New Techniques - Cryogenic Bolometers

CUORE & Cuoricino: A Bolometric Search for Neutrinoless Double Beta Decay

Reina Maruyama

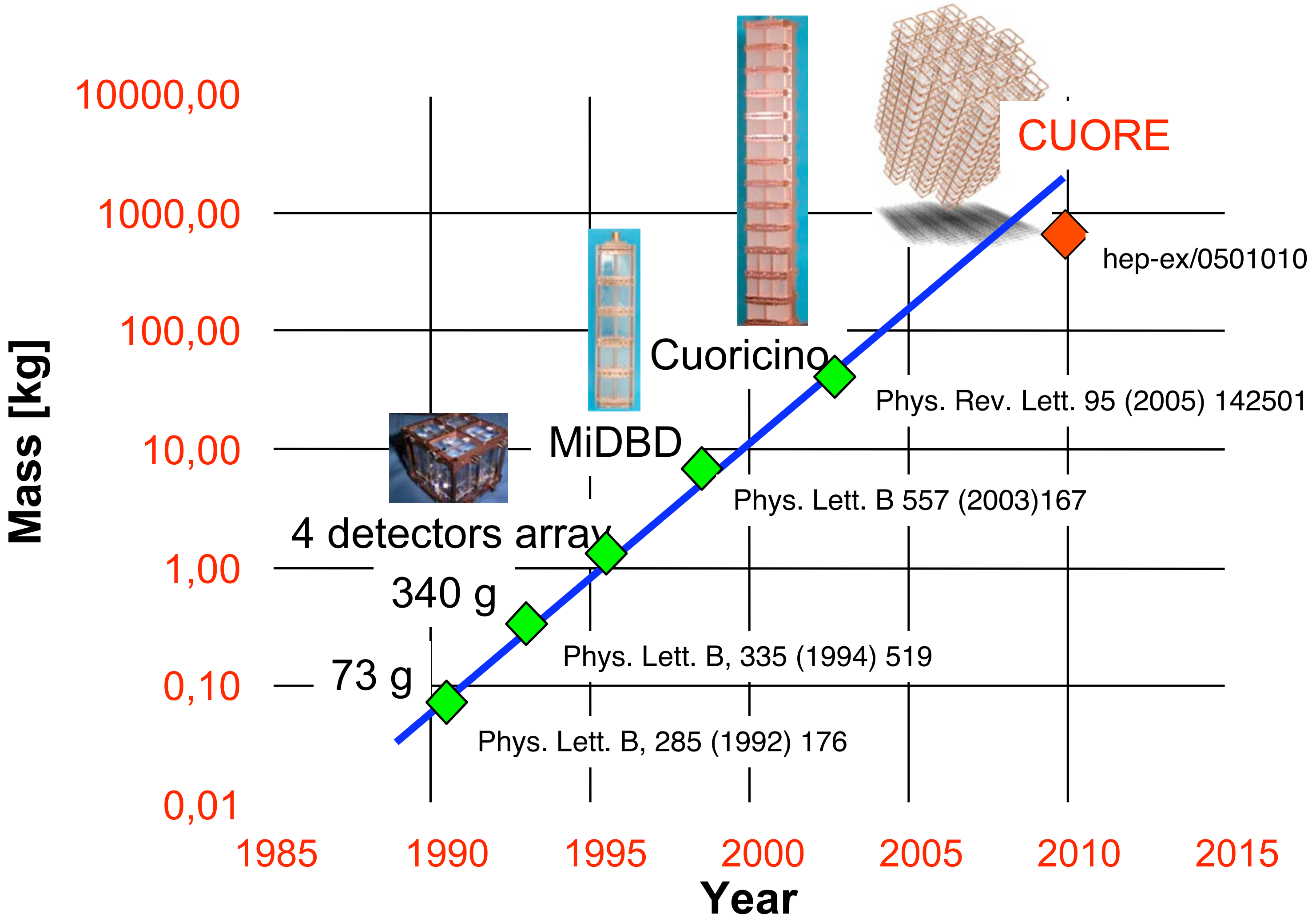
For the CUORE Collaboration

UC Berkeley / LBNL / University of Wisconsin

Neutrino 2006, Santa Fe

June 15, 2006

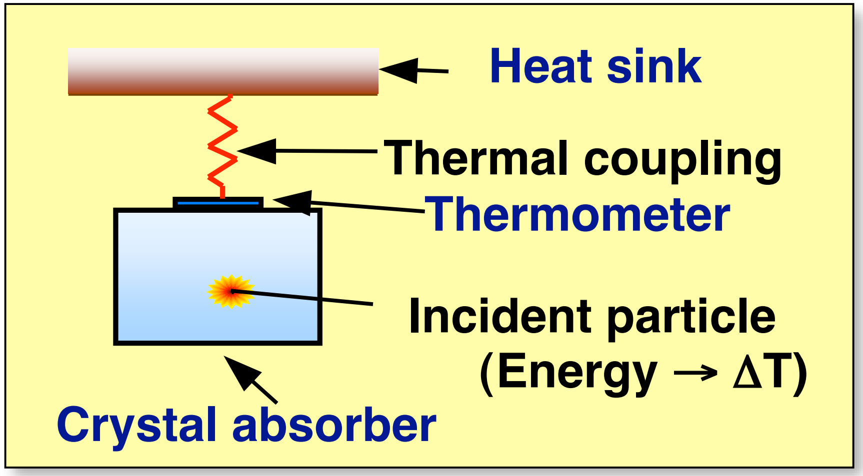
Bolometric $0\nu\beta\beta$ Experiments: Past & Future

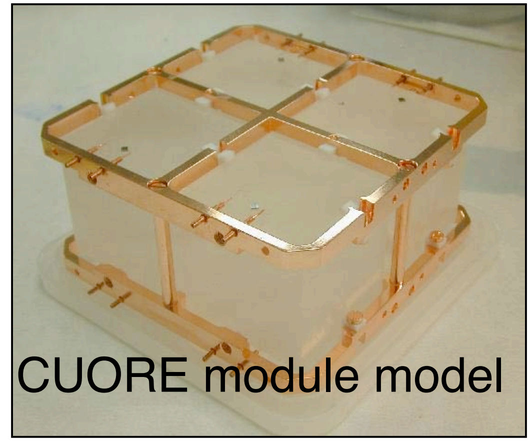


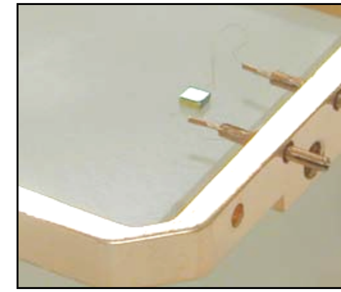
Cuoricino: Currently the largest bolometer & most sensitive $0\nu\beta\beta$ experiment running

CUORE: Next generation with 741 kg of TeO_2 (200 kg of ^{130}Te)

Cryogenic Bolometers for 0νββ Experiments




CUORE module model

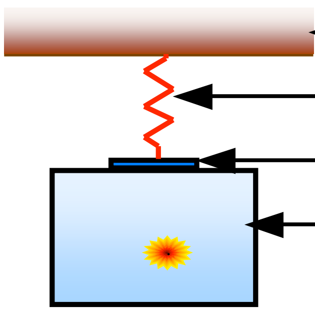


- ☺ **Detector = Source**
  - Maximize source mass
  - minimize background
- ☺ **Energy measured thermally**
  - Measurable temperature change
  - Energy fully detected
- ☺ **Excellent energy resolution**
  - 5 keV @ 2.5 MeV

- ☺ **Multiple material choices**
  - ^{130}**Te**O_2, ^{48}**Ca**F_2, ^{76}**Ge**, ^{100}**Mo**PbO_4, ^{116}**Cd**WO_4 (^{150}**Nd**F_3 ^{150}**Nd**GaO_3)
- 😐 **Requires low temperature**
  - Low heat capacity necessary for detectable temperature change
- 😐 **No event-type discrimination**
  - R&D underway (SSB, scintillation)

CUORE/Cuoricino Bolometer

TeO_2 Bolometer: Source = Detector



Heat sink: Cu structure (8 mK)
Thermal coupling: Teflon (G = 4 pW/mK)
Thermometer: NTD Ge-thermistor (dR/dT ≅ 100 kΩ/μK)
Absorber: TeO_2 crystal (C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK)

For E = 1 MeV:

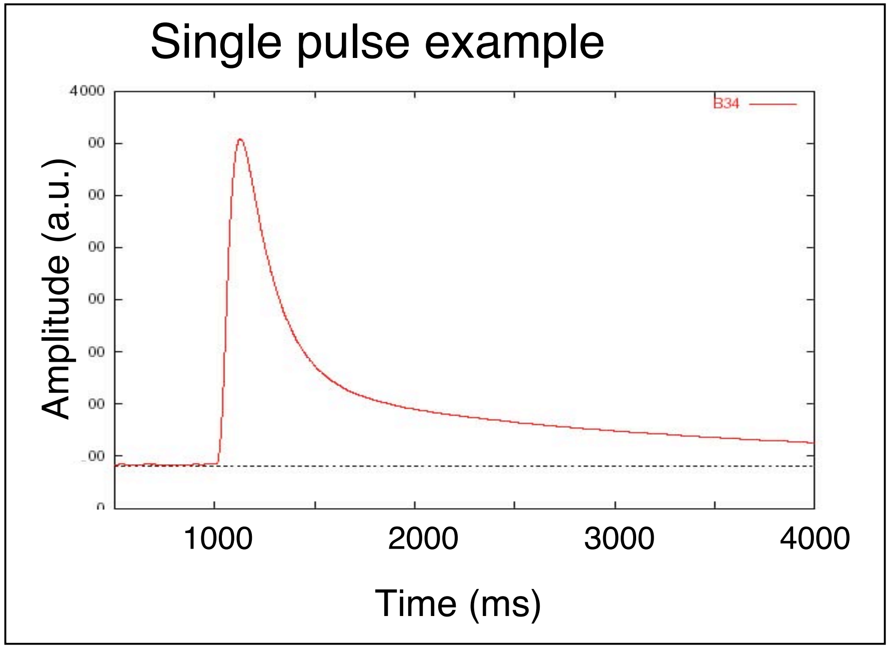
$\Delta T = E/C \cong 0.1$ mK

Signal size: 1 mV

Time constant:

$\tau = C/G = 0.5$ s

Energy resolution (FWHM):
~ 5-10 keV at 2.5 MeV



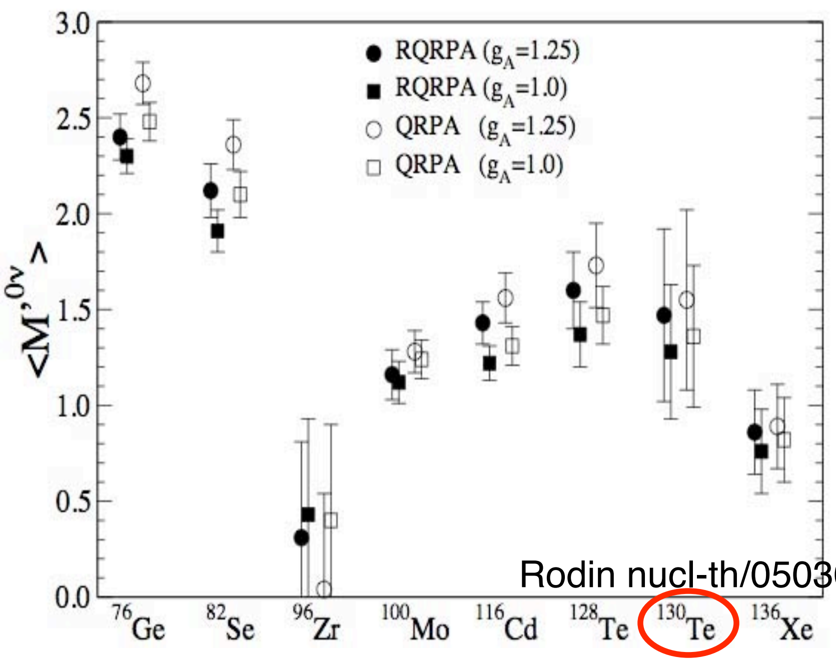
Tellurium-130

High natural isotope abundance of 33.8%: **No enrichment**

Q = 2530 keV

- Large phase space
- Low background: above most U/Th γ's, between ^{232}Th compton edge (2360 keV) and full γ (2615 keV)

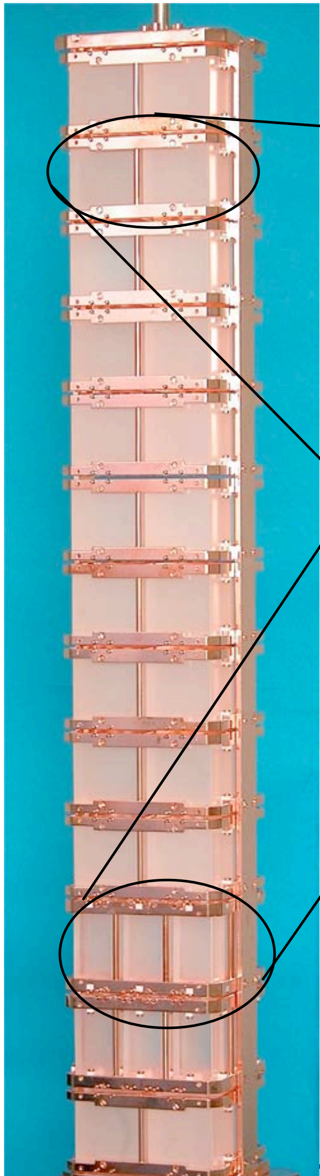
Geo-chemical measurements: $T^{2\nu\beta\beta}_{1/2} = (0.7 - 2.7) \times 10^{21}$ y



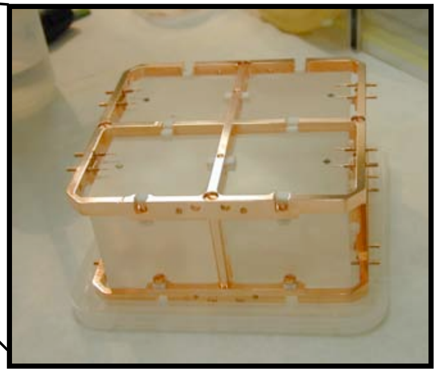
Rodin nucl-th/0503063

Nuclear transition	g_A	M^{exp}_{GT} $[MeV^{-1}]$	$\langle M'^{0\nu}\rangle$ RQRPA	$\langle M'^{0\nu}\rangle$ QRPA	$\varepsilon_{exp.}$	$T^{0\nu}_{1/2}$ ($\langle m_{\beta\beta}\rangle$ = 50 meV) [yrs]
$^{76}Ge \to {}^{76}Se$	1.25	0.15 ± 0.006	2.40(0.07)	2.68(0.06)	±0.05	$2.29^{+0.17}_{-0.16}\ 10^{27}$
	1.00	0.23 ± 0.01	2.30 (0.04)	2.48 (0.05)	±0.05	$2.49^{+0.15}_{-0.13}\ 10^{27}$
$^{82}Se \to {}^{82}Kr$	1.25	0.10 ± 0.009	2.12 (0.10)	2.36 (0.09)	±0.04	$6.60^{+0.73}_{-0.62}\ 10^{26}$
	1.00	0.16 ± 0.008	1.91 (0.05)	2.10 (0.07)	±0.05	$8.13^{+0.64}_{-0.57}\ 10^{26}$
$^{96}Zr \to {}^{96}Mo$	1.25	$0.11^{+0.03}_{-0.06}$	0.31 (0.08)	0.04 (0.10)	$^{+0.20}_{-0.43}$	$1.45^{\infty}_{-0.96}\ 10^{28}$
	1.00	$0.17^{+0.05}_{0.06}$	0.43 (0.11)	0.40 (0.02)	$^{+0.25}_{-0.45}$	$0.77^{\infty}_{-0.48}\ 10^{28}$
$^{100}Mo \to {}^{100}Ru$	1.25	0.22 ± 0.01	1.16(0.11)	1.28(0.09)	±0.02	$1.36^{+0.30}_{-0.23}\ 10^{27}$
	1.00	0.34 ± 0.015	1.12 (0.09)	1.24 (0.08)	±0.02	$1.45^{+0.27}_{-0.21}\ 10^{27}$
$^{116}Cd \to {}^{116}Sn$	1.25	0.12 ± 0.006	1.43 (0.08)	1.56 (0.10)	±0.03	$8.20^{+1.07}_{-0.90}\ 10^{26}$
	1.00	0.19 ± 0.009	1.22 (0.07)	1.31 (0.08)	±0.02	$11.3^{+1.48}_{-1.23}\ 10^{26}$
$^{128}Te \to {}^{128}Xe$	1.25	0.034 ± 0.012	1.60 (0.11)	1.73 (0.13)	±0.09	$1.85^{+0.38}_{-0.29}\ 10^{28}$
	1.00	0.053 ± 0.02	1.37 (0.07)	1.47 (0.05)	±0.1	$2.52^{+0.52}_{-0.40}\ 10^{28}$
$^{130}Te \to {}^{130}Xe$	1.25	$0.036^{+0.03}_{-0.009}$	1.47 (0.15)	1.55(0.17)	$^{+0.3}_{-0.09}$	$0.87^{+0.25}_{-0.16}\ 10^{27}$
	1.00	$0.056^{+0.05}_{-0.15}$	1.28 (0.08)	1.36 (0.10)	$^{+0.27}_{-0.08}$	$1.15^{+0.23}_{-0.38}\ 10^{27}$
$^{136}Xe \to {}^{136}Ba$	1.25	0.030	0.98(0.09)	1.03(0.08)		$1.84^{+0.39}_{-0.30}\ 10^{27}$
	1.00	0.045	0.90 (0.07)	0.94 (0.05)		$2.18^{+0.25}_{-0.16}\ 10^{27}$
	1.25	0	0.73(0.09)	0.77(0.10)		$3.32^{+1.00}_{-0.69}\ 10^{27}$
	1.00	0	0.63 (0.07)	0.67 (0.08)		$4.45^{+1.18}_{-0.85}\ 10^{27}$
$^{150}Nd \to {}^{150}Sm$	1.25	$0.07^{+0.009}_{-0.03}$	2.05 (0.13)	2.25 (0.16)	$^{+0.07}_{-0.20}$	$0.92^{+0.26}_{-0.12}\ 10^{26}$
	1.00	$0.11^{+0.014}_{-0.05}$	1.79 (0.05)	1.96 (0.04)	$^{+0.06}_{-0.19}$	$1.21^{+0.32}_{-0.10}\ 10^{26}$

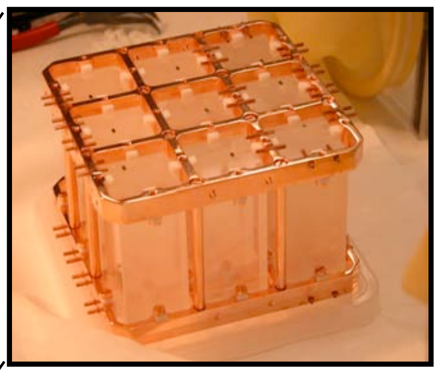
Cuoricino



Total detector mass: 40.7 kg ⇒ 11.64 kg ^{130}Te



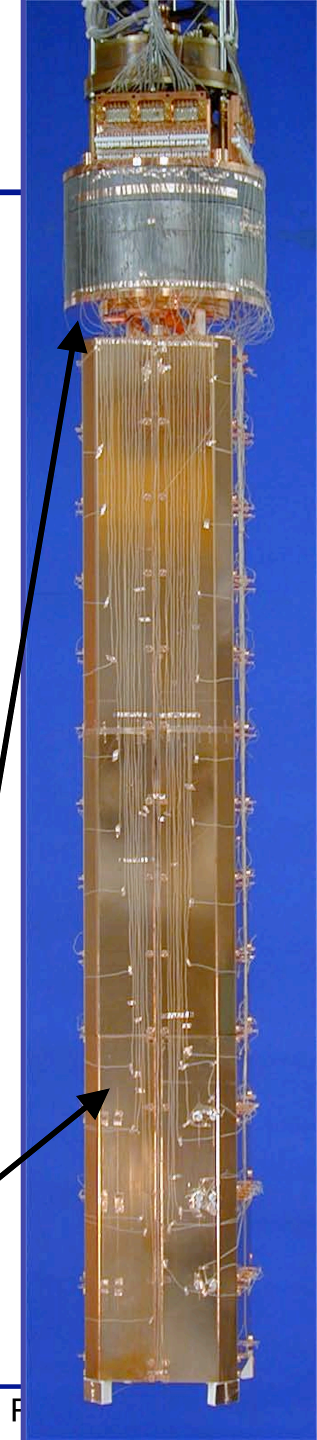
11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 790 g
44 x 0.79 = **34.76 kg of TeO_2**



2 modules x 9 crystals each
crystal dimension: 3x3x6 cm^3
crystal mass: 330 g
9 x 2 x 0.33 = **5.94 kg of TeO_2**
(2 enriched in ^{128}Te @82.3%)
(2 enriched in ^{130}Te @75%)

Shielding:

- Cu box + Roman Pb inside cryostat
- 20 cm Pb & 10 cm borated polyethylene outside





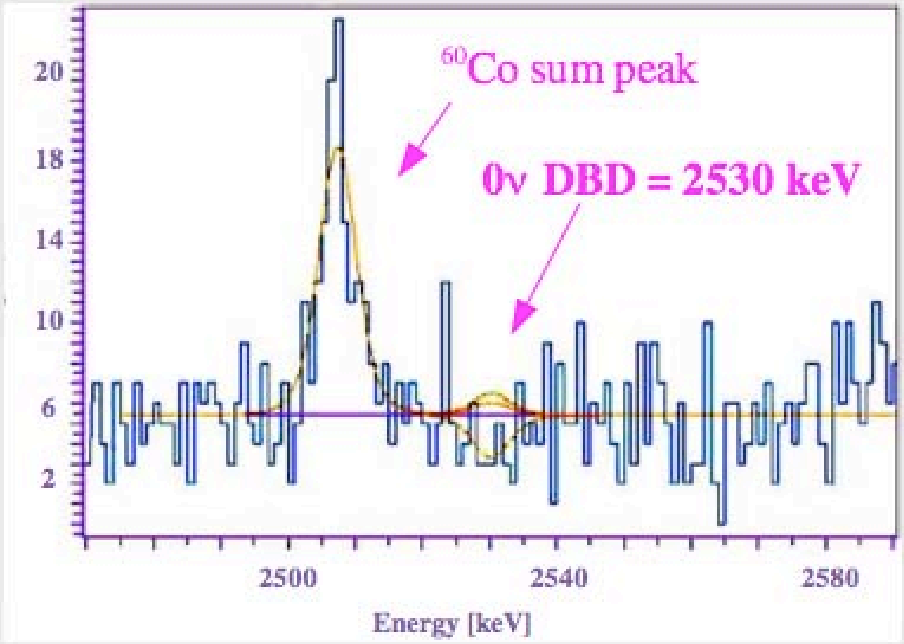
Cuoricino Results

Total Exposure: **8.38 kg-y of ^{130}Te**
BKG: **0.18 ± 0.01 cnts/(keV-kg-y)**
FWHM at 2615 keV: **~ 8 keV**

April 2003 - May 2006

0ν –DBD result

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

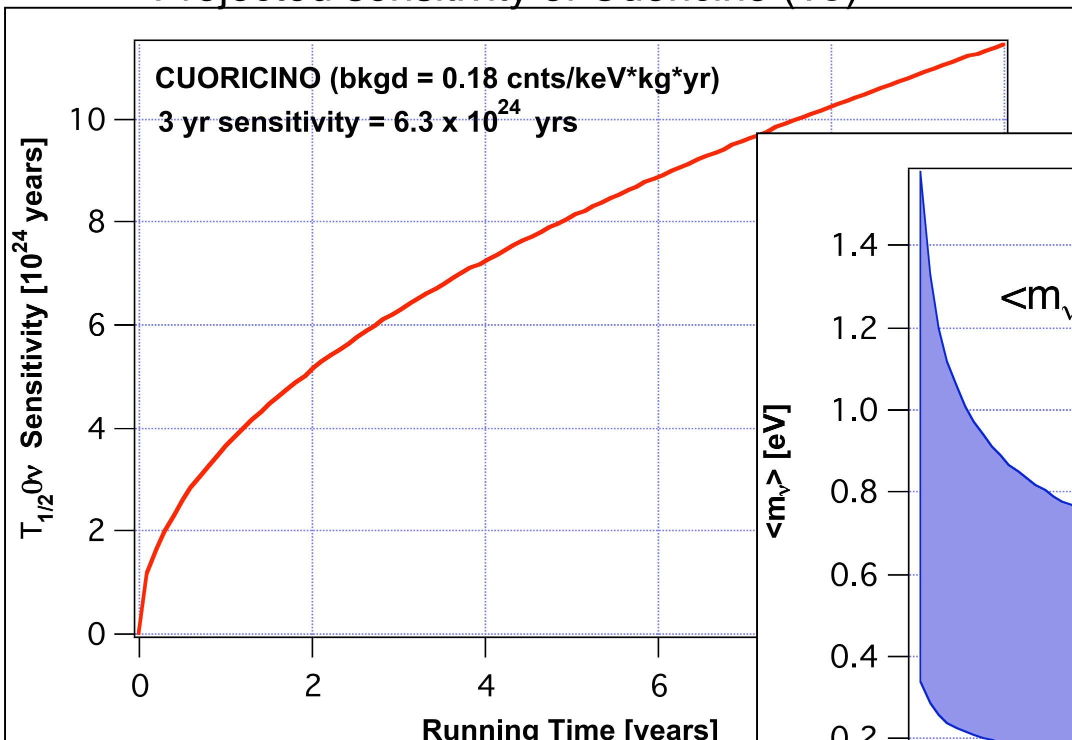


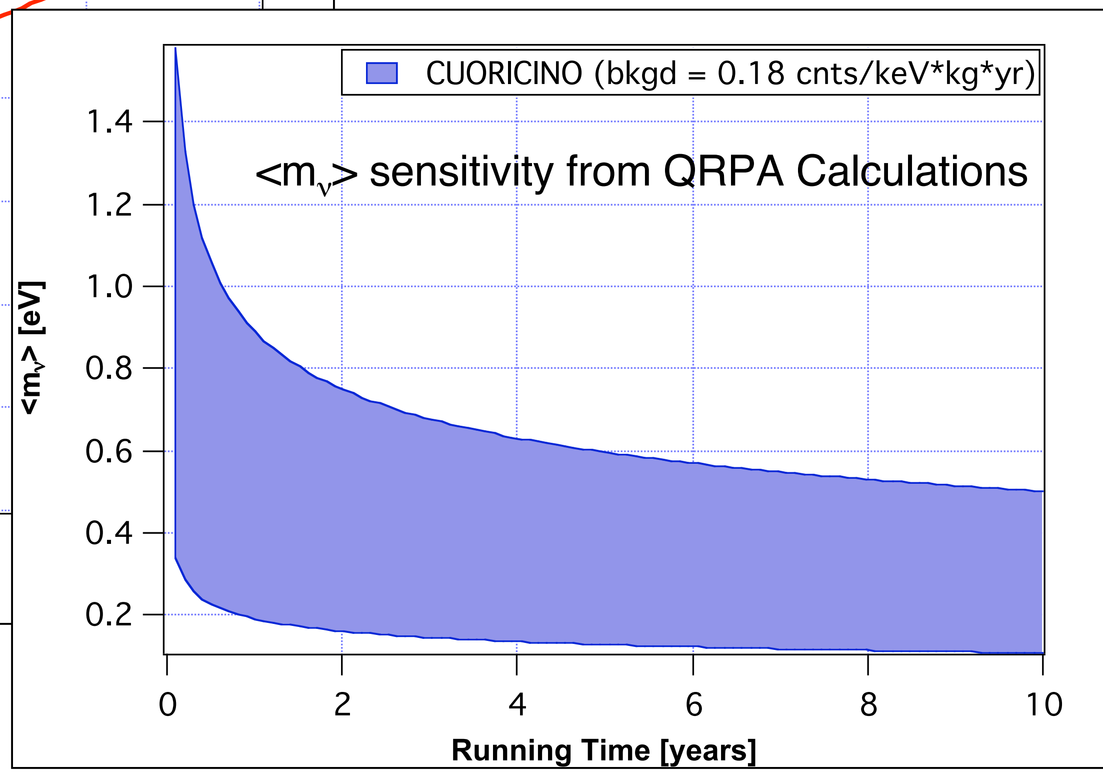
See poster by S. Capelli for more details

Projected Cuoricino Sensitivity

$$T_{1/2}^{0\nu} = \ln 2 \cdot \frac{N_A(\text{det.efficiency})(\text{isotopic.abundance})}{\text{mol.mass}} \sqrt{\frac{(\text{detector.mass})(\text{time})}{(\text{bkgd}) * (\text{resolution})}}$$

Projected sensitivity of Cuoricino (1σ)





60% live time for 3 yrs = 4 x10^{24} yrs (90% CL)

<m> range from various QRPA calculations:

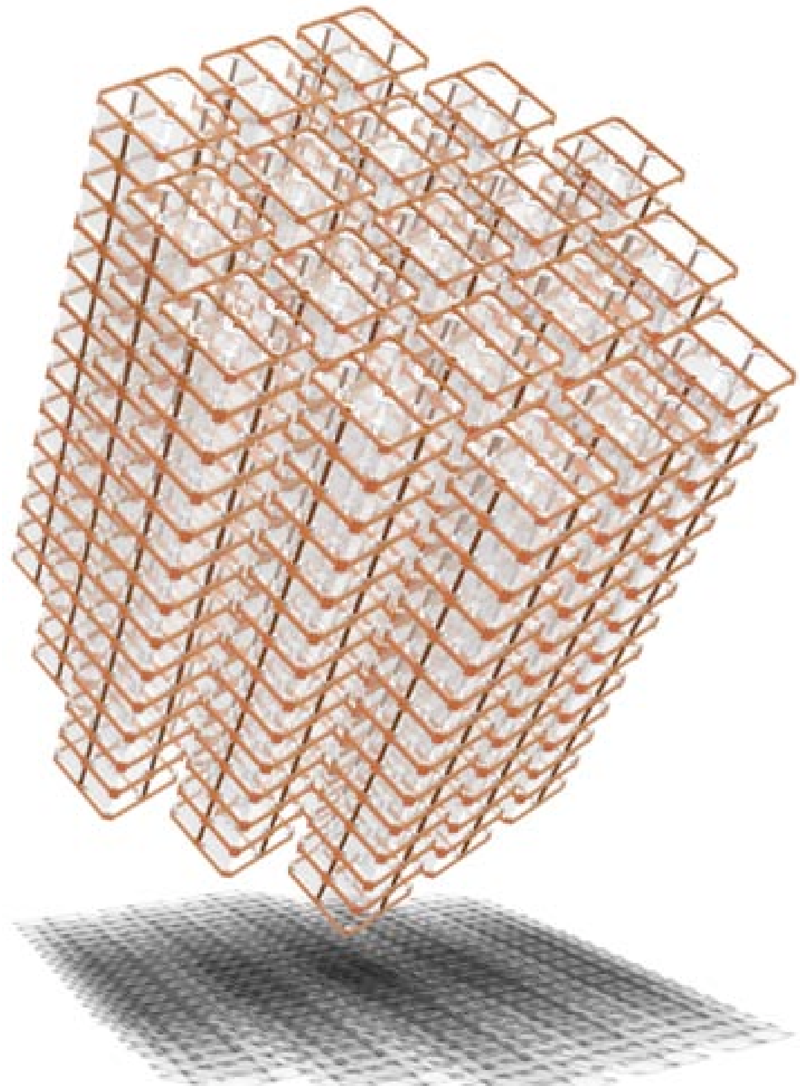
Rodin, Faessler, Simkovic, & Vogel Nucl. Phys. A **766** 107 (2006)

Staudt, Kuo & Klapdor-Kleingrothaus, PRC **46** 871 (1992)

CUORE

Array of 988 TeO_2 crystals

- **19** Cuoricino-like towers
- **13** levels, **4** crystals per tower
- 5x5x5 cm^3 (750 g each)
- ^{130}Te: 33.8% isotope abundance
- **741 kg TeO_2 ⇒ 200 kg ^{130}Te**



Goal

background < 0.01 cnts/keV/kg/y

Resolution = 5 keV

5 year sensitivity

$F^{0\nu}$ > 2.1 x10^{26} y

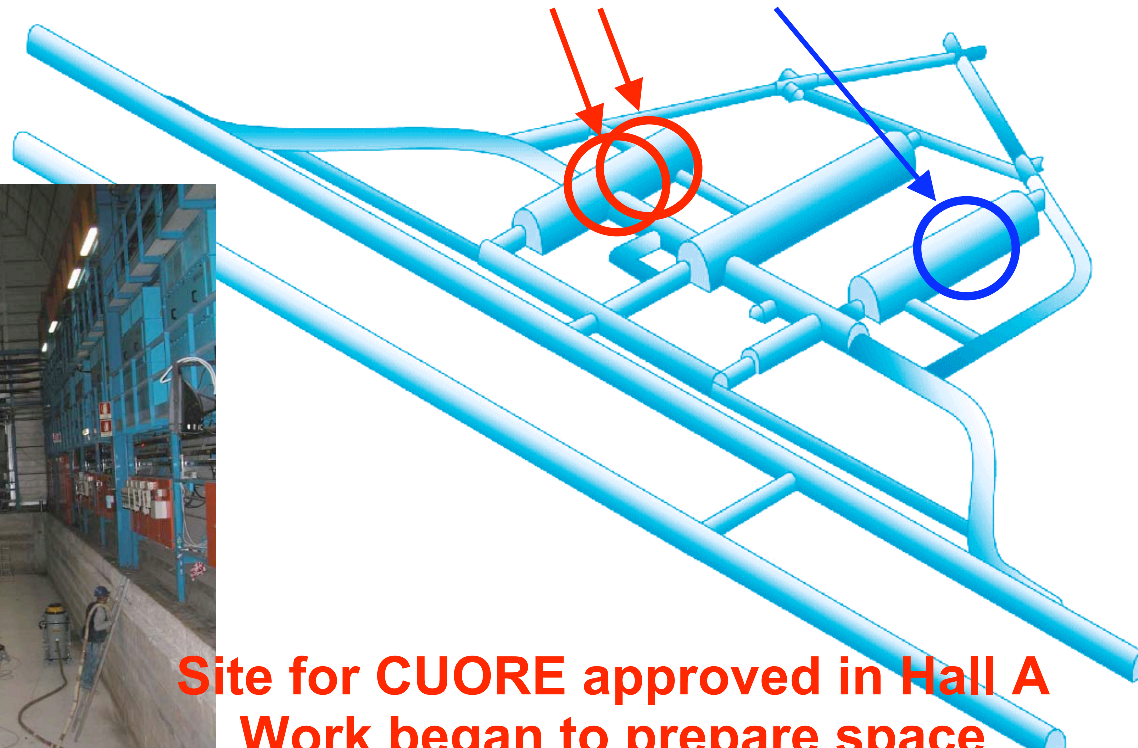
m_{ee} < ~ 19 – 100 meV

(approved by INFN and the Science Council of Gran Sasso Laboratory)

Gran Sasso National Underground Laboratory

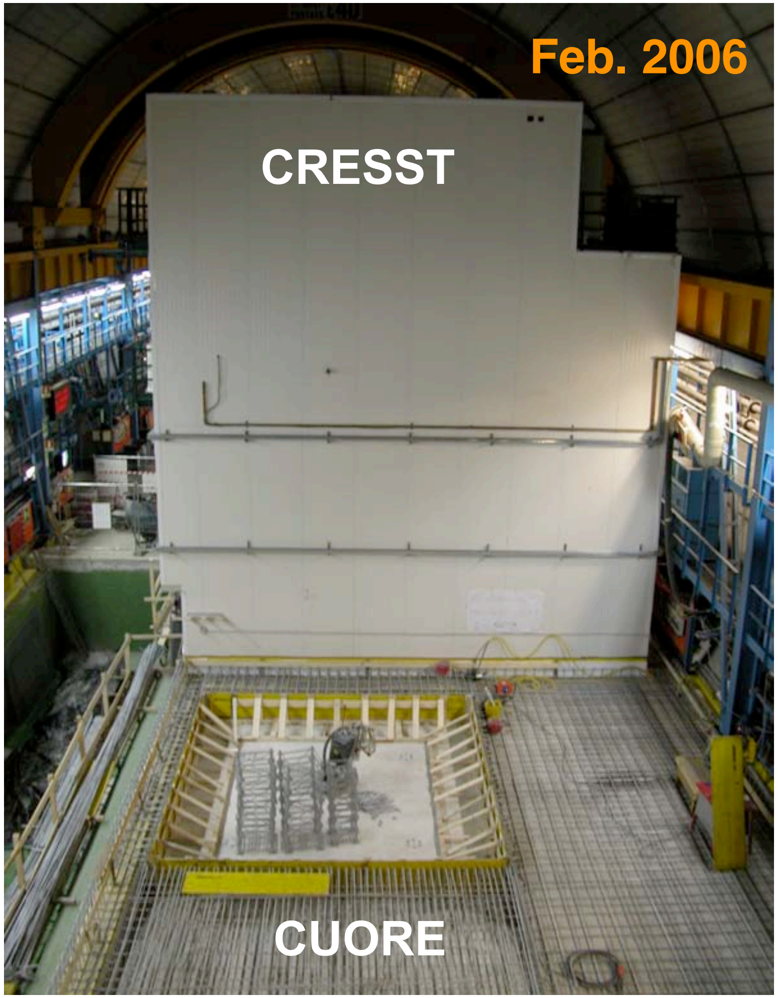
Overburden at LNGS: 3200 m.w.e

Two dilution refrigerators:
Hall A: CUORICINO
CUORE: next to Cuoricino
Hall C (R&D final tests for CUORE)

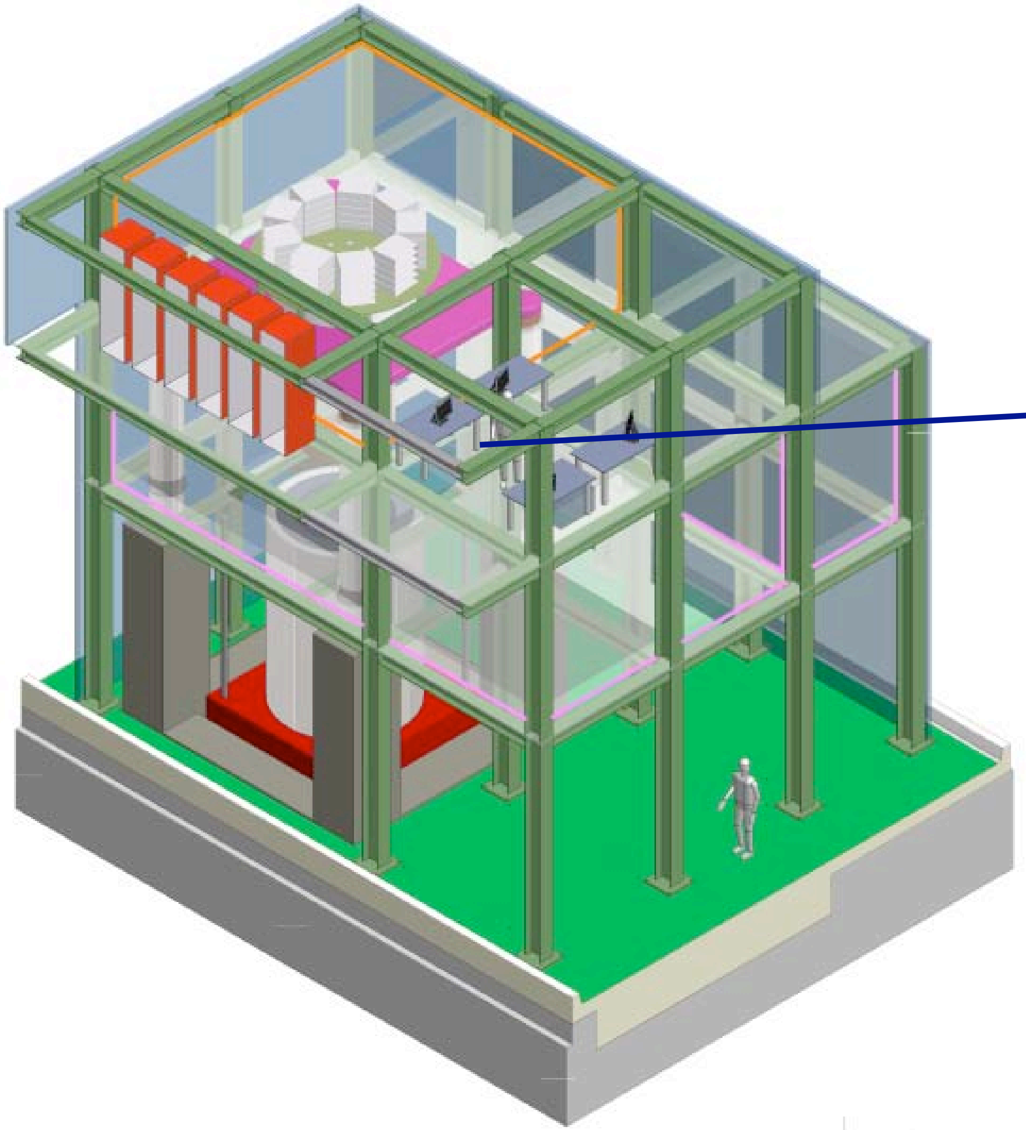


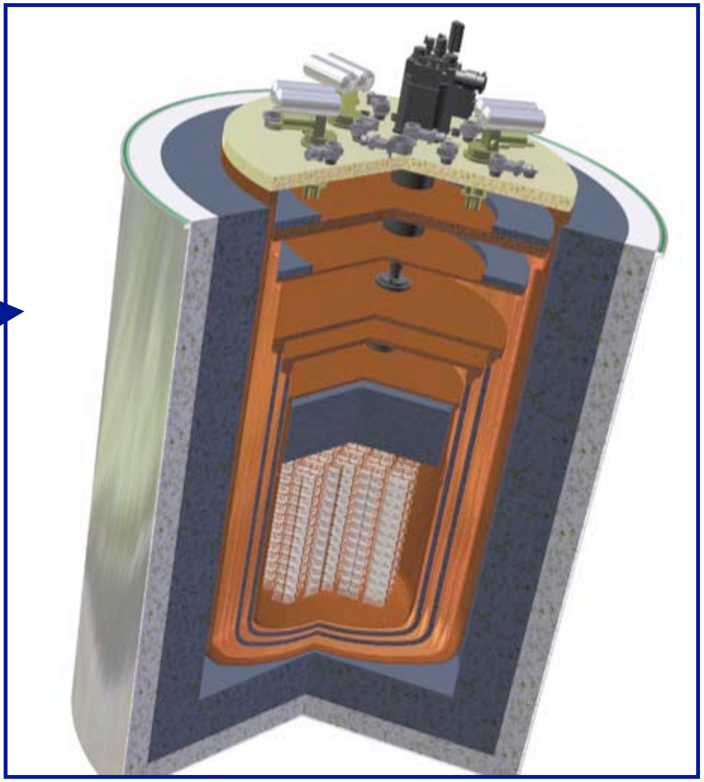
Site for CUORE approved in Hall A
Work began to prepare space

CUORE Site in Hall A at LNGS



CUORE Housing and Cryostat Design

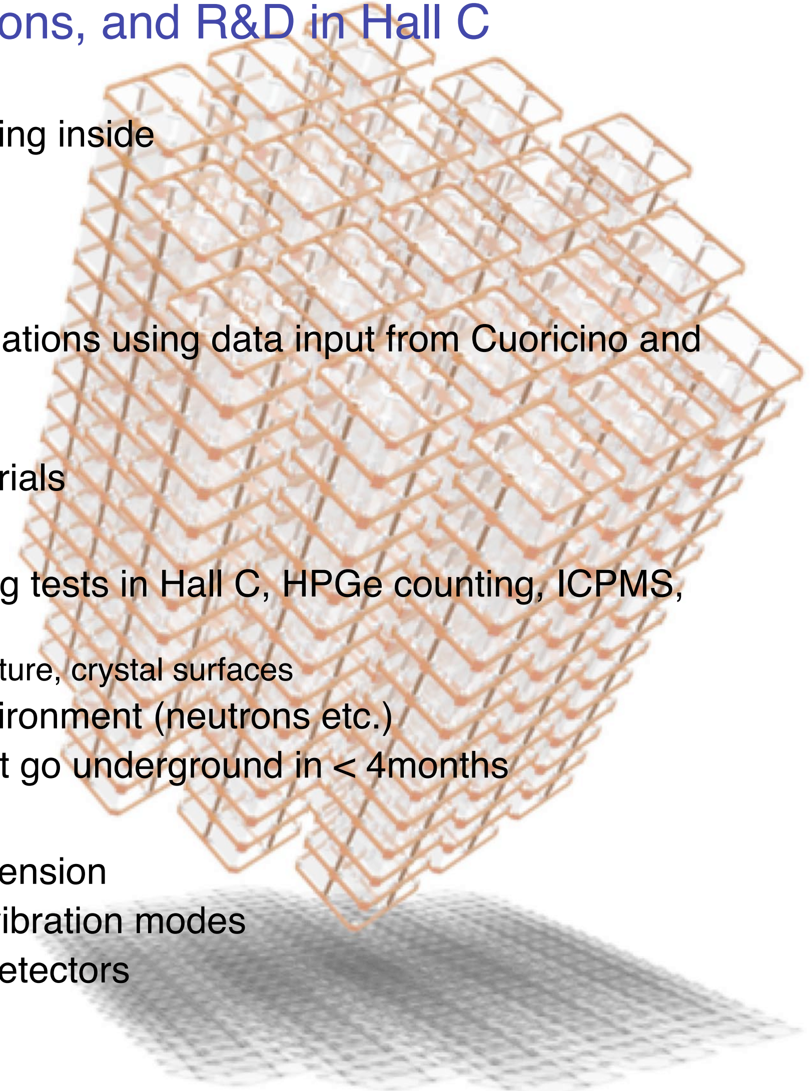




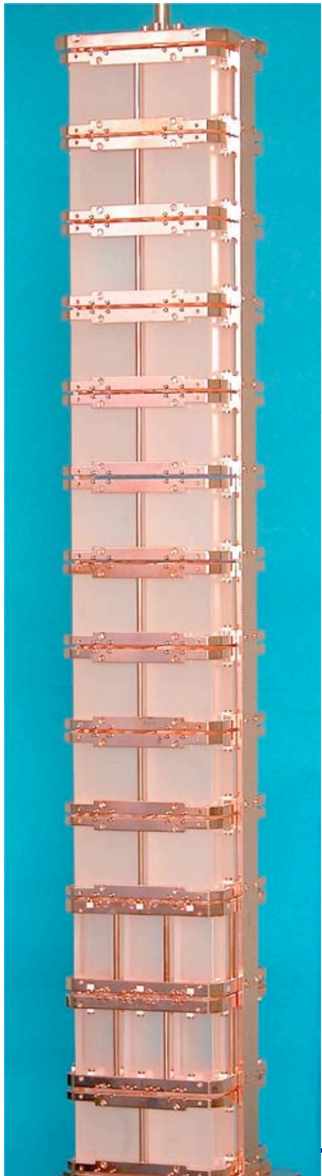
Designing CUORE

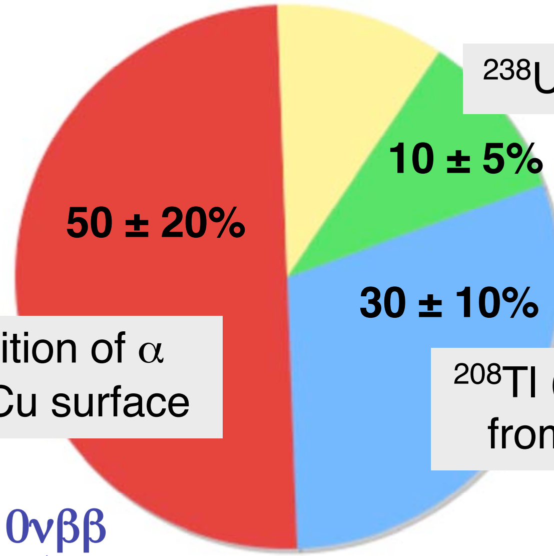
Use knowledge gained from Cuoricino, simulations, and R&D in Hall C

- **Custom designed cryostat**
  - Designed to accommodate the required shielding inside
  - Clean materials selected for dewars
  - Improve reliability for higher live-time
- **Improved shielding**
  - Specifically designed and optimized with simulations using data input from Cuoricino and Hall C tests
  - Improved shielding inside cryostat
  - Use of specially selected clean shielding materials
- **Radioactive background reduction**
  - Select materials and cleaning procedures using tests in Hall C, HPGe counting, ICPMS, NAA, etc.
    - e.g.Raw Te, NTD Ge Thermistors, copper structure, crystal surfaces
  - Simulations of possible backgrounds from environment (neutrons etc.)
  - Proton activation studies indicate crystals must go underground in < 4months
- **New detector structure design**
  - Improved vibration isolation and detector suspension
  - Structure designed to minimize surfaces and vibration modes
  - Uniform and better energy resolution among detectors
  - Ease of assembly



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

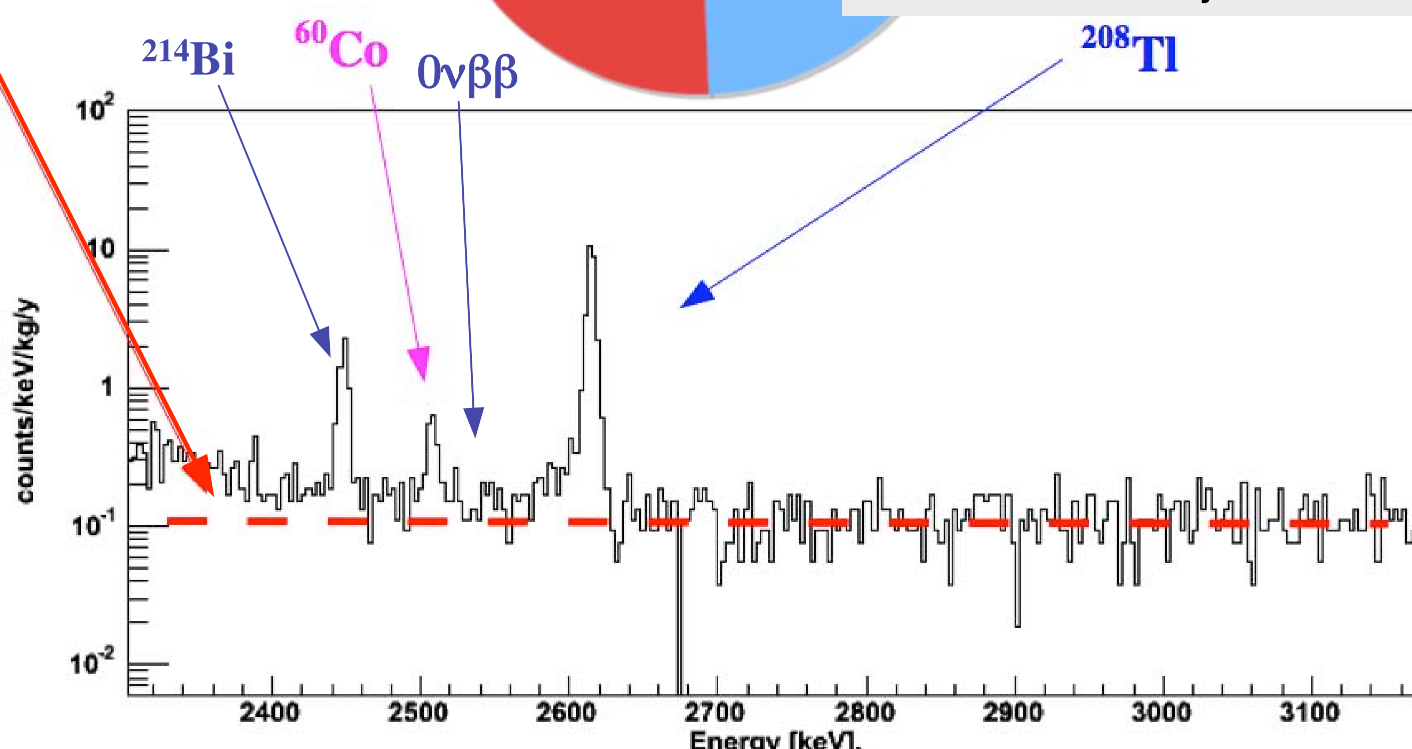




$^{238}U/^{232}Th$ on crystal surface

Partial energy deposition of α from ^{238}U & ^{232}Th on Cu surface

^{208}Tl (2615 keV) Compton events from ^{232}Th in cryostat shields



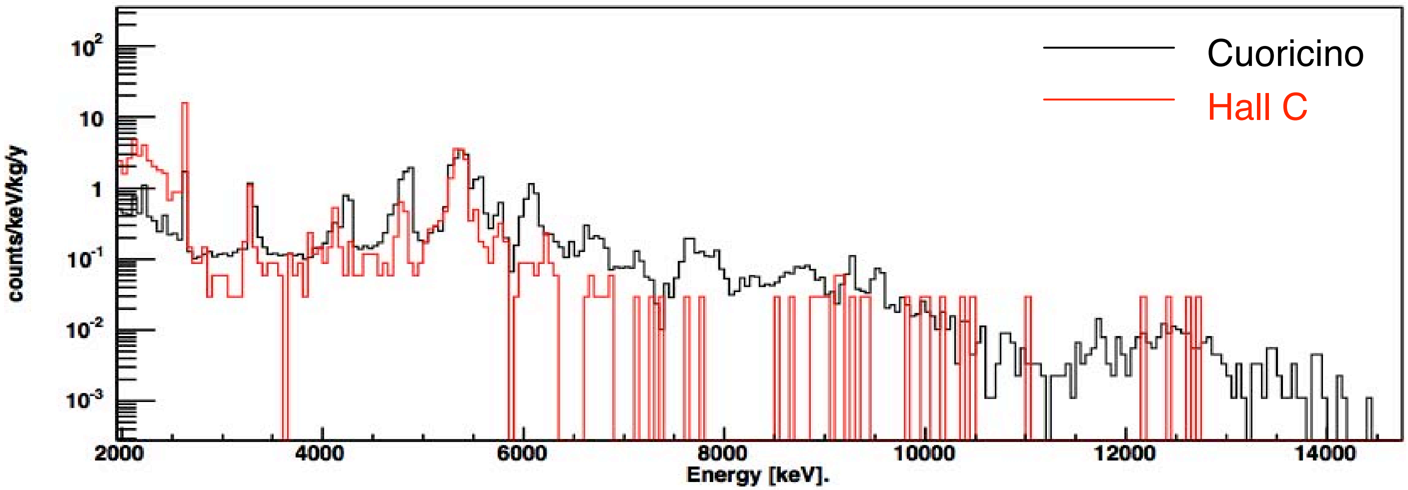
Background Reduction Studies

α source studies from Cuoricino, series of tests in Hall C, & Monte Carlo

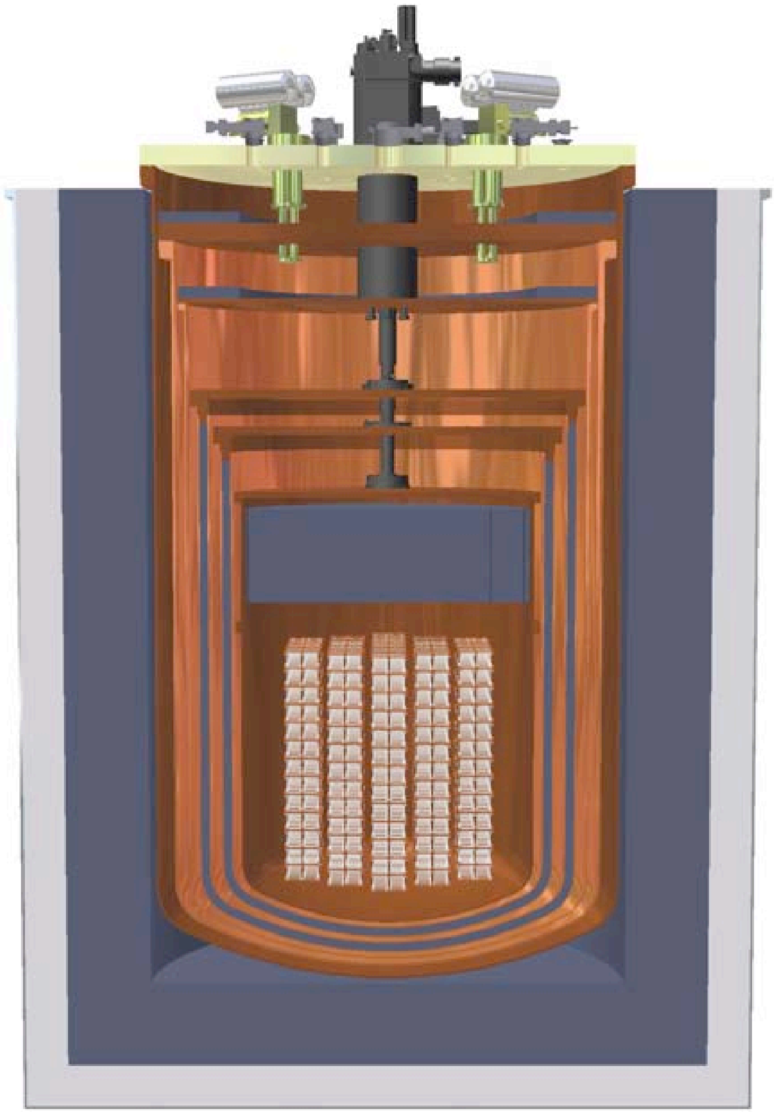
- Cryostat in Hall C has higher γ rates than in Cuoricino resulting in higher rates < 2.6 MeV. Possible to study α backgrounds only.
- **Significant reduction shown above 3 MeV**
- Tested items: cleaning procedures, mounting schemes, material selections
- Most tests underway to reach goal of < 0.01 c/keV/kg/yr

Expected background from materials near crystals ~ (2 - 4) x 10^{-2} c/keV/kg/yr

Comparison of Cuoricino and Hall C measurements



CUORE Shielding



Roman lead (^{210}Pb < 4mBq/kg)

- ~15 cm layer directly above detector
- ~3 cm layer immediately around detector

Low activity lead

- Two disks above detector, at 50 mK and 600 mK, both 10 cm thick.
- 16 Bq/kg of ^{210}Pb inner layer (~10cm)
- 150 Bq/kg outer layer (~10cm)

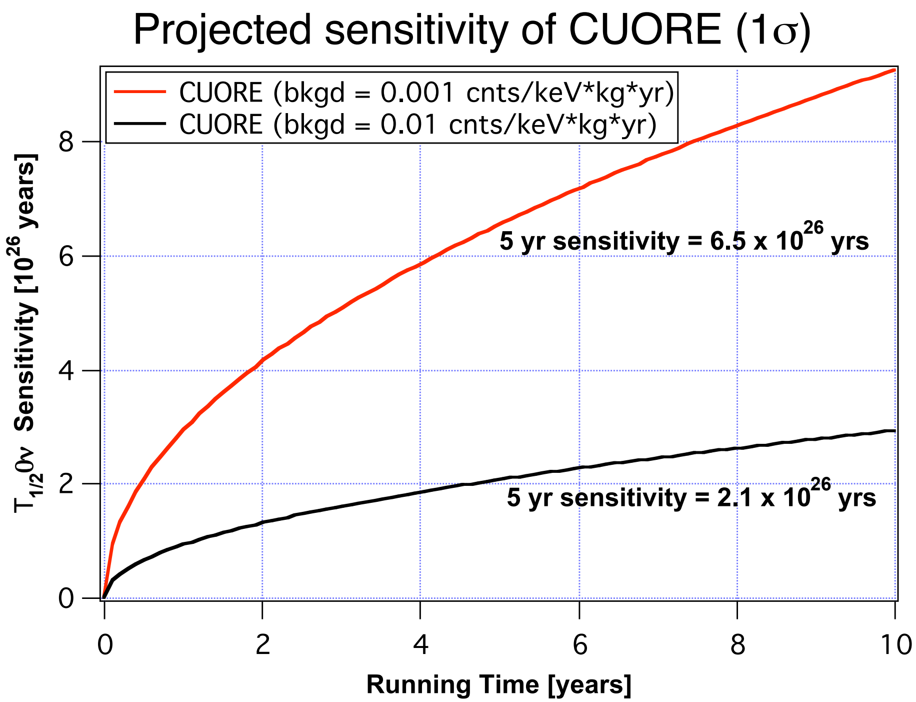
Borated polyethylene box

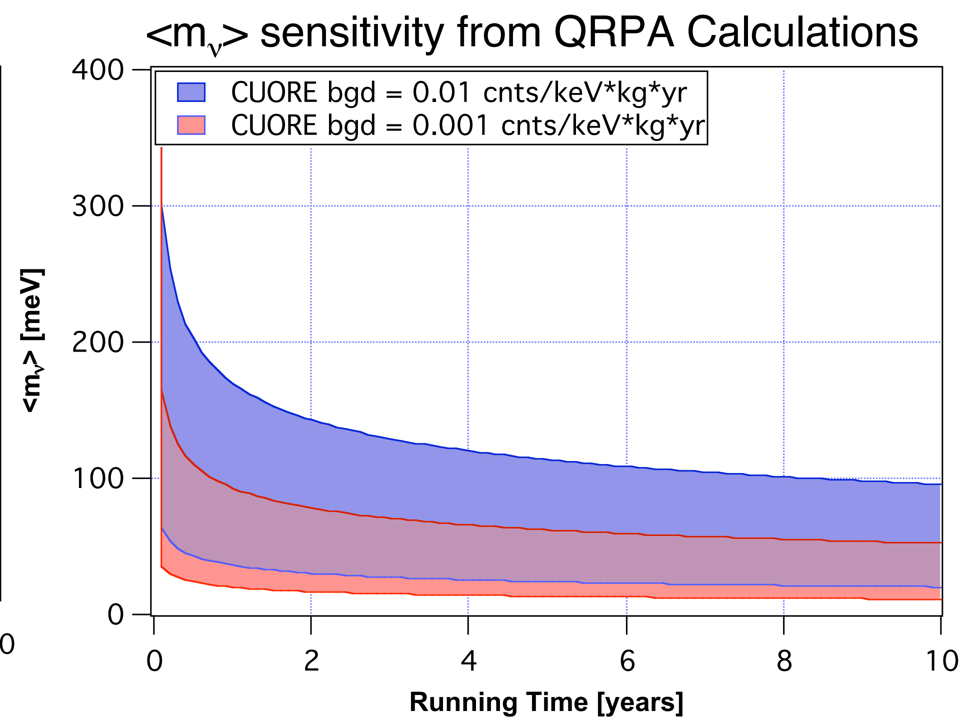
- most neutrons eliminated w/ ~10 cm
- hermetically sealed & flushed with N_2 to exclude radon
- Simulation shows no measurable background contribution in DBD region

Faraday cage

- Important for near-threshold events

CUORE Sensitivity





* <m> range from various QRPA calculations:

high: Rodin, Faessler, Simkovic, & Vogel Nucl. Phys. A **766** 107 (2006)

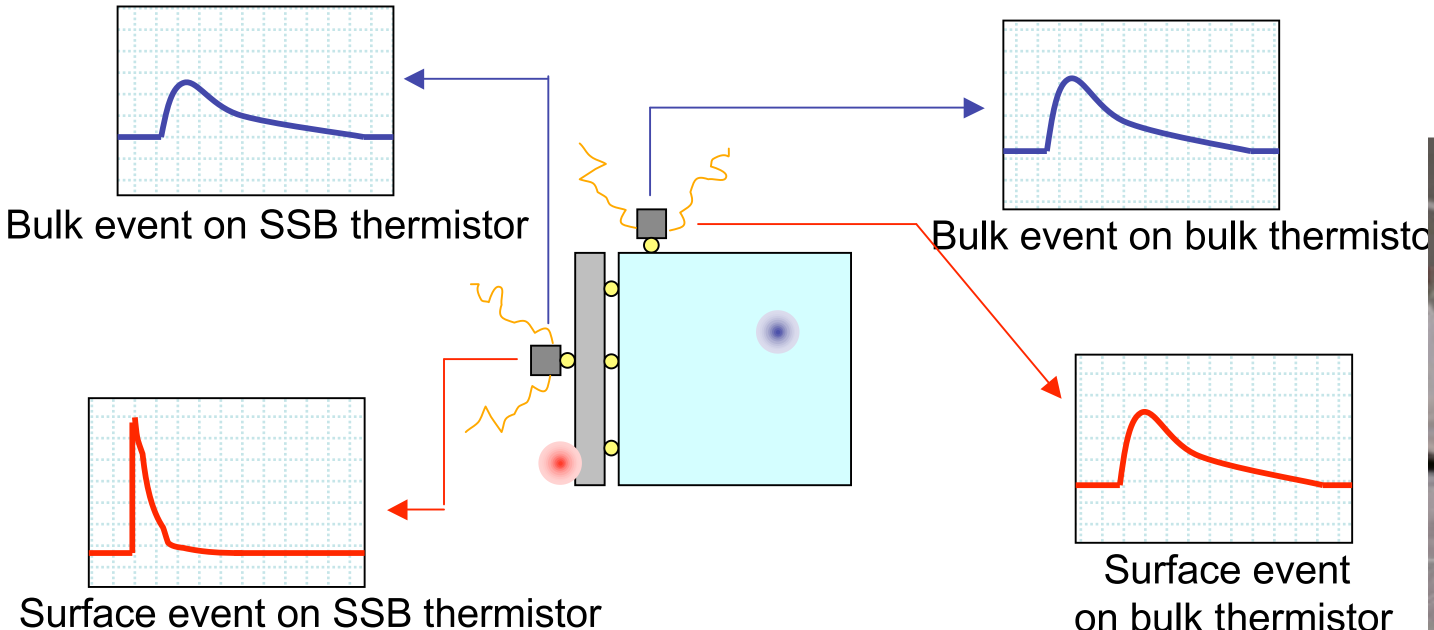
low: Staudt, Kuo & Klapdor-Kleingrothaus, PRC **46** 871 (1992)

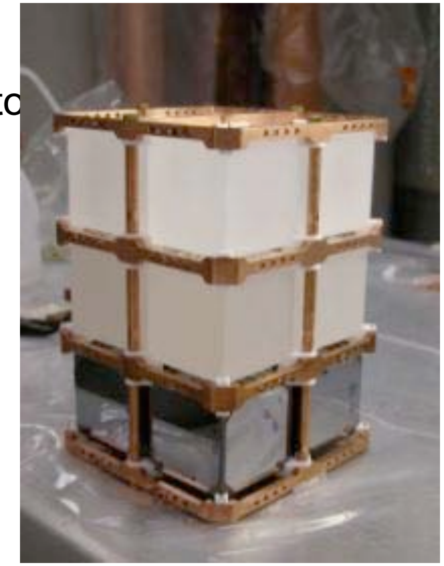
Beyond CUORE

Possible event discrimination in bolometers

- Scintillating Crystals ← **See poster by P. Gorla**
- Surface Sensitive Bolometers (SSB) ← **See poster by S. Sangiorgio**

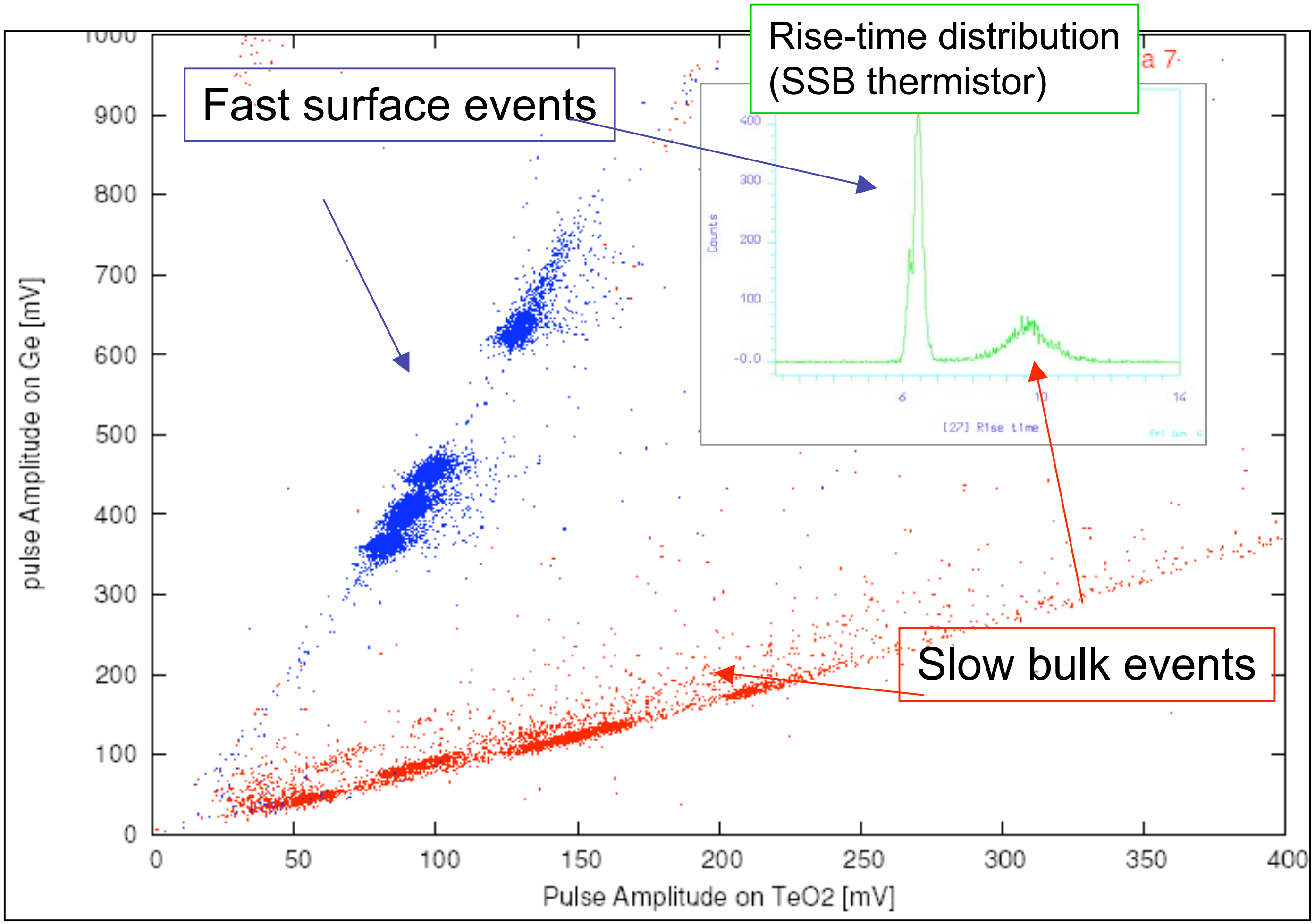
A composite bolometer with a thin crystal of TeO2





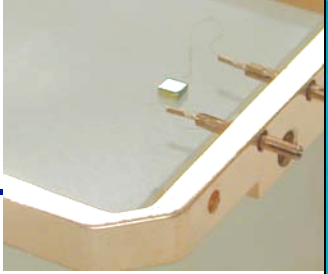
Beyond CUORE

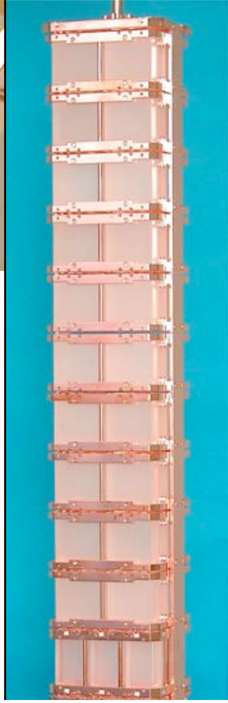
Surface Sensitive Bolometer Tests with Ge



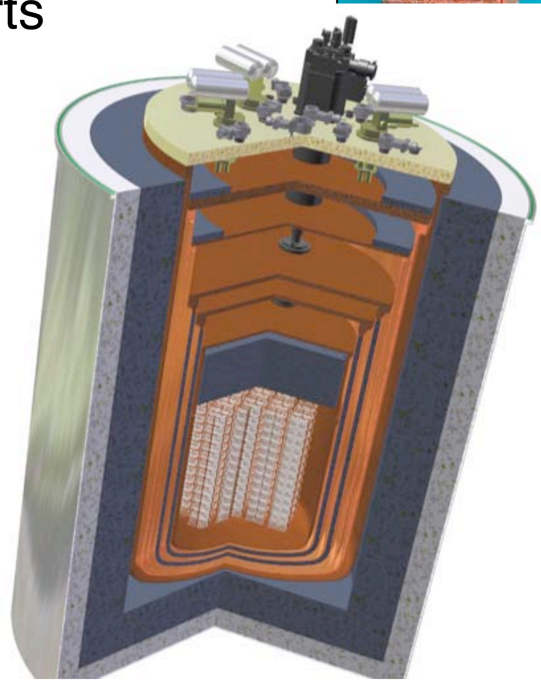
See poster by S. Sangiorgio for details on surface sensitive bolometers

Conclusion





- Cryogenic bolometers
  - good efficiency & high resolution
  - low radioactive backgrounds
- Cuoricino:
  - running since April 2003
  - great prototype and R&D for CUORE
  - will continue to set new limits until CUORE starts
- CUORE
  - Designed to probe inverse hierarchy
  - Technology in place and tested as Cuoricino
  - Background reduction well underway



CUORE Collaboration

University of California at Berkeley
M.P. Decowski[2] , M.J. Dolinski[3] , S.J. Freedman[2], Yu.G. Kolomensky[2], E.E. Haller[2]

University of South Carolina
D.R. Artusa, F.T. Avignone III, I. Bandac, R. J. Creswick, H.A. Farach, C. Rosenfeld

Lawrence Berkeley National Laboratory
J.W. Beeman, R.W. Kadel, A.R. Smith, N. Xu

Lawrence Livermore National Laboratory
E.B. Norman

University of California, Los Angeles
H. Huang, C. Whitten Jr.

University of Wisconsin, Madison
K.M. Heeger[4] , R.H. Maruyama[4]

California Polytechnic State University
T.D. Gutierrez[4]

[2]also at LBNL
[3]also at LLNL
[4] currently at LBNL

Universita' di Milano-Bicocca - INFN Sezione di Milano
F. Alessandria, R. Ardito[1] , C. Arnaboldi, C. Brofferio, S. Capelli, L. Carbone, M. Clemenza, O. Cremonesi, E. Fiorini, C. Nones, A. Nucciotti, M. Pavan, G. Pessina, S. Pirro, E. Previtali, M. Sisti, L. Torres, L. Zanotti

Politecnico de Milano
G. Maier

Laboratori Nazionali del Gran Sasso
M. Balata, C. Bucci, S. Nisi

Universita' di Firenze e INFN, Firenze
M. Barucci, L. Risegari, G. Ventura

University of Zaragoza
S. Cebrian, P. Gorla, I.G. Irastorza

Universita' dell'Insubria e Sezione di Milano dell'INFN, Como
A. Giuliani, M. Pedretti, S. Sangiorgio

Universita di Genova
S. Cuneo, S. Didomizio, A. Giachero, E. Guardincerri, M. Olcese, P. Ottonello, M. Pallavicini

Laboratori Nazionali di Legnaro
V. Palmieri

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

Posters:

1. **D. Schaffer: MARE: ^{187}Re neutrino mass measurement**
12. **S. Capelli: Cuoricino Results**
17. **M.J. Dolinski: neutron cross sections on tellurium**
21. **S. Sangiorgio: surface sensitive bolometers**
23. **P. Gorla: scintillating bolometers**