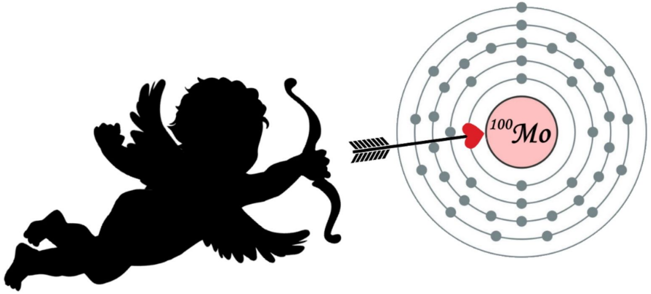
The CUPID-Mo experiment for 0νββ decay



Giovanni Benato

Séminaires du DPhP, December 7th, 2020

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso
Fellowship for Innovation at INFN

Matter producing 0νββ decay

What is matter?

- Everyday life: matter is made of atoms ⟹ Fails at high energy
- SM definition: matter is made of leptons and baryons (or quarks)

What is conserved in the SM?

- ~~B and L~~ ⟹ Non-perturbative effects at high energy
- (B-L), ~~$(L_e - L_\mu)$, $(L_\mu - L_\tau)$, $(L_\tau - L_e)$~~ ⟹ Oscillation experiments

S. Dell'Oro, S. Marcocci and F. Vissani, PoS NEUTEL2017 (2018) 030

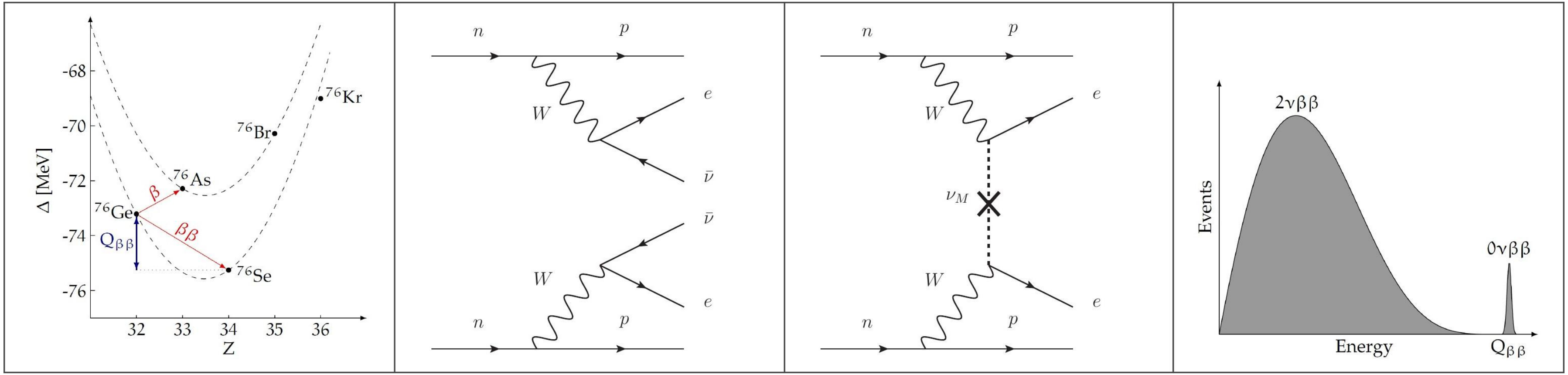
M. Agostini, G. Benato, J. Detwiler, J. Menendez and F. Vissani
Review paper coming out soon(ish)

How can we test the conservation of B, L, (B-L)?

ΔL	ΔB	Δ(B-L)	Process
-1	**-1**	0	$p \rightarrow e^+ + \pi^0$
+2	0	-2	$(A,Z) \rightarrow (A,Z+2) + 2e^-$

⟹ **Matter creation and destruction**

Expected 0νββ decay signature



ββ decay signature

- Continuum for 2νββ decay
- Peak at $Q_{\beta\beta}$ for 0νββ decay
  ⟹ Energy peak is the only necessary and sufficient signature to claim a discovery
- Additional signatures from signal topology, pulse shape discrimination, multiple channel readout, daughter tagging, …

0νββ decay rate

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot |f|^2 / m_e^2$$

- $T_{1/2}^{0\nu}$ = 0νββ decay halflife
- $G_{0\nu}$ = phase space (known)
- $M_{0\nu}$ = nuclear matrix element (NME)
- f = new physics term

Neutrino masses and 0νββ decay

- Neutrinos are purely left handed
  ⟹ Not true: experimentally $\Delta m_{ij} \neq 0$
- Majorana condition: in the rest frame, $\nu_{lR} = \nu_{lL}{}^{c}$
  ⟹ $\nu_l^c = \bar{\nu}$
  ⟹ ν and $\bar{\nu}$ are only distinguished by the spin
- Majorana condition is not Lorentz invariant
  ⟹ L must be violated at the (m_ν / p_ν) scale
- Majorana mass term:

$$\mathcal{L}_M = \tfrac{1}{2} \sum_{l,l'} \bar{\nu}_l \, m_{ll'} \, \nu_{l'}^c + h.c.$$

- **What mechanism generates $m_{ll'}$?**
- **What predictions can we make on |f|?**

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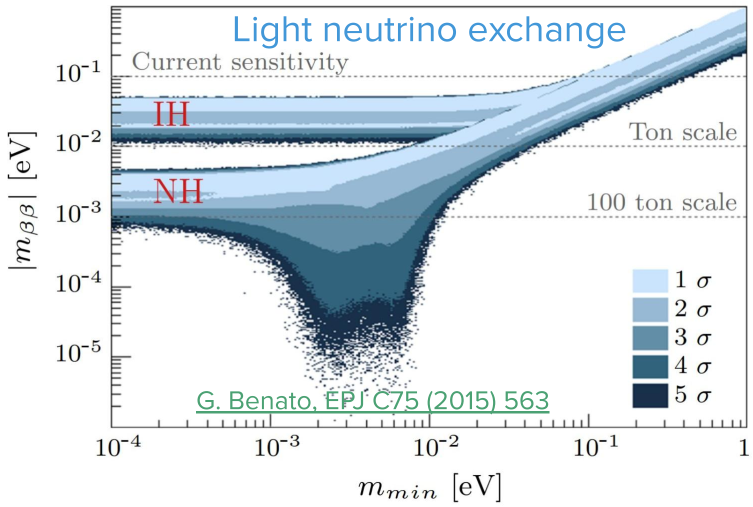
- **What predictions can we make on $T_{1/2}^{0\nu}$?**



$$|f| = |m_{\beta\beta}| = |\textstyle\sum_i U_{ei}^2 m_i|$$

- "Minimal" model: add just one term to the Lagrangian
- "Simple" goal for future experiments
- "Easy" to compare results obtained with different isotopes

Neutrino masses and $0\nu\beta\beta$ decay

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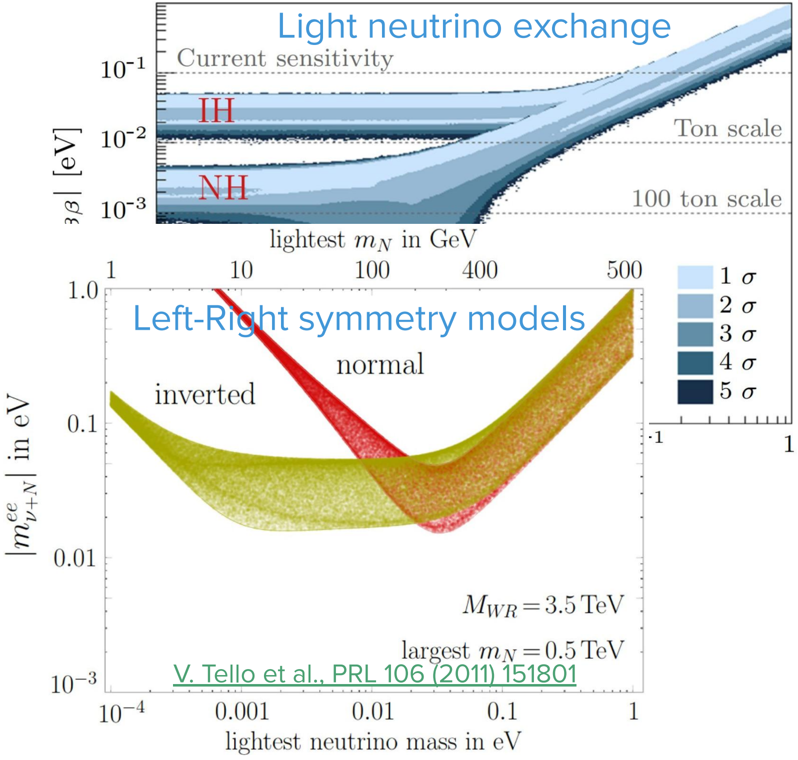

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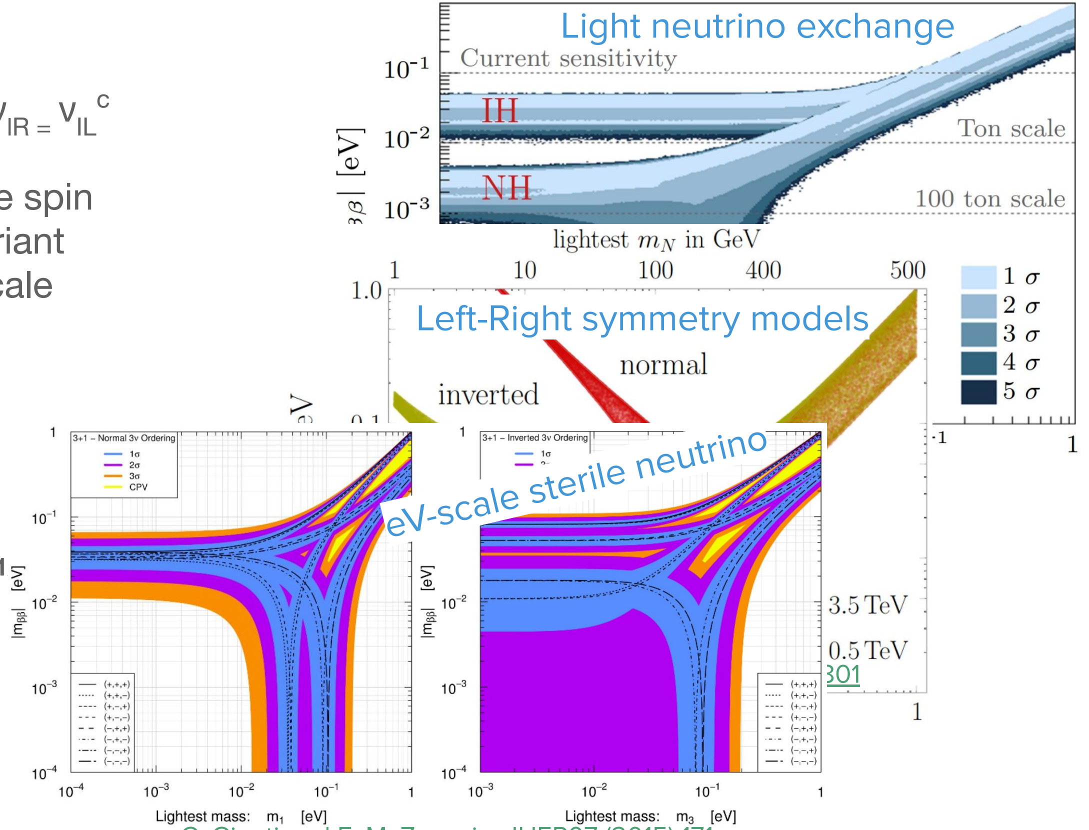
- **What mechanism generates $m_{ll'}$?**
- **What predictions can we make on $T_{1/2}$?**



C. Giunti and E. M. Zavanin, JHEP07 (2015) 171

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$\mathcal{L}_M = ½ \sum_{l,l'} \bar{\nu}_l m_l$

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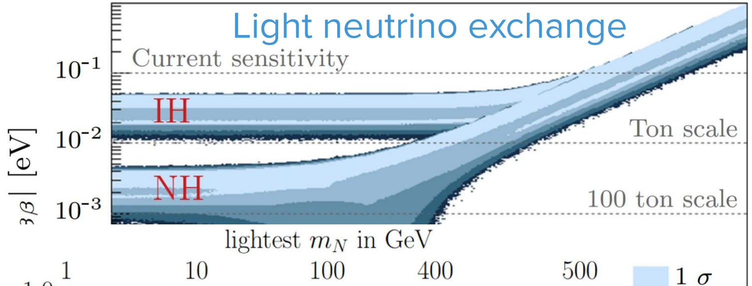
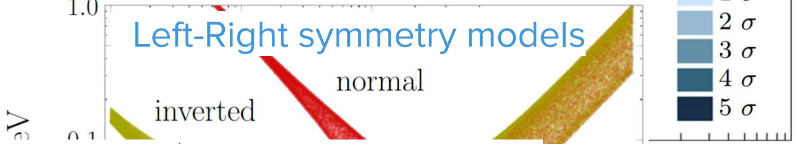
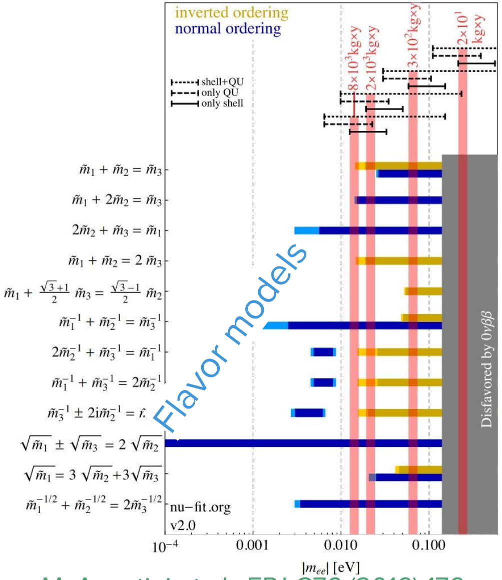
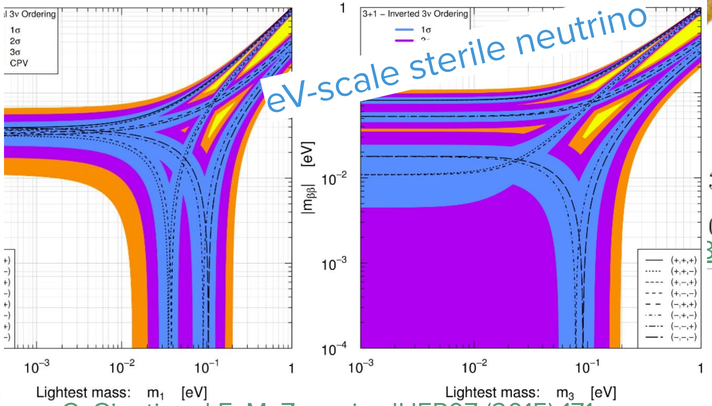






M. Agostini et al., EPJ C76 (2016) 176



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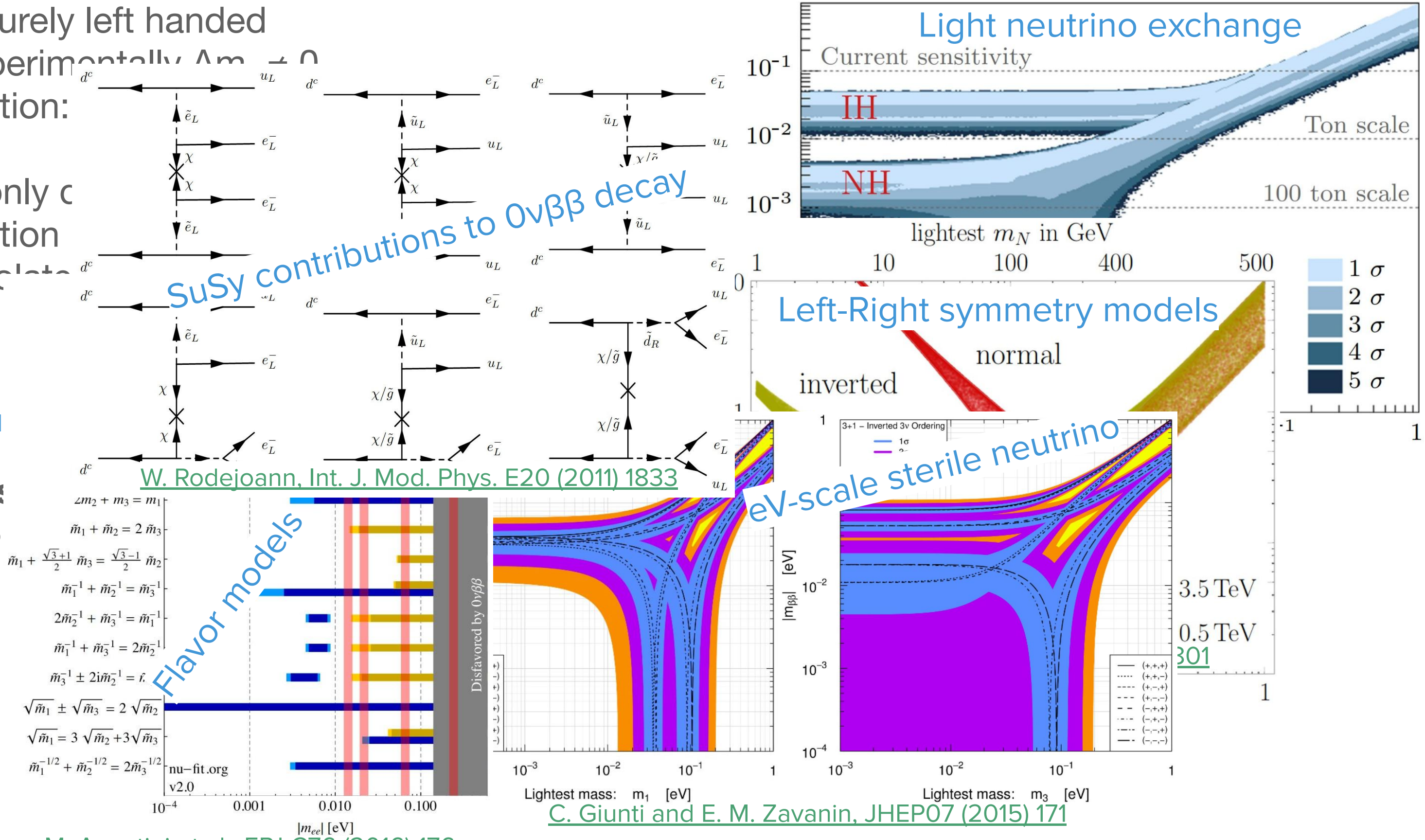

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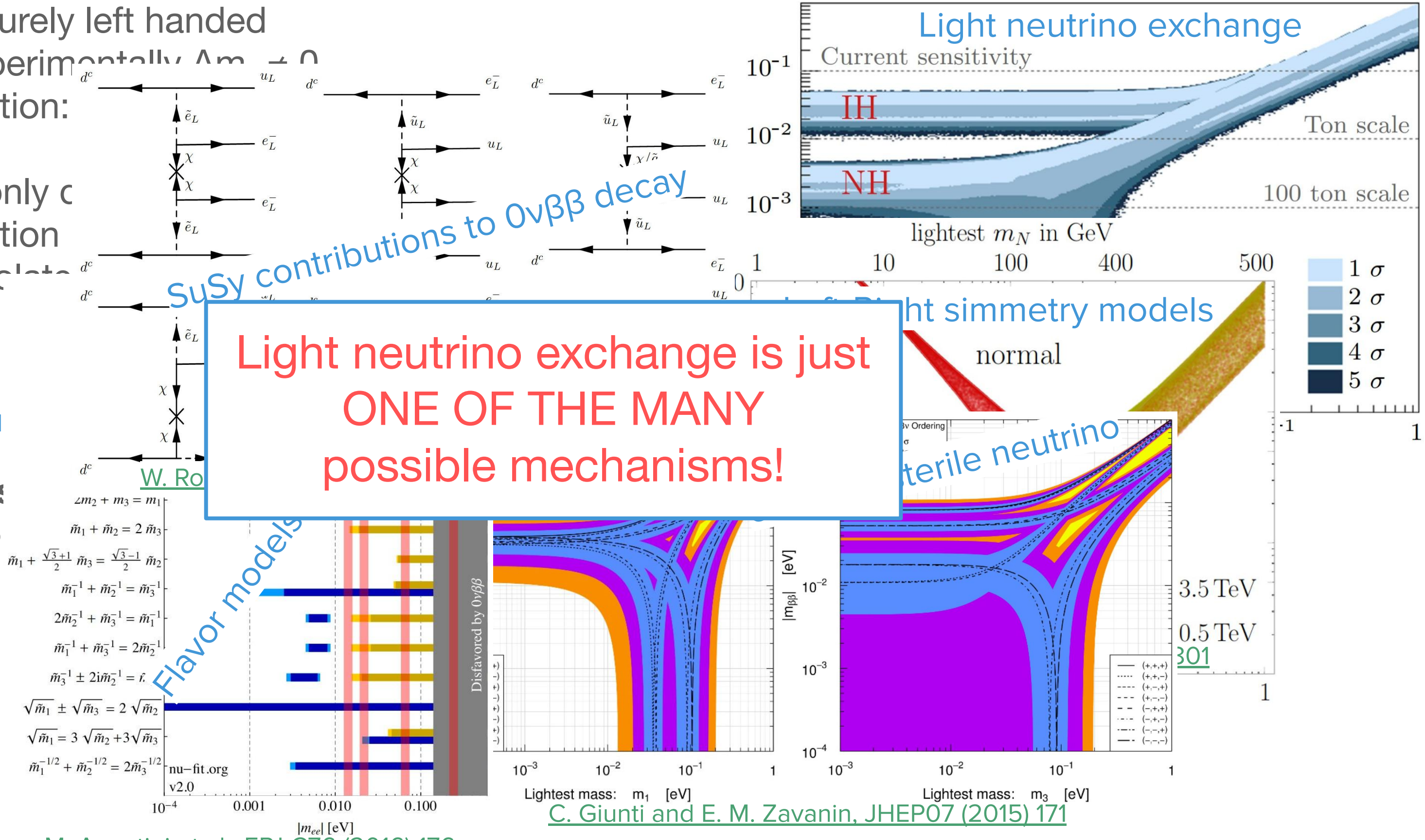


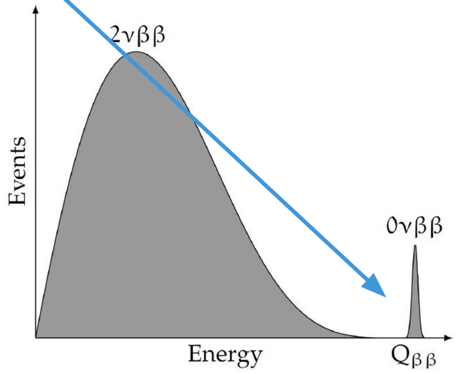
Light neutrino exchange is just ONE OF THE MANY possible mechanisms!

C. Giunti and E. M. Zavanin, JHEP07 (2015) 171

M. Agostini et al., EPJ C76 (2016) 176

Backgrounds

- $Q_{\beta\beta}$ in the 2-3.5 MeV range for most used isotopes
- Cosmic muons
  ⟹ Operate underground
- Neutrons (muon induced, fission, …)
  ⟹ Neutron absorbers (water, PE, borated PE, …)
- Actinides (^{238}U and ^{232}Th) decay chains + Rn
  - α up to 8 MeV
  - β up to 3.3 MeV
  - γ up to 2.6 MeV
  ⟹ Material selection
  ⟹ Cleaning protocol
  ⟹ Avoid recontamination
  ⟹ Shielding and self-shielding
  ⟹ Event topology
  ⟹ Particle discrimination via pulse shape
- Irreducible 2νββ background
  - Tail of 2νββ spectrum
    ⟹ Energy resolution
  - Pile-up of 2νββ events
    ⟹ Time resolution



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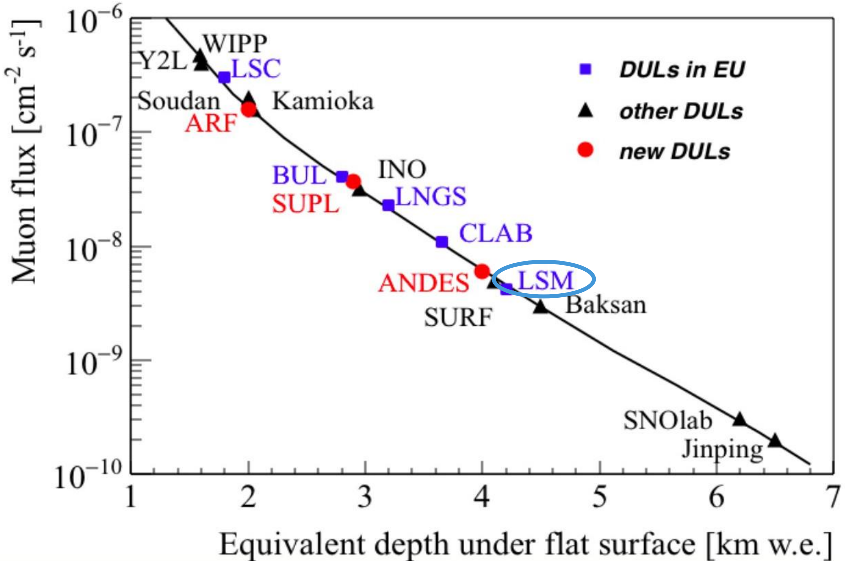

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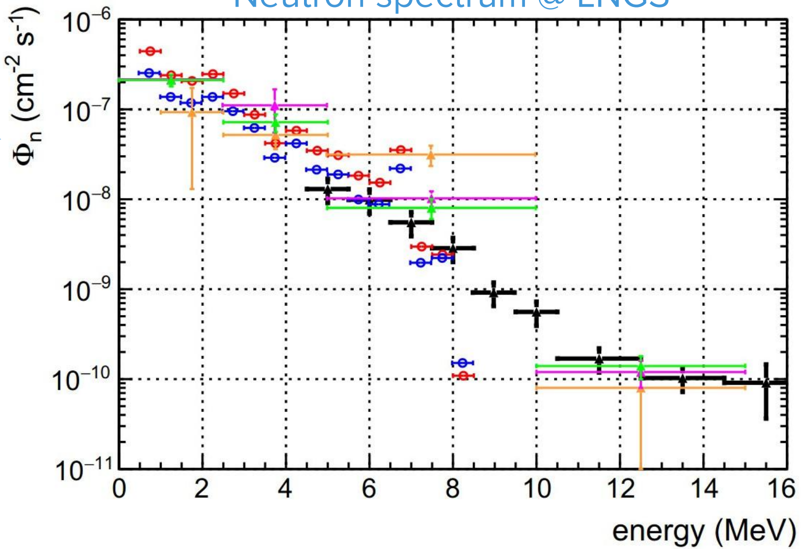
Neutron spectrum @ LNGS



G. Bruno and B. Fulgione, EPJ C79 (2019) 747

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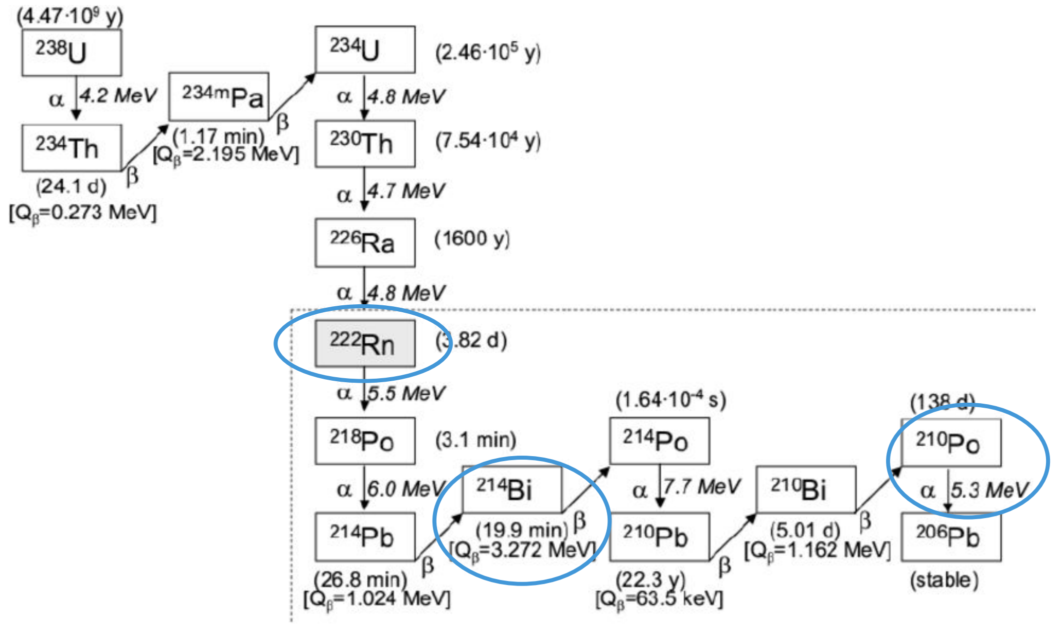

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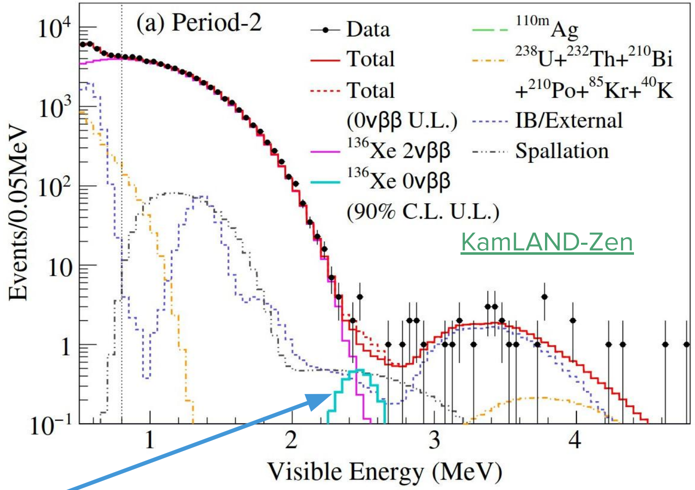
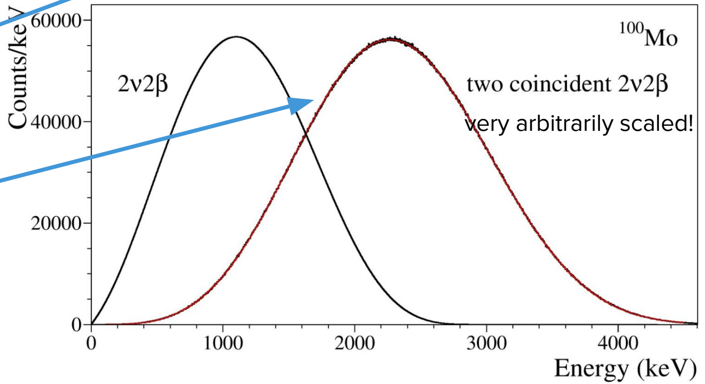
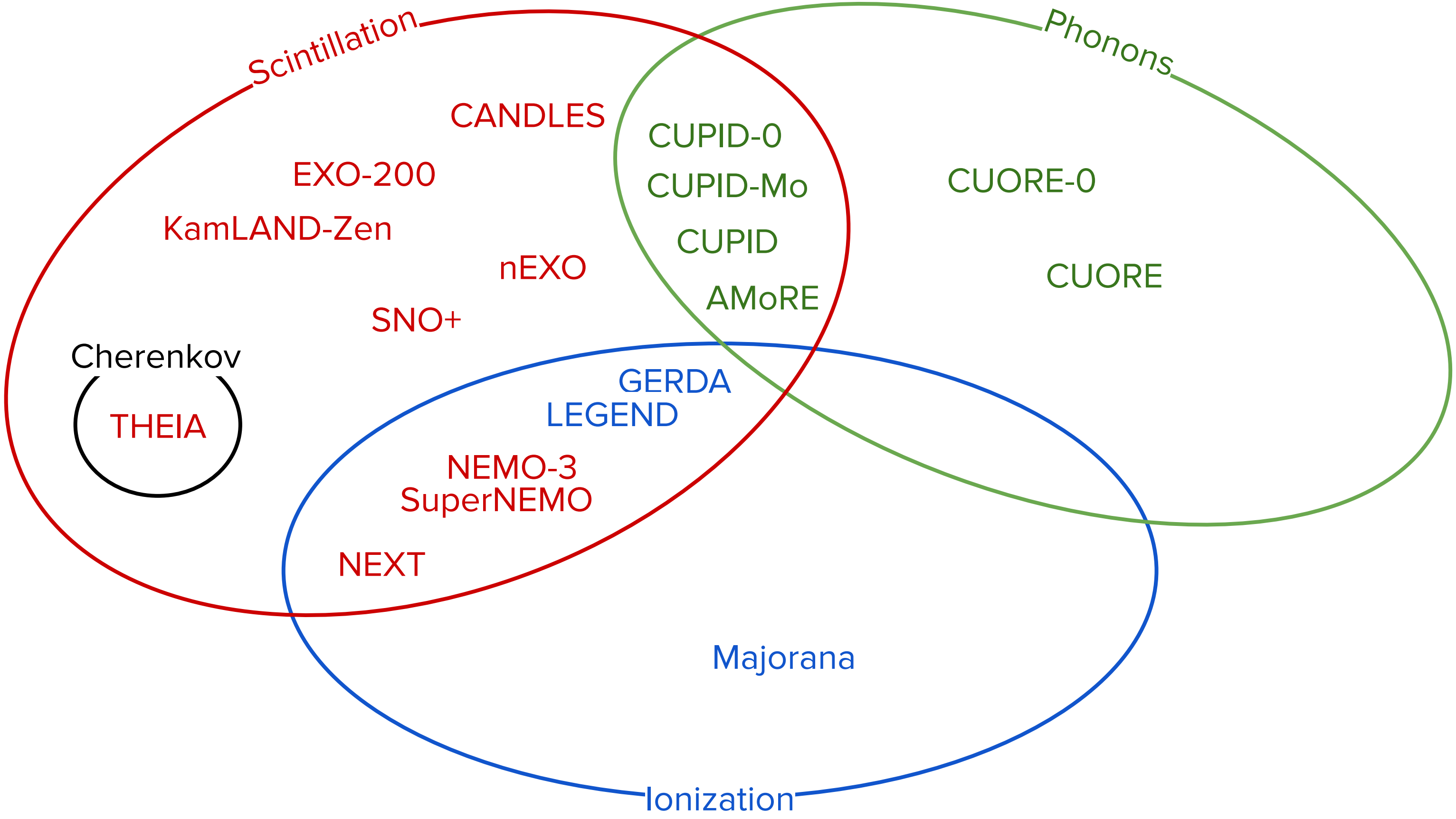


KamLAND-Zen



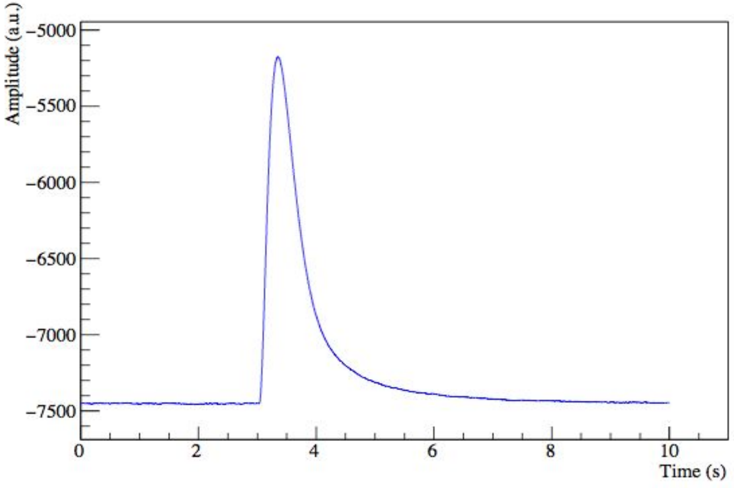
D. M. Cherniak et al., EPJ C72 (2012) 1989

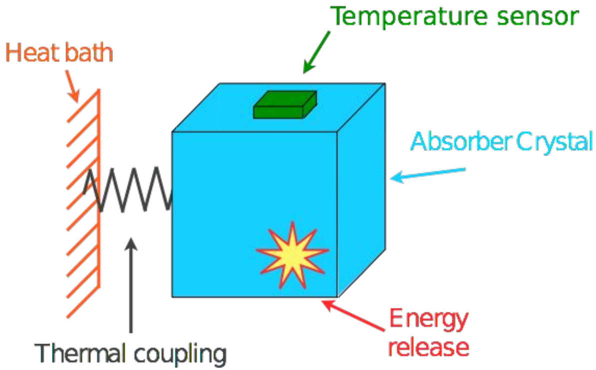
0νββ decay experimental fauna



Cryogenic calorimeters a.k.a bolometers

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





Simplified thermal model

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

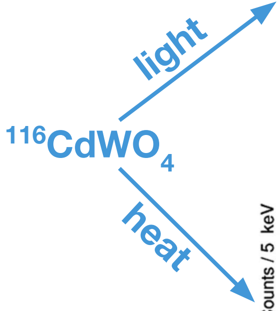
Scintillating crystals

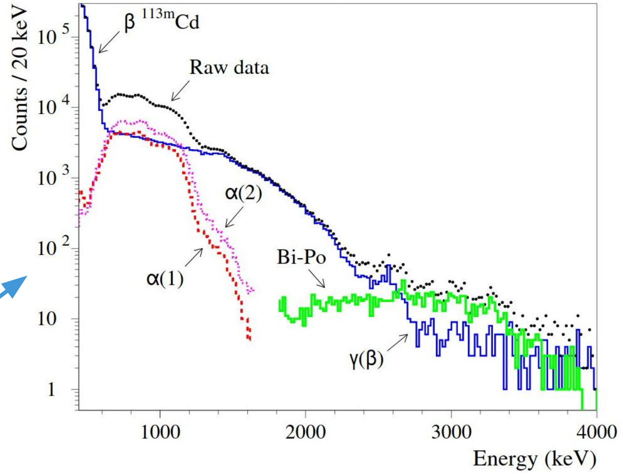
Scintillation light features

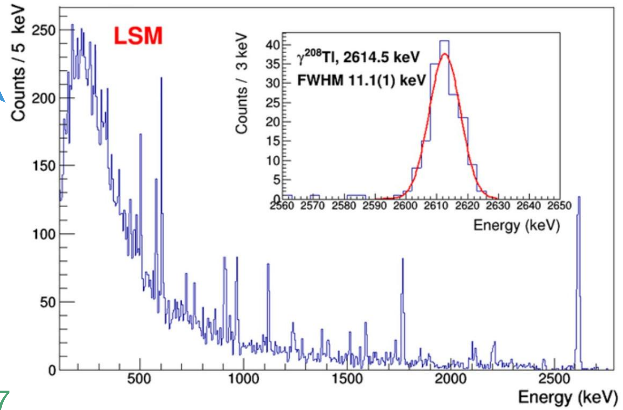
- Typical light yield (LY): O(10) photons/keV
  → Expected energy resolution: few %
- Amount of emitted light is particle dependent
- For some crystals, time profile of scintillation light is particle dependent

Scintillating crystals for 0νββ decay

- Heat to measure energy
- Scintillation light for particle identification (PID)

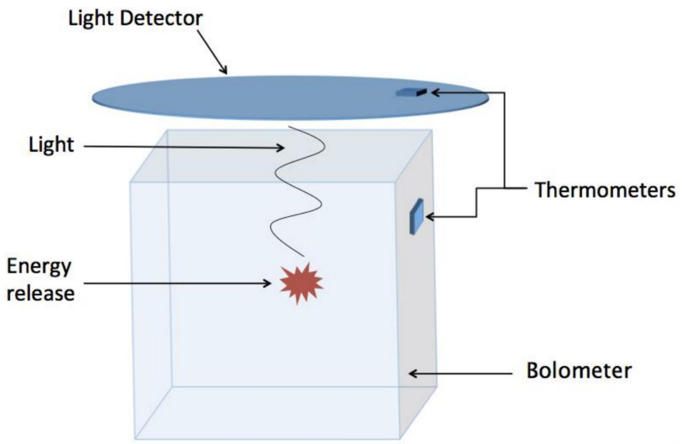


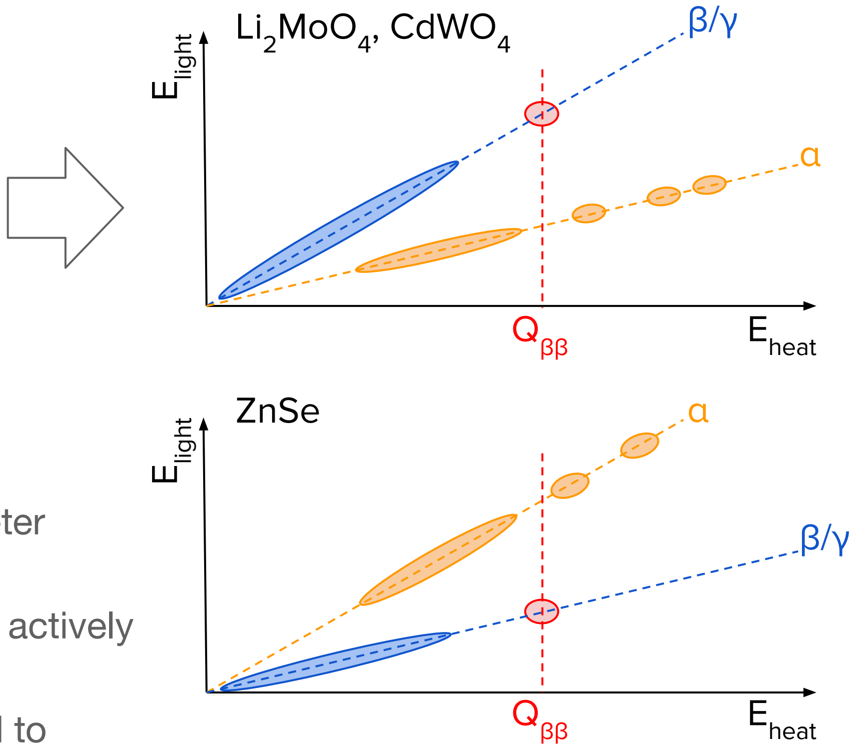




D. Helis et al., LTD 2018, 467
A. S. Barabash et al, Phys.Rev. D98 (2018) 092007

Scintillating bolometers

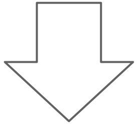




- Main background: surface α events
- Couple main crystal with secondary bolometer reading the scintillation (or Cherenkov) light
- Exploit different light yield (LY) of α vs β/γ to actively suppress background
- Typical light detector: thin Ge wafer coupled to thermometer (NTD, TES, KID, MMC)

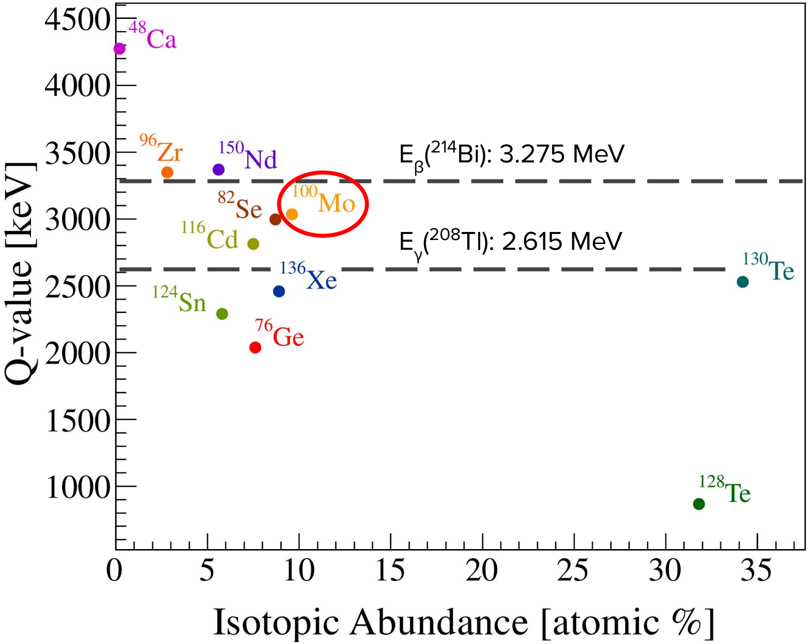
Isotope choice for bolometric experiments

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

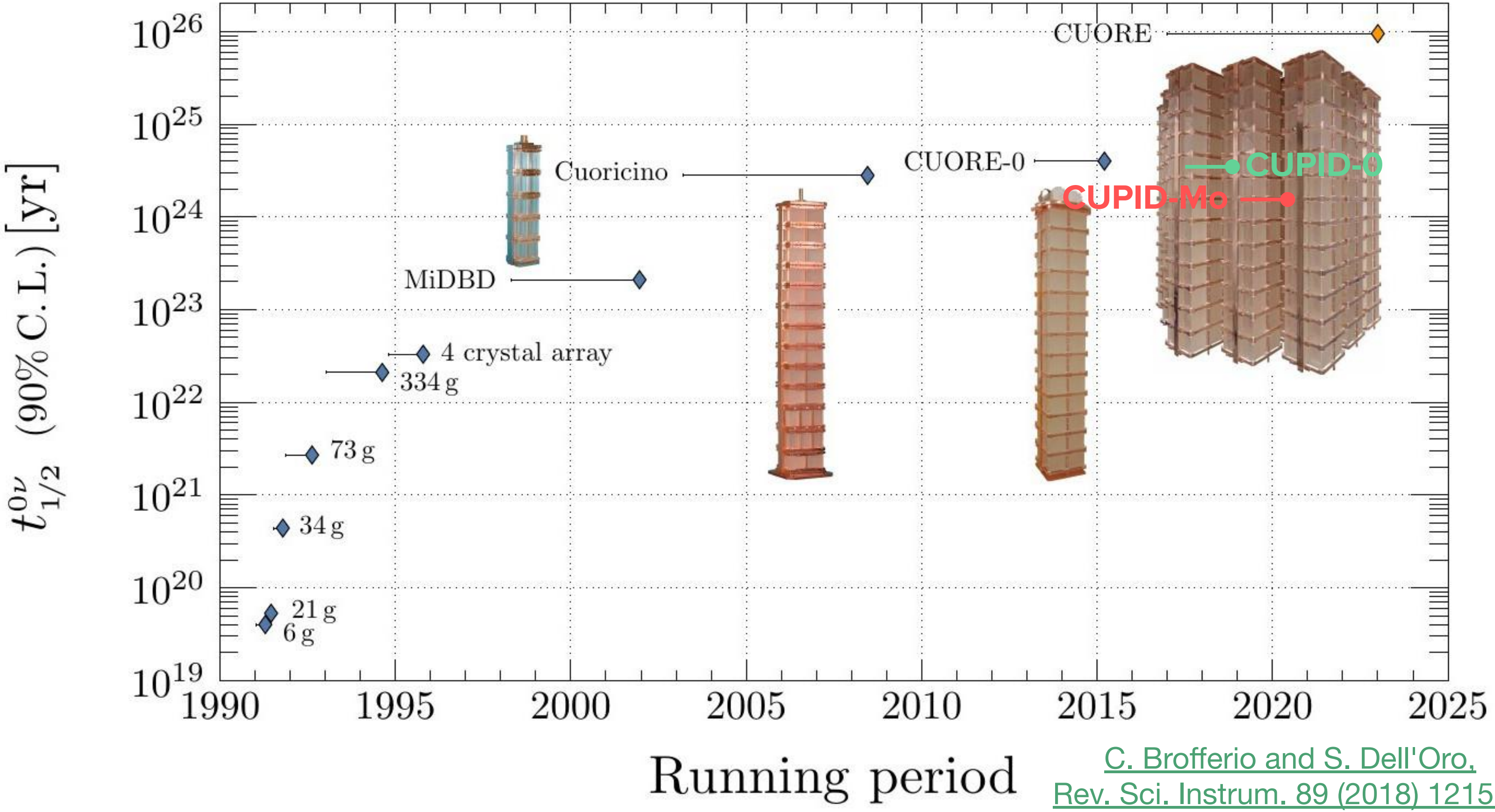


Advantages of bolometric approach

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



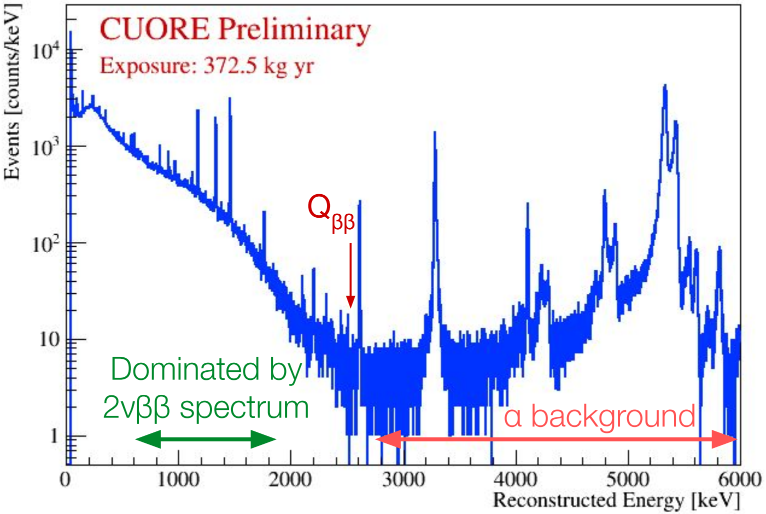
History of bolometric 0νββ decay searches



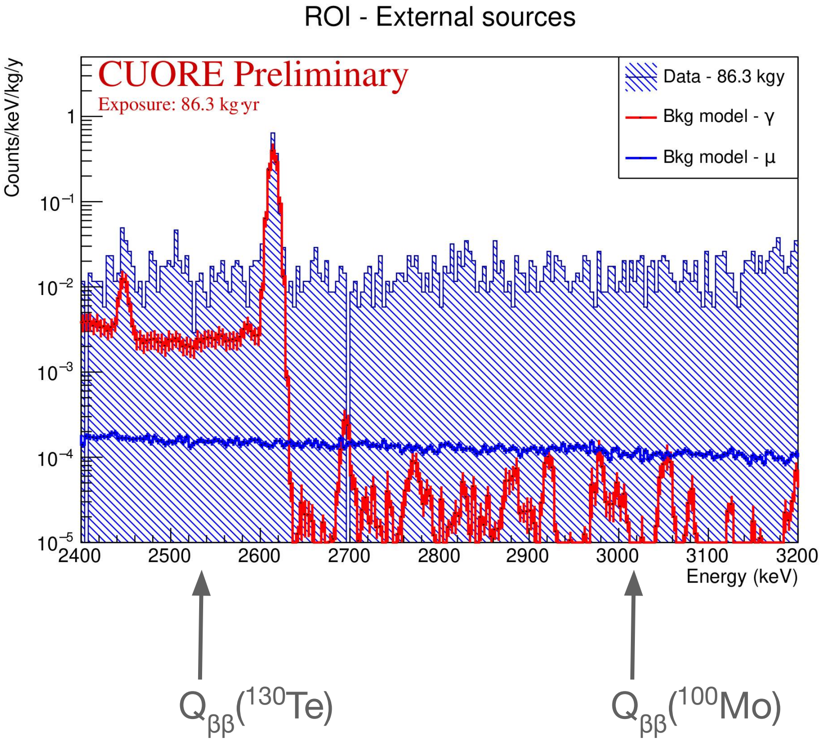
C. Brofferio and S. Dell'Oro, Rev. Sci. Instrum. 89 (2018) 121502

CUORE: the Cryogenic Underground Observatory for Rare Events

- 988 TeO_2 crystals with natural Te composition
  → **742 kg of total mass**, 206 kg of ^{130}Te mass
- Located in Hall A of the Gran Sasso National Lab
- Current limit: $\mathbf{T^{0\nu}_{1/2} > 3.2 \cdot 10^{25}}$ **yr @ 90% C.I.**
- $Q_{\beta\beta}(^{130}Te) = 2527.5$ keV
  → Above most γ background, below the ^{208}Tl 2.6 MeV line
- TeO_2 crystals do not scintillate
  → no particle discrimination



Lessons learned from CUORE



- Most measured background is due to α particles (U/Th close to TeO_2 crystals)
  → α/β discrimination is required
- A $Q_{\beta\beta}$ > 2.6 MeV would automatically reduce the remaining non-α background by >1 order of magnitude
- Muons are the dominant contribution after α's
  → active muon veto

CUPID: the CUORE Upgrade with Particle IDentification

Goals:

- ~1500 $Li_2{}^{100}MoO_4$ scintillating crystals
  → ~250 kg of ^{100}Mo
- FWHM: 5 keV at $Q_{\beta\beta}$
- α rejection via PID with light detectors (LD)
- Background: 10^{-4} counts/keV/kg/yr
- Discovery sensitivity: $T^{0\nu}_{1/2} = 10^{27}$ yr

How do we get there?

- Large cryogenic infrastructure
  → Re-use CUORE cryostat
- Demonstrate LMO resolution
- Demonstrate PID performance of LDs
- Demonstrate reproducibility of performance
- Demonstrate low background

→ **CUPID-Mo!**

CUPID-Mo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CUPID-Mo


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Milano
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Zaragoza
Barcelona
Villarodin-Bourget
Saint-André
Modane
La Norma
Freney
Fourneaux
Pointe des Sarrasins
2963
Aiguille de Scolette
3506
Le Mounioz
2745
Punta Nera cima NW
3047
Le Grand Séru
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Roche Bernaude
Punta Melmise
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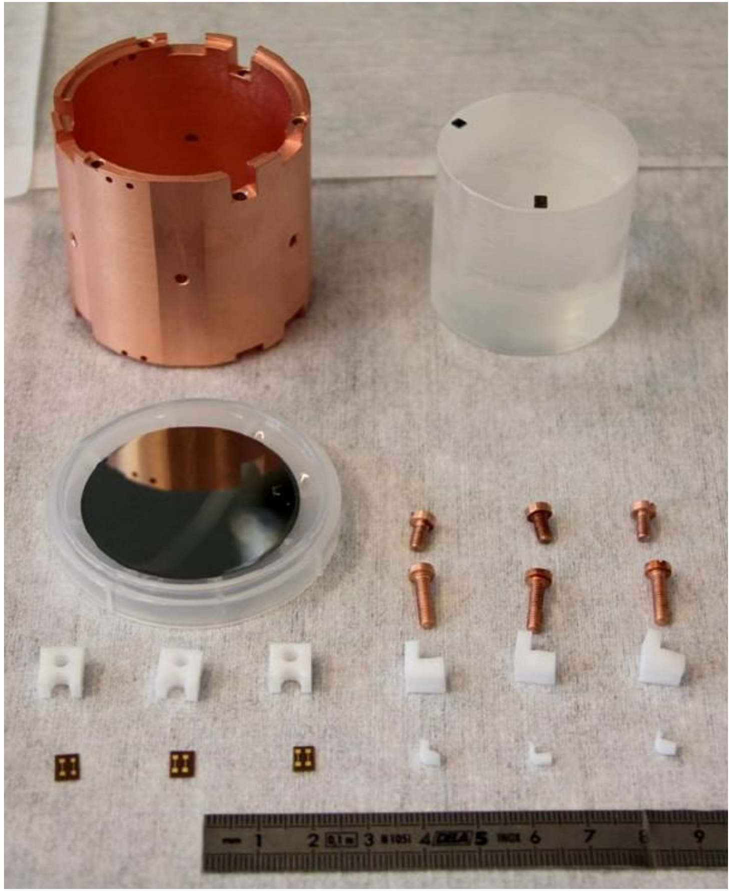
Monte Jafferau
2815
Bardonecchia
Edelweiss

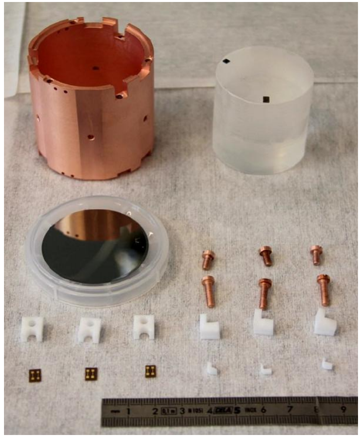
CUPID-Mo

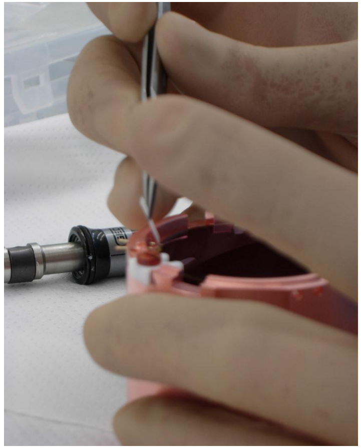


Ingredients

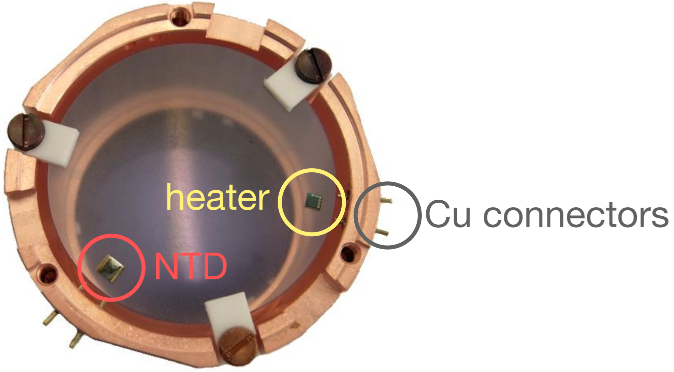
- 20 ^{enr}LMO crystals
  → Dimensions: ∅ 44mm, h 45mm
  → Crystal mass: ~210 g each
  → ^{100}Mo isotopic fraction: 96.6±0.2%
- 20 Ge wafers
  → Dimensions: ∅ 44.5mm, h 175μm
  → SiO coating on both sides to increase light collection
- Neutron transmutation doped (NTD) thermistors
  → $3{\times}3{\times}1mm^3$ for LMOs
  → $3{\times}0.8x1mm^3$ for LDs
- Silicon-based resistors
  → To be used as heaters to inject pulser events

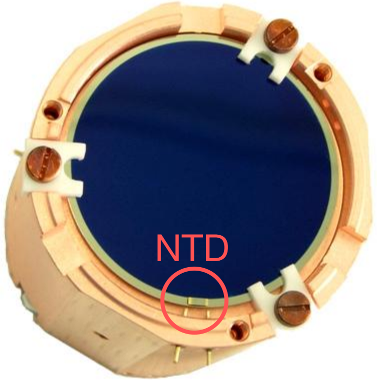
CUPID-Mo construction

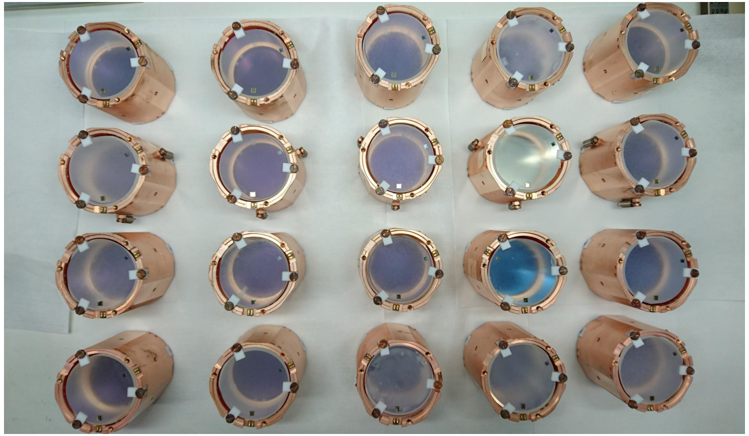




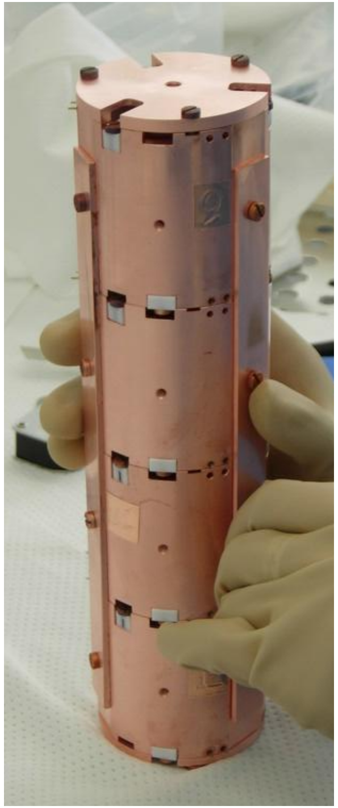
CUPID-Mo construction







CUPID-Mo installation @ LSM



CUPID-Mo data taking

- Physics data: March 2019 - June 2020
- Analysed data: March-2019 - April 2020

  → 82% duty cycle

  → 73 days of calibration data

  → 240 days of physics (0νββ) data

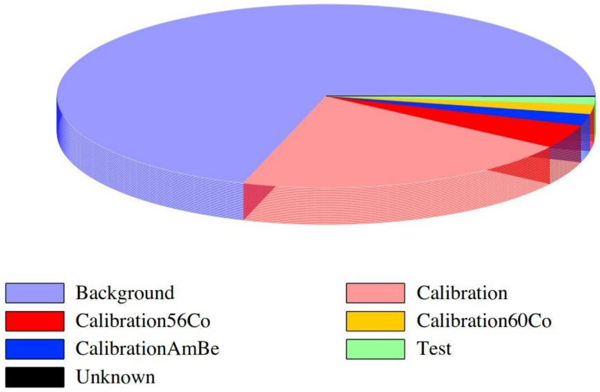
    → 27 days excluded due to poor statistics in calibration

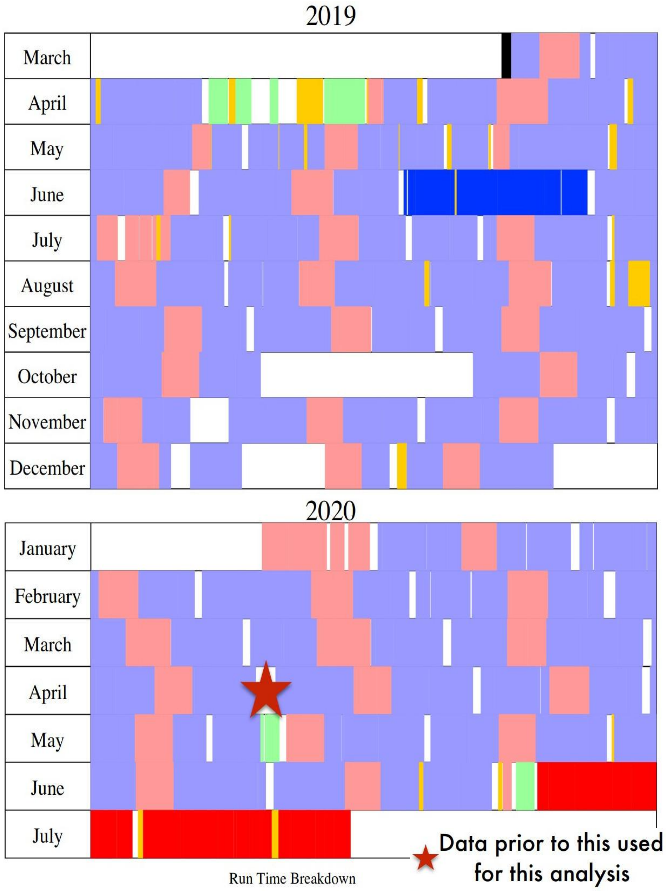
    → 213 days (7 datasets) of physics data good for analysis

      → Further 6% of data removed due to instabilities

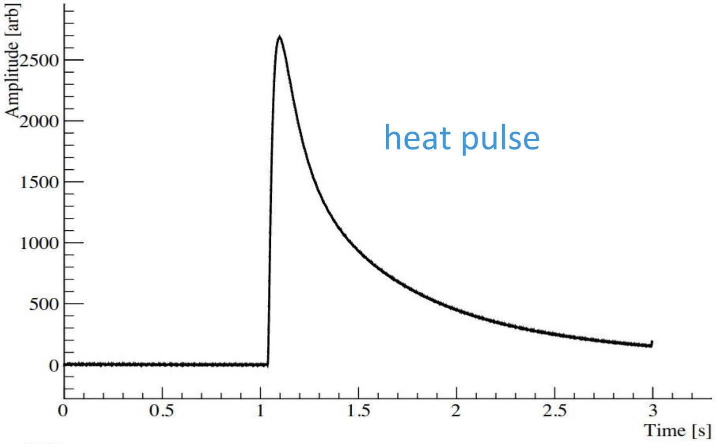
      → One LMO removed due to poor performance

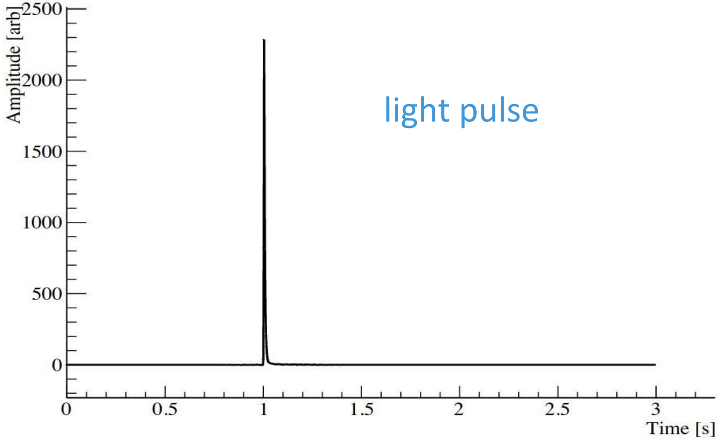
        → **Analyzed exposure: 2.16 kg·yr**





CUPID-Mo data processing



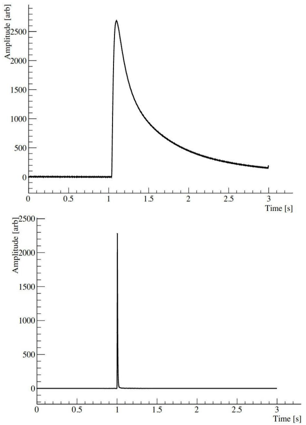


Data format

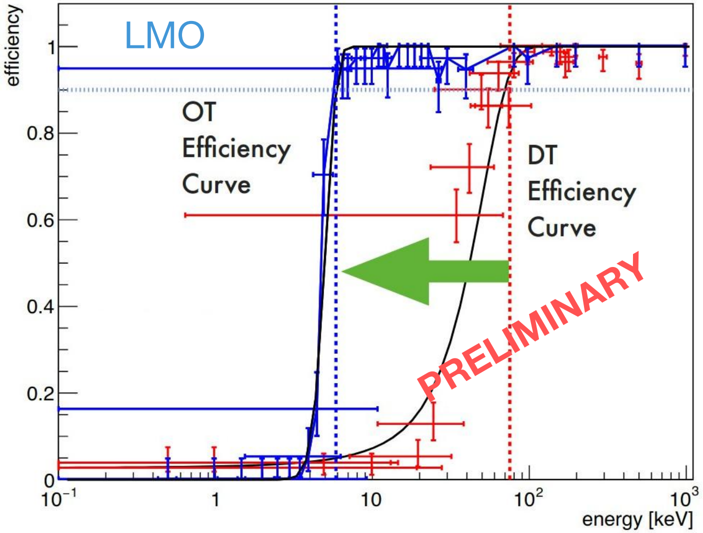
- 500 Hz sampling frequency
- Continuous data, no hardware trigger
- Data processed with Diana

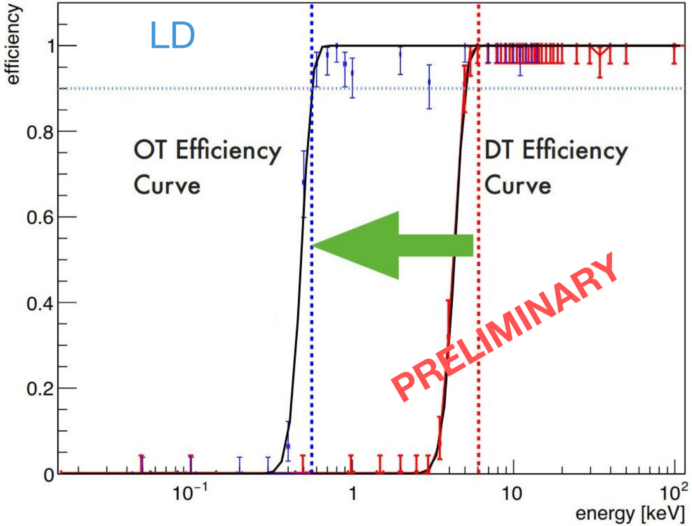
CUORE Collaboration, Phys. Rev. C93 (2016) 045503
CUPID-0 Collaboration, EPJ C78 (2018) 734

CUPID-Mo data processing

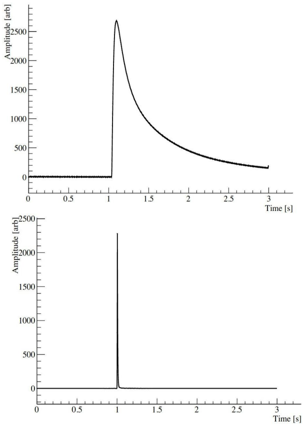


Optimum trigger

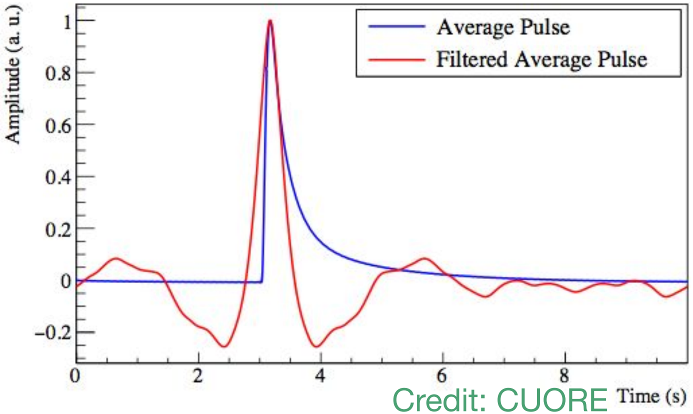


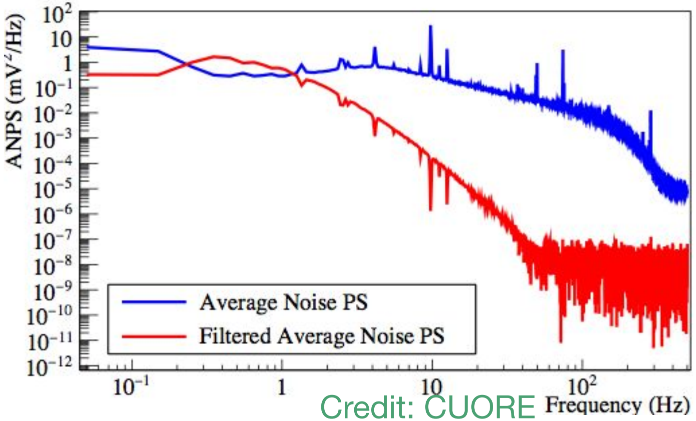


CUPID-Mo data processing

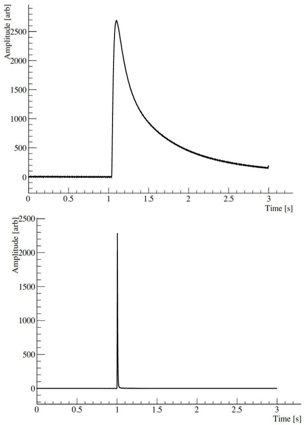


Optimum filter: matched filter that optimizes signal-to-noise ratio

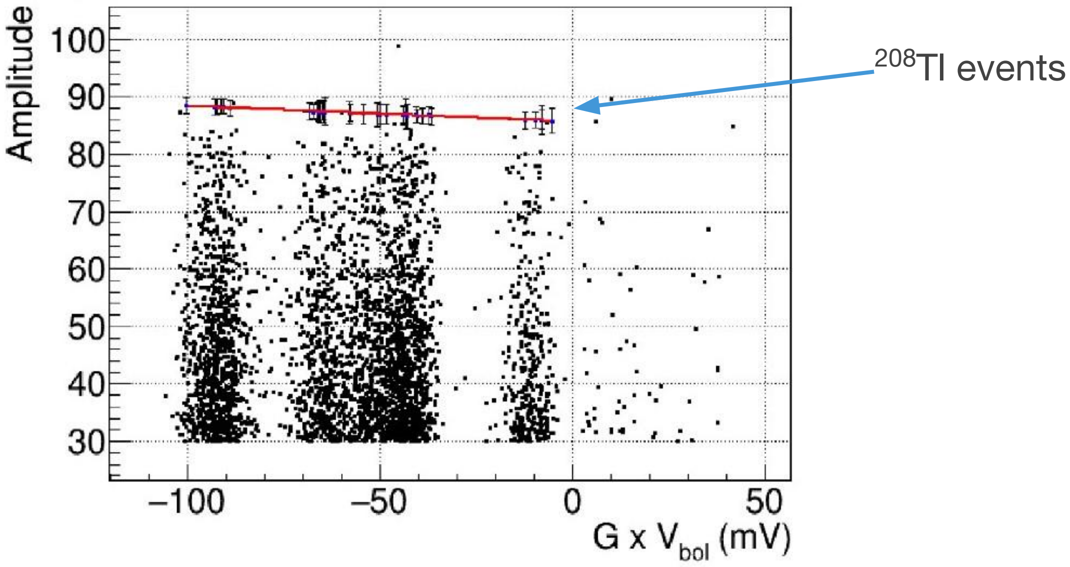




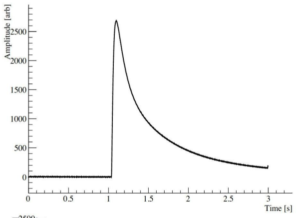
CUPID-Mo data processing

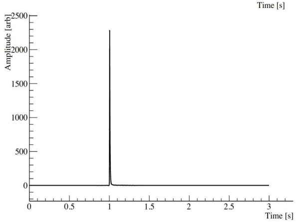


Optimum trigger → Optimum filter → Gain correction

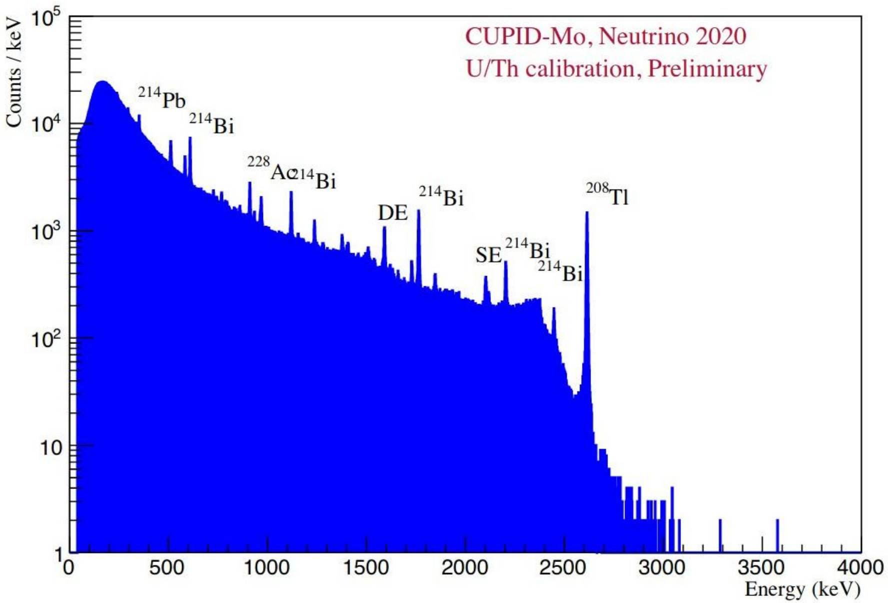


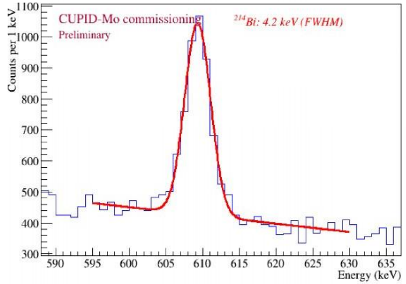
CUPID-Mo data processing

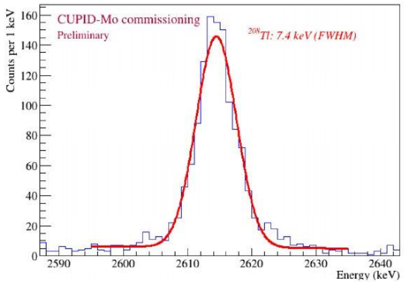




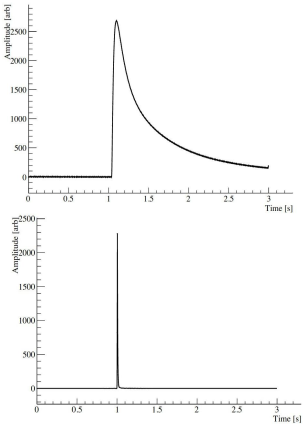
Optimum trigger → Optimum filter → Gain correction → Energy calibration



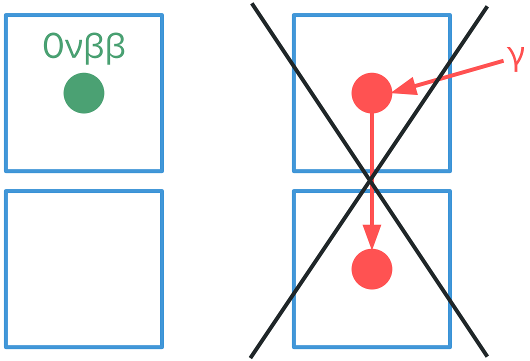




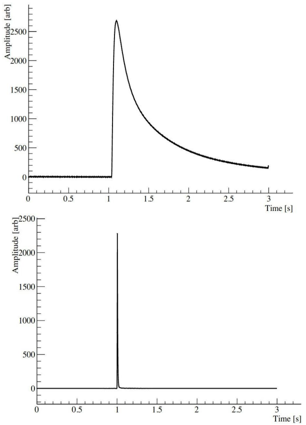
CUPID-Mo data processing



Optimum trigger → Optimum filter → Gain correction → Energy calibration → Coincidences

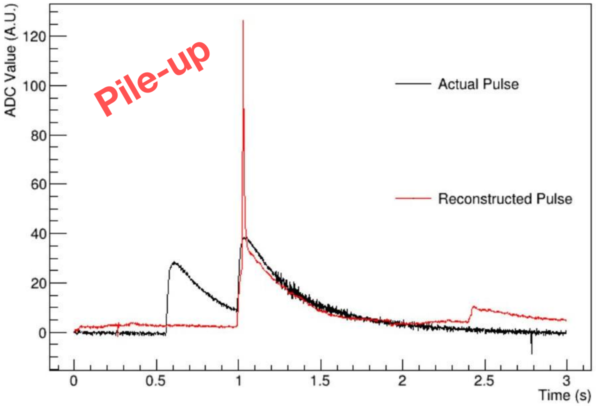


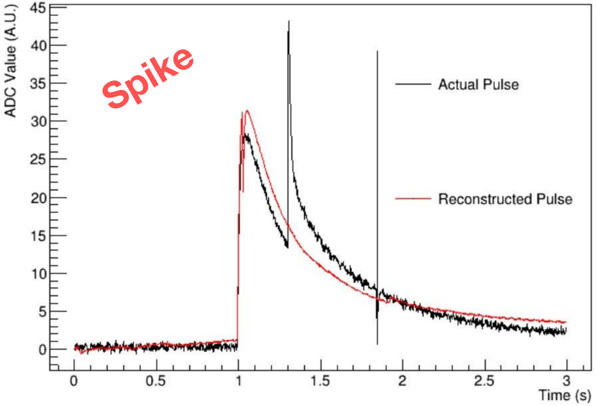
CUPID-Mo data processing

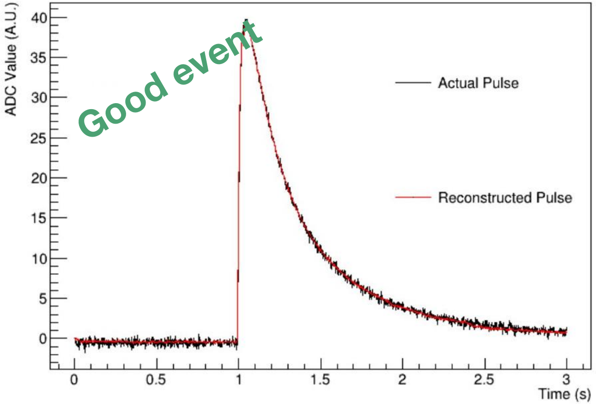


Optimum trigger → Optimum filter → Gain correction → Energy calibration → Coincidences → Quality cuts

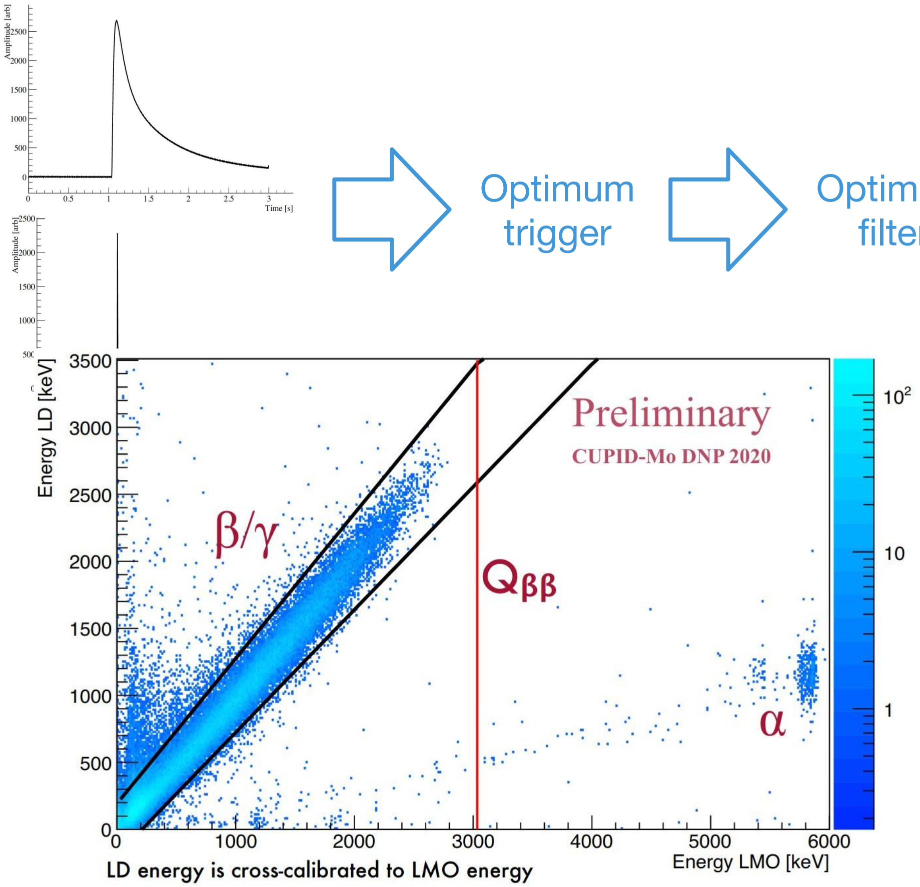
[CUPID-Mo, arXiv:2010.04033 (submitted to JINST)]

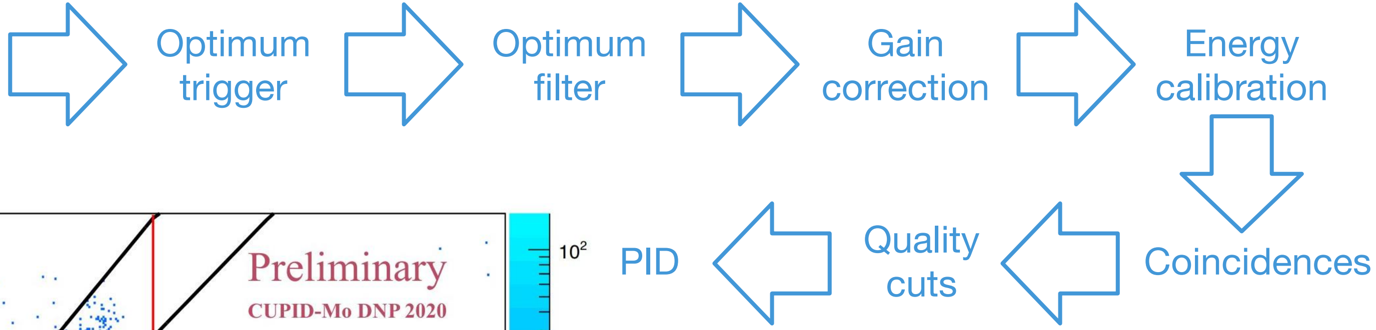




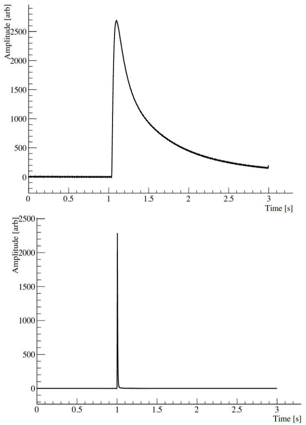


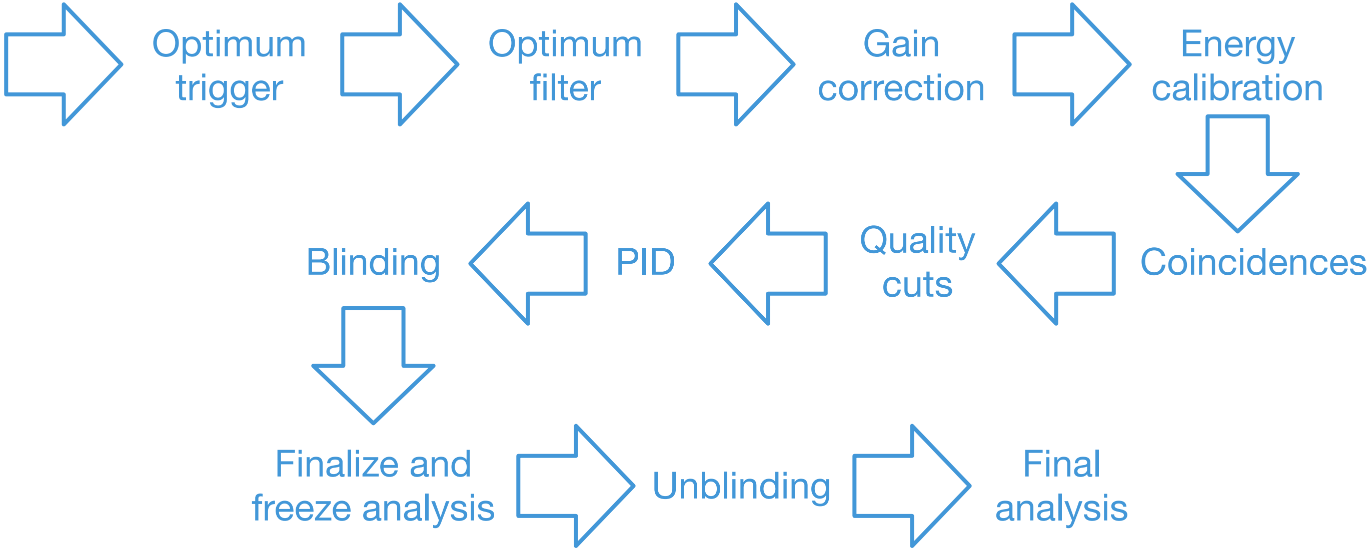
CUPID-Mo data processing





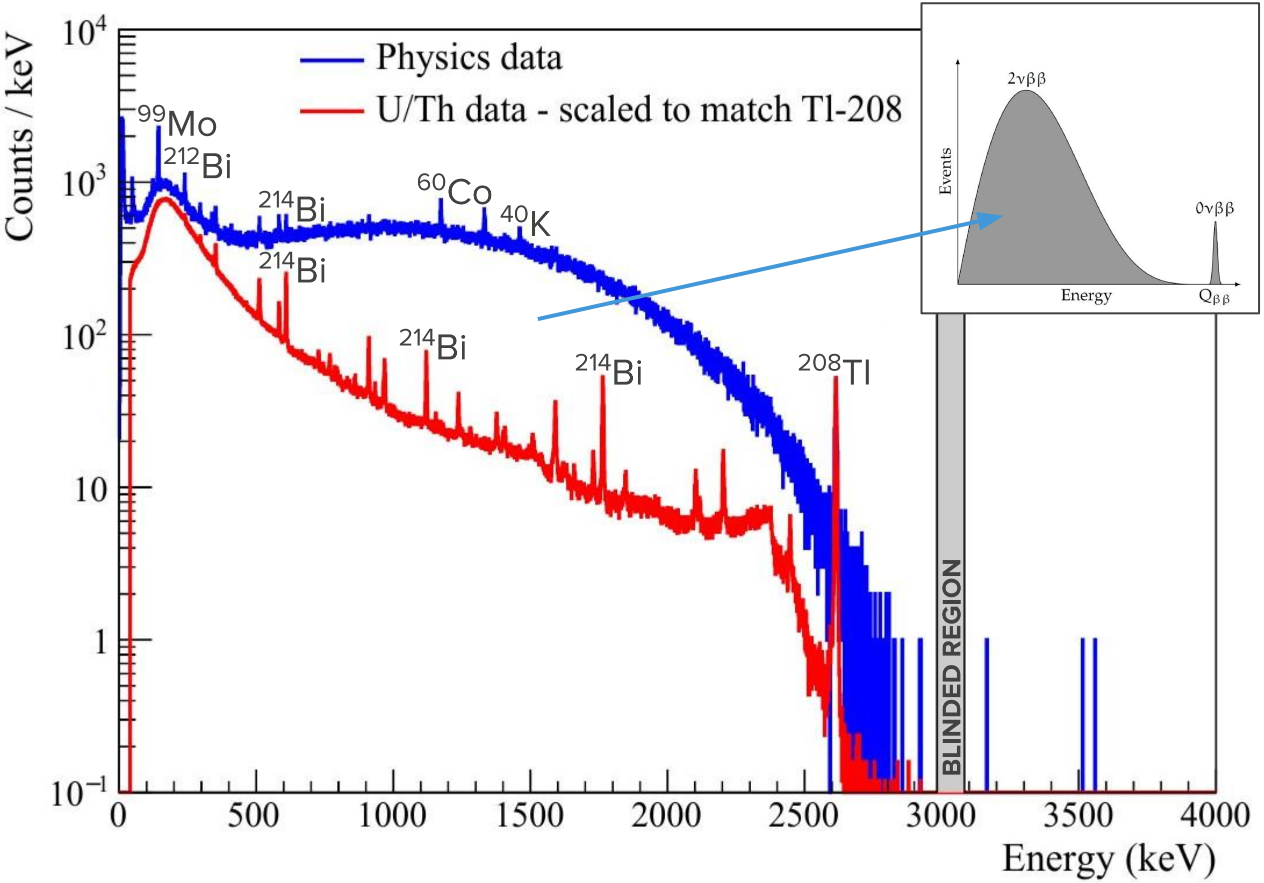
CUPID-Mo data processing



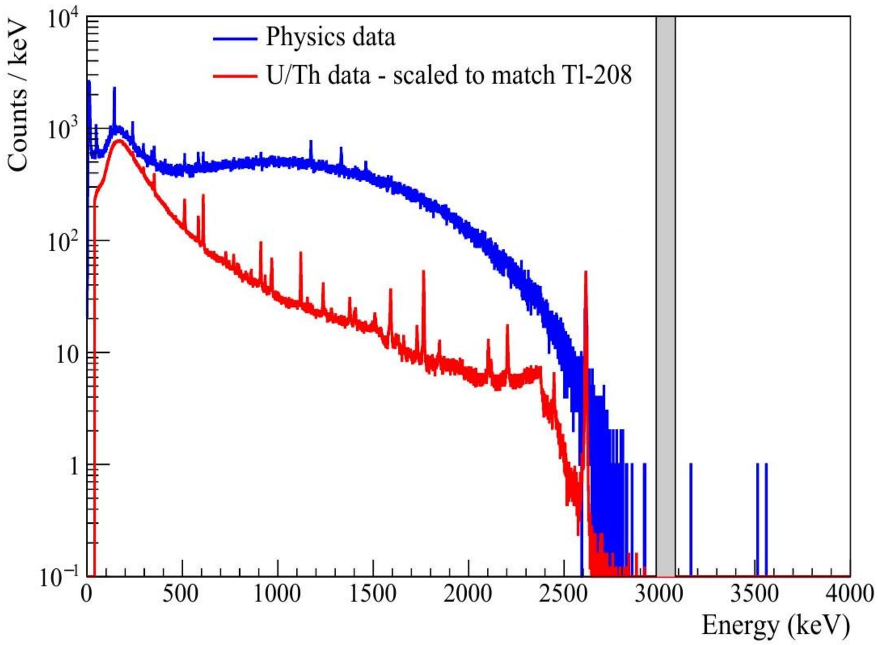


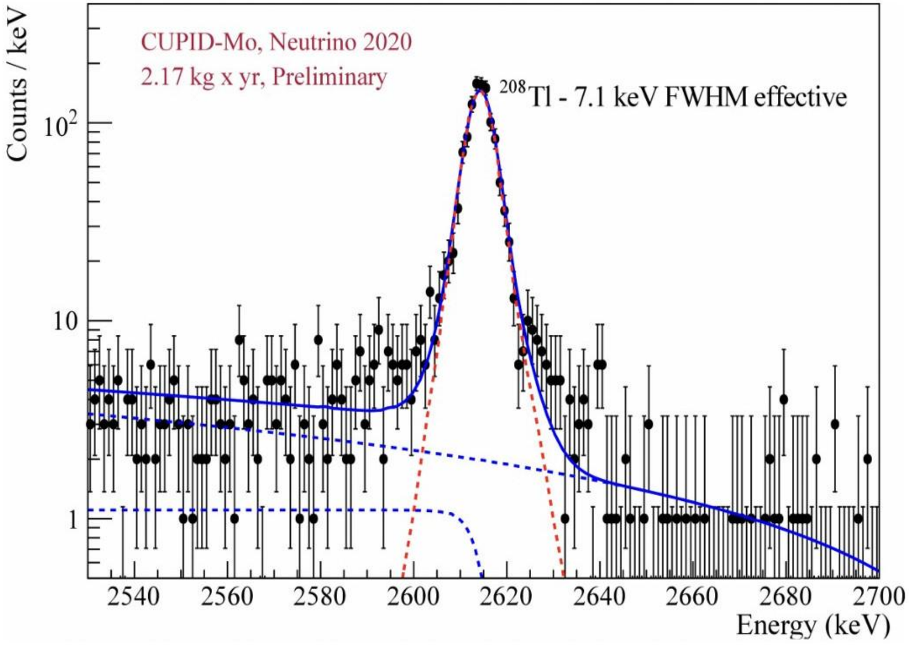
CUPID-Mo physics spectrum

- Blindied region: $Q_{\beta\beta}$±50 keV
- Dominant 2νββ spectrum
- Most γ lines from external background sources
- Very few counts >3 MeV after PID cut



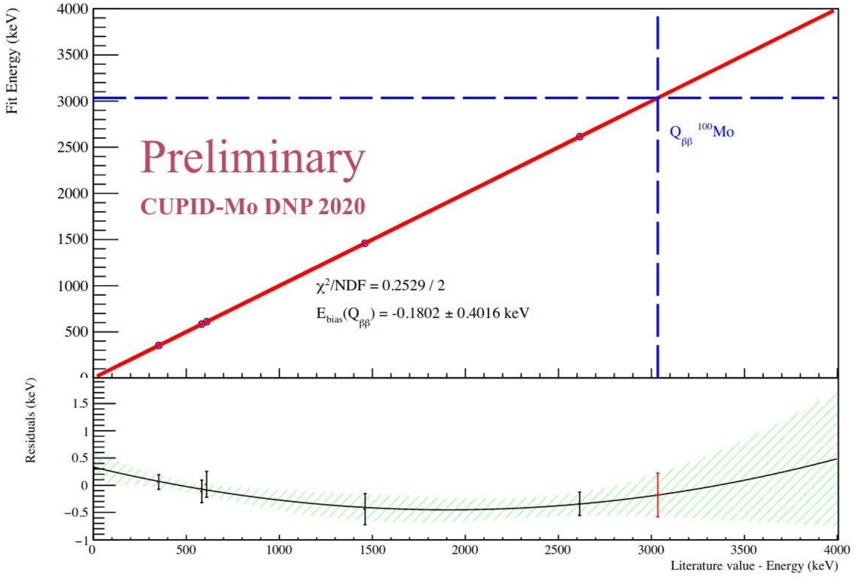
Peak-shape fit on physics data



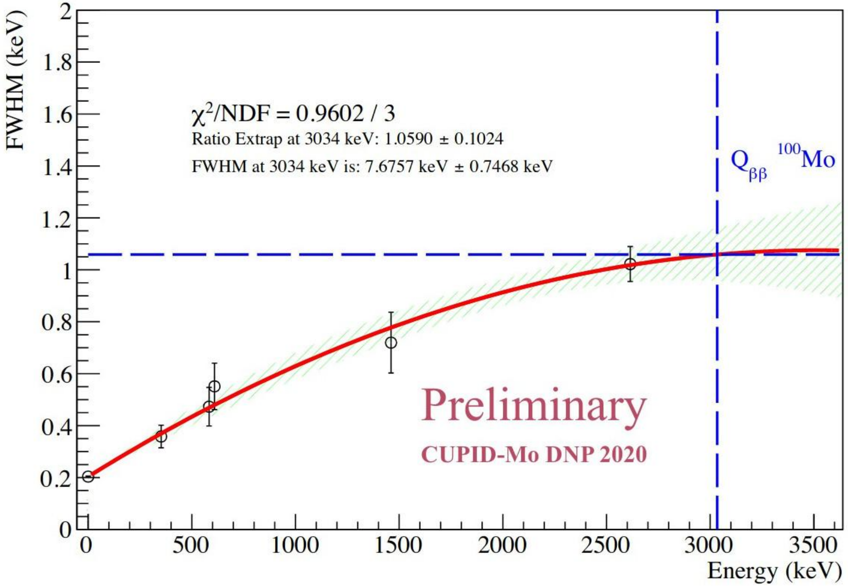


- Fit visible peaks in physics data to study:
  → residual non-linearities
  → resolution on physics data
- Peak shape fit with Gaussian + smeared step (multi-Compton) + linear background

Energy scale and resolution in physics data



Energy scale



Energy resolution

- Residuals fit with 2nd order polynomial
- Extrapolation to $Q_{\beta\beta}$ compatible with 0

- Fitted ratio of resolution in physics and calibration peaks
- Phenomenological fit to 2nd order polynomial
- **FWHM at $Q_{\beta\beta}$: 7.6±0.7 keV**
  → Sub-optimal noise conditions

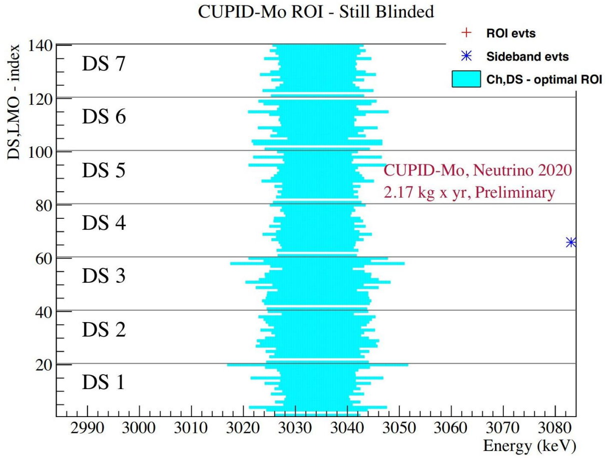
CUPID-Mo 0νββ decay analysis

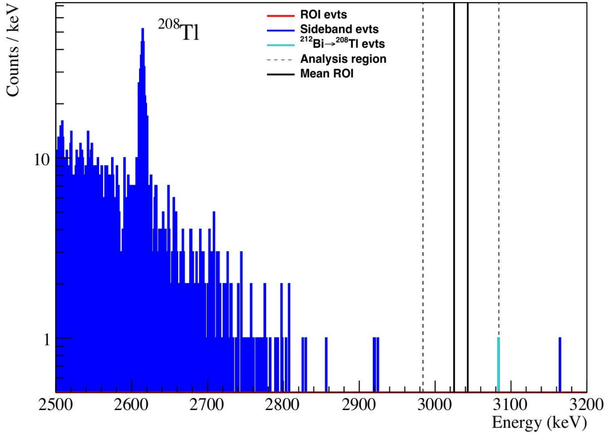
0νββ decay analysis recipe

- Bayesian counting analysis in $Q_{\beta\beta}\pm 50$ keV
  → Side bands with background only
  → Central ROI with signal+background
- Two alternative background modelizations:
  → Flat+exponential (extrapolated from calibration spectrum)
  → Flat only component
- Resolution is channel-dataset dependent
  → ROI optimized independently
  → Mean ROI width: 17.9 keV

Unblinding

- First step: unblind 25 keV side-bands and check for surprises
  → One event found, so proceed
- Second step: unblind central 50 keV band
  → No events found





CUPID-Mo $0\nu\beta\beta$ decay analysis

Analysis recipe:

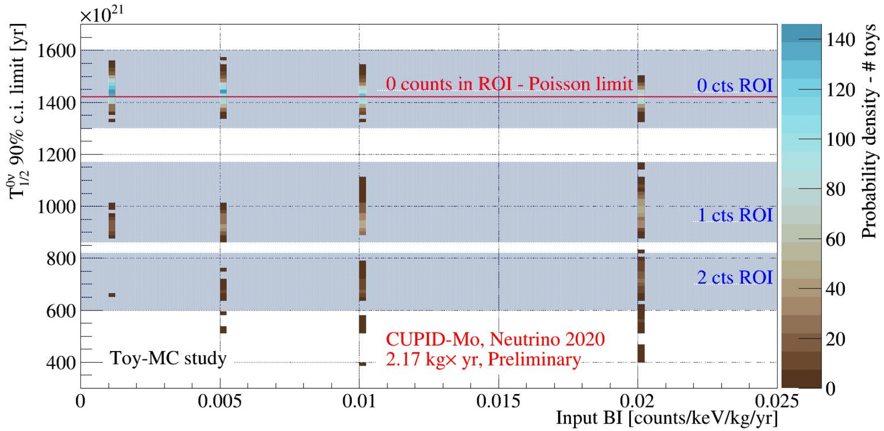
- Likelihood: $\mathscr{L} = \prod_i e^{-\lambda i} \cdot \lambda_i^{ni} / n_i!$
  where i = band index = left side band / central ROI / right side band
- $\lambda_i = \Gamma_{0v} \cdot N_A \cdot f_{100} \cdot \varepsilon_{containment,i} \cdot \varepsilon_{analysis} \cdot mt/m_a$ → Signal
  $+ BI \cdot mt \cdot \Delta E_i$ → Flat background
  $+ \tau \cdot A \cdot mt \cdot [\exp(-(E_{min}-Q_{\beta\beta})/\tau)-\exp(-(E_{max}-Q_{\beta\beta})/\tau)]$ → Exponential background (optional)
- Signal component in both ROI and side bands, but with very different containment
- Side bands used to evaluate background amplitude, central ROI to evaluate signal contribution
- Systematics implemented as additional nuisance parameters
- Gaussian prior on exponential amplitude (A) and decay constant (τ)
- Result on $0\nu\beta\beta$ decay rate extracted marginalizing over the nuisance parameters

Systematic	Value	Prior
Isotopic fraction	0.966±0.002	Gaussian
$0\nu\beta\beta$ containment MC	1.000±0.015	Gaussian
$0\nu\beta\beta$ cont. detector response	0.95-1.00	Flat
Analysis efficiency	0.906±0.004	Gaussian
Light yield selection	0.998-1.008	Flat

CUPID-Mo 0νββ decay analysis

Sensitivity study

- Toy spectra with various background levels: → BI = 10^{-3}, $5\cdot10^{-3}$, 10^{-2}, $2\cdot10^{-2}$ counts/keV/kg/yr
- Amplitude of exponential fixed to its best fit
- Poisson smearing on both flat and exponential background component
- 1000 toy-MC spectra generated for each BI



Results

- **$T_{1/2}^{0\nu}$ > 1.5·10^{24} yr** @ 90% C.I.
- **$m_{\beta\beta}$ < 0.3-0.5 eV** (depending on NME)
- BI O(10^{-3}) counts/keV/kg/yr

→ Best result so far in ^{100}Mo!

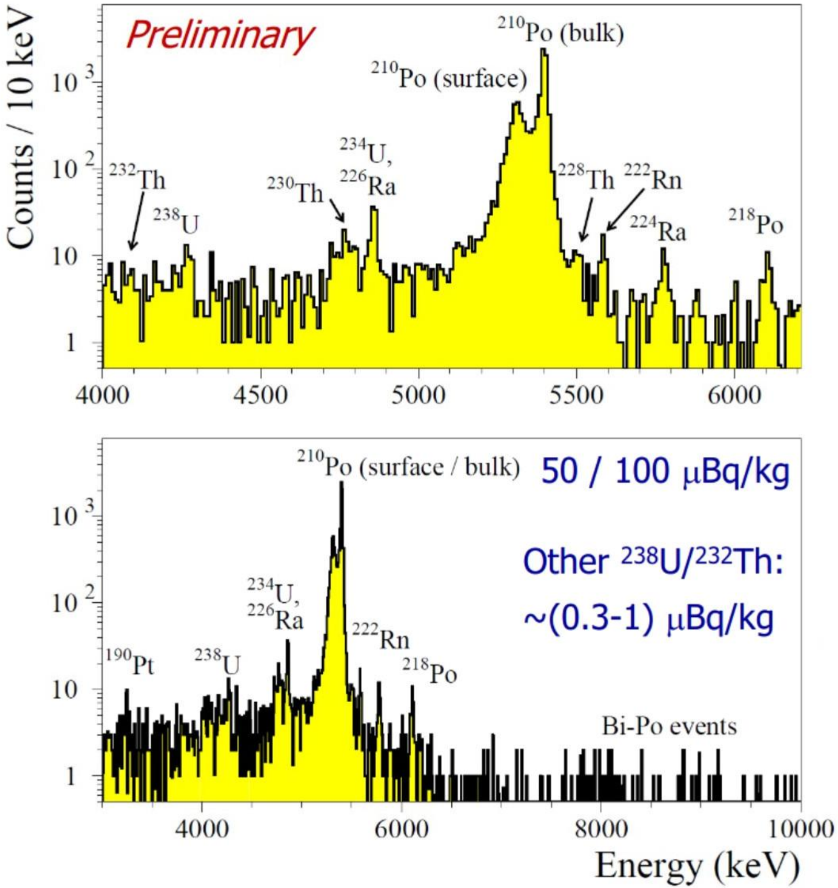
→ 4^{th} most stringent limit with just 1.19 kg·yr of ^{100}Mo!

→ Precise evaluation with background model ongoing

CUPID-Mo is a real experiment, not just a demonstrator!

CUPID-Mo, arXiv:2011.13243 (submitted to PRL)

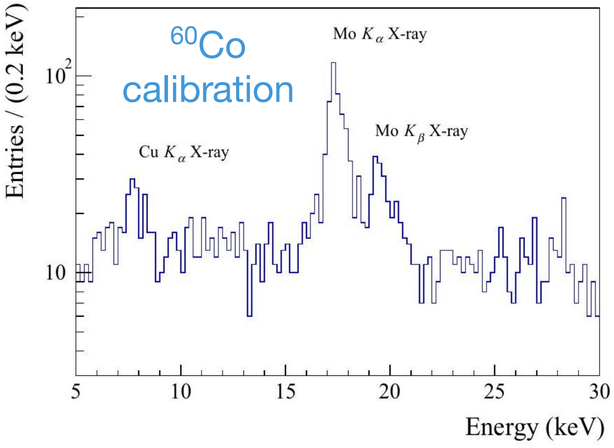
CUPID-Mo crystal purity

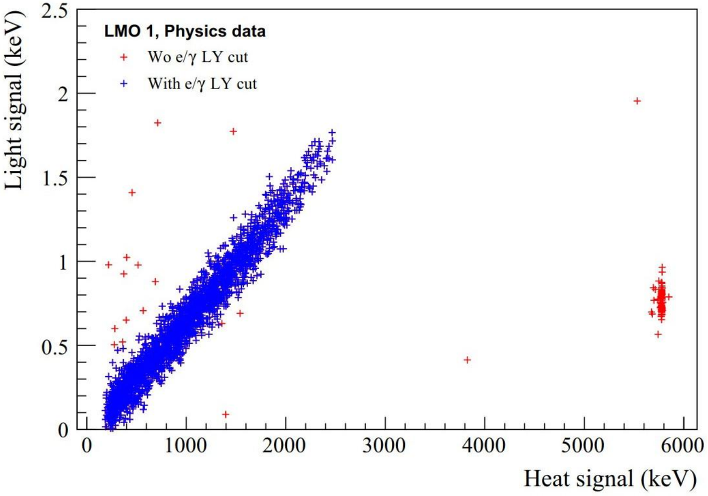


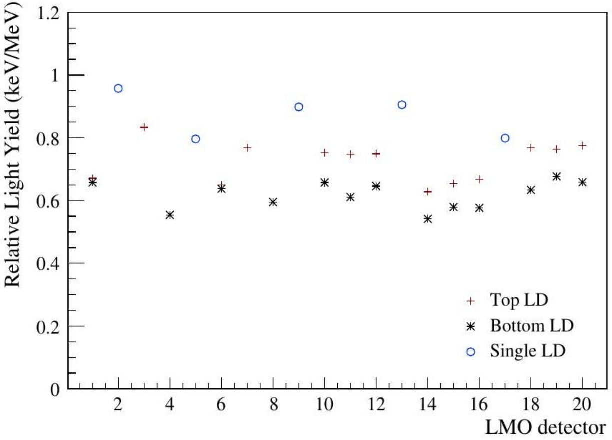
Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{232}Th	0.22(9)
	^{228}Th	0.38(9)
	^{224}Ra	0.34(9)
	^{212}Bi	0.22(7)
^{238}U	^{238}U	0.35(10)
	^{234}U+^{226}Ra	1.22(17)
	^{230}Rh	0.48(12)
	^{222}Rn	0.47(10)
	^{218}Po	0.35(9)
	^{210}Po	98(6)
	^{190}Pt	0.19(8)

D. Poda, Poster @ Neutrino 2020

CUPID-Mo PID performance







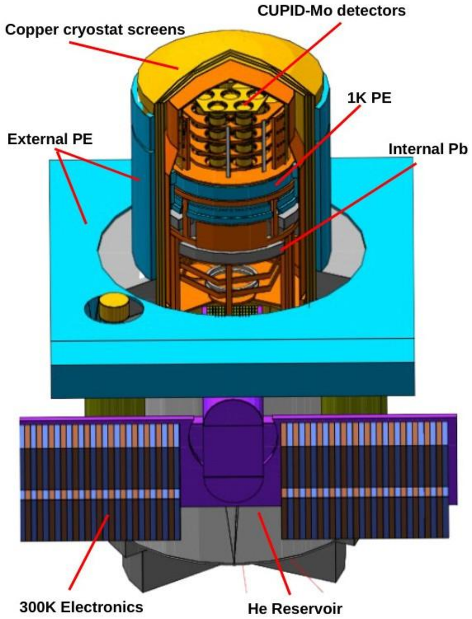
- PID performance quantified in terms of discrimination power:

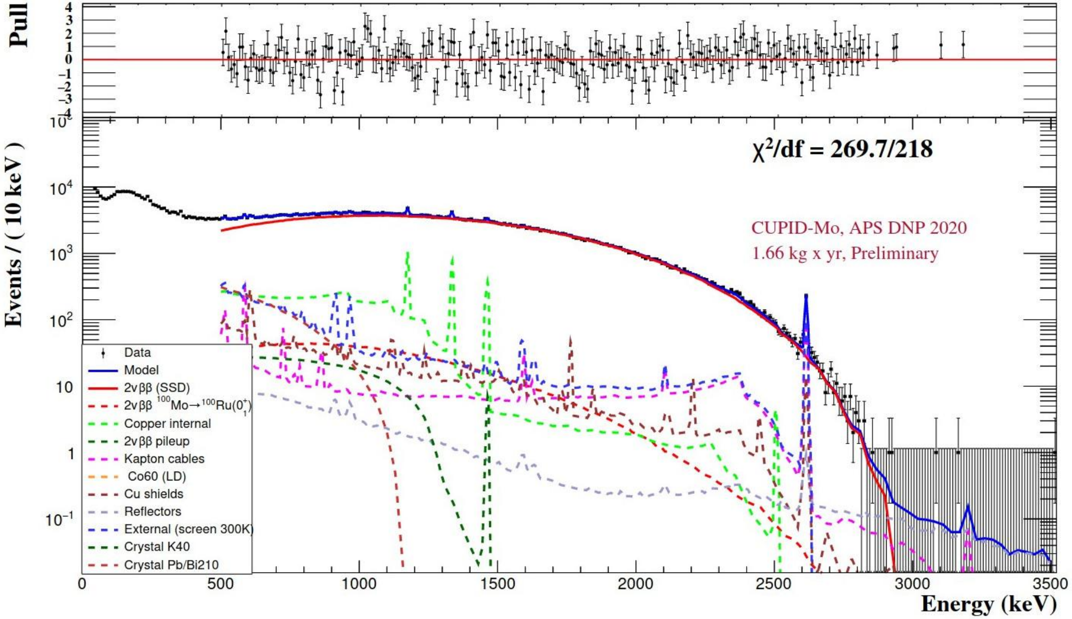
$$DP = \frac{\mu_\gamma - \mu_\alpha}{\sigma_\gamma^2 + \sigma_\alpha^2}$$

- Median DP=15, worst detector DP=6.3
  → α rejection >99.9% for all detectors
  → β/γ efficiency > 99.9% for all detectors

CUPID-Mo Collaboration, EPJ C80 (2020) 44

CUPID-Mo work-in-progress



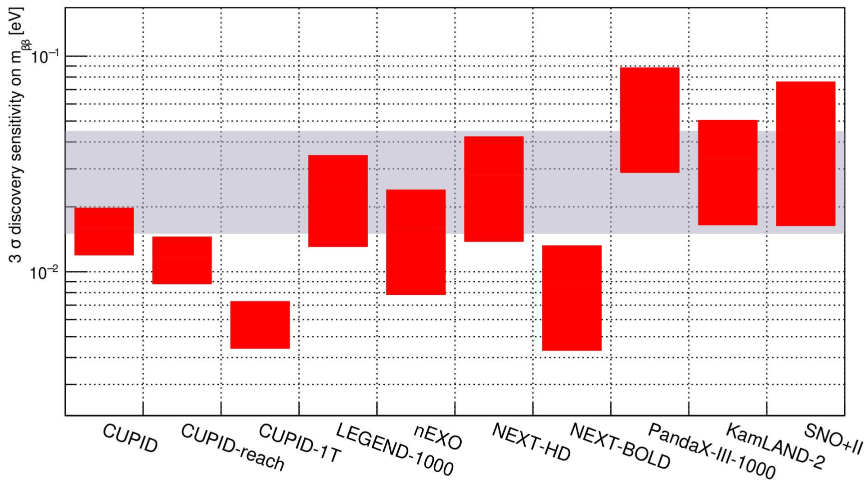


Full background-model fit will allow:

- a precise measurement of the LMO bulk and surface contamination
- a precise measurement of ^{100}Mo 2νββ decay half life to ground and excited states
- a test of nuclear physics models for the prediction of the 2νββ decay spectrum

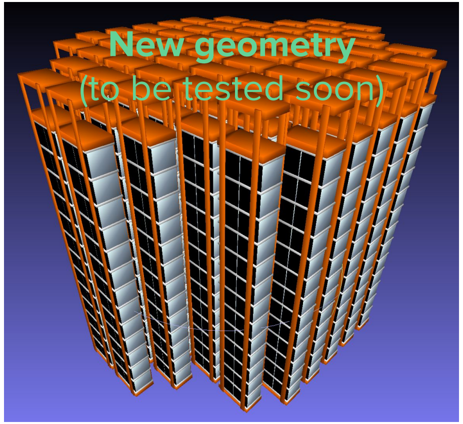
CUPID

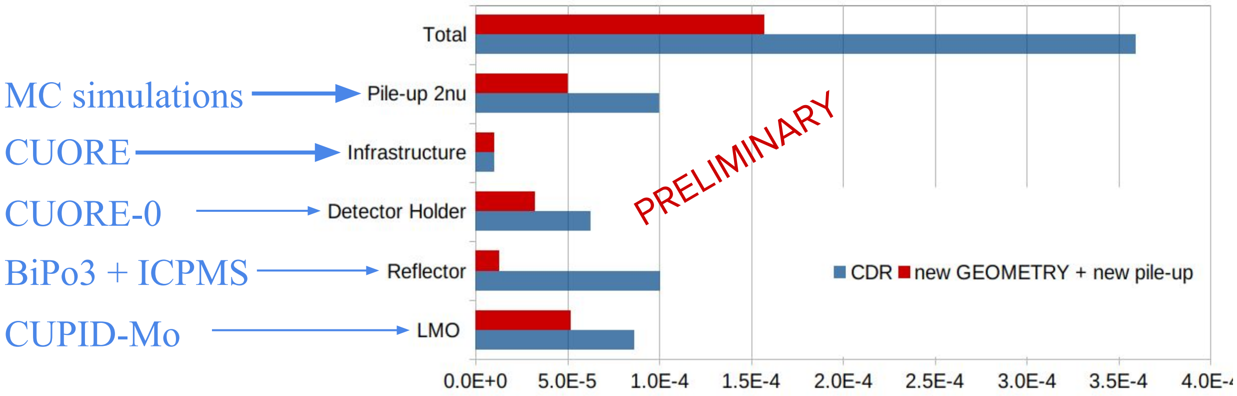
- CUPID pre-CDR: very conservative
  → Exactly what we could start building today.
  → No improvement assumed!
- CUPID reach: assume improvement at reach before construction
  → Improved signal timing with TES on LD
  → Improved radiopurity
  → Zero-bkg condition: $2 \cdot 10^{-5}$ counts/keV/kg/yr
-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



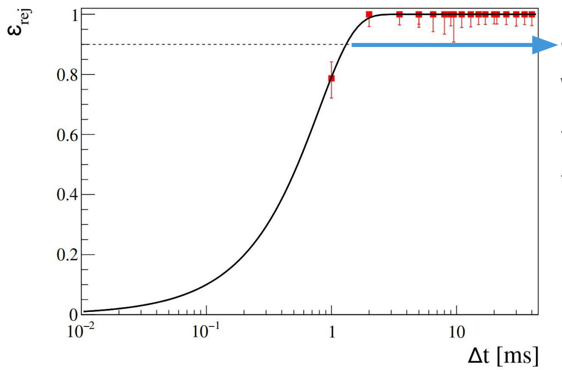
Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency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

To-do list for CUPID





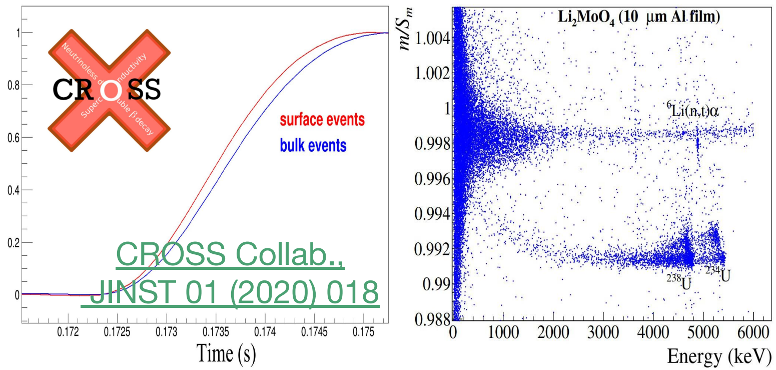
Suppression of 2νββ background



< 2 ms resolution on LMO with space for improvement
→ Higher sampling freq.
→ LD are faster!

CUPID Collaboration, arXiv:2011.11726

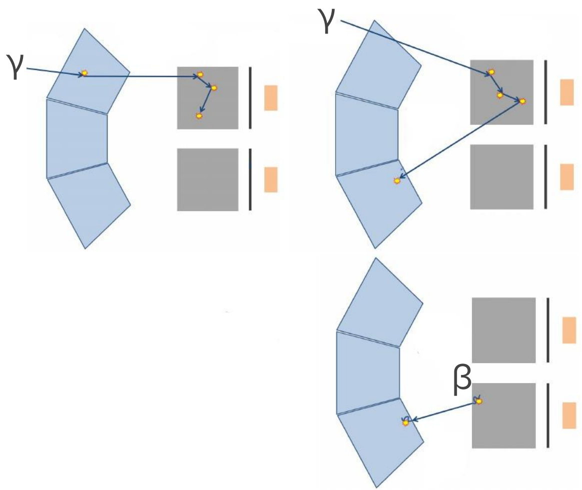
CROSS: pulse shape on heat channel



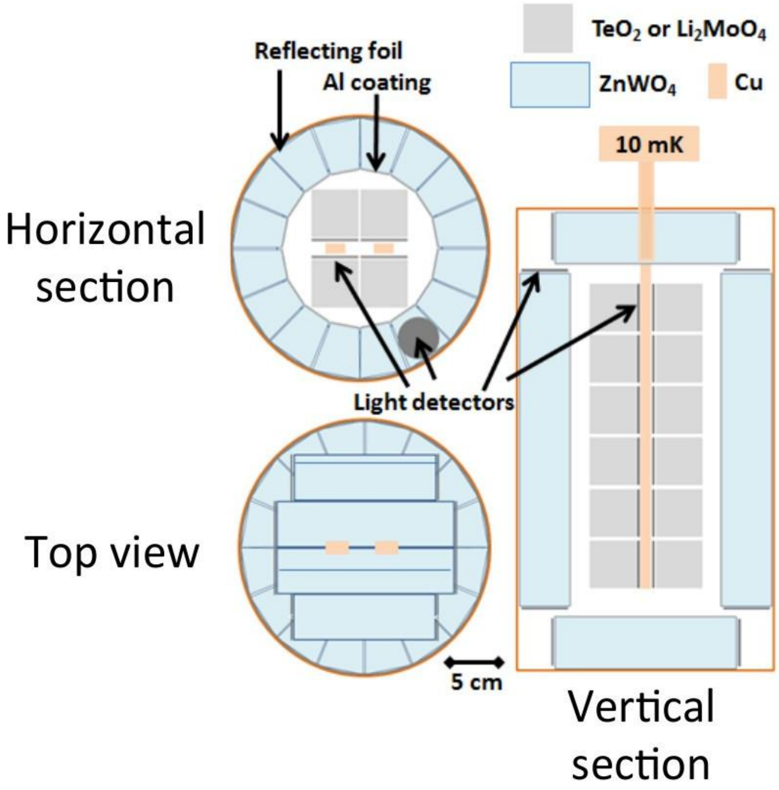
CROSS Collab., JINST 01 (2020) 018

How do we proceed beyond CUPID?

- Increase mass
  → Easy, just need to find money 😜
- Reduce background
  → Active shield, active crystal mounting
  → Faster and more sensitive LDs,
  e.g. TES or Neganov-Luke assisted LDs
- Multi-isotope approach allows confirmation of discovery with same setup



Ongoing ERC: **BINGO**



THANK YOU!