Windows on the Universe

Rencontres du Vietnam - 30th Anniversary

6-12 August, 2023 - Quy Nhon, Vietnam

The CUORE and CUPID double beta decay experiments

Stefano Ghislandi*, on behalf of the CUORE and CUPID collaboration*

CUORE

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN LNGS

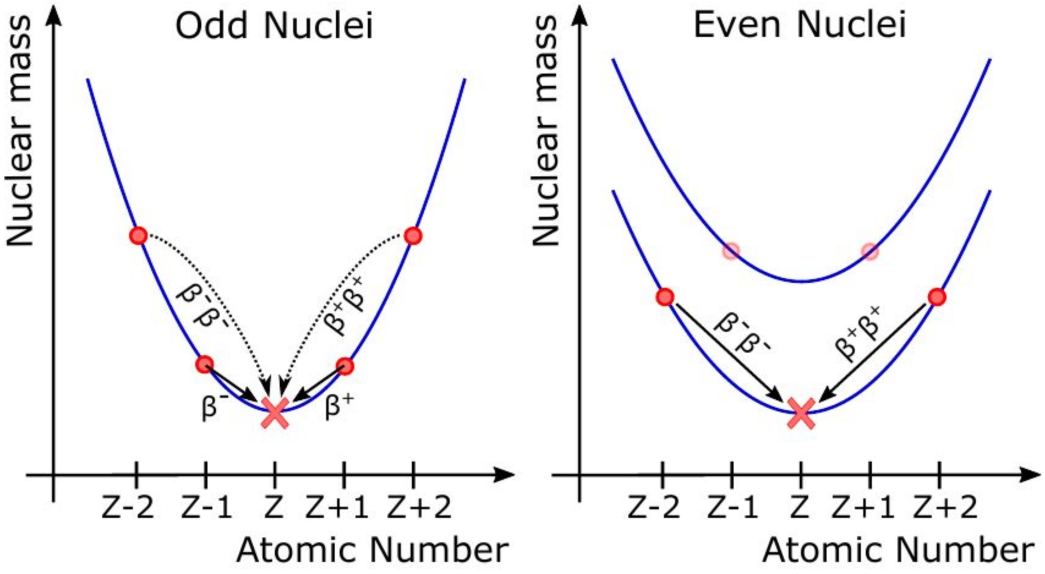
CUPID

Double Beta Decay ($2\nu\beta\beta$)

$$\beta^-\beta^- \qquad (A,Z) \longrightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

$$\beta^+\beta^+ \qquad (A,Z) \longrightarrow (A,Z-2) + 2e^+ + 2\nu_e$$

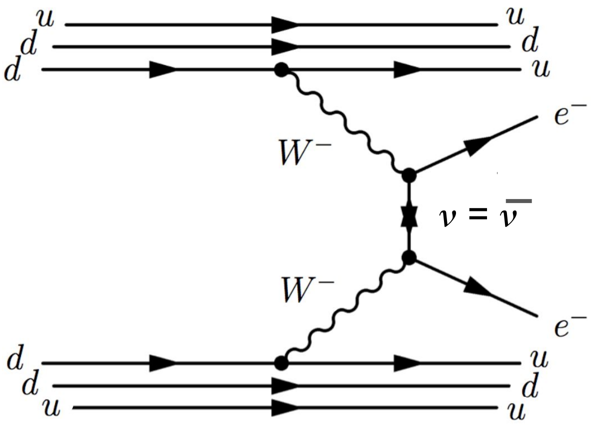
- 2^{nd} order SM process
- Only **even mass number nuclei** (i.e. ^{76}Ge, ^{82}Se, ^{100}Mo, ^{128}Te, ^{130}Te, ^{136}Xe)
- Half-lives in the order of 10^{18}-10^{21} yr
- Precision measurements of the spectral shape → **tests of the nuclear models**



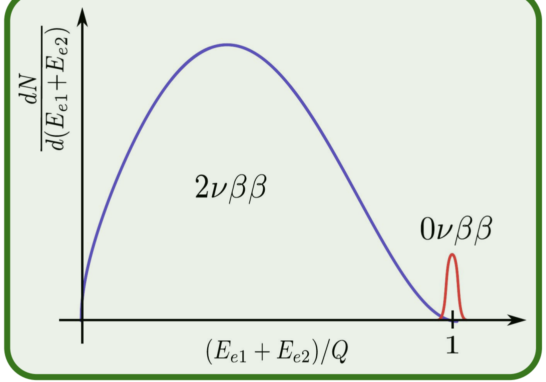
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

WHY IT'S IMPORTANT

- Beyond SM (ΔL = 2)
- **Constraints on neutrino mass** hierarchy and scale
- **Neutrino nature:** Majorana / Dirac



THE ENERGY SPECTRUM



THE SENSITIVITY

$$S^{0\nu} \propto \sqrt{\frac{M\,T}{B\,\Delta}}$$

- $M\,T$ → Mass · Active Time
- Δ → Energy resolution in the ROI
- B → Background index

PARAMETER OF INTEREST

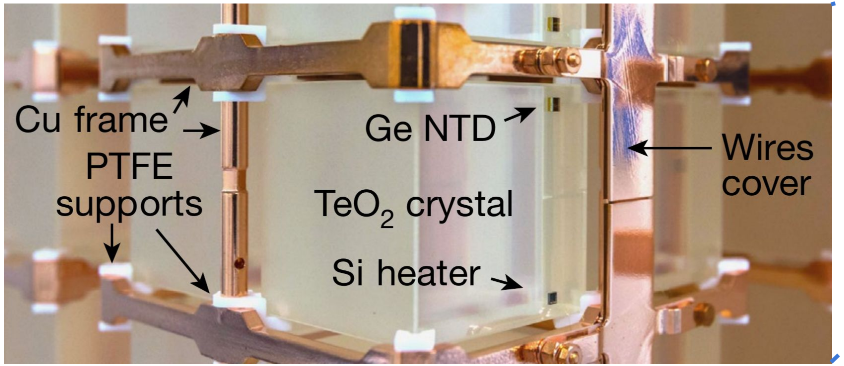
$$T^{1/2}_{0\nu} = \left[G_{0\nu} |\mathcal{M}_{0\nu}|^2 g_A^4 \left(\frac{m^2_{\beta\beta}}{m^2_e} \right) \right]^{-1}$$

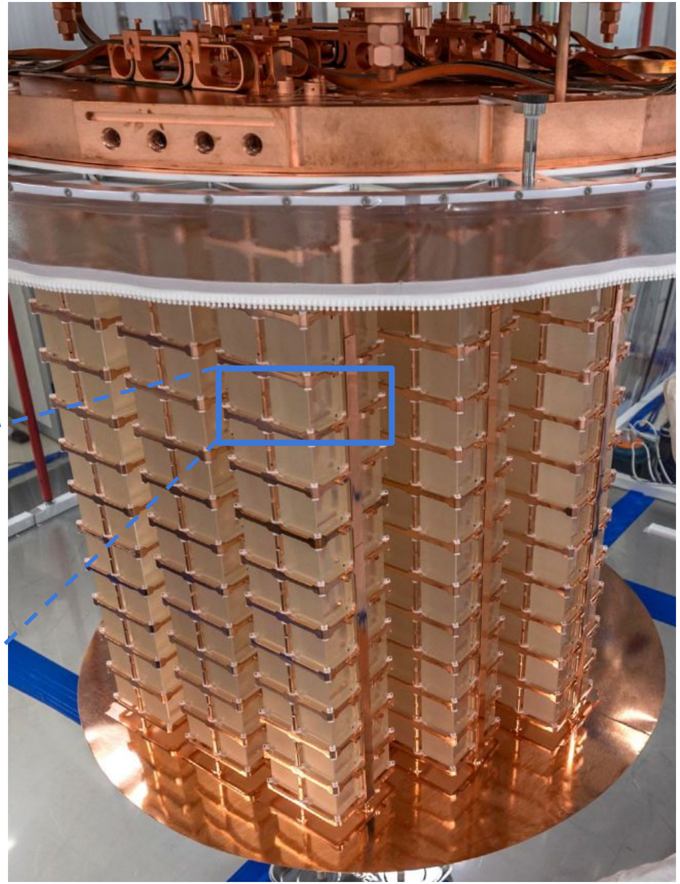
- $T^{1/2}_{0\nu}$: Experimental observable
- $G_{0\nu}$: Phase space factor (computed)
- $\mathcal{M}_{0\nu}$: Nuclear physics (models + experiments)
- $m_{\beta\beta}$: Majorana mass (parameter of interest)

The CUORE experiment

***C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents*

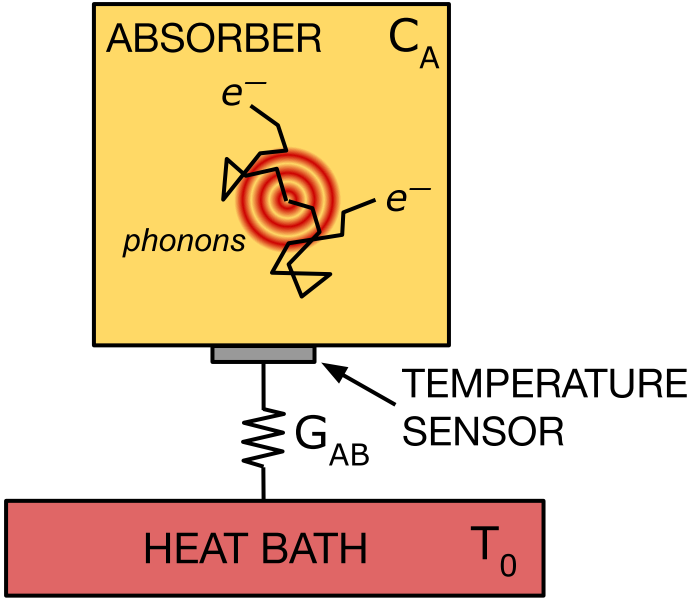
- Experiment running since 2017 in the **Gran Sasso underground laboratories** in Italy (~ 3600 m.w.e.)
- **988 TeO_2 crystals operated at ~ 15 mK** with natural ^{130}Te abundance
- Low background index ~ 10^{-2} counts / keV / kg / yr and good energy resolution ~ 7.8 keV FWHM @ $Q_{\beta\beta}$



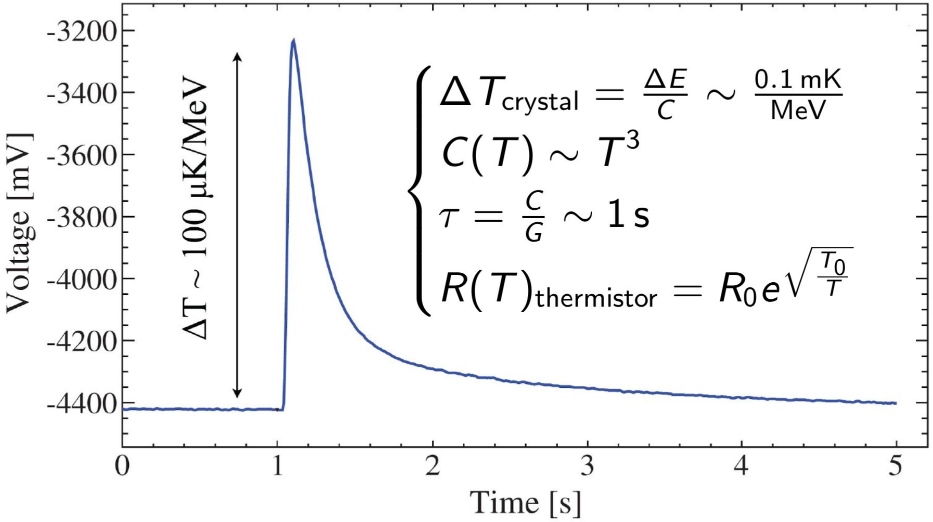


Cryogenic calorimeters technique

Source ≡ Detector ➡ High efficiency



SAMPLE PULSE



Low temperatures ➡ ✔ E resolution (≳0.3%)
✘ Slow signals (~1s)

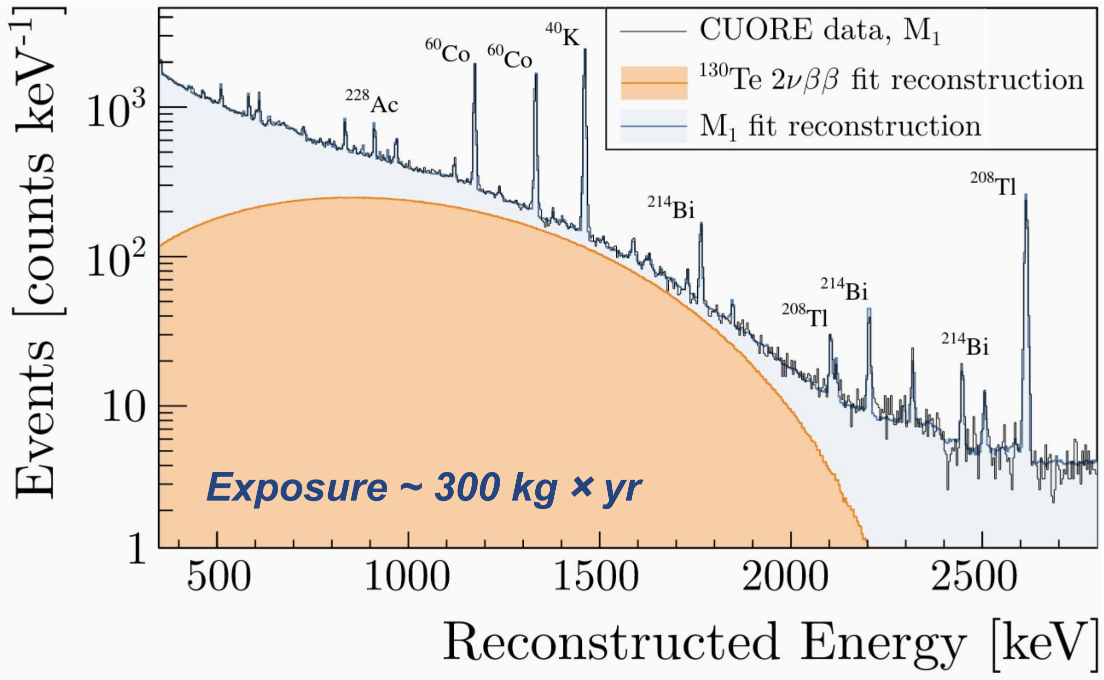
CUORE: $2\nu\beta\beta$ results

SPECTRAL FIT

- ^{130}Te $2\nu\beta\beta$ component from background model fit to single hits (M1) data
- **^{130}Te $2\nu\beta\beta$ > 50% of events in the 1-2 MeV** energy region

SYSTEMATICS

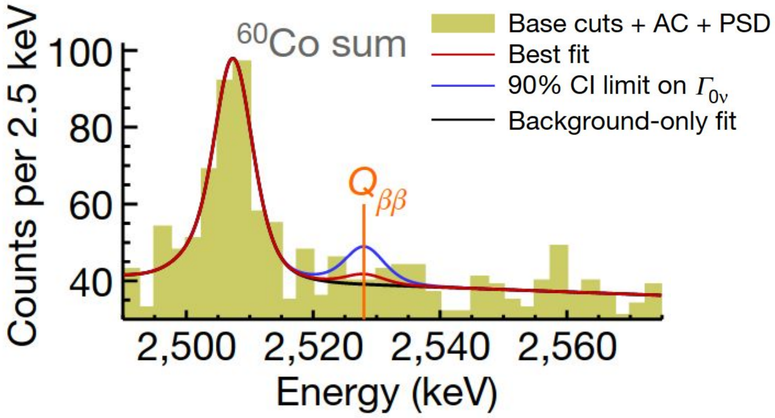
- 2 model (SSD vs HSD)
- ^{90}Sr inclusion (high correlations)
- Detector geometrical splitting



$$T^{2\nu}_{1/2} = 7.71^{+0.08}_{-0.06}(\text{stat})^{+0.12}_{-0.15}(\text{syst}) \times 10^{20} \text{ yr}$$

Phys. Rev. Lett. 126, 171801 (2021)

CUORE: $0\nu\beta\beta$ results (2)

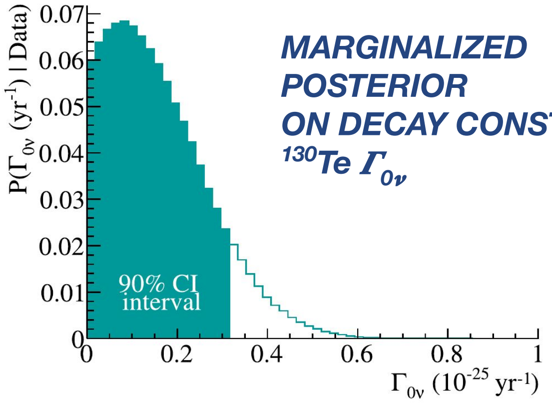


No evidence for $0\nu\beta\beta$:

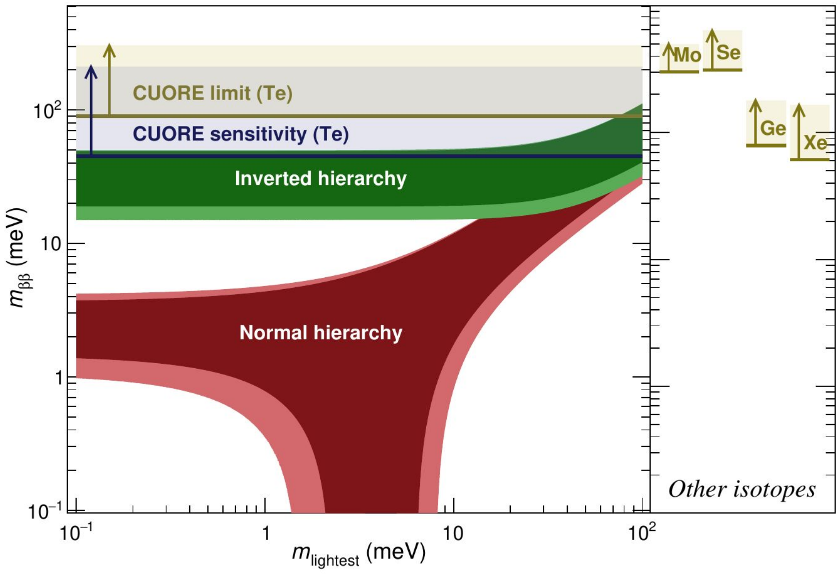
$T^{0\nu}_{1/2} > 2.2 \cdot 10^{25}$ yr (90% C.I.)

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

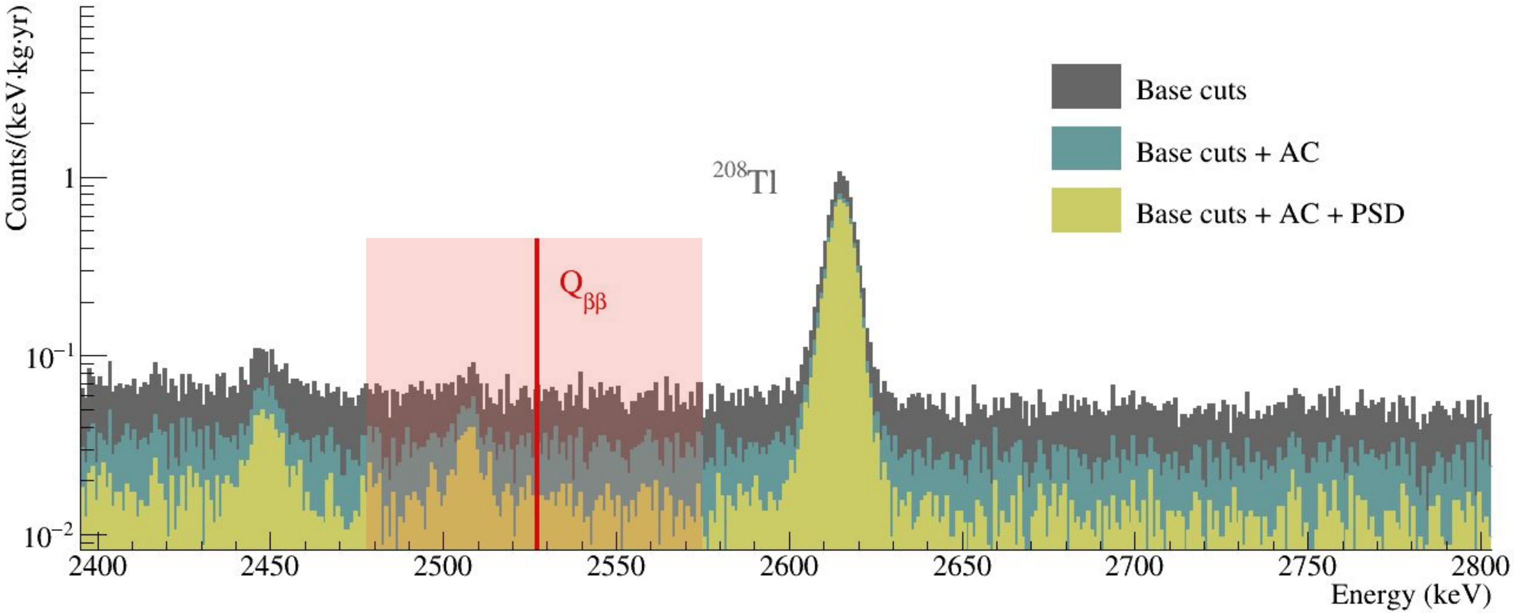
Nature 604, 53-58 (2022)



MARGINALIZED POSTERIOR ON DECAY CONSTANT $^{130}Te\ \Gamma_{0\nu}$



CUORE background

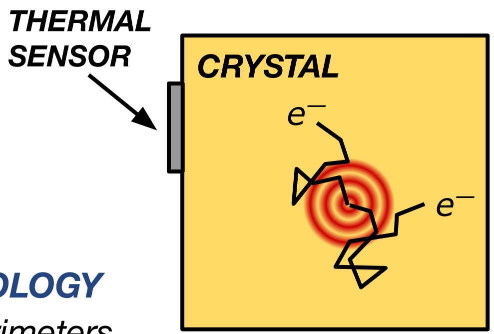


Background in the region of interest of CUORE
(1.49(4) ± 1.4) · 10^{-2} Counts / keV / kg / yr

- ~ 10% β/γ radioactivity
- **~ 90% α contamination (degraded)**
- < 1% muons → segmented detector

From CUORE to CUPID

CUORE

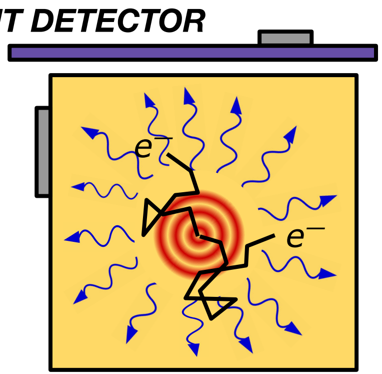


DETECTOR TECHNOLOGY

TeO_2 cryogenic calorimeters equipped with NTDGe thermal sensors

- Tonne scale experiment at millikelvin temperatures
- Pure thermal detector
- ^{130}Te → High natural abundance (34%)
- Q(^{130}Te) ~ 2527 keV
- No Particle IDentification

CUPID



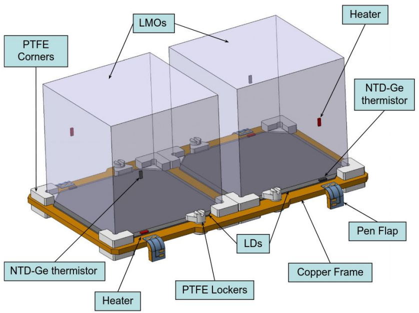
DETECTOR TECHNOLOGY

Li_2MoO_4 scintillating calorimeters (NTDGe readout) + Ge light detectors (NTDGe / Neganov-Trofimov-Luke / TES)

- Scintillating crystals → ***heat + light*** measurement
- ^{100}Mo → enrichment ~ 95%
- ***Q(^{100}Mo) ~ 3034 keV*** → beyond natural γ radioactivity
- ***Particle IDentification*** → α-induced background reduced by a factor 100
- Other pilot-experiments (CUPID-Mo, CUPID-0)

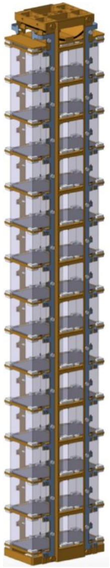
The CUPID experiment

1. SINGLE MODULE



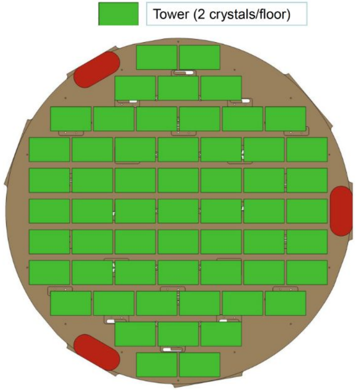
Stacked modules

2. TOWER



Multi - towers

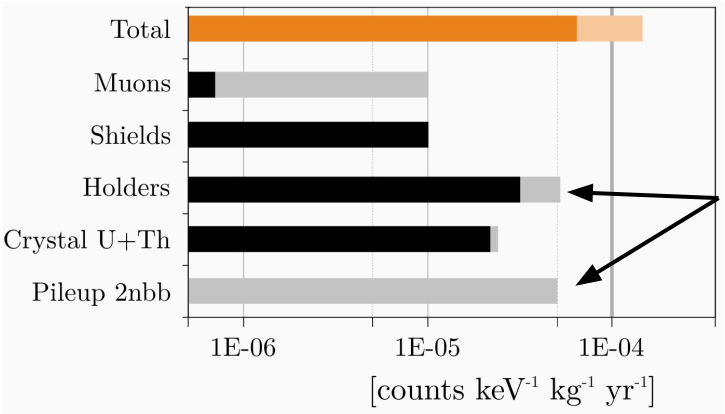
3. EXPERIMENT



CUPID Baseline Parameters (DOE Portfolio Review)

- 45x45x45 mm^3 $Li_2{}^{100}MoO_4$ crystals
- 1596 crystals → ~ 240 kg ^{100}Mo (95% enrichment)
- Crystal resolution ~ 5 keV (FWHM @ ^{208}Tl line)
- Crystal light yield ~ 0.3 keV$_{light}$ / MeV$_{heat}$
- Ge light detectors (LD) with SiO anti-reflective coating (top and bottom of crystals)
- LD resolution: <100 eV RMS, < 80 ms · eV (FWHM)

Background Budget (from data driven background model)



Highest contributions

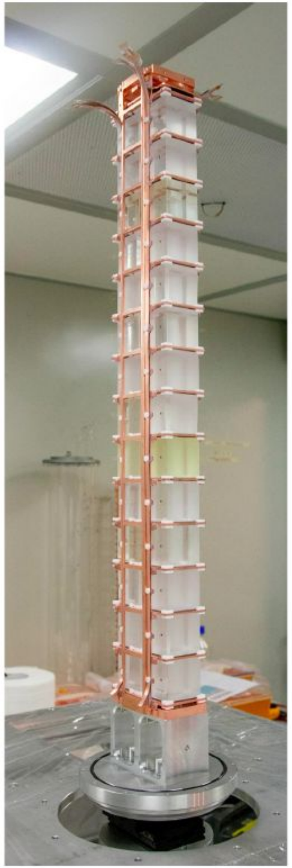
R&Ds

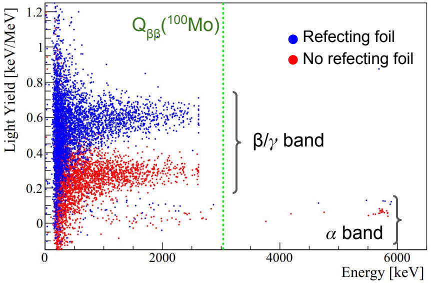
R&D PROGRAM

- 3 different cryogenic facilities operational
  - *Test baseline detector performance*
  - *Test alternative technologies*
  - *Background control*
- Simulations of detector and facility
  - Background budget
  - Develop new analyses techniques

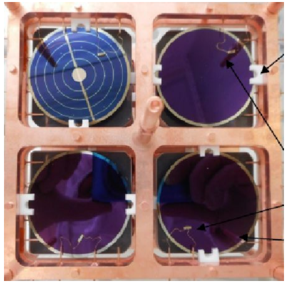
FIRST VALIDATION OF DETECTOR BASELINE DESIGN

- Baseline Design Prototype Tower
  - *Validation assembly procedure*
  - *Studies on LMOs and LDs performance*
  - *Vibrational noise optimizations*
- 14-floors tower tests ongoing
  - *Run1 → Jul-Aug 2022*
  - *Run2 → Sep-Oct 2022*
  - *Run3 → foreseen in Sep 2023*

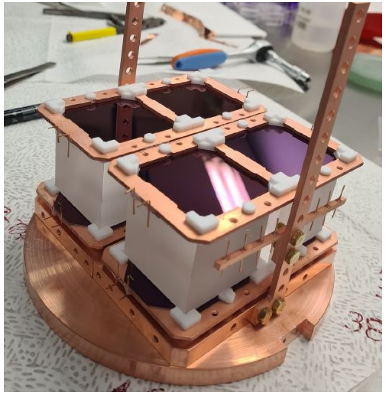


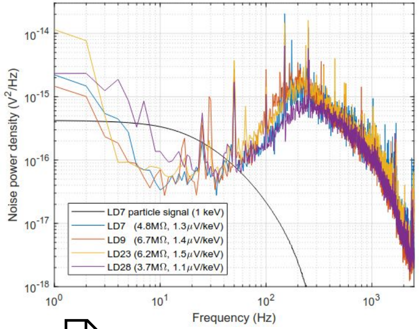


Eur. Phys. J. C **82**, 810 (2022)



JINST **18** P06018 (2023)





JINST ***18*** *P06033 (2023)*

The CUPID ultimate target

CUPID-baseline

- ^{100}Mo mass: **240 kg**
- Background index: **1 · 10^{-4} ckky**
- Infrastructure: CUORE cryostat
- $T^{0\nu}_{1/2} > 1.4 \cdot 10^{27}$ yr

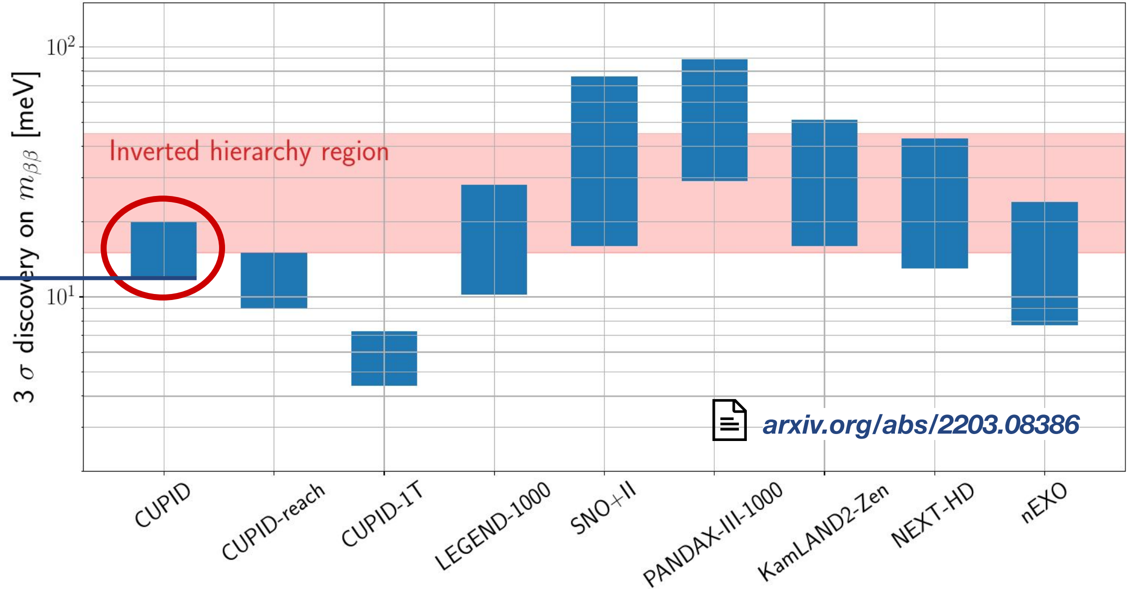
CUPID-reach

- ^{100}Mo mass: **240 kg**
- Background index: **2 · 10^{-5} ckky**
- Infrastructure: CUORE cryostat
- $T^{0\nu}_{1/2} > 2.2 \cdot 10^{27}$ yr

CUPID-1T

- ^{100}Mo mass: **1000 kg**
- Background index: **5 · 10^{-6} ckky**
- Infrastructure: new cryostat
- $T^{0\nu}_{1/2} > 9.1 \cdot 10^{27}$ yr

Here we will go



arxiv.org/abs/2203.08386

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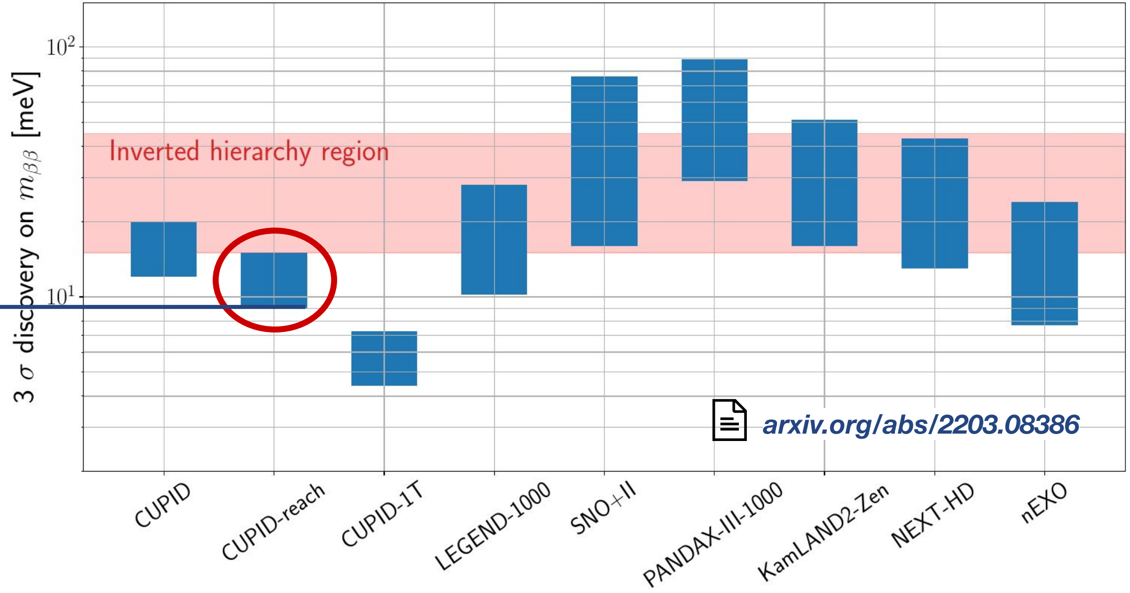
The best CUPID baseline can do



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CUPID-1T

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- Infrastructure: new cryostat
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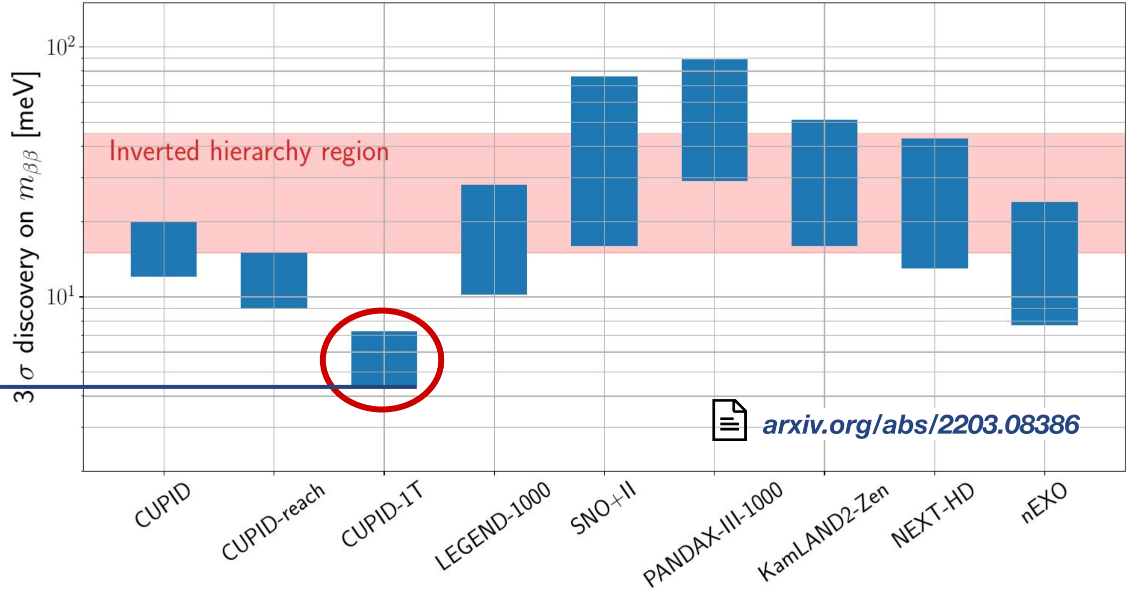
Ultimate target



arxiv.org/abs/2203.08386

Conclusions and Remarks

CUORE

- Demonstrated the feasibility of a tonne-scale experiment operating cryogenic detectors
- Collecting data since 2017 (~2.3 ton yr as for now)
- ***No evidence of $0\nu\beta\beta$ in ^{130}Te*** with 1038.4 kg · y exposure:
  - $T^{0\nu}_{1/2} > 2.2 \cdot 10^{25}$ yr (90% C.I.)
  - $m_{\beta\beta} < 90\text{-}305$ meV (90% C.I.)
- **Most precise measurement of ^{130}Te $2\nu\beta\beta$:**
  - $T^{0\nu}_{1/2} = 7.71^{+0.08}_{-0.06}(\text{stat})^{+0.12}_{-0.15}(\text{syst}) \times 10^{20}$ yr

CUPID

- Experience from previous experiments (CUORE, CUPID-0, CUPID-Mo) and existing infrastructures
- R&D ongoing to define the final design
- The goal is to **explore the full inverted hierarchy** (target sensitivity > 10^{27} yr for ^{100}Mo)
- CUPID foresees an ultimate stage with 1t of isotope in the CUPID-1T experiment

Thanks for your attention!