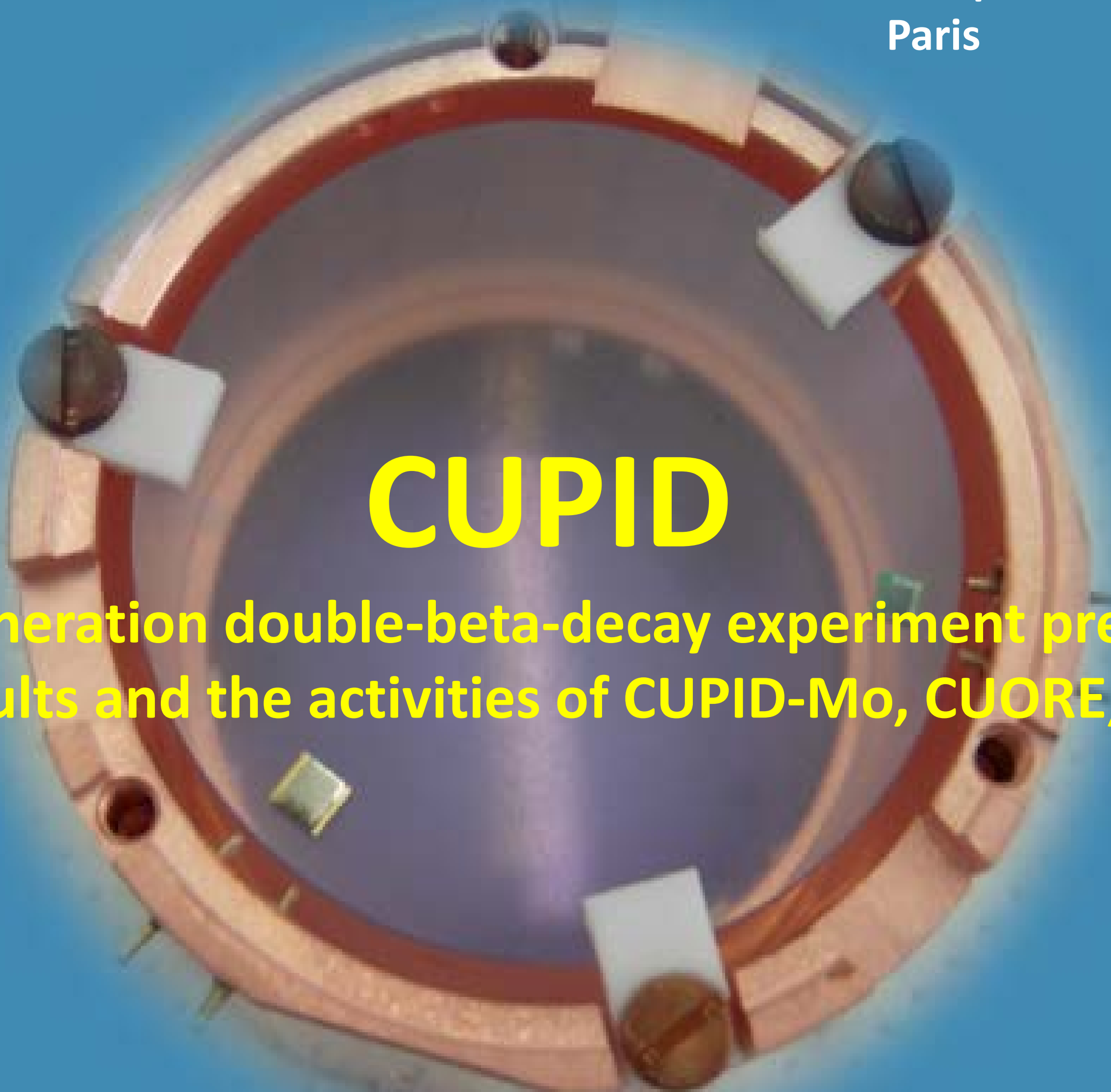
Conseil Scientifique
de l'IN2P3

October 25th, 2018
Campus Michel-Ange - CNRS
Paris



CUPID

A next-generation double-beta-decay experiment prepared by the results and the activities of CUPID-Mo, CUORE, CROSS

Andrea Giuliani (CSNSM)
(on behalf of the bolometric Double Beta Decay community in France)

Strategy

Objective

Build a **word-leading** next-generation experiment on $0\nu\beta\beta$ decay: **CUPID**

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Context

- International collaboration (France, Italy, US, China…)
- **Drive** and **leadership roles** from France

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Build a **word-leading** next-generation experiment on $0\nu\beta\beta$ decay: **CUPID**

Context

- International collaboration (France, Italy, US, China…)
- **Drive** and **leadership roles** from France

How to reach this objective:

R&D on LMO technology + (done)

CUORE infrastructure + (done)

Demonstrators + (ongoing)

Enrichment/Crystallization =

CUPID

$Li_2{}^{100}MoO_4$ scintillating bolometers developed in **ANR LUMINEU** (2012-2017)

CUORE is taking data in LNGS: successful implementation of 1 ton bolometric mass

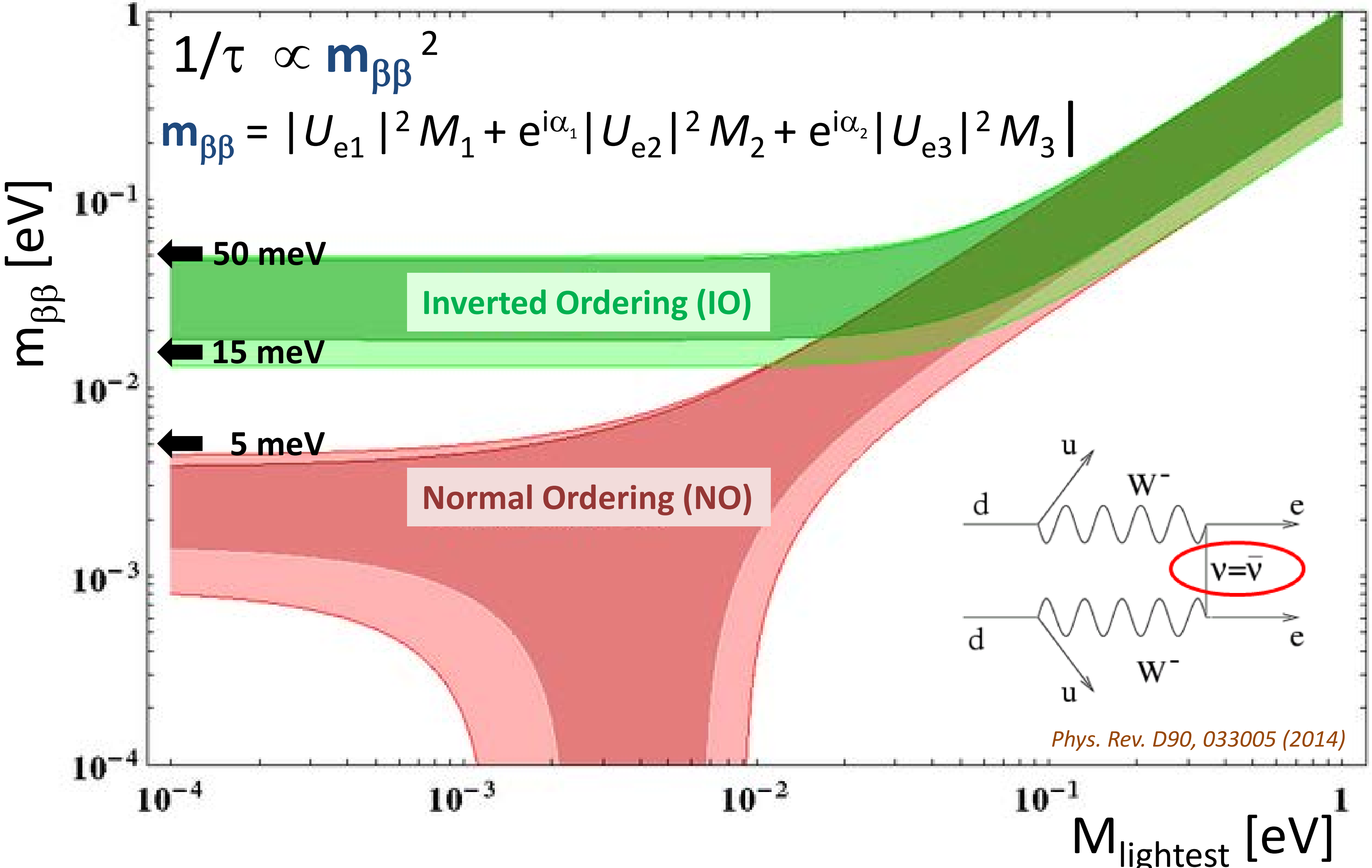
Test of the technology at the ~10 kg scale **CUPID-Mo** is installed in LSM – two more setups in LNGS, LSC (**ERC CROSS** (2018-2022)

Russian companies
Encouraging results in France with crystals from **ANR CLYMENE** (2016-2020)

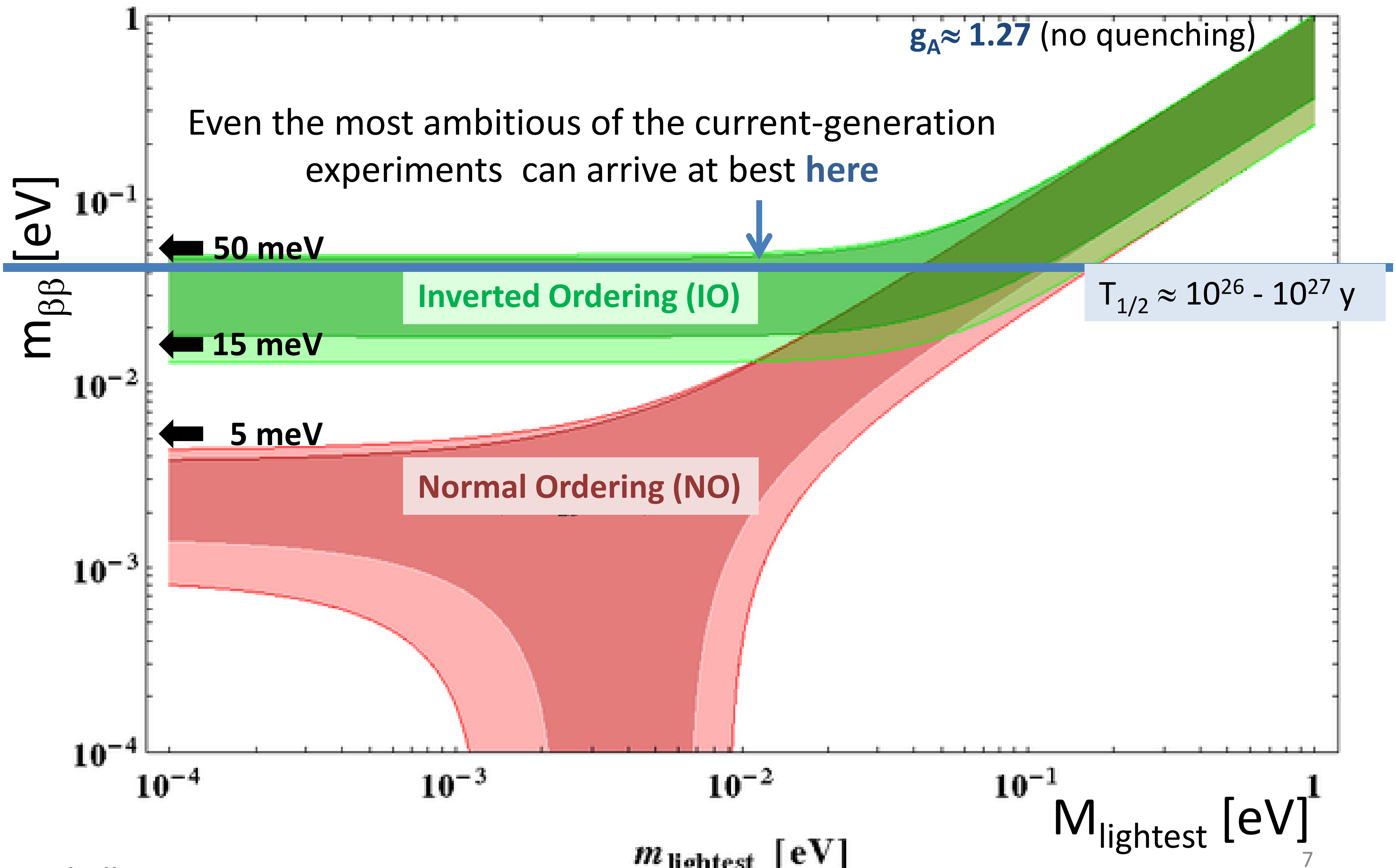
Outline

1. Challenges in $0\nu2\beta$ decay and the CUPID way
2. Scintillating bolometers made of $Li_2{}^{100}MoO_4$ crystals
3. Demonstrators: CUPID-Mo, CROSS and CUPID-Te
4. CUPID and its physics reach
5. Collaboration, tasks and resources

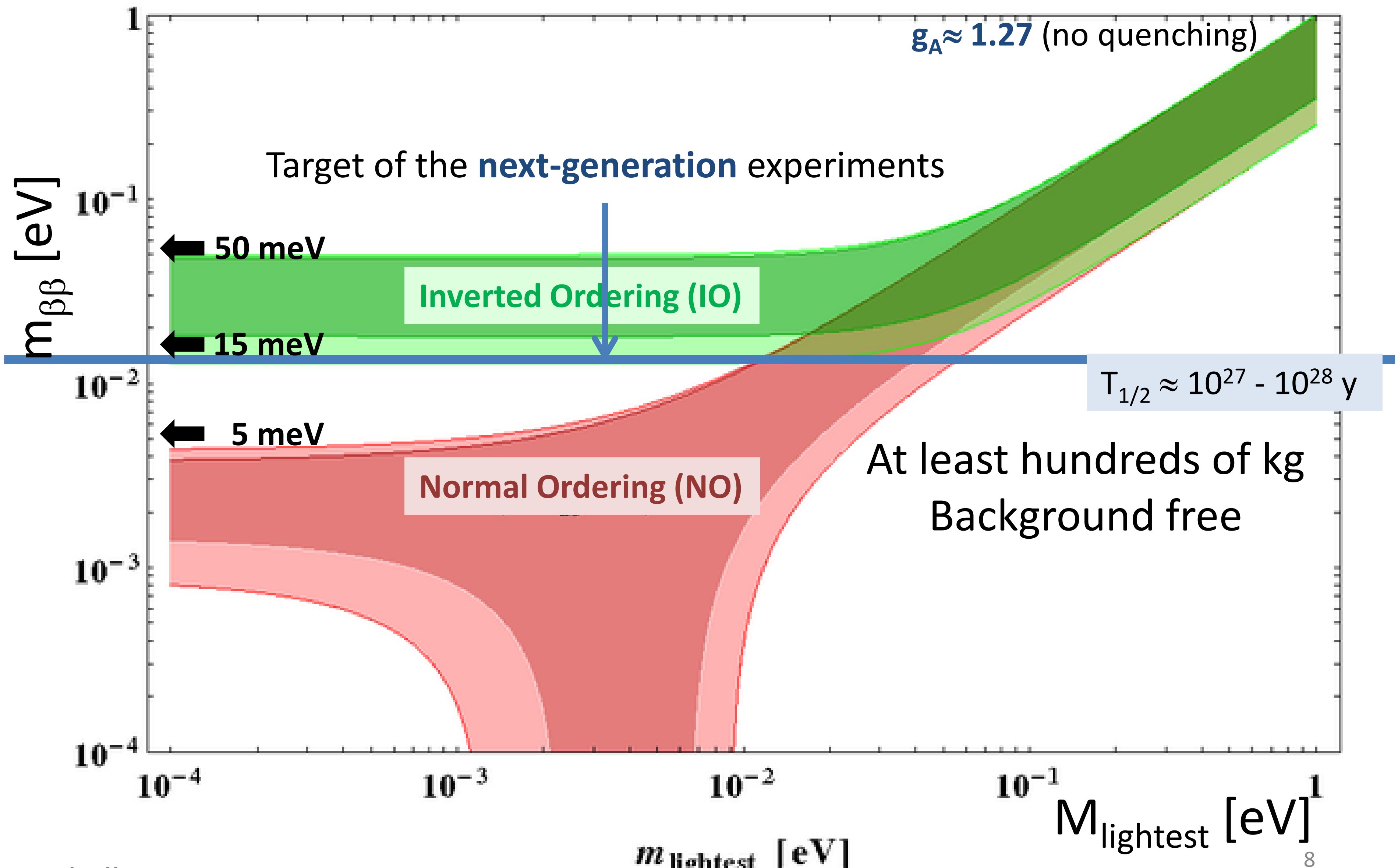
Standard mechanism: $m_{\beta\beta}$ vs. lightest ν mass



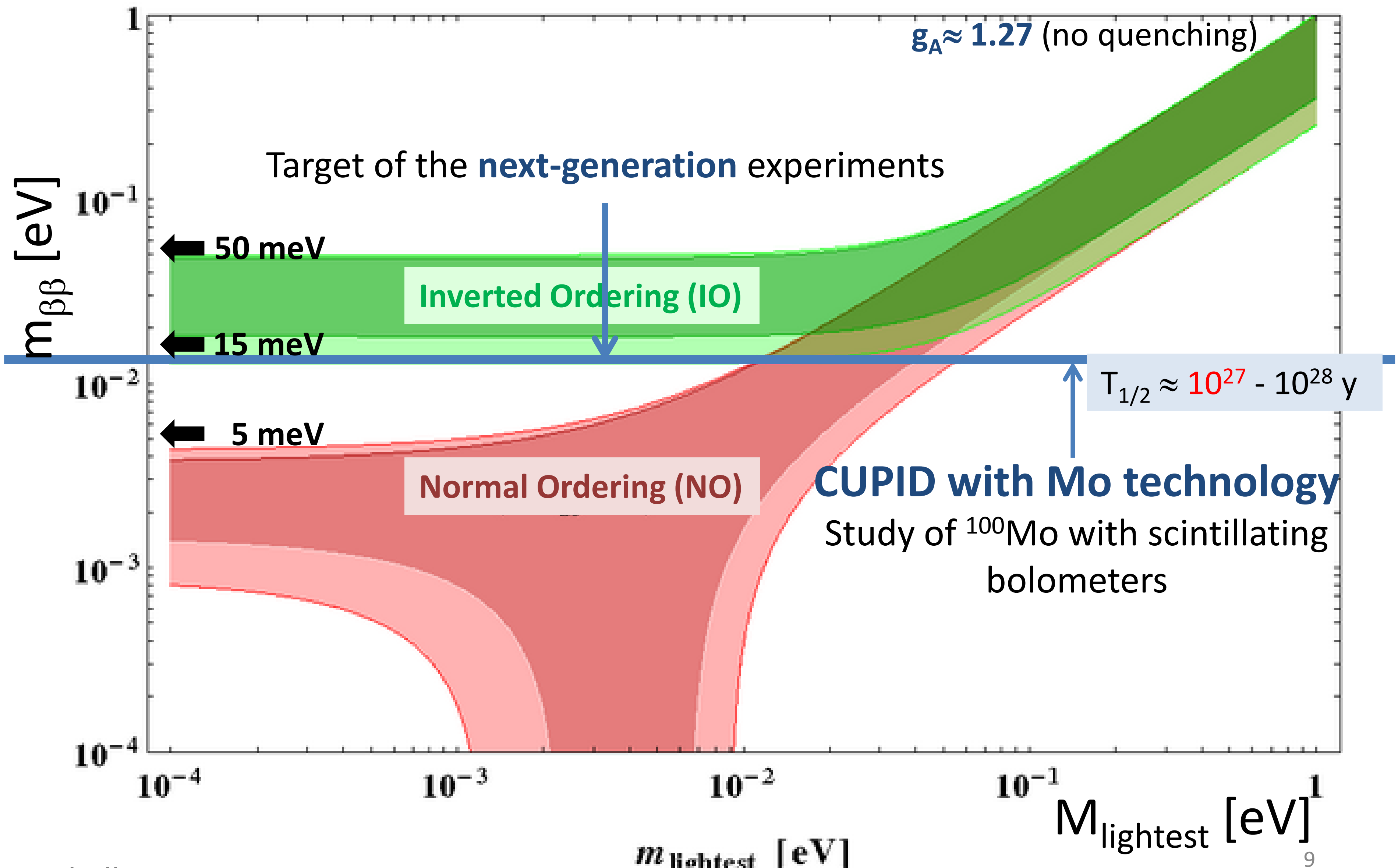
Current-generation experiments



Next-generation experiments



Next-generation experiments

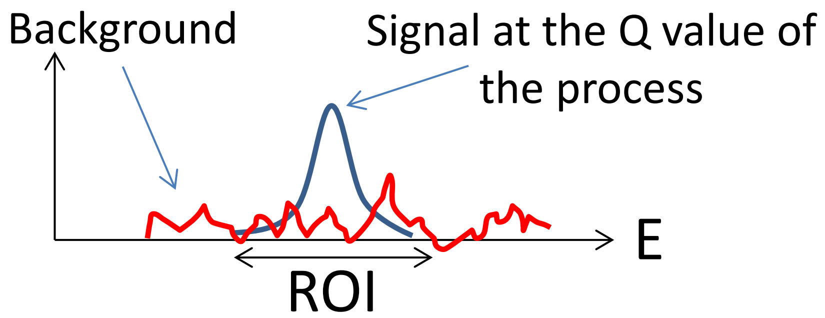


Request for the background index

Background index

***b* [counts/(keV kg y)]**

defined as



$$\frac{\textbf{number of background counts}}{\textbf{sensitive mass} \times \textbf{live time} \times \textbf{energy interval}}$$

around the region of interest (ROI)

in the source=detector approach with high energy resolution technique

$\Delta E_{FWHM} < 10$ keV

zero background at the tonne scale means

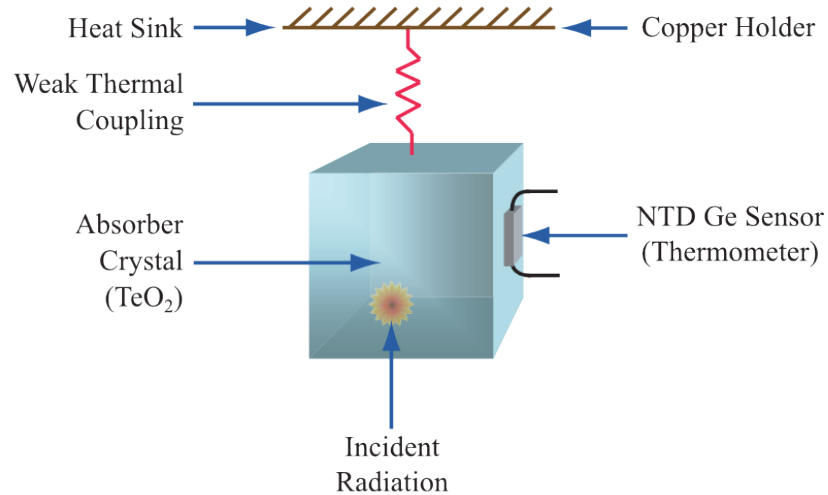
$b \leq 10^{-4}$ [counts/(keV kg y)]

Present record: GERDA (^{76}Ge) – b~ 7 x 10^{-4} counts/(keV kg y) – ΔE_{FWHM} ~ 3 keV

How we do it: bolometers

Bolometric approach: the source is embedded in a crystal, which is cooled down to 10-20 mK and works as a **perfect calorimeter**

$$\Delta T = E/C$$



- High energy resolution (~ **5 keV FWHM**)
- **~ 0.1 - 0.5 kg** source in each crystal → arrays
- High efficiency **(~ 70 – 90 %)**
- **Cuoricino – CUORE** experiments → crystals of **TeO_2** (isotope **^{130}Te**)
- **Large flexibility in the detector material choice:**

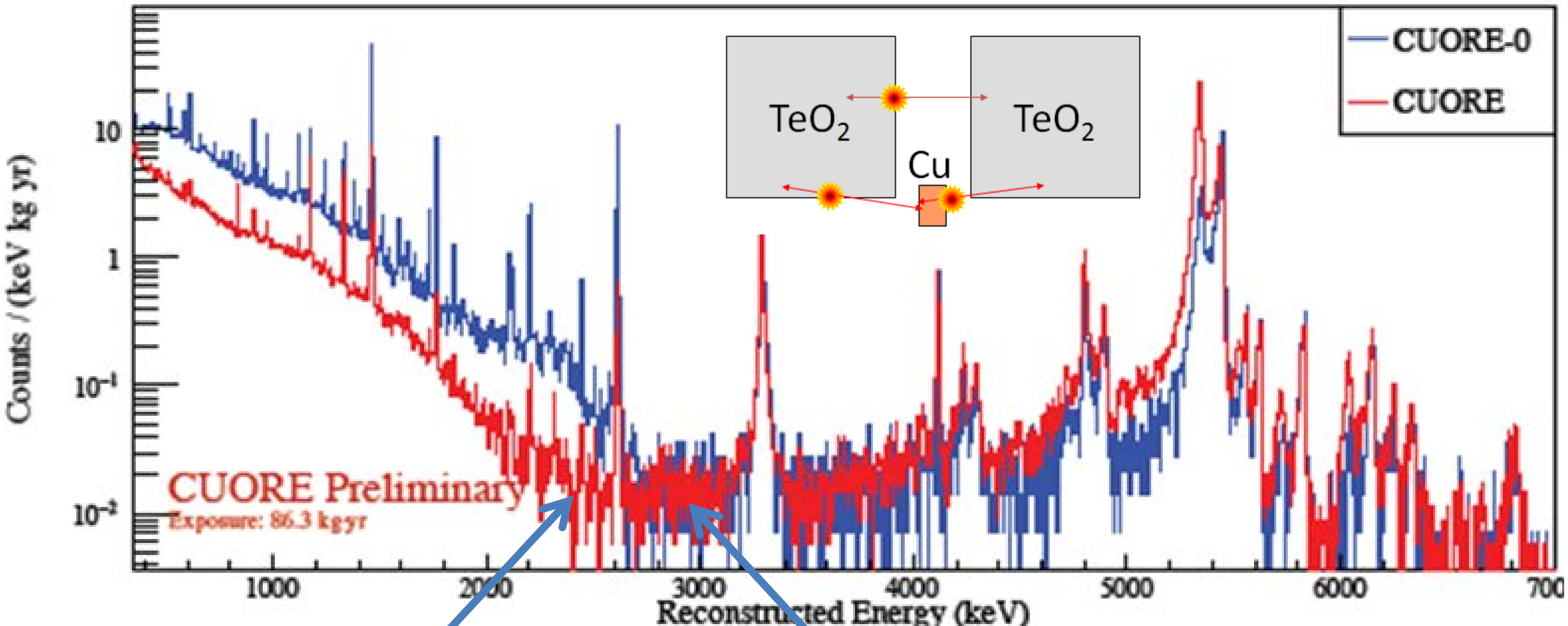
^{130}Te, and **three isotopes with Q > 2615 keV (^{82}Se, ^{100}Mo, ^{116}Cd) can be studied**

→ **Single multi-isotope experiment** → *AG et al., Eur. Phys. J. C 78 (2018) 272*

E. Fiorini, T.O. Niinikoski
Low-temperature calorimetry for rare decays
NIM 224 (1984) 83

CUORE-technology lessons about background

CUORE and its precursors are affected by **alpha particle background**



Irreducible background due to **alpha particles**, emitted at the **surfaces** and energy-degraded

b ~ 10^{-2} [counts/(keV kg y)]

CUORE is not background free – **50 BKG counts/y in ROI**

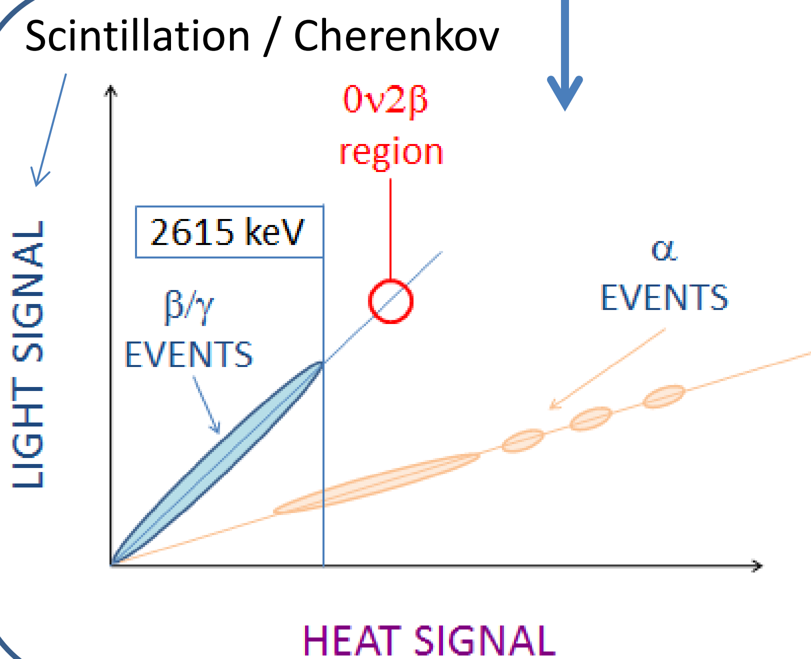
Improvement by a factor 10^2 is required

Current solution: scintillating / Cherenkov bolometers

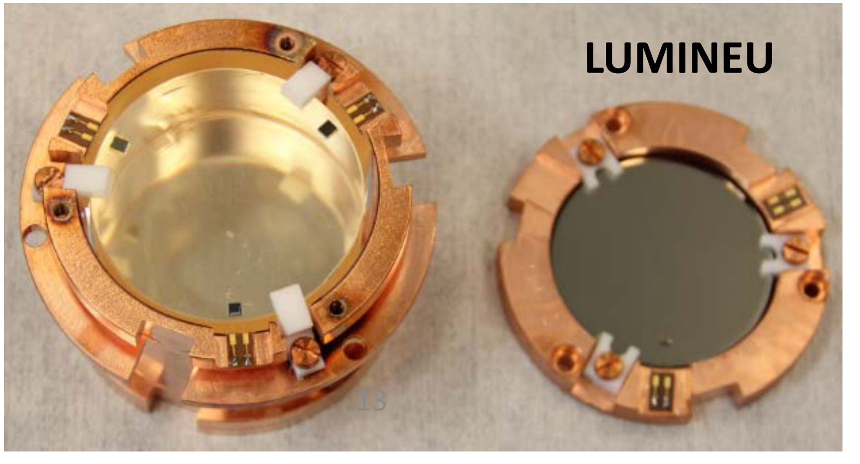
Alpha / beta separation

Alphas emit a different amount of light with respect to **beta/gamma** of the same energy (normally lower → **α QF < 1, but not in all cases**)

A **scatter plot light vs. heat** separates alphas from betas / gammas.



A bolometric light detector is needed, facing the main crystal



The two most promising isotopes: ^{100}Mo and ^{130}Te

R&D activity in France about the bolometric search for double beta decay (2012-2017)

~15 papers in international journals – **4** concluded **PhD theses** – **3 ongoing**

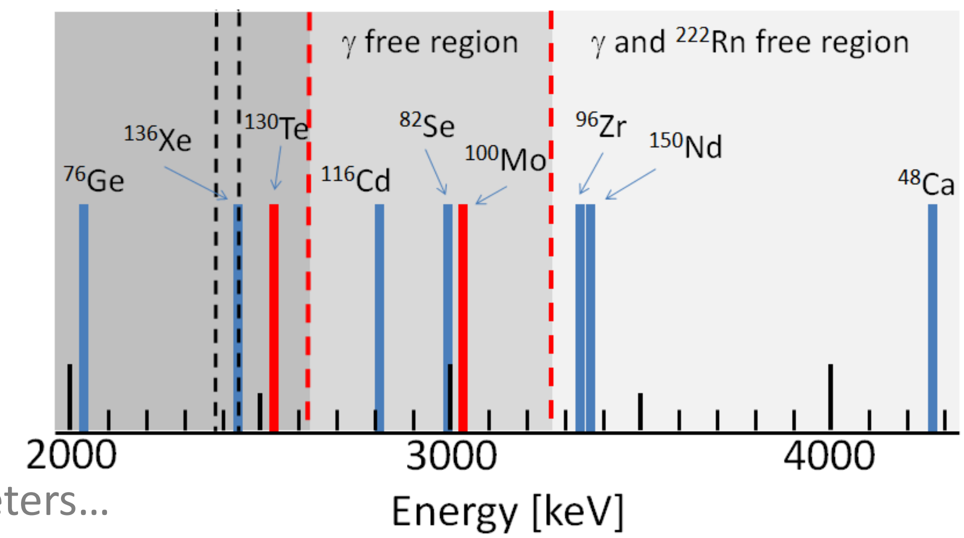
Scintillating bolometers containing the isotope **^{100}Mo**

$Q_{\beta\beta}$ = **3034 keV**

Favorable nuclear phsyics

Cherenkov bolometers containing the isotope **^{130}Te**

$Q_{\beta\beta}$ = **2527 keV**



Preparing a ^{100}Mo experiment: LUMINEU

Funding (total envelop **~750 k€**) and resources from:

- **ANR (France) – main fund provider (LUMINEU: 2012-2017)**
- **CEA-Saclay – substantial funds / 2 PhD fellowships**
- **CSNSM direction – funds for crystals (« AP interne »)**
- **EDELWEISS – underground facility, electronics & DAQ**
- **ISOTTA project – ASPERA R&D common call (2012-2014)**
- **IN2P3 – dedicated personnel / PICS**
- KINR Kiev – radiopure scintillator know-how, simulation, – enriched ^{100}Mo
- ITEP Moscow – enriched ^{100}Mo
- NIIC Novosibirsk - crystals
- INFN / LUCIFER – underground facility and manpower for R&D

\+

46 participants
30 from France
~28% from IN2P3

$Li_2{}^{100}MoO_4$ scintillating bolometers: a mature technology

LUMINEU has succesfully developed the $Li_2{}^{100}MoO_4$ technology

Multiple tests with **natural and enriched crystals** (2014-2017) in **LSM** and LNGS with outstanding results in terms of:

EDELWEISS set-up

High-purity crystals	→	negligible loss of enriched material
Reproducibility	→	excellent performance uniformity
Energy resolution	→	~ **4-6 keV FWHM** in RoI
α/β separation power	→	**> 99.9 %**
Internal radiopurity	→	**< 5 μBq/kg in ^{232}Th, ^{238}U**; **< 5 mBq/kg in ^{40}K**

→ Compatible with $b \leq 10^{-4}$ **[counts/(keV kg y)]**

NIM A 729, 856 (2013)
JINST 9, P06004 (2014)
EPJC 74, 3133 (2014)
JINST 10, P05007 (2015)

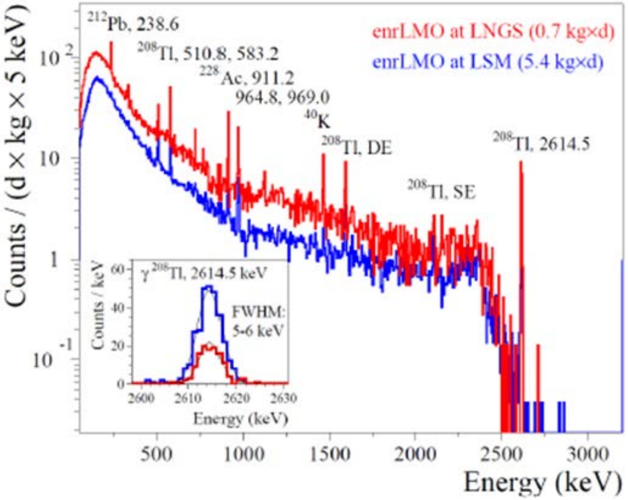
Eur. Phys. J. C (2017) 77:785
https://doi.org/10.1140/epjc/s10052-017-5343-2
THE EUROPEAN PHYSICAL JOURNAL C
CrossMark
Regular Article - Experimental Physics

Development of ^{100}Mo-containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search

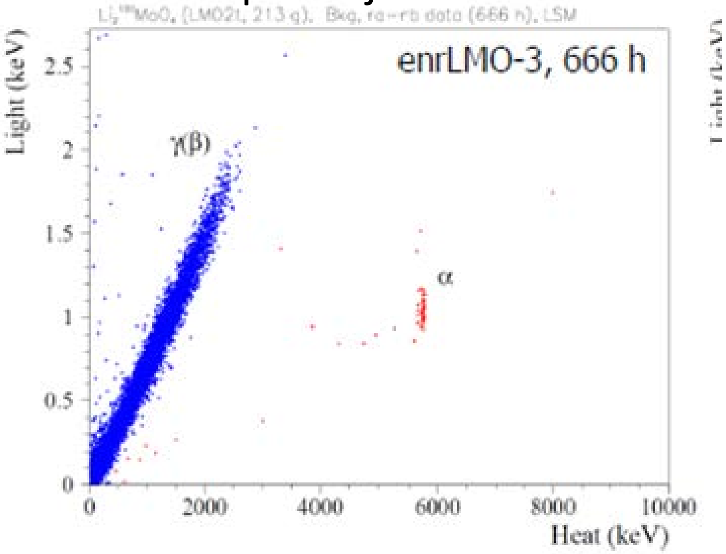
$Li_2{}^{100}MoO_4$ scintillating bolometers: a mature technology

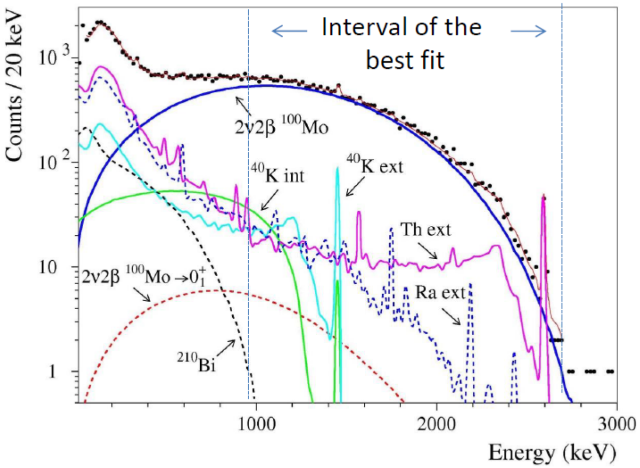
Crystallization

Energy resolution



Alpha rejection





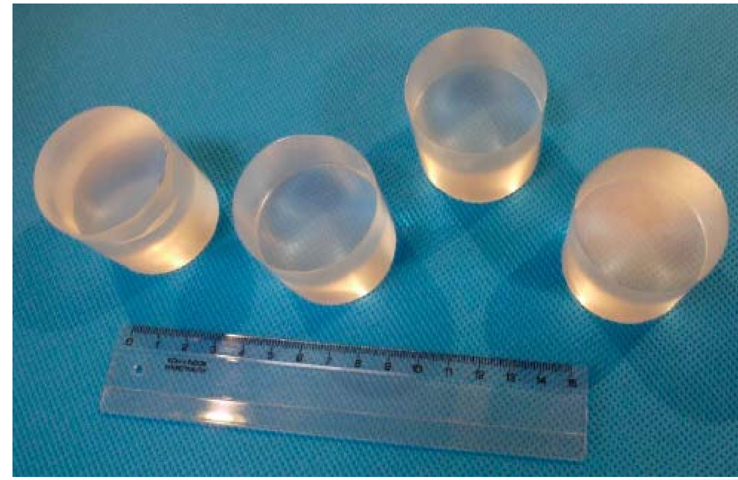
$$T_{1/2}^{2\nu2\beta} = (6.95 \pm 0.13)\times10^{18}\ \mathrm{yr}$$

The CUPID-Mo demonstrators

CUPID-Mo-LSM (20 crystals)

- **20 ^{100}Mo-enriched (97%) Li_2MoO_4**
  (∅44×45 mm, 0.21 kg each; 4.18 kg total)
  ⇒ ~**2.5 kg of ^{100}Mo**
- **20 Ge light detectors** (∅44×0.175 mm)+SiO
- **EDELWEISS set-up** @ **LSM (France)**

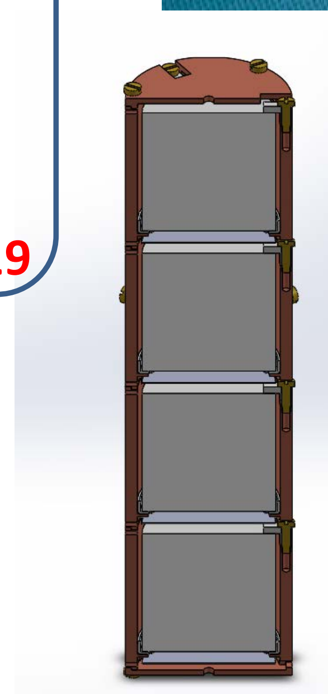
COMMISSIONING May - June 2018

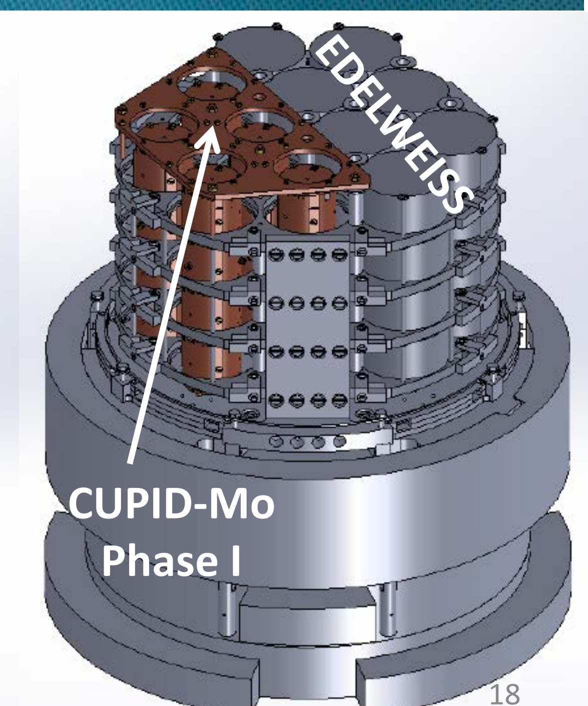


CUPID-Mo-LNGS (26 crystals)

- Additional **26 cubic $Li_2{}^{100}MoO_4$**
  (45x45x45 mm, 0.28 g each)
  ⇒ **~4 kg of ^{100}Mo**
- **CUPID-0 set-up** @ **LNGS (Italy)**

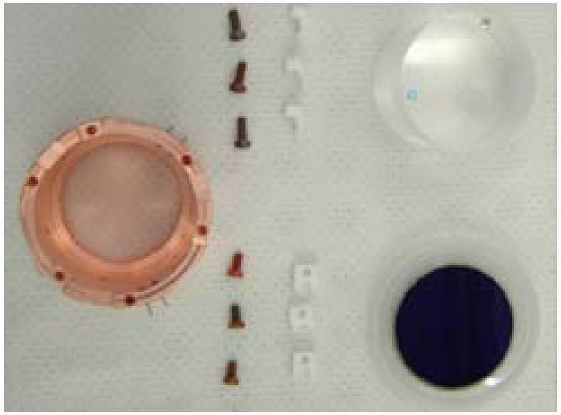
PLANNED START DATA TAKING: late 2019





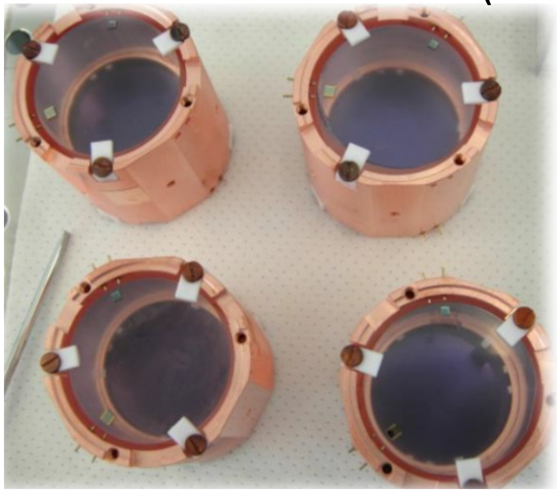
Assembly and installation of CUPID-Mo-LSM

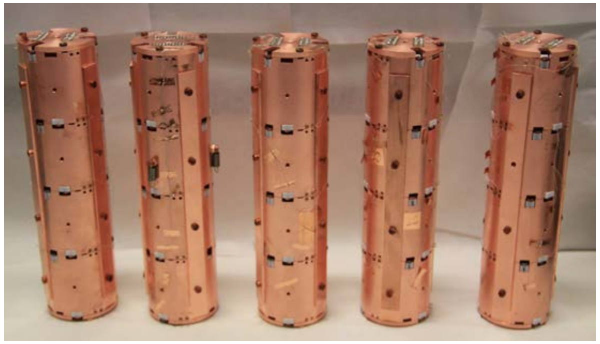
Elements for a single module



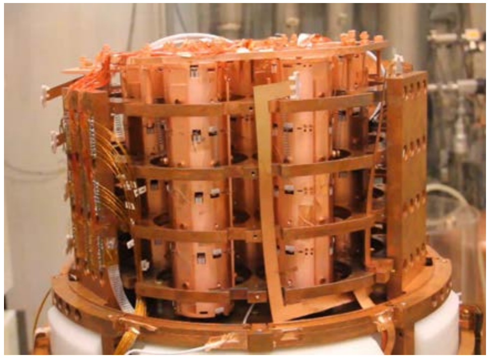
Cleaning and assembly in the LAL clean room

Four modules (one tower) and five towers





Installation in the EDELWEISS cryostat



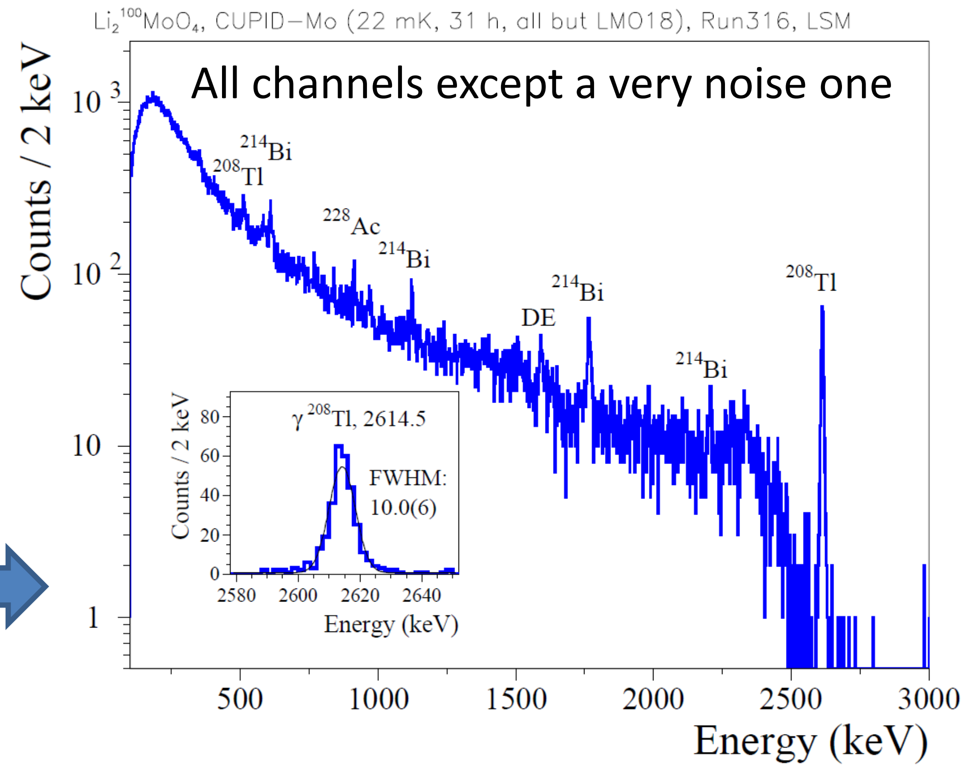
CUPID-Mo-LMS (Phase I)
Preliminary results at 22 mK

Long delay of the run start due to cryogenics (Nov 2017 → Apr 2018)

Preliminary data acquired at **22 mK**

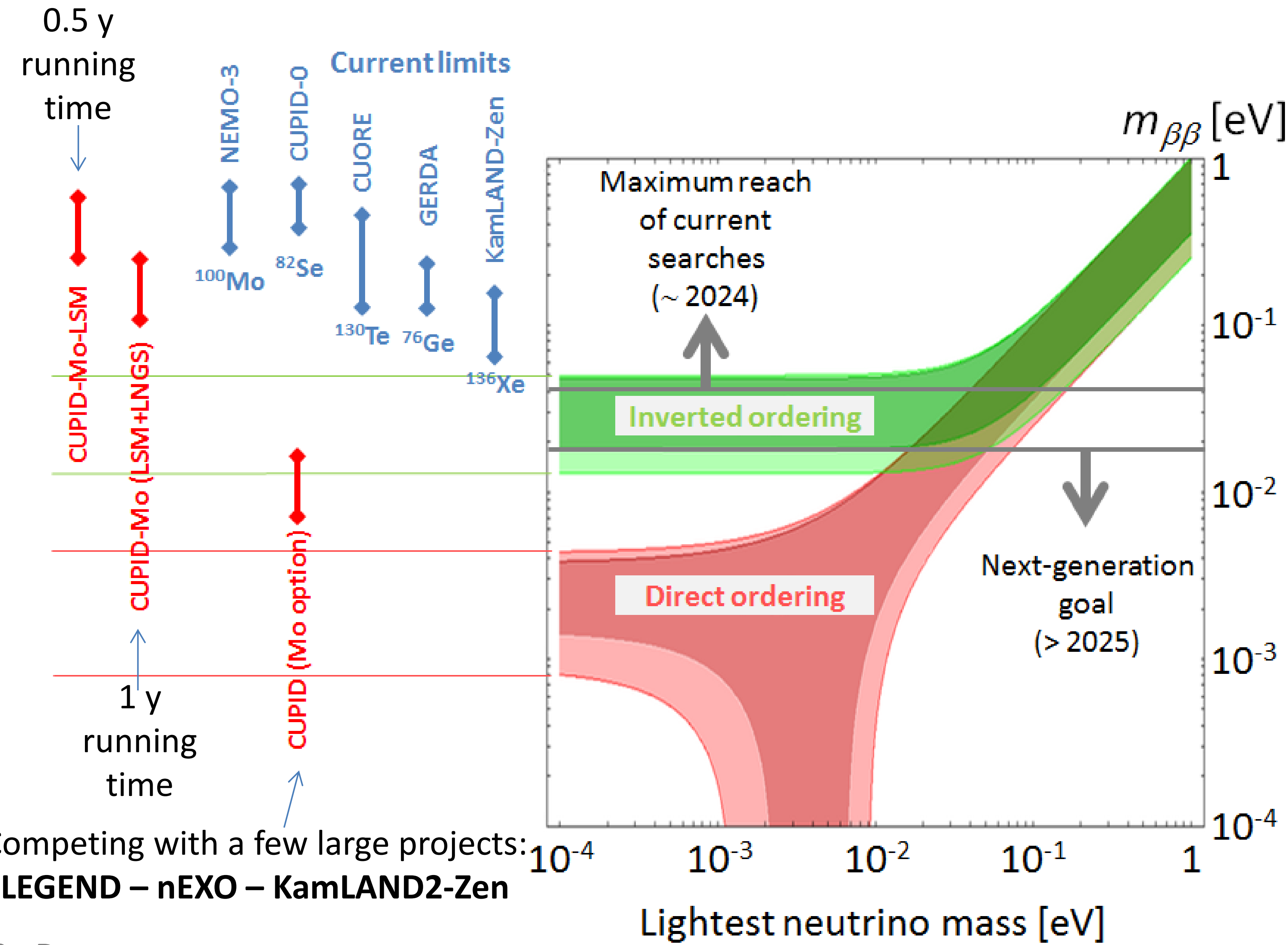
- Large microphonic noise, related in part to persisting cryogenic problems
- 2 heat channels are lost

In spite of that, satisfactory performance of the detectors



- **Cryostat failure** forced us to stop the run at August 7th, 2018
- Maintenance of the cryostat is now ongoing
- Run resume is foreseen in December 2018

Physics reach of the two CUPID-Mo demonstrators



Competing with a few large projects:
LEGEND – nEXO – KamLAND2-Zen

Beyond light detectors: CROSS

ERC advanced grant CROSS (2018-2022)

Cryogenic **R**are-event **O**bservatory with **S**urface **S**ensitivity

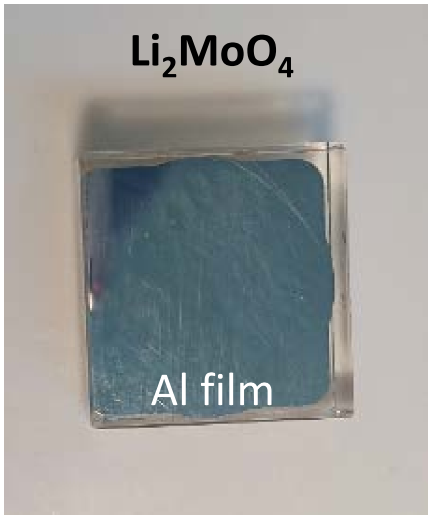
CROSS develops an innovative bolometric technology to search for 0ν-DBD

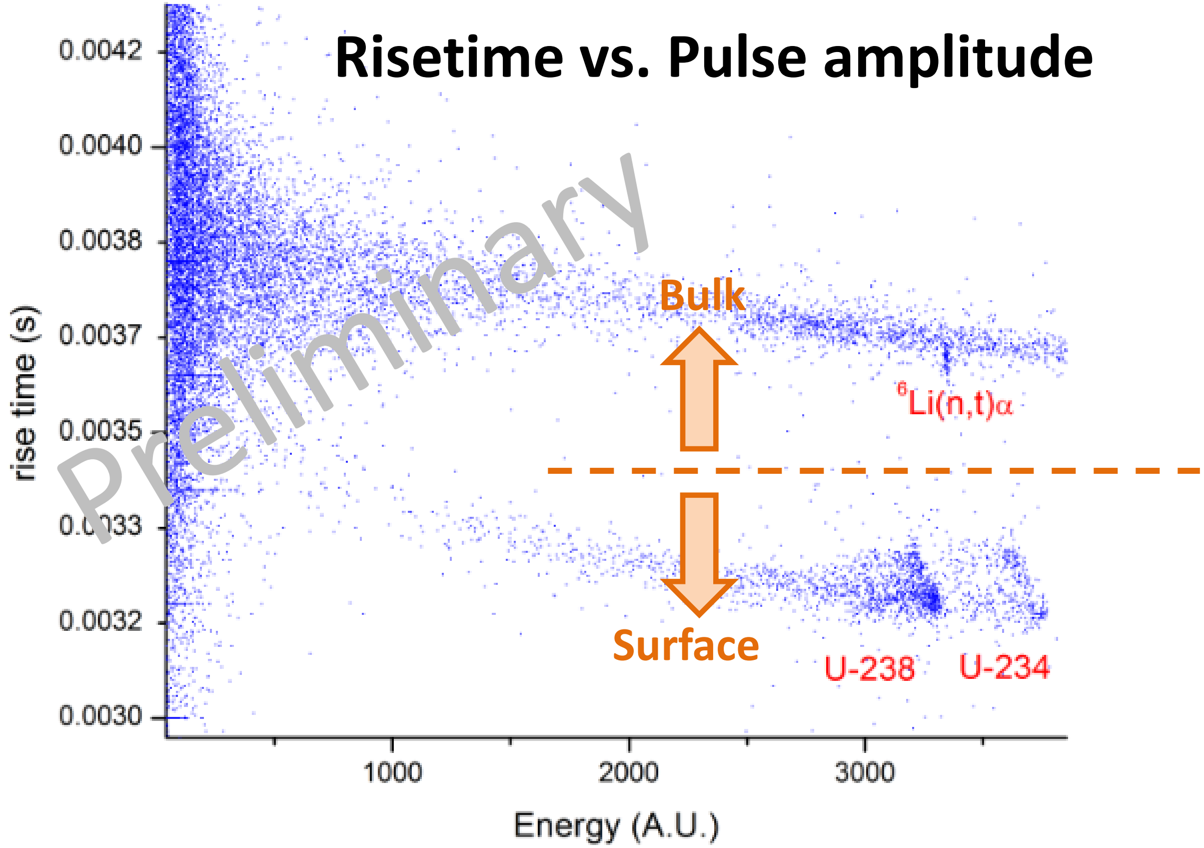
- **Core of the project** (high risk / high gain)
  Background rejection through **pulse shape discrimination**
  - **Surface sensitivity** through **superconductive Al film coating**

    → **get rid of light detectors**
- Complete crystallization of available ^{100}**Mo (10 kg)** in Li_2MoO_4 elements → **cubic crystals** for **CUPID-Mo-LNGS (Phase II)**
- Purchase / crystallize ^{130}**Te (up to 10 kg)** in TeO_2 elements
- Run demonstrator in a dedicated cryostat **(LSC – Spain)**

Encouraging preliminary results

Above-ground tests (CSNSM) with **20x20x10 mm Li_2MoO_4 and TeO_2 crystals**





Alphas impacting on the film side are clearly discriminated

Dilution refrigerator under construction to host CROSS demonstrator

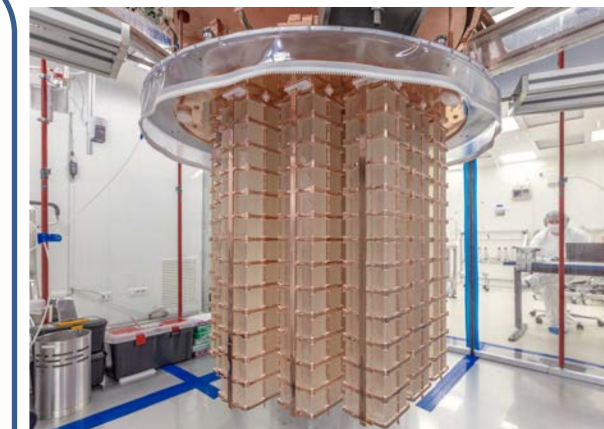
Commissioning in Canfranc (Spain) in April 2019

CUORE → CUPID

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)

Three important messages from CUORE

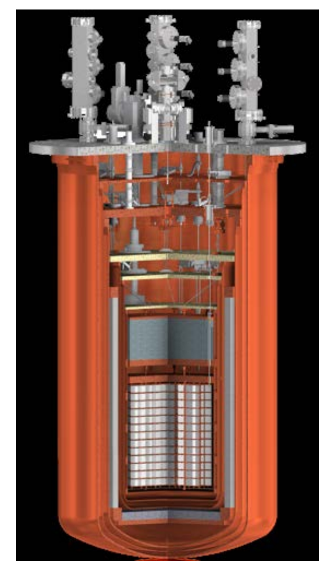
1. A tonne-scale bolometric detector is technically feasable
2. Analysis of ~1000 individual bolometers is handable
3. An infrastructure to host a bolometric next-generation $0\nu\beta\beta$ experiment is already available



CUORE is not background free

→ **~50 counts/y in the ROI**, dominated by **surface alpha background**

It is time to work on CUPID, the natural evolution of CUORE



CUPID (CUORE Upgrade with Particle ID) is a proposed $0\nu2\beta$ bolometric experiment exploiting the **CUORE infrastructure** and with a **background 100 times lower at the ROI**

Prospects for CUPID

^{100}Mo, ^{130}Te

Results of the ongoing R&D and demonstrators + CUORE background model

1. $Li_2{}^{100}MoO_4$ scintillating bolometers → promising **baseline option** for CUPID

2. $^{130}TeO_2$ Cherenkov bolometers → mature viable alternative

→ Fast and high-sensitivity light detectors are a common R&D

- Detection of Cherenkov light in TeO_2
- Rejection of $2\nu2\beta$ random coincidences in $Li_2{}^{100}MoO_4$

- **CUPID CDR under writing (working meeting in LNGS, Nov 19-20)**
- **CUPID kick-off meeting is being planned in mid 2019**

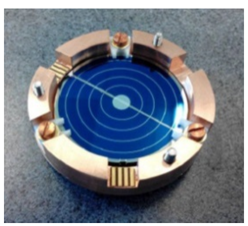
Rejection of α background in TeO_2

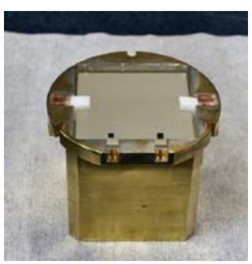
Reject α's by detecting the feeble **Cherenkov light** emitted by β's
→ α's are below the Cherenkov threshold

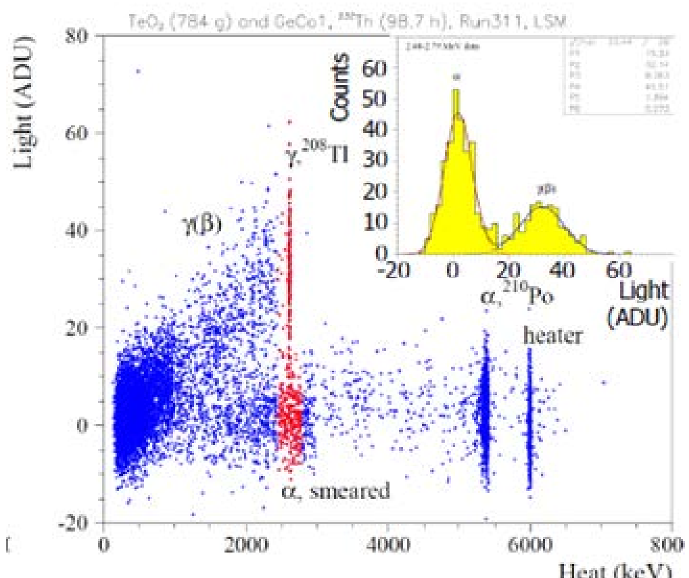
Very difficult: **light carries an energy amount 30 times smaller than for Li_2MoO_4**

Vibrant R&D on ultra-sensitive low-temperature light detectors
Best results achieved so far in France (CSNSM) with a CUORE-size crystal

Neganov-Luke-amplified light detector







Phys. Rev. C 97, 032501(R) (2018)

Develop a demonstrator with 6 or 8 modules in LSM (data taking in 2020)

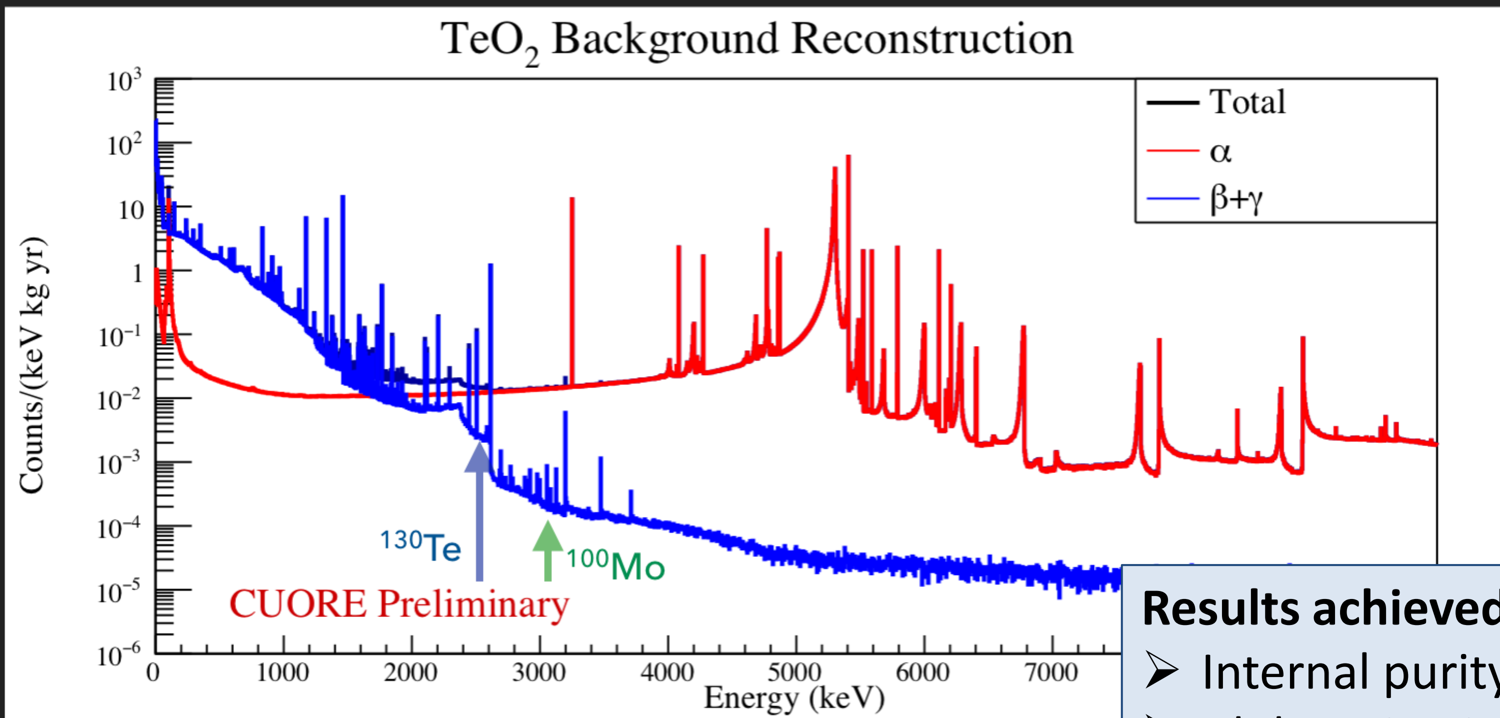
CUPID-Te

(in the EDELWEISS set-up)

To be submitted to ANR

^{100}Mo or ^{130}Te ?

Background Model Contamination Levels (Very Preliminary!)



Results achieved in LMO R&D

- Internal purity
- Alpha rejection factor

TeO_2 γ background at 2527 keV	~2.6×10^{-3} cnts/(keV·kg·yr)
Li_2MoO_4 γ background at 3034 keV	~1×10^{-4} cnts/(keV·kg·yr)

(Based on assumptions)

Possible configurations in CUPID (^{100}Mo)

Single element	Number of elements	Isotope mass [kg]	Number of ^{100}Mo nuclei
50×50×50 mm – 380 g	1150	~250	$\sim 1.4 \times 10^{27}$
45×45×45 mm – 280 g	1600		

→ Same size as in CUORE

→ Already achieved size in the R&D

Preliminary

Background [counts/(keV kg y)]	Number of BKG counts [5 keV, 10 y]	Count limit Feldman Cousins [90% c.l.]	Half life limit [y] [90% c.l.]	$M_{\beta\beta}$ [meV]
1×10^{-4}	2.2	4.1	1.8×10^{27}	**6.6 – 19**

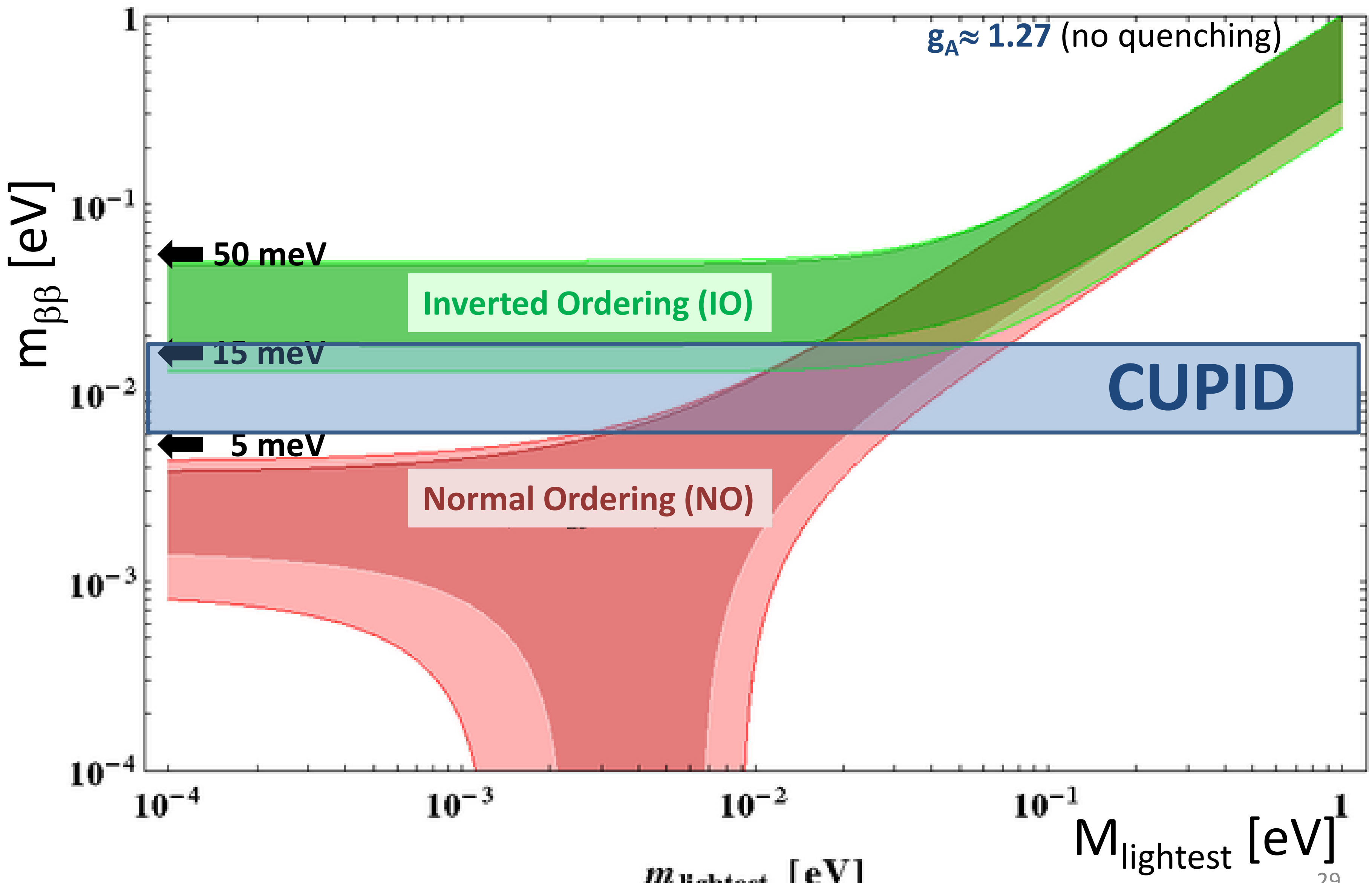
Next generation experiment → cover completely the inverted ordering region

Enrichment cost: ~ 20 M€

Crystallization cost: ~ 5 M€

→ Bottle neck – 40 kg/y → Phased approach

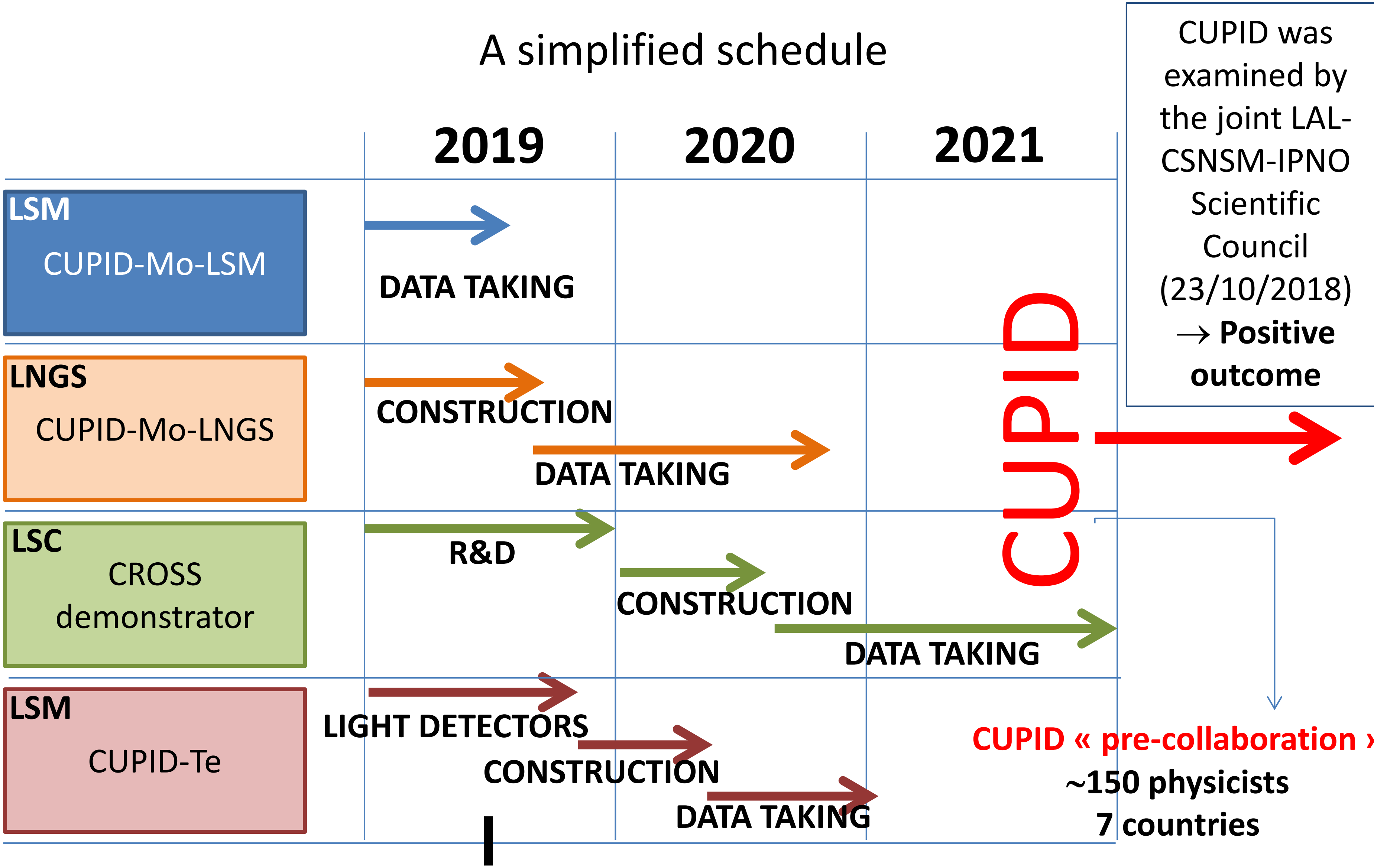
CUPID reach



$g_A \approx$ 1.27 (no quenching)
50 meV
Inverted Ordering (IO)
15 meV
CUPID
5 meV
Normal Ordering (NO)
$m_{\beta\beta}$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$M_{lightest}$ [eV]
$m_{lightest}$ [eV]

Demonstrators towards full CUPID

A simplified schedule



CUPID CDR

The CUPID-Mo collaboration

Major extension with respect to LUMINEU

http://cupid-mo.mit.edu

CSNSM
LAL
IPNL
CEA/IRFU

KIT

INFN
LNGS

KINR

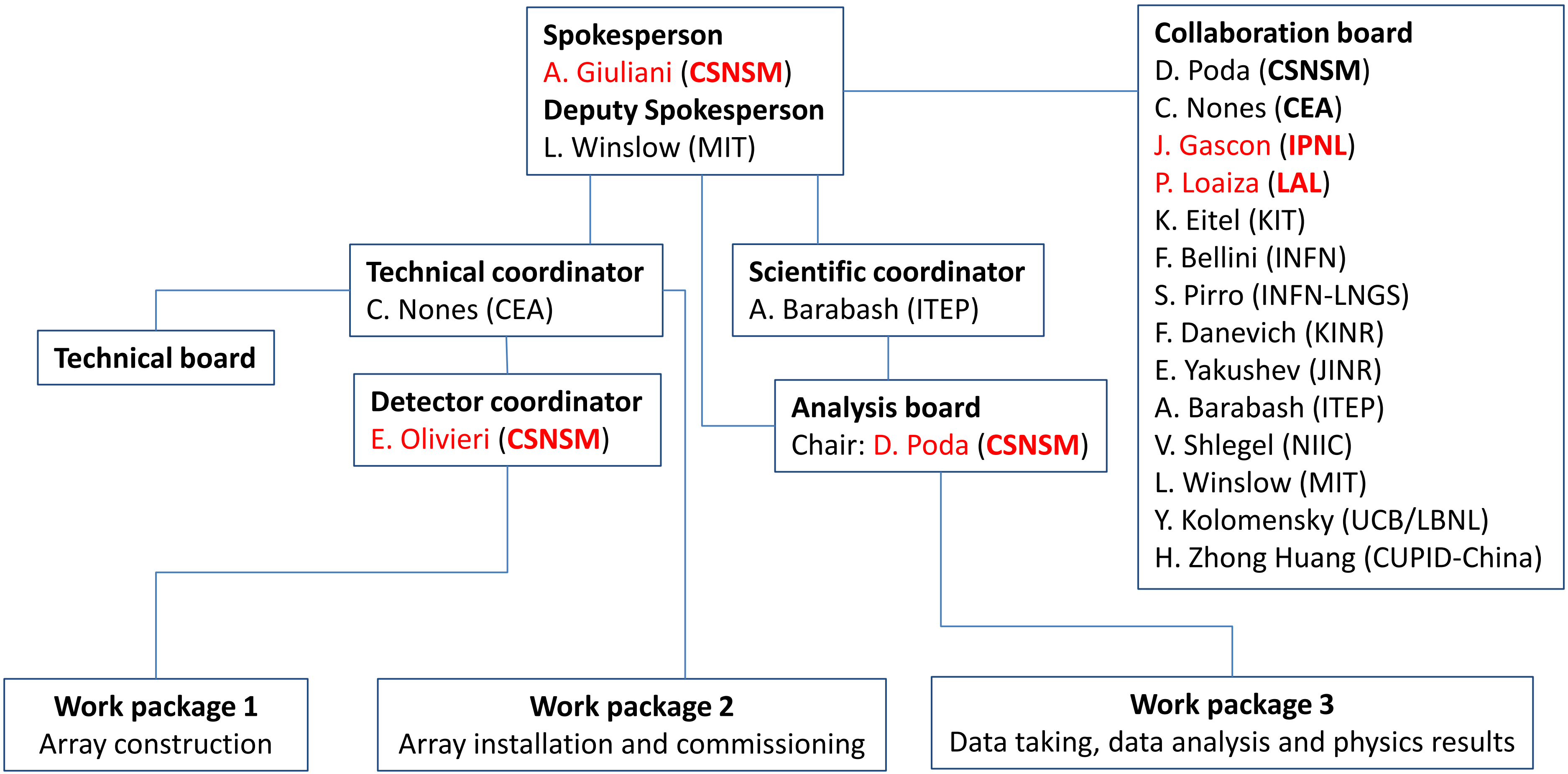
ITEP
NIIC
JINR

MIT
UCB/LBNL

FUDAN
USTC

Strong interest in China
Large CUPID group.
Project for a “parallel CUPID”
at JinPing laboratory

CUPID-Mo organizational structure



The collaboration comprises **85 members**. (**~ 30% from IN2P3**)

French component: **38 members** from 4 sites: CSNSM, LAL, IPNL, CEA)

(France-38, Italy-15, US-10, China-4, Germany-4, Russia-10, Ukraine-4)

Collaboration agreement signed by the PI's in January 2018

Personnel in IN2P3 laboratories

2019 FTE's (estimation)

	CSNSM		IPNL		LAL	
	Name	FTE	Name	FTE	Name	FTE
Researchers and Professors	**A. Giuliani**	0.6	**J. Gascon**	0.15		
	S. Marnieros	0.25	C. Augier	0.2		
	P. de Marcillac	0.8	V. Sanglard	0.1		
	C. Marrache	0.2	A. Cazes	0.1		
	L. Dumoulin	0.2	J. Billard	0.1		
Research Engineers	E. Olivieri	0.5			**P. Loaiza**	0.5
	C. Oriol	0.2				
Technical Engineers and Technicians	L. Bergé	0.3			Ch. Bourgeois	0.05
	T. Redon	0.5			M. Brière	0.4
					E. Guerard	0.1
					B. Leluan	0.1
Post-docs	D. Poda	1.0				
	A. Zolotarova	1.0				
TOTAL FTE	**5.55**		**0.65**		**1.15**	

Main roles in France

IN2P3

CSNSM

- **Data analysis of CUPID-Mo-LSM**
- **Prototypes for CUPID-Mo-LNGS and CROSS**, **advanced Neganov-Luke light detectors**
- **Assembly of CUPID-Mo-LNGS** (with INFN), **CROSS demonstrator** and **CUPID-Te**
- **Commissioning of the CROSS cryostat** (with LAL, Canfranc)
- **Installation and commissioning** of the **three future demonstrators**
- **Data analysis of sample channels** of all the demonstrators

LAL

- **Radiopurity assessment** of the materials
- **Mechanics** for the the **three future demonstrators**
- **Assembly of the CROSS and CUPID-Te demonstrators** in collaboration with CSNSM
- **Background model** in collaboration with Italian and US institutions

IPNL

- **Data taking in the LSM-based demonstrators**
- Data analysis for **pulse shape discrimination**

CEA

- **Technical coordination of the underground operation**
- **Electronics and DAQ in LSM**
- In prospect **slow control and perhaps DAQ for CROSS**

Grenoble (SIMaP, Cristallinov)

- **Radiopure Li_2MoO_4 crystal growth**

Reinforce the Orsay group : a permanent position to provide a **combined expertise** on **(scintillating) bolometer conception**, **radiopurity** and **data analysis / simulation**

Budget

The budget to operate CUPID-Mo-LSM and to build and operate CUPID-Mo-LNGS and CUPID-Te **is not secured**.

CROSS (**budget 3.2 M€**) can contribute only marginally (it has its own program)

Cost item	Cost (k€)	Comments
Modane running costs	27	Total: 14 k€/month →84 k€ for six months Reasonable expectations: EDELWEISS will cover half of this cost and CUPID-Mo-LSM foreign collaborators will contribute with 15 k€ 84/2-15 = 27
Missions to Modane	5	5 person.weeks for measurement maintenance
Missions to LNGS	10	10 person.weeks for CUPID-Mo-LNGS assembly / commissioning
Mechanics for demonstrators	15	Tools and sub-commissioning
Material for holders	10	Ultrapure copper and PTFE
Advanced light detector construction	10	Ge wafer and clean-room miscellaneous items
TOTAL	**77**	

Request to CEA/IRFU: **30 k€ for year 2019** (~same amount received in 2018)

→ This covers less than half of the expected 2019 costs → **50 k€ missing**

Final considerations

Advantages of CUPID in LMO version (baseline):

- The **infrastructure** already **exists** (CUORE cryostat)
- The **R&D** on the single modules of the detectors is **completed**

The objetives are achieved in terms of

- Internal radiopurity
- Alpha rejection factor
- Energy resolution

Possible simplifcation with the CROSS approach

- **CUORE background model** indicates **b ~ 10^{-4} counts/(keV kg y)**
- **Crystallization** and **enrichement** at large scale are **possible**

Uniquely favorable position when compared to other next-generation searches