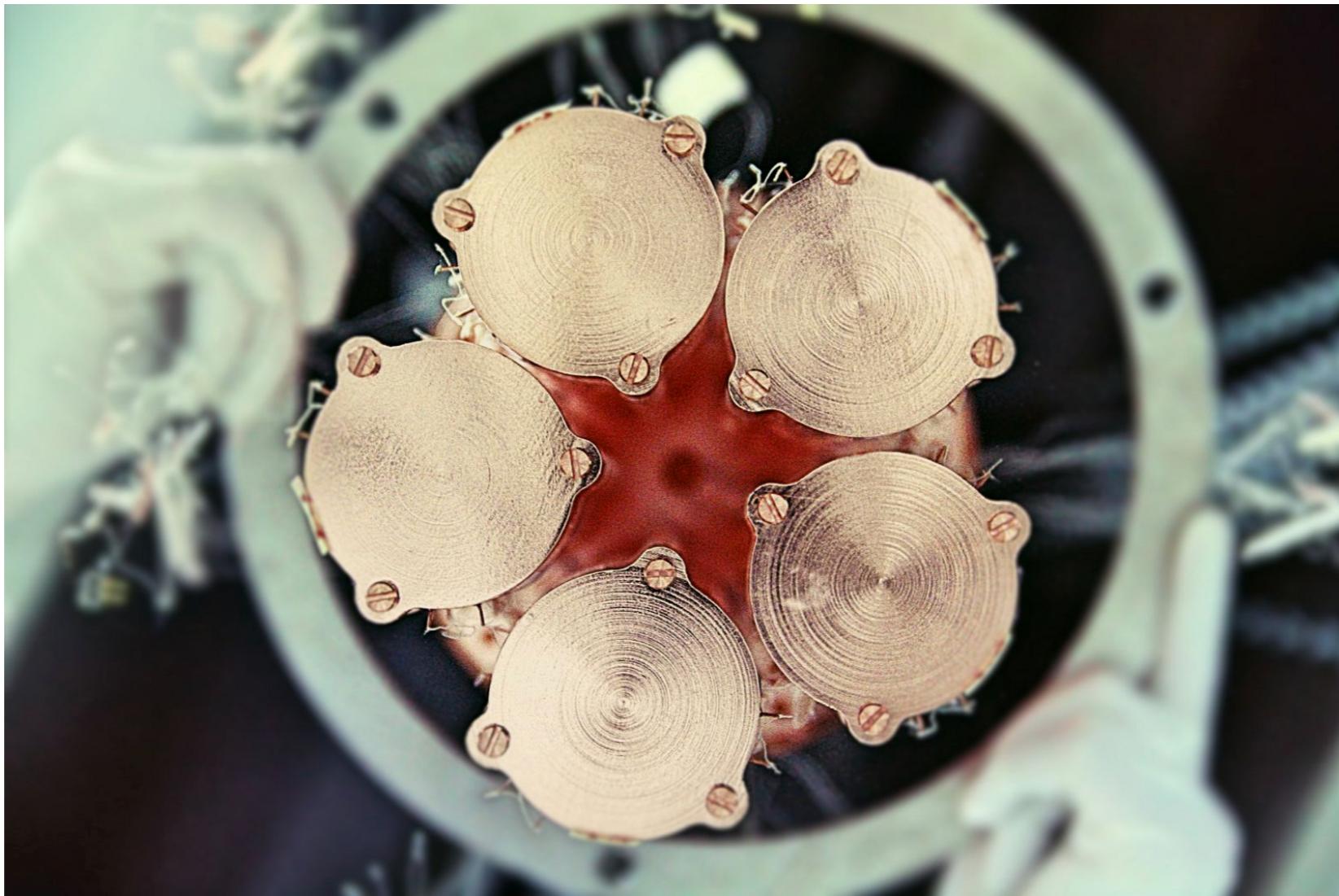


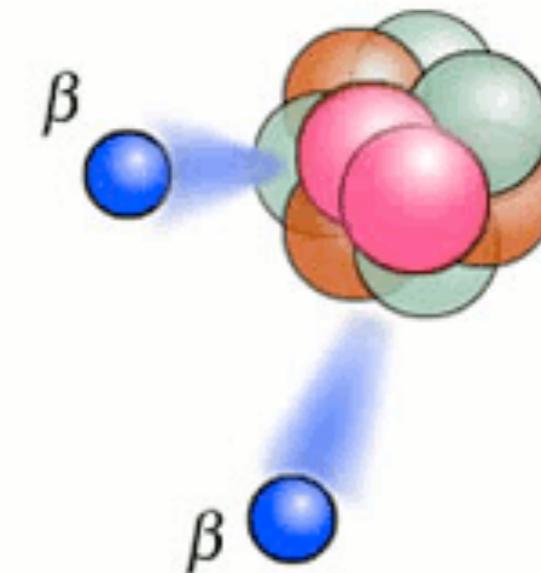
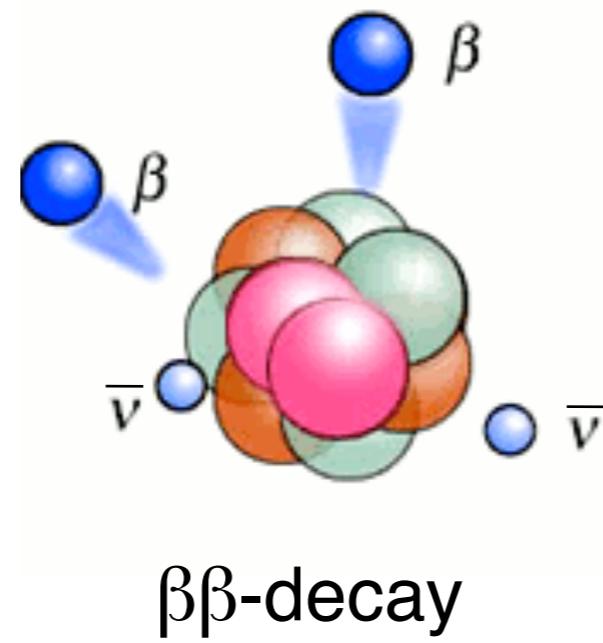
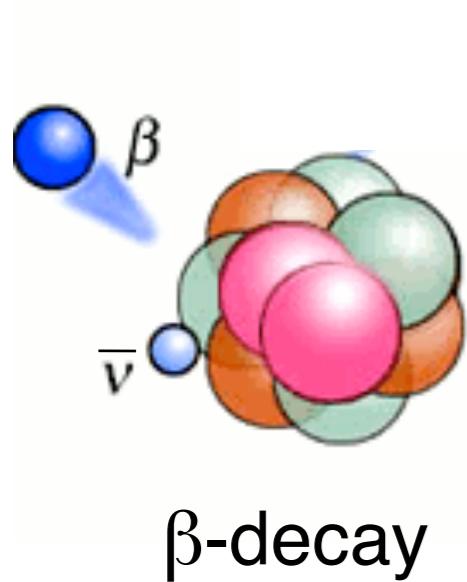
# CUPID: a new bolometric detector for rare events experiment



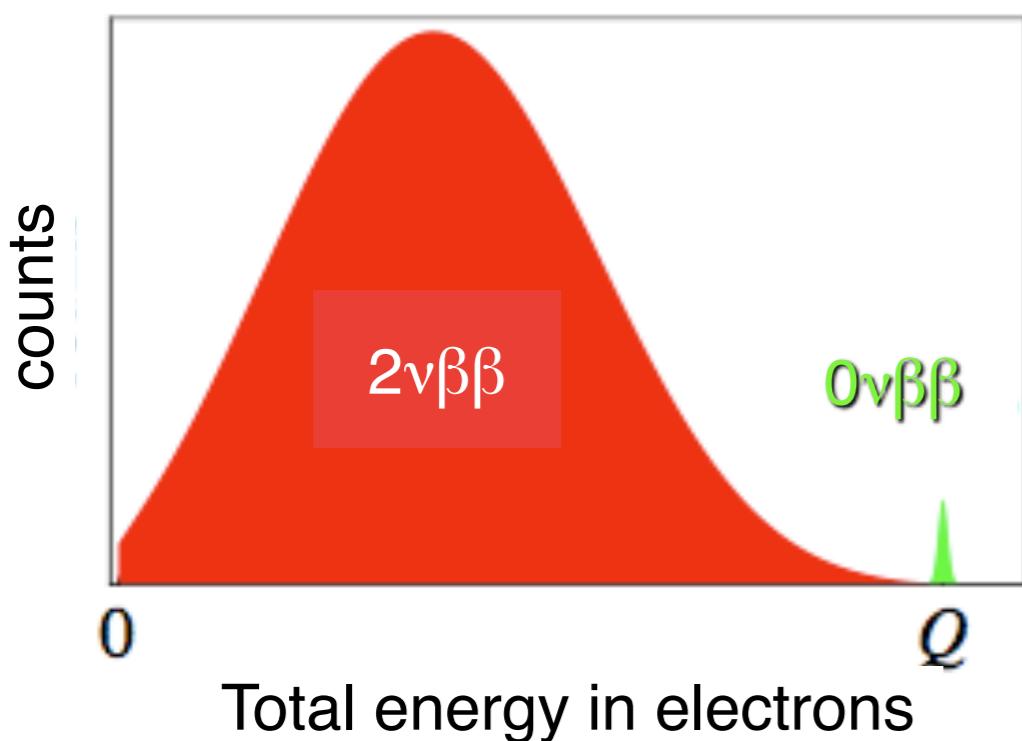
***Claudia Tomei - INFN Sezione di Roma  
for the CUPID collaboration***

*15th Topical Seminar on Innovative Particle and Radiation Detectors  
Siena, 14-17 October 2019*

# Double beta decay



possible only if vs have  
Majorana nature

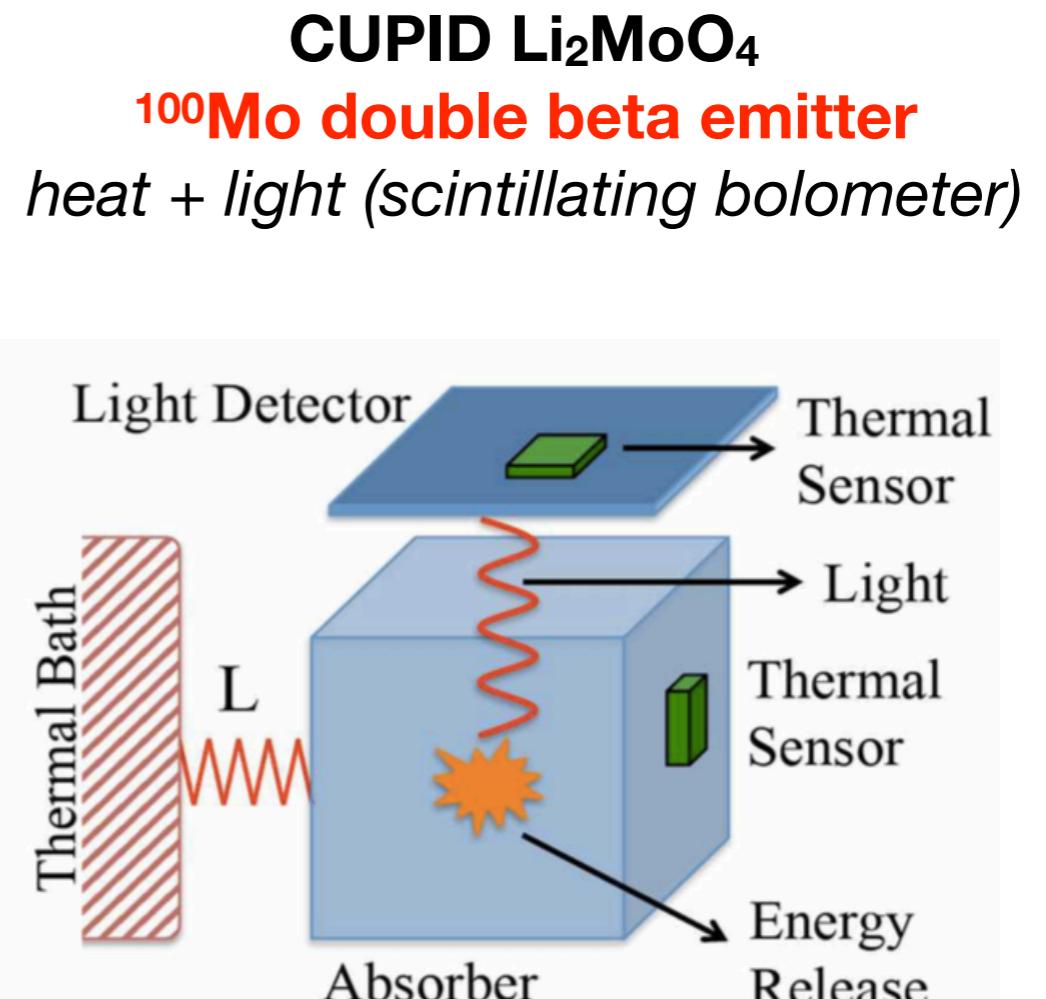
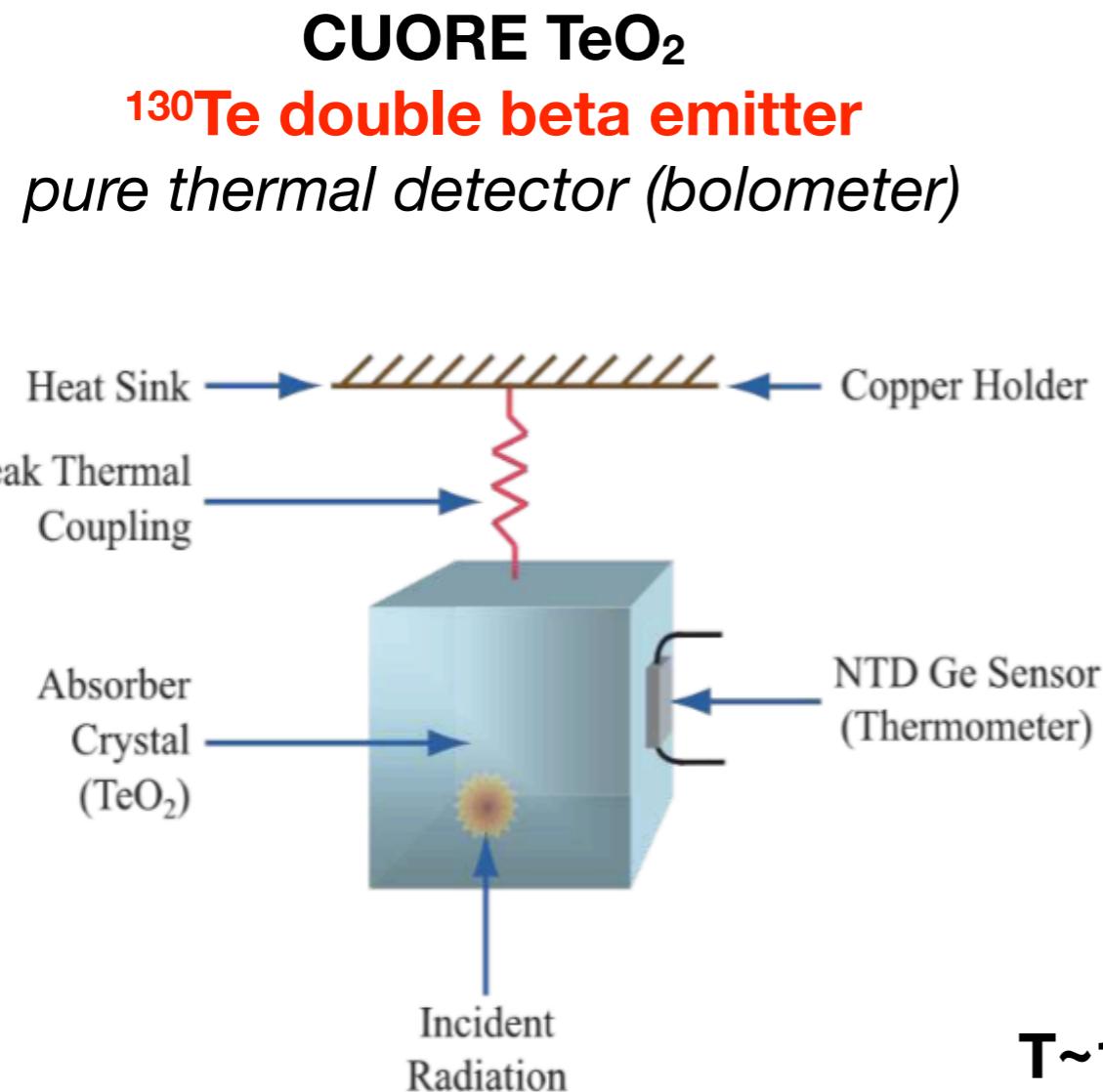


$0\nu\beta\beta$  can occur only in a few natural isotopes,  
e.g.:  $^{130}\text{Te}$ ,  $^{76}\text{Ge}$ ,  $^{136}\text{Xe}$ ,  $^{100}\text{Mo}$ ,  $^{82}\text{Se}$ .

Present half-life limits are  $> 10^{24-26}$  years.

Several nuclei (100 - 1000 kg) are needed.  
Almost **zero background** is needed

# CUPID: CUORE Upgrade with Particle IDentification



T~10 mK

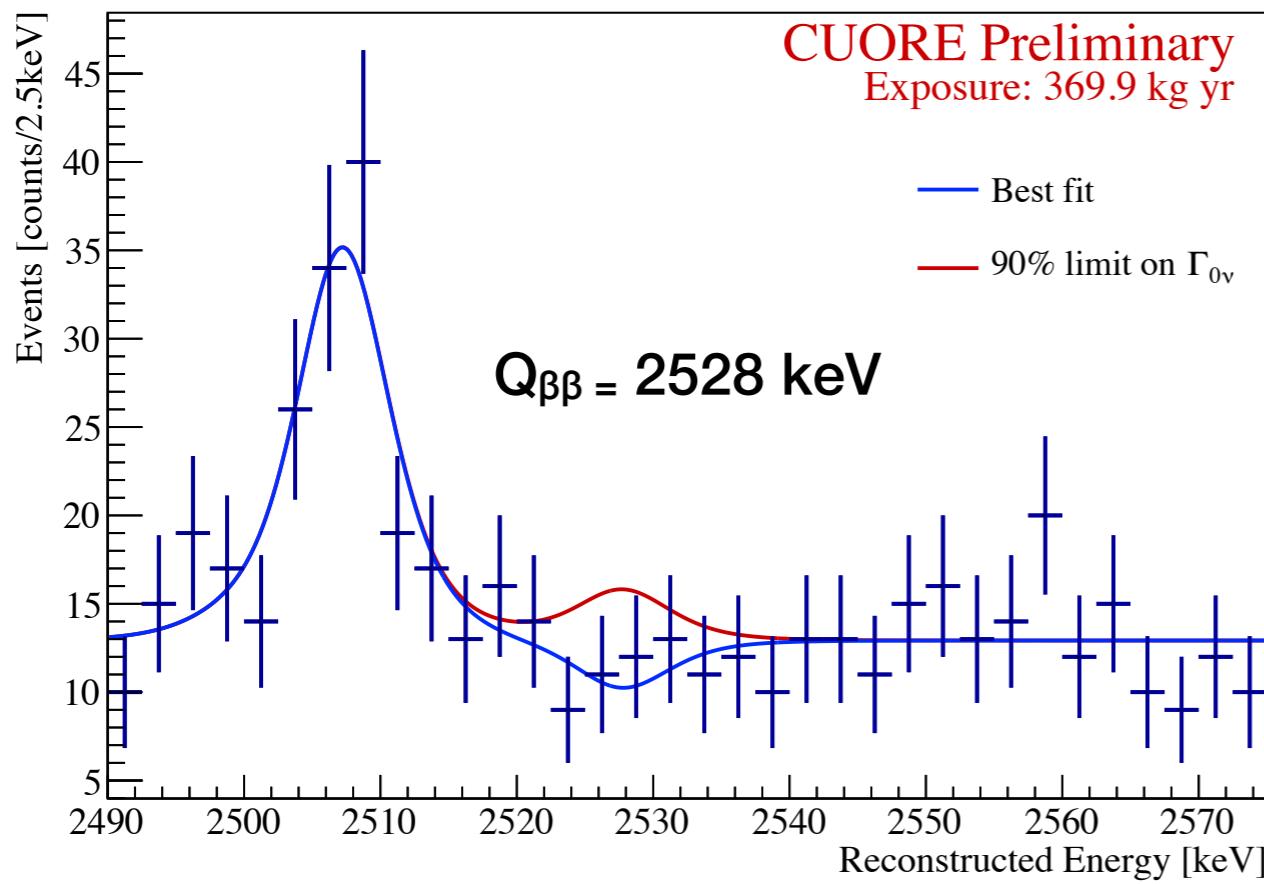
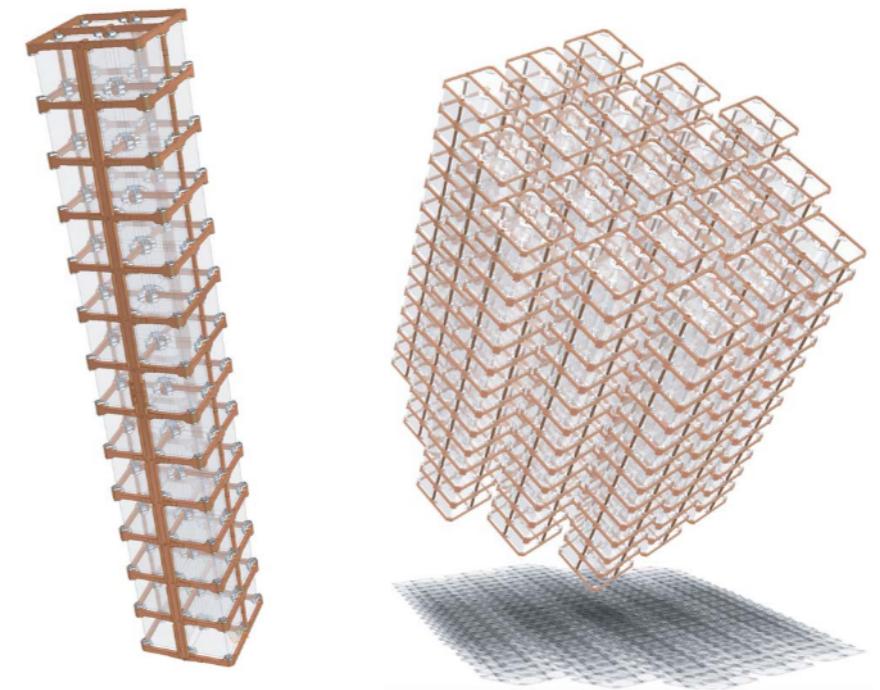
**No Particle IDentification**  
 $Q_{\beta\beta} < 2615 \text{ keV}$

**Particle IDentification**  
 $Q_{\beta\beta} > 2615 \text{ keV}$

# CUORE: the tonne-scale macro-calorimeters array

CUORE: 988 TeO<sub>2</sub> cryogenic calorimeters;

Total mass: 742 kg TeO<sub>2</sub> (natural Te)  
<sup>130</sup>Te mass: 206 kg



PRELIMINARY

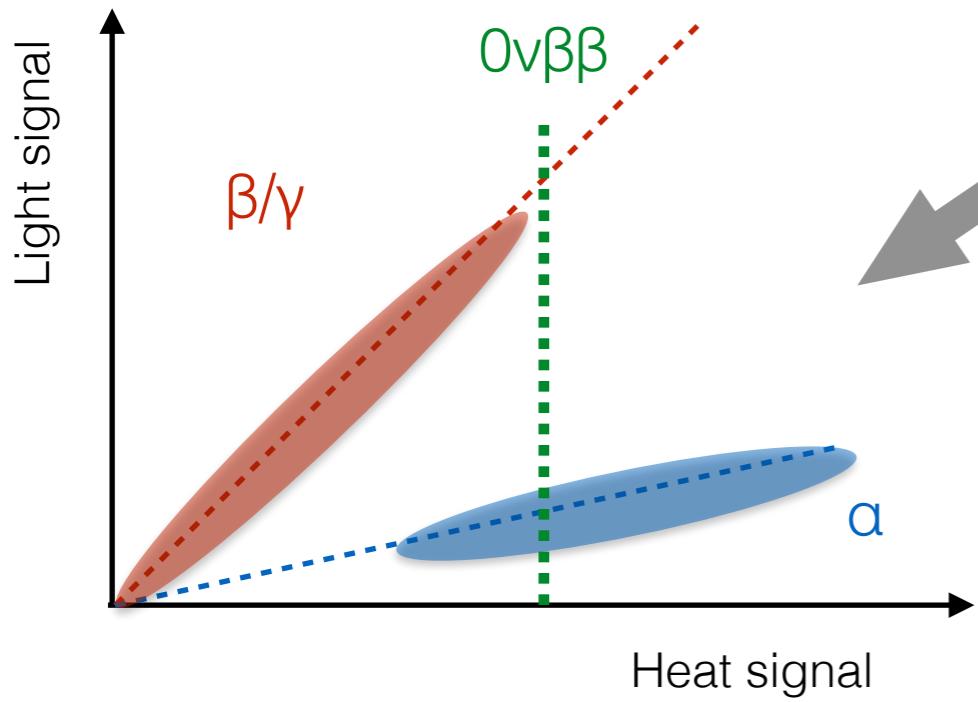
Bkg :  $(1.37 \pm 0.07) \times 10^{-2} \text{ cky}$   
(mainly from  $\alpha$  particles)

No evidence of 0νββ:

$T_{1/2}^{0\nu} > 2.3 \times 10^{25} \text{ y}$  (90% C.I.)

$m_{\beta\beta} < 0.09-0.42 \text{ eV}$  (90% C.I.)

# CUPID: CUORE Upgrade with Particle IDentification



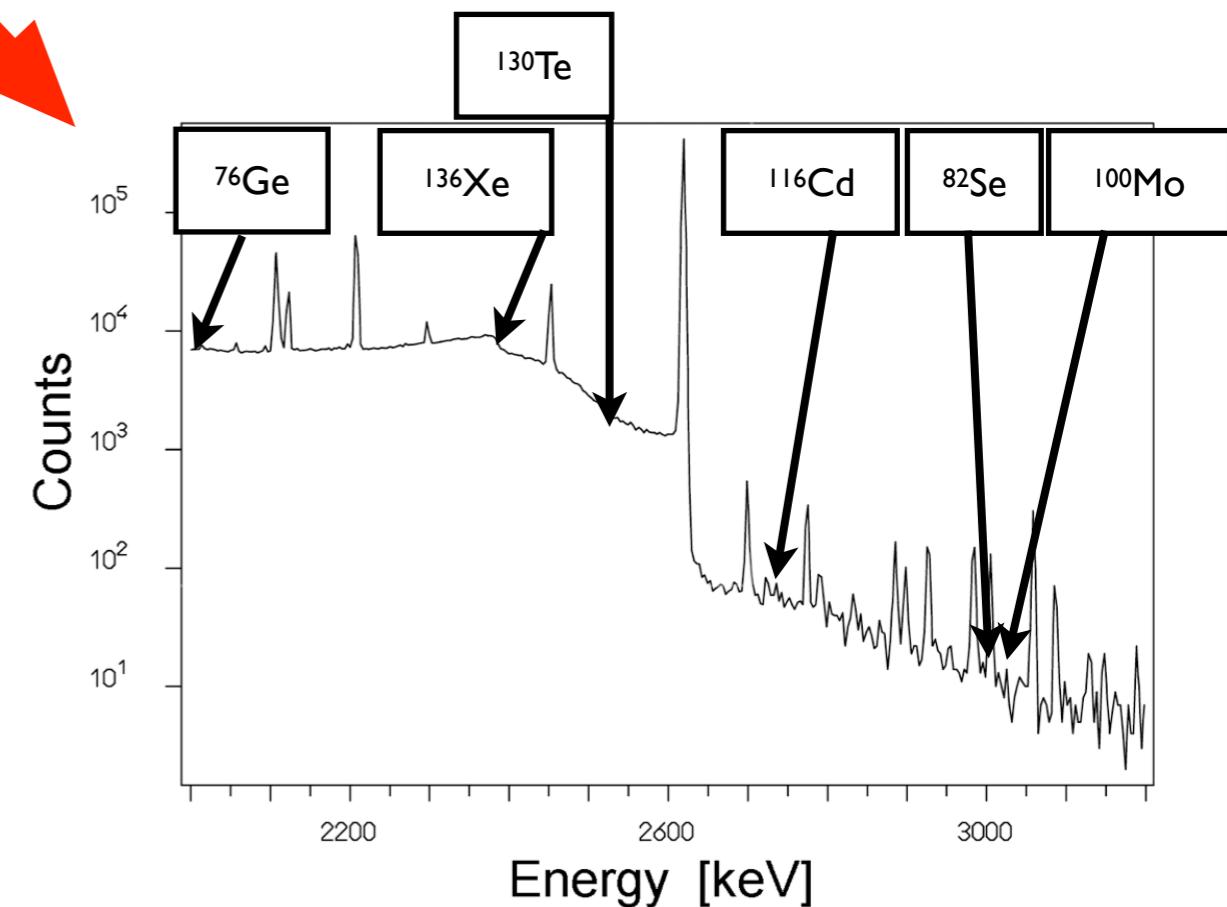
Couple to each cryogenic calorimeter  
a light detector  
Exploit differences in the LY between  
 $\alpha$  and  $\beta/\gamma$  events

High Q-Value ensures a lower  $\beta/\gamma$  background

Possibility to use the CUORE infrastructure  
for a future ton-scale  $0\nu\beta\beta$  experiment

250 kg of emitting isotope  
(isotopic enrichment)

BKG in the RoI  $\sim 10^{-4}$  counts/keV kg yr  
( $\times 100$  lower than CUORE)

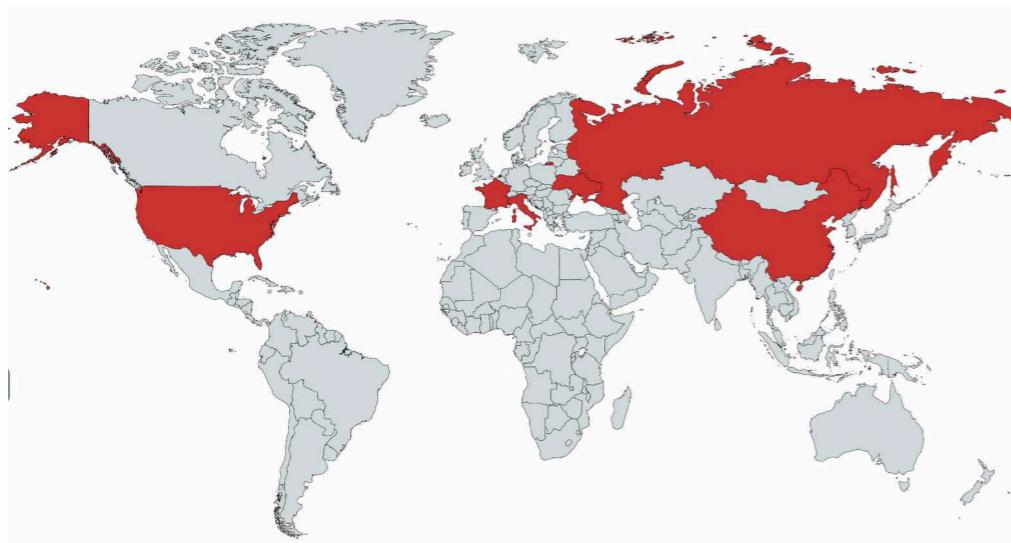


# CUPID CDR

$\text{Li}_2^{100}\text{MoO}_4$  scintillating crystals

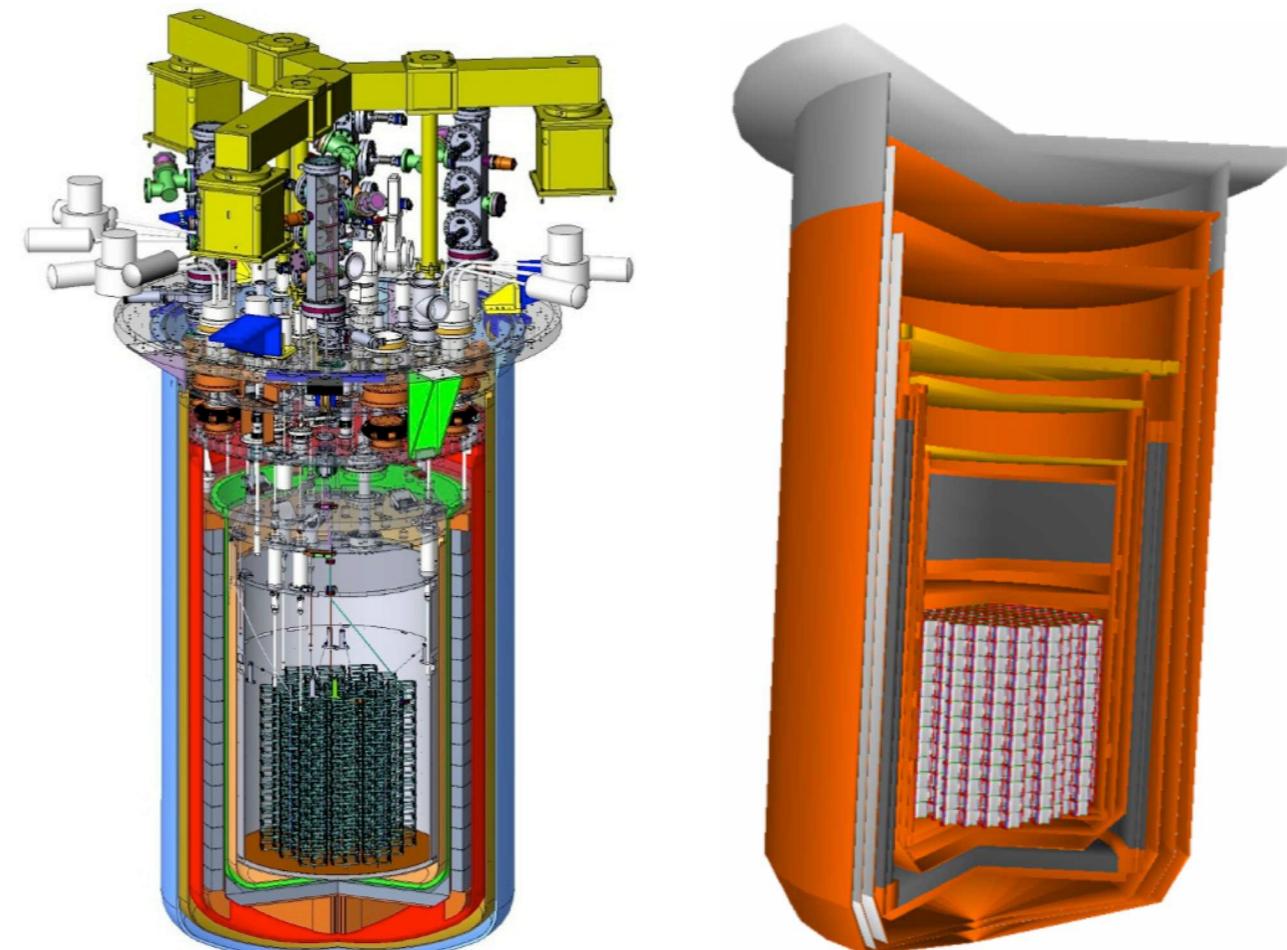
- ◆ enrichment > 95%
- Ø=50mm, h=50mm → 308 g
- ◆ ~1534 crystals ~250 kg of  $^{100}\text{Mo}$
- ◆ FWHM ~ 5 keV at  $Q_{\beta\beta} \sim 3034$  keV
- ◆ alpha rejection using light signal

CUPID CDR: [arXiv:1907.09376](https://arxiv.org/abs/1907.09376)



~170 authors in 7 countries

conservative, mature and data driven  
baseline design

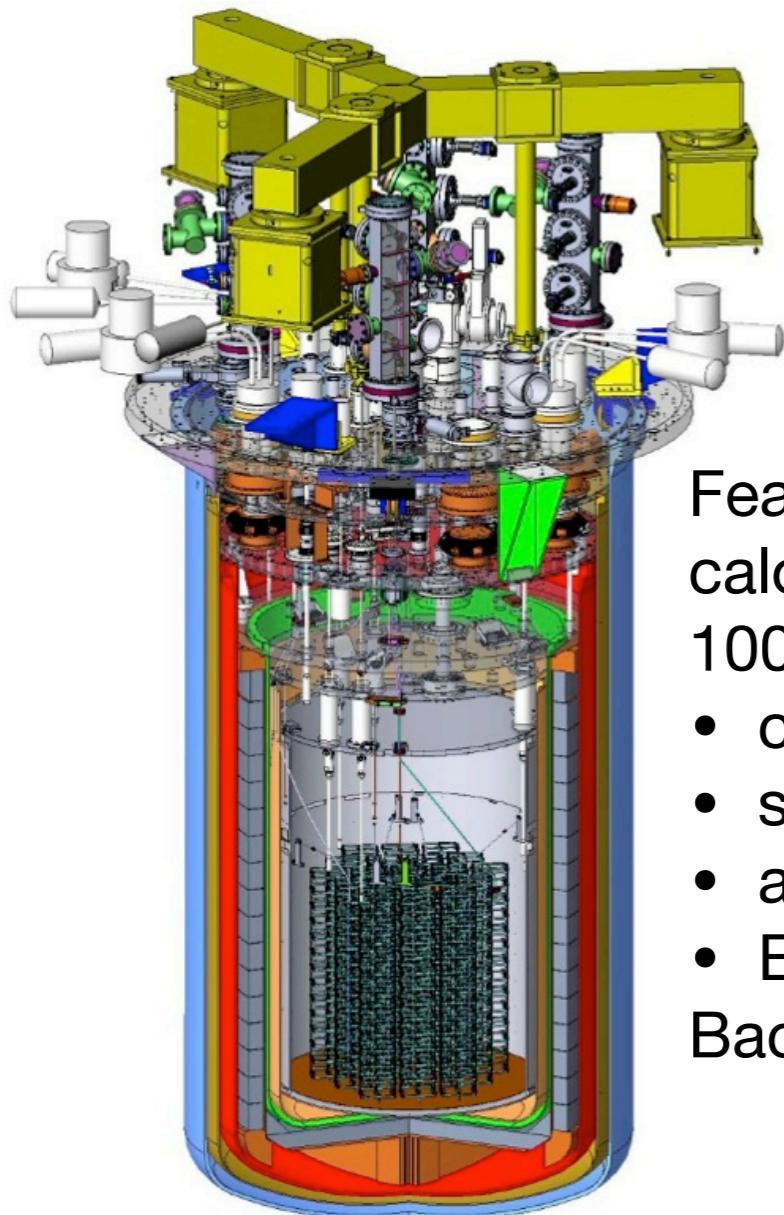


**CUORE infrastructure  
with a new detector**

**Discovery sensitivity:**

$T_{1/2}^{0\nu} ({}^{100}\text{Mo}) > 10^{27} \text{ y}$   
 $m_{\beta\beta} < 20 \text{ meV}$

# The global effort to CUPID



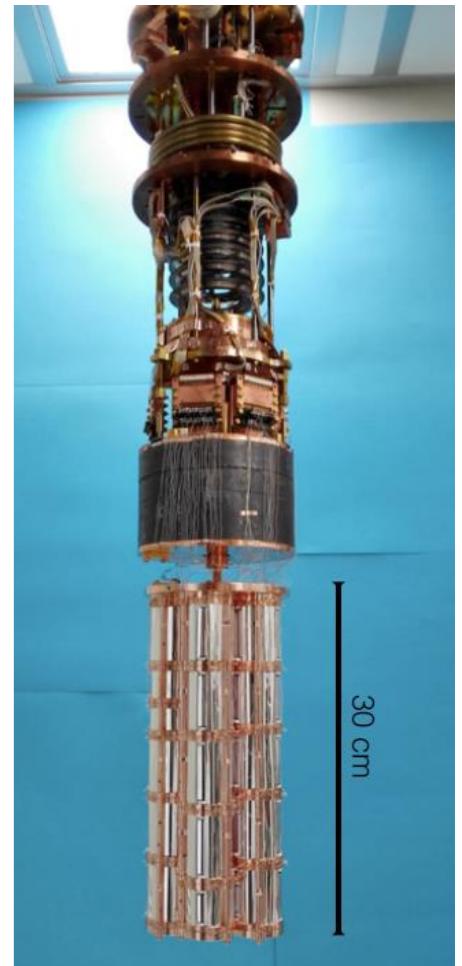
Feasibility of tonne-scale calorimeters array with 1000 crystals

- cryogenics
- shield system
- assembly
- Electronics + DAQ+DA

Background Model

CUPID0

25 crystals of  $Zn^{82}Se$   
(5.5 kg of  $^{82}Se$   
LNGS Hall A)  
Demonstrator of dual read-out technique:  
proved background at the level  $10^{-3}$  cky

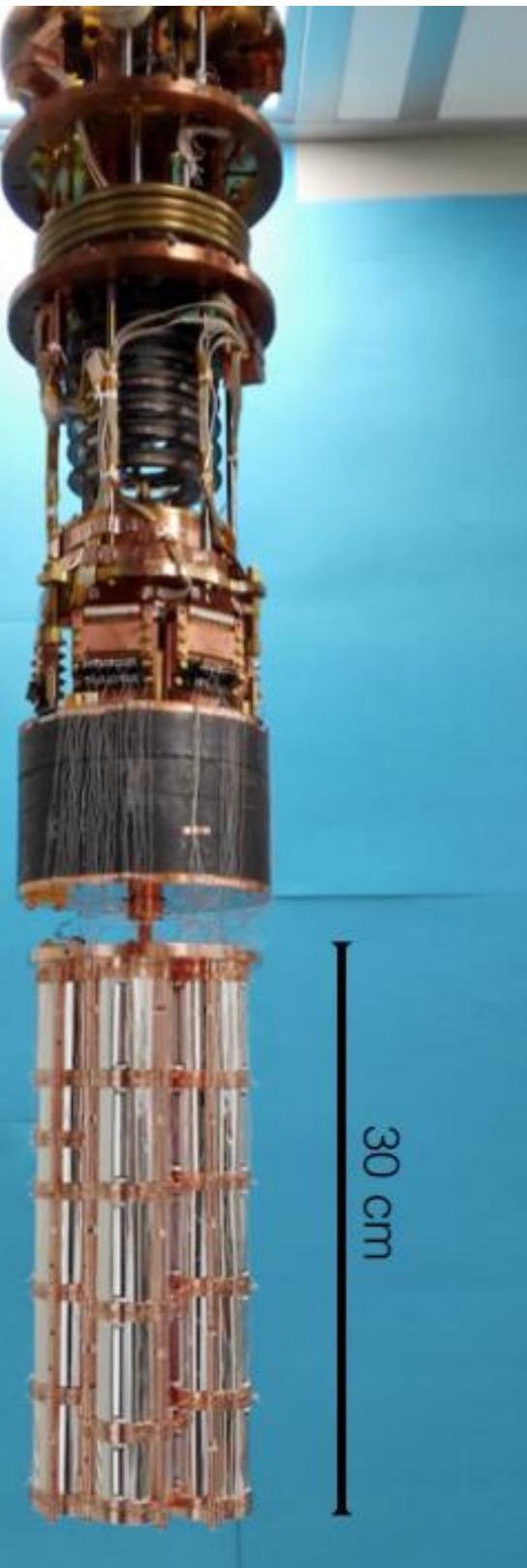


CUPID-Mo

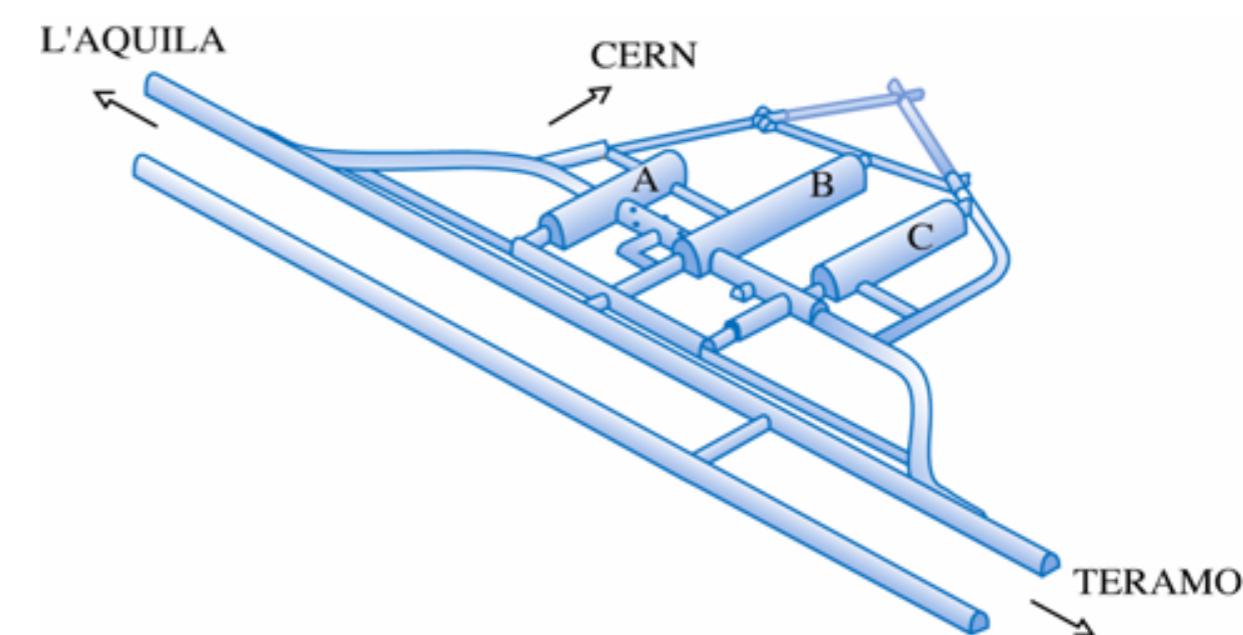
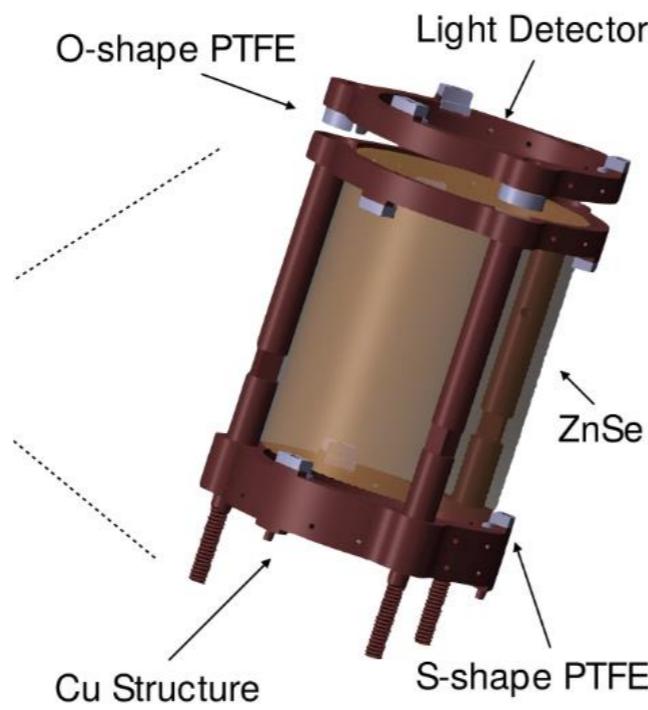
20 crystals  $Li_2^{100}MoO_4$   
(2.264 kg of  $^{100}Mo$  @ Modane)  
Same technique as CUPID-0 but proved:  
 $Li_2MoO_4$  radio-pure crystals  
Better energy resolution



# CUPID-0: the first demonstrator

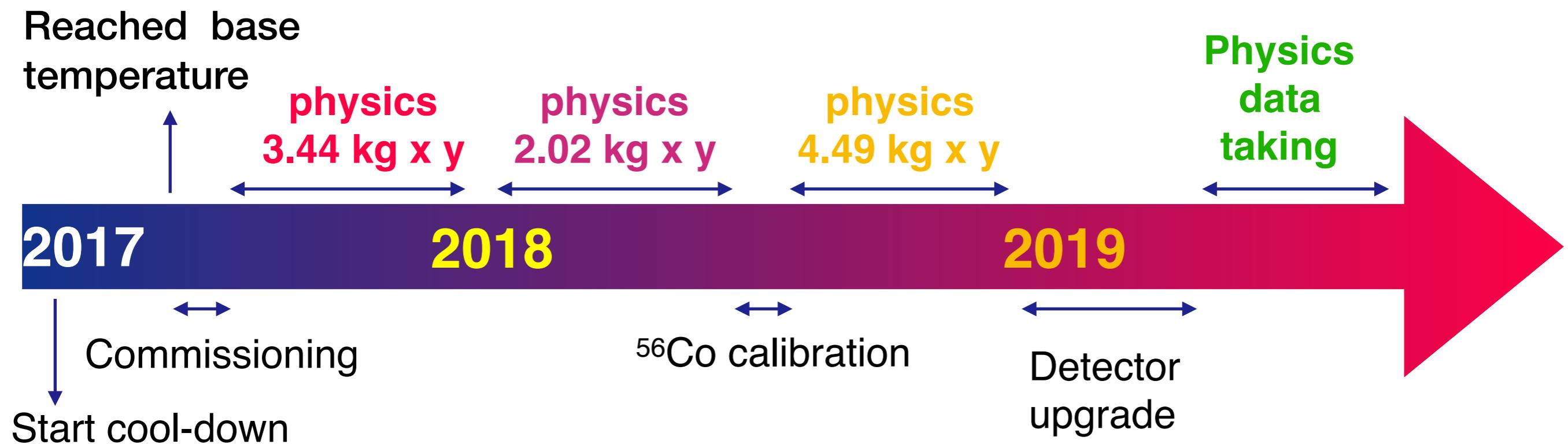


- 26 ZnSe (24 95% enriched + 2 natural)
- $^{82}\text{Se}$  0v $\beta\beta$  decay Q-Value: 2998 keV
- 31 Ge slabs (Light Detector)
- Arranged in 5 towers -> ( $3.8 \times 10^{25} {}^{82}\text{Se}$  nuclei)

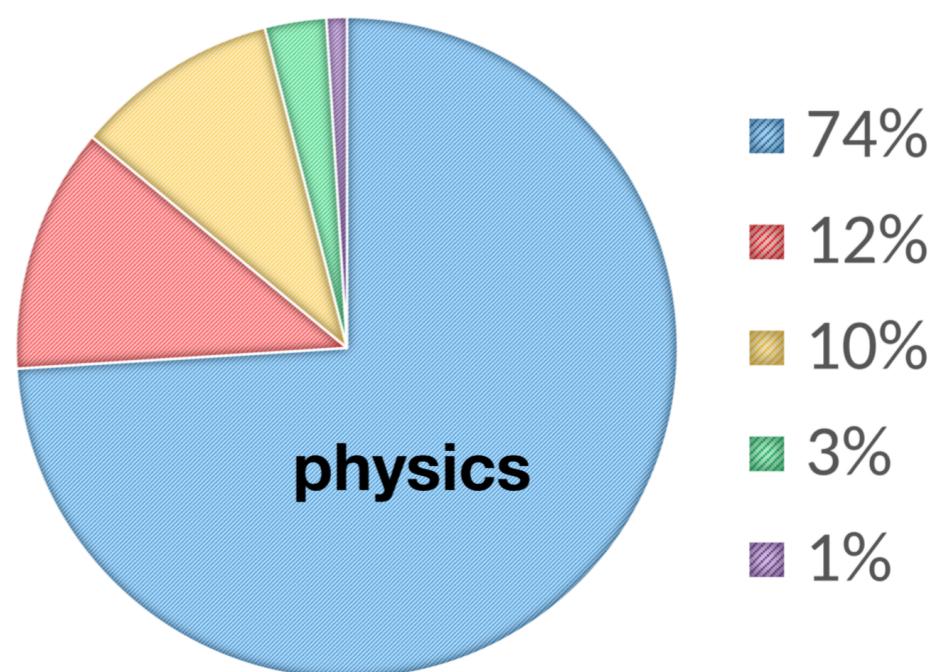


Assembled in an underground radon free clean-room @ LNGS  
Hosted in the same CUORE-0 dilution refrigerator (Hall A)

# CUPID-0 time-line

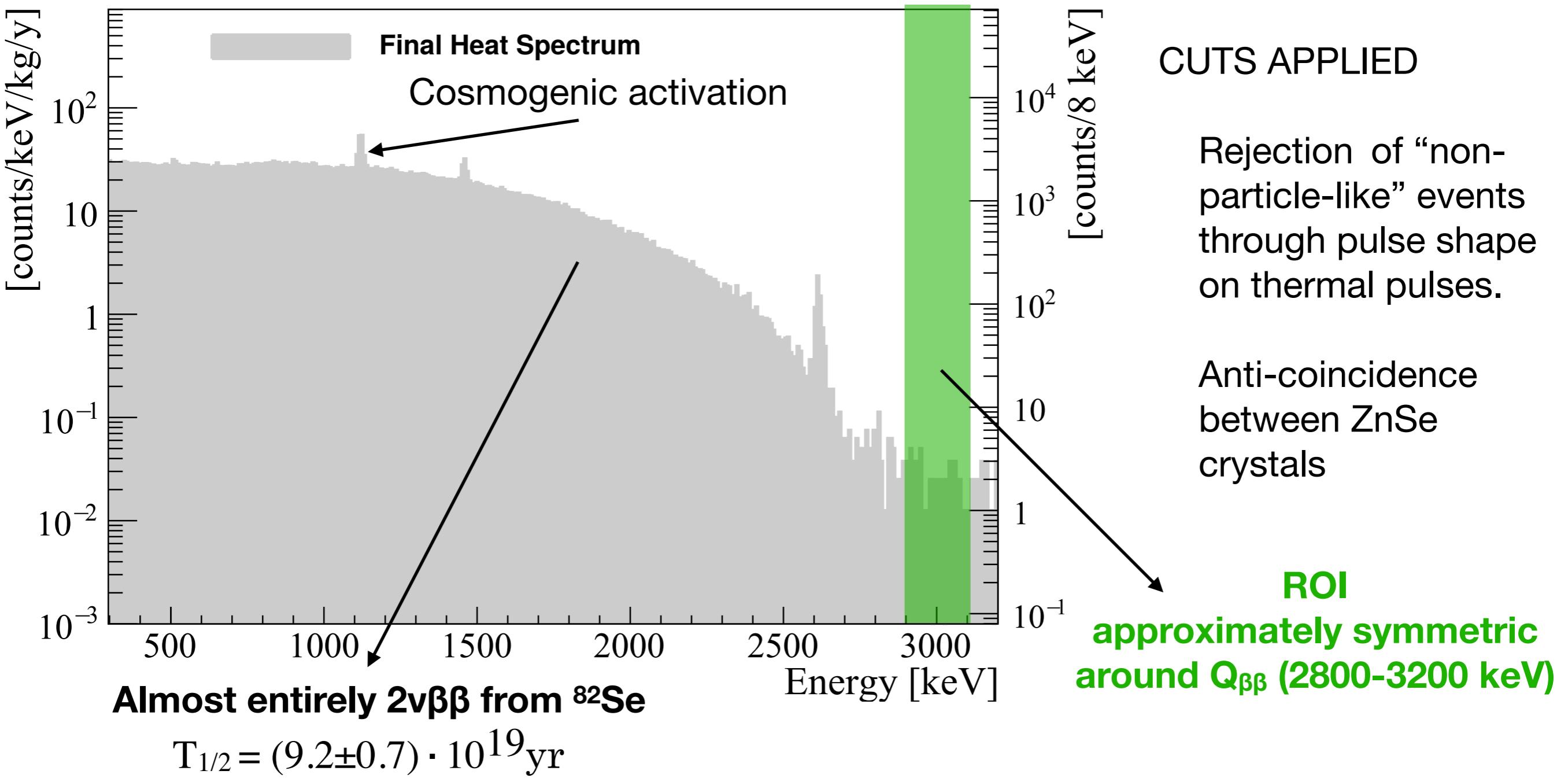


- This talk: full statistics acquired in ~1.5 years  
(phase-I):  $9.95 \text{ kg} \times \text{yr}$  of  $\text{Zn}^{82}\text{Se}$
- At the end of 2018 detector warm-up and upgrade
- June 2019: start phase-II

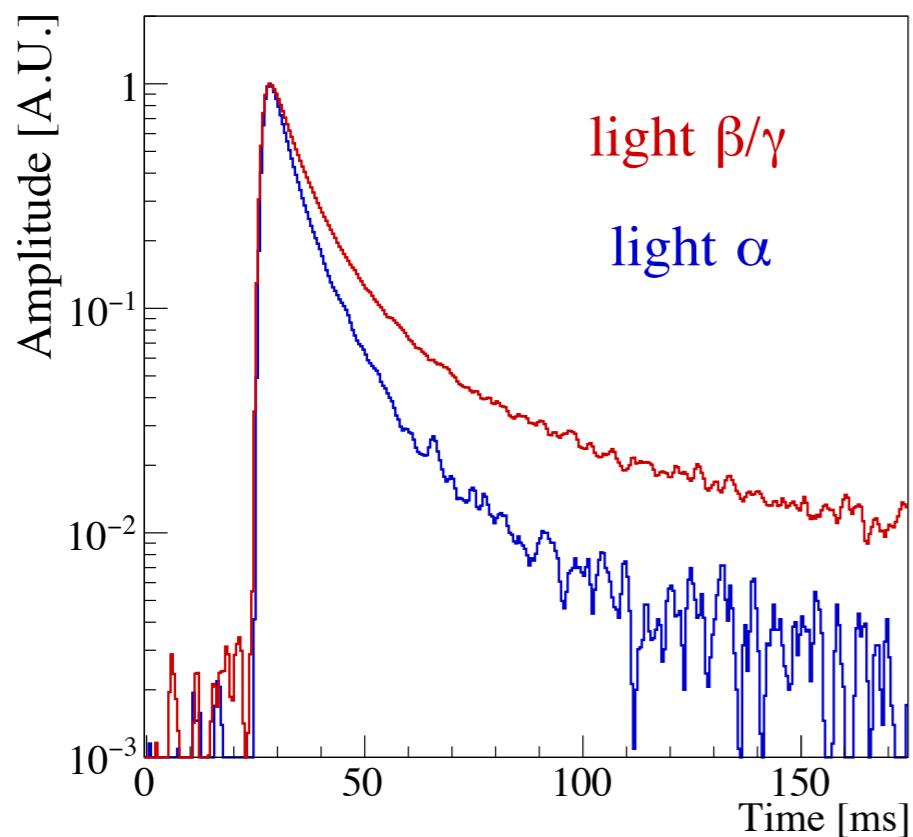


# Physics spectrum

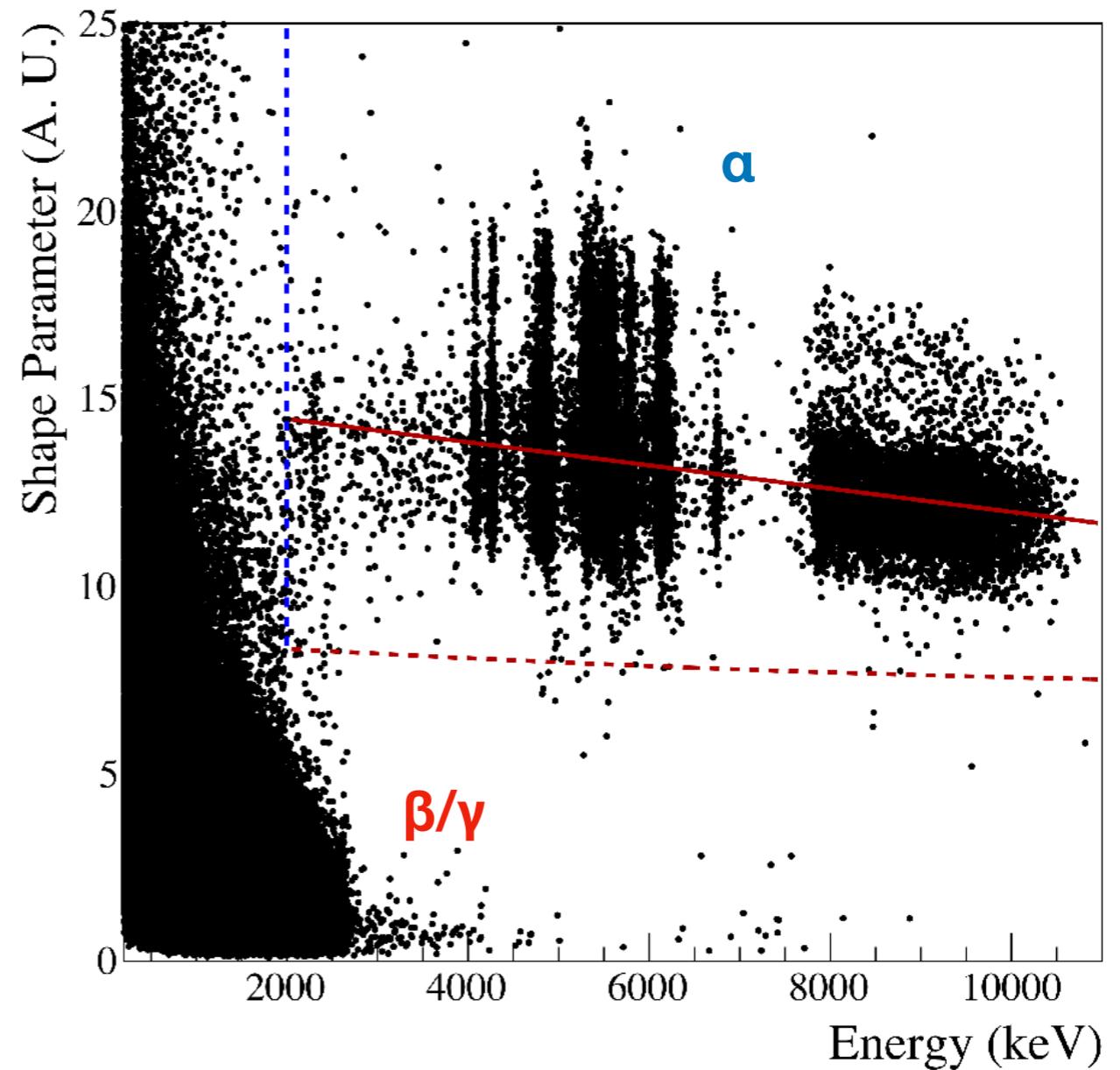
## 9.95 kgxy ZnSe



# a rejection with light shape

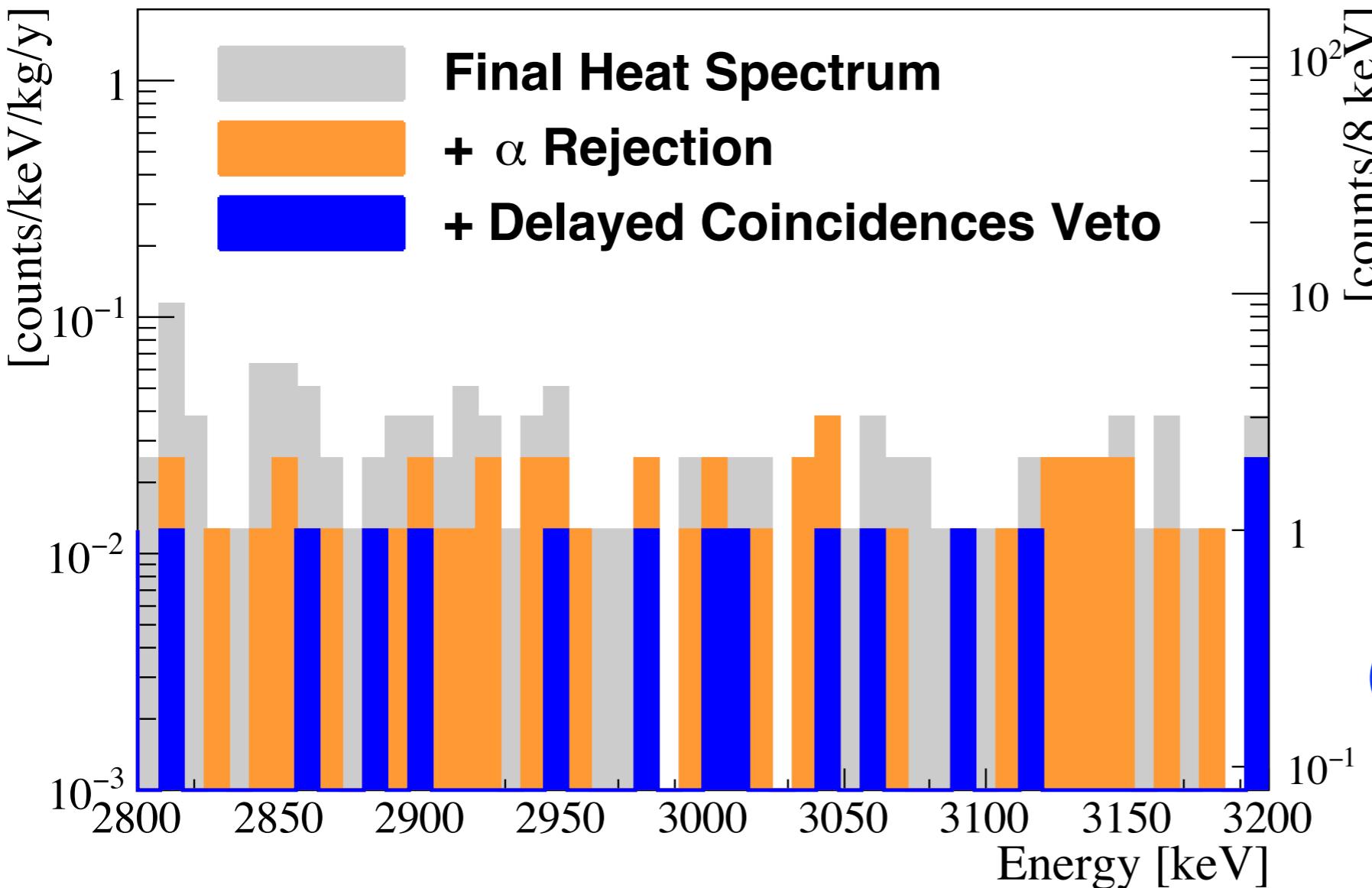


The light signal shape depends on  
the particle type



Cut optimized in the RoI with a pure  $\beta/\gamma$  sample  
-> conservative at high energy

# Rol energy spectrum + a rejection + Delayed coincidences veto



CUTS APPLIED

Rejection of “non-particle-like” events through pulse shape on thermal pulses.

Anti-coincidence between ZnSe crystals



**$\alpha$  particles rejection  
Delayed coincidence  
veto**

**14 events survive all cuts**

**BKG =  $3.2 \times 10^{-2}$  counts/(keV kg yr)**

**BKG =  $1.3 \times 10^{-2}$  counts/(keV kg yr)**

**BKG =  $3.5 \times 10^{-3}$  counts/(keV kg yr)**



**Lowest Background  
for Cryogenic  
Calorimeters**

# Results on $0\nu\beta\beta$ and $2\nu\beta\beta$

**Final efficiency:  $(70 \pm 1)$  %**

**Cuts efficiency  $(86 \pm 1)\%$**

**$0\nu\beta\beta$  electrons containment  $(81.0 \pm 0.2)$  %**

**Energy resolution in ROI:  $(20.05 \pm 0.34)$  keV**

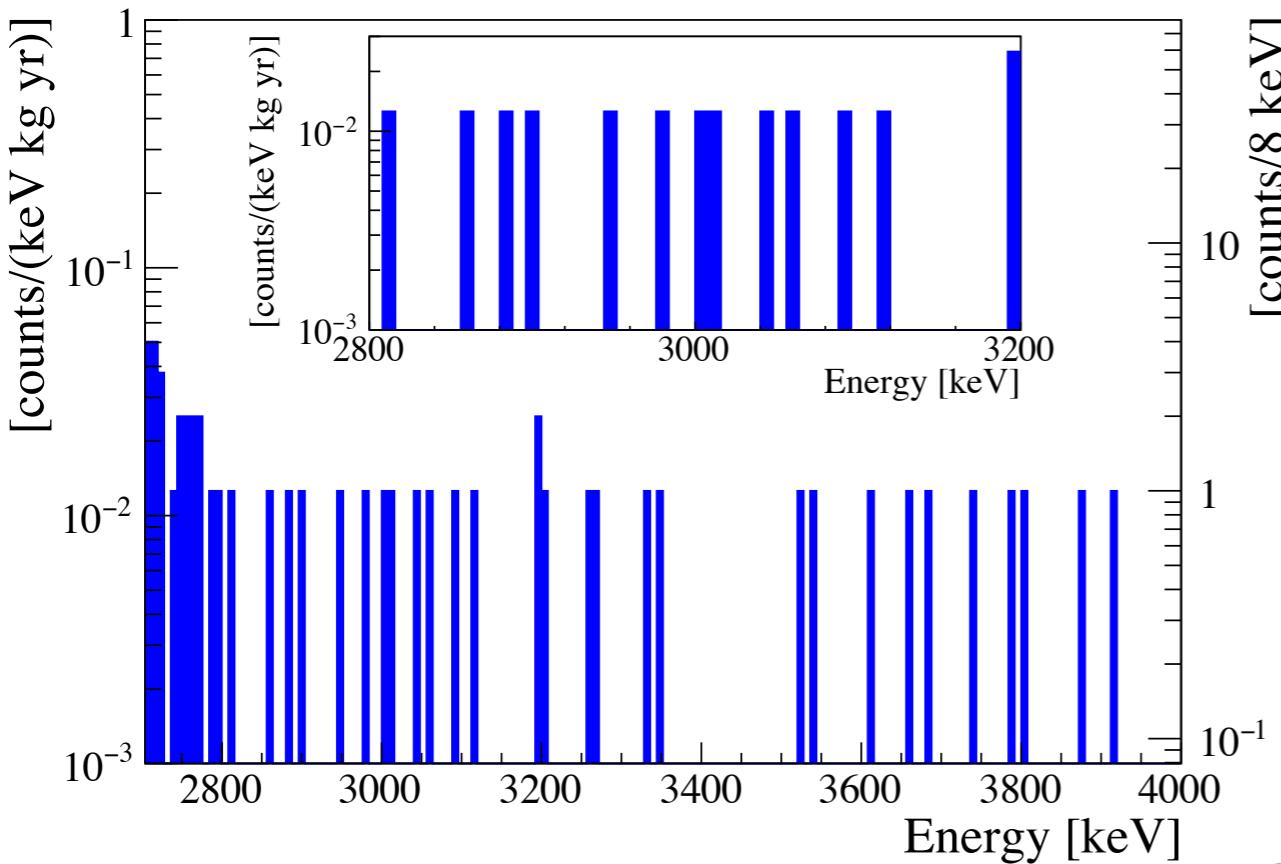
**Bayesian Lower Limit**

$T_{1/2} > 3.5 \times 10^{24}$  yr (90% C.I.)

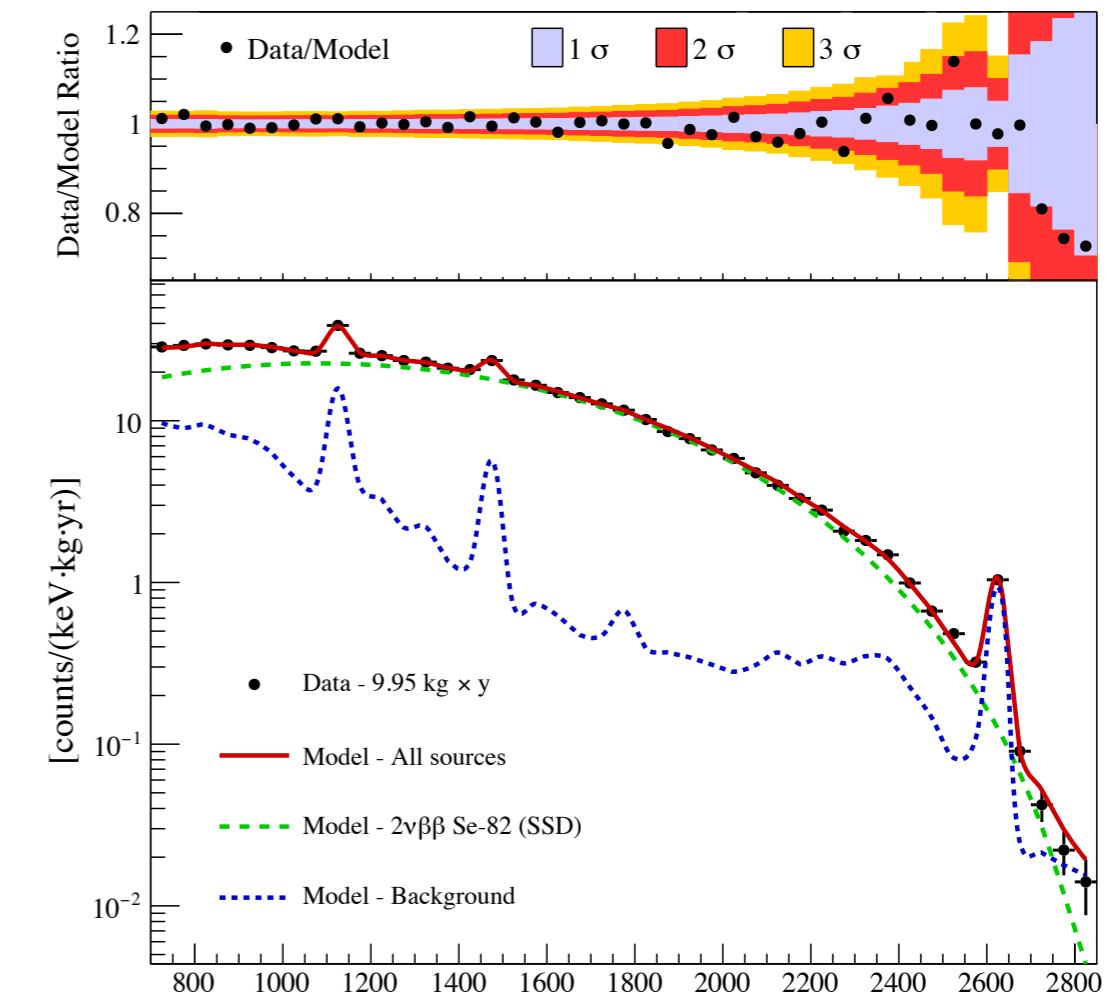
**Median Sensitivity**

$T_{1/2} > 5.0 \times 10^{24}$  yr (90% C.I.)

**No evidence for  $0\nu\beta\beta$  signal  
Improve previous limits x 10**

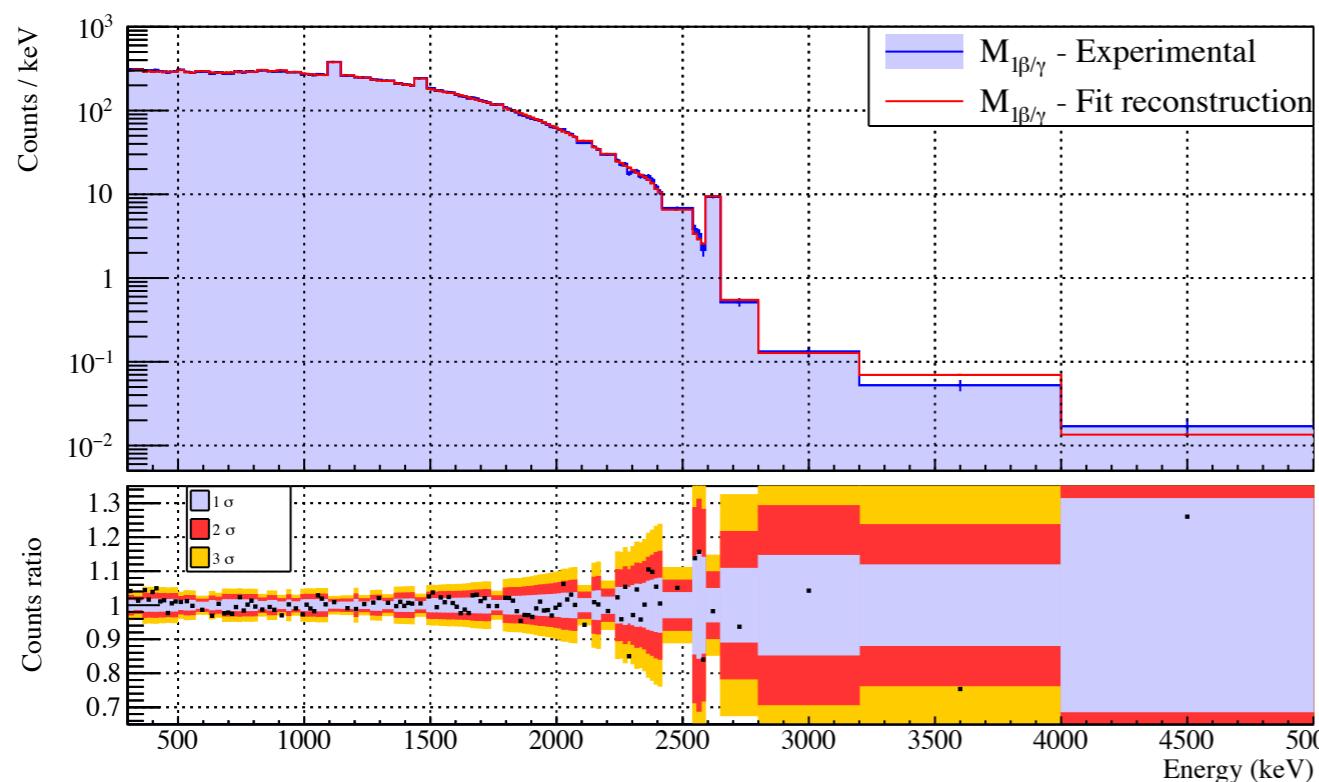
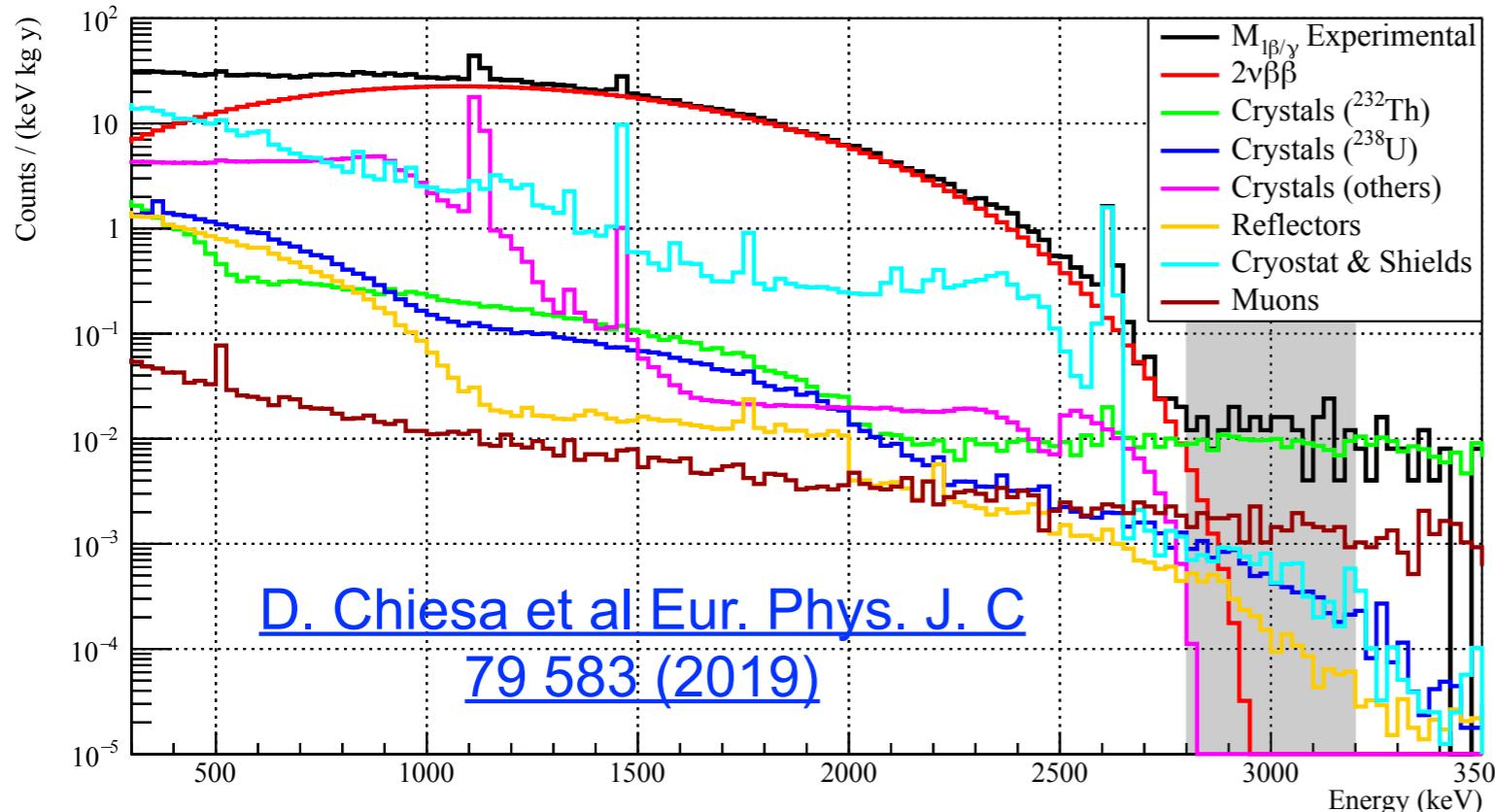


[N.Casali et al PRL 123 032501 \(2019\)](#)



$$T_{1/2}^{2\nu} = [8.60 \pm 0.03(\text{stat.}) \pm 0.17(\text{syst.})] \times 10^{19} \text{ yr}$$

# Background Model

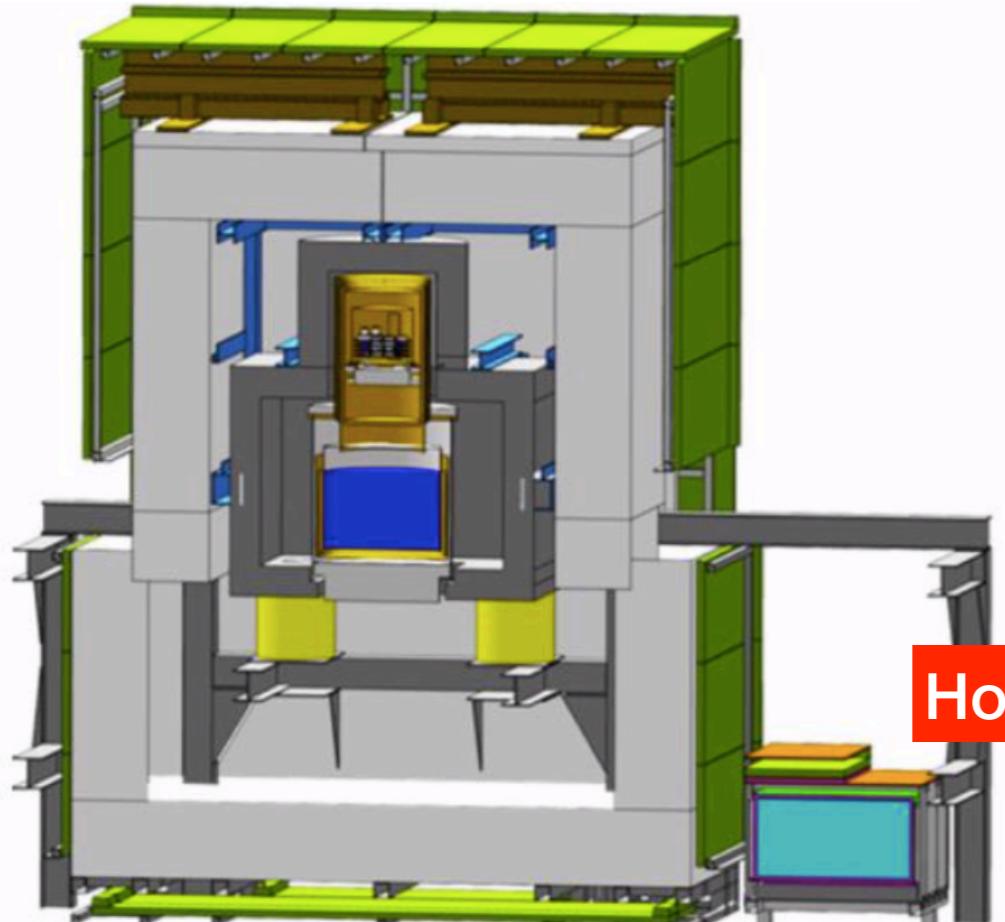
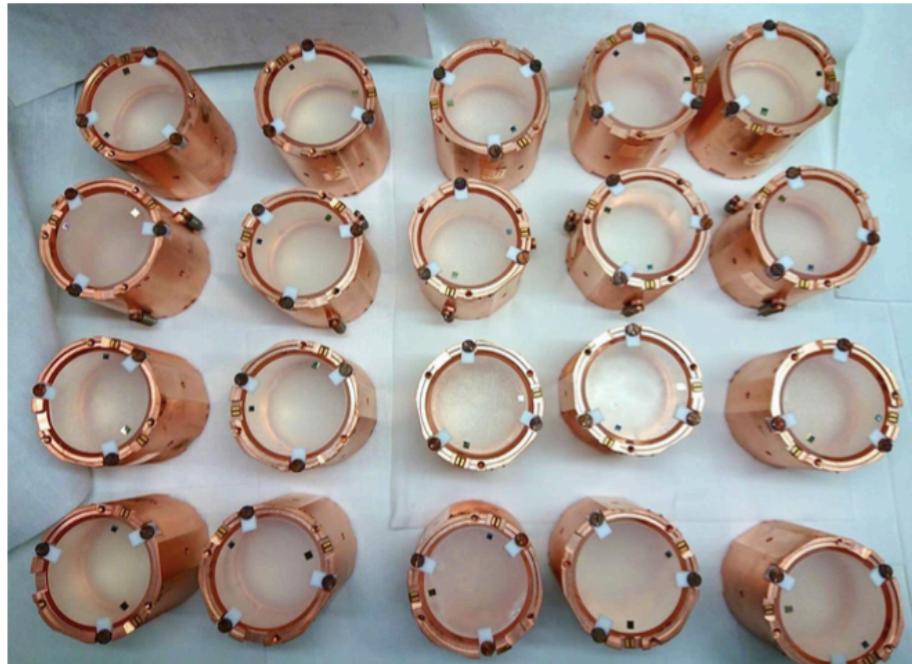


Full background reconstruction with a Bayesian fit  
Fit components: contaminations located across the cryostat + muons  
Each component is simulated with a detailed Geant4 MC simulation

$$\text{BKG} = 3.5 \times 10^{-3} \text{ counts/(keV kg yr)}$$

- ~44% muons
- ~33% contaminations ZnSe crystals
- ~17% cryostat
- ~6% reflecting foil and holders

# CUPID-Mo: the $\text{Li}_2\text{MoO}_4$ demonstrator

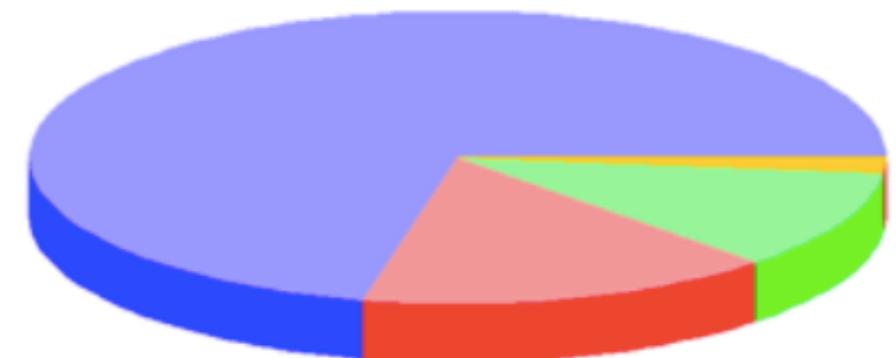
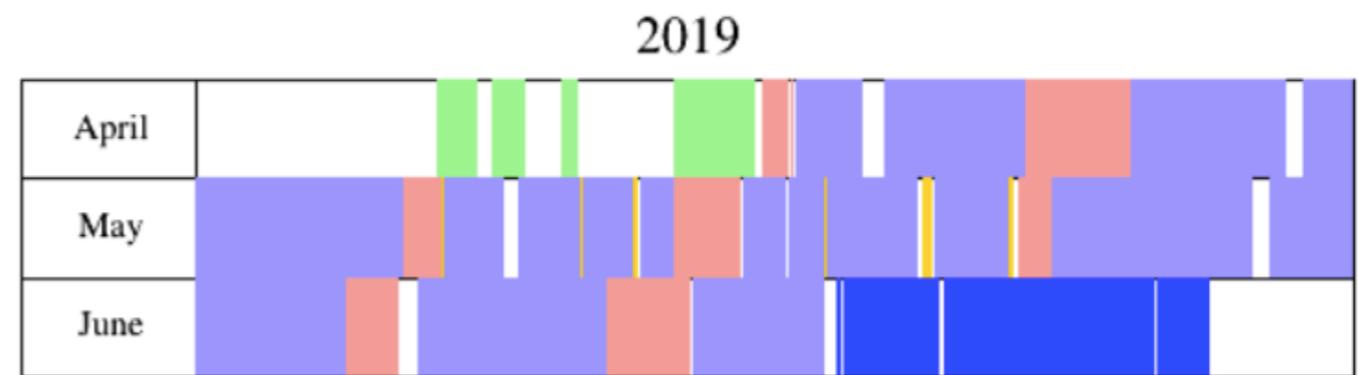
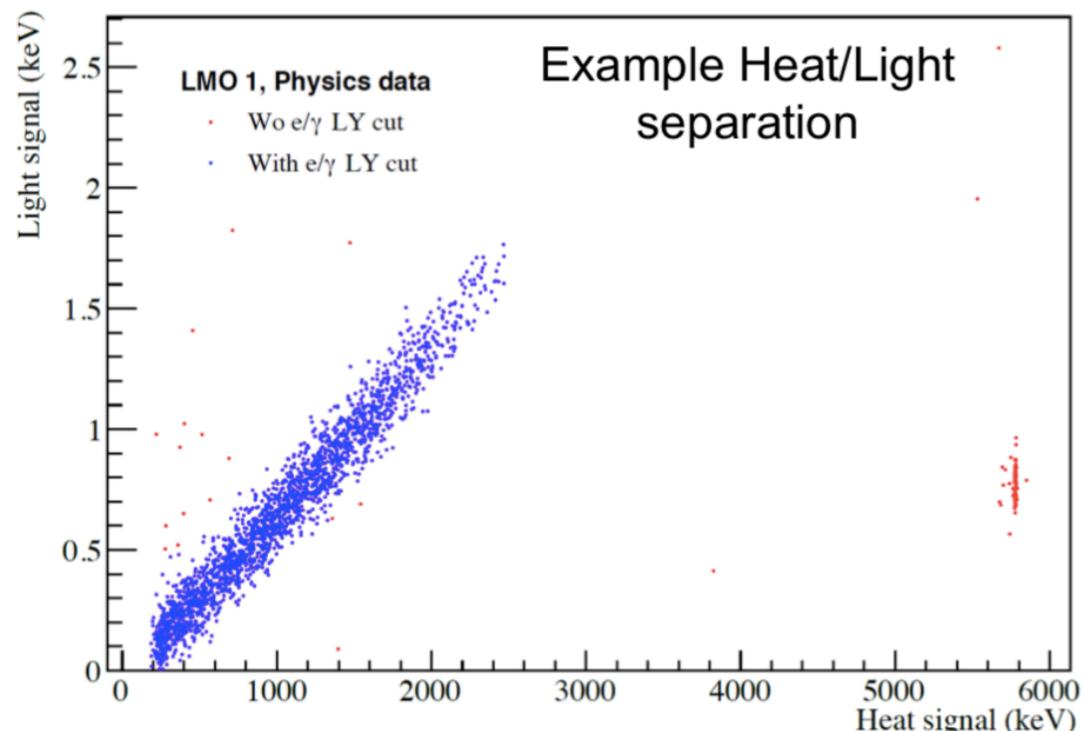


- Follow up of the LUMINEU experiment, operated at LSM by the EDELWEISS/CUPID-Mo collaborations
- 20 x ~210 g cylindrical  $\text{Li}_2\text{MoO}_4$  crystals enriched to ~97% in  $^{100}\text{Mo}$ , dimensions:  $\varnothing 44 \text{ mm} \times 45 \text{ mm}$
- Ge wafer with SiO anti-reflective coating as light detector
- Ge-NTD (on both  $\text{Li}_2\text{MoO}_4$  and Ge light detector)
- 3M Vikuiti reflectors: LY ~0.7 keV/MeV (peaked at ~600 nm)

Hosted @ Modane Underground Laboratory (France)

# CUPID-Mo time-line

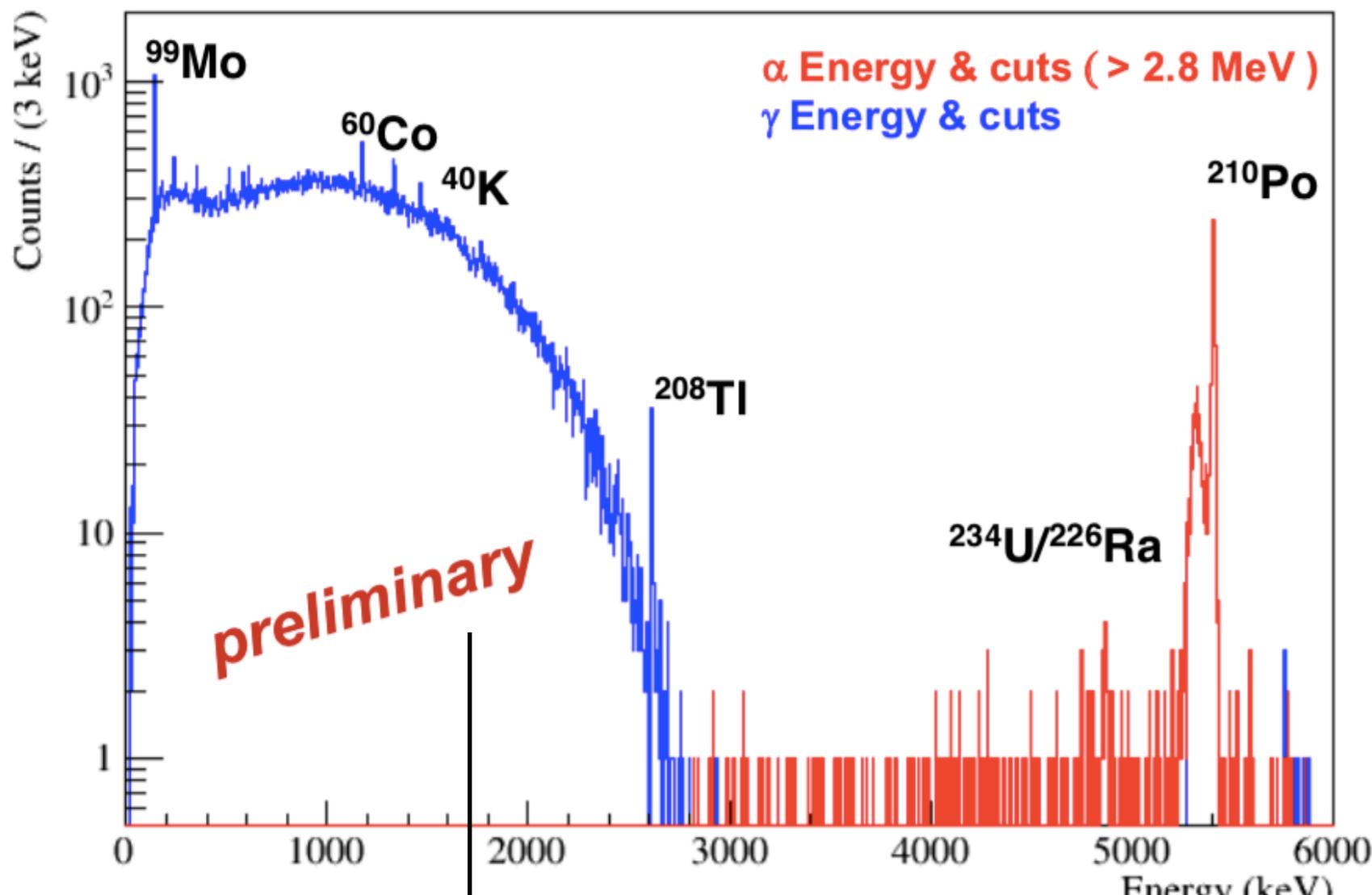
Commissioning phase proved good uniformity/performance  
—>suitable for larger arrays!



- Commissioning & setup March/April 2019  
(arXiv:1909.02994 )
- Physics data taking since April – June 2019



# Physics spectrum and FWHM



Exposure:  $0.5 \text{ kg} \cdot \text{y}$  (2 months)

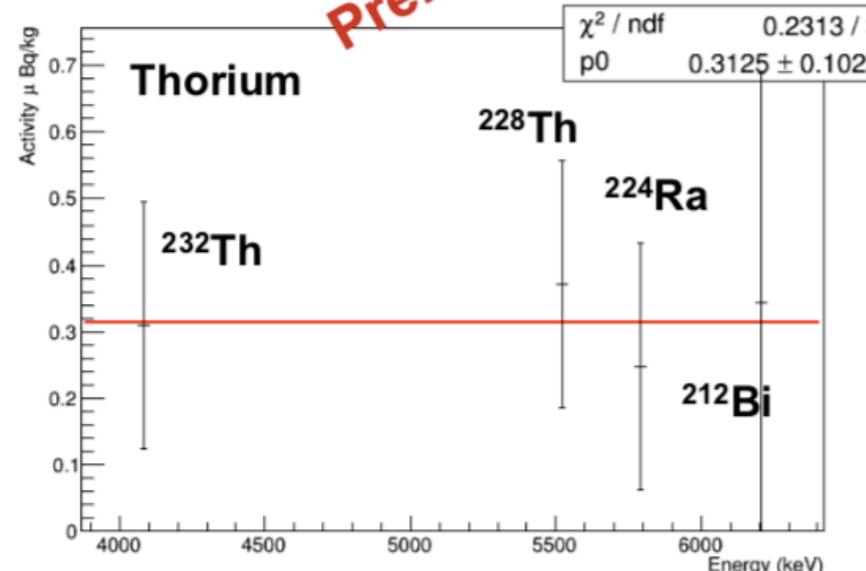
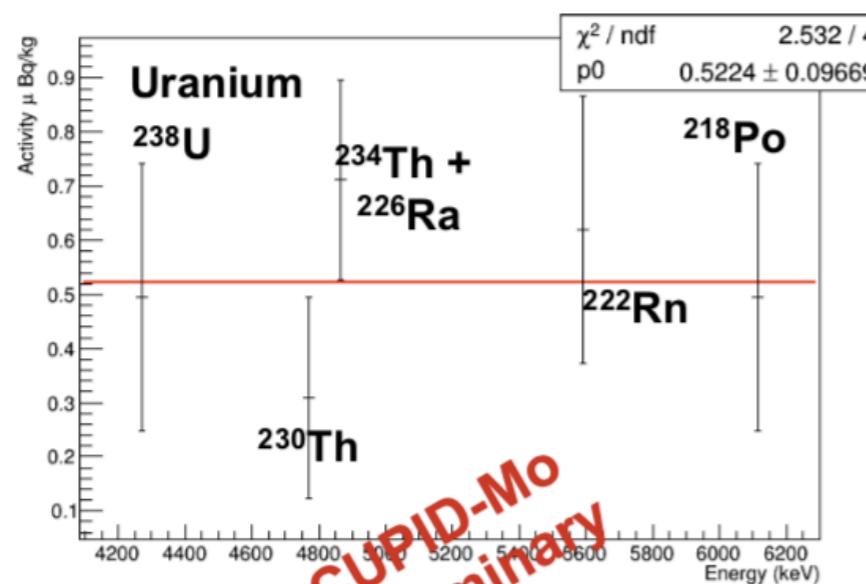
Rejection by Light Yield:  
Detector performance  
compatible with  $> 99.9\%$   
gaussian separation

Will be further studied from  
data with high statistics  
AmBe calibration

**ROI symmetric around  
 $Q_{\beta\beta} @ 3034 \text{ keV}$**

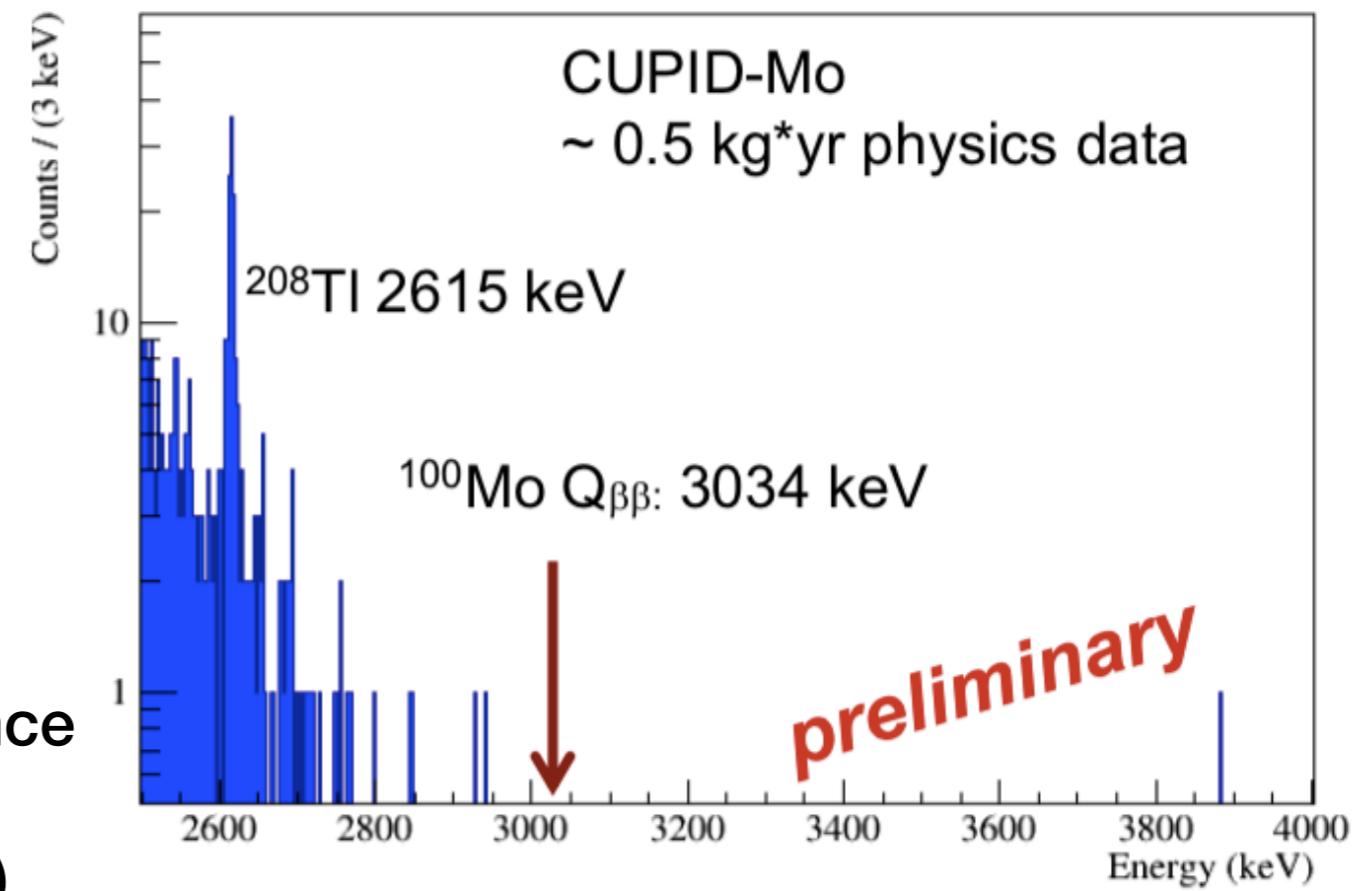
$$T_{1/2} = 6.90 \pm 0.15 \text{ (stat.)} \pm 0.37 \text{ (syst.)} \cdot 10^{18} \text{ yr} \quad \text{Eur. Phys. J. C (2017) 77: 785}$$

# Radiopurity of $\text{Li}_2^{100}\text{MoO}_4$



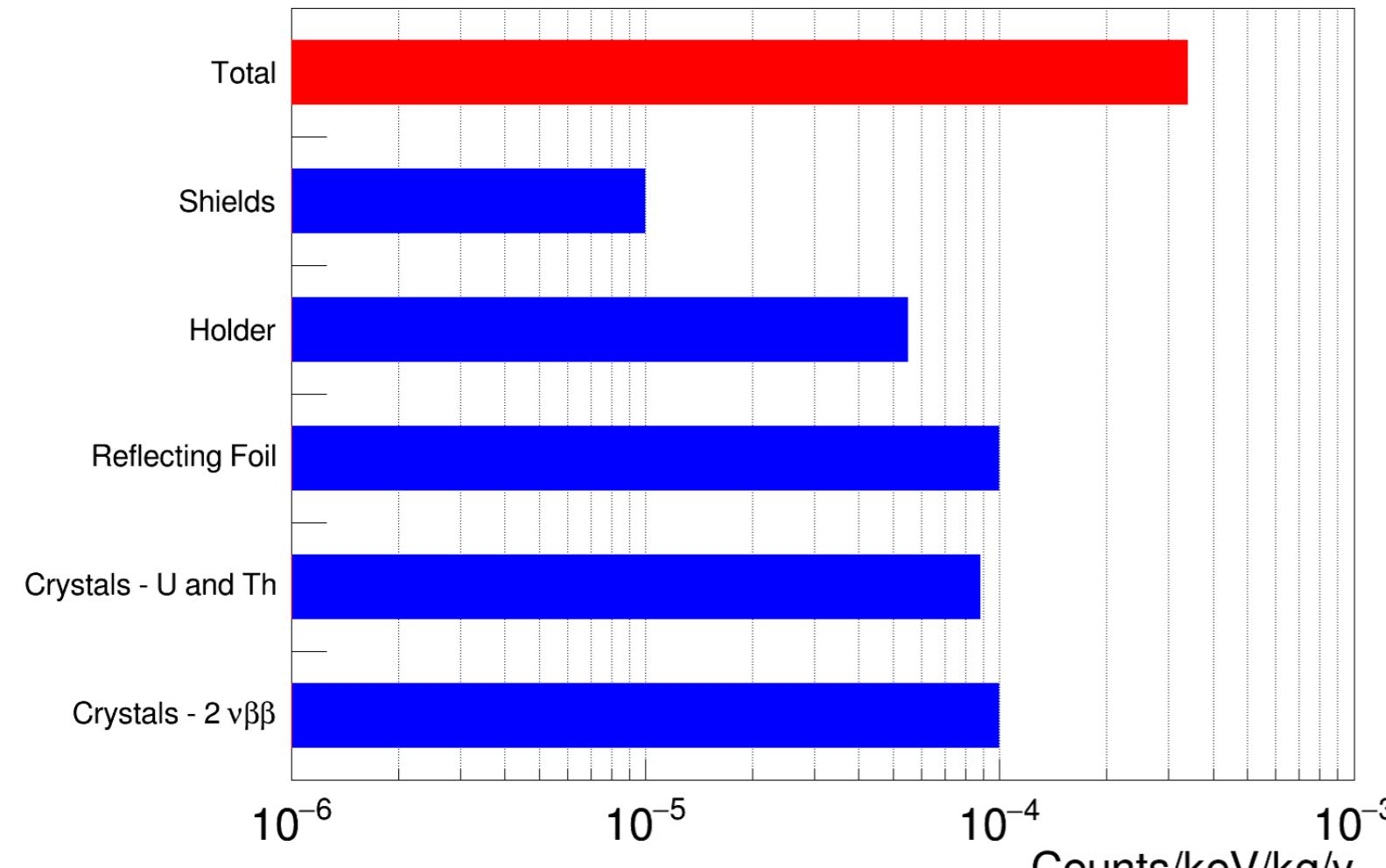
Contamination for both Thorium and Uranium series are  $\sim 10x$  better than assumed in CUPID CDR

**U:  $\sim 0.5 \text{ mBq/kg}$**   
**Th:  $\sim 0.3 \text{ mBq/kg}$**



Confirmed: Bolometric performance & reproducibility, exceeded expectations for radiopurity (bulk)

# CUPID background projection



## Crystals

- U/Th bulk (from CUPID-Mo)
- U/Th surface (CUORE bkg model)
- 2nbb pile-up  
( $t_{1/2} = 7.1 \cdot 10^{18}$  y  
crystal mass is a compromise)

## Holder

- U/Th surfaces (CUPID-0 bkg model)

## Cryogenic & Shielding Infrastructure

- U/Th bulk (CUORE bkg model)

## External (cosmogenic muons)

- VETO

**Ultraconservative: no improvement in signal timing (2nbb pile-up)  
no improvement in reflecting foil contribution (coating)**

# CUPID Sensitivity

CUPID CDR = ultraconservative approach → exactly what we have today

CUPID reach = improvement at reach before construction  
→ signal timing (from NTD performances to TES)  
→ surface radiopurity & crystal coating  
**zero bkg condition ~  $2 \cdot 10^{-5}$  c/keV/kg/y**

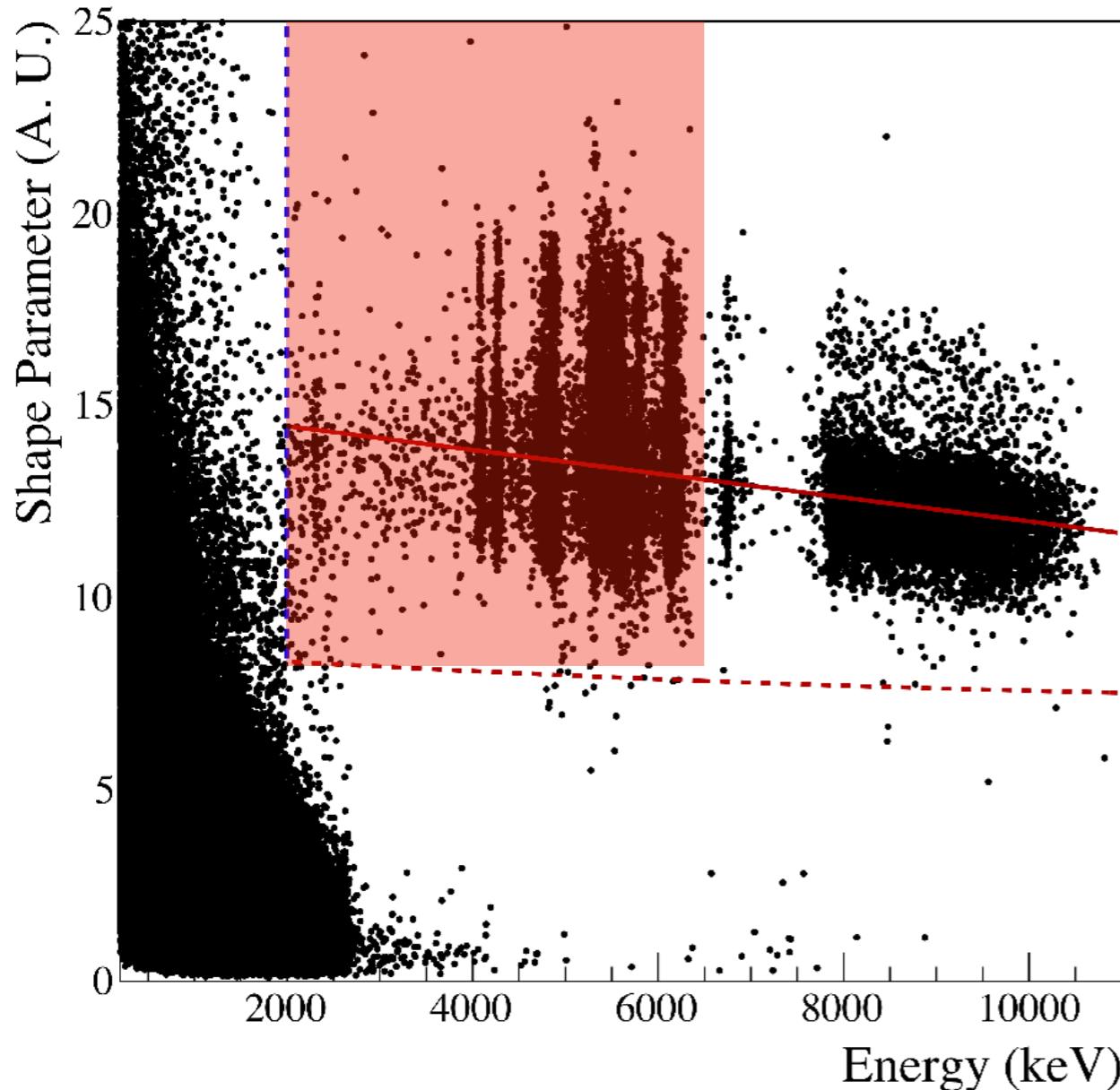
CUPID1-ton = new 4 times larger cryostat  
1 ton  $^{100}\text{Mo}$  and (in case of discovery) other isotopes  
**bkg ~  $5 \cdot 10^{-6}$  c/keV/kg/y**

THANKS for your attention!

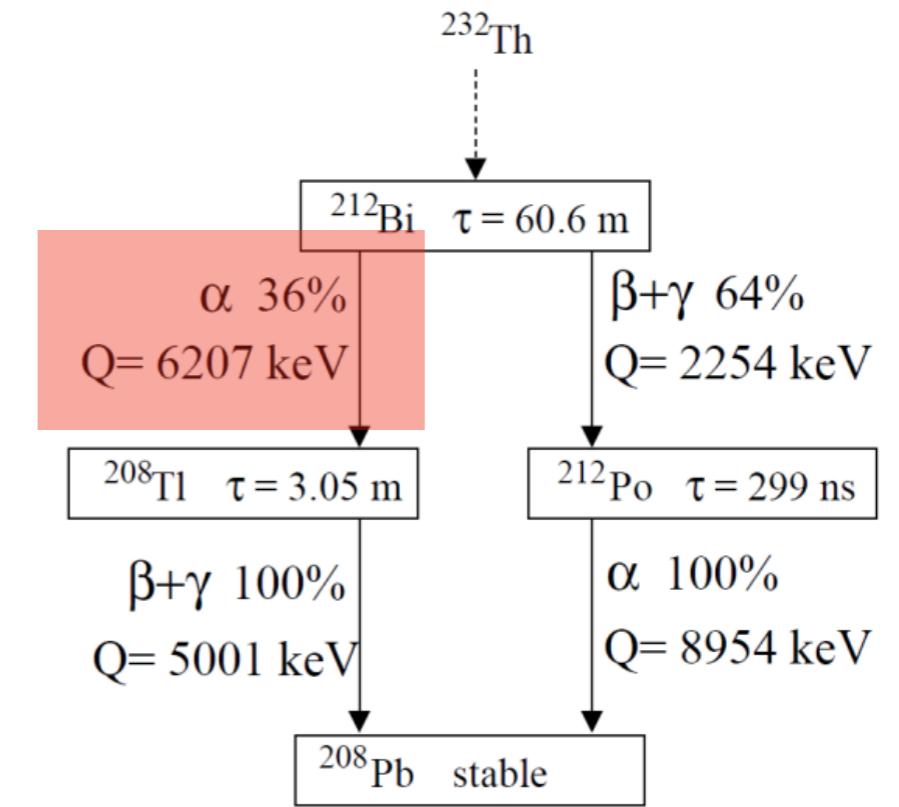
TDR and construction readiness for end 2021  
Schedule and budget will be driven by  $^{100}\text{Mo}$  enrichment ~4 years  
Modest cost, compared to the next-generation experiments with similar sensitivity.

# **Backup**

# $\beta/\gamma$ background from internal&surface contaminations



Tag

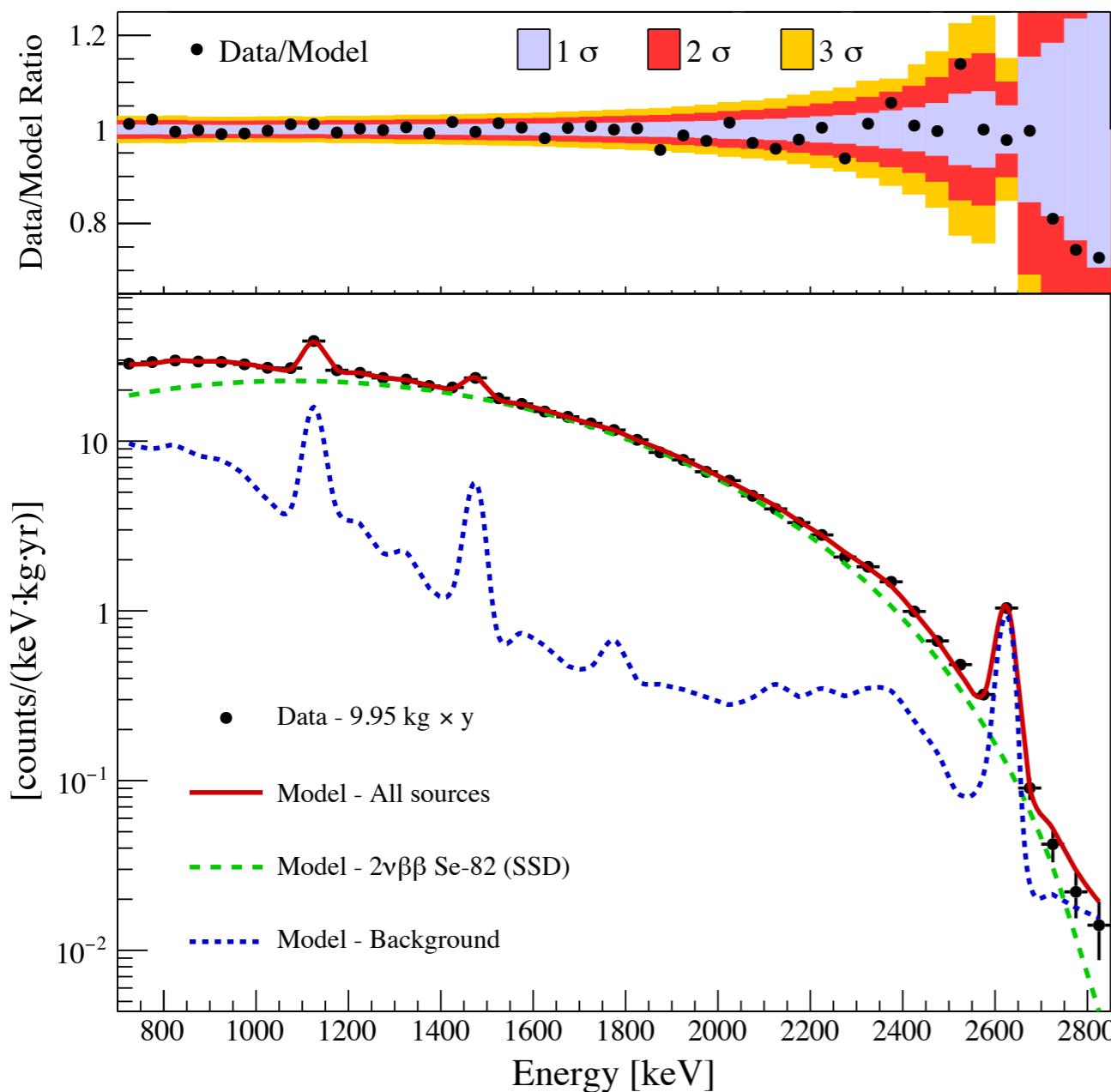


We apply a 7 half-life time veto after all  $^{212}\text{Bi}$   $\alpha$  events

Rejection of  $^{208}\text{Tl}$  induced background (internal and surface crystal contamination)

# $^{82}\text{Se}$ $2\nu\beta\beta$ half-life

[L. Pagnanini et al, arXiv 1909.03397](#)



	Systematic Source	$\Delta A_{2\nu}$
<b>Fit</b>	Source localization	$+0.36 \%$ $-0.21 \%$
	Reduced sources list	$-0.10 \%$
	$^{90}\text{Sr}/^{90}\text{Y}$	$-1.57 \%$
	Fixed step binning	$+0.16 \%$
	Threshold of $\mathcal{M}_1$	$+0.15 \%$
	$\alpha$ -identification	$-0.01 \%$
	Energy scale	$-0.39 \%$
<b>Detector</b>	Prior distributions	$+0.04 \%$
	Combined	$+0.4 \%$ $-1.6 \%$
<b>Total</b>	Efficiency	$\pm 0.5 \%$
	$^{82}\text{Se}$ atoms	$\pm 1.0 \%$

$$T_{1/2}^{2\nu} = [8.60 \pm 0.03(\text{stat.}) \quad {}^{+0.17}_{-0.10}(\text{syst.})] \times 10^{19} \text{ yr}$$