

From Cuoricino to CUORE: Neutrinoless Double Beta Decay Measurements with TeO_2 Bolometers

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Representing the CUORE and Cuoricino Collaborations

Joint JPS/APS DNP DBD Workshop

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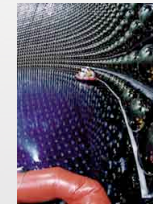


Context: Recent Developments in Neutrino Physics



Since 1998 SuperKamiokande, SNO, and KamLAND have shown:

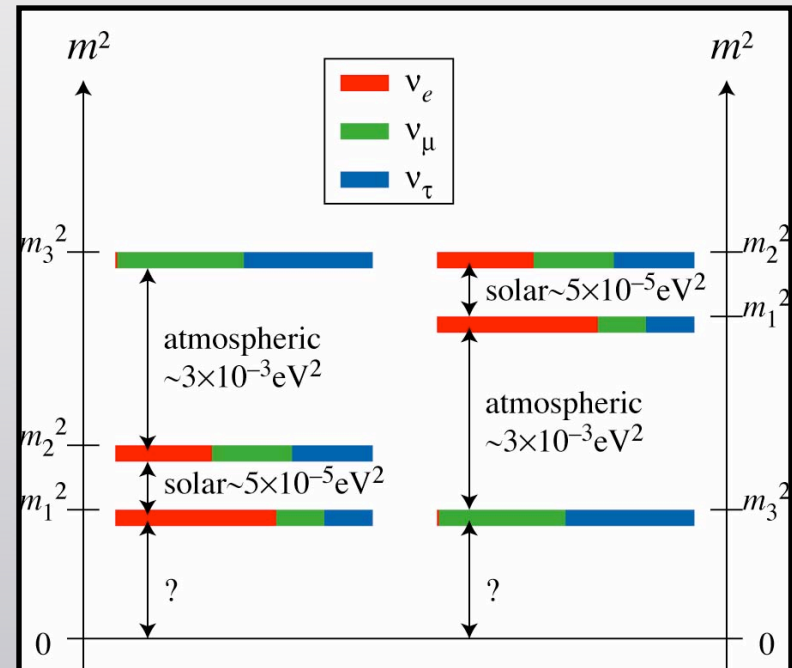
- Neutrinos undergo flavor-changing oscillations
- Neutrinos have finite masses



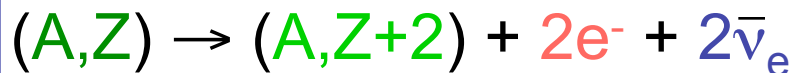
Two important open questions in ν physics

- What is absolute scale of the ν mass ?
- Are they Majorana or Dirac particles?

$\beta\beta 0\nu$ can address these



$\beta\beta 0\nu$: a powerful observational tool



allowed by the Standard Model

$$\tau \geq 10^{18} \text{ y}$$

Measured in real systems
(NEMO, geochemical, etc.)



open discussion on its observation

$$\tau \geq 10^{25} \text{ y}$$

Observation of $\beta\beta 0\nu$ implies Physics beyond the Standard Model

- Rate of decay sets ν mass scale
- Process only occurs if neutrinos are Majorana particles
- Violation of lepton number

“Trivia”

NASA’s WMAP mission
(2003) sets the age of the
universe at
 $13.7 \pm 0.2 \times 10^9$ years

$\beta\beta 0\nu$ Rate and Neutrino Mass



0ν -DBD rate
 Phase space $\propto Q^5$
 Nuclear matrix element
 Effective neutrino mass

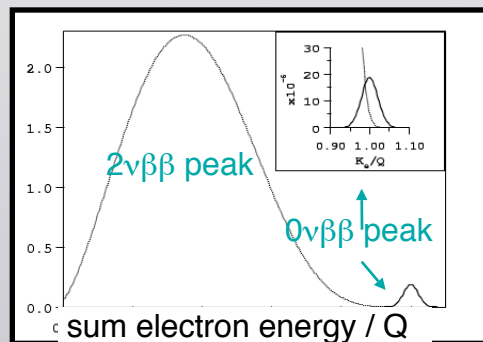
$$1/\tau = G(Q,Z) |M_{\text{nucl}}|^2 \langle m_{\beta\beta} \rangle^2$$



high Q candidates preferred

large phase space

low background



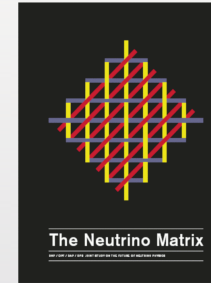
^{238}U γ end at 2.4 MeV
 ^{232}Th γ end at 2.6 MeV

[2039 keV (^{76}Ge) $\Leftrightarrow$ 4271 keV (^{48}Ca)]

Strategies and Tactics



$\beta\beta 0\nu$

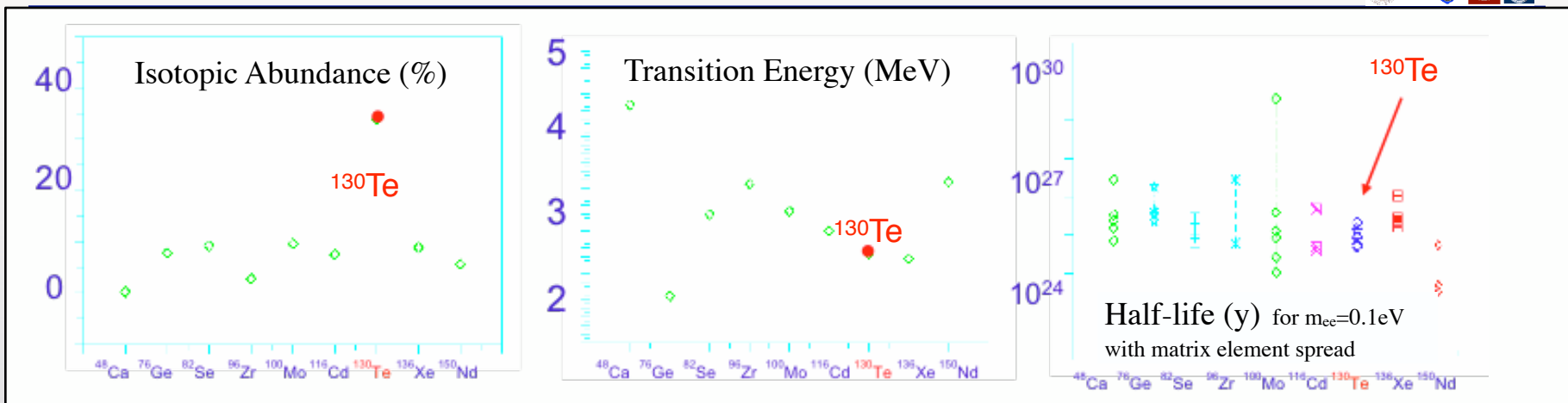


- $\beta\beta 0\nu$ is one of the two top priorities in neutrino physics
- Near term: 200 kg active mass
 - KKDC result must be addressed
 - Different isotopes
 - Different methods
 - If necessary
 - Completely explore the degenerate hierarchy
 - Start digging into inverse hierarchy
- Prepare for the one-ton generation
 - Fully explore inverse hierarchy
- Prepare for the über-challenge: the normal hierarchy

The massive tellurium
cryogenic bolometers
Cuoricino and
CUORE are prepared
to play their role this
grand neutrino
adventure



Why Tellurium?

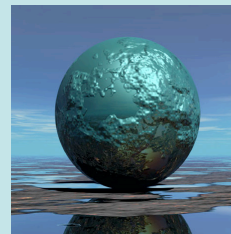


- Cost effective: Enrichment not required
 - Natural abundance 33.87%
- Reasonable $Q = 2528.8 \text{ keV}$
 - Large phase space
 - Low gamma background: Q sits between the Compton edge (2360 keV) and full ^{208}Tl energy (2615 keV)
- $\beta\beta 2\nu$ observed with geochemical techniques
- Extensive existing R&D with TeO_2 bolometers

Discovered : by Baron Franz Muller von Reichenstein in 1783
Isolated in Sibiu, Romania
Origin : The name is derived from the Latin 'tellus', meaning Earth.

"Its compounds are to be avoided because not only are they poisonous but contact with even the tiniest amounts leads to unpleasant body odors!"

^{130}Te



TeO_2 crystals used today in very high end opto-acoustic laser printers for lithography

<http://www.chemsoc.org/viselements/>

Why Bolometry?



- Il Buono

- Proven, tested, and true calorimetric technique
 - Measurement of temperature changes through heat exchange
- Source=Detector method measures all energy deposited: very high efficiency
- Wide isotope and absorber material choice: ^{48}Ca , ^{76}Ge , ^{100}Mo , ^{116}Cd , ^{130}Te
- Best measured energy resolution is 4 keV @ 2615keV (0.15%)
- Very large masses are possible

- Il Cattivo

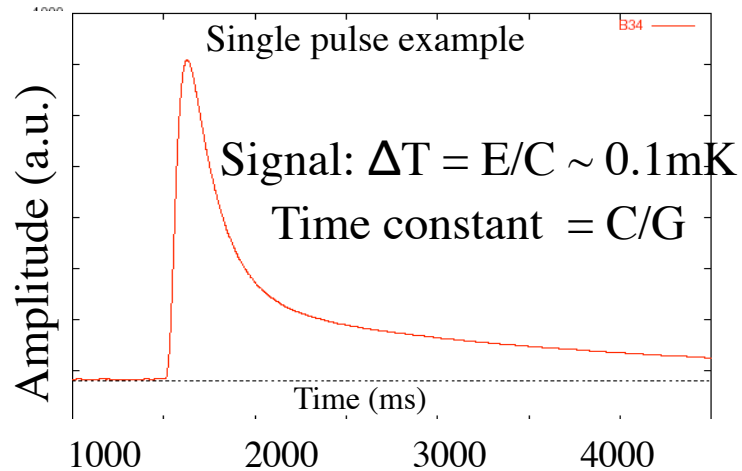
- Sensitive to surface radioactivity
- Difficult to reduce close materials: holders, cryostat, wires, etc.
- No vertex determination
- Slow response time (~seconds)



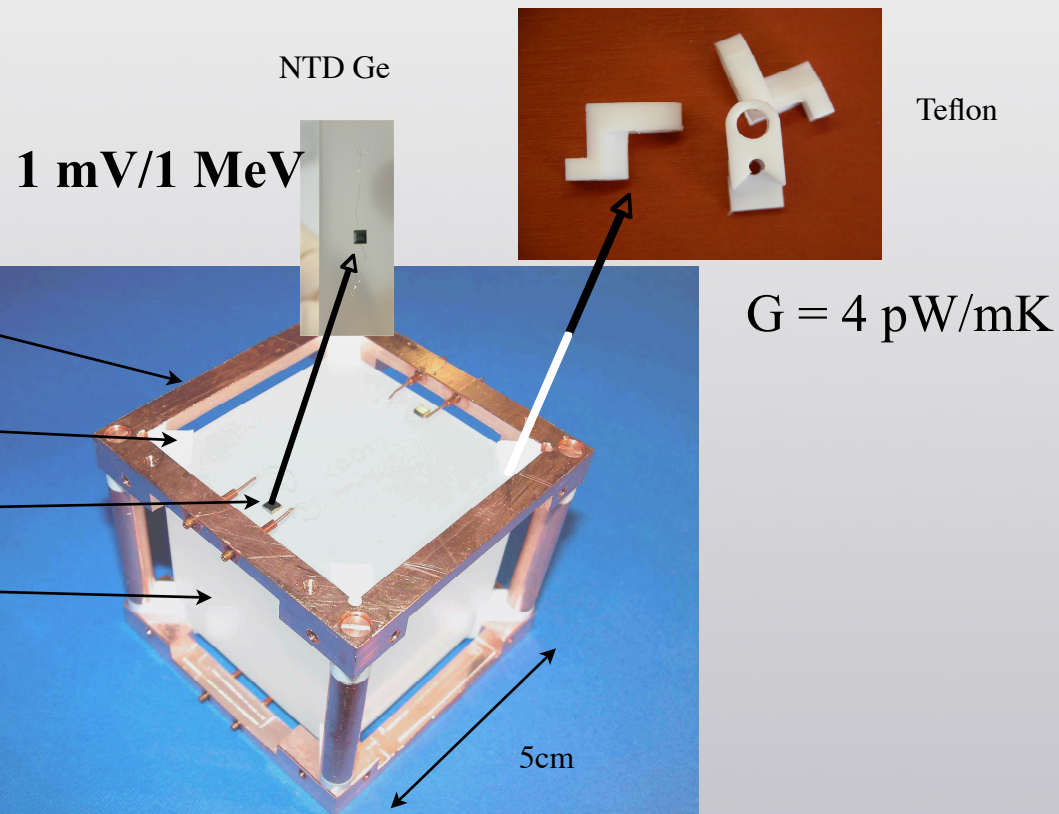
- Il Brutto

- Phonons can be tricky beasts: detailed microscopic models of the detector physics are elusive

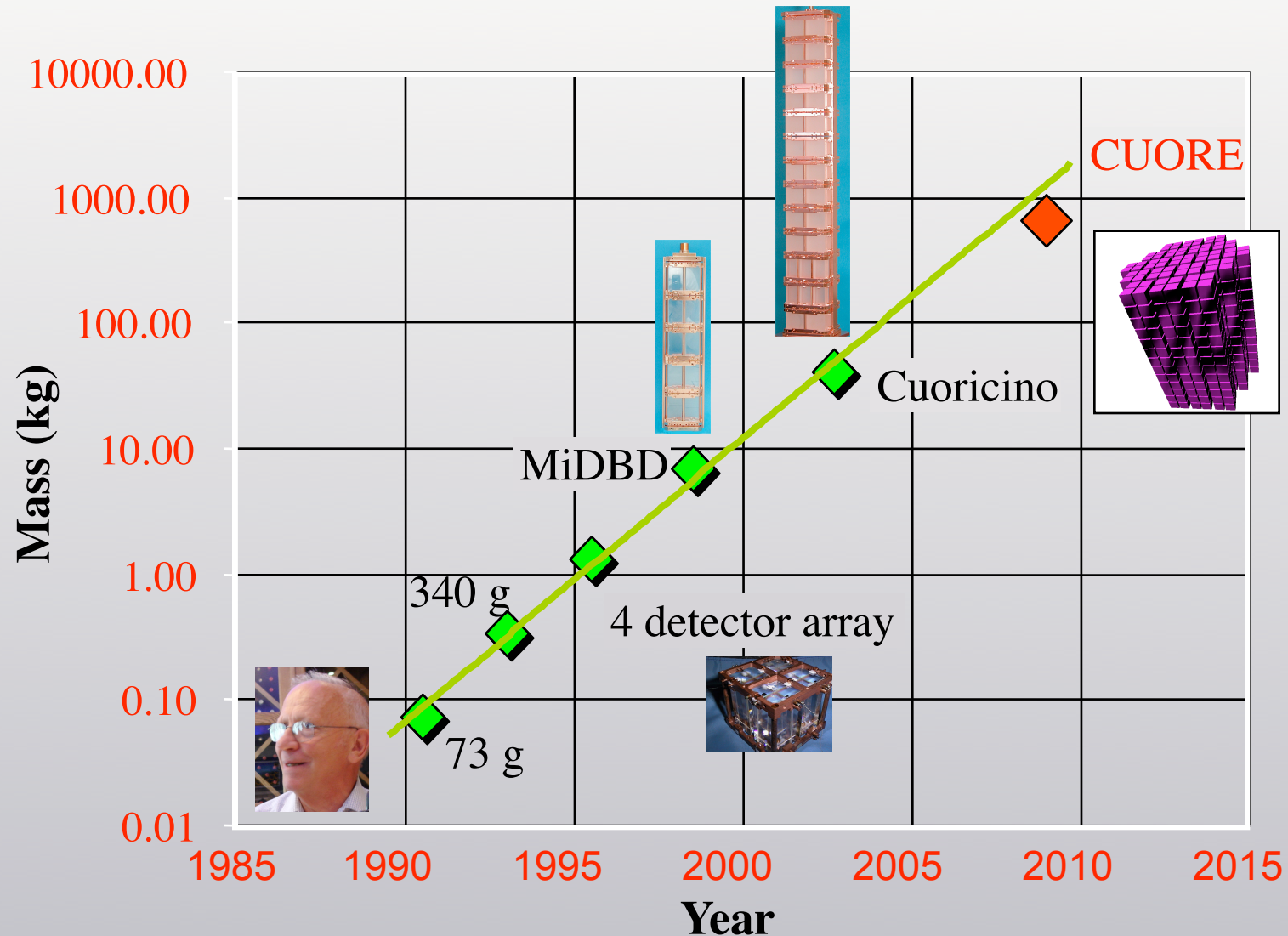
Cryogenic Bolometers



- Dielectric diamagnetic materials
- Low temperatures ($\sim 10\text{mK}$)
- Low heat capacity
 - $C \sim 2 \text{ nJ/K} = 1 \text{ MeV} / 0.1 \text{ mK}$



“Moore’s Law” Scaling of TeO_2 Bolometry Experiments



Gran Sasso National Laboratory (LNGS)



Shielding: ~ 3500 m.w.e.

Two dilution refrigerators

1. Hall A (Cuoricino) $\Rightarrow$ Running!

2. Hall C (R&D final tests for CUORE)

Cuoricino is currently the largest operating bolometer in the world



Site for proposed CUORE project approved in Hall A



Cuoricino, the “little heart” of Gran Sasso

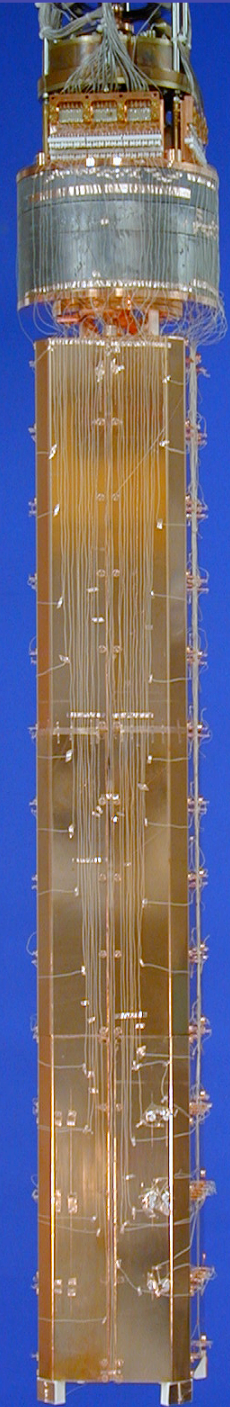
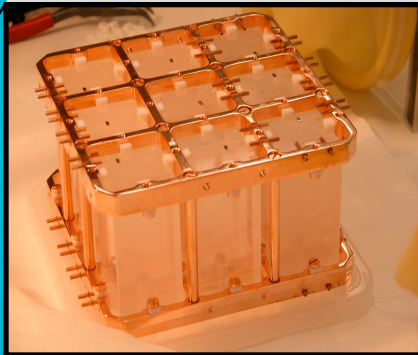
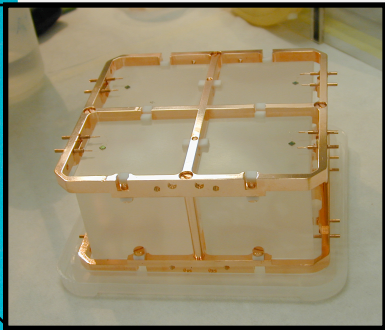
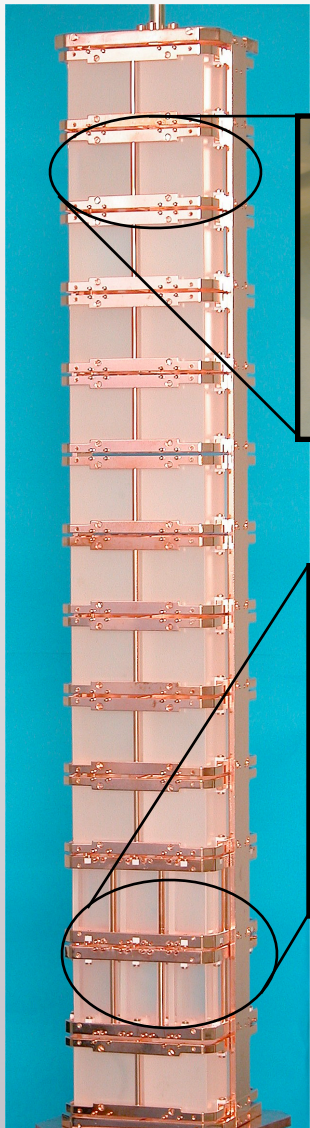
Cooled to 10mK

11 modules, 4 detector each,
crystal dimension: $5 \times 5 \times 5 \text{ cm}^3$
crystal mass: 790 g
 $44 \times 0.79 = 34.76 \text{ kg of TeO}_2$

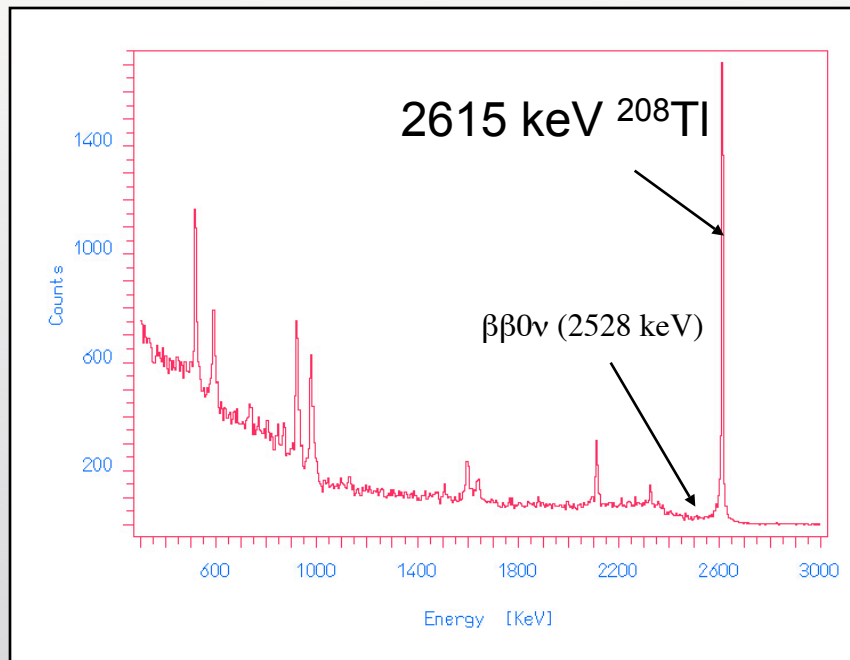
Encased in a cryostat, lead shield, nitrogen box, neutron shield, and Faraday cage

2 modules x 9 crystals each
crystal dimension: $3 \times 3 \times 6 \text{ cm}^3$
crystal mass: 330 g
 $18 \times 0.33 = 5.94 \text{ kg of TeO}_2$

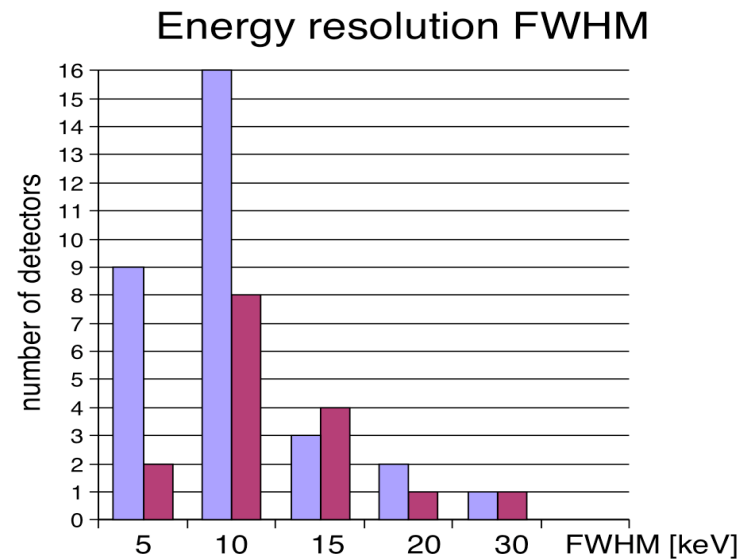
Total detector mass: $40.7 \text{ kg TeO}_2 \Rightarrow 11.34 \text{ kg } ^{130}\text{Te}$



Cuoricino Performance



← Energy calibration spectrum obtained with ^{232}Th source (summed over all crystals)



Resolution limited by

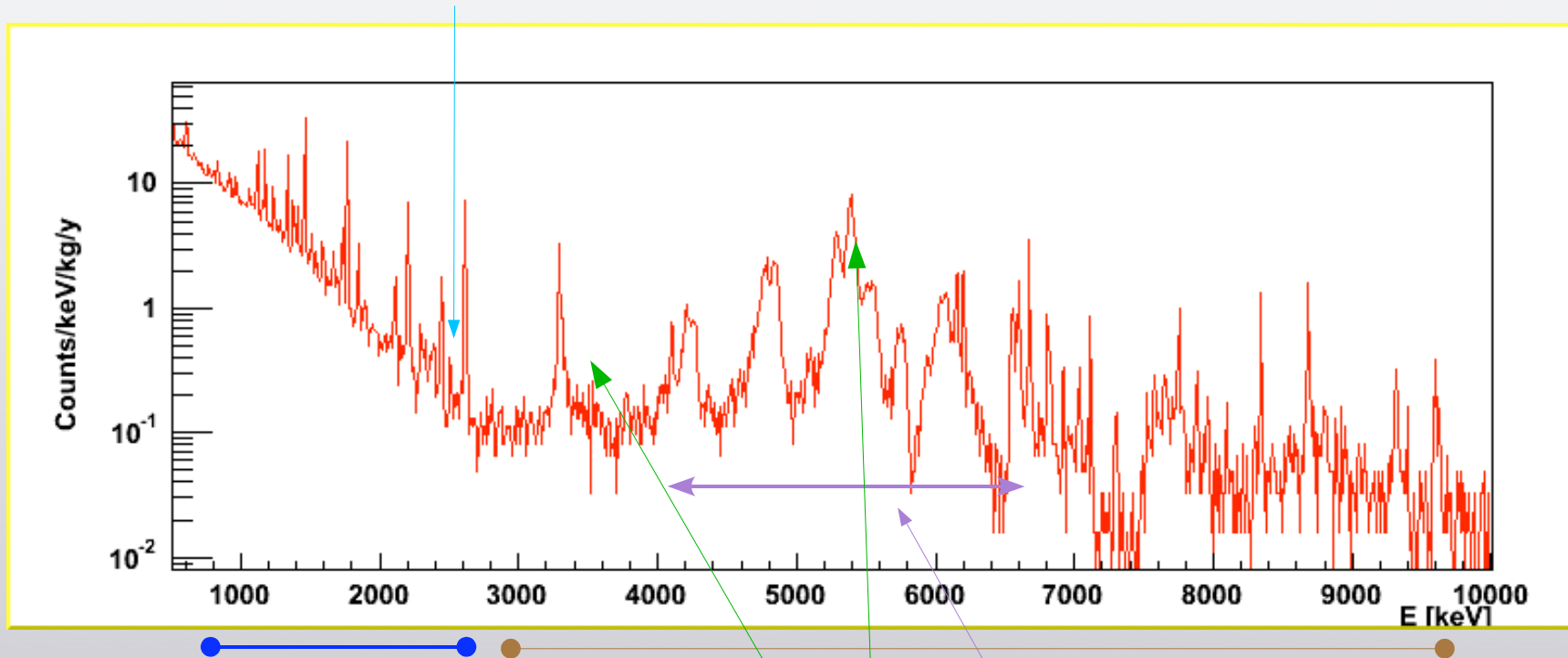
- Thermal/Phononic ($\Delta \sim \text{eV}$)
- Electronic noise ($\Delta \leq 1 \text{ keV}$)
- Microphonics ($\Delta \leq 1 \text{ keV}$)
- Detector responses $\Delta \sim \text{keV}$

- Average 5x5x5 cm³ crystals $\sim 7.8 \text{ keV}$
- Average 3x3x6 cm³ crystals $\sim 12.3 \text{ keV}$
- The best energy resolution @ 2615 keV is 3.9 keV
- Absolute energy resolution (keV) gets better @ low E while relative resolution stays around 0.2%

Cuoricino Backgrounds



$$\beta\beta 0\nu$$



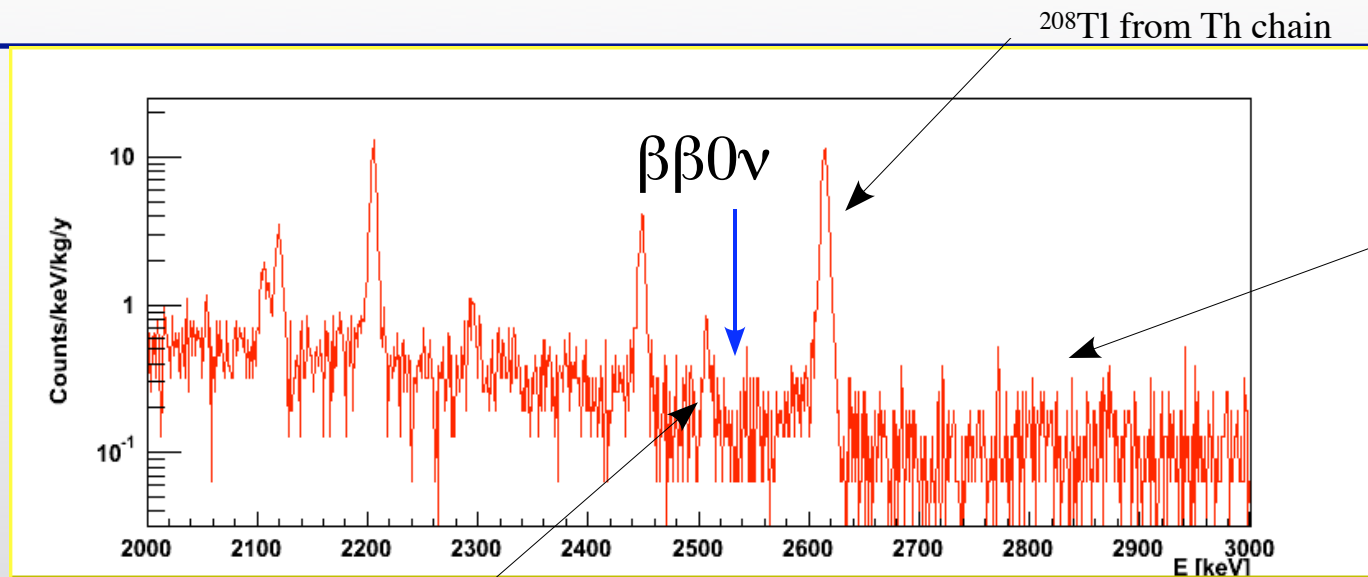
“Gamma region”: dominated by γ 's and β 's

“Alpha region”: all α 's

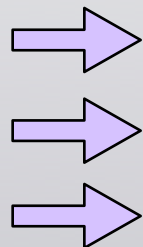
- Highest γ line is 2615 keV ^{208}Tl from ^{232}Th
- Contributes $\sim 30\%$ to $\beta\beta 0\nu$ background
- Probably due to Th contamination of materials between internal shielding and cryostat

- Due to internal and surface contaminations in Cu and Te
- Distorted because they are emitted 1-10 μm within Cu surface and loose energy
- MC agrees well with observed spectra

Cuoricino: Background in $\beta\beta 0\nu$ Region



^{60}Co at 2505 keV (1173+1332 keV gammas)



- $\sim 30\%$ in $\beta\beta 0\nu$ region from ^{208}Tl at 2615 keV
- α and β from inert material facing detector (e.g. Cu): $\sim 50\%$
- α and β from surface contamination of crystals: $\sim 20\%$
- Tiny contributions from neutrons and ^{60}Co at 2505 keV

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

Cuoricino Results from Runs 1&2: No Peak

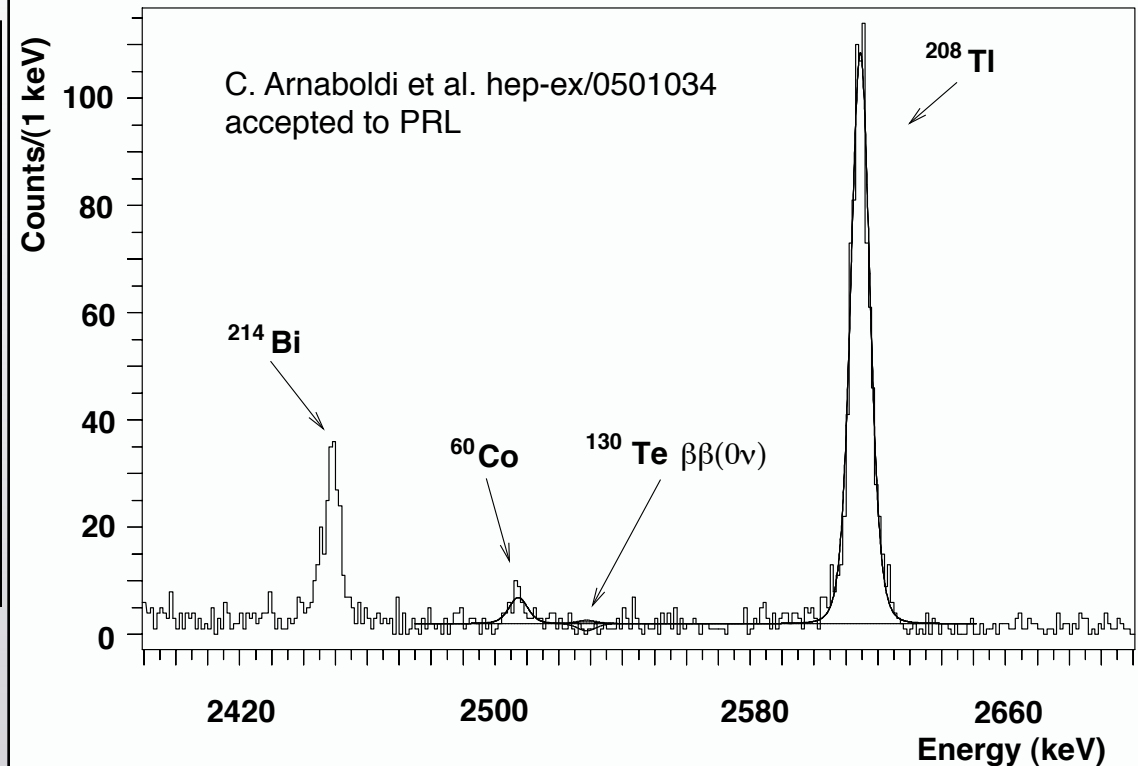


Exposure
= 10.85 kg y

Resolution:
FWHM at 2615 keV
= 9.2 ± 0.5 keV

Background:
In the $\beta\beta 0\nu$ region
= 0.18 ± 0.01 counts / (keV kg y)

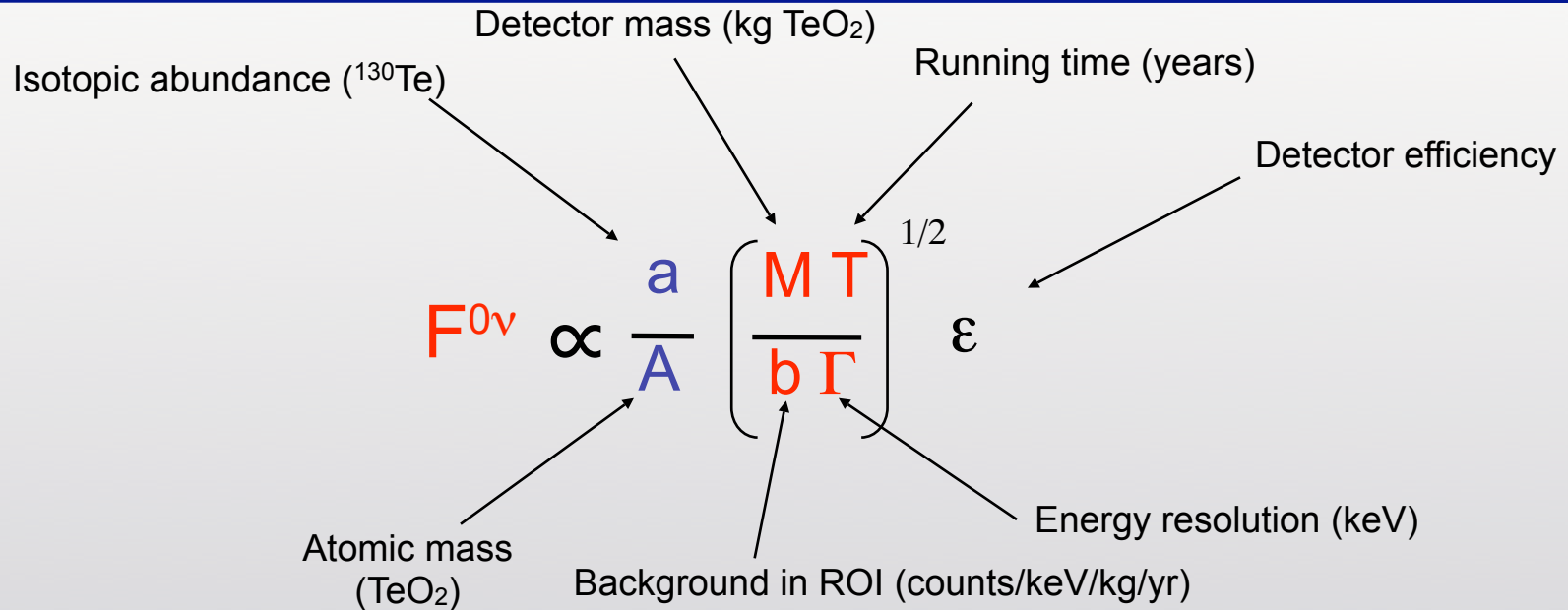
- Anticoincidence spectrum
- $\epsilon \sim 85\%$
- Maximum Likelihood + Flat + ^{60}Co (2505 keV)
 - energy region: 2480-2650 keV
- $\sim 5\%$ systematic error upon parameter variation
- N-Gaussian response function with individual FWHM detector resolution @ 2615 keV



No peak found
 $\tau^{0\nu}_{1/2} > 1.8 \times 10^{24}$ y at 90% C.L.
 $m_\nu < 0.2 - 1.1$ eV

Spread is due to a range of published matrix elements

Cuoricino Sensitivity and KKDC



5 years of Cuoricino

$$F^{0\nu} = 8.9 \times 10^{24} \text{ y} \quad \langle m_{ee} \rangle \approx 0.09 - 0.81 \text{ eV}$$

KKDC Result

$T = (0.67 - 4.45) \times 10^{25} \text{ years (99.73\% C.L.)}$
 $m_\nu = (0.1 - 0.9) \text{ eV 99.73\% C.L.}$
 $m_{\nu \text{ best}} = 0.45 \text{ eV}$ Klapdor et al., Phys. Lett B 586 (2004) 198

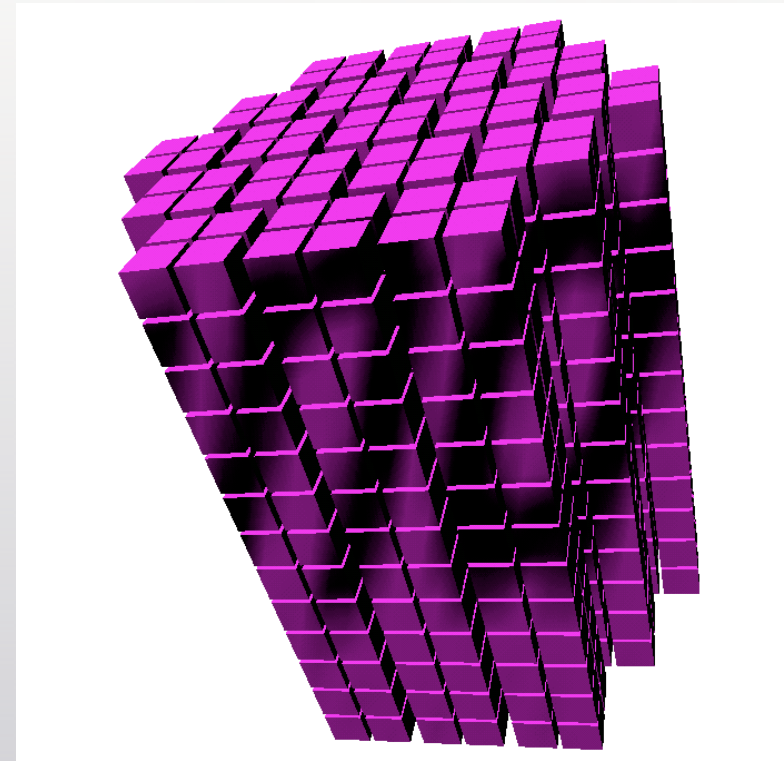
Cuoricino can see 3σ effect after 3 years if
 nuclear matrix elements are favorable
 No signal does not disprove KKDC

CUORE: Cryogenic Underground Observatory for Rare Events



- Array of 988 TeO_2 crystals
- 19 Cuoricino-like towers suspended in a cylindrical structure
- 13 levels of 4 $5 \times 5 \times 5 \text{ cm}^3$ crystals (750g each)
- ^{130}Te : 33.8% isotope abundance
- Time of construction: 4 years
- Total cost: 14-17M USD (depends on Euro...)
- 1st Data target: Jan 1, 2010

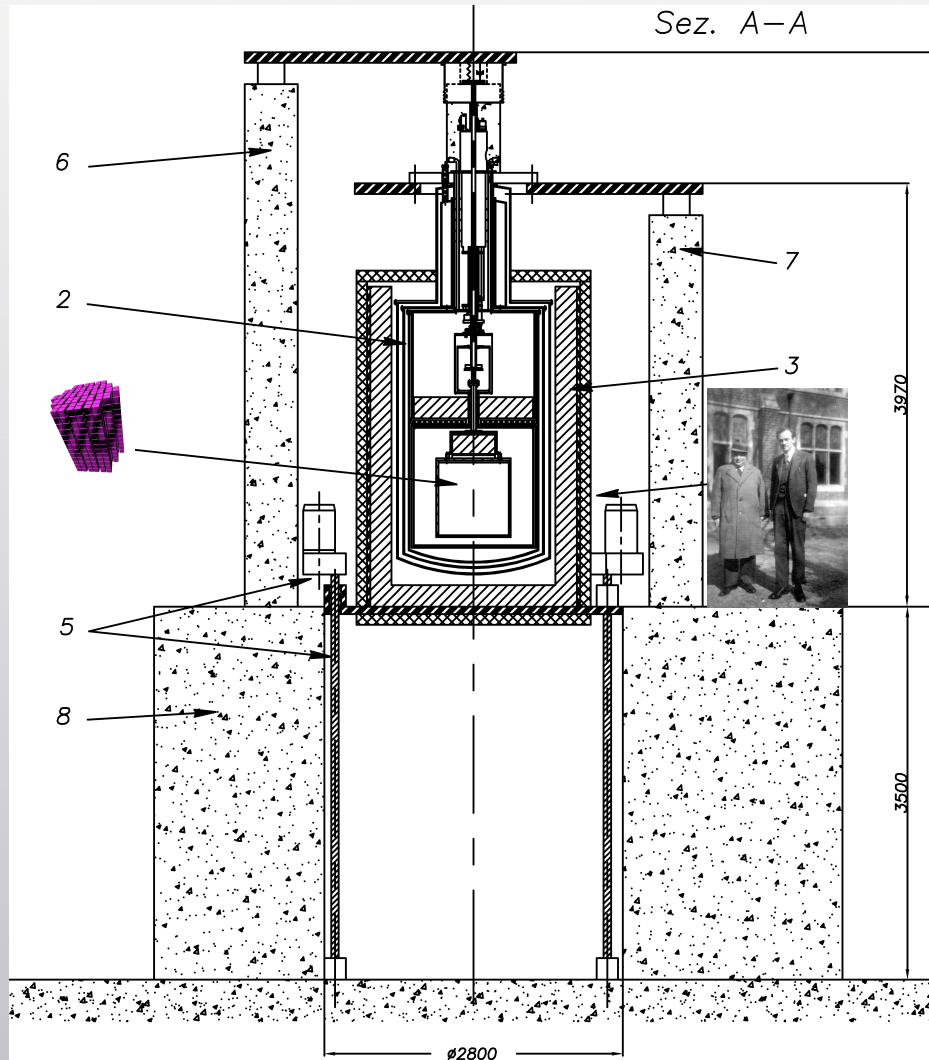
$750 \text{ kg TeO}_2 \Rightarrow 200 \text{ kg } ^{130}\text{Te}$



Acts as a single,
highly segmented,
detector

Approved by the Science Counsel of Gran Sasso Laboratory and by INFN

CUORE Structure



Powerful dilution refrigerator

- Operation at 7 - 10 mK
- Similar to Nautilus Collaboration (2-ton gravitational antenna)
- 10 μ W

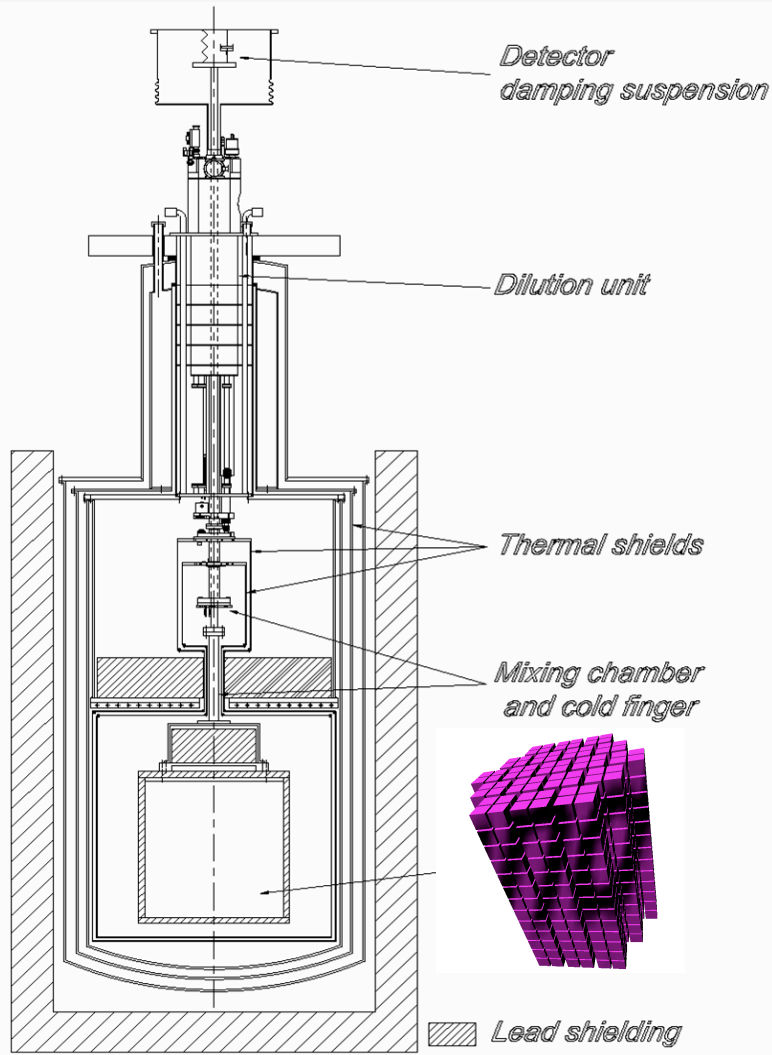
Heat sources (total $\sim 1 \mu$ W):

- Residual helium gas in the inner vacuum chamber (IVC)
- Power radiated from the 50 mK shield facing the detector
- Vibrational energy (microphonic noise)

Mechanical isolation

Access to crystals

CUORE Shielding



Roman Lead

- 3 cm immediately around detector with $^{210}\text{Pb} < 4 \text{ mBq/kg}$

Low activity lead

- 16 Bq/kg of ^{210}Pb for the inner layer
- 150 Bq/kg for the outer layer

Borated polyethylene box

- neutrons reduced
- hermetically sealed & dry nitrogen flushing to exclude radon

Faraday cage

- Important for near-threshold events
 - Dark matter and solar axions searches

CUORE Backgrounds



Bulk contaminations

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

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

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

Surface contamination

$$\sim 10^{-9} \text{ g/g for TeO}_2 \text{ and Cu} \Rightarrow < 7 \times 10^{-2} \text{ counts/kev/kg/y}$$

Bulk backgrounds from Cu and Te are not a problem in CUORE
Will not prevent it from reaching overall background goals

Surface Contamination is another issue



CUORE Backgrounds



For more information on CUORE backgrounds please see
Michelle Dolinski's talk at this APS/JPS DNP meeting:
"Radioactive background studies for the CUORE
neutrinoless double beta decay experiment"

Session JG: Techniques for Neutrino Science
9:45 AM–10:00 AM, Thursday, September 22, 2005
Ritz-Carlton Hotel - Plantation 2



Milestone reached

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

Surface sensitive bolometer also promising



CUORE Neutron Background



Extensive MC simulations along with existing studies and Cuoricino results have convinced us that neutrons are not a major source of background in CUORE at the LNGS

from thermal to 1 keV → *absorbed by a "thin" n shield*

from 1keV to 10 MeV → flux from measurements + simulation of radioactivity in the rock

total	$8 \cdot 10^{-3} \text{ c/keV/kg/y}$
global anticoincidence	$2 \cdot 10^{-4} \text{ c/keV/kg/y}$

can be further reduced
by a n shield !!

from 10 MeV to 2 GeV → flux simulation of muons interaction in the rock

total	$6 \cdot 10^{-5} \text{ c/keV/kg/y}$
global anticoincidence	$1 \cdot 10^{-6} \text{ c/keV/kg/y}$

from 1 keV to 2 GeV → flux simulation of muons interaction in the CUORE lead shield

total	$2 \cdot 10^{-3} \text{ c/keV/kg/y}$
global anticoincidence	$1 \cdot 10^{-4} \text{ c/keV/kg/y}$

can be further reduced
by a muon veto !!

Rock radioactivity → $2 \cdot 10^{-4} \text{ c/keV/kg/y}$

can be further reduced by a neutron shield

Depth → $1 \cdot 10^{-6} \text{ c/keV/kg/y} + 1 \cdot 10^{-4} \text{ c/keV/kg/y}$

the main contribution ($1 \cdot 10^{-4} \text{ c/keV/kg/y}$ from muon interaction in the lead shield) can be reduced by a muon veto

→ **with a muon veto the main neutron contribution to CUORE background is due to rock radioactivity**

→ **no limit to CUORE sensitivity due to neutrons flux in LNGS**

CUORE Sensitivity



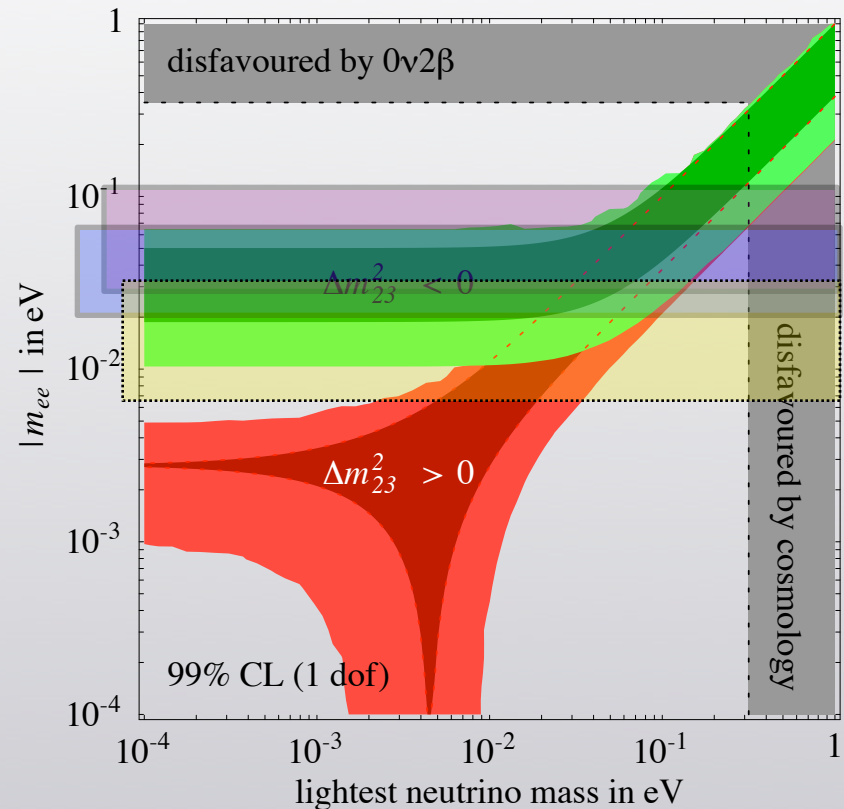
Five year sensitivity based on
detector resolution, background, and
matrix element spread

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

More optimistic but plausible case:
eliminate degenerate hierarchy and
continue excavation deeper into
inverse hierarchy

Fantasy: 99% enriched CUORE after
10 years with 5 keV resolution and 0.001 c/keV/kg/y

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



10 years from now, with input
from different isotopes, the
theoretical mass spread will
hopefully be smaller

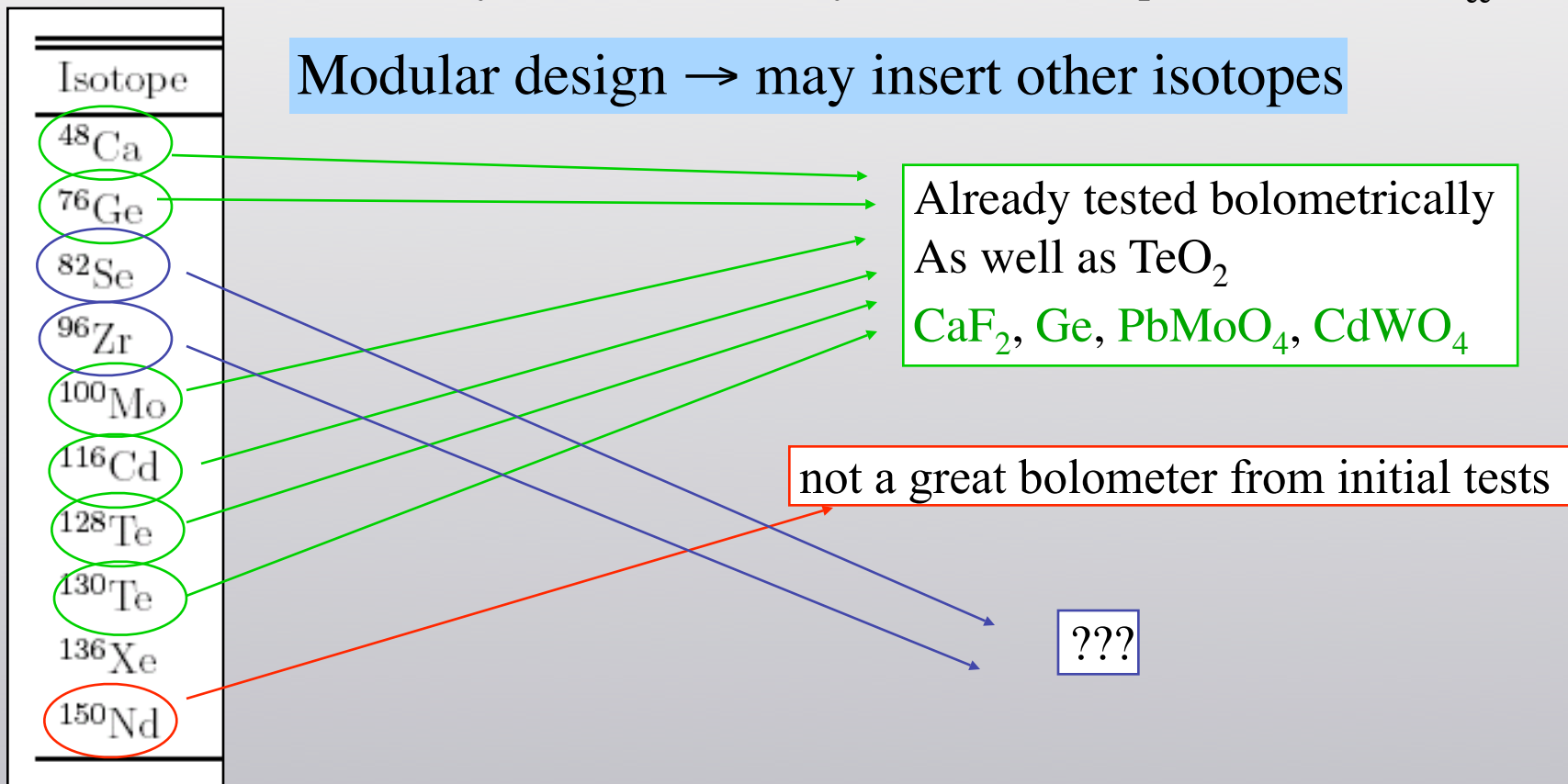
CUORE for Multi-Isotope Search



In case of discovery (or hints of 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}

Modular design → may insert other isotopes



Cuoricino

- Currently operating at LNGS
- Powerful proof-of-principle in large mass TeO_2 bolometry
- Current result: No peak found $\tau^{0\nu}_{1/2} > 1.8 \times 10^{24} \text{ y}$ at 90% C.L.
- Potential to confirm KKDC result by 2008

CUORE

- Nicely compliments the current array of future experiments
- Very competitive physics potential at a modest cost
- Strong upgrade options: enrichment and different isotopes



The CUORE Collaboration



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