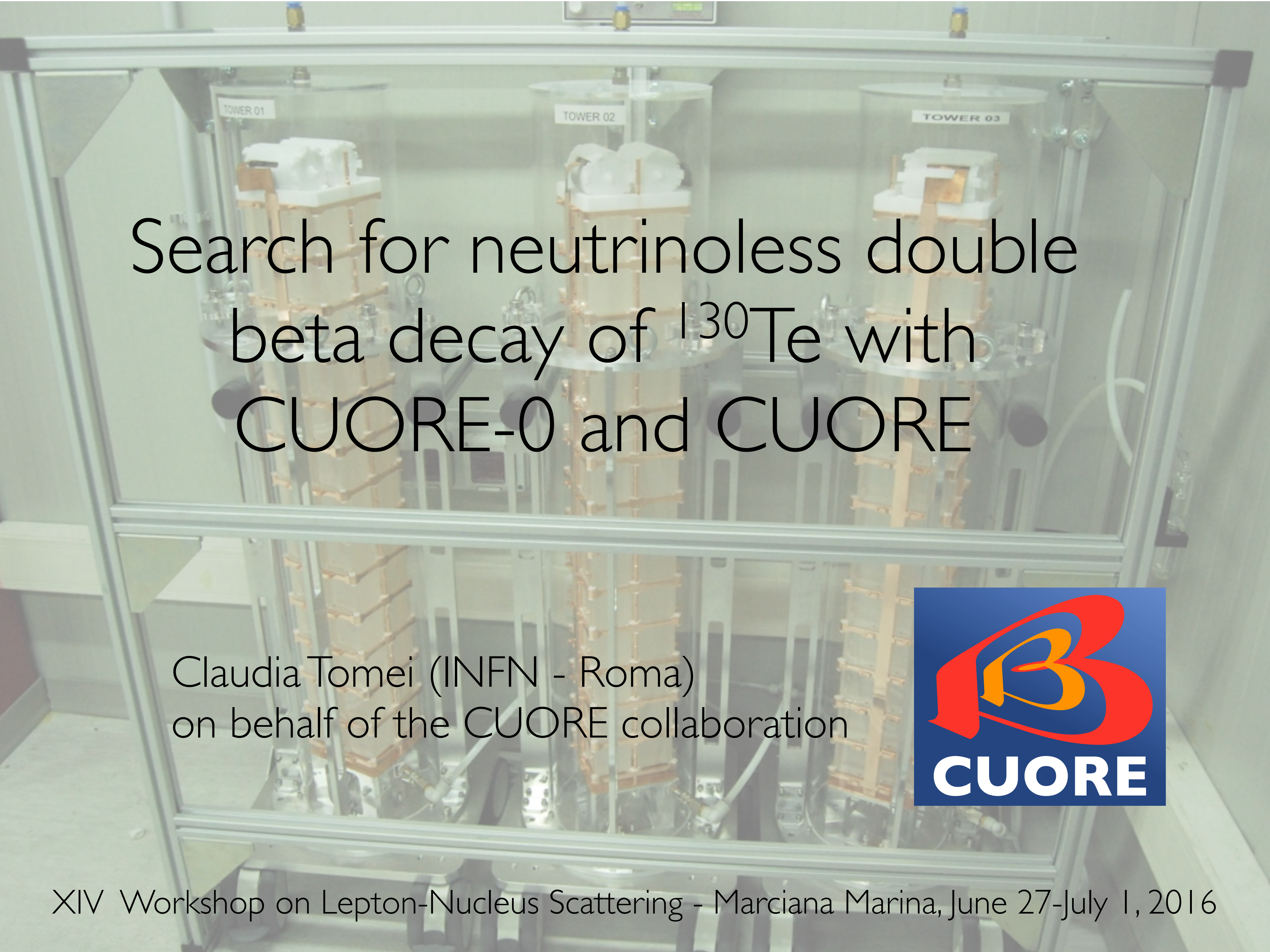


Search for neutrinoless double beta decay of ^{130}Te with CUORE-0 and CUORE

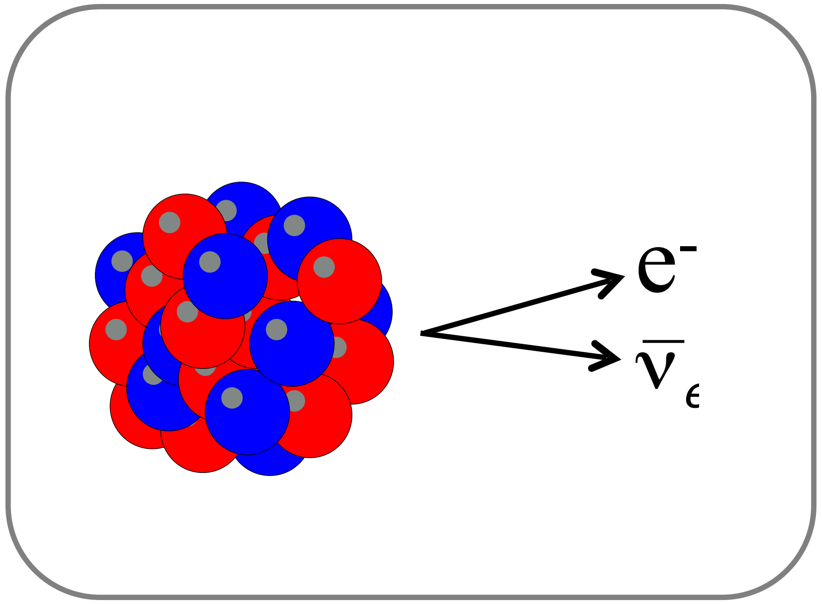
Claudia Tomei (INFN - Roma)
on behalf of the CUORE collaboration

XIV Workshop on Lepton-Nucleus Scattering - Marciana Marina, June 27-July 1, 2016

The CUORE Collaboration

- 157 collaborators
  - 120 researchers/authors
    - Italy: 71
    - USA: 38
    - Associated Institutions: 17

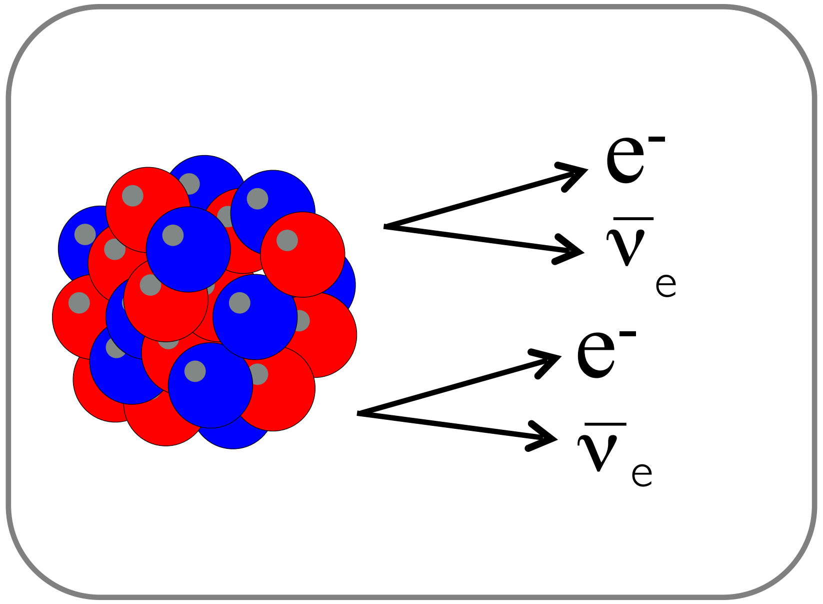
The double beta decay



$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{X} + e^- + \bar{\nu}_e$$

β decay

Well known weak process

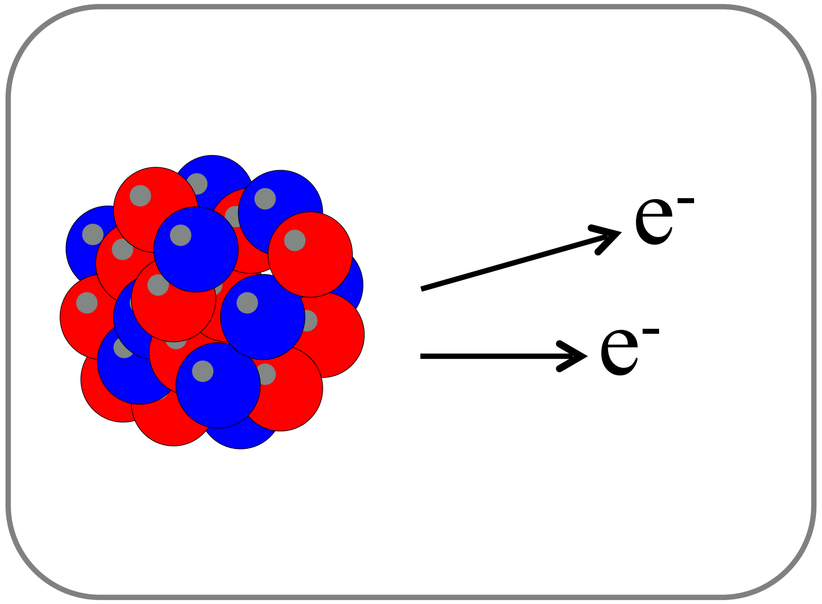


$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+2}\mathrm{X} + 2e^- + 2\bar{\nu}_e$$

2νββ

Observed, but rare ($T_{1/2} > 10^{19}$ yr)

Only visible in nuclei with forbidden single β



$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+2}\mathrm{X} + 2e^-$$

0νββ

Even rarer than 2νββ (if it occurs at all)

Not observed so far (one controversial claim of observation)

Neutrinoless double beta decay (0νββ)

Observation of 0νββ would:

Demonstrate that lepton number is not conserved

Establish neutrinos as Majorana particles

Set constraints on the effective Majorana mass $m_{\beta\beta}$ and provide info on absolute ν mass scale

The observable is the half life:

Decay mechanism (particle physics)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}_{\eta}|^2\eta^2$$

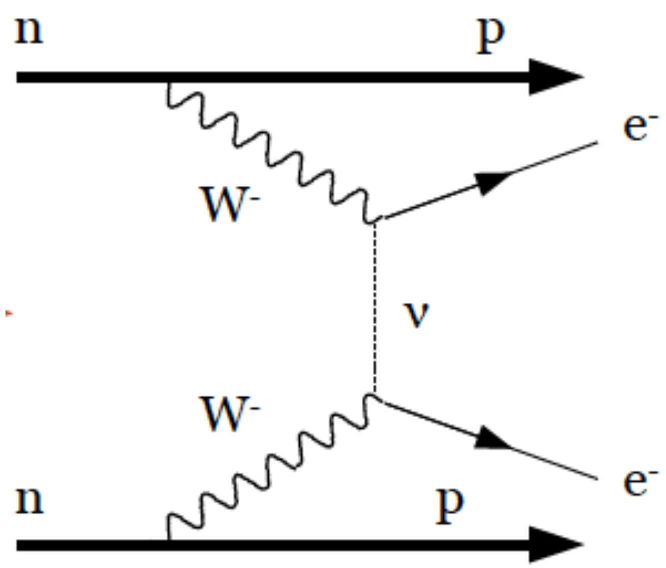
Phase space factor: known with good accuracy from atomic physics

Nuclear matrix element (nuclear physics) is affected by a large uncertainty

Exchange of light Majorana neutrinos: mass scale and hierarchy

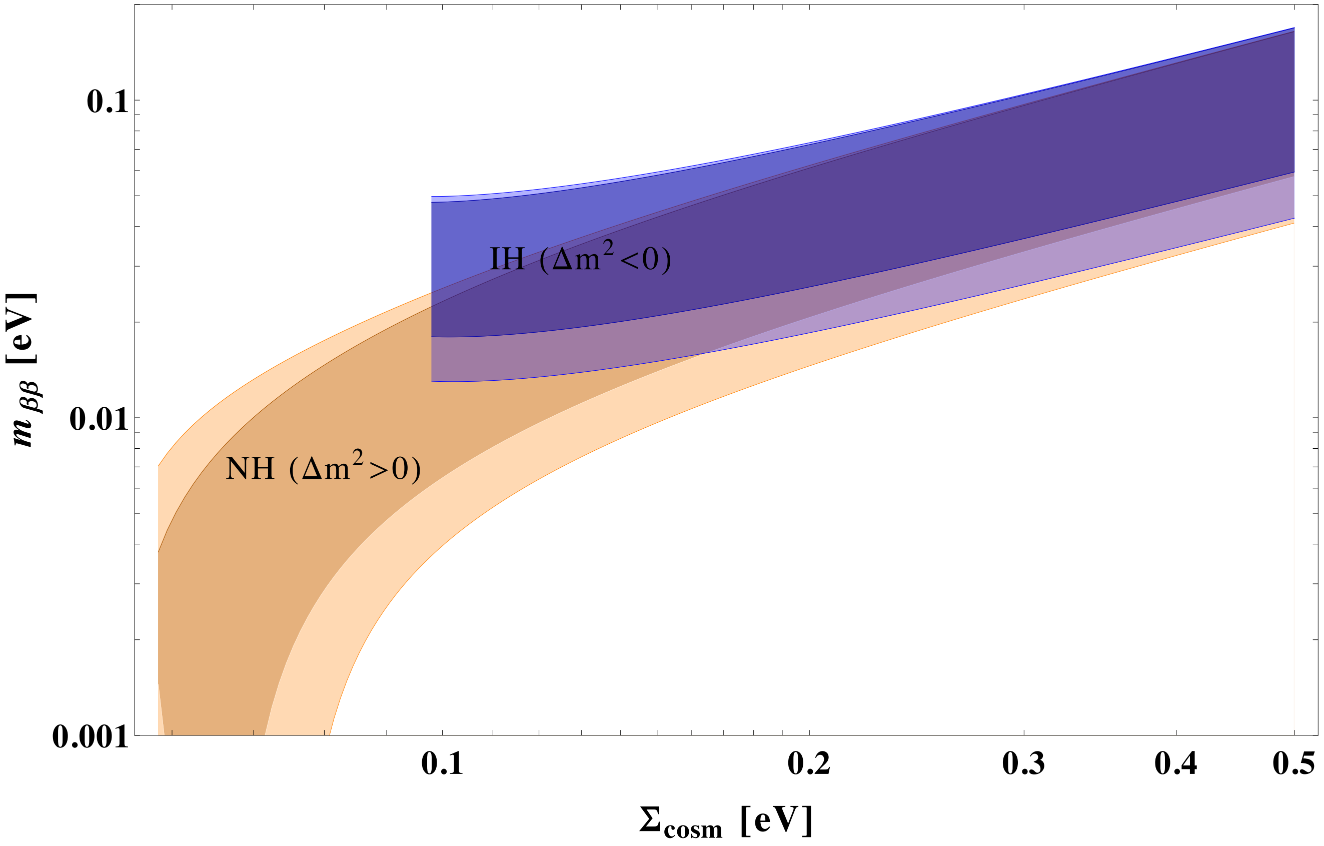
This is the simplest mechanism where massive neutrinos (the ones that oscillate) mediate the double beta decay.

A right-handed anti-neutrino is emitted in one vertex and a left-handed neutrino is absorbed in a second vertex.



$$T^{0\nu}_{1/2} = \frac{m_e^2}{G_{0\nu} \cdot M^2_{nucl} \cdot m^2_{\beta\beta}}$$

$$m_{\beta\beta} = |\sum_i m_{\nu_i} U^2_{ei}|$$



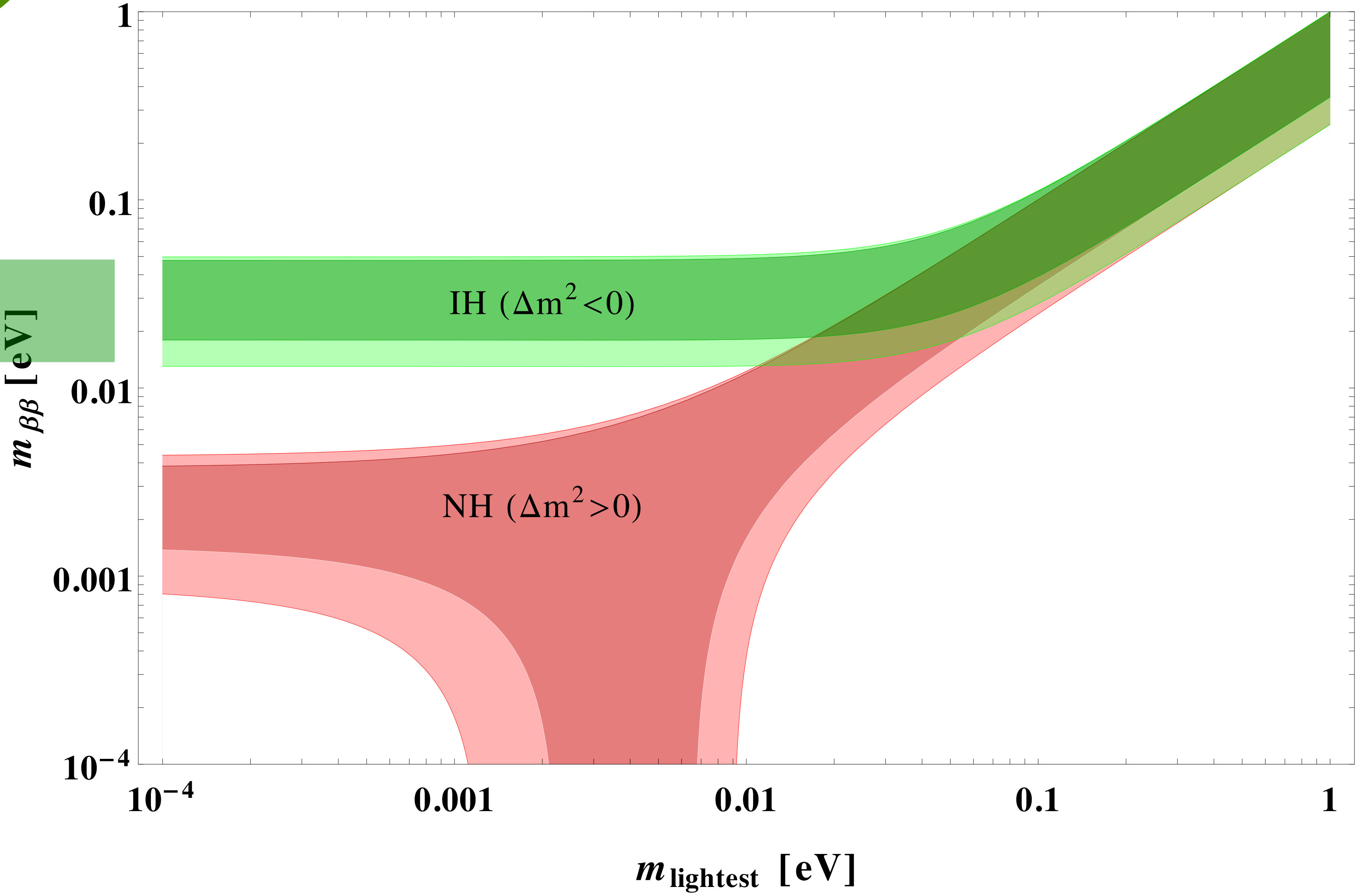
Stefano Dell'Oro, Simone Marcocci, Francesco Vissani, Advances in High Energy Physics, Volume 2016 (2016), Article ID 2162659.

Effective Majorana mass

$$m_{\beta\beta} = |\sum_i m_{\nu_i} U_{ei}^2|$$

Testing this region is the goal of next generation experiments

Standard scenario: can be modified by different theoretical assumptions (es. light sterile neutrinos)



Stefano Dell'Oro, Simone Marcocci, Francesco Vissani, Advances in High Energy Physics, Volume 2016 (2016), Article ID 2162659

NME - Nuclear Matrix Element

Calculations of nuclear matrix elements, especially for heavy nuclei, is extremely complex.

Several methods used:

- Nuclear Shell Model (NSM)
- Quasi-Random Phase Approximation (QRPA)
- Interacting Boson Model (IBM)
- Projected Hartree-Fock-Bogoliubov (PHFB)
- Generating coordinate method extensions of PHFB (GCM o EDF)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|\boxed{M^{0\nu}_{\eta}}|^2 m^2_{\beta\beta}$$

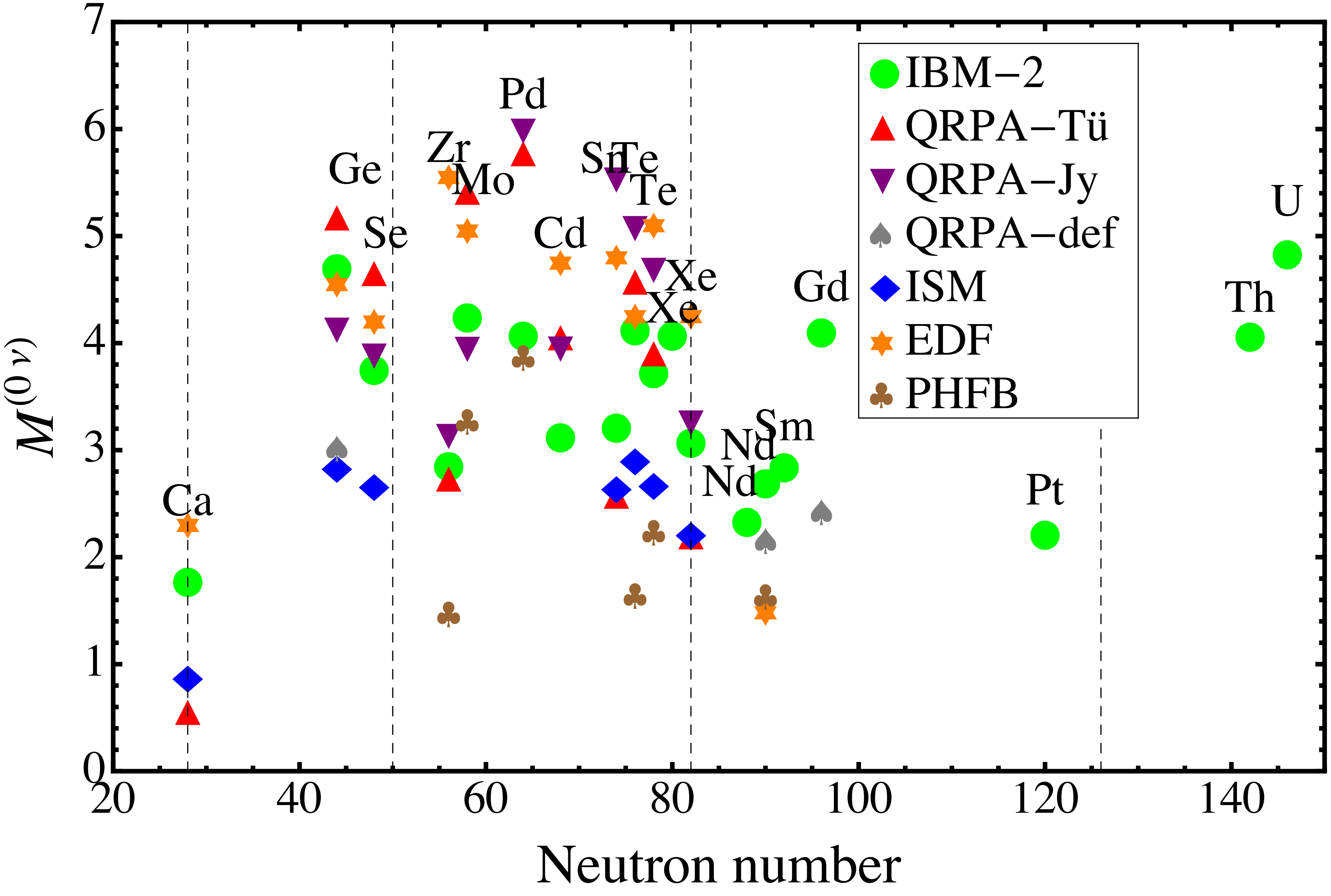
Each method gives a range of values, due to uncertainties on many parameters (correlations, g_A, etc…).

The usual approach is to use the spread in NME calculated values as an estimation of the theoretical uncertainty.

Measurement (limit) on the half-life ⇒ range of values (limits) for $m_{\beta\beta}$

NME - Nuclear Matrix Element

QRPA / IBM-2 within ~ 30%



J. Barea, J. Kotila, F. Iachello, PRC 91 034304 (2015)

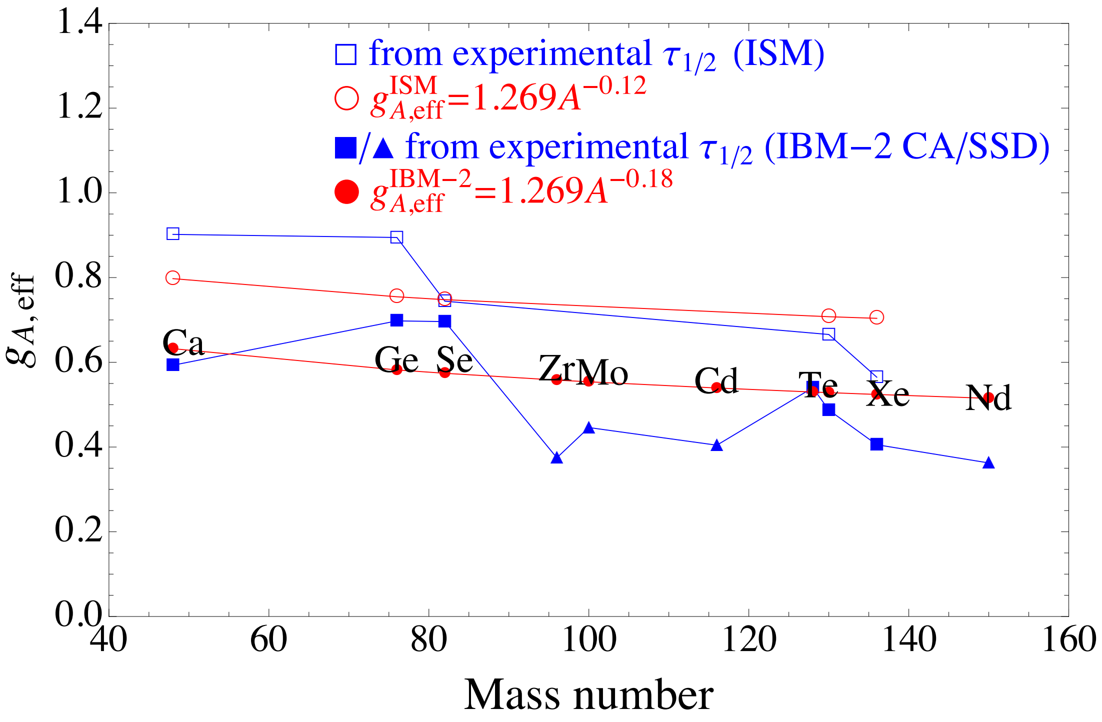
g_A quenching

Both the phase space factor G and the nuclear matrix element M depend on the value of g_A (axial coupling constant).

- g_A (free nucleon) ~ 1.27
- quenching in the nuclear medium?
- Limits on $m_{\beta\beta}$ are given in the standard quenching assumption $g_{A,eff}$ ~1 (quarks);
- A higher quenching $g_{A,eff} < 1$ produces a weaker limit on $m_{\beta\beta}$;
- still unknown if the quenching in $0\nu\beta\beta$ and $2\nu\beta\beta$ is the same;
- $(T_{1/2})^{-1}$ goes with the fourth power of g_A so the effect of quenching is relevant.

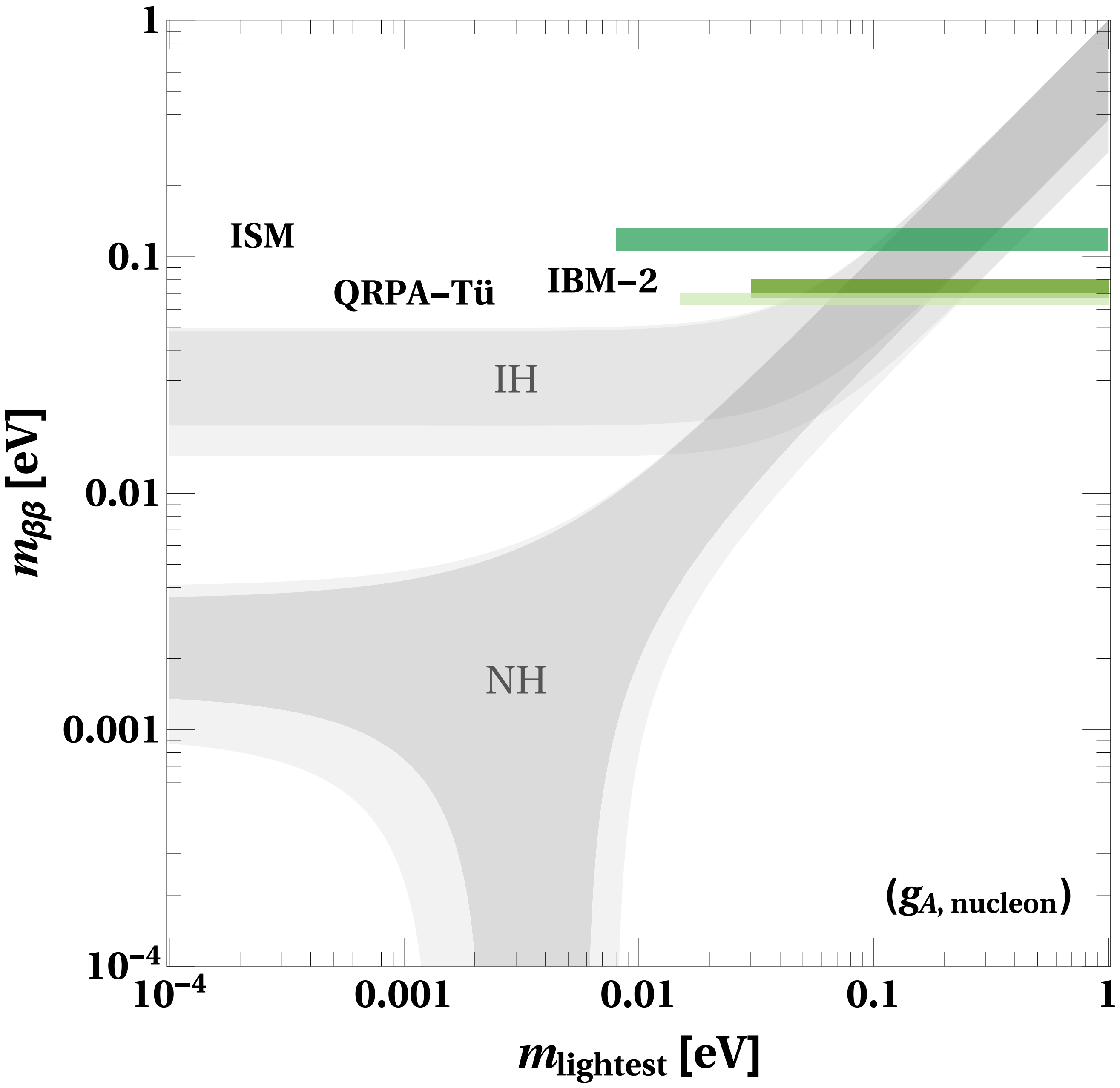
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}_{\eta}|^2 m^2_{\beta\beta}$$

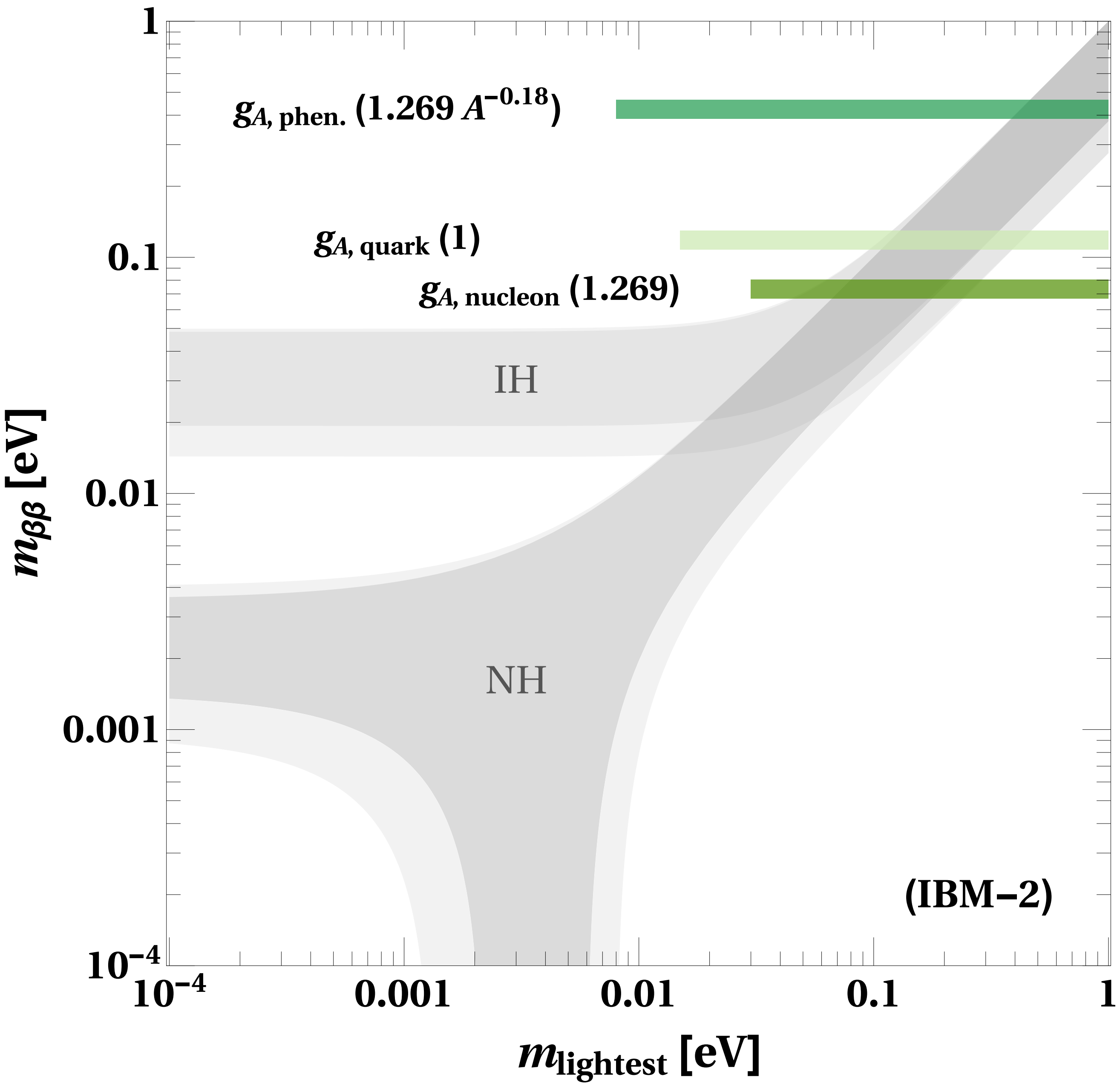
$$\frac{g_{A,eff}}{g_A} \quad \text{(quenching)}$$



J. Barea, J. Kotila, F. Iachello, PRC 91 034304 (2015)

Effect of g_A quenching



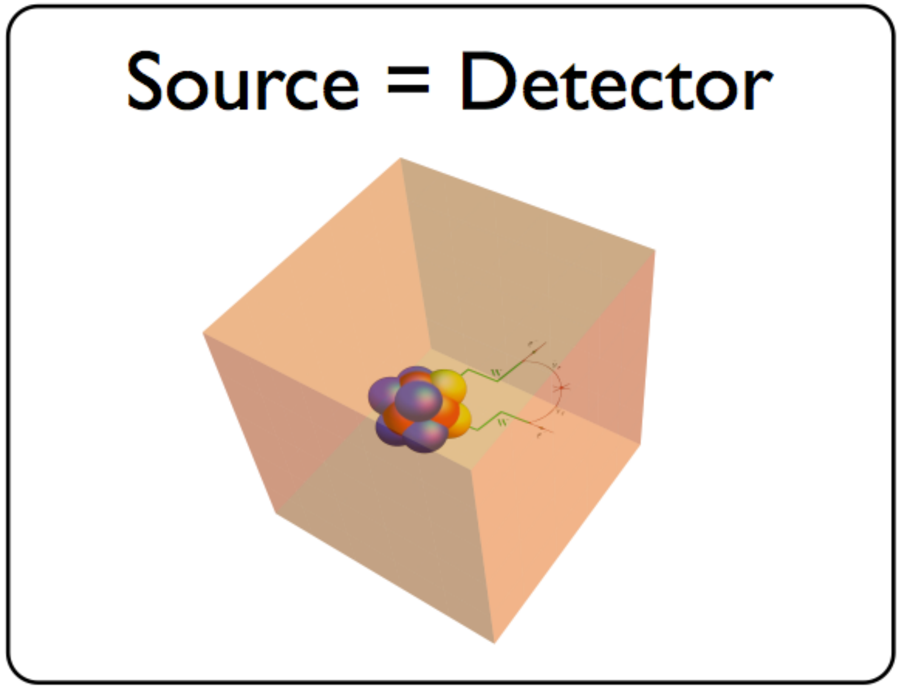


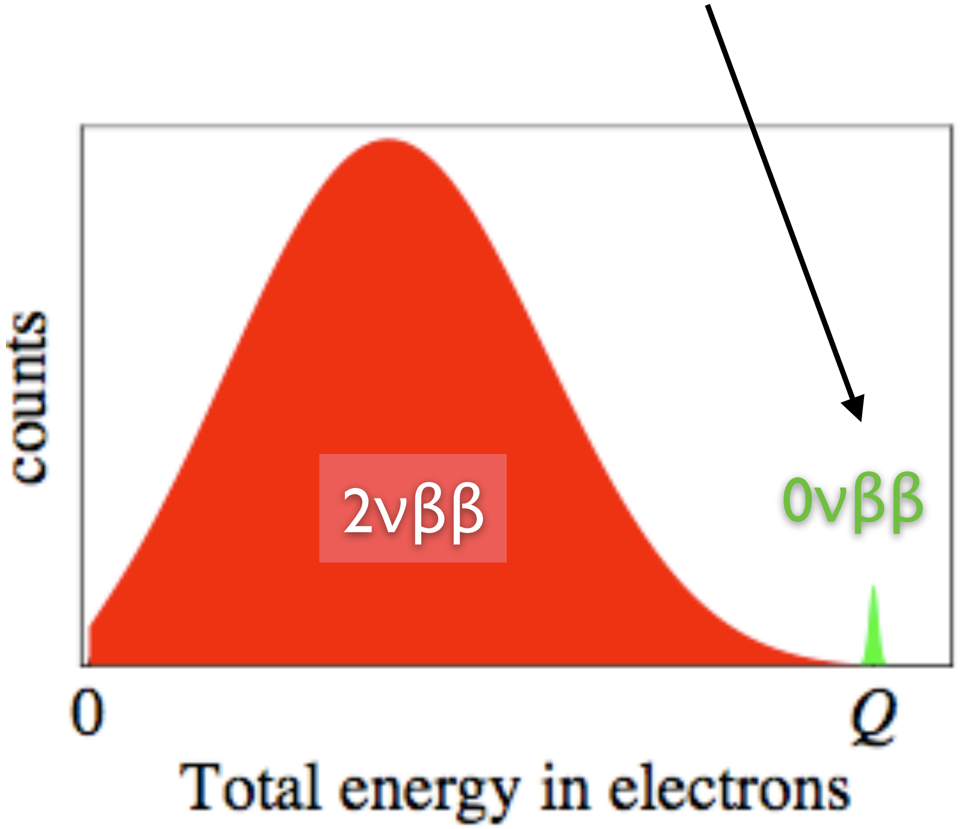
- Different NMEs, fixed g_A
- Different g_A, fixed NME

Stefano Dell'Oro, Simone Marcocci, Francesco Vissani, Advances in High Energy Physics, Volume 2016 (2016), Article ID 2162659

Signature of neutrinoless double beta decay

In the general experimental approach of detecting the sum energy of the two final-state electrons, the signature of 0νββ decay is a peak at Q-value ($Q_{\beta\beta}$)

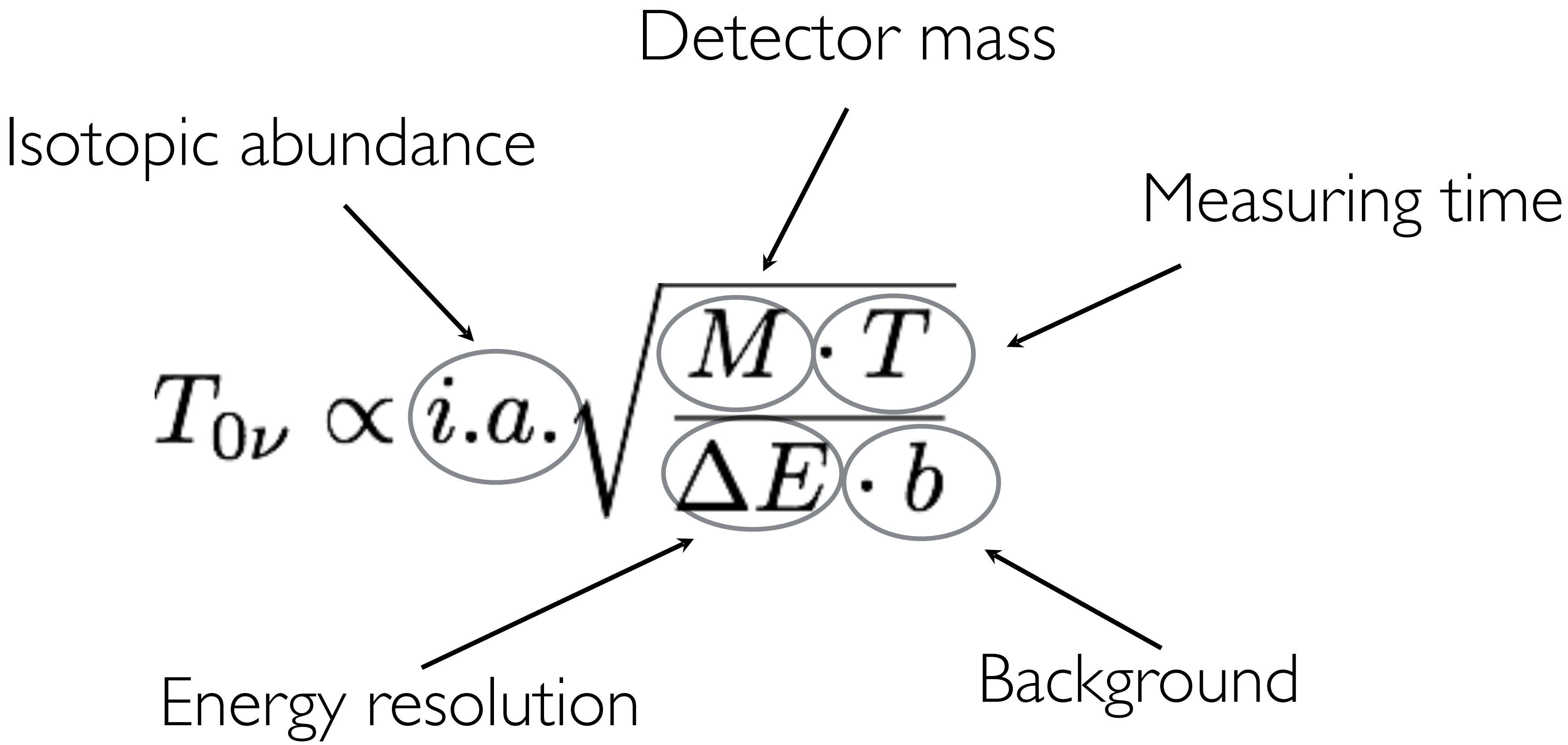




Reducing the background (if you can't discriminate against it) is the challenge

Experimental sensitivity to 0νββ

Half-life corresponding to the minimum number of detectable signal events above background at a given C.L.



Isotopic abundance

Detector mass

Measuring time

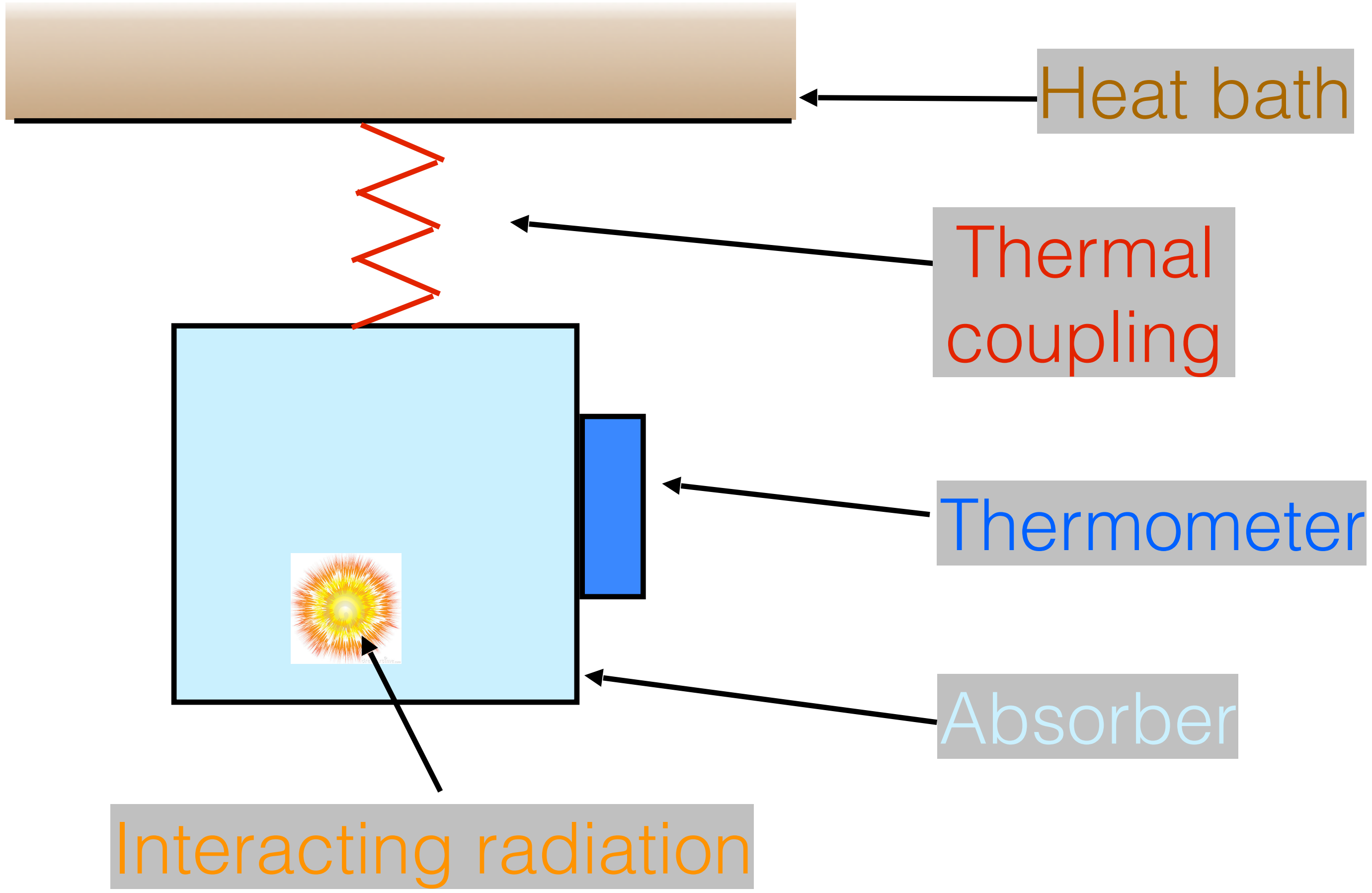
$$T_{0\nu} \propto i.a. \sqrt{\frac{M \cdot T}{\Delta E \cdot b}}$$

Energy resolution

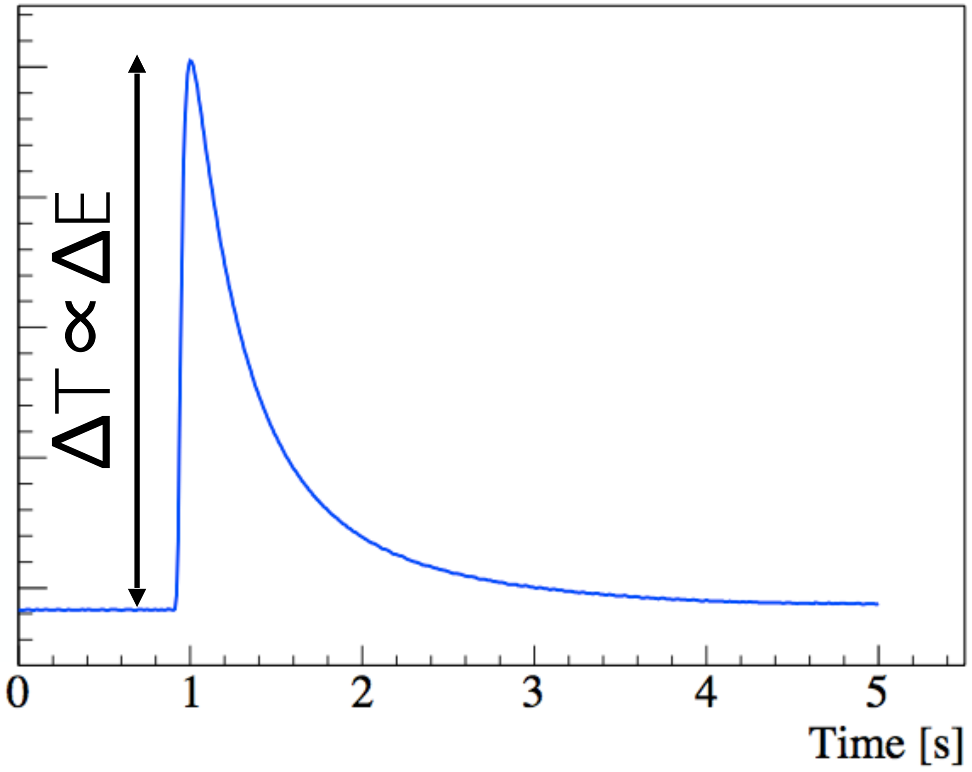
Background

Thermal detectors

Ultracold crystals function as highly sensitive calorimeters



The energy deposited by a particle interaction in the absorber is converted to a measurable temperature variation.



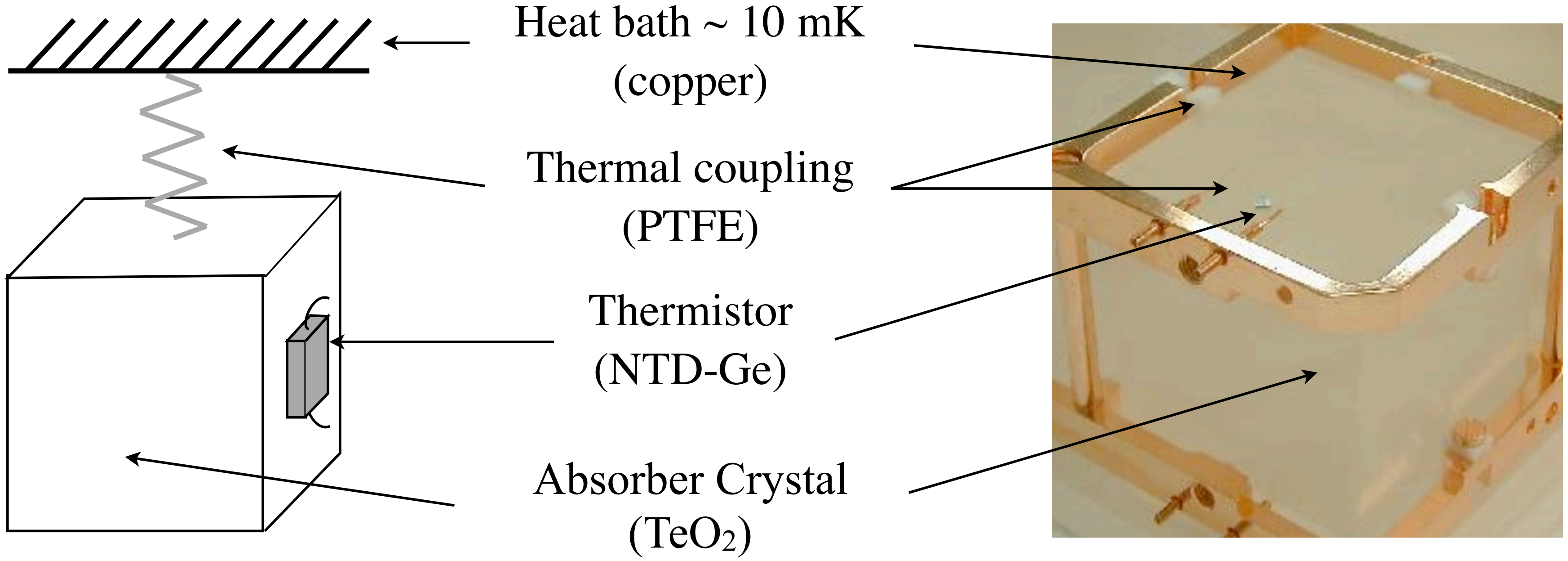
wide choice of detector materials

source embedded in the detector

excellent energy resolution

CUORE bolometers for double beta decay

CUORE searches for $0\nu\beta\beta$ of ^{130}Te with TeO_2 bolometers

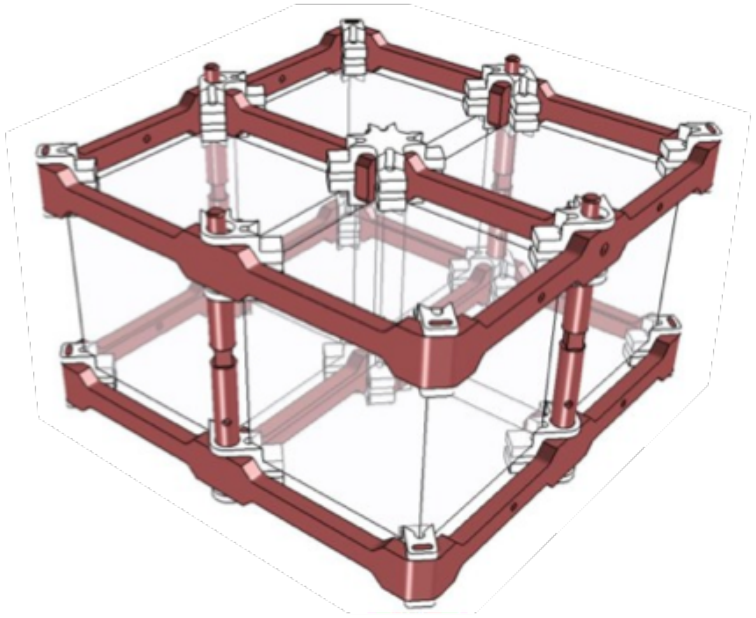


Heat bath ~ 10 mK
(copper)

Thermal coupling
(PTFE)

Thermistor
(NTD-Ge)

Absorber Crystal
(TeO_2)



Energy release → ΔT → ΔR in the thermistor → ΔV

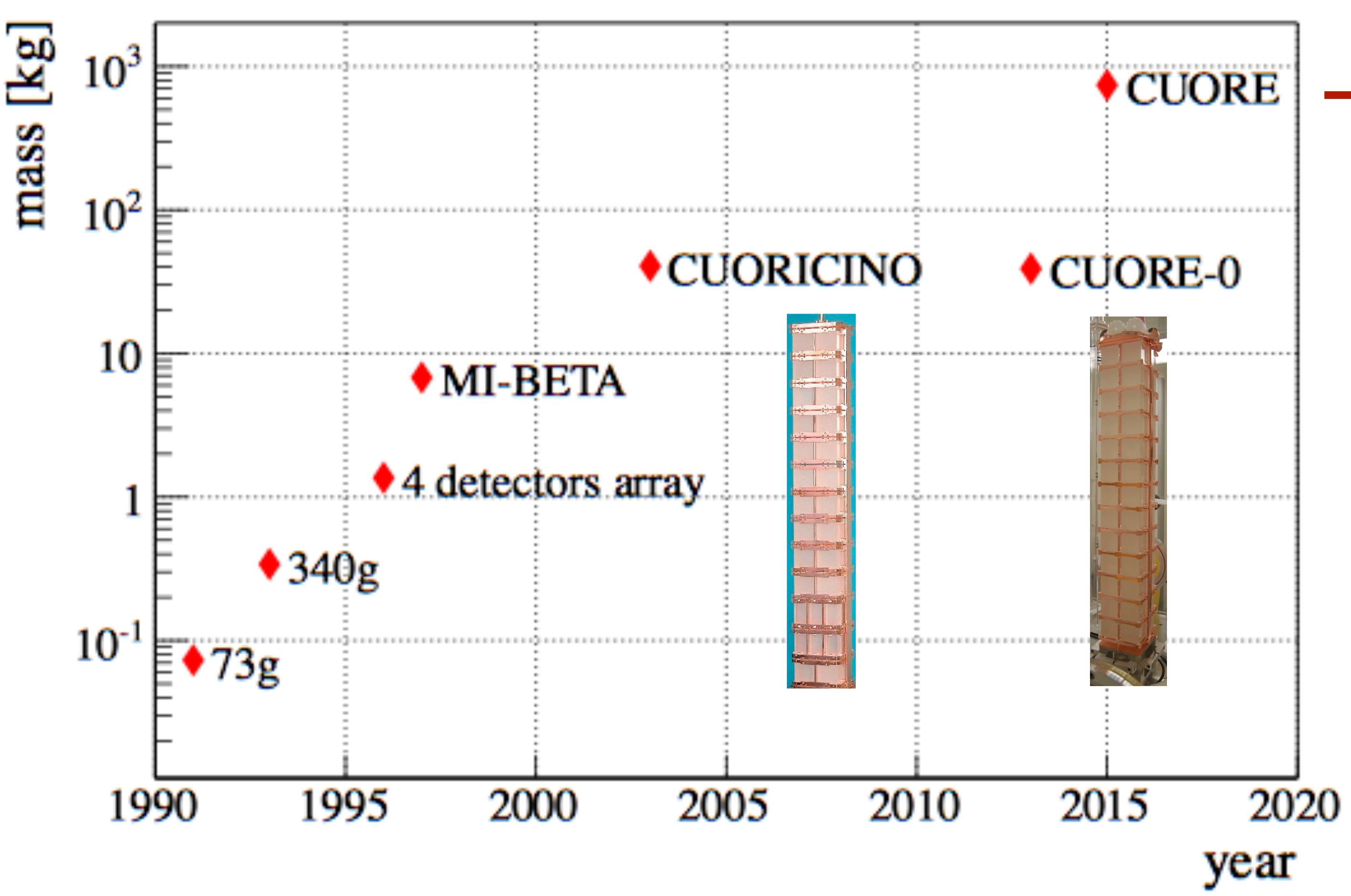
$\Delta T_{thermistor} \sim$ 10-20 μK/MeV
$\Delta T_{crystal} \sim$ 100 μK/MeV

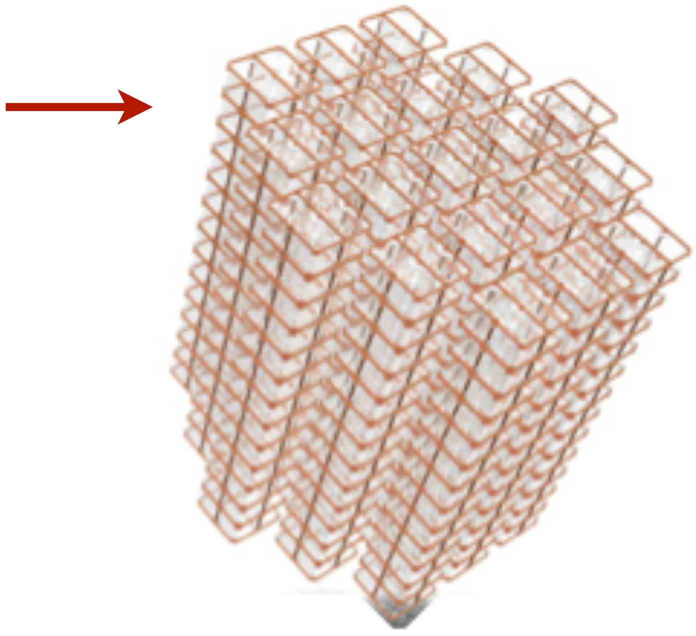
$\Delta V_{thermistor} \sim$ 300 μV/MeV
$\Delta R_{thermistor} \sim$ 3 MΩ/MeV

Arrays of TeO_2 bolometers

Advantages:

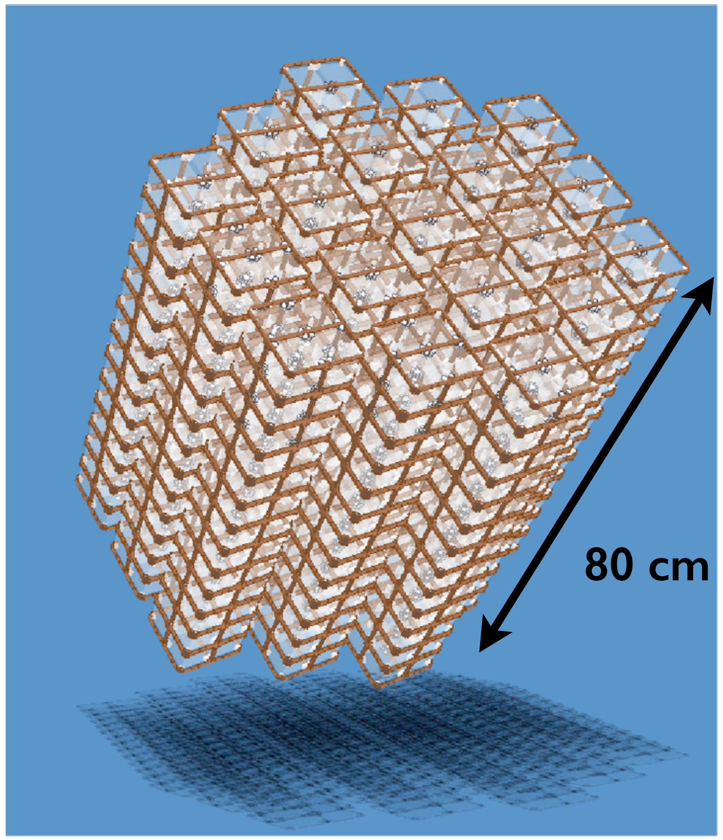
- high natural isotopic abundance (34.2%) of the ββ emitter (highest among the isotopes of interest)
- excellent energy resolution: 5 keV FWHM @ Q-value (2528 keV)

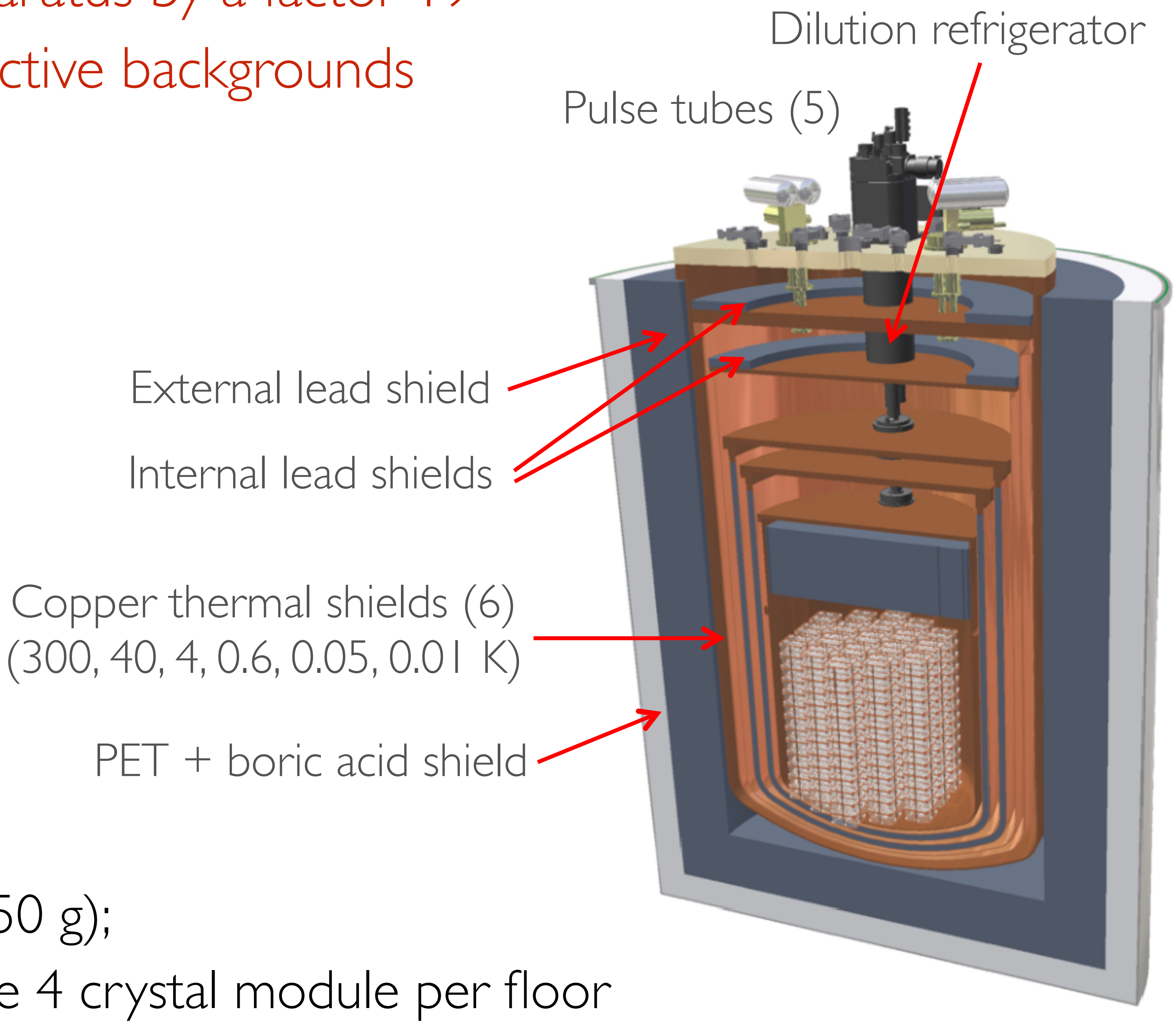




CUORE (Cryogenic Underground Observatory for Rare Events)

Scale up the bolometric apparatus by a factor 19 while also reducing radioactive backgrounds



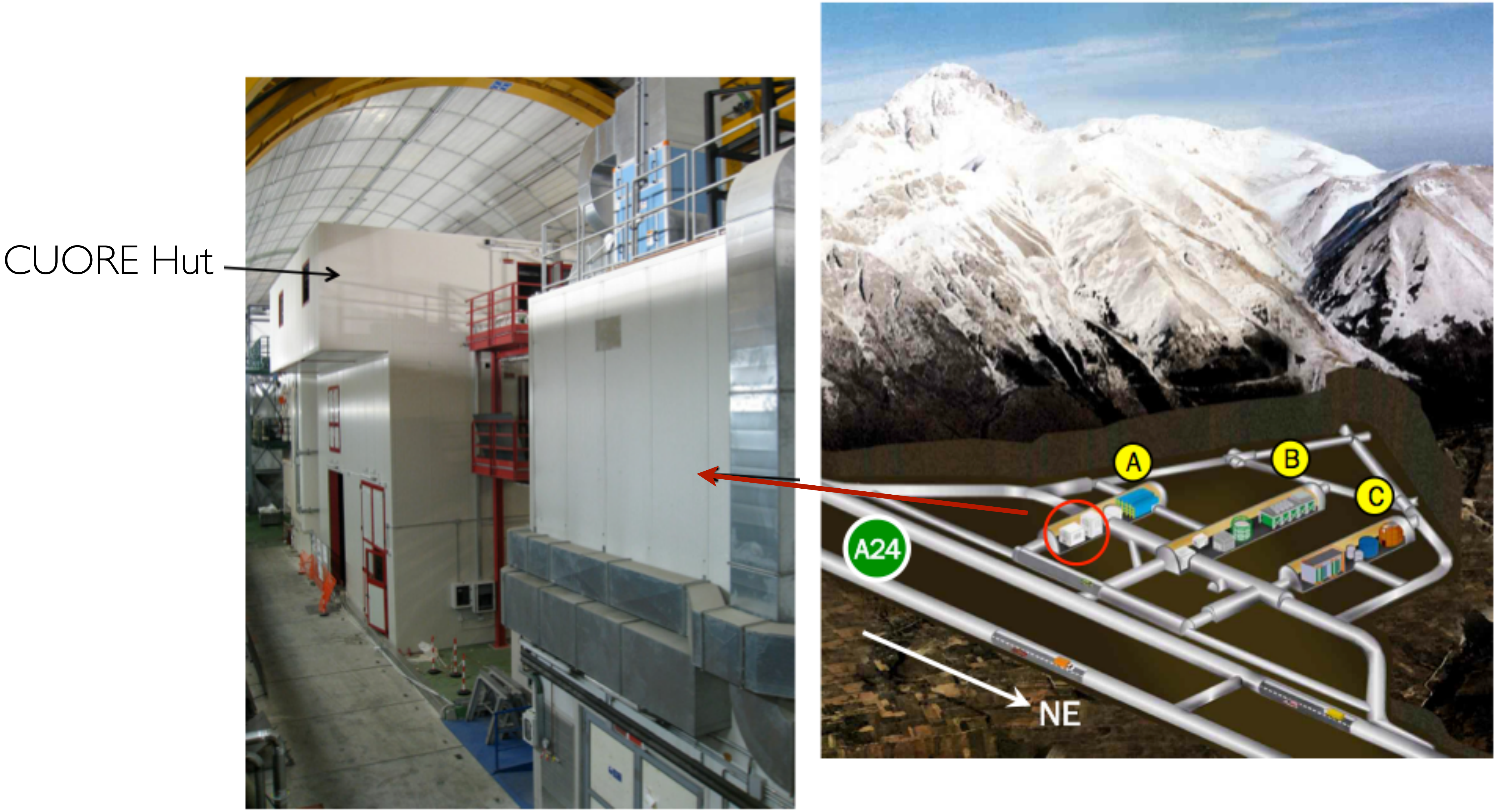


Array of 988 TeO_2 crystals:

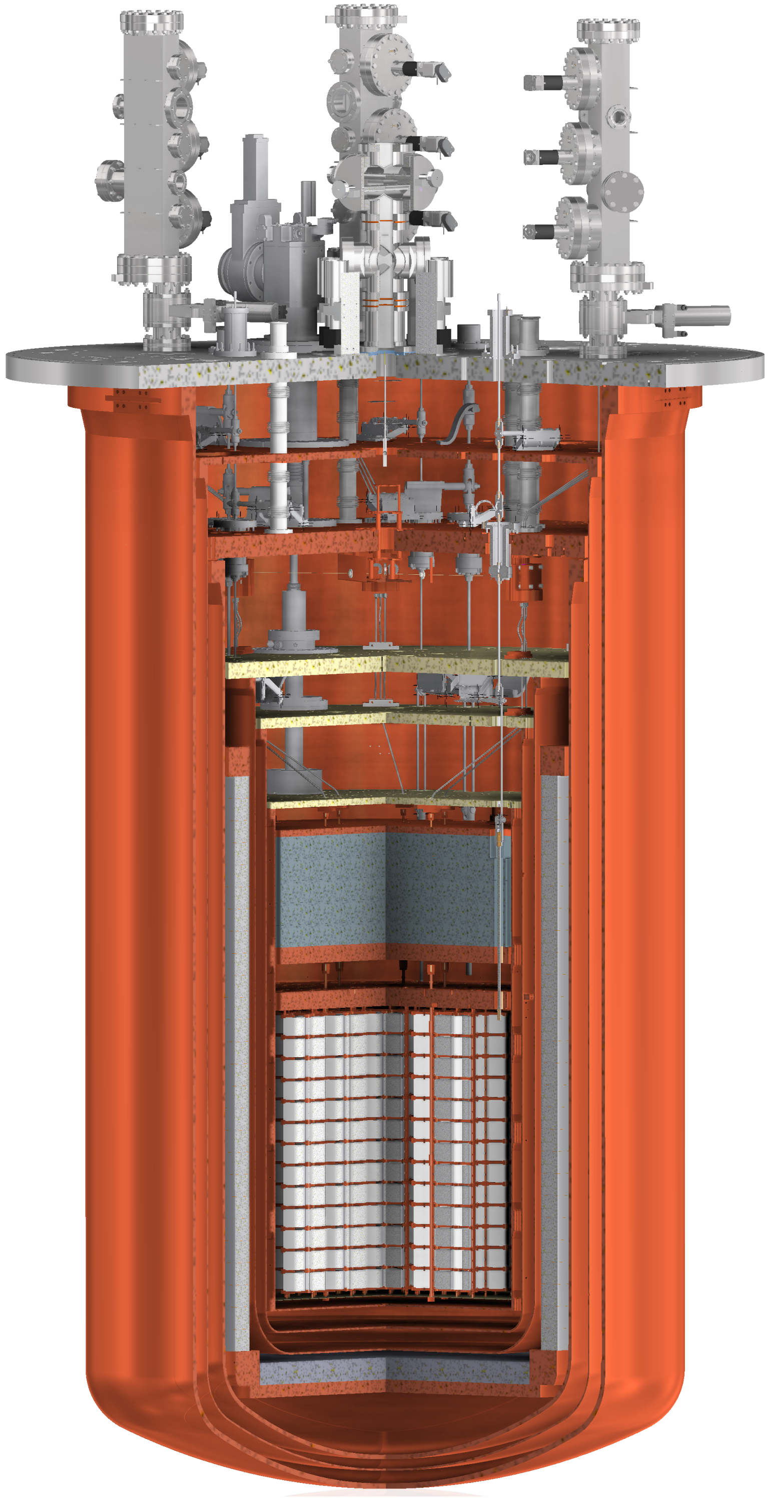
- each crystal 5x5x5 cm^3 (750 g);
- 19 towers - 13 floors - one 4 crystal module per floor
- 741 kg total mass - 206 kg of ^{130}Te (~10^{27} ^{130}Te nuclei)

CUORE (Cryogenic Underground Observatory for Rare Events)

Located underground at LNGS



CUORE main challenges: cryostat



The challenge: operate a huge bolometric array, in an extremely low radioactivity and low vibrations environment.

CUORE cryostat:

- Custom made pulse tube dilution refrigerator and cryostat. Mass to be cooled: 15 tons @T < 4 K (lead, copper and TeO_2)
- Radio-pure material and clean assembly to achieve low background at ROI
- Independent suspension of the detector array from the dilution unit: smaller vibrational noise.

CUORE main challenges: cleaning

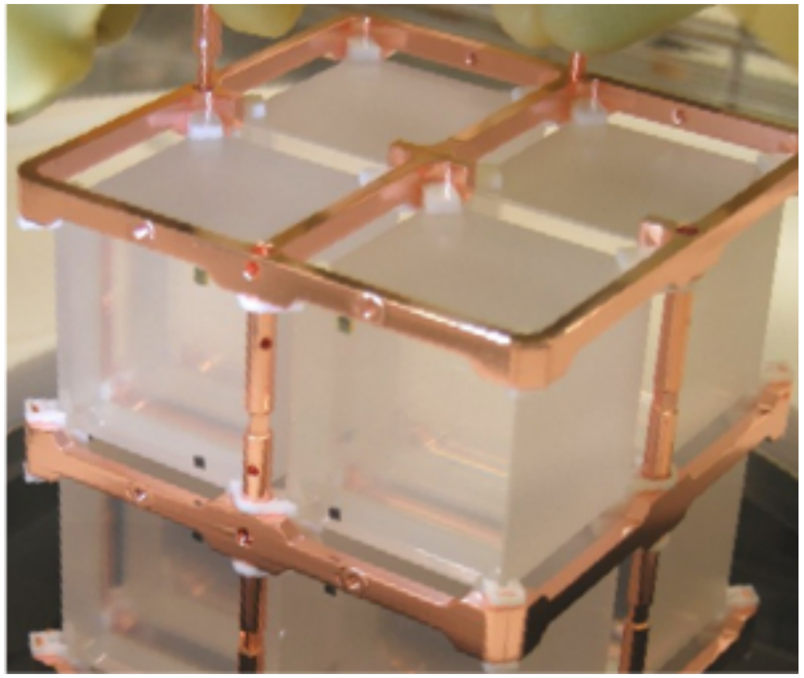
CUORE cleaning:

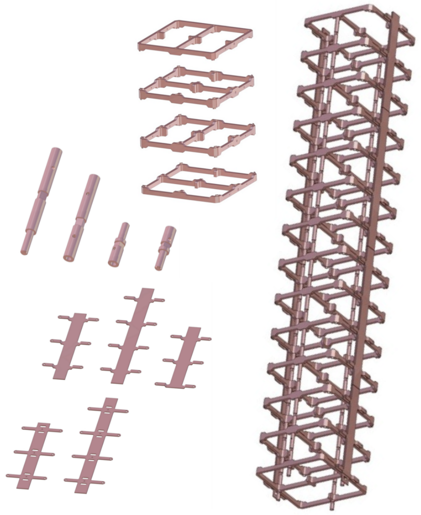
Crystals:

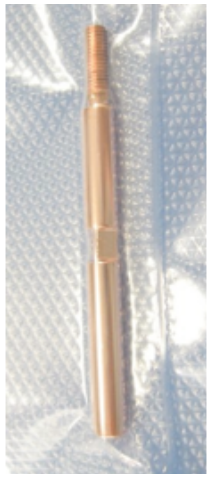
- strict radiopurity control protocol to limit bulk and surface contaminations in crystal production
- transportation at sea level to LNGS
- bolometric test to check performances and radiopurity (CCVR, Cuore Crystals Validation Run)

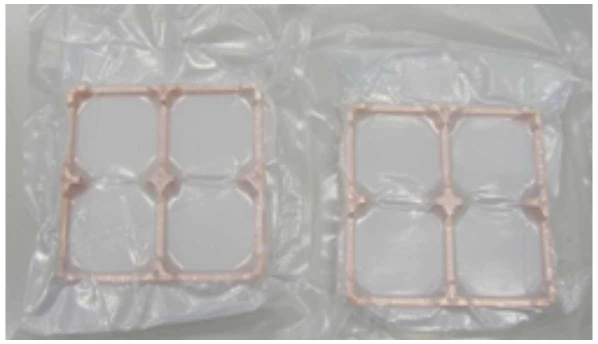
Copper:

- TECM (Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching) cleaning for copper surfaces
- Cleaner copper, and less of it per kg TeO_2
- Cleaner assembly environment









Goal and status of CUORE

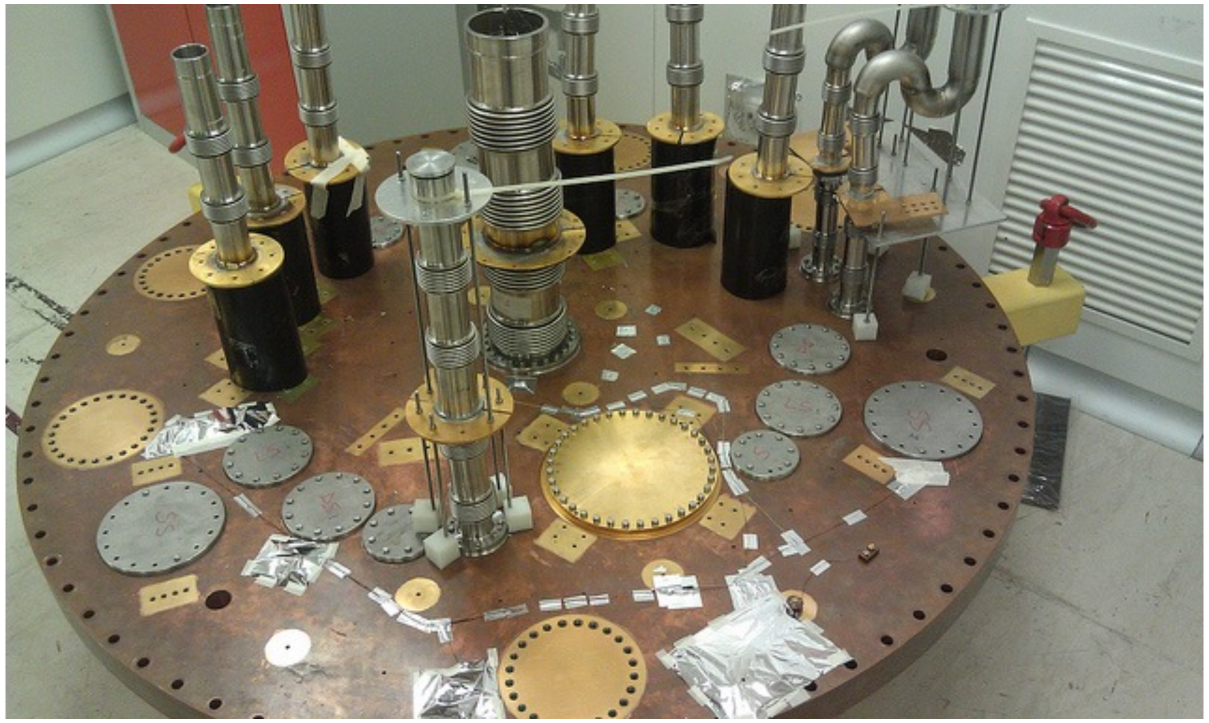
Energy resolution @ ROI: 5 keV

Background goal: 0.01 c/(keV kg y)

Sensitivity 90% C.L. (5 y):

$T_{1/2} = 9.5 \times 10^{25}$ y $m_{\beta\beta} = 50\text{-}130$ meV

- ☑ CUORE towers assembly
- ☑ Cryogenic system commissioning
- ☑ Bolometers and readout commissioning



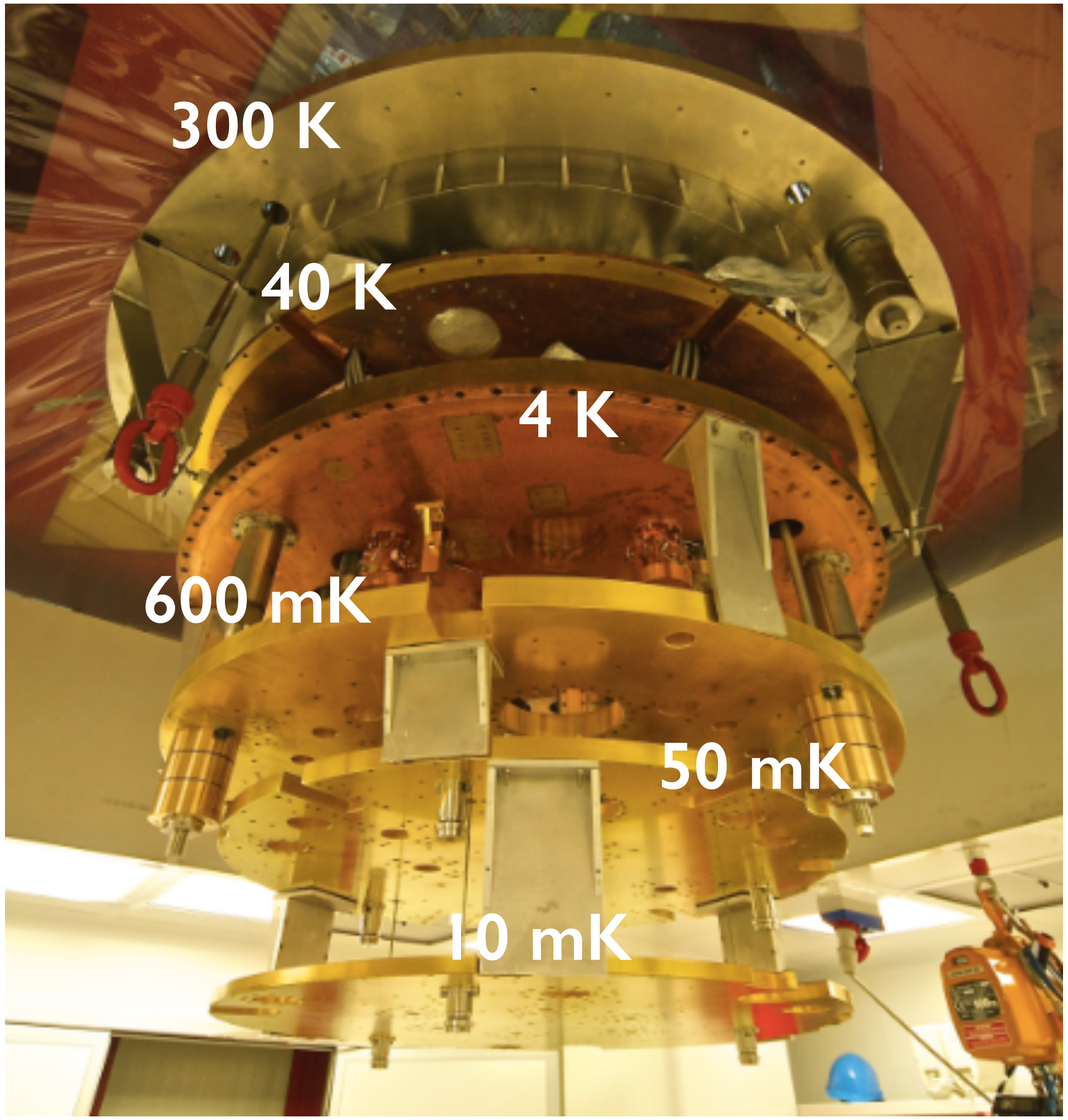
CUORE Towers Assembly

Assembly of all the 19 CUORE towers completed in 2014

Assembly line improved after CUORE-0

988 NTD thermistors connected - 988 heaters connected

Cryogenic system commissioning



All the cryostat components well thermalised at the different stages (including top Pb @ 50 mK and lateral roman Pb @ 4 K).

No evident temperature gradient or heat leak.

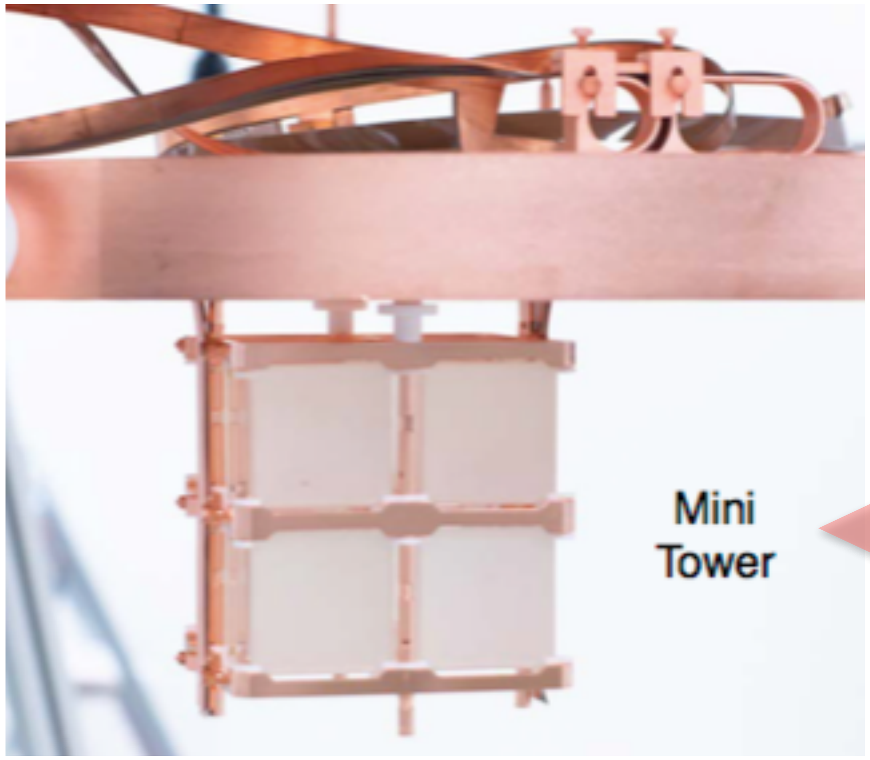
Stable base temperature (allows CUORE bolometers operation) @ 6.3 mK
Base T stable for more than 70 days. Proved nominal cooling power: 3 **µ**W @ 10 mK.

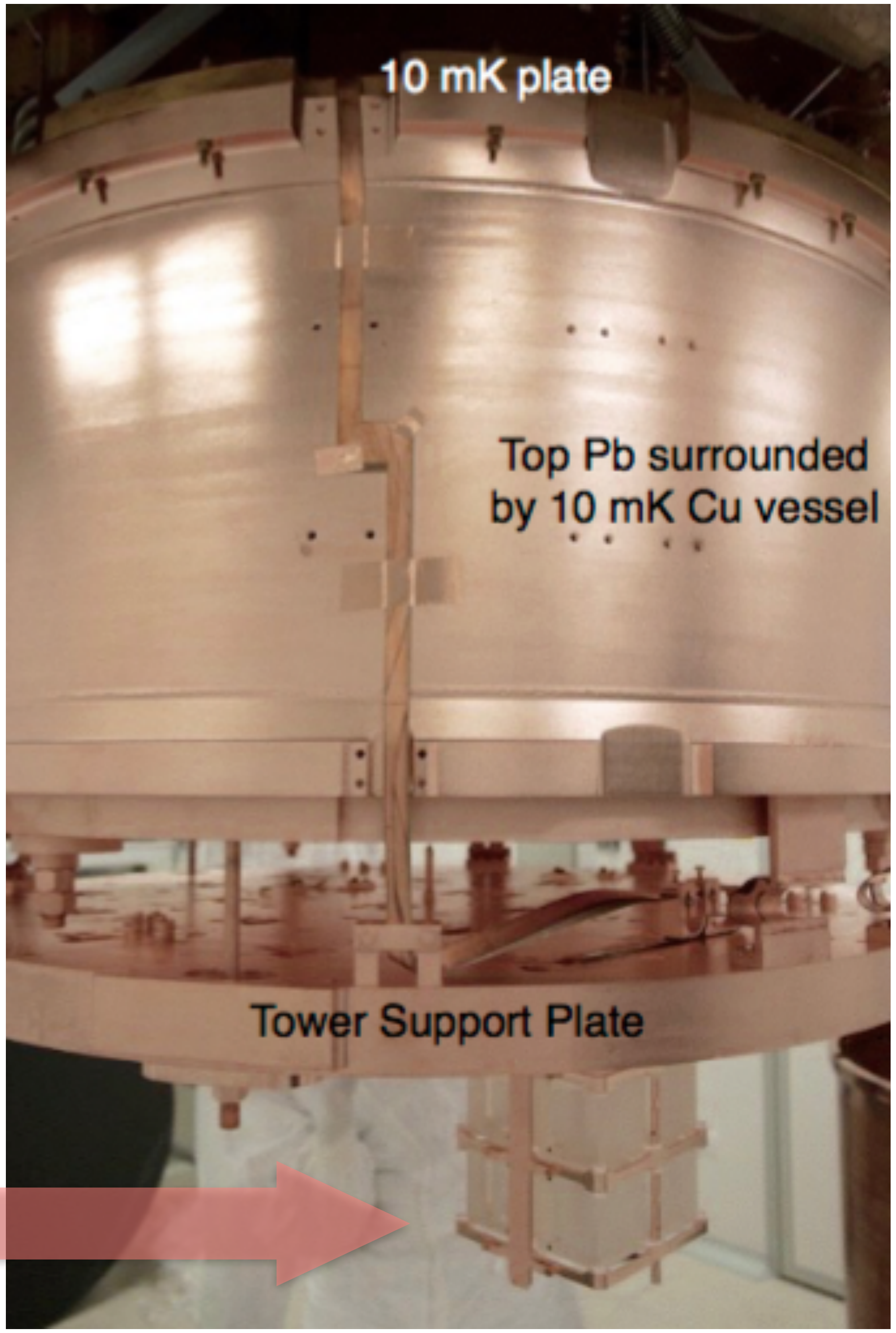
Base temperature allows to stabilise operating temperature around 10 mK for a stable detector response.

Bolometers and readout commissioning

Encouraging detector performance (energy resolution) on 8 detectors array (Mini-Tower).

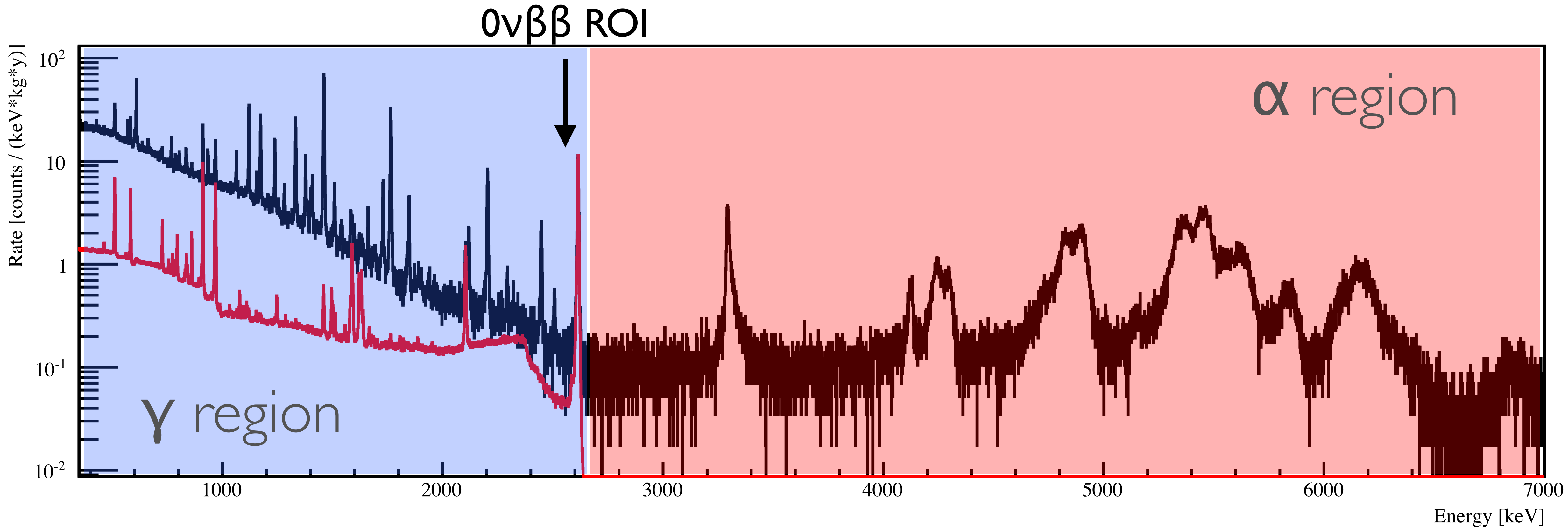
Commissioned electronics, DAQ, temperature stabilization, and detector calibration systems.



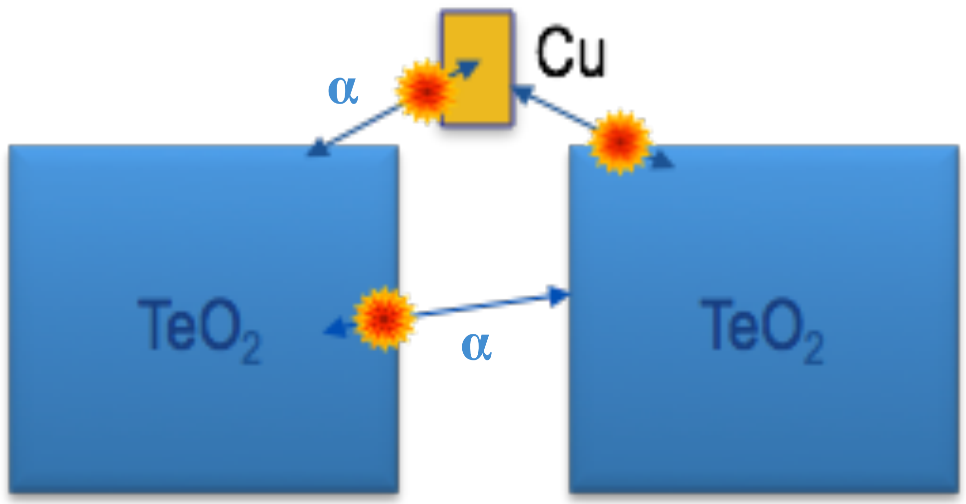


CUORE-0

CUORICINO background



Main sources of background in the region around the Q value:



35% Compton from ^{208}Tl (^{232}Th chain) decays in cryostat (2615 keV line)

55% Degraded alphas from ^{238}U- and ^{232}Th-chain decays on copper surfaces

10% Degraded alphas from ^{238}U- and ^{232}Th-chain decays on crystal surfaces

CUORE-0: the 0-th CUORE-like tower

Single CUORE-like tower & technical prototype. Assembled from detector components manufactured, cleaned and stored following the same stringent protocols defined for CUORE.

First tower from the CUORE detector assembly line

52 TeO_2 crystals, total mass = 39 kg TeO_2 = 10.9 kg ^{130}Te

Purpose:

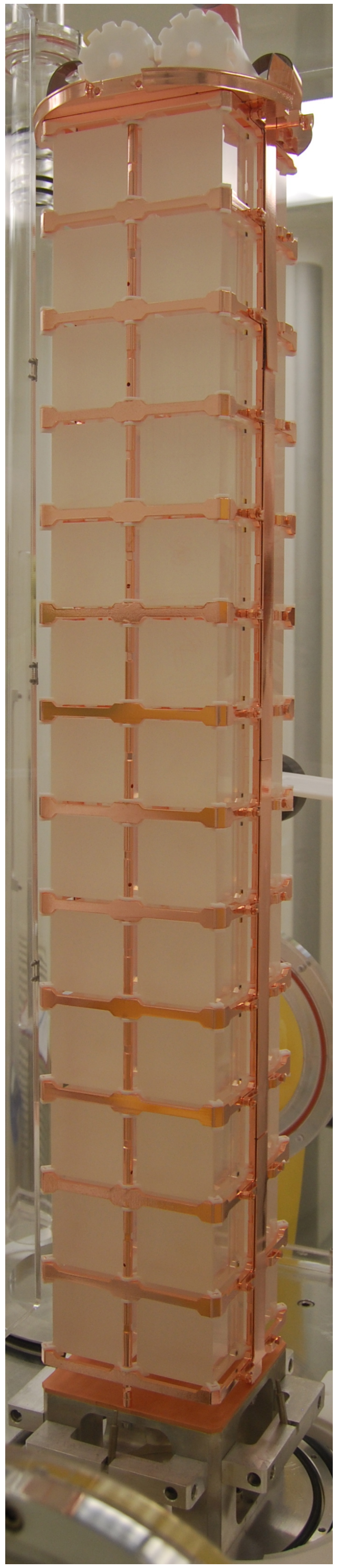
Commission assembly line

Run as standalone experiment while CUORE is being constructed, with aim of surpassing Cuoricino sensitivity

Validate CUORE detector design

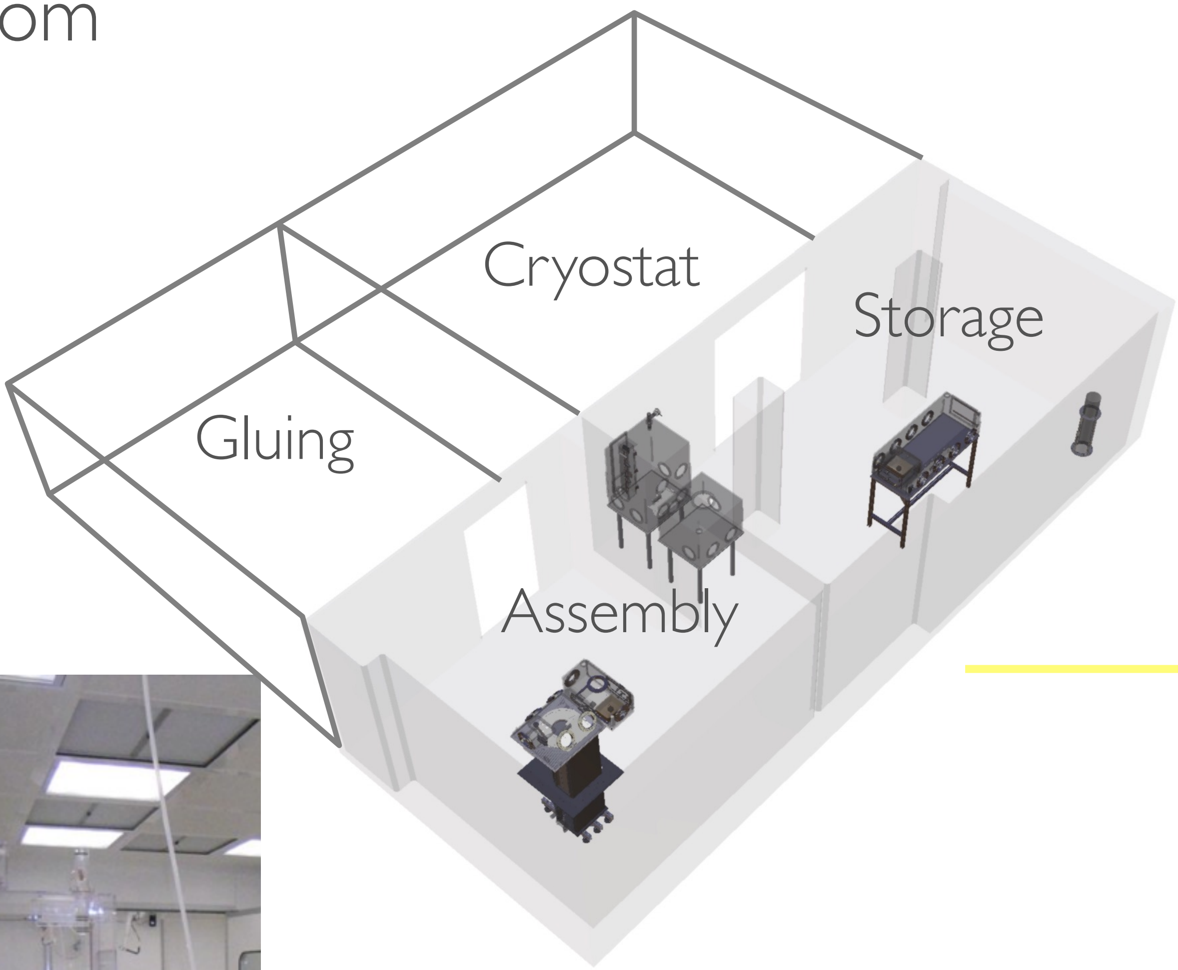
Provide test bed for developing DAQ & analysis framework

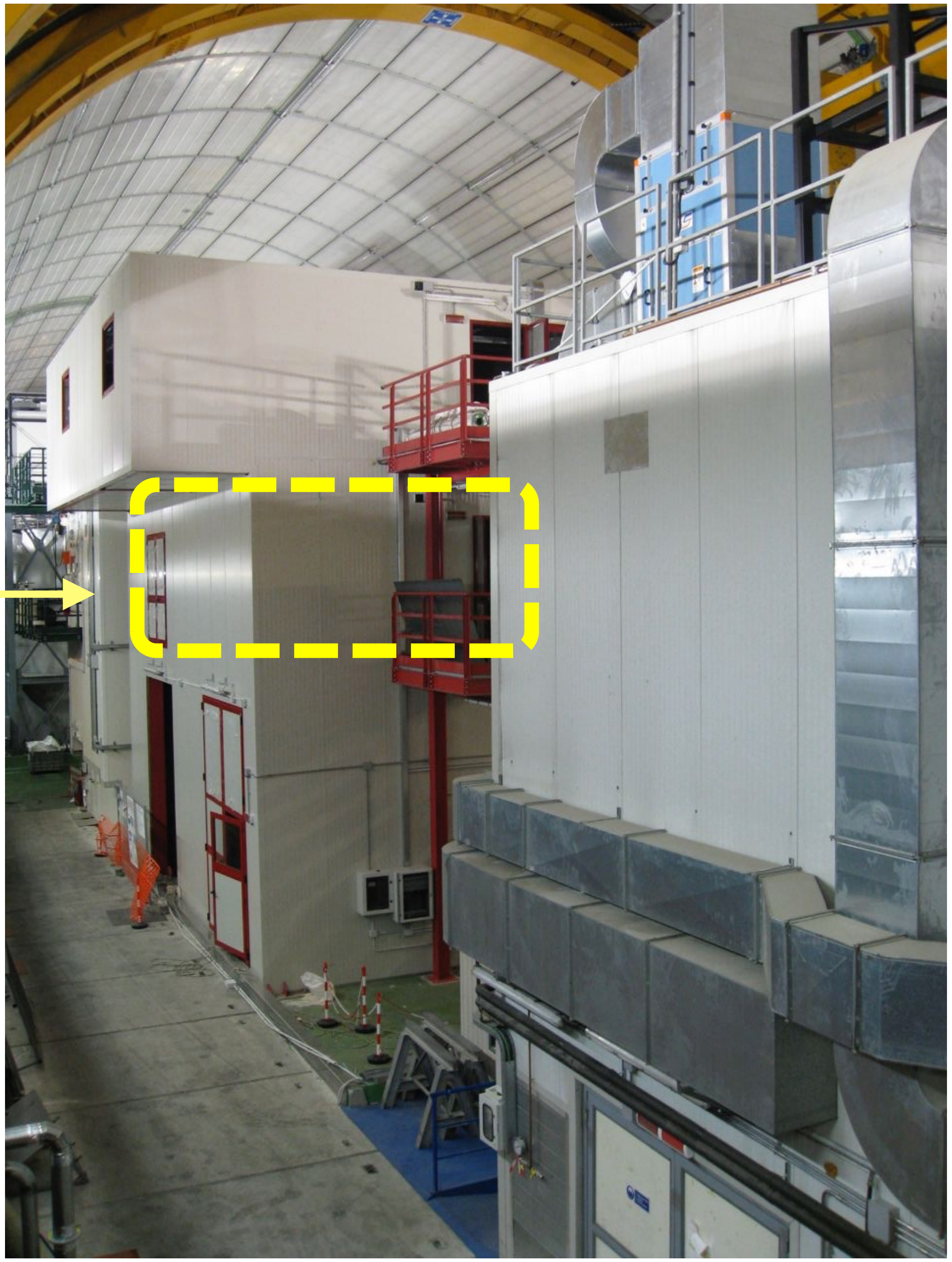
Operated in former Cuoricino cryostat from March 2013 to September 2015



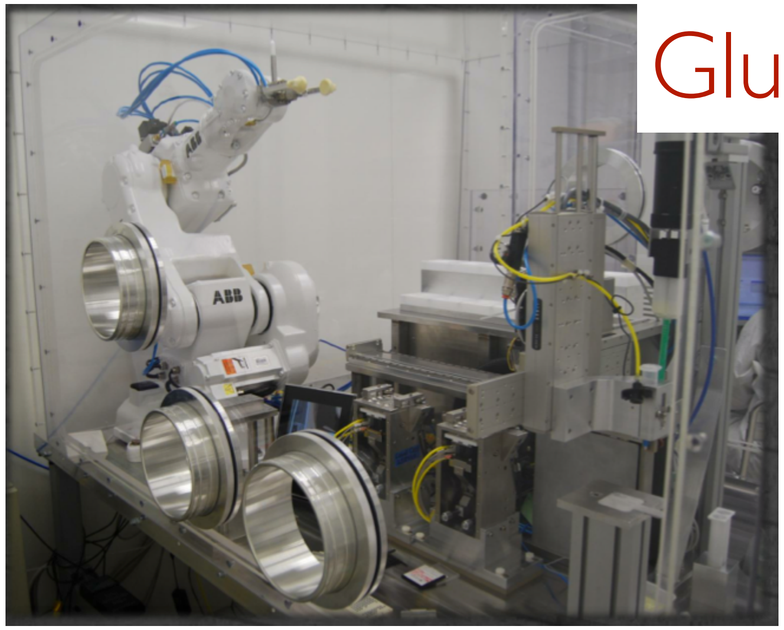
CUORE-0 assembly @ CTAL (Cuore Tower Assembly Line)

Construction was carried out inside N_2-flushed glove boxes in CUORE hut's clean room

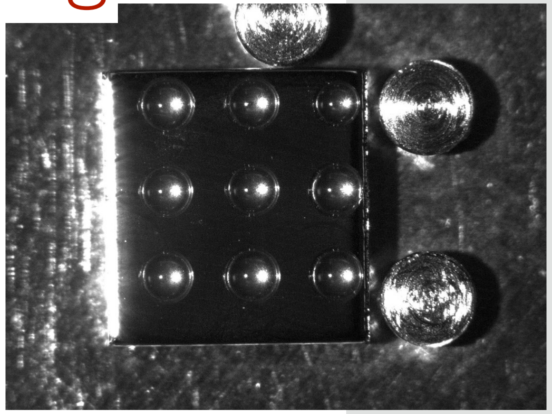


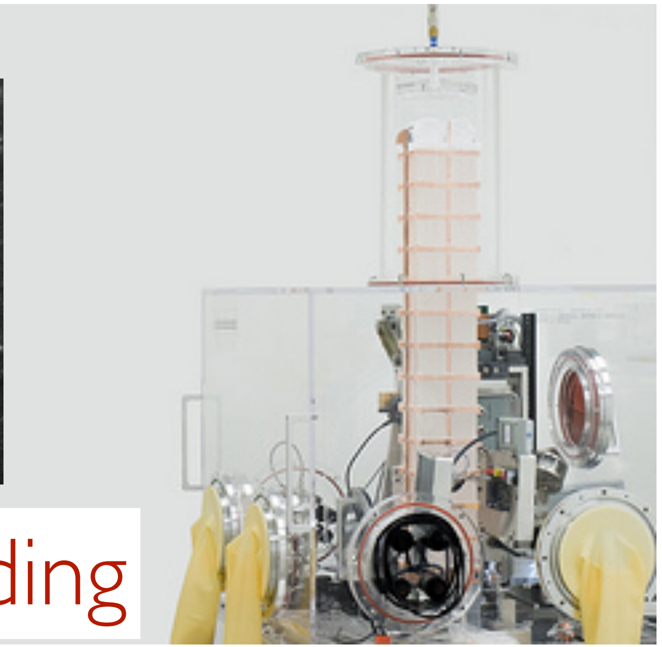


CUORE-0 assembly @ CTAL (Cuore Tower Assembly Line)

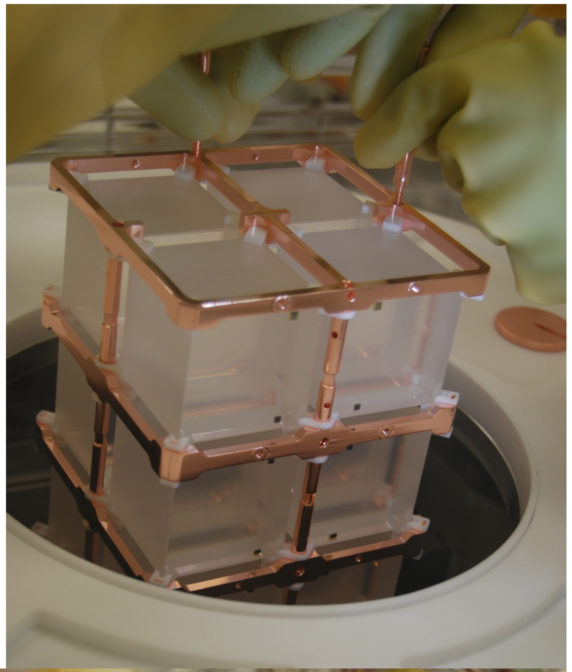


Gluing

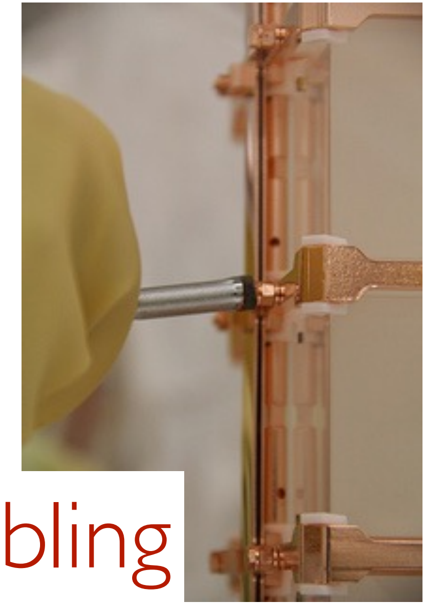




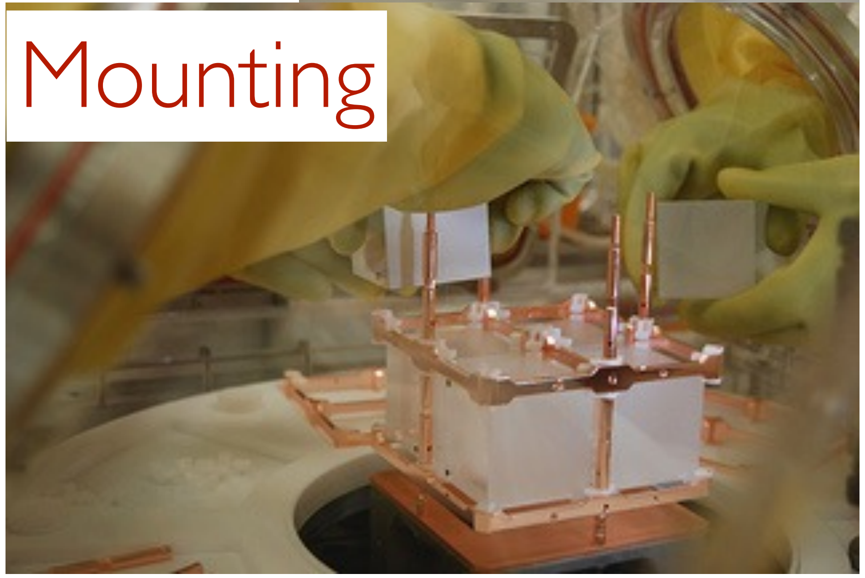
Bonding



Clean room



Cabling



Mounting

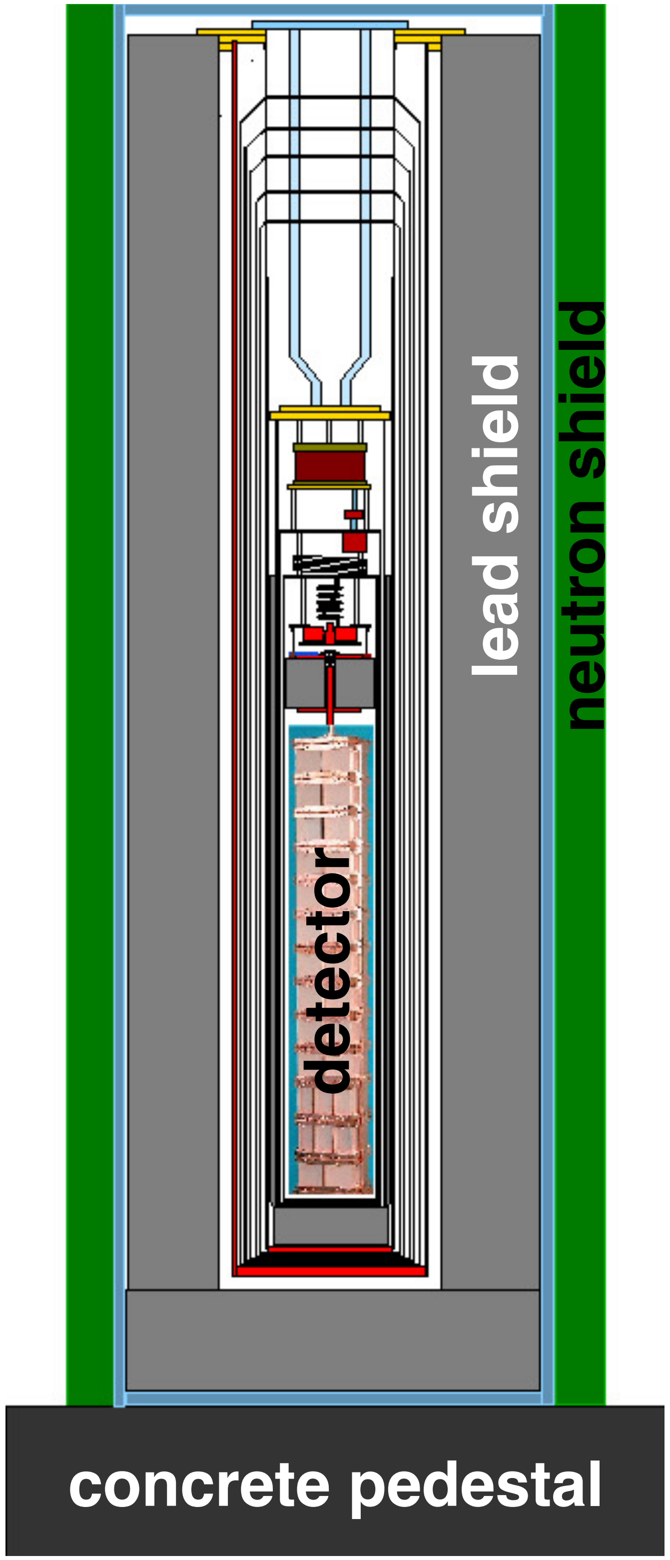
The successful operation of CUORE-0 demonstrated the validity of the CUORE tower assembly line and of the CUORE cleaning procedures.

CUORE-0 shielding

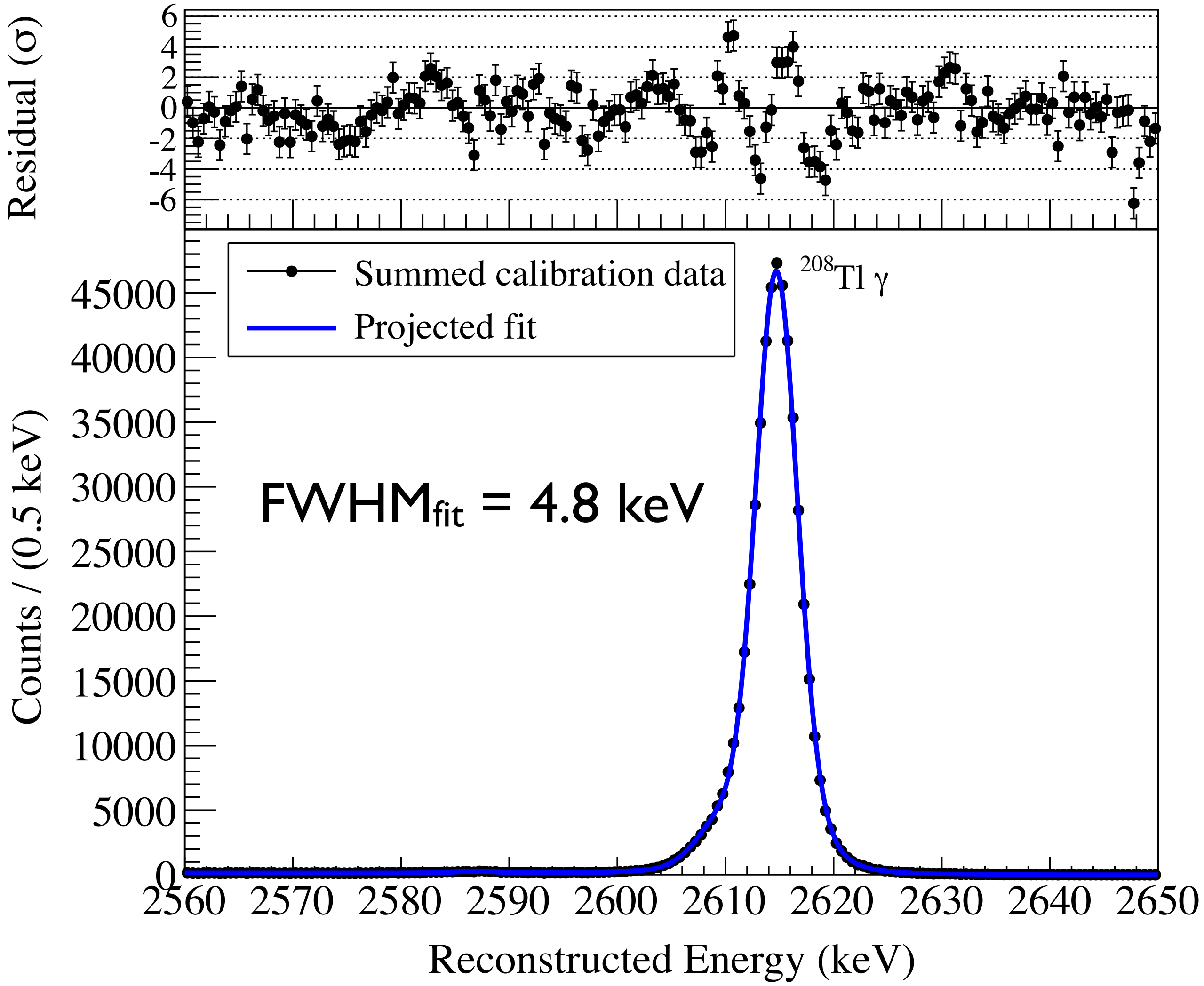
Same (old) cryostat as Cuoricino:

- Inner shields of Roman lead (1 cm lateral thickness)
- Outer shields of modern lead (20 cm lateral thickness)
- Borated PET lateral shield
- Faraday cage flushed with N_2 to suppress Rn

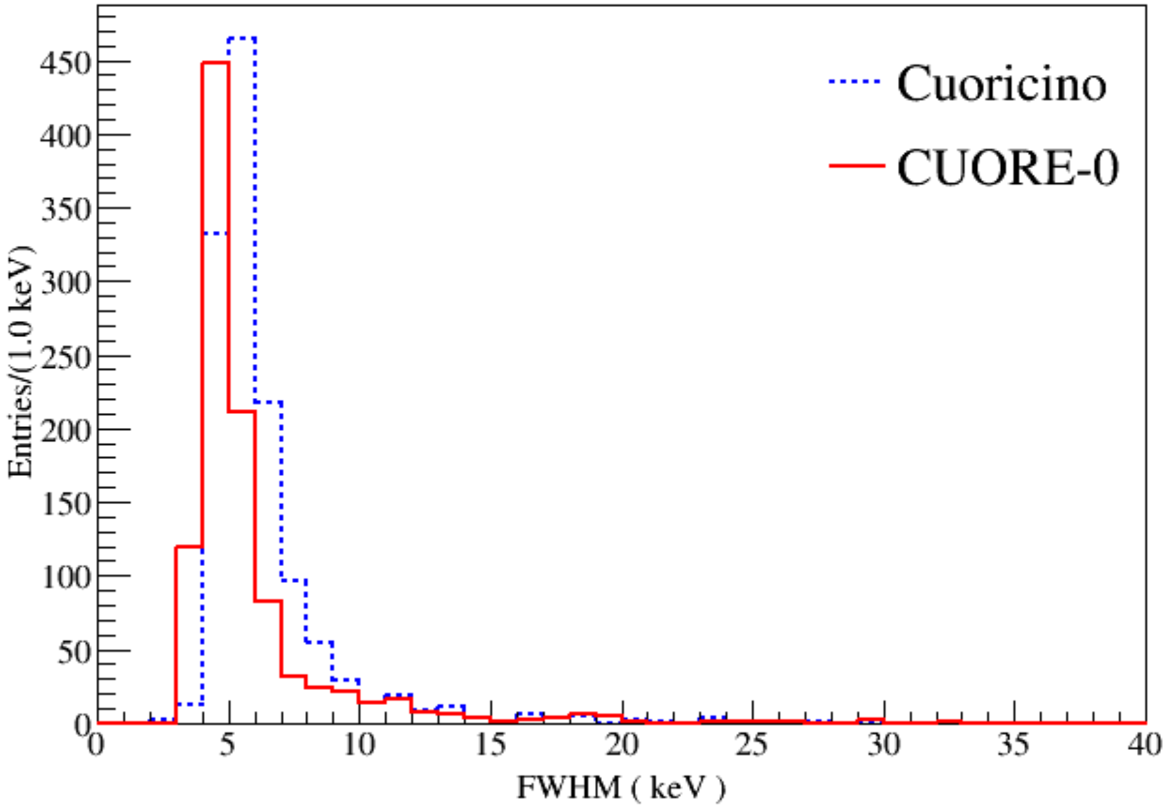
Gamma backgrounds not expected to change compared to Cuoricino, except for the improved radon control.



CUORE-0 energy resolution



FWHM_{fit} = 4.8 keV



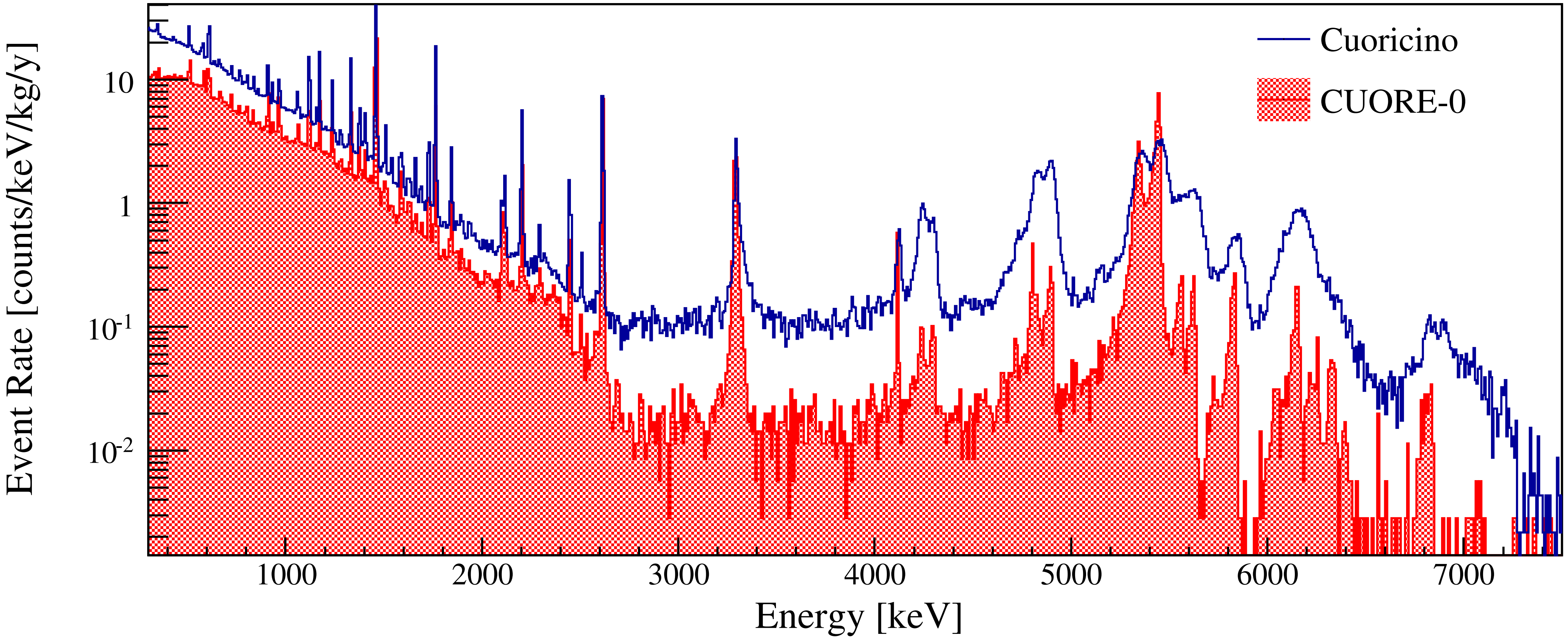
The 5 keV CUORE goal has been reached

Physics-exposure-weighted harmonic mean

	Average FWHM [keV]	RMS of FWHM [keV]
Cuoricino	5.8	2.1
CUORE-0	5.1	2.9

CUORE-0 background

Background in ROI is due to degraded **α** particles from contamination on copper and crystal surfaces and compton-scattered **γ**s from ^{208}Tl in cryostat and frames

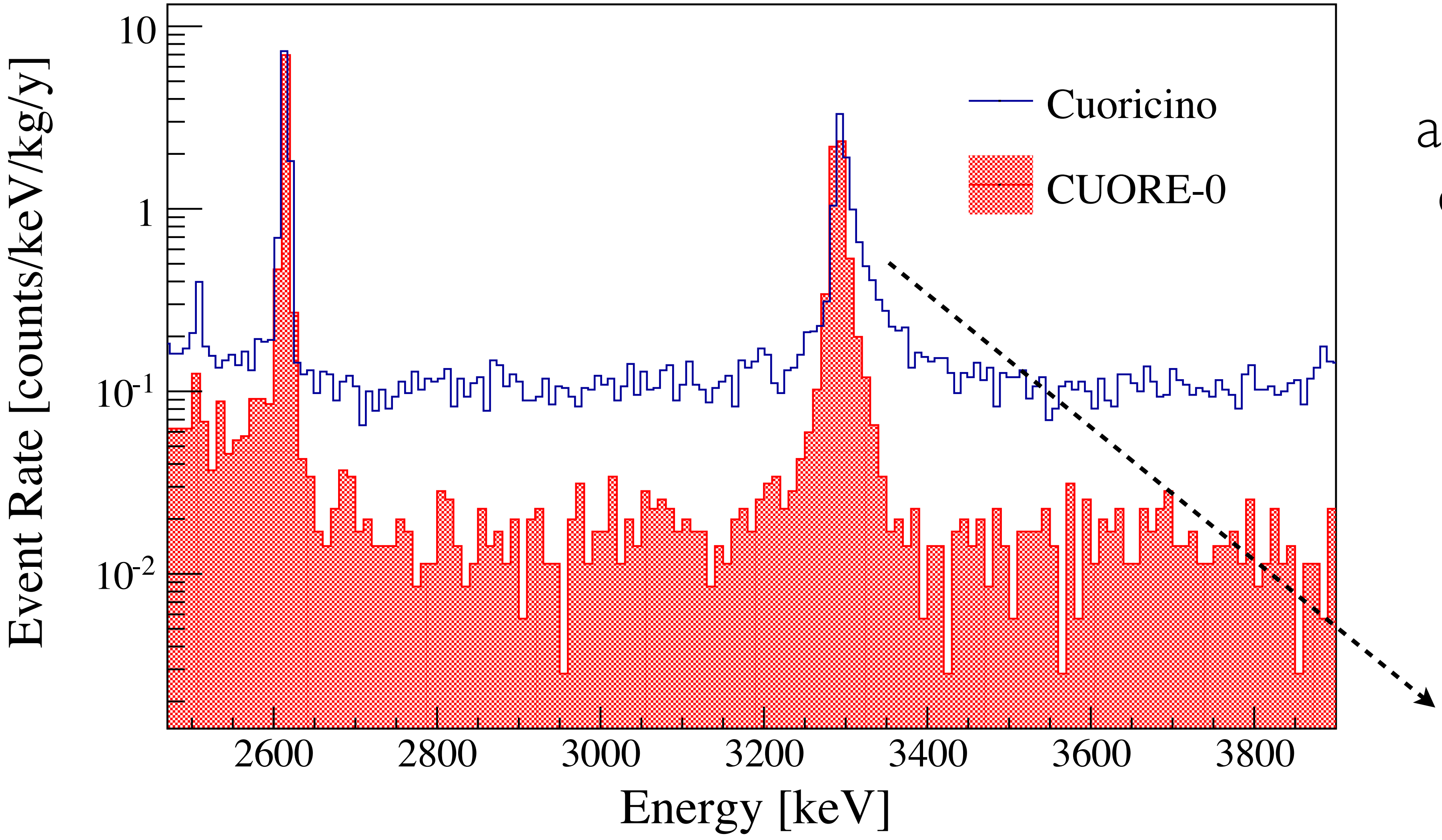


gamma lines from ^{238}U decay chain reduced by a factor 2 (better radon control)

gamma lines from ^{232}Th decay chain not reduced (same cryostat of CUORICINO)

alphas from ^{238}U/^{232}Th decay chain reduced (surface treatment)

CUORE-0 alpha background reduction



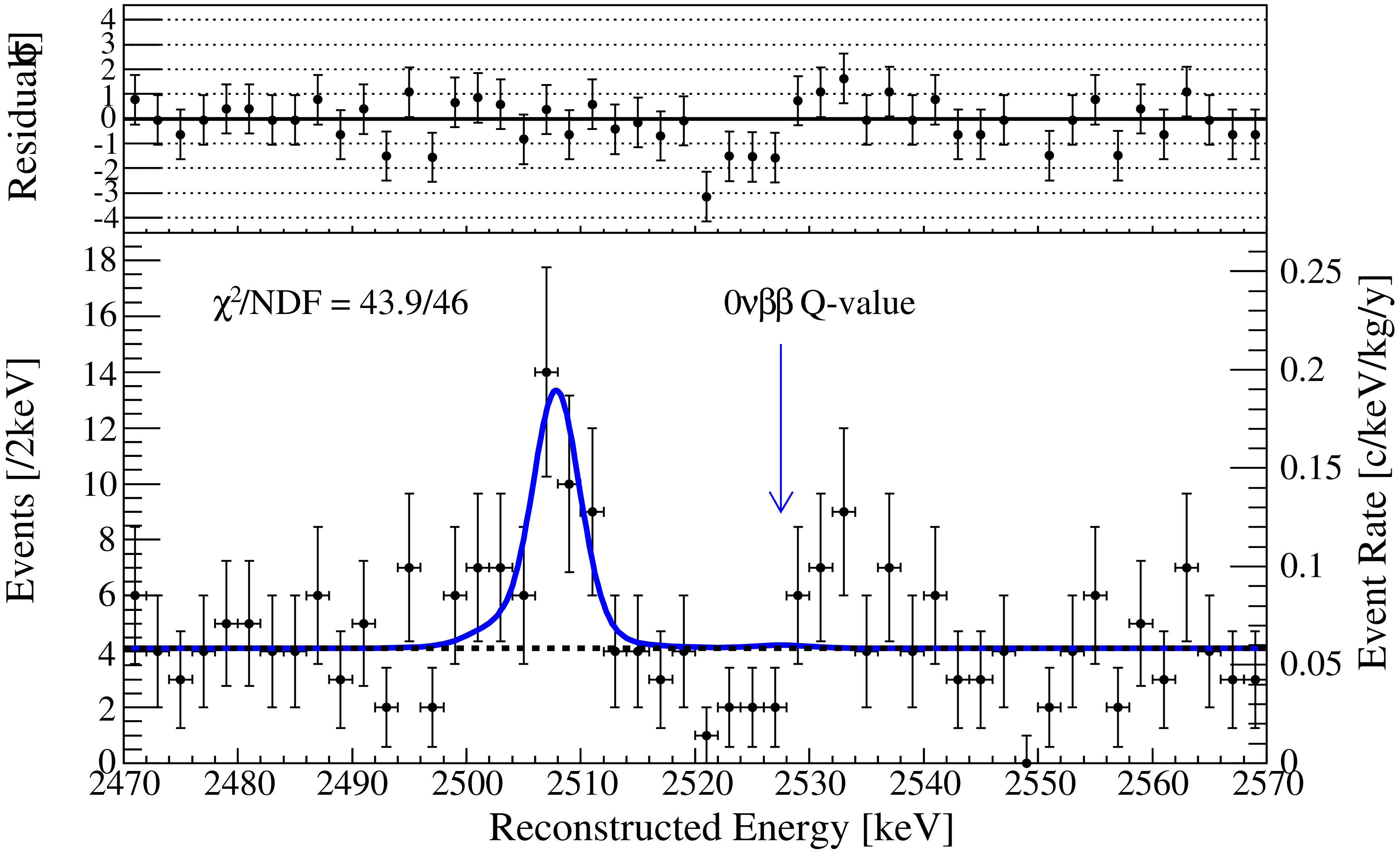
The background in the alpha-dominated region is evaluated in the interval (2700-3900) keV

We obtain a factor 6 reduction in the alpha continuum region

^{190}Pt alpha peak, due to platinum inclusions from the crucible used to grow crystals

	2.7-3.9 MeV	eff [%]
CUORE-0	0.016 ± 0.001	81 ± 1
Cuoricino	0.110 ± 0.001	83 ± 1

CUORE-0 limit



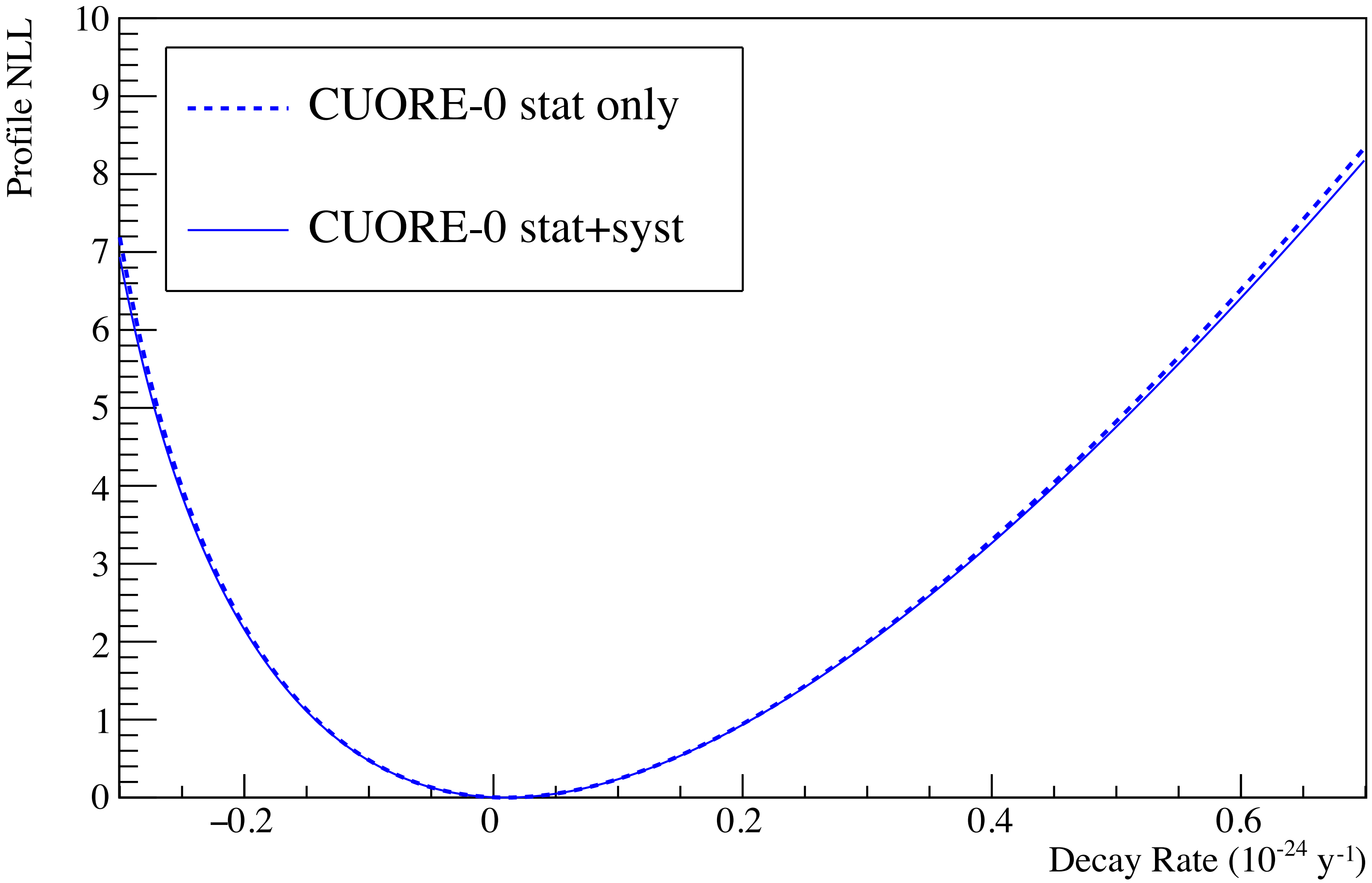
Best fit Γ $\Gamma_{0\nu} = 0.01 \pm 0.12\,(\text{stat.}) \pm 0.01\,(\text{syst.}) \times 10^{-24}\text{yr}^{-1}$

Best fit ROI background index $0.058 \pm 0.004\,(\text{stat.}) \pm 0.002\,(\text{syst.})\ \text{c/keV/kg/yr}$

CUORE-0 limit

We find no evidence for a signal and set 90% C.L. Bayesian lower limits:

$\Gamma^{0\nu} < 0.25 \times 10^{-24}$ yr $T_{1/2}(0\nu) > 2.7 \times 10^{24}$ yr



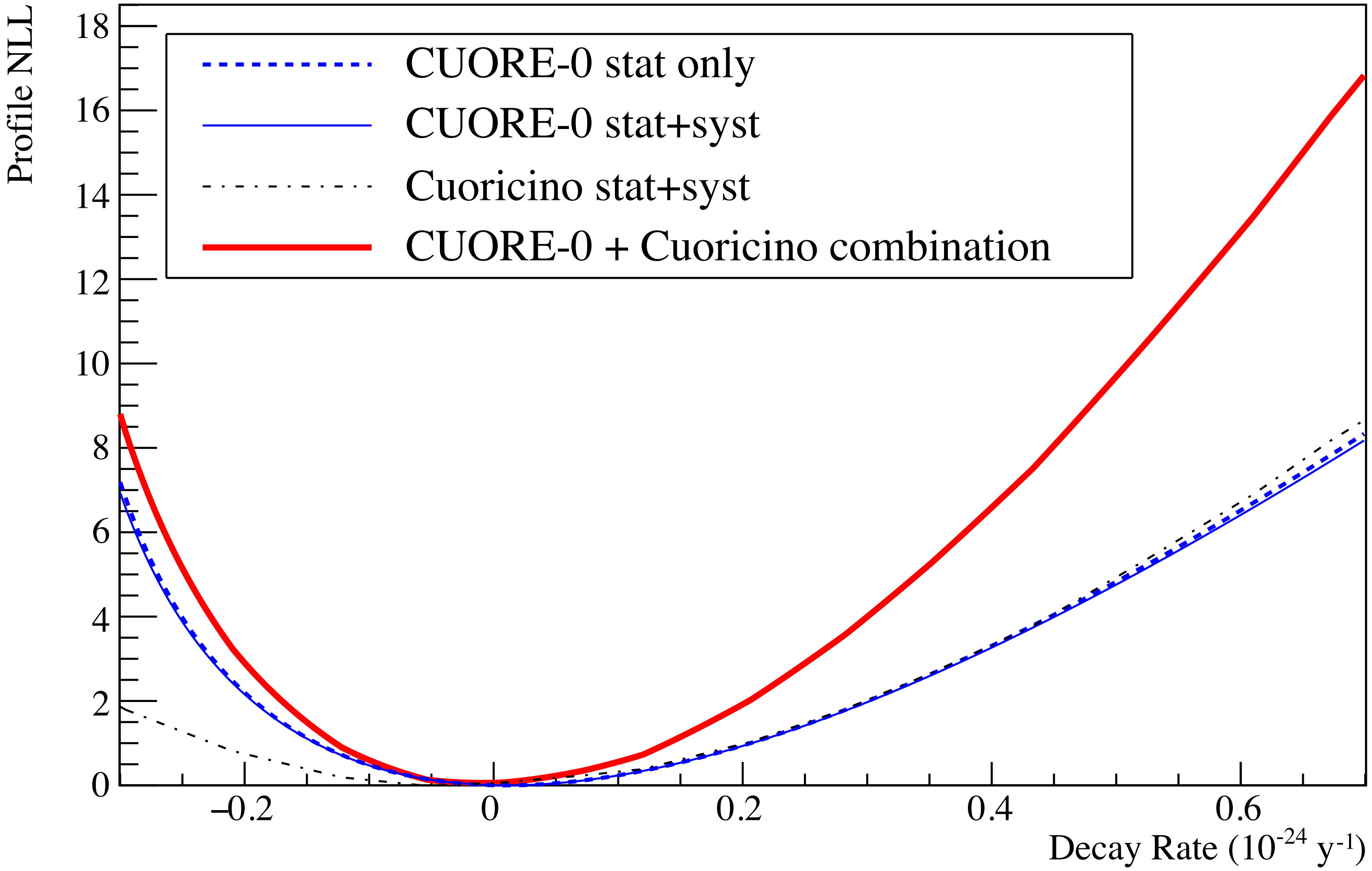
The median 90% C.L. lower limit sensitivity is: 2.9×10^{24} yr

The probability of obtaining a more stringent limit is 54.7%

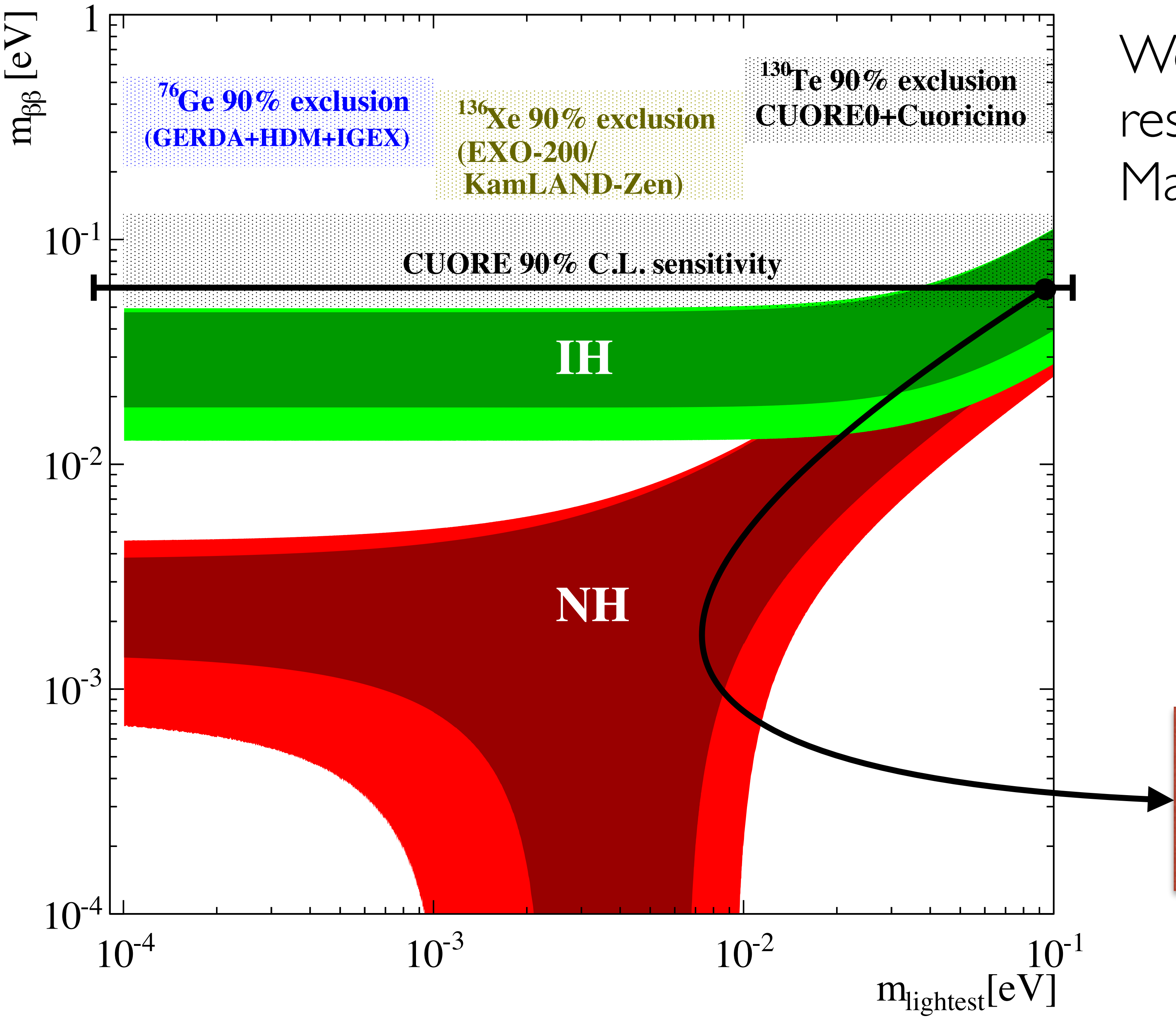
CUORICINO/CUORE-0 combined limit

We combine the CUORE-0 result with the existing 19.75 kg · yr of ^{130}Te exposure from Cuoricino

The combined 90% C.L. limit is $T_{0\nu} > 4.0 \times 10^{24}$ yr



Extrapolation to $m_{\beta\beta}$



We interpret our combined half-life result as a limit on the effective Majorana neutrino mass:

$$m_{\beta\beta} < (270\text{-}650)\ \text{meV}$$

IBM-2 Phys. Rev. C 91, 034304 (2015)
QRPA-TU Phys. Rev. C 87, 045501 (2013)
pnQRPA Phys. Rev. C 91, 024613 (2015)
ISM Nucl. Phys. A 818, 139 (2009)
EDF Phys. Rev. Lett. 105, 252503 (2010)

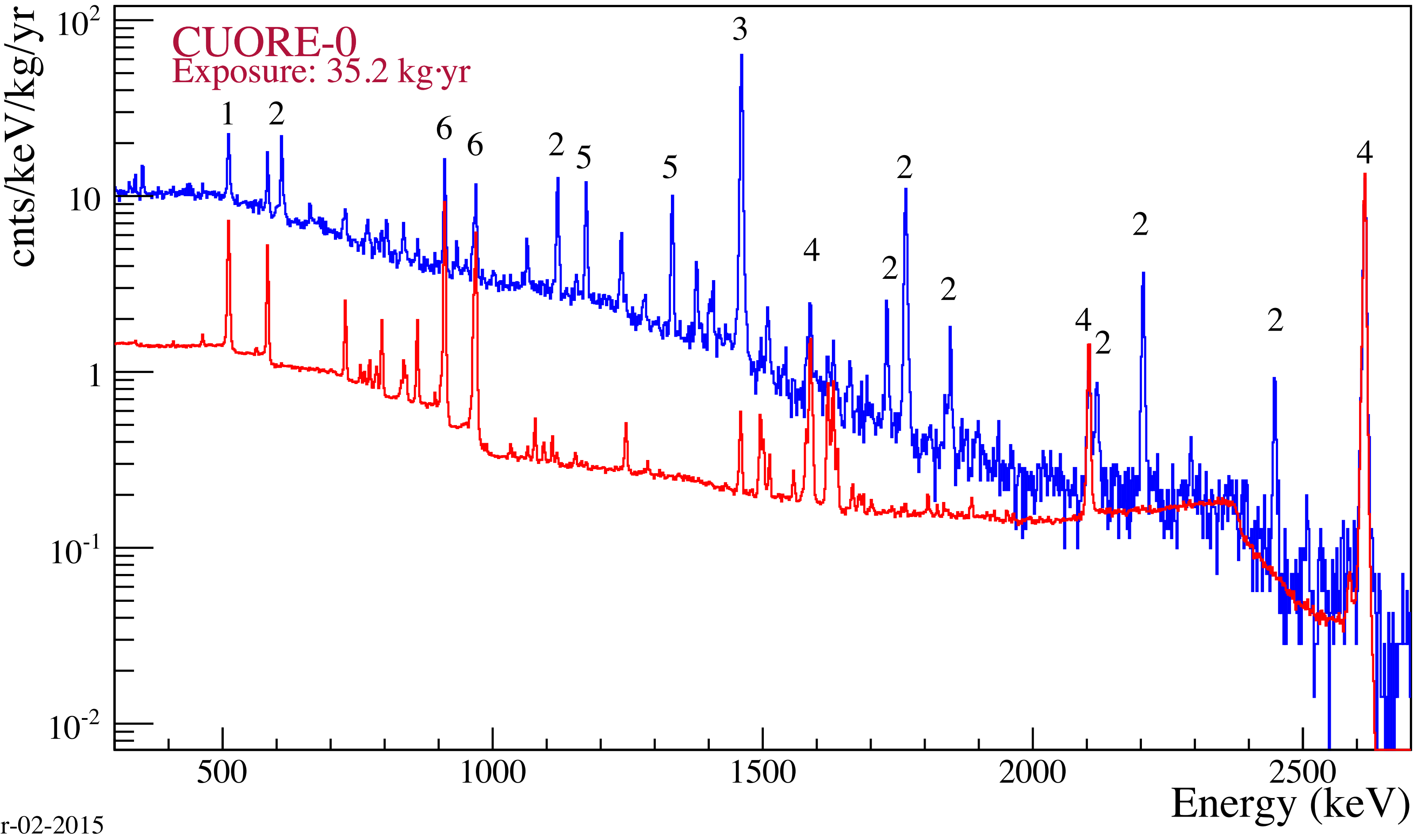
recent KamLAND-Zen result
$m_{\beta\beta}$ < (60 - 161) meV
http://arxiv.org/pdf/1605.02889.pdf

CUORE-0 Background Model and ^{130}Te 2νββ half-life

Goal: Disentangle and describe quantitatively the main background sources, evaluating their impact in the 0νββ ROI. Evaluate the half-life of 2νββ decay of ^{130}Te.

First Step:
Identify the background sources

Exploit a priori information from previous experiments, radioassay measurements of materials and cosmogenic activation calculations



Extract the maximum information directly from CUORE-0 data: analysis of gamma and alpha peaks coincidence analysis (particularly useful to identify contaminations on crystal surfaces)

(1) e^+e^- annihilation - (2) ^{214}Bi
(3)^{40}K - (4)^{208}Tl - (5) ^{60}Co - (6) ^{228}Ac

CUORE-0 Background Model and ^{130}Te 2νββ half-life

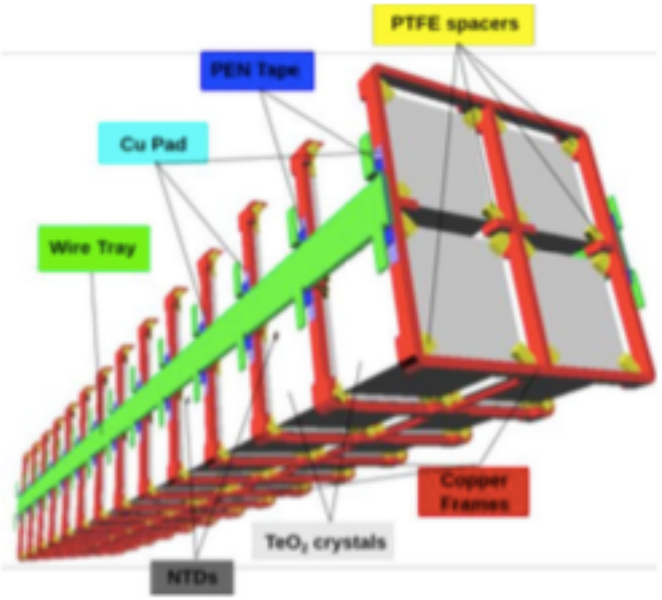
Second Step:
Model each source through MC

Background sources simulated by means of a GEANT4 based MC code. CUORE-0 geometry modelled with high detail, Careful reproduction of detector features (coincidences, resolution, thresholds…).

NEAR sources

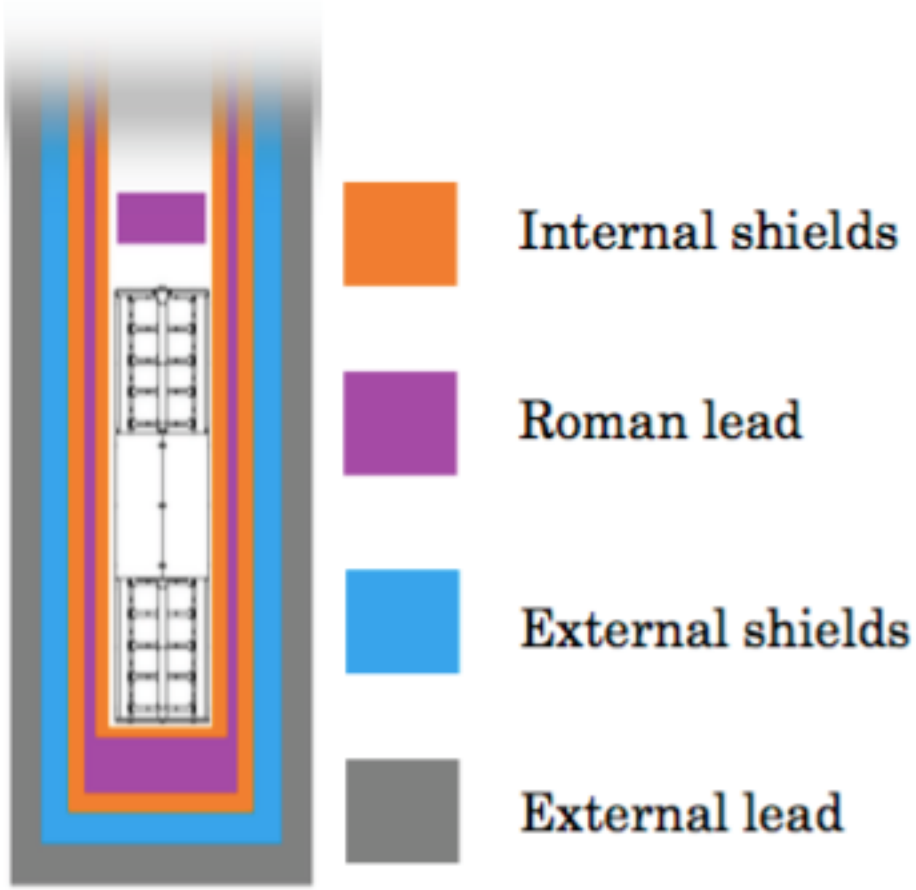
Crystals + Holder

α, β, γ radiation



FAR sources

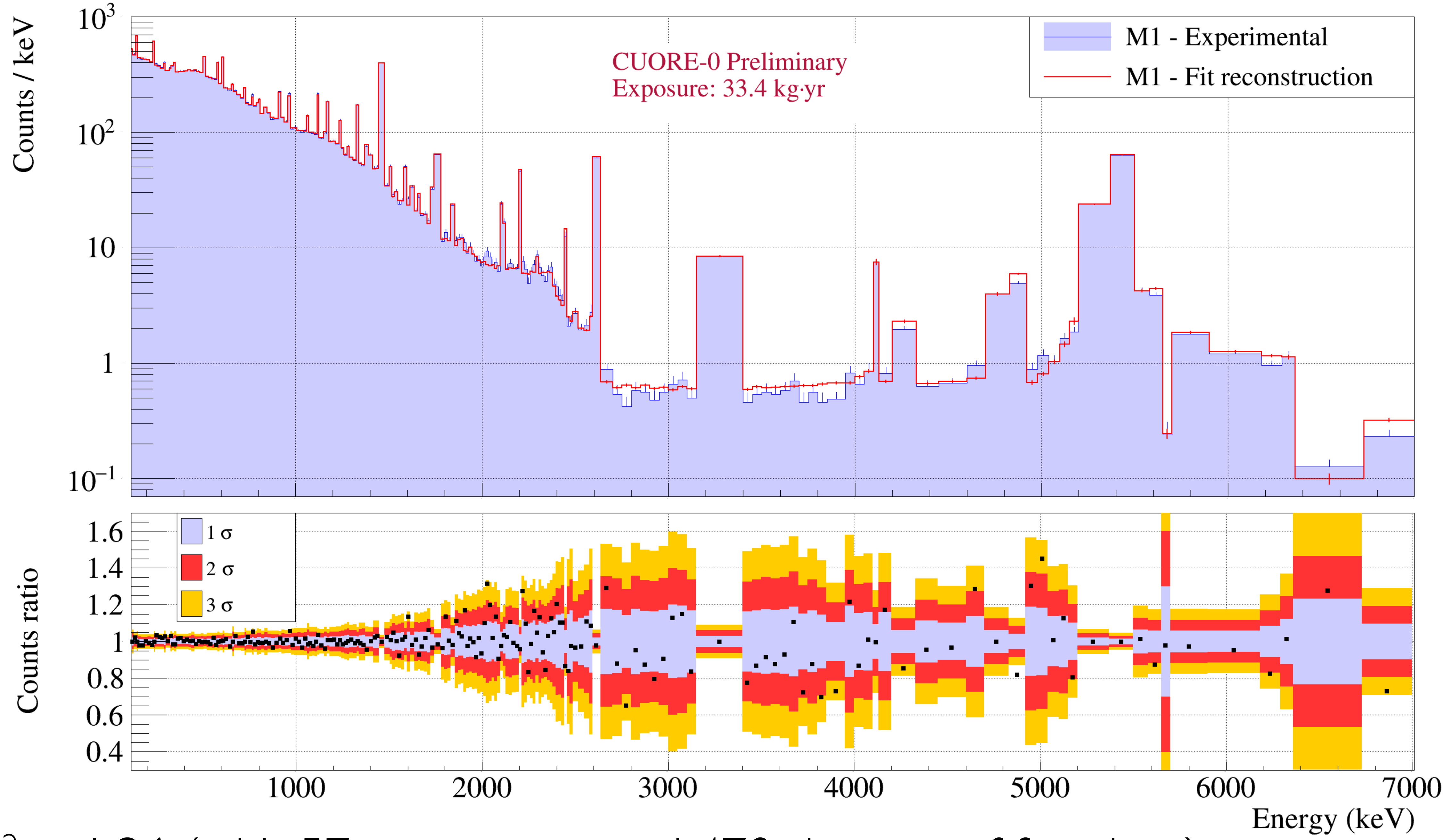
Only γ radiation



CUORE-0 background fit result

Final Step: Fit the measured spectra

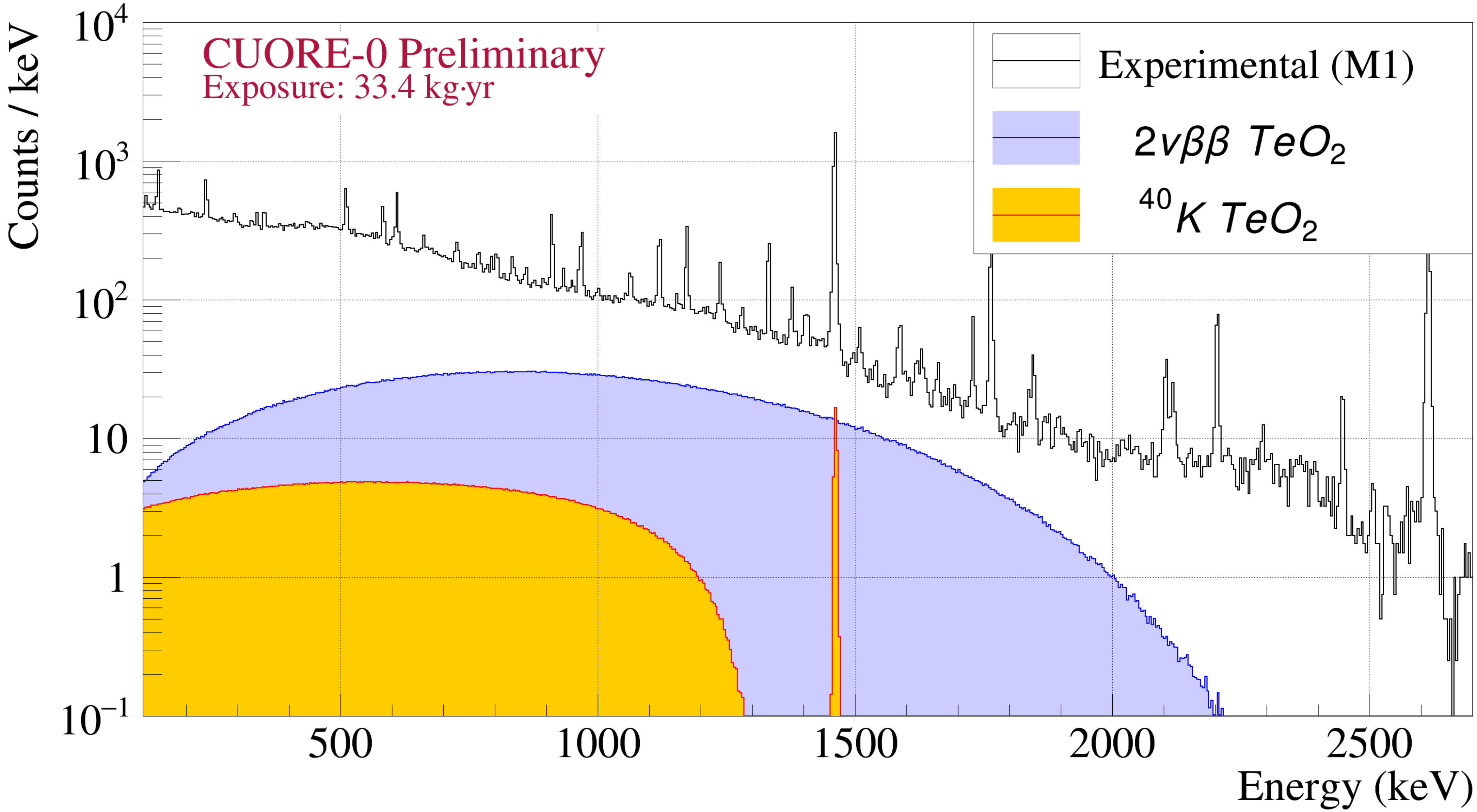
Reconstruction within 3σ range for most of bins (also in multiplicity 2 spectra)



χ^2 = 1.36 (with 57 parameters and 478 degrees of freedom)

CUORE-0 result on ^{130}Te 2νββ half-life

$T_{1/2}(2\nu) = [8.2 \pm 0.2\ (\text{stat}) \pm 0.6\ (\text{syst})] \times 10^{20}$ y



$T_{1/2}(2\nu) = [7.0 \pm 0.9\ (\text{stat.}) \pm 1.1\ (\text{syst.})] \times 10^{20}$ y
[R. Arnold et al. (NEMO-3 Collaboration), Phys. Rev. Lett., 107, 062504 (2011)]
$T_{1/2}(2\nu) = [6.1 \pm 1.4\ (\text{stat.})\ {+2.9}/{-3.5}\ (\text{syst.})] \times 10^{20}$ y [C. Arnaboldi et al., Phys. Lett. B, 557, 167 (2003)]

Conclusions

TeO_2 bolometers offer a well-established, competitive technique in the search for $0\nu\beta\beta$ decay

CUORE-0

Achieved its energy resolution and background level goals, surpassing Cuoricino sensitivity in half the time.

Indicated CUORE sensitivity goal is within reach.

Did not find evidence of ^{130}Te $0\nu\beta\beta$ decay and after combination with CUORICINO data set the best limit to date on $T_{1/2}$ of the decay.

$2\nu\beta\beta$ half-life evaluated (paper in preparation).

CUORE:

Assembly of the 19 CUORE towers is complete.

Commissioning of the cryogenic system and readout completed.

Ready for detectors installation.