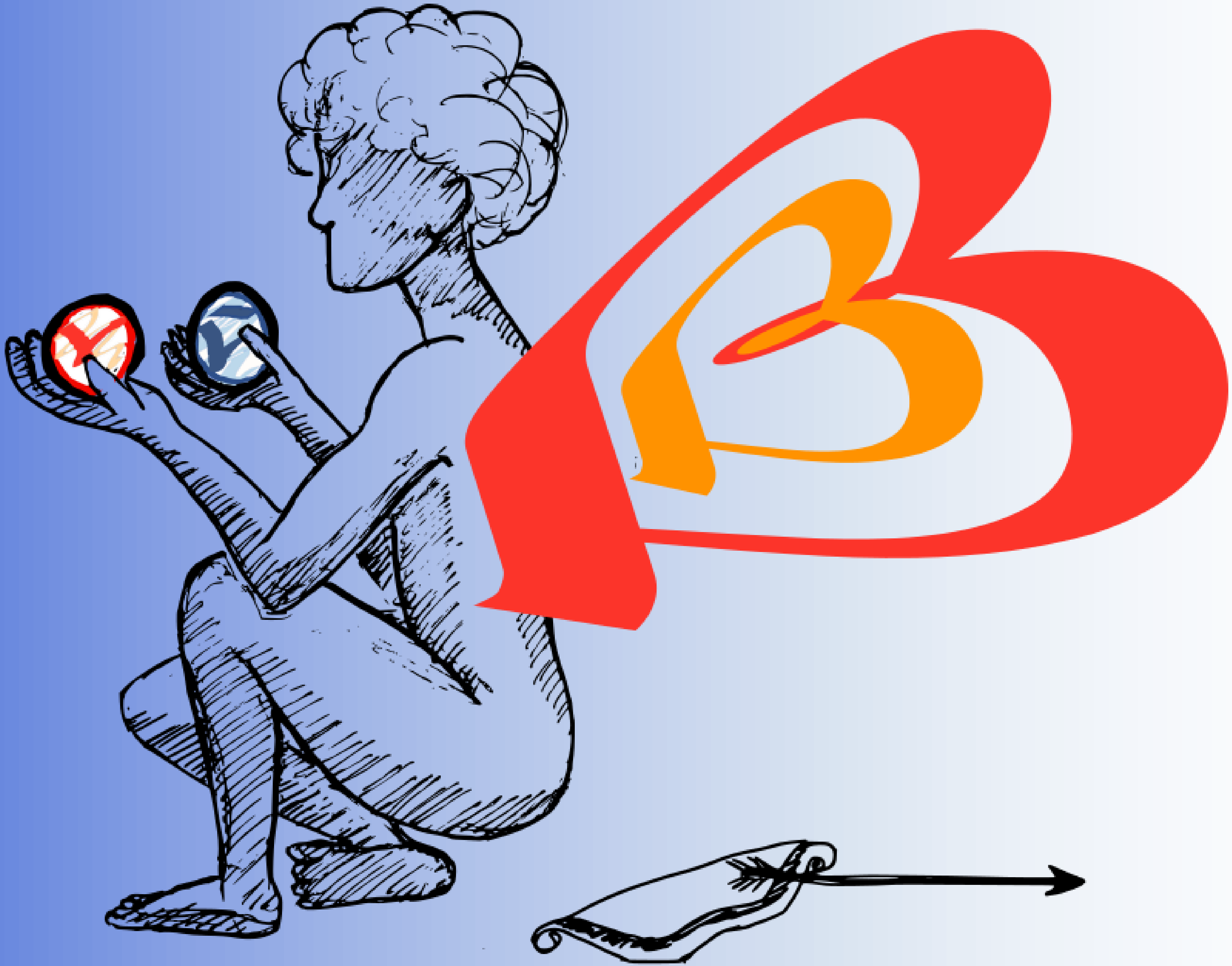


The CUPID project

Mattia Beretta on behalf of the CUPID collaboration

Berkeley
UNIVERSITY OF CALIFORNIA

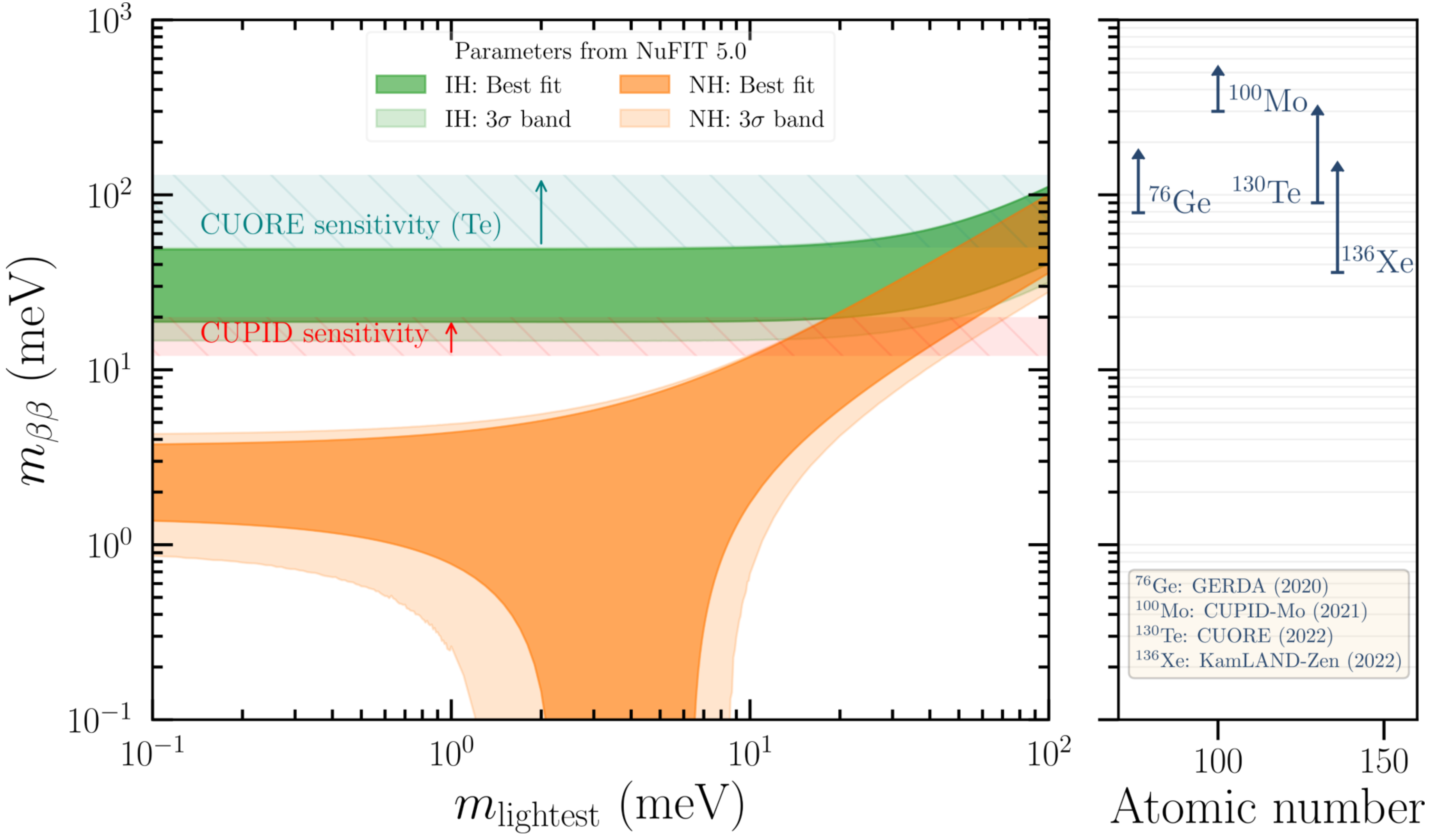
20/07/2022 – 18th Rencontre du Vietnam – Neutrino Physics

The CUORE Upgrade with Particle IDentification (CUPID)

Next generation 0νββ detector

Scan the whole

inverted ordering



Start from CUORE experience

Using the same cryostat

Understanding the limits

Improve the sensitivity

Applying a new technology

Handles for improving sensitivity

Experimental sensitivity

Maximum measurable half-life at a given C.L.

$$\max\ T^{0\nu}_{1/2} \propto \sqrt{\frac{M \cdot T}{B \cdot \Delta}}$$

Isotope Mass

Mass scalability

High isotopic abundance

Energy resolution

$\Delta \sim$ ‰ at Q_{value}

↕

$2\nu\beta\beta$ induced background

Background

High purity materials

Rejection techniques

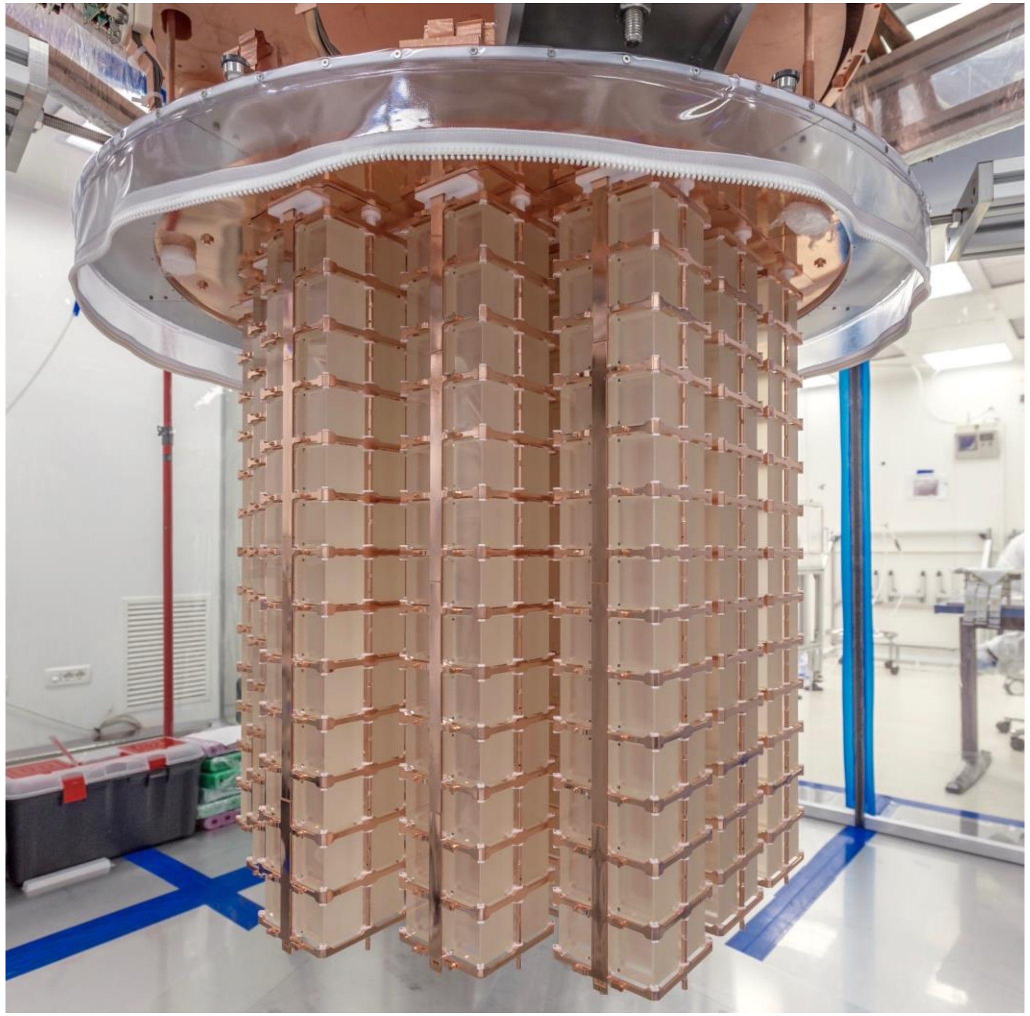
Multi-parameter optimization

Already explored in CUORE

CUORE experience

Nature **604**, pages 53–58 (2022)

The first tonne-scale operating cryogenic 0νββ decay experiment

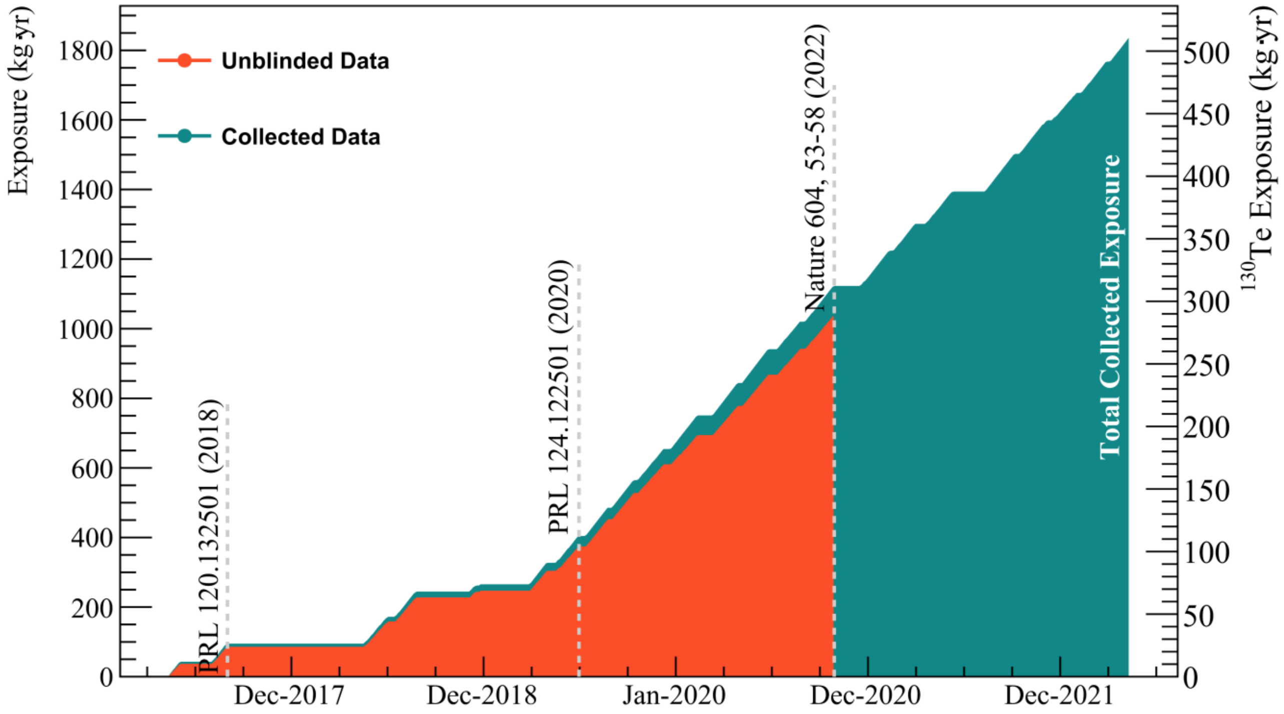


988 crystals simultaneously operated at 11-15mK

Operated as cryogenic calorimeters

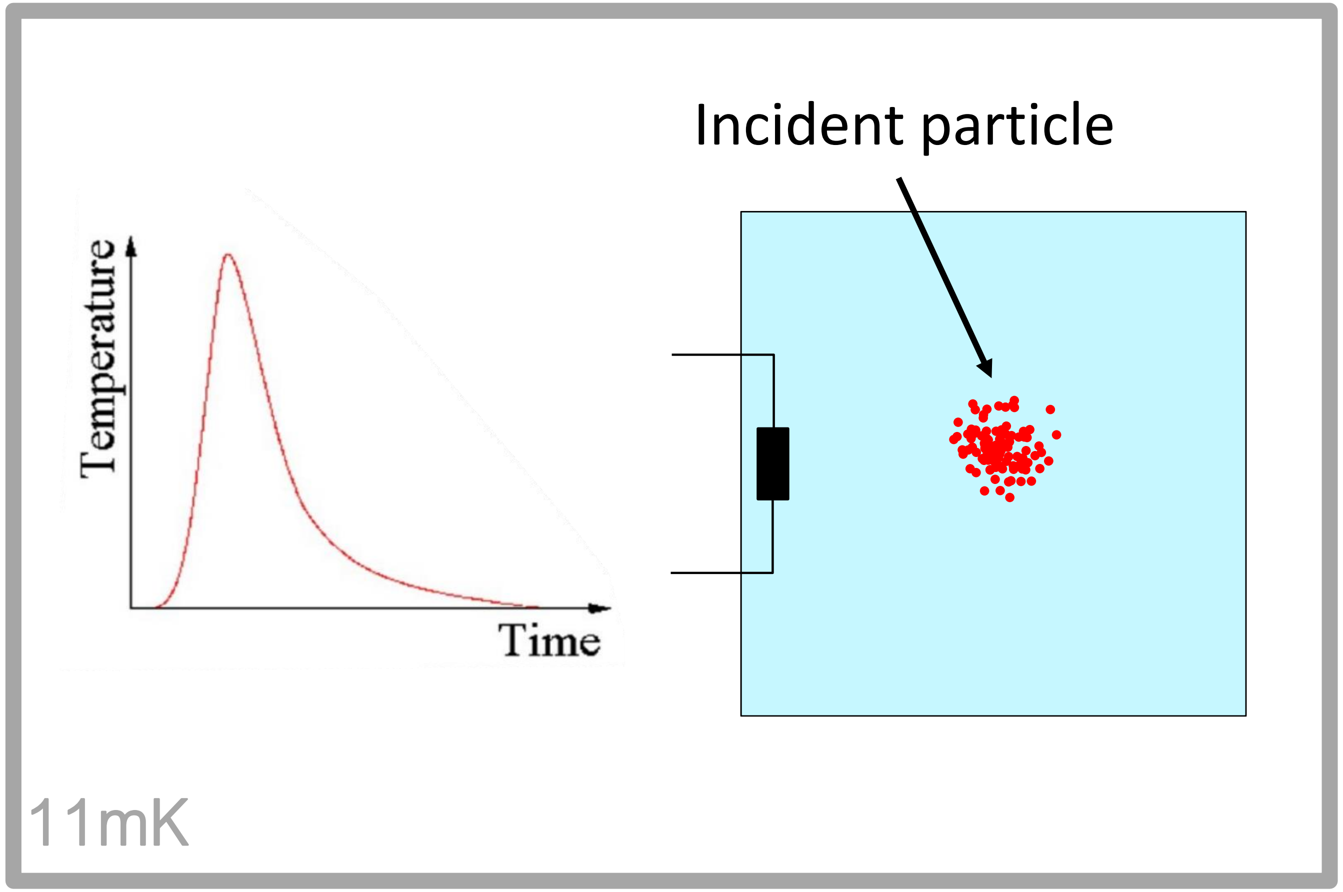
High efficiency data taking

Striding towards 5 ton·yr of data



CUORE technology: cryogenic calorimeters

Detecting energy as temperature increase



Thermometer is made of neutron transmutation doped germanium

Energy resolution

Provided by the technique

Background

Control of materials

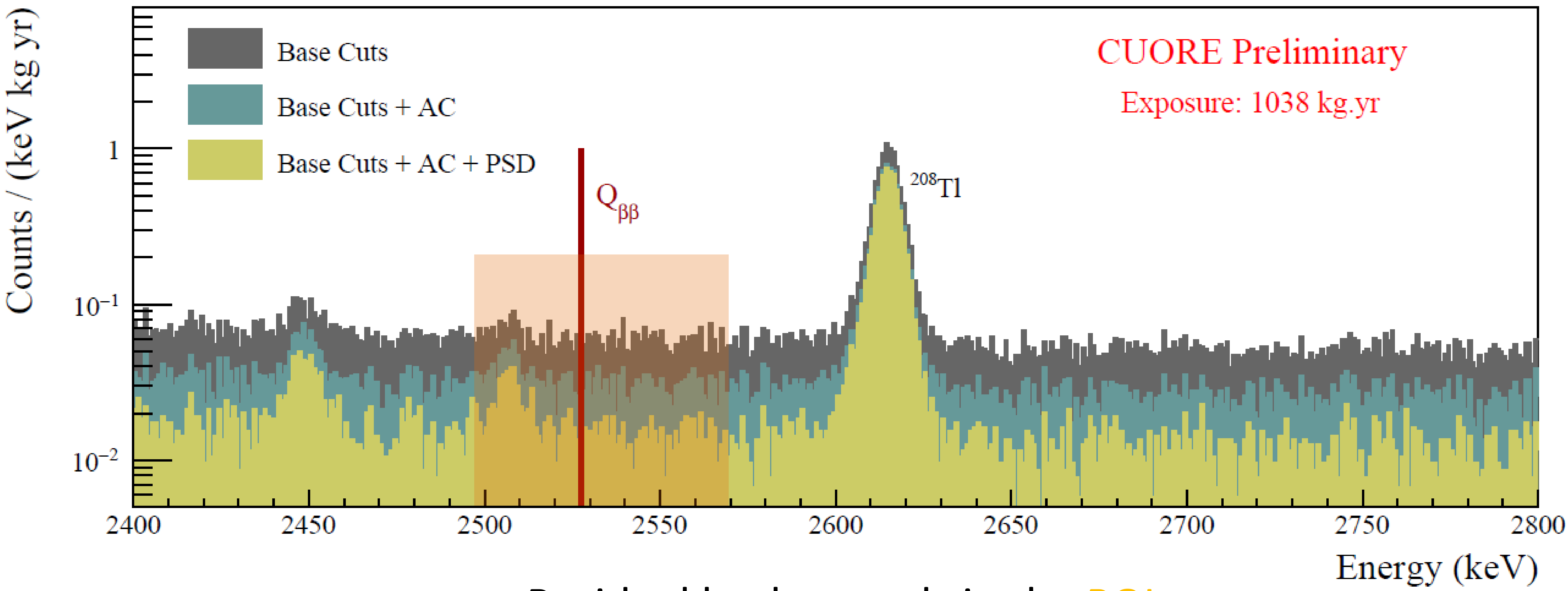
Isotope Mass

^{130}Te has ~34% natural istotopic abundance

Multiple modules

Needed improvements highlighted by CUORE

Nature **604**, pages 53–58 (2022)



Residual backgrounds in the ROI

~10% β/γ radioactivity

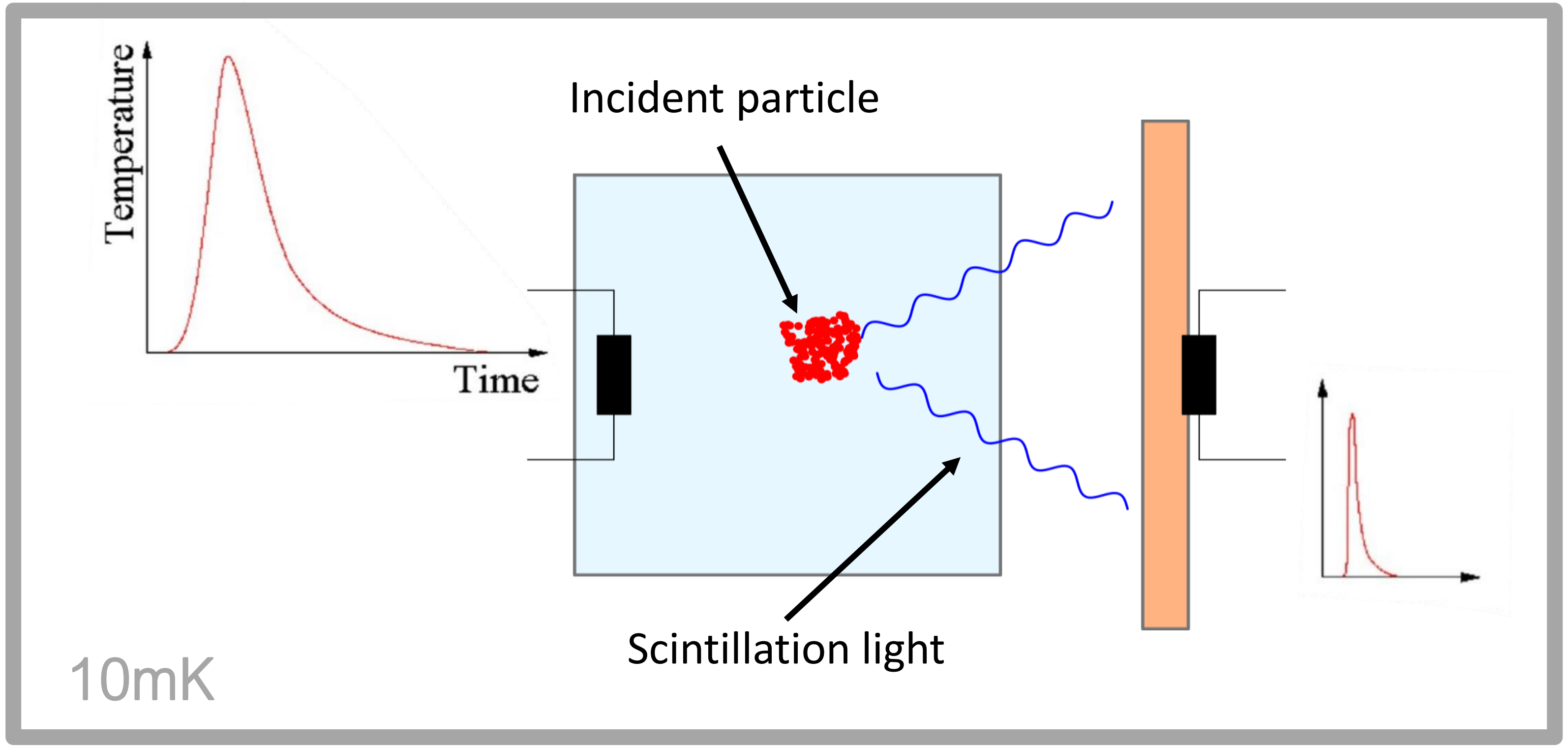
~90% degraded αs

<1% muons

CUPID technology: scintillating cryogenic calorimeters

Scintillating crystal enriched in 0νββ candidate

Operated as a cryogenic calorimeter



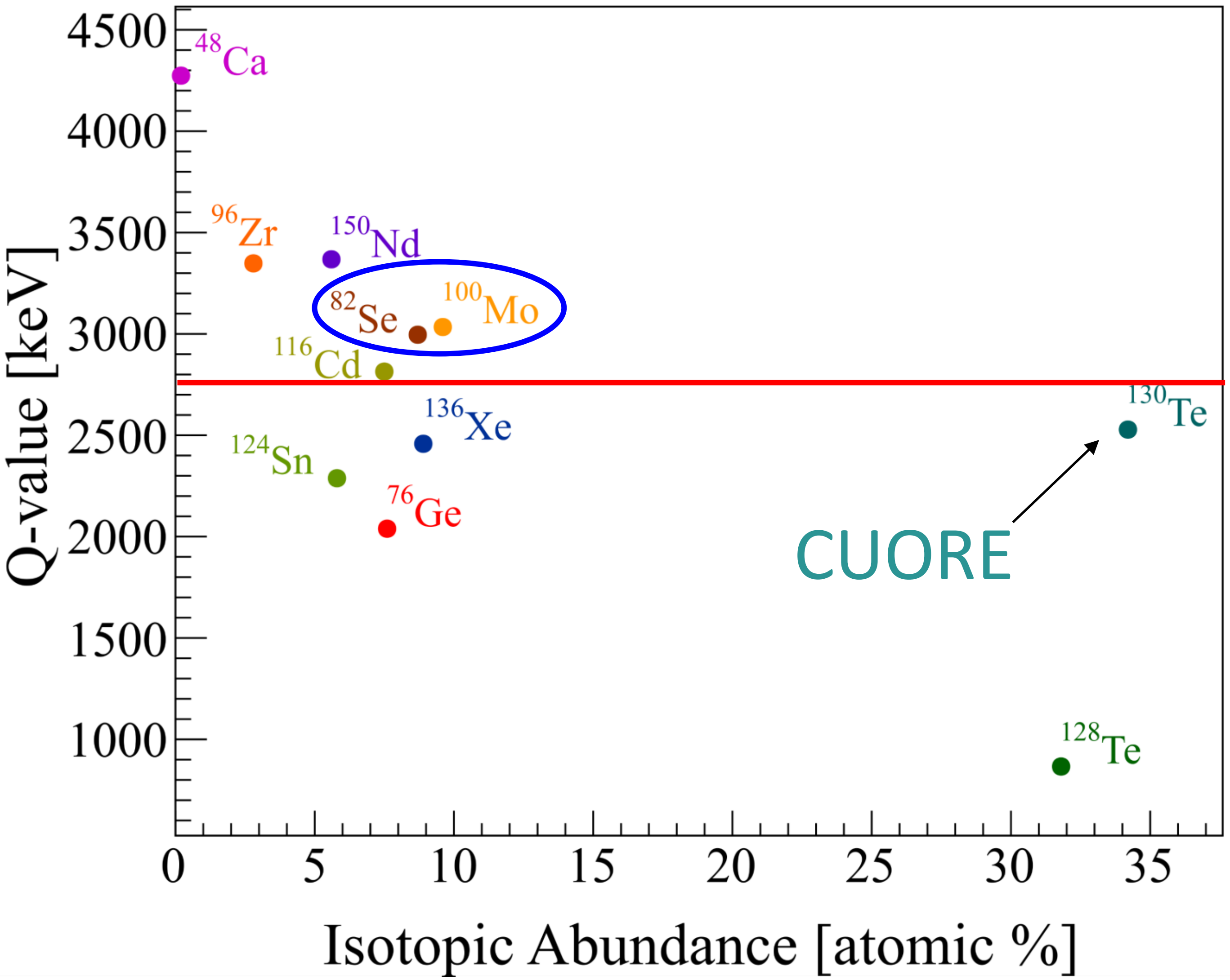
Cryogenic calorimeter used as light detector

Particle identification with pulse shape and light output

Discrimination of degraded α particles

Main residual CUORE background

Choice of the isotope under study



Above the endpoint of ^{208}Tl radioactivity

Reduction of the residual background in CUORE

Highest possible isotopic abundance

Mass efficiency

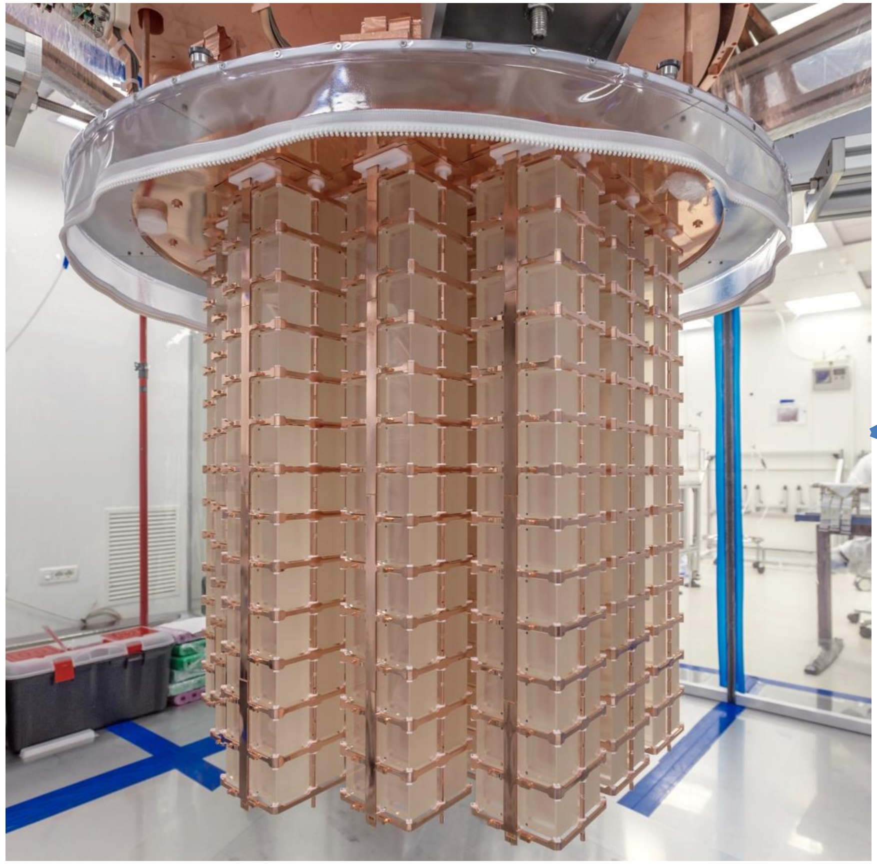
Easier enrichment

Included in a scintillating crystal

^{100}Mo and ^{82}Se are the best choices

The steps taken for the definition of CUPID

Decades-long R&D lead to CUORE



CUPID-0

Experiment based on ^{82}Se

CUPID-Mo

Experiment based on ^{100}Mo

Proven technology

Ton-scale cryogenic detector is feasible

Development of expertise

Background control, analysis, operation , …

Test the two isotopes

With scintillating cryogenic calorimeters

Evaluate the technology potential

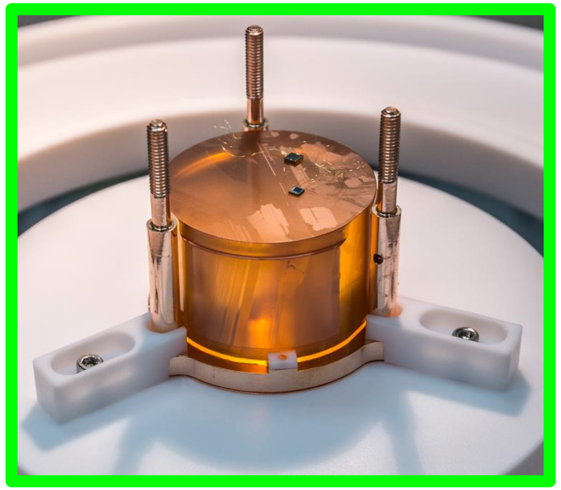
Build a solid start for CUPID

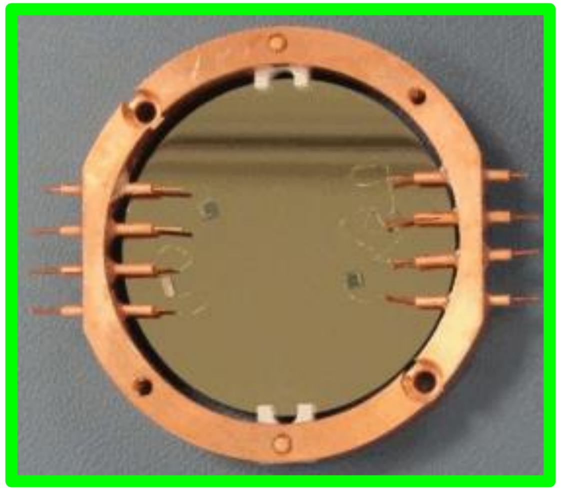
CUPID-0 detector – phase I

Scintillating **ZnSe** crystals.

Heat signal:

bolometric high resolved output



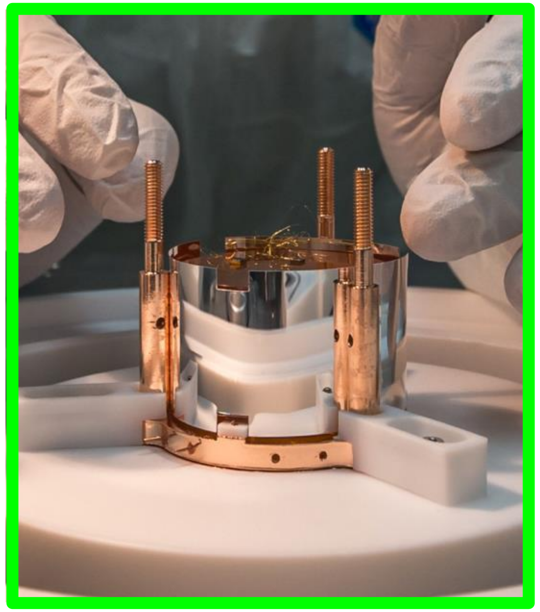


Bolometric **Ge Light detectors**

Light signal:

particle identification

- **26 ZnSe crystals**
  - 24 with 95% ^{82}Se
- **Total mass= 10.5 kg**
  - ^{82}Se mass =5.17 kg

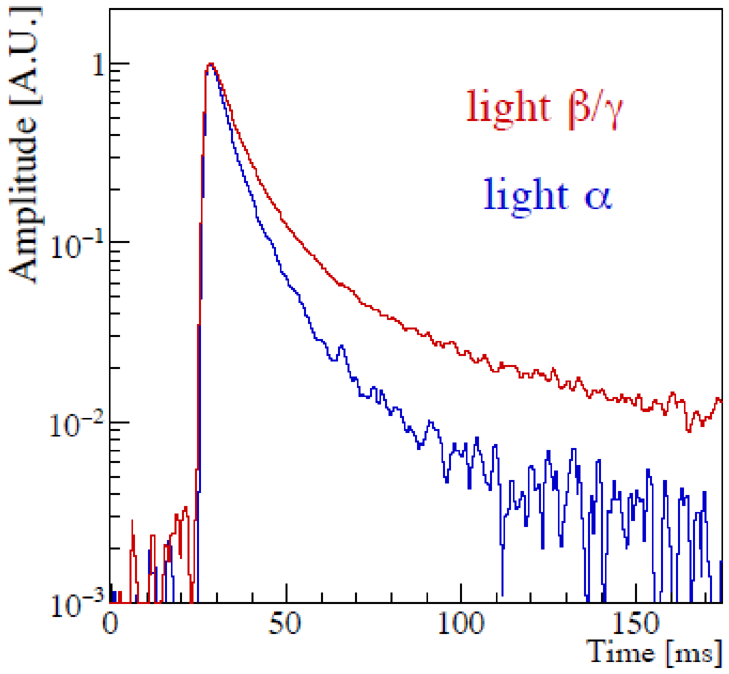


Vikuiti Reflector

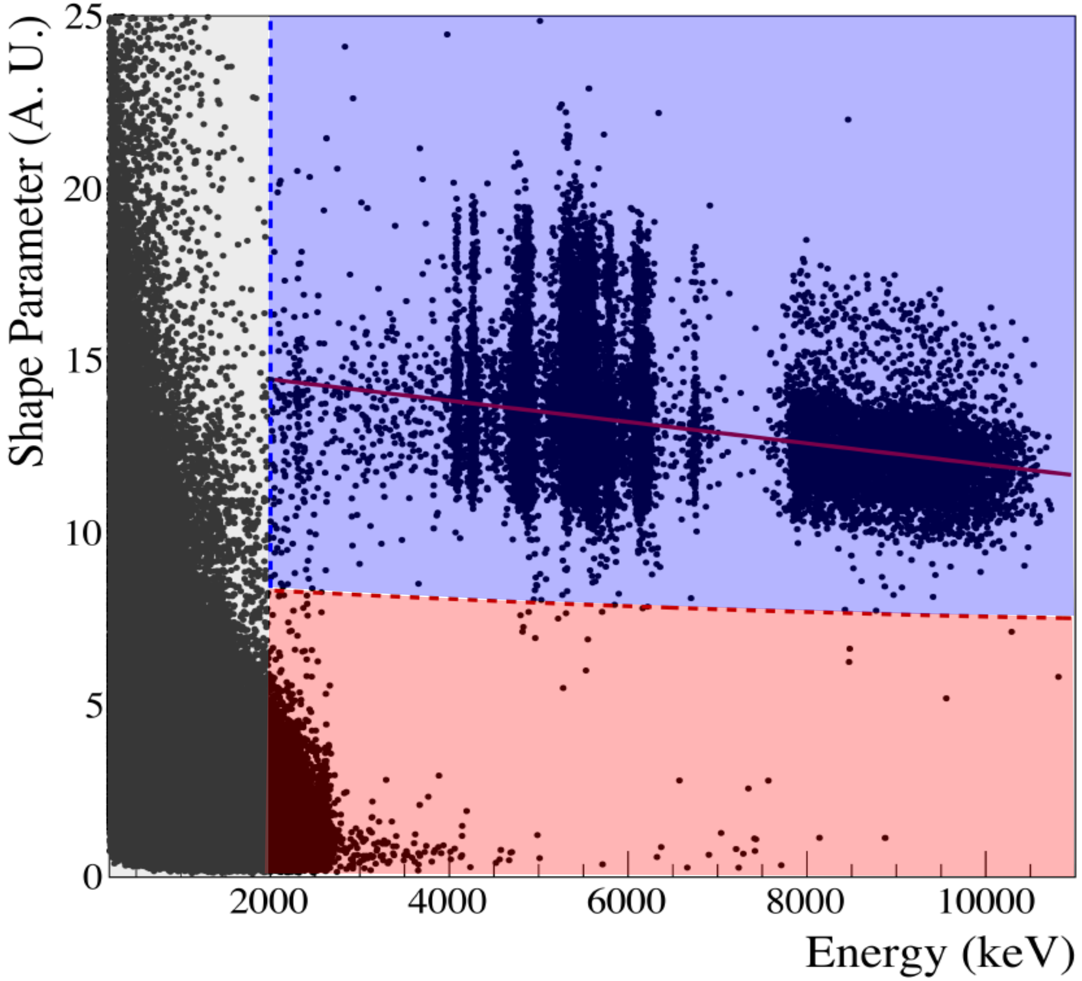
More collected light

Light-based alpha rejection

Light Signal depends on particle type



Selection based on light shape parameter



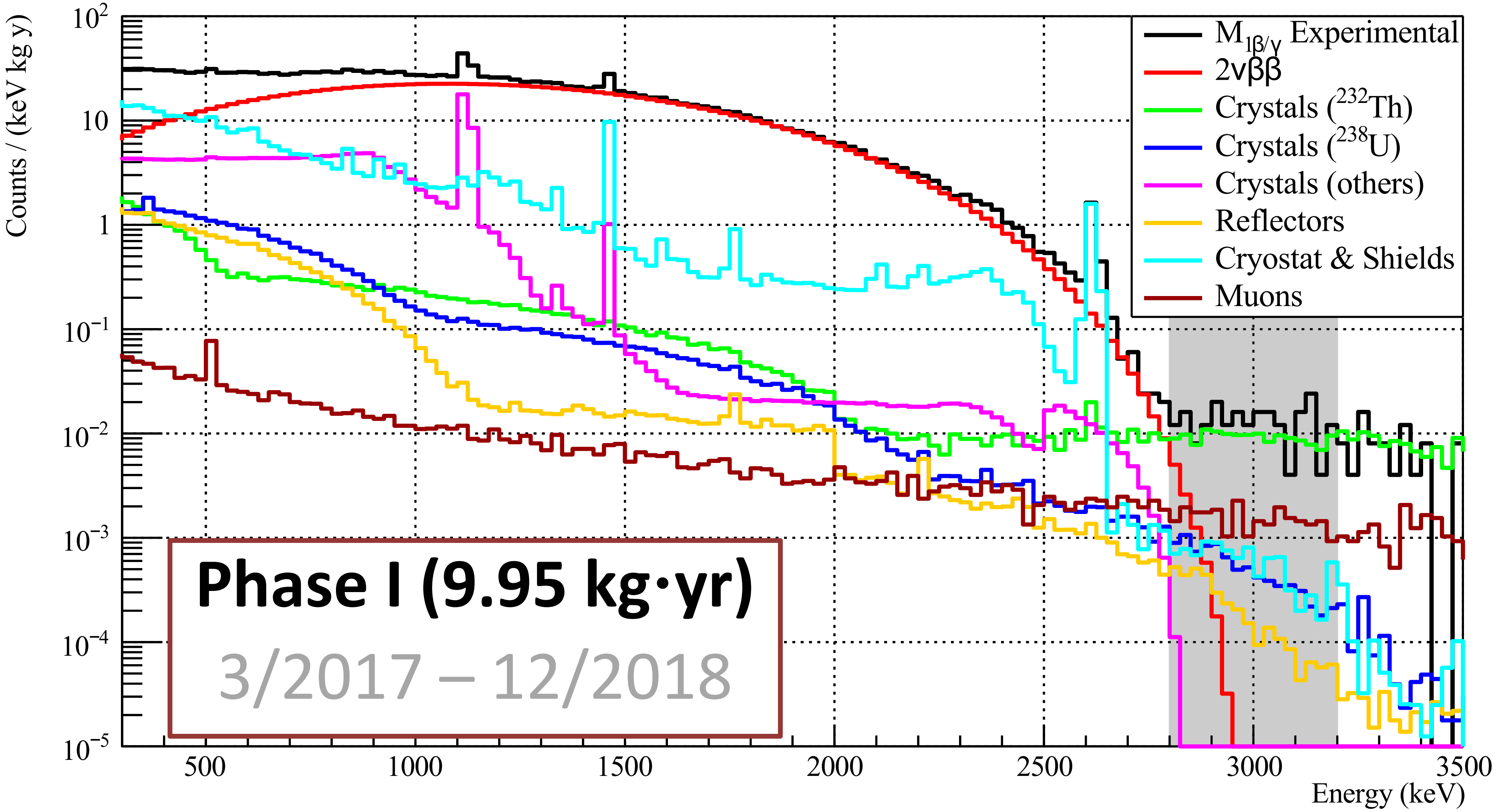
α events

β/γ events

Unresolved events

Background model

Eur. Phys. J. C (2019) 79: 583 (2019)



In the ROI

^{232}Th is dominant, because no delayed cut is applied

Delayed coincidences

Muons give 44% of residual background

2νββ is a dominant spectral feature

Possibility to perform detailed study on this decay

Phys. Rev. Lett 123, 262501 (2019)

Phys. Rev. D 100, 092002

CUPID-0 Phase II

arXiv:2206.05130

From background model residual backgrounds are known

~44% muons, residual close contaminations

Design change to study these categories of events

Phase II (5.74 kg·yr)

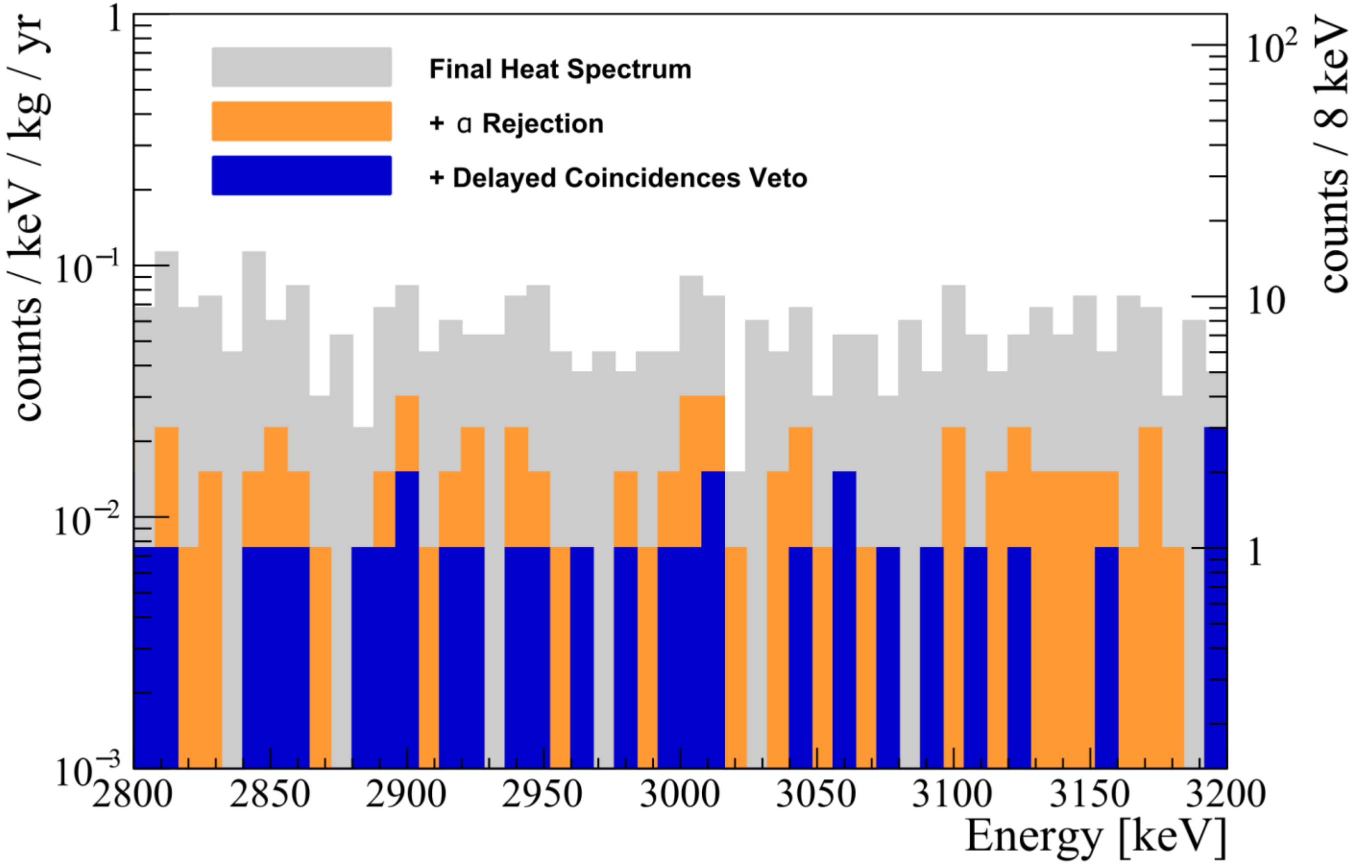
6/2019 – 2/2020

No reflector (coincidences)

Muon veto (lateral+top)

Internal copper shield

Background in the ROI



Residual background after α and delayed rejection

Phase I

$$(3.5 \pm 1) \cdot 10^{-3}\ \mathrm{cnts/(keV \cdot kg \cdot y)}$$

Phase II

$$(5.5 \pm 1.5) \cdot 10^{-3}\ \mathrm{cnts/(keV \cdot kg \cdot y)}$$

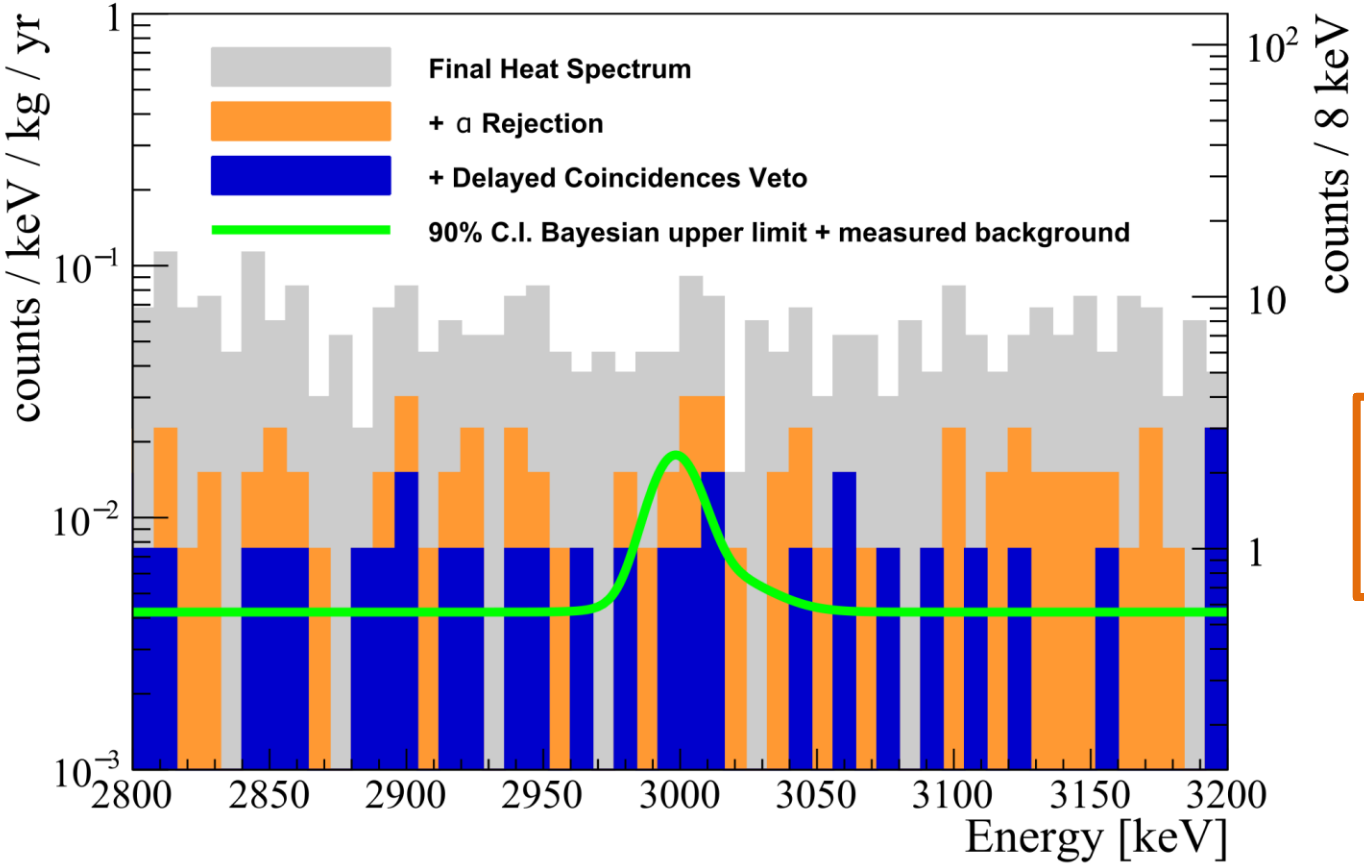
Total exposure:
16.59 kg·yr

Energy resolution (@Q_{Val})
(20.05±0.34) keV

Total selection efficiency:
(69.2±1.2)%

Trigger, PID, pulse shape, delayed veto, containment

Final result on the half life



Lower limit to ^{82}Se 0νββ half life

Bayesian analysis including systematics

$$\boxed{T^{0\nu}_{1/2} > 4.6 \cdot 10^{24}\ \mathrm{y} \quad (90\%\mathrm{C.I.})}$$

Best limit on ^{82}Se

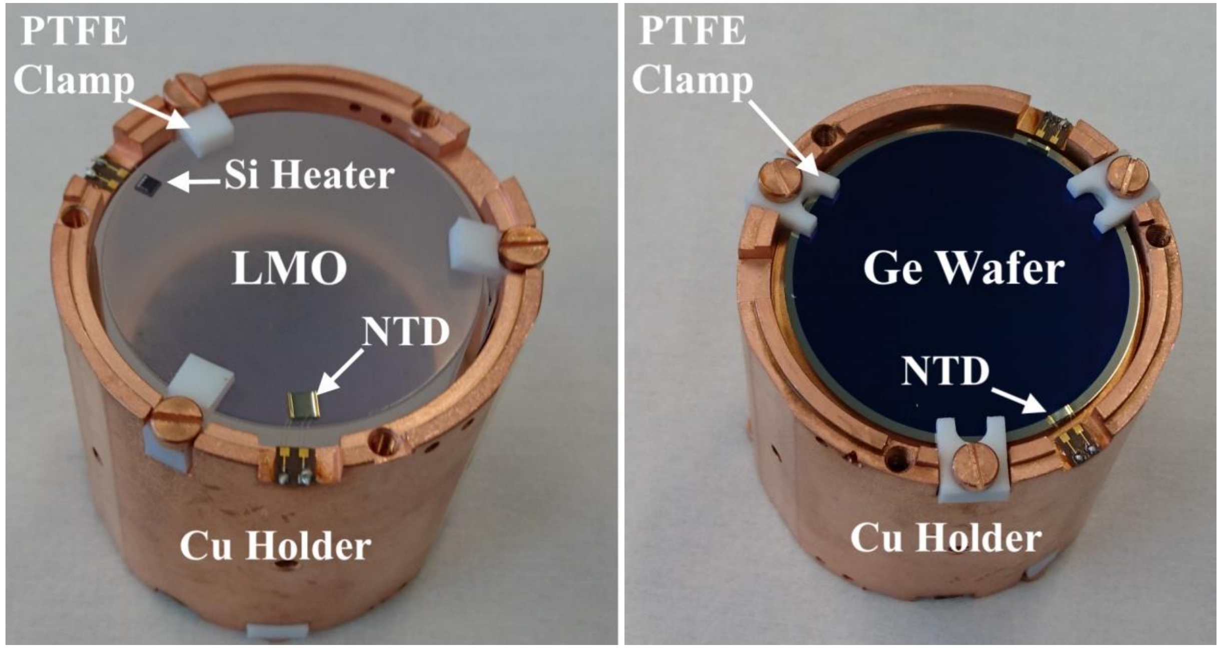
Considering matrix elements, limit on Majorana mass

$$m_{\beta\beta} < 263 - 454\ \mathrm{meV}$$

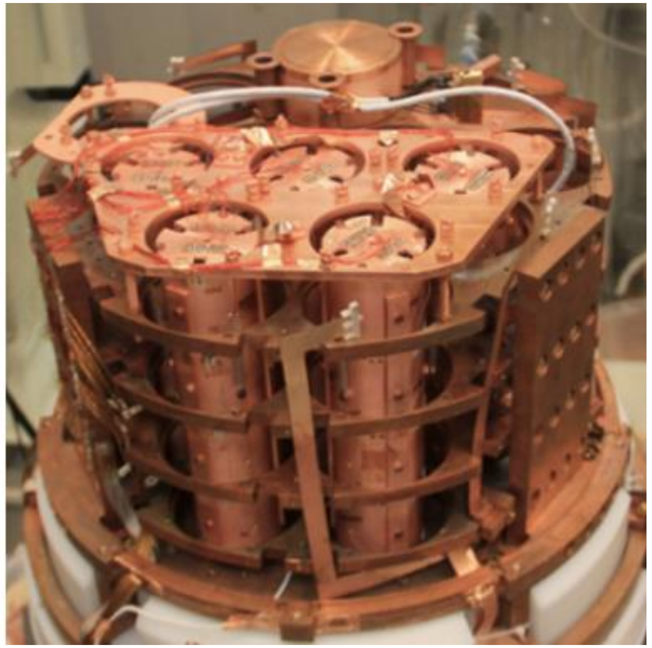
CUPID-Mo detector

Eur. Phys. J. C **80,** 44 (2020)

Scintillating
$Li_2{}^{100}MoO_4$ crystals
ø44 mm x 45mm,
210g
97% ^{100}Mo

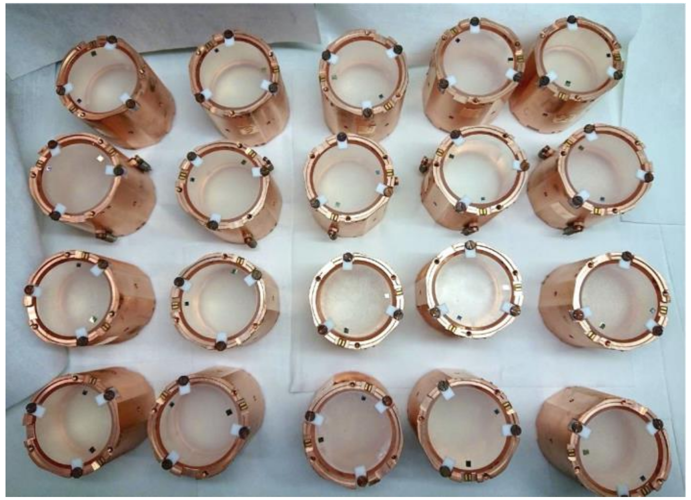


2 Ge wafer with
SiO anti-reflective
coating
Light detector

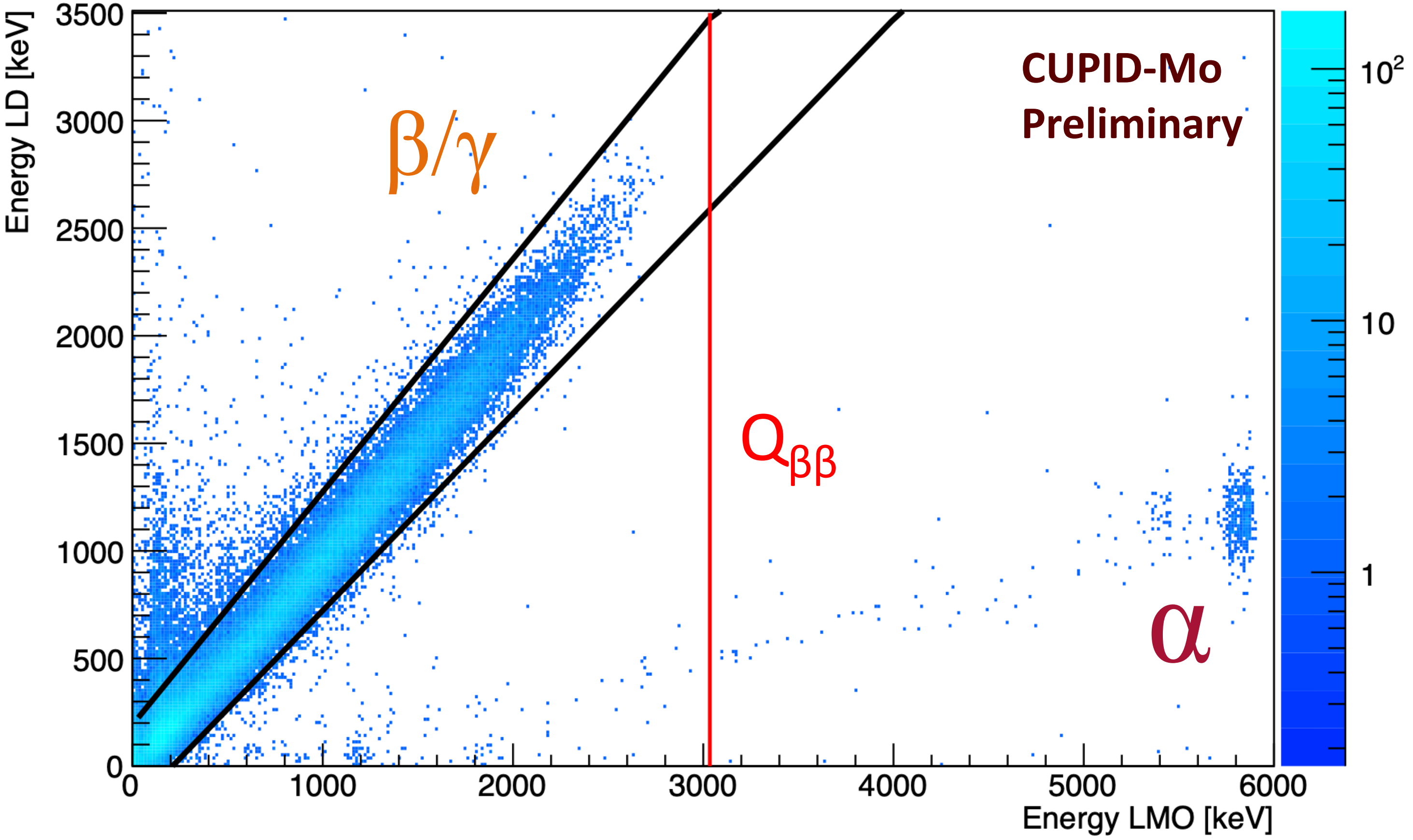


20 detector modules

Operated in Modane in the EDELWEISS
cryostat
Data taking: 03/2019 to 06/2020
2.71 kg·yr



Particle discrimination



Light yield vs energy discriminates particles

LD output calibrated with 17.5 keV Mo X-rays

β/γ band modelled as function of the LMO energy

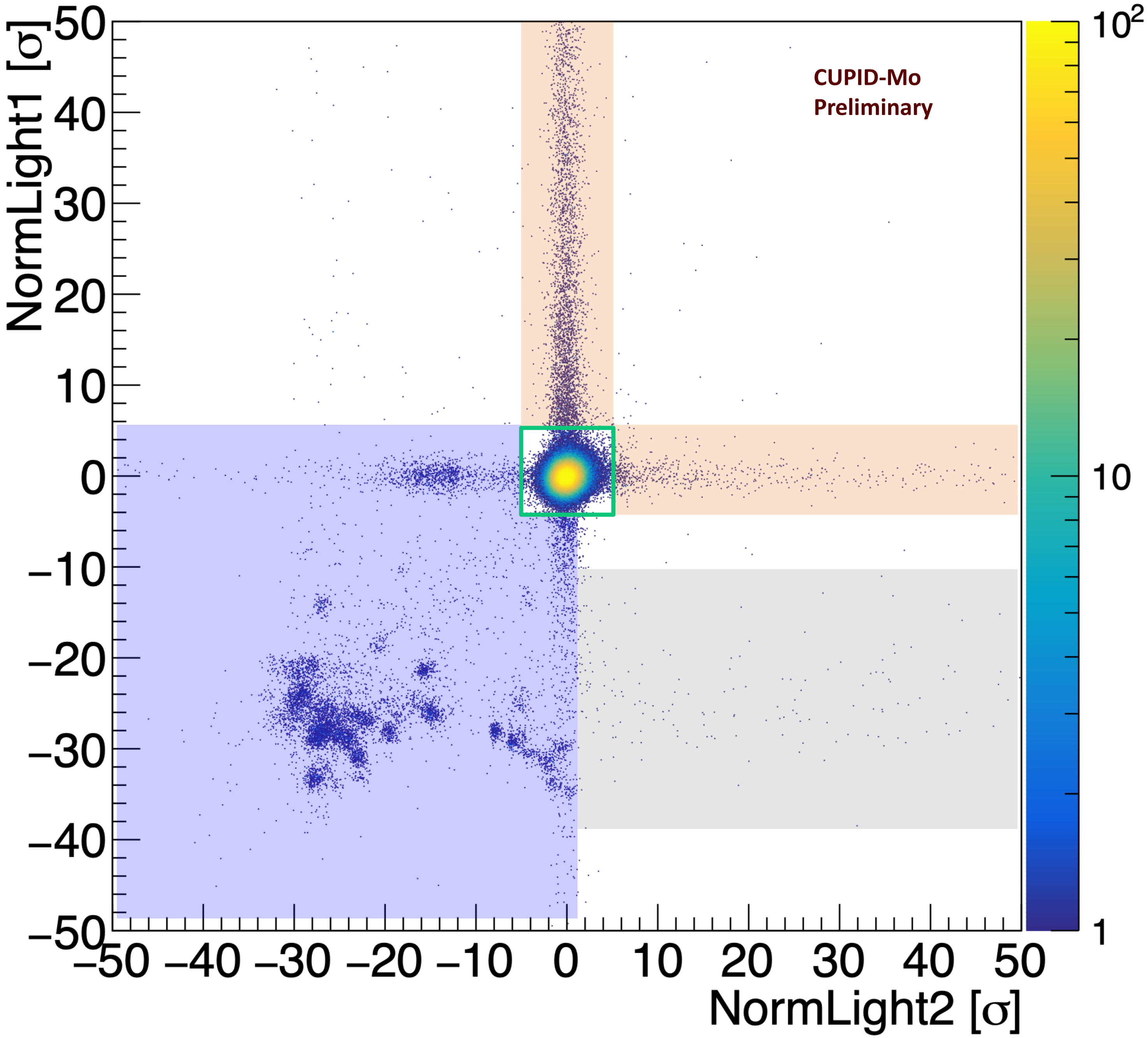
Gaussian fit in slices of energy

Using normalized light for the selection

Modellization gives L(E) (LY) and σ(E)

$$N(E) = \frac{L_{obs} - L(E)}{\sigma(E)}$$

Normalized light cut



Normalized light for the 2 LDs in each module

Different events can be identified

α and non-light events

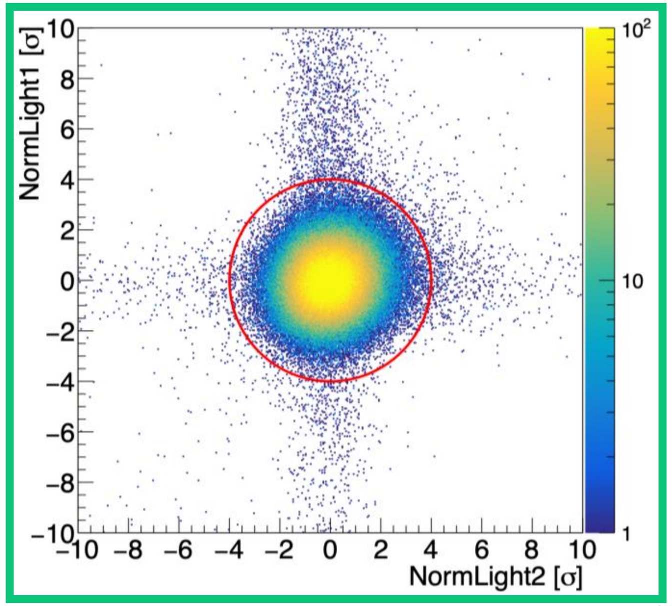
β on single LD

Nuclear recoils on LD

Final selection:

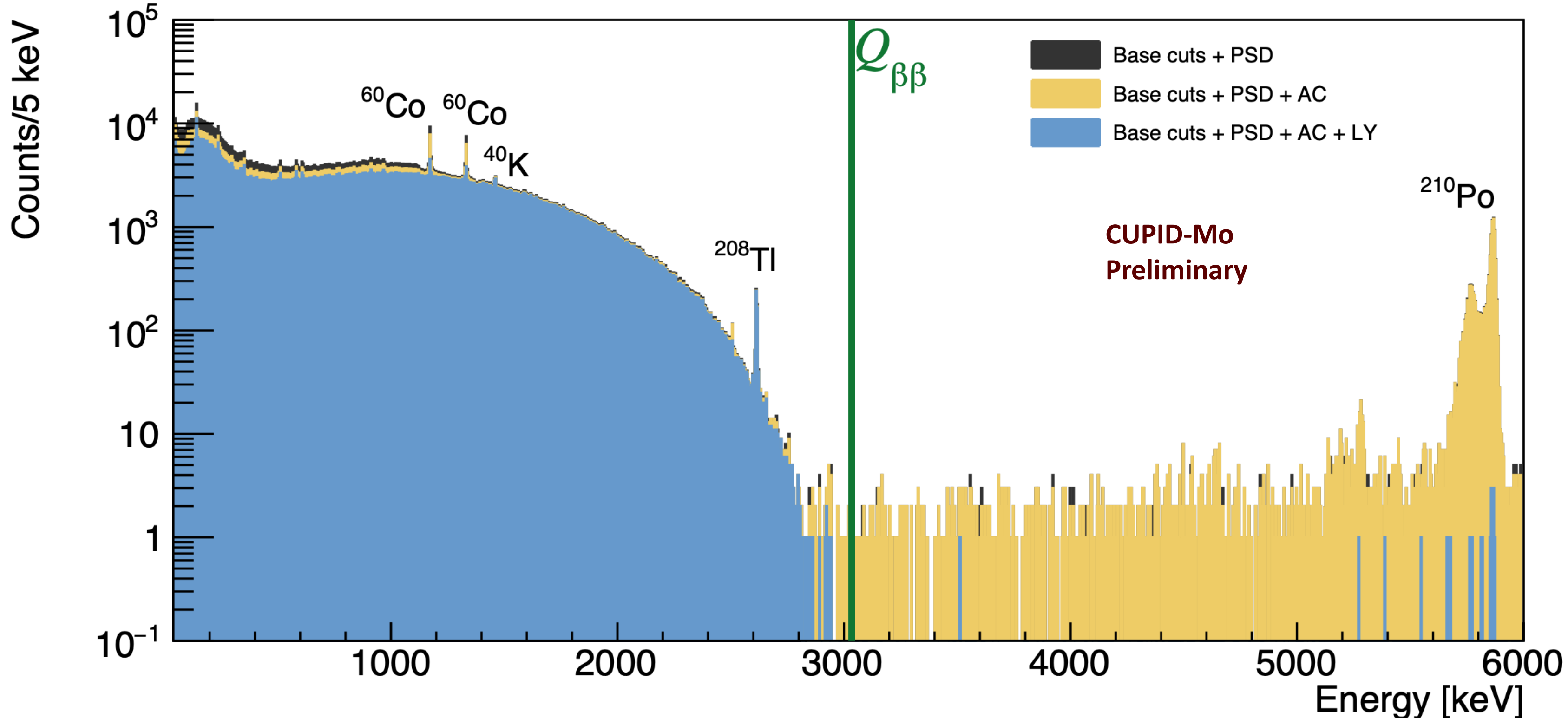
Circle with radius 4

3.5 sigma equivalent



Limit on ^{100}Mo half life

arXiv: 2202.08716



Unblinded background spectrum

Total efficiency: (88.4±1.8)%

PSD through PCA analysis

Anti-Coincidence rejection

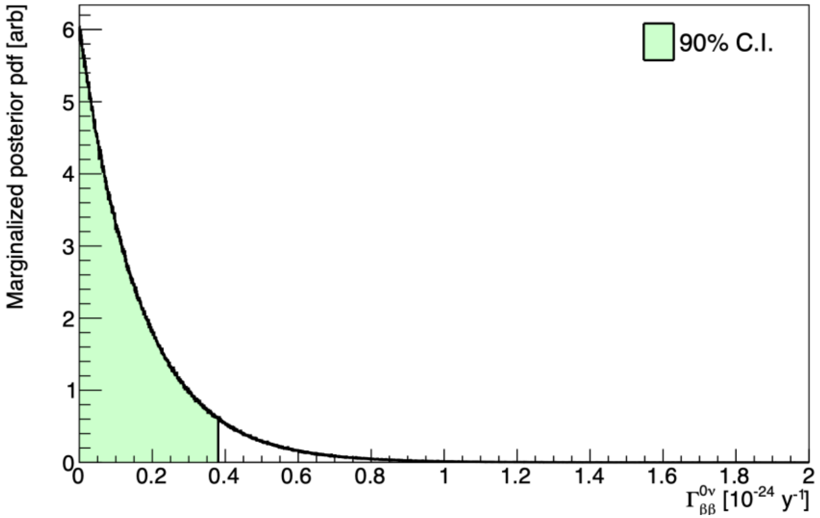
LY through norm-light cut

Energy resolution: (7.4±0.4) keV

No events in the ROI

90% Bayesian limit

Including systematics



$$T^{0\nu}_{1/2} > 1.8 \cdot 10^{24}\ \mathrm{y} \quad (90\%\mathrm{C.I.})$$

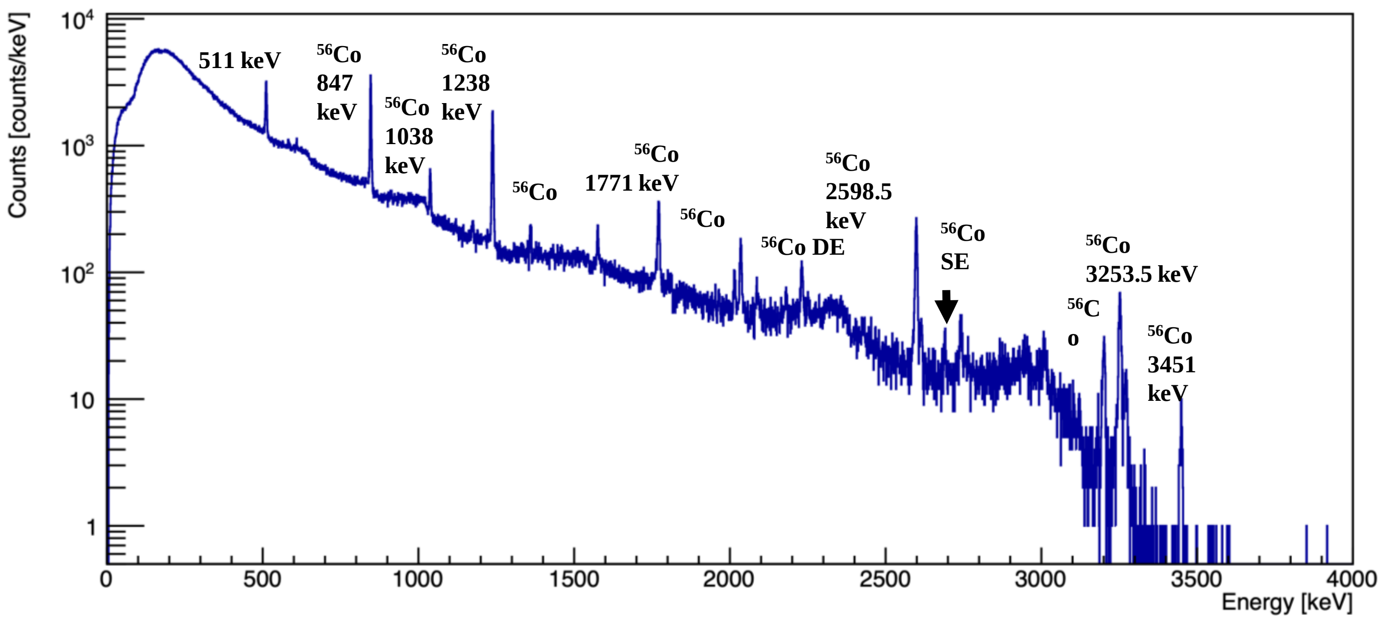
$$m_{\beta\beta} < 280 - 490\ \mathrm{meV}$$

Best limit for ^{100}Mo

Other analyses are underway

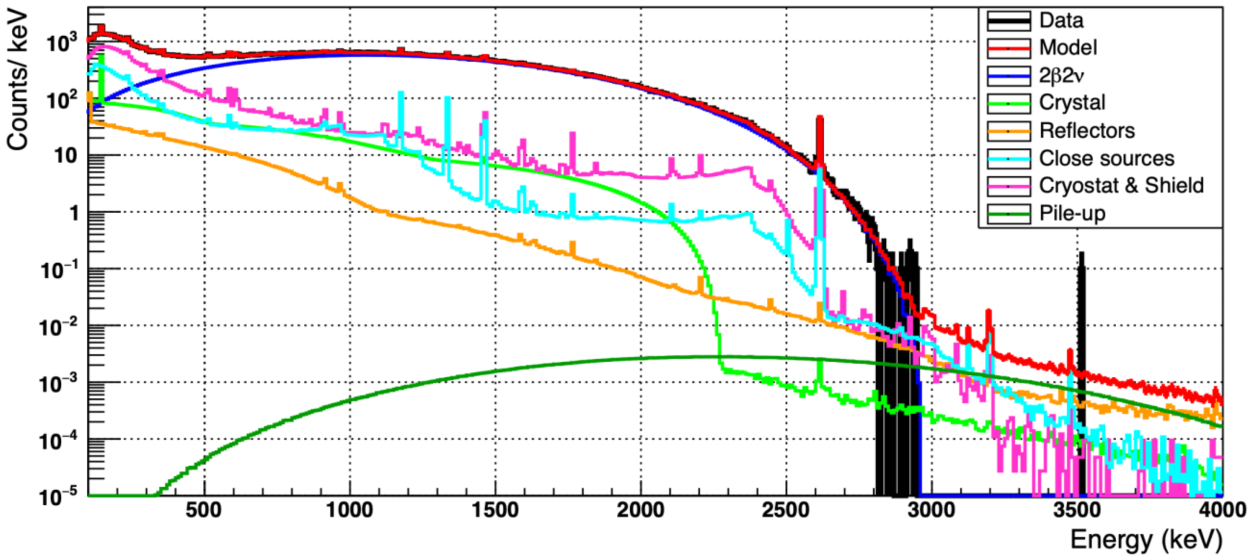
^{56}Co Calibration analysis

Detailed energy dependence of detector performance



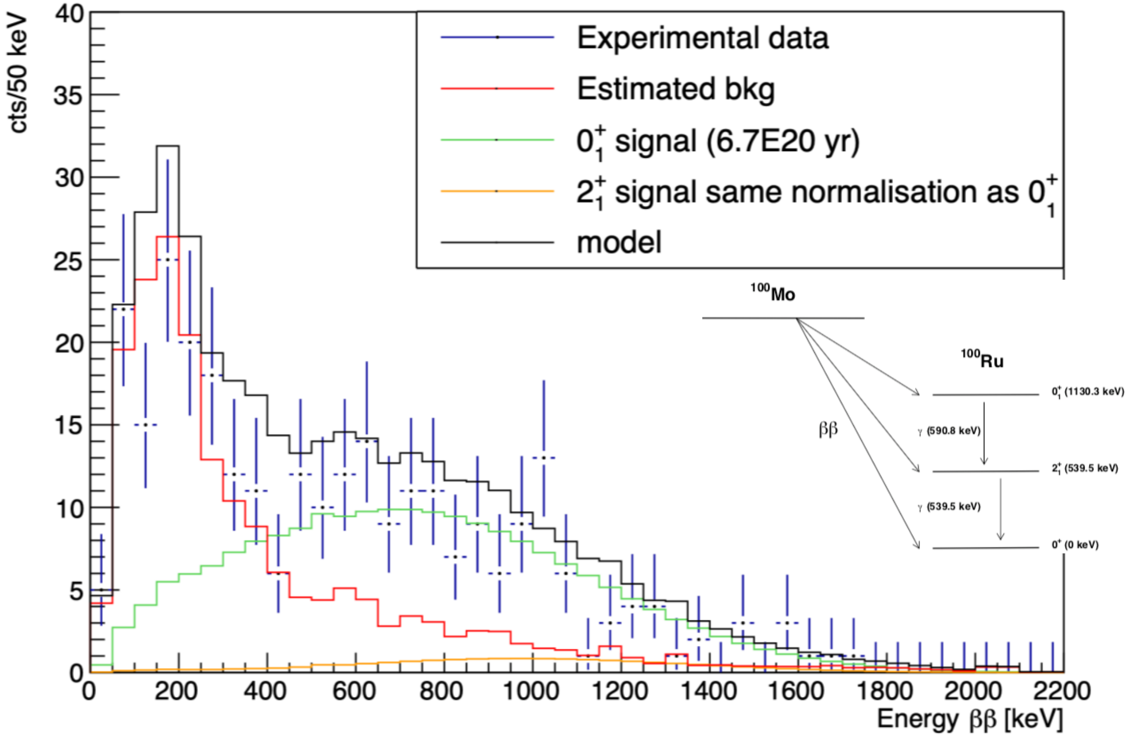
Definition of a complete background model

Understanding all the contaminations



ββ decay to excited states

Paper in progress!



And more …

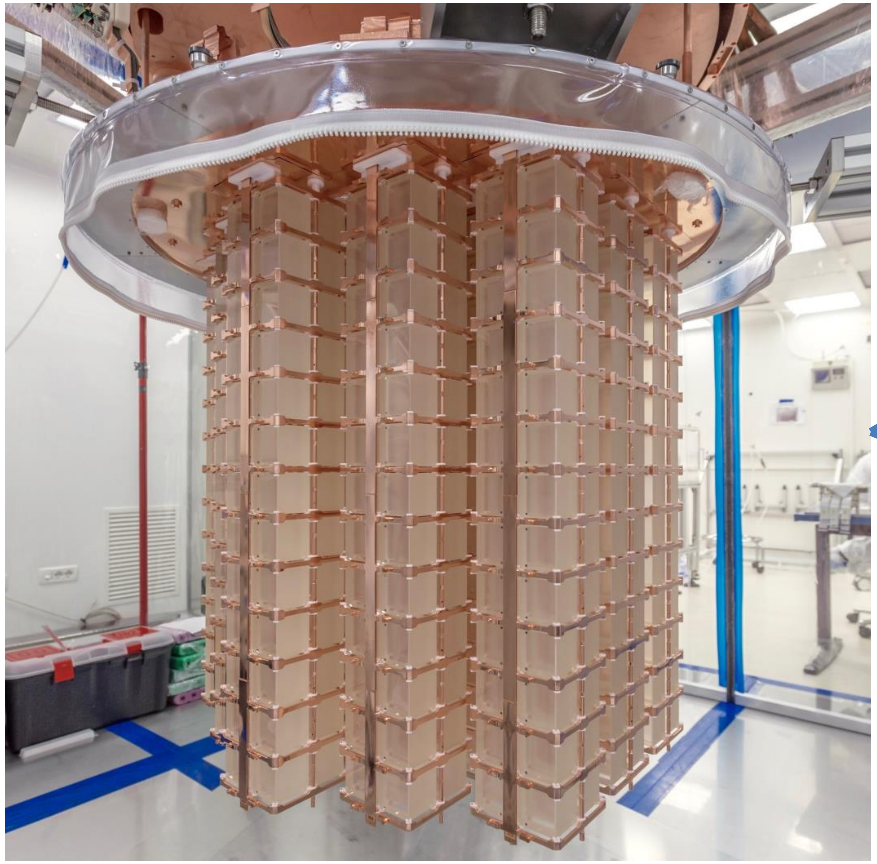
Low mass DM searches

Solar axion searches

Stay tuned for updates

The steps taken for the definition of CUPID

Decades-long R&D lead to CUORE



CUPID-0

Experiment based on ^{82}Se

CUPID-Mo

Experiment based on ^{100}Mo

Scintillating cryogenic calorimeters proven effective

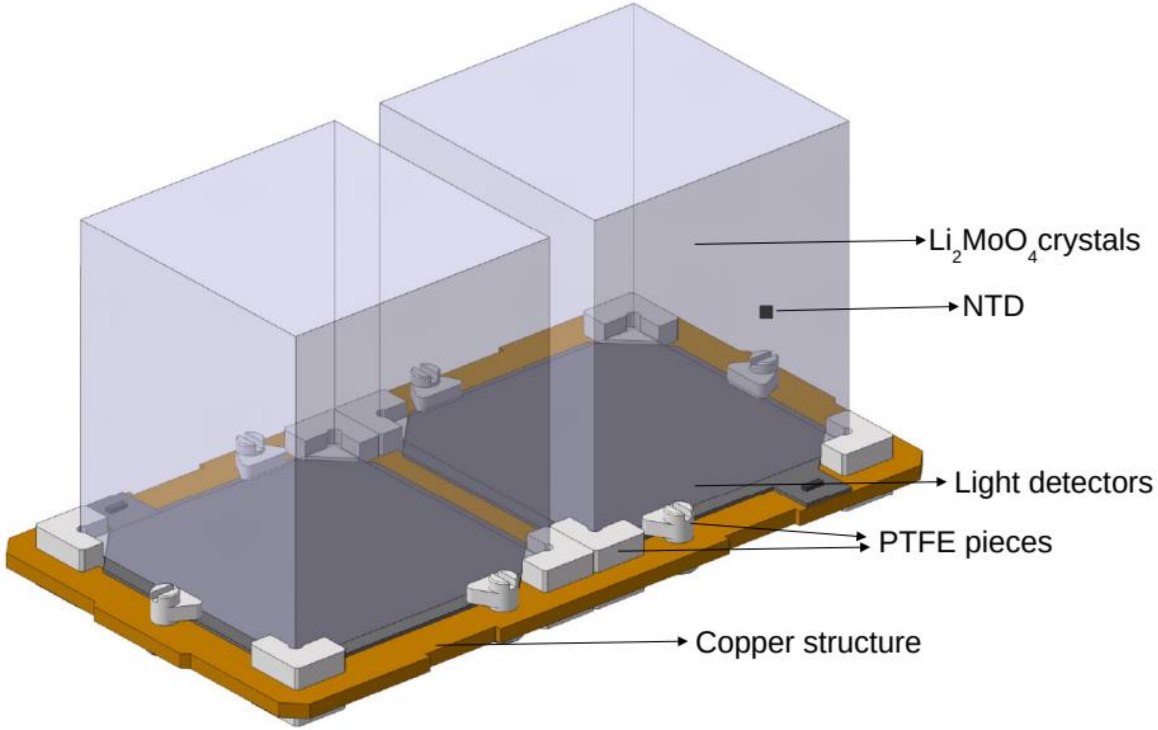
$Li_2{}^{100}MoO_4$ crystals are better

Energy resolution, growth and contaminations

Baseline CUPID design

Single module

Minimizing copper near the crystals



45x45x45 mm^3 crystals

Crystal mass: 280 g

95% enrichment in ^{100}Mo

Ge light detectors

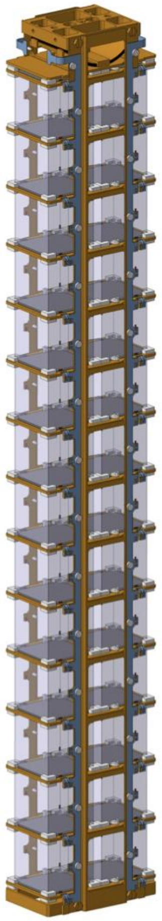
SiO anti-reflective coating

No reflective foil

Stacked in towers

14 floors

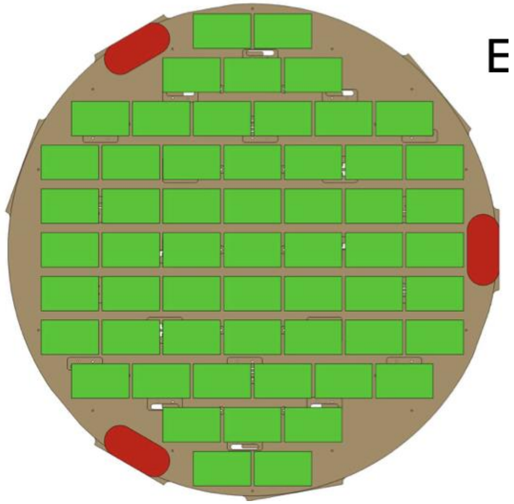
28 crystals



Inside the CUORE cryostat

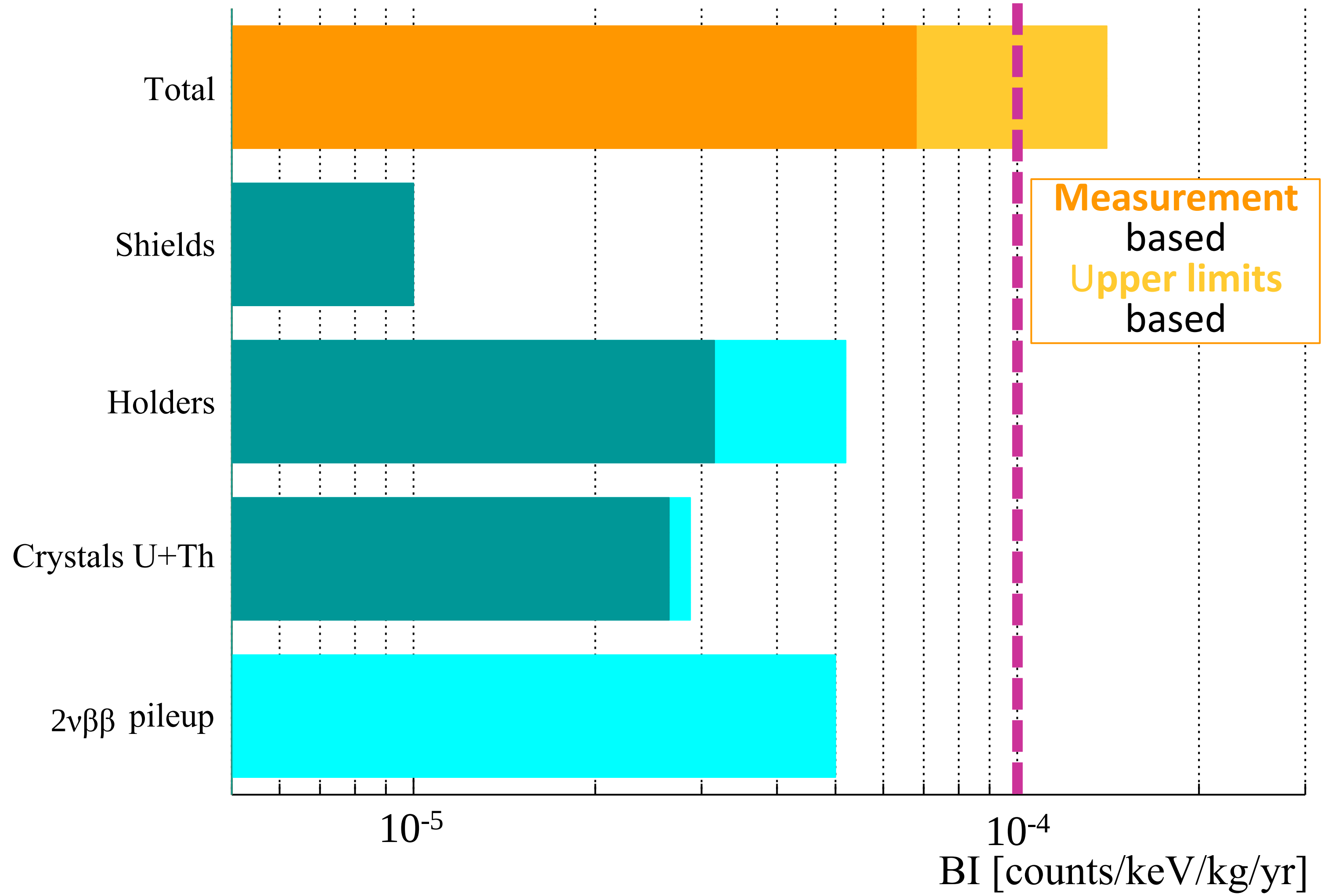
57 towers

1596 Crystals



Muon veto around the detector

The background index



CUPID sensitivity goal is

$$T_{1/2}^{0\nu} > 10^{27}\ \mathrm{y}$$

Translates to ROI Background limit

$$< 10^{-4}\ \mathrm{cnts}/(\mathrm{keV}\cdot\mathrm{kg}\cdot\mathrm{y})$$

Feasible given current **measurements** and **upper limits**

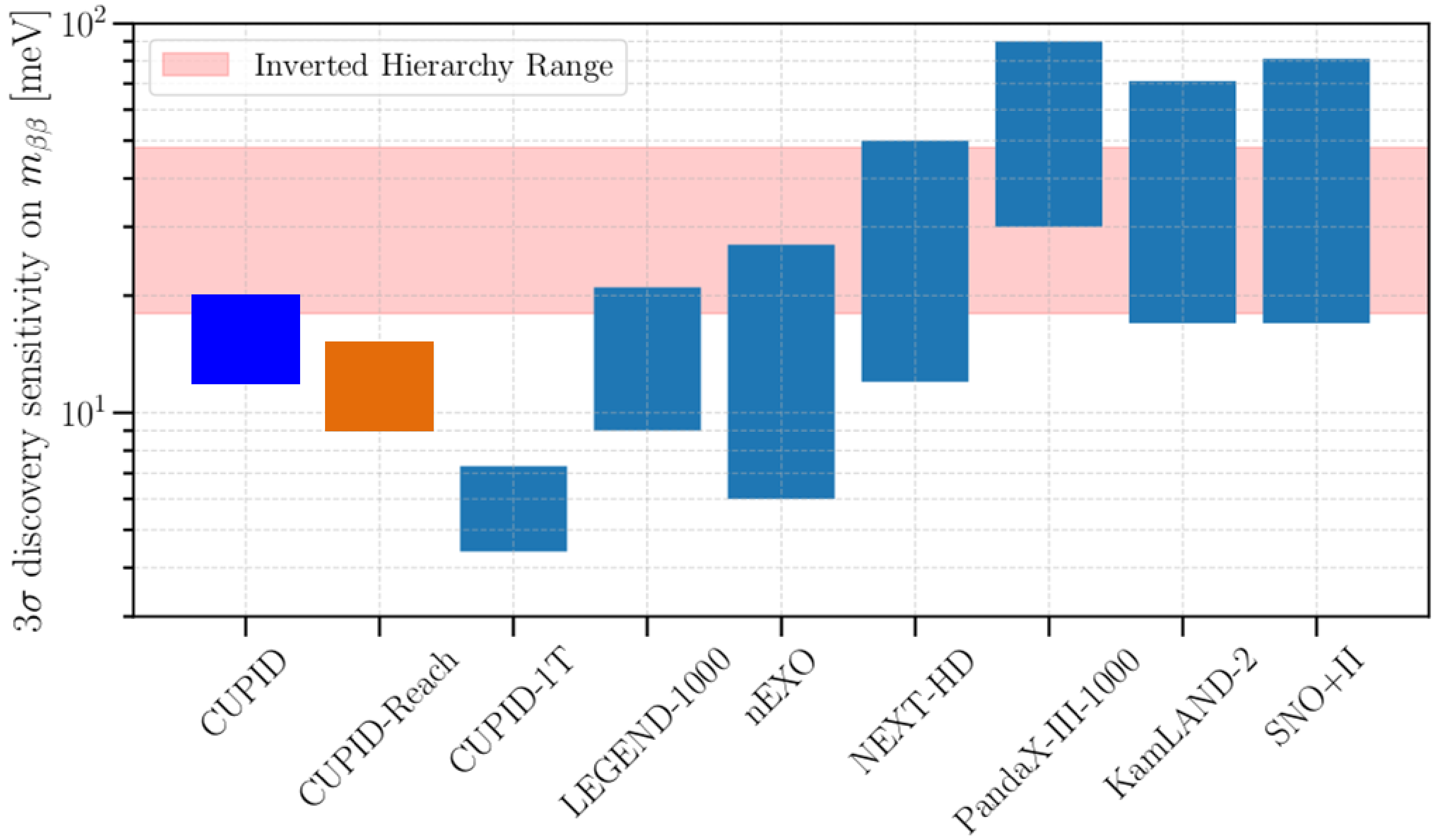
From CUORE, CUORE-0 and CUPID-Mo

Expected CUPID sensitivity

arXiv:1907.09376

Scan the inverted hierarchy range

	CUPID	CUPID Reach
Mass (kg)	450	450
^{100}Mo Mass (kg)	240	240
Resolution (keV FWHM)	5	5
Background Index (counts/(keV kg yr))	10^{-4}	2×10^{-5}
90% CL Half-life Exclusion (meV)	1.4×10^{27}	2.2×10^{27}
3σ Half-life Discovery (meV)	1×10^{27}	2×10^{27}
90% CL $m_{\beta\beta}$ Exclusion (meV)	10 - 17	8.4 - 14
3σ Discovery (meV)	12 - 20	9 - 15

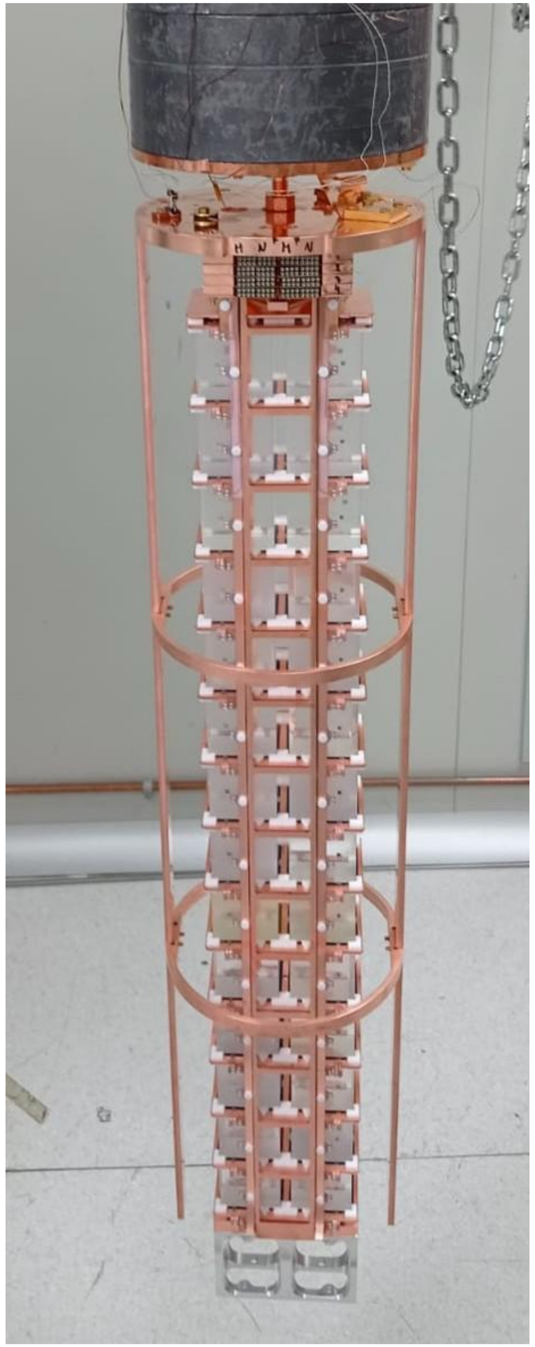


What we know we can do

What is a small step ahead

CUPID has a place amongst the next generation experiments

What is going on: Single tower test



First tower of the baseline design

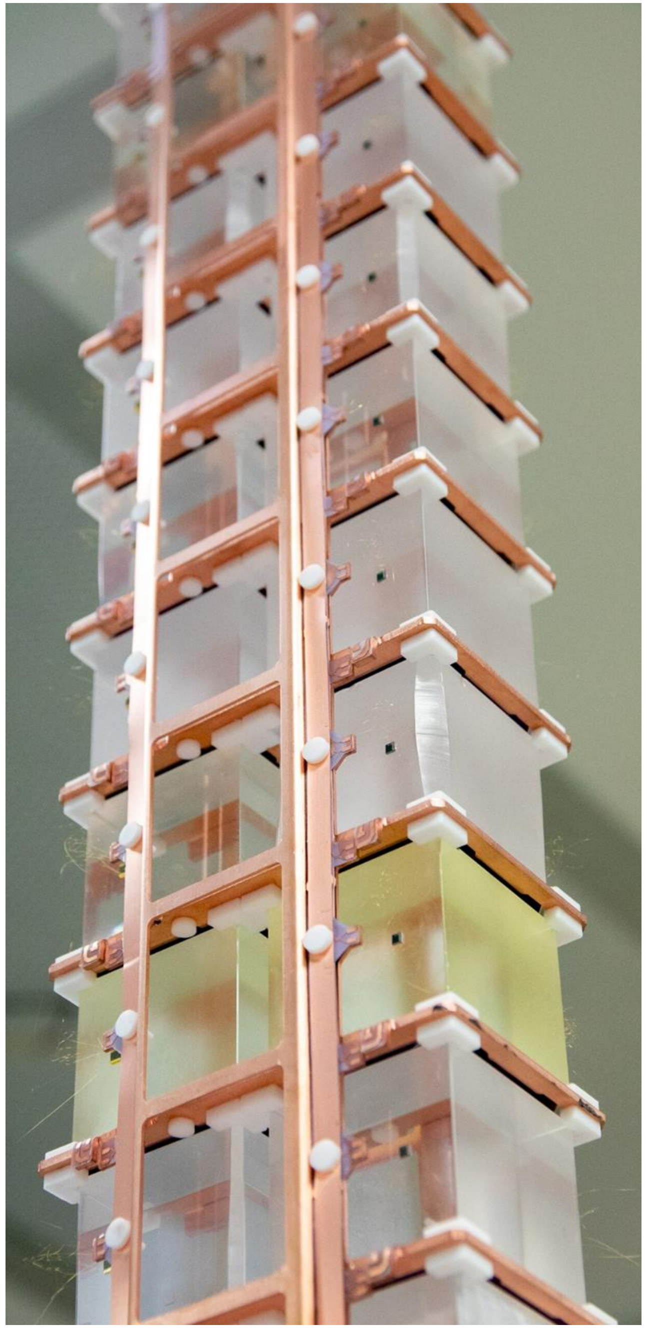
Test the new structure

Thermalization, mounting procedure

Test crystals from different origin

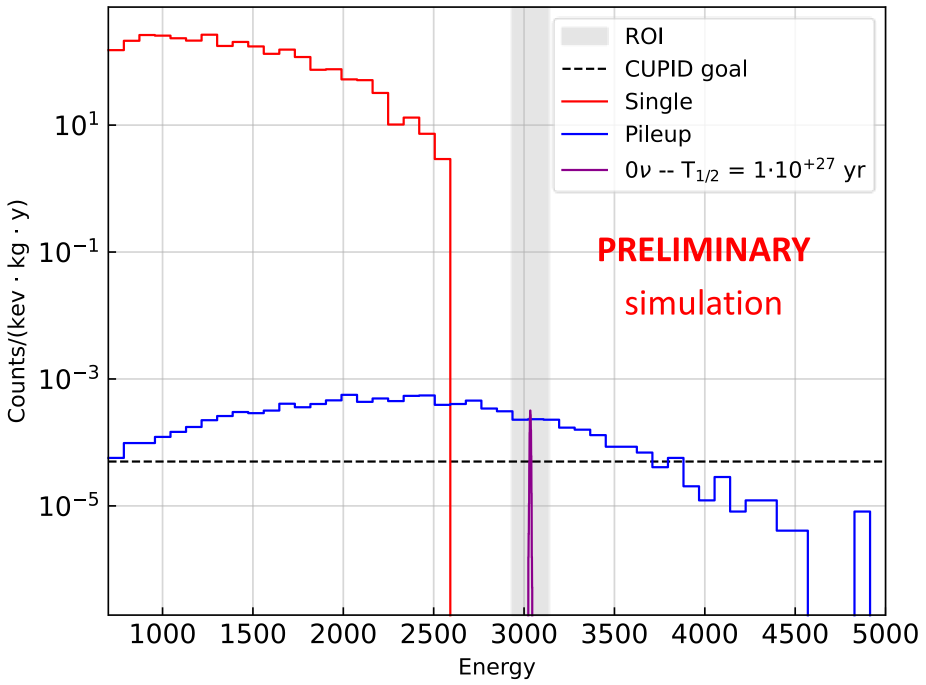
Bolometric performances

Currently in operation in Hall-A @LNGS!!



Current additional studies (Pileup)

Phys. Rev. C 104, 015501



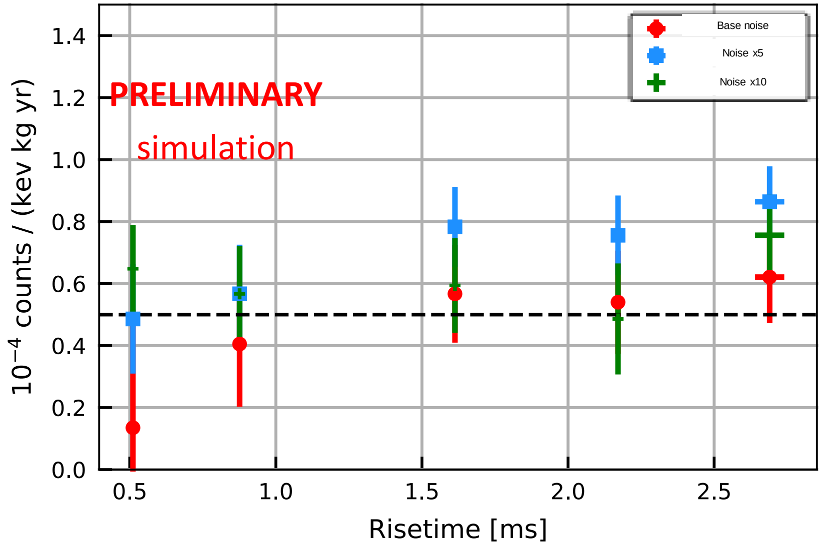
Relatively fast ^{100}Mo 2ν mode

$$T^{2\nu}_{1/2} = 7.1 \times 10^{18}\ y$$

High mass, enriched detector

High probability of 2ν events pileup

Pileup effect is 0 → 2·Q_{value} background



Current work on simulations and measurements

Test mitigation strategies

Set detector requirements

machine-learning algorithms

Timing-focused analysis

The next-to-next generation: CUPID 1-ton

4x scale up

1871 kg of $Li_2{}^{100}MoO_4$ → 1000 kg of ^{100}Mo

Cryogenics are achievable with current technology

Distributed multi-cryostat setup

Or single large cryostat

Quantum sensors

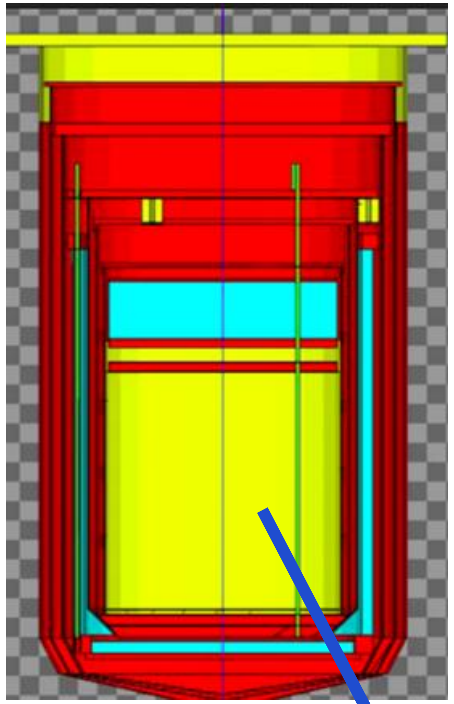
Low-noise, high-bandwidth, multiplexing

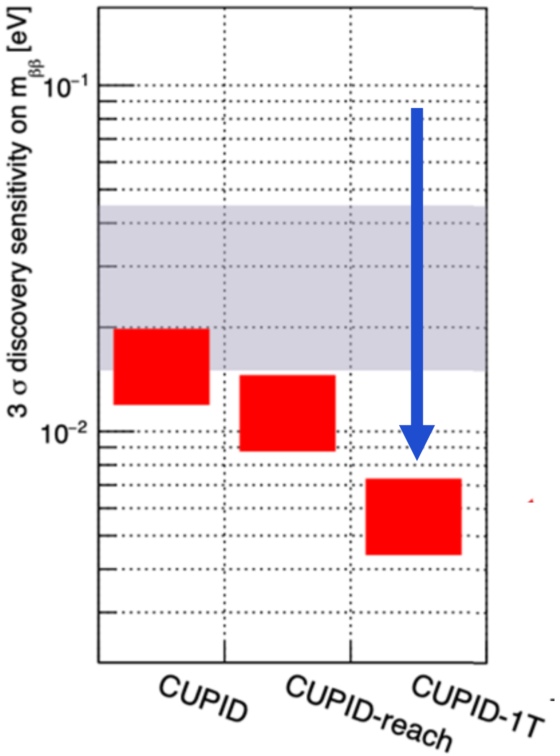
TES/mKIDs superconducting sensors

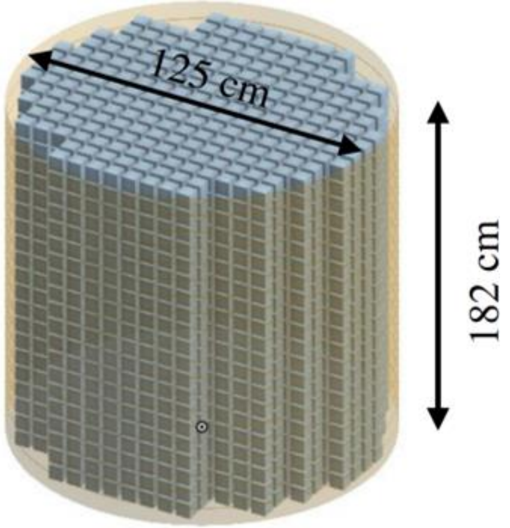
Active R&D

Background goal: 5×10^{-6} counts/(keV·kg·yr)

Reduce all main and subdominant sources







CUPID-1T is an Inverted Hierarchy precision measurement device across multiple isotopes or a Normal Hierarchy explorer

Summary

CUPID will be a next generation $0\nu\beta\beta$ decay experiment

Aim to explore all the full inverted hierarchy

Build upon a multi-decade experience in the field

CUORE: the first ton-scale cryogenic calorimeter

CUPID-0 and CUPID-Mo: demonstrator of the technology

Mature and solid design

Geared towards the next-to-next generation

The CUPID Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazionale di Fisica Nucleare (INFN); by the European Research Council (ERC) under the European Union Horizon 2020 program; by the Italian Ministry of University and Research (MIUR). This material is also based upon work supported by the US Department of Energy (DOE) Office of Science and Office of Nuclear Physics. This work was also supported by the Russian Science Foundation and the National Research Foundation of Ukraine. This research used resources of the National Energy Research Scientific Computing Center (NERSC). This work makes use of both the DIANA data analysis and APOLLO data acquisition software packages, which were developed by the CUORICINO, CUORE, LUCIFER and CUPID-0 Collaborations.

Thank you for your attention from all the CUPID collaboration!

Over 100 scientists from over 30 world-wide institutions

Constantly improving towards the next generation experiments