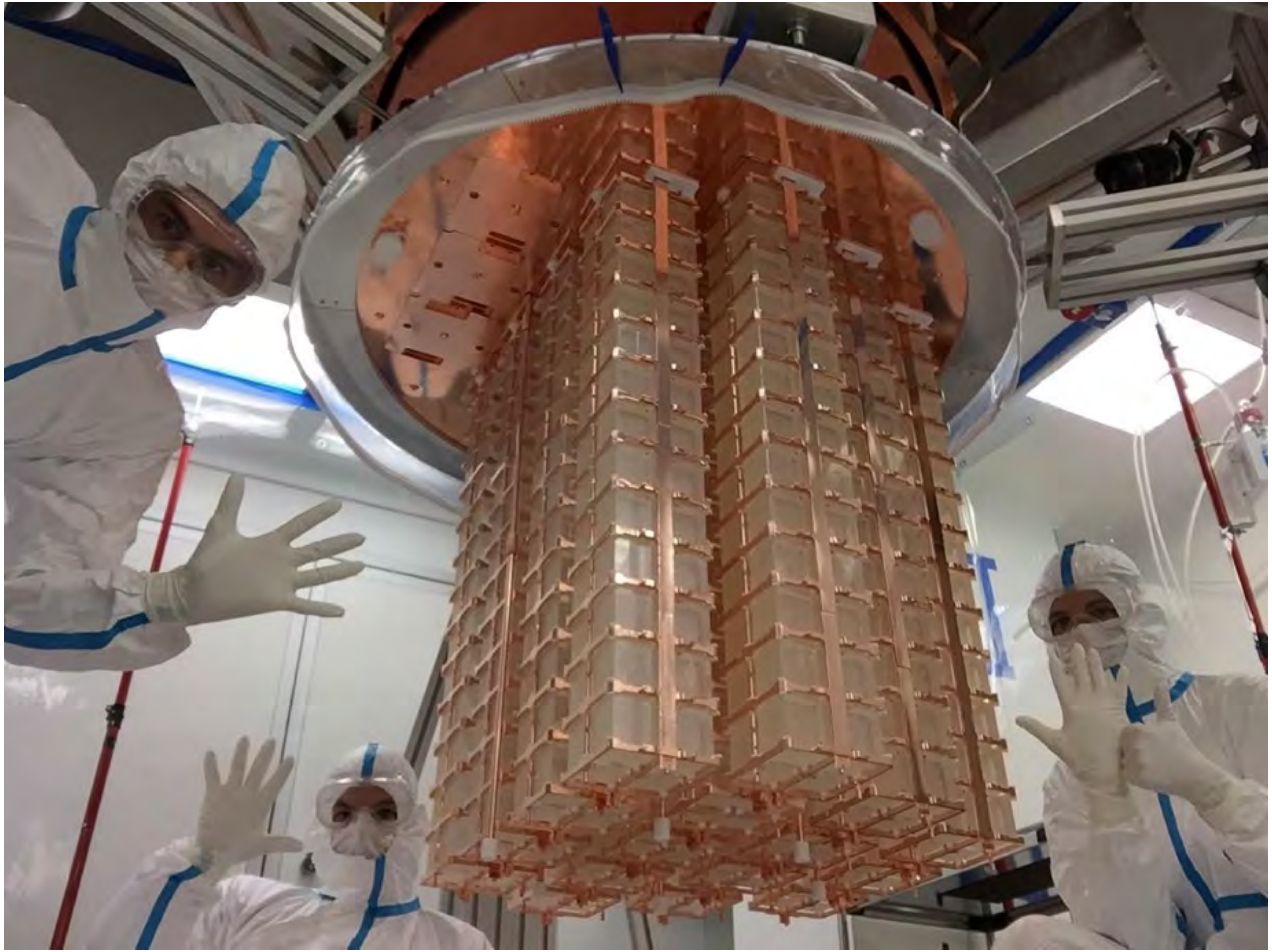
CUORE

CUORE

O.Cremonesi
LNF - 10/12/2018



Outline

- Neutrinoless Double Beta Decay
- CUORE
    - Construction
    - Operation
    - Results
- Future perspectives

NEUTRINO-LESS DOUBLE BETA DECAY

ββ decay

Rare nuclear decay between isobar nuclei with |ΔQ|=2

Even-even nuclei: **ONLY** direct $0^+ \rightarrow 0^+$ transition

Different modes:

- (A,Z) → (A,Z+2) + 2e– + $2\bar{\nu}$ (2νββ)
  - Standard 2nd order weak nuclear transition
  - Long lifetime ($10^{18\text{-}24}$ yr)
- **(A,Z) → (A,Z+2) + 2e⁻ (0νββ)**
  - Lepton number violation (LNV): physics beyond the SM

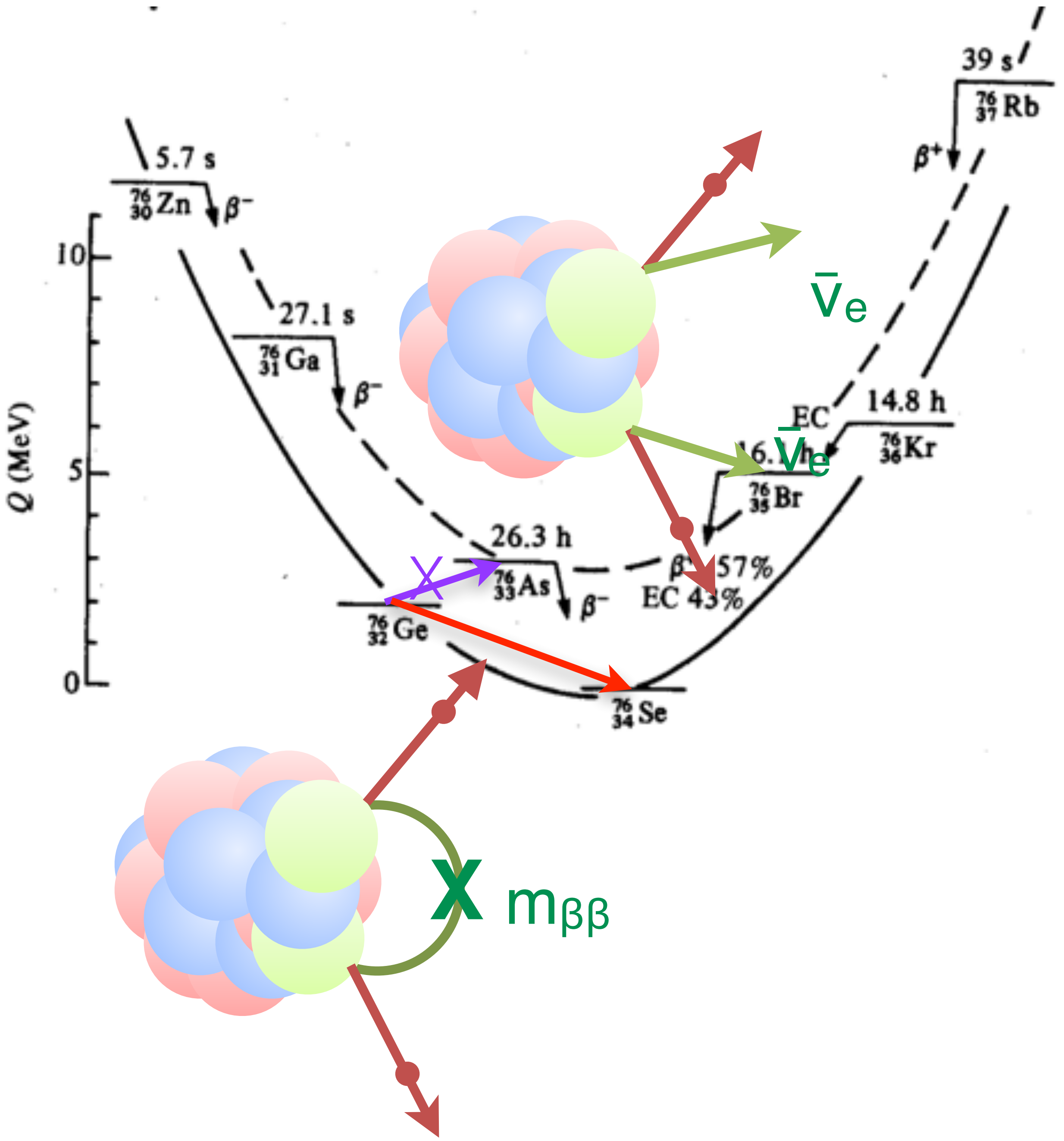
    Only possible if neutrinos are Majorana fermions

    → LNV (ΔL=2)

    → absolute neutrino mass scale

    → Majorana phases

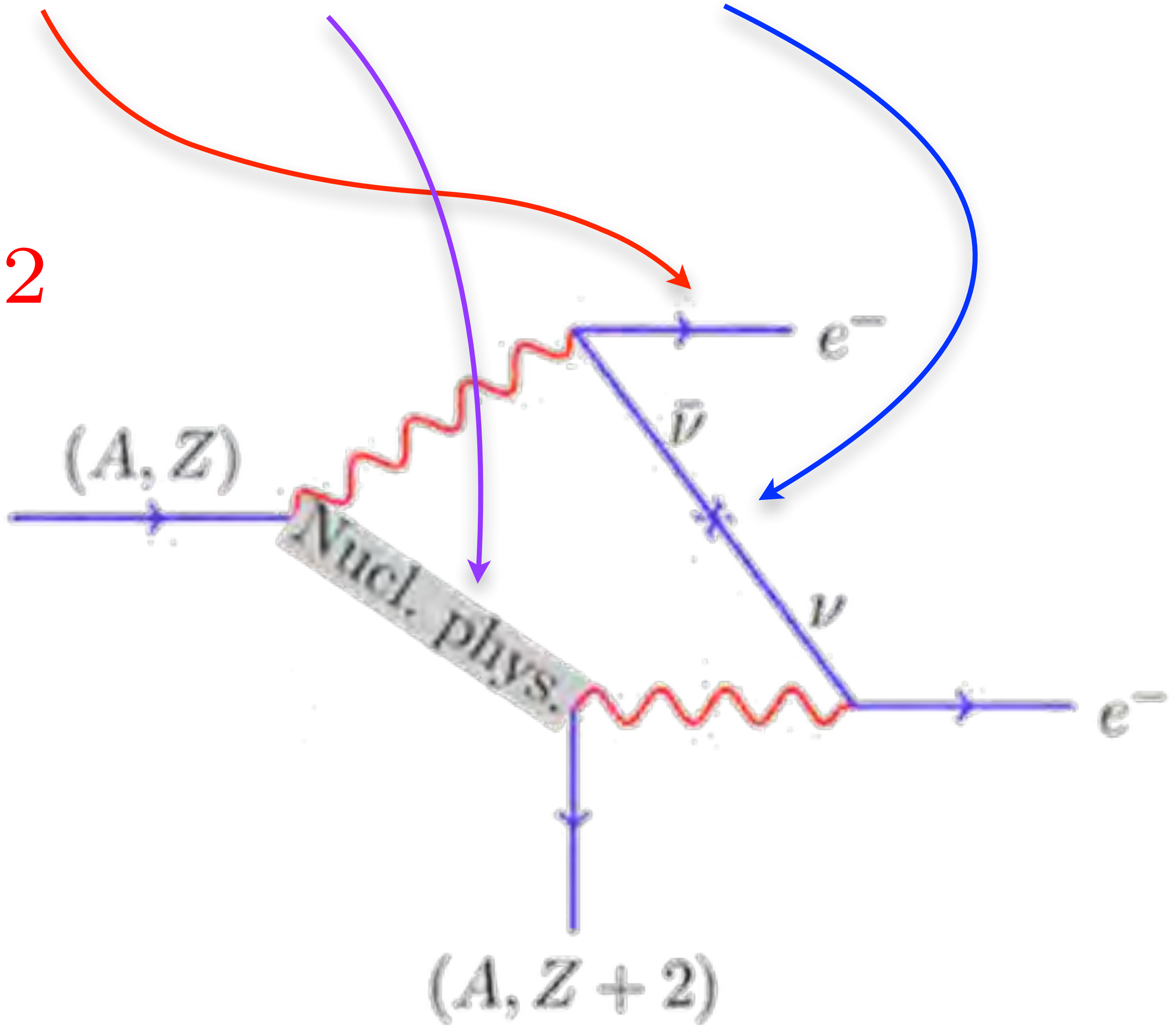
    SM extensions
- (A,Z) → (A,Z+2) + nχ (exotic modes)



0νββ decay width

Under non trivial approximations it is possible to separate atomic, nuclear and particle contributions and factoring the transition width as

$$\Gamma^{0\nu} = G_x(Q,Z)|M_x(A,Z)|^2|\eta_x|^2$$



$G_x(Q,Z)$ = phase space factor → precisely calculable

$M_x(A,Z)$ = nuclear matrix element → problematic

η_x = particle physics parameter → model dependent

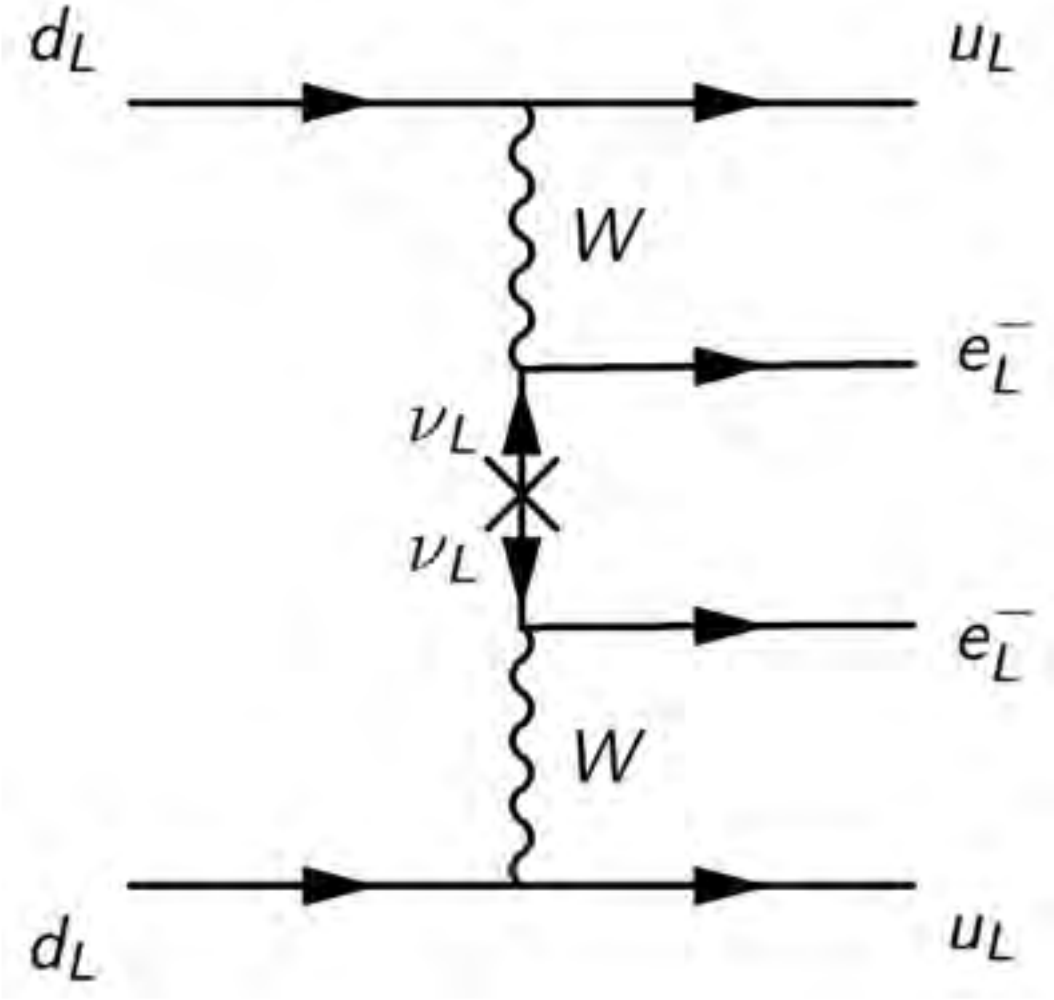
- massive Majorana neutrinos
- GUT's
- SUSY
- …

Lepton number violation (LNV) and *0νββ*

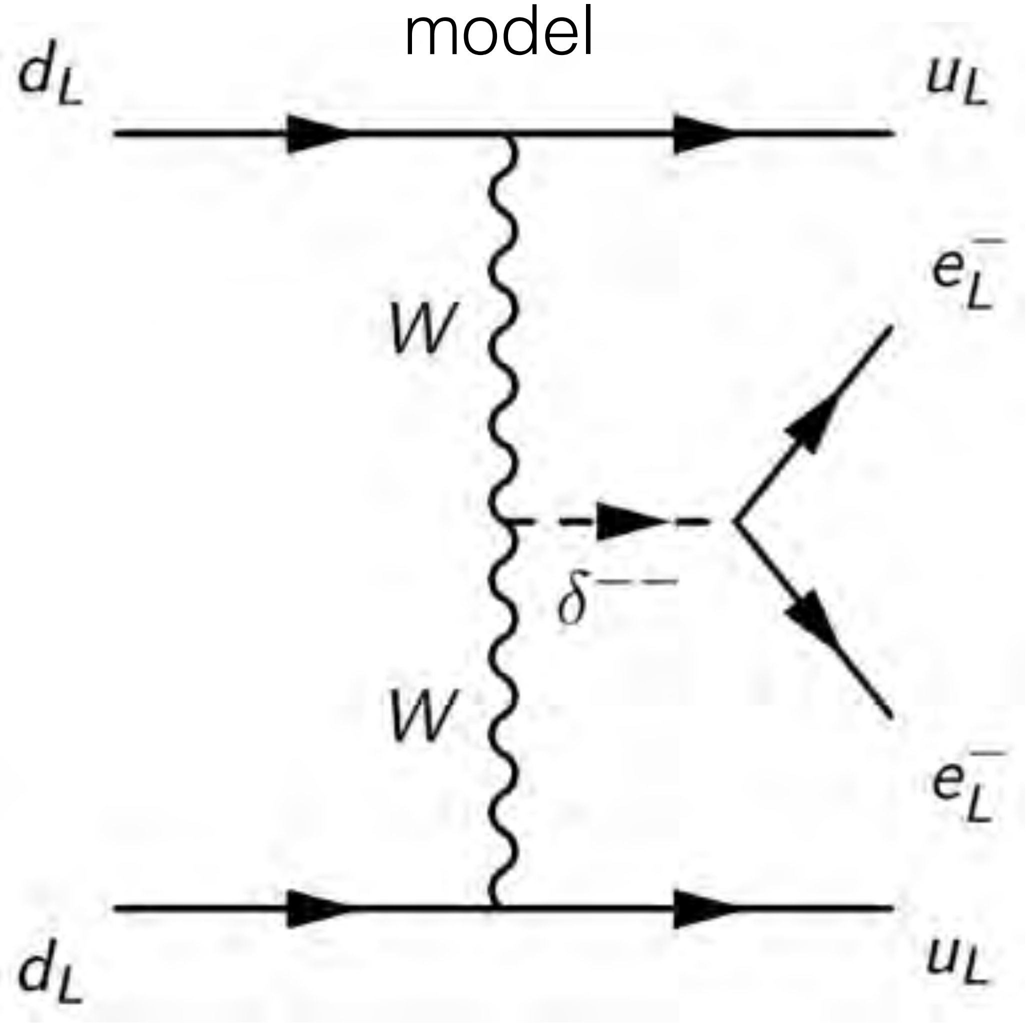
$A_{\beta\beta} \sim m_{ee}$

$A_{\beta\beta} \sim$ LNV parameters

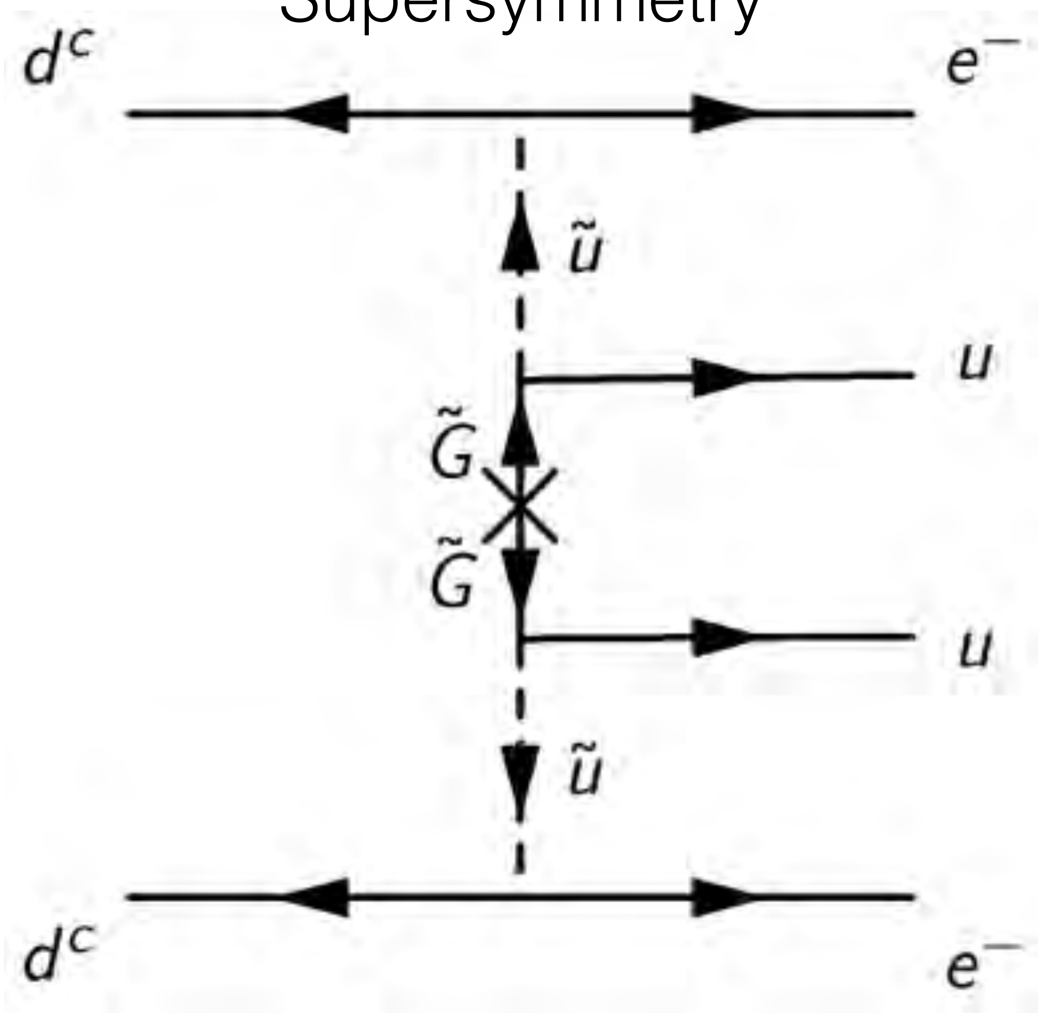
Mass mechanism



Higgs triplet model



Supersymmetry



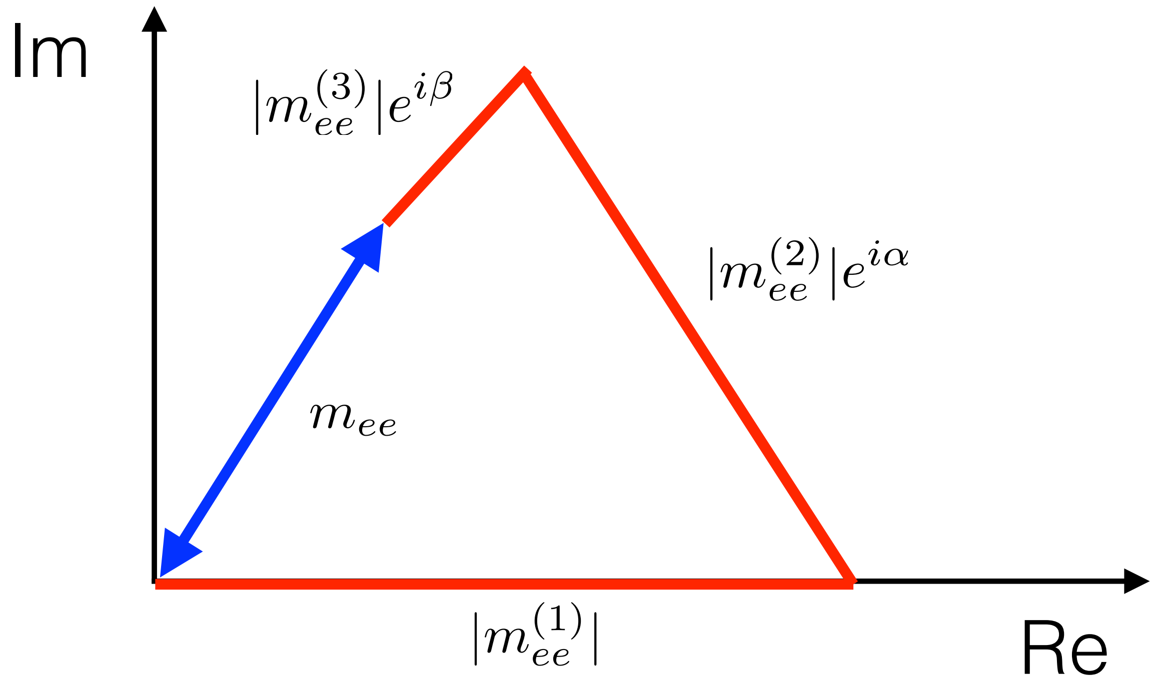
ββ0ν standard interpretation: light Majorana neutrino

- Neutrinoless Double Beta Decay is mediated by light massive Majorana neutrinos and all other potential mechanisms give negligible or no contribution

$$\eta_x = < m_{ee} >= \sum_k U_{ek}^2 m_k$$

$$= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

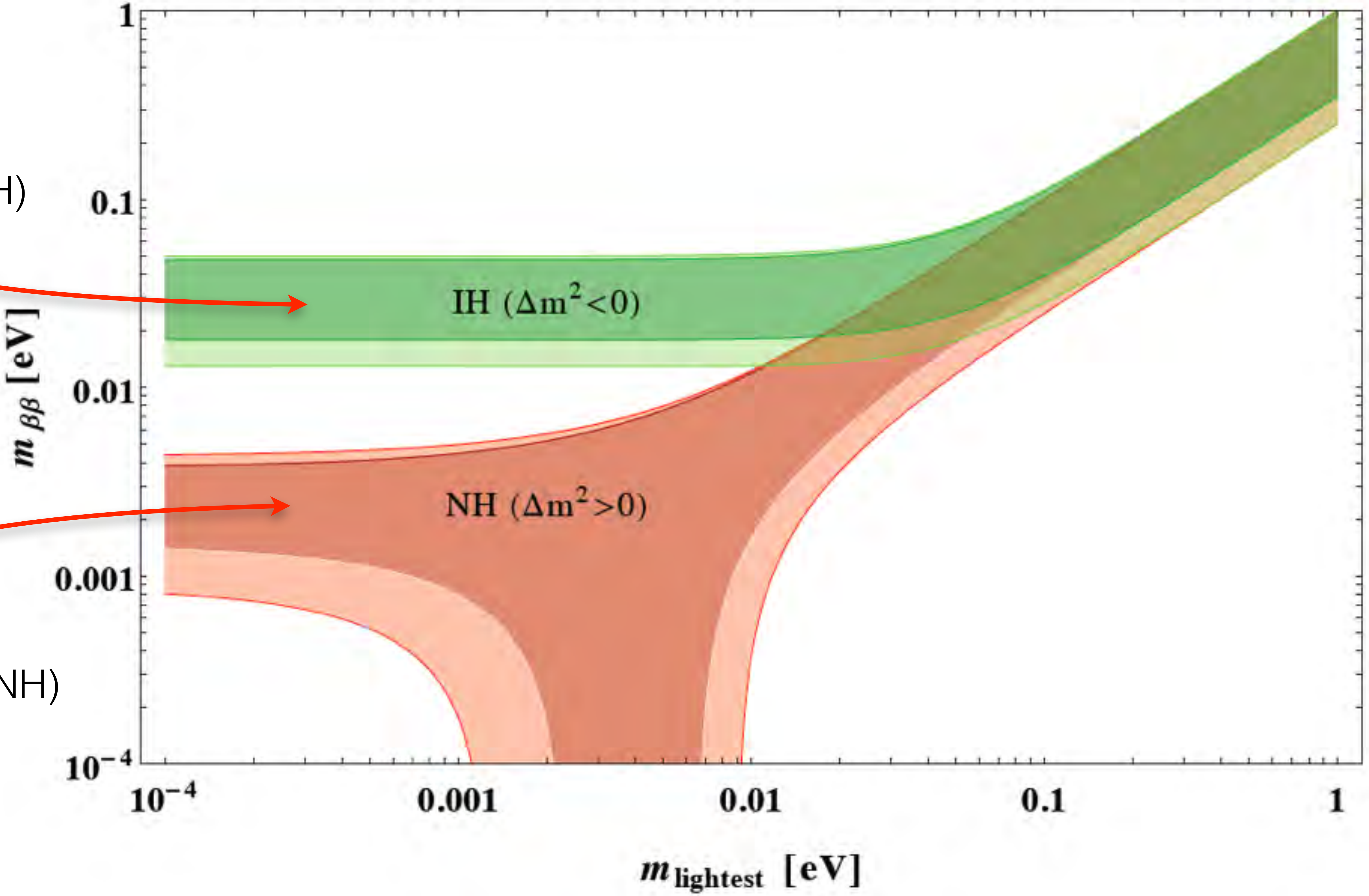
- The transition amplitude is proportional to coherent sum of neutrino masses
- Majorana phases play a crucial role: possible cancellations



Light Majorana neutrino

Inverse Ordering (IO or IH)

Normal Ordering (NO or NH)



Dell'Oro, Marcocci, Vissani, PRD 90.033005

Distinguishing 0νββ mechanisms

A single measurement of total rate cannot pin down underlying 0νββ mechanisms.

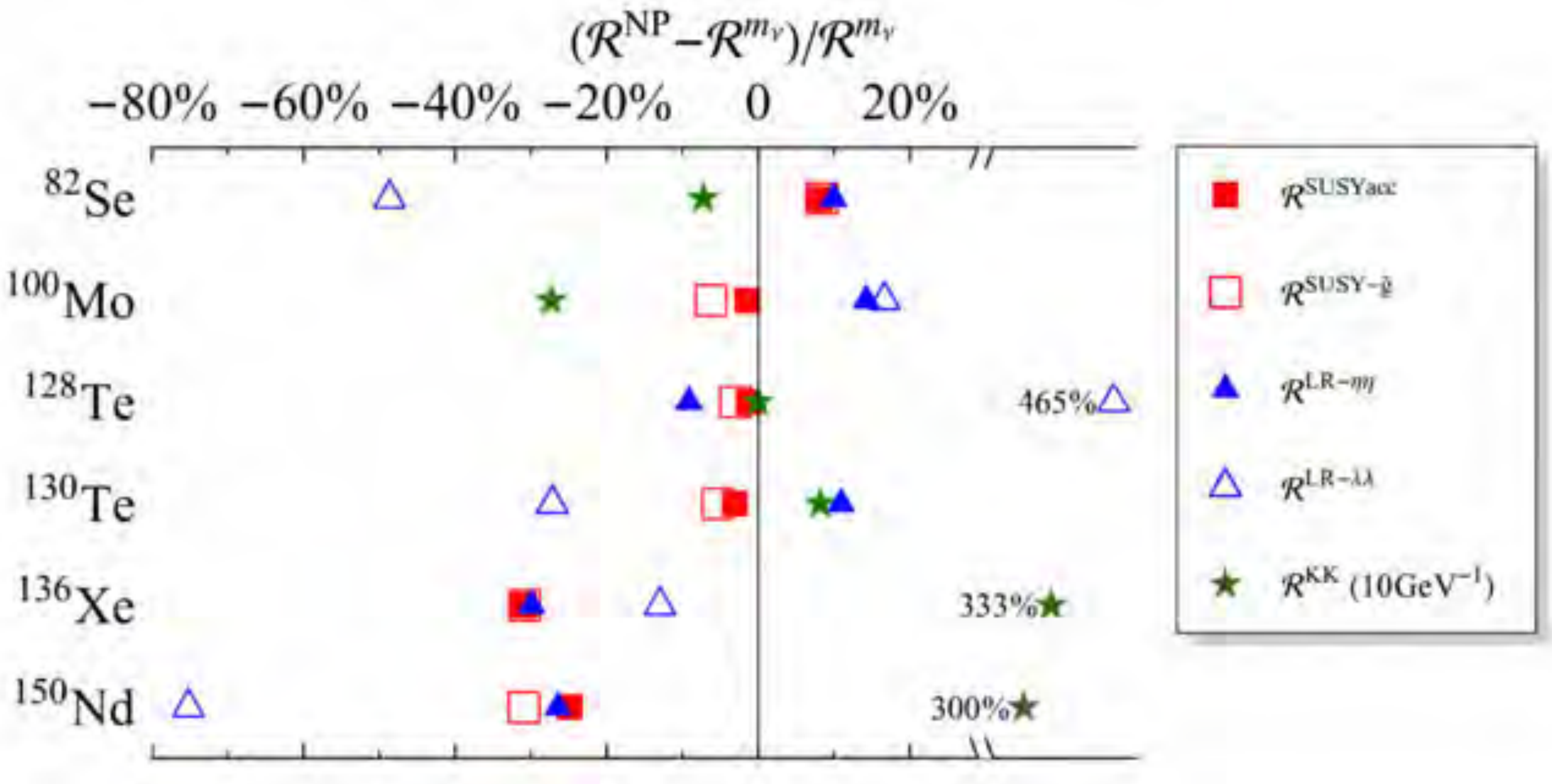
- Half life ratios of different isotopes

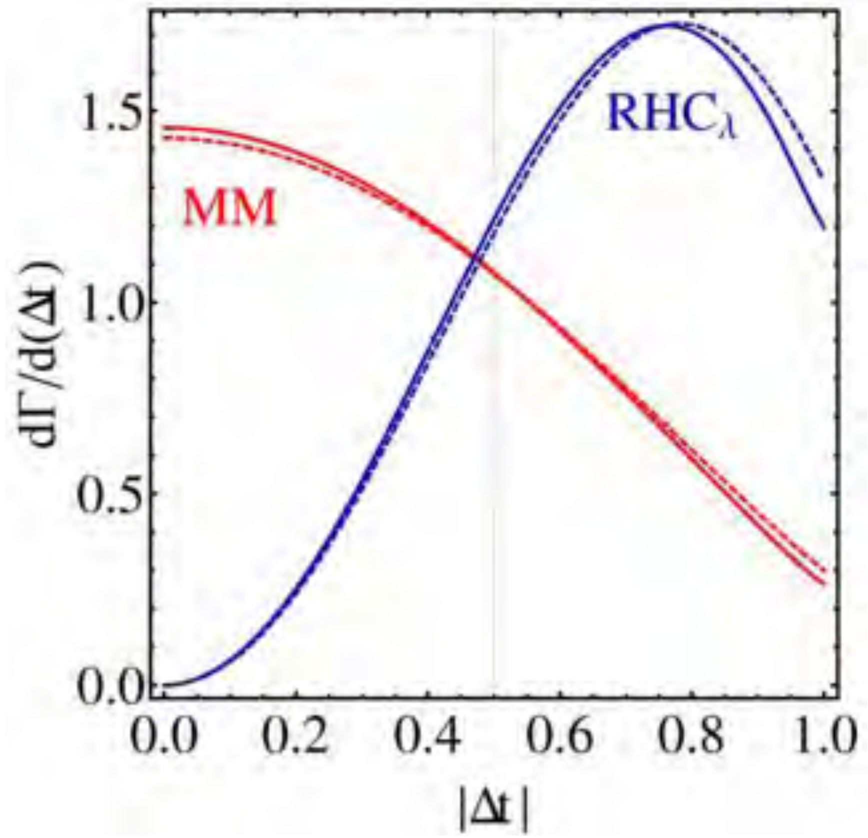
  Deppisch,Päs 06 , Gehman,Elliot 07 , Fogli,Lisi,Rotunno 09
- Electron angular correlations

  Ali,Borisov,Zhuridov 07
- Decay to excited states and other rare decays

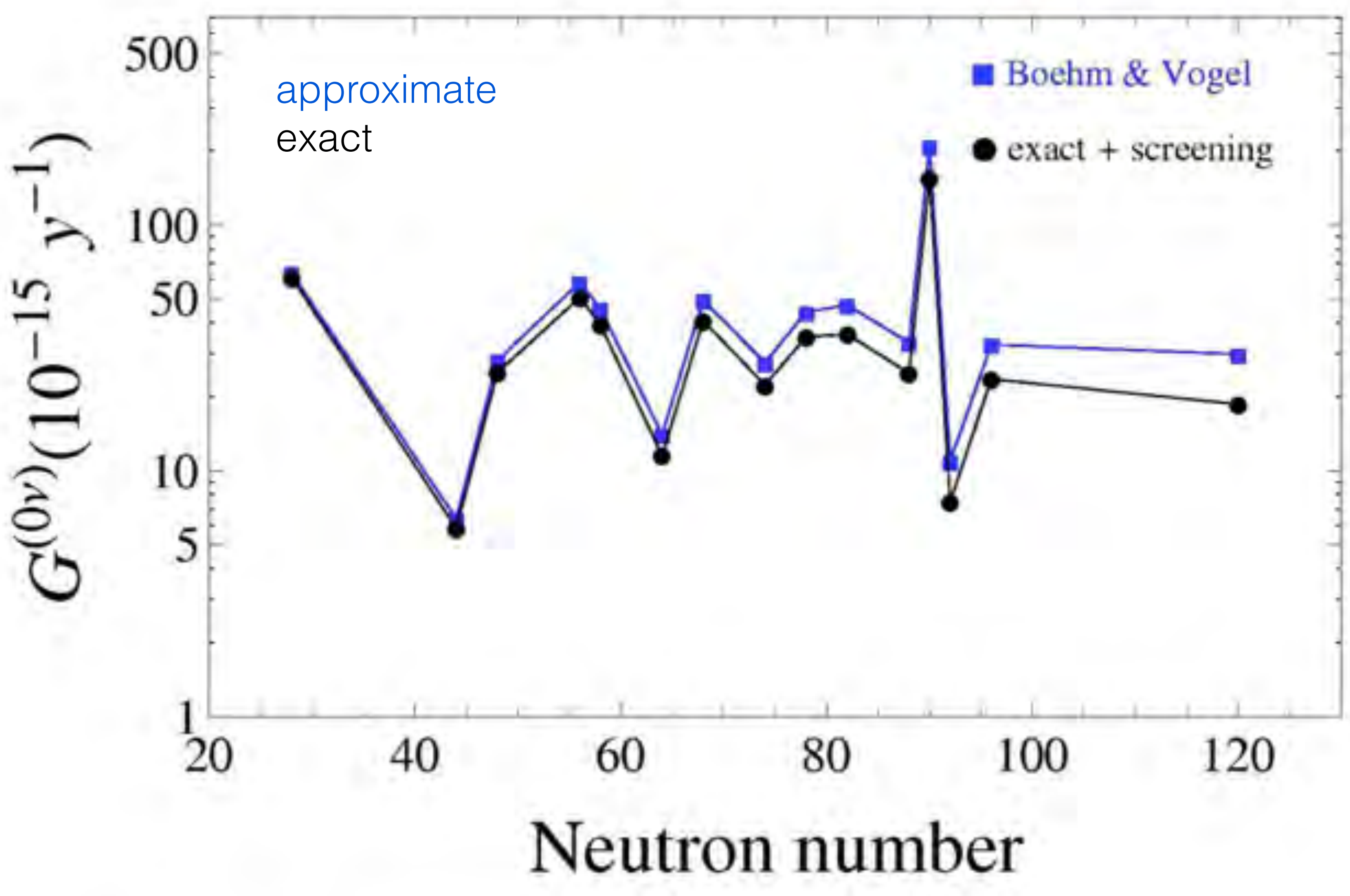
  Faessler et.al. 94
- LNV processes at the LHC

  Allanach,CHK,Päs 09





Extract m_{ee} from data: a hard job



F. Böhm and P. Vogel, *loc. cit.*

J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012)

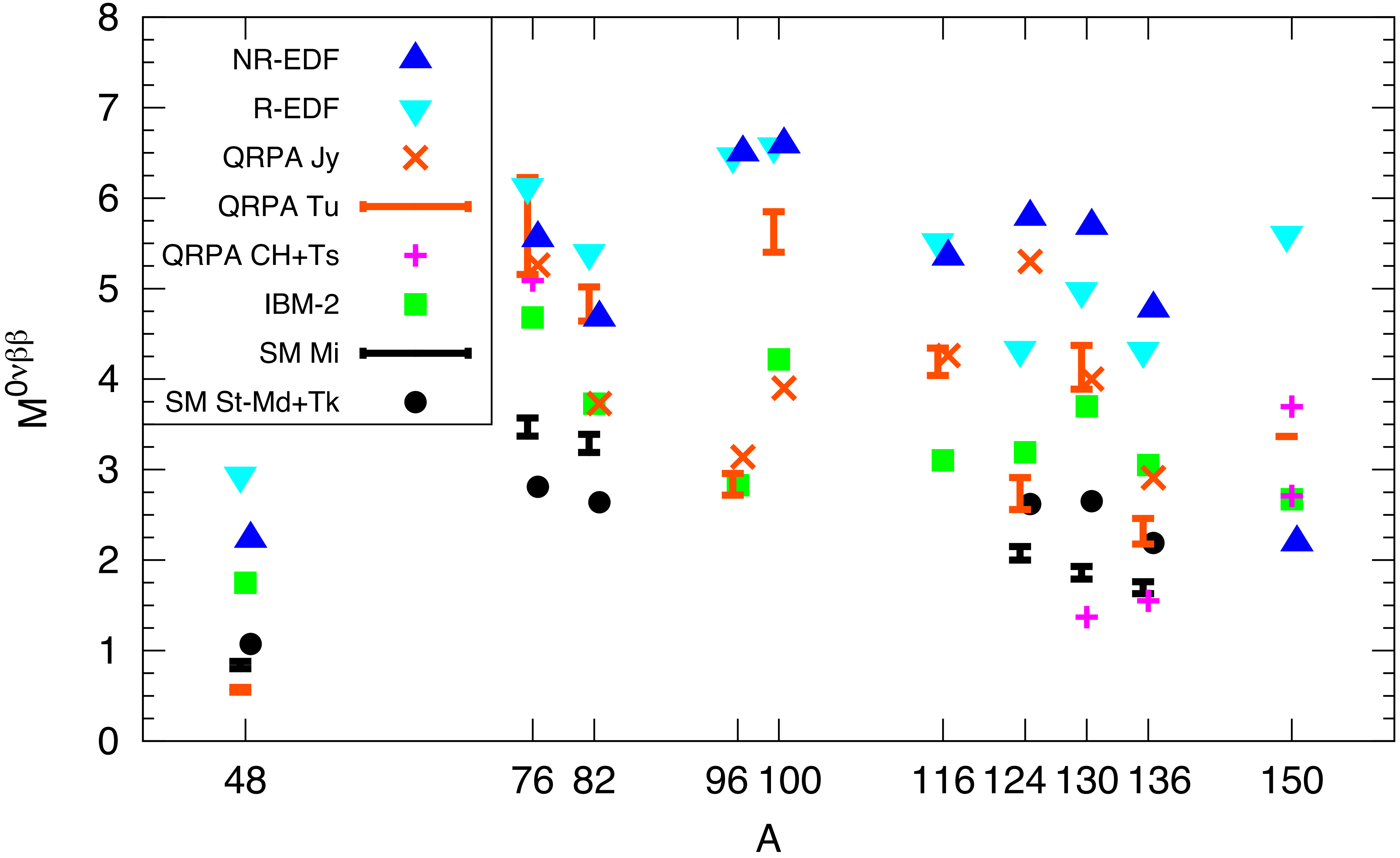
$$\Gamma^{0\nu} = G_{0\nu}(Q,Z)|M_{0\nu}(A,Z)|^2|m_{ee}|^2$$

The easy part:
phase space factor
→ precisely calculable

Extract m_{ee} from data: a hard job

Full estimated range of $M^{0\nu}$ within different calculation methods

$$\Gamma^{0\nu} = G_{0\nu}(Q,Z)|M_{0\nu}(A,Z)|^2|m_{ee}|^2$$



Jonathan Engel and Javier Menéndez 2017 *Rep. Prog. Phys.* **80** 046301

Much more problematic:
nuclear matrix elements

- Significant spread
- Absolute values inaccuracy

quenching of g_A?

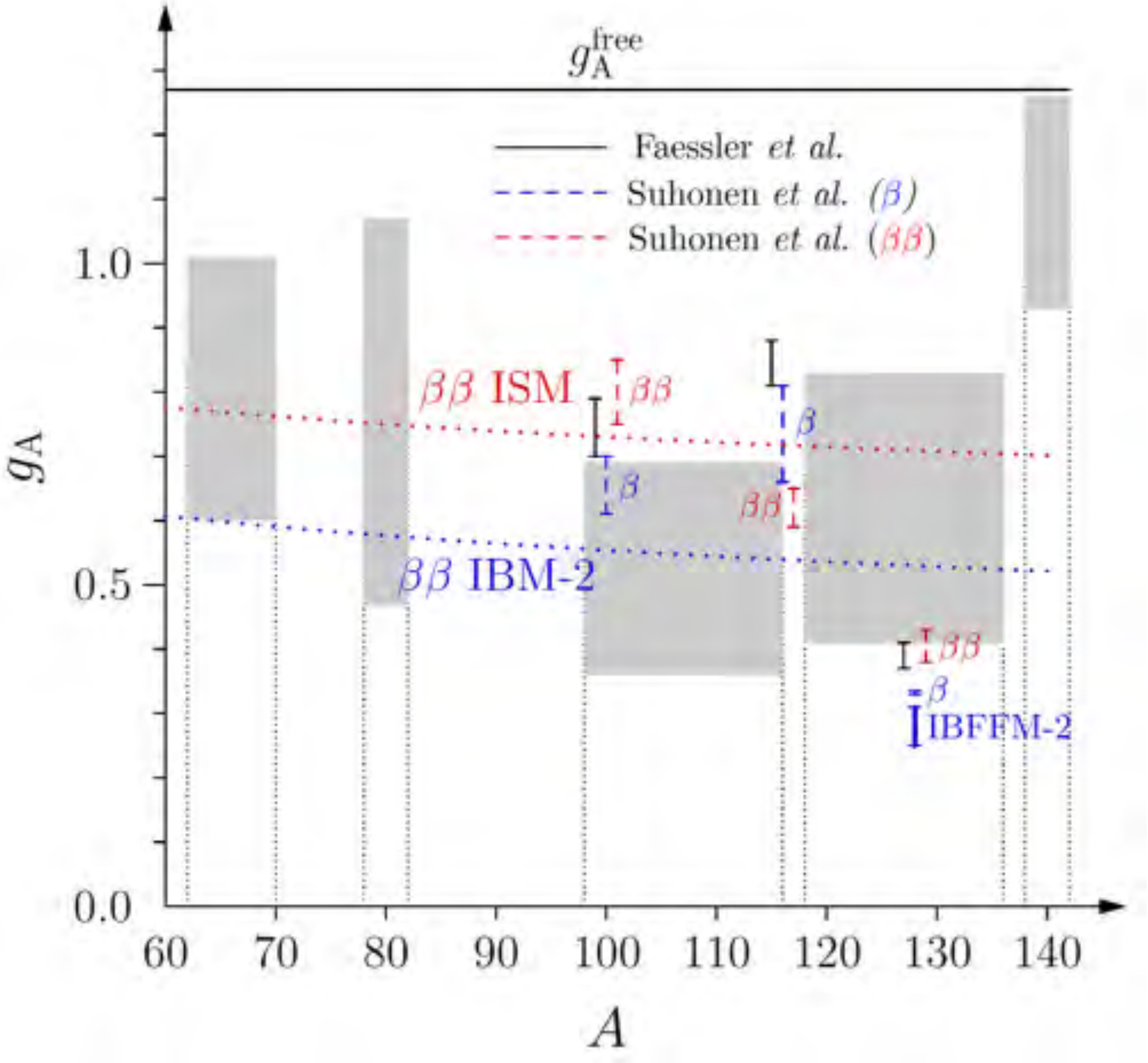
$\Gamma_{\beta\beta} \sim g_A^4$

g_A quenching

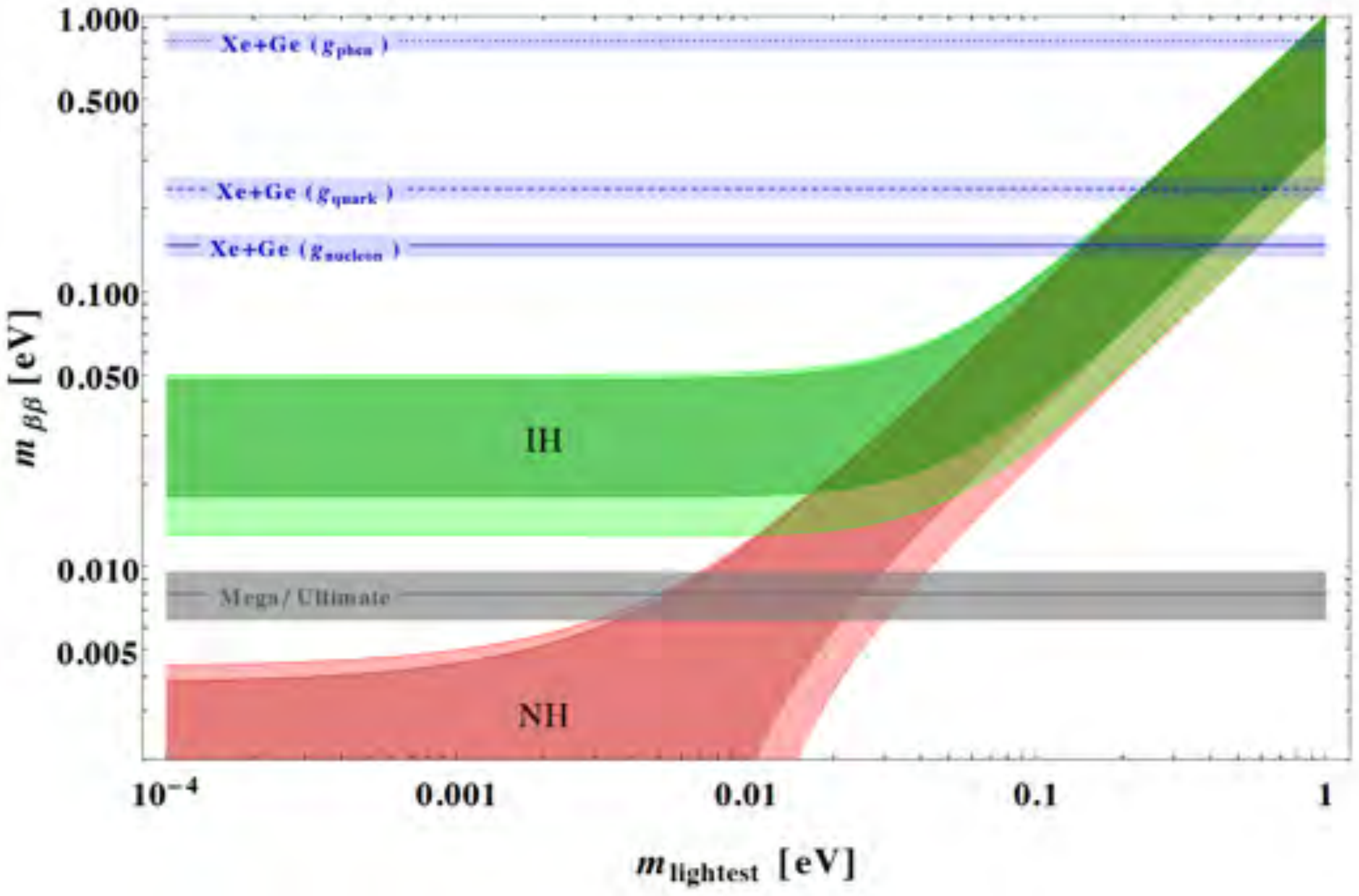
Allowed “beta” decays

- Recent analysis of pn-QRPA, ISM and IBM based calculations of single β and 2νββ decays shows an evident dependence of the g_A quenching on A (J.Suhonen, Neutrino 2018):

Mass range	76-82	100-116	122-136
g_A	0.7-0.9	0.5	0.5-0.7



Dell’Oro, Marcocci, Vissani arXiv:1404.2616



What about 0νββ?

Forbidden “beta” decays

- Possible extrapolation to 0νββ (large momentum transfer)
- Crucial role of high forbiddance non unique transitions

^{94}Nb, ^{98}Tc, ^{99}Tc, ^{113}Cd,^{115}In, ^{138}Cs

Caveat: 0νββ decay is a high-momentum transfer process (q~100 MeV) ➝ less quenching

Experimental signature

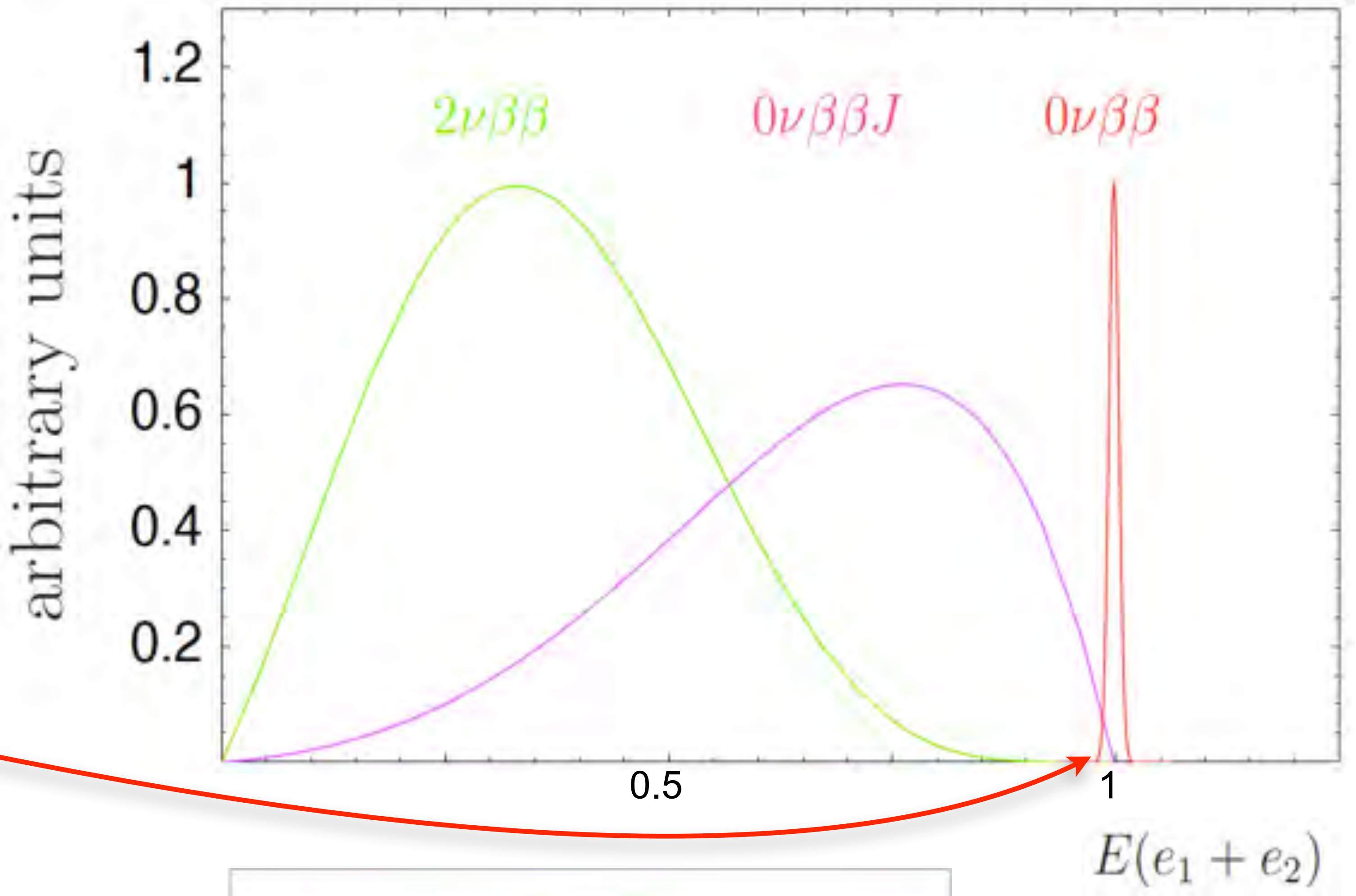
$(A,Z) \rightarrow (A,Z+2)^{++} + 2\,e^-$

- A new (ionised) isotope
- Two electrons

Minimal information:

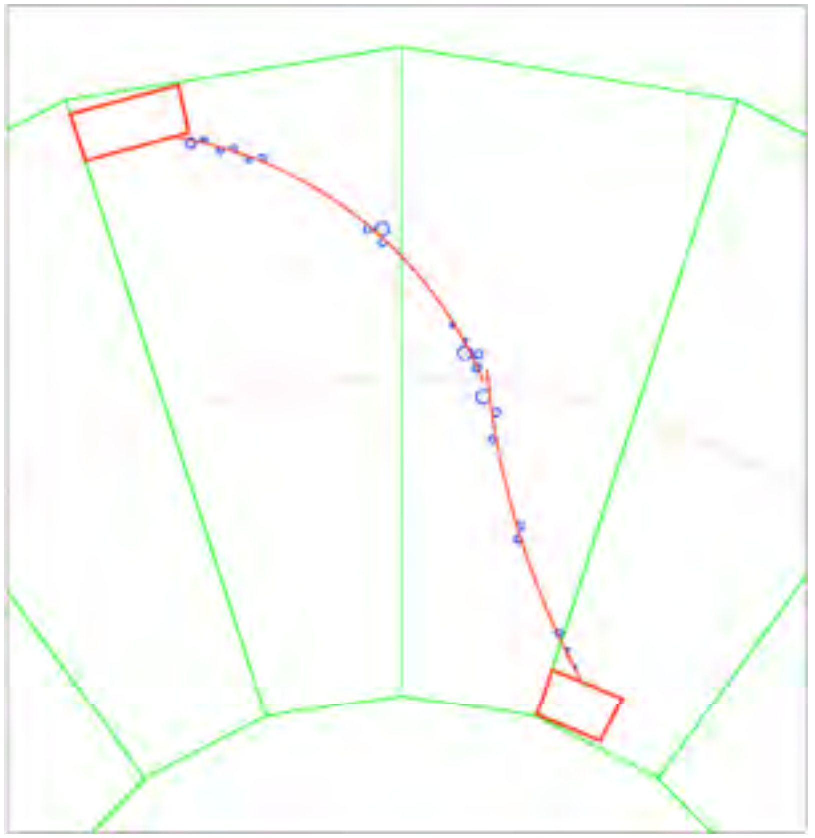
- two e^- energy sum spectrum (total deposited energy)

0νββ exhibits a peak at Q over 2νββ tail
(and background contributions)



Additional signatures:

- Daughter nuclear species
- Single electron energy spectrum
- Angular correlation between the two electrons
  - → Track and event topology
  - → Time Of Flight



Two experimental approaches:

- homogeneous (source ≡ detector) → calorimeters
- inhomogeneous (source ≠ detector) → trackers

… and mixed solutions

Experimental sensitivity

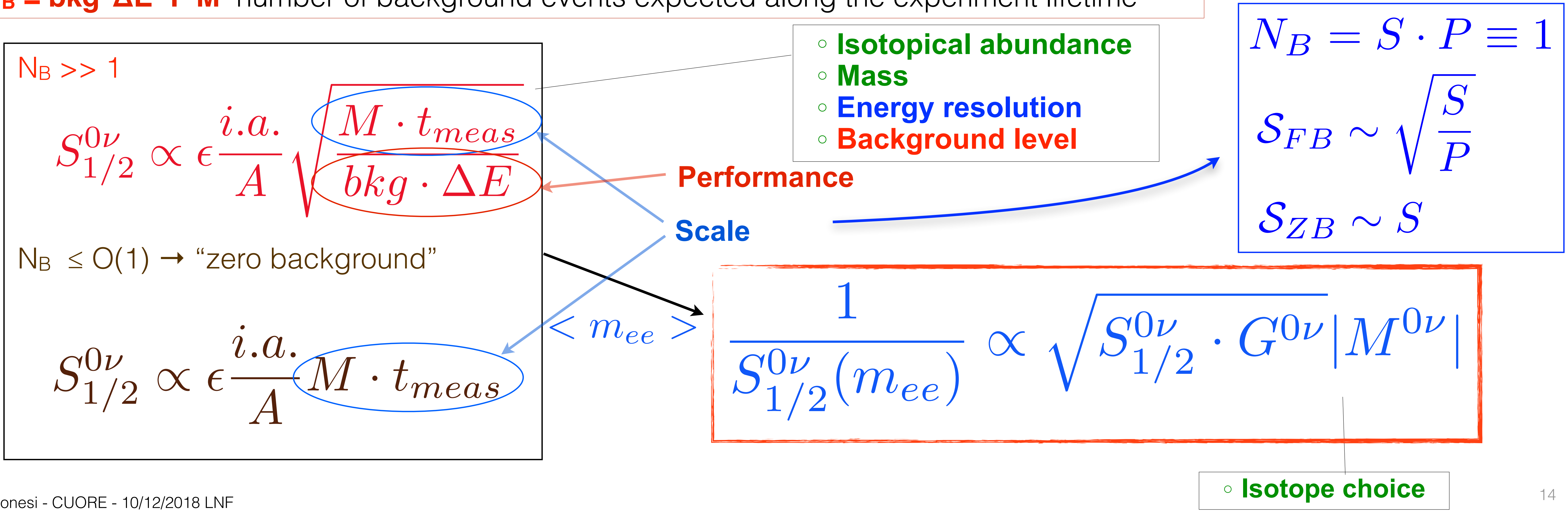
$$\tau^{0\nu}_{1/2} = ln2\frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

Lifetime corresponding to the minimum detectable number of events over background at a given confidence level

$$N_{\beta\beta} \leq \sqrt{bkg \cdot \Delta E \cdot M \cdot t_{meas}}$$

N_{nuclei}	number of active nuclei in the experiment
t_{meas}	measuring time [y]
M	detector mass [kg]
ε	detector efficiency
i.a.	isotopic abundance
A	atomic number
ΔE	energy resolution [keV]
bkg	background [c/keV/y/kg]

N_B = bkg·ΔE·T·M number of background events expected along the experiment lifetime



$N_B >> 1$

$$S^{0\nu}_{1/2} \propto \epsilon\frac{i.a.}{A}\sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

$N_B \leq O(1)$ → "zero background"

$$S^{0\nu}_{1/2} \propto \epsilon\frac{i.a.}{A} M \cdot t_{meas}$$

- **Isotopical abundance**
- **Mass**
- **Energy resolution**
- **Background level**

Performance

Scale

$$N_B = S \cdot P \equiv 1$$

$$S_{FB} \sim \sqrt{\frac{S}{P}}$$

$$S_{ZB} \sim S$$

$$< m_{ee} >$$

$$\frac{1}{S^{0\nu}_{1/2}(m_{ee})} \propto \sqrt{S^{0\nu}_{1/2} \cdot G^{0\nu}} |M^{0\nu}|$$

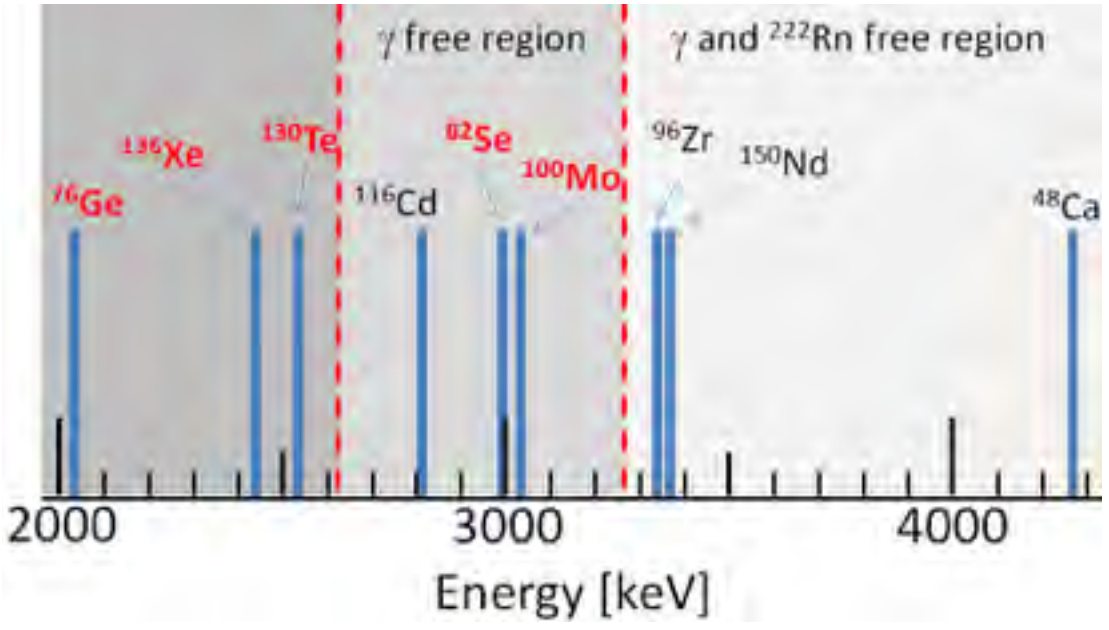
- **Isotope choice**

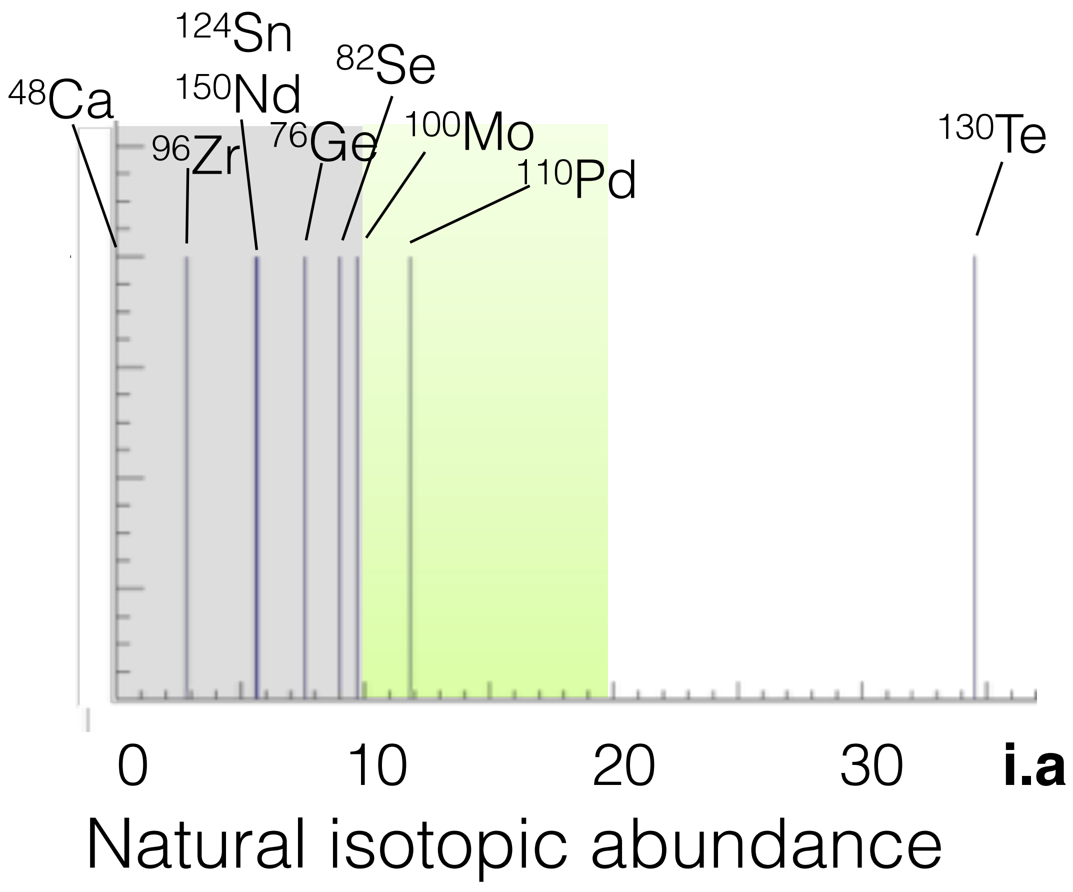
Choice of the isotope

Transition	T0 (keV)	Abundance (%)	first 2+ (keV)
46Ca→46Ti	985	0.0035	889
48Ca→48Tit	4272	0.187	984
70Zn→70Ge	1001	0.62	-
76Ge→76Se	2045	7.8	559
80Se→80Kr	136	49.8	-
82Se→82Kr	3005	9.2	776
86Kr→86Sr	1249	17.3	1077
94Zr→94Mo	1148	17.4	871
96Zr→96Mo	3350	2.8	778
98Mr→98Ru	111	24.1	-
1OOMo→1OORu	3033	9.6	540
104Ru→104pd	1301	18.7	556
110Pd→110Cd	2014	11.8	658
114Cd→114Sn	540	28.7	-
116Cd→116Sn	2808	7.5	1294
122Sn→122Te	358	4.56	-
124Sn→124Te	2278	5.64	603
128Te→128Xe	869	31.7	443
130Te→130Xe	2533	34.5	536

Transition	T0 (keV)	Abundance (%)	first 2+ (keV)
134Xe→134Ba	843	10.4.	605
136Xe→136Ba	2481	8.9	819
142Ce→142Nd	1414	11.1	-
146Nd→146Sm	61	17.2	-
148Nd→148Sm	1928	5.7	550
150Nd→150Sm	3367	5.6	334
154Sm→154Gd	1250	22.6	123
160Gd→16oDy	1731	21.8	87
170Er→110Yb	655	14.9	84
176Yb→176Hf	1077	12.6	88
186W→186Os	489	28.6	137
192Os→192Pt	408	41.0	317
198Pt→198Hg	1043	7.2	412
204Hg→204Pb	414	6.9	-
232Th→232U	850	100	48
232U→232Pu	1146	99.275	44

Transition energy





DBD experiments summary

Experiment	Isotope	m_{fid}(ßß) [kg]	Technique	Laboratory	Status
CANDLES	48Ca	305	CaF2 crystals - liq. scintillator	Kamioka	**Construction**
CARVEL	48Ca		48CaWO4 crystal scint.		R&D
GERDA I	76Ge	14	Ge diodes in LAr	LNGS	**Complete**
GERDA II	76Ge	31	Point contact Ge in LAr	LNGS	**Operating**
Majorana D	76Ge	26	Point contact Ge	SURF	**Operating**
LEGEND-200	76Ge	172	Point contact Ge in LAr	LNGS	CDR→TDR
NEMO3	100Mo/82Se	6.9/0.9	Foils with tracking	LSM	**Complete**
SuperNEMO D	82Se	6.3	Foils with tracking	LSM	**Construction**
SuperNEMO	82Se	126	Foils with tracking		R&D
CUPID-0	82Se	5	ZnSe scint. bolometer	LNGS	**Operating**
AMoRE	100Mo	50	CaMoO4 scint. bolometer	Y2L	R&D
MOON	100Mo	200	Mo sheets		R&D
CUPID	100Mo	200	Li2MoO4	LNGS	R&D→CDR
COBRA	116Cd	10/183	CdZnTe detectors	LNGS	R&D
CUORICINO	130Te	10	TeO2 Bolometer	LNGS	**Complete**
CUORE-0	130Te	11	TeO2 Bolometer	LNGS	**Complete**
CUORE	130Te	206	TeO2 Bolometer	LNGS	**Operating**
SNO+	130Te	55	0.1% natNd suspended in Scint	SNOlab	**Commissioning**
KamLAND-ZEN	136Xe	380	2.7% in liquid scint.	Kamioka	**Operating**
NEXT-100	136Xe	90	High pressure Xe TPC	LSC	**Construction**
EXO-200	136Xe	60	Xe liquid TPC	WIPP	**Operating**
nEXO	136Xe	450/3330	Xe liquid TPC	SNOlab	R&D
PandaX-III	136Xe	200	High pressure Xe TPC	CJPL-II	R&D
DCBA	150Nd		Nd foils & tracking chambers		R&D

CUORE

CUORE

Cryogenic Underground Observatory for Rare Events

Primary goal: search for 0νββ decay in ^{130}Te

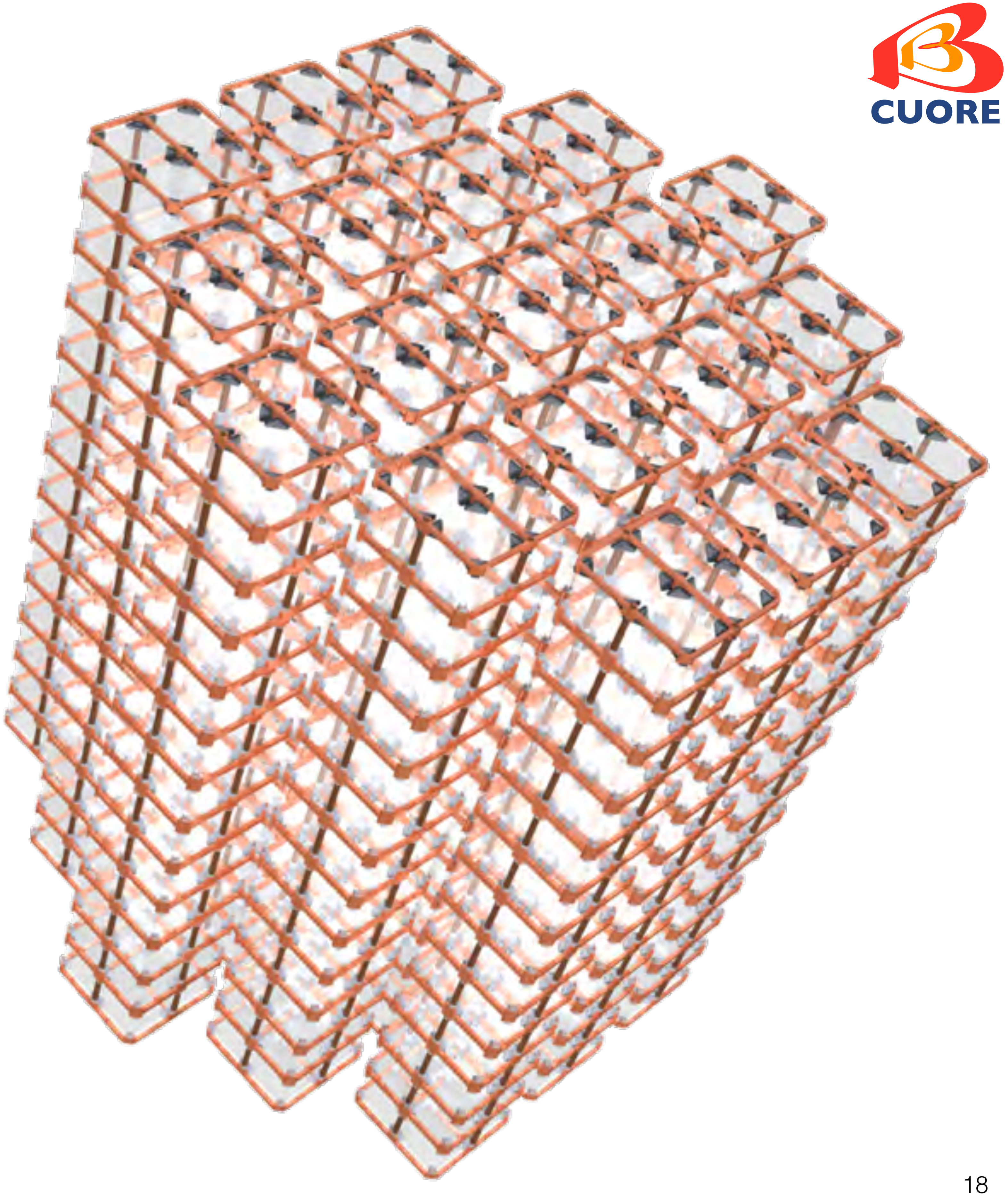
Detector design:
closely packed array of 988 TeO_2 crystals arranged in 19 towers

Design parameters:

- mass of TeO_2: **742 kg** (206 kg of ^{130}Te)
- low background aim: **10^{-2} c/(keV·kg·yr)**
- target energy resolution: **5 keV** FWHM in the Region Of Interest (ROI)
- high granularity
- deep underground location
- strict radio-purity controls on materials and assembly

CUORE projected sensitivity (5 years, 90% C.L.):

$T_{1/2} > 9 \times 10^{25}$ yr



The CUORE Collaboration

CUORE

UCLA

Universitas Studii Paduani MCCXXII

Yale

INFN LNGS

Berkeley Lab

Cal Poly
San Luis Obispo

The University of California 1868

Massachusetts Institute of Technology

VirginiaTech 1872
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Lawrence Livermore National Laboratory

Sapienza Università di Roma

Università degli Studi di Milano Bicocca

Shanghai Jiao Tong University 1896

Alma Mater Studiorum Università di Bologna A.D. 1088

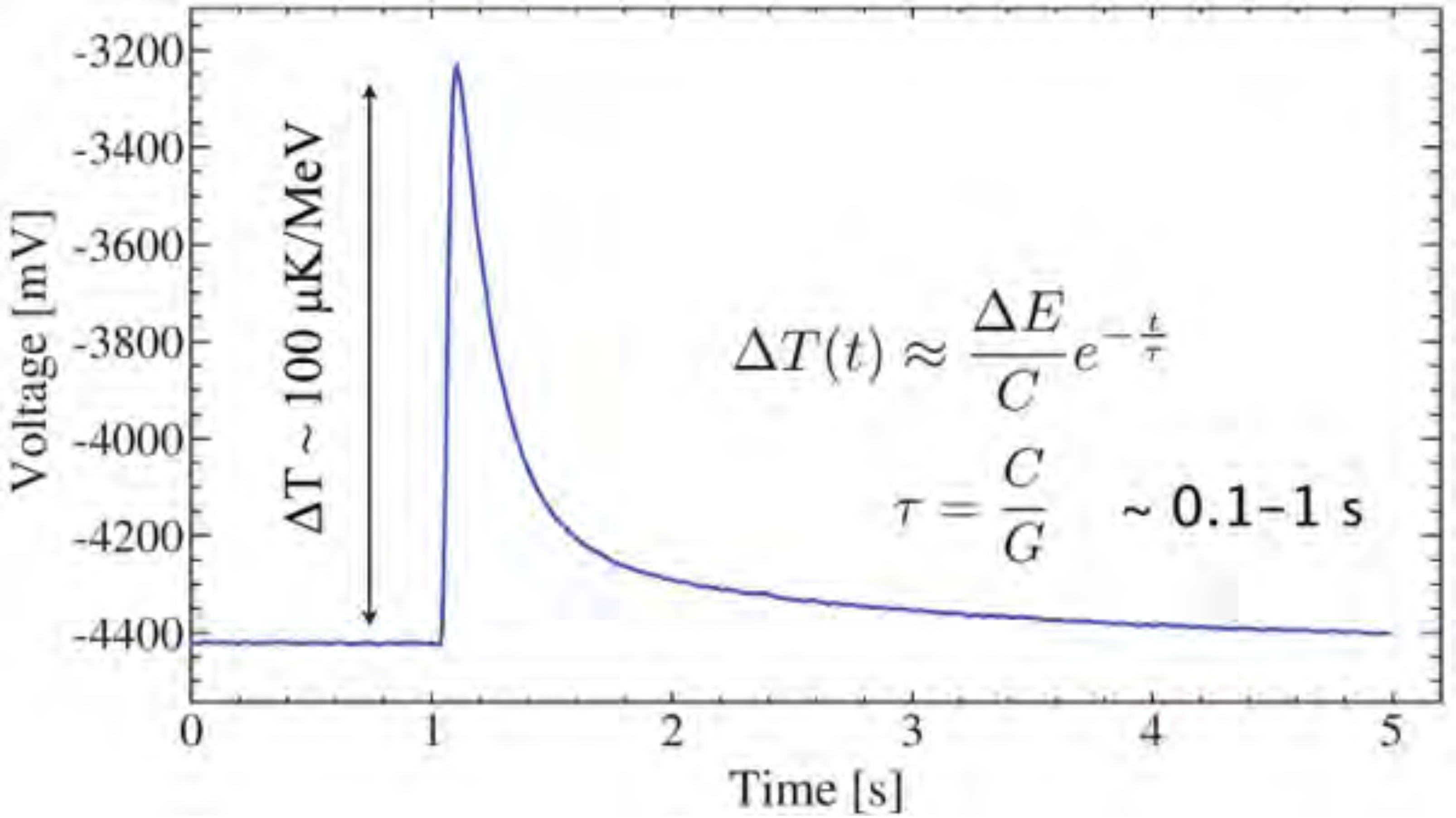
SINAP

Università degli Studi di Cassino e del Lazio Meridionale – 1979 –
Sol per noctem

University of South Carolina

The CUORE detectors

CUORE is a large array of thermal detectors
- low heat capacity @ T_{work} ($C \sim T^3$)
- excellent energy resolution (~0.2% FWHM)
- same detector response for different particles
- slowness (suitable for rare event searches)



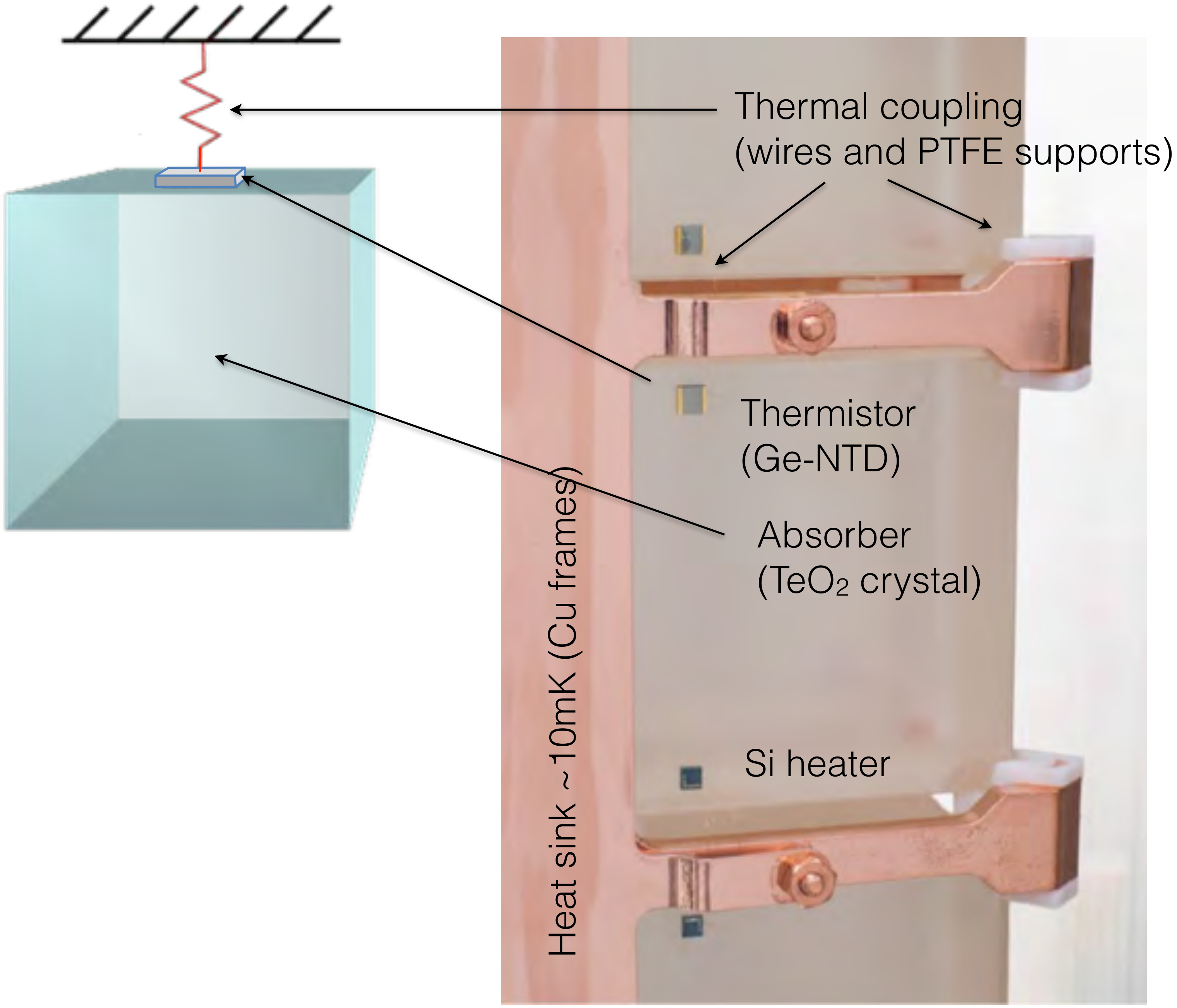
ΔT ~ 100 µK/MeV

$$\Delta T(t) \approx \frac{\Delta E}{C} e^{-\frac{t}{\tau}}$$

$$\tau = \frac{C}{G}$$ ~ 0.1–1 s

The concept: a pure calorimeter

The absorbed energy is converted into a variation of the crystal temperature, measured by the thermistor



Thermal coupling (wires and PTFE supports)

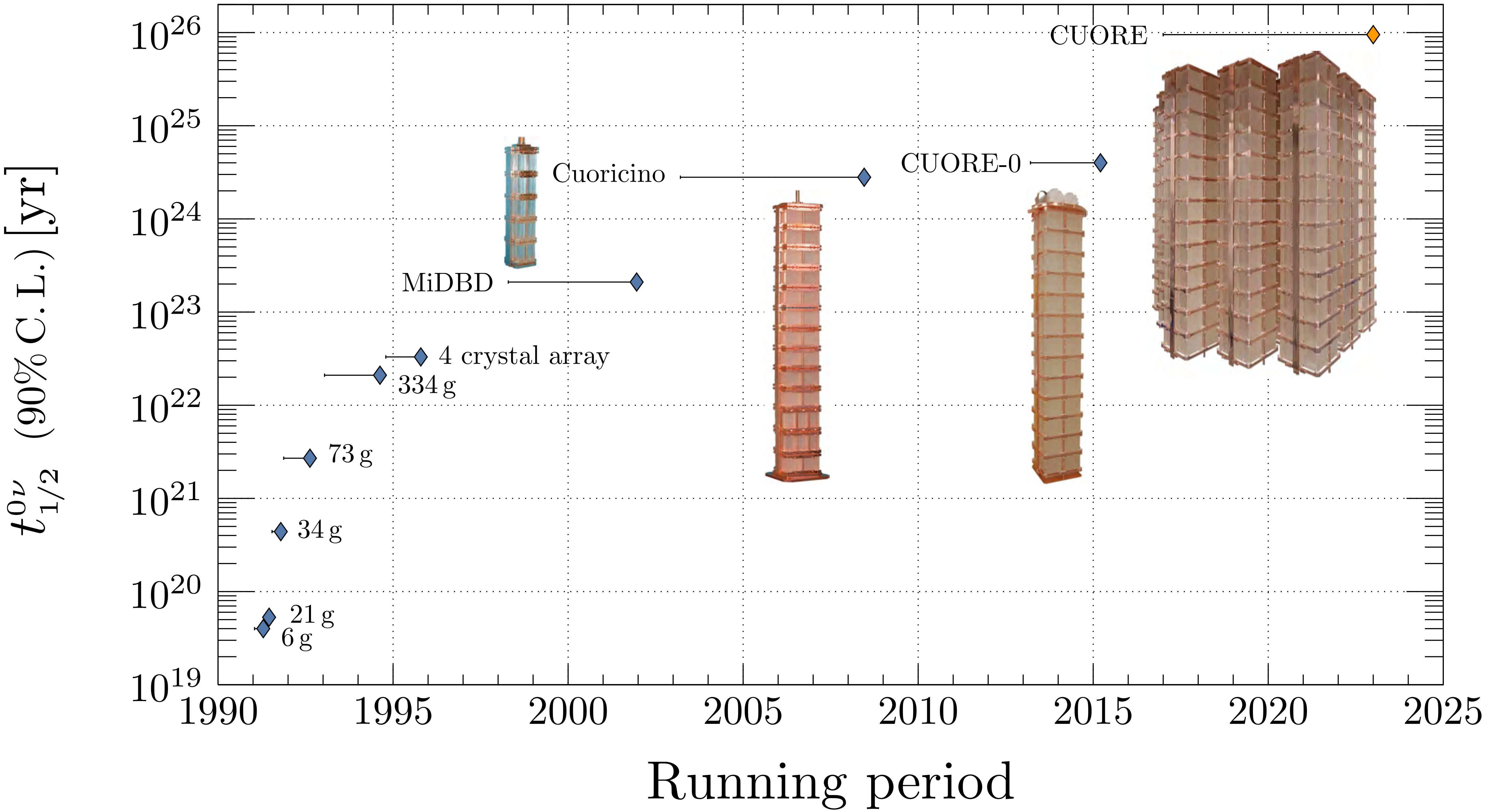
Thermistor (Ge-NTD)

Absorber (TeO_2 crystal)

Si heater

Heat sink ~10mK (Cu frames)

TeO_2 arrays

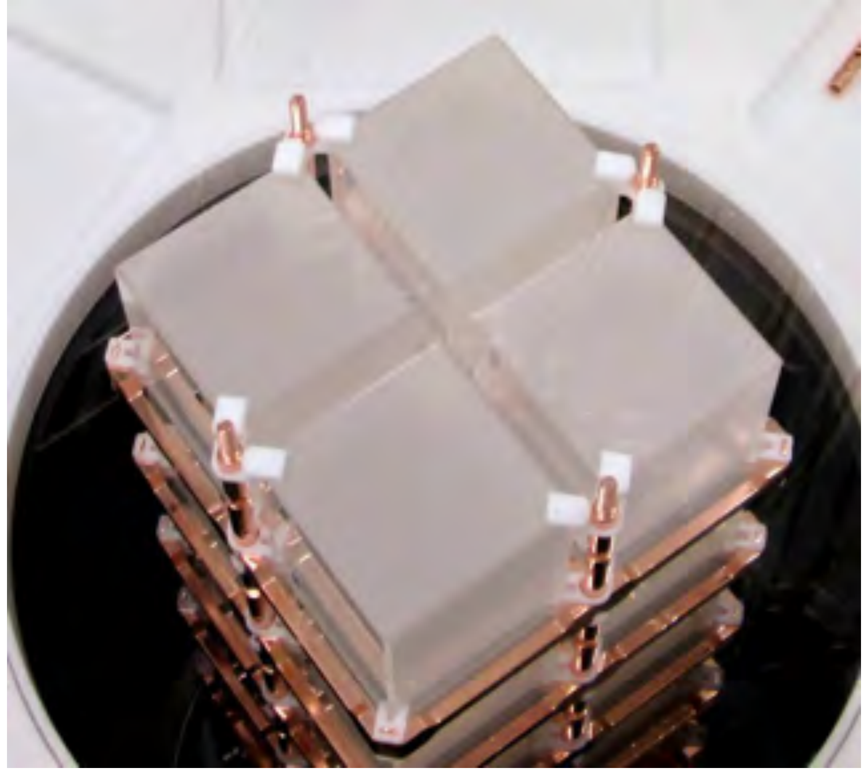


CUORE is the latest step in a long series of TeO_2 detectors which included two large demonstrators:

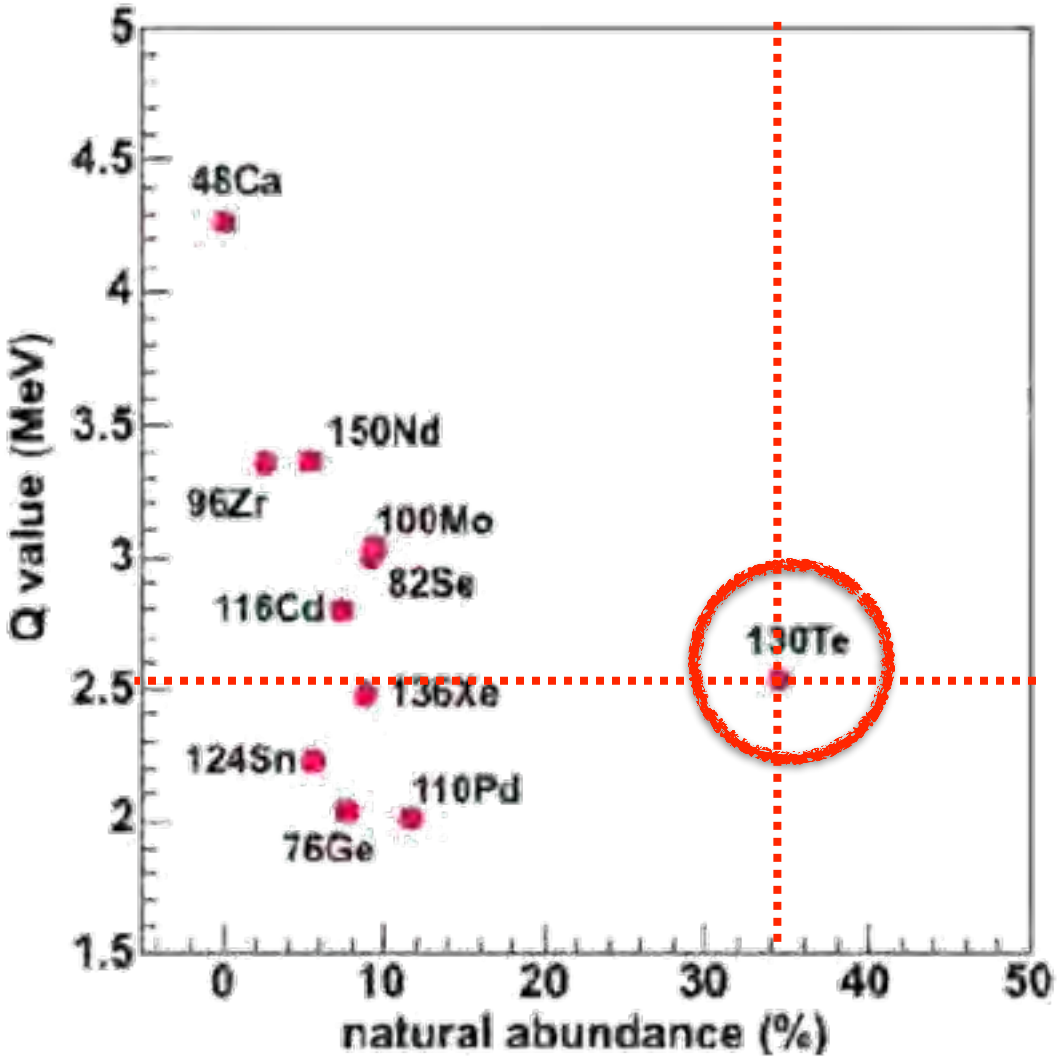
- Cuoricino
- CUORE-0

Why Tellurium?

- High natural isotopic abundance of source isotope (^{130}Te)
- ^{130}Te included in the detector: high efficiency
- $Q_{\beta\beta}$ = 2527.5 keV, in a region with relatively low β/γ background
- Excellent energy resolution (5 keV FWHM @ $Q_{\beta\beta}$)
- Reproducible growth of high quality crystals



Isotope	**i.a.(%)**	**Q [MeV]**
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.1	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

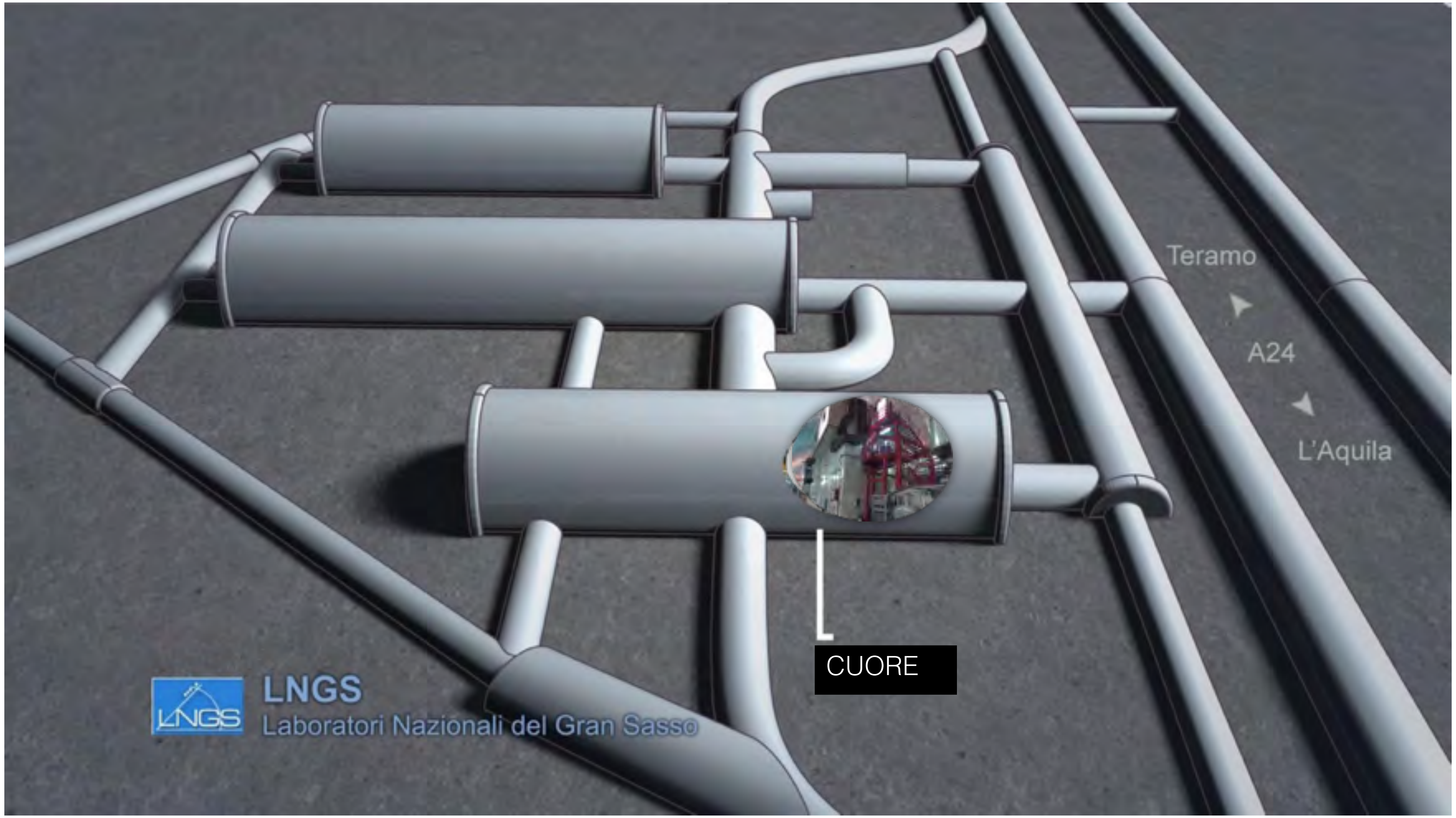


CUORE @ LNGS

1400 m of rock (~3600 m.w.e.) deep

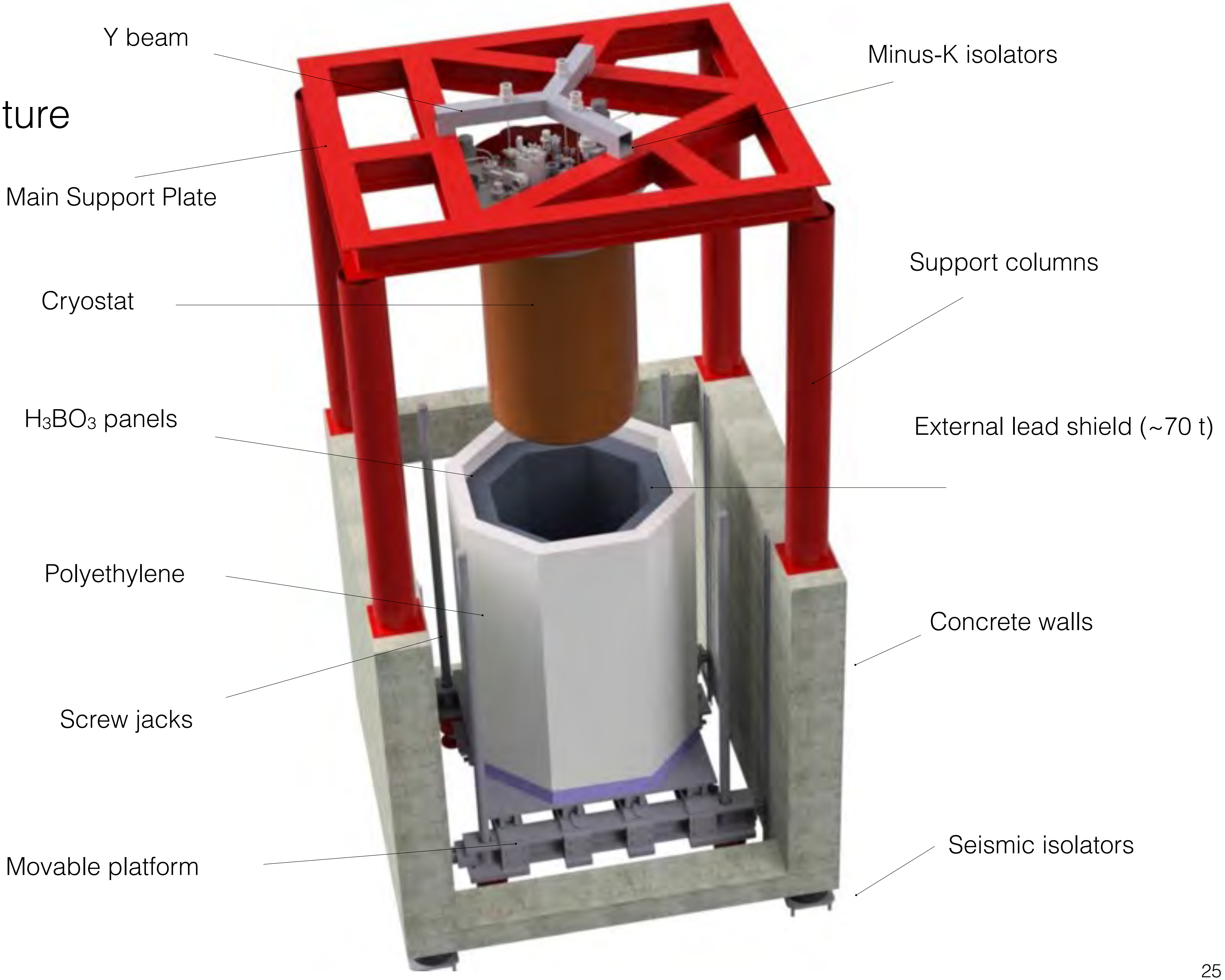
- μ's: ~3×10^{-8} / (s·cm^2)
- γ's: ~0.73 / (s·cm^2)
- neutrons: 4×10^{-6} n/(s·cm^2) below 10 MeV

CUORE @ LNGS


Teramo
A24
L'Aquila
CUORE
LNGS
Laboratori Nazionali del Gran Sasso

Underground Laboratory

- Three-story building
- Hosting the cryostat supporting structure

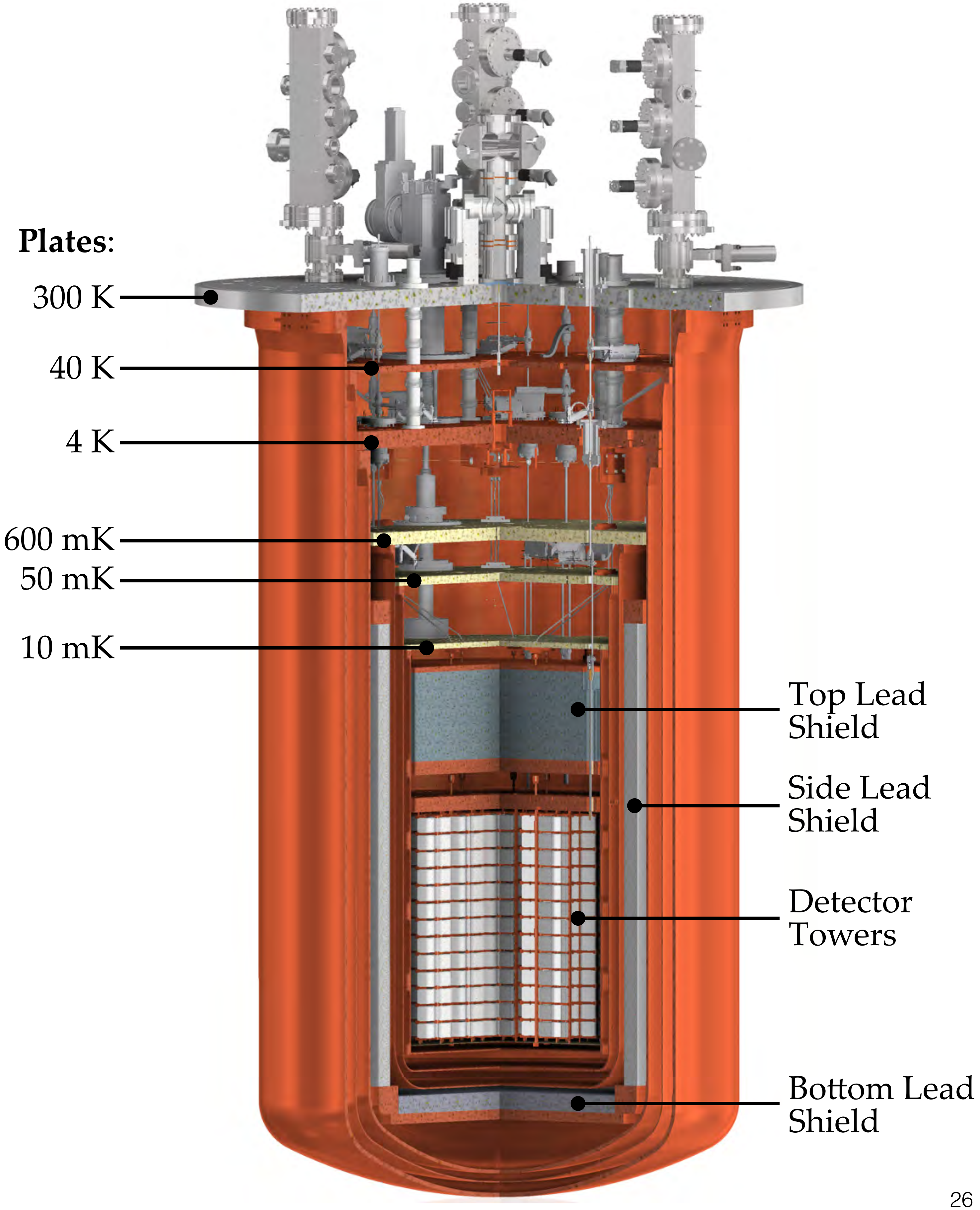


The CUORE cryostat

Challenges:

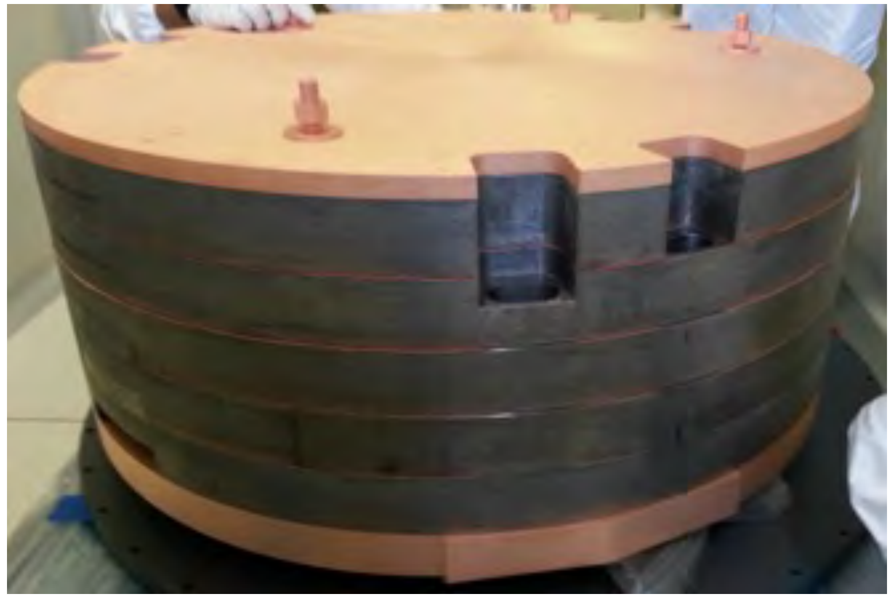
- Cool down ~1 ton detector to ~10 mK
- Mechanically decoupled for extremely low vibrations
- Low background environment

- Cryogen-free cryostat
- Fast Cooling System (^{4}He gas) down to ~50K
- 5 pulse tubes cryocooler down to ~4K
- Dilution refrigerator down to operating temperature ~10 mK
- Nominal cooling power: 3 μW @ 10mK
- 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)

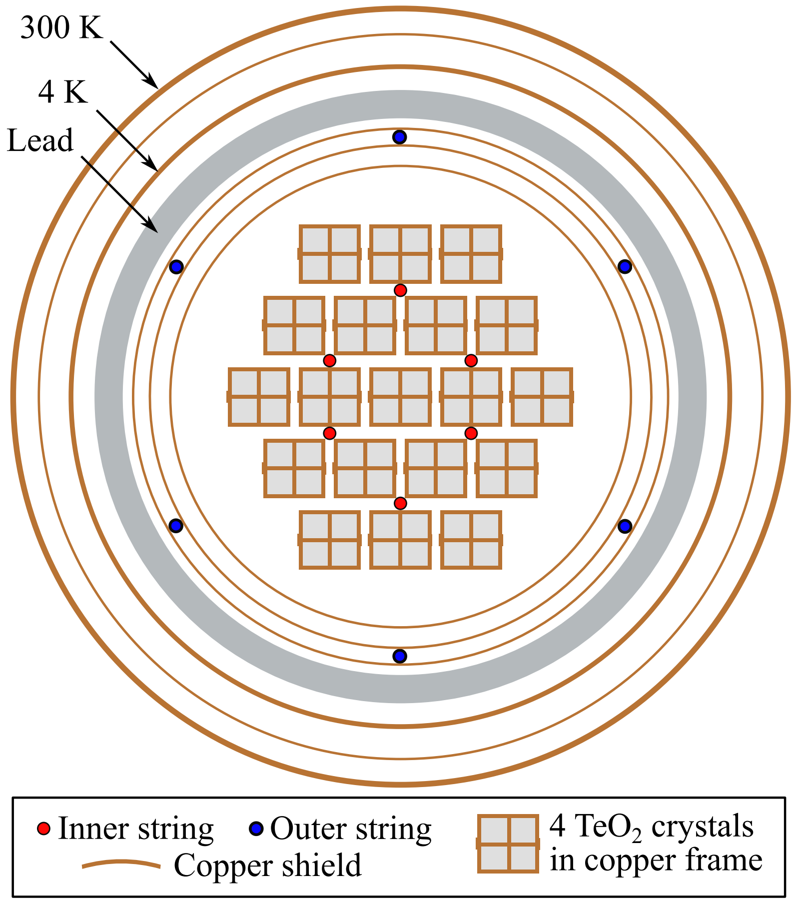


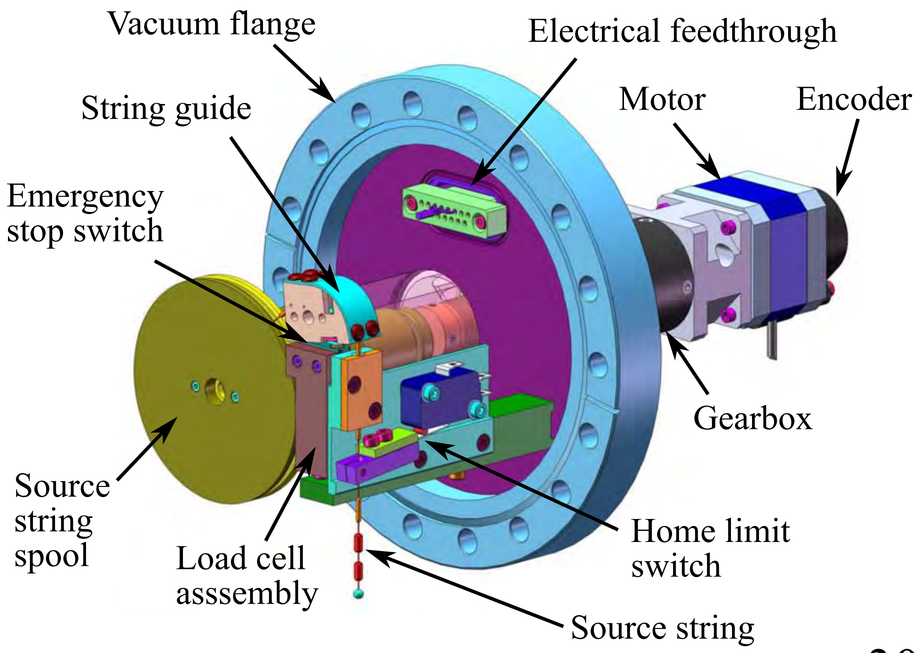
Passive shielding

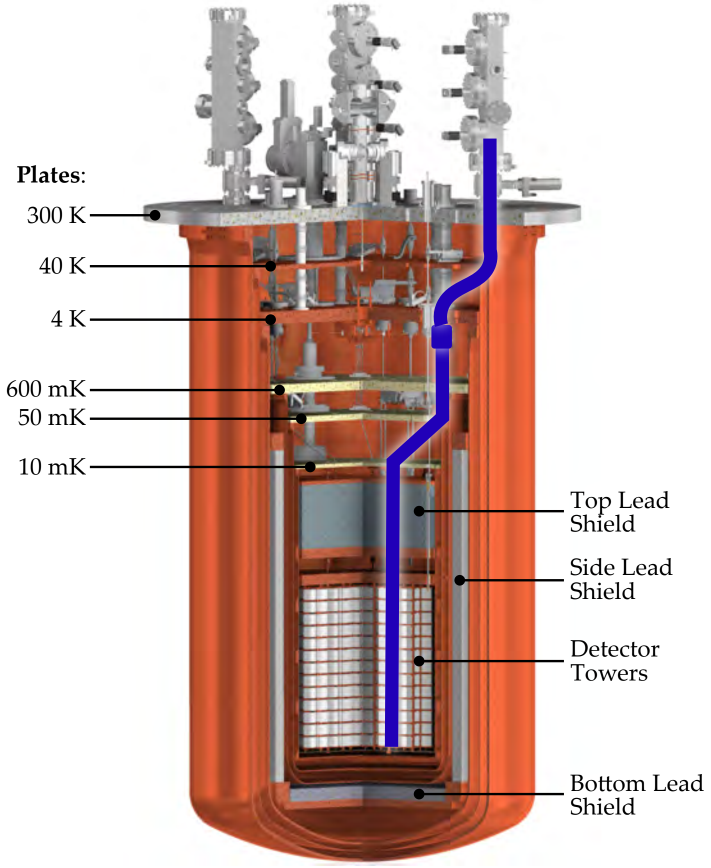
- Protect the detectors with a heavy shield against gamma and neutron activity from external sources (~70 tonnes lead + H_3BO_3)
- Select materials that don't contribute themselves to the background level (ancient roman lead and selected NOSV copper)
- Cool down inner layers of the shielding to the correct temperature (2.5 tonnes @ 50mK + 5.5 tonnes @ 4K)

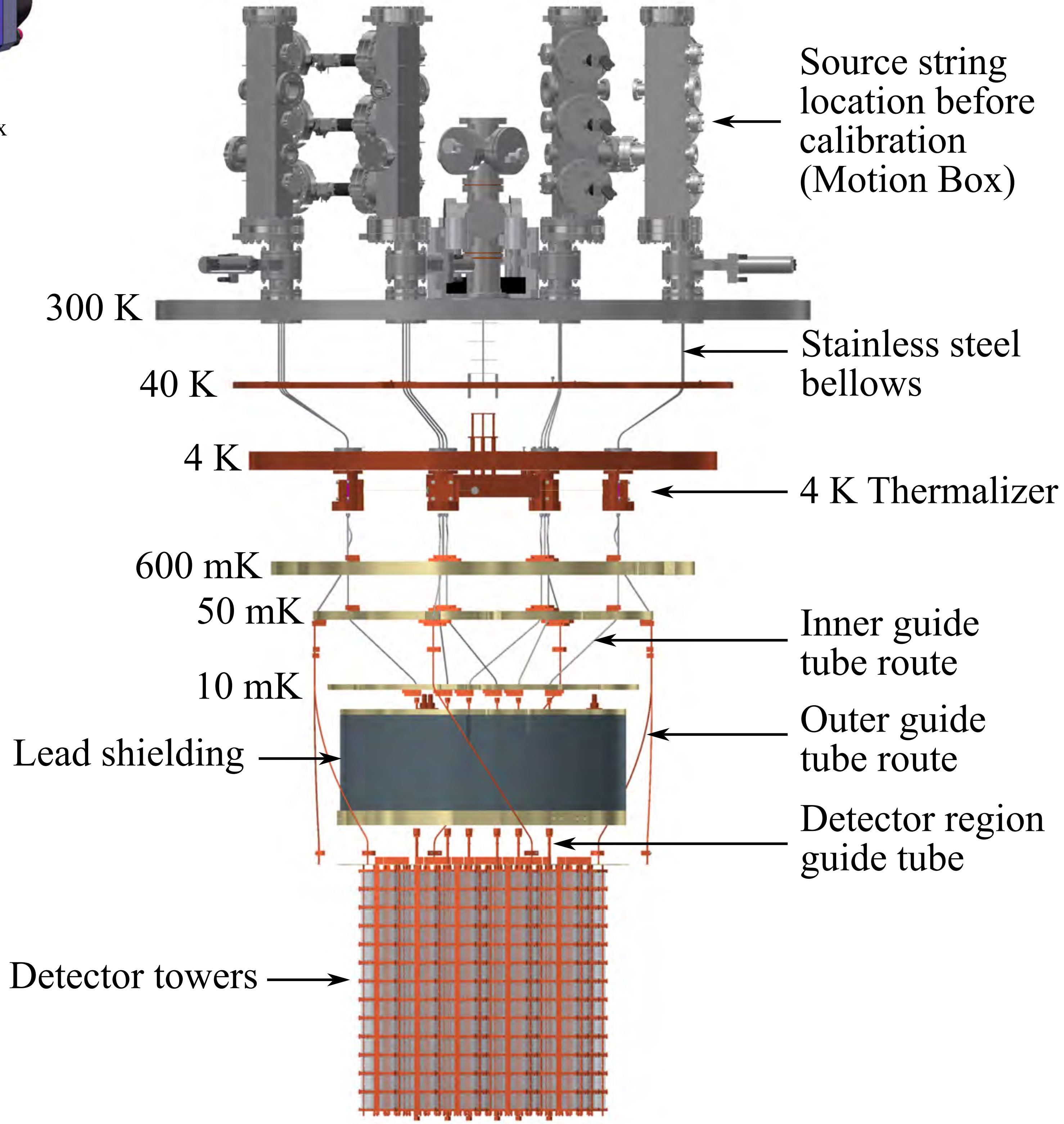


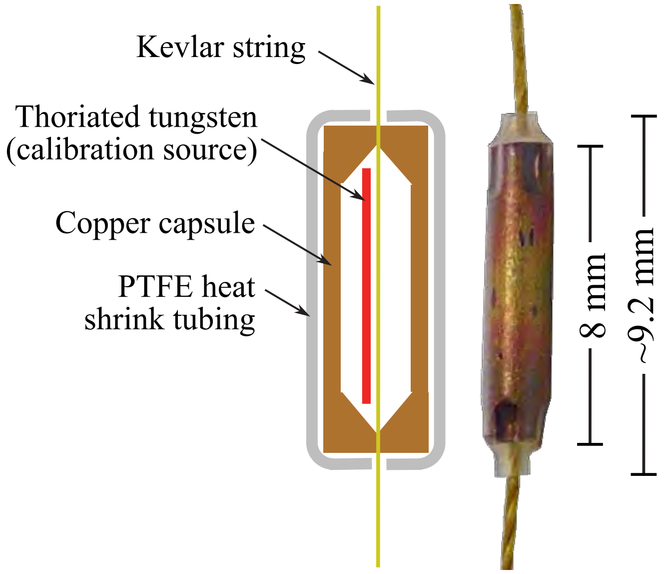
DCS


300 K
4 K
Lead
● Inner string
● Outer string
4 TeO$_2$ crystals in copper frame
Copper shield


Vacuum flange
Electrical feedthrough
String guide
Motor
Encoder
Emergency stop switch
Gearbox
Source string spool
Load cell asssembly
Home limit switch
Source string


Plates:
300 K
40 K
4 K
600 mK
50 mK
10 mK
Top Lead Shield
Side Lead Shield
Detector Towers
Bottom Lead Shield


Source string location before calibration (Motion Box)
300 K
Stainless steel bellows
40 K
4 K
4 K Thermalizer
600 mK
50 mK
Inner guide tube route
10 mK
Outer guide tube route
Lead shielding
Detector region guide tube
Detector towers


Kevlar string
Thoriated tungsten (calibration source)
Copper capsule
PTFE heat shrink tubing
8 mm
~9.2 mm


59 mm
6 mm

Detector installation

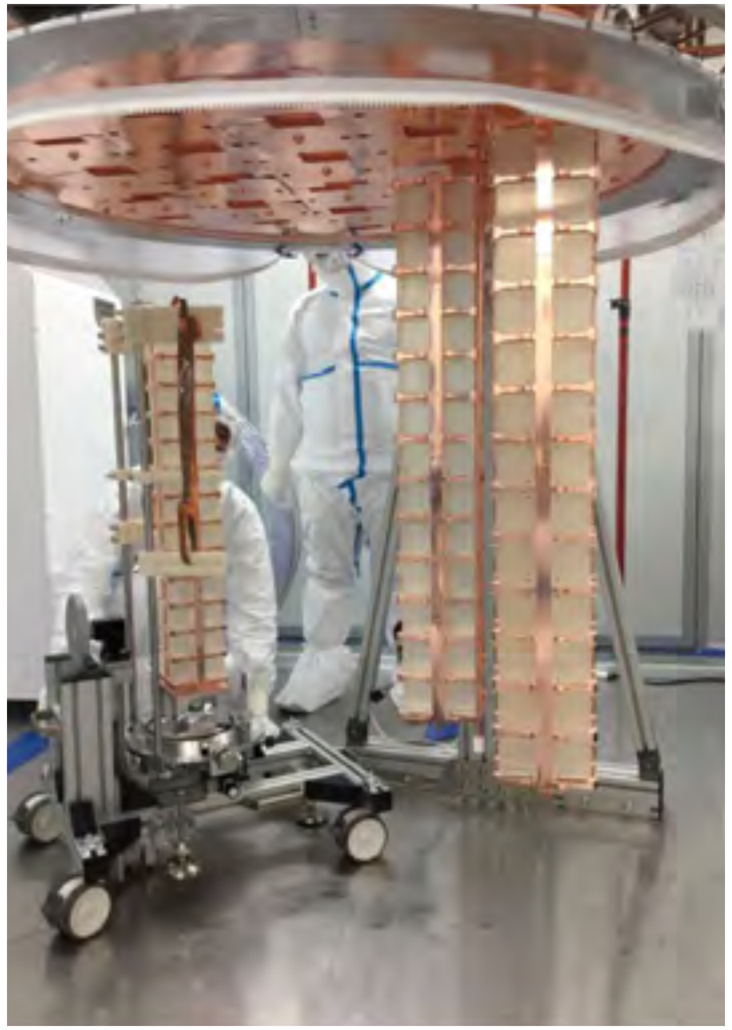
Performed in a radon-free environment:

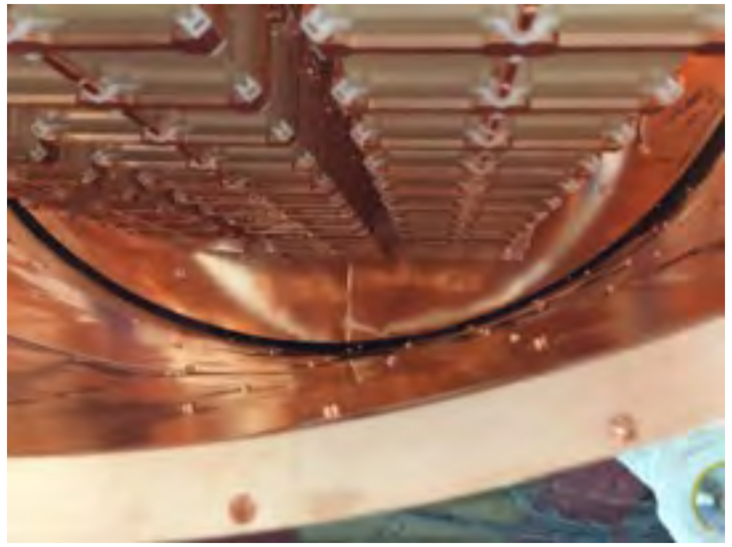
- protected area inside the CUORE clean room flushed with radon-free air (Rn concentration < 0.1 Bq/m^3) for operators life support
- protective bags flushed with nitrogen for overnight and emergency storage
- teams composed of 3 operators spending the minimum amount of time in the cleanroom, following strict protocols developed during months of training and test with mockup components

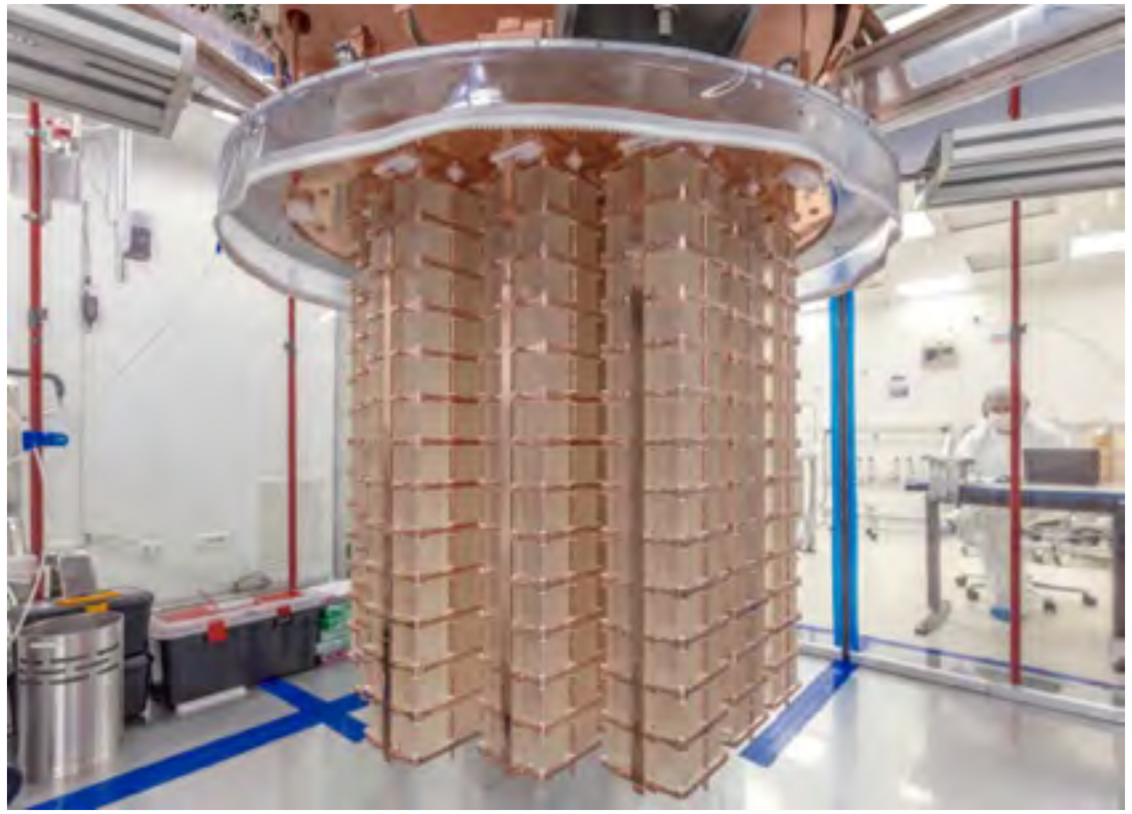
Towers installation completed on August 26, 2016

September-October 2016:

- installation of the cryostat interfaces (protective tiles) and radiation shields
- read-out tests



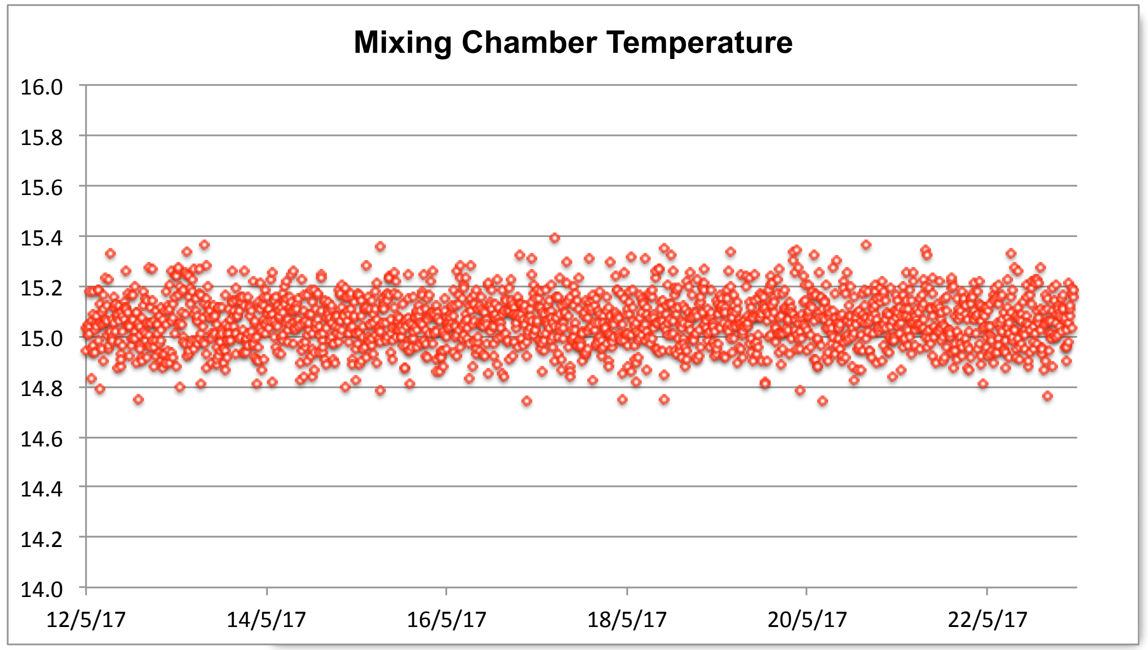


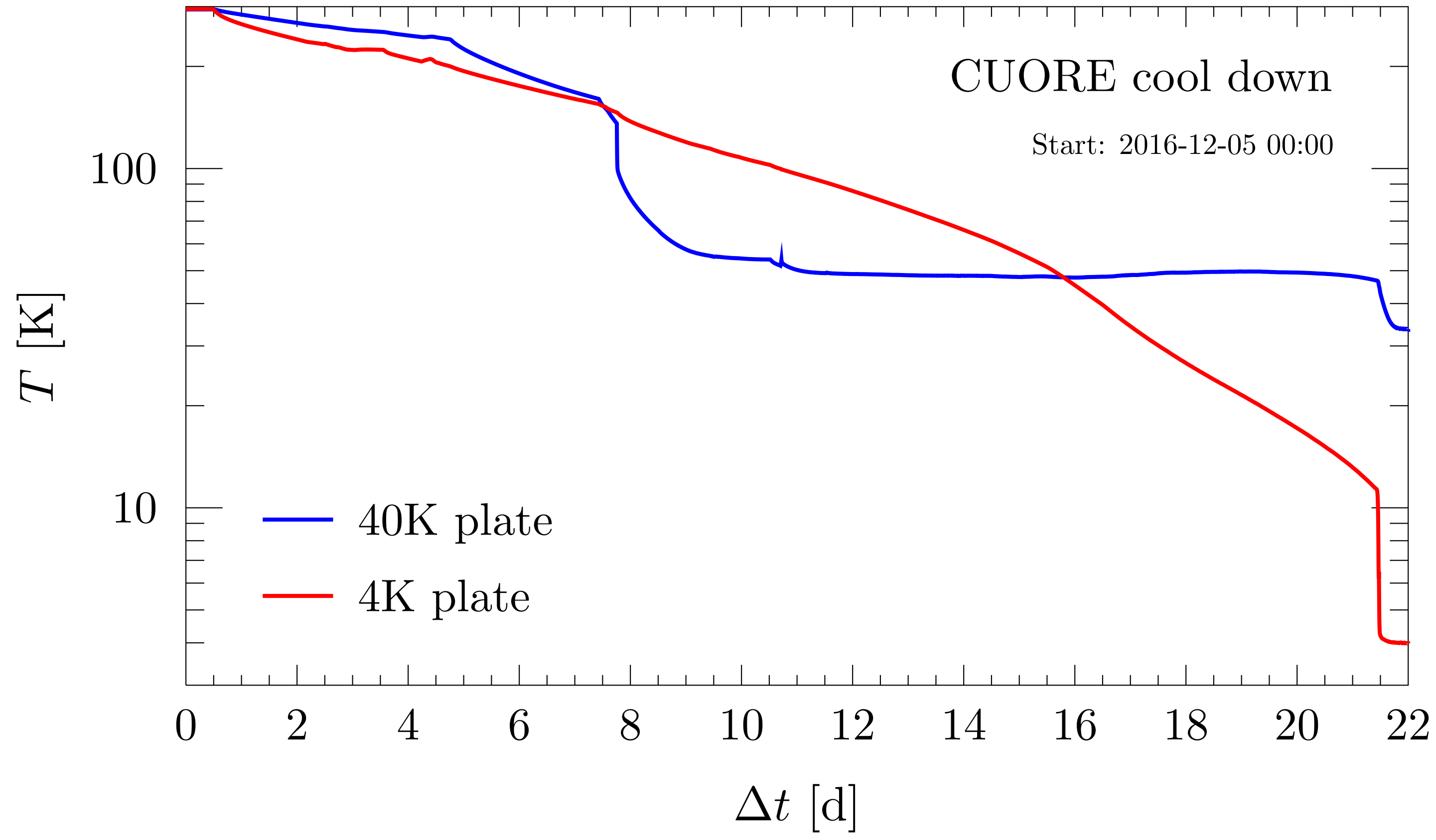


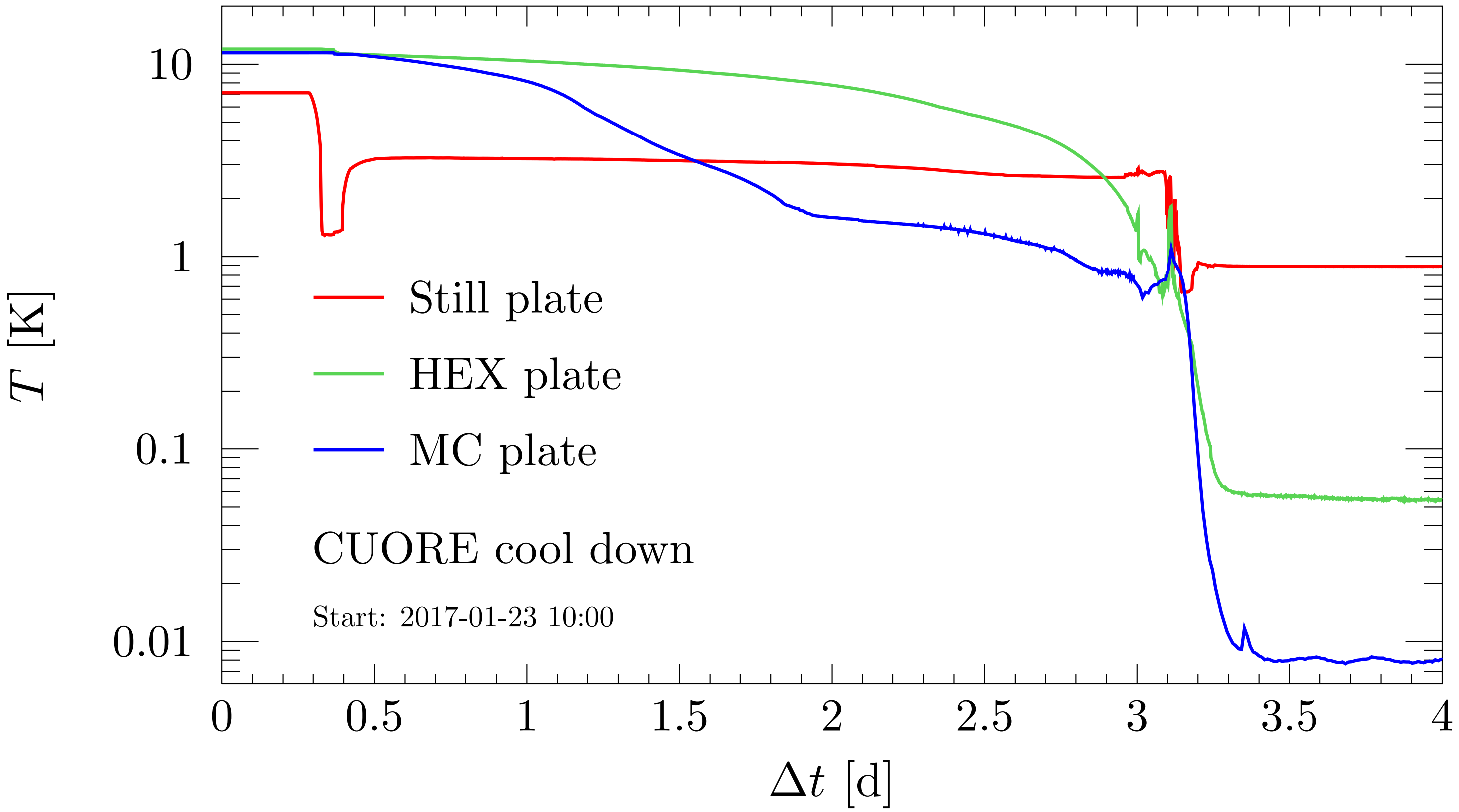
Detector cool down

Started at the beginning of December 2016:

- 300 K —> 4 K in about 22 days
- 4 K —> 7 mK in 3.5 days
- reached a stable base temperature of ~7 mK on Jan 27, 2017
- lowest observed temperature: 6.7 mK
- observed first detector pulses just after the cool down without any optimisation!







OPERATION & PERFORMANCE

CUORE (pre-)operation

2 scientific runs:
Phys. Rev. Lett. 120 (2018) 132501

02/12/2016	Construction is complete
05/12/2016 - 23/01/2017	Cooldown
09/01/2017 - 12/04/2017	Detector commissioning (optimisation phase I)
14/04/2017 - 14/06/2017	Science run n. 1
11/06/2017 - 26/07/2017	Optimisation phase II (warm-up to ~100K)
27/07/2017 - 17/09/2017	Science run n. 2
18/09/2017 - 13/05/2018	Optimisation phase III (new warm-up)

19/05/2018 - 03/09/2018	Science run
03/09/2018 - 04/12/2018	System maintenance
04/12/2018 - 01/02/2019	Science run
01/02/2019 - 17/04/2019	System maintenance
17/04/2019 -	Science run

Detector pre-operation

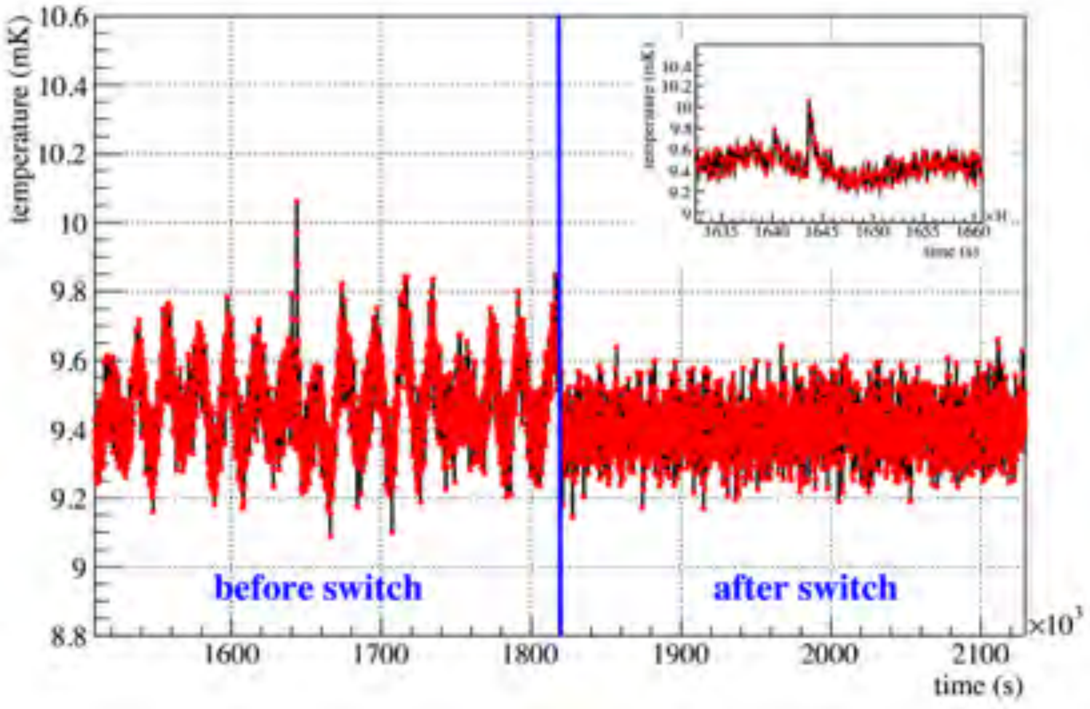
After the successful cool-down we faced the challenge to operate a thousand bolometers in a completely new system.

A long list of tests and activities

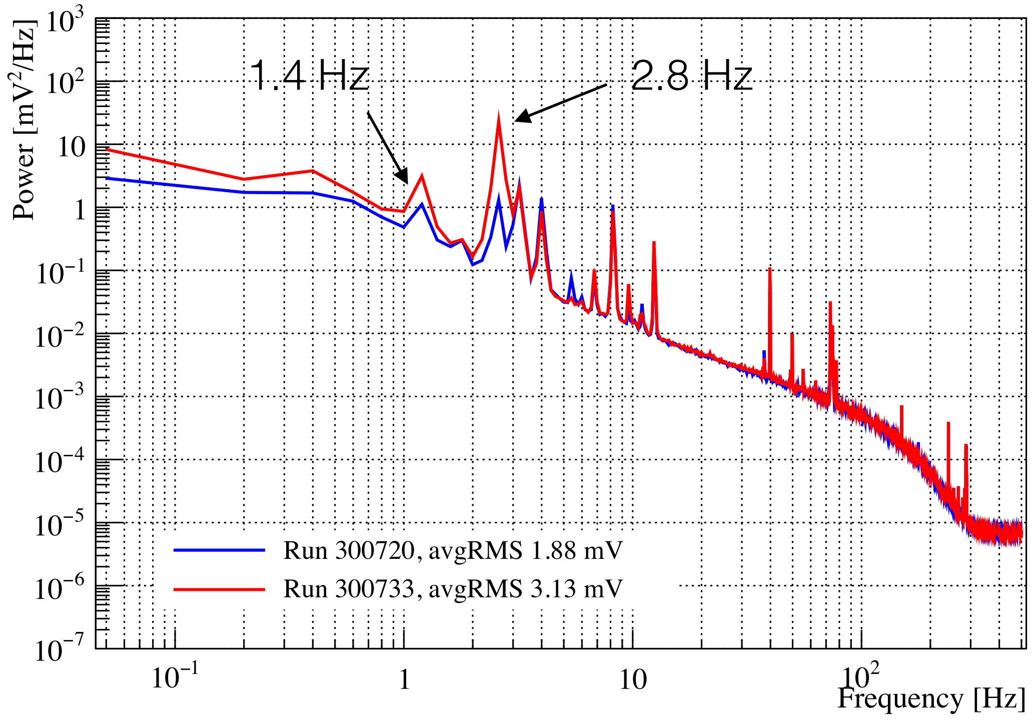
- DAQ and front-end electronics optimization
- Detector working points
    - Select representative subset
    - Load curves (to select optimal working points)
    - Temperature scan for the best operating conditions
- Noise reduction
    - Linear drives to control the pulse tube (PT) motor-heads
    - Monitor and control the relative phase shifts between different PT's using pressure sensors installed on the PT lines
    - Impressive results both in terms of temperature stabilisation and noise abatement

End of March 2017:

- Closed first optimisation phase
- **Ready to start calibrations and science runs**
- Selected working temperature: 15 mK



Average Noise Power Spectrum: ch. 142 runs 300720, 300733



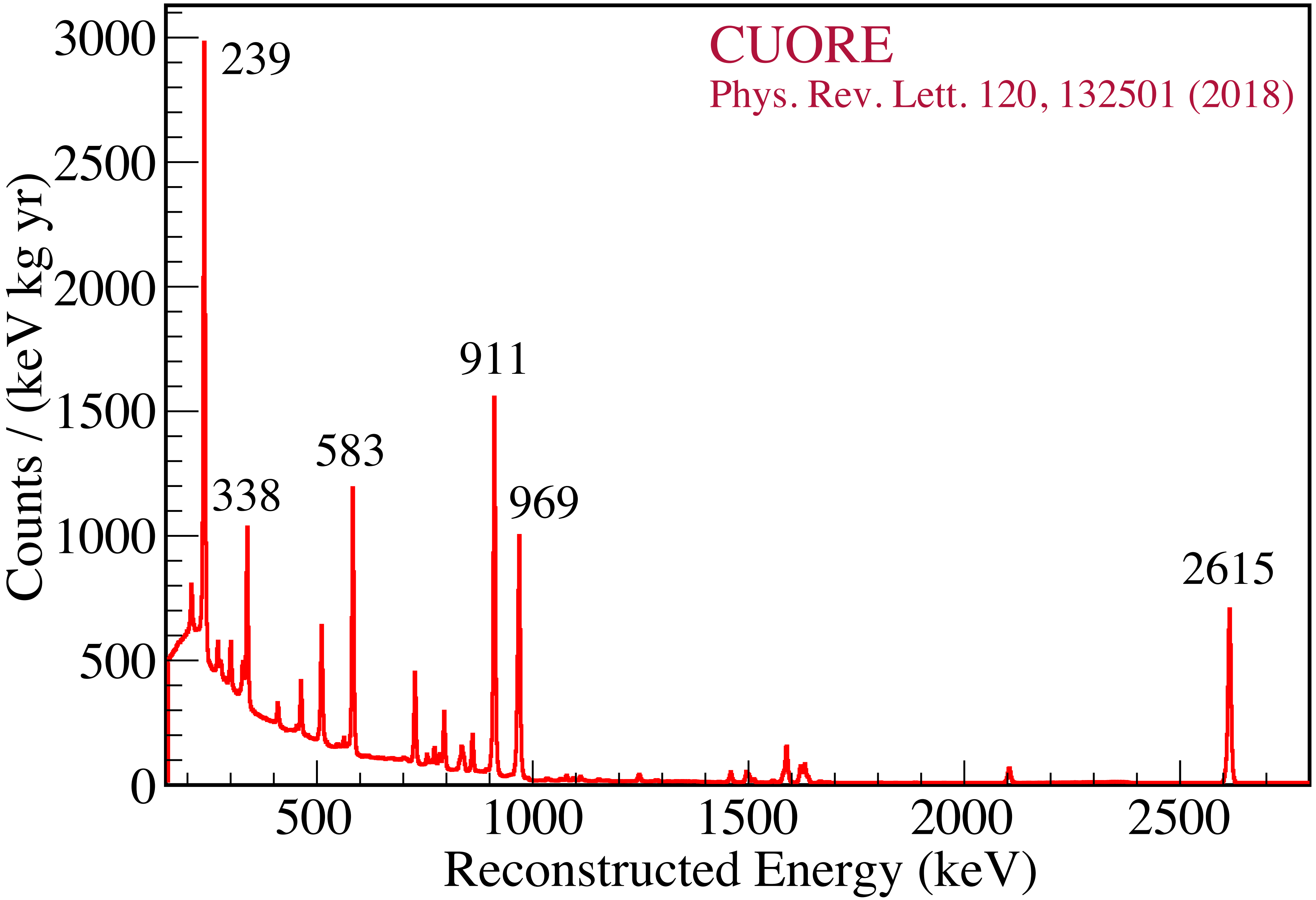
Calibration spectrum

239 keV - ^{212}Pb

338, 911, 969 keV - ^{228}Ac

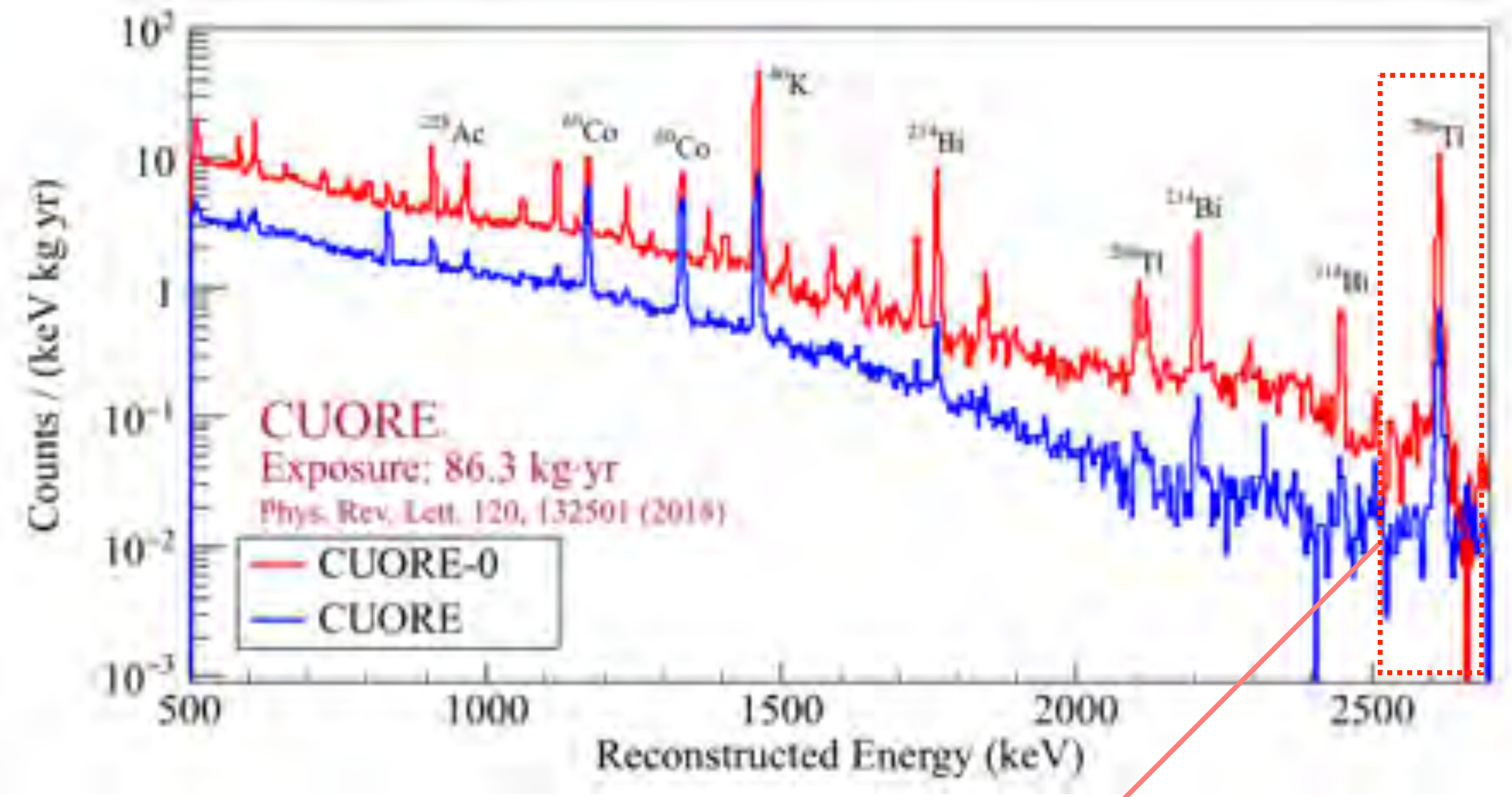
583, 2615 keV - ^{208}Tl

- Calibration strings deployed inside the CUORE detector
- Summed energy spectrum of all the CUORE detectors-datasets
- Calibration data used for:
  - energy scale calibration
  - thermal gain stabilisation
  - detector response (line shape) study

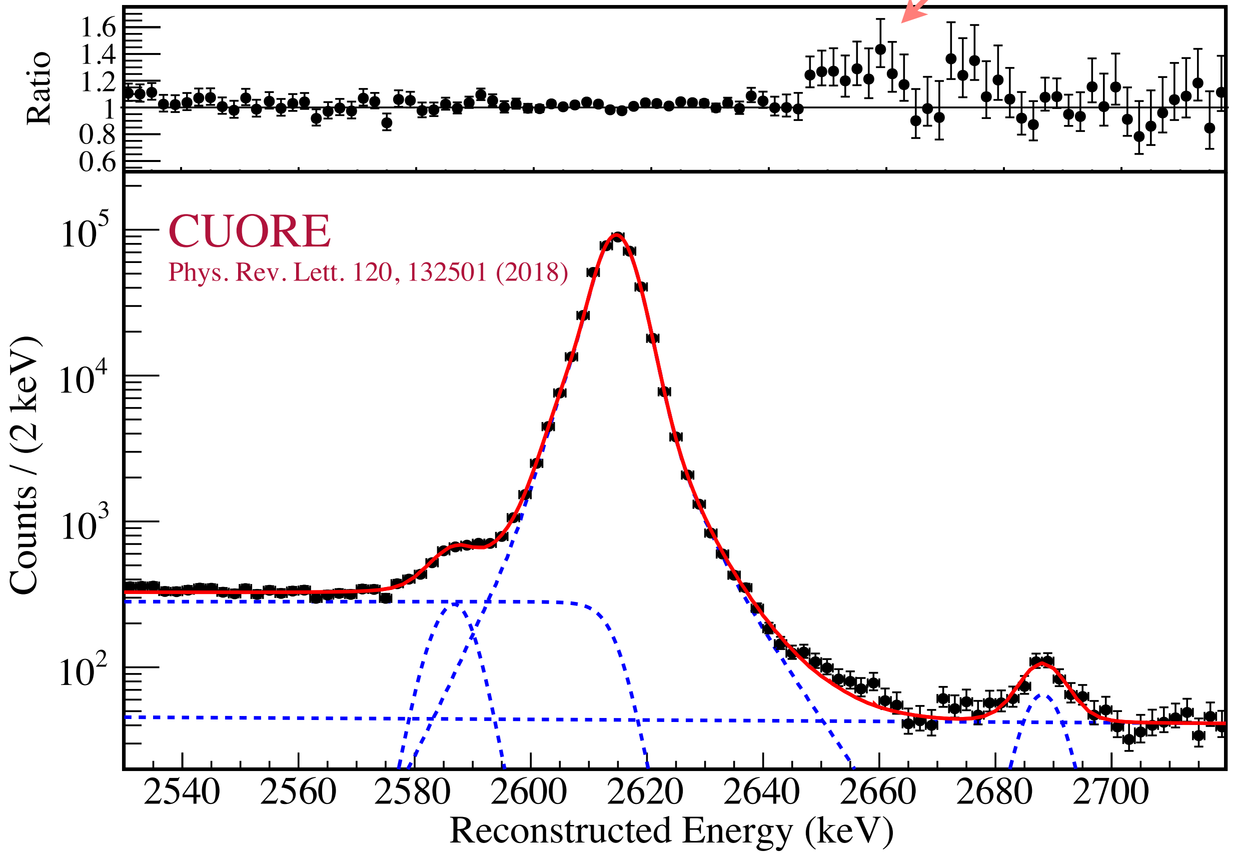


Detector performance: line shape

- The prominent ^{208}Tl line in the calibration spectrum are used to model the detector response to a monochromatic electron-like energy deposition
- 19 simultaneous fit on the data from all the channels of each tower, with some parameters (backgrounds) common to the whole tower and some defined channel-by-channel (resolutions, normalisations)
- Eventually only channel-dependent parameters (**signal**) are used to build the PDF for the ROI fit



- Fit components:
  - (a) **triple gaussian for the photopeak**
  - (b) step-wise smeared multi-compton background
  - (c) combination of gaussian X-rays escape lines
  - (d) linear background
  - (e) single gaussian line for the coincident absorption of 2615-keV and 583-keV followed by a single escape process

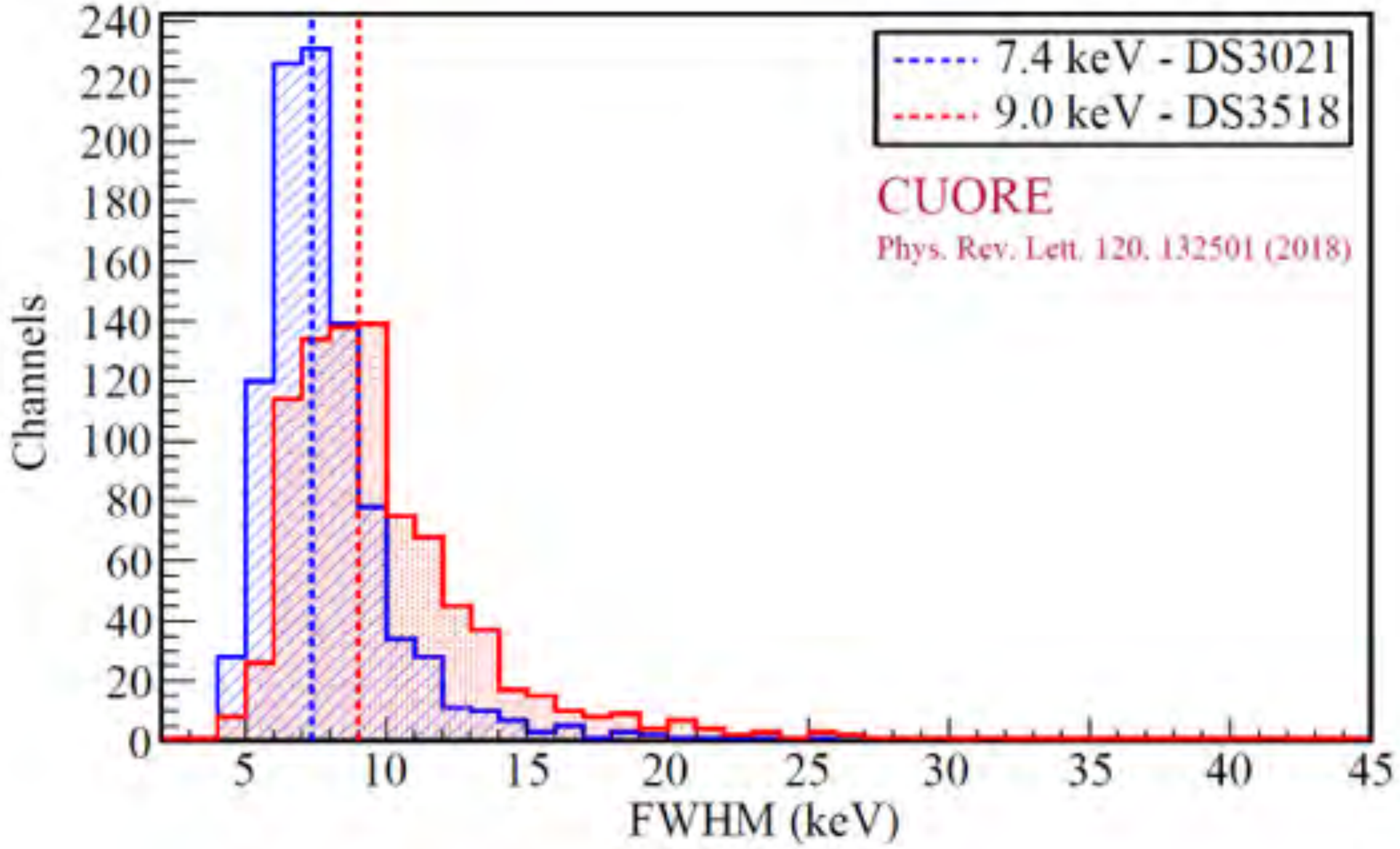


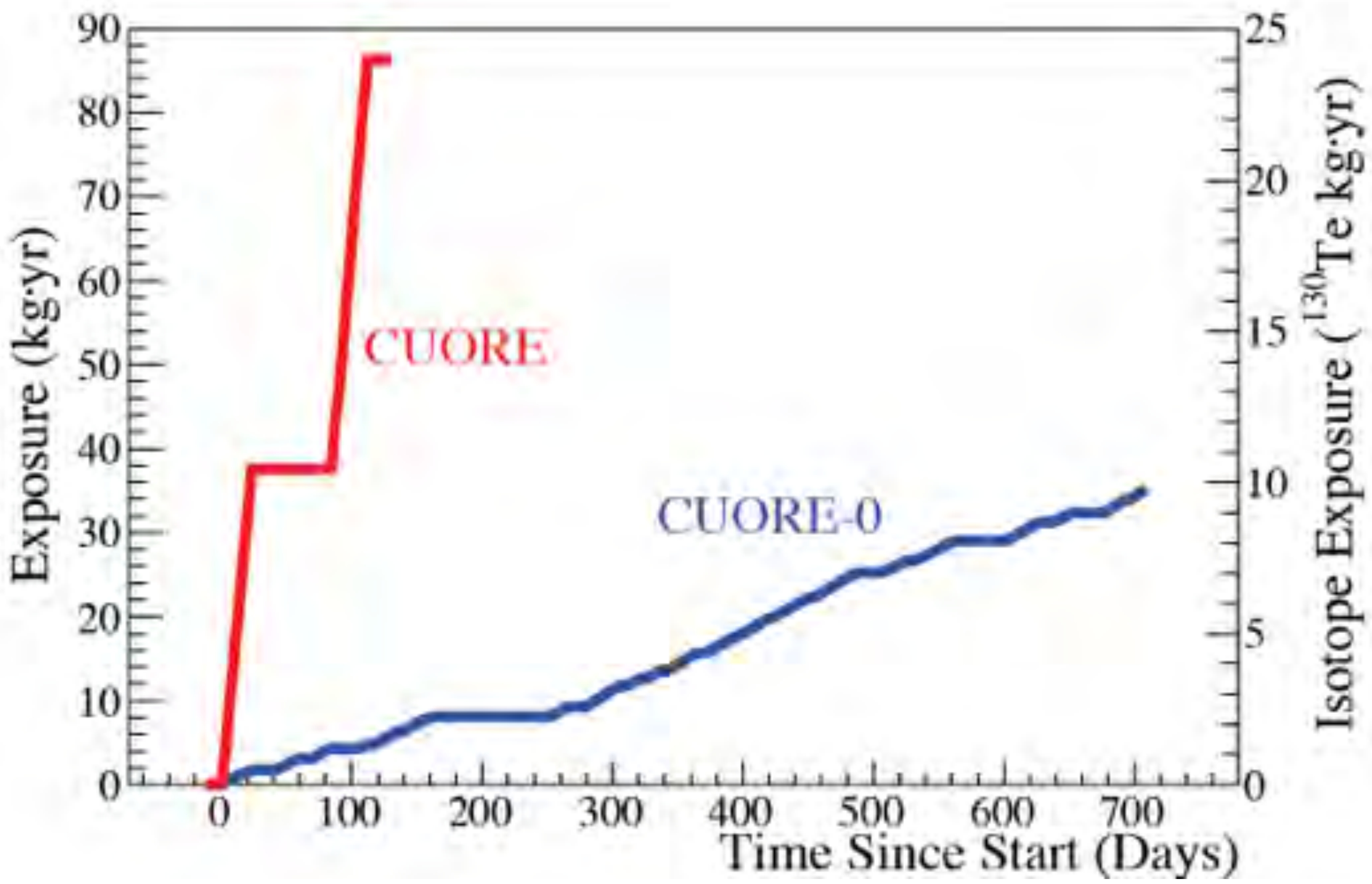
CUORE: 2017 science runs

Collected 86.3 kg·yr of TeO_2 over 7 weeks in summer 2017

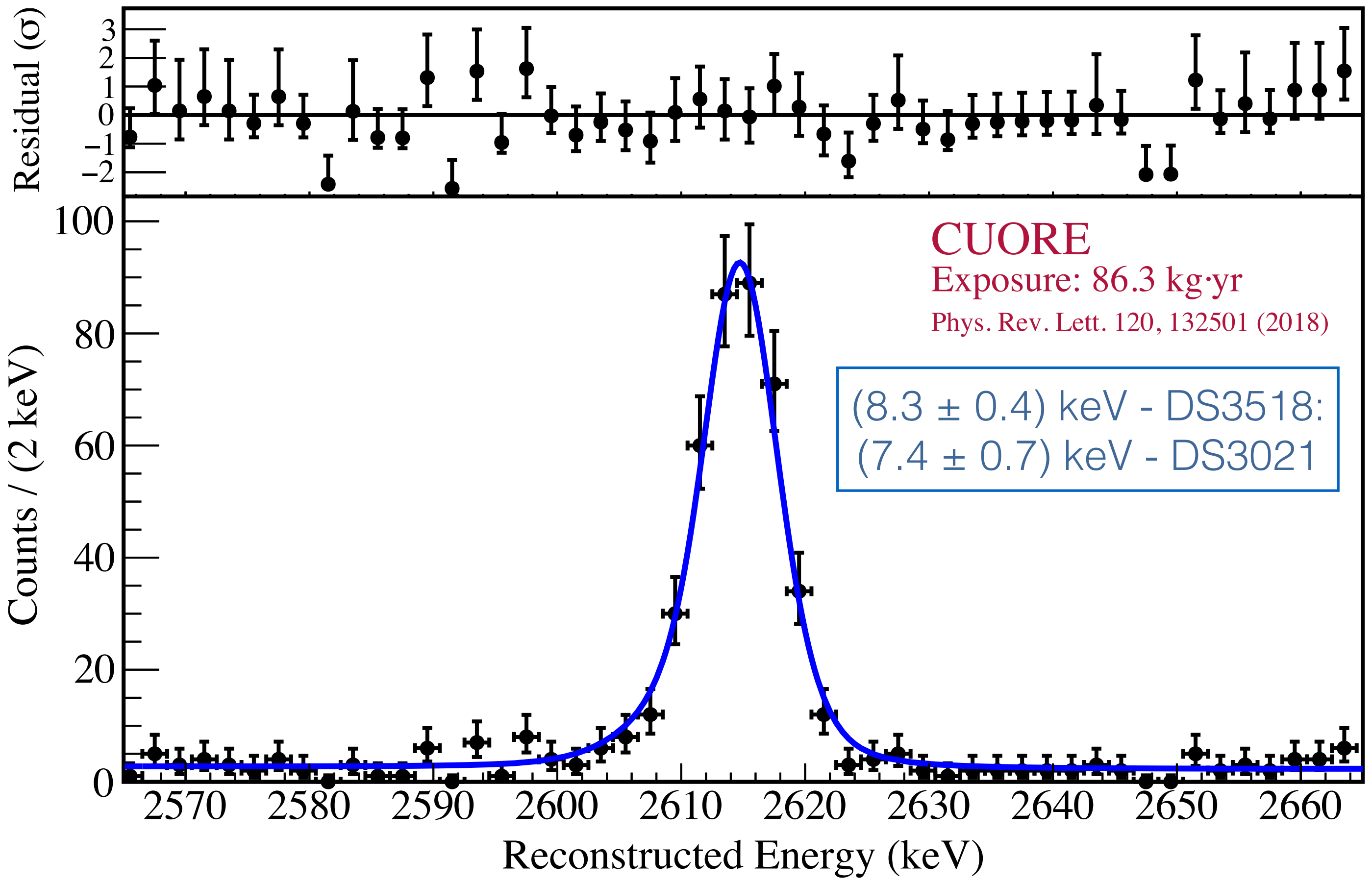
- 99.6% of channels active
- 92% of channels passing analysis cuts
- average (exposure weigthed) energy resolution: (7.7±0.5) keV FWHM
- signal efficiency: ~80%

Calibrations





Science runs

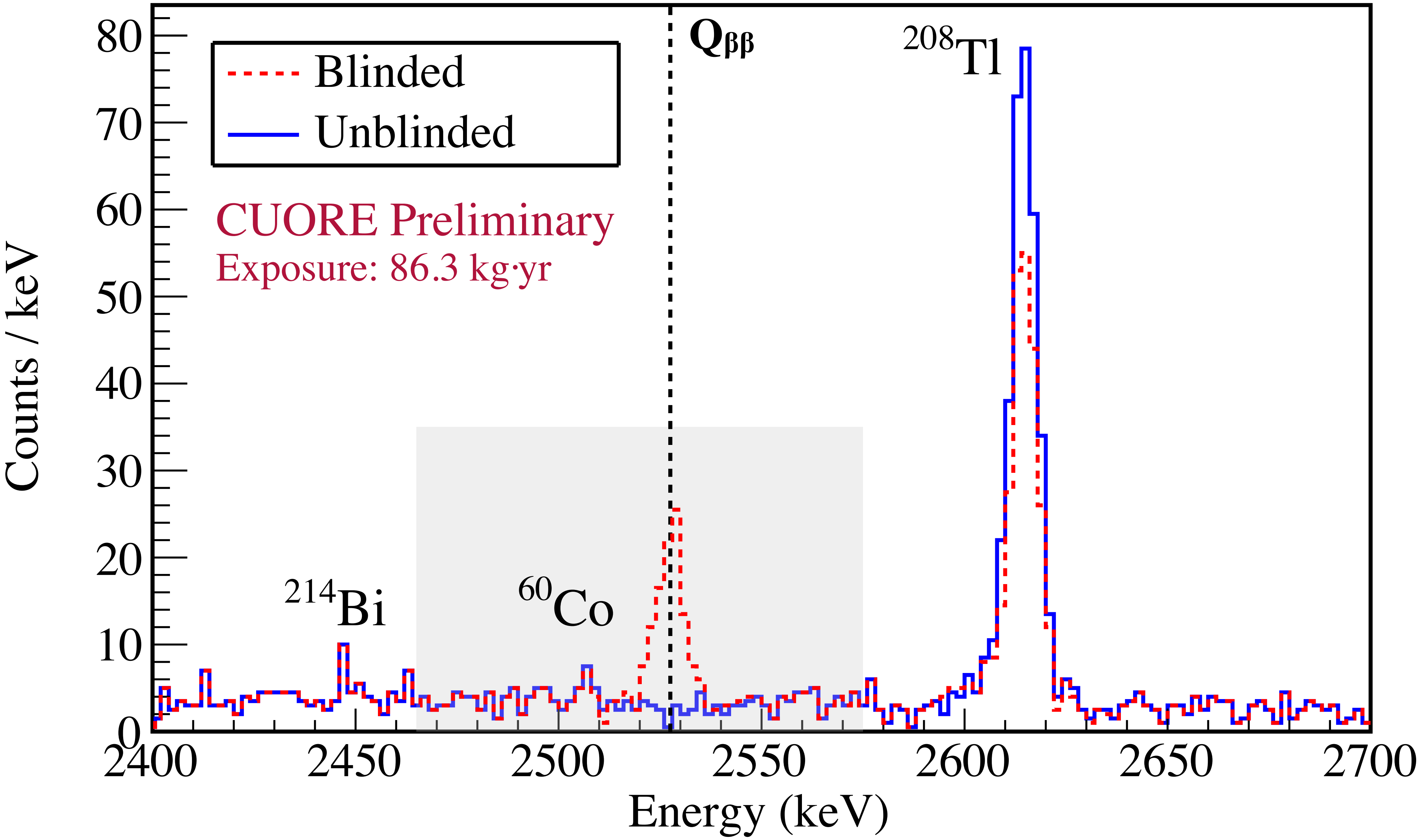


(8.3 ± 0.4) keV - DS3518:
(7.4 ± 0.7) keV - DS3021

RESULTS

Blinding procedure

- To blind our data we randomly move a fraction of events from +/- 20 keV of 2615 keV to the Q-value and vice versa
- The blinding algorithm produces an artificial peak around the 0vDBD Q-value hiding the real 0vDBD rate of ^{130}Te
- This method of blinding the data preserves the integrity of the possible 0vDBD events while maintaining the spectral characteristics with measured energy resolution and introducing no discontinuities in the spectrum
- When all data analysis procedures are fixed the data are eventually unblinded



Fit in the ROI

- Simultaneous **UEML** (Unbinned Extended Maximum Likelihood) fit in the energy region **2465-2575 keV**
- The fit has 3 components:
  1. **posited peak at the Q-value** of ^{130}Te:
     - energy scale defined relative to the ^{208}Tl line in calibration data to account for residual mis-calibration between channels
     - signal normalisation common to all detectors-datasets (1 free parameter)
  2. **floating peak to account for the ^{60}Co** sum gamma line (2505 keV):
     - energy scale defined relative to the ^{208}Tl line in calibration data to account for residual mis-calibration between channels
     - rate common to all detectors-dataset, with a correction accounting for the time elapsed between the two datasets (1 free parameter)
  3. **flat background**, attributed to multi scatter Compton events from ^{208}Tl and surface alpha events:
     - common to all detectors in a single dataset, two independent parameters for the two datasets to account for differences in the background rejection efficiency (2 free parameters)
- The peaks in each channel-dataset are fitted with its own line shape (fixed from calibration data)

Fit in the ROI: results

Region of interest: **2465 to 2575 keV**

Overall signal efficiency: **(75.7 ± 3.0)% - ds3018**

(83.0 ± 2.6)% - ds3021

Events in the region of interest: **155**

ROI background index: **$(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ c/(keV·kg·yr)**

$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$ c/(keV·kg·yr)

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.)$)\times10^{-25}$ / yr**

No evidence of signal

Limit calculation

Profile likelihood integrated on the physical region ($\Gamma^{0\nu} > 0$)

Decay rate limit (90% CL, including systematics):

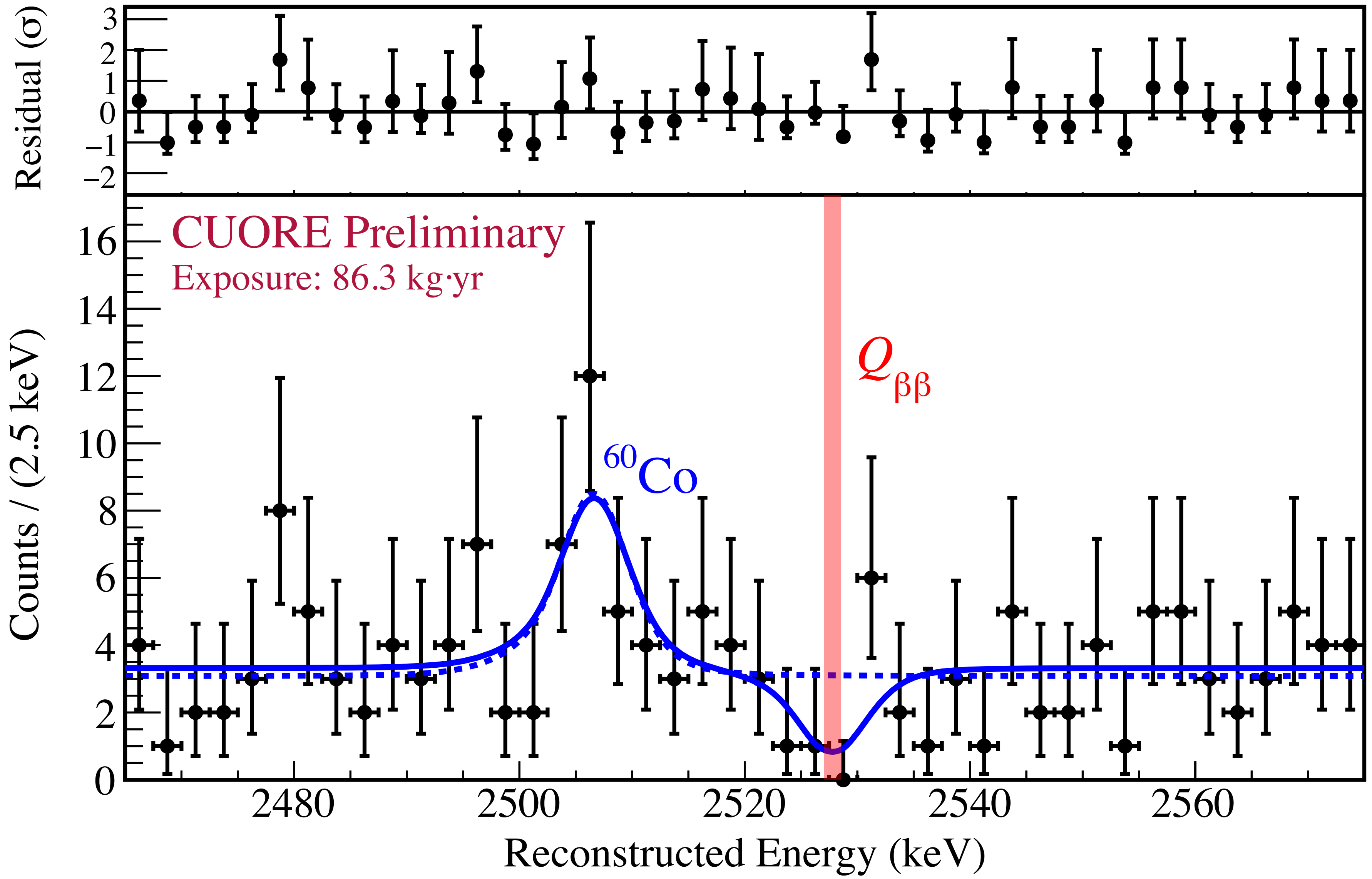
0.51×10^{-25} / yr

Half-life limit (90% CL, including systematics):

1.3×10^{25} yr

Median expected sensitivity:

7.0×10^{24} yr



Combination with previous results

- We combined the CUORE result with the existing ^{130}Te data:
  - 19.75 kg·yr of Cuoricino
  - 9.8 kg·yr of CUORE-0

- The combined 90% C.L. limit is

$T_{0\nu} > 1.5 \times 10^{25}$ yr

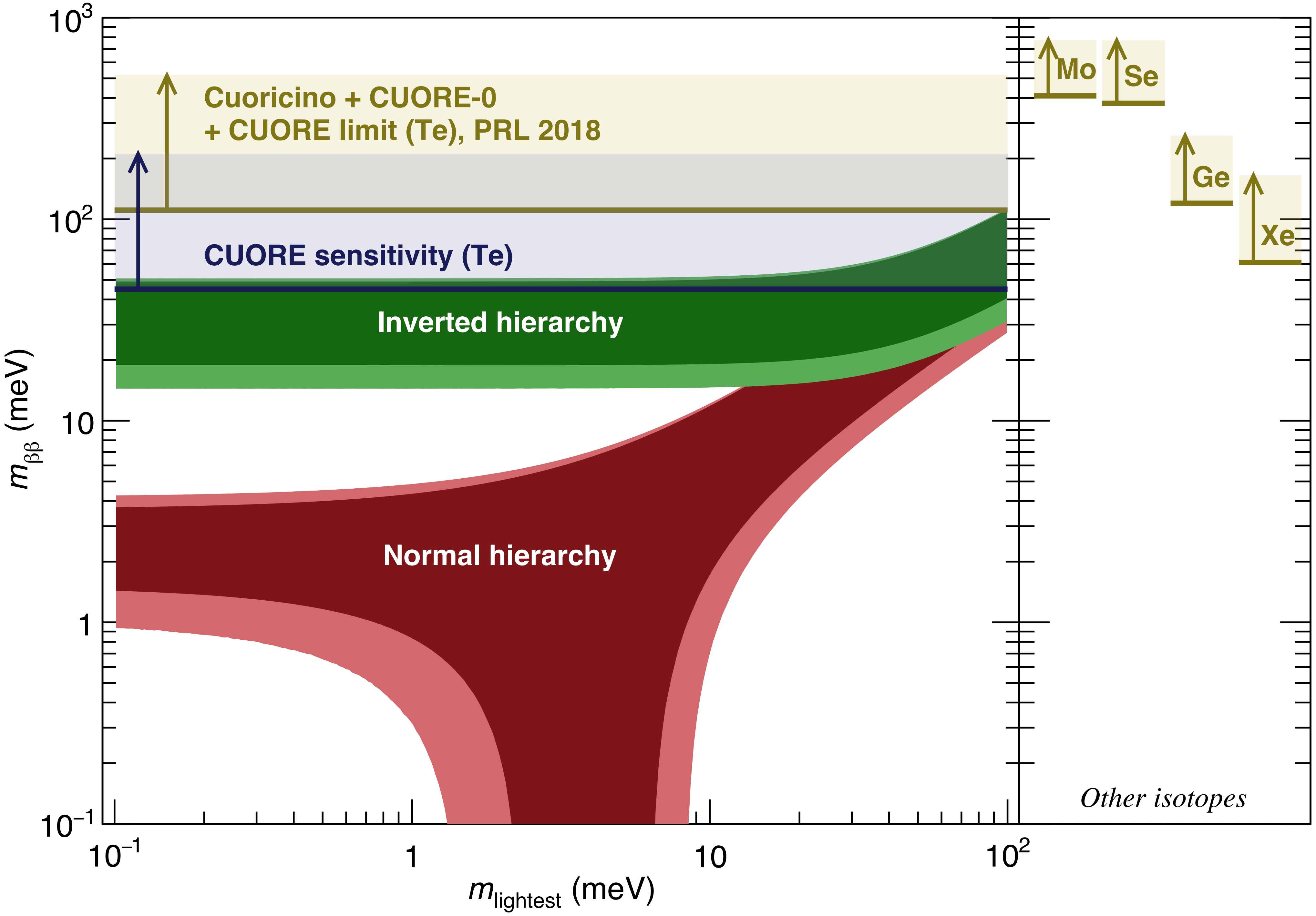
$m_{\beta\beta} <$ 110–520 meV

NME:

JHEP02 (2013) 025
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 87, 064302 (2014)
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 91, 024613 (2015)
Phys. Rev. C 91, 024309 (2015)
Phys. Rev. C 91, 024316 (2015)
Phys. Rev. Lett. 105, 252503 (2010)
Phys. Rev. Lett. 111, 142501 (2013)

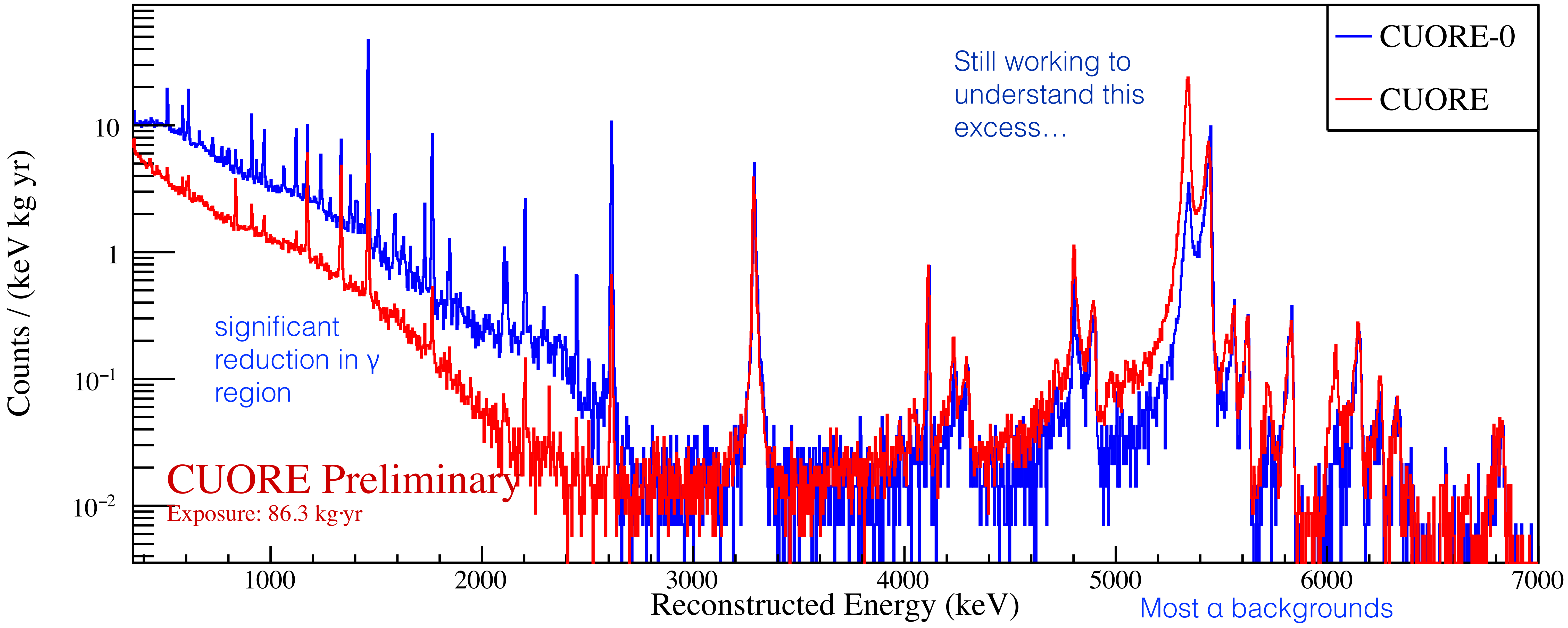
Experiments:

^{130}Te: 1.5 × 1025 yr from PRL 120, 132501 (2018)
^{76}Ge: 8.0 × 1025 yr from PRL 120, 132503 (2018)
^{136}Xe: 1.1 × 1026 yr from Phys. Rev. Lett. 117, 082503 (2016)
^{100}Mo: 1.1 × 1024 yr from Phys. Rev. D 89, 111101 (2014)
^{82}Se: 2.4 × 1024 yr from Phys. Rev. Lett 120, 232502 (2018)
CUORE sensitivity: 9.0 × 10^{25} yr



Background spectra

- Backgrounds generally consistent with expectations
- ^{210}Po excess appears to be from shallow contamination in copper around the detectors (estimated contribution to ROI at the level of ~ 10^{-4} cnts/(keV kg yr))



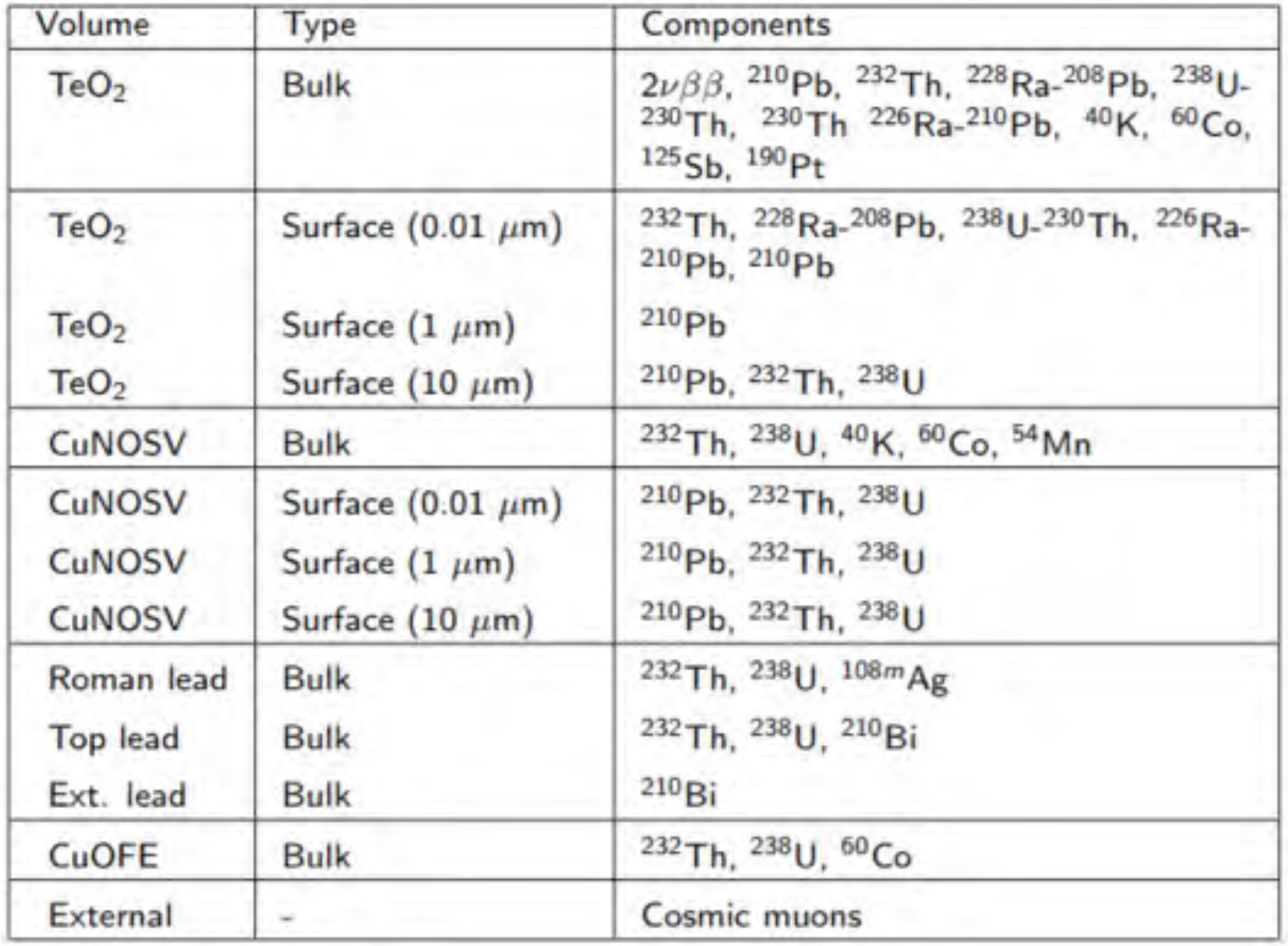
significant reduction in γ region

Still working to understand this excess…

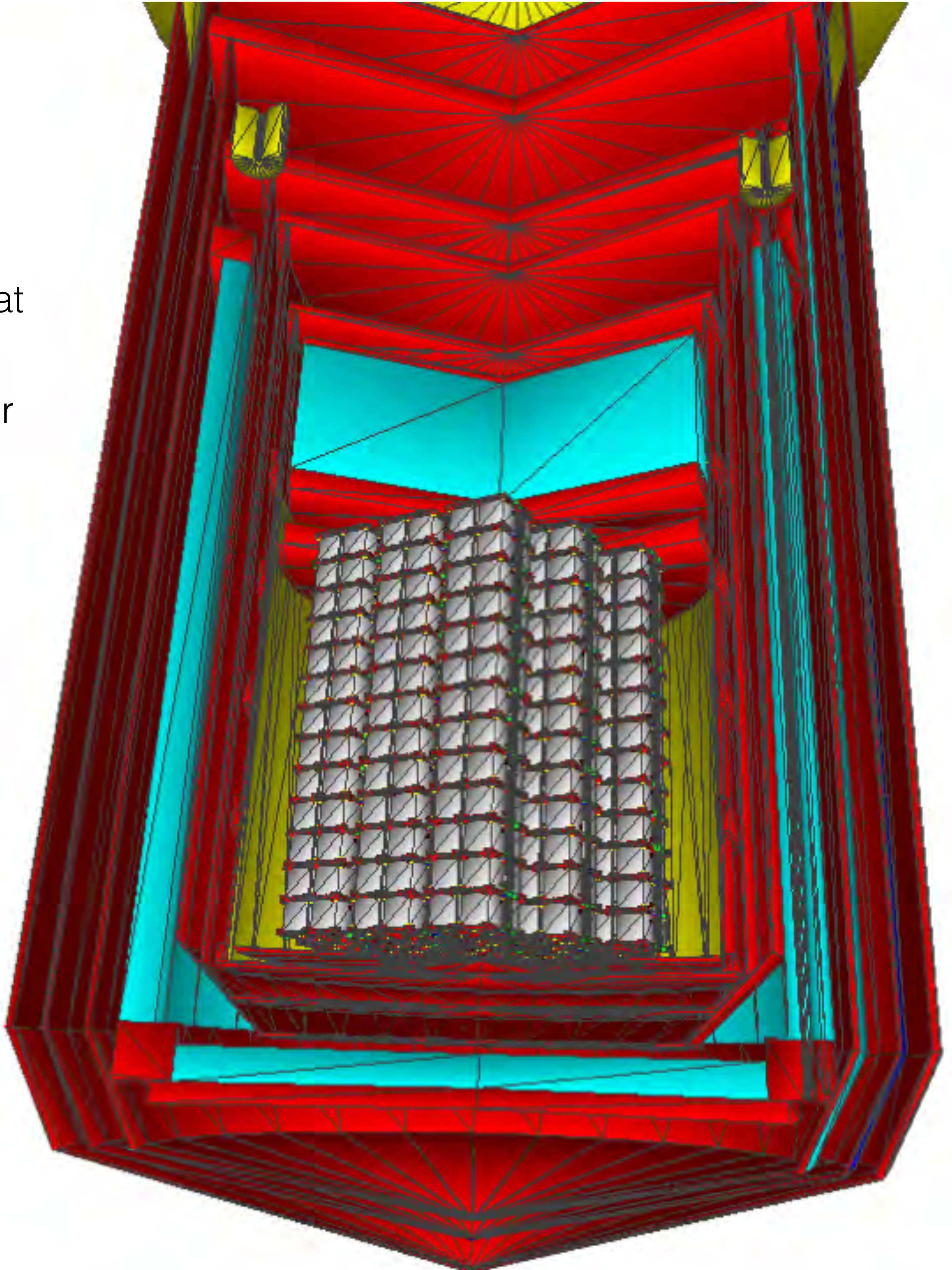
Most α backgrounds consistent with CUORE-0

Background model

- Simulate the contaminations coming from different cryostat components using a detailed Geant4 MC simulation
- ~60 independent parameters representing various contaminations that could contribute to the CUORE background model
- Perform a large Bayesian fit to the data using a MCMC Gibbs sampler
- Flat priors on all parameters



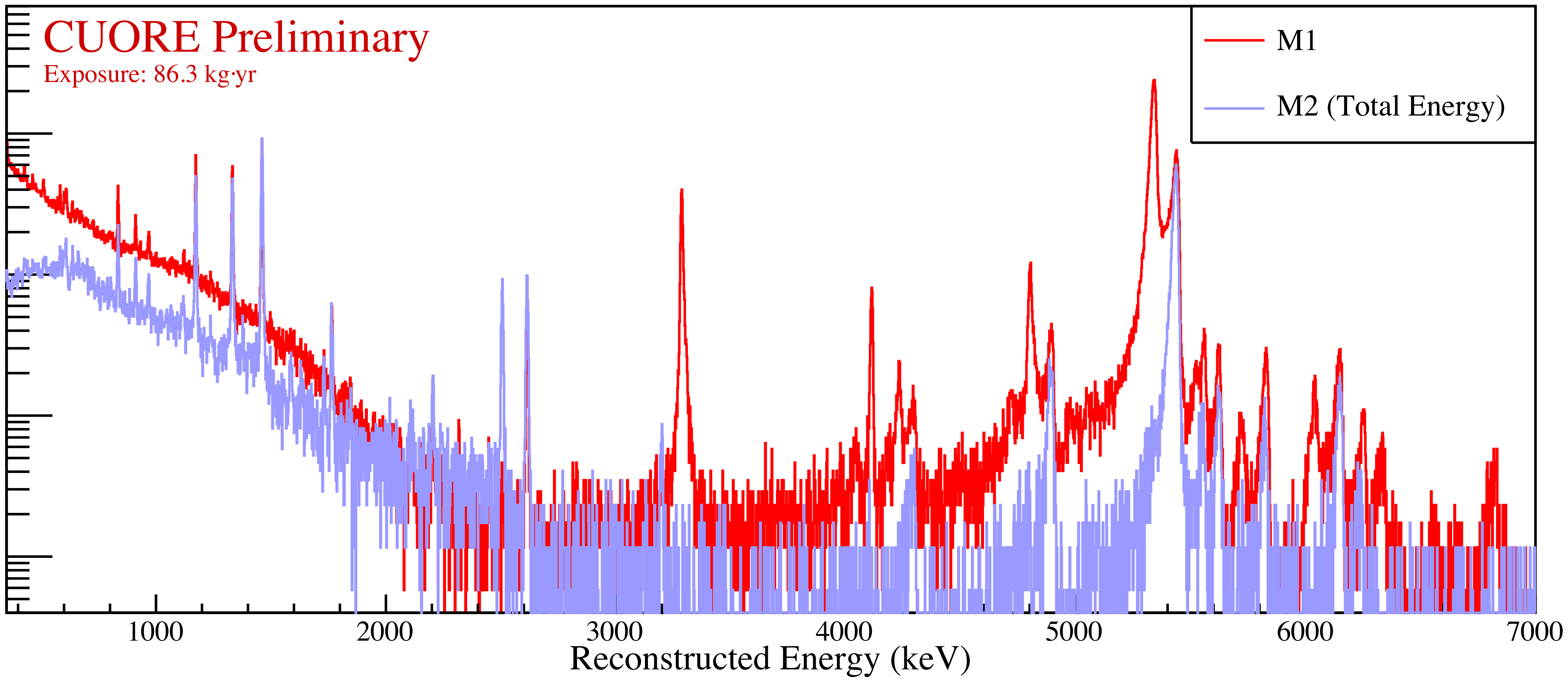
Volume	Type	Components
TeO_2	Bulk	$2\nu\beta\beta$, ^{210}Pb, ^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{230}Th ^{226}Ra-^{210}Pb, ^{40}K, ^{60}Co, ^{125}Sb, ^{190}Pt
TeO_2	Surface (0.01 μm)	^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{226}Ra-^{210}Pb, ^{210}Pb
TeO_2	Surface (1 μm)	^{210}Pb
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

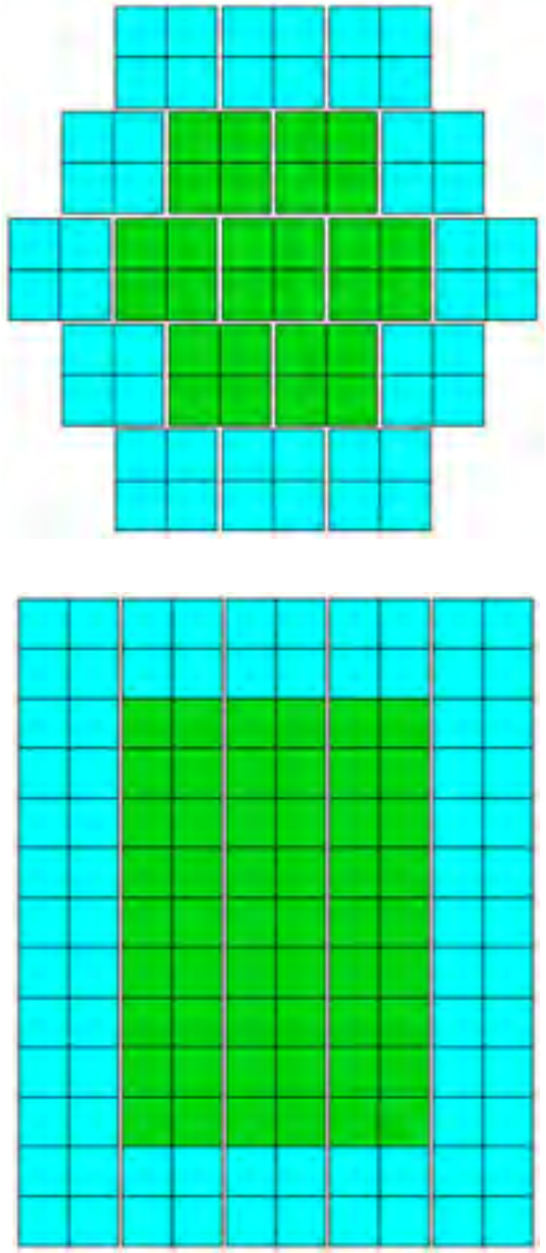


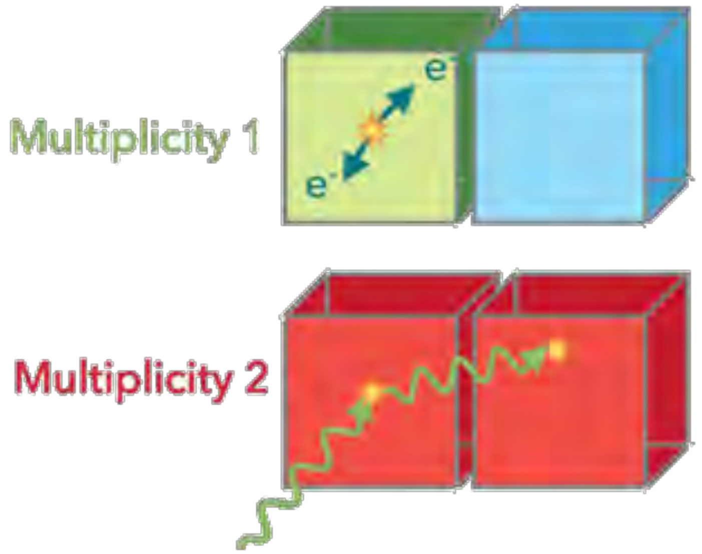
Background model

86.3 kg·yr of TeO_2 from summer 2017

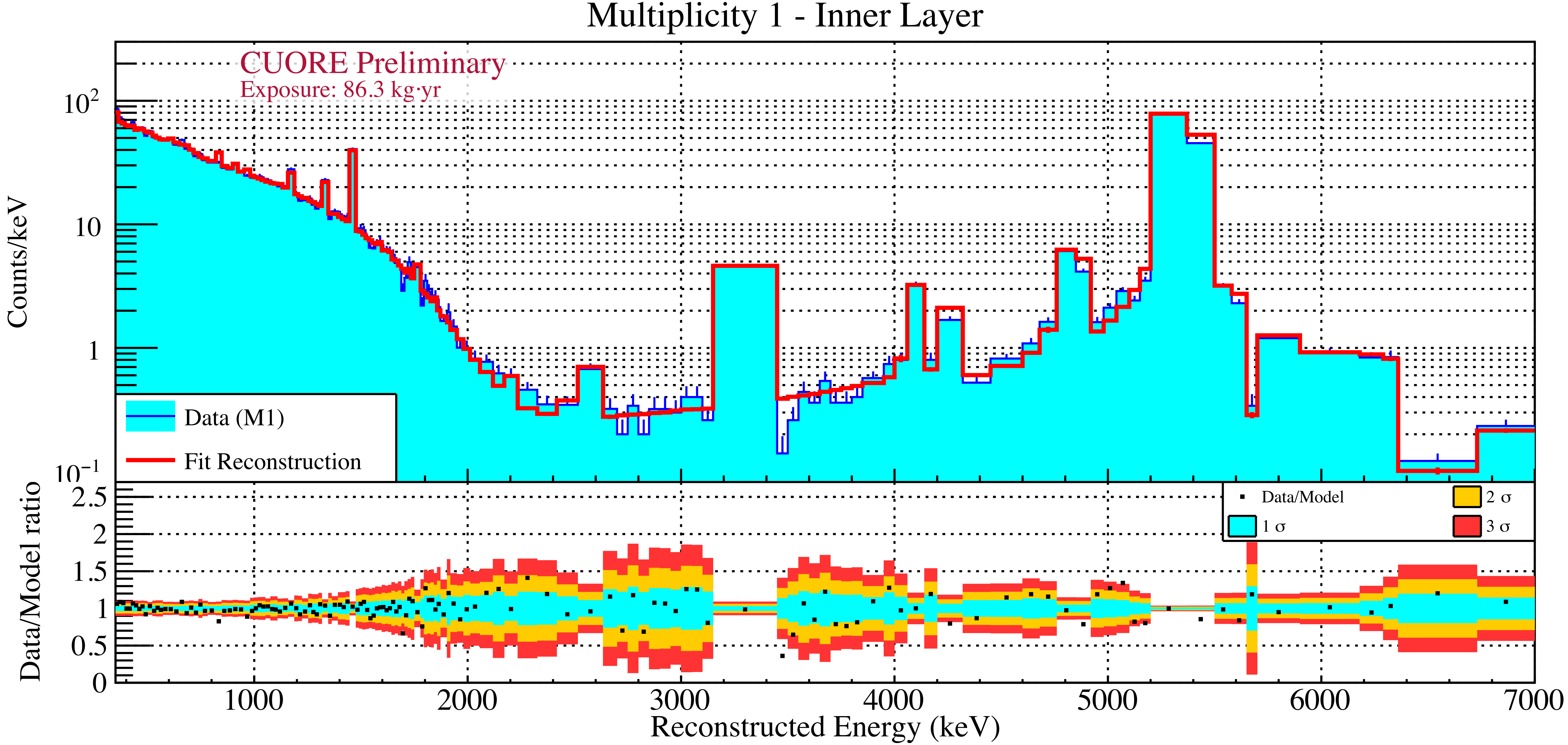
- split data into inner and outer layers
- split data into Multiplicity 1 (M1), Multiplicity 2 (M2), and Multiplicity 2 Sum (Σ2) spectra
  - higher multiplicity spectra sensitive to different backgrounds





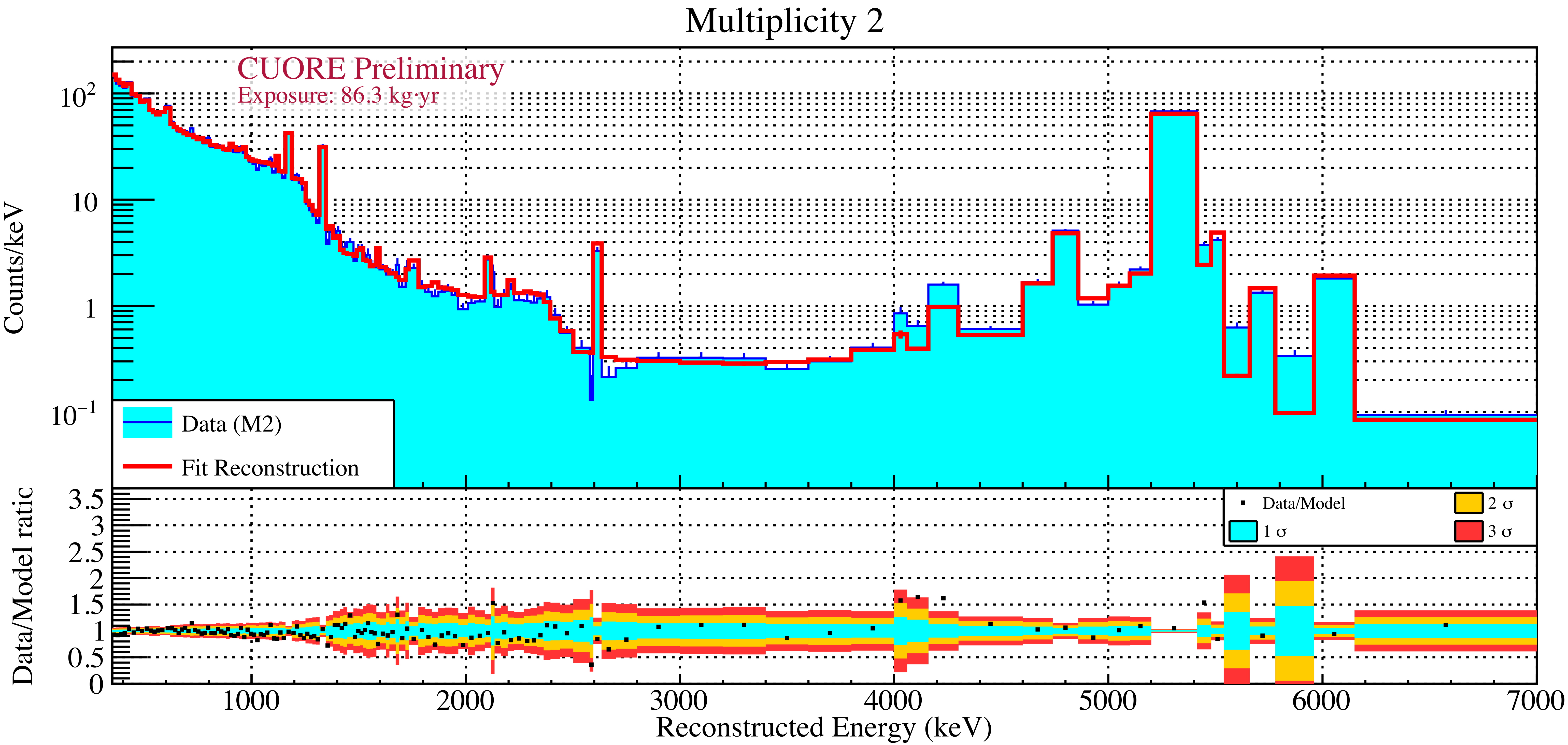


Background model



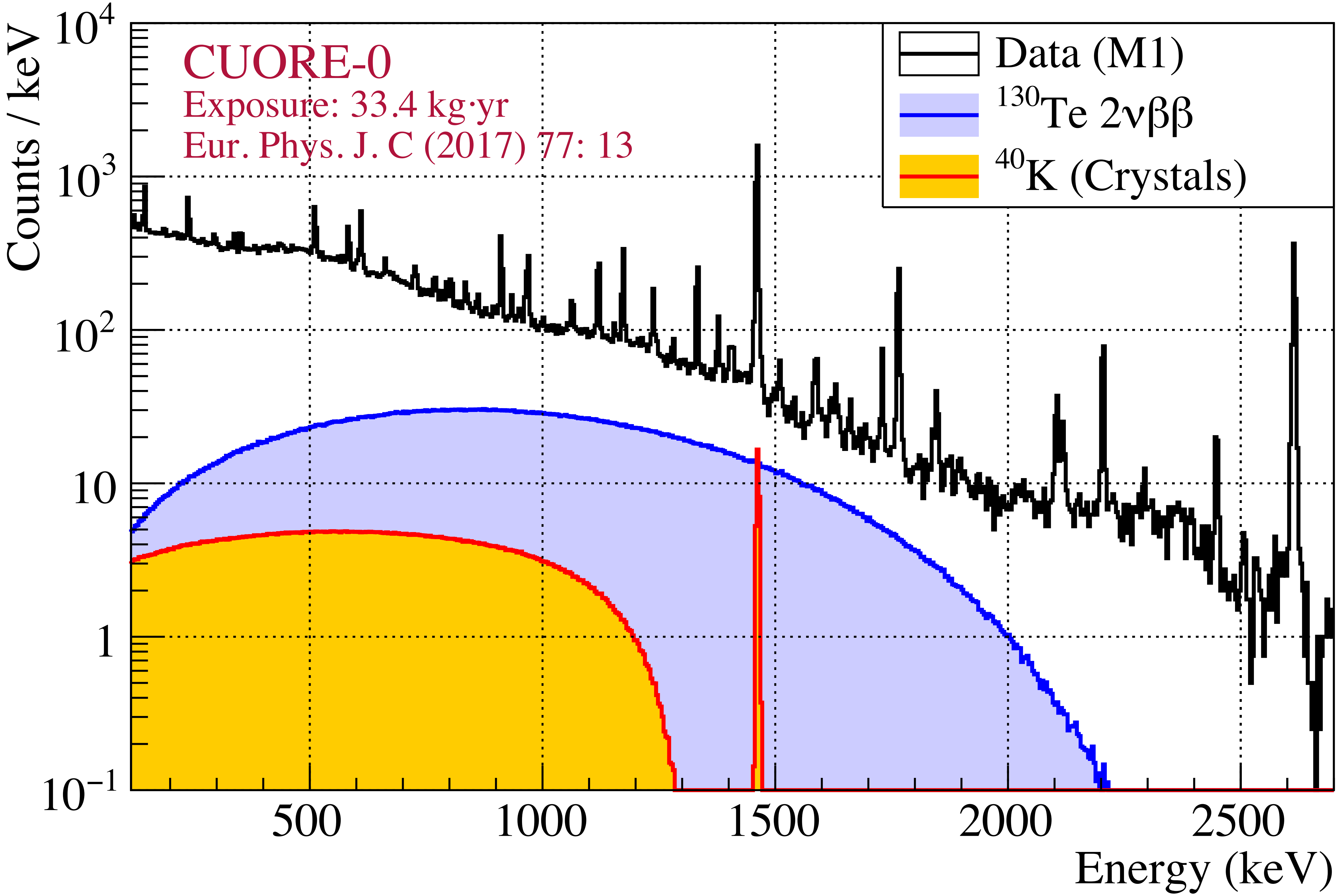
Able to reconstruct the major features of the observed spectrum in CUORE

Background model



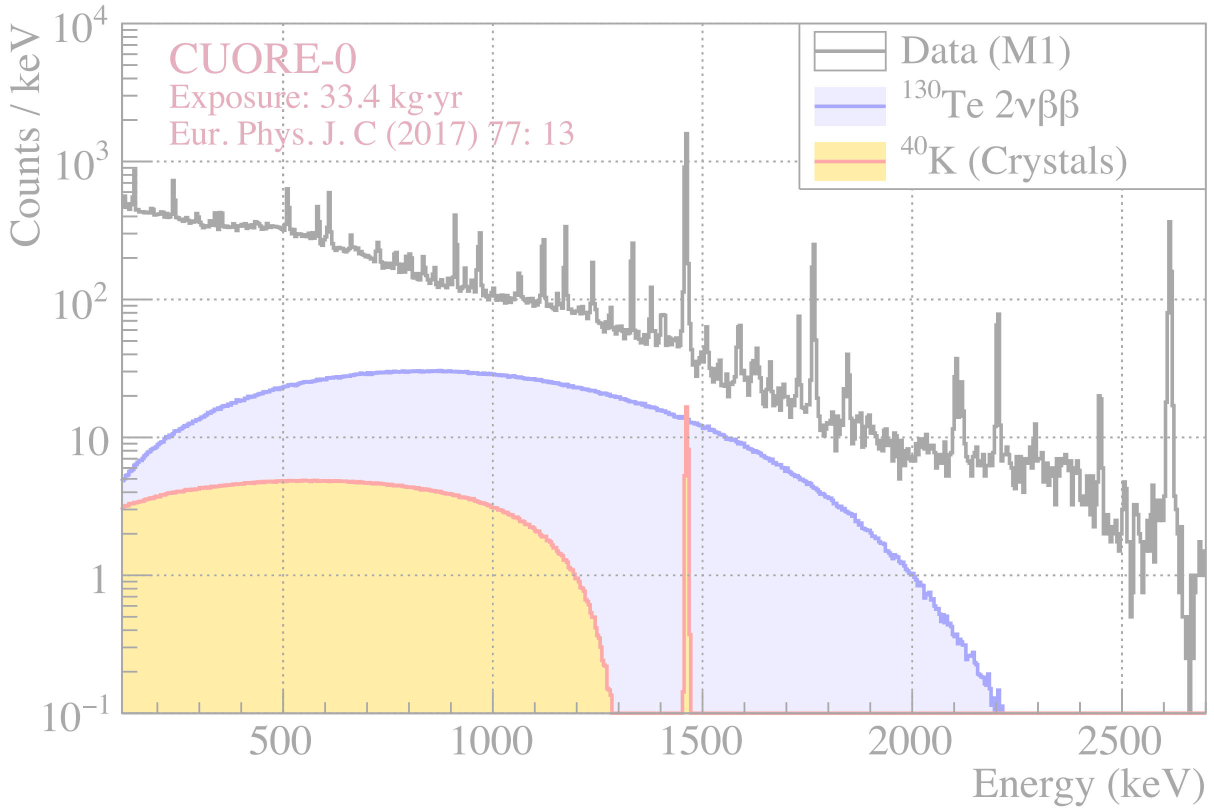
Many contaminations constrained by the higher multiplicity spectra

ββ2ν half-life measurement: CUORE-0

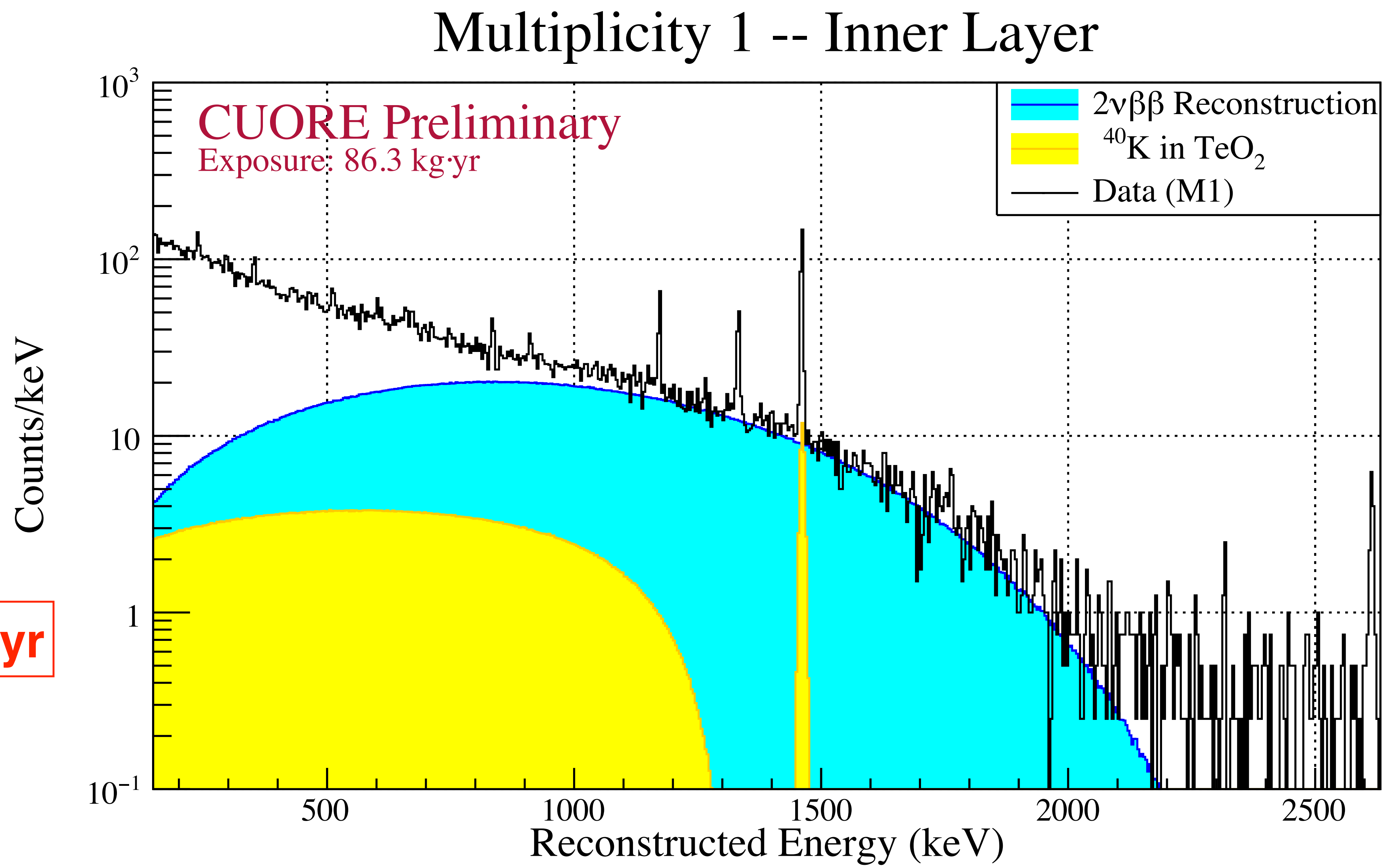


In CUORE-0, 2νββ decay spectrum accounts for ~20% of the signal in the range 1 - 2 MeV

ββ2v half-life measurement:CUORE



In CUORE-0, 2νββ decay spectrum accounts for ~20% of the signal in the range 1 - 2 MeV

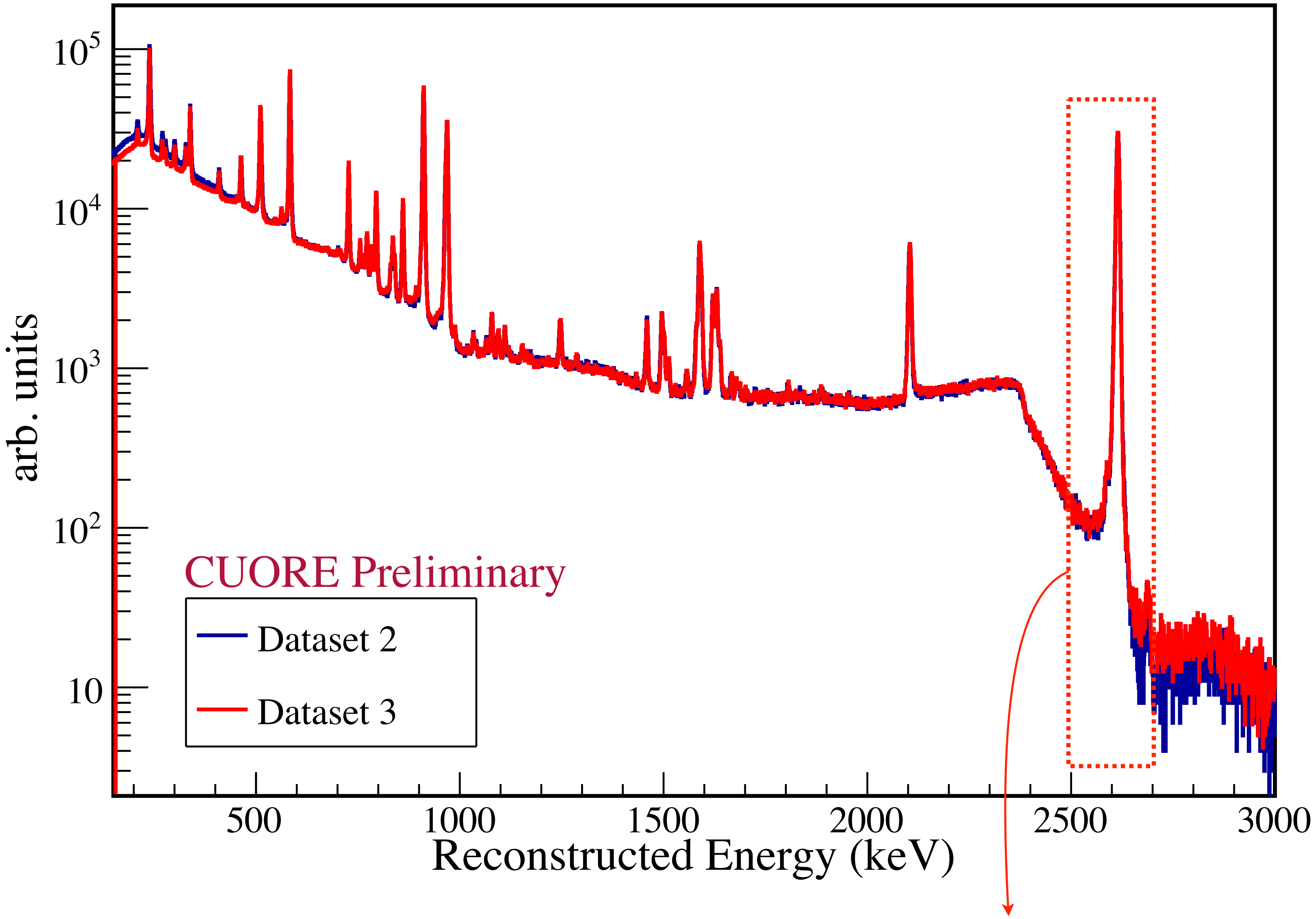


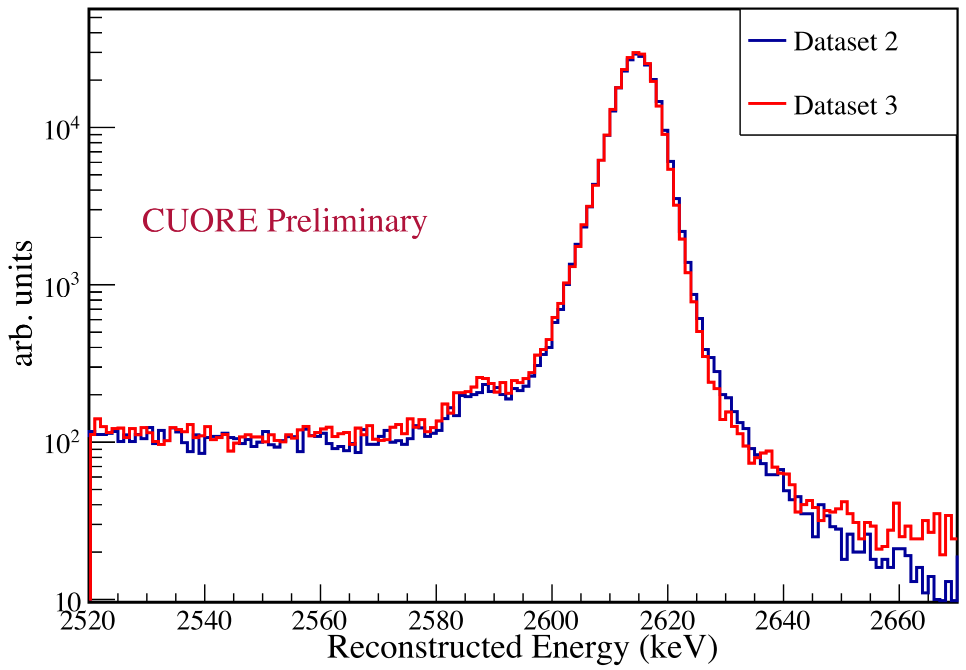
In CUORE, 2νββ decay spectrum accounts for nearly all of the signal in the range 1 - 2 MeV

$T_{1/2}$ = [7.9 ± 0.1 (stat.) ± 0.2 (syst.)] → 10^{20} yr

CUORE-0 : [8.2 ± 0.2 (stat.) ± 0.6 (syst.)] → 10^{20} yr
NEMO-3 : [7.0 ± 0.9 (stat.) ± 1.1 (syst.)] →10^{20} yr

2018 science runs





- Operating temperature: 11 mK
- April calibration data characterized by energy resolution of 7.6 keV FWHM with 93% of channels passing cuts (using same processing procedures)
- Still working to achieve the energy resolution goal of 5 keV FWHM
- Back to stable physics data taking in May 2018

Conclusions

- CUORE is the first ton-scale cryogenic detector array in operation, more than an order of magnitude larger than its predecessors
- The successful commissioning and operation of this large-mass, low-background cryogenic bolometer array represents a major advancement in the application of this technique to ββ0ν decay searches and demonstrates the feasibility of future large-mass bolometer arrays for rare-event searches.
- Thanks to the increased mass of the detector a number of physics processes can be studied with high precision
- With the first data of CUORE:
  - Set the most stringent limit on 0νββ half-life of ^{130}Te to date
  - Made the most precise measurement of 2νββ half-life of ^{130}Te
- After a period of detector optimization, data taking has restarted in May 2018
- CUORE will continue taking data in the coming years, with an ultimate sensitivity to 0νββ half-life in ^{130}Te of $T_{1/2}^{0\nu} > 9 \times 10^{25}$ yr

FUTURE PESPECTIVES: CUPID

CUORE

CUORE is collecting data succesfully

- 5 y projected half-life sensitivity: ~10^{26} y ($m_{\beta\beta} < 50 – 190$ meV)
- Background according to expectations: $(1.4 \pm 0.2)\times10^{-2}$ c/(keV · kg · yr)
- Energy resolution close to expectations: 7.6 keV FWHM (still margins for improvement)
- Analysis of ~1000 individual bolometers is handable

Two important messages from CUORE

1. A tonne-scale bolometric detector is feasible
2. An infrastructure to host a bolometric next-generation 0νββ experiment is already available

CUPID is the natural evolution of CUORE

CUPID

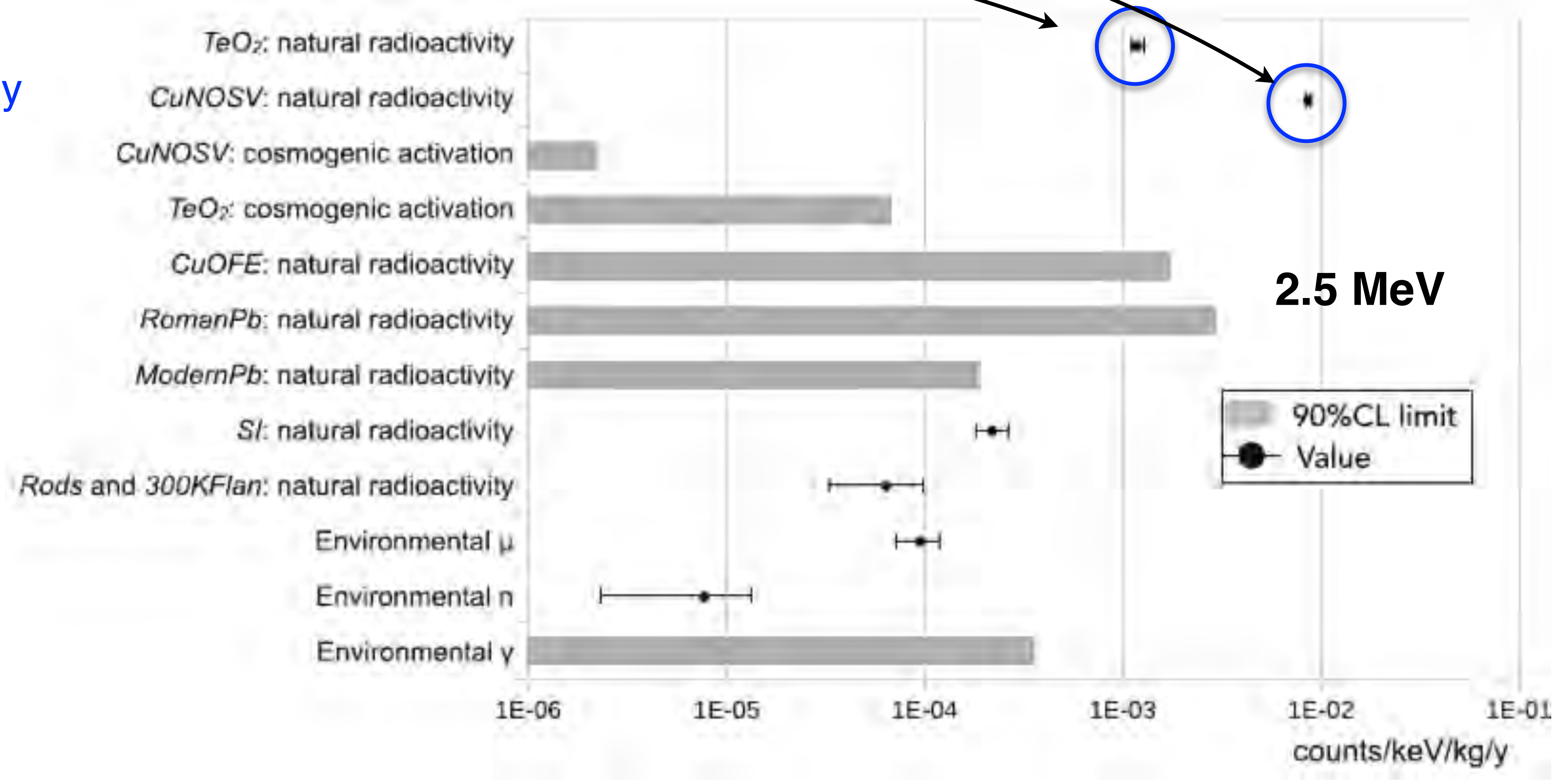
CUORE background presently dominated by alpha particles from surface contamination

Moving to CUPID requires:

1. Rejection of alphas
2. Control of the residual background

New detector technology:

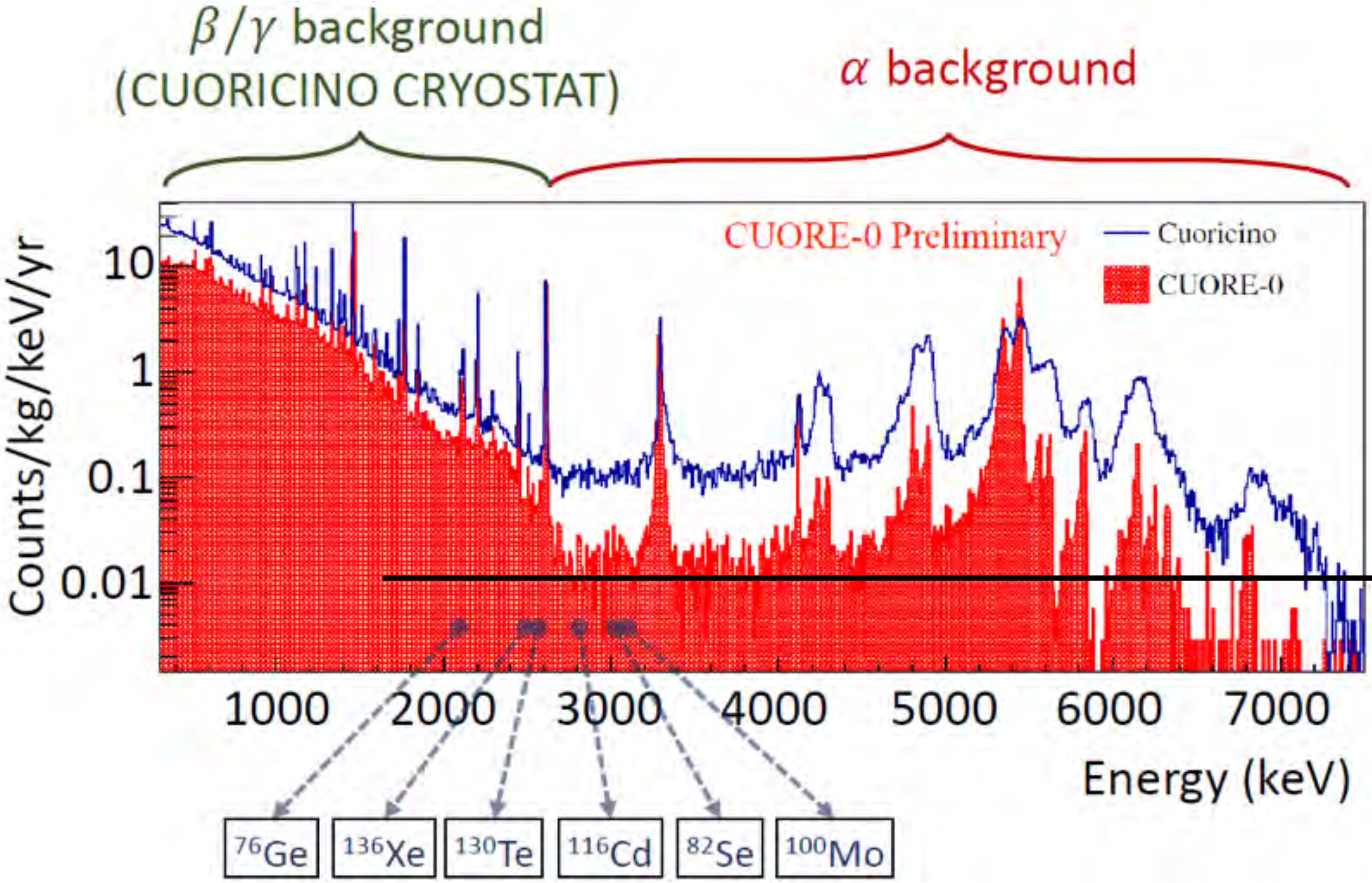
- luminescent bolometers
- Isotopic enrichment



R&D and demonstrators

- Full CUORE background model + information from demonstrators
    - ^{130}Te in TeO$_2$ crystals and detection of Cherenkov light → prototypes
    - ^{82}Se in scintillating ZnSe crystals → demonstrator CUPID-0
    - ^{100}Mo in scintillating Li$_2$MoO$_4$ crystals → demonstrator CUPID-Mo

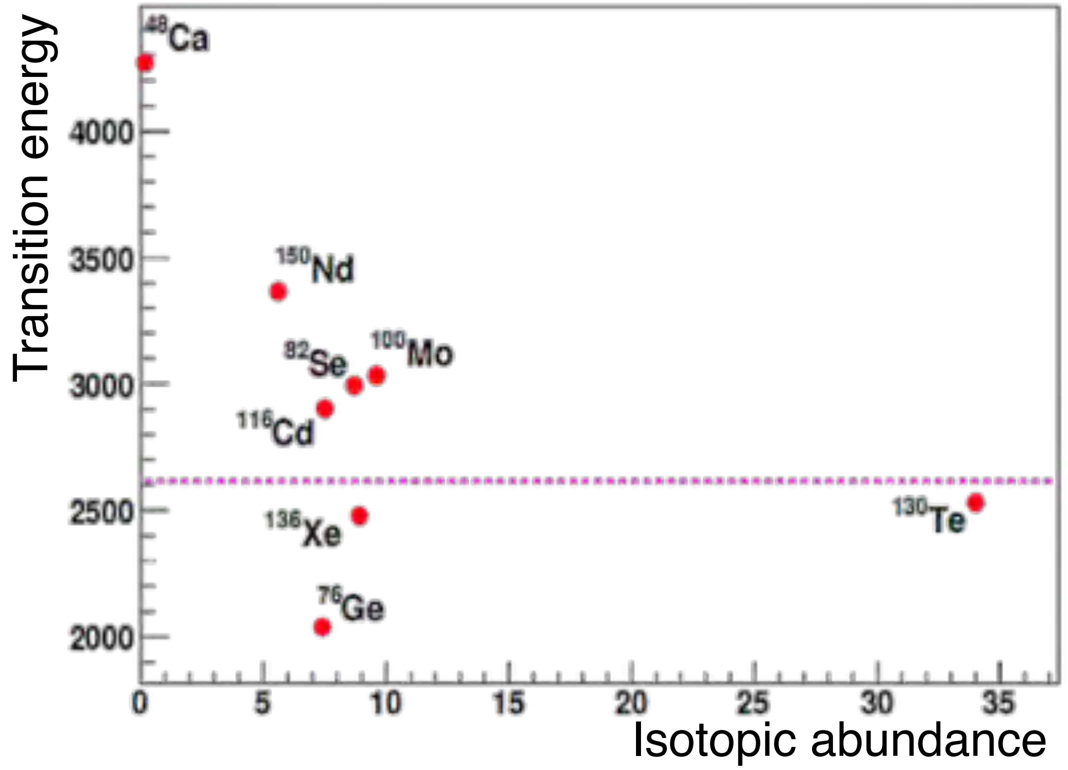
CUPID



Energy-degraded alpha background

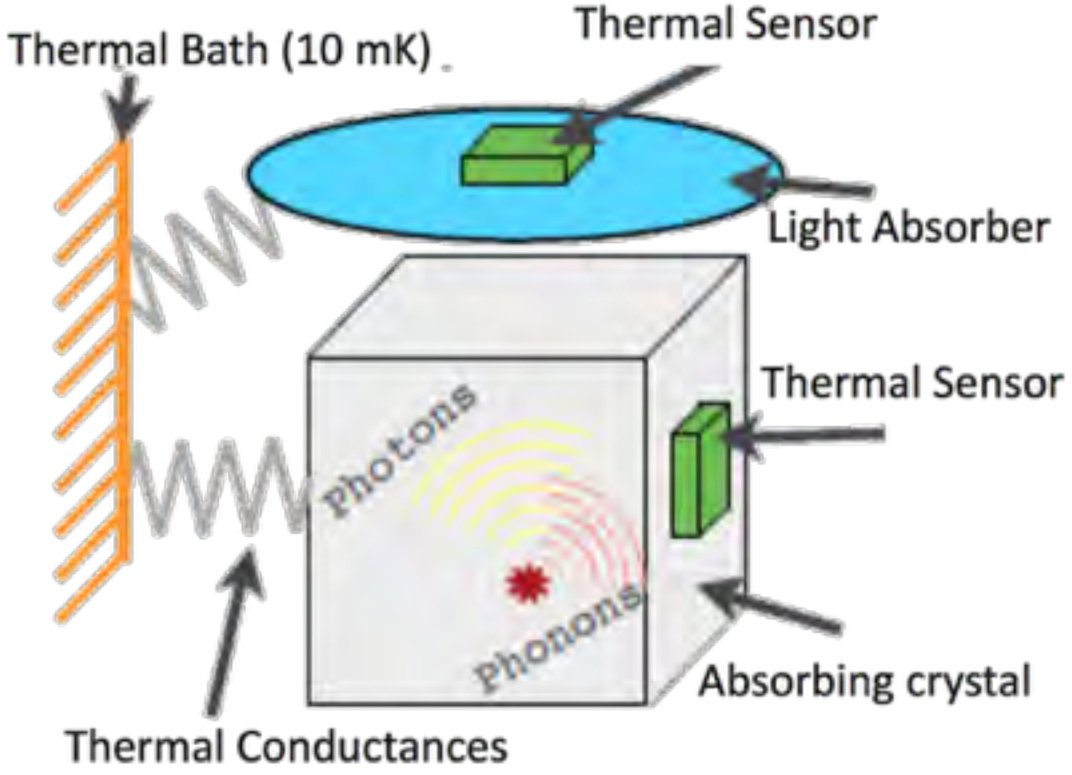
→ α/β discrimination is needed

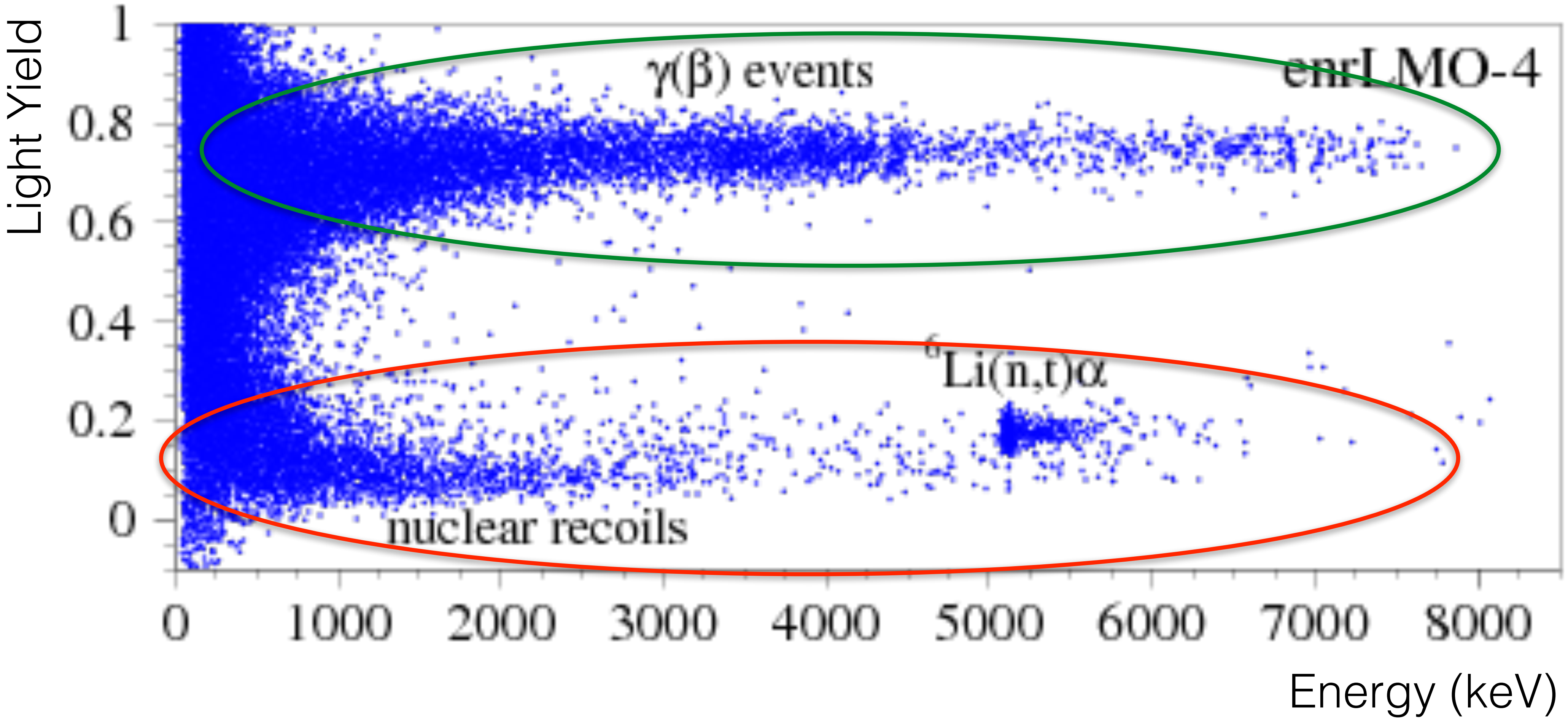
A number of viable ββ isotopes
+ Background reduction
- Isotopic enrichment needed

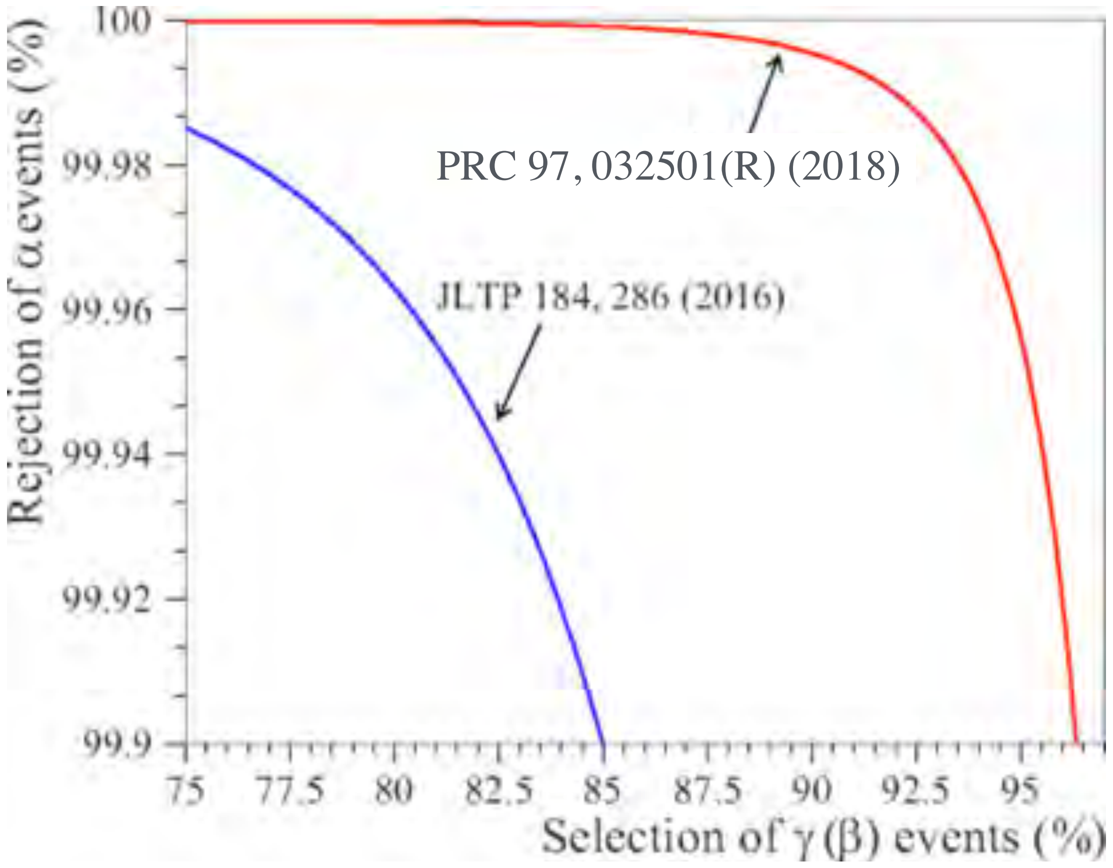


CUPID CUORE Upgrade with Particle ID

- Goal of reducing the background in the ROI by rejecting all α events with particle ID
- Add the ability to read out the light emitted in a particle interaction (scintillation/Cherenkov)
- Combine the energy resolution of bolometers with the background discrimination of a dual channel detector

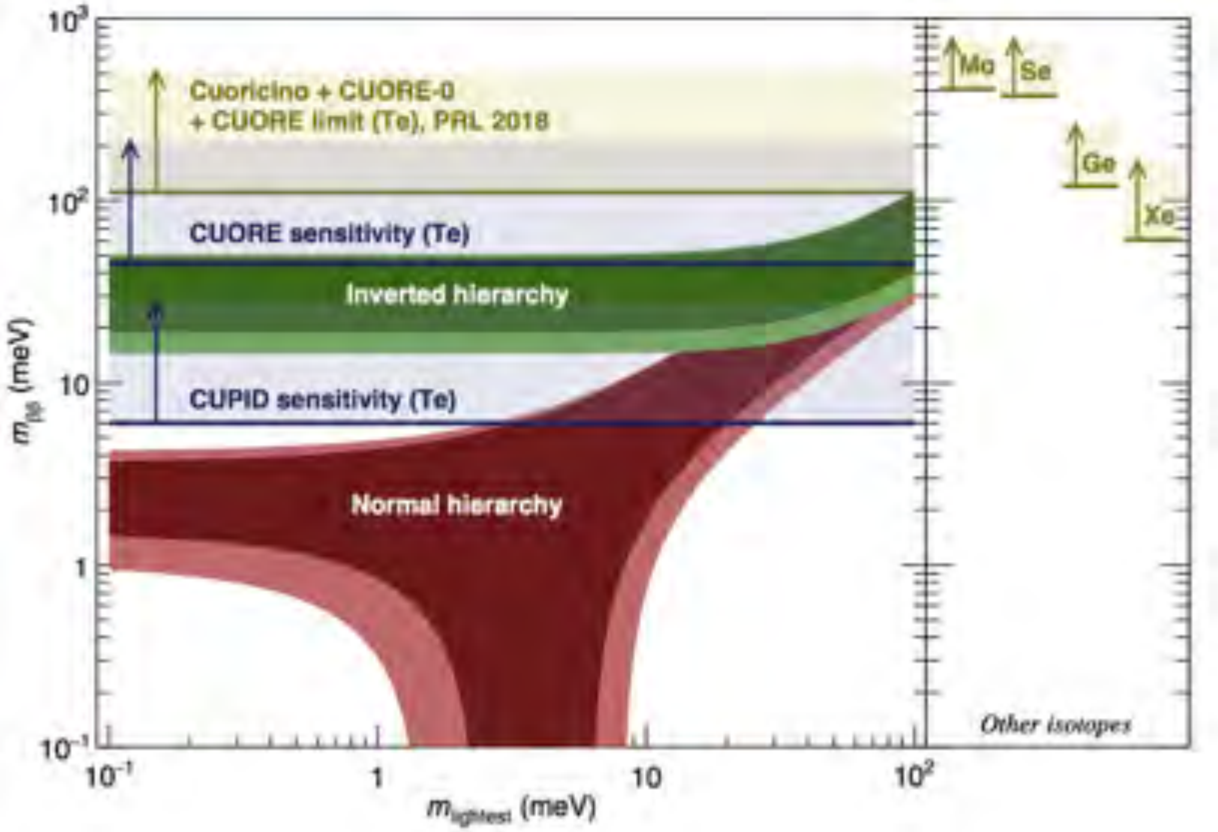


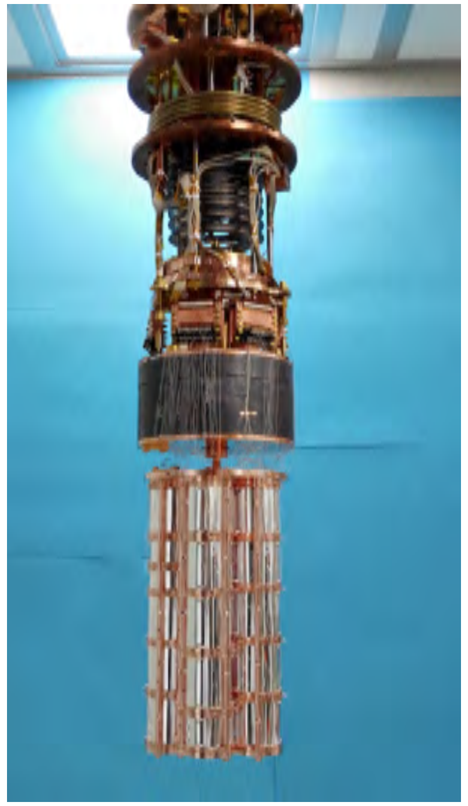




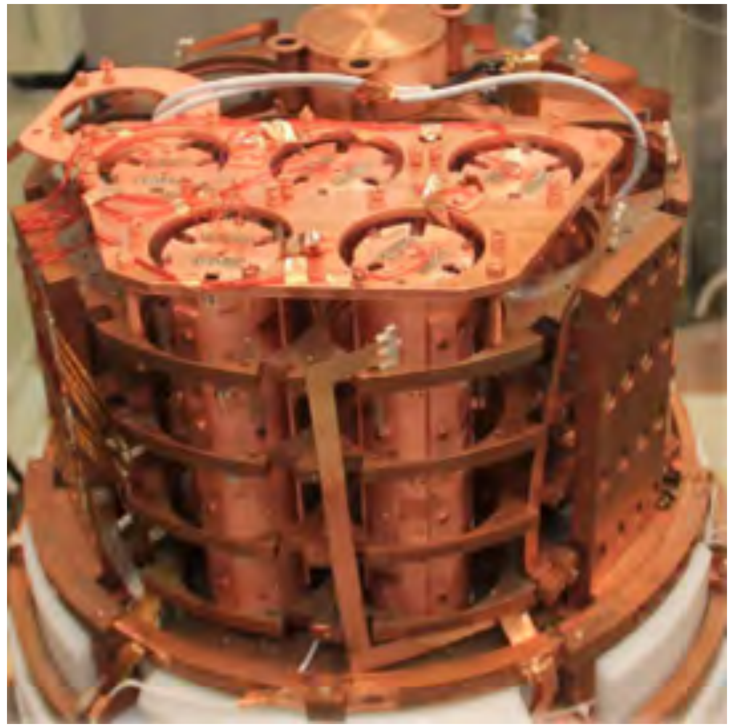
CUPID CUORE Upgrade with Particle ID

- Next generation of 0νββ decay experiments seek to be sensitive to the full IH region (mββ ~ 6 - 20 meV, T1/2 ~ 1027 yr)
- ~1000 enriched light emitting bolometers mounted in the CUORE cryostat
- Nearly zero background goal of ~ 0.1 cnts/(ROI·yr)
- Worldwide effort focused on demonstrating readiness to construct a tonne-scale bolometric experiment

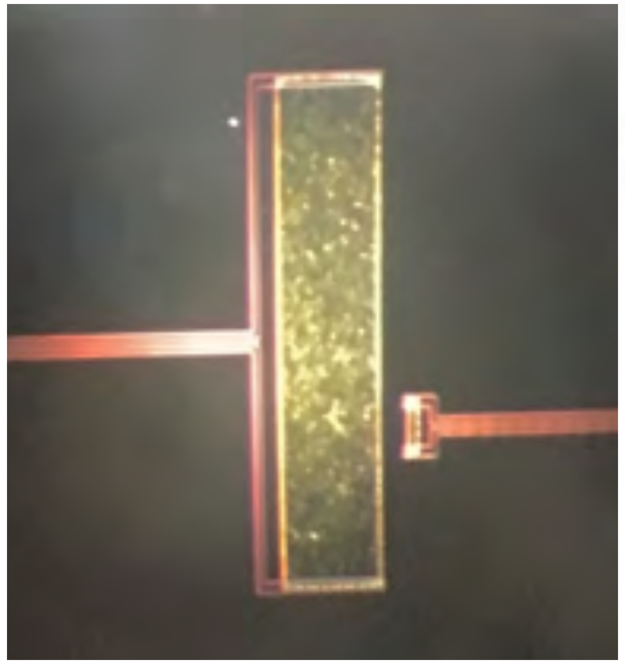




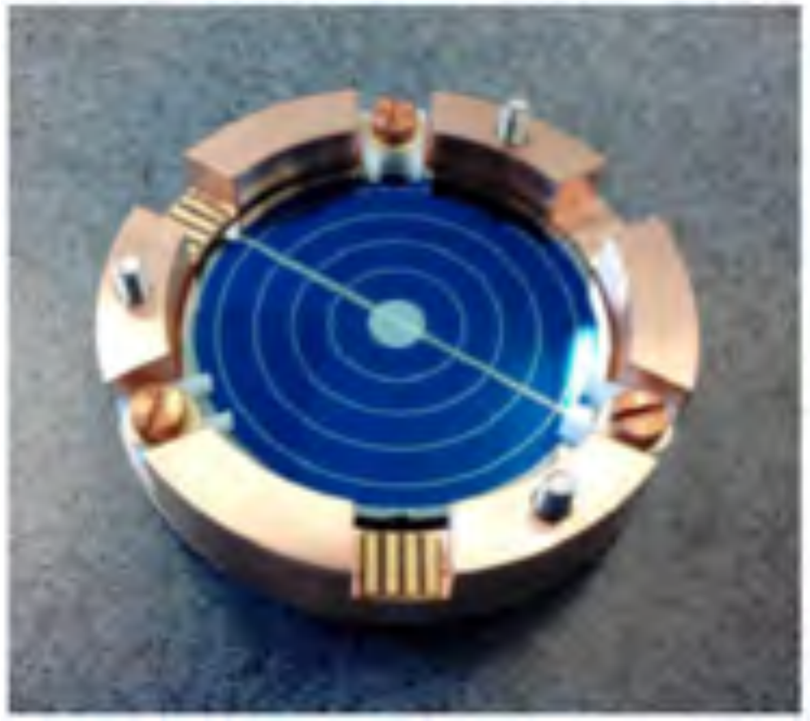
CUPID-0/Se at LNGS: $Zn^{82}Se$



CUPID-Mo at Modane: $Li_2{}^{100}MoO_4$



TES-based and Neganov-Luke light detectors for TeO_2



CUPID prospects

Results of the ongoing R&D and demonstrators + CUORE background model

- **$Li_2{}^{100}MoO_4$ scintillating bolometers → promising baseline option for CUPID**
- **$^{130}TeO_2$ Cherenkov bolometers → mature viable alternative**

- Fast and high-sensitivity light detectors are a common feature
  - Detection of Cherenkov light in TeO_2
  - Rejection of $2\nu\beta\beta$ random coincidences in $Li_2{}^{100}MoO_4$

The purpose of CUPID is to fully explore the IO region:

- Mission: half-life sensitivity higher than 10^{27} y
- With background < 0.1 counts/(ton·y) in the ROI:
  - ^{100}Mo sensitivity is $2.1 \cdot 10^{27}$ y
  - $m_{\beta\beta} < 6 – 17$ meV

CUPID … moving forward

- CUORE will execute its scientific program to completion.
- CUORE's success motivates a next-generation bolometric experiment

- Based on the results of the ongoing R&D and demonstrator experiments, **Li_2MoO_4 scintillating bolometers have been identified as the most promising baseline** for a next-generation high-sensitivity bolometric experiment.
- Enriched **TeO_2 is a mature viable alternative**, with R&D towards demonstrating its sensitivity proceeding.
- Light detector technologies being developed for both TeO_2 and Li_2MoO_4 readout are common and R&D is beneficial to both.
- CUPID plan is under development

- We aim to form the CUPID collaboration in the near future:
  - CDR under preparation
  - kickoff meeting is being planned