Neutrinoless Double Beta Decay search with CUORICINO and CUORE experiments

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on behalf of the CUORE collaboration

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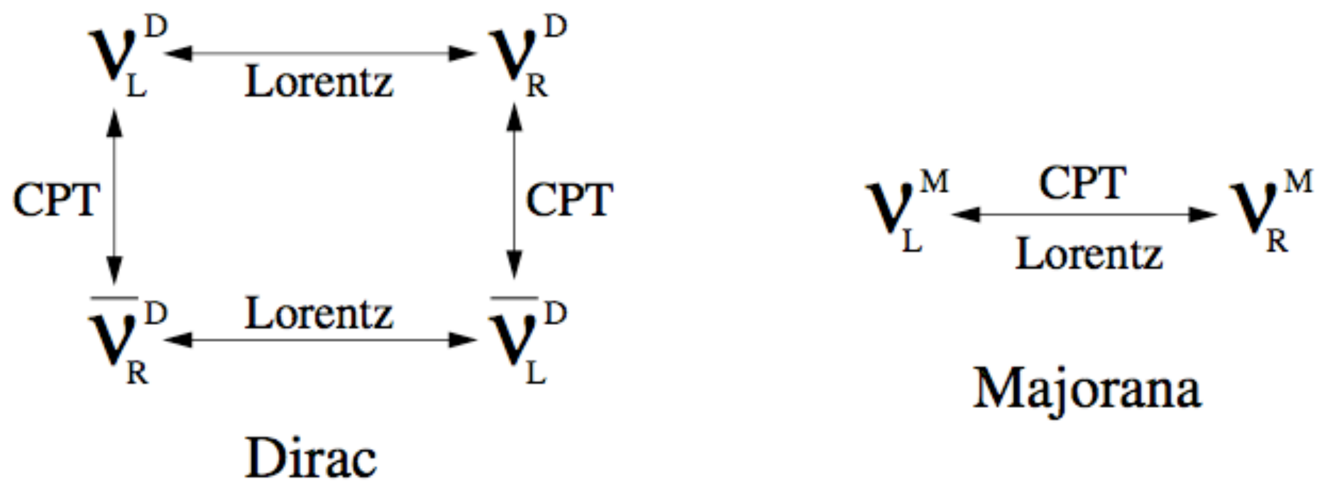
Outline

- The problem of neutrino mass and nature.
- Neutrinoless double beta decay (0νDBD), a golden probe to measure neutrino mass and nature.
- Tellurium dioxide bolometers for 0νDBD search.
- CUORICINO, an array of TeO_2 bolometers.
- CUORE: the CUORICINO successor.
- Background reduction R&D for CUORE.

Neutrino nature

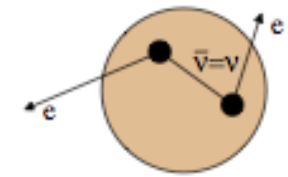
- If we discard leptonic number neutrino is a neutral fermion
- So if leptonic number is not conserved neutrinos can be Majorana particles:
    - Particle and antiparticle differs only by chirality.

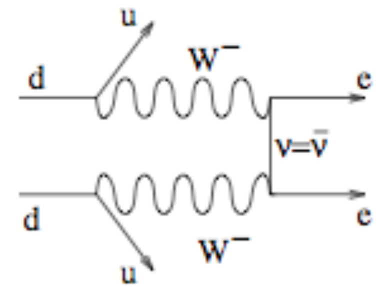


- It is still not clear today whether neutrinos are Dirac or Majorana particles.

0νDBD in Theory

- Nuclear process: (A,Z) → (A,Z+2) + 2 e^-
- Can only happen if lepton number is not conserved.
- The decay amplitude depends on the effective Majorana mass $m_{\beta\beta}$:





$$m_{\beta\beta} = \cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}$$

- The measurable quantity is the half-life ($\tau^{0\nu}_{1/2}$):

Phase space factor: ~ Q^5

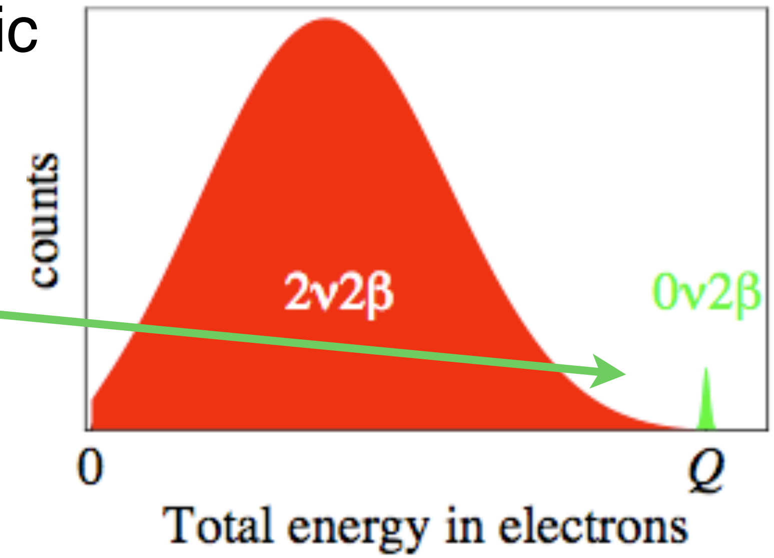
Effective neutrino mass

$$\frac{1}{(\tau^{0\nu}_{1/2})} = G(Q,Z)|M_{nucl}|^2|m_{\beta\beta}|^2 = F_N\frac{|m_{\beta\beta}|^2}{m_e^2}$$

Nuclear Matrix element

0νDBD in Experiments

- Experiments measure the sum of the kinetic energies of the two emitted electrons.
  - Signature: monochromatic line at the Q-value of the decay.
- Sensitivity ($S^{0\nu}$): lifetime corresponding to the minimum number of detectable events above background at a given C.L.:



$$S^{0\nu} = \ln 2 N_A \cdot \frac{a}{A} \left(\frac{Mt}{B \Delta E} \right)^{1/2} \cdot \epsilon$$

Isotopic abundance → a

Detector mass (kg) → M

Measurement time (y) → t

Efficiency → ϵ

Atomic mass → A

Background (counts/KeV/Kg/y) → B

Energy Resolution (KeV) → ΔE

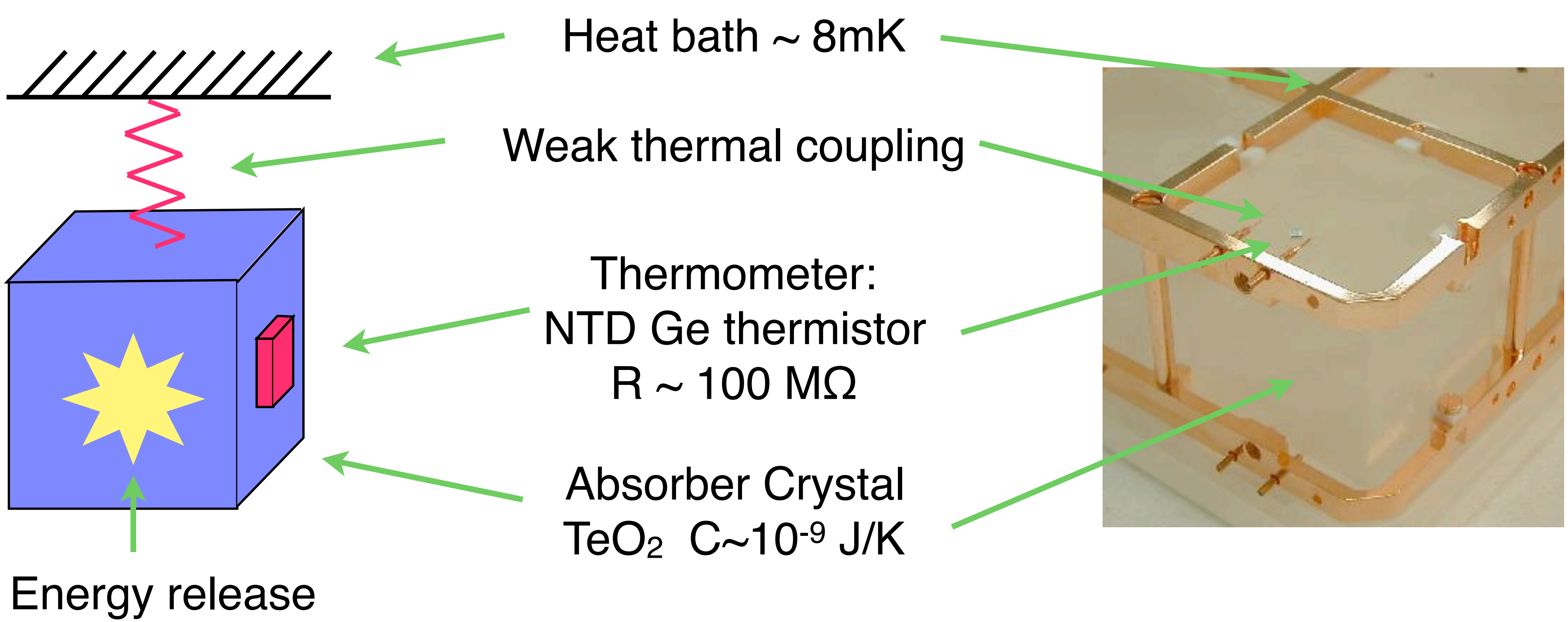
0νDBD with Tellurium

- Active isotope: ^{130}Te, Decay: $^{130}Te \rightarrow {}^{130}Xe + 2\, e^-$
- Natural abundance: 33.9 % → no need for enrichment
- Q-value = 2530 KeV → reasonably high: leads to high phase space and is almost above natural radioactivity background.
- 2β emitters of experimental interest:

Parent Isotope	$F_N (y^{-1})$	$Q_{\beta\beta}$ (KeV)	Ab(%)
^{48}Ca	$(5.4^{+3.0}_{-1.4}) \cdot 10^{-14}$	4271	0.187
^{76}Ge	$(7.3 \pm 0.6) \cdot 10^{-14}$	2039	7.8
^{82}Se	$(1.7^{+0.4}_{-0.3}) \cdot 10^{-13}$	2995	9
^{100}Mo	$(5.0 \pm 0.15) \cdot 10^{-13}$	3034	9.6
^{116}Cd	$(1.3^{+0.7}_{-0.3}) \cdot 10^{-13}$	2902	7.5
^{130}Te	$(4.2 \pm 0.5) \cdot 10^{-13}$	2530	33.9
^{136}Xe	$(2.8 \pm 0.4) \cdot 10^{-14}$	2479	8.9
^{150}Nd	$(5.7^{+1.0}_{-0.7}) \cdot 10^{-12}$	3367	5.6

Bolometric technique

- Particle energy converted into phonons → temperature variation.
- TeO_2 crystals (dielectric, diamagnetic) → detector = source
- Low crystal heat capacity and low base temperature to see small temperature variations. → $\Delta T \sim E/C$



- Detector response in this configuration: ~ 0.2 mK / MeV
- Resolution @0νDBD ~ 0.3% FWHM

Bolometer signal

- The thermistor resistance depends on its temperature:

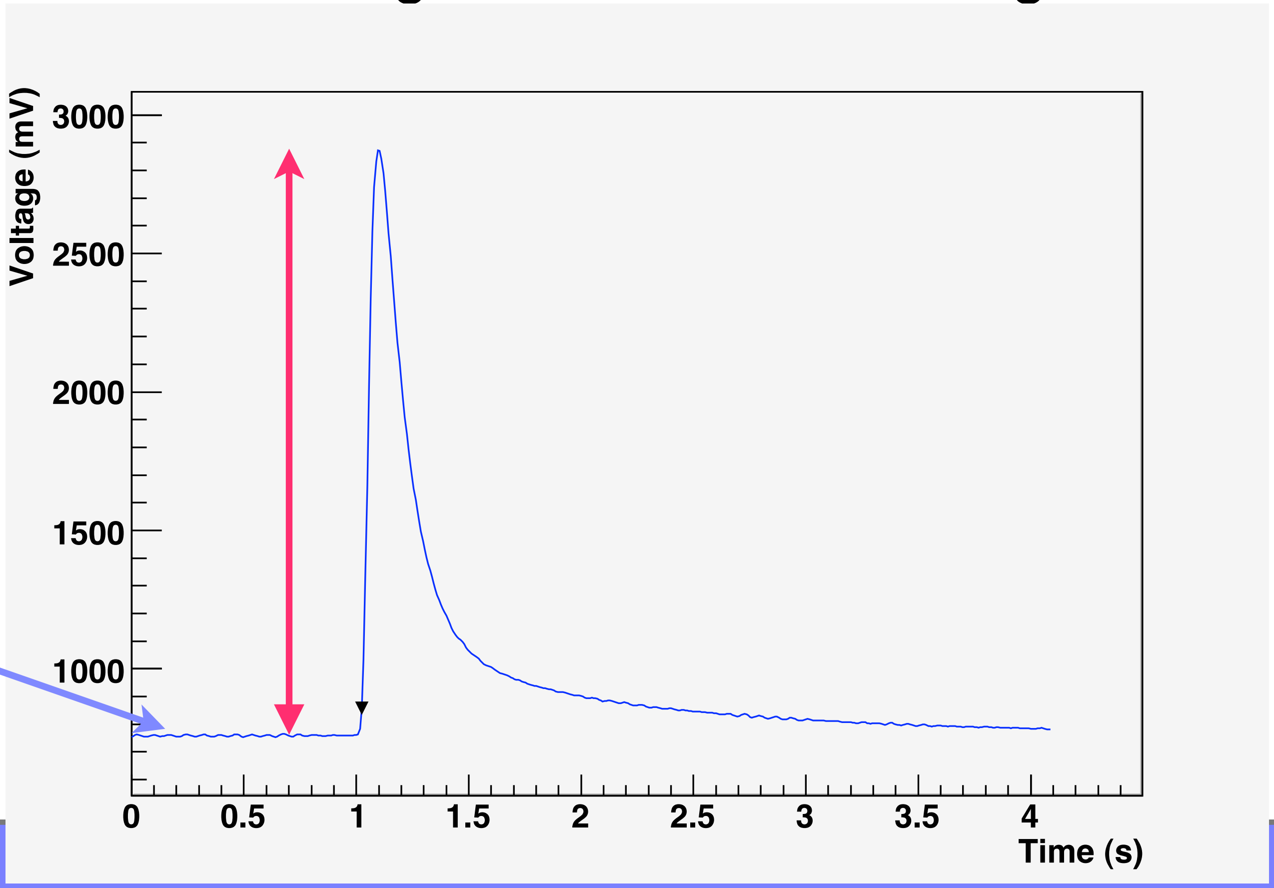
$$R(T) = R_0 e^{\left(\frac{T_a}{T}\right)^\gamma}$$

typical parameters are $R_0 = 1.5\ \Omega$, $T_a = 3$ K and $\gamma = 1/2$.

- When energy is released in the crystal the temperatures varies and the variation of the resistance in time gives a measurable signal:

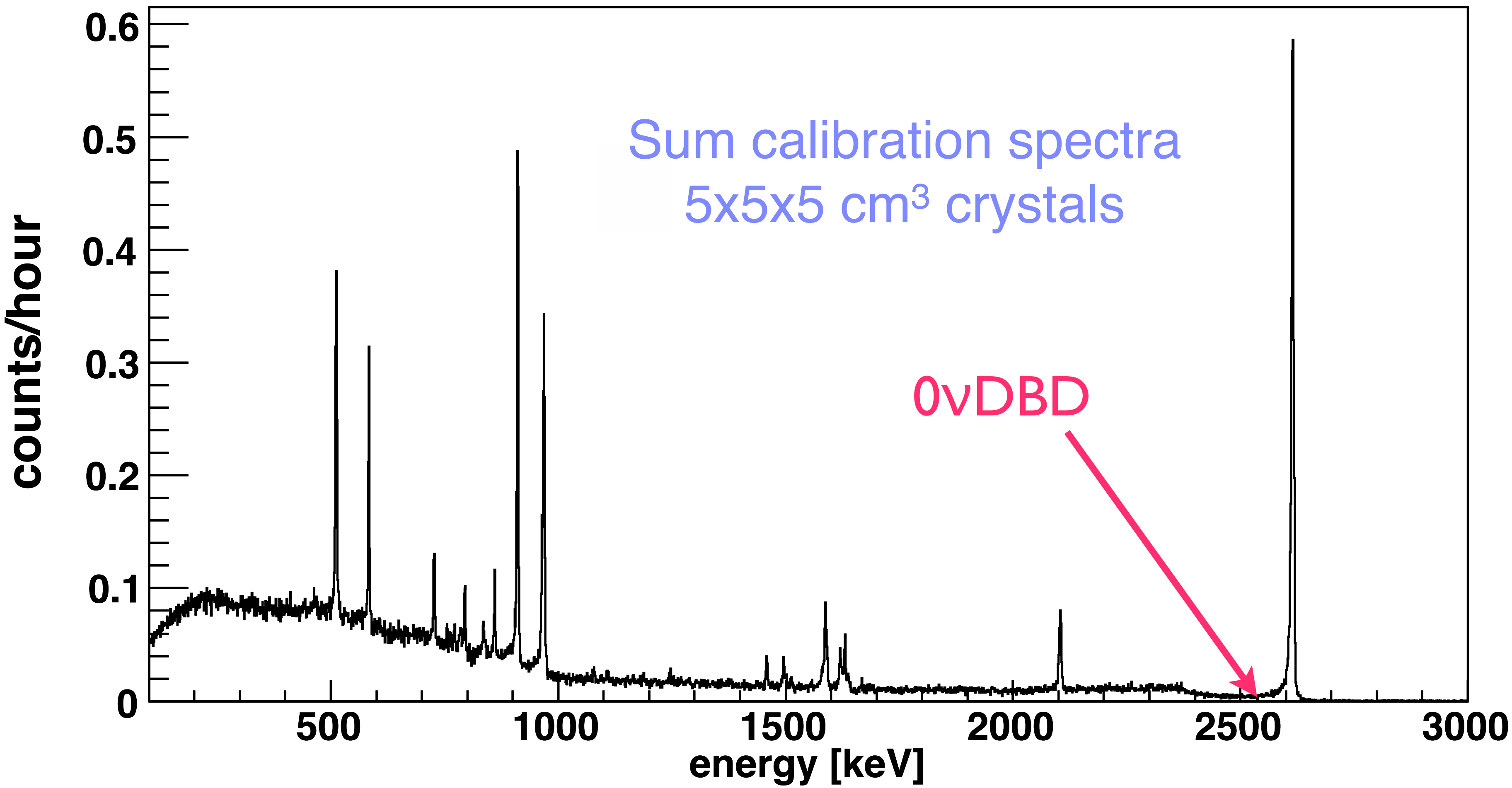
Pulse amplitude related to the energy released into the crystal

Baseline related to the base temperature ($T_0 \sim 10$ mK)



Energy resolution

- Calibration spectra: ^{232}Th source (3 days measurement every month)
- Average FWHM @ 2615 keV (^{208}Tl γ line) = 7.5 keV



Cuoricino

Hosted @ Laboratori Nazionali del Gran Sasso, Italy.
A natural shield of 1500 m of rock (3500 m.w.e.)

Active mass:

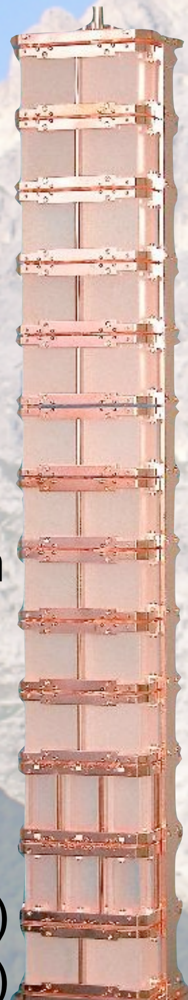
- TeO_2: 40.7 Kg
- ^{130}Te: 11.3 Kg
- ^{128}Te: 10.5 Kg

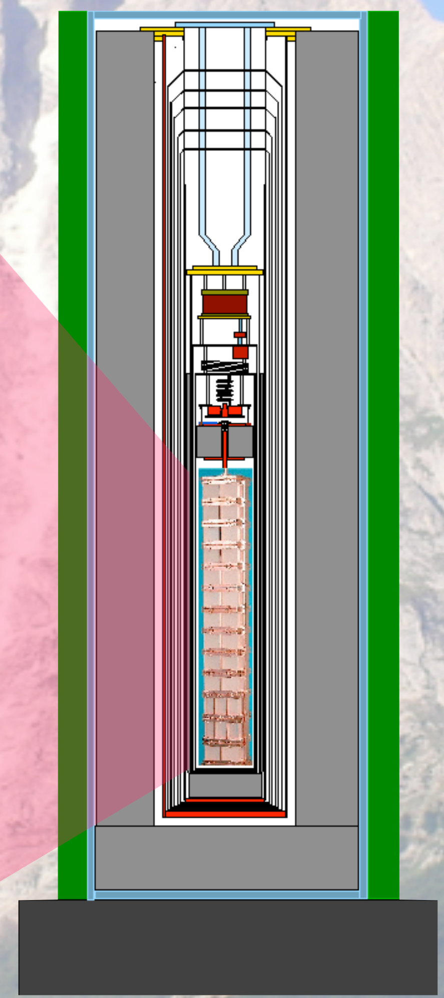
11 modules:

- 4 detectors of
  5x5x5 cm^3 = 790 g each

2 modules:

- 9 detectors of
  3x3x6 cm^3 = 330 g each
  2 enriched in ^{128}Te (82%)
  2 enriched in ^{130}Te (75%)





Installed in a dilution refrigerator:

- Inner shield:
  - 1cm Roman Pb
    A (^{210}Pb) < 4 mBq/Kg
- External Shield:
  - 20 cm Pb
  - 10 cm Borated polyethylene
- Nitrogen flushing to avoid Rn contamination.

Data taking ended at the beginning of June!

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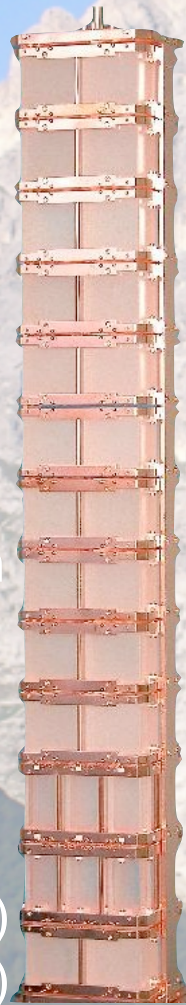

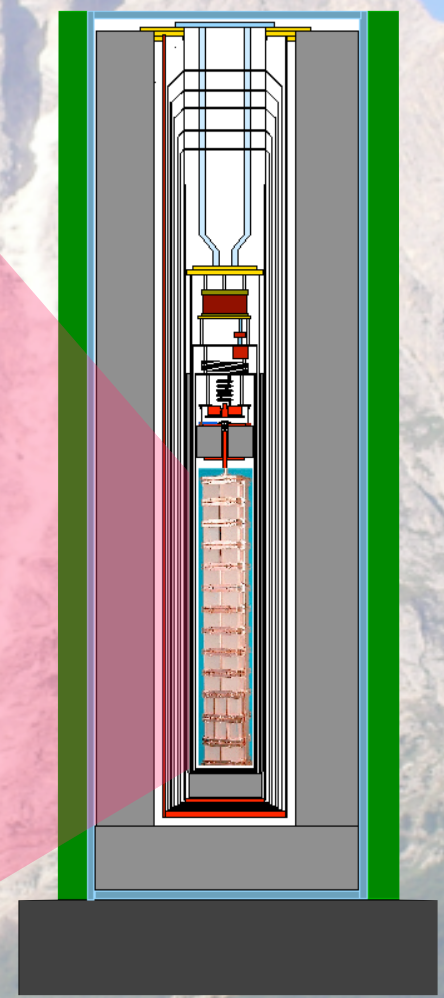

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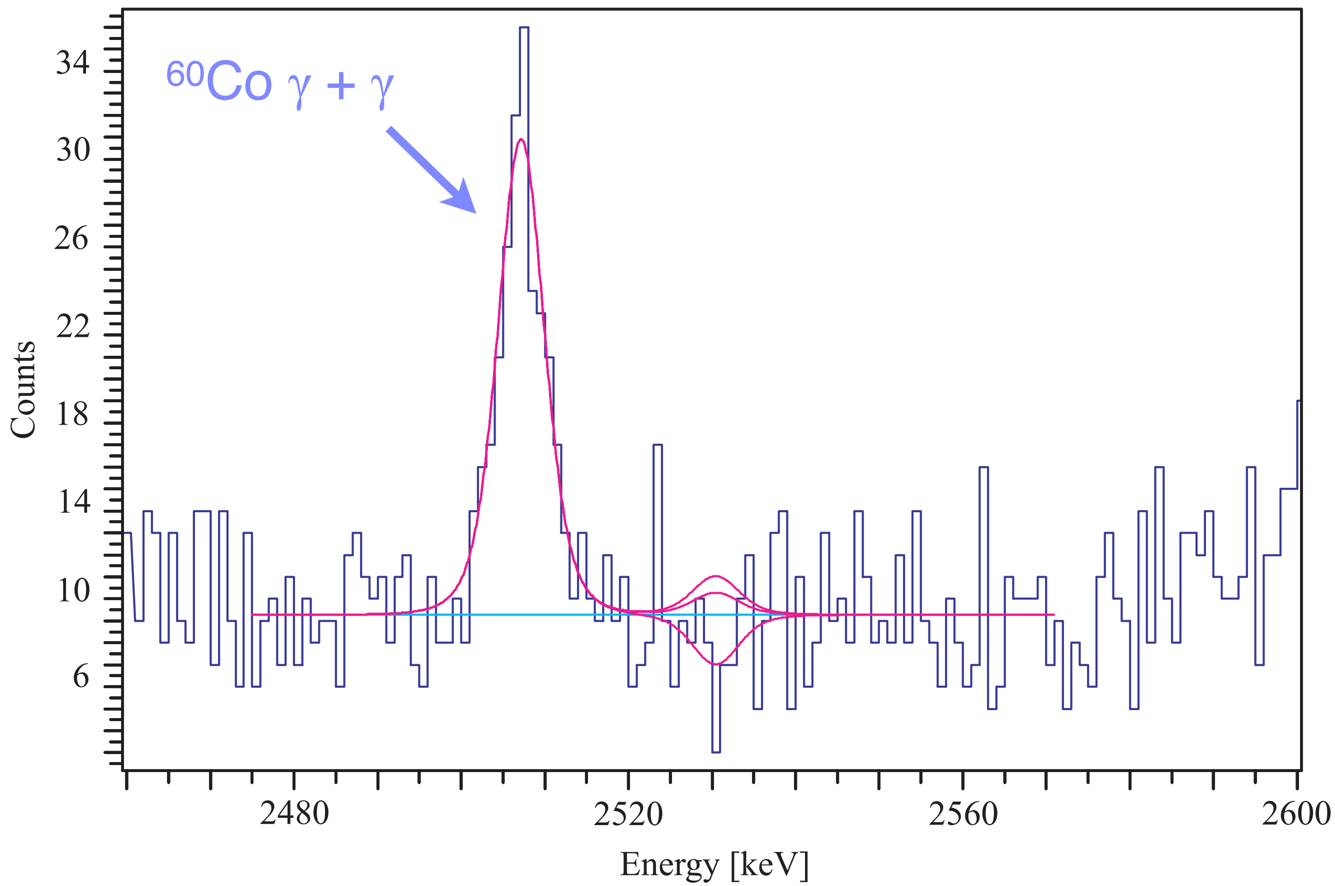
Cuoricino Result

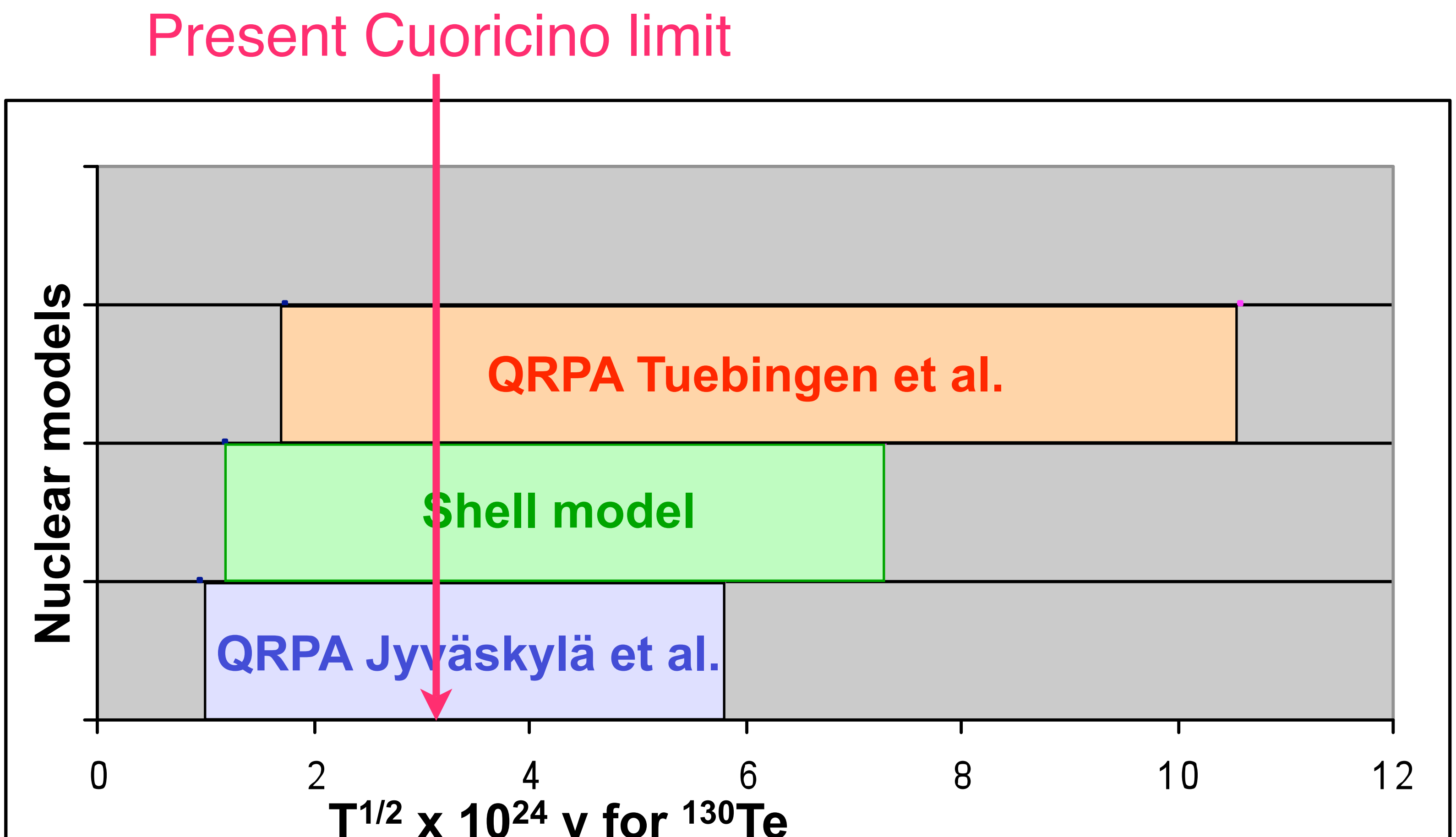
- Analyzed statistics (Aug '07): $M \cdot t = 15.53 \text{ Kg } ^{130}\text{Te} \cdot \text{y}$
- Background level: $b = 0.18 \pm 0.01 \, (\text{c/keV/kg/y})$
- 0νDBD Half-life limit (90% C.L): $\tau^{0\nu}_{1/2} > 3.1 \cdot 10^{24} \text{ y}$
- Effective neutrino mass limit: $m_{\beta\beta} < 0.20 \div 0.68 \, \text{eV}$



Cuoricino vs HM-KK claim

- Express the ^{130}Te 0νDBD half-life in terms of the ^{76}Ge half-life measured by HM-KK

$$T^{0\nu}_{1/2}(^{130}\mathrm{Te}) = \frac{T^{0\nu}_{1/2}(\mathrm{HM-KK})}{\frac{G^{0\nu}_{^{130}\mathrm{Te}}}{G^{0\nu}_{^{76}\mathrm{Ge}}} \cdot \left| \frac{M^{0\nu}_{^{130}\mathrm{Te}}}{M^{0\nu}_{^{76}\mathrm{Ge}}} \right|^2}$$



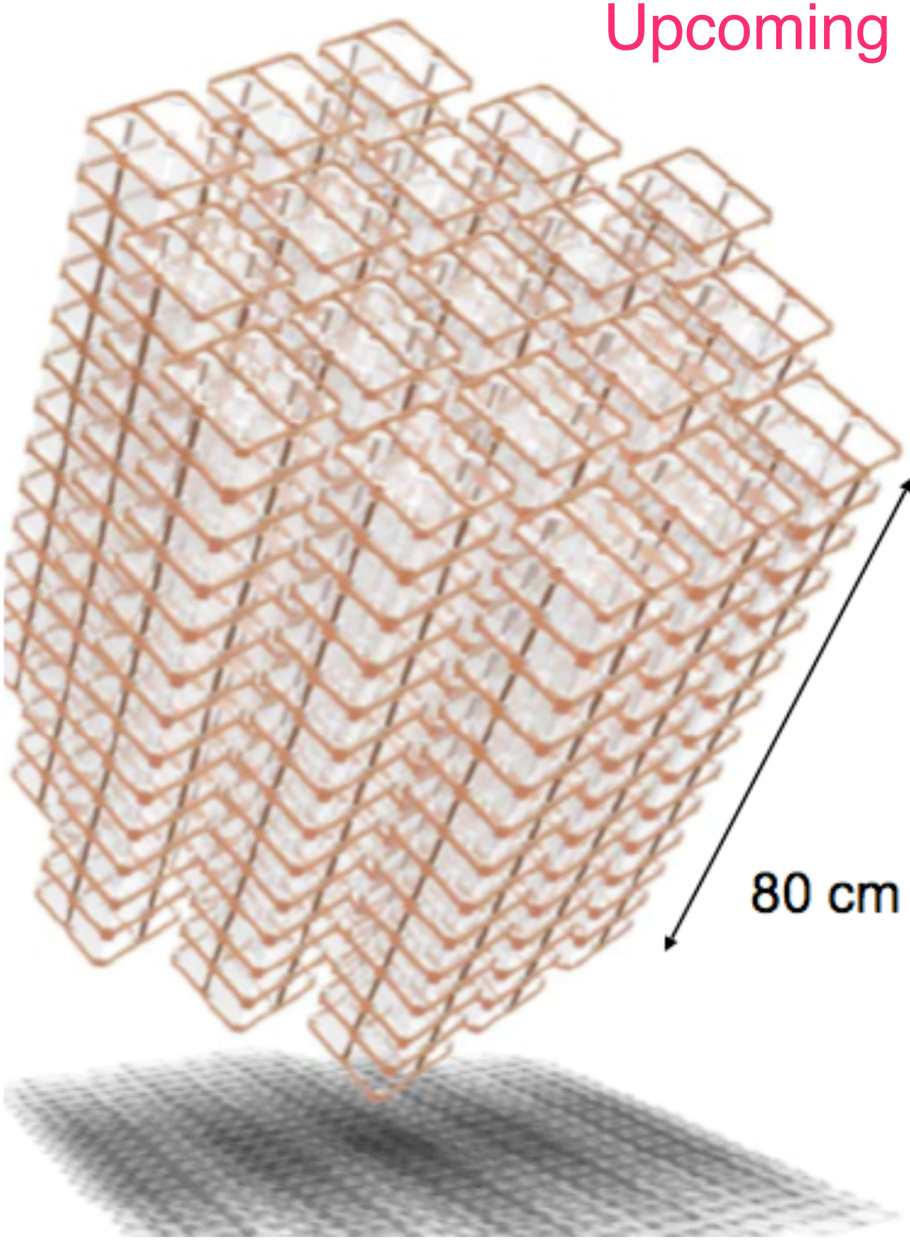
QRPA TBC group: Nucl. Phys. A 766 (2006) 107 and Erratum:Nuclear Physics A 79 (2007) 213;

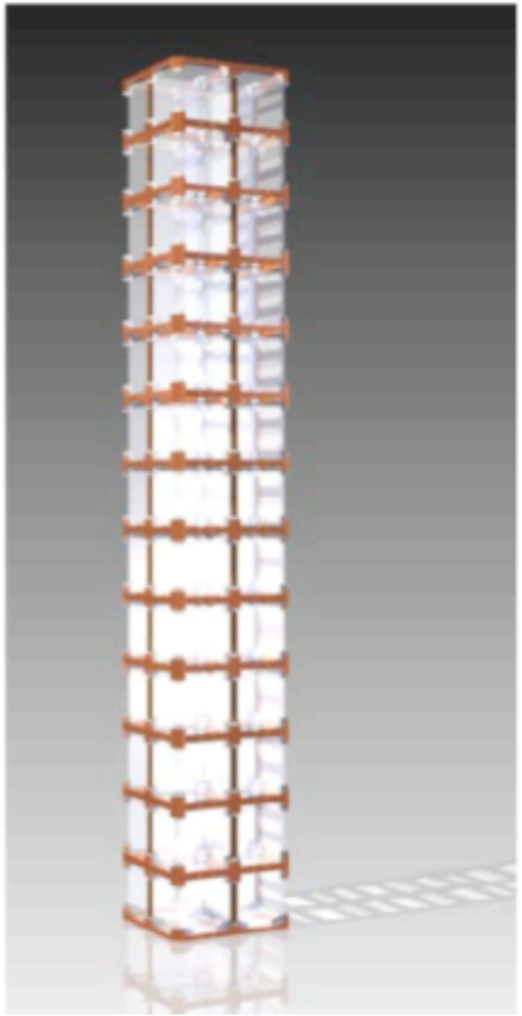
Shell model: arXiv:0809.2183v1

QRPA Jyväskylä group: AIP Conf.Proc. 972:128-136,2008

CUORE

Upcoming new experiment: 19 times CUORICINO





- 988 TeO_2 crystals
- 19 towers of 52 crystals each
- 741 Kg Te
- 203 Kg ^{130}Te
- Start in 2012

CUORE hut

CUORE Sensitivity

- Our ability to explore the inverted hierarchy depends on the background level and on the resolution, consider two scenarios:

5 y sensitivity (1σ) with conservative assumptions:

B = 0.01 counts/(keV kg y)

FWHM = 5 keV

→ $S^{0\nu} = 2.1 \cdot 10^{26}$ y

→ $m_{\beta\beta} < 20 \div 100$ meV

5 y sensitivity (1σ) with optimistic assumptions:

B = 0.001 counts/(keV kg y)

FWHM = 5 keV

→ $S^{0\nu} = 6.5 \cdot 10^{26}$ y

→ $m_{\beta\beta} < 11 \div 60$ meV

- CUORE present R&D is focused on background reduction.

Where we are and where we will be

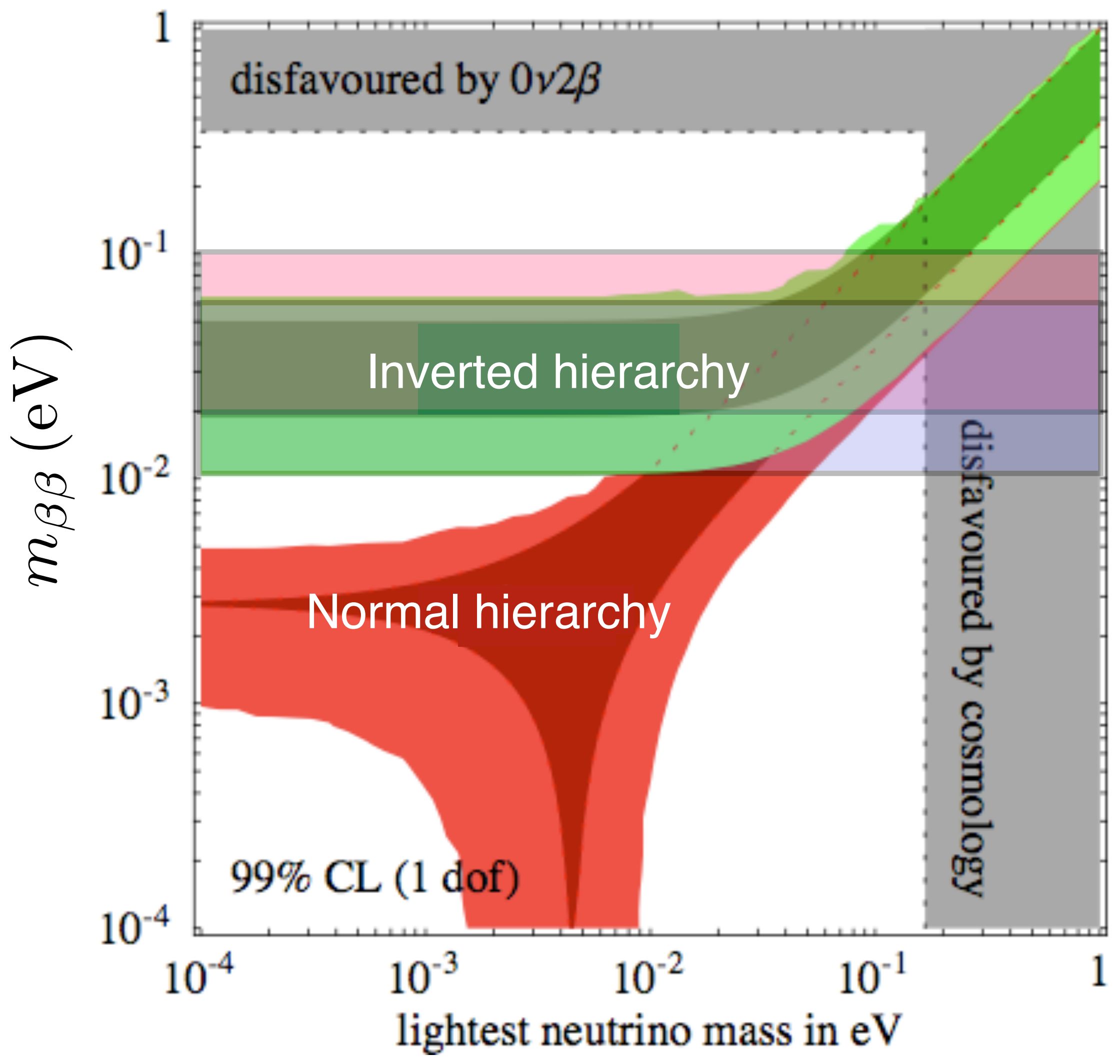
- Express the effective neutrino Majorana mass in terms of the measured oscillation parameters and the unknown lightest neutrino mass: $m_{\beta\beta} = f(U_{ek}, m_{lightest}, \Delta m_{12}, \Delta m_{13})$

CUORICINO →

CUORE conservative →

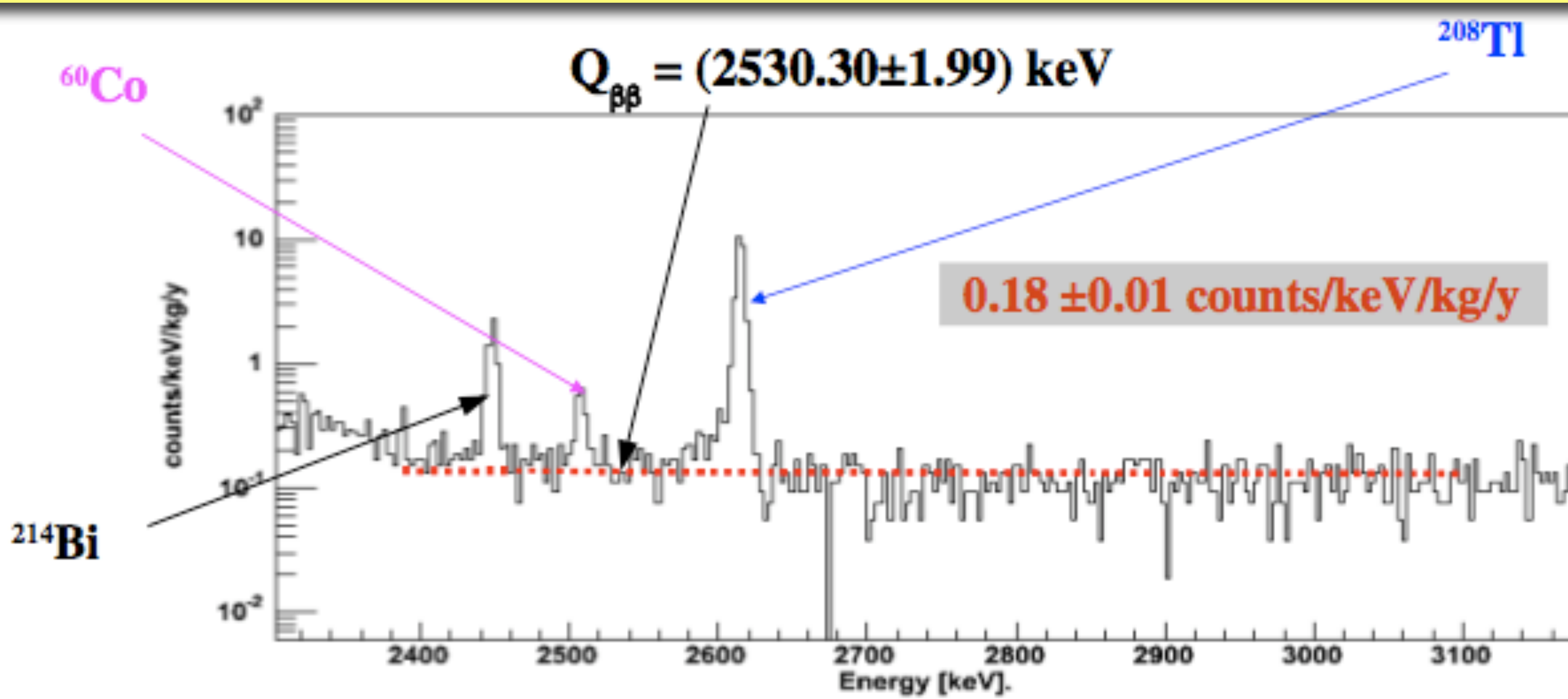
CUORE optimistic →

Future generation experiments →



A. Strumia, F. Vissani, arXiv.org/abs/hep-ph/0606054

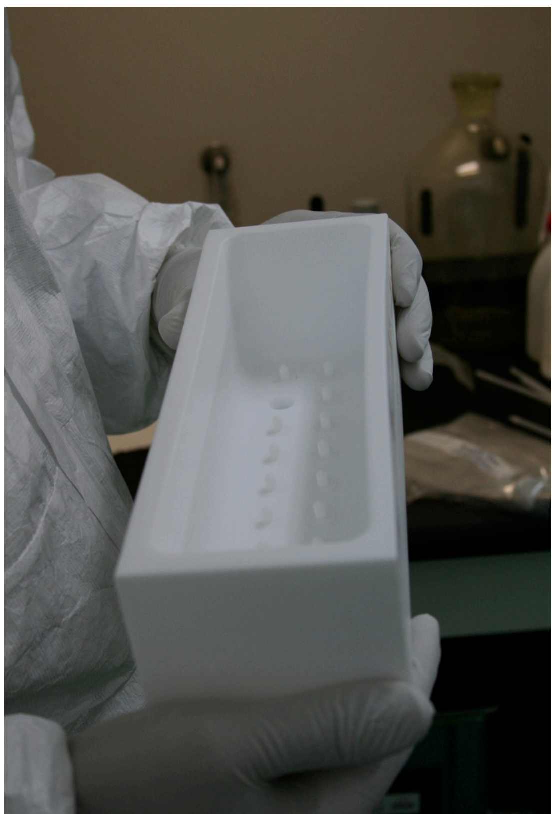
Background in CUORICINO



- ^{60}Co : Cu cosmogenic activation(~3 FWHM apart) -> negligible
- ~40%: multi-Compton ^{208}Tl 2615 kev γ line(^{232}Th cryostat contamination)
- ~10%: degraded α from crystal surface contamination
- ~50%: degraded α from Cu surface contamination

Crystal Cleaning

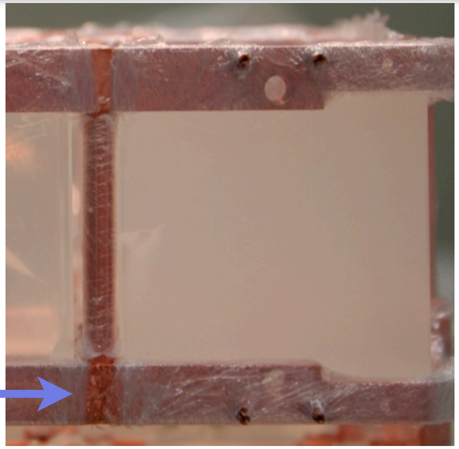
- Reduce crystal surface contamination by:
  - Etching with ultra-pure HNO_3 → remove 10 - 15 μm
  - Lapping with pure SiO_2 powder → remove 10 - 15 μm

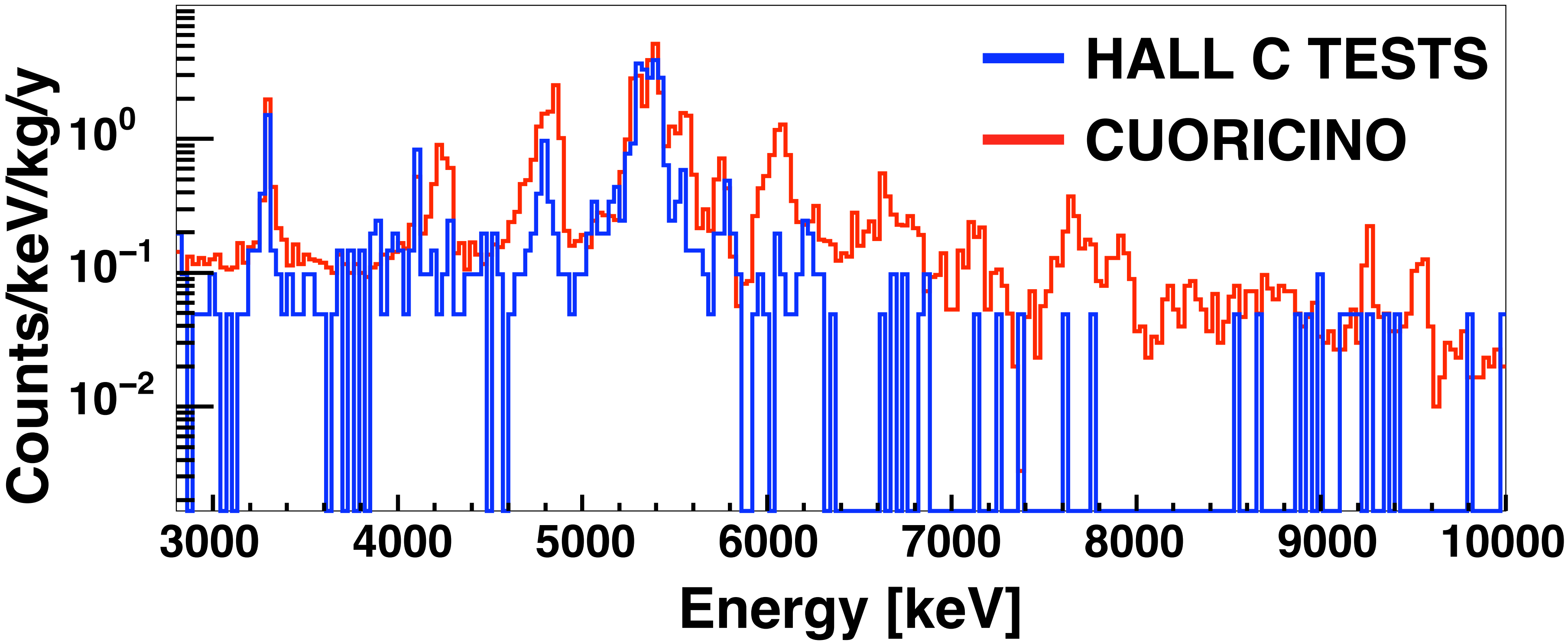


Background Reduction test

- Dedicated test measurements with bolometers in Hall C refrigerator @LNGS

- tested the TeO_2 cleaning procedure and Cu coverage with clean polyethylene





- reduction of factor ~4 on Crystals surface and ~2 on Cu surface

Foreseen CUORE Background

Component	Background in 0νDBD region (10^{-3} c/Kev/Kg/y)
Environmental gamma	< 1
Apparatus gamma	< 1
Crystal bulk	< 0.1
Crystal surfaces	< 3
Close-to-det. material bulk	< 1
Close-to-det. material surface	~ 20 - 40
Neutrons	~ 0.1
Muons	~ 0.4

- Crystal cleaning program reached the required goals
- We are now trying to improve the Cu cleaning techniques

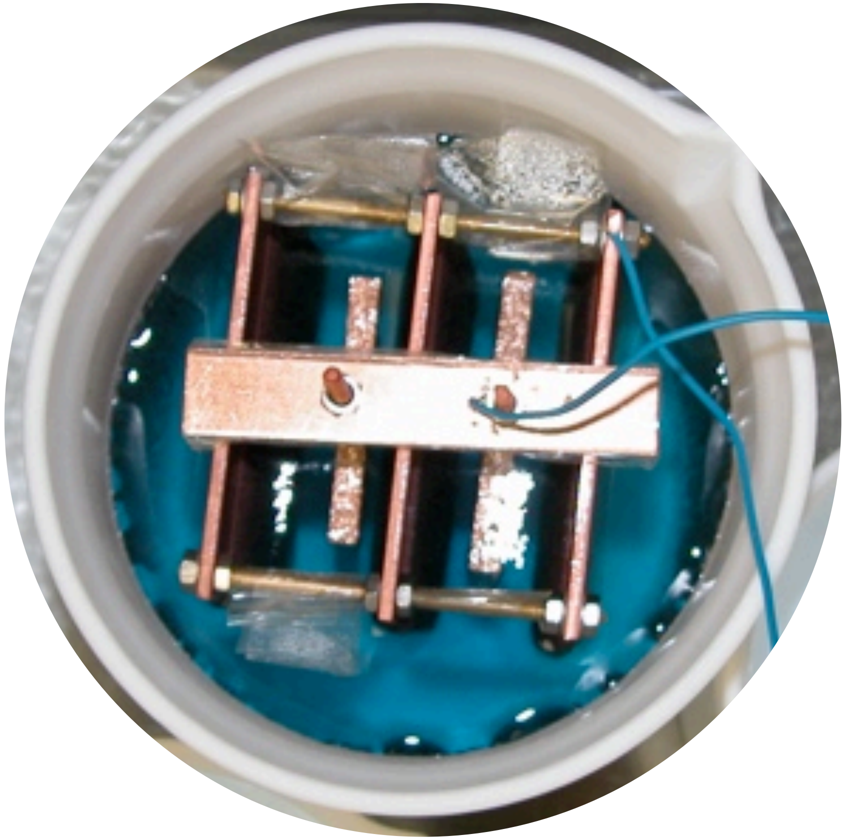
Copper Cleaning @LNGS

- The remaining alpha background could come from the polyethylene and/or from not well covered Cu parts.
- We will test new copper cleaning techniques against the polyethylene coverage. The cleaning steps are:

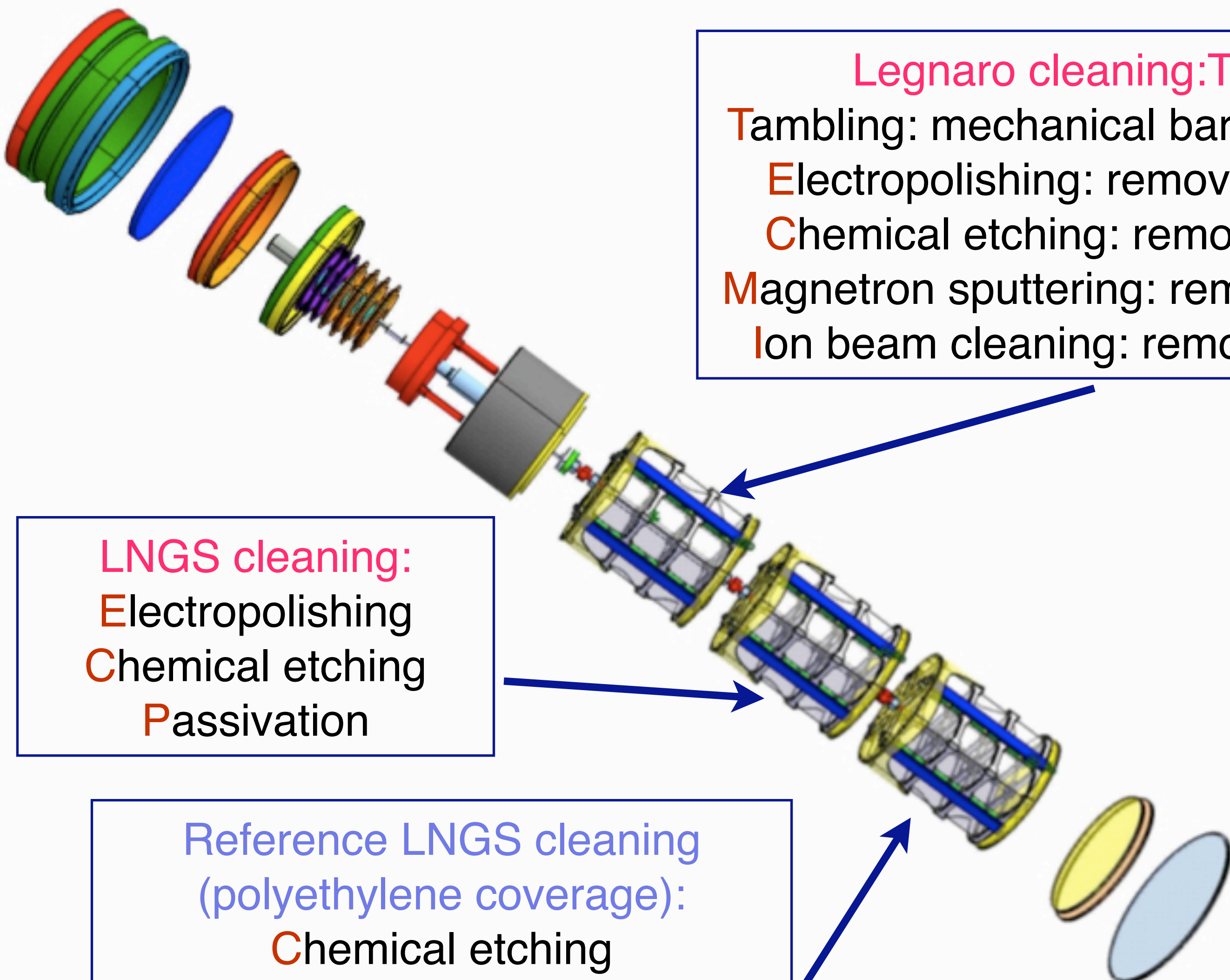
1) Electropolishing for 90 min @ 1.8 V in a mixture of:
   - 85% orthophosphoric acid
   - 5% 1-butanol
   - 10% ultra-pure water

2) Chemical etching using a mixture of:
   - 10% ultra pure nitric acid
   - 90% ultra pure water

3) Passivation using a mixture of:
   - 50 ml hydrogen peroxide
   - 50 ml ultra pure water
   - 100g crystalline citric acid



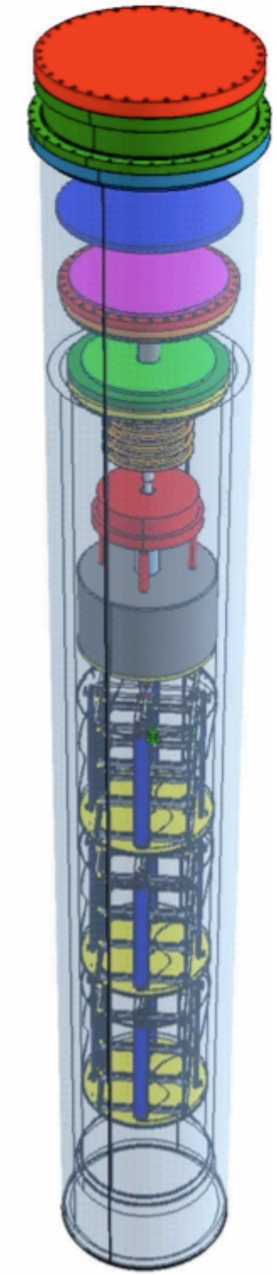
Last test: The Tree Tower Run



Legnaro cleaning:TECMI
Tambling: mechanical barrel polishing
Electropolishing: remove~100 µm
Chemical etching: remove~10 µm
Magnetron sputtering: remove few µm
Ion beam cleaning: remove few nm

LNGS cleaning:
Electropolishing
Chemical etching
Passivation

Reference LNGS cleaning (polyethylene coverage):
Chemical etching
Passivation
Cu: 80µm PP coverage



- Run start scheduled for december 2008

Conclusions

- 0νDBD might be the only chance to probe the absolute neutrino mass scale and to determine whether it is Dirac or Majorana.
- CUORICINO demonstrate the feasibility of a large scale bolometric detector with good energy resolution and background.
- The construction of CUORE, a second generation detector, is started.
- The First CUORE tower (CUORE-0) will be operated in 2009
- CUORE will have the capability to start to explore the inverse hierarchy mass region.
- CUORE data taking is scheduled in 2012.