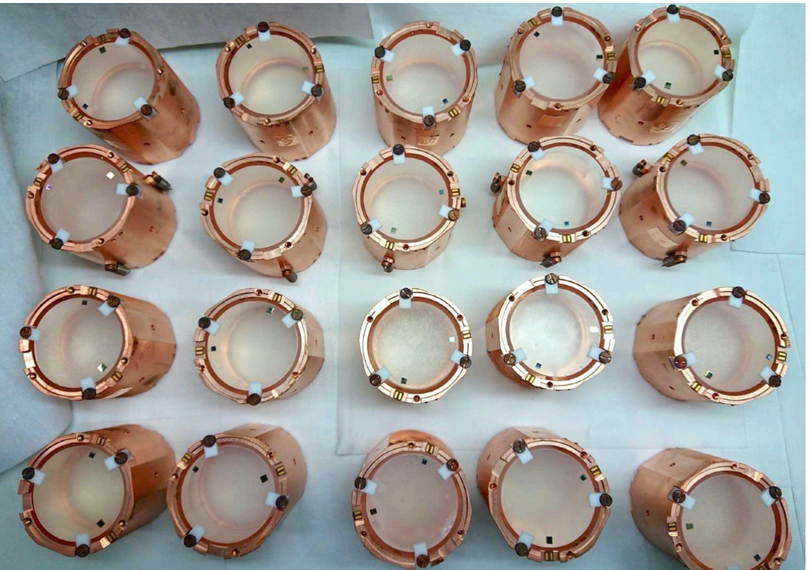
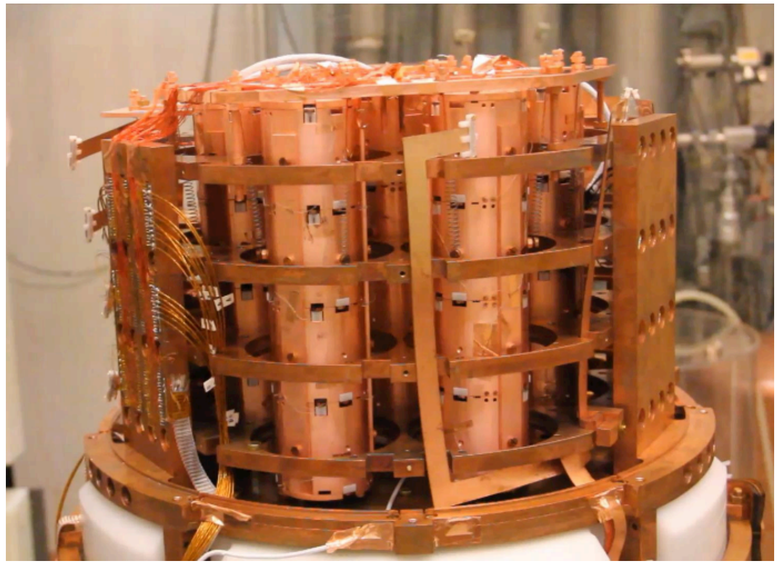
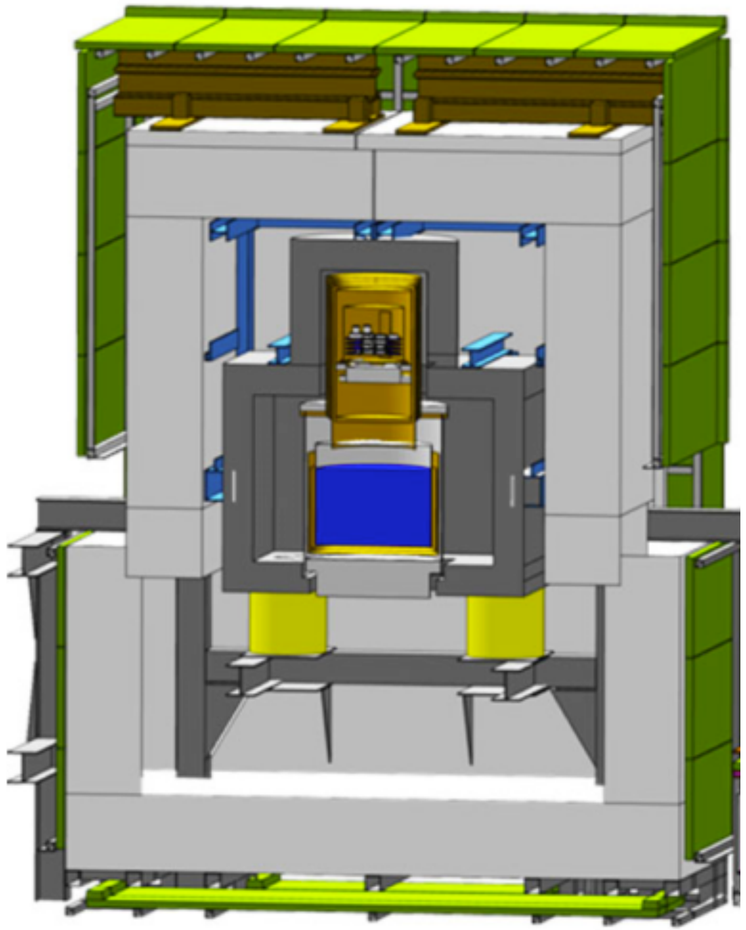
Lawrence Berkeley National Laboratory - 06/20/2020

A new limit on $0\nu\beta\beta$-decay of ^{100}Mo from the CUPID-Mo demonstrator for CUPID

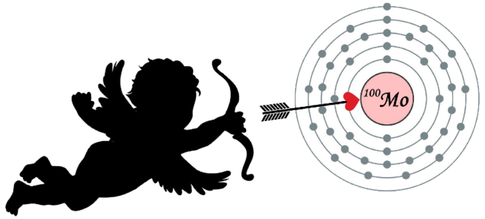
Benjamin Schmidt (CUORE, CUPID/CUPID-Mo)







Single beta decay and the neutrino



Wolfgang Pauli,
“Letter to the radioactive ladies and gentlemen”,
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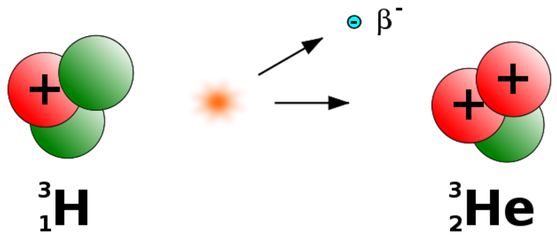
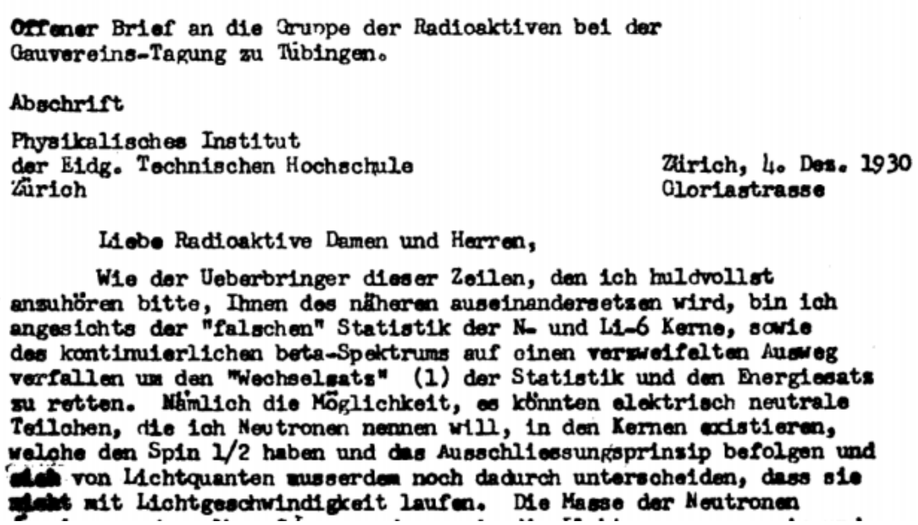




Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

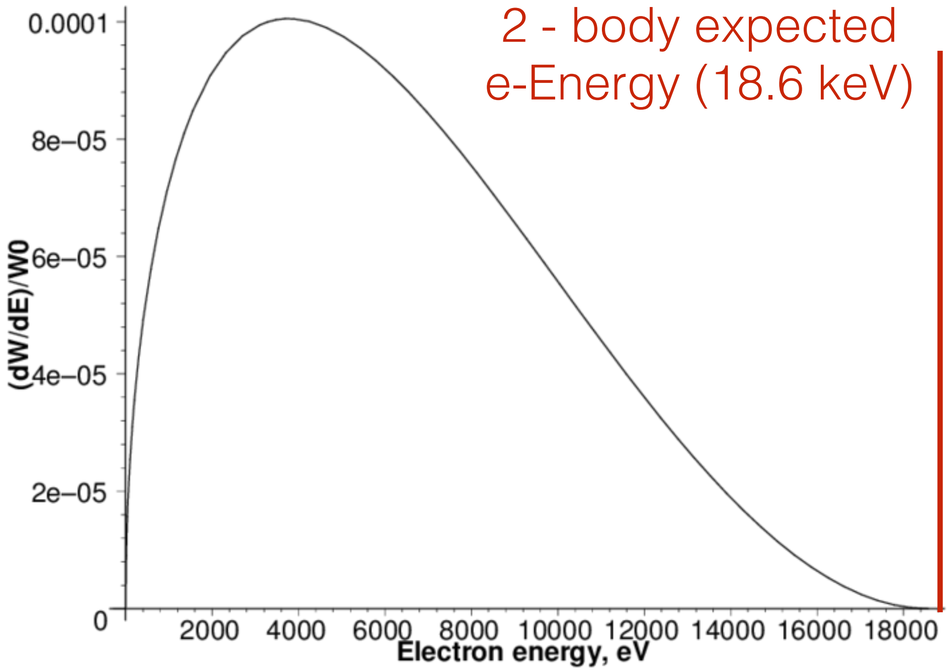
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

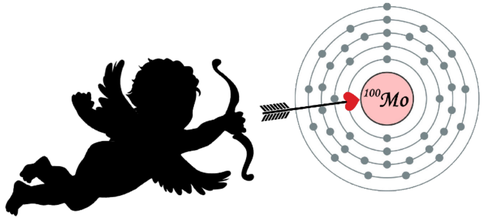
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen



Phys. Lett. B 590 (2004) 35-38

Single beta decay and the neutrino



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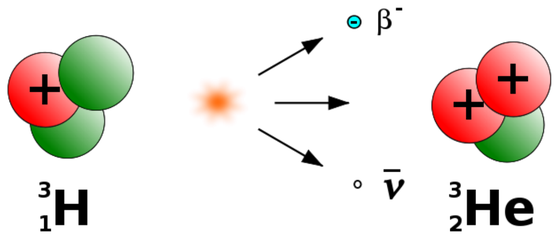

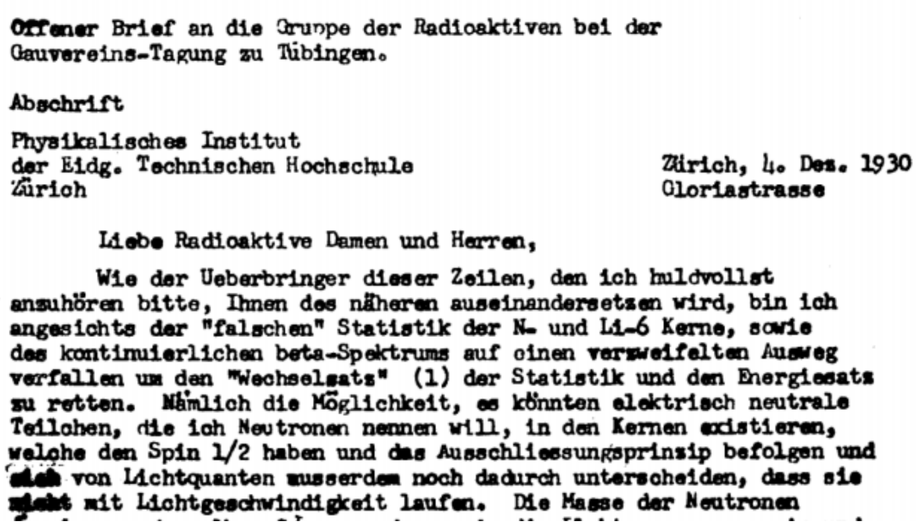

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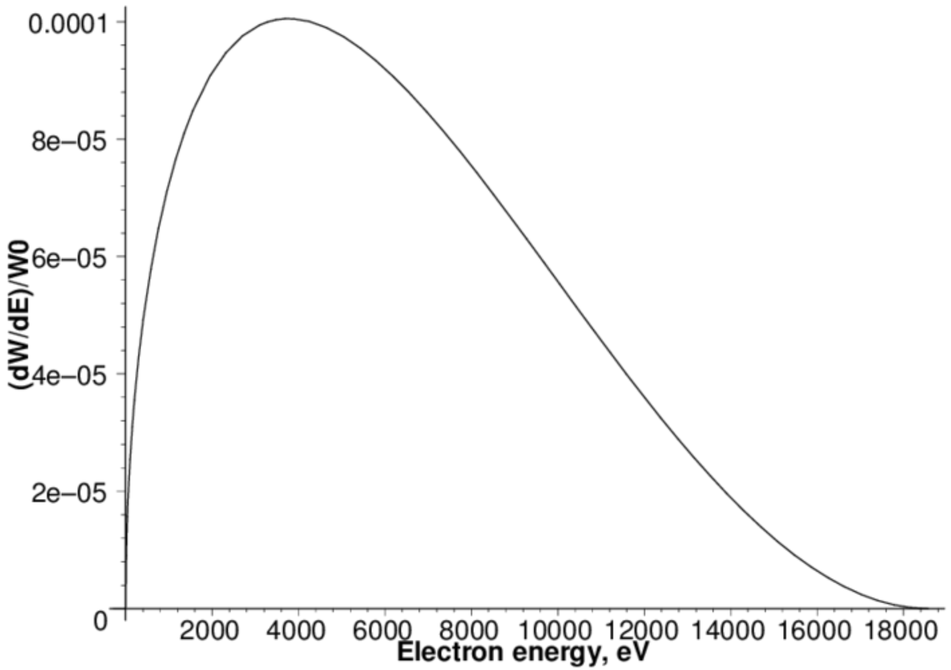
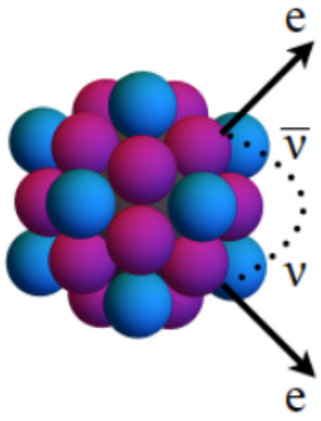
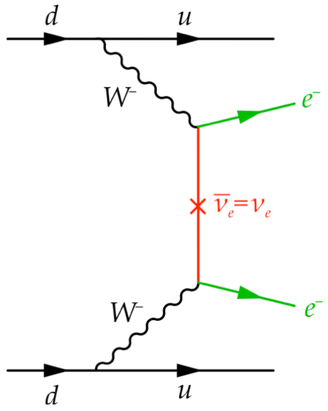


Phys. Lett. B 590 (2004) 35-38

Neutrinoless double beta decay
Light Majorana neutrino exchange

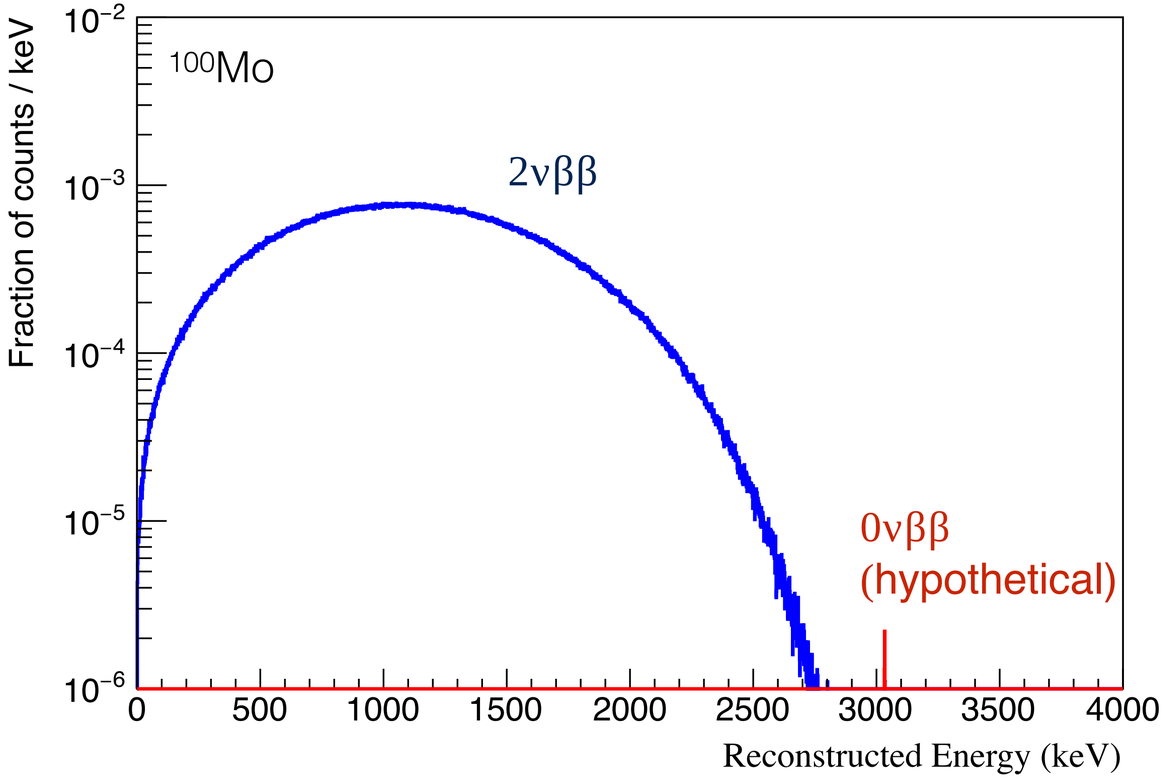




$$(T_{1/2}^{0\nu\beta\beta})^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Effective Majorana mass:

$$\langle m_{\beta\beta}\rangle^2 = \left|\Sigma_{i=1,2,3} U_{e,i}^2 m_i\right|$$



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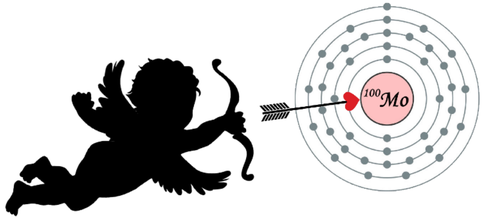
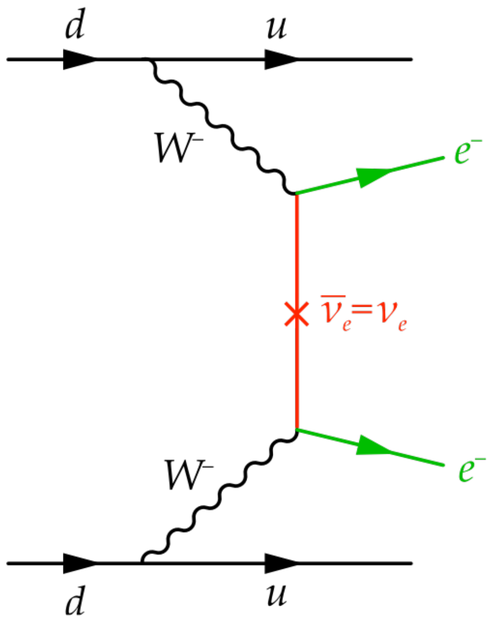
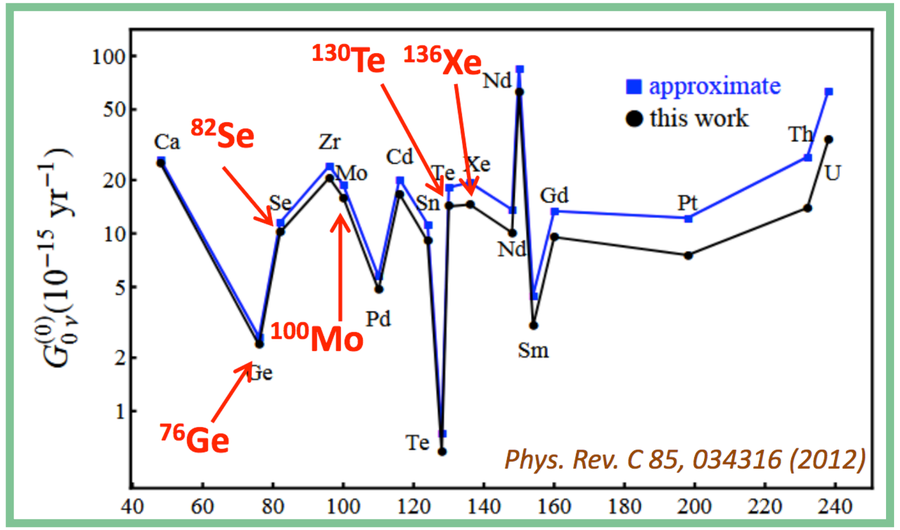


$$(T^{0\nu\beta\beta}_{1/2})^{-1} = G^{0\nu} \, |M^{0\nu}|^2 \, \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

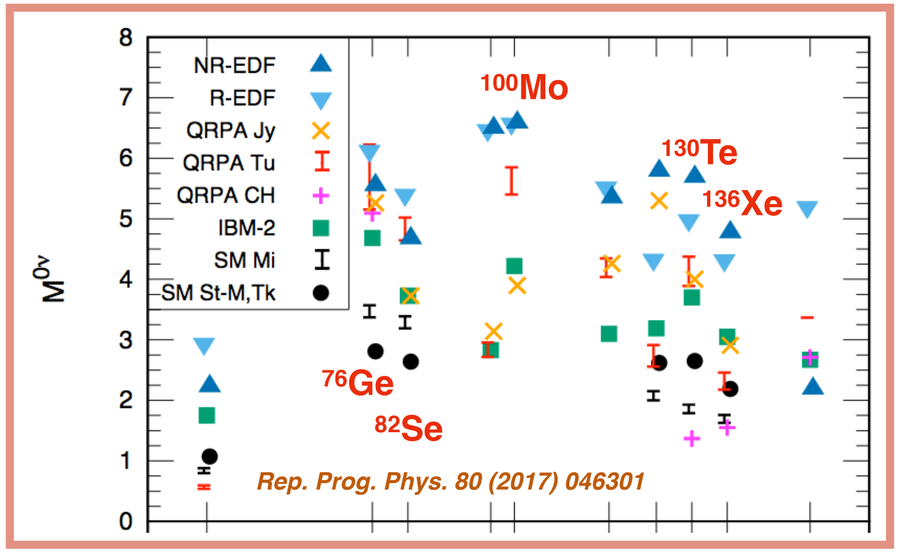
Effective Majorana mass
$\langle m_{\beta\beta}\rangle^2 = |\Sigma_{i=1,2,3} U^2_{e,i} m_i|$

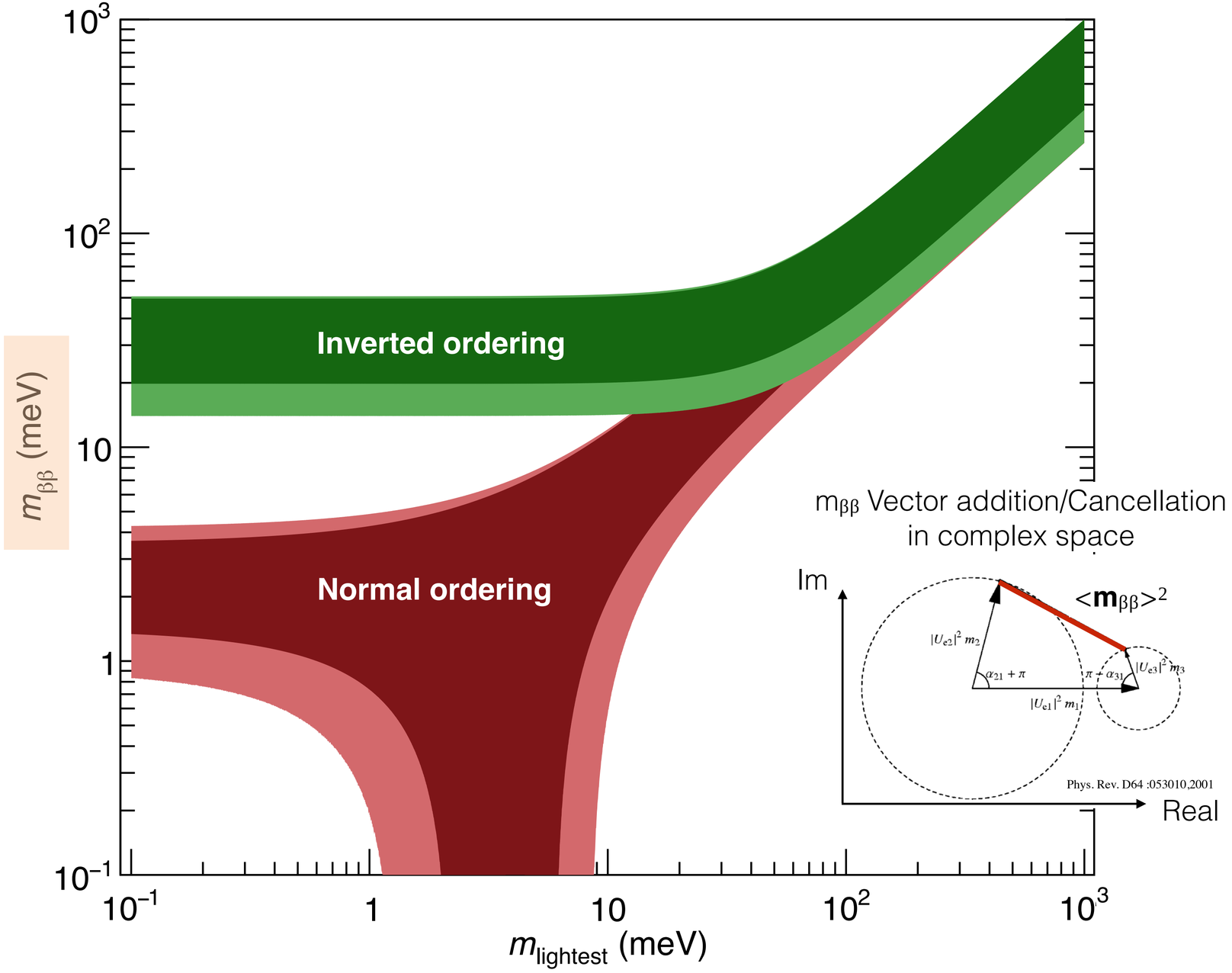


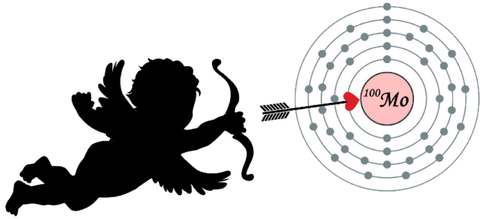
Phase space

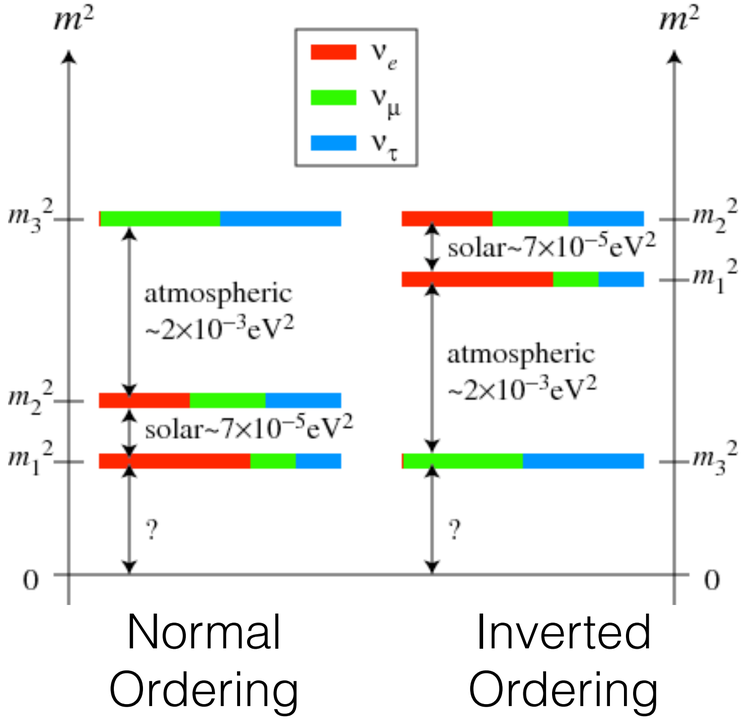


Nuclear Matrix Element (NME)

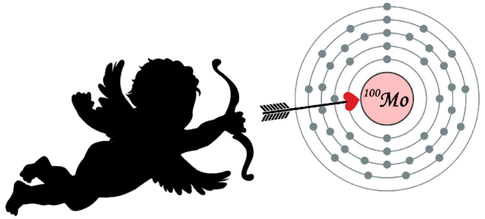



Inverted ordering
Normal ordering
$m_{\beta\beta}$ (meV)
$m_{lightest}$ (meV)
10^{-1}
1
10
10^2
10^3
mββ Vector addition/Cancellation in complex space
Im
Real
<mββ>2
$|U_{e2}|^2 m_2$
$|U_{e1}|^2 m_1$
$|U_{e3}|^2 m_3$
$\alpha_{21} + \pi$
$\pi - \alpha_{31}$
Phys. Rev. D64 :053010,2001

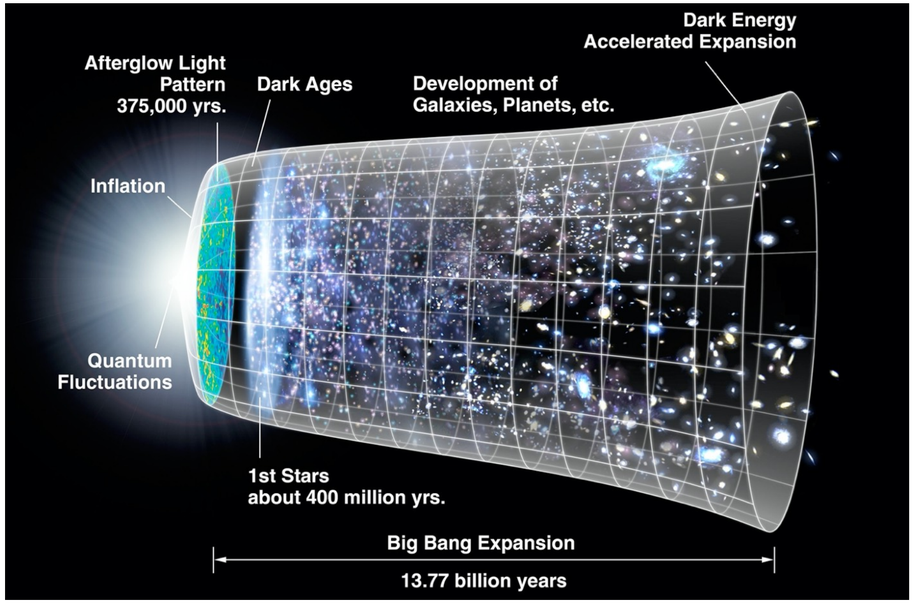

^{100}Mo


m^2
ν_e
ν_μ
ν_τ
m_3^2
m_2^2
m_1^2
0
atmospheric ~2×10^{-3}eV^2
solar~7×10^{-5}eV^2
?
Normal Ordering
Inverted Ordering

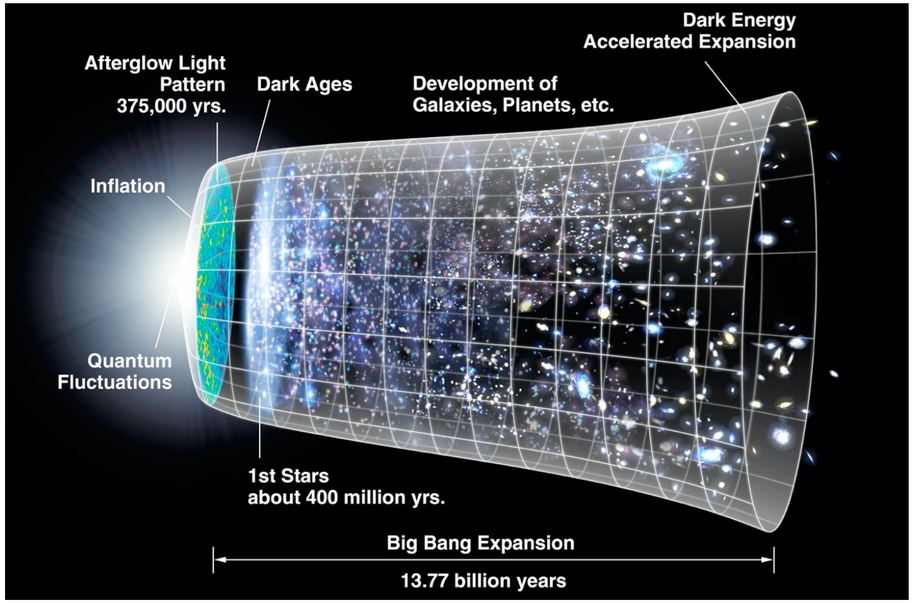
The experimental challenge



Probe a process with a half-life larger > 10^{25} yr - 10^{26} yr



x



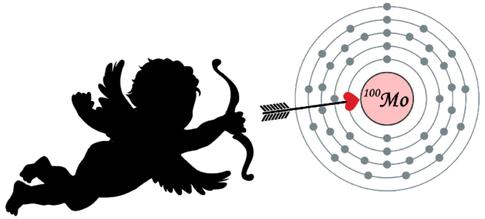
x 10^5 yr

15 Bq / banana

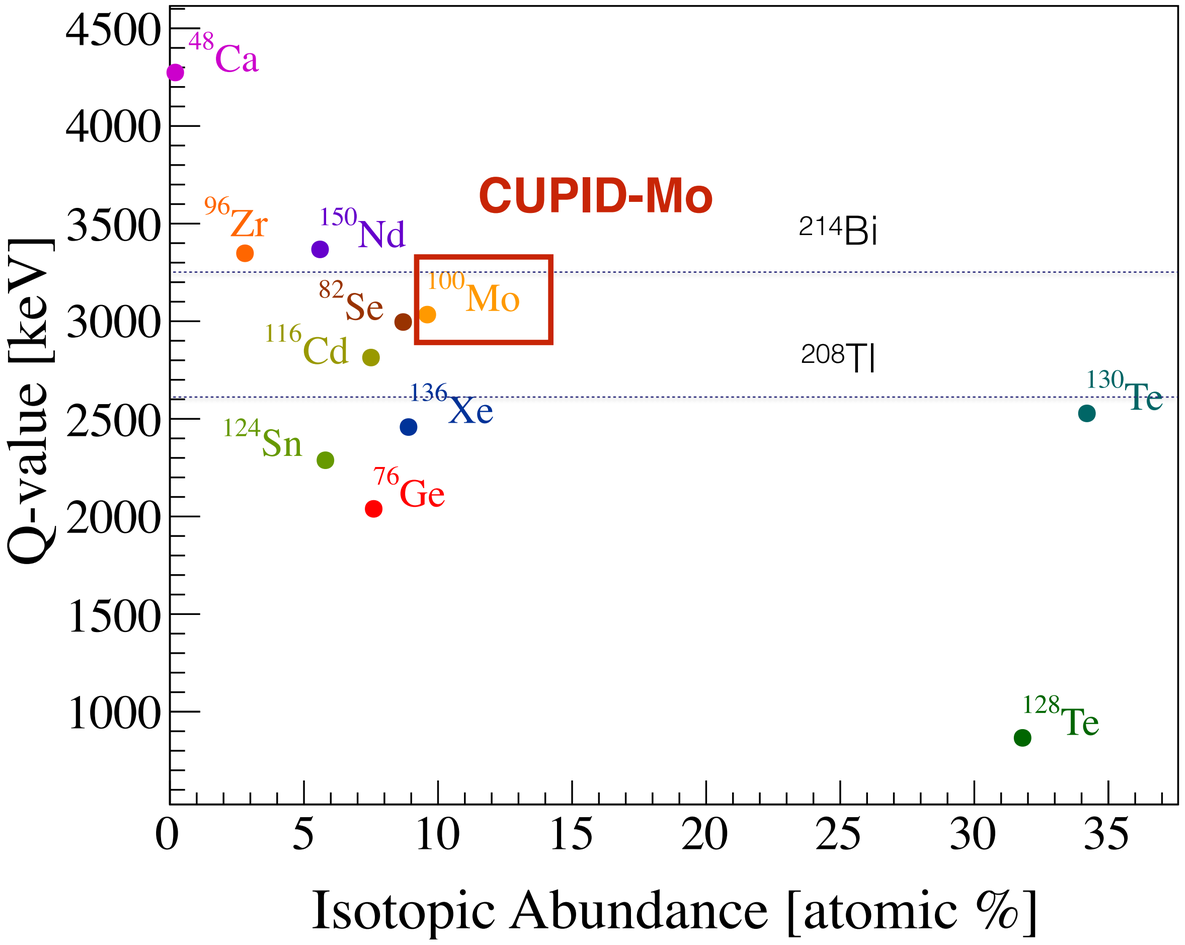
Next generation:
Need to find single events in a ton of isotope x year(s) of exposure!
3 x 10^{-14} Bq/g

We go to extreme length to limit ubiquitous radioactivity

Experimentally considered $0\nu\beta\beta$ isotopes



11 / 35 experimentally considered candidate isotopes

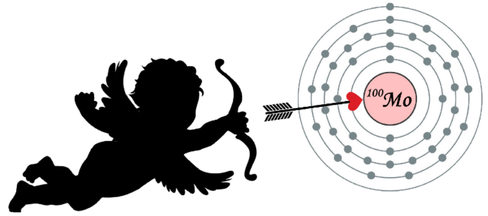


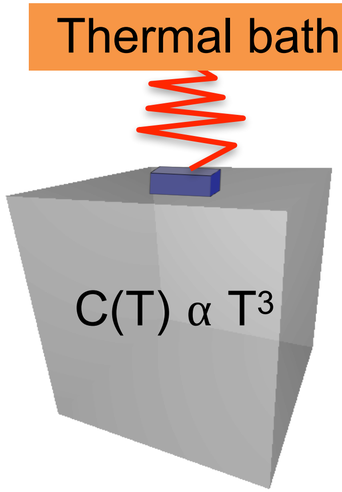
Isotope choice considerations:

high Q-value (3034 keV) -> large phase space, typically low natural radioactivity backgrounds

Backgrounds
-> improve signal/background through good energy resolution
-> dedicated Background suppression/particle ID

Scintillating cryogenic Li_2MoO_4 calorimeters

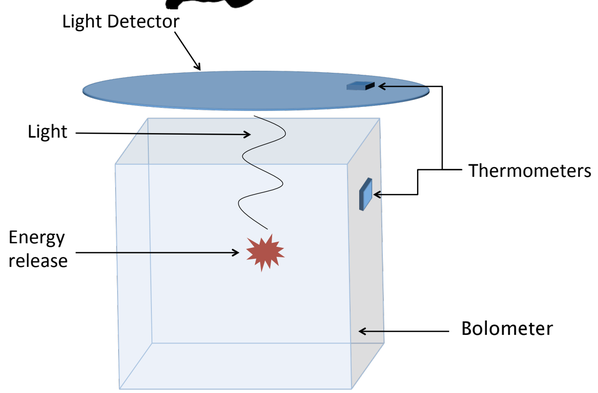




NTD-Ge thermistor as sensor

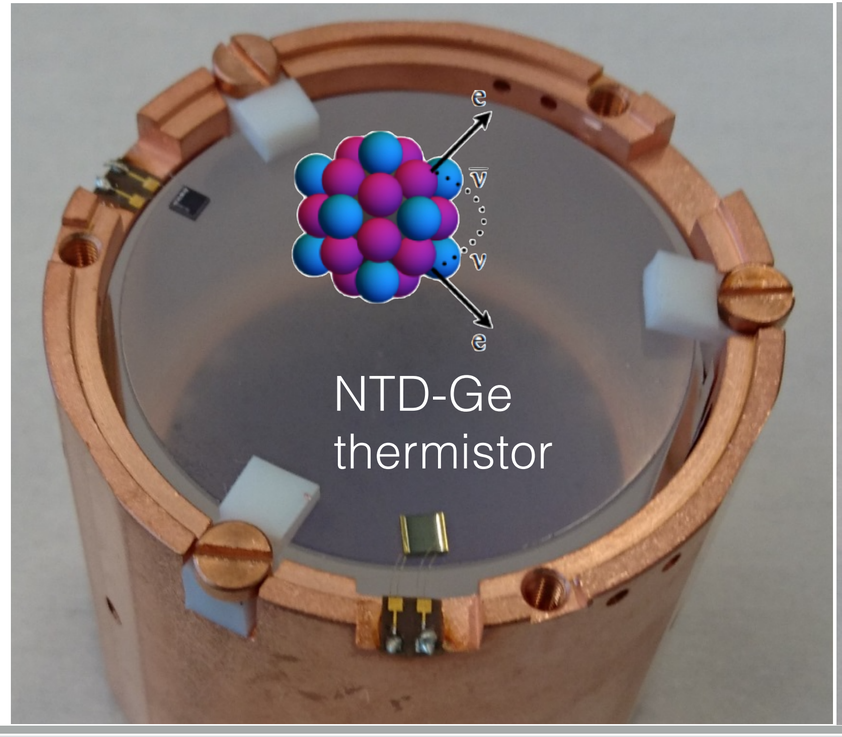
$$R(T) = R_0 e^{\sqrt{T_0/T}}$$

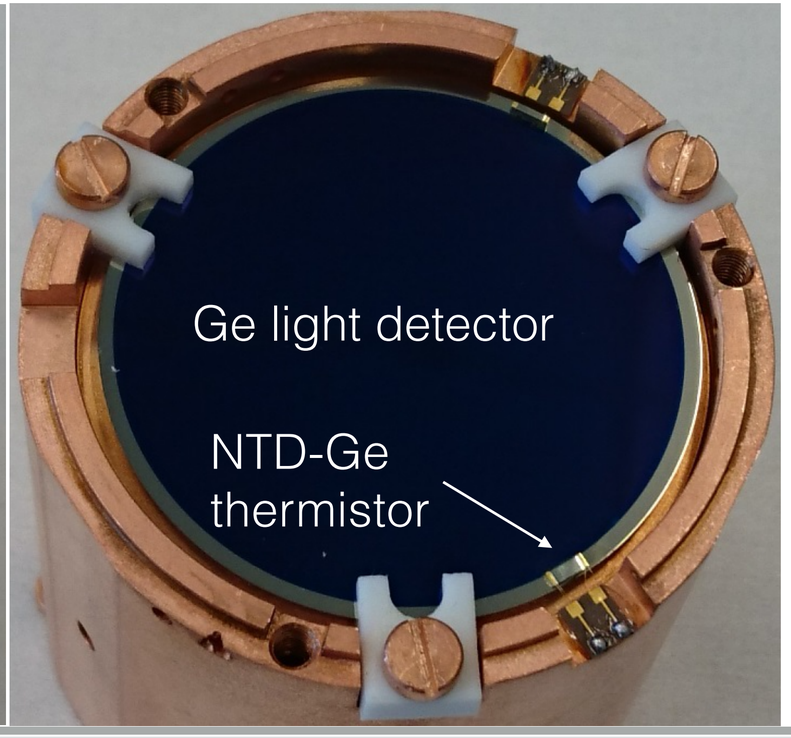
Source ^{100}Mo = Detector Li_2MoO_4 high efficiency



Teflon: weak thermal link

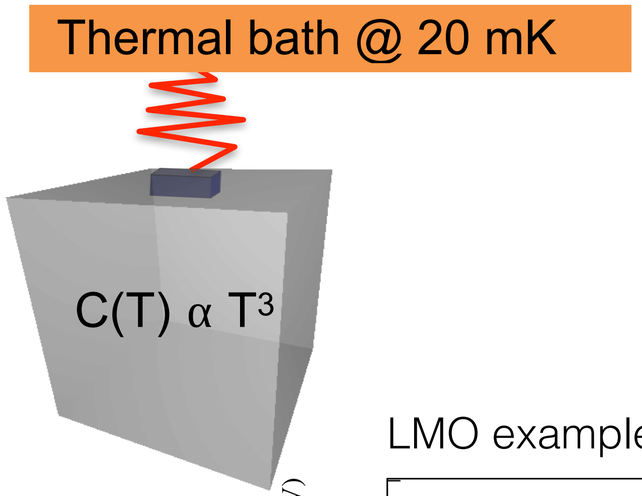
Copper: Thermal Bath

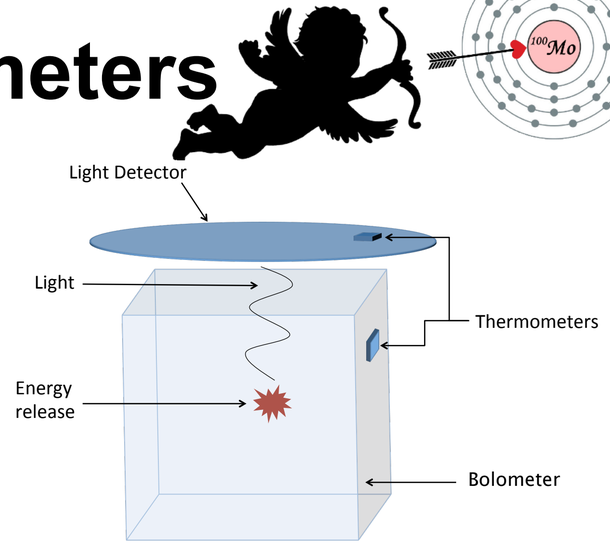




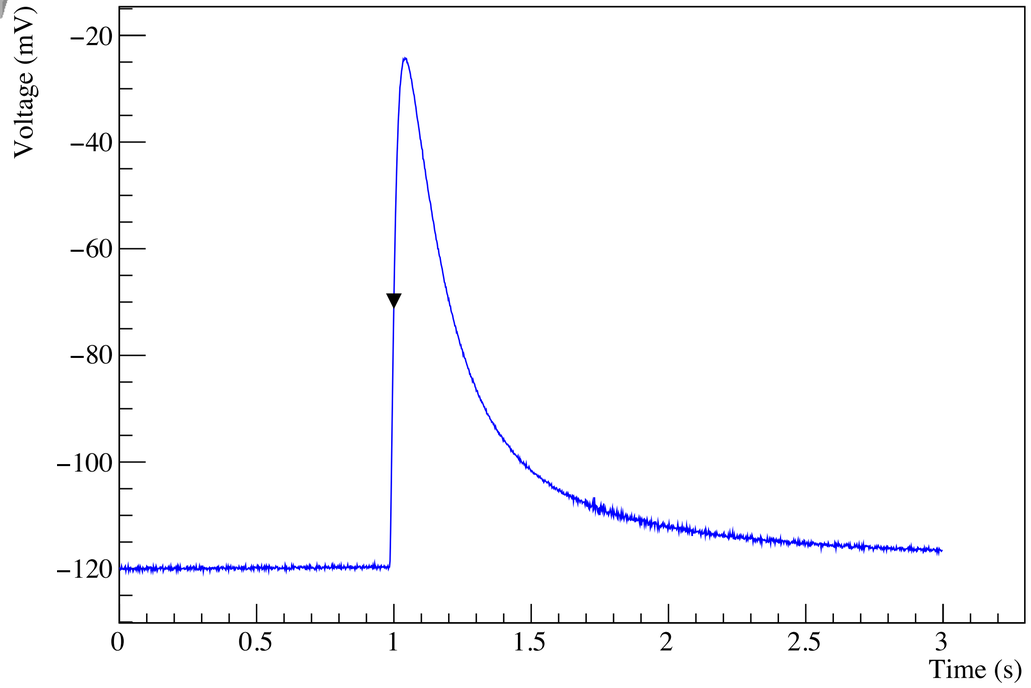
Copper: Thermal Bath

Scintillating cryogenic Li_2MoO_4 calorimeters

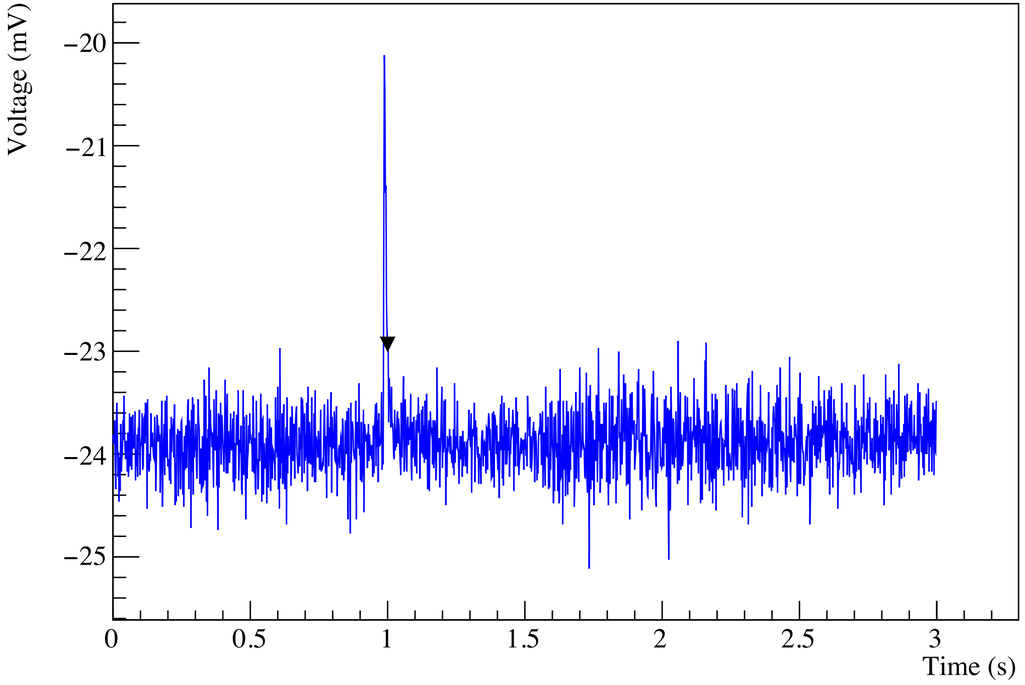




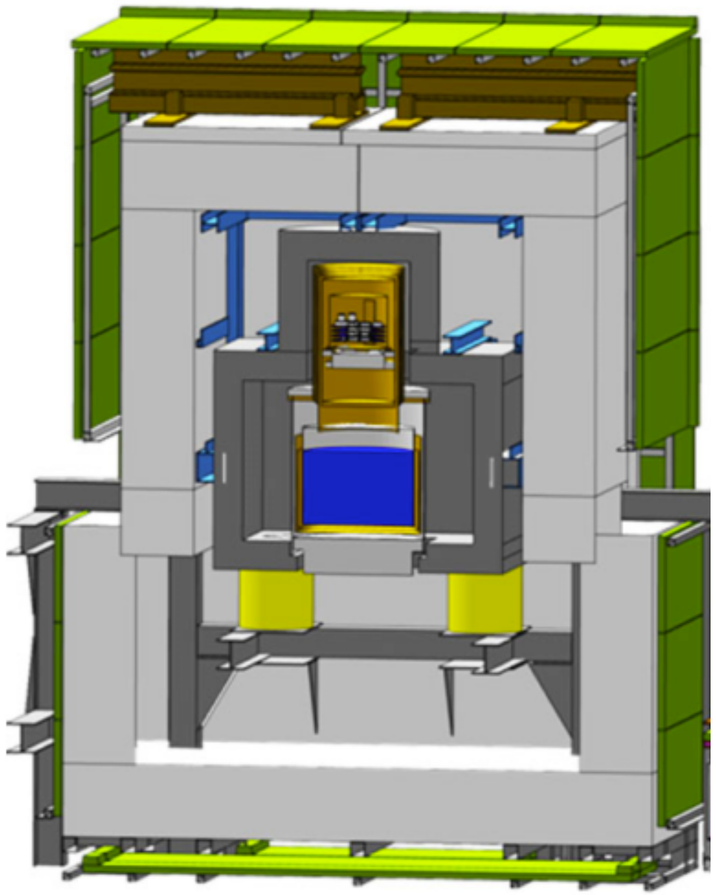
LMO example pulse @ 2615 keV



LD example pulse @ 2615 keV (LMO)

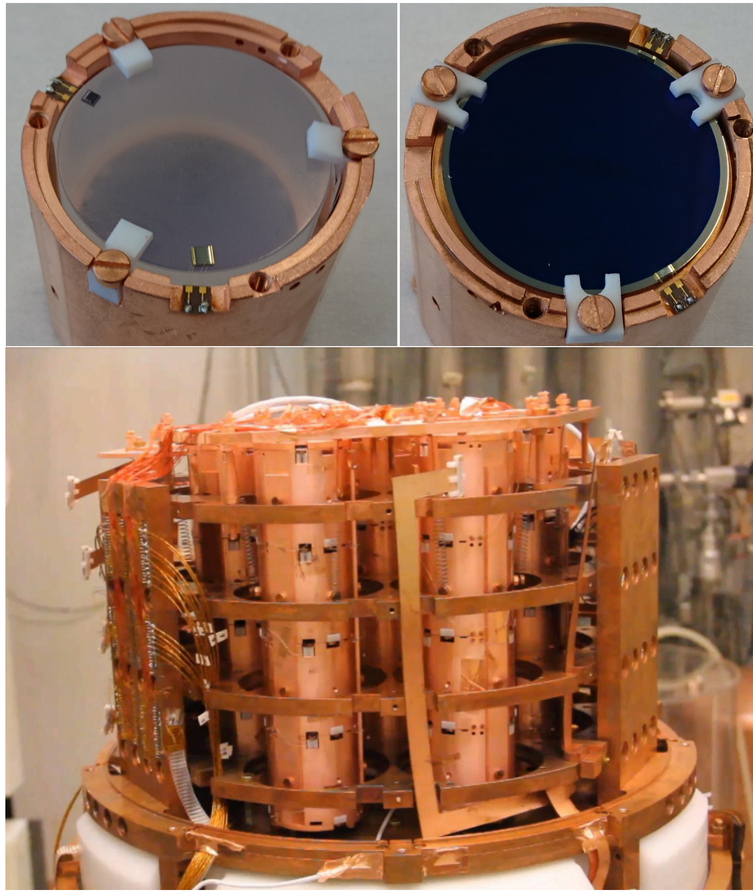


CUPID-Mo at Laboratoire Souterrain de Modane France (2018 - 2020)



- 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

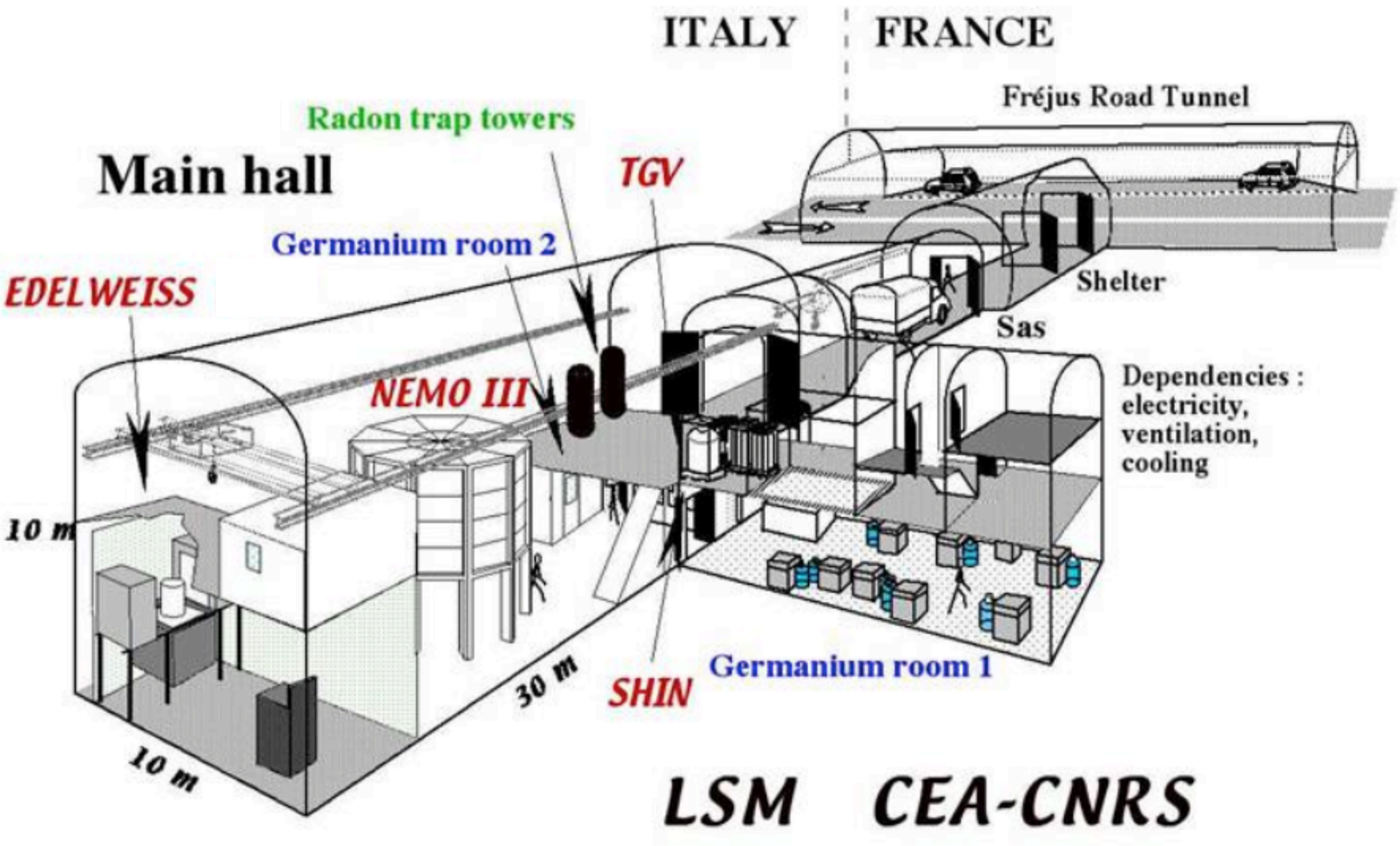
- **All $Li_2{}^{100}MoO_4$, 19 light detectors operational**
- physics data taking
  March 2019 - June 2020



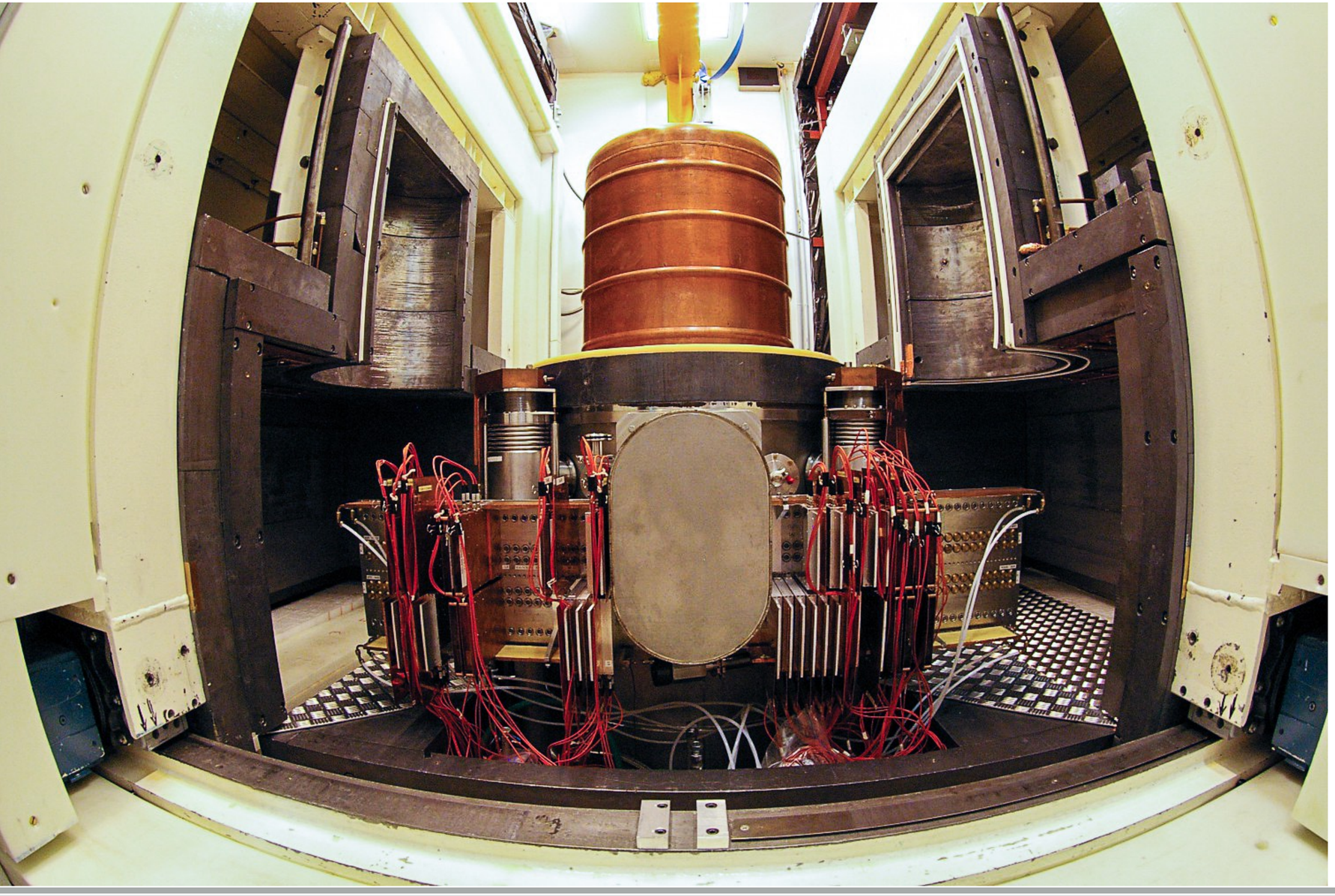

Modane
Lyon
Tourin

Laboratoire Souterrain de Modane

Laboratoire Souterrain de Modane



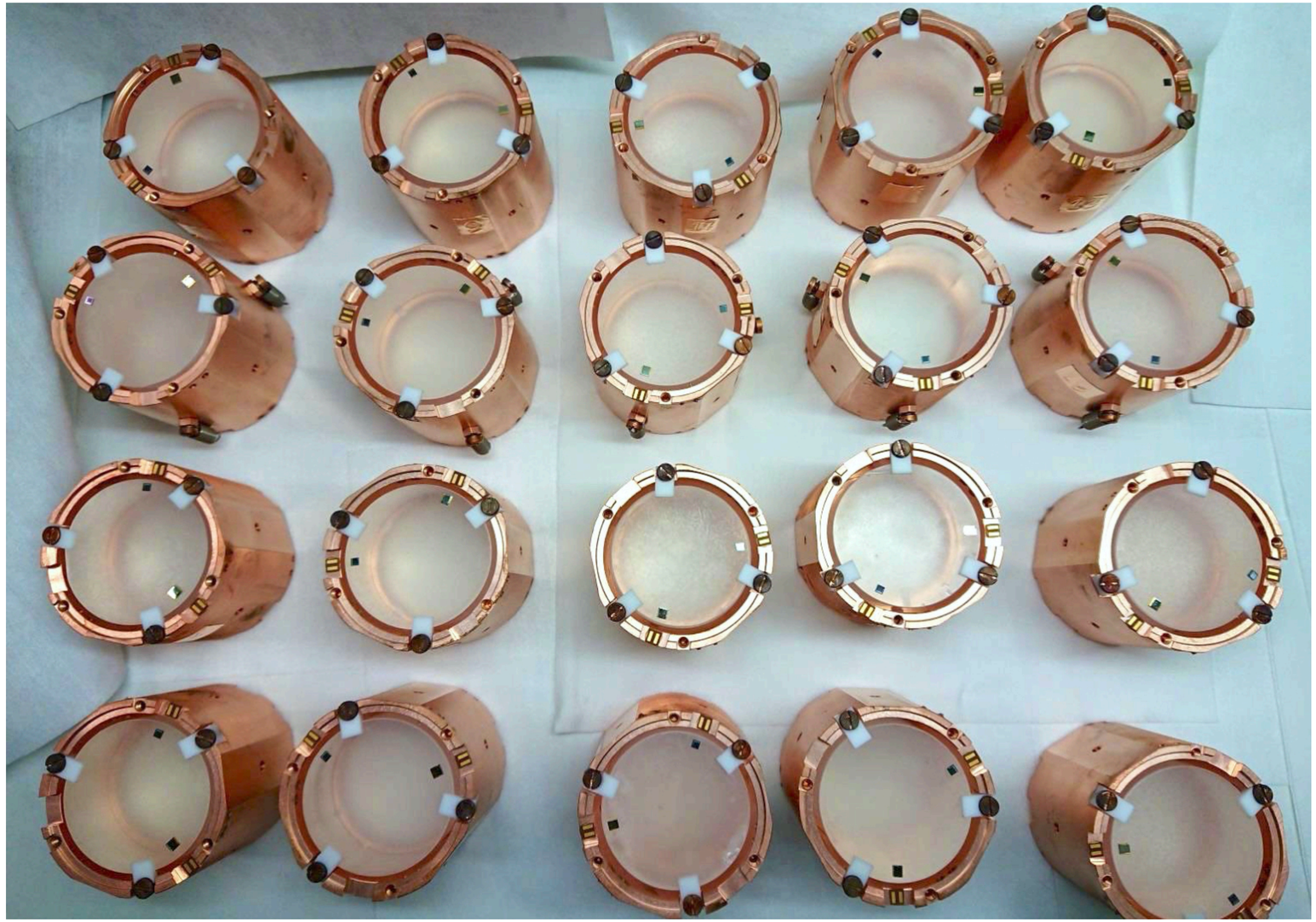
The EDELWEISS/CUPID-Mo cryogenic infrastructure



Active and passive shielding designed for the EDELWEISS-II dark matter search (Final results in 2010)

- 100 m^2 plastic scintillator muon-veto system
- 50 cm PE shielding
- 20 cm lead shield
  innermost 2 cm is roman lead
- Radon free air circulation in between lead and Cu cryostat
- Inversed geometry wet dilution refrigerator with GM cryocoolers for 100K screen and He liquefier
  - 10 days between LHe refill
- In-house front end electronics (Grenoble)

The CUPID-Mo design



Crystal growth and ^{100}Mo enrichment

NIIC, Novosibirsk, Russia

- purification of enriched Mo (from the NEMO-3 experiment) to MoO_3
- low radioactivity Li_2CO_3
- double crystallization (low thermal gradient Czochralski technique)
- surface polish with radio-pure SiO_2 oil based slurry
- Storage in dry N_2 atmosphere (Li_2MoO_4 is slightly hygroscopic)

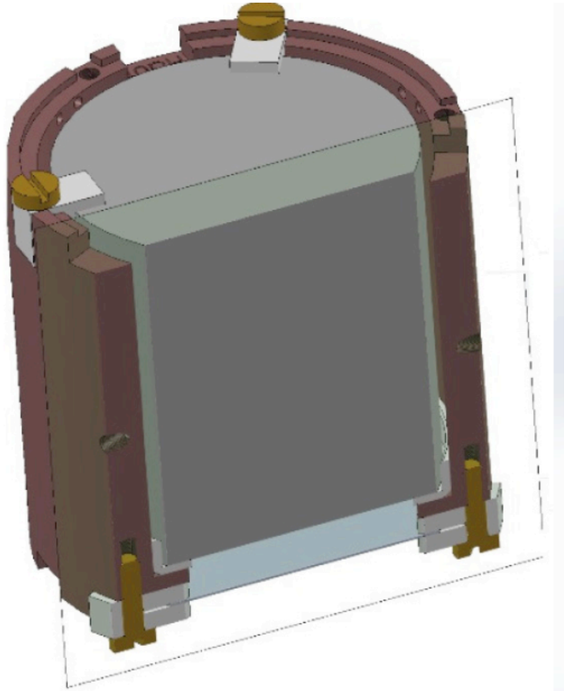
4.158 kg Li_2MoO_4

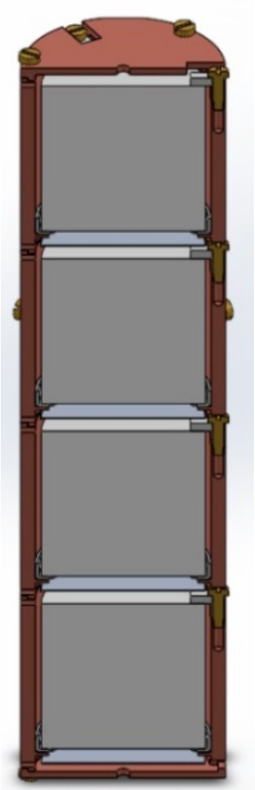
2.264 kg ^{100}Mo

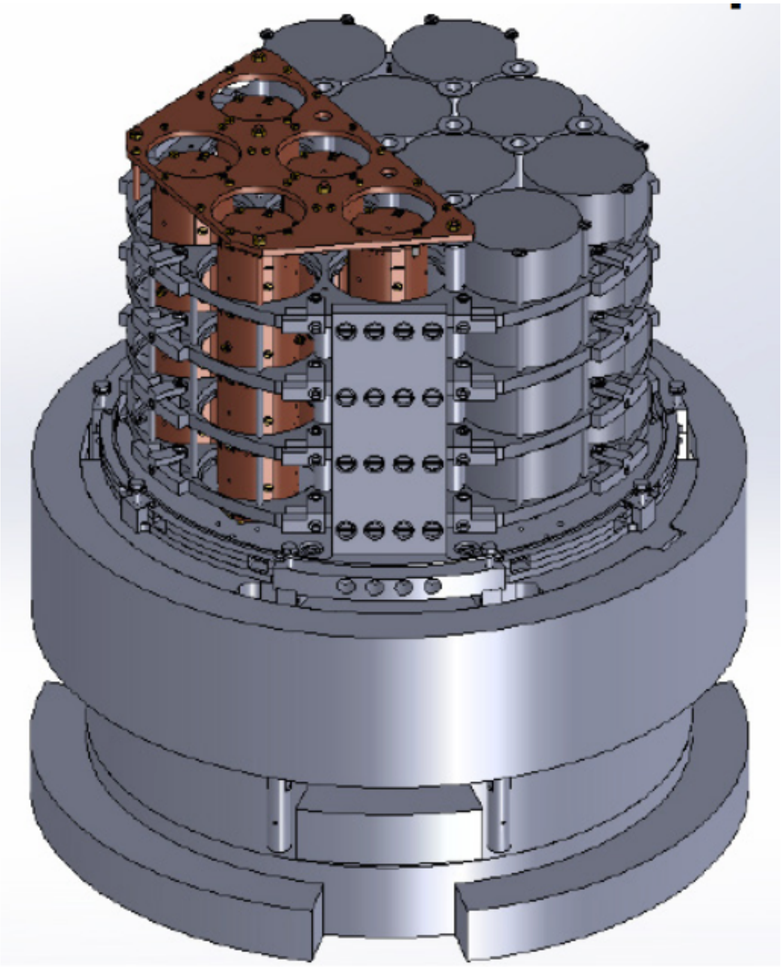
Modular tower design:

CUPID-Mo design

- Compatible with existing EDELWEISS cryostat design
- Detector mounting in CSNSM & LAL clean-rooms (Orsay)
- Decoupling of LMO and light detectors from vibrations
- NOSV-Cu for radio-purity



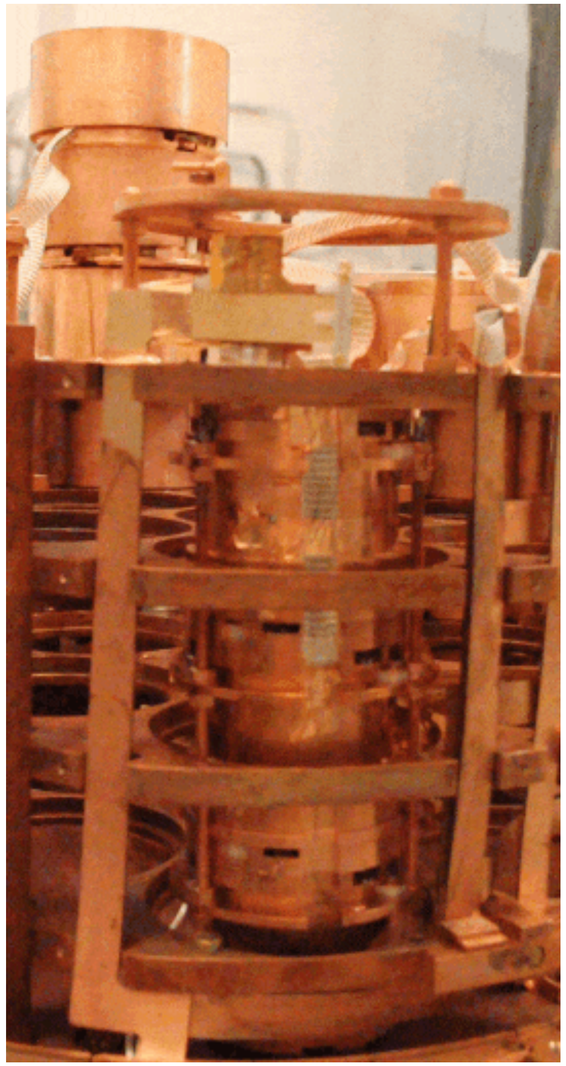




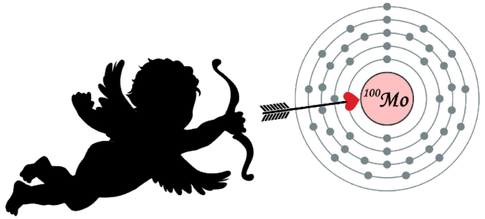
CUPID-Mo tower suspension

Suspended tower design

Particularly important for the LD operation in (dry + wet) cryostat with vibrations from thermal machines

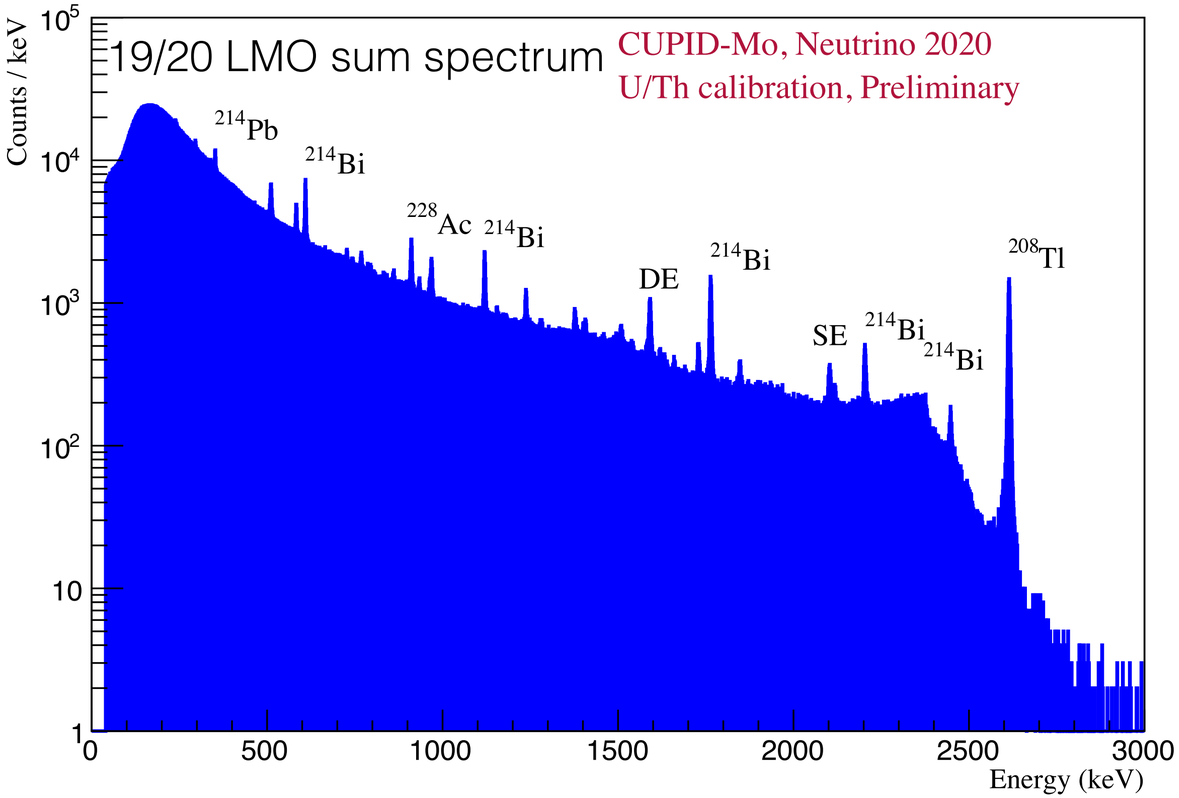


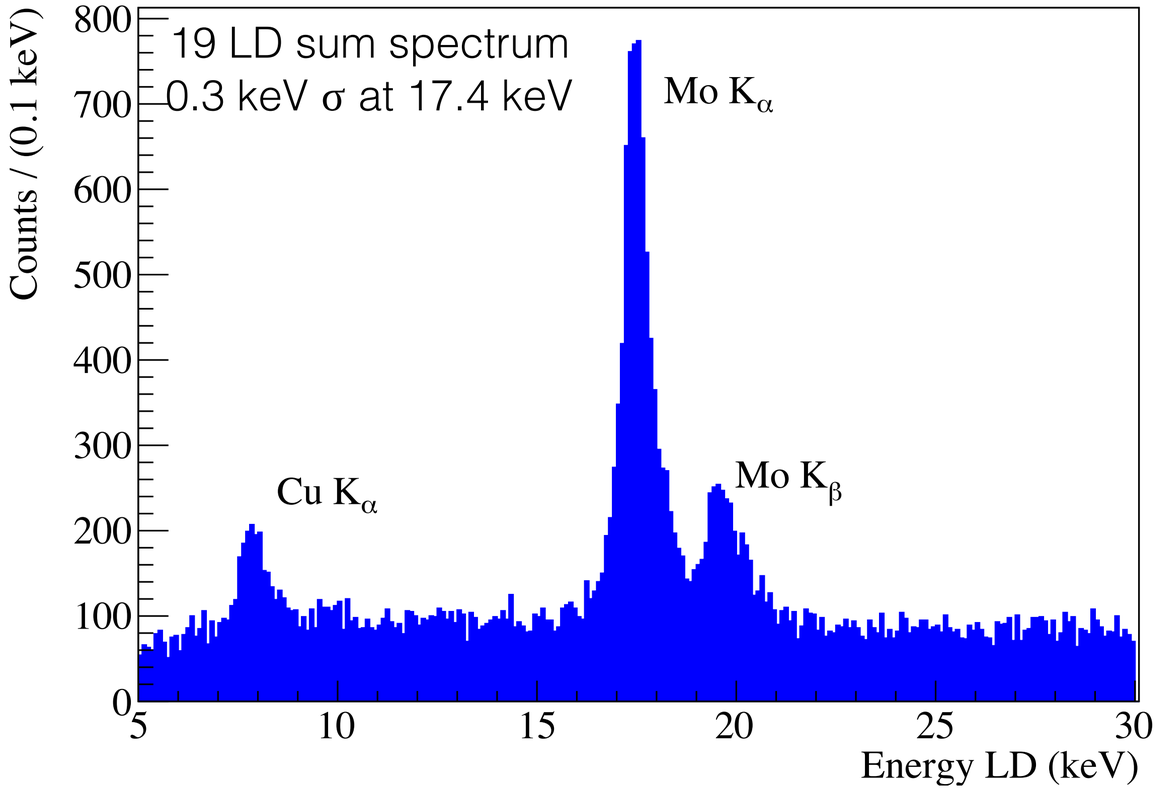
CUPID-Mo calibration



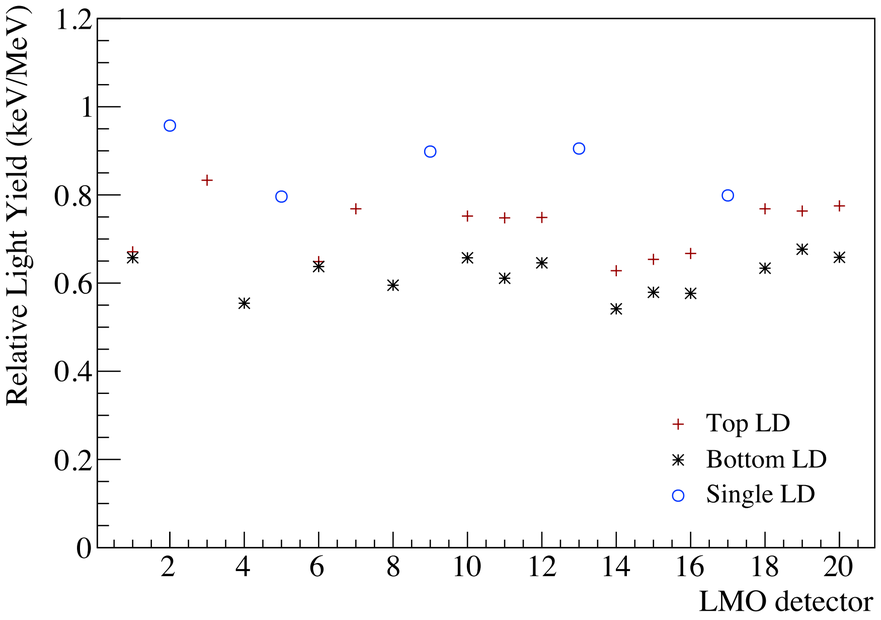
- LMO detectors have relatively low mass ~210 g and low density 3.07 g/cm^3
- Significant amount of time dedicated to calibration
  (2 days / LHe refill) 20-25% of data taking

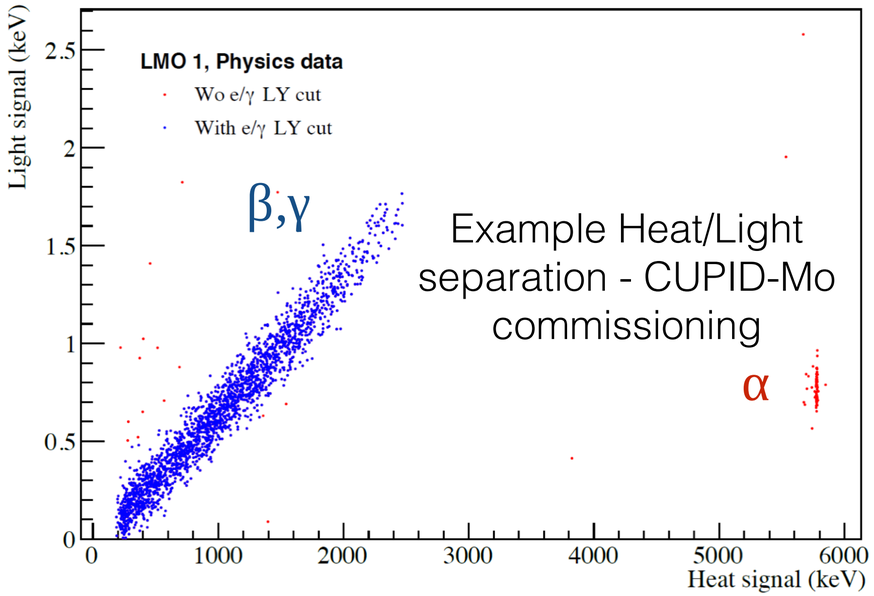
- Low energy calibration sources are potentially dangerous for the EDELWEISS dark matter search
- Use the Mo x-ray escape peak from high intensity irradiation of the crystals (^{60}Co)





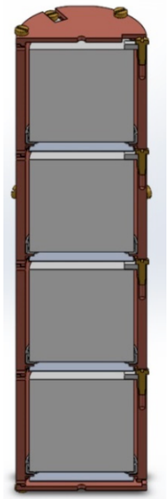
CUPID-Mo performance



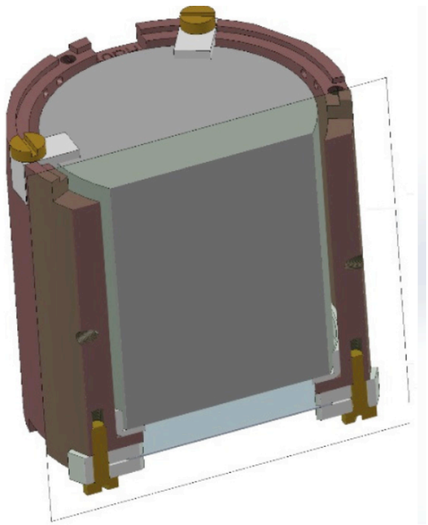


Example Heat/Light separation - CUPID-Mo commissioning

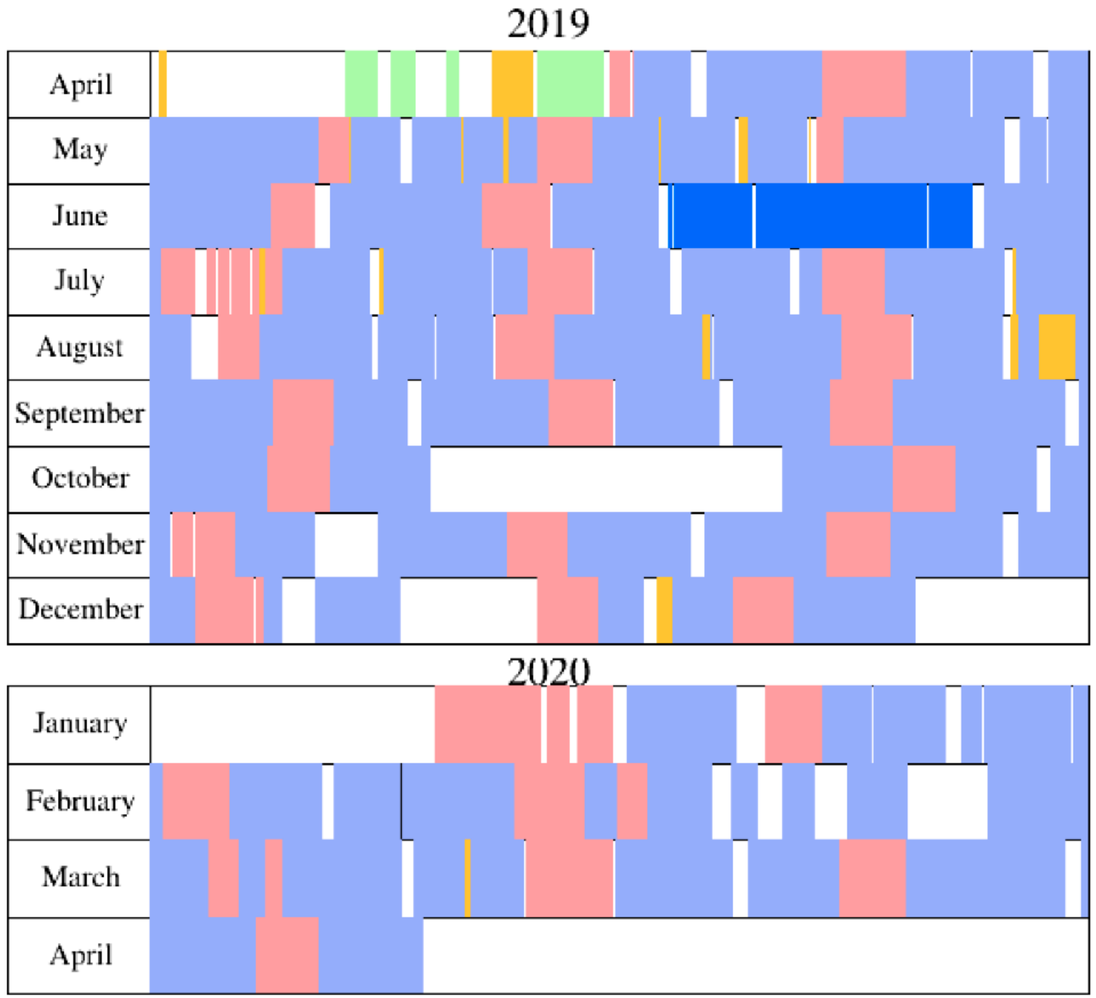
- $Li_2{}^{100}MoO_4$ scintillates at 600 nm
  - Typical measured light yield of ~0.6/0.7/0.9 (keV/MeV) for β,γ
    - Difference in light yield expected from tower design
  - α scintillation light yield of 20% - compared to β,γ
  - **> 99.9% alpha separation extrapolated for all detectors**

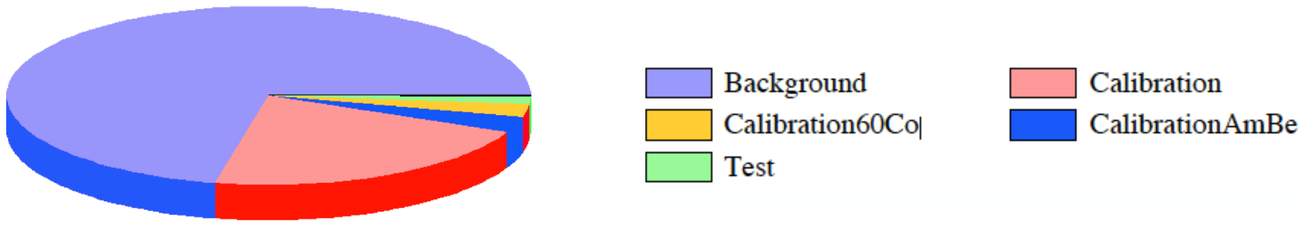


- **Good uniformity/performance suitable for larger arrays!**
  CUPID-Mo commissioning results
  EPJ-C 80:44 (2020)



CUPID-Mo: The Neutrino 2020 data

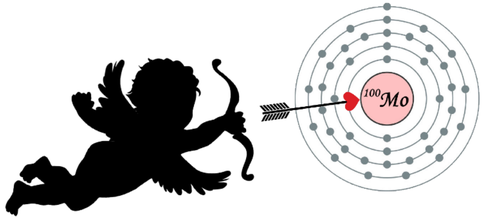




- March 2019 - April 2020 (380 days)
  - **7 Long datasets**, 1-2 month scale
  - 3 Short datasets (single calibration periods)
    Not used in the Neutrino analysis - extra work needed on energy-scale uncertainty
  - Rejection of periods of temperature instabilities

	Days (tot)	Days (sel)	Exposure kg x yr	Retained
Physics	240	200 (224)	**2.17** (2.4)	94%
Calibration	73	59 (65)	0.6 (0.7)	88%
Special	21	—	—	—
Downtime	46	—	—	—

CUPID-Mo: Data production and cuts



CUORE based data production chain at NERSC

Trigger efficiency

Base cuts

Single trigger
BaselineSlope

Multiplicity

Pulser rejection
M1 - single crystal

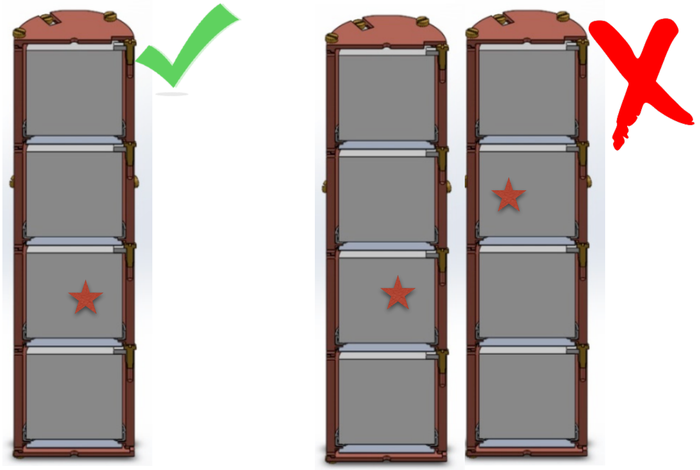
Pulse Shape analysis

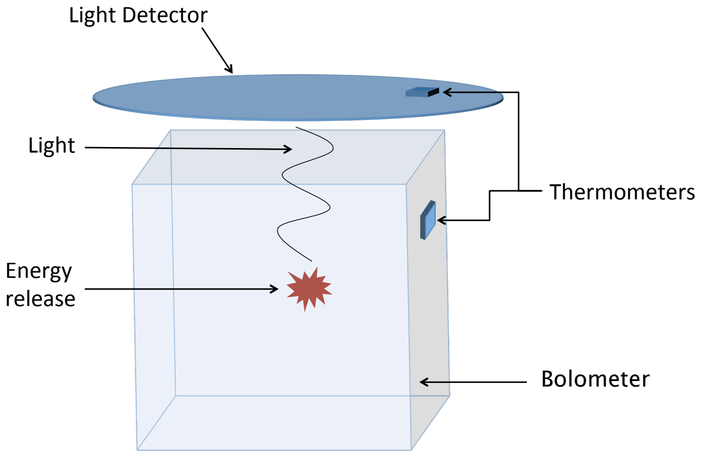
Principal component analysis (PCA)

Light Yield

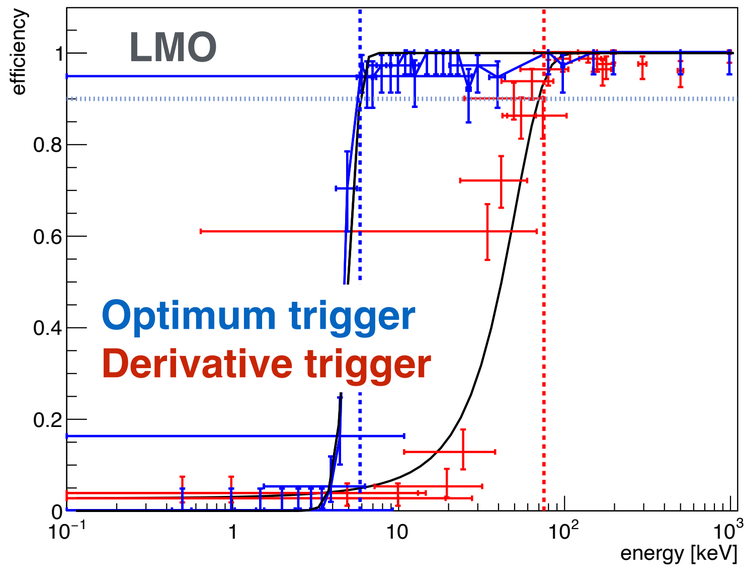
Sum of LD
Consistency of LD

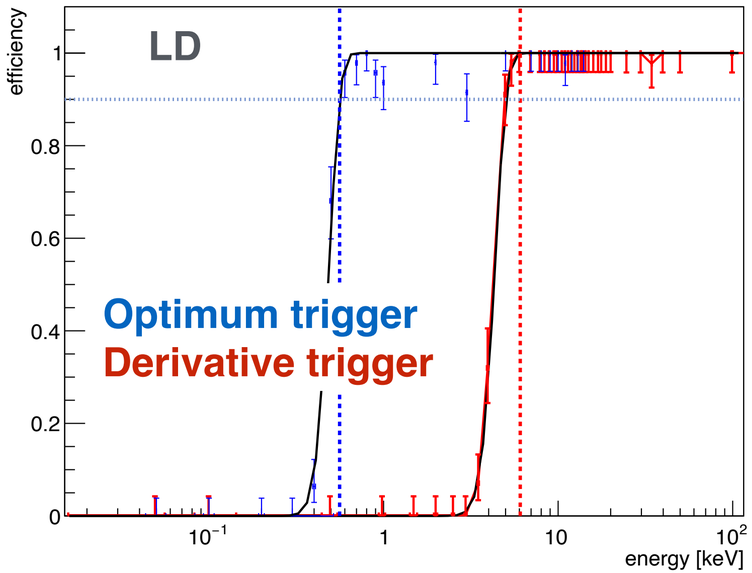
Muon veto anti-coincidence



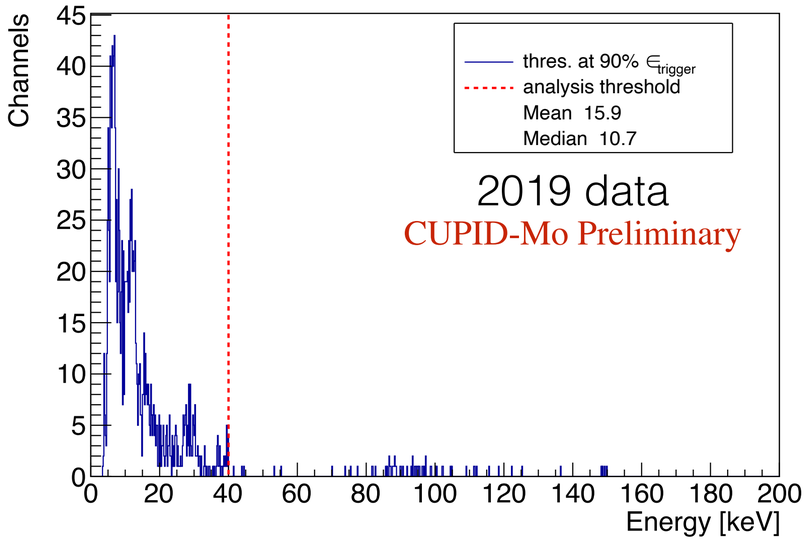


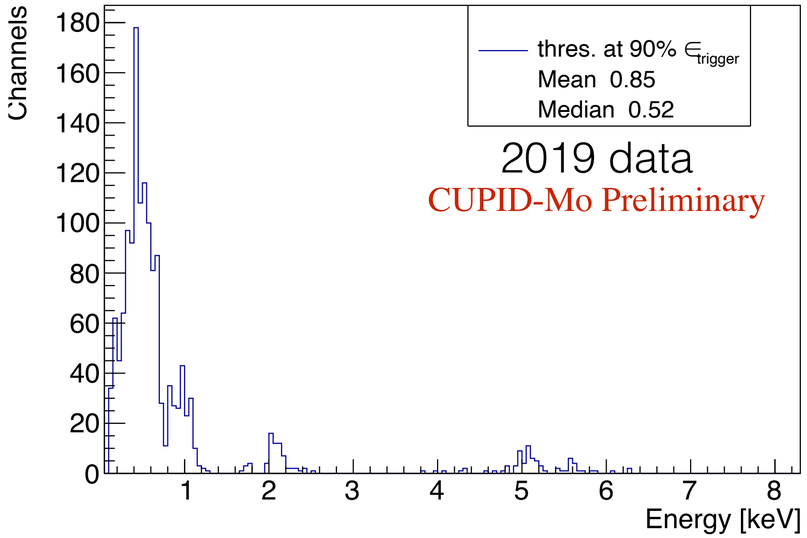
CUPID-Mo: Trigger efficiency





- Use of Optimum Filter to obtain lower thresholds
  - Surplus coincidence information
  - Choose conservative 10 sigma trigger threshold
- Evaluation of trigger efficiency: Inject avg. pulse template into noise
- —> Typical LMO threshold ~ 11 keV (90% efficiency), fully efficient above analysis threshold (45 keV)
  —> Typical LD threshold ~ 0.5 keV (90% efficiency)





CUPID-Mo: Data quality cuts

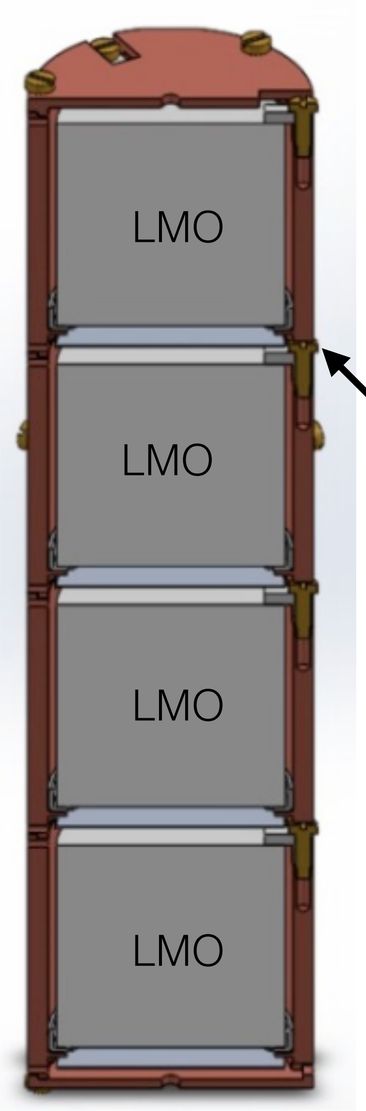
Base cuts

Single trigger
BaselineSlope

Multiplicity

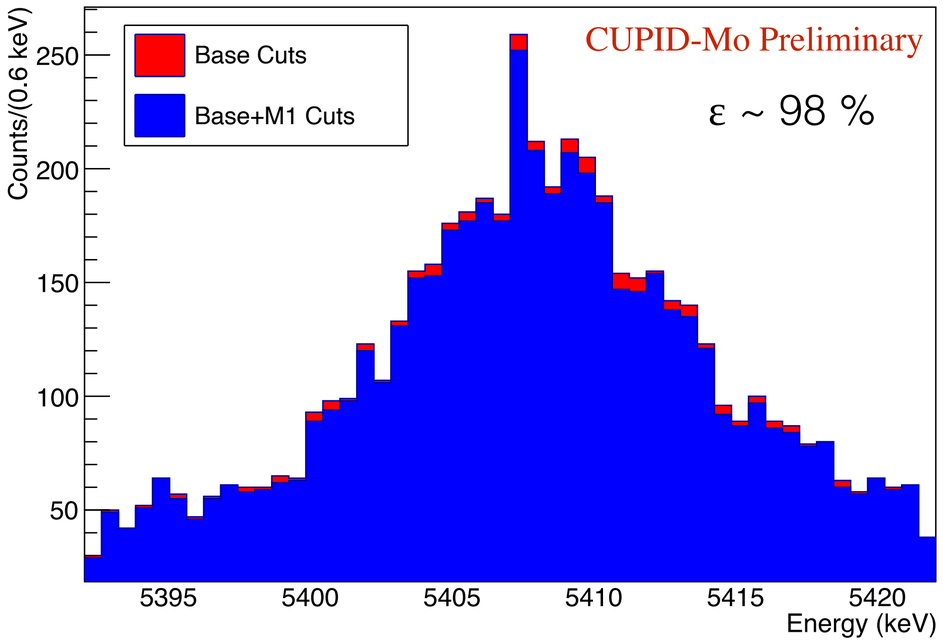
Pulser rejection
M1 - single crystal

(Muon veto anti-coincidence)



Light detector

- No energy dependence of these cuts
- No line of sight between LMO detectors
- Appreciable ^{210}Pb, ^{210}Po presence
- ^{210}Po serves as a clean sample of events (no pulser, heat-only other event contamination) for the efficiency estimate



Pulse Shape analysis

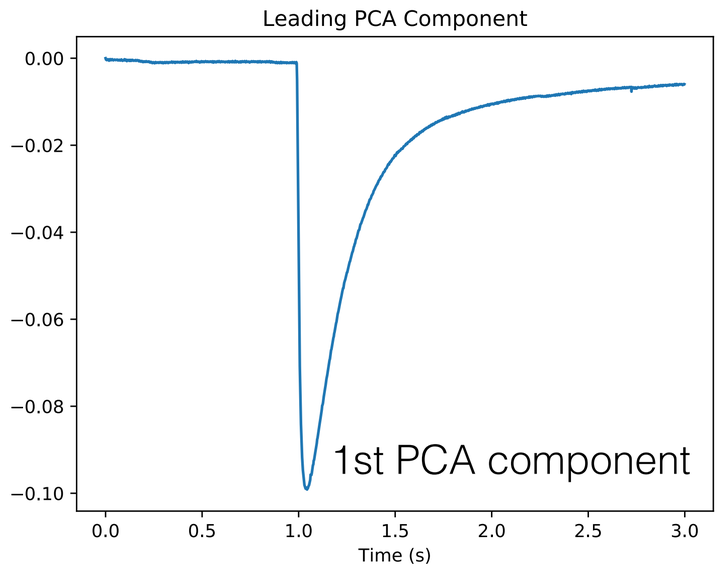
Principal component analysis (PCA)

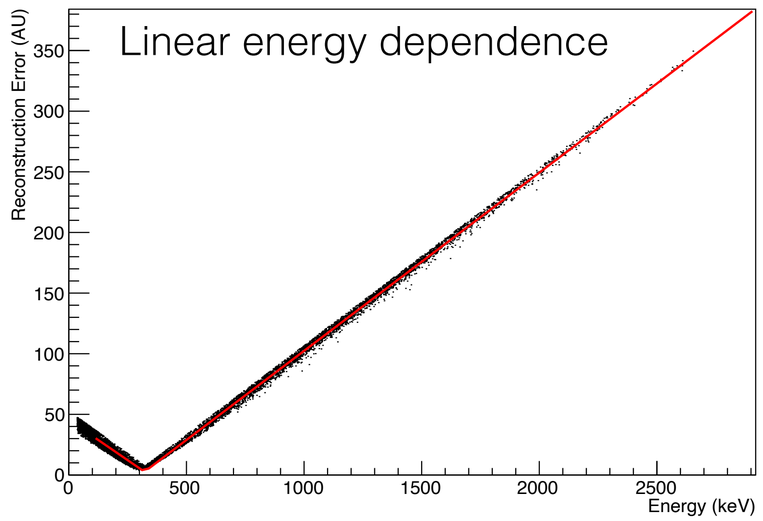
CUPID-Mo - Pulse Shape Analysis

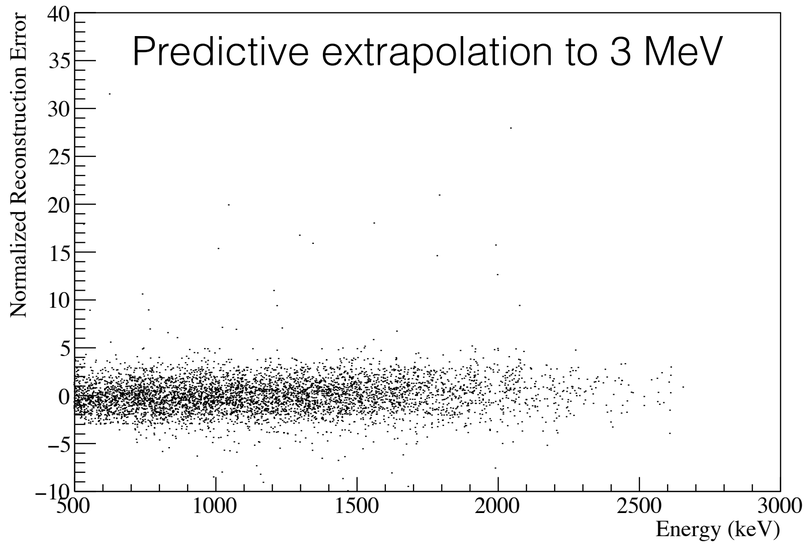
- Perform a Principal Component Analysis (PCA)
  - Train on 1 MeV - 2 MeV 2νββ events in physics data
  - 1st component - contains main amplitude information - similar to average pulse
- Define the (Normalized) Reconstruction Error E with respect to 1st (1st plus 2nd) PCA component as pulse shape analysis variable

$$E = \sum_i (x_{i,rec.} - x_i)^2$$

CUPID-Mo Preliminary







Pulse Shape analysis

Principal component analysis (PCA)

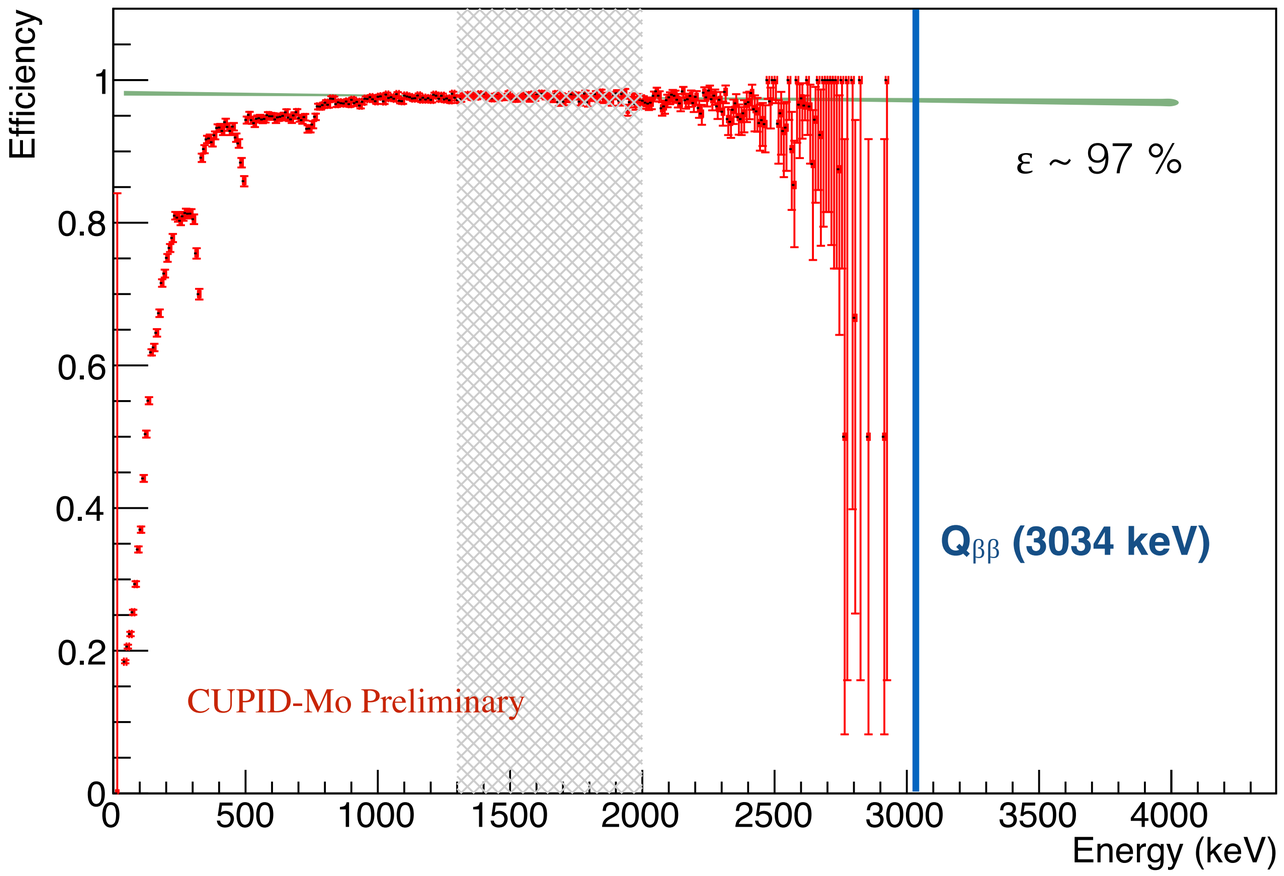
CUPID-Mo - Pulse Shape Analysis

- Optimize PCA cut based on the goal of mitigating pile-up on calibration data
  - Maximize signal sensitivity using Cowan's metric

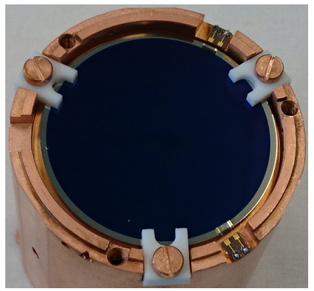
$$\sqrt{2(S+B)\cdot ln(1+\frac{S}{B})-S}$$

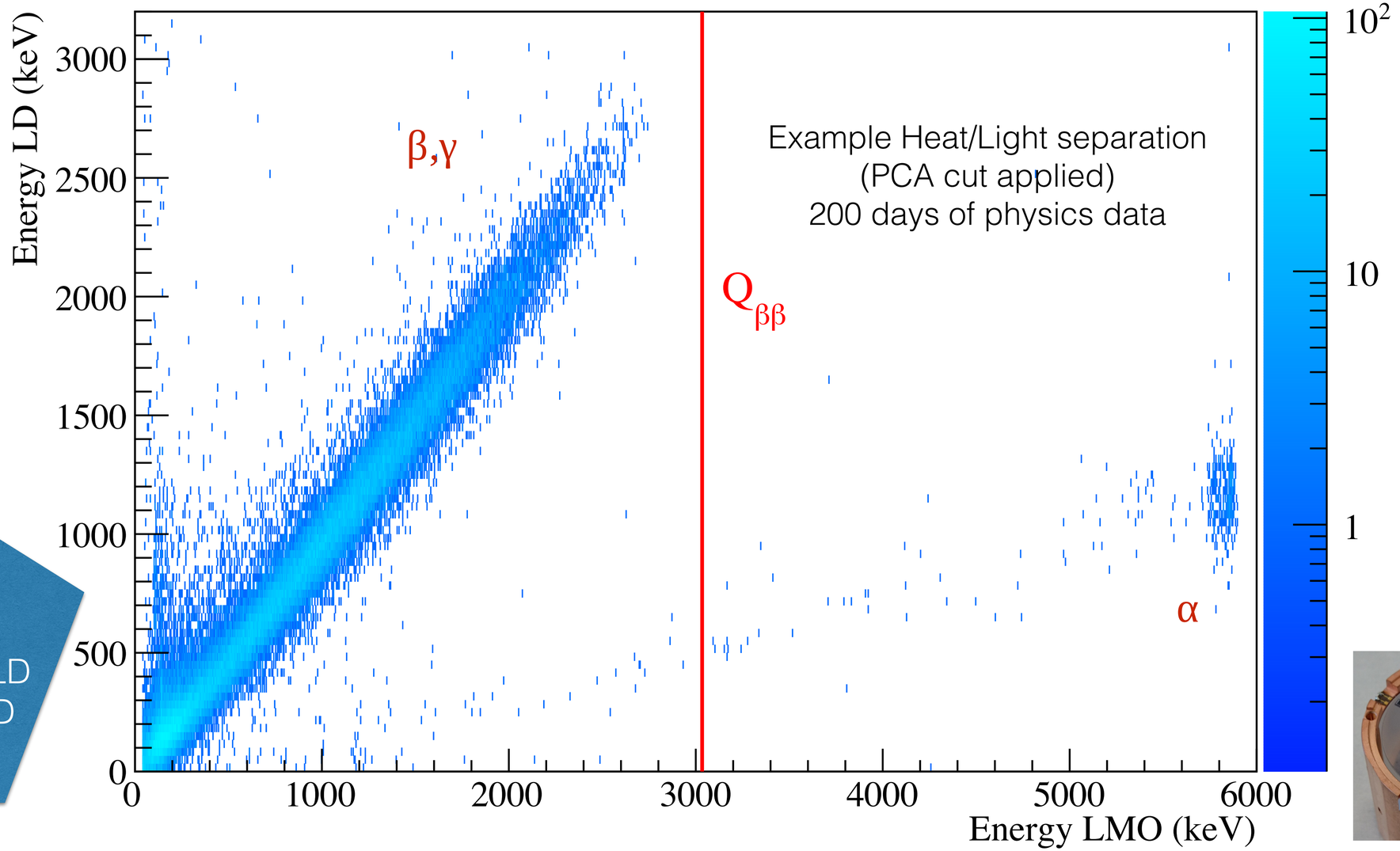
    - S = NEMO-3 exclusion limit
    - B = Bg from 2615 keV tails (scaled)
  - Under further study to improve pile-up rejection

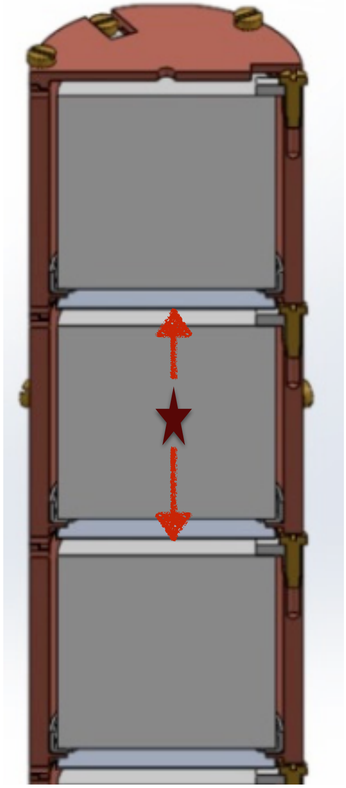
- Efficiency evaluation (physics data)
  - Evaluate PCA cut with LY cuts applied
  - Fit of 1st order polynomial in high stat. $2\nu\beta\beta$ region
  - Evaluation of fit uncertainty at $Q_{\beta\beta}$; 1% Dataset level



CUPID-Mo - The light yield cuts

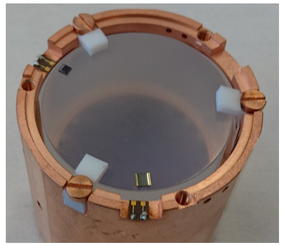




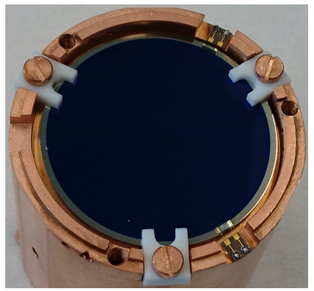


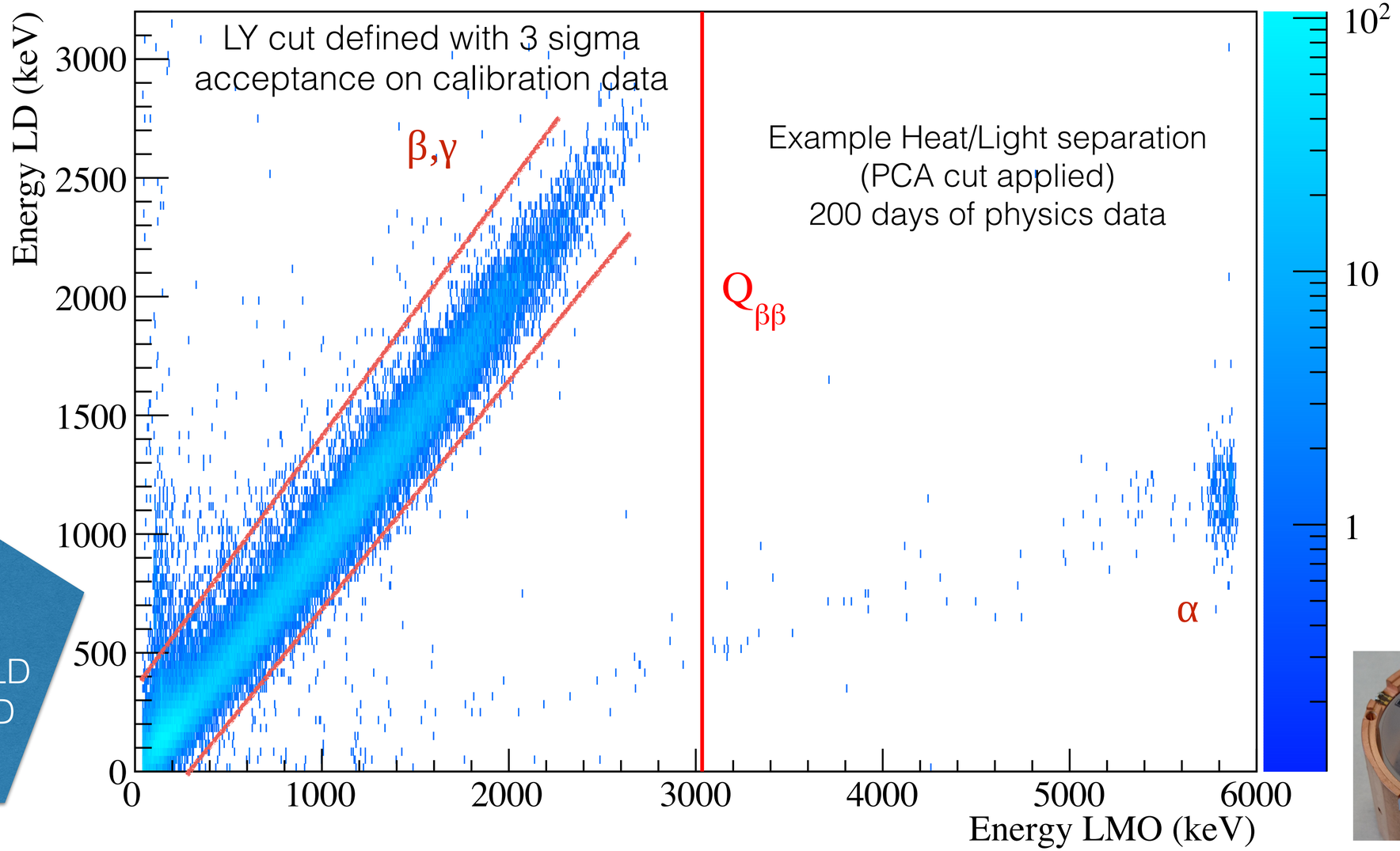
Light Yield

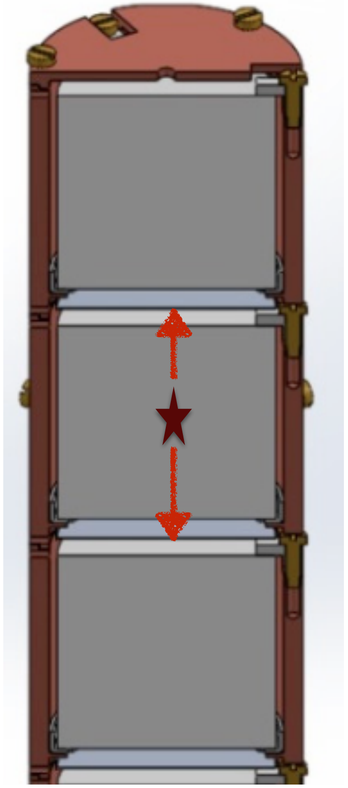
Weighted sum of LD
Consistency of LD



CUPID-Mo - The light yield cuts

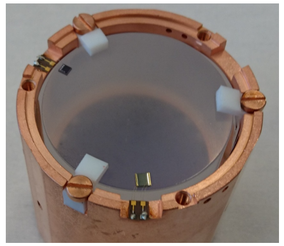


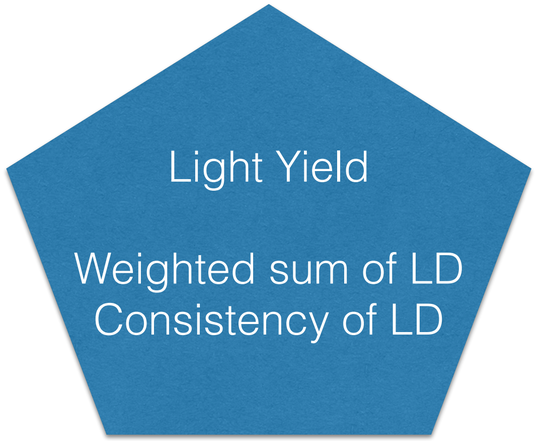




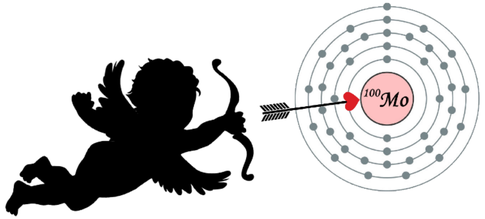
Light Yield

Weighted sum of LD
Consistency of LD

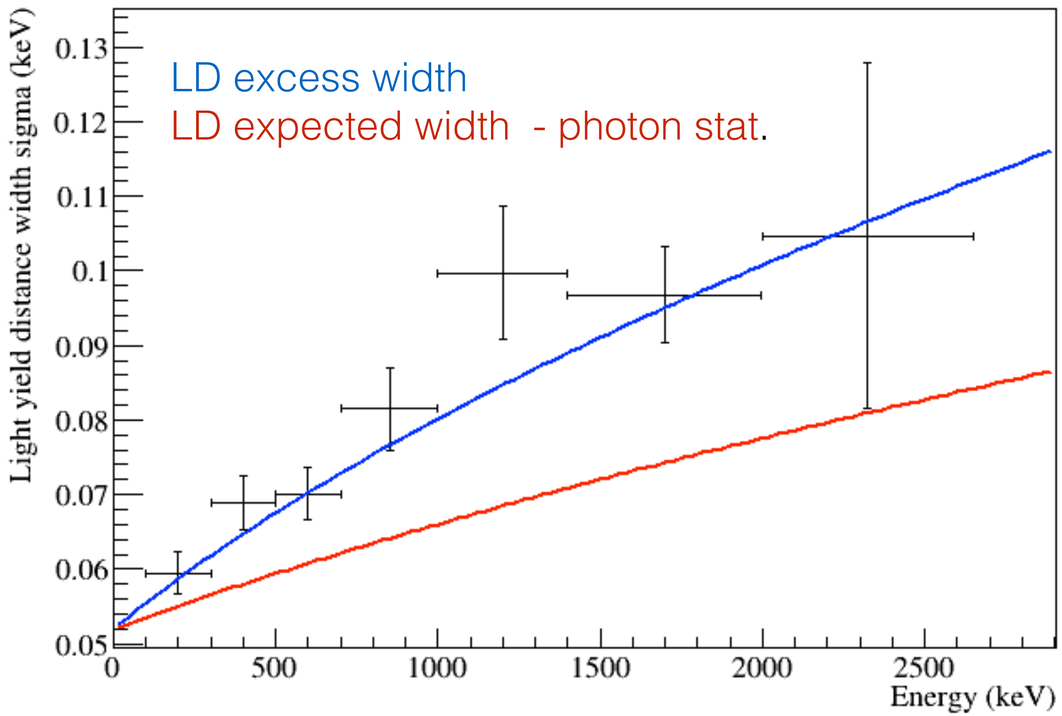




CUPID-Mo - The light yield cuts



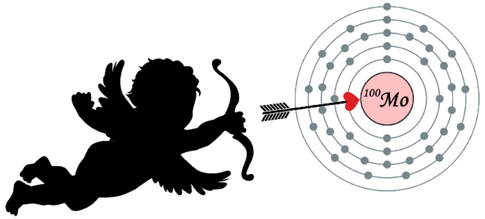
- Efficiency evaluation (physics data)
  - Evaluate the LD cut efficiency from the $2\nu\beta\beta$ spectrum after applying the PSA cut
- Systematics from energy extrapolation
  - Excess broadening with respect to expected LD width, sqrt(σ_B^2 + n_{Scint} * 2.07 eV) observed
  - Consider two models
    Excess broadening α E — excess broadening α sqrt(E)
  - systematic quantification with Toy MC incl. fit uncertainties $^{+0.9}_{-0.2}$ %



Pulse Shape analysis

Principal component analysis (PCA)

CUPID-Mo - Analysis cut efficiencies

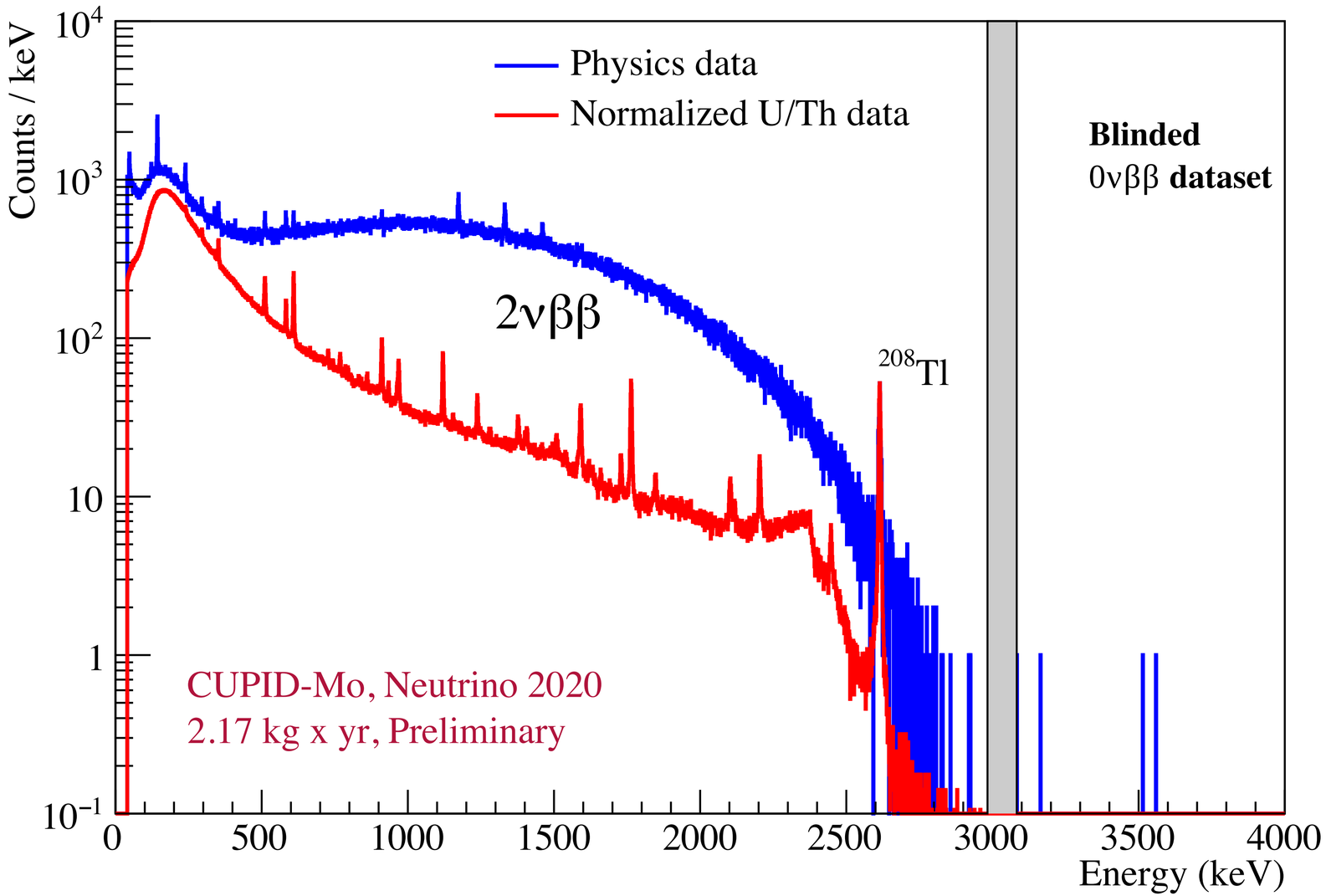


Cut \ DATASET	1	2	3	4	5	6	7
Base	99.0(3)	100	99.8(2)	99.9(1)	99.9(1)	99.7(3)	99.7(2)
Slope	98.2(1)	98.6(2)	98.4(1)	98.8(1)	98.9(1)	98.9(1)	99.0(1)
M1	97.3(6)	98.0(6)	97.2(6)	97.6(5)	98.3(5)	98.8(6)	97.8(5)
Light Det	96.8(2)	96.7(2)	95.5(2)	97.5(1)	97.5(2)	97.2(2)	97.2(2)
PCA	96.6(9)	96.8(11)	97.2(7)	96.2(7)	96.6(10)	97.6(11)	98.9(10)
Total	88.4(11)	90.5(12)	88.6(9)	90.4(9)	91.4(11)	92.3(13)	92.9(13)

CUPID-Mo Preliminary

Total efficiency (exposure weighted avg.) $\epsilon = (90.5 \pm 0.4\ (\text{stat.})\ ^{+0.9}_{-0.2}\ (\text{syst.}))\ \%$

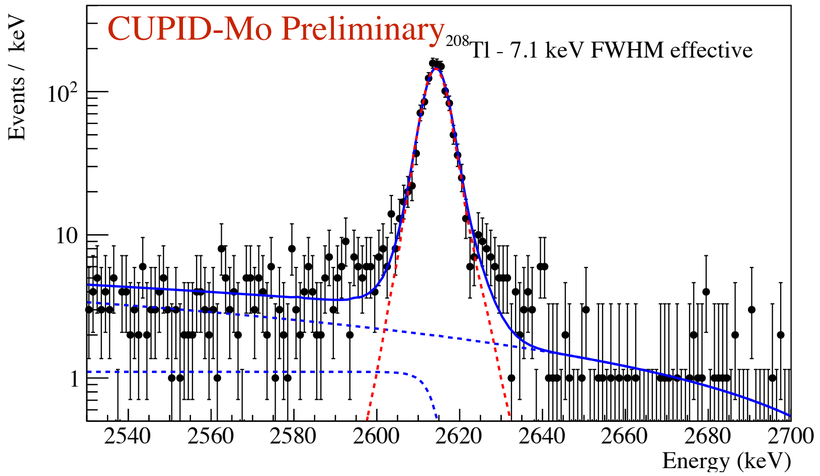
CUPID-Mo the blinded data



- 19/20 detectors with good performance
- Analysis efficiency 90.5 %
- 200 days of physics data,
  ~7 keV FWHM @ 2615 keV (calibration)

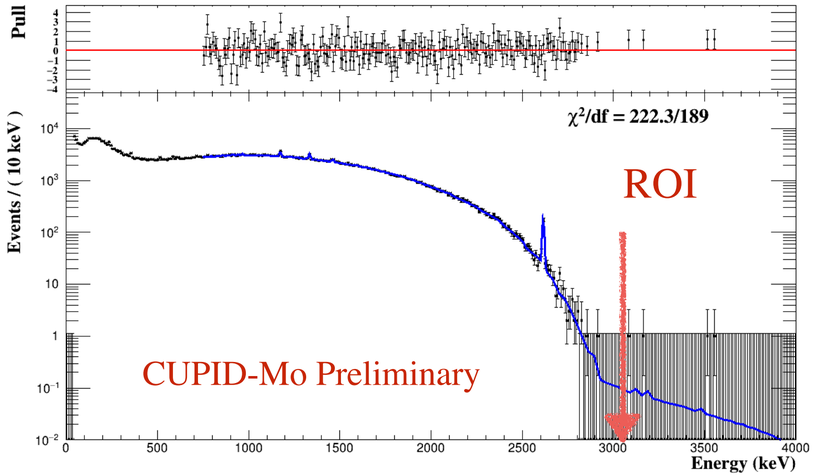
CUPID-Mo - ROI definition for counting analysis

Detector resolution



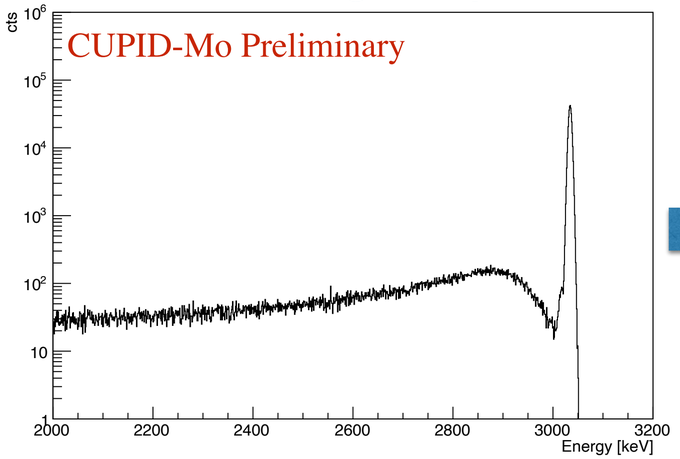
+

BG Index

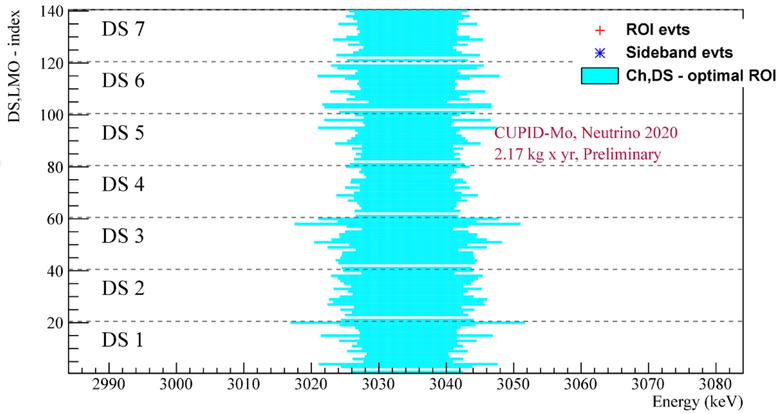


+

$0\nu\beta\beta$ containment
Bremsstrahlung escape

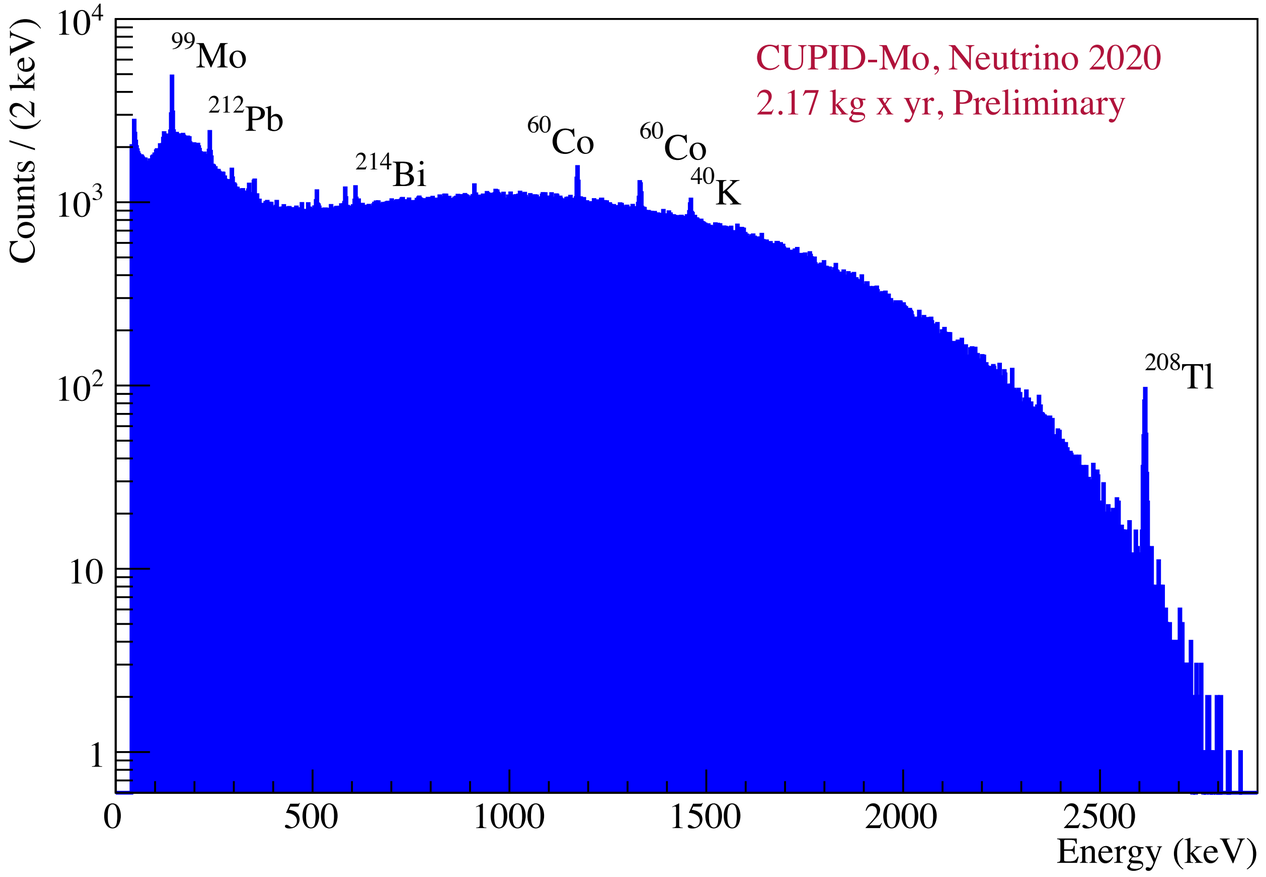


ROI definition

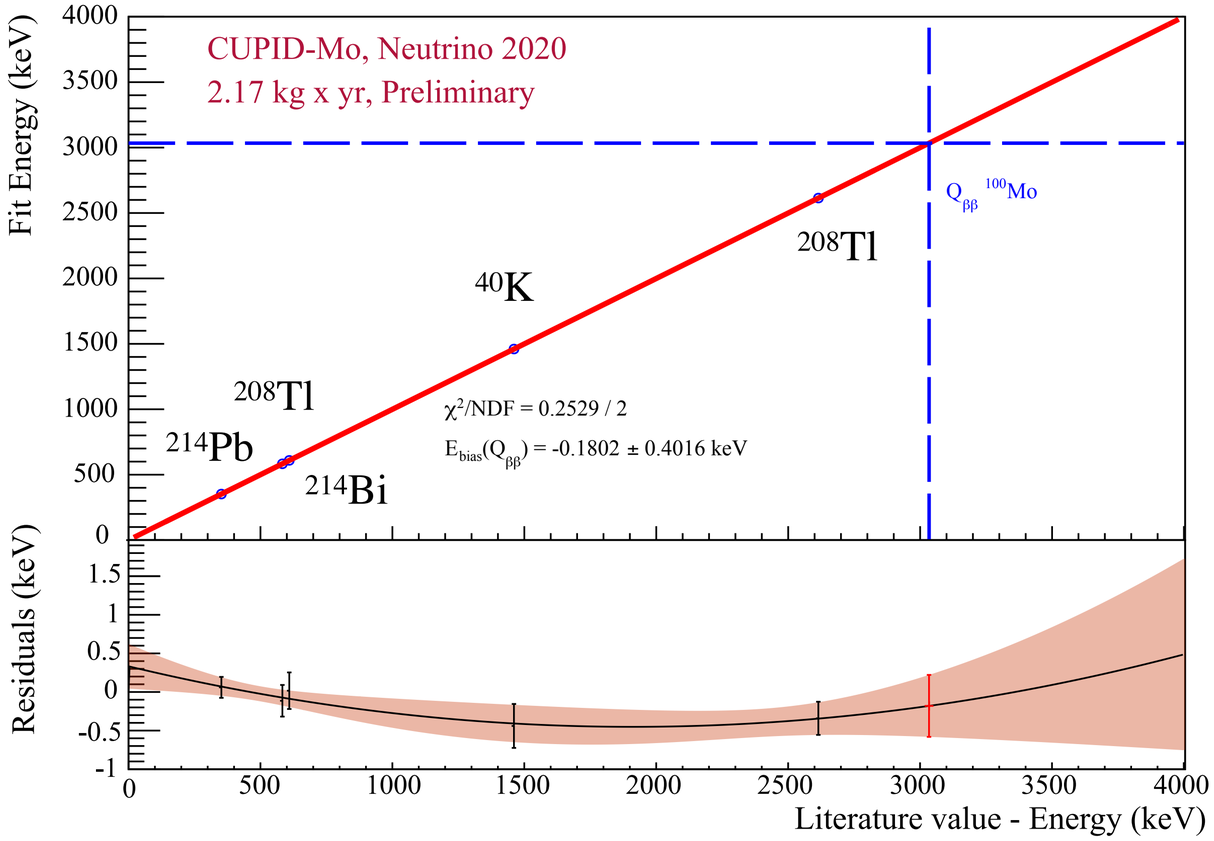


CUPID-Mo - Energy scale

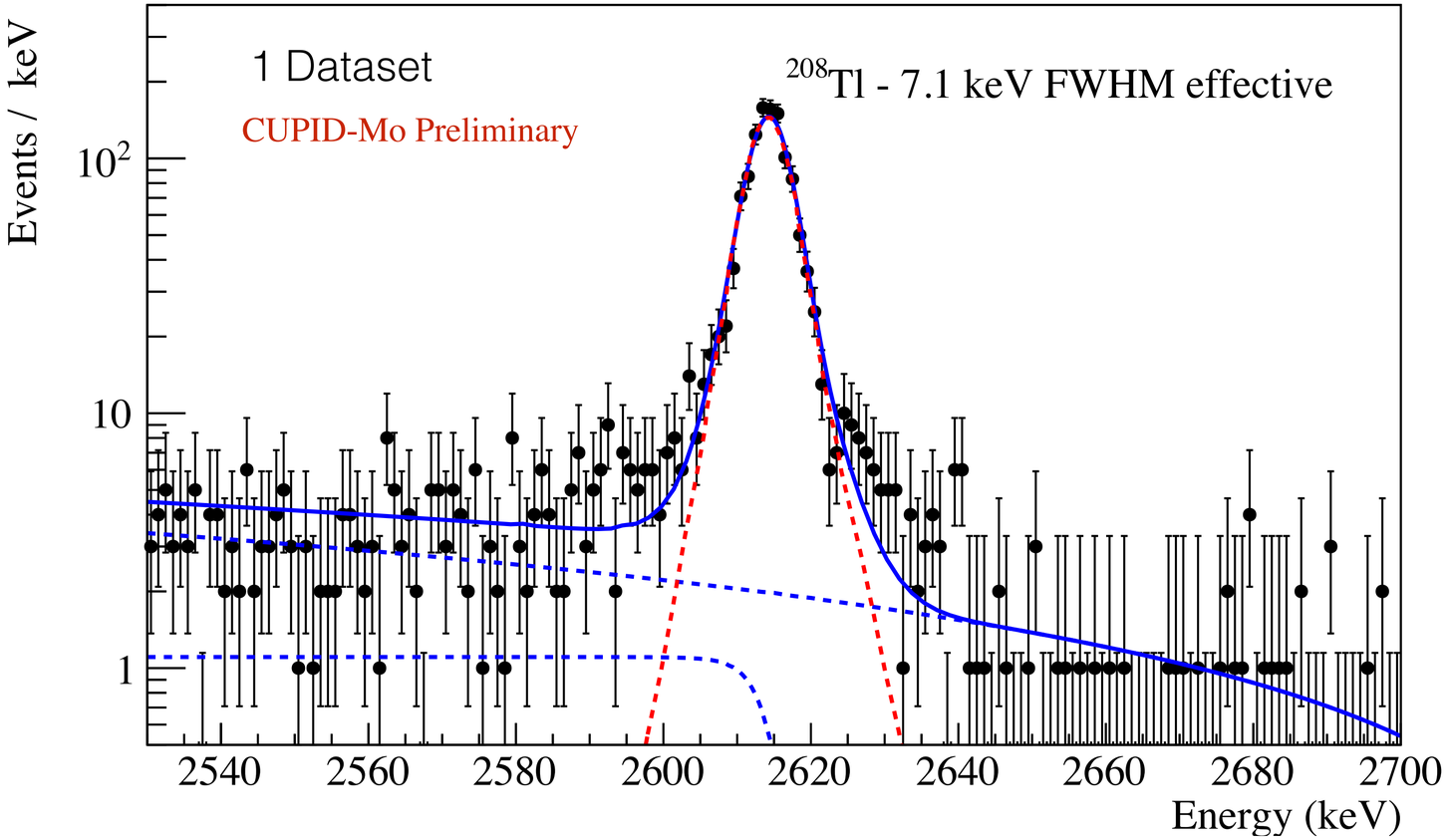
- Energy scale is set with pol2 in calibration data
- Check consistency in time in calibration data



- Estimate possible energy bias based on physics data, E_B = (-0.2 ± 0.4) keV



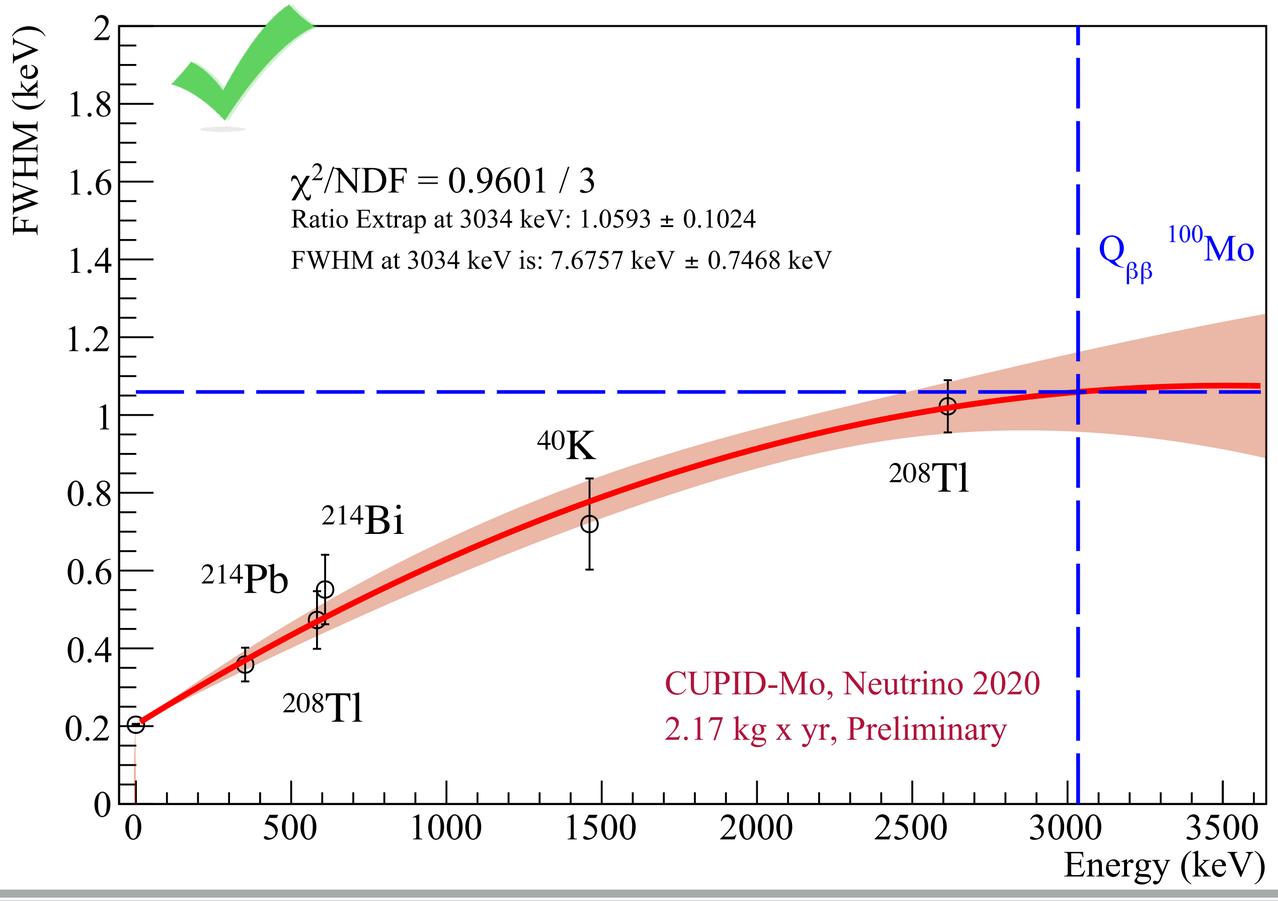
CUPID-Mo - ROI (Ch,DS) based resolution

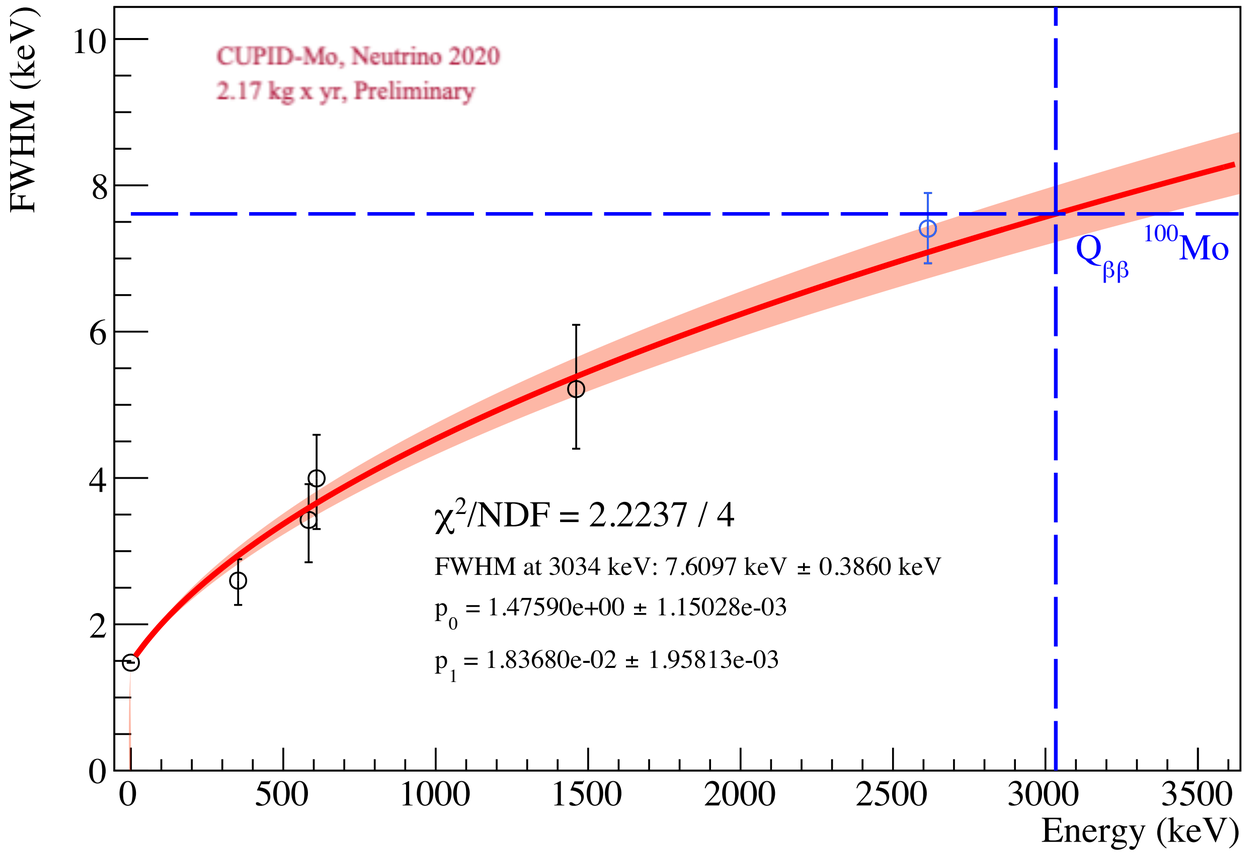


- Simultaneous unbinned extended maximum likelihood (UEML) fit to extract the Ch,DS - based resolutions
  - Fit model:
    smeared step function (multi-compton)
    Gauss (photopeak)
    Linear (multi-photon + $2\nu\beta\beta$)
- —> Extract the gaussian width on a Ch,DS basis

CUPID-Mo ROI resolution scaling

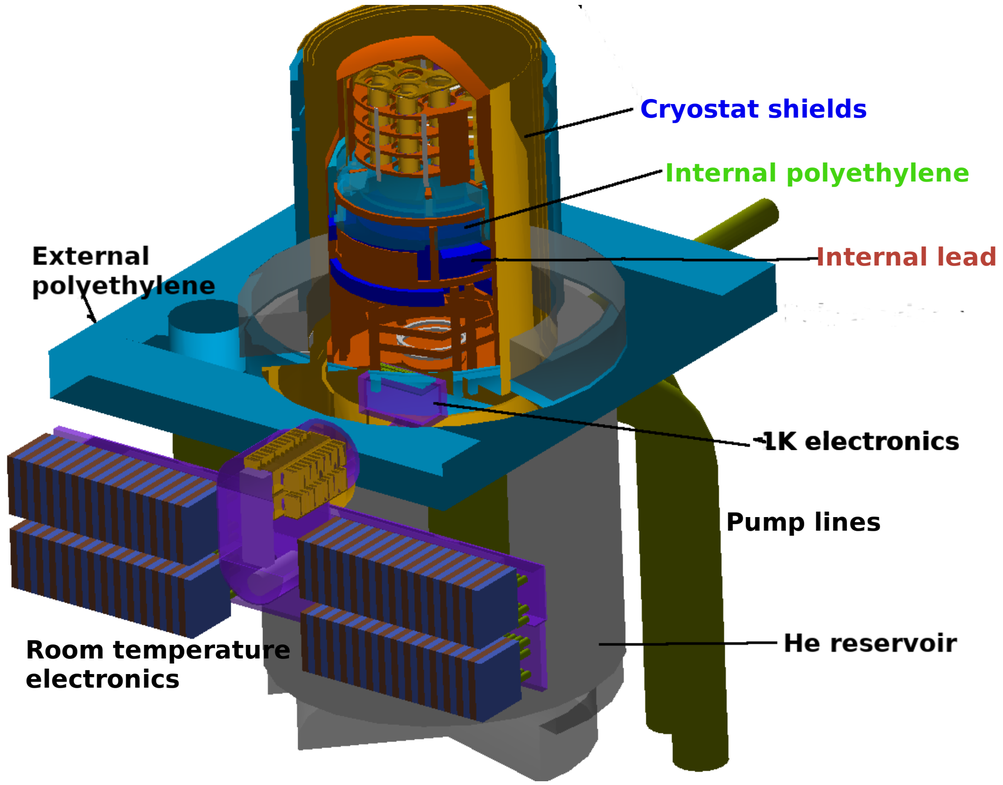
- Obtain a global scaling factor Calibration @2615 keV <-> Physics @3034 keV
- Test several hypothesis:
  - linear, sqrt, pol2 fit -> linear is ruled out by calibration data -> take remaining more conservative estimate (pol2)



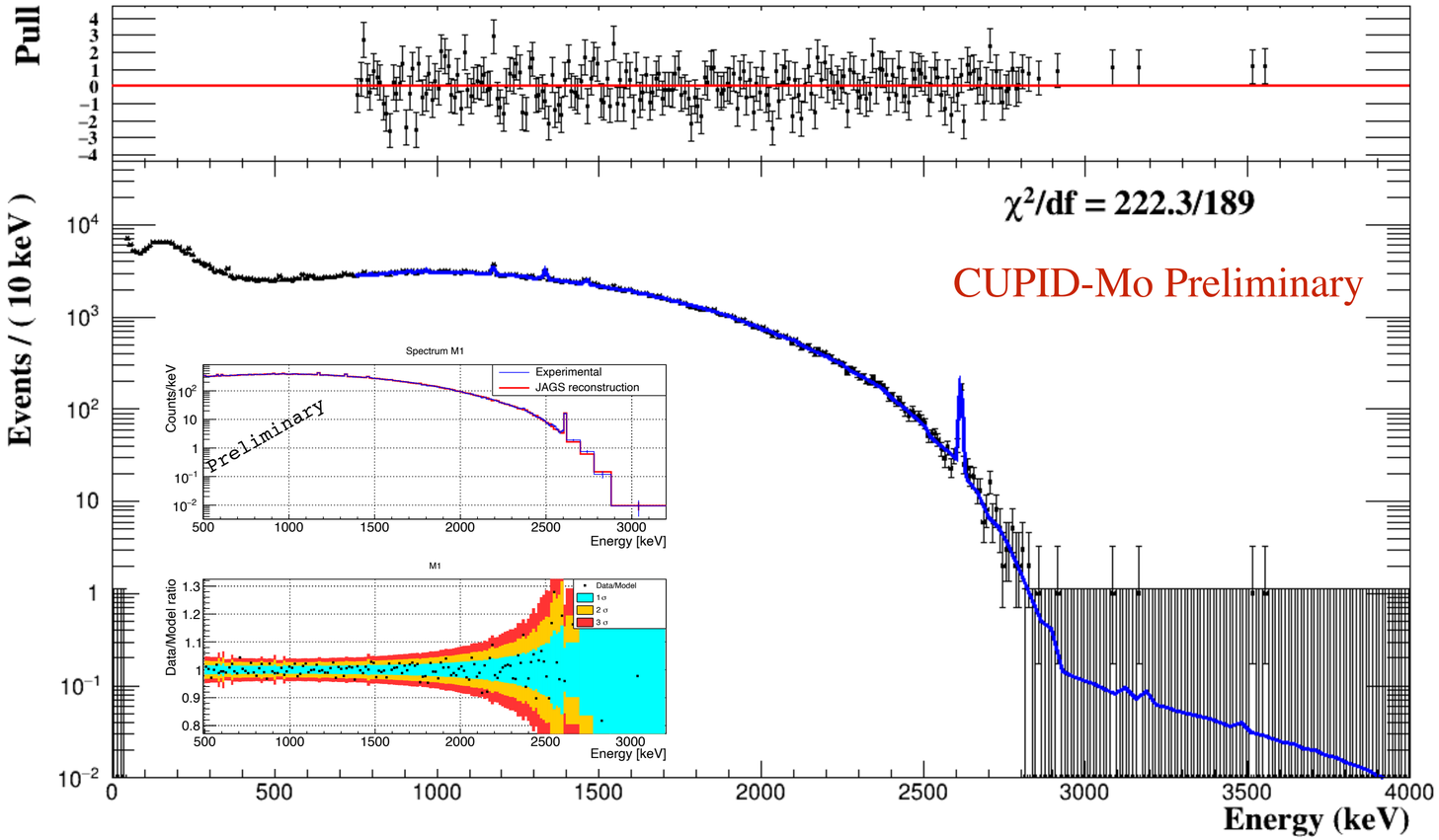


CUPID-Mo ROI definition
Bg index from Geant4 MC model

- Detailed Geant4 MC model

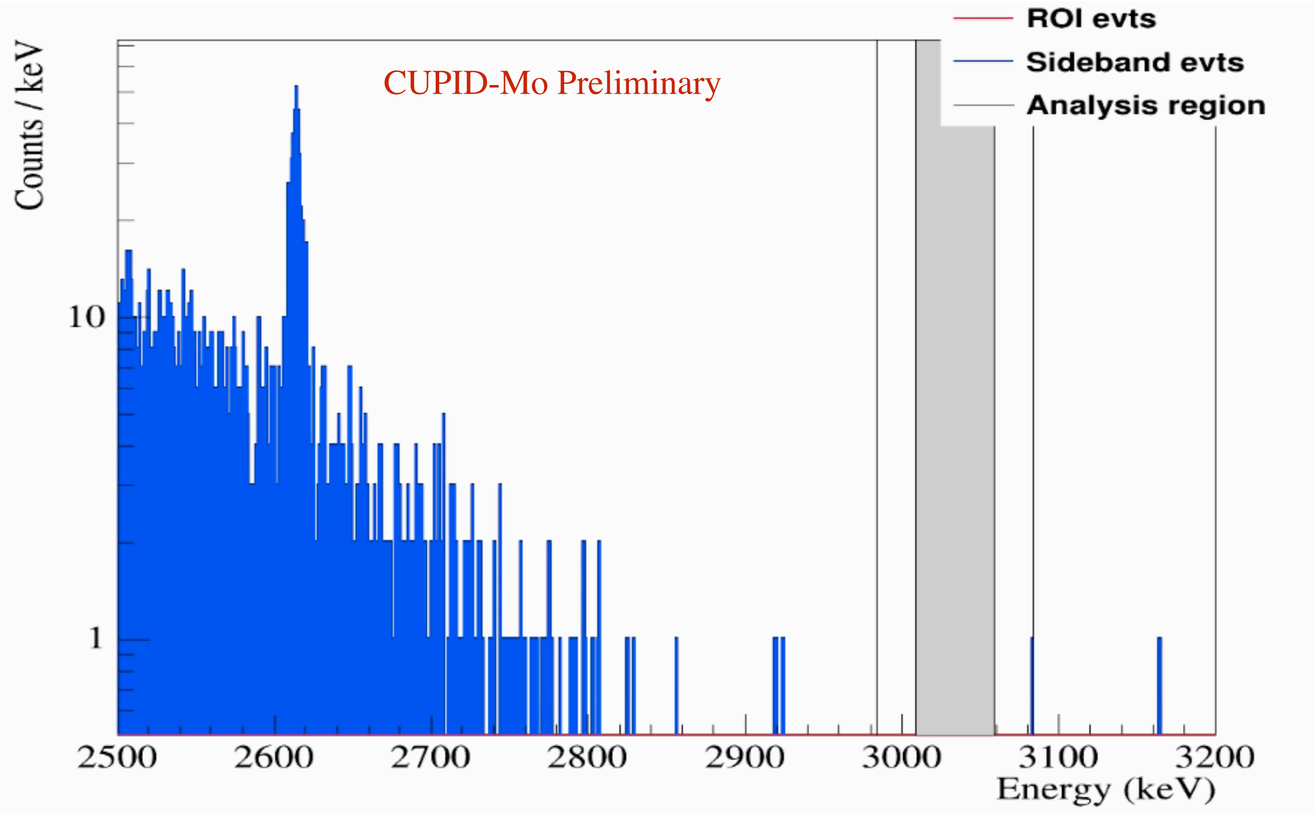


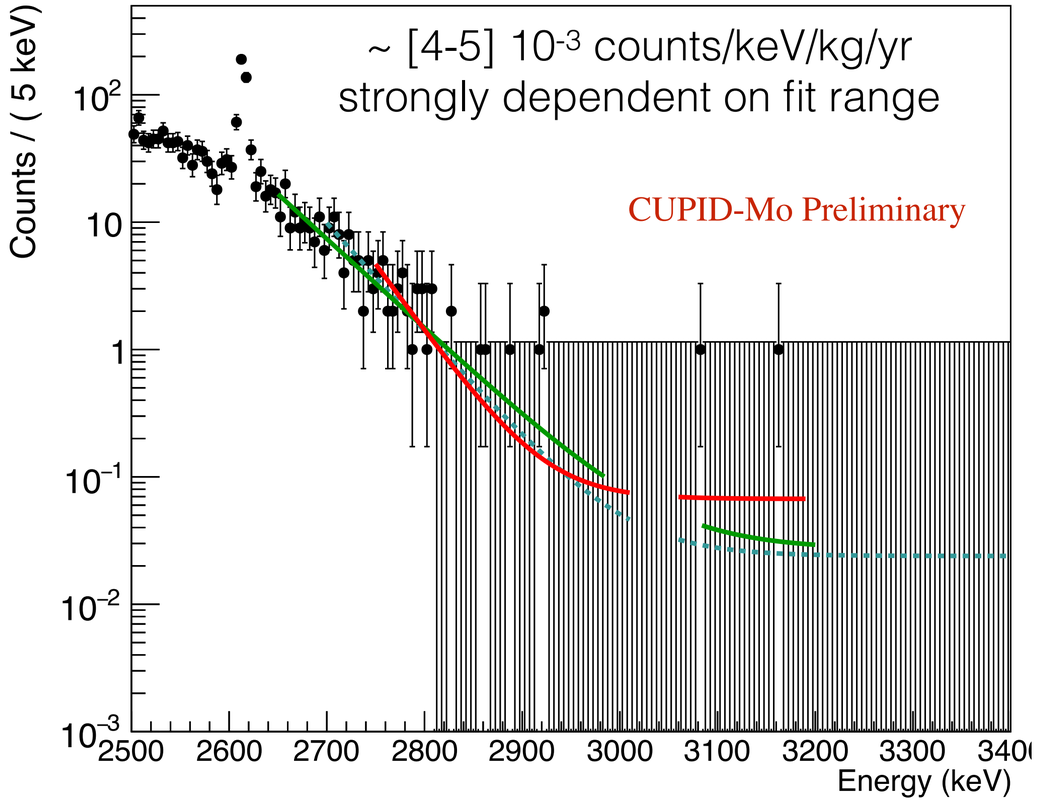
- Two fits: RooFit and JAGS (MCMC)
  - M1 - Gamma analysis: BI expectation for $0\nu\beta\beta$ ROI
    4 ± 2 counts /keV/kg/yr



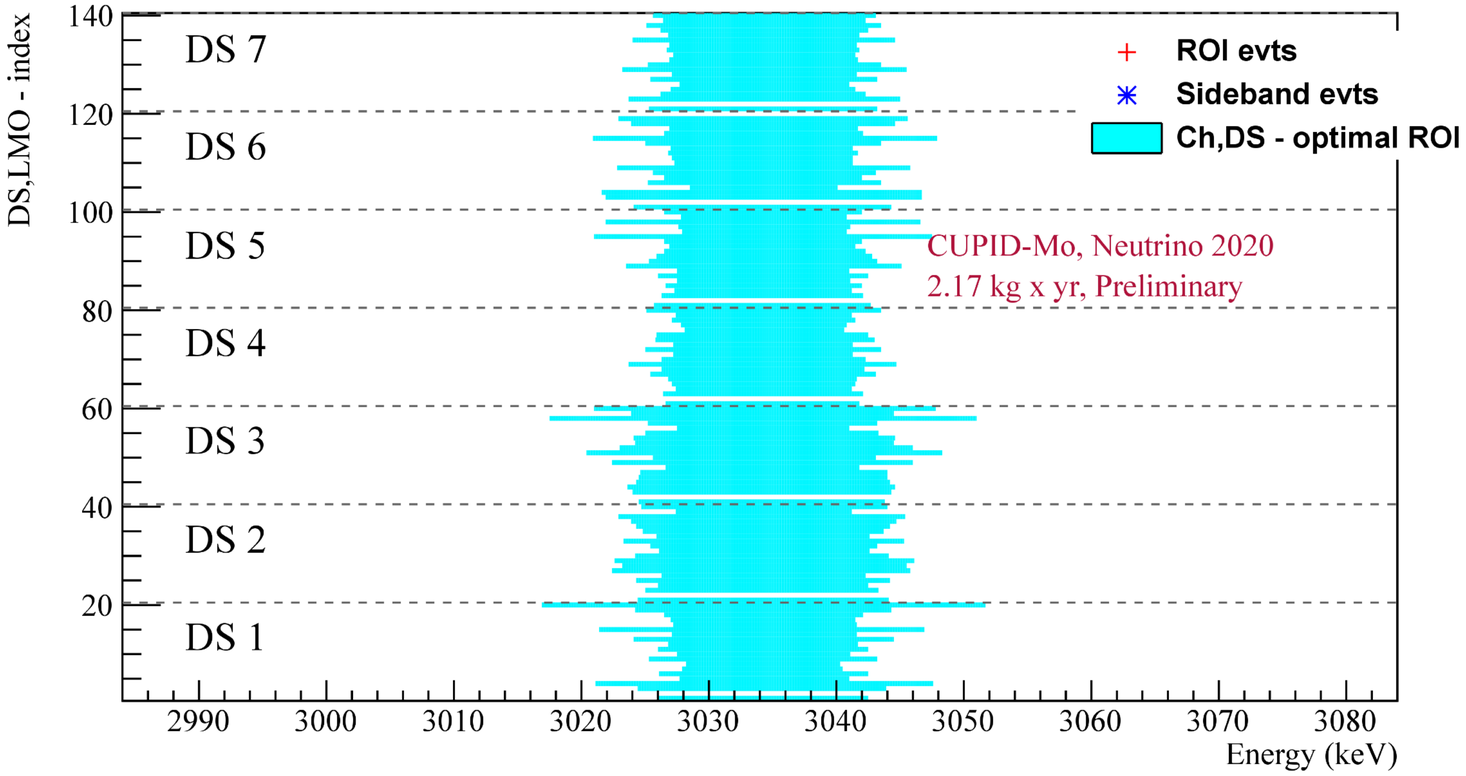
CUPID-Mo ROI definition
Bg index from sideband data

- Perform unbinned extended maximum likelihood fit on Bg data excluding [3010, 3060] keV
- Phenomenological Bg model:
  Exponential - approximates both 2νββ spectral shape and U/Th calibration tail
  Flat component - conservative estimate of 2νββ pile-up and remaining muon-induced events





CUPID-Mo - ROI

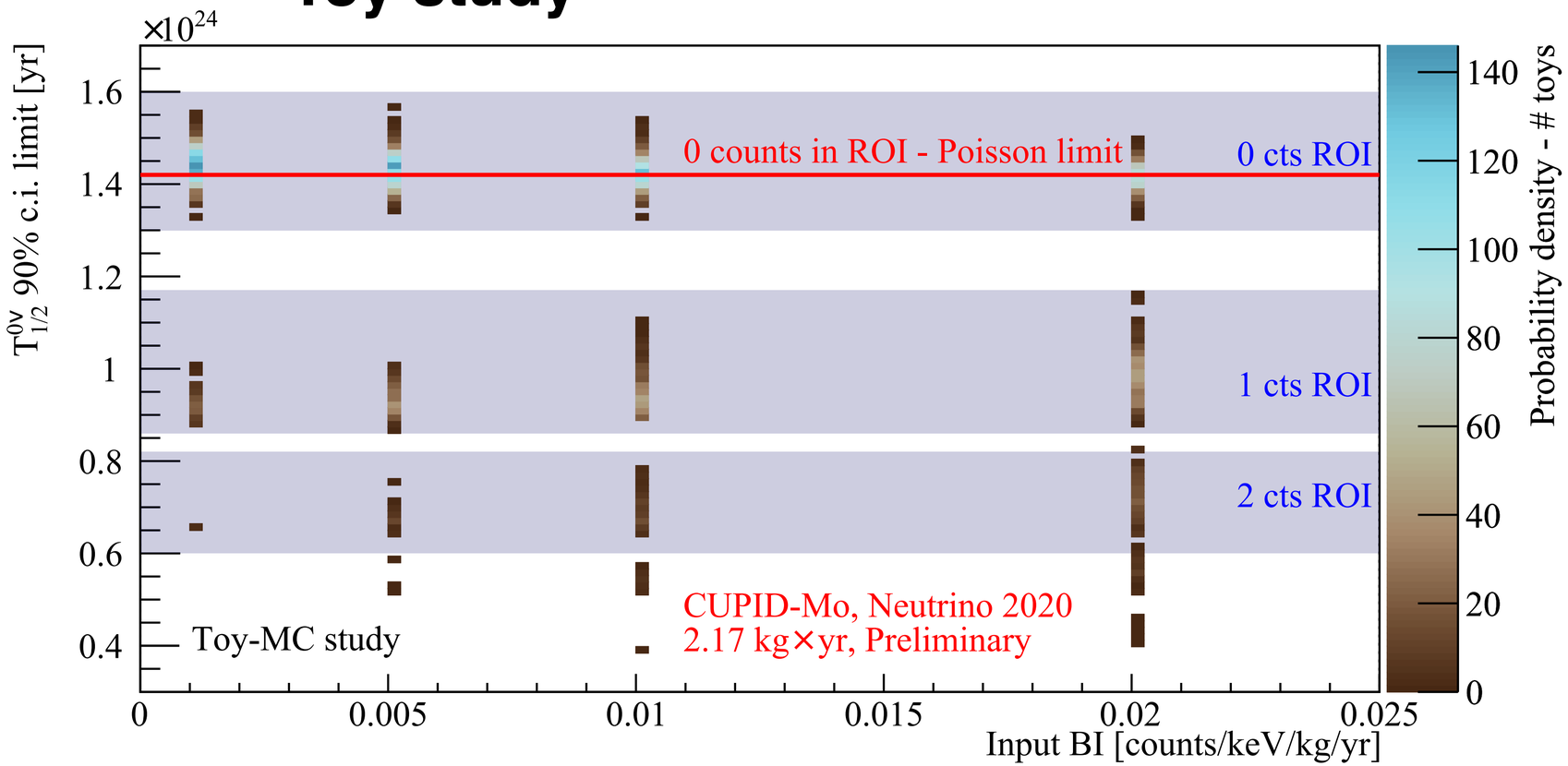


- Optimize signal ROI for Poisson counting analysis in Signal, Background likelihood space
- Maximize mean limiting setting sensitivity for a poisson counting analysis with
  - an expected final CUPID-Mo exposure of 2.8 kg x yr
  - a background index of 0.005 counts /keV/kg/yr

—> Large central ROI ~18 keV average width

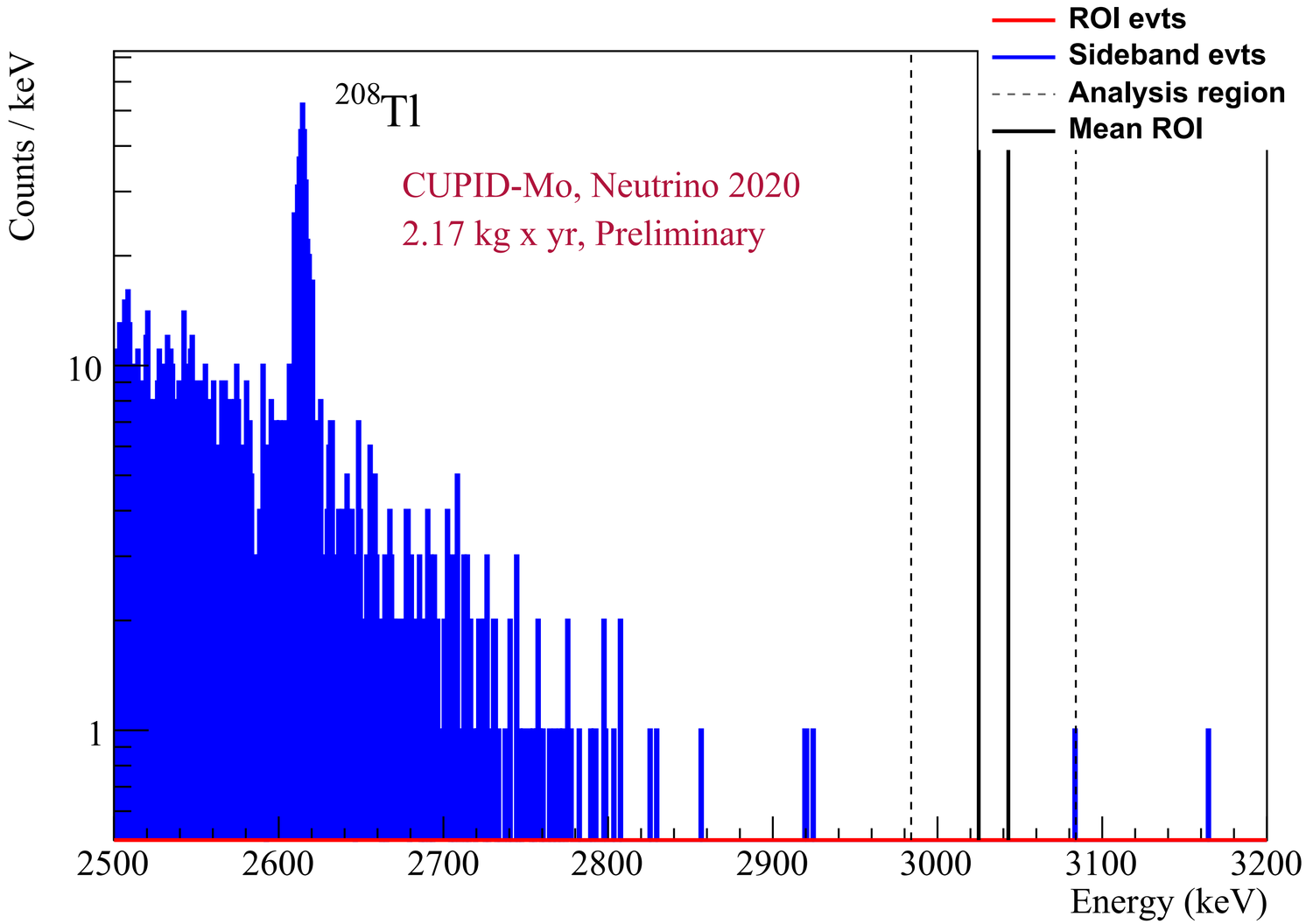
CUPID-Mo - Limit setting

Toy study



- Two analyses:
- Bayesian counting analysis in central ROI + sidebands (3 bin fit)
  - Central bin/ROI: 75% Signal & Bg
  - Sideband: 1% Signal & Bg
  - Bg: Exponential + flat
  - Use Gaussian priors on exponential from fit in [2650,2980] keV region
- Poisson counting analysis as cross-check

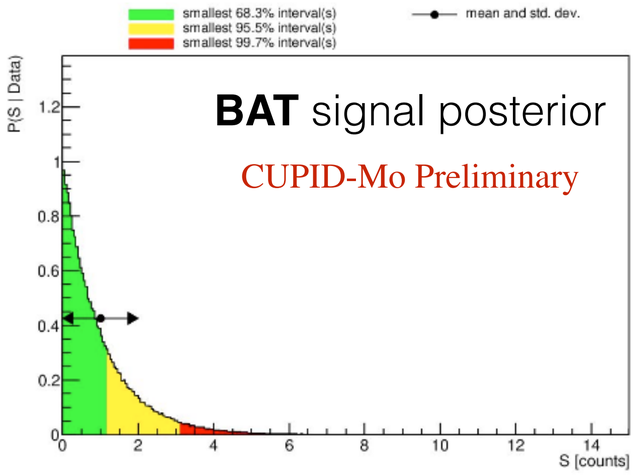
CUPID-Mo - New $0\nu\beta\beta$ result



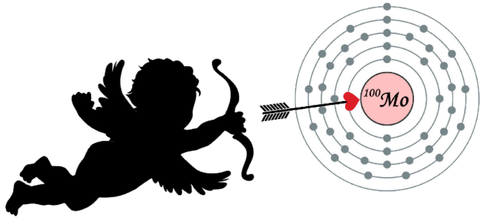
New world leading limit on $0\nu\beta\beta$ of ^{100}Mo

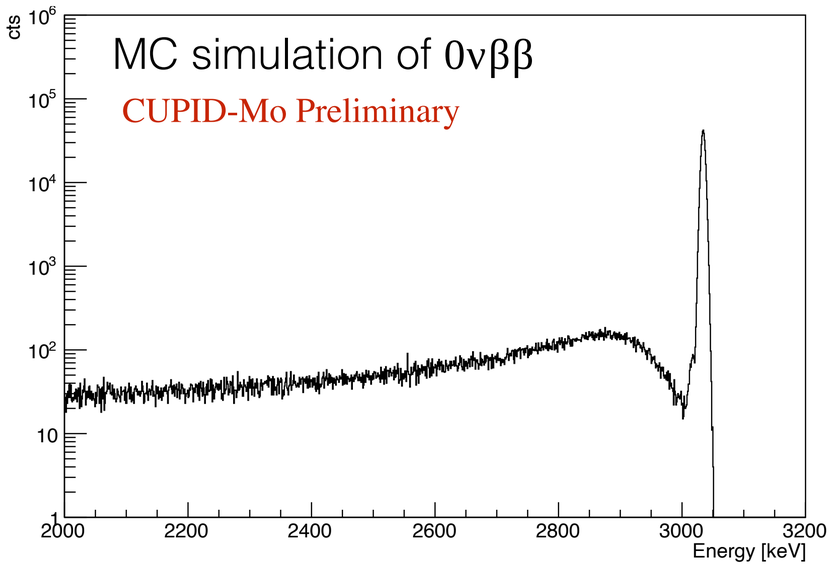
$$T^{0\nu}_{1/2} > 1.4 \cdot 10^{24}\,\mathrm{yr},\ 90\%\ \mathrm{c.i.} \quad (\mathrm{stat.} + \mathrm{syst.})$$

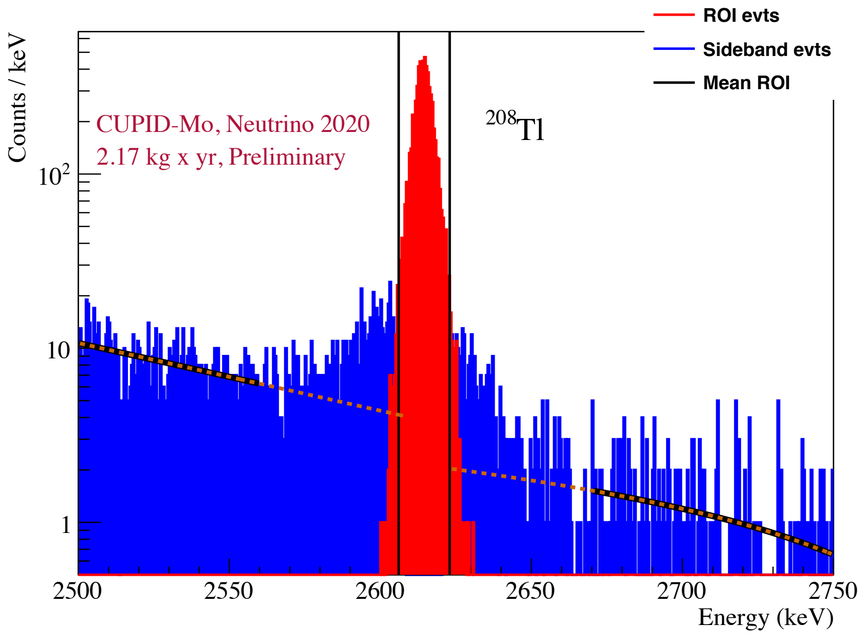
perfectly consistent with Poisson analysis



CUPID-Mo systematics





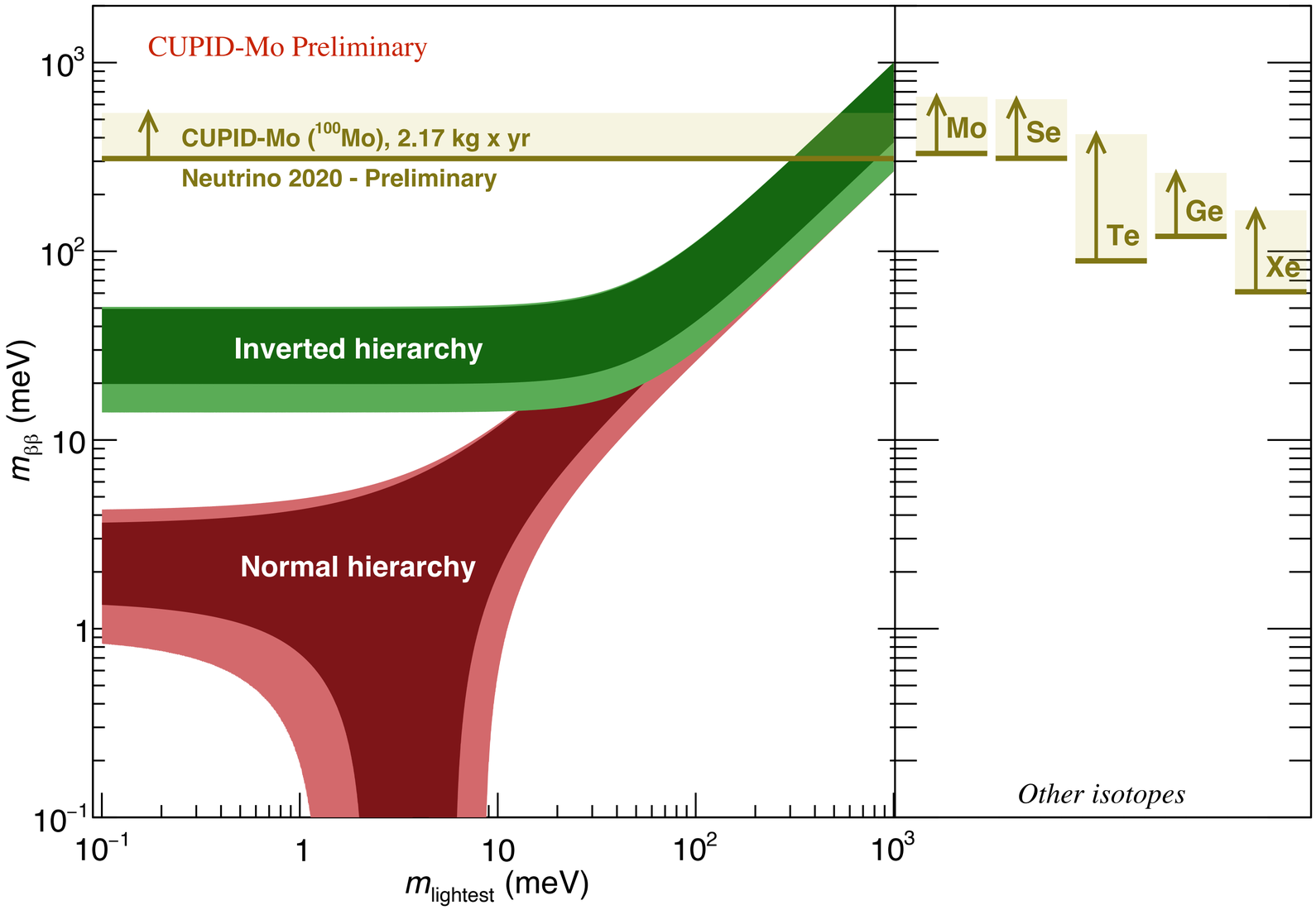


- Isotope concentration (96.6 ± 0.2) %
- Containment (~75% on average in peak)
  - Geant4 modeling & density/volume uncertainty: 1.1 %
  - Energy scale and resolution uncertainties included with MC sampling in containment of chosen ROI
- Analysis efficiency
  - All cuts stat. & PCA extrapolation - Gaussian prior
  - LD resolution model - Uniform, asymmetric

$$\epsilon = (90.5 \pm 0.4\ (\text{stat.})\ ^{+0.9}_{-0.2}\ (\text{syst.}))\ \%$$

- Potential non gaussianity - Containment reduction
  - Use 2615 keV peak in calibration data - (2.5 ± 2.5)%

CUPID-Mo - Effective Majorana Neutrino mass

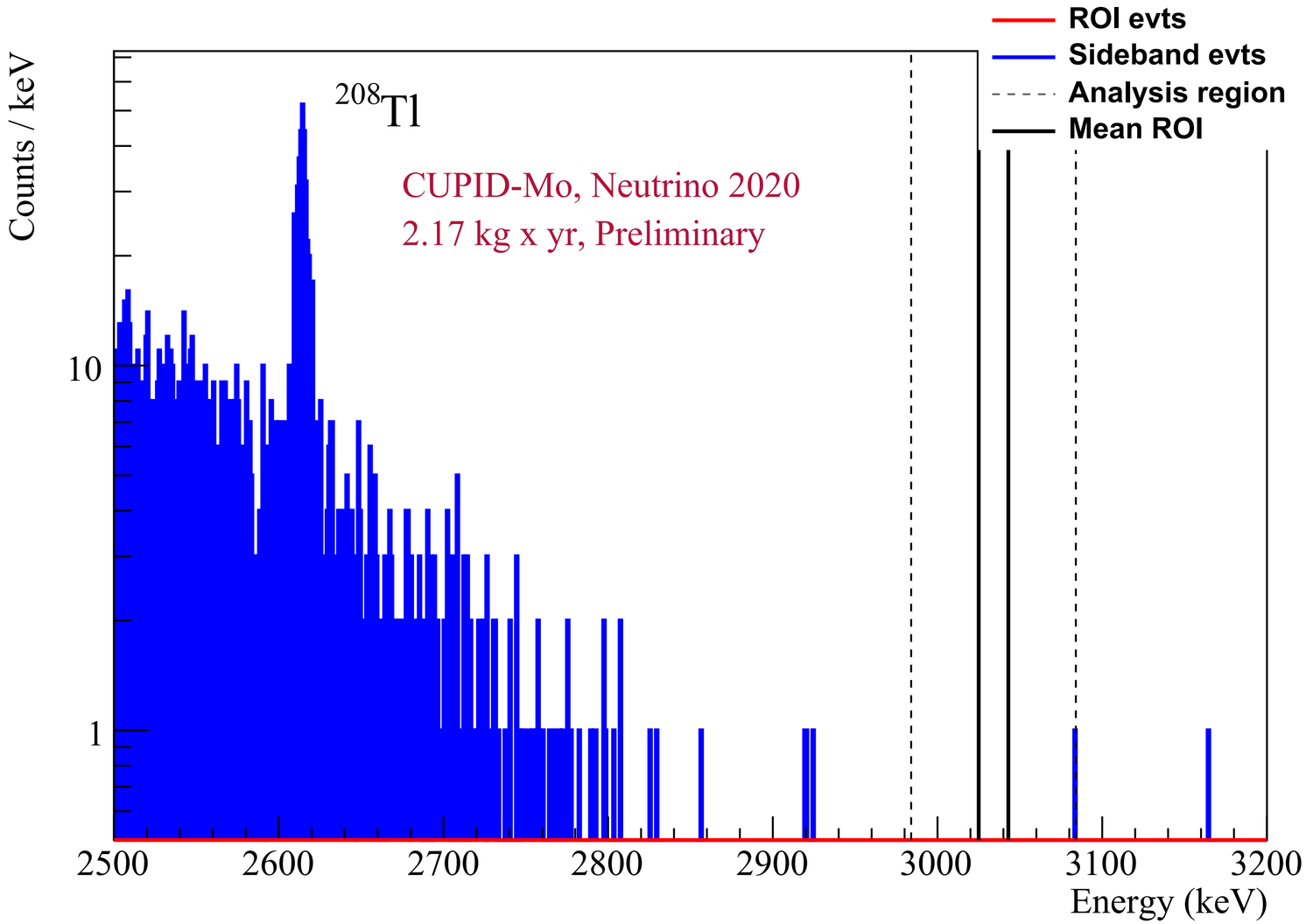


With only 1 year of data and ~2 kg of ^{100}Mo CUPID-Mo is able to set a limit of **$m_{\beta\beta}$ < (0.31-0.54) eV 90% c.i.**

considering g_A = 1.27 and the following NME calculations:

F. Šimkovic, V. Rodin, A. Faessler, P. Vogel, Phys. Rev. C 87, 045501 (2013). https://doi.org/10.1103/PhysRevC.87.045501
N.L. Vaquero, T.R. Rodríguez, J.L. Egido, Phys. Rev. Lett. 111, 142501 (2013). https://doi.org/10.1103/PhysRevLett.111.142501
J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 91, 034304 (2015). https://doi.org/10.1103/PhysRevC.91.034304
J. Hyvärinen, J. Suhonen, Phys. Rev. C 91, 024613 (2015). https://doi.org/10.1103/PhysRevC.91.024613
L.S. Song, J.M. Yao, P. Ring, J. Meng, Phys. Rev. C 95, 024305 (2017). https://doi.org/10.1103/PhysRevC.95.024305
P.K. Rath et al., Phys.Rev.C88, 064322 (2013). https://doi.org/10.1103/PhysRevC.88.064322
F. Šimkovic, A. Smetana, and P. Vogel, Phys. Rev. C 98, 064325 (2018). https://doi.org/10.1103/PhysRevC.98.064325
P.K. Rath, Ramesh Chandra, K. Chaturvedi and P. K. Raina, Front. Phys. 64, 1 (2019). https://doi.org/10.3389/fphy.2019.00064

CUPID-Mo at Neutrino 2020



New world leading limit on $0\nu\beta\beta$ of ^{100}Mo,
Neutrino 2020 poster #419

$$T^{0\nu}_{1/2} > 1.4 \cdot 10^{24}\,\mathrm{yr},\ 90\%\ \mathrm{c.i.}\quad (\mathrm{stat.} + \mathrm{syst.})$$

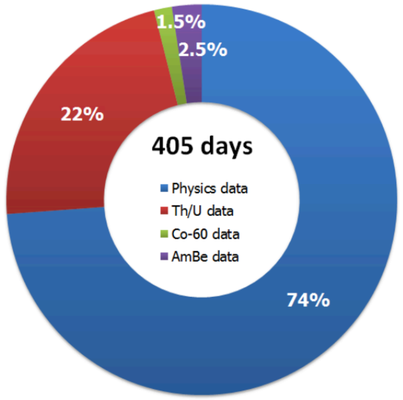
- $2\nu\beta\beta$ result, CUPID-Mo technology
  (arXiv: 1912.07272), **Neutrino 2020 poster #525**

$$T^{2\nu}_{1/2} = \left[7.12^{+0.18}_{-0.14}\ (\mathrm{stat.}) \pm 0.10\ (\mathrm{syst.})\right] \cdot 10^{18}\ \mathrm{yr}$$

- Preliminary status/results from Bg model analysis
  Neutrino 2020 poster #418
  - Bg index of [4 - 5] x 10^{-3} counts/keV/kg/yr in $0\nu\beta\beta$ ROI with non-optimized setup for dark matter search, (lower than expected)

- Further CUPID-Mo updates at NEUTRINO 2020:
  - $0\nu\beta\beta/2\nu\beta\beta$ decay to excited states & low energy prospects, ^{56}Co high energy calibration
    Neutrino 2020 posters #374, #382, #448

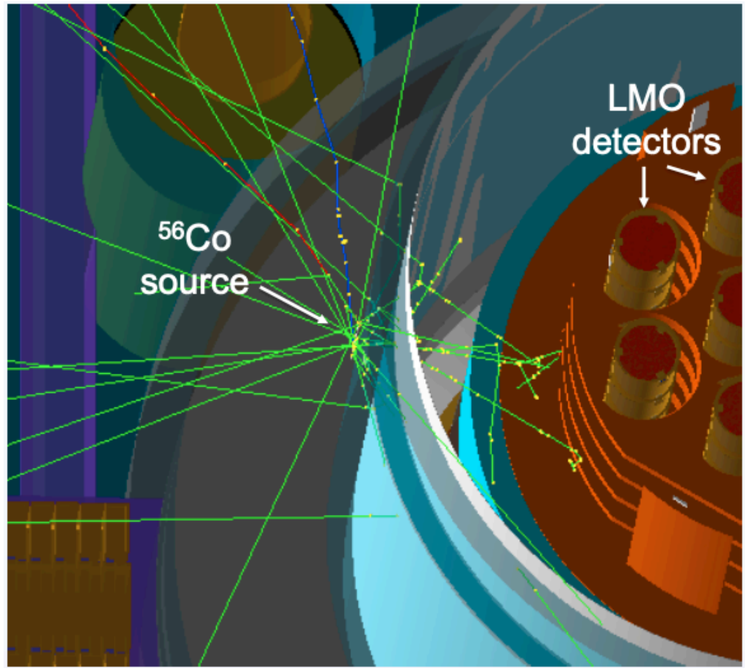
CUPID-Mo - What's next ?

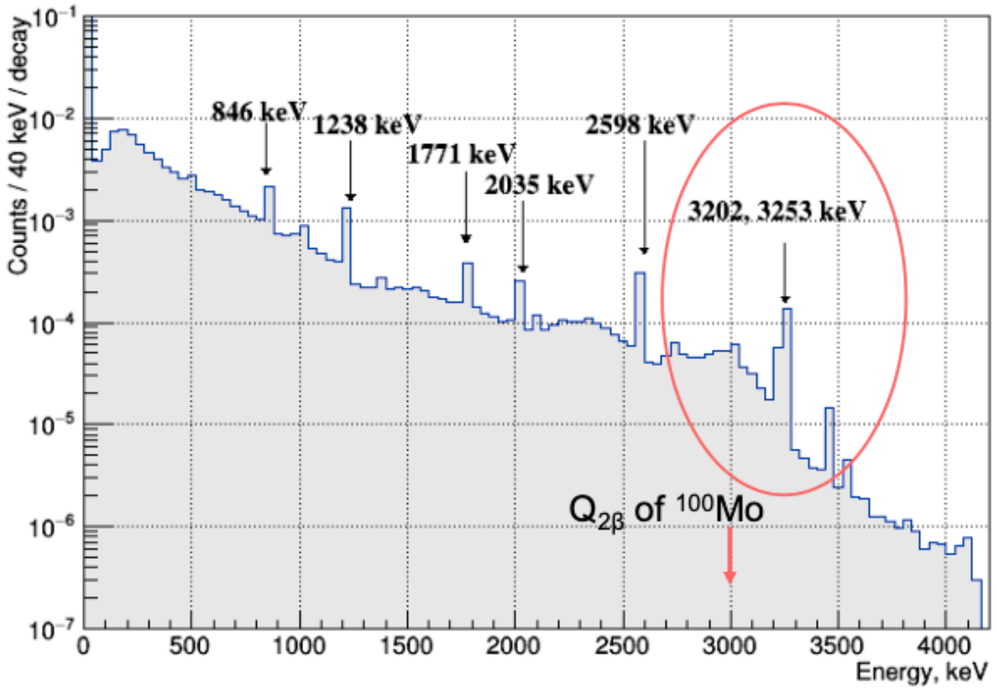


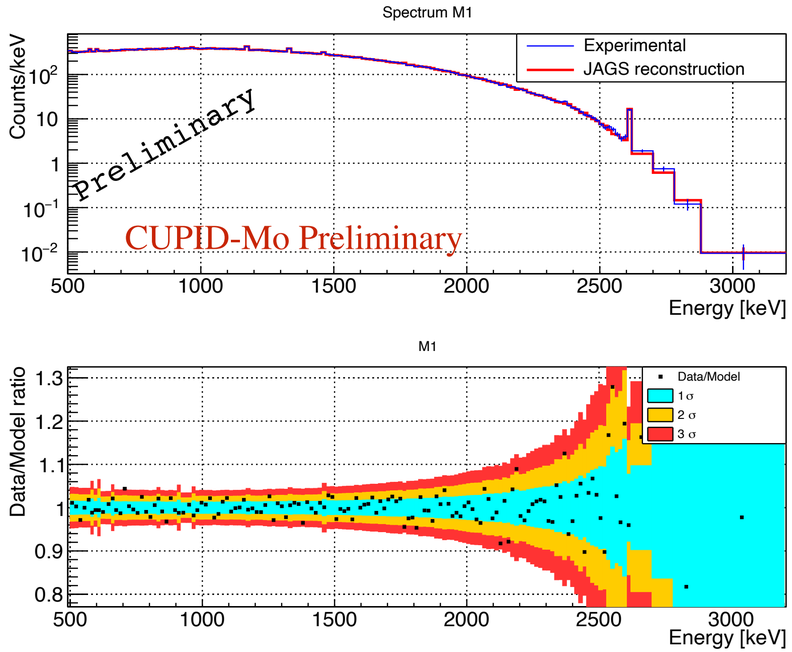
Physics data taking finished as of June 20th
2.8 kg x yr total (before cuts) - 20-30 % more data

Currently ongoing high energy calibration campaign
Fe wire irradiated at 88-inch (LBNL) in collaboration by
Andew Voyles and Rick Normann -> ~660 Bq activity in ^{56}Co
Currently deployed at Laboratoire Souterrain de Modane

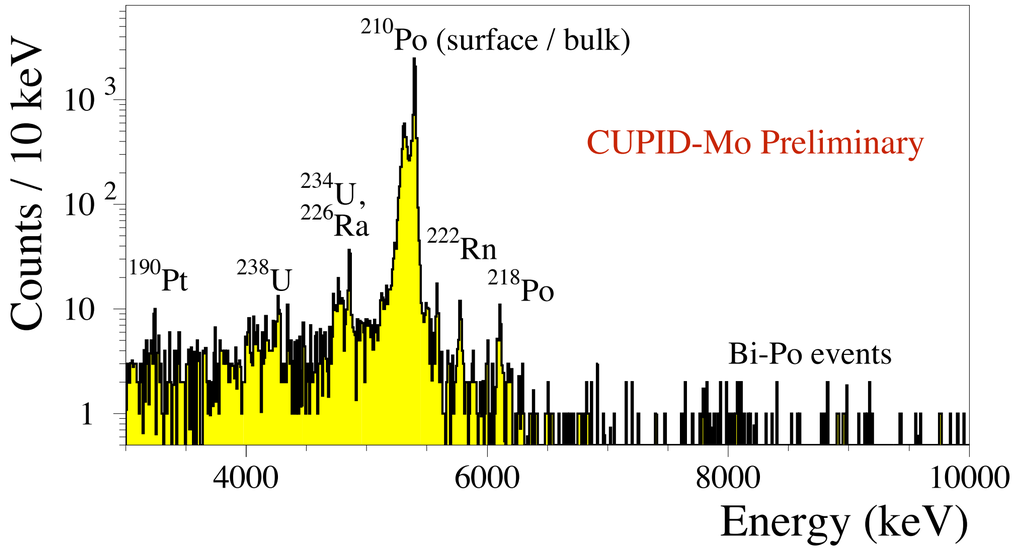
Next up:
Focus on Bg model and
2νββ precision analyses,
0νββ/2νββ to excited states
and low mass dark matter search

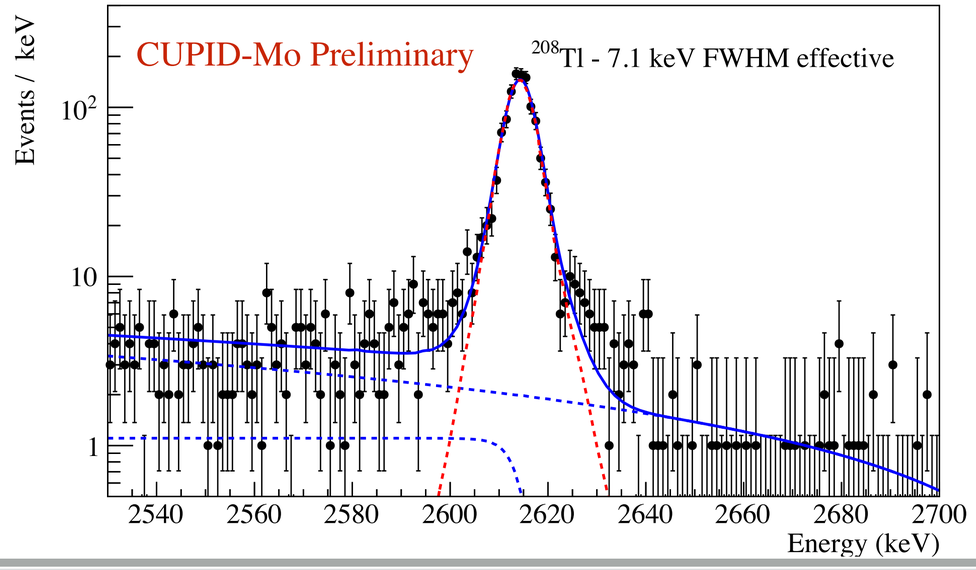






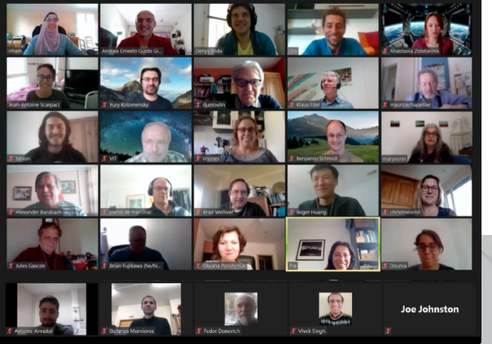
CUPID-Mo results for CUPID





- Excellent crystal radiopurity (**Neutrino 2020 poster #404)**
  - [0.3 - 1] µBq/kg for U/Th
    100 µBq/kg ^{210}Pb
- Li_2MoO_4 bolometric performance in non-optimal environment
  - Efficient alpha rejection over 1 year of data taking
    - LD performance hit due to AC-biasing/demodulation sampling limitation (0.5 kHz)
  - High analysis efficiency $\epsilon = (90.5 \pm 0.4\ (\text{stat.})\ ^{+0.9}_{-0.2}\ (\text{syst.}))\ \%$
  - ~7 keV calibration resolution @ 2615 keV
    ~8 keV physics resolution @ 3034 keV
    - ~20 mK instead of ~10-15 mK
    - Sub-optimal/(No) heater based gain-stabilization

The CUPID-Mo collaboration



Zoom Unblinding

UCB and LBNL led analysis team: Giovanni Benato, Toby Dixon, Roger Huang, Laura Marini, Benjamin Schmidt, Vivek Singh and Bradford Welliver

Backup

Neutrino 2020 Poster links:

CUPID-Mo $0\nu\beta\beta$ analysis
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-419.pdf

CUPID-Mo performance
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-404.pdf

CUPID-Mo 56Co calibration campaign
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-374.pdf

CUPID-Mo background model
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-418.pdf

CUPID-Mo low energy analysis prospects
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-448.pdf

CUPID-Mo sensitivity for $0\nu\beta\beta/2\nu\beta\beta$ decay to excited states
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-382.pdf

2nbb analysis with CUPID-Mo technology
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-525.pdf