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

Thomas D. Gutierrez

Lawrence Berkeley National Laboratory

Representing the CUORE and Cuoricino Collaborations

Joint JPS/APS DNP DBD Workshop

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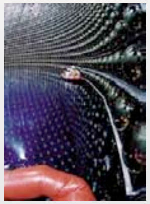
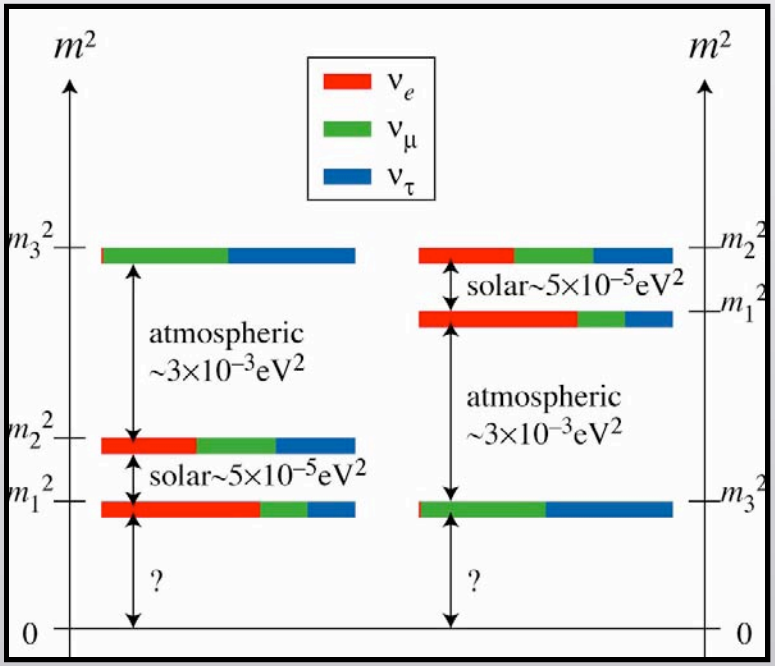
Maui, Hawaii

Context: Recent Developments in Neutrino Physics

Since 1998, SuperKamiokande, SNO, and KamLAND have shown:



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



Two Open Questions in ν Physics:

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

ββ0ν can address these

$\beta\beta0\nu$: a powerful observational tool

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$ ← allowed by the Standard Model $\tau \geq 10^{19}$ y

$(A,Z) \rightarrow (A,Z+2) + 2e^-$ ← open discussion on its observation $\tau \geq 10^{25}$ y

$(A,Z) \rightarrow (A,Z+2) + 2e^- + \chi$ ← Majoron (light neutral boson)

Observation of $\beta\beta0\nu$ implies Physics beyond the Standard Model

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

$\beta\beta0\nu$ Rate and Neutrino Mass

0ν-DBD rate

Phase space $\propto Q^5$

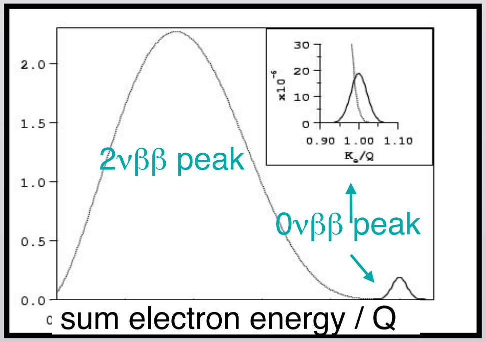
Nuclear matrix elements

Effective neutrino mass

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

high Q candidates preferred

large phase space



low background

^{238}U γ end at 2.4 MeV

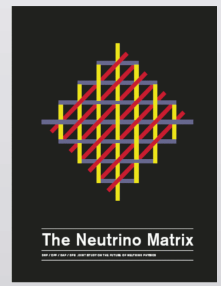
^{232}Th γ end at 2.6 MeV

[2039 keV (^{76}Ge) ⇔ 4271 keV (^{48}Ca)]

Strategies and Tactics

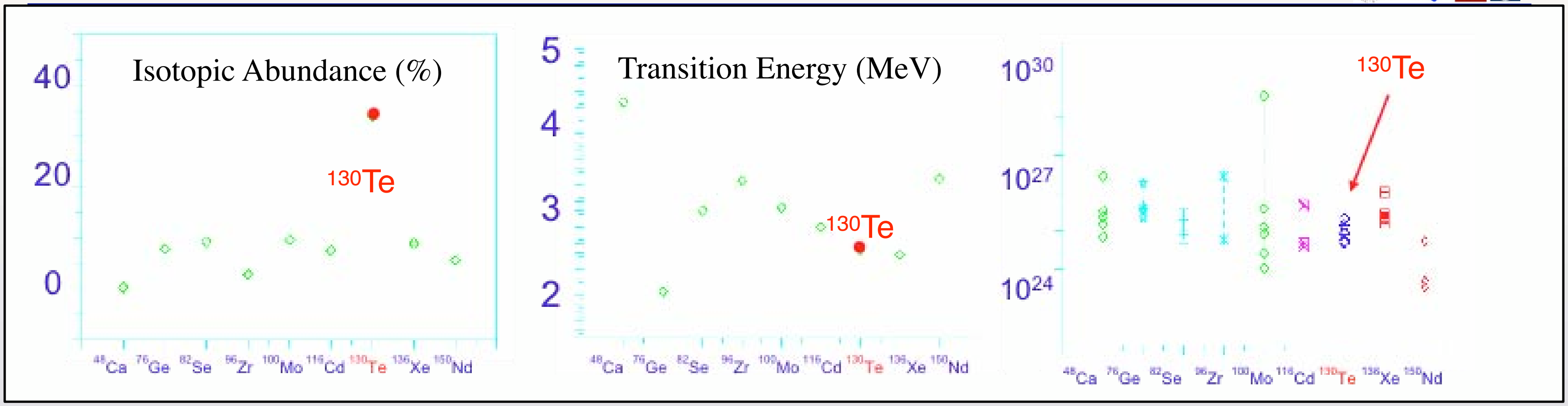
	isotope	i.a. [%] nat	$Q_{\beta\beta}$ [eV]	i.a. [%] enrich	size [kmol]	T_M [y]	σ_E [keV]	b [c/y]	$T_{1/2}^{0\nu}$ [10^{28} y]	technique	$\langle m_\nu \rangle$ [eV] min	max	status
CUORE	^{130}Te	34	2533	-	1.7	5	2.5	7.5	0.02	b	27	170	approved
GERDA II	^{76}Ge	7.8	2039	90	0.6	5	2	0.05	0.02	i	92	297	approved+R&D
Majorana I	^{76}Ge	7.8	2039	90	2.5	3	2	0.1	0.04	i	65	210	R&D
SuperNEMO	^{82}Se	8.7	2995	90	1.2	5	76	1	0.02	t,s	54	167	R&D
EXO	^{136}Xe	8.9	2476	65	48.0	10	49	0.55	1.30	t	12	31	R&D
MOON III	^{100}Mo	9.6	3034	85	8.5	10	66	3.8	0.17	t	13	48	

- ββ0ν is one of the two top priorities in neutrino physics
- Near term: ≤ 200 kg active mass
  - KKDC result must be addressed
  - If necessary: completely explore the degenerate hierarchy
    - Different isotopes
    - Different methods
  - Start digging into inverse hierarchy
- Prepare for the one-ton generation
  - If necessary, 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 <u>not</u> *required*
  - Natural abundance 33.87%
- Reasonable Q = 2528.8 keV
  - Large phase space
  - Low gamma background: Q sits between ^{232}Th Compton edge (2360 keV) and full energy (2615 keV)
- $\beta\beta2\nu$ 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

Trivia

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

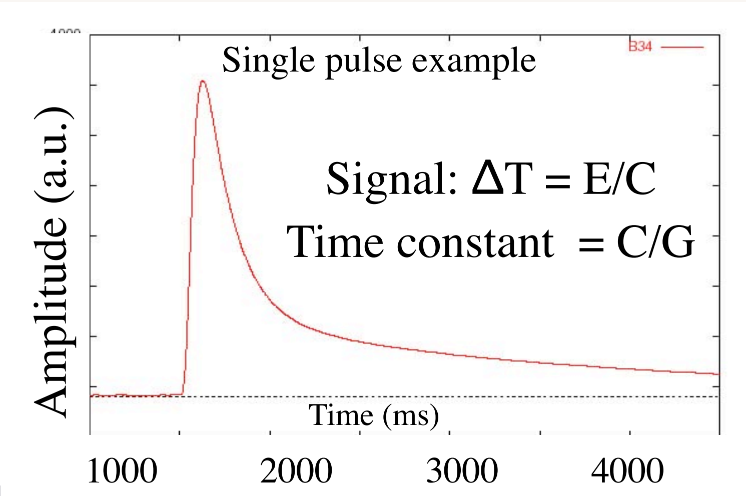
http://www.chemsoc.org/viselements/

Why Bolometry?

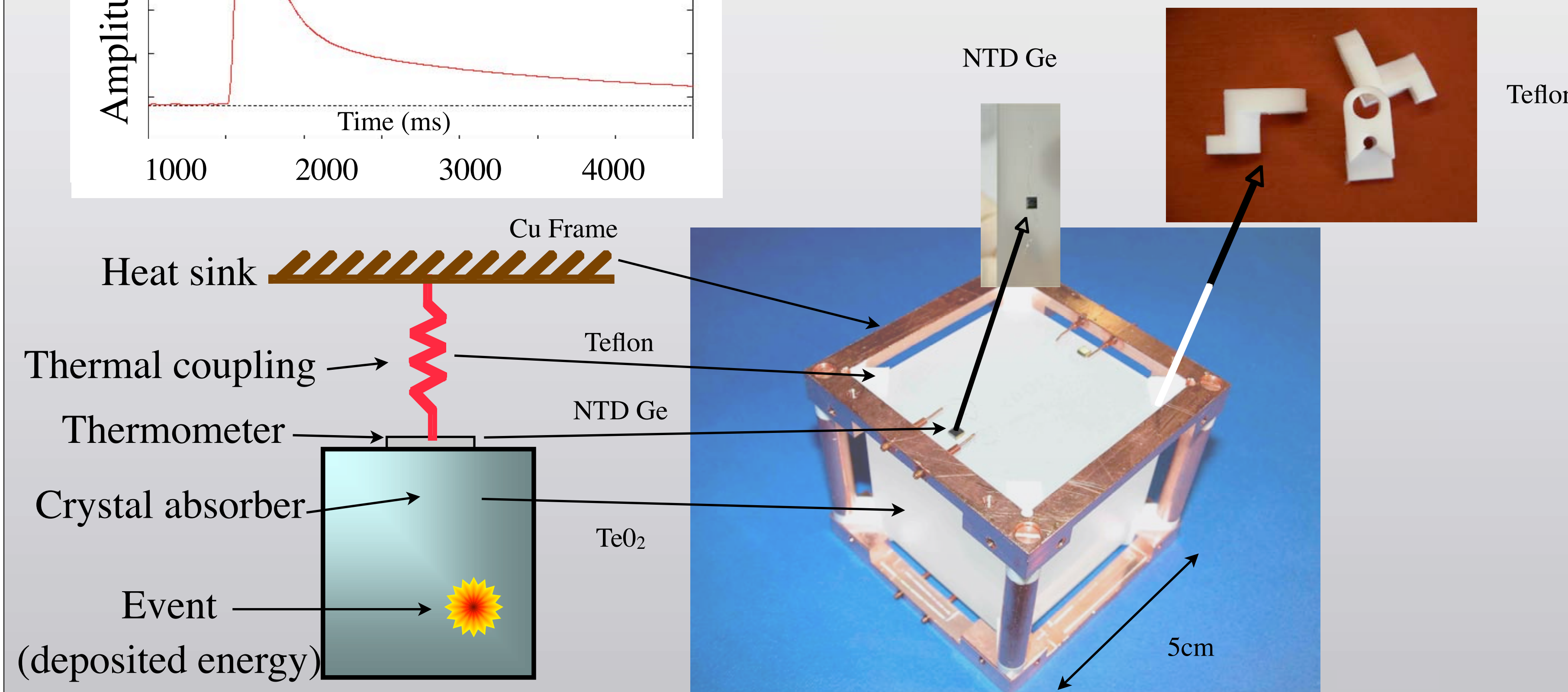
- Il Buono
  - Proven, tested, and true calorimetric technique
    - Measurement of temperature changes through heat exchange
  - Source=Detector method measures all energy deposited: very high efficiency
  - Wide isotope and absorber material choice: ^{48}Ca, ^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te
  - Good energy resolution: 4-10 keV @ 2615keV (0.15-0.38%)
  - Very large masses are possible

- Il Cattivo
  - Sensitive to surface radioactivity
  - Difficult to reduce close materials: holders, cryostat, wires, etc.
  - Added technology need required for vertex (e.g. scintillation)
  - Slow response time (~seconds)
- Il Brutto
  - Phonons can be tricky beasts: detailed microscopic models of the detector physics are elusive

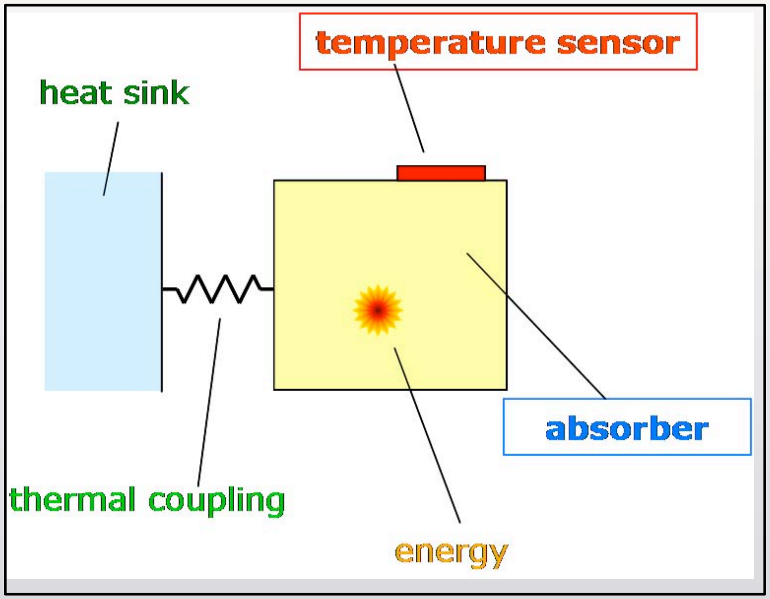
Cryogenic Bolometers



- Low heat capacity (Debye limit C~T^3)
- Low temperatures (~10mK)
- Dielectric diamagnetic materials



Cryogenic Bolometers



Heat sink: 8-10 mK

Weak thermal coupling (teflon holders):
$G = 4$ pW/mK

Thermister: NTD Ge-thermistor
$R \cong 100$ MΩ, $dR/dT \cong 100$ kΩ/μK

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

Temperature signal for E=1 MeV: → **$\Delta T = E/C \cong 0.1$ mK**

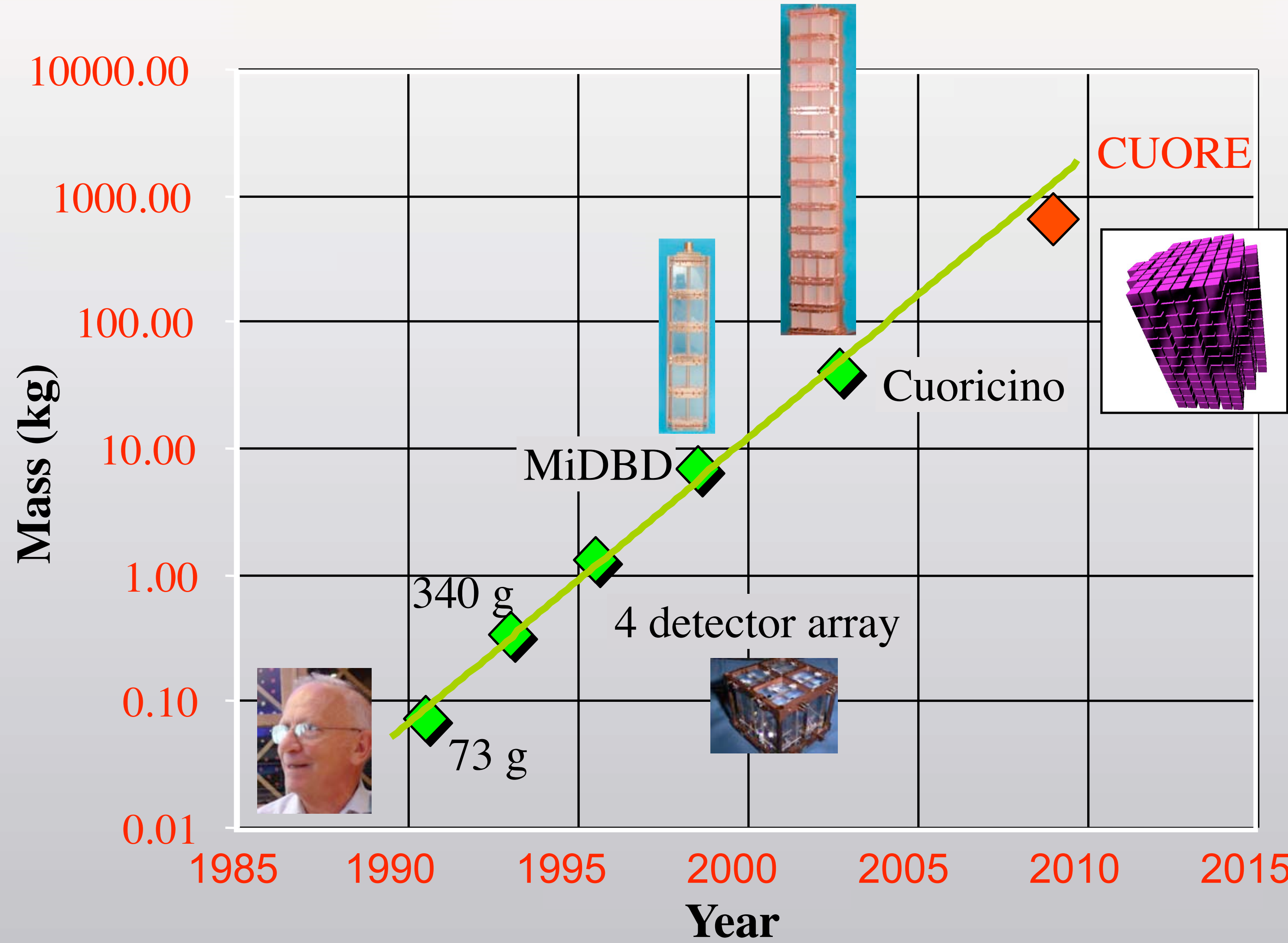
Signal size: $\Delta V = I \times dR/dT \times \Delta T$ → **1 mV/1 MeV**

Signal recovery time: $\tau = C/G$ → **0.5 s**

Noise over signal bandwidth (few Hz): → **$V_{rms} = 0.2$ μV**

Energy resolution (FWHM): ≅ 1 keV (in theory)

“Moore’s Law” Scaling of TeO_2 Bolometry Experiments

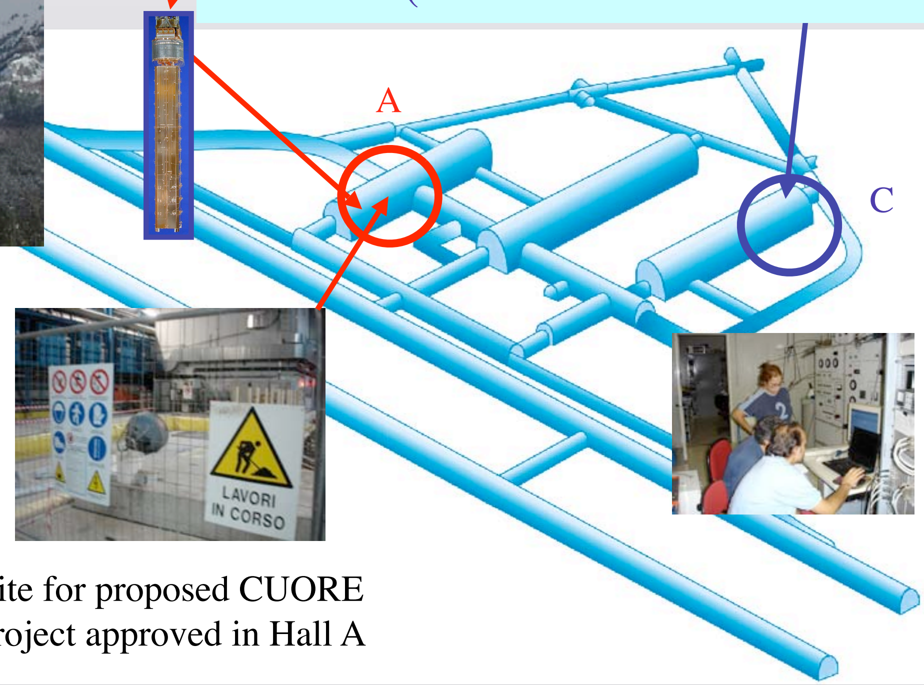


Gran Sasso National Laboratory (LNGS)

Shielding: ~3500 m.w.e.

Two dilution refrigerators:

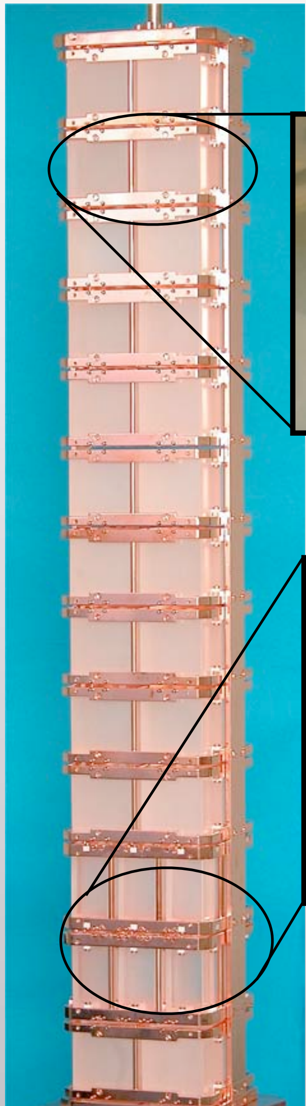
1. Hall A (Cuoricino) ⇒ Running!
2. Hall C (R&D final tests for CUORE)

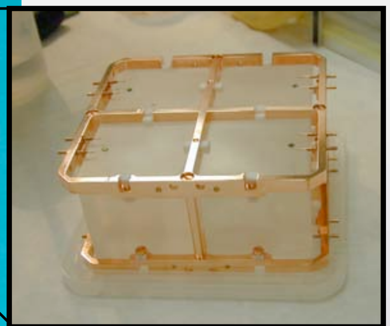


Site for proposed CUORE project approved in Hall A

Cuoricino is currently the largest operating
bolometer in the world

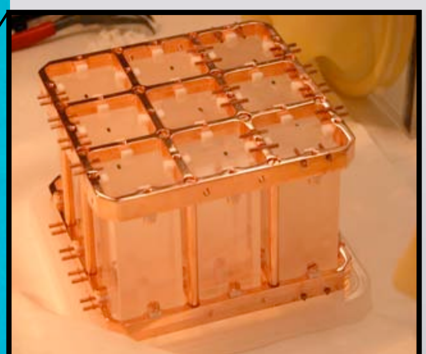
Cuoricino, the "little heart" of Gran Sasso





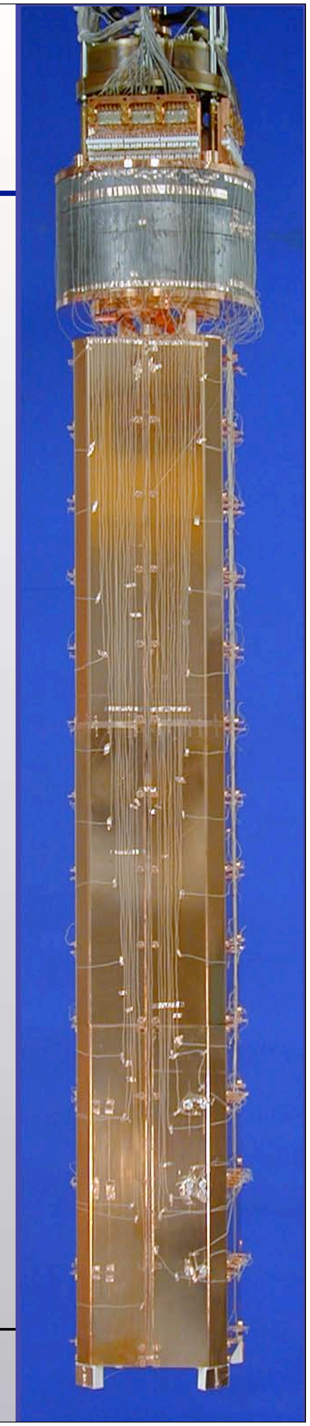
11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 750 g
44 x 0.79 = 34.76 kg of TeO_2

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

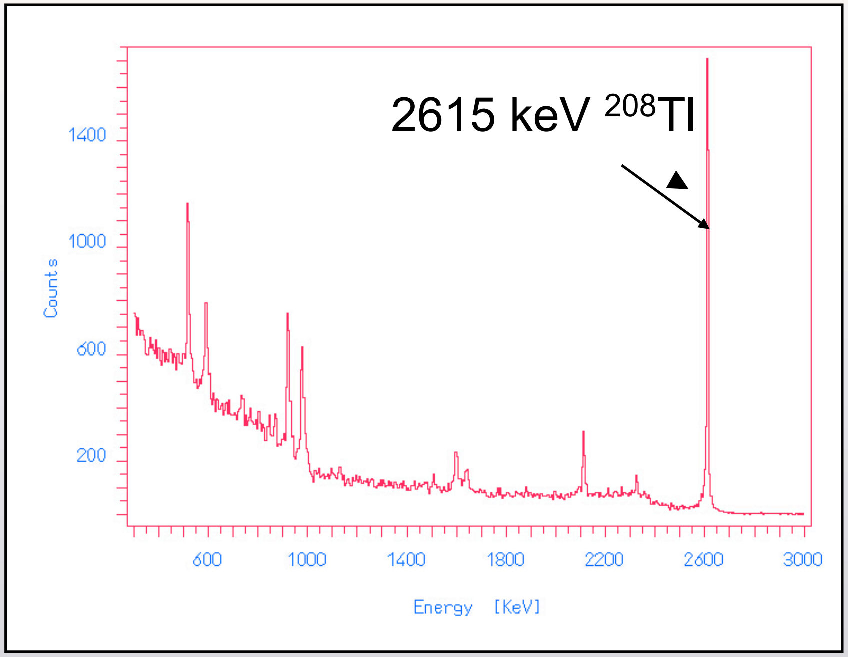


2 modules x 9 crystals each
crystal dimension: 3x3x6 cm^3
crystal mass: 330 g
18 x 0.33 = 5.94 kg of TeO_2

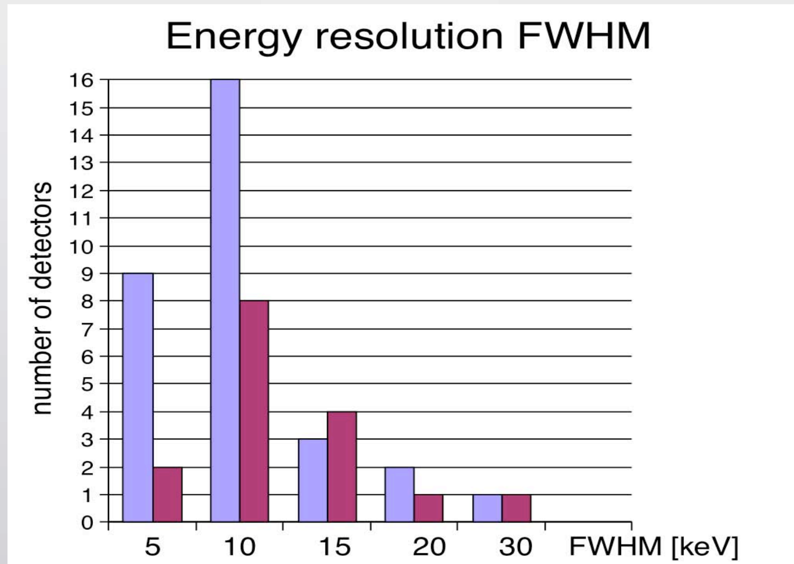
Total detector mass: 40.7 kg TeO_2 $\Rightarrow$ **11.64 kg ^{130}Te**



Cuoricino Performance



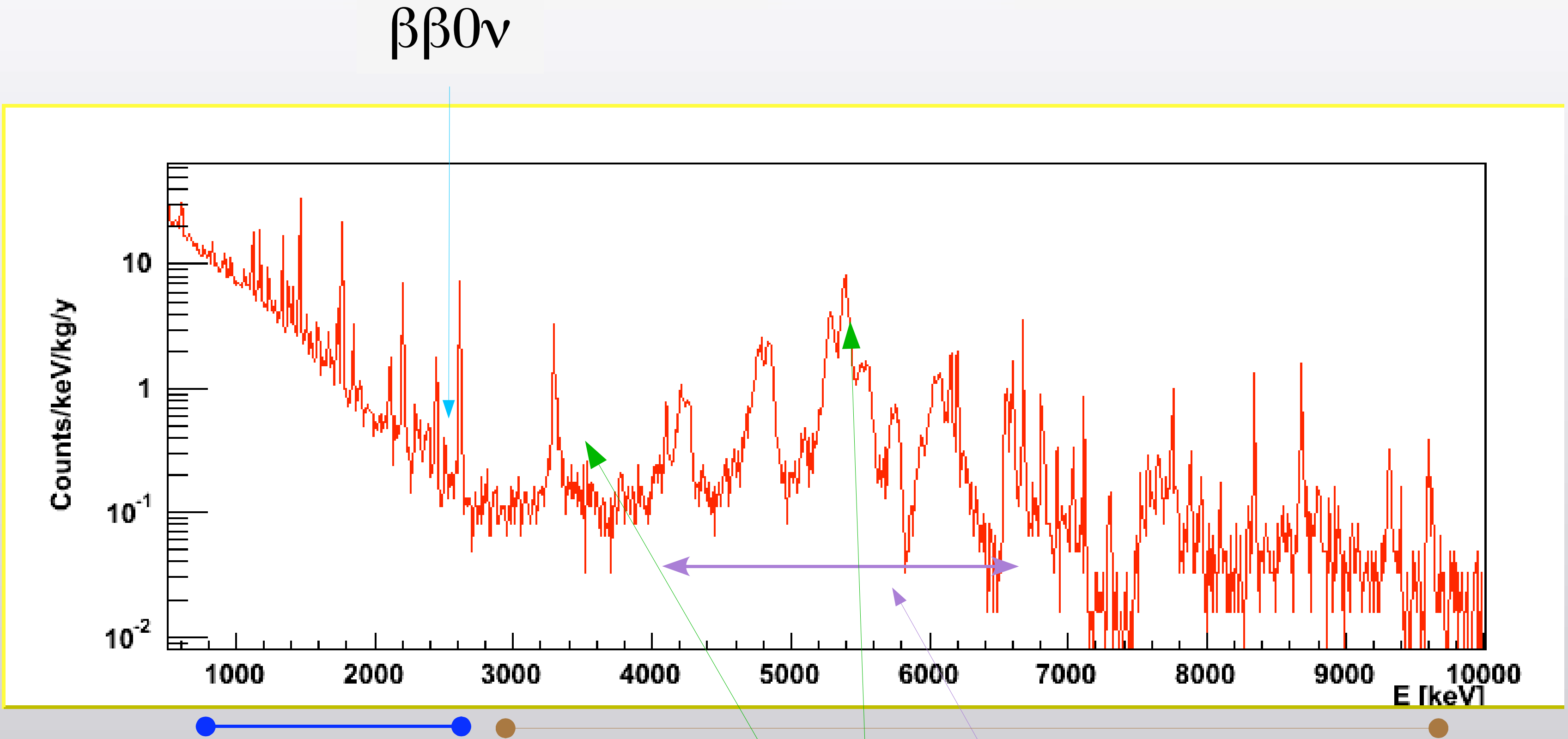
← Energy calibration spectrum obtained with ^{232}Th source (summed over all crystals)



Resolution limited by
- Thermal/Phononic (Δ ~ eV)
- Electronic noise (Δ ≤ 1 keV)
- Microphonics (Δ ≤ 1 keV)
- Detector responses Δ ~ keV

- average 5x5x5 cm3 crystals ~ 7.5 keV
- average 3x3x6 cm3 crystals ~ 12 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



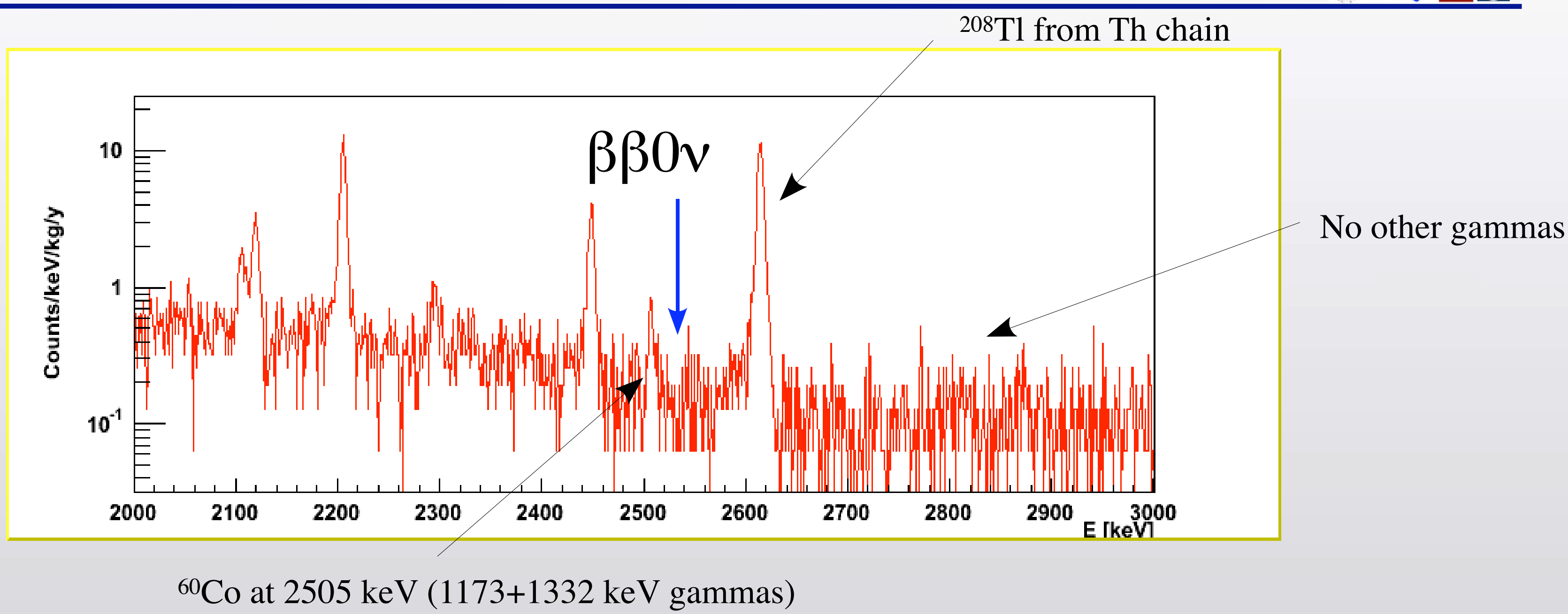
"Gamma region": dominated by γ's and β's

- Highest γ line is 2615 keV ^{208}Tl from ^{232}Th
- Contributes about 40% to ββ0ν background
- Probably due to Th contamination of materials between internal shielding and cryostat

"Alpha region": all α's

- Due to internal and surface contaminations in Cu and Te
- Distorted because they are depleted: 1-10μm surface embedding in MC agrees well with observed spectra

Cuoricino: Background in ββ0ν Region



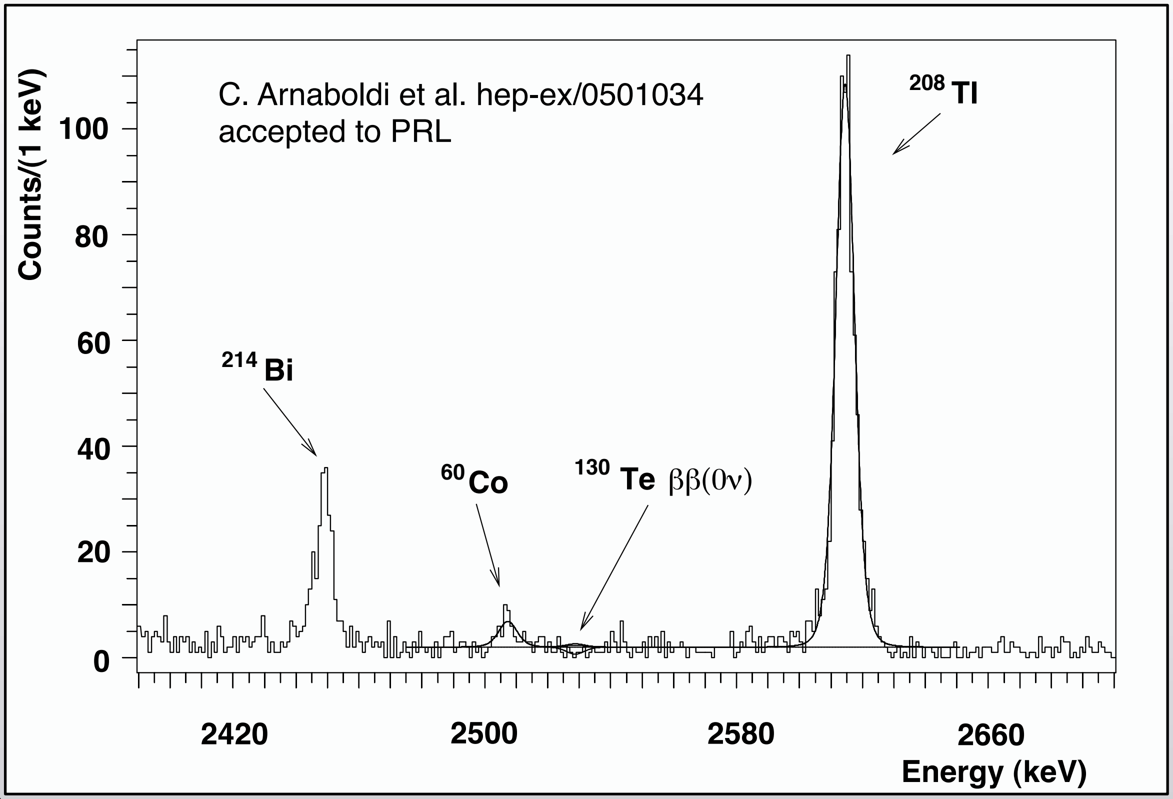
- Roughly 40% in ββ0ν region from ^{208}Tl at 2615 keV
- Degraded alphas from inert material facing detector (e.g. Cu): ~50%
- Degraded alphas from surface contamination of crystals: ~10%
- Tiny contributions from
  - neutrons
  - ^{60}Co at 2505 keV (1173+1332 keV gammas)

Cuoricino Results from Runs 1&2: No Peak

<u>Exposure</u>
= 10.85 kg y

<u>Resolution</u>:
FWHM at 2615 keV
= 9.2 ± 0.5 keV

<u>Background</u>:
In the ββ0ν region
= 0.18 ± 0.01 counts /(keV kg y)



- Anticoincidence spectrum
- ϵ~85%
- Maximum Likelihood+flat+^{60}Co (2505)
  - energy region: 2470-2560 keV
- ~5% systematic error upon parameter variation
- N-Gaussian response function with individual FWHM detector resolution

<u>No peak found</u>

$\tau^{0\nu}_{1/2} > 1.8 \times 10^{24}$ y at 90% C.L.

$m_\nu < 0.2 - 1.1$ eV

Cuoricino Sensitivity and KKDC

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

Isotopic abundance (^{130}Te)

Detector mass (kg TeO_2)

Running time (years)

Detector efficiency

Atomic mass (TeO_2)

Background in ROI (counts/keV/kg/yr)

Energy resolution (keV)

3 years of Cuoricino

$F^{0\nu} = 1 \times 10^{25}$ y $\langle m_{ee} \rangle \approx 0.16 - 0.38$ eV

KKDC Result

$T = (0.67 - 4.45) \times 10^{25}$ years (99.73% C.L.)

$m_\nu = (0.1 - 0.9)$ eV 99.73% C.L.

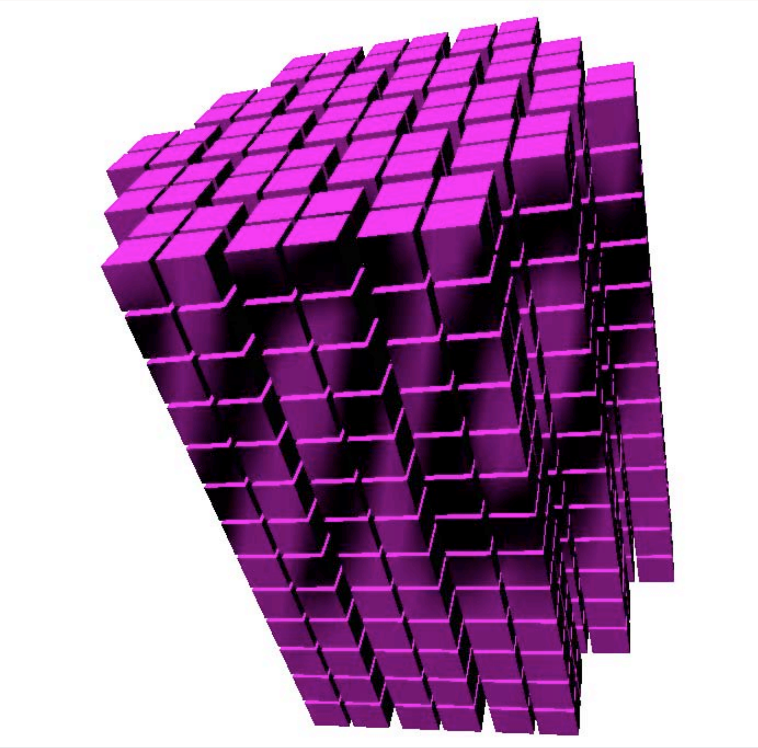
$m_{\nu\ best} = 0.45$ eV Klapdor et al., Phys. Lett B 586 (2004) 198

Cuoricino can see 3σ effect 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 5x5x5 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

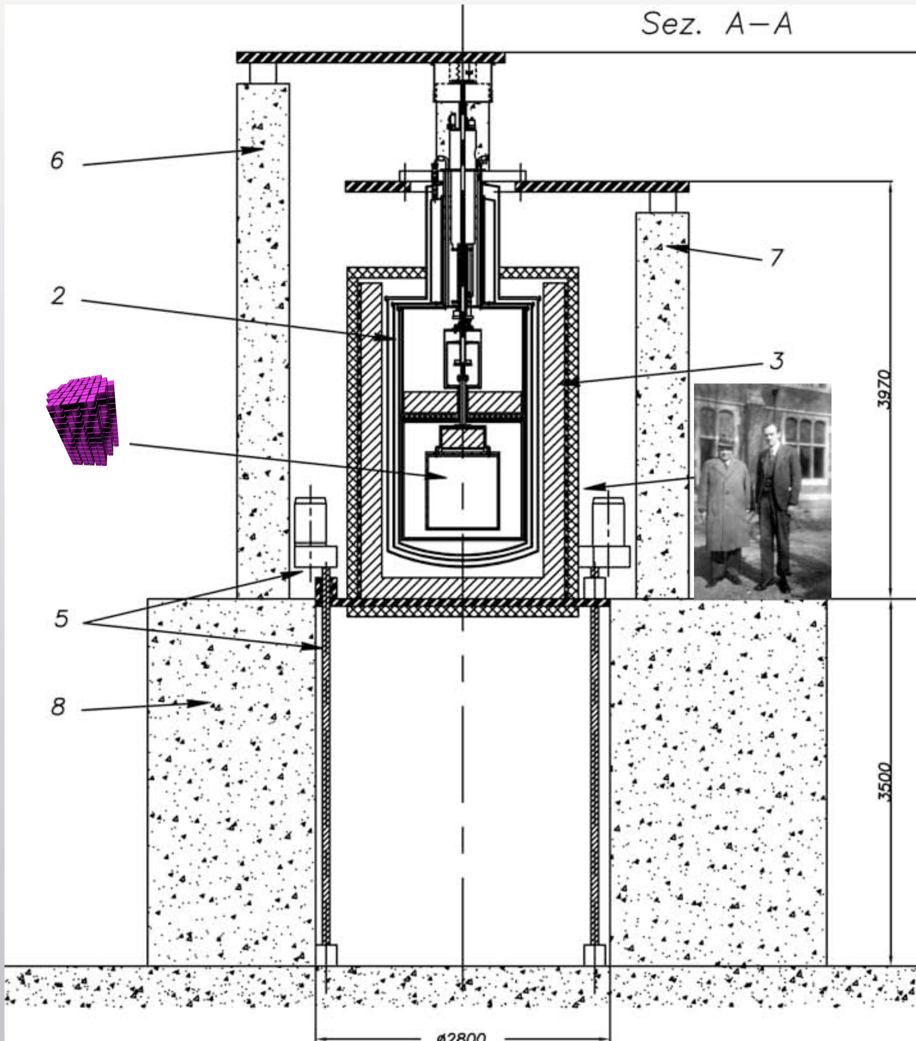


Acts as a single, highly segmented, detector

750 kg TeO_2 => 200 kg ^{130}Te

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 μW

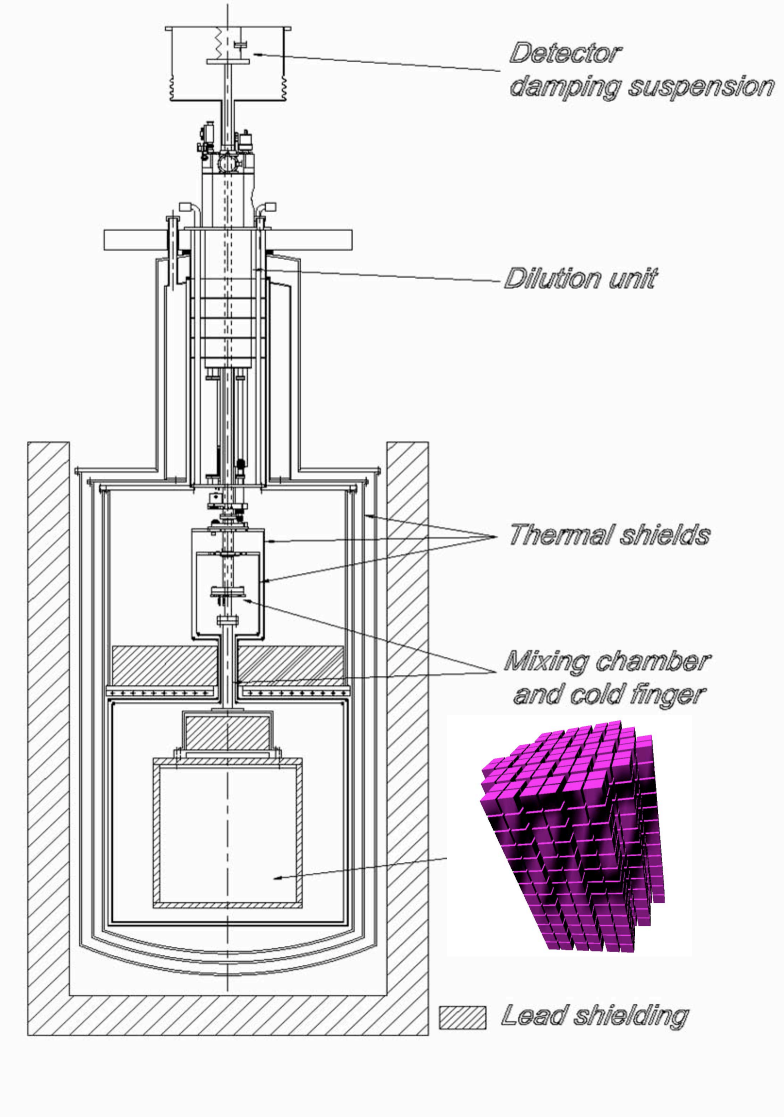
Heat sources (total ~1μW):

- 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}Pb < 4 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 eliminated
- hermetically sealed & dry nitrogen flushing to exclude radon

Faraday cage

- Important for near-threshold events
- 5keV - 10 keV for dark matter and solar axion searches

CUORE Backgrounds

Bulk contaminations

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

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

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

Surface contamination

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

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

Surface Contamination is another issue

CUORE Backgrounds

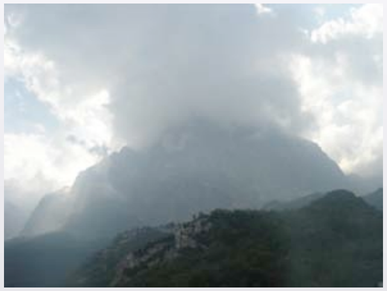
For more information on CUORE backgrounds please see Michelle Dolinski's APS/JPS DNP talk
"Radioactive background studies for the CUORE neutrinoless double beta decay experiment"
Session JG: Techniques for Neutrino Science
9:45 AM–10:00 AM, Thursday, September 22, 2005
Ritz-Carlton Hotel - Plantation 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
Muon tag and veto under consideration

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 measures + simulation of radioactivity in the rock

total	$8\ 10^{-3}$ c/keV/kg/y
global anticoincidence	**$2\ 10^{-4}$ 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	$6\ 10^{-5}$ c/keV/kg/y
global anticoincidence	**$1\ 10^{-6}$ c/keV/kg/y**

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

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

can be further reduced by a muon veto !!

Rock radioactivity → 2 **10^{-4} c/keV/kg/y**

can be further reduced by a neutron shield

Depth → 1 **10^{-6} c/keV/kg/y + 1 10^{-4} c/keV/kg/y**

the main contribution (1 10^{-4} 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

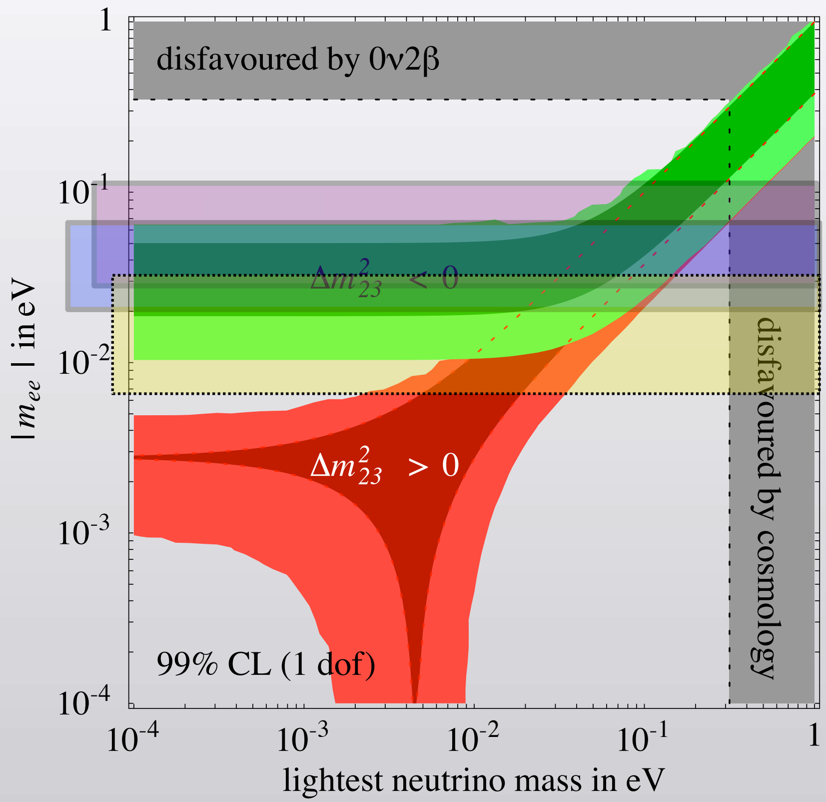
Five year sensitivity based on detector resolution, background, and matrix element spread

B(counts/keV/kg/y)	Δ(keV)	$T_{1/2}$(y)	$\lvert\langle m_\nu \rangle\rvert$ (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

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

Isotope
^{48}Ca
^{76}Ge
^{82}Se
^{96}Zr
^{100}Mo
^{116}Cd
^{128}Te
^{130}Te
^{136}Xe
^{150}Nd

Already tested bolometrically
As well as TeO_2
CaF_2, Ge, $PbMoO_4$, $CdWO_4$

not a great bolometer from initial tests

???

Summary

<u>Cuoricino</u>

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

<u>CUORE</u>

- 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

J. Beeman[1], M.Dolinski[1], T.D. Gutierrez[1], E.E. Haller[1,2], R. Maruyama[1], B. Quiter[1], A.R. Smith[1] and N. Xu[1]

[1]Lawrence Berkeley National Laboratory [2]University of California, Berkeley CA 94720, USA

A. Giuliani, M. Pedretti and S.Sangiorgio

Dipartimento di Fisica e Matematica dell'Università dell'Insubria e Sezione di Milano dell' INFN, Como I-22100, Italy

M. Barucci, E. Olivieri, L. Risegari, and G. Ventura

Dipartimento di Fisica dell' Università di Firenze e Sezione di Firenze dell' INFN, Firenze I-50125, Italy

M. Balata, C. Bucci, and S.Nisi

Laboratori Nazionali del Gran Sasso, I-67010, Assergi (L'Aquila), Italy

V. Palmieri

Laboratori Nazionali di Legnaro, Via Romea 4, I-35020 Legnaro (Padova)

A. de Waard

Kamerling Onnes Laboratory, Leiden University, 2300 RAQ Leiden

E.B. Norman

Lawrence Livermore National Laboratory, Livermore, California, 94550, USA

C. Arnaboldi, C. Brofferio, S. Capelli, F. Capozzi, L. Carbone, M.Clemenza, O. Cremonesi, E. Fiorini, C.Nones, A. Nucciotti, M. Pavan, G. Pessina, S. Pirro, E. Previtali, M. Sisti, L.Torres and L.Zanotti

Dipartimento di Fisica dell'Università di Milano-Bicocca e Sezione di Milano dell'INFN, Milano I-20126, Italy

R. Ardito, G. Maier

Dipartimento di Ingegneria Strutturale del Politecnico di Milano, Milano I-20133, Italy

E.Guardincerri, P. Ottonello and M.Pallavicini

Dipartimento di Fisica dell'Universita' diGenova e Sezione di Genova dell'INFN, Genova I-16146, Italy

D.R. Artusa, F.T. Avignone III, I. Bandac, R.J. Creswick, H.A. Farach, and C. Rosenfeld

Department of Physics and Astronomy, University of South Carolina, Columbia S.C. 29208 USA

S. Cebrian, P. Gorla, I.G. Irastorza

Lab. of Nucl. and High Energy Physics, University of Zaragoza, 50009 Zaragoza, Spain

F.Bellini, C.Cosmelli, I.Dafinei, M.Diemoz, F.Ferroni, C.Gargiulo, E.Longo, S. Morganti

Dipartimento di Fisica dell'Universita' di Roma e Sezione di Roma 1 dell'INFN, Roma I-16146, Italy