# THE CUORE EXPERIMENT: A SEARCH FOR NEUTRINOLESS DOUBLE BETA DECAY

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in Memoriam Engin Arık and Her Colleagues
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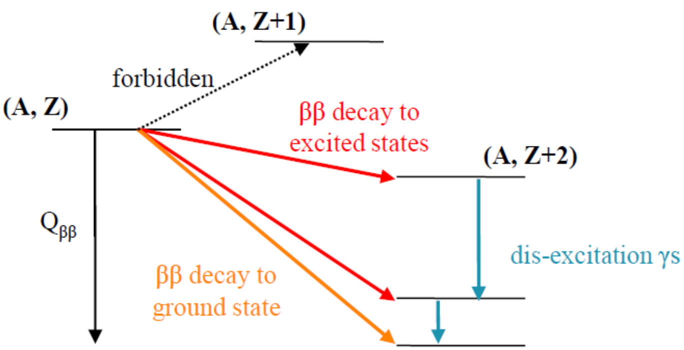
# Outline

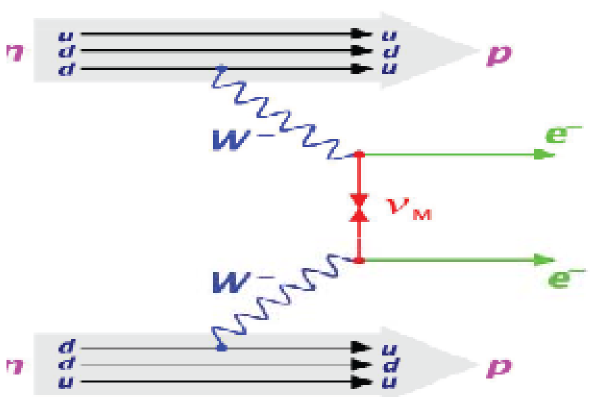


- Theoretical and experimental context:
  - Neutrinoless Double Beta Decay (0ν–DBD)
  - Sensitivity
  - Bolometric Approach
- The CUORE experiment
  - Set-up and properties
- CUORICINO: the demonstrator
- On the road to CUORE: CUORE-0
- Conclusions

# Why Neutrinoless Double Beta Decay?






<u>Different channels :</u>

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ ← 2ν Double Beta Decay allowed by the Standard Model already observed – $\tau \geq 10^{19}$ y

$(A,Z) \rightarrow (A,Z+2) + 2e^-$ ← 0ν Double Beta Decay forbidden by the Standard Model ΔL=2

Neutrino Nature is crucial :

$$0\nu DBD \Leftrightarrow \begin{array}{l} m_\nu \neq 0 \\ \nu = \bar{\nu} \end{array}$$

$$\Gamma^{0\nu} \propto G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ |\langle m_{\beta\beta}\rangle|^2$$

- $\Gamma^{0\nu}$: DBD rate
- $G^{0\nu}(Q,Z)$: Phase space
- $|M^{0\nu}|^2$: Nuclear matrix element
- $|\langle m_{\beta\beta}\rangle|^2$: Effective Majorana Mass

# Probing the neutrino mass

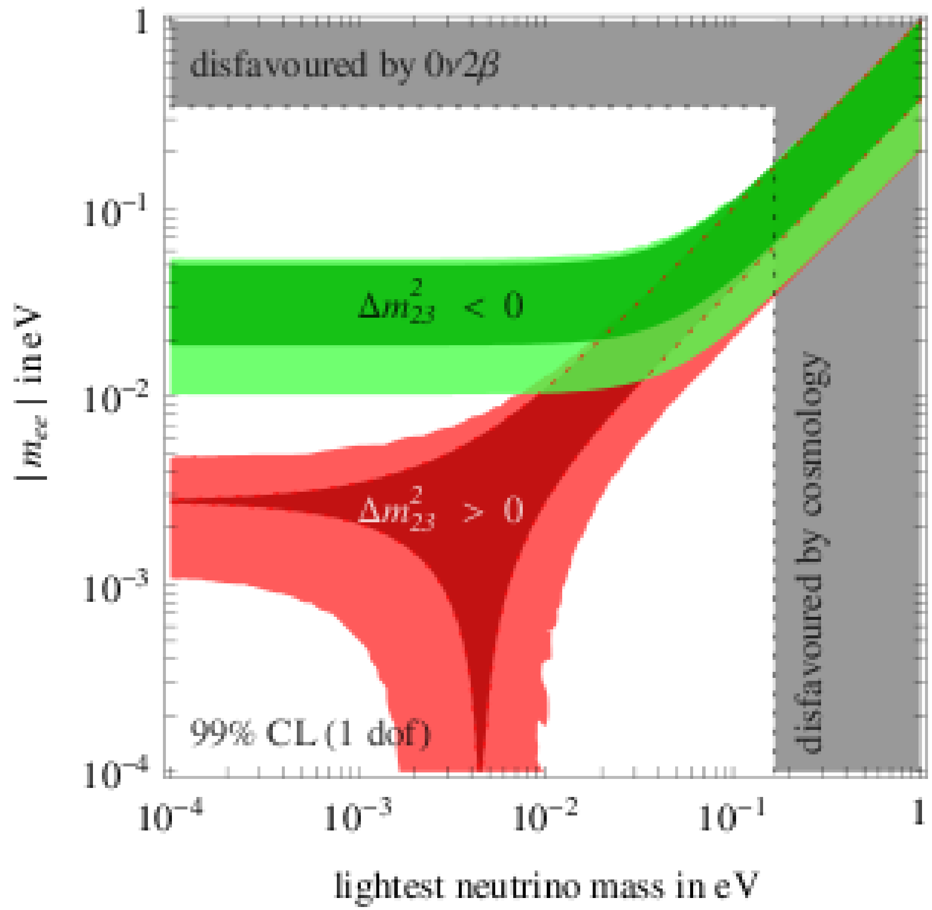


$$\langle m_{\beta\beta} \rangle = \left| \sum m_i U_{ei}^2 e^{i\alpha_i} \right|$$

Two bands appear, corresponding to inverted and direct hierarchy, merging in the degenerate one

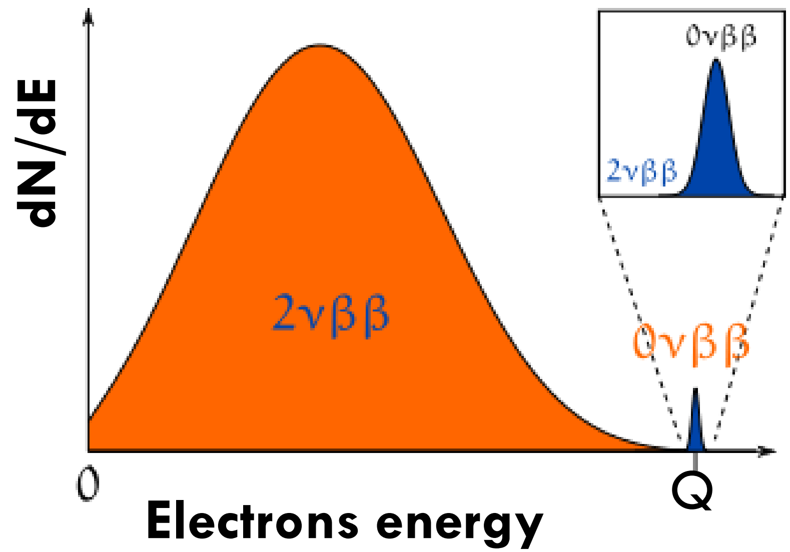
Uncertainties mainly due to nuclear matrix elements difficult calculation

Strumia&Vissani hep-ph/0503243



# Signature and sensitivity

In a source=detector approach we expect a peak at the q-value Q of the transition (energy sum of the two electrons)



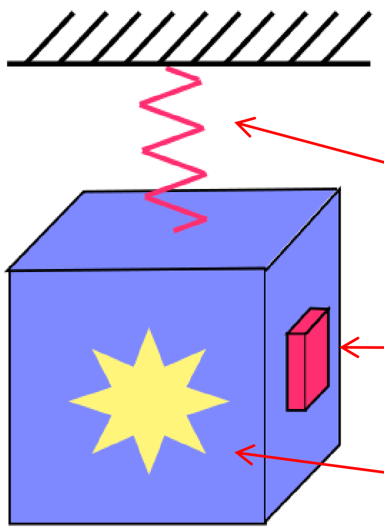

**Sensitivity:** Defined as the decay time corresponding to the minimum number of detectable events above a background (B) at a given C.L.

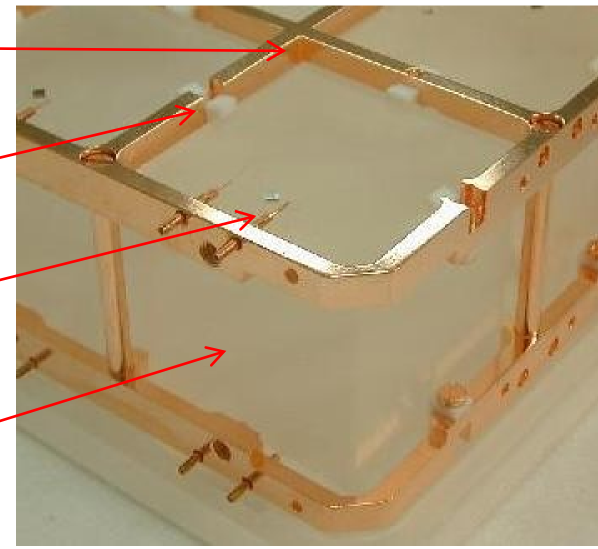
$$S^{0\nu} \propto \epsilon \cdot i.a \cdot \sqrt{\frac{M \cdot T}{B \cdot \Gamma}}$$

Isotopic Abundance (i.a), Detector Mass (M), Live time (T), Efficiency ($\epsilon$), Background (B), Energy Resolution ($\Gamma$)

# Bolometric approach

Ideal Calorimeter: Energy to phonons conversion



Operating principle: $\Delta T = \frac{\Delta E}{C}$

Dielectric and diamagnetic crystals: low thermal capacity @ low temperature

Pros:

- High resolutions
- Wide choice of materials

Cons:

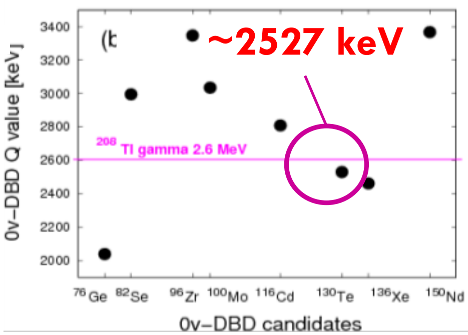
- Slow signals
- No particle distinction

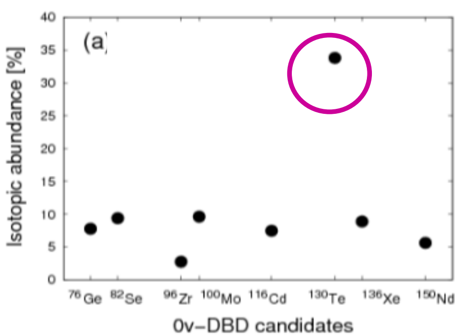
# Energy absorber & temperature sensor

## $TeO_2$ cubic crystal

- $5x5x5\ cm^3$
- The choice of the material is driven by the choice of the candidate nuclide

$^{130}Te$



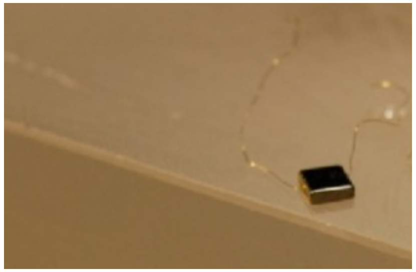

$TeO_2$

**A.** Dielectric with $T_D$=232 K: C minimized

**B.** Easy to grow large crystals with good radio-purity

**C.** Resistance to series of thermal cycles at very low temperatures

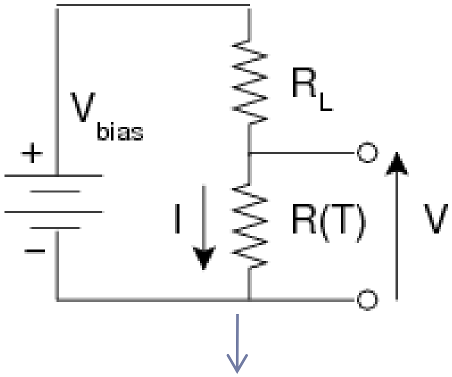
## NTD-Ge thermistor



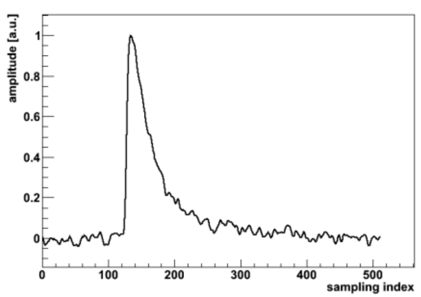
- $3x3x1\ mm^3$
- Ge doped by Neutron Transmutation Doping

$$\Delta V = I \times \frac{\partial R}{\partial T} \times \Delta T$$

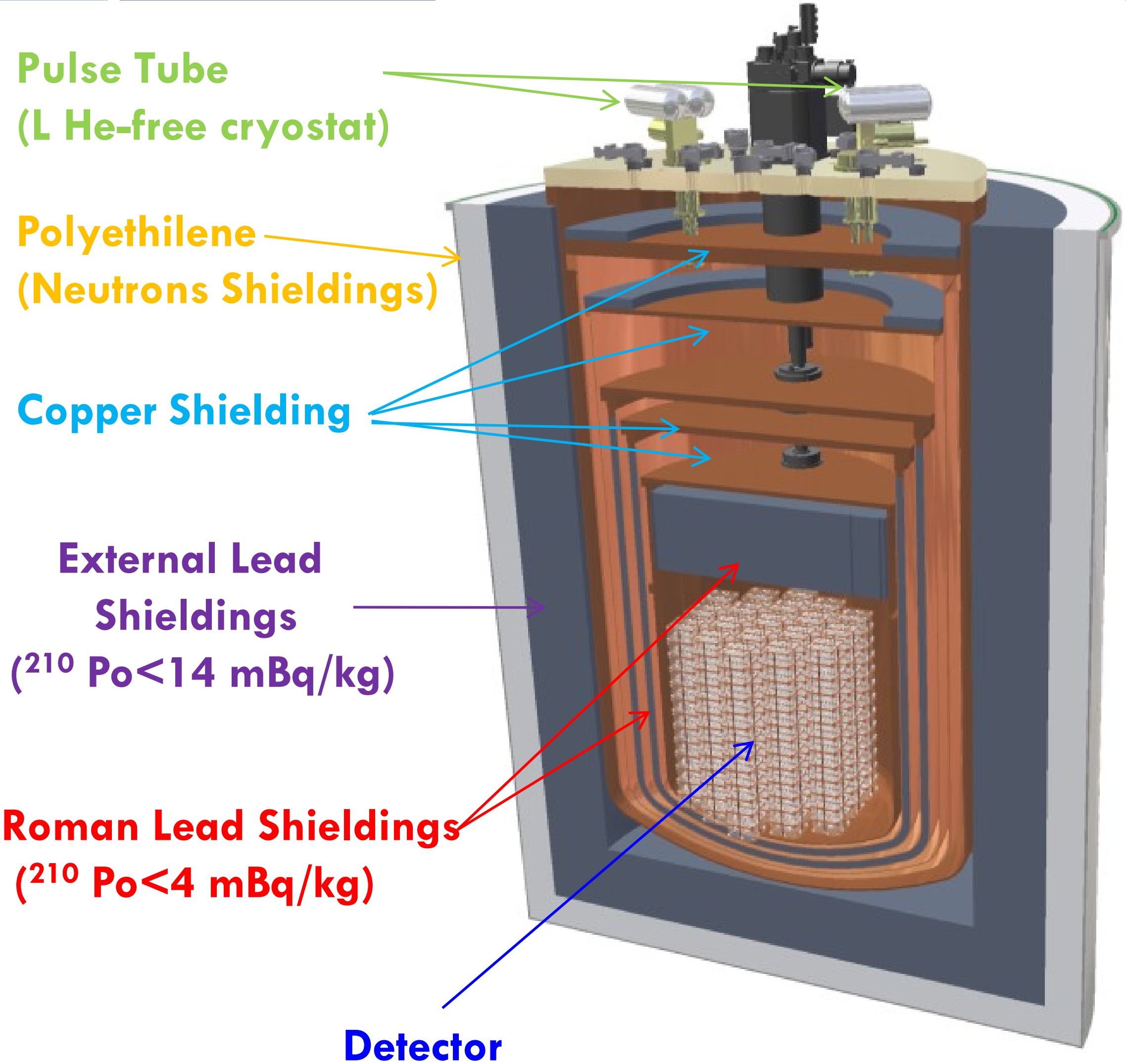
$$R(T) = R_0 \exp \sqrt{\frac{T_0}{T}}$$




A typical acquired particle signal



# CUORE (Cryogenic Underground Experiment for Rare Events)




- 988 $TeO_2$ crystals 5x5x5cm$^3$ (750g), arranged in 19 towers;
- 741 kg of $TeO_2$ -> 206 kg of $^{130}Te$
- Resolution 5 keV @ 2615 keV (FWHM)
- Background aim: 0.01-0.001 c/keV/kg/y

Main concepts:

- Stringent controls on radioactivity
- Heavy shielded (Roman lead)
- High efficiency in bkg rejection thanks to close packet geometry

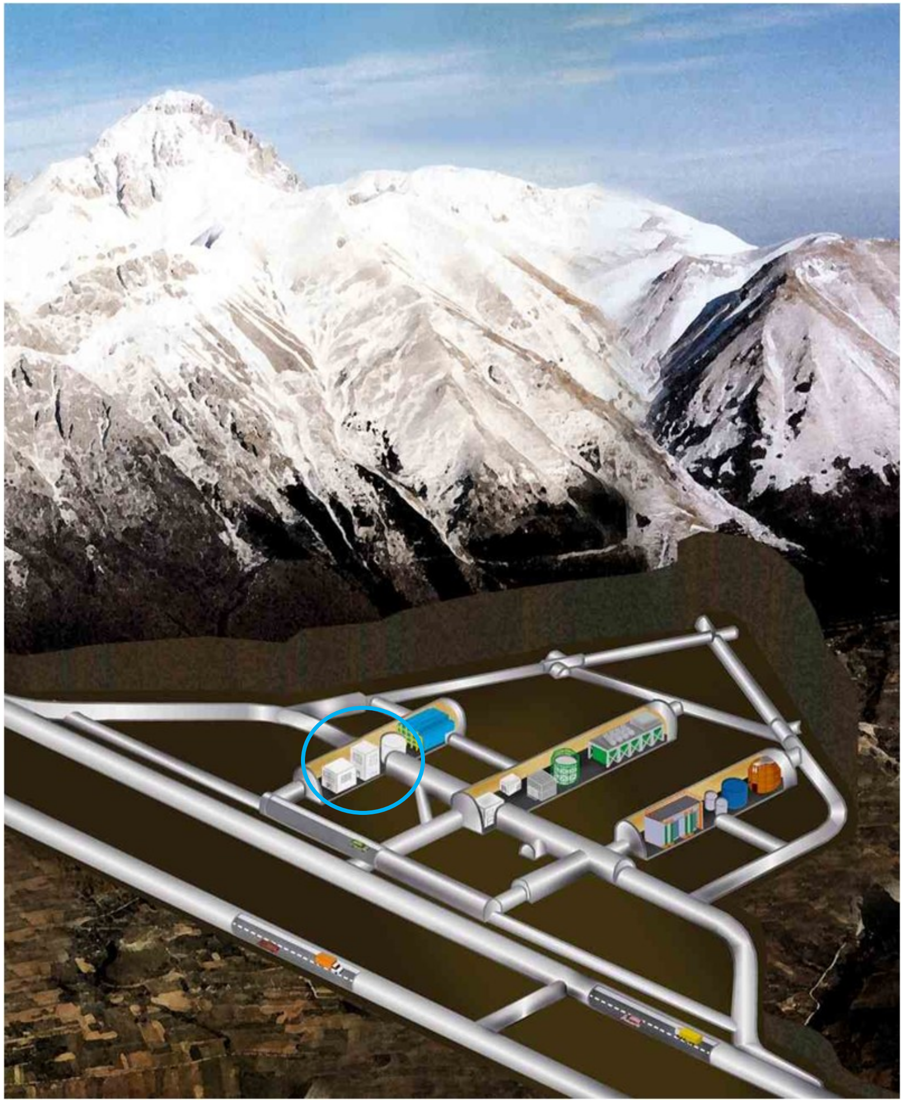
# LNGS



CUORE will be located in the Hall A of the Gran Sasso national laboratories (L'Aquila – Italy)

- Depth: 3650 m.w.e.
- Muon flux: $(2.58\pm0.3)\times10^{-8}\ \mu/s/cm^2$
- Neutron flux $\cong 4\times10^{-6}\ n/s/cm^2$
- Gamma flux: $0.73\ \gamma/s/cm^2$

Cosmic rays are not a problem!



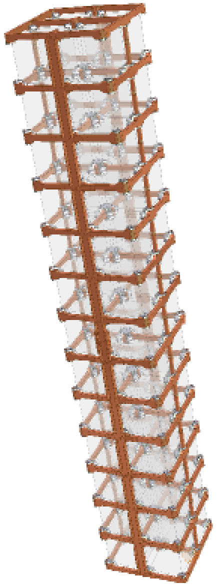
# The CUORE program



CUORICINO
2003-2008

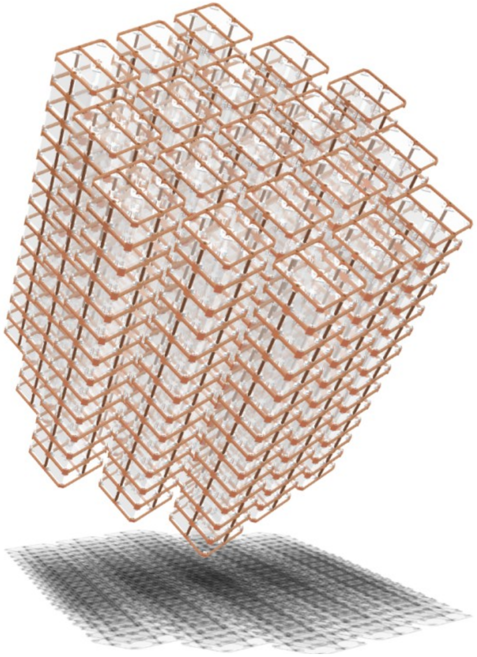
1 Tower
62 crystals
M ≅11 kg of $^{130}Te$
Bkg ≅ 0.15 c/keV/kg/yr

CUORE – 0
2011 - 2014



1 Tower
52 crystals
M≅11 kg of $^{130}Te$
Bkg 0.05 ÷ 0.1 c/keV/kg/yr

CUORE
2014-2019



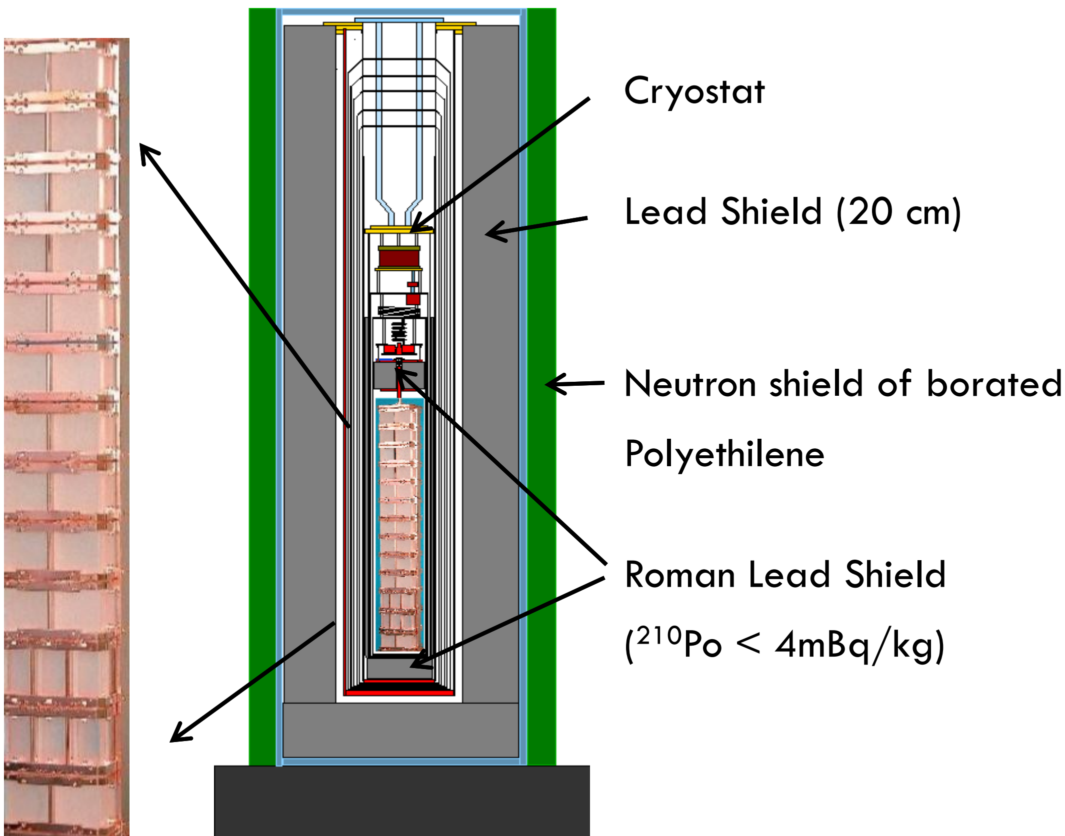
19 Tower
998 crystals
M≅ 206 kg of $^{130}Te$
Bkg 0.01 ÷ 0.001 c/keV/kg/yr

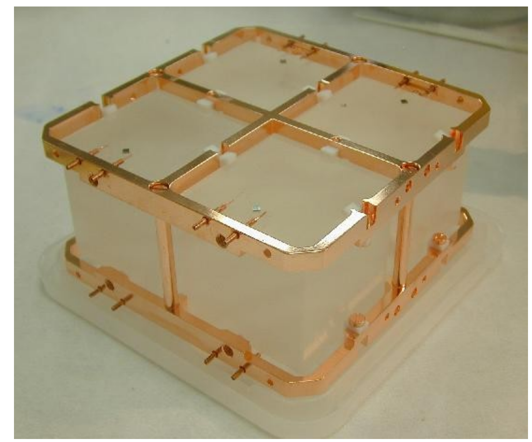
# Cuoricino: the demonstrator



$^{130}Te \rightarrow {}^{130}Xe + 2e^{-}$ $Q_{\beta\beta}^{0\nu} \sim 2527$ keV

The Cuoricino experiment (LNGS, 2003-2008) is the result of years of research on bolometers containing $^{130}Te$, by using $TeO_2$ energy absorbers



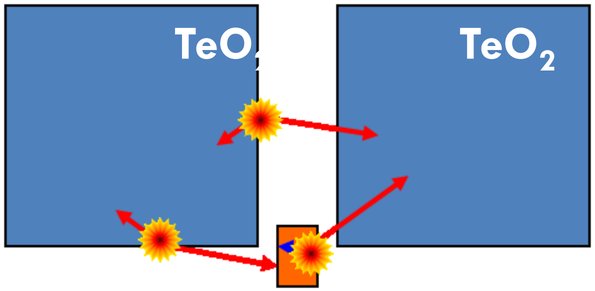



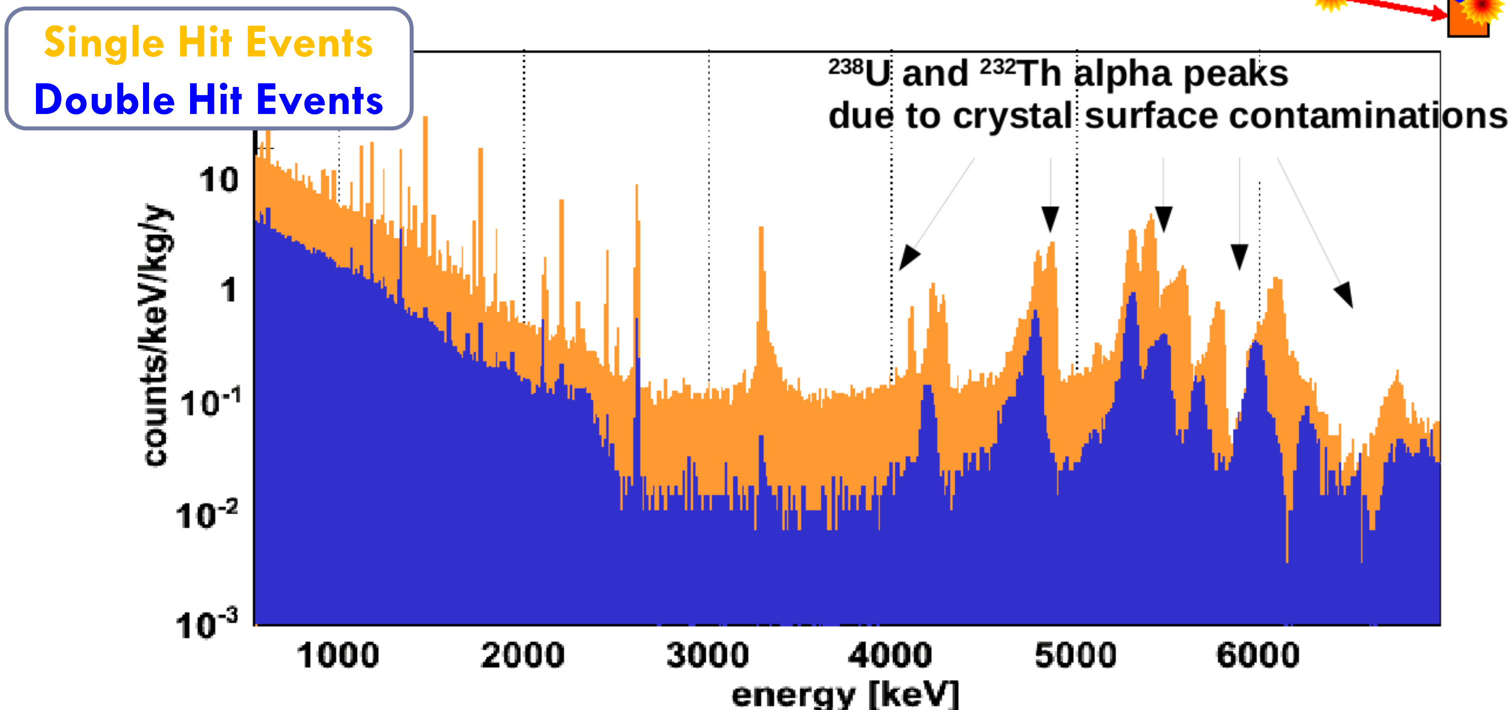
| Mass |
|---|
| 40.7 kg $TeO_2$ (11.3 kg $^{130}Te$) |
| **Total exposure** |
| 19.75 kg y [$^{130}Te$] |

# Cuoricino main operating principle

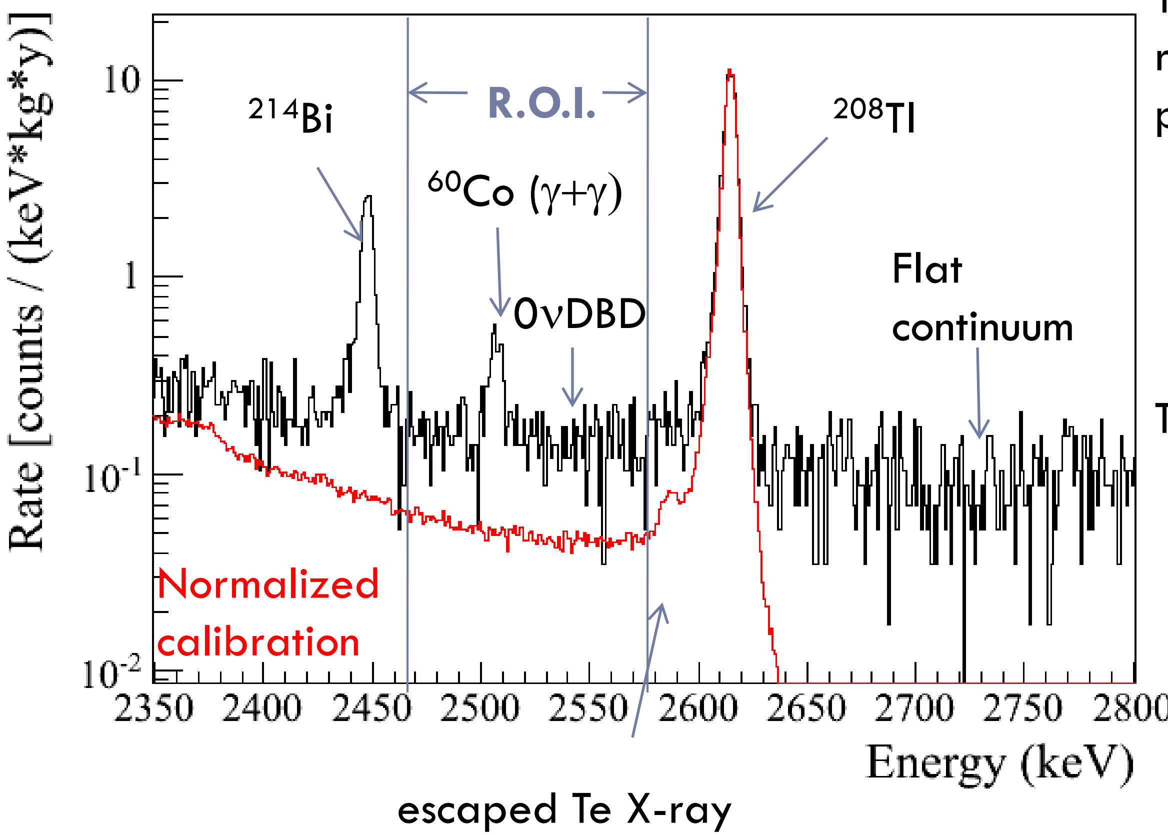


- The analysis is carried out on anti-coicinidence spectra in order to reduce:
  - Contribution from crystal surfaces
  - Compton or multi-compton events
- Accidental coincidences 0.7%
- Bkg reduction : 15%



# 0ν-DBD region of interest




The anti-coincidence spectrum in the region of interest shows three main peaks:

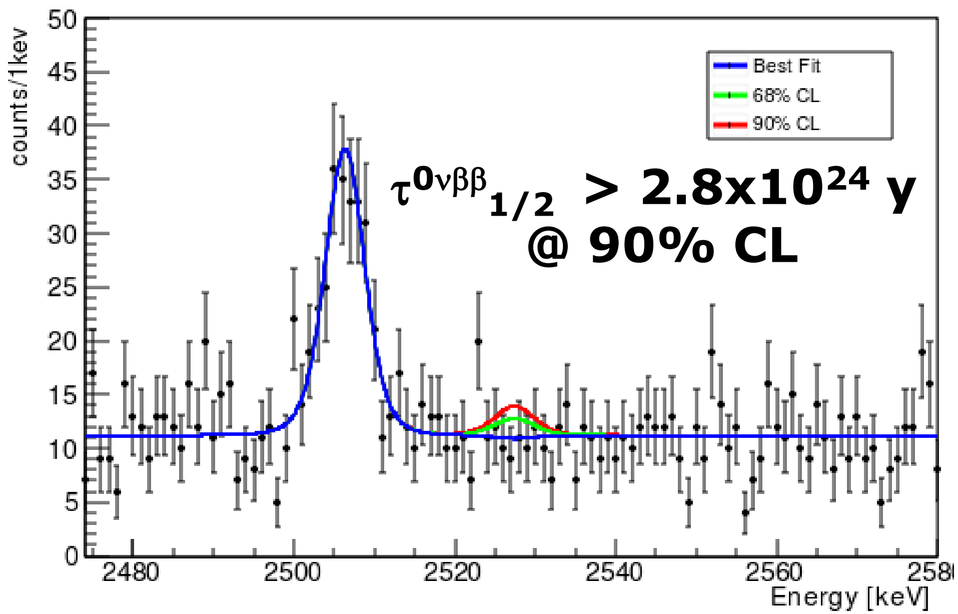
- $^{208}$Tl : (probably in the cryostat)
- $^{60}$Co: cosmogenic origin
- $^{214}$Bi: Rn contamination

The main background contributions are:

- Multicompton events of $^{208}$Tl (30%)
- Flat background coming from degraded alphas on the surface of materials facing the crystals (70%)

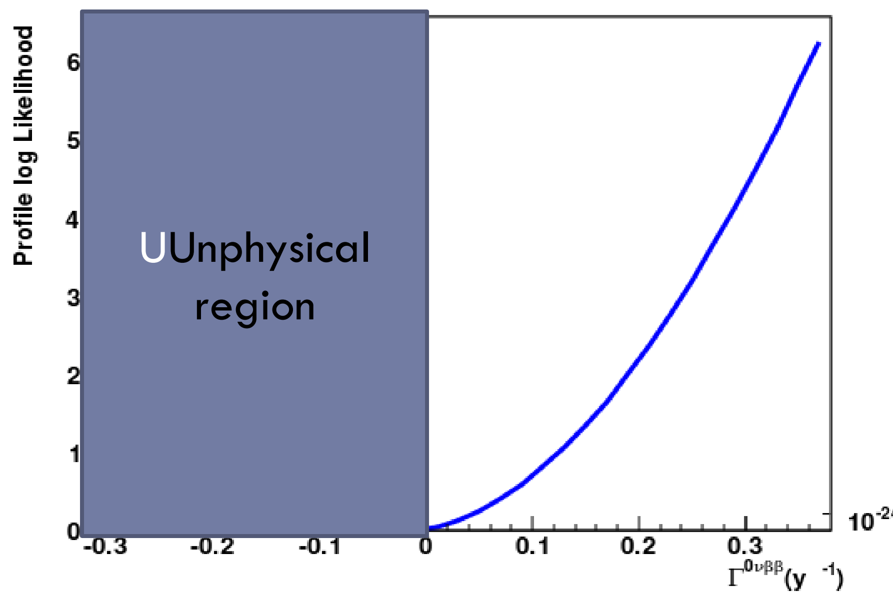
# Cuoricino Result

Astropart. Phys. (2011), doi:10.1016/j.astropartphys.2011.02.002




$m_{ee}$<300-701 meV*

$$\Gamma_{0\nu}^{best} = (-0.2 \pm 1.4(\text{stat}) \pm 0.3(\text{syst})) \times 10^{-25}\, y^{-1}$$




Method:

- Best fit: maximum likelihood-chisquare
- Limit: bayesian (flat prior on $\Gamma_{0\nu}$)

Avg Background in the region of interest:

0.169±0.006 c/keV/kg/y

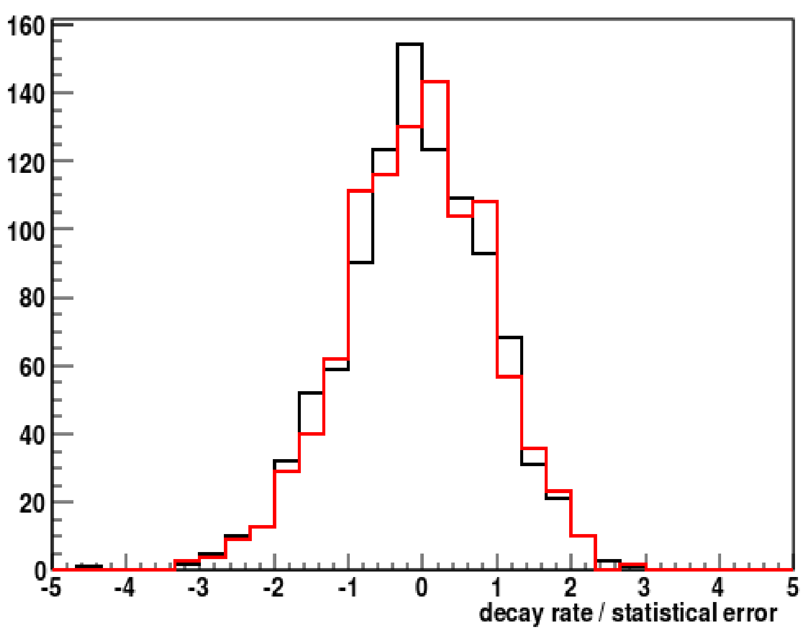
Avg resolutio: ΔE≅7 keV FWHM

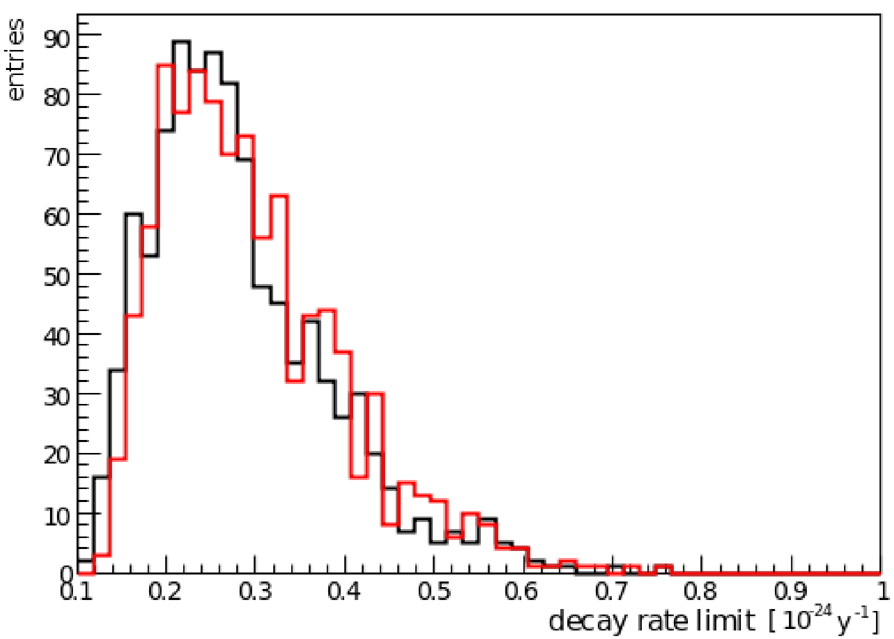
* Spread introduced by NME

# Two parallel analysis: validation on Monte Carlo



- Two indepentent analysis were carried out on data and simulation with an exeptional agreement
- Both the methods proved to be unbiased and robust.
- On the simulations (1000 Cuoricino-like experiments) they show a wide distribution of possible outcomes.
- The median outcome of these experiments corresponds to a limit on the half life of $2.6\times10^{24}$ y comparable to the experimental limit



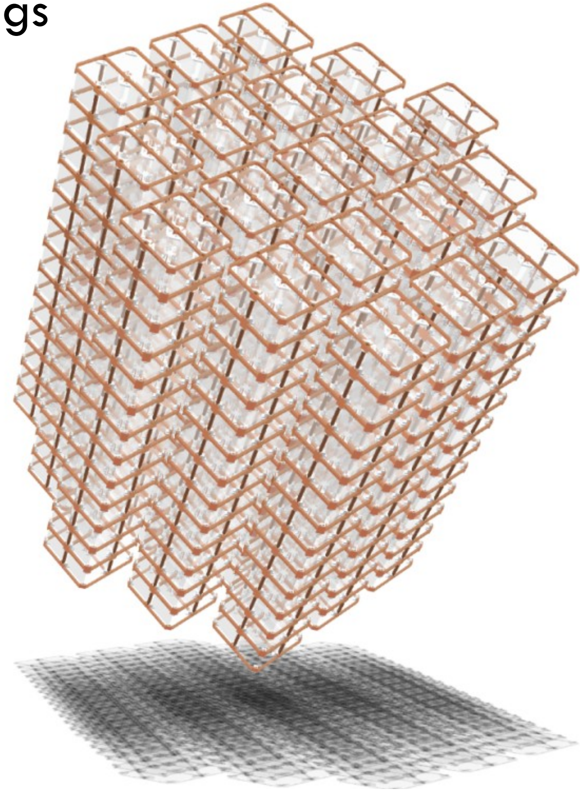



# From Cuoricino to CUORE



Challenging effort on every crucial aspects of the experiments

- Extensive study of the background sources
- Design of the experiment
- Cryostat and shieldings
- Radioactivity control
- Electronics
- DAQ
- Crystals
- Software
- Calibration system
- Tower assembly
- …



# CUORE Crystals



The 1000 CUORE crystals are produced by SICCAS (Shanghai, China):
- 560 crystals ordered by INFN (now @LNGS);
- 500 crystal ordered by DoE (91 already in @LNGS, end in Sept. 2012)

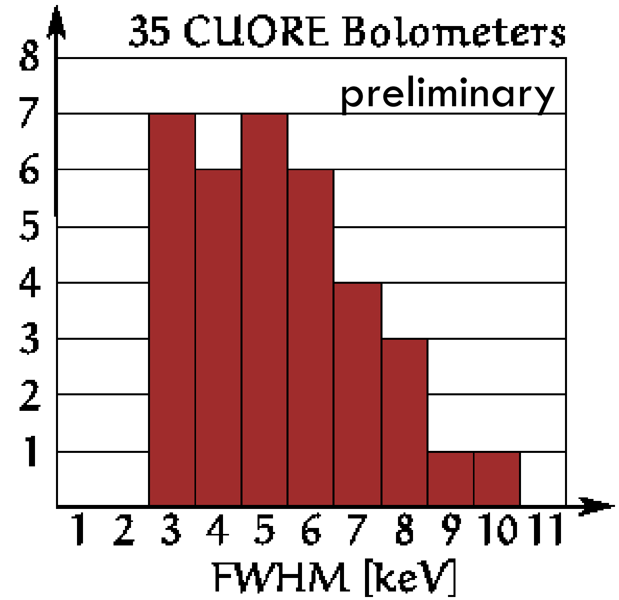
For each production batch 2 or more crystals are tested in the Hall C R&D Cryostat:
- Same single module as CUORE;
- New Data Acquisition and online as CUORE;
- All material cleaned CUORE-like;

6 CCVR measurements were analyzed (preliminary results):

Bulk: $< 6 \cdot 10{-}14$ g/g in $^{238}$U; $< 8 \cdot 10{-}14$ g/g in $^{232}$Th

Surface : $<$ nBq/cm$^2$

Resolution : avg $\Delta E = (4.9 \pm 1.9)$ keV FWHM

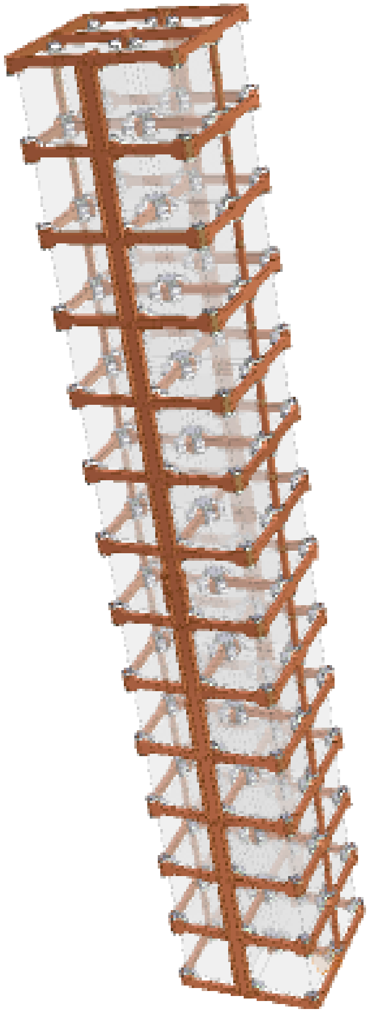



$\langle FWHM \rangle_{CCVR} = (4.9 \pm 1.9)$ keV

$\langle FWHM \rangle_{QINO} = (6.3 \pm 2.5)$ keV

Production requirements perfectly fulfilled!

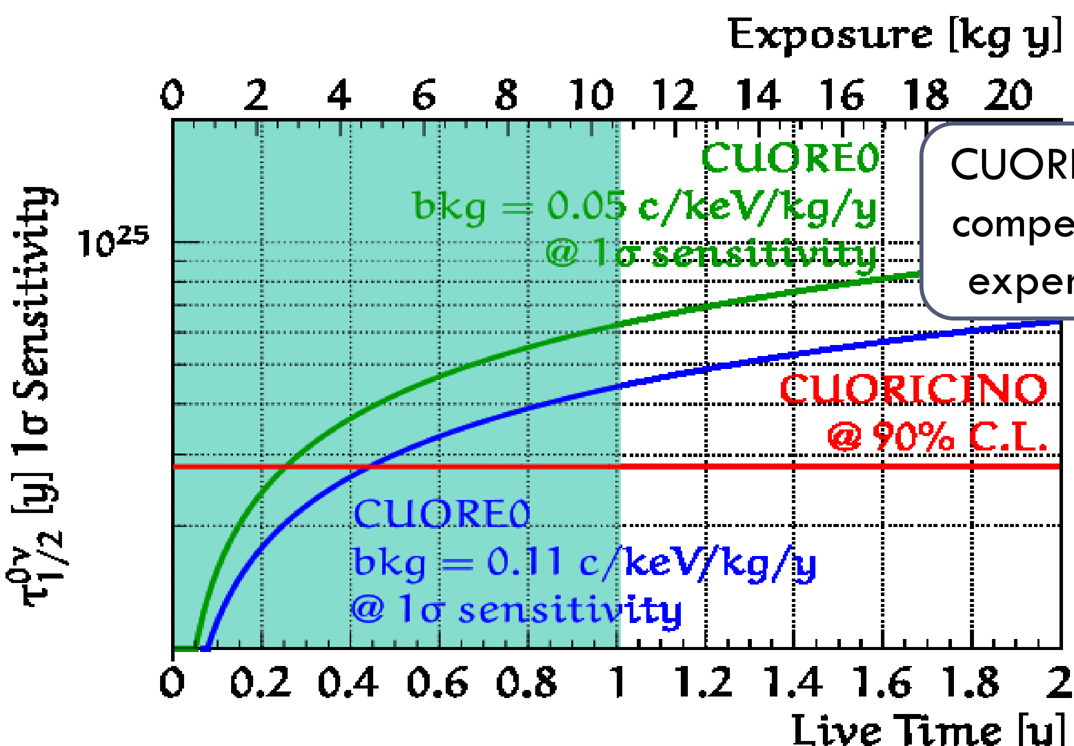
# The answer to CUORE-0



The full assembly of a CUORE-like tower: data taking starts this fall

High statistic test of the background achievements: crucial importance for surface background studies

Two irreducible background predicted (realistic and optimistic case)




CUORE-0 will be a competitive 0nDBD experiment itself!

# CUORE scientific goal

In 5 years of live time, CUORE has a 1σ sensitivity of $\tau^{DBD}_{1/2} = 2.1 \times 10^{26}$ y

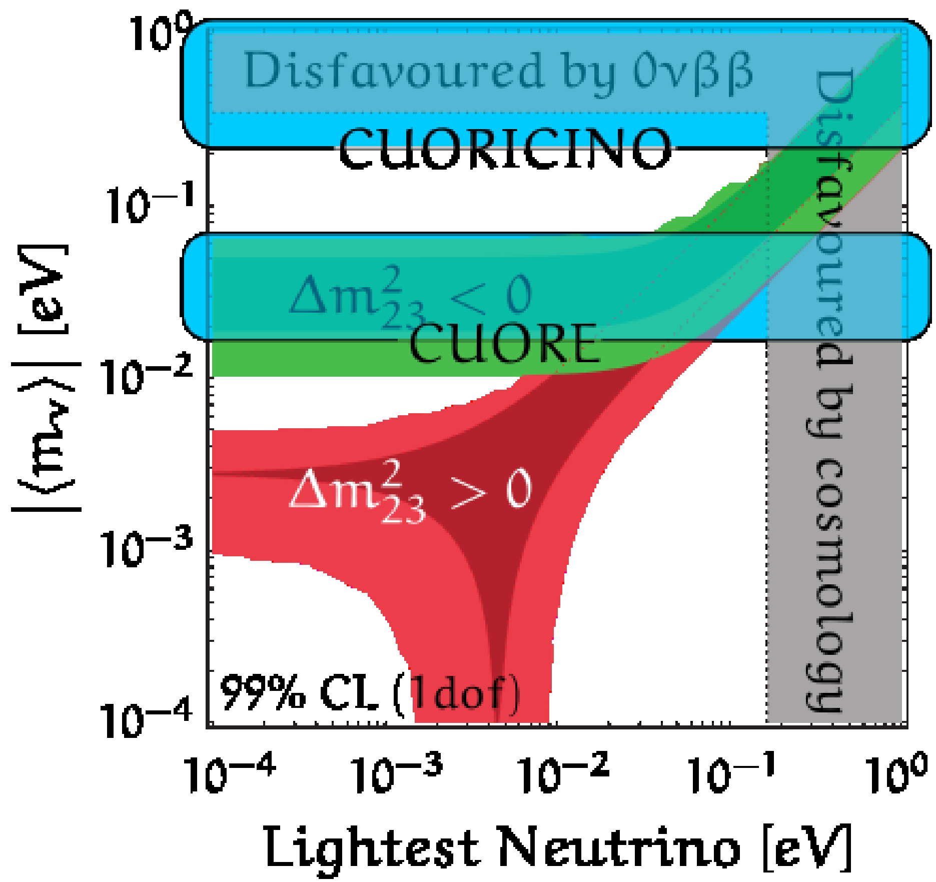
$\Rightarrow$ effective Majorana neutrino mass down to 35 ÷ 82 meV

With the foreseen aim of

0.01 c/keV/kg/y

CUORE will be able to probe

the inverted scale



# Conclusions



- $TeO_2$ bolometers proved to be a competitive tool for the DBD search
- Cuoricino proved to be not only an important experiment, but also a great prototype, showing that an experiment like CUORE is feasible
- CUORE-0 will be the first test of a CUORE-like tower from the assembly to data taking and a competitive experiment itself
- CUORE data taking is foreseen for 2014

# Conclusions



Thank you for you attention