NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics
Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

CUPID and its demonstrators: scintillating bolometers for 0ν2β search

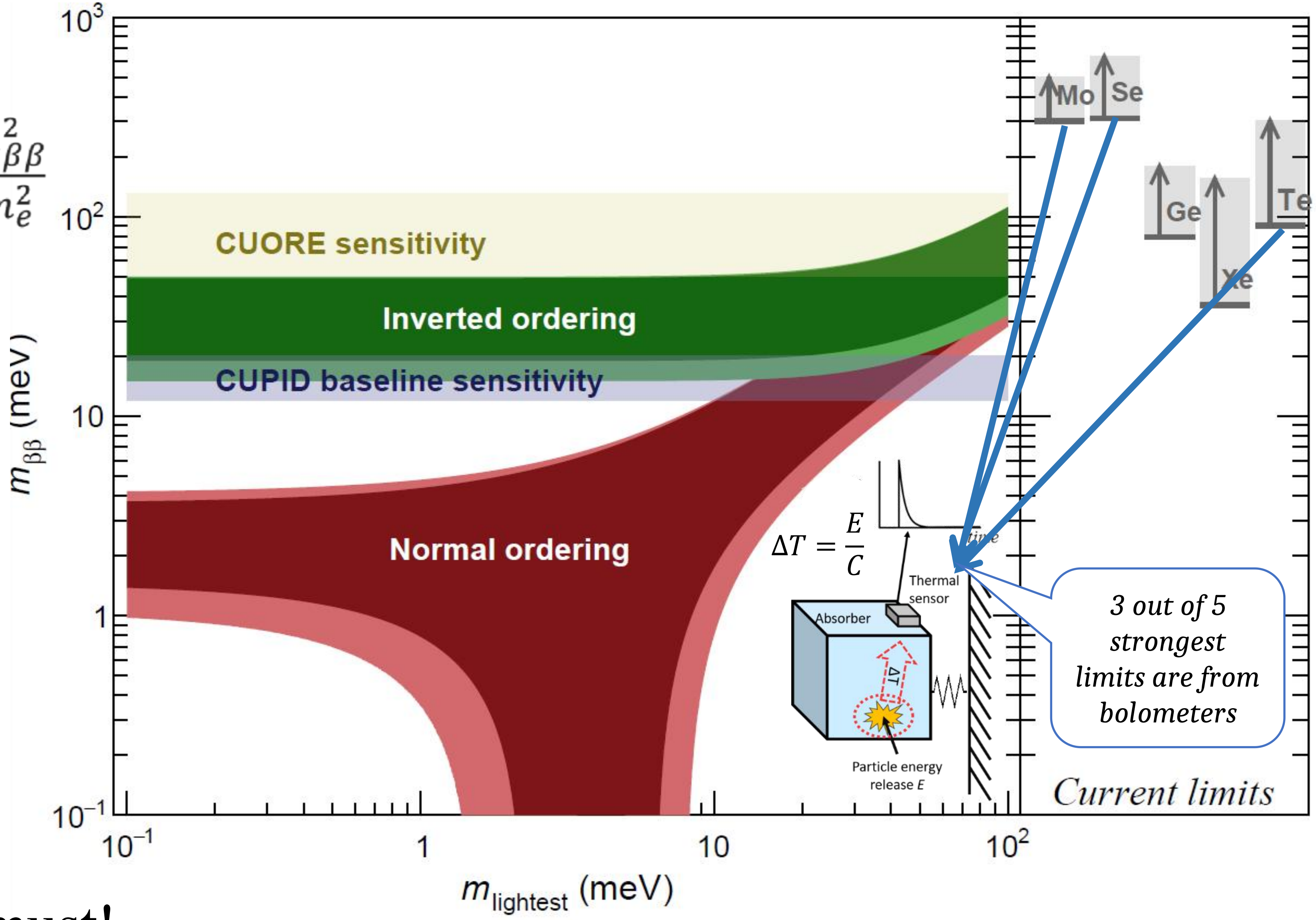
Anastasiia ZOLOTAROVA on behalf of the CUPID, CUPID-0, CUPID-Mo collaborations

CEA-Saclay, IRFU/DPhP

Next generation sensitivity goals

$$(T_{1/2}^{0\upsilon 2\beta})^{-1} = G^{0\upsilon}(Q,Z)\,|M^{0\upsilon}|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

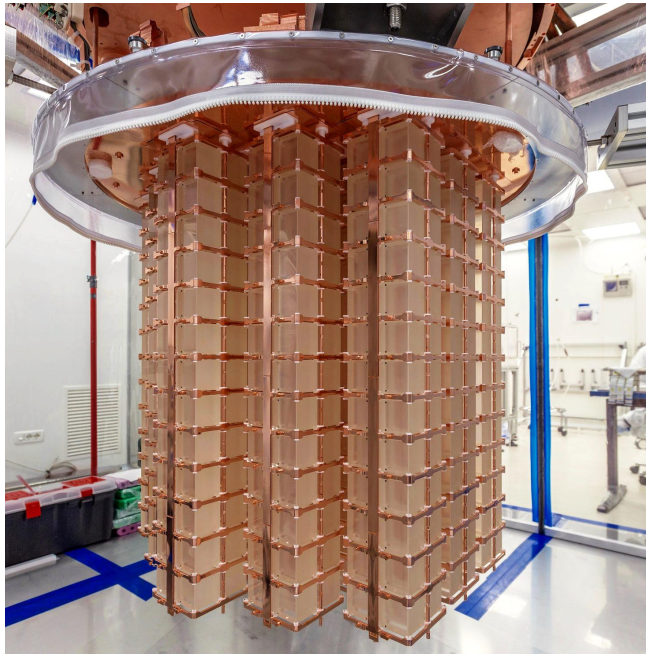
Next generation of experiments aim to fully cover the inverted ordering range



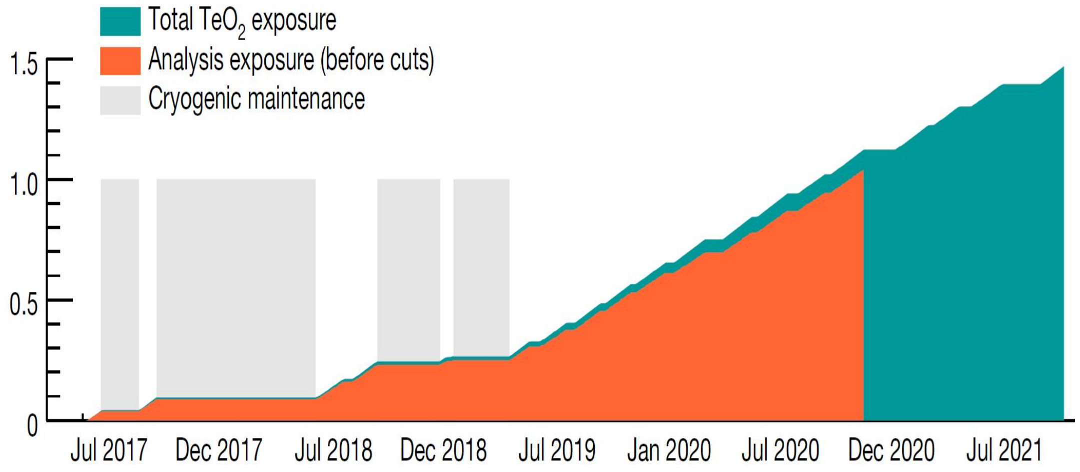
Very low background is a must!

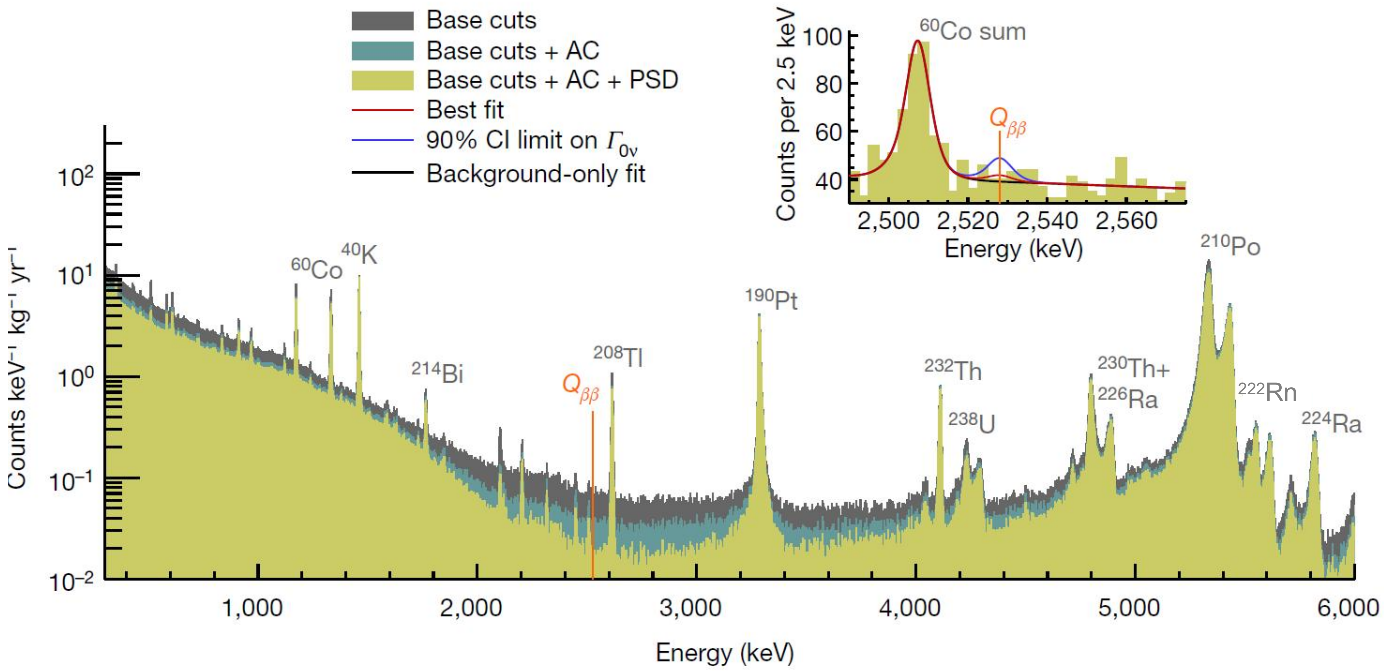
CUORE: lessons learned

- CUORE cryogenic facility is an unprecedented technological challenge, which is now **taking data in steady and reliable conditions** (after ~1 yr of optimization)
- About **90%** of CUORE background is **from α particles**
- About 10% is β/γ from environmental radioactivity
- <1% muons background



Nature 604, 53–58 (2022)

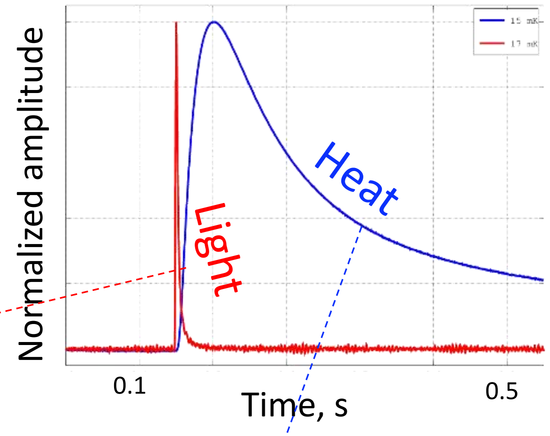


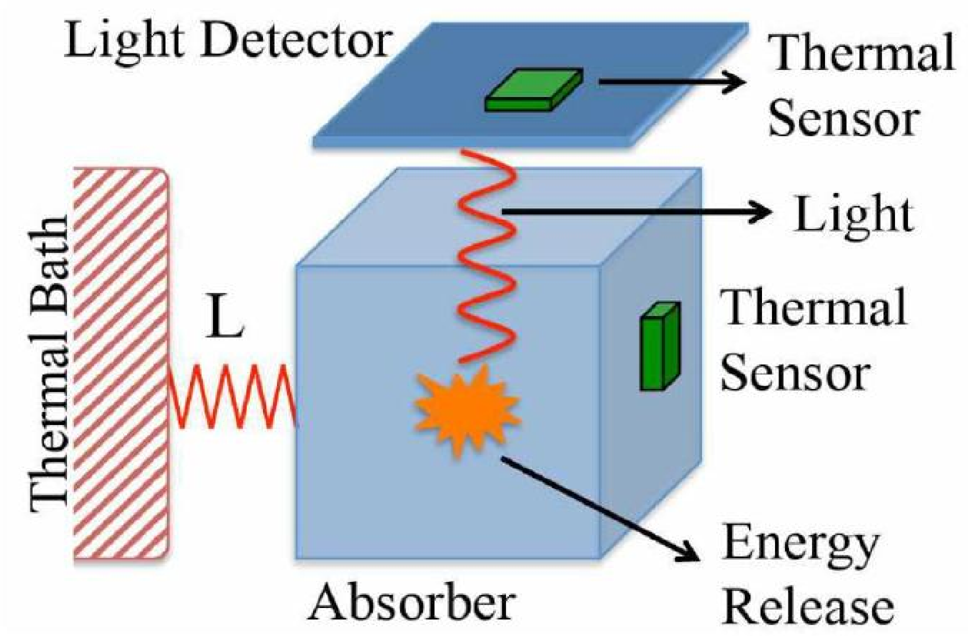


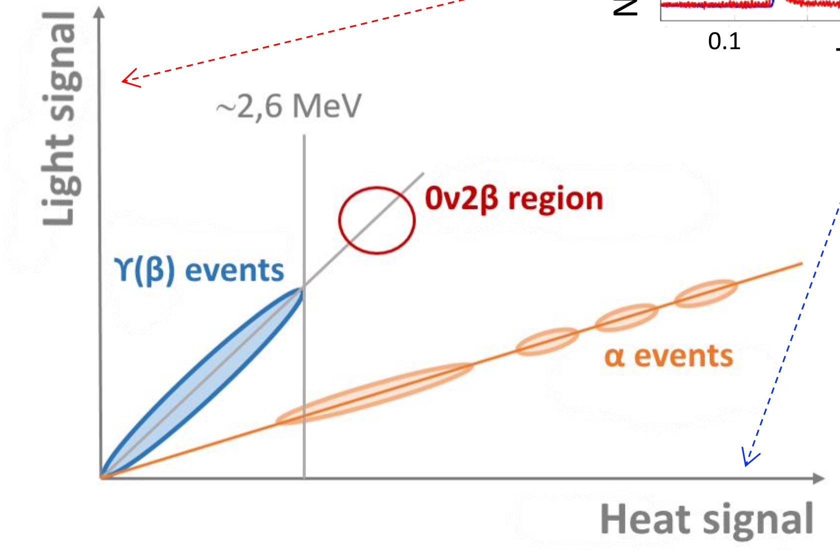
α rejection: scintillating bolometers

- Use of scintillating crystals: Particle discrimination with light: >99.9 % α rejection
- Double read-out with thin auxilary bolometers
- High energy resolution: ~5 keV FWHM (~0.2%) at the $Q_{\beta\beta}$

Typical signal: **0.1 mK/MeV**, converted to **0.1-0.2 mV/MeV**





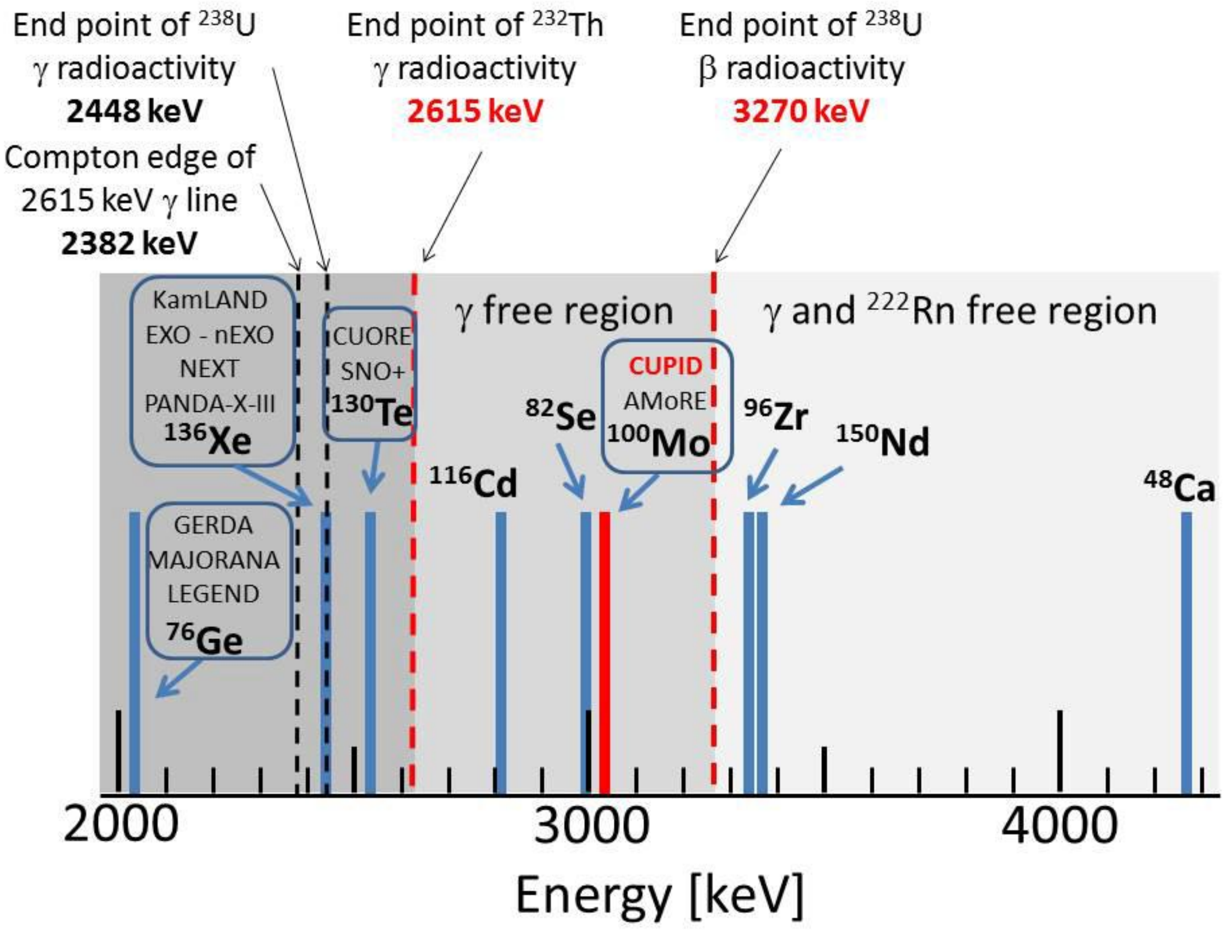


$0\nu2\beta$ decay isotopes

- Allowed in 35 nuclei, but only few are applicable for the experiments
- Isotopic abundance is highly important, as well as possibility of mass-scale enrichment

- **Q-value** is significant for the background level in ROI and $0\nu2\beta$ decay rate

- For bolometers, the isotope should be embedded in dielectric and diamagnetic crystal - right compounds to be found



CUPID: past and future

CUORE: first ton-scale
DBD experiment at 10 mK
No particle ID

CUPID: past and future

CUPID-Mo

CUPID demonstrators:
α rejection with light
Best limits on
^{100}Mo and ^{82}Se 0ν2β

CUPID-0

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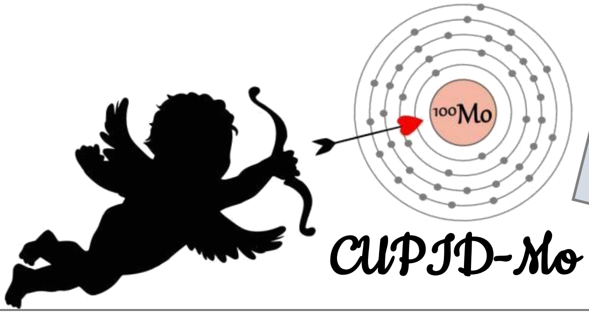

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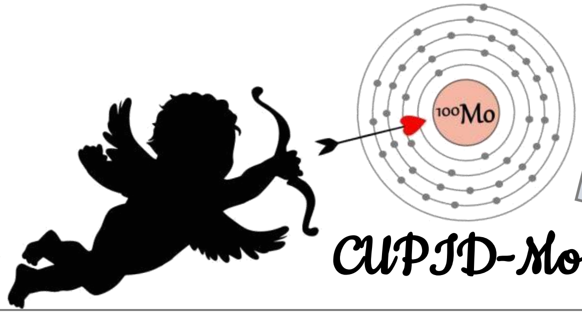

CUPID-Mo

CUPID demonstrators:
a rejection with light
Best limits on
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CUPID-0

New demonstrators for deeper investigations of normal mass ordering (CUPID-1T)

CUPID

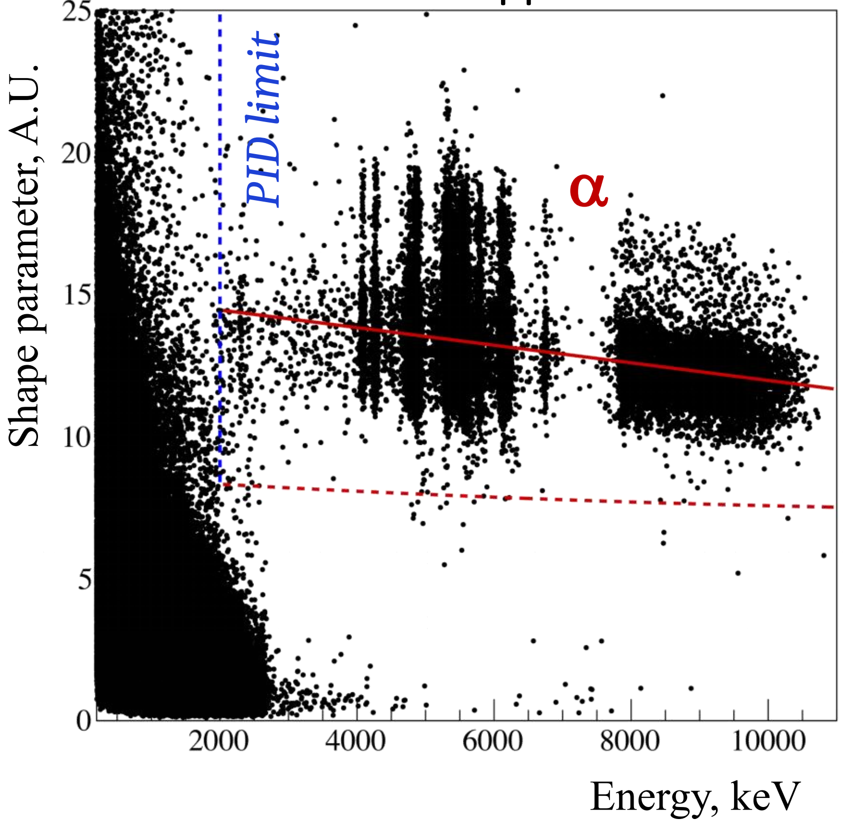
BINGO
Poster 186

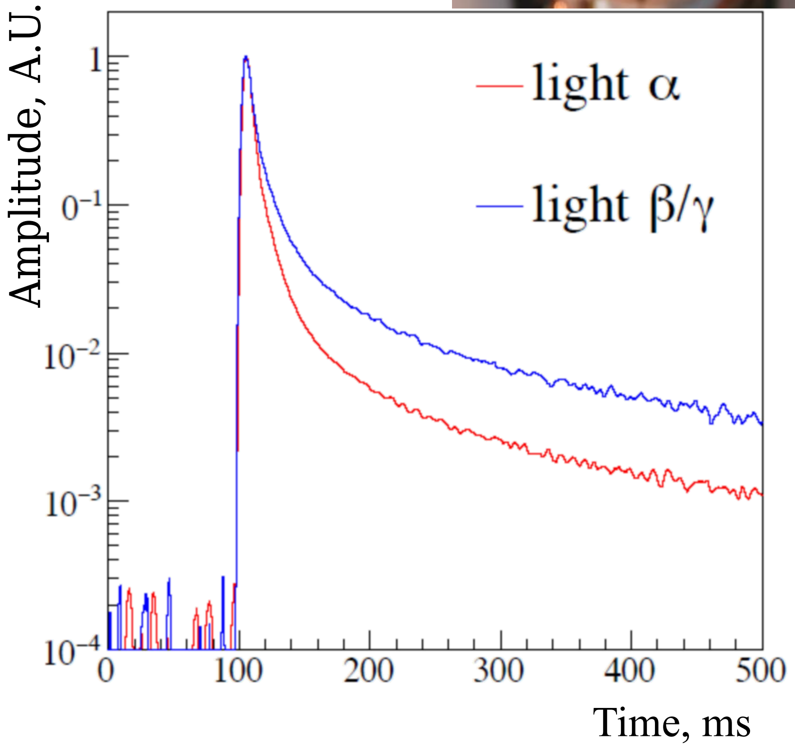
DEMETER
Poster 291

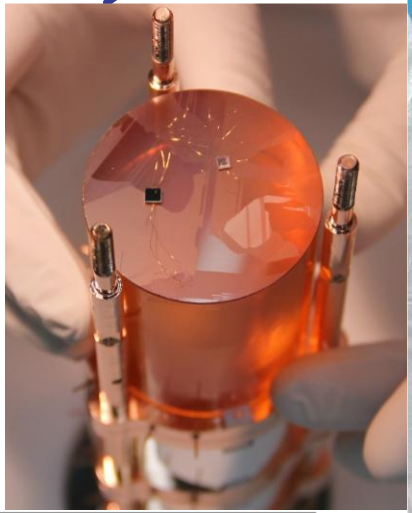
CROSS
Neutrinoless double β decay
Superconductivity

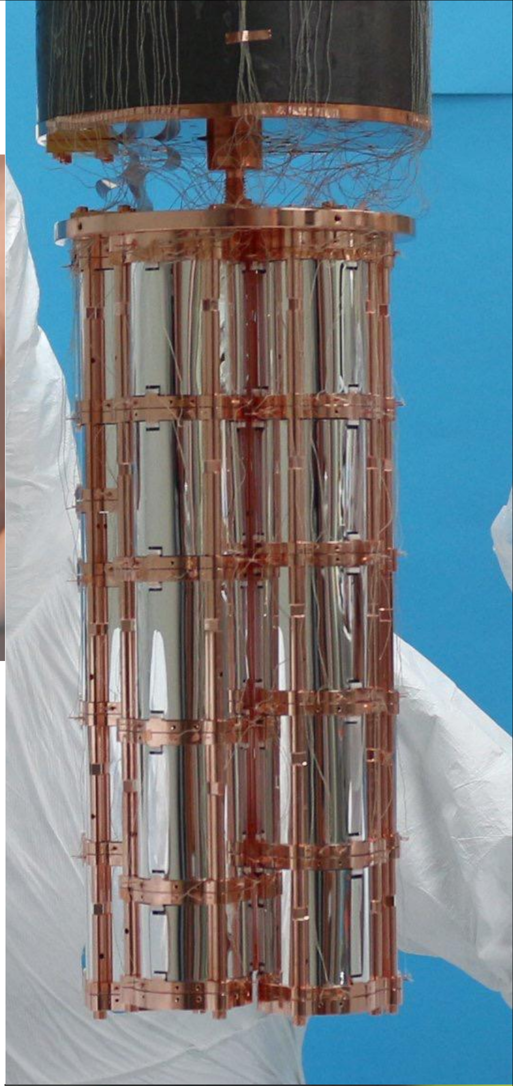
CUPID-0 demonstrator (^{82}Se)

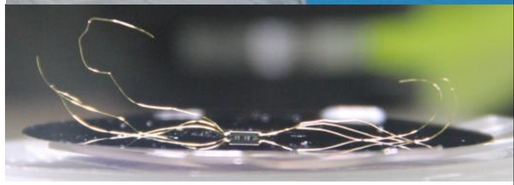
- The first pilot experiment for CUPID with scintillating bolometers in LNGS
- 95% enriched $Zn^{82}Se$ bolometers **(5.17 kg of ^{82}Se, $Q_{\beta\beta}$=2998 keV)**











EPJC (2018) 78:428

CUPID-0 background

Several cuts applied:

- Selecting only particle signals:

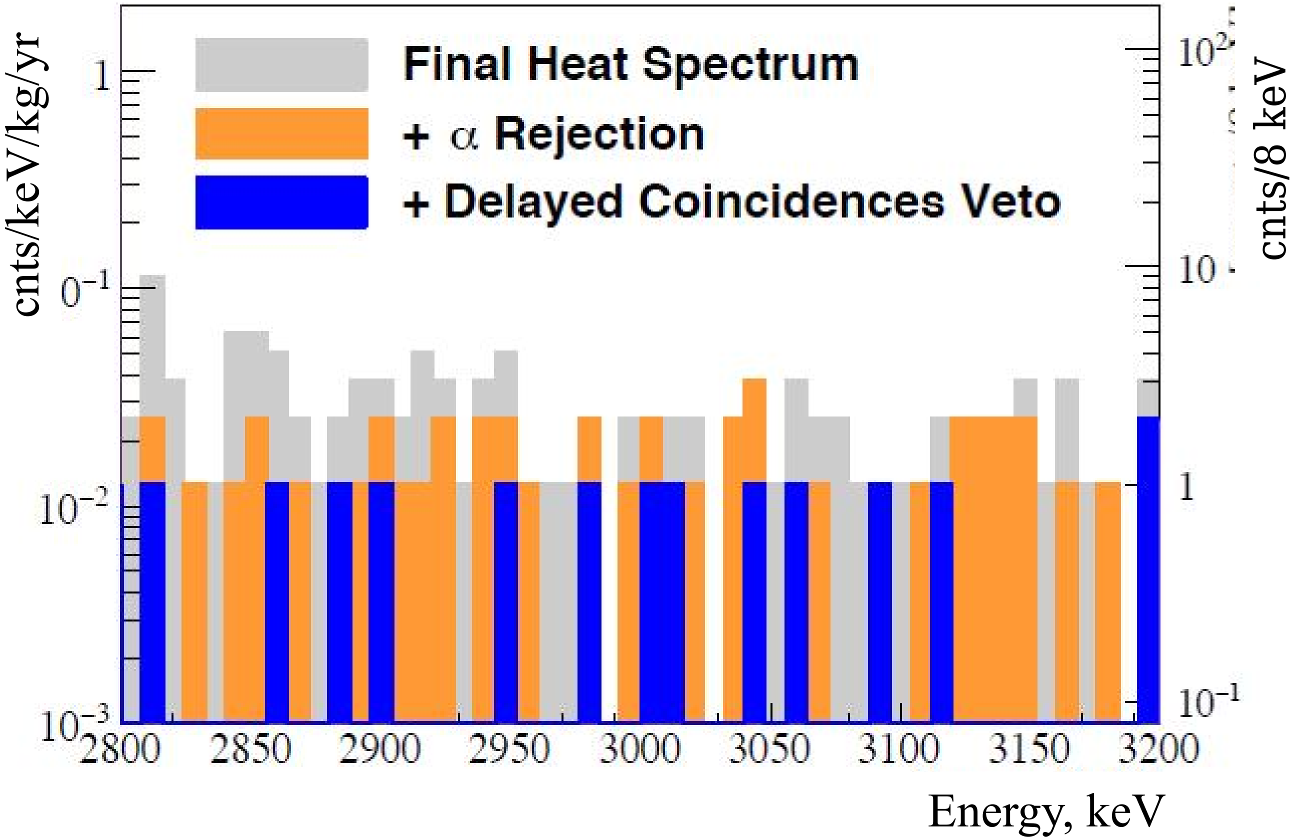
⇒ 3.2×10^{-2} cnts/(keV kg yr)

- Selecting only β/γ:

⇒ 1.3×10^{-2} cnts/(keV kg yr)

- Removing ^{208}Tl events:

⇒ 3.5×10^{-3} cnts/(keV kg yr)

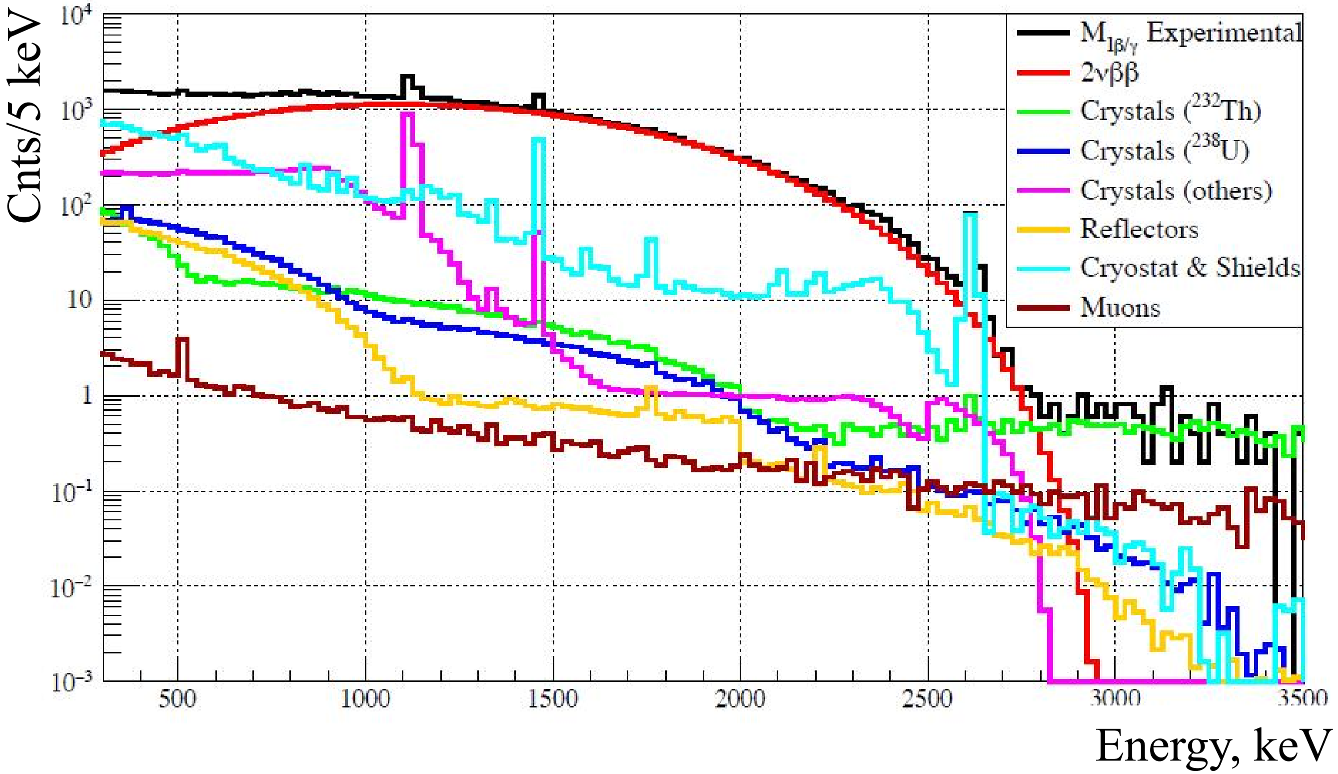


Important insights for design of the next generation experiment

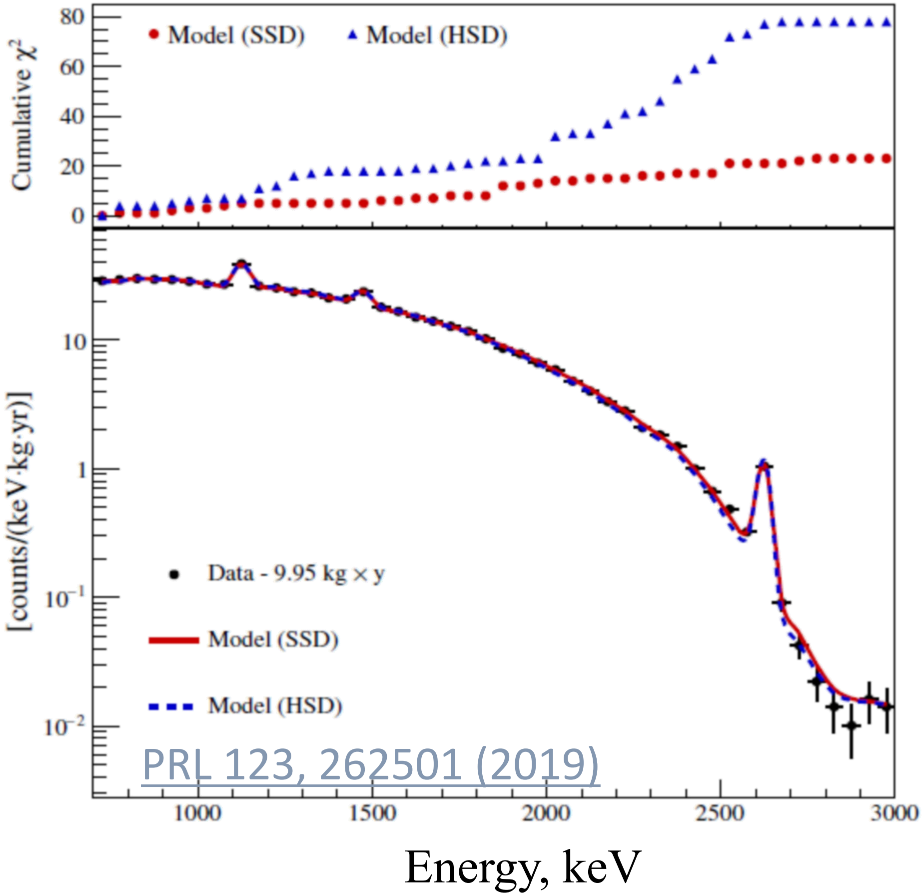
CUPID-0 results

FWHM @ $Q_{\beta\beta}$=(20.05 ± 0.34) keV

- Successfull demonstration of advantages of **dual-readout technique**
- High scientific potential: best limit on 0ν2β, most precise measurement of ^{82}Se 2ν2β, CPT violation search, SSD vs HSD, excited states



$$T^{2\nu}_{1/2} = [8.60 \pm 0.03(\text{stat})^{+0.19}_{-0.13}(\text{syst})] \times 10^{19}\ \text{yr}$$



PRL 123, 262501 (2019)

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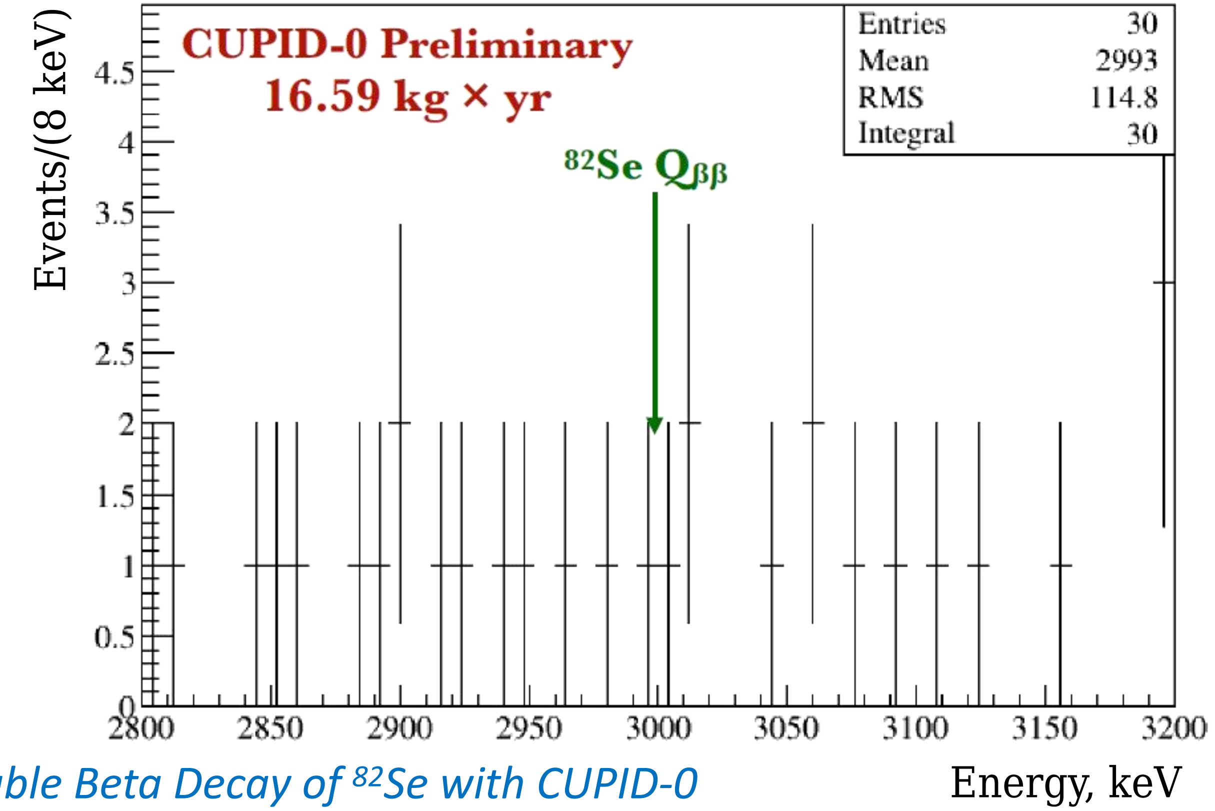
- High scientific potential: best limit on 0ν2β, most precise measurement of ^{82}Se 2ν2β, CPT violation search, SSD vs HSD, excited states

$$T^{0\nu}_{1/2} > 4.7 \times 10^{24} yr \text{ (90\% C. I. limit)}$$

$$m_{\beta\beta} < 276\text{-}570 \text{ meV}$$

PRD 100, 092002 (2019)
PRL 123, 262501 (2019)
EPJC 79, 583 (2019)
EPJC 81, 722 (2021)

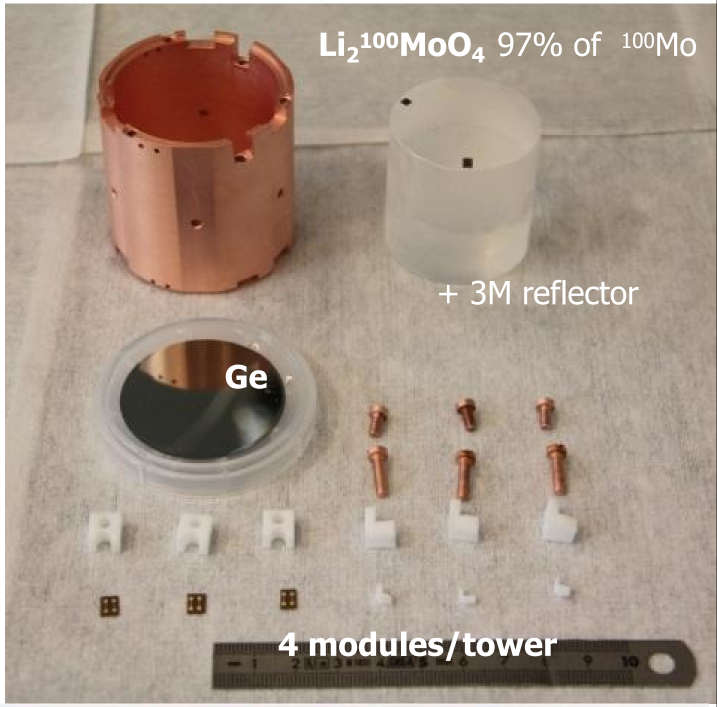


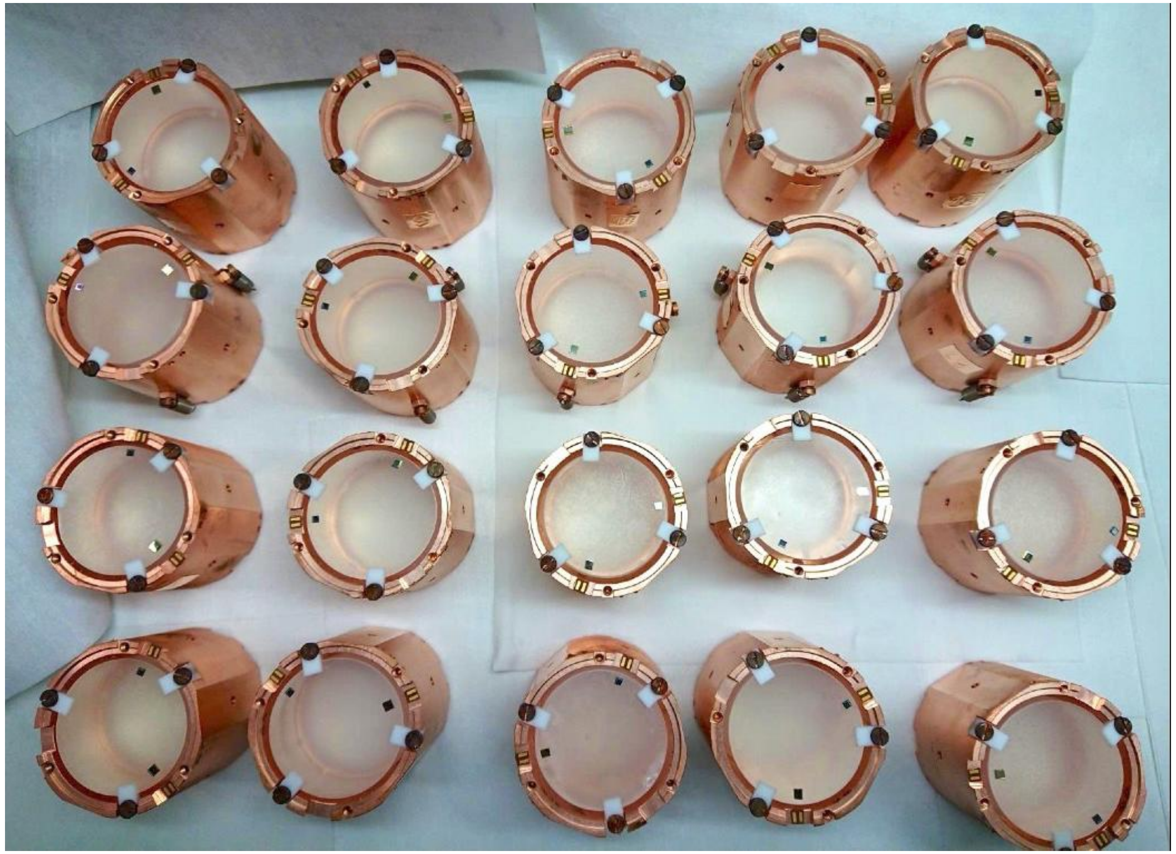
See also posters:

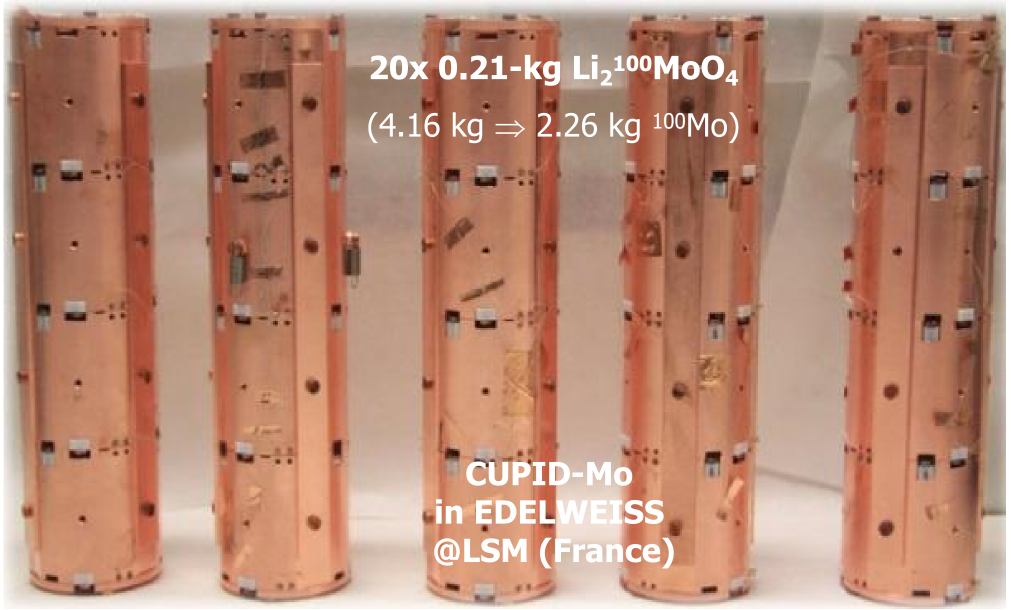
- **492, Pagnanini, Lorenzo:** *Final Result on the Neutrinoless Double Beta Decay of ^{82}Se with CUPID-0*
- **539, Ressa, Alberto:** *Search for new physics in double beta decay of ^{82}Se with the CUPID-0 Background Model*

CUPID-Mo

- **$Li_2{}^{100}MoO_4$** scintillating crystals - high energy resolution and radiopurity, array of 20 modules at LSM
- **Total of 2.26 kg of ^{100}Mo, $Q_{\beta\beta}$ = 3034 keV**



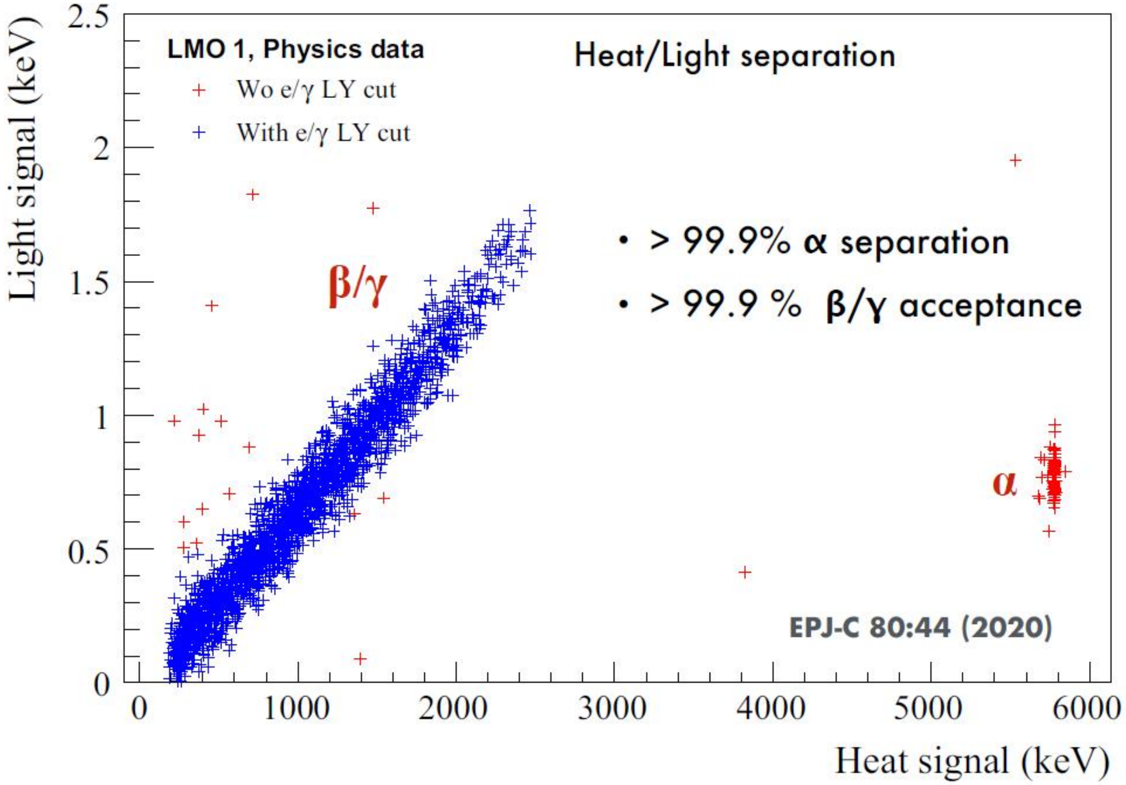


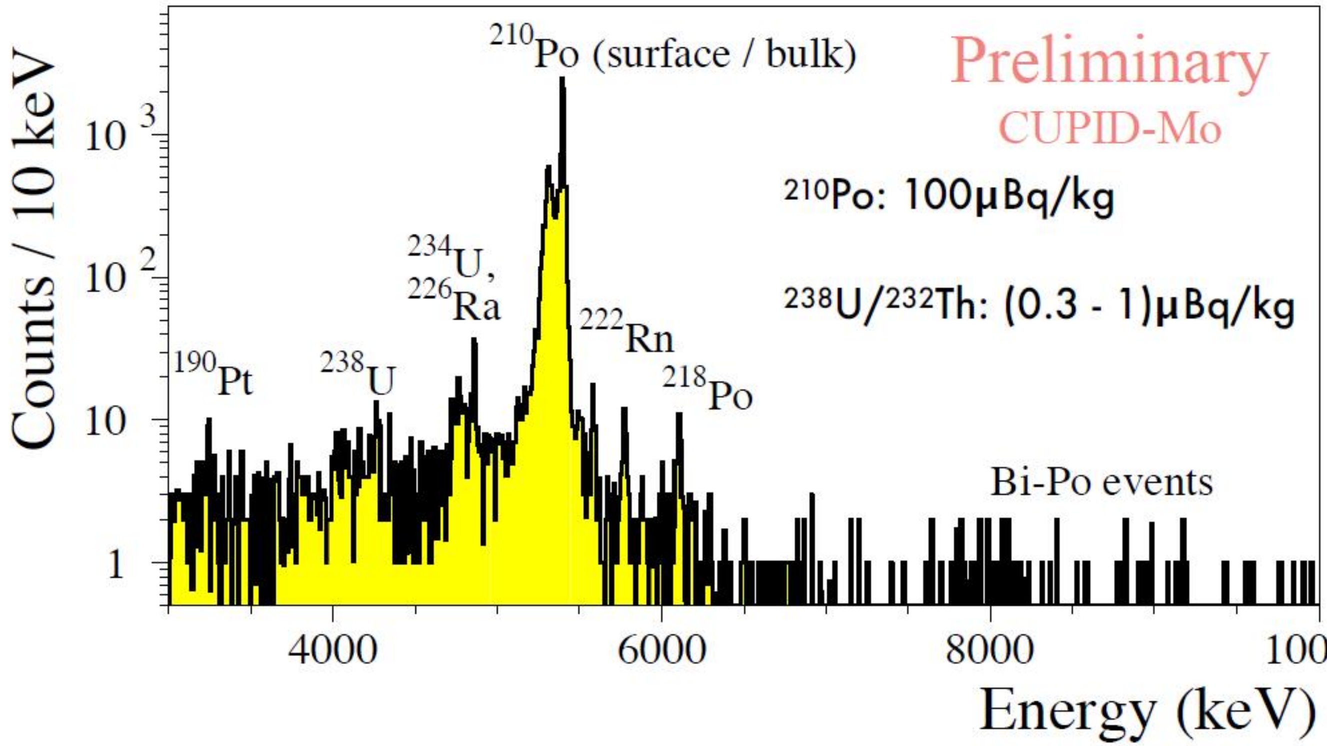


EPJC 80, 44 (2020)

CUPID-Mo features

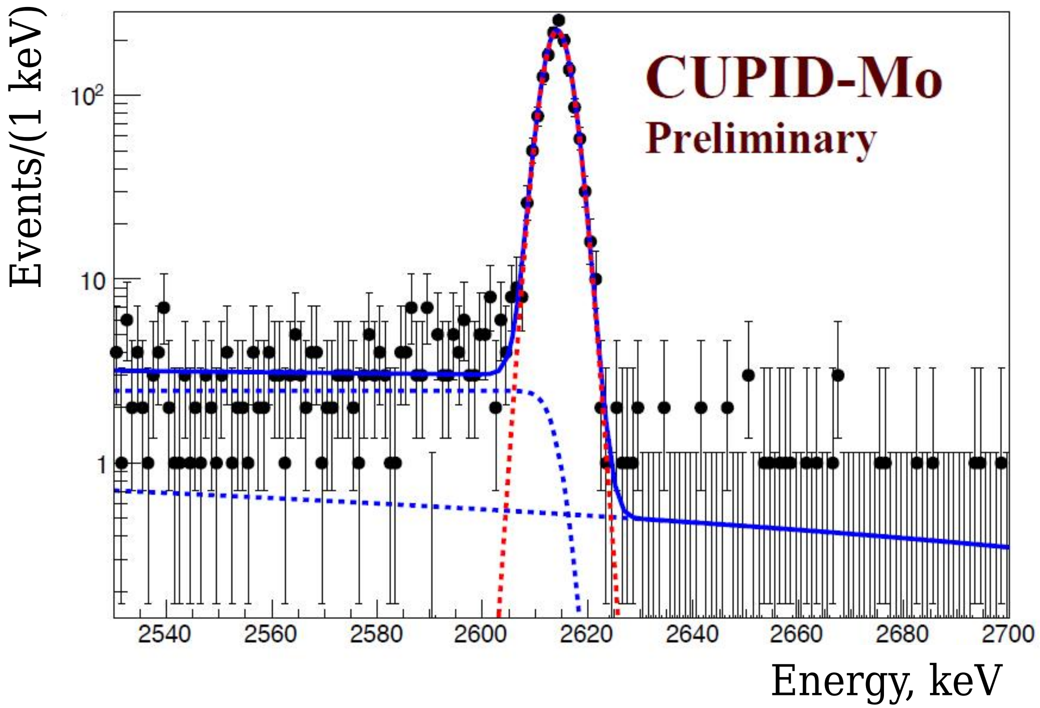
- Excellent internal radiopurity of crystals: ^{210}Po and U/Th well within CUPID requirements

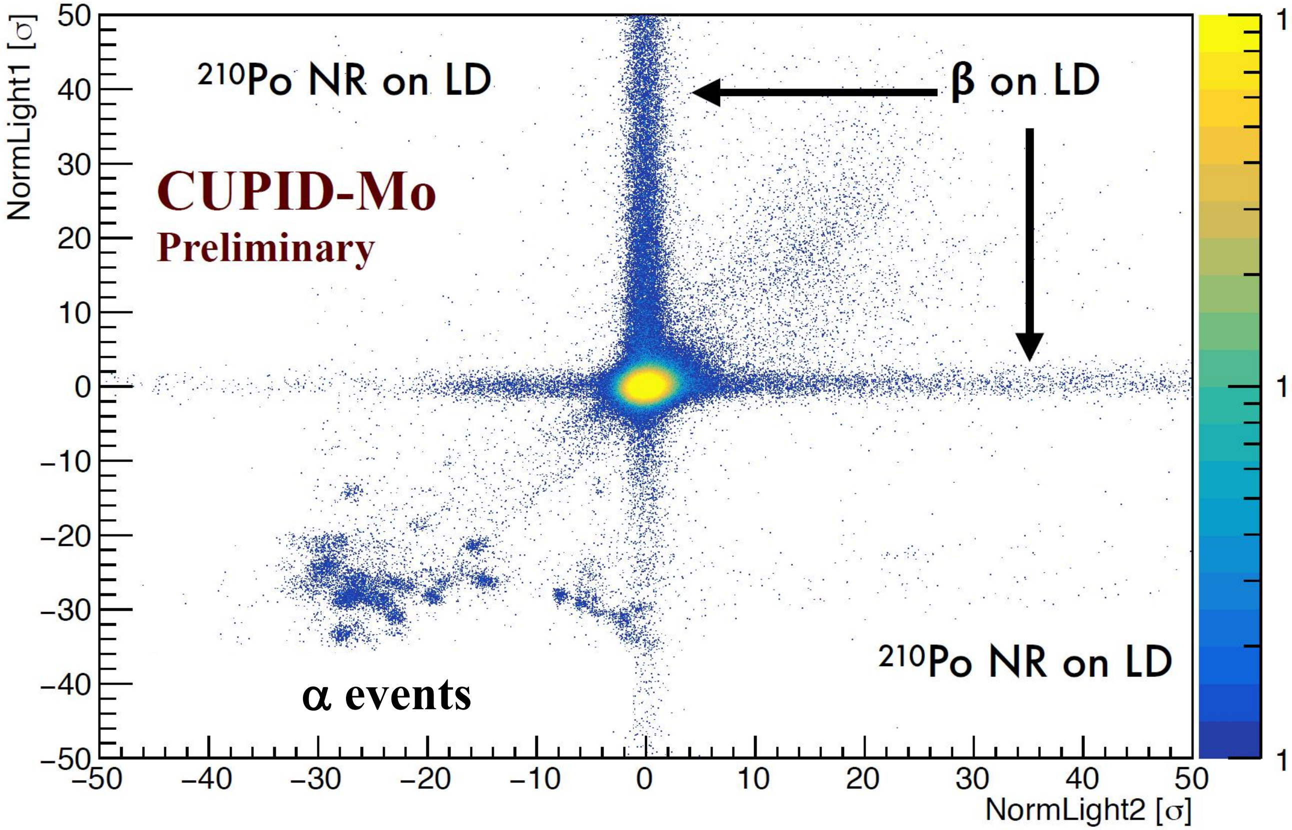




CUPID-Mo features

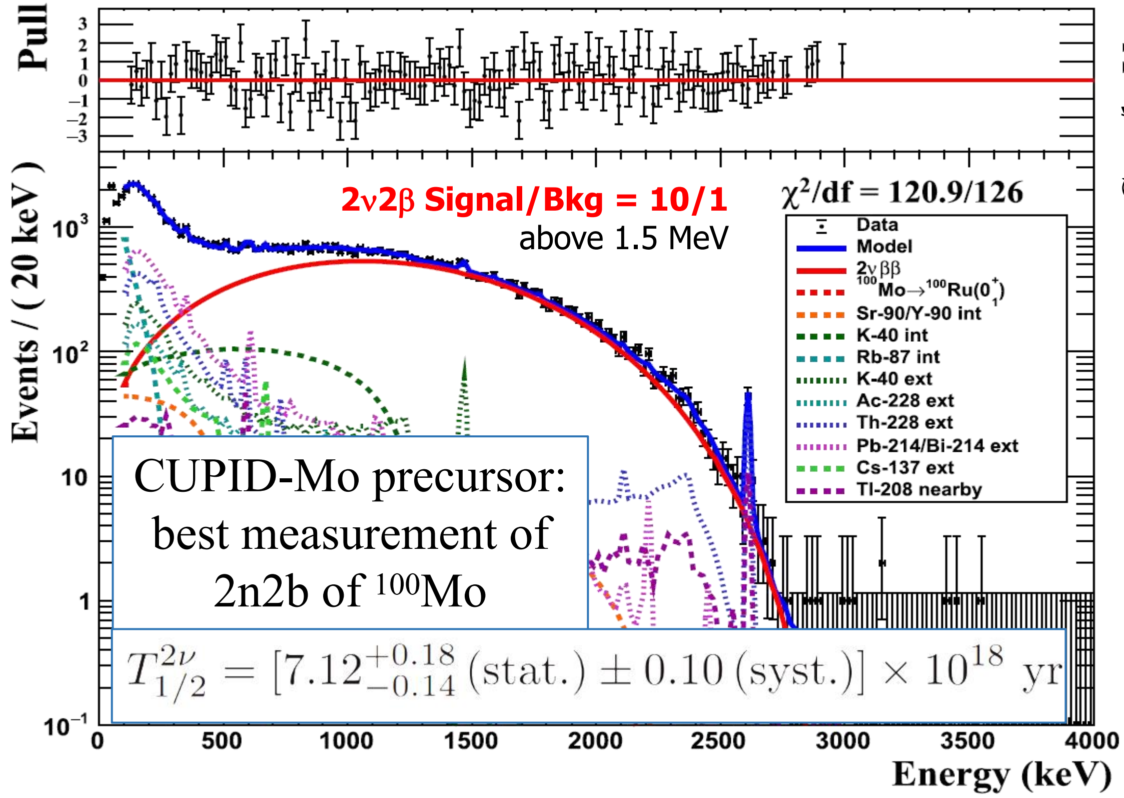
- Excellent internal radiopurity of crystals: ^{210}Po and U/Th well within CUPID requirements
- Anticoincidence, light yield and pulse shape cuts applied for background reduction
- **FWHM @ $Q_{\beta\beta}$=(7.38 ± 0.35) keV**

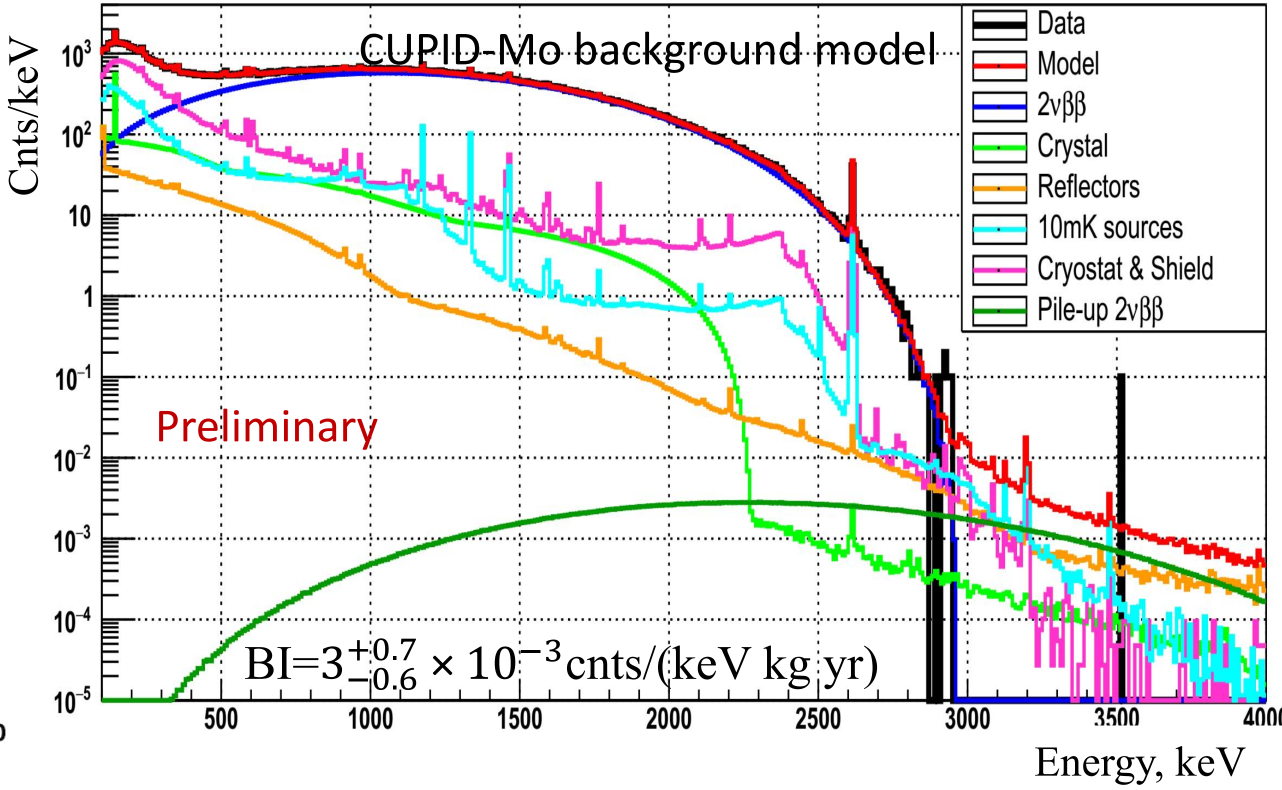




CUPID-Mo results

- Excellent performance and radiopurity - **chosen for ton-scale experiment**
- Best limit on ^{100}Mo 0ν2β half- life, the most precise measurement of ^{100}Mo 2ν2β (new results are expected from full CUPID-Mo) and excited states
- Work in progress: other analyses are under way

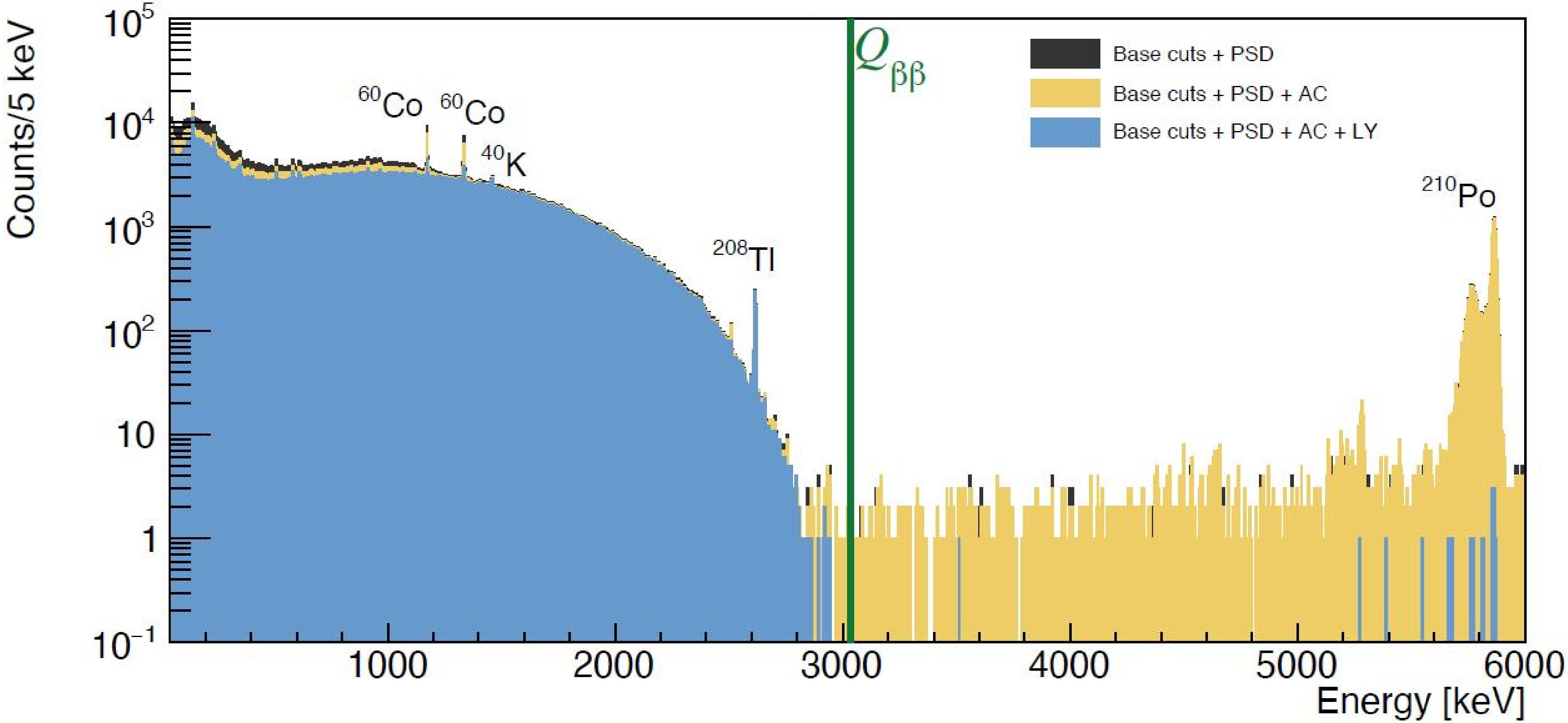




CUPID-Mo results

$T^{0\nu}_{1/2} > 1.8 \times 10^{24} yr$
(90% C. I. limit)
$m_{\beta\beta}$<280-490 meV
2.7 kg×yr

PRL 126, 181892 (2021)
JINST 16 (2021) P03032
EPJC 80, 44 (2020)
EPJC 80, 674 (2020)



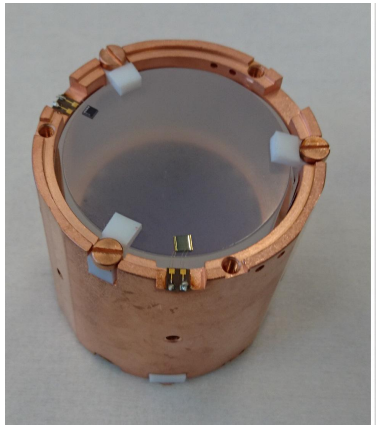
See also posters:

- **202, Zarytsky, Mykola:** Studies of the CUPID-Mo detector performance using a dedicated ^{56}Co calibration
- **369, Welliver, Bradford:** Final Results on the 0νββ Decay Half-Life Limit in ^{100}Mo Using the Full Exposure of CUPID-Mo
- **509, Imbert, Leonard:** *The background model of CUPID-Mo experiment*
- **535, Dixon, Toby:** *Results of the search for resonant absorbtion of ^{7}Li solar axions using the CUPID-Mo data*
- **602, Shmidt, Benjamin:** *First measurement of double beta decays to excited states in the CUPID-Mo experiment*

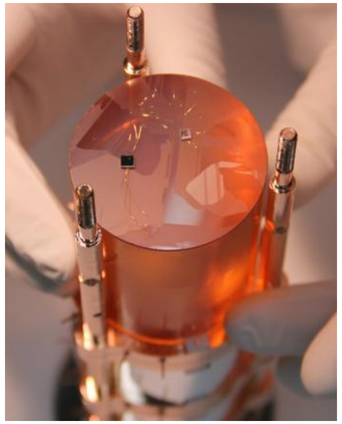
Choice for CUPID

- Both demonstrators have shown excellent perspectives for double beta decay searches with scintillating bolometers: high efficiency, background rejection in ROI, good energy resolution

- Few features pushed the choice towards $Li_2{}^{100}MoO_4$:



- Higher energy resolution (7.4 vs 20 keV)
- Excellent radiopurity (ZnSe crystals have much higher U\Th contamination, ~30 times)
- Easier crystal growth



CUPID: baseline

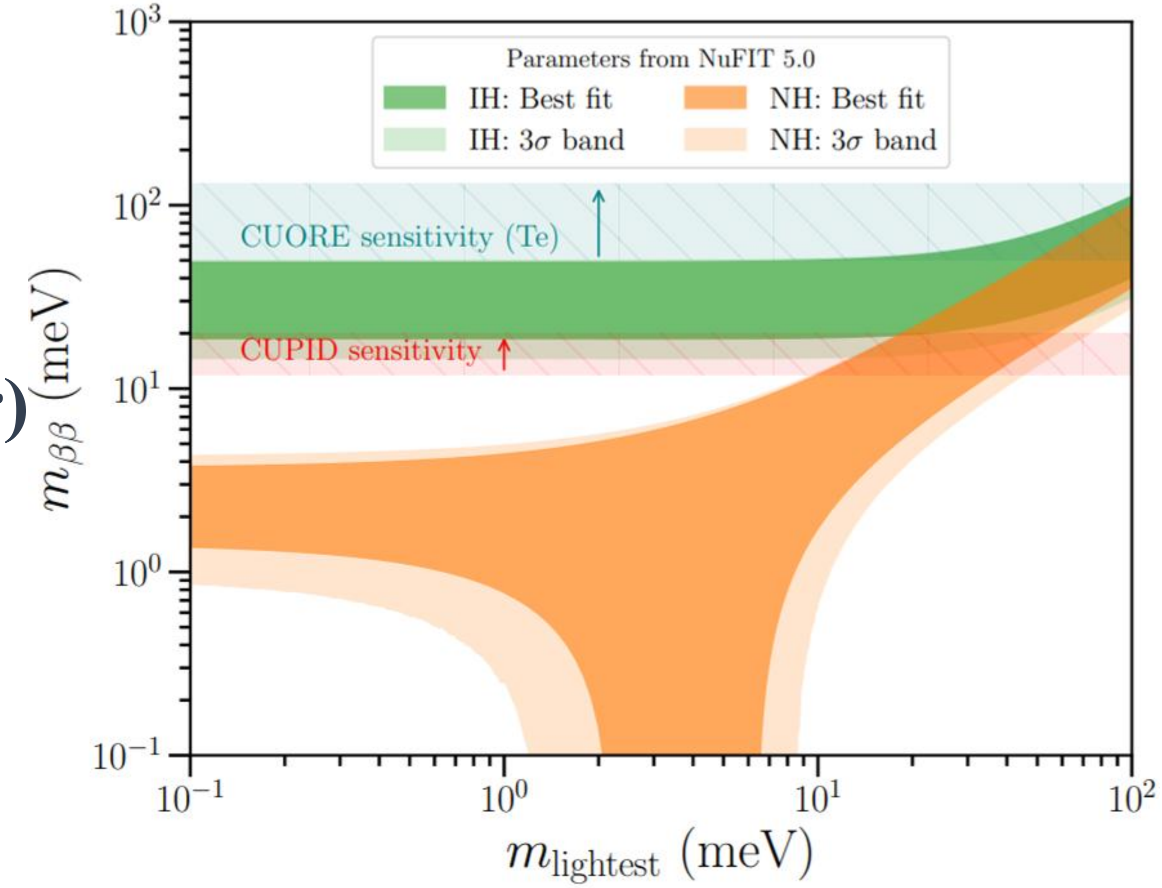
- **$Li_2{}^{100}MoO_4$ scintillating bolometers**
- α rejection using light signal
- Enrichment > 95%
- 1596 crystals and 240 kg of ^{100}Mo
- FWHM <10 keV at $Q_{\beta\beta}$ (3034 keV)

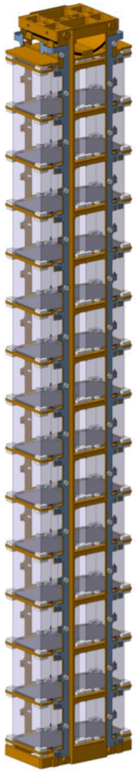
Background goal: 10^{-4} cnts/(keV kg yr)

Discovery sensitivity at 3σ:

$T_{1/2}(^{100}Mo) = 10^{27}$ yr

$m_{\beta\beta}$ ~12-20 meV





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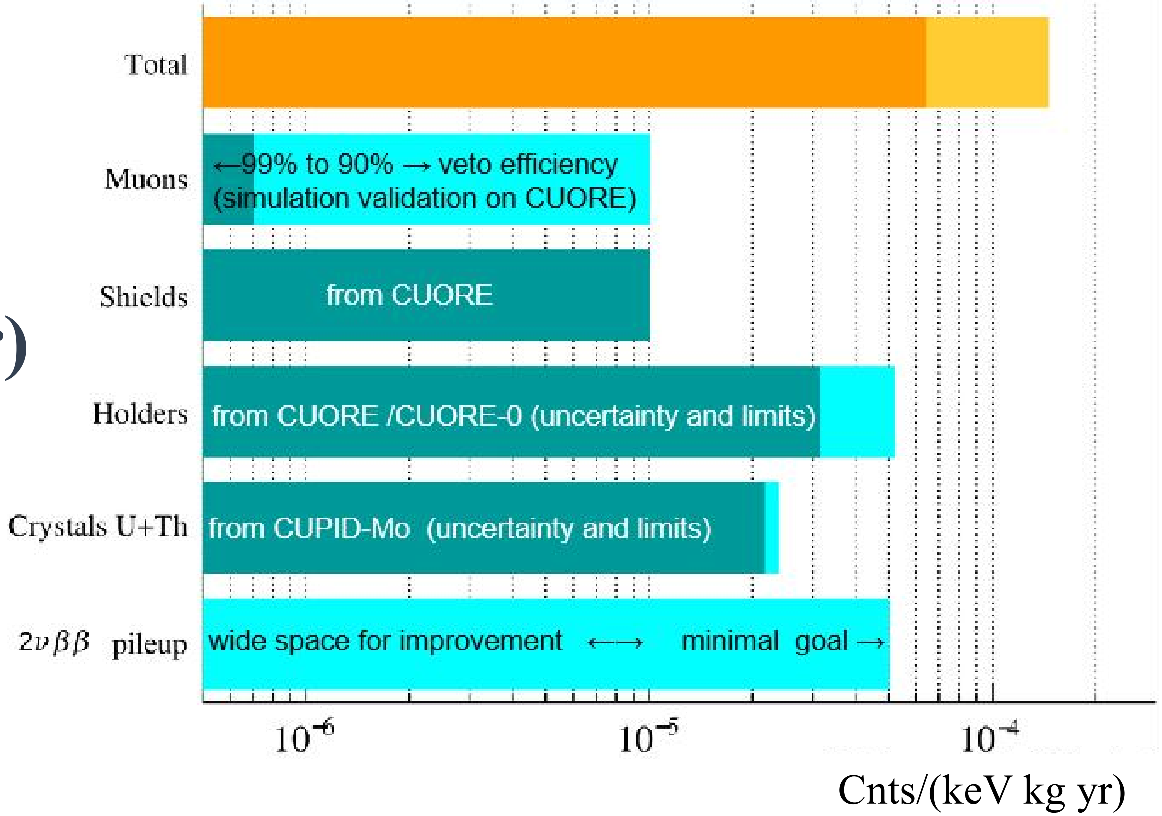
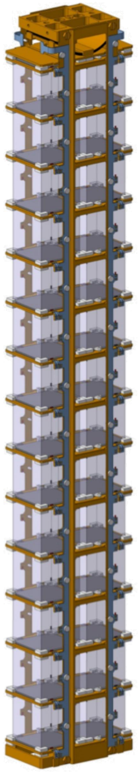
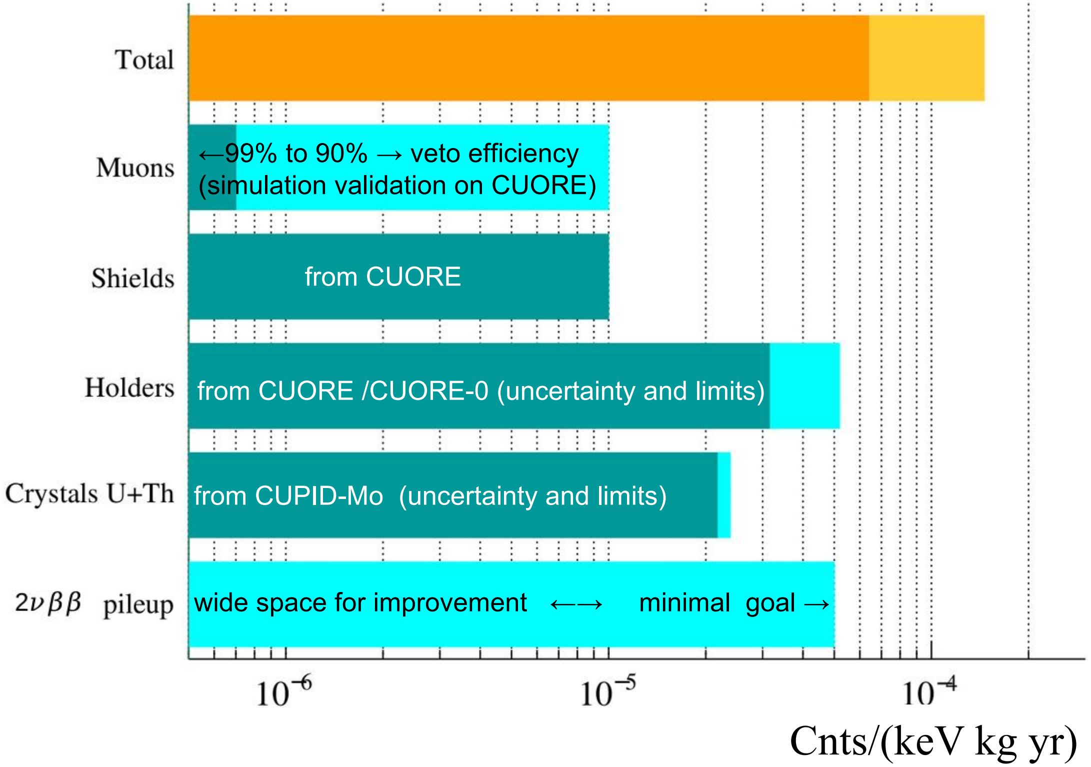




CUPID background model

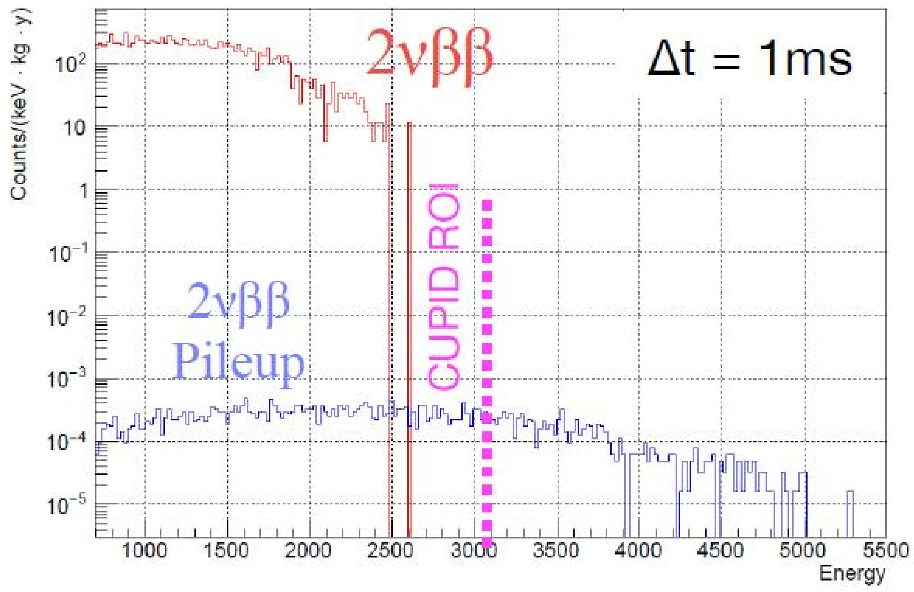
α background effectively eliminated by PID

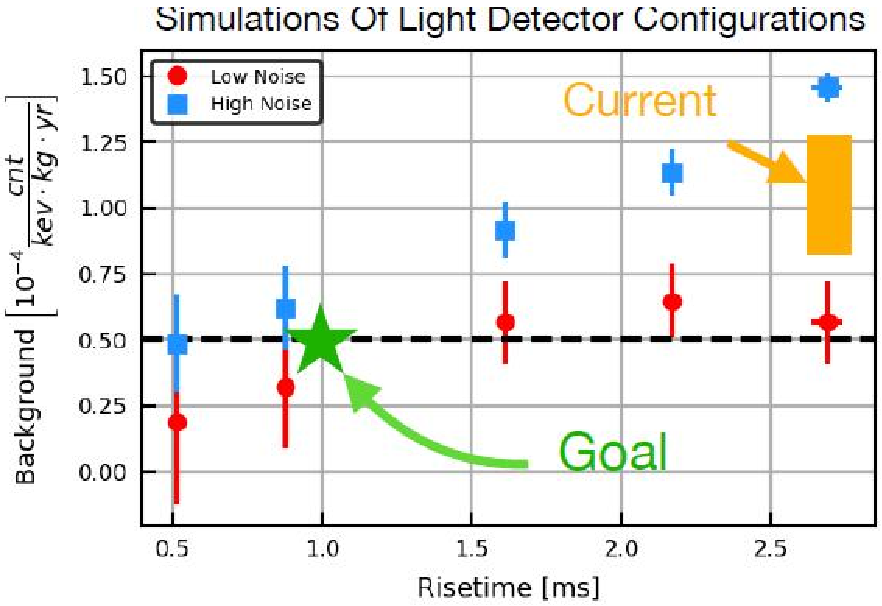


β/γ backgrounds reduced to $< 5\times10^{-5}$ cnts/(keV kg yr):

- Achievable with existing material selection, parts cleaning and handling, cryostat shielding
- Delayed coincidence cuts remove backgrounds from U/Th decay chains

CUPID background model



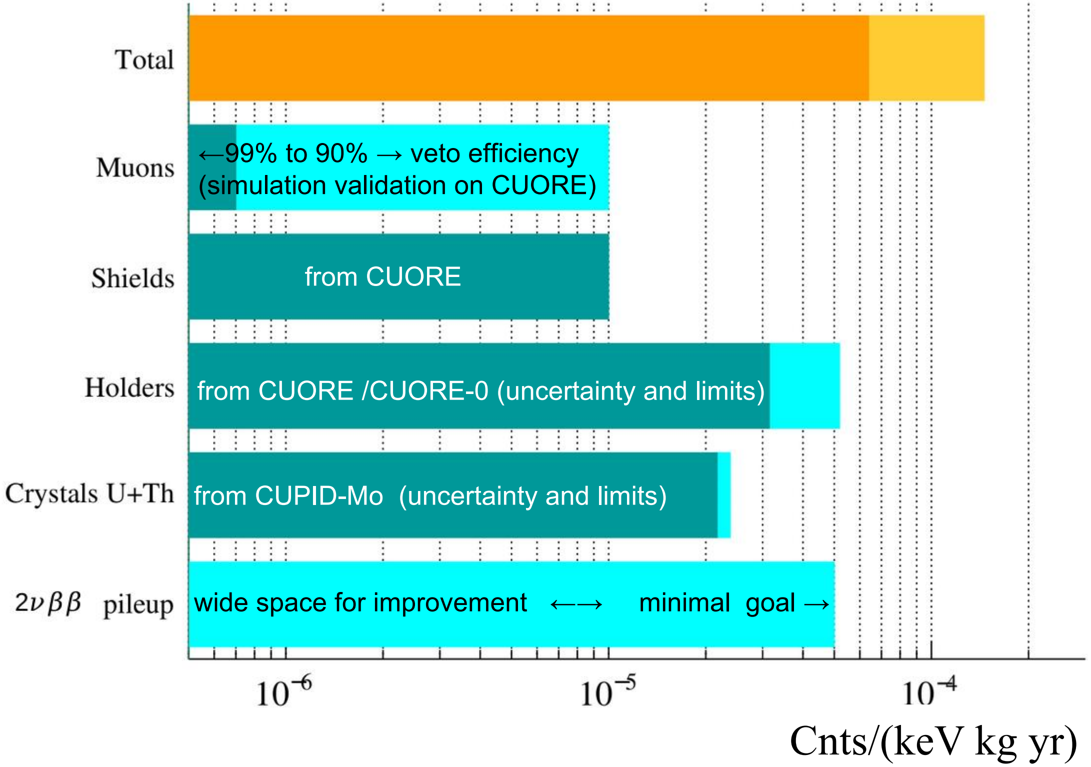


2ν2β decay pileup reduction to
< 5×10^{-5} cnts/(keV kg yr):

- Requires high light detector timing resolution (160 us)
- Higher DAQ dynamic range and sampling rate, lower noise, new NTDs, machine learning techniques
- Requires hardware improvements of factor of ~2 on light detectors

CUPID background model

α background effectively eliminated by PID



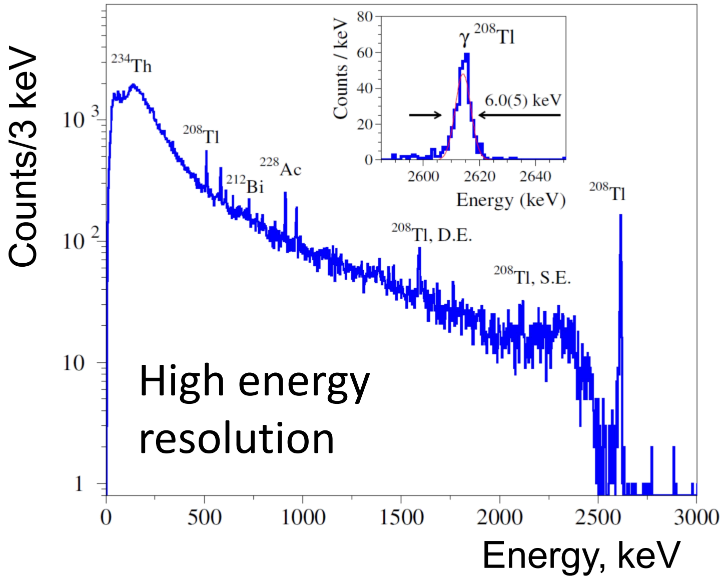
Muons reduced by an order of magnitude:

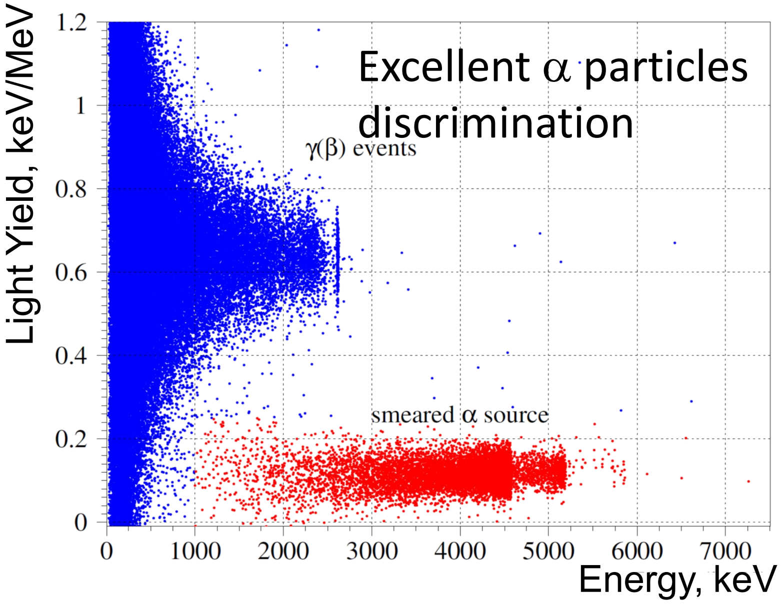
- Muon veto system with >90% geometric efficiency

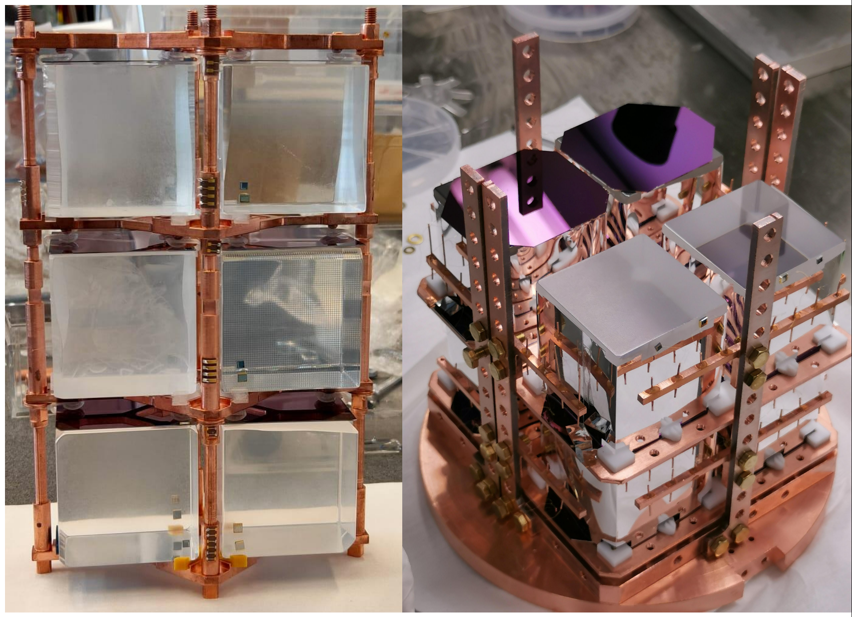
CUPID: R&D

- Series of cryogenic tests at LNGS and LSC performed to define the final **structure of CUPID**
- Maximally effective use of experimental space
- Studies of pile-up rejection: both synthetic and induced pulses used for analysis

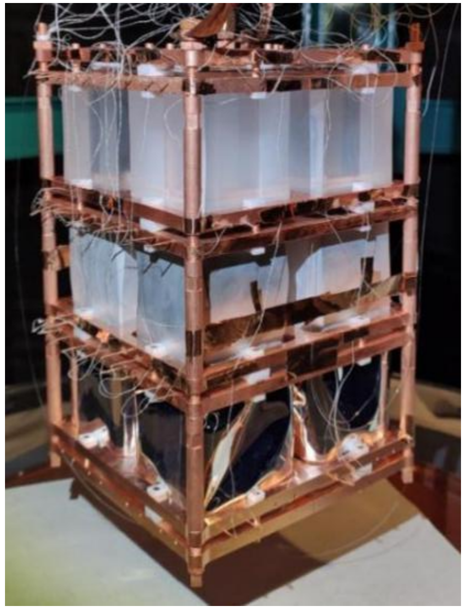
Eur. Phys. J. C (2021) 81: 104
JINST 16 (2021) P02037
arXiv:2011.11726
arXiv:2202.06279



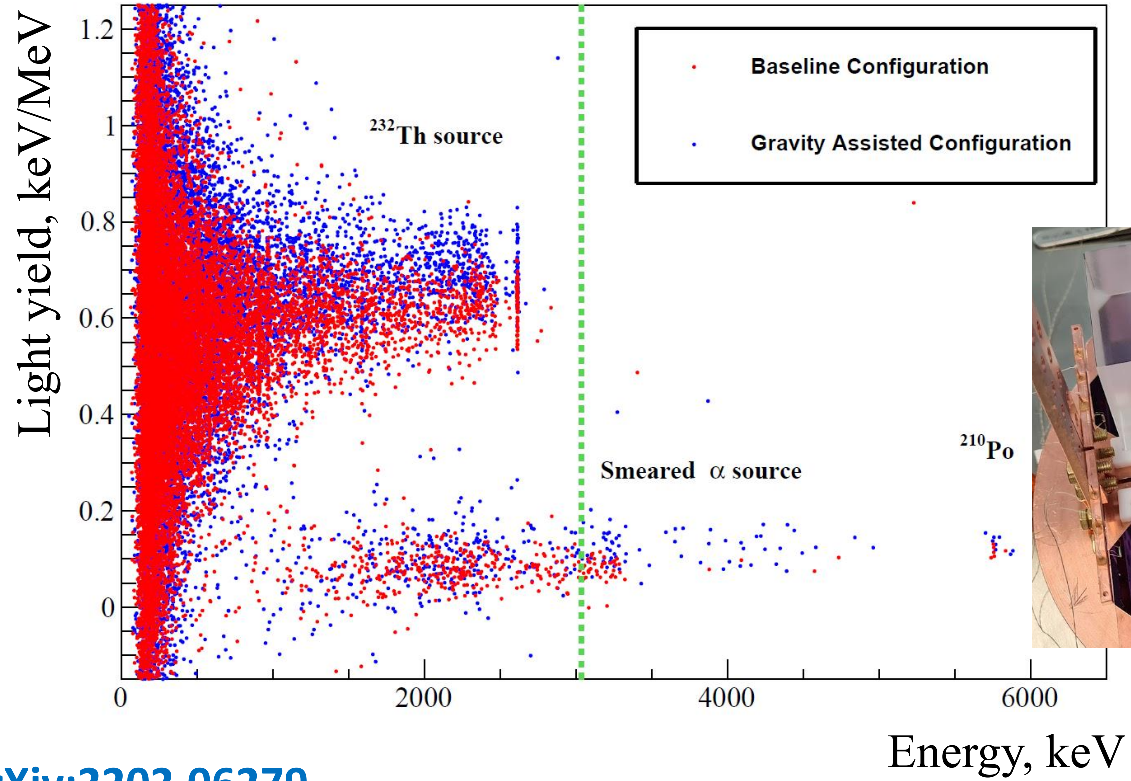


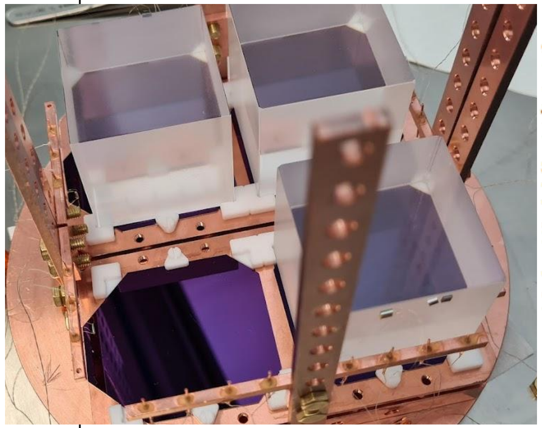


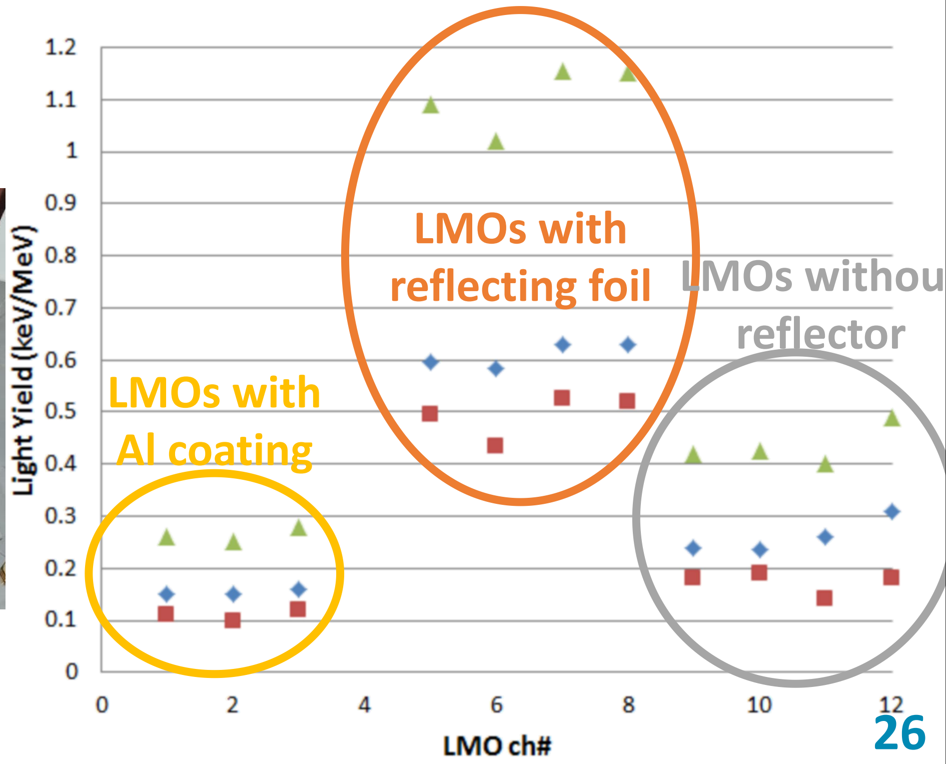
CUPID: light collection studies



- Light yield comparison leads to rejection of reflecting foil - lower background with sufficient light yield for α discrimination
- Optimisation of the detector structure to maximise the light collection



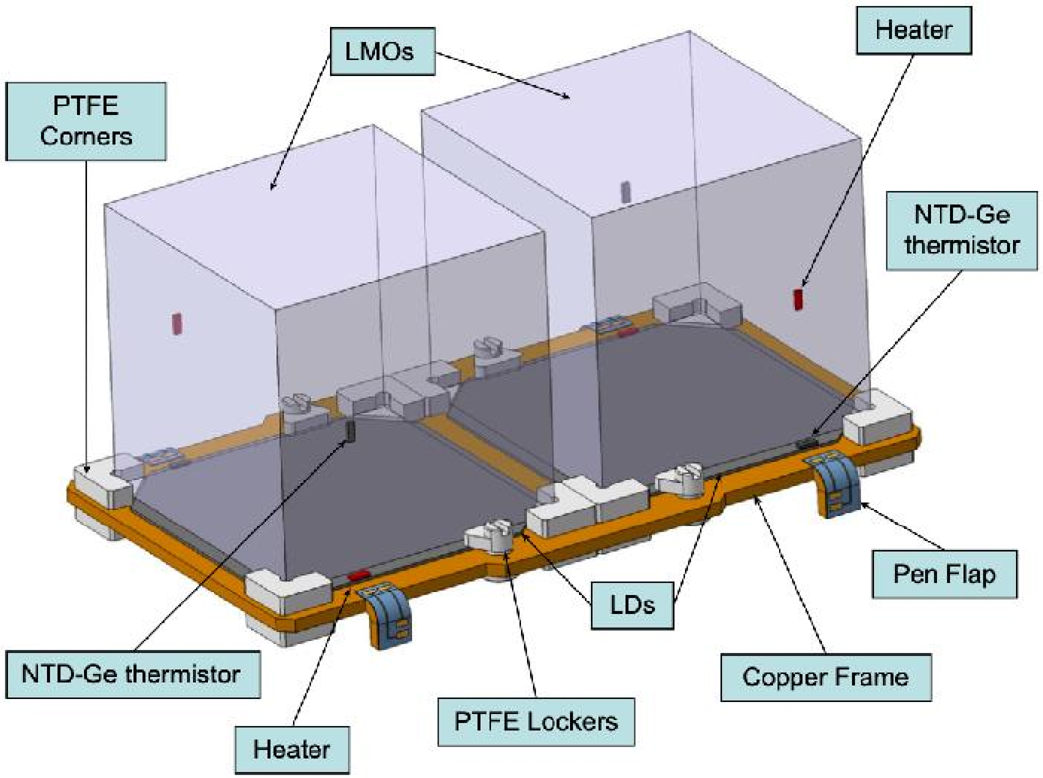


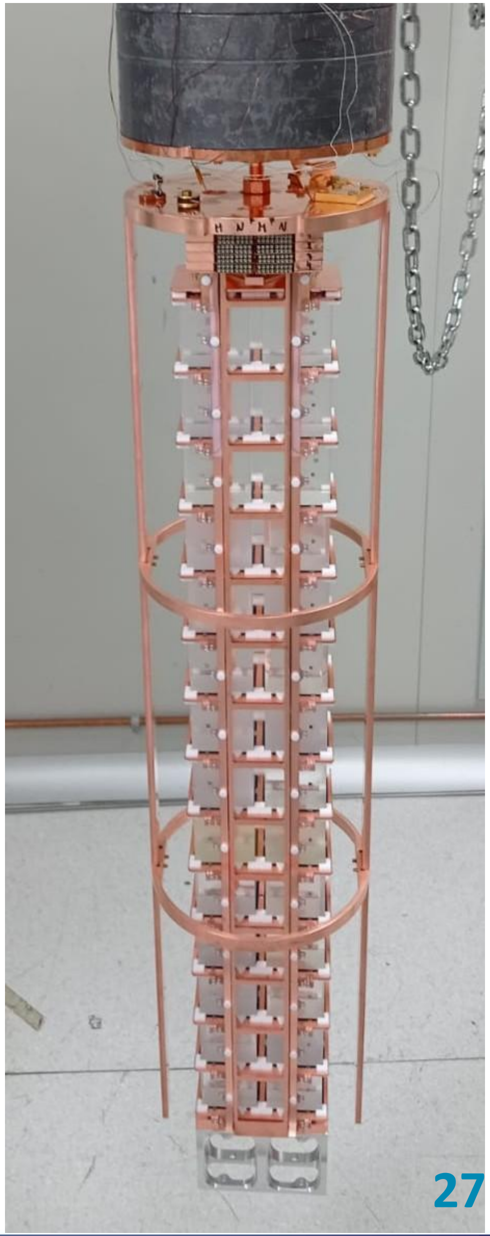


arXiv:2202.06279

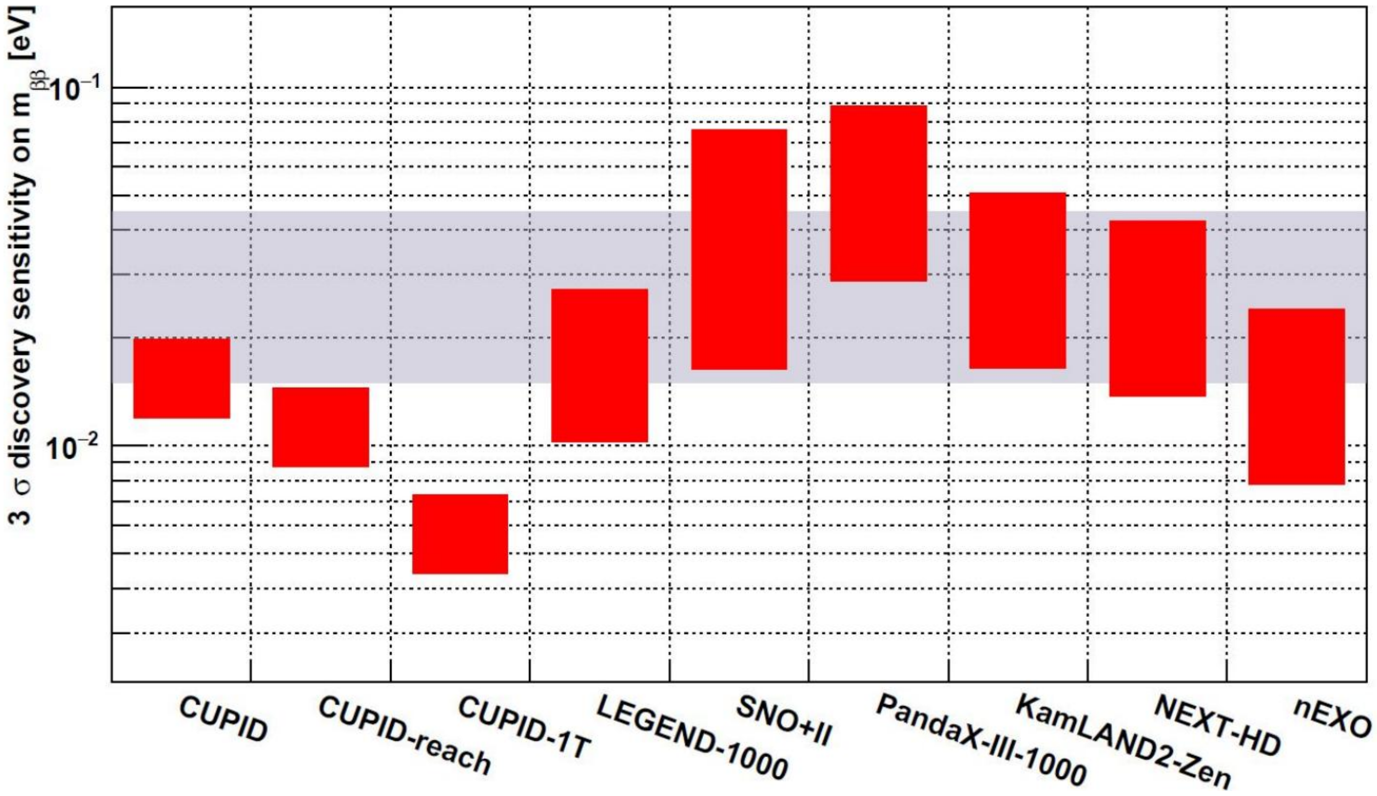
CUPID: single tower measurement

- The tower with 28 crystals and 30 light detectors is in the cryostat at LNGS
- Validation of the CUPID detector structure and performance
- New exciting results coming soon!





CUPID sensitivity



- CUPID: Exactly what we start building: **10^{-4}** cnts/keV/kg/yr
- CUPID-reach: improvements before construction: **2×10^{-5}** cnts/keV/kg/yr
- CUPID-1T: 1 ton ^{100}Mo in new cryostat: **5×10^{-6}** cnts/keV/kg/yr

Conclusions

- Bolometers are a very **flexible and highly competitive technology** for 0ν2β decay search:
  - Extremely good energy resolution, flexible choice of isotope, high efficiency, efficient α background rejection
- CUPID-0 and CUPID-Mo demonstrated the advantage of scintillating bolometers:
  - The **most precise measurements** of 2ν2β for both ^{82}Se and ^{100}Mo;
  - The **best limits on 0ν2β** for both ^{82}Se and ^{100}Mo;
- **CUPID-Mo technology** with scintillating Li_2MoO_4 bolometers to be applied for CUPID:
  - **High energy resolution, high radiopurity** of detectors
- CUPID will use infrastructure of CUORE, the largest bolometric array ever built:
  - Established and **well understood infrastructure and environment**, cost effective, **stable and reliable operation** over multiple years of exposure
- CUPID is recognised as the next generation experiment with high potential:
  - **Data driven** background model based on CUORE, CUPID-0, and CUPID-Mo experiments
  - Projected background index **of 10^{-4} cnts/(keV kg yr)**
  - Probe the full Inverted Hierarchy down to **$m_{\beta\beta}$ of 12 meV** (3σ, favorable NME) with only **240 kg of ^{100}Mo**

Conclusions

- Bolometers are a very **flexible and highly competitive technology** for 0ν2β decay search:
  - ➢ Extremely good energy resolution, flexible choice of isotope, high efficiency,

See also posters:
- **091, Capelli, Chiara:** *Pileup rejection studies for the CUPID experiment*
- **165, Celi, Emanuela:** *Searching for New Physics in two-neutrinos Double Beta Decay with CUPID*
- **249, Fu, Shihong:** *The CUORE cryostat: current performance and future upgrade towards CUPID*
- **291, Hansen, Erin:** *CUPID, CUPID-1T and the DEMETER Demonstrator*
- **368, Singh, Vivek:** *Optical photon detectors for CUPID using Transition-Edge Sensors*
- **204, Torres, Jorge:** *Mitigation of cosmogenic muon-induced backgrounds for the CUPID experiment*

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