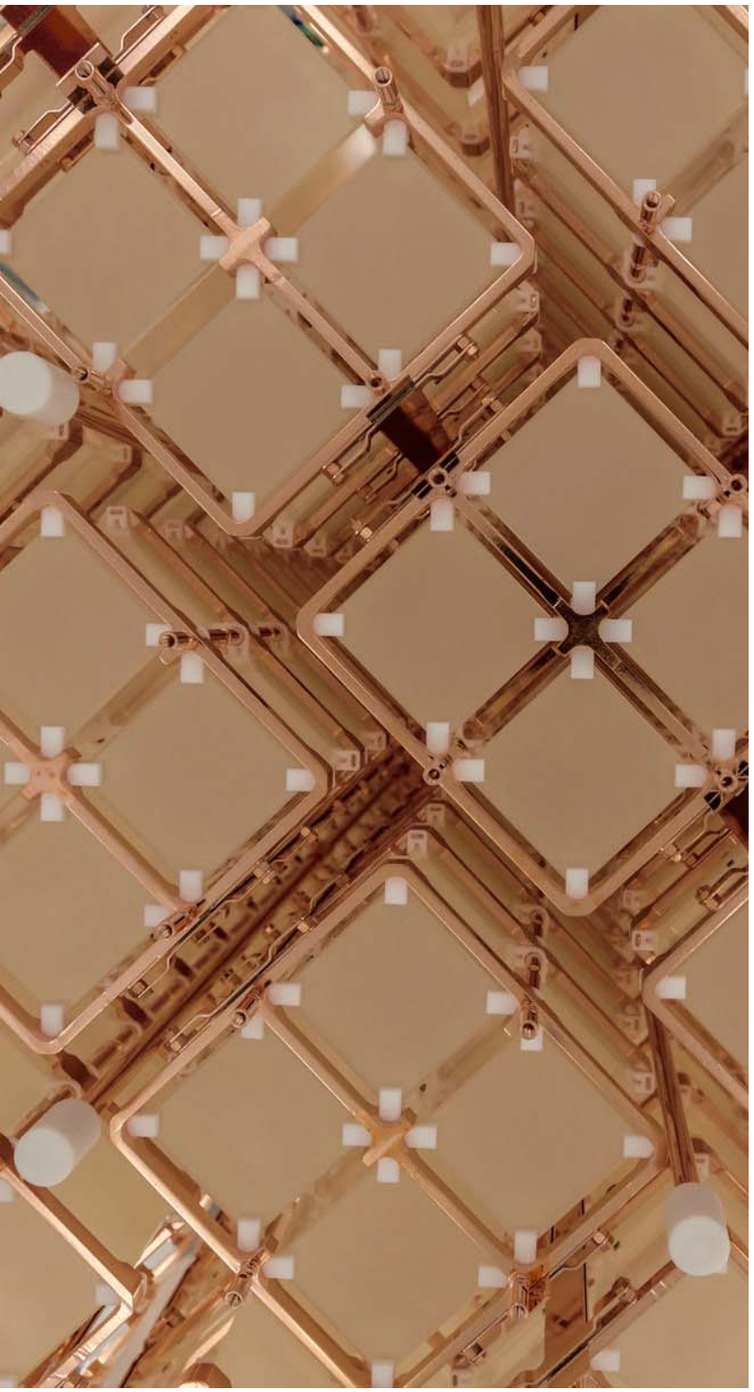


Status and Outlook of the CUORE and CUPID Experimental Calorimetry Programs: An Overview

Danielle H. Speller for the CUORE and CUPID Collaborations

Johns Hopkins University

August 5, 2020

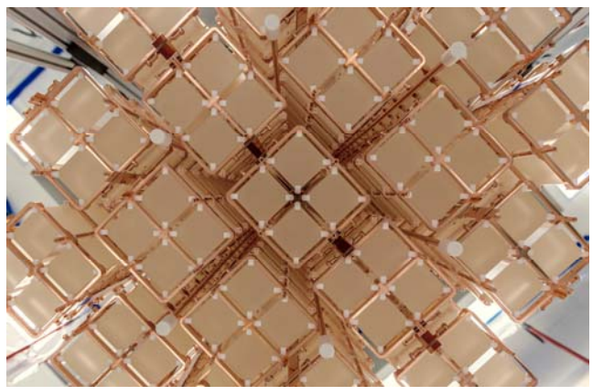
Acknowledgements

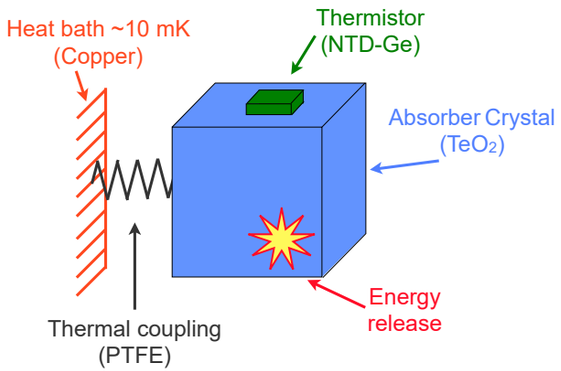
Slides provided by CUORE, CUPID, CUPID-Mo, and CUPID-0 Collaborations

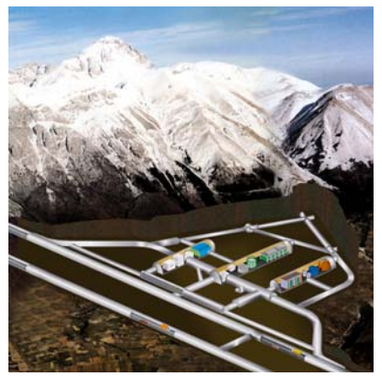
Searching for Neutrinoless Double-Beta Decay with CUORE

CUORE: The Cryogenic Underground Observatory for Rare Events

- **The first tonne-scale 0νββ experiment operating with thermal detectors**
  - Main objective: 0νββ in ^{130}Te
  - 988 TeO_2 crystals, 5×5×5 cm^3 each
  - Total mass: 742 kg TeO_2
  - ^{130}Te mass: 206 kg (all natural abundance)
  - Macrocalorimeter operation in $T \sim O(10\ \mathrm{mK})$ cryostat
  - Located underground at LNGS (Italy)
  - Expected energy resolution at 2615 keV: 5 keV FWHM
  - Background goal: 0.01 cts/(keV·kg ·yr) at $Q_{\beta\beta}$
  - Sensitivity: $T_{1/2}^{0\nu} = 9\times10^{25}$ yr (90% C.I.) in 5 years of data collection (Eur. Phys. J. C (2017) 77:532)





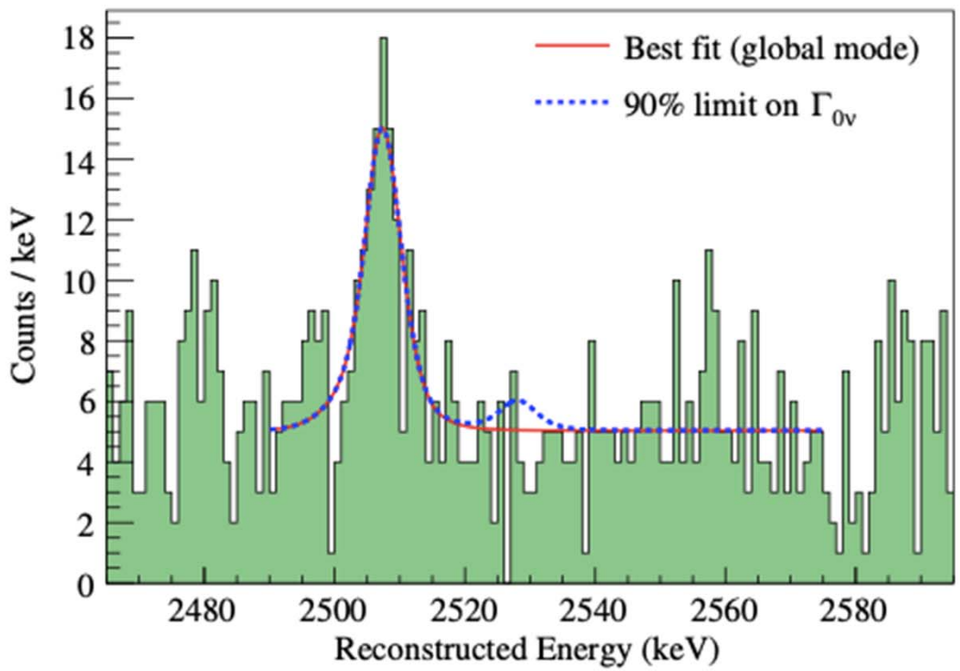


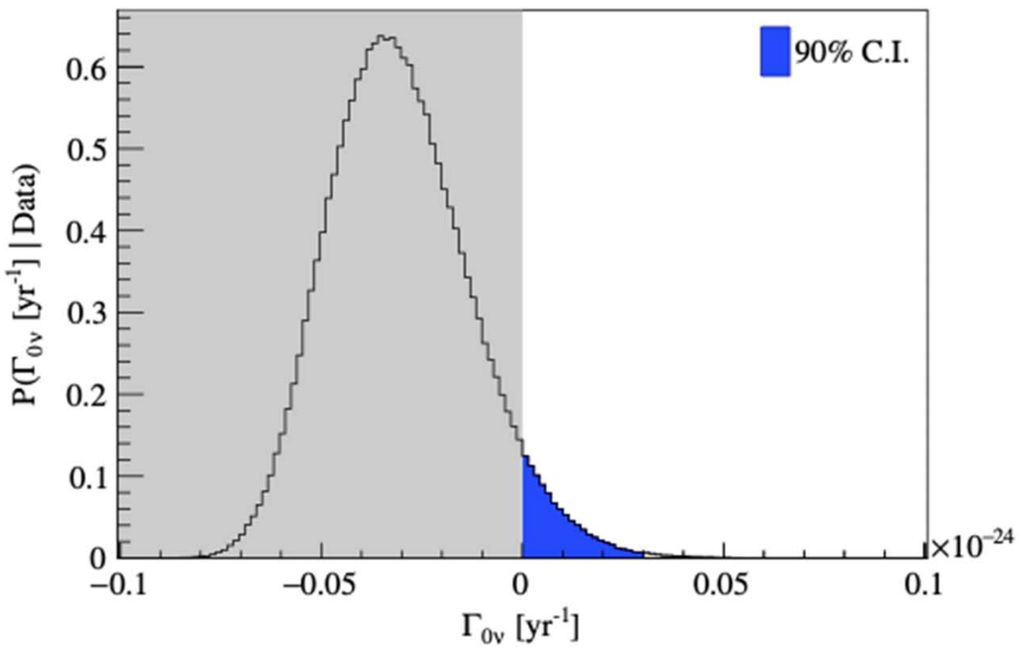
*Cryogenics **102**, 9-21 (2019).*
arxiv:1904.05745

*Cryogenics **93**, 56-65 (2018).*
arxiv:1712.02753

Recent Results: Improved Limit on 0νββ in ^{130}Te with CUORE (2020)

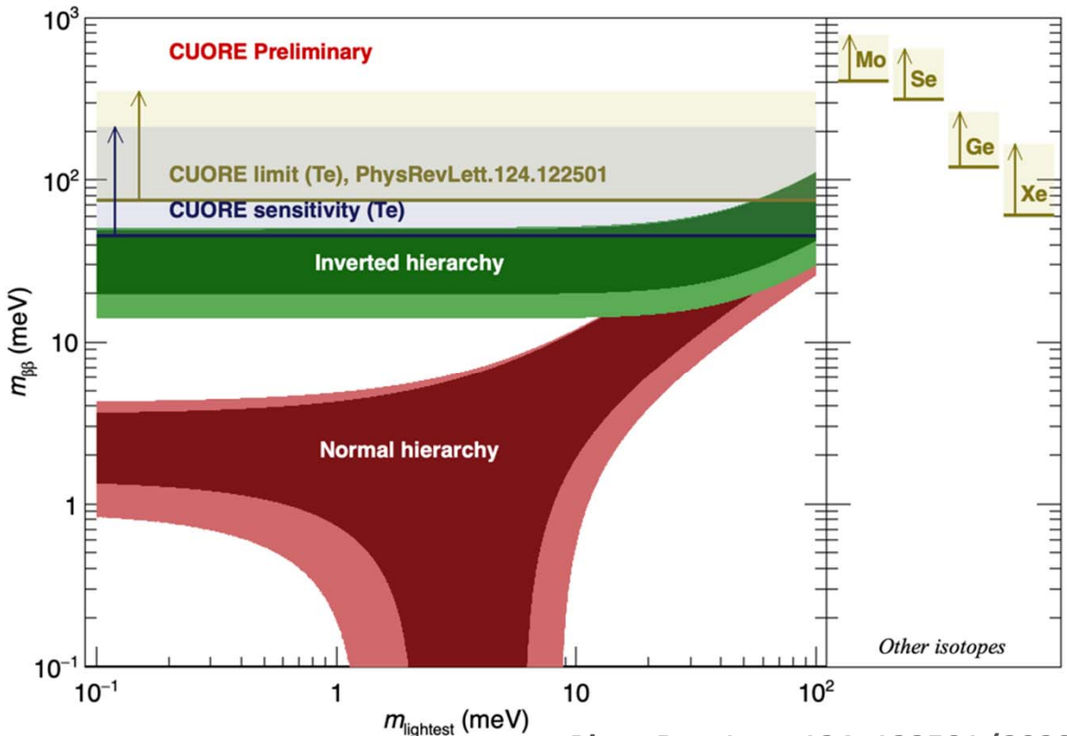
- **Total analyzed exposure**: 372.5 kg·yr
- **Resolution (expo.-weighted harmonic avg, $Q_{\beta\beta}$)**: 7.0±0.4 keV
- **Background**: 1.38±0.07 x 10^{-2} cts/(keV·kg·yr) in the 0νββ region of interest
- **Median exclusion sensitivity**: 1.7 x 10^{25} yr
- **$T_{1/2}^{0\nu} > 3.2 \times 10^{25}$ yr (90% C.I.)** Bayesian lower limit on ^{130}Te half-life





Phys. Rev. Lett. 124, 122501 (2020)

Recent Results from CUORE (continued)



Phys. Rev. Lett. 124, 122501 (2020)

- ***Next release: 1000 kg·yr exposure (Fall 2020)***
- ***Total cumulative exposure: 940.8 kg·yr (as of July 26, 2020)***

0νββ of ^{130}Te: Improved Limit (2020)

CUORE limit on effective Majorana mass:
$m_{\beta\beta}$<0.075-0.350 eV at 90% C.I.

Notes

- *Depends on nuclear matrix elements (model-dependent calculation)*
- *Any discovery of 0νββ points toward new physics, regardless of hierarchy reach*
- *Multiple systems & multiple isotopes needed for discovery*

Further Recent and Ongoing Searches

2νββ decay of ^{130}Te (in preparation)

Majorons (2019, PhD. Davis)

CPT violation (2019, PhD. Nutini)

Solar axions (2018, PhD. Chott)

^{130}Te to excited 0+ states (ongoing)

^{128}Te 0νββ decay (ongoing)

^{120}Te β^++ EC (ongoing)

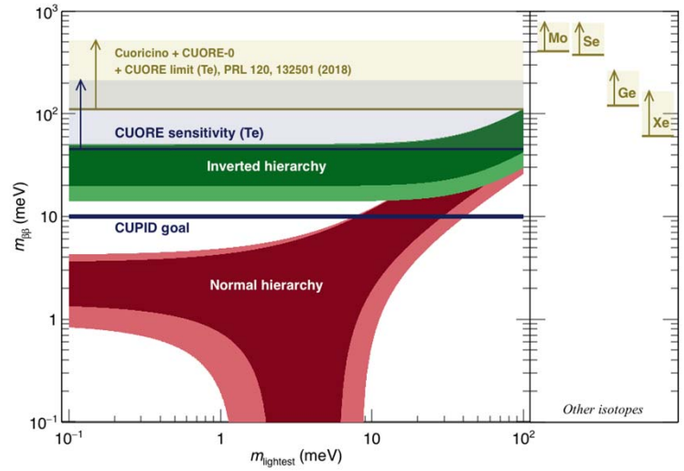
The CUORE Upgrade with Particle Identification (CUPID)

R. Artusa et al., Eur.Phys.J. **C74**, 3096 (2014)
White papers: arXiv:1504.03599 & arXiv:1504.03612
CUPID pre-CDR: arXiv:1907.09376

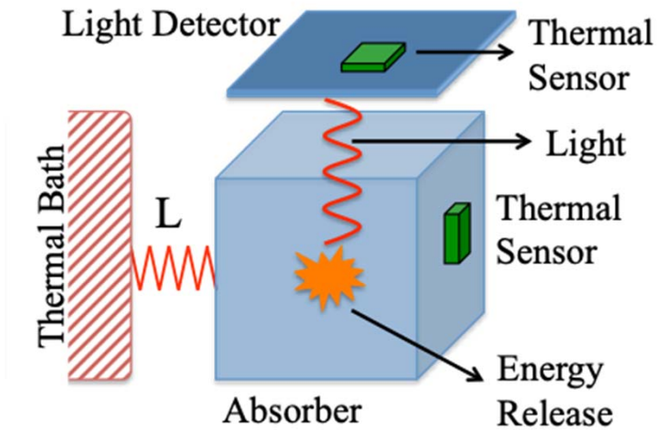
NEXT-GENERATION BOLOMETRIC TONNE-SCALE EXPERIMENT AT LNGS

Mission: Discover $0\nu\beta\beta$ if $m_{\beta\beta} > 10$ meV (half-life in ^{100}Mo $> 10^{27}$ years)

Mature concept based on:



- ***CUORE Achievements:***
  - Tonne-scale bolometric detector is technically feasible
  - Operation and analysis of 1000 bolometers demonstrated
  - Reliable data-driven background model constructed
  - Infrastructure for next-generation experiment exists

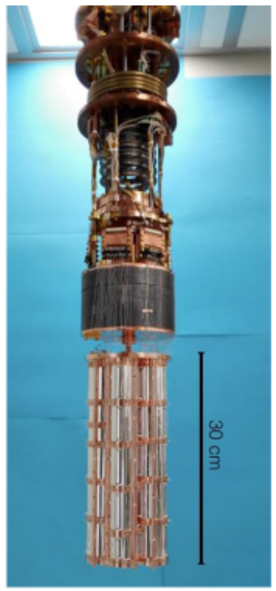


- ***Scintillating Bolometer R&D by LUCIFER/CUPID-0, LUMINEU/CUPID-Mo***
  - Demonstrated large-scale enriched crystal production capability
  - Internal radio-purity targets met
  - Demonstrated active background rejection
  - Energy resolution ~5 keV demonstrated
  - Total background of ~0.1 cts/(ton·keV·yr) achievable

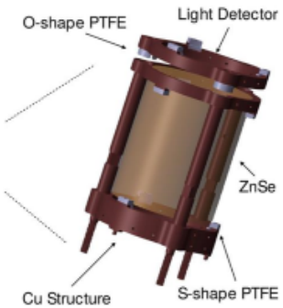
CUPID-0 – The First CUPID Demonstrator

8/5/2020

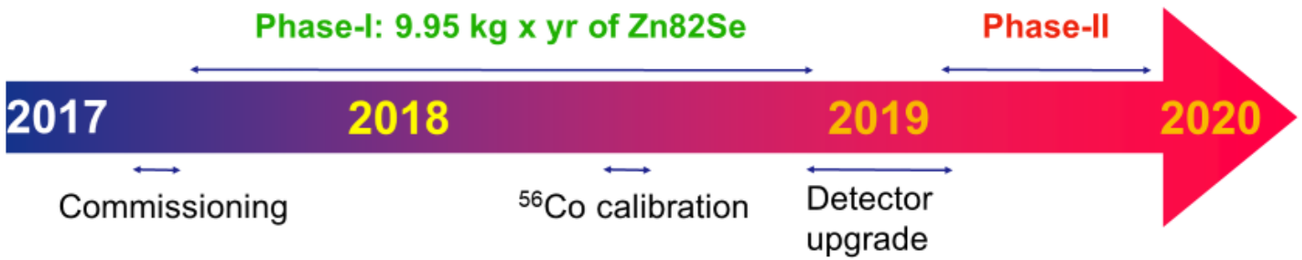
CUPID-0: the first CUPID demonstrator



- 26 ZnSe (24 95% enriched + 2 natural) -> (3.8×10^{25} ^{82}Se nuclei)
- ^{82}Se 0νββ decay Q-Value: 2998 keV
- 31 Ge slabs (Light Detector)



- Hosted in the same CUORE-0 dilution refrigerator (Hall A)

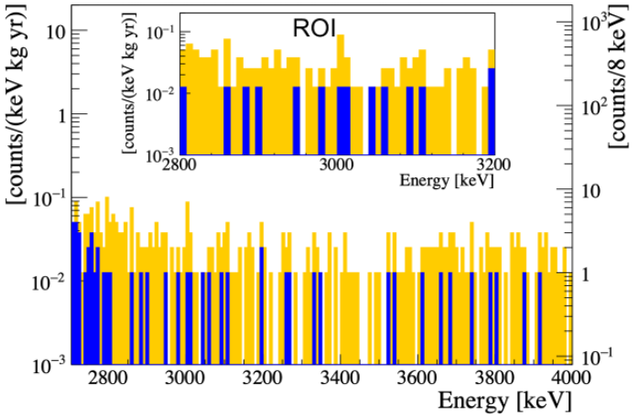


Slide: Nicola Casali

CUPID-0: Conquering the Background

PHASE I:

Results with 9.95 kg yr exposure



BKG = 2.8 x 10^{-2} counts/(keV kg yr) α + β/γ events

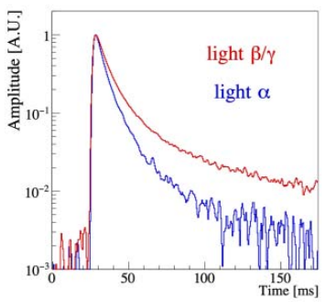
BKG = 3.5 x 10^{-3} counts/(keV kg yr) after α rejection

Lowest Background for Cryogenic Calorimeters

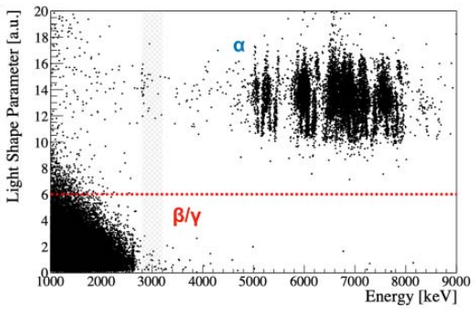
World-leading limit on 0νββ decay of ^{82}Se:

$T^{0\nu}_{1/2} > 3.5 \times 10^{24}$ yr (90% CI)

Alpha rejection capability

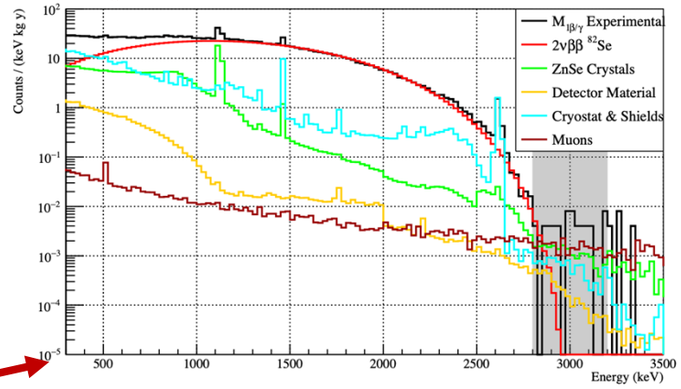


The light signal shape depends on particle type



Complete alpha rejection for Energy > 2 MeV

Analysis of cryogenic calorimeters with light and heat read-out for double beta decay searches, Eur. Phys. J. C 78, 734 (2018).



Source	ROI Background Index
ROI = 2.8 - 3.2 MeV	[10^{-4} counts/(keV·kg·y)]
$2\nu\beta\beta$ ^{82}Se	6.0 ± 0.3
ZnSe Crystals	$11.7 \pm 0.6\ ^{+1.6}_{-0.8}$
Detector Material	$2.1 \pm 0.3\ ^{+2.2}_{-1.0}$
Cryostat & Shields	$5.9 \pm 1.3\ ^{+7.2}_{-2.9}$
Muons	$15.3 \pm 1.3 \pm 2.5$
Total	$41 \pm 2\ ^{+9}_{-4}$

Background Model: ***Background model of the CUPID-0 experiment, Eur. Phys. J. C 79, 583 (2019).***

PHASE II:

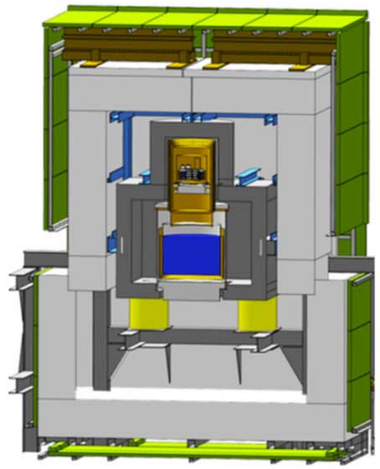
- Data collection now completed, results in preparation
- Total exposure (Phase I + Phase II): 15.6 kg·yr

Slides: Nicola Casali

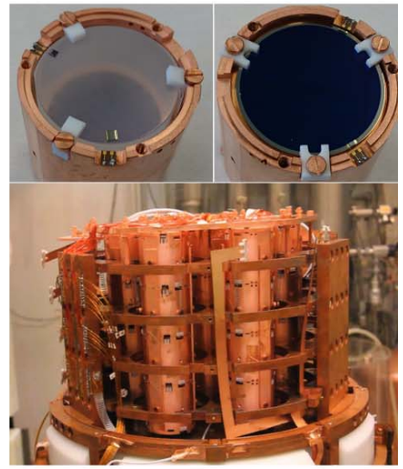
CUPID-Mo

8/5/2020

CUPID-Mo at Laboratoire Souterrain de Modane France (2018 - 2020)



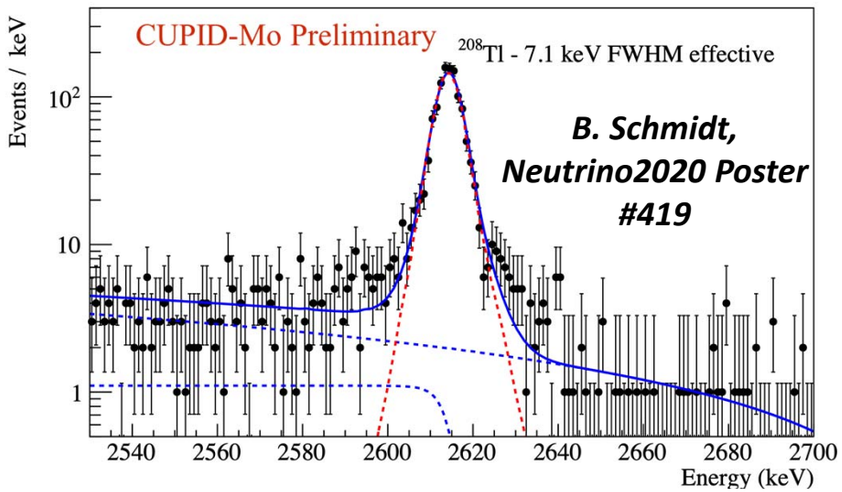
- 4800 m.w.e. rock overburden
- shared EDELWEISS cryogenic infrastructure operated at @ 20 - 22 mK
- 20 $Li_2{}^{100}MoO_4$ detectors of ~210 g, ~97% enriched (2.26 kg ^{100}Mo)
- Ge light detectors
- Ge-NTD based sensor readout
- **All $Li_2{}^{100}MoO_4$, 19 light detectors operational**
- physics data taking March 2019 - June 2020



Benjamin Schmidt, Lawrence Berkeley National Laboratory 12 CUPID-Mo Neutrino 2020 results, LBNL seminar 06/29/2020

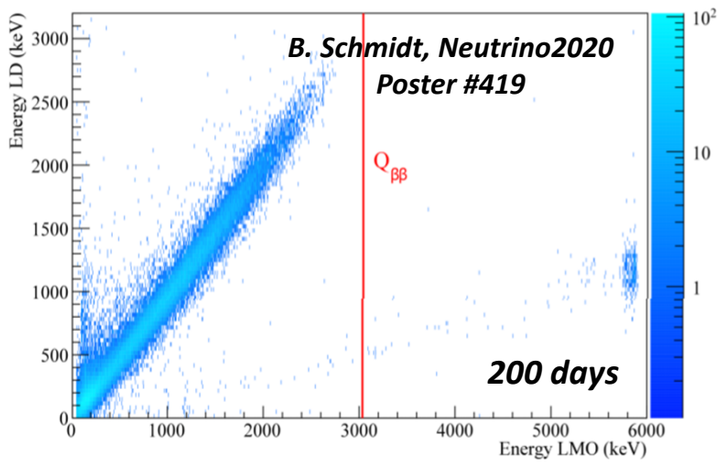
Slide: Benjamin Schmidt

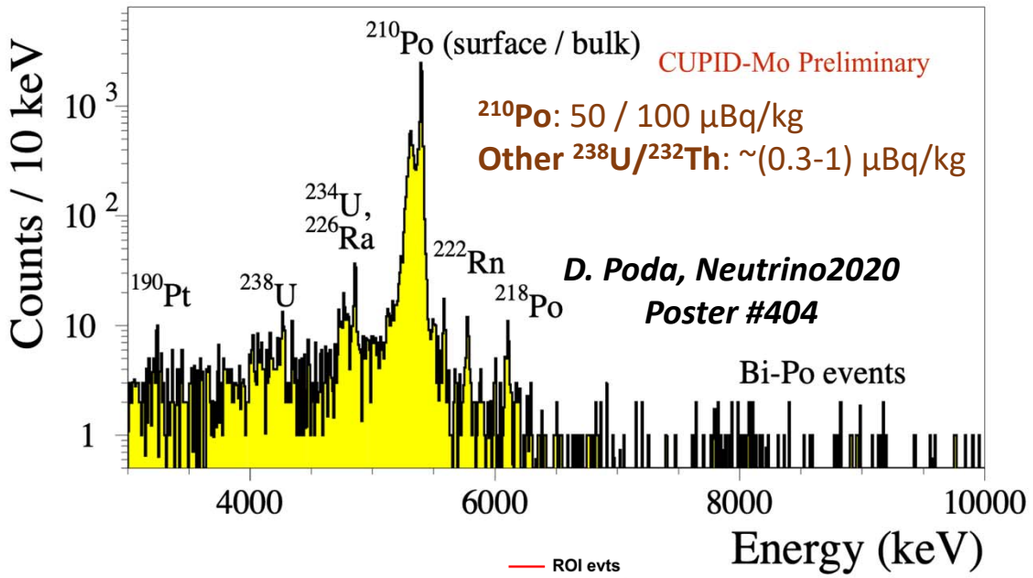
CUPID-Mo: Resolution & Radiopurity

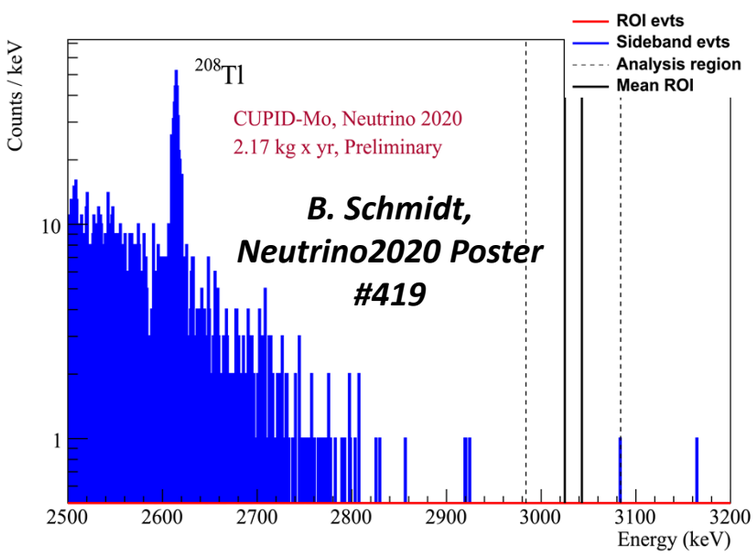


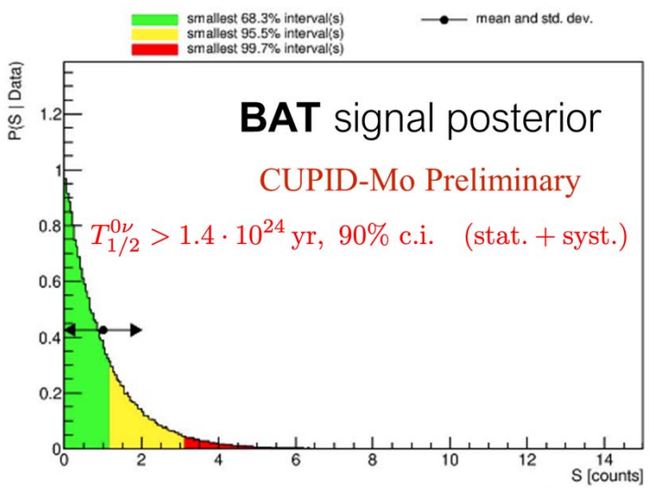
**7.1 keV resolution achieved in non-optimal conditions*

- *T≈21 to 22 mK*
- *Issues with noise and detector stablilization*



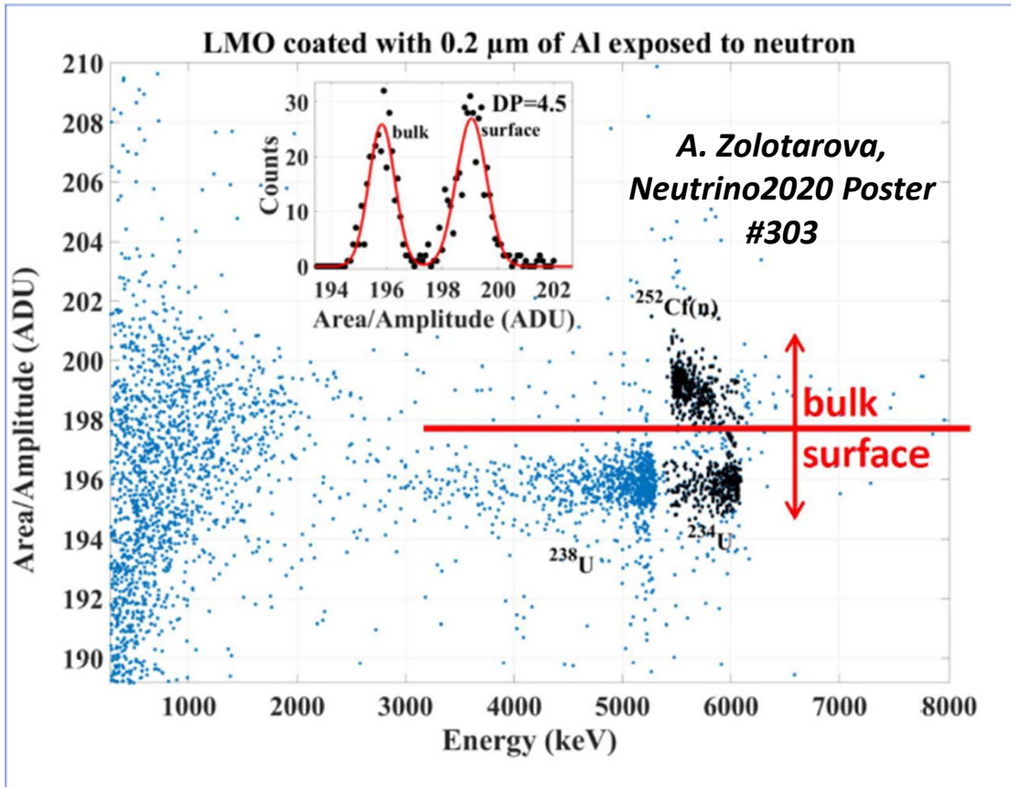


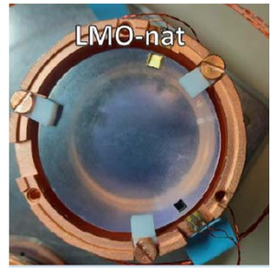




- ***Excellent resolution***
- ***High crystal purity***
- ***>99.9% alpha discrimination***
- ***New world-leading limit on 0νββ in ^{100}Mo***

CROSS: The Cryogenic Rare-event Observatory with Surface Sensitivity





Recent Results:

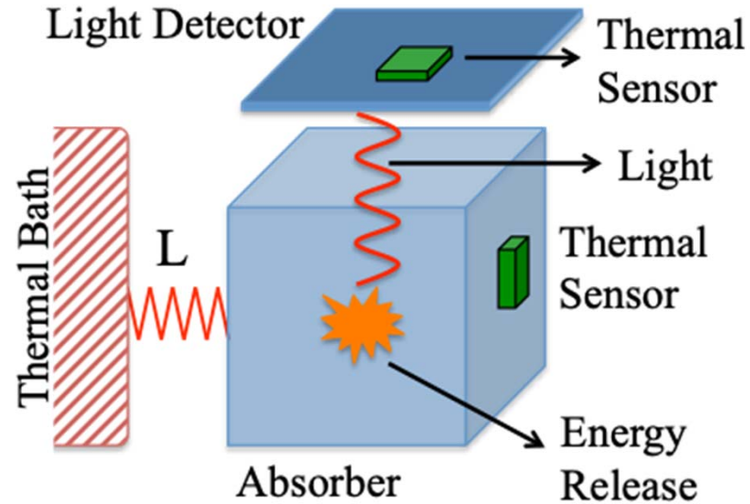
- The 0*ν2β*-decay CROSS experiment: preliminary results and prospects: J. High Energy Phys. 2020: 18 (2020)
- The CROSS Experiment: Rejecting Surface Events by PSD Induced by Superconducting Films, J. Low Temp. Phys. 199, 19-26 (2020).
- High-Resolution Digitization System for the CROSS Experiment, J. Low Temp. Phys. 199, 833–839 (2020).
- The CROSS experiment: search for 0v2b decay with surface sensitive bolometers, J. Phys. Conf. Ser. 1468, 012147 (2020).
- Neutrino 2020: https://nusoft.fnal.gov/nova/nu2020postersession/ posters # 246, 303, 308

Ongoing R&D Efforts

- 32 cubic ^{100}Mo-enriched LMO crystals produced (45×45×45 mm)
- Tower structure
- Crystal coating
- NTD modifications

Prospects for CUPID

- *Demonstrators with active science programs have attained all key benchmarks required for CUPID*
- *Ongoing R&D for key upgrades and infrastructure improvements*



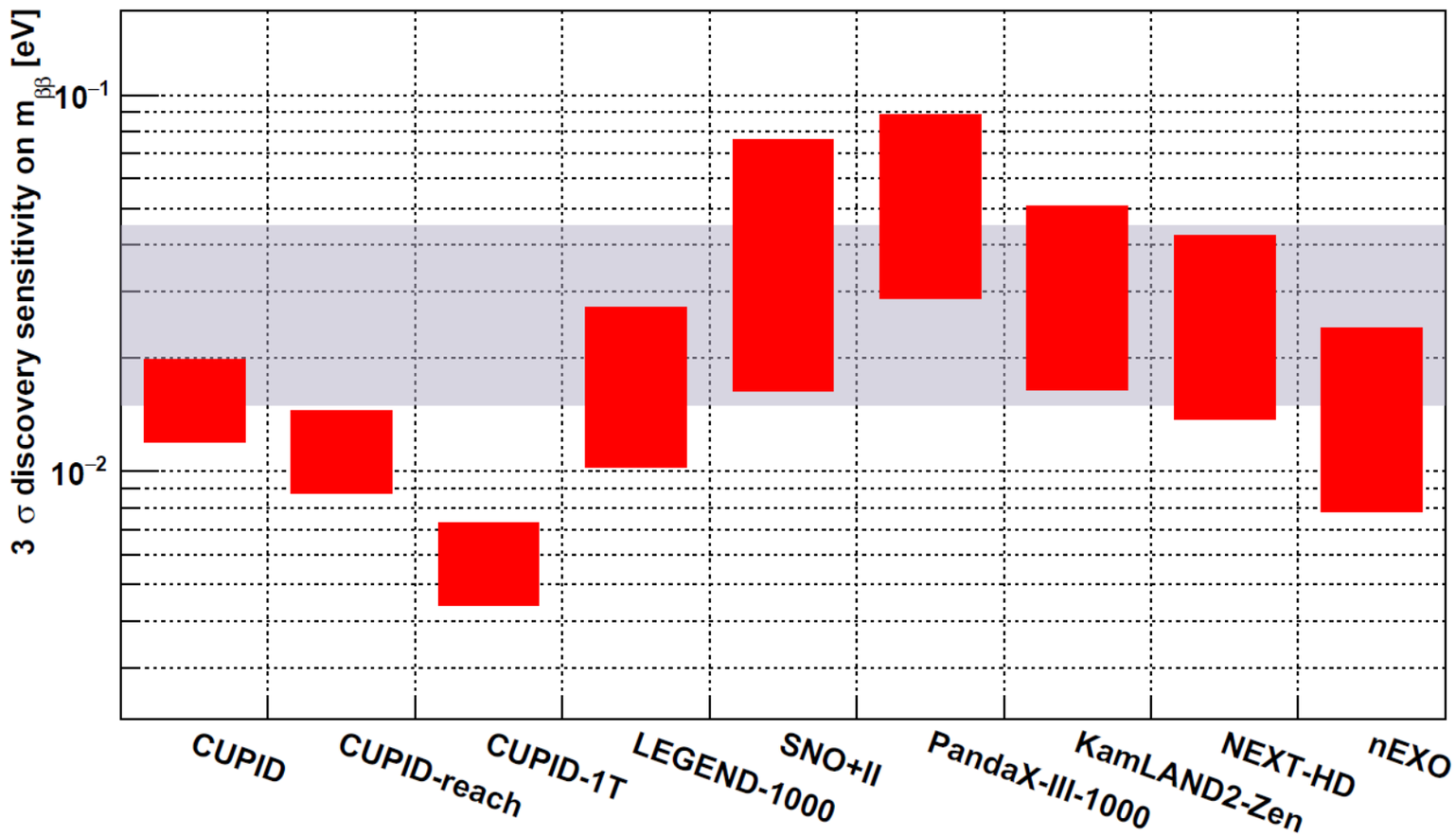
- **Goal:** TDR and construction readiness for end of 2021
- ***Schedule and budget* will be driven by ^{100}Mo enrichment**; expectation ~4 years
- ***Modest cost*** *(Enriched material < 20M Euro),* compared to the next-generation experiments with similar sensitivity.
- ***Future:***
  - Demonstrated Background Rejection and Scalability
  - Possibility of exploring multiple isotopes with the same technique:
    - **Te**O_2
    - Zn**Se**
    - Li_2**Mo**O_4
    - **Cd**WO_4

Eur. Phys. J. C 78 (2018) 272

CUPID:

- *enrichment > 95% ⇒ ~250 kg of ^{100}Mo*
- *~ 1500 crystals, ~300 g each*
- *ΔE FWHM ~5 keV at $Q_{ββ}$ ~3034 keV*
- *alpha-particle rejection using light signal*

Sensitivity Goals of CUPID, CUPID-Reach, and CUPID-1T



CUPID pre-CDR: exactly what we could start building today: 10^{-4} counts/keV/kg/yr

CUPID reach: assume improvement at reach before construction: $2 \cdot 10^{-5}$ counts/keV/kg/yr

CUPID 1Ton: new, 4 times larger (in volume) cryostat, 1 ton 100Mo : $5 \cdot 10^{-6}$ counts/keV/kg/yr

M. Pavan, CUPID Project Update 13 July 2020

Toward CUPID-1T

- CUORE/CUPID technology scales to the normal hierarchy scale bolometric experiment: CUPID-1T (4x volume of CUORE, ~1 ton of isotope)
- Active U.S. involvement in R&D for CUPID and CUPID-1T
- Synergy with HEP & QIS efforts
- Continued reduction of backgrounds
  - Deployment of high-resolution sensors
  - Explore cleaner materials for new cryostats

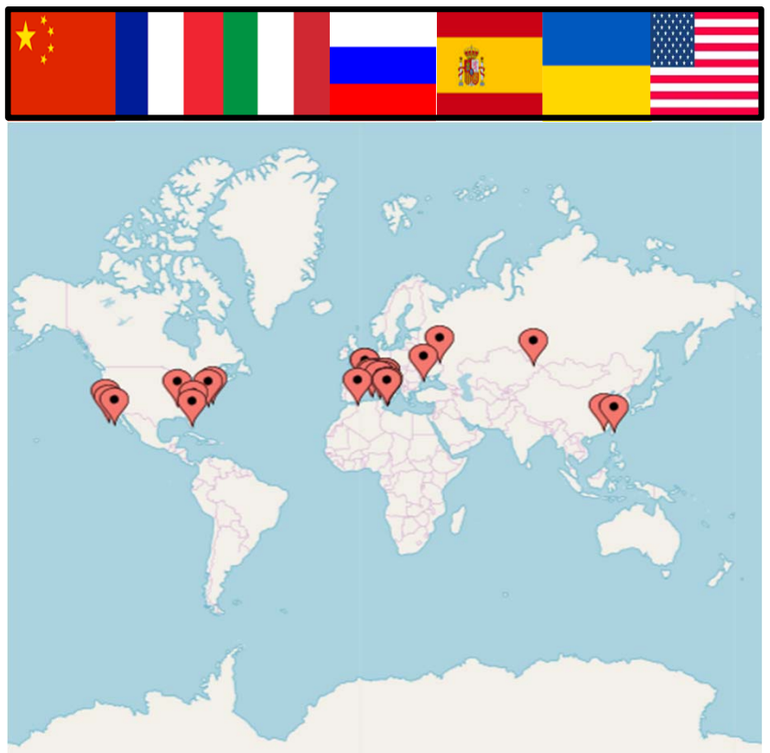
US CUPID R&D Focus

- **Detector readout technologies to mitigate technical risks**
  - Core competence: NTD sensors
  - Cryogenic electronics, multiplexing solutions: synergy with QIS
  - High-performance sensors (TES)
- **Readiness to deploy a tonne-scale experiment**
  - Development of US-based vendors for LMO crystals
  - Participation in LMO pilot experiments at Modane and LNGS
  - Isotopic enrichment of ^{100}Mo, ^{130}Te, TeO_2 crystal production
  - Cryogenic operations, in-situ calibration schemes
- **Verification of cosmogenic backgrounds in TeO_2 and LMO**
  - Muon veto in CUORE

Needed Before Downselect

Long Lead Time

CUPID Collaboration



CUPID pre-CDR: arXiv:1907.09376

INFN Sezione di Milano Bicocca and University of Milano Bicocca, Italy
INFN Sezione di Roma and Sapienza University of Rome, Italy
INFN Sezione di Roma and Gran Sasso Science Institute, Italy
INFN Laboratori Nazionali del Gran Sasso, Italy
INFN Sezione di Bologna and University of Bologna, Italy
INFN Laboratori Nazionali di Frascati, Italy
INFN Laboratori Nazionali di Legnaro, Italy
INFN Sezione di Padova, Italy
INFN Sezione di Genova and University of Genova, Italy
CSNSM Orsay, France
CEA Saclay, France
IPNL Lyon, France
LAL Orsay, France
SIMAP Grenoble, France
Universidad de Zaragoza, Spain
Argonne National Laboratory, USA
Lawrence Berkeley National Laboratory and University of California, Berkeley, USA
Cal Poly, San Luis Obispo, USA
Johns Hopkins University, USA
Massachusetts Institute of Technology, USA
University of South Carolina, USA
University of California Los Angeles, USA
Virginia Tech, USA
Yale University, USA
University of Science and Technology of China, China
Fudan University, China
Shanghai Jiao Tong University, China
KINR Kiev, Ukraine
ITEP Moscow, Russia
NIIC Novosibirsk, Russia

Summary

- **CUORE** is a tonne-scale cryogenic bolometer designed to measure the half-life of the neutrinoless double-beta decay of ^{130}Te to a sensitivity **of $O(10^{26})$** years. **CUORE is in full, stable operation**, continuing to collect physics-sensitive data until the CUPID upgrade. Now approaching 1T exposure benchmark. **372.5 kg·yr of analyzed data to date**; current lower limit, 0νββ of **^{130}Te: 3.2×10^{25} yr (90% C.I.)**.

- **CUPID** builds on the success of CUORE with an **increased exposure** and the **addition of germanium light detectors** for enhanced particle identification, to search for the half-life of the neutrinoless double-beta decay of **^{100}Mo** to a sensitivity of **$O(10^{27}$-$10^{28})$** years. Several demonstrators have already successfully achieved high levels of α-discrimination and radiopurity of enriched LMO.

- Due to large exposure and exquisite resolution, CUORE and CUPID both sensitive to additional rare event and BSM searches, and CUPID will play a critical role in next-generation searches for neutrinoless double-beta decay.

We are now entering the phase of next-generation programs!