New CUORICINO results and status of CUORE

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on behalf of the CUORE collaboration

- LTD's for Neutrinoless Double Beta Decay
- CUORICINO
  - construction
  - detector performance
  - results
  - background
- Perspectives for CUORE

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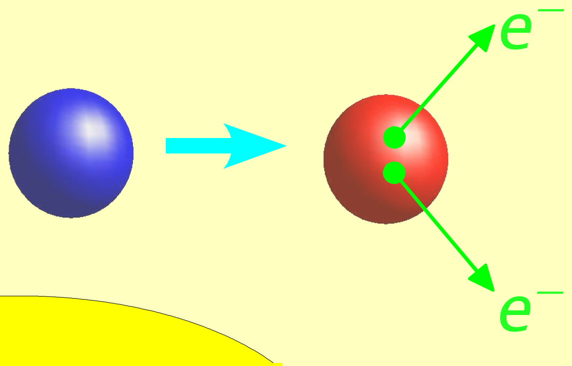
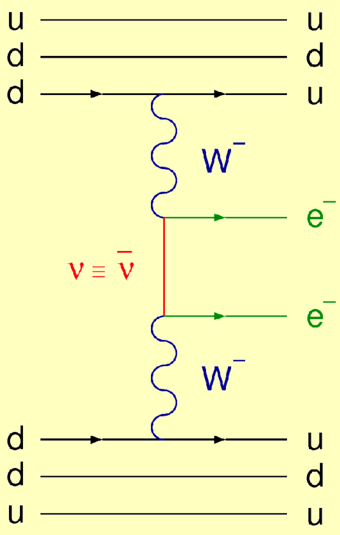
Neutrinoless Double Beta Decay

$\beta\beta$-0ν: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

- **not allowed in Standard Model:**
  - *lepton number violation ($\Delta L=2$)*
  - *Majorana nature of neutrino*
  - *massive neutrino*





$$\beta\beta\text{-}0\nu \Leftrightarrow \begin{matrix} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{matrix}$$

- **expected lifetime:**

Phase space factor

nuclear matrix element

uncertainties

$$\tau^{-1} = G_{0\nu} |M^{0\nu}|^2 |\langle m_\nu \rangle|^2$$

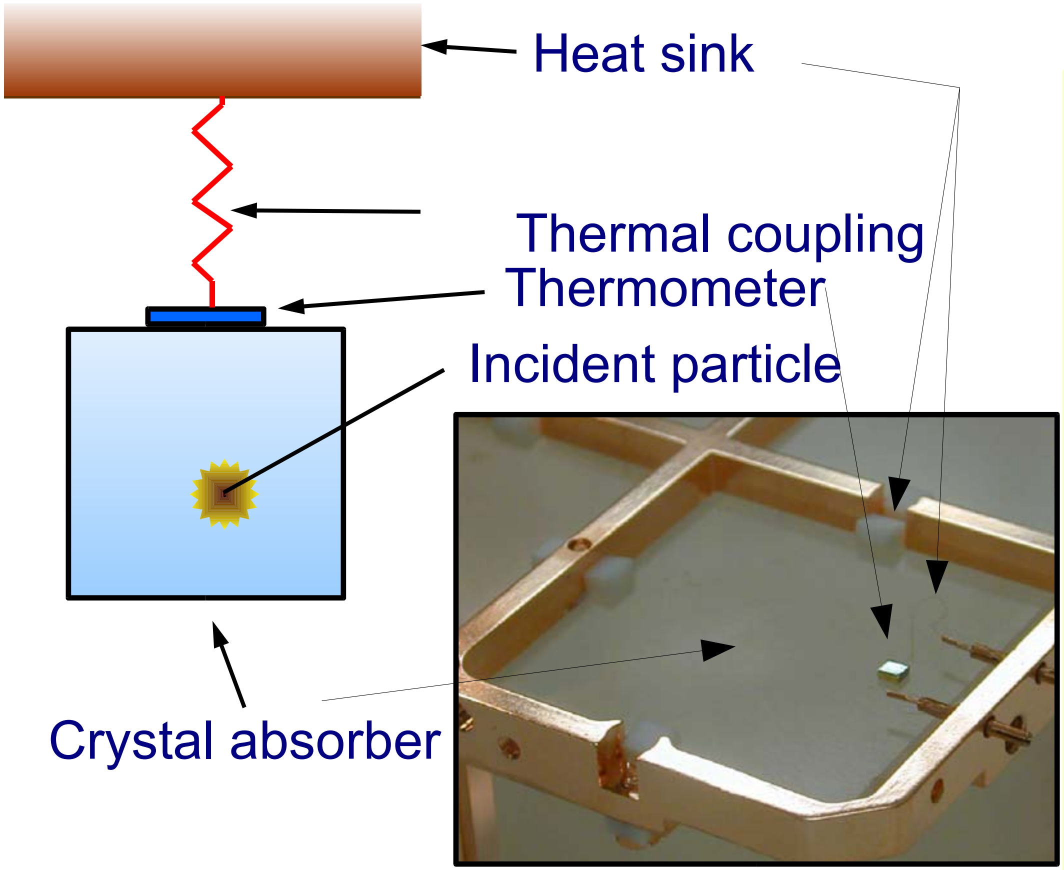
Effective neutrino mass

$$\langle m_\nu \rangle = \sum_k m_{\nu_k} \eta_k |U_{ek}|^2$$

neutrino mixing matrix

⇨ **constraints on $\langle m_\nu \rangle$ can translate in constraints on m_{min}**

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

Thermal Detectors Properties

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

example: 760 g of TeO_2 @ 10 mK

$C \sim T^3$ (Debye) $\Rightarrow C \sim 2\times10^{-9}$ J/K

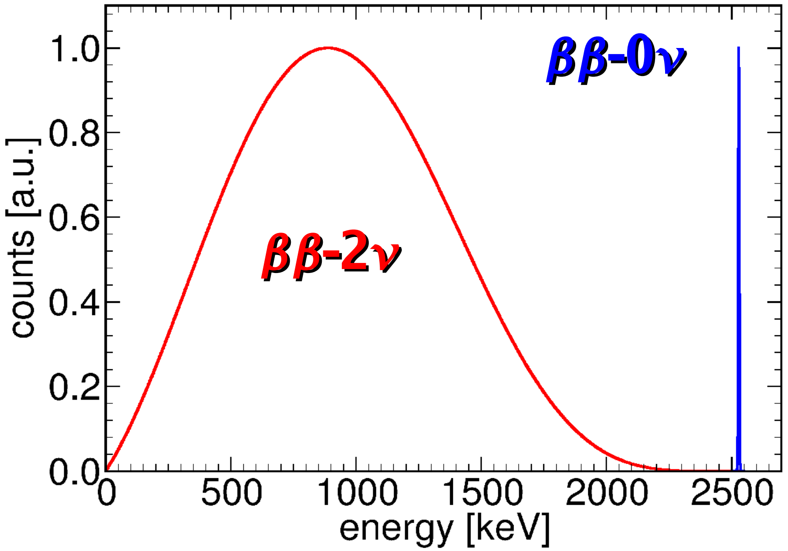
1 MeV γ-ray $\Rightarrow \Delta T \sim 80\ \mu\text{K}$

$\Rightarrow \Delta U \sim 10$ eV

TeO2 LTD's

Calorimeters

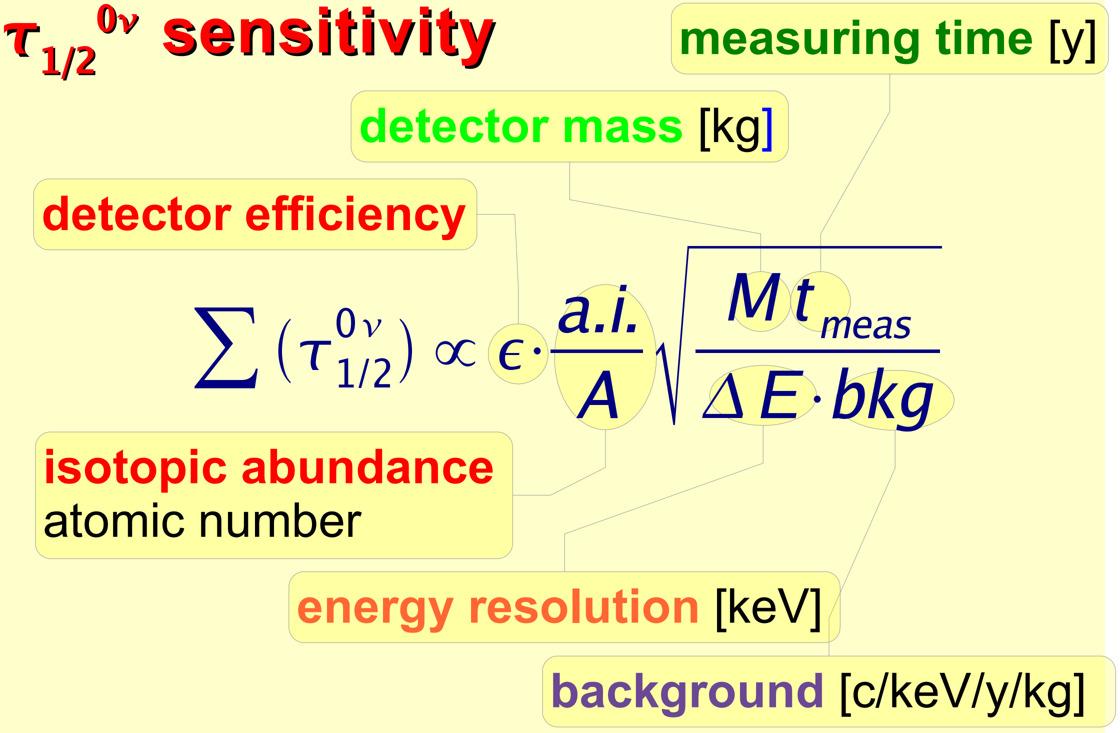
- source ⊆ detector
  - large N_{nuclei}
  - high energy resolution ΔE
  - high efficiency
- measure $E = E_{\beta_1} + E_{\beta_2}$
- signature: a peak at $Q_{\beta\beta}$



TeO$_2$ thermal calorimeters

- Active isotope ^{130}Te
  - natural abundance: a.i. = 33.9%
  - transition energy: $Q_{\beta\beta}$ = 2529 keV
  - encouraging predicted half life $\langle m_\nu \rangle \approx 0.3$ eV ⇔ $\tau_{1/2}^{0\nu} \approx 10^{25}$ years
- Absorber material TeO$_2$
  - low heat capacity
  - large crystals available
  - radiopure

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



measuring time [y]

detector mass [kg]

detector efficiency

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

isotopic abundance
atomic number

energy resolution [keV]

background [c/keV/y/kg]

The CUORE project

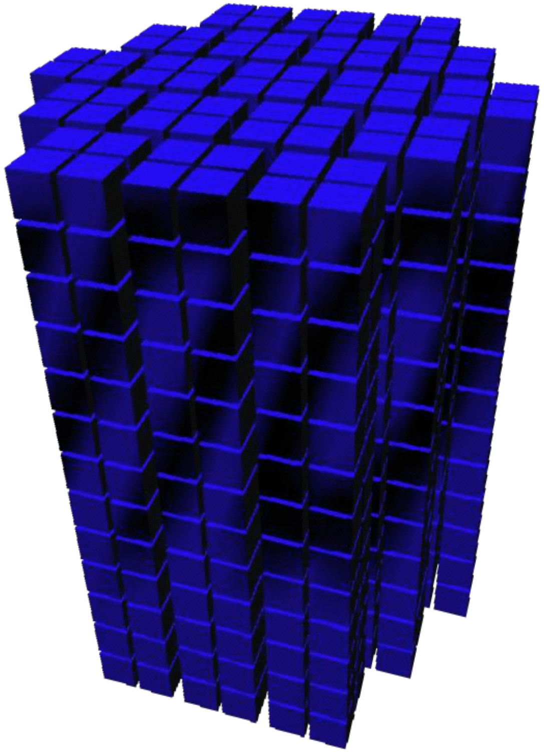
Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

- **array of 988 TeO_2 crystals 5×5×5 cm^3 (750 g)**
  - **741 kg TeO_2 granular calorimeter**
  - **600 kg Te = 203 kg ^{130}Te**
- **$\beta\beta(0\nu)$, Cold Dark Matter, Axions** searches

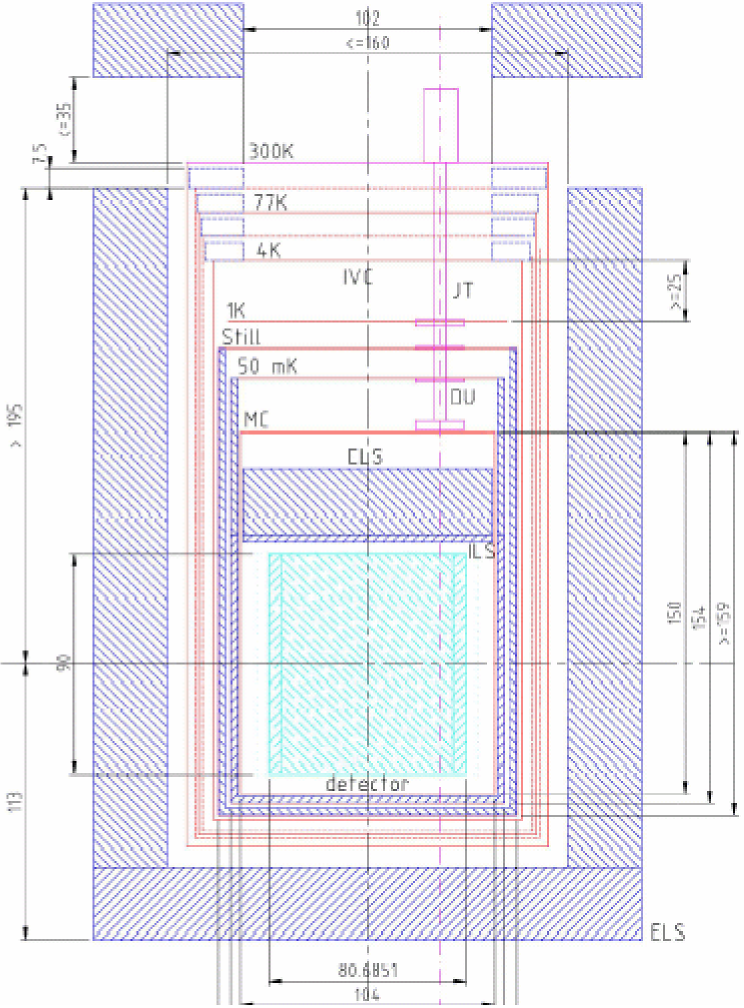
single dilution refrigerator (~ 10 mK)

SINGLE HIGH GRANULARITY DETECTOR

Crystals grouped in a “cylindrical” matrix of 19 towers



Single tower: thirteen (4 crystal) modules



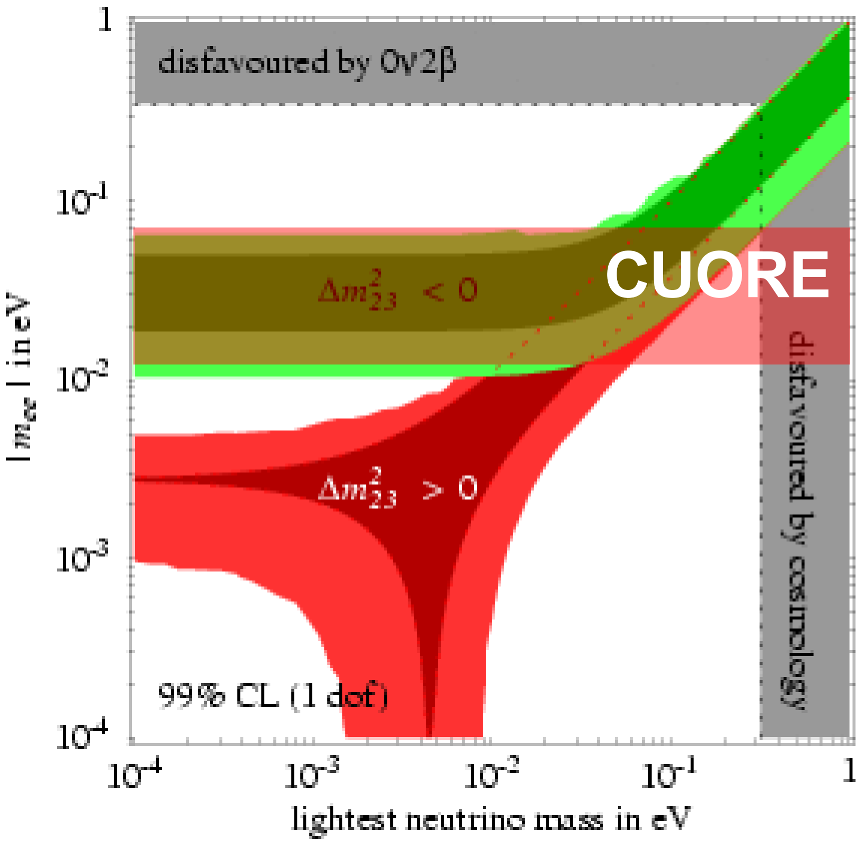
CUORE expected sensitivity

CUORE $\beta\beta(0\nu)$ 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)	$\lvert\langle m_\nu\rangle\rvert$ (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 $\langle m_\nu\rangle$ from **nuclear matrix element uncertainty**

CUORICINO

Slightly modified single **CUORE** *tower*

test:

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

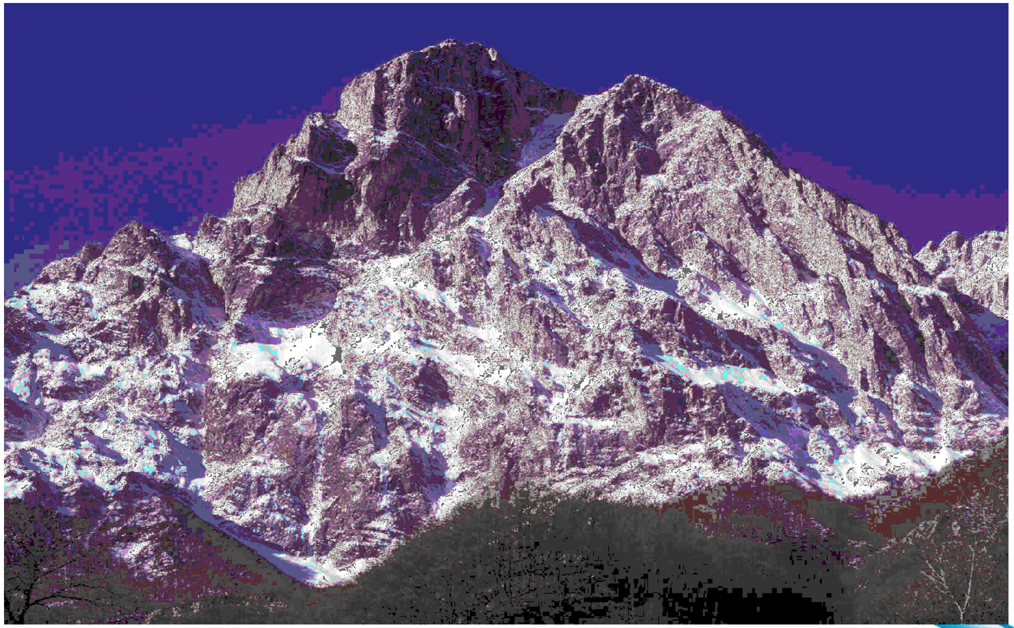
independent experiment:

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

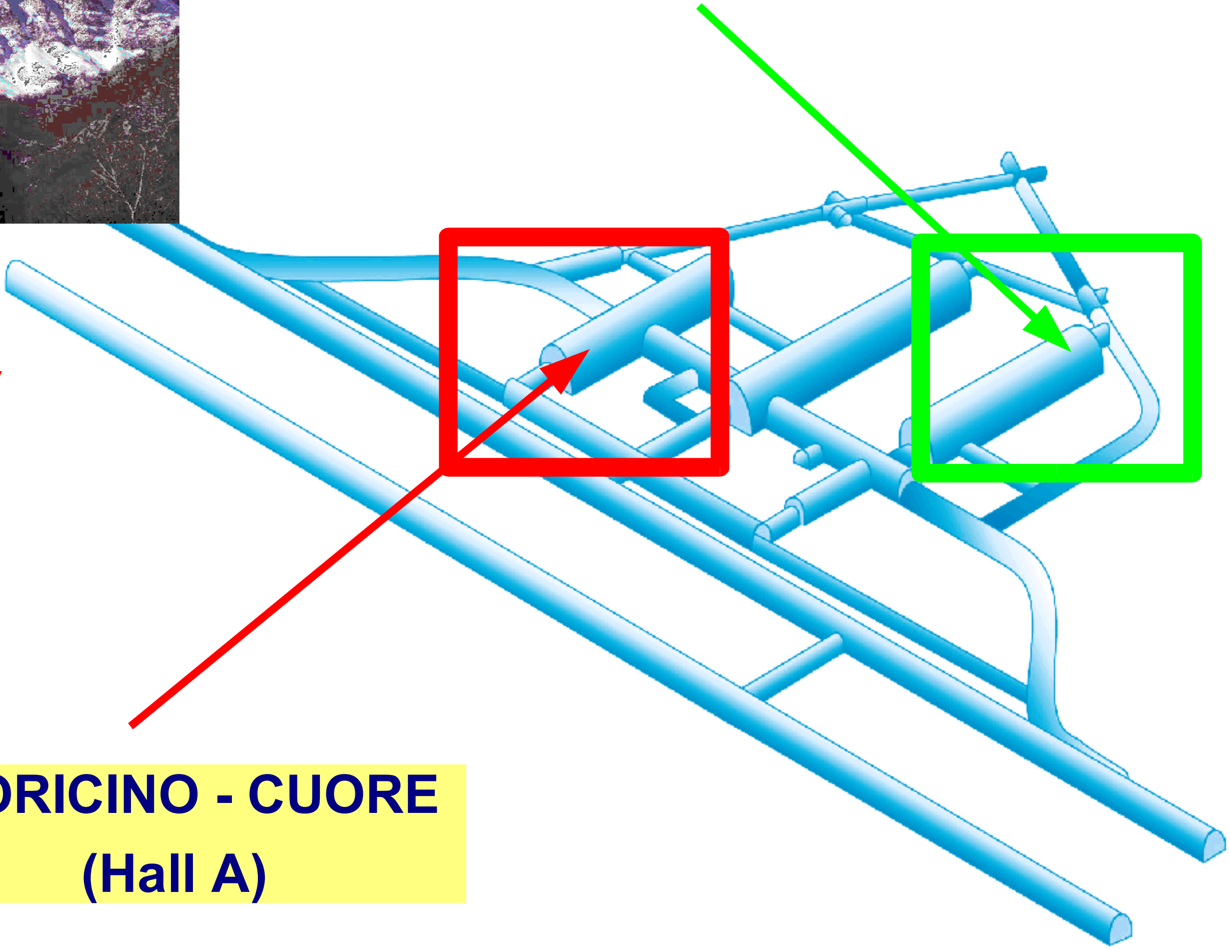
Laboratori Nazionali del Gran Sasso, Hall A

same cryostat which hosted Mi-DBD 20 crystal array

LNGS LTD Underground Facilities



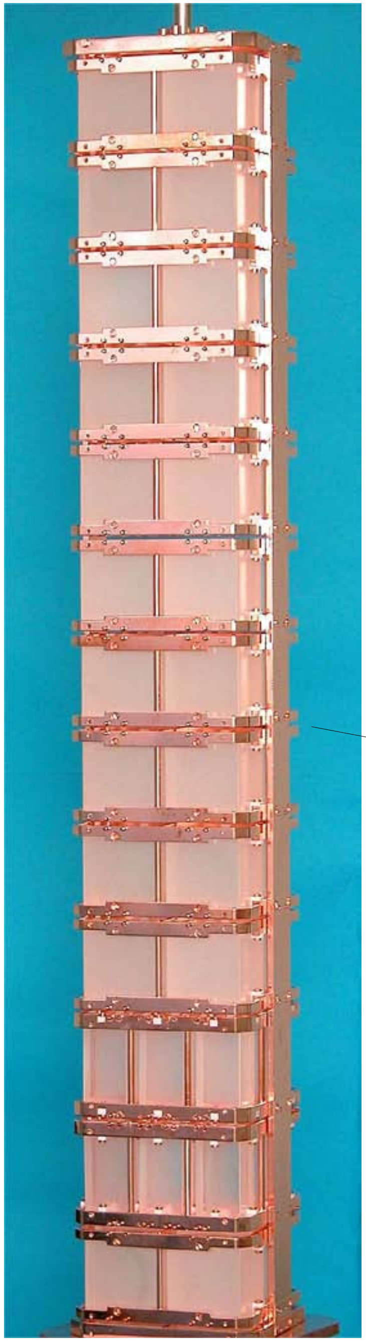
Underground National Laboratory
of Gran Sasso
L'Aquila – ITALY
3500 m.w.e.



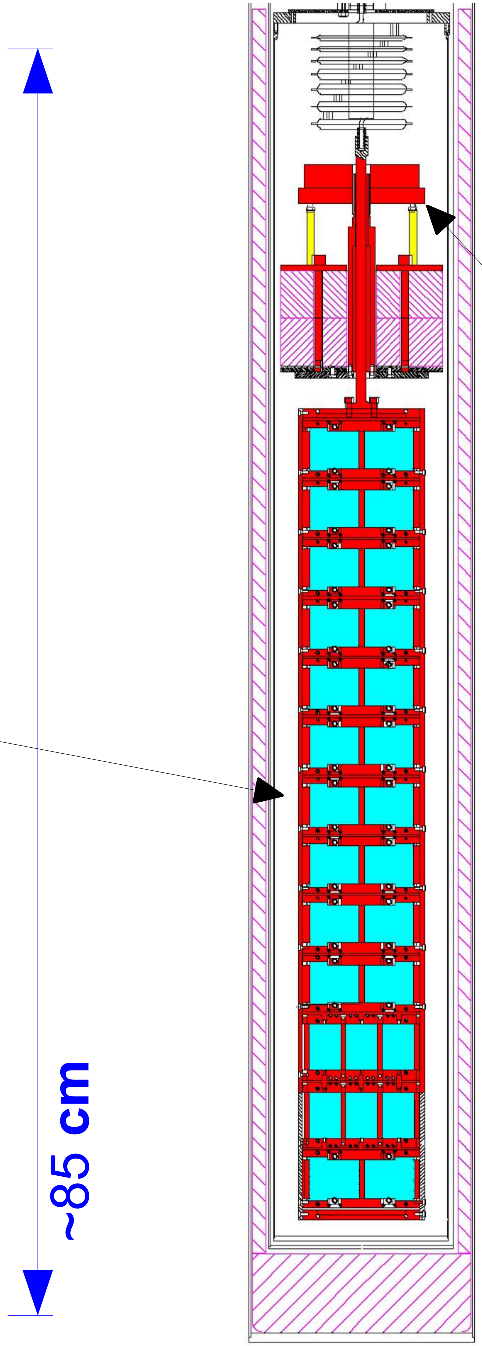
CUORE R&D (Hall C)

CUORICINO - CUORE
(Hall A)

CUORICINO tower



Cuoricino *tower*: 62 TeO_2 crystals

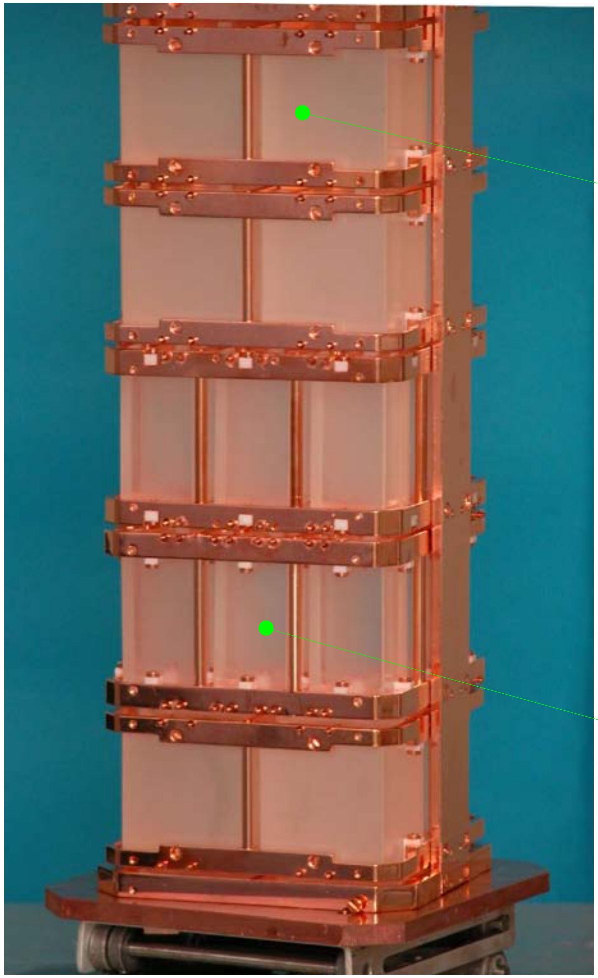


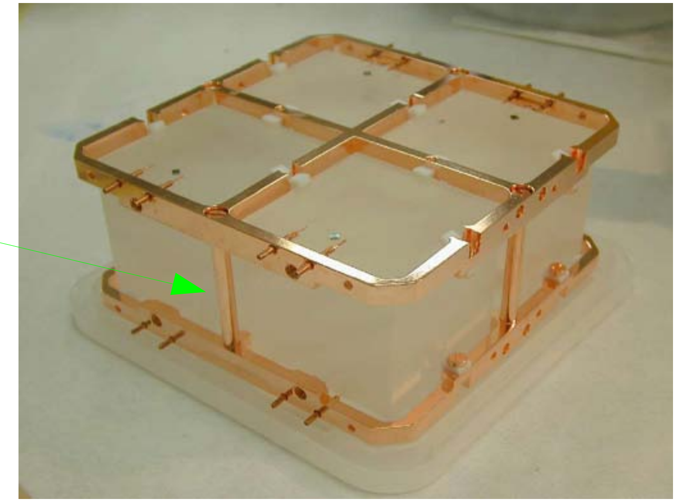
roman Pb shielding (1 cm lateral)

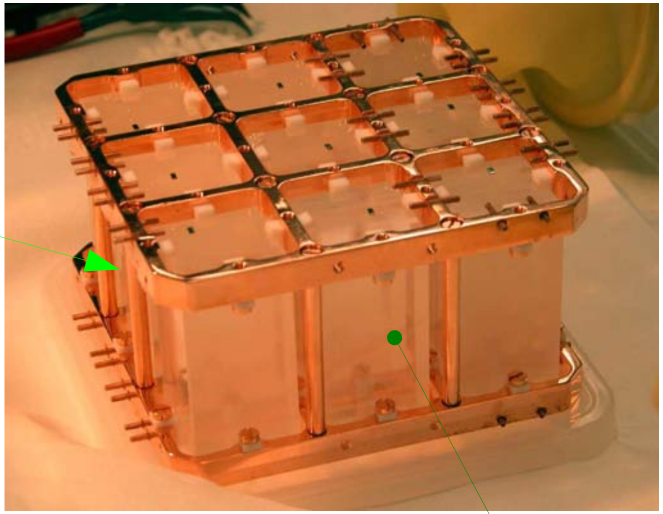
external shields:

- 10 cm Pb + 10 cm low act Pb
- neutron shield: B-polyethylene
- nitrogen flushed anti-radon box

CUORICINO tower (2)





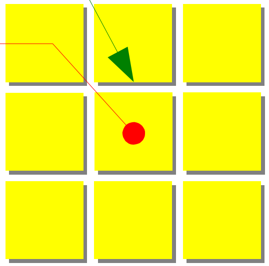


- 11 modules with 4 *big* detectors
  - 44 TeO_2 crystals
  - 5×5×5 cm^3 ⇒ 790 g
  - ▷ **TeO_2 mass ⇒ 34.76 kg**

Total number of detectors: 62

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

- **total active mass**
  - ▷ **$TeO_2 \rightarrow 40.7$ kg**
  - ▷ **${}^{130}Te \rightarrow 14.1$ kg**
  - ▷ **${}^{128}Te \rightarrow 0.54$ kg**



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

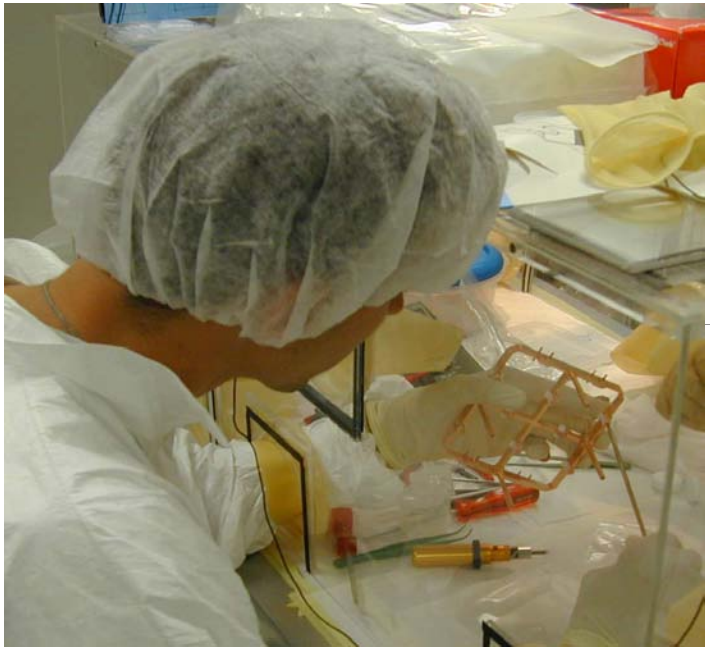
CUORICINO assembly

crystal surface cleaning

thermistor & heater gluing

- careful material selection
- careful cleaning of Cu and TeO_2 surfaces
- clean conditions for detector assembling
  - clean room
  - nitrogen atmosphere to avoid radon contaminations

CUORICINO assembly (2)



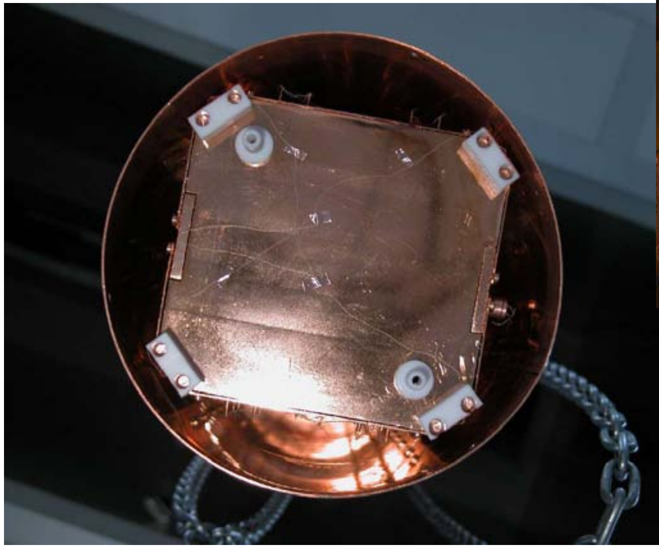
detector frame

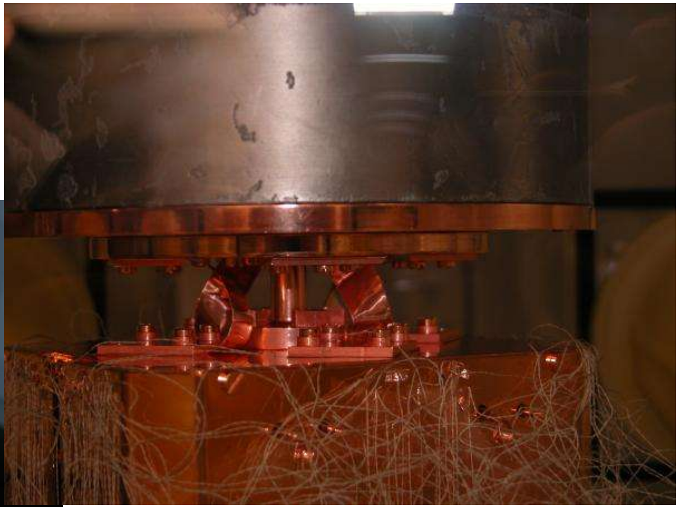
tower

4 detector module

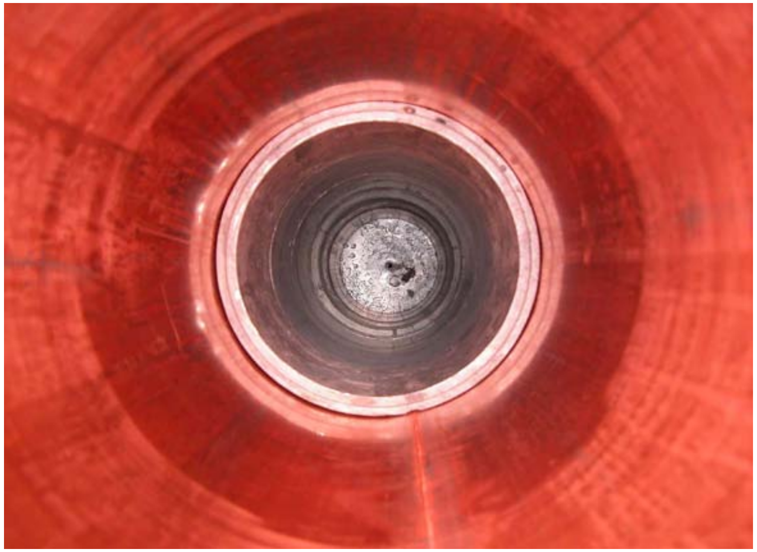
CUORICINO final assembly

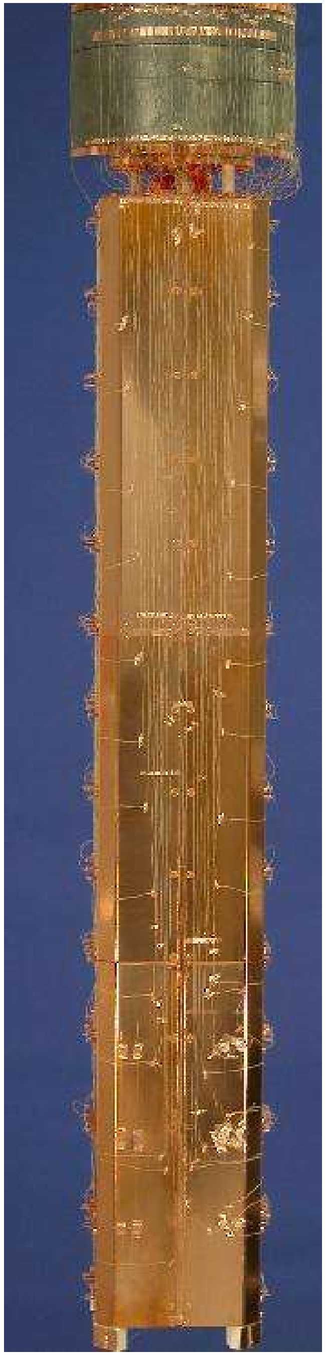
Tower positioning system





Roman lead shield
and suspension





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
  - ▷ $TeO_2 \rightarrow$ 29 kg
  - ▷ $^{130}Te \rightarrow$ 7.98 kg
  - ▷ $^{128}Te \rightarrow$ 7.36 kg

- 40 790g detectors
- 18 330g detectors
  - ▷ $TeO_2 \rightarrow$ 37.5 kg
  - ▷ $^{130}Te \rightarrow$ 10.3 kg
  - ▷ $^{128}Te \rightarrow$ 9.53 kg

RUN II

Cool down: May 2004

Detectors: two unrecovered detectors and two with excess noise

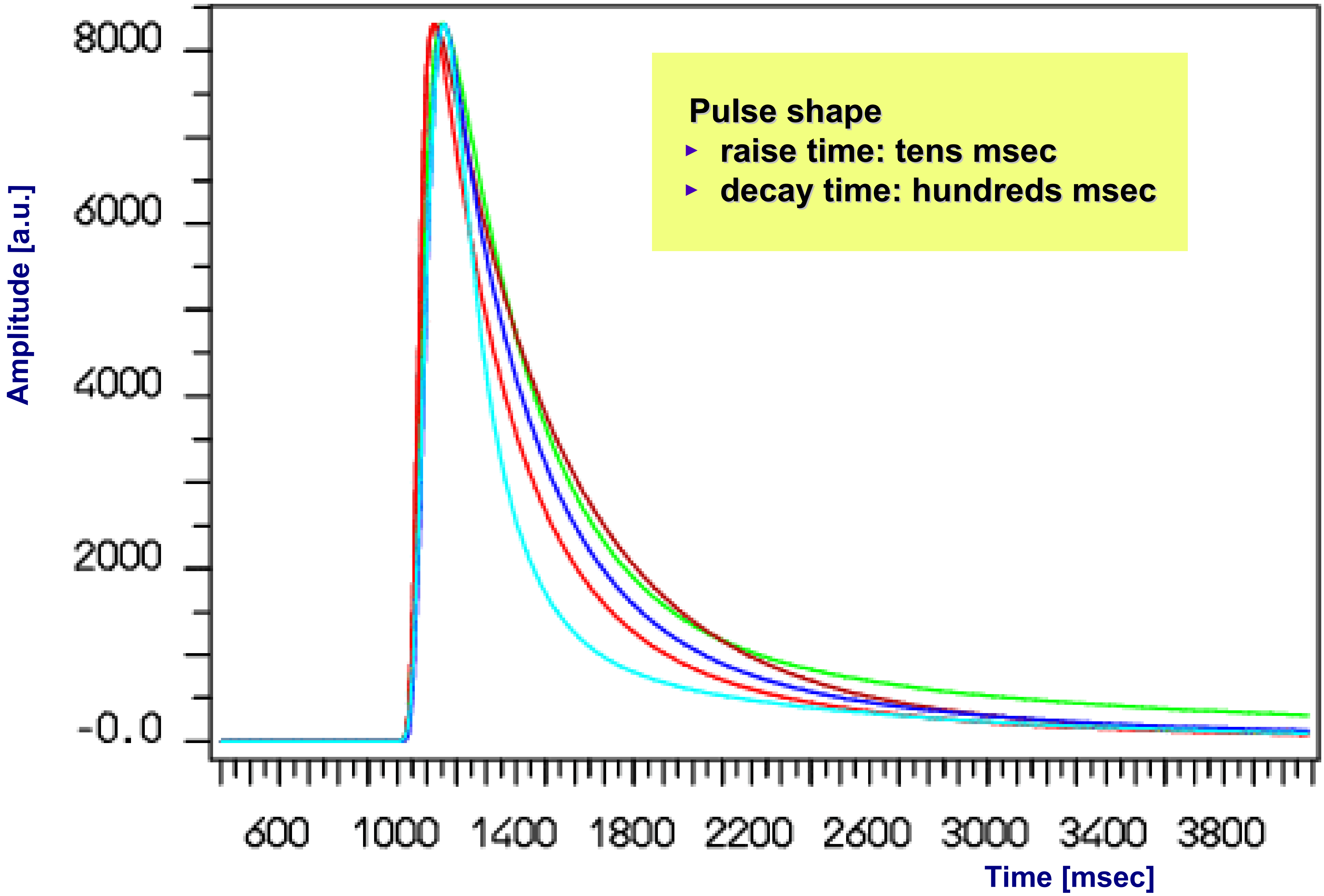
CUORICINO DUTY CYCLE

Source calibration: Th wire ~ 3 days

Background measurement: 3-4 weeks

ββ (background) live time ~ 64%

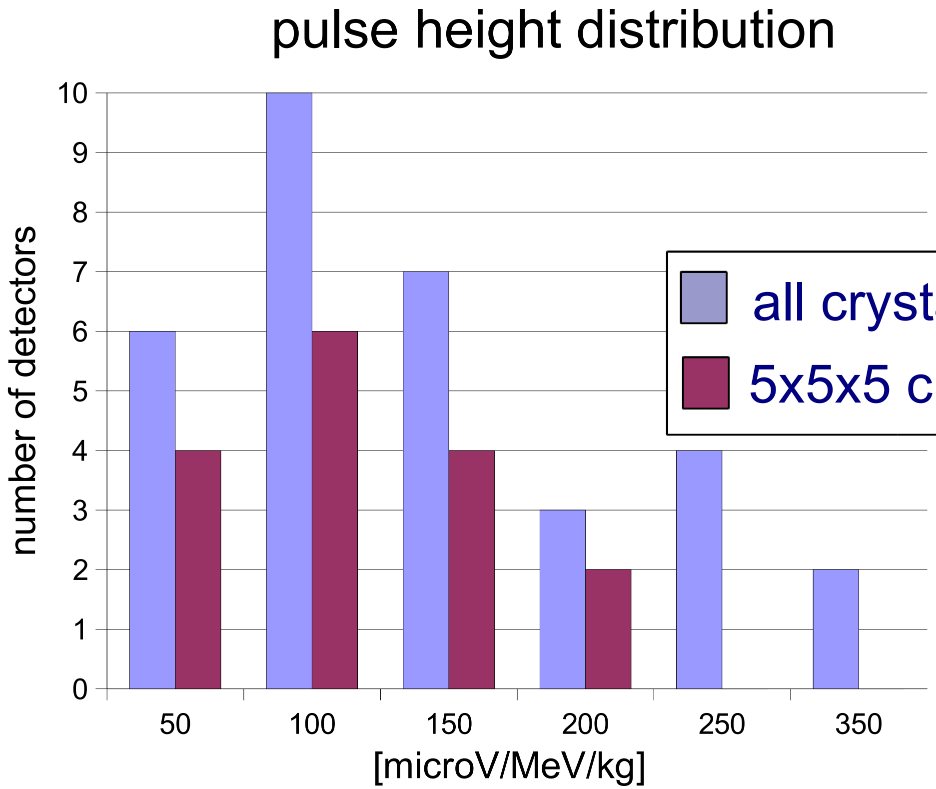
Detector response



Pulse shape

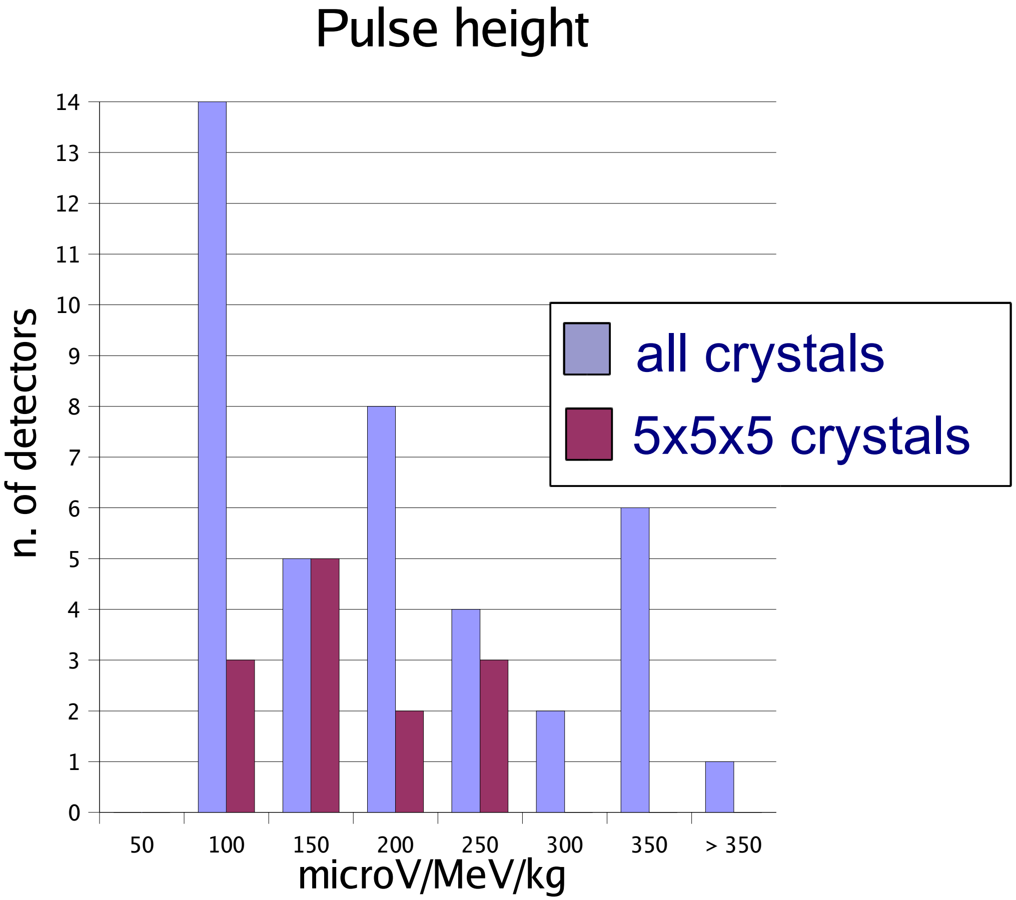
- raise time: tens msec
- decay time: hundreds msec

Detector response



RUN I

3x3x6 cm^3	104 ± 35 mV/MeV*kg
5x5x5 cm^3	120 ± 75 mV/MeV*kg



RUN II

3x3x6 cm^3	147 ± 60 mV/MeV*kg
5x5x5 cm^3	167 ± 99 mV/MeV*kg

Calibration spectra: energy resolution

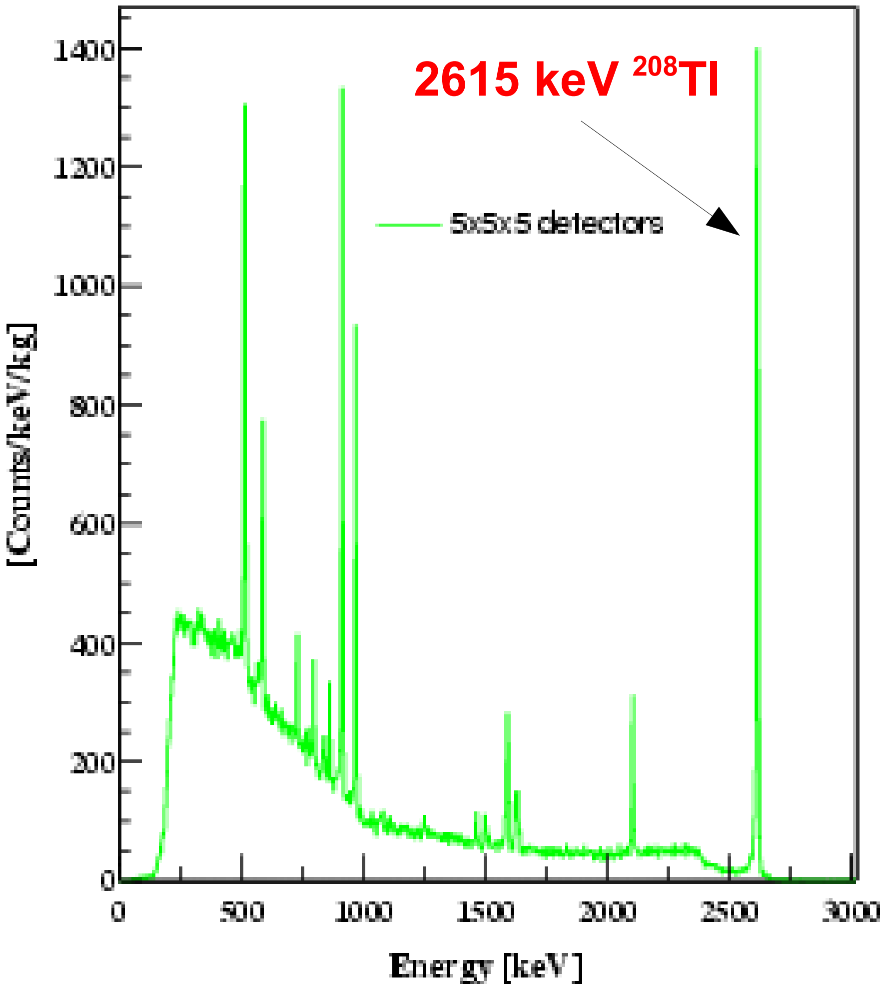
^{232}Th (and ^{238}U) γ-sources

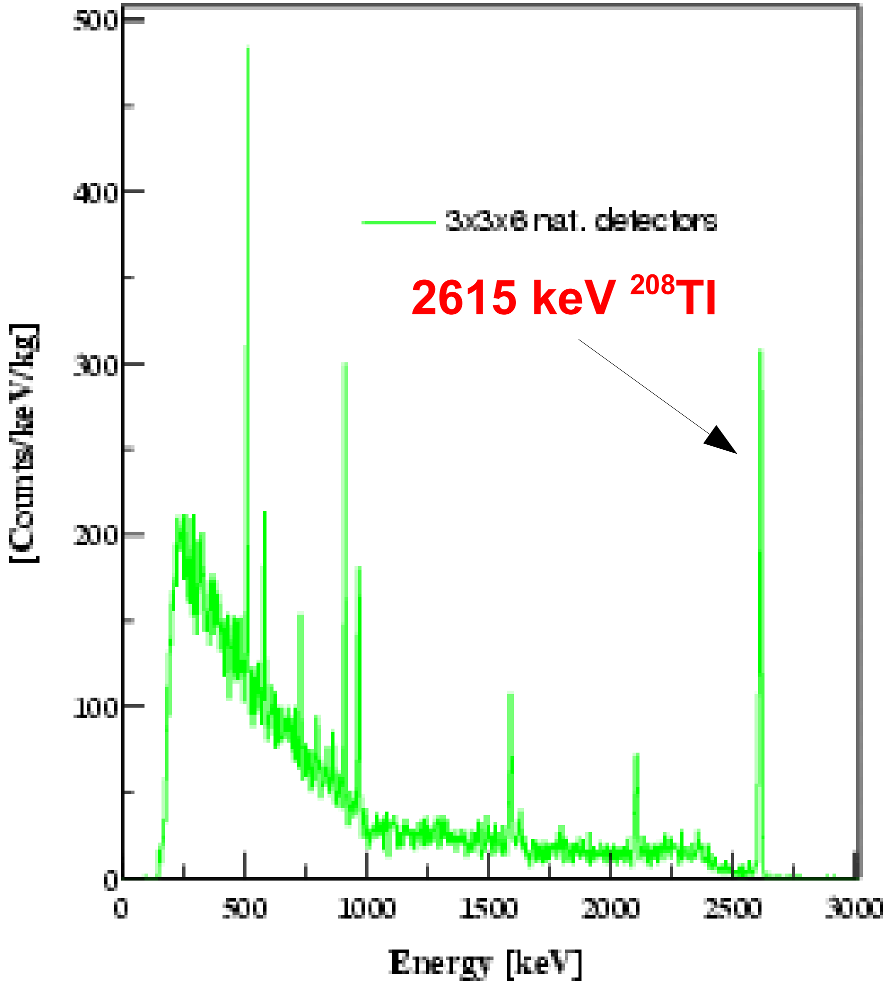
- External to the cryostat in contact with OVC

$\langle \Delta E \rangle$ @ 2615 keV

790 g crystals ~ 7.5+/-2.9 keV

330 g crystals ~ 9.6+/-2.5 keV

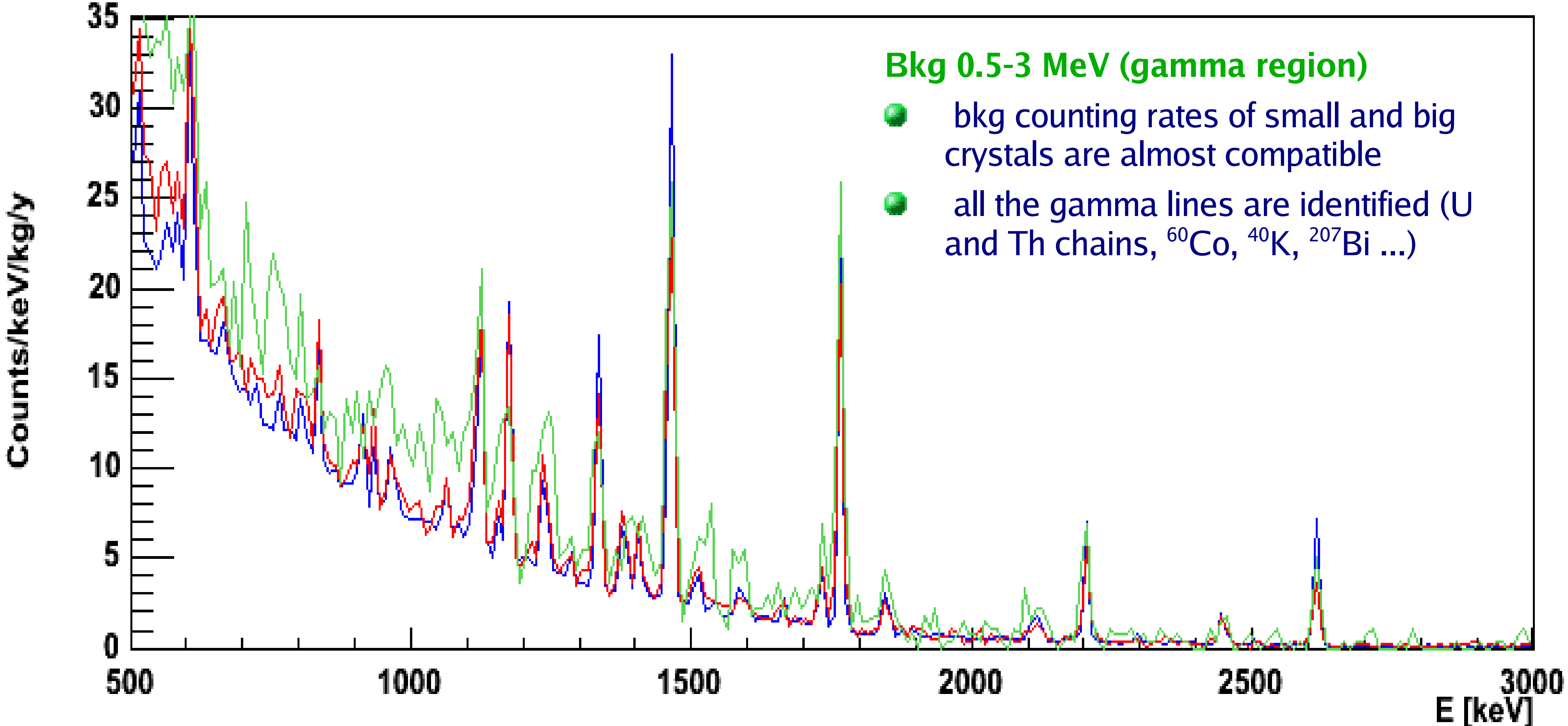

2615 keV ^{208}Tl


2615 keV ^{208}Tl

Detector performance: background

$\langle \Delta E \rangle$ @ 2615 keV in the sum bkg spectra of:

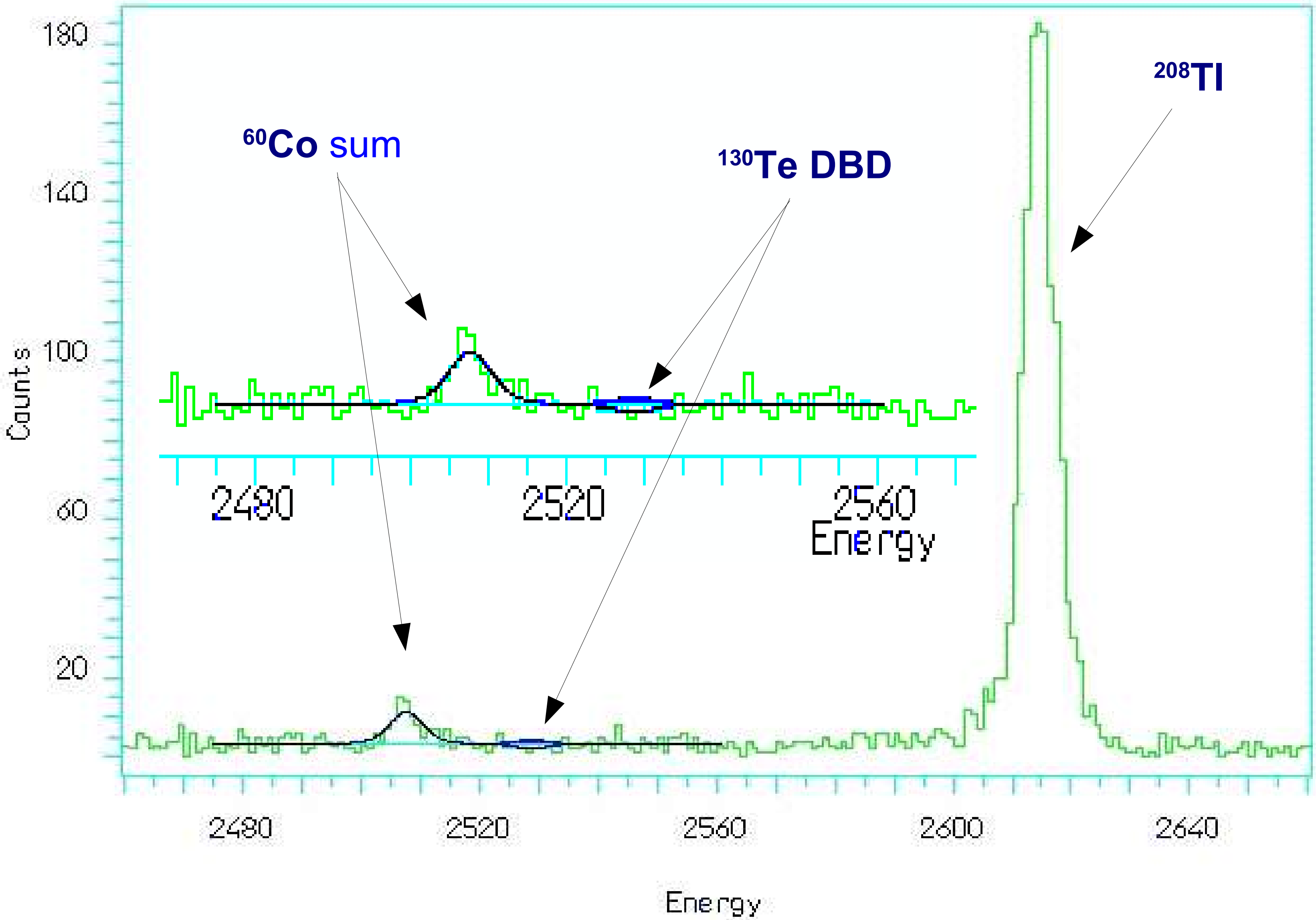
5x5x5 cm^3 cryst.	4.3 kg ^{130}Te * y - FWHM ~ 7.5 keV
3x3x6 cm^3 nat. cryst.	0.5 kg ^{130}Te * y – FWHM ~ 12 keV
3x3x6 cm^3 enrich. cryst.	0.2 kg ^{130}Te * y – peak not visible



Bkg 0.5-3 MeV (gamma region)

- bkg counting rates of small and big crystals are almost compatible
- all the gamma lines are identified (U and Th chains, ^{60}Co, ^{40}K, ^{207}Bi ...)

Neutrinoless DBD results



Neutrinoless DBD results

statistics:

- anticoincidence 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 0νDBD transition energy (2528.8 keV)
- Bkg counting rate in the 0nDBD 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 nth detector

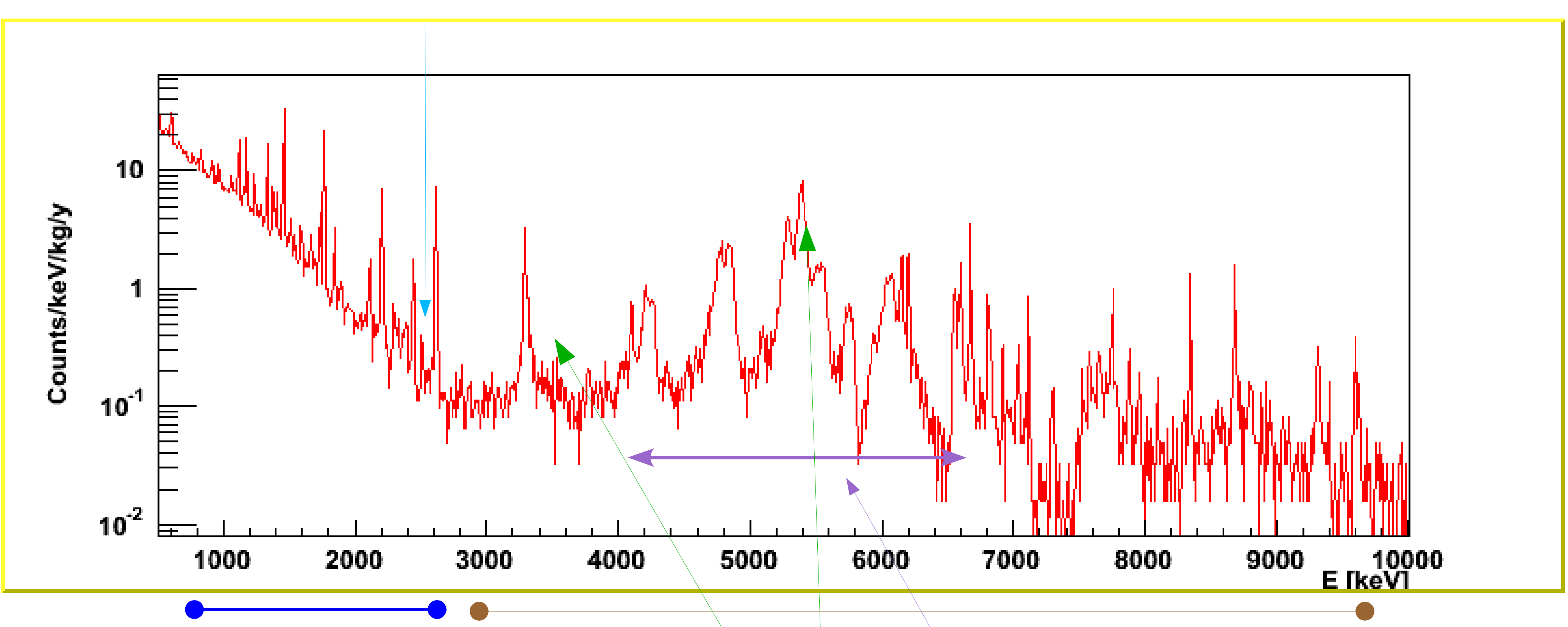
result:

$\tau_{1/2}$ > 1.8 10^{24} at 90% C.L. (<mν> < [0.2÷1.1] 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

CUORICINO: background

0νDBD



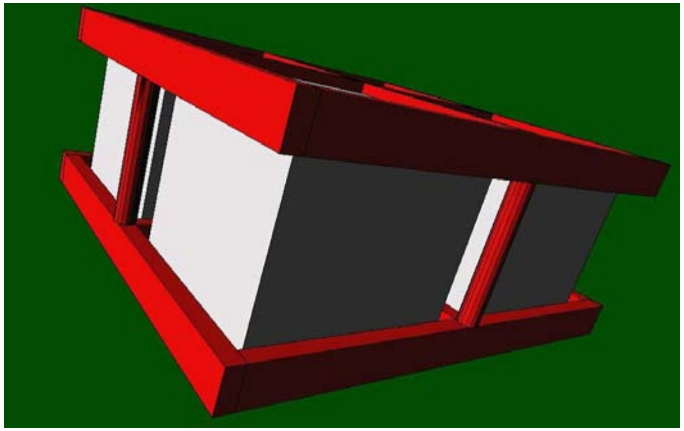
Gamma region, dominated by gamma and beta events, highest gamma line = 2615 keV ^{208}Tl line (from ^{232}Th chain)

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

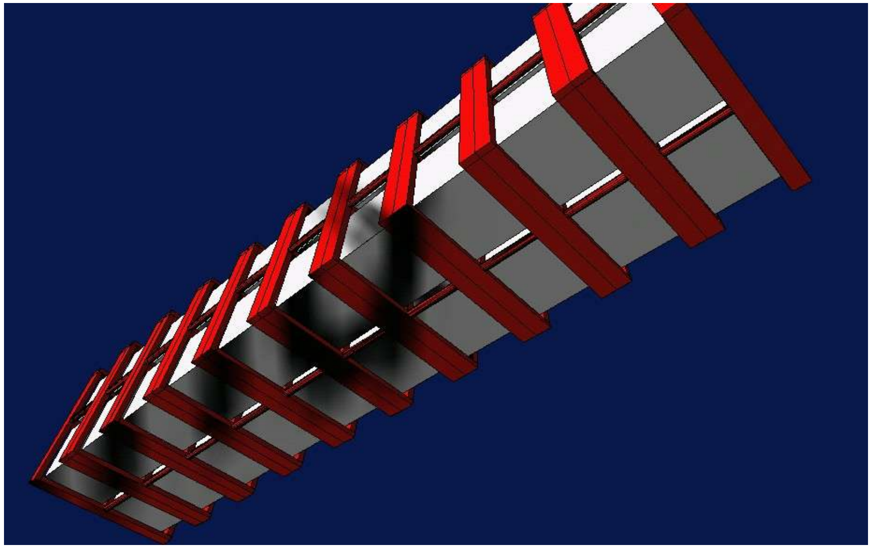
- MiDBD I+II
- CUORICINO

Monte Carlo simulations

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

detailed description of

- Detector
- Cryogenic setup
- Radiatiopn shields



Background results and CUORE perspectives

CUORICINO

γ-region

- bulk contaminations of detector and cryogenic setup materials
  - required contamination levels in agreement with Ge detector measurements

α-region

- surface contaminations of detector materials (crystal & mounting structure)
  - exponential density profile ($e^{-\lambda x}$: λ=0.1-10 μm)
  - required contamination levels (when considered as distributed over a thin surface layer)

    are 2-3 orders of magnitude larger than the bulk values of the corresponding materials
- **preliminary** HR ICPMS measurements of CUORICINO copper samples seem to confirm both contamination levels and density profiles
- **Surface cleaning procedure can be improved**

CUORE

ββ(0ν) Monte Carlo evaluations based of CUORICINO background results and available bulk contamination limits from Ge measurements:

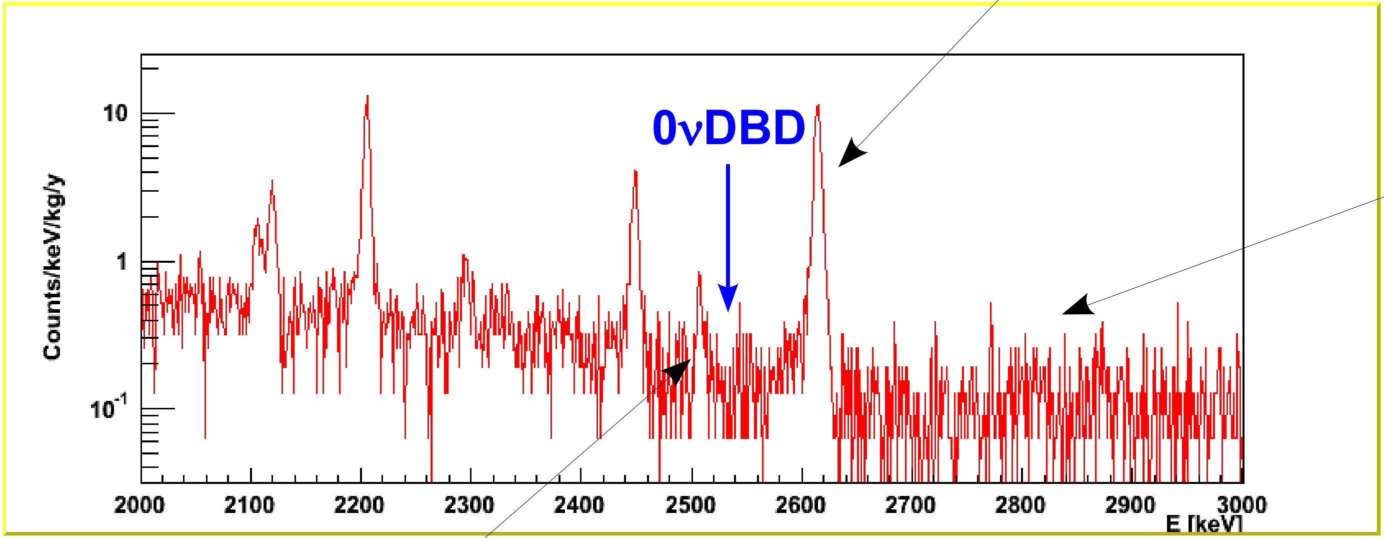
bulk	**3.8×10^{-3}**	**couns/keV/kg/y**
surface (TeO2)	**2×10^{-2}**	**couns/keV/kg/y**
surface (Copper)	**5×10^{-2}**	**couns/keV/kg/y**

CUORE sensitivity goal can be reached

CUORICINO background

2615 keV Tl line ⇒ 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: ~ 40% (preliminary)**



No other gamma lines identified near or above the 0νDBD transition energy ⇒ no contributions from other gamma sources.

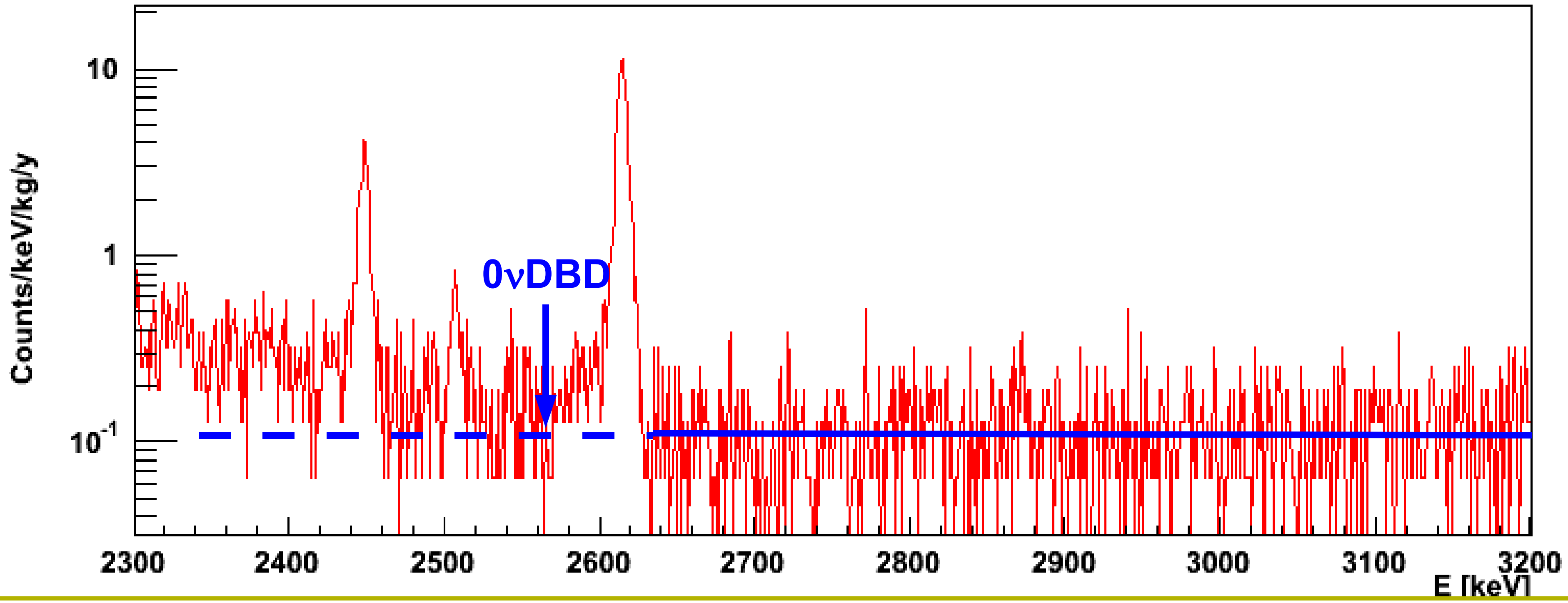
2505 keV line: sum of the 2 ^{60}Co gammas(1173 and 1332 keV)

- **Individual ^{60}Co lines:** clearly observed in the bkg spectrum (almost uniform counting rate on the different TeO2 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)

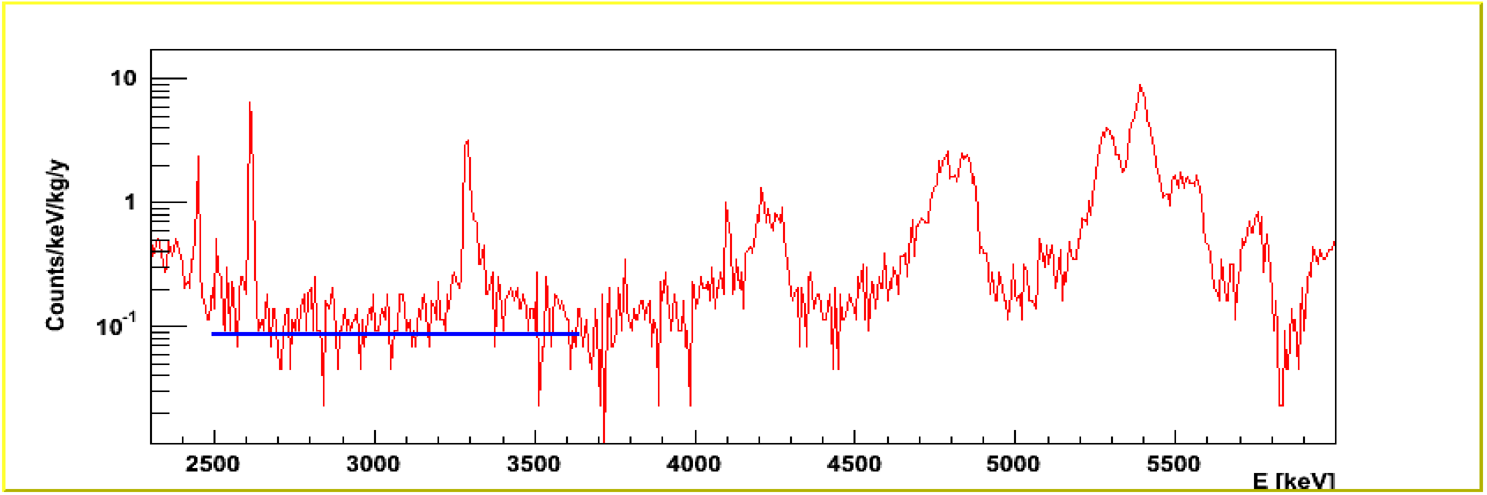
Flat background in the energy region above the ^{208}Tl 2615 line

- Natural extrapolation to the region below the 2615 keV peak
- Contribution to the counting rate in the 0nDBD region: ~ 60% (preliminary)



What are the possible sources of this flat background?

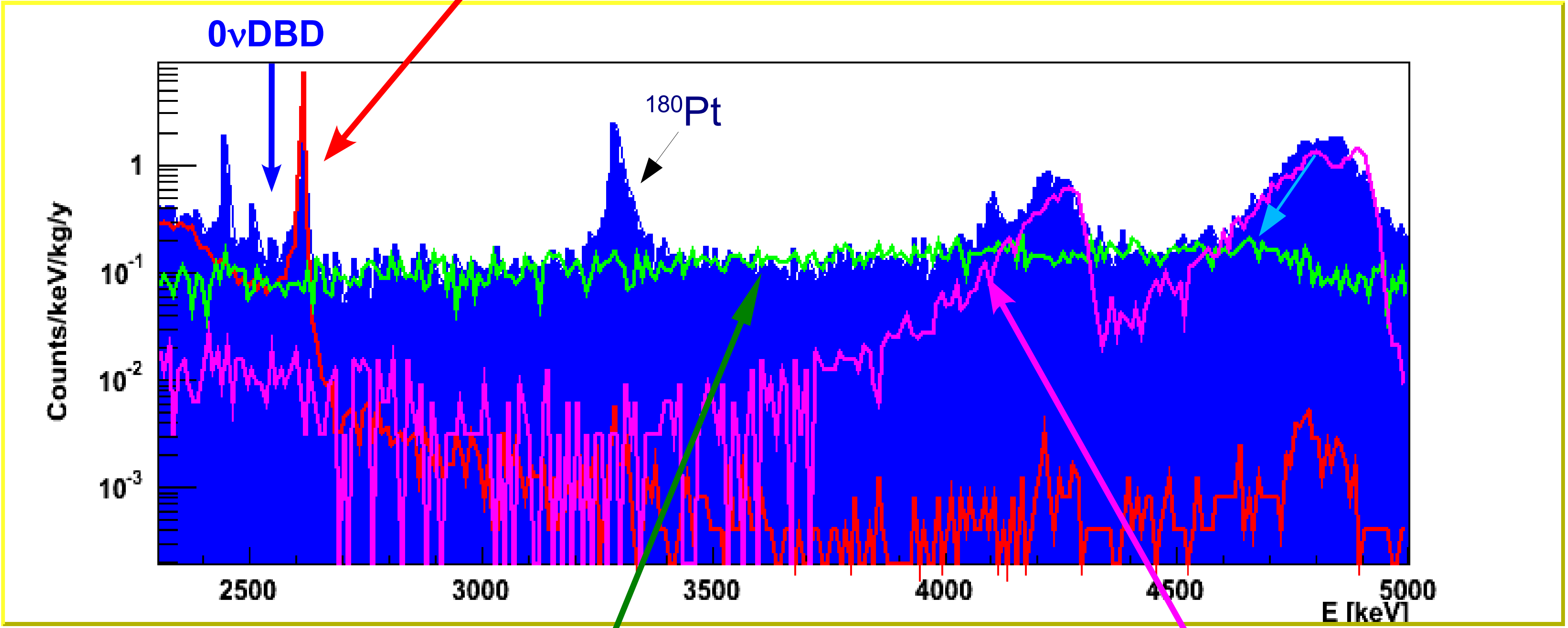
CUORICINO flat background



- **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 ⇒ 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): **~ 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.
  - Most likely source of the missing **50%** necessary to account for the 0νDBD counting rate

CUORICINO sum spectrum

Th calibration normalized to the 2615 keV line of the Cuoricino bkg sum spectrum



MonteCarlo simulation
Bkg contribution due to Cu mounting structure surface contamination (^{232}Th, 5 micron depth)

MonteCarlo simulation
Bkg contribution due to crystal surface contaminations

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

$TeO_2 \sim 10^{-13}$ g/g

Cu ~ 10^{-12} g/g

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

Surface contamination

~ 10^{-9} g/g for TeO_2 and Cu $\Rightarrow$ < 7×10^{-2} counts/kev/kg/y

Required reduction factors:

- ✓ 10 in Cu surface contamination
- ✓ 4 in TeO_2 surface contamination

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 crystat (20 year)
  - reduced experimental space: no room for massive ultrapure lead shield inside the cryostat
  - relaxed constraints on cryostat construction material selection
- CUORE
  - cryostat specifically designed in order to maximize the shield efficiency this
  - severe selection of construction materials

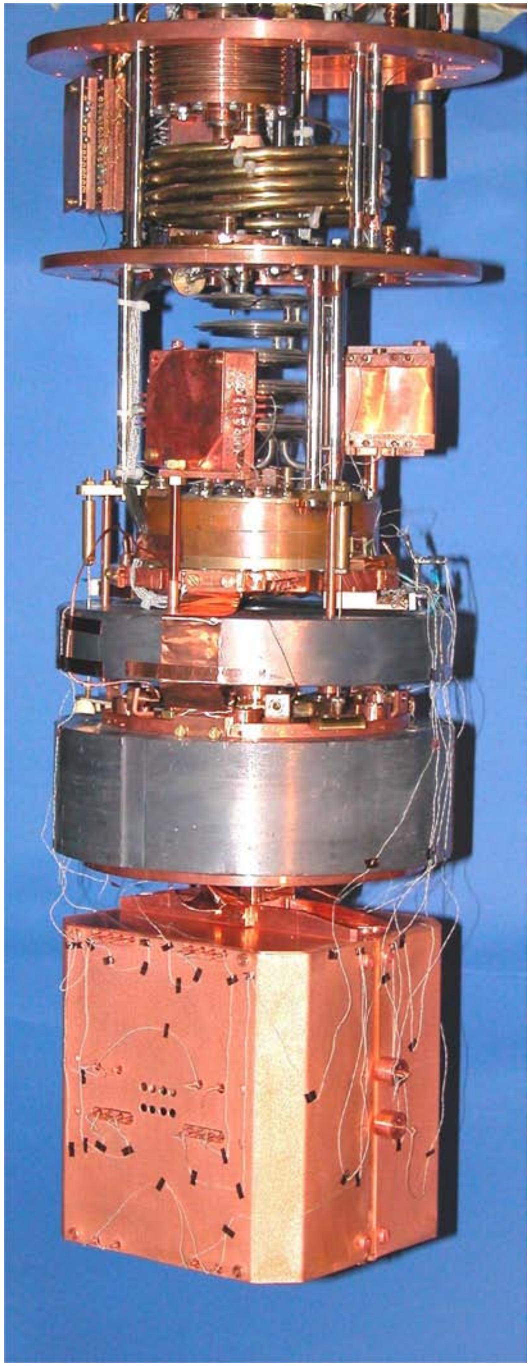
SURFACE Contaminations: 3-4 MeV continuous background

- 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 5x5x5 cm3 crystals operated in Hall C
  - ICMPS bulk and surface measurement
  - low bkg Ge spectroscopy
- Surface Sensitive Bolometers (SSB)

RAD

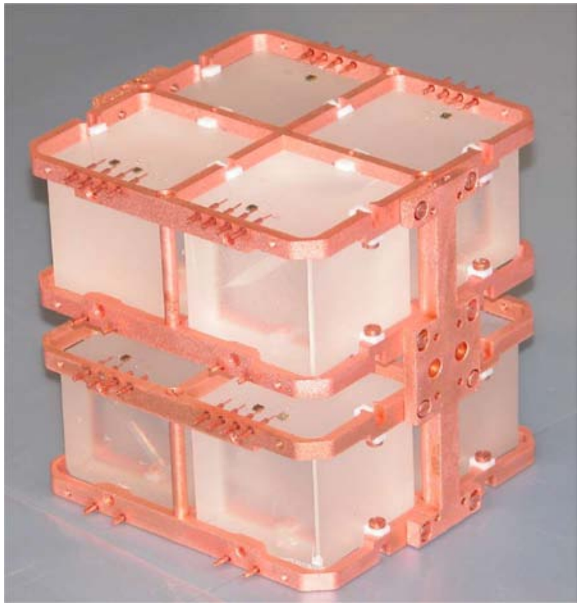
Radioactivity analysis Array of 8 Detectors:

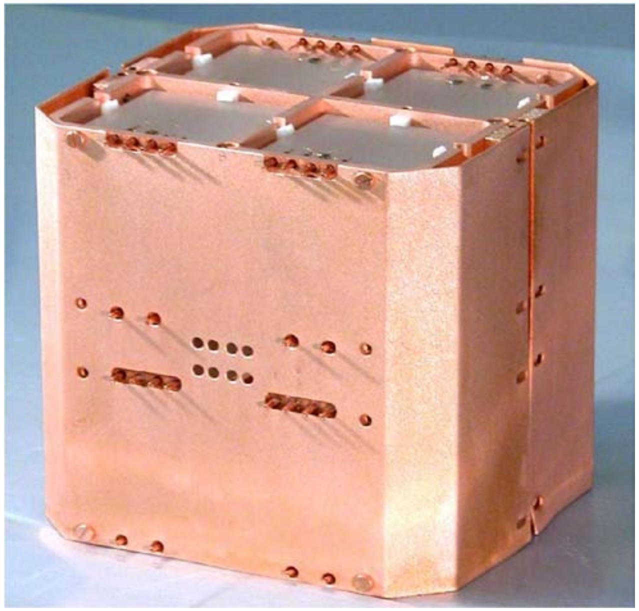
- mini-tower of two single CUORE modules
- cleaned with ultra-radiopure materials and procedures
    - Cu: etching, electropolishing and passivation
    - TeO2: etching and lapping with radiopure acid and powders
    - Assembling with clean materials
- most sensitive detector for surface contaminations
    - sensitive to secular equilibrium breaks



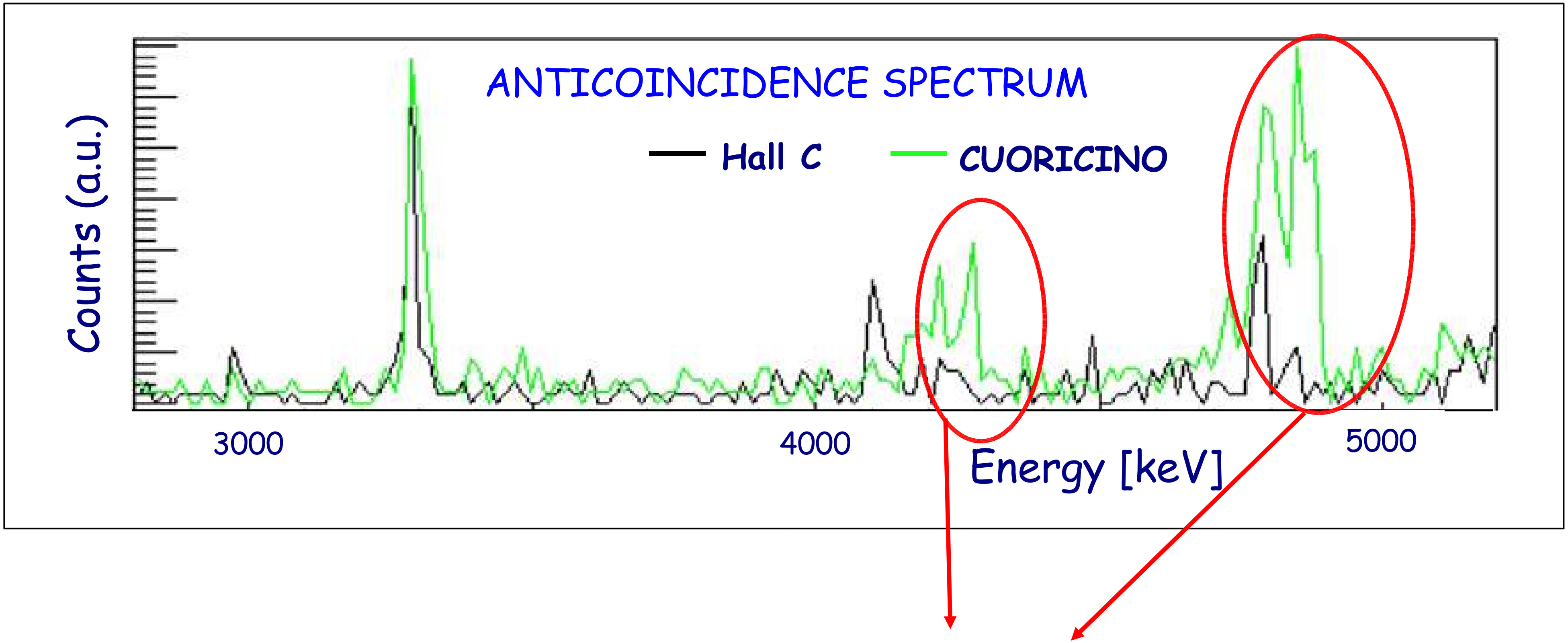
RAD November 2004 run

- 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 ~ 10^{-14} g/g in U and Th

April 2005 measurement:

significant contributions from PTFE, wires anf Si heaters excluded

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

Ongoing activities:

- 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, detetor and setup structure optimization)

CUORE: status

2nd April 2004 Experiment approval by S.C. of LNGS

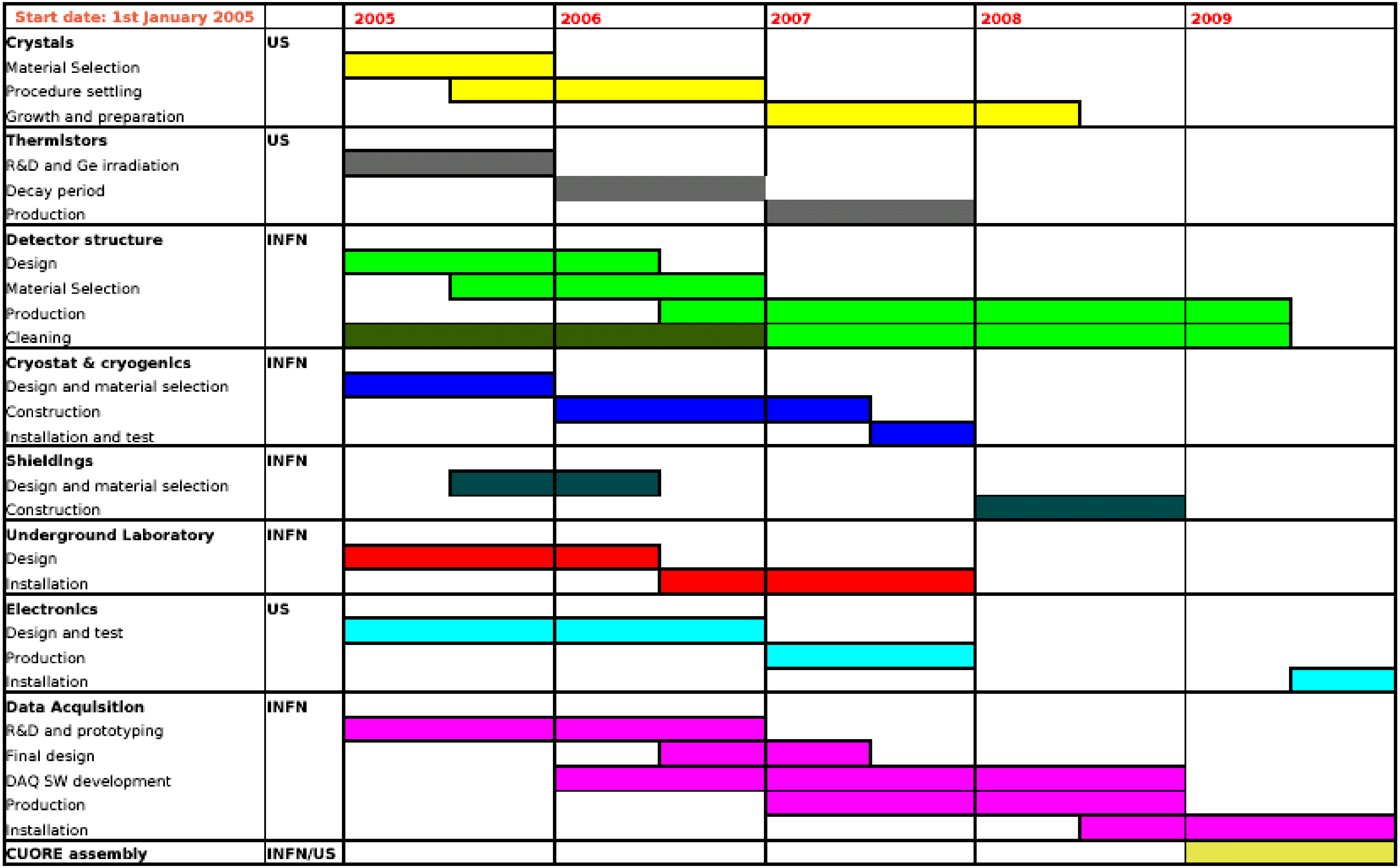
7th June 2004 Scientific approval CSN2 of INFN

September 2004 Final location @ LNGS

September 2004 Approval of CUORE plan by CSN2

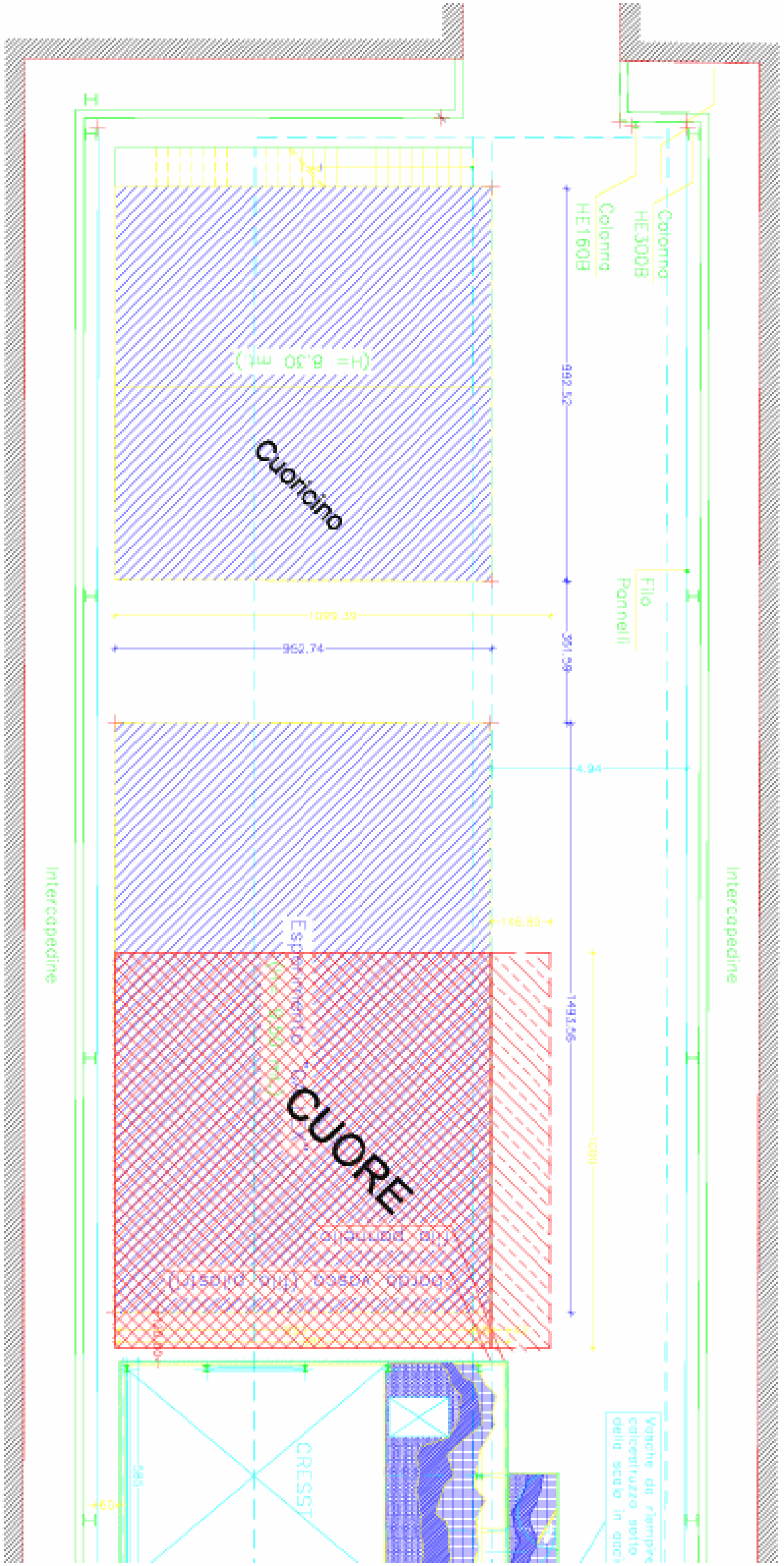
2005 activities + CUORE dilution refrigerator funded by INFN

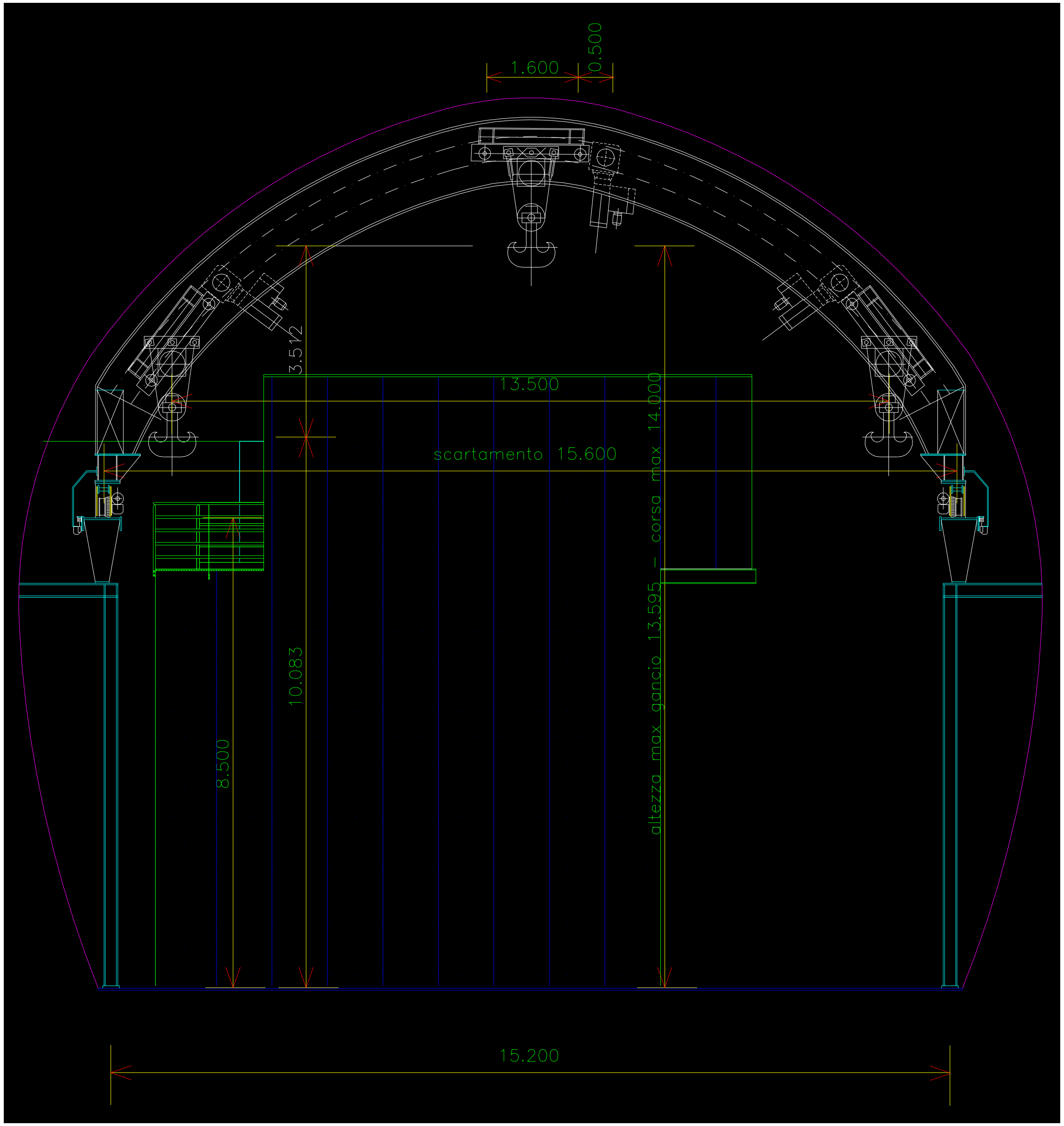
CUORE time schedule



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					🟨🟨

CUORE site
Hall A @ LNGS





CUORE construction

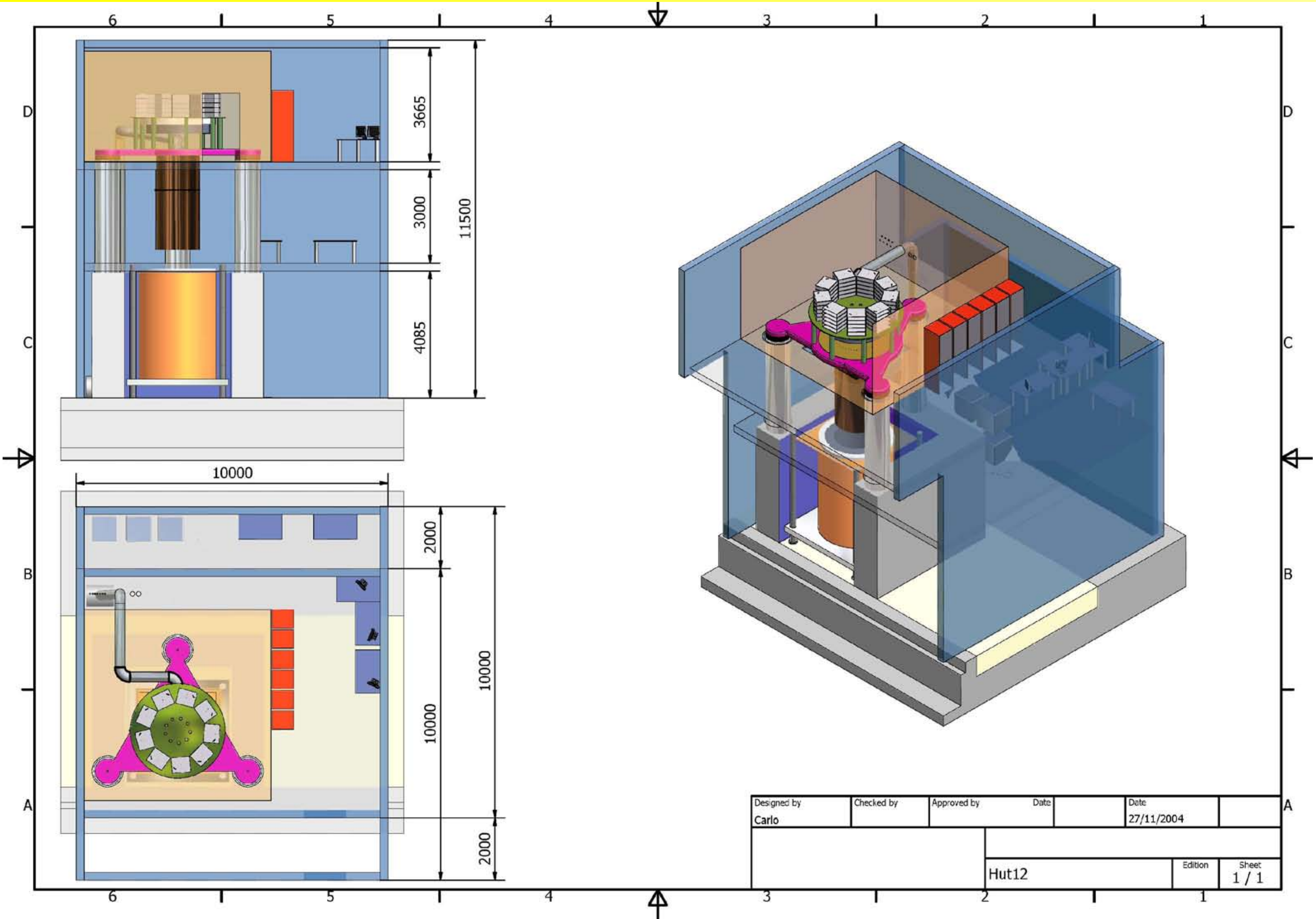
Ongoing activities:

- Underground Laboratory (hut) design, material selection and site preparation (2006: tenders, 2007: construction)
- Dilution refrigerator tender and final design (2006-2007: construction)
- Shieldings final design and material selection
- Best TeO_2 producer selection
- Germanium irradiation for NTD thermistor preparation
- Detector structure optimization for
  - lower background contribution
  - decoupling from setup vibrations
  - Better performance and reproducibility
  - Detector standardization
  - easier and Fast assembling procedure
- Front-end electronics prototypes

and, to be preliminarly tested on CUORICINO

- DAQ prototype
- DAQ + online analysis software

CUORE hut



Designed by Carlo

Checked by

Approved by

Date

Date 27/11/2004

Hut12

Edition

Sheet 1 / 1

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, $\langle \Delta E \rangle = 8$keV**
  - **$\tau_{1/2} \geqslant 1.8 \times 10^{24}$ years at 90% C.L.** ($\langle m_\nu \rangle \leqslant 0.2 \div 1.1$ eV)
  - $S^{1\sigma}_{3\ \mathrm{years}}$ **$\geqslant 6 \times 10^{24}$ years** - $\langle m_\nu \rangle \leqslant 0.11 \div 0.60$ 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