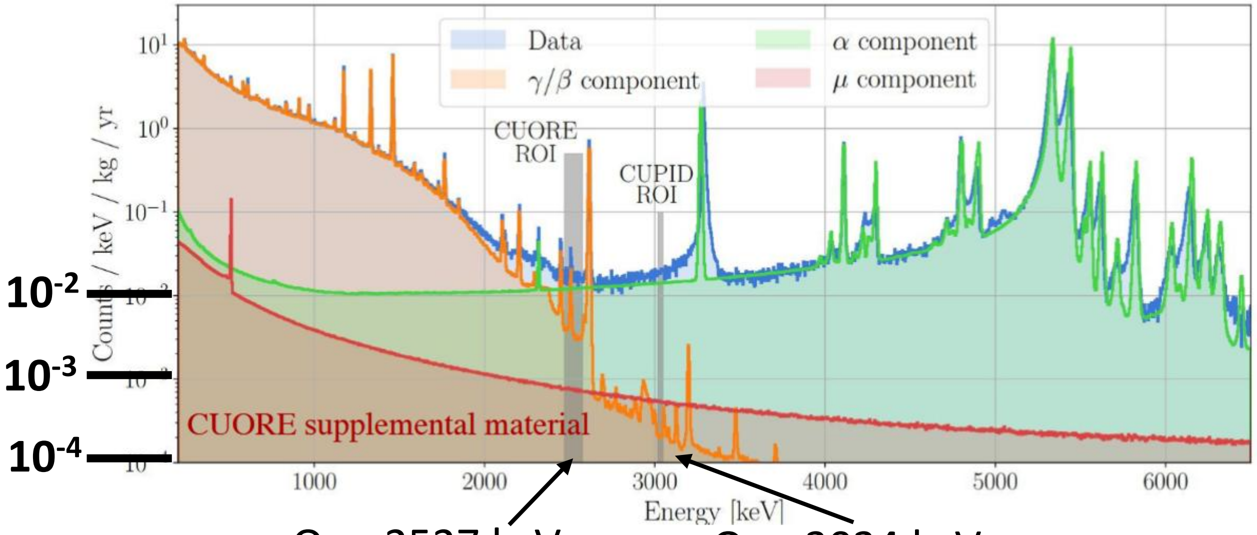
1. **A tonne-scale bolometric detector** is technically feasable
2. **Analysis of ~1000 individual bolometers** is handable
3. **An infrastructure to host a bolometric next-generation 0ν2β experiment exists** and will be available at the end of the CUORE physics program (30/6/2026)

CUPID (CUORE Upgrade with Particle ID) is a future 0ν2β bolometric experiment exploiting the **CUORE infrastructure** and with a **background 100 times lower at the ROI**

CUPID background goal:
b ~ 1×10^{-4} counts/(keV·kg·y)

CUORE background model

b
[counts/(keV·kg·y)]



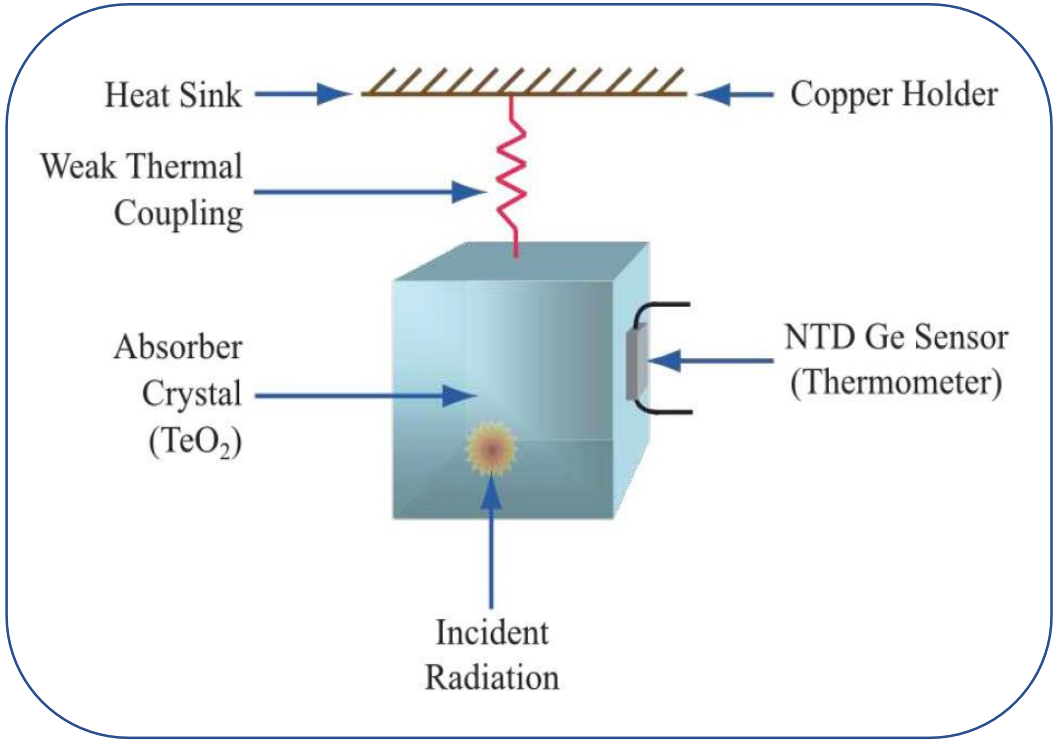
$Q_{\beta\beta}$: 2527 keV (^{130}Te)

$Q_{\beta\beta}$: 3034 keV (^{100}Mo)

- Reject α background with **scintillating bolometers**
- Mitigate γ background by **moving to ^{100}Mo**
  → $Q_{\beta\beta}$: 2527 keV (^{130}Te) → 3034 keV (^{100}Mo)
- Increase isotope mass by **enrichment** (natural isotopic abundance: 9.7%)

CUPID rationale

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



No PID

$Q_{2\beta}$ = 2527 keV **< 2615 keV**

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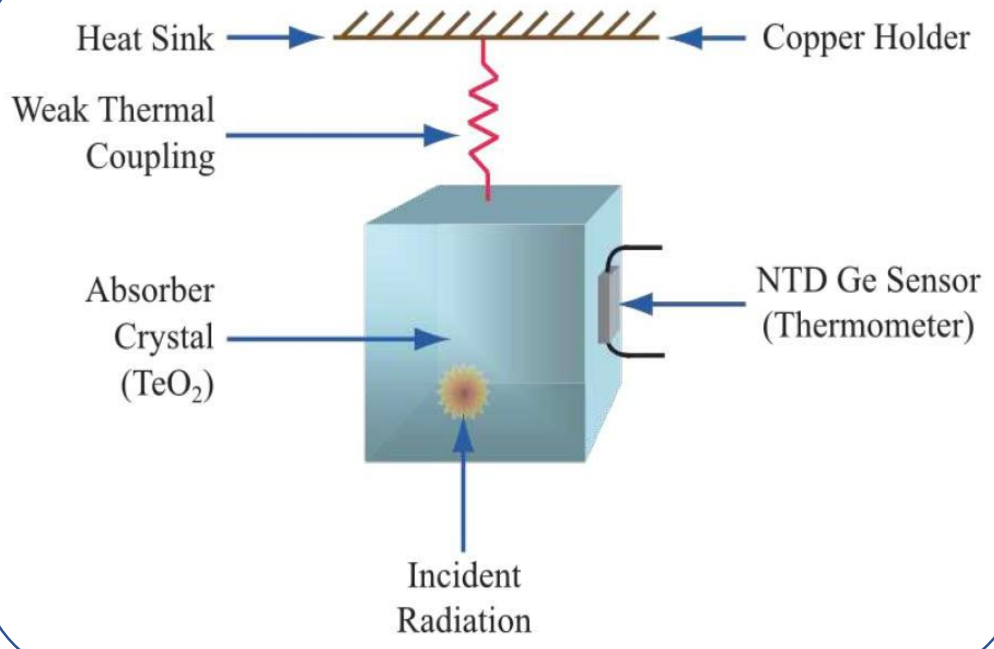
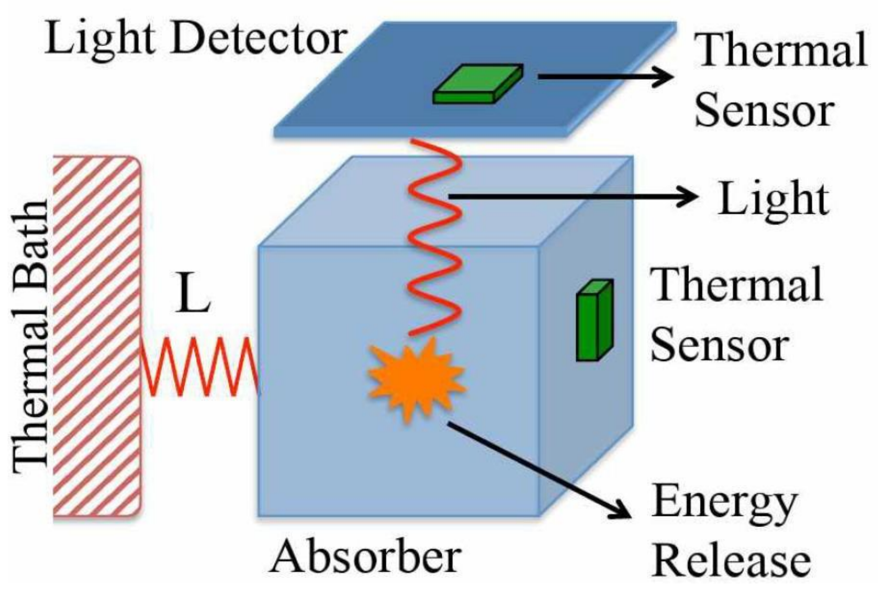


CUPID ^{100}Mo
heat + light
(**scintillating bolometer**)



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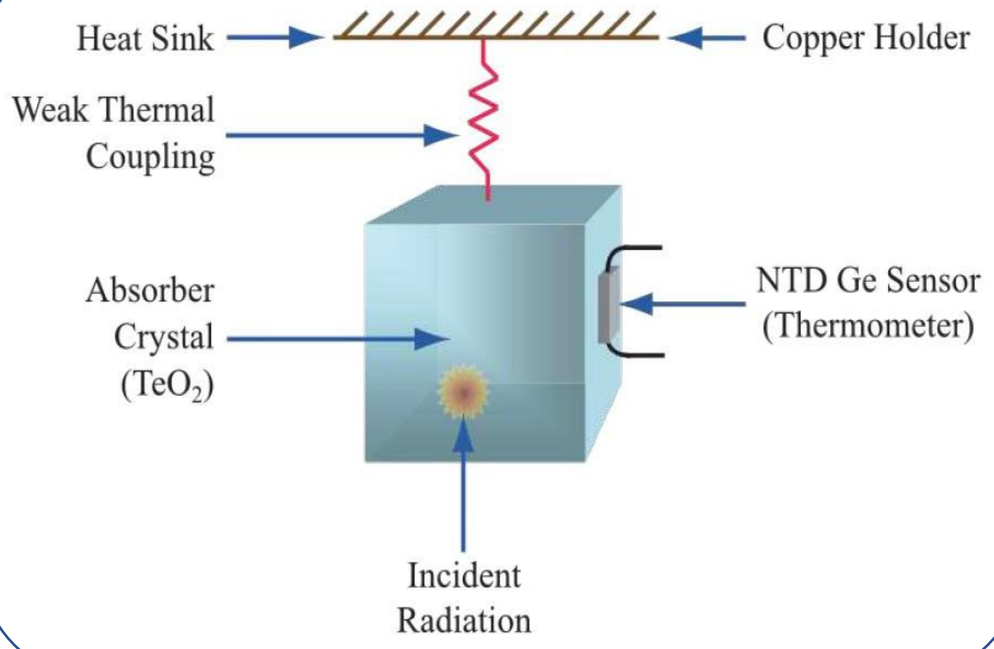

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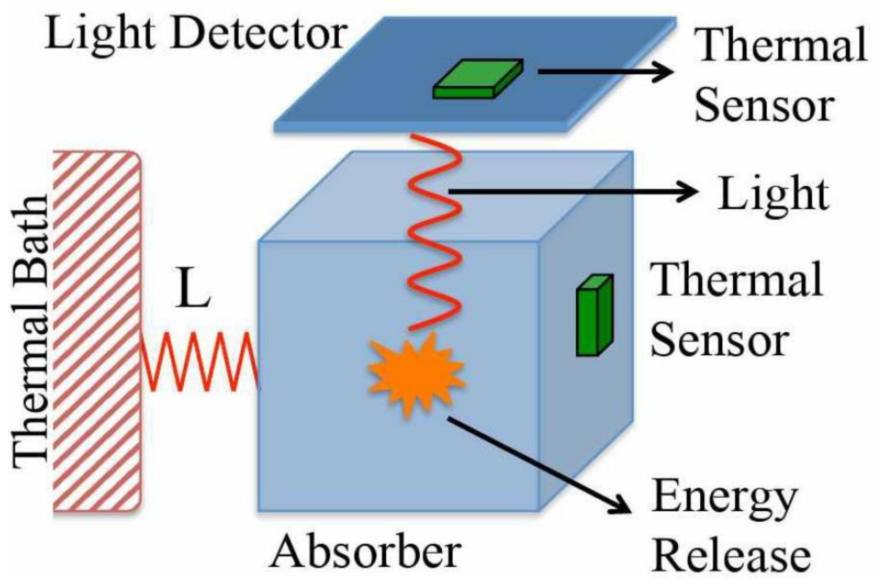

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~~α background~~ ← **PID**
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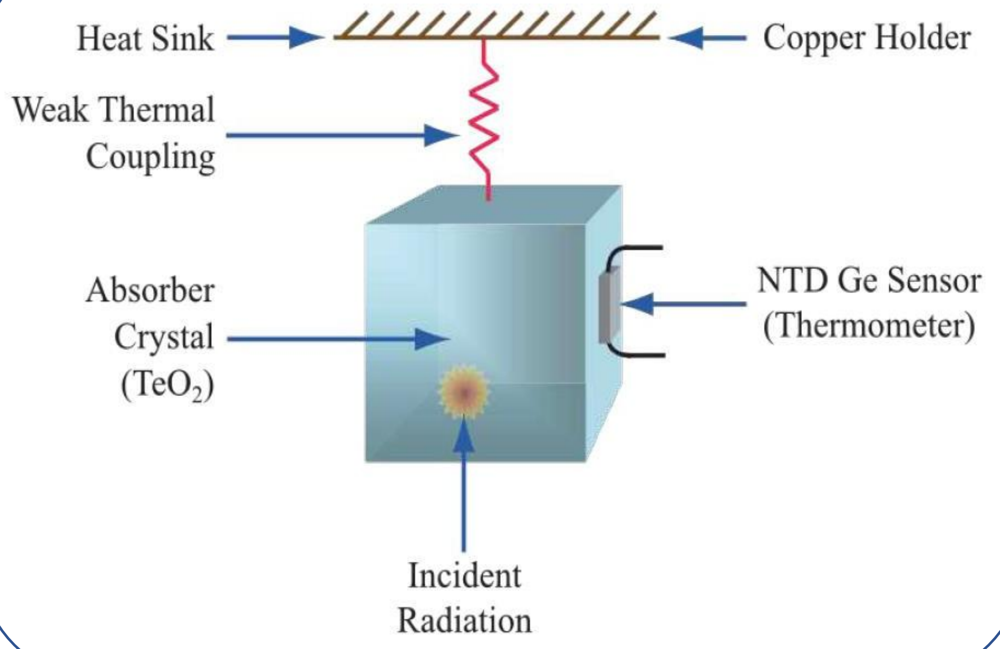

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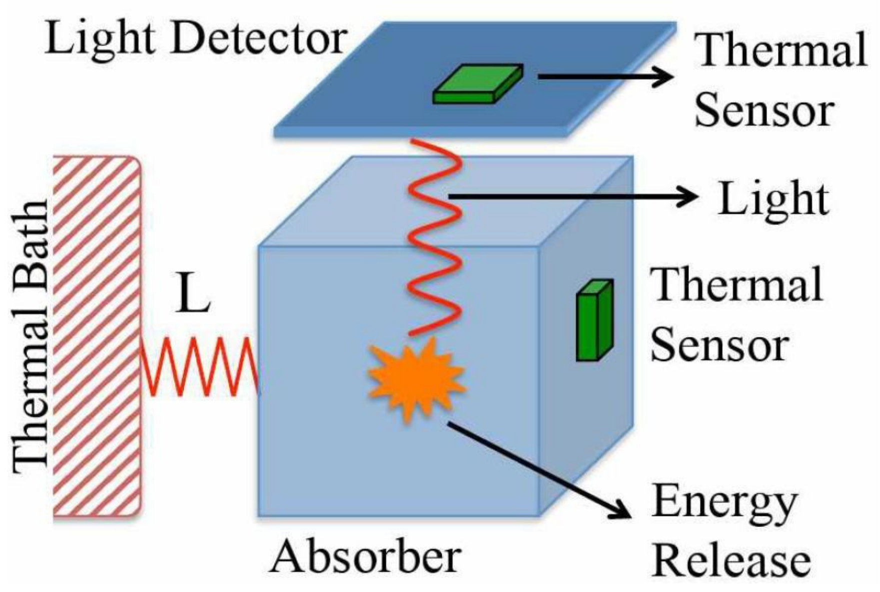

~~α background~~

~~γ background~~

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PID

$Q_{2\beta}$ = 3034 keV > 2615 keV

Choice of the isotope and compound

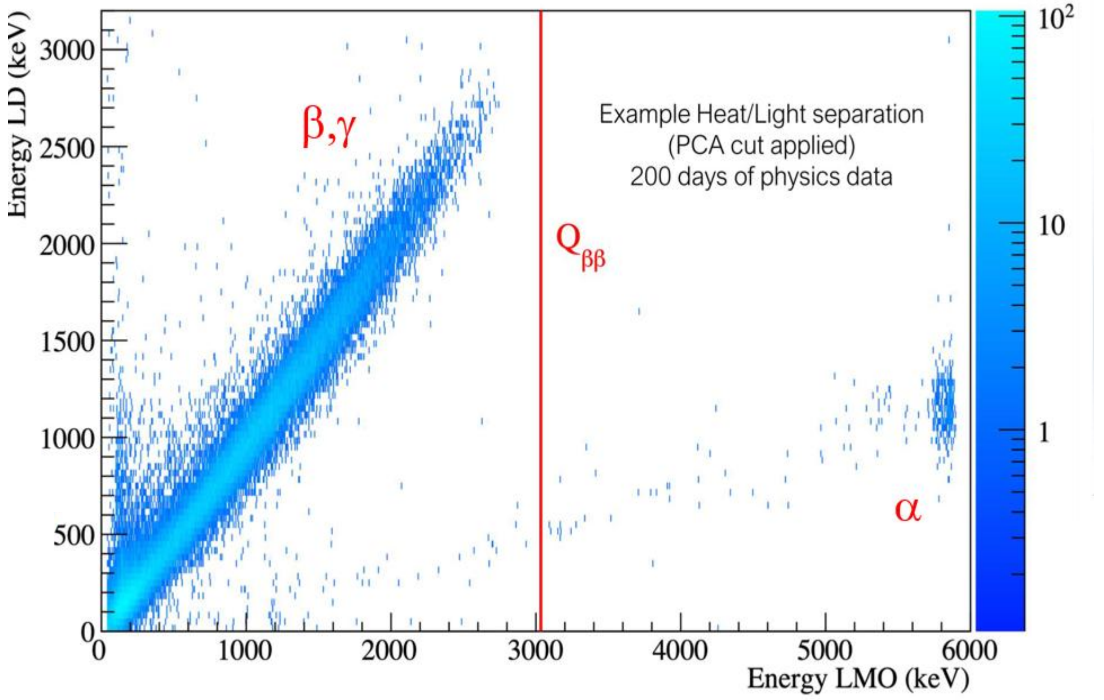
- Successful R&D in France on Li_2MoO_4 scintillating bolometers (LUMINEU, ISOTTA projects)

- Culmination in the **CUPID-Mo experiment**

Conceived and built at IJCLab (CSNSM) / IRFU
20 crystals (enriched in ^{100}Mo) – **2.34 kg ^{100}Mo**
Energy resolution: ~**5-7 keV FWHM**
Installed in the EDELWEISS cryostat in LSM
Physics data taking: April 2019 – June 2020

Best limit on ^{100}Mo at the time
$T^{0\nu}_{1/2} > 1.8\times10^{24}$ y
b = 2.7×10^{-3} counts/(keV·kg·yr)
No counts in ROI with 1.47 kg·yr exposure

Full α rejection
Radiopure crystals: U/Th $\lesssim$0.5 μBq/kg



Phys.Rev.Lett. 126(2021)181802 - Eur.Phys.J. C 82,1033(2022)

Essential CUPID requirements met

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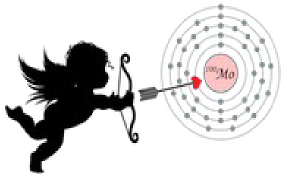

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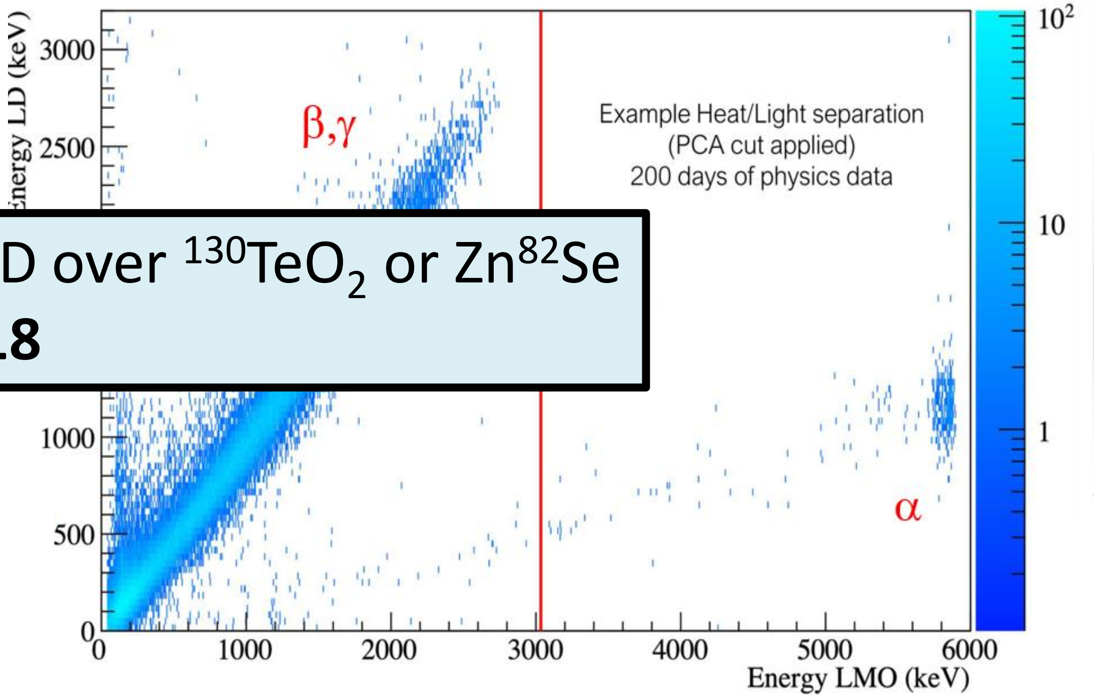
$Li_2{}^{100}MoO_4$ is selected for CUPID over $^{130}TeO_2$ or $Zn^{82}Se$
May 2018



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Phys.Rev.Lett. 126(2021)181802 - Eur.Phys.J. C 82,1033(2022)

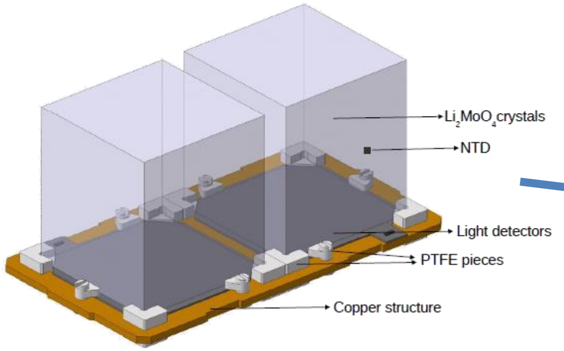
CUPID structure

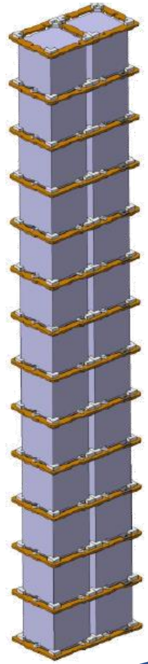
- **CUPID pre-CDR** *arXiv:1907.09376*
- **Upgraded structure** *Eur. Phys. J. C 82, 810 (2022), Eur. Phys. J. C 85, 737 (2025)*
- **TDR under finalization**

- Crystal: $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~280 g – enrichment ≥ 95%**
- Thermal sensor: **neutron transmutation doped (NTD) Ge thermistor**
- **Si heater** to stabilize the detector response
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo**
- **~1.6×10^{27}** ^{100}Mo atoms

Baseline design

Gravity stacked structure

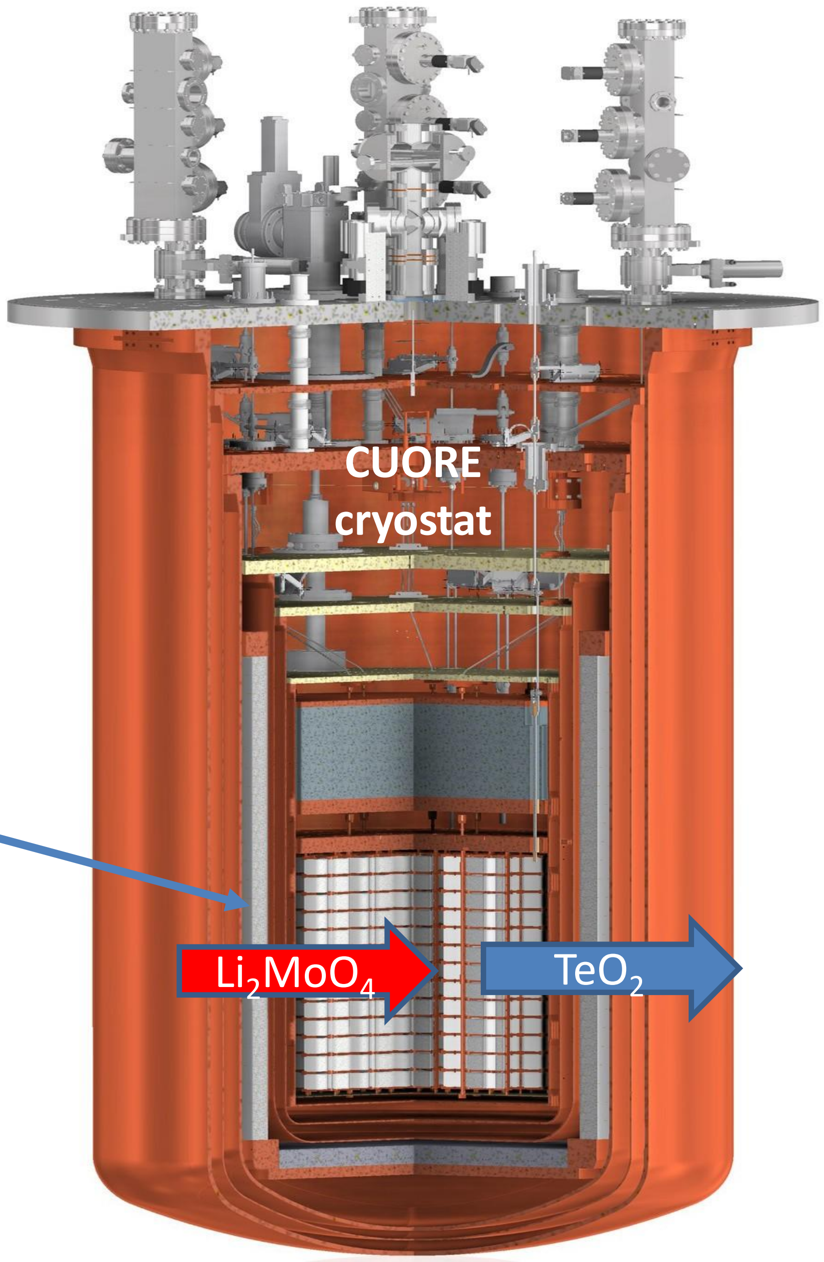




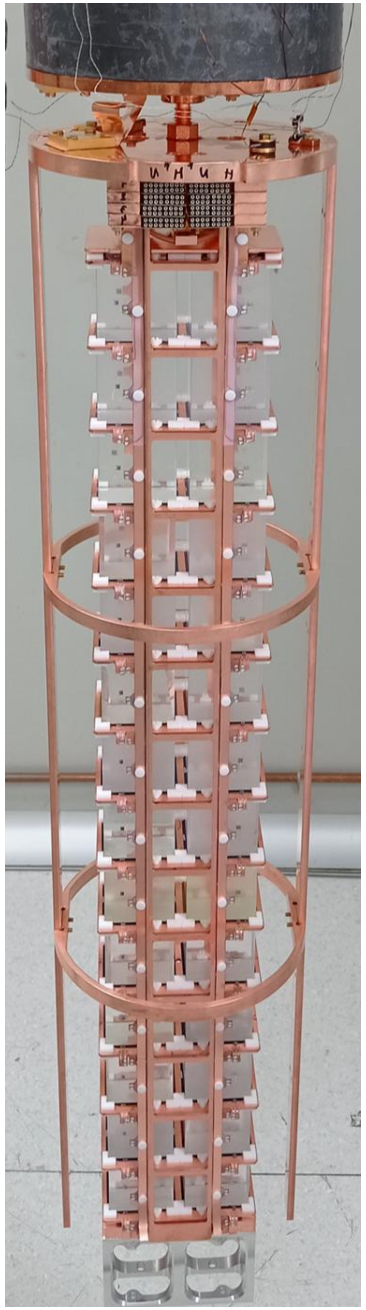
Light detectors

- Ge wafers with NTD sensor and SiO antireflective coating
- Each crystal has top and bottom LD
- No reflective foil

Muon veto for muon induced background suppression



Test of prototype towers at LNGS



GDPT
Eur. Phys. J. C 85, 935 (2025)

(Gravity Detector Prototype Tower)

- 28 Li_2MoO_4 crystals
- 30 Ge light detectors
- Tested at LNGS, Italy
- French contributions: gluing at IJCLab, participation in on site assembly

Results:

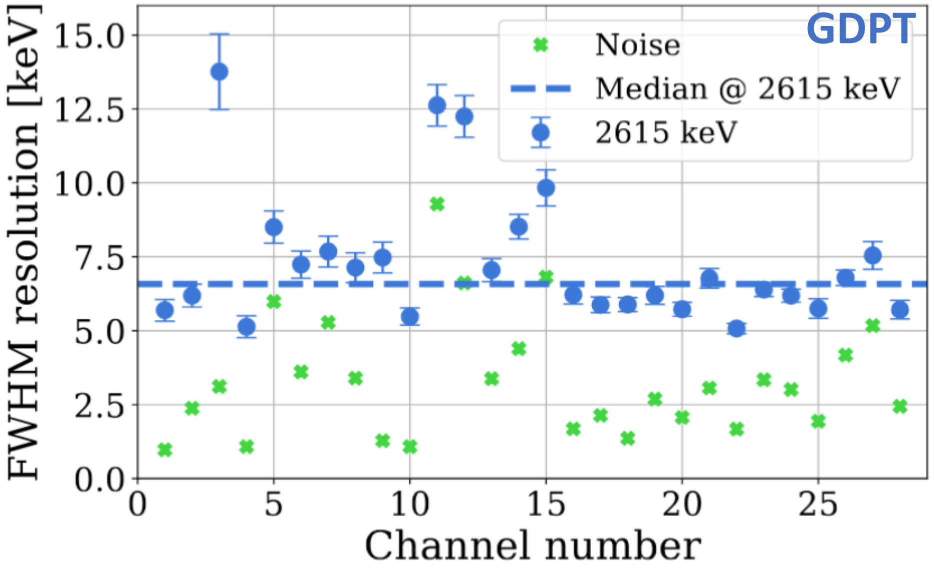
- Detectors successfully reached baseline temperature ~15 mK
- Baseline stable over the time
- LMO performance: median $FWHM_{2615\ keV}$ = 6.2 keV
- Median light yield: 0.36 keV/MeV
- Some excess noise on the LD -> changes to the LD assembly structure for the next test

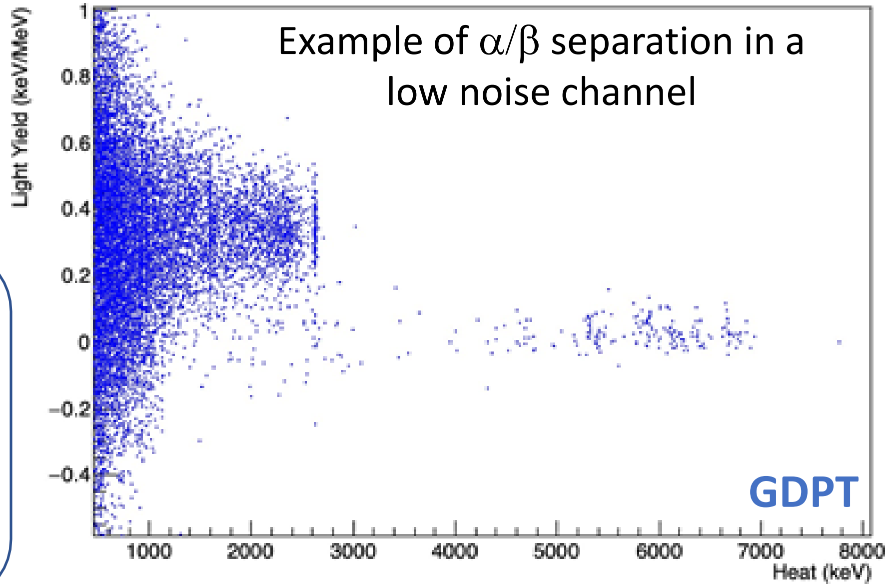
Current test: VSTT (Vertical Slice Test Tower)

- Under operation in LNGS now

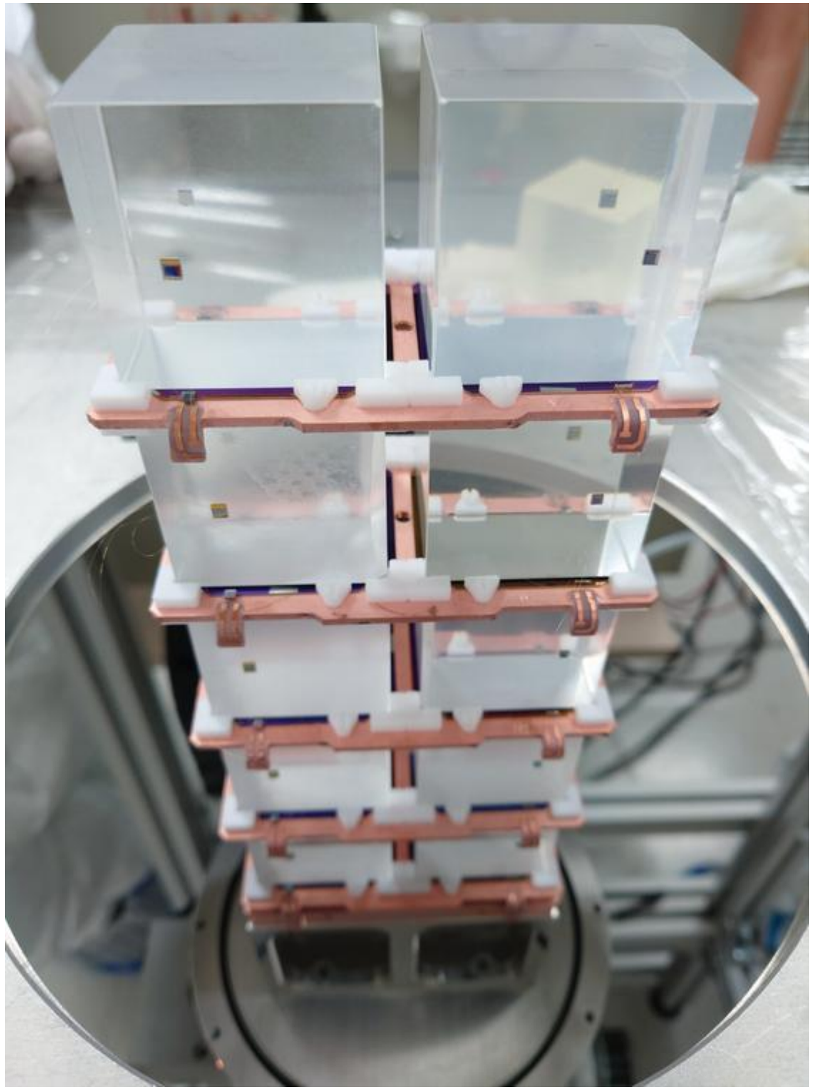
What's new?

- Enhanced light detectors (NTL amplification)
- Changes to the LD holding system to mitigate the noise
- Full test of the assembly line





GDPT assembly



Enriched crystal production

FWHM ~ 5-7 keV - LY ~ 0.3 keV/MeV - internal radioactivity (U, Th) ≤ 0.5 μBq/kg

- Outstanding **performance** and **radiopurity** obtained with **Russian crystals**: **Enrichment** (**Rosatom**) + **Crystallization** (**NIIC, Novosibirsk**) → **CUPID-Mo**, **CROSS**
- Because of the invasion of Ukraine the procurement of enriched crystals from Russia is now **impossible**

Chinese baseline: IPCE (subsidiary of CNNC) for **enrichment** + **SICCAS** (Shanghai) for **crystals**

IPCE: it has already produced several kg of ^{100}Mo in 2024 for CUPID/CROSS
Active in medical production

SICCAS: extremely reliable company with excellent tracking record in large scale experiments:

- ~1000 TeO_2 crystals in CUORE
- ~4000 $PbWO_4$ crystals for CMS, Jlab Hybrid EmCal, PANDA EMCal, NPS project

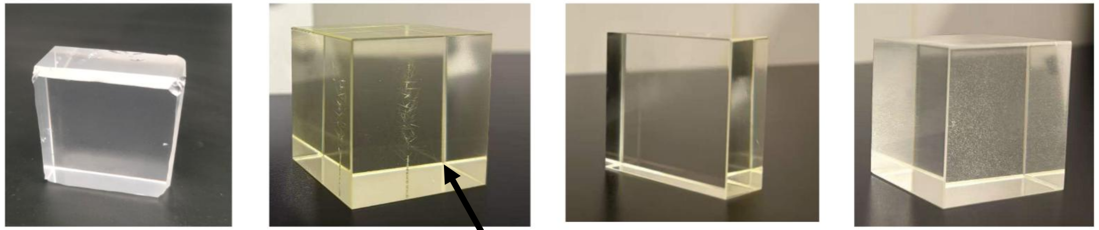
French alternative:

- Crystallization technique from ANR CLYMENE at SIMaP/INP Grenoble
- Companies LUXIUM (Gières, Grenoble) for crystals and ORANO (Tricastin) for ^{100}Mo enrichment

Enriched crystal production

IPCE + SICCAS: production and experimental tests

- Pre-production – French + Italian contracts
- **Seven** enriched crystals **produced** so far (**Bridgman method**)



LMO-600 45×45×21 mm³

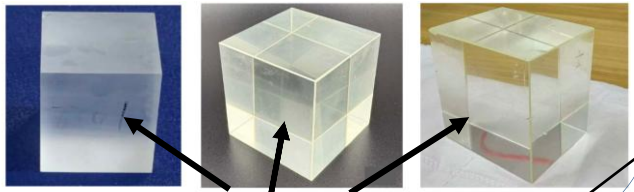
LMO-G8382 45×45×45 mm³

LMO-G8383 45×45×19 mm³

LMO-G8384 45×45×38 mm³

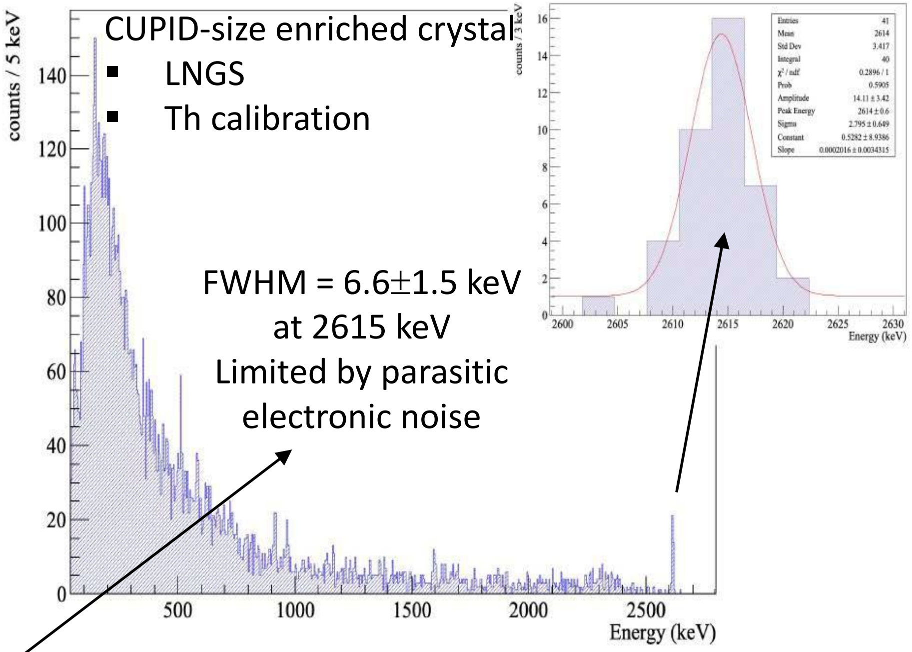
Nominal CUPID size

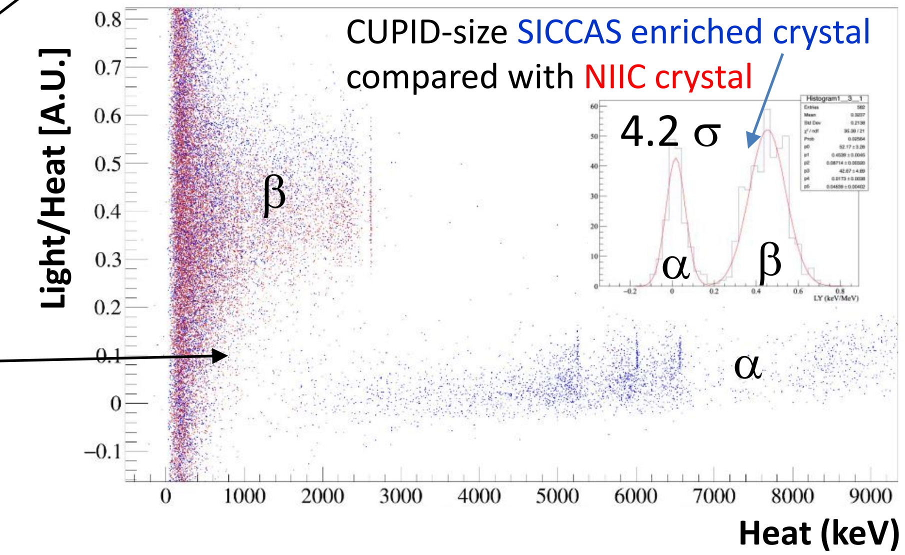
- **Four** crystals have been **tested** in IJCLab, LNGS and CEA/IRFU
- **Three** additional CUPID-size crystals will be tested at LNGS soon



Nominal CUPID size

- **Results** obtained with the tested crystals show that:
  - Sensitivity complies with CUPID goal energy resolution
  - LY is similar or even higher than for Russian crystals (0.24 – 0.45 keV/MeV depending on geometrical configuration)
  - α/β discrimination power is well within CUPID goals
  - Pulse shape is compatible with that obtained with Russian crystals





Enriched crystal production

- **Radiopurity was not a priority so far** → Optimization of crystallization process and test of bolometric performance

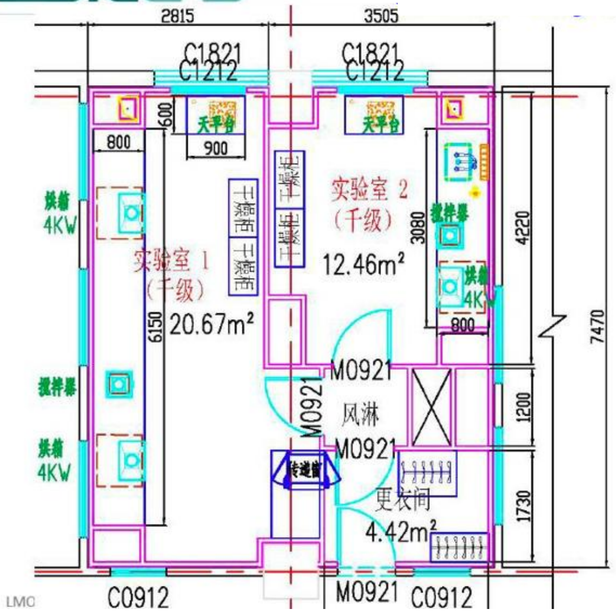
Now the radiopurity phase has started

- IPCE and SICCAS are working together to produce **ultra-pure Li_2MoO_4 powder** ready to be placed in crucible
- Big furnaces for mass production will be fabricated with **low radioactivity materials**
- **Reduction of dust** in the furnace area
- Develop a **dedicated clean room** for **crystal processing** (cutting, grinding, polishing and packaging)
- Selection of **grinding and polishing material**

Objective

Purchase contract in **mid 2026** for **CUPID-Stage-I**

SICCAS Since 1928 — Clean room for processing

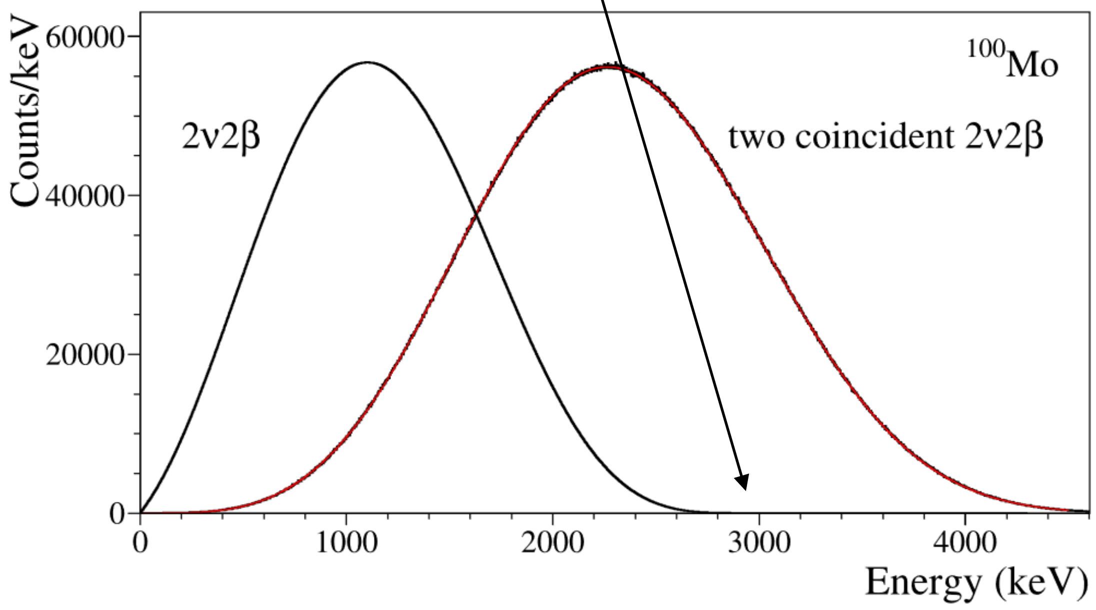


Random coincidences of 2ν2β events

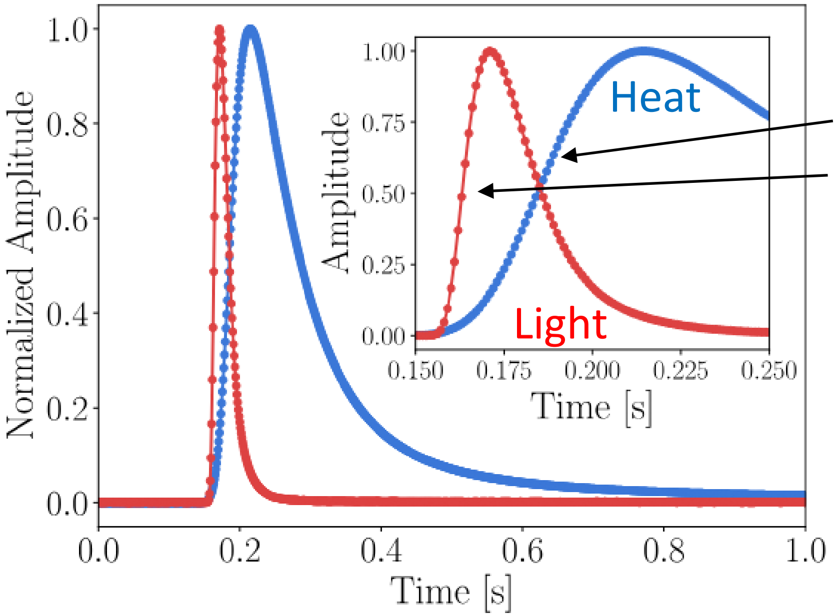
- **Fast 2ν2β transition in ^{100}Mo:** $T^{2\nu}_{1/2}$ **= 7×10^{18} y** → 2ν2β activity in a CUPID crystal: **~2.6 mBq**
- Significant pile-up probability due to a **random coincidence of 2ν2β events** → background in the region of interest
- **$b_{2\nu2\beta}$ = (δT / 1 ms) · 3.3 x 10^{-4} counts/(keV·kg·y)** → **δT ~ 0.17 ms** is required to meet the CUPID 2ν2β background goal

pulse pair resolving time

0.5 x 10^{-4} counts/(keV·kg·y)



Heat-light coincidence



Rise-time ~ 15 ms

Rise-time ~ 1 ms

Use light detector for pile-up discrimination

But SNR ~ 10 only

Light detectors and NTL effect

Light detectors are essential to **reject surface α background** → **rejection at 99.9%** with ordinary light detectors

In June 2023, the collaboration decided to enhance light detector performance exploiting the **Neganov-Trofimov-Luke effect (NTL)** according to a **technology fully conceived and developed in France**

- **Improve pile-up rejection** thanks to increase of SNR: **~ 10 → ~ 100**
- Mitigation of background induced by **random coincidences of ordinary 2ν2β events**

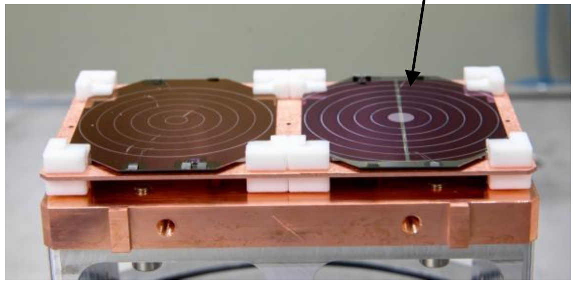
NTL effect applied to light detectors

NIMA 940, 320 (2019)

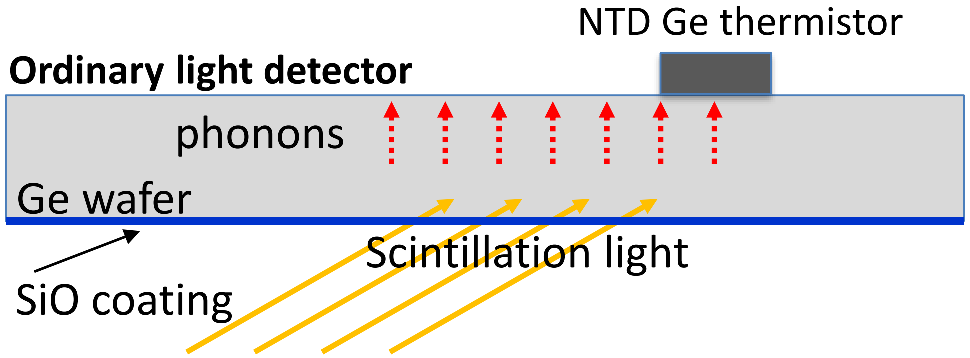
- **Electric field** in the light detector wafer via **a set of Al electrodes**
- Electron-hole pairs created by scintillation light absorption drift in the field and produce **additional heat**
- An **amplification of the thermal signal** by a factor 10-20 is technically possible
- **SNR is increased by a factor ~ 10**

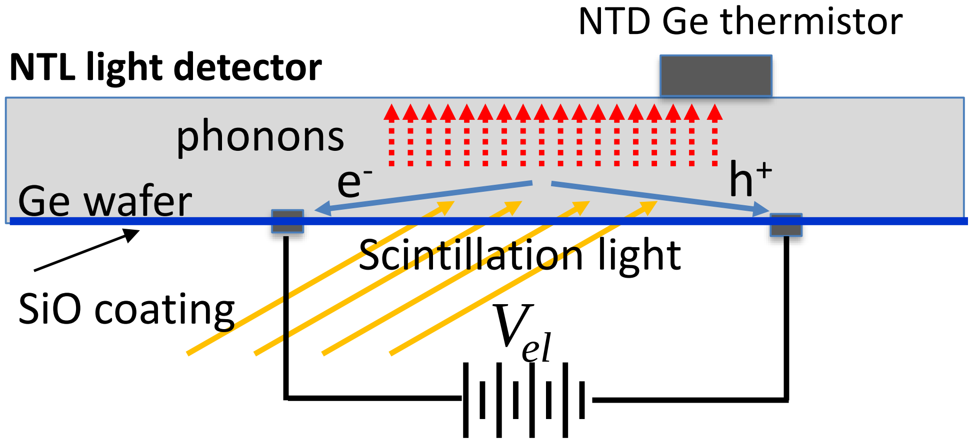
Amplified heat **Initial heat** **Voltage at the electrodes**

$$E_{tot} = E_0 \left(1 + \frac{q \cdot V_{el} \cdot \eta}{\epsilon}\right)$$



Limitation: leakage currents at V_{el} ~ 100 V





CUPID maturity

Eur. Phys. J. C 82, 810 (2022)

CUPID is a mature experiment, ready for construction

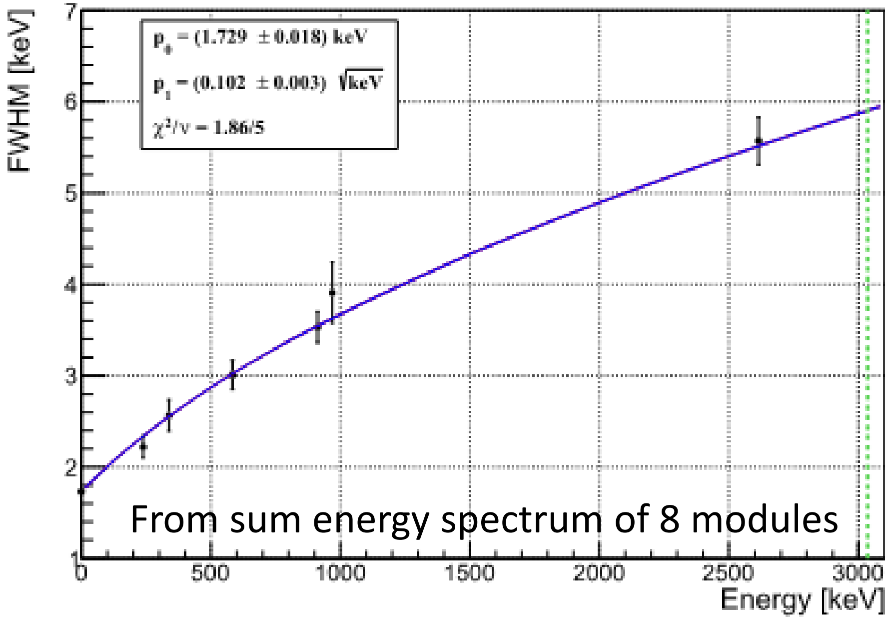
- High energy resolution (**5-7 keV FWHM**)
- Excellent α/β separation (**> 99.9% α rejection**)
- High radiopurity achievable (**≤ 0.5 µBq/kg in U/Th**)

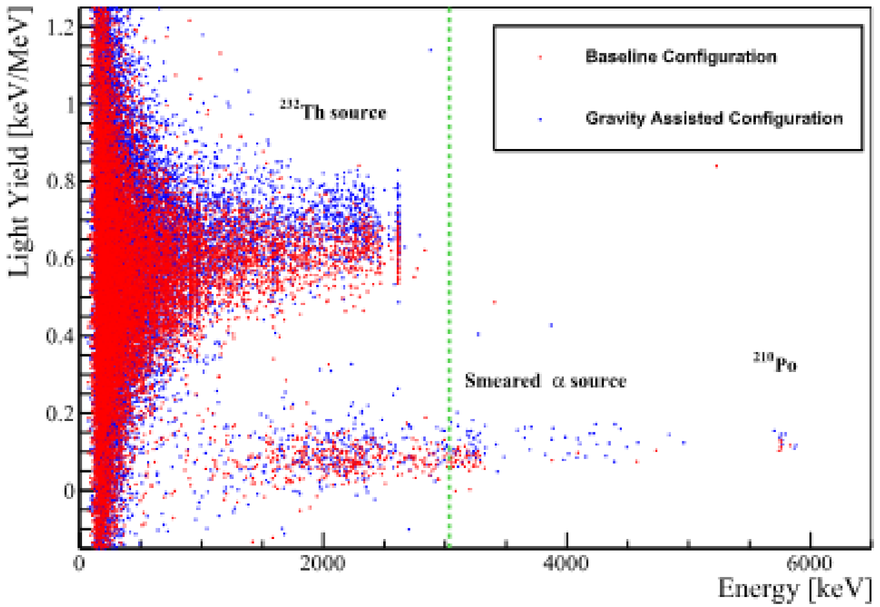
demonstrated in tens of large mass scintillating bolometers based on enriched Li_2MoO_4 crystals

CUPID-Mo, GDPT, CUPID and CROSS prototypes

- **Enhanced-sensitivity light detectors** bring the $2\nu2\beta$-induced background down to the desired level

- An **enrichment-purification-crystallization** line is under advanced development in China, replacing the original Russian option



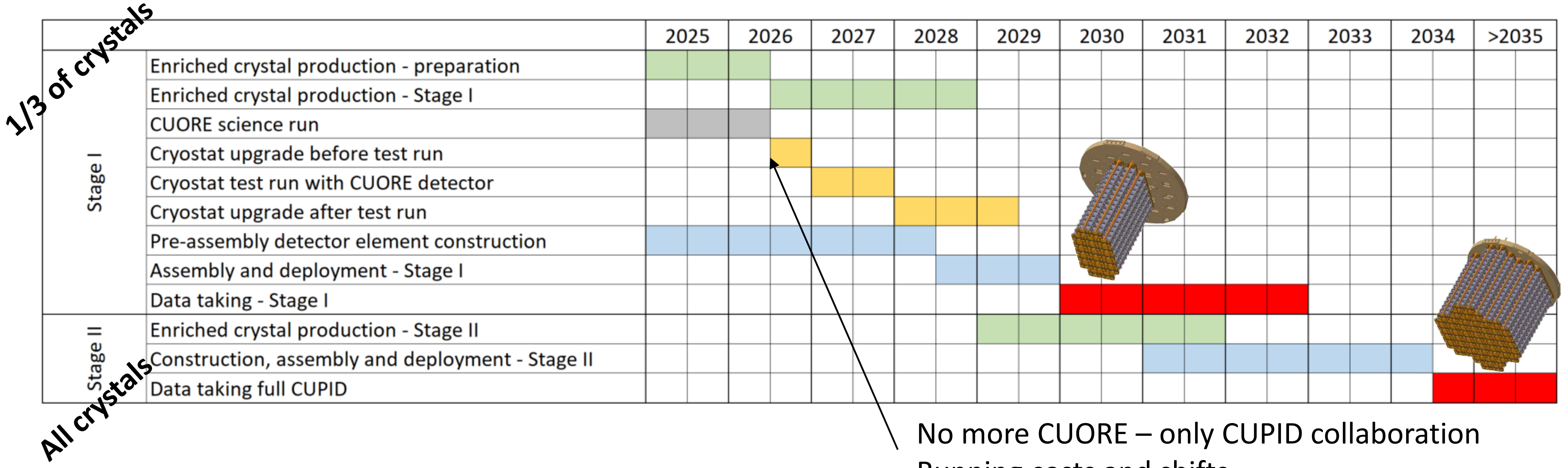


CUPID timeline

The collaboration decided to move to a **staged deployment** for CUPID implementation

Three key advantages

1. **Data taking starting in 2030** while the remaining crystals are still being produced $\rightarrow$ **early leading role in $0\nu2\beta$ search**
2. **Preservation of critical expertise** in running detectors and cryogenics **during the CUORE-to-CUPID transition**
3. **Room for optimization, improvement, and risk mitigation**.



No more CUORE – only CUPID collaboration
Running costs and shifts

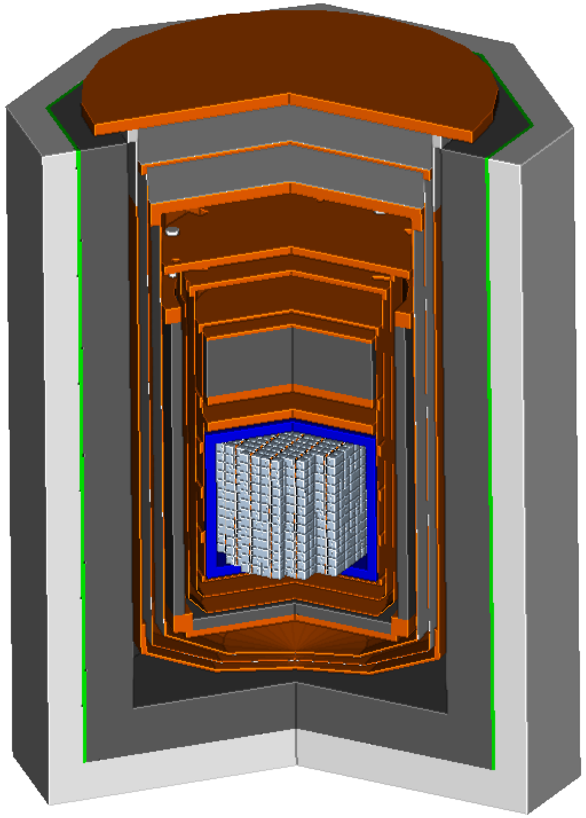
Part II - Background and Sensitivity of CUPID
Benjamin Schmidt - Senior physics board coordinator

CUPID Physics Board - 2025

Senior Coordinator - Ben Schmidt
Analysis Coordinator - Alberto Ressa
Science Coordinator - Pranava Teja Surukuchi
Software Coordinator - Brad Welliver
Simulations Coordinator - Mattia Beretta
Background Model Coordinator - Pia Loaiza
Detector Performance Coordinator - Irene Nutini
Public Data Coordinator - Penny Slocum
Publication Coordinator - Denys Poda
Outreach Board - Dounia Helis

Leading contributions from IJCLab and CEA/IRFU members

CUPID BG projection



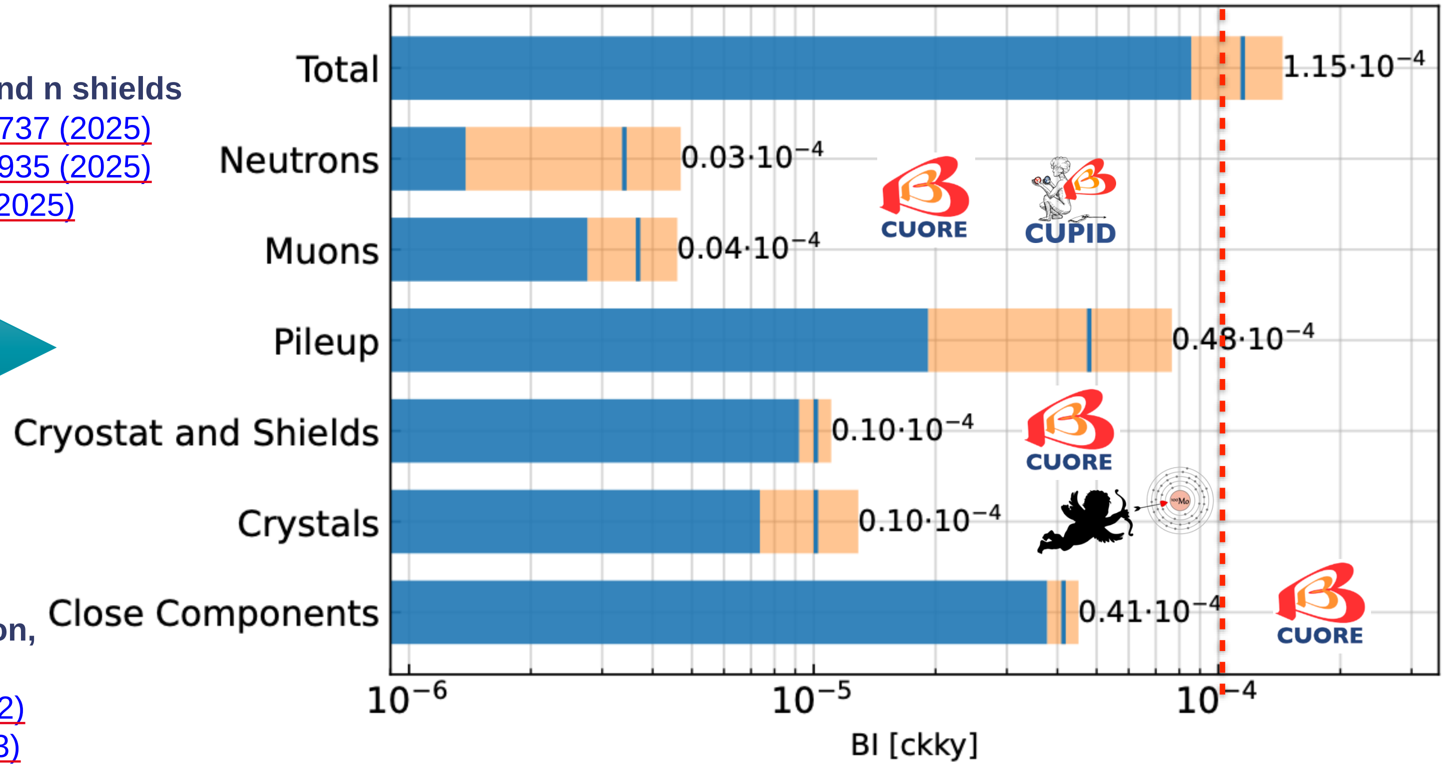
Cryostat and Background model
Phys. Rev. Lett. 126, 171801 (2021)
Phys. Rev. D 110, 052003 (2024)
arXiv:2509.05528

Tower design, μ and n shields
Eur. Phys. J. C 85, 737 (2025)
Eur. Phys. J. C 85, 935 (2025)
JINST 20 P08020 (2025)

Li_2MoO_4 crystals & α rejection, pile-up
Eur. Phys. J. C 82, 1033 (2022)
Eur. Phys. J. C 83, 675 (2023)
Phys. Rev. Lett. 131, 16250 (2023)
arXiv:2507.15732v1 (2025)

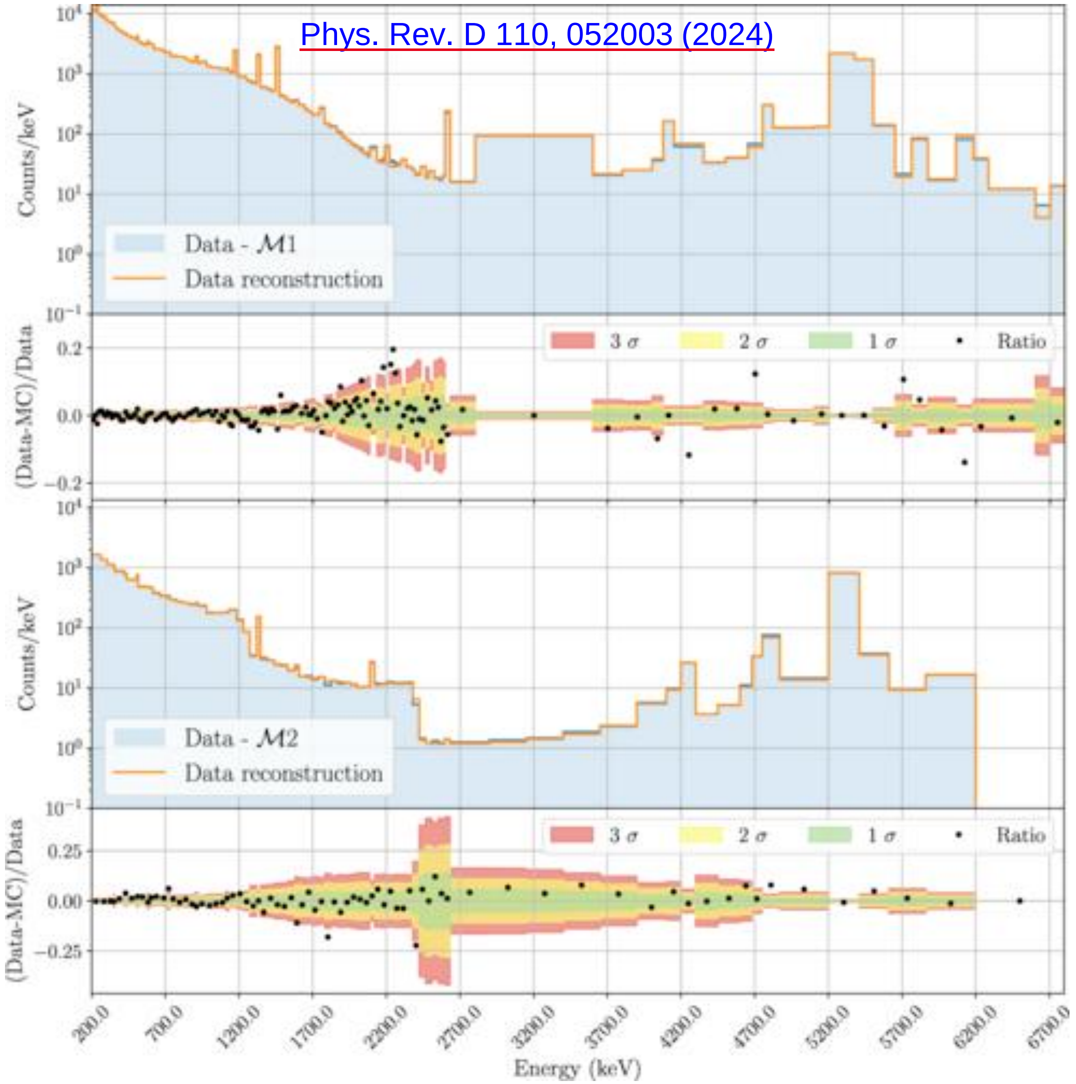
Scintillating bolometer & α rejection

CUPID BG simulation



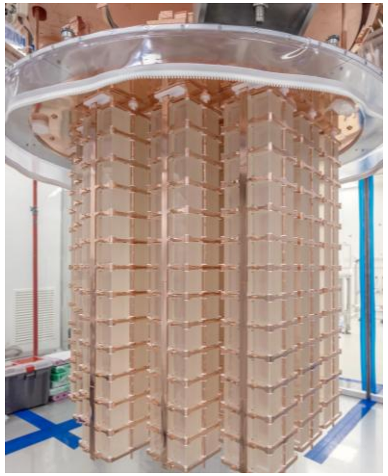
CUORE BG model - input for CUPID

Phys. Rev. D 110, 052003 (2024)



CUORE Background model

- **In-situ background assessment of the infrastructure for CUPID!**
- 7 source locations,
  46 bulk sources (partial decay chains, location)
  47 surface sources (partial decay chains, depth, location)
- Uses pre-screening geometric information, time information, event topology (M1, M2, priors where reliably available)
- Overall very good agreement with data

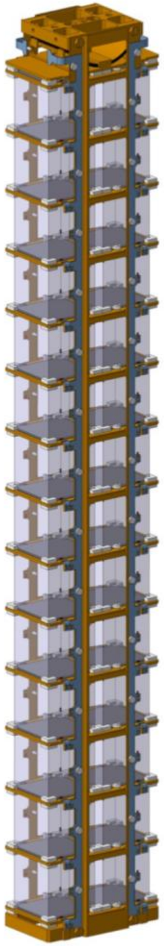


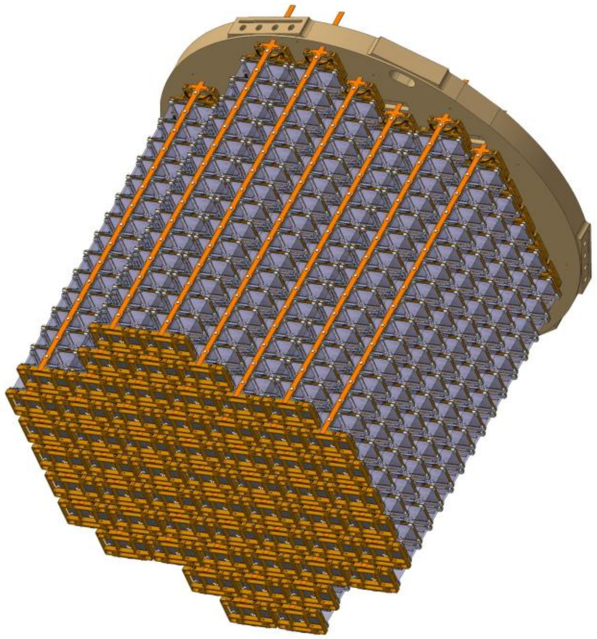
Surface α contaminations dominant!

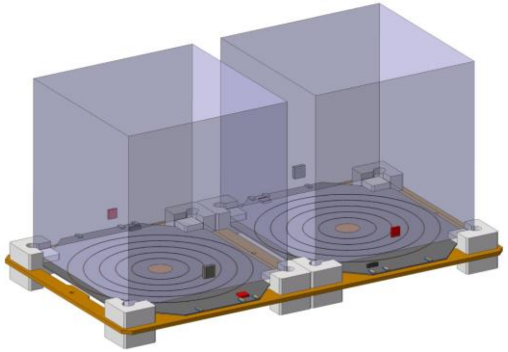
From CUORE to the CUPID Bg model

Eur. Phys. J. C 85, 737 (2025)
Eur. Phys. J. C 85, 935 (2025)

arXiv:2509.05528
JINST 20 P08020 (2025)





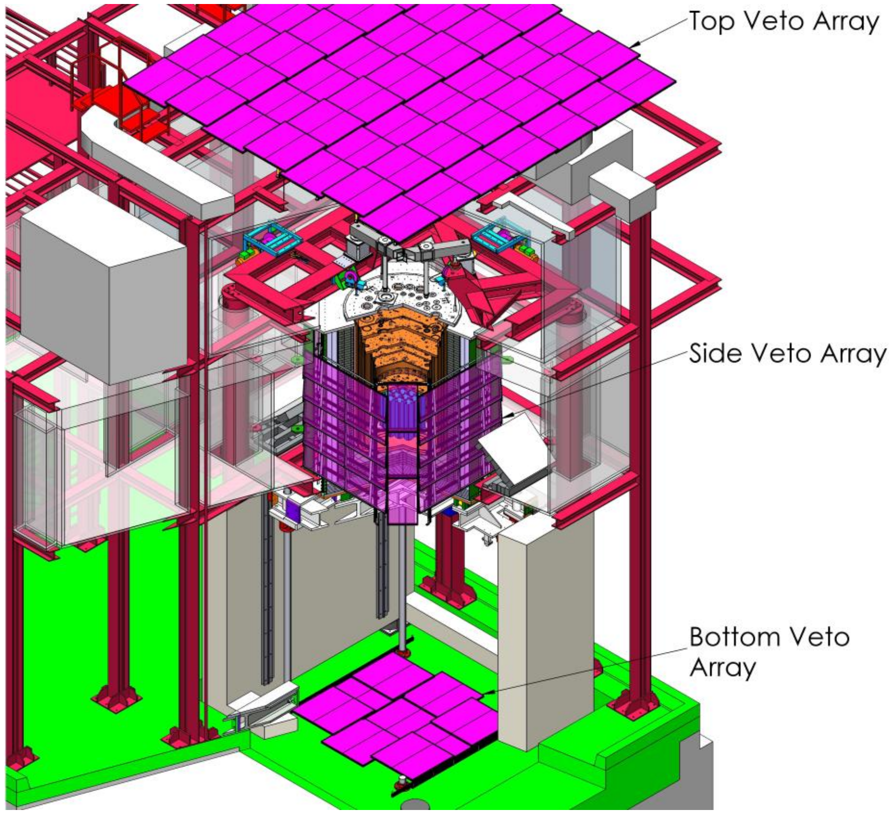


CUPID Background model

- CUORE infrastructure
- + New detector array:
  Scintillating detectors
  Full detector response model
- Muon veto system
- Extra neutron shielding

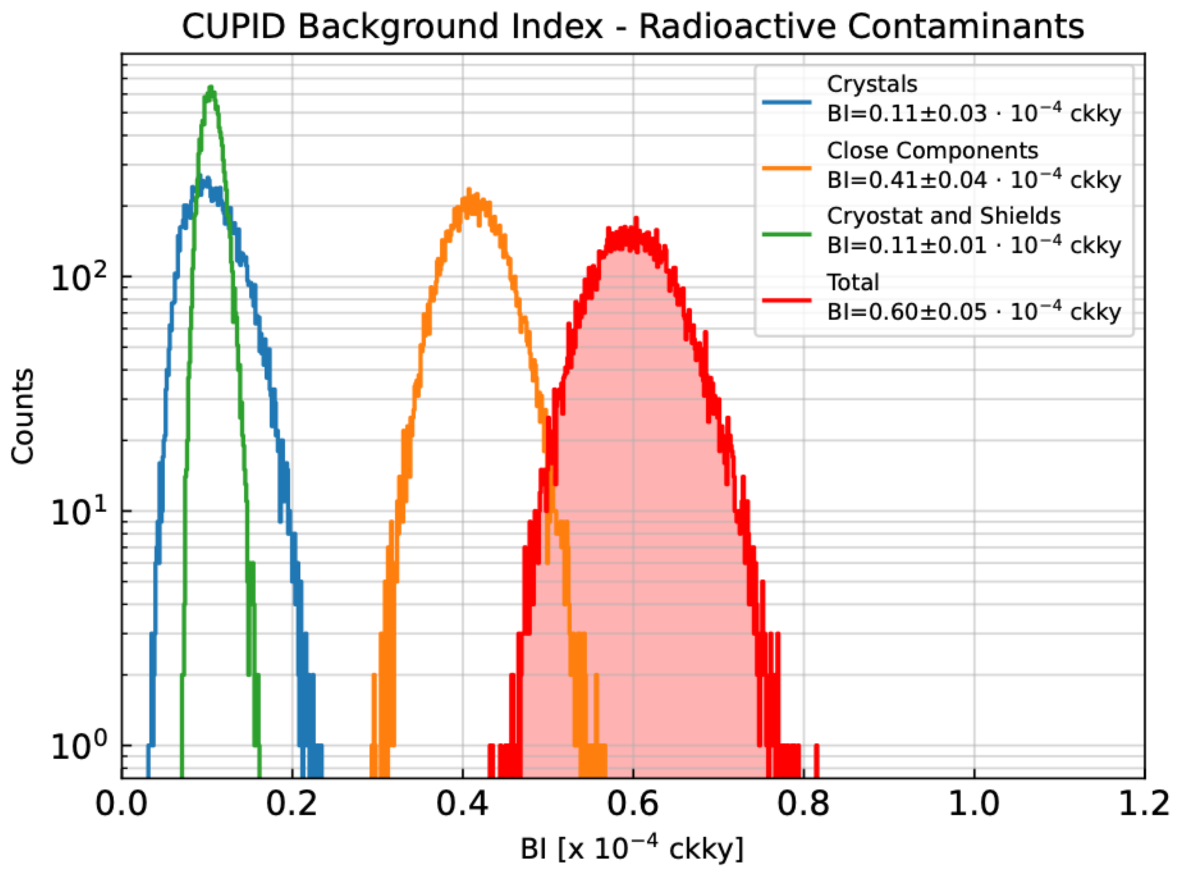
Geant 4 for radiogenic and muons

MCNP for neutrons (n,γ)
+Prompt gammas in Geant 4
with full custom detector response



Robust data-driven background predictions
Software/Techniques validated in situ on CUORE data

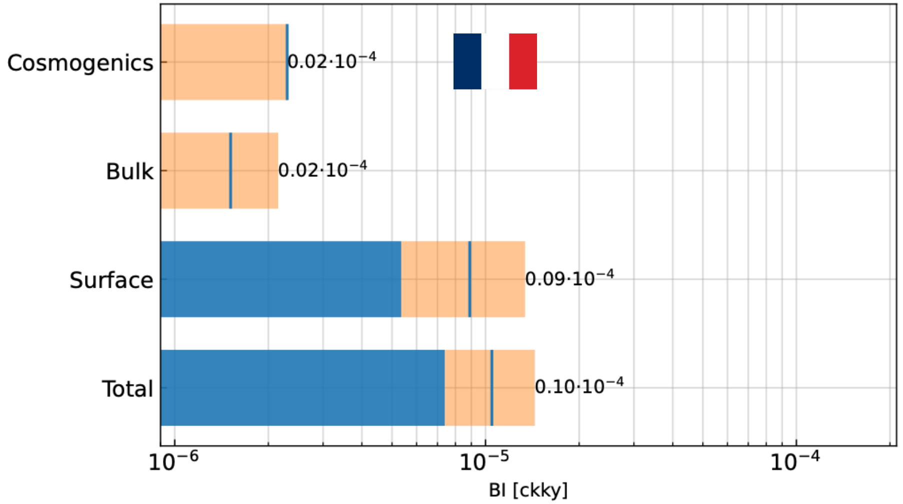
CUPID BG projection - Radiogenics



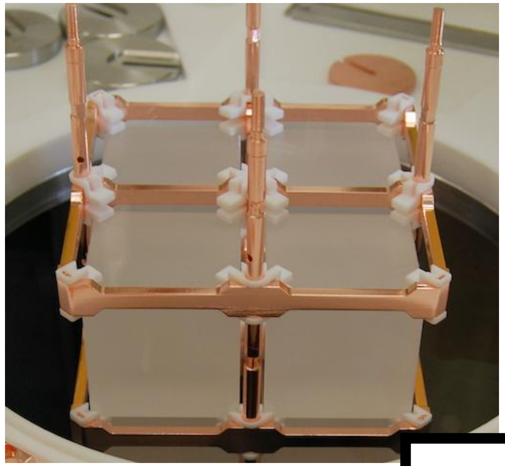
For CUPID: After surface α removal:
Surface β contaminations remain very important!

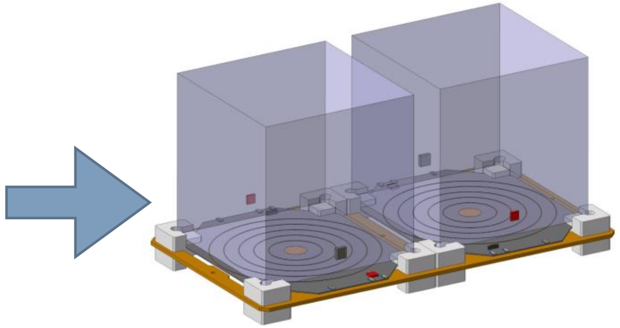
Cosmogenic activation

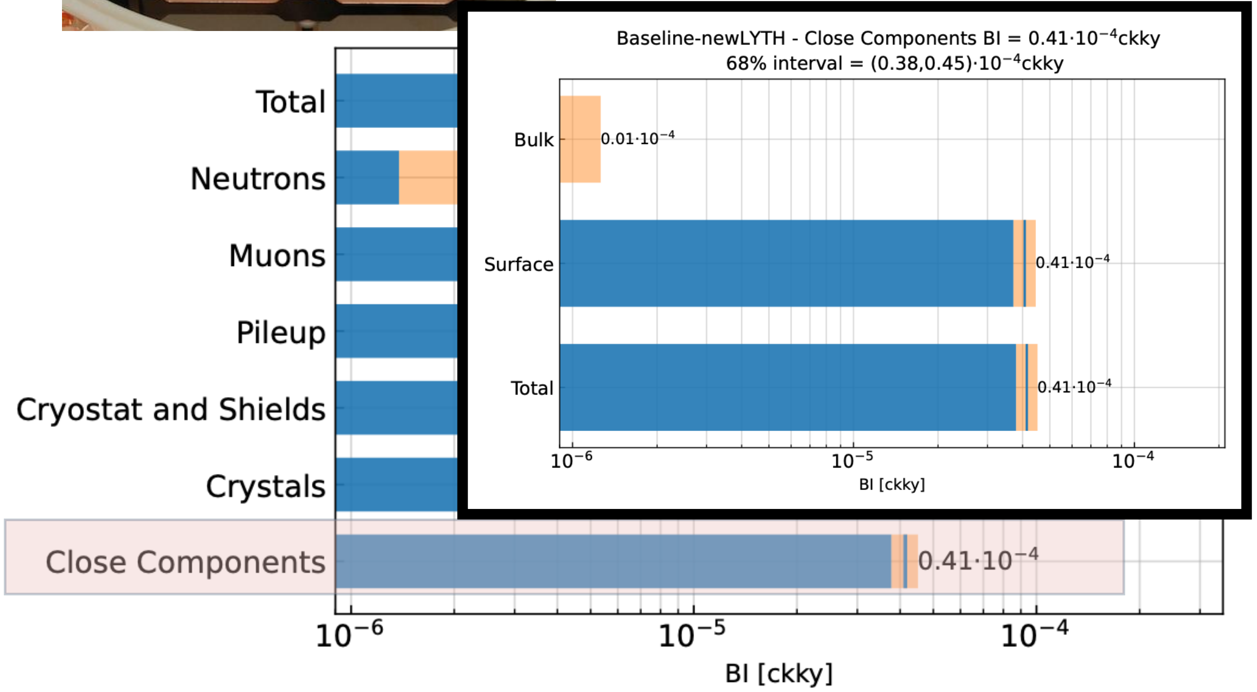
- 3 month at sea level, 1 yr underground before data taking
  - No transport by airplane
  - Crystals will be delivered in batches and stored underground at LNGS significantly increasing the storage (“cool down”) time for most crystals
- Negligible Background from underground activation

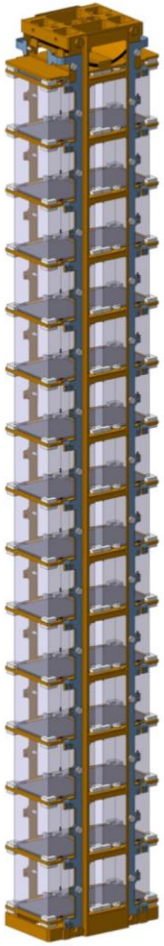


CUPID BG projection - Design improvements









Improvements to be evaluated:

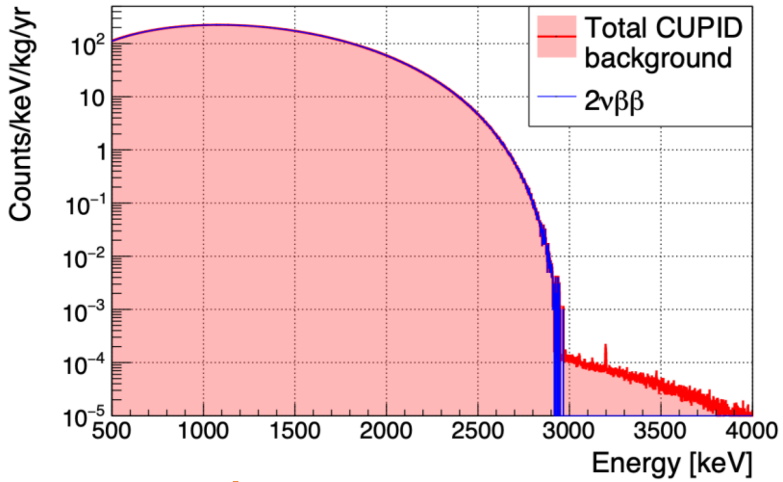
- New simplified mechanical tower design: less machining & handling
  - Lamination + contact-less production with laser cutting
  - No shadowing during etching/cleaning
- Improved radiopurity protocols during construction & storage

New screening campaigns to qualify surface backgrounds of machined pieces of CuPEN/PTFE/Copper ongoing

Target:
1/2 contamination compared to CUORE

CUPID: Pile-up background challenge

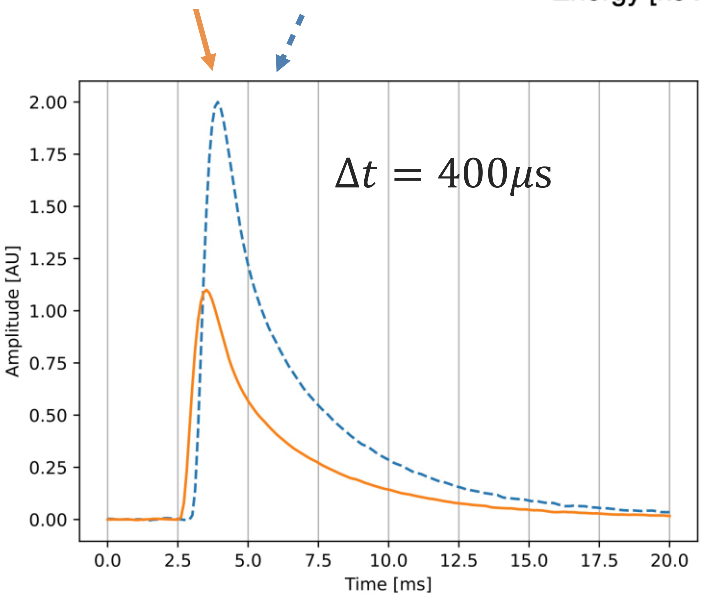
Phys. Rev. Lett. 131, 16250 (2023) $T_{1/2} = 7.1 \cdot 10^{18}\text{yr}$



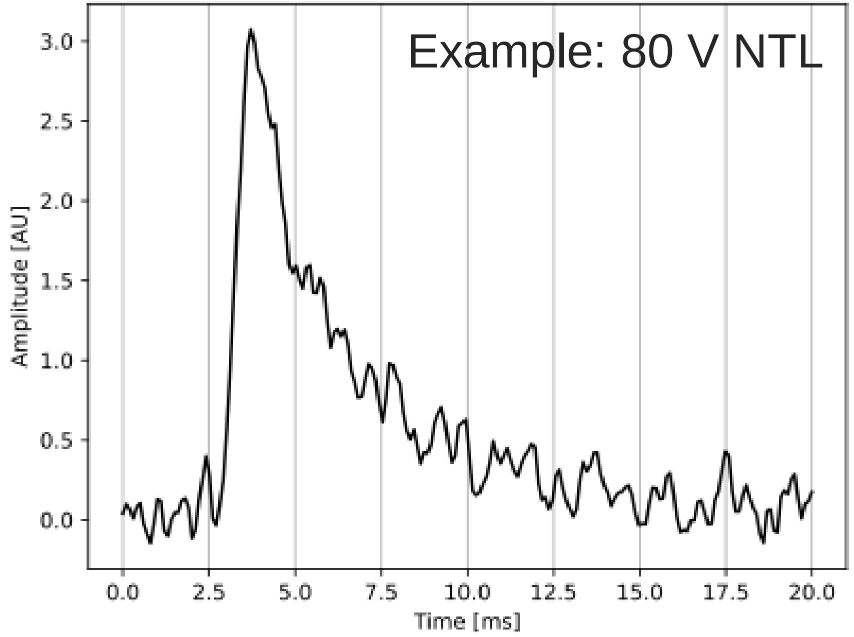
Simulations in addition to experimental testing:

Background prediction for pile-up

Randomly sample coincidences from the CUPID background model

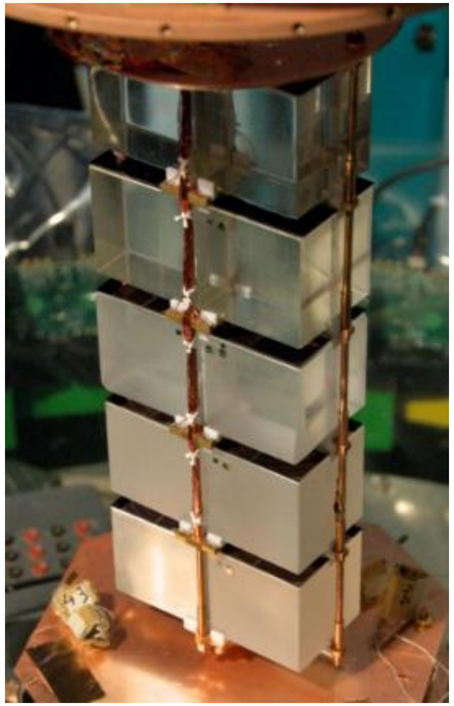


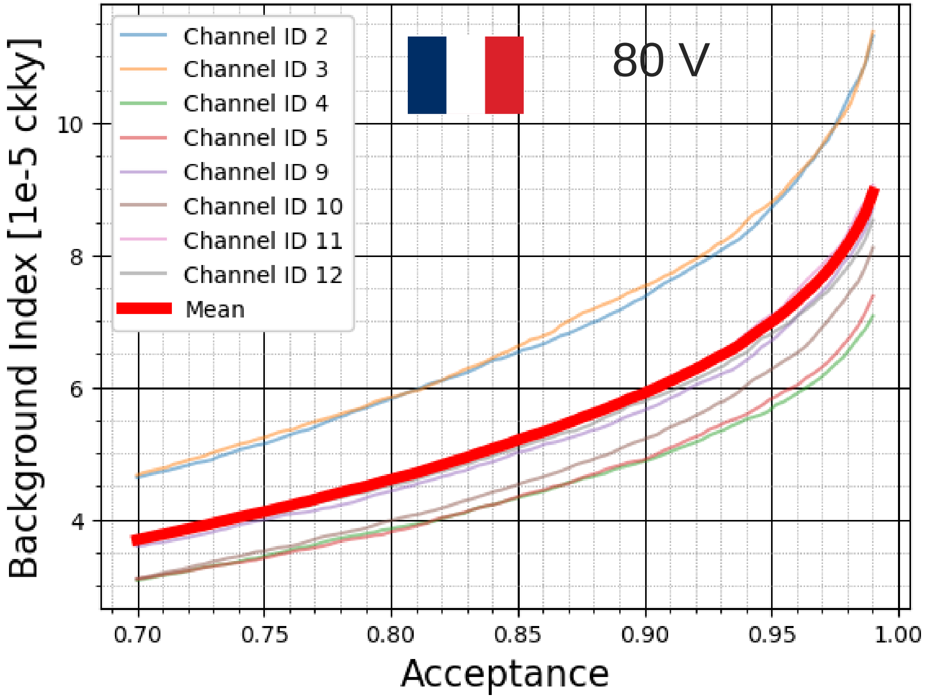
Vary time separation & add measured noise



CUPID - Improvements: NTL light detectors

EPJ-C 74,2913 (2014)
EPJ-C 77, 3 (2017)
NIM A 940, 320 (2019)
EPJC 83, 373 (2023)
https://arxiv.org/abs/2507.15732v1 (2025)

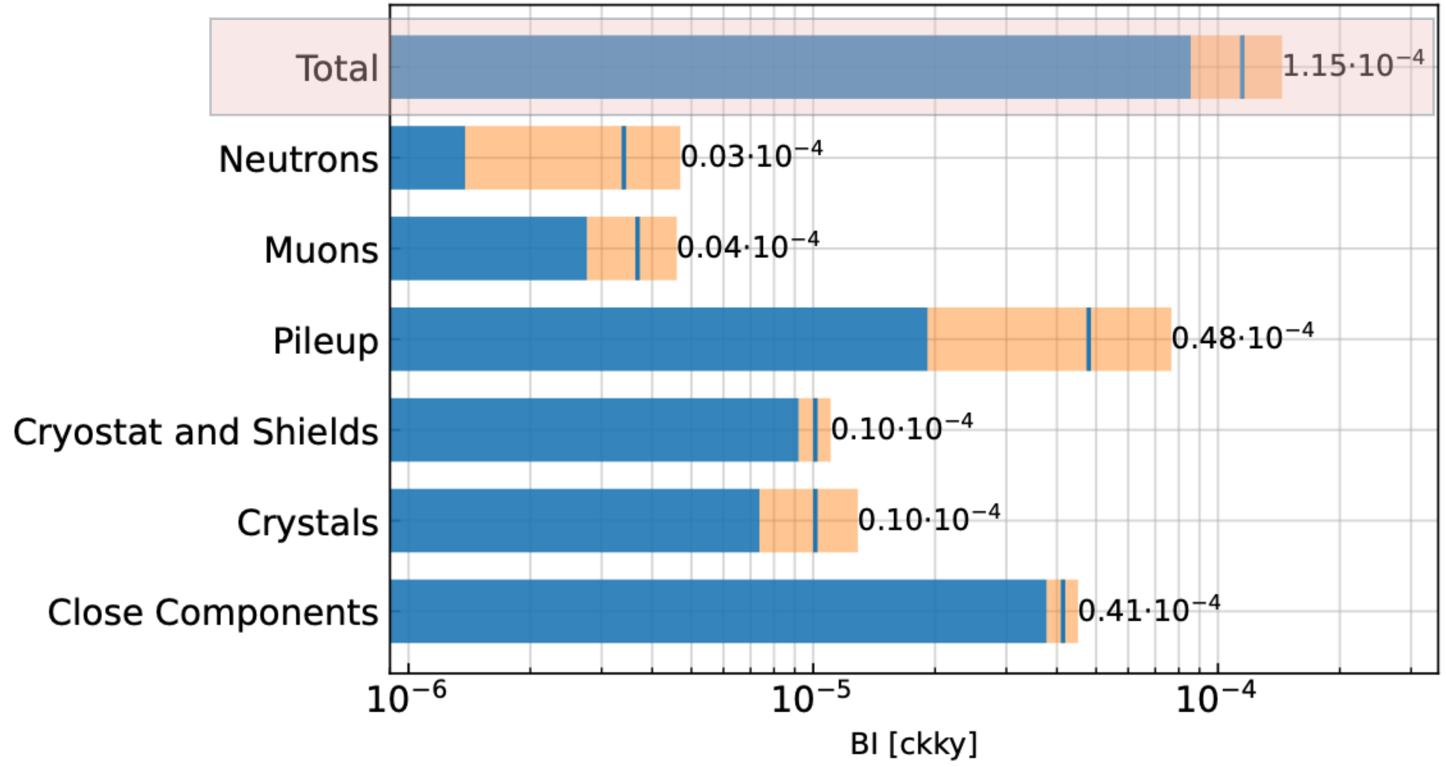




- Over 10 yrs of pile-up background characterisation and NTL detector development in France (Subset of publications on the left)
- Transfer of NTL technology to US for risk mitigation and production schedule
- Recent progress (2025)
  - Detailed control and optimisation of ANPS is very important
  - Analysis techniques:
    - Gained 28% improvement on BI with respect to OF (16% with respect to arXiv:2507.15732)
- Full electrode coverage to improve gain by ~25% in reach
- Full pre-testing to use higher NTL voltage
- New results (CROSS & VSTT) imminent

NTL light detectors ->Pile-up can be reduced to less than 5 x 10^{-5} counts/keV/kg/yr

CUPID BG projection - Summary



Conservative prediction

1 σ range: [0.86, 1.44] 10^{-4} counts/keV/kg/yr

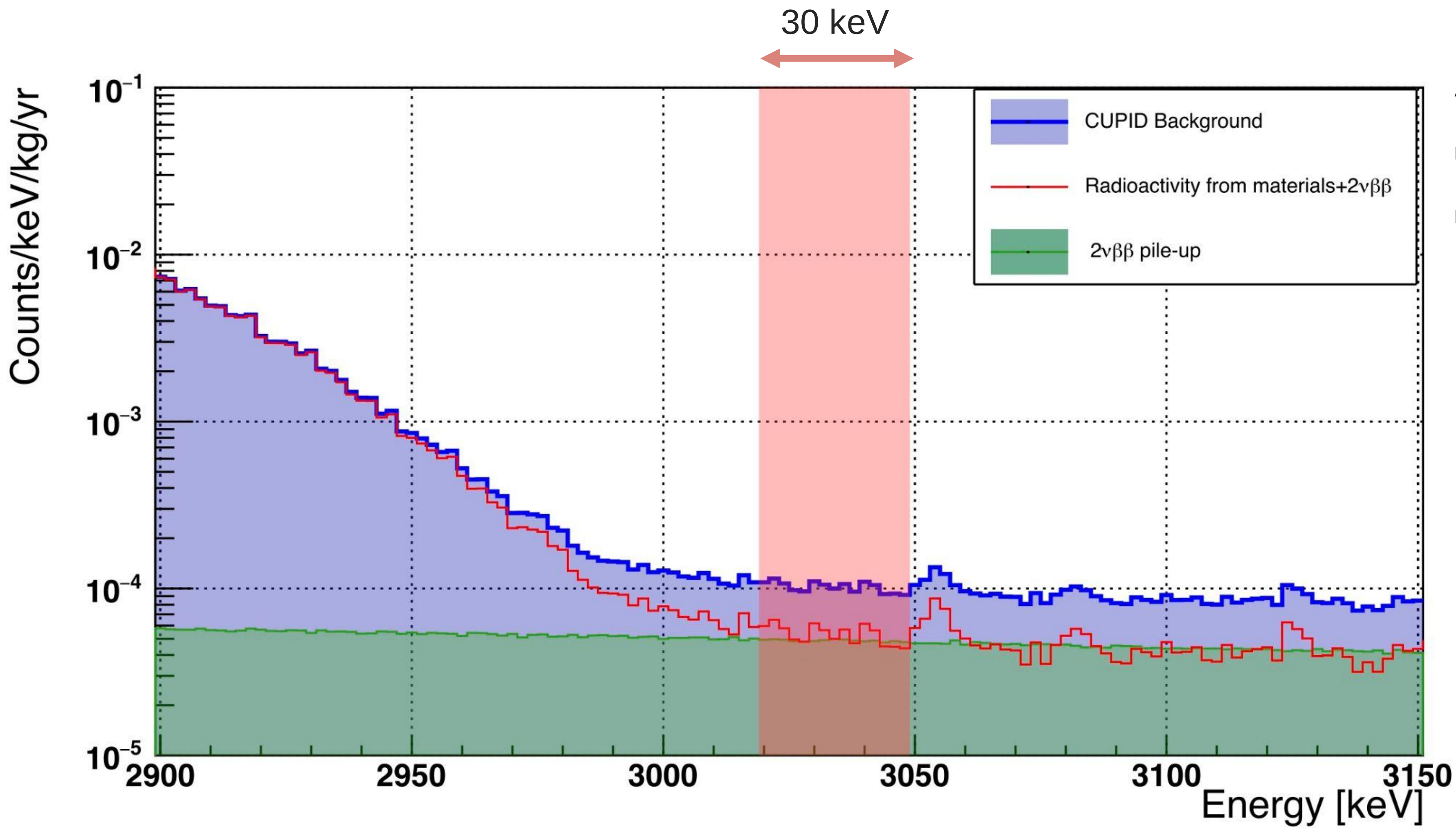
Improvements expected by experiment construction

- Pile-up (Analysis ML / LD design)
- Surface contamination levels for close components
- Delayed coincidence tags - Extension to NR tagging

CUPID's background projections are robust using in-situ characterisation and conservative assumptions

10^{-4} counts/keV/kg/yr as project target or better are in reach

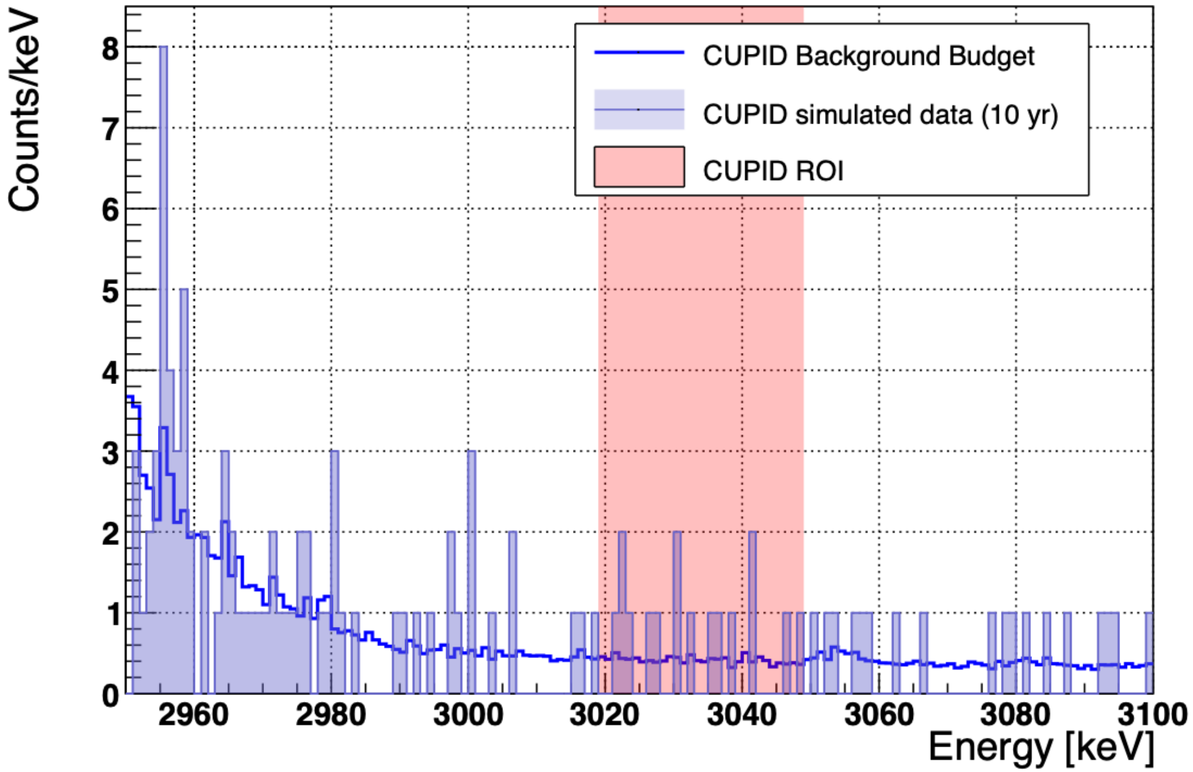
CUPID ROI - Background shape

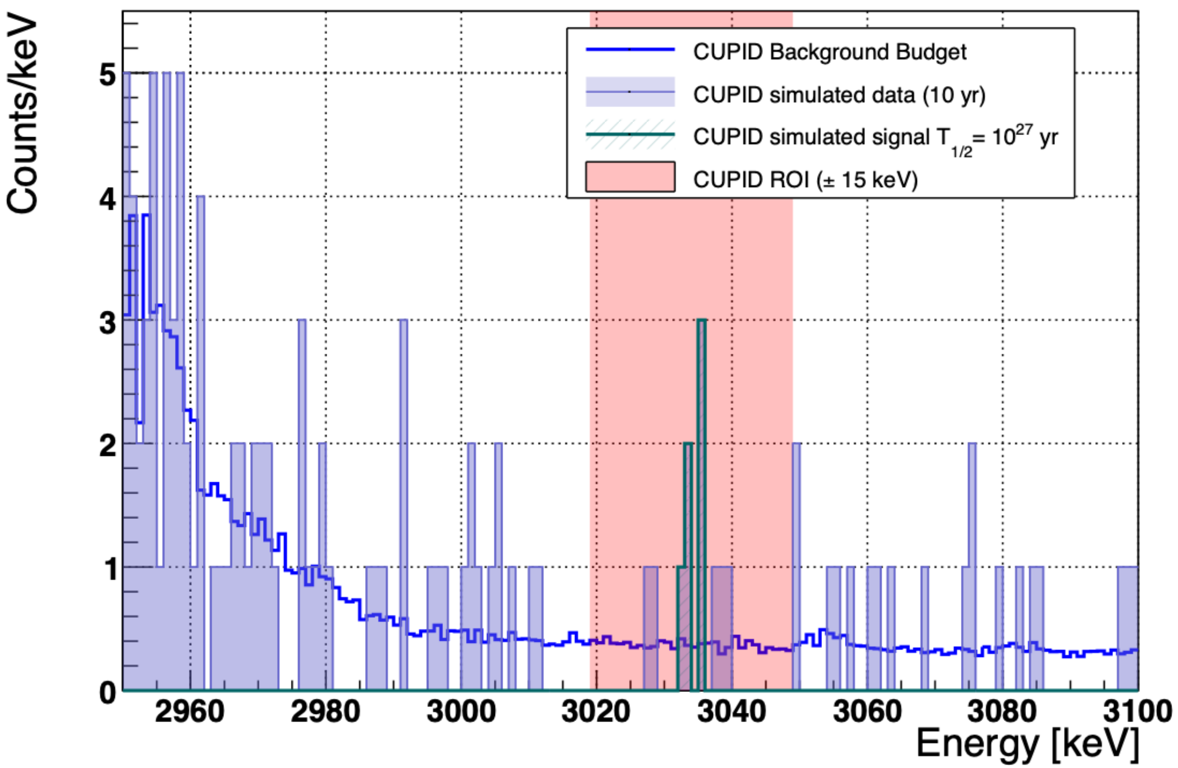


Analysis

- ^{100}Mo: $Q_{\beta\beta} = 3034\text{keV}$
- Excellent energy resolution
  - Target: 5 keV FWHM
  - We expect no influence from the $2\nu\beta\beta$ endpoint
  - Both $2\nu\beta\beta$ pile-up and radiogenic contributions show a flat spectrum in the ROI
  - Expect a very clean analysis!

CUPID ROI - Background and Signal after 10 yr

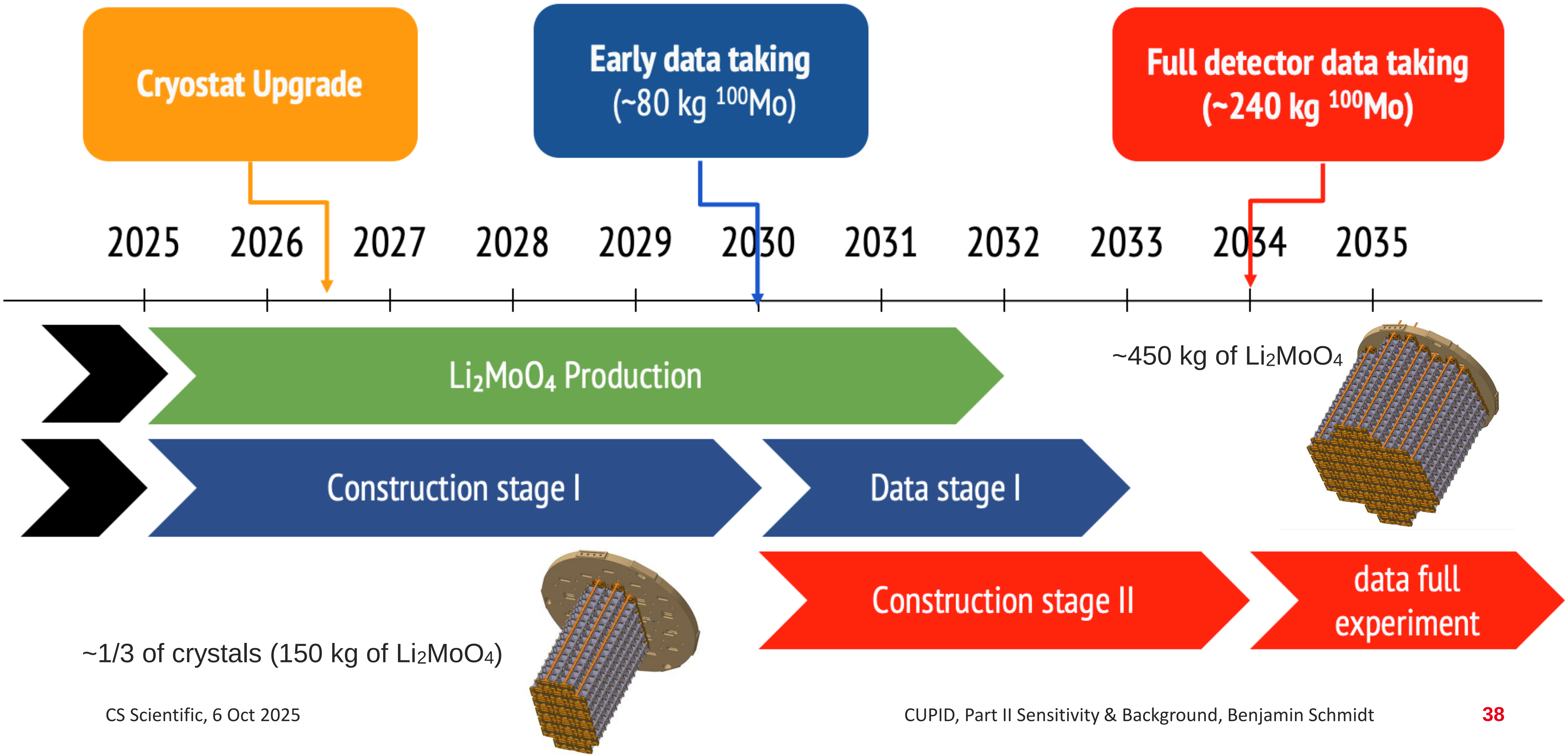




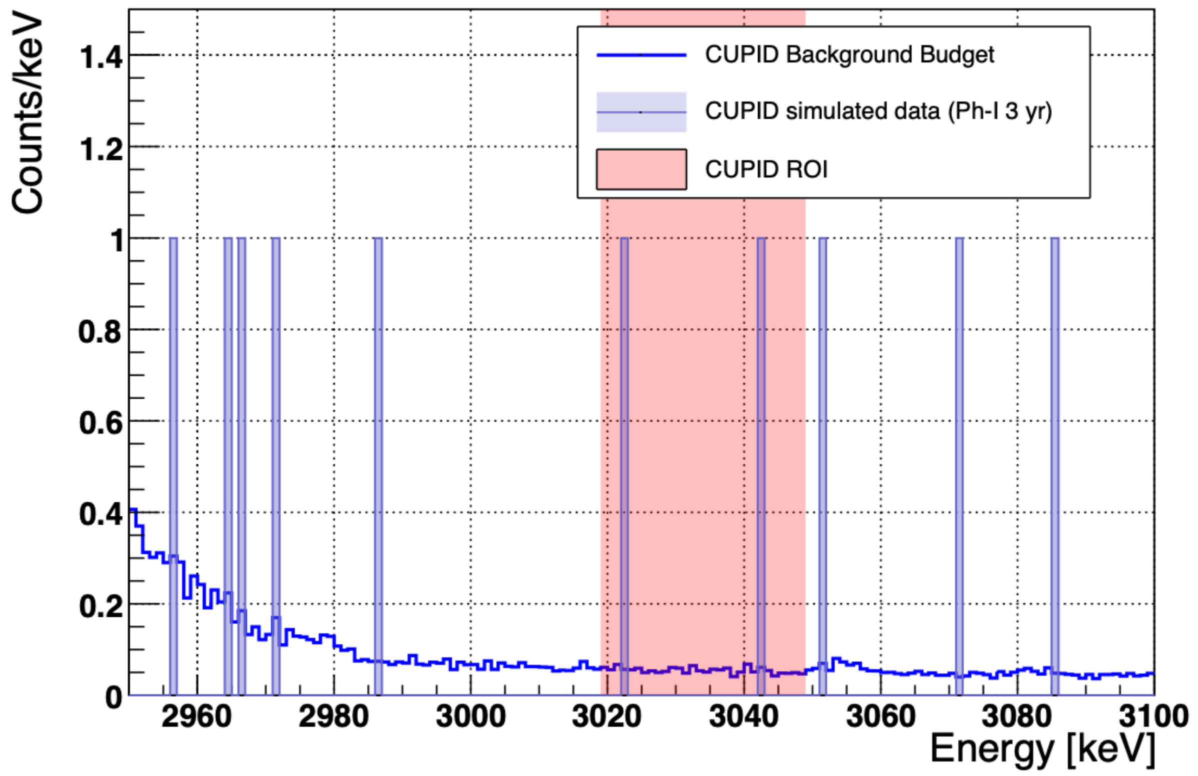
CUPID is a discovery experiment with a clear peak signature over a flat background
Median 3 σ discovery sensitivity of 10^{27}yr

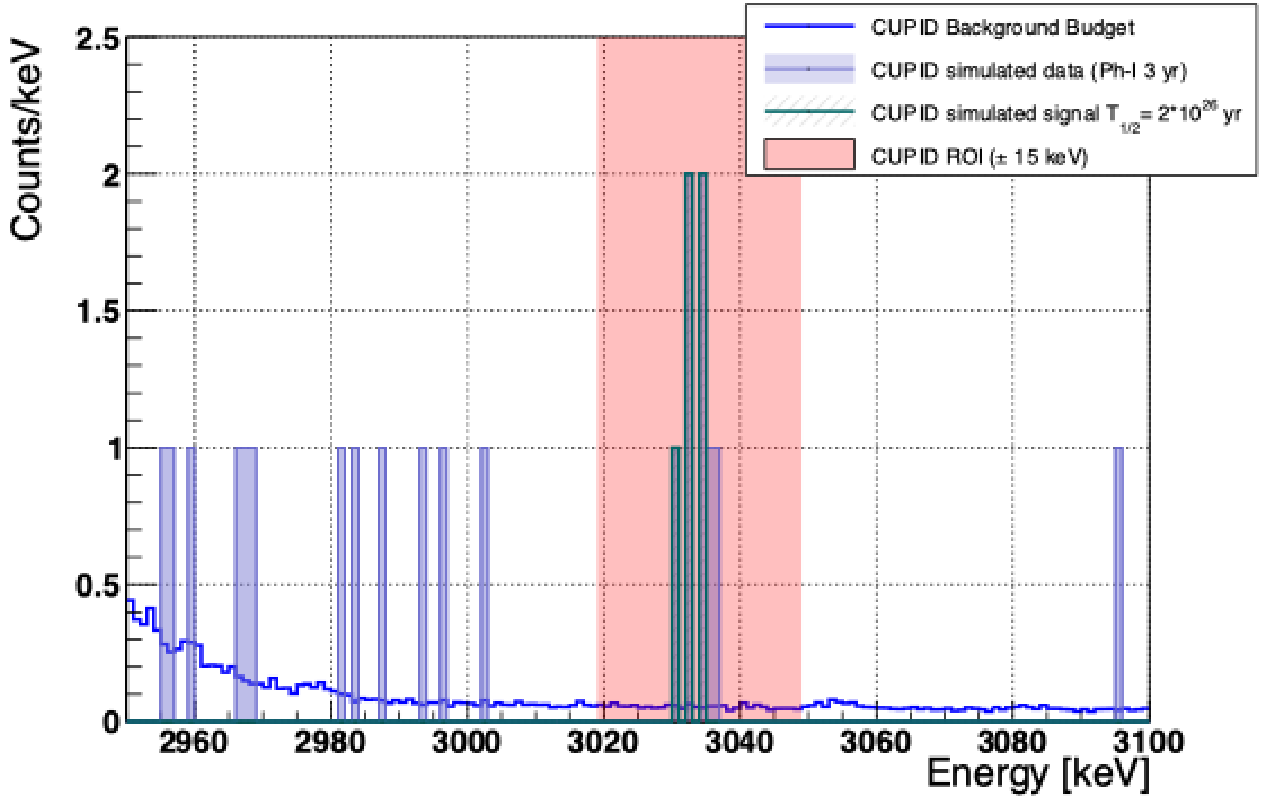
Bonus: $2\nu\beta\beta$ dataset with O(10^{10}) events: Excellent potential for nuclear physics and precision studies

CUPID Timeline



CUPID ROI - Stage I after 3 yr

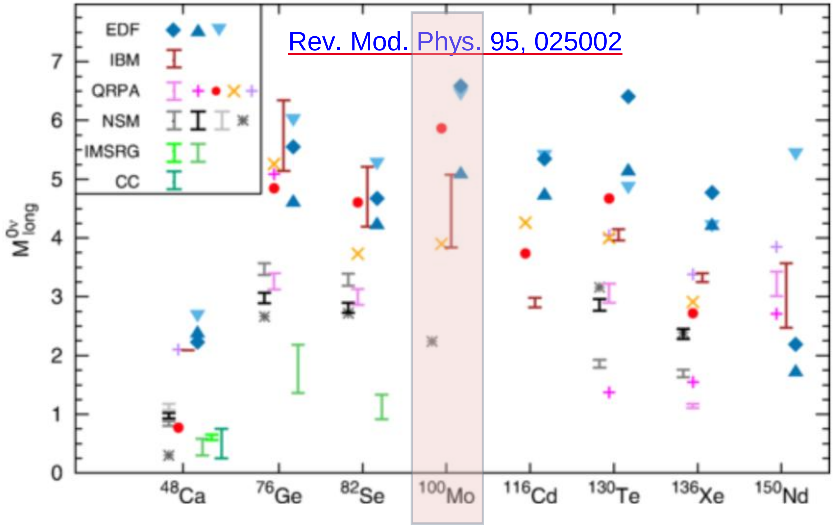




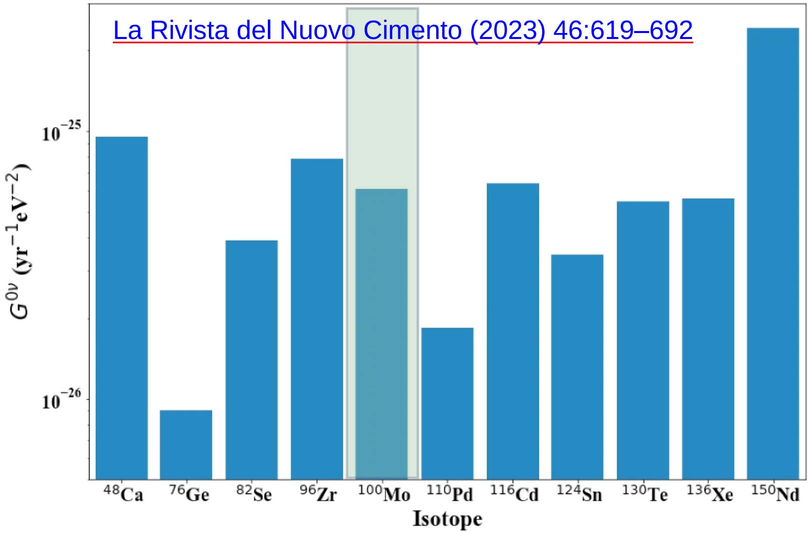
CUPID Phase-I is quasi background free BI = ~1.5 x 10^{-4} counts/keV/kg/yr:

- With 5 keV FWHM expect less than 1 background event in $\pm 3\sigma$ range around $Q_{\beta\beta}$
- Median 3 σ discovery sensitivity (3 yr) of 2 x 10^{26} yr

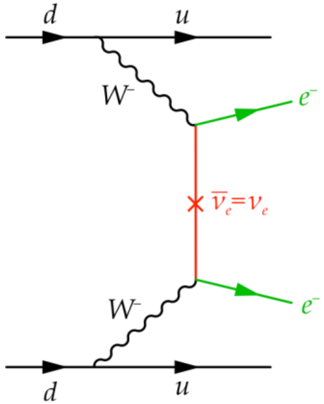
From half-life to effective Majorana mass (Light Majorana neutrino exchange)



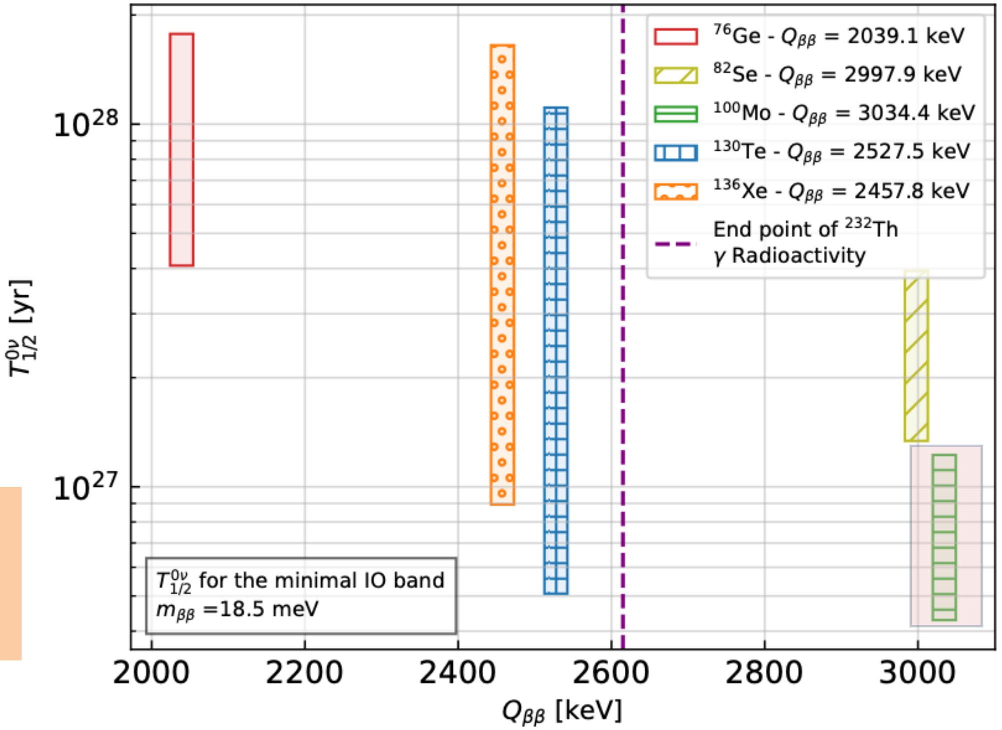
Rev. Mod. Phys. 95, 025002



La Rivista del Nuovo Cimento (2023) 46:619–692



$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim g_A^4 \cdot G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

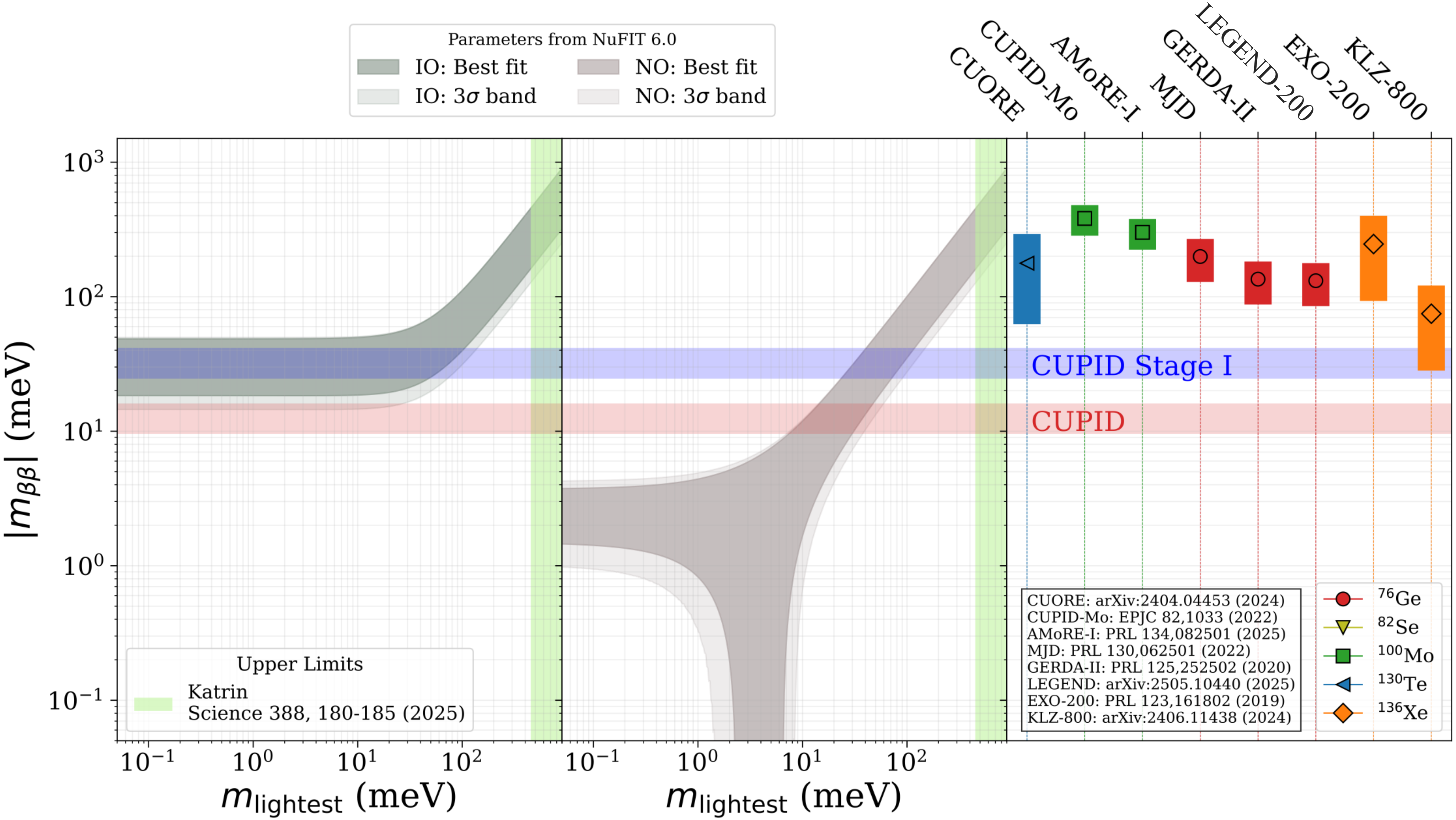


Effective Majorana mass:

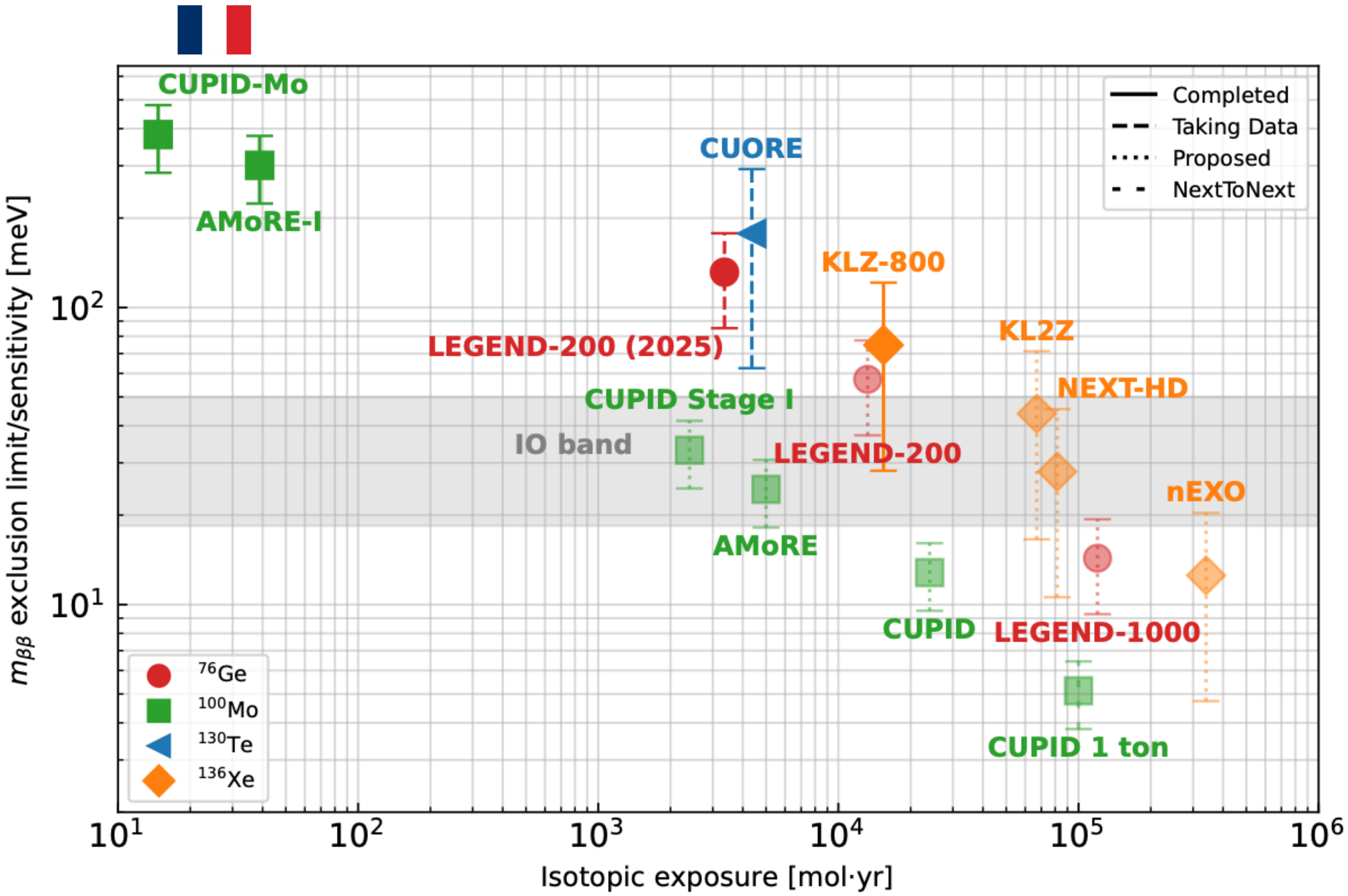
$$\langle m_{\beta\beta}\rangle = |\sum_{i=1,2,3} U_{e,i}^2 m_i|$$

^{100}Mo is very advantageous thanks to its combination of NME and phase space factor

CUPID and current exclusion results



Exclusion sensitivity in the field



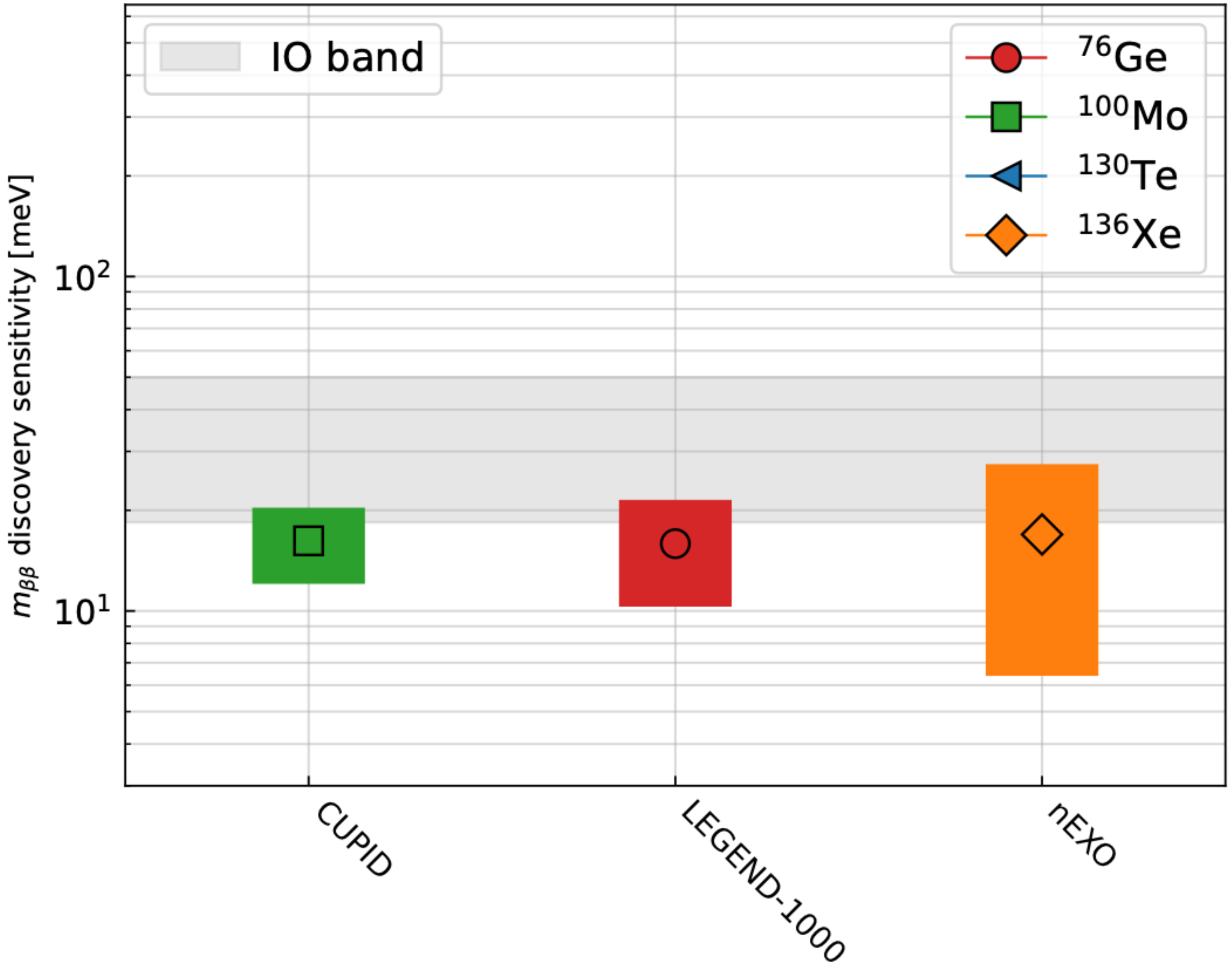
CUPID Stage I (3 yr) arXiv:2504.14369

Is on a similar sensitivity/timeline/trajectory as
LEGEND-200 (5 yr), arxiv:2107.11462
KL2Z (10 yr), Rev. Mod. Phys., Vol. 95, No. 025002
NEXT-HD (10 yr), arxiv:2005.06467
AMoRE-II (5.2 yrs) 2nd phase, EPJC 85,9

CUPID's and CUPID "France" strength

- Cost-effective
- More sensitive than LEGEND-200 (5 yr)
- More advanced/mature compared to AMoRE - Existing infrastructure, background model, operational & analysis experience
- A discovery type experiment with a clear peak signature
- French leadership in the technology development for CUPID and crucial role in simulation and sensitivity estimates

Discovery sensitivity - Stage II



CUPID Stage II (10 yr) Eur. Phys. J. C 85, 737 (2025)

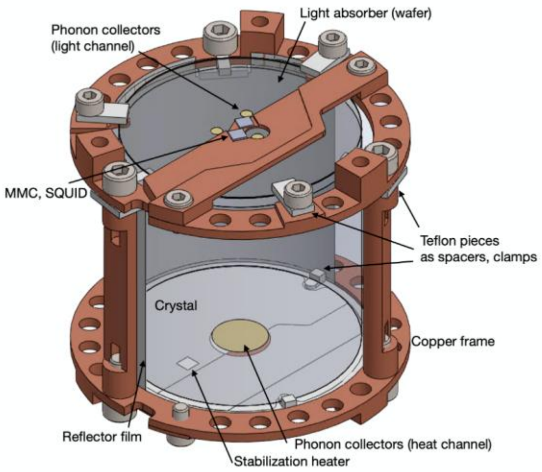
Is on a similar sensitivity/timeline as
LEGEND-1000 (10 yr), arxiv:2107.11462
nEXO (10 yr), J. Phys. G: Nucl. Part. Phys. 49 015104

CUPID's and CUPID "France" strength

- Cost-effective
- Mature: Existing infrastructure & experience, Robust predictions for background improvements of x 30 compared to CUPID-Mo
- Significant remaining potential for technological improvement
- Discovery type experiment based on technology developed in France

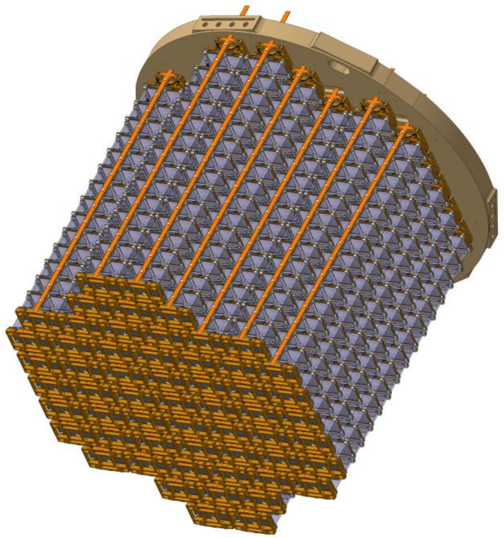
AMoRE | CUPID | CUPID-China
(The ^{100}Mo landscape)

Long term community goal: International, collaborative effort at the tonne-scale, with CUPID-style experiments distributed at multiple sites around the world



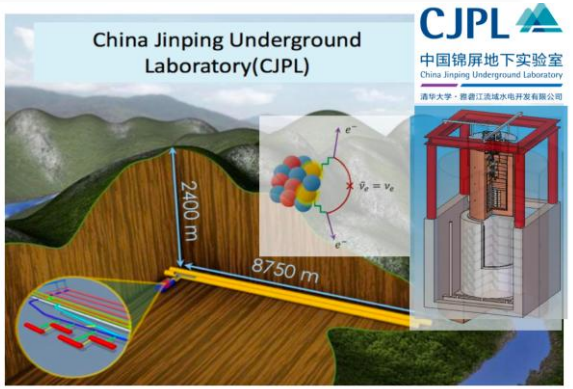
AMoRE-II (100 kg ^{100}Mo)
Different technology (MMC) faster

Needs to demonstrate a background reduction by a factor ~250 from AMoRE-I
2.5 x 10^{-2} ckky to 10^{-4} ckky



CUPID (240 kg ^{100}Mo):
Mature & low risk

Builds on CUORE legacy and proven technology and experience



CUPID-China: Partially part of CUPID in particular implicated in crystal production for CUPID

Goals: Short to Mid-term Demonstrator type experiment at CJPL (O 10 kg) Crystal production coordinated with CUPID

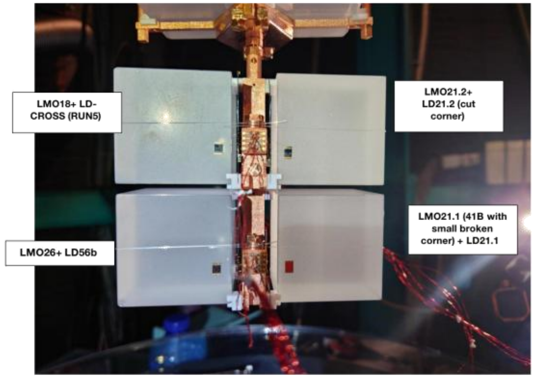
Long-term ambition to contribute a CJPL-based experimental site for tonne-scale ^{100}Mo experiment

Long term perspectives - R&D status

Goal: Distributed international tonne-scale or multi tonne-scale experiment with ^{100}Mo or ^{130}Te:

Economically possible
Requires background reduction by O(10) for ^{100}Mo, by O(1000) for ^{130}Te
R&D well on its way!

Many ideas and strong visibility in France:



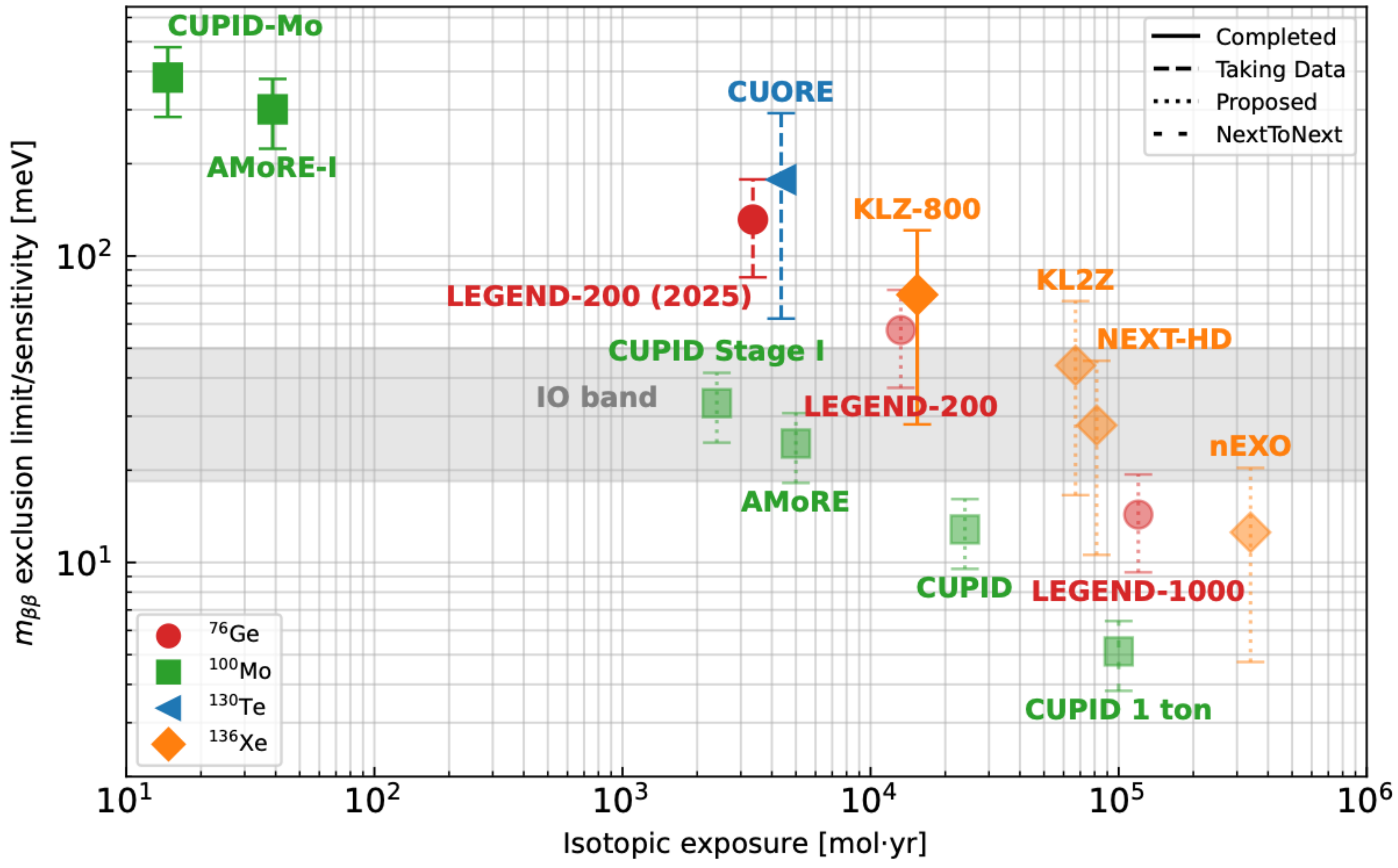
Significant further suppression of radiogenic bg possible

Bolometers with surface sensitivity JHEP 2020, 18 (2020)
Novel assembly & active veto NIM A 1069, 169936 (2024)
New isotopes (TINY ERC)

and elsewhere:

- LD with fast sensors (MMC, TES, KID)
  - MMC: AMoRE EPJ-C 85, 172 (2025)
  - TES: Phys. Rev. Applied 20, 064017 (2023)
  - KID: EPJ-C 79, 724 (2019)
- Next up: Neganov-Trofimov-Luke assisted Light Detectors + fast sensors (MMC, TES)
- Faster sensors on LMO (MMC, TES, KID)
  - Potential for extra position/topology information (Opossum ERC)
  - TES: EPJ-C 85,118 (2025) - French involvement
  - MMC: AMoRE (EPJ-C 85, 172 (2025))
- Multiplexing: arXiv2509.07223
- New active holder materials EPJ-P 138, 384 (2023)

Conclusion on Sensitivity



CUPID is competitive for Stage I

It will be (among) the leading experiments until full next generation experiments come online LEGEND-1000, nEXO

CUPID Phase II competes with nEXO and LEGEND-1000 at a fraction of the cost

R&D and community building for a (multi-) tonne future of cryogenic ^{100}Mo experiments is advancing rapidly

The French CUPID groups had and have leading roles in the technology development, projections and future R&D efforts

Last but not least

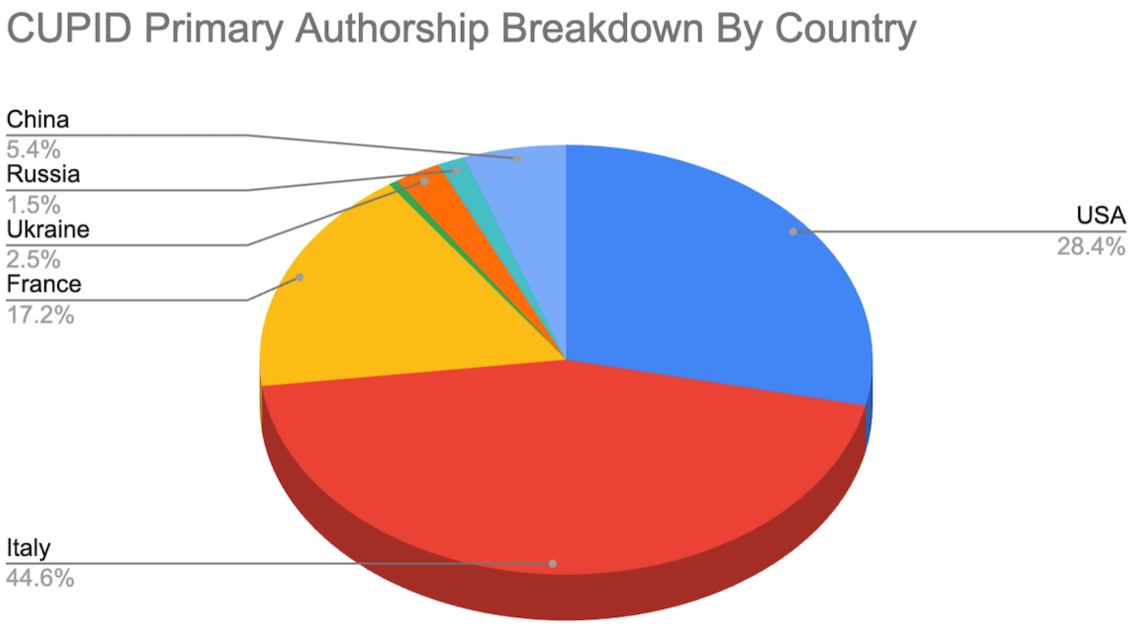
Part III – CUPID collaboration structure, IRFU and IN2P3 responsibilities, resources and means

Claudia Nones- FR EB member

The CUPID collaboration

36 institutions
Main countries: Italy, France, US, China

192 authors – last published paper
- 18% France
- 49% INFN
- 33% DOE



CUPID-France (october 2025)

CUPID

French CUPID Collaboration

cea irfu

Saclay

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Orsay

LP2i Bordeaux

Bordeaux

In prospect

iP2i LES 2 INFINIS LYON

cnrs

Lyon

SIMaP

cnrs

Grenoble

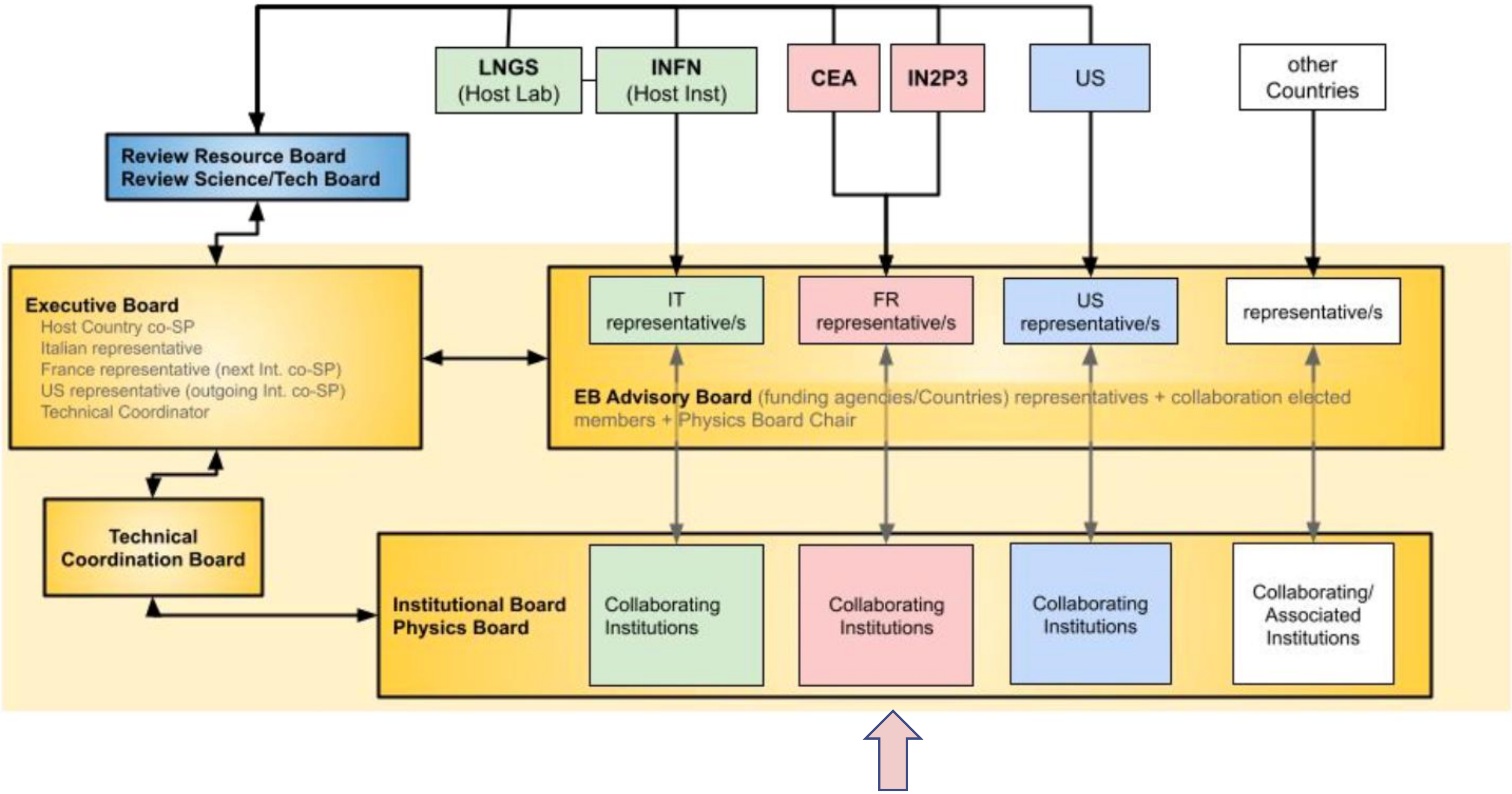
4 laboratories and 1 in prospect

CUPID gouvernance

Maura Pavan Host Country Co-SP

Karsten Heeger International Co-SP (outgoing, US)

Andrea Giuliani International Co-SP (incoming, France)

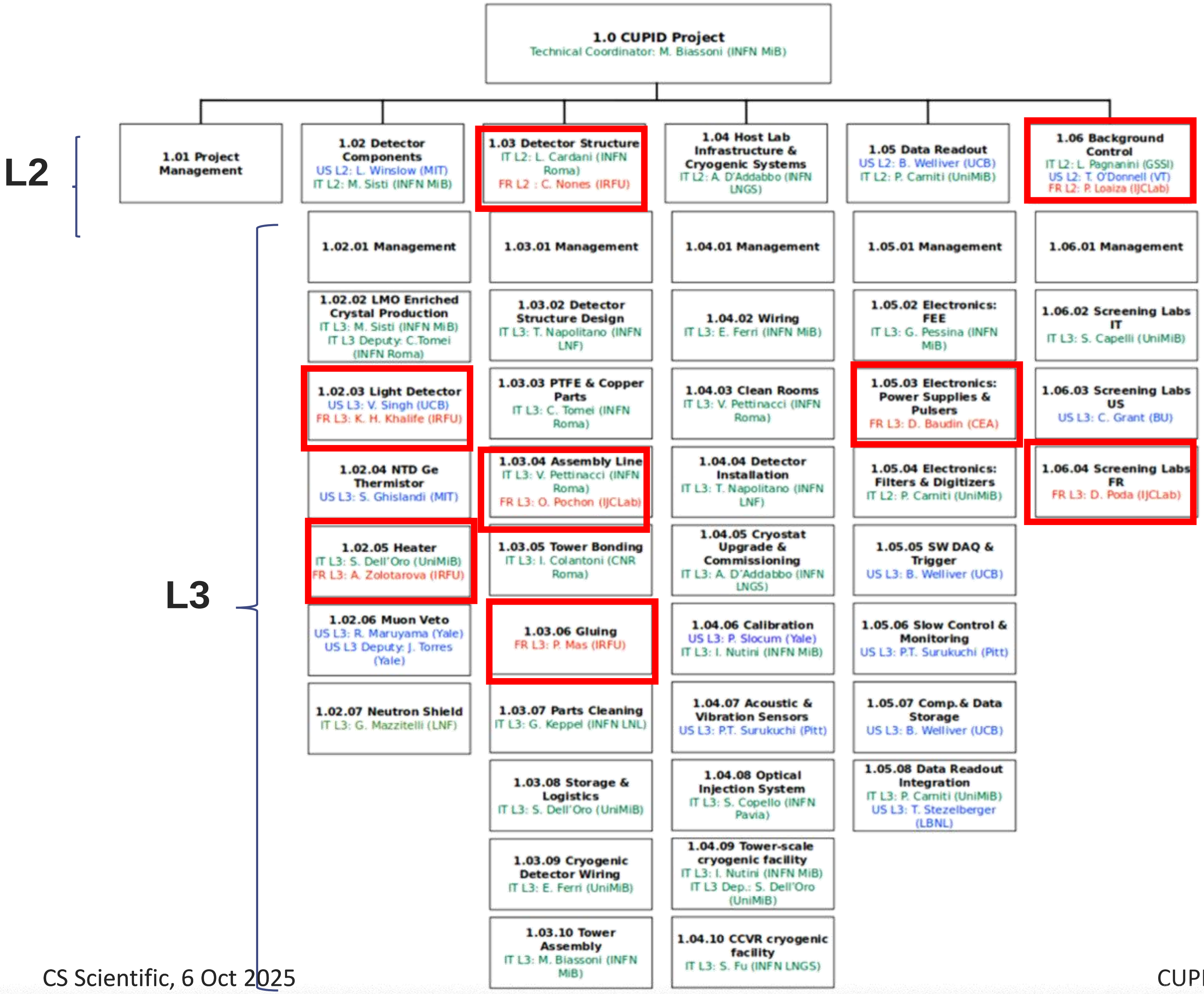


4 Institute members in the council

3 main countries
IT, FR, US

- A Review Resource Board (waiting for MoUs)
- An Exective Advisory Board
- An Institutional Board
- A Technical Board

Work Breakdown Structure



France is represented by:

- **2 L2 managers** (1 IRFU, 1 IJCLAB)
  - ➢ Detector structure
  - ➢ Background control

- **6 L3 managers** (4 IRFU, 2 IJCLAB)
  - ➢ Light detectors
  - ➢ Heaters
  - ➢ Assembly line
  - ➢ Gluing
  - ➢ Electronics – Pulsers and Power Supplies
  - ➢ Radioactivity screening

The CUPID boards

CUPID Physics Board - 2025

Senior Coordinator - Ben Schmidt (IRFU)
Analysis Coordinator - Alberto Ressa
Science Coordinator - Pranava Teja Surukuchi
Software Coordinator - Brad Welliver
Simulations Coordinator - Mattia Beretta
Background Model Coordinator - Pia Loaiza (IJCLAB)
Detector Performance Coordinator - Irene Nutini
Public Data Coordinator - Penny Slocum
Publication Coordinator - Denys Poda (IJCLAB)
Outreach Board - Dounia Helis

Vetting Board
Public Data Coordinator - Penny Slocum
S. Quitadamo
H. Khalife (IRFU)

Speakers Board
Stefano Dell'Oro
Chris Grant
Pia Loaiza (IJCLAB) –-> A. Armatol (IP2I)

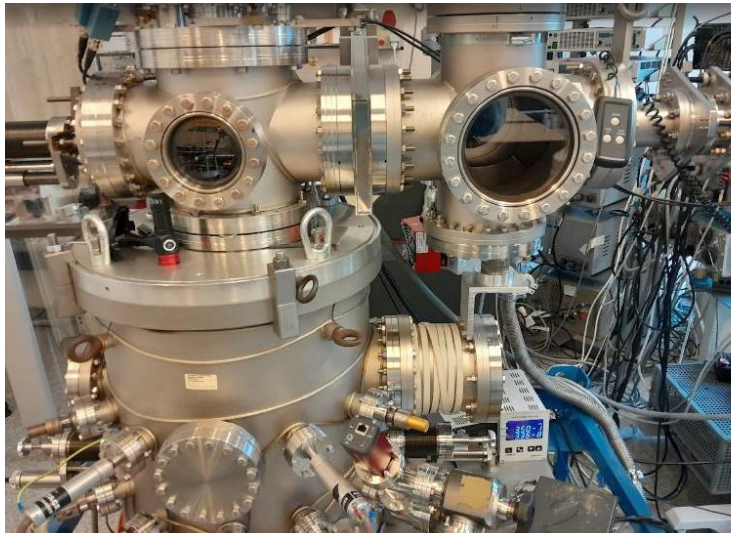
Role and visibility of French institutions

- France has been **central to CUPID baseline technologies**:
  - Purification, growth and selection of **Li_2MoO_4 crystals**
  - **Li_2MoO_4 scintillating bomometers**
  - Development of **NTL light detectors**
  - Design of **gluing systems and electronics**
- Leading institutions: **IJCLab, CEA/IRFU,** IP2I, SIMaP, LP2i in future
- French researchers hold **key leadership roles** (co-Spokesperson, board chairs, WP leaders)
- **Future success depends on strong and timely support** from IN2P3 & CEA/IRFU
  - Funding for crystal production and detector components
  - Reinforcement of **human resources** (researchers, engineers, PhDs, postdocs)
- **Risks if support is delayed/insufficient**:
  - Loss of France’s technological leadership to other partners
  - Reduced international visibility and prestige
  - Missed opportunity to secure France’s place at the forefront of next-generation neutrino physics

Production and characterization of light detectors

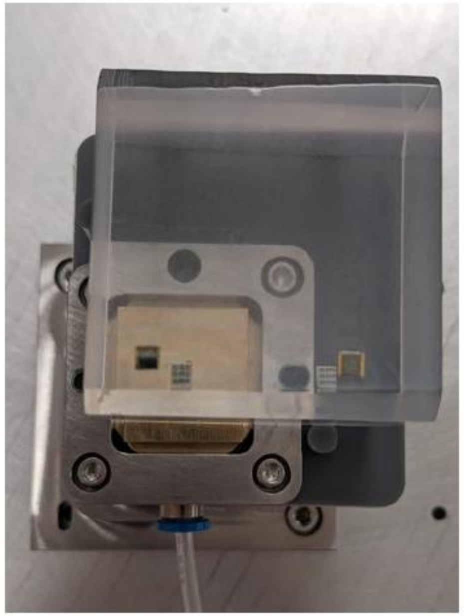
- CUPID light detectors: ultrapure **Ge wafers** with **Al electrodes** for NTL amplification
- Study of Si wafers as risk mitigation
- Up to now, fabrication developed at **IJCLab** using existing electron-beam evaporators
- Scaling up with **CRYOVAP (2026)** → from 8 detectors/week to **tens per week**
- Yield: ~80% meet NTL amplification; individual testing remains mandatory
- Characterization: new **4 K cryostat** (semi-automatic, 50 detectors/run)
- Produce and characterize **~900 light detectors** in 2027-2028, **keep 600**

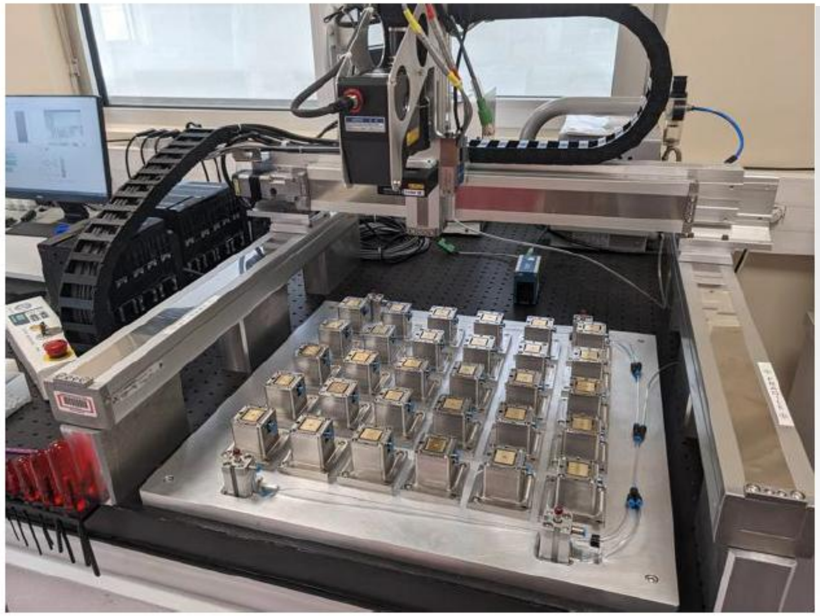
cnrs IN2P3 IJCLab Irène Joliot-Curie cea

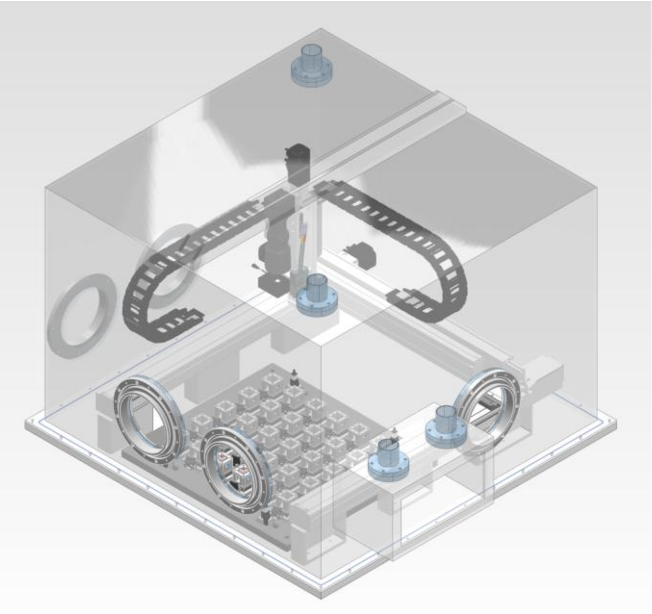


Detector assembly: sensor gluing station

- **CEA/IRFU gluing station**: attaches NTDs and heaters to crystals & wafers
- Fully robotic with **XYZ motion system, metrology camera, glove box**
- Specs: <10% glue variation, >99.9% success, 100 sensors/week
- Validated in **CUPID tower prototype** and **CROSS demonstrator**
- Cryogenic tests ongoing; glove box integration expected in 2026







Pulser board

- **CEA/IRFU + Milano-Bicocca**: development of calibration board
- Injects **stable, programmable pulses** (square, sinusoidal, pseudo-Gaussian)
- Drives up to **100 heaters in parallel** with **16-bit precision**
- Prototype built, testing ongoing; **65 units** planned (one per tower)

Storage and transport system

- Developed at **IJCLab** to protect detector towers before installation.
- **Storage modules**: reduced-radon environment with continuous **N_2 flushing**.
- **Transport modules**: damping system to reduce mechanical stress; deliver towers underground at LNGS.
- Initial order: **20 storage modules (2025)** for CUPID Stage-I.

Characterization and validation activities, assembly

NTD Ge thermistors and **Radioactivity**

- **NTD thermistors**: fabricated in US
- Characterization shared across US and France (IJCLab, CEA/IRFU, IP2I)
- Radiopurity: France & Italy lead **Background Control WG**
- Materials: **450 kg Li_2MoO_4, 102 kg Cu, 10 kg Ge, 9 kg PTFE**, etc
- Screening via **HPGe γ-spectroscopy, NAA, ICP-MS, α-spectroscopy**, and bolometric tests
- LSM (France) hosts **ultra-low-radioactivity HPGe detectors**

Activities at LNGS

- **CCVRs**: systematic cryogenic testing of enriched crystals → verify bolometric performance, radiopurity, scintillation.
- Focus: **energy resolution, contamination, light yield**.
- Runs at **LNGS** (main) and possibly **LSC (CROSS facility)**.
- French teams provide manpower for **detector preparation, cryostat operation, data analysis**
- Shifts: CUORE cryostat upgrade, prototype tower tests, CUPID data taking (shared by FR, IT, US)
- CUPID-Stage-I assembly

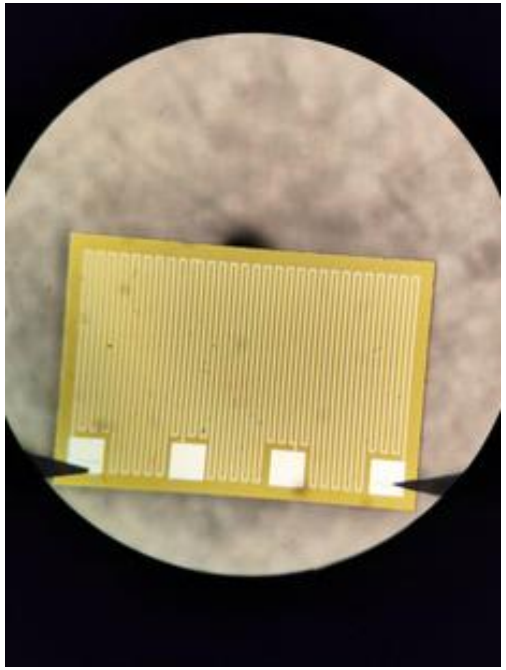
Alternative heater production

- Baseline heaters: **Si chips with ion-implanted meanders** (CUORE)

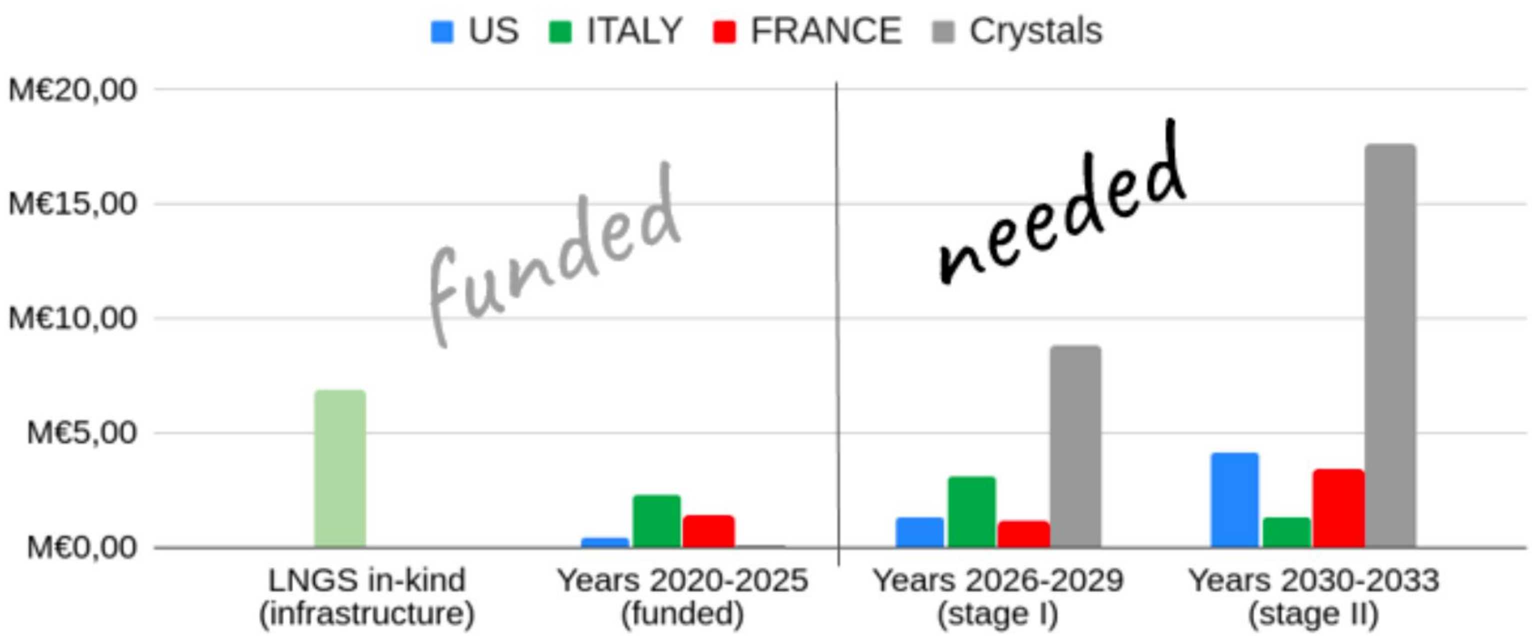
- French alternative: **metal-film meanders** (CEA/IRFU)

  - Pros: no pre-characterization at low T, reproducible, robust
  - Large scale demonstration to be done
  - Goal: ensure **stable detector response** against cryogenic fluctuations

- France will be involved in **heater characterization**, regardless of the technique ultimately chosen by the collaboration



Indicative proposal for budget split



TOTAL needed for CUPID Stage1: 14 M€

~ **5 M€** construction costs:
- IT
- FR
- US

~ **9 M€** for enriched crystal production

French contribution: the pre-CUPID phase [2012-2018]

Investment in the period 2012-2018: ~ 1.4 M€

- Finalization of the scintillating bolometer Li_2MoO_4 technology
- CUPID-Mo experiment
- Crucial for the selection of the CUPID technology

This has been possible thanks to:

- IRFU & CSNSM own funds
- ISOTTA (2012-2015)
- ANR LUMINEU (2012-2017)
- ANR CLYMENE (2016-2021)

French contribution: the pre-CUPID phase [2012-2018]

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- ANR LUMINEU (2012-2017)
- ANR CLYMENE (2016-2021)

French contribution: CUPID [2019-now]

Investment in the period 2019-now: ~ 3.2 M€

Several crucial contributions to CUPID construction

- CRYOVAP (series production of light detectors)
- 4K facility for leakage current test
- Gluing station (initial investment)
- Enriched crystals
- Electronic prototypes
- Part of the tower storage / transportation system

This has been possible thanks to:

- IRFU & IN2P3 own funds
- ANR CUPID-1 (2021-2026)
- ANR CRYOLUX (2025-2028)
- ANR P2IO Labex Flagship BSM-nu
- SESAME Ile de France
- ERC AdG CROSS
- ERC CoG BINGO

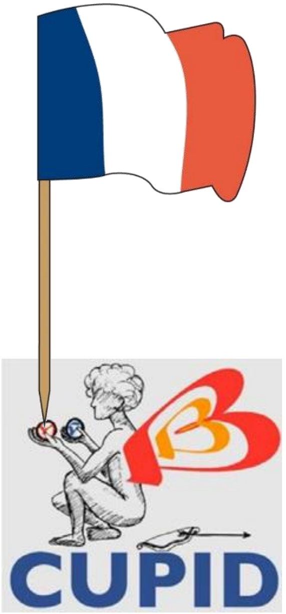
Financial requests (CUPID-Stage-I)

Total request (construction) over two agencies and four years [2027-2030]: ~ 1.1 M€

Contribution to enrichment-crystallization CUPID-Stage-1: 10%-20% of 9 M€ (total cost)

This investment will allow us to fulfill our engagements in:

- Light detector production & testing
- Gluing station
- Pulser and power supplies for electronics
- NTD and heater characterization
- Radiopurity measurements
- Shifts for crystal validation runs
- Shifts for tower test runs at LNGS
- Participation to the assembly of CUPID stage1
- Common funds based on the number of authors



Investment for the development of the technology	2012-2018	~1.4 M€
Investment for R&D finalization and development of facilities for the construction	2019-2025	~3.2 M€
Requested funding to fulfil France's construction commitments	2026-2030	~1.1 M€
Possible French contribution to enrichment and crystallization (10% – 20%)	2026-2029	~1 – 2 M€

Human resources – october 2025

Permanent staff

IJCLab-Orsay	IP2I-Lyon	LP2i-Bordeaux	CEA/IRFU-Saclay
Researchers	**Researchers**	**Researchers**	**Researchers and Engineers**
Andrea Giuliani	Jules Gascon	Christine Marquet	Claudia Nones
Pierre de Marcillac	Antoine Armatol	Emmanuel Chauveau	Benjamin Schmidt
Stefanos Marnieros	Corinne Augier		Anastasiia Zolotarova
Jean-Antoine Scarpaci	Antoine Cazes		Federico Ferri
			David Baudin
			Philippe Mas
			Philippe Gras
IR (Ingénieurs Recherche)	**IR (Ingénieurs Recherche)**		
Ion Cojocari	Alexandre Juillard		
Pia Loaiza			
Emiliano Olivieri			
Denys Poda			
Philippe Rosier			
IE (Ingénieur d'Etudes)			
Laurent Bergé			
AI (Assistant Ingénieur)			
Olivier Pochon			
Total permanent researchers and engineers: 24			
Total FTE: 7.4			

Temporary Staff

Typically
2 PhD student
1 Post-doc
both at IJCLab and IRFU

Corresponding to **6 FTE**

Current situation:

IJCLab
PhD students
Mariia Buchynska
Roberto Serino

CEA/IRFU
PhD students
Mathieu Pageot
Sara Vesce (Dec25)
Post-doc
David Cintas
Hawraa Khalife

Total FTE with temporary staff: ~ 13
(LP2I not yet included)

PhD theses

Pre-CUPID phase and the current finalization phase → highly productive in terms of PhD theses (**11 achieved theses**)

CSNSM/IJCLab		
Student	**Defense year**	**Title**
Margherita Tenconi	2015	Development of luminescent bolometers and light detectors for neutrinoless double beta decay search
Dmytro Cherniak	2015	Development of cryogenic low background detector based on enriched zinc molybdate crystal scintillators to search for neutrinoless double beta decay of ^{100}Mo
Michele Mancuso	2016	Development and optimization of scintillating bolometers and innovative light detectors for a pilot underground experiment on neutrinoless double beta decay
Valentina Novati	2018	Sensitivity enhancement of the CUORE experiment via the development of Cherenkov hybrid TeO_2 bolometers
Hawraa Khalife	2021	CROSS and CUPID-Mo: future strategies and new results in bolometric search for $0\nu\beta\beta$
Léonard Imbert	2023	Étude du bruit de fond des expériences CUPID-Mo, CUPID, et CROSS de double désintégration bêta sans émission de neutrinos
CEA/IRFU		
Anastasiia Zolotarova	2018	Study and selection of scintillating crystals for the bolometric search for neutrinoless double beta decay
Dounia Helis	2021	Searching for neutrinoless double-beta decay with scintillating bolometers
Antoine Armatol	2023	Innovative methods for background rejection in next-generation neutrinoless double beta decay bolometric experiments
Vladyslav Berest	2025	Towards BINGO: Development of Advanced Background Reduction Technologies for Neutrinoless Double-Beta Decay Bolometric Experiments
SIMaP		
Abdelmounaim Ahmine	2021	Croissance Czochralski, comportement et propriétés mécaniques de cristaux massifs de Li_2MoO_4 pour bolomètres scintillants

Three former students hold permanent positions in French research institutions

Chargée de Recherche
CNRS/IN2P3–LPSC Grenoble

Researcher
CEA/IRFU
ERC grantee (2022)

Chargé de Recherche
CNRS/IN2P3–IP2I Lyon

Excellence of the training provided within the French CUPID research groups

Human resource requests

Additional team support to meet French commitments is essential

- **One CR position** (*chargé de recherche*) at **IJCLab** to support data analysis, simulations, and provide onsite manpower. We note that the researcher group at IJCLab has a critical age profile: of its four members, the youngest is 54 years old and the others are all over 60, with no new recruitment since 2011.
- **One IR position** (*ingénieur de recherche*) at **LP2i** (if participation is approved by LP2i) to assist the Bordeaux group during its transition to CUPID activities.
- **One engineer position** at **CEA/IRFU** to handle the group numerous technical responsibilities.
- **One temporary AI position** (*assistant ingénieur*) (2027-2028) at **IJCLab** to support large-scale light-detector production.

- Contribute with **PhD and Post-doc fellowships** at IJCLab, CEA/IRFU and LP2i

13 FTE vs.
17 FTE needed

CUPID

SWOT ANALYSIS

STRENGTH

- Solid foundations: CUORE
- French technological contributions
- Proven track record: LUMINEU, CUPID-Mo, CROSS, etc.
- International recognition
- Leadership positions for French researchers

WEAKNESS

- Human resources: aging permanent staff at IJCLab
- Staffing gaps: need for reinforcements
- High dependence on enrichment
- Complex coordination

THREAT

- Funding uncertainty
- International competition
- Supply chain risks
- Staff turnover: retirement/loss of key experts
- Coordination risks

OPPORTUNITY

- Scientific breakthrough
- French visibility
- Synergies
- Technology transfer
- Ton-scale expansion
- Valorisation of Modane (LSM)

Conclusions

- CUPID technology is mature, and infrastructure already exists in LNGS
- Detector technology was conceived, developed and demonstrated by French laboratories
- CUPID construction can start next year – INFN prepared to fund most of isotope cost
- Support from French agencies for construction and isotope is essential
- CUPID-Stage-I has the potential to lead the field at the beginning of the next decade
- Full CUPID will be a leading experiment with significant discovery potential
- CUPID is cost effective and expandable: CUPID-1T can explore deeply the normal ordering
- CUPID-1T is a long-term strong opportunity for science at Modane
- The CUPID program will place France at the forefront of neutrino physics

We would like to thank IN2P3, CEA/IRFU and three European underground laboratories (Modane, Gran Sasso, Canfranc) for their continuous and valuable support

Strengths

- **Solid foundations**: CUPID builds directly on the success of CUORE, with established infrastructure at LNGS and expertise in large bolometric arrays
- **French technological contributions**: France pioneered purification and growth of Li_2MoO_4 crystals, developed Neganov-Trofimov-Luke (NTL) light detectors, and designed key assembly/gluing systems
- **Proven track record**: Demonstrator experiments (LUMINEU, CUPID-Mo, CROSS, etc.) validated background rejection, energy resolution, and material purity
- **International recognition**: CUPID is consistently listed alongside LEGEND and nEXO as a top next-generation neutrinoless double beta decay experiment
- **Leadership positions**: French researchers hold prominent collaboration roles in CUPID (co-Spokesperson, Physics Board chair, Executive Board membership, WP leads)

Weaknesses

- **Human resources**: Aging permanent staff at IJCLab (no hires since 2011, all >54 years old in the CUPID researchers' group in this laboratory) create a sustainability risk
- **Staffing gaps**: Need for reinforcements (CR at IJCLab, IR at LP2i, engineer at CEA/IRFU, temporary AI for detector production at IJCLab), as the current FTE count is insufficient for the construction of CUPID Stage-I.
- **High dependence on enrichment**: The largest cost (~9 M€ for Stage-I) is dominated by isotope enrichment, with limited alternatives
- **Complex coordination**: Large, international collaboration requires strong project management and synchronized commitments from INFN, IN2P3, CEA/IRFU, DOE, etc.

Opportunities

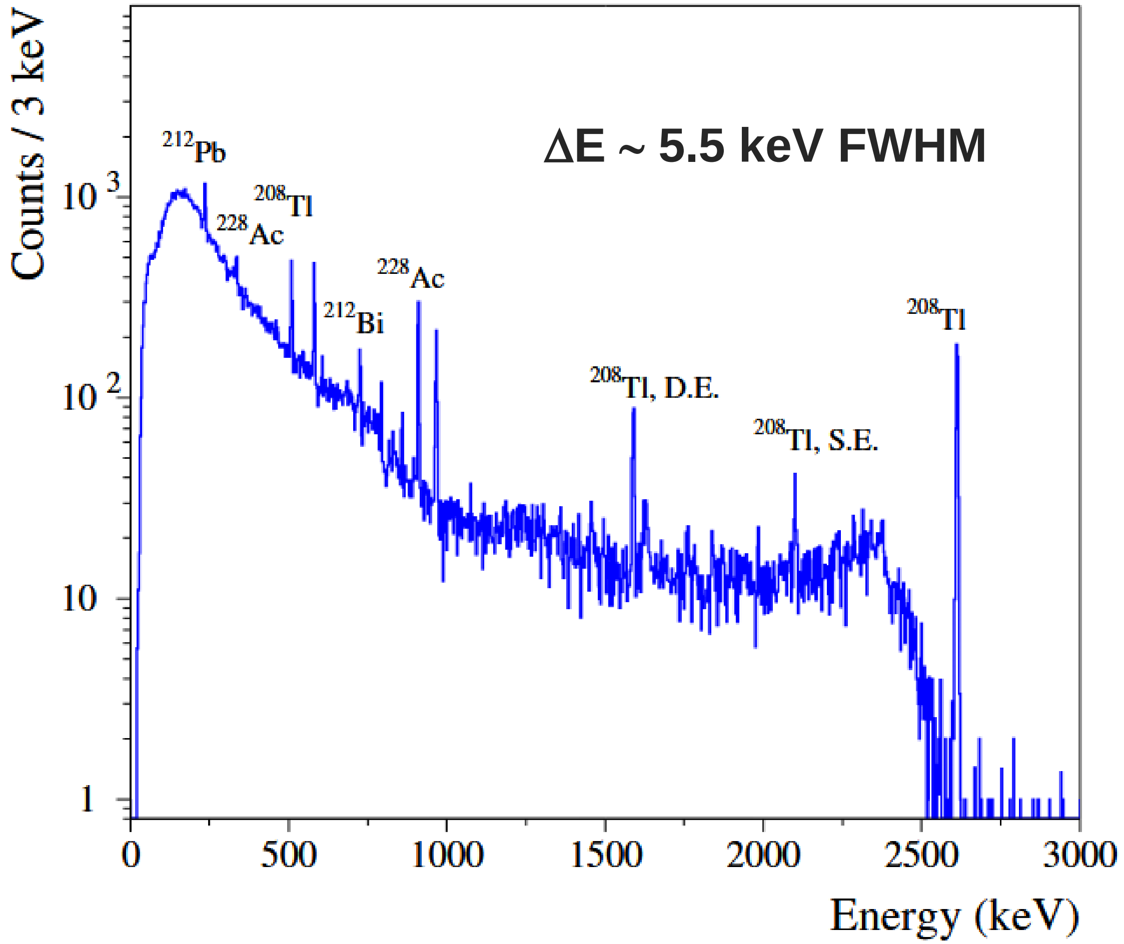
- **Scientific breakthrough**: CUPID could be the first experiment in the 2030s to explore the inverted hierarchy region fully, with high discovery potential for $0\nu2\beta$, and even CUPID Stage-I, starting in 2030 with one third of the final mass, will already surpass all current experiments and achieve world-leading sensitivity
- **French visibility**: Continued investment secures France's role as a global leader in bolometric technology and neutrino physics
- **Synergies**: Links to other communities (detector R&D, material science at SIMaP Grenoble, quantum sensors, cryogenics) may foster cross-disciplinary advances
- **Technology transfer**: Light detector know-how already transferred to U.S. groups, opening opportunities for shared responsibilities and cost reduction
- **Ton-scale expansion**: CUPID can be regarded as a crucial step toward a future ton-scale experiment (CUPID-1T), developed in convergence with other collaborations (e.g. AMoRE) and designed to deeply probe the normal hierarchy region of neutrino masses
- **Valorisation of Modane (LSM):** Since LNGS is not deep enough for CUPID-1T or a similar experiment, hosting it at LSM within 10 - 15 years would represent a major opportunity for the laboratory

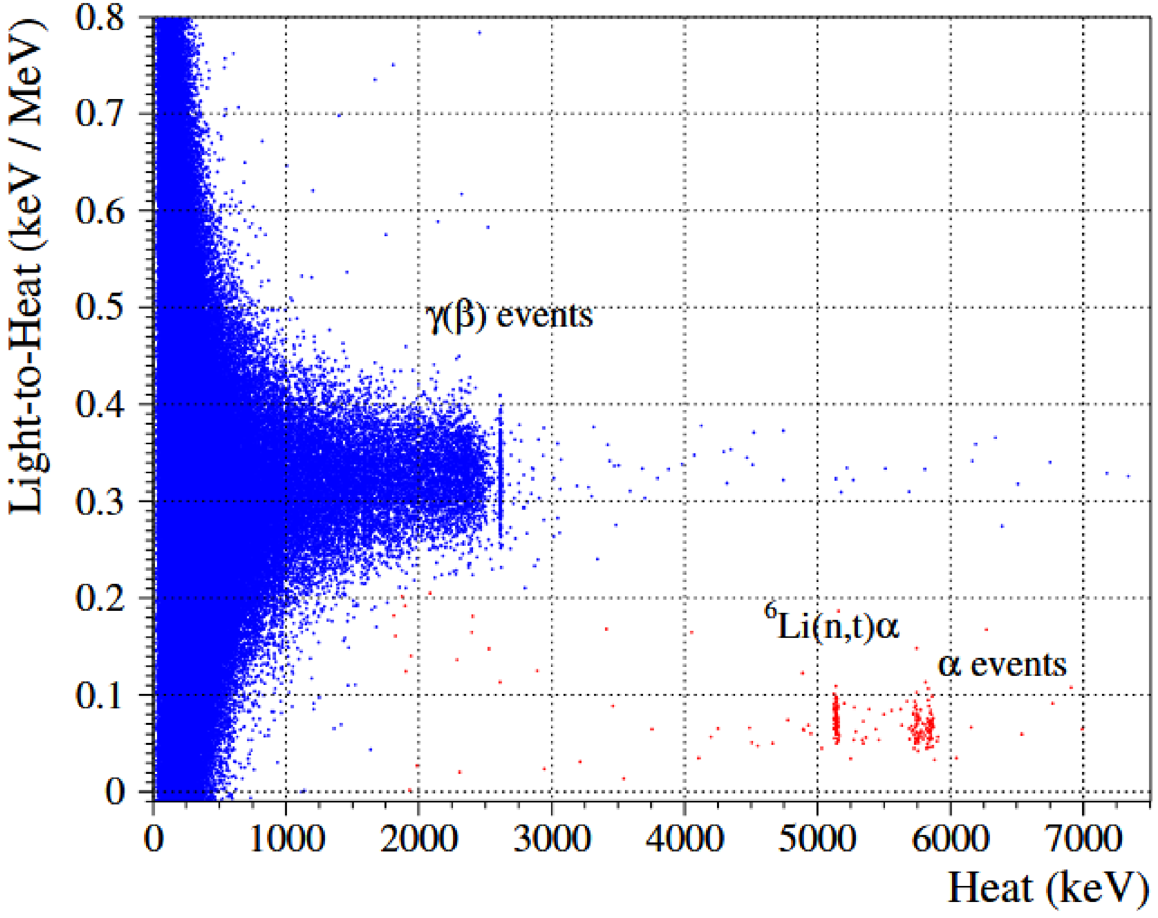
Threats

- **Funding uncertainty**: Without immediate funding (notably for enrichment and personnel), CUPID-Stage-I risks delays, losing its timing advantage over LEGEND and nEXO
- **International competition**: LEGEND-1000 (^{76}Ge) and nEXO (^{136}Xe) are strong competitors with alternative technologies
- **Supply chain risks**: Initial reliance on a Russian partner for enrichment and crystallization slowed progress on the experiment, and shifting to a Chinese partner could likewise introduce geopolitical and logistical vulnerabilities
- **Staff turnover**: Retirement of key experts without timely recruitment may erode technical capacity
- **Coordination risks**: A delay by one partner (e.g. France in light detector construction, U.S. in NTD production) could impact the whole project schedule

NIIC crystal – Th calibration – Energy spectrum and Light/Heat vs. Heat plot

CROSS facility (Canfranc)





SIMaP crystal – Th calibration – Energy spectrum and Light/Heat vs. Heat plot

CROSS facility (Canfranc)