From CUORICINO to CUORE: To probe the inverted hierarchy region

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and
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On behalf of the CUORE collaboration

Adapted from Andrea Giuliani's TAUP presentation
Sendai Japan, September 11-15, 2007

The CUORE collaboration

ITALY

- Dipartimento di Fisica dell'Universita' di Milano-Bicocca e Sezione di Milano Bicocca dell'INFN
- INFN - Sezione di Milano
- Dipartimento di Ingegneria Strutturale del Politecnico di Milano
- Dept.of Physics and Astronomy, University of South Carolina
- Laboratori Nazionali del Gran Sasso
- Dipartimento di Fisica dell'Universita' di Firenze e Sezione di Firenze dell'INFN
- Nuclear Science Division, Lawrence Berkeley National Laboratory,
- Laboratorio de Fisica Nuclear y Altas Energias, Universidad de Zaragoza
- Dipartimento di Fisica e Matematica dell'Universita' dell'Insubria
- Dipartimento di Fisica dell'Universita' di Genova e Sezione di Genova dell'INFN
- Department of Physics, University of California, Berkeley
- Department of Materials Science and Mineral Engineering, University of California
- Laboratori Nazionali di Legnaro,
- Lawrence Livermore National Laboratory,
- Dipartimento di Fisica dell'Universita' di Roma La Sapienza e Sezione di Roma dell'INFN
- California Polytechnic State University
- University of Wisconsin

UNITED STATES

Outline

- Double Beta Decay: physics/experimental techniques
- ^{130}Te bolometers
- Structure of CUORICINO, present results
- From CUORICINO to CUORE
- The background: model, investigation and solution
- CUORICINO/CUORE potential according to recent nuclear structure calculations
- Conclusions

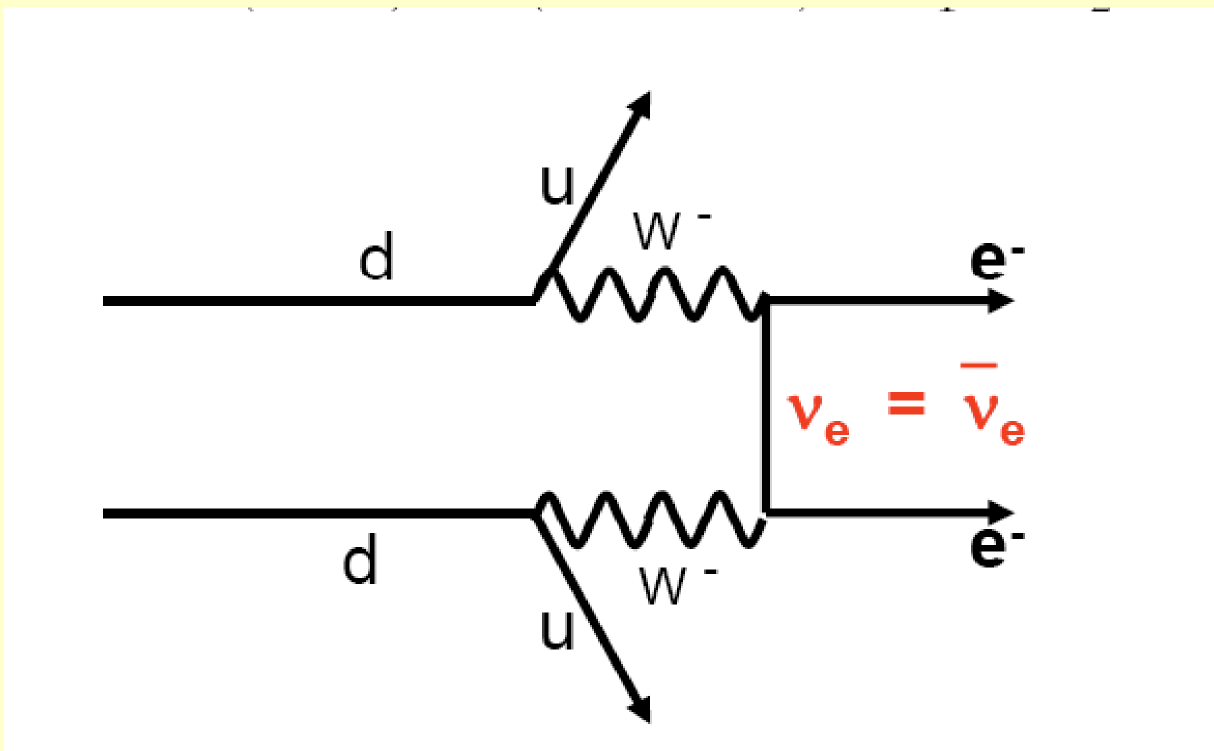
Decay modes for Double Beta Decay

$(A,) \rightarrow (A,Z+2) + 2e^{-} + 2\nu_e$

2ν Double Beta Decay
allowed by the Standard Model
observed : $T_{1/2} = 10^{19}$ -10^{21}y

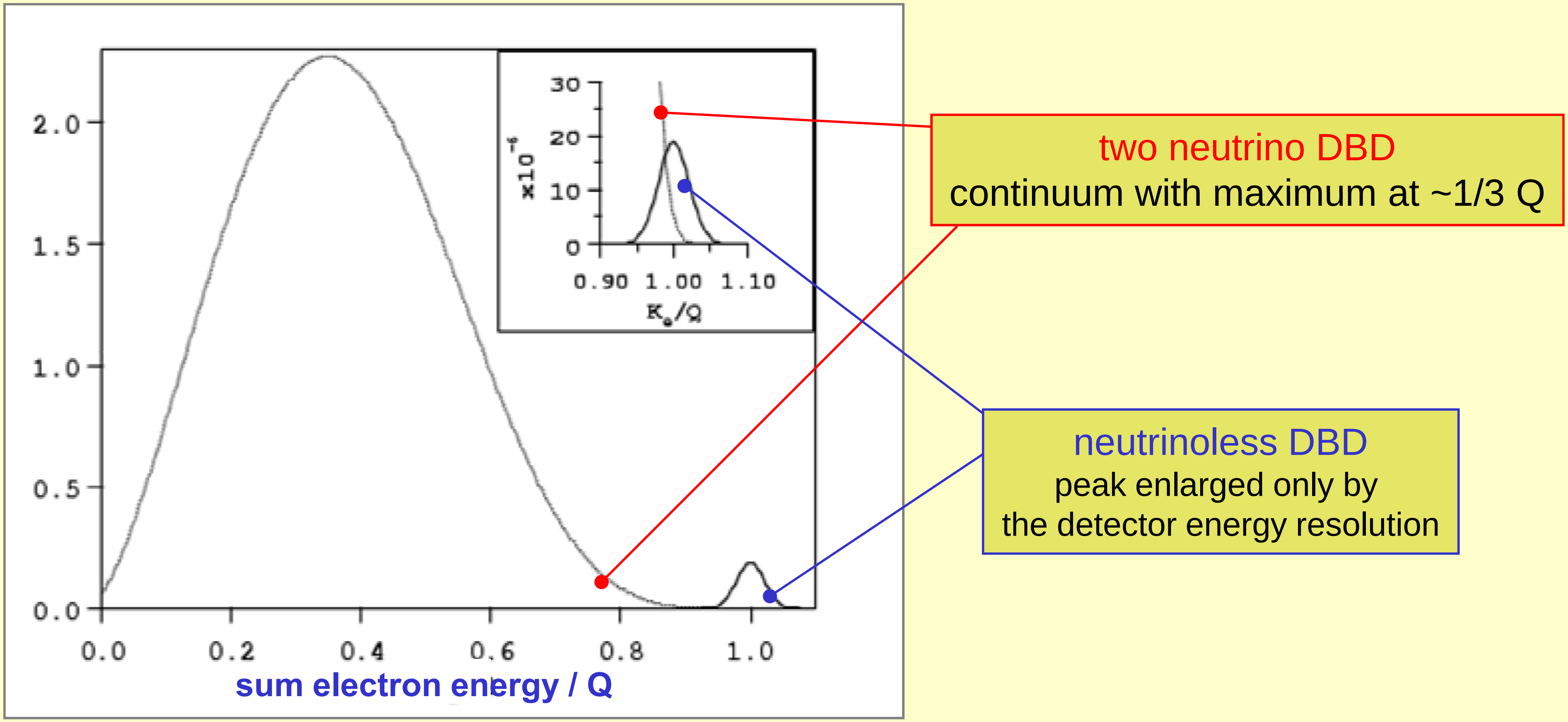
$(A,Z) \rightarrow (A,Z+2) + 2e^{-}$

neutrinoless Double Beta Decay (0ν-DBD)
never observed (except KKDK claim)
$T_{1/2} > 10^{25}$ y



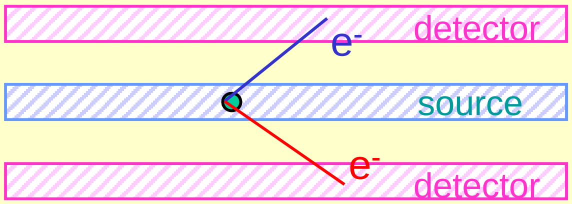
Electron sum energy spectra in DBD

The shape of the two electron sum energy spectrum enables us to distinguish between the two decay modes



Experimental approaches to direct searches

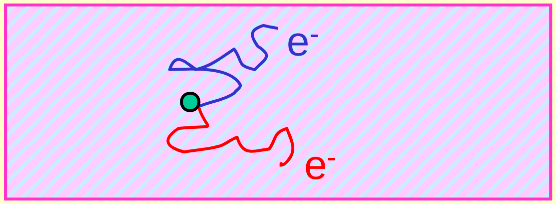
Two approaches for the detection of the two electrons:

① 

Source ≠ Detector

- scintillation (Elegants, MOON)
- gaseous/foil TPC (Moe)
- gaseous drift chamber with magnetic field and calorimetry (NEMO-3)

Event reconstruction
Relatively low efficiency
Energy resolution ~1%

② 

Source ≡ Detector
calorimetric technique
Fiorini 1967 Ge, 1984,Te

- scintillation (Zdesenko)
- solid-state devices (Ge)
- gaseous/liquid TPC (EXO)
- **cryogenic macrocalorimeters (bolometers) CUORE/CUORICINO**

Restricted in background identification
High efficiency
Energy resolution~ 0.1%

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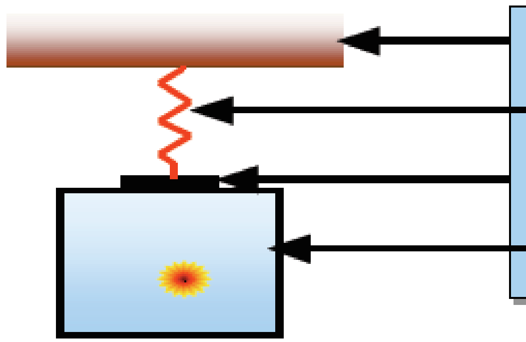
^{130}Te as a DBD candidate

Large natural abundance
Low-cost
Expandability of Double-Beta Decay experiments

- high natural isotopic abundance (nat. abundance = 33.87 %)
- high transition energy (Q = 2530 keV)
- encouraging theoretical matrix element $\langle m_\nu \rangle = 50\,meV \Rightarrow T_{1/2}^{0\nu} \approx 3 \times 10^{26}\,y$
- observed with geo-chemical techniques
($T_{1/2\ incl}$ = (0.7 - 2.7) × 10^{21} y)
- 2ν DBD decay observed by a precursor bolometric experiment (MIBETA) and by NEMO-3 at the level $T_{1/2}$ = (7.6) × 10^{20} y

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

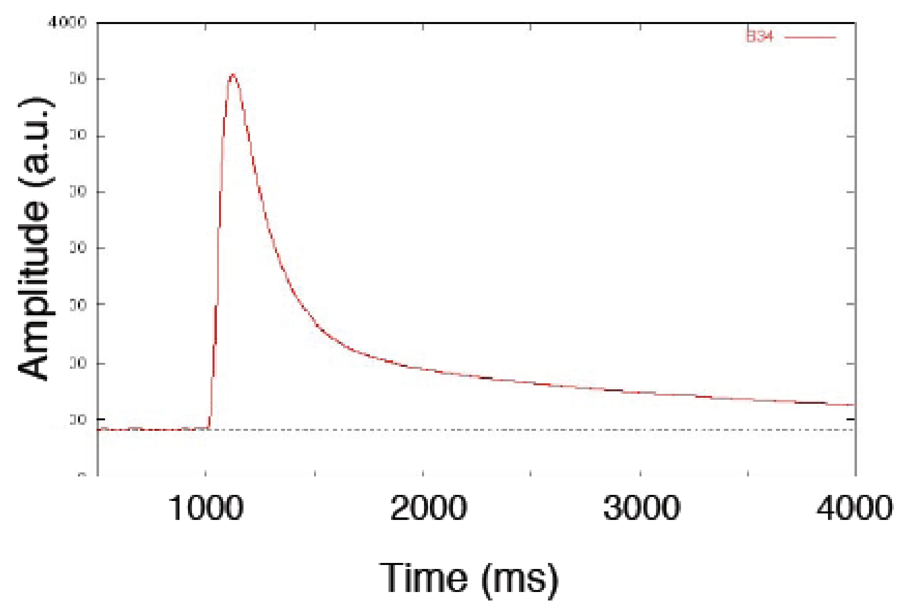
signal size: 1 mV

Time constant:

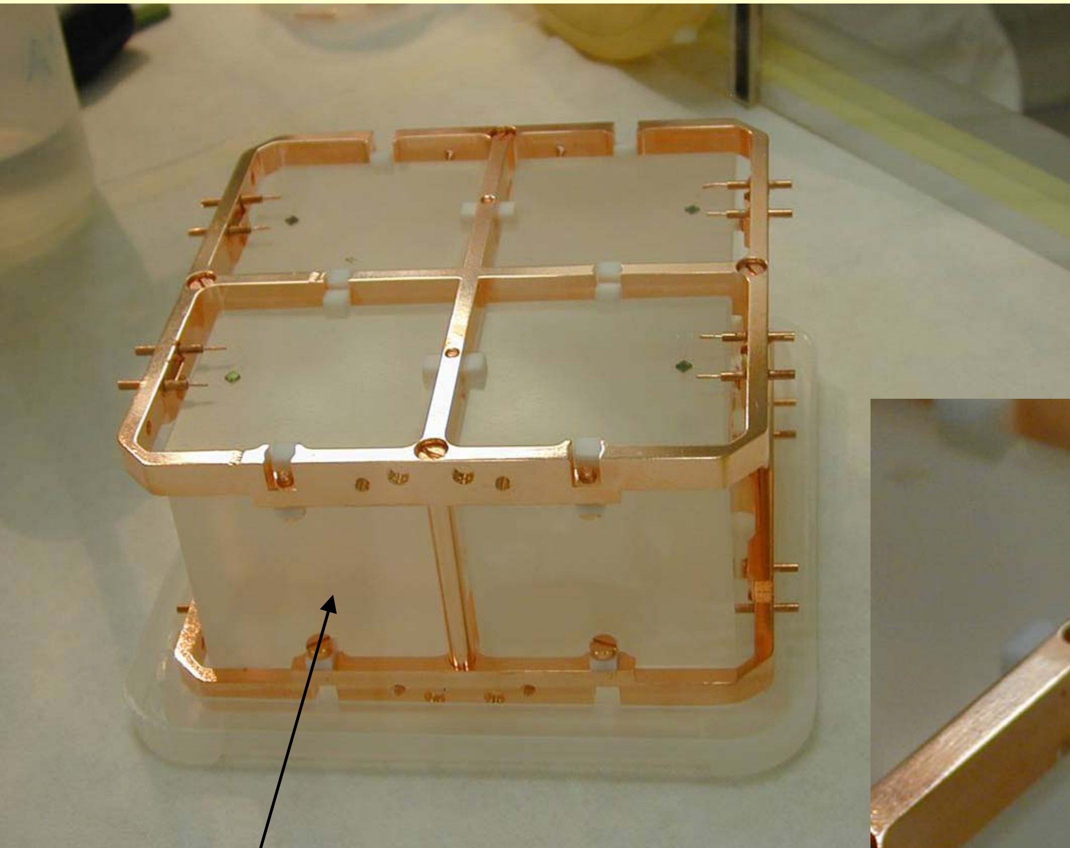
$\tau = C/G = 0.5$ s

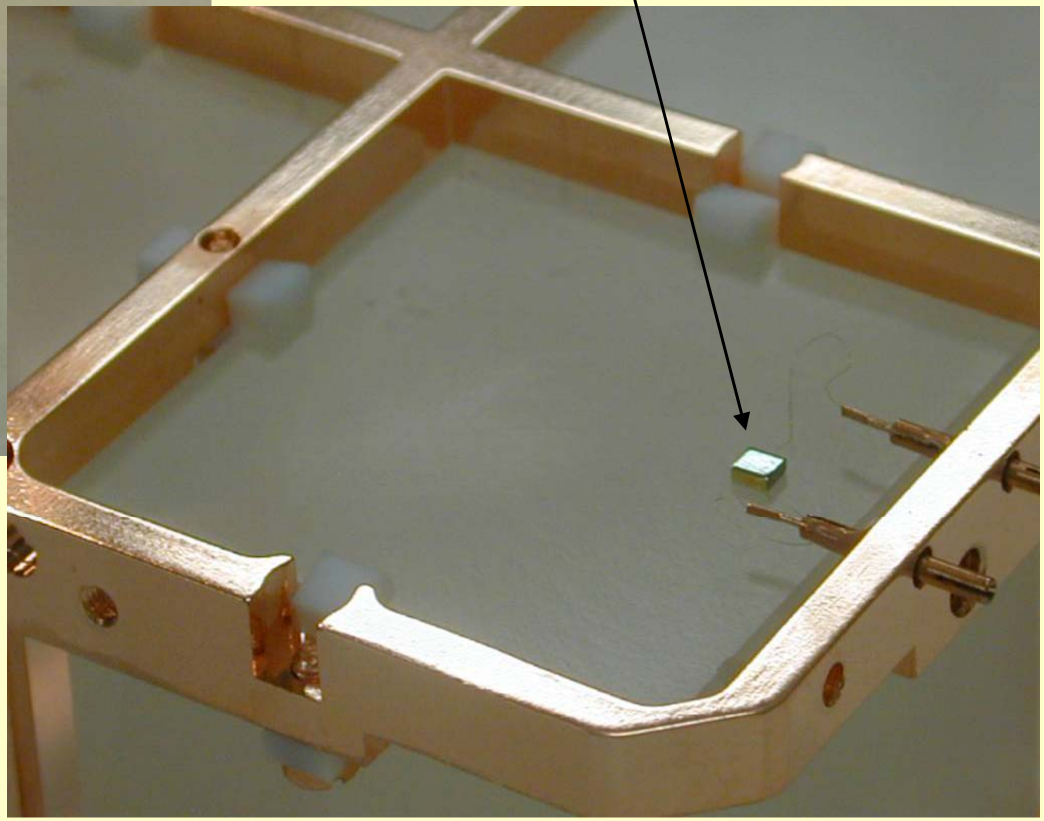
Energy resolution (FWHM):
~ 5-10 keV at 2500 keV

Single pulse example



Tellurium oxide bolometers for DBD





Thermometer
(Neutron transition doped Ge chip)

Energy absorber
single TeO_2 crystal

- 790 g
- 5 x 5 x 5 cm

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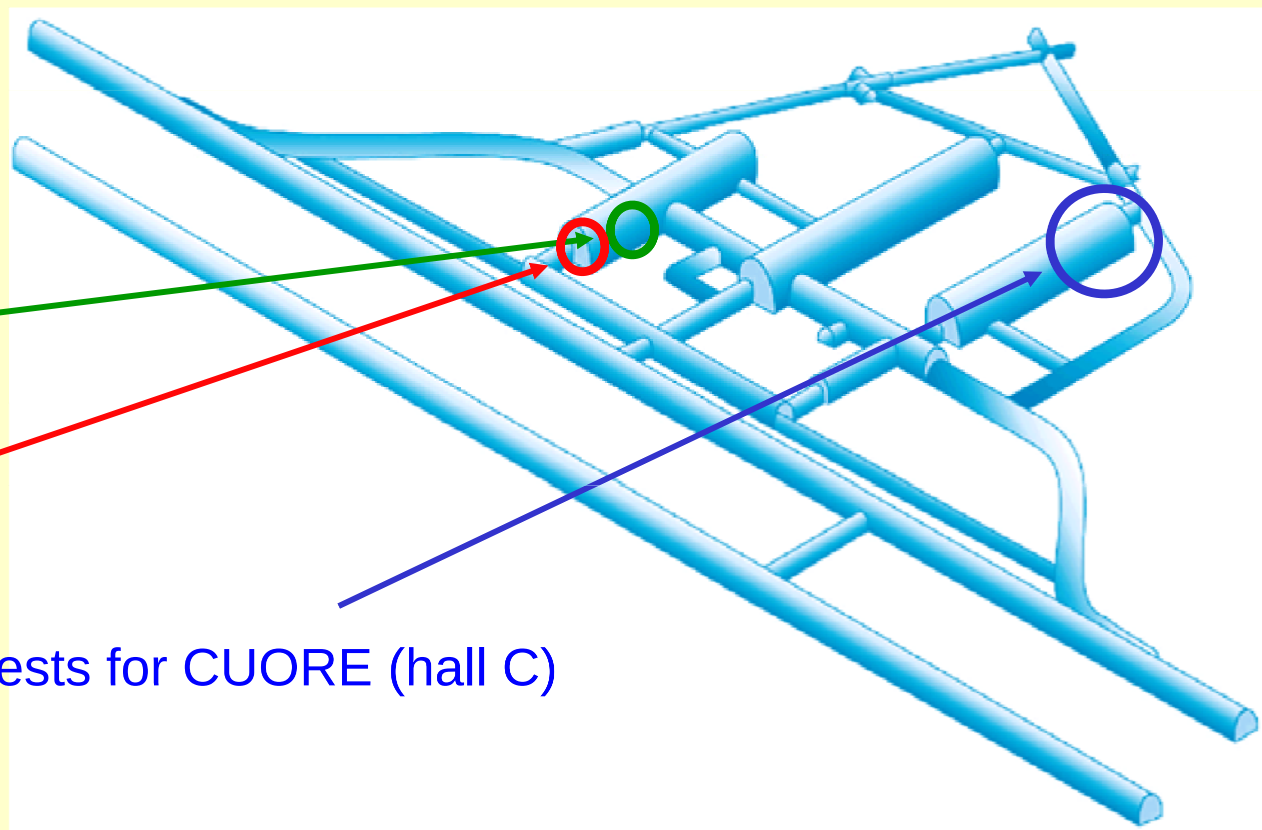
CUORICINO/CUORE Location

CUORICINO experiment installed in
Laboratori Nazionali del Gran Sasso
L'Aquila – ITALY

the mountain provides a 3500 m.w.e. shield against cosmic rays



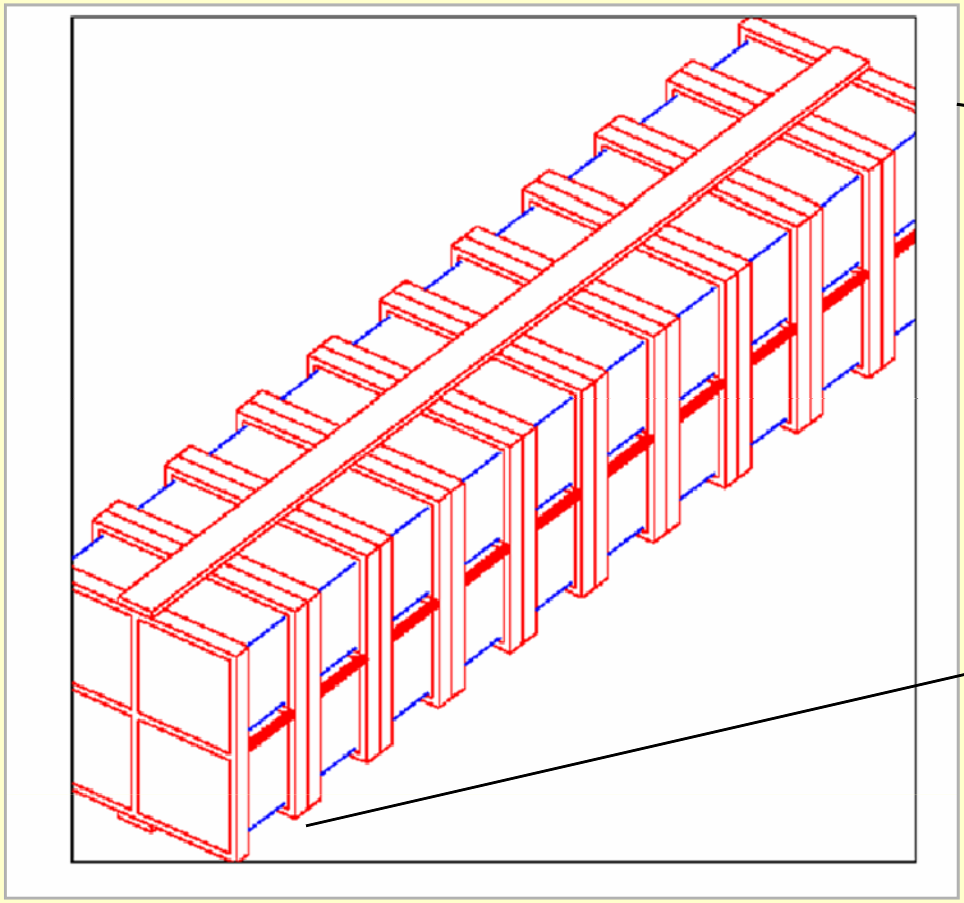
The CUORICINO structure

CUORICINO = tower of 13 modules,

11 modules x 4 detector (790 g) each

2 modules x 9 detector (340 g) each

$M = \sim 41$ kg $\Rightarrow$ $\sim 5 \times 10^{25}$ ^{130}Te nuclei

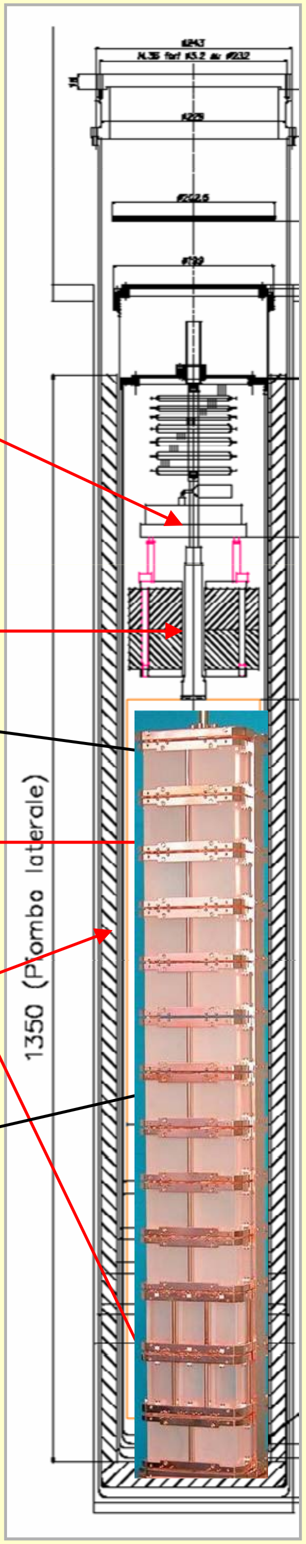


Coldest point

Cold finger

Tower

Lead shield

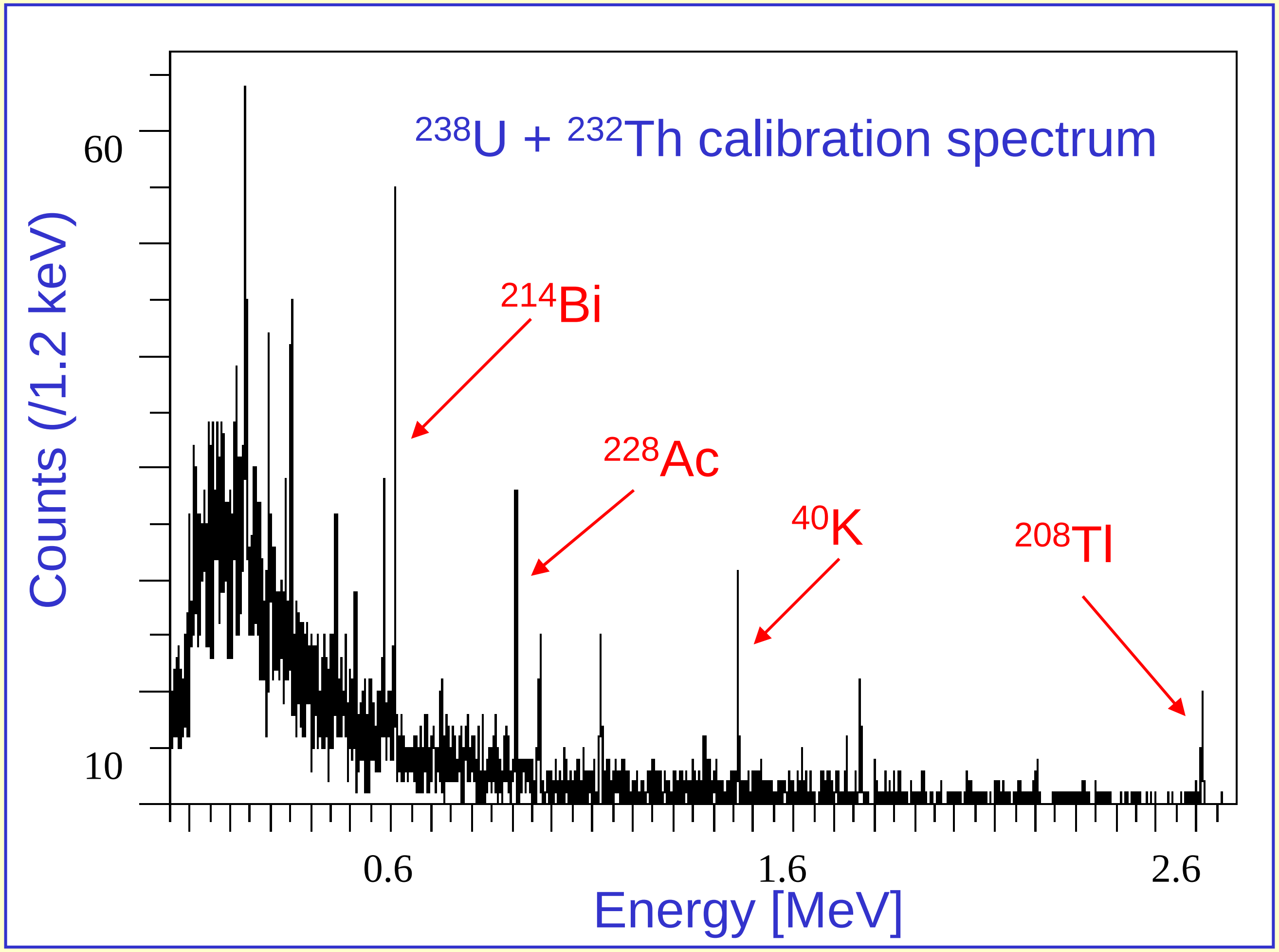


Same cryostat and similar structure as previous pilot experiment

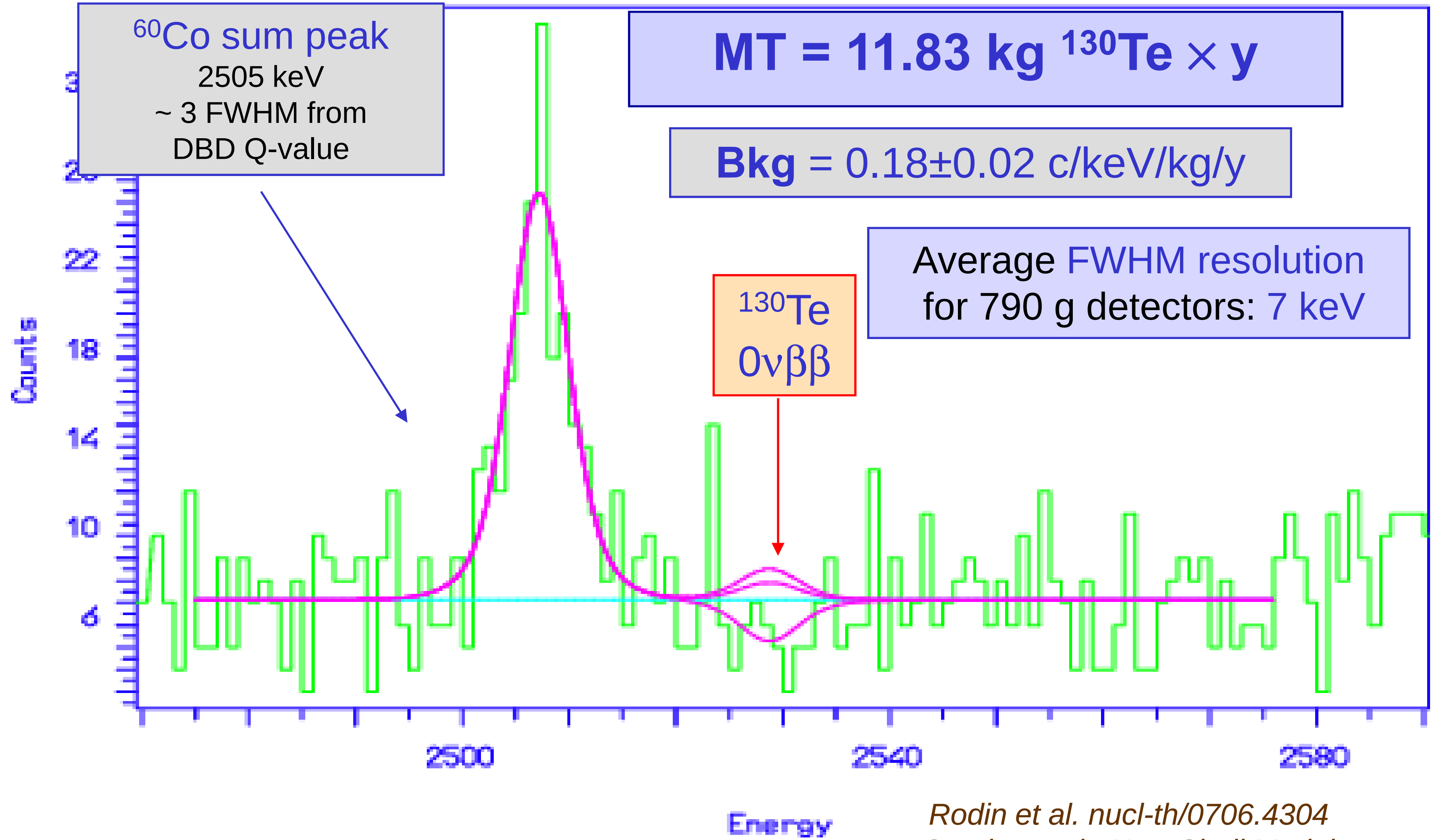
Detector performance

Performance of CUORICINO detectors (5×5×5 cm^3 - 790 g):

- Detector base temperature: ~ 7 mK
- Detector operation temperature: ~ 9 mK
- Detector response: ~ 250 μV/ MeV
- FWHM resolution: ~ 3.9 keV @ 2.6 MeV



CUORICINO results



Rodin et al. nucl-th/0706.4304
Caurier et al., New Shell Model

$T_{1/2}^{0\nu}$ (y) > 3.0 × 10^{24} y (90% CL) → $\langle M_{\beta\beta}\rangle$ < 0.38 – 0.58 eV

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From CUORICINO to CUORE

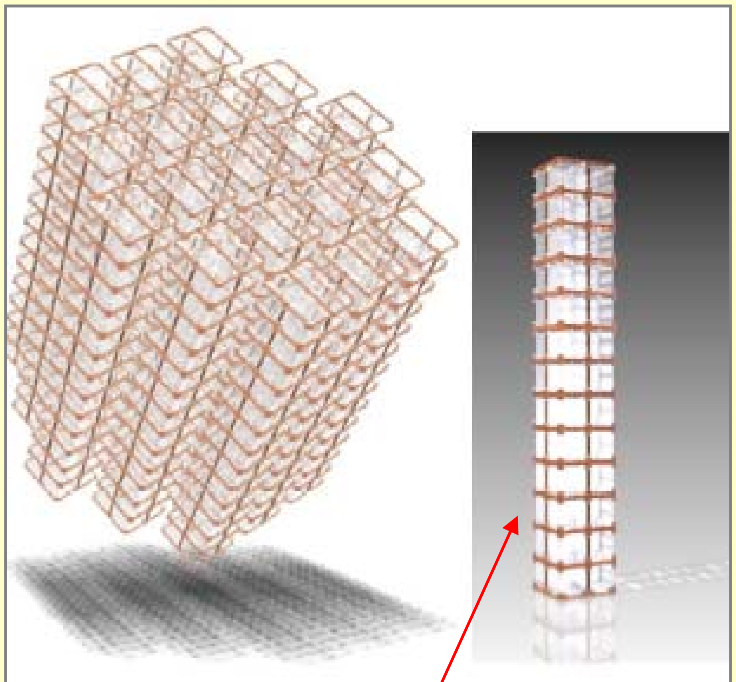
(Cryogenic Underground Observatory for Rare Events)

CUORE = close-packed array of 988 detectors

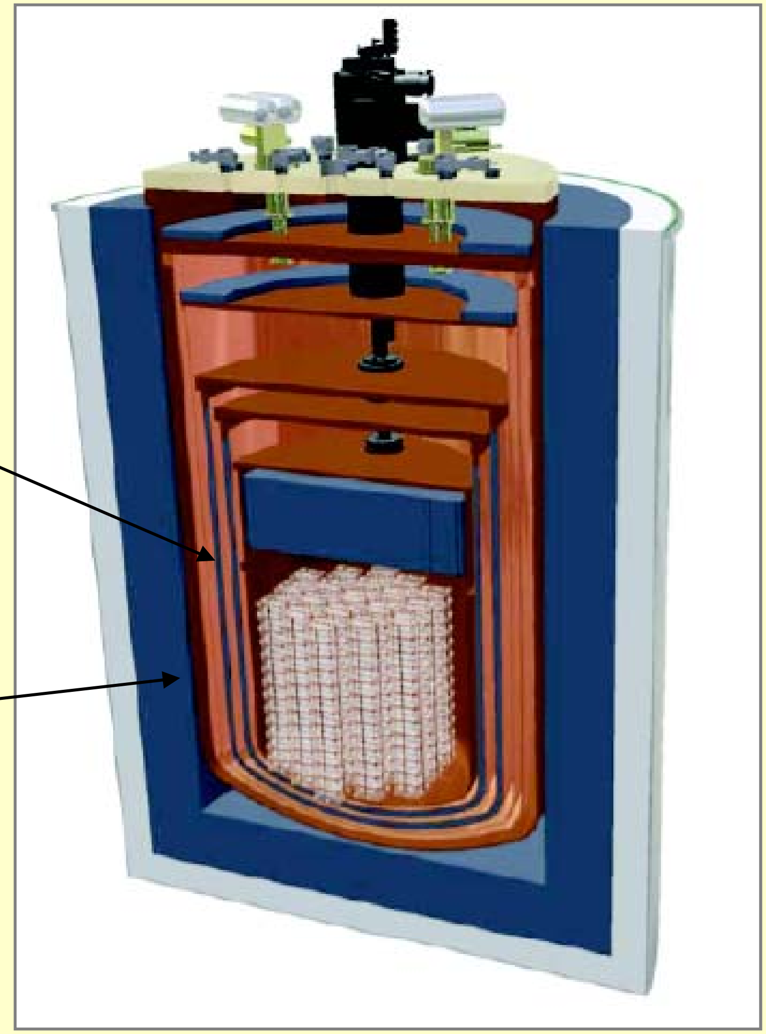
19 towers - 13 modules/tower - 4 detectors/module

M = 741 kg ~ 10^{27} ^{130}Te nuclei

Compact structure, ideal for active shielding and granularity



Each tower is a CUORICINO-like detector



Special dilution refrigerator

CUORE funding and schedule

- CUORE has a dedicated site in LNGS and the construction of site started
- The CUORE refrigerator is fully funded and has been ordered
- 1000 crystals: promised funding by INFN and US DOE
- The CUORE Electronics will be funded by the NSF via USC

First CUORE tower “CUORE-0" assembled in 2008 and operated in 2009 in CUORICINO Cryostat
CUORE scheduled to begin in January 2011

CUORE sensitivity

Montecarlo simulations of the background show that

b ~ 0.001 counts / (keV kg y)

is possible with the present bulk contamination of the bolometers

The problem is surface background (energy-degraded alpha, beta)

must be reduced by more than a factor of 10 below that of CUORICINO: work in progress!

10 y sensitivity (1 σ) with conservative Assumption: b = 0.01 counts/(keV kg y)
FWHM = 10 keV

$$T_{1/2}^{0\nu} = 3.0 \times 10^{26} y$$

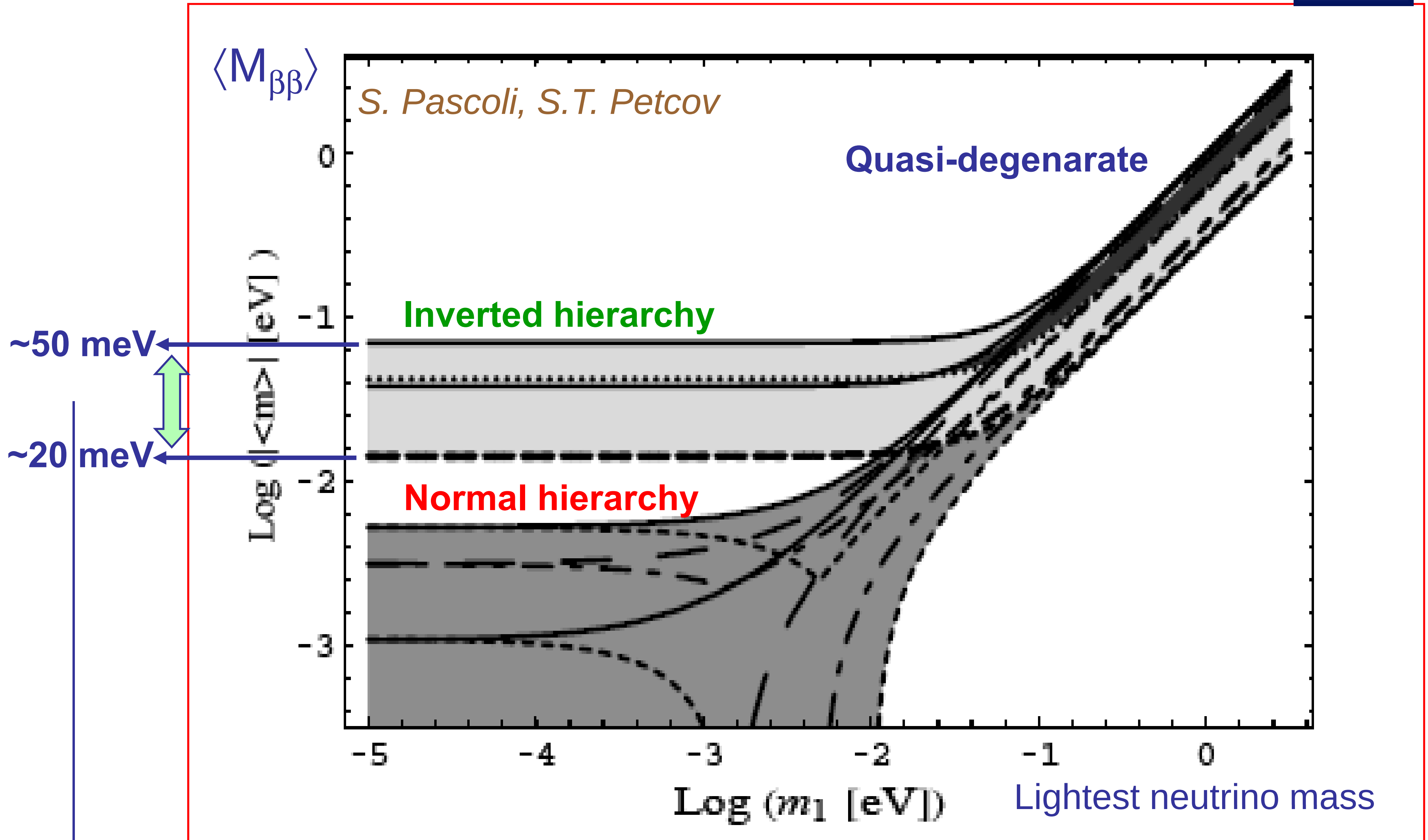
$\langle M_{\beta\beta} \rangle$ < 38-58 meV
QRPA-SM

10 y sensitivity (1 σ) with aggressive assumption: b = 0.001 counts/(keV kg y)
FWHM = 5 keV

$$T_{1/2}^{0\nu} = 9.2 \times 10^{26} y$$

$\langle M_{\beta\beta} \rangle$ < 23-33 meV
QRPA-SM

CUORE and the inverted hierarchy region



Inverted hierarchy band

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The CUORE background model

Sources of the background

1. Radioactive contamination in the detector materials (bulk and surface)
2. Radioactive contamination in the set-up, shielding included
3. Neutrons from rock radioactivity
4. Muon-induced neutrons

Monte Carlo simulation of the CUORE background based on:

1. CUORE baseline structure and geometry
2. Gamma and alpha counting with HPGe and Si-barrier detectors
3. CUORICINO experience $\Rightarrow$ CUORICINO background model
4. Specific measurements with dedicated bolometers in test DR in LNGS

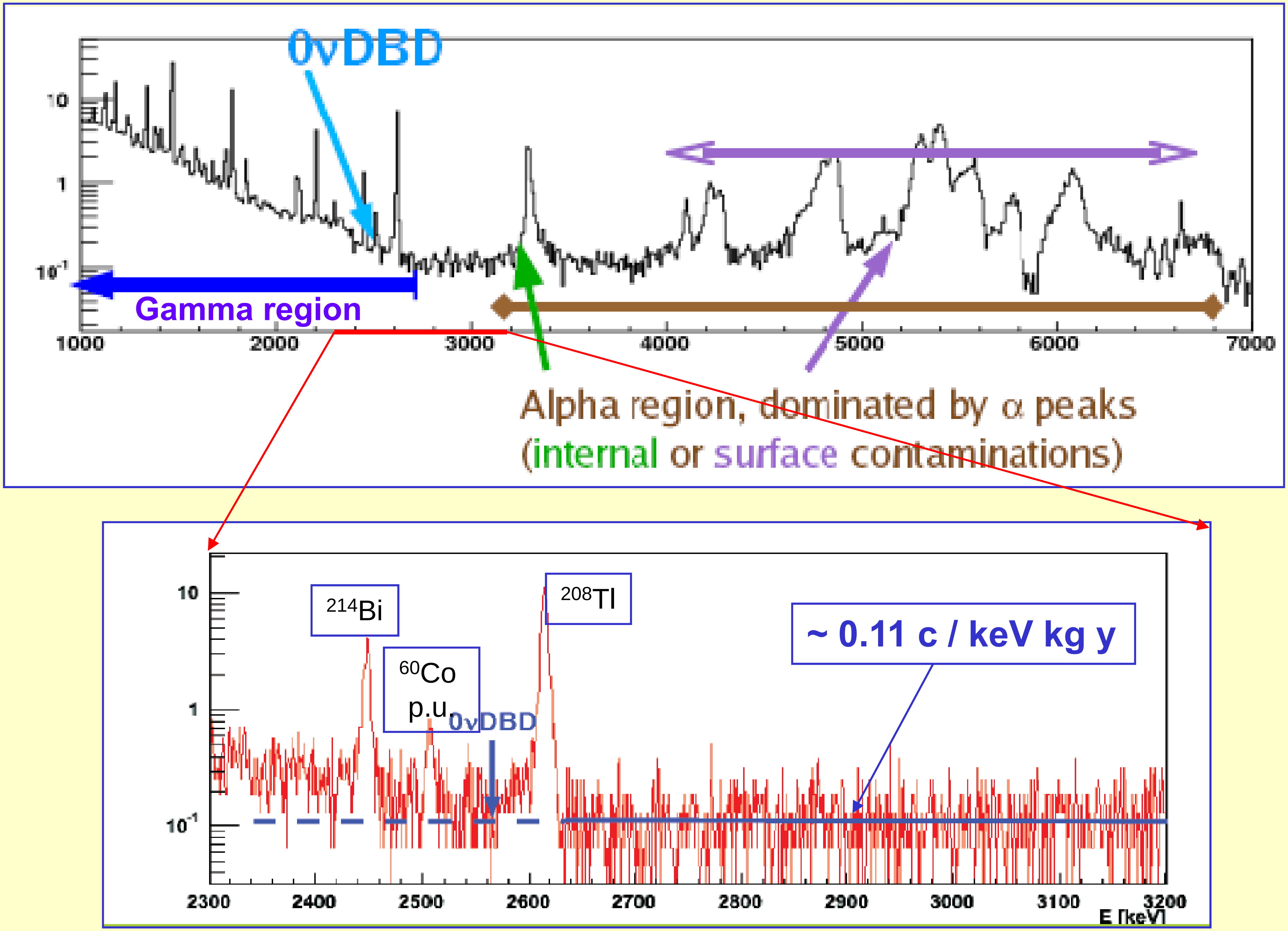
Results…..

The CUORE background components

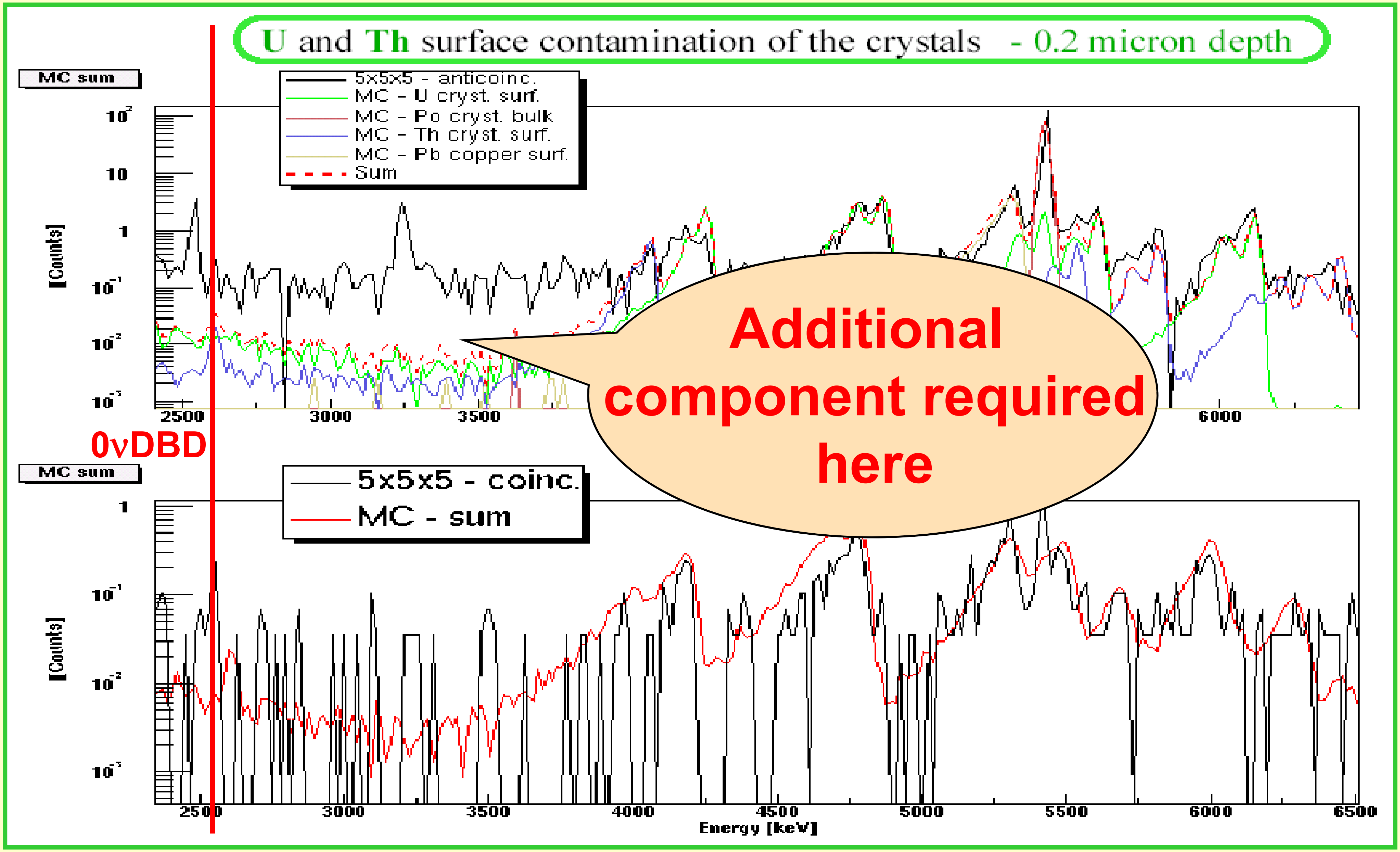
Component	Background in DBD region (10^{-3} counts/keV kg y)
Environmental gamma	< 1
Apparatus gamma	< 1
Crystal bulk	
Crystal surfaces	
Close-to-det. material bulk	< 1
Close-to-det. material surface	~ 20 – 40
Neutrons	~ 0.01
Muons	~ 0.01

The only limiting factor

The CUORICINO background and the surface radioactivity model

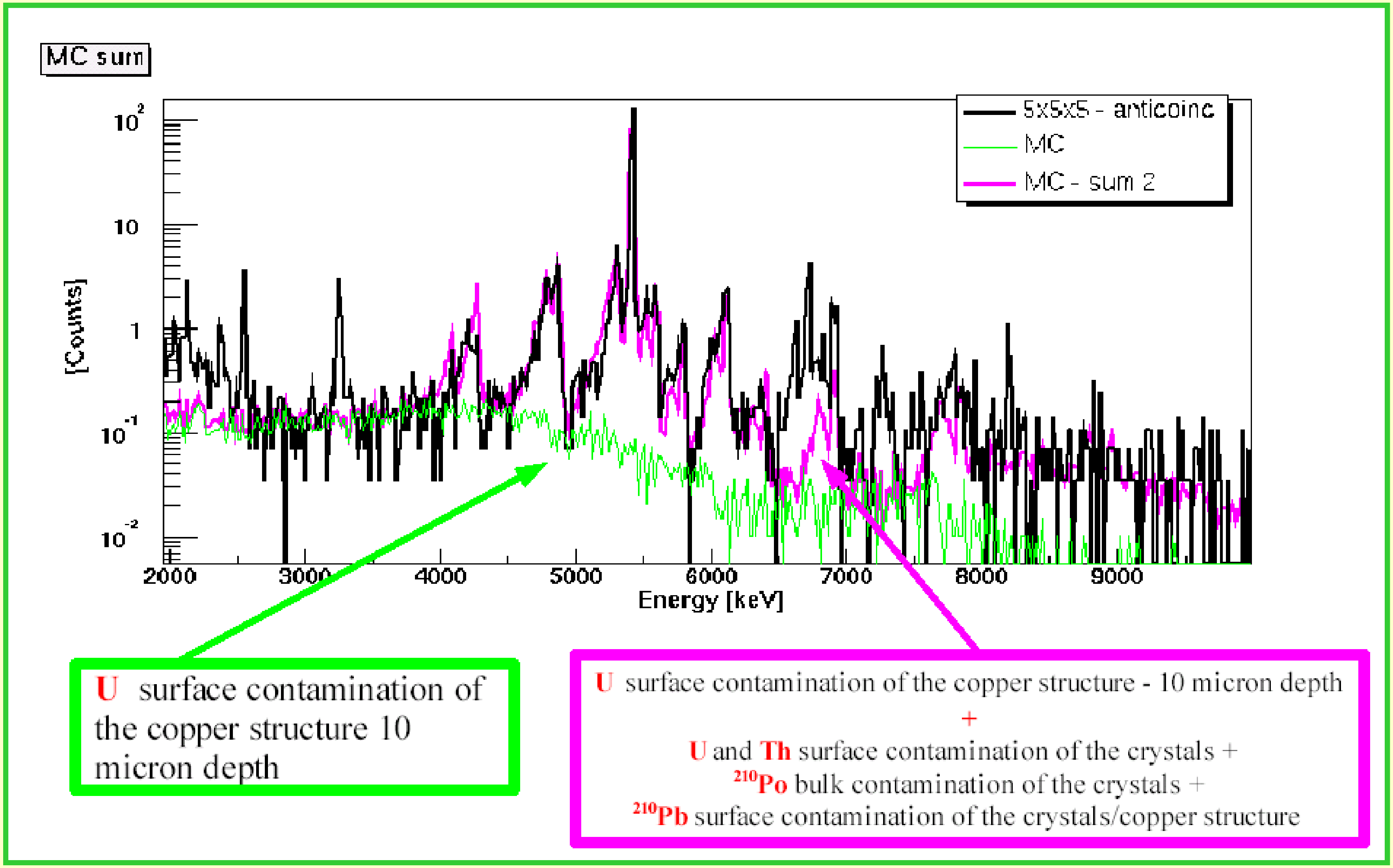


Reconstruction of the CUORICINO spectrum in the region 2.5 – 6.5 MeV



The additional component: inert material surface contamination

In order to explain the 2.0 - 4 MeV region BKG, one has to introduce ^{238}U or ^{210}Pb surface contamination of the copper structure facing the detectors



Strategies to control surface background

(A) Passive methods $\Rightarrow$ surface cleaning

- Mechanical action
- Chemical etching / electrolitic processes
- Surface passivation

(B) Active methods ("reserve weapons" and diagnostic) $\Rightarrow$ events ID

- surface sensitive bolometers
- scintillating bolometers able to separate α from electrons

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CUORICINO and the KKDK claim of evidence

Evidence of $0\nu\beta\beta$–decay of ^{76}Ge claimed by a subset of the Heidelberg-Moscow collaboration (Klapdor-Kleingrothaus et al.)

$T_{1/2}^{0\nu}$ (y) = (0.69-4.18) $\times$ 10^{25} (3σ range)

Best value: 1.19×10^{25} y

Klapdor-Kleingrothaus et al.
Physics Letters B 586 (2004) 198-212,
Nuc. Instrum. Meth.,A 522, 371(2004).

$m_{\beta\beta}$= 0.22 – 0.58 eV (3σ range)

Nuclear matrix element of Rodin et al., Erratum

nucl-th/0706.4304

Can CUORICINO challange the KKDK claim of evidence?

Compare experiments with different isotopes

$$F_N \equiv G^{0\nu}\left|M^{0\nu}\right|^2$$

$T_{1/2}^{0\nu}$ (Klapdor et al.) → Choose a nuclear model → $T_{1/2}^{0\nu}$ (^{130}Te)

$$T_{1/2}^{0\nu}\left({}^{130}Te\right)=\frac{T_{1/2}^{0\nu}\left({}^{76}Ge\right)_{Klapdor}}{F_N\left({}^{130}Te\right)/F_N\left({}^{76}Ge\right)}$$

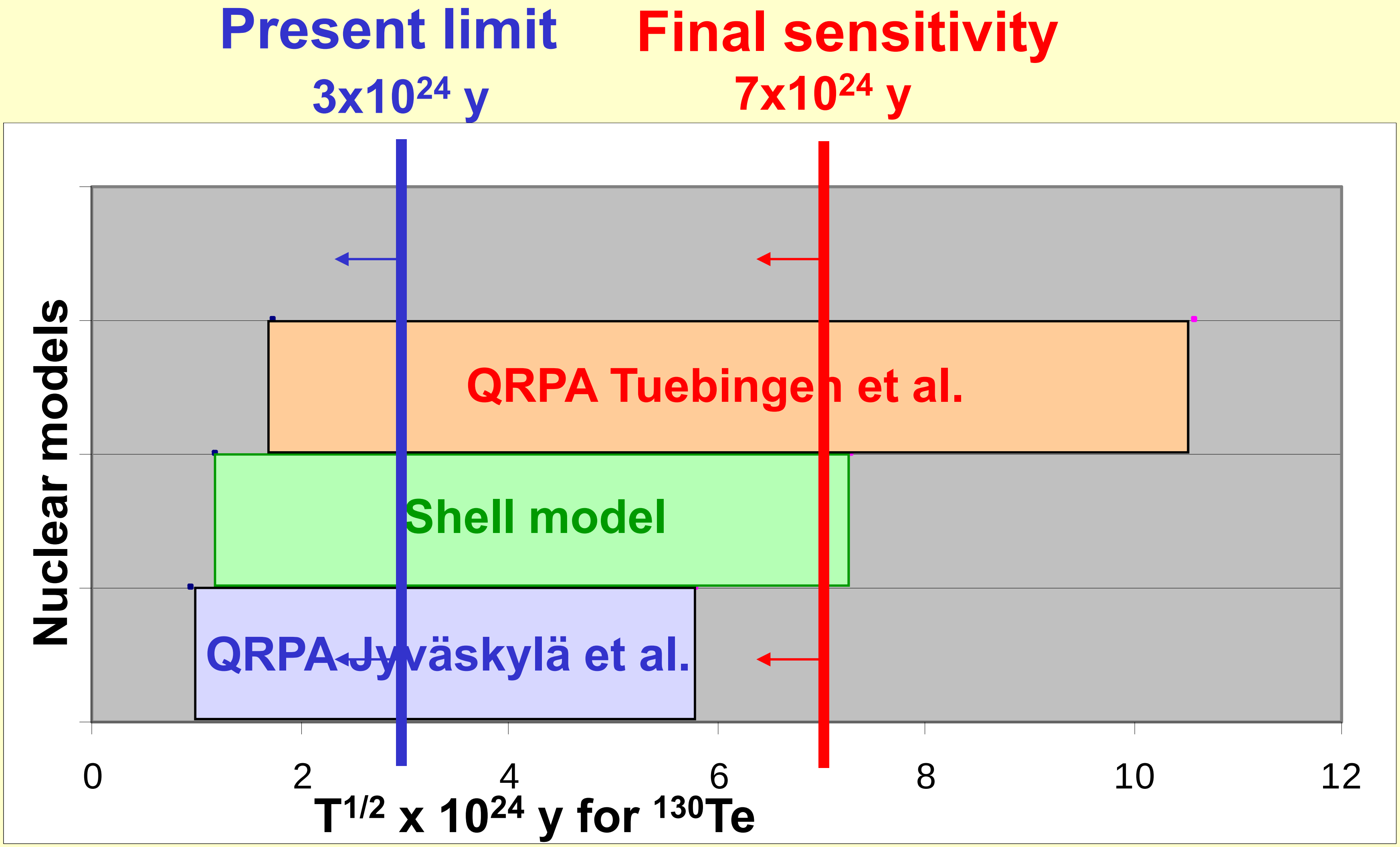
$T_{1/2}(^{76}Ge)=1.19 \times 10^{25}$y equivelent to $T_{1/2}(^{130}Te) = 3 \times 10^{24}$y, CUORICINO bound

Use three recent nuclear structure models:

- **QRPA Tuebingen-Bratislava -Caltech** group: erratum: nucl-th/0706.4304
- **QRPA Jyväskylä group**: nucl-th/0208005
- **Shell Model**: Poves' talk @ 4th ILIAS Annual Meeting - Chambery

CUORICINO and the ^{76}Ge claim of evidence

The KKDK claim half life range (3σ) is converted into a corresponding range for ^{130}Te using the three mentioned models



ERRATUM

Since this analysis we have learned that we missed a New analysis by Klapdor-Kleingrothaus and Krivosheina That included only pulse shape analysis data. The new Half life from Heidelberg-Moscow Experiment data is

$$T_{1/2}^{0\nu}(^{76}Ge) = 2.23_{-0.31}^{+0.44} \times 10^{25} y$$

This will make it a bit more difficult to confirm or refute this result with CUORICINO with one QRPA, but a bit more readibly with Shell model matrix elements.

Thank you Vladimir Tretyak for pointing that out!

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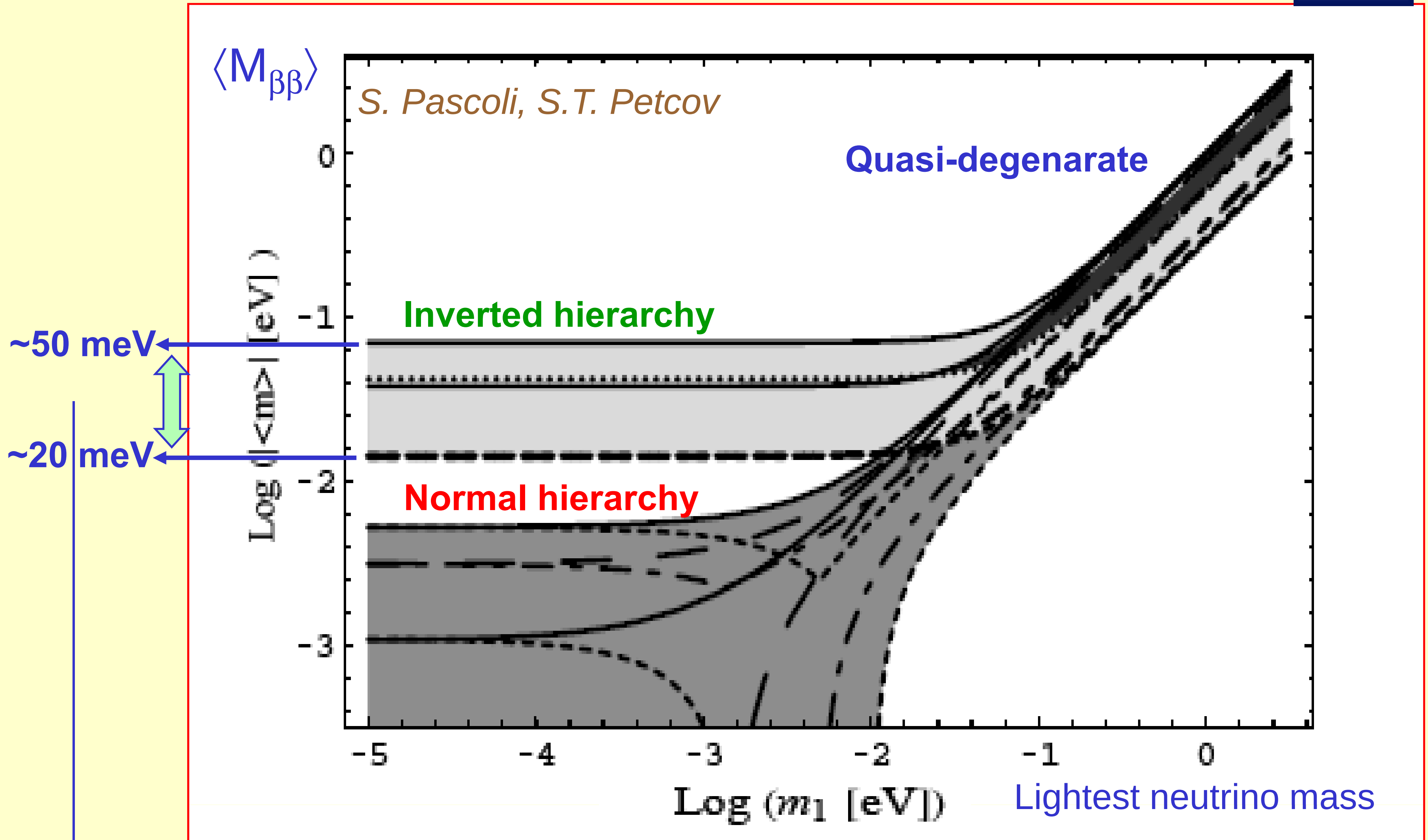

Inverted hierarchy band

Conclusions

- Bolometers represent a well established technique, very competitive for neutrinoless DBD search

- CUORICINO and NEMO-3 are presently the most sensitive 0ν DBD running experiments, with chance to confirm the HM claim of evidence if this is correct

- CUORICINO demonstrates the feasibility of a large scale bolometric detector (CUORE) with good energy resolution and background

- CUORE is a next generation detector; it is funded and is scheduled to begin operation in January 2011

- Recent results on background suppression confirm the capability to explore the inverted hierarchy mass region with CUORE