

CUORE

Cryogenic Underground Observatory for Rare Events

Ezio Previtali*

*INFN, Sezione di Milano and
Università di Milano-Bicocca, Milano, Italia
on behalf of the CUORE collaboration*



- The CUORE project
- CUORICINO
 - structure
 - detector performance
 - results
 - background
- Perspectives for CUORE

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The CUORE Collaboration

J. Beeman¹, M.Dolinski¹, T.D. Gutierrez¹, E.E. Haller^{1,2}, R. Maruyama¹, B. Quiter¹, A.R. Smith¹ and N. Xu¹

¹Lawrence Berkeley National Laboratory

²University of California, Berkeley CA 94720, USA

A. Giuliani, M. Pedretti and S.Sangiorgio

Dipartimento di Fisica e Matematica dell'Università dell'Insubria e Sezione di Milano dell' INFN, Como I-22100, Italy

M. Barucci, E. Olivieri, L. Risegari, and G. Ventura

Dipartimento di Fisica dell' Università di Firenze e Sezione di Firenze dell' INFN, Firenze I-50125, Italy

M. Balata, C. Bucci, and S.Nisi

Laboratori Nazionali del Gran Sasso, I-67010, Assergi (L'Aquila), Italy

V. Palmieri

Laboratori Nazionali di Legnaro, Via Romea 4, I-35020 Legnaro (Padova), Italy

A. de Waard

Kamerling Onnes Laboratory, Leiden University, 2300 RAQ Leiden, Nederland

E.B. Norman

Lawrence Livermore National Laboratory, Livermore, California, 94550, USA

C. Arnaboldi, C. Brofferio, S. Capelli, F. Capozzi, L. Carbone, M.Clemenza, O. Cremonesi, E. Fiorini, C.Nones, A. Nucciotti, M. Pavan, G. Pessina, S. Pirro, E. Previtali, M. Sisti, L.Torres and L.Zanotti

Dipartimento di Fisica dell'Università di Milano-Bicocca e Sezione di Milano dell'INFN, Milano I-20126, Italy

R. Ardito, G. Maier

Dipartimento di Ingegneria Strutturale del Politecnico di Milano, Milano I-20133, Italy

E.Guardincerri, P. Ottonello and M.Pallavicini

Dipartimento di Fisica dell'Universita' di Genova e Sezione di Genova dell'INFN, Genova I-16146, Italy

D.R. Artusa, F.T. Avignone III, I. Bandac, R.J. Creswick, H.A. Farach, and C. Rosenfeld

Department of Physics and Astronomy, University of South Carolina, Columbia S.C. 29208 USA

S. Cebrian, P. Gorla, I.G. Irastorza

Lab. of Nucl. and High Energy Physics, University of Zaragoza, 50009 Zaragoza, Spain

F.Bellini, C.Cosmelli, I.Dafinei, M.Diemoz, F.Ferroni, C.Gargiulo, E.Longo, S. Morganti

Dipartimento di Fisica dell'Universita' di Roma e Sezione di Roma 1 dell'INFN, Roma I-16146, Italy

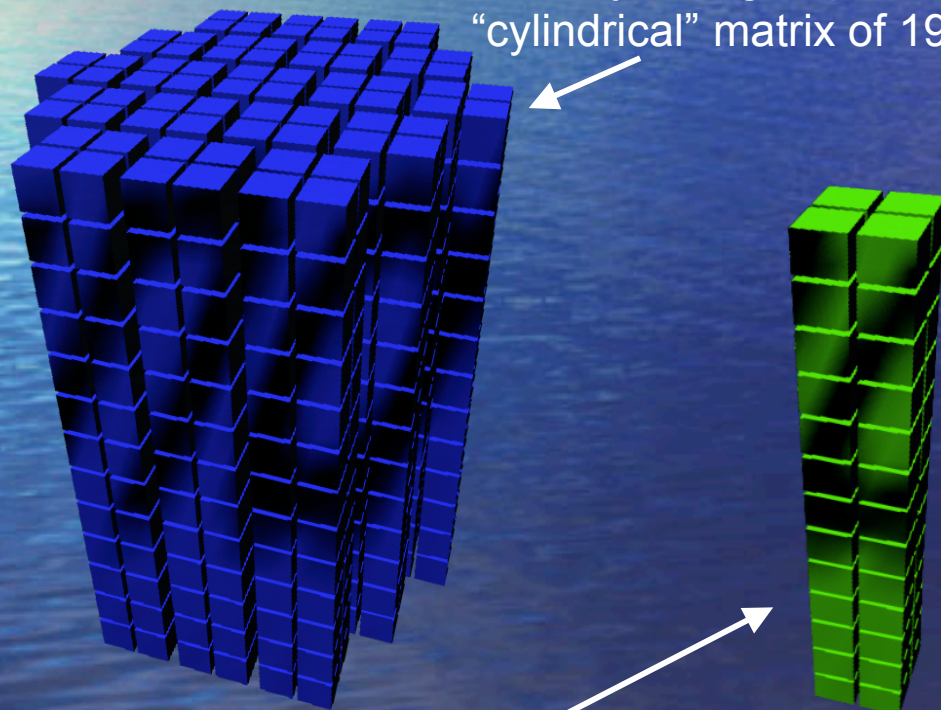
The CUORE project

Cryogenic Underground Observatory for Rare Events

- array of 988 TeO₂ crystals 5×5×5 cm³ (750 g)
 - 741 kg TeO₂ granular calorimeter
 - 600 kg Te = 203 kg ¹³⁰Te
- $\beta\beta 0\nu$, Cold Dark Matter, Axions searches

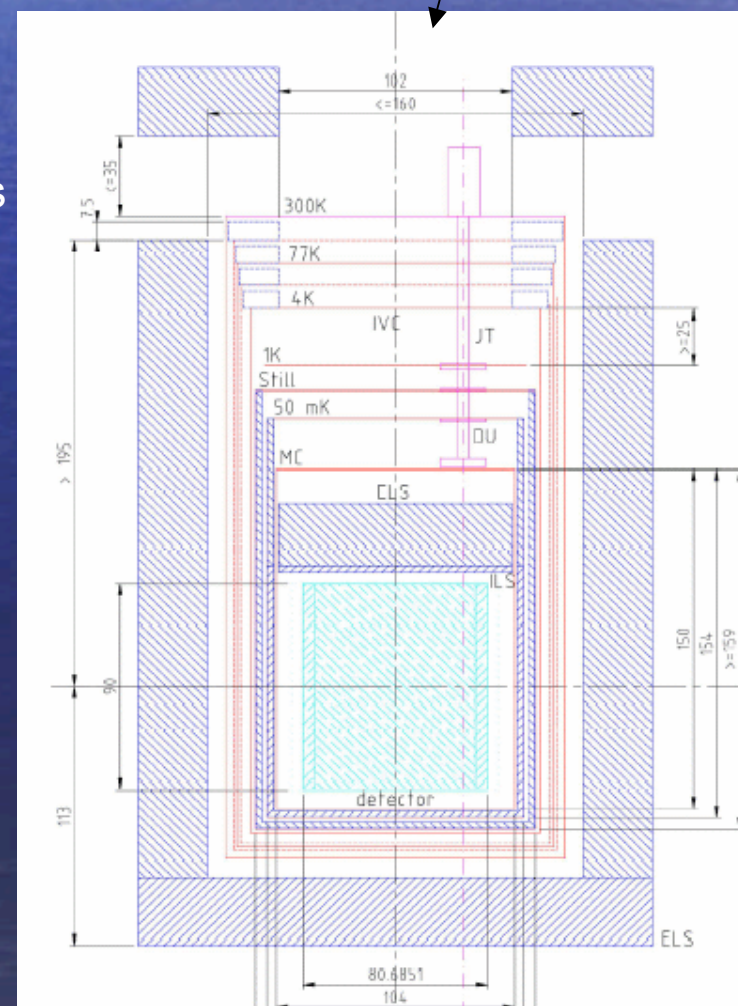
SINGLE HIGH GRANULARITY DETECTOR

Crystals grouped in a
“cylindrical” matrix of 19 towers

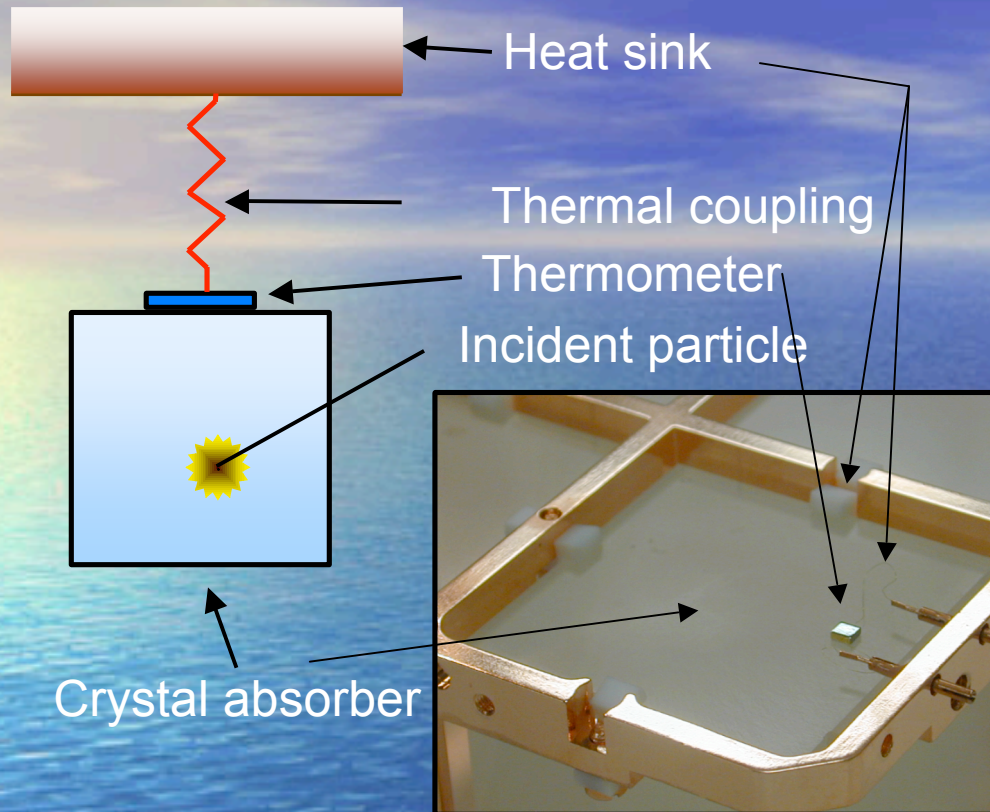


Single tower:
thirteen (4 crystal) modules

single dilution
refrigerator (~ 10 mK)



Low Temperature Detectors (LTD)



Detection Principle

$$\Delta T = E/C$$

C: thermal capacity

⇒ low C

⇒ low T (i.e. $T \ll 1\text{K}$)

⇒ dielectrics, superconductors

ultimate limit to E resolution:

statistical fluctuation of internal energy U

$$\Delta U^2 = k_B T^2 C$$

Thermal Detectors Properties

- ▲ good energy resolution
- ▲ wide choice of absorber materials
- ▲ true calorimeters
- ▼ slow $\tau = C/G \sim 1 \div 10^3$ ms

example: 750 g of TeO_2 @ 10 mK

$$C \sim T^3 \text{ (Debye)} \Rightarrow C \sim 2 \times 10^{-9} \text{ J/K}$$

$$1 \text{ MeV } \gamma\text{-ray} \Rightarrow \Delta T \sim 80 \text{ } \mu\text{K}$$

$$\Rightarrow \Delta U \sim 10 \text{ eV}$$

TeO₂ LTD's

Calorimeters

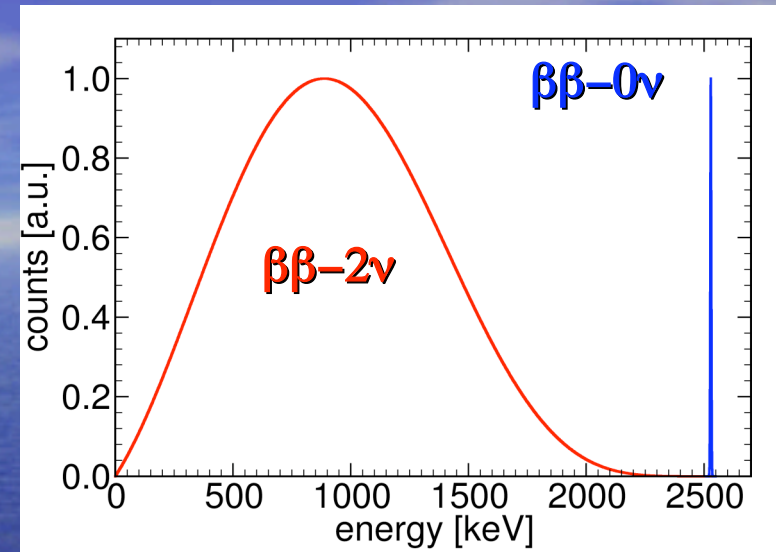
- source = detector
 - ▲ large N_{nuclei}
 - ▲ high energy resolution E
 - ▲ high efficiency

▪ measure $E = E_{e1} + E_{e2}$

▪ signature: a peak at $Q_{\beta\beta}$

TeO₂ thermal calorimeters

- Active isotope ^{130}Te
 - ▲ natural abundance: a.i. = 33.9%
 - ▲ transition energy: $Q_{\beta\beta} = 2529 \text{ keV}$
 - ▲ encouraging predicted half life $m_\nu \approx 0.3 \text{ eV}$ $\tau_{1/2}^{0\nu} = 10^{25} \text{ years}$
- Absorber material TeO₂
 - ▲ low heat capacity
 - ▲ large crystals available
 - ▲ radiopure



$\tau_{1/2}^{0\nu}$ sensitivity

measuring time [y]

detector mass [kg]

detector efficiency

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

isotopic abundance
atomic number

energy resolution [keV]

background [c/keV/y/kg]

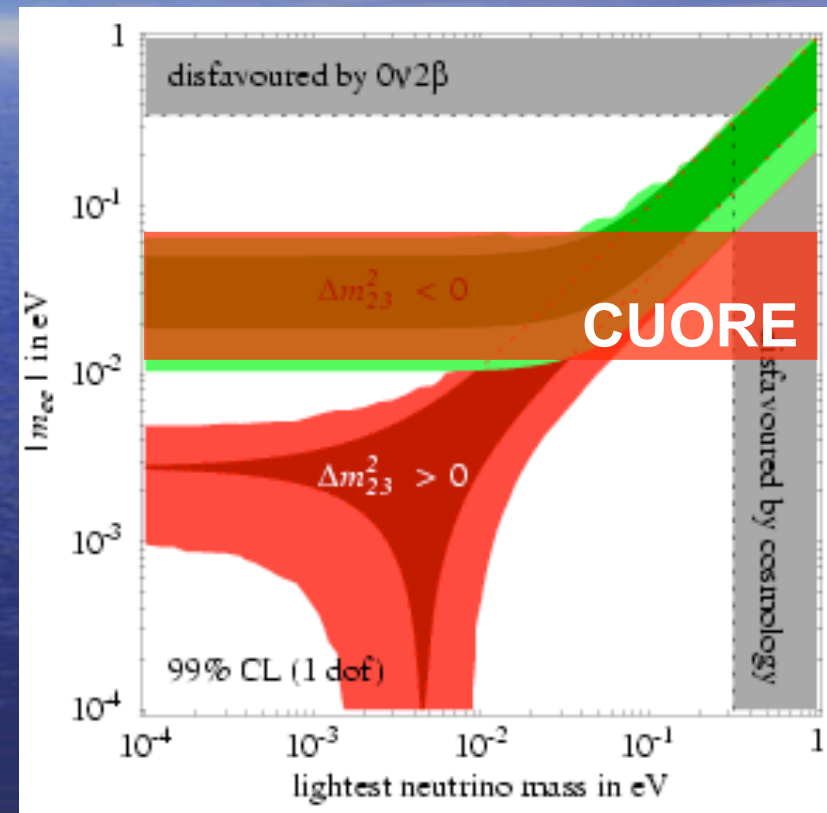
CUORE expected sensitivity

CUORE sensitivity will depend strongly on the background level and detector performance.

In *five years*:

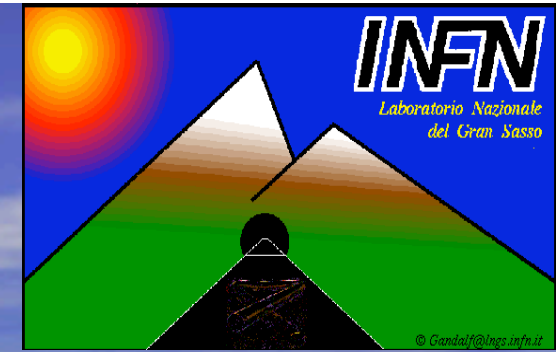
B(counts/keV/kg/y)	Δ (keV)	$T_{1/2}$ (y)	$ \langle m_\nu \rangle $ (meV)
0.01	10	1.5×10^{26}	23–118
0.01	5	2.1×10^{26}	19–100
0.001	10	4.6×10^{26}	13–67
0.001	5	6.5×10^{26}	11–57

A.Strumia and F.Vissani.: hep-ph/0503246



Spread in $|m_\nu|$ from nuclear matrix element uncertainty

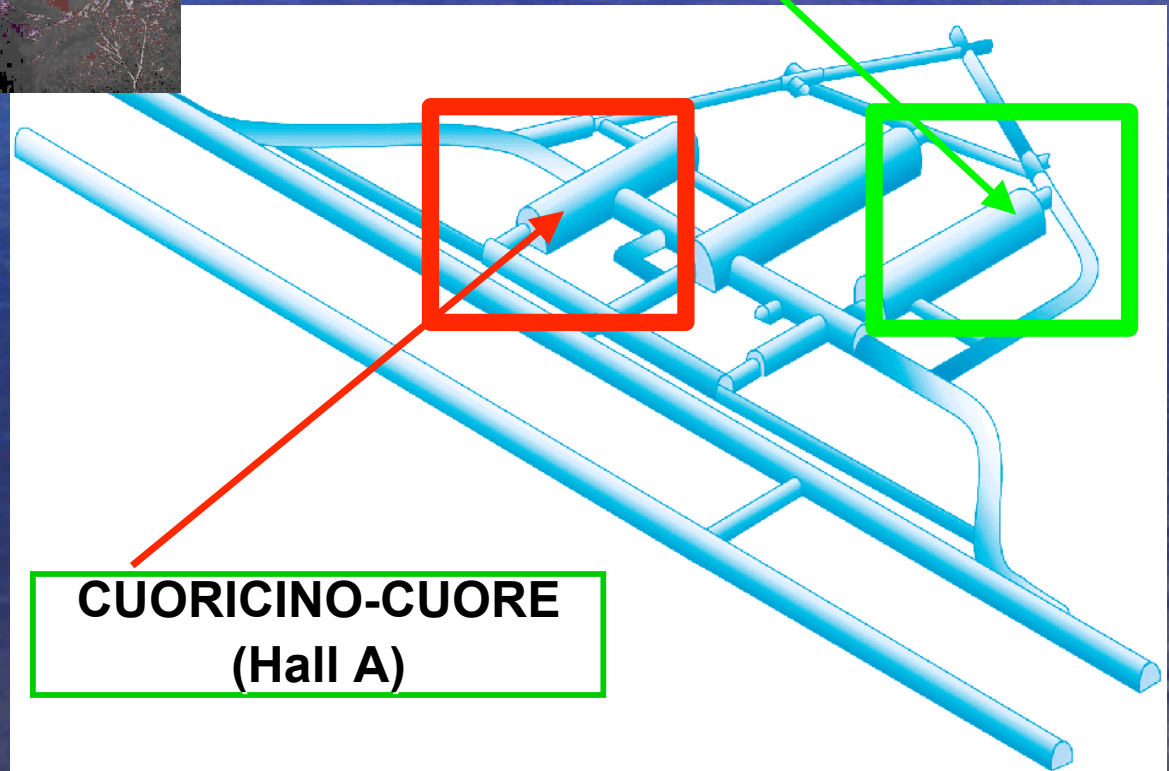
LNGS Underground Facilities



Underground National Laboratory
of Gran Sasso
L'Aquila – ITALY
3650 m.w.e.

CUORE R&D (Hall C)

**CUORICINO-CUORE
(Hall A)**



CUORICINO detector

Slightly modified single CUORE tower

test:

- large mass TeO_2 detectors
- tower-like structure of CUORE sub-elements
- background origin and reduction techniques

independent experiment:

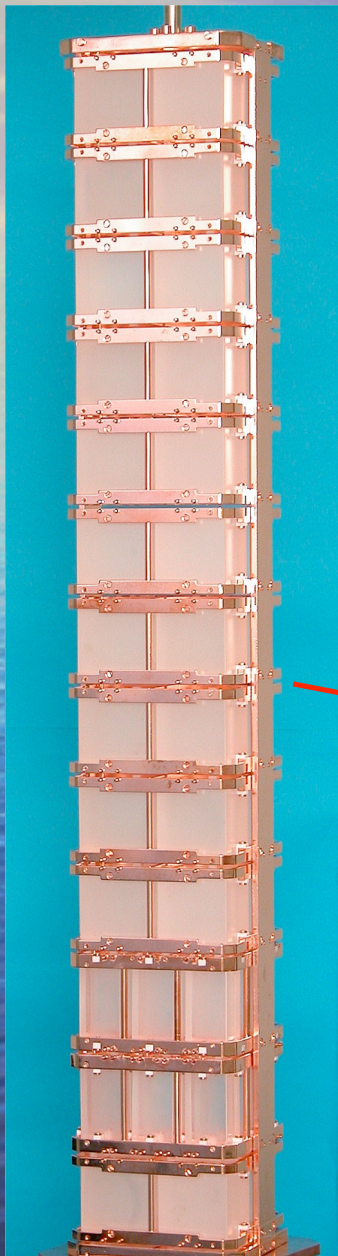
important results on

- WIMP Dark Matter
- ^{130}Te Neutrinoless Double Beta Decay

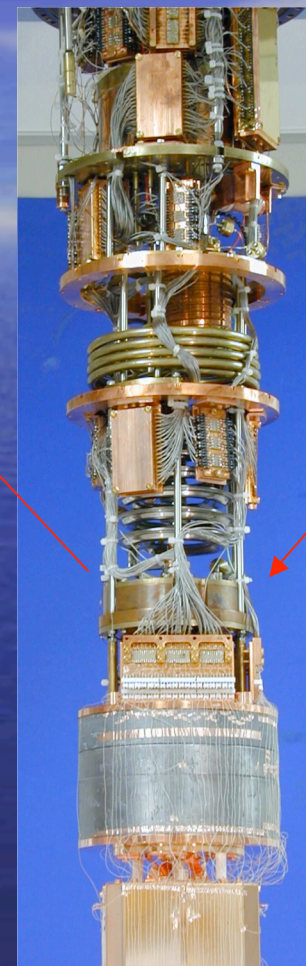
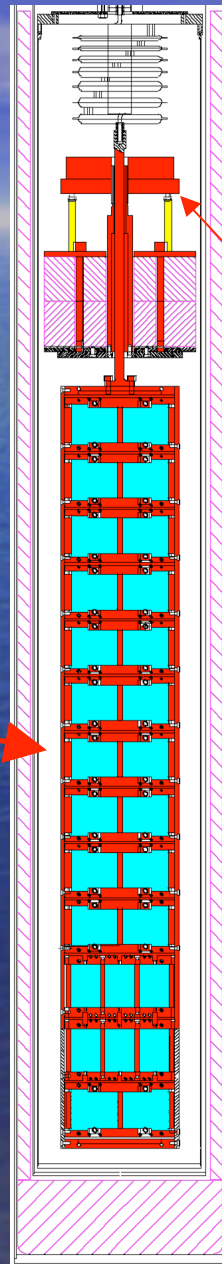
Laboratori Nazionali del Gran Sasso, Hall A
same cryostat which hosted Mi-DBD 20 crystal array

CUORICINO tower

Cuoricino tower: 62 TeO₂ crystals



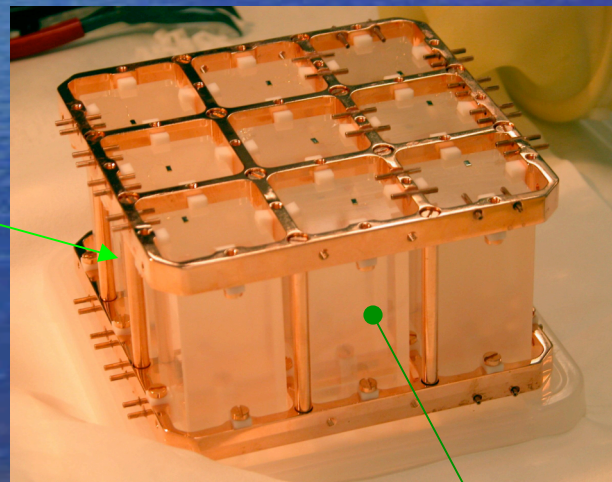
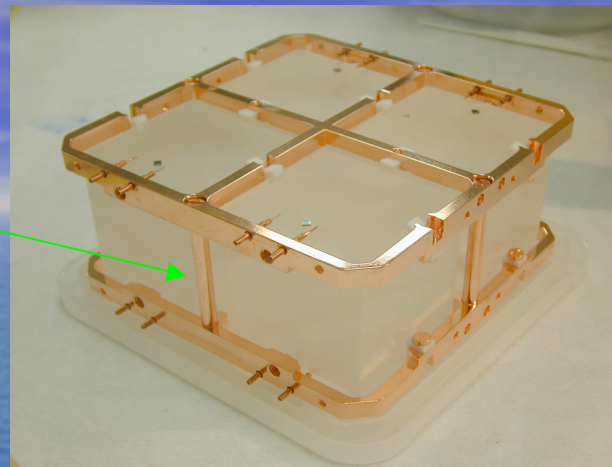
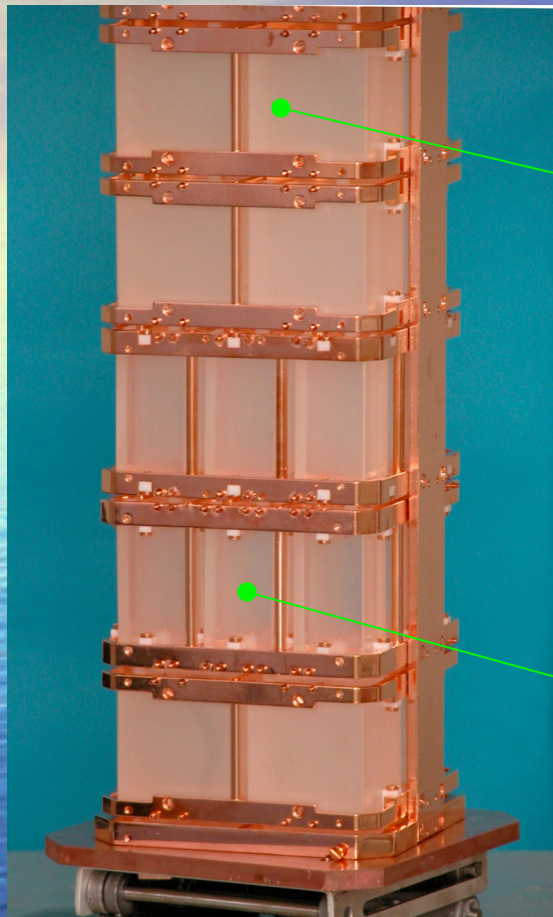
~85 cm



mixing chamber
 $T \approx 6$ mK

roman Pb shielding (1 cm lateral)
external shields:
❖ 10 cm Pb + 10 cm low act Pb
❖ neutron shield: B-polyethylene
❖ nitrogen flushed anti-radon box

CUORICINO tower (2)



- 11 modules with 4 *big* detectors
 - 44 TeO_2 crystals
 - $5 \times 5 \times 5 \text{ cm}^3 \Rightarrow 790 \text{ g}$
 - $\text{TeO}_2 \text{ mass} \Rightarrow 34.76 \text{ kg}$

Total number of detectors: 62

- 2 modules with 9 *small* detectors
 - 18 TeO_2 crystals
 - $3 \times 3 \times 6 \text{ cm}^3 \Rightarrow 330 \text{ g}$
 - $\text{TeO}_2 \text{ mass} \Rightarrow 5.94 \text{ kg}$
- 4 crystals are enriched
 - $2 \times {}^{130}\text{TeO}_2 + 2 \times {}^{128}\text{TeO}_2$

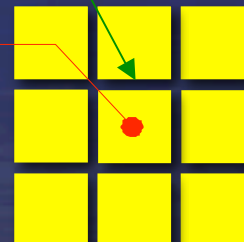
total active mass

$\text{TeO}_2 \rightarrow 40.7 \text{ kg}$

${}^{130}\text{Te} \rightarrow 11.2 \text{ kg}$

${}^{128}\text{Te} \rightarrow 10.3 \text{ kg}$

central crystal has a 4π *active shielding*
like in CUORE configuration
for anti-coincidence *background reduction*



CUORICINO data taking

February 2003 - April 2005

RUN I

Cooling down: **February 2003**

Detectors: some electrical connection lost
during tower cooldown

- **30** 790g detectors
- **16** 330g detectors
 - ▷ $\text{TeO}_2 \rightarrow 29 \text{ kg}$
 - ▷ $^{130}\text{Te} \rightarrow 7.98 \text{ kg}$
 - ▷ $^{128}\text{Te} \rightarrow 7.36 \text{ kg}$

- **40** 790g detectors
- **18** 330g detectors
 - ▷ $\text{TeO}_2 \rightarrow 37.5 \text{ kg}$
 - ▷ $^{130}\text{Te} \rightarrow 10.3 \text{ kg}$
 - ▷ $^{128}\text{Te} \rightarrow 9.53 \text{ kg}$

RUN II

Cooling down: **May 2004**

Detectors: two unrecovered detectors and two
with excess noise

CUORICINO DUTY CYCLE

Source calibration: Th wire ~ 3 days

Background measurement: 3-4 weeks

DBD (background) live time ~ 64%

Calibration spectra: energy resolution

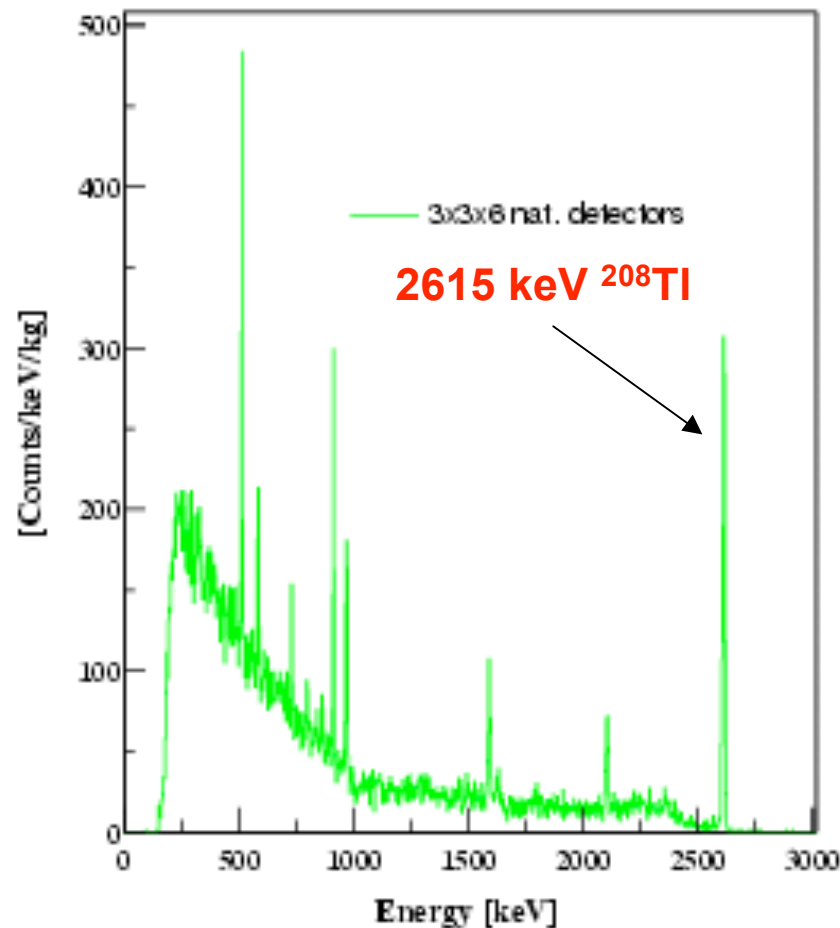
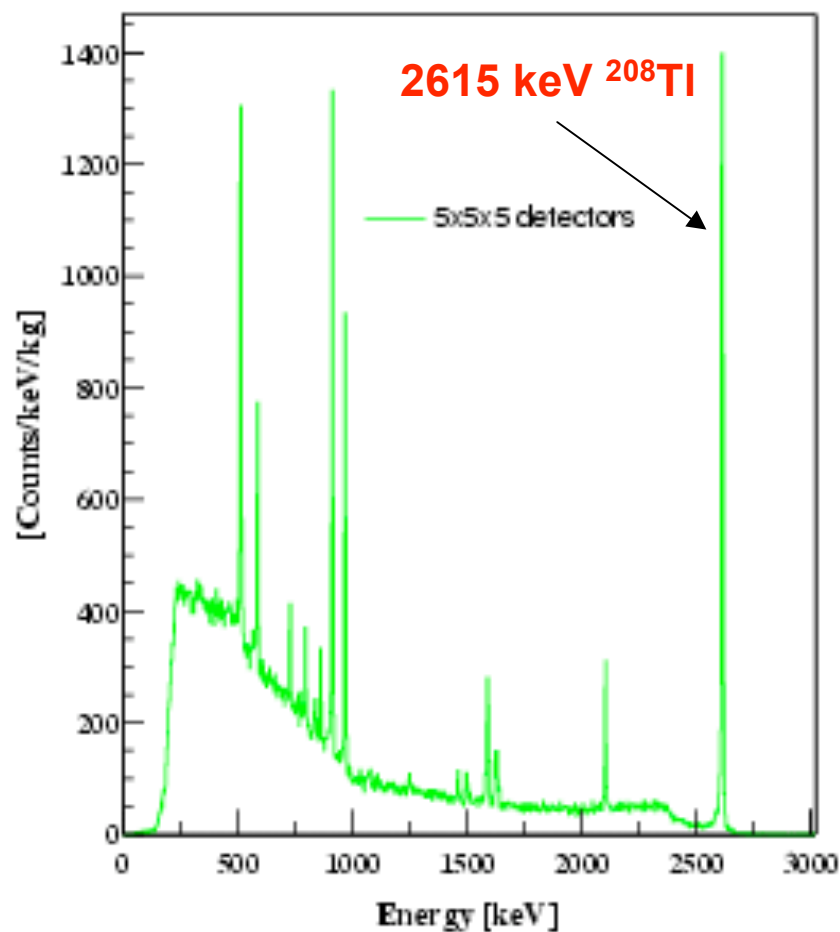
^{232}Th (and ^{238}U) γ -sources

► External to the cryostat in contact with OVC

ΔE ! @ 2615 keV

790 g crystals $\sim 7.5 \pm 2.9$ keV

330 g crystals $\sim 9.6 \pm 2.5$ keV



Detector performance: background

ΔE ! @ 2615 keV in the sum bkg spectra of:

5x5x5 cm³ cryst.

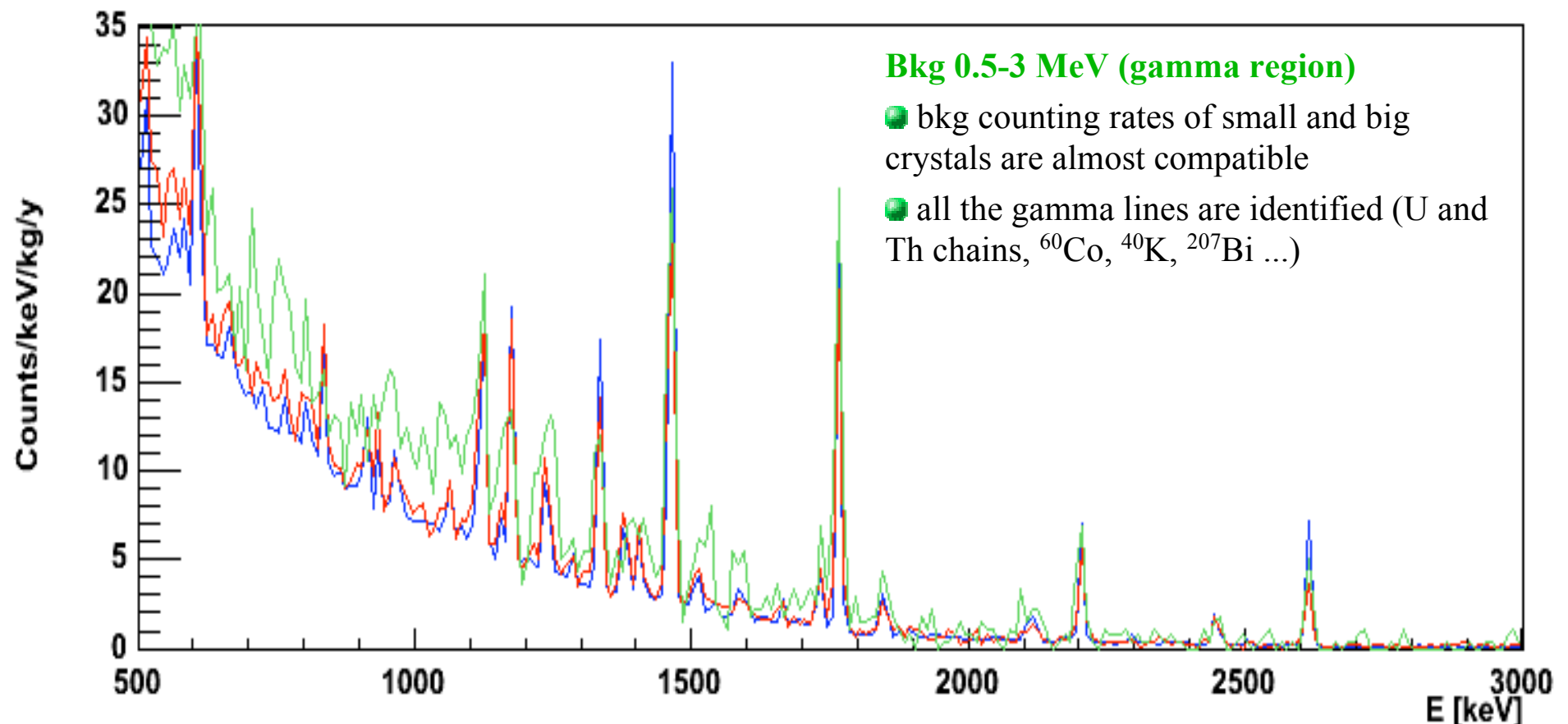
3x3x6 cm³ nat. cryst.

3x3x6 cm³ enrich. cryst.

4.3 kg ¹³⁰Te * γ - FWHM ~ 7.5 keV

0.5 kg ¹³⁰Te * γ - FWHM ~ 12 keV

0.2 kg ¹³⁰Te * γ - peak not visible



Neutrinoless DBD results

statistics:

- antineutrino spectrum

detector efficiencies: 86.4% (790g) and 84.5% (330g)

- run I + run II (3 April 2005) = 5 kg ^{130}Te x year
- No peak is observed at the $0\nu\text{DBD}$ transition energy (2528.8 keV)
- Bkg counting rate in the $0\nu\text{DBD}$ region = 0.18 ± 0.02 c/keV/kg/y

procedure:

- Maximum Likelihood + flat background + fit of the 2505 keV peak
- energy region = 2470 - 2560 keV
- response function = sum of N gaussian each with the characteristic FWHM resolution at 2615 keV of the n^{th} detector

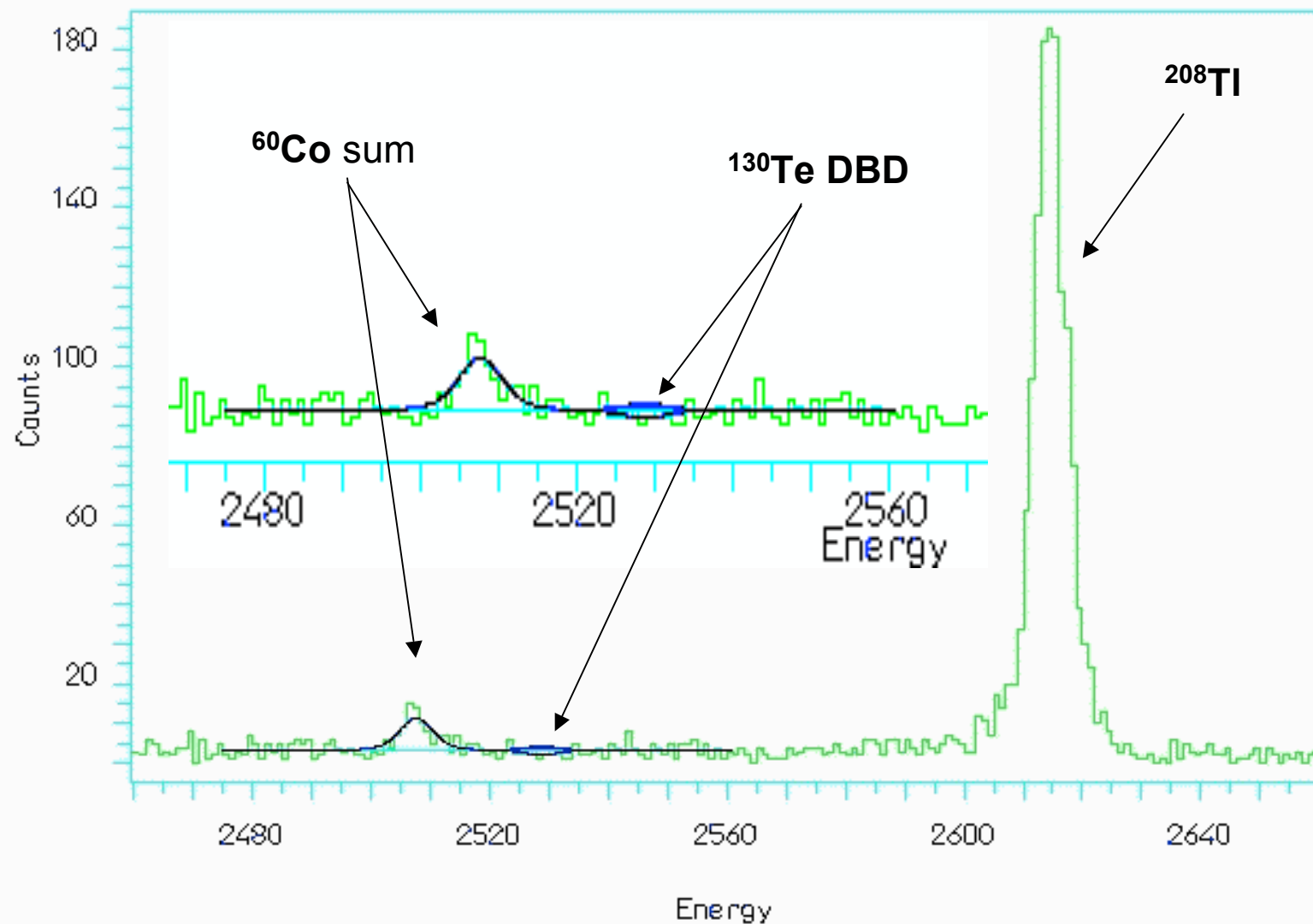
result:

$$t_{1/2} > 1.8 \cdot 10^{24} \text{ y at 90\% C.L. } (<m_\nu> < [0.2 \div 1.1] \text{ eV})$$

→ best fit yields a negative effect ...

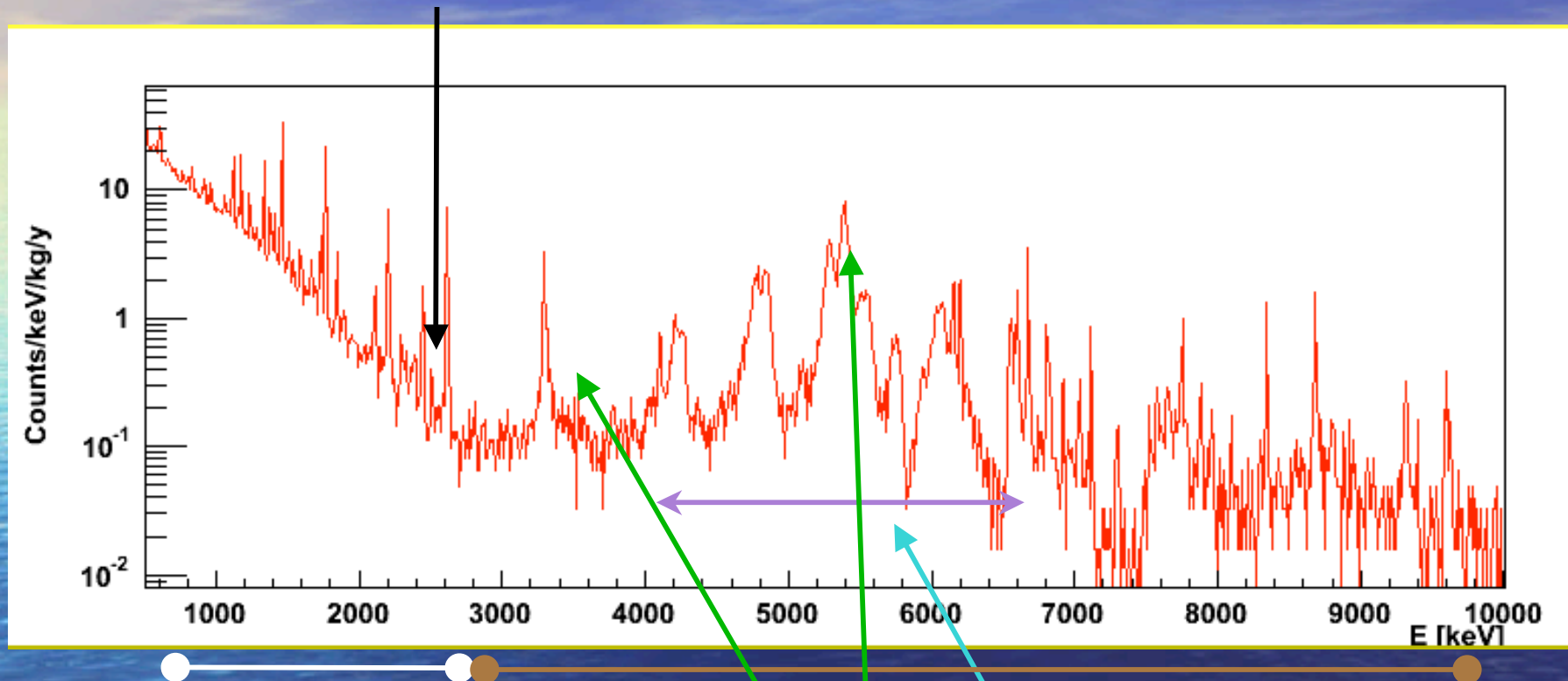
→ ~5% variation of the limit when changing the energy region, the bkg shape (linear or flat) and when including/excluding the 2615 keV peak

Neutrinoless DBD results



CUORICINO: background spectrum

0_vDBD



Gamma region, dominated by
gamma and beta events,
highest gamma line = 2615
keV ²⁰⁸Tl line (from ²³²Th chain)

Alpha region, dominated by alpha peaks
(**internal** or **surface** contaminations)

Background model

Background sources

- ▶ bulk contaminations of setup materials
- ▶ cosmic rays
- ▶ Neutrons
- ▶ surface contaminations ($e^{-\lambda x}$) of detector elements

Experimental measurements

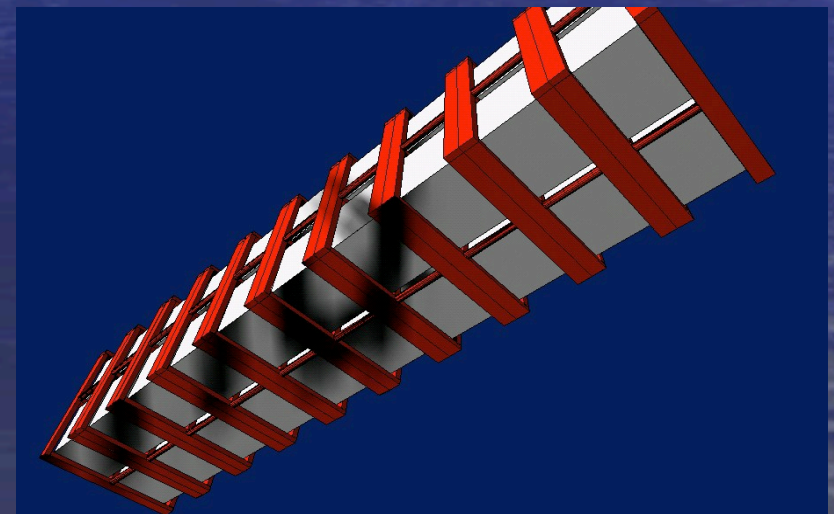
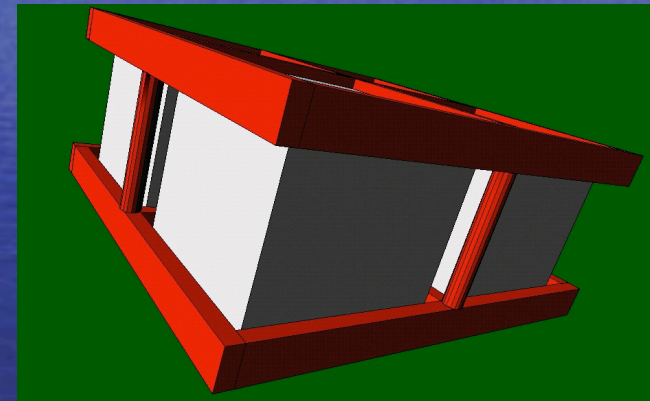
- ▶ MiDBD I+II
- ▶ CUORICINO

Monte Carlo simulations

- ▶ GEANT4 (+decay chains generator)
- ▶ FLUKA
- ▶ YIELDX

detailed description of

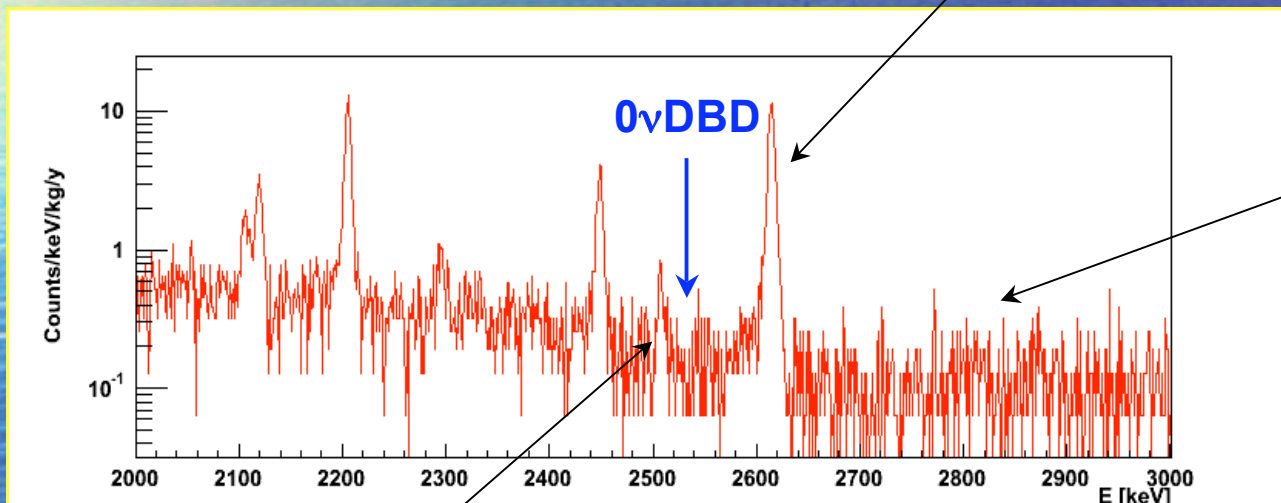
- ▶ Detector
- ▶ Cryogenic setup
- ▶ Radiation shields



CUORICINO background

2615 keV Tl line $\Rightarrow$ contribution to the DBD bkg due to a **Th** contamination.

- **Most probable location:** in between the inner Roman lead shield and the external lead shield (clear indications from the intensity ratios of Th gamma lines at different energies).
- **Measured bkg shape:** good agreement with MonteCarlo simulations and source calibration measurement (Th wire inserted just outside the cryostat OVC).
- **Th(Tl) contribution to DBD background: $\sim 40\%$ (preliminary)**



No other gamma lines identified near or above the $0\nu\text{DBD}$ transition energy $\Rightarrow$ no contributions from other gamma sources.

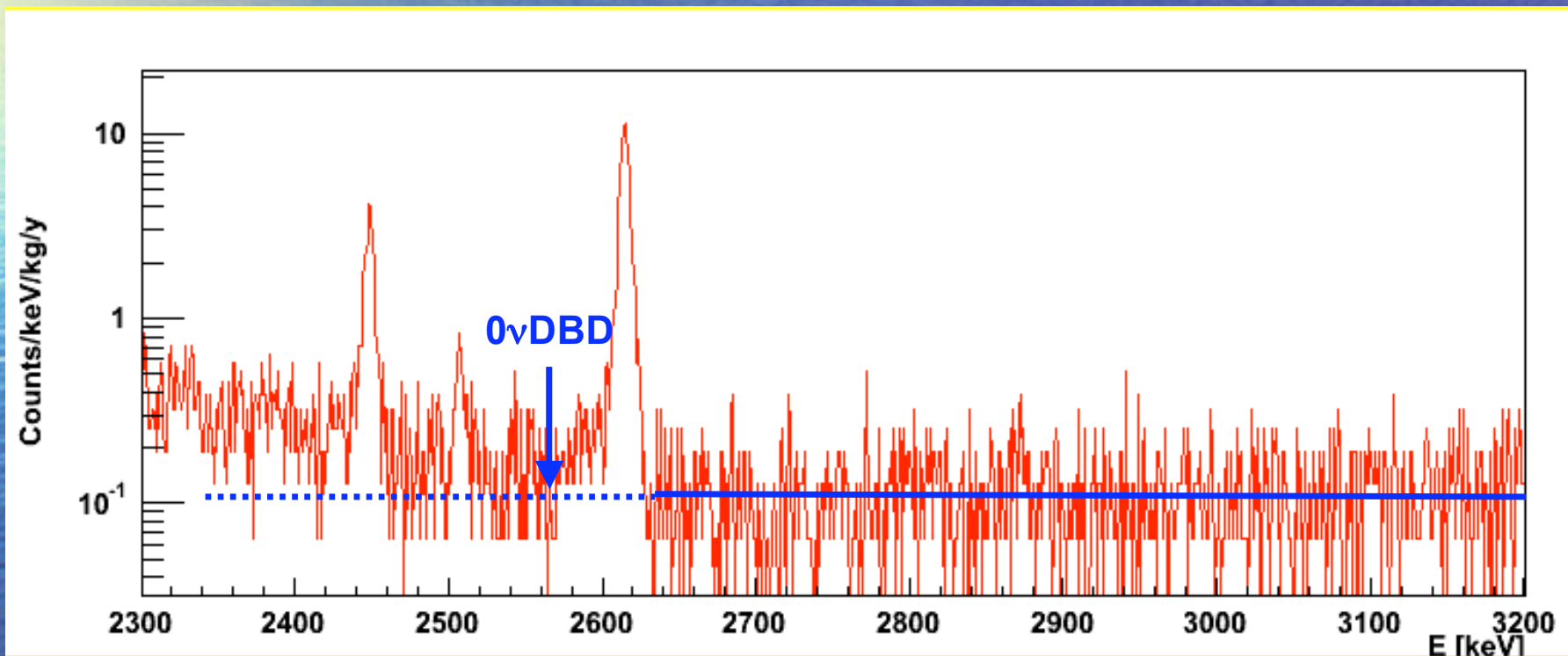
2505 keV line: sum of the 2 ^{60}Co gammas (1173 and 1332 keV)

- **Individual ^{60}Co lines:** clearly observed in the bkg spectrum (almost uniform counting rate on the different TeO_2 bolometers)
- **Most probable source:** neutron activation of the Copper detector structure
- **Contribution to DBD background:** negligible (beta tail accompanying the 2505 peak)

CUORICINO background (2)

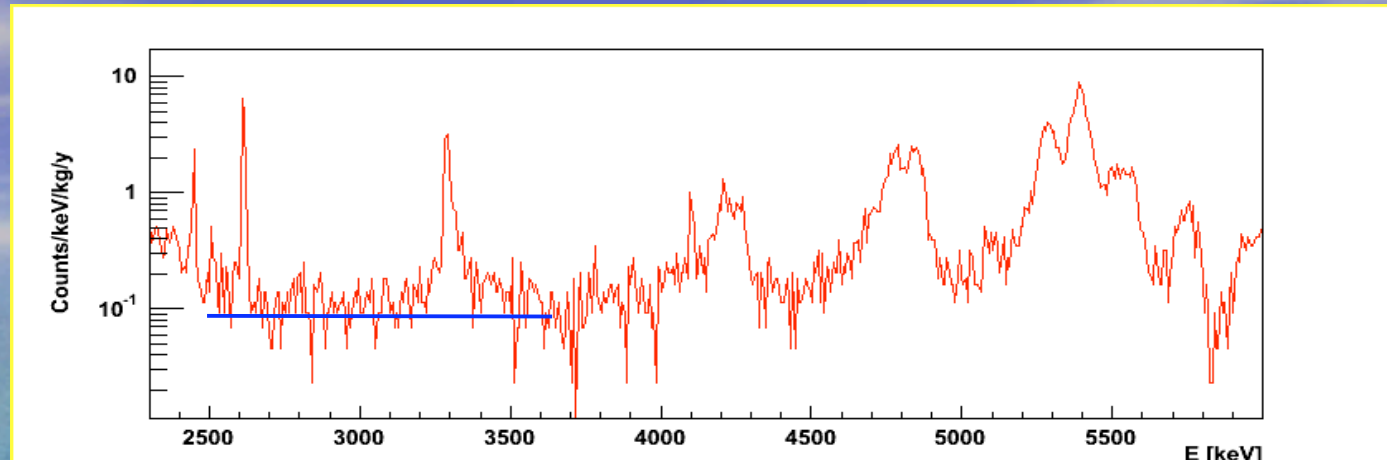
Flat background in the energy region above the ^{208}Tl 2615 keV line

- Natural extrapolation to the region below the 2615 keV peak
- Contribution to the counting rate in the $0\nu\text{DBD}$ region: $\sim 60\%$ (preliminary)



What are the possible sources of this flat background?

CUORICINO flat background



→ neutrons

- Cuoricino neutron shield (10 cm borated polyethylene) didn't show any significant variation in the 3-4 MeV counting rate when mounted around the MiDBD experiment
- Low statistics $\Rightarrow$ poor limit: neutrons can still account for a fraction of the observed background

→ degraded alpha particles from crystal surface contaminations,

- various alpha peaks observed in the background spectrum,
- central energies, low energy tails and scatter plots of coincident events prove that these peaks are due to a surface contamination of the crystals (mainly in ^{238}U)
- Estimated contribution (spectra of coincident events on facing crystals): $\sim 10\%$

→ degraded alpha particles contaminations of the inert materials facing the crystals

- No direct evidence of the existence of this contamination that according to our MonteCarlo simulations (few micron surface layers) give simply a continuum background with no clear signature.
- $\sim 50\%$ necessary to account for the $0\nu\text{DBD}$ counting rate (Most likely source)

CUORE background

Evaluation of the expected CUORE background based on the contamination levels measured so far (MiDBD, CUORICINO and Ge measurements) for available materials

Bulk contaminations

$\text{TeO}_2 \sim 10^{-13} \text{ g/g}$

$\Rightarrow < 2 \times 10^{-3} \text{ counts/kev/kg/y}$

$\text{Cu} \sim 10^{-12} \text{ g/g}$

Surface contamination

$1.9 \times 10^{-8} \text{ Bq/cm}^2$ for TeO_2

$\Rightarrow < 1.6 \times 10^{-2} \text{ counts/kev/kg/y}$

$4.9 \times 10^{-8} \text{ Bq/cm}^2$ for Cu (Th)

$\Rightarrow < 4.1 \times 10^{-2} \text{ counts/kev/kg/y}$

$3.4 \times 10^{-8} \text{ Bq/cm}^2$ for Cu (U)

$\Rightarrow < 2.7 \times 10^{-2} \text{ counts/kev/kg/y}$

Required reduction factors:

✓ 10 in Cu surface contamination

✓ 4 in TeO_2 surface contamination

CUORE background (2)

Neutron background in CUORE:

❖ neutron produced in the rock by radioactivity

total $8 \cdot 10^{-3}$ c/keV/kg/y

anticoincidence $2 \cdot 10^{-4}$ c/keV/kg/y

Can be reduced by neutron shield

❖ neutron produced in the rock by muon

total $6 \cdot 10^{-5}$ c/keV/kg/y

anticoincidence $1 \cdot 10^{-6}$ c/keV/kg/y

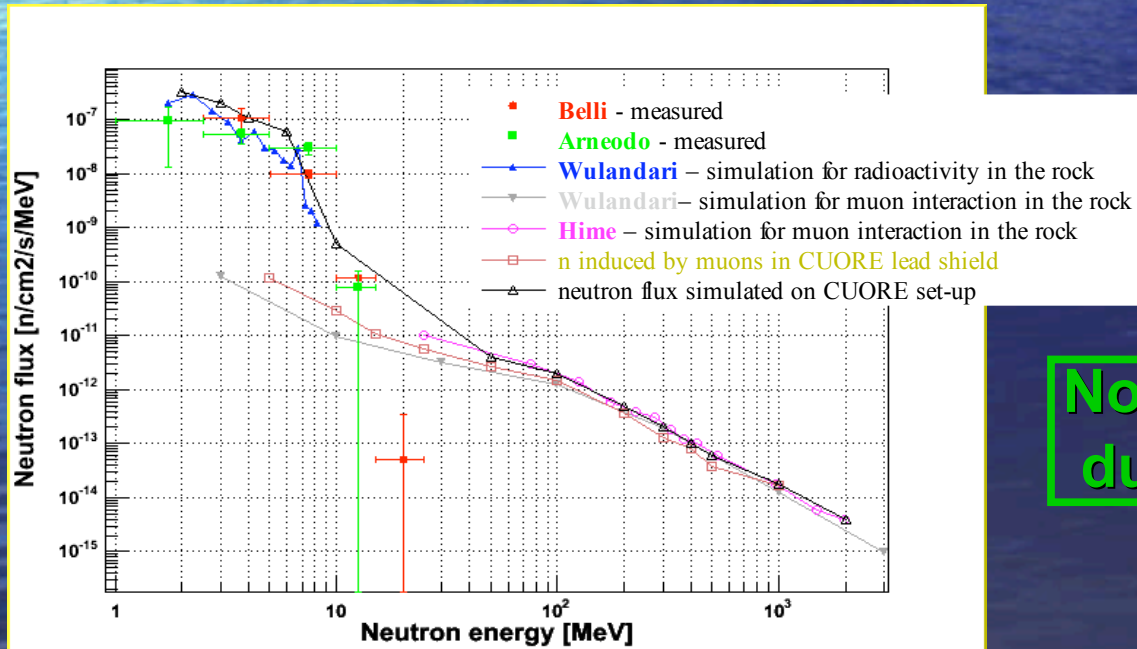
Negligible

❖ neutron produced in the lead shield by muon

total $2 \cdot 10^{-3}$ c/keV/kg/y

anticoincidence $1 \cdot 10^{-4}$ c/keV/kg/y

Can be reduced by muon veto



**No limit to CUORE sensitivity
due to neutron flux @ LNGS**

CUORICINO vs. CUORE: background

BULK Contaminations: ^{208}Tl 2615 keV line

^{208}Tl 2615 keV line ascribed to a ^{232}Th contamination of the cryostat structure

→ CUORICINO: old crystal (20 year)

- reduced experimental space: no room for massive ultrapure lead shield in the cryostat
- relaxed constraints on cryostat construction material selection

→ CUORE

- cryostat specifically designed in order to maximize the shield efficiency
- severe selection of construction materials

SURFACE Contaminations: 3-4 MeV continuous background

- Proper **surface treatments** (with ultrapure materials and tools) of all the detector components + Proper **diagnostics**
- Bolometric measurements
- ★ **Recent test on 8 crystals** (CUORE-like): improved surface treatment (developed@LNGS) reduced crystal surface contamination by a factor ~ 4
- ★ a dedicated array of 8 $5 \times 5 \times 5 \text{ cm}^3$ crystals operated in Hall C
- ICPMS bulk and surface measurement
- low bkg Ge spectroscopy
- **Surface Sensitive Bolometers (SSB)**

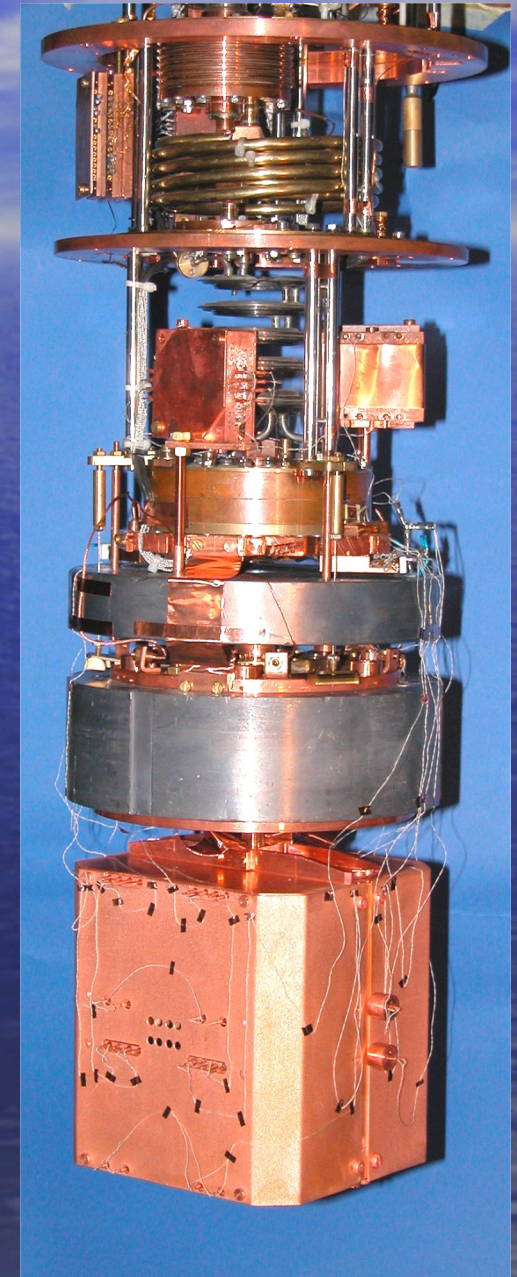
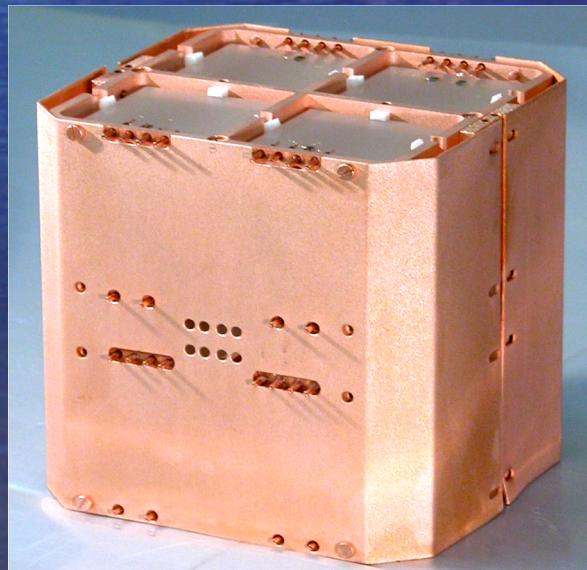
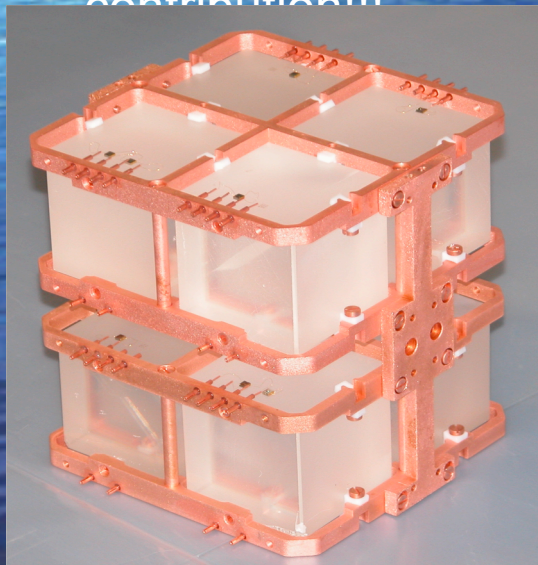
RAD

Radioactivity analysis Array of 8 Detectors:

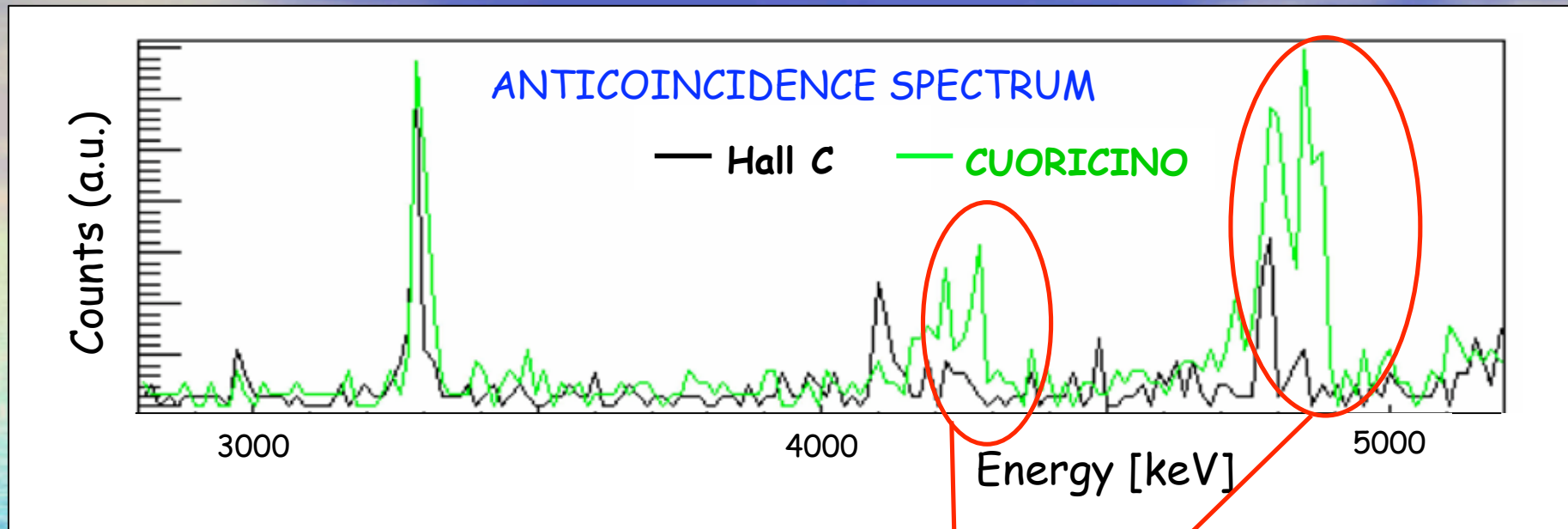
- mini-tower of two single CUORE modules
- cleaned with ultra-radiopure materials and procedures
- Cu: etching, electropolishing and passivation
- TeO_2 : etching and lapping with radiopure acid and powders
- Assembling with *clean materials*
 - most sensitive detector for surface contaminations
 - *sensitive to secular equilibrium breaks*

RAD November 2004 run

- sensitive reduction of TeO_2 crystal surface contribution



RAD results



Reduction of a factor ~ 4 on crystal surface contaminations:
CUORE milestone for this task reached

Crystal Bulk contamination $\sim 10^{-14}$ g/g in U and Th

April 2005 measurement:

significant contributions from **PTFE, wires, Si heaters** excluded
other measurement (different techniques) confirm these data

From CUORICINO to CUORE

CUORICINO

- Relatively large size crystals (790 g) without loss of performance
- Large bolometric array with the tower-like structure
- Long runs with excellent duty cycle
- Most relevant background sources identification
- First steps towards background reduction

CUORE

- Completely new set-up with optimized shielding structure
- specifically designed to reduce as far as possible the amount of materials interposed between the crystals
- high granularity for background events identification and rejection (coincidence/anticoincidence technique)
- radiopure materials for detector and cryostat structure
- Construction material selection is started
- Big efforts for the identification/reduction and control of the source responsible of the Cuoricino DBD background (cleaning techniques, radiactivity level measurement, surface sensitive detectors, detector and setup structure optimization)

Summary

CUORICINO: 19st April 2003 →

- successfully operating independent experiment on ^{130}Te $\beta\beta(0\nu)$
- ▶ 40.7 kg of TeO_2 , $B_{\beta\beta(0\nu)} = 0.18 \pm 0.02$ c/keV/kg/y, $\Delta E = 8\text{keV}$
- ▶ $\tau_{1/2} > 1.8 \times 10^{24}$ years at 90% C.L. ($m_\nu < 0.2 \div 1.1$ eV)
- ▶ $S_{3\text{ years}}^{1\sigma} > 6 \times 10^{24}$ years - $m_\nu < 0.11 \div 0.60$ eV
- good technical performance
- ▲ reproducibility, stability, energy resolution
- crucial informations for background sources identification

CUORE:

- approved by LNGS S.C.: location in Hall A
- approved and funded by INFN
- intense activity for the optimization of the background reduction procedures
- construction phase started:
- start data taking: 1st January 2010

CUORE time schedule

Start date: 1st January 2005		2005	2006	2007	2008	2009
Crystals	US					
Material Selection						
Procedure settling						
Growth and preparation						
Thermistors	US					
R&D and Ge irradiation						
Decay period						
Production						
Detector structure	INFN					
Design						
Material Selection						
Production						
Cleaning						
Cryostat & cryogenics	INFN					
Design and material selection						
Construction						
Installation and test						
Shieldings	INFN					
Design and material selection						
Construction						
Underground Laboratory	INFN					
Design						
Installation						
Electronics	US					
Design and test						
Production						
Installation						
Data Acquisition	INFN					
R&D and prototyping						
Final design						
DAQ SW development						
Production						
Installation						
CUORE assembly	INFN/US					