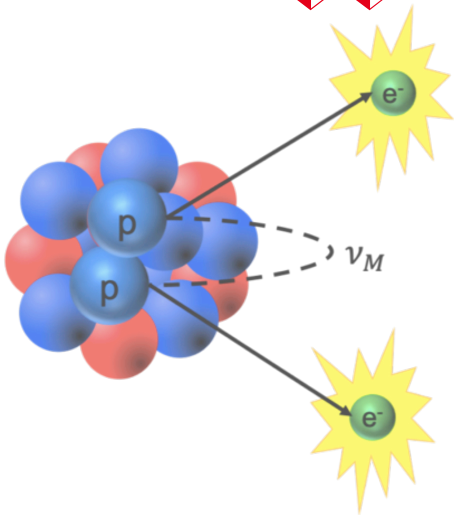


Décroissance double beta et CUPID

Claudia Nones

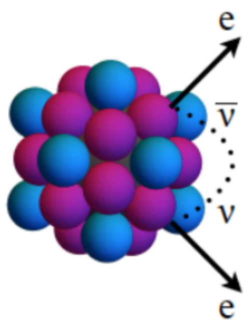
IRFU/DPhP

CUPID

Outline

- What neutrinoless double beta decay is – why it is important
- How much it is difficult – isotopes and technologies
- The bolometric approach: from CUORE to CUPID
- CUPID – an experiment up to the challenge
- The future and the role of CUPID-related developments

Nuclear Double Beta Decay



Double Beta Decay is the **rarest nuclear weak process**

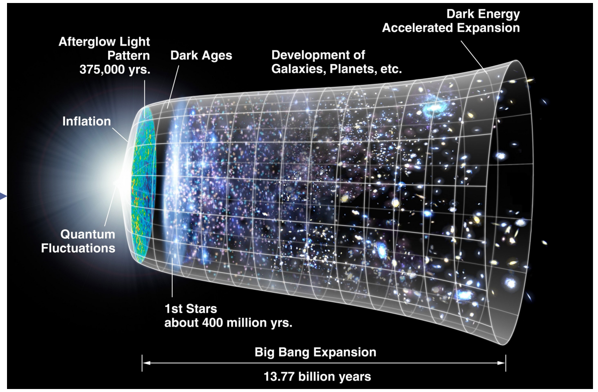
It takes place between **two even-even isobars**

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

If only electrons and nothing else:

Half-life larger than 10^{25} yr - 10^{26} yr

Age of the Universe



x 10^{15} (!!!)

- Need to find single events in a ton of isotope x year(s) of exposure!
- Double beta decay specific activity: 3 x 10^{-11} Bq/kg

vs. 15 Bq / banana

- Keywords: background, background, background!

Decay channels for Double Beta Decay

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ → 2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \sim 10^{18} - 10^{21}$ y

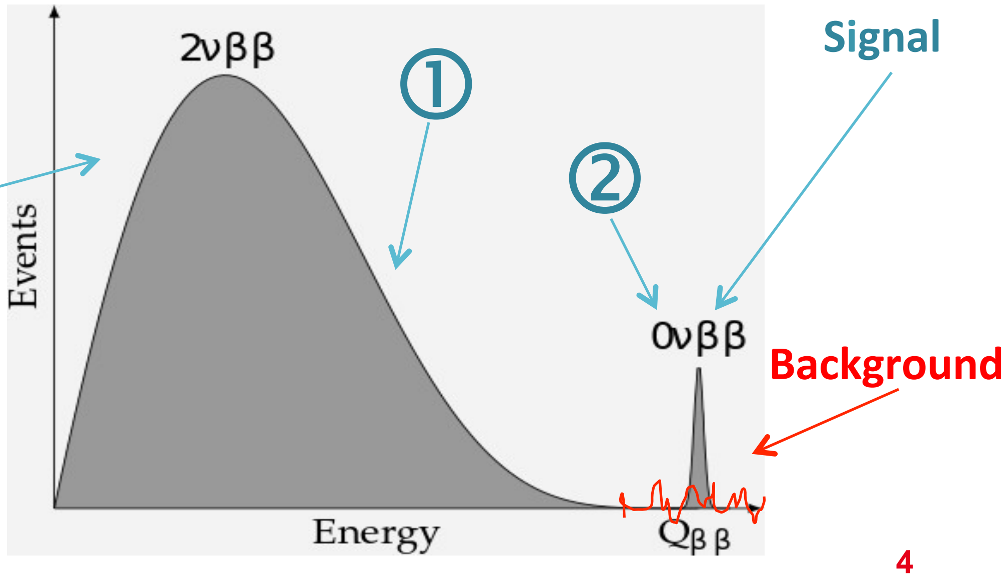
② $(A,Z) \rightarrow (A,Z+2) + 2e^-$
$2n \rightarrow 2p + 2e^-$
→ **Neutrinoless Double Beta Decay (0νββ)**
never observed
$\tau > 10^{25} - 10^{26}$ y

Processes ② would imply new physics beyond the Standard Model

Violation of total lepton number conservation
Creation of matter with no anti-matter partners

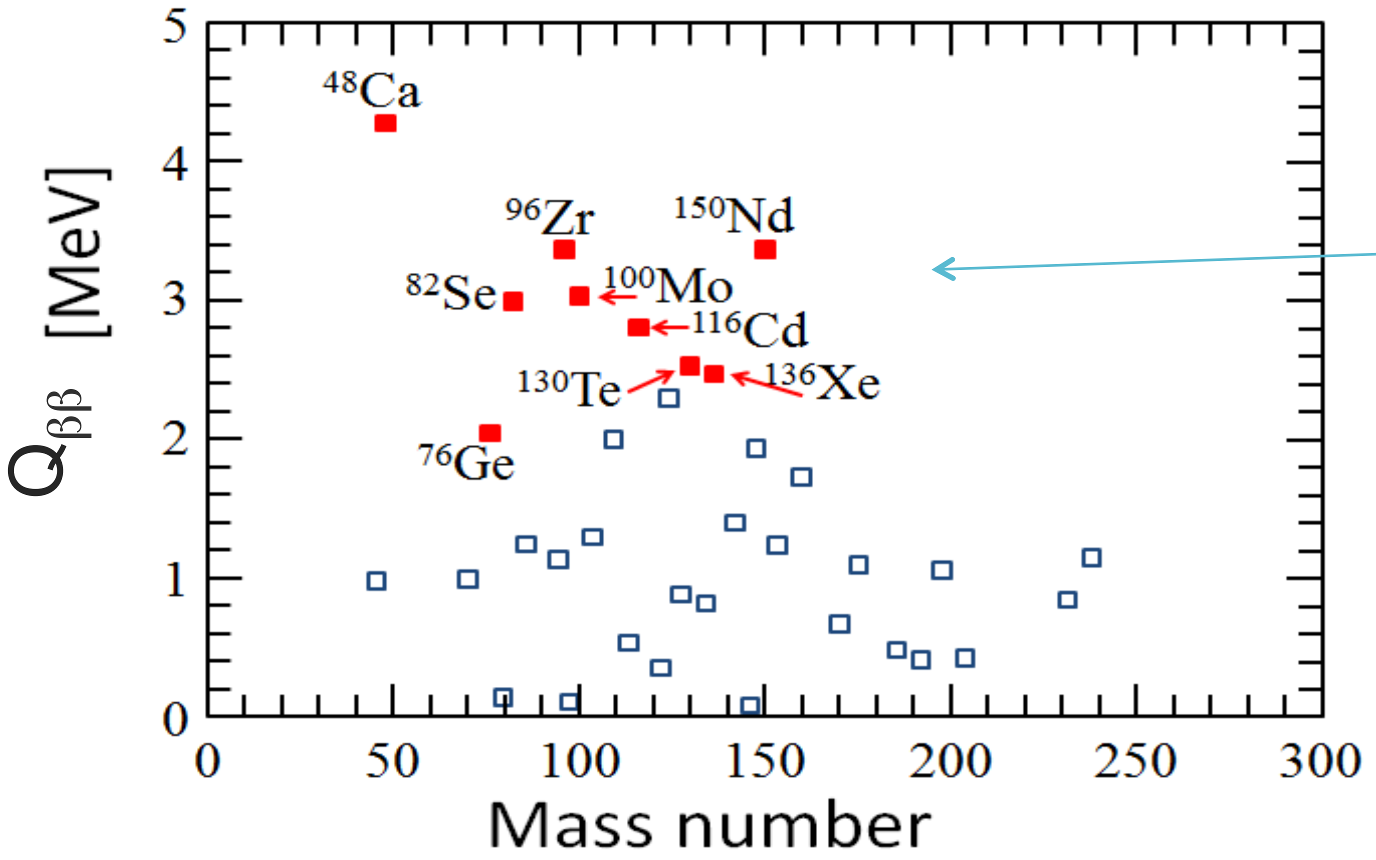
Experimental signatures based on the
Sum energy spectrum of the two electrons

Kinetic energy available for the products → **$Q_{\beta\beta}$ ~ 2-3 MeV**
for the most promising candidates



Which and how many nuclei?

Double Beta Decay is the main decay channel for 35 nuclei, with a large span of $\mathbf{Q_{\beta\beta}}$



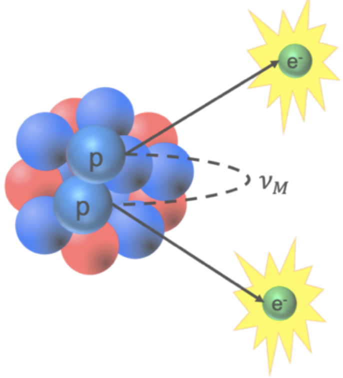
The magnificent 9: the most promising candidates

High $Q_{\beta\beta}$

Why Neutrinoless Double Beta Decay is important

Most of theories and models beyond the Standard Model imply neutrinoless double beta decay

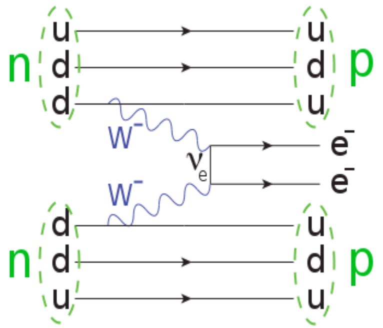
- Majorana nature of neutrino (irrespectively of the mechanism)
- See-saw mechanism ⇒ naturalness of small neutrino masses
- Leptogenesis and matter-antimatter asymmetry in the Universe
- Neutrino mass scale and hierarchy



Minimal straightforward extension of the Standard Model
to accommodate neutrino masses

Mass mechanism

$0\nu2\beta$ is mediated by
light massive Majorana neutrinos
(exactly those which oscillate)



Metric to compare experiments and technologies

A pletora of other more exotic mechanisms:
Sterile ν, LNV,…

Not necessarily neutrino physics

Rate in case of mass mechanism

how **0ν-DBD** is connected to **neutrino mixing matrix** and **masses**
in case of process induced by light ν exchange (**mass mechanism**)

Neutrinoless Double Beta Decay **rate**

Phase Space (calculable)

Axial vector coupling constant

Nuclear matrix elements

Effective **Majorana mass**

$$1/\tau = G(Q,Z)\, g_A^4\, |M_{nucl}|^2 \langle M_{\beta\beta} \rangle^2$$

what the experimentalists try to measure

what the nuclear theorists try to calculate

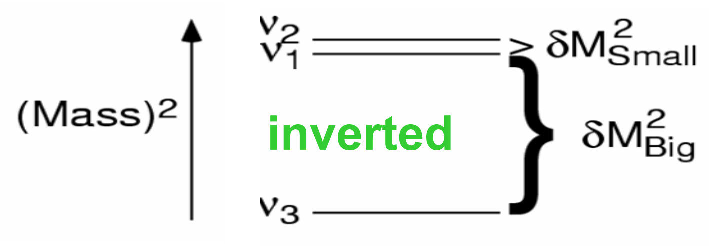
parameter containing neutrino physics: **Effective Majorana mass**

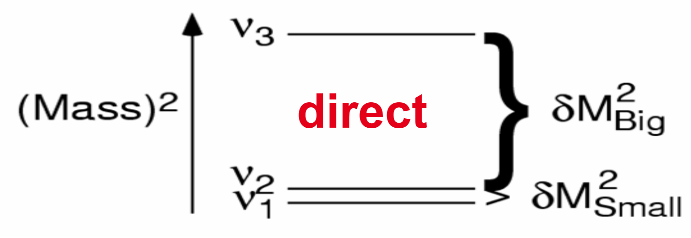
Majorana phases

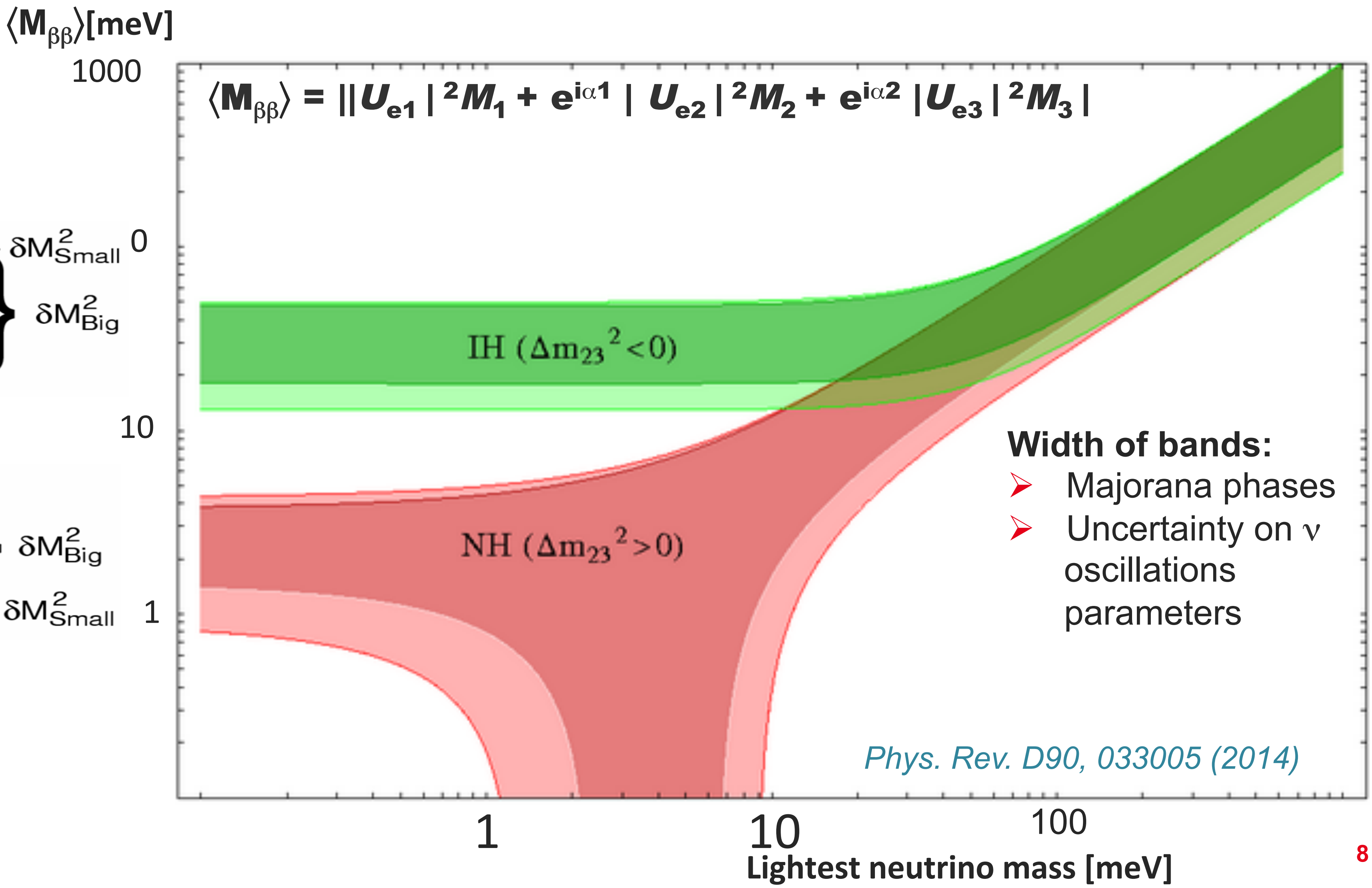
$$\langle M_{\beta\beta} \rangle = \left| |U_{e1}|^2 M_1 + e^{i\alpha_1} |U_{e2}|^2 M_2 + e^{i\alpha_2} |U_{e3}|^2 M_3 \right|$$

The effective Majorana mass

A reference plot



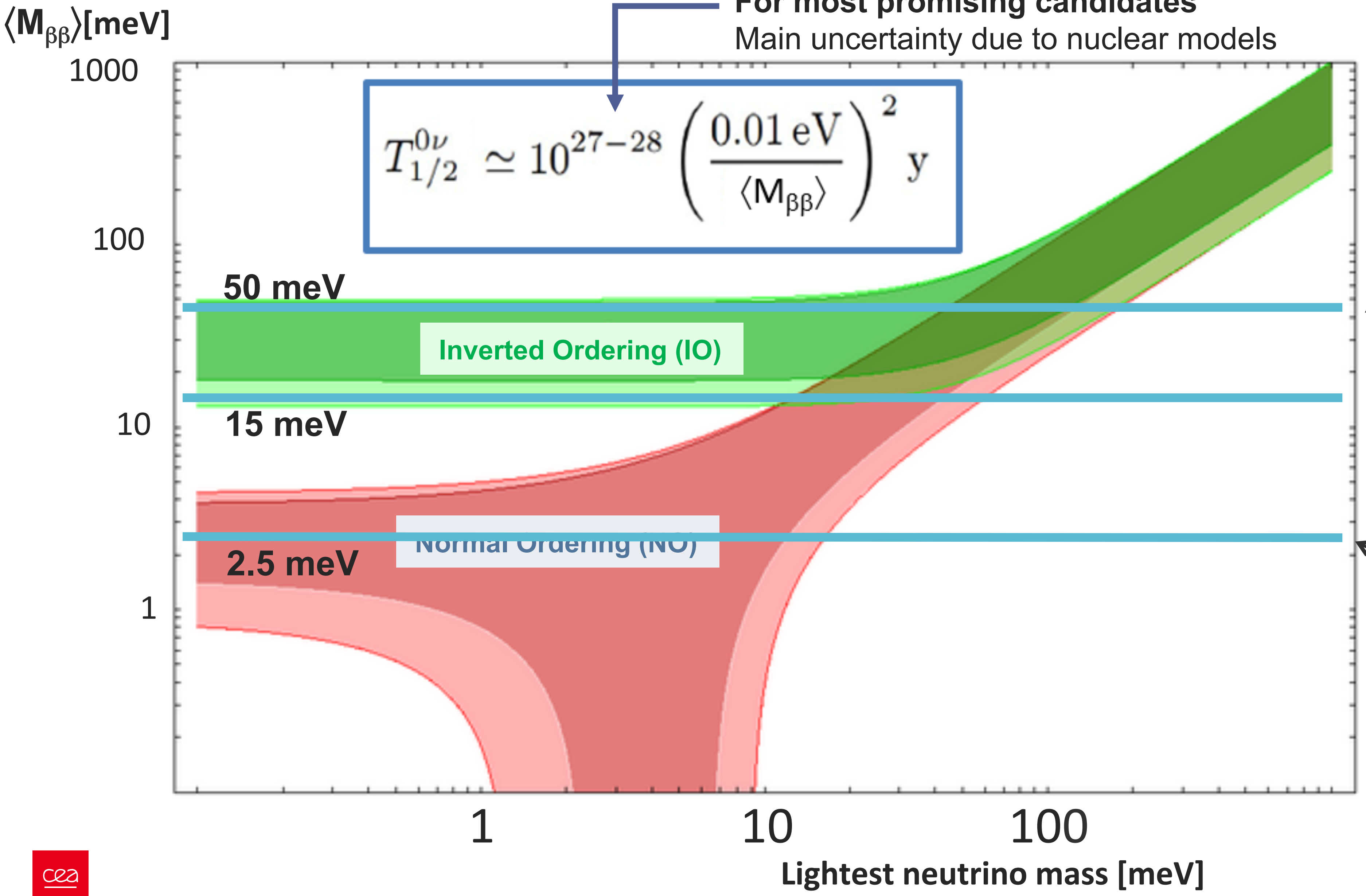




Experimental challenge

For most promising candidates
Main uncertainty due to nuclear models

$$T^{0\nu}_{1/2} \simeq 10^{27-28} \left(\frac{0.01\,\mathrm{eV}}{\langle M_{\beta\beta} \rangle} \right)^2 \mathrm{y}$$

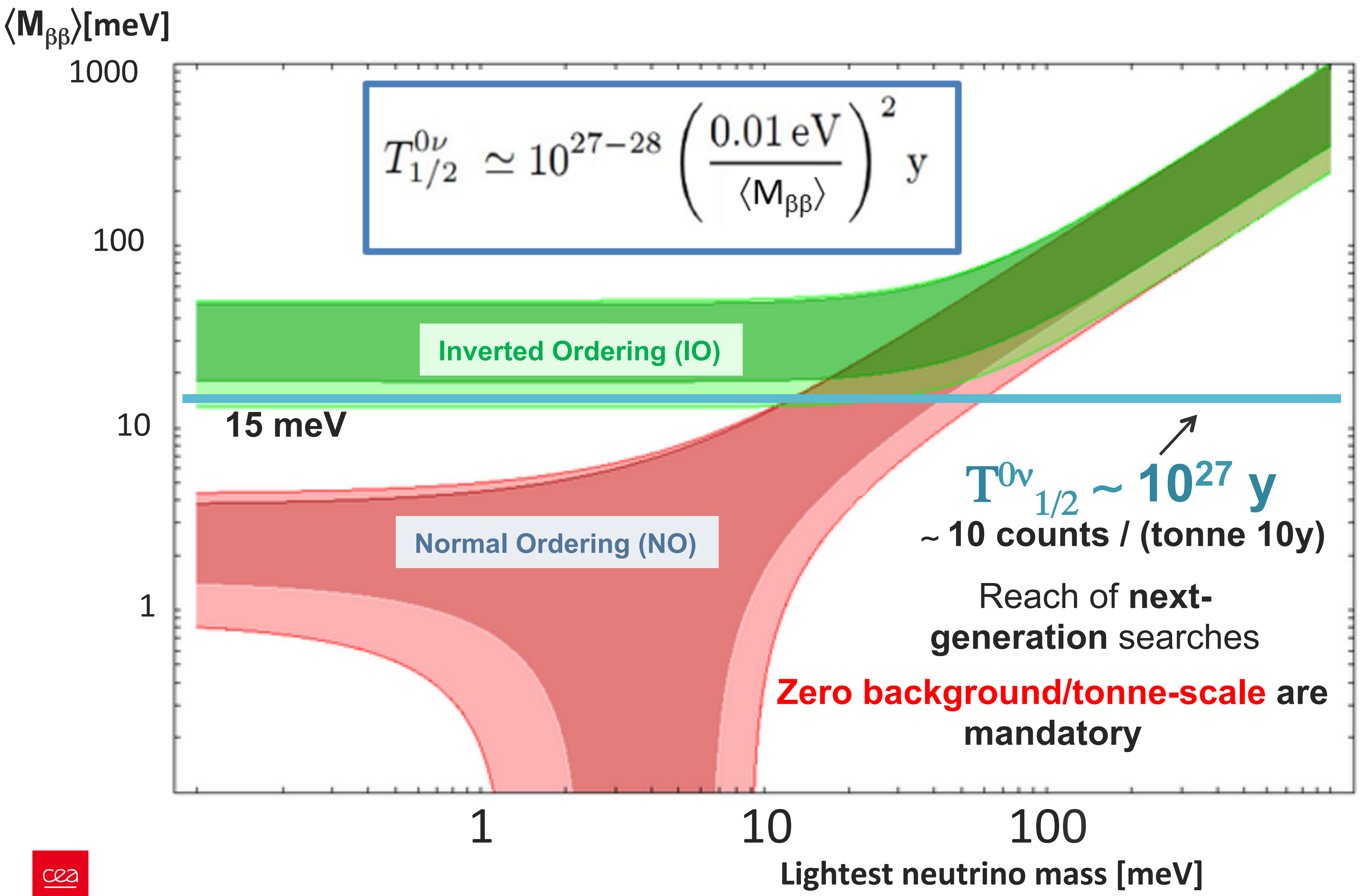


$T^{0\nu}_{1/2} \sim 10^{26}$ y
~ 10 counts / (tonne y)
Reach of the **current** searches

$T^{0\nu}_{1/2} \sim 10^{27}$ y
~ 10 counts / (tonne 10y)
Reach of **next-generation** searches

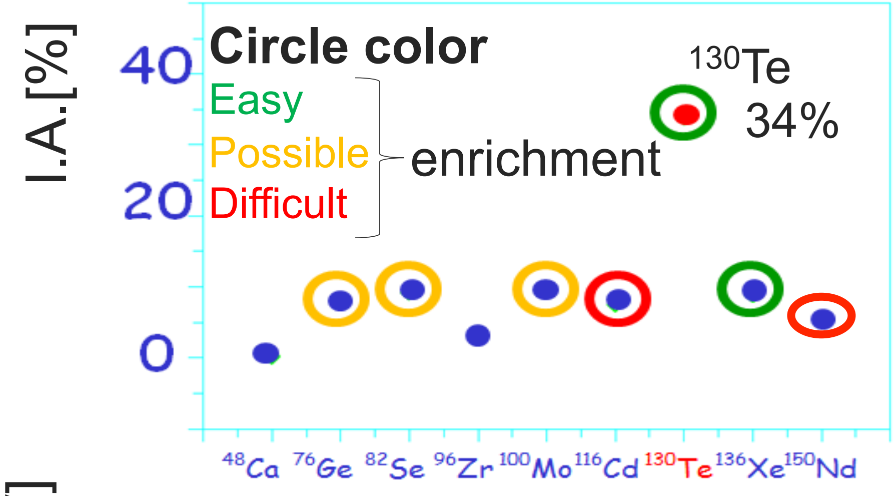
$T^{0\nu}_{1/2} \sim 10^{29}$ y
~ 0.1 counts / (tonne 10y)
Next-to-next generation

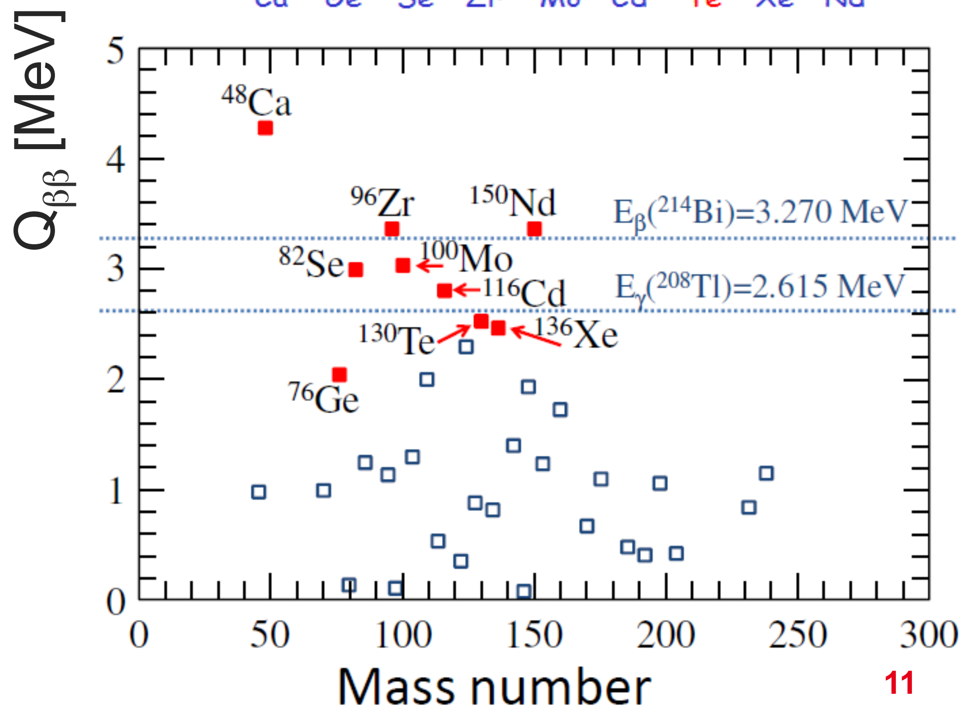
Next generation



Factors guiding isotope selection

- **High isotopic abundance** (I.A.) and/or **easy enrichment**
- **High $Q_{\beta\beta}$**
  - Larger phase space: $G(Q,Z) \propto Q^5$
  - Easier background control
- Compatibility with a beneficial **detection technique**
  - **High energy resolution**
  - **Background identification**
  - **Efficiency and scalability**



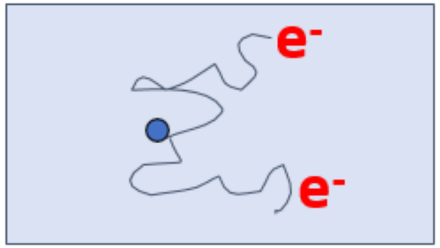


General features for 0νββ searches

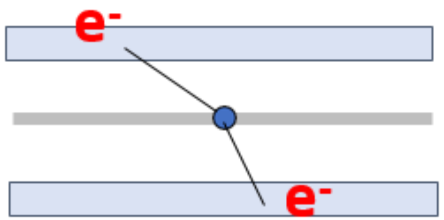
Requests for the source

① **Large source** → tonne scale → > 10^{27} nuclei

② **Maximize efficiency**
→ The option in which the source is separated from the detector is abandoned for next-generation experiments



Source ⊆ Detector



Source ⊈ Detector

However, this option may be interesting in case of discovery to investigate the mechanism of 0νββ

SuperNEMO demonstrator
Modane

Requests for the background

Generic measures as underground operation, shielding (passive and active), radiopurity of materials, vetos are common to 0νββ and other rare event search

Specific desirable features for 0νββ

- High energy resolution
- Particle identification
- Tracking / Event topology
- Multi-site vs. single-site events
- Surface vs. bulk events
- Fiducial volume / Active shielding
- Final-state nucleus identification

Currently competing technologies / experiments

① **Source dilution in a liquid scintillator**

- Re-use of existing infrastructures
- Large amount of isotopes (multi-ton)
- Isotope dilution (a few %)
- Energy resolution ~ 10 % FWHM
- Rough space resolution

KamLAND-Zen (^{136}Xe)
(leading experiment)

SNO+ (^{130}Te)

② **TPCs**

- Large amount of isotopes (multi-ton)
- Full isotope concentration
- Energy resolution ~ 1 % - 2 % FWHM
- Event topology

NEXT
EXO-200
nEXO
} **(^{136}Xe)**

③ **Semiconductor detectors**

④ **Bolometers**

- Crystal array (~1 ton scale in total)
- (Almost) full isotope concentration
- Energy resolution ~ 0.1 % - 0.2 % FWHM
- Particle identification
- Pulse shape discrimination

GERDA
MAJORANA
LEGEND
} **(^{76}Ge)**

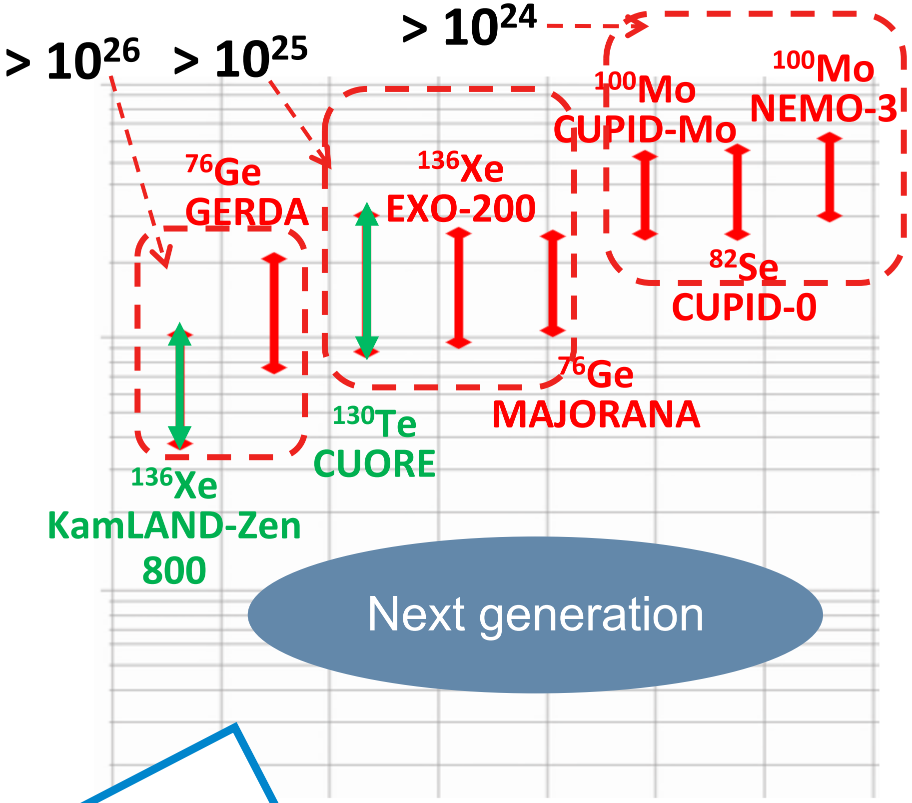
CUORE (^{130}Te)

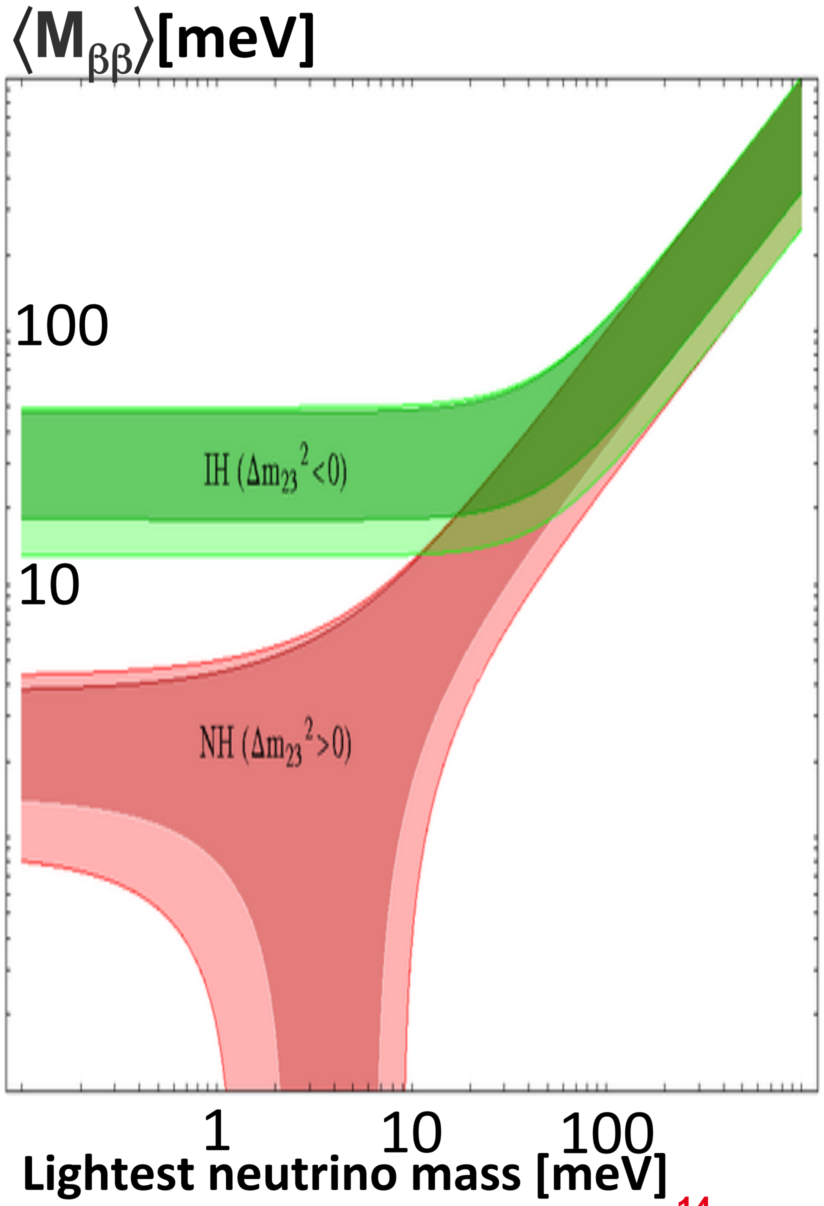
CUPID
AMoRE
} **(^{100}Mo)**

0νββ: status and prospects

Current generation

(final sensitivity for recently concluded - running - on- commissioning projects)





KamLAND-Zen 400/800 - $T_{1/2} > 2.3\times10^{26}$ y

GERDA - $T_{1/2} > 1.8\times10^{26}$ y

EXO-200 - $T_{1/2} > 3.5\times10^{25}$ y

MAJORANA dem. - $T_{1/2} > 8.3\times10^{25}$ y

CUORE - $T_{1/2} > 2.2\times10^{25}$ y

CUPID-0 - $T_{1/2} > 4.6\times10^{24}$ y

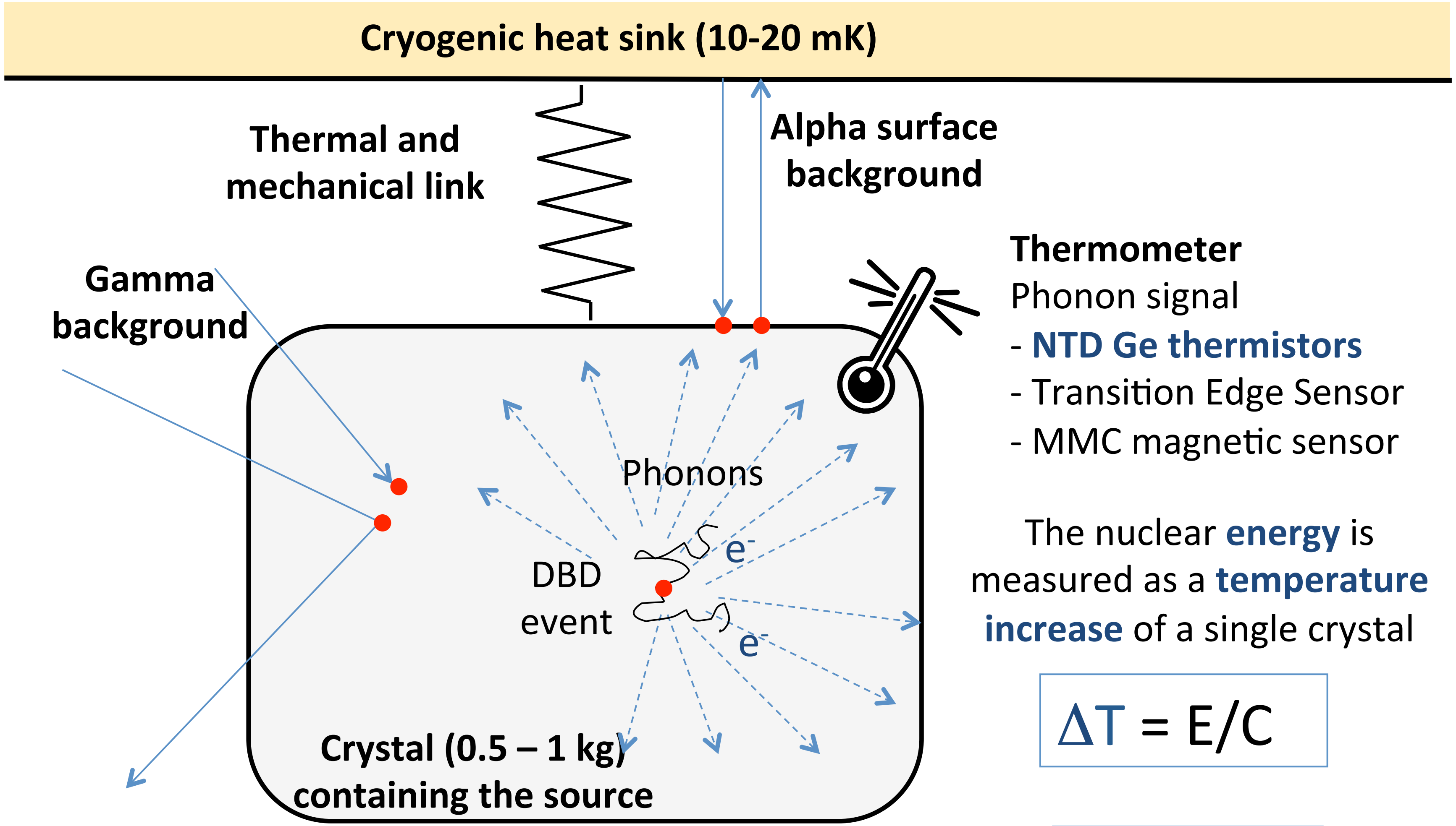
CUPID-Mo - $T_{1/2} > 1.8\times10^{24}$ y

NEMO-3 - $T_{1/2} > 1.1\times10^{24}$ y

$T_{1/2} > 10^{24}$ y 90% C.I.
restricted club

All experiments stopped except **KamLAMD-Zen 800** and **CUORE**

The bolometric technique



Thermometer
Phonon signal
- **NTD Ge thermistors**
- Transition Edge Sensor
- MMC magnetic sensor

The nuclear **energy** is measured as a **temperature increase** of a single crystal

$$\Delta T = E/C$$

Thanks to the thermistor $\Delta T \Rightarrow \Delta V$

Advantages

- High energy resolution (~0.5 % @ $Q_{\beta\beta}$)
- Wide choice of detector materials (dielectric diamagnetic crystals) ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te
- Crystals can be extremely radiopure
- Big detector masses achievable through large arrays
- PID or surface/bulk event rejection with sophisticated detector technologies

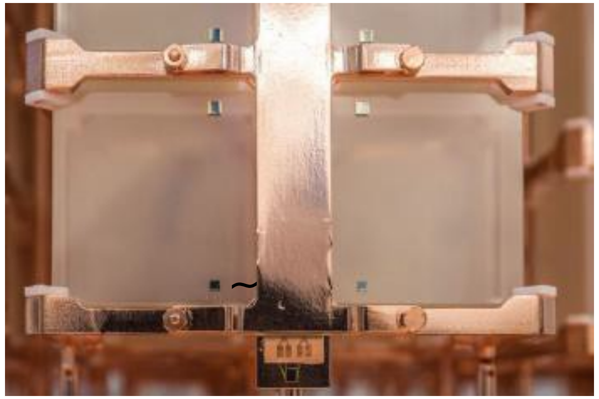
Typical signal sizes: **0.1 mK / MeV**, converted to about **0.1-0.5 mV / MeV**

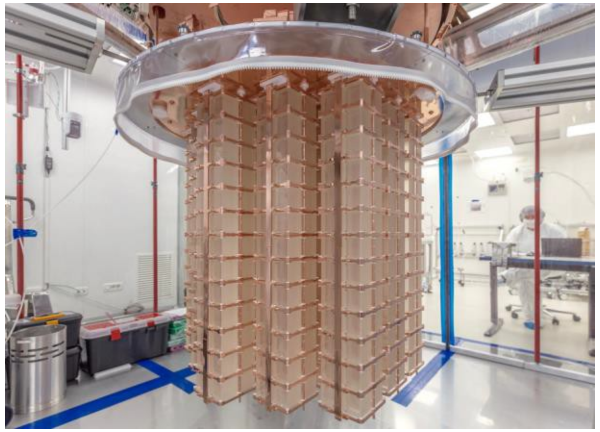
CUORE in a nutshell

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

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**)
- Background according to expectations
- **$1.30(3)\times10^{-2}$ counts/(keV·kg·y)**
- Energy resolution at $Q_{\beta\beta}$ close to expectations: **7.26 keV FHWM**





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

- Exposure for the current limit: **2023 kg·y** **(> 2 ton·y collected!!)**
- Current limit ($T_{1/2}^{0\nu2\beta}$) : **> 3.3×10^{25} y** *Preliminary*
  → $\langle M_{\beta\beta}\rangle$ < 75 – 255 meV
- 5 y projected $T_{1/2}$ sensitivity: ~**9×10^{25} y**
  → $\langle M_{\beta\beta}\rangle$ < 50 – 130 meV

CUORE is not background free

→ ~**50 counts/y in the region of interest**, dominated by **surface alpha background**

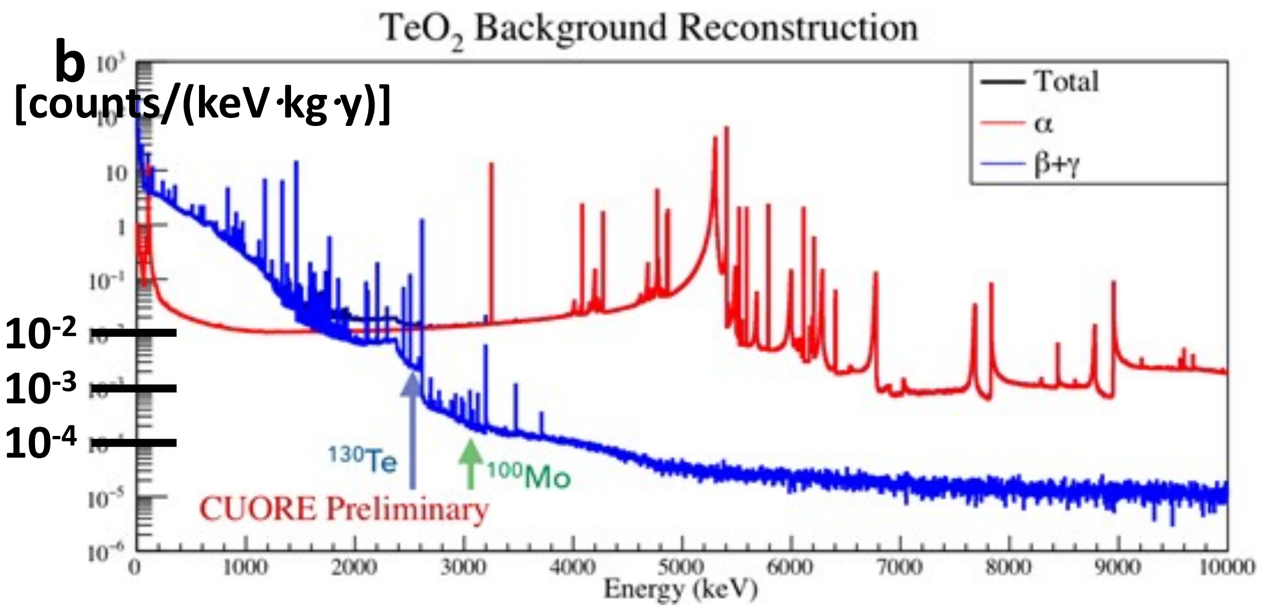
From CUORE to CUPID

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 $0\nu\beta\beta$ experiment exists** and will be available at the end of the CUORE physics program (~2024-2025)

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

CUORE background model



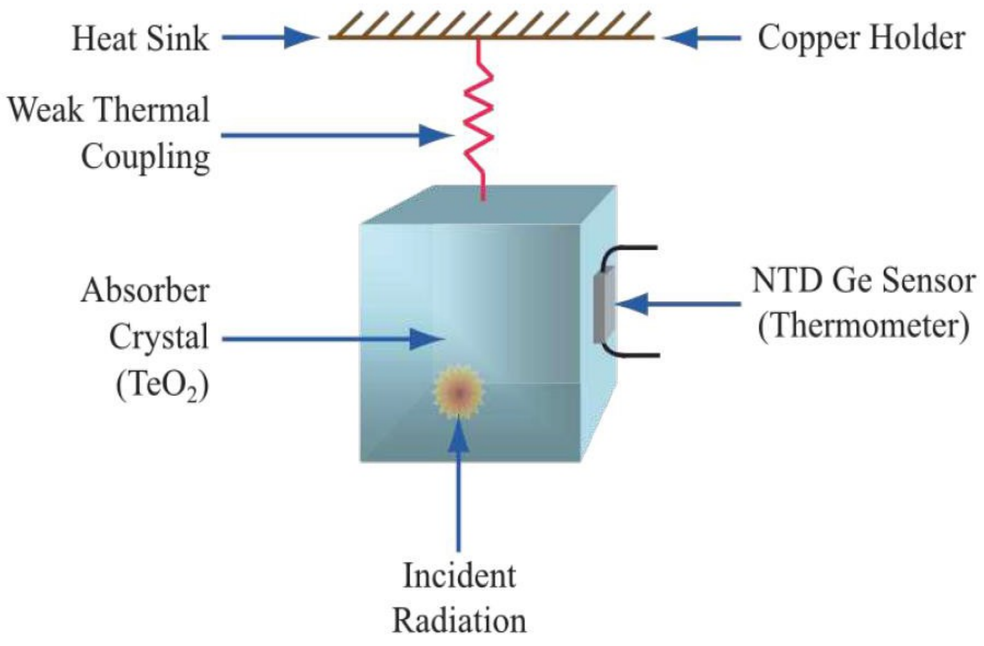
- Reject α background with **scintillating bolometers**
- Mitigate γ background by **moving to ^{100}Mo**

  $Q_{2\beta}$: 2527 keV (^{130}Te) → 3034 keV (^{100}Mo)

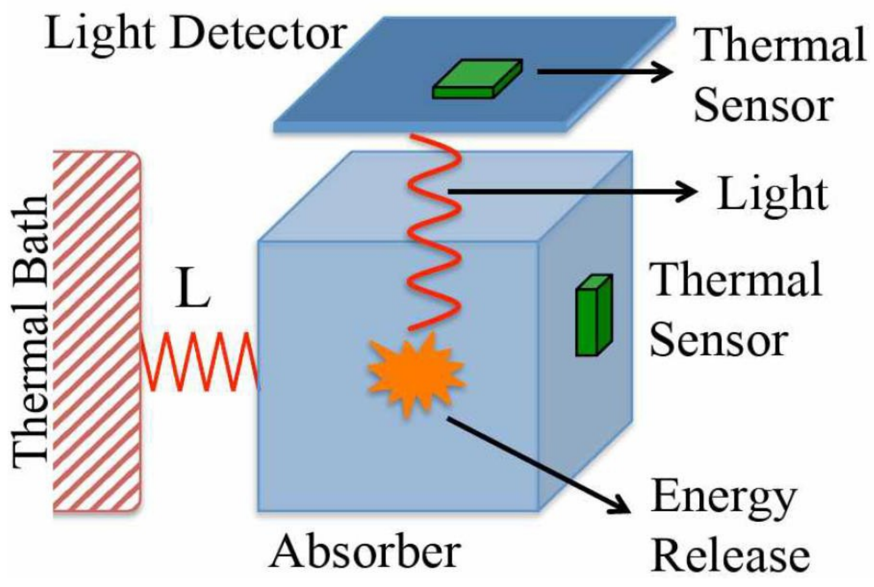
- Increase isotope mass by **enrichment** (natural isotopic abundance: 9.7%)

CUPID rationale

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



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



No PID

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

~~α background~~ ← **PID**

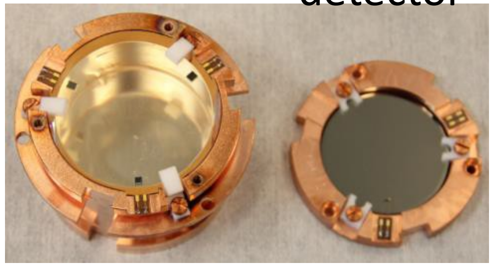
~~γ background~~ ← $Q_{\beta\beta}$ = 3034 keV **> 2615 keV**

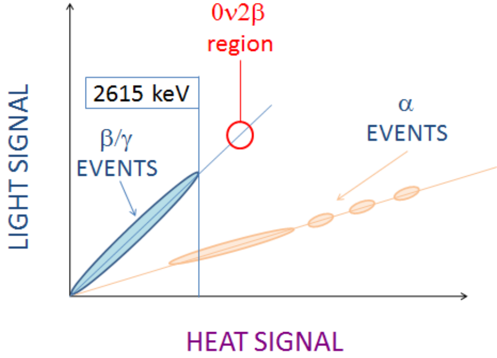
CUPID: choice of the isotope and crystal

Scintillating bolometers

↓

α particle rejection





CUPID-0 – $Zn^{82}Se$ $Q_{\beta\beta}$ = 2998 keV

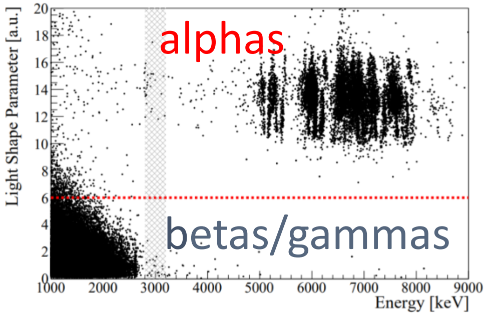
(evolution of **LUCIFER** erc)

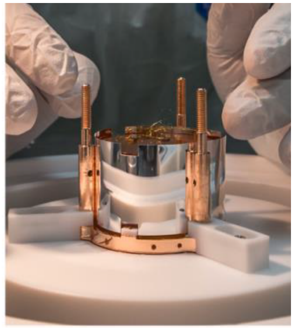
First running demonstrator (2017-2020)

24 crystals (enriched in ^{82}Se) – 5.28 kg ^{82}Se

Best limit on ^{82}Se: $T_{1/2}$ > 4.6×10^{24} y

Energy resolution: ~ **23 keV FWHM**





LNGS – Italy

Useful information for the CUPID background model

Direct proof that α's dominate background above 2.6 MeV

CUPID-Mo – $Li_2{}^{100}MoO_4$ $Q_{\beta\beta}$ = 3034 keV

(evolution of **LUMINEU** ANR)

Physics data taking: April 2019 – June 2020

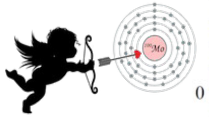
20 crystals (enriched in ^{100}Mo) – 2.34 kg ^{100}Mo

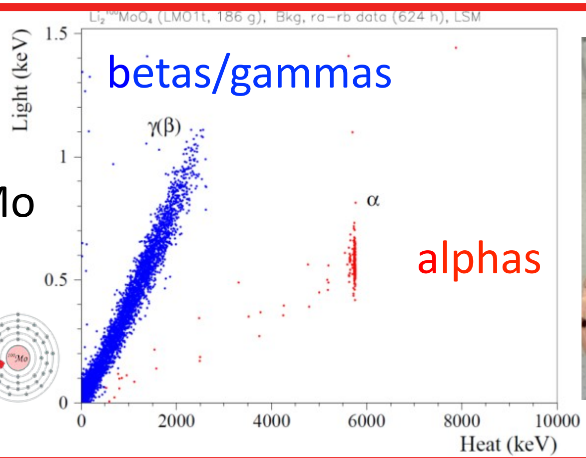
Energy resolution: ~**5-7 keV FWHM**

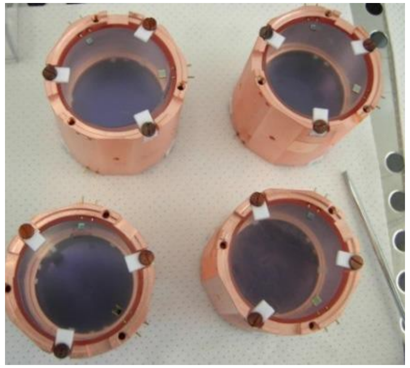
Best limit on ^{100}Mo: $T_{1/2}$ > 1.8×10^{24} y

Full α rejection

Radiopure crystals: U/Th ≤ 1 μBq/kg







LSM – France

Conceived and built by IJCLab/IRFU

Zero background in ROI

Essential CUPID requirements met

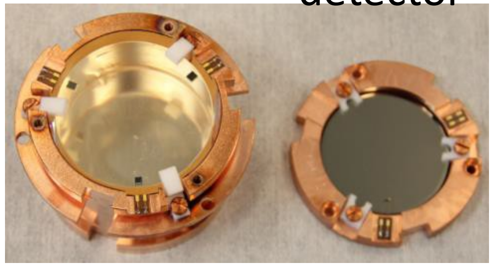
CUPID: choice of the isotope and crystal

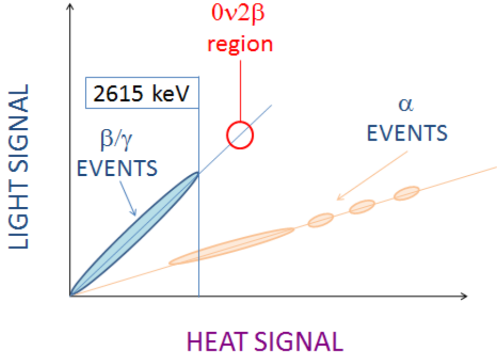
Scintillating bolometers

↓

α particle rejection

Main crystal   Light detector





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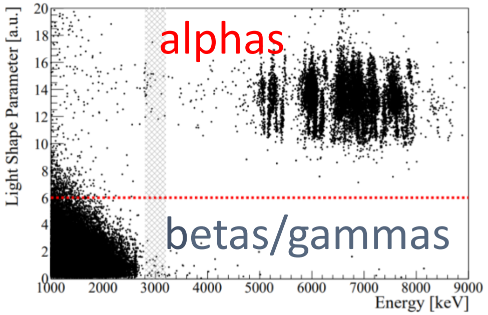
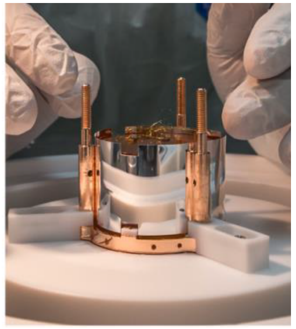
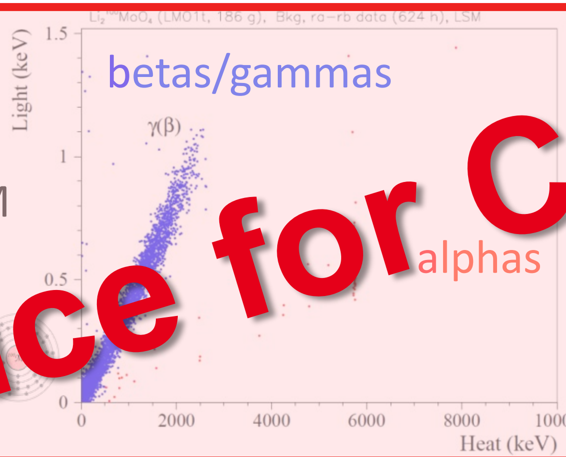
Energy resolution: ~ **23 keV FWHM**





LNGS – Italy
Useful information for the CUPID background model
Direct proof that α's dominate background above 2.6 MeV

CUPID-Mo – $Li_2{}^{100}MoO_4$ $Q_{\beta\beta}$= 3034 keV
(evolution of **LUMINEU** ANR)
Physics data taking: April 2019 – June 2020
20 crystals (enriched in ^{100}Mo) – 2.34 kg ^{100}M
Energy resolution: ~**5-7 keV FWHM**
Best limit on ^{100}Mo: $T_{1/2} > 1.8\times10^{24}$ y
Full α rejection
Radiopure crystals: U/Th ≤ μBq/kg

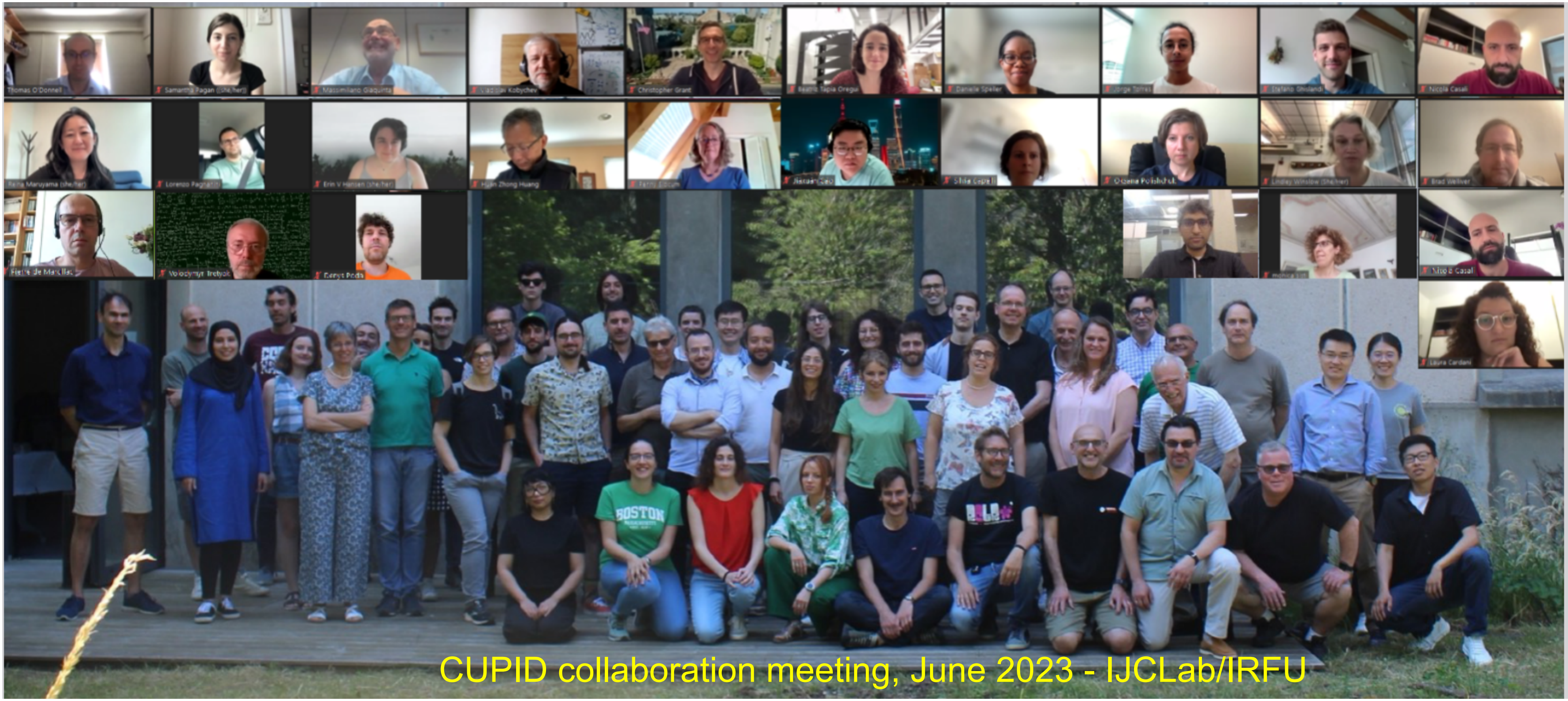


LSM – France
Conceived and built by IJCLab/IRFU
Zero background in ROI
Essential CUPID requirements met

Choice for CUPID

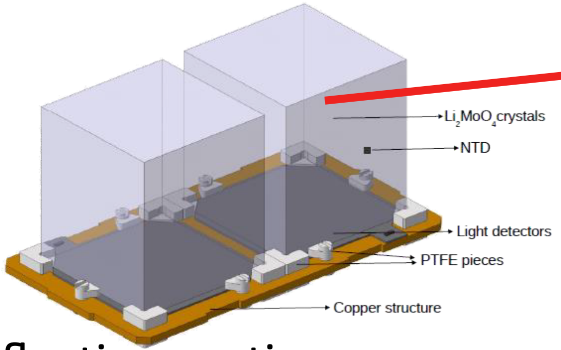
The CUPID collaboration

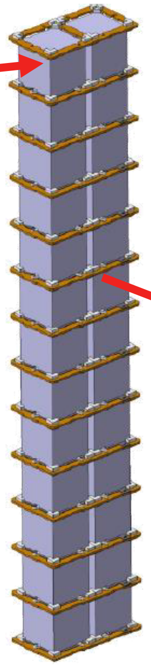
7 countries
~180 members

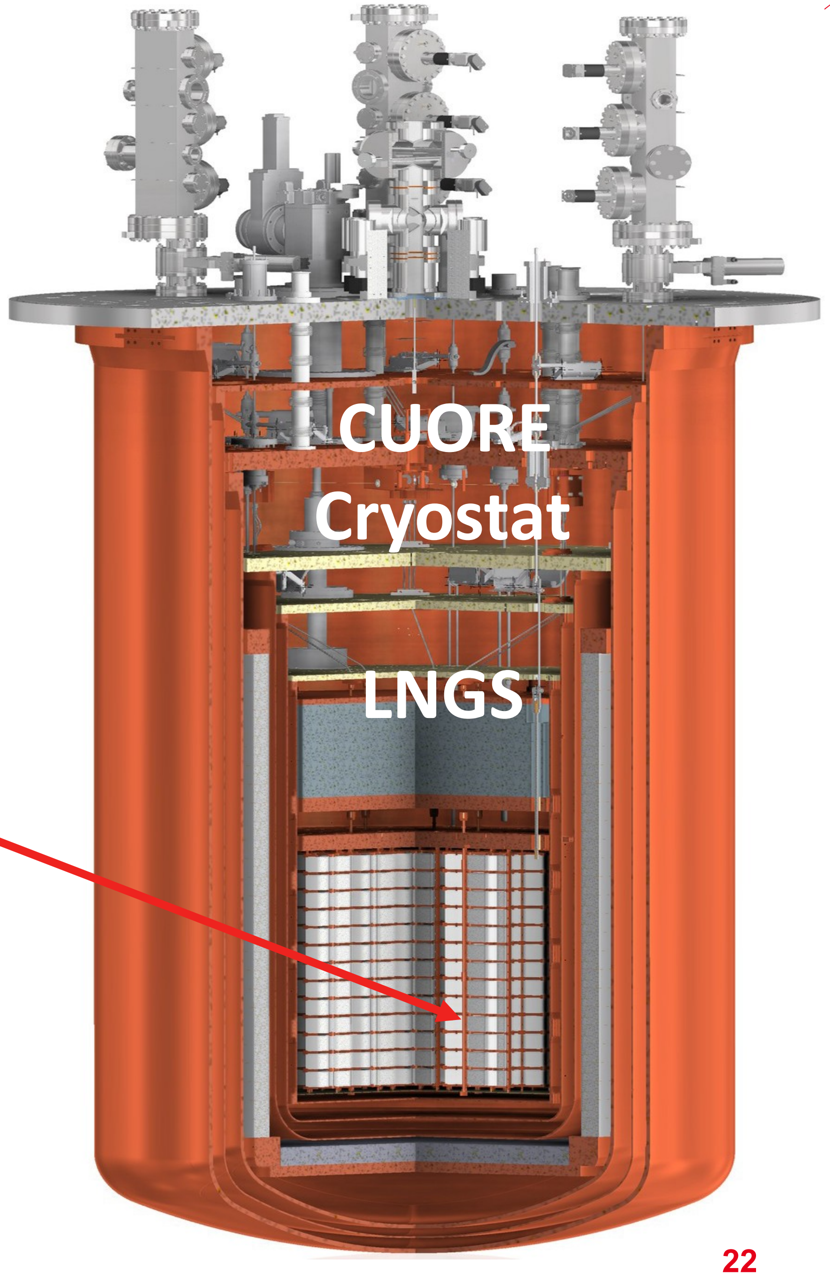


CUPID structure

- Single module:
  - 2 x $Li_2{}^{100}MoO_4$ **45×45x45 mm** – ~ **280 g**
  - 2 x Ge light detectors
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~ 240 kg of ^{100}Mo** with >95% enrichment
- **~ 1.6×10^{27}** ^{100}Mo atoms







Baseline design : Gravity stacked structure, with crystals thermally interconnected

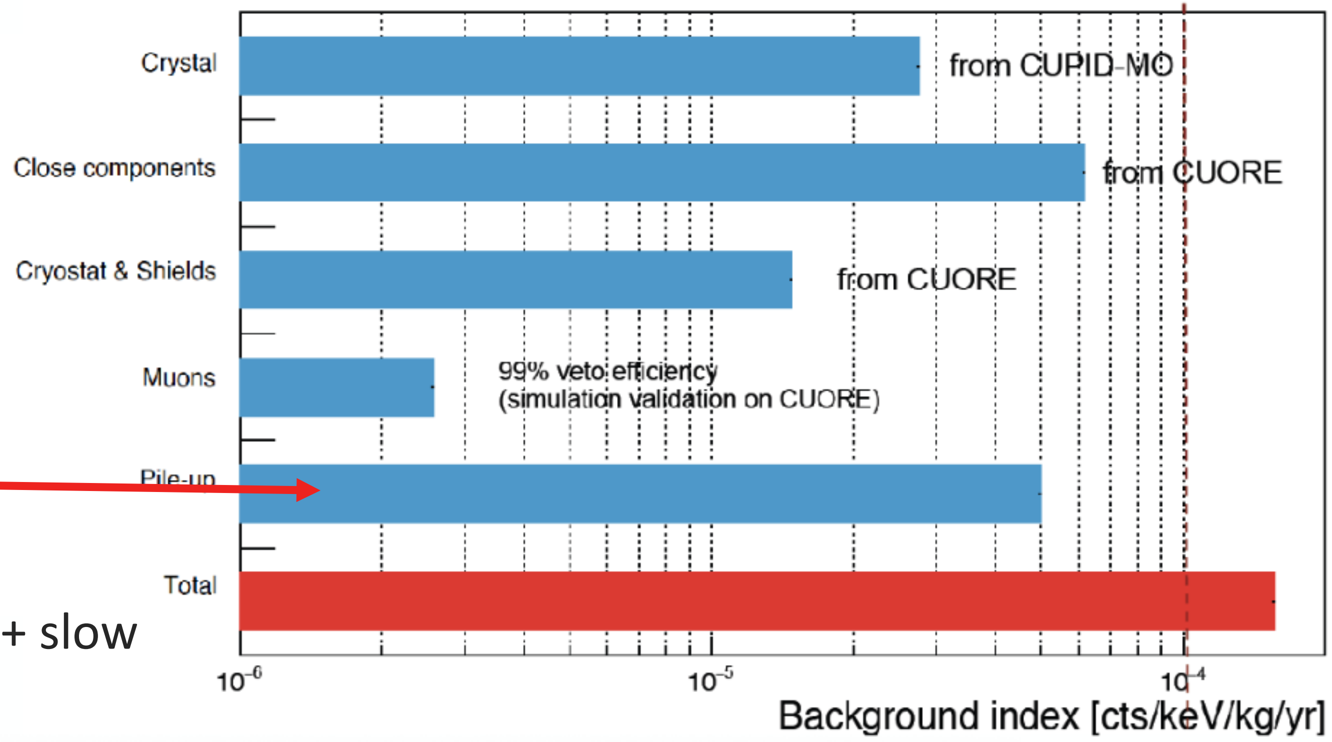
Ge light detectors with SiO antireflective coating (each crystal has top and bottom LD)
No reflective foil

Muon veto for muon induced background suppression

CUPID goals

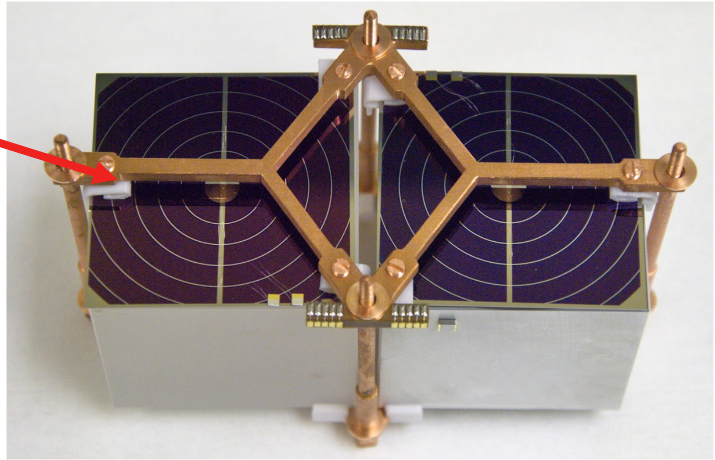
- Energy resolution: 5 keV FWHM
- Light Yield: 0.3 keV/MeV
- LD: σ baseline ≤100 eV for PID
- Background index : 10^{-4} ckky (counts/keV/kg/y)

Data driven background model



Critical background component:
random coincidence of $2\nu\beta\beta$ events
(^{100}Mo fastest $2\nu\beta\beta$ emitter: $T_{1/2} = 7.1\times10^{18}$ y + slow bolometric response)

Use upgraded light detectors to reject pile-up by PSD
→ Neganov Trofimov Luke (NTL) effect
CUPID adopts as a baseline the BINGO technology for light detectors developed at IJCLab/IRFU

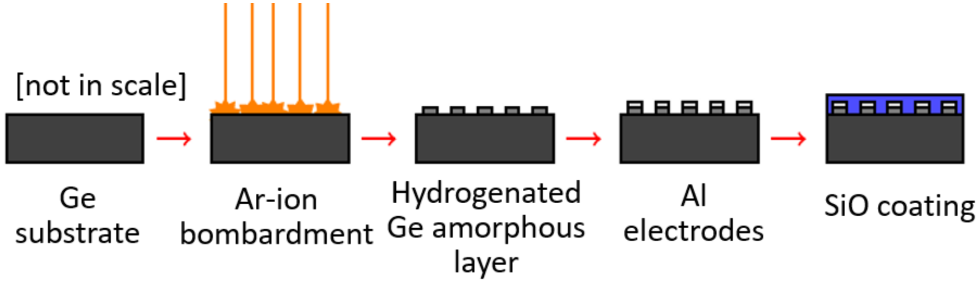


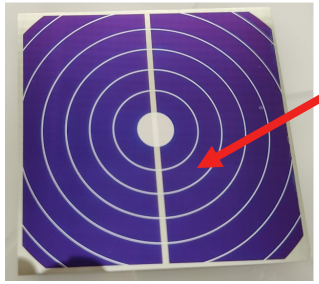
Successful test in the CROSS set-up at Canfranc

CUPID light detectors and CRYOVAP

NTL light detectors are conceived, optimized, fabricated and tested thanks to a IJCLab/IRFU collaboration

Thanks to **SESAME 2023** **(Ile de France)**, funding is secured for a piece of equipement for massive CUPID light detector construction → **large evaporation chamber for coating and electrode fabrication on Ge wafers**





Electrodes establish an electric field in the Ge wafer which enhances the S/N ratio in light detectors by a factor 10-20, allowing for pile-up discrimination

- CRYOVAP will be a facility with unique features to develop **bolometric low-temperature detectors incorporating thin-film technology**
- CRYOVAP has a rich research program and is open to external users for multiple applications

CUPID sensitivity

Energy resolution: **5 keV FWHM**

Background index: **1×10^{-4} counts/(keV·kg·y)**

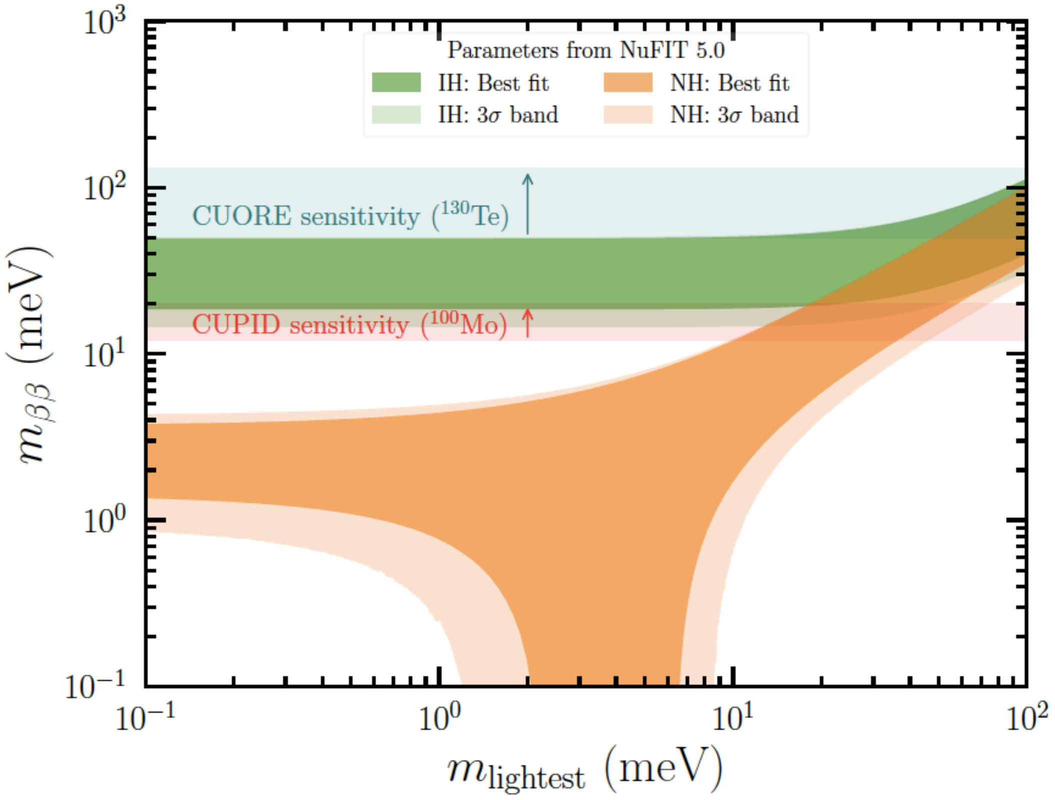
Livetime: **10 y**

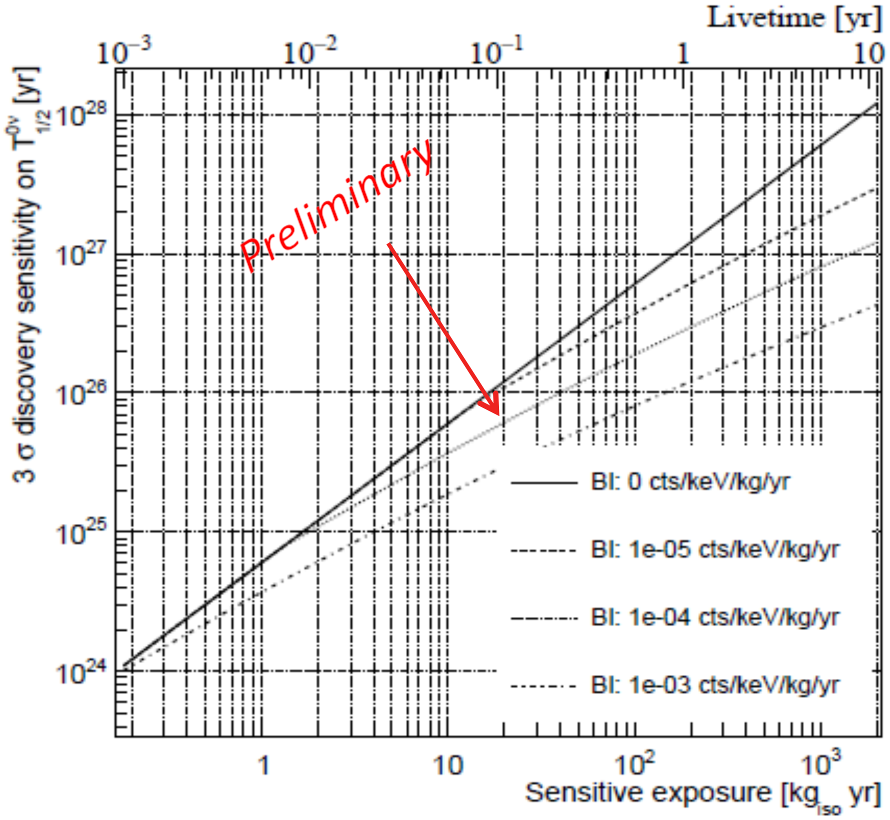
Half-life exclusion sensitivity

1.4×10^{27} y – $m_{\beta\beta} < 10\text{-}17$ meV

Half-life 3σ discovery sensitivity

1×10^{27} y – $m_{\beta\beta} < 12\text{-}20$ meV





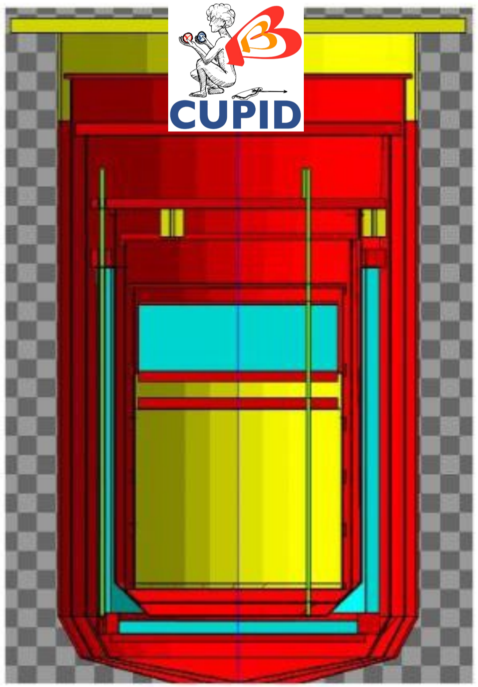
CUPID physics reach

10 y discovery sensitivity:
1.1×10^{27} y

$\langle M_{\beta\beta} \rangle < 12 - 20$ meV

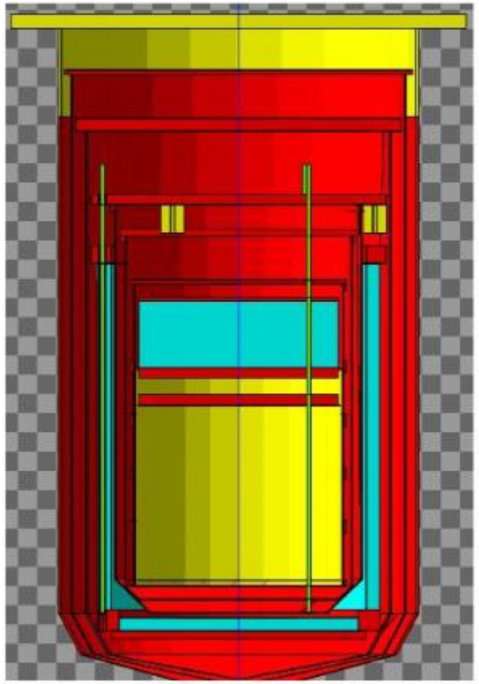
CUPID technology is expandable and can deeply explore the Normal Ordering region

Technically ready
CUPID Baseline



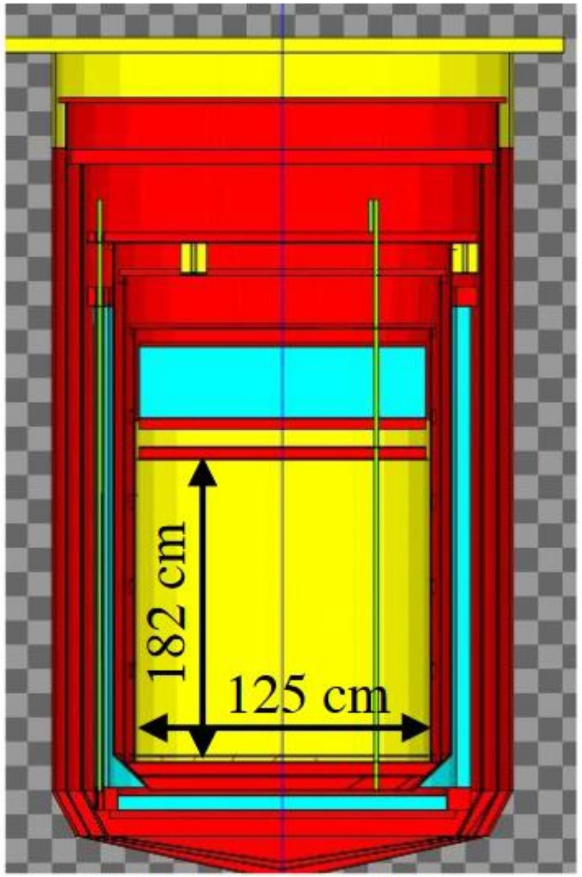
240 kg of ^{100}Mo
CUORE cryostat
Bkg 1×10^{-4} ckky
Excl. sensitivity:
$T_{1/2} > 1.4 \times 10^{27}$ y

CUPID-reach



240 kg of ^{100}Mo
CUORE cryostat
Bkg 2×10^{-5} ckky
Excl. sensitivity:
$T_{1/2} > 2.3 \times 10^{27}$ y

CUPID-1T



1000 kg of ^{100}Mo
New cryostat
Bkg 5×10^{-6} ckky
Excl. sensitivity:
$T_{1/2} > 9.2 \times 10^{27}$ y

0νββ: prospects and major CUPID role

Current generation

(final sensitivity for recently concluded - running - on- commissioning projects)

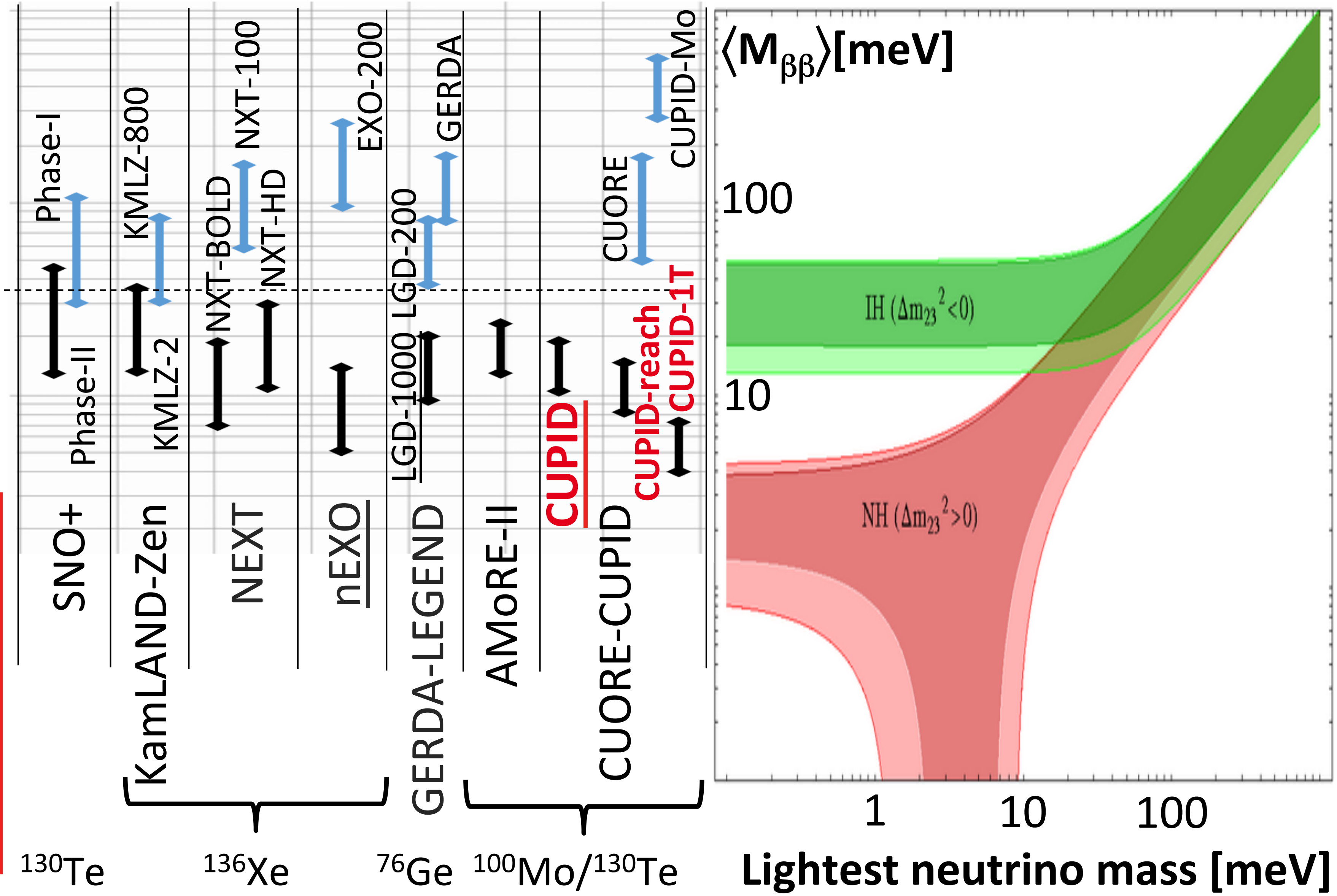
Next generation

(projects to be started during the next decade)

CUPID, **LEGEND**, **nEXO**
Supported by North-American and European agencies
Under DOE review

APPEC - Sijbrand de Jong, Bruxelles, 7/12

Mass & Nature: *APPEC strongly supports the CUPID and LEGEND 1000 double-beta decay experiments selected in the US-European process and endorses the development of NEXT.*



Preparing the next-next generation of bolometric experiments

In case of **no discovery** for next generation experiments
the technological bondaries will have to be pushed further

It is crucial to start to prepare now this eventuality:

- **Larger isotope masses (>1-10 ton**)
  → Increase of the cost

- **Further background reduction required (<10^{-5} ckky)**
  → Need of innovative technologies

This is the goal of BINGO and TINY !

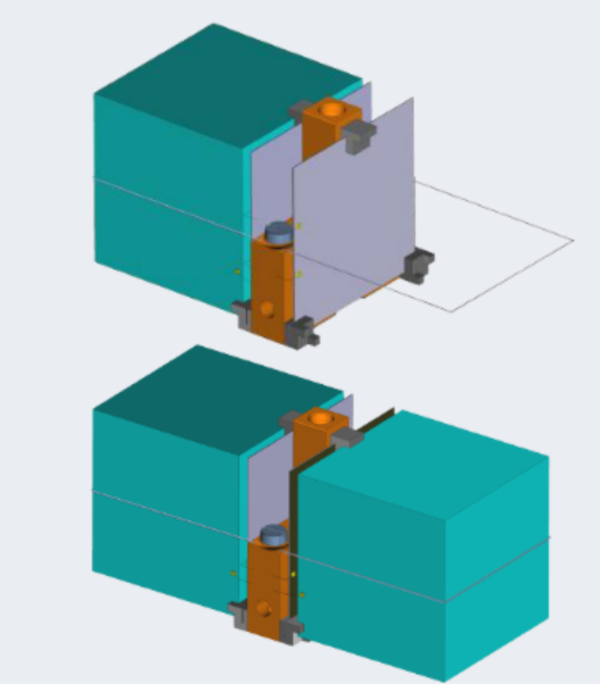
Three innovations to reject background in ββ decay experiments based on Li_2MoO_4 and TeO_2

- **Revolutionary assembly** to reject surface background
- **Enhanced-sensitivity** light detectors (Neganov-Trofimov-Luke)
- **Internal veto** (ultrapure BGO/ $ZnWO_4$ scintillators)

→ mitigate γ background in TeO_2

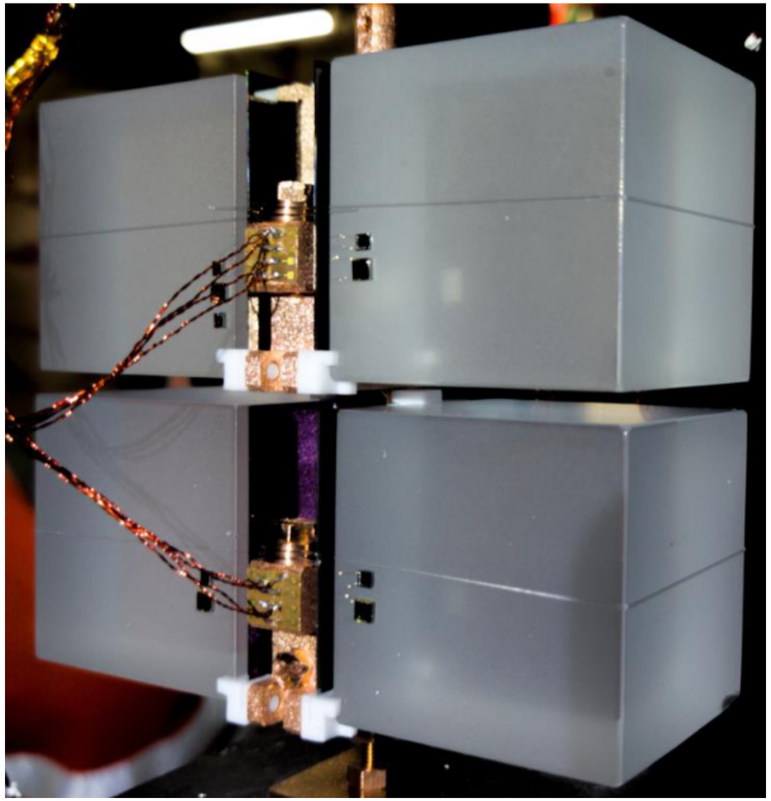
The light detector shields the passive materials

- Less passive materials
- Compact assembly



→ **Mini-BINGO demonstrator in LSM**

VETO prototype
BGO scintillators



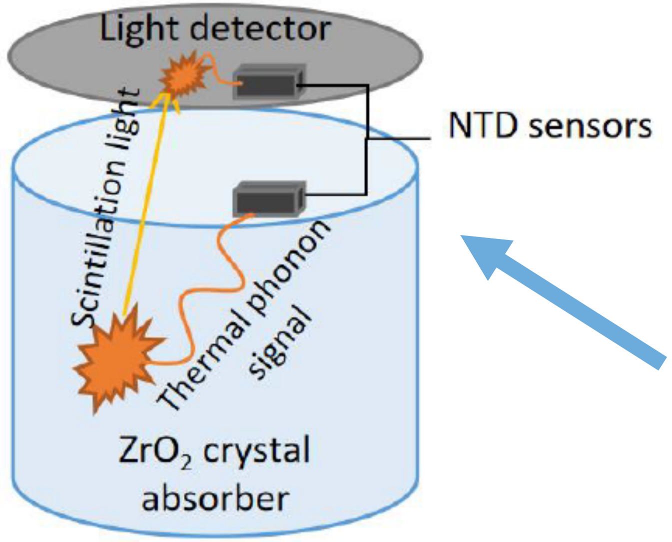
Satisfactory performance of prototypes

TINY

Development of bolometric detectors containing **the most promising ββ isotopes** ^{96}Zr and ^{150}Nd

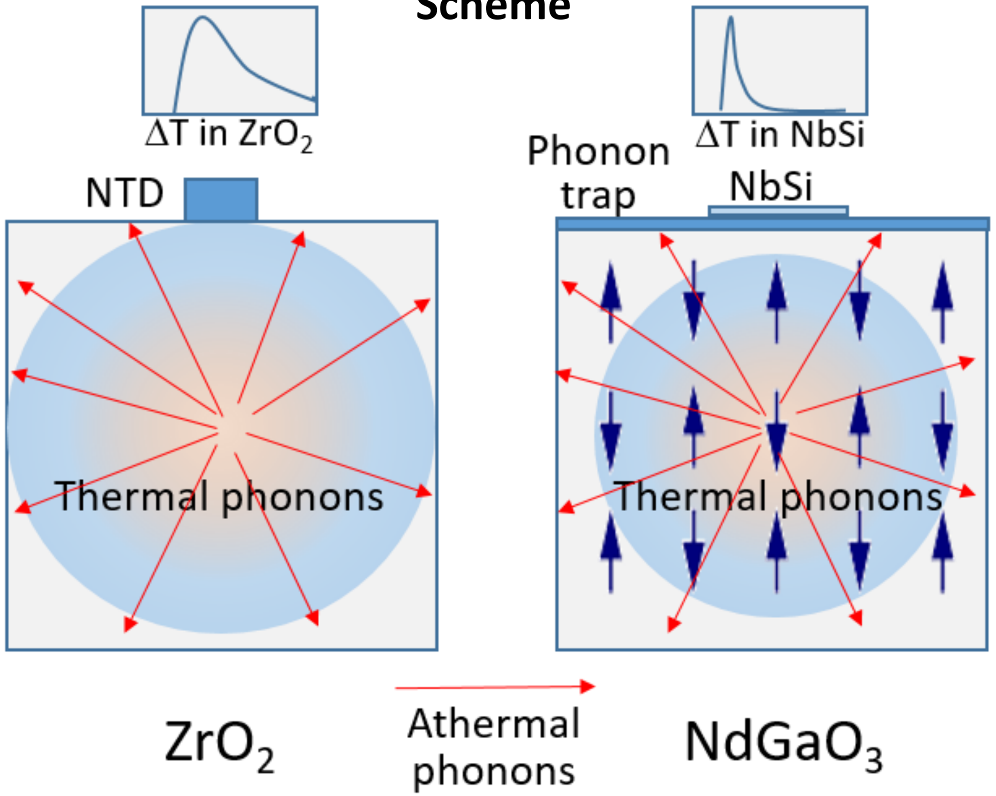
Main challenge in Nd-based compounds: high specific heat from magnetism → detect phonons before thermalization

Implementation



Classical scintillating bolometers with thermal signals

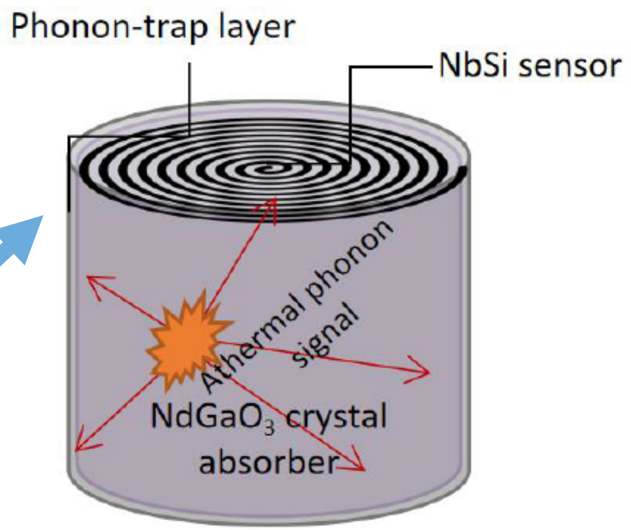
Scheme



Dielectric diamagnetic

Antiferromagnetic order

Implementation



Athermal-phonon bolometer with phonon trap and NbSi high impedance TES

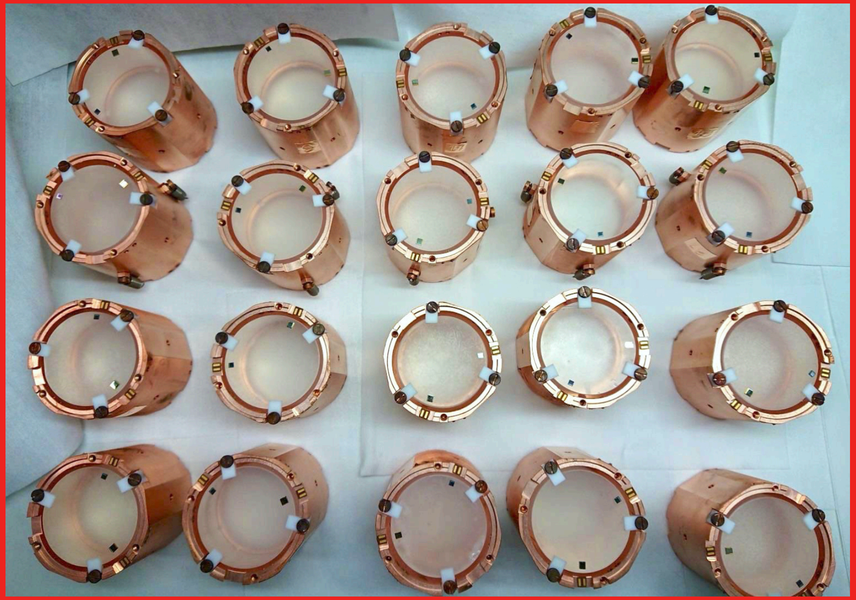
TINY objective: develop a demonstrator with a 2 kg mass detector distributed in a few elements for each isotope

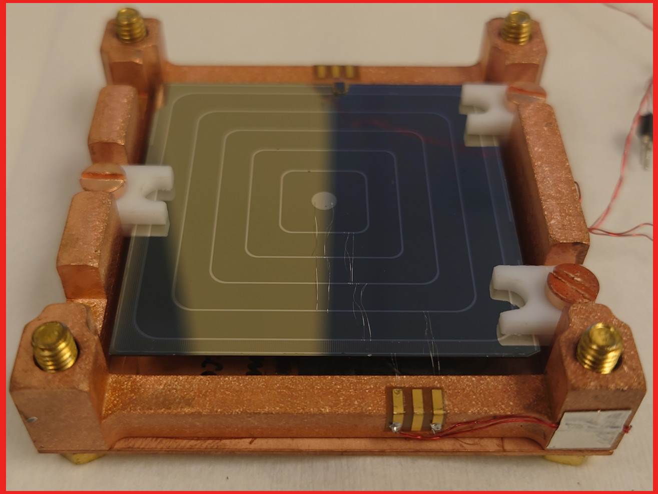
Conclusions

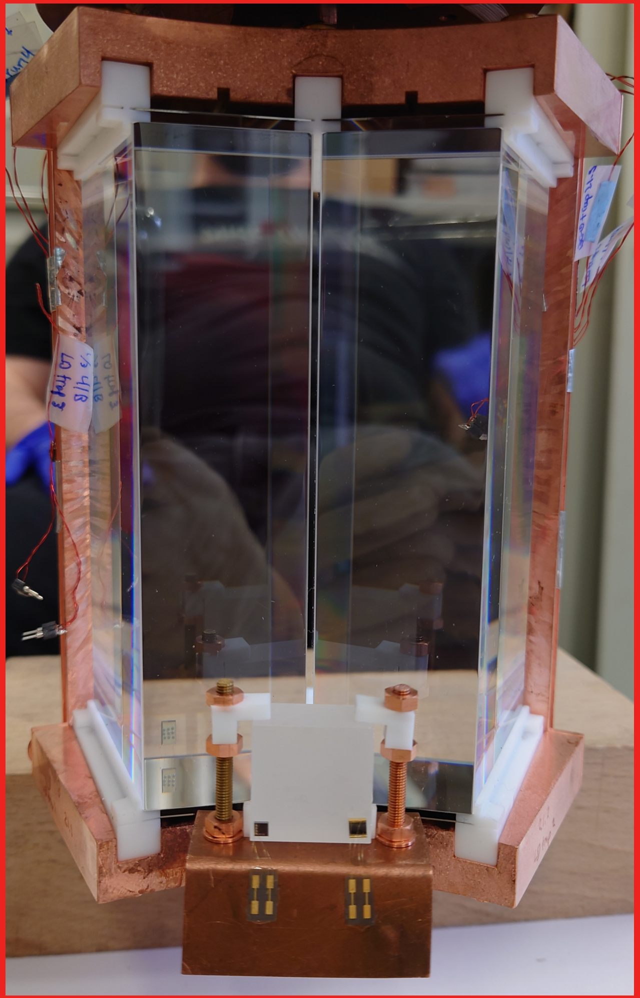
- The discovery of 0νββ decay would dramatically revise our foundational understanding of physics and cosmos
  - Lepton number is not conserved
  - Neutrino is a Majorana fermion – in case of mass mechanism, the absolute neutrino mass scale is fixed
  - There is a potential path for understanding the matter-antimatter asymmetry in the universe, through leptogenesis
  - There is a new mechanism demonstrated for the generation of particle mass
- The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics
- CUPID is one of the three most promising next-generation experiments and has a remarkable discovery potential
- The bolometric technology – implemented in CUPID and in future ambitious projects – promises to play a leading role in next-to-next generation experiments.

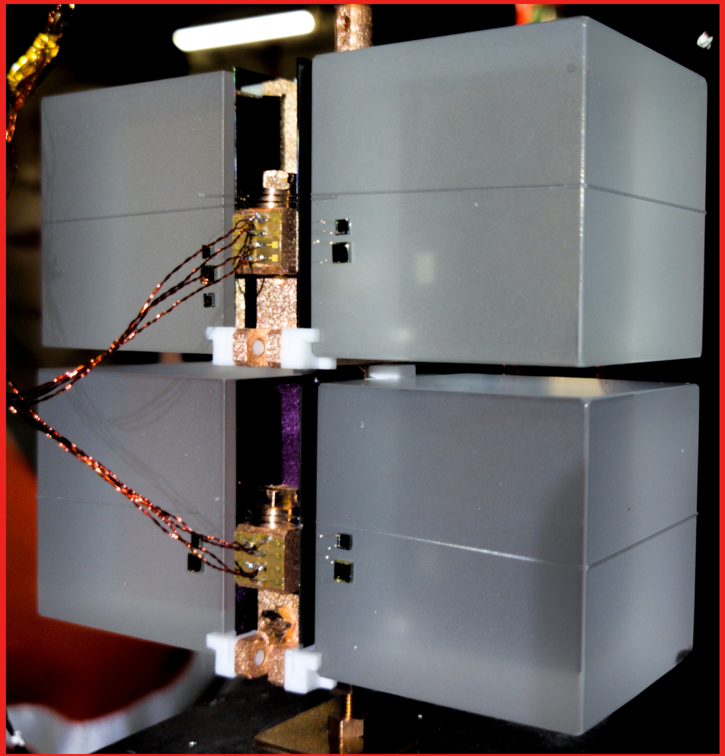
STAY TUNED

Thanks for your attention









BINGO

erc

TINY EXPERIMENT

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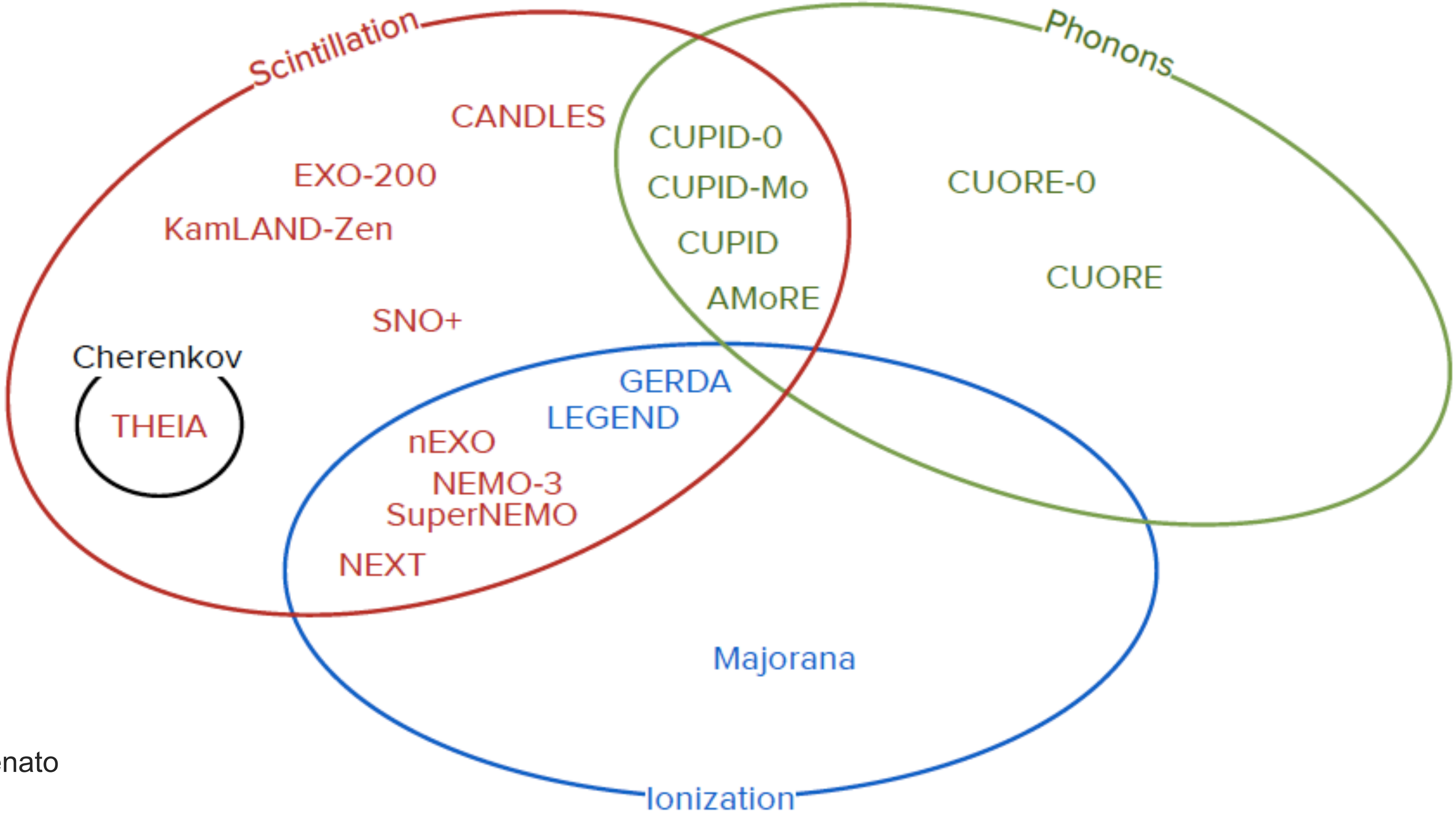
Currently competing technologies / experiments

Combining different detection methods



Courtesy of G. Benato

The CUPID experiment in a nutshell

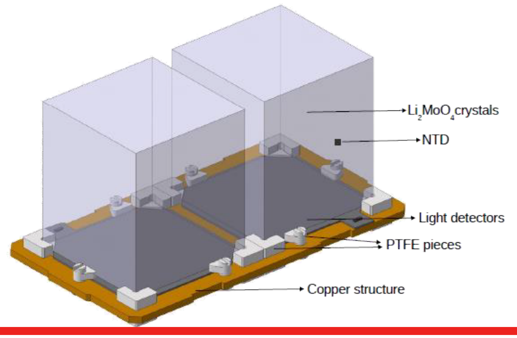
CUPID pre-CDR ***arXiv:1907.09376*** **upgrade to CDR ongoing**

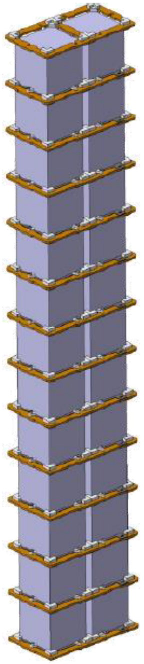
- Single module:
  - 2 x $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~ 280 g**
  - 2 x Ge light detectors
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo** with >95% enrichment (**~1.6×10^{27}** ^{100}Mo atoms)
- **1710 Ge light detector** (CUPID-Mo, CUPID-0 basic technology + Neganov-Trofimov-Luke effect)

Baseline design

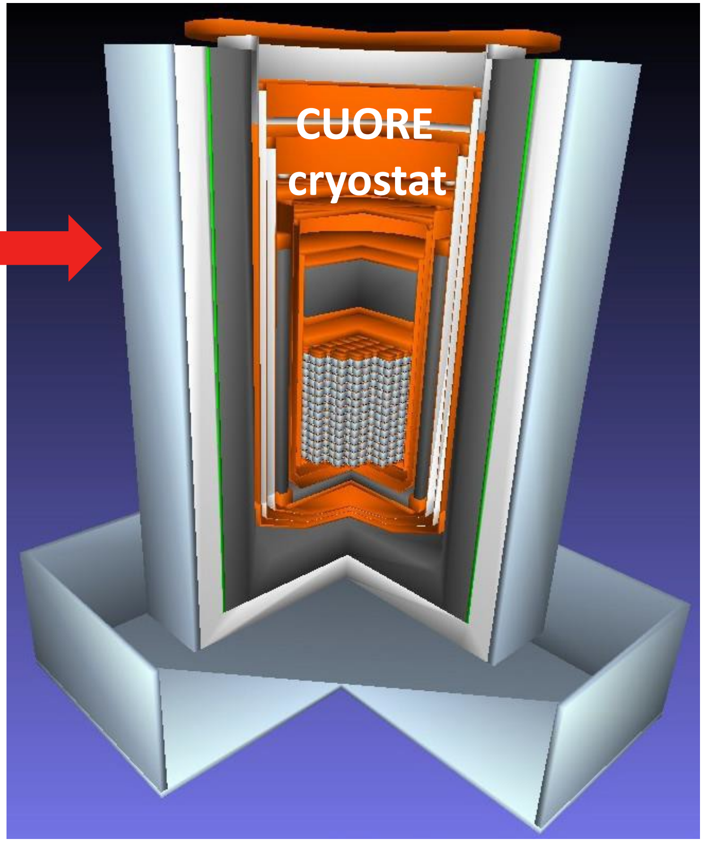
Gravity stacked structure

(innovative approach with respect to CUORE and CUPID precursors)





Ton-scale array of high-resolution cryogenic calorimeters to search for $0\nu\beta\beta$ and other rare events



CUPID objectives

- Energy resolution at $Q_{\beta\beta}$: ≤ 5 keV FWHM
- Light signal: 0.3 keV/MeV
- Light detector baseline resolution: ≤ 100 eV RMS (for PID)
- Light detector timing resolution: ≤ 0.17 ms (for pile-up)
- Background index: ≤ 10^{-4} counts/(kg keV yr)
- $0\nu\beta\beta$ half-life exclusion sensitivity (90% C.L.): 1.4×10^{27} yr

Test of the tower structure

A prototype single CUPID tower was cooled down in July and October 2022 in LNGS

The tower was installed in the Cuoricino-CUORE0-CUPID-0 cryostat

- **Primary goal**: validate the tower structure in terms of assembly procedure, **detector temperature values and distribution**
- **Secondary goals**: Analysis of **detector performance** - Study of the **crystal radiopurity** – Dependence of detector behavior on **glue type**, **crystal origin**, **light-detector coating** method

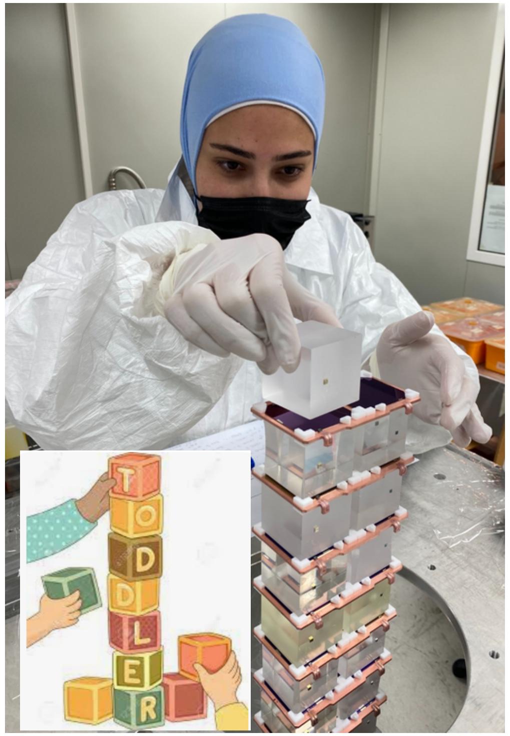
14-floor tower run

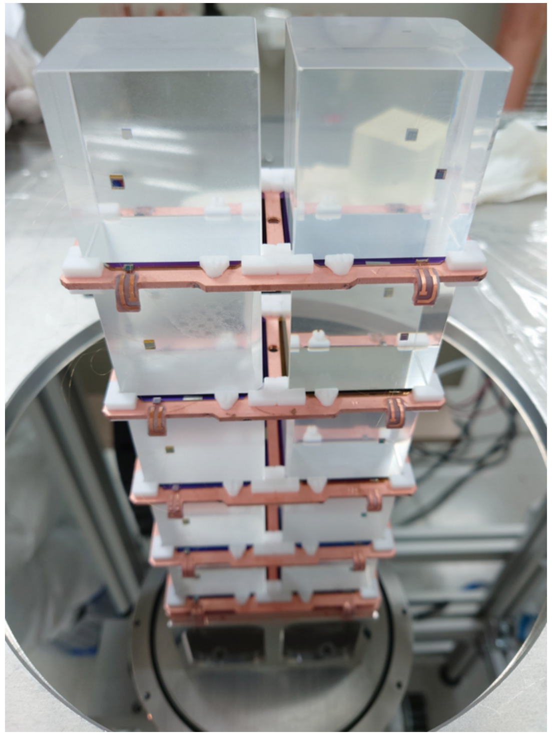
- 28 LMO crystals
- 30 Ge light detectors

The primary goal is achieved - All the channels cool down without problems with a reasonably narrow temperature distribution and no dependence on the position in the tower

→ **The thermal scheme of the tower is validated**

LMO: 7-8 keV FWHM @$Q_{\beta\beta}$
LD: 180 eV median RMS
New test in the coming months



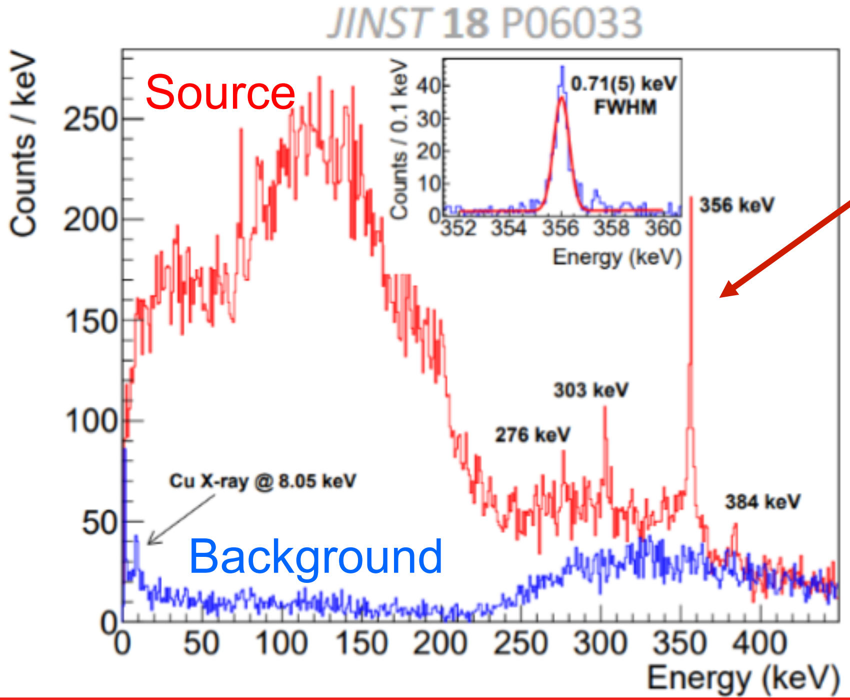


Test of the light-detector structure

The **validation of the new CUPID-baseline light-detector assembly** performed in a pulse-tube cryostat at IJCLab (Orsay)

→ Similar vibrational noise as in CUORE/CUPID cryostat

- 2 Cu frames with 2 light detectors each (0.5 mm in thickness) mounted on top of each other (CUPID configuration)
- Check of the bolometric performance
- **Baseline energy resolution 70-90 eV RMS (CUPID goal for PID met)**



Light detector calibration

Irradiating the detector with a ^{133}Ba source we achieved an outstanding energy resolution:

0.71 keV FWHM at **356 keV**