# Neutrinoless Double Beta Decay:
# CUORICINO results & perspectives for CUORE


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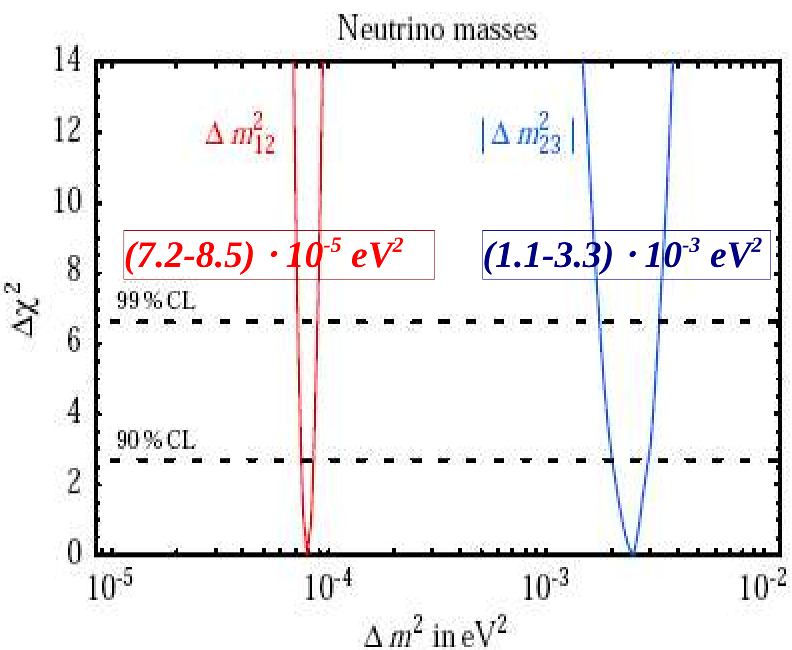
# All we know from Neutrino oscillation

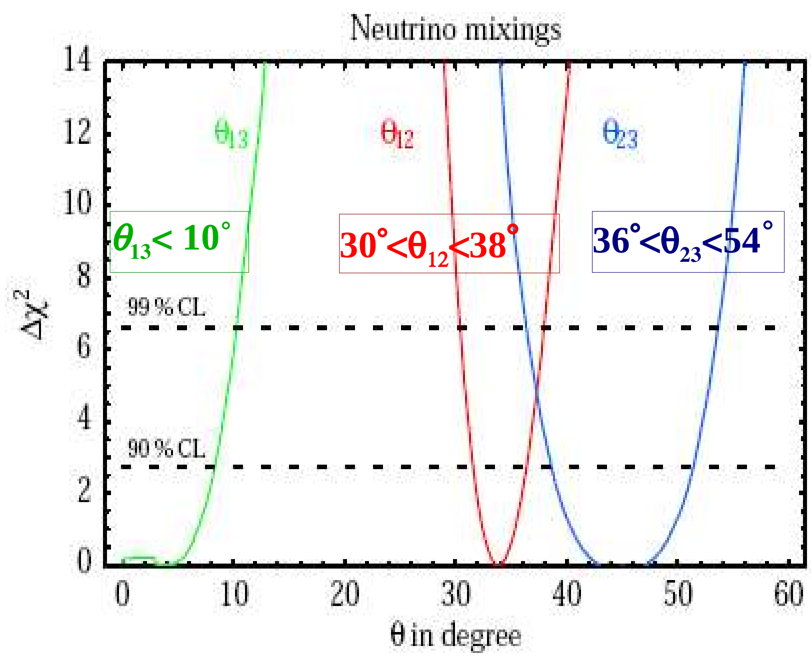
- **Neutrinos have mass ≠0 and mix** $(\nu_e, \nu_\mu, \nu_\tau)^T = U(\nu_1, \nu_2, \nu_3)^T$
- **9 independent parameters: $\theta_{23}$, $\theta_{13}$, $\theta_{12}$, CP phase $\phi$, Majorana phases $\alpha$, $\beta$, $m_1$, $m_2$, $m_3$**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\phi} \\ 0 & 1 & 0 \\ -s_{13}e^{i\phi} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Pontecorvo
Maki
Nakagawa
Sakata

**$\theta_{23}$:Atm. $\nu$ oscillation** **$\theta_{13}$:cross mixing** **$\theta_{12}$:Solar $\nu$ oscillation**




**Strumia, Vissani**
**hep/ph 0503246**

# We don't know from neutrino oscillation

- **Dirac or Majorana nature**
- **Absolute mass scale and hierarchy**

$\Delta m^2 = m_3^2 - m_2^2 \approx m_3^2 - m_1^2 \approx (1.1\text{-}3.3) \cdot 10^{-3}\ eV^2$

$\delta m^2 = m_2^2 - m_1^2 \approx (7.2\text{-}8.5) \cdot 10^{-5}\ eV^2$

- Limit on ν mass:
  - Model dependent limit from **cosmology**

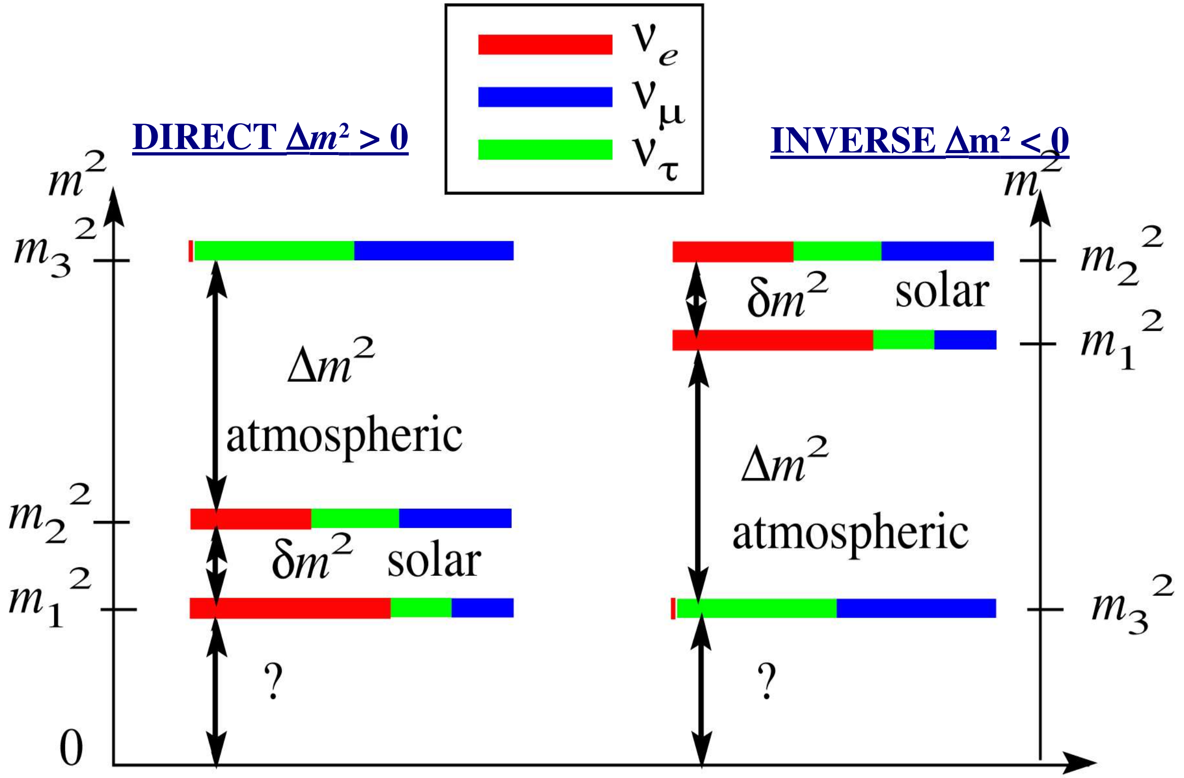
$$\sum m_{\nu_k} < 0.94\, eV$$

  - Model independent limit from **direct β decay**

$$m_\beta = \left(\sum m_{\nu_k}^2 |U_{ek}|^2\right)^{0.5} < 2.2\, eV$$

  - **Neutrinoless ββ0ν**

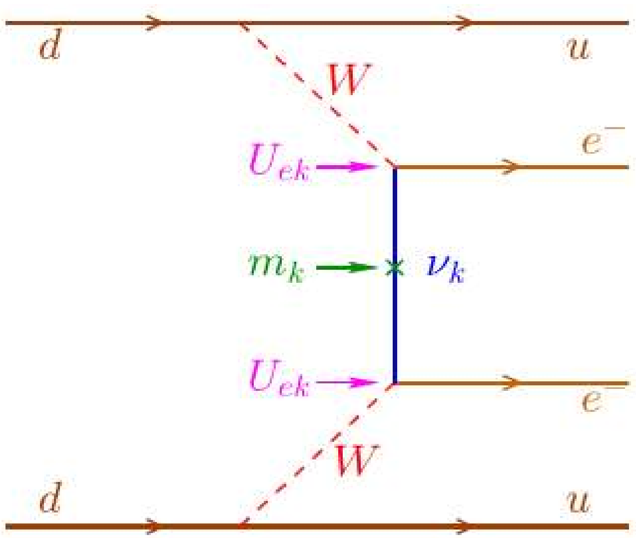
$$m_{\beta\beta} = \sum m_{\nu_k} \eta_k |U_{ek}|^2 < (0.2 - 1.1)\, eV$$




Degenerate if $m_1 \gg \Delta m^2$

# Neutrinoless Double Beta Decay: $\beta\beta 0\nu$

Forbidden in Standard Model for Dirac massive ν




$$\beta\beta 0\nu : (A,Z) \rightarrow (A,Z+2) + 2e^-$$

$$chirality\ flip : m_\nu \neq 0$$

$$\nu_{majorana} : \nu \equiv \bar{\nu}\ (Lepton\ number\ violation)$$

$$Many\ non\ SM\ decays\ can\ contribute$$

phase space ~$Q^5$

Effective Majorana mass

$$(\tau^{\beta\beta 0\nu})^{-1} = G(Q,Z)\,|M_{nucl}|^2\,|\langle m_{\beta\beta}\rangle|^2$$

Nuclear matrix element(NME): big uncertainties

**need to measure $\beta\beta 0\nu$ in different isotopes**

Majorana phases

ν mixing matrix and phases

$$\langle m_{\beta\beta}\rangle = \sum m_{\nu_k}\,\eta_k\,|U_{ek}|^2$$

Constraints on $m_{\beta\beta}$ translate in limits on $m_{\nu min}$

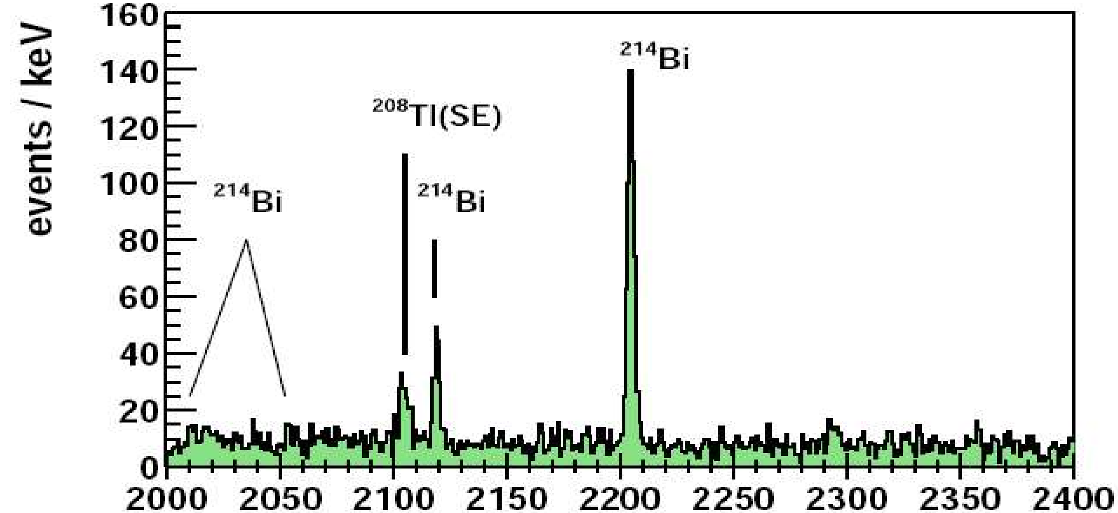
# KK-Heidelberg Moscow claim

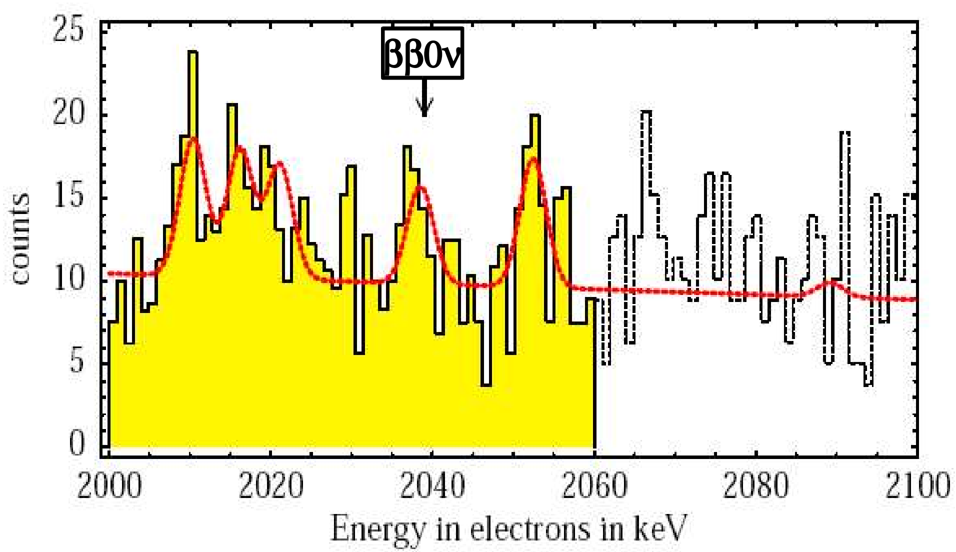
- **5 Ge diodes: 10.9Kg total active mass enriched (86%) in $^{76}$Ge**
- **Run from 1999 to 2003 in LNGS lab**
- **2001: *part* of the collaboration claimed ββ0ν evidence @ 2.2σ**
- **2004: claim confirmed @ 4.4σ with a total statistics of 71.7 Kg•y (2.5 10^26 nuclei•y)**

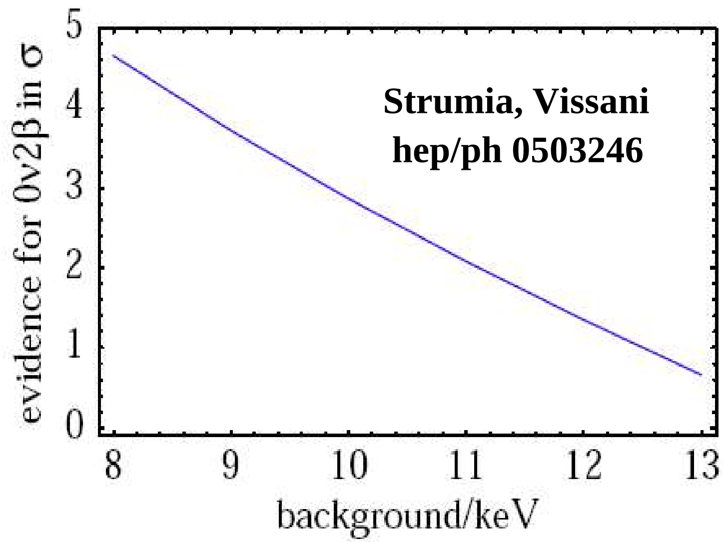
Klapdor-Kleingrothaus et al.
Phys. Lett. B 586 (2004) 198

$$\langle m_\nu \rangle < [0.1 \div 0.9]\, eV$$

$$best\ value\ \langle m_\nu \rangle = 0.44\, eV$$



# Detector sensitivity

- Experimental rate with $N_{\beta\beta0\nu}$ observed

$$\tau_{1/2}^{\beta\beta0\nu}=\frac{ln2\,\epsilon\,N_{nuclei}\,T}{N_{\beta beta0\nu}}\,(\tau_{1/2}^{\beta\beta0\nu}\gg T)$$

Sensitivity $S^{\beta\beta0\nu}$: lifetime corresponding to the min. number of detectable events above bkgd @ a given C.L.

**Exposure = detector mass [kg] • measuring time [y]**

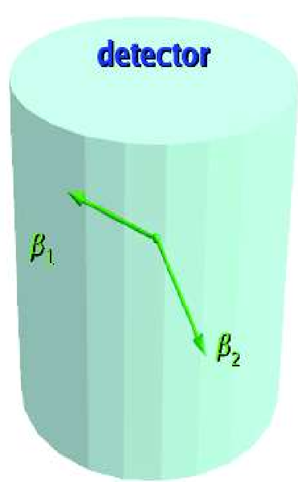
$$S^{\beta\beta0\nu}\propto a\cdot\epsilon\cdot\left(\frac{M\,T}{\Gamma\,b}\right)^{1/2} \quad\Rightarrow\quad \langle m_{\beta\beta}\rangle\propto\frac{1}{(a\,\epsilon\,G)^{1/2}|M_{nucl}|}\cdot\left(\frac{b\,\Gamma}{M\,T}\right)^{1/4}$$

**isotopic abundance • detector efficiency**

**energy resolution[keV] •bkgd [counts/keV/Kg/y]**

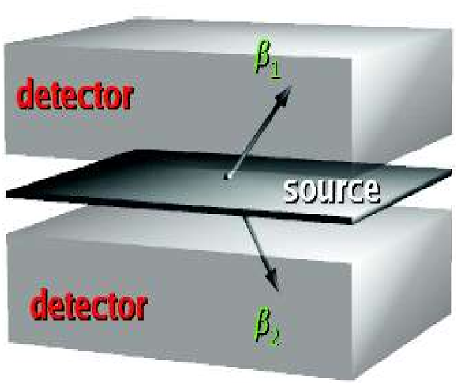
Source = detector

large Mass
bkgd
very good Γ



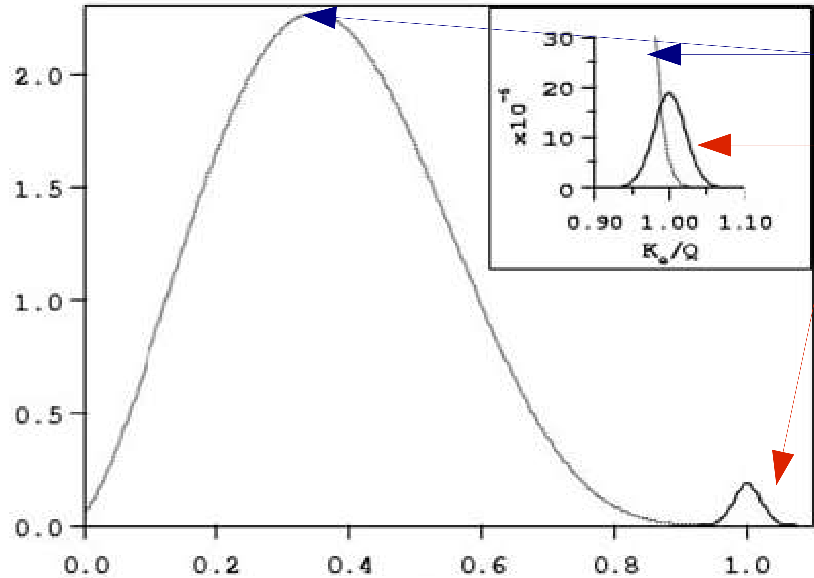

Source≠ detector

different isotopes
small Mass
bkgd(topology)
Γ



# ββ2νbackground

- **Irreducible background from SM allowed ββ2ν:** $(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$

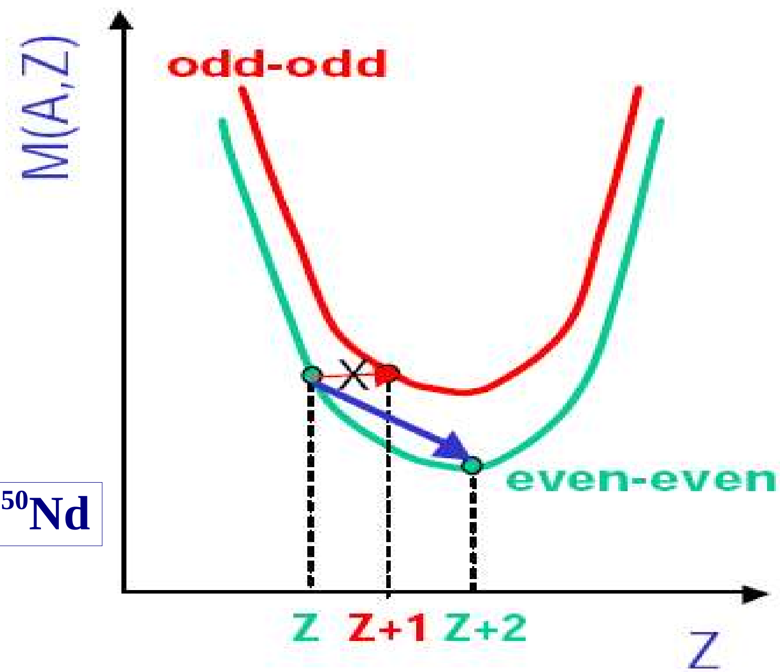



Sum electron energy/total energy Q

- **ββ2ν:continuum with maximum @ Q/3**
- **ββ0ν:sharp peak at $Q_{max}$ smeared by detector resolution**

- $N_{\beta\beta2\nu}/N_{\beta\beta0\nu} \sim \Gamma(E)/Q^5$ → **excellent ΔE resolution**

- **Look for (A-Z) even-even nuclei: ββ2ν suppressed**




**Studied nuclei: $^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{116}$Cd, $^{130}$Te, $^{136}$Xe, $^{150}$Nd**

# *CUORICINO: the bolometric way*

- **Bolometric technique: energy is measured as a temperature increase in the detector**

- **Low temperature calorimeter**
  - **$\Delta T = E/C \Rightarrow$ low C**

    **$\Rightarrow$ dielectrics @ low T (~ 10mK) :**

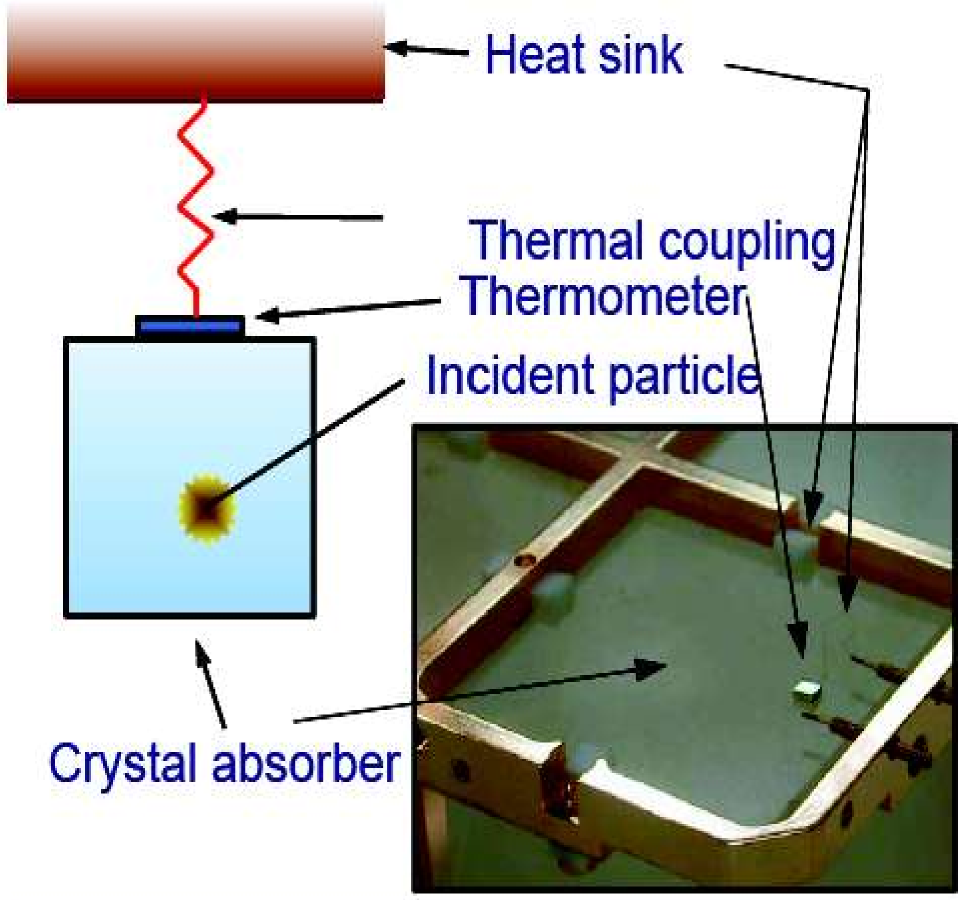
    **$C \sim T^3 \sim 10^{10}$ eV/K**

- **Thermometer: NTD Ge thermistor**

  **$\Delta T \Rightarrow \Delta R$**

  **$R \sim R^0 \exp(T^0/T)^{\sim 0.5}$**

  **$\Rightarrow$ 0.1 mK/MeV -> 0.1mV/MeV**

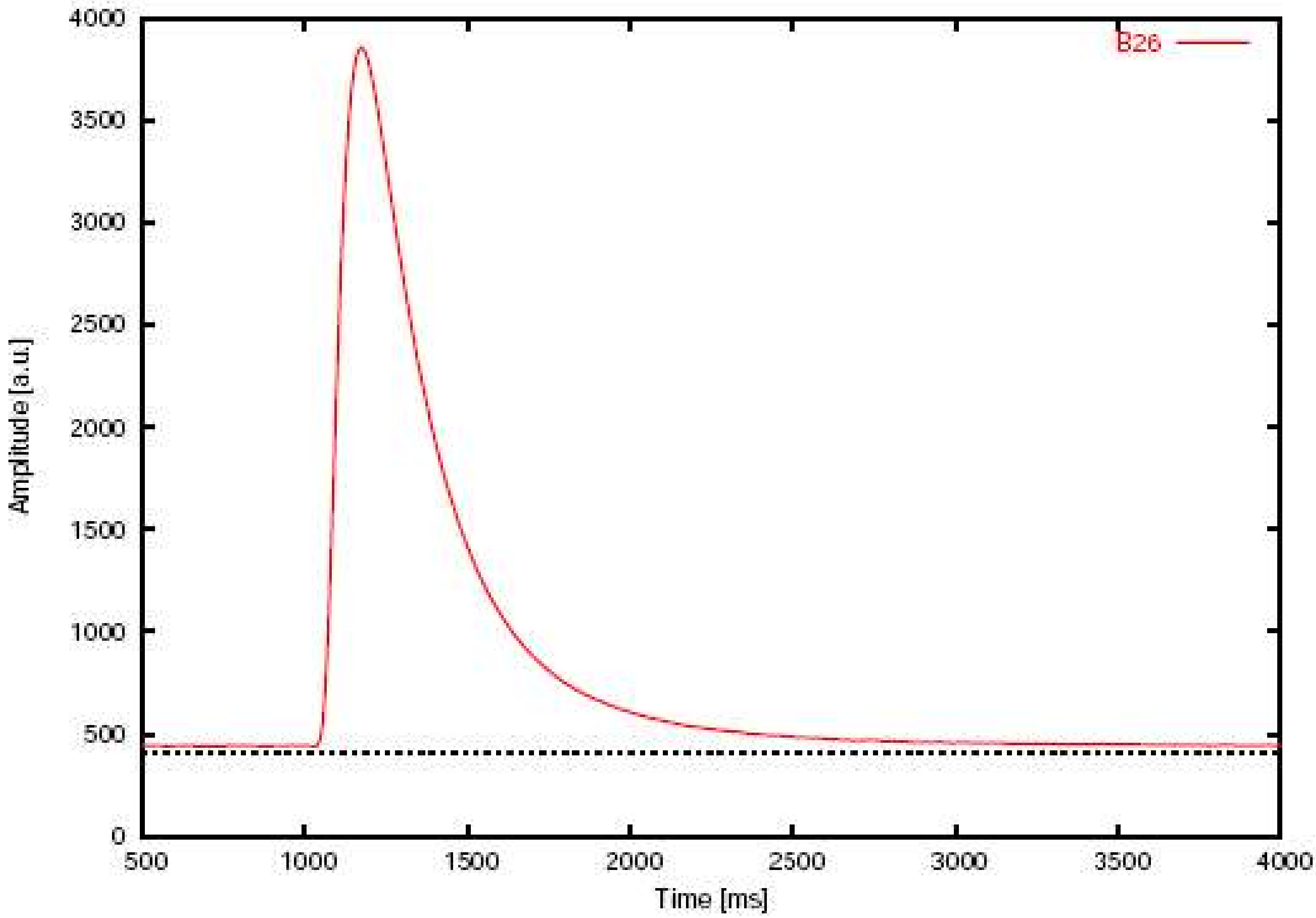



- **Phonon energy eccitation: $\varepsilon \sim K_B T \sim \mu$eV ,**

  **Statistical fluctuation: $\sigma(E) = (K_B C T^2)^{0.5} \sim 10$ eV**

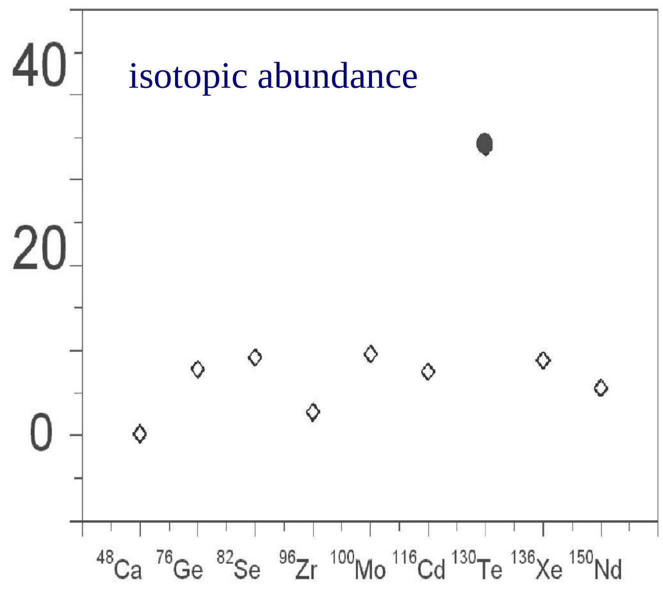
- **Typical pulse decay time: $\tau \sim C/G \sim 10^{2\text{-}3}$ ms**

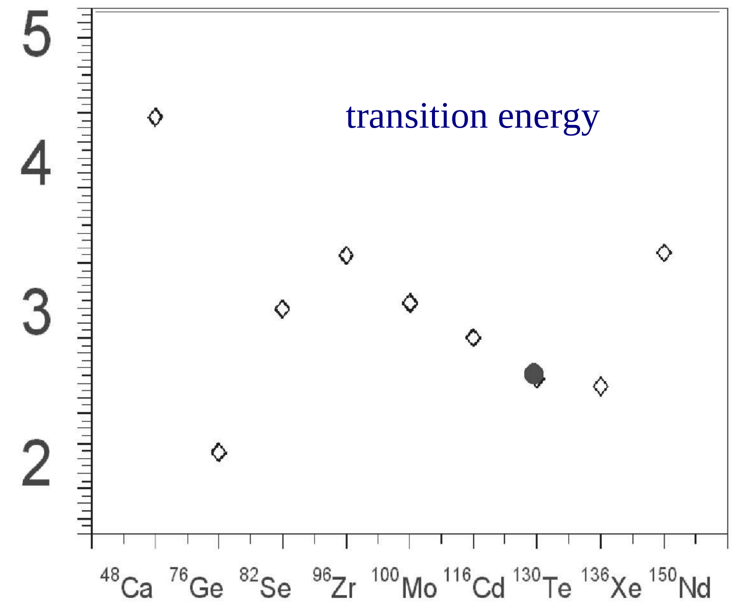
# Typical Pulse



# Why Tellurium?

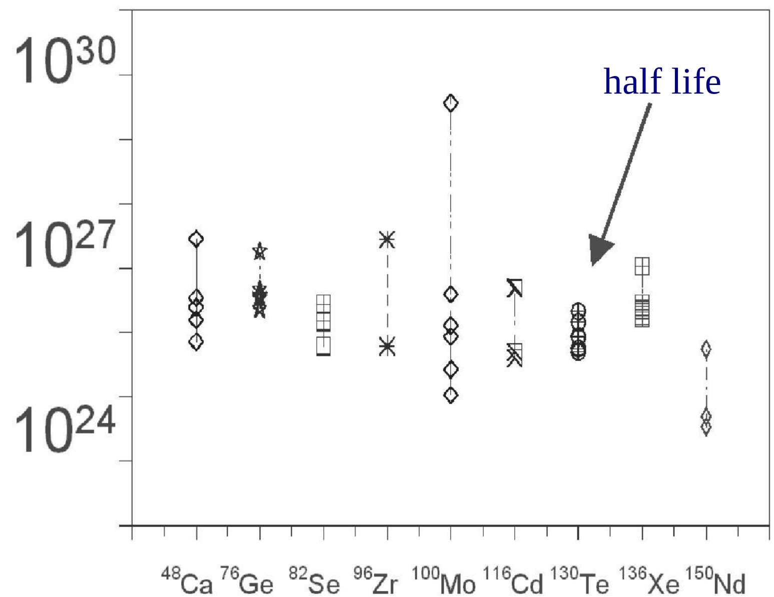
- **Active isotope: $^{130}Te$**
  - **Natural abundance**
    **33.9% ⇒ low cost**
  - **Transition energy**
    **$Q_{\beta\beta}$ = (2528.8±1.2) KeV**
    ***large phase space***
    ***low background***



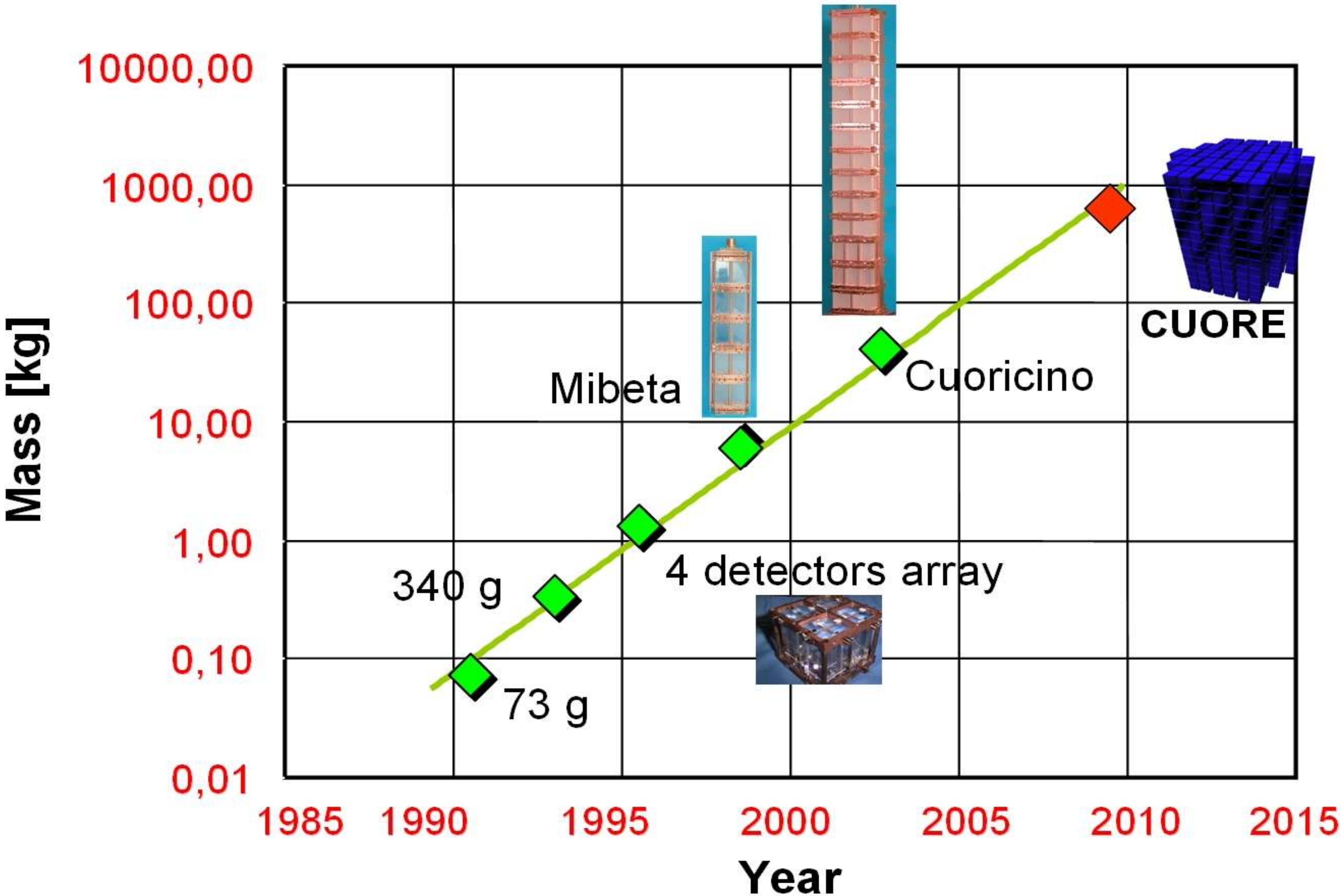

- **Predicted half life:**

$$\langle m_\nu \rangle \approx 0.3\, eV \rightarrow \tau^{\beta\beta 0\nu} \approx 10^{25}\, y$$




- **Absorber material: $TeO_2$**
  - **Low heat capacity**
  - **Possibility to grow large crystals**
  - **Good intrinsic purity**

# *Moore's scaling law of $TeO_2$ bolometers*

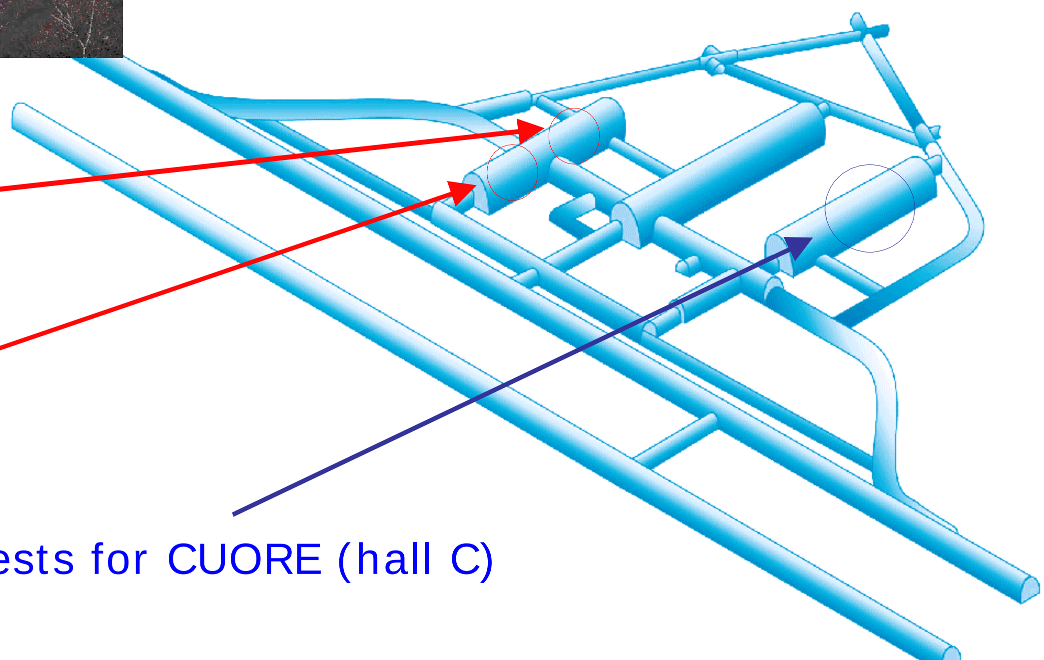


# CUOR(ICINO) @ LNGS

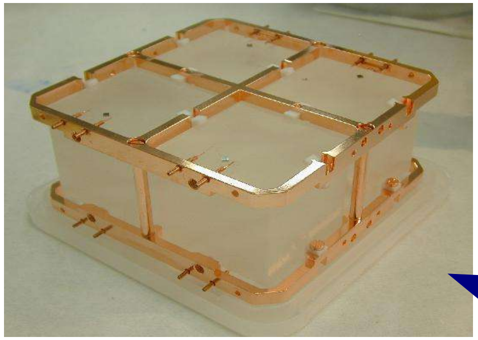
**Cuoricino** experiment is installed in the

**Underground National Laboratory**
**of Gran Sasso**
**L'Aquila – ITALY**

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



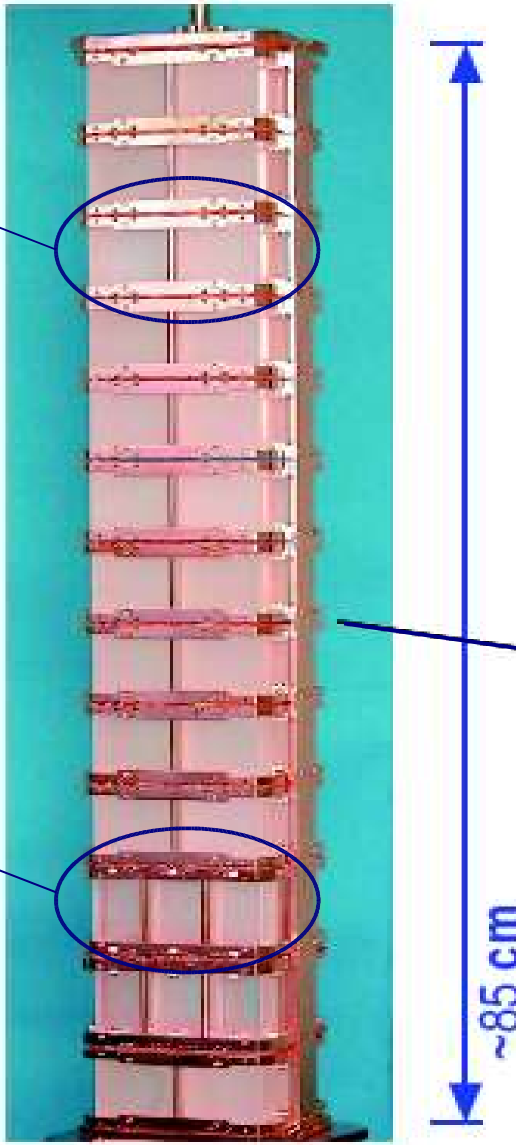
# CUORICINO Tower

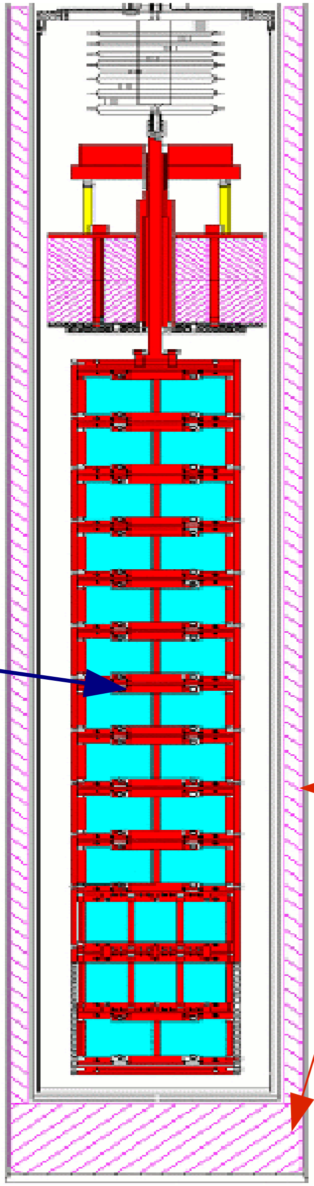


11 modules: 4 detector
5x5x5 $cm^3$=790 g each

2 modules 9 detector
3x3x6 $cm^3$=330 g each

4 enriched: 2 $^{130}$Te + 2$^{128}$Te



**Total Active mass:**

- **$TeO_2$ = 40.7 Kg**
- **$^{130}$Te = 14.1 Kg**
- **$^{128}$Te = 0.54 Kg**

**Installed in a dilution refrigerator (10 mK) surrounded by:**

- **Roman Pb inner shield (1cm) lateral**
- **20 cm Pb external shield**
- **Neutron shield: B-polyethylene ~10 cm**
- **Anti-radon box: nitrogen overpressure**

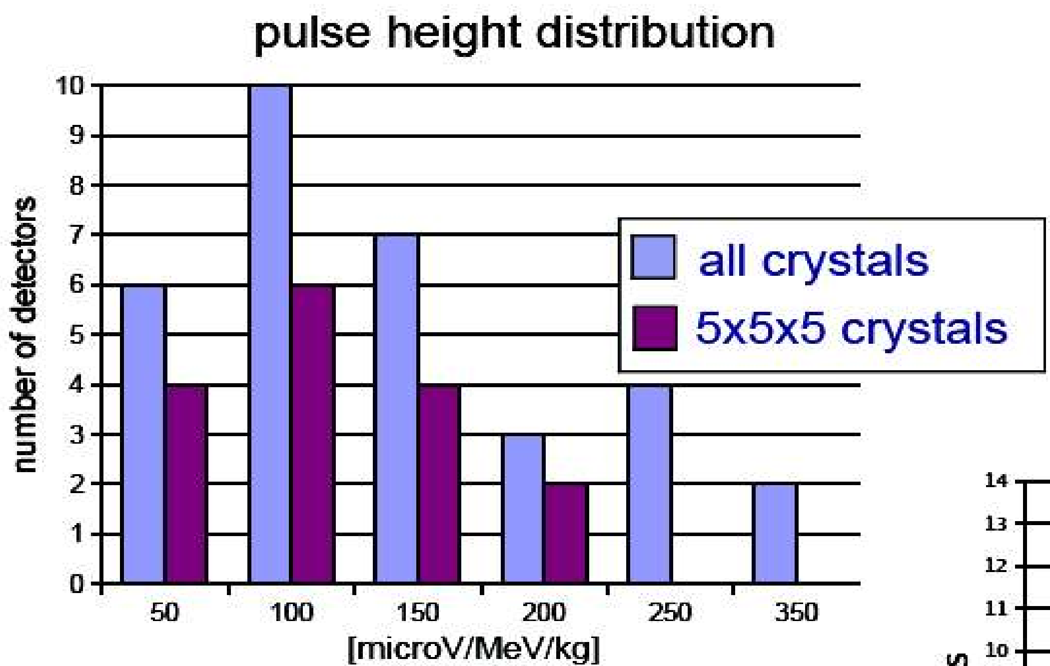
# CUORICINO assembly

- **Careful material selection: crystals grown from pre-tested activity powders**
- **Careful cleaning of PTFE, Cu and $TeO_2$ surfaces**
- **Clean conditions for detector assembling**

# Data taking and performances

- **CUORICINO duty cycle: Source calibration Th wires ~3days**
  **Bkgd measurements ~3-4weeks**

**live time ~64%**



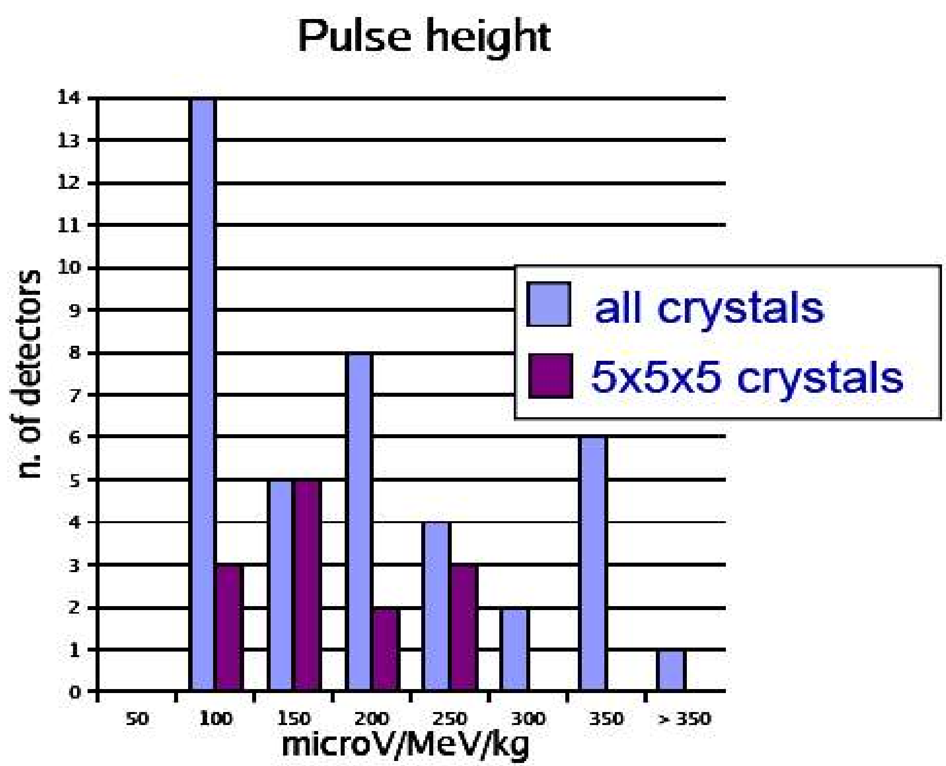

**RUN I: February -November 2003**

**Cooling down problems:**

**some electrical connection lost**

3x3x6 cm$^3$ (104±35) μV/MeV/Kg

5x5x6 cm$^3$ (120±75) μV/MeVKg




**RUN II: May -December 2004**

3x3x6 cm$^3$ (147±60) μV/MeV/Kg

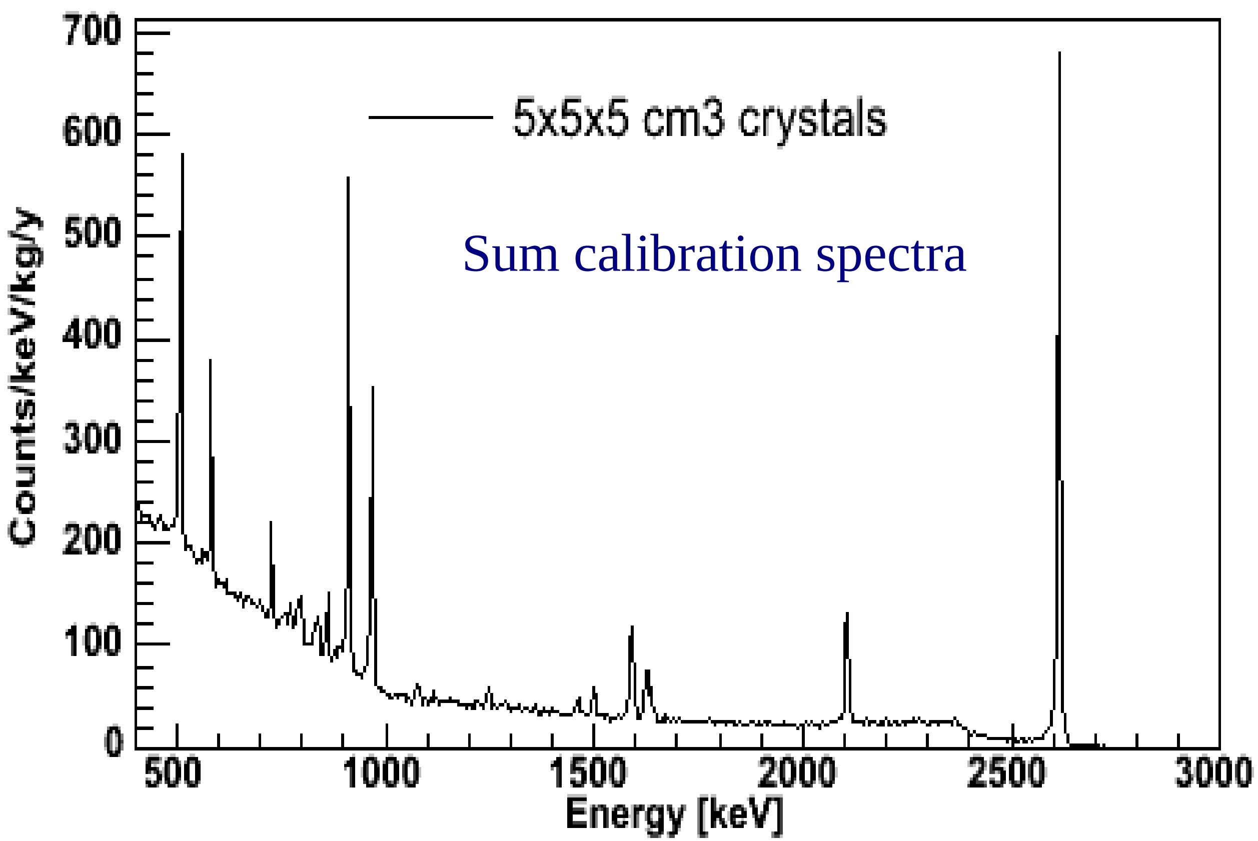
5x5x6 cm$^3$ (167±99) μV/MeV/Kg

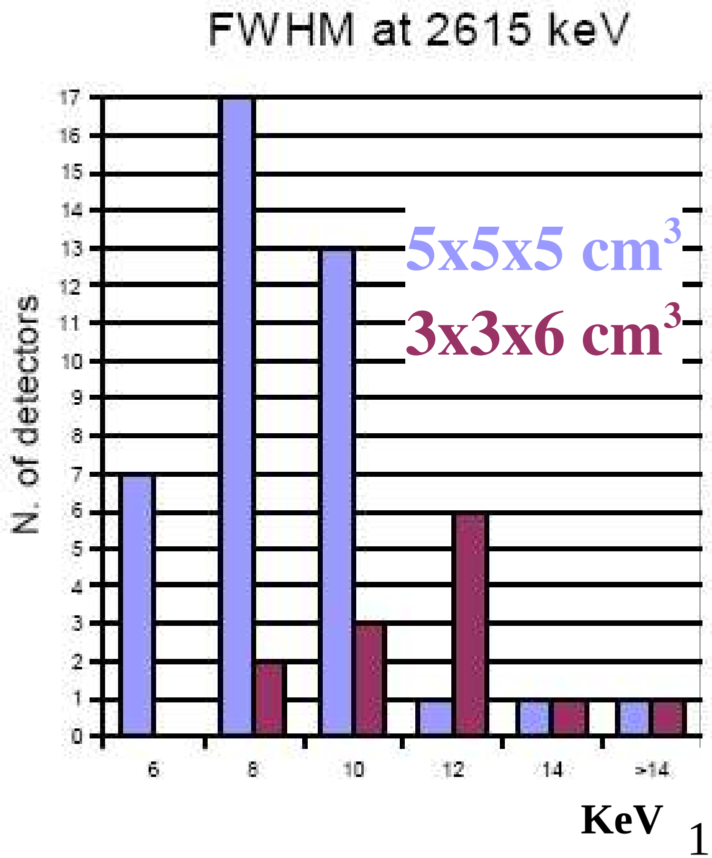
# Calibration spectra: energy resolution

- $^{232}$Th γ–source external to the cryostat:

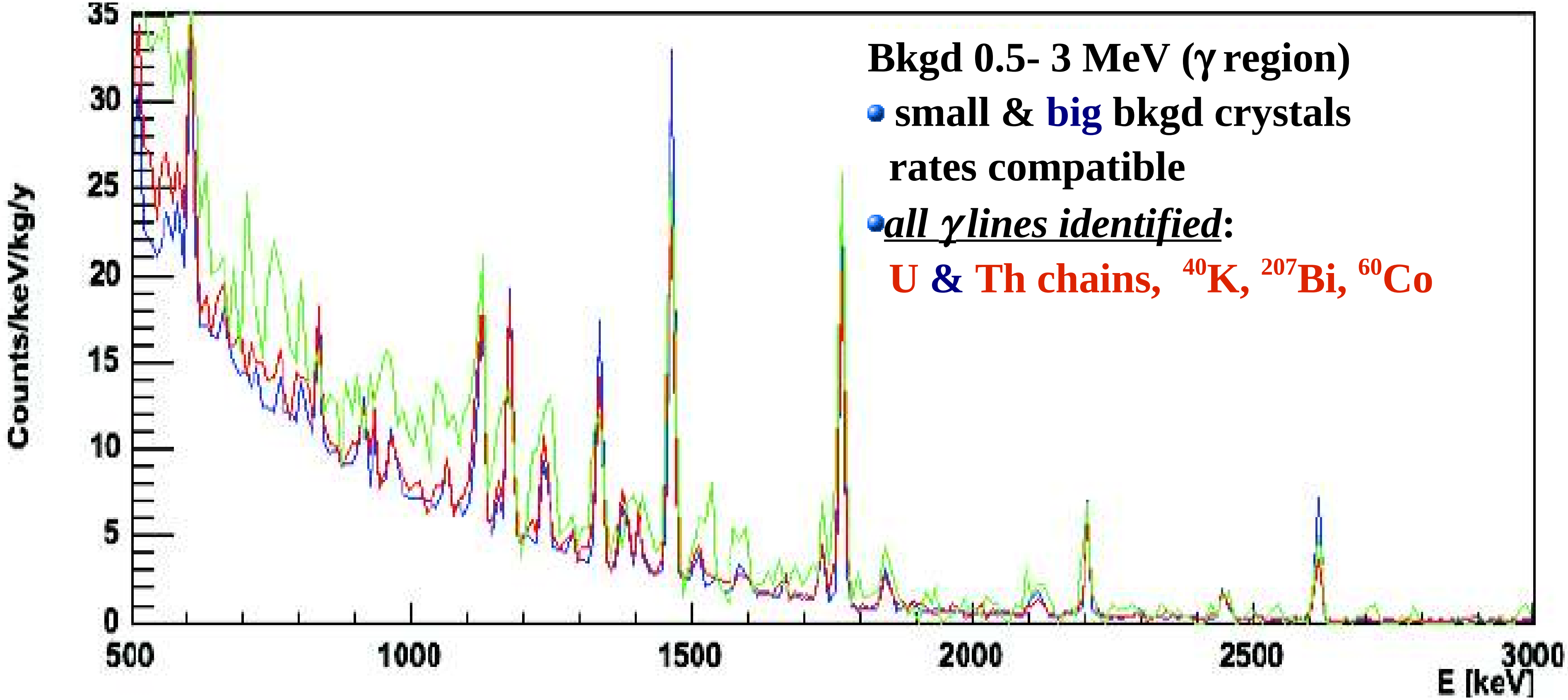
<ΔE> @2615 KeV $^{208}$Tl γ–line
average 5x5x5 cm$^3$ crystal: **FWHM 7.5±2.9 KeV**
average 3x3x6 cm$^3$ crystal: **FWHM 9.6±2.5 KeV**

**Resolution limited by:**
- **phononic ~10 eV**
- **electronic <1 KeV**
- **microphonic < 1 KeV**



# Sum background spectra




Bkgd 0.5- 3 MeV (γ region)

- small & big bkgd crystals rates compatible
- ***all γ lines identified***:
  U & Th chains, $^{40}K$, $^{207}Bi$, $^{60}Co$

<ΔE> @2615 KeV $^{208}Tl$ γ–line

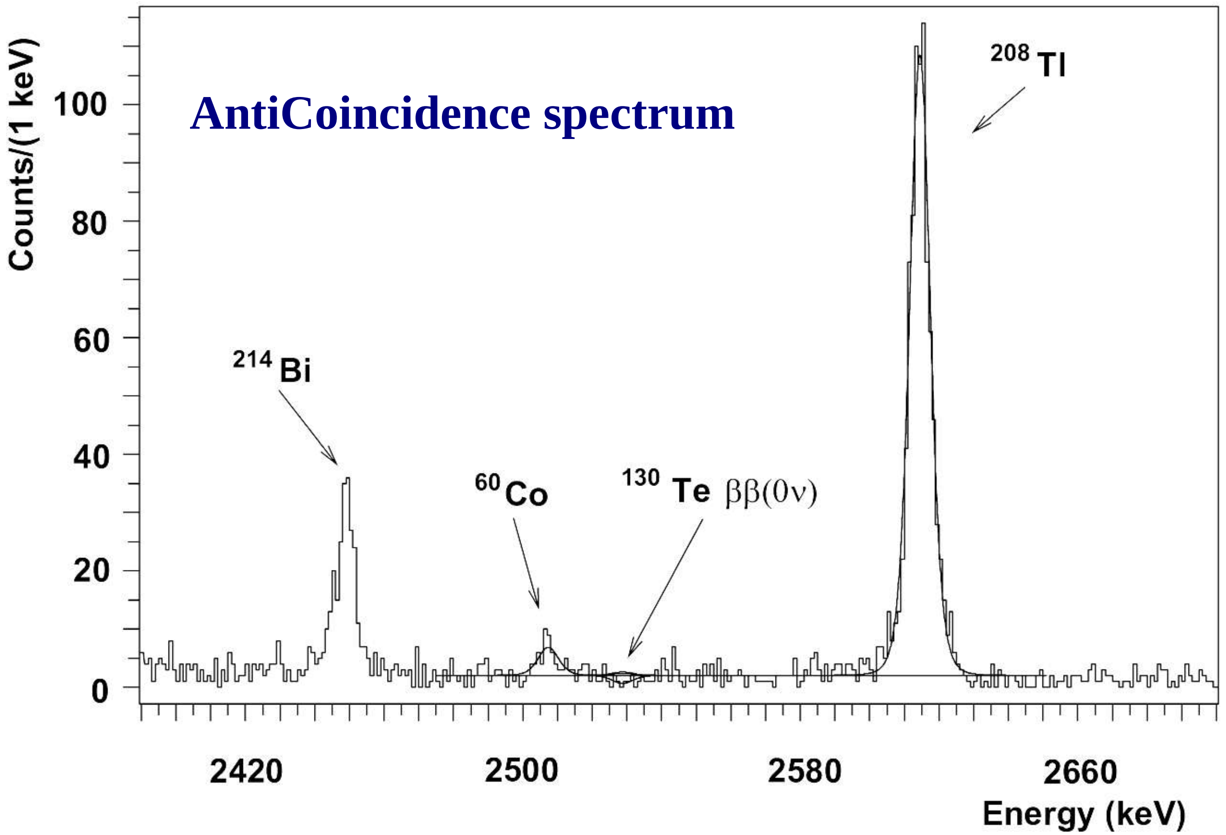
| | | |
|---|---|---|
| 5x5x5 cm$^3$ crystal | 4.3Kg $^{130}Te$•y | FWHM ~7.5KeV |
| 3x3x6 cm$^3$ natural crystal | 0.5Kg $^{130}Te$•y | FWHM ~12KeV |
| 3x3x6 cm$^3$ enriched crystal | 0.2Kg $^{130}Te$•y | peak not visible |

# CUORICINO ββ0ν result

- Total statistics: **3.09( $^{130}$Te) Kg•y (1.43•10$^{25}$ nuclei•y)**

**Phys. Rev. Lett. 95 142501 2005**

- ML fit in **2470-2560 KeV** region
  N gaussian response function with individual FWHM @ 2615KeV
- **No peak found** @ ββ0ν energy
- Bkgd (ββ0ν region): **0.18 ±0.01 c/KeV/Kg/y**
- Detector efficiencies: **~85%**
- Fitting systematic error: **~5%**




$$\tau_{1/2}^{\beta\beta 0\nu} > 1.8\cdot 10^{24}\, y \,@\, 90\, C.L. \quad \Rightarrow \quad \langle m_{\beta\beta 0\nu}\rangle < [0.2 - 1.1]\, eV$$

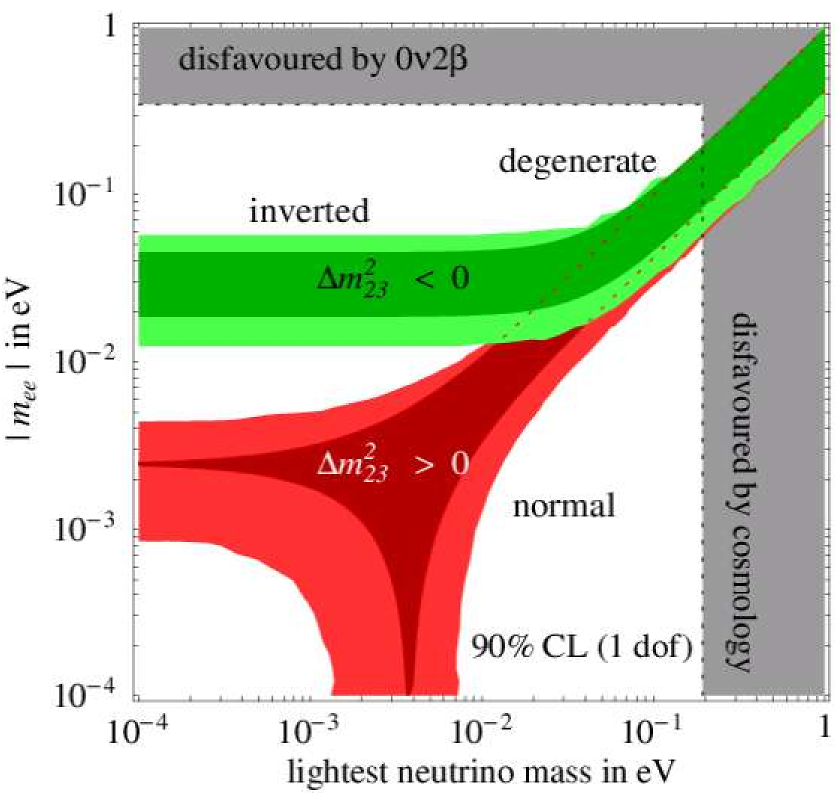
Expected sensitivity in 5 years : $\langle m_\nu \rangle < [0.09 - 0.8]\, eV$

**Spread due to NME uncertainties**

# CUORICINO sensitivity & discovery potential

**CUORICINO results:** $\langle m_{\beta\beta0\nu}\rangle = \sum m_{\nu_k}\eta_k |U_{ek}|^2 < [0.2-1.1]\,eV$

Klapdor-Kleingrothaus HM: $\langle m_\nu\rangle < [0.1 \div 0.9]\,eV$ $\langle m_\nu\rangle = 0.44\,eV$




**A. Strumia, F. Vissani hep-ph 0503246**

- Could CUORICINO test HM result?

**Nuclear Matrix Element Staudit et al.**

| Ref.: | (20) | (80) | (81) | (82) | (24,83) | (84) |
|---|---|---|---|---|---|---|
| Expected event number in 3 y in a 16 keV energy window (2 FWHM) | 141 | 37 | 251 | 57 | 44 | 53 |
| S/N ratio (σ) | 7.4 | 2.0 | 13 | 3.0 | 2.3 | 2.8 |

1 σ BKG fluctuation = $(0.18 * 16 * 40.7 * 3)^{0.5} = 19$

- **Good chances to have a positive indication**
- **But : cannot falsify HM if no signal is seen**

# Present experimental situation

- positive result
- running experiments

| isotope | experiment | latest result | i.a. [%] | $Q_{\beta\beta}$ [eV] | enrich [%] | exp [kg×y] | tech | material | $\tau_{1/2}^{0\nu}$ [$10^{23}$ y] | $\langle m_\nu \rangle$ [eV] min | $\langle m_\nu \rangle$ [eV] max |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $^{48}$Ca | Elegant VI | 2004 | 0.19 | 4271 | - | 4.2 | s | $CaF_2$ | 0.14 | 7.20 | 44.70 |
| $^{76}$Ge | Heidelberg/Moscow | 2001 | 7.8 | 2039 | 87 | 71.7 | i | Ge | 190.0 | *0.12* | 1.00 |
| $^{76}$Ge | Klapdor et al. | 2004 | 7.8 | 2039 | 87 | 71.7 | i | Ge | 120.0 | *0.44* | - |
| $^{82}$Se | NEMO-3 | 2005 | 9.2 | 2995 | 97 | 0.93 | t | Se | 1.0 | 1.75 | 4.86 |
| $^{100}$Mo | NEMO-3 | 2005 | 9.6 | 3034 | 95-99 | 6.9 | t | Mo | 4.6 | 0.66 | 2.81 |
| $^{116}$Cd | Solotvina | 2003 | 7.5 | 3034 | 83 | 0.5 | s | $CdWO_4$ | 1.7 | *1.70* | - |
| $^{130}$Te | Cuoricino | 2005 | 33.8 | 2529 | - | 5 | b | $TeO_2$ | 18.0 | 0.20 | 1.10 |
| $^{136}$Xe | DAMA | 2002 | 8.9 | 2476 | 69 | 4.5 | s | Ge | 12.00 | 1.10 | 2.90 |
| $^{150}$Nd | Irvine TPC | 1997 | 5.6 | 3367 | 91 | 0.01 | t | $Nd_2O_3$ | 0.012 | *3.00* | - |

Range of uncertainties in NME

- s scintillation
- i ionization
- t tracking
- b bolometric

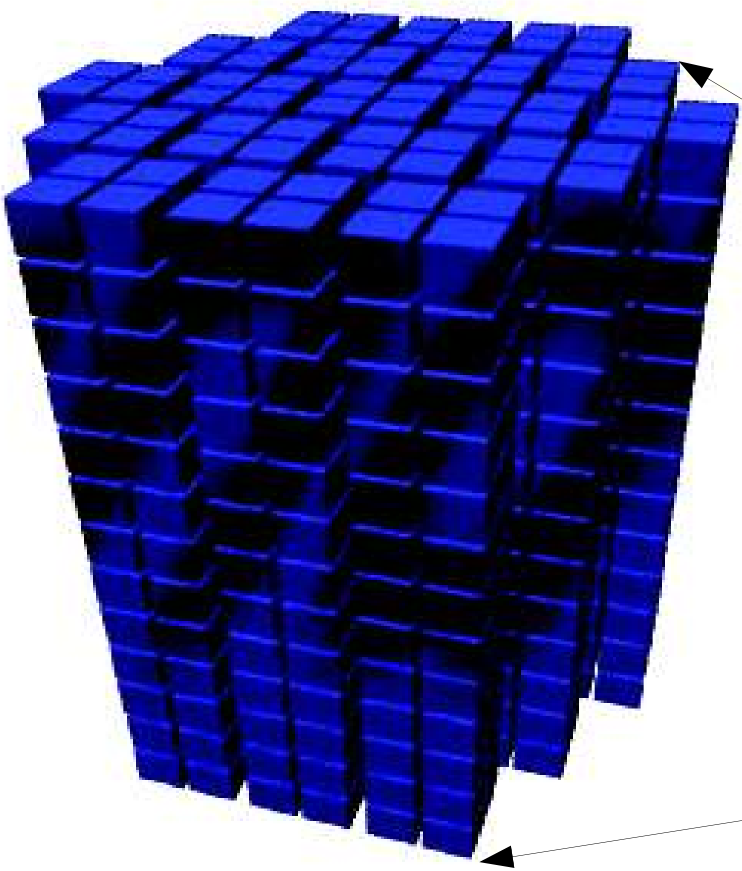
# *Cryogenic Underground Observatory for Rare Events*

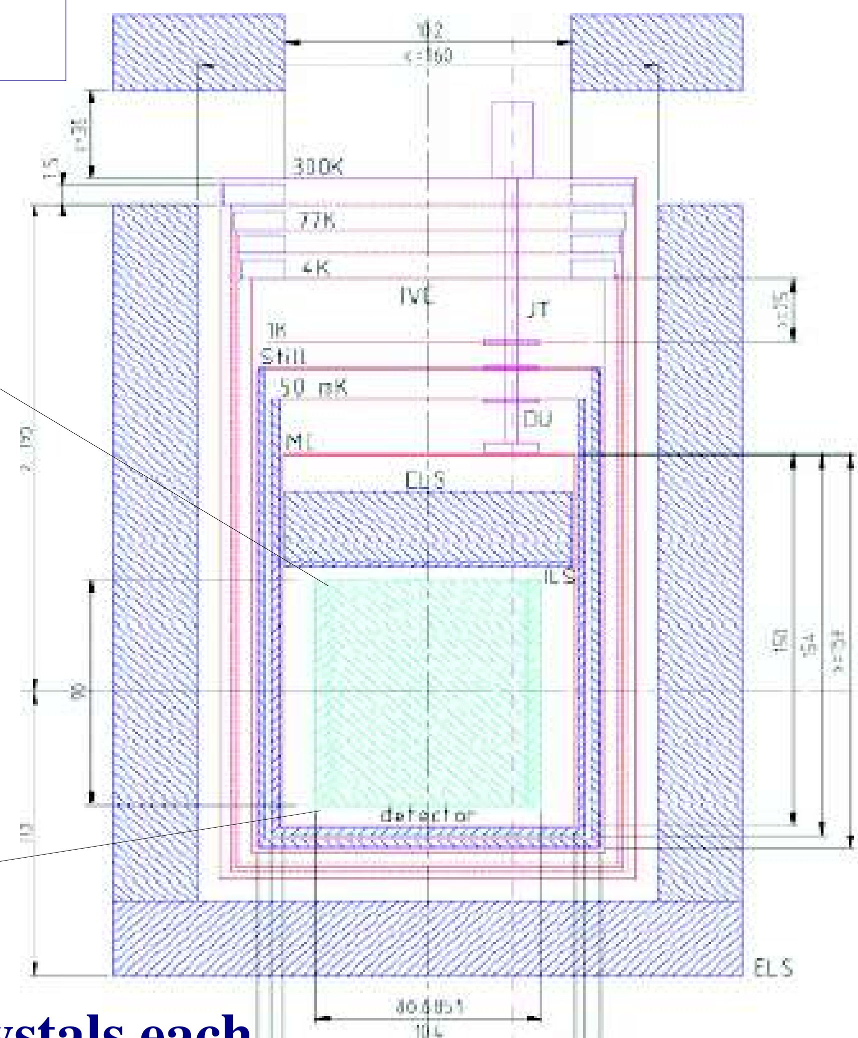
- $\beta\beta0\nu$, Cold Dark Matter, Axion searches    **proposal hep/ph 0501010**

**Closed packed array of 988 $TeO_2$ 5x5x5 $cm^3$ crystals**

**741 Kg $TeO_2$ $\Rightarrow$ 203Kg $^{130}Te$**

**Single dilution refrigerator ~10 mk**

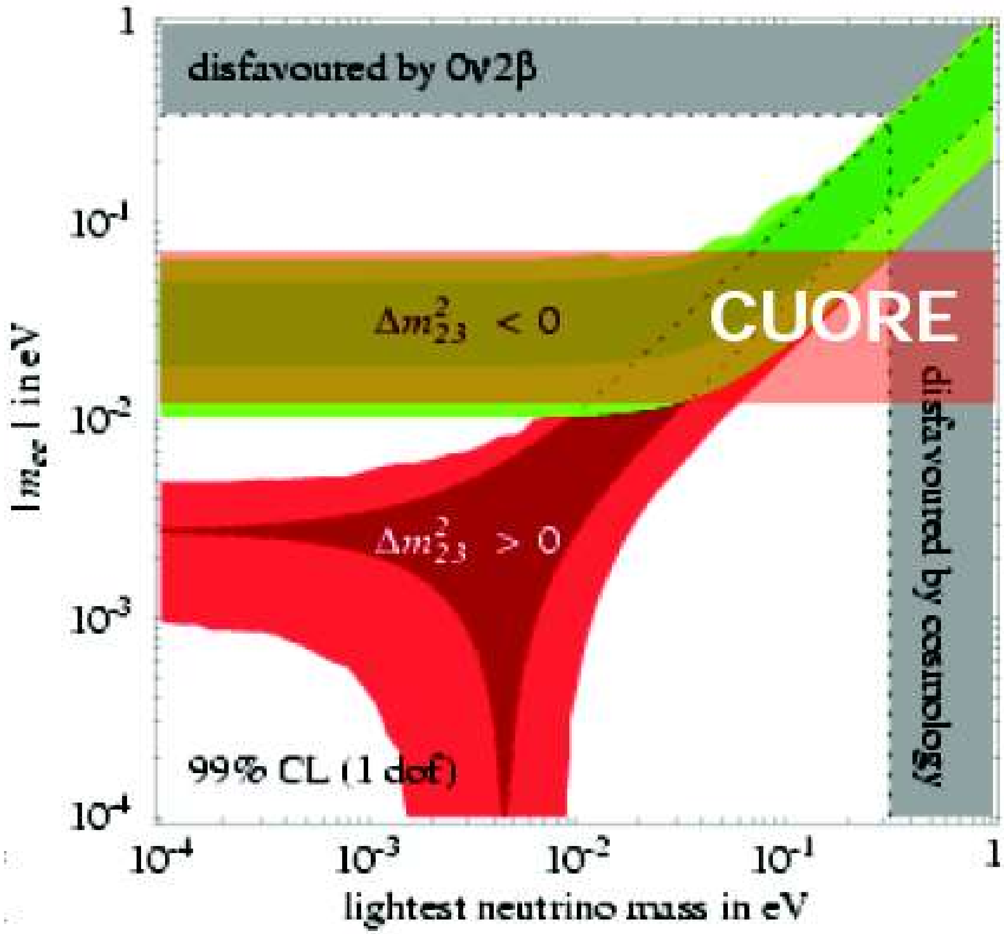





**19 CUORICINO like towers:  13 planes of 4 crystals each**

# CUORE expected sensitivity

**CUORE ββ0ν sensitivity will depend strongly on the bkgd level and detector performance**




**CUORE GOAL:**

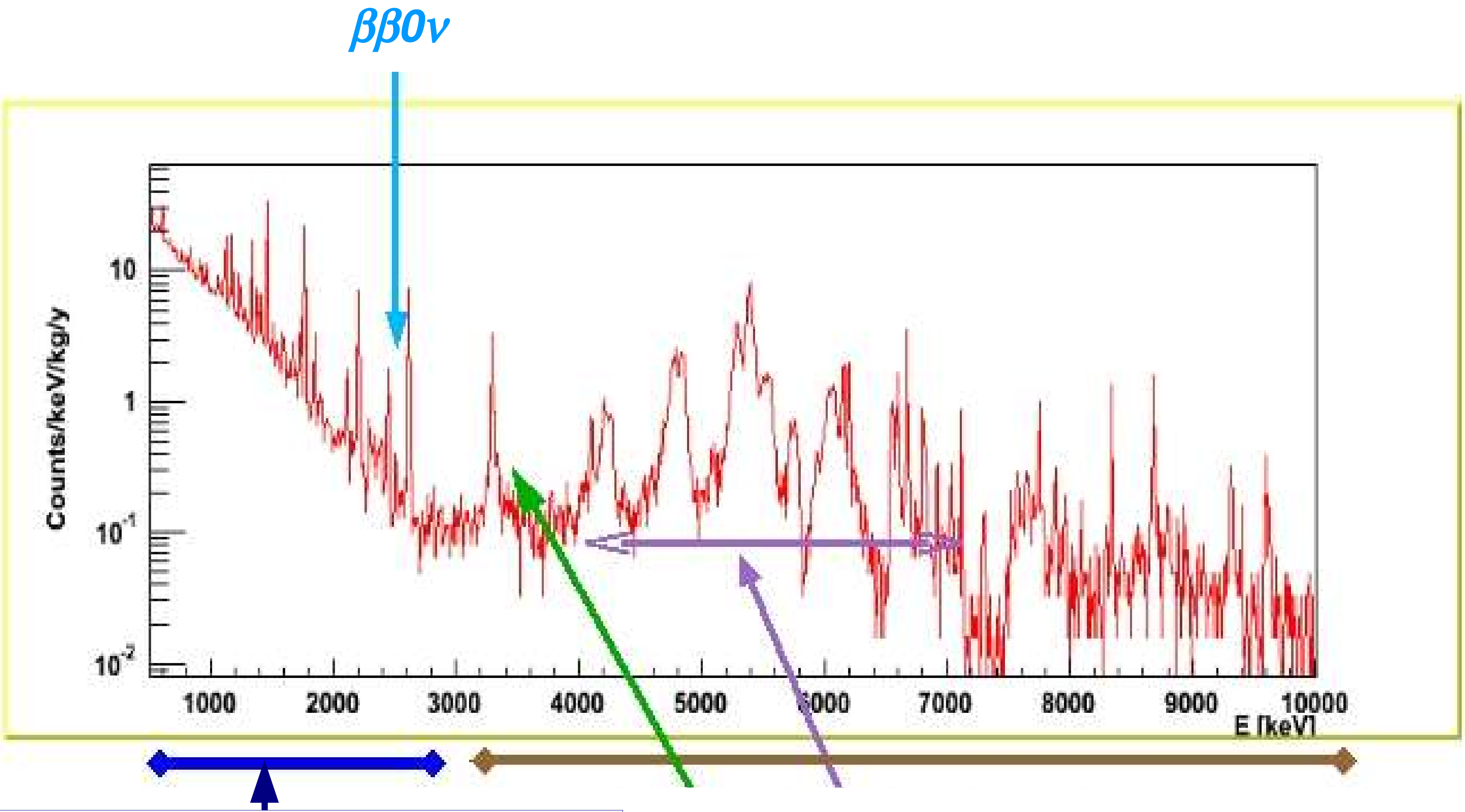
**test inverse hierarchy: 10-50 meV**

**In five years of data taking**

| B(counts/keV/kg/y) | Δ(keV) | $T_{1/2}$(y) | $\vert\langle m_\nu\rangle\vert$ (meV) |
|---|---|---|---|
| 0.01 | 10 | $1.5\times10^{26}$ | 23–118 |
| 0.01 | 5 | $2.1\times10^{26}$ | 19–100 |
| 0.001 | 10 | $4.6\times10^{26}$ | 13-67 |
| 0.001 | 5 | $6.5\times10^{26}$ | 11-57 |

**Spread due to NME uncertainties: main obstacle to answer basic questions on ν nature**

# CUORICINO background

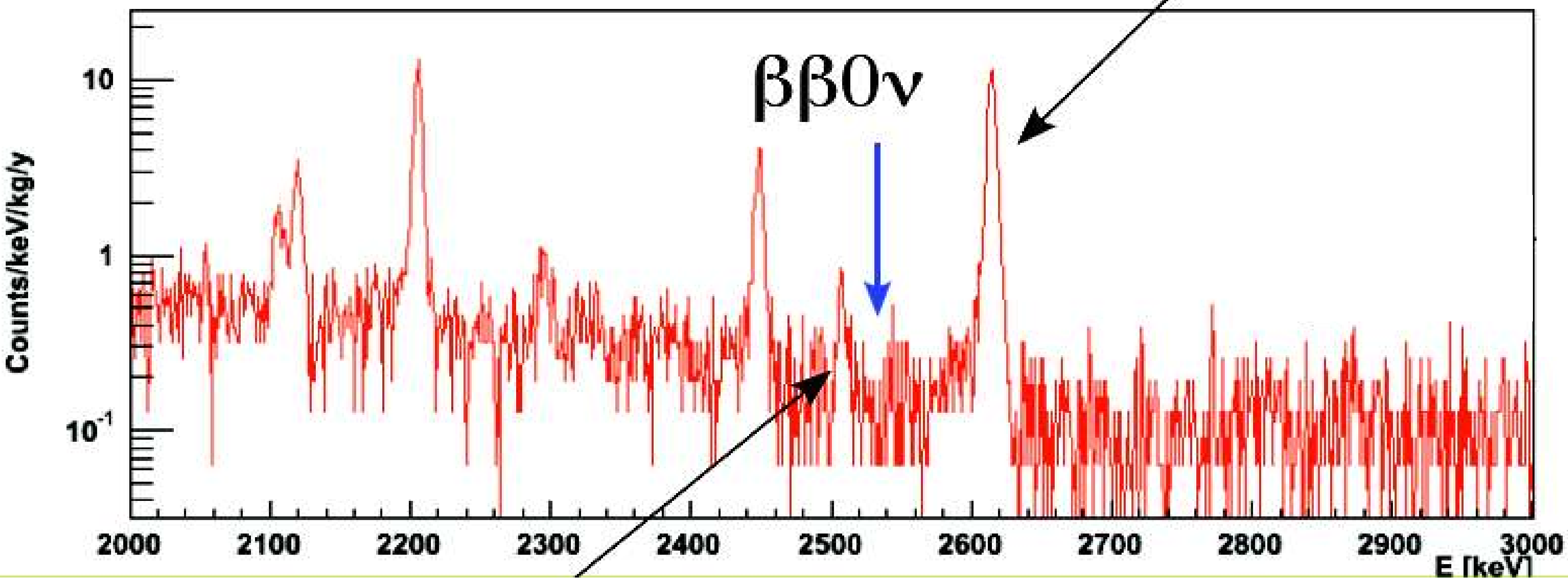



•Gamma region: dominated by γ's and β' s
highest γ line:
2615keV $^{208}$Tl line tail from $^{232}$Th

Alpha region: all α' s
internal and surfaces contamination in Cu and Te

# CUORICINO background: ββ0ν region

2615 KeV $^{208}$Tl line tail




2505 KeV $^{60}$Co line (1173+1332 KeV gamma)

- **CUORICNO ββ0ν background:**
  - **~30% 2615keV $^{208}$Tl line tail**: from **Th** chain via multi-Compton events. *Source located in the cryostat*
  - **~60% flat bkgd**: degraded α particles from **crystal surface(20%)** & **material facing crystals (50%)**
- ~**negligible** contribution from 2505 KeV $^{60}$Co tail due *Cu cosmogenic activation*

# CUORICINO vs CUORE background

**CUORE Evaluation (MonteCarlo simulation based on CUORICINO, miDBD, Ge measurements)**

- **Neutron & environmental** background reduced by **lead and neutron shield**
- **Cosmogenic Cu and Te activation** reduced by **underground storage of materials**
- $\beta\beta2\nu$ decay contribution < **$10^{-3}$ counts/Kg/keV/y**

no problem

- **Bulk contaminations: $TeO_2$ ~$10^{-13}$g/g, Cu ~$10^{-12}$g/g** $\Rightarrow$ $2 \bullet 10^{-3}$ **counts/Kg/keV/y**

  2615keV $^{208}$Tl reduced by properly shielding in CUORE cryostat + selection of construction materials

- **Surface contamination ~$10^{-9}$g/g for $TeO_2$ & Cu** $\Rightarrow$ $7 \bullet 10^{-2}$ **counts/Kg/keV/y**

problem!!

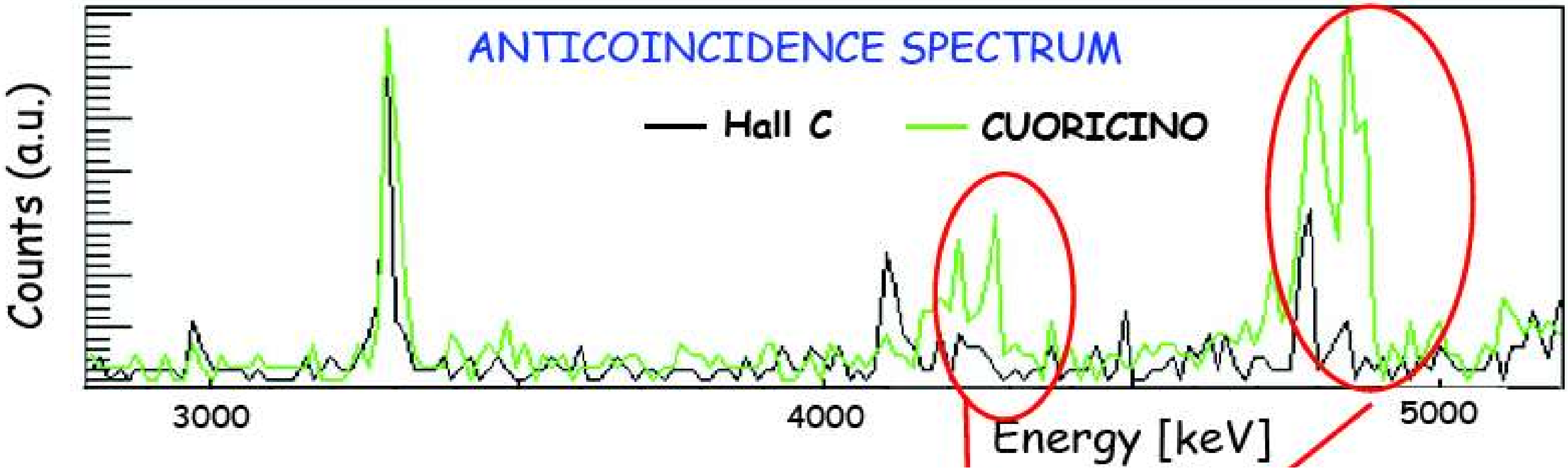
Reduced by **compact and granular** CUORE structure **(self-shielding detector)** but not enough

***to reach CUORE goal: require reduction factor 4 for $TeO_2$ & 10 for Cu surface***

# CUORE R&D: passive bkgd rejection

**Cleaning test (Hall C  Sept-Nov 2004):**

- **Cu: etching, electro-polishing, passivation**
- **Crystal: etching (Nitric acid),  lapping with clean powder (2μ $SiO_2$)**
- **New assembling procedure with selected materials**

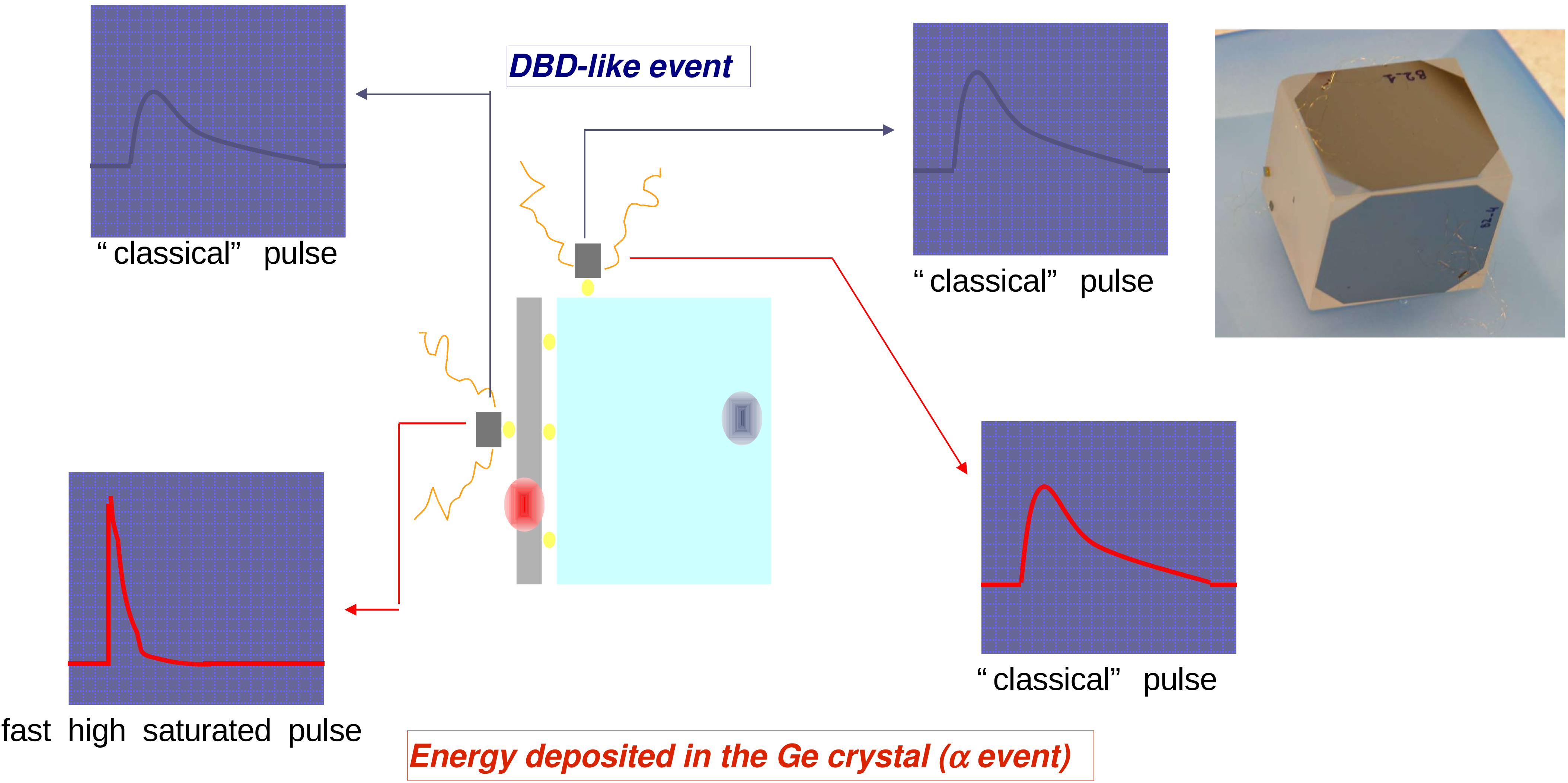



- **Reduction of a factor 4 on crystal surface contamination(*CUORE milestone reached*) and a factor 2 on Cu surfaces (still a factor 5 missing)**
- **Excluded contribution from Wires, Teflon, Thermistors**

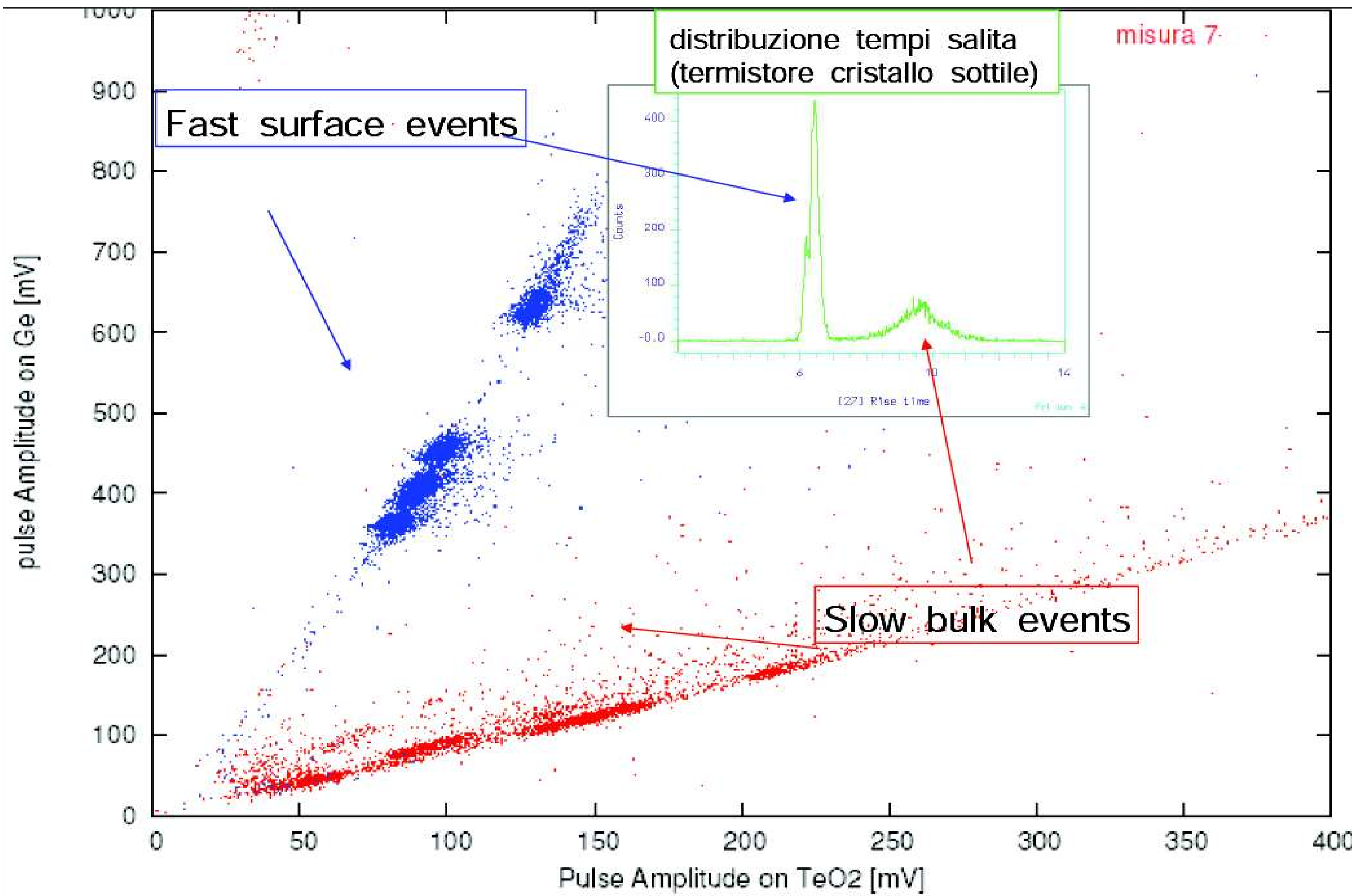
**- New passive procedure (plasma cleaning)**

# *CUORE R&D:active bkgd rejection*

**Surface sensitive detectors:** ***composited bolometer with a thin Ge, SI, te02 crystal***



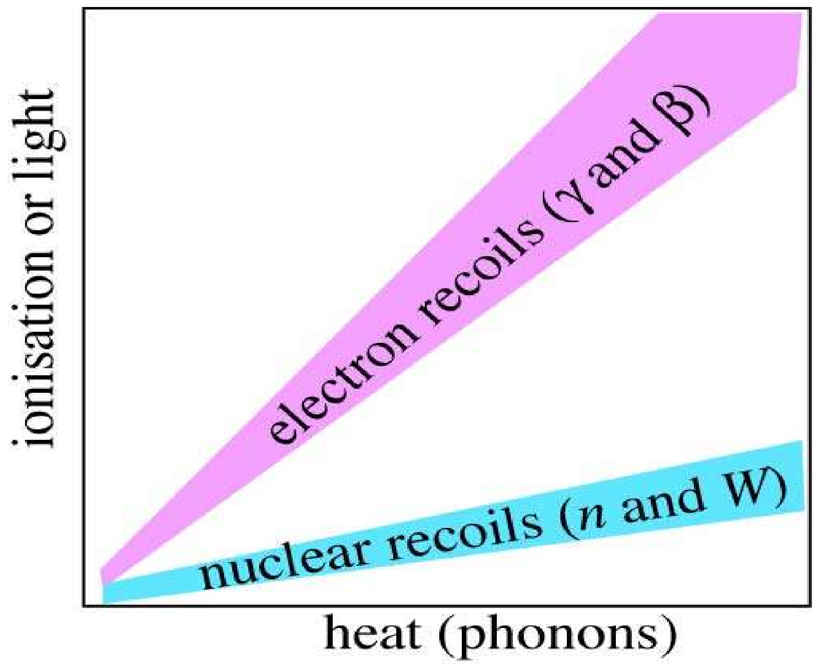
# CUORE R&D: active bkgd rejection

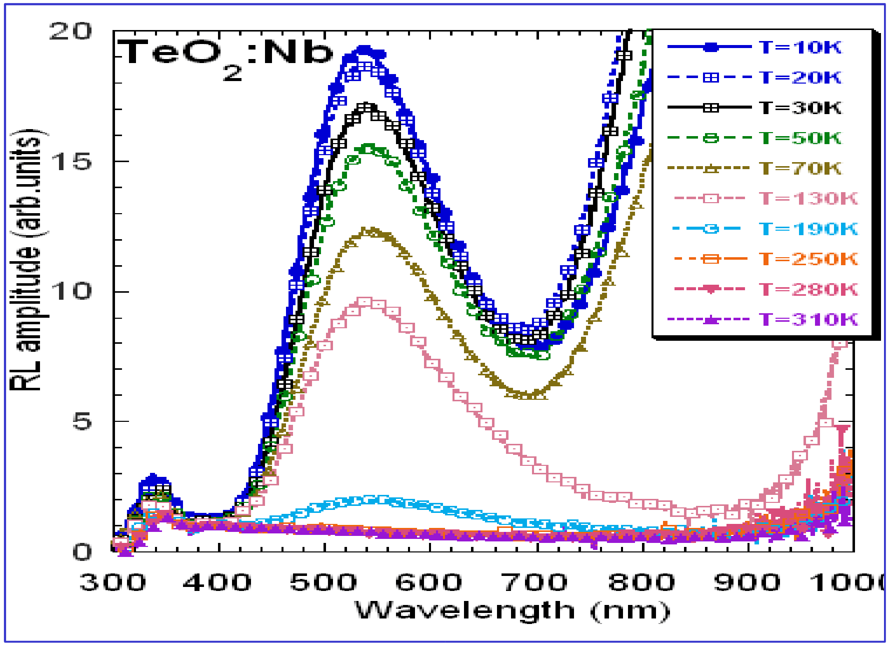


# CUORE R&D: scintillating crystal

Rome

- Measure heat phonon and light to disentangle β, γ from n,W
- Crucial for dark matter search: wimp ⇒ elastic scattering on nuclei



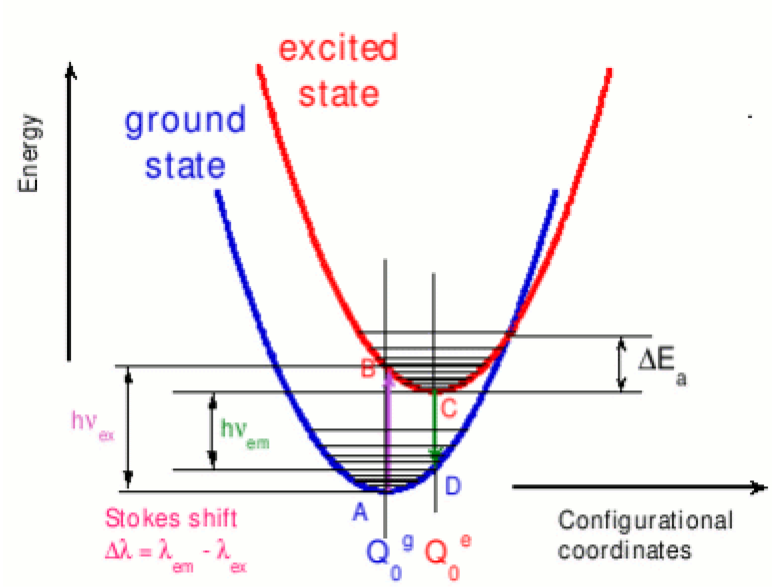

Mg, Mn, Nb, Zr doped $TeO_2$ crystal

First results: X ray excited steady-state luminescence

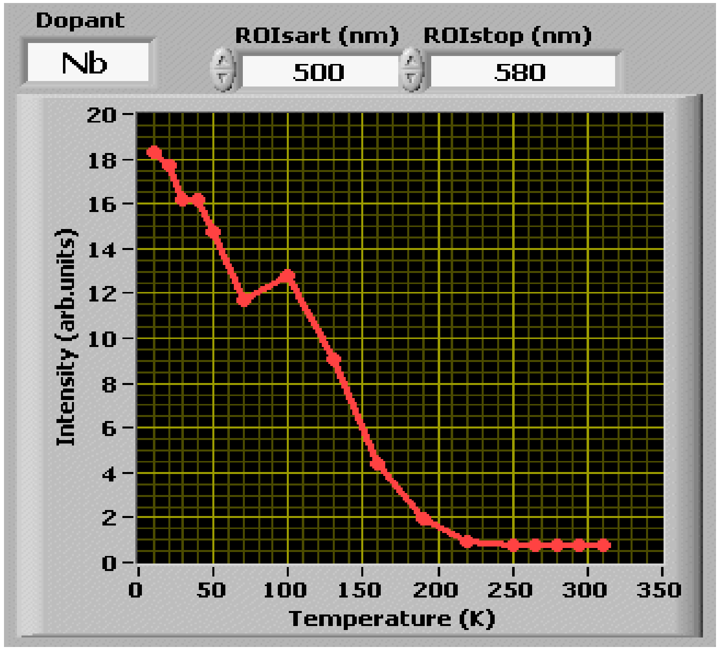
# CUORE R&D: scintillating crystal

Rome

## Thermal quenching




$$q(T)=\frac{1}{1+C\cdot e^{-\frac{\Delta E_a}{k_B\cdot T}}}$$




**Next steps:**

- **Low temperature photoluminescence**
- **Specific heat of doped crystal**
- **Search for best dopant concentration**

**Echoes in "inorganic scintillators"world : scintillating bolometer taken into account for the first time @ scint05**

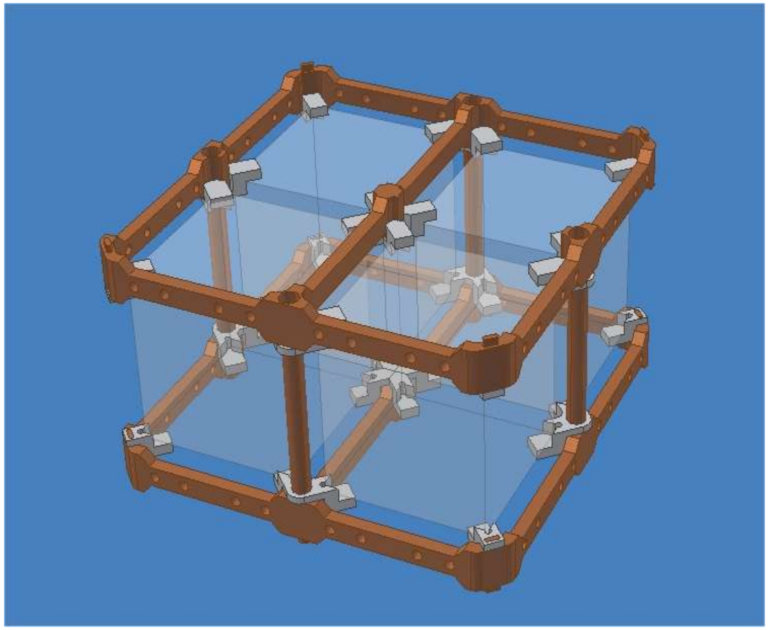
# R&D: new CUORE structure

CUORE = 16 · CUORICINO ⇒ impossible to use CUORICINO assembly procedure

Rome

- Goal:
  - reduce to a minimum Cu facing crystals
  - simplify assembly procedure and material cleaning (eliminate screws)
  - improve reproducibility
  - better thermal & mechanical coupling

*can use only Teflon and Cu*

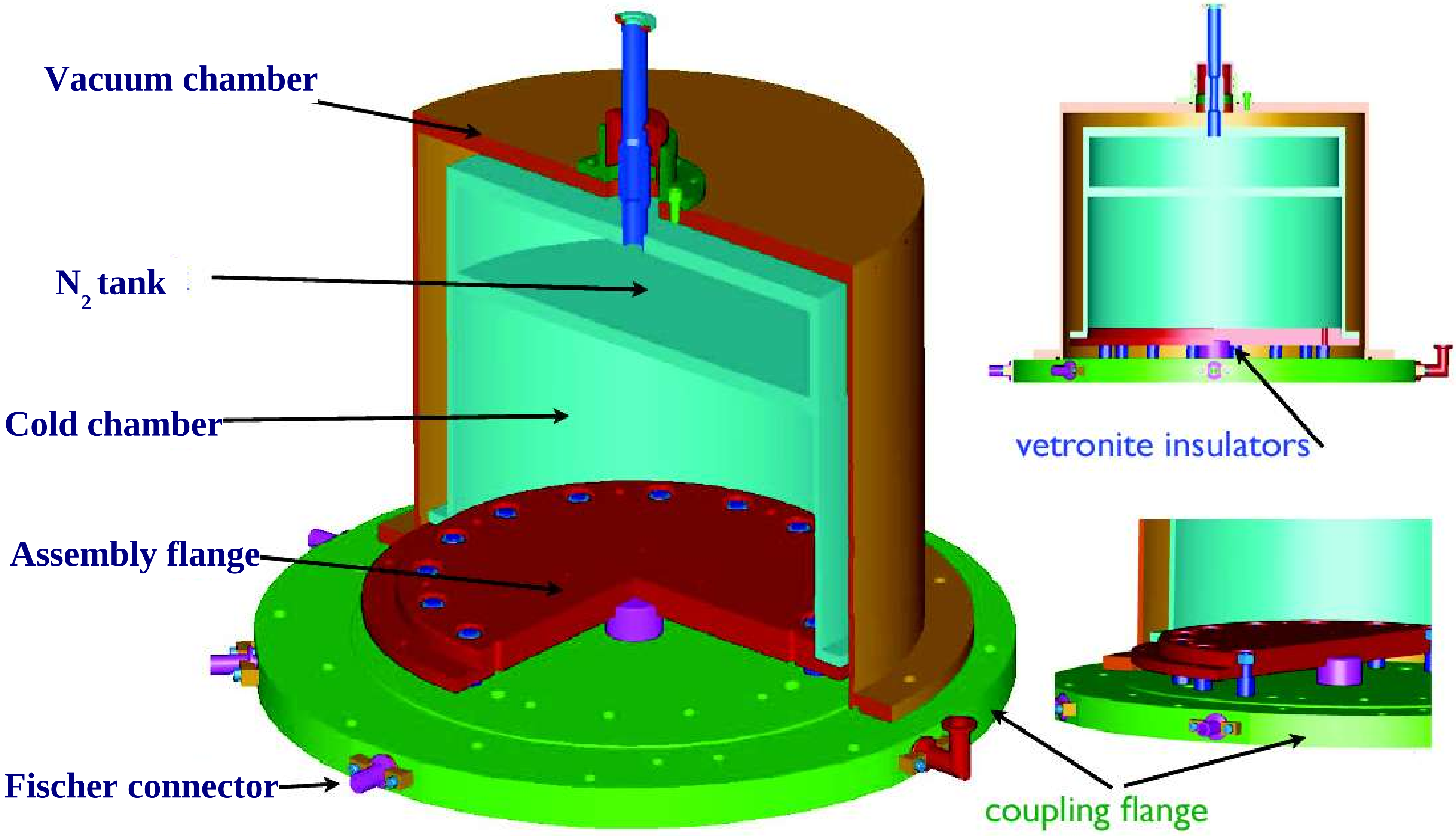


- Vibrational test performed in Collaboration with Enea Lab
  - hot test @ room temperature
  - cold test @$LN_2$ temperature (90% total thermal contraction)
- Study the modal cage behavior w/out crystals
  - Optimal stress to hold crystals bound to the frame
  - check reproducibility
  - check stability after thermal cycle

# *The pot*

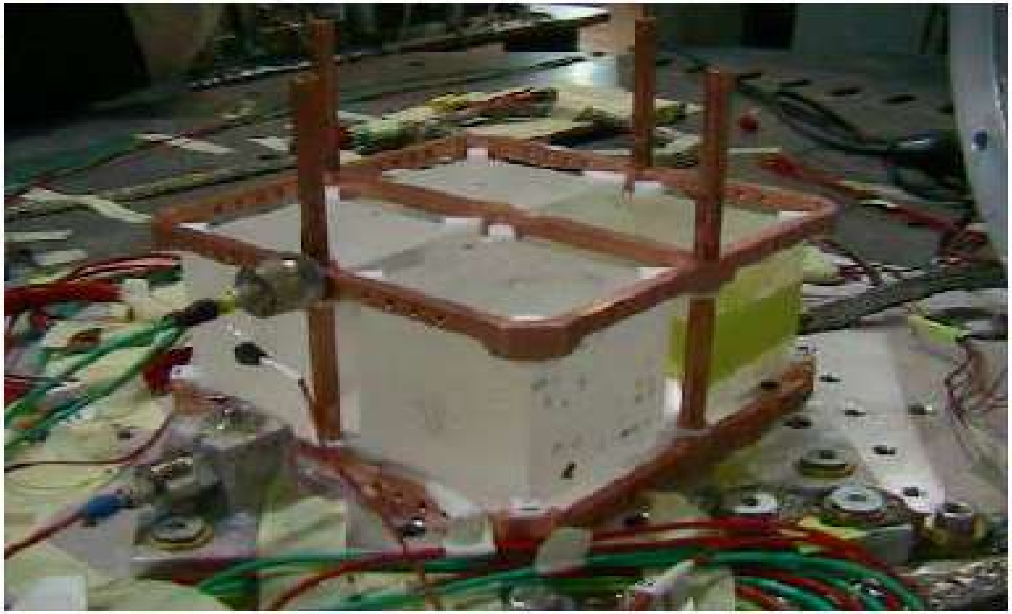
**Rome**

**The “Pot”: design, project & realization by Corrado Gargiulo**



# The pot in reality

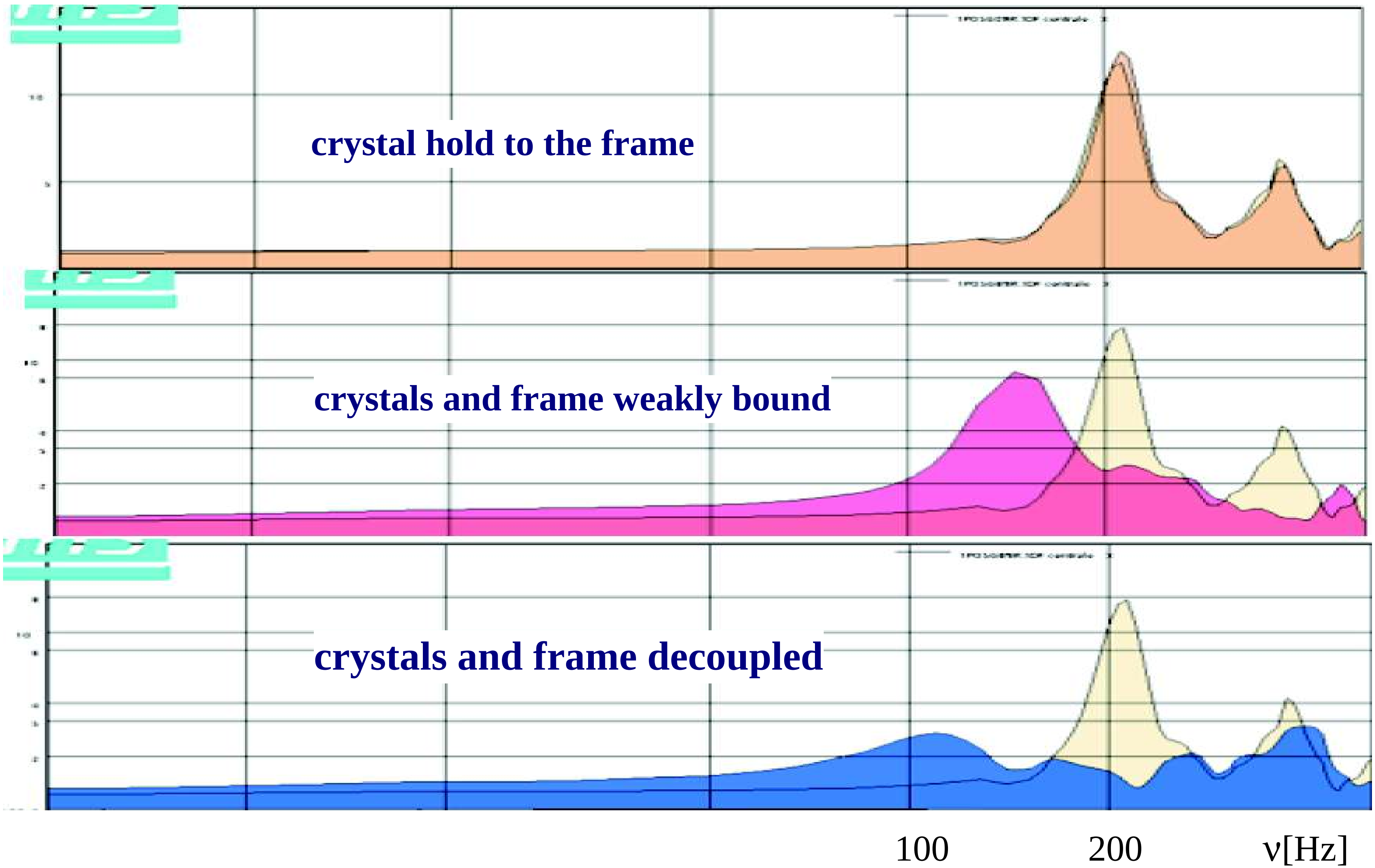
Rome



# The Analysis

**Rome**

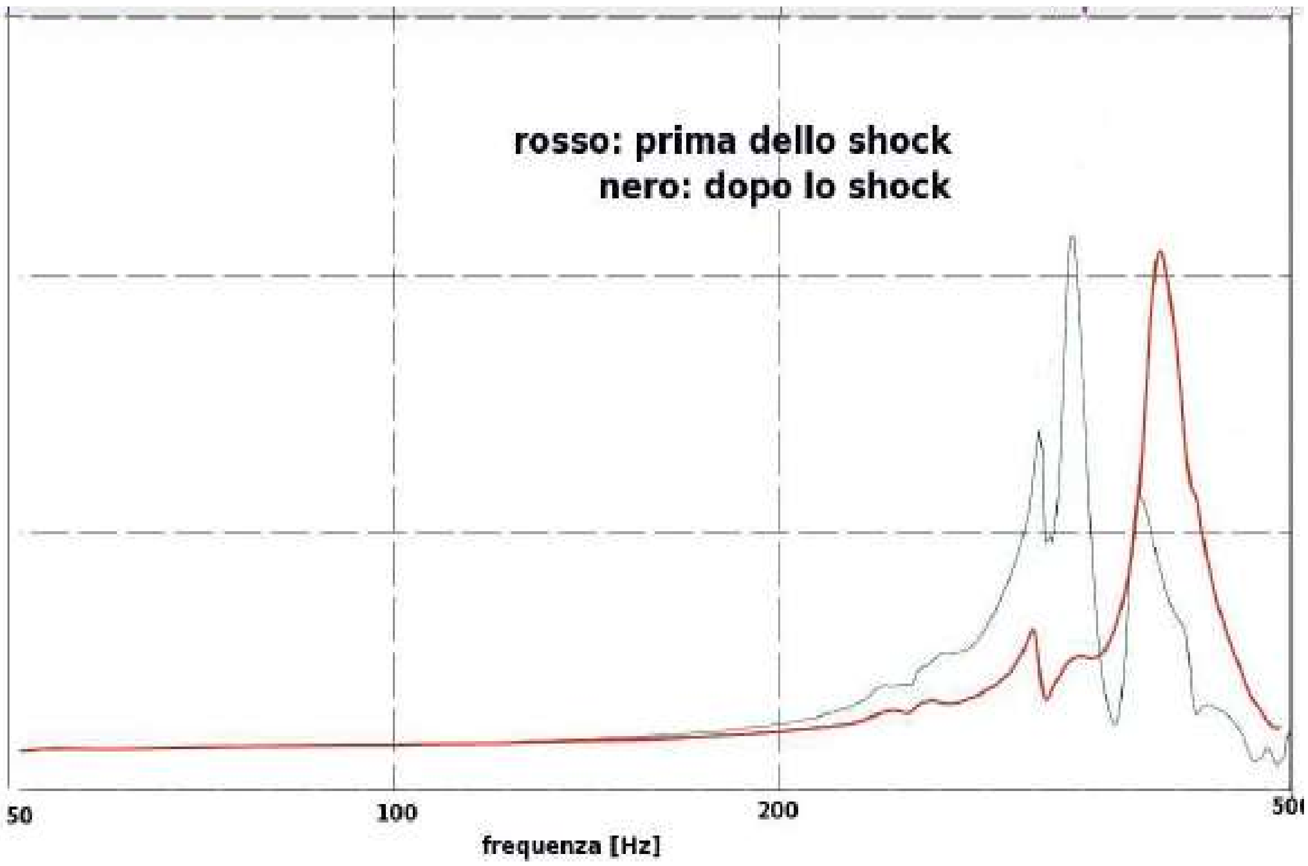
- **Frequency response function (signal/reference excitation amplitude ratio) for different applied stress on crystals**

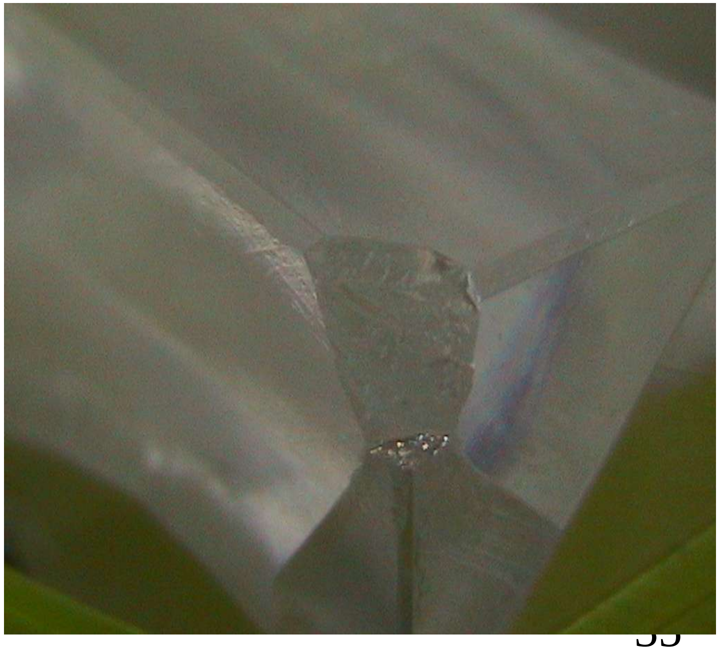


# The survivors

Rome

track different modal behavior after crystal crack

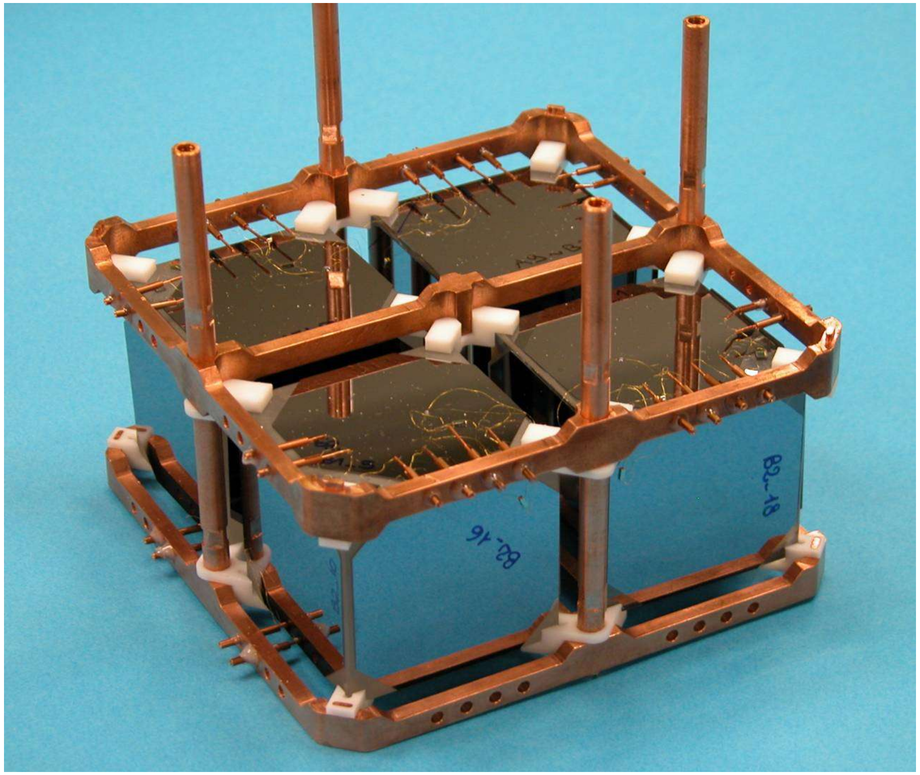


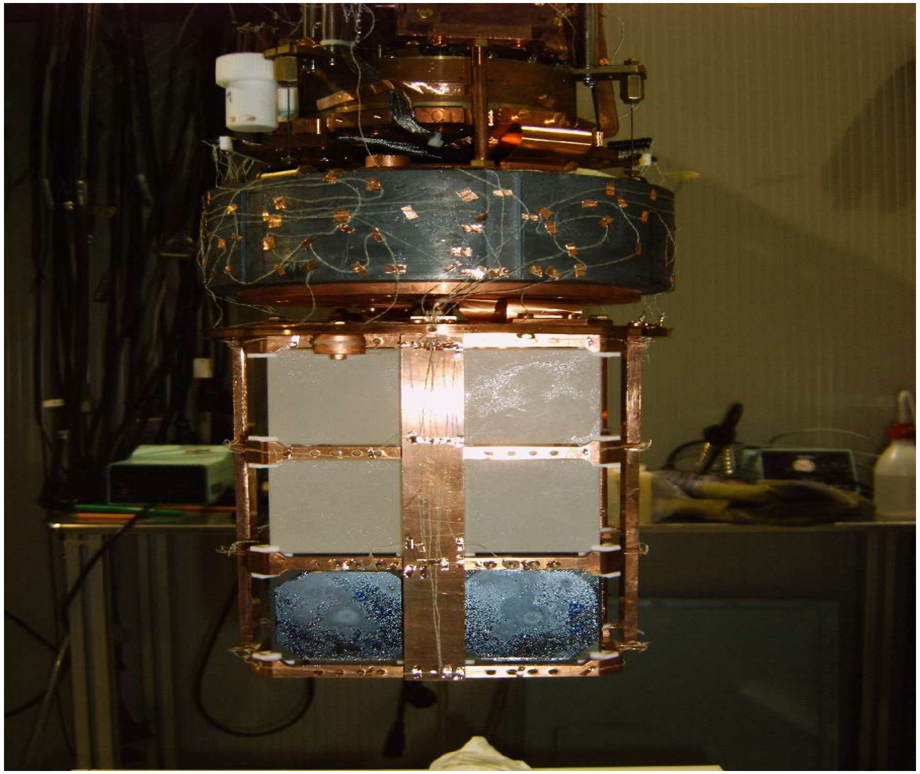



# Summer bolometric test

**Rome**

- **Teflon pieces and Cu frame modified using ENEA results**
- **Bolometric test performed in this summer: preliminary good results!!**





- **New cage and assembly procedure adopted, ultimate test in January....**

# Summary

- CUORICNO:
  - The most sensitive ββ0ν decay running experiment:

$$\tau_{1/2}^{\beta\beta0\nu} > 1.8 \cdot 10^{24}\, y\ @\ 90\, C.L. \quad \Rightarrow \quad \langle m_{\beta\beta0\nu} \rangle < [0.2 \div 1.1]\, eV$$

  - Good chances to confirm KK-HM experiment
  - CUORICNO proved the feasibility of CUORE
  - Crucial information for background identification

- CUORE:
  - Cryostat and hut construction will start soon
  - Intense R&D activity to reduce background and optimize construction and assembly
  - Enrichment option still open: only core ($2^{nd}$ phase)
  - The inverse hierarchy will be explored
  - Start data taking: $1^{st}$ January 2010

# Next Generation proposed experiments

| | isotope | i.a. [%] nat | $Q_{\beta\beta}$ [eV] | i.a. [%] enrich | size [kmol] | $T_M$ [y] | $\sigma_E$ [keV] | $b$ [c/y] | $\tau_{1/2}^{0\nu}$ [$10^{28}$ y] | technique | $\langle m_\nu \rangle$ [meV] min | max | Staudt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CUORE | $^{130}Te$ | 34 | 2533 | 90 | 1.7 | 5 | 2.5 | 3.8 | 0.18 | b | 9 | 57 | 17 |
| GERDA III | $^{76}Ge$ | 7.8 | 2039 | 90 | 13.0 | 5 | 2 | 3.5 | 0.20 | s | 29 | 94 | 34 |
| Majorana | $^{76}Ge$ | 7.8 | 2039 | 90 | 6.6 | 10 | 2 | 0.6 | 0.40 | i | 21 | 67 | 24 |
| GENIUS | $^{76}Ge$ | 7.8 | 2039 | 90 | 13.0 | 10 | 2 | 0.4 | 1.00 | t | 13 | 42 | 15 |
| SuperNEMO | $^{82}Se$ | 8.7 | 2995 | 90 | 1.2 | 5 | 76 | 1 | 0.02 | t,s | 54 | 167 | 55 |
| EXO | $^{136}Xe$ | 8.9 | 2476 | 65 | 48.0 | 10 | 49 | 0.55 | 1.30 | t | 12 | 31 | 13 |
| MOON III | $^{100}Mo$ | 9.6 | 3034 | 85 | 8.5 | 10 | 66 | 3.8 | 0.17 | t | 13 | 48 | 27 |
| DCBA-II | $^{150}Nd$ | 5.6 | 3367 | 80 | 2.7 | | 85 | | 0.01 | t | 16 | 22 | 16 |
| CANDLES IV+ | $^{48}Ca$ | 0.19 | 4271 | 2 | 1.3 | 5 | 73 | 0.35 | 0.30 | s | 29 | 54 | - |
| CARVEL | $^{48}Ca$ | 0.19 | 4271 | ? | 0.4 | 10 | 46 | - | 0.10 | s | 50 | 94 | - |
| GSO | $^{160}Gd$ | 21.8 | 1730 | 21.8 | 2.5 | 10 | 83 | *200* | 0.02 | s | 65 | 65 | 65 |

projected experimental parameters

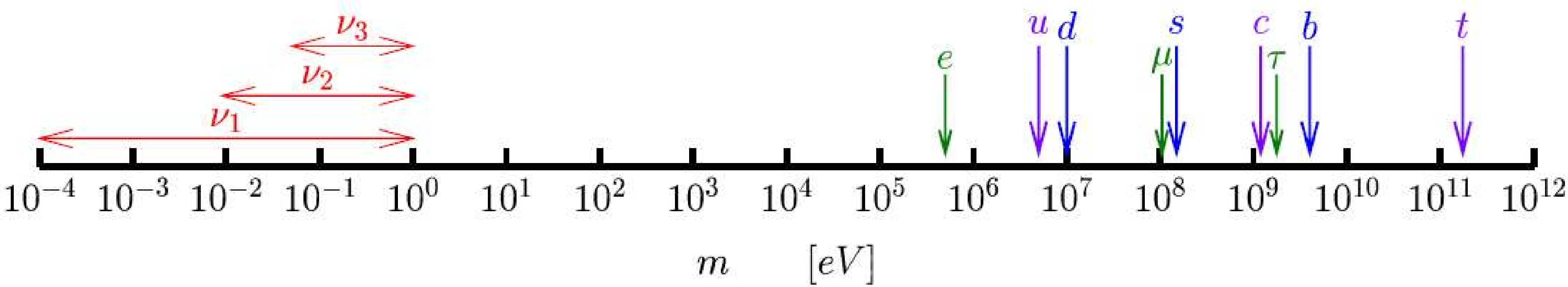
- projected background levels
  - ▶ large spread
  - ▶ too large gap with respect to present

nuclear matrix elements $F_N$ selected by Elliott & Vogel *

$\langle m_\nu \rangle$ evaluated according to staudt et al Europhys. Lett. 13 (1990) 31

# Some like it Majorana.....

- **Natural explanation of smallness of ν mass**




- **Most general Majorana-Dirac Mass term**

$$-\mathcal{L}^{\nu}_{\text{mass}} = \frac{1}{2}\left[\nu_L \quad (\nu_R)^c\right] C \begin{pmatrix} m_{M,L} & m_D \\ m_D & m_{M,R} \end{pmatrix} \begin{bmatrix} \nu_L \\ (\nu_R)^c \end{bmatrix} + \text{h.c.}$$

**Gauge invariance**

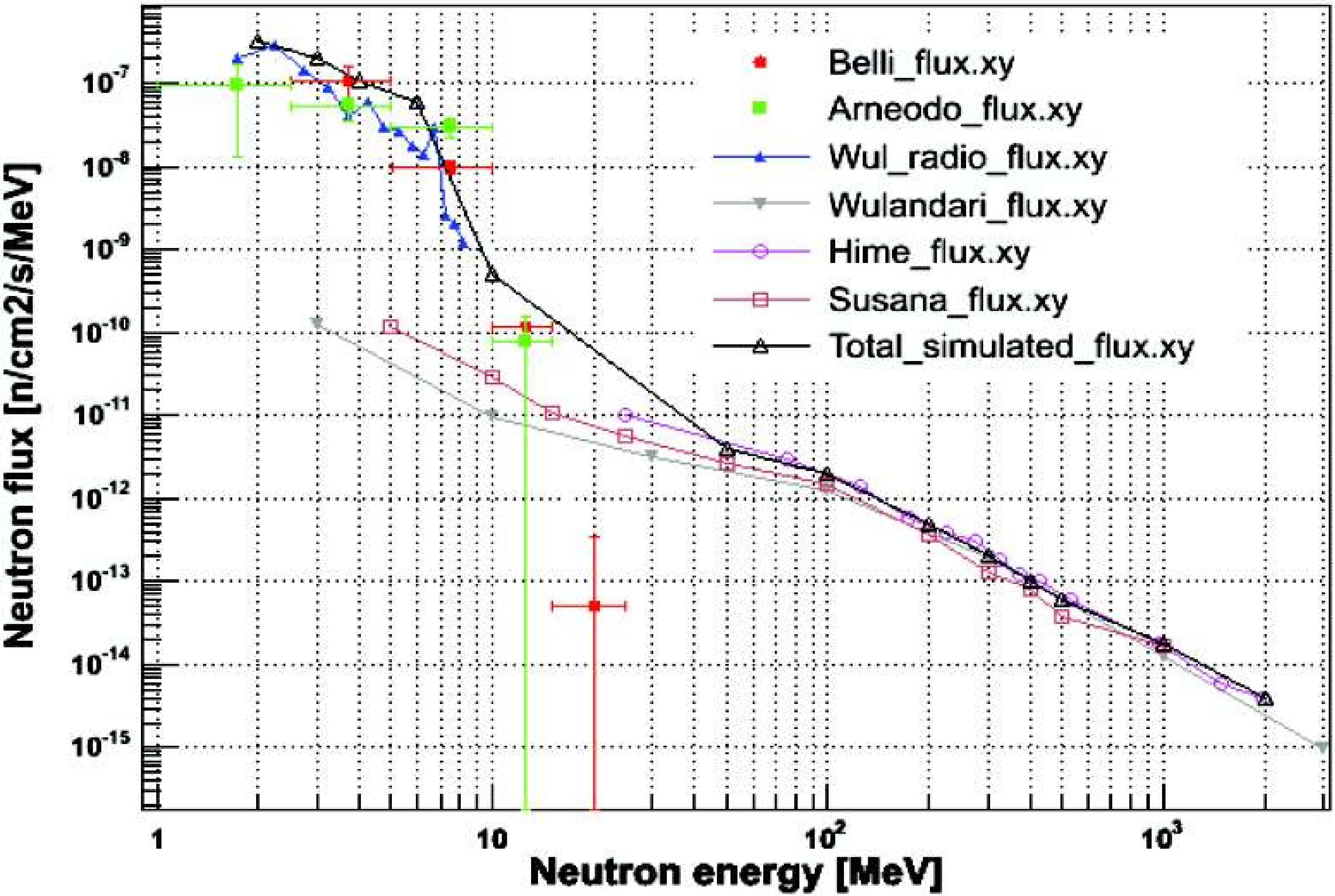
- **See-saw mechanism:** $\mathcal{M} \simeq \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$

**Dirac mass ~$M_{EW}$**

**Majorana mass ~$M_{GUT}$**

- **Diagonalize Matrix Mass:** $m_N \simeq M$ and $m_\nu \simeq m_D^2/M$

# Neutron Fluxes @ LNGS



# Neutron bkgd @ Cuore in ββ0νregion

- from thermal to 1keV → absorbed by a "thin" n shield

- from 1keV to 10 MeV → flux from measures + simulation of radiation in the rock
  - total $7 \bullet 10^{-3}$ counts/Kg/keV/y
  - global anticoincidence $2 \bullet 10^{-4}$ counts/Kg/keV/y

Can be further reduced by a n shield

- from 10 MeV to 2 GeV → flux simulation of muon interaction in the rock
  - total $3 \bullet 10^{-5}$ counts/Kg/keV/y
  - global anticoincidence $6 \bullet 10^{-7}$ counts/Kg/keV/y

- from 1keV to 2 GeV → flux simulation of muon interaction in the muon shield
  - total $3 \bullet 10^{-3}$ counts/Kg/keV/y
  - global anticoincidence $2 \bullet 10^{-4}$ counts/Kg/keV/y

Can be further reduced by a muon veto

**Same background in Dark Matter search region**

**No limit to CUORE sensitivity due to neutron flux in LNGS**

# Nuclear Matrix Spread

TABLE I. Effective Majorana mass of the electron neutrino, $\langle m_\nu \rangle$, corresponding to $T^{0\nu}_{1/2}(^{130}\mathrm{Te}) = 1.8 \times 10^{24}$ yr derived from various nuclear (QRPA) models.

| Authors/Reference | Method | $\langle m_\nu \rangle$ (eV) |
|---|---|---|
| [47] Staudt *et al.*, 1992 | pairing (Paris) | 0.21–0.22 |
| | pairing (Bonn) | 0.22–0.24 |
| [48] Pantis *et al.*, 1996 | no $p$-$n$ pairing | 0.66 |
| | $p$-$n$ pairing | 1.05 |
| [49] Vogel, 1986 | | 0.61 |
| [50] Civitarese, 1987 | | 0.54 |
| [51] Tomoda, 1991 | | 0.54 |
| [52] Barbero *et al.*, 1999 | | 0.43 |
| [53] Simkovich, 1999 | $pn$-RQRPA | 0.88 |
| [54] Suhonen *et al.*, 1992 | | 0.83 |
| [55] Muto *et al.*, 1989 | | 0.51 |
| [56] Stoica *et al.*, 2001 | large basis | 0.77 |
| | short basis | 0.72 |
| [57] Faessler *et al.*, 1998 | | 0.72 |
| [58] Engel *et al.*, 1989 | seniority | 0.37 |
| [59] Aunola *et al.*, 1998 | Woods Saxon (WS) | 0.50 |
| | Adjusted WS | 0.54 |