CUPID:

Cuore
Upgrade with
Particle
IDentification

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Physics Beyond the Standard Model

ν oscillations gave us evidence of physics **B**eyond the **S**tandard **M**odel, now the question is **which physics ?** what are our **expectations for the BSM Theory**

we aim at a BSB theory that addresses open questions such as:

1. quark & lepton masses (lightness of neutrino mass)
2. Matter-Antimatter asymmetry in the Universe
3. Dark Matter & Dark Energy
4. …

meanwhile we expect to fill a knowledge gap: $\nu \overset{\neq}{=} \overline{\nu}$? lepton number is conserved ?

Majorana neutrino

a much appreciated extension of the Standard Model:

- assumes that $\nu = \overline{\nu}$ (we say neutrinos are Majora particles)
- addresses **1+2** (fermion masses + matter dominated Universe)

the best (experimentally sensitive) way to prove neutrino are Majorana particle is to search for a special nuclear decay:

$0\nu\beta\beta$ (A, Z)→(A, Z+2) + 2e$^-$

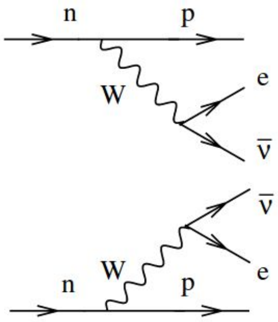
neutrinoless double beta decay

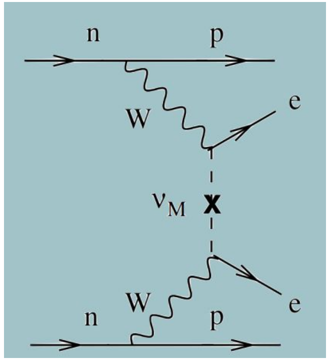
SM compliant $\beta\beta$-decay

BSM $\beta\beta$-decay

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

$0\nu\beta\beta$ $(A, Z) \rightarrow (A, Z+2) + 2e^-$





$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot m^2_{ee}$$

- we call this 2ν-mode
- lepton number is conserved
- extremely rare but observed, $\tau > 10^{18}$ y

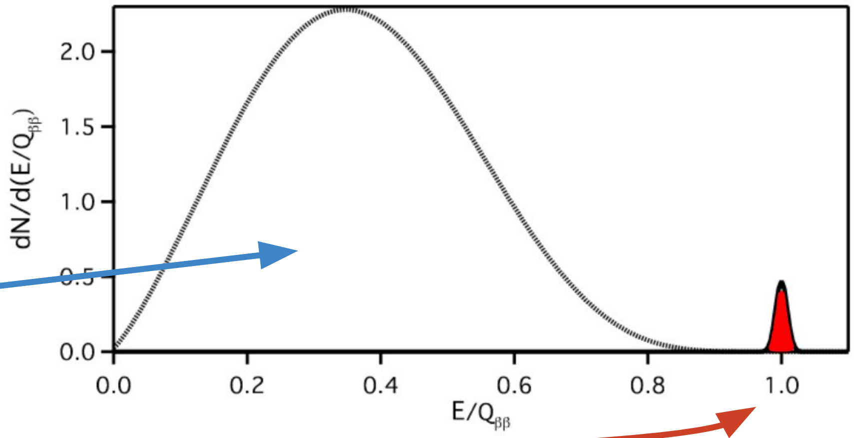
- we call this 0ν-mode
- $\Delta L=2$ process

can proceed with different mechanisms, the dominant is the one where the Fermi description holds but ν is a massive Majorana particle that can change its helicity

- never observed, $\tau > 10^{24}$ y

Experimental signature

detector measure **E_{tot}** sum kinetic energy of the two electrons



$2\nu\beta\beta$ $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$

$0\nu\beta\beta$ $(A,Z) \rightarrow (A,Z+2) + 2e^-$

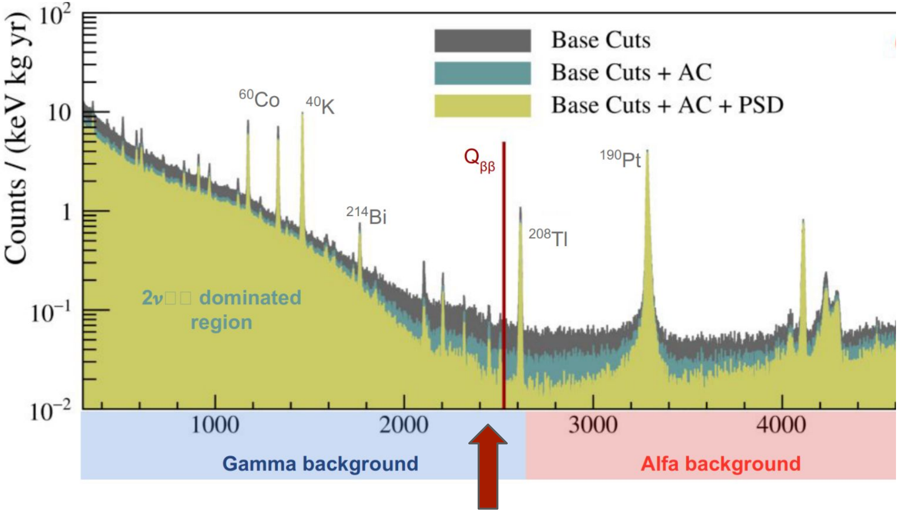
- a peak at **$E_{tot} = Q_{\beta\beta}$** typically ~ 1-3 MeV
- MeV electrons have a short range **the source needs to be embedded in the detector**
- **high energy resolution** implies an incontrovertible identification of the signal

Two experimental approaches

solid state arrays (Ge diodes & bolometers)

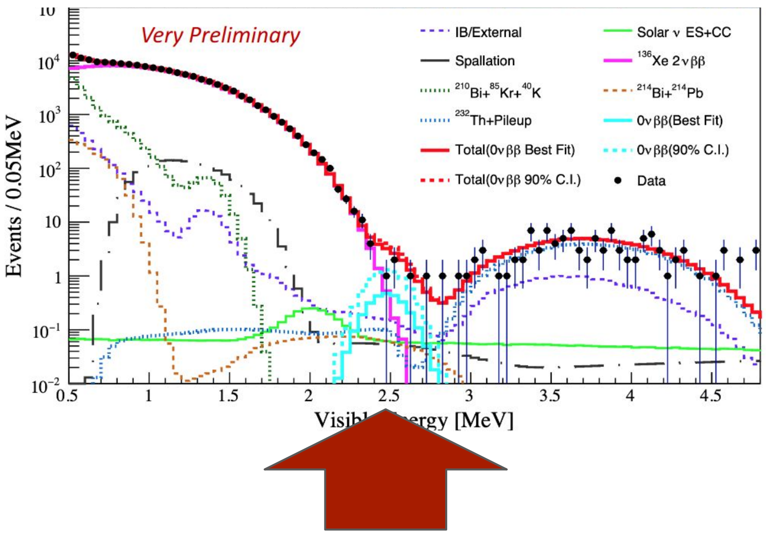
liquid or high pressure gases (scintillators, LXe)

CUORE



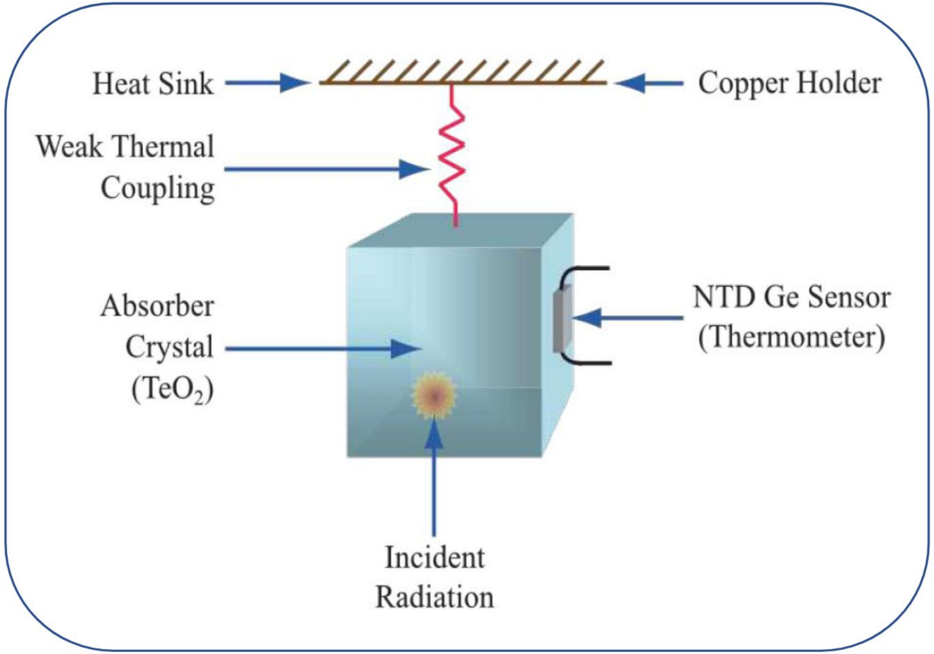
ROI

Kamland-ZEN 800

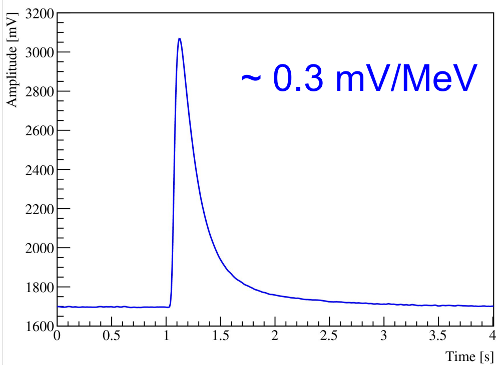


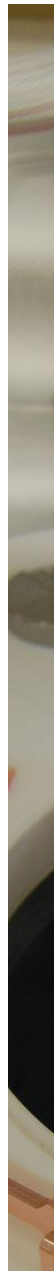
ROI

Cryogenic Particle Detectors or **Bolometers**



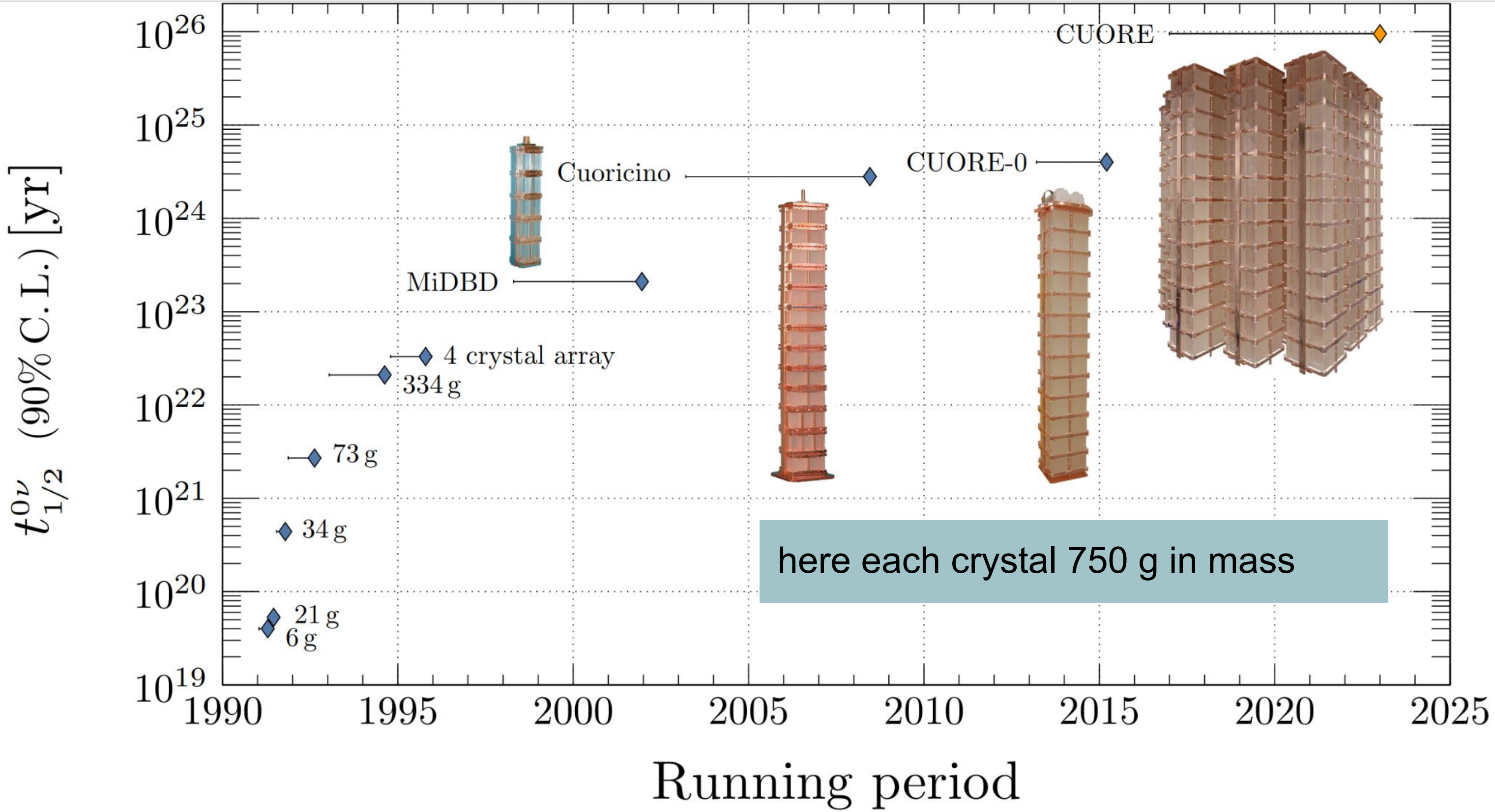
$$R(T) = R_0 \cdot e^{(T_0/T)^\gamma}$$





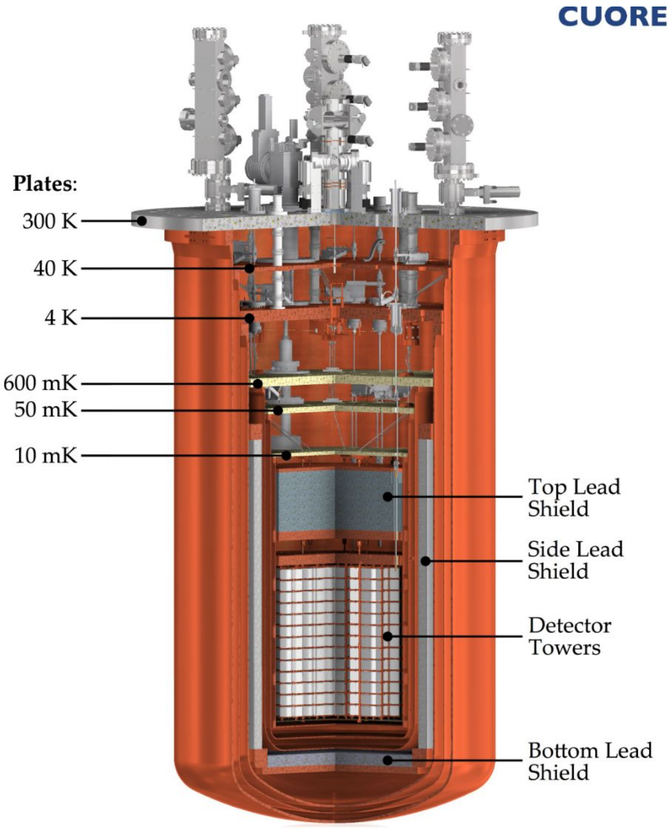
- dielectric crystals ~ 1 kg each
- signal amplitude identical whatever the particle →no particle ID
- FWHM ~ 5 keV at 2.6 MeV

CUORE bolometers



here each crystal 750 g in mass

CUORE



array of TeO_2 bolometers operated at 10 mK

- $\beta\beta$ candidate embedded in the detector ~ 246 kg ^{130}Te
- 988 crystals arranged in 19 towers
- FWHM ~ 7 keV
- no sensitivity to particle id

- target 5 yr sensitivity
  - $T_{1/2} > 9.0 \times 10^{25}$ yr
  - $m_{\beta\beta} <$ 50-130 meV

^{130}Te: $Q_{\beta\beta}$ ~2527 keV
$2\nu\beta\beta$ $\tau_{1/2}$ ~ 8.2 10^{20} y

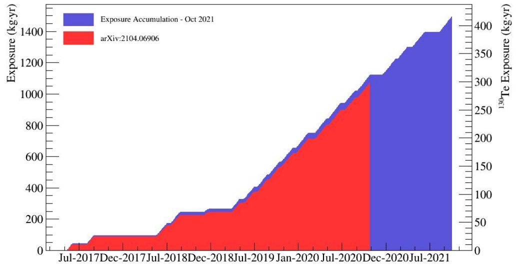
CUORE successes

1-ton cooled at 10 mK

Scienze Nel CUORE del Gran Sasso il metro cubo più freddo dell'Universo

Nei Laboratori Nazionali del Gran Sasso un metro cubo di materia solida è stato portato quasi allo zero assoluto: un record, anche di tecnologie.

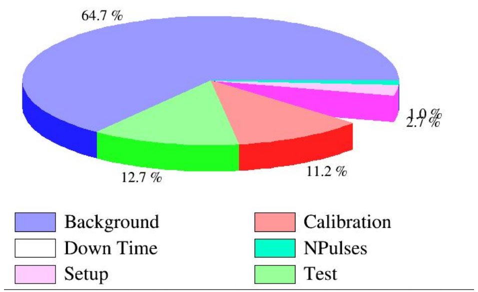
exposure > 1 ton * year

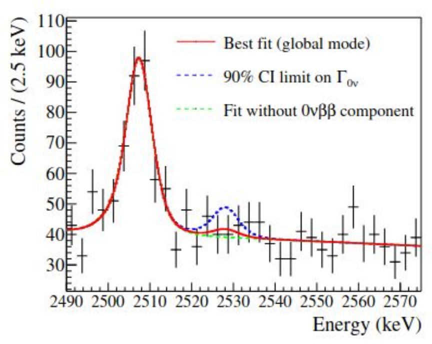


$T_{1/2}^{0\nu} > 2.2 \times 10^{25}$ yr at 90% C.I.

~65% live-time on physics data

CUORE Run Time Breakdown





median exclusion sensitivity: $T_{1/2}^{0\nu} = 2.8 \times 10^{25}$ yr

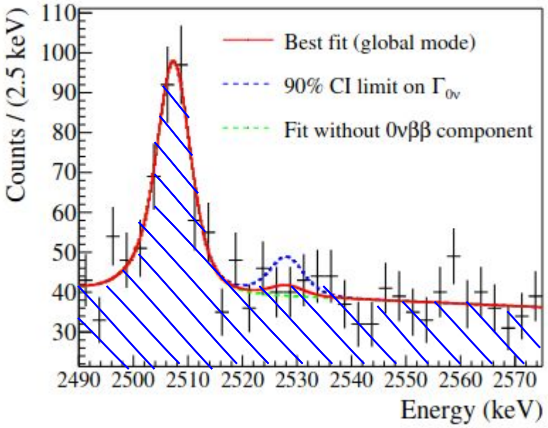
$T_{1/2}^{0\nu} > 2.2 \times 10^{25}$ yr at 90% C.I.

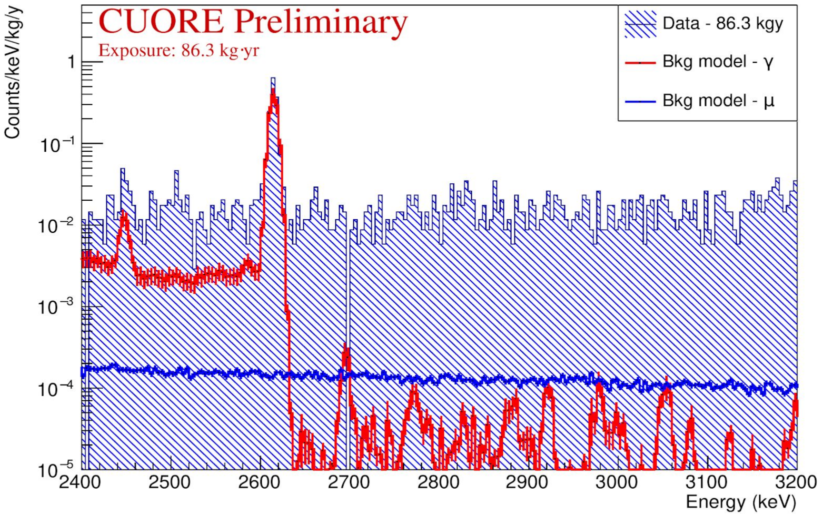
probability to get a more stringent limit given the current sensitivity: 72%.

effect of systematics on $T_{1/2}^{0\nu}$ ~ 0.8%.

$m_{\beta\beta} < 90 - 305$ meV at 90% C.I.

CUORE: what is α particles in





advantages in moving ROI above 2.6 MeV
new $Q_{\beta\beta}$!

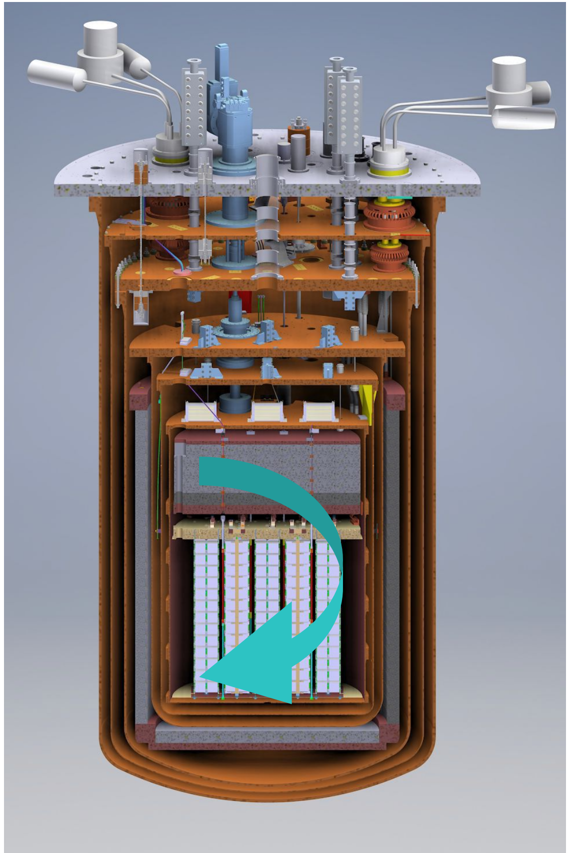
CUPID in a nutshell

→ **replace** the CUORE TeO_2 detector with a new array, based on Li_2MoO_4

this is enough to take a leap forward in sensitivity because we reduce dramatically the background in the ROI (see next slide)

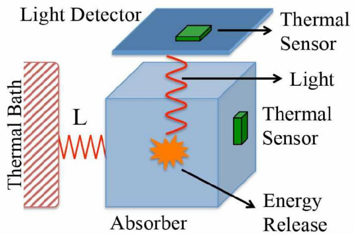
we put in place two strategies for bkg reduction

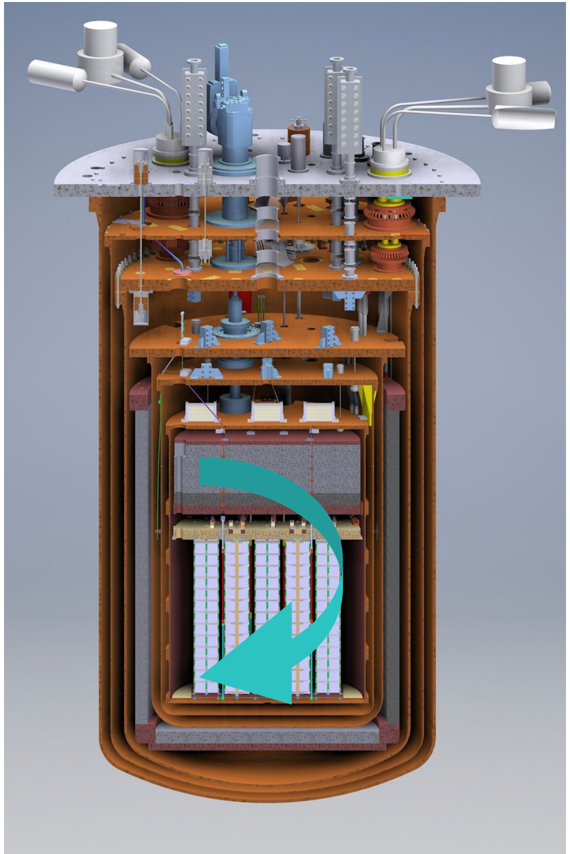
- the new ββ candidate **^{100}Mo** has a higher transition energy than the ^{130}Te CUORE candidate: **less γ-induced background in ROI**
- the new detector has a very efficient **α particle rejection** capability: **remove the dominant background source seen in CUORE**



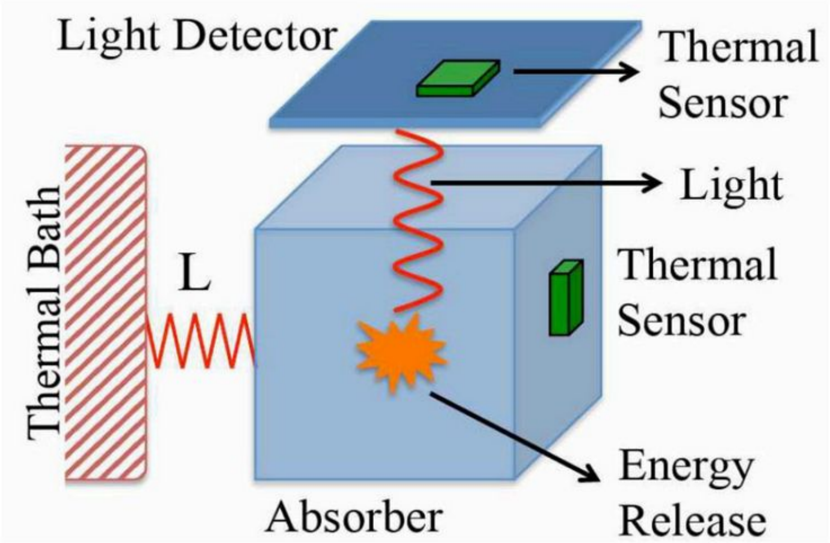
CUPID in a nutshell

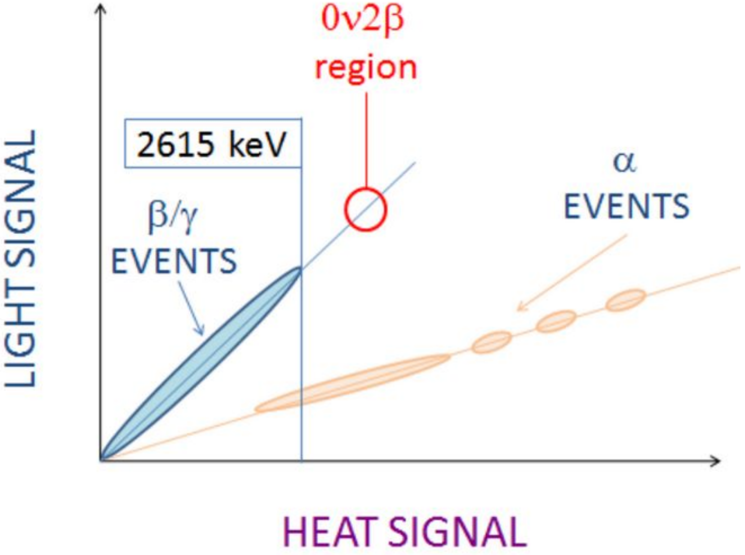
- **same mass scale** of CUORE: basically we repeat what already done, with improved expertise
- **same cryogenic infrastructure**: quite challenging for CUORE, now an established technology
- the major change **is an additional functionality** in the single element (particle identification through light read-out)





CUPID scintillating bolometer





we developed this technology for over 10 years

now it is quite mature and demonstrated by **CUPID-0** and **CUPID-Mo**

Scintillating bolometer technology

- scintillating crystal (typically undoped to avoid excess heat capacity and the radioactivity of rare earths): CaF_2, ZnSe, $ZnMoO_4$, … Li_2MoO_4

Crystal - Experiment	Relative Light Yield β/γ	Relative Light Yield α
ZnSe - CUPID-0	3 - 5 keV/MeV	9 - 14 keV/MeV
Li_2MoO_4 - CUPID-Mo	0.6 keV/MeV	0.1 keV/MeV

- **light detector** a bolometer with **eV** energy threshold (to be sensitive to optical photons)

  Ge wafer (small mass→small heat capacity→ low energy threshold)

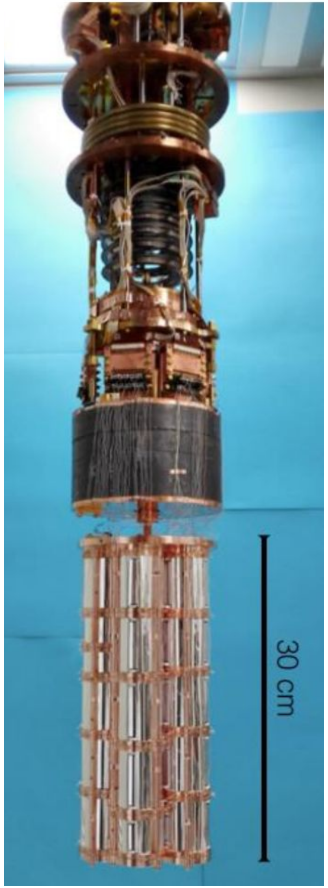
risetime	signal height	baseline noise RMS
1 ms	1 µV/keV_{light}	0.4 µV

to avoid heat (phonon) transmission from the scintillating crystal to the light detector they can’t be in touch with each other → **light extracted is very low**

example

for a 0vbb signal	LMO Heat Signal	LMO Light Signal
signal height	150 µV	1.8 µV/MeV
noise RMS	0.1 µV	0.4 µV

CUPID-0 and α particle rejection



CUPID-0 is the **first small scale experiment using scintillating** bolometers

- 25 crystals of Zn^{82}Se
- 5.5 kg of ^{82}Se @LNGS Hall A

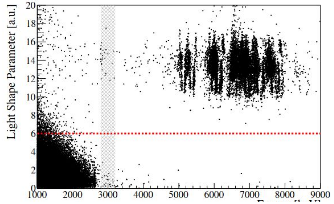
optimization of scint. bolometer technique

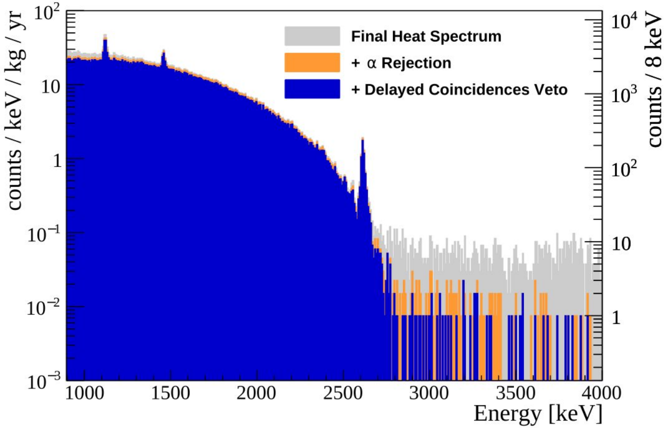
- light detectors
- dual read-out
- analysis

➔ first direct prove that flat background is due to alpha particles !

^{82}Se: $Q_{\beta\beta}$ ~3000 keV

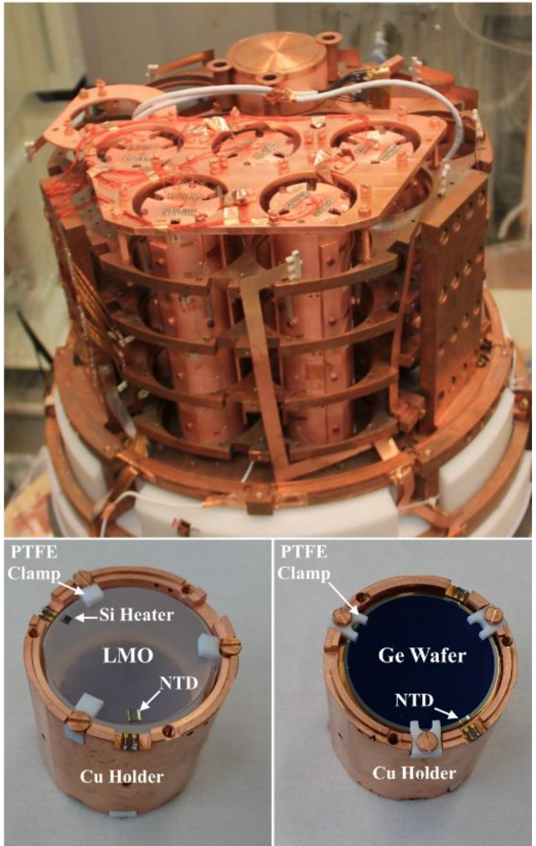
$2\nu\beta\beta$ $\tau_{1/2}$ ~ 8.6 10^{19} y





LNF - 2022

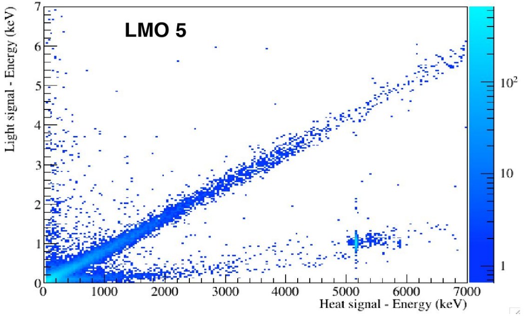
CUPID-Mo and LMO crystals



CUPID-0 is the **first small scale experiment using** $Li_2{}^{100}MoO_4$

- crystals $Li_2{}^{100}MoO_4$ (LMO)
- 2.264 kg of ^{100}Mo @ Modane

➔ demonstrator of LMO performances & evaluation of achievable LMO radiopurity



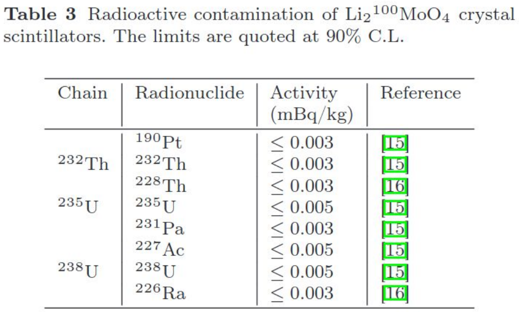


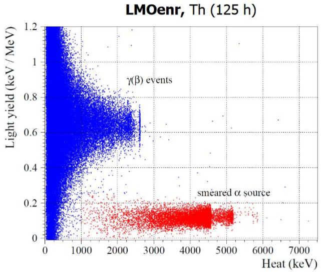
Table 3 Radioactive contamination of $Li_2{}^{100}MoO_4$ crystal scintillators. The limits are quoted at 90% C.L.

Chain	Radionuclide	Activity (mBq/kg)	Reference
	^{190}Pt	≤ 0.003	[15]
^{232}Th	^{232}Th	≤ 0.003	[15]
	^{228}Th	≤ 0.003	[16]
^{235}U	^{235}U	≤ 0.005	[15]
	^{231}Pa	≤ 0.003	[15]
	^{227}Ac	≤ 0.005	[15]
^{238}U	^{238}U	≤ 0.005	[15]
	^{226}Ra	≤ 0.003	[16]

CUPID

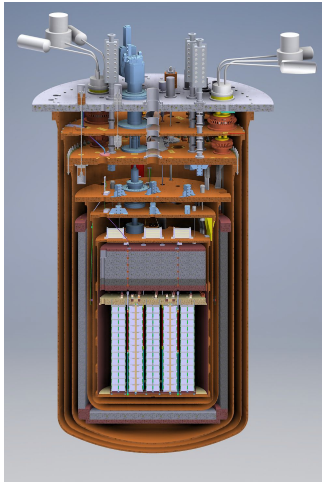
1596 cubic L^{enr}MO crystals 45x45x45 mm

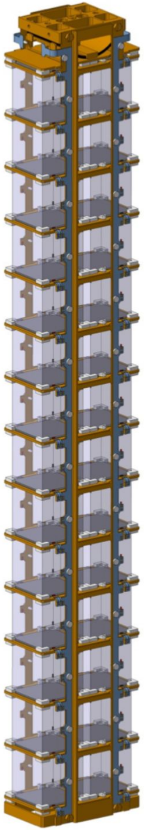
- 450 kg LMO
- 240 kg ^{100}Mo



CUORE-like structure

- close packed array: 56 towers, each with 14x2 crystals
- minimum amount of inert material in between crystals
- two light detectors for each crystal





Main Detector Requirements

★ Heat ch. ~ **5 keV FWHM**

★ Light ch. needs to **select α's with >90% efficiency**

★ Heat+Light need to r**eject pile-up events** in the ROI

goal: bkg counting rate in the ROI ~ 10^{-4} counts/keV/kg/yr

Technical Design and on-going activities

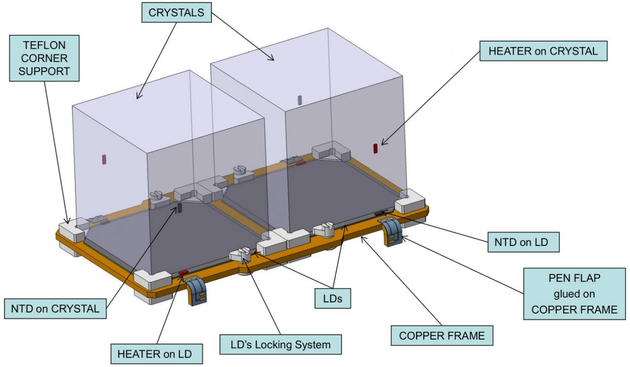
1. **isotope & crystal procurement** - negotiation will start after full validation of production
2. **new design of the detector holder** - final validation on a 14x2 crystal tower will start in the next months
3. **upgrade of the cryogenic apparatus** - R&D on going but upgrade will take place at CUORE end (2016)
4. **upgrade of external shield system** - design study
5. **detector optimization focused on pile-up rejection** - ongoing

A new concept for the **detector holder**

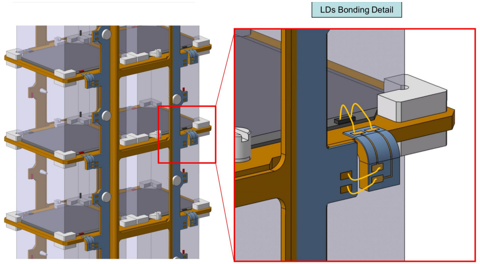
the challenges:

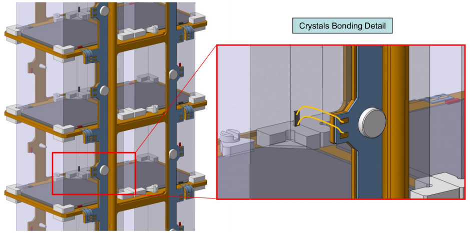
- integrate the Light Detector without adding complexity
- address weaks point in CUORE design (e.g. reduce the time needed for the assembly despite the higher number of detectors)
- respect radioactive constraints

the solution: stacked floors without connecting elements

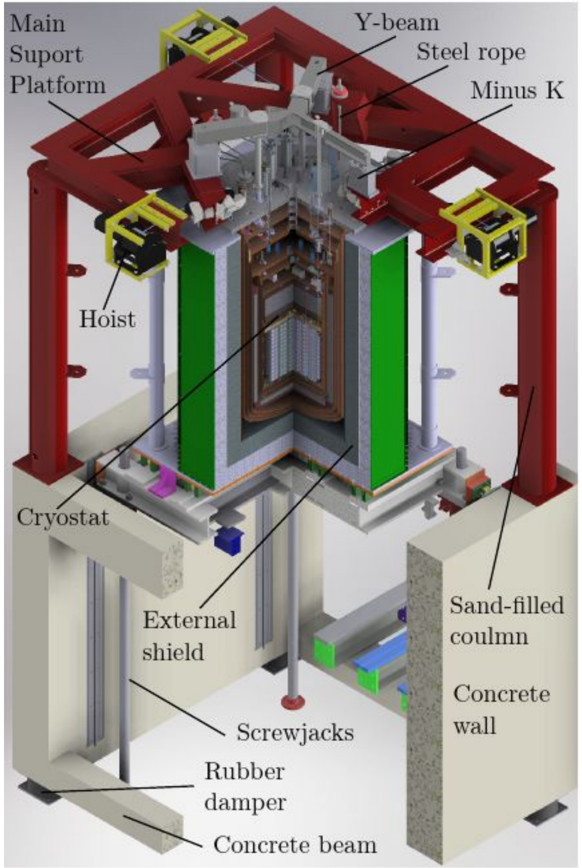


- copper parts have a simpler design
  - easy to produce (laser cut of Cu sheets)
  - easy to clean
  - **assembly can be much faster**
  - notable relaxation of the tolerances
- better integration of wiring





Shields



CUORE shields

- PE 20 cm (moderator) + 3 cm H_3BO_3 (absorber)
- Pb 25 cm
- Roman Pb 6 cm
- **no muon veto**

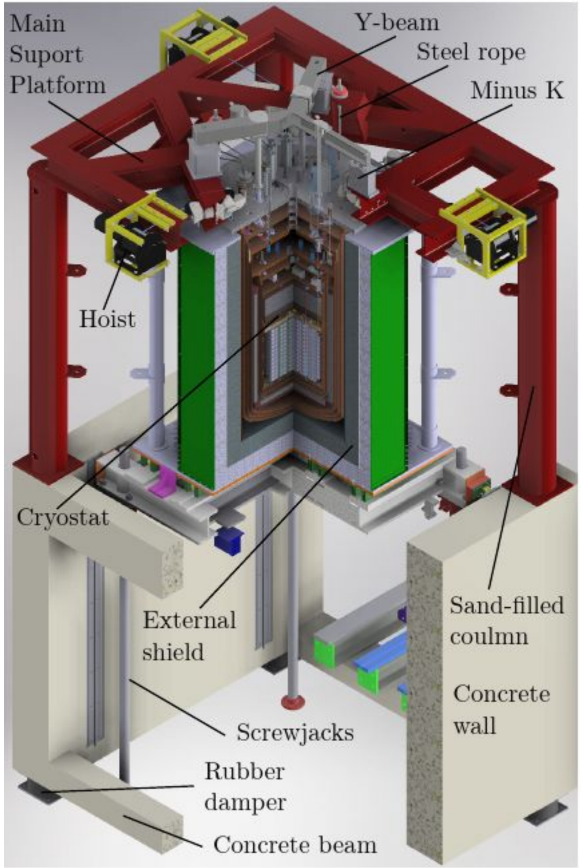
muon induced background at LNGS

- mostly prompt events (muon direct interaction and showers)
- both in TeO2 and LMO no delayed events

in CUORE:
detector anti-coincidence is enough for muon background suppression

in CUPID:
we need a further suppression →a veto system

Shields



CUPID upgrade

- additional 10-20 cm moderator ?

  optimal thickness still under study, main challenge is to validate GEANT simulation

- muon veto with 95-99% tag efficiency

work

- overall design, not trivial integration in the infrastructure
- integration of muon veto in DAQ and DA

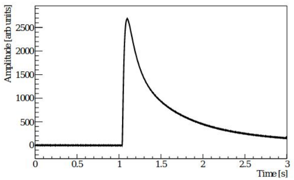
Pile-up

^{82}Se: $Q_{\beta\beta}$ ~3034 keV

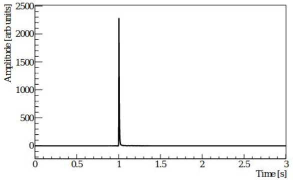
$2\nu\beta\beta$ $\tau_{1/2}$ ~ 7.1 10^{18} y

2νββ decay rate in a single crystal ~ 2.6 mHz

- improving detector timing and S/N

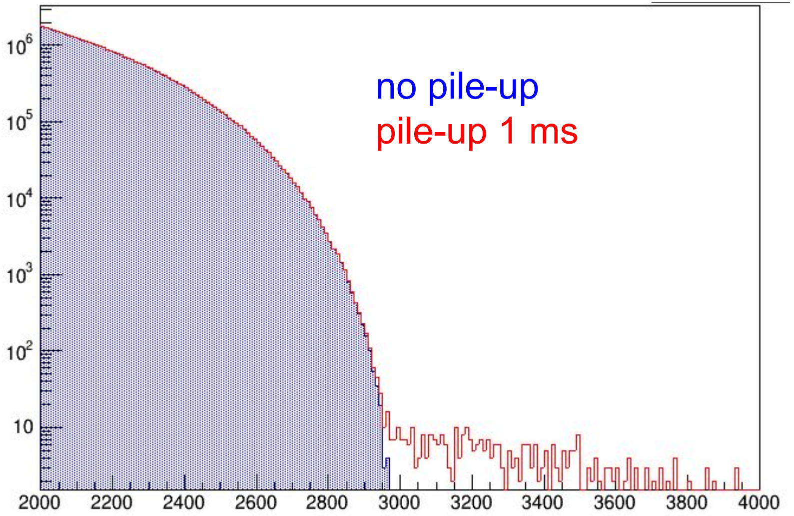


LMO
- slow signal - rise ~ 15 ms
- high S/N



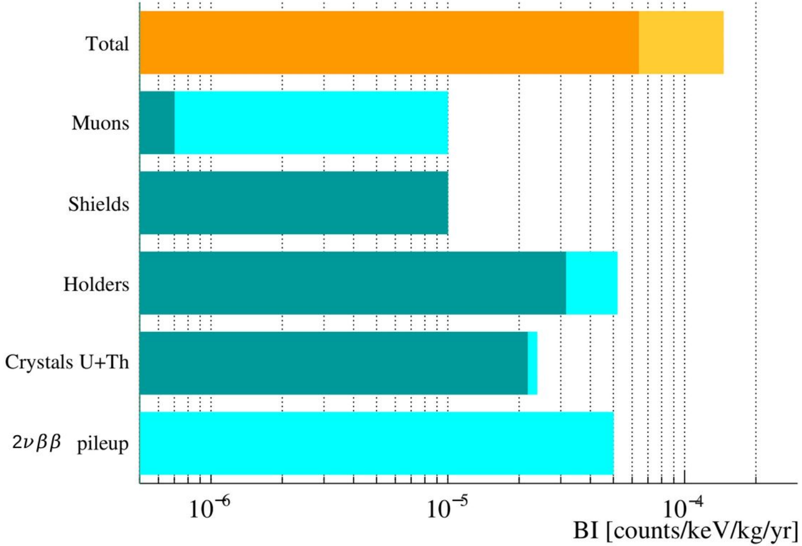
Light Detector
- slow signal - rise ~ 1 ms
- low S/N

- develop dedicate algorithms to pile-up rejection



Background Model

background model based on previous experiments:



- Shields = cryostat - same as in CUORE
- Holders = mainly the surface contamination of Cu - same as in CUORE
- Crystals = bulk and surface contamination, need to validate on CUPID dedicated production
- 2νββ pile-up = in progress

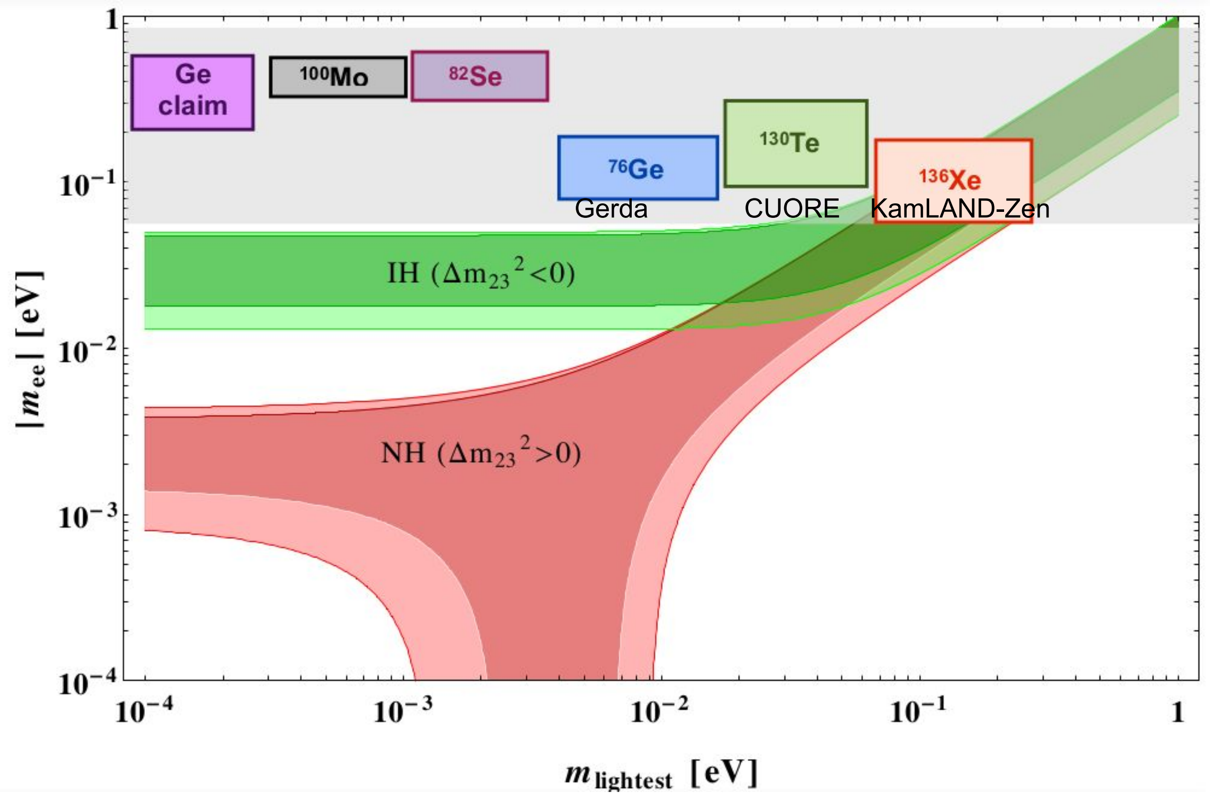
CUPID GOAL

- bkg ~ 10^{-4} counts/(keV kg y)

Majorana mass - present result

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot m^2_{ee}$$

Nuclear Factor, model dependent, usually converted into a range of values



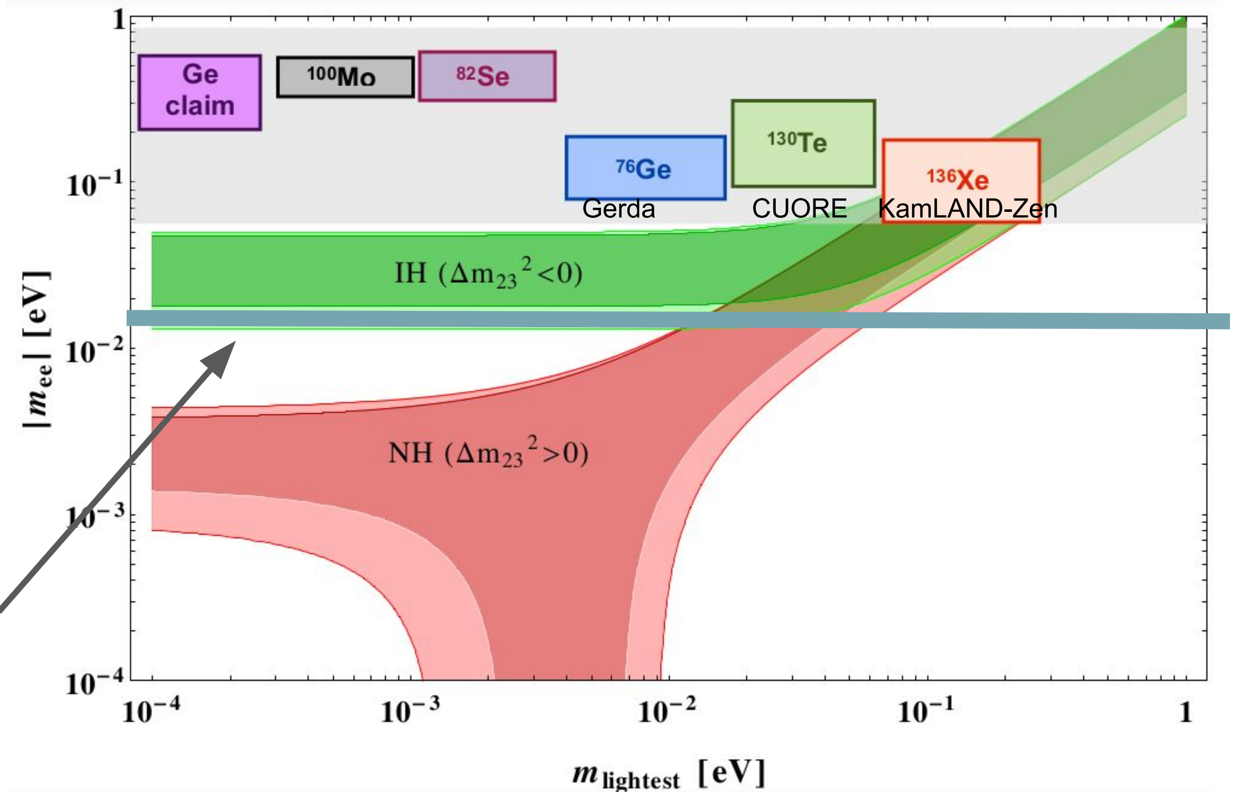
Majorana mass - CUPID sensitivity

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot m_{ee}^2$$

Nuclear Factor, model dependent, usually converted into a range of values

CUPID GOAL

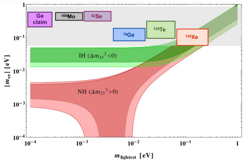
- bkg ~ 10^{-4} counts/(keV kg y)
- 10 yr sensitivity
  - ○ 1.4 10^{27} yr
  - ○ m_{ee} ~ 12-20 meV



Majorana mass - the competitors

Three experiments in the EU-North America area

- CUPID @ LNGS
- LEGEND-100 @ LNGS or SNOLab
- n-EXO @ SNOLab

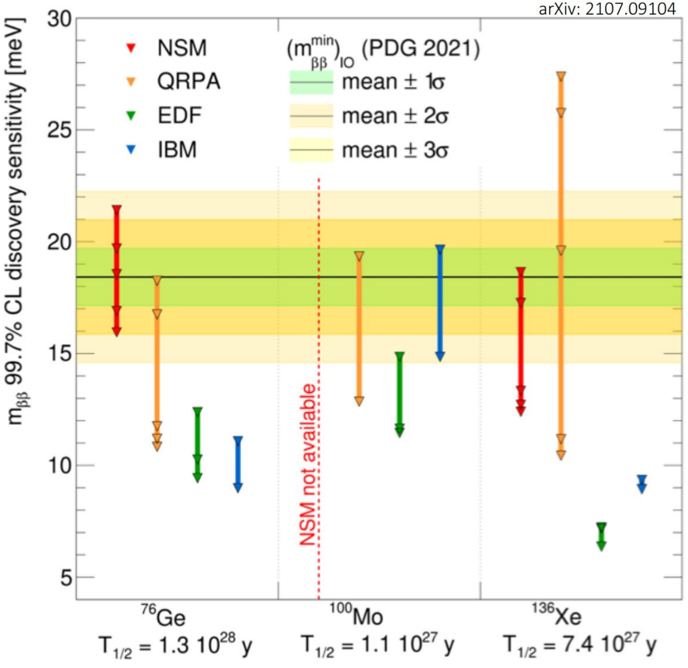


these 3 experiments were discussed in joint meeting of EU and North America funding agencies in Sept. 2021 at LNGS in order to agree on a coordinate strategy for approval and financing

expected in the near future also KamLAND-Zen @ Kamioka

they all leverage on a long history of successes →highly credible in their plans

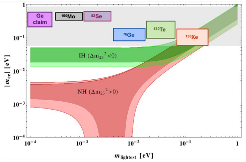
Agostini, Detwiler, Benato, Menendez, Vissani
"Testing the Inverted Neutrino Mass Ordering with 0νββ Decay"
arXiv: 2107.09104



Majorana mass - the competitors

Three experiments in the EU-North America area

- CUPID @ LNGS
- LEGEND-100 @ LNGS or SNOLab
- n-EXO @ SNOLab



these 3 experiments were discussed in joint meeting of EU and North America funding agencies in Sept. 2021 at LNGS in order to agree on a coordinate strategy for approval and financing

expected in the near future also KamLAND-Zen @ Kamioka

CUPID has two big advantages: same mass scale as CUORE & same infrastructure !

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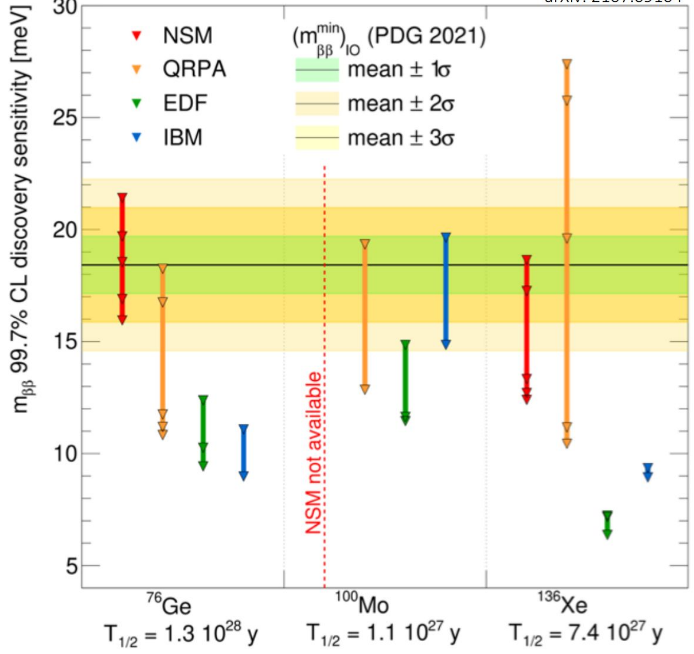
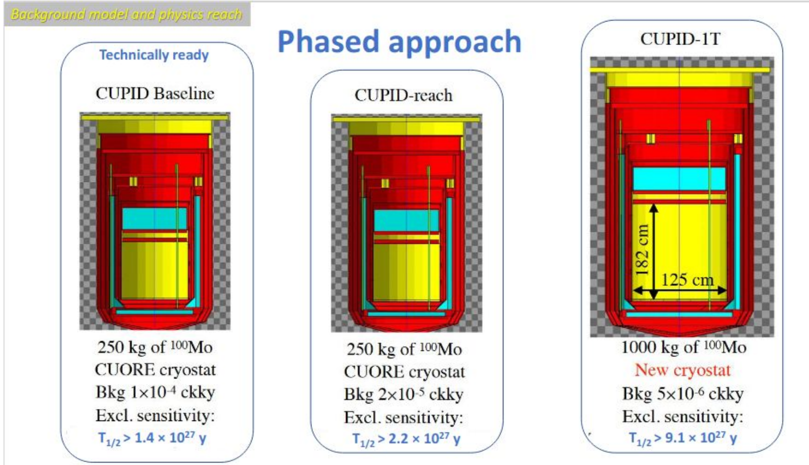


Majorana mass - the future and the far future

among other experiments that could become competitors we have Amore, NEXT, SNO+II …

for CUPID we have already a viable strategy to go beyond the IH !



Background model and physics reach

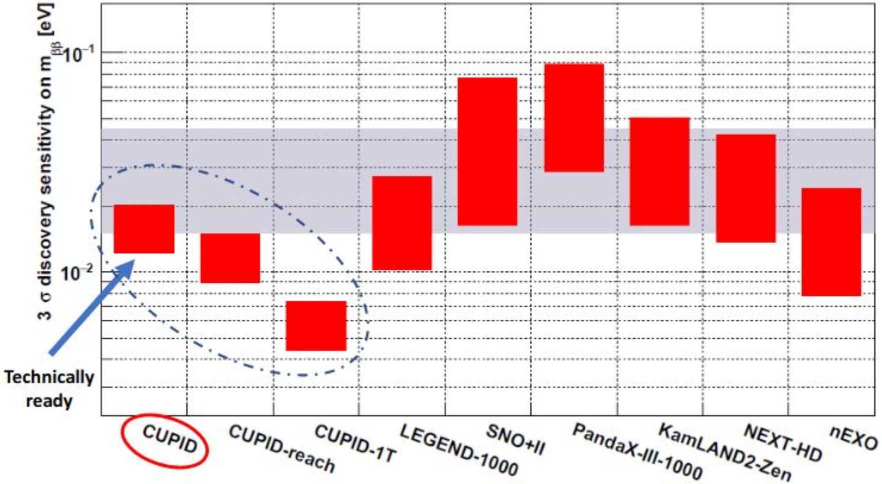
Phased approach

Technically ready

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

CUPID-reach
250 kg of ^{100}Mo
CUORE cryostat
Bkg 2×10^{-5} ckky
Excl. sensitivity:
$T_{1/2} > 2.2 \times 10^{27}$ y

CUPID-1T
1000 kg of ^{100}Mo
New cryostat
Bkg 5×10^{-6} ckky
Excl. sensitivity:
$T_{1/2} > 9.1 \times 10^{27}$ y



THE END

thanks for your attention !