CUPID, CUPID-1T, and the DEMETER demonstrator

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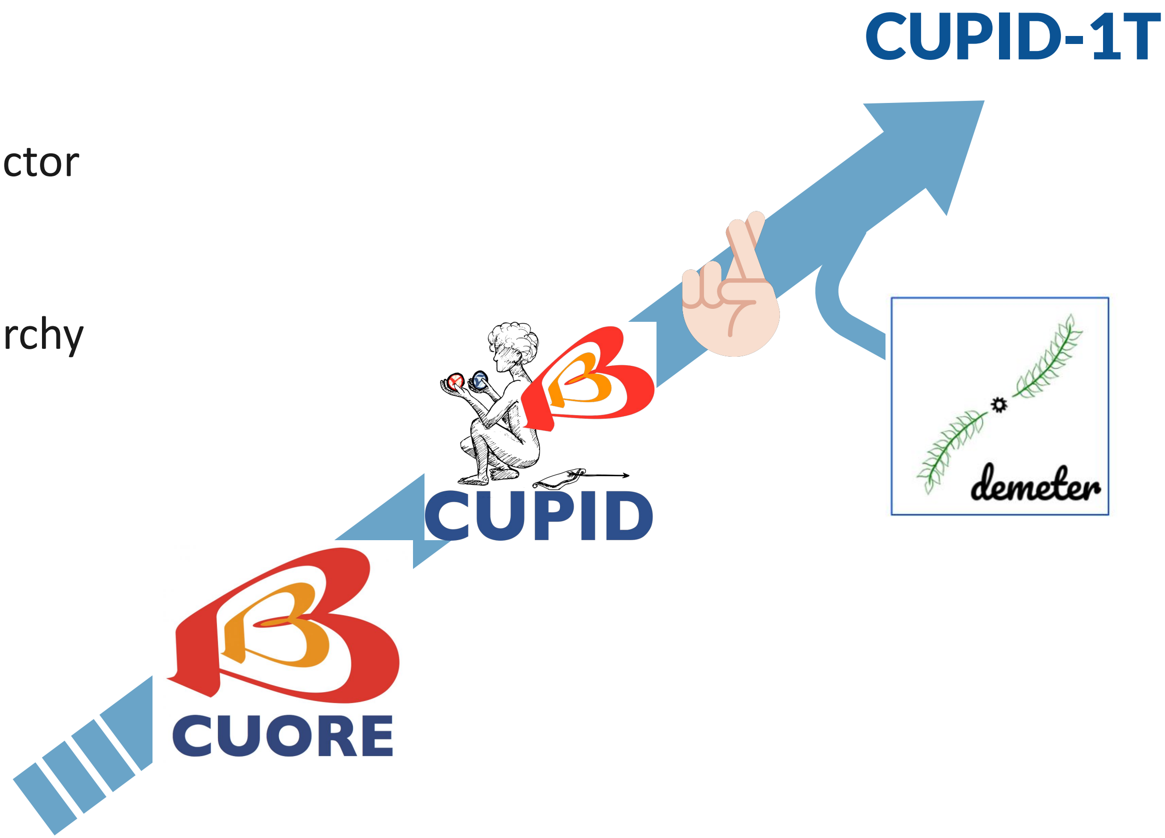
Snowmass CSS
Neutrino Early Career Talks
“The Future is Now”
24 July 2022

CUPID, CUPID-1T, and the DEMETER demonstrator

- How to build a 0νββ detector
- The CUPID experiment
- Towards the normal hierarchy
  - CUPID-1T
  - DEMETER



Double Beta Decay

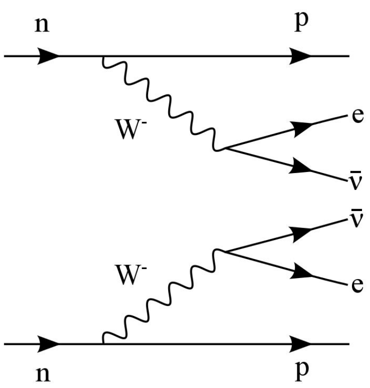
Rare radioactive decay, found in even-even nuclei where single-beta decay is energetically forbidden (e.g. ^{100}Mo)

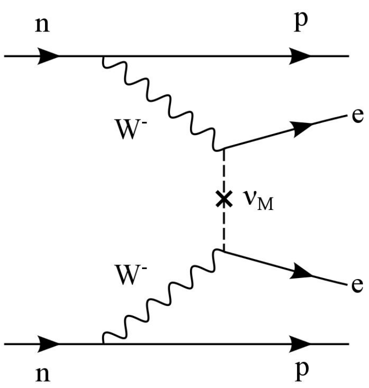
- Two-neutrino (2vββ) ⇒ Observed with $T_{1/2} > 10^{18}$ years

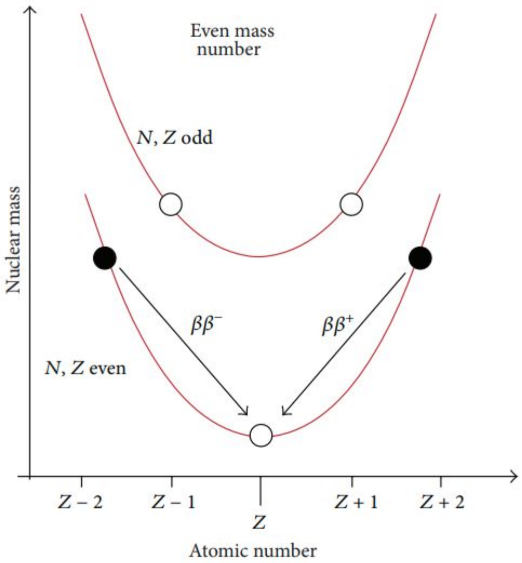
$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\bar{\nu}_e$$

- Neutrinoless (0vββ) ⇒ Expected $T_{1/2} > 10^{25}$ years

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





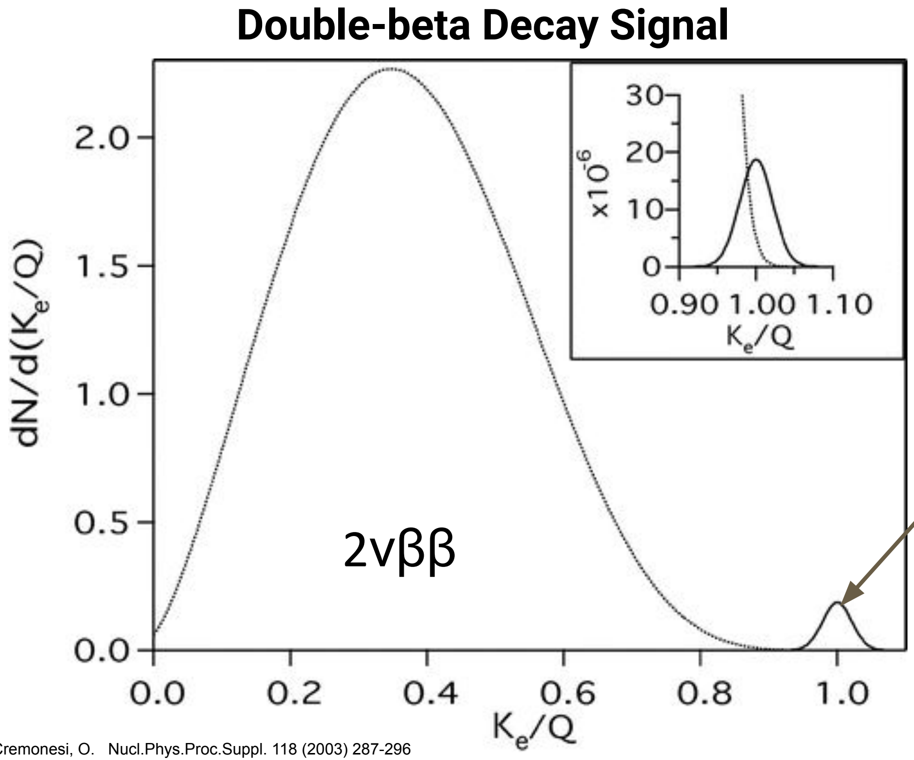


Observation of 0vββ is a critical tool to study neutrinos:

- Majorana or Dirac nature
- Lepton Number violation (ΔL = 2)
- ν mass scale and ordering

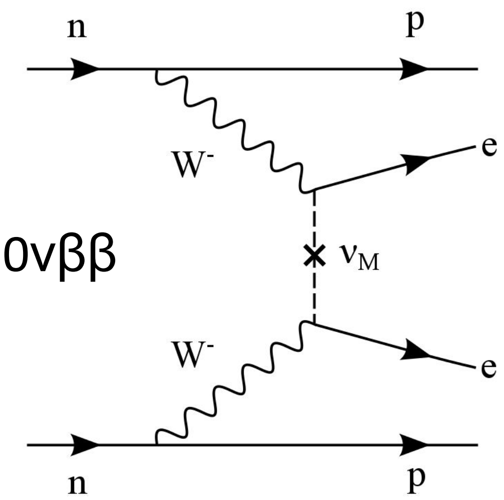
$$\boxed{\nu = \bar{\nu}\ ?}$$

How to build a 0νββ detector

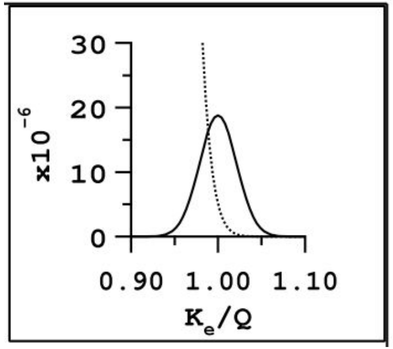


Cremonesi, O. Nucl.Phys.Proc.Suppl. 118 (2003) 287-296

0νββ



How to build a 0νββ detector



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

** assumes nonzero background in ROI*

Four fundamental requirements for modern experiments:

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

Large exposure (M*T)
(large mass, long live-time)

Large η
(isotopic abundance or enrichment)

Large ε
(signal efficiency)

Small b
(low background)

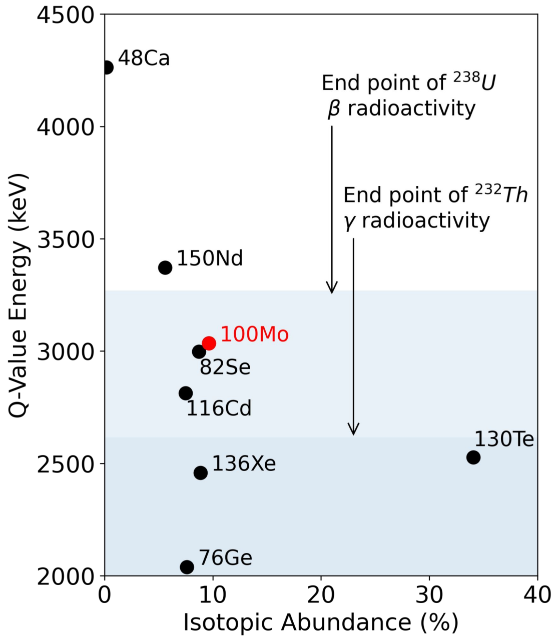
Small ΔE
(good energy resolution)

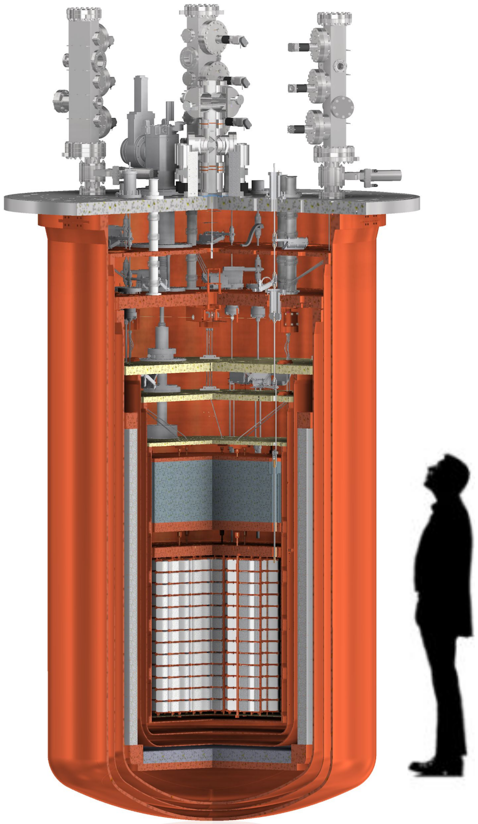
CUPID: CUORE Upgrade with Particle IDentification

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

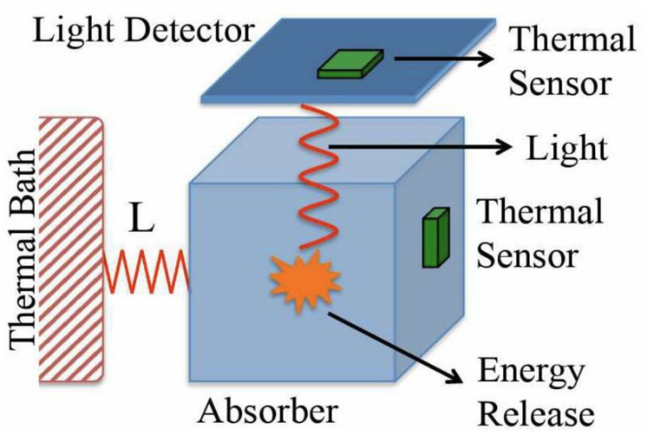
^{100}Mo is an excellent candidate for this search:

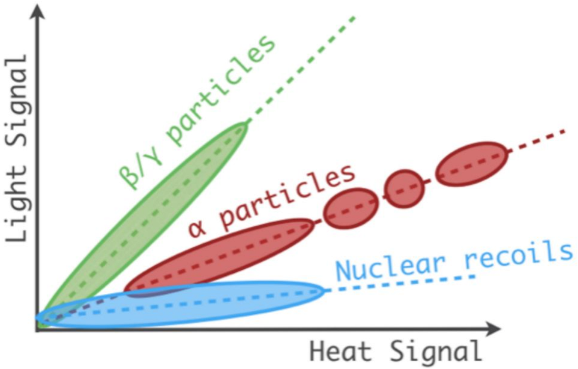
- a high Q-value (3034 keV) above the bulk of γ environmental background,
- favorable nuclear & kinematic factors which yield an expected decay rate 10x faster than other leading isotopes, and
- ease of embedding into scintillating crystals.

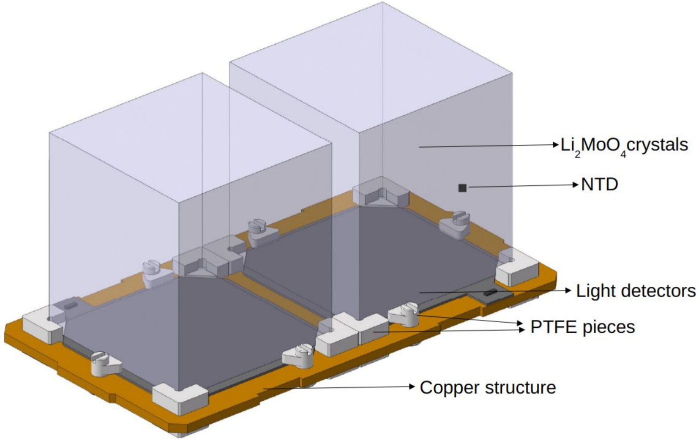




CUPID: CUORE Upgrade with Particle IDentification







- 1596 Li_2MoO_4 cryogenic calorimeters will be instrumented with NTD thermistors for heat signal read out.
- Each crystal will be 45 x 45 x 45 mm^3, corresponding to a mass of ~280 g each and enriched to >95% ^{100}Mo.
- Each LMO crystal will also face two Ge light detectors, instrumented with NTDs (a total of 1710 light collectors).
- The addition of a photon signal allows for rejection of α backgrounds — CUPID-0 [1] and CUPID-Mo [2] have demonstrated this technique with a success rate of >99%.

[1] Phys. Rev. Lett. 123, 032501 (2019) [2] Phys. Rev. Lett. 126, 181802 (2021)

CUPID

Discovery sensitivity (3σ, 10 yr)

1 x 10^{27} year
$m_{\beta\beta}$ < 10-17 meV

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

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)

CUPID

CUPID Collaboration Meeting (2022)

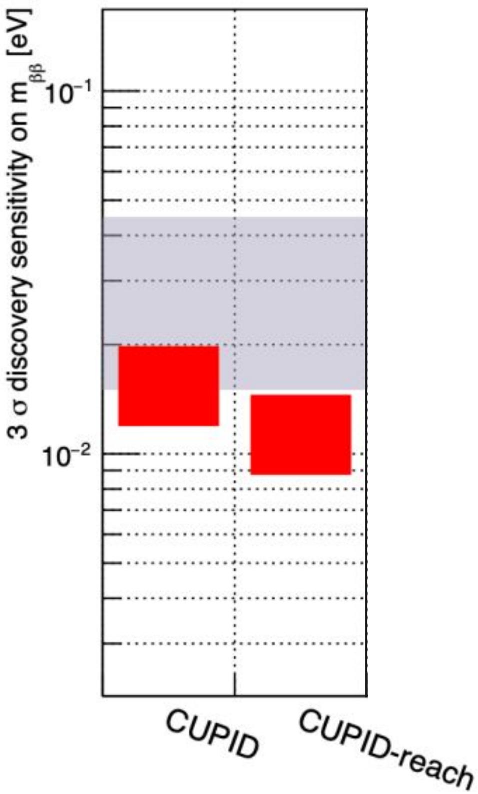
The CUPID Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazional di Fisica Nucleare (INFN); by the European Research Council (ERC) under the European Union Horizon 2020 program;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



CUPID Reach

Identical detector to CUPID-Baseline, but operating in near-zero background.

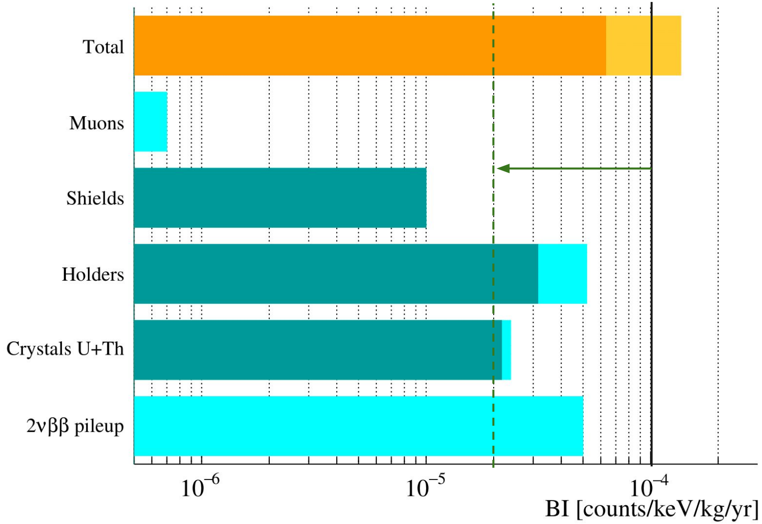
Additional R&D:

- Reduce bulk and surface backgrounds from crystals
  - Additional purification of LMO crystals
  - Elimination of backgrounds by PSD
- Replace some cryogenic vessels and shields with cleaner materials
- Reduce $2\nu\beta\beta$ pileup background

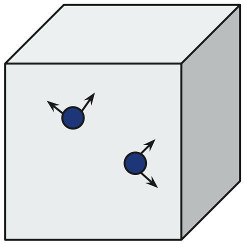
Pileup:

- Slow pulses ⇒ O(10) ms risetime
- Fast ^{100}Mo $2\nu\beta\beta$ decay ⇒ 7.1 x 10^{18} year
- High mass, enriched detector

⇒ High probability of simultaneous $2\nu\beta\beta$ events in the same crystal



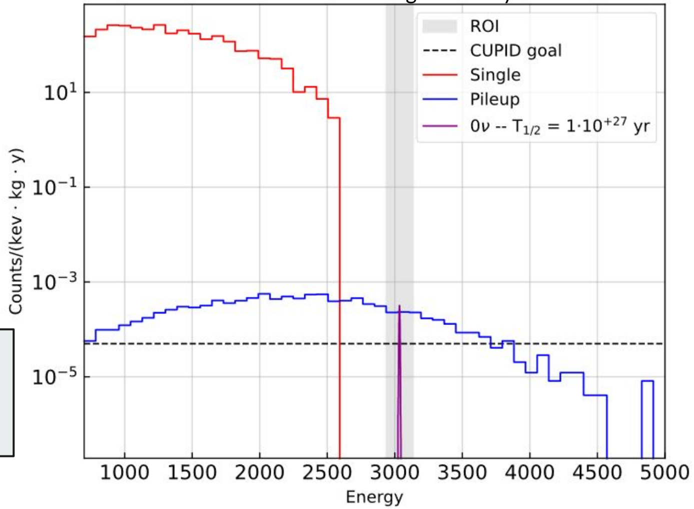
Dark = measurements, Light = upper limits



Mitigation ongoing:

- CNN algorithms
- Timing-focused analysis

Image courtesy M. Beretta

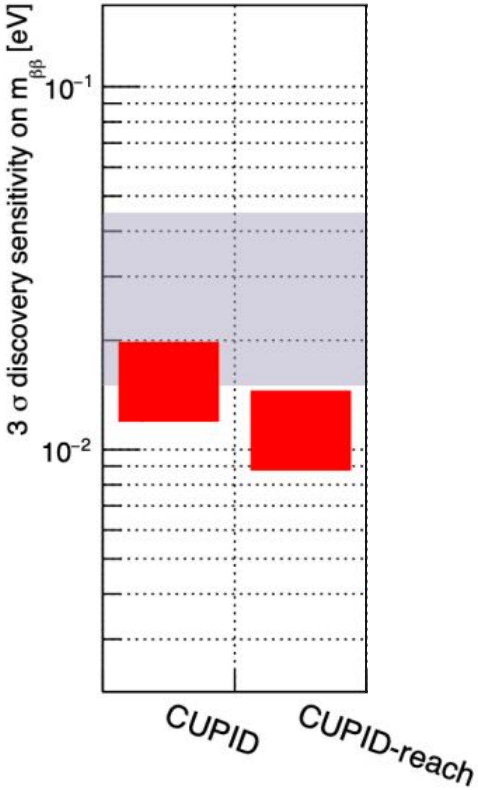


The Future of CUPID: CUPID-Reach

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



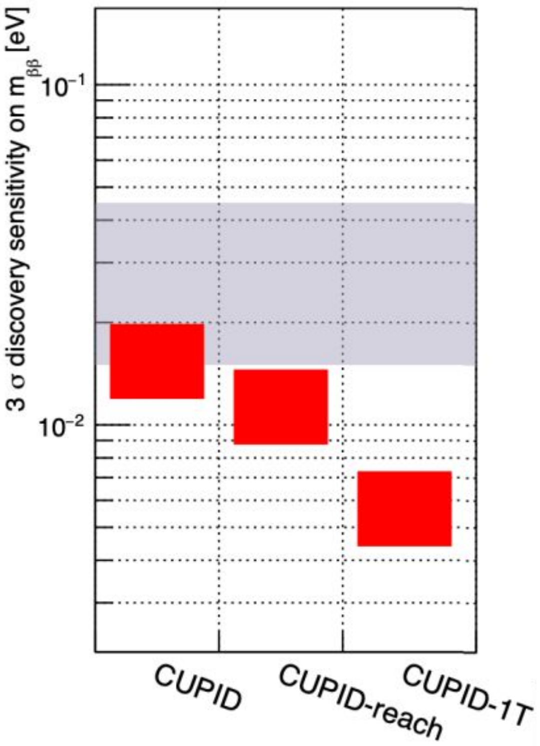
One Possible Future of CUPID: CUPID-1T

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 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

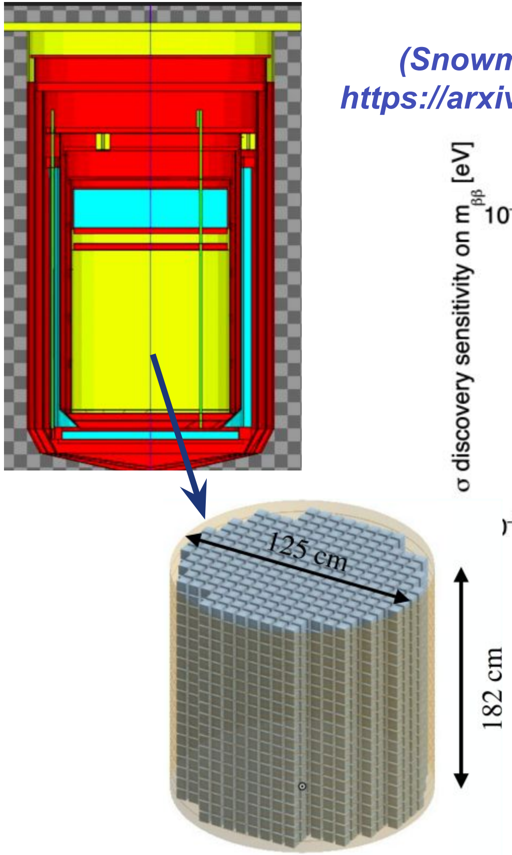
Possible multi-isotope deployment
$Zn^{82}Se$, $Li_2{}^{100}MoO_4$, $^{116}CdWO_4$, $^{130}TeO_2$

Possible modes of deployment:

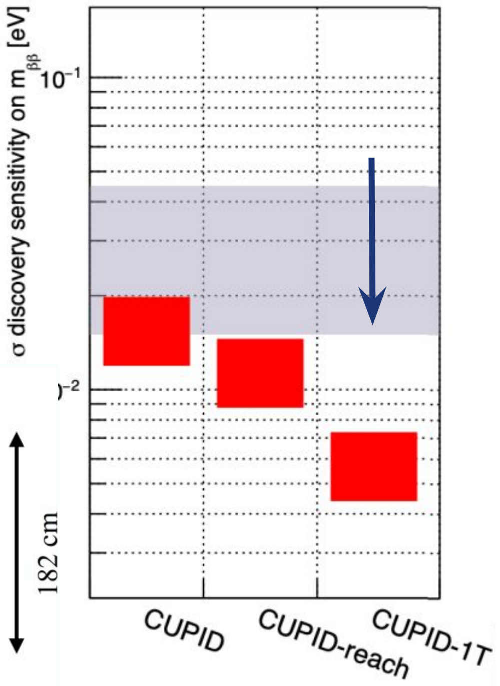
- Larger cryostat allows for self-shielding
- Distributed multi-cryostat setup

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



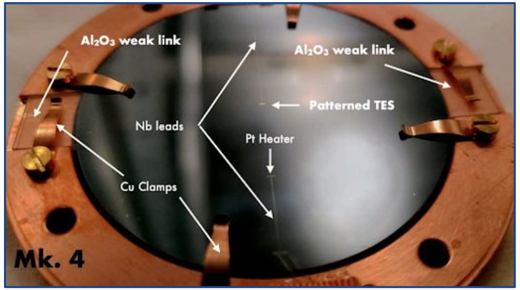
R&D towards CUPID-1T

Quantum sensors   ... for > 10,000 channels!

- Would require low-noise, fast-rise time, high-bandwidth TES or MKID superconducting sensors
- Reasonable level of multiplexing
- Active R&D toward background reduction

Low-impedance TES: Production is easy to scale, & compatible with multiplexing.

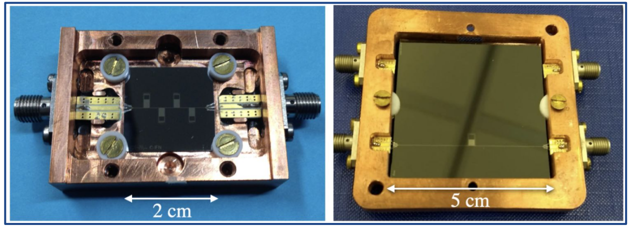
Energy resolution = 100 eV   Timing resolution = 10 μsec



Hennings-Yeomans et.al. Journal of Applied Physics 128, 154501 (2020)

MKIDs: Natively pairs with frequency MUX through tuning of individual devices. Ongoing work of CALDER.

Noise RMS = 90 eV (vibration dominated)   Risetime = 120 μsec



Cardani et.al. Eur. Phys. J. C 81, 636 (2021)

R&D towards CUPID-1T

Quantum sensors … for > 10,000 channels!

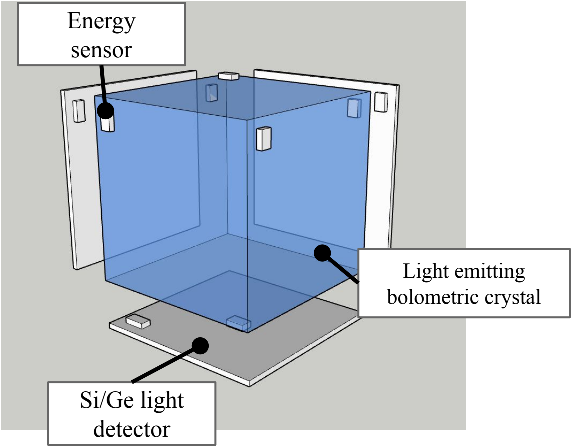
- Would require low-noise, fast-rise time, high-bandwidth TES or MKID superconducting sensors
- Reasonable level of multiplexing
- Active R&D toward background reduction

DEMETER

Demonstrator Experiment with Multiplexed Event Topology and Energy Reconstruction

DEMETER is a collaboration between UC Berkeley CUPID and LBNL CMB groups.

⇒ test stand for development of multiplexing applications, which will be required for CUPID-1T >10k channels.



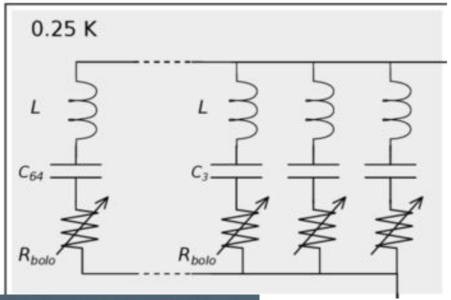
DEMETER: MUX at Ultra-Cryogenic Temperatures

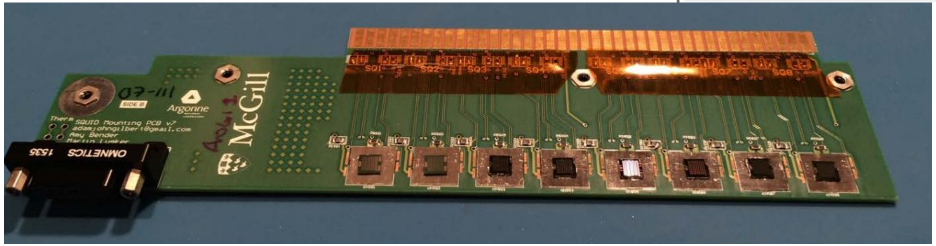
TES readouts at the level of ten thousand channels have been demonstrated using multiplexing technologies.

We have selected frequency-domain multiplexing (FDM) for our preliminary tests.

MHz FDM

- Independent TES AC bias, individual optimization, amplified with DC SQUIDs.
- CMB experiments have multiplexing factors as high as 68. [SPT-3G]
- CUPID can plan on a factor of O(10)





(Top&Bottom) Partial figures from A.N. Bender et al., Proc. SPIE Int. Soc. Opt. Eng. 9914, 99141D (2016)

Alternative options:

Time-division multiplexing (TDM)

- Requires thousands of wires from cryogenic stage to room temperature electronics
- Decreasing wire density has reportedly degraded noise performance
- Cryo CMOS (JINST 15 (2020) P06026)

GHz FDM ("µMUX")

- Sets of TES, coupled to RF SQUIDs, & DC biased.
- Significant thermal loading on cryogenic stage
- Multiplexing factors projected at $O(10^3)$ but not fielded at that scale.

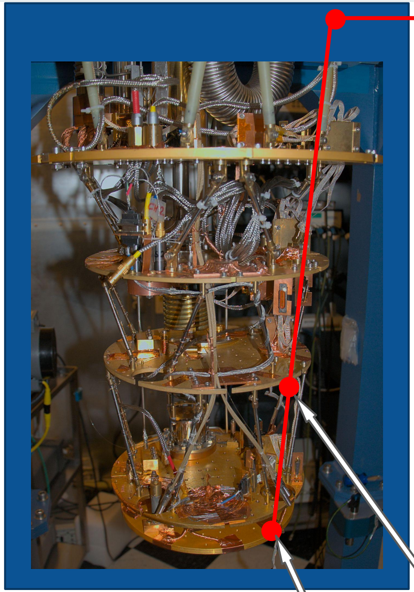
DEMETER: MUX at Ultra-Cryogenic Temperatures

Implementing in ultra-cryogenic experiments like CUPID-1T will need R&D.

MUX has not been demonstrated at operating temperatures of mK at this scale including the following: (outside to inside)

- Cables must be shielded from magnetic flux, which has not been demonstrated in CUPID-like environments
- Cable impedance must allow for signal-readout without additional modulation
- Crosstalk between TES devices is a predicted issue, and must be resolved at this scale

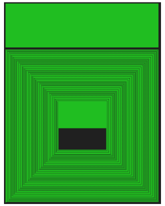
Also, radioactivity is naturally occurring in the normal materials for readouts ⇒ backgrounds in CUPID-like experiments.

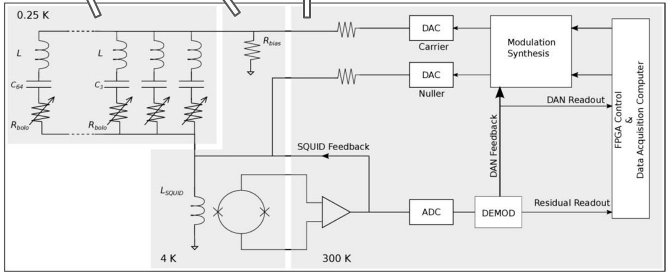


Room temperature electronics

Starting with electronics from CMB, modifying for our use.

Inductor chip for TES fMUX testing, courtesy Chiara Capelli (LBL)





From A.N. Bender et al., Proc. SPIE Int. Soc. Opt. Eng. 9914, 99141D (2016)

DEMETER: Event Topology at the Crystal Level

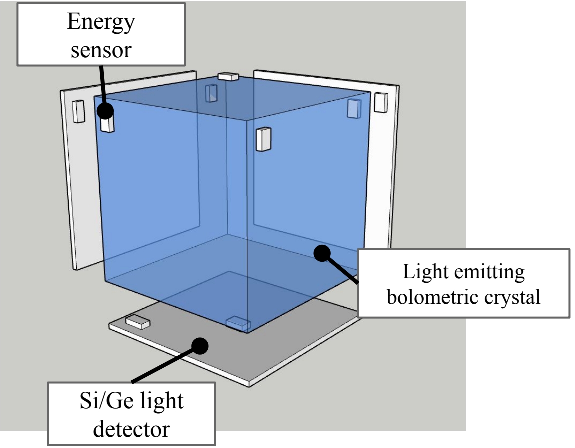
Berkeley
UNIVERSITY OF CALIFORNIA

Quantum sensors
- Would require low-noise, fast-rise time, high-bandwidth TES or MKID superconducting sensors
- Reasonable level of multiplexing
- Active R&D toward background reduction

demeter

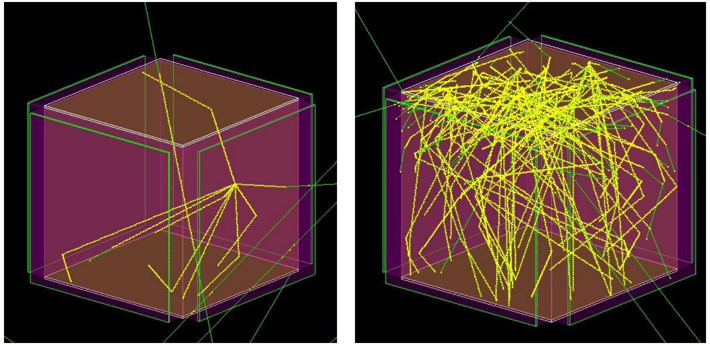
DEMETER
Demonstrator Experiment with Multiplexed Event Topology and Energy Reconstruction

- CUPID's heat/light collection provides excellent particle discrimination, but there's not yet sensitivity to topology (energy / position reconstruction) at the **single-crystal level**.
- DEMETER focuses on both phonon and photon reconstruction at the single-crystal scale to provide physics information & background identification to large scale detectors like CUPID-1T. **We could distinguish between one- and two-electron events for a truly background-free measurement.**
- Potentially transformative technology: Modular TeO_2 calorimeters with topological reconstruction and PID (Cherenkov and phonon imaging) could **mitigate the need for enriched detectors.**



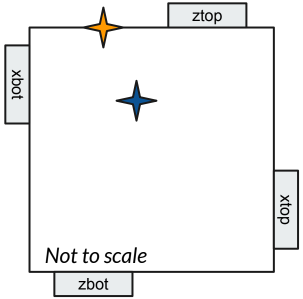
DEMETER: Simulations Status

Detailed simulations ongoing:
- Scintillation & Cherenkov photon simulations
  - With and without reflective surfaces, with and without anti-reflective coatings.
  - Preparing to calibrate w/ CUPID-like setup (Co-60 source) above ground.
  - Currently limited by understanding microscopic properties of LMO at 10mK.



Images courtesy K. Graham

- Complemented by phonon simulations based on G4CMP (CMS) (photon simulations of LDs are mature, simulations of crystal are in development)
  - Surface events show obvious position dependence!
  - Volume events show some, but we need convincing.



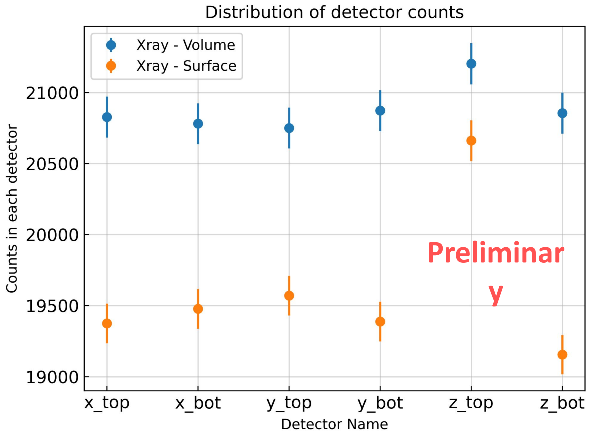


Image courtesy M. Beretta

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Brian Fujikawa
Chiara Capelli
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Berkeley Bolometer R&D

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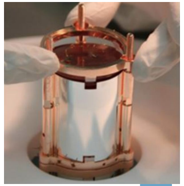
One future of cryogenic calorimeters for 0νββ

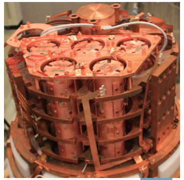
Toward CUPID-1T
(Snowmass Contributed Paper)
https://arxiv.org/pdf/2203.08386.pdf

CUORE

CUPID-0



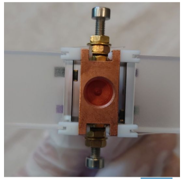
CUPID-Mo



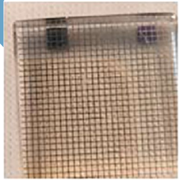
CUPID

You are here!

BINGO



CROSS



DEMETER

demeter

CUPID-1T