Searching for 0νββ decay with CUPID

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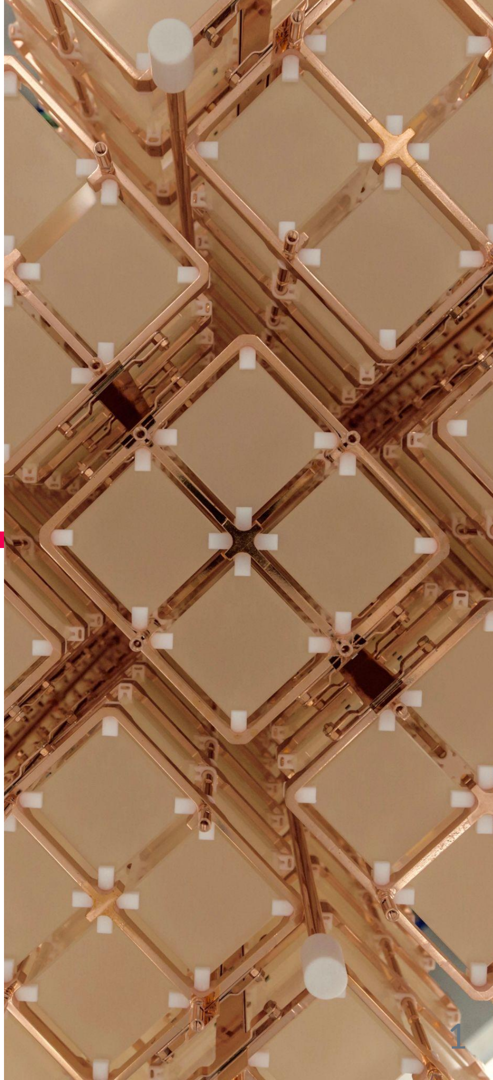
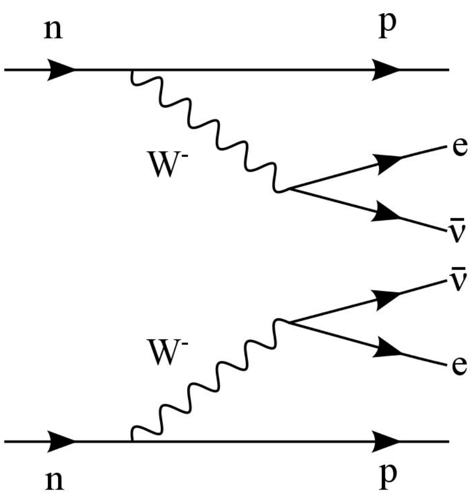
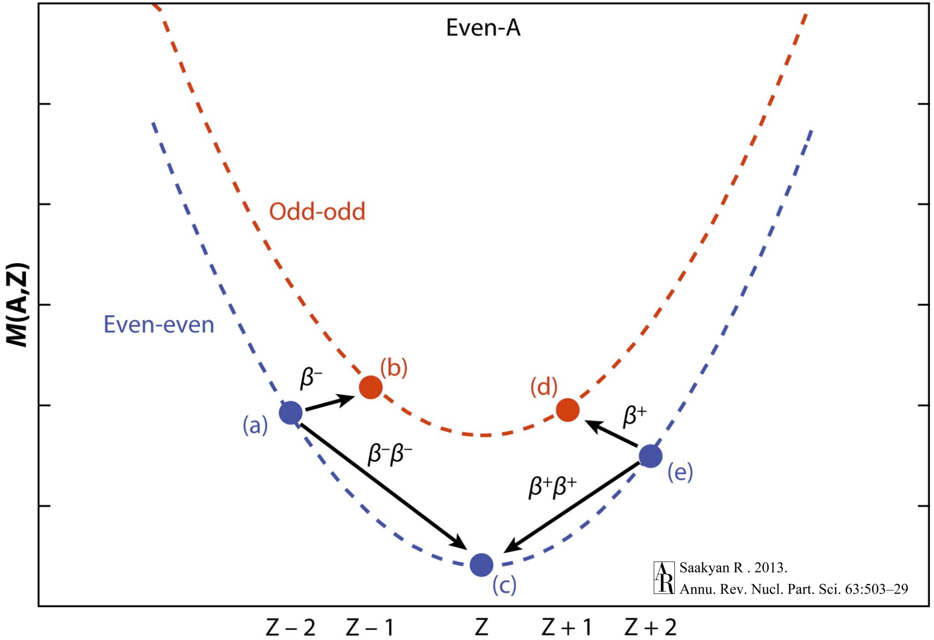
4 March 2024



Two Neutrino Double Beta Decay (2νββ)



$$\boxed{\nu = \bar{\nu}\ ?}$$



- Two-neutrino double beta decay is a rare weak nuclear process
- Measured in 14 isotopes ($T_{1/2} > 10^{18}$ yrs)
- Only occurs in even-even nuclei where single-beta decay is forbidden
    - Shell Model → Maria Goeppert-Mayer (1935)

- Indirectly measured in 1950 (Te-130) [1]
- Directly measured in 1987 (Se-82) [2]

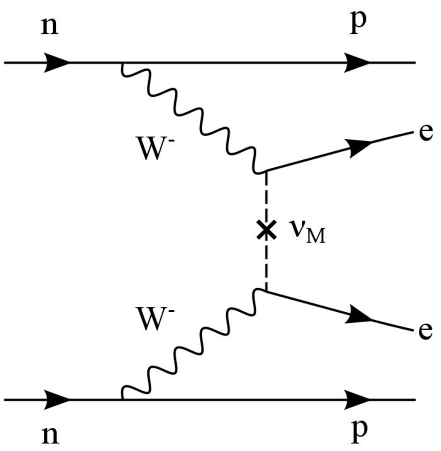
1. Inghram, M. G.; Reynolds, J. H. (1950). Physical Review. 78 (6)
2.Elliott, S. R.; Hahn, A. A.; Moe; M. K. (1987). Physical Review Letters. 59 (18)

Neutrinoless Double Beta Decay (0νββ)

1937 Majorana calculated that beta decay didn't change if $\nu = \bar{\nu}$

1939 Furry proposed that if $\nu = \bar{\nu}$, double beta decay could proceed with no emitted neutrinos.

- Second-order weak interaction, not yet observed
- Observation requires neutrinos to be their own antiparticle (Majorana)



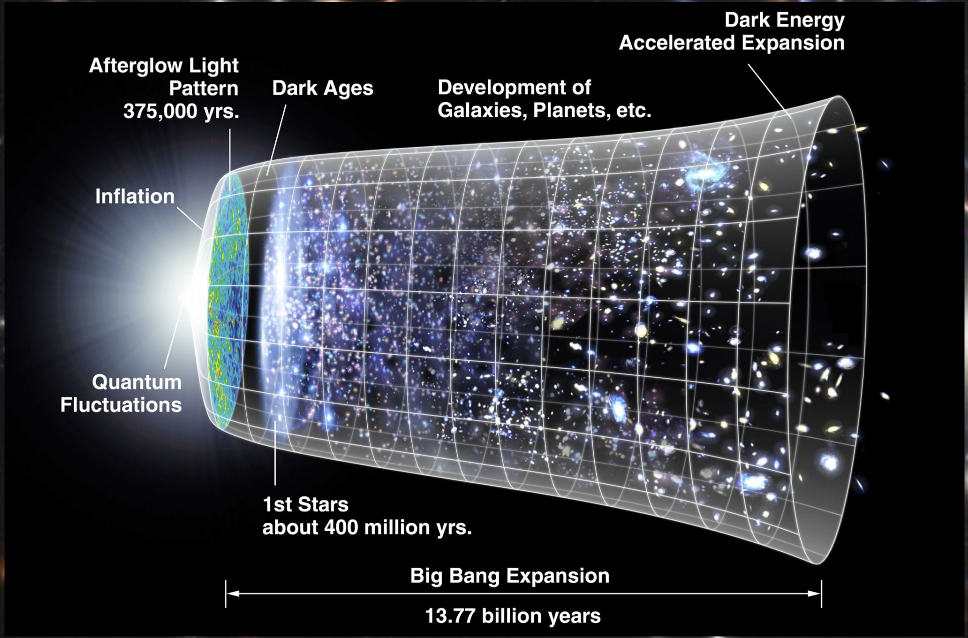
Isotope	$T_{1/2}$ lower limit (yr)	$\langle m_{\beta\beta} \rangle$ (meV)	Experiment
^{76}Ge	8.3×10^{26}	< 113-269	MAJORANA DEMONSTRATOR [1]
^{82}Se	4.6×10^{24}	< 263 - 545	CUPID-0 [2]
^{100}Mo	1.8×10^{24}	< 280 - 490	CUPID-Mo [3]
^{130}Te	2.2×10^{25}	< 90 - 305	CUORE [4]
^{136}Xe	2.3×10^{26}	< 36 - 156	KamLAND-Zen [5]

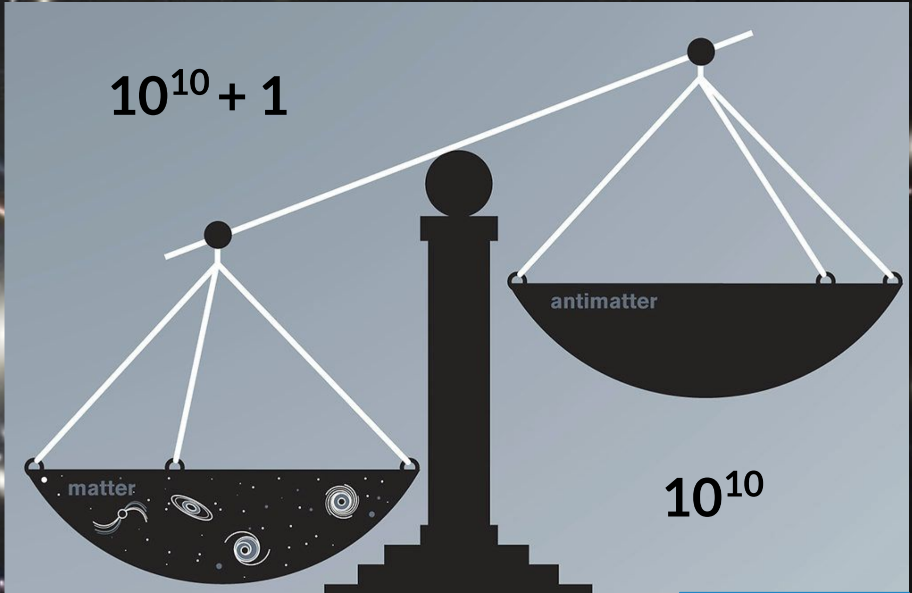
$$\Gamma_{0\nu} = (T_{1/2}^{0\nu})^{-1} = G_{0\nu}|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

$$\langle m_{\beta\beta} \rangle = |U_{ei}^2 m_i^2|$$

[1] Phys. Rev. Lett. 130, 062501 (2023)
[2] Phys. Rev. Lett. 129, 111801 (2022)
[3] Eur. Phys. J. C 82, 1033 (2022)
[4] Nature volume 604, pages 53–58 (2022)
[5] Phys. Rev. Lett. 130, 051801 (2023)

Why Majorana Neutrinos are a big deal





Symmetry Magazine

Why Majorana Neutrinos are a big deal

$$\mathcal{L} = \mathcal{L}_D + \mathcal{L}_M$$
$$= \underbrace{-m_D\overline{\nu_R}\nu_L}_{\text{Dirac Mass}}\underbrace{-\frac{1}{2}m_R\overline{(\nu_R)^C}\nu_R-\frac{1}{2}m_L\overline{(\nu_L)^C}\nu_L}_{\text{Majorana Mass}}+h.c.$$

Mass generated via ??

Mass generated via Higgs

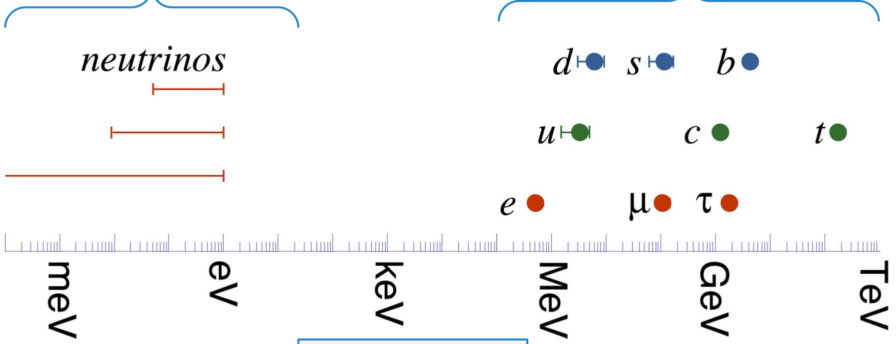
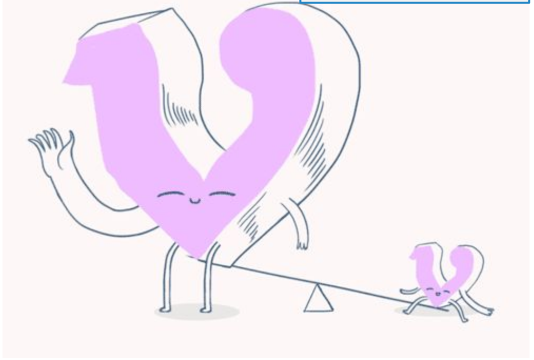


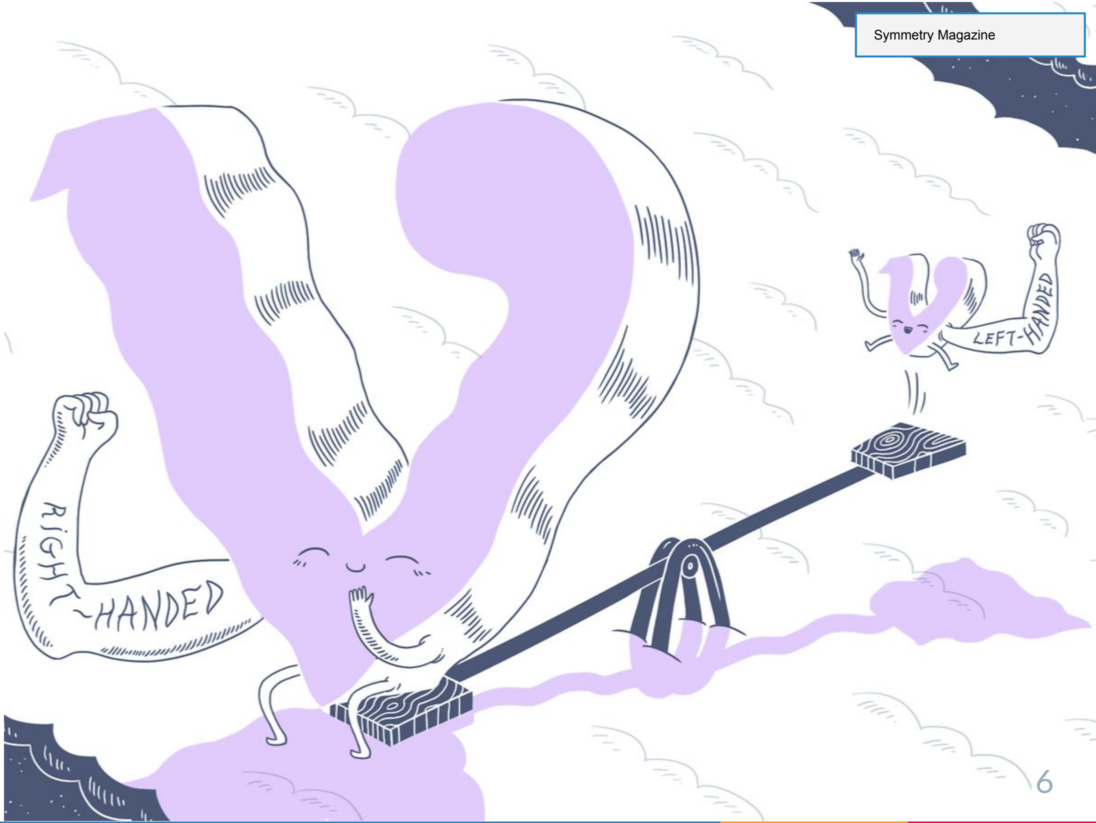
Image credit: Hitoshi Murayama



Symmetry Magazine

Why Majorana Neutrinos are a big deal

- A fundamentally new kind of elementary particle.
- Generates mass without the Higgs Mechanism
- Allows for CP symmetry breaking
- $0\nu\beta\beta$ violates lepton number conservation ($\Delta L = 2$)



Symmetry Magazine

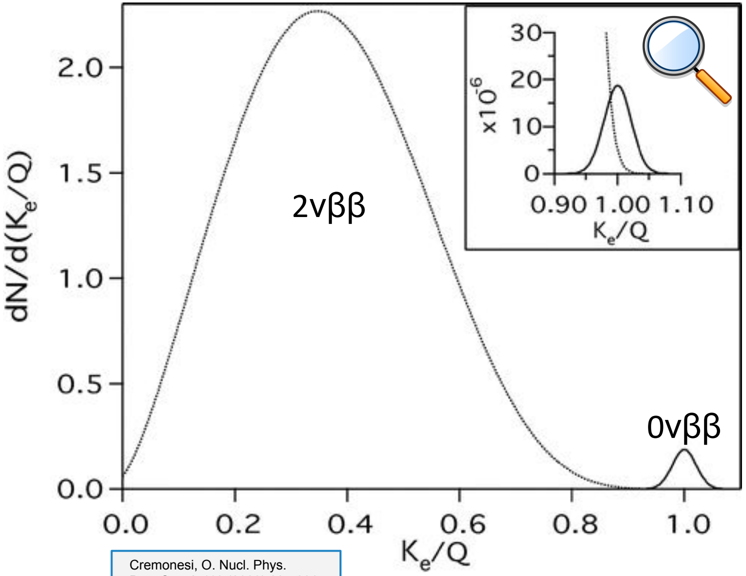
Finding Majorana neutrinos could help us understand why we exist in a matter-dominated universe.

How to search for neutrinoless double beta decay

$$F_{T_{1/2}} \propto \frac{\epsilon \cdot \eta}{A} \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$$

* *assumes nonzero background in ROI*

Double-beta Decay Signal



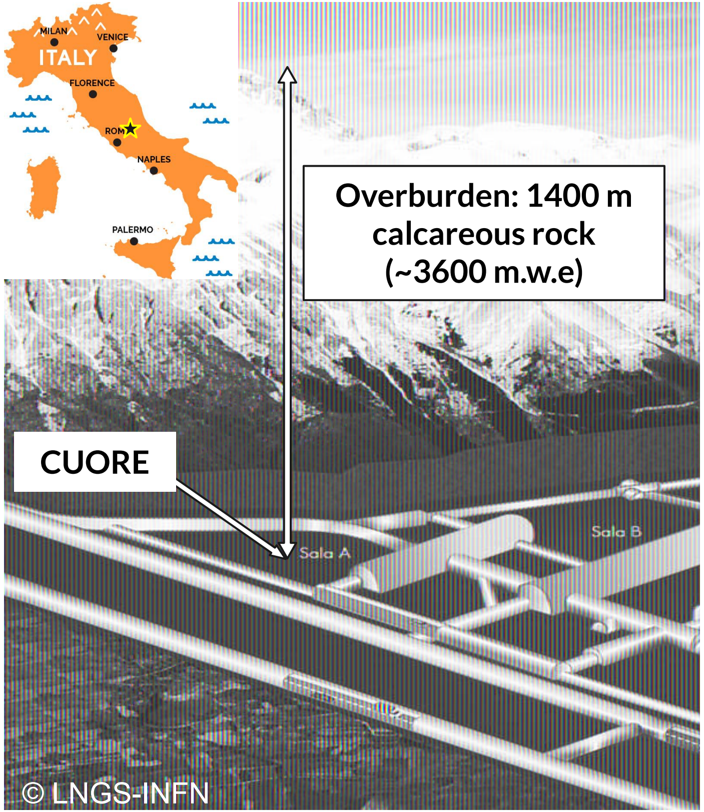
Cremonesi, O. Nucl. Phys. Proc.Suppl. 118 (2003) 287-296

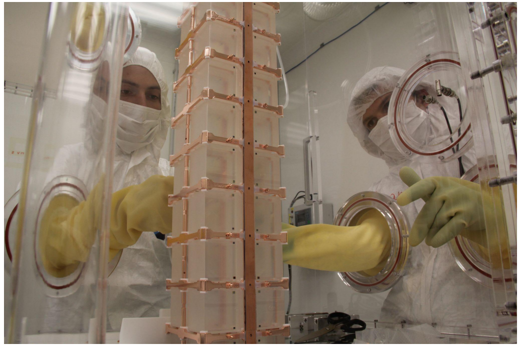
- Large exposure (M*T) (large mass, long live-time)
- Large η (isotopic abundance or enrichment)
- Large ε (signal efficiency)
- Small b (low background)
- Small ΔE (good energy resolution)

Four fundamental requirements for modern experiments:

- Large amount of candidate isotope
- Underground location
- Ultra low background materials
- Signal / background discrimination

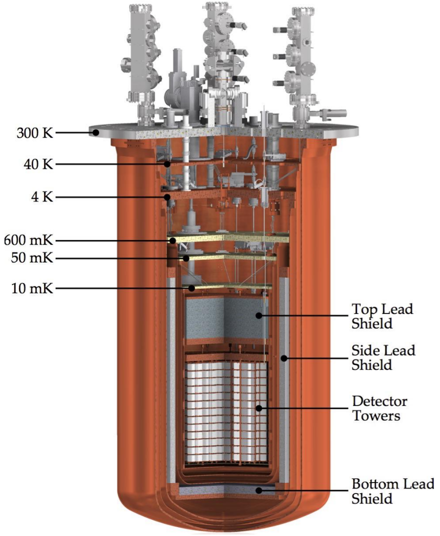
CUORE (Cryogenic Underground Observatory for Rare Events)

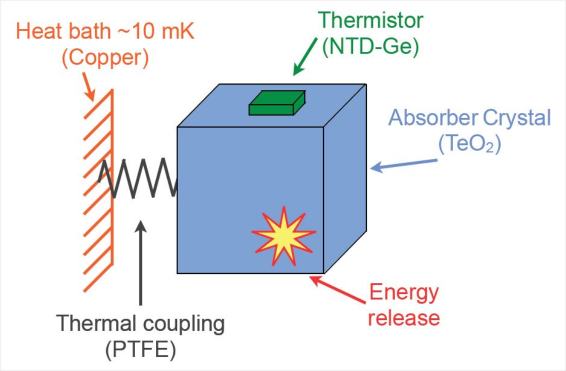


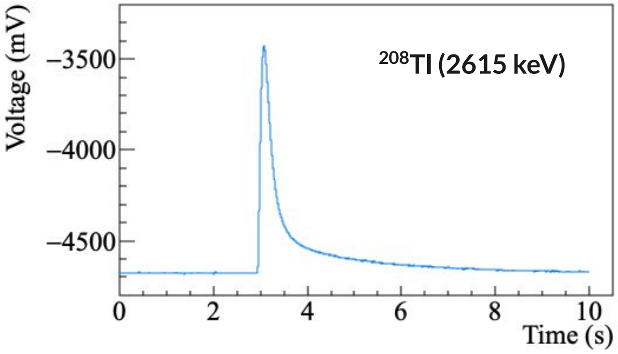


- Gran Sasso National Laboratory
- Timeline
  - 2017 Data Taking Starts
  - 2021 1st tonne-year data release + Nature publication
  - 2023 2nd tonne-year data release
  - **2024 Full 2 tonne-year data release** **(Moriond '24)**
  - Looking to 3 tonne-year…

CUORE (Cryogenic Underground Observatory for Rare Events)

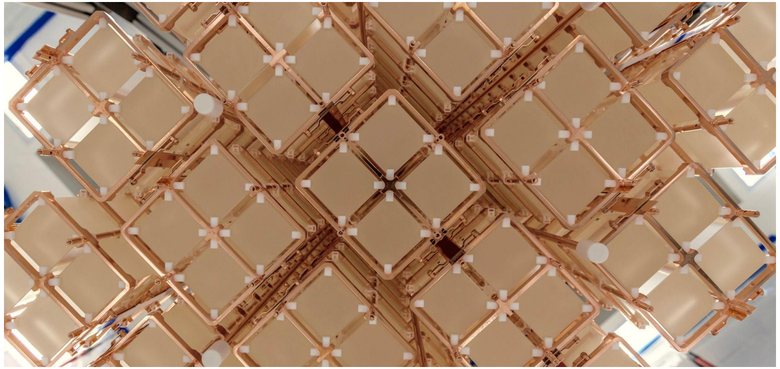






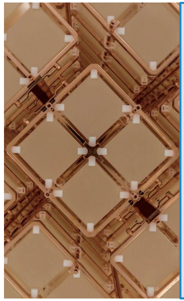
$^{130}Te \rightarrow {}^{130}Xe + 2e^-$

- 988 TeO_2 cryogenic calorimeters (206 kg ^{130}Te)
- Detector array cooled to operating temp of ~10 mK
- Stringent radiopurity control on materials and assembly



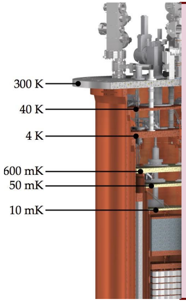
CUORE (Cryogenic Underground Observatory for Rare Events)

$$F_{T_{1/2}} \propto \frac{\epsilon \cdot \eta}{A} \sqrt{\frac{\boxed{M} \cdot \boxed{T}}{\boxed{b} \cdot \boxed{\Delta E}}}$$



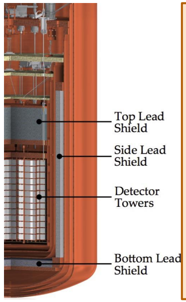
Active Mass: 742 kg TeO_2
(206 kg ^{130}Te)

Close-packed array of 988 nat. TeO_2 crystals



> 90% duty cycle since 2019
(~50 kg.yr/month exposure rate)

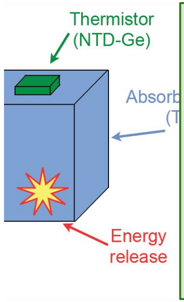
Custom multistage cryogen-free cryostat



BI: ~10^{-2} ckky @ 2528 keV

Strict radio-purity controls on materials and assembly

Passive shielding



Cryogenic detection technique
(~10 mK)

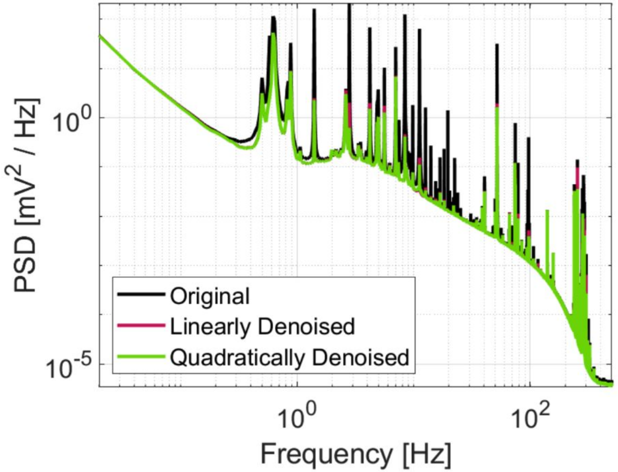
$Q_{\beta\beta}$ energy resolution:
$\Delta E/E$ ~ 0.3 % @ 2528 keV

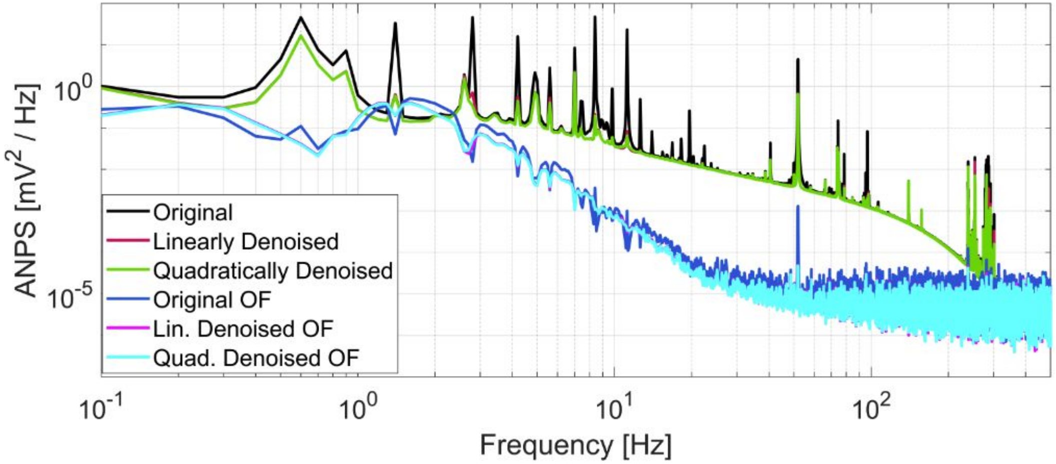
CUORE Signal Processing

Denoising Algorithm

- Reduces noise correlated with measured vibrations
- Auxiliary devices: microphones, accelerometers, seismometers

- Publication accepted to EPJC Vetter et.al. arXiv:2311.01131





CUORE 2nd TY preliminary results (TAUP '23)

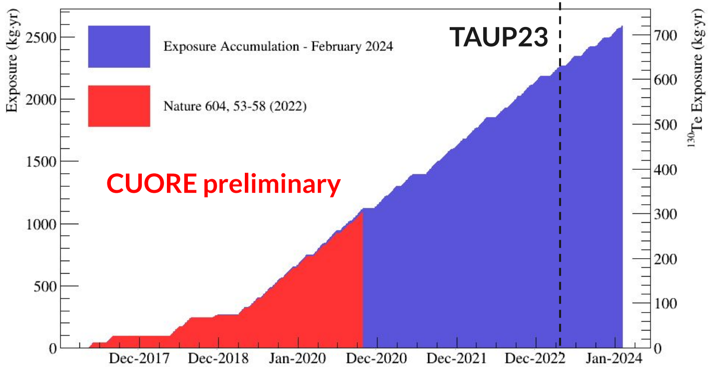
2nd TY results:

- **$T_{1/2}^{0\nu}$ > 2.7 x 10^{25} yr (90% C.I.)**
- BI: 1.30(3) x 10^{-2} ckky

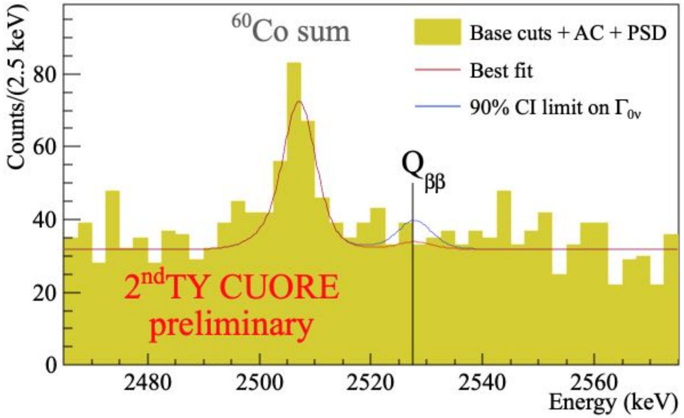
Combining with results from 1TY:

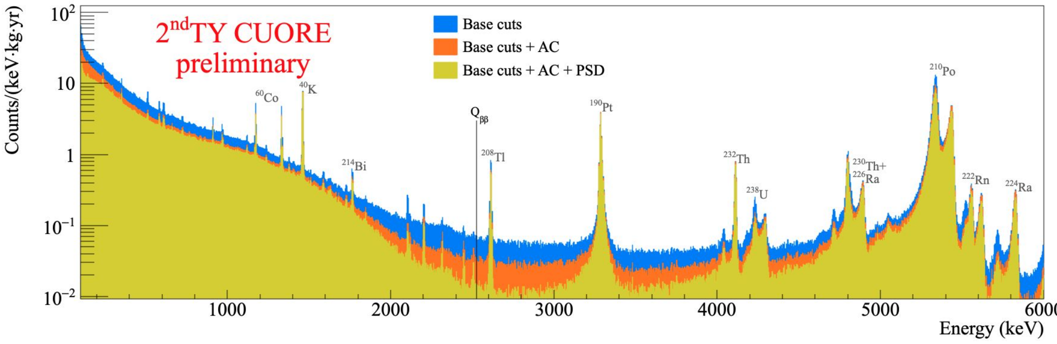
- **$T_{1/2}^{0\nu}$ > 3.3 x 10^{25} yr (90% C.I.)**

Full 2 tonne-year reprocessed data release publication expected this Spring!



Nature '22 Exposure: 1038.4 kg yr
Background Collected Exposure*: 2485
** does not take into account analysis efficiency, Jan '24*





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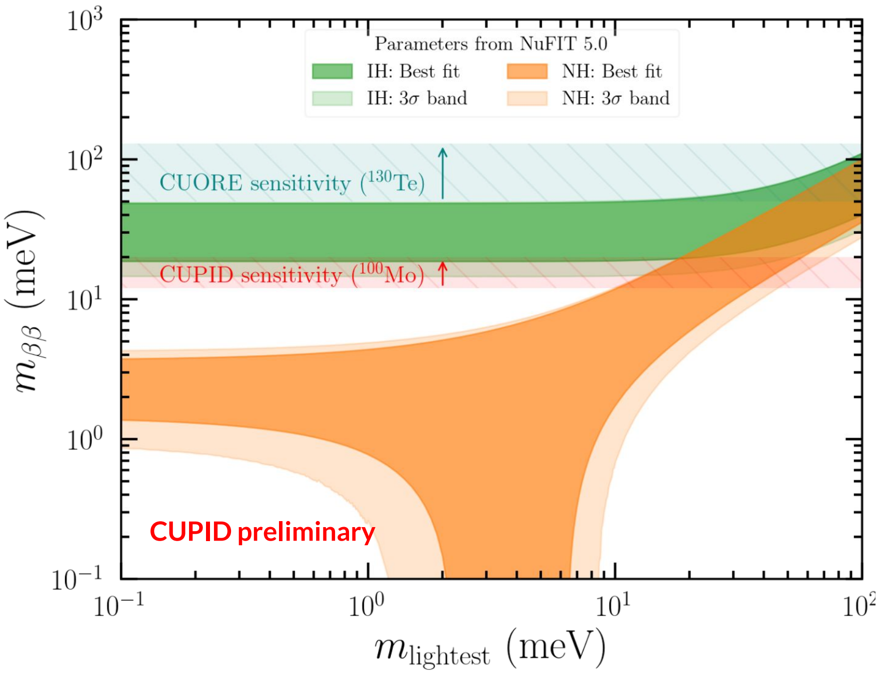
CUPID (CUORE Upgrade with Particle IDentification)

Upgrade to the successful CUORE experiment.

- Discovery Sensitivity
  - $T_{1/2}^{0\nu} > 1.0 \times 10^{27}$ yr
  - $m_{\beta\beta}$ = (13-21) meV
- Probing the full Inverted Hierarchy region
- New technology to decrease backgrounds and increase sensitivity

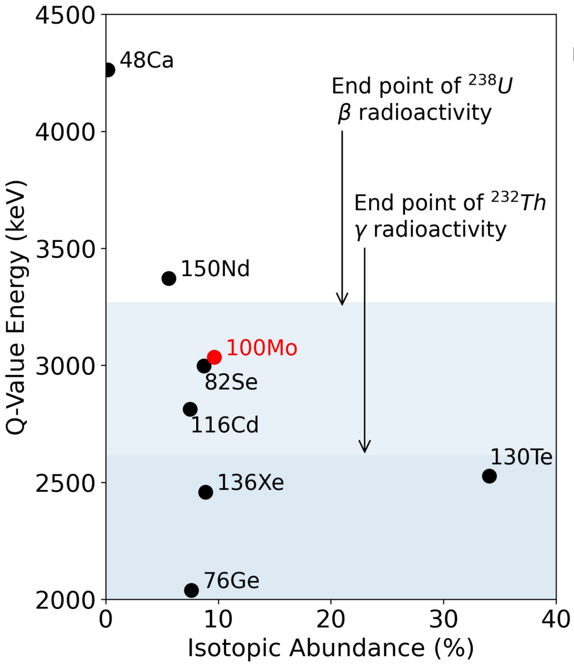


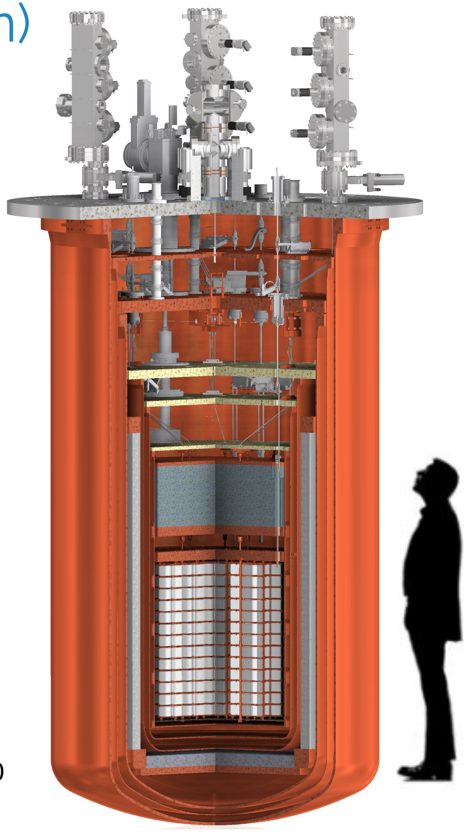
CUPID (CUORE Upgrade with Particle IDentification)

$^{100}Mo \rightarrow ^{100}Ru + 2e^-$

^{100}Mo is an excellent candidate for this search:

- a high Q-value (3034 keV) above the bulk of γ environmental background,
- favorable nuclear & kinematic factors which yield an expected decay rate 10x faster than other leading isotopes, and
- ease of embedding into scintillating crystals.



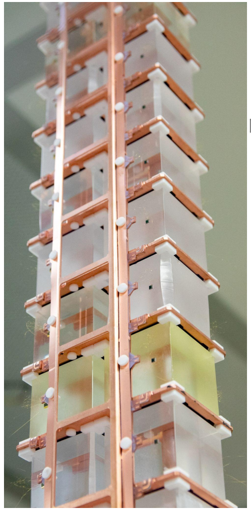


CUPID (CUORE Upgrade with Particle IDentification)

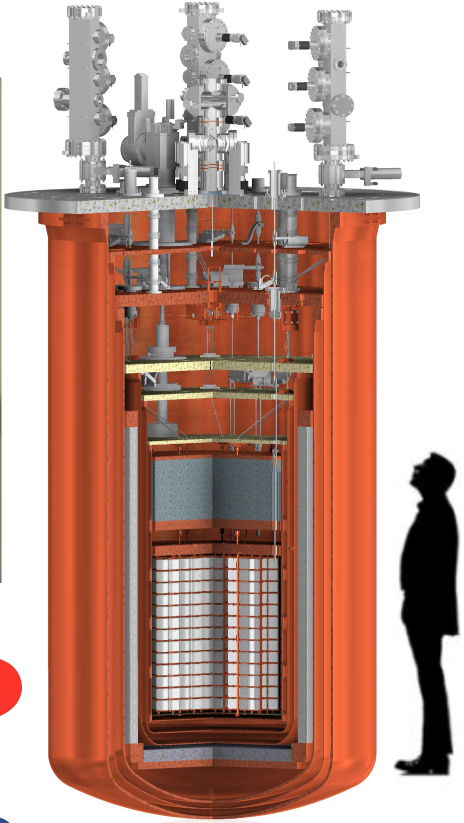
$$^{100}Mo \rightarrow {}^{100}Ru + 2e^-$$

- ~1600 Li_2MoO_4 ("LMO") scintillating crystals
- 95% enriched in ^{100}Mo. 450 kg of LMO / 240 kg of ^{100}Mo
- Muon veto for muon-induced background suppression
- Same cryogenic infrastructure as CUORE

	CUPID	CUPID Reach	
Resolution	5	5	keV FWHM
Background Index	10^{-4}	2×10^{-5}	ckky
90% CL Half-life Exclusion	1.4×10^{27}	2.2×10^{27}	meV
90% CL $m_{\beta\beta}$ Exclusion	10 - 17	8.4 - 14	meV



CUPID



CUPID

Li_2MoO_4 crystals

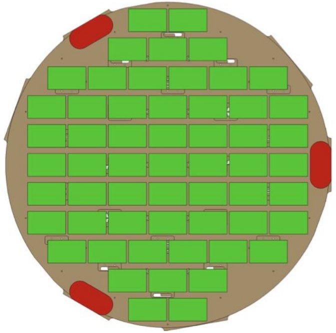
- 95% enriched in ^{100}Mo (240 kg)
- ~1600 crystals, 57 towers of 28 crystals
- Source = Detector

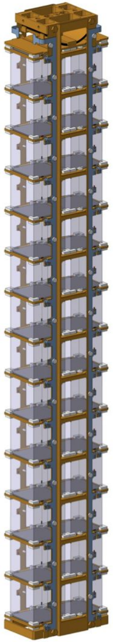
Ge light detectors

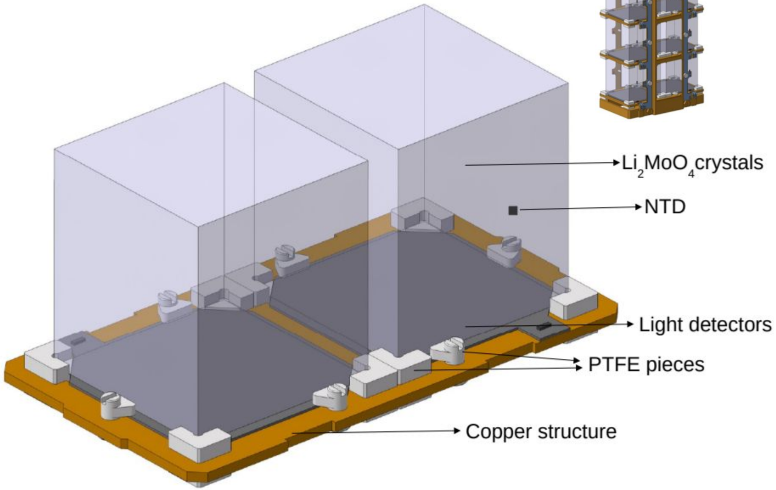
- SiO anti-reflective coatings to maximize light collection
- Top and bottom LDs, most shared

Pulse-tube dilution refrigerator

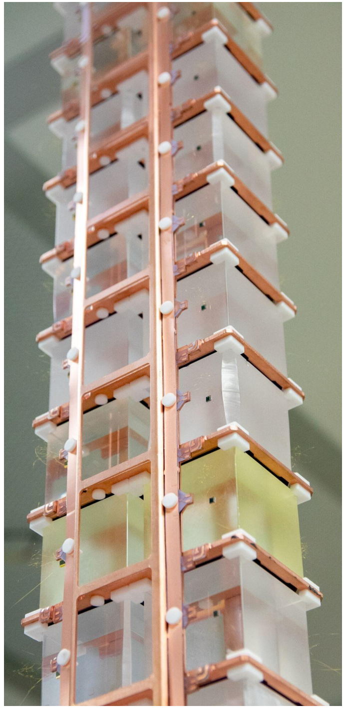
- O(10) mK operating temperature
- Passive radiation shielding
- Active muon veto



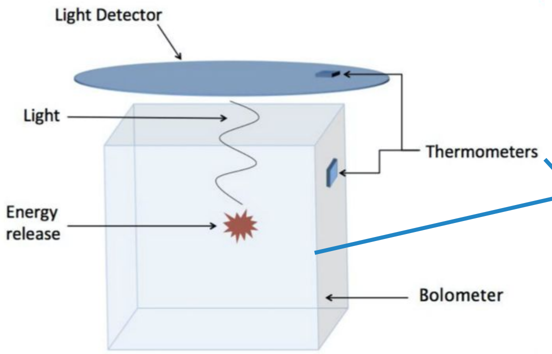


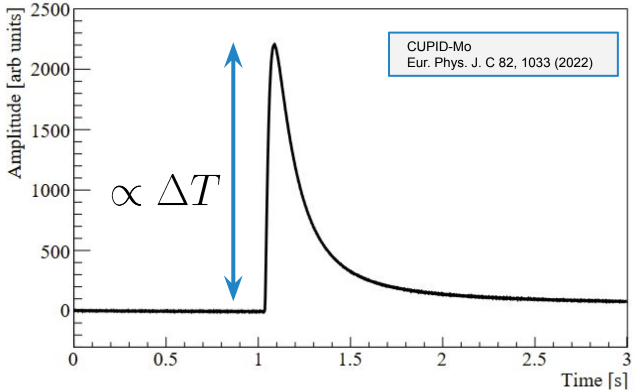


Prototype tower



CUPID Detector Modules: Calorimeter





$$\Delta T = \frac{\Delta E}{C}$$

Low crystal heat capacity
⇒ large change in temperature

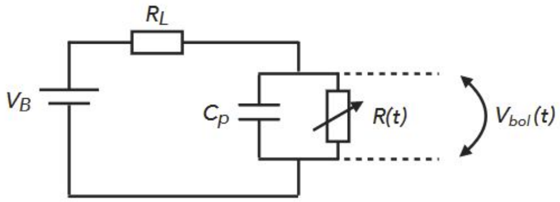
$$C \propto T^3$$

Low operating temperature
→ O(10) mK

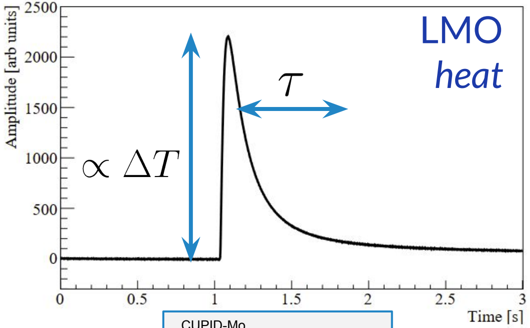
$$R(t) \propto e^{1/\sqrt{T}}$$

Thermistor resistance changes dramatically as a function of temperature.

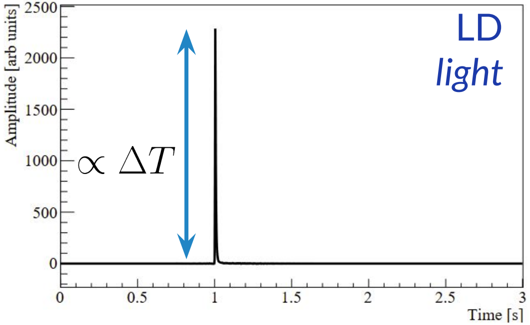
ΔV can be read out across the NTD to produce the signal (at left)
~100 nV / keV ⇒ ~300 μV for 3034 keV energy deposit

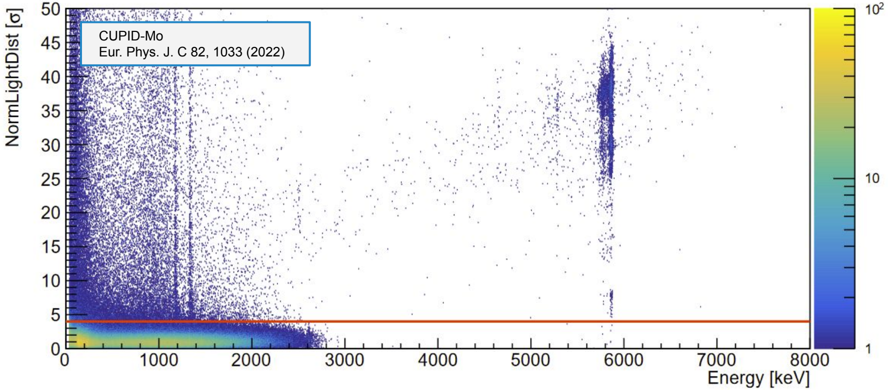


CUPID Detector Modules: Adding Light



CUPID-Mo
Eur. Phys. J. C 82, 1033 (2022)



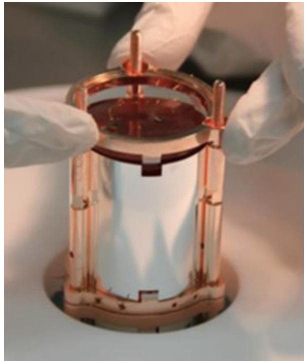


- Phonon (heat) signal cannot distinguish particle types (α, β, γ)
- Ratio of photon (light) : phonon (heat) signal depends heavily on particle type (α vs β / γ)

$$\tau \sim C/G$$

- Heat capacity of Ge light detectors *significantly* smaller than LMO
  ⇒ *significantly* faster pulses for light

CUPID Detector Modules: Adding Light



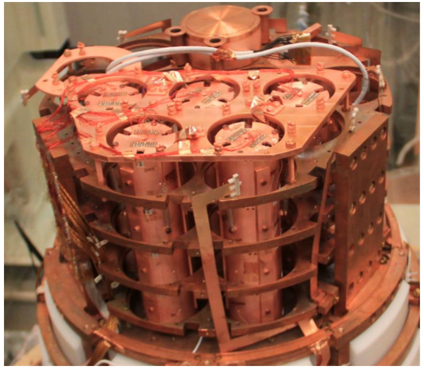
CUPID-0
26 ZnSe crystals enriched with 5.17 kg of ^{82}Se and equipped with a Ge light detector for PID.

- 20.05±0.34 keV FWHM at the Q-value
- 99% α rejection

0νββ of ^{82}Se
$T_{1/2} > 4.6 \times 10^{24}$ yr
$m_{\beta\beta} < [0.26 - 0.54]$ eV

90% CI , 8.82 kg·yr

PRL 129, 111801 (2022)



CUPID-Mo
20 ~0.2kg enriched Li_2MoO_4 crystals.

20 Ge wafers coated with SiO instrumented with NTDs acted as light detectors for PID.

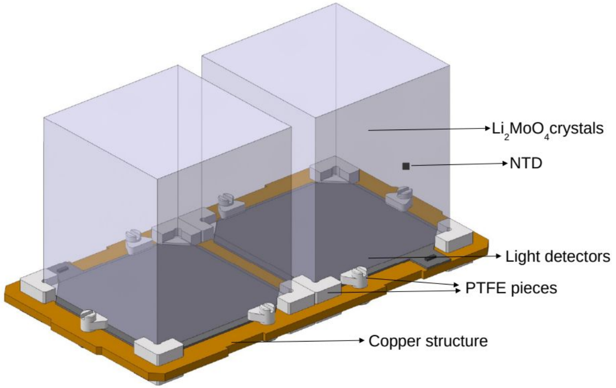
- 7.4(4) keV FWHM at the Q-value
- > 99% α rejection

0νββ of ^{100}Mo
$T_{1/2} > 1.8 \times 10^{24}$ yr
$m_{\beta\beta} < [0.28 - 0.49]$ eV

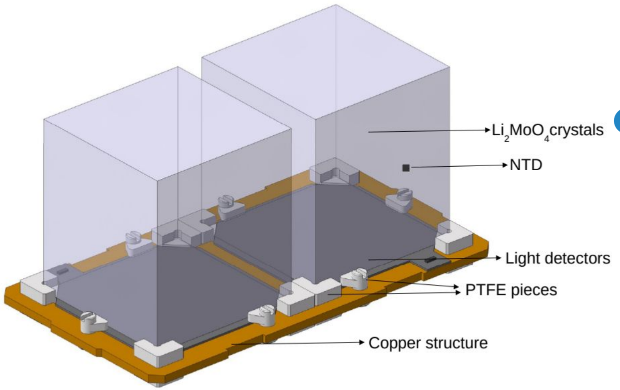
90% CI , 2.71 kg·yr

Eur.Phys.J.C 82 (2022) 11, 1033

CUPID Status



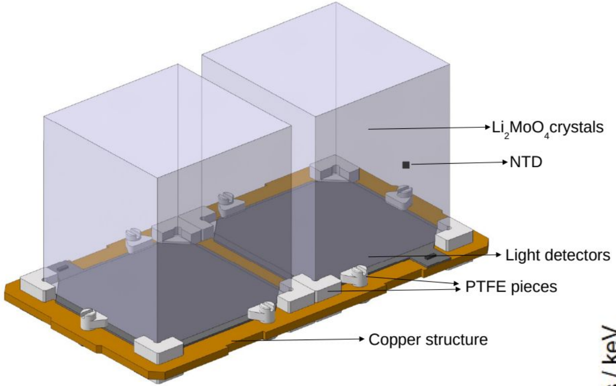
CUPID Status



Li_2MoO_4 crystals

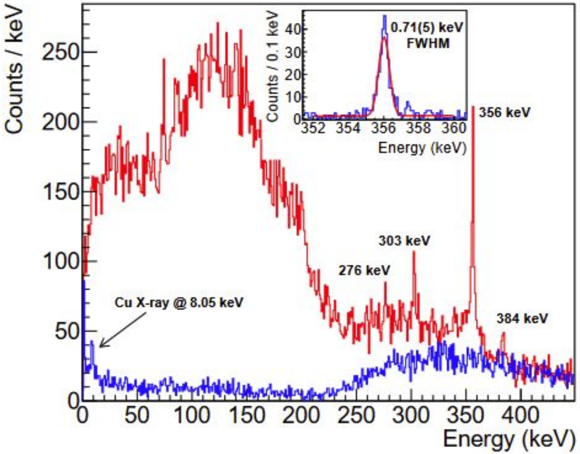
- Ongoing pre-production in China (SICCAS)
- Enriched MoO_3 powder to be produced in China
- Tests at Gran Sasso to validate performance/radio purity and assess contamination.
- Strategies to improve crystal surface cleaning, and thus reach CUPID's bkg goal, being developed.
- Full production at large scale for CUPID is viable and currently under negotiation.

CUPID Status



Light Collection Optimization & Module Validation

- Performed studies with Ge wafer with anti-reflective SiO coating and NTD readout for CUPID baseline.
- Performed in a pulse tube cryostat at IJCLab.
- Baseline energy resolution 70-90 eV RMS.
- Results show that CUPID baseline meets necessary α-rejection capabilities, but saturates pile-up background constraint



ΔE = 0.71 keV FWHM @ 356 keV

K. Alfonso et al (2023) JINST 18 P06033

CUPID Pileup

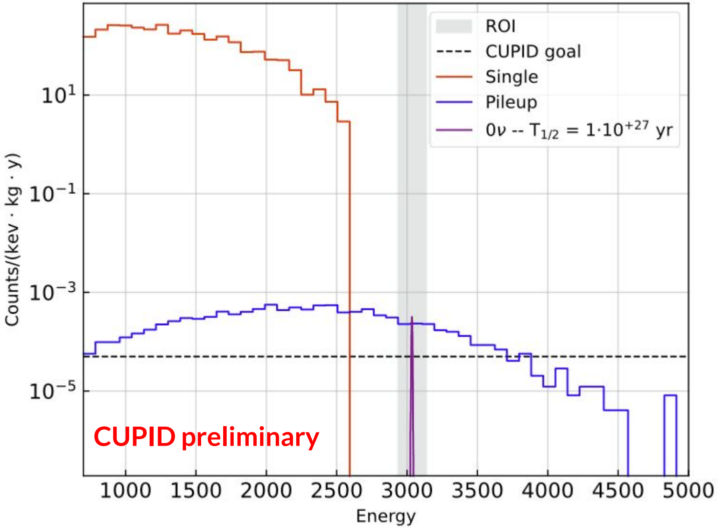
R&D toward CUPID includes **reducing 2vββ pileup background**

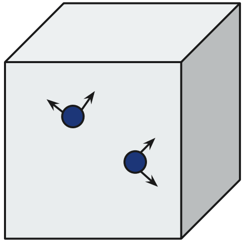
- Slow pulses ⇒ O(10) ms rise time
- Fast ^{100}Mo 2vββ decay ⇒ 7.1 x 10^{18} year
- High mass, enriched detector

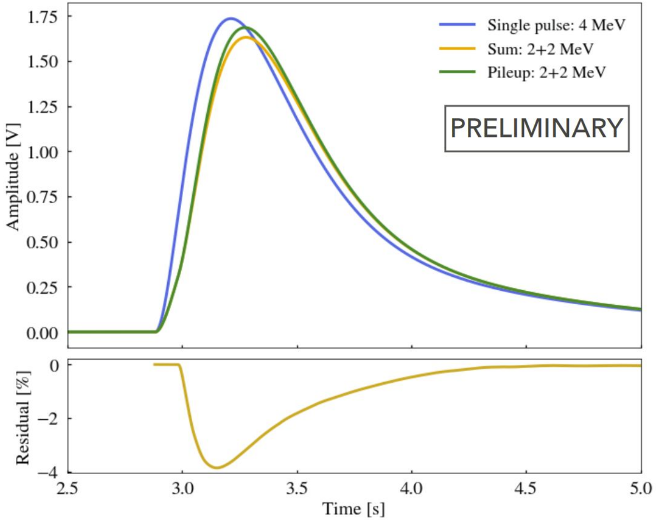
⇒ **High probability of simultaneous 2vββ events in the same crystal**

- Pileup Background Goal: 5 x 10^{-5} ckky
- Rejection time goal: 0.17 ms
- Heat rise time O(10) ms
- Light rise time O(1) ms

These are incompatible!







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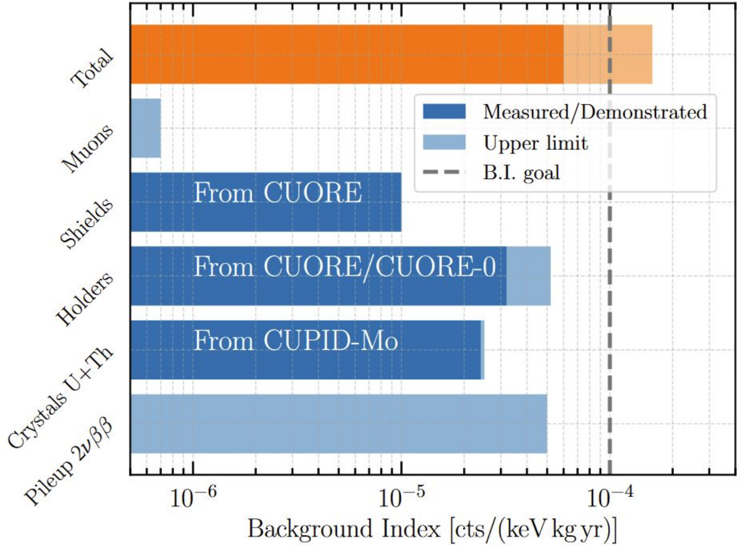
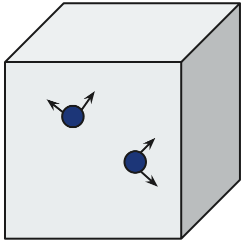
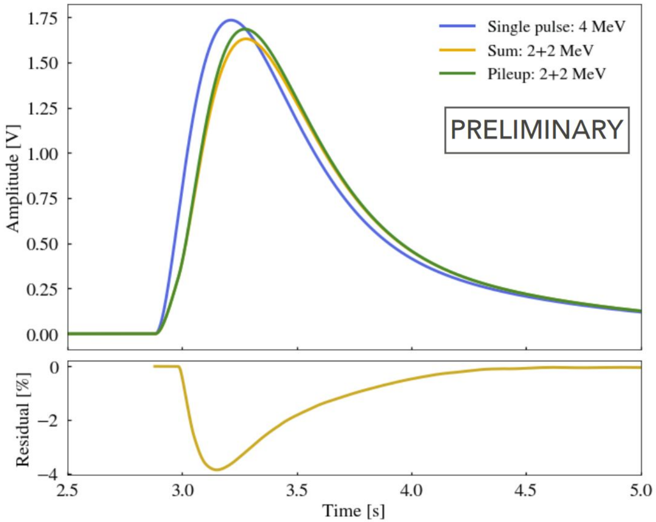
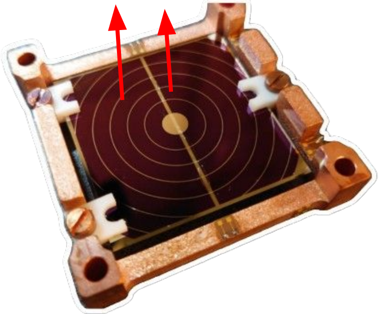


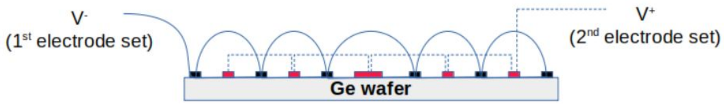


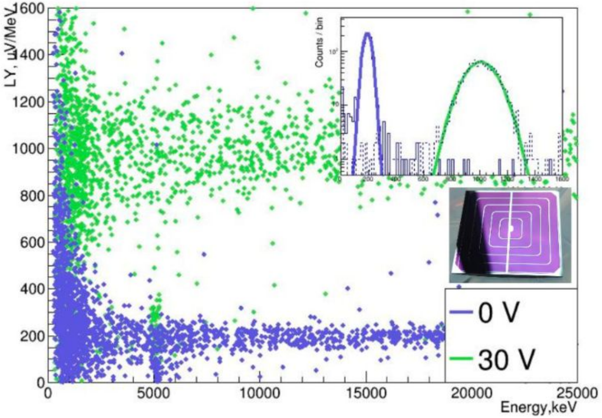
We need something faster that can work in cryogenic environments.



Neganov-Trofimov-Luke light detectors







Ge wafer with Al electrodes evaporated on the surface and operated with NTD Ge thermistor.

NTL effect: Applying a voltage difference V through the electrodes causes the e-h pairs created by an event to drift, amplifying the heat signal.

Operation point: Between 50 and 100 V

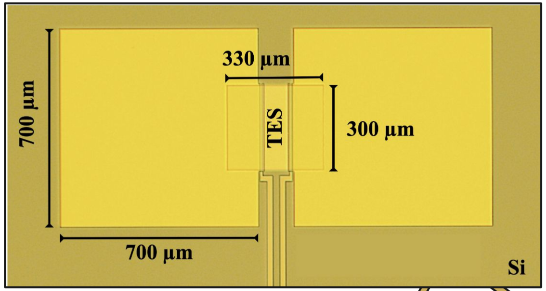
SNR: ~50-100

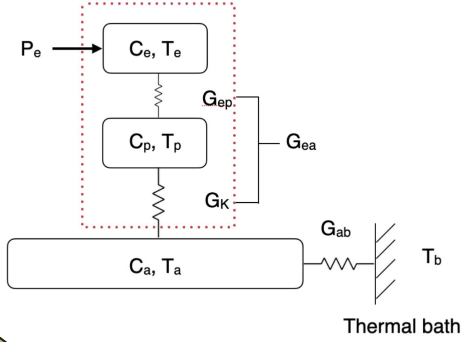
Pulse rise-time: ~1 ms

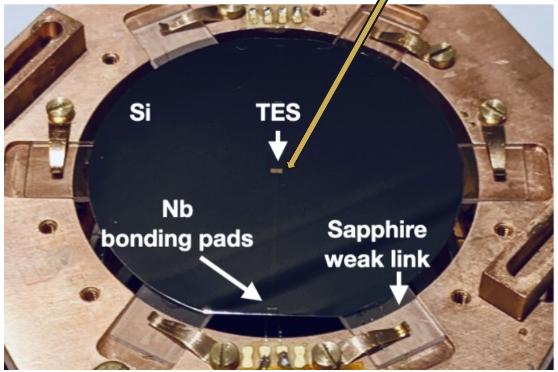
R&D Ongoing:

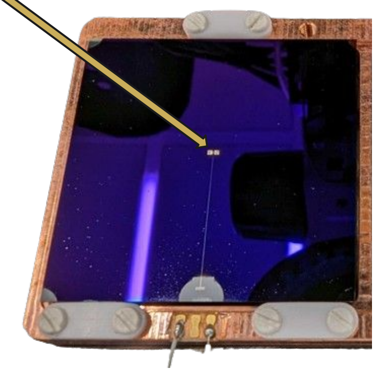
- Electrode geometries
- US production
- Surface treatment

Ir/Pt Transition-edge Sensors (TES) for CUPID-like Light Detectors



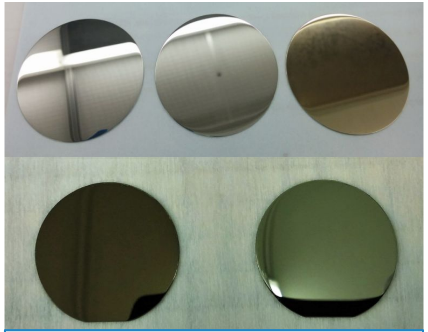






Si wafer equipped with Ir/Pt TES measured on dc-SQUID

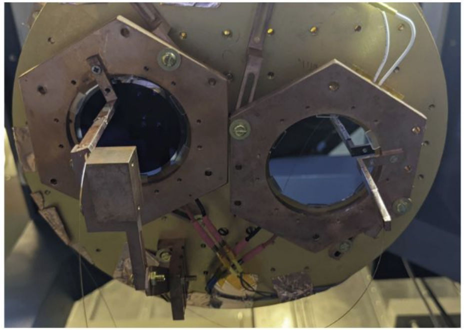
TES: low impedance superconductive thin film operated in a small region around its transition temperature T_c.

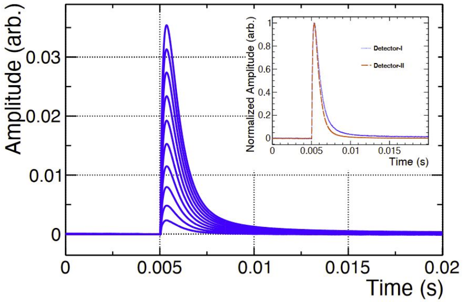


Wafers coated with ARC
Hansen et.al. JINST 12, no. 09, P09018

Ir/Pt Transition-edge Sensors (TES) for CUPID-like Light Detectors

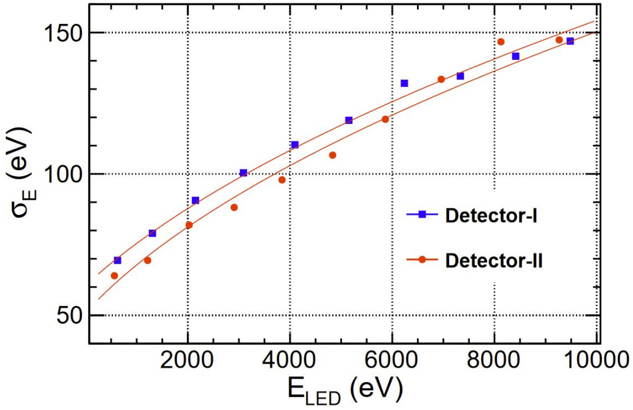
Phys. Rev. Applied 20, 064017 (2023)



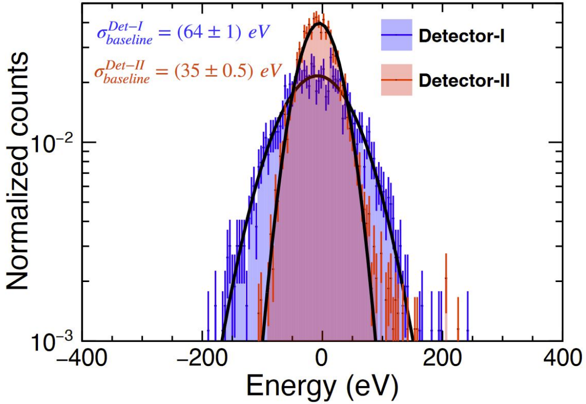


Injected pulse width ≫ rise time of the detector. LED square pulses ~ 600 nm

ΔT = 40 - 340 ns



- Typical rise times ~ 175 μs
- Typical decay times ~ 800-1000 μs



- Baseline resolution well below 100 eV
- Satisfies CUPID-1T requirements for pileup discrimination

R&D Ongoing:

- Resonator board upgrade
- Scale multiplexing for CUPID
- Improve noise performance

CUPID Collaboration Meeting (2023)

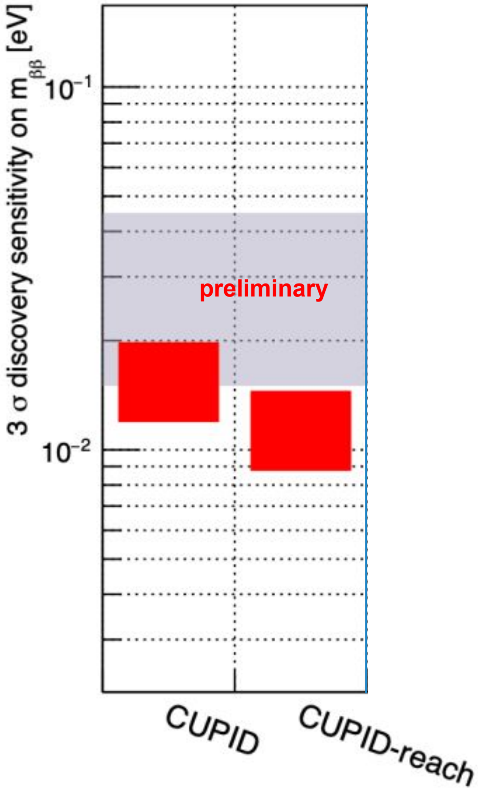
The CUPID Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazional di Fisica Nucleare (INFN); by the European Research Council (ERC) under the European Union Horizon 2020 program; 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.

The Future of CUPID: CUPID-Reach

CUPID-Baseline is conservative.

CUPID-Reach is feasible.

Parameter	CUPID-Baseline	CUPID-Reach
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	450	450
^{100}Mo mass (kg)	240	240
Containment efficiency	78%	78%
Selection efficiency	90%	90%
Energy resolution FWHM (keV)	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}
Livetime (years)	10	10
Half-life exclusion sensitivity (90% C.L.)	1.4×10^{27} y	2.2×10^{27} yr
Half-life discovery sensitivity (3σ)	1×10^{27} y	2×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.) preliminary	10–17 meV	8.4–14 meV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	9–15 meV



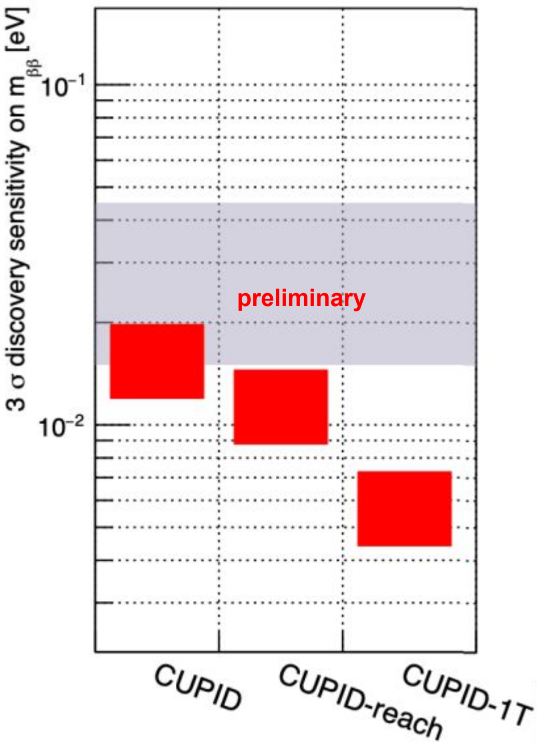
One Possible Future of CUPID: CUPID-1T

CUPID-Baseline is conservative.

CUPID-Reach is feasible.

CUPID-1T is a possible future for CUPID.

Parameter	CUPID-Baseline	CUPID-Reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	450	450	1871
^{100}Mo mass (kg)	240	240	1000
Containment efficiency	78%	78%	78%
Selection efficiency	90%	90%	90%
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.4×10^{27} y	2.2×10^{27} yr	9.1×10^{27} yr
Half-life discovery sensitivity (3σ)	1×10^{27} y	2×10^{27} y	8×10^{27} yr
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.) preliminary	10–17 meV	8.4–14 meV	4.1–6.8 meV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	9–15 meV	4.4–7.3 meV



CUPID-1T

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

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

⇒ 4x scale up of CUPID-baseline

Possible multi-isotope deployment

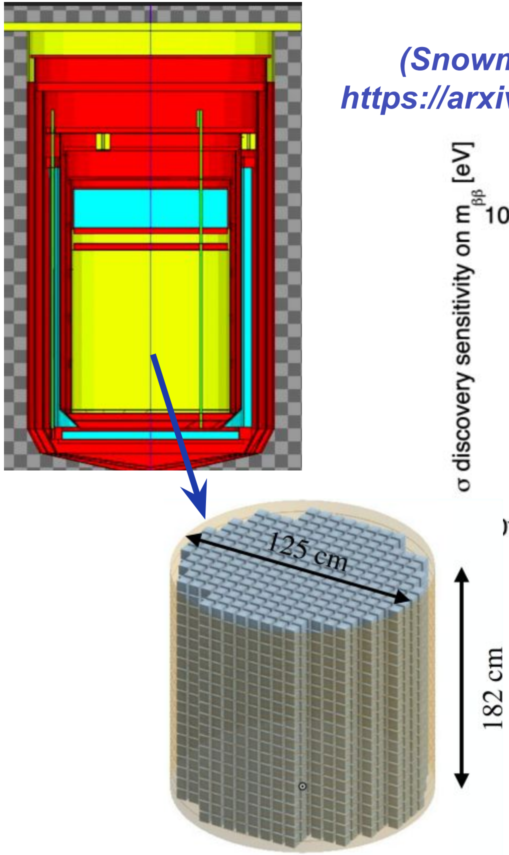
$Zn^{82}Se$, $Li_2{}^{100}MoO_4$, $^{116}CdWO_4$, $^{130}TeO_2$

Possible modes of deployment:

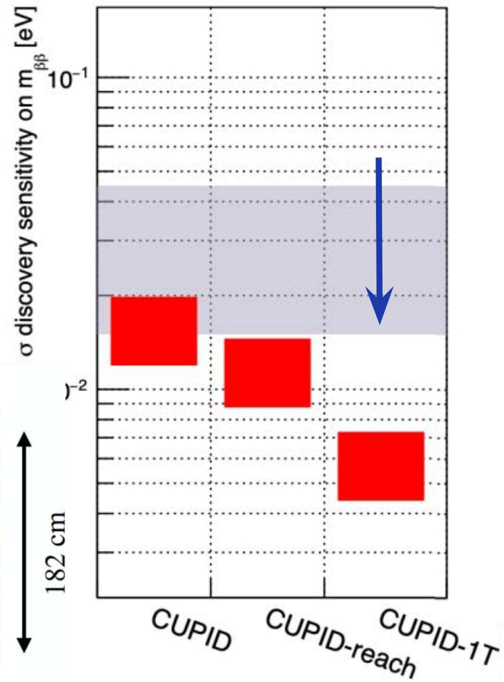
- Larger cryostat allows for self-shielding
- Distributed multi-cryostat setup

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

- ▷ Reduce background μ, β/γ, α discrimination
- ▷ Consider pileup and subdominant backgrounds



Toward CUPID-1T
(Snowmass Contributed Paper)
https://arxiv.org/pdf/2203.08386.pdf

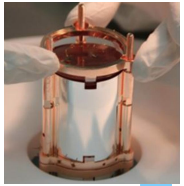


One future of cryogenic calorimeters for 0νββ

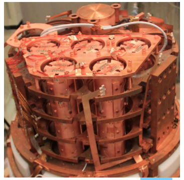
Toward CUPID-1T
(Snowmass White Paper)
https://arxiv.org/pdf/2203.08386.pdf

CUPID-1T

CUPID-0



CUPID-Mo

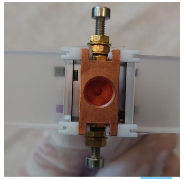


CUORE

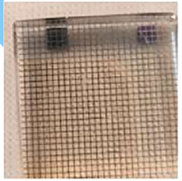
CUPID

You are here!

BINGO



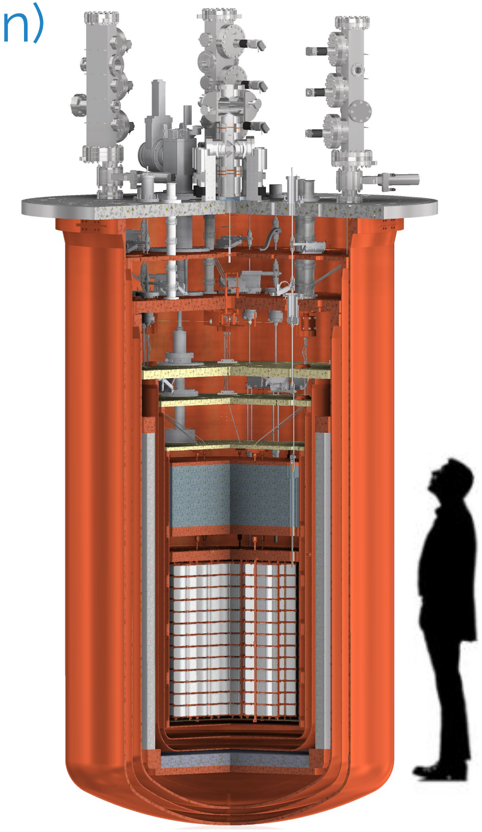
CROSS



DEMETER

demeter

CUPID (CUORE Upgrade with Particle IDentification)



- CUPID builds on the success of the CUORE experiment
    - CUORE 2TY results out later this spring!
- Addition of Particle ID demonstrated to significantly reduce α-background
- R&D ongoing on light collection methods, with demonstrator tests expected '24-'25.
- Planning to take data by the end of the decade.

Thank you!

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