CUORE/Cuoricino: double beta decay searches with low T-detectors

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the CUORE collaboration:

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INFN - Sezione di Milano

Dipartimento di Ingegneria Strutturale del Politecnico di Milano

Dept.of Physics and Astronomy, University of South Carolina

Laboratori Nazionali del Gran Sasso

Dipartimento di Fisica dell'Universita' di Firenze e Sezione di Firenze dell'INFN

Nuclear Science Division, Lawrence Berkeley National Laboratory,

Laboratorio de Fisica Nuclear y Altas Energias, Universidad de Zaragoza

Dipartimento di Fisica e Matematica dell'Universita' dell'Insubria

Dipartimento di Fisica dell'Universita' di Genova e Sezione di Genova dell'INFN

Department of Physics, University of California, Berkeley

Department of Materials Science and Mineral Engineering, University of California

Laboratori Nazionali di Legnaro,

Lawrence Livermore National Laboratory,

Dipartimento di Fisica dell'Universita' di Roma La Sapienza e Sezione di Roma dell'INFN

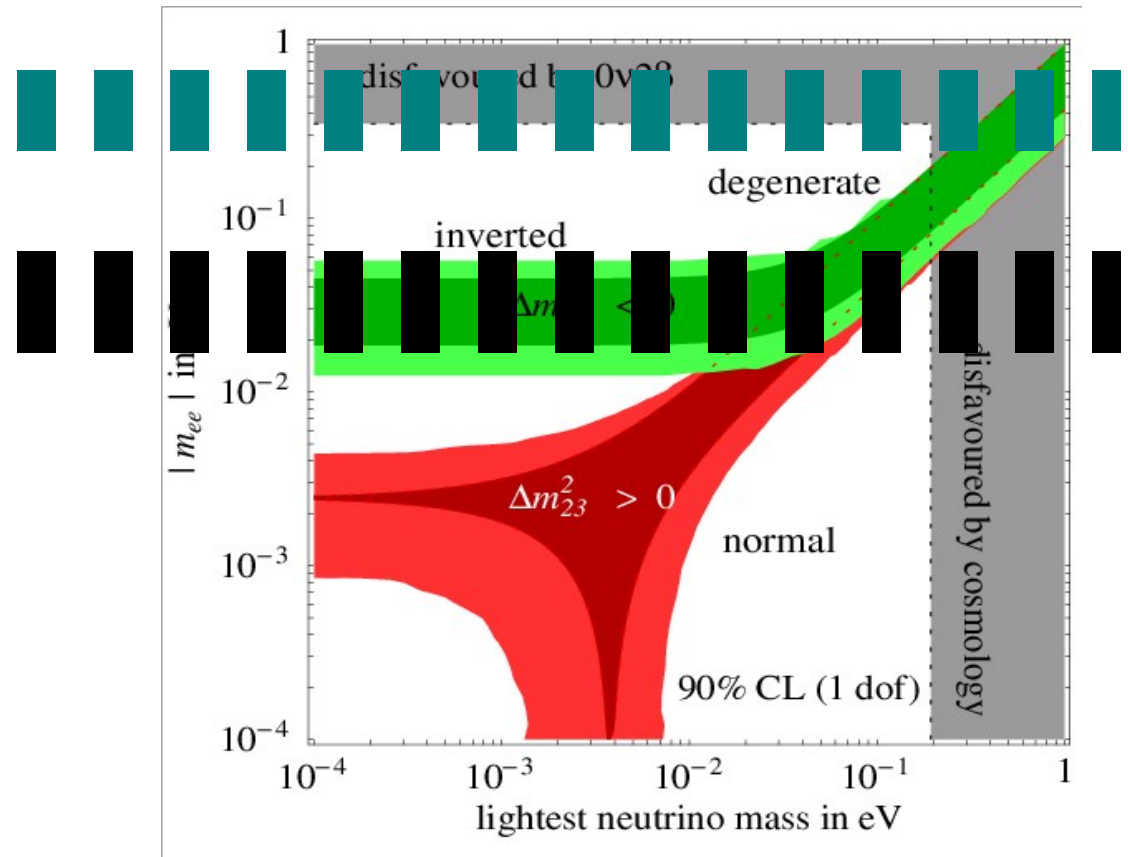California Polytechnic State University

University of Wisconsin

Outline

Neutrinoless Double Beta Decay: ^{130}Te Story

Experimental Status: Cuoricino

CUORE

.... this story begin at the end of the eighties ...

Once upon a time ....

the Standard Model included a <u>massless, Dirac neutrino particle</u>

that was the Standard Model "Era", a period of marvelous successes and discoveries for Particle Physics...

Majorana neutrinos were not much popular, even if in the years the first proves of not "Standard" properties of neutrinos were coming from ν solar experiments, still the deficit could find some explanation that did not imply a Majorana neutrino

Anyway Majorana neutrino had, even then, his fans and many experimentalist were on the stage seraching for 0νDBD

Exp. techniques

$$(A, Z) => (A, Z+2) + 2\,\nu_e$$

In the years two different experimental approaches had been developed:

source≠detector –
tracking detector + calorimeter - searches 2e tracks

source=detector –
calorimeter measures E1+E2≅Q - strong signature + low background

When our story begin the source=detector technique was already giving great results – at least in the case of the high resolution HPGe diodes
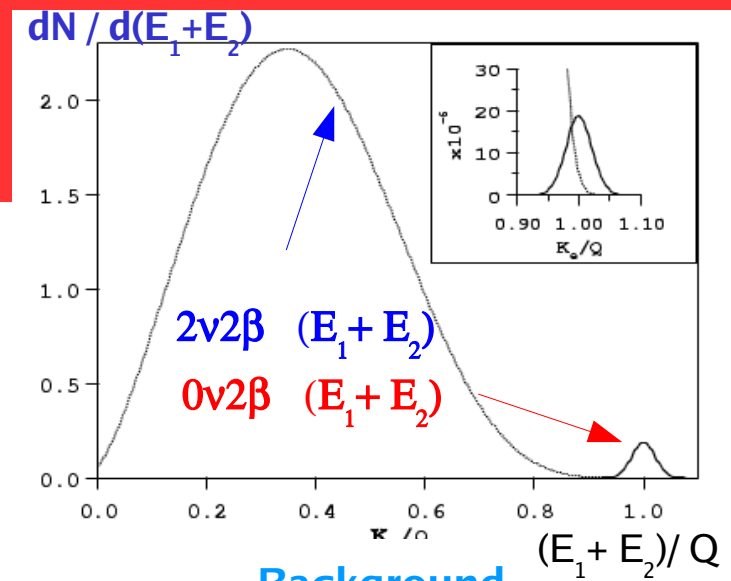
It was clear to the - not so many - fans of 0nDBD that this technique would have had a great future in mass scale up
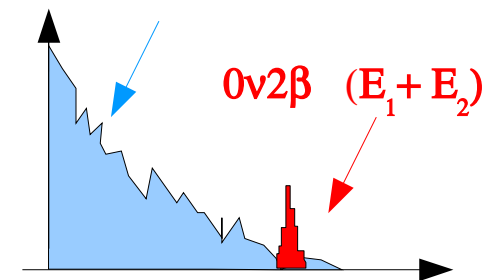BUT
also that Ge was just one of the DBD candidate, probably not the best
AND
that due to the NME problem exploring more than one isotope was mandatory.

dN / d(E_1+E_2)

$2\nu2\beta$ (E_1+ E_2)

$0\nu2\beta$ (E_1+ E_2)

(E_1+ E_2)/ Q

Background

$0\nu2\beta$ (E_1+ E_2)

Searching for the best candidate

0νDBD transition probability is:

$$\Gamma^{0\nu}_{1/2} = G(Q,Z)\ |M|^2\ \langle m_\nu \rangle^2$$

$G(Q,Z)$ = phase space ~ Q^5

$\langle m_\nu \rangle^2$ = Majorana mass

$|M|^2$ nuclear matrix element
theoretically evaluated (shell model, QRPA models ...) BUT with different results

The best candidate has the lowest $G*M^2$ BUT M is not exactly determined !!!
⇒ there is an <u>ensemble</u> of best candidates

and ... short half-life
is not enough

⇒ high Q
⇒ high isotopic abundance
⇒ ...

^{130}Te

- good NME

- high natural **isotopic abundance** (i.a. = 33.87 %)

- high **transition energy** (Q = (2528.8 ± 1.3) keV)

May be not the best certainly a very good candidate !!!

The only point was that no solid state detector – made of Te - with performances competitive with Ge diodes did exist

the solution: **JUST "INVENT" IT (this looked like a DREAM)**

that is: build a bolometric detector (at that time - '80 – maximum size was ~ grams) and reach energy resolution and masses as good as HPGe

than you will have one of the best detectors for DBD decay you could do !!!

**AND WHAT IS INCREDIBLE ...
THE DREAM BECAME REALITY**

- tech. suggested in 1985 by E. Fiorini and T.O. Niinikoski
- the first Te detector worked in 1989
- first bolometric DBD experiment in 1997
- predecessor of CUORICINO : 20 crystal array

$$\tau_{1/2}^{0n} < 2.1 \ 10^{23} \ y \ @ \ 90\% \ C.L. \ \text{(Phys. Lett B 557 - 2003)}$$

^{130}Te ... from 73 g to 1 ton

... AND THE REALITY OVERCAME THE DREAM ...
from few people in Milano we are now 66 people 3 countries 17 institution
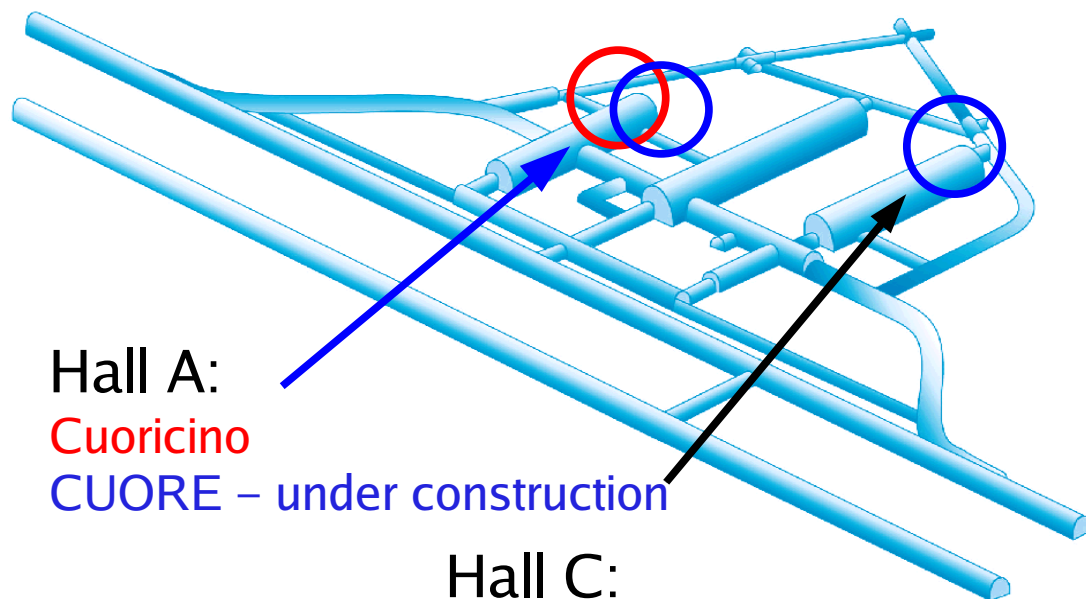from few grams we have a 40 kg experiment running and a 1 ton project

The Moore's law of TeO$_2$ bolometers
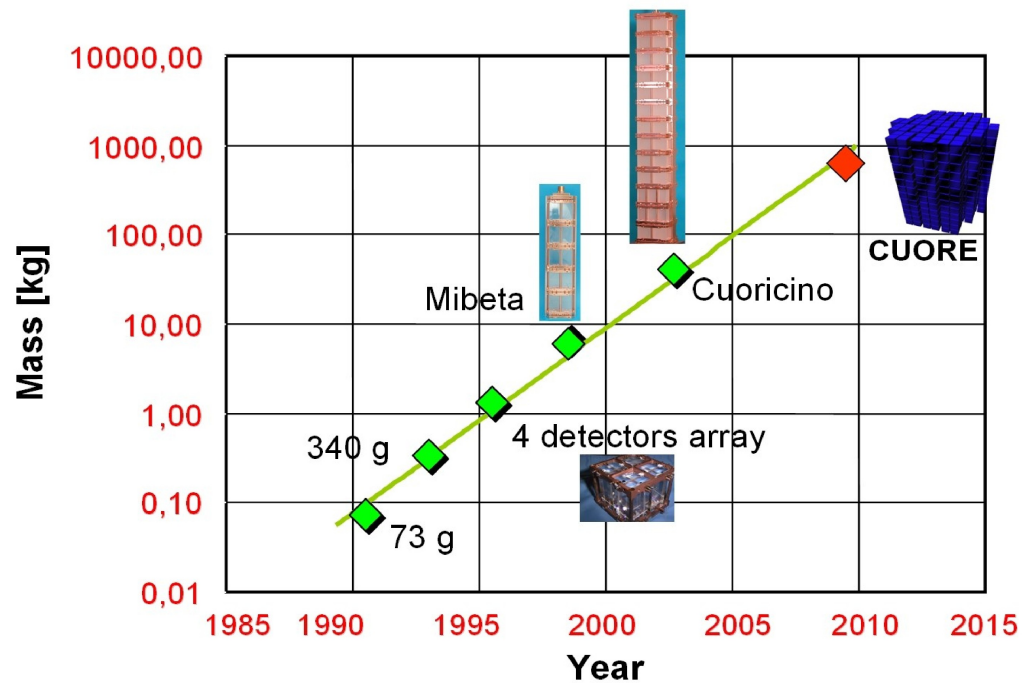
location = Laboratori Nazionali del Gran Sasso

L'Aquila - Italy

Hall A:
Cuoricino
CUORE – under construction

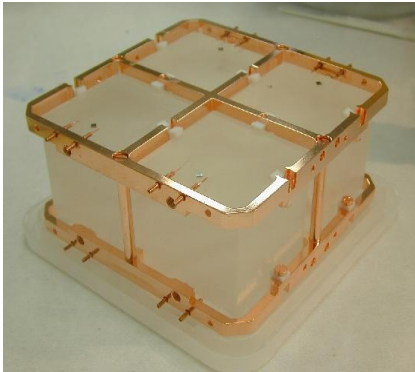Hall C:
R&D + final test for CUORE

3200 m.w.e overburden
cosmic rays are no more a bkg problem

n flus is reduced to ~10^{-6} n/cm2/s
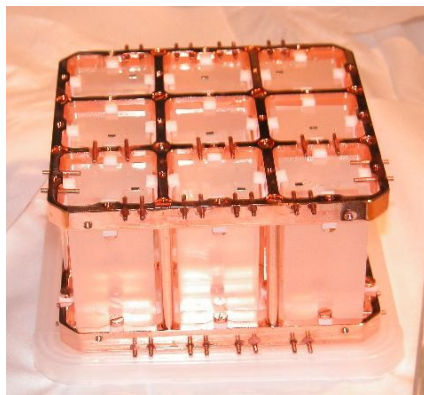muon flux is ~ 2/m^2/h (they can contribute to bkg only through (mu-n) reactions)

Cuoricino

44 TeO$_2$ crystals 5x5x5 cm^3 + 18 TeO$_2$ crystals 3x3x6 cm^3

array with a CUORE tower-like structure

**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$_2$

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

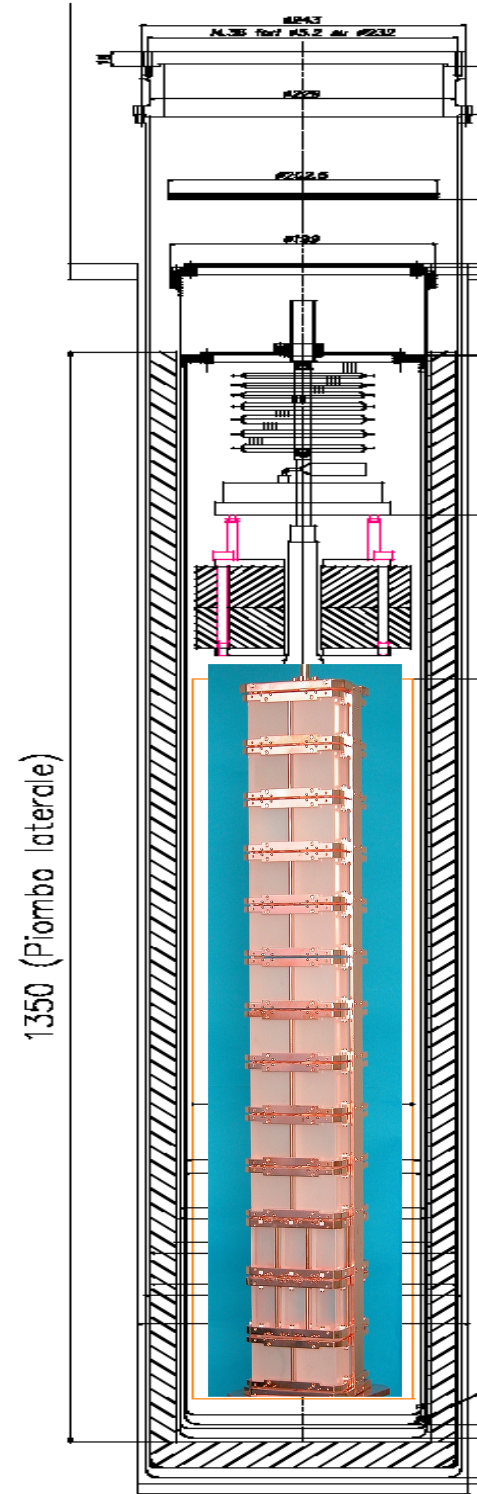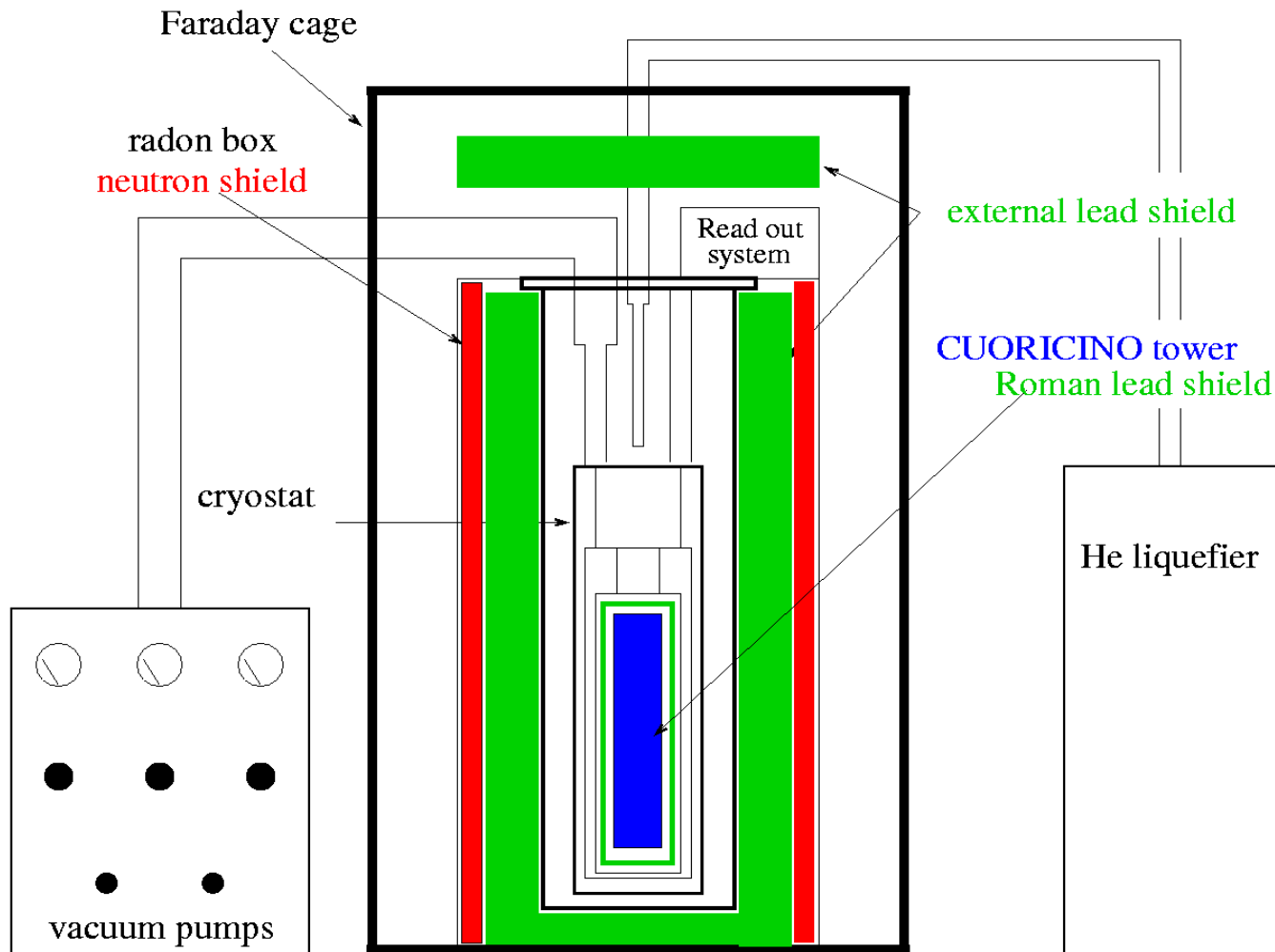**9 x 2 x 0.33 = 5.94 kg of TeO$_2$**
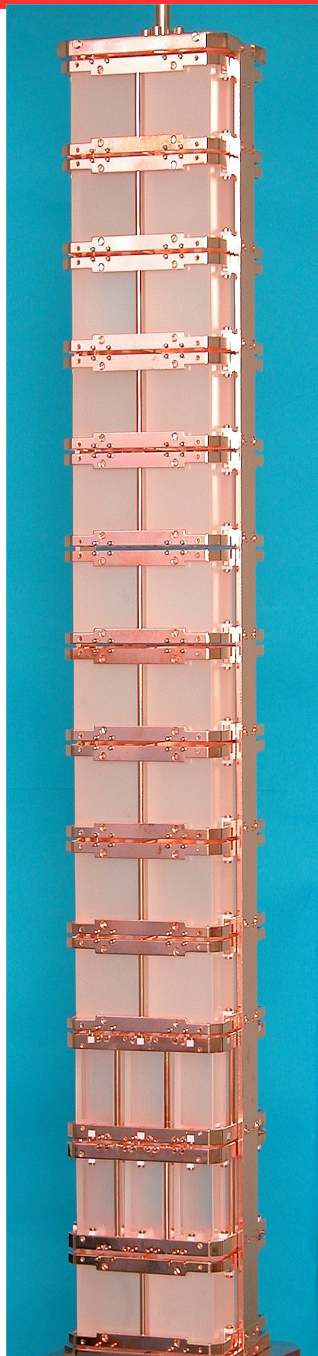
Cuoricino – set up

- array closed in a Cu box and shielded with Roman lead
- detectors operated at ~ 10 mK by means of a He^3/He^4 refrigerator
- refrigerator shielded with 20 cm Pb + 10 cm borated polyethylene

Faraday cage

radon box
neutron shield

Read out system

external lead shield

CUORICINO tower
Roman lead shield

cryostat

He liquefier

vacuum pumps

1350 (Piombo laterale)

Cuoricino performances

started = **April 2003 – presently WORKING**

DBD live time = **60% in standard conditions**

- long interruption between run I and run II in 2004
- few long stops - maintenance of the 17 year old refrigerator
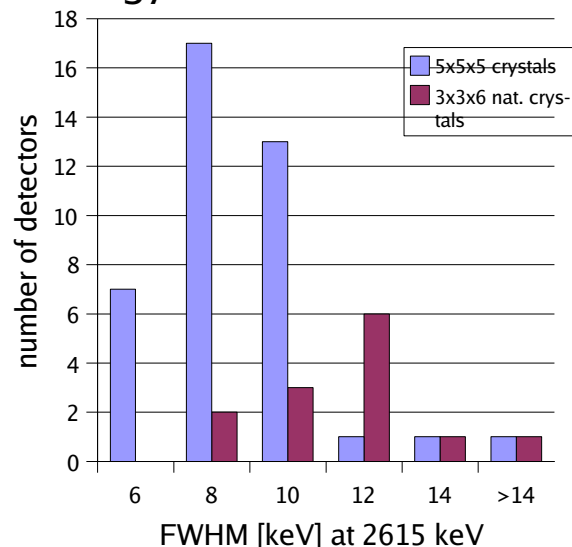- problems due to LNGS renovation works

performances

- detector energy resolution is measured – on the single bolometer - in monthly source (^{232}Th) calibration

- FWHM measured on SUM bkg spectrum at 2.6 MeV ~ 8 keV

Energy resolution distribution

FWHM [keV] at 2615 keV

Statistic =8.38 kg y ^{130}Te

- updated May 2006
- ++ data to be analyzed

Crystal type	Work. Det.	Statistic kg(^{130}Te)*y	FWHM [keV] Source	FWHM [keV] Bkg.
Big	29	0.94	7.8	9.2
Small-nat	11	0.09	9.1	14
Small-enriched	2	0.03	24.3	–
Big	40	6.25	7.5	6.3
Small-nat	13	0.76	9.6	11
Small-enriched	2	0.31	16.3	10
Total natural crystals		8.04	kg(^{130}Te)*y	
Total		8.38		

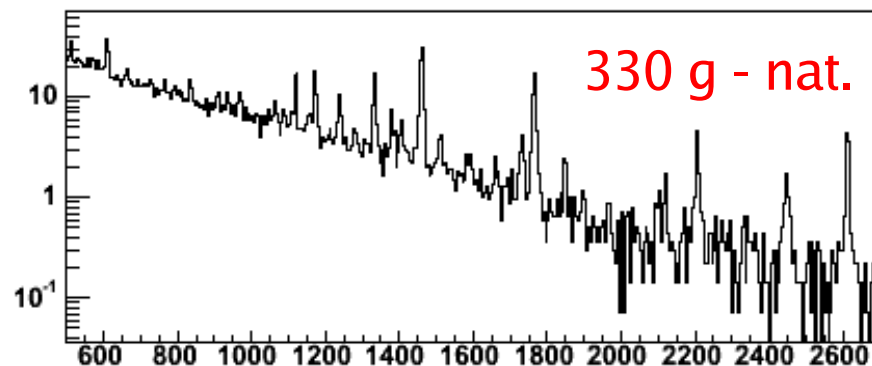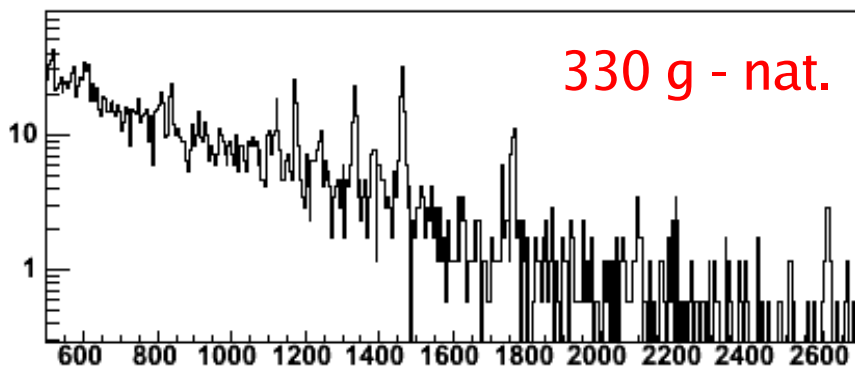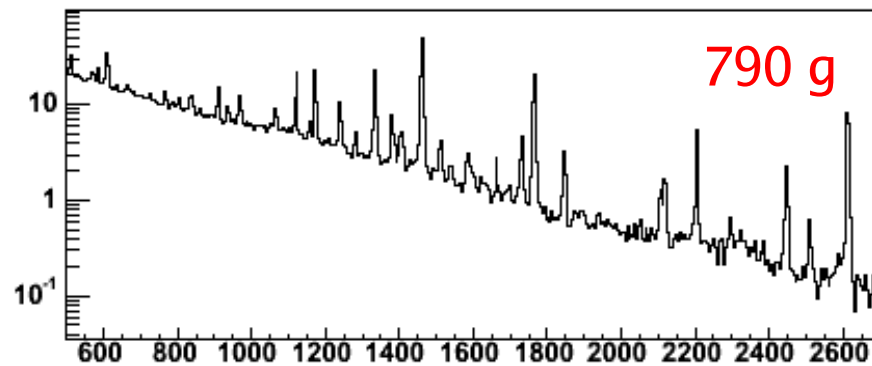# Cuoricino: sum spectra in the g region

Run I

Run II

790 g

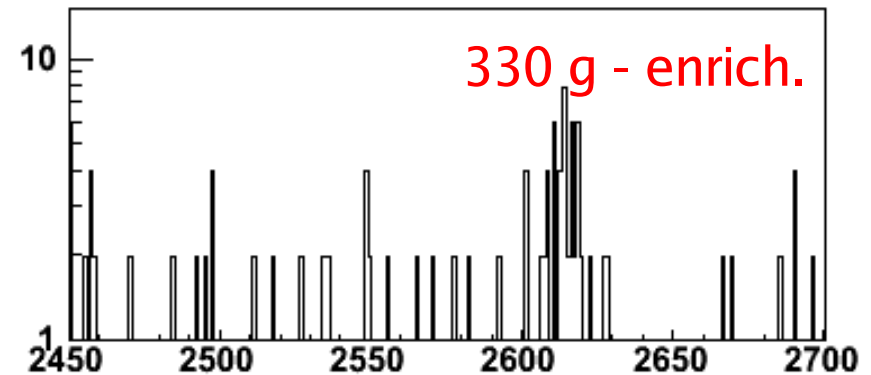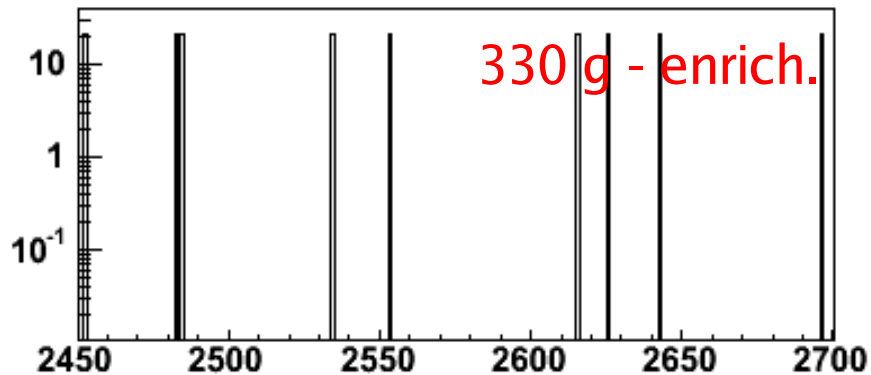790 g

330 g - nat.

330 g - nat.

330 g - enrich.

330 g - enrich.

c/keV/gk/y
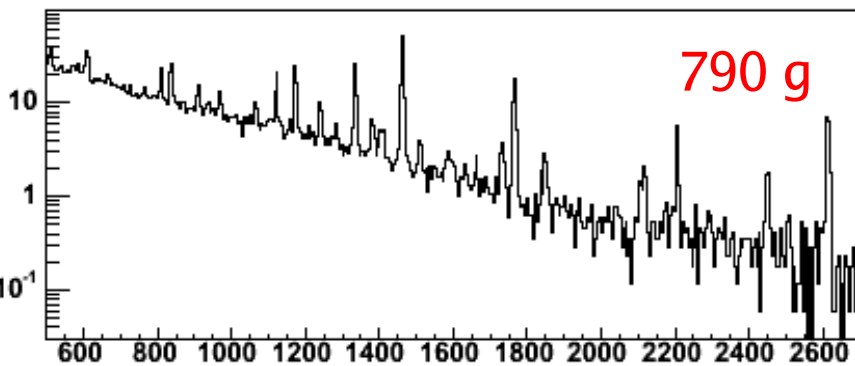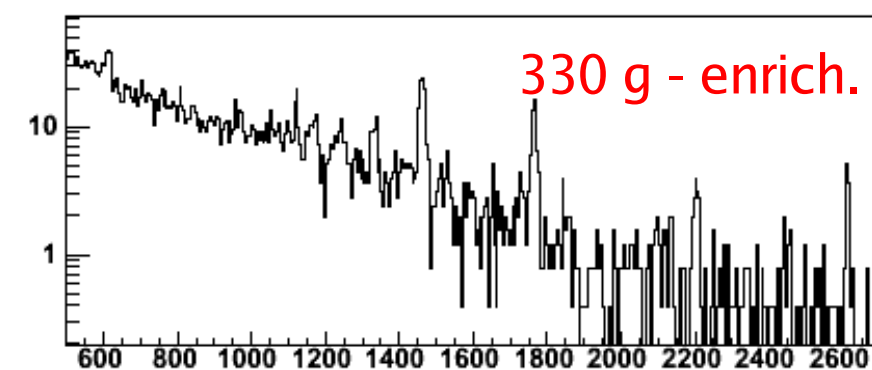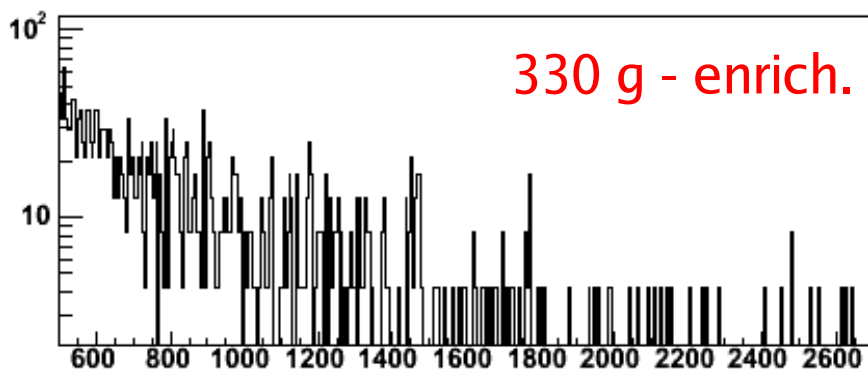
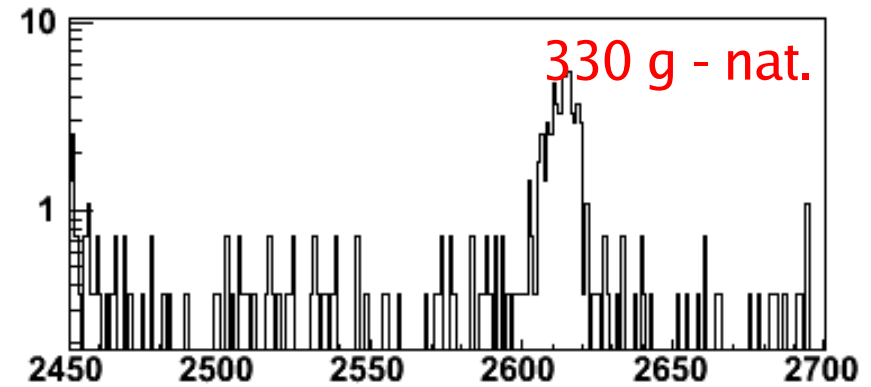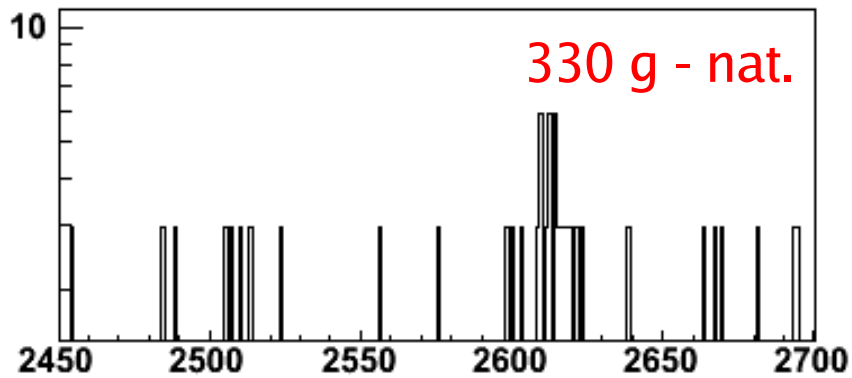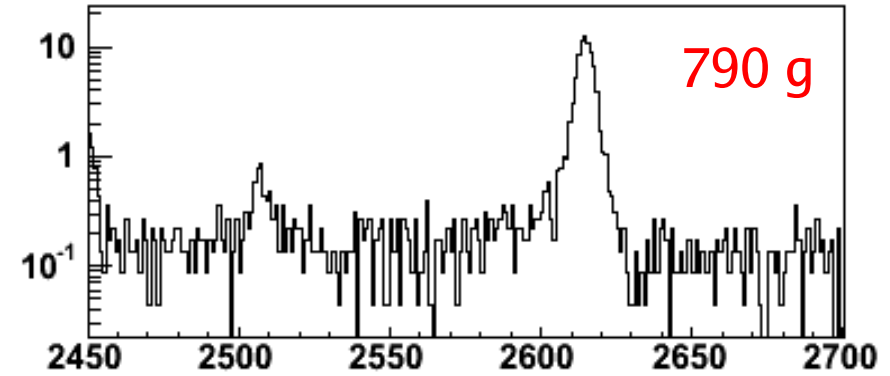# Cuoricino: sum spectra in the DBD region
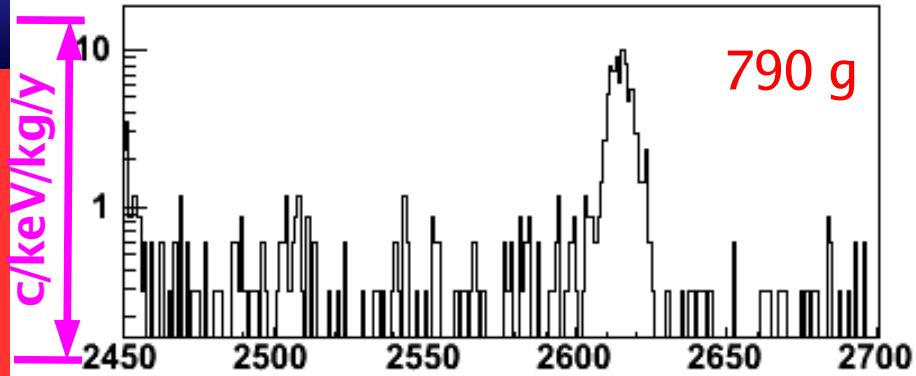
Cuoricino DBD result

Fit with N gaussian + flat bkg

to account for the different energy resolutions we use -as response function - the sum of N Gaussians (N= number of detectors) having each a FWHM equal to the average FWHM measured (on the 2615 keV line of Th source) for that detector during the run considered

2505 keV peak included in the fit

the sum peak of the ^{60}Co gamma lines is ~ 3 FWHM away from the 0nDBD, therefore cannot be excluded from the fit region

Maximum Likelihood procedure – likelihood of the 6 spectra are combined toghether

Big – Small – Enriched crystals are kept separated because of:
- different efficiency and i.a.
- different background

run I and run II are kept separate because of:
- different energy resolution
- different detectors

free parameters =
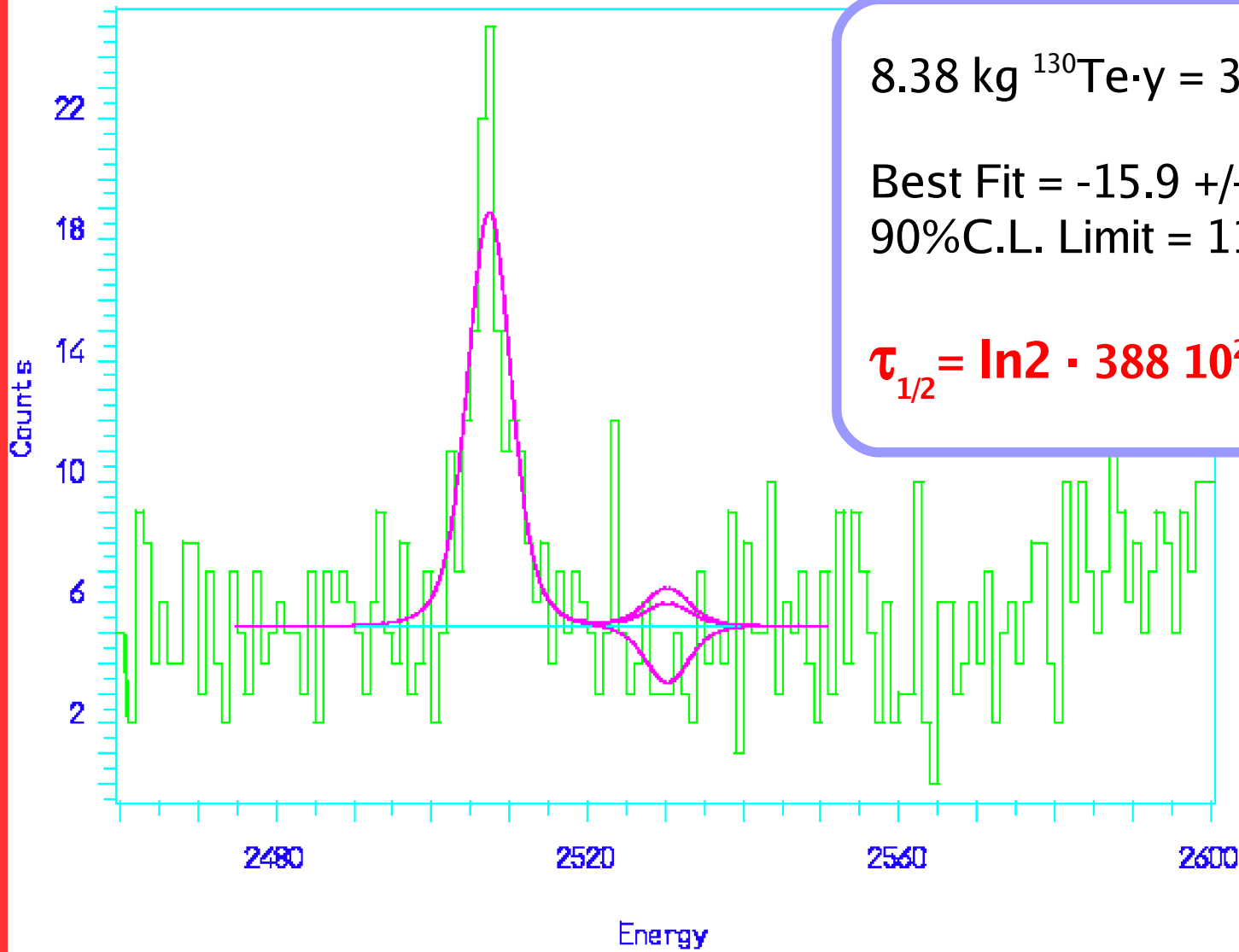**^{60}Co peak intensity and position + 0nDBD peak intensity + bkg coefficients**

$\tau_{1/2} > 2.4 \ 10^{24}$ y at 90% C.L.

$<m_\nu> < (0.18 - 0.90)$ eV

NME as in PRL 95, 142501 (2005)

8.38 kg ^{130}Te·y = 386 10^{23} atoms·y

Best Fit = -15.9 +/- 7.8 counts
90%C.L. Limit = 11 counts

$\tau_{1/2} = \ln 2 \cdot 388 \ 10^{23} \cdot 1/N$ [y]

Cuore: $\langle m_\nu \rangle \sim 50$ meV

750 g TeO$_2$ *x 988*

988 detectors
(cilindric array)
M = 741 kg

0.75 kg x 988 = **741 kg TeO$_2$**

~ 600 kg Te = **200 kg ^{130}Te**

80 cm

Dilution refrigerator
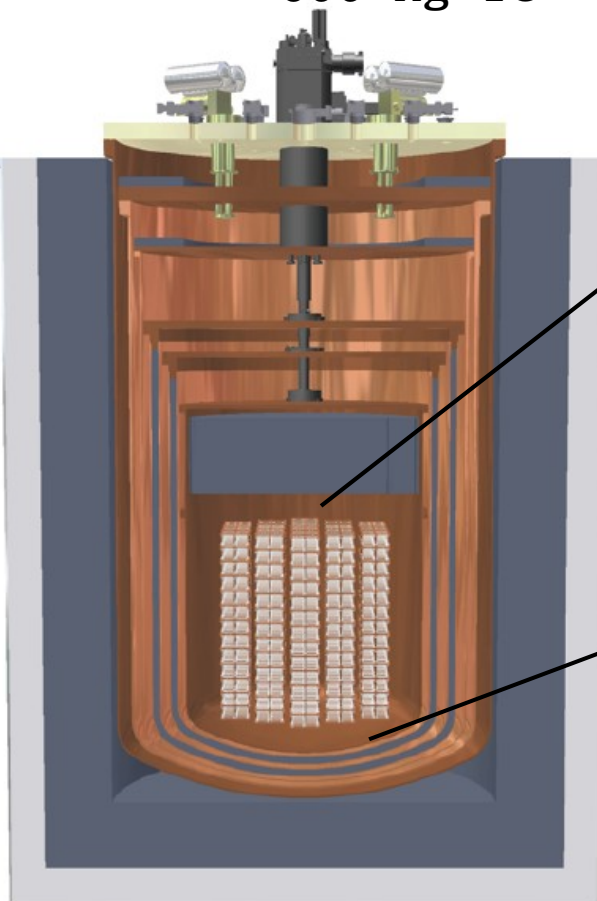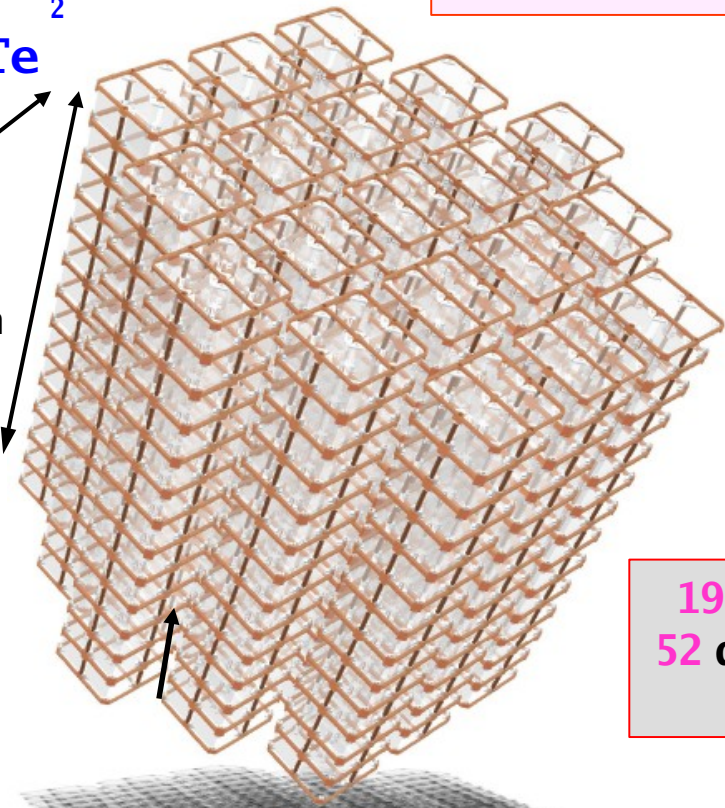
19 towers
52 detectors
each

A single-tower test (CUORICINO) was
started in 2002 and is presently running

Cuore status

Detectors will be almost identical to Cuoricino ones 5x5x5 cm3 = 750 g, the structure of the single tower will be a little bit different and has already been tested in hall C

Cuoricino+hallC tests proves that performances parameter are almost stable

The detector is completely designed !!!

Cryostat: will be a custom refrigerator designed for CUORE with special precaution in order to minimize microphonics and to guarantee temperature stability

The cryostat is designed and will use a standard dilution units and the bid will start soon ...

Electronics and DAQ designed

Hut including clean room, shield structure ... is designed and the bid will start

CUORE is approved – partially funded – space in LNGS allocated

READY TO START BY END 2009 !!!

Cuore sensitivity

$$S^{0n}_{1/2} = \ln 2 \, N_{bb} \left(\frac{T}{B \, \Gamma} \right)^{1/2} \varepsilon$$

Mass ($N_{\beta\beta}$), efficiency (ε) and energy resolution (Γ) are almost fixed – the sensitivity depends on measuring time (T) and background (B)

Bkg	[c/keV/kg/y]	0.01	0.001
FWHM	[keV]	10	5
S_{0n} - 3 years	[y]	1.1×10^{26}	9.2×10^{26}
$<m_\nu>$	[meV]	20-100	15-55

Our bgk prediction for Cuore are based on the measured Cuoricino bkg, on the model we have drawn for that and on MonteCarlo simulations that use as input measured values or limit for the different possible bkg sources

The real challenge of CUORE will be control and reduction of background

BKG SOURCES

- *Radioactive contaminations in the detector materials, on the detector surfaces*
- *Radioactive contaminations of the set-up – shielding included*
- *Neutrons*
- *Muon induce neutrons*

THE SOLUTION

- *Select construction materials according to their contamination (ICPMS, n-activation, HPGe)*
- *Avoid typically contaminated materials (use Cu, Pb and TeO2 everywhere obviously not possible if you have to build a refrigerator, electronics chain ....)*
- *Avoid activation (cosmogenic isotopes ... reduce exposure above grounds)*
- *Build thick efficient gamma and neutron shields*
- *BUILD a muon veto to tag muons and then n muon induced*

A NIGHTMARE !!!

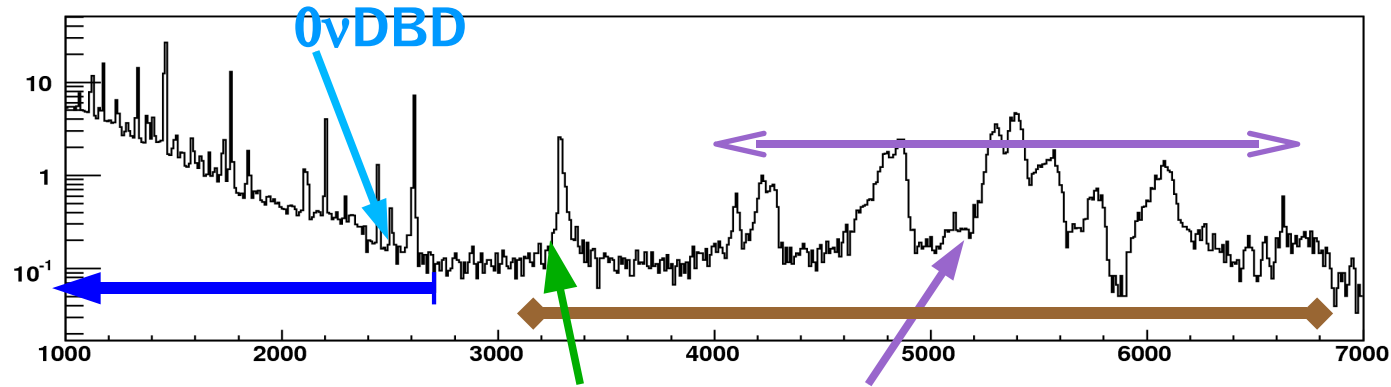a knowledge of what is critical is mandatory !!!

use Cuoricino experience – Cuoricino bkg model
+ specific measurement with a dedicated detector **(RAD - HallC)**
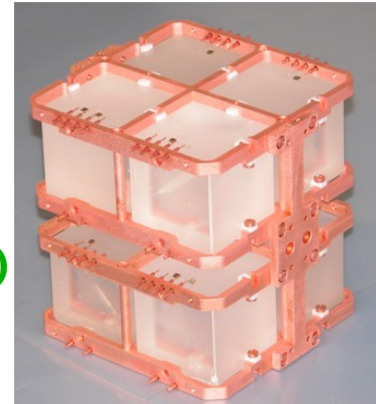
Cuoricino background

0νDBD

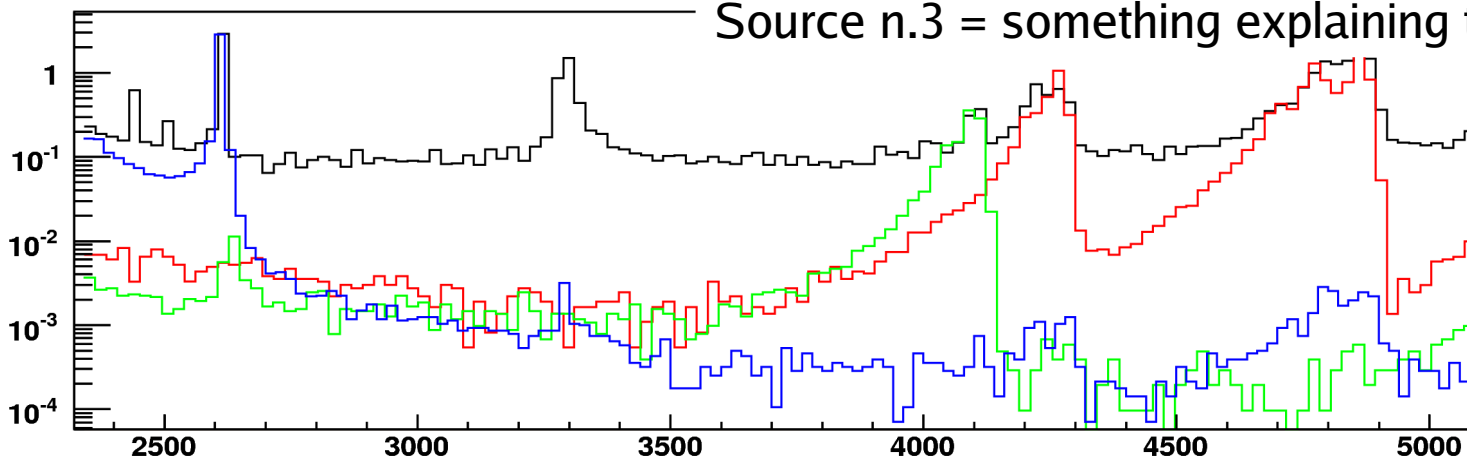Gamma region, dominated by γ and β, highest gamma line = 2615 keV ^{208}Tl line (from ^{232}Th chain)

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

DBD region: 2 clearly identified sources + 1 unknown source

Source n.1 = ^{208}Tl 2615 keV Compton events
Source n.2 = U and Th crystal surface contaminations
Source n.3 = something explaining the 3-4 MeV flat bkg

Cuoricino bkg model and extrapolation

Tl 2615 keV line -> just a problem of shielding

in Cuoricino the 2615 keV line is ascribed to a cryostat ^{232}Th contamination, CUORE cryostat is specifically designed to maximize the shield efficiency + severe selection of construction materials should guarantee a relevant reduction of Tl bkg proved by MC simulation of the CUORE apparatus based on measured contaminant levels of the construction materials

CUORE Tl line bkg = **< 10^{-3} c/keV/kg/y**

3-4 MeV continuous background -> work in progress

● Crystal surface: the contamination can be controlled with proper surface treatments (including chemical etching and polishing with "clean" powders). A recent test on 8 crystals (CUORE-like) proved that the new surface treatment studied in LNGS reduces the contamination by a factor ~ 4

Hall C measured contamination projected in CUORE < 3 10^{-3} c/keV/kg/y

● Unknown source: candidates are surface contamination of inert part of the detector

Hall C measured contamination projected in CUORE ~ 2/4 10^{-2} c/keV/kg/y

- ● a dedicated array of 8 5x5x5 cm^3 crystals operated in Hall C
- ● ICMPS bulk and surface measurement
- ● low bkg Ge spectroscopy
- ● some more investigation on neutrons contribution

Cuore bkg summary

Measured contamination projected (MonteCarlo) on CUORE

|	Background 10^{-3} c/keV/kg/y	
External gamma	< 1	
Exp. Apparatus	< 1	
Detector structure bulk	< 1	
Crystal bulk	< 0.1	
Detector surfaces	~ 20-40	⟶ The ONLY limiting factor
Crystal surfaces	< 3	
Neutrons	0.01	
Muons	0.01	

Conclusions

CUORICINO

- It is giving pretty good results on DBD
- It is fundamental for Cuore bkg predictions
- has proved the technical feasibility of CUORE !!

CUORE

- **It is (partially) funded + space is allocated !!!**
- Cryostat and hut will be soon realized
- **The real challenge of CUORE is background reduction !!**
  - Presently 2-4 times higher than our conservative prediction
  - We are studying innovative solution that could solve the problem of surfac contamination (surface sensitive detectors)
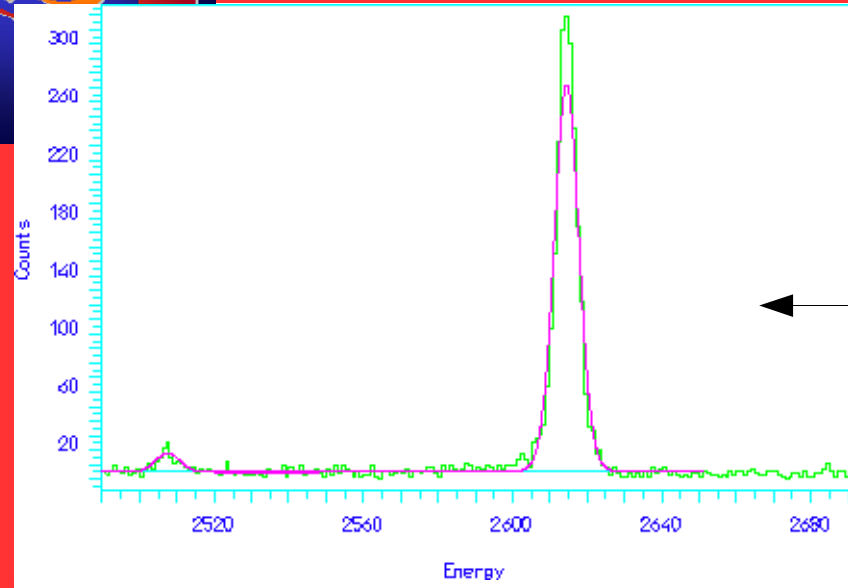
²¹⁴Bi 2448 keV ²⁰⁸Tl 2614.5 keV

~ 0.4 keV

⁶⁰Co 2505.7 keV
Fit position ~ 2507.5 keV
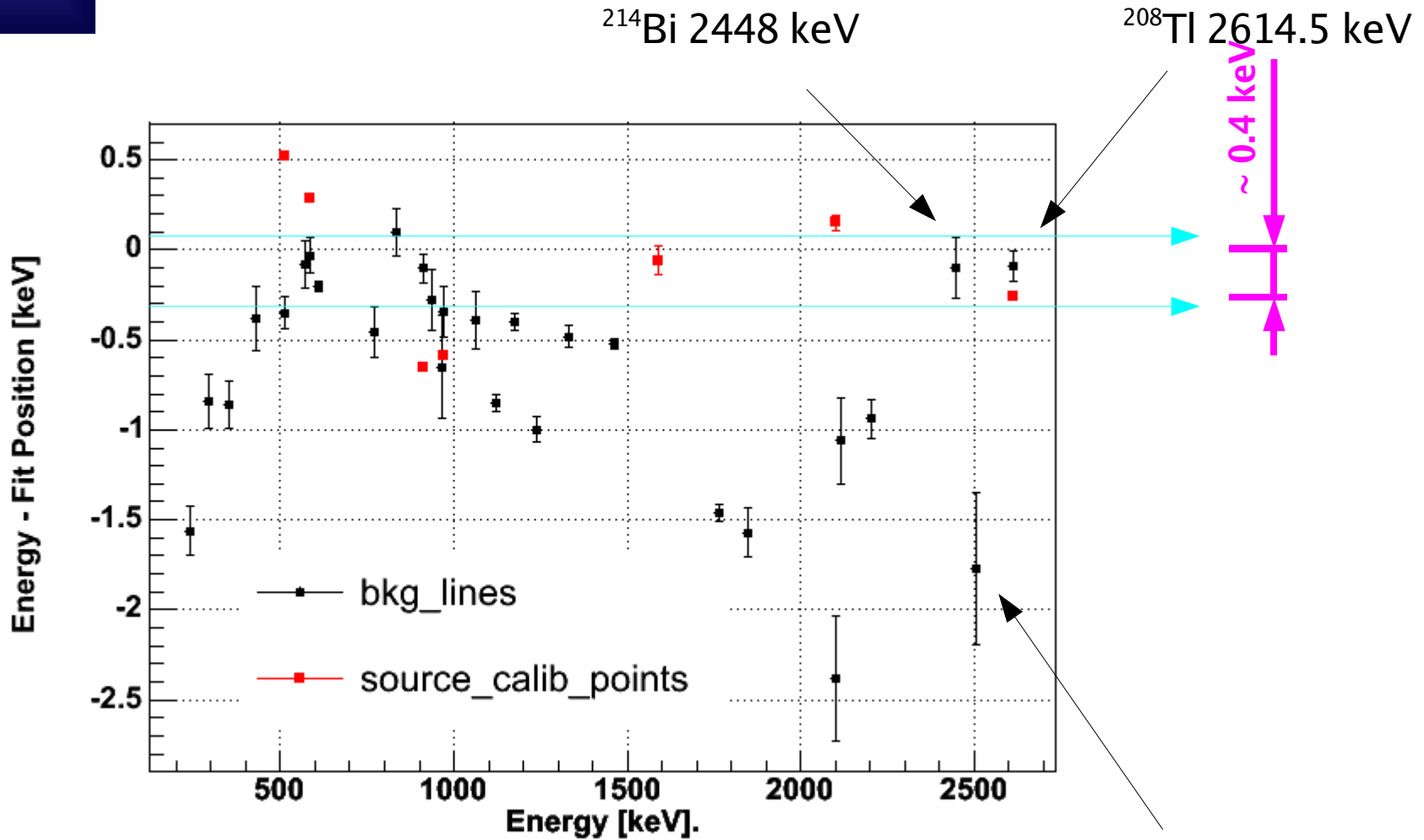
*all the peaks are fitted
with a single simmetric gaussian
+ linear bkg*

Line shape and resolution ...

single symmetric Gaussian
FWHM evaluation from sum bkg spectrum

N symmetric Gaussian
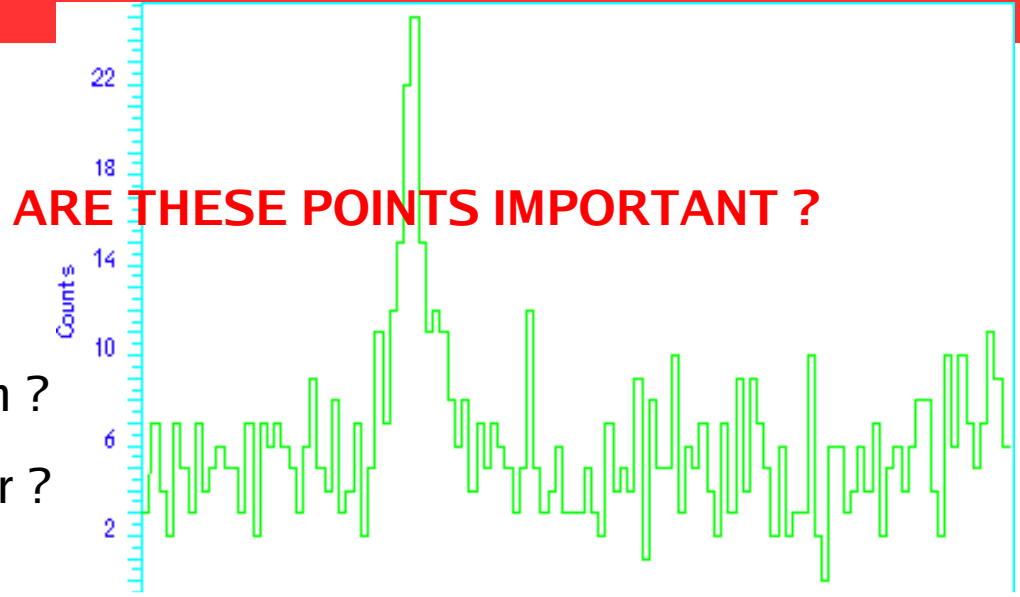*FWHM evaluation from source measurement spectra*
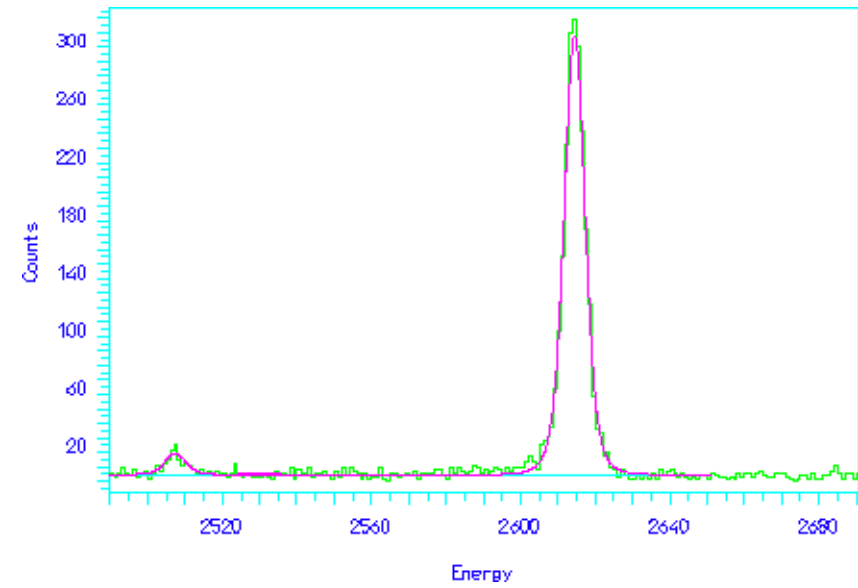
... however no change in the limit evaluation using the one or the other response function
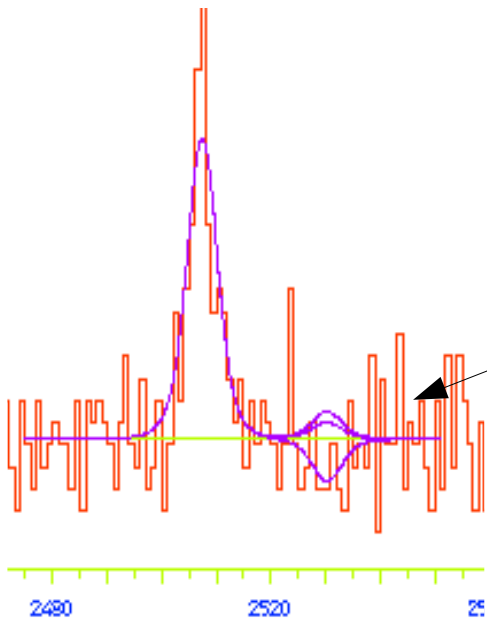
0νDBD limit study of the possible systematics

the energy transition (Q-value) has large errors (+/- 2 keV)

the bkg IS NOT flat

is the peak shape exactly Gaussian ?

which is the energy calibration error ?

ARE THESE POINTS IMPORTANT ?

JUST SEE WHAT HAPPENS IF WE CHANGE THE Q-VALUE

2527 keV	**1.91 10^{24}**
2528 keV	2.15 10^{24}
2529 keV	2.32 10^{24}
2530 keV	**2.43 10^{24}**
2531 keV	2.48 10^{24}
2532 keV	2.48 10^{24}
2533 keV	2.41$10^{24}$