The CUORE and CUORICINO Experiments

(Cryogenic Underground Observatory for Rare Events)

Susana Cebrián

on behalf of the CUORE collaboration

(Università di Milano-Bicocca/Universidad de Zaragoza)

AHEP 2003, Valencia

Outline:

- Description of CUORE
- Results of CUORICINO
- Physics Potential and Prospects

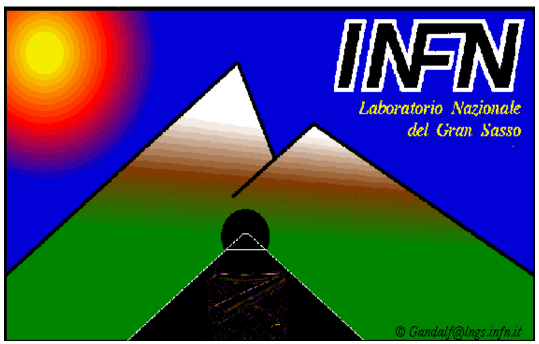
Description of CUORE

The CUORE Collaboration

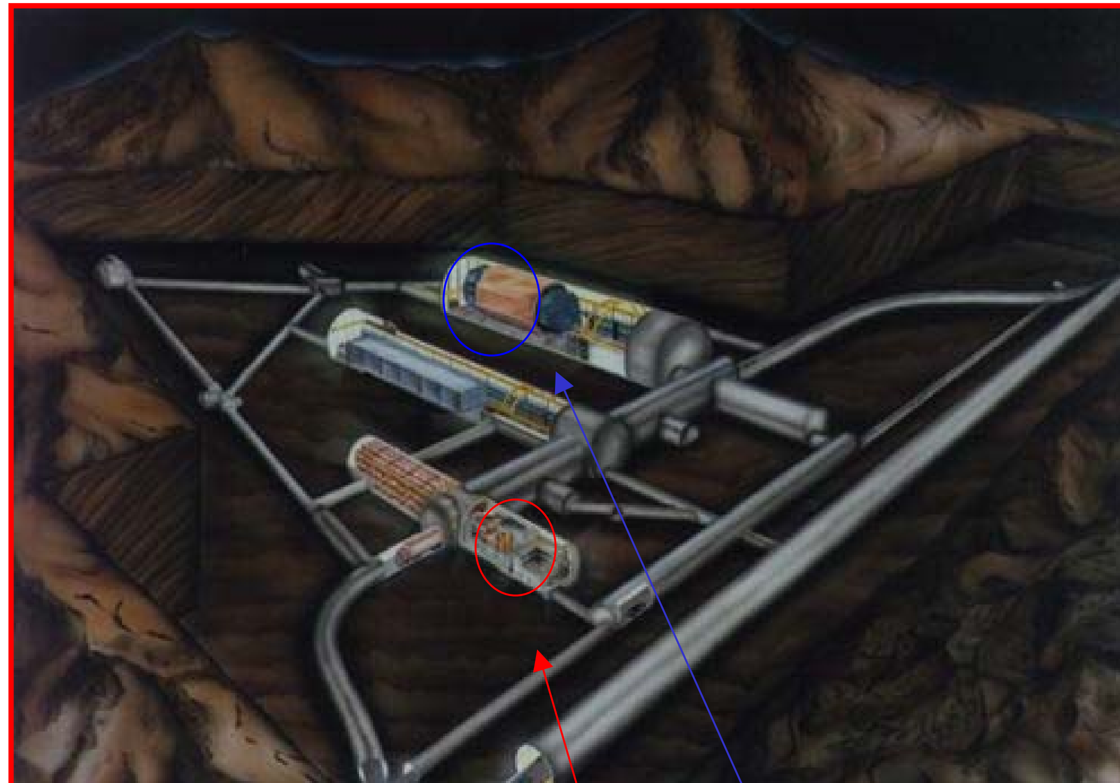
- Dipartimento di Fisica dell'Università di Milano-Bicocca e Sezione di Milano dell'INFN, Milano I-20126, Italy
- Dipartimento di Ingegneria Strutturale del Politecnico di Milano, Milano I-20133, Italy
- Dept. of Physics and Astronomy, University of South Carolina, Columbia S.C. 29208 USA
- Laboratori Nazionali del Gran Sasso, I-67010, Assergi (L'Aquila), Italy
- Dipartimento di Fisica dell' Università di Firenze e Sezione di Firenze dell' INFN, Firenze I-50125, Italy
- Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA
- Lab. of Nucl. and High Energy Physics, University of Zaragoza, 50009 Zaragoza, Spain
- Kamerling Onnes Laboratory, Leiden University, 2300 RAQ Leiden, The Netherlands
- Dipartimento di Scienze Chimiche, Fisiche e Matematiche dell'Università dell'Insubria e Sezione di Milano dell' INFN, Como I-22100, Italy
- Dipartimento di Fisica dell'Università di Genova e Sezione di Genova dell' INFN, Genova I-16146, Italy
- Dept. of Materials Science and Engineering, University of California, Berkeley CA 94720, USA
- Laboratori Nazionali di Legnaro, I-35020 Legnaro (Padova), Italy

Location: LNGS

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



- At a depth of 3500 m.w.e.

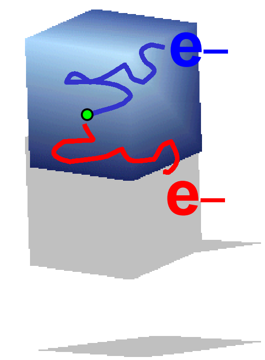


Two dilution refrigerators:

Hall A (CUORICINO)

Hall C (R&D final tests for CUORE)

Why using TeO_2 bolometers?



- Advantages of the *source = detector* approach with bolometers
  - wide choice of materials ⟶ study new DBD candidates
  - detectors with an energy resolution comparable with that of Ge diodes

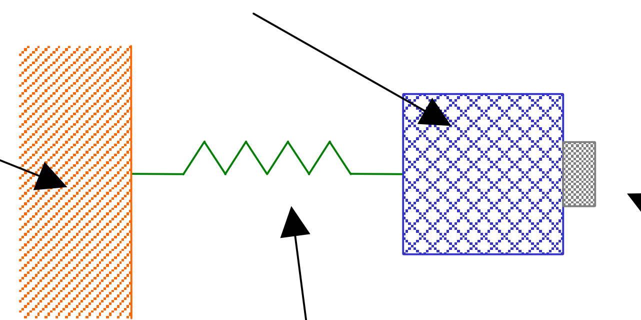
- Advantages of ^{130}*Te*
  - high natural isotopic abundance i.a. = 33.87 % ⟶ excellent feature for future reasonable-cost expansion of DBD experiments
  - high transition energy Q = (2528.8 ± 1.3) keV ⟶ large phase space, lower background (clean window between full energy and Compton edge of ^{208}Tl photons)
  - encouraging theoretical calculations for 0ν–DBD lifetime ⟶ $\langle m_\nu \rangle \approx 0.1$ eV ⇔ $\tau \approx 10^{26}$ y
  - already observed DBD with geo-chemical techniques $\tau_{1/2\ incl} = (0.7 - 2.7) \times 10^{21}$ y

Cryogenic detectors

Energy absorber
TeO_2 crystal
$C \cong 2$ nJ/K $\cong$ 1 MeV / 0.1 mK

Excellent mechanical and thermal properties

Heat sink
$T \cong 10$ mK



Thermometer
NTD Ge-thermistor
$R \cong 100$ MΩ
$dR/dT \cong 100$ kΩ/μK

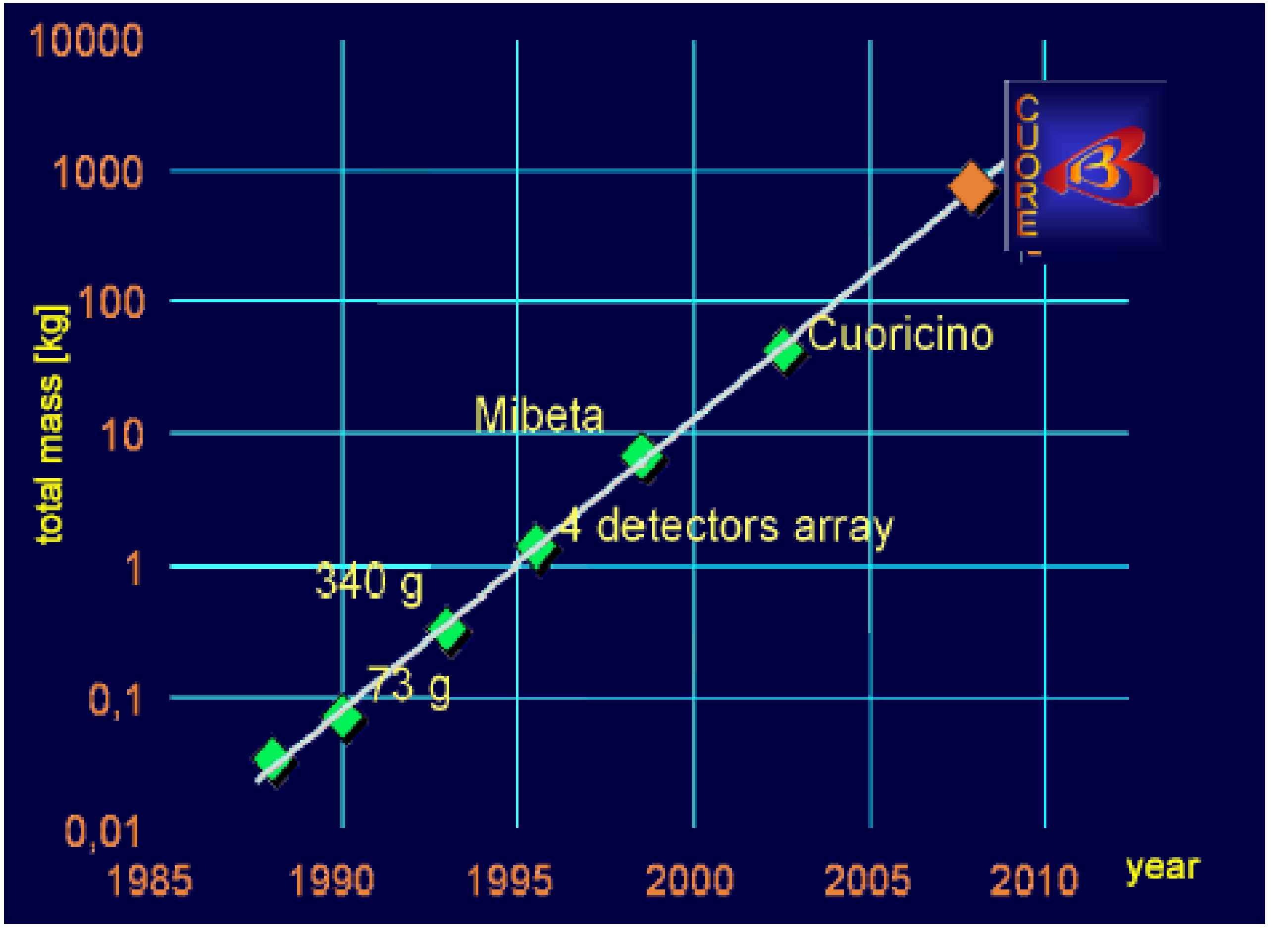
Thermal coupling
$G \cong 4$ nW / K = 4 pW / mK

- Temperature signal: $\Delta T = E/C \cong 0.1$ mK for $E = 1$ MeV
- Voltage signal: $\Delta V = I \times dR/dT \times \Delta T \Rightarrow \Delta V = 1$ mV for $E = 1$ MeV
- Signal recovery time: $\tau = C/G \cong 0.5$ s
- Noise over signal bandwidth (a few Hz): $V_{rms} = 0.2\ \mu V$

Energy resolution (FWHM): $\cong$ 1 keV

MiDBD Experiment

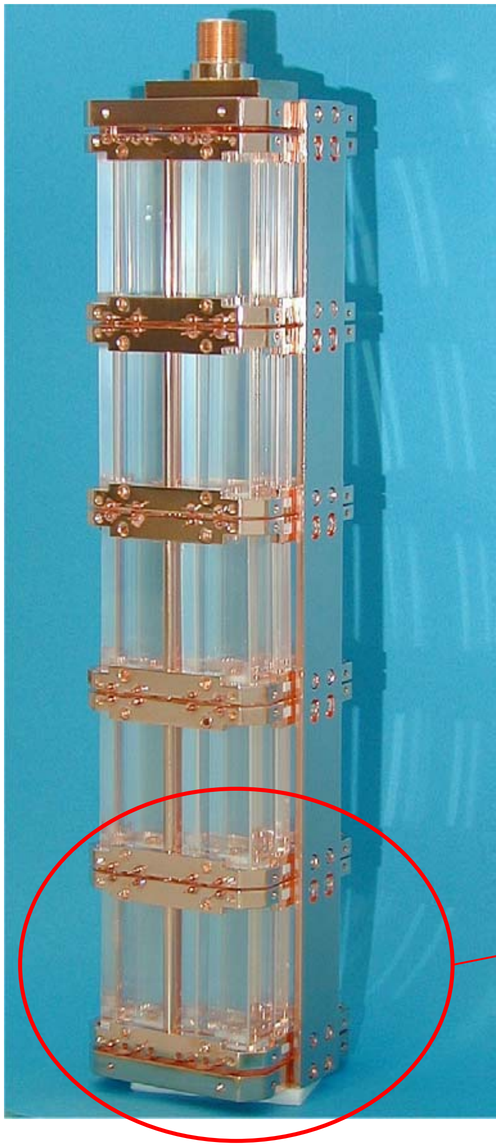
1990: the first TeO_2 bolometer
1993: the first experiment with a 334 g TeO_2detector
1995: the first array with 4 334 g crystals
1997: the 20 (340 g) crystal array (**Mi-DBD I**)
1998-2002: tests on 750 g TeO_2 crystals
2001: the 20 crystal array is rebuilt with a new structure and with cleaner materials (**Mi-DBD II**)

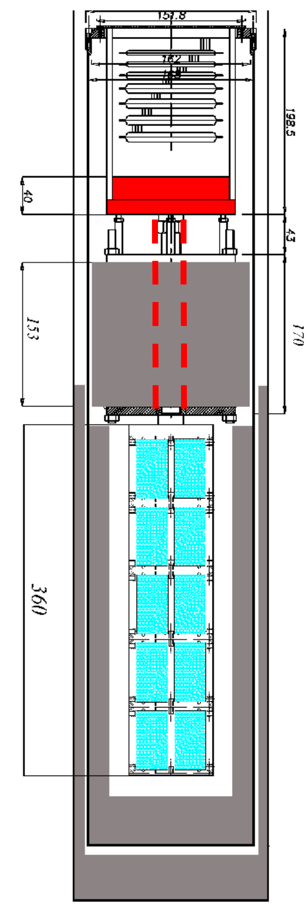


Mi-DBD experimental set-up: a general test for the CUORICINO set-up

MiDBD Experiment

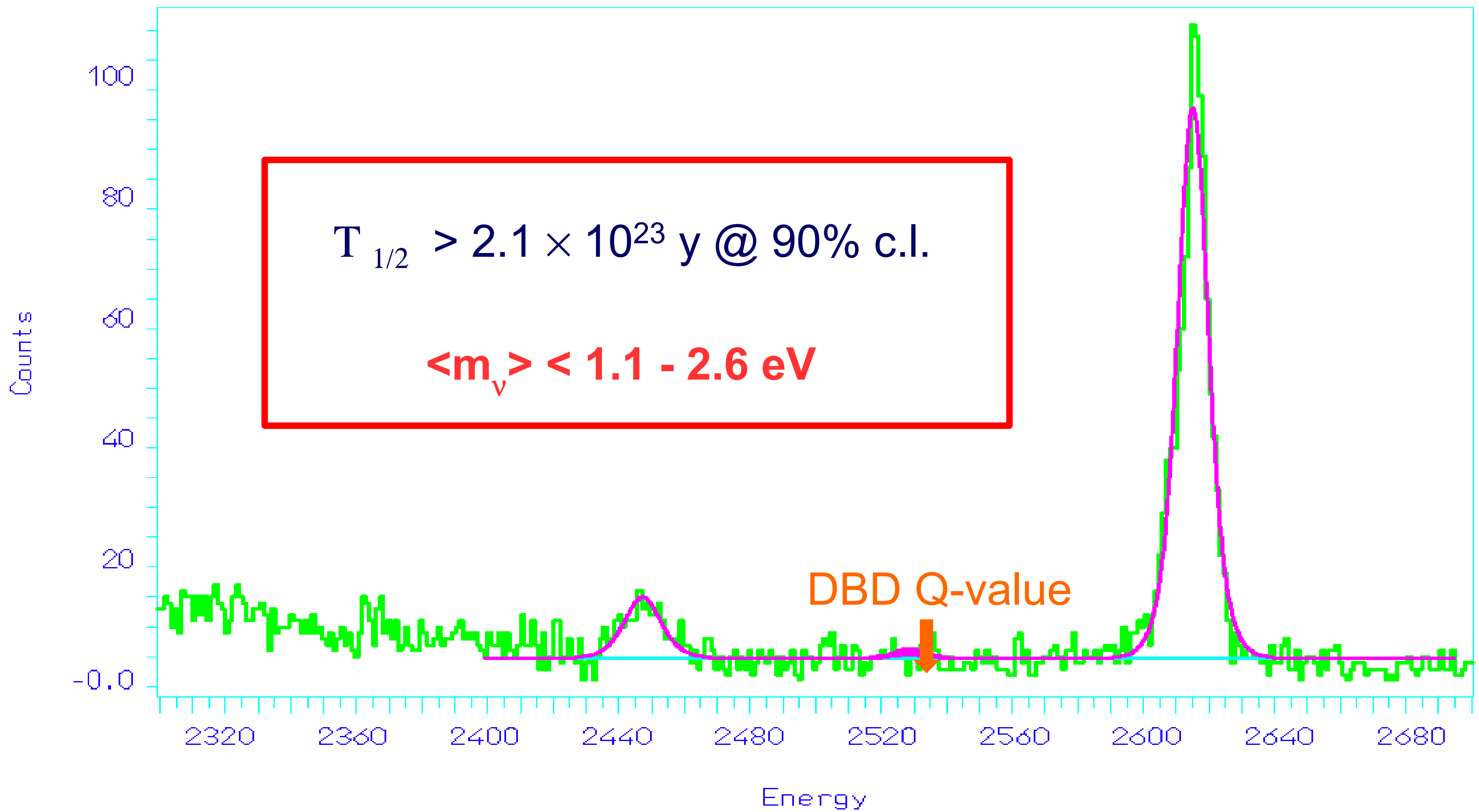
- 5 modules, 4 detector each (3x3x6 cm^3 TeO_2 crystals, 340 g) arranged in a tower-like compact structure (6.8 kg)
- the tower mounted inside a dilution refrigerator
- the tower surrounded by an inner Roman lead shield,
- all the refrigerator by a 20 cm thick outer lead shield
  + borated PET shield





MiDBD Experiment

limits on ^{130}Te 0νDBD: total statistics: 4.3 kg y, bkg ~ 0.3 c/keV/kg/y

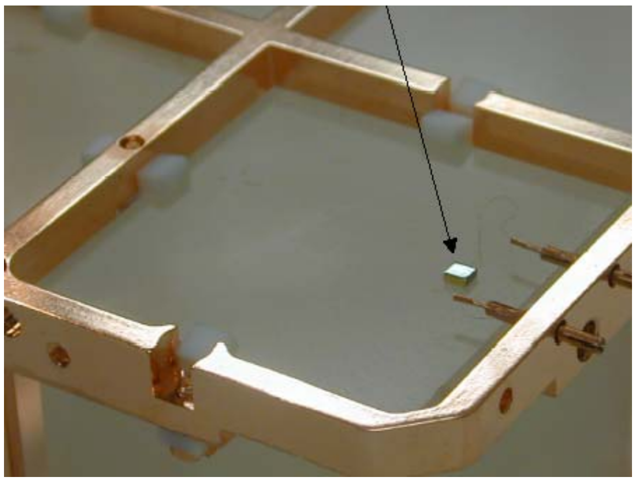


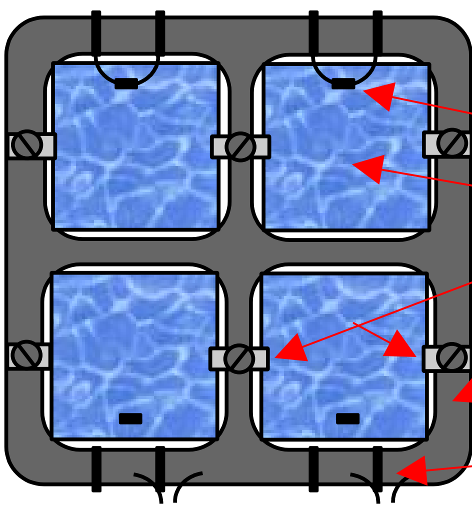
Ref.: C. Arnaboldi et al. Phys. Lett. B 557 (2003) 167-175

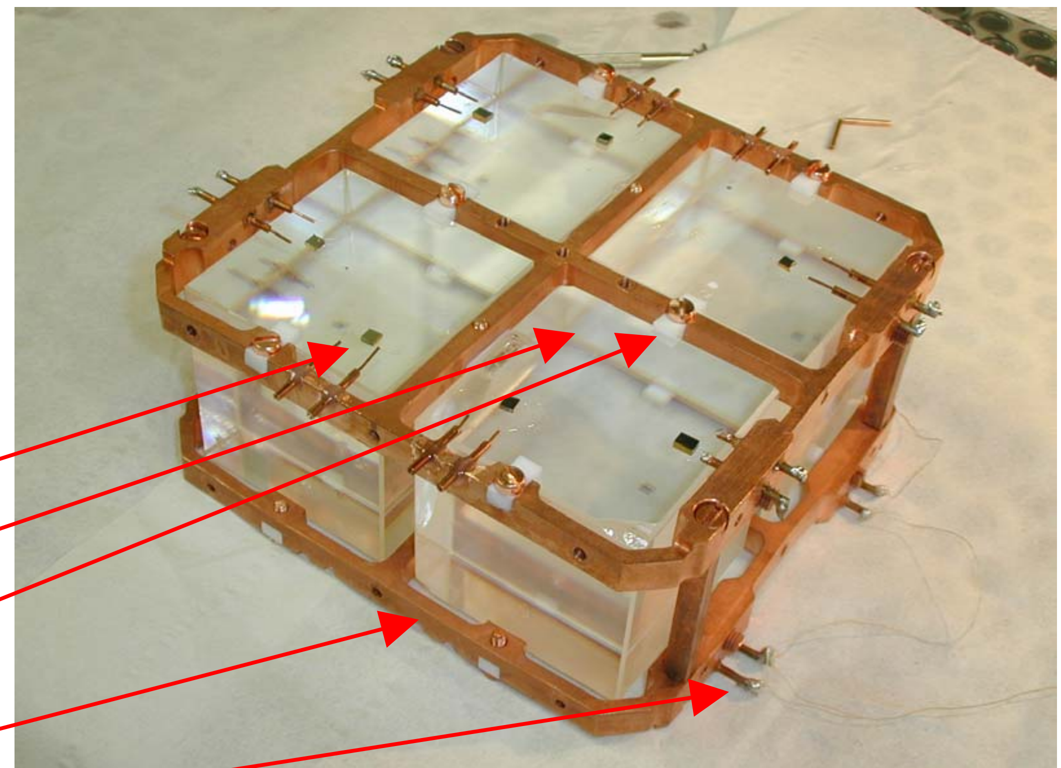
Detectors: the elementary module

a 4-crystal plane is a mechanically independent module made of 4 TeO_2 crystals (760 g each, 5x5x5 cm^3), various 4-crystal planes have been tested with good results on both reproducibility and reliability

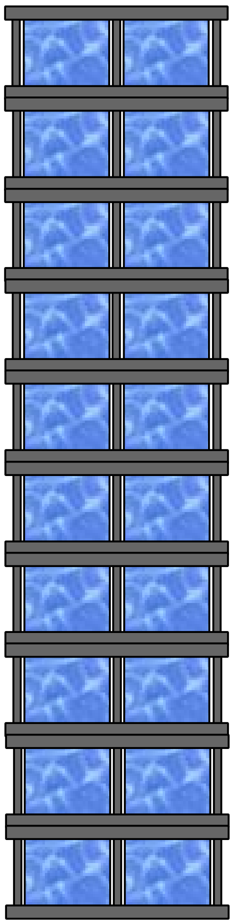
energy resolution	~ 1 keV at threshold
	5 - 10 keV at 3 MeV



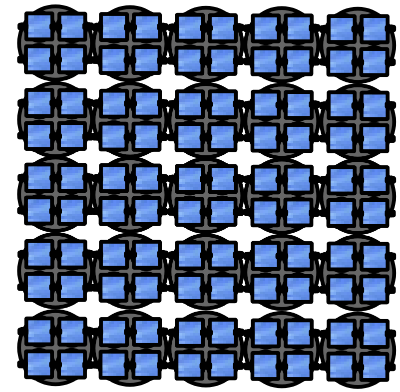




Detectors: the tower and the array

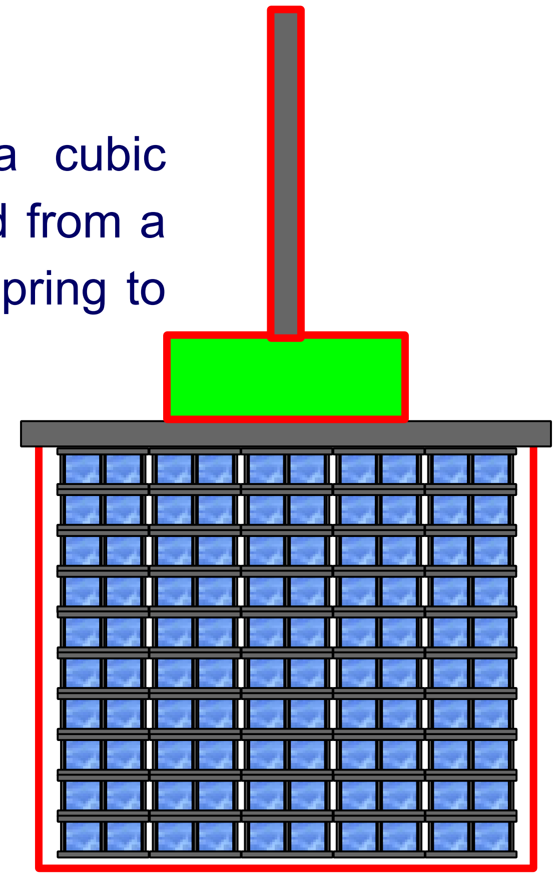


a tower contains 10 modules, as in the case of the 4-crystal modules, towers are independent structures



a single tower of CUORE has been already built and is installed in Hall A

the 25 towers, 1000 crystals are organized in a cubic structure (a 5x5 matrix), the towers will be suspended from a large square copper plate connected with a vertical spring to the dilution refrigerator



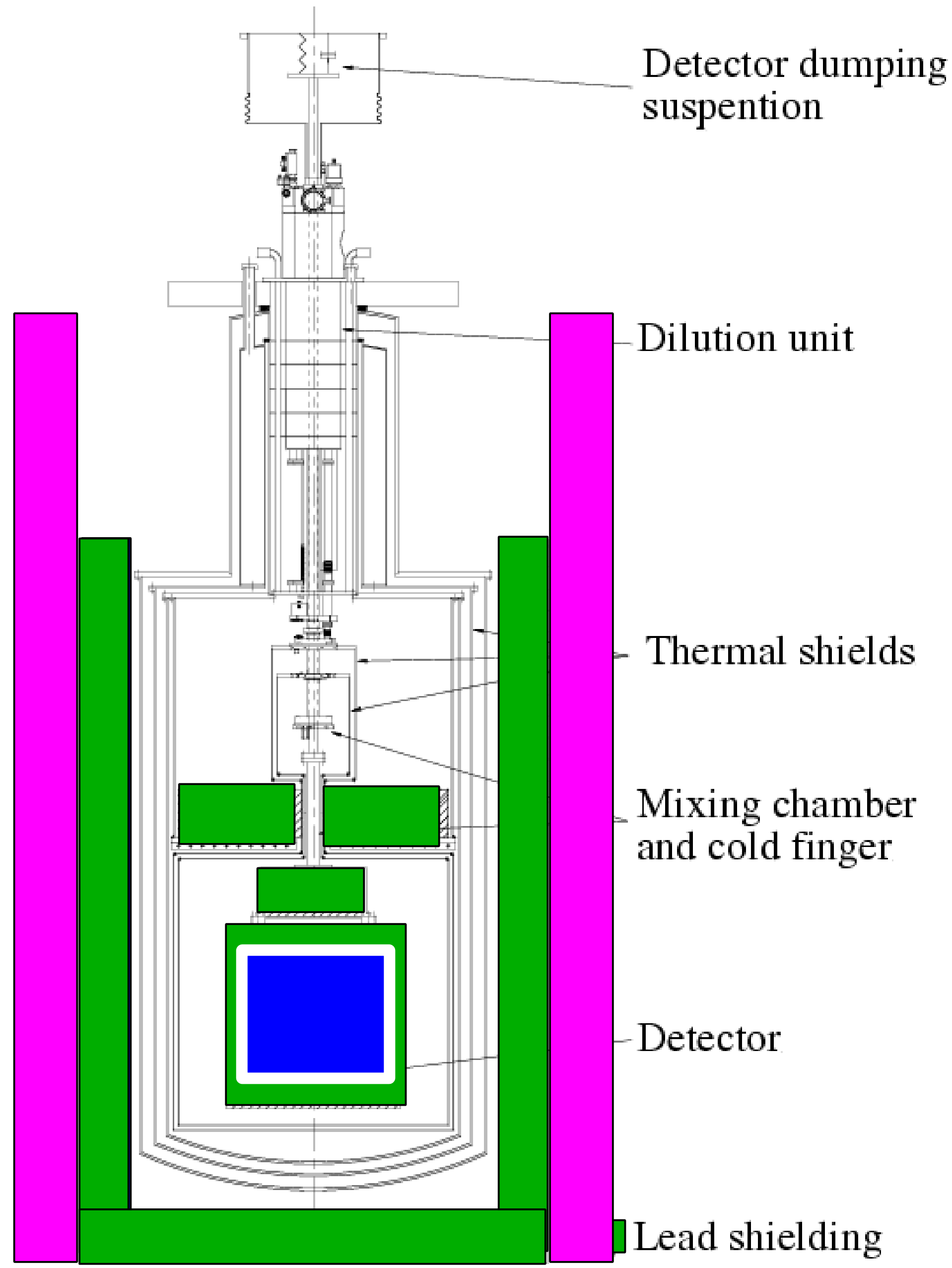
0.75 kg x 1000 = **750 kg TeO_2**
= 600 kg Te = **203 kg ^{130}Te**

A SINGLE HIGH GRANULARITY DETECTOR

Experimental set-up: refrigerator and shielding

the **CUORE** array:

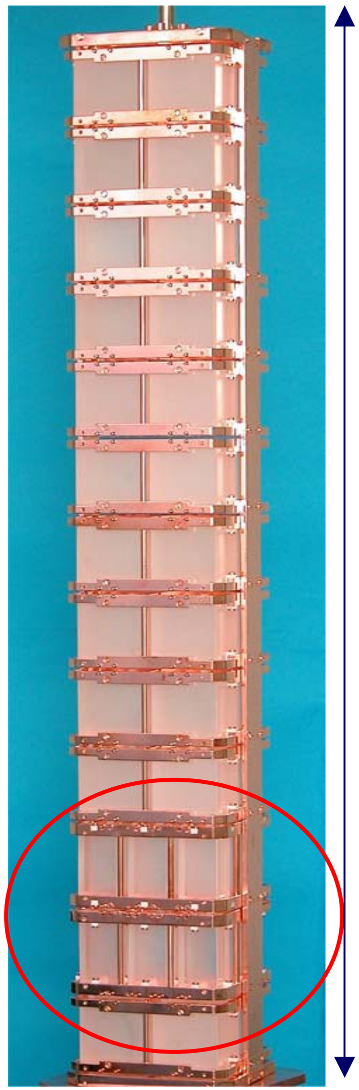
- bolometers placed in a new, specifically designed single dilution refrigerator at **~10 mK**
- as close as possible, with a minimum amount of material among them, inside a cubic copper box
- surrounded by 3 cm of **roman lead**
- an additional 20 cm layer of **low activity lead** will be used to shield the array from the refrigerator dilution unit
- a **lead shield** and a **borated PET** neutron shield will surround completely the cryostat



Results of CUORICINO

CUORICINO detectors

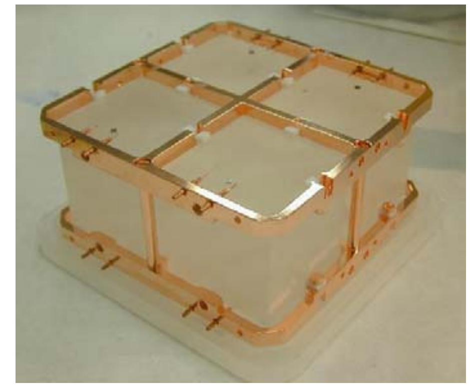
44 TeO_2 crystals 5x5x5 cm^3 + 18 TeO_2 crystals 3x3x6 cm^3



0.8 m

11 modules, 4 detector each,
crystal dimension 5x5x5 cm^3
crystal mass 790 g

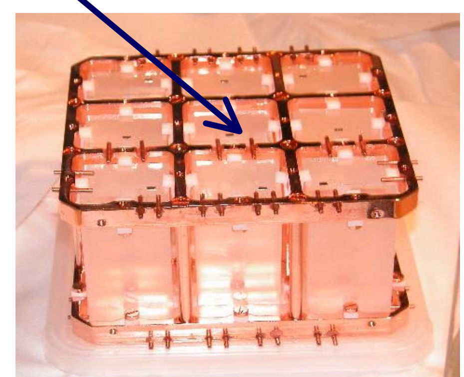
4 x 11 x 0.79 = 34.76 kg of TeO_2



This detector is completely surrounded by active materials -> substantial improvement in BKG reduction

2 modules, 9 detector each,
crystal dimension 3x3x6 cm^3
crystal mass 330 g

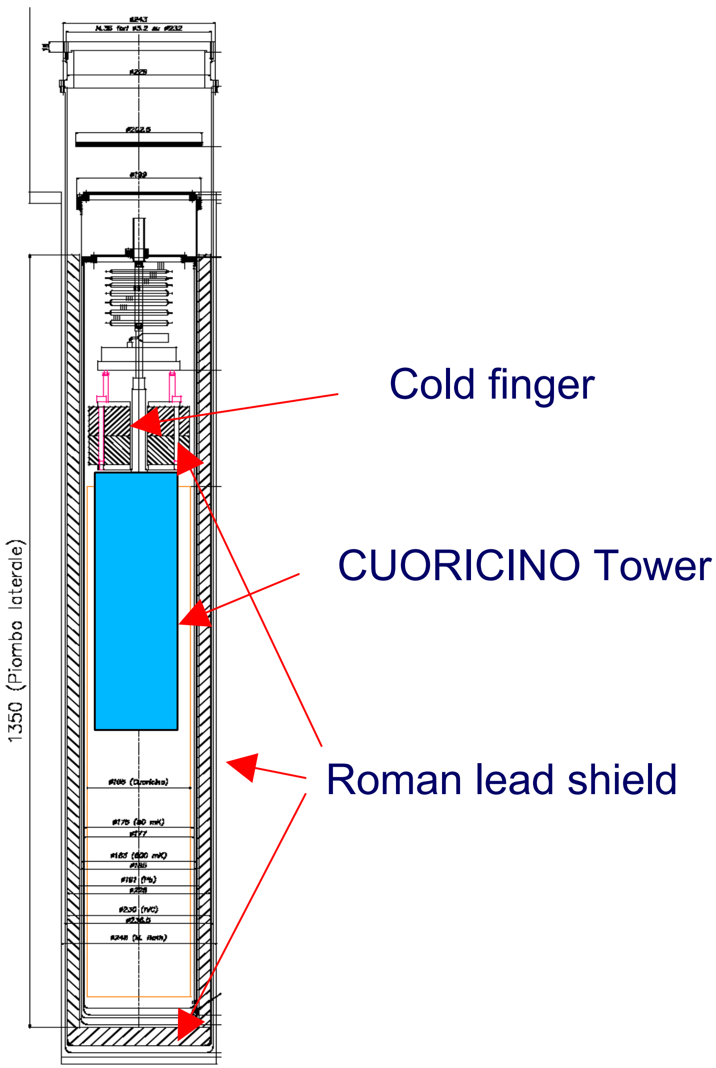
9 x 2 x 0.33 = 5.94 kg of TeO_2

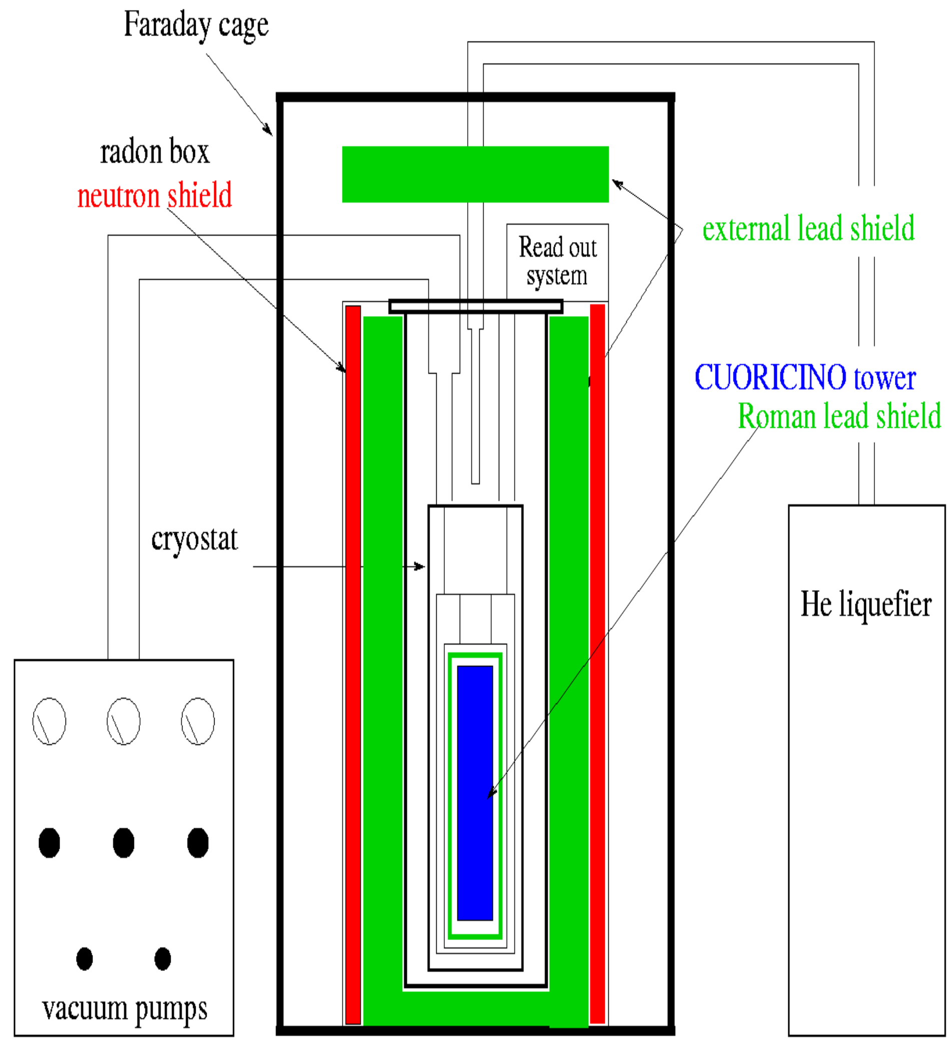


CUORICINO TOTAL ACTIVE MASS = 40.7 kg of TeO_2

CUORICINO set-up

- In the Hall A refrigerator where the Mi-DBD 20 array worked
- Array with a tower-like structure similar to the single tower of CUORE (the only difference is that it contains 2 planes of 3x3x6 crystals)





CUORICINO Assembling

Detectors: all the operations done in nitrogen atmosphere

Tower: almost completely done in nitrogen atmosphere

Data Taking

april - july 2003

Cool down: february 2003

Detectors: 14 electrical connections were lost during the cooling of the tower, as a result 14 detectors cannot be read-out (to recover the electrical connections it is necessary to warm up the cryostat)

4x11 = 44 large size crystals (~5x5x5 cm^3 av. mass = 790 g) 32 working, 25000 h kg

9x2 = 18 small size crystals (~3x3x6 cm^3 av. mass = 330 g) 16 working, 2300 h kg

Active mass during this run:

32 x 0.790 = 25.28 kg

12 x 0.330 = 3.96 kg

} 29.24 kg = 9.9 kg ^{130}Te - 72%

2 (^{130}Te-enriched) x 0.330 = 0.660 kg = 0.495 kg ^{130}Te

2 (^{128}Te-enriched) x 0.330 = 0.660 kg = 0.543 kg ^{128}Te

→ **10.4 kg ^{130}Te**

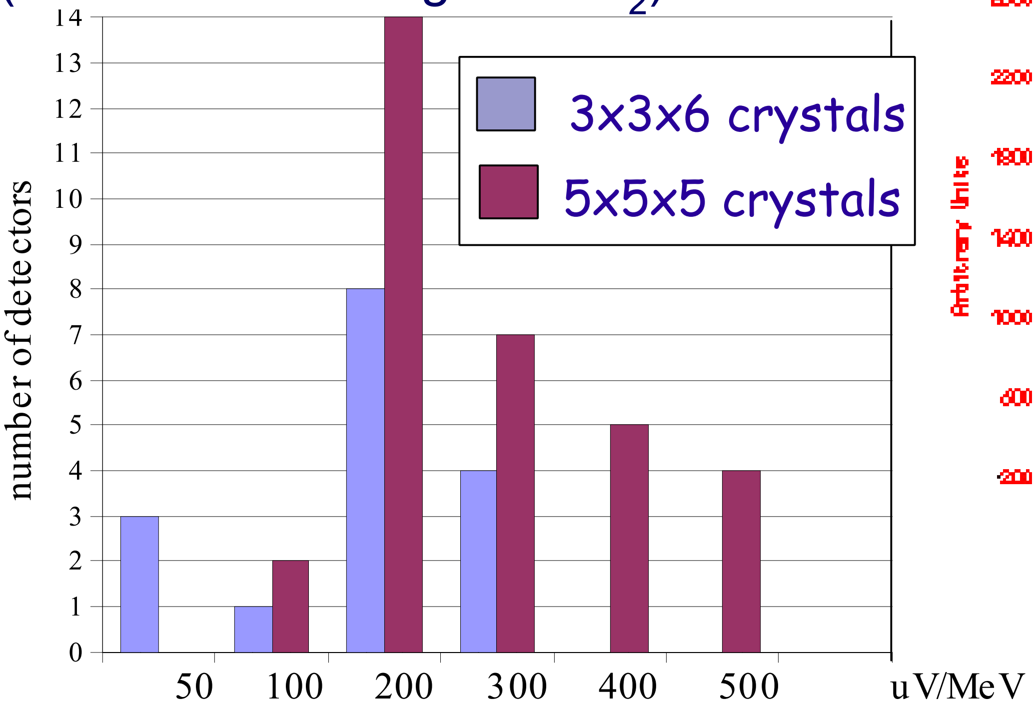
Detector Performance: pulse height

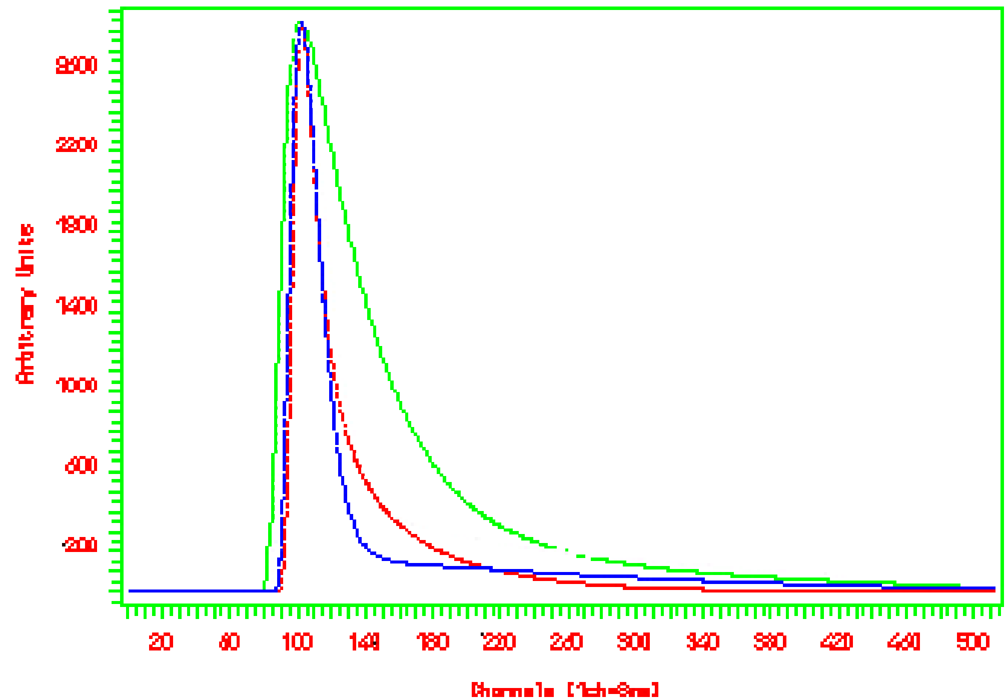
average pulse height for 5x5x5 crystals = 340 μV/MeV

average pulse height for 3x3x6 crystals = 440 μV/MeV

Pulse height distribution μV/MeV

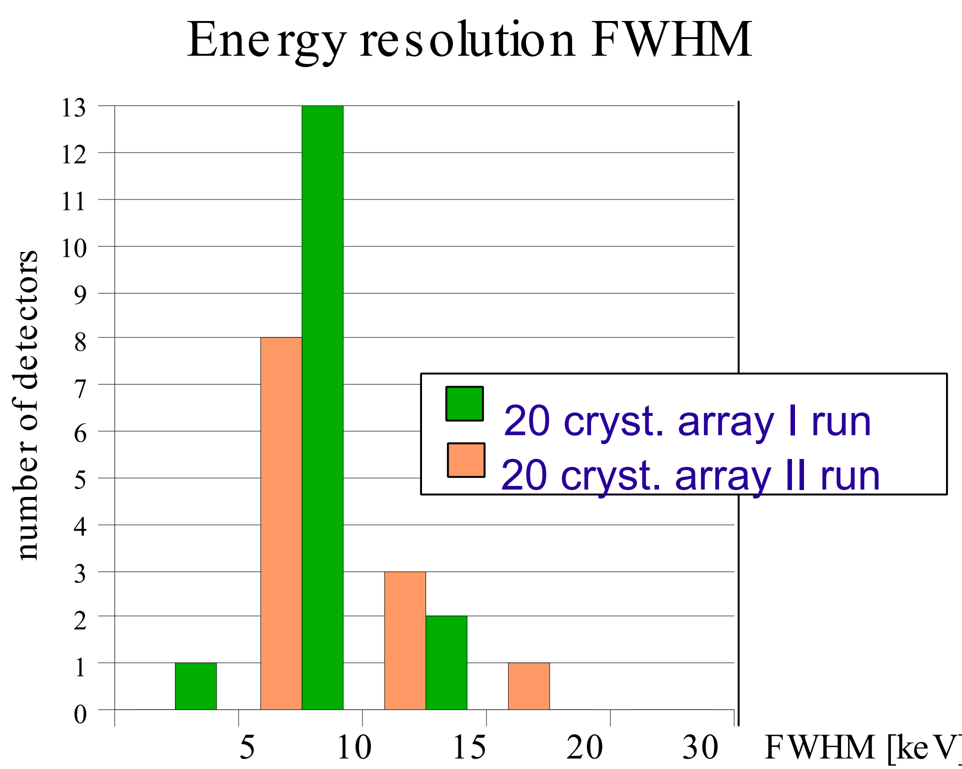
(normalized to 1 kg of TeO_2)

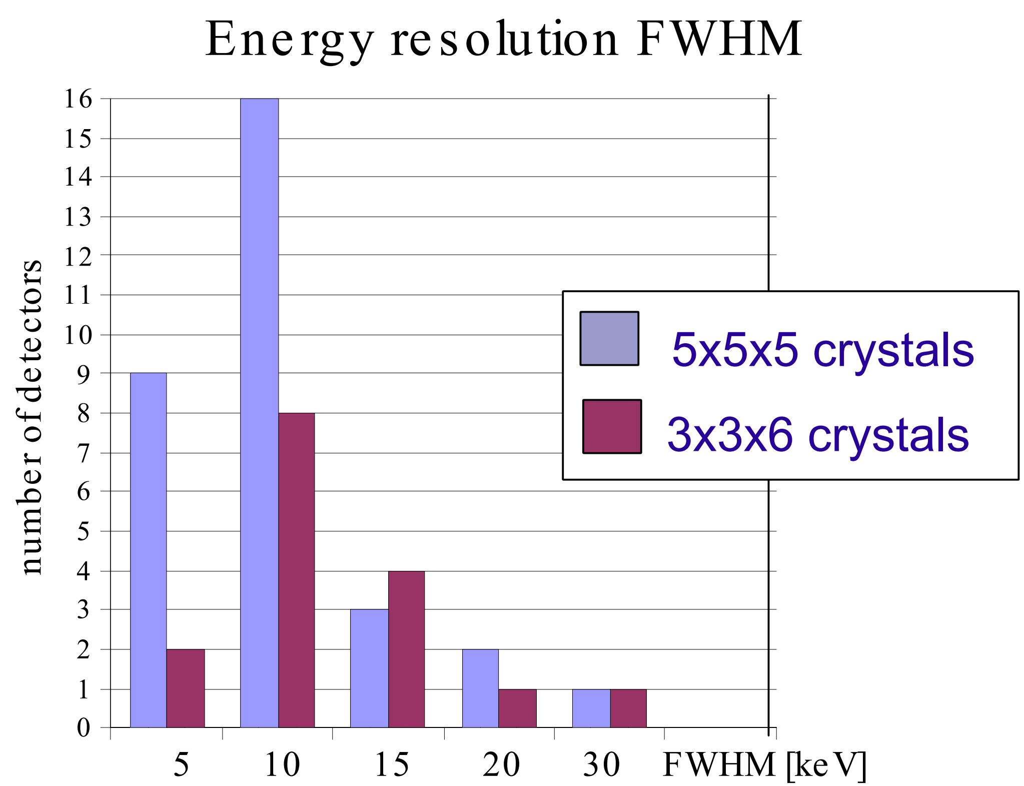




Detector Performance: energy resolution

FWHM [keV] of the **2615 keV gamma line** of ^{208}Tl (3-day calibration ^{232}Th source)
average 5x5x5 cm^3 crystals ~ 7 keV
average 3x3x6 cm^3 crystals ~ 9 keV



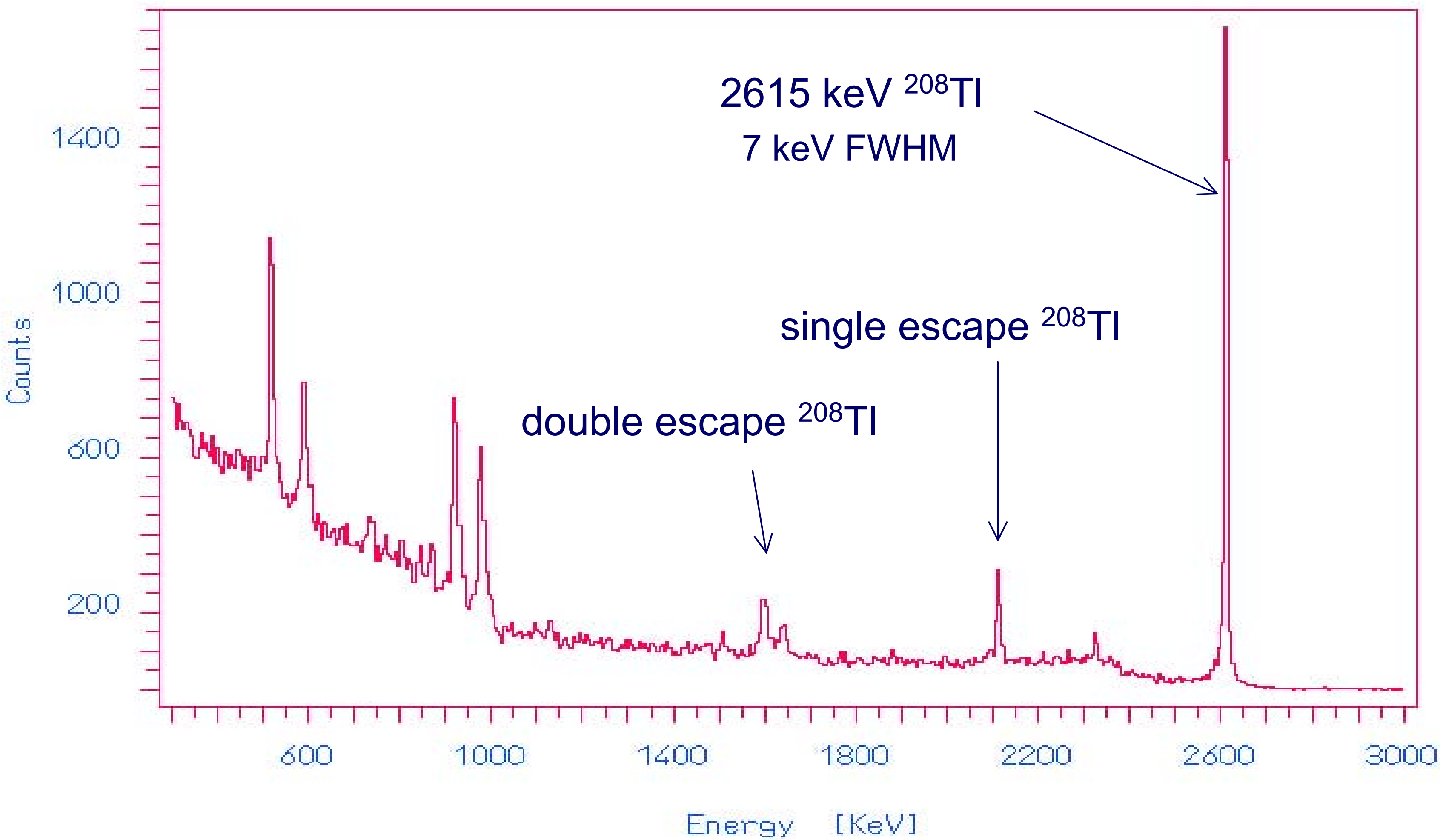


FWHM [keV] of the **122 keV gamma line** of ^{57}Co
average 5x5x5 cm^3 crystals ~ 2.8 keV
average 3x3x6 cm^3 crystals ~ 1.5 keV

Detector Performance: energy calibration

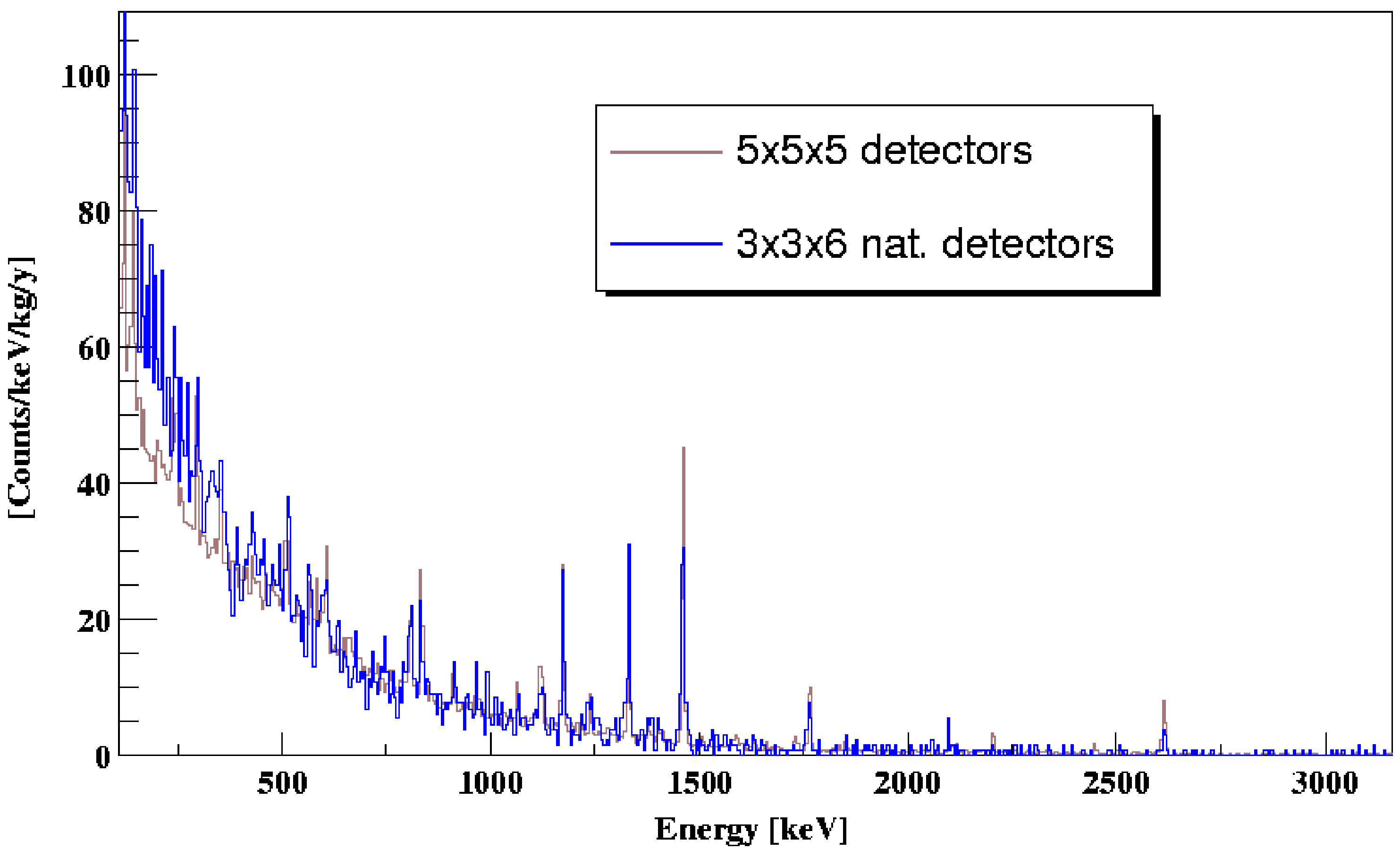
^{232}Th calibration

5x5x5 cm^3 crystals

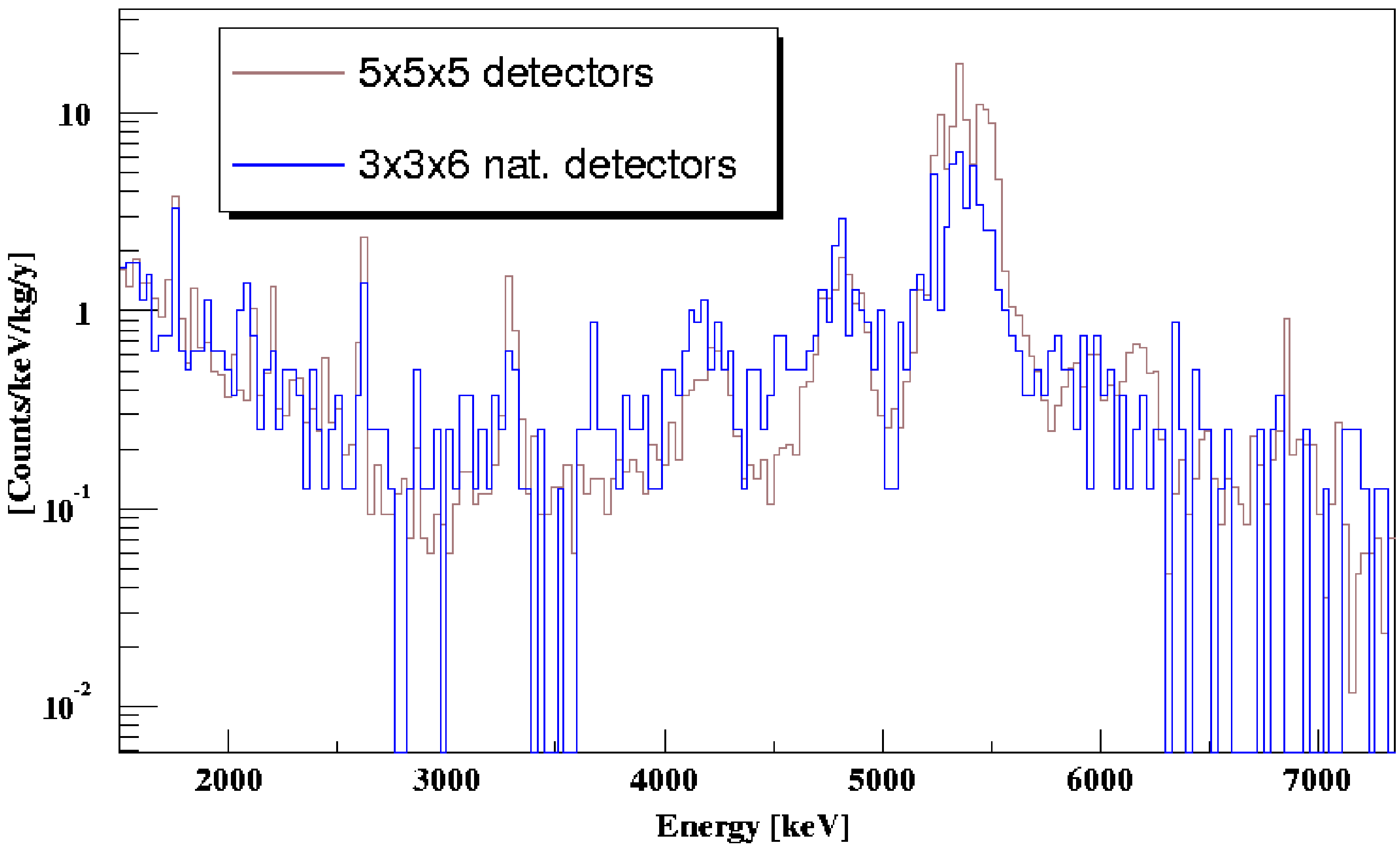


Background: gamma region

- Gamma lines due to ^{60}Co, ^{40}K, ^{238}U and ^{232}Th
- Gamma lines due to Te and Cu cosmogenic activation



Background: alpha region



Background: MiDBD II vs CUORICINO

- gamma peaks of ^{60}Co, ^{40}K, ^{208}Tl have a higher intensity in CUORICINO but the internal roman lead shield has a lateral thickness much reduced (2 cm less)
- continuum background in the 2-3 MeV region is reduced
- alpha peaks due to surface contamination of the crystals are reduced

counts/keV/kg/year	1-2 MeV	2-3 MeV	3-4 MeV	4-5 MeV
MiDBD-II	3.21±0.08	0.61±0.04	0.29±0.02	1.88±0.06
3x3x6 natural	3.29±0.11	0.38±0.04	0.24±0.03	0.78±0.05
5x5x5	3.25±0.09	0.41±0.03	0.17±0.02	0.55±0.03

First Results

Background in the ββ region 2480-2600 keV

(ββ ^{130}Te transition energy = 2528.8 keV)

anticoincidence spectrum, only 5x5x5 crystals

b = 0.23 ± 0.04 c/keV/kg/y

3 year sensitivity CUORICINO (full mass): b=0.23 Γ=8 keV

$F^{0\nu}_{3\ years} = 7.5 \times 10^{24}$ y $\quad <m_\nu> \sim 0.15 - 0.38$ eV

Sensitivity:

$$F^{0\nu} = 4.17 \times 10^{26} \times \frac{a}{A} \left(\frac{M\,T}{b\,\Gamma} \right)^{1/2} \times \varepsilon$$

Isotopic abundance (a)

Atomic mass (A)

Detector mass (kg) (M)

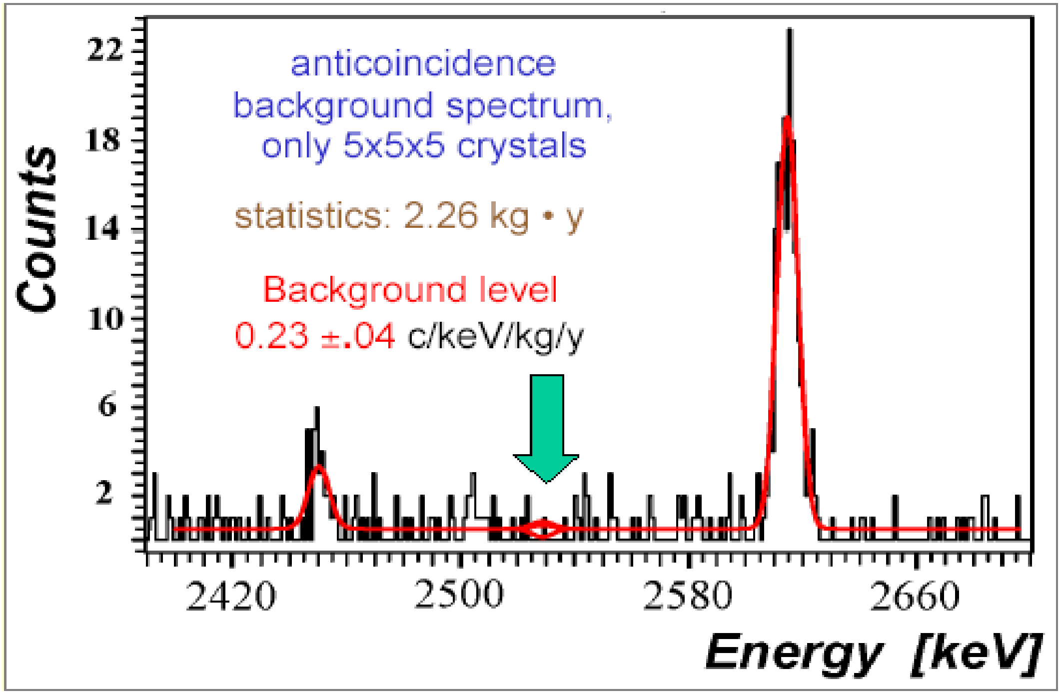
Running time (y) (T)

BKG (counts/keV/kg/y) (b)

Energy resolution (keV) (Γ)

Detector efficiency (ε)

First results on 0ν–ββ ^{130}Te decay



Authors/Ref.	Method	$T_{1/2}(\langle m_\nu \rangle = 1$ eV) (10^{23} y)	F_N (10^{-13})	$\langle m_\nu \rangle$ l.l. (eV)
Staudt et al., 1992 [6]	pairing (Paris)	0.77-0.88	34-29	0.39-0.42
	pairing (Bonn)	0.9-1.1	29-24	0.42-0.46
Pantis et al., 1996 [7]	no p-n pairing	8.64	3.0	1.31
	p-n pairing	21.1	1.24	2.05
Tomoda, 1991 [8]		5.2	5.03	1.02
Barbero et al., 1999 [9]		3.36	7.77	0.82
Simkovich, 1999 [10]	pn-RQRPA	14.5	1.79	1.7
Suhonen et al., 1992 [11]		8.34	3.13	1.29
Muto et al., 1989 [12]		4.89	5.34	0.99
Stoica et al., 2001 [13]	large basis	10.7	2.44	1.46
	short basis	9.83	2.66	1.40
Faessler et al., 1998 [14]		9.4	2.78	1.37
Engel et al., 1989 [15]	general seniority	2.4	10.9	0.69
Aunola et al., 1998 [16]	WS	4.56	5.72	0.96
	AWS	5.16	5.06	1.02

$\tau_{1/2}^{0\nu}$ > 5.0 10^{23} years at 90% C.L.

$\langle m_\nu \rangle$ < 0.4 – 2 eV

Conclusions from CUORICINO to CUORE

from CUORICINO …

- apparatus: proves the feasibility of a large bolometric array
- detectors: shows that detector performances are not affected by the increase in crystal size (from 340 g to 790 g)
- background achievements: the improvement in bkg obtained in CUORICINO, despite the reduced shield, proves the reproducibility of cleaning and handling procedures (MiDBD-II was used as a test bench to verify surface cleaning techniques)
- background study: CUORICINO data will be used to further study bkg sources in CUORE

… to CUORE

- apparatus: R&D will be dedicated to cryostat and mechanical apparatus design (it will contain 25 towers similar to the CUORICINO one)
- detectors: R&D underway to guarantee detector reproducibility and uniformity
- **the real challenge of CUORE will be the control and reduction of background:**
  - only low radioactivity materials will be employed to build the refrigerator and the entire mechanical set up for CUORE
  - special techniques for surface cleaning will be applied.

Physics Potential and Prospects

MC simulation for background contributions

❖ Bulk contamination is not a problem **< 0.004 counts/keV/kg/y**
(MC simulation with MEASURED 90% upper limits on material contaminations)

❖ Surface contamination from passive materials is potentially dangerous, but the amount of Cu facing the detector will be reduced by a factor 10 -100 with respect to now **~ 0.01 – 0.001 counts/keV/kg/y**

❖ Environmental radioactivity contribution is reduced to a minimum thanks to the lead and neutron shields

❖ Cosmogenic activation of Cu and Te will be reduced to a minimum by the underground storage of materials

❖Two neutrino double beta decay contribution **< 0.0001 counts/keV/kg/y**

Physics Potential: Double Beta Decay

$$0\nu \text{ sensitivity} = \ln 2 \; N_A \frac{a.i.}{A} \sqrt{\frac{M\,t}{b\Gamma}}\;\varepsilon = 2.1\;10^{25}\sqrt{\frac{t}{B\Gamma}}$$

CUORE

Pessimistic estimation: b = 0.01 c/keV/kg/y , Γ = 5 keV

$F^{0\nu} = 9.4 \times 10^{25} \times (T[y])^{1/2}$

$\langle m_\nu \rangle <$ 40 – 249 meV $\times (T[y])^{1/4}$
(27-167 meV in 5 years)

Optimistic estimation: b = 0.001 c/keV/kg/y, Γ = 5 keV

$F^{0\nu} = 2.96 \times 10^{26} \times (T[y])^{1/2}$

$\langle m_\nu \rangle <$ 22.4 - 140.6 meV $\times (T[y])^{1/4}$
(15-94 meV in 5 years)

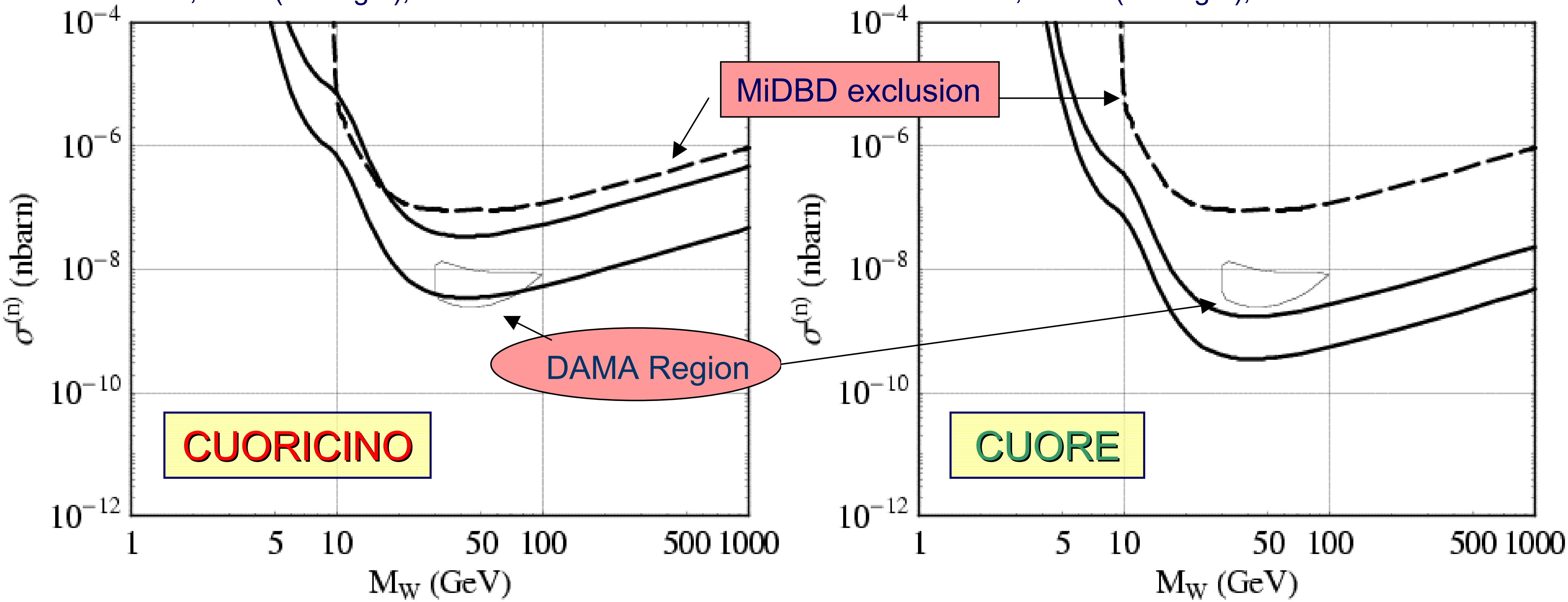
Physics Potential: Dark Matter WIMPs

- Direct Detection of WIMPs filling the galactic halo
- Expected **exclusion plots** for Scalar Spin Independent Interactions

Ref.: C. Arnaboldi et al, Astrop. Phys. In press, hep-ex/0302021

Energy Threshold: 10 keV, Exposure: 2 years
B=1, 0.1 c/(keV kg d), FWHM=1 keV

Energy Threshold: 10 keV, Exposure: 1 years
B=0.05, 0.01 c/(keV kg d), FWHM=1 keV

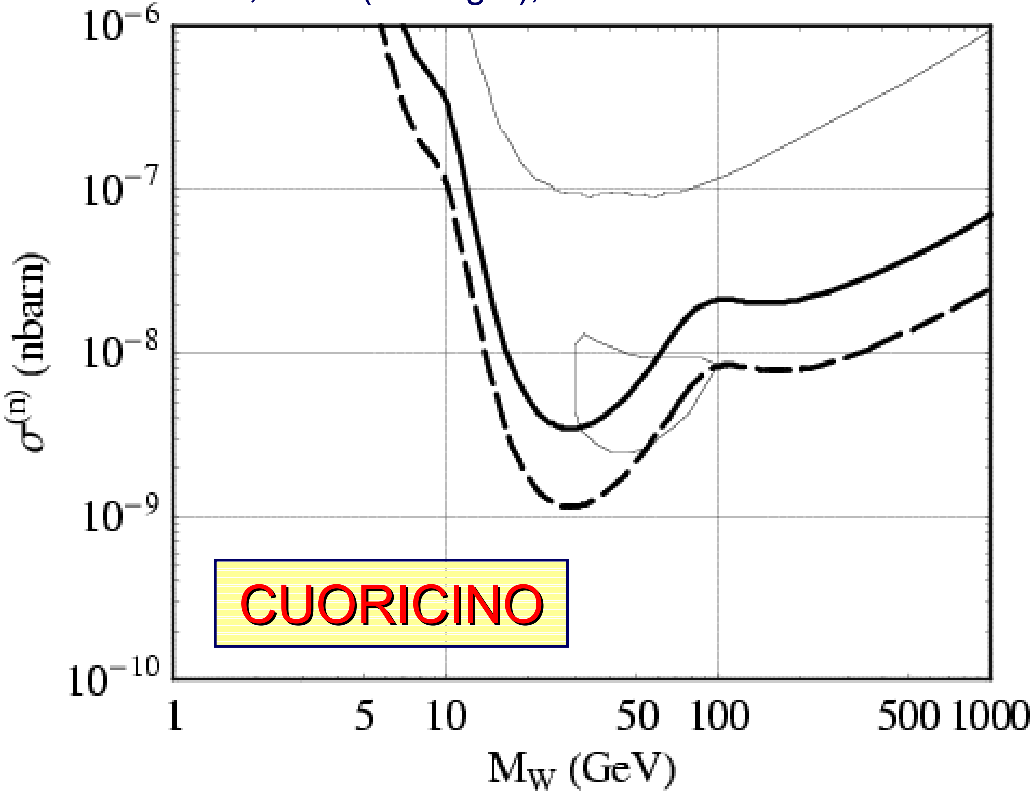


Physics Potential: Dark Matter WIMPs

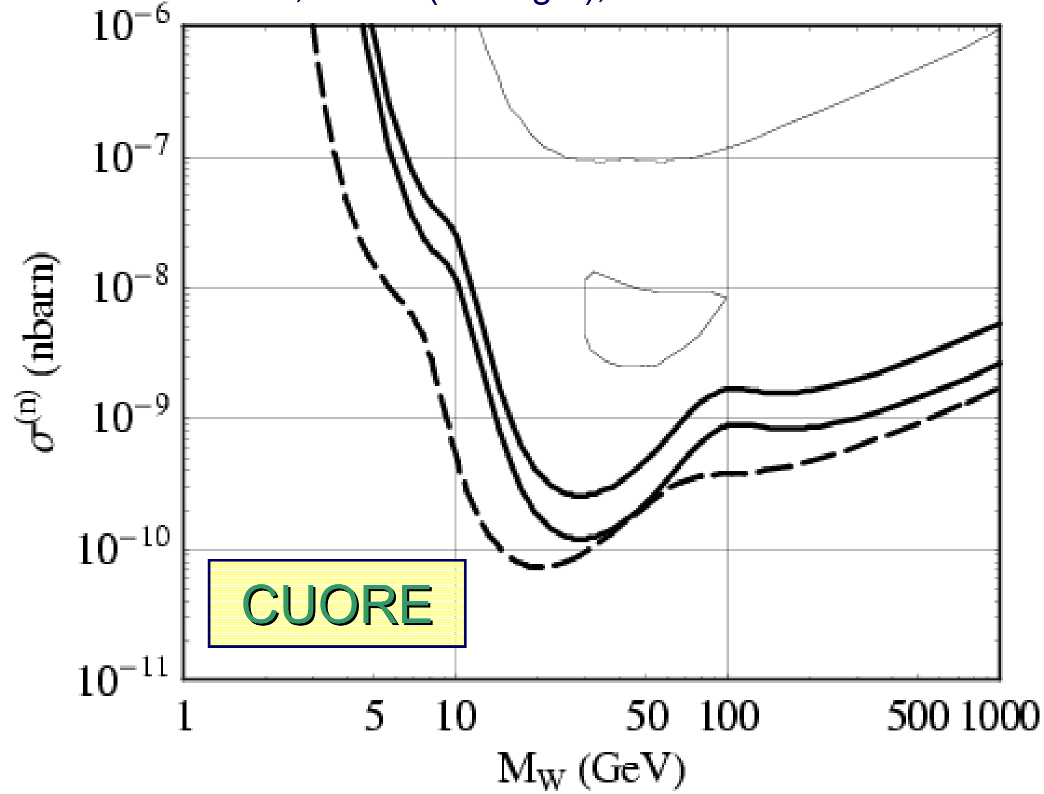
- Search for the annual modulation effect on the counting rates
- **Sensitivity plots**: regions of WIMPs which produce a 90% CL positive signal with a 50% probability

Ref.: S. Cebrián et al, Astrop. Phys. 14 (2001) 339-350.

Energy Threshold: 10 keV, Exposure: 2 years
B=1, 0.1 c/(keV kg d), FWHM=1 keV

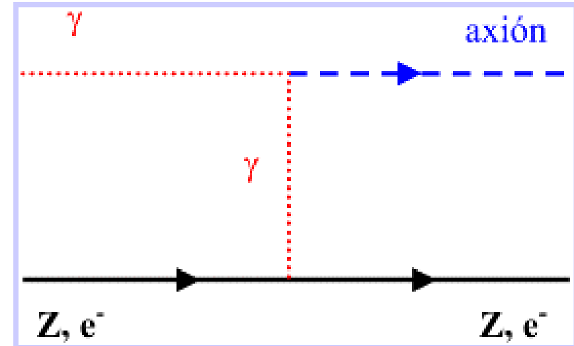


Energy Threshold: 10, 5 keV, Exposure: 2 years
B=0.05, 0.01 c/(keV kg d), FWHM=1 keV



Physics Potential: Solar Axions

- Search for Primakoff conversion of solar axions into X-rays (peaked at ~4 keV) in a crystal

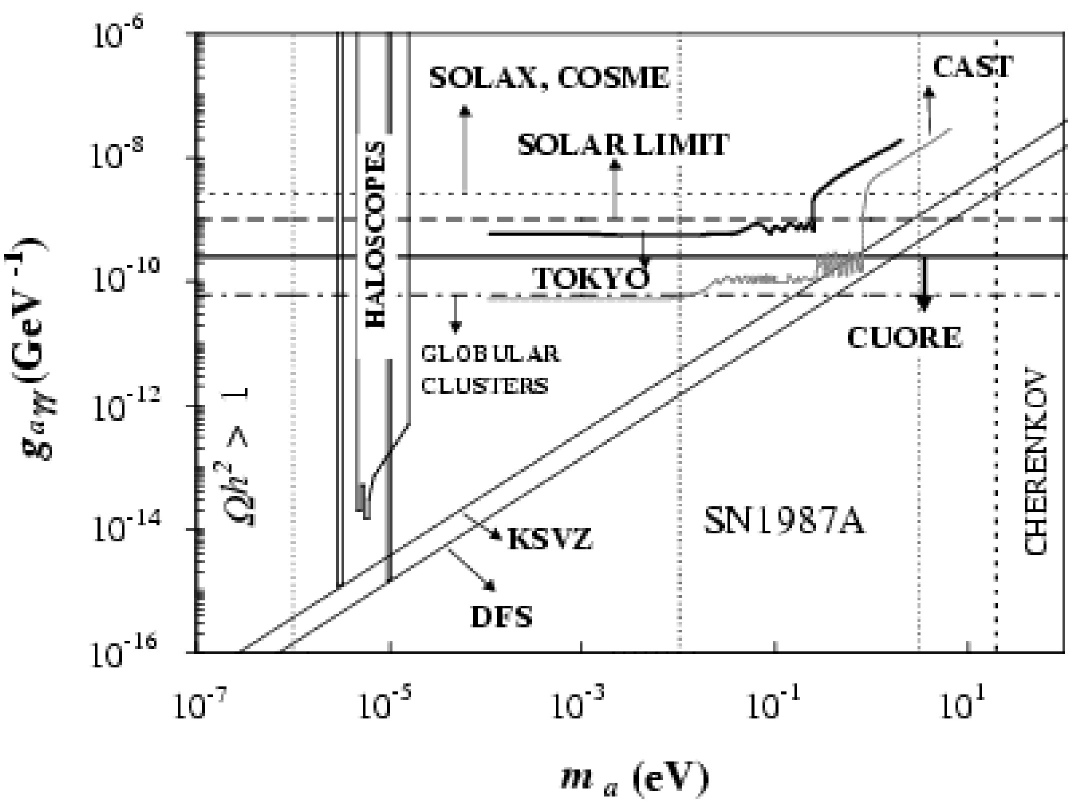


- Expected **bounds on axion-photon coupling** for exposure 2 years and threshold 5 keV:

$$g_{a\gamma\gamma} \leq k\left(\frac{b}{c/keV\,kg\,d}\,\frac{kg}{M}\,\frac{years}{T}\right)^{\frac{1}{8}} 10^{-9}\,GeV^{-1}$$

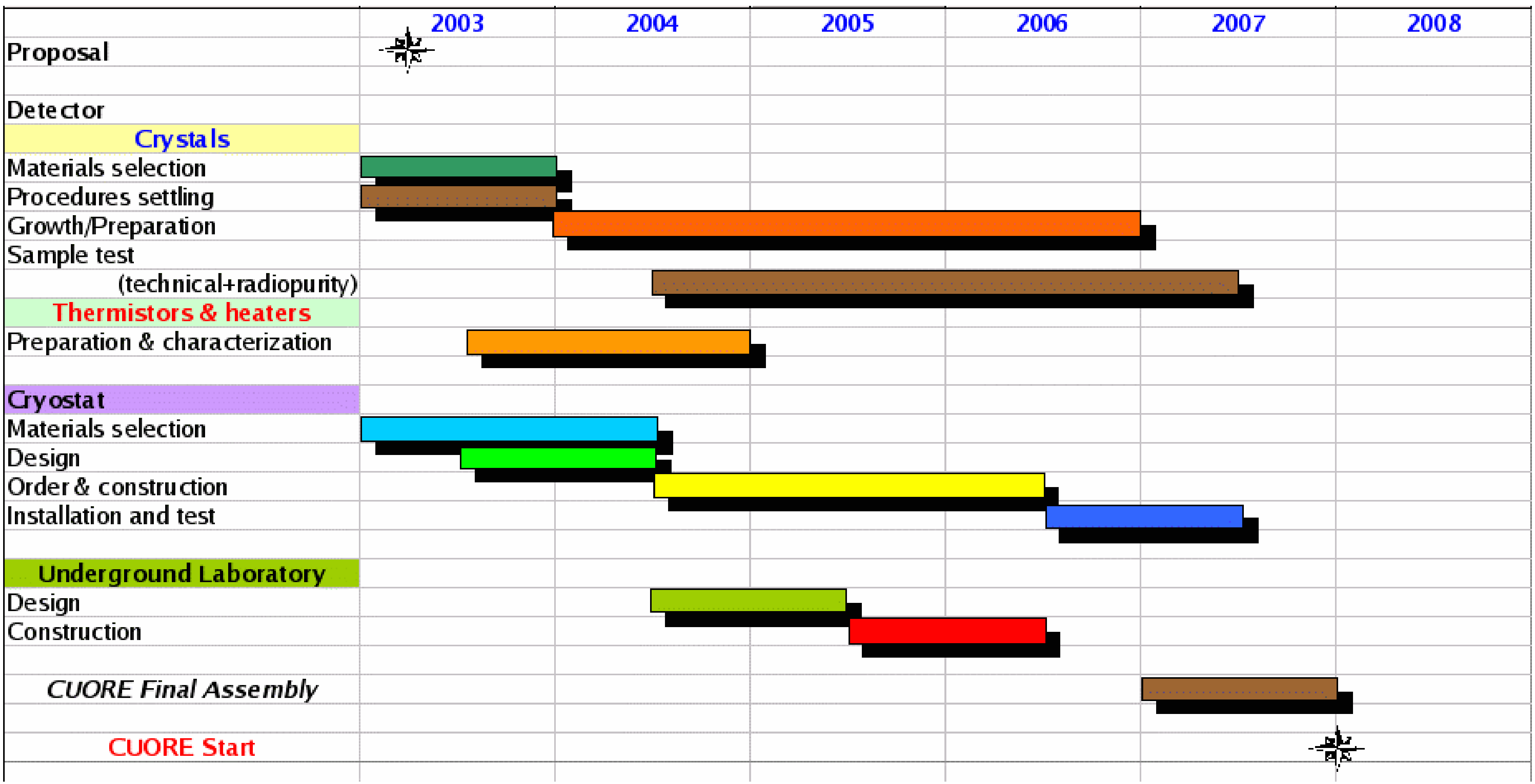
k~3 for TeO_2

Mass (kg)	FWHM (keV)	Background (c/(keV kg d))	Bound $g_{a\gamma\gamma}$ (10^{-9} GeV^{-1})
40.7	1	0.1	1.3
40.1	1	1	1.7
750	1	0.01	0.65
750	1	0.05	0.8



Ref.: A. Morales et al. Astrop. Phys. 10 (1999) 397

CUORE temptative schedule



CUORE cost estimation

Item	Total Cost
Crystals	4300
Shield materials	600
Electronics	590
Dilution refrigerator	700
Cryogenic equipment	300
Underground laboratory	850
Detector structure	560
DAQ	450
Surface cleaning	700
NTD	600
Installation	1000
Contingency	1000
Total	11650

(k US $)

Summary

- **CUORE** projects to construct and operate an array of **1000 cryogenic thermal detectors of TeO_2**, having a mass of 760 g each, to investigate **rare events**.

- A first step towards CUORE is **CUORICINO**, an array of 62 bolometers (40.7 kg) currently running in the **Gran Sasso** Laboratory.

- First results for **neutrinoless DBD in ^{130}Te**: encouraging!

$$\tau_{1/2}^{0\nu} > 5.0\ 10^{23} \text{ years at 90\% C.L.}$$
$$\langle m_\nu \rangle < 0.4 - 2 \text{ eV}$$

- Good prospects for CUORE at a reasonable cost.

- Other rare processes investigated: WIMPs, solar axions, rare α, β decays …