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The bolometric technique as a powerful tool to study neutrinoless double beta decay

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Outline

- Double Beta Decay (DBD) and the bolometric technique
- ^{130}Te as a neutrinoless DBD emitter
- Progress in the bolometric ^{130}Te experiment
- Status and prospects for CUORICINO
- CUORE: detector structure and sensitivity
- The background model
- New ideas for background rejection
- CUORE for multi-isotope search

Decay modes for Double Beta Decay

Three decay modes are usually discussed:

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ ← 2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \geq 10^{19}$ y

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$ ← neutrinoless Double Beta Decay (0ν-DBD)
open discussion on its observation
$\tau \geq 10^{25}$ y

③ $(A,Z) \rightarrow (A,Z+2) + 2e^- + \chi$ ← Double Beta Decay
with Majoron (light neutral boson)
never observed – $\tau > 10^{22}$ y

Processes ② and ③ would imply new physics beyond the Standard Model

violation of lepton number conservation

They are very sensitive tests to new physics since the phase space term is much larger for them than for the standard process (in particular for ②)

interest for 0ν-DBD lasts for 65 years !

Goeppert-Meyer proposed the standard process in 1935
Racah proposed the neutrinoless process in 1937

The choice of the candidate nuclide

In case of dominant mass mechanism, the rate of 0ν-DBD is connected to kinematical parameters, nuclear physics effects and neutrino properties:

0ν-DBD rate

Phase space $\propto Q^5$

Nuclear matrix elements

Effective neutrino mass (sometimes noted as $\langle m_\nu \rangle$ or $\langle m_{\beta\beta} \rangle$)

$$1/\tau = G(Q,Z)\, |M_{nucl}|^2\, m_{ee}^{\;2}$$

high Q candidates are by far preferred

large phase space

low background

^{238}U chain stops at 2.4 MeV

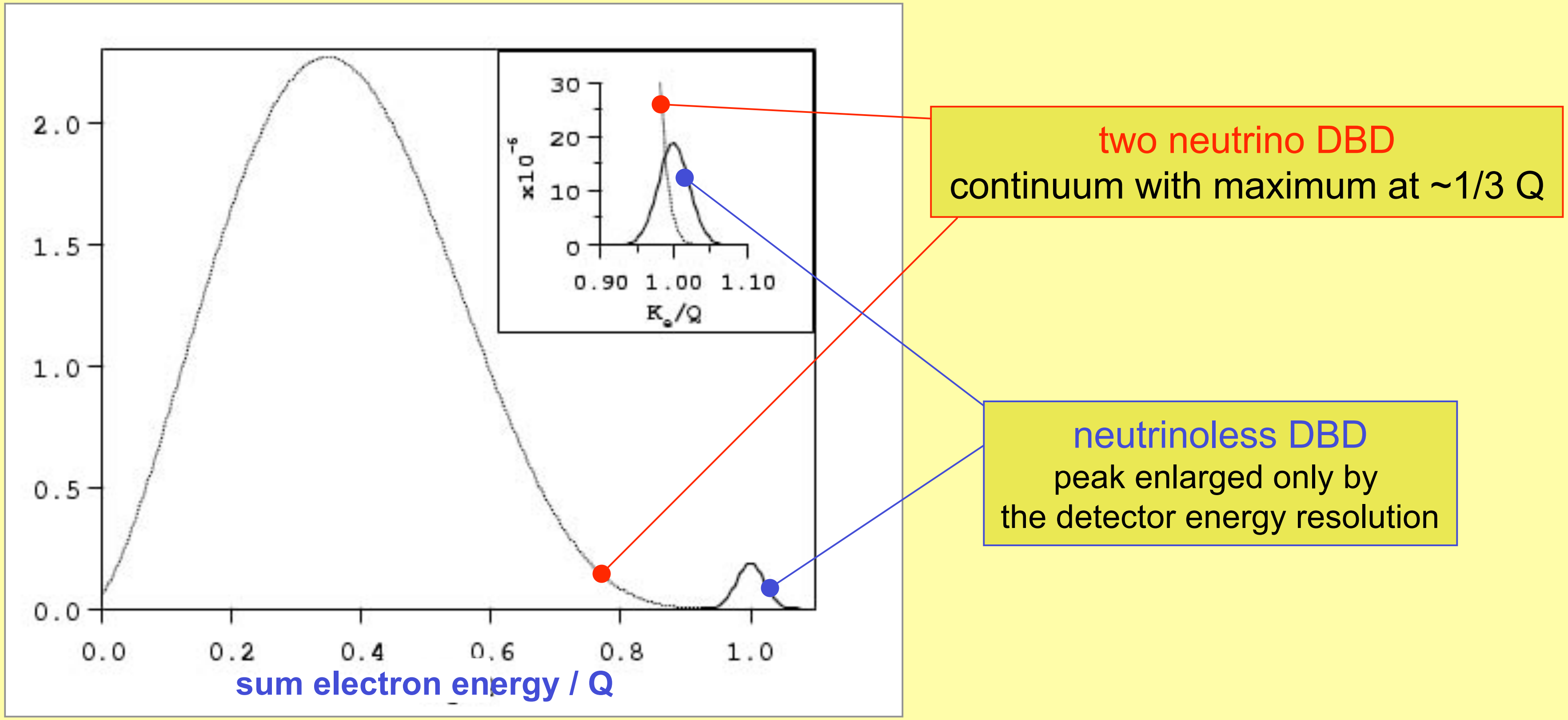
^{232}Th chain stops at 2.6 MeV

interesting range ⇒ [2039 keV (^{76}Ge) - 4271 keV (^{48}Ca)]

10 candidates

Electron sum energy spectra in DBD

The shape of the two electron sum energy spectrum enables to distinguish among the three different discussed decay modes



The Majoron spectrum is a continuum with maximum close to Q

(phase space for a particle decaying to three light objects)

additional signatures:

- single electron energy distribution
- angular distribution

Experimental strategies

① Detect and identify the daughter nuclei (indirect search)

geochemical experiments
radiochemical experiments

it is not possible to distinguish the decay channel
important in the 70s-80s – no more pursued now

② Detect the two electrons with a proper nuclear detector (direct search)

desirable features

- high energy resolution
- low background
- large source (many nuclides under control)
- event reconstruction method

a peak must be revealed over background (0ν-DBD)

shield cosmic rays (direct interactions and activations)
→ underground

very radio-pure materials
$^{238}U - ^{232}Th \Rightarrow \tau \sim 10^{10}$ y
signal rate $\Rightarrow \tau \sim 10^{25}$ y

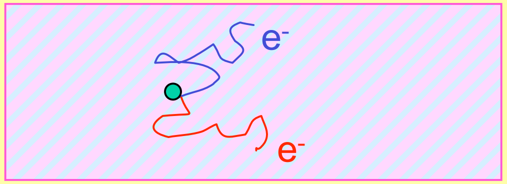
present more sensitive experiments: 10 - 100 kg
future goals: ~ 1000 kg $\Rightarrow 10^{27} - 10^{28}$ nuclides

- reject background
- study electron energy and angular distributions

Experimental approaches to direct searches

Two approaches:

①



Source ≡ Detector

(calorimetric technique)

- scintillation
- phonon-mediated detection
- solid-state devices
- gaseous detectors

☹ constraints on detector materials

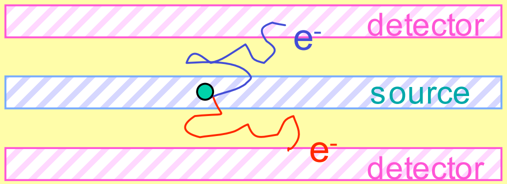
☺ very large masses are possible
demonstrated: up to ~ 50 kg
proposed: up to ~ 1000 kg

☺ with proper choice of the detector, very high energy resolution
Ge-diodes
bolometers

☺ in gaseous/liquid xenon detector, indication of event topology

☹ in contradiction

②



Source ≠ Detector

- scintillation
- gaseous TPC
- gaseous drift chamber
- magnetic field and TOF

☺ neat reconstruction of event topology

☹ it is difficult to get large source mass

☹ it is difficult to get high energy resolution

☺ several candidates can be studied with the same detector

The (source ≡ detector) technique

This is the most sensitive experimental technique up to now
With high energy resolution, it can be realized in two ways:

① Ge diodes + ^{76}Ge

This technique has been dominating the field for decades and is still one of the most promising for the future
E. Fiorini – **60s**

high energy resolution
3.5 keV FWHM

reasonable candidate
(Q=2039 keV)

② Bolometers + ^{130}Te, ….

The bolometric technique for the study of DBD was proposed by **E. Fiorini** and **T.O. Niinikoski** in **1983**

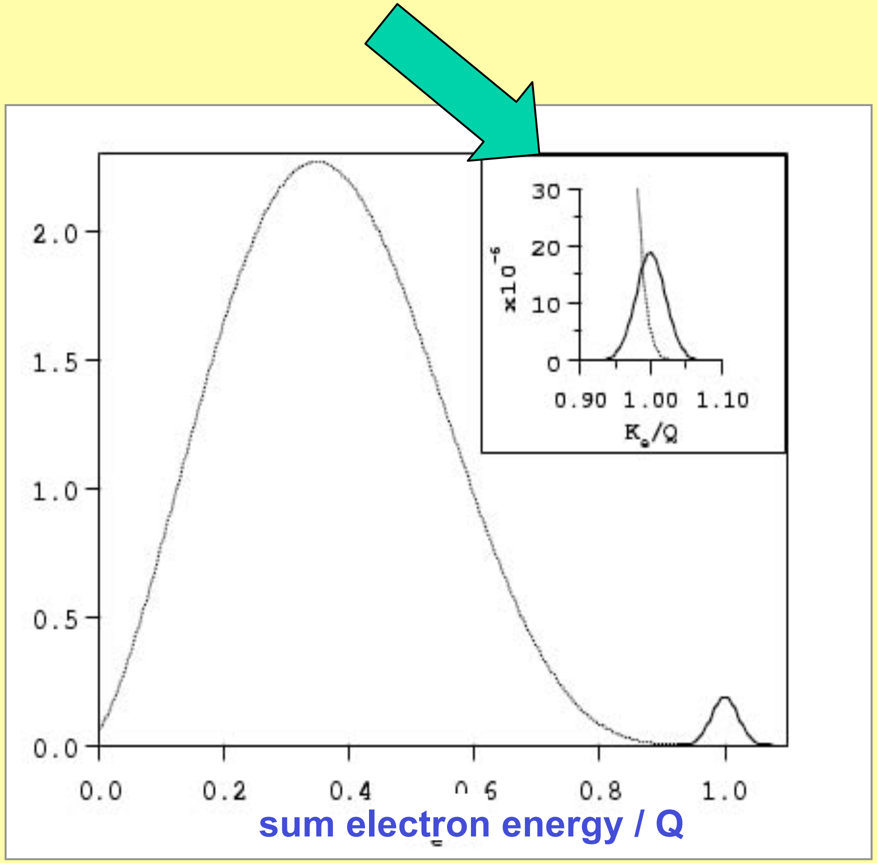
good candidate
(Q=2528 keV)

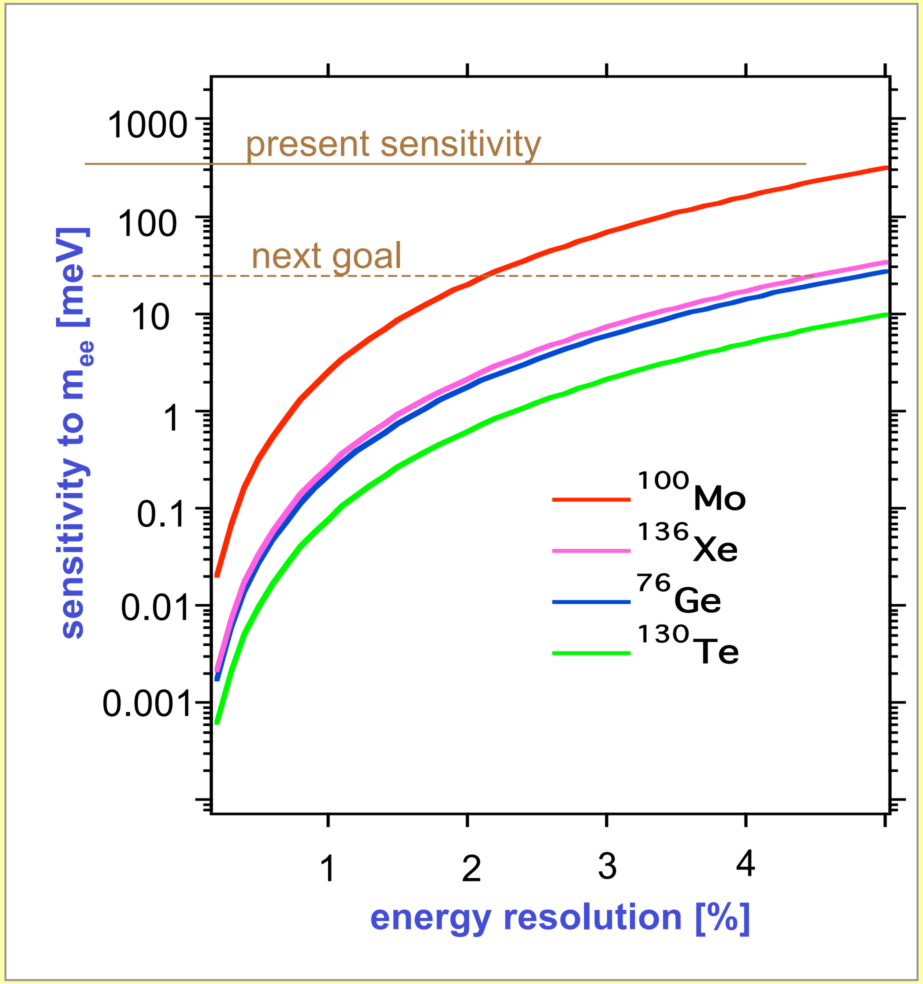
high energy resolution
4 keV FWHM exceptionally
7 keV FWHM routinely

other good or excellent candidates can be studied

2ν-DBD as a background source for 0ν-DBD

2ν-DBD is a potential source of background, especially for low energy resolution technique (> 5%) ⇒ Ge-diodes and bolometers are best techniques in this aspect





Experimental sensitivity to 0ν-DBD

sensitivity F: lifetime corresponding to the minimum detectable number of events over background at a given (1 σ) confidence level

b: specific background coefficient **[counts/(keV kg y)]**

$b \neq 0$

live time, source mass, energy resolution

$$F \propto (MT / b\,\Delta E)^{1/2}$$

$b = 0$

$$F \propto MT$$

importance of the nuclide choice
(but large uncertainty due to nuclear physics)

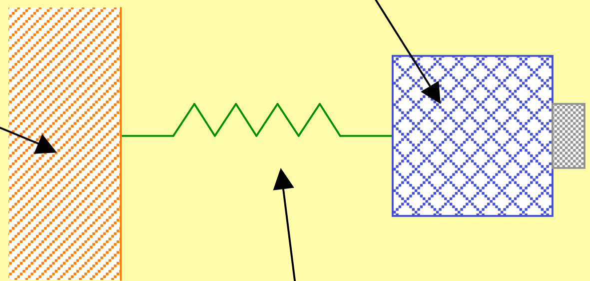
$$\text{sensitivity to } m_{ee} \propto (F/Q\,|M_{nucl}|^2)^{1/2} \propto \frac{1}{Q^{1/2}\,|M_{nucl}|}\left(\frac{b\,\Delta E}{MT}\right)^{1/4}$$

The bolometric technique for ^{130}Te: detector concepts

Te dominates in mass the compound
Excellent mechanical and thermal properties

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

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
- Bias: $I \cong 0.1$ nA ⇒ Joule power $\cong$ 1 pW ⇒ Temperature rise $\cong$ 0.25 mK
- Voltage signal: $\Delta V = I \times dR/dT \times \Delta T$ ⇒ $\Delta V = 1$ mV for $E = 1$ MeV
- Signal recovery time: $\tau = C/G \cong 0.5$ s
- Noise over signal bandwidth (a few Hz): $V_{rms} = 0.2$ μV

In real life signal about a factor 2 - 3 smaller

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

Properties of ^{130}Te as a DBD emitter

^{130}Te features as a DBD candidate:

- high natural isotopic abundance (I.A. = 33.87 %)
- high transition energy (Q = 2528.8 ± 1.3 keV)
- encouraging theoretical calculations for 0ν−DBD lifetime
- already observed with geo-chemical techniques ($\tau_{1/2\ incl}$ = (0.7 - 2.7) × 10^{21} y)

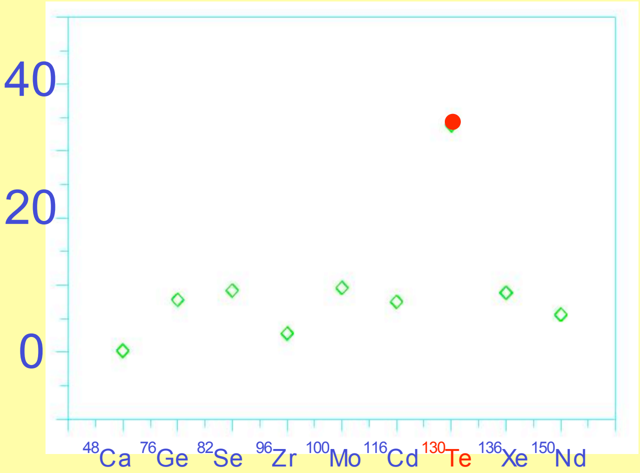
excellent feature for future reasonable-cost expansion of Double Beta Decay experiments

large phase space, lower background (clean window between full energy and Compton edge of ^{208}Tl photons)

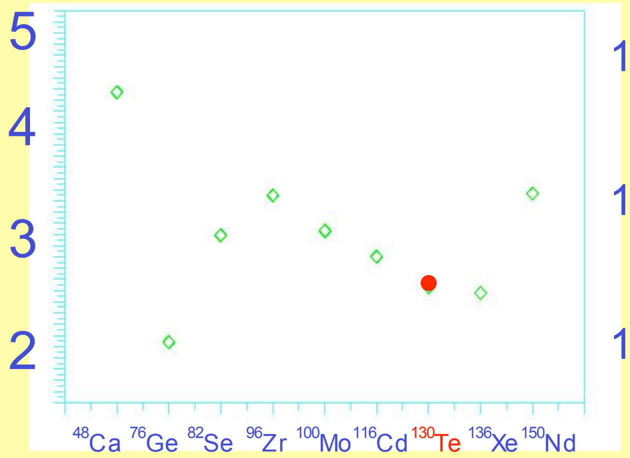
$m_{ee} \approx 0.1$ eV ⇔ $\tau \approx 10^{26}$ y

Comparison with other candidates:

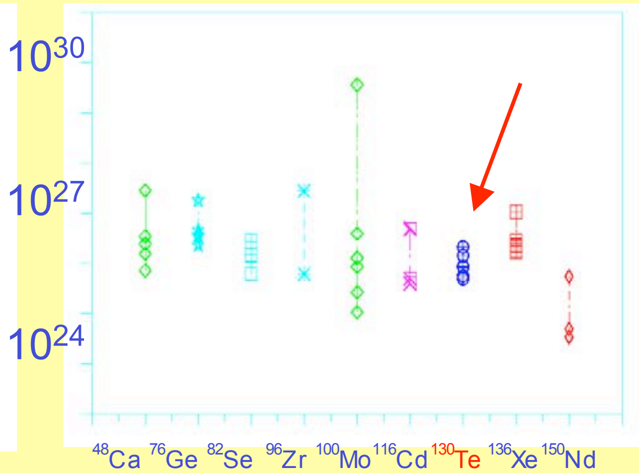
Isotopic abundance (%)



Transition energy (MeV)



0ν−DBD half-life (y) for m_{ee} = 0.1 eV (different calculations)



Phases of the bolometric experiments on TeO_2 at LNGS

Past, present and future:

1997 The first large mass array of bolometers was operated
20 crystals × 340 g = 6.8 kg (Mi DBD - I experiment)

1998-2001 Tests on larger crystals (760 g) were successfully carried on aiming at more powerful experiments

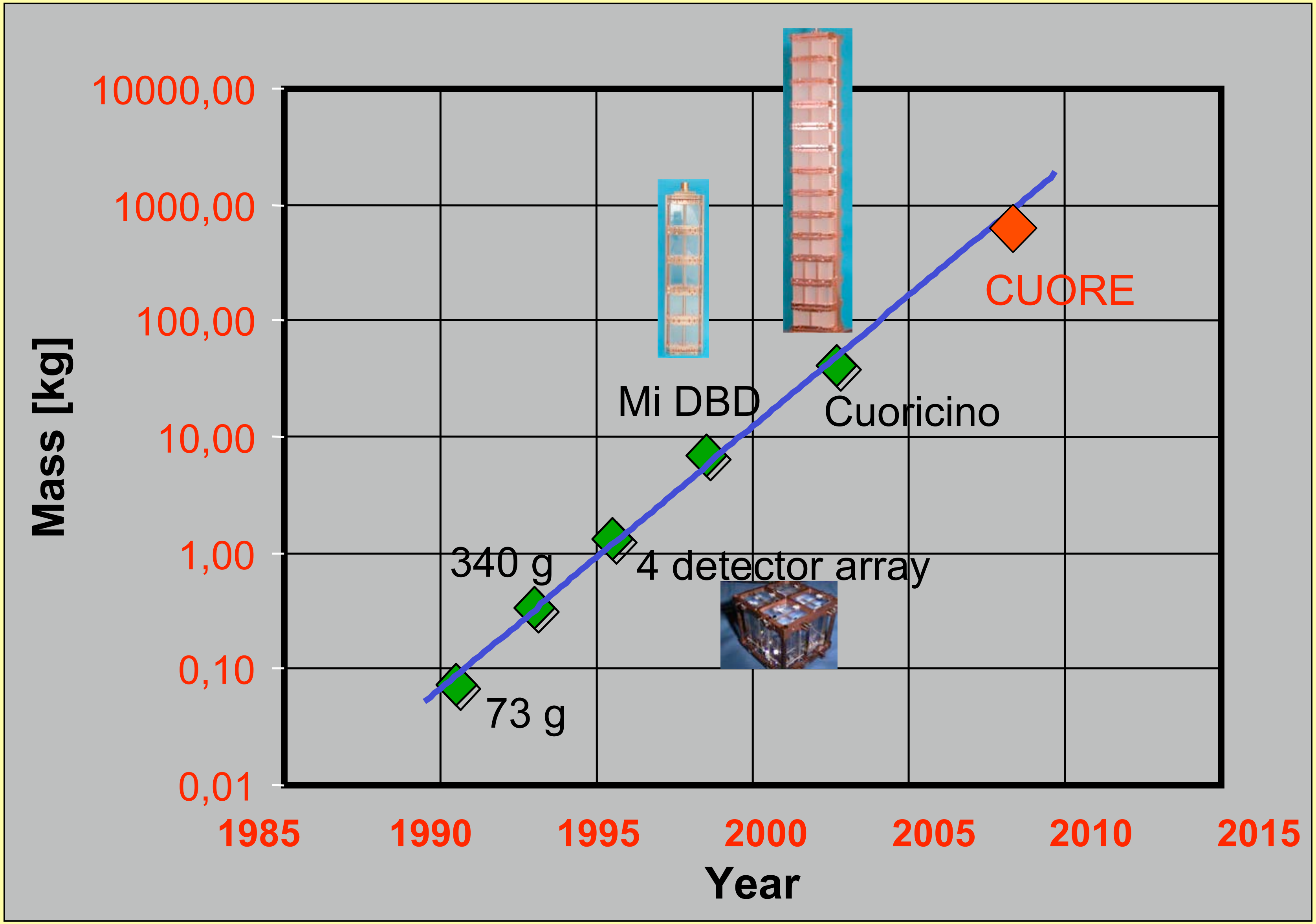
2001 The 20 crystal array was rebuilt with improved BKG features (Mi DBD - II experiment)

2002 A new, larger mass array is assembled
44 crystals × 790 g
18 crystals × 340 g ≈ 40 kg (CUORICINO)

2003-2004 Full data taking of CUORICINO

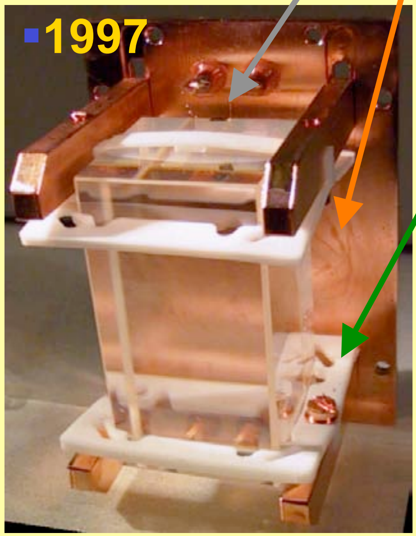
2004-2009 Construction of a second generation array
1000 crystals × 760 g = 760 kg (CUORE experiment)

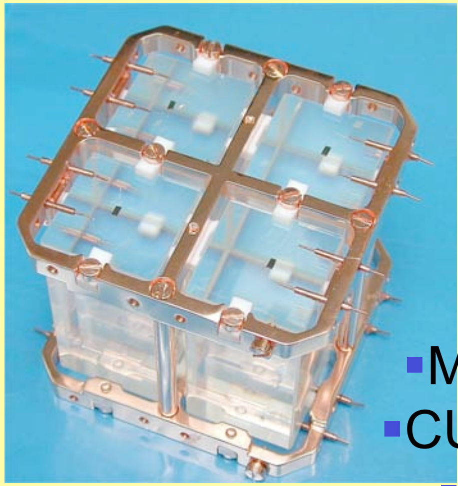
Temporal law for mass increase of TeO_2 detectors

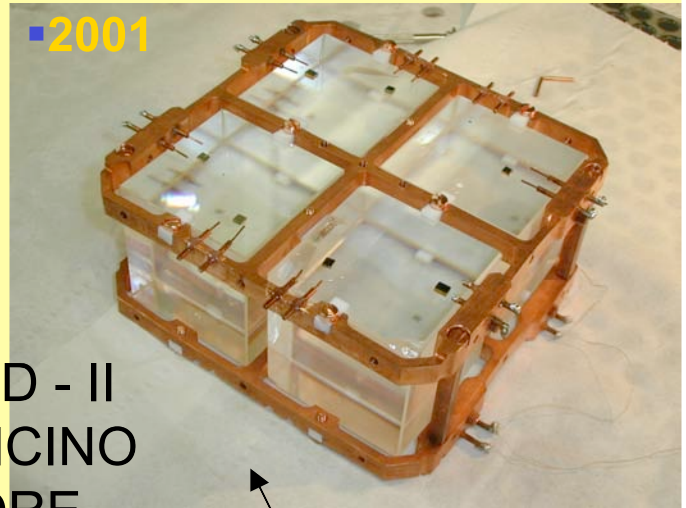


Evolution of the detectors

Common points: Thermistor: NTD Ge chip glued with epoxy
Heat sink: Cu plates, frames and bars
Holding method and thermal contact: Teflon elements







- Mi DBD - II
- CUORICINO
- CUORE

- Mi DBD - I

- Crystal mass: 340 g
- Elementary module: 1 detector
- Large amount of Teflon
- Crystal surfaces: lapped in China with ^{238}U-contaminated power

- Crystal mass: 340 g - 760 g
- Elementary module: 4 detectors
- Small amount of Teflon
- Crystal surfaces: lapped by us with radio-pure power

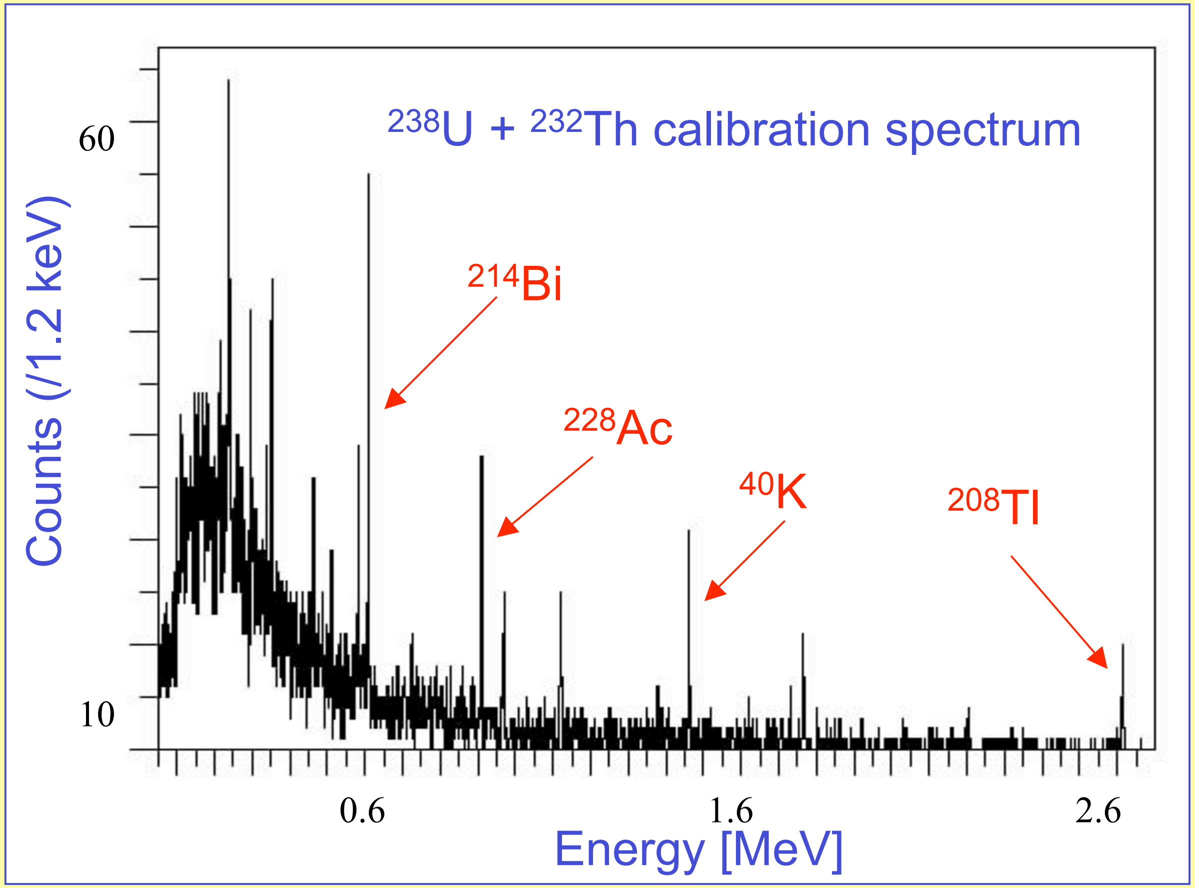
Technical results on detector performances

Performances of CUORICINO-type detectors (5×5×5 cm^3 - 760 g):

- Detector base temperature: ~ 7 mK
- Detector operation temperature: ~ 9 mK
- Detector response: ~ 250 μV/ MeV

similar to 340 g crystal thanks to improved detector design

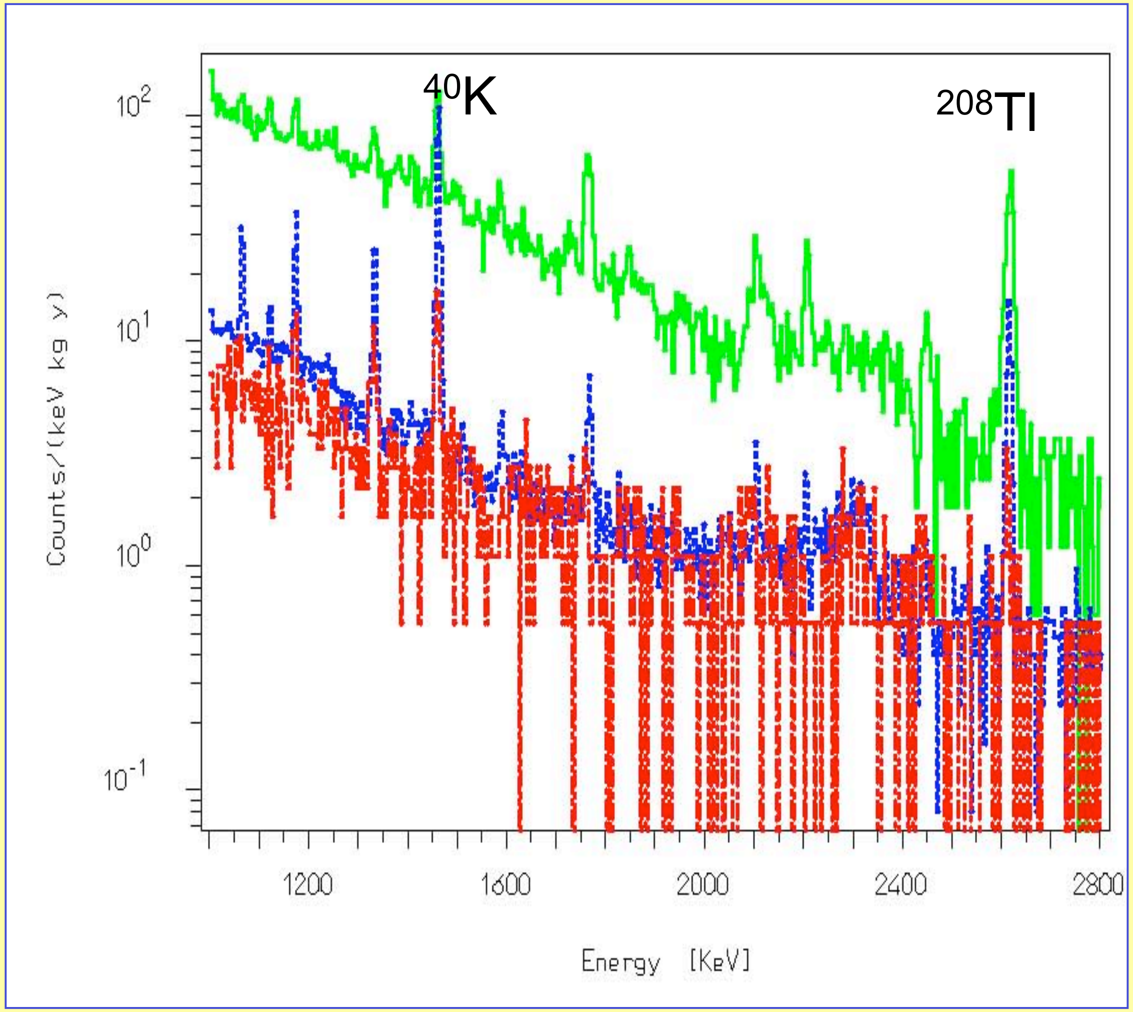
- FWHM resolution: ~ 3.9 keV @ 2.6 MeV



The background in the experiments preceding CUORICINO

History of the background (BKG)

BKG in the range 1.0 - 2.8 MeV



BKG obtained with
single 340 g detector
0.41 kg y

Operation in clean conditions

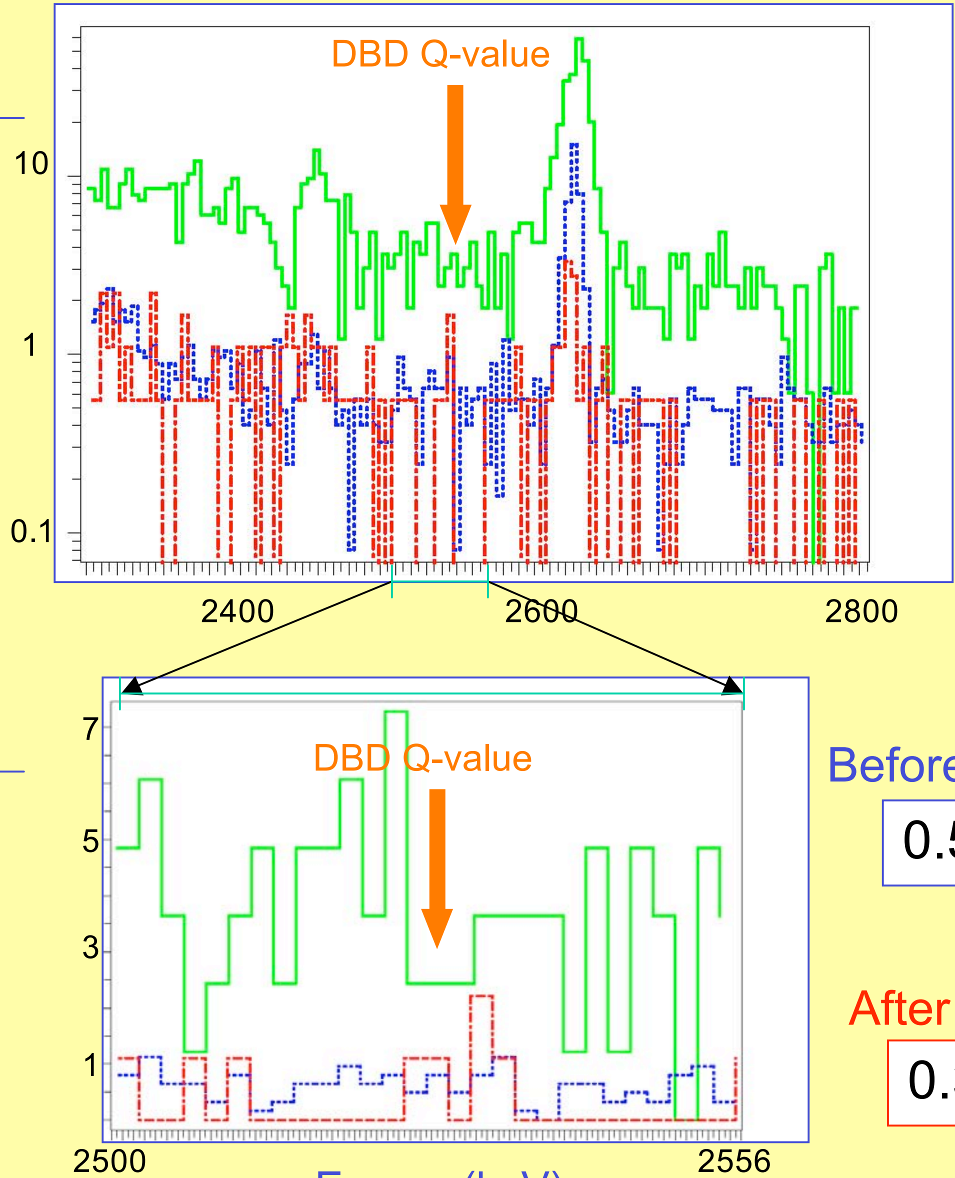
BKG obtained with
Mi DBD - I
3.10 kg y

Polishing, etching and passivation of copper
Lapping of crystals with ultra-pure powder

BKG obtained with
Mi DBD - II
0.45 kg y

The background in the region of 0ν-DBD before CUORICINO

Counts / keV kg y



Energy (keV)

Counts / keV kg y

Energy (keV)

BKG in the range
2.3 - 2.8 MeV

BKG levels

Before crystal and Cu treatment

0.59 ± 0.06 c/kev/kg/y

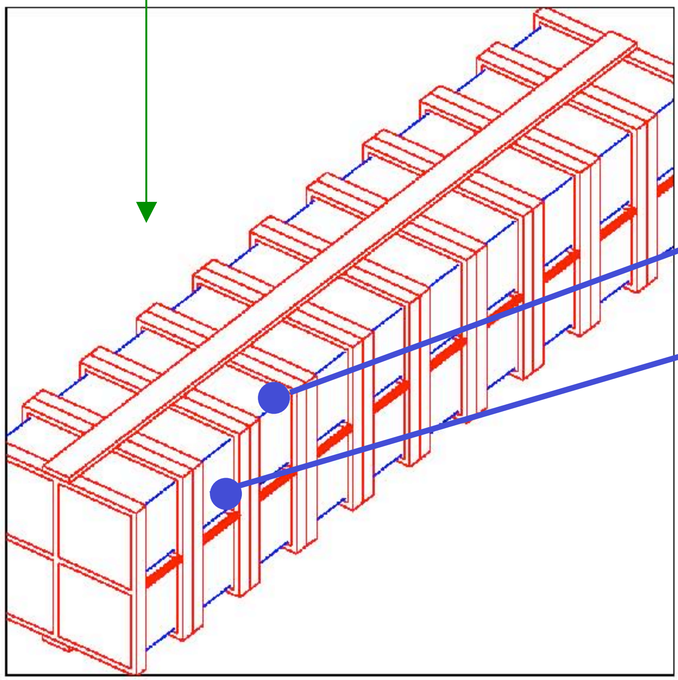
After crystal and Cu treatment

0.33 ± 0.11 c/kev/kg/y

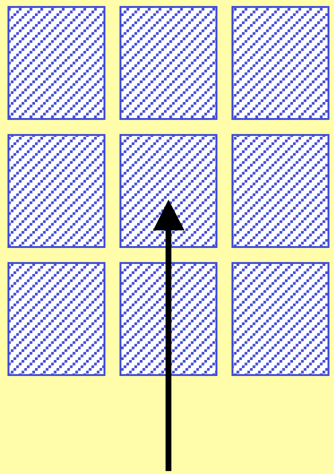
The CUORICINO set-up

CUORICINO = tower of 11 modules, 4 detector (760 g) each
2 modules, 9 detector (340 g) each

M = ~ 41 kg ➡ 6.4×10^{25} ^{130}Te nuclei



Plane section



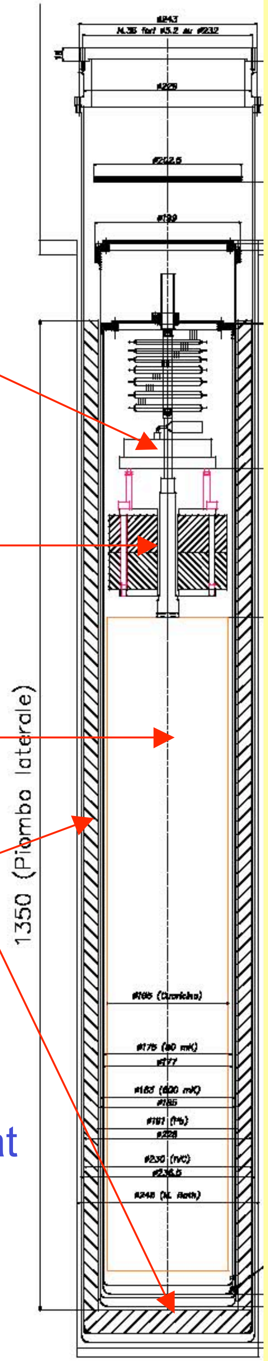
This detector will be completely surrounded by active materials.
Test for BKG origin

Coldest point

Cold finger

Tower

Lead shield

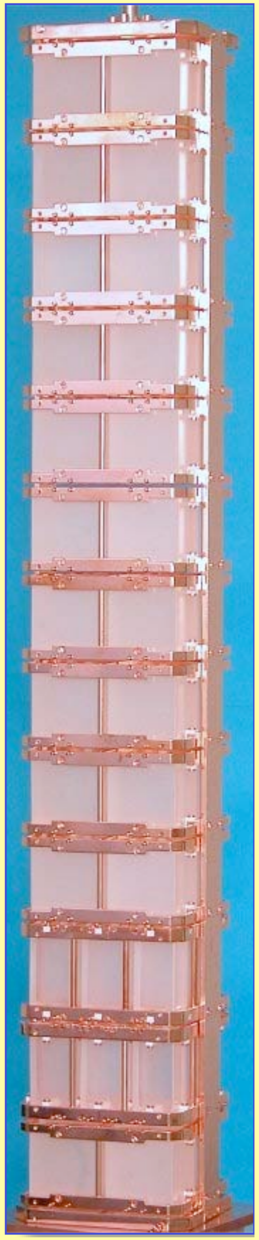


Same cryostat and similar structure as Mi DBD

The CUORICINO set-up

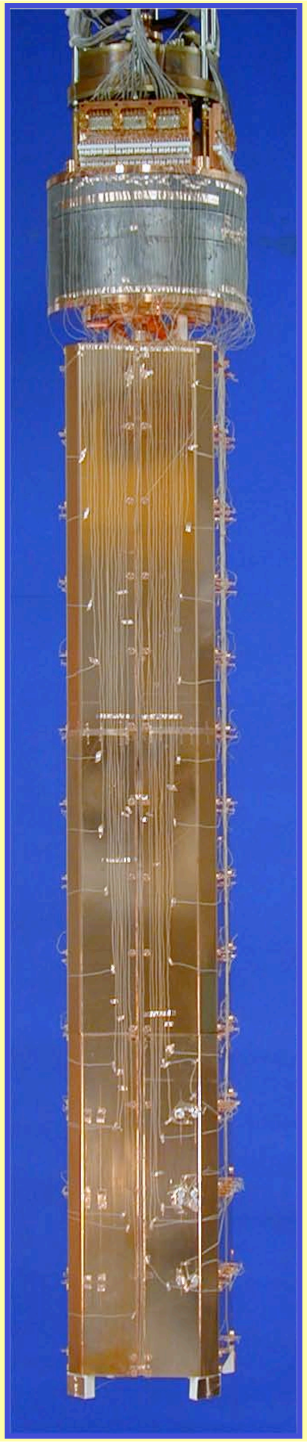
40 cm

from Mi DBD-II
to CUORICINO

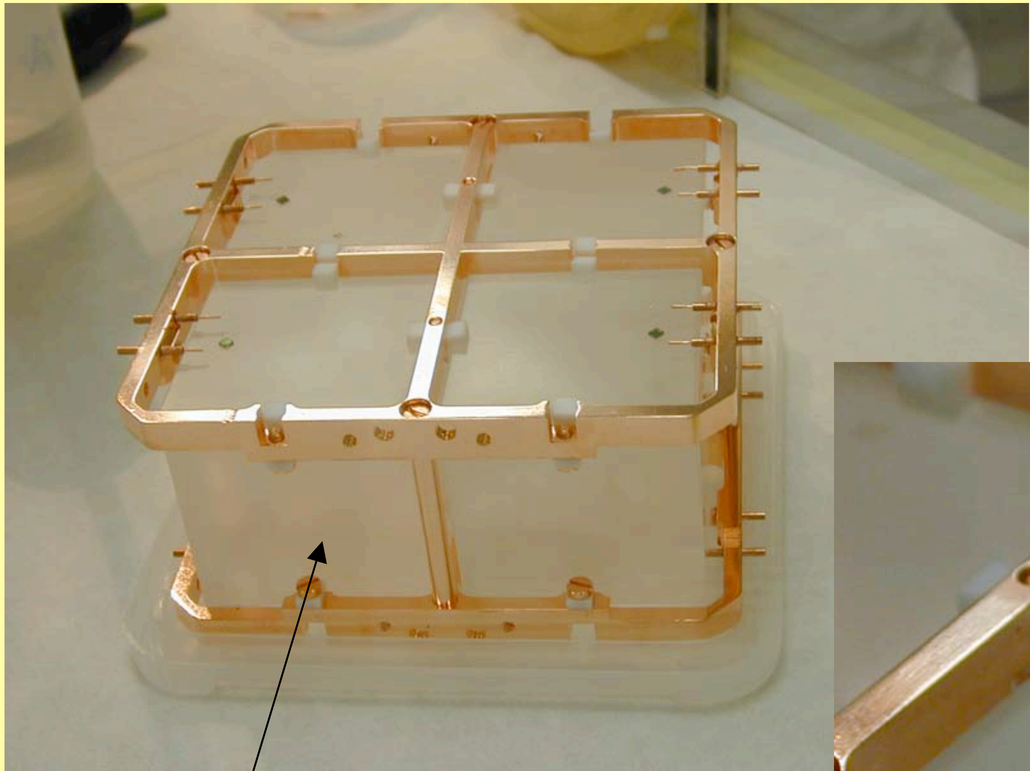


80 cm

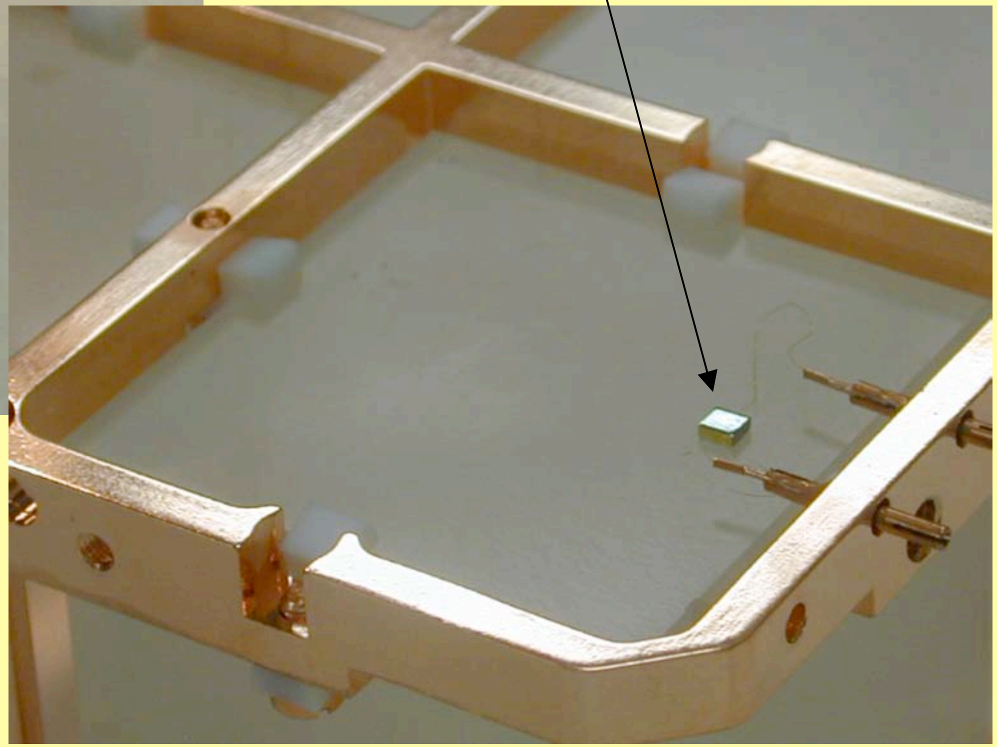
inside the
cryostat



CUORICINO modules



thermometer
(doped Ge chip)



single TeO_2 crystal
- 790 g
- 5 x 5 x 5 cm

CUORICINO assembly

CUORICINO status

I run - 2003

I period: (no "external" problem): Apr 19th – Jun 21st – 72% live time

stop due to failure of water supply for the compressors

II period: July 9th – July 21st

stop due to liquefier problem + safety problem in LNGS

all the results here presented refer to this run

long interruption due to

- lack of cooling water (safety problem in LNGS)
- re-wiring of part of the detectors

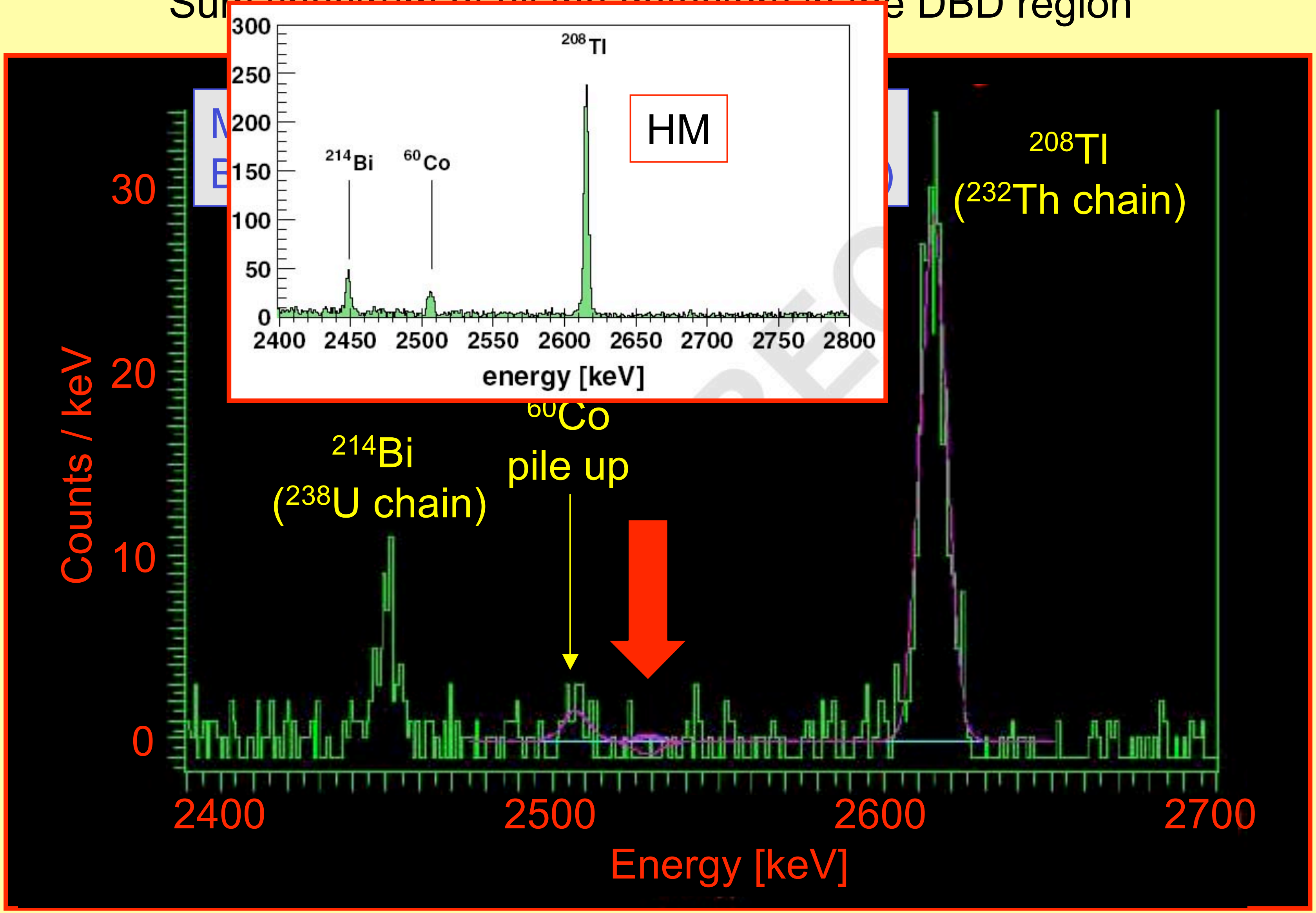
II run - 2004

start a few weeks ago

all detectors but one are providing data

CUORICINO results

Sum spectrum of all the detectors in the DBD region



CUORICINO prospects

Is CUORICINO able to scrutinize the HM experiment claim?

m_{ee} = 50 meV – half life for different nuclei and models [10^{26} y]

Nucleus	Ref.: (20)	(80)	(81)	(82)	(24, 83)	(84)	
^{48}Ca	12.7	35.3	-	-	-	10.0	
^{76}Ge	6.8	70.8	56.0	9.3	12.8	14.4	
^{82}Se	2.3	9.6	22.4	2.4	3.2	6.0	
^{100}Mo	-	-	4.0	5.1	1.2	15.6	
^{116}Cd	-	-	-	1.9	3.1	18.8	
^{130}Te	0.6	23.2	2.8	2.0	3.6	3.4	
^{136}Xe	-	48.4	13.2	8.8	21.2	7.2	
^{150}Nd$^{a)}$	-	-	-	0.1	0.2	-	
^{160}Gd$^{a)}$	-	-	-	3.4	-	-	
$T_{1/2}$ (^{76}Ge)/$T_{½}$(^{130}Te)	**11.3**	**3.0**	**20.0**	**4.6**	**3.5**	**4.2**	
expected $T_{½}$(^{130}Te) (units: 10^{24} y)	**1.06**	**4.0**	**0.6**	**2.6**	**3.4**	**2.8**	limit: > 0.75

Elliot Vogel 2002

CUORICINO prospects

Ref.: (20)	(80)	(81)	(82)	(24, 83)	(84)
115	**30**	**204**	**47**	**36**	**43**
7.2	**1.9**	**13**	**2.9**	**2.3**	**2.7**

Expected event number in 3 y in a 12 keV energy window (1.5xFWHM: 92% of signal) → row 1 of values above

(to be compared with **28.75** events of the HM claim,
with a BKG level which is 0.11 / 0.19 = 0.6 lower in HM
and with an energy resolution which is 2 higher in HM)

1 σ BKG fluctuation = $(0.19 * 12 * 40 * 3)^{0.5}$ = 16

S/N ratio (σ) → row 2 of values above

3 y CUORICINO ≡ 10 y HEIDELBERG - MOSCOW

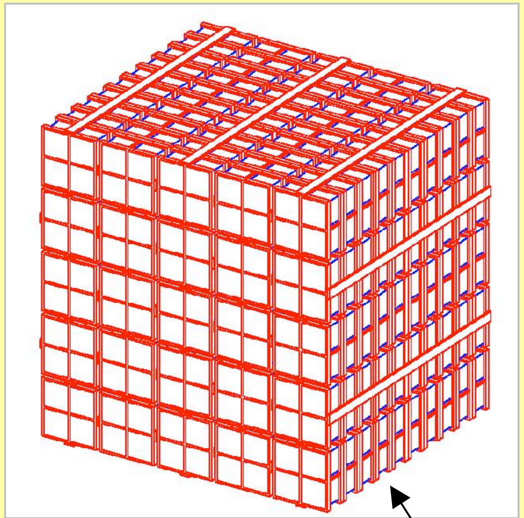
good chance to see HM signal

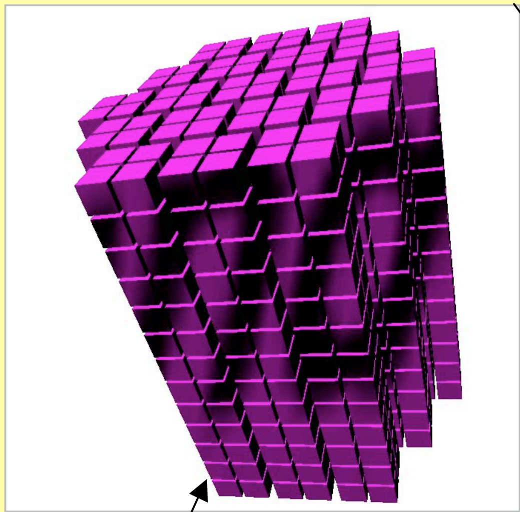
cannot falsify HM if no signal is seen

From CUORICINO to CUORE

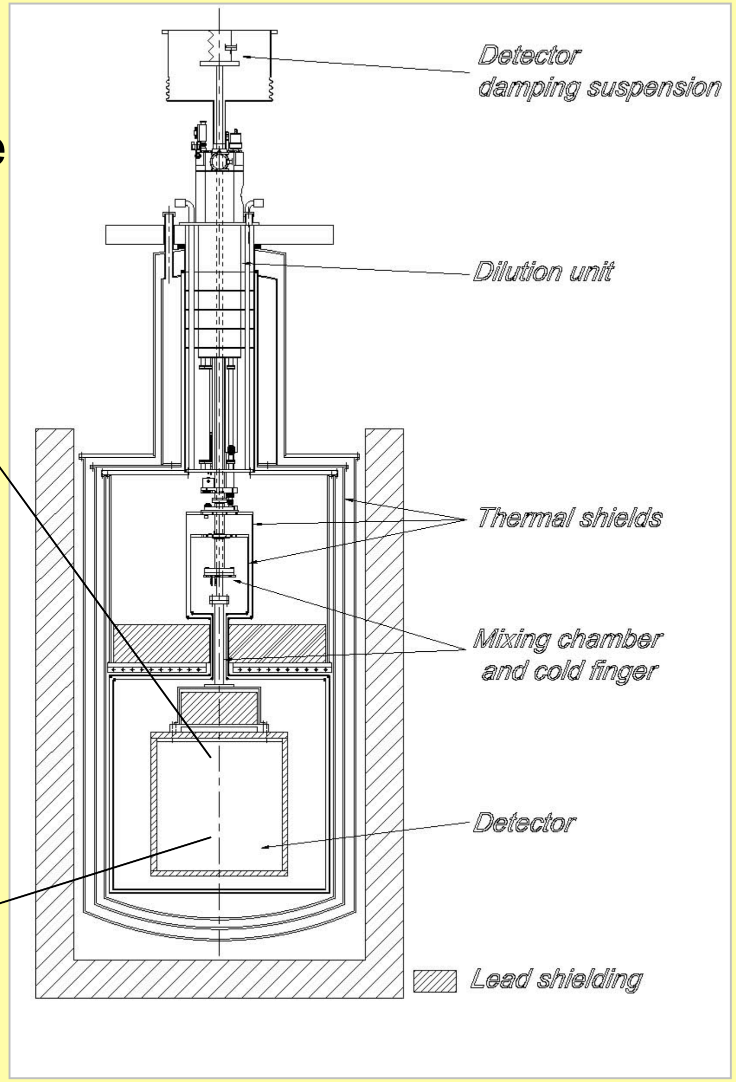
CUORE = closely packed array of 1000 detectors
25 towers - 10 modules/tower - 4 detector/module
M = 790 kg (cubic option)

Cubic or cylindrical structure
ideal for active shielding



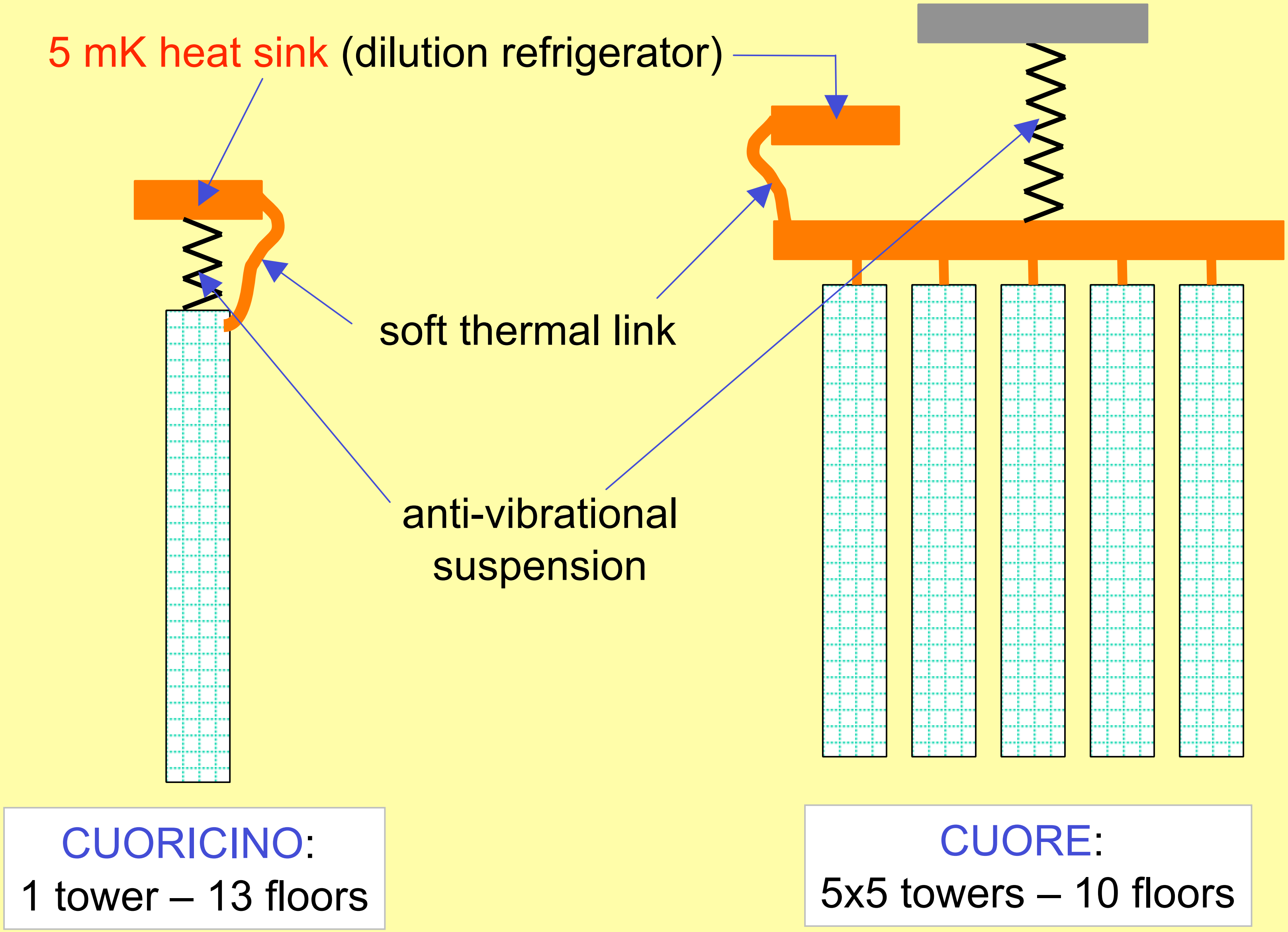


Each tower is a CUORICINO-like detector



Special dilution refrigerator

CUORE is technically feasible



CUORE background and sensitivity

Montecarlo simulations of the background show that

b ~ 0.001 counts / (keV kg y)

is possible with the present bulk contamination of detector materials

The problem is the surface background (alpha, beta energy-degraded)

it must be reduced by a factor 10 – 100

work in progress!

---

5 y sensitivity with pessimistic background:

b = 0.01 counts/(keV kg y)

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

$m_{ee} < 28 – 68$ meV

5 y sensitivity with optimistic background:

b = 0.001 counts/(keV kg y)

$$F^{0\nu} = 2.9 \times 10^{26} \times (T [y])^{1/2}$$

$m_{ee} < 16 – 38$ meV

enriched CUORE → $m_{ee} < 9 – 22$ meV

Mi DBD and CUORICINO background model

We have identified 4 possible sources for the residual BKG in the DBD region:

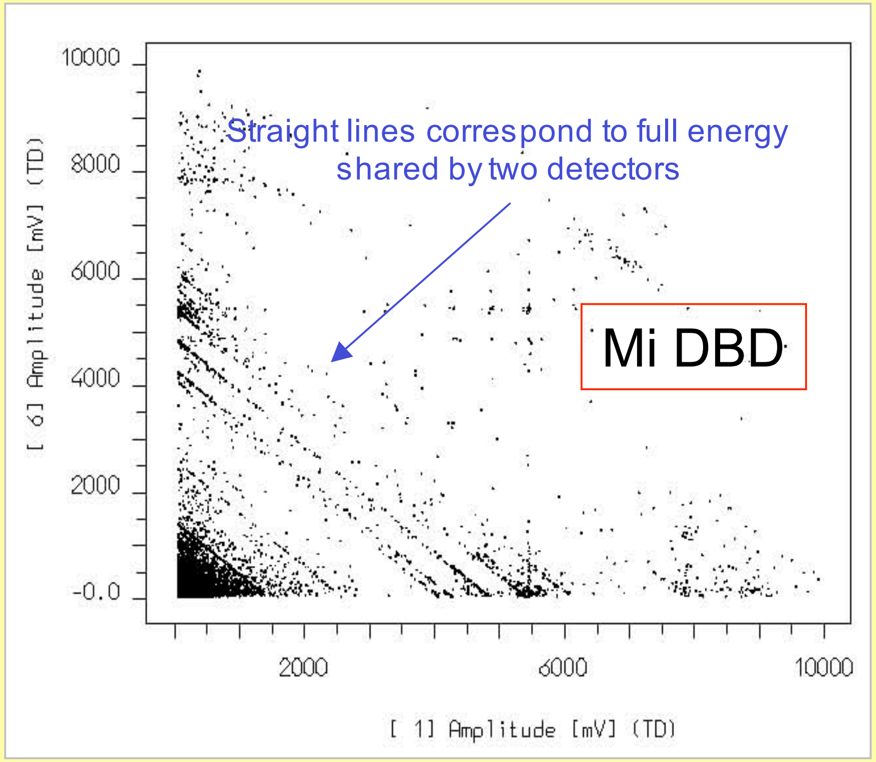
- Neutrons ← Excluded since adding B-polyethilene shield had no effect
- Degraded alphas from TeO_2 surface
- Degraded alphas from Cu frame and plate surface

} The alpha continuum extends down to the DBD region

- Energy degraded 2615 keV photons

Coincidences between adjacent detectors show that crystal surfaces emit alphas belonging to ^{238}U and ^{232}Th series (Mi DBD data)

Crystal contamination determines peaks more than continuum.



Mi DBD and CUORICINO background model

Further proof that the BKG in the DBD region is presently dominated by degraded alpha particles (surface effect):

Clear correlation between:

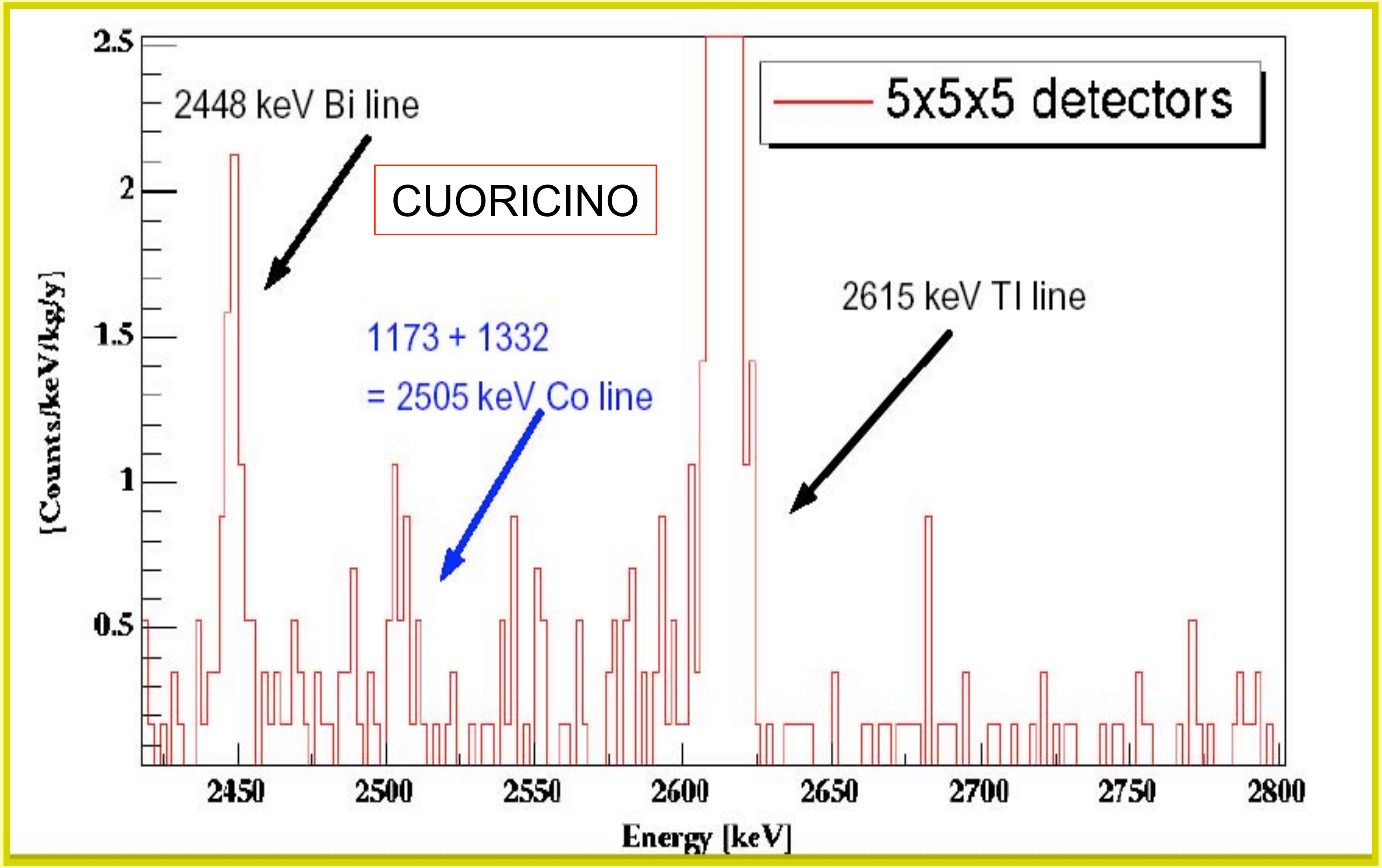
BKG in the DBD region ⇔ BKG in the region 3-4 MeV

free from alpha and gamma peaks

	Mi DBD - I	Mi DBD - II
BKG $_{2500\text{-}2556\ keV}$ (c/keV/kg/y)	0.59±0.06	0.33±0.11
BKG $_{3000\text{-}4000\ keV}$ (c/keV/kg/y)	0.66 ±0.01	0.27±0.03

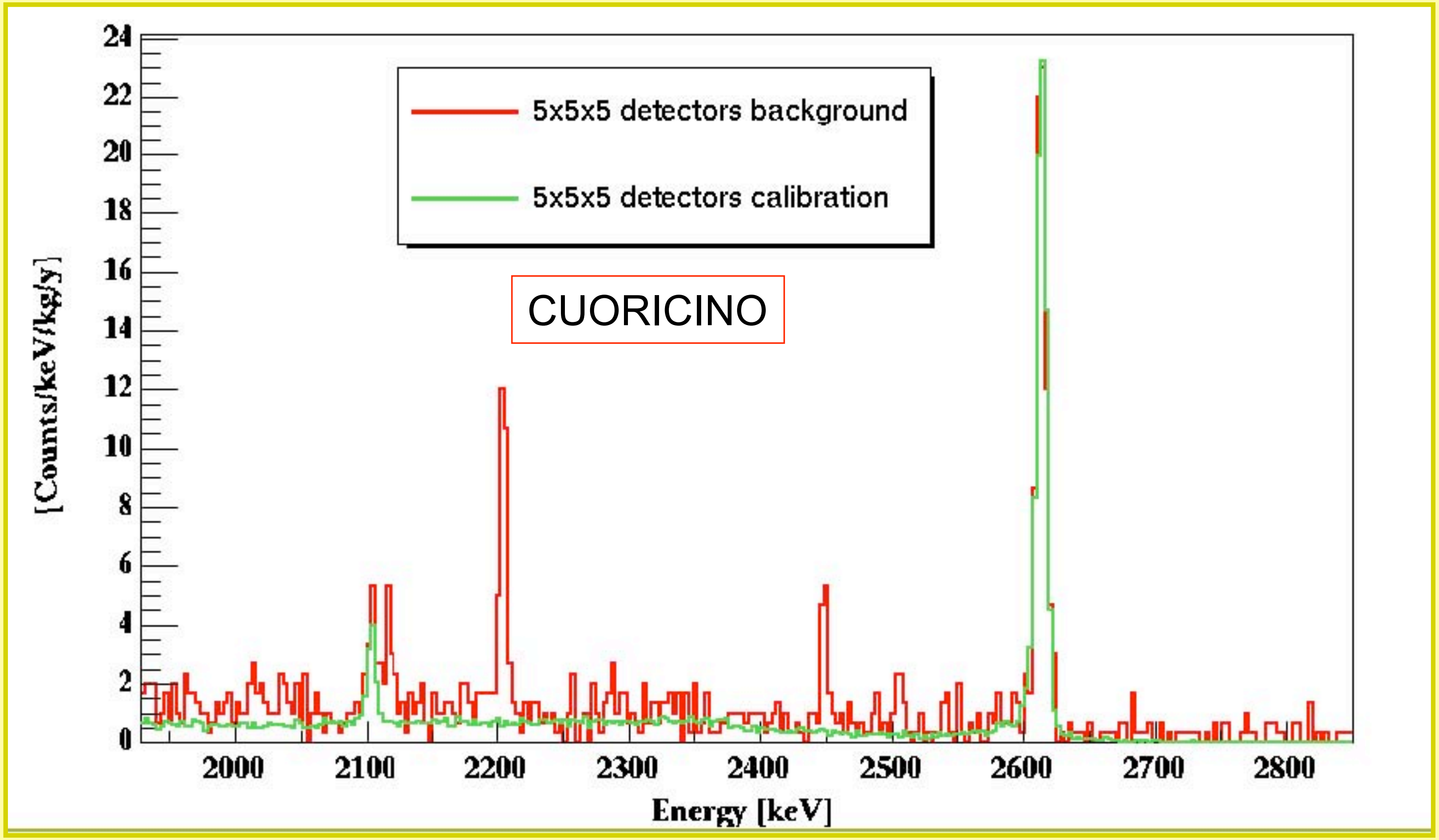
Mi DBD and CUORICINO background model

CUORICINO BKG in the DBD region and above
the alpha continuum is clearly leaking into the interesting range



Mi DBD and CUORICINO background model

A contribution comes also from a cryostat ^{232}Th contamination, probably located in between the inner and outer lead shield



Mi DBD and CUORICINO background model

BKG components in the DBD region and above
Results of a detailed MC simulation

Mi DBD – I ~0.6 counts/ kev kg y

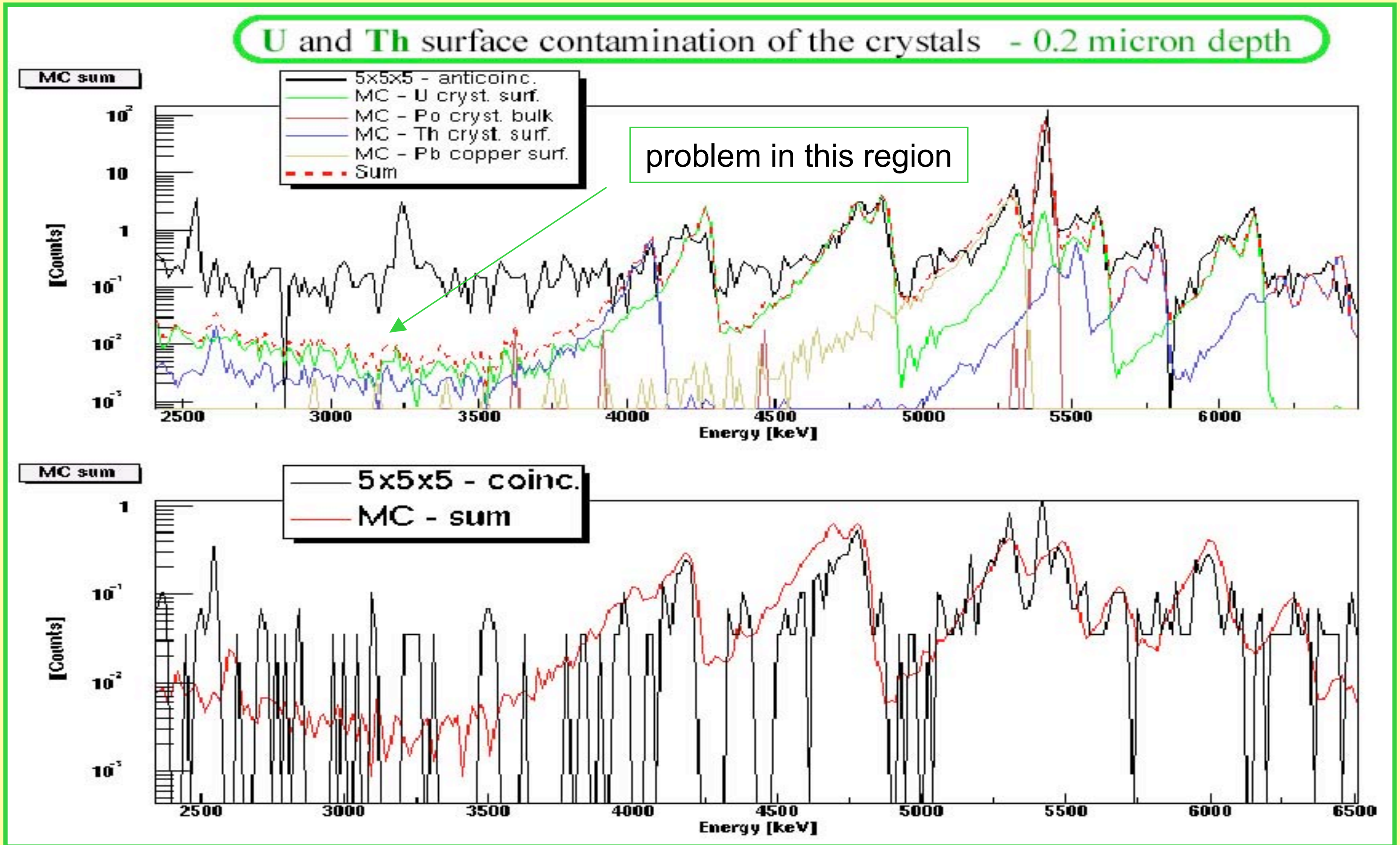
Source	^{208}Tl	$\beta\beta(0\nu)$ region	3-4 MeV region
TeO_2 ^{238}U and ^{232}Th surface contamination	-	43± 13%	33± 10%
Cu ^{238}U and ^{232}Th surface contamination	~10%	23± 11%	67± 20%
^{232}Th contamination of cryostat Cu shields	~90%	20± 5%	-

CUORICINO ~ 0.2 counts/ keV kg y

Source	^{208}Tl	$\beta\beta(0\nu)$ region	3-4 MeV region
TeO_2 ^{238}U and ^{232}Th surface contamination	-	20± 15%	20± 10%
Cu ^{238}U and ^{232}Th surface contamination	~15%	50± 20%	80± 10%
^{232}Th contamination of cryostat Cu shields	~85%	30± 10%	-

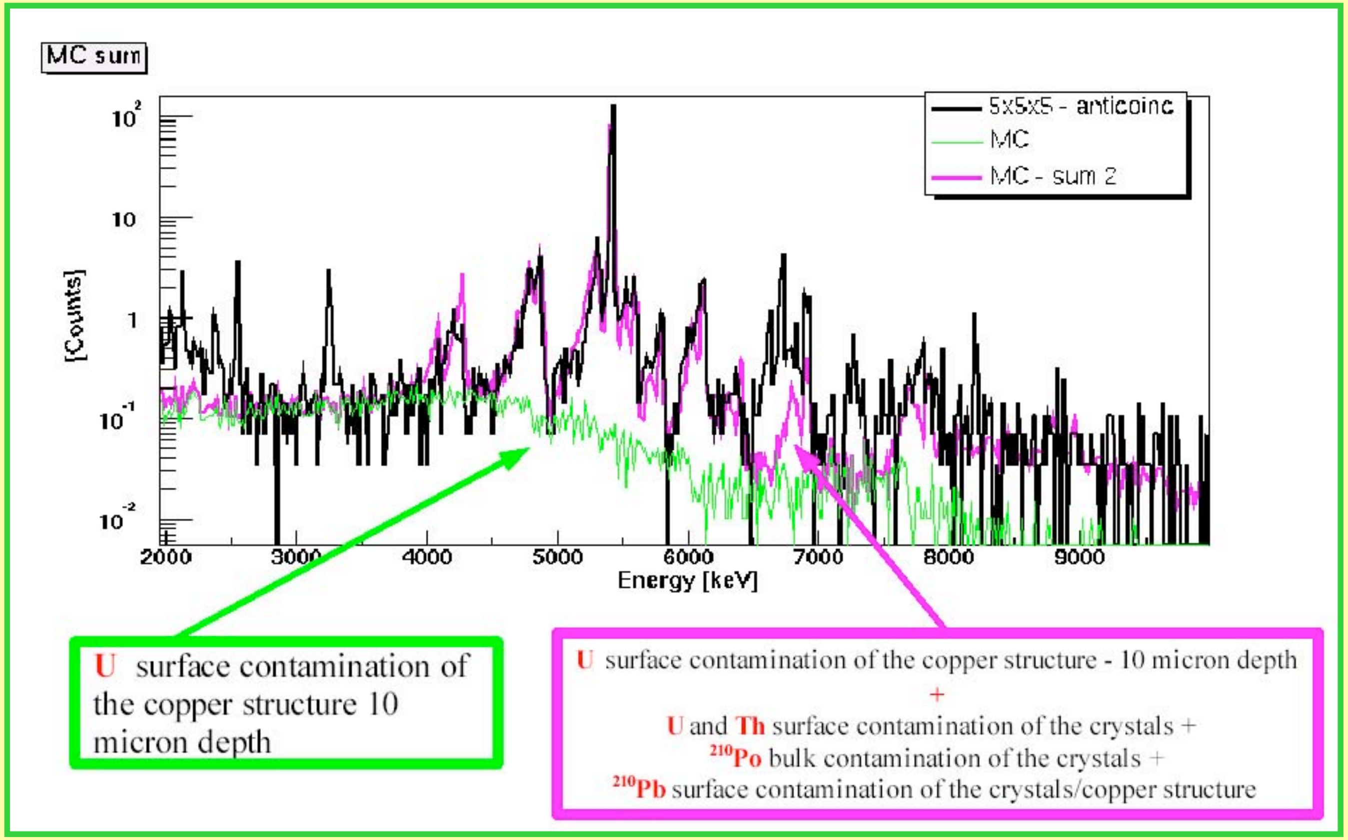
Mi DBD and CUORICINO background model

Reconstruction of the spectrum in the spectral region 2.5 – 6.5 MeV



Mi DBD and CUORICINO background model

In order to explain the 2.0 - 4 MeV region BKG, one has to introduce ^{238}U or ^{210}Pb surface contamination of the copper structure facing the detectors



surface contamination level: ~ 100 pg/g vs bulk c.l. : < 1 (0.1) pg/g for Cu (TeO_2)

contamination depth: ~ 10 μm

in agreement with direct measurement on Cu

The CUORE background on the basis of the information achieved by Mi DBD and CUORICINO

Full Montecarlo simulation on the basis of the CUORICINO and Mi DBD background analysis

- Bulk contamination of Cu and $TeO_2 \Rightarrow$ < 0.004 counts / kev kg y
- Contamination in the cryostat shields $\Rightarrow$ made negligible by the granular structure
- Surface contamination as it is $\Rightarrow$ 0.04 counts / kev kg y (reduction due to decrease of Cu area, but not enough)

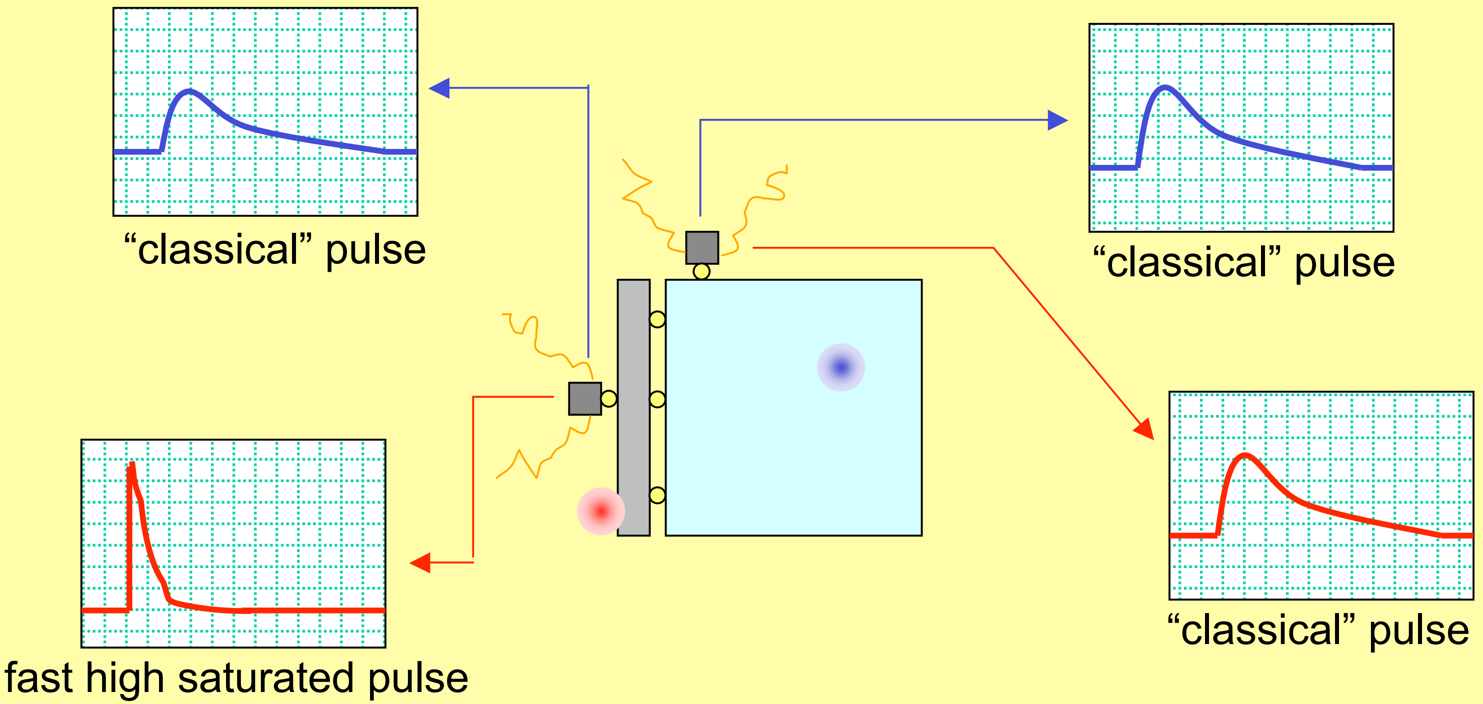
A reduction by a factor 10 in Cu surface contamination and by a factor 4 in TeO_2 surface contamination is mandatory for the success of CUORE

Copper cleaning procedure by chemical etching and surface passivation under development

Development of surface-sensitive bolometers

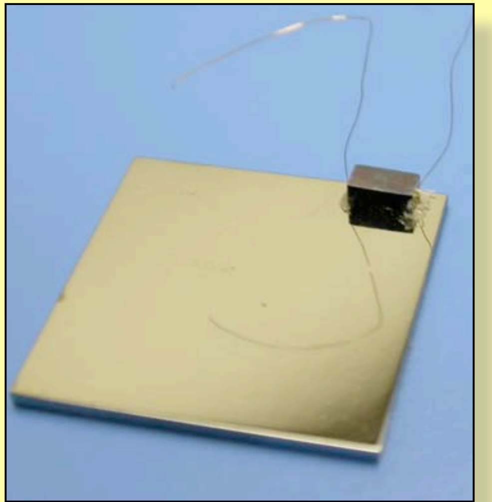
Use a thin Ge (or Si) crystal to make a composite bolometers

Energy deposited in the TeO_2 crystal (DBD-like event)



Energy deposited in the Ge crystal (degraded alpha event)

Development of prototypes



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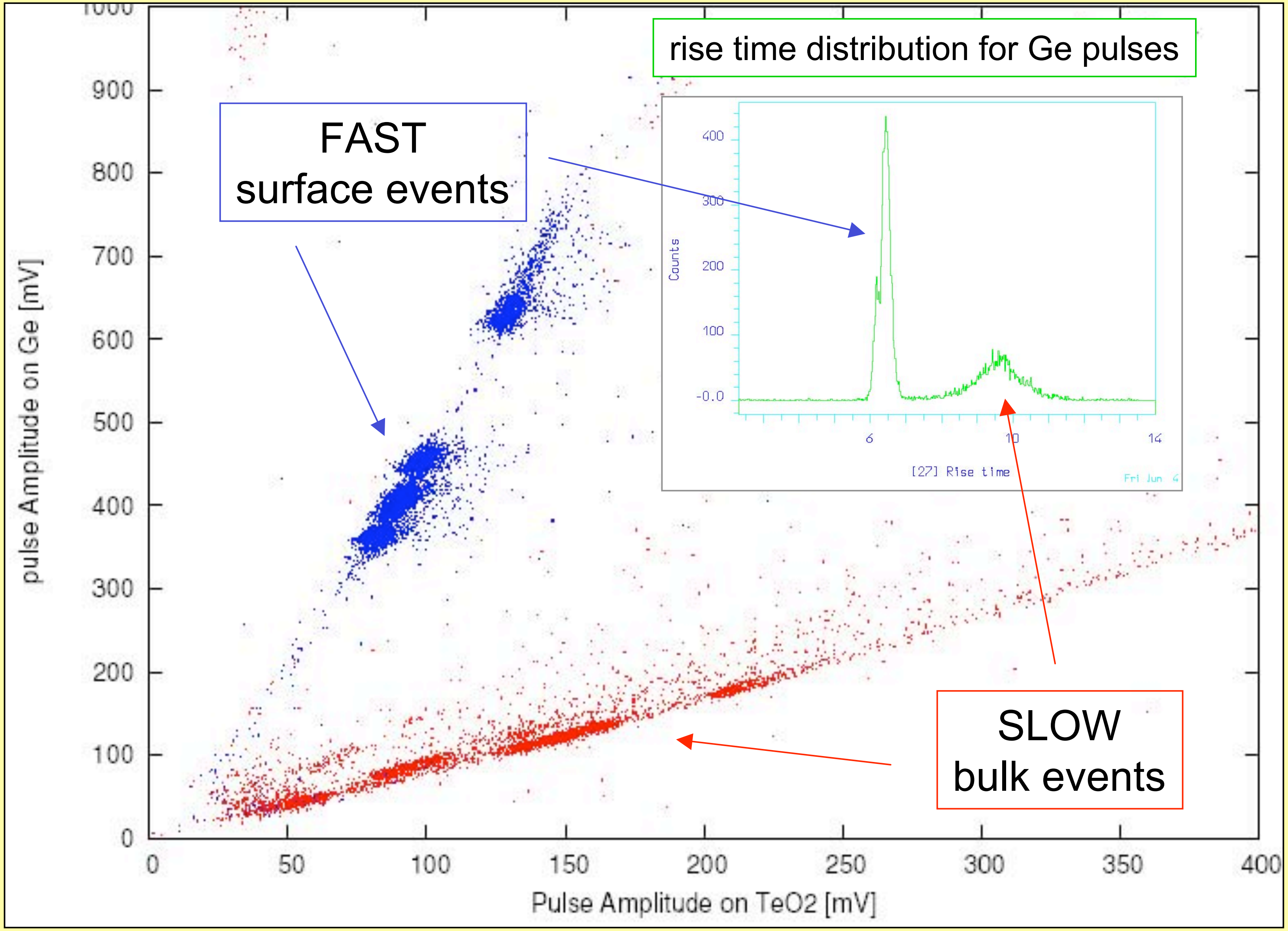
Preliminary very encouraging results (Insubria, Como)



CUORE for multi-isotope search

Calorimetric technique is powerful, but provides limited information

In case of discovery or hints for discovery, cross checks are mandatory

- remove doubts about unexplained lines of other origin
- test nuclear models
- reduce systematic uncertainty on the relevant parameters, like m_{ee}