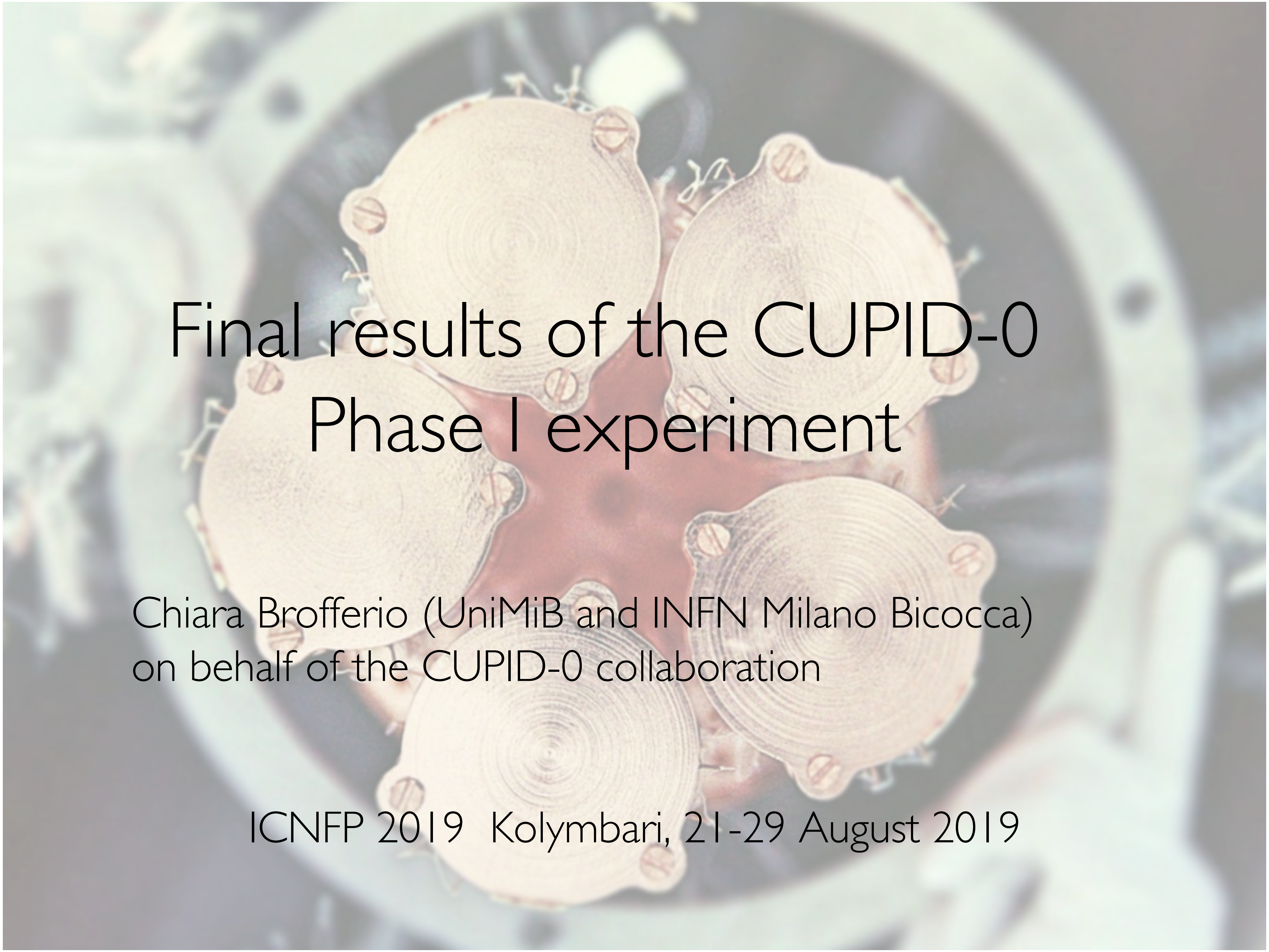


Final results of the CUPID-0 Phase I experiment

Chiara Brofferio (UniMiB and INFN Milano Bicocca)
on behalf of the CUPID-0 collaboration

ICNFP 2019 Kolymbari, 21-29 August 2019

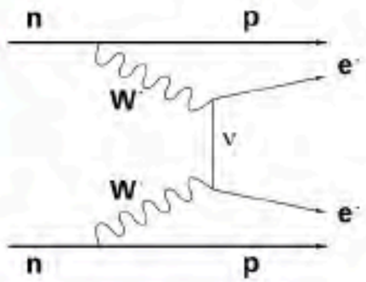
Experimental search for 0νββ

WHAT WE ARE LOOKING FOR

2νββ: $(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$

- allowed in the SM and already observed with $T_{1/2} > 10^{18}$ y

0νββ: $(A,Z) \rightarrow (A,Z+2) + 2e^{-}$



- not allowed in the SM
- expected with $T_{1/2} > 10^{25}$ y

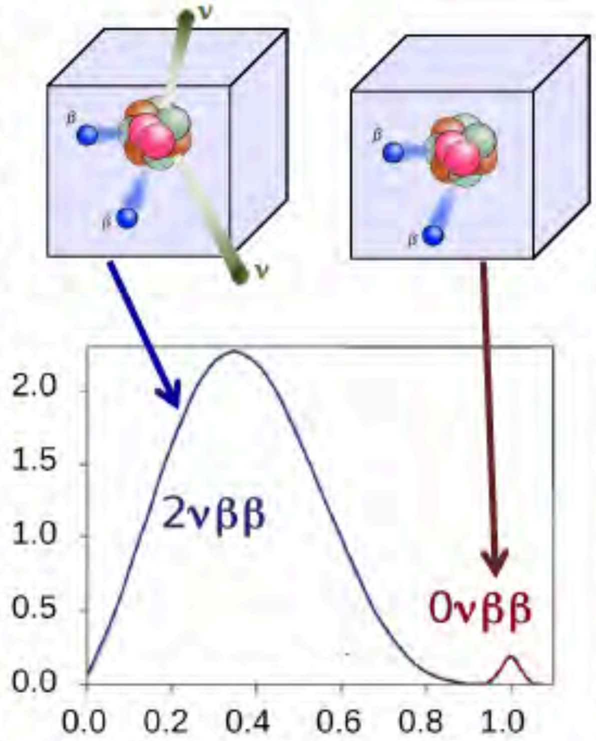
If observed:

- lepton number violation
- neutrinos are Majorana particles
- measures effective electron neutrino mass

$$m_{\beta\beta} \equiv |e^{i\alpha_1}|U_{ei}^2|m_1 + e^{i\alpha_2}|U_{e2}^2|m_2 + |U_{e3}^2|m_3|$$

EXPERIMENTAL SIGNATURE

Approach:
SOURCE = DETECTOR



Main signature:
Peak at Q-value over 2νββ tail enlarged only by detector resolution

EXPERIMENTAL SENSITIVITY

Lifetime corresponding to the minimum detectable number of events over background at a given C.L.:

$$S^{0\nu} \propto \epsilon\, i.a. \sqrt{\frac{MT}{b\Delta E}} \qquad b \neq 0$$

$$S^{0\nu} \propto \epsilon\, i.a. MT \qquad b = 0$$

M: Total active mass in kg

ϵ: Detector efficiency

$i.a.$: Isotopic abundance

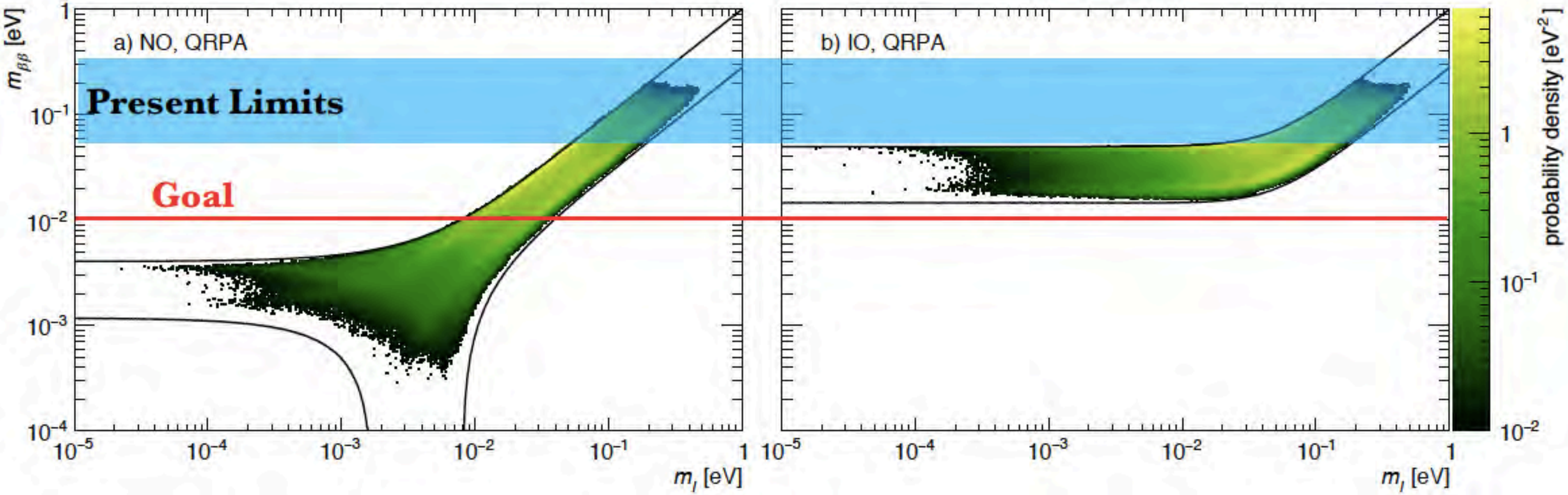
b: Background in c/keV/kg/y

ΔE: Detector resolution @ ROI in keV

T: Exposure time in y

Experimental search for 0νββ: Motivations

Next generation experiments will explore the whole **Inverted Hierarchy** and the most favored region of the **Normal one**.



Two are the fundamental ingredients to reach the required sensitivity:

- Background reduction (<10^{-4} counts/keV kg y)
- ββ emitter increase

Scintillating Thermal Detectors

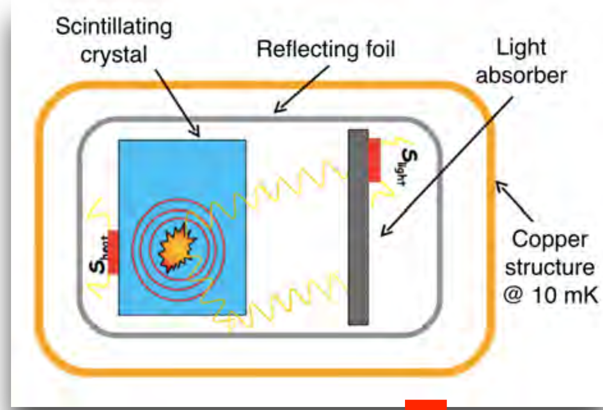
A Thermal Detector is a highly sensitive **calorimeter** operated @ cryogenic temperature (~10 mK).

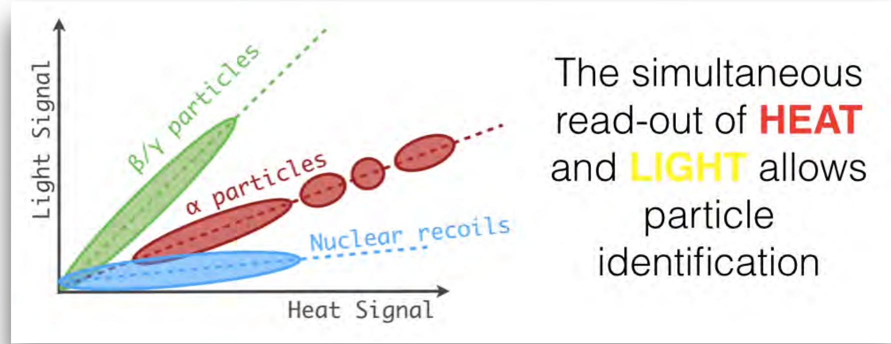
Energy depositions are measured as **temperature** variations of the absorber.

TDs features:

- high energy resolution O(1/1000)
- wide choice of compound TeO_2, Li_2MoO_4, ZnSe
- high detection efficiency (source = detector)
- scalable to large masses

If the absorber is also an **efficient scintillator** the energy is converted into **heat + light**





A background-free experiment is possible:

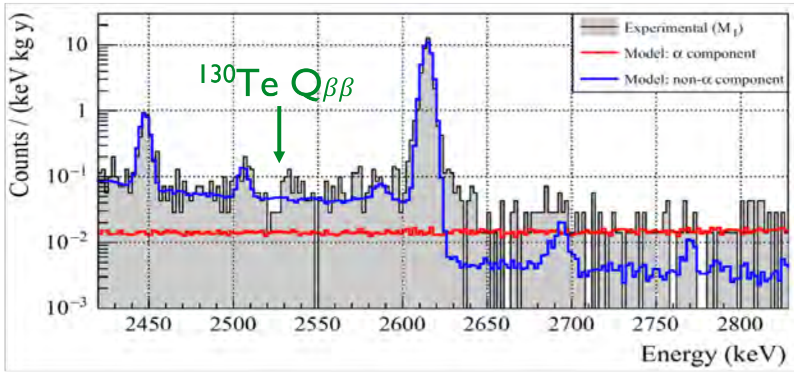
α-background: identification and rejection

β-background: ββ isotope with large Q-value

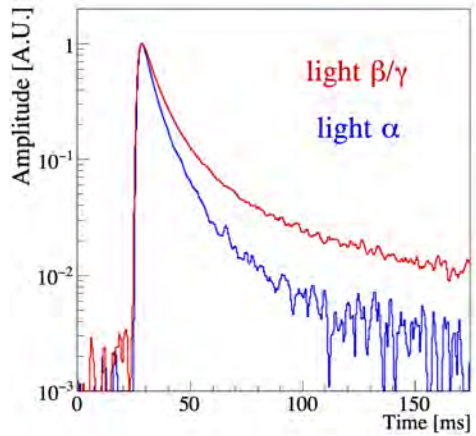
CUPID-0 strategy

Since bolometers are fully active detectors, they show a large background component due to energy degraded α particles

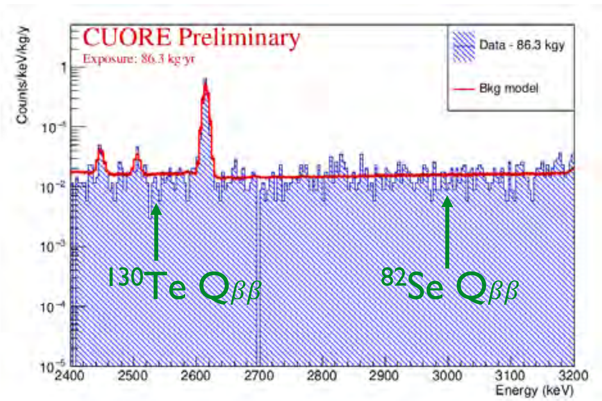
In CUORE-0 the degraded α background was a minor contribution at ^{130}Te $Q_{\beta\beta}$ (2527.5 keV)



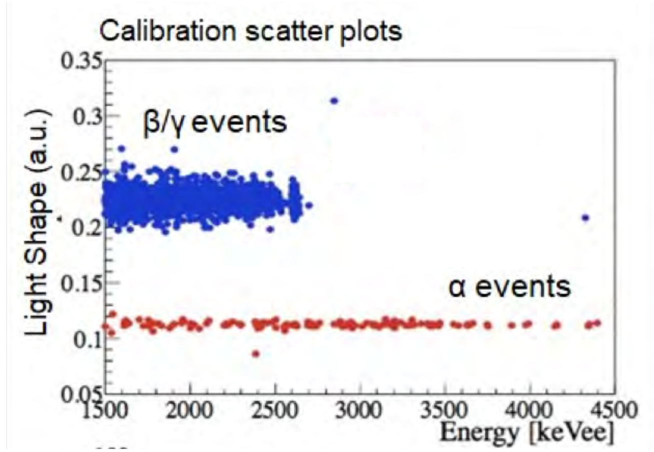
CUPID-0 use a higher $Q_{\beta\beta}$ isotope and rejects α signals using the scintillation LIGHT



In CUORE it dominates over the 2615 keV (^{208}Tl) multi-Compton: it's the major component in the ROI



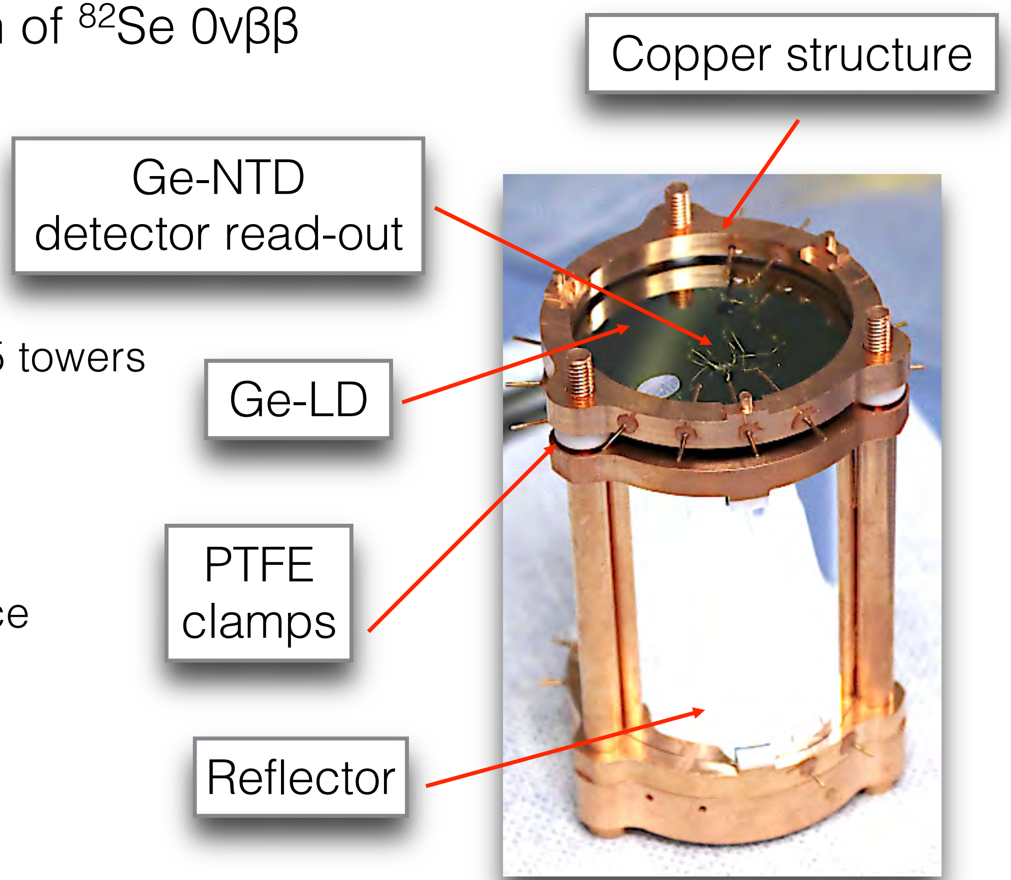
Excellent discrimination can be obtained based on the shape of the light pulse



CUPID-0 (**C**UORE **U**pgrade with **P**article **ID** prototype)

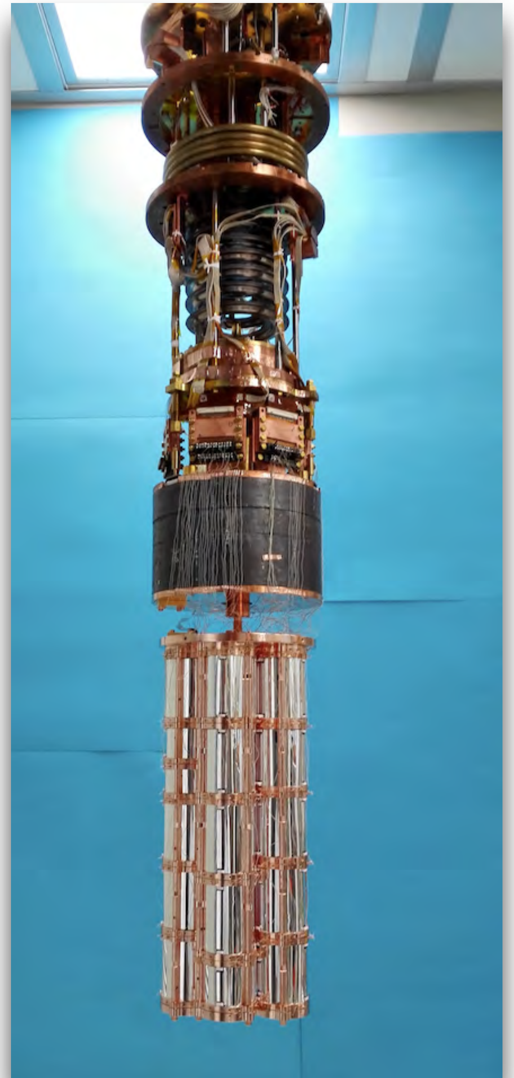
CUPID-0 is the first array of scintillating bolometers
for the investigation of ^{82}Se 0νββ

- ^{82}Se Q-value 2998 keV (above ^{208}Tl line)
- 95% enriched Zn^{82}Se bolometers
- 26 bolometers (24 enr + 2 nat) arranged in 5 towers
  - 10.5 kg of ZnSe
  - 5.17 kg of ^{82}Se —> 3.8x10^{25} ββ nuclei
- LD: Ge slab operated as bolometer. One face coated with 60 nm SiO_2 —> Light collection enhancement ~50%
- Simplest modular detector -> scale up
  - Copper structure (ElectroToughPitch)
  - PTFE clamps
  - Reflecting foil (VIKUITI 3M)



Main goal :
Minimize mass of passive materials next to the detector

CUPID-0 installation



Detector installed in the former CUORE-0 cryostat with major upgrades:

- Rn-abatement system next to the cryostat
  - Reduction and Control of ^{214}Bi
- Double stage pendulum for low vibrational noise
  - LD performance
- Cryostat wiring: can host up to 120 detectors

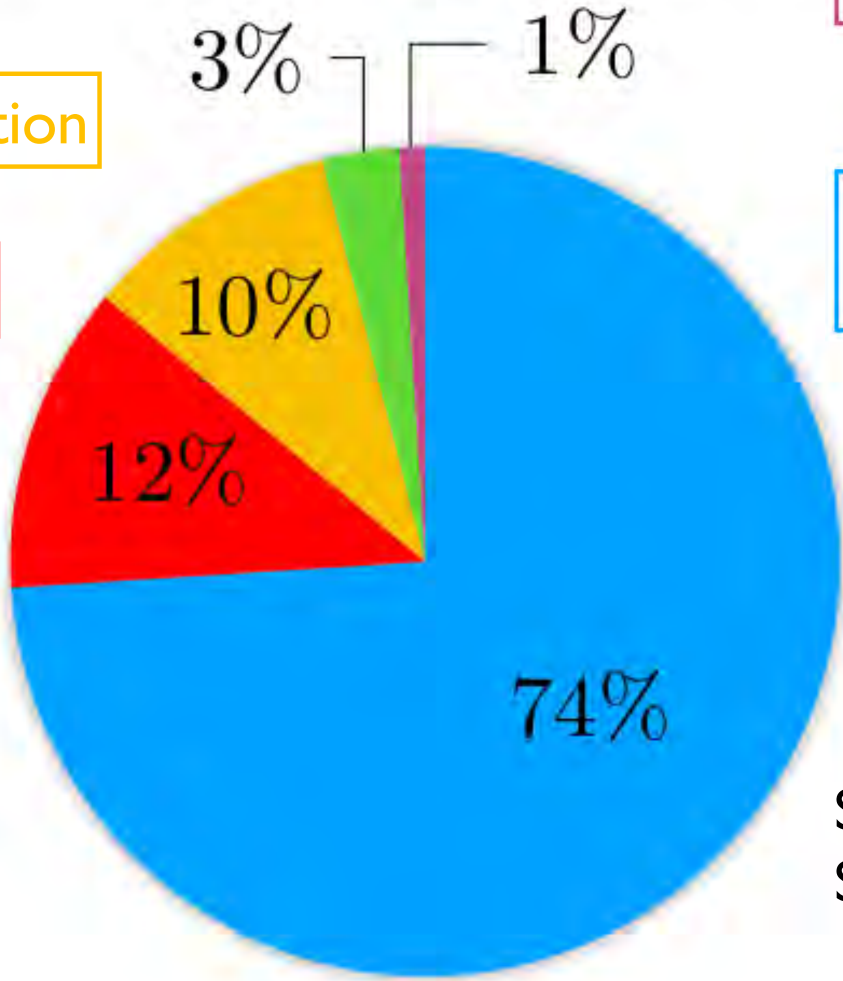
☞ Eur. Phys. J. C (2018) 78:428 (Detector Paper)

CUPID-0 Phase-I total live-time

^{56}Co Energy Calibration

^{232}Th Energy Calibration

System maintenance



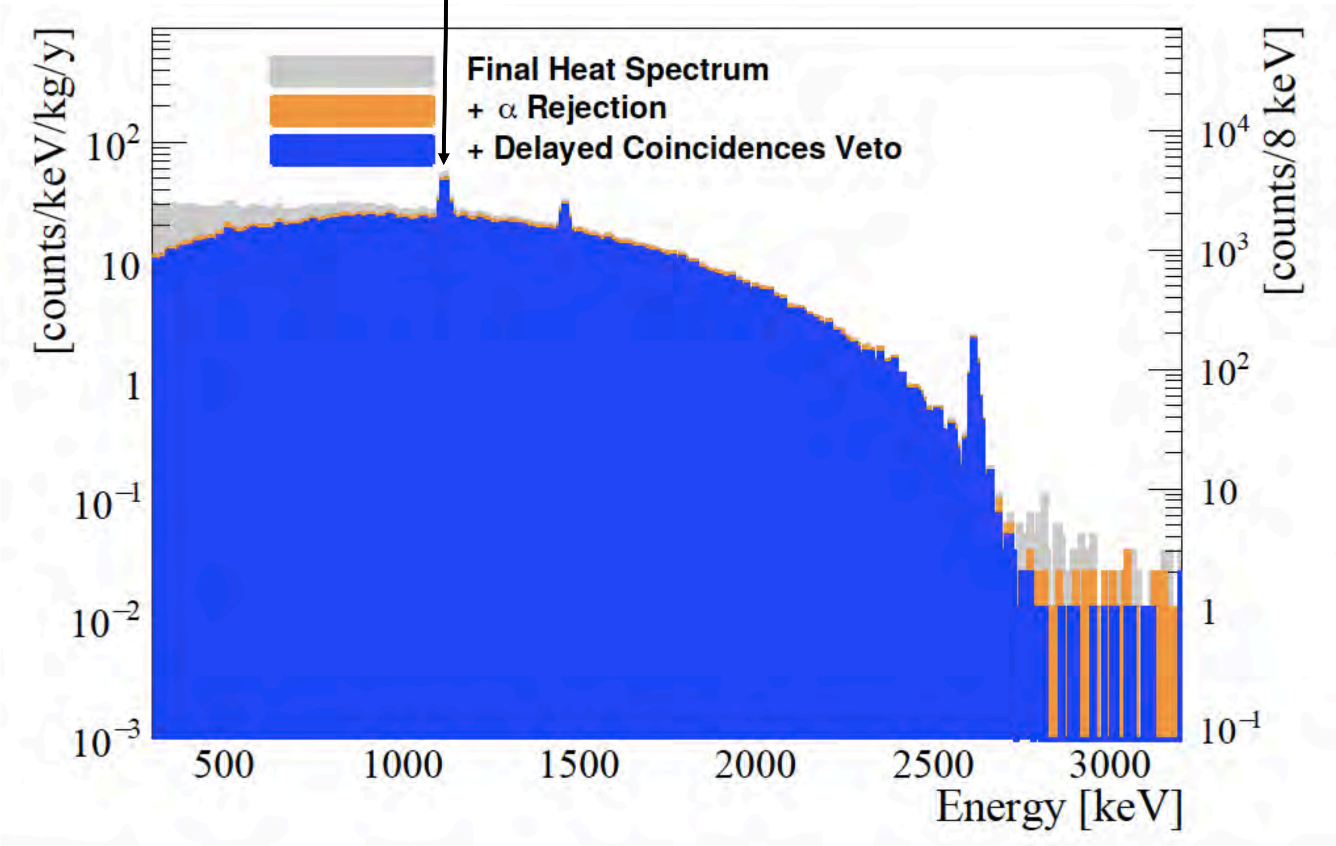
AmBe source
$\beta\gamma$ Shape Characterization in the ROI

$\beta\beta$ physics
Exposure: 9.95 kg·y

Start: March 2017
Stop: December 2018

CUPID-0 Phase I full spectrum - 5.29 ^{82}Se kg y exposure

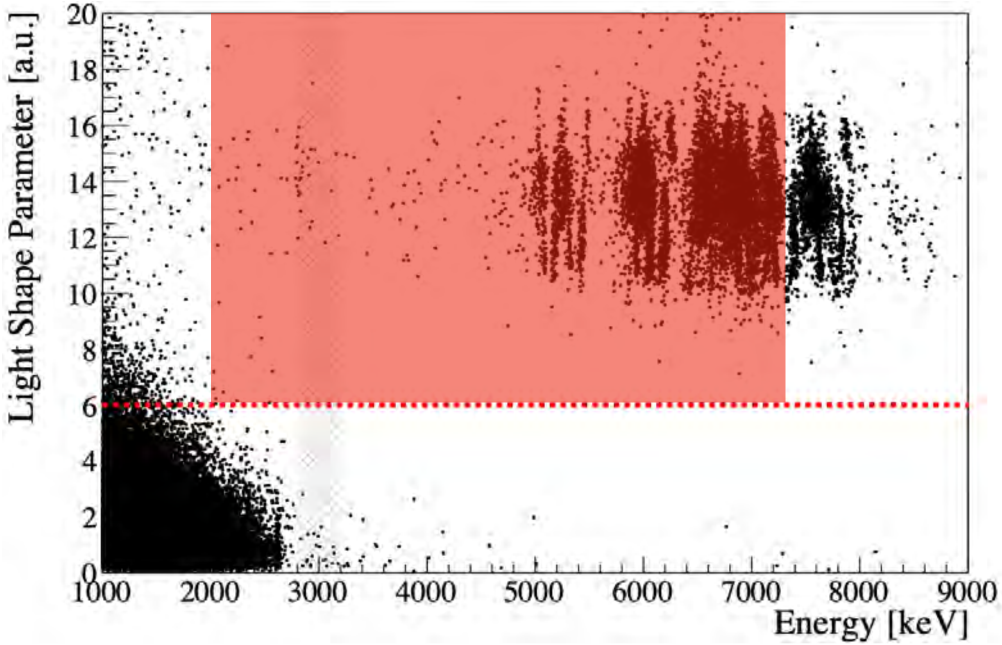
^{65}Zn: Cosmogenic activation



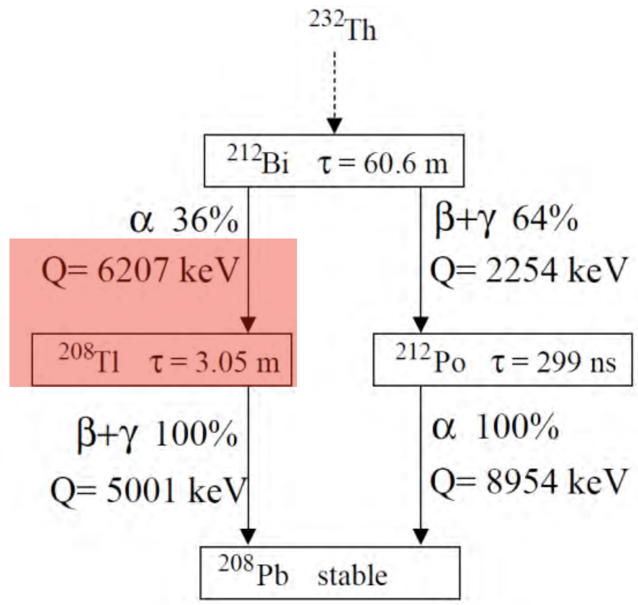
- Rejection of "non-particle-like" events through pulse shape on thermal pulses. Reduces exposure by 7%
- Anti-coincidence between ZnSe crystals
- α rejection by light shape
- Delayed coincidences veto

☞ Eur. Phys. J. C (2018) 78:734 (Analysis technique)

β/γ background: ^{232}Th internal and surface contaminations



Tag

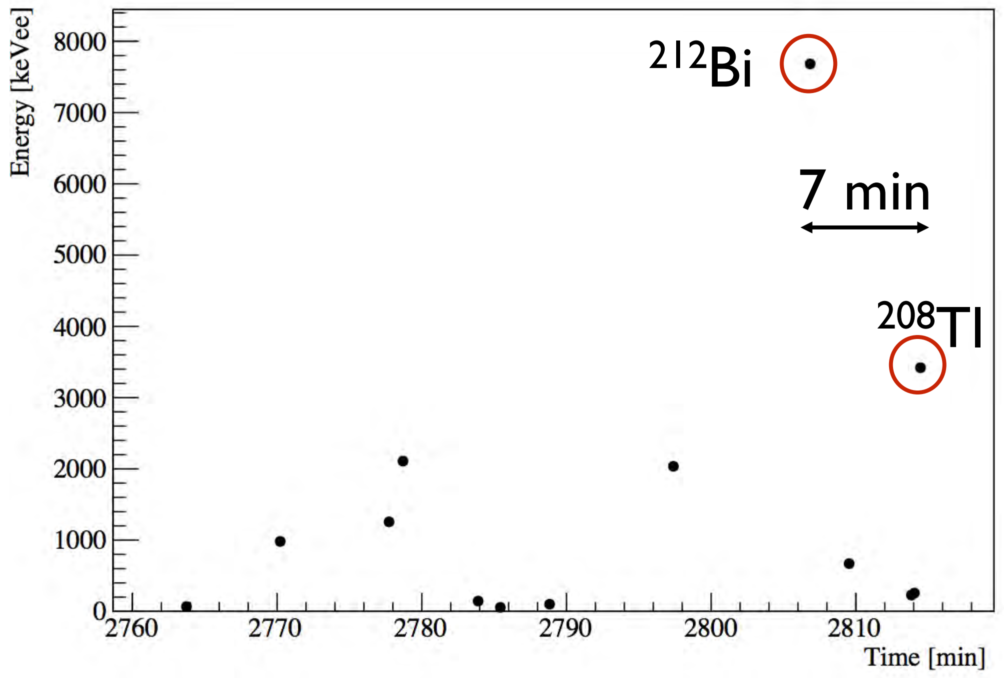


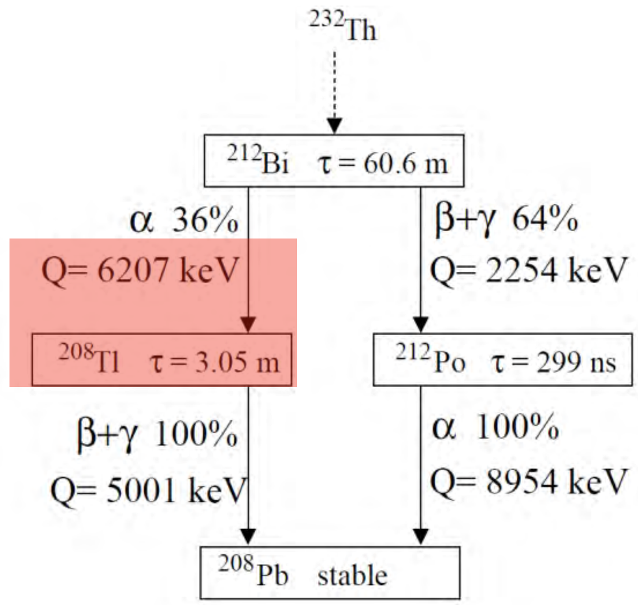
We apply a 3 half-life time veto after all ^{212}Bi α events

Rejection of the ^{208}Tl induced background (**internal** crystal contamination)

Surface crystal contamination -> we veto after all α interactions with energy between 2 and 6.5 MeV

β/γ background: ^{232}Th internal and surface contaminations





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Rejection of the ^{208}Tl induced background (**internal** crystal contamination)

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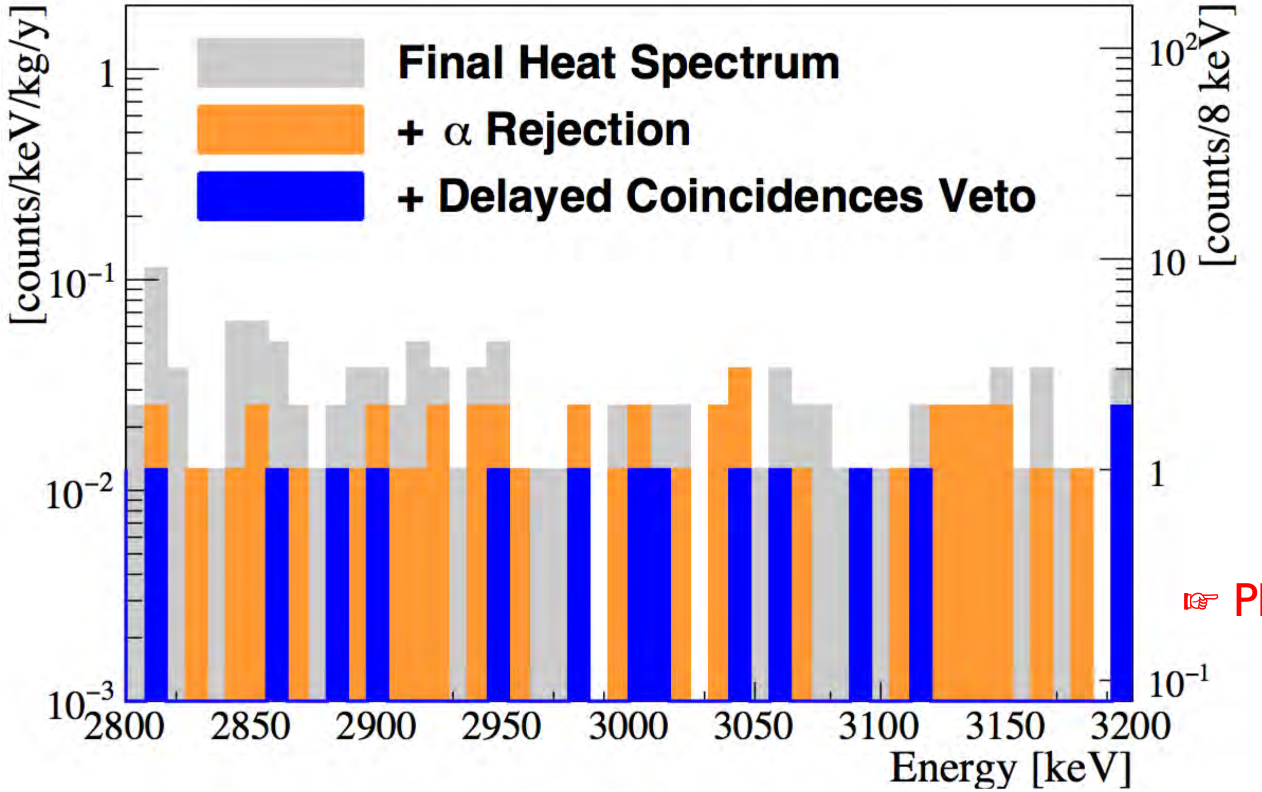
CUPID-0 Phase I limit with 9.95 ($Zn^{82}Se$) kg y exposure



3.2×10^{-2} counts/(keV kg y)

1.3×10^{-2} counts/(keV kg y)

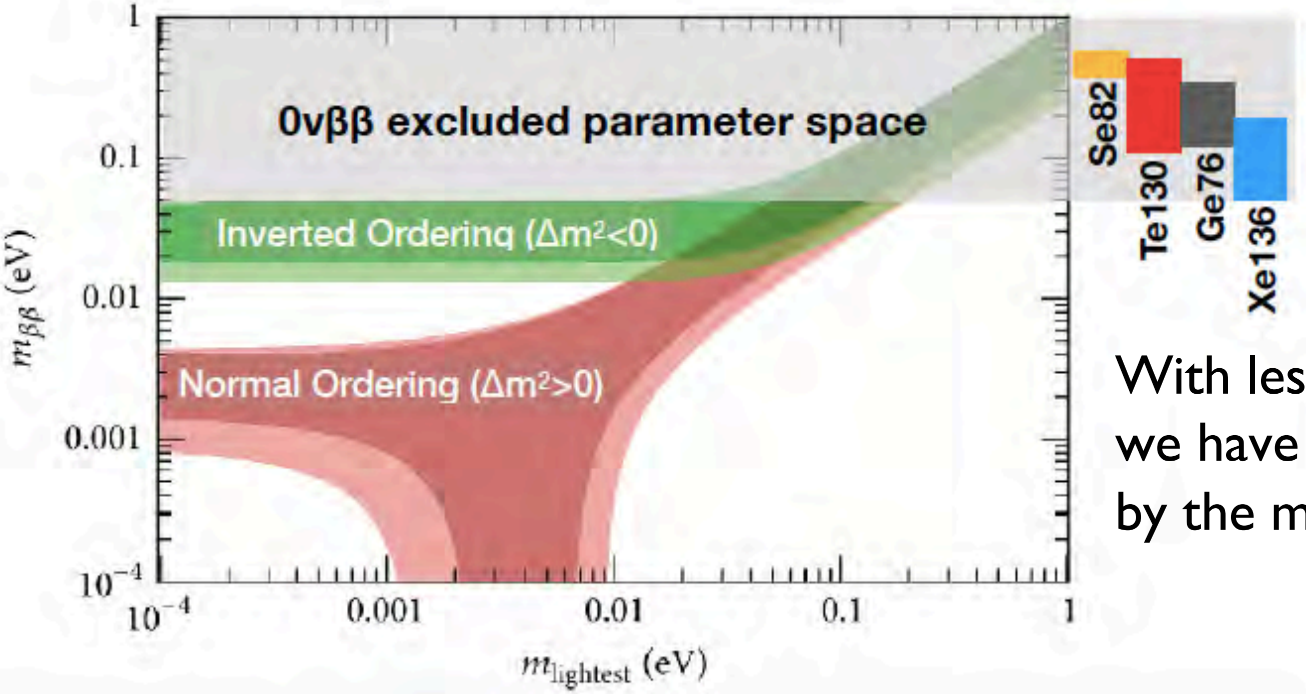
3.5×10^{-3} counts/(keV kg y)

Lowest background measured for cryogenic calorimeters

☞ Phys.Rev.Lett. 123 (2019) no.3, 032501

Exposure	5.29 ^{82}Se kg y
Background	$3.5^{+1.0}_{-0.9}$ counts/keV/ton/y ($Zn^{82}Se$)
Lower limit, half-life:	$T_{1/2}(0\nu) \geq 3.5 \times 10^{24}$ y (90% C.L.)
Eff. (trigger + data sel. + ββ containment)	70 ± 1 %

CUPID-0 Phase I limit with 9.95 ($Zn^{82}Se$) kg y exposure



With less than 10 kg y det. exposure we have entered the region studied by the major experiments

Best half-life limit on ^{82}Se:
$T^{0\nu} > 3.5 * 10^{24}$ yr (90%C.I.)

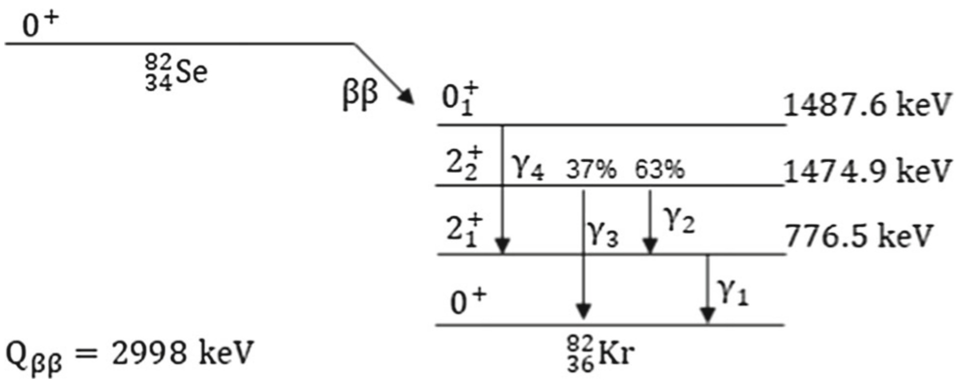
Corresponding to a neutrino mass limit

$$m_{\beta\beta} < 311 - 638\ meV^{*}$$

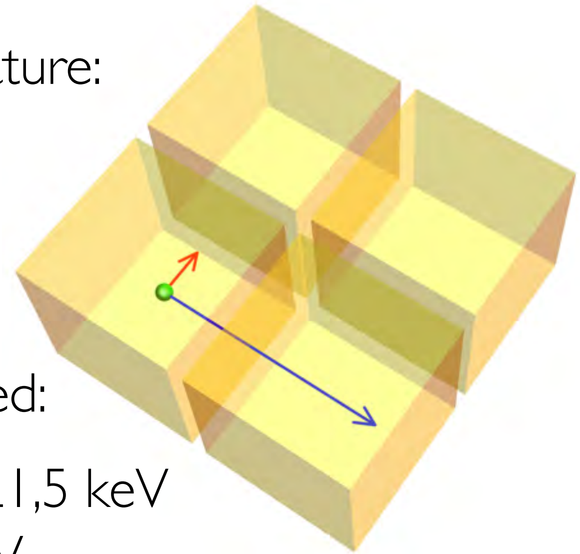
* depending on the Nuclear Matrix element adopted

Other analyses: CUPID-0 0ν$\beta\beta$ into the excited states of ^{82}Kr

Alternative models would benefit from the study of the decay into exc. states



Example of Signature:



2 crystals involved:

$\beta\beta + \gamma_2$ =2221,5 keV
γ_1 = 776,5 keV

CUPID- 0 meas. of 0νββ on exc. states

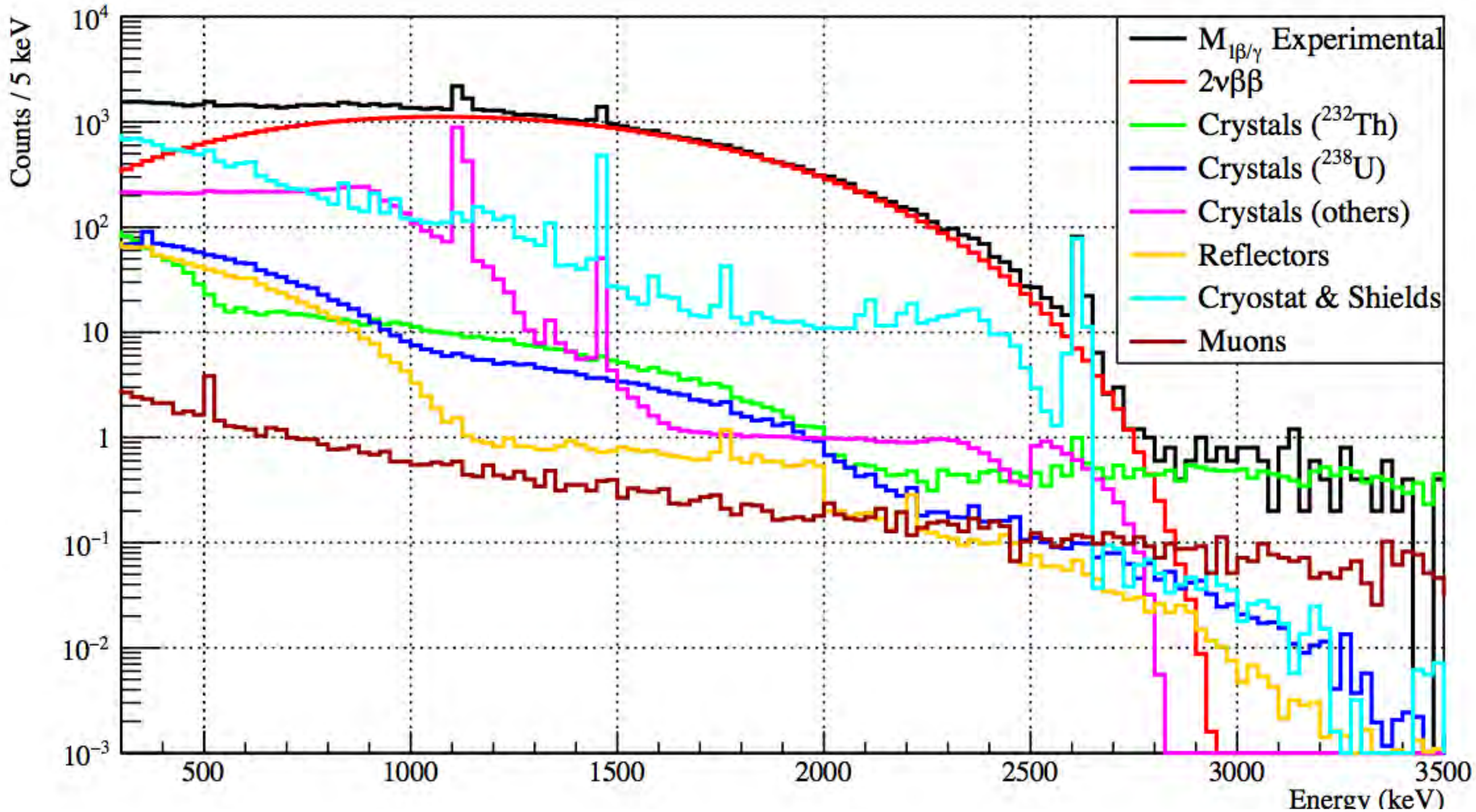
☞ Eur. Phys. J. C (2018) 78:888

$$T_{1/2}^{\beta\beta}(^{82}\text{Se} \rightarrow ^{82}\text{Kr}_{0_1^+}) > 8.11 \times 10^{22}\ \text{y}$$
$$T_{1/2}^{\beta\beta}(^{82}\text{Se} \rightarrow ^{82}\text{Kr}_{2_1^+}) > 1.11 \times 10^{23}\ \text{y}$$
$$T_{1/2}^{\beta\beta}(^{82}\text{Se} \rightarrow ^{82}\text{Kr}_{2_2^+}) > 8.40 \times 10^{22}\ \text{y}$$

Soon also 2νββ on exited states from CUPID-0

Other analyses: CUPID-0 2v$\beta\beta$

Evaluation of the 2v$\beta\beta$ half-life from the analysis of the different bkg sources



☞ **Eur.Phys.J. C 79 (2019) 7:583 (Background Model)**

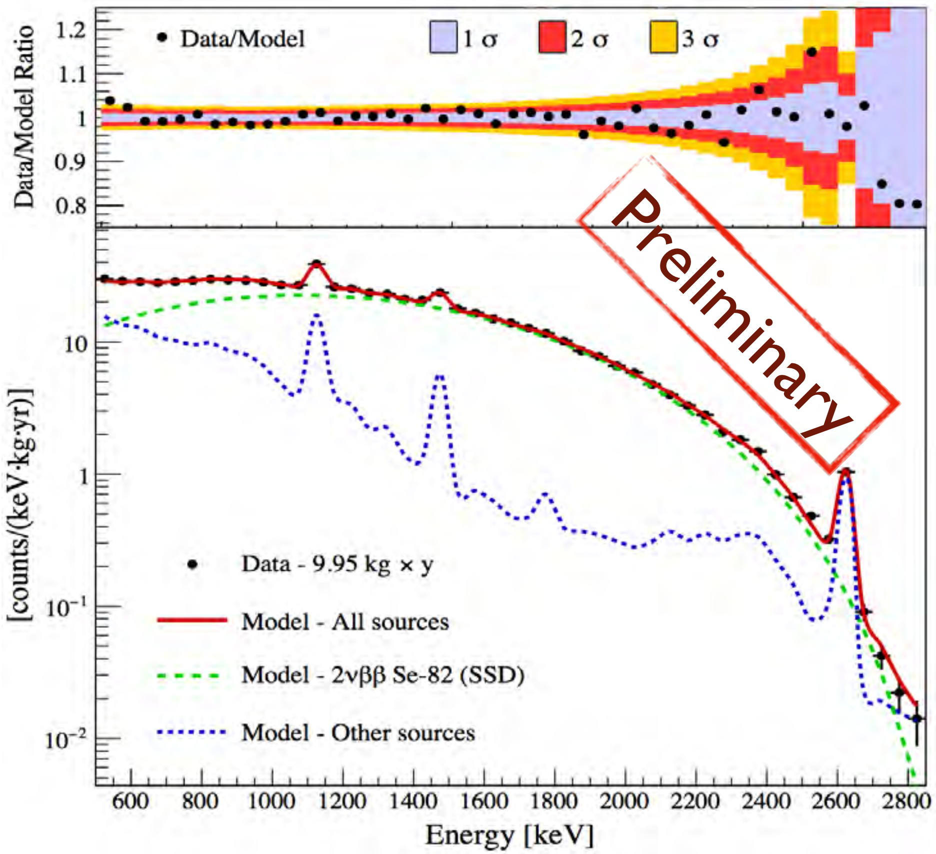
Other analyses: CUPID-0 $2\nu\beta\beta$

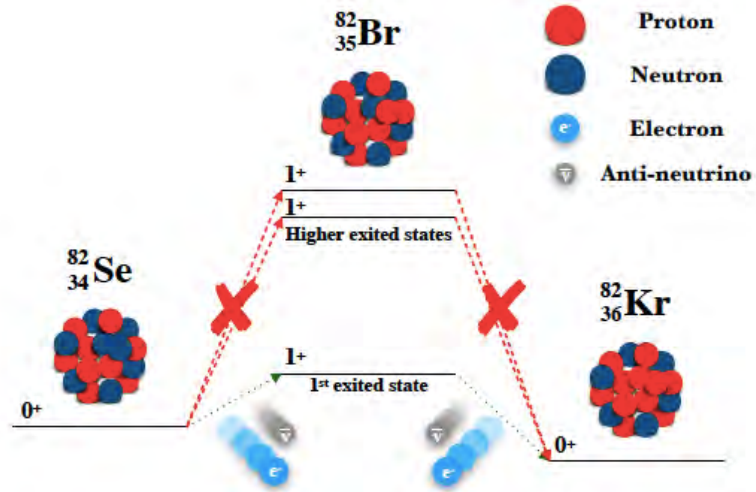
Evidence of Single State Dominance through $2\nu\beta\beta$ energy spectrum

Spectra from nucleartheory.yale.edu and Jenni Kotila

SSD: $\chi^2/ndf = 253/233 = \mathbf{1.1}$ (p-value =0.18)

HSD: $\chi^2/ndf = 360/233 = \mathbf{1.55}$ (p-value <0.00001)





$$T_{1/2}^{2\nu} = [8.62 \pm 0.03(\text{stat.})\ ^{+0.10}_{-0.12}(\text{syst.})] \times 10^{19}\ \text{yr}$$

Compatible at 1.3 σ with the recent NEMO-3 results

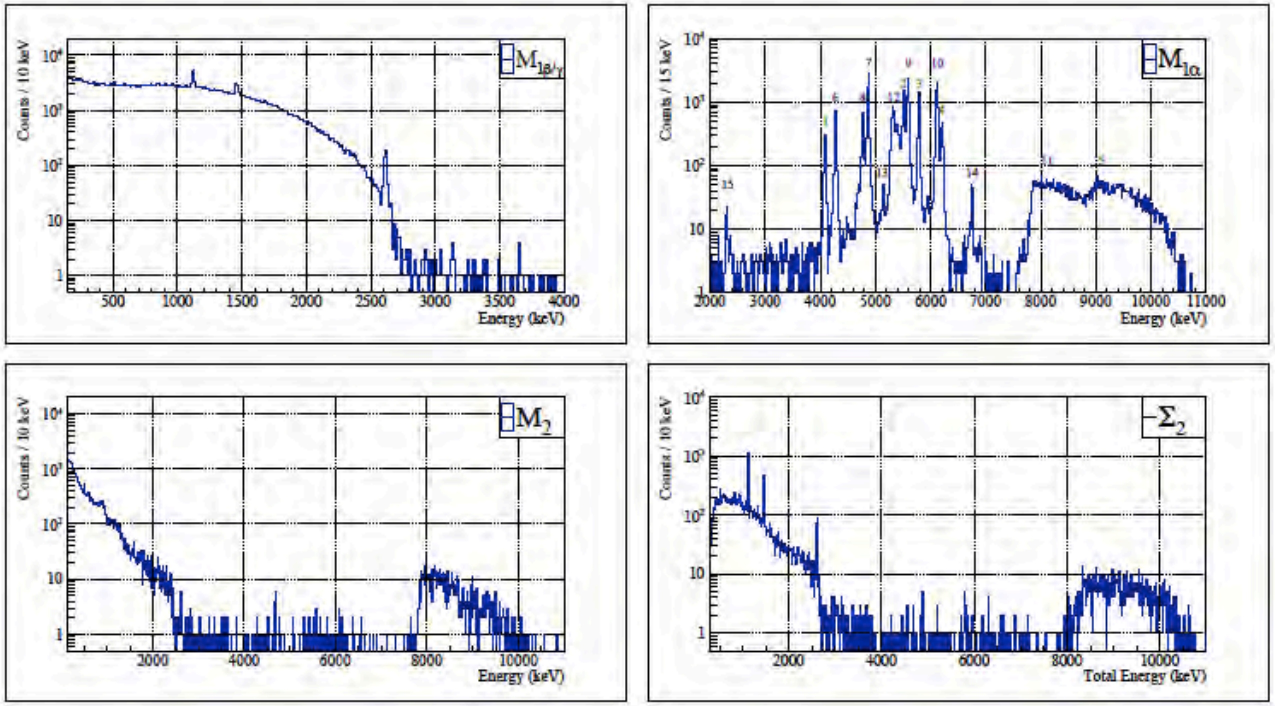
From $(T_{1/2}^{2\nu})^{-1} = G_{2\nu} \cdot (g_A^{eff})^4 \cdot \mathcal{M}_{2\nu}^2$

$$\mathcal{M}_{2\nu}^{eff} = (g_A^{eff})^2 \cdot \mathcal{M}_{2\nu} = 0.0762\ ^{+\,0.0005}_{-\,0.0006}$$

Other analyses: CUPID-0 Background Model

Where does the residual background come from?

Make use of information extracted from 4 different energy spectra



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

+ higher multiplicity spectra to normalise cosmic rays

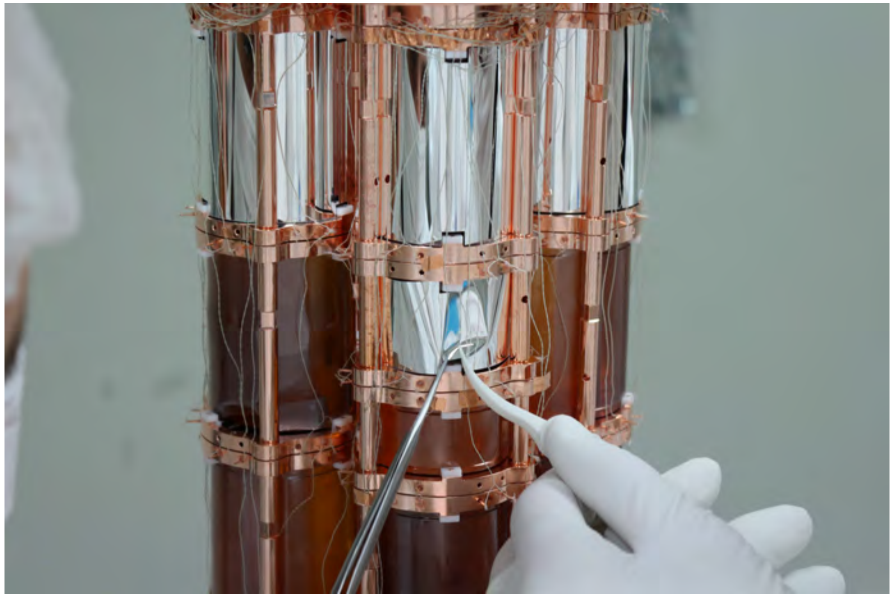
Bkg components in the Region Of Interest ([2800 – 3200] keV)

After all cuts:

Component	ROI_{bkg} rate (10^{-4}counts/(keV kg yr))	Source	ROI_{bkg} rate (10^{-4}counts/(keV kg yr))
Crystals	$11.7 \pm 0.6\ ^{+1.6}_{-0.8}$	^{232}Th– bulk	$3.4 \pm 0.6 \pm 0.1$
		^{232}Th–surf	$3.4 \pm 0.5\ ^{+1.0}_{-0.7}$
		^{238}U–surf	$4.9 \pm 0.3\ ^{+1.3}_{-0.3}$
Reflectors & Holder	$2.1 \pm 0.3\ ^{+2.2}_{-1.0}$	^{232}Th	< 3.3
		^{238}U	$1.8 \pm 0.3\ ^{+1.4}_{-0.9}$
Cryostat & Shields	$5.9 \pm 1.3\ ^{+7.2}_{-2.9}$	^{232}Th	$3.5 \pm 1.3\ ^{+7.4}_{-3.3}$
		^{238}U	$2.4 \pm 0.4\ ^{+4.1}_{-0.7}$
Subtotal	$19.8 \pm 1.4\ ^{+6.6}_{-2.7}$		
Muons	$15.3 \pm 1.3 \pm 2.5$		
$2\nu\beta\beta$	6.0 ± 0.3 ($< 3 \times 10^{-6}$ counts/(keV kg yr) in [2.95–3.05] MeV range)		
Total	$41 \pm 2\ ^{+9}_{-4}$		
Experimental	$35\ ^{+10}_{-9}$		

Essential insights for the next-generation detector design
CUPID-0 Phase II will validate the current model

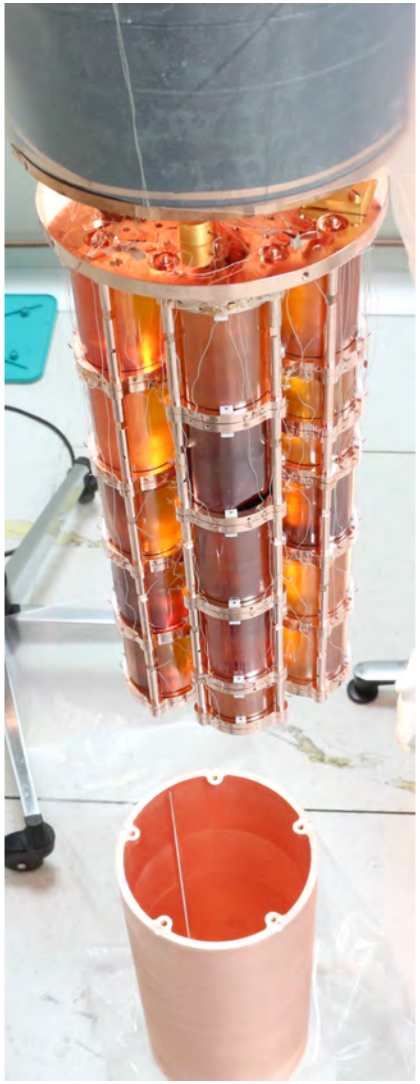
CUPID-0 Phase II



January 2019: stop data taking for a major detector upgrade:

- Remove the reflective foils
- Install a new clean copper shield
- Introduce a (partial) muon veto

Physics data collection started on June



CUPID-0: What Next?

What can we learn with detector upgrades:

- Check the bulk/surface ratio of the external radio-contaminations
- Improve the detector stability and understand ^{208}Tl rates
- Study the muon contribution via MC/data comparison or muon tagging
- …

Conclusions

CUPID-0: first large array of enriched scintillating bolometers for the study of ^{82}Se $0\nu\beta\beta$

Proved the potential of PID for background rejection

Despite the small exposure, best 90% C.I. limit on the $0\nu\beta\beta$ of ^{82}Se

$\tau_{1/2} > 3.5 \cdot 10^{24}$ yr in 5.29 kg yr of ^{82}Se

(Nemo results: $\tau_{1/2} > 3.6 \cdot 10^{23}$ yr in 3.5 kg yr of ^{82}Se)

Several important hints for nuclear physicists: $0\nu\beta\beta$ on exc. st., SSD-$2\nu\beta\beta$, $\mathcal{M}_{2\nu}^{eff}$…

CUORE, CUPID-0, and CUPID-Mo are laying the foundation for the next generation CUPID experiment (pre-CDR arXiv:1907.09376)