Searching for $0\nu\beta\beta$ decay with cryogenic calorimeters

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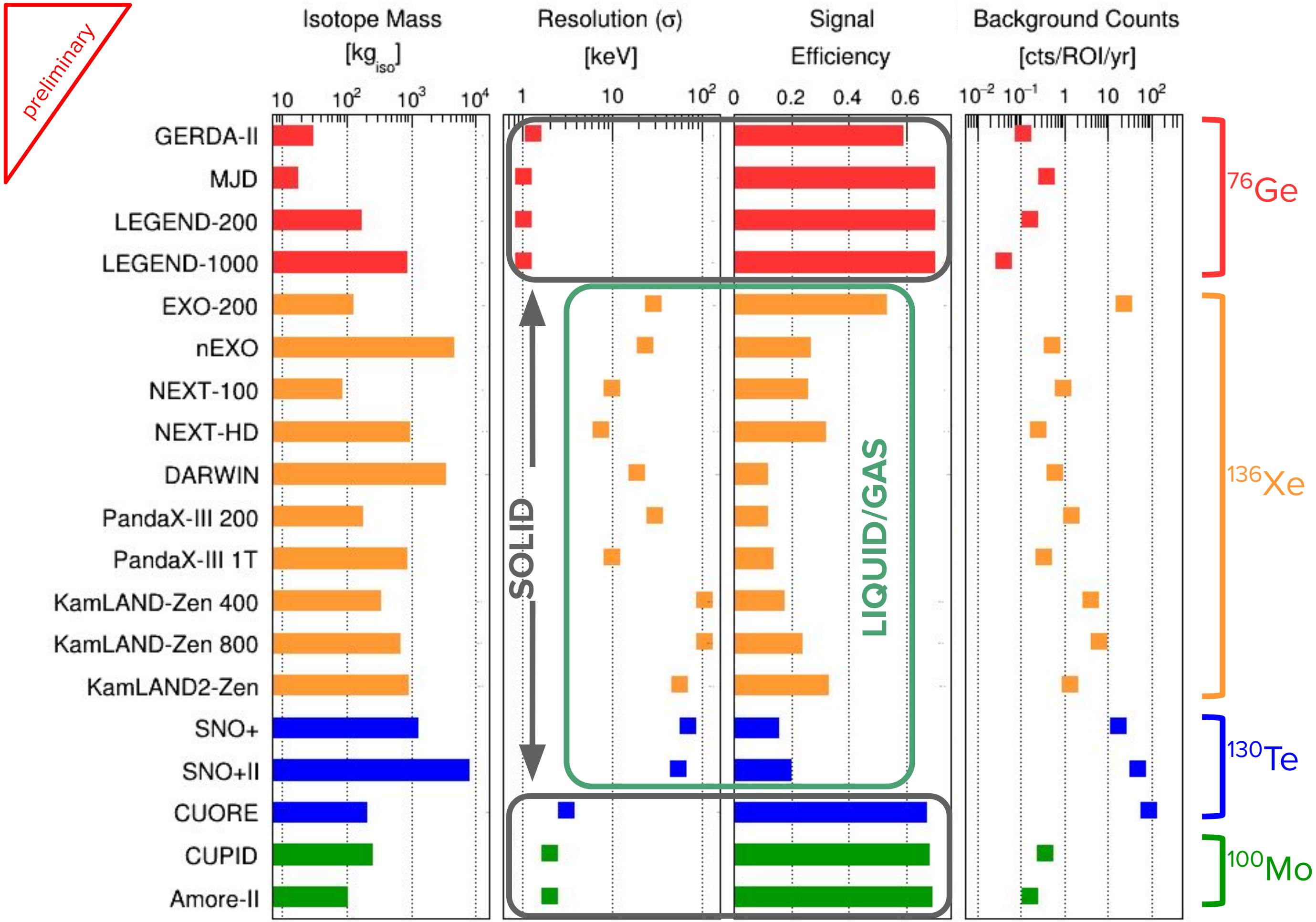
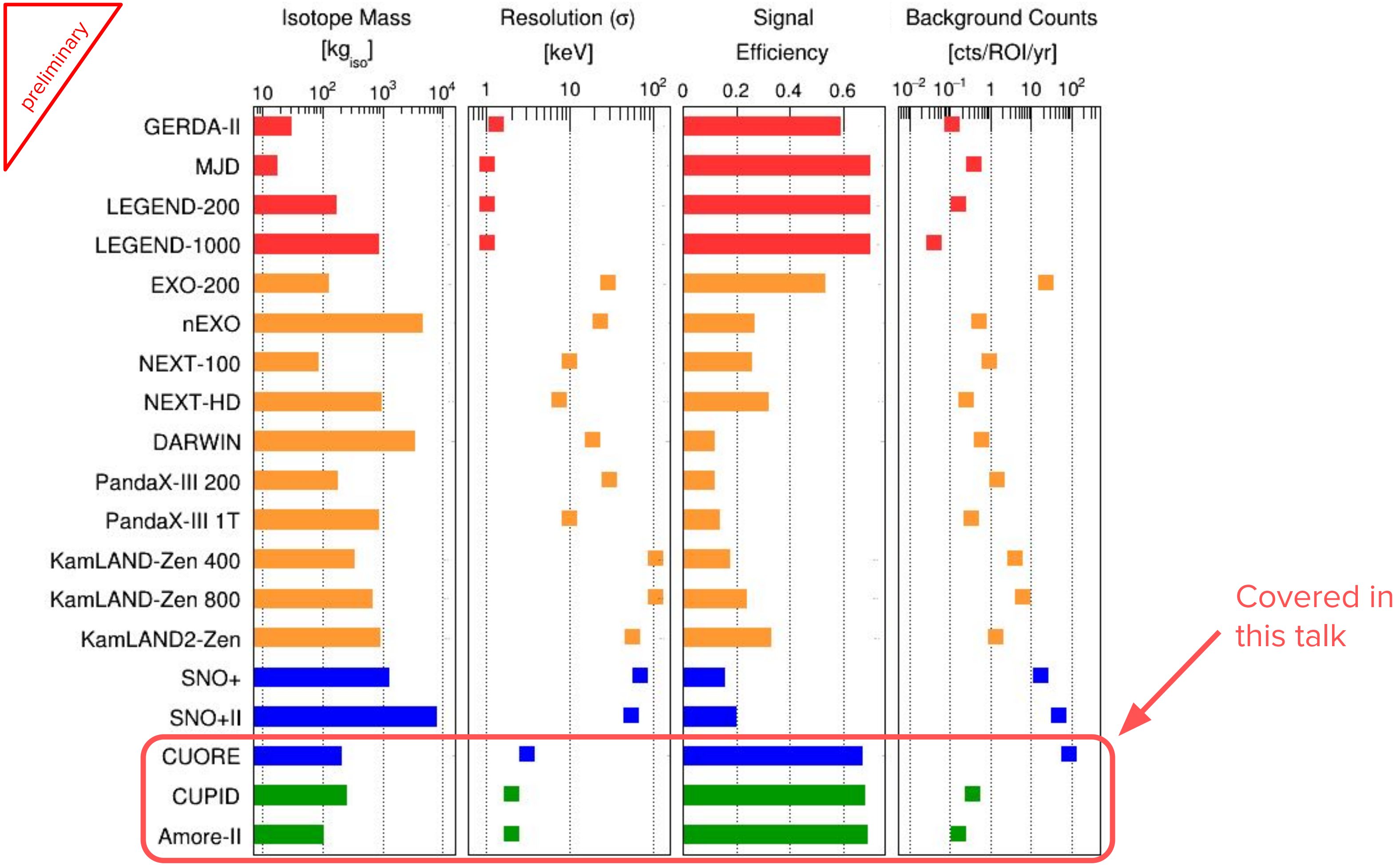
Berkeley
UNIVERSITY OF CALIFORNIA

Sources

- M. Agostini, Discovery potential of next-generation double-β decay experiments, talk at TAUP'19
- S. Pozzi, CUORE talk at TAUP'19, J. Ouellet, CUORE talk at Neutrino'18
- B. Schmidt, CUPID-Mo talk at TAUP'19, CUPID-Mo instrument paper
- CROSS experiment
- N. Casali, CUPID-0 talk at TAUP'19, CUPID-0 final results, CUPID-0 $2\nu\beta\beta$ paper, CUPID-0 background model paper
- M. Pavan, CUPID talk at TAUP'19, CUPID Pre-CDR
- K. Seo, AMoRE talk at TAUP'19, AMoRE-pilot results, AMoRE TDR
- K. Tetsuno, CANDLES talk at TAUP'19


preliminary
Isotope Mass [kg_iso]
10 10^2 10^3 10^4
Resolution (σ) [keV]
1 10 10^2
Signal Efficiency
0 0.2 0.4 0.6
Background Counts [cts/ROI/yr]
10^-2 10^-1 1 10 10^2
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
DARWIN
PandaX-III 200
PandaX-III 1T
KamLAND-Zen 400
KamLAND-Zen 800
KamLAND2-Zen
SNO+
SNO+II
CUORE
CUPID
Amore-II
SOLID
LIQUID/GAS
76Ge
136Xe
130Te
100Mo



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10
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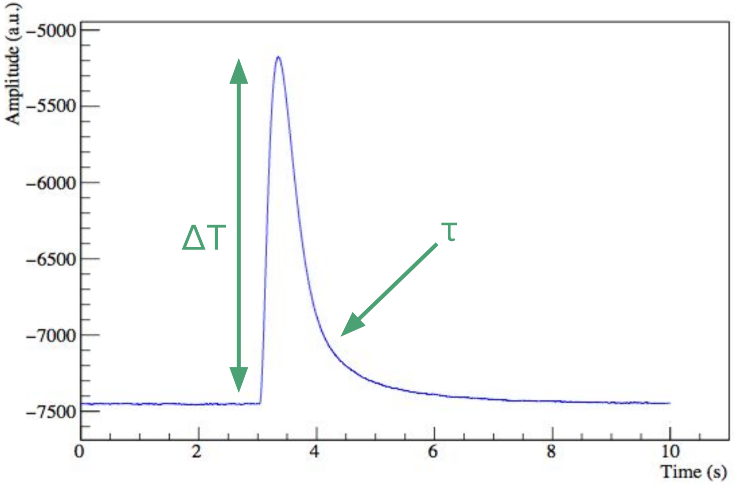
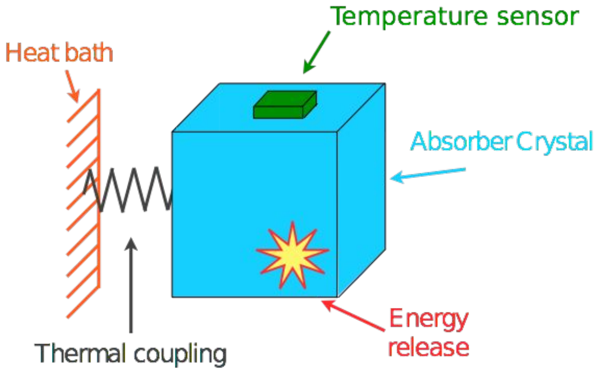
0.2
0.4
0.6
10^-2
10^-1
1
10
10^2
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
DARWIN
PandaX-III 200
PandaX-III 1T
KamLAND-Zen 400
KamLAND-Zen 800
KamLAND2-Zen
SNO+
SNO+II
CUORE
CUPID
Amore-II
Covered in this talk

The bolometric technique

- Low heat capacity @ T ~ 10 mK
- Excellent energy resolution (~0.2% FWHM)
- Detector agnostic to origin of energy deposition
- Detector response of O(1) sec if readout with Neutron Transmutation Doped (NTD) Ge sensors

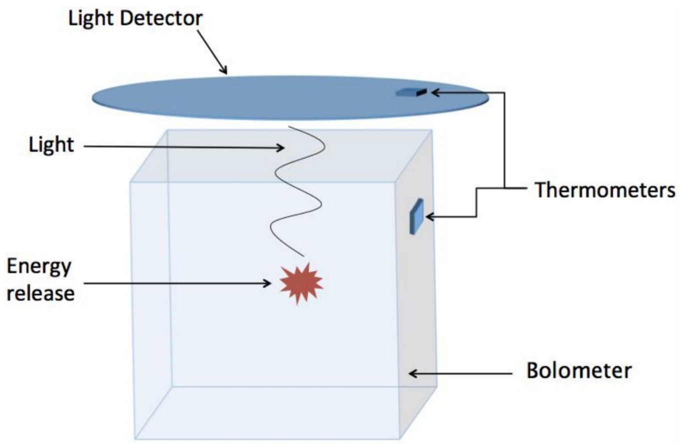


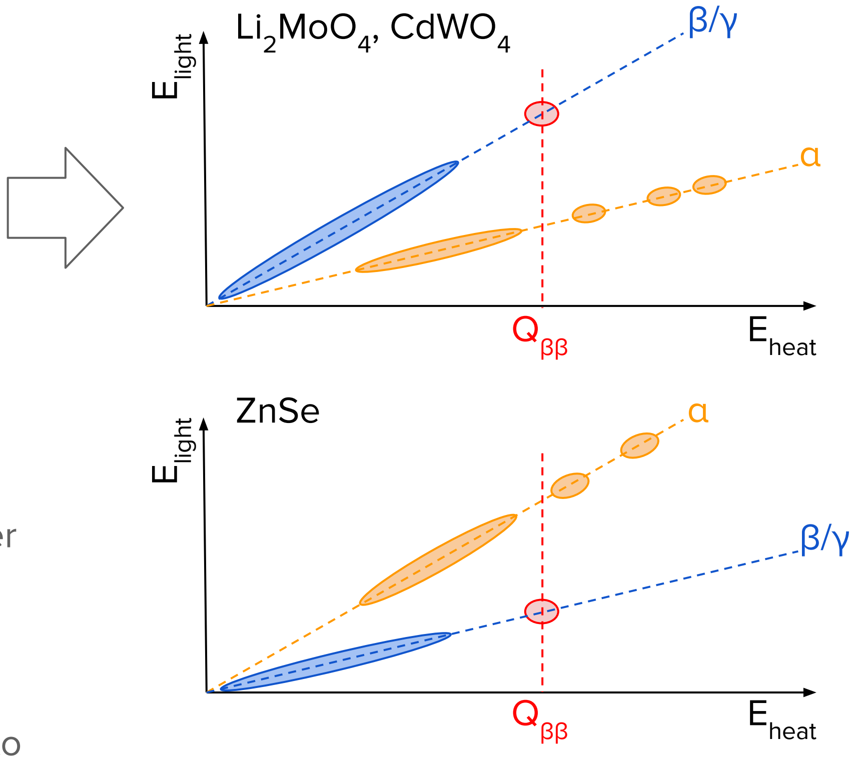


Simplified thermal model

- Crystal heat capacity: C
- Conductivity of coupling to thermal bath: G
- Signal amplitude ∝ $\Delta T = E_{dep} / C$
- Decay constant: $\tau = G / C$

Background suppression via Particle IDentification (PID)





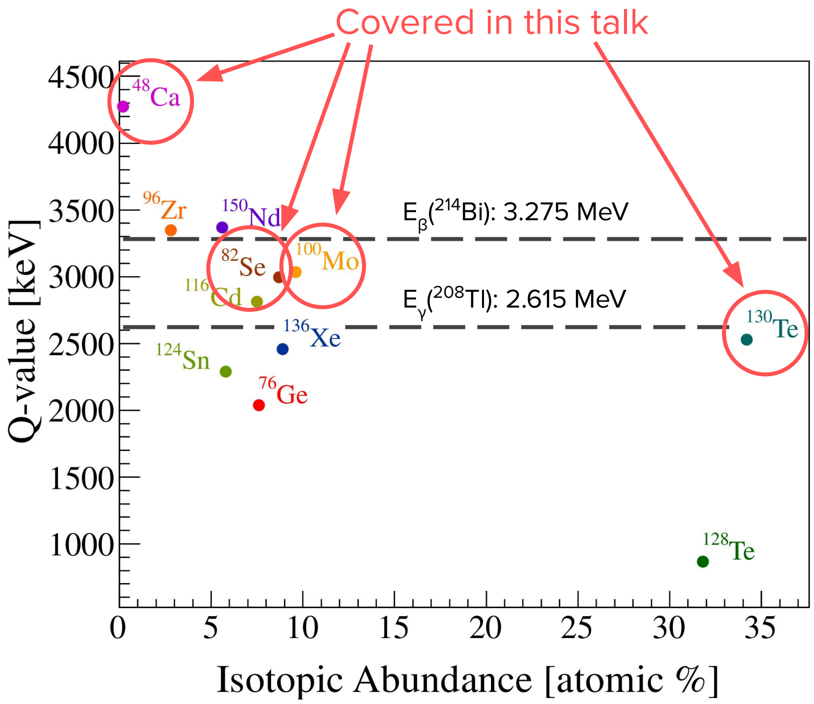
- Main background: surface α events
- Couple main crystal with secondary bolometer reading the scintillation (or Cherenkov) light
- Exploit different light yield (LY) of α vs β/γ to actively suppress background
- Typical light detector: thin Ge wafer coupled to thermometer (NTD, TES, KID, MMC)

Isotope choice for bolometric experiment

- High isotopic abundance
- Enrichment possible at reasonable cost?
- $Q_{\beta\beta}$ above end point of β or γ radiation?
- Scintillating crystal available?
- Large scale crystal production possible?

Advantages of bolometric approach

- Detectors and infrastructure are decoupled. Same cryogenic infrastructure re-usable with different isotopes and/or crystals
- Perfect for test of discovery or precision measurements



The present: CUORE

CUORE: the Cryogenic Underground Observatory for Rare Events

- 988 TeO_2 crystals with natural Te composition ➡
  742 kg total mass, 206 kg ^{130}Te mass
- $Q_{\beta\beta}(^{130}Te) = 2527.5$ keV ➡ Above most natural γ background
- Located in Hall A of the Gran Sasso National Lab
- Background goal: 10^{-2} counts/keV/kg/yr at $Q_{\beta\beta}$
- Sensitivity goal on $T^{0\nu}_{1/2} = 9{\cdot}10^{25}$ yr with 5 yr of live time

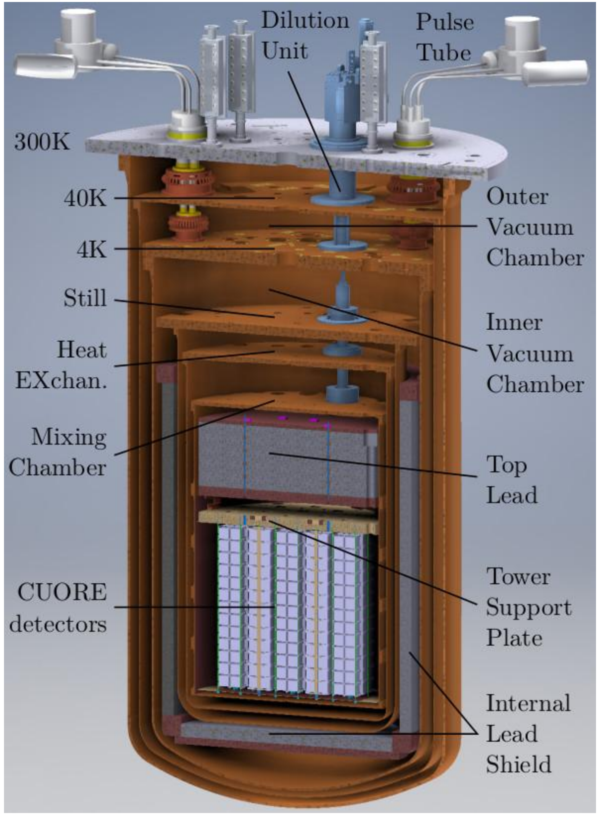
CUORE infrastructure

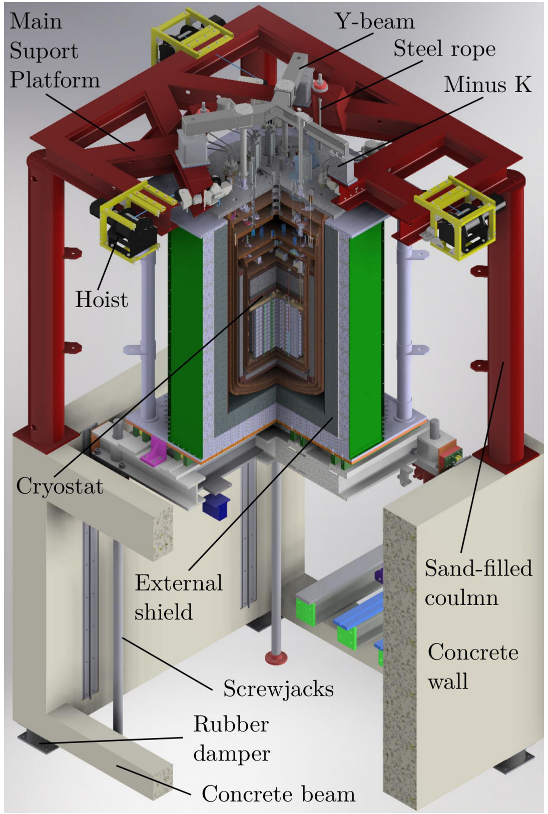
The coldest cubic meter in the known Universe

- Multistage cryogen-free cryostat: nested vessels at decreasing temperature
- Cooling systems: fast cooling system, Pulse Tubes (PTs), and Dilution Unit (DU)
- ~15 tons @ < 4 K
- ~ 3 tons @ < 50 mK
- Mechanical vibration isolation
- Active noise cancelling

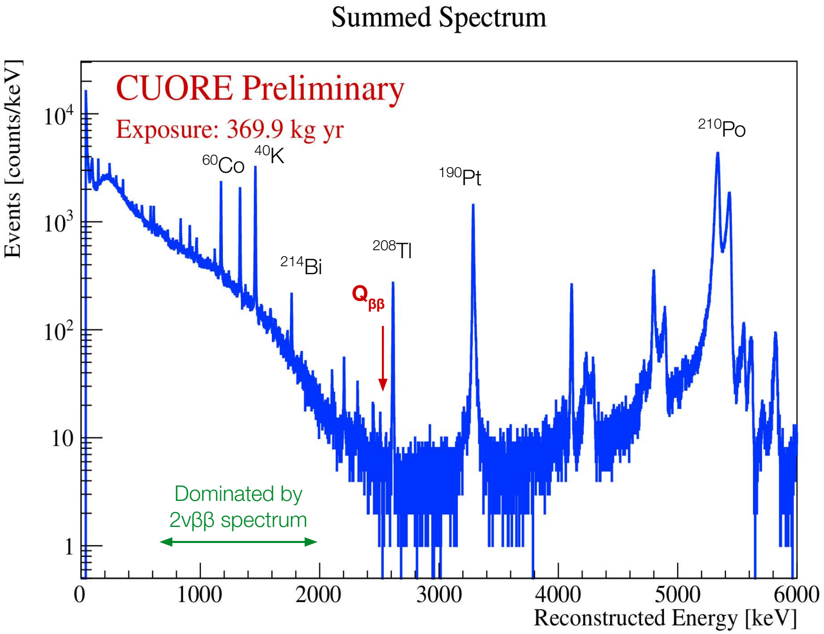
CUORE (passive) shielding

- Roman Pb shielding in cryostat
- External Pb shielding
- H_3BO_3 panels
- Polyethylene

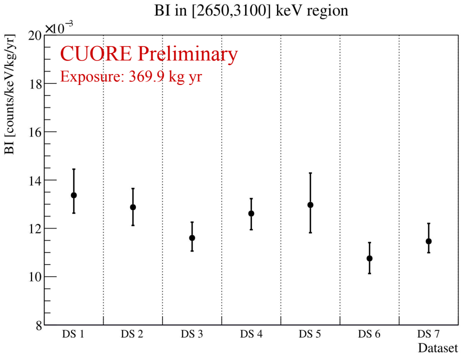


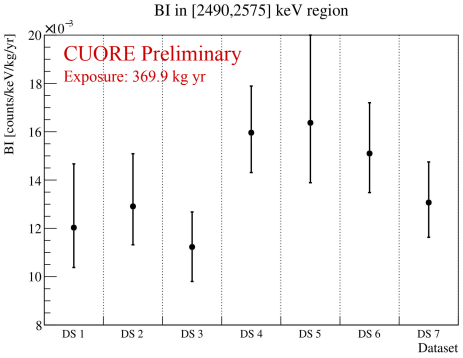


CUORE background

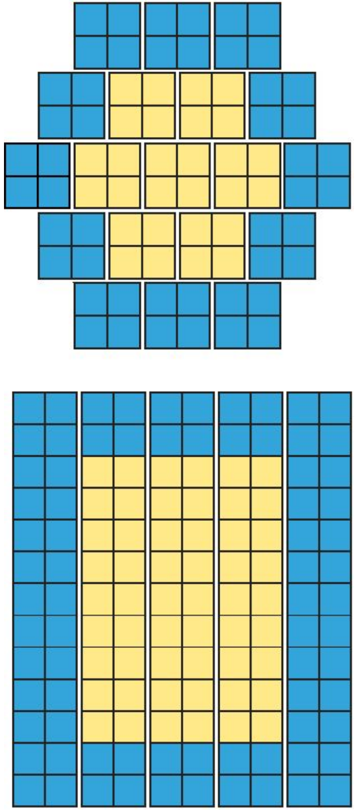


- High energy: α contaminants in TeO_2 and Cu parts; muons
- Low energy: γ's from Pb and Cu parts; β's from TeO_2 and Cu parts
- 90% of background at $Q_{\beta\beta}$ from surface α's

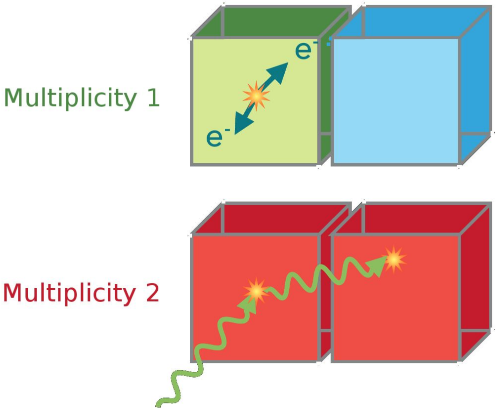


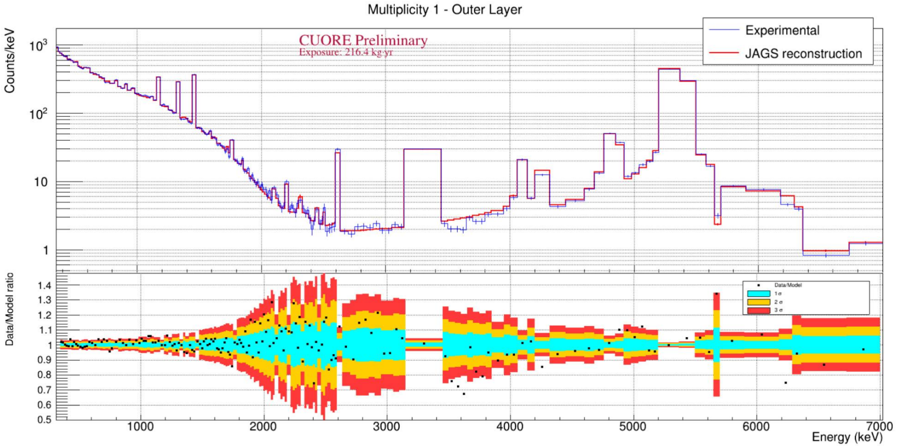


CUORE background

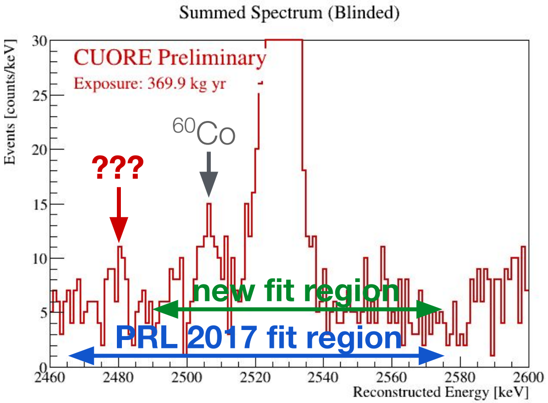


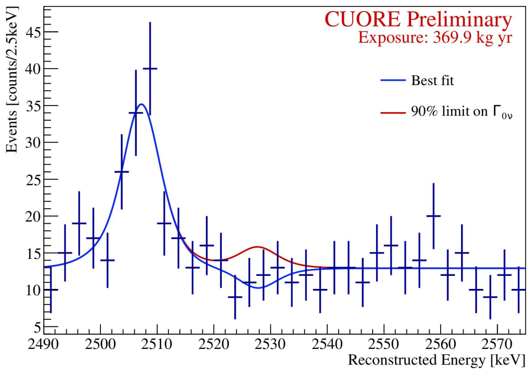
- Full background reconstruction with a Bayesian fit
- Fit components: 60 contaminations spread across the cryostat + muons
- Each component is simulated with a detailed Geant4 MC simulation
- Split the data according to event multiplicity
- Split the detector outer layer (sensitive to cryostat contaminants) and inner layer (sensitive to crystal and frame contaminants)
- **$T^{2\nu}_{1/2}$ = (8.2±0.1(stat))·10^{21} yr (Preliminary)**

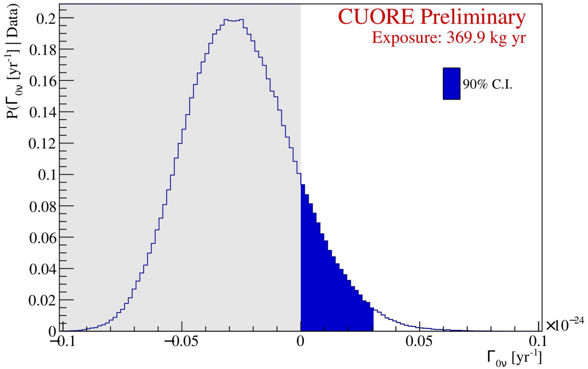




New CUORE results on $0\nu\beta\beta$ decay



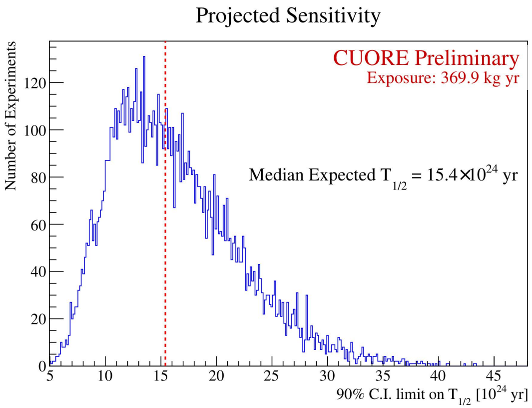




- Fit range: [2490, 2575] keV
- Components: flat background, ^{60}Co peak, $0\nu\beta\beta$ peak
- Marginalized limit computed on physical range: $\Gamma_{0\nu} < 3.0 \cdot 10^{-26}$ yr $^{-1}$

$T_{1/2} > 2.3 \cdot 10^{25}$ yr at 90% C.I.

- Systematics affect the limit by ~1%
- Probability of getting a stronger limit: 13%
- Assuming light neutrino exchange: **$m_{\beta\beta} < 0.09$-0.42 eV at 90% C.I.**

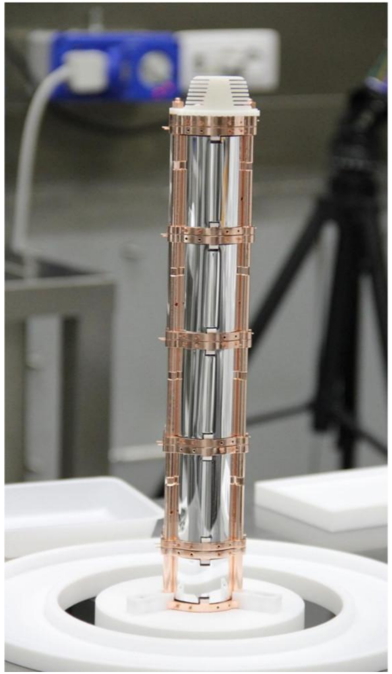


Preparing the future: CUPID-0

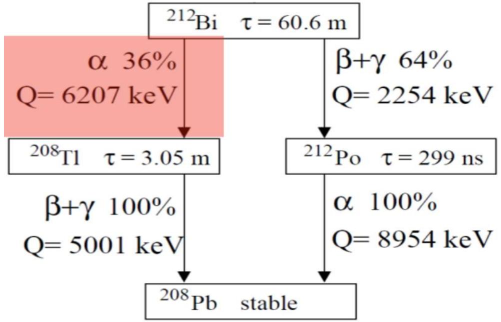
3.44 kg·yr — 2.02 kg·yr — 4.49 kg·yr — physics

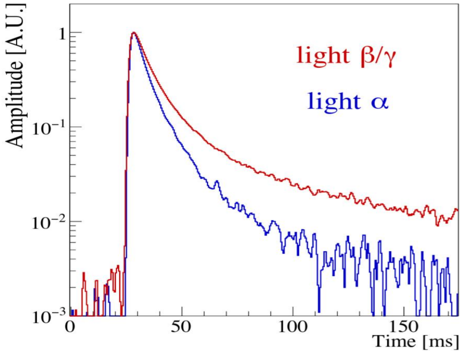
2017 — 2018 — 2019

Cool-down — Commissioning — ^{56}Co calibration — Upgrade

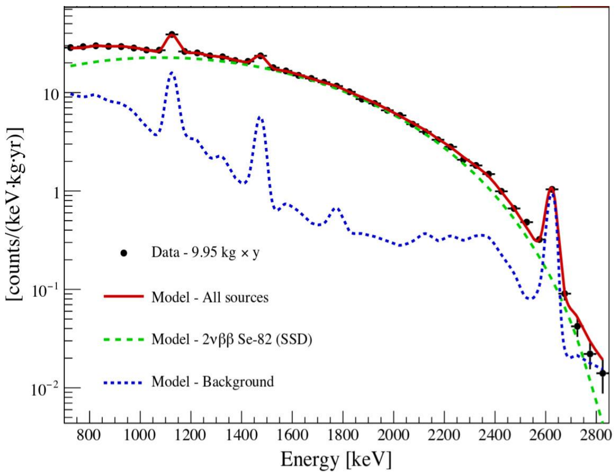


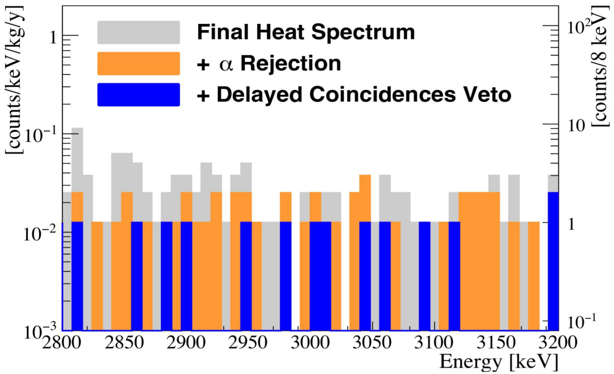
- 26 ZnSe crystals (24 enriched at 95% in ^{82}Se)
- Light detectors: Ge wafer + NTDs
- Crystals + LDs encapsulated in copper + reflector foil
- 5 towers, located in old Cuoricino/CUORE-0 cryostat at LNGS
- Total Phase-I exposure: 9.95 kg·yr
- α rejection via PID
- Rejection of ^{212}Bi/^{208}Tl delayed coincidences
- FWHM @ $Q_{\beta\beta}$: 20 keV

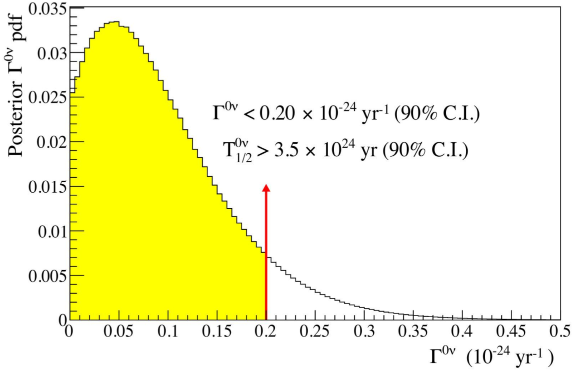




Preparing the future: CUPID-0







- Background at $Q_{\beta\beta}$: **$3.5 \cdot 10^{-3}$ counts/keV/kg/yr**
- 44% muons → muon veto installed in early 2019
- 33% ZnSe crystals → removed reflector foils
- 17% cryostat → new, cleaner copper shield
- 6% reflector foils → removed

2νββ results

- **$T^{2\nu}_{1/2} = [8.6 \pm 0.03(stat)^{+0.17}_{-0.10}(syst)] \cdot 10^{19}$ yr**
- Tested SSD vs HSD for ^{82}Se → HSD excluded

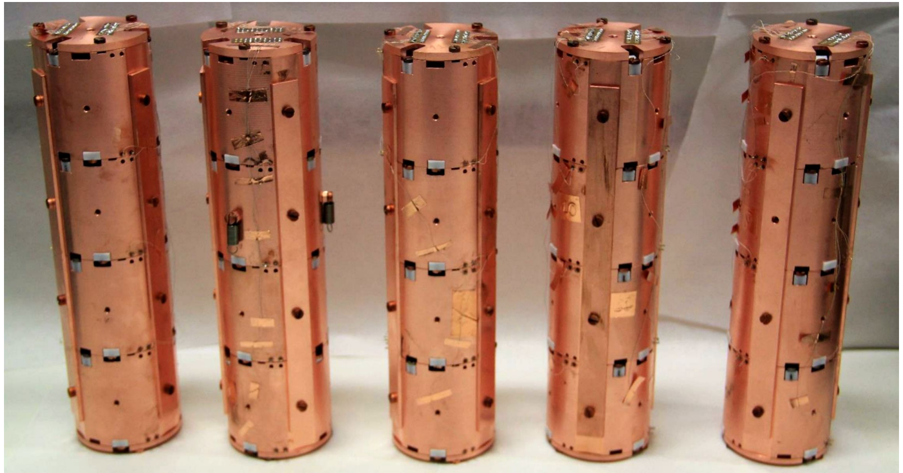
0νββ results

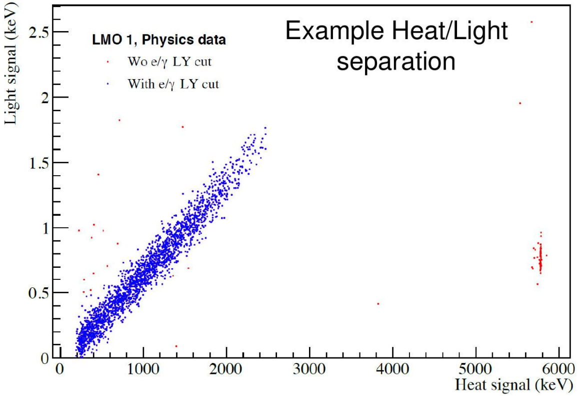
- Fit in [2800,3200] keV

$T^{0\nu}_{1/2} > 3.5 \cdot 10^{24}$ yr @ 90% C.I.

Preparing the future: CUPID-Mo

- 20 x 210g Li_2MoO_4 crystals 97% enr. in ^{100}Mo
- Ge wafer with SiO anti-reflective coating + NTD as light detector
- Cu frames + reflector foil
- Collecting physics data in Edelweiss cryostat since spring 2019

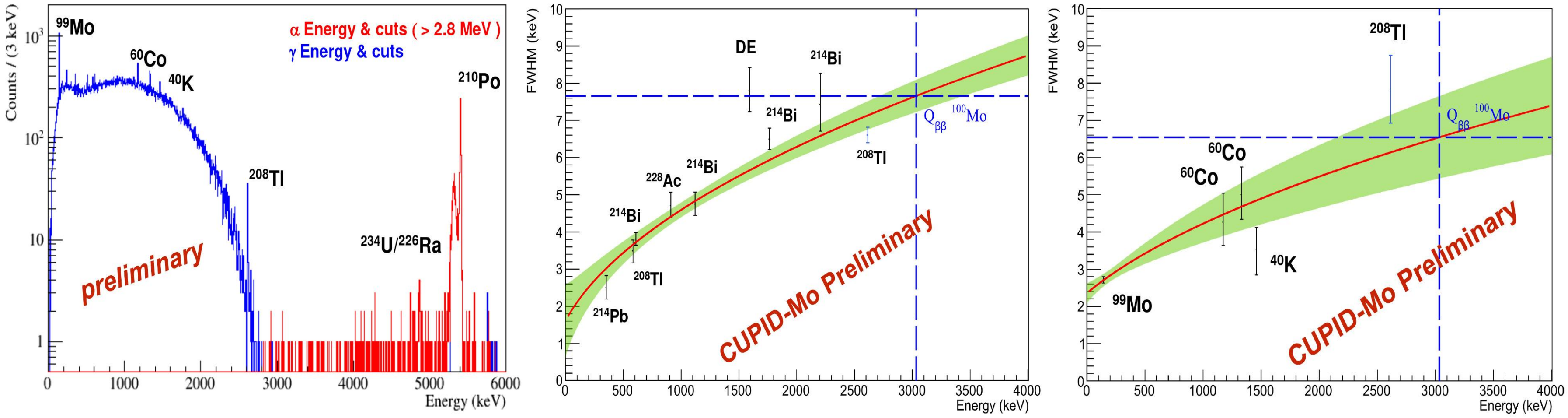




Goal is to evaluate:

- Energy resolution
- PID performance
- $2\nu\beta\beta$ pileup rate (short half-life for ^{100}Mo)
- Crystal bulk and surface purity
- Reproducibility/homogeneity of crystal and light detector performance

Preparing the future: CUPID-Mo

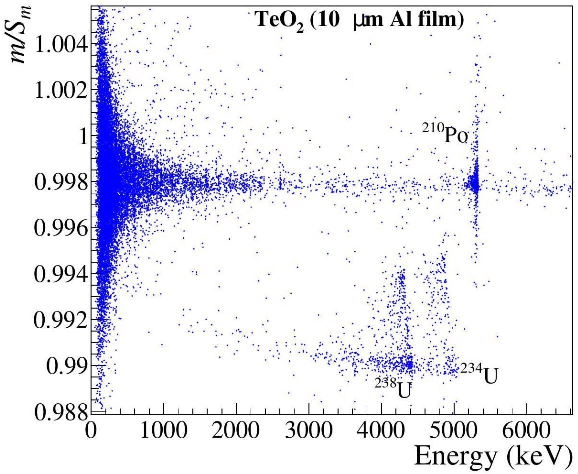


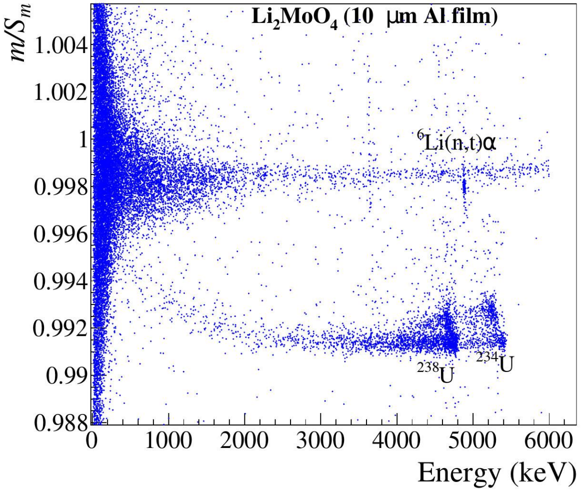
- Exposure: 0.5 kg·yr (~2 months)
- Energy resolution in calibration data: 7.7±0.4 keV FWHM @ $Q_{\beta\beta}$ (3034 keV)
- Energy resolution in physics data: 6.6±1.1 keV ➜ Dominated by suboptimal environment
- Contamination for Th and U chains < μBq/kg level ➜ 10 times better than expected
- Detector performance compatible with 99.9% α vs β/γ Gaussian separation
- $T^{0\nu}_{1/2} > 3.3 \cdot 10^{23}$ yr @ 90% C.L.
- Data collection ongoing. Will reach a sensitivity comparable with NEMO-3 limit in ~0.5 yr.

Preparing the future: CROSS

Conceptual design

- Use signal pulse-shape to discriminate between bulk and surface events in Al-coated crystals
- Room to reject also surface β
- Less channels, less material





Results

- Measured α from coated vs non-coated sides
- ≥5 σ bulk/surface separation proven in few cm^3 TeO_2 and Li_2MoO_4 crystals
- 1 µm Al film thickness sufficient (TeO_2 tested)
- Indications for possible measurement of energy deposition depth

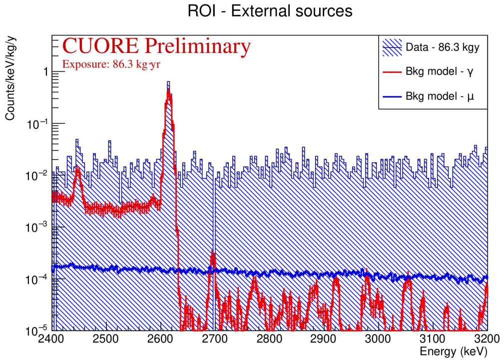
Prospects

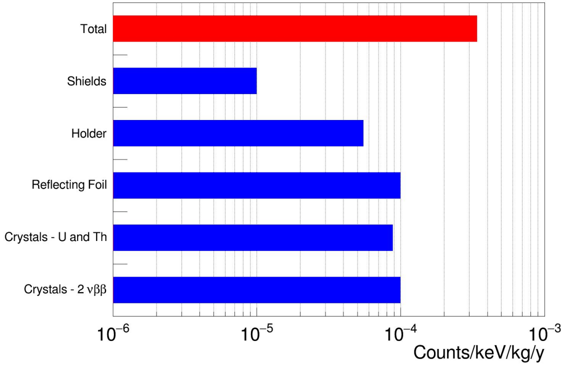
- New, 150 L dilution refrigerator under installation/commissioning at Canfranc
- 32 enriched cubic 45x45 mm Li_2MoO_4 crystals available and ready for installation
- Eventual TeO_2 phase considered

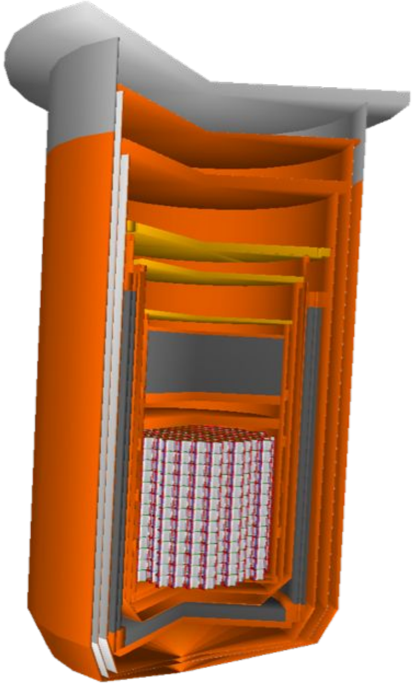
The near future: CUPID

CUPID: CUORE Upgrade with Particle Identification

- Li_2MoO_4 scintillating crystals
- Enrichment > 95%
- ∅ 50 mm, h 50 mm ➔ 308 g
- ~1534 crystals ➔ ~250 kg of ^{100}Mo
- Goal FWHM: 5 keV at $Q_{\beta\beta}$
- α rejection via PID
- Goal background: 10^{-4} counts/keV/kg/yr
- Discovery sensitivity: $T^{0\nu}_{1/2} = 10^{27}$ yr
  ➔ $m_{\beta\beta}$ = 12-20 meV

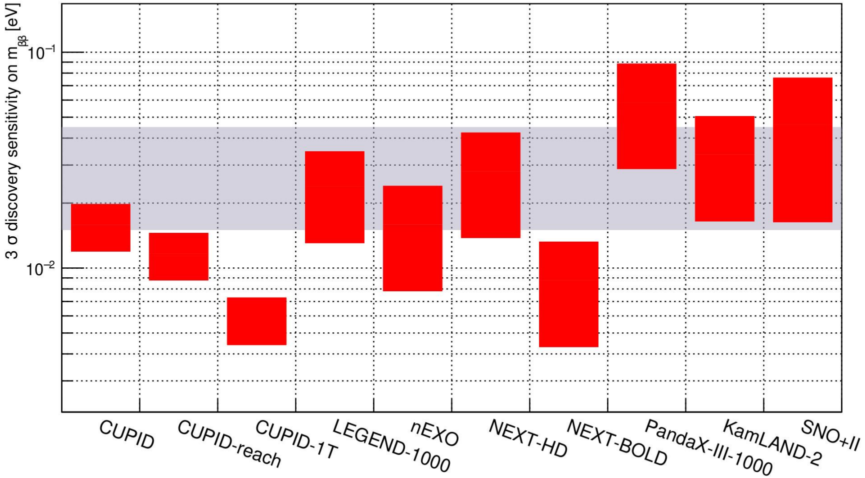






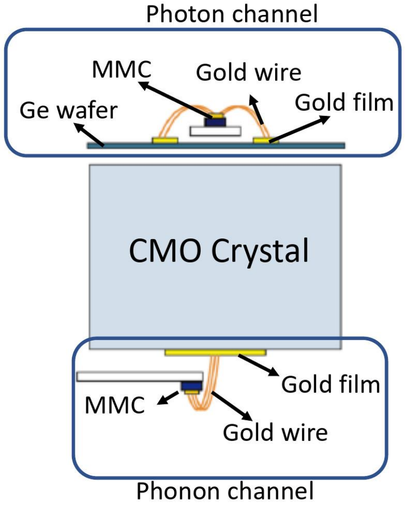
The near future: CUPID

- CUPID pre-CDR: very conservative
  - Exactly what we could start building today. No improvement assumed!
- CUPID reach: assume improvement at reach before construction
  - Improved signal timing with TES on LD
  - Improved radiopurity
  - Zero-bkg condition: $2{\cdot}10^{-5}$ counts/keV/kg/yr
- CUPID 1 ton: new 4x larger cryostat
  - 1 ton of ^{100}Mo, plus possibly other isotopes
  - BI: $5{\cdot}10^{-6}$ counts/keV/kg/yr

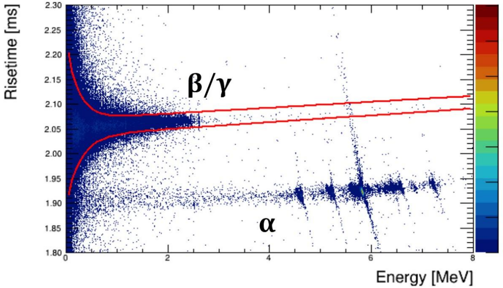


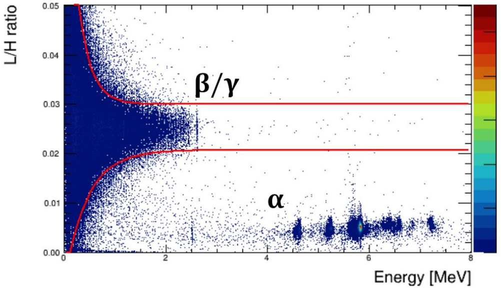
Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV

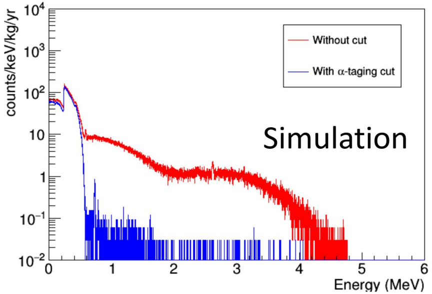
Preparing the future: AMoRE pilot



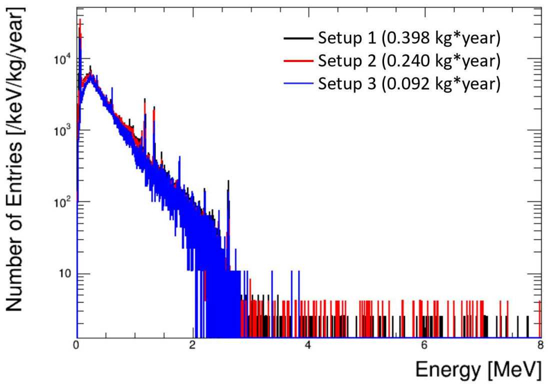
- AMoRE: Advanced Mo-based Rare process Experiment
- $^{48depl}Ca^{100}MoO_4$ scintillating crystals
  ➔ < 0.001% ^{48}Ca; >95% ^{100}Mo
- Readout with Metallic Magnetic Calorimeter (MMC): temperature-dependent magnetization read with SQUID
- PID via rise-time and scintillation light
- Rejection of ^{212}Bi/^{208}Tl delayed coincidences
- Low-background Pb shield + neutron shield
- Active muon veto

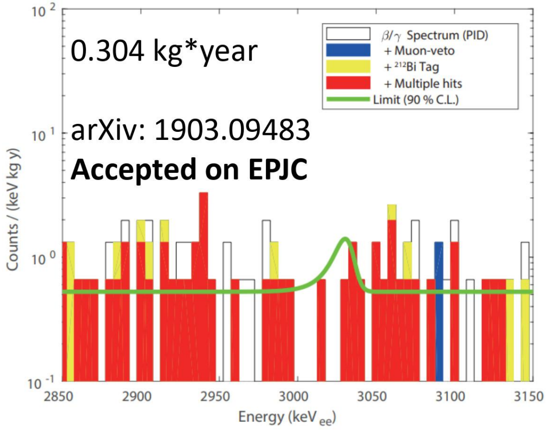






Towards the ton-scale AMoRE





AMoRE-pilot results

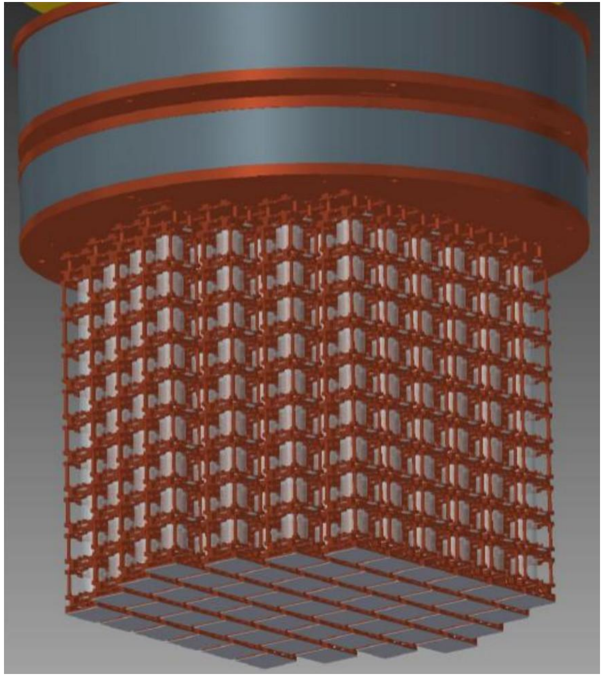
- BI: 0.14±0.09 counts/keV/kg/yr
- FWHM ~ 15 keV
- $T^{0\nu}_{1/2} > 9.5 \cdot 10^{22}$ yr @ 90% C.L.
- $m_{\beta\beta} < 1.2\text{-}2.1$ eV

AMoRE-I

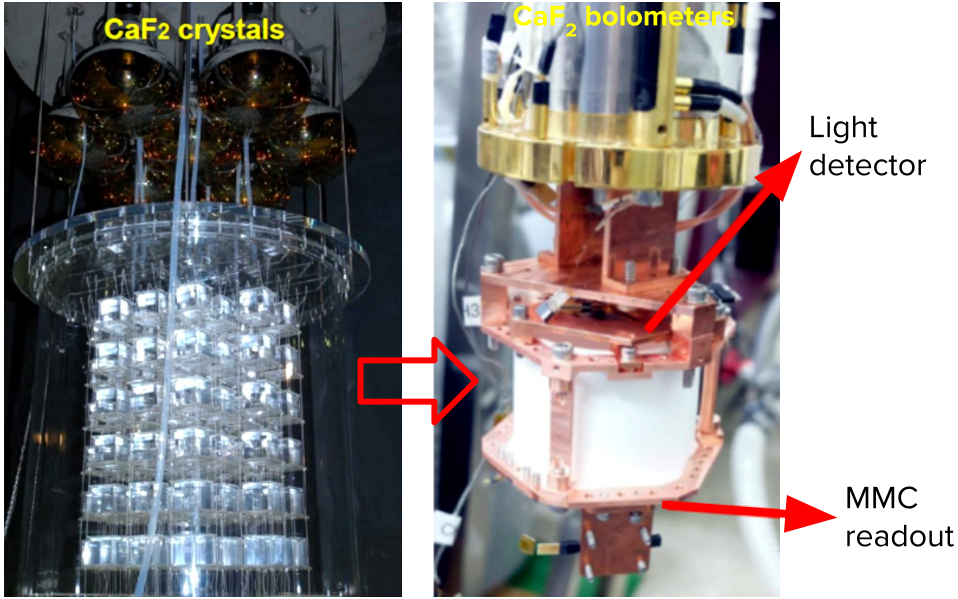
- 13 CaMoO + 8 LiMoO crystals
- 6.1 kg total mass
- DAQ upgrade

AMoRE-II

- ^{100}Mo-based crystals (LiMoO?)
- Net ^{100}Mo mass: 100 kg
- Goal BI: 10^{-4} counts/keV/kg/yr
- Goal FWHM: 5 keV

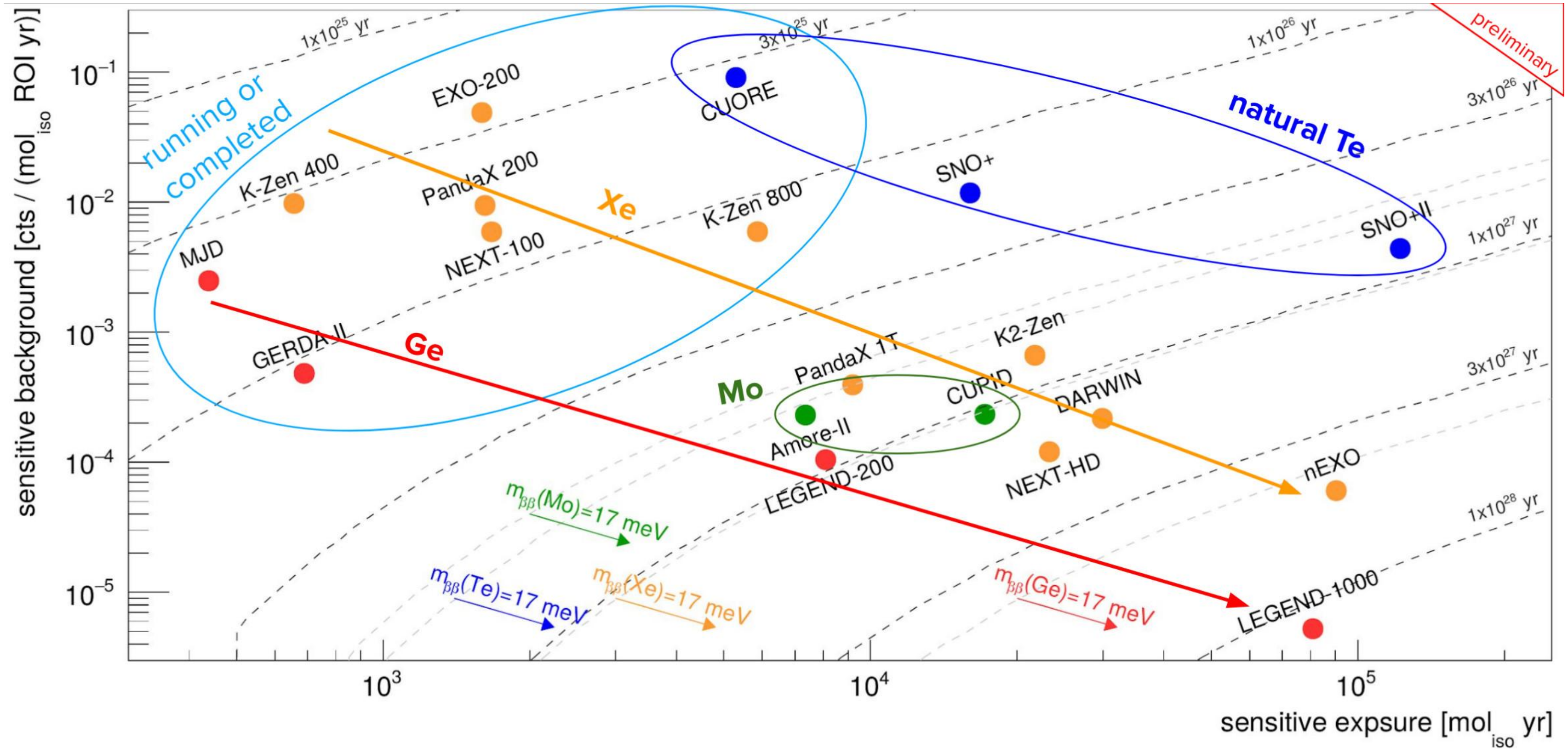


High-yield long-term investment: bolometric ^{48}Ca experiment



- Candles III: nat. CaF_2 crystals + liquid scintillator + PMTs
- Intrinsic backgrounds: 2νββ, ^{238}U α decay
  ➔ develop CaF_2 scintillating bolometer to improve energy resolution ➔ 0.18% FWHM and 5 σ separation demonstrated with 300 g crystal
- Enrichment under investigation:
  ➔ Crown ether resin + chromatography
  ➔ Crown ether resin + micro reactor
  ➔ Laser separation (up to 90%)
  ➔ Multi-channel counter current electrophoresis
- If scalable enrichment method is developed, this could be the ultimate bolometric 0νββ experiment!

Summary


preliminary
sensitive background [cts / (mol_iso ROI yr)]
sensitive expsure [mol_iso yr]
running or completed
natural Te
Xe
Ge
Mo
EXO-200
CUORE
K-Zen 400
PandaX 200
NEXT-100
K-Zen 800
MJD
GERDA II
SNO+
SNO+II
PandaX 1T
K2-Zen
CUPID
DARWIN
Amore-II
NEXT-HD
LEGEND-200
nEXO
LEGEND-1000
1x10^25 yr
3x10^25 yr
1x10^26 yr
3x10^26 yr
1x10^27 yr
3x10^27 yr
1x10^28 yr
mββ(Mo)=17 meV
mββ(Te)=17 meV
mββ(Xe)=17 meV
mββ(Ge)=17 meV