CUORE & Cuoricino
A Search for Neutrinoless Double Beta Decay

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LBNL / University of Wisconsin, Madison

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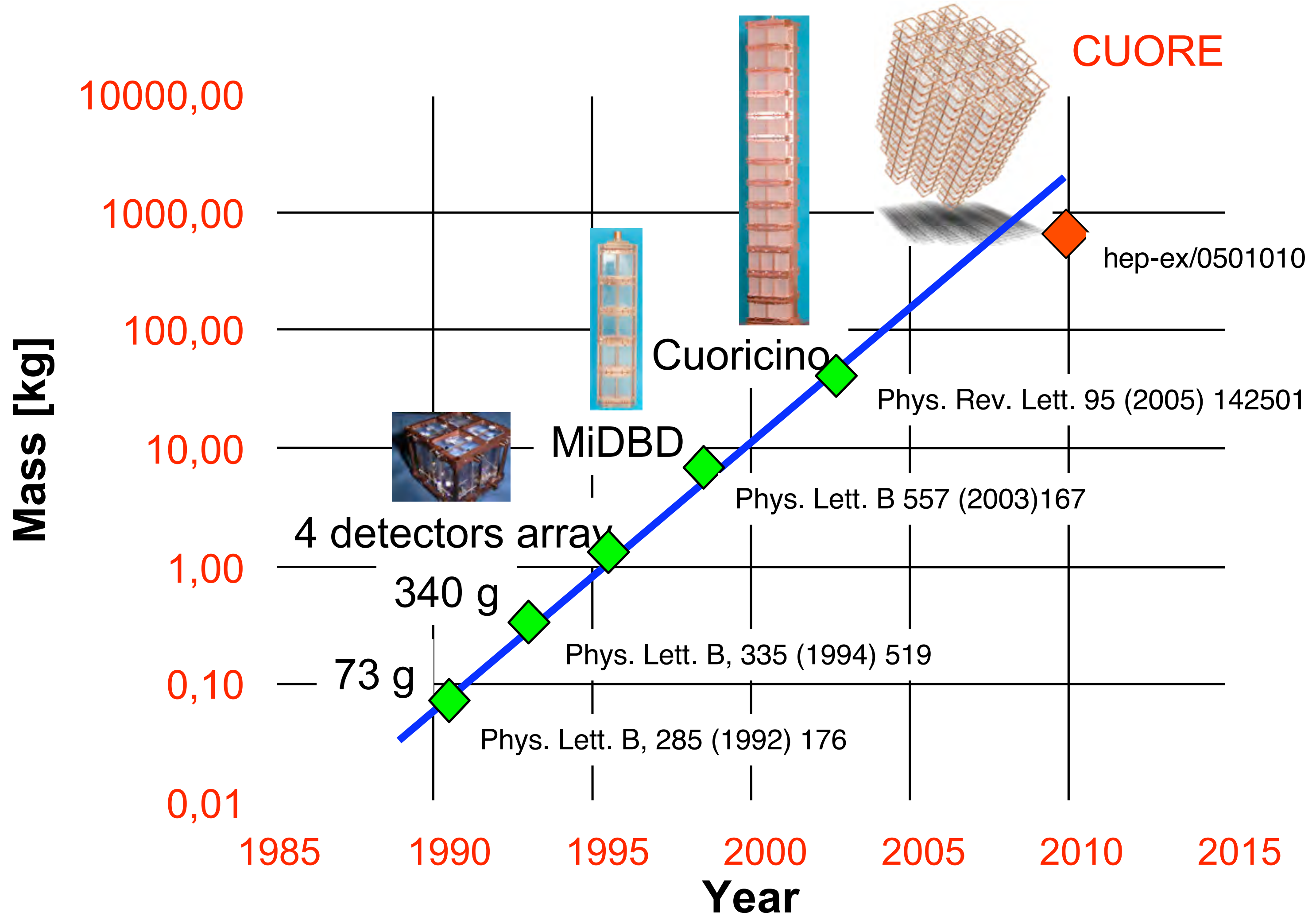
Bolometric 0νββ Experiments: Past & Future



Cuoricino: Currently the largest bolometer & most sensitive 0νββ experiment running
CUORE: Next generation with 741 kg of TeO_2 (204 kg of ^{130}Te)

Tellurium-130

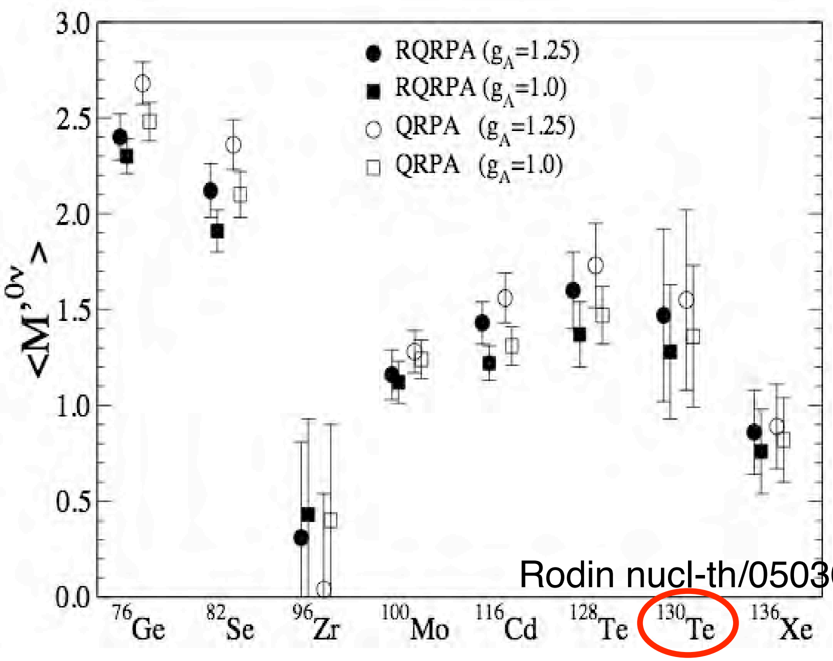
High natural isotope abundance of 33.8%: **No enrichment**

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

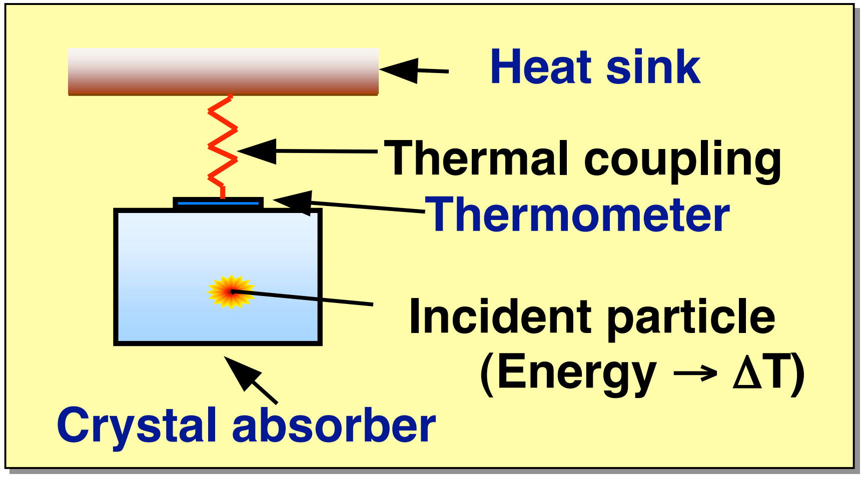
MiDBD: $T^{2\nu\beta\beta}_{1/2} = (6.1 \pm 1.4\ (+2.9 - 3.5)) \times 10^{20}$ y

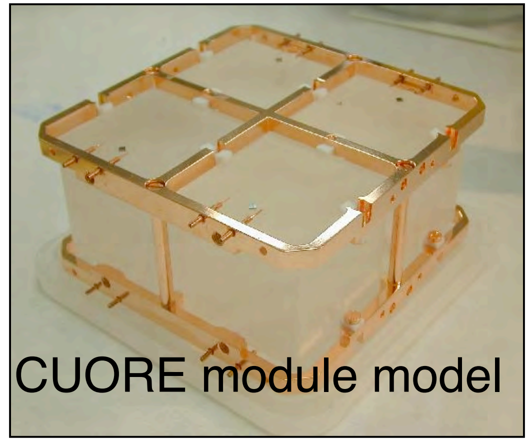


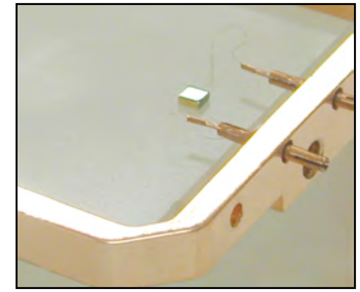
Rodin nucl-th/0503063

Nuclear transition	g_A	M_{GT}^{exp} $[MeV^{-1}]$	$\langle M'^{0\nu}\rangle$ RQRPA	$\langle M'^{0\nu}\rangle$ QRPA	$\varepsilon_{exp.}$	$T^{0\nu}_{1/2}$ ($\langle m_{\beta\beta}\rangle$ = 50 meV) [yrs]
$^{76}Ge \rightarrow {}^{76}Se$	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	$2.49^{+0.15}_{-0.13}\ 10^{27}$
$^{82}Se \rightarrow {}^{82}Kr$	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	$8.13^{+0.64}_{-0.57}\ 10^{26}$
$^{96}Zr \rightarrow {}^{96}Mo$	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)	$^{+0.25}_{-0.45}$	$0.77^{\infty}_{-0.48}\ 10^{28}$
$^{100}Mo \rightarrow {}^{100}Ru$	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	$1.45^{+0.27}_{-0.21}\ 10^{27}$
$^{116}Cd \rightarrow {}^{116}Sn$	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	$11.3^{+1.48}_{-1.23}\ 10^{26}$
$^{128}Te \rightarrow {}^{128}Xe$	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	$2.52^{+0.52}_{-0.40}\ 10^{28}$
$^{130}Te \rightarrow {}^{130}Xe$	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)	$^{+0.27}_{-0.08}$	$1.15^{+0.23}_{-0.38}\ 10^{27}$
$^{136}Xe \rightarrow {}^{136}Ba$	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)		$4.45^{+1.18}_{-0.85}\ 10^{27}$
$^{150}Nd \rightarrow {}^{150}Sm$	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)	$^{+0.06}_{-0.19}$	$1.21^{+0.32}_{-0.10}\ 10^{26}$

Cryogenic Bolometers for 0νββ Experiments



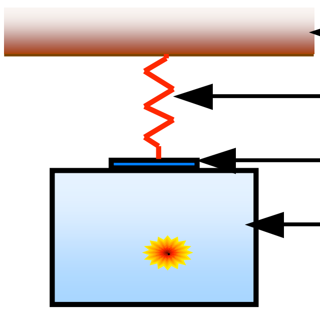

CUORE module model



- ☺ **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**
  - $^{130}\mathbf{Te}O_2$, $^{48}\mathbf{Ca}F_2$, $^{76}\mathbf{Ge}$, $^{100}\mathbf{Mo}PbO_4$, $^{116}\mathbf{Cd}WO_4$ ($^{150}\mathbf{Nd}F_3$ $^{150}\mathbf{Nd}GaO_3$)
- 😐 **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 ($dR/dT \cong 100$ kΩ/μK)
- **Absorber**: TeO_2 crystal ($C \cong 2$ nJ/K $\cong$ 1 MeV / 0.1 mK)

For E = 1 MeV:

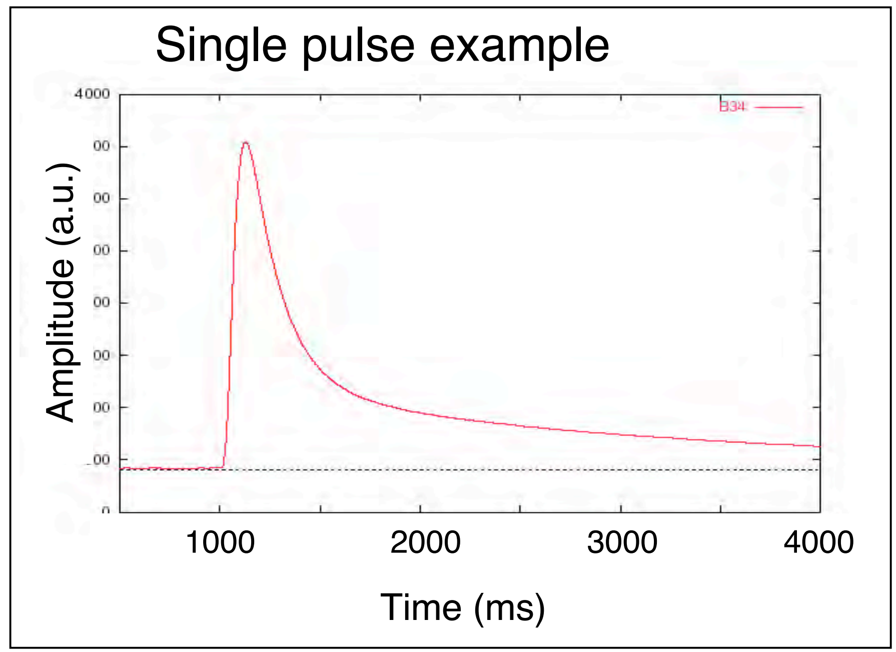
$\Delta T = E/C \cong 0.1$ mK

Signal size: 1 mV

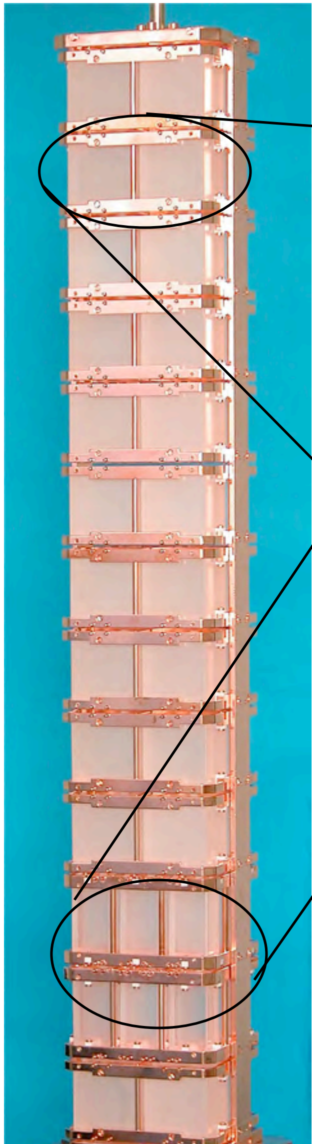
Time constant:

$\tau = C/G = 0.5$ s

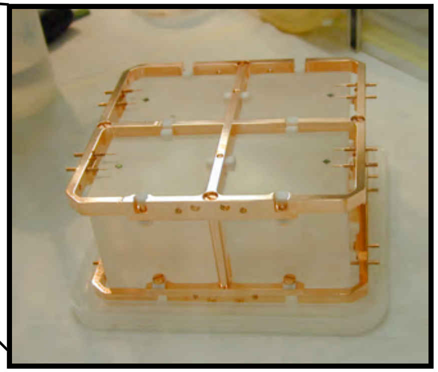
Energy resolution (FWHM):
~ 5-10 keV at 2.5 MeV



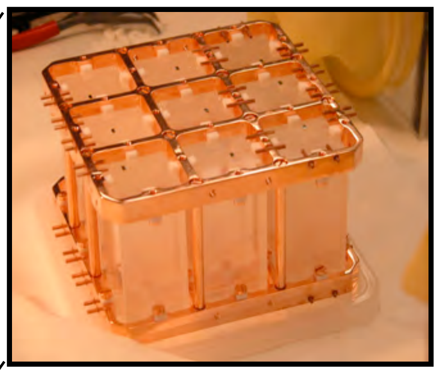
Cuoricino



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



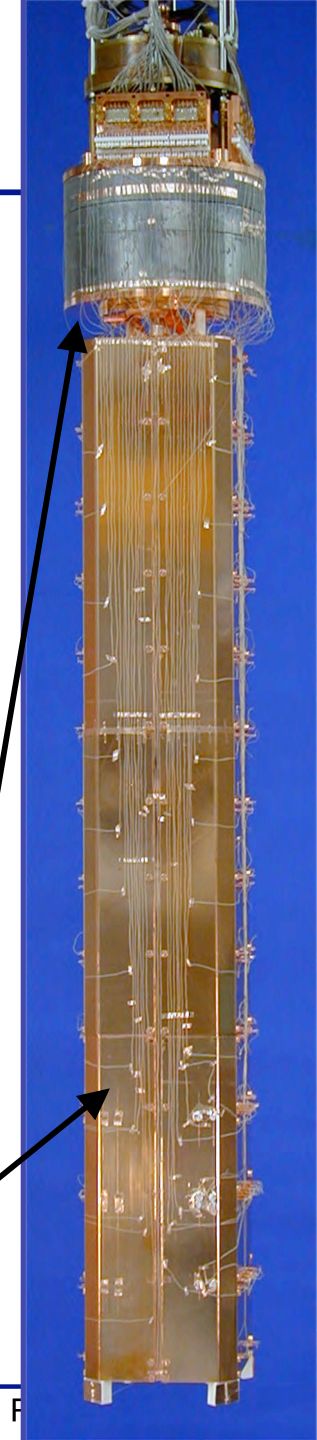
11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 790 g
44 x 0.79 = **34.76 kg of TeO_2**



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

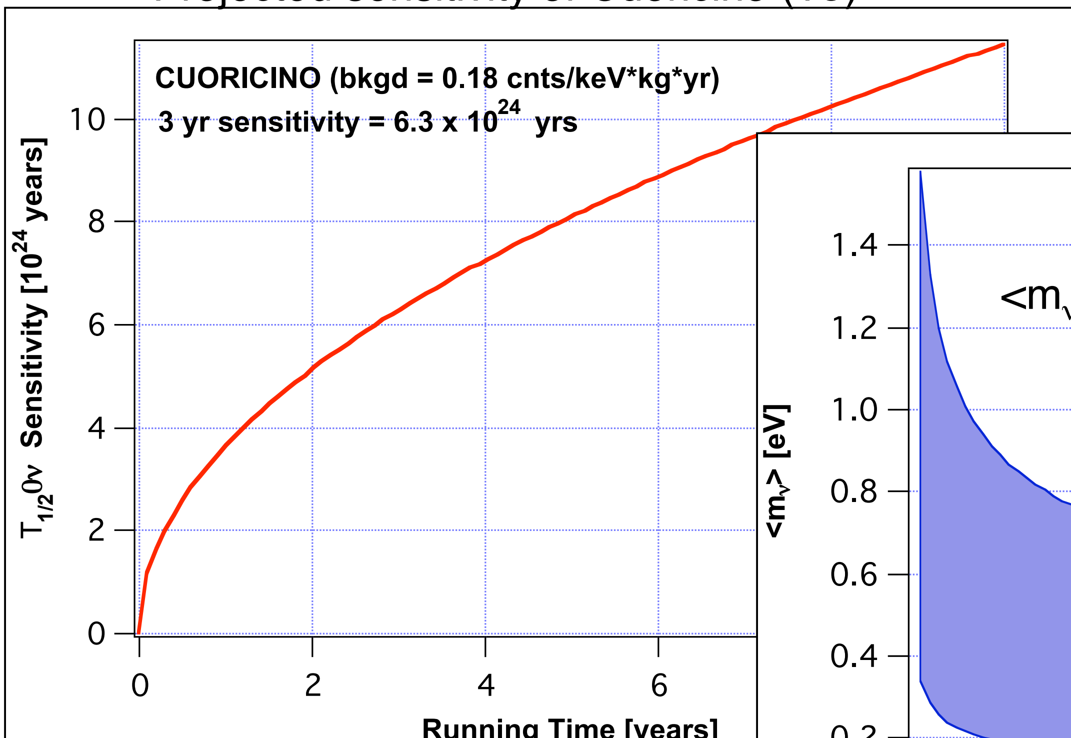


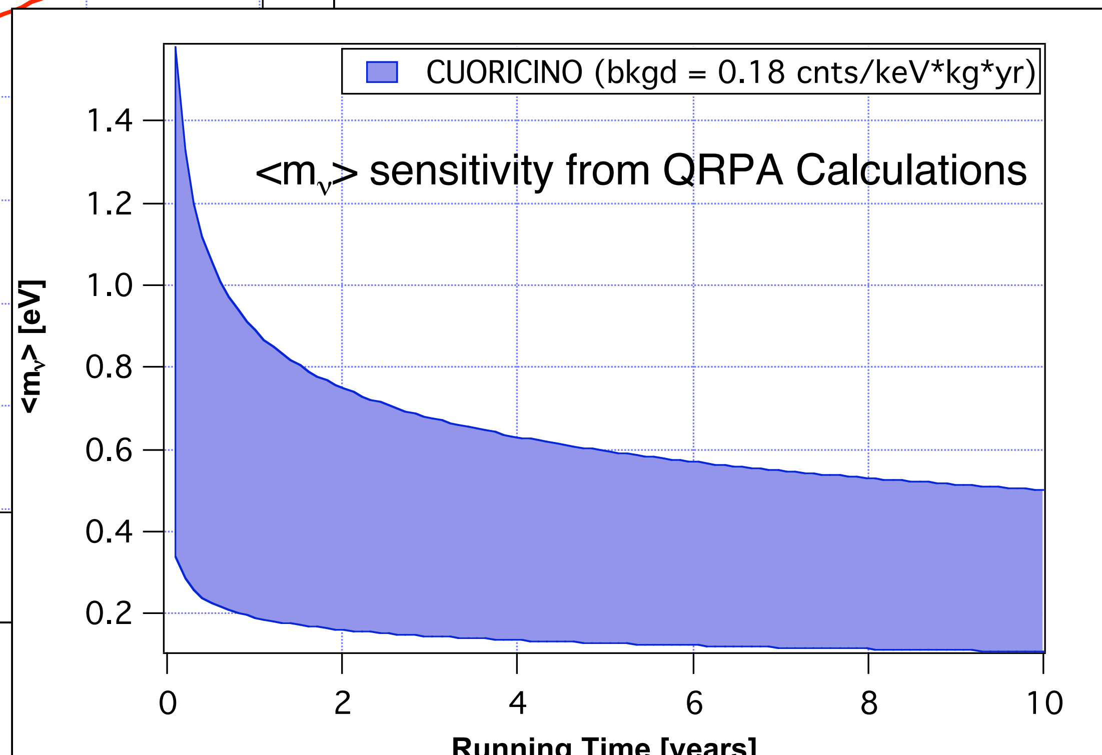


Projected Cuoricino Sensitivity

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

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)

Cuoricino Results

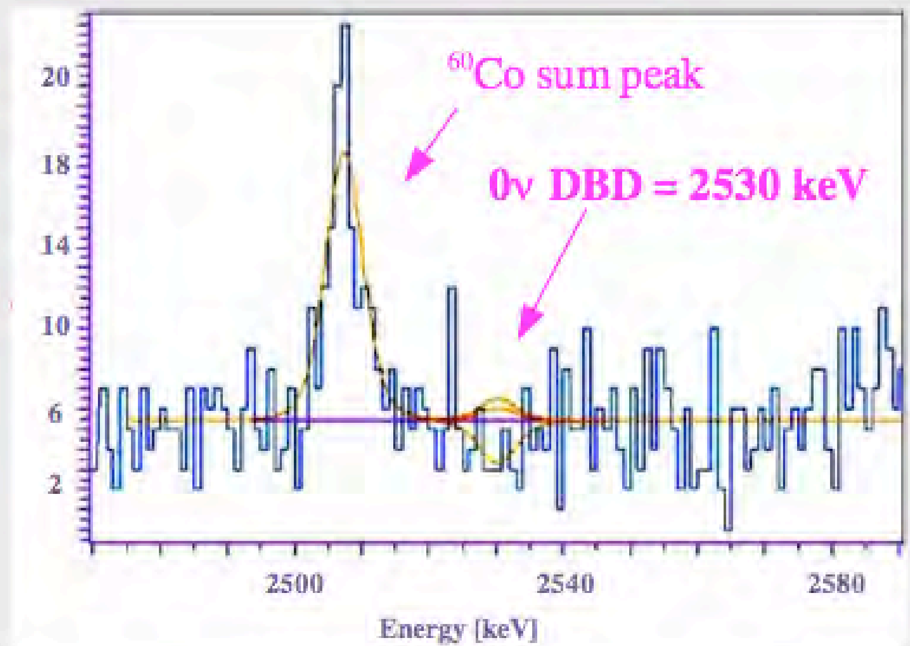
Total Exposure: **8.38 kg-y of ^{130}Te**
BKG: **0.18 ± 0.01 cnts/(keV-kg-y)**
FWHM at 2615 keV: **~ 8 keV**

April 2003 - May 2006

0ν –DBD result

$\tau_{1/2} > 2.4\ 10^{24}$ [y]

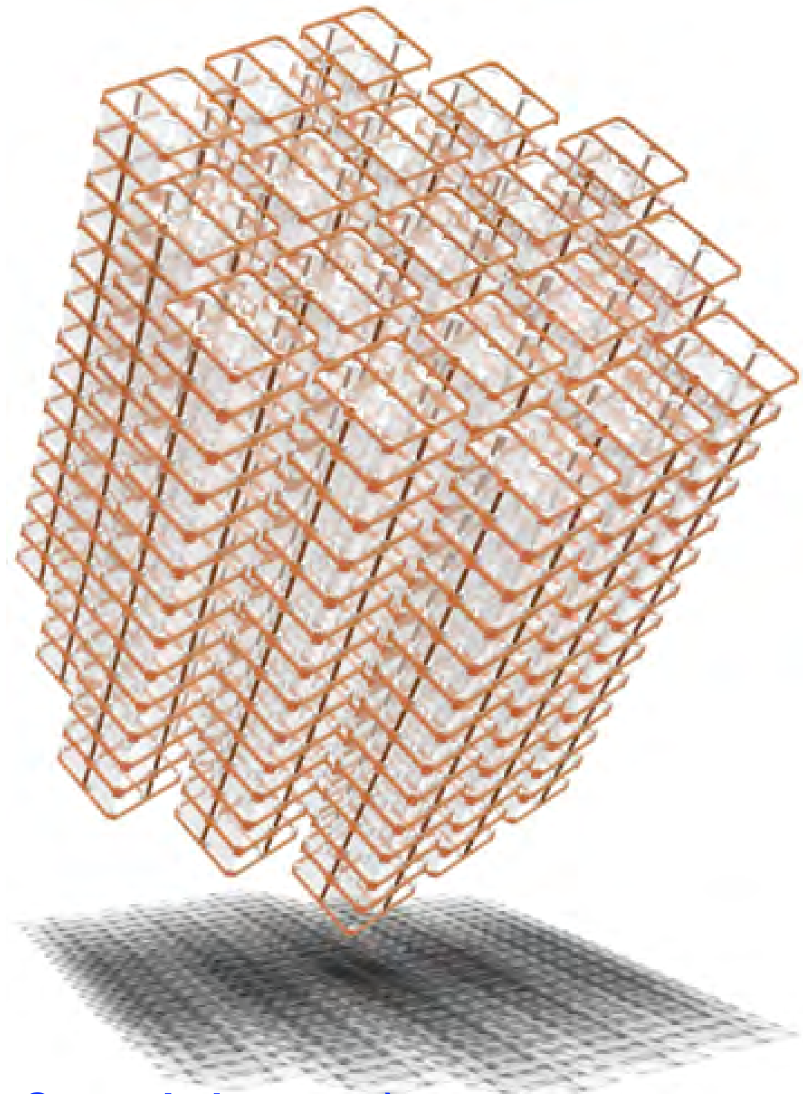
@ 90% C.L.



CUORE

Array of 988 TeO_2 crystals

- **19** Cuoricino-like towers
- **4** crystals x **13** levels per tower
- 5x5x5 cm^3 (750 g each)
- ^{130}Te: 33.8% isotope abundance
- **741 kg TeO_2 ⇒ 204 kg ^{130}Te**



Goal

background < 0.01 cnts/keV/kg/y

Resolution = 5 keV

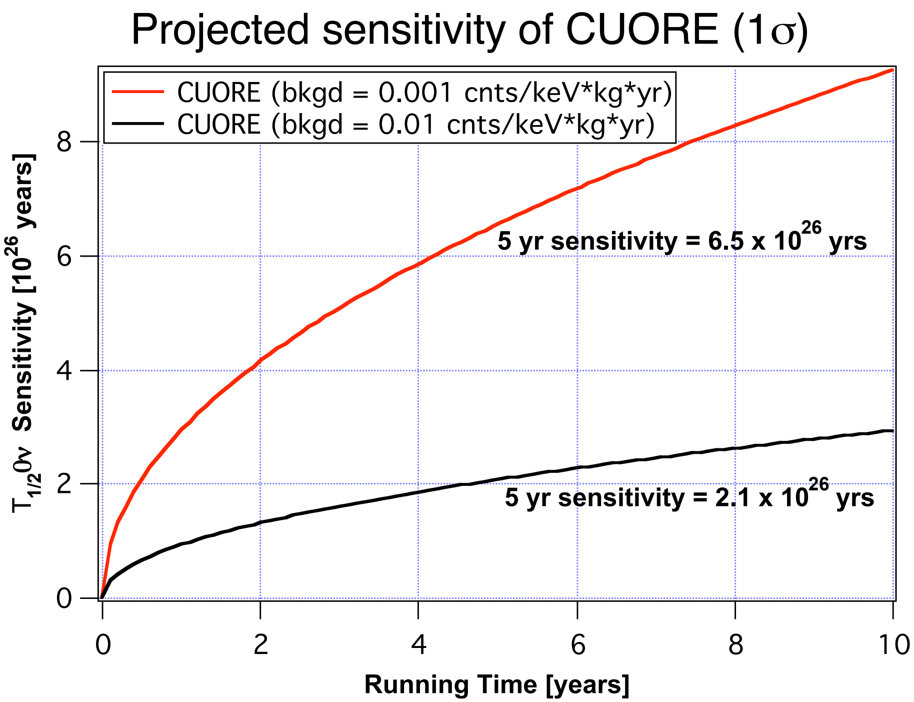
5 year sensitivity

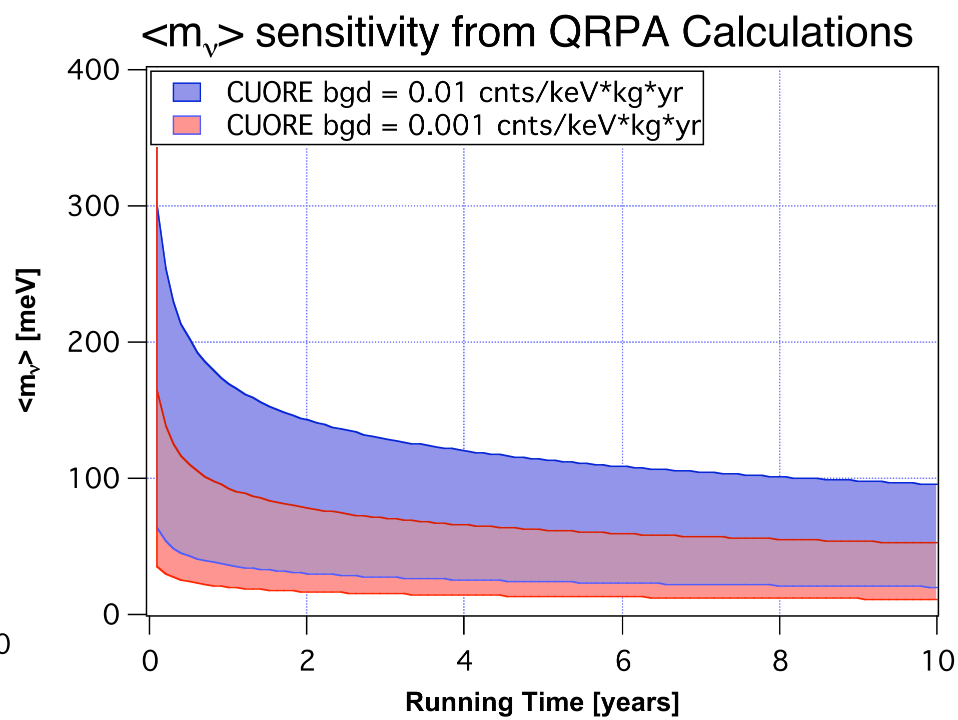
$F^{0\nu}$ > 2.1 x10^{26} y

m_{ee} < ~ 19 – 100 meV

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

CUORE Sensitivity



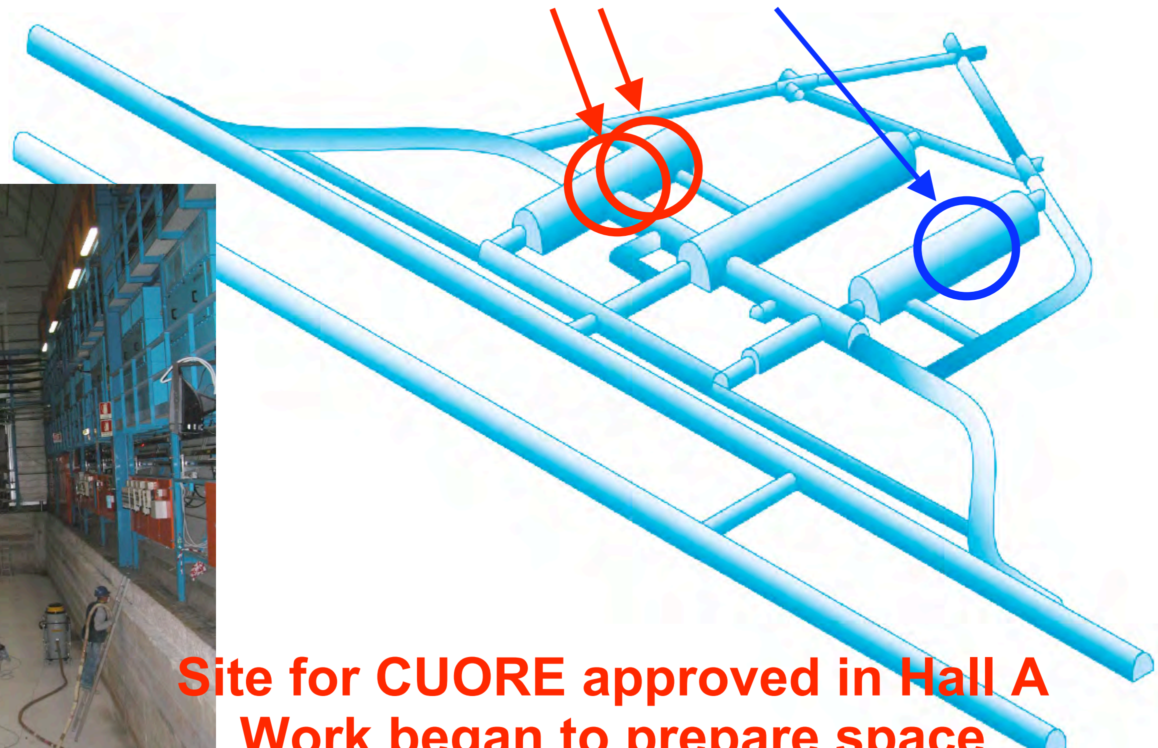


* <m> range from various QRPA calculations:
high: Rodin, Faessler, Simkovic, & Vogel Nucl. Phys. A **766** 107 (2006)
low: Staudt, Kuo & Klapdor-Kleingrothaus, PRC **46** 871 (1992)

Gran Sasso National Underground Laboratory

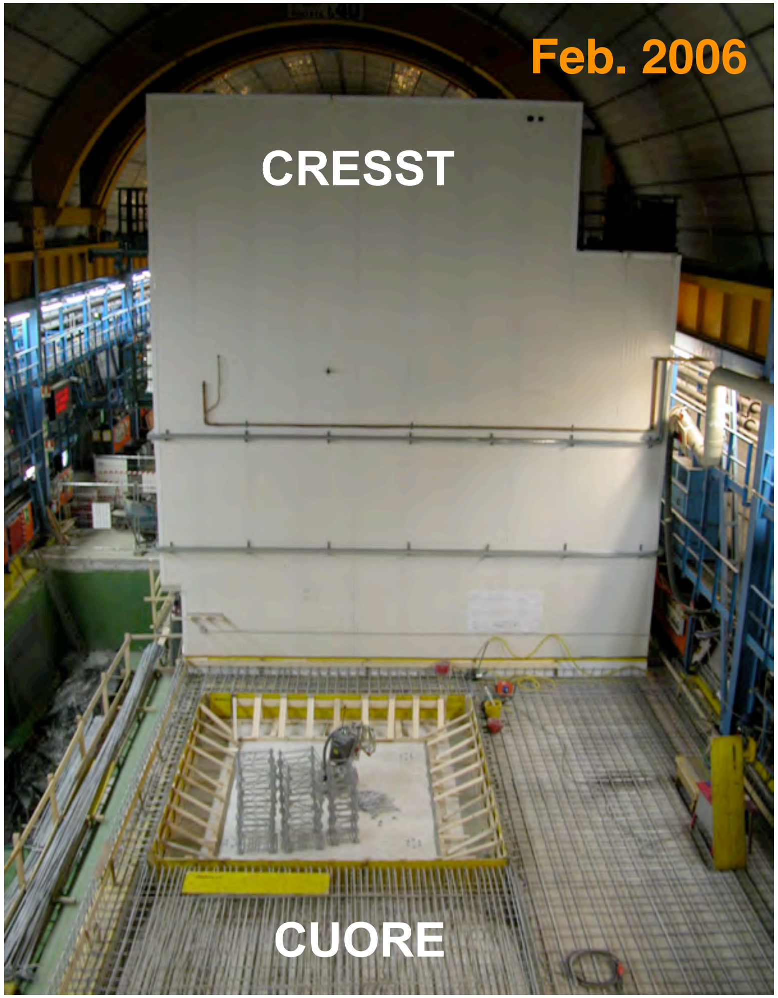
Overburden at LNGS: 3200 m.w.e

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

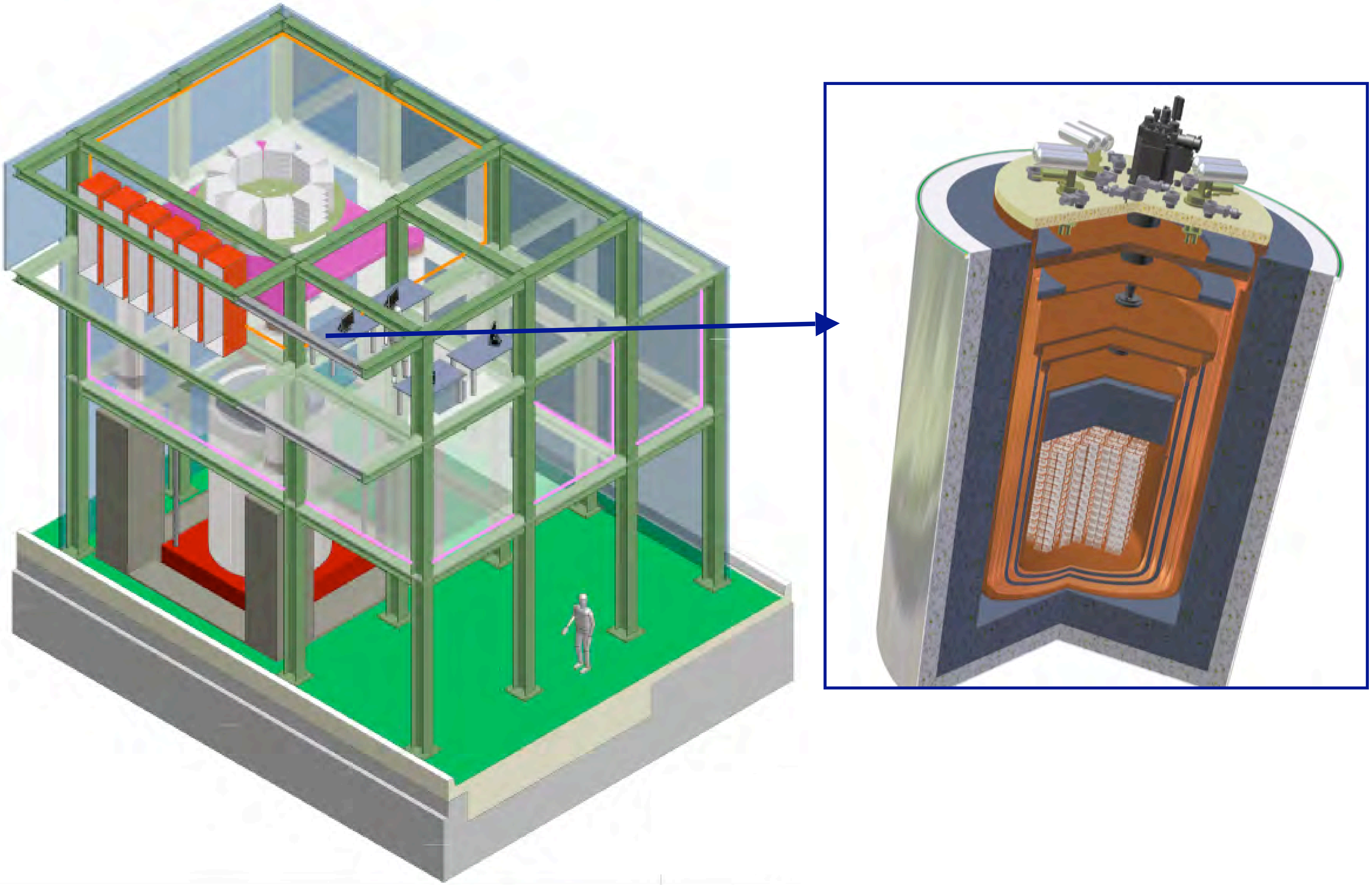


Site for CUORE approved in Hall A
Work began to prepare space

CUORE Site in Hall A at LNGS



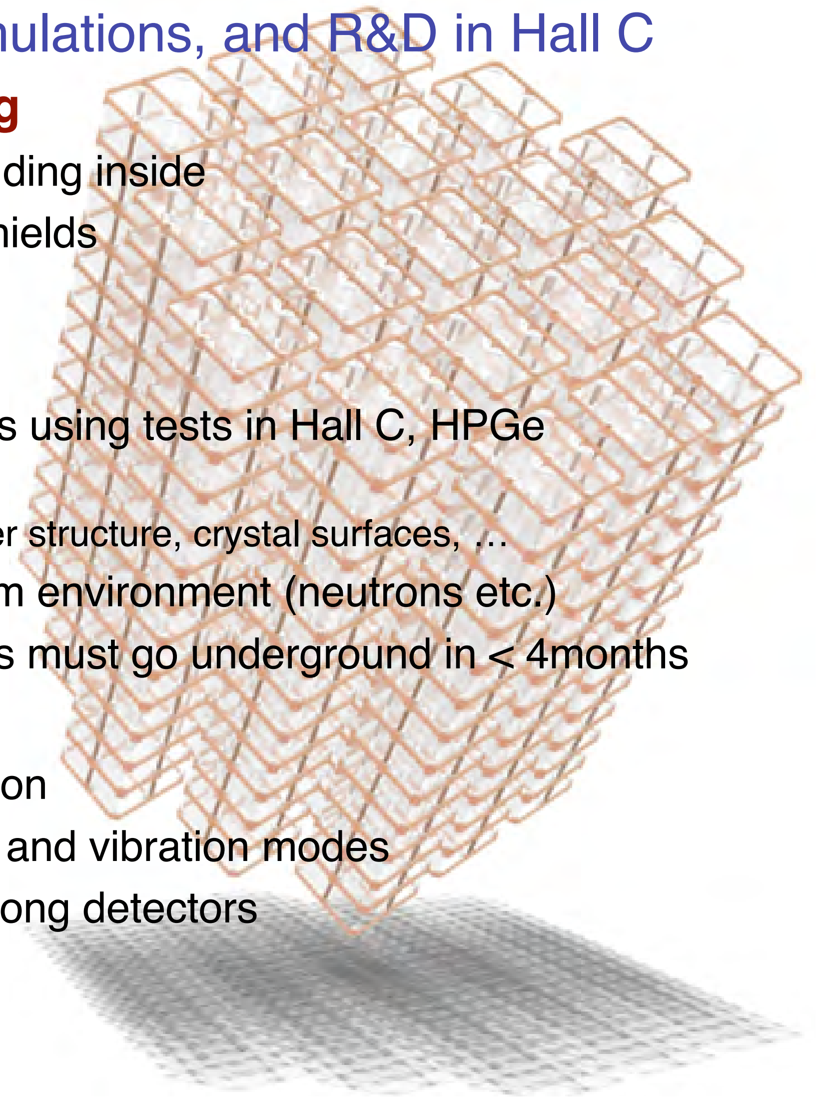
CUORE Housing and Cryostat Design



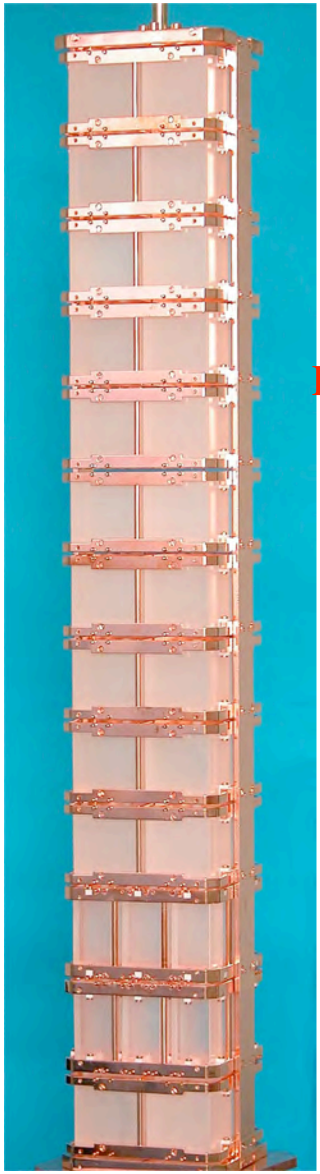
Designing CUORE

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

- **Custom designed cryostat & Shielding**
  - Need to accommodate the required shielding inside
  - Clean materials selected for dewars & shields
  - Improve reliability for higher live-time
- **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**
  - Vibration isolation and detector suspension
  - Structure designed to minimize surfaces and vibration modes
  - Uniform and better energy resolution among detectors
  - Ease of assembly

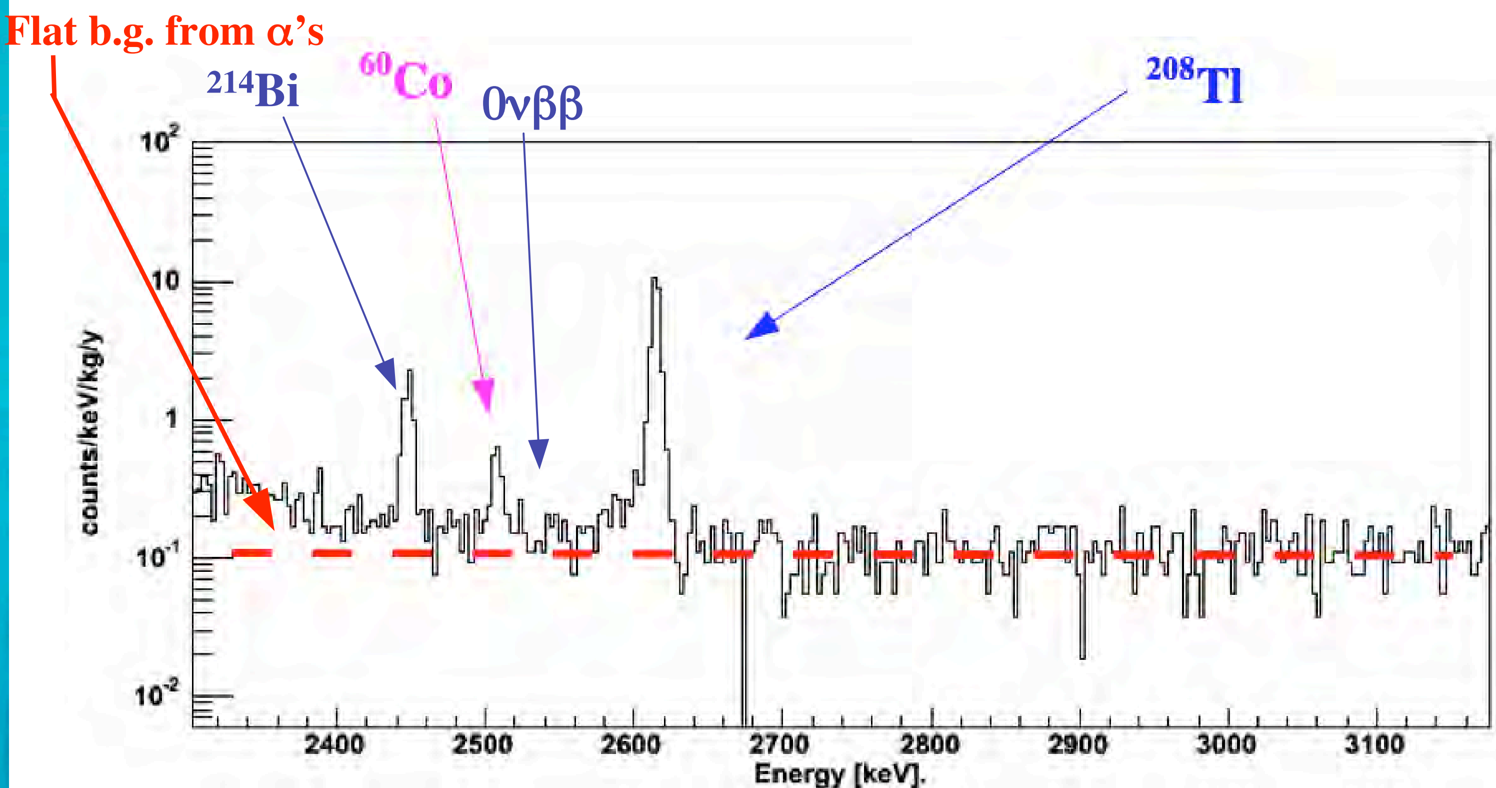


Cuoricino Background in the 0νββ Region



Cuoricino background (2520 - 2590 keV): 0.18 ± 0.01 cnts/(keV-kg-y)

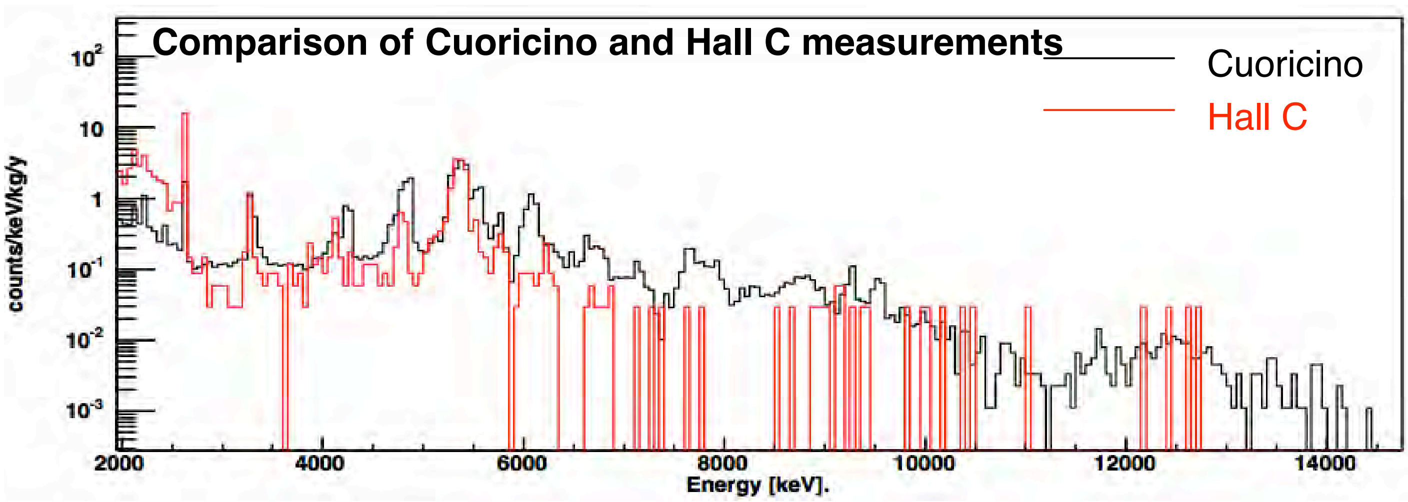
30 ± 10% from ^{208}Tl (2615 keV) Compton events from Th in cryostat shields
10 ± 5% from α's from U/Th on crystal surfaces
50 ± 20% from α's from U/Th, mainly from copper surfaces



Backgrounds: Cuoricino to CUORE

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

- < 2.6 MeV: Higher rates due to higher γ rates in Hall C cryostat than in Cuoricino. Possible to study α backgrounds only.
- > 3 MeV: Significant reduction shown
- Tested items: cleaning procedures, mounting schemes, structure design, material selections
- Factor of **4** reduction seen in crystal surface contamination, **~2** in Cu surfaces
- More tests underway to reach goal of < 0.01 c/keV/kg/yr



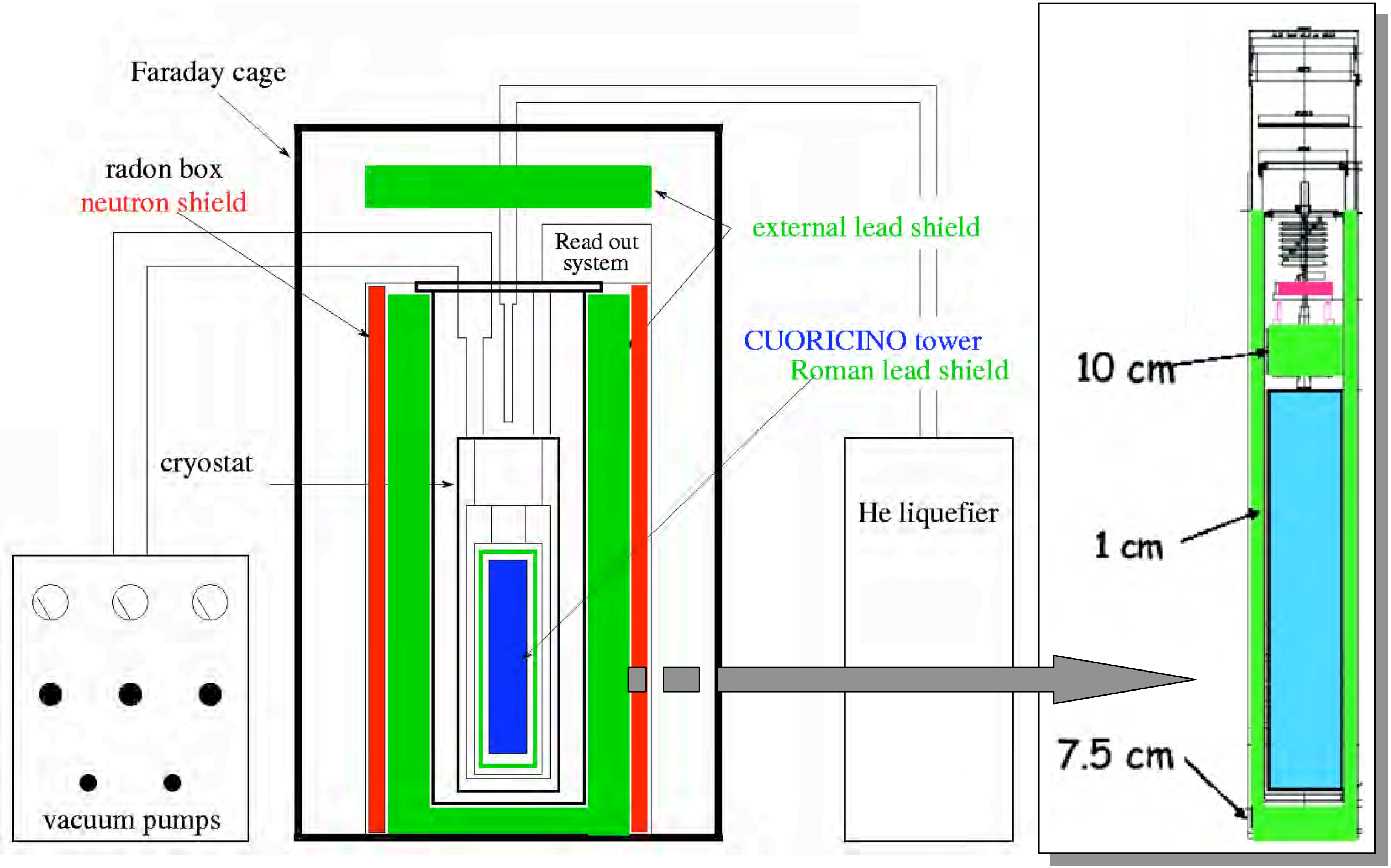
Expected Backgrounds in CUORE

Monte Carlo simulation for CUORE:

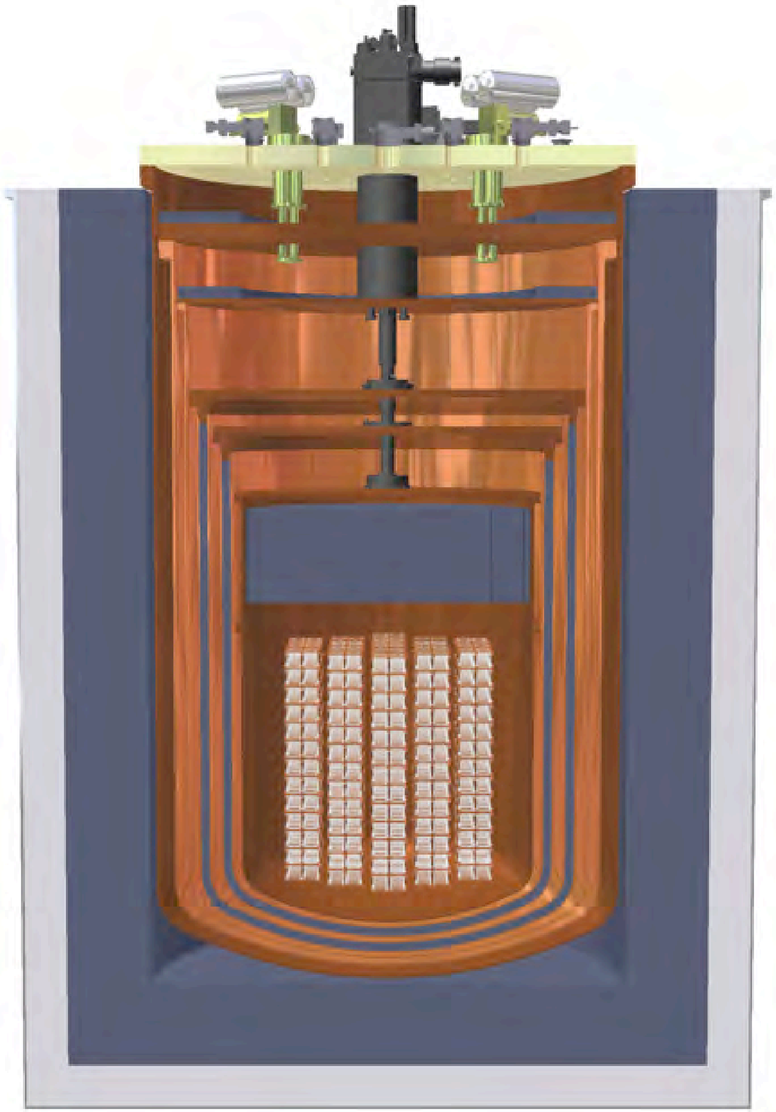
Use background levels measured in CUORICINO, HPGe counting, R&D in Hall C, ICPMS, neutron activation analysis etc.

	Source	Expected background (cnts/keV/kg/yr)
√	Outside inner Pb shield (environmental, cryostat, induced n's…)	$< 10^{-3}$
√	Internal Pb shield & Cu structure bulk	$< 10^{-3}$
√	Small parts (NTD Ge, PTFE, Au wires…)	$< 10^{-3}$
➡	Inert surfaces (e.g. Cu structure, shields)	$\sim (2\text{-}4) \times 10^{-2}$
√	TeO_2 Bulk (Hall C: measurement)	$< 10^{-4}$
√	TeO_2 Surface (Hall C: measurement)	$< 3 \times 10^{-3}$
√	$2\nu\beta\beta$	$\sim 10^{-4}$

Cuoricino Shielding



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

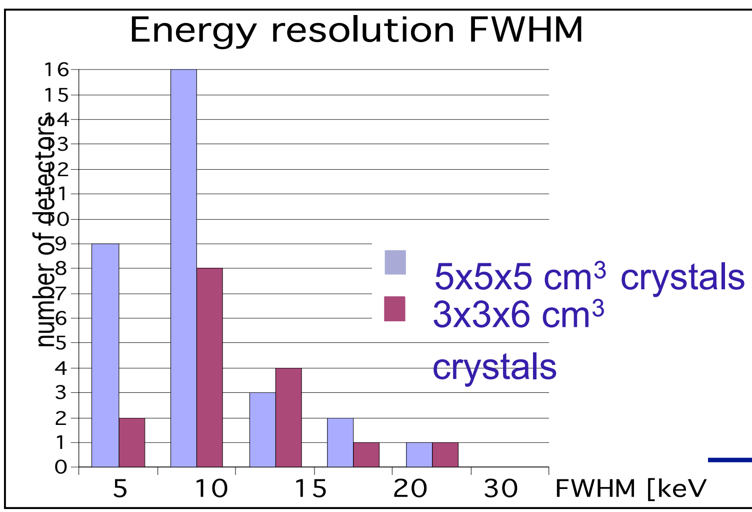
Faraday cage

- Important for near-threshold events

CUORE Detector Energy Resolution

CUORE Goal: 5 keV @ 2500 keV

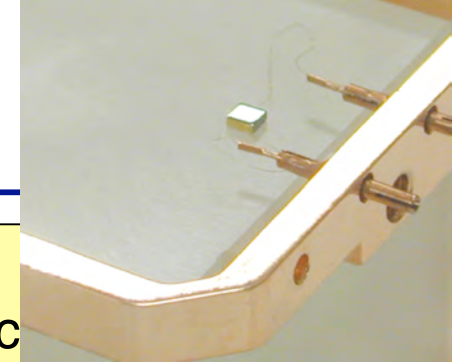
- Cuoricino's best: 3.9 keV @ 2615 keV
- All crystals: 9 keV average
- 5x5x5 cm^3 crystals: 7 keV average
- Improvements
  - Production of uniform thermistors
  - Uniform thermal coupling of crystal to thermistor
  - Better design of crystal holders
  - Improved gain stabilization through heater pulses



Resolution: 5x5x5 cm^3 crystal

0.8 keV FWHM @ 46 keV
1.4 keV FWHM @ 351 keV
2.1 keV FWHM @ 911 keV
2.6 keV FWHM @ 2615 keV (.1%)
3.2 keV FWHM @ 5407 keV

NTD Ge Thermistors



Neutron Transmutation Doped Ge Thermistors

- Developed at Berkeley by E.E. Haller (material scienc

Ge doped with Ga & As by neutron irradiation

- provides very uniform doping
- Few % variation in doping results in performance variation

Reliable, reproducible, and stable, Good energy resolution

Irradiation for CUORE thermistors underway

Nominal neutron dose

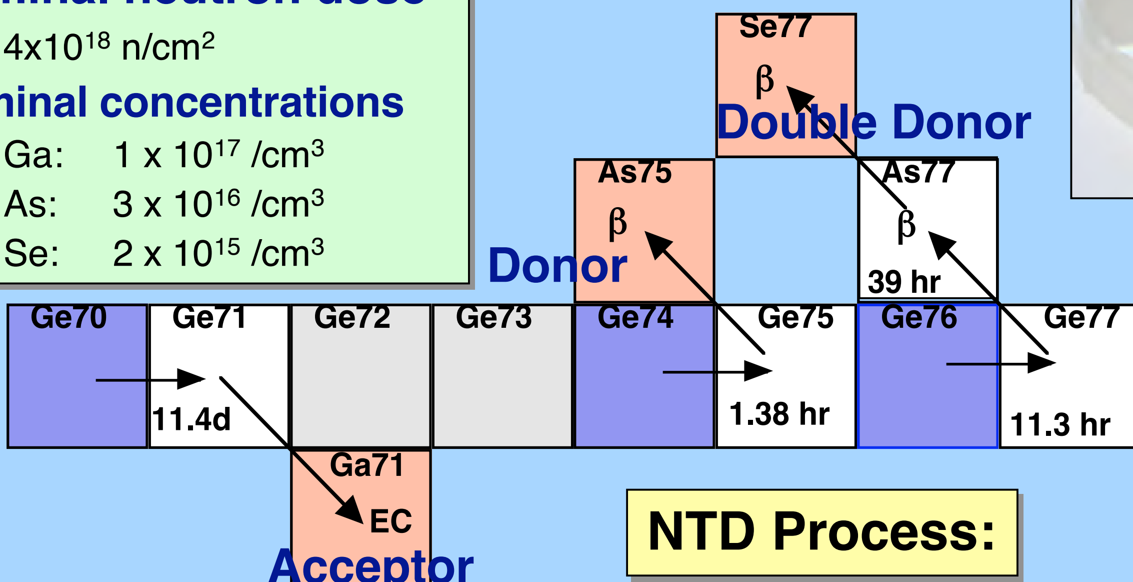
4×10^{18} n/cm^2

Nominal concentrations

Ga: 1×10^{17} /cm^3

As: 3×10^{16} /cm^3

Se: 2×10^{15} /cm^3



NTD Process:

Beyond CUORE

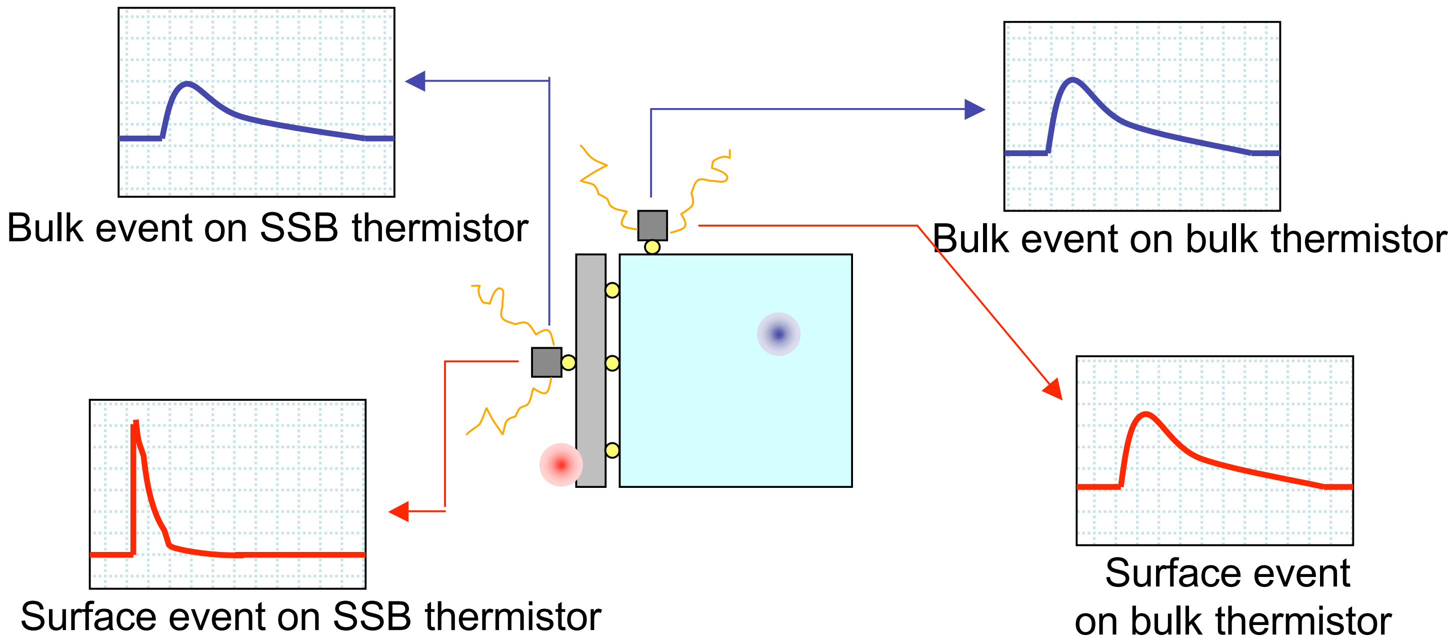
Enriched crystals for increased sensitivity

Other Isotopes (CaF_2, Ge, $PbMoO_4$, $CdWO_4$)

Possible event discrimination in bolometers

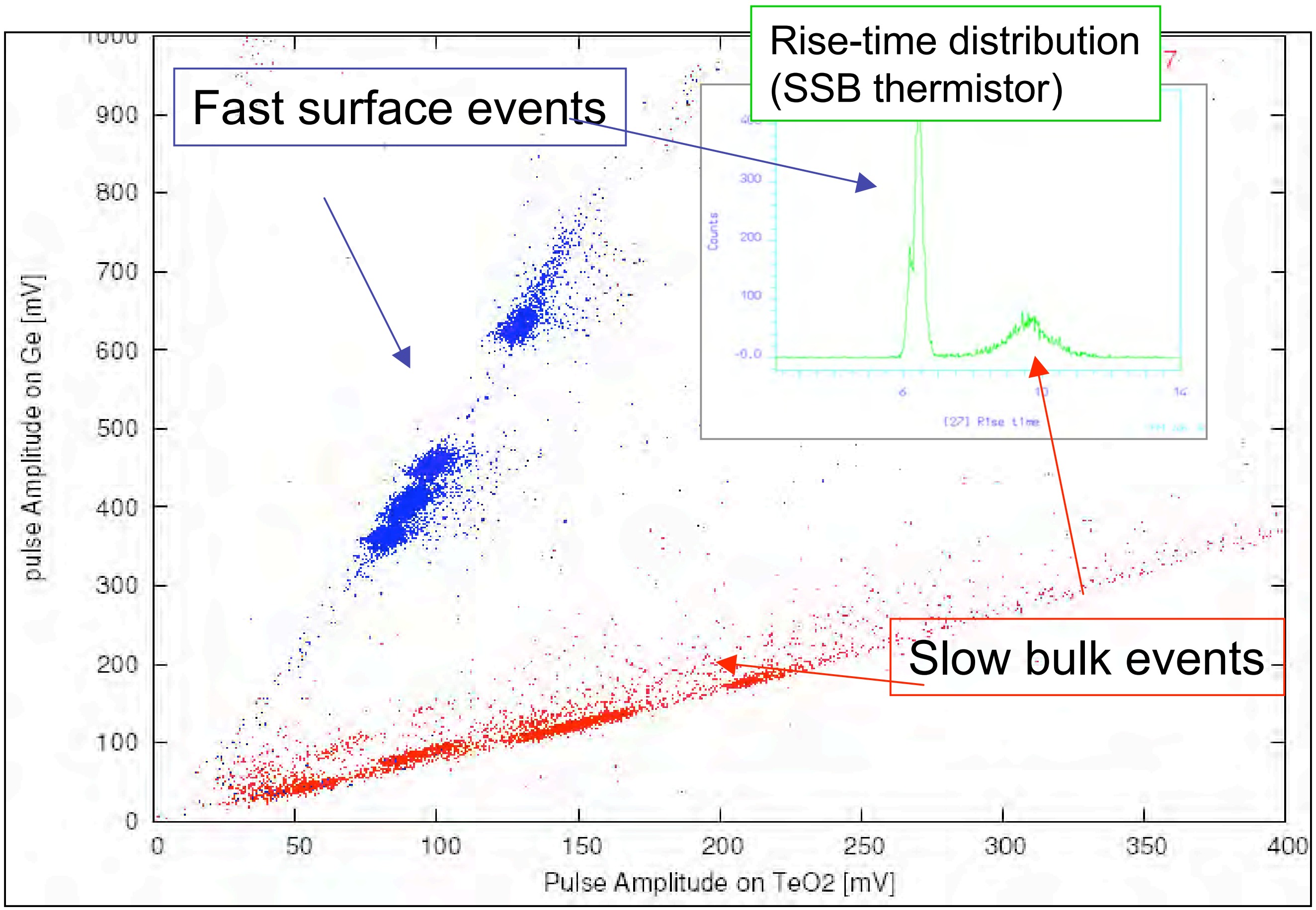
- Scintillating Crystals: use both heat and light for b.g. rejection
- Surface Sensitive Bolometers (SSB)

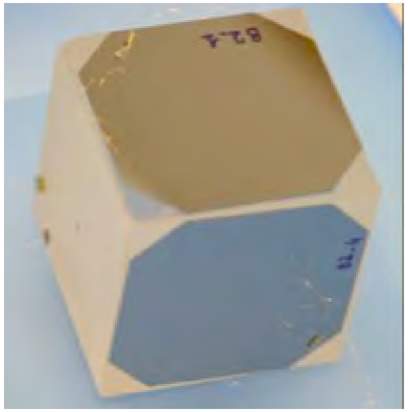
A composite bolometer with a thin crystal of TeO_2

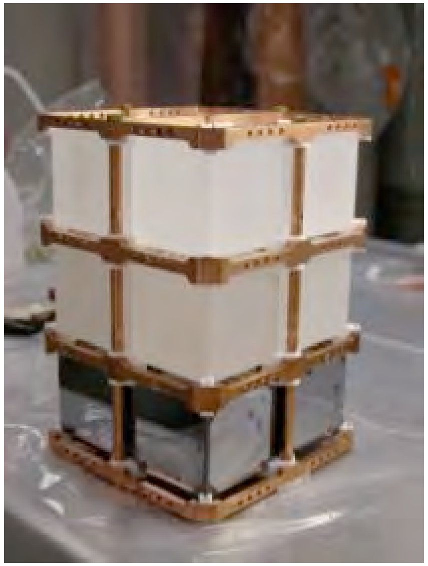


Beyond CUORE

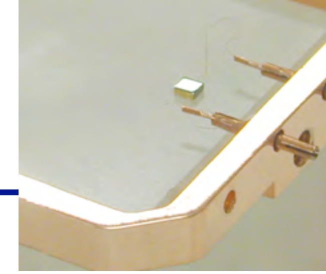
Surface Sensitive Bolometer Tests with Ge
(tests of SSB with TeO_2 underway in Gran Sasso)

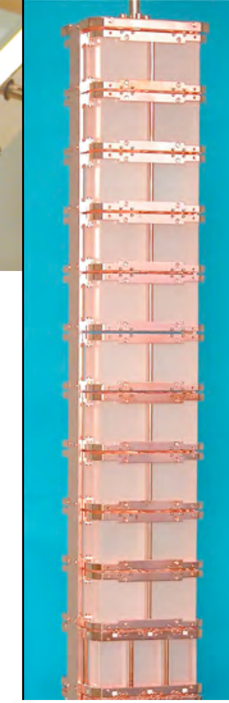




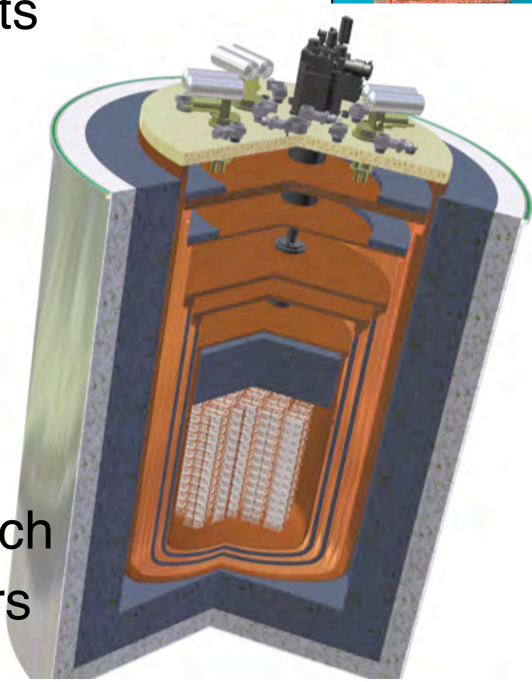


Conclusion





- 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 studies well underway
- Future…
  - isotope enrichment
  - modular design allows for multiple isotope search
  - further background reduction w/ hybrid detectors



CUORE Collaboration

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