Monday
June 29th, 2020
11:00 AM

# CUPID-Mo: a new limit on neutrinoless double beta decay of $^{100}$Mo


Andrea Giuliani

*On behalf of the CUPID-Mo collaboration*


A2C Astroparticles, Astrophysics & Cosmology

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

# Beta decays and new phsyics

Single β decay $$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$

**Wolfgang Pauli**,
"Letter to the radioactive ladies and gentlemen",
(1930)

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

**Enrico Fermi**,
"Attempt at a beta-ray emission theory",
(1933)

VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

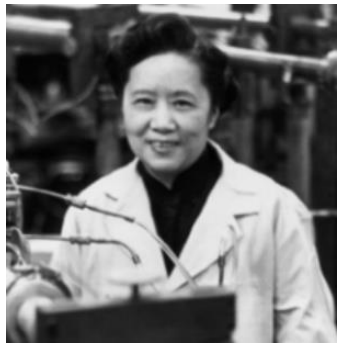
Note del prof. ENRICO FERMI

**Riassunto:** Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

# Beta decays and new phsyics

## $^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e$

**Chieng-Shiung Wu**,
Parity Violation
(1956)



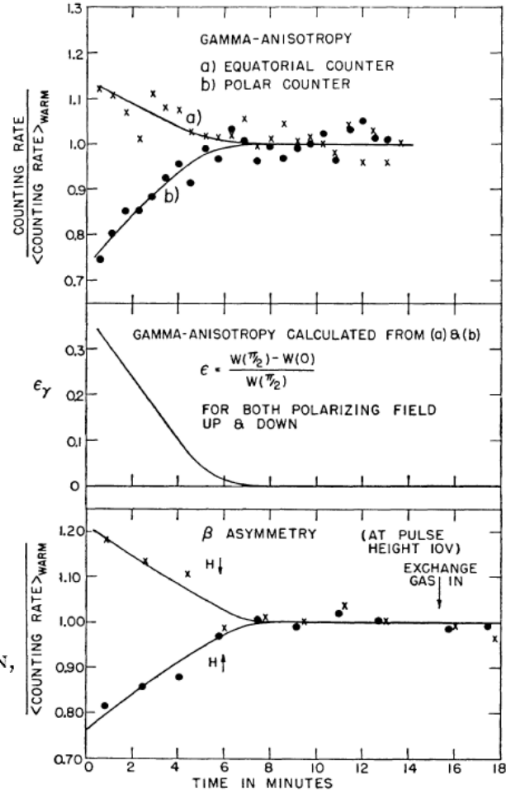
**Experimental Test of Parity Conservation in Beta Decay***

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

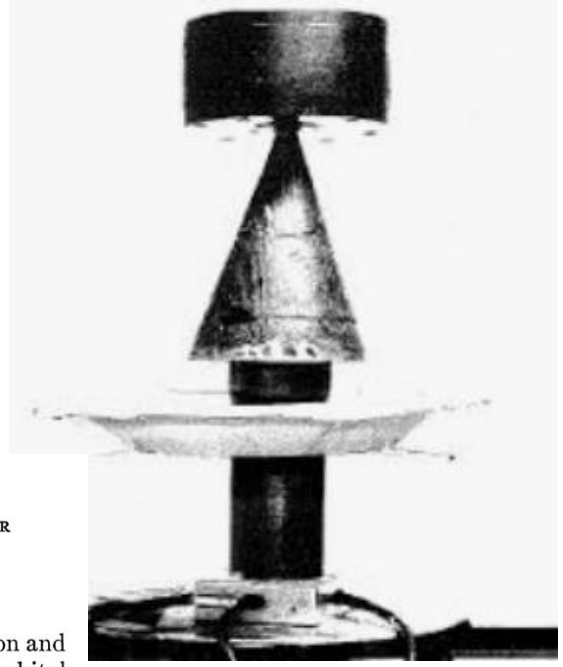
(Received January 15, 1957)




**At millikelvin temperatures!**

## $Eu + e^- \rightarrow Sm^* + \nu_e \rightarrow Sm + \gamma + \nu_e$

**Maurice Goldhaber**,
Helicity of neutrinos
(1957)



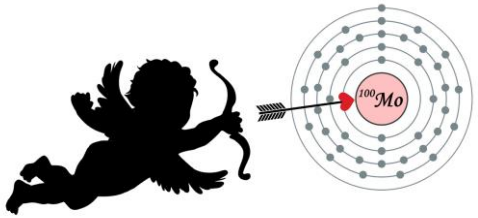
**Helicity of Neutrinos***

M. Goldhaber, L. Grodzins, and A. W. Sunyar

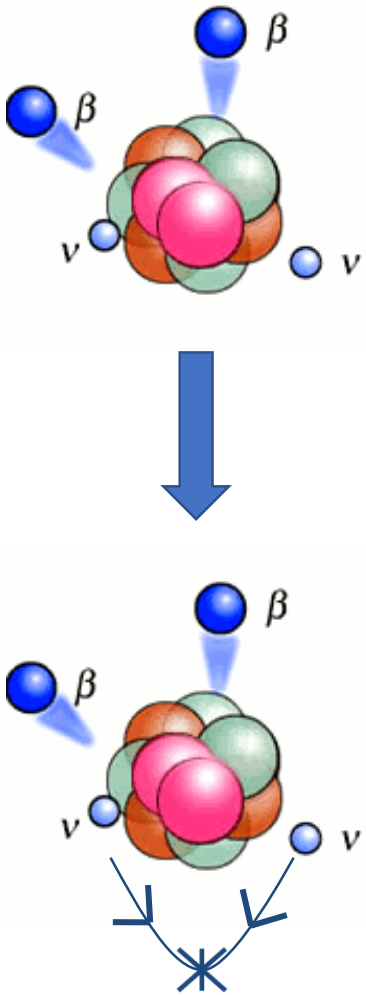
*Brookhaven National Laboratory, Upton, New York*

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of $\gamma$ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with $Eu^{152m}$, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).




# Double beta decay



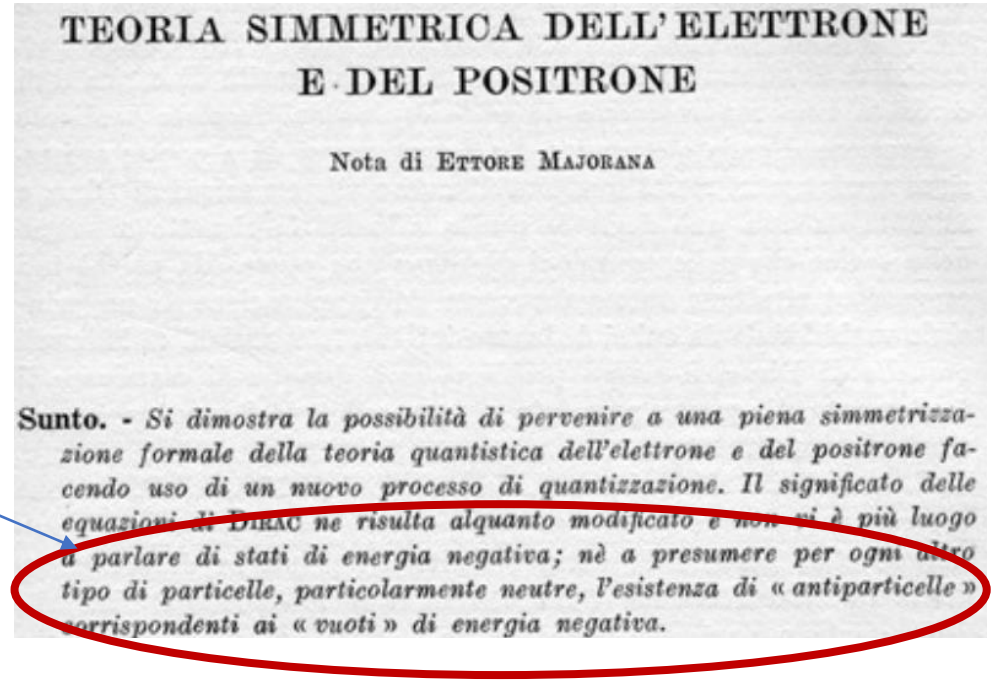

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e \qquad 2\nu2\beta$$

**Ettore Majorana**

"No reason to assume the existence of antiparticles for neutral particles"

$$\nu \equiv \bar{\nu}$$

**Nuovo Cimento 14( 1937 )171-184**

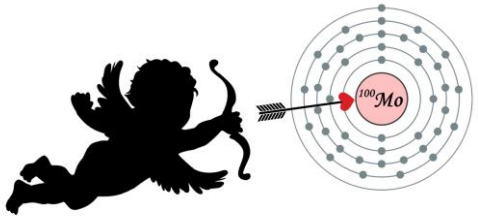


TEORIA SIMMETRICA DELL' ELETTRONE E DEL POSITRONE

Nota di Ettore Majorana

**Sunto.** - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di Dirac ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

$$(A,Z) \rightarrow (A,Z+2) + 2e^- \qquad 0\nu2\beta$$

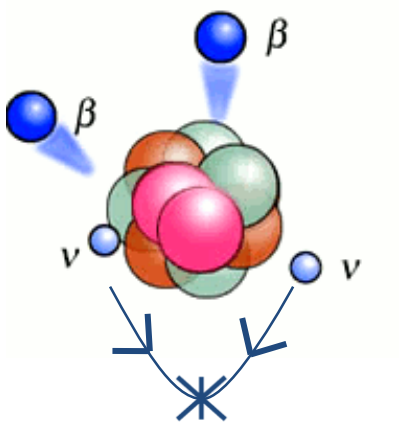


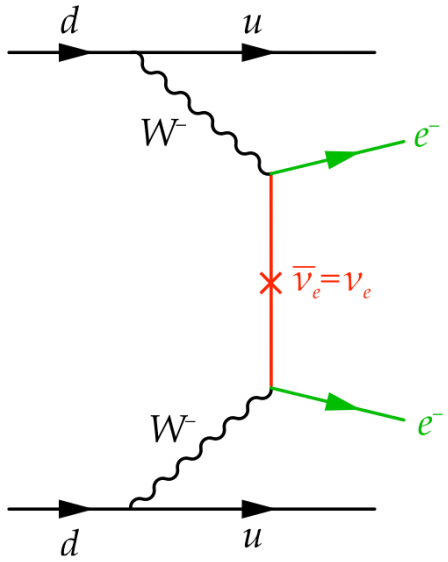

# $0\nu2\beta$ and its implications

**Neutrinoless double beta decay is the only experimentally viable process that can ascertain the Majorana nature of neutrinos**

- New form of matter: **self-conjugate fermions**
- Natural extension of Standard Model, with **Majorana mass term** (in addition to Higgs mechanism)
- Fix the **neutrino mass scale** (not accessible to $\nu$ oscillation experiments)
- Explain **smallness of neutrino masses** (See-saw mechanism)
- Can explain **matter / antimatter asymmetry** in the Universe (Leptogenesis)

# Light Majorana neutrino exchange




## Two key formulae

**0ν2β decay rate**

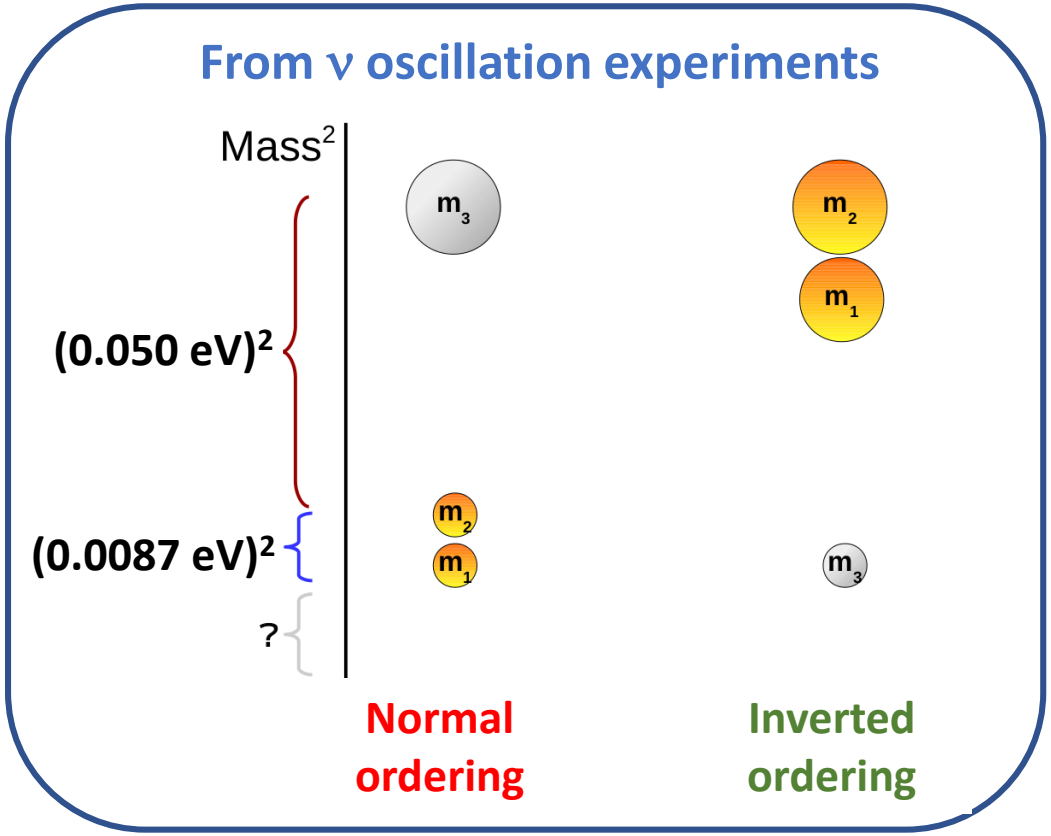
$$1/\tau = G^{0\nu}\, g_A^{\,4}\, |M^{0\nu}|^2 m_{\beta\beta}^{\,2}$$

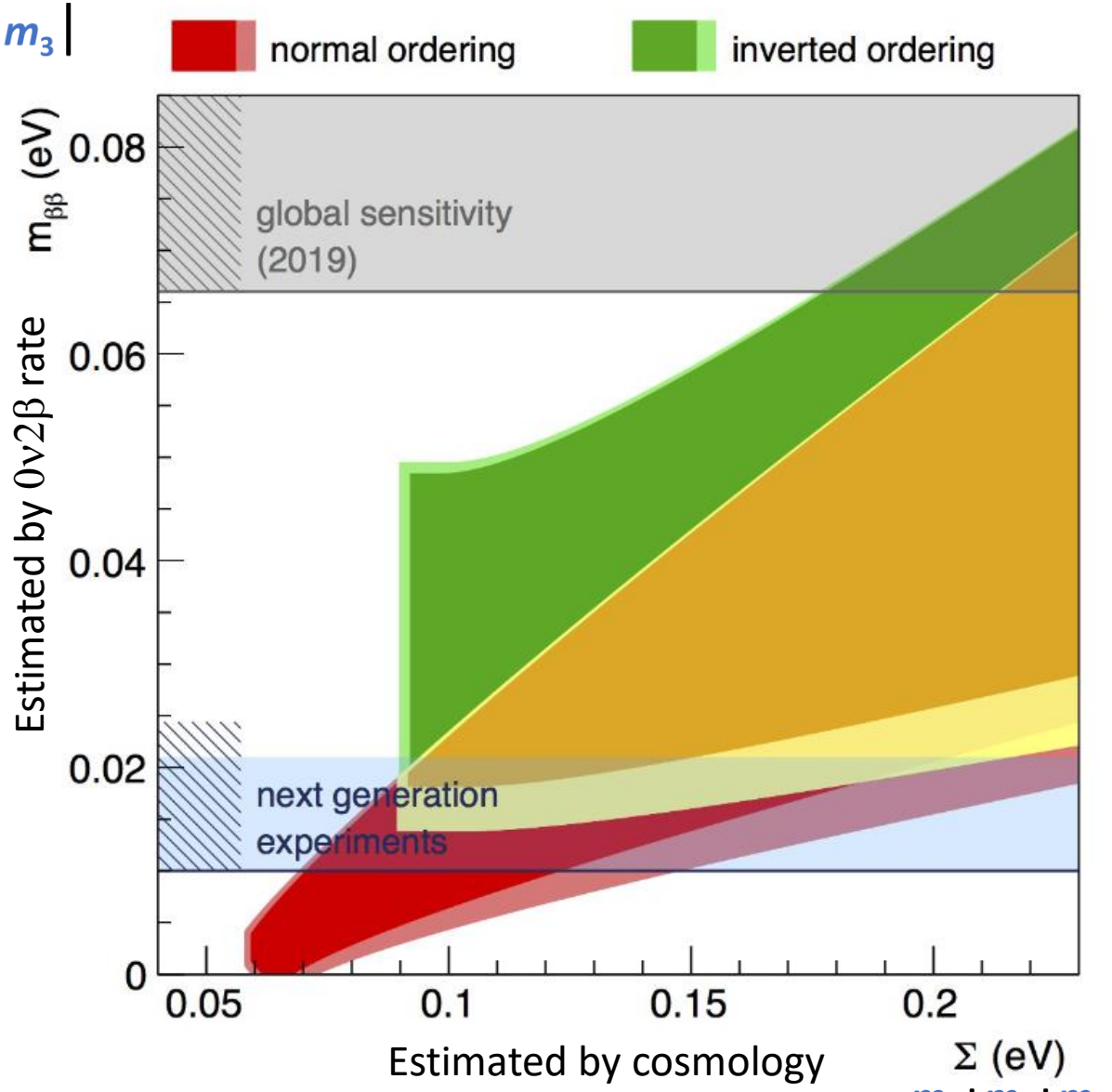
**Effective Majorana neutrino mass**

$$m_{\beta\beta} = \left| \, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$

# Light Majorana neutrino exchange

$$m_{\beta\beta} = \left| \, |U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3 \right|$$

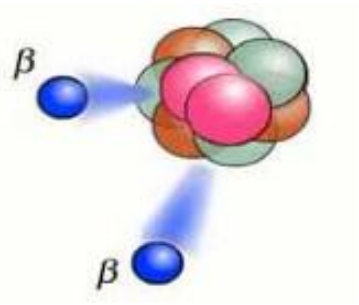


# 0ν2β : other mechanisms

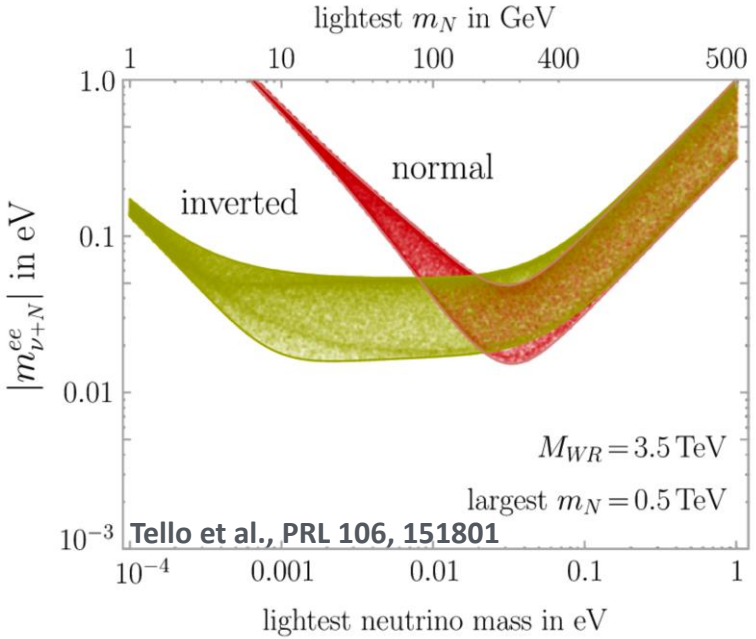
0ν2β is an inclusive test for the « creation of leptons »:

**2n → 2p + 2e⁻ ⇒ LNV (Letpon Number Violation)**



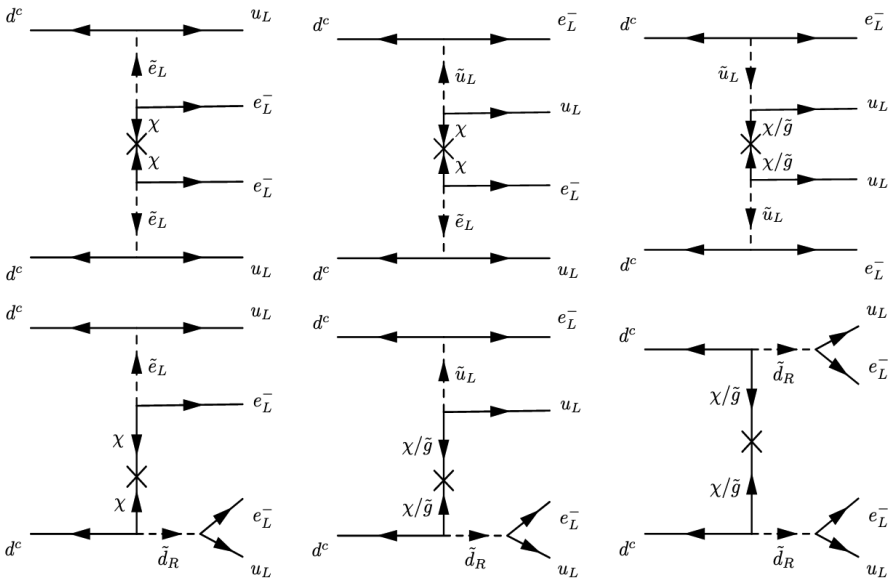

This test is implemented in the nuclear matter: **(A,Z) → (A,Z+2) + 2e⁻**

Left - Right symmetric models




Tello et al., PRL 106, 151801

R-Parity violating SUSY models



W. Rodejohann et al., Int. J. Mod. Phys E 20, 09, 1833

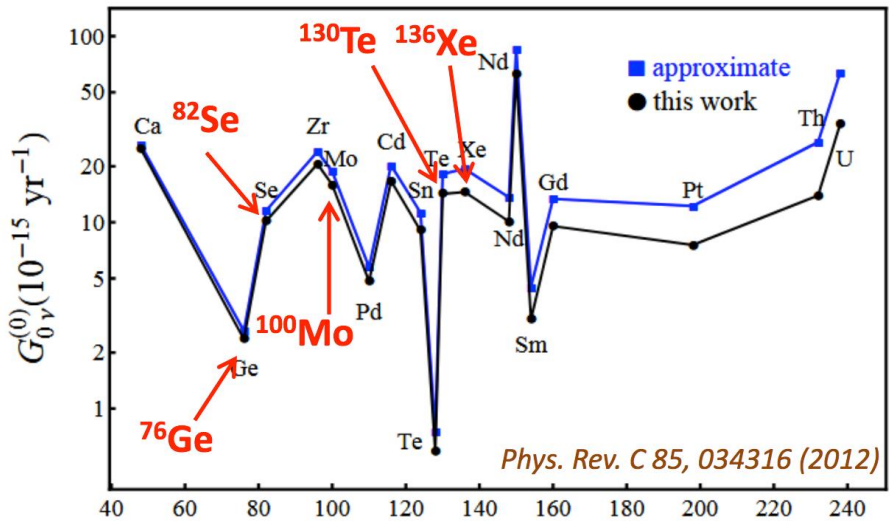
# 0ν2β : the challenge

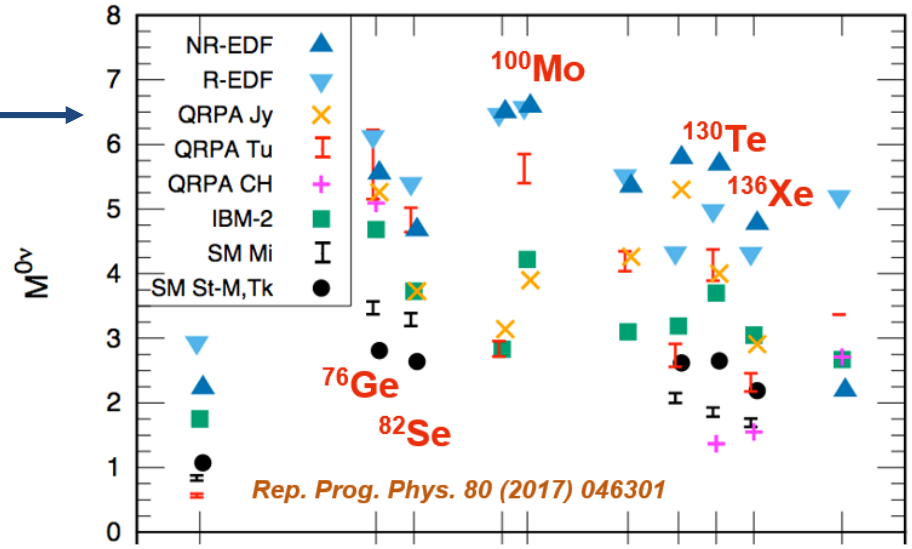
**0ν2β decay rate**

$$1/\tau = G^{0\nu}\, g_A^{\,4}\, |M^{0\nu}|^2 m_{\beta\beta}^{\,2}$$

**Effective Majorana neutrino mass**

$$m_{\beta\beta} = \left| \, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$



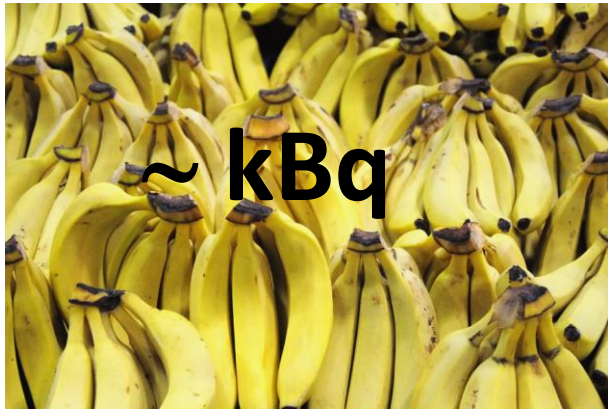



# 0ν2β : the challenge

Look for single events in a ton x year exposure

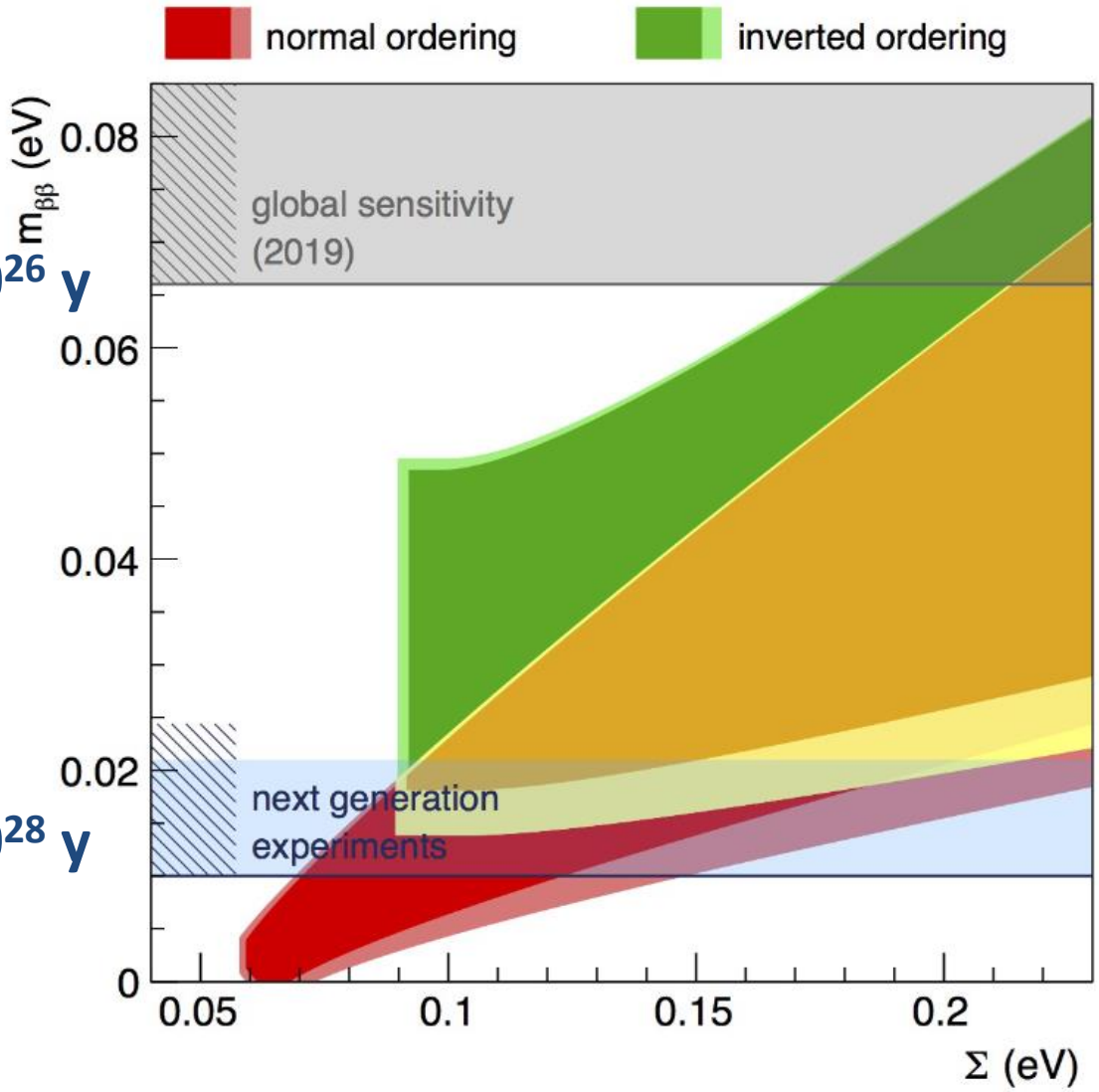
Look for radioactivity of $3 \times 10^{-14}$ Bq/g

Limited by ubiquitous radioactivity



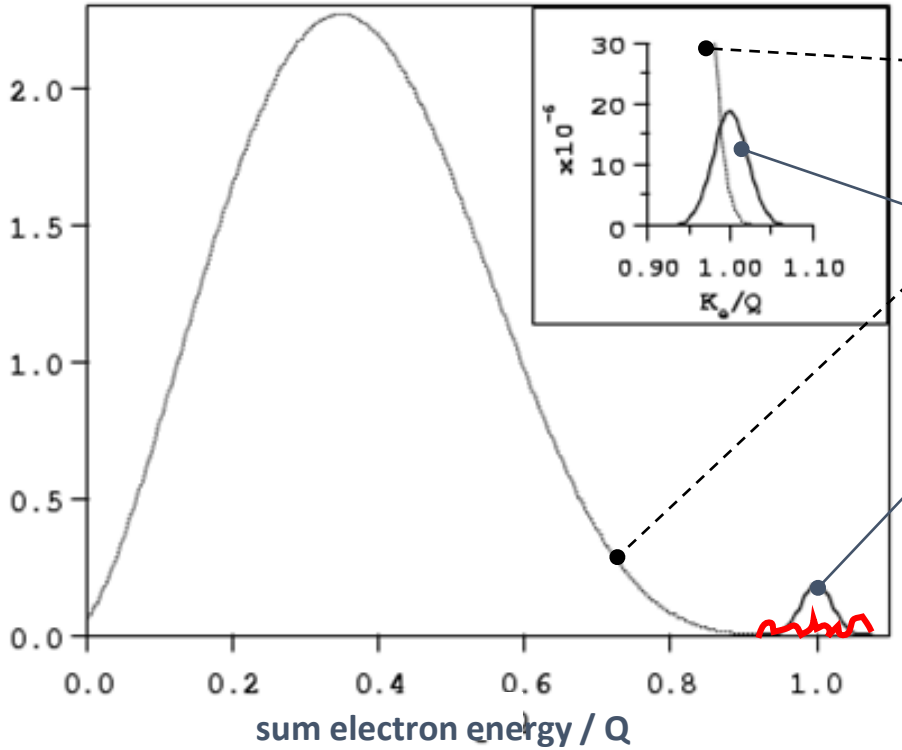

$T^{0\nu}_{1/2} \sim 10^{25} - 10^{26}$ y

$T^{0\nu}_{1/2} \sim 10^{27} - 10^{28}$ y



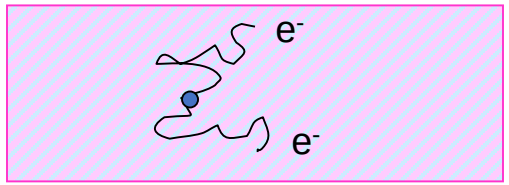
# Searching for 0ν2β

The **shape of the two-electron sum-energy spectrum** enables to distinguish between the **0ν** (new physics) and the **2ν** decay modes



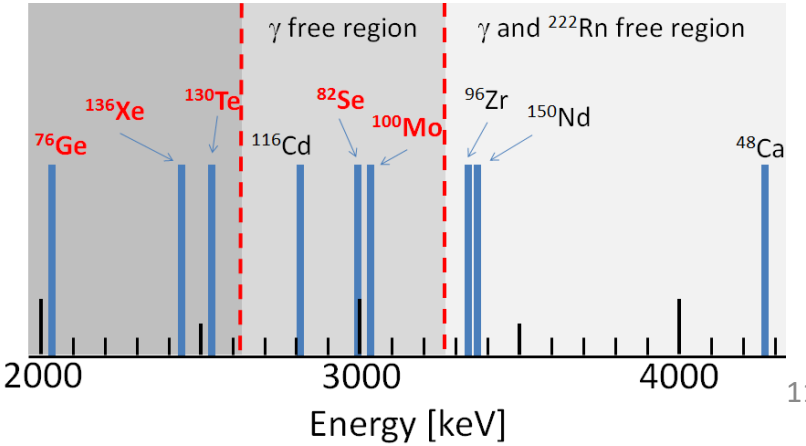

**2νββ: (A,Z)→(A,Z+2)+2e+2ν**
**Continuum** with maximum at ~1/3 Q

**0νββ: (A,Z)→(A,Z+2)+2e**
**Peak** enlarged only by the detector energy resolution




Source ≡ Detector
(calorimetric technique)

Q ~ 2-3 MeV for the most promising candidates



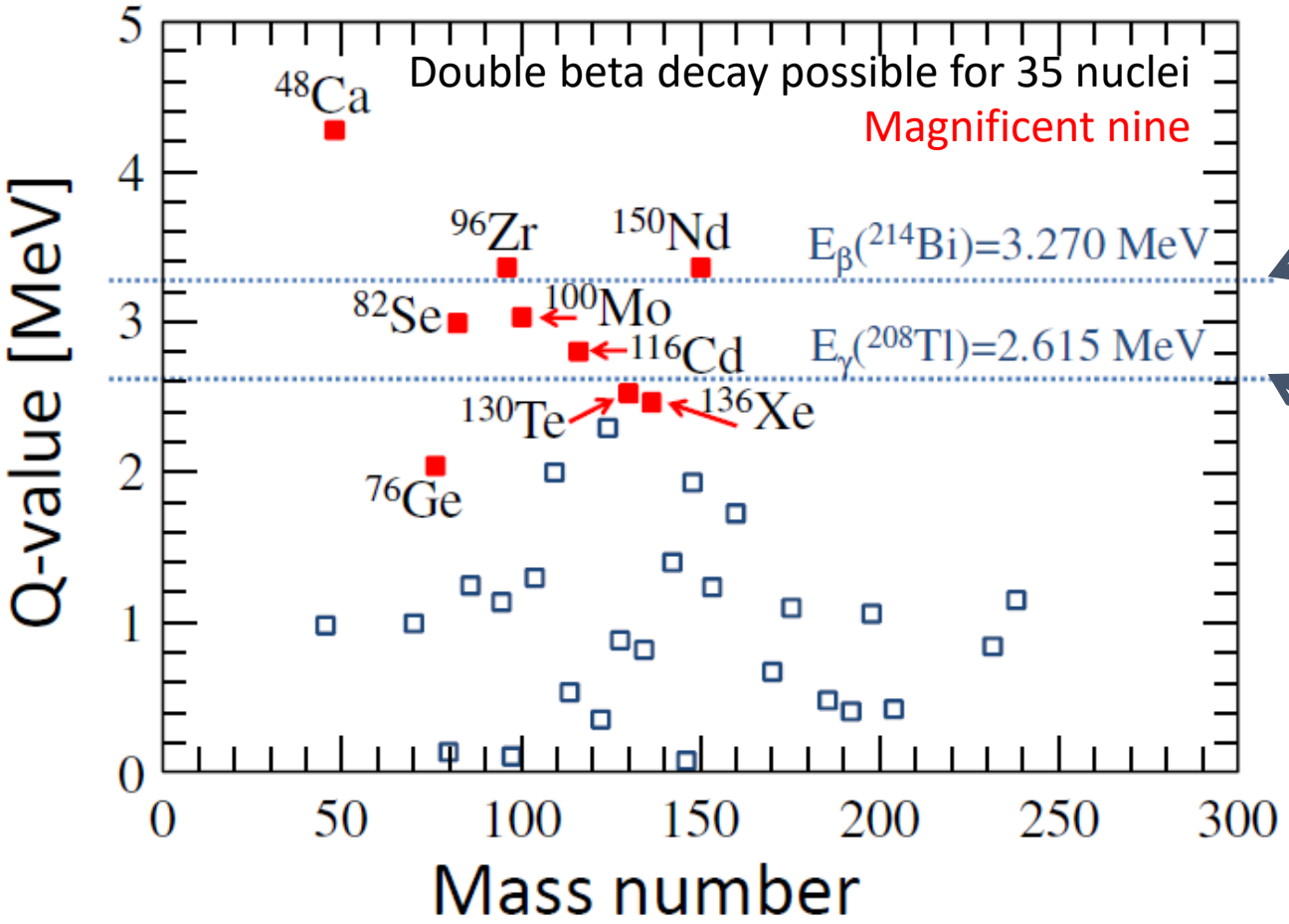

**Backround index b**
counts/(keV kg y)

The signal is a **peak (at the Q-value)** over an almost flat **background**

# Isotope, enrichment and technique

**Q** is the crucial factor – the higher the better

- Phase space: $G^{0\nu} \propto Q^5$
- Background




End-point of $^{222}$Rn-induced radioactivity

End-point of natural γ radioactivity

# Isotope, enrichment and technique

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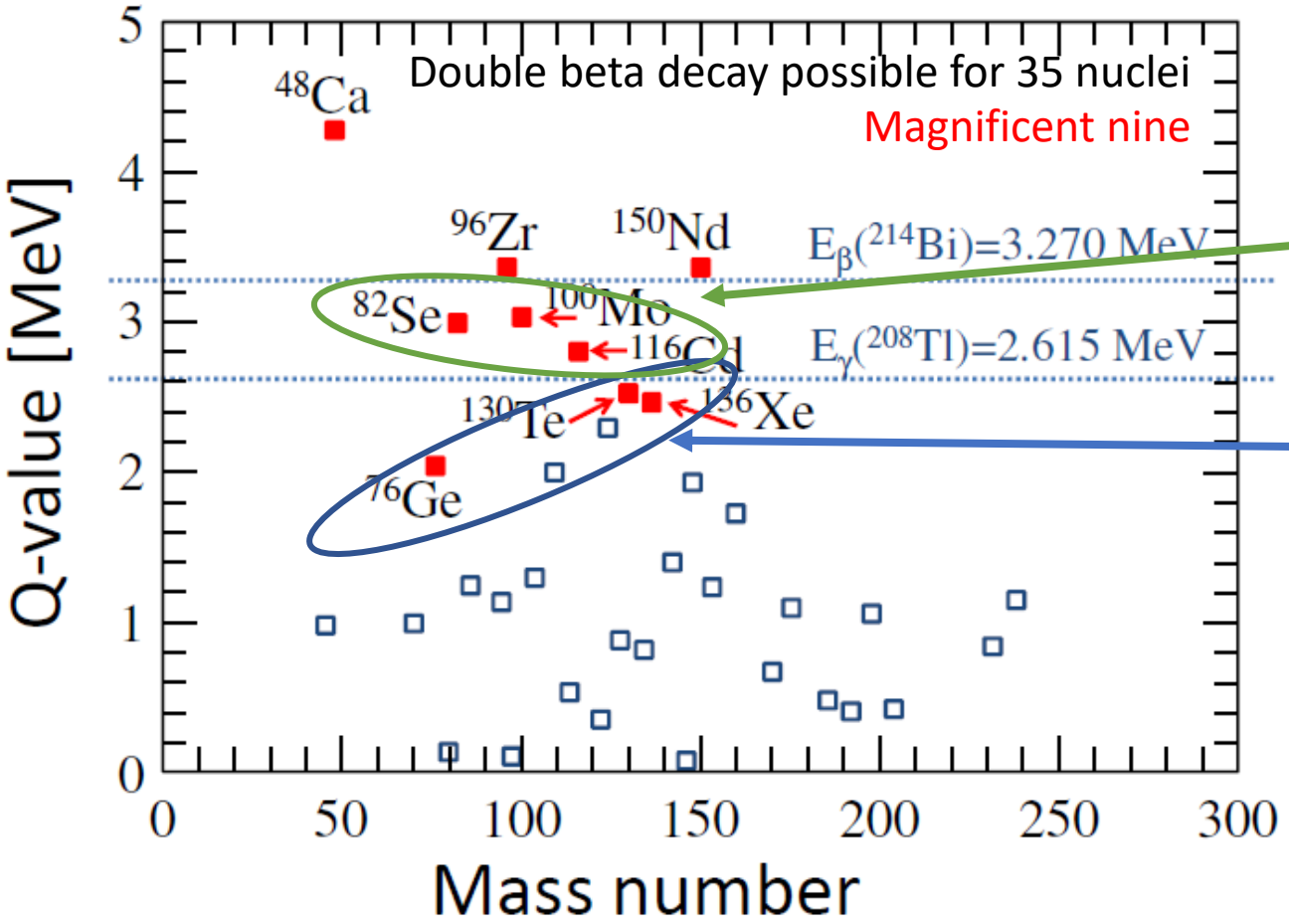
- Phase space: $G^{0\nu} \propto Q^5$
- Background



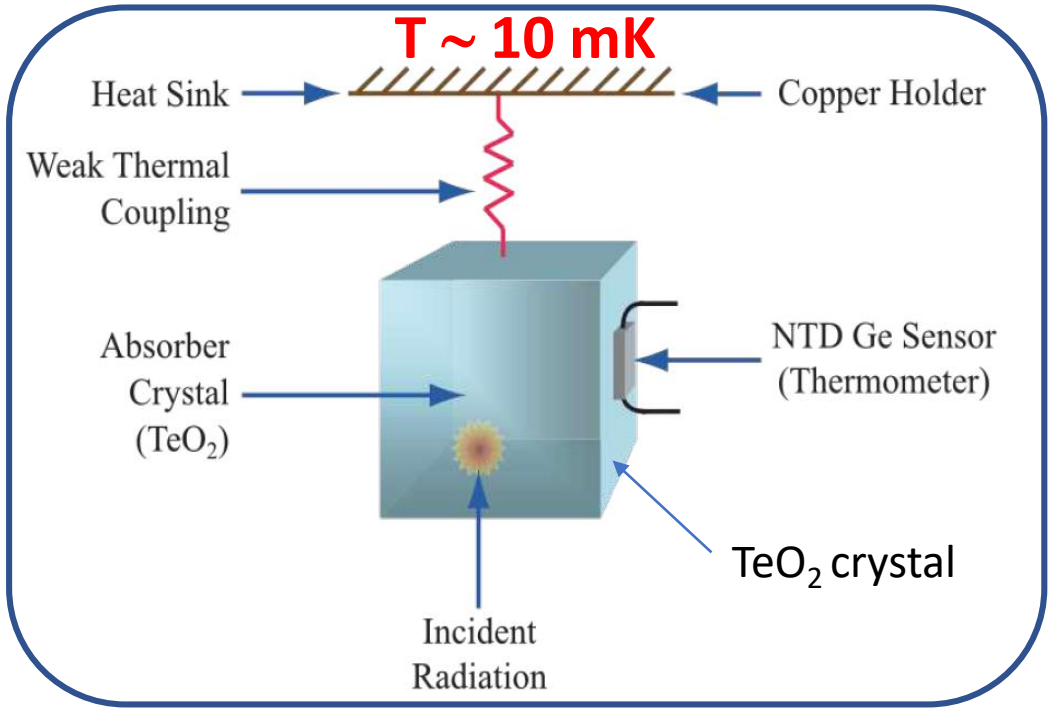

Revolutionary detection technology
Scintillating bolometers

"Classical" detection technology

**Enrichement in the isotope of interest at > 90% is possible for all these 6 candidates**

# CUPID-Mo rationale

**CUORE** $^{130}$Te
pure thermal detector
(**bolometer**)



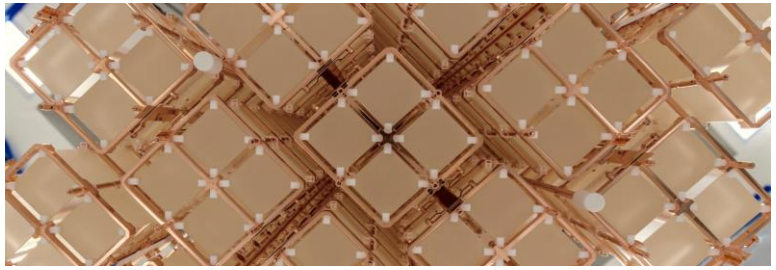

**No PID**

**Q = 2527 keV < 2615 keV**

**CUORE** - Cryogenic Underground Observatory for Rare Events

- Located in Gran Sasso, Italy
- Main objective: 0νββ in $^{130}$Te
- 988 $TeO_2$ crystals, 5x5x5 $cm^3$ each
- Total mass: 742 kg $TeO_2$ (natural Te)
- $^{130}$Te mass: 206 kg
- **$T_{1/2}^{0\nu} > 3.2 \times 10^{25}$ yr at 90% C.I.**
- **$m_{\beta\beta} < 75 - 350$ meV at 90% C.I.**

(one of the world leading experiments)



α background

γ background

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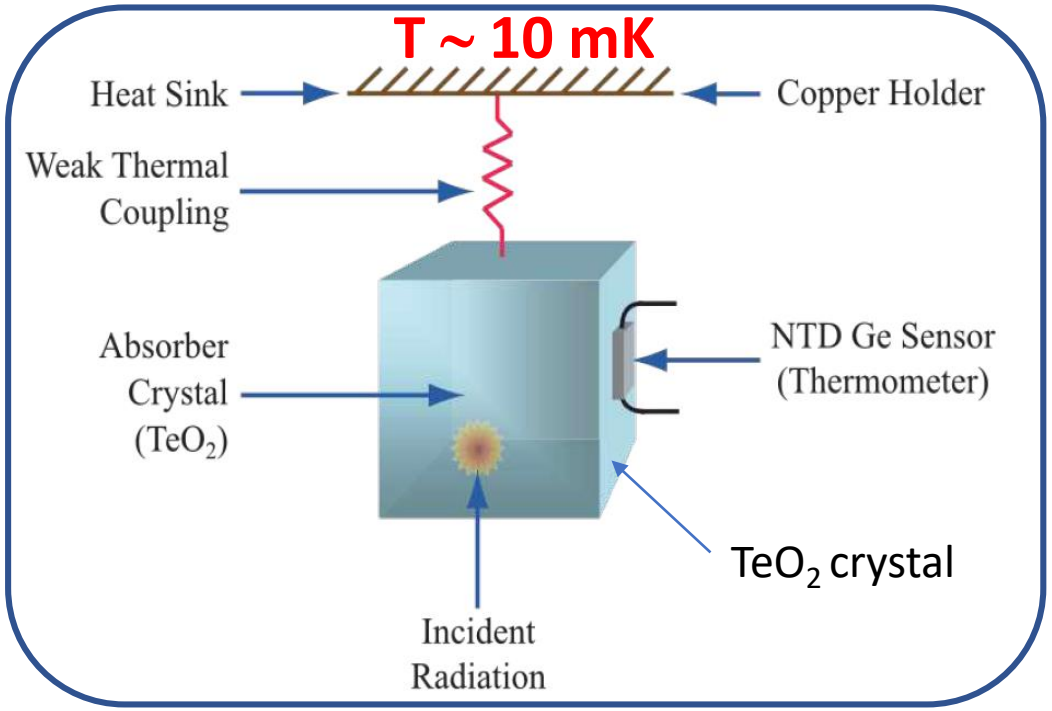


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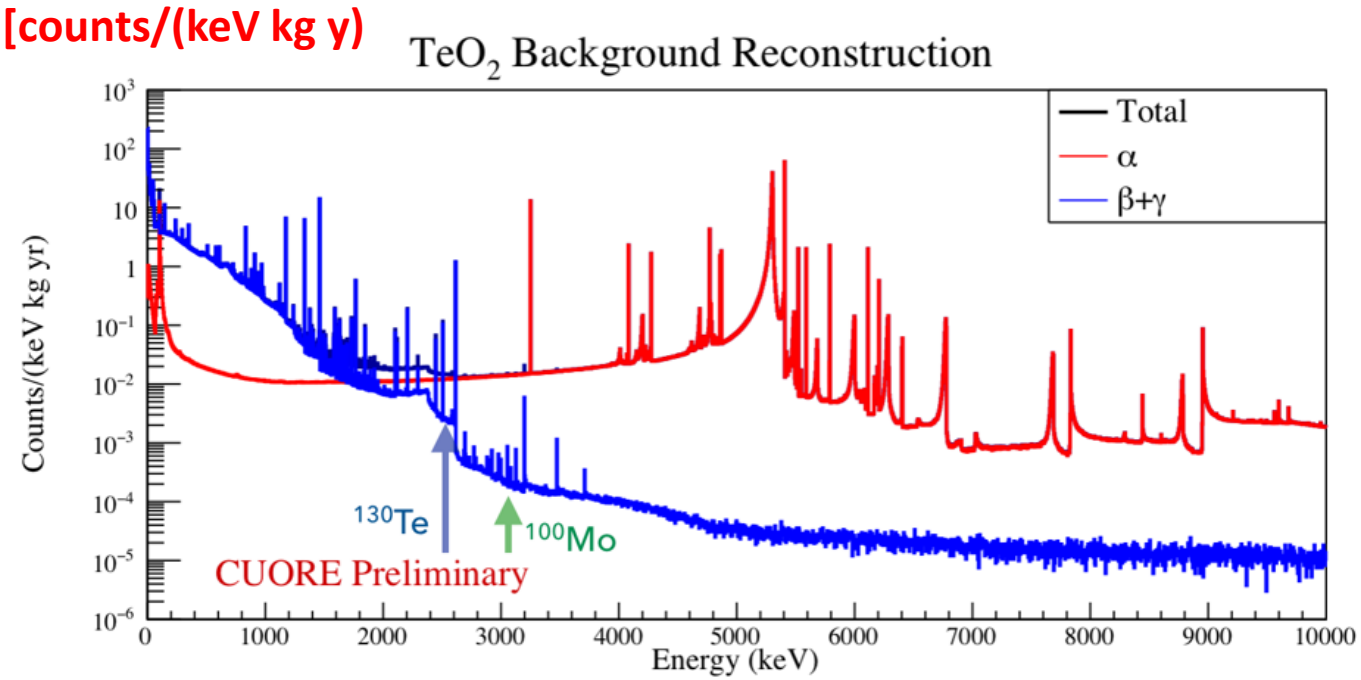
**CUORE** – Background model



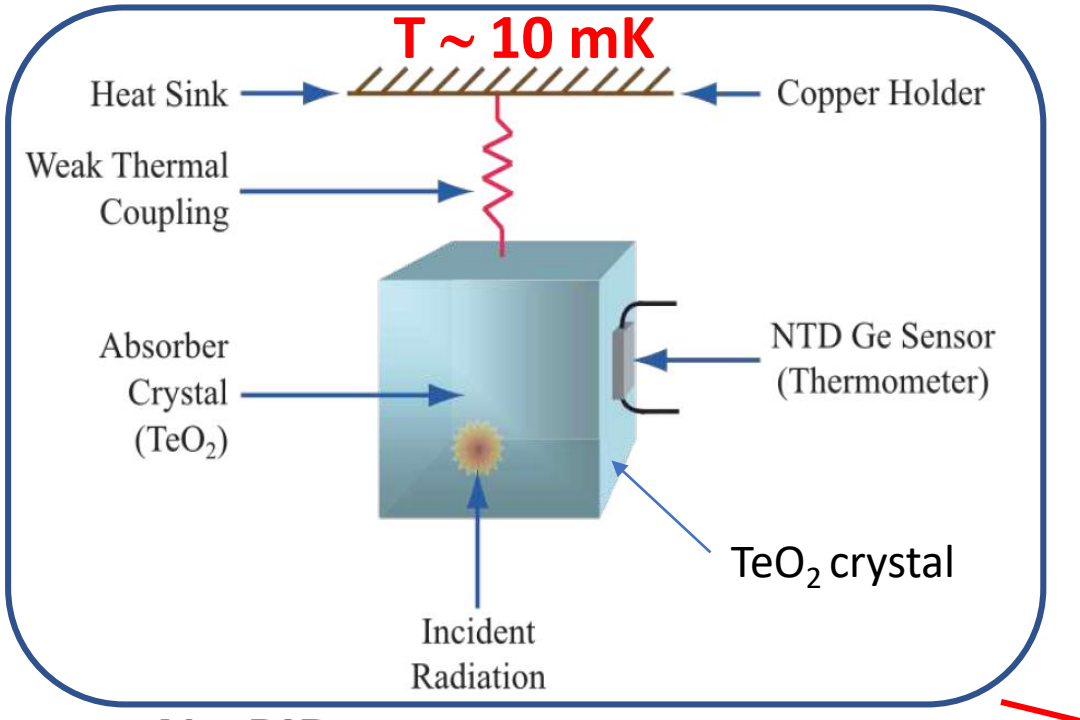

α background

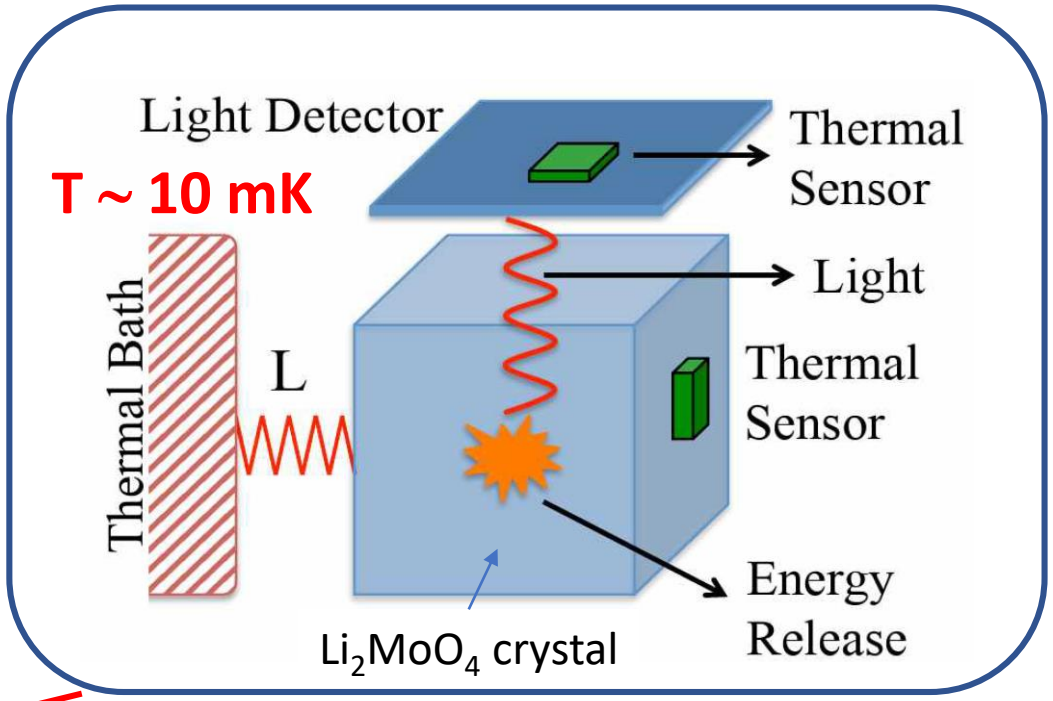
γ background

# CUPID-Mo rationale

**CUORE** $^{130}$Te
pure thermal detector
(**bolometer**)

**CUPID-Mo** $^{100}$Mo
heat + light
(**scintillating bolometer**)




**No PID**

**Q** = **2527 keV** < **2615 keV**

~~α background~~

~~γ background~~

**PID**

**Q** = **3034 keV** > **2615 keV**

Background Improvement by a **factor 100** with respect to CUORE

# CUPID-Mo rationale

**CUORE** $^{130}$Te
pure thermal detector
(**bolometer**)

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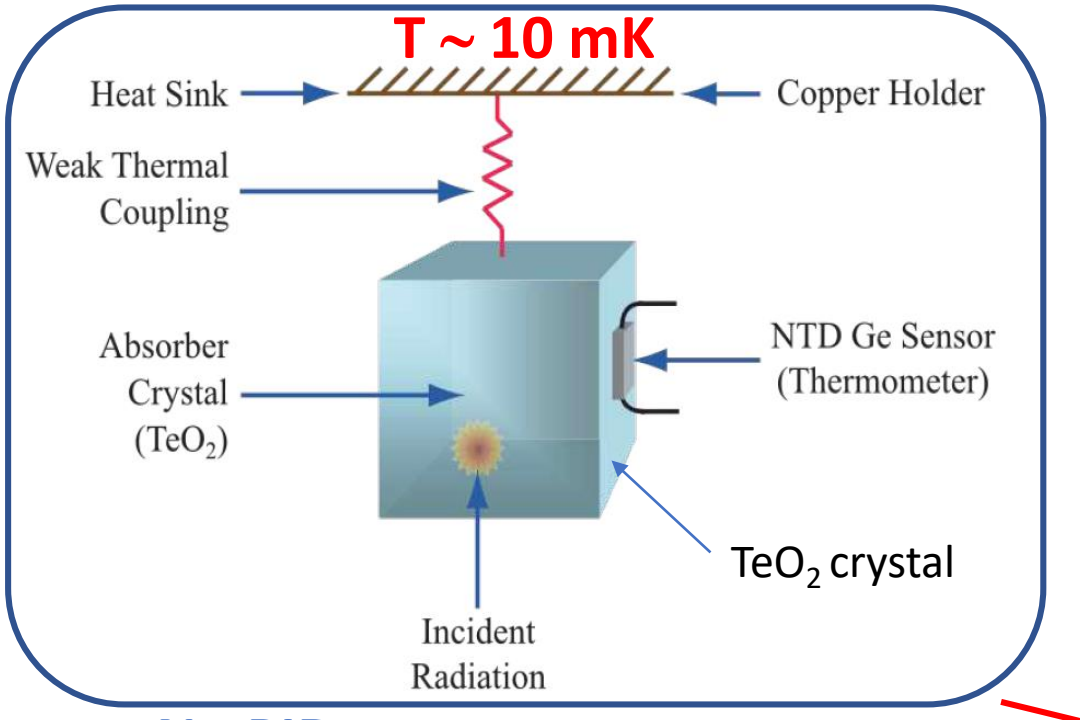


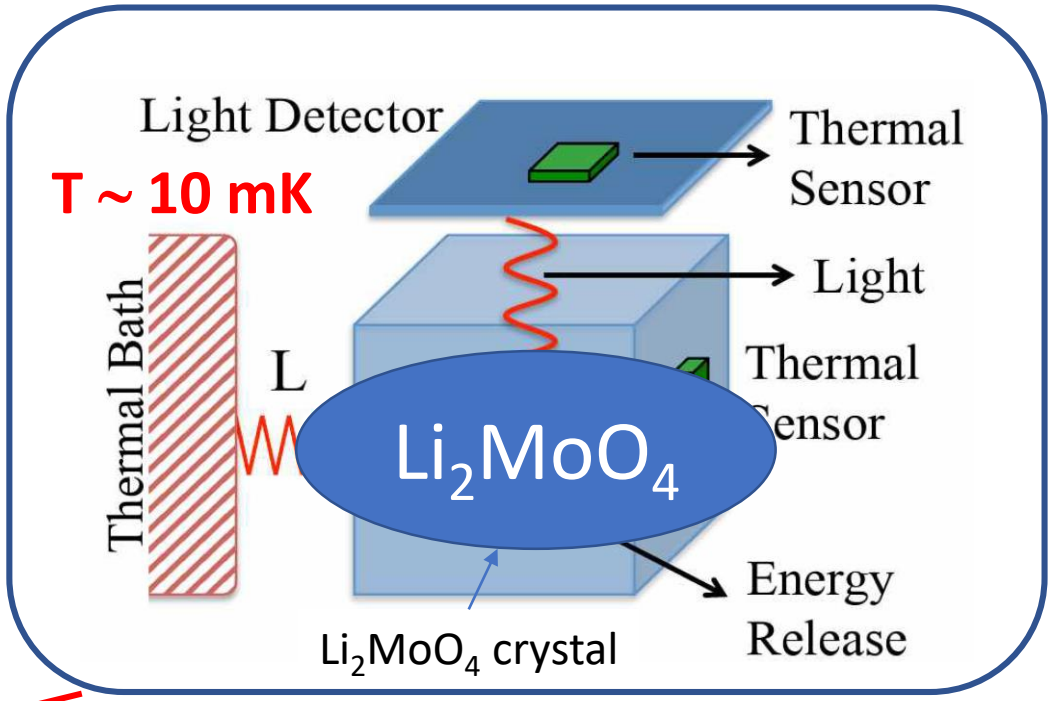


**No PID**

**Q** = **2527 keV** < **2615 keV**

~~α background~~

~~γ background~~

**PID**

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Background Improvement by a **factor 100** with respect to CUORE

# Preparing a $^{100}$Mo experiment: LUMINEU

**LUMINEU has succesfully developed the $Li_2{}^{100}MoO_4$ technology**

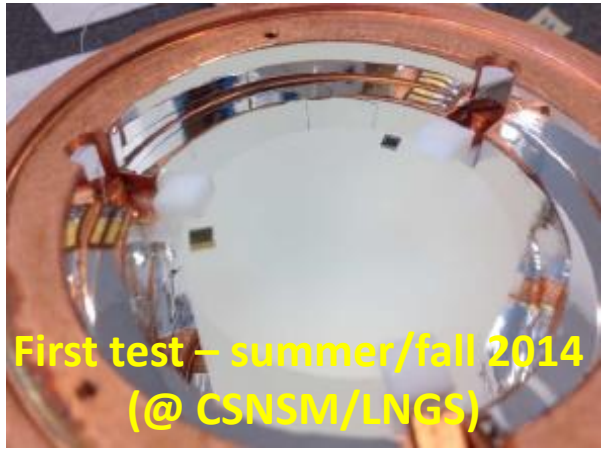
**Multiple tests** with **natural and enriched crystals** (2014-2017) in **LSM** and LNGS with outstanding results in terms of:

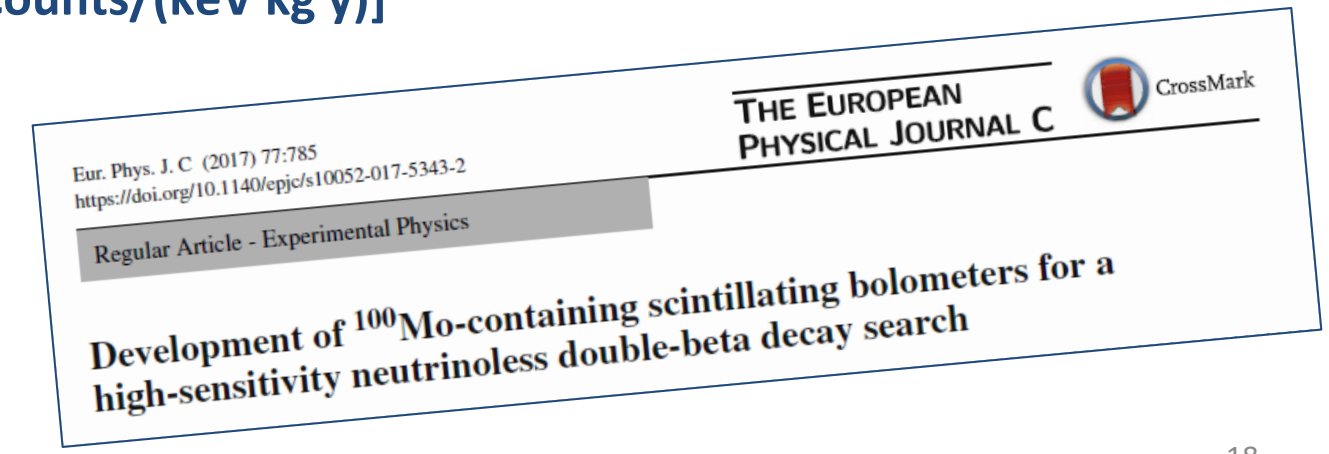
EDELWEISS set-up

| | | |
|---|---|---|
| High-purity crystals | → | **negligible loss of enriched material** |
| Reproducibility | → | excellent performance uniformity |
| Energy resolution | → | **~ 4-6 keV FWHM** in RoI |
| $\alpha/\beta$ separation power | → | **> 99.9 %** |
| Internal radiopurity | → | **< 5 μBq/kg in $^{232}$Th, $^{238}$U; < 5 mBq/kg in $^{40}$K** |

→ Compatible with $b \leq 10^{-4}$ [counts/(keV kg y)]

*NIM A 729, 856 (2013)*
*JINST 9, P06004 (2014)*
*EPJC 74, 3133 (2014)*
*JINST 10, P05007 (2015)*



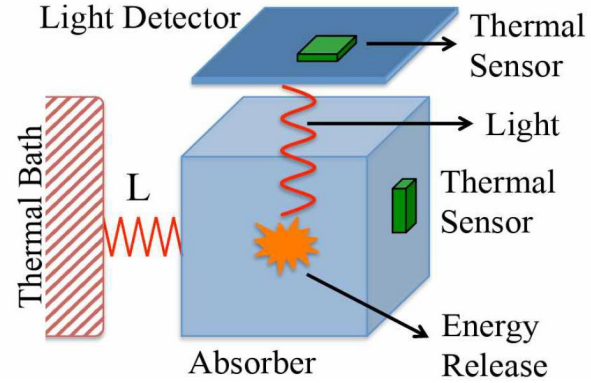


Eur. Phys. J. C (2017) 77:785
https://doi.org/10.1140/epjc/s10052-017-5343-2

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Development of $^{100}$Mo-containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search

# CUPID-Mo single module

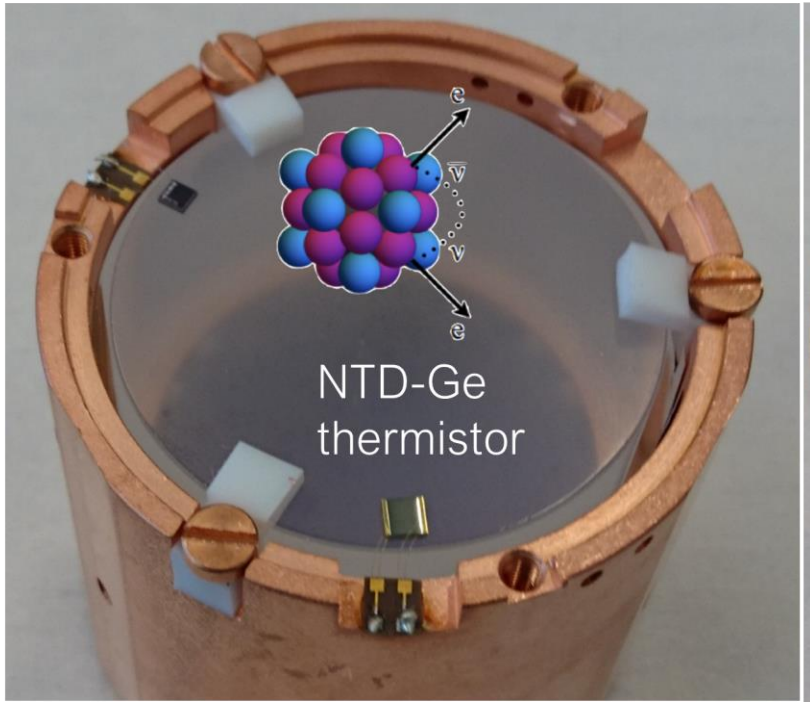


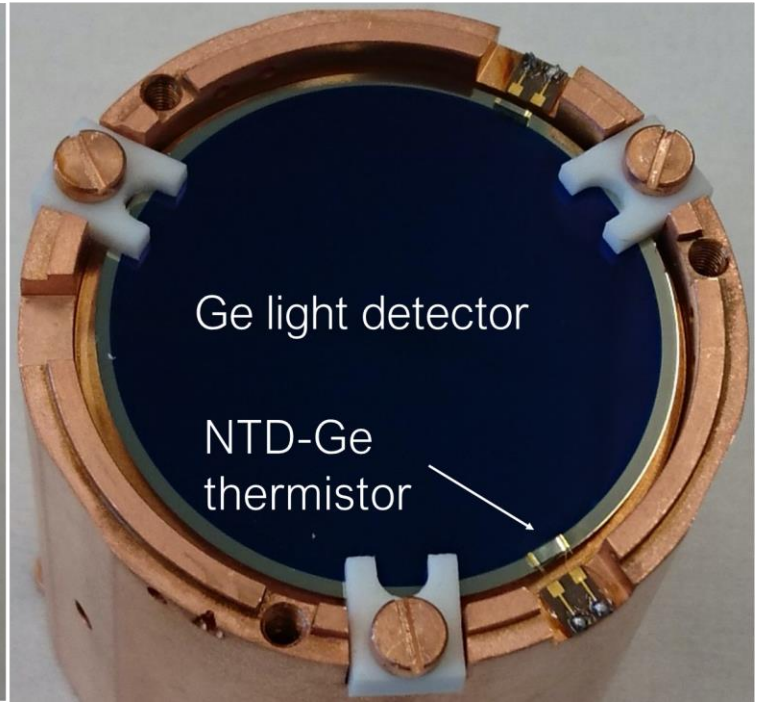

NTD $\rightarrow$ $R(T) = R_0 e^{\sqrt{T_0/T}}$

Source $^{100}Mo$ = Detector $Li_2MoO_4$
High efficiency

Teflon: weak thermal link

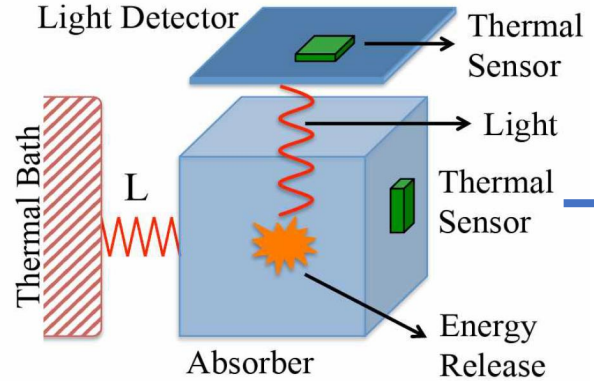
Copper: Thermal Bath

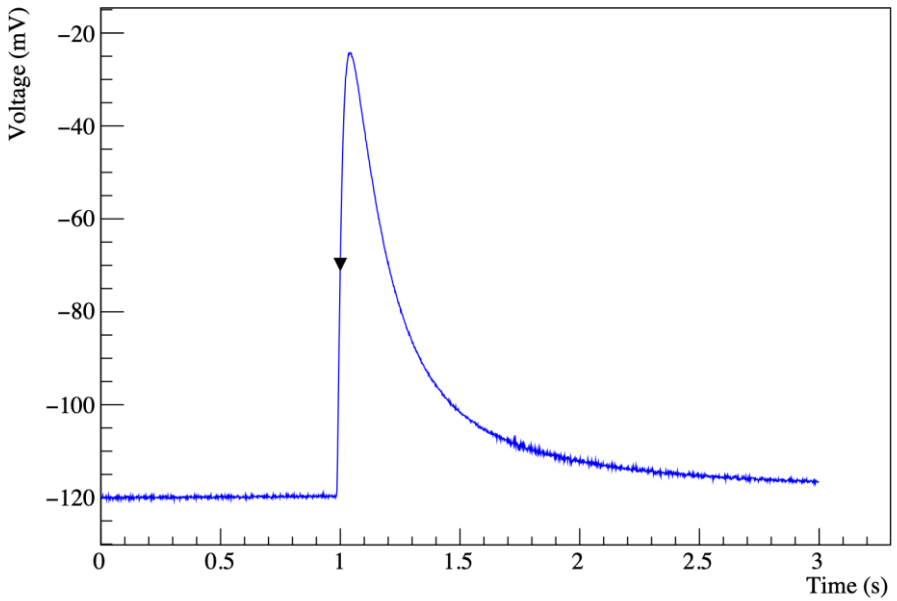


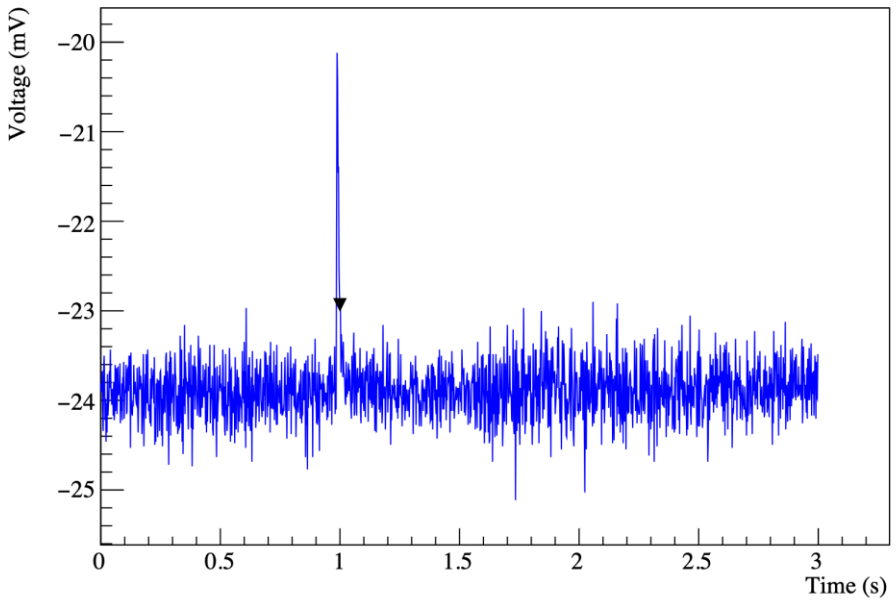




Copper: Thermal Bath

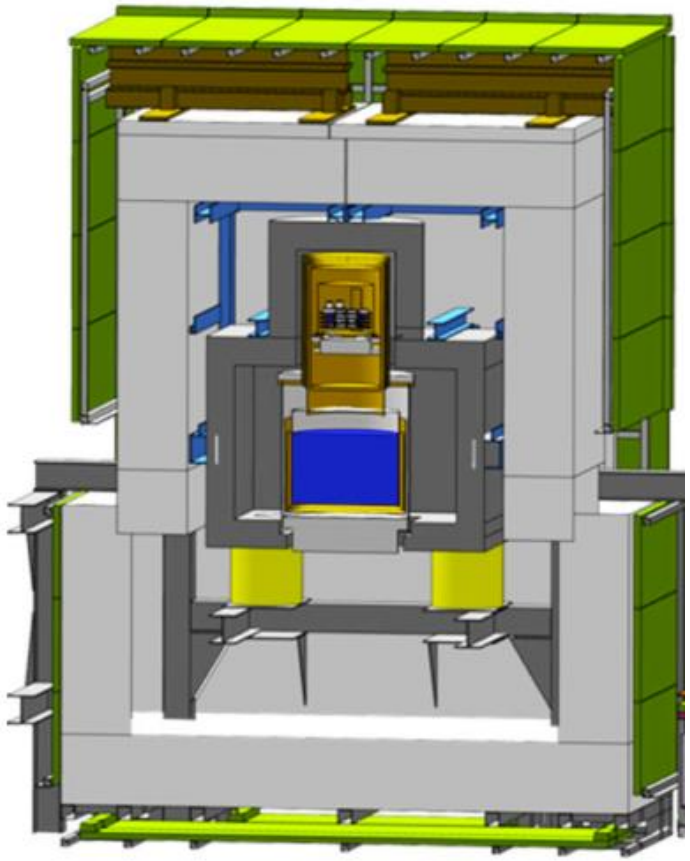
# CUPID-Mo detector response



# CUPID-Mo at Modane



4800 m.w.e. rock overburden

shared EDELWEISS cryogenic infrastructure operated at **@ 20 - 22 mK**

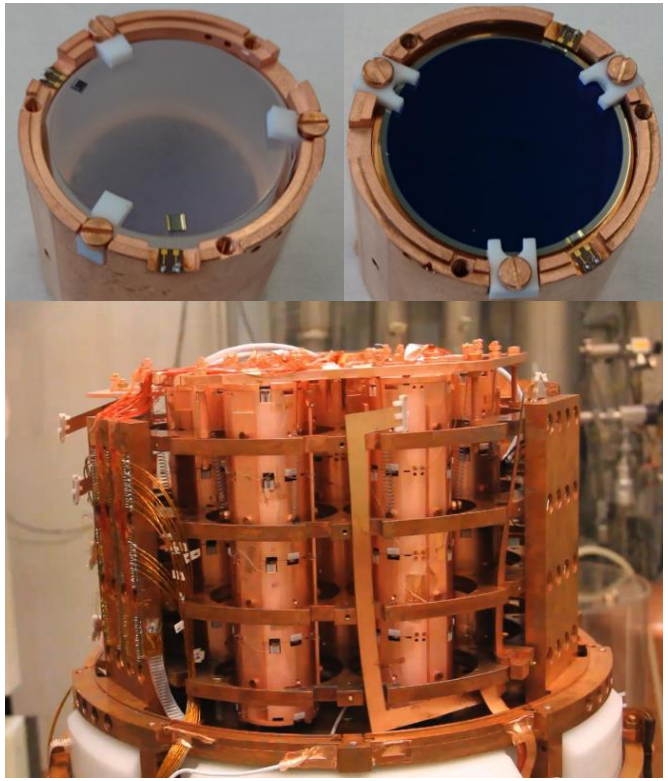
**20 $Li_2{}^{100}MoO_4$ detectors of ~210 g**, ~97% enriched (**2.26 kg $^{100}$Mo**)

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

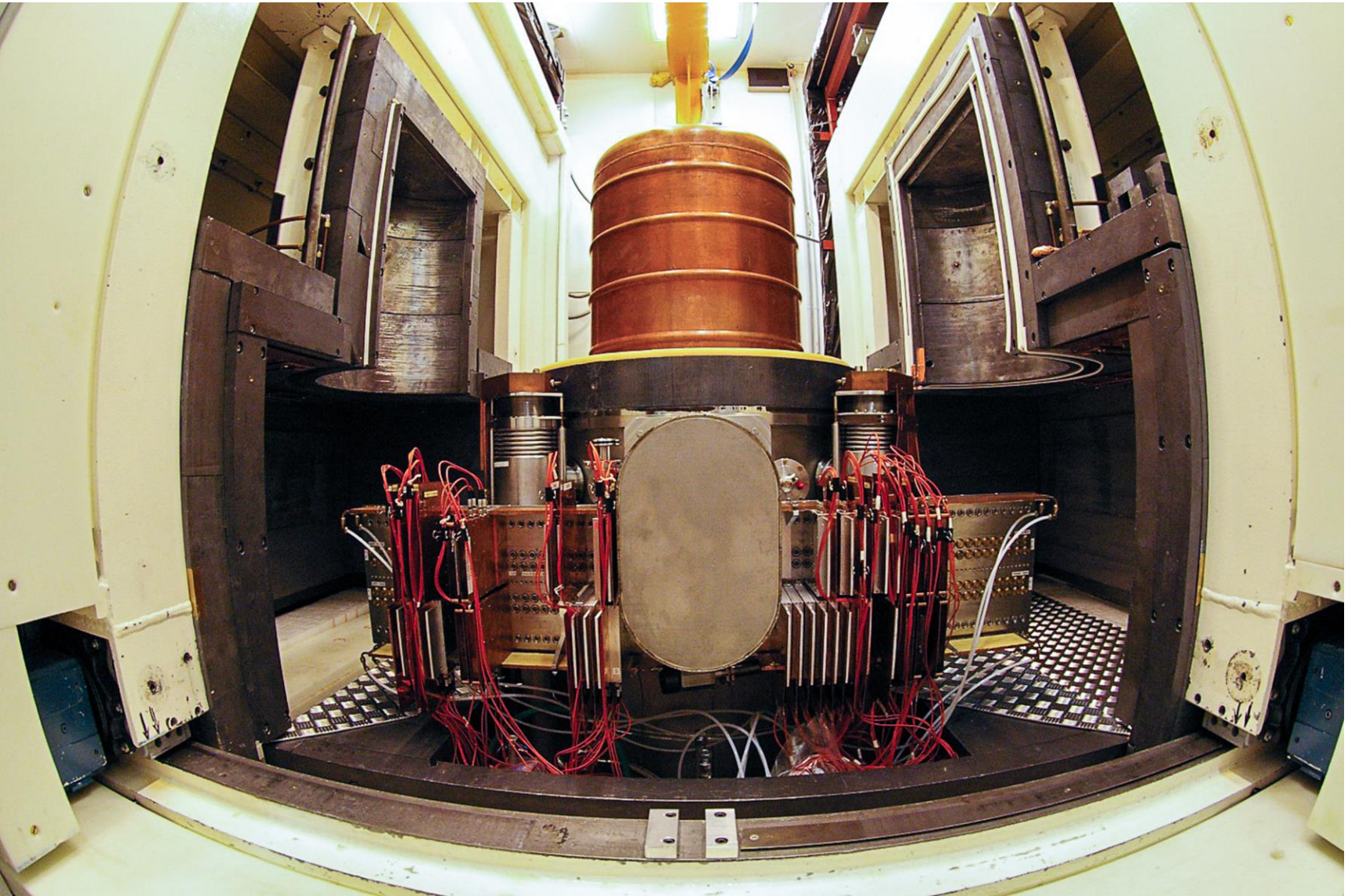


Modane
Lyon
Tourin
LSM

# Laboratoire souterrain de Modane

CUPID-Mo inauguration – December 2019

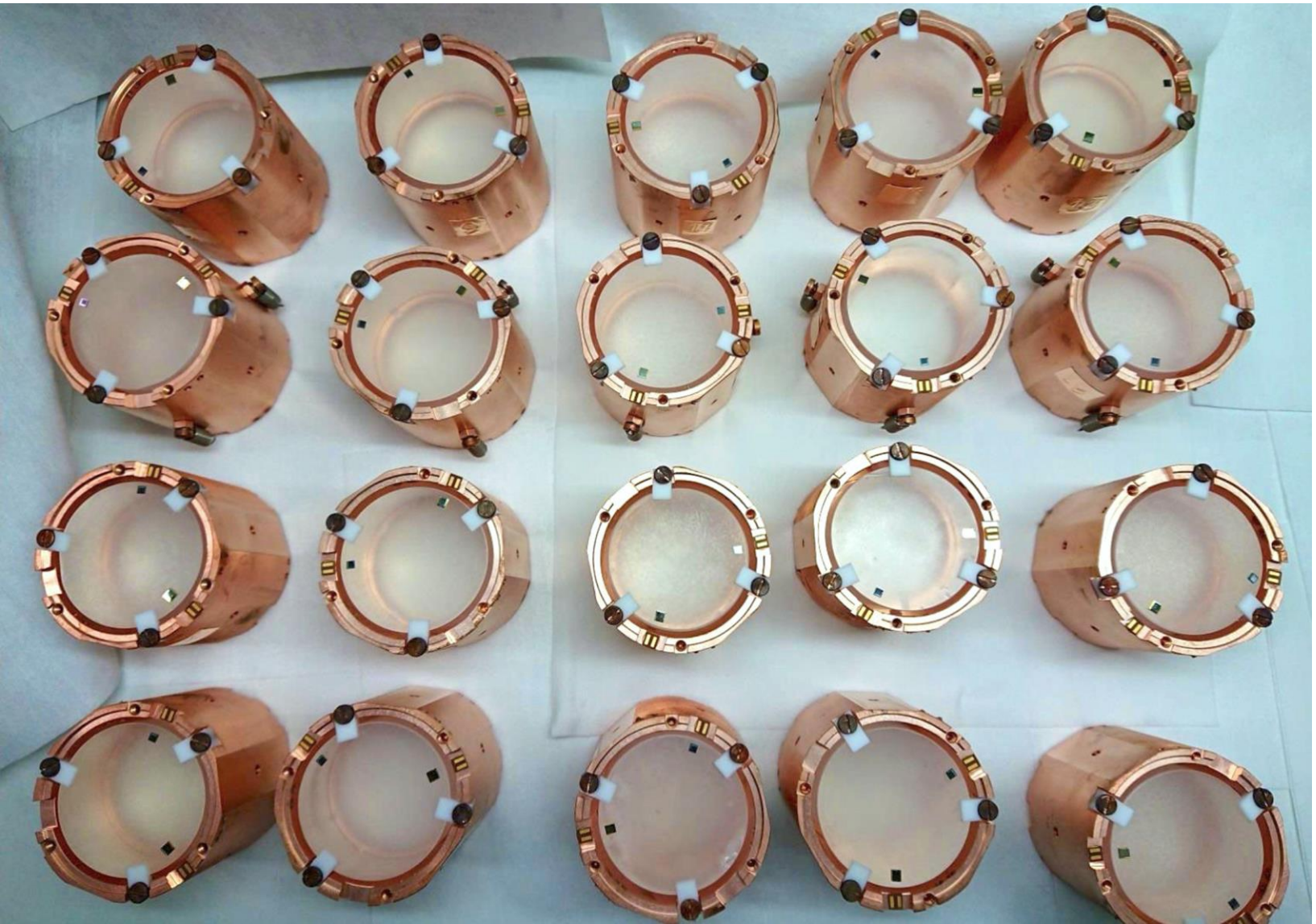
# EDELWEISS/CUPID-Mo cryogenic facility



Active and passive shielding designed for the **EDELWEISS dark matter search**

- 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, CEA-Saclay)

# 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)

**Isotope concentration: 96.6±0.2 %**

**4.158 kg $Li_2MoO_4$**

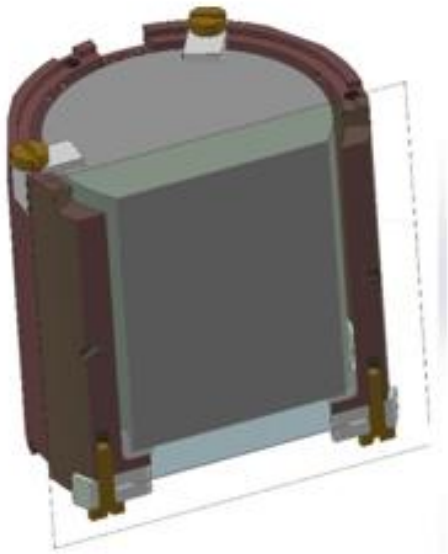
**2.264 kg $^{100}$Mo**

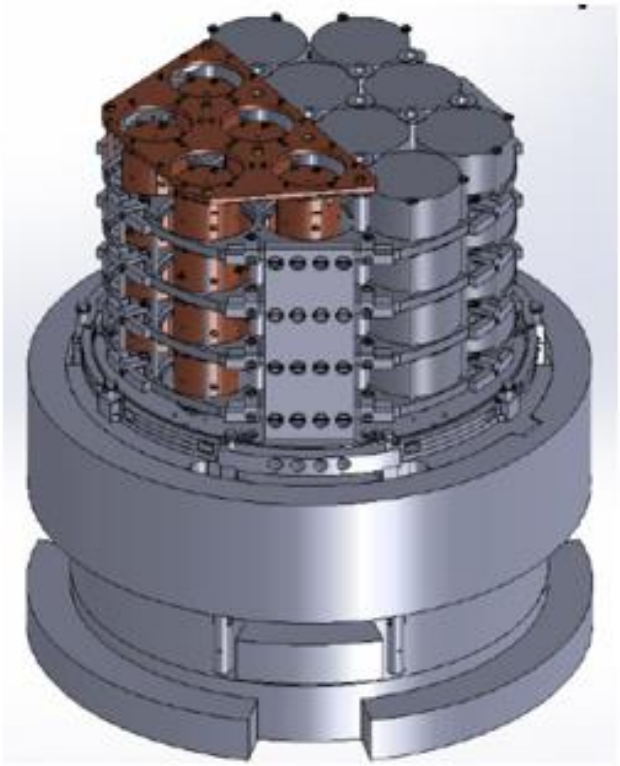
# The CUPID-Mo design

**Modular tower 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

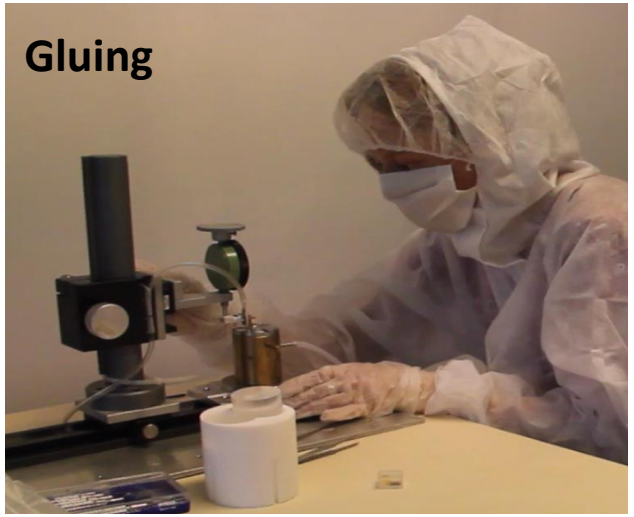
Designed at CEA/SPEC
Machined at LAL and CEA/SPEC



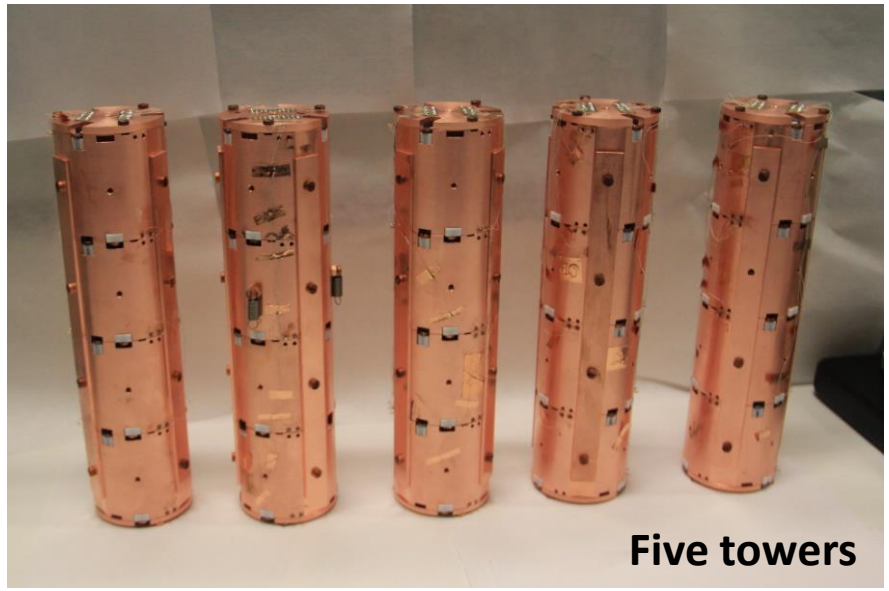


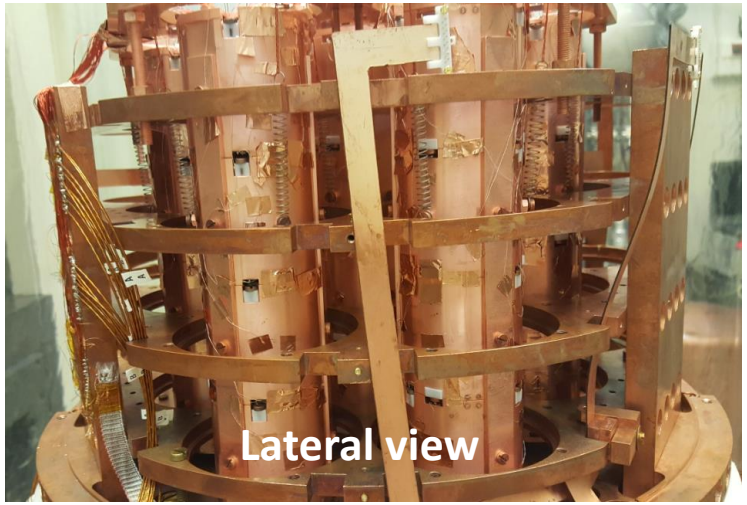
$$1 \times 4 \times 5 = 20$$

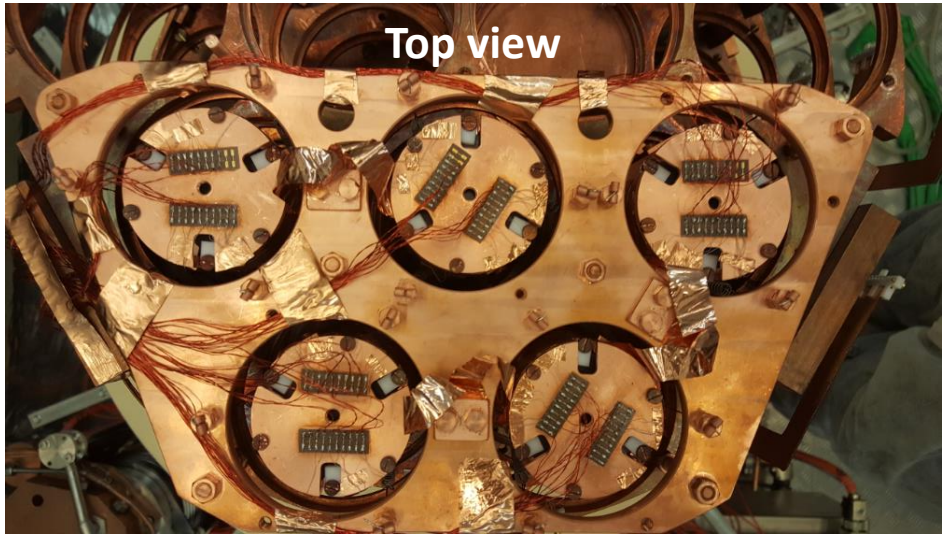
# The CUPID-Mo assembly at LAL clean room

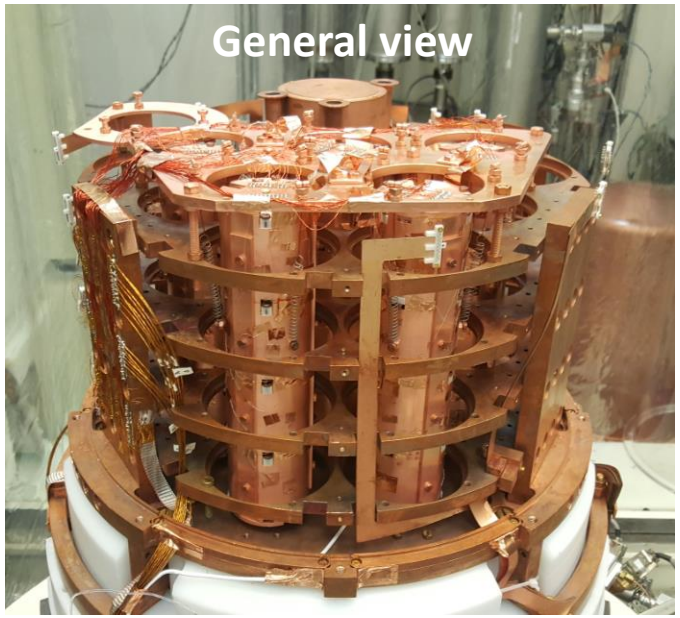


# The CUPID-Mo installation at LSM



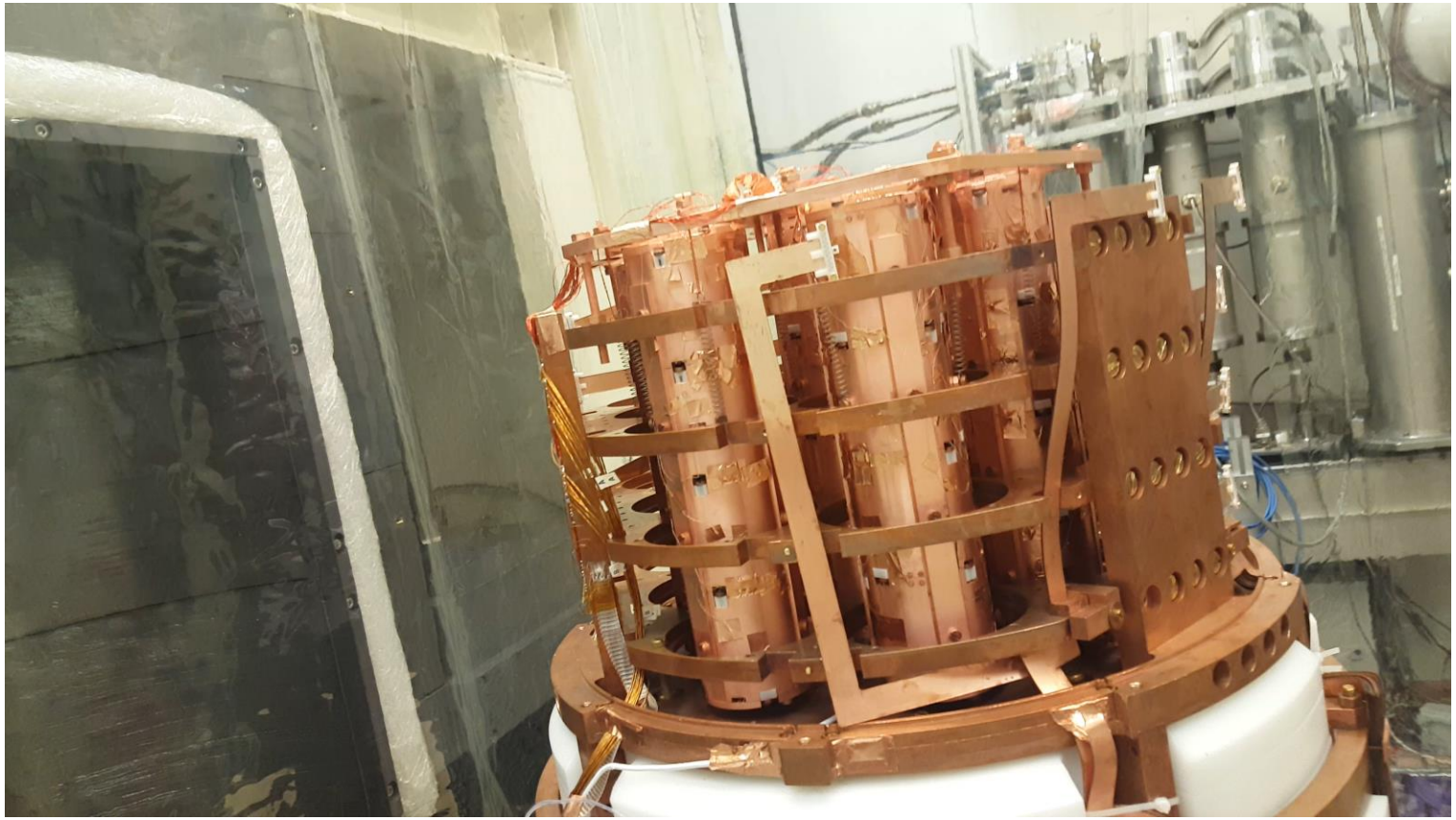



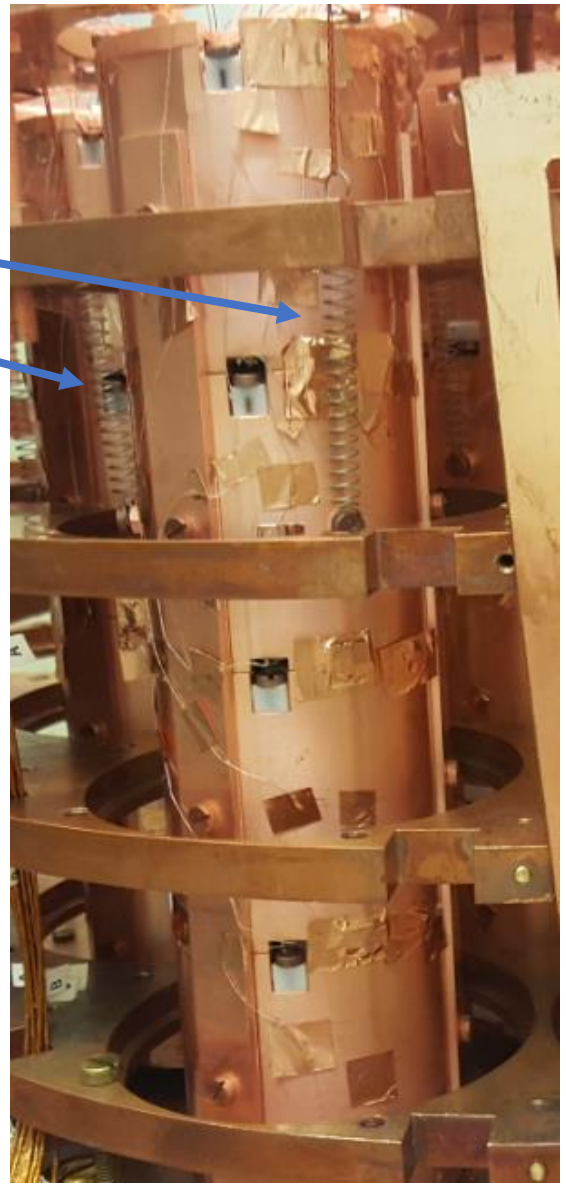
# Cutting vibrations in CUPID-Mo

**Suspended tower design:**

Particularly important for the light detector operation in cryostat with vibrations from thermal machines

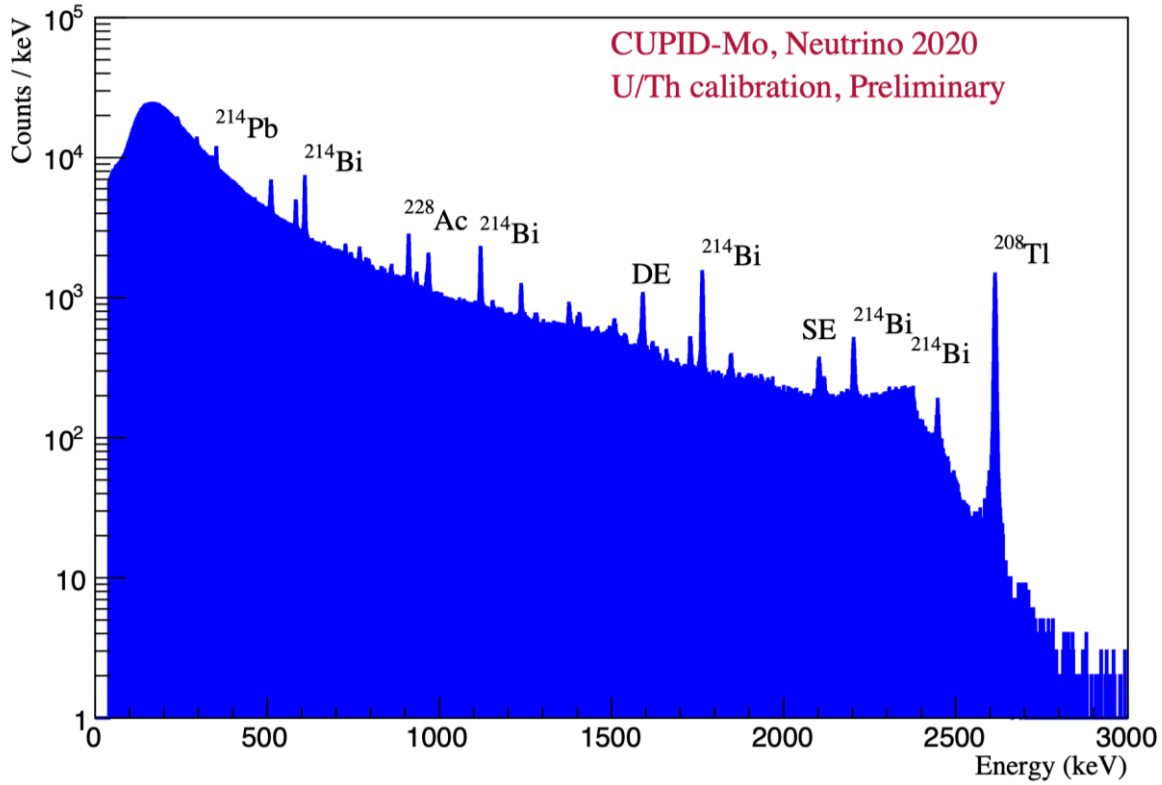
Stainless steel springs

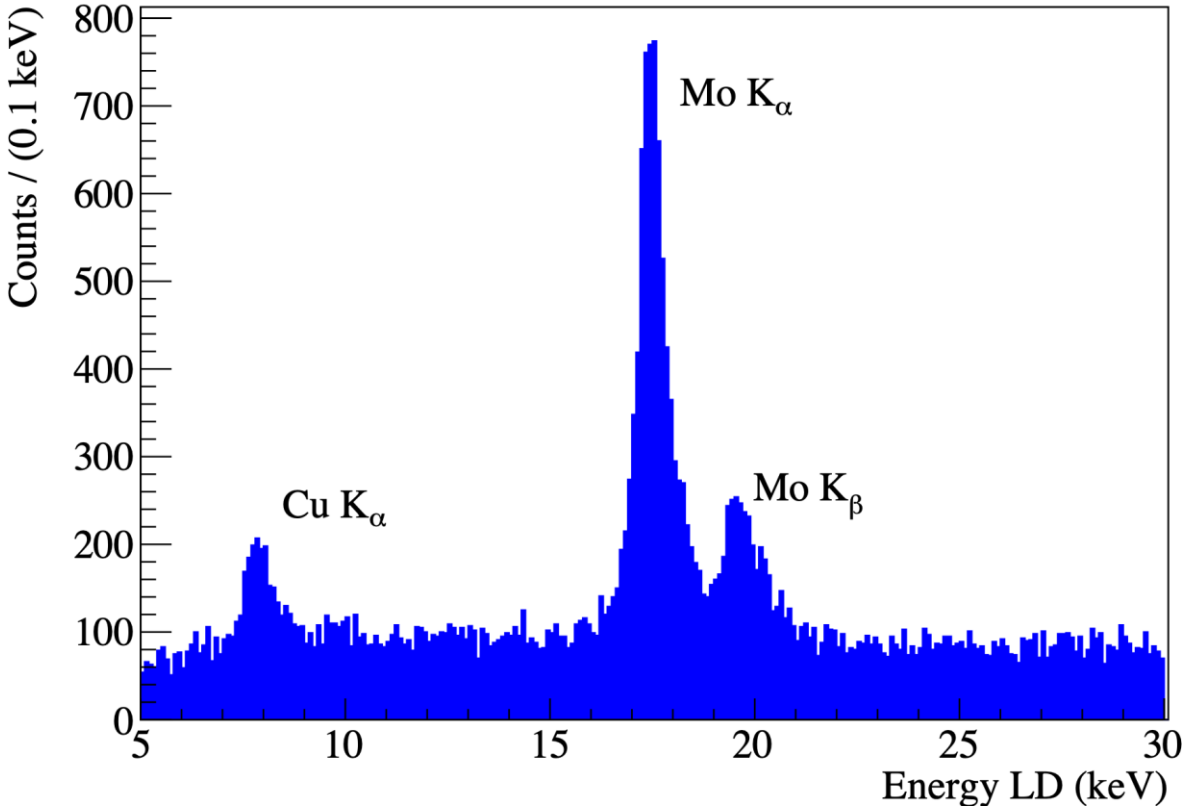




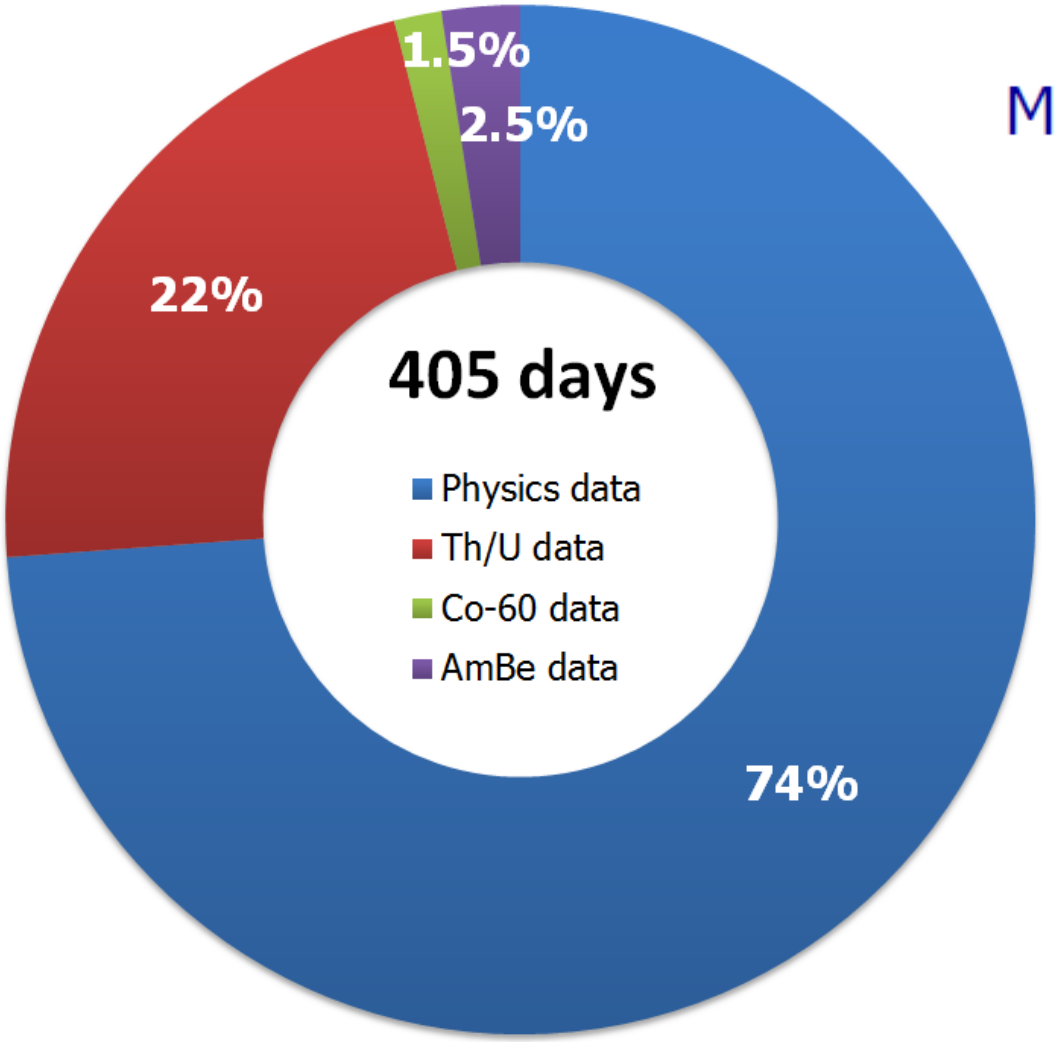
# CUPID-Mo calibration

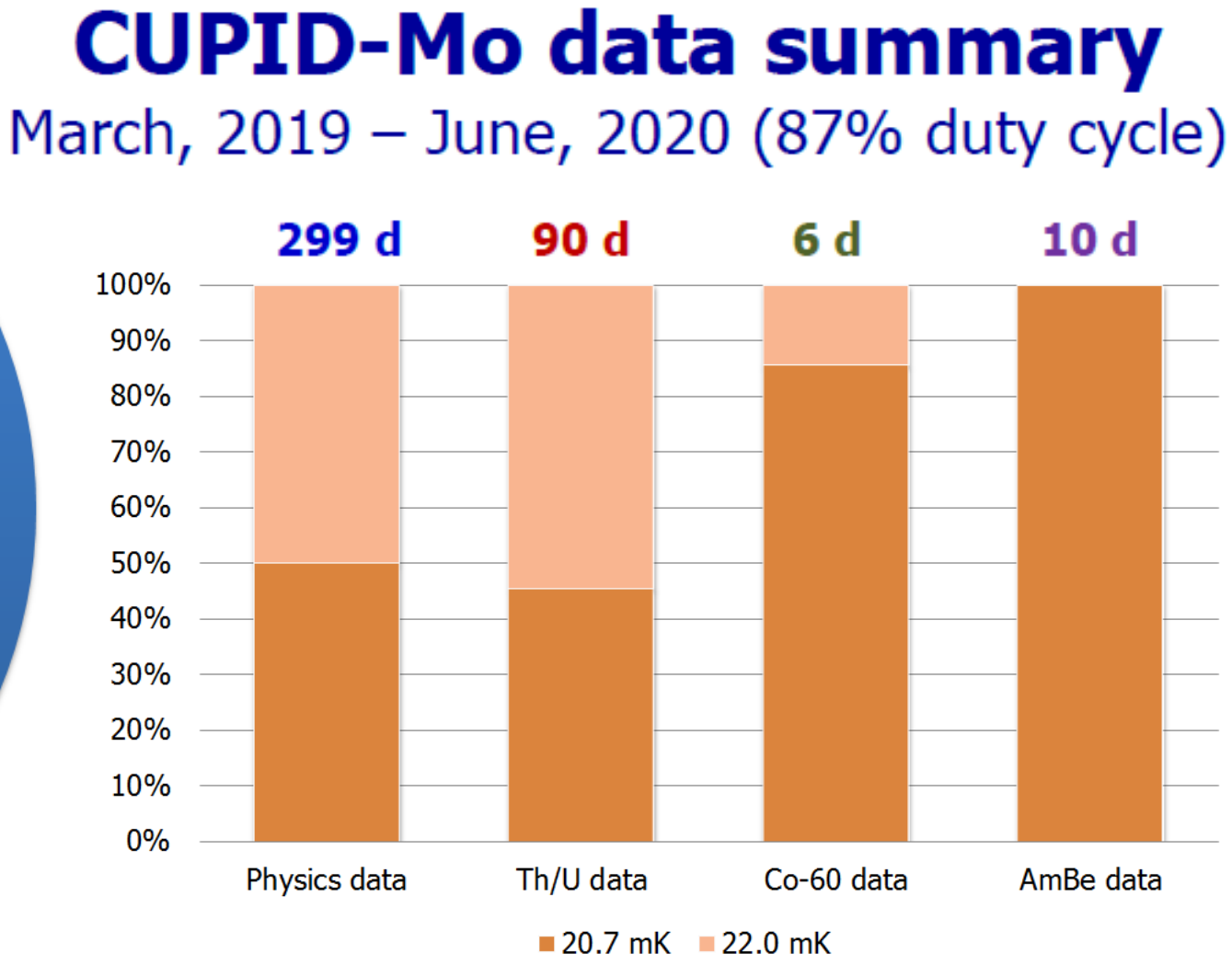
- LMO detectors have relatively low mass ~210 g and low density 3.07 g/cm$^3$
- Significant amount of time dedicated to calibration (2 days / LHe refill) 20-25% of data taking
- Low energy calibration sources are potentially dangerous for the EDELWEISS dark matter search
- Use the Mo x-ray escape peak from high intensity irradiation of the crystals ($^{60}$Co)



# CUPID-Mo data taking



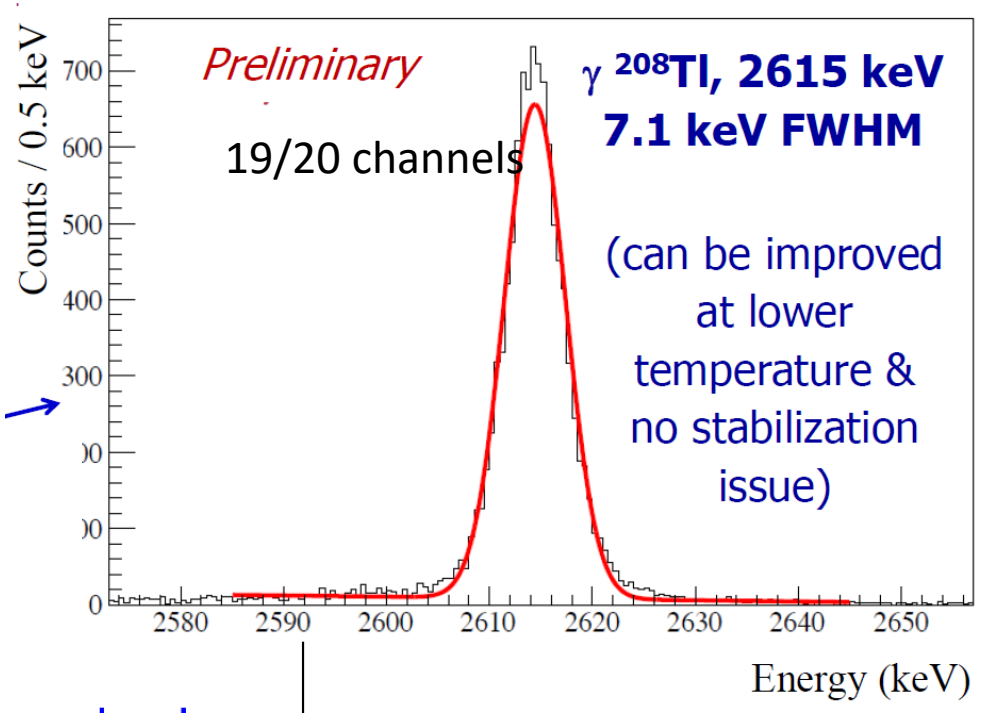
# CUPID-Mo performance

Good uniformity/performance, suitable for larger arrays

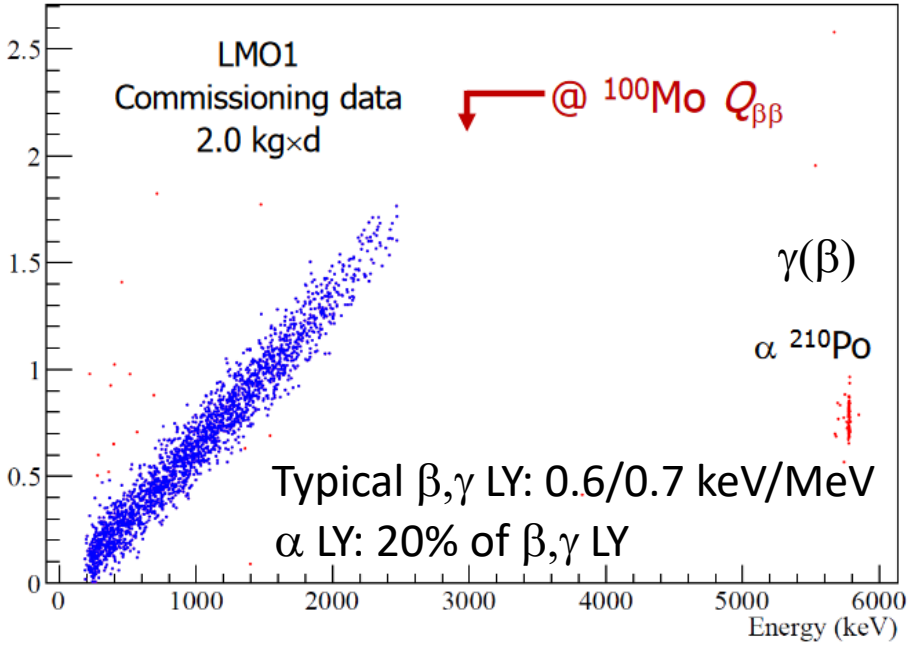
**CUPID-Mo commissioning paper**

*EPJC 80(2020)44*

**Energy resolution**




**α rejection power: > 99.9% for all detectors**




**Radiopurity**

**Crystals bulk α activity**
(19/20 $Li_2{}^{100}MoO_4$, 2.17 kg×yr)

| Chain | Nuclide | Activity [μBq/kg] |
|---|---|---|
| $^{232}$Th | $^{232}$Th | 0.22(9) |
| | $^{228}$Th | 0.38(9) |
| | $^{224}$Ra | 0.34(9) |
| | $^{212}$Bi | 0.22(7) |
| $^{238}$U | $^{238}$U | 0.35(10) |
| | $^{234}$U+$^{226}$Ra | 1.22(17) |
| | $^{230}$Th | 0.48(12) |
| | $^{222}$Rn | 0.47(10) |
| | $^{218}$Po | 0.35(9) |
| | $^{210}$Po | 95(6) |
| | $^{190}$Pt | 0.19(8) |

U / Th: ≤ 1 μBq/kg

# CUPID-Mo data production and cuts

CUORE based data production chain at NERSC

**Total efficiency (exposure weighted avg.)**

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

Trigger efficiency

Base cuts

Single trigger
BaselineSlope

Multiplicity

Pulser rejection
M1 - single crystal

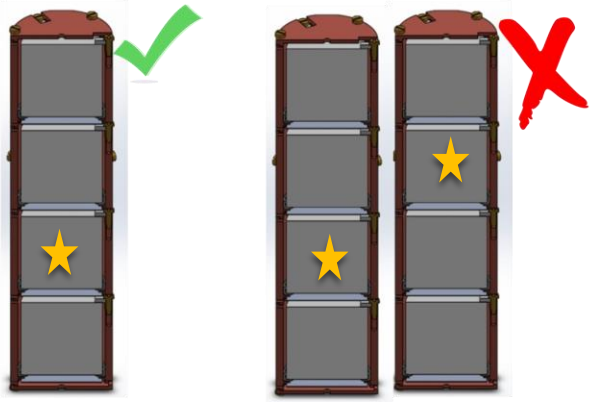
Pulse Shape analysis

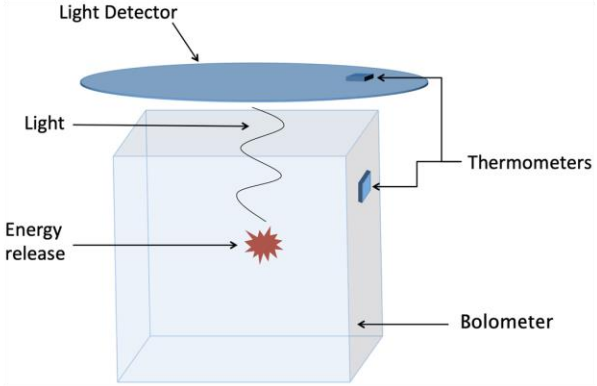
Principal component analysis (PCA)

Light Yield

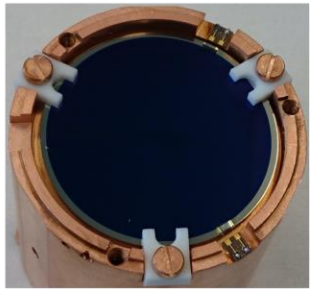
Sum of LD
Consistency of LD

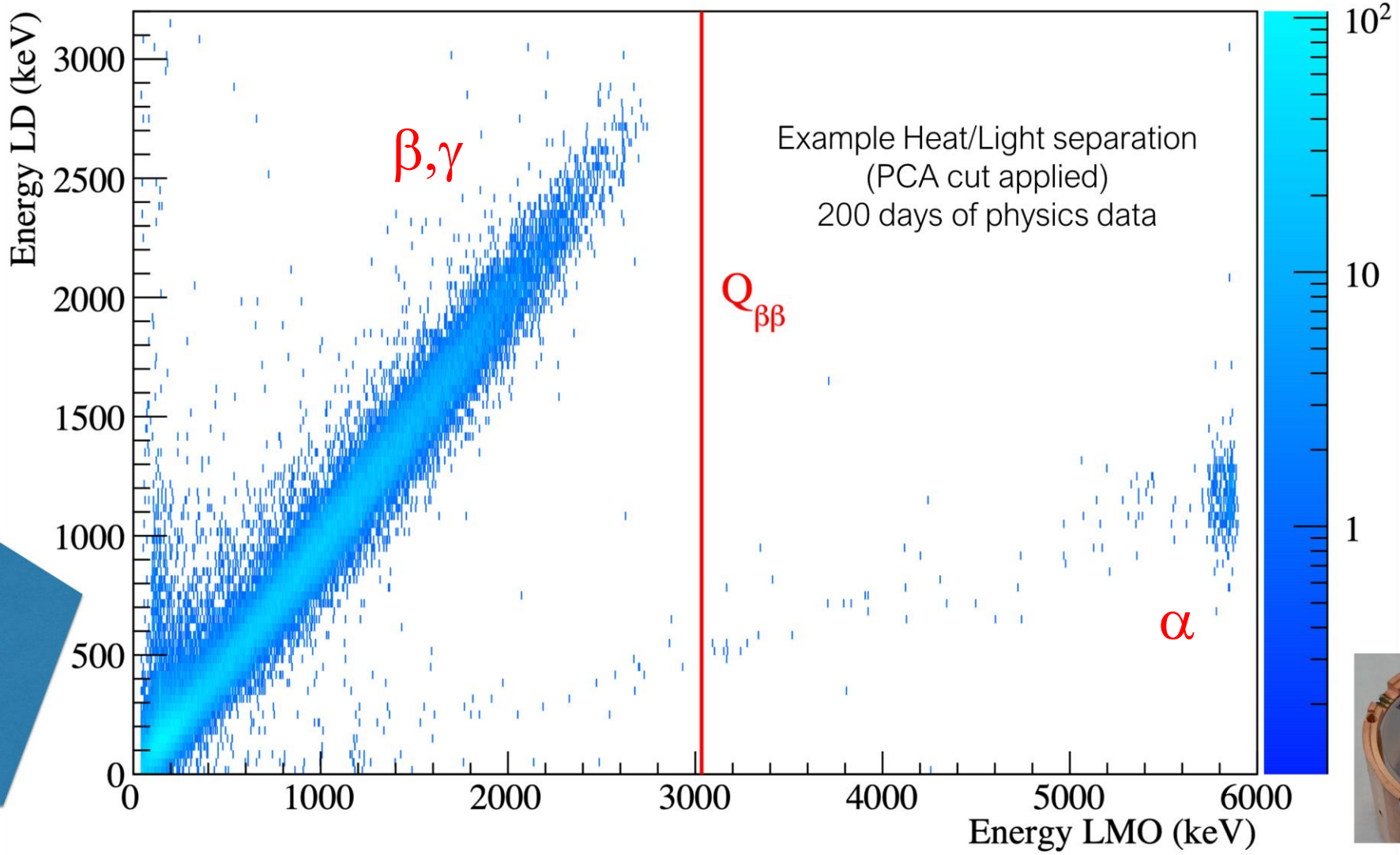
Muon veto anti-coincidence

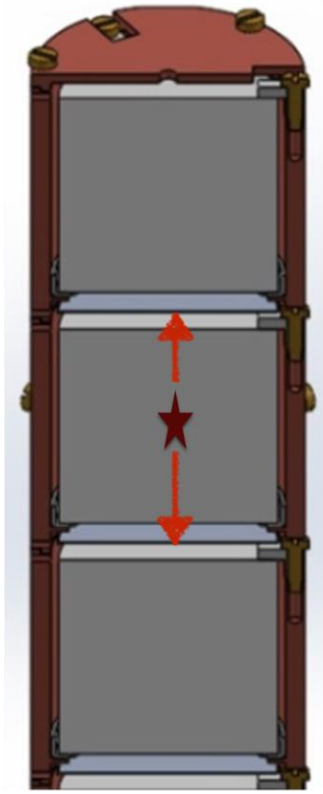




# Light yield cut



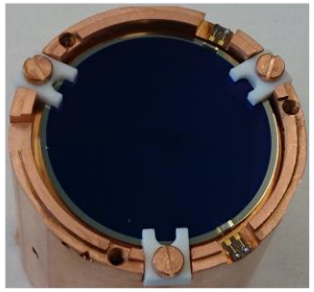


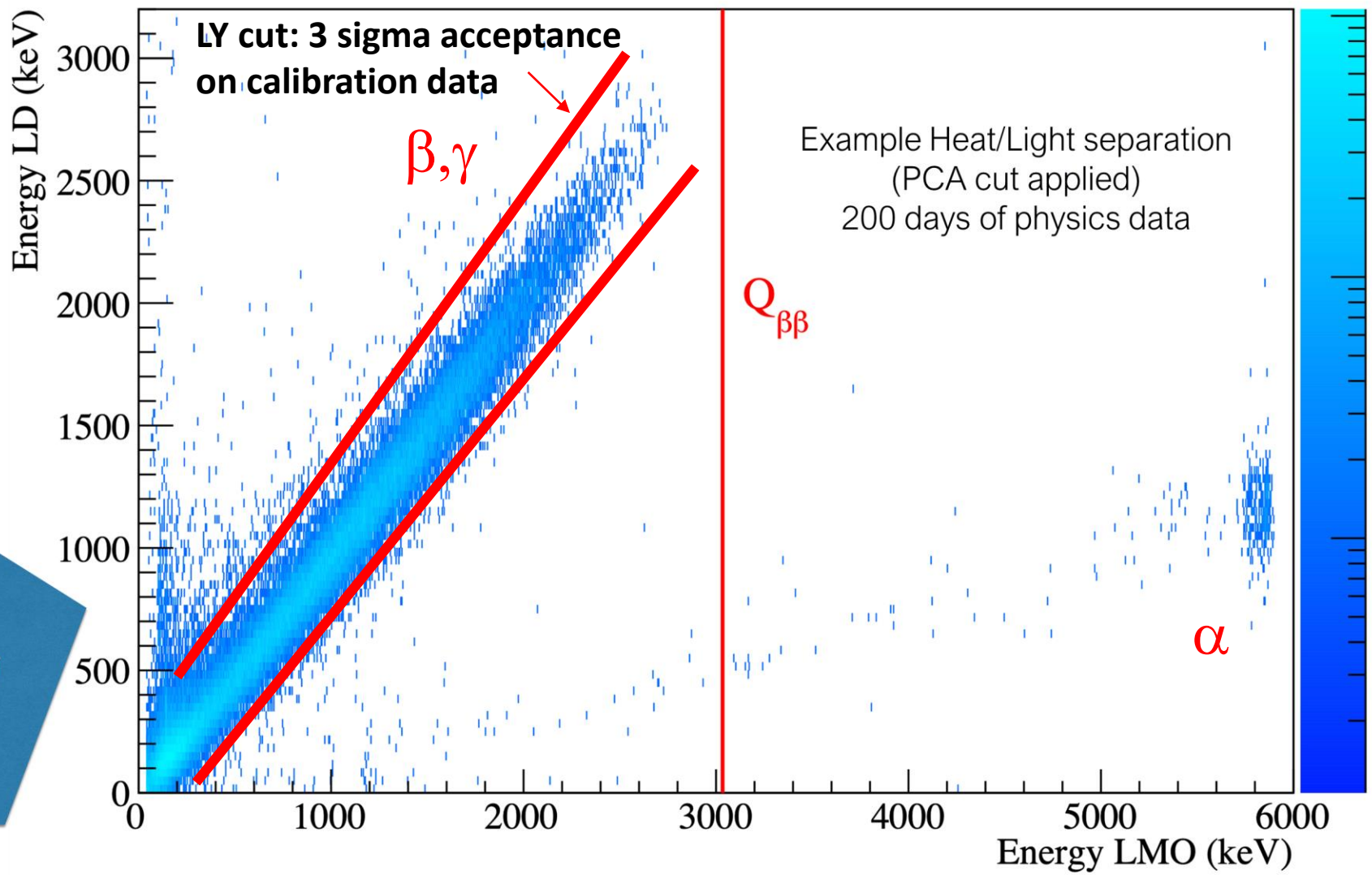



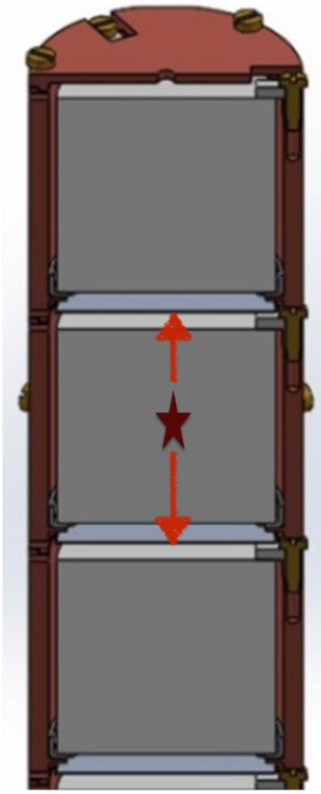
Light Yield

Weighted sum of LD
Consistency of LD

# Light yield cut



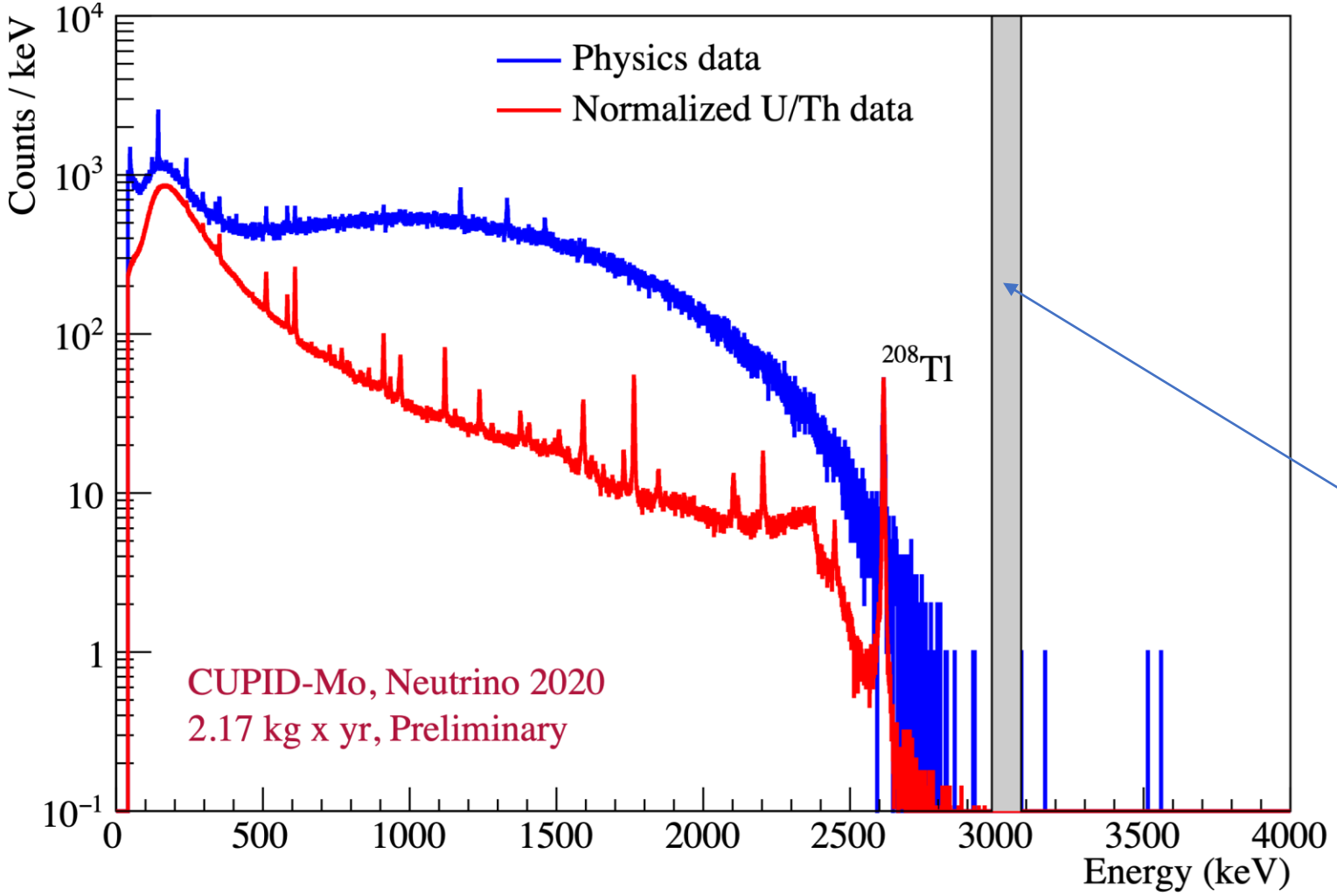


Light Yield

Weighted sum of LD
Consistency of LD

# CUPID-Mo blinded data




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

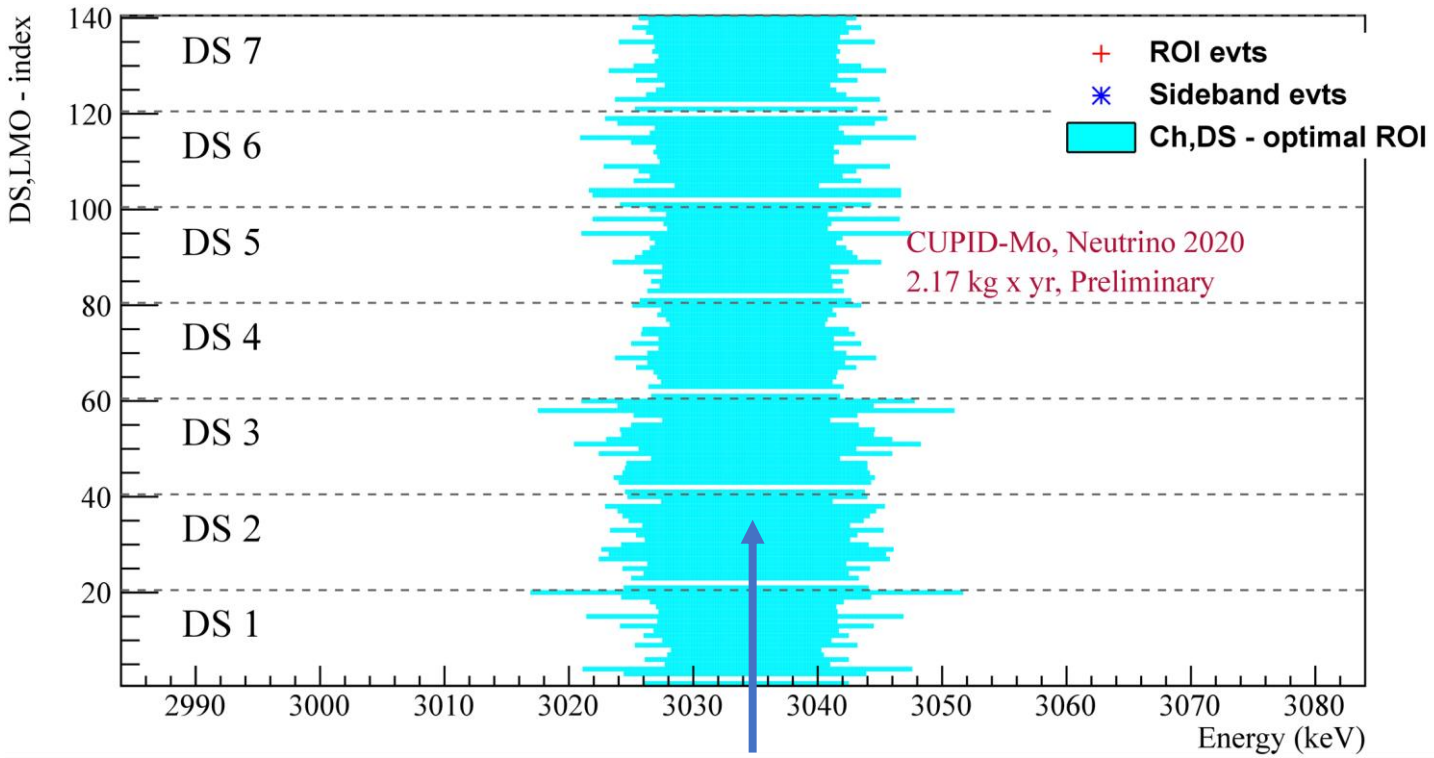
**Blinded region:**
100 keV centered around 3034 keV
Q-value of $^{100}$Mo

# Definition of the ROI

Before unblinding, we have defined the ROI for each data set and for each channel

Optimization of the signal ROI based on Poisson counting analysis in Signal, Background likelihood space, assuming:

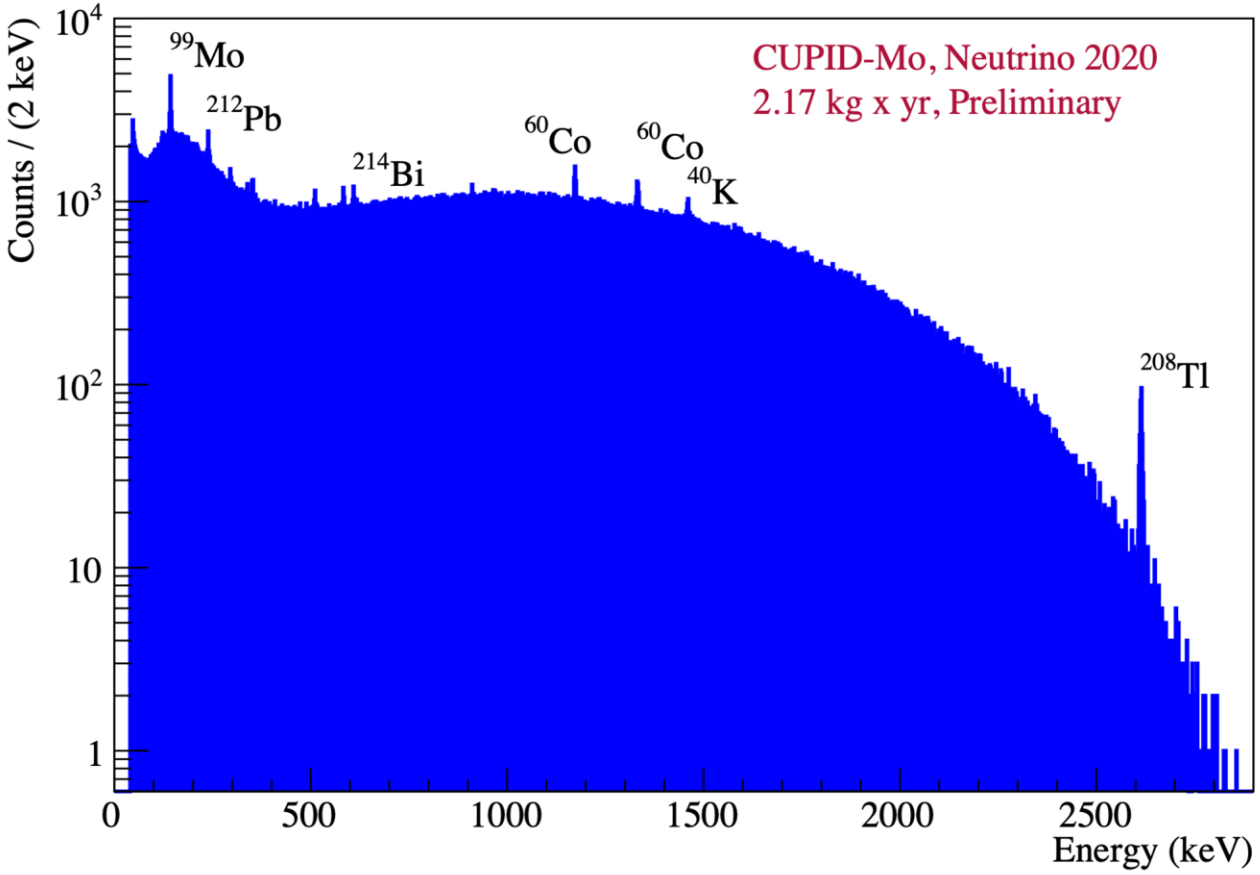
- An expected final CUPID-Mo exposure of 2.8 kg × y
- A background index b = 5 × $10^{-3}$ counts/(keV kg y)



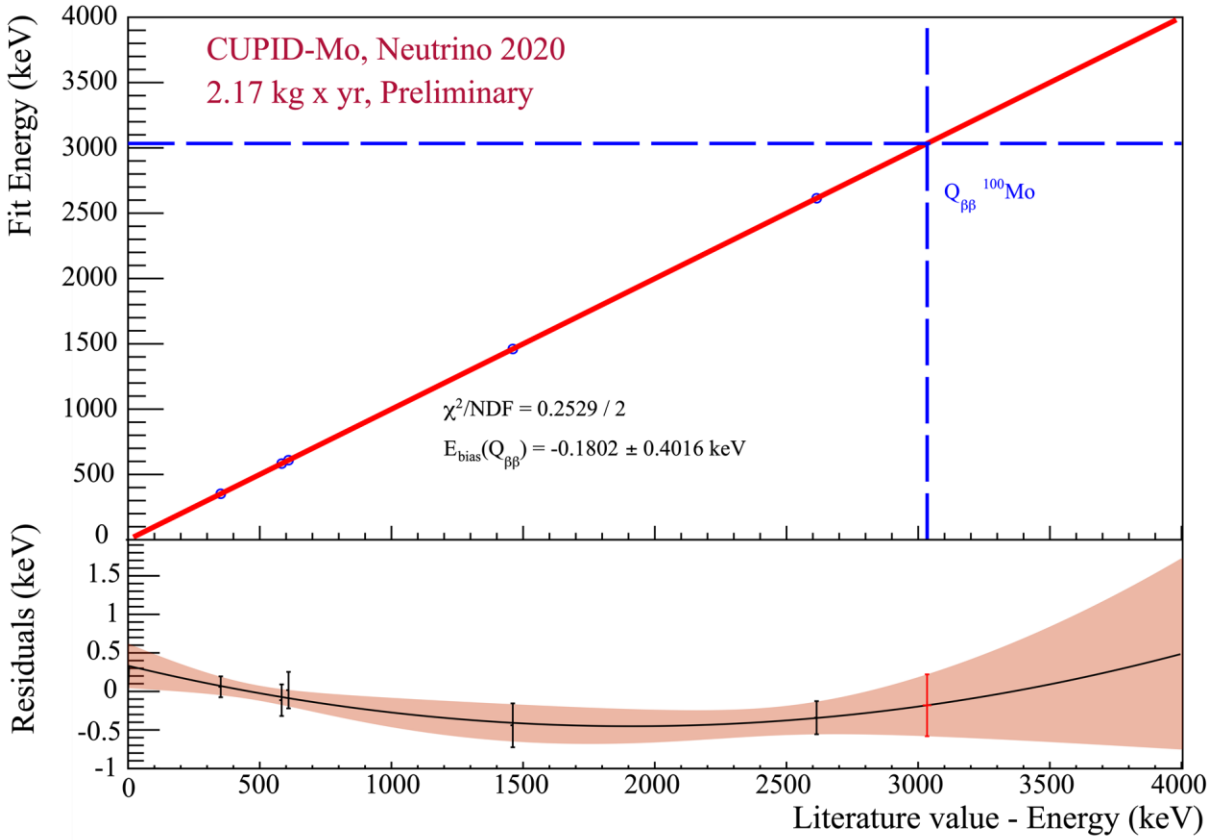

**Large central ROI ~ 18 keV average width**

# Ingredients for ROI definition: energy scale

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

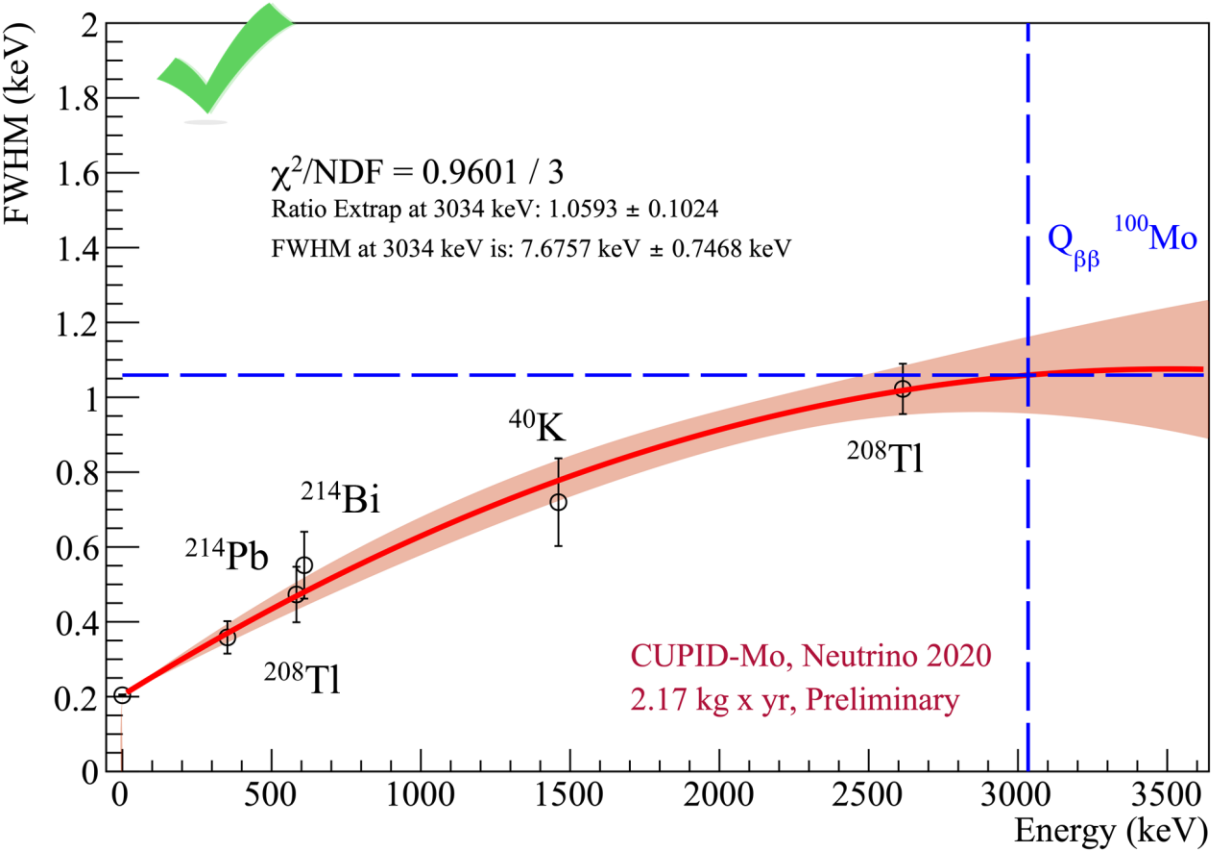


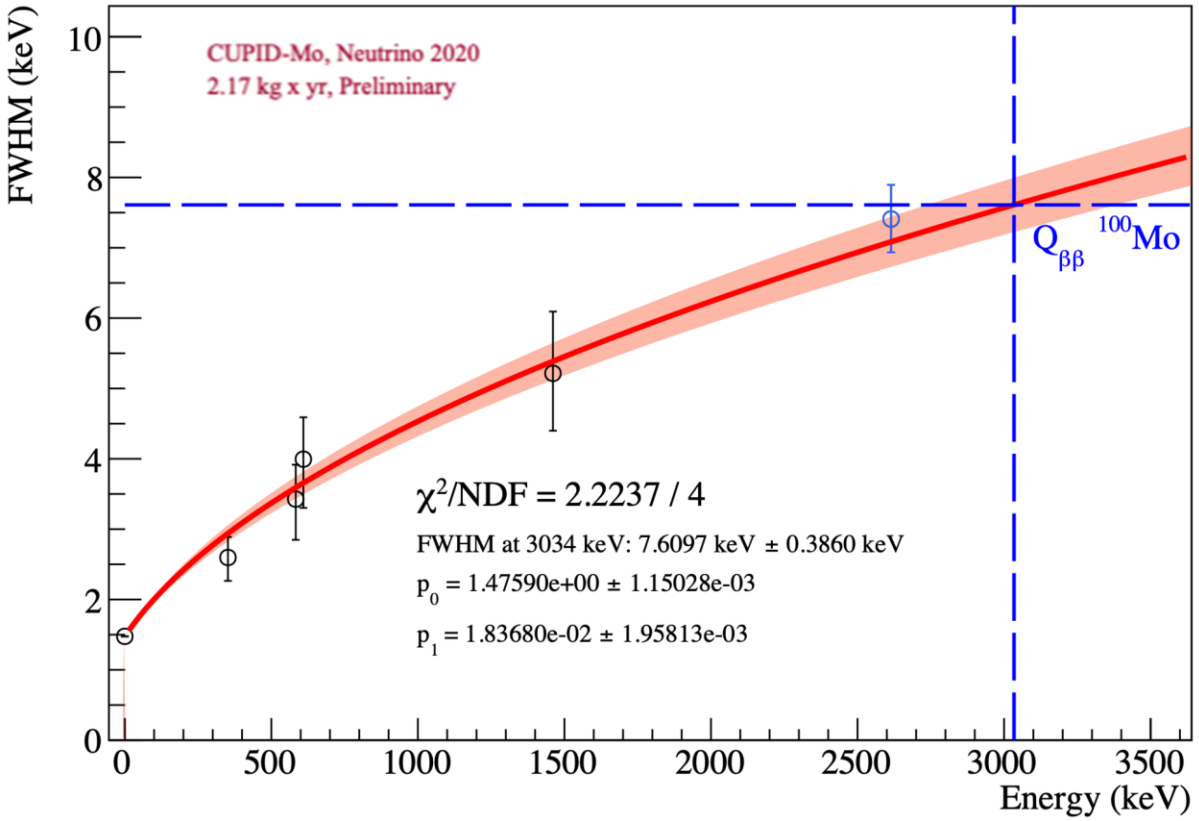

- Estimate possible energy bias based on physics data, $E_B$ = (-0.2 ± 0.4) keV



# Ingredients for ROI definition: energy resolution

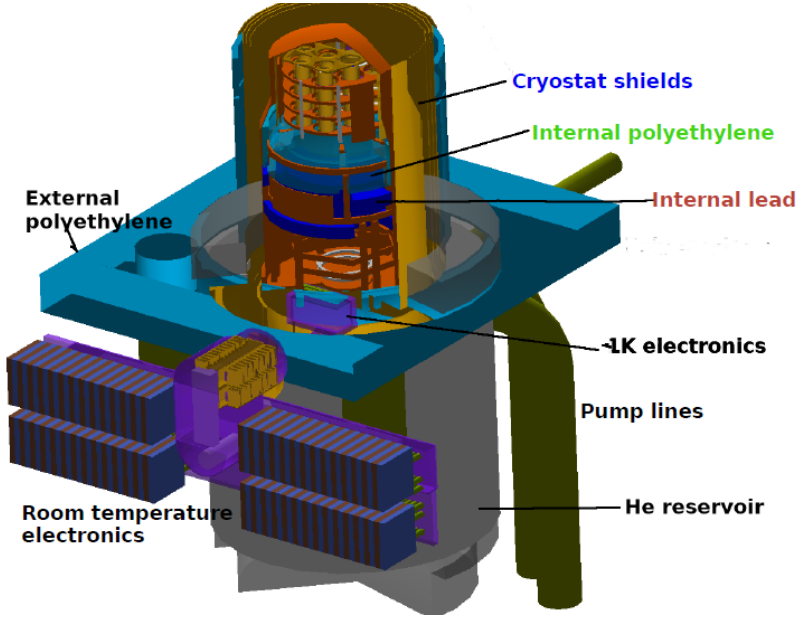
- Obtain a global scaling factor Calibration @2615 keV <-> Physics @3034 keV
- Test several hypothesis:
  - linear, sqrt, pol2 fit -> linear is ruled out by calibration data -> take remaining more conservative estimate (pol2)

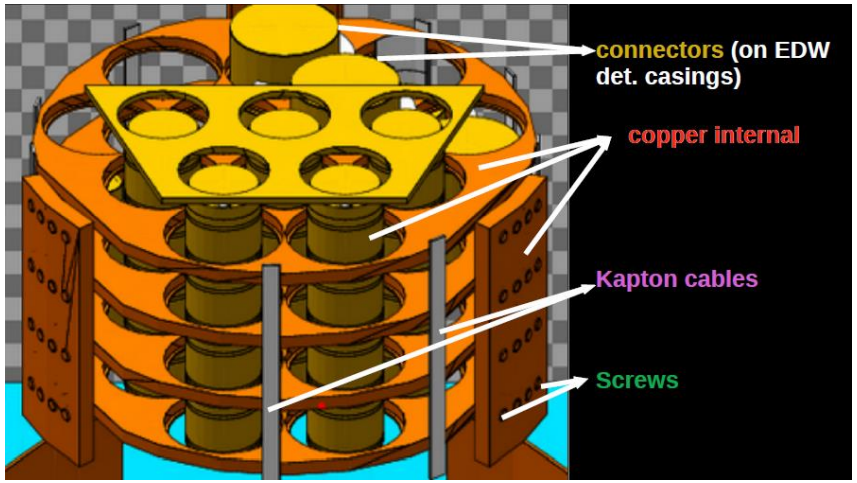


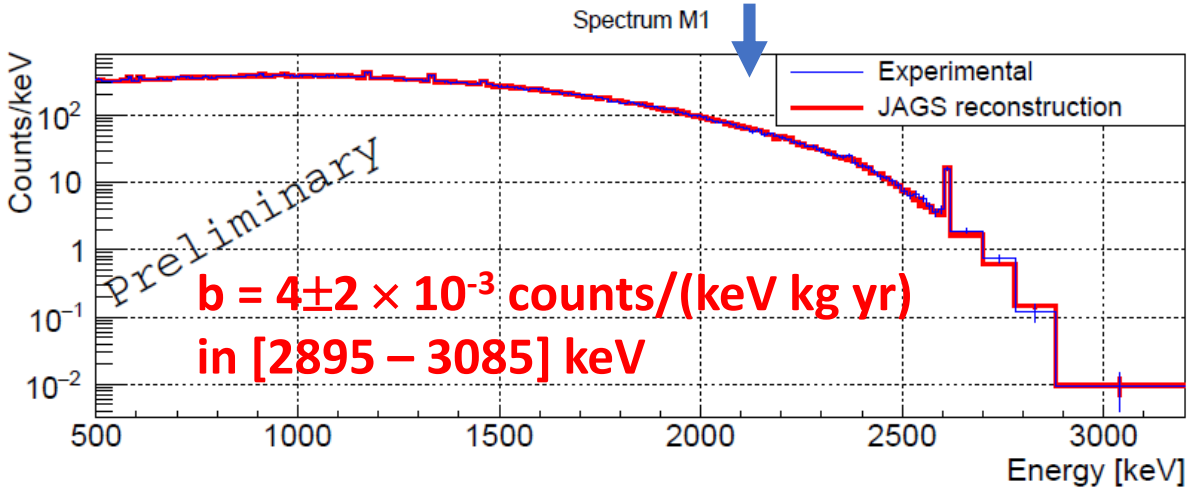
# Ingredients for ROI definition: background model

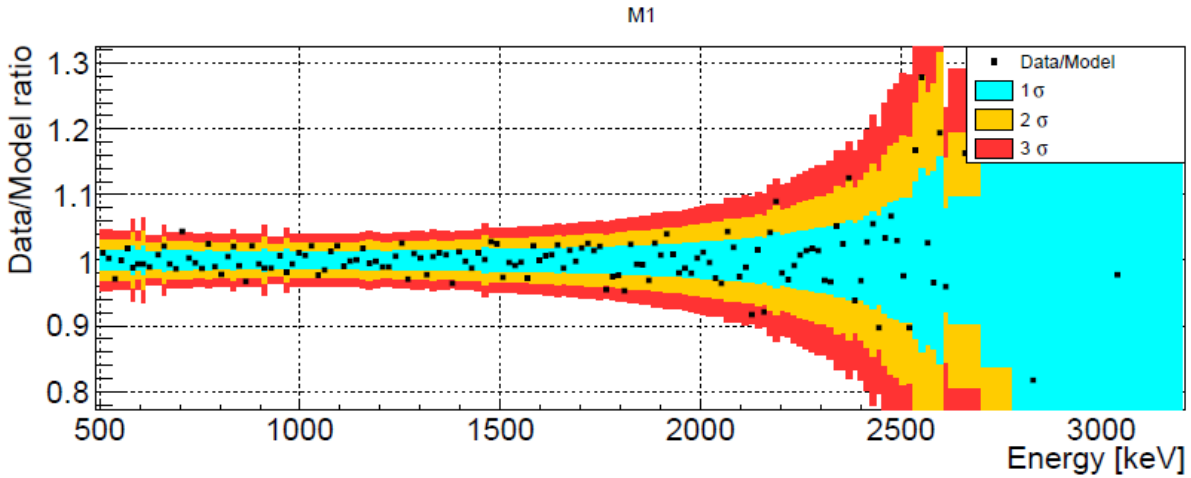
**Detailed Geant4 Monte Carlo model**



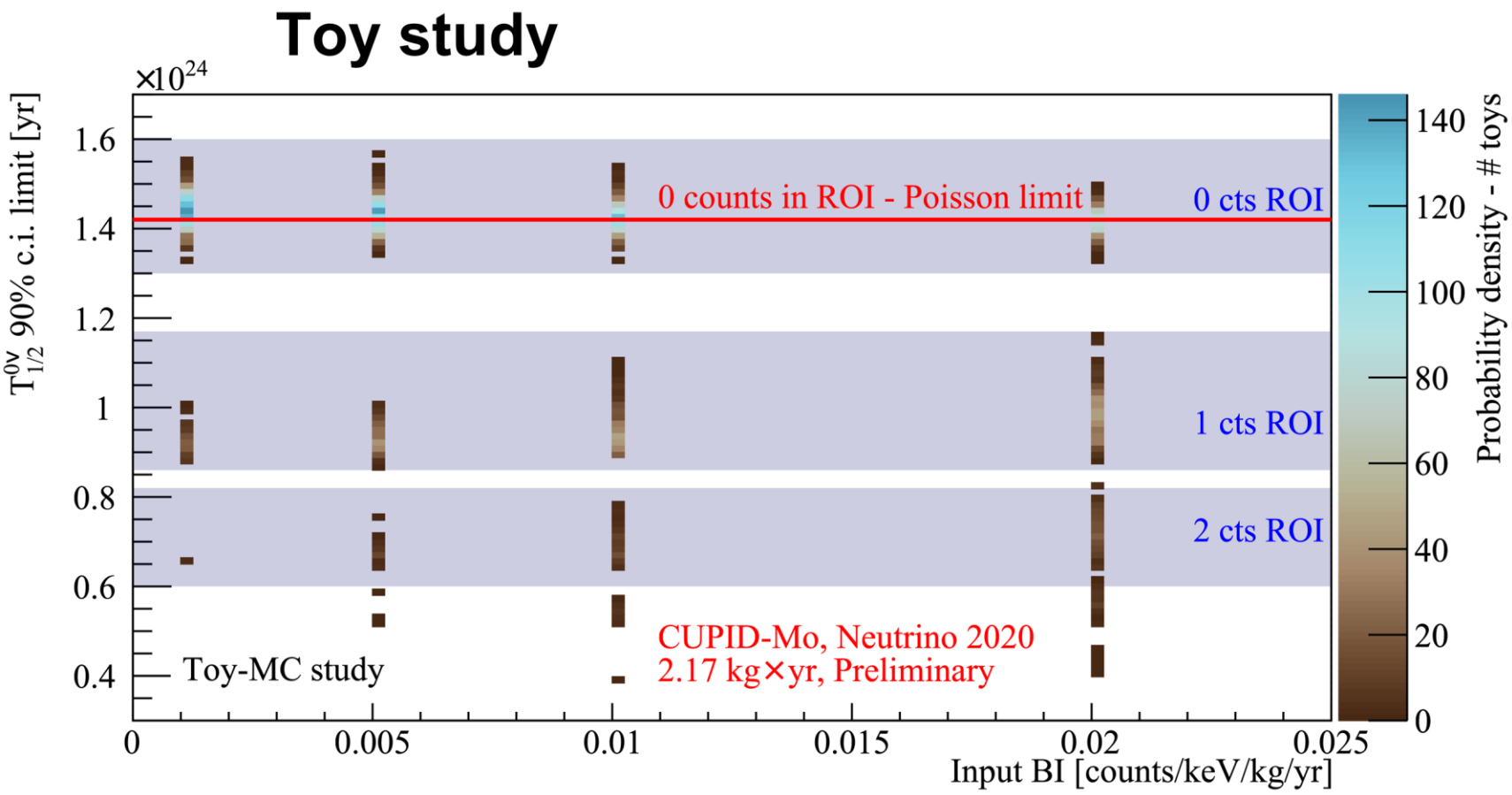

Two fits: RooFit and **JAGS (MCMC)**




Consistent with independent estimation based on the fit of M1 $\gamma/\beta$ data with exponential + constant

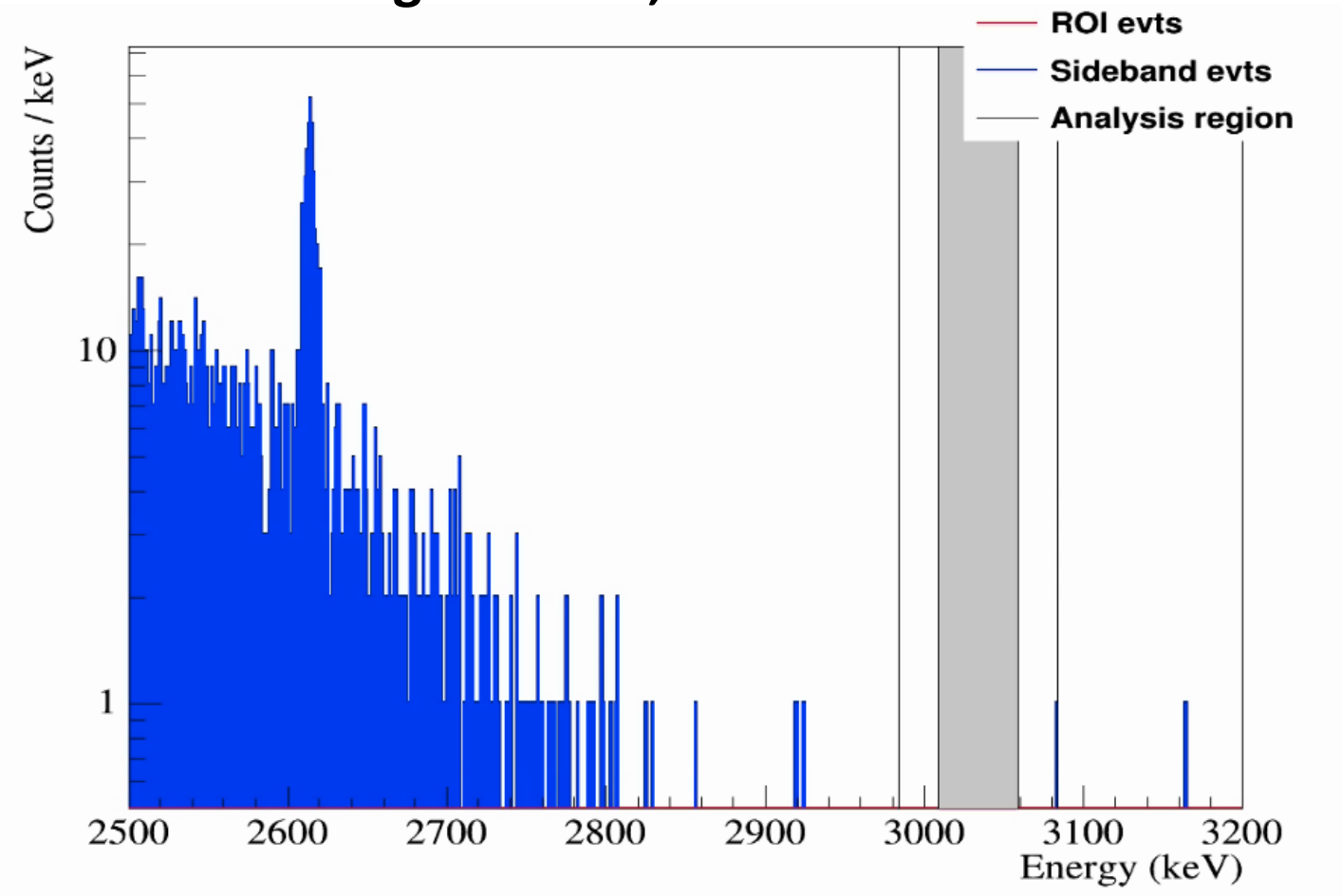
# CUPID-Mo – limit setting




- 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 – limit setting

**Unblinding: June 9th, 2020**



# CUPID-Mo – limit setting

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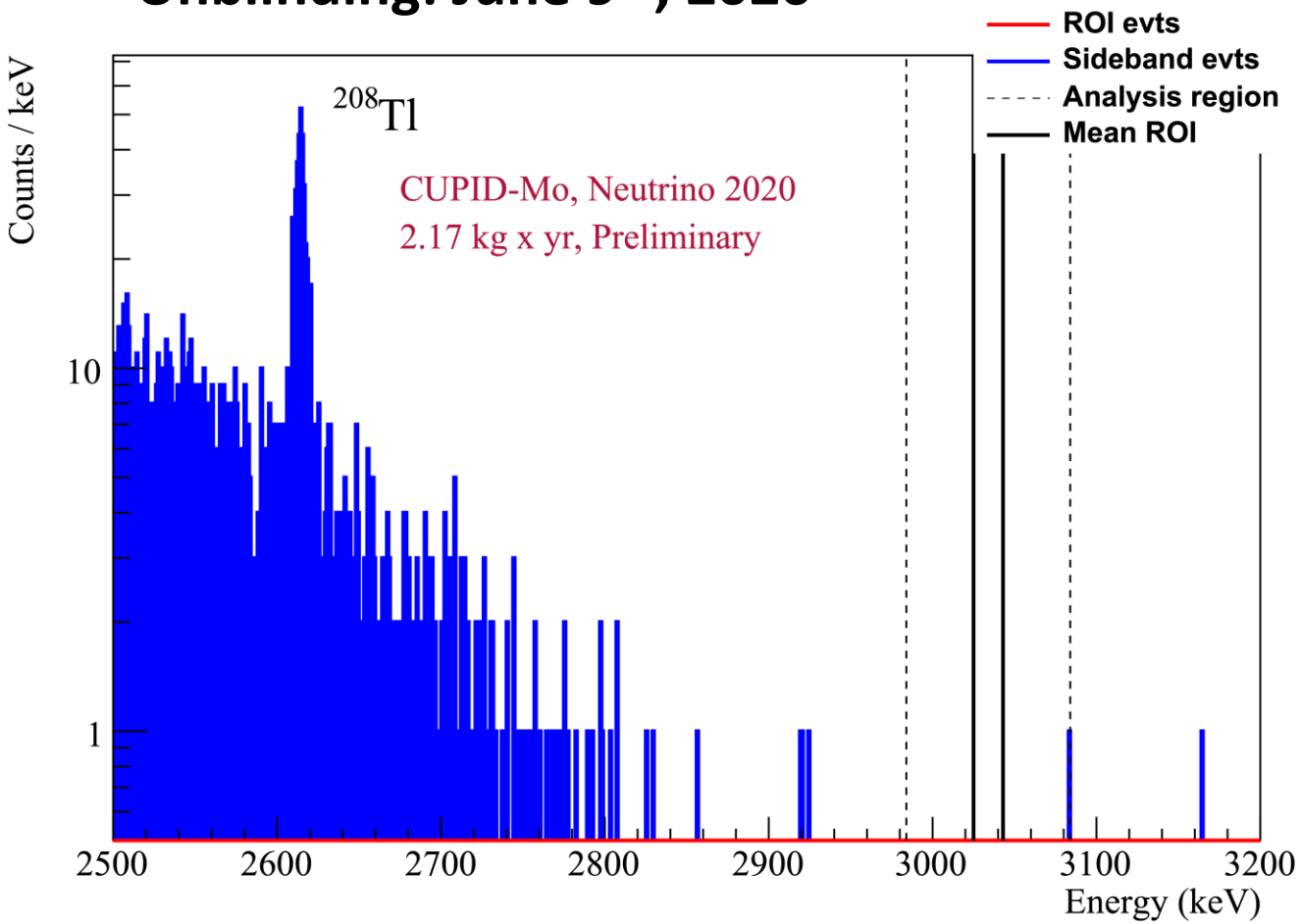



New world leading limit on $0\nu2\beta$ of $^{100}$Mo

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

**Neutrino 2020 poster #419**
**h 16:25 – Today**
**Connect to virtual poster room!**

With CUPID-Mo technology:
Most precised measurement of $2\nu2\beta$ of $^{100}$Mo

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

**Neutrino 2020 poster #525**

# CUPID-Mo – rich physics program

**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 $^{56}$Co calibration campaign
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-374.pdf

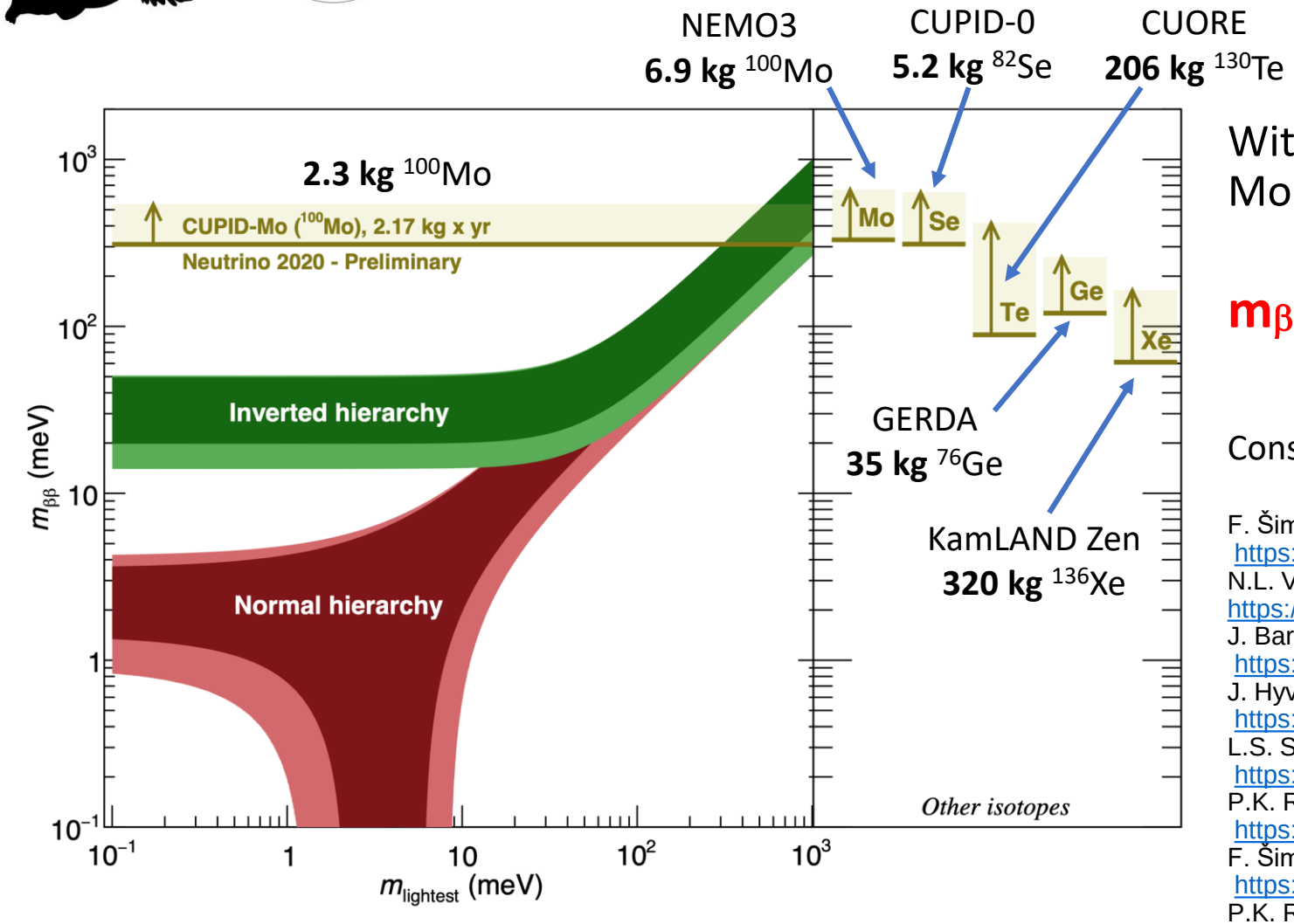
CUPID-Mo background model
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-418.pdf

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

$2\nu\beta\beta$ analysis with CUPID-Mo technology
https://nusoft.fnal.gov/nova/nu2020postersession/pdf/posterPDF-525.pdf

# CUPID-Mo – limit setting




With only 1 year of data and ~2 kg of $^{100}$Mo CUPID-Mo is able to set a limit of

**$m_{\beta\beta}$ < (310-540) meV 90% c.i.**

Considering $g_A$ = 1.27 and the following NME calculations:

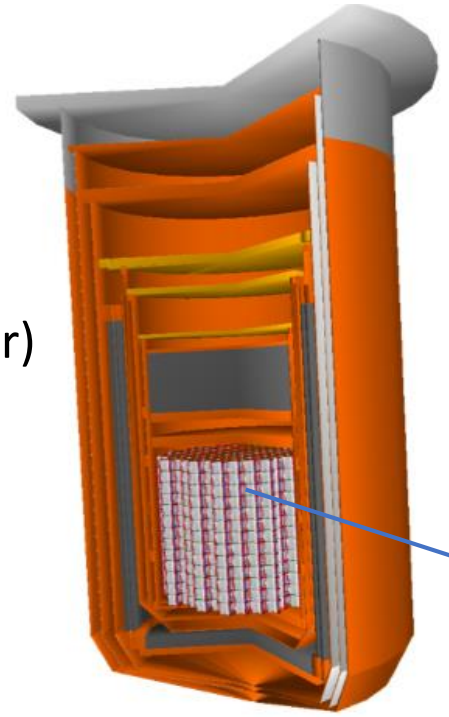

F. Šimkovic, V. Rodin, A. Faessler, P. Vogel, Phys. Rev. C 87, 045501 (2013). https://doi.org/10.1103/PhysRevC.87.045501
N.L. Vaquero, T.R. Rodríguez, J.L. Egido, Phys. Rev. Lett. 111, 142501 (2013). https://doi.org/10.1103/PhysRevLett.111.142501
J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 91, 034304 (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

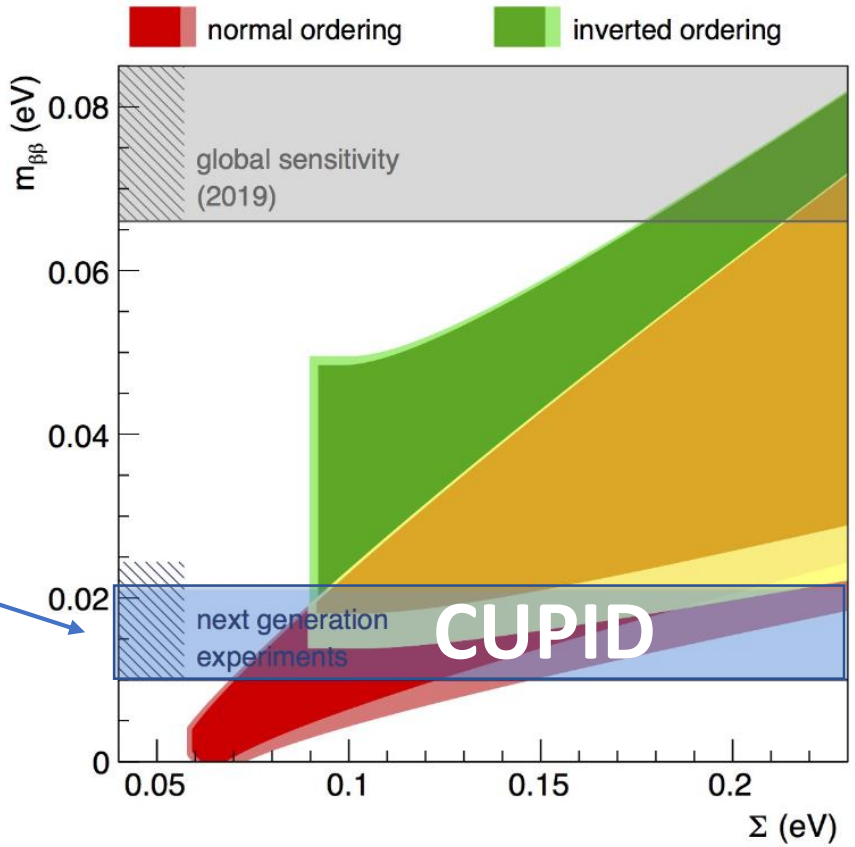
# CUPID

## CUPID in a nutshell

- ~1500 $Li_2{}^{100}MoO_4$ scintillating crystals
- (~250 kg of $^{100}Mo$)
- FWHM: 5 keV at $Q_{\beta\beta}$
- α rejection via light yield cut: > 99.9%
- Background index: $10^{-4}$ counts/(keV × kg × yr)
- **$T^{0\nu}_{1/2}$ > 1.1 × $10^{27}$ yr (3 σ)**
- **$m_{\beta\beta}$ < 12-20 meV (IH)**

CUORE cryostat, mature design, data-driven background model






Can be built now!

- TDR and construction readiness for end 2021
- Schedule and budget will be driven by $^{100}Mo$ enrichement → ~ 4 years

# The CUPID-Mo collaboration

Zoom Unblinding

IJCLab-Orsay, CEA-Saclay, IP2I-Lyon, CNRS-Néel-Grenoble, SIMAP-Grenoble,
UCB/LBNL-Berkeley, MIT-Cambridge, Univ. South Carolina-Columbia,
INR-Kyiv,
ITEP-Moscow, NIIC-Novosibirsk, JINR-Dubna,
INFN-Milano Bicocca, INFN-Roma La Sapienza, INFN-LNGS,
Fudan-Shanghai, USTC-Hefei,
KIT-Karlsruhe, TUM-Garching

CUPID-Mo general meeting, March 2018, CSNSM

# The CUPID-Mo collaboration

Zoom Unblinding

## Special thanks to:

**EDELWEISS collaboration** – cryostat, electronics, DAQ, low radioactivity, help in data taking

**LSM direction and staff**

**ANR – LUMINEU**

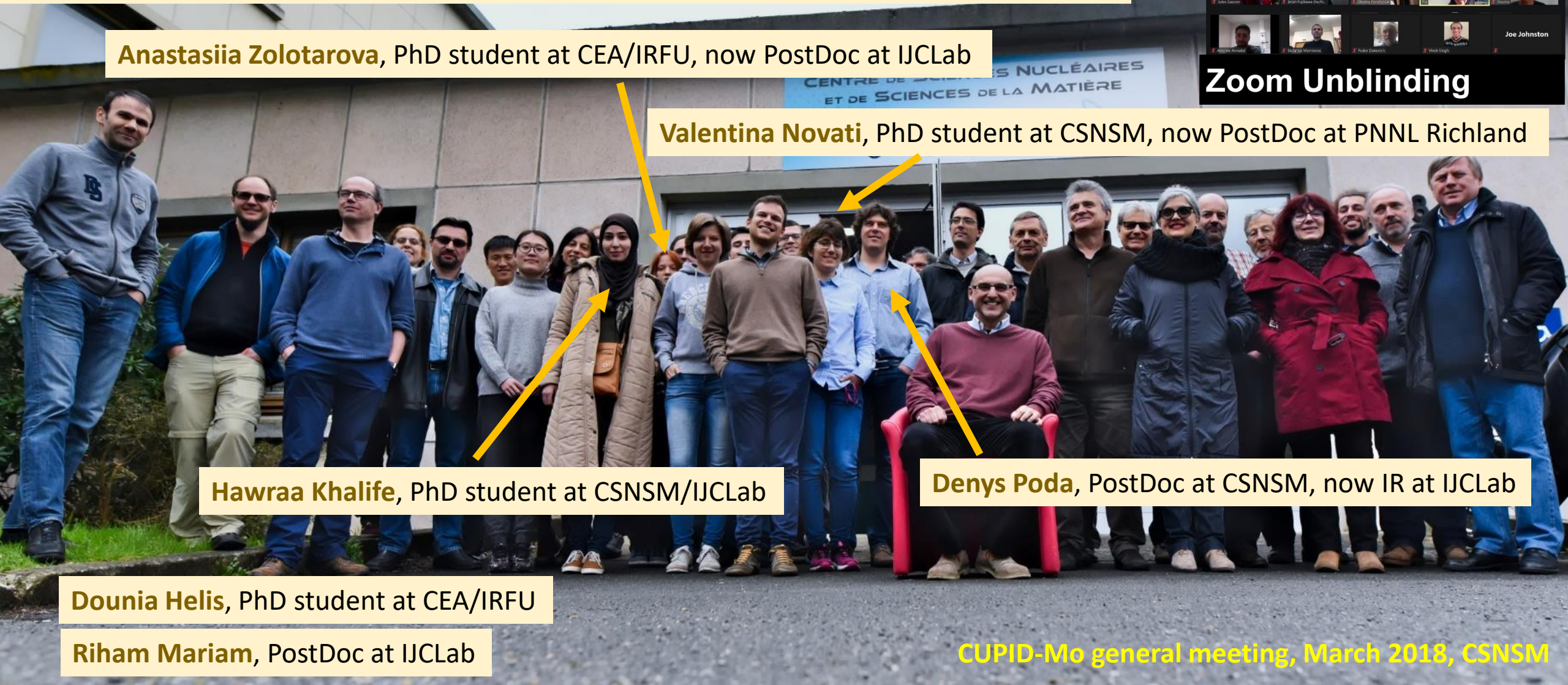
**LABEX P2IO – BSM_nu project**

**CUORE collaboration** – data analysis and Monte Carlo simulation tools

CUPID-Mo general meeting, March 2018, CSNSM

# The CUPID-Mo collaboration

**Invaluable support from a fantastic group of young researchers in the Orsay-Saclay region**




**Anastasiia Zolotarova**, PhD student at CEA/IRFU, now PostDoc at IJCLab

**Valentina Novati**, PhD student at CSNSM, now PostDoc at PNNL Richland

**Hawraa Khalife**, PhD student at CSNSM/IJCLab

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**Zoom Unblinding**

**CUPID-Mo general meeting, March 2018, CSNSM**

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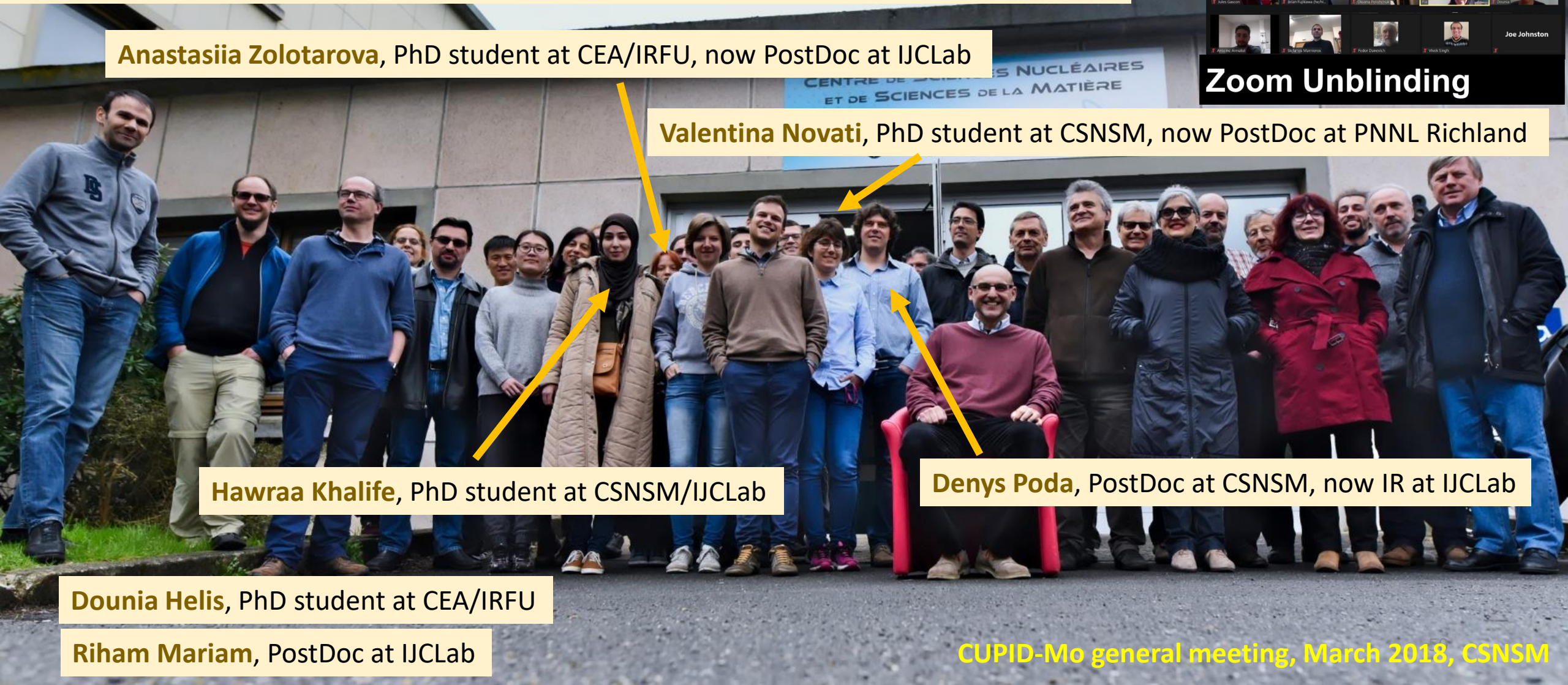


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**CUPID-Mo general meeting, March 2018, CSNSM**

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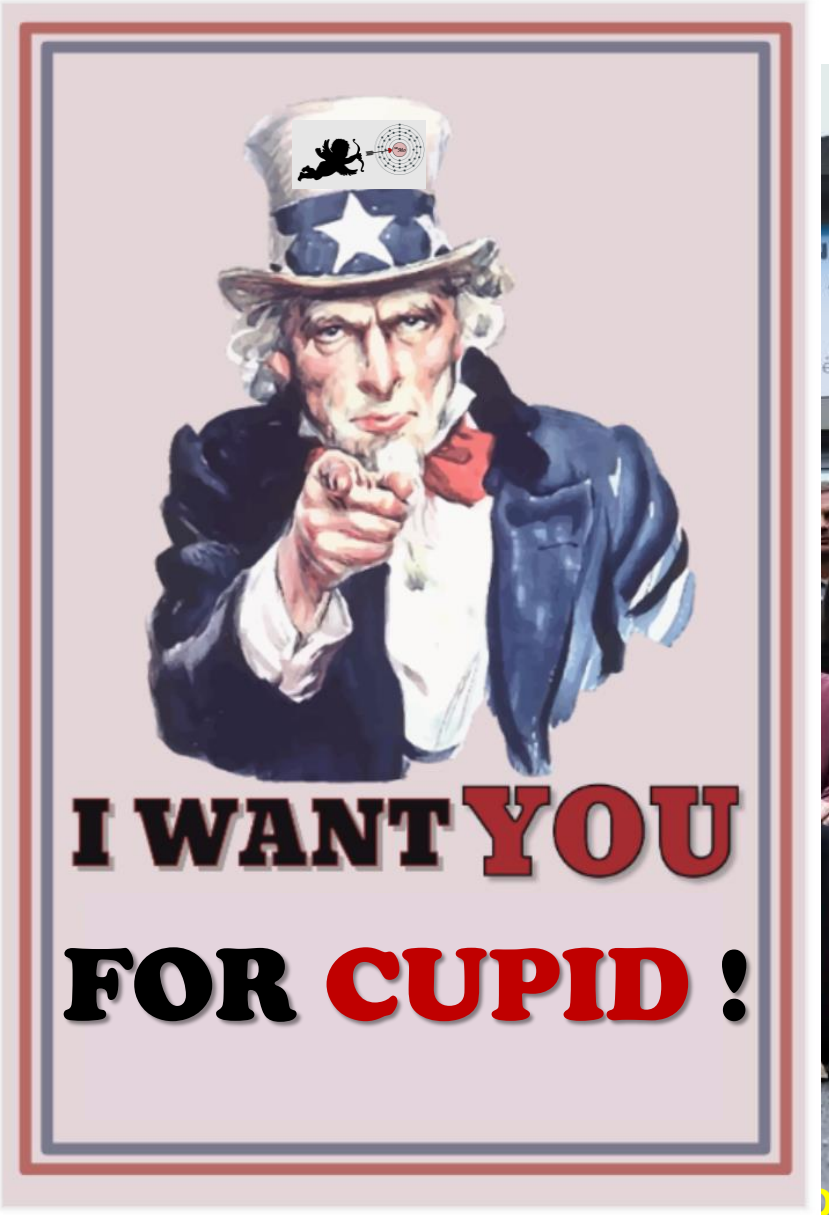


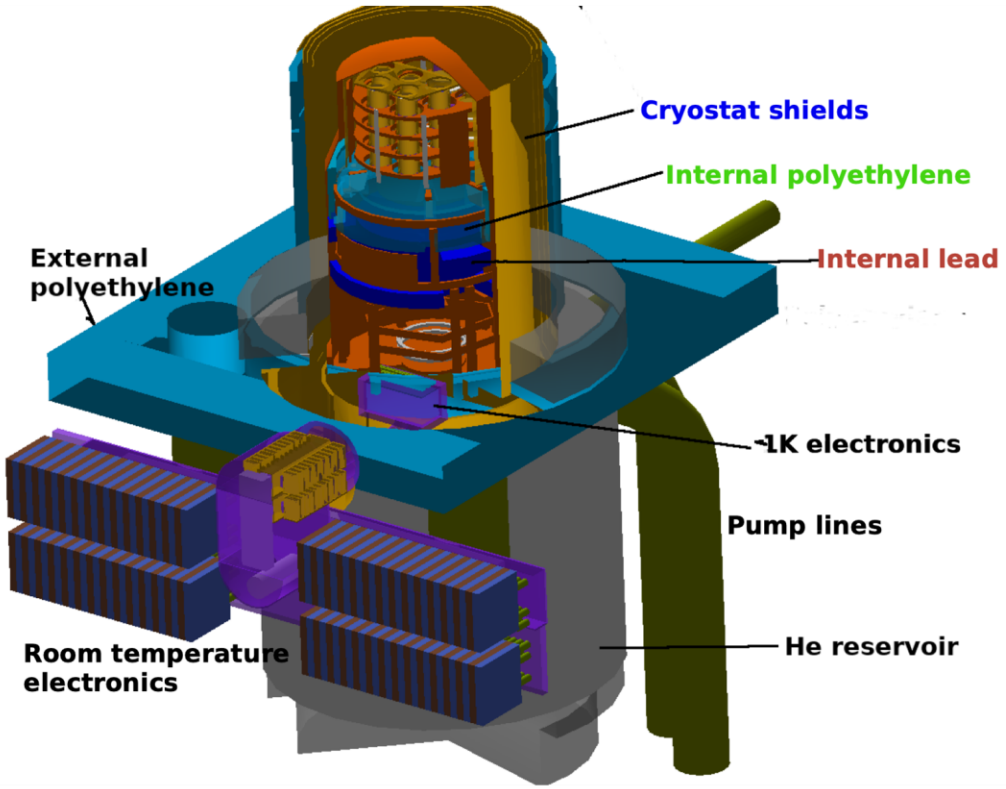
Zoom Unblinding

-Mo general meeting, March 2018, CSNSM

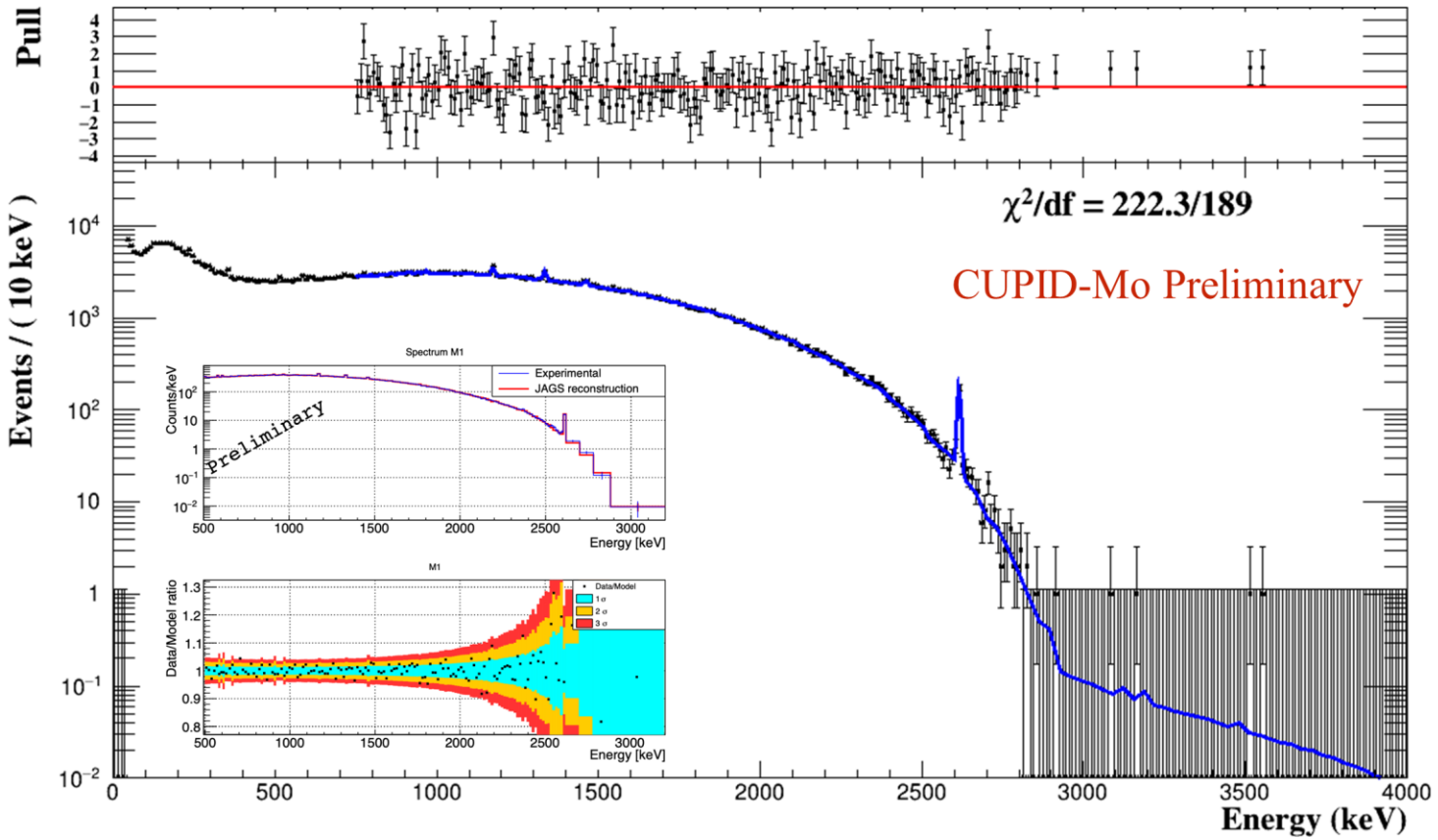
# BACK-UP

# Ingredients for ROI definition: background model

**Detailed Geant4 Monte Carlo model**



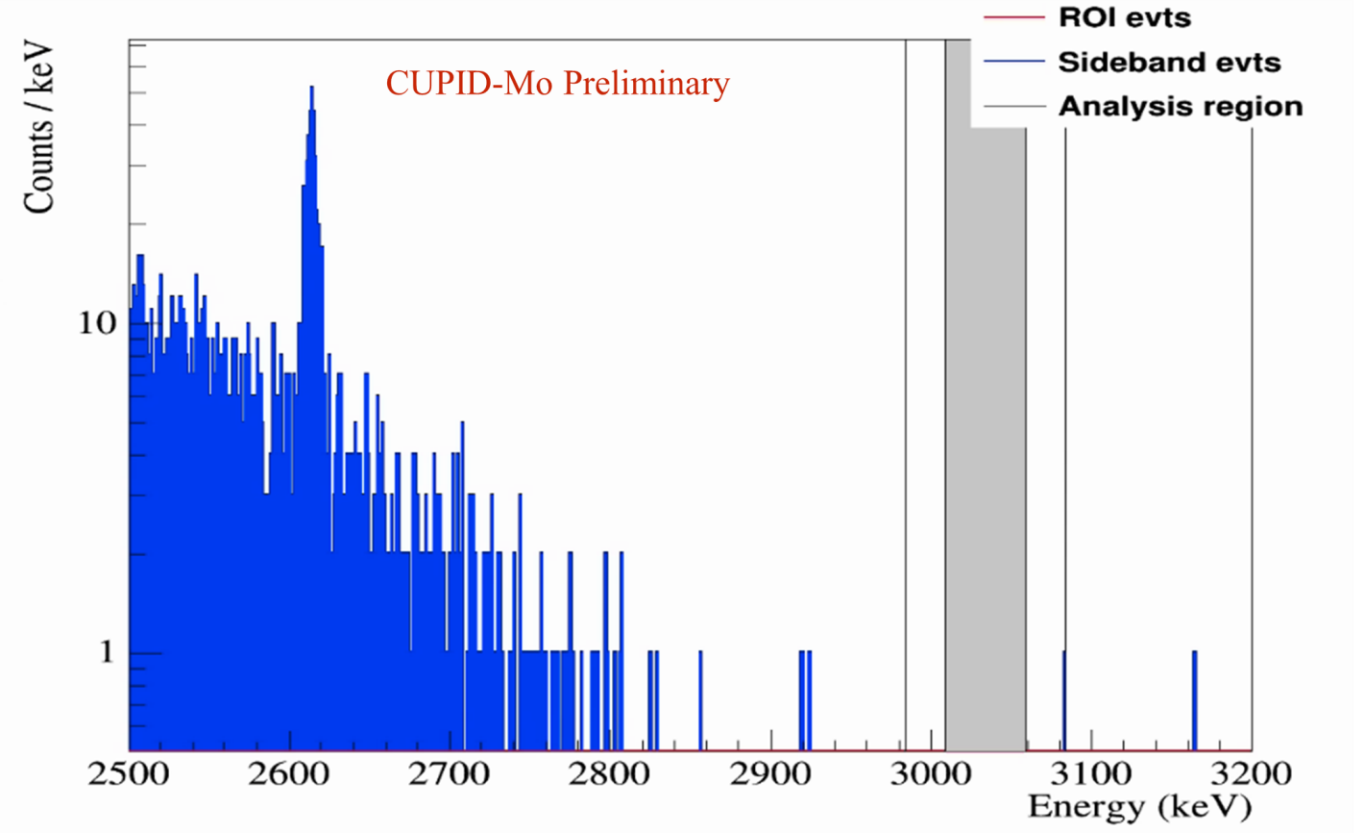

- Two fits: RooFit and JAGS (MCMC)
  - M1 - Gamma analysis: BI expectation for **0nbb** ROI
    **4 ± 2 x $10^{-3}$ counts / (keV x kg x yr)**

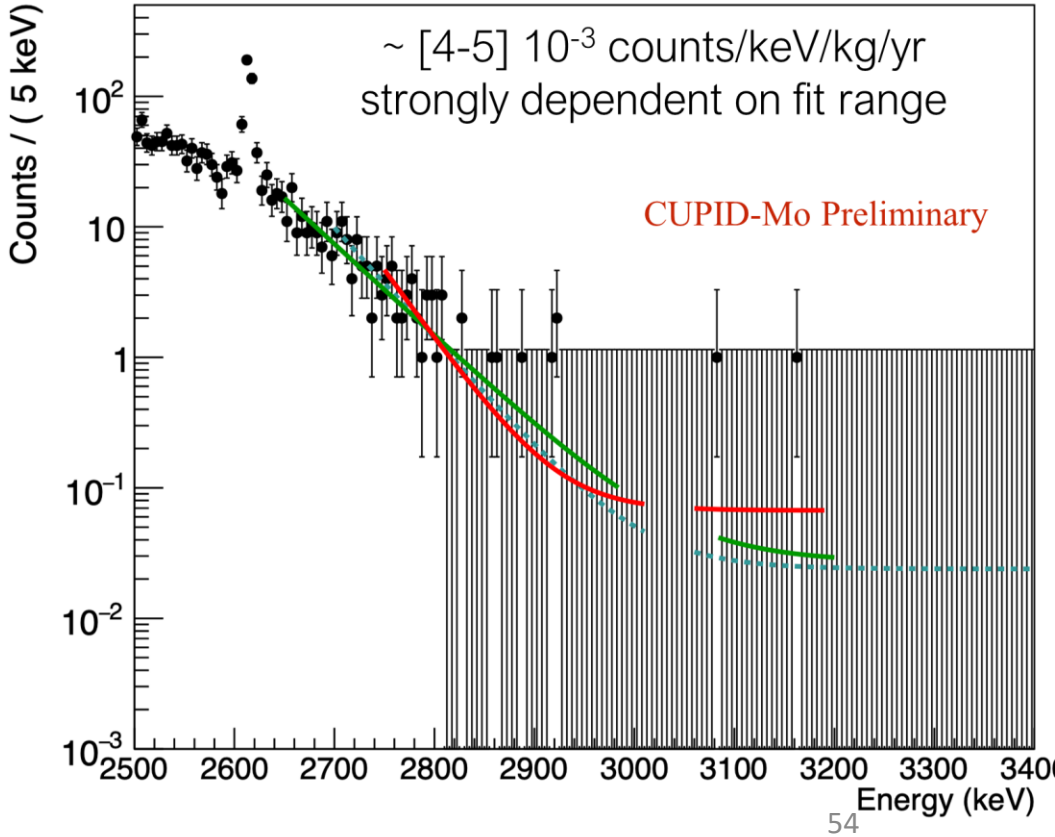


# Ingredients for ROI definition: background model

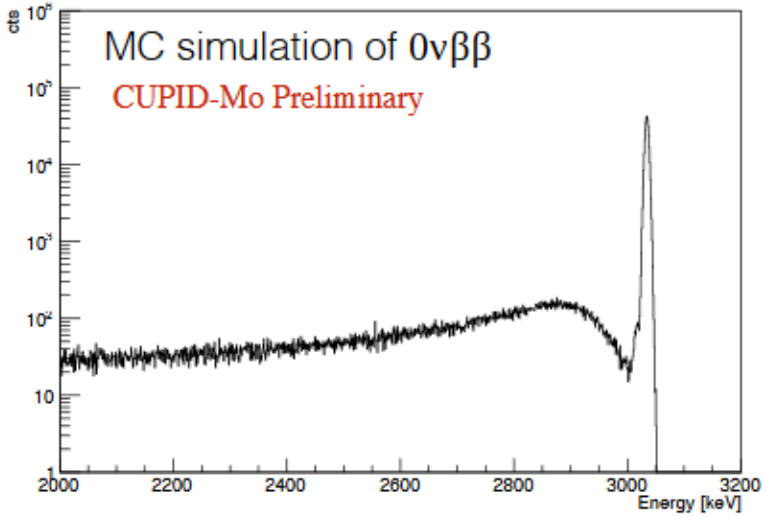
**Alternative phenomenological approach**

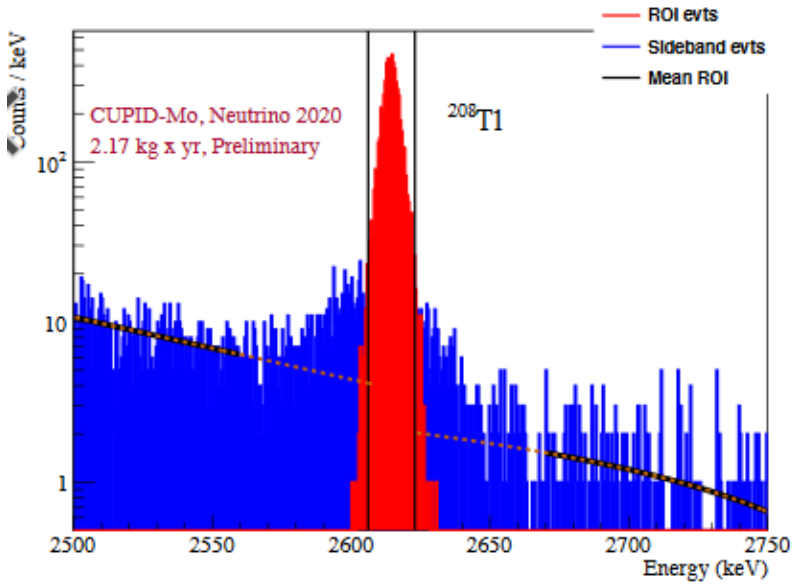
- Perform unbinned extended maximum likelihood fit on Bg data excluding [3010, 3060] keV
- Phenomenological Bg model:
  Exponential - approximates both $2\nu\beta\beta$ spectral shape and U/Th calibration tail
  Flat component - conservative estimate of $2\nu\beta\beta$ pile-up and remaining muon-induced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



# CUPID-Mo systematics



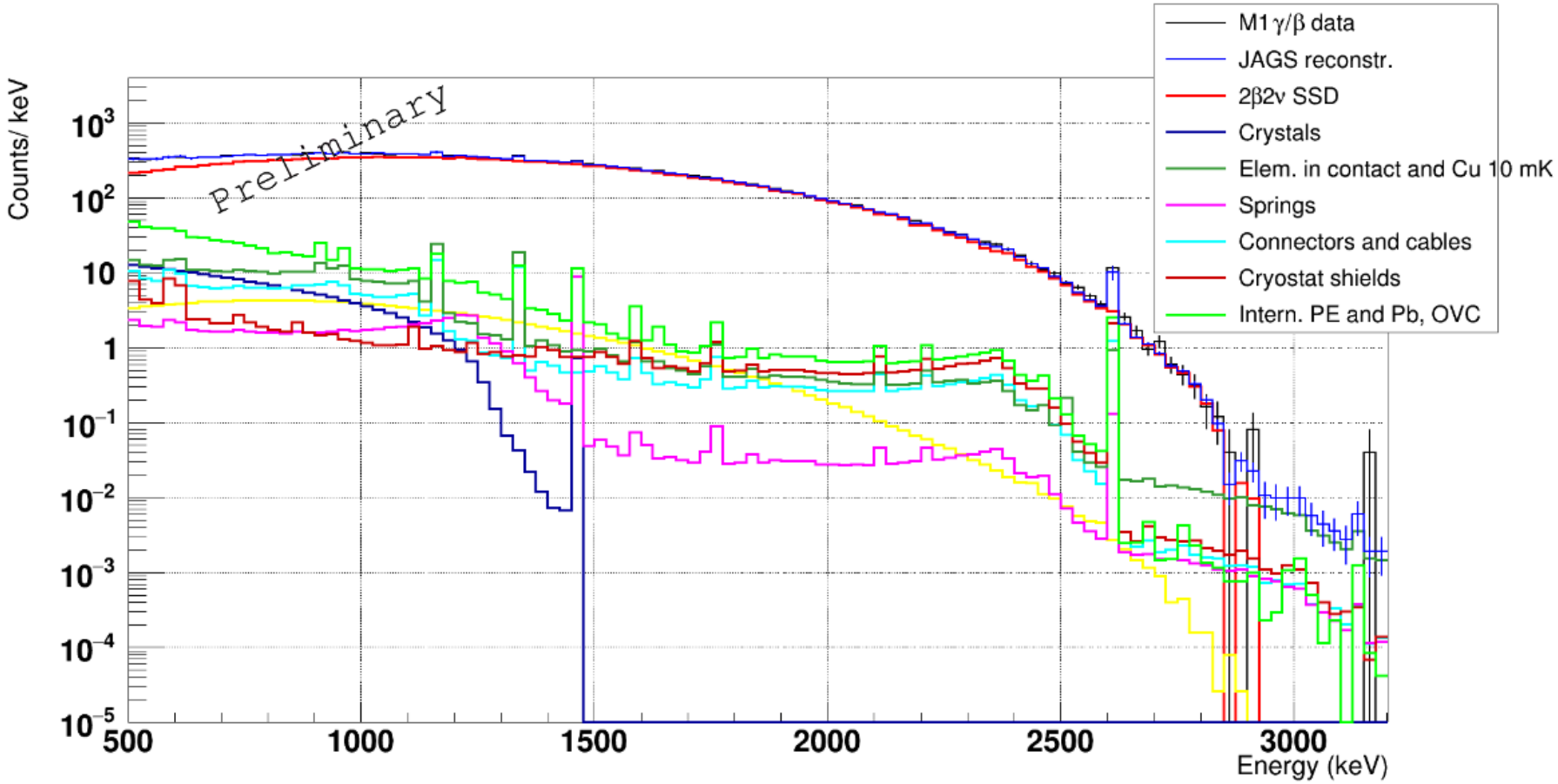




- Isotope concentration (96.6 ± 0.2) %
- Containment (~75% on average in peak)
  - Geant4 modeling & density/volume uncertainty: 1.1 %
  - Energy scale and resolution uncertainties included with MC sampling in containment of chosen ROI
- Analysis efficiency
  - All cuts stat. & PCA extrapolation - Gaussian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

# Background model: JAGS – detail of the sources



# CUPID Timeline

| Task | Activity | Y1Q1 | Y1Q2 | Y1Q3 | Y1Q4 | Y2Q1 | Y2Q2 | Y2Q3 | Y2Q4 | Y3Q1 | Y3Q2 | Y3Q3 | Y3Q4 | Y4Q1 | Y4Q2 | Y4Q3 | Y4Q4 | Y5Q1 | Y5Q2 | Y5Q3 | Y5Q4 | Y6Q1 | Y6Q2 | Y6Q3 | Y6Q4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | YEAR 1 | | | | YEAR 2 | | | | YEAR 3 | | | | YEAR 4 | | | | YEAR 5 | | | | YEAR 6 | | | |
| 1,1 | **Mo-100 enrichment** | | | | | | | | | | | | | | | | | | | | | | | | |
| 2,1 | **LMO crystal production** | | | | | | | | | | | | | | | | | | | | | | | | |
| 2,2 | **LMO crystal preparation** | | | | | | | | | | | | | | | | | | | | | | | | |
| 3.1-3.2 | NTD irradiation | | | | | | | | | | | | | | | | | | | | | | | | |
| 3,2 | NTD production and characterization | | | | | | | | | | | | | | | | | | | | | | | | |
| 4,1 | Heater production and characterization | | | | | | | | | | | | | | | | | | | | | | | | |
| 5,1 | Light detector material procurement | | | | | | | | | | | | | | | | | | | | | | | | |
| 5,2 | Light detector production and test | | | | | | | | | | | | | | | | | | | | | | | | |
| 6.1-6.2 | Material selection and procurement | | | | | | | | | | | | | | | | | | | | | | | | |
| 6,3 | Detector parts production | | | | | | | | | | | | | | | | | | | | | | | | |
| 6,4 | Detector parts cleaning | | | | | | | | | | | | | | | | | | | | | | | | |
| 7,1 | Radiopurity: material screening | | | | | | | | | | | | | | | | | | | | | | | | |
| 7,2 | Radiopurity validation | | | | | | | | | | | | | | | | | | | | | | | | |
| 8,1 | **Detector assembly line** | | | | | | | | | | | | | | | | | | | | | | | | |
| 8,2 | **Detector assembly** | | | | | | | | | | | | | | | | | | | | | | | | |
| 8,3 | **Detector assembly validation** | | | | | | | | | | | | | | | | | | | | | | | | |
| 9,1 | Parts storage | | | | | | | | | | | | | | | | | | | | | | | | |
| 10,1 | Electronics design and production | | | | | | | | | | | | | | | | | | | | | | | | |
| 10,2 | Electronics installation | | | | | | | | | | | | | | | | | | | | | | | | |
| 10,3 | DAQ | | | | | | | | | | | | | | | | | | | | | | | | |
| 10,3 | Computing and data storage | | | | | | | | | | | | | | | | | | | | | | | | |
| 11,1 | Muon veto construction | | | | | | | | | | | | | | | | | | | | | | | | |
| 11,2 | Muon veto installation | | | | | | | | | | | | | | | | | | | | | | | | |
| 12,1 | Calibration system construction | | | | | | | | | | | | | | | | | | | | | | | | |
| 12,2 | Source preparation | | | | | | | | | | | | | | | | | | | | | | | | |
| 13,1 | Clean room | | | | | | | | | | | | | | | | | | | | | | | | |
| 13,2 | Rn-free air | | | | | | | | | | | | | | | | | | | | | | | | |
| 14,1 | Cryostat maintanence | | | | | | | | | | | | | | | | | | | | | | | | |
| 14,2 | Cryostat wiring design | | | | | | | | | | | | | | | | | | | | | | | | |
| 14,3 | Cryostat wiring | | | | | | | | | | | | | | | | | | | | | | | | |
| 14,4 | Cryogenic tests | | | | | | | | | | | | | | | | | | | | | | | | |
| 15,1 | **Detector installation** | | | | | | | | | | | | | | | | | | | | | | | | |
| 15,2 | Cryostat closure | | | | | | | | | | | | | | | | | | | | | | | | |
| 16,1 | **Cooldown and comissioning** | | | | | | | | | | | | | | | | | | | | | | | | |

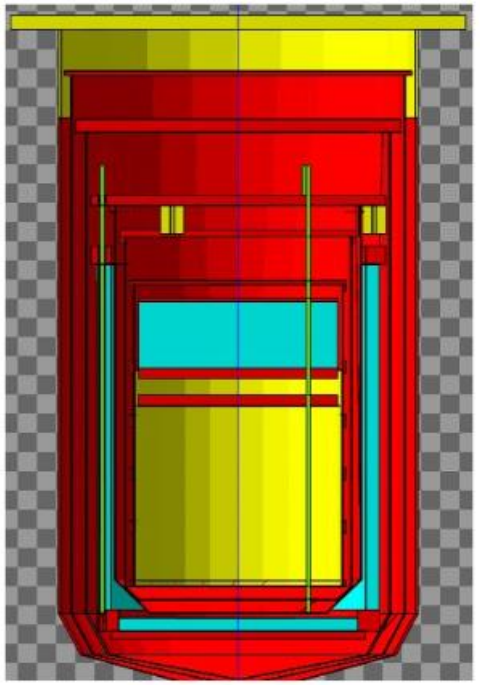
Technically-limited **schedule**, **dominated by isotope procurement** (schedule may be accelerated if multiple isotope vendors are available)

**5-year construction**, followed by installation and commissioning → **10 years of operation**

# CUPID sensitivity (1)

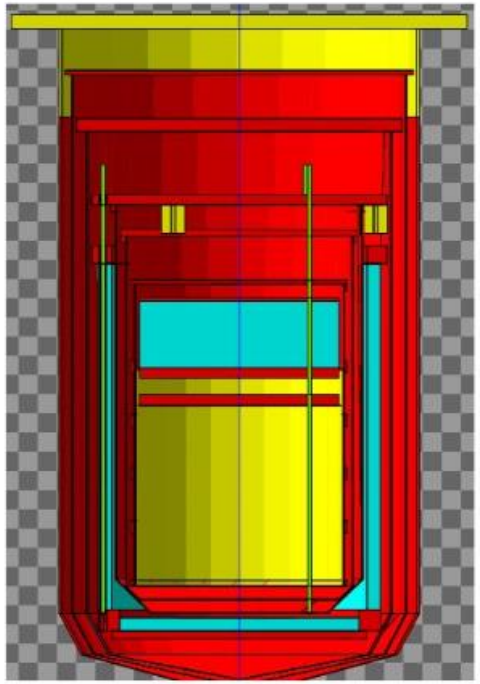
**Technically ready**

CUPID Baseline



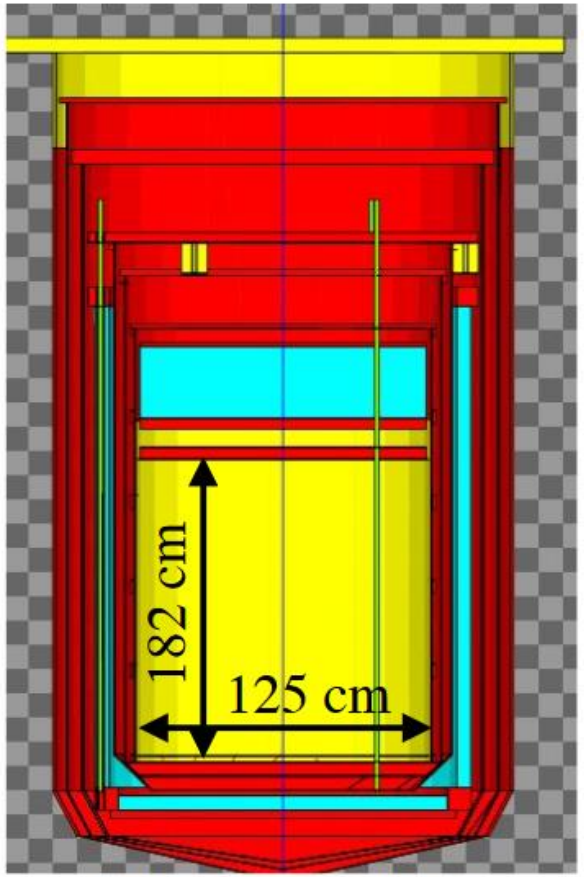
250 kg of $^{100}$Mo
CUORE cryostat
Bkg $1\times10^{-4}$ ckky
Excl. sensitivity:
$T_{1/2}$> $1.5\times10^{27}$ years (IH)

CUPID-reach



250 kg of $^{100}$Mo
CUORE cryostat
Bkg $2\times10^{-5}$ ckky
Excl. sensitivity:
$T_{1/2}$> $2.3\times10^{27}$ years (IH)

CUPID-1T




1000 kg of $^{100}$Mo
New cryostat
Bkg $5\times10^{-6}$ ckky
Excl. sensitivity:
$T_{1/2}$> $9.2\times10^{27}$ years (NH)

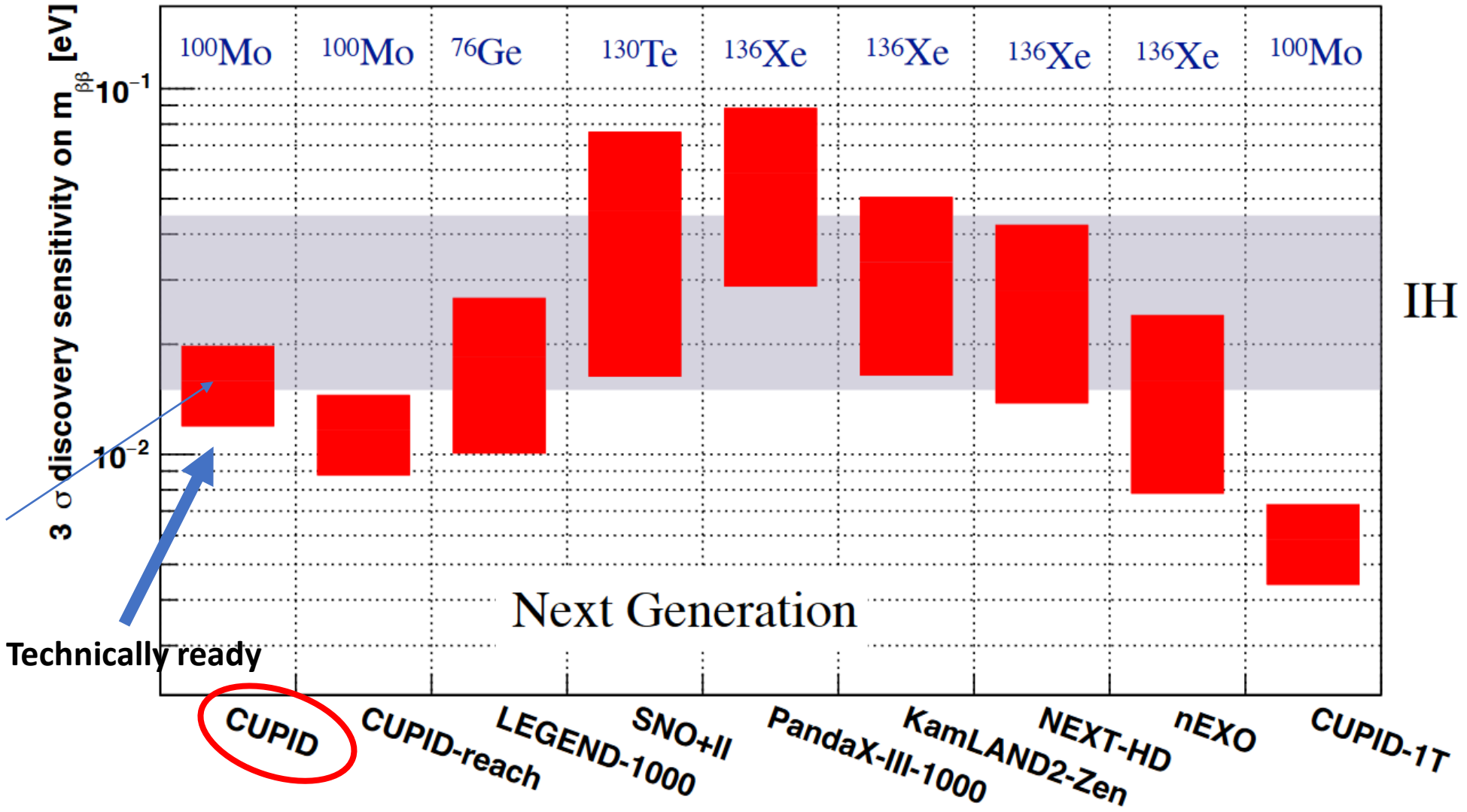
# CUPID sensitivity (2)

90% C.L. limit

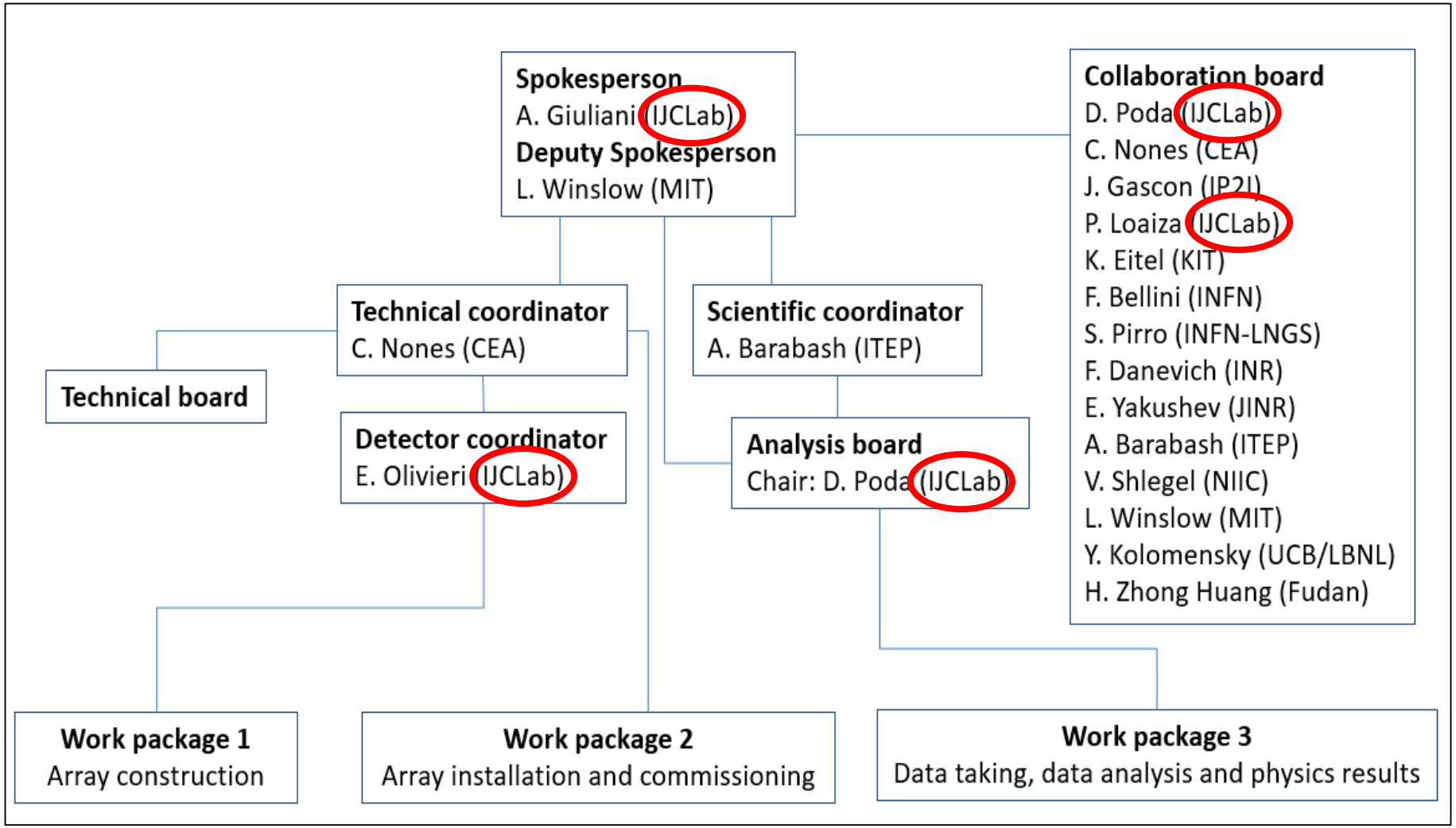
**$m_{\beta\beta}$ < 10 – 17 meV**

3σ discovery sesntivity

**$m_{\beta\beta}$ < 12 – 20 meV**




Methodology from Phys. Rev. **D96**, 053001 (2017)

Parameters from PRD96, 053001 (2017); arXiv:1910.04688

# CUPID-Mo collaboration