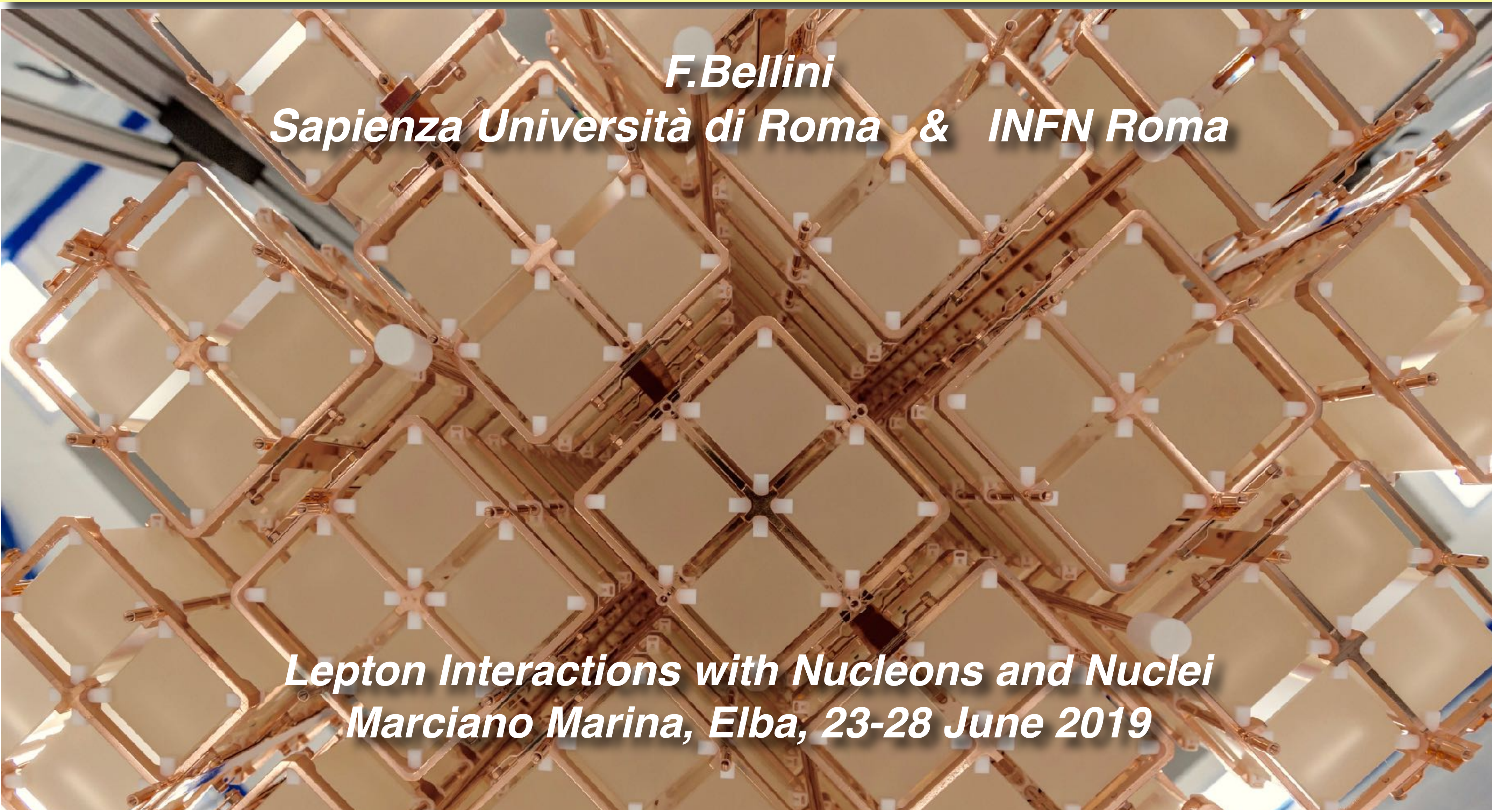
Neutrinoless Double Beta Decay with CUORE and CUPID



F.Bellini
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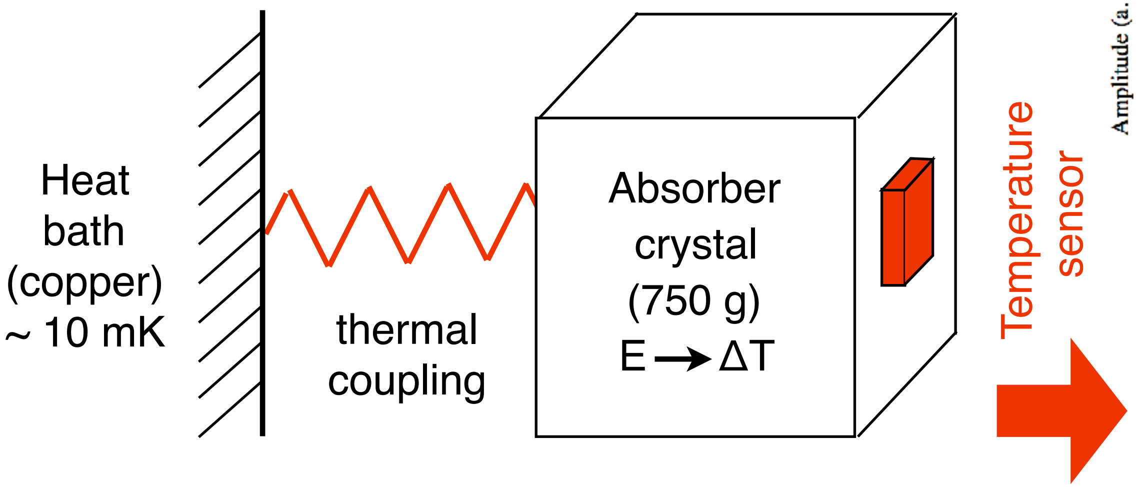
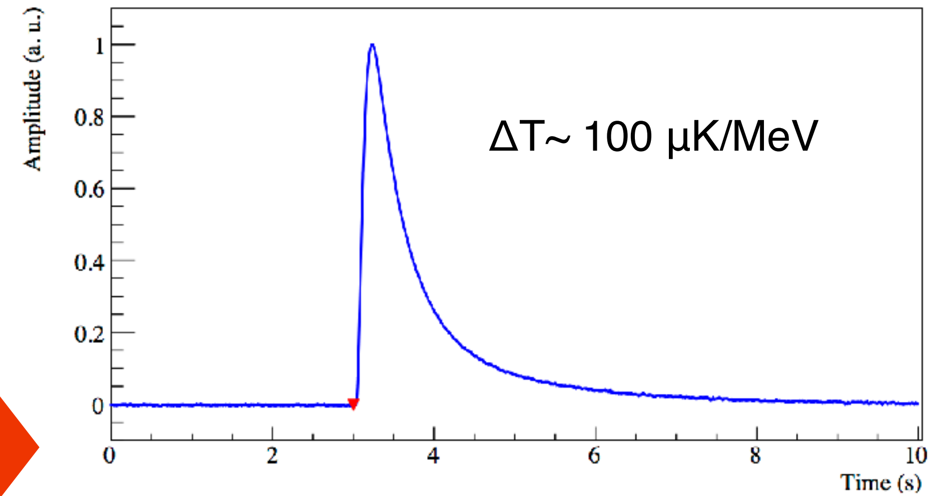
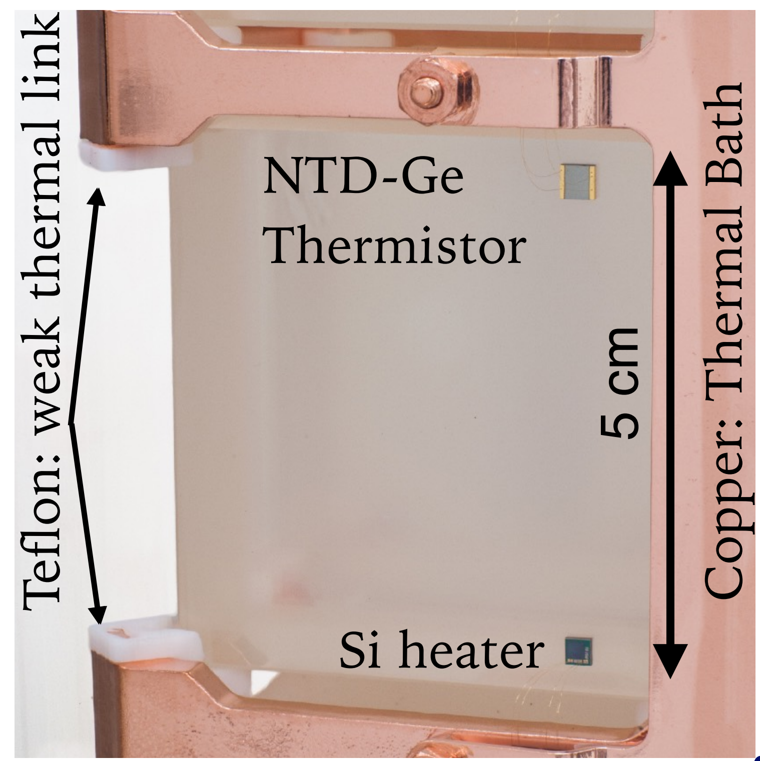
Lepton Interactions with Nucleons and Nuclei
Marciano Marina, Elba, 23-28 June 2019

Bolometric technique in CUORE

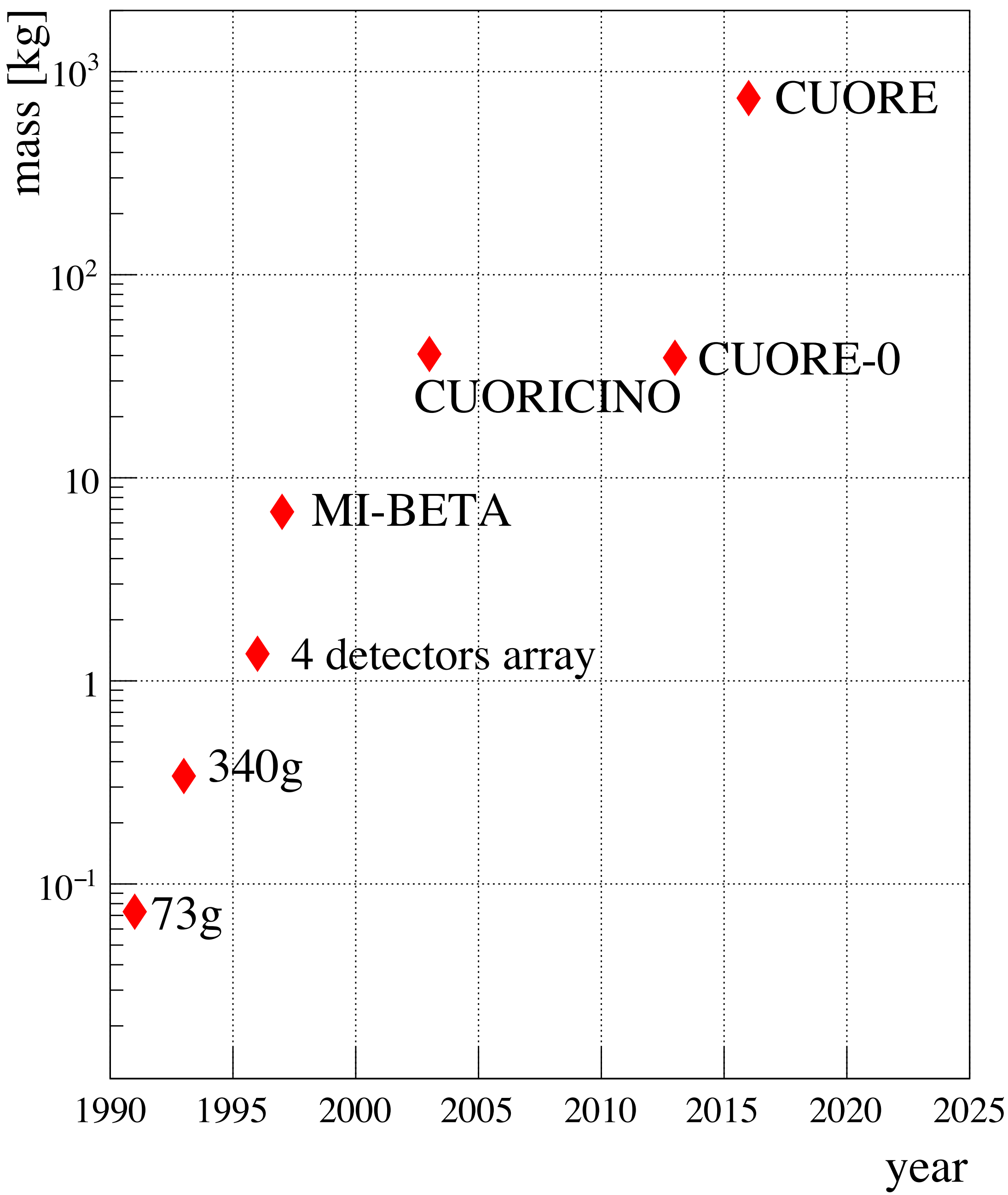




- Cubic $^{nat}TeO_2$ crystals: ^{130}Te source embedded in the detector
- NTD-Ge thermistor: $R(T) \simeq 1\,\Omega \cdot \exp\left(\frac{3\,\mathrm{K}}{T}\right)^{\frac{1}{2}}$
- Resolution @$0\nu\beta\beta$ energy: ~0.2% FWHM



Arrays of TeO_2 bolometers



Cryogenic Underground Observatory for Rare Events

- 988 $^{nat}TeO_2$ bolometers
  19 towers, 13 floors.
- Active mass: 742 kg.
- Isotope mass: 206 kg ^{130}Te.
- ^{130}Te abundance ~34%
- $Q_{\beta\beta}$=2528 keV
- Expected background:
  10^{-2} cts/keV/kg/year
- Sensitivity to 0νββ in 5yr
  $T_{1/2}$ = 9x10^{25} yr @90% C.L.
- Sensitivity to $m_{\beta\beta}$ in 5yr
  56 - 160 meV @90% C.L.

LNGS Laboratory

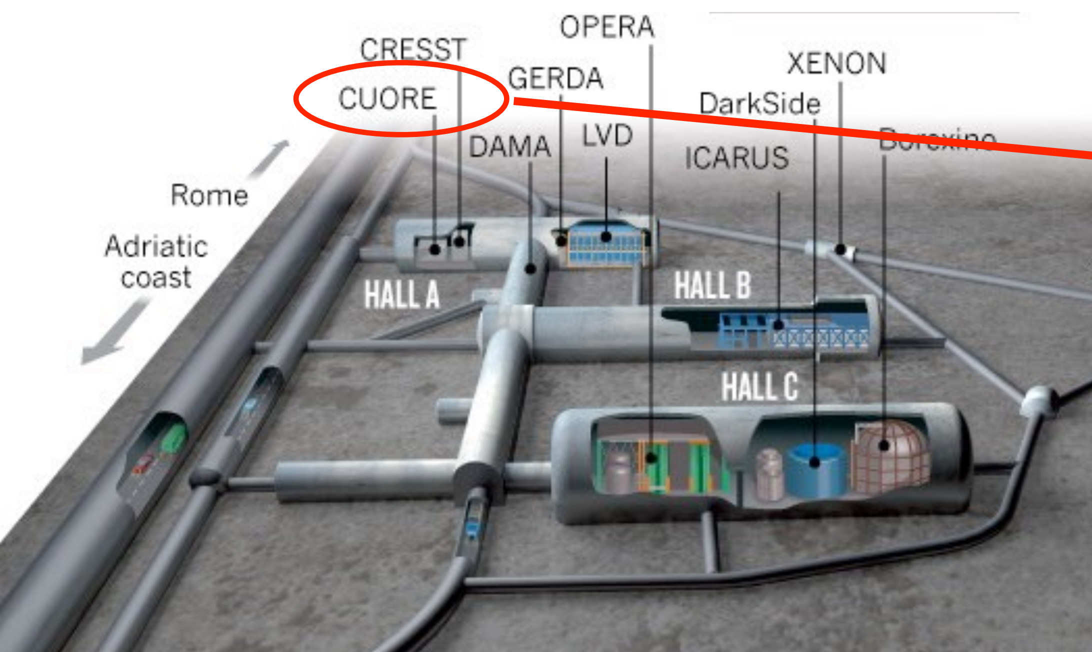
120 km from Rome

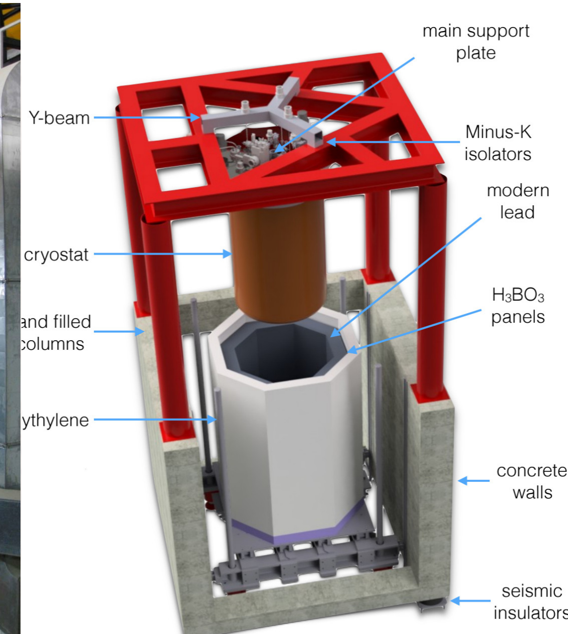
~ 3600 m.w.e. deep

μ flux: ~ 3×10^{-8}/(s cm^2)

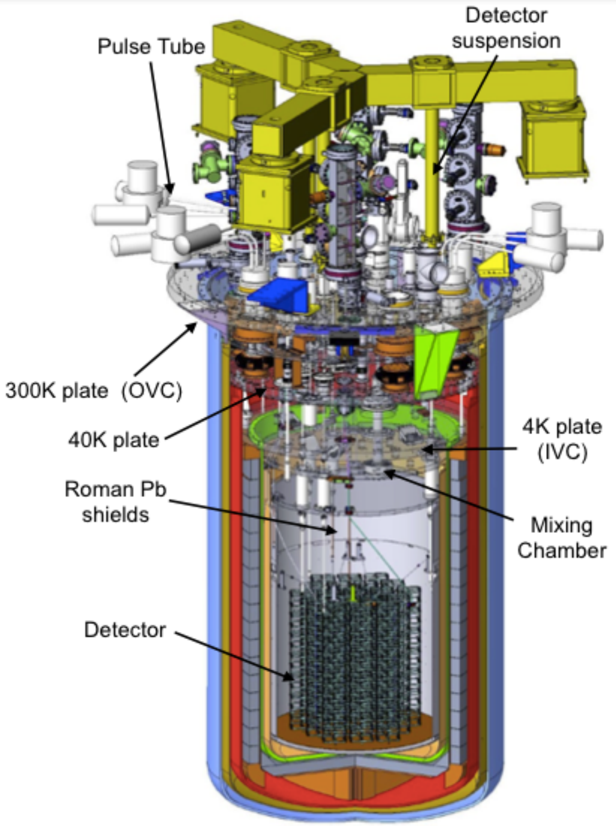
γ flux: ~ 0.73/(s cm^2)

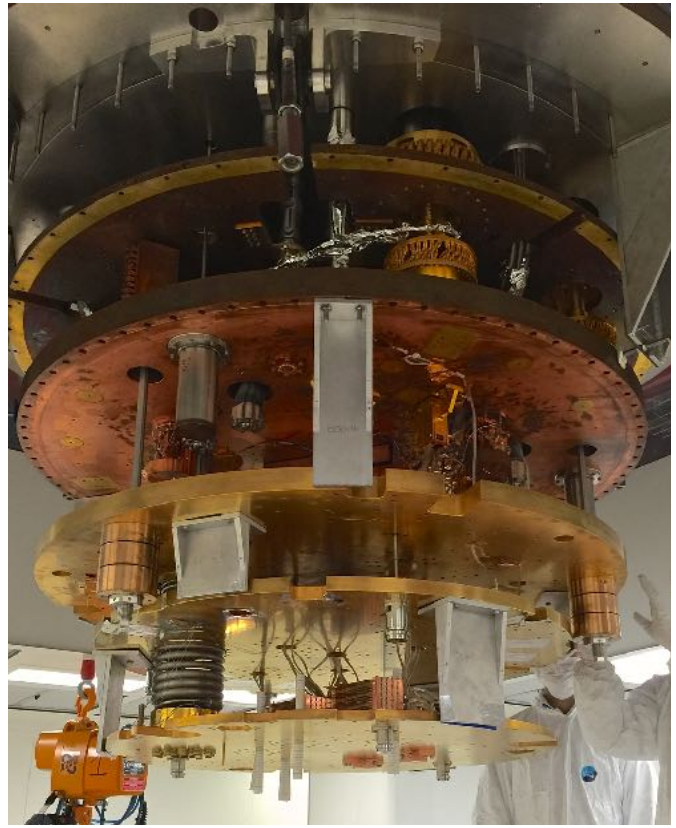
neutrons: 4×10^{-6} n/(s cm^2) below 10 MeV





CUORE cryostat

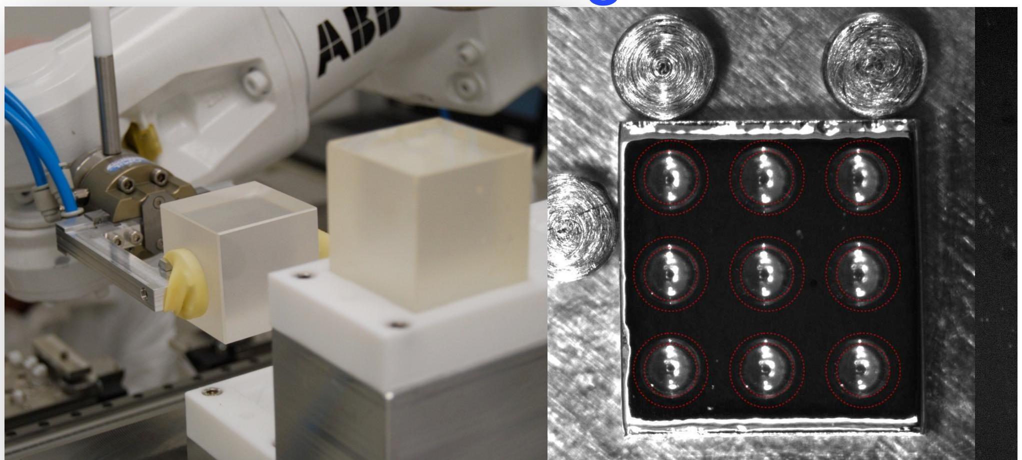




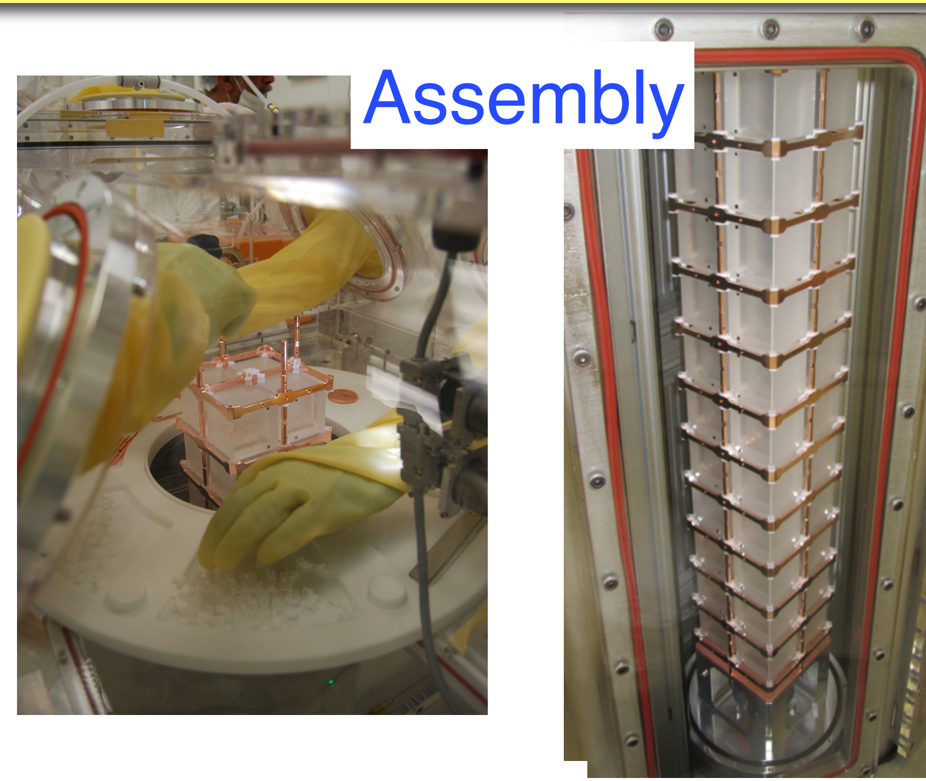
- **Goals:** Cool down ~1 ton detector to ~10 mK. Large duty cycle and long term stability. Mechanically decoupled for extremely low vibrations. Low background environment.
- Cryostat total mass ~30 tons. Mass to be cooled < 4K: ~15 tons. Mass to be cooled < 50 mK: ~3 tons (Pb, Cu and TeO_2).
- Minimum base temperature of 6.3 mK reached, detector optimal performance @ 10-15 mK.

CUORE Assembly Line

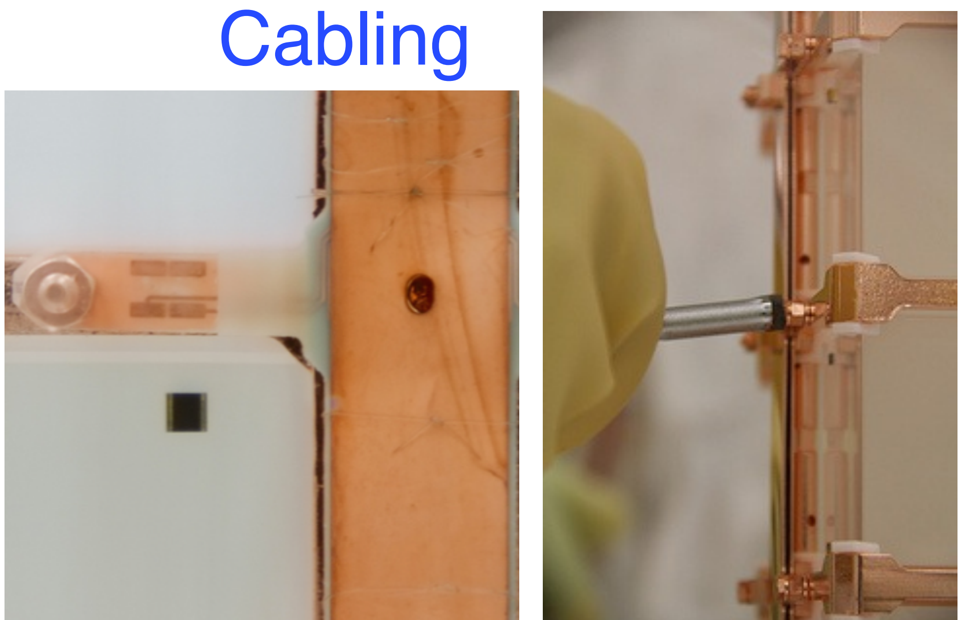
Gluing



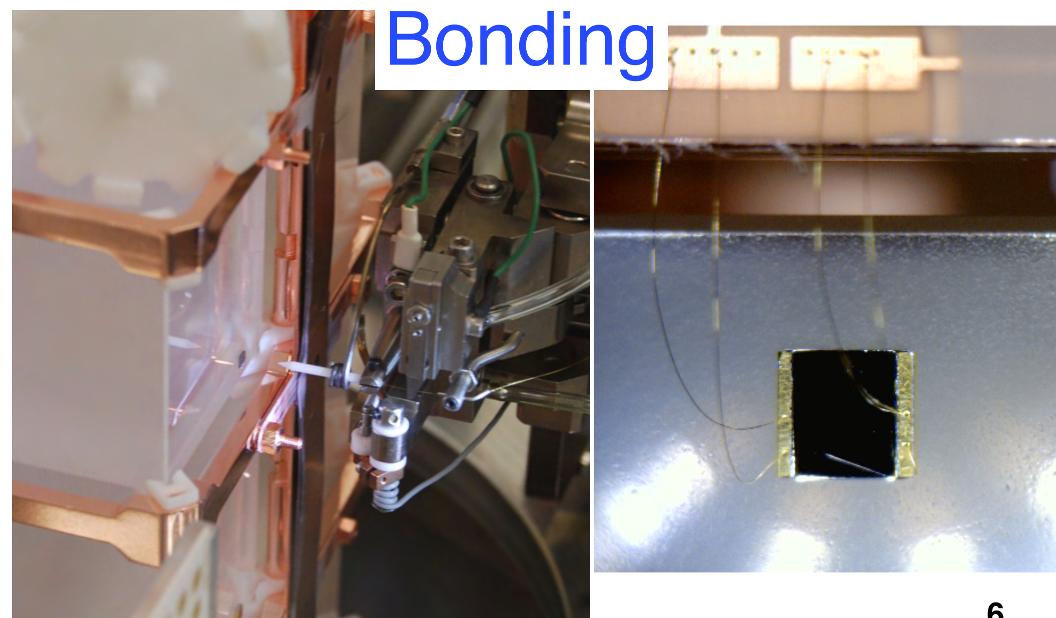
Assembly



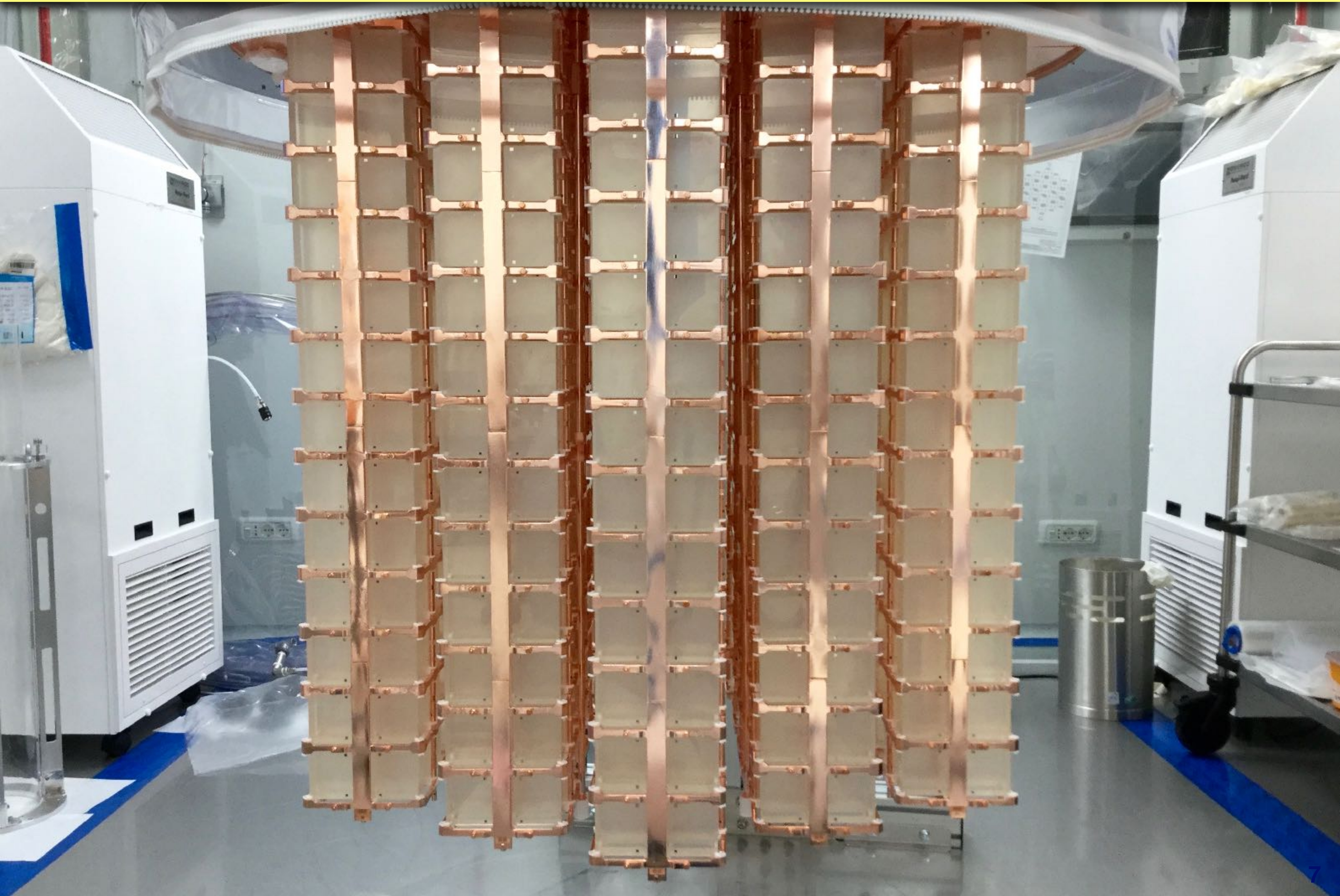
Cabling



Bonding

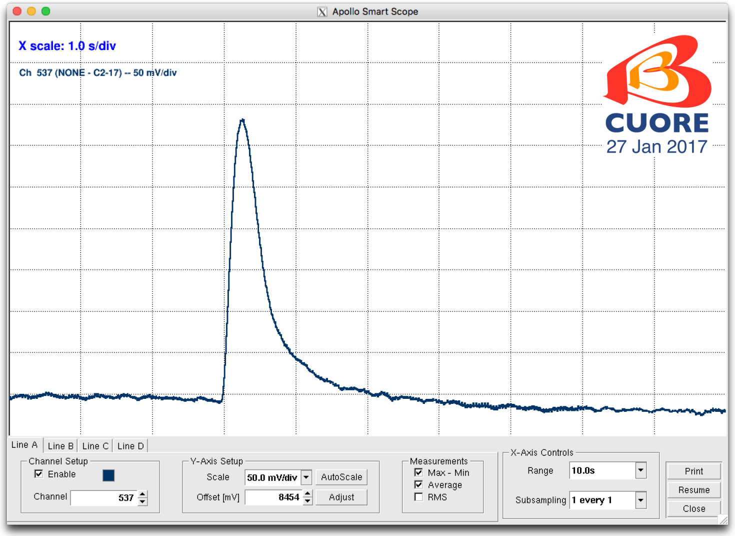


CUORE



Science runs

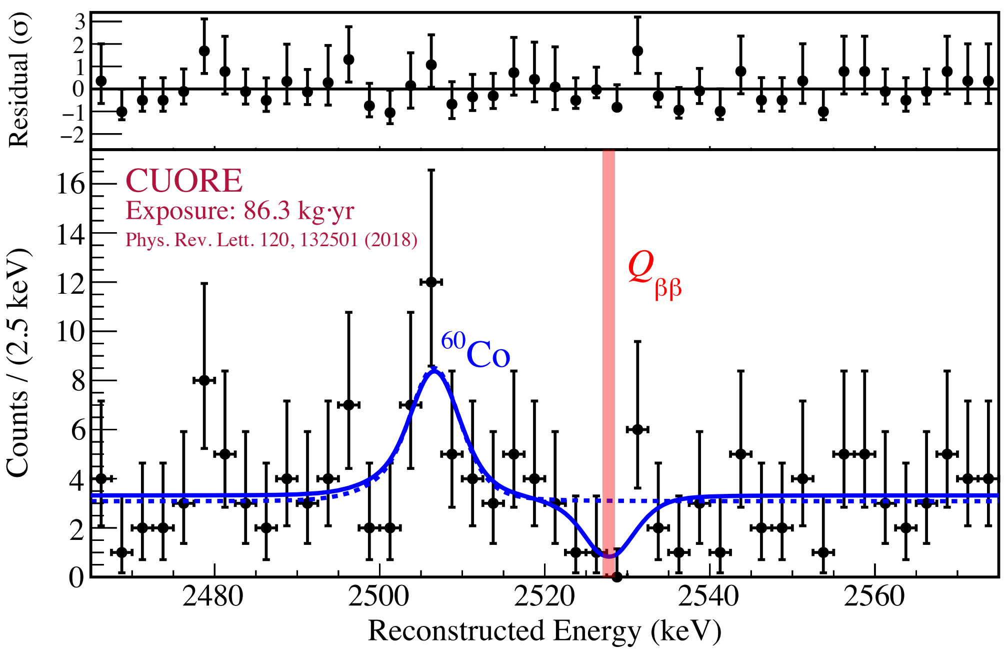
- Apr 17: first physics data
  - Working T set at 15 mK
  - Dataset 1: 37.6 kg yr of TeO_2
  - Optimization Campaign
  - Dataset 2: 8.7 kg yr of TeO_2
  - TeO_2 exposure: 86.3 kg yr

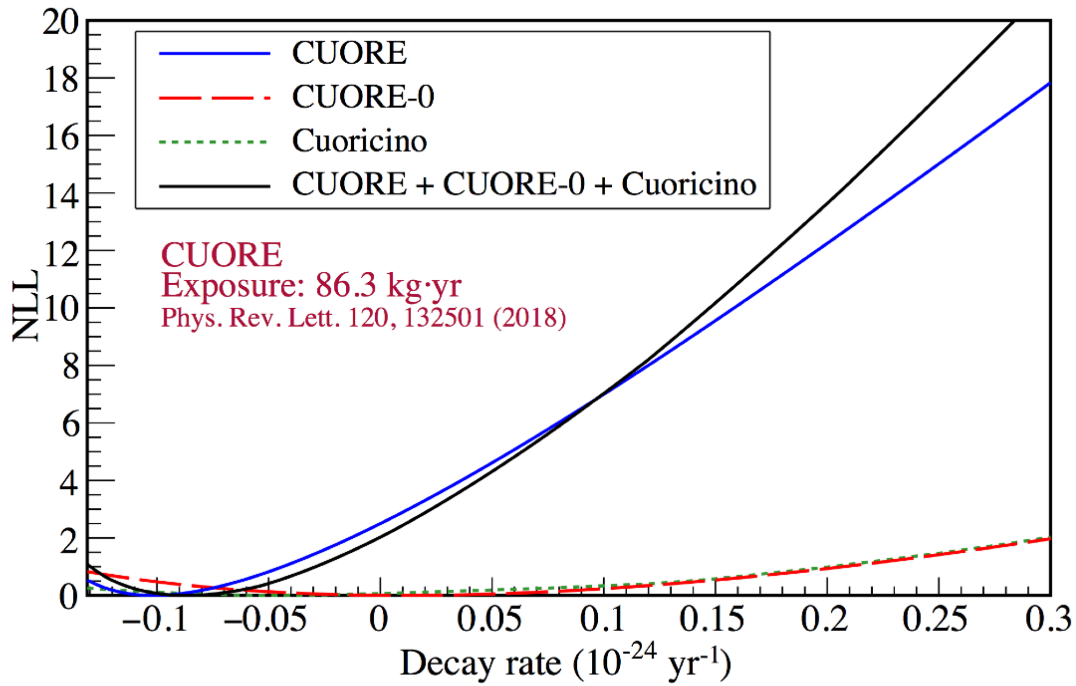


- Operational perfomances
- 984/988 bolometers are operational
- Rate in physics runs: 6 mHz / bolometer
- Energy resolution at $Q_{\beta\beta}$~7.7 FWHM
- Signal efficiency~ 80%

0νββ analysis

Phys. Rev. Lett. 120, 132501 (2018)





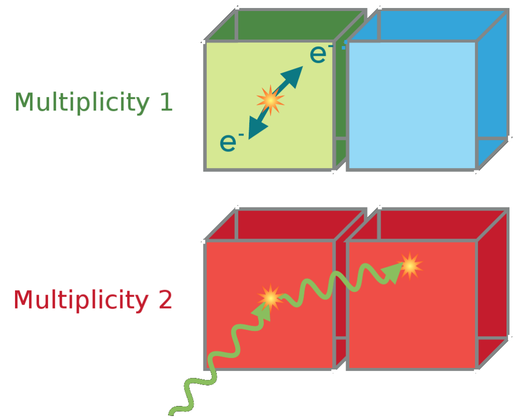
Region of interest : [2465..2575] keV
Overall efficiency : (75.7 ± 3.0)%
(83.0 ± 2.6)%
ROI background index: $(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ counts/(keV·kg·yr)
$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$ counts/(keV·kg·yr)
Events in the ROI : 155
Best fit for ^{60}Co mean : (2506.4 ± 1.2) keV
Best fit decay rate: $[-1.0_{-0.3}^{+0.4}$ (stat.) ± 0.1 (syst.)$] \times 10^{-25}$ yr^{-1}

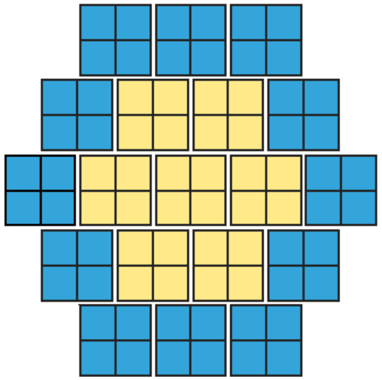
Limits combining CUORE with CUORE-0 and Cuoricino:

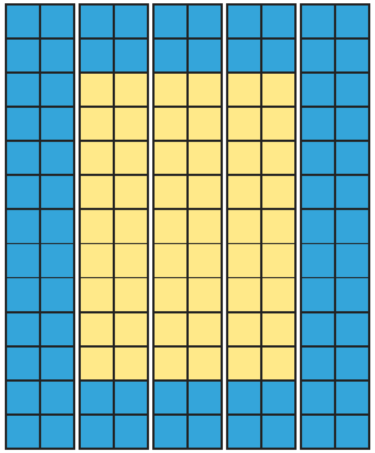
- Bayesian limit @ 90% c.i. (flat prior for $\Gamma_{\beta\beta}>0$):
  1.5×10^{25} yr
- Profile likelihood ("frequentist") limit @ 90% CL:
  2.2×10^{25} yr

CUORE Background model

- Maximise use of available information
  - Split data into inner and outer layers
  - Split data into Multiplicity 1 (M1), Multiplicity 2 (M2), Multiplicity 2 Sum (Σ2)



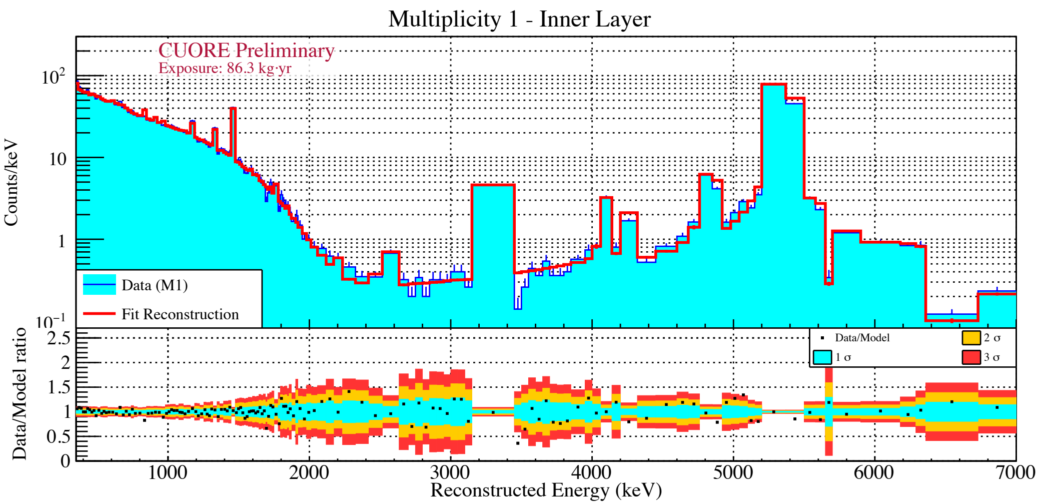




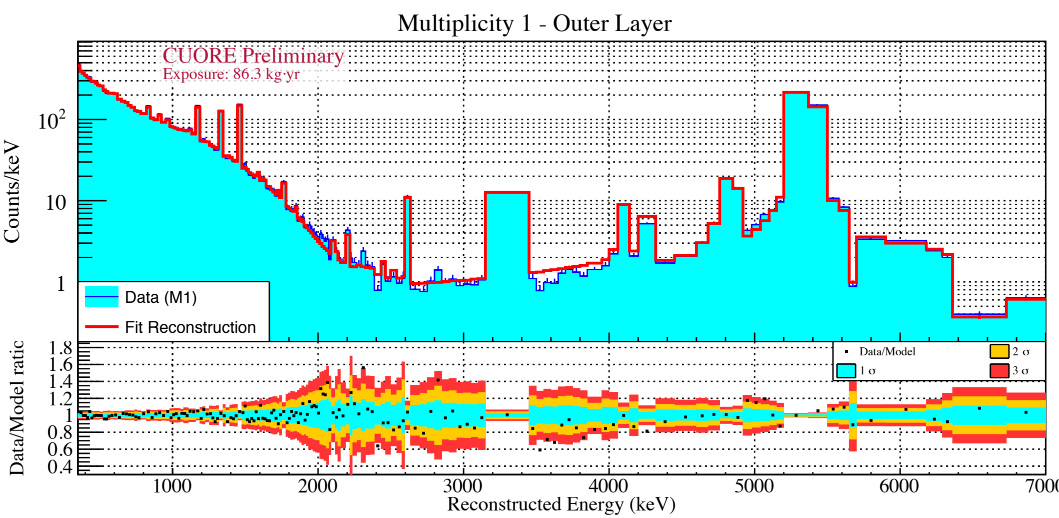
Volume	Type	Components
TeO_2	Bulk	$2\nu\beta\beta$, ^{210}Pb, ^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{230}Th ^{226}Ra-^{210}Pb, ^{40}K, ^{60}Co, ^{125}Sb, ^{190}Pt
TeO_2	Surface (0.01 μm)	^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{226}Ra-^{210}Pb, ^{210}Pb
TeO_2	Surface (1 μm)	^{210}Pb
TeO_2	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Bulk	^{232}Th, ^{238}U, ^{40}K, ^{60}Co, ^{54}Mn
CuNOSV	Surface (0.01 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (1 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
Roman lead	Bulk	^{232}Th, ^{238}U, ^{108m}Ag
Top lead	Bulk	^{232}Th, ^{238}U, ^{210}Bi
Ext. lead	Bulk	^{210}Bi
CuOFE	Bulk	^{232}Th, ^{238}U, ^{60}Co
External	-	Cosmic muons

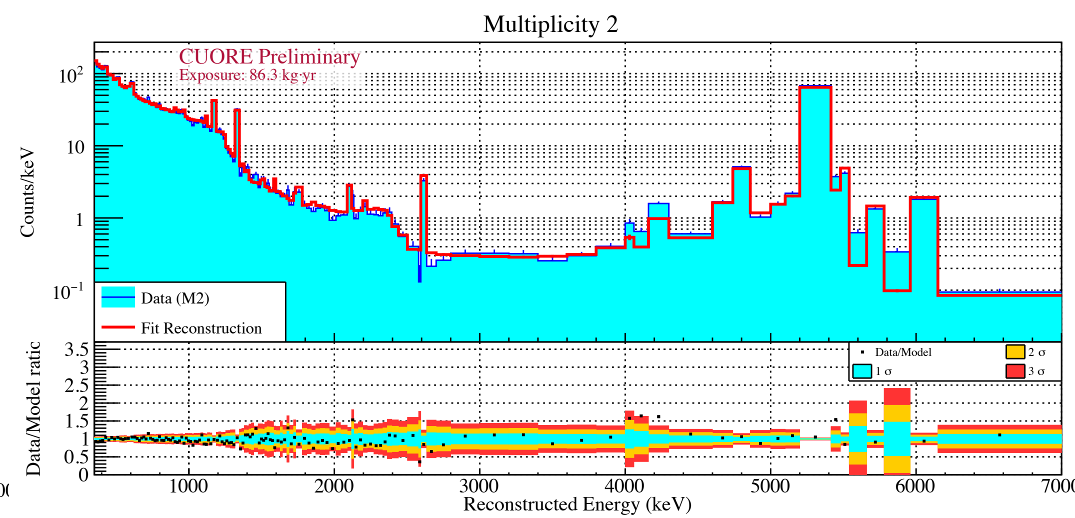
- Background Model
  - Geant4 simulation of ~60 source/ locations in setup
  - Simultaneous Bayesian fit using MCMC Gibbs sampler (JAGS)
  - Priors from material screening, assays and cosmogenic analysis

CUORE Background model



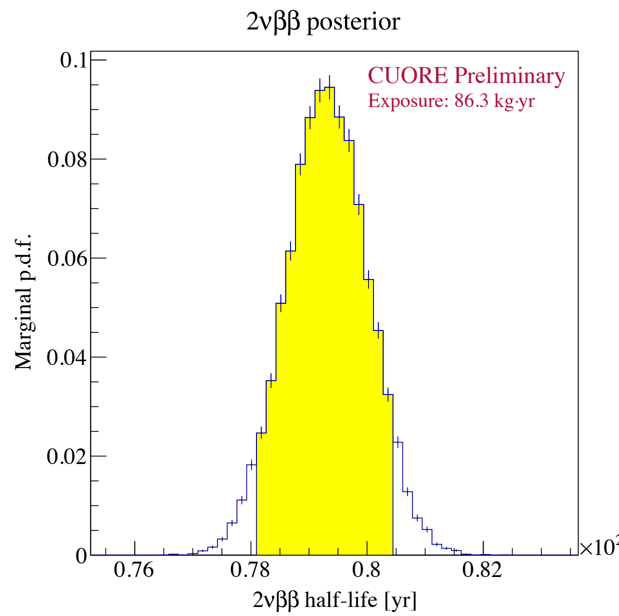
- Inner layers very sensitive to signal (lower background)
- Outer layers sensitive to external background
- M2 and Σ2 spectra constrain a subset of backgrounds

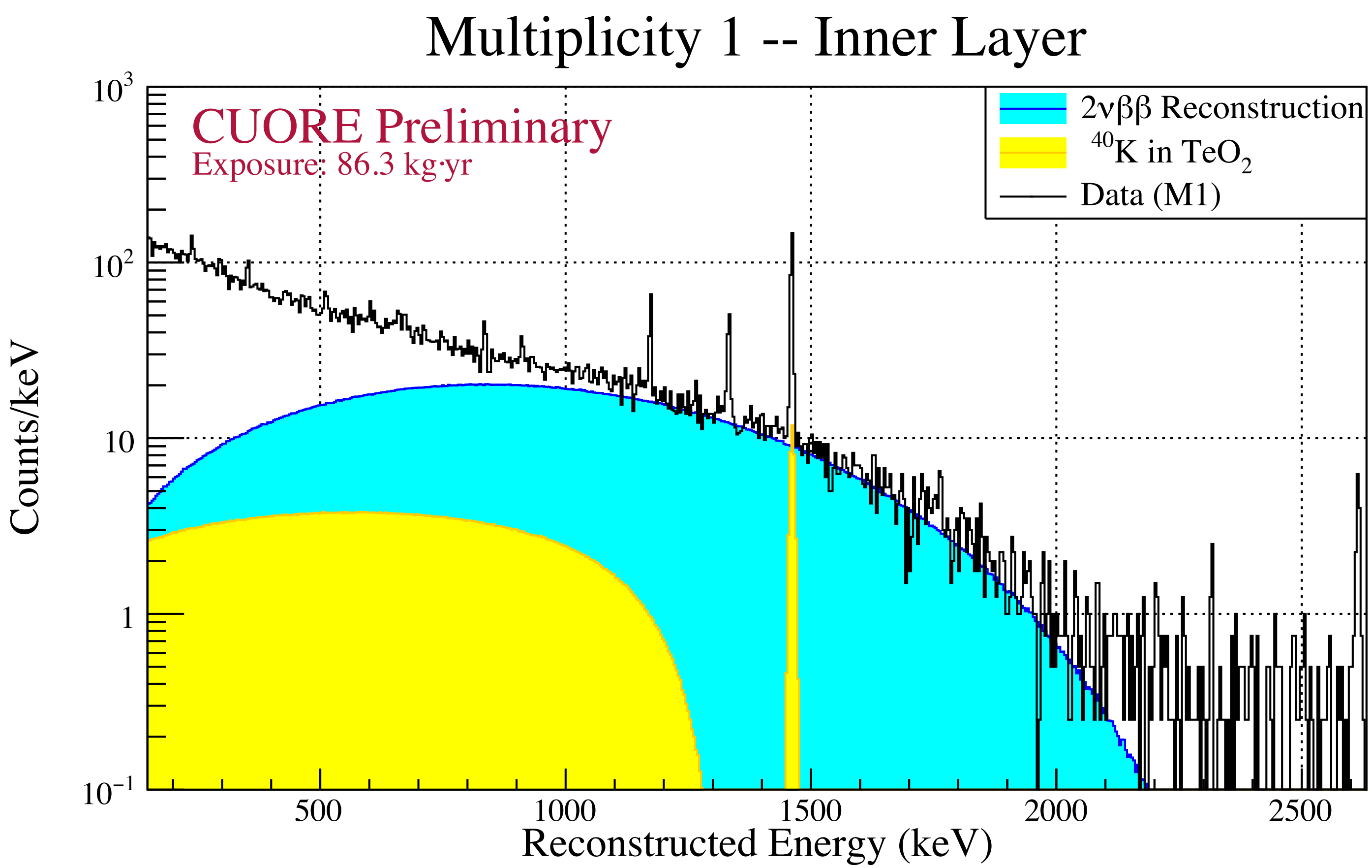




2νββ decay analysis

- Almost all events in 1-2 MeV range are 2νββ events (20% in CUORE-0)
  - $T^{2\nu}_{1/2}$ =[7.9 ± 0.1(stat) ± 0.2(syst)] · 10^{20} yr (**preliminary**)
  - CUORE-0 $T^{2\nu}_{1/2}$ [8.2 ± 0.2(stat) ± 0.6(syst)] · 10^{20} yr
  - NEMO $T^{2\nu}_{1/2}$ =[7.0 ± 0.9(stat) ± 1.1(syst)] · 10^{20} yr

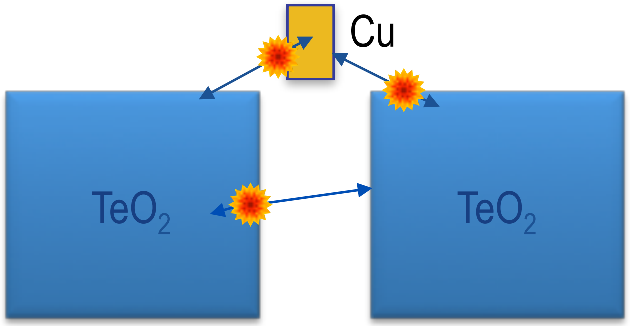


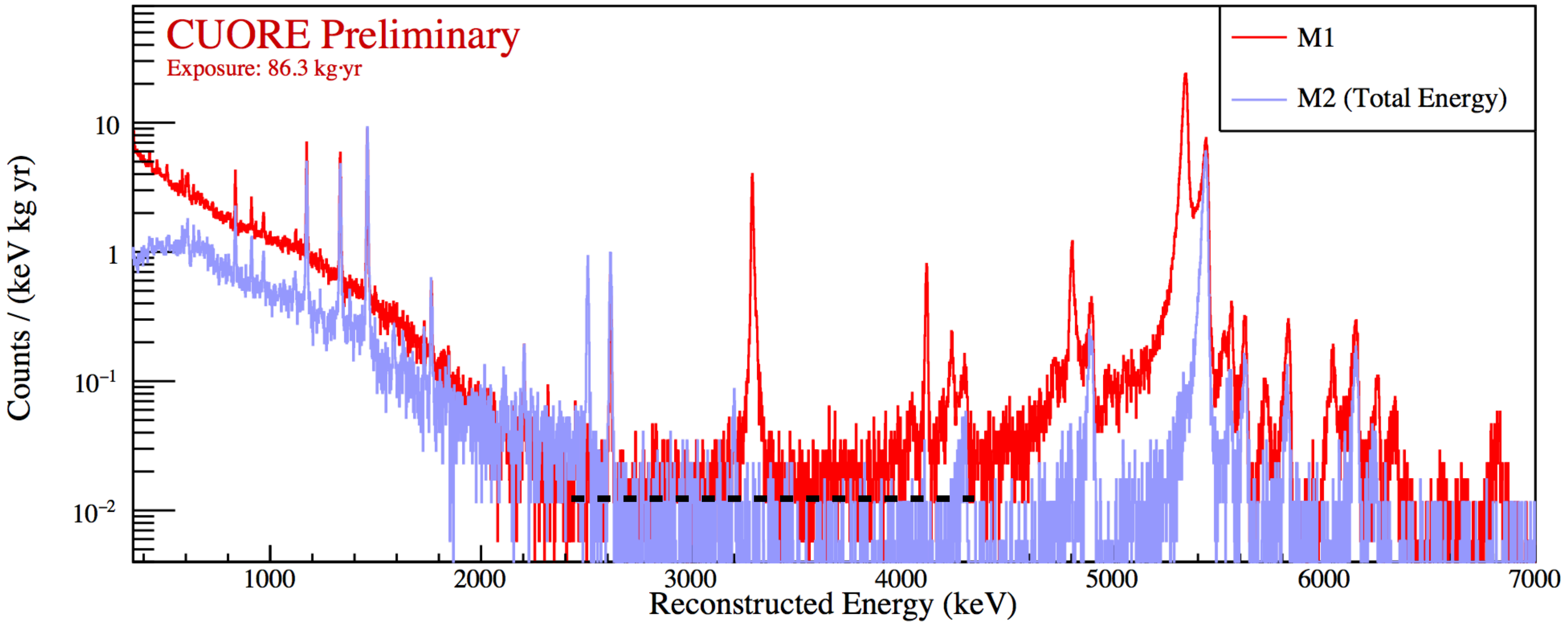


- Systemstics
  - Primary systematics from geometry splitting
  - No dependence on fit threshold over the range 100-750 keV

Beyond CUORE

- Lesson learned from CUORE
  - background at $Q_{\beta\beta}$ dominated by degraded αs from TeO_2 & Cu surface

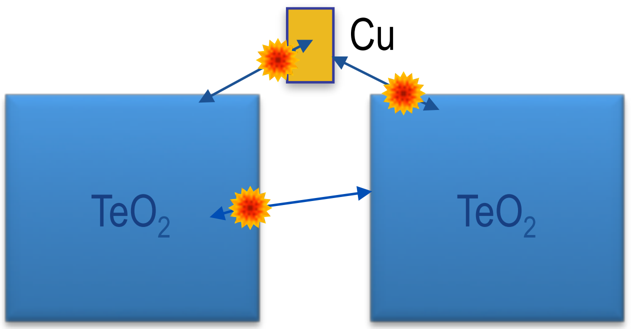


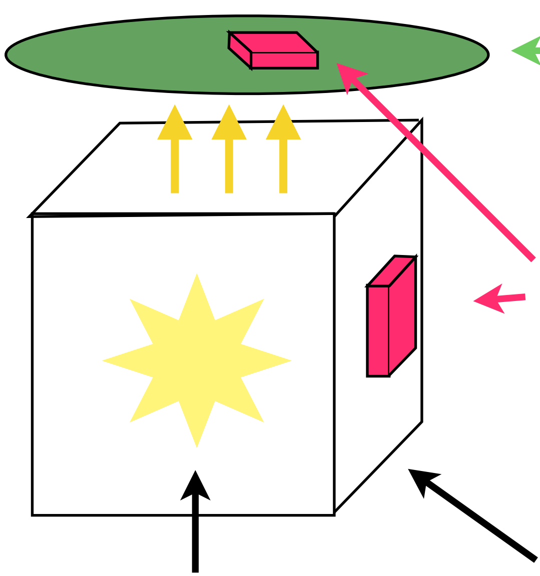


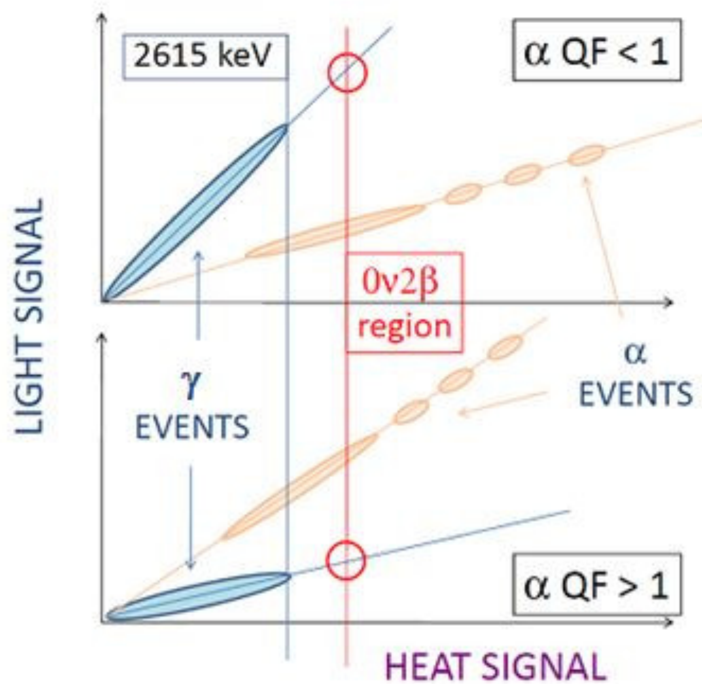
Beyond CUORE

- Lesson learned from CUORE
  - background at $Q_{\beta\beta}$ dominated by degraded αs from TeO_2 & Cu surface
  - need α/β discrimination

    ⇒ use a scintillating bolometer + light detector







Beyond CUORE

- Lesson learned from CUORE
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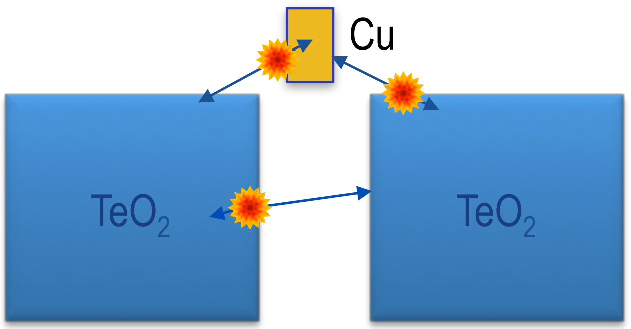
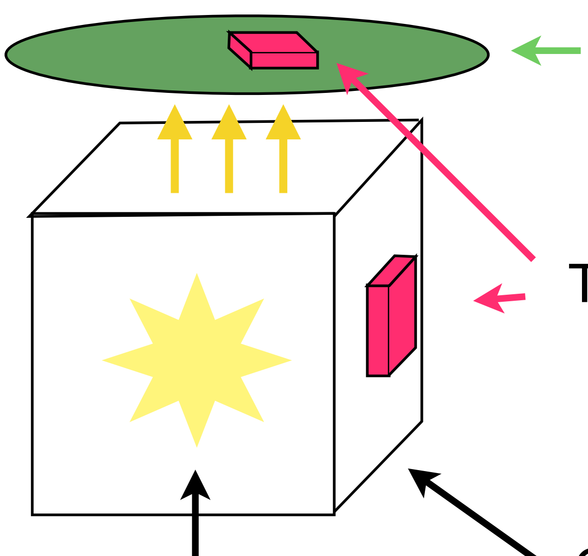
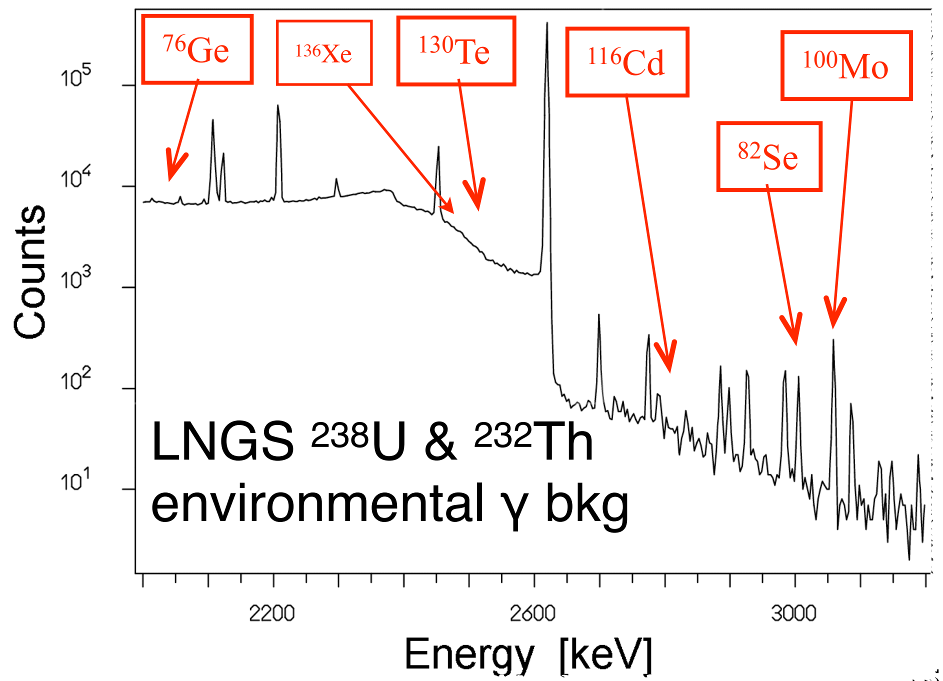


⇒ use a scintillating bolometer: $Li_2{}^{100}MoO_4$ + light detector

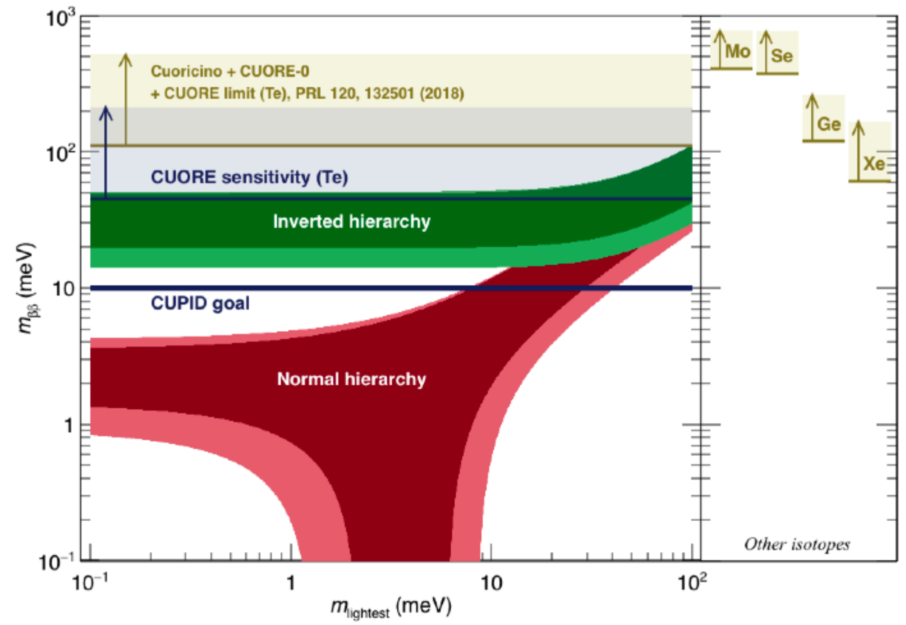
$Q_{\beta\beta} > 2615$ keV ⇒ bkgd ~10^{-4} cts/(keV kg yr) with CUORE infrastructure





CUPID: CUORE Upgrade with PID

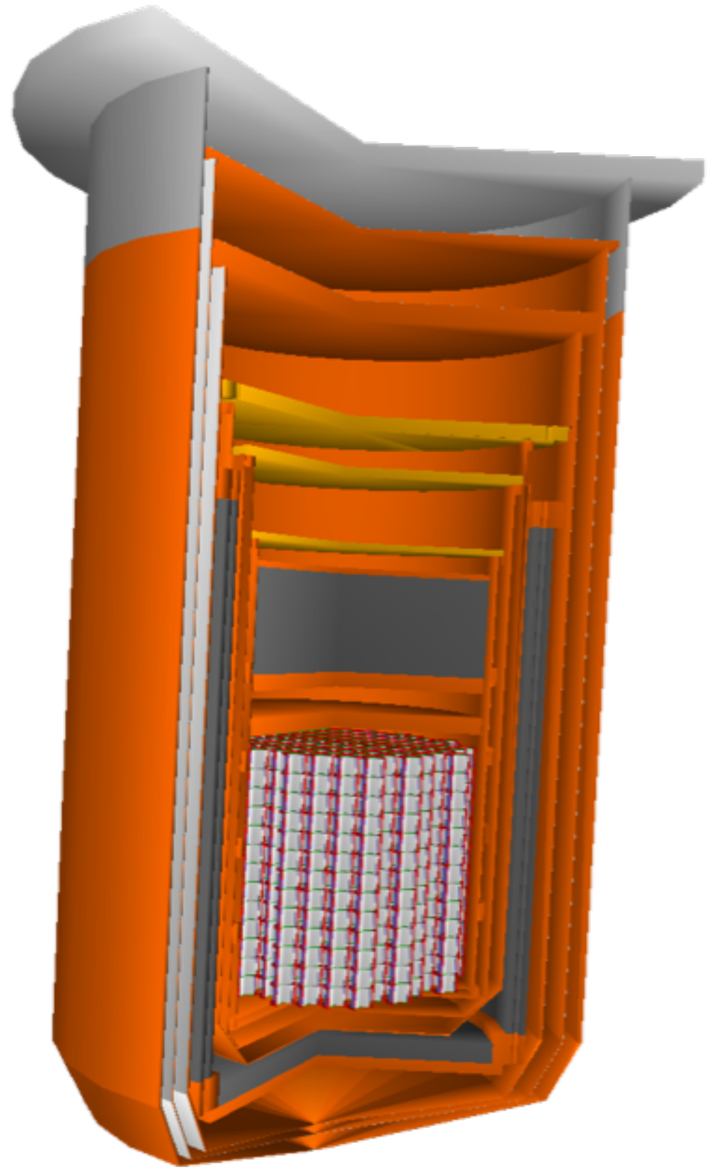
- Mission: discovery $0\nu\beta\beta$ if $m_{\beta\beta}$ >10meV
- CUORE achievements
  - Ton scale detector in data taking
  - 1000 channels analysis demonstrated
  - Infrastructure for next generation experiment exist
  - Reliable data driven background constructed



- Scintillating bolometers (CUPID-0, Lumineu, CUPID-Mo)
  - Demonstrated large-scale enriched crystals production capability
  - Internal radio-purity target met
  - Demonstrated active background rejection and energy resolution
  - Background 10^{-4} cts/(keV kg yr) within reach

CUPID: Conceptual design

- Re-use CUORE infrastructure
- $Li_2{}^{100}MoO_4$ scintillating crystals
  - Enrichment >95%
  - ~1500 crystals for a for ~250 kg of ^{100}Mo
  - ΔE_{FWHM} ~ 5 keV at $Q_{\beta\beta}$~3034 keV
- Active background rejection
  - LY ~0.75 keV/MeV
  - Ge light detectors
- Option for Multi-isotope possible
- TDR and construction readiness for 2021
- **Conservative, mature, data driven baseline design**



CUPID Collaboration

High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA
Materials Science Division, Argonne National Laboratory, Argonne, IL, USA
INFN - Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
Department of Nuclear Engineering, University of California, Berkeley, CA, USA
Department of Physics, University of California, Berkeley, USA
Università di Bologna and INFN Bologna, Bologna, Italy
Massachusetts Institute of Technology, Cambridge, MA, USA
Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
Technische Universität München, Physik-Department E15, Garching, Germany
Dipartimento di Fisica, Università di Genova and INFN - Sezione di Genova, Genova, Italy
Institute for Nuclear Research, Kyiv, Ukraine
INFN - Laboratori Nazionali di Legnaro, Legnaro, Italy
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Nikolaev Institute of Inorganic Chemistry, SB RAS, Novosibirsk, Russia
Sobolev Institute of Geology and Mineralogy, SB RAS, Novosibirsk, Russia
Centre de Sciences Nuclèaires et de Sciences de la Matière (CSNSM), CNRS/IN2P3, Orsay, France
INFN - Sezione di Padova, Padova, Italy
Institut de Chimie de la Matière Condensè de Bordeaux (ICMCB), CNRS, 87, Pessac, France
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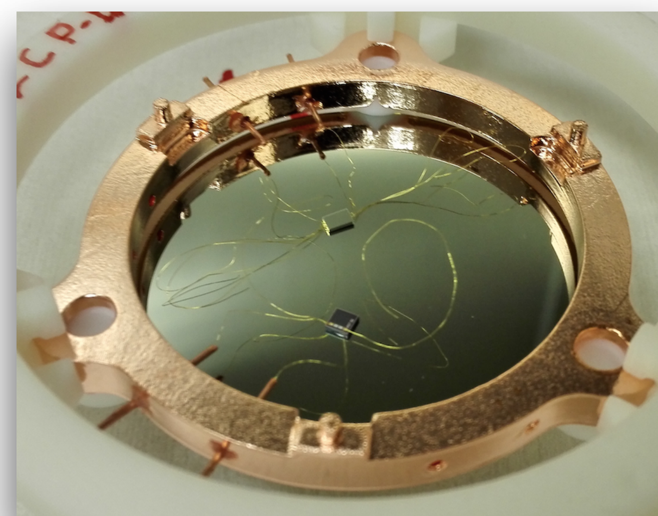
Service de Physique des Particules, DSM/IRFU, CEA-Saclay, France
Physics Department, California Polytechnic State University, San Luis Obispo, CA, USA
Shanghai Institute of Applied Physics (SINAP), China
Institut de Physique Nuclèaire de Lyon, Universitè Claude Bernard, Lyon 1, Villeurbanne, France
Wright Laboratory, Department of Physics, Yale University, New Haven, CT, USA
Laboratorio de Fisica Nuclear y Astropartculas, Universidad de Zaragoza, Zaragoza, Spain

CUPID-0 demonstrator

- $0\nu\beta\beta$ candidate: ^{82}Se
  - Q-value ~2998 keV
- $Zn^{82}Se$ bolometers:
  - enrichment: 8.7% ⇒ 95%
  - no long-living cosmogenic activated isotopes

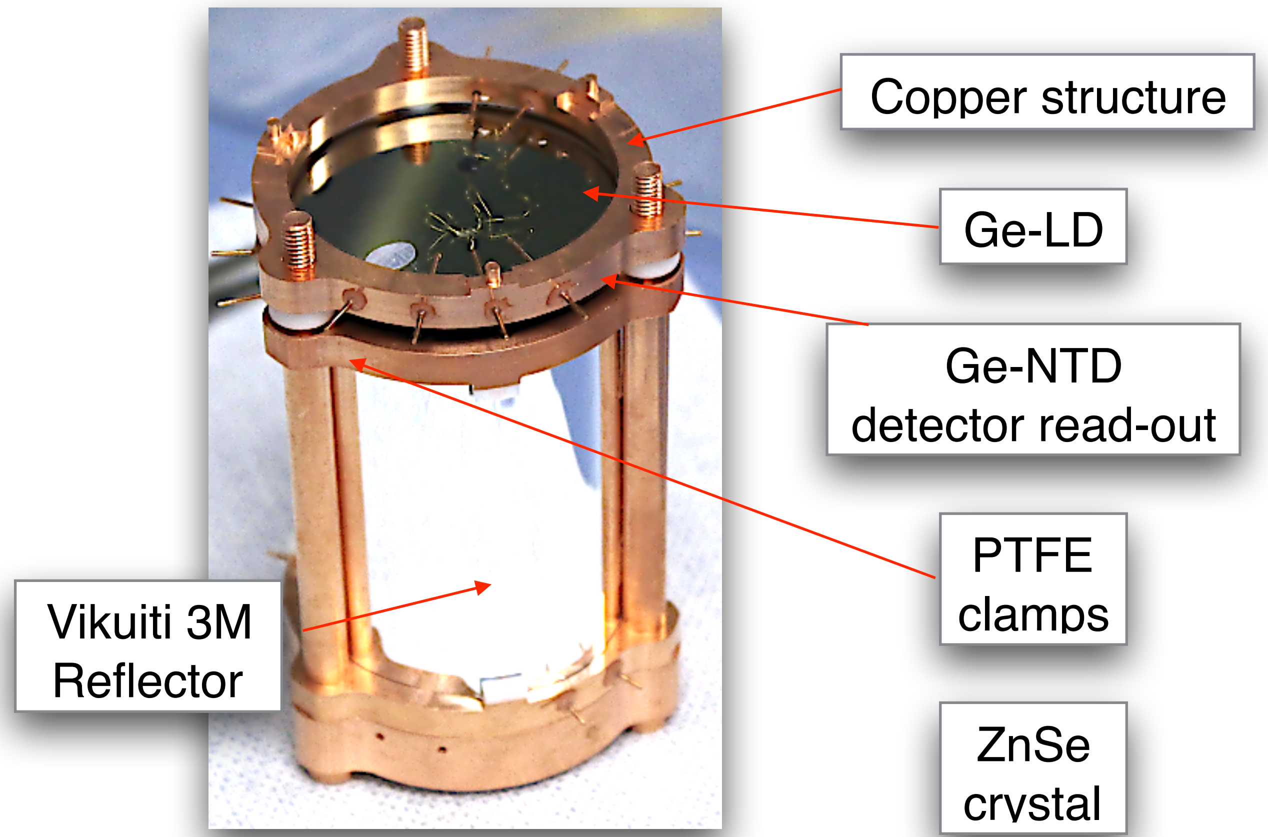
- Light Detector (LD) bolometer
  - Ge disk (∅=44.5mm, h=0.17mm) with 60nm SiO_2 anti-reflective coating

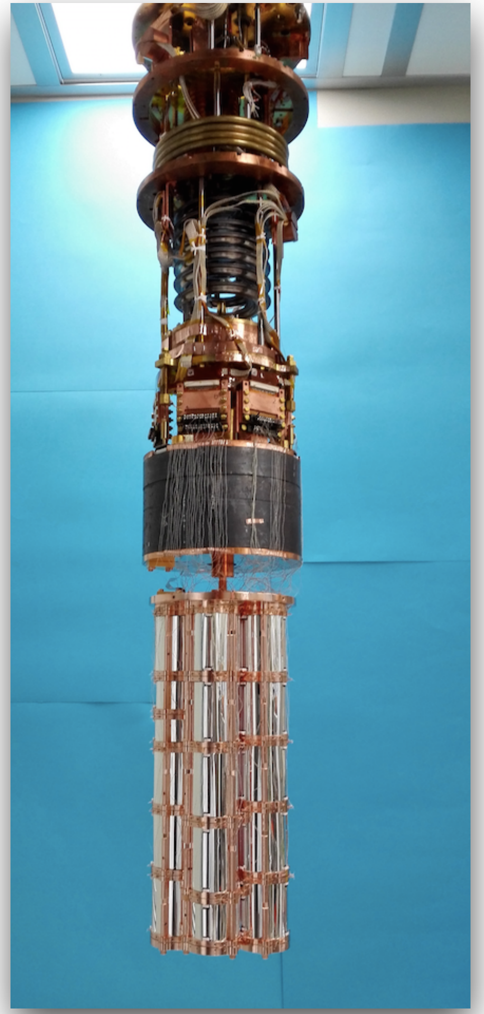


- Thermal sensor: NTD Ge thermistor for both ZnSe & LD

CUPID-0

- 24 $Zn^{82}Se$ bolometers + 2 ZnSe in 5 towers + 31 Light Detectors
  - Total mass: 10.5 kg
  - ^{82}Se mass: 5.17 kg ⇒ $3.8 \cdot 10^{25}$ ββ nuclei





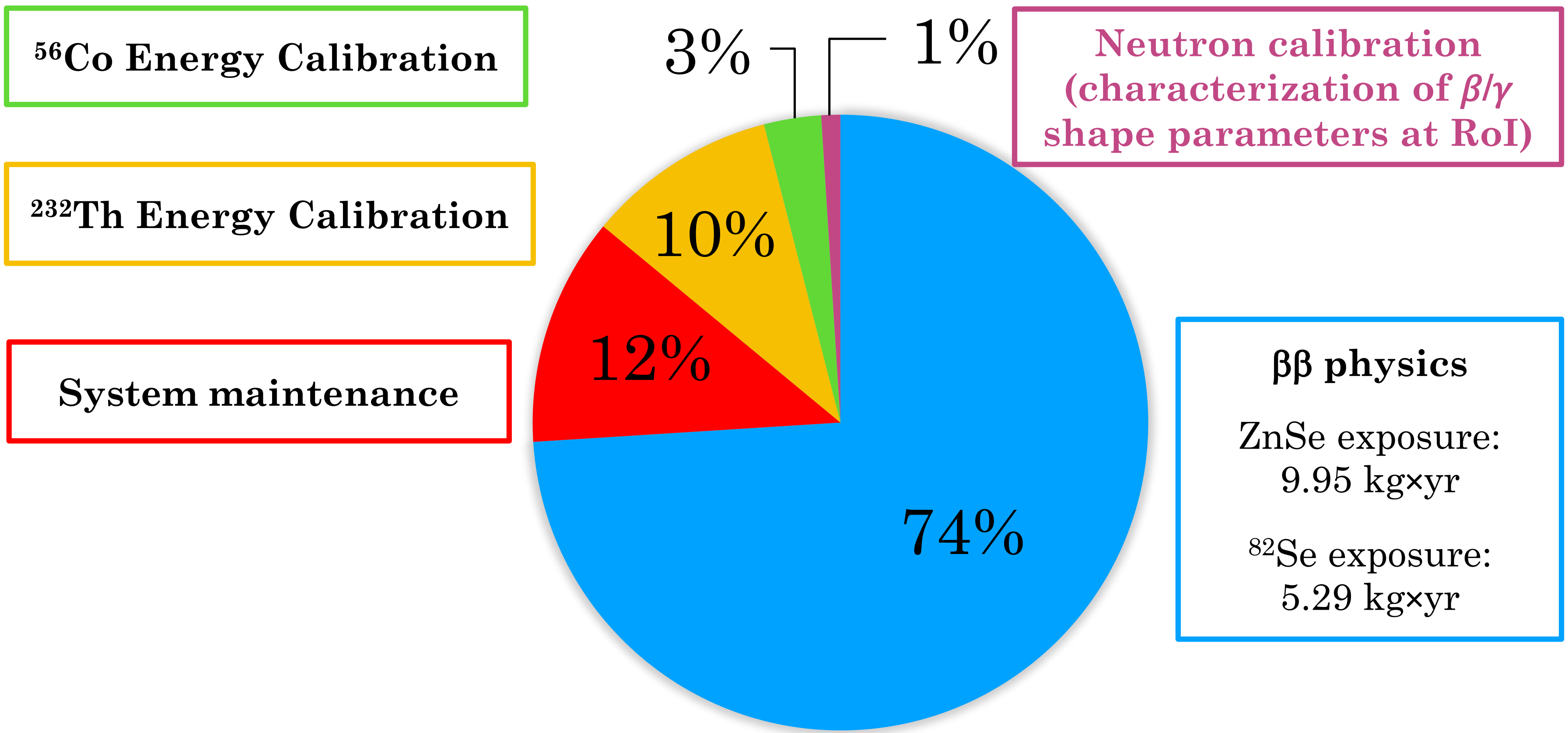
Installed in former CUORE-0 cryostat

CUPID-0 Data Taking (Phase 1)

- Data taking started on March 17th, 2017
- This talk: full statistics collected between June 2017 and Dec 2018

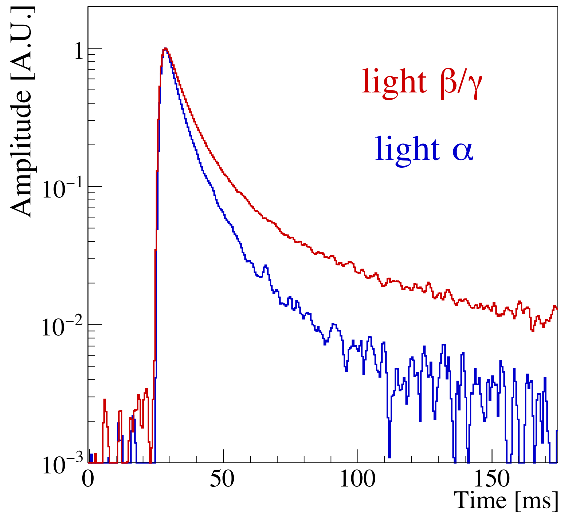
arXiv: 1904.10397 accepted by EPJC

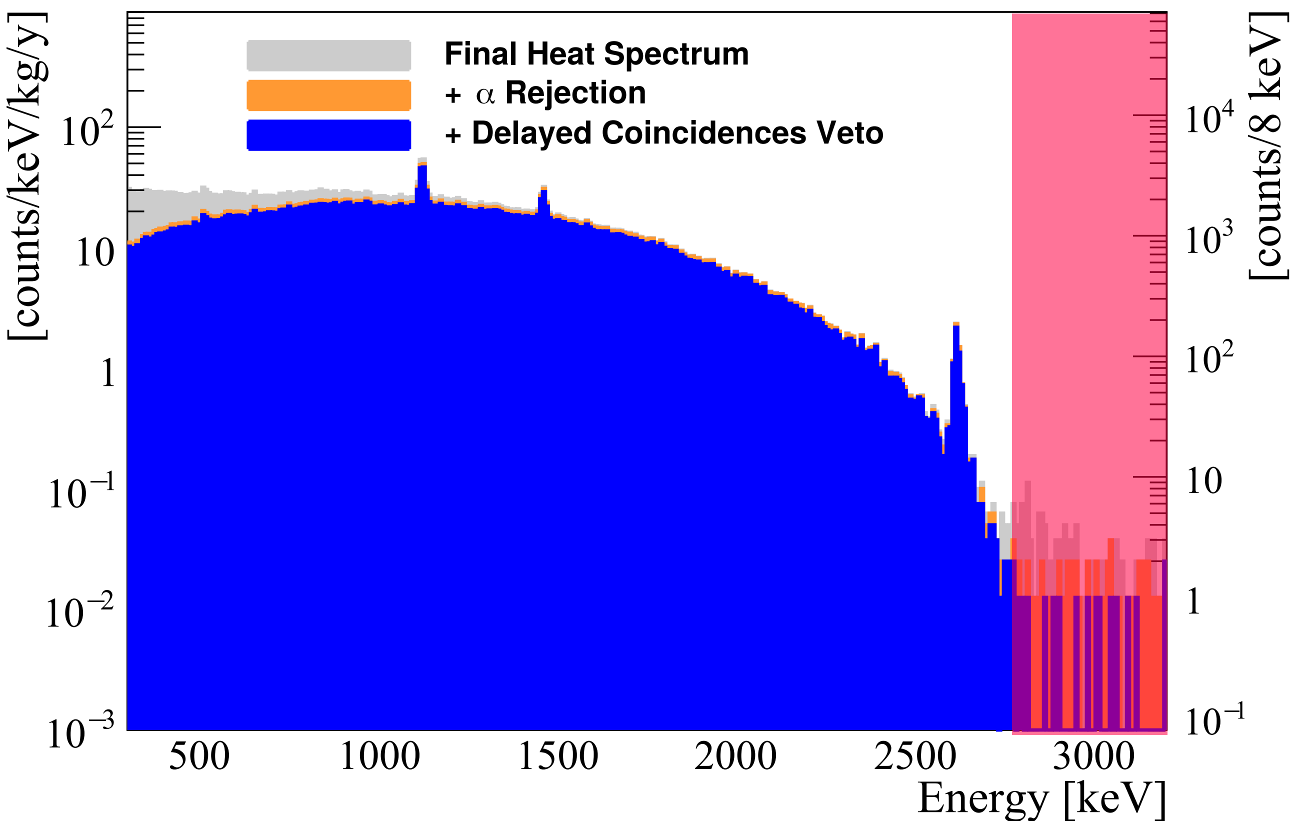
arXiv: 1906.05001 accepted by PRL

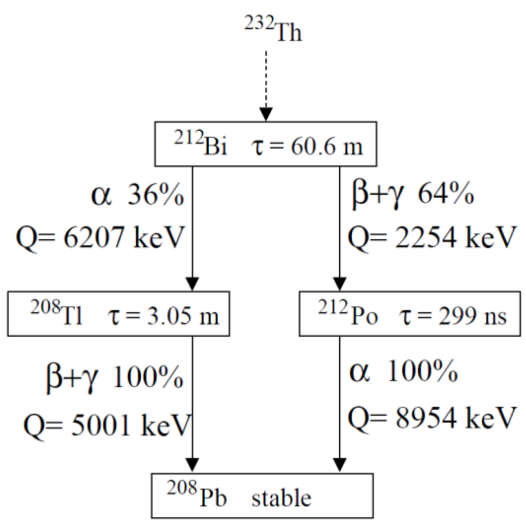


Data Analysis

- Reject "non-particle-like" events through pulse shape of thermal pulses
- Reject αs through pulse shape of light pulses
- Tag both internal and surface ^{212}Bi thanks to PID

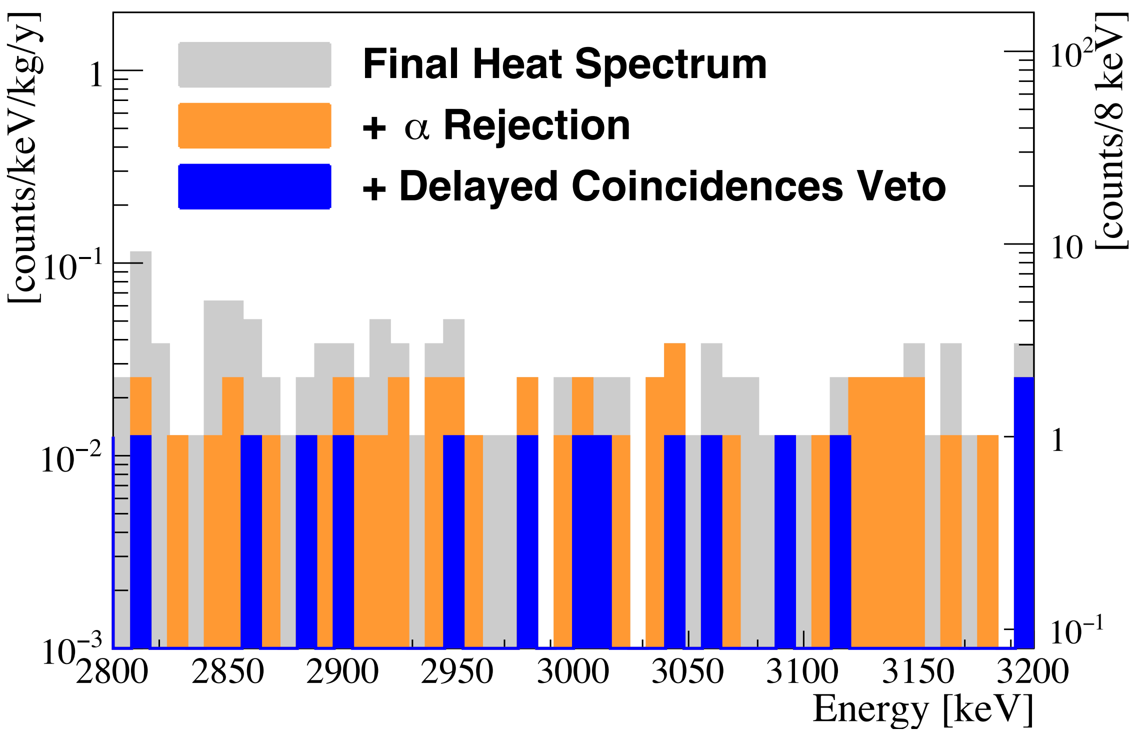






0νββ result

- Exposure: 5.29 kg yr of ^{82}Se
- Energy resolution at $Q_{\beta\beta}$: (20.0 ± 0.3) keV
- Efficiency (trigger + data selection + ββ containment): (70 ± 1)%
- Perform a UEML fit in the signal region



bkg = $(3.5^{+1.0}_{-0.9}) \cdot 10^{-3}$ cts/(keV kg yr)

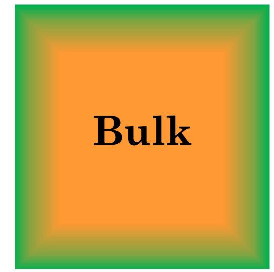
$T_{1/2}(^{82}Se \rightarrow ^{82}Kr) > 3.5 \cdot 10^{24}$ yr (90% C.I.)

Background model

- Use CUORE-like tool
- Model 33 sources

Internal/near sources to fit M1α spectrum

- **Crystals**: bulk / shallow surface $\mathcal{O}$(10nm) / deep surface $\mathcal{O}$(10μm)
- **Reflectors & Holder surface**: shallow surface $\mathcal{O}$(10nm) / deep surface $\mathcal{O}$(10μm)



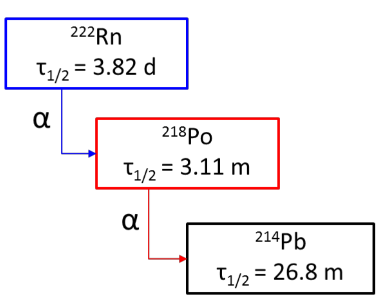
Surface: exponential profile

External sources

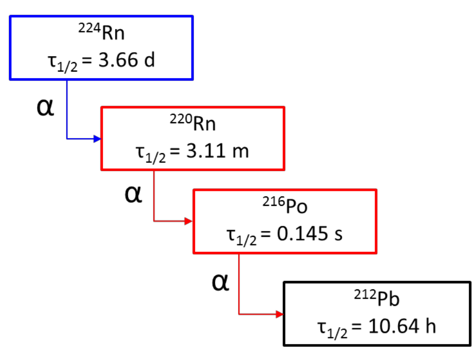
- **CryoInt**: 50mK and 600mK cryostat internal shields & holder bulk
- **IntPb**: ancient roman lead shield
- **CryoExt**: IVC, OVC, superinsulation, main bath & Extern... Lead shield

Exploit α-α delayed coincidences to access position contamination

^{238}U CHAIN



^{232}TH CHAIN



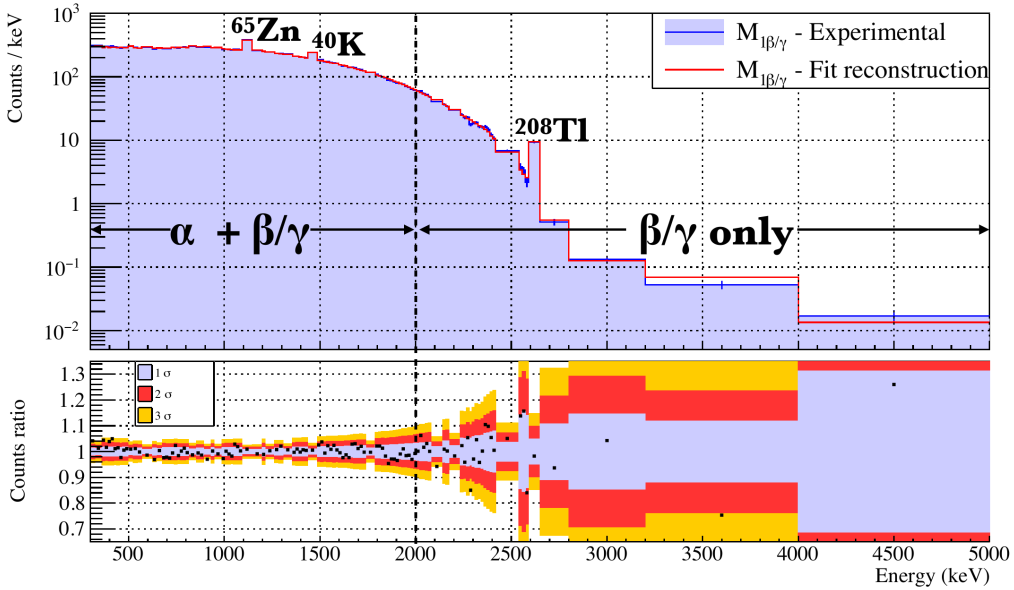
Given a ***parent*** event @ Q-value (P_Q), the probability to observe a time-correlated ***daughter*** event @ Q-value (D_Q):

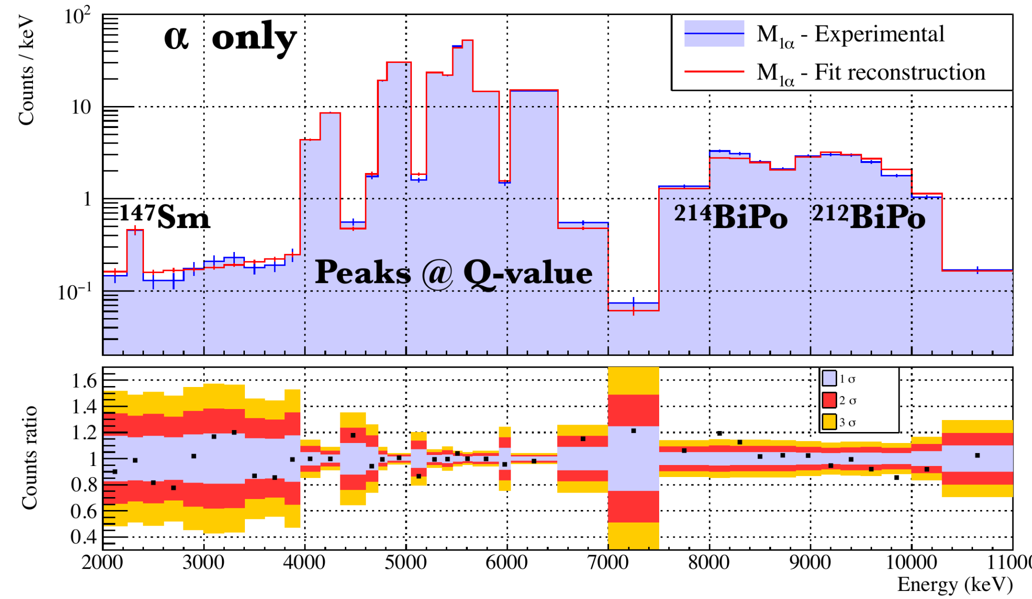
$$P(D_Q \mid P_Q)$$

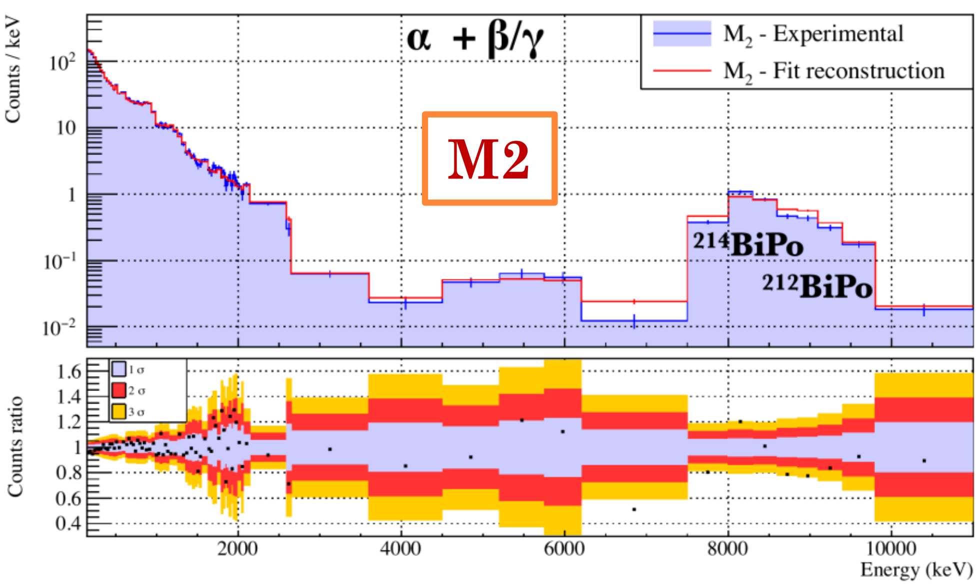
depends on source position (bulk vs surface).

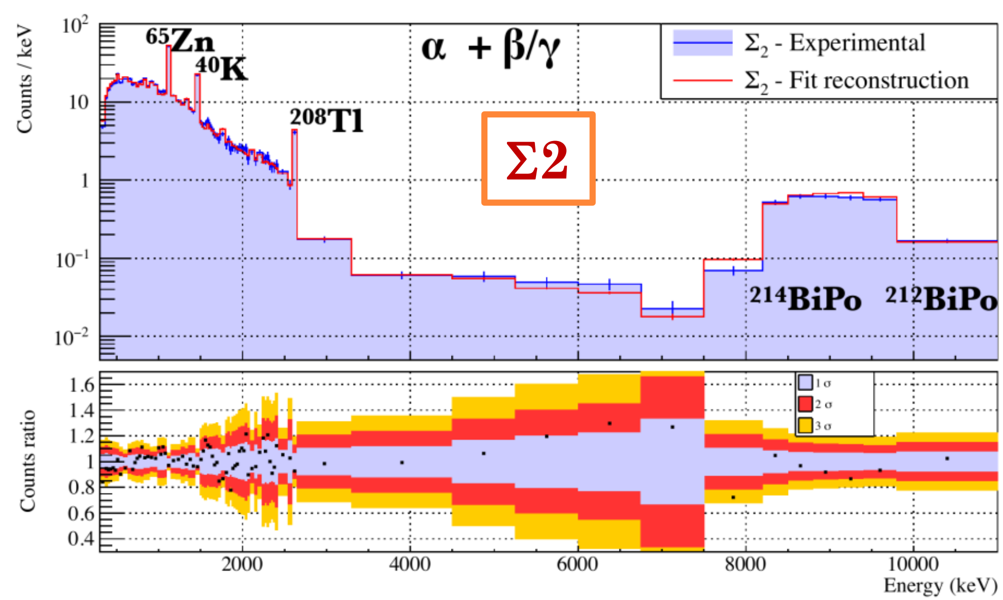
Background model results

- Use 4 spectra accordingly to particle type & multiplicity



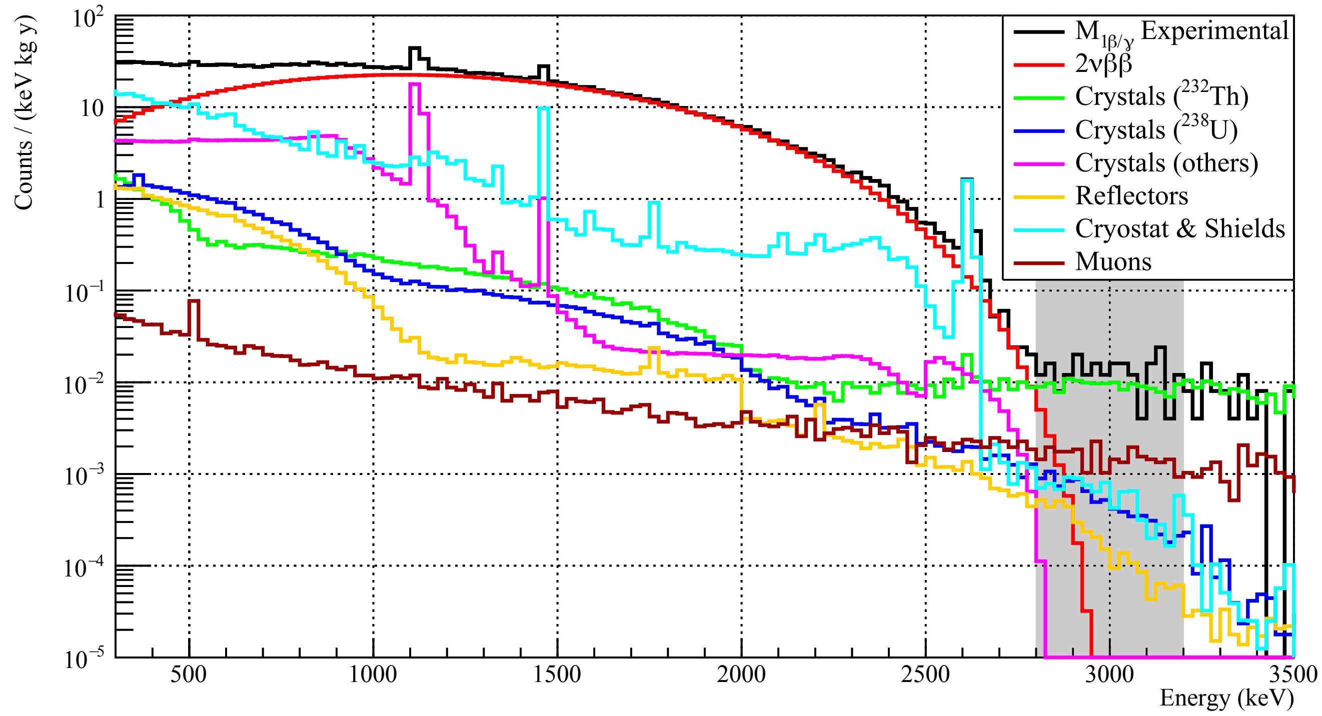






Background model (M1β/γ)

- 2νββ is the dominant contribution
- Delayed coincidence not applied in this plot



Background rate in the ROI (2.8 - 3.2 MeV) after the **delayed coincidences** cut.

Source	Rate (counts/(keV·kg·y))	Systematics
$2\nu\beta\beta$	$(6.0 \pm 0.3) \times 10^{-4}$	
Crystals bulk – ^{232}Th	$(3.4 \pm 0.6) \times 10^{-4}$	
Crystals surf – ^{232}Th	$(3.4 \pm 0.5) \times 10^{-4}$	$[2.2 - 4.7] \times 10^{-4}$
Crystals surf – ^{238}U	$(5.3 \pm 0.4) \times 10^{-4}$	$[5 - 7] \times 10^{-4}$
Reflectors – ^{232}Th	$< 7 \times 10^{-5}$	
Reflectors – ^{238}U	$(1.8 \pm 0.3) \times 10^{-4}$	$[1 - 3] \times 10^{-4}$
Cryostat & Shields – ^{232}Th	$(4.0 \pm 1.3) \times 10^{-4}$	$[0.7 - 11] \times 10^{-4}$
Cryostat & Shields – ^{238}U	$(2.2 \pm 0.4) \times 10^{-4}$	$[1.5 - 2.6] \times 10^{-4}$
Muons	$(1.53 \pm 0.13) \times 10^{-3}$	$[1.3 - 1.8] \times 10^{-3}$
Total	$(4.2 \pm 0.2) \times 10^{-3}$	$[4.1 - 4.8] \times 10^{-3}$

- Muons represent 44% of the background
- In Phase 2:
  - Muon veto
  - Reflector removed

^{82}Se 2νββ Half Life measurement

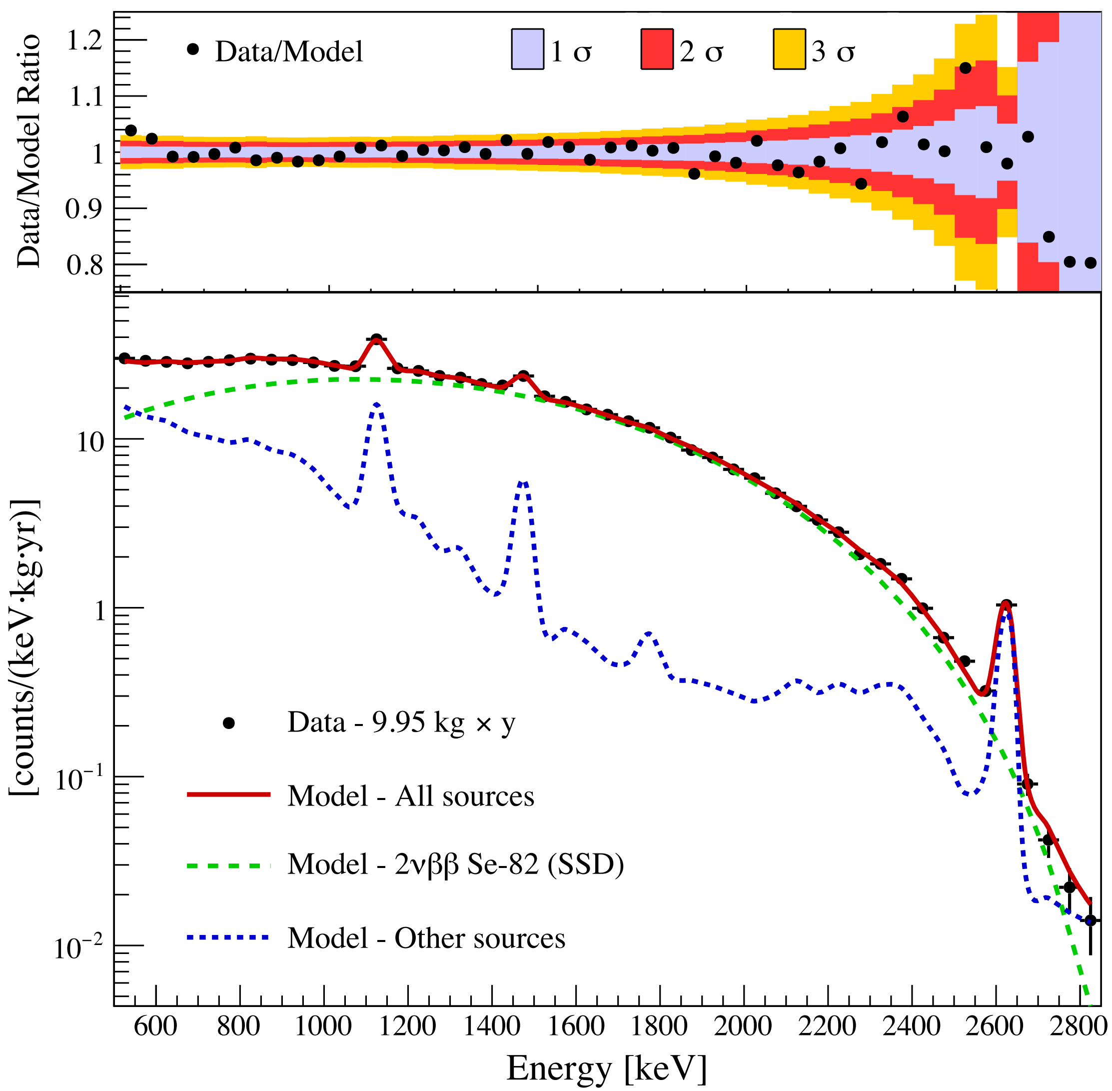
Evidence of Single State Dominance

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)

Spectra from nucleartheory.yale.edu and Jenni Kotila

	1600 - 2500	500 - 3000
S	6.2×10^4	2.7×10^5
B	0.4×10^4	0.7×10^4
S/B	~16	~4



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

Compatible at 1.3 σ with the recent NEMO-3 results

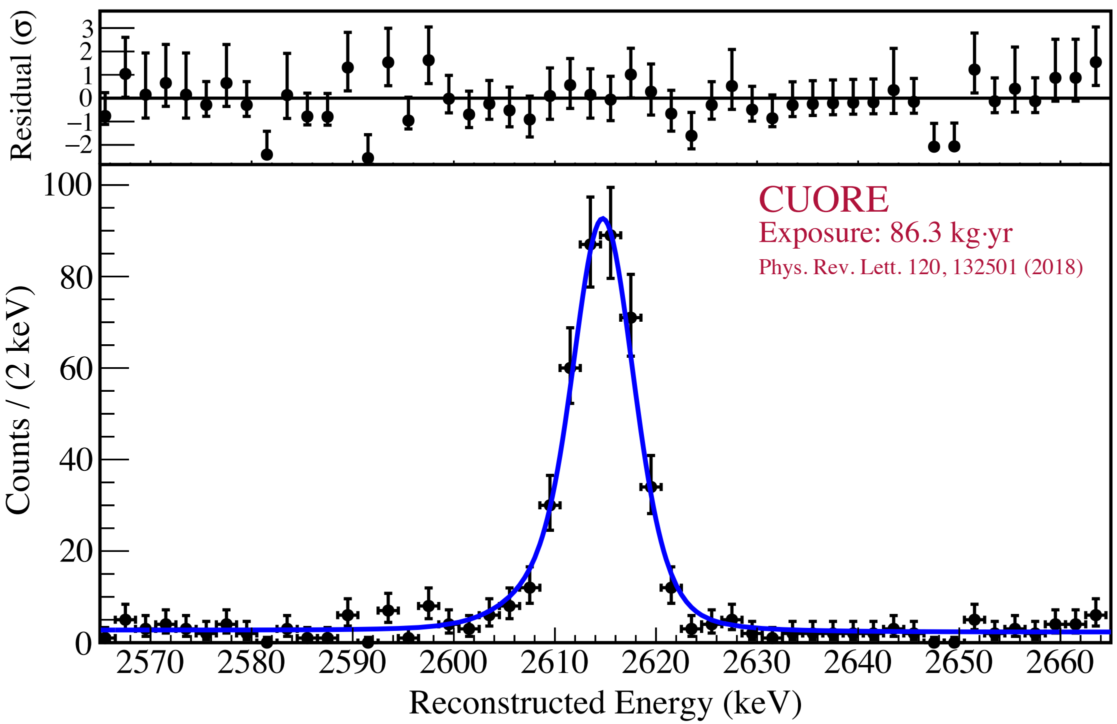
$$\mathcal{M}^{eff}_{2\nu} = g_A^2 \mathcal{M}_{2\nu} = 0.0762\ ^{+\ 0.0005}_{-\ 0.0006}$$

	Systematic Source	$\Delta A_{2\nu}$
Fit	Source localization	$^{+0.74}_{-0.23}$ %
	Reduced sources list	-0.11 %
	Fixed step binning	$+0.22$ %
	Threshold of $\mathcal{M}_1$	$^{+0.18}_{-0.06}$ %
	α-identification	$+0.01$ %
	Prior distributions	$+0.02$ %
	Combined	$^{+0.8}_{-0.3}$ %
Detector	Efficiency	± 0.5 %
	^{82}Se atoms	± 1.0 %
Total		$^{+1.4}_{-1.2}$ %

backup

Energy resolution

2615 keV ^{208}Tl γ peak



Resolution FWHM in Physics runs:

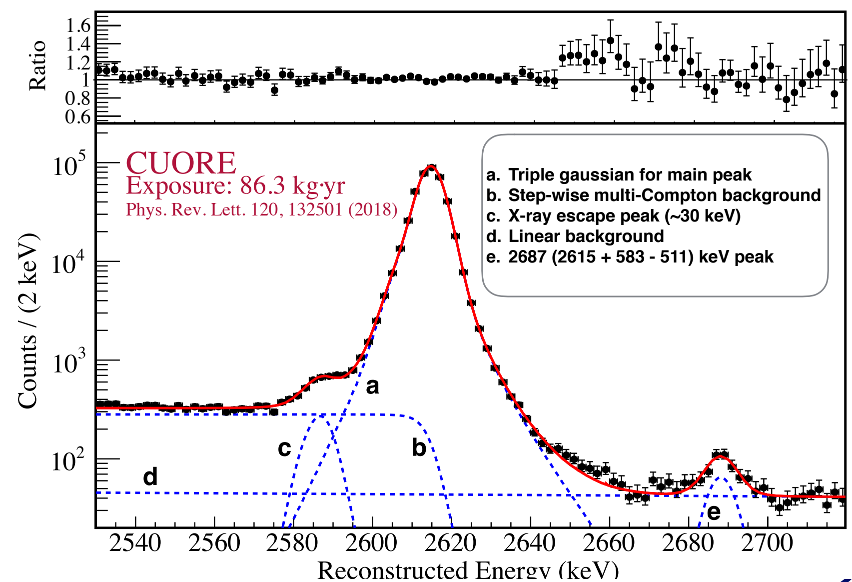
- Dataset 1: (8.3 ± 0.4) keV
- Dataset 2: (7.4 ± 0.7) keV
- Weighted avg: (7.7 ± 0.5) keV

Line shape per bolometer

Triple gaussian (a)

+ multi compton (b)+ linear background (d)

+ Te X-ray escape peak (c) + sum peak (e)



Crystals

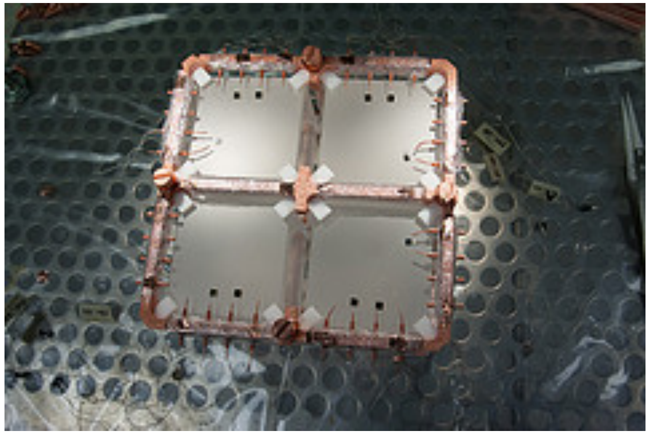
- Radio-purity control protocol to limit bulk & surface contaminations in crystal production

J. Crys.Growth 312 (2010) 2999-3008

Isotope	Allowed Contamination
^{238}U	$< 3 \cdot 10^{-13}$ g/g
^{232}Th	$< 3 \cdot 10^{-13}$ g/g
^{210}Pb	$< 1 \cdot 10^{-5}$ Bq/kg
^{210}Po	< 0.1 Bq/kg

- Benchmarked in dedicated runs at LNGS

Astropart. Phys. 35 (2012) 839–849



	Bulk(90% C.L. U.L.)	Surface(90% C.L.U.L)
^{238}U	$5 \cdot 10^{-14}$ g/g	$1 \cdot 10^{-9}$ Bq/cm^2
^{232}Th	$2 \cdot 10^{-13}$ g/g	$2 \cdot 10^{-9}$ Bq/cm^2
^{210}Pb	$3.3 \cdot 10^{-6}$ Bq/kg	$9.8 \cdot 10^{-7}$ Bq/cm^2
^{210}Po	0.05 Bq/kg	

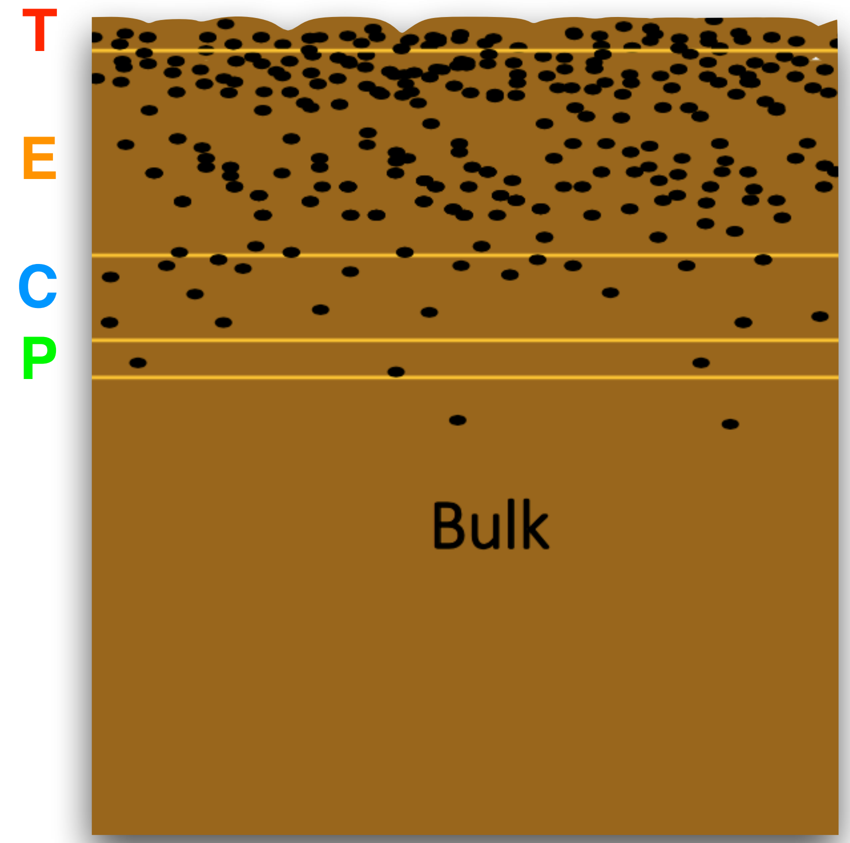
-

Copper Cleaning

- Bolometers: fully-active detectors, slow (~few sec)
  - Reduce near ^{232}Th bkgd: 2615+583 keV γ lines
  - Reduce detector counting rate: pile-up

	Surface (90% C.L.U.L)
^{238}U	$7 \cdot 10^{-7}$ Bq/cm^2
^{232}Th	$7 \cdot 10^{-8}$ Bq/cm^2
^{210}Po	$9 \cdot 10^{-7}$ Bq/cm^2

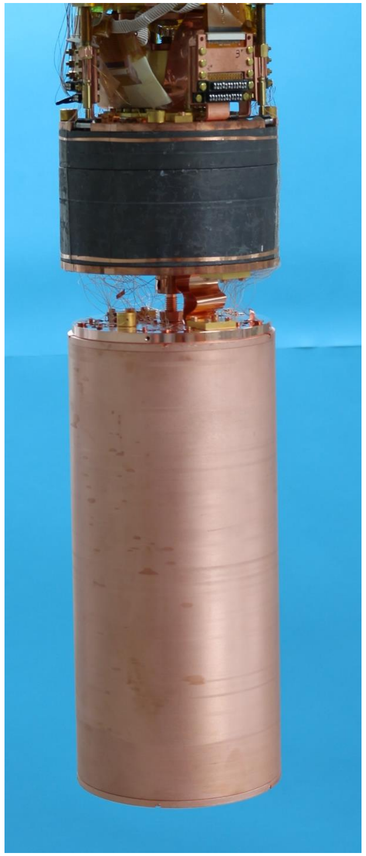
- **Pre-cleaning**: lubricant removal from machining
- **Tumbling**: abrasion + smoothening
  - removal 1.2 um (0.06 um/h)
- **Electropolishing**: smoothening+contaminants dissolution
  - removal 100 um (12 um/h)
- **Chemical etching**: SUBU+passivation
  - removal 10 um (120 um/h)
- **Plasma etching**: desorption
  - 0.2 um (1um/h)



CUPID-0 Phase 2

- μ are the main residual background
  - Installation of μ-veto

New clear Cu Shield
- Thermalization
- Additional shielding

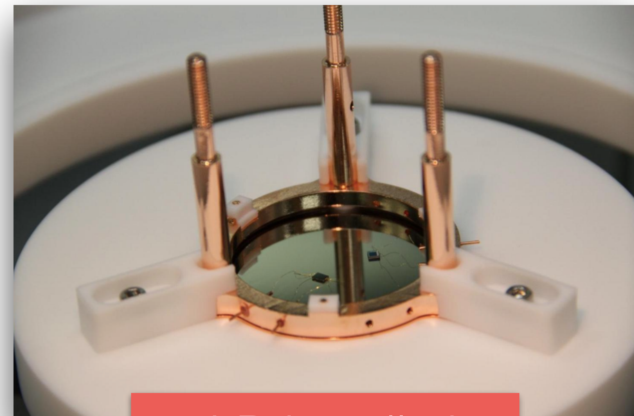


No reflective foil
- Sensitivity to M2 α events

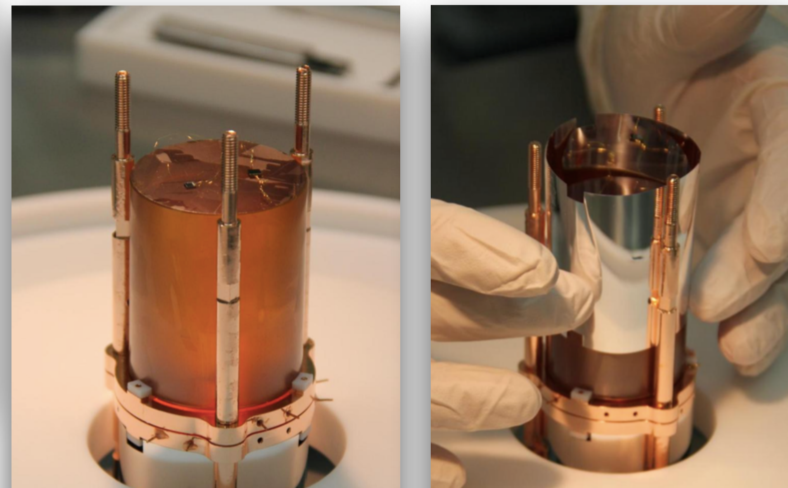
- Data taking already started

Detector assembly (II)

Performed in ~2 weeks inside a low-Rn underground clean room @ LNGS

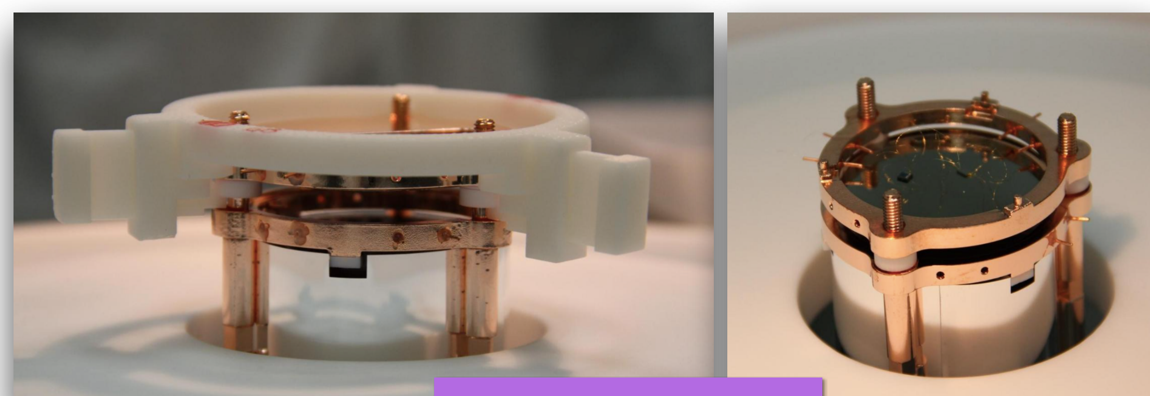


#1 LD installation

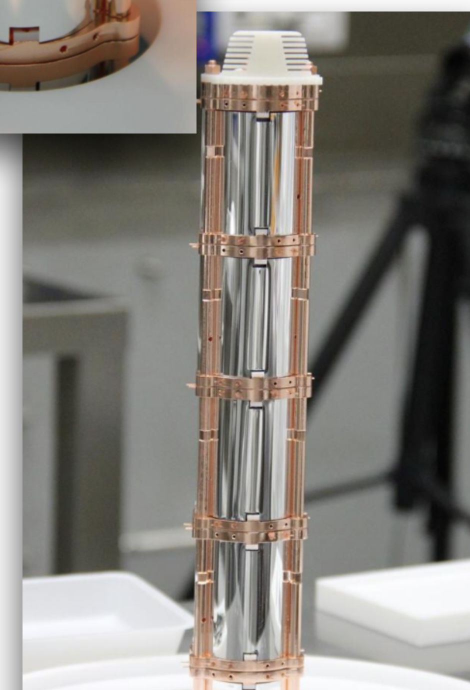


#2 ZnSe and light reflector installation

#3 Fixing of ZnSe



#4 LD installation

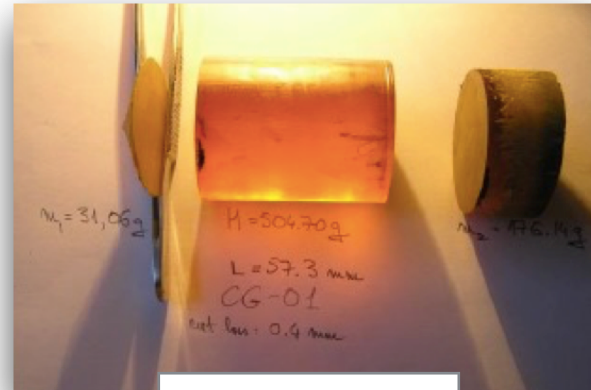


#5 Tower completed

ZnSe Crystal Production

- Complex process in extreme conditions: 20 bar in Ar & T~1500C
  - Synthesis + growth yield 85%
  - Manufacturing yield 60%

J Crys. Growth 475 (2017) 158



Crystal as grown

Crystal ready to be used

Radio-pure material selection

metal ^{82}Se

Chain	Nuclide	Activity [μBq/kg]
^{232}Th		
	^{228}Ra	< 61
	^{228}Th	< 110
^{238}U		
	^{226}Ra	< 110
	^{234}Th	< 6200
	^{234m}Pa	< 3400

metal Zn

Chain	Nuclide	Activity [μBq/kg]
^{232}Th		
	^{228}Ra	< 95
	^{228}Th	< 36
^{238}U		
	^{226}Ra	< 66
	^{234}Th	< 6200
	^{234m}Pa	< 4700

Eur. Phys. J. C (2015) 75:591

	Zn^{82}Se-1 (μBq/kg)	Zn^{82}Se-2 (μBq/kg)	Zn^{82}Se-3 (μBq/kg)	Array (μBq/kg)
^{232}Th	13 ± 4	13 ± 4	<5	7 ± 2
^{228}Th	32 ± 7	30 ± 6	22 ± 4	26 ± 2
^{224}Ra	29 ± 6	26 ± 5	23 ± 5	27 ± 3
^{212}Bi	31 ± 6	31 ± 6	23 ± 5	29 ± 3
^{238}U	17 ± 4	20 ± 5	<10	10 ± 2
^{234}U+^{226}Ra	42 ± 7	30 ± 6	23 ± 5	33 ± 4
^{230}Th	18 ± 5	19 ± 5	17 ± 4	18 ± 3
^{218}Po	20 ± 5	24 ± 5	21 ± 5	21 ± 2
^{210}Pb	100 ± 11	250 ± 17	100 ± 12	150 ± 8

Zn^{82}Se test run

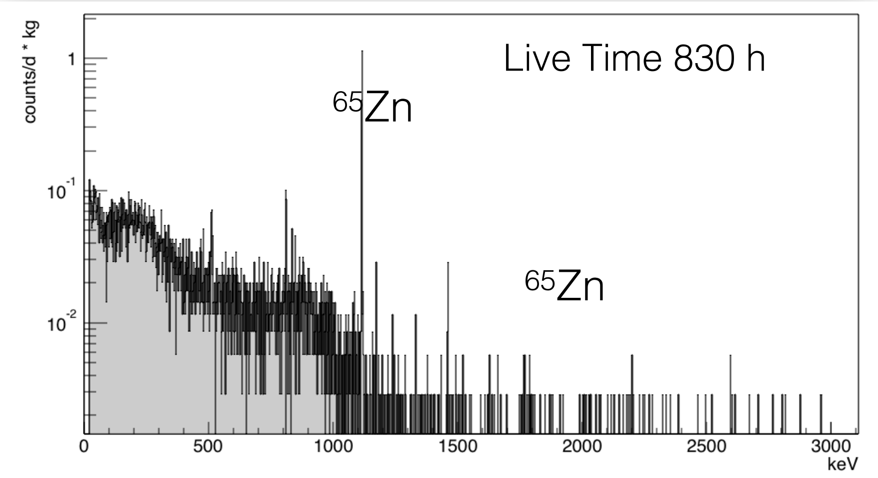
Eur. Phys. J. C76 (2016) 7, 364

Starting material: HP-Zinc

Producer: National Science Center KITP (Ukraine)

Internal radioactive and chemical contaminations measured @ LNGS

10 kg of zinc on a HP-Ge detector



^{238}U and ^{232}Th contaminations below the detector sensitivity.
No lines over 1 month of measurement

with HP-Ge GeMPI4

Limits @ 90%CL

Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{228}Ra	< 95
	^{228}Th	< 36
^{238}U	^{226}Ra	< 66
	^{234}Th	< 6200
	^{234m}Pa	< 4700
^{235}U	^{235}U	< 91
	^{40}K	< 380
	^{60}Co	< 36
	^{65}Zn	5200±600
	^{56}Co	80±20
	^{57}Co	200±90
	^{58}Co	220±40
	^{54}Mn	110±20

@ 25 OCT 2014

Not dangerous for bkg
low Q-value
and/or short half-life

with ICP-MS

Cd < 2.3 ppm
others < 0.2 ppm

^{56}Co:
β- Q:4566 keV
but $T_{1/2}$=77 days

J Crys. Growth 475 (2017) 158

Starting materials: ^{82}Se

Internal radioactive and chemical contaminations measured @ LNGS

15 kg of ^{82}Se from URENCO (Netherlands)

Natural SeF_6

centrifuge cascade (dedicated line)

chemical conversion: SeF_6 gas to ^{82}Se metal

^{82}Se metal:
- ➜ @ 95% enrichment
- ➜ @ 99.5% chemical purity

with HP-Ge GeMPI4

Limits @ 90%CL

Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{228}Ra	< 61
	^{228}Th	< 110
^{238}U	^{226}Ra	< 110
	^{234}Th	< 6200
	^{234m}Pa	< 3400
^{235}U	^{235}U	< 74
^{40}K	^{40}K	< 990
^{60}Co	^{60}Co	< 65
^{75}Se	^{75}Se	110 ± 40

@ 8 OCT 2014

with ICP-MS

S	130÷250 ppm
others	<0.5 ppm

$^{76}Se(n,2n)^{75}Se$ has a rather large neutron interaction cross section: 979 ± 90 mb for 16 MeV neutrons

Selenium isotopic abundance

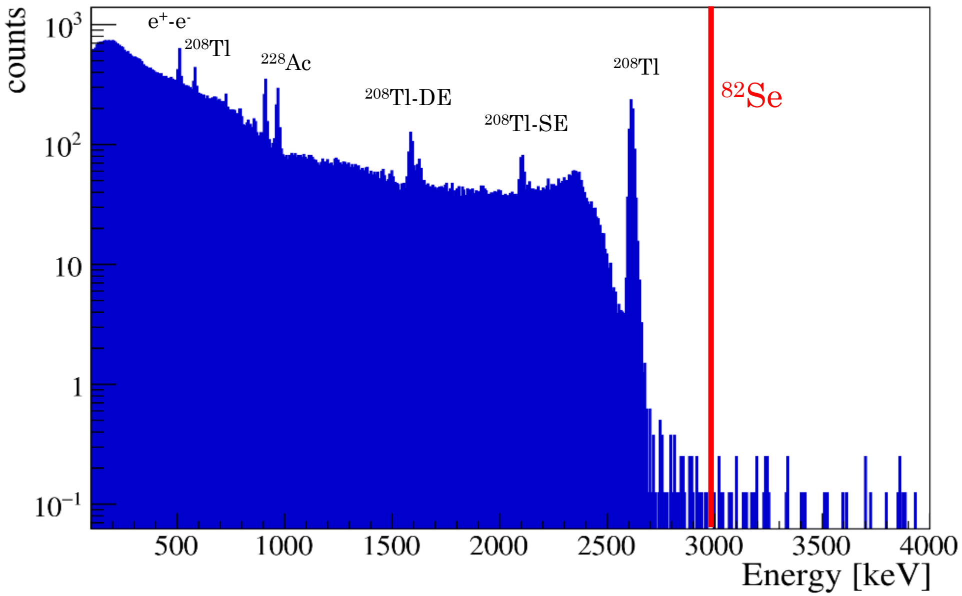
	^{74}Se	^{76}Se	^{77}Se	^{78}Se	^{80}Se	^{82}Se
Nat. Se [%]	0.87	9.36	7.63	23.78	49.61	8.73
Enr. Se [%]	<0.01	<0.01	<0.01	<0.01	3.67±0.14	96.33±0.31

J Crys. Growth 475 (2017) 158

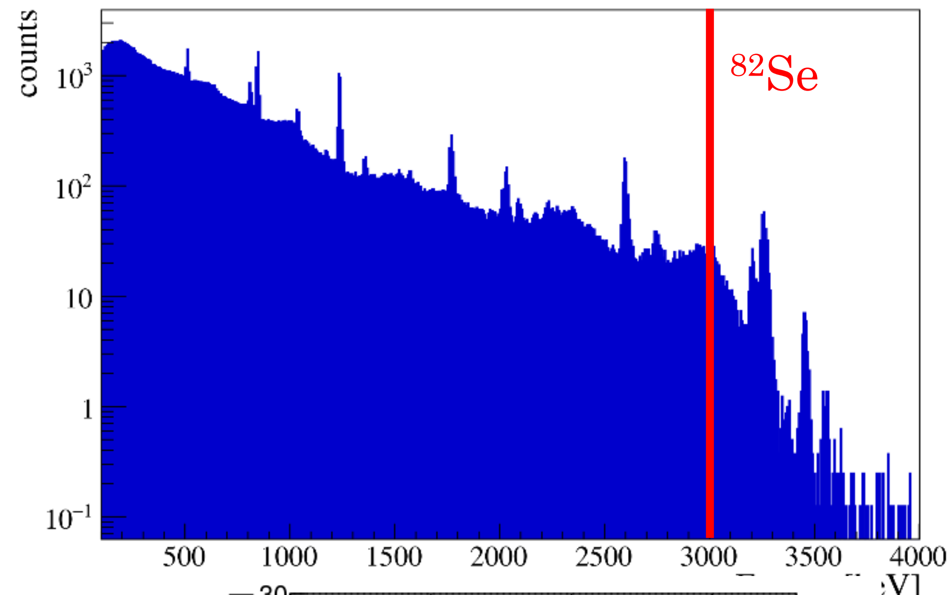
Eur. Phys. J. C (2015) 75:591

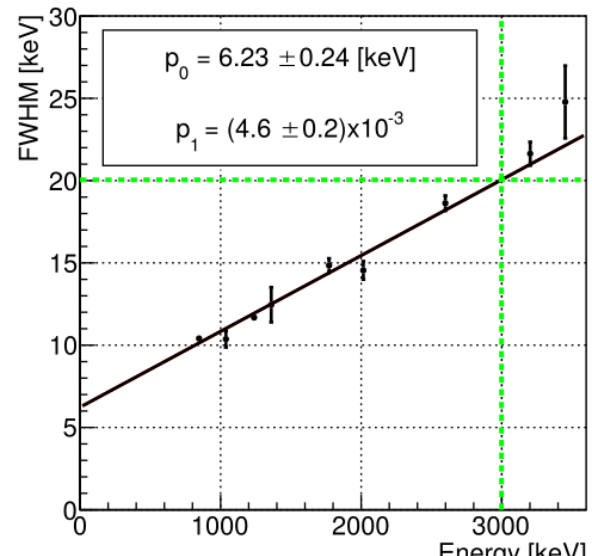
Energy Calibration (I)

Periodical calibration with ^{232}Th sources



Cross-check with ^{56}Co calibration (Q-value ~ 4.57 MeV, $T_{1/2}$ ~ 77 d

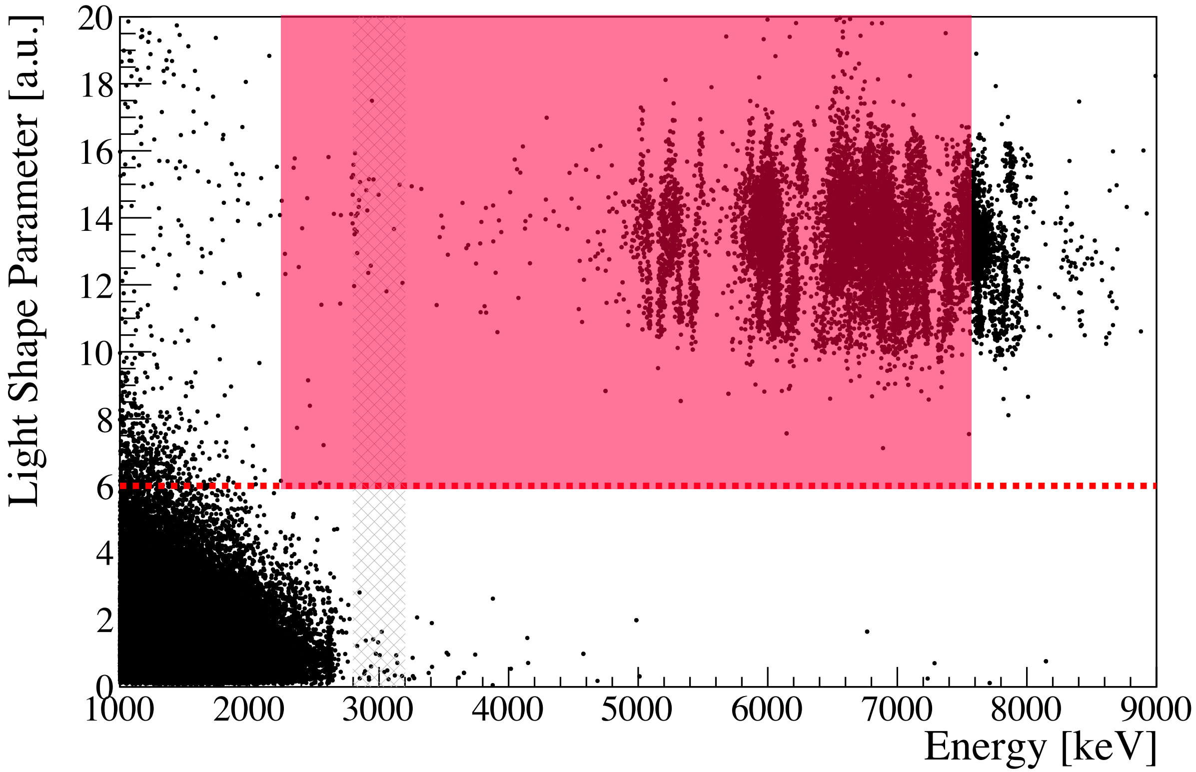


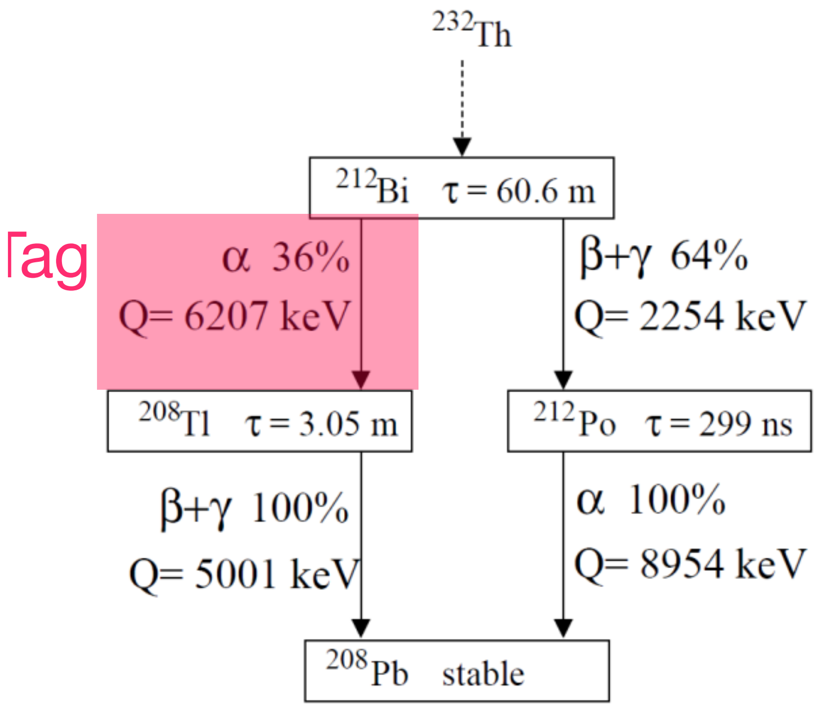


ΔE_{FWHM} at $Q_{\beta\beta}$: (20.0 ± 0.3) keV

Delayed coincidences

- ^{208}Tl internal β/γ decay (Q_{value} ~5 MeV) produces background
- It decays with $\tau_{1/2}$ ~3 min following a ^{212}Bi α decay
- Veto events occurring after a ^{212}Bi decay in $\Delta T = 7\ \tau_{1/2}$

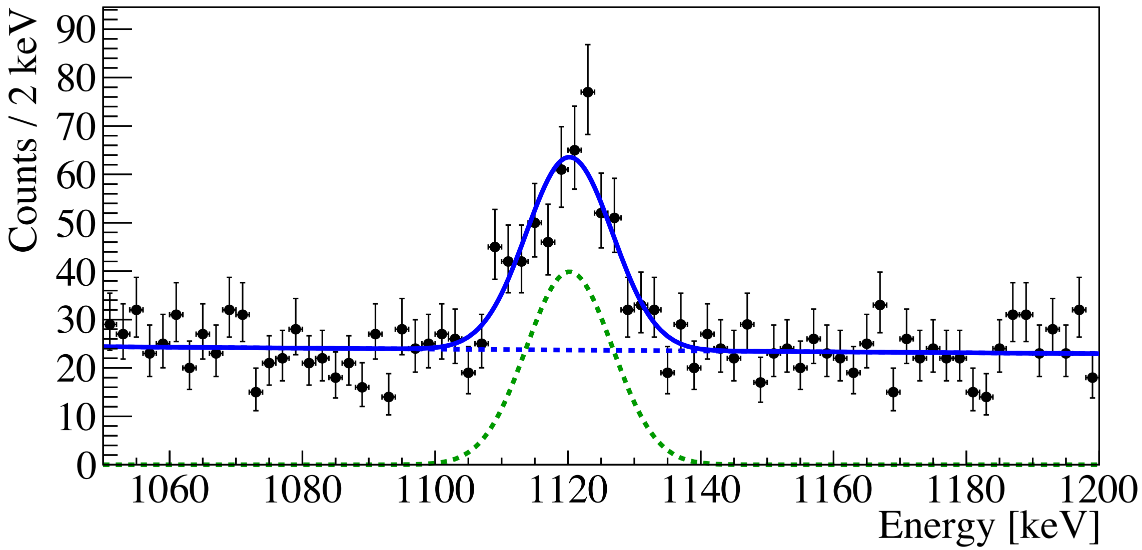


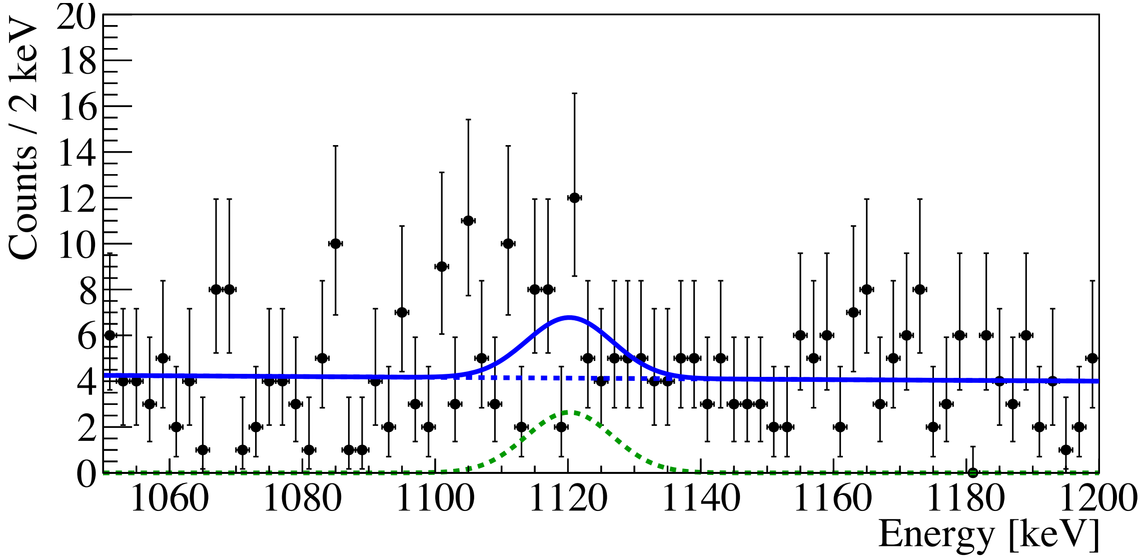


- We can tag both internal and surface ^{212}Bi thanks to the Particle ID
- Global Data Selection Efficiency: (93 ± 2)%

Efficiency on heat channel

- Fit of the most prominent peak (^{65}Zn). Cross check on ^{40}K peak and double coincident events





Efficiency on light channel

- Select electromagnetic showers induced by muons interactions,
  - Signals in 5 or more ZnSe crystals
- Set the cut to have 100% efficiency on these events