The CUPID double beta decay experiment

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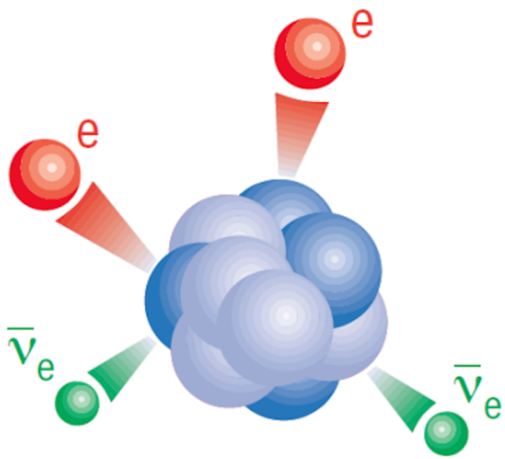
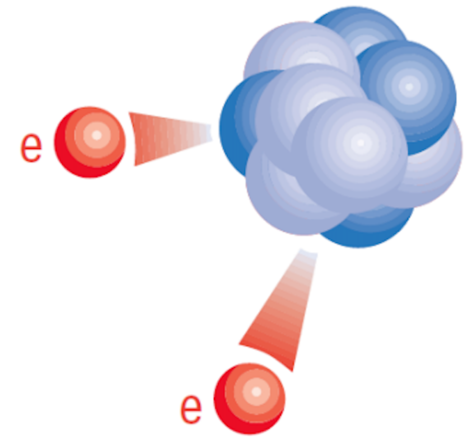
WIN2023, July 3-8, 2023, Zhuhai, China

Neutrinoless double beta decay



$${}^{A}_{Z}X_{N} \longrightarrow {}^{A}_{Z+2}X_{N-2} + 2e^{-} + 2\bar{\nu}_e$$



$${}^{A}_{Z}X_{N} \longrightarrow {}^{A}_{Z+2}X_{N-2} + 2e^{-}$$

"Are massive neutrinos and antineutrinos identical?"
-- E. Majorana, 1937

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

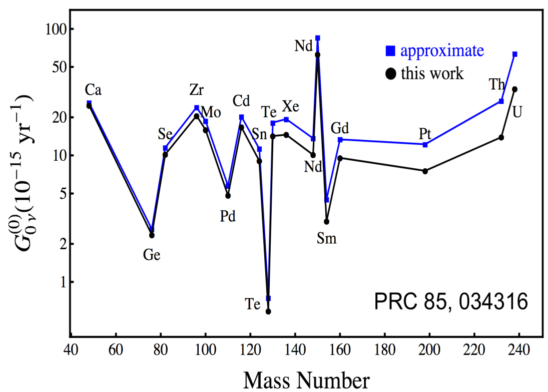
- **2ν2β decay:** Standard Model process
  => observed in several isotopes

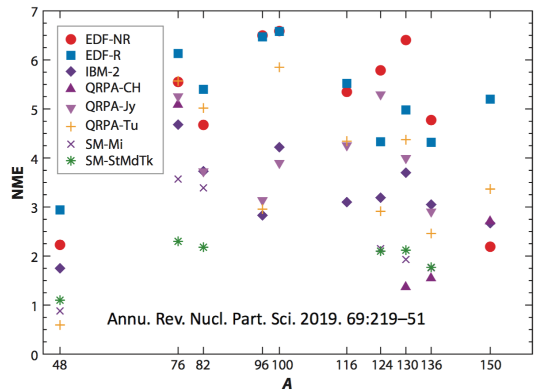
- **Observation of 0ν2β decay:**
  - reveal the Majorana nature of ν => beyond SM
  - provide direct evidence of lepton number violation process (LNV)， ΔL = +2
  - model-dependent constraint of absolute ν mass
  - may explain matter-antimatter asymmetry

Neutrinoless double beta decay

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase Space Factor | Nuclear Matrix Element | Effective ν Mass





$$|\langle m_{\beta\beta}\rangle| = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

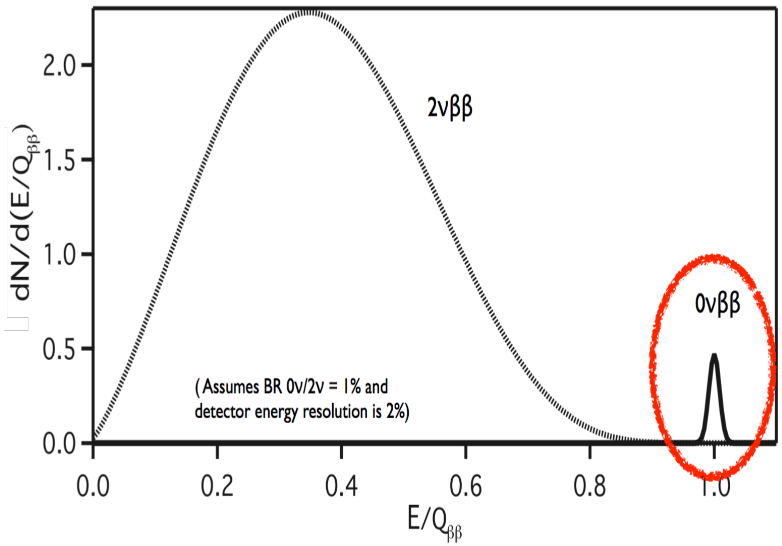
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Double beta decay **half life**

- $T^{2\nu}_{1/2} = 10^{19} \sim 10^{24}$ yr
- $T^{0\nu}_{1/2} > 10^{26}$ yr (>10^{15} times the age of the universe ~1.37×10^{10} yr)

  -- very difficult to observe !

Experimental search for 0νββ



detection efficiency | isotope abundance | total exposure

$$S^{0\nu}(T_{1/2}) \propto \frac{\epsilon \cdot \eta}{A}\sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$$

background rate | energy resolution

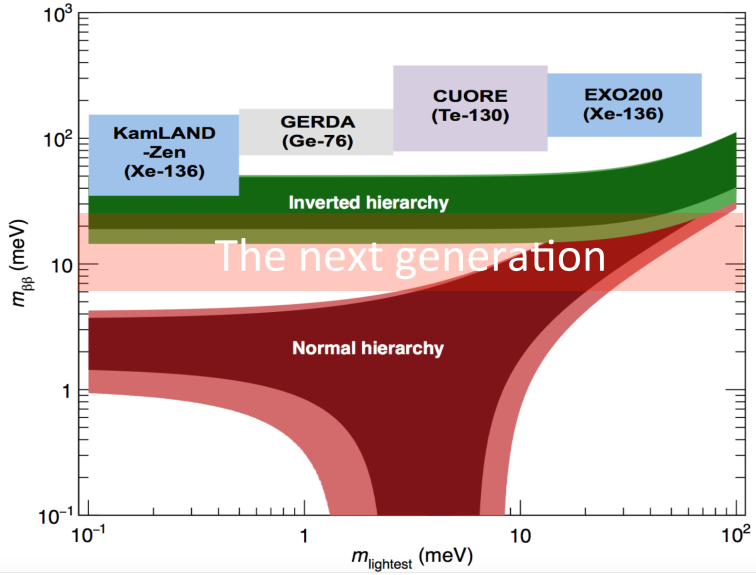
- Experimental search: looking for monochromatic peak at the Q-value in the kinetic energy sum spectrum of two emitted electrons

- Experimental challenge ➡ Sensitivity

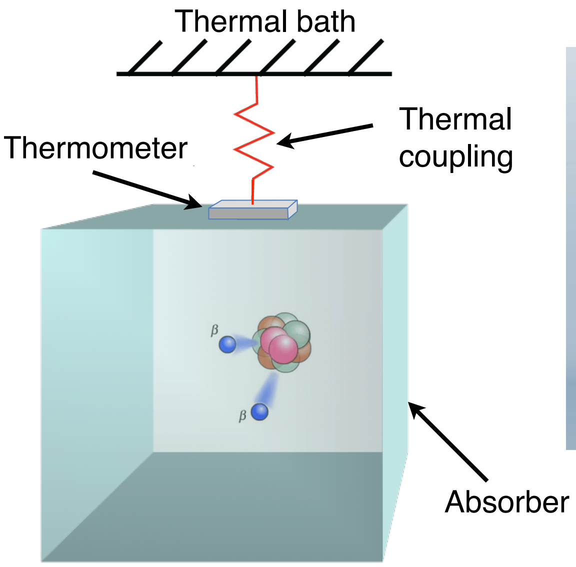
Large exposure (mass x live-time)
Large η (isotopic abundance)
Large ε (signal efficiency)
Small b (background level)
Small ΔE (energy resolution)
*assuming nonzero background in ROI

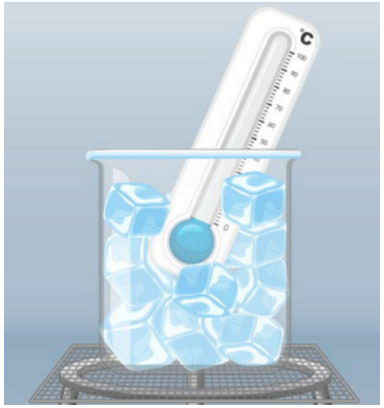
Experimental search for 0νββ

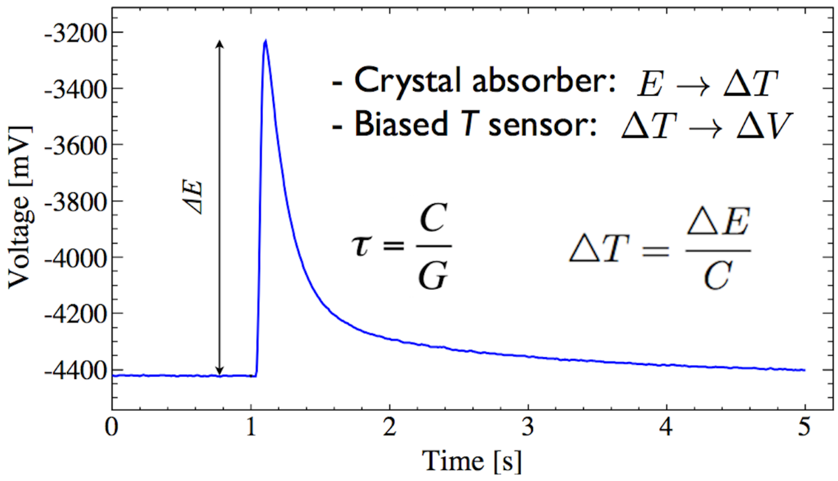
- Multiple technologies have been applied for 0νββ search
- Current experiments based on different technologies and isotopes have achieved comparable measurement sensitivity
- The next generation experiments
  - explore the full inverted hierarchy region !



Bolometric experiment







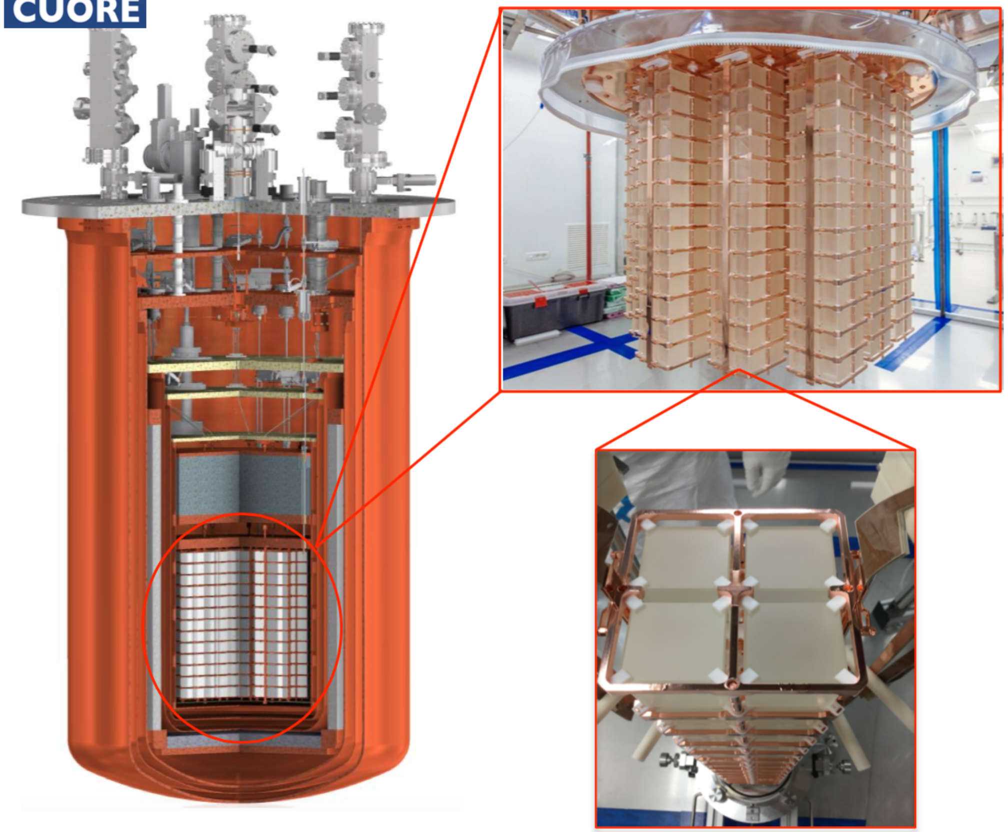
G: thermal coupling constant
ΔT: ~ 0.1-1 mK/MeV, τ: ~ 0.1-1 s

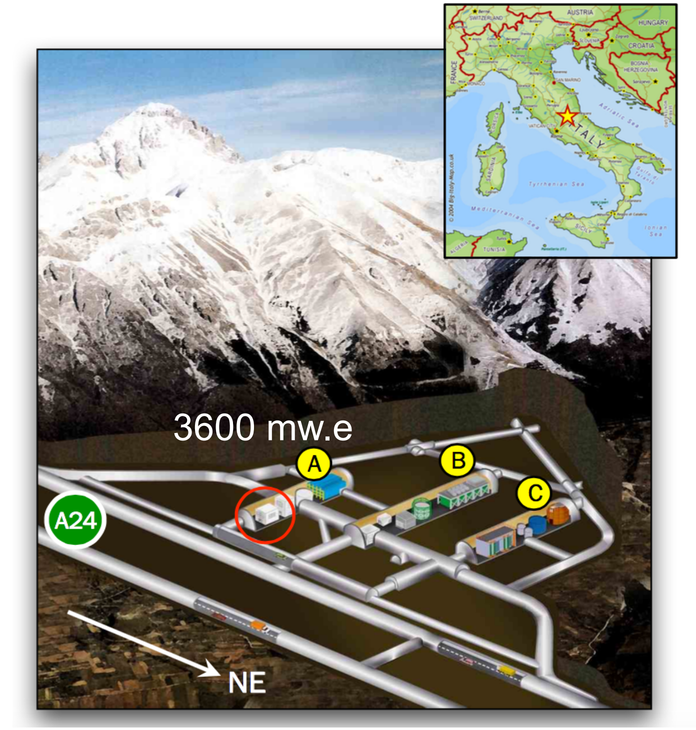
- **Cryogenic bolometer**
- Crystal detector operating at extremely low T (~10 mK)
- High sensitivity measurement of the energy deposition (phonon) via T variation (ΔT)
- Thermometer: neutron transmutation doped germanium thermistor (NTD-Ge)
- **Technical merits:**
  - ✓ Low energy threshold: eV~keV
  - ✓ High efficiency: Source = Absorber
  - ✓ High energy resolution: ~0.2% (FWHM)
  - ✓ Multi-isotope deployment => cross check discoveries

Competitive technology for rare event search !

CUORE

CUORE: searching for 0νββ decay of ^{130}Te





- Location: Italy-LNGS

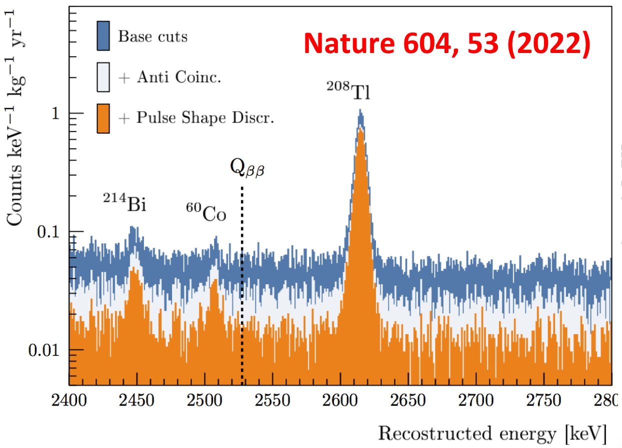
➢ **Tonne-scale detector**

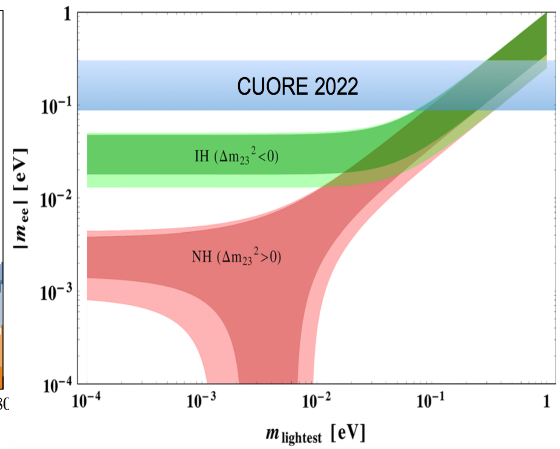
- 988 TeO_2 natural crystals (741 kg, ^{130}Te ~206kg)
- ~15 ton @ T < 4K
- ~3 ton @ T < 50 mK

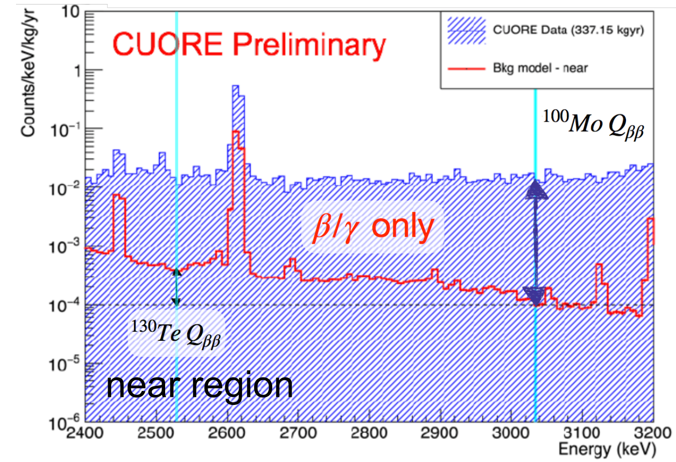
World's largest bolometric 0νββ experiment !

Cryogenics 102, 9 (2019)

CUORE





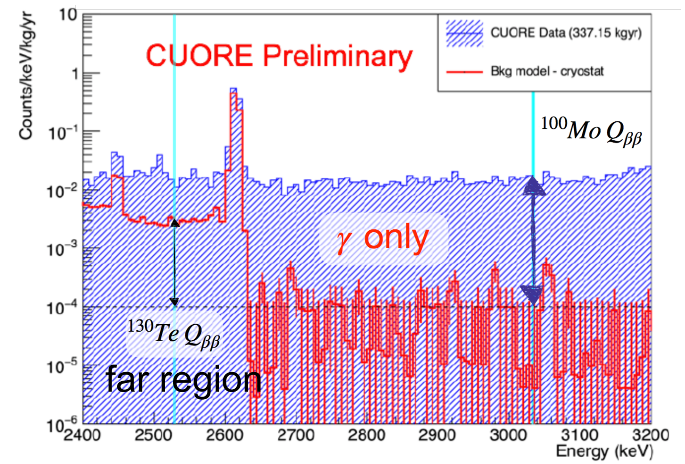


Detector performance

Γ(ROI): ~7.8 keV(FWHM)
BI(ROI): ~1.5 x 10^{-2} ckky

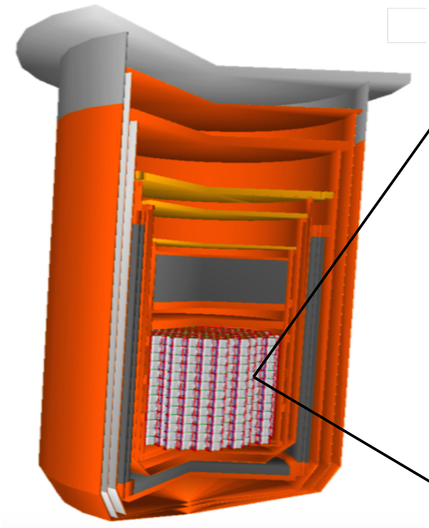
Physics results
(1 ton.yr TeO_2 exposure)

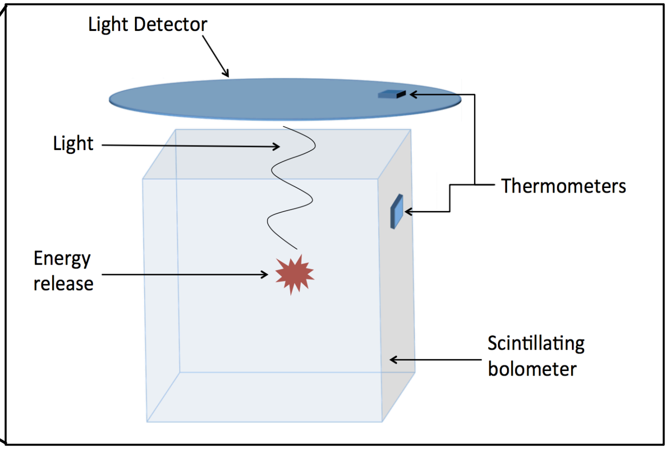
$T_{1/2}^{0\nu}$ > 2.2x10^{25} yr (90% C.L)
$m_{\beta\beta}$ < (90-305) meV

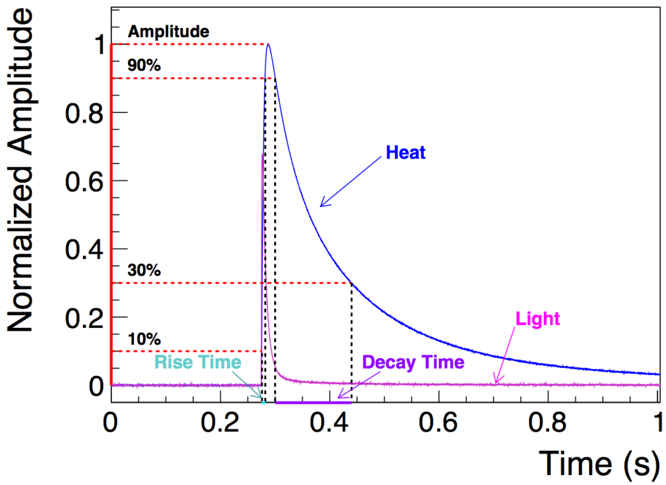


- ➢ Competitive 0νββ results from 1 ton.yr data
- ➢ Lessons learned:
- tonne-scale 0νββ bolometric experiments are feasible
- ~90% of CUORE Bkg in the ROI is from αs
- ~10% in the ROI is γ/β from environmental radioactivity
- Background model fit to the data: degraded αs at 3 MeV ~99% of the total Bkg (expect ~100 reduction of background after α rejection)
- Reducing background is the key to increasing experimental sensitivity

CUPID





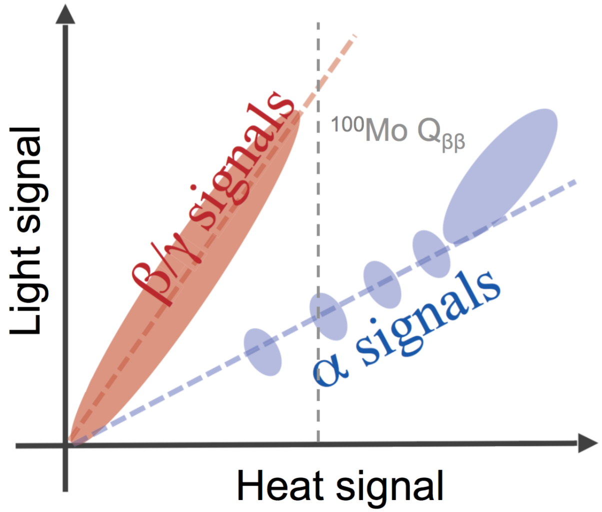


CUPID (CUORE Upgrade with Particle Identification)

- new generation $0\nu\beta\beta$ bolometric experiment
- CUORE cryogenic infrastructure with detector upgrades
- ^{100}Mo-enriched Li_2MoO_4 crystal bolometers for search for $0\nu\beta\beta$ decay of ^{100}Mo

➢ **Scintillating bolometer technology**

- PID via heat-light dual readout: particle discrimination (**>99.9% α rejection** @ E>3 MeV)
- Sensitivity goal : **fully cover the inverted neutrino mass hierarchy region**

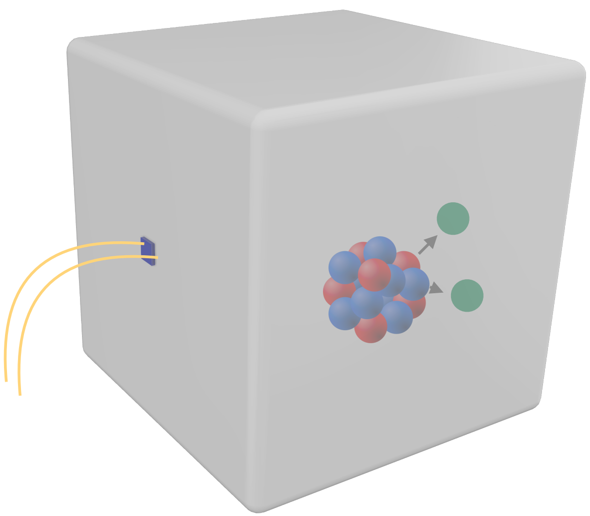


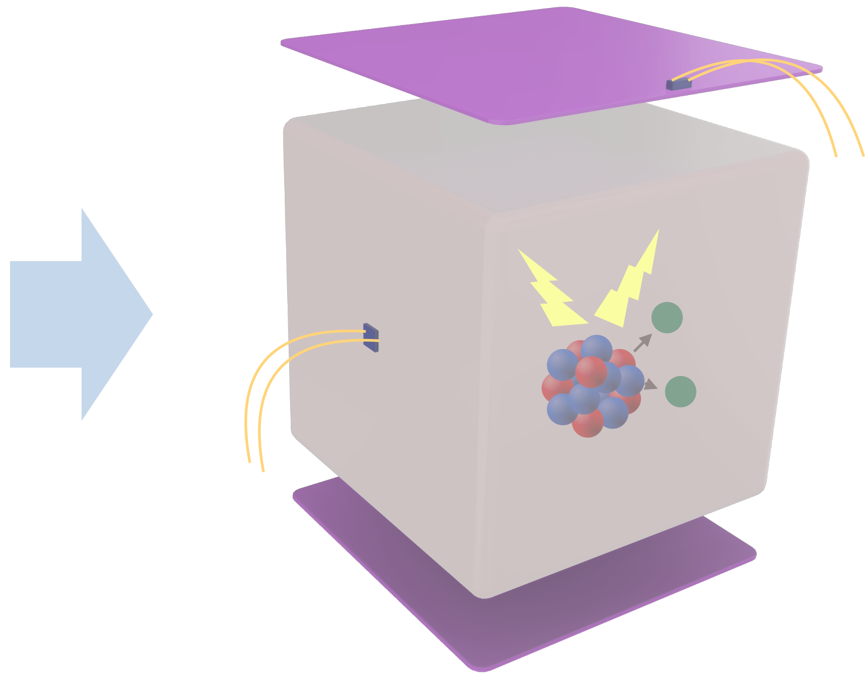
arXiv:1907.09376 (CUPID pre-CDR)

CUPID

CUORE bolometer
- pure thermal detector
- measure only heat (phonon) signal
- No PID

CUPID bolometer
- scintillating crystal
- measure heat+light signals
- PID (α vs. β/γ discrimination)

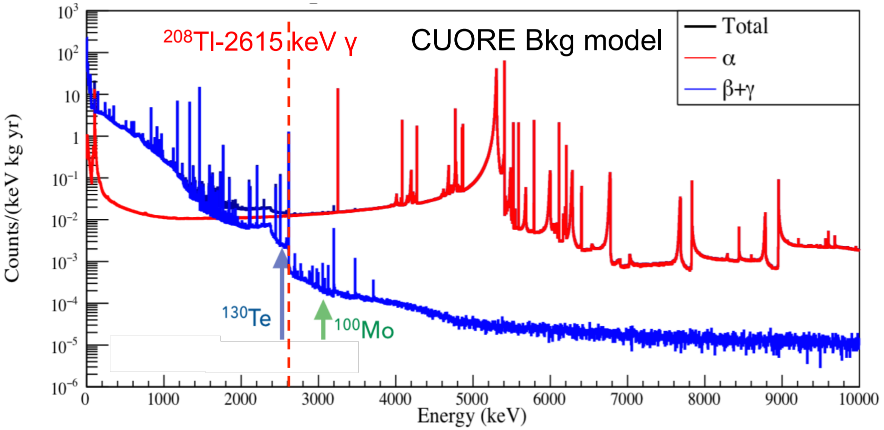


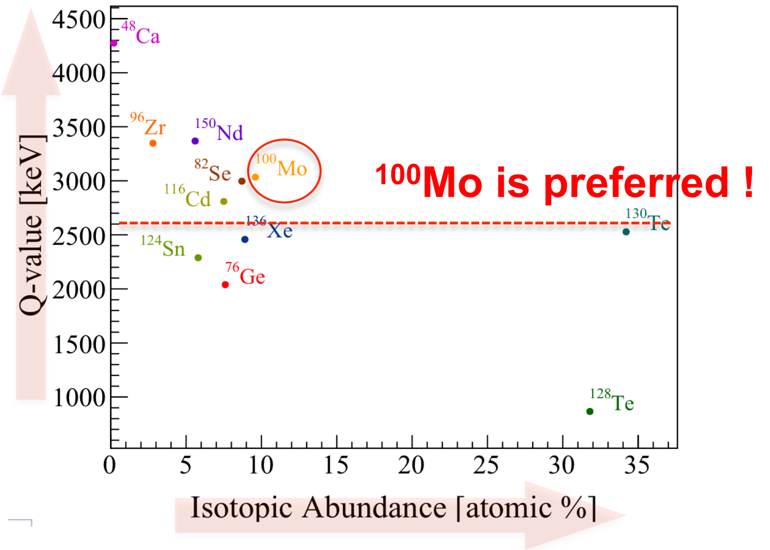


1D => 2D : A big leap!

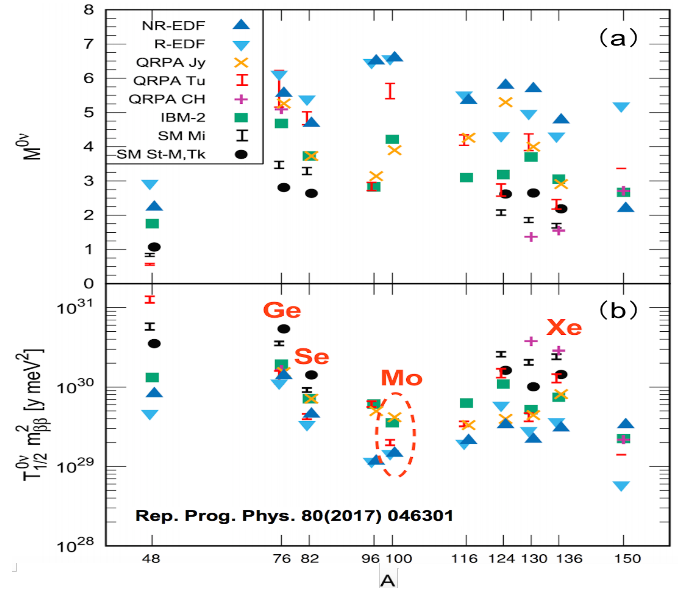
CUPID: the target isotope

- **Q-value and natural abundance**
  - background level and enrichment cost





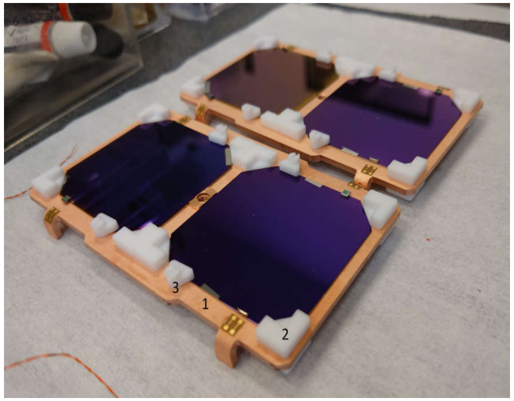
- **Event rate**
  - For finite target mass, $r^{0v} \propto |M^{0v}|^2 G^{0v}$ or $(T^{0v}_{1/2} \mid m_{\beta\beta} \mid ^2)^{-1}$

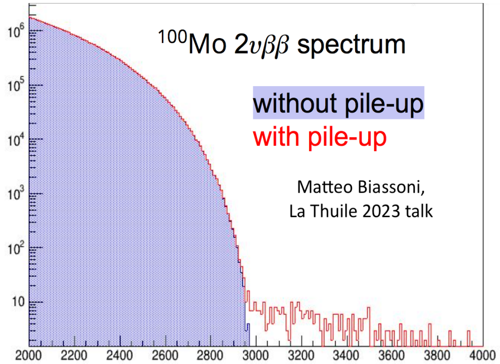


^{100}Mo

1) high $Q_{\beta\beta}$ (~3034keV, reduced γ Bkg)
2) relative high abundance ~10%
3) existing enrichment technology

CUPID: the light detector

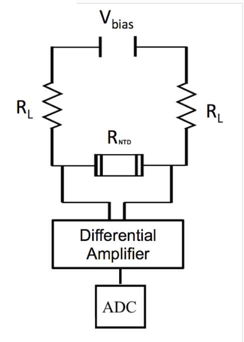


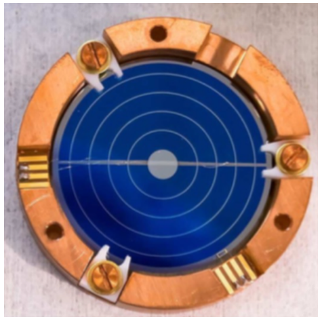


- **The light detector (LD)**
- a bolometer with eV energy threshold and fast readout => important for pile-up rejection

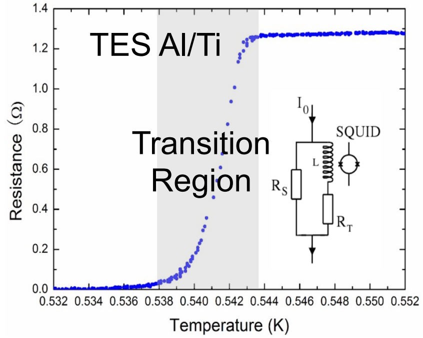
- **CUPID prototypal LD (baseline)**
- Ge wafers with anti-reflecting coating and NTD readout
- <100 eV RMS and >90% absorption efficiency (arXiv:2304.04674)
- optimized size, geometry and absorber coupling
- Competitive technical solutions: **NL-LD, TES-LD**

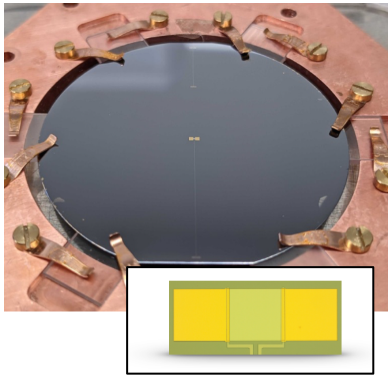
- **Neganov-Luke** light detector (**NL-LD**)
- enhances signal-to-noise & signal response
- wide dynamical range





- **Transition-Edge-Sensor** light detector (**TES-LD**)
- fast readout, good timing resolution ~10 μsec
- easy to scale & compatible with multiplexing

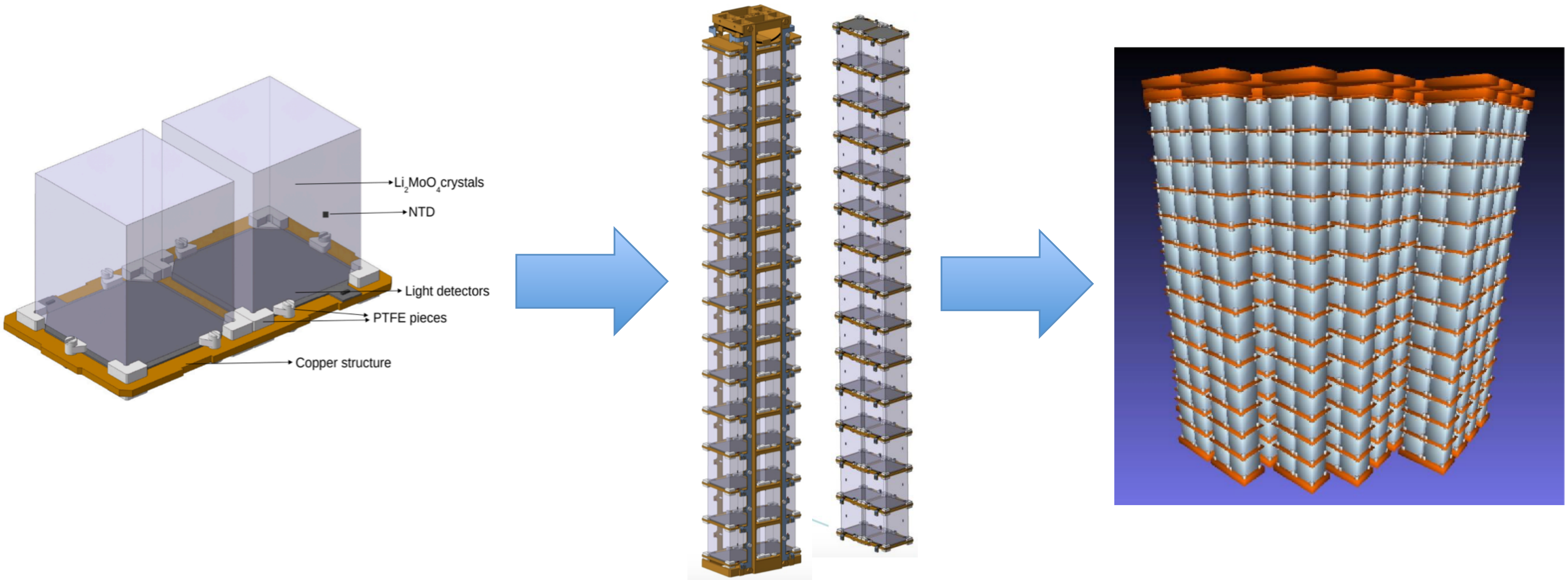




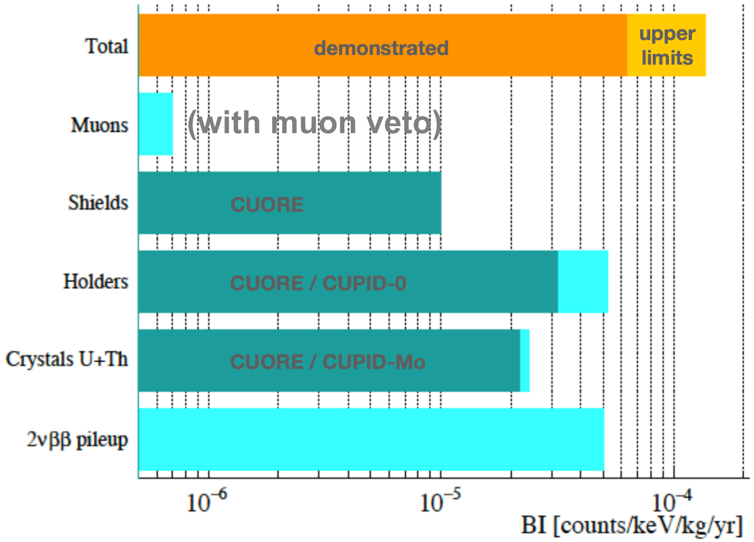
CUPID: the conceptual design

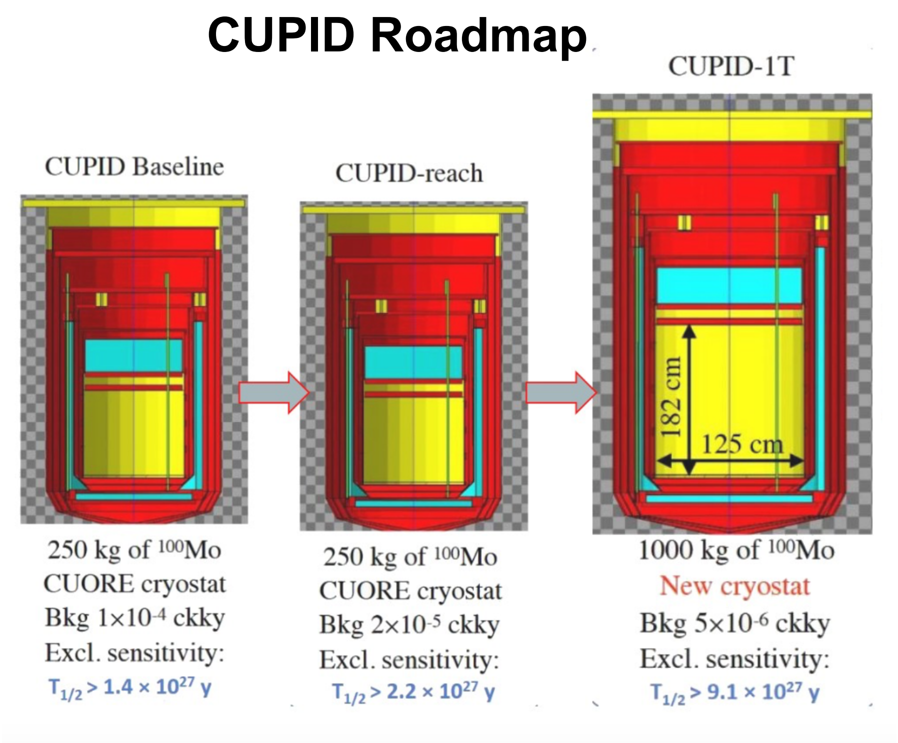
- 1596 $Li_2{}^{100}MoO_4$ crystals, total mass ~450 kg (~240 kg ^{100}Mo)
- Single crystal size: 45×45×45mm^3 (~280 g)
- Tower structure: 57 towers of 14 floors
- 1710 Ge light detectors with anti-reflecting coating
- Cryostat (CUORE): T~10 mK
- Muon veto for muon induced background suppression

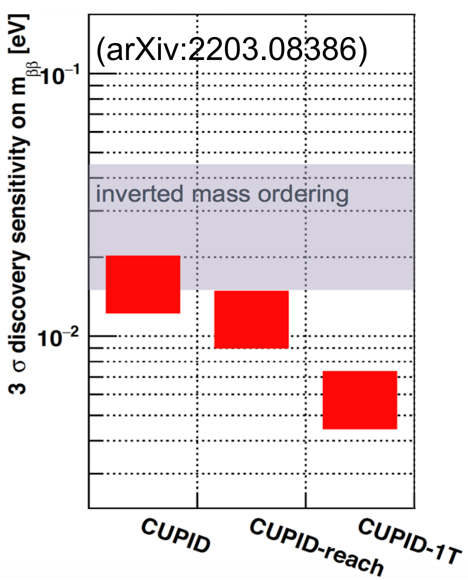
...



CUPID: sensitivity projection







- Bkg estimated based on data-driven background models of CUPID demonstrators and CUORE results
- **CUPID-baseline**: 240 kg ^{100}Mo, BI<10^{-4} cts/keV/kg/yr, Γ_E ~ 0.2%(FWHM) @ $Q_{\beta\beta}$, Sensitivity (3σ, 10 yr runtime): $T^{0\nu}_{1/2} > 10^{27}$ yr , $m_{\beta\beta} < (12\text{-}20)$ meV

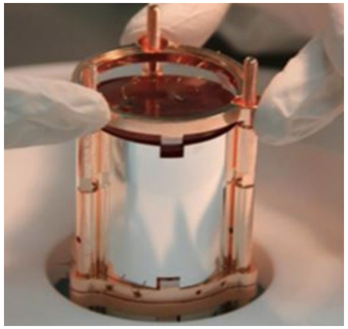
CUPID: pilot experiments

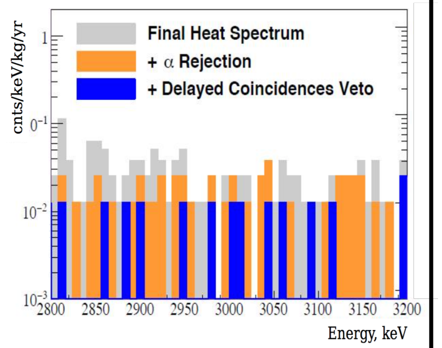
- **CUPID-0:** the first pilot experiment for CUPID (enriched $Zn^{82}Se$ crystal bolometer)
- **CUPID-Mo:** pilot experiment using $Li_2{}^{100}MoO_4$ scintillating crystals

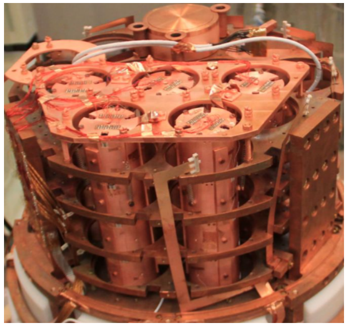
✓ Well demonstrated perspectives for 0νββ search based on scintillating bolometers:

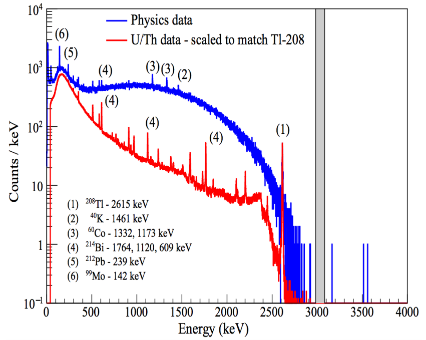
- high efficiency
- good energy resolution
- background rejection…

Phys. Rev. Lett.123,032501; Phys. Rev. Lett. 126,181802





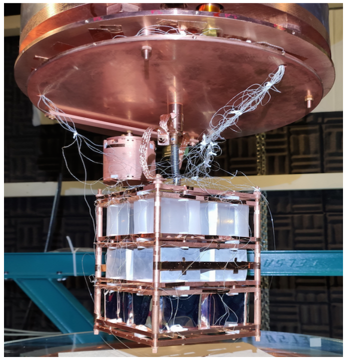


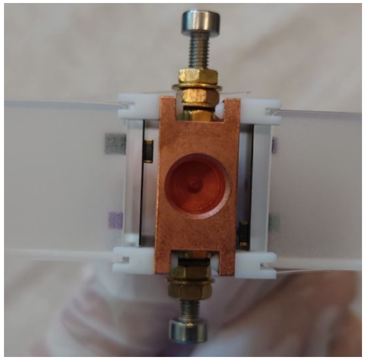


- **Exploratory experiments**

- **CROSS:** surface-event identification (discriminate surface vs bulk events)
- **BINGO:** geometry optimization, active γ veto and square LD with NL

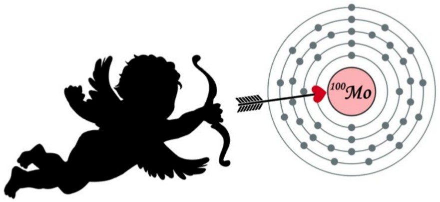
J. High Energ. Phys. 2020: 18; arXiv.2204.14161



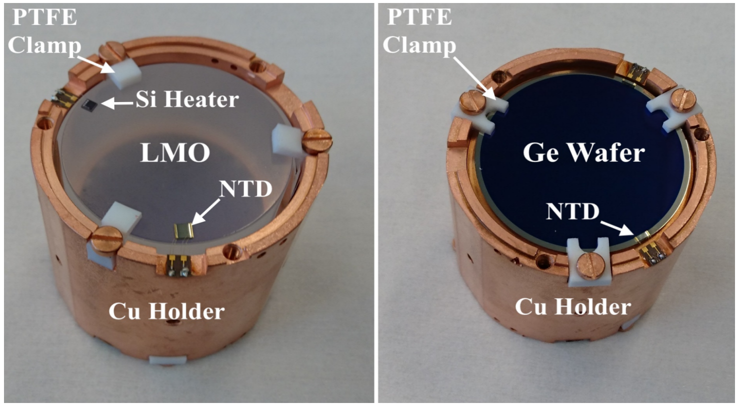


Selected results: CUPID-Mo

➢ **Experimental setup**



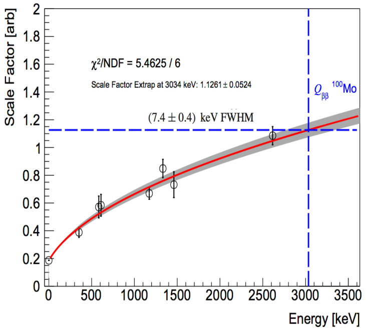
- 20 scintillating Li_2MoO_4 cylindrical crystals, (2.34 kg of ^{100}Mo, >95% enrichment)
- 20 Ge light detectors
- Operated at LSM during 2019-2020

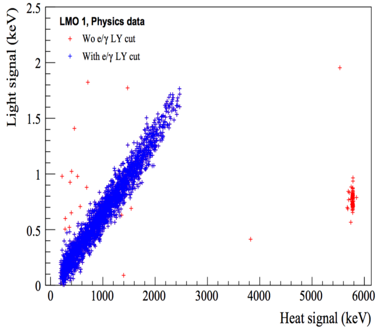


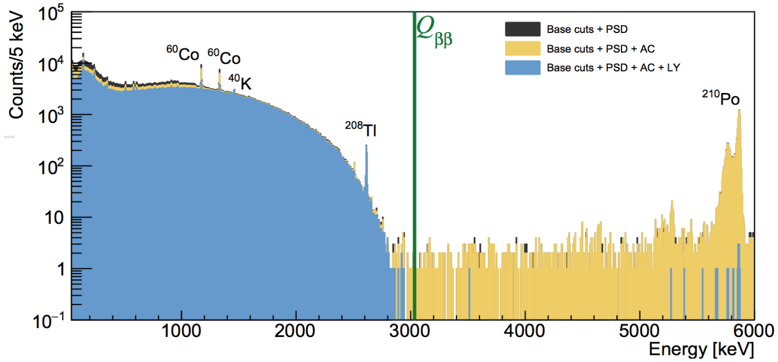
➢ **Detector performance and physics results**

- Good energy resolution: 7.4 keV FWHM at $Q_{\beta\beta}$
- Good PID performance: > 99.9 α separation
- Excellent internal radiopurity of crystals: ^{238}U/^{232}Th:(0.3-1) μBq/kg, ^{210}Po:100 μBq/kg
- Constraint on $m_{\beta\beta}$ (^{100}Mo exposure of 1.47 kg.yr): $\langle m_{\beta\beta} \rangle$ < 280-490 meV

Eur. Phys. J. C 80:44
Eur. Phys. J. C 82:1033



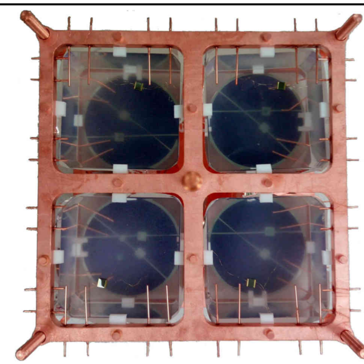


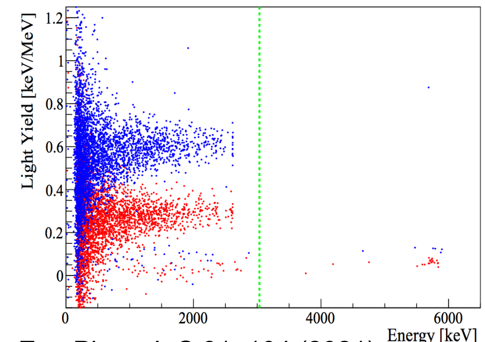


R&D progress: mini-tower run

- ➢ A series of cryogenic tests in multiple cryogenic facilities (LNGS/LSC)
- validate baseline decisions
- explore alternative design & technologies
- background control study

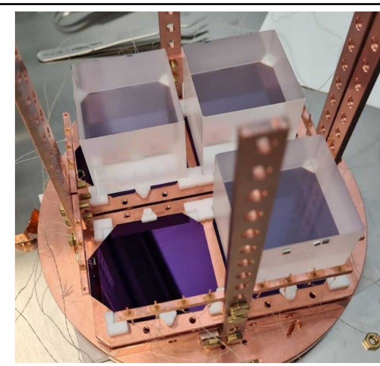
➢ **8-LMO run (**LNGS Hall C)
- ^{100}Mo enriched crystal
- Ge wafer with SiO AR coating
- Main goal :light collection study
- \- crystal geometry
- \- reflective foil
- \- light detector

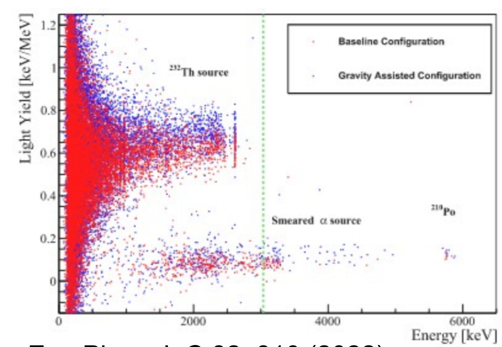




Eur. Phys. J. C 81, 104 (2021)

➢ **8-LMO run (**LNGS Hall C)
- natural crystal
- 12 Ge wafers with SiO AR coating
- Main goal: PID performance study and detector structure optimization
- \- LD noise level: LD RMS_{bsl}=35-70 eV
- \- PID performance: α rejection > 99.9 %
- \- Energy resolution at Q-value : 5.9 keV (FMWH)





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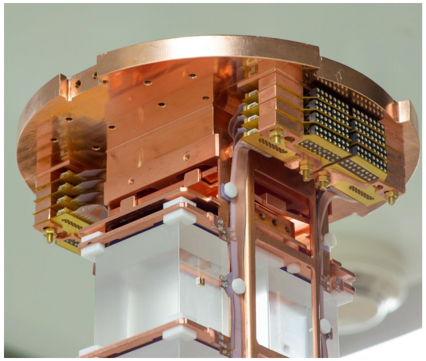
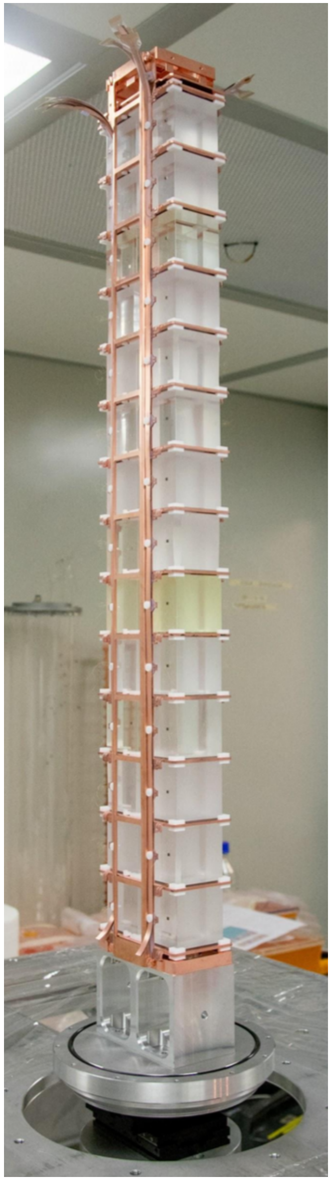
R&D progress: BDPT run

- **BDPT**: **B**aseline **D**esign **P**rototype **T**ower
- first validation of detector baseline design at LNGS
- small scale baseline design successfully deployed

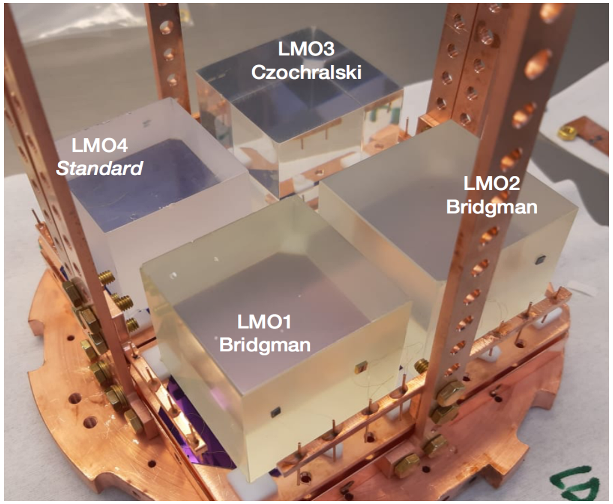
- 14-floor tower run

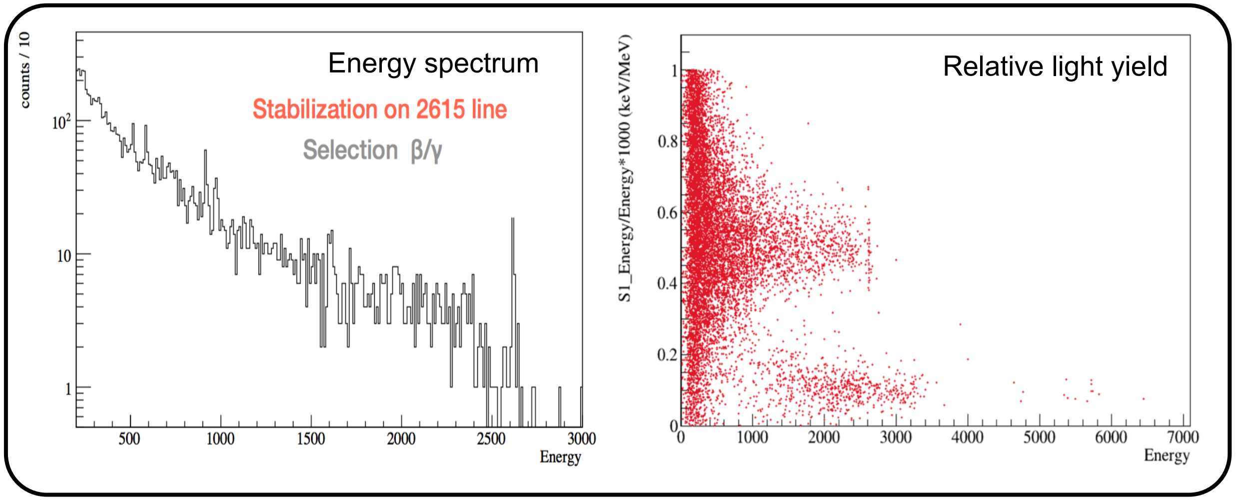
- 28 LMO crystals from different origins
- 30 Ge light detectors
- Main goal: validation of the CUPID detector structure and performance
- validation of tower assembly procedures completed
- **Run3 ongoing**: further test on vibration and thermal characteristics

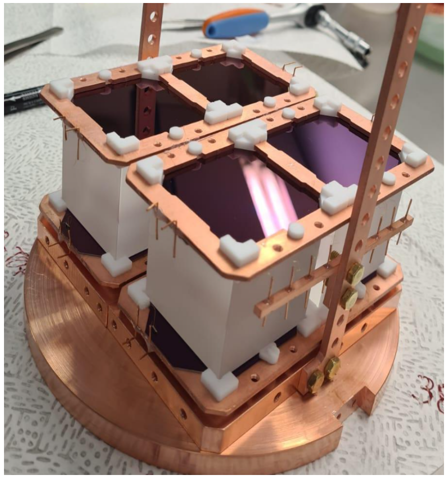


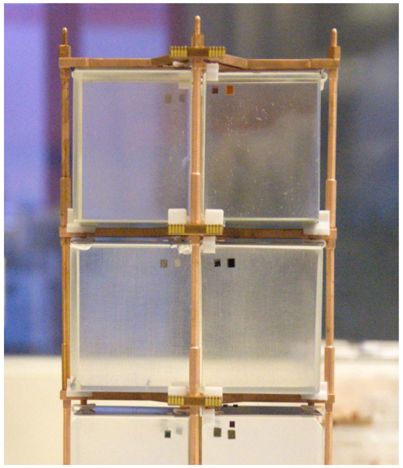


R&D progress: CCVR run









- ➢ Underground bolometric test of crystals in different cryogenic facilities (LNGS/LSC)
- Typical configuration: 4 crystals of each type/ producer (Bridgman/Czochralski) assembled in a 2x2 array with 8 light detectors for light readout
- Main goal: sensitive radiopurity assessment **=> crystal quality evaluation**
- reach required sensitivity on U, Th and K

The CUPID collaboration

~ 30 institutes, >150 collaborators

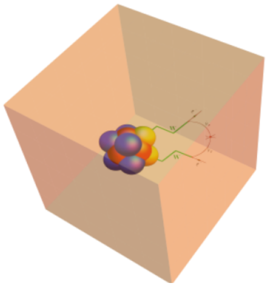
Integrate the experience from CUORE, CUPID-0 and CUPID-Mo in operating bolometric detectors with particle identification technology !

CUPID potential for multiple physics studies

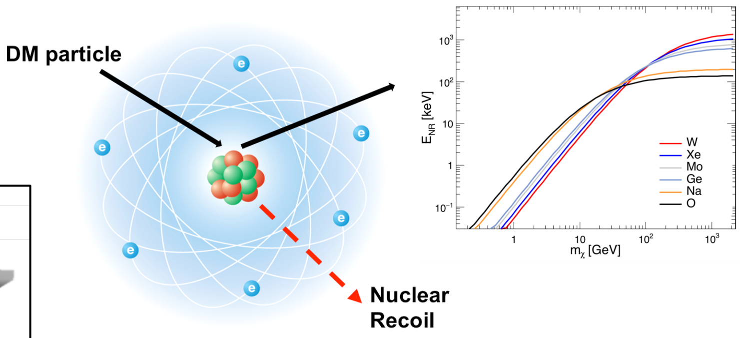
0vDBD/2vDBD

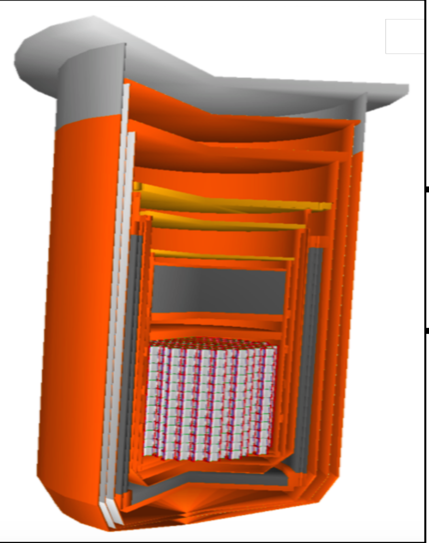
- Multiple isotopes

$^{130}TeO_2$
$Zn^{82}Se$
$Li_2{}^{100}MoO_4$
$Na_2{}^{100}MoO_4$
$Cd^{100}MoO_4$



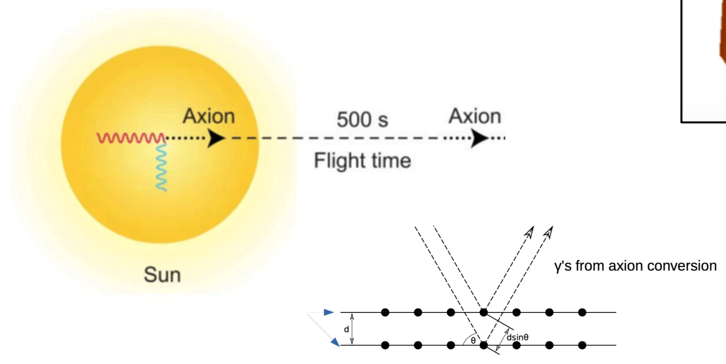
Dark matter





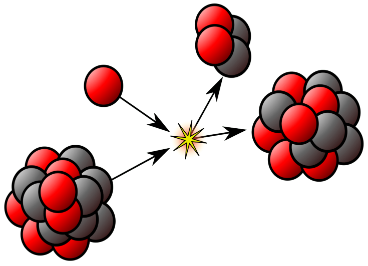
CEvNS
Supernova ν
…

Solar axion



Rare nuclear decay

e. g. excited states/tri-nucleon



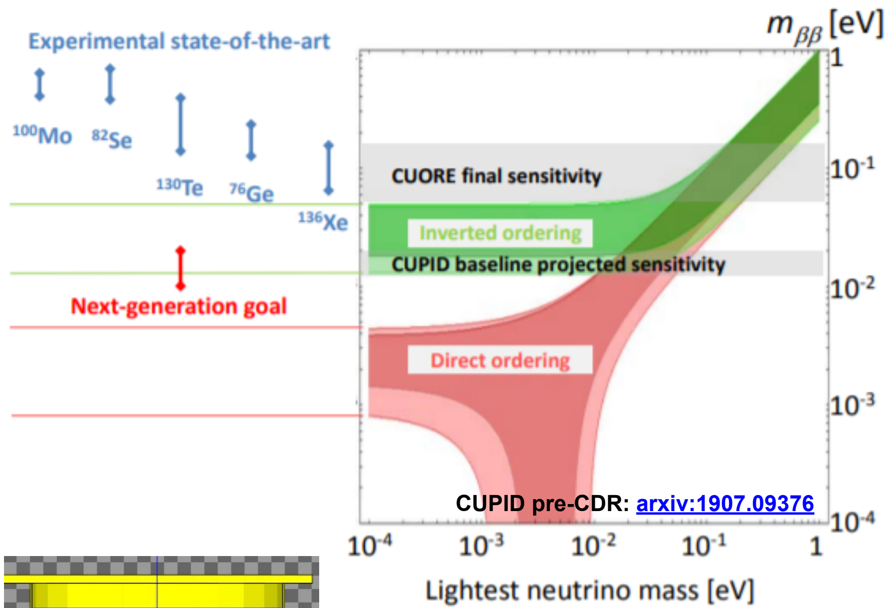
Summary

- CUPID is a next generation bolometric experiment aiming at high sensitivity search for 0νββ of ^{100}Mo
- The project takes advantage of existing CUORE expertise & infrastructures
- Performance of small scale module (mini-tower composed of Li_2MoO_4 crystal bolometers) is well demonstrated
- Multiple R&D programs are ongoing towards a future tonne-scale (CUPID-1T) experiment

Backups: CUPID-1T

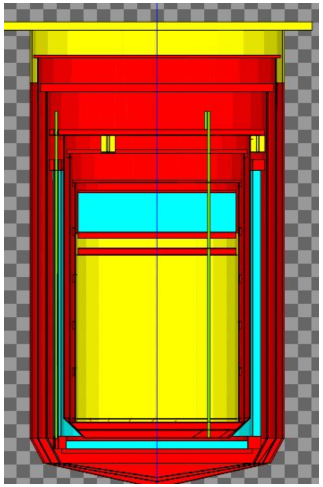
CUPID-1T: HALLMARKS

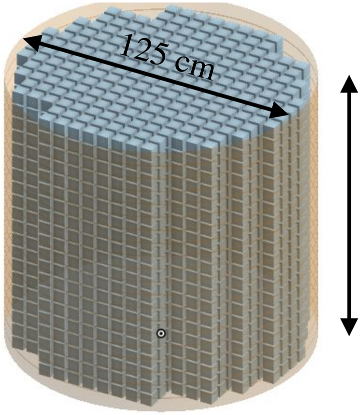
- ➢ 1000 kg of ^{100}Mo in a single cryostat or multiple facilities world wide
- ➢ Sensitivity: $m_{\beta\beta}$<10 meV (NH)



POTENTIAL EXPANSIONS

- ➢ Large volume cryogenic facilities in multiple Underground Labs worldwide





Towards CUPID-1T. Snowmass 2021 Planning workshop

Backups: the background goal

Path to reach CUPID background requirement:

- crystal purity quality control
- cleaning of passive elements
- further reduce contamination in cryogenic infrastructure
- fast readout - reduce pile-up contribution