CUORICINO results and CUORE R & D

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on behalf of the

CUORE Collaboration

21st International Workshop on Weak Interactions and Neutrinos

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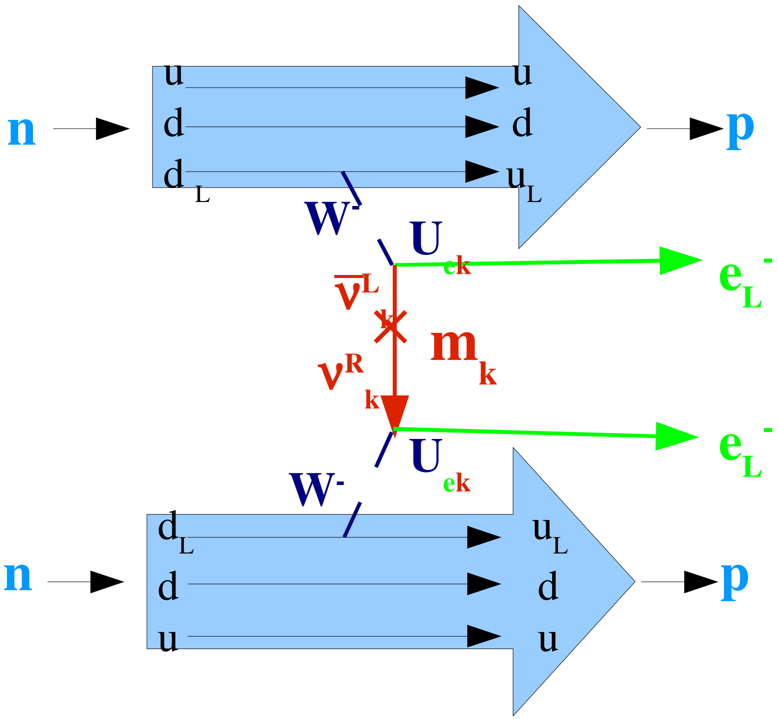
Neutrino-less Double Beta Decay

The standard lore: light Majorana neutrino exchange



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

$$\nu_{majorana}: \nu \equiv \bar{\nu}$$

$$(Lepton\ number\ violation)$$

If observed:

Proof of Majorana nature of Neutrino

Schetcher, Valle Phys. Rev. D25 2951 1982

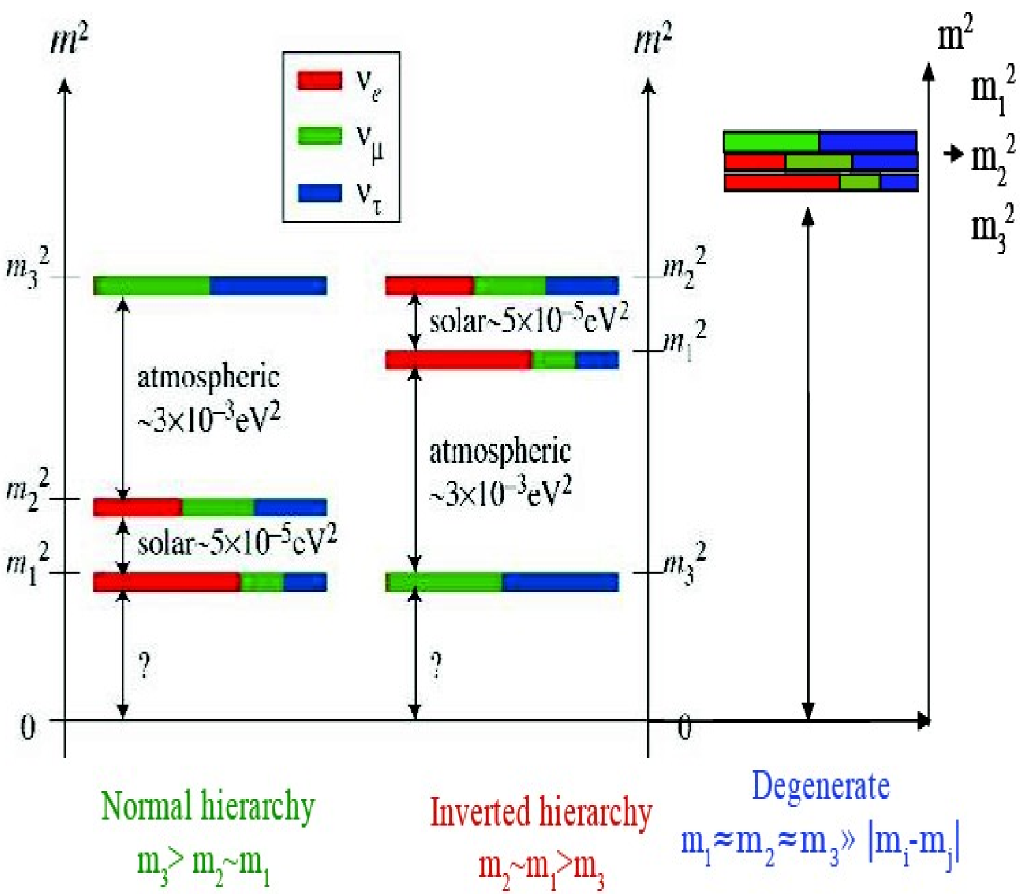
$$(\tau_{1/2}^{0\nu\beta\beta})^{-1} = G(Q,Z)|M_{nucl}|^2 |m_{\beta\beta}|^2$$

$$m_{\beta\beta} = \sum m_{\nu_k} U_{ek}^2$$

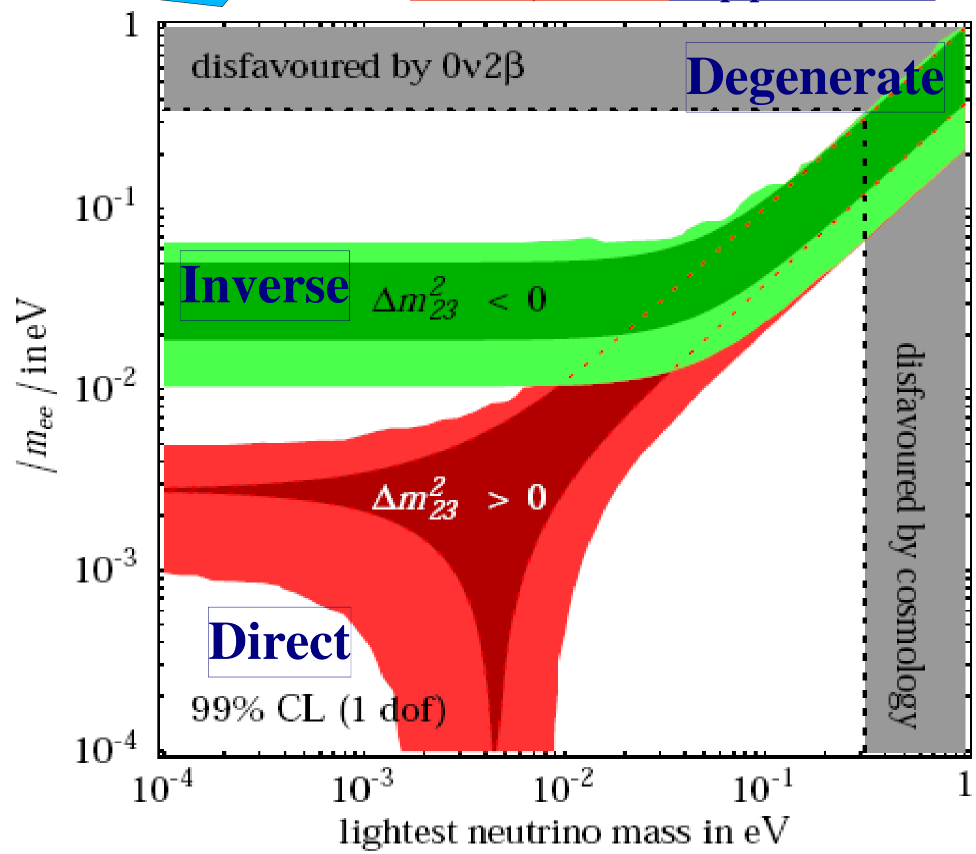
phase space **Nuclear matrix element** **Effective neutrino mass**

Does 0νββ measure the mass?

$$m_{\beta\beta} = \sum m_{\nu_k} U_{ek}^2 = \cos^2\theta_{13}\left(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}\right) + m_3 e^{2i\beta}\sin^2\theta_{13}$$



Strumia, Vissani hep/ph 0606054

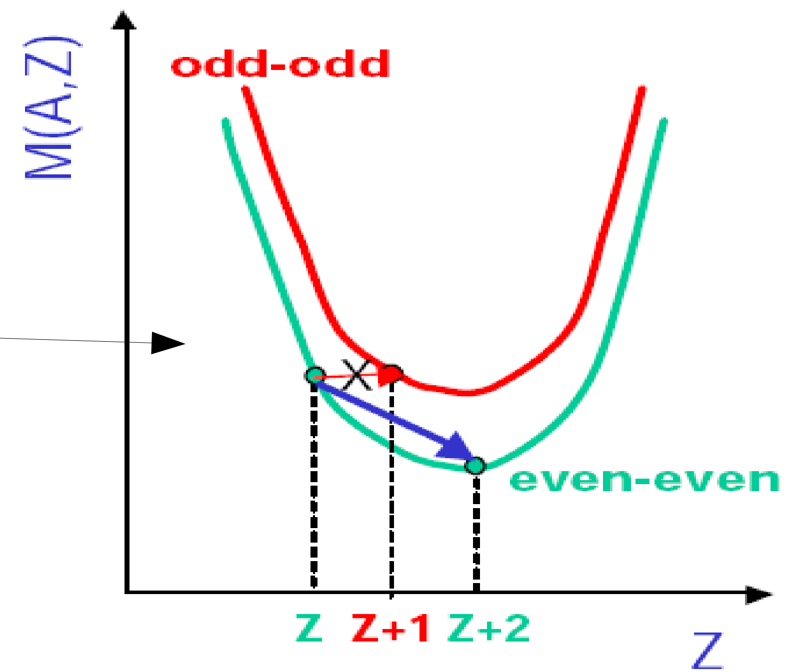


Degenerate and inverted hierarchy testable by "realistic" experiments

The $0\nu\beta\beta$ elements shall have:

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

- A large **Q**
  - because rate $\propto Q^5$
  - because the natural γ-lines end around 2.6 MeV (^{208}Tl from ^{232}Th)
- A large matrix element
- A large isotopic abundance
- Should be (A-Z) even-even nuclei: $2\nu\beta\beta$ suppressed



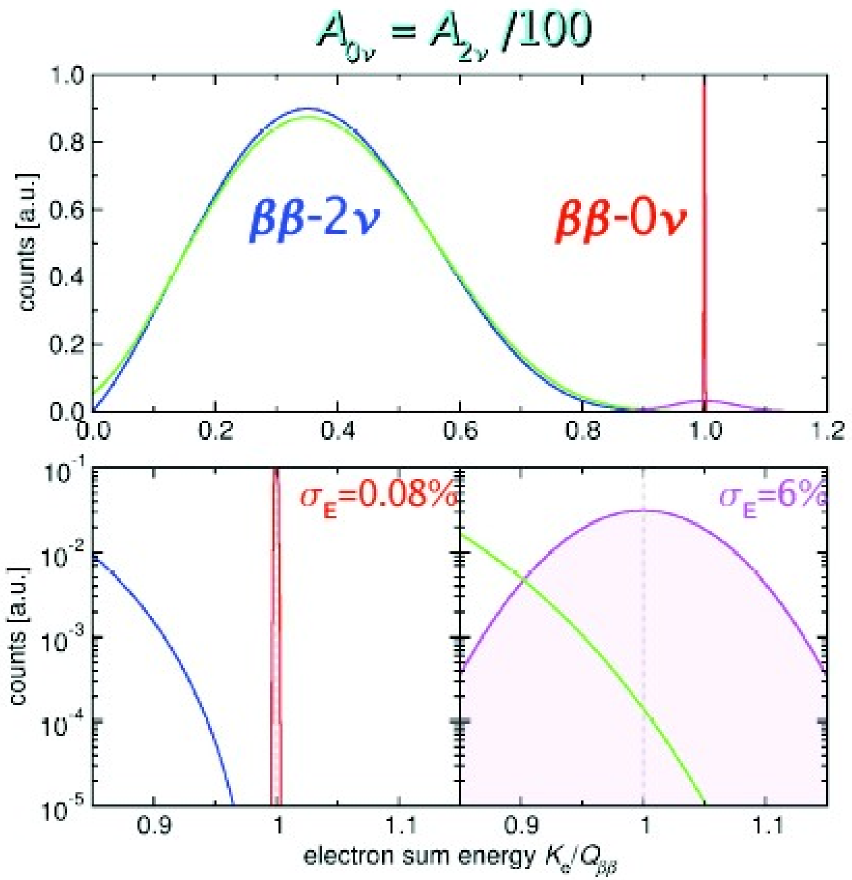
^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd

$2\nu\beta\beta$ background-ΔE

- Reducible bkg will accumulate proportionally to the window dictated **by energy resolution.** You can always hope to reduce the background and alleviate the problem.
- **Irreducible background however cannot be reduced;** **2νββ tail will always be there**

$$\delta = \frac{\Delta E^{FWHM}}{Q_{\beta\beta}}$$

$$\frac{S}{B} \approx \frac{m_e}{7 Q_{\beta\beta}\delta^6}\frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$



Please note δ^6

$\mathrm{T}^{0\nu} \simeq 10^{28} y$ $\quad$ $\mathrm{S/B} = 1$

$\mathrm{T}^{2\nu} \simeq 10^{20} y$ $\quad$ $\mathrm{Q} \simeq 3\mathrm{MeV}$

$$\delta = \Delta E^{FWHM}/Q \simeq 2.5\%$$

The less noble background

- Internal to source
  - Primordials (^{238}U, ^{232}Th, ^{40}K)
  - Cosmogenic activation
- External to source
  - Cosmic rays
  - Neutrons
  - Primordials in surrounding materials
- Detector specific

ββ2ν: $\tau \sim 10^{(19\text{-}21)}$ y
ββ0ν: $\tau \geq 10^{24}$ y
Primordials: $\tau \sim 10^{(9\text{-}10)}$ y

- Bkg estimate and reduction hard(few counts/y): intermediate size experiment often required

On the back of the envelope

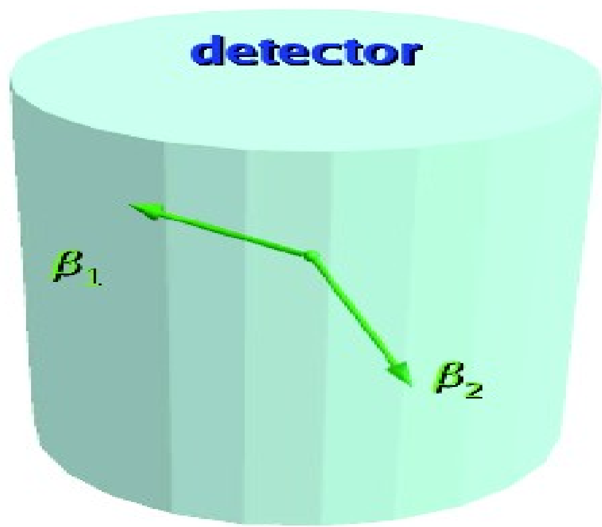
bkg free

$$\tau_{1/2}^{0\nu} = ln2 \cdot a \cdot N_a \cdot M \cdot T / N_{\beta\beta} \quad (\tau_{1/2}^{0\nu} \gg T)$$

50 meV $m_{\beta\beta}$ implies half lifes $\sim 10^{26\text{-}27}$ y: 1 event/y ⇒ 10^3 isotope moles ⇒ O(100kg)
now you can only loose: nat. abundance, efficiency, background....

Two techniques

Source ⊆ detector

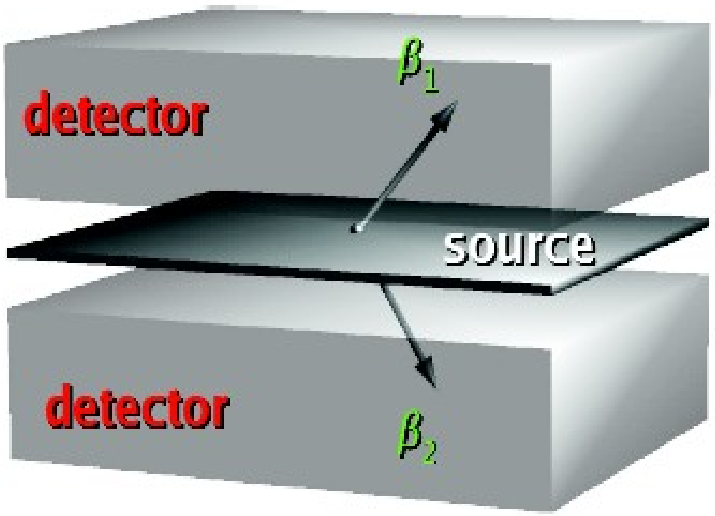


M, ΔE, ε

Topology, bkg

^{76}Ge diodes (MAJORANA, GERDA)
^{130}Te bolometers (CUORE)
^{48}Ca, ^{116}Cd, ^{160}Gd, ^{136} Xe
scintillators (EXO)

Source≠detector



Bkg topology, different isotopes

M, ΔE, ε

Tracking chamber: ^{82}Se, ^{100}Mo,^{96}Zr
(NEMO, MOON)

CUORICINO: the bolometric way

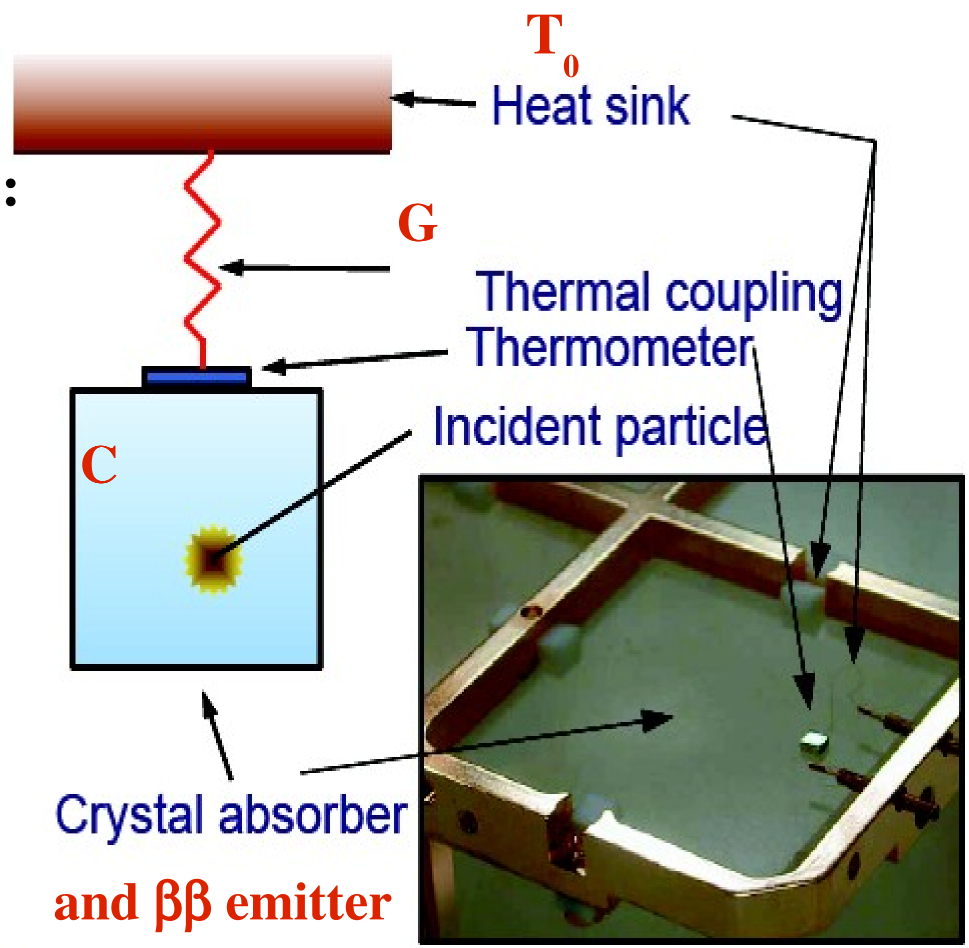
- (Very) Low temperature homogeneous calorimeter:
  - basic physics of Bolometry: $\Delta T = E/C$

    $\Rightarrow$ low C

    diamagnetic dielectrics @ low T_0 (~ 10mK) :

    $C \sim (T/\Theta_D)^3 \sim 2$ nJ/K $\sim 10^{10}$ eV/K

    $G \sim 4$ nW/K



- Thermometer: NTD Ge thermistor

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

  $\Delta T \Rightarrow \Delta R$

  $\Rightarrow 0.1$ mK/MeV $\Rightarrow 0.1$mV/MeV

- Bonus: no intrinsic limit to $\sigma(E)$

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

detect μK jumps:
0.1 % resolution
on MeVsignal

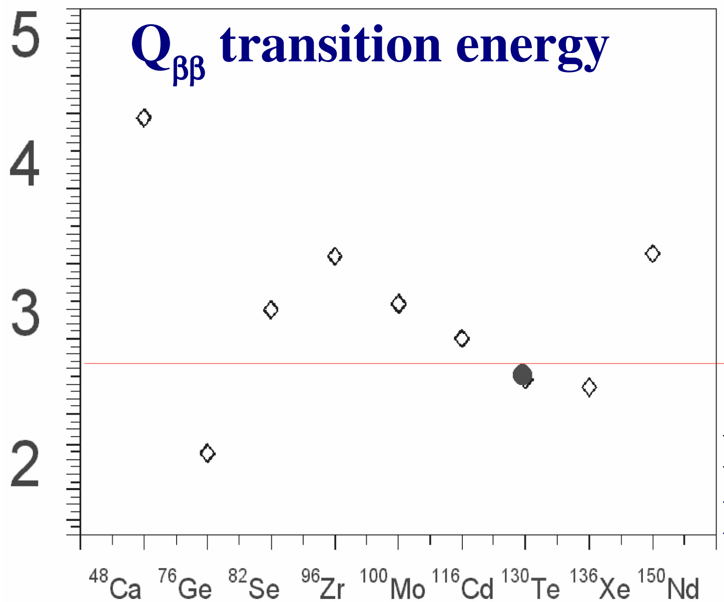
- (Not for all) Typical pulse decay time: $t \sim C/G \sim 10^{2\text{-}3}$ ms

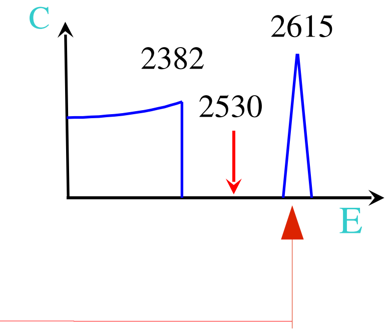
Why Tellurium?

- **Active isotope: ^{130}Te**
  - **Transition energy**

$Q_{\beta\beta}$ = (2530.30±1.99) keV

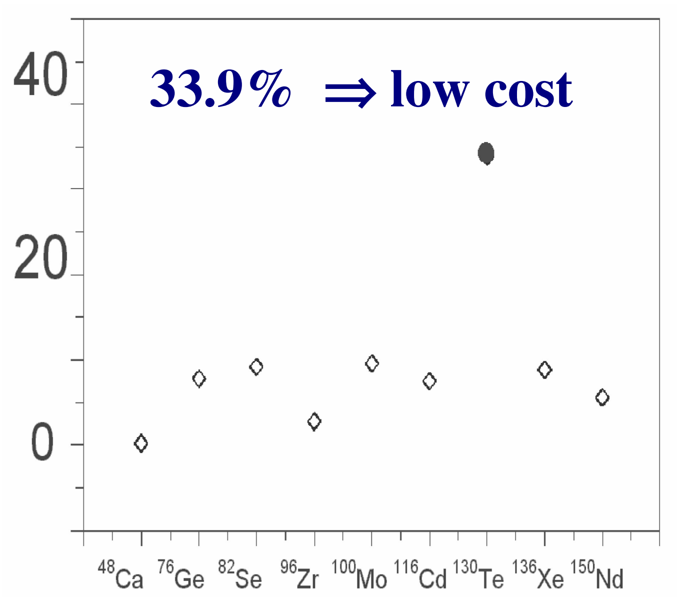
Nuclear Physics A 729 (2003) 337



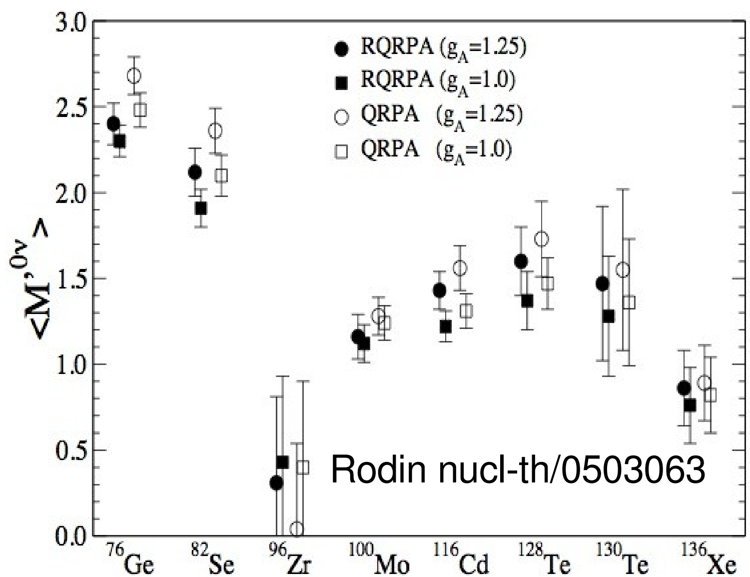


Between the highest natural γ line (^{208}Tl) and Compton edge

Natural abundance



Nuclear matrix element



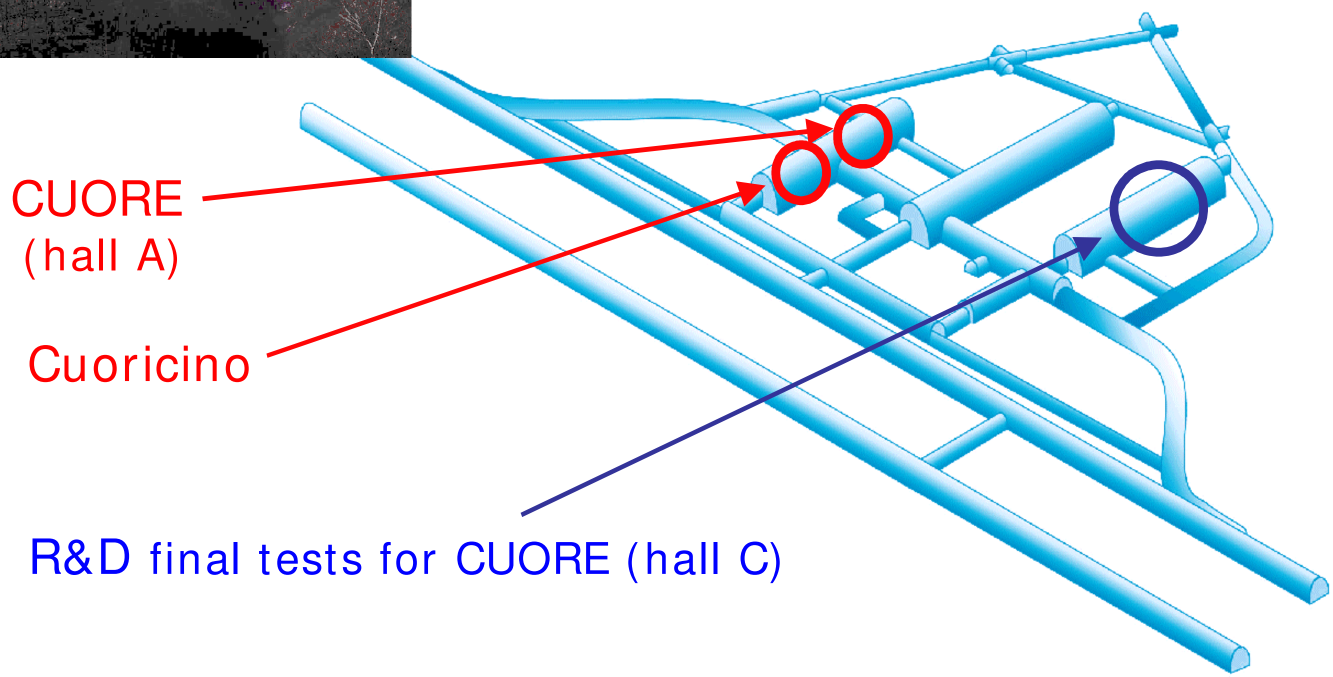
- **Absorber material: TeO_2**
  - **Low heat capacity**
  - **Possibility to grow large crystals**
  - **Good intrinsic purity**

CUOR(ICINO) @ LNGS

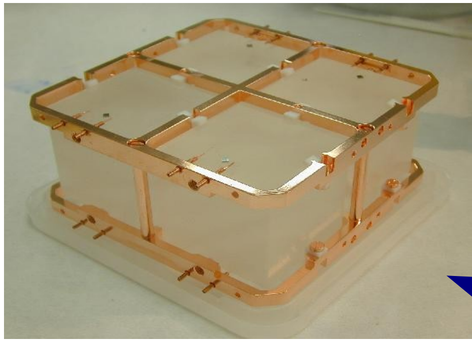
Cuoricino experiment is installed in the

Underground National Laboratory of Gran Sasso L'Aquila – ITALY

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



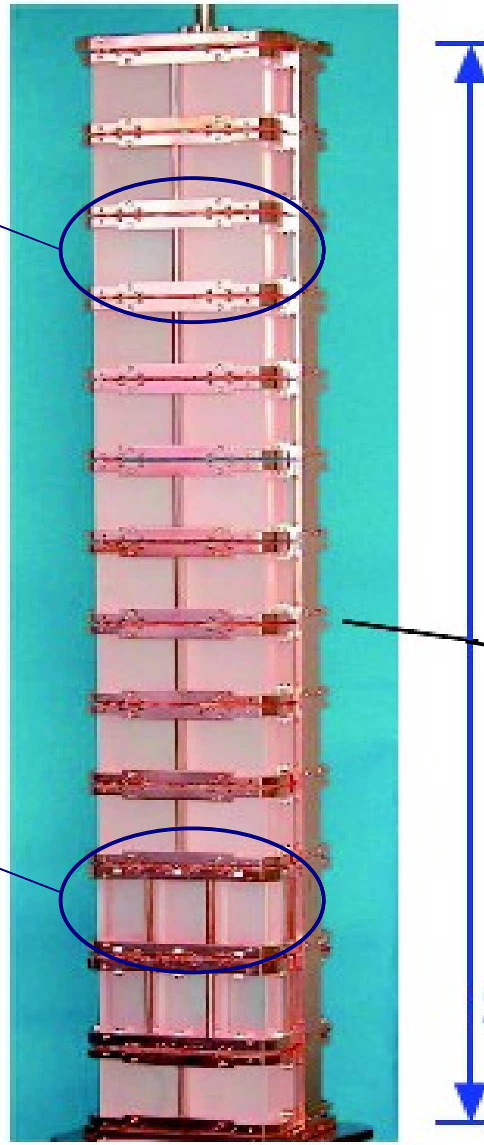
CUORICINO: the demonstrator



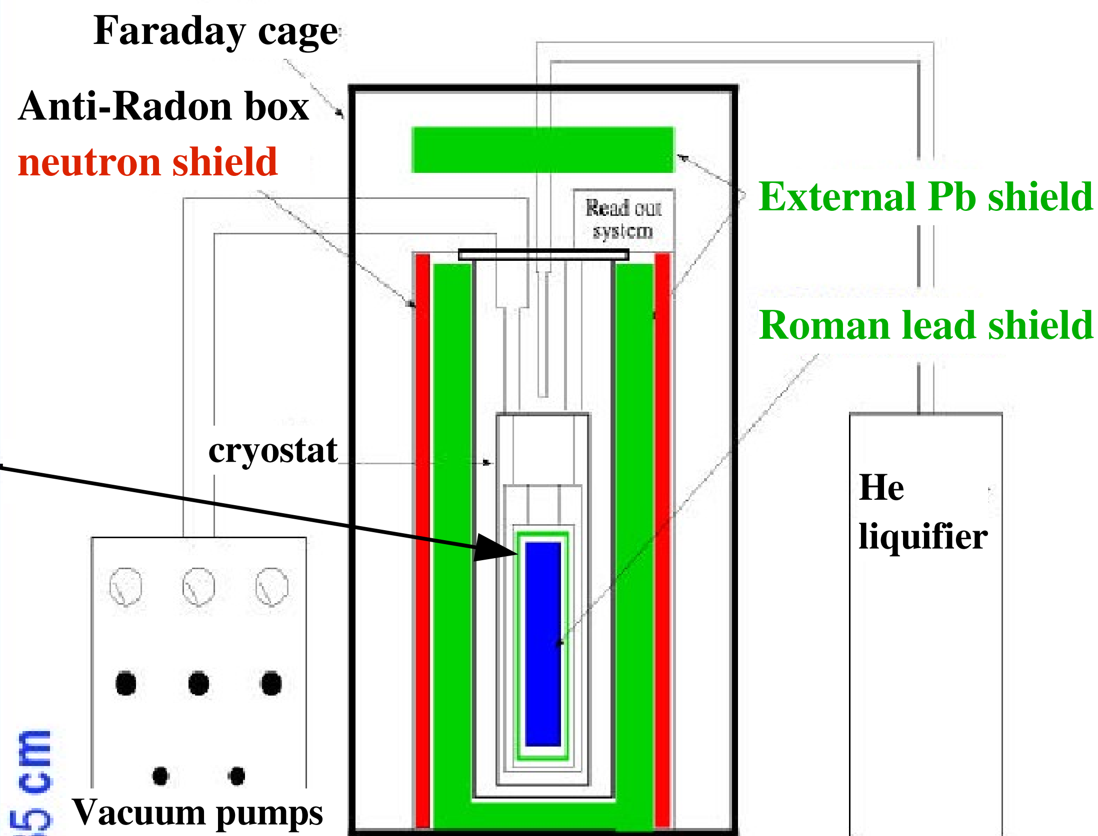
11 modules: 4 detector
5x5x5 cm^3=790 g each

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

4 enriched: 2 @75% ^{130}Te
2 @82.3% ^{128}Te

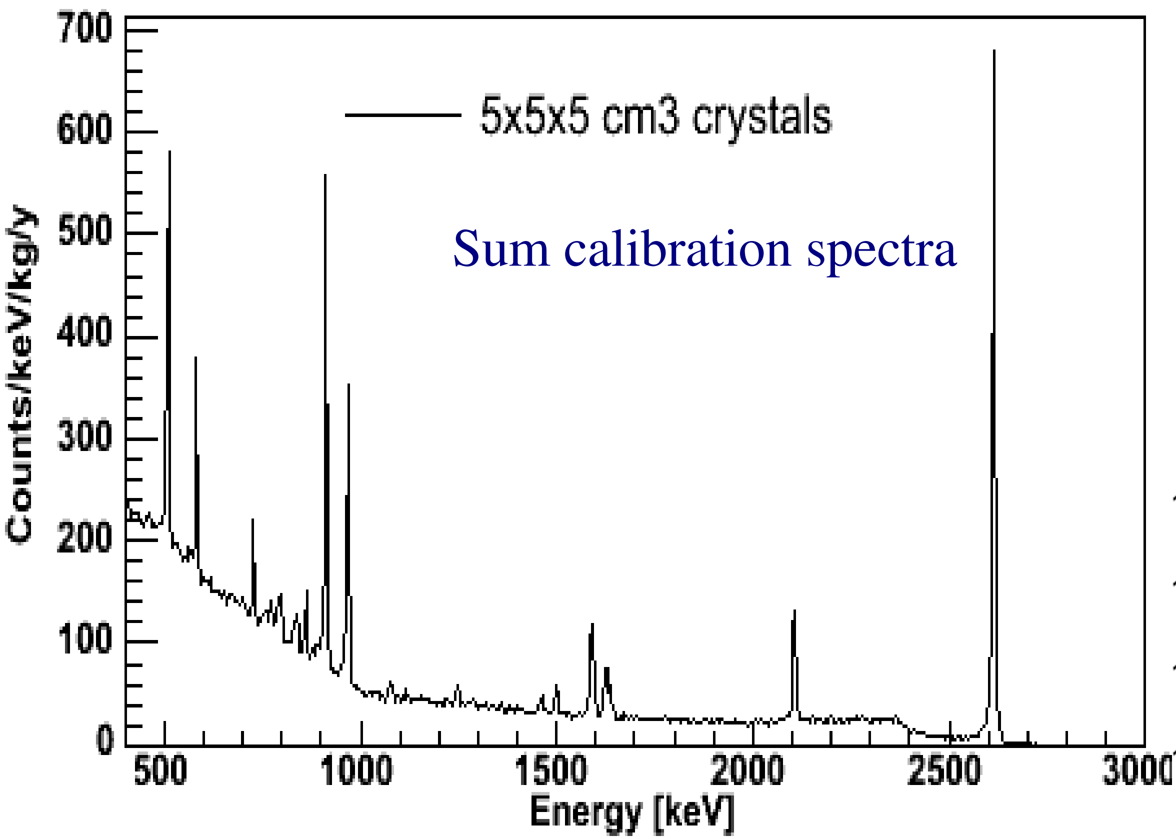


Total Active mass:
- TeO_2 = 40.7 kg
- ^{130}Te = 11.34 kg

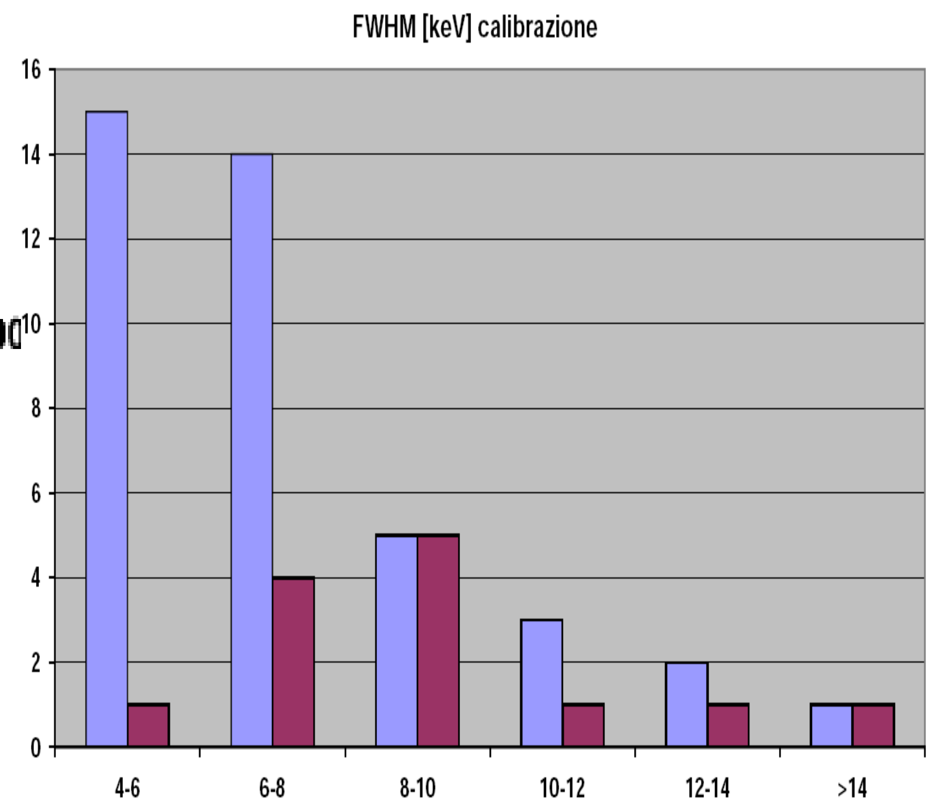


Started on April 2003

Calibration spectra: energy resolution



^{232}Th γ–source external to the cryostat:
3 days measurement every month



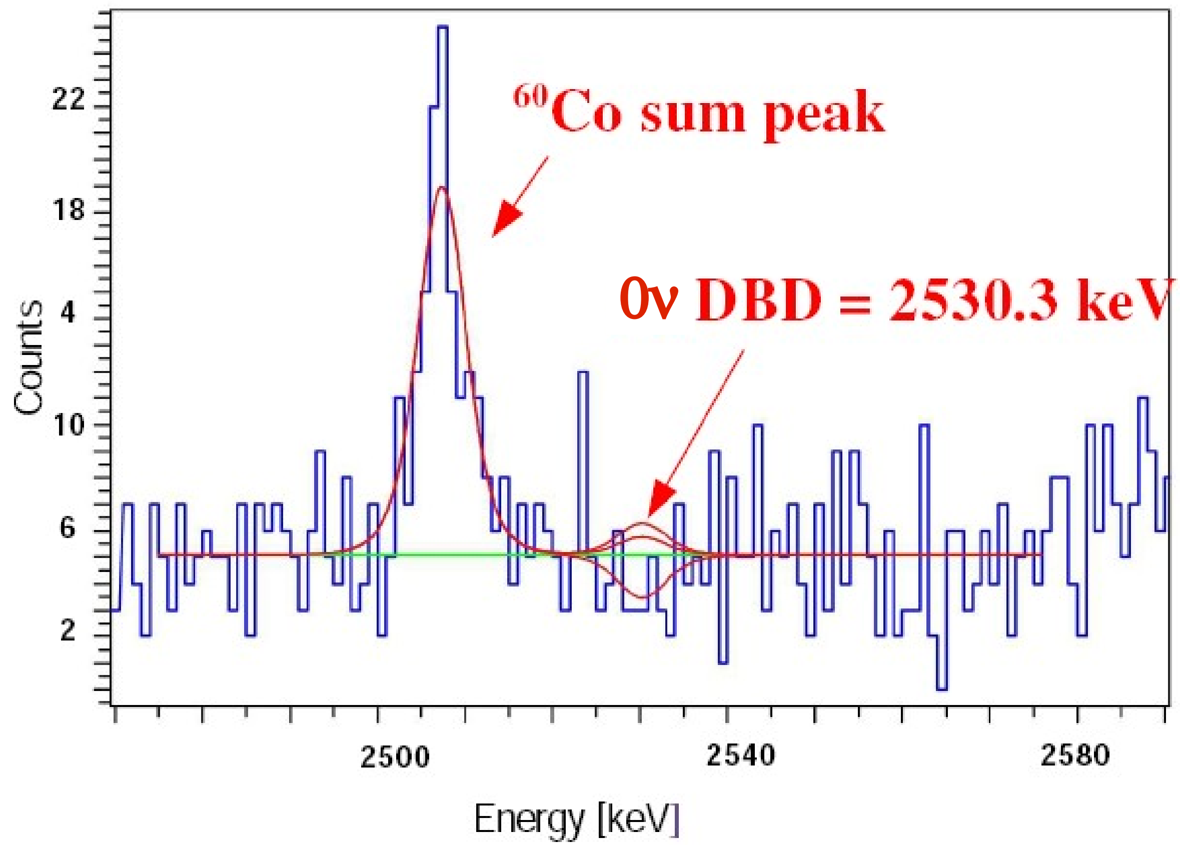
FWHM @ 2615 keV ^{208}Tl γ–line

5x5x5 cm^3 crystal: FWHM 7.5±2.9 keV

3x3x6 cm^3 crystal: FWHM 9.6±3.5 keV

CUORICINO 0νββ result

- Total statistics: **8.38 kg ^{130}Te•y**
- Bkg (ββ0ν region):
  0.18 ±0.01 counts/keV/kg/y
- FWHM measured on bkg spectrum
  @ 2.6 MeV **~ 8 keV**
- Detector efficiency: ~**86.4%**
- ML fit in **2475-2550 keV** region



  - flat bkg + 2505 keV peak
  - peak shape = N-gaussian
    to account for the different – measured - energy resolutions
  - best fit yields negative effect

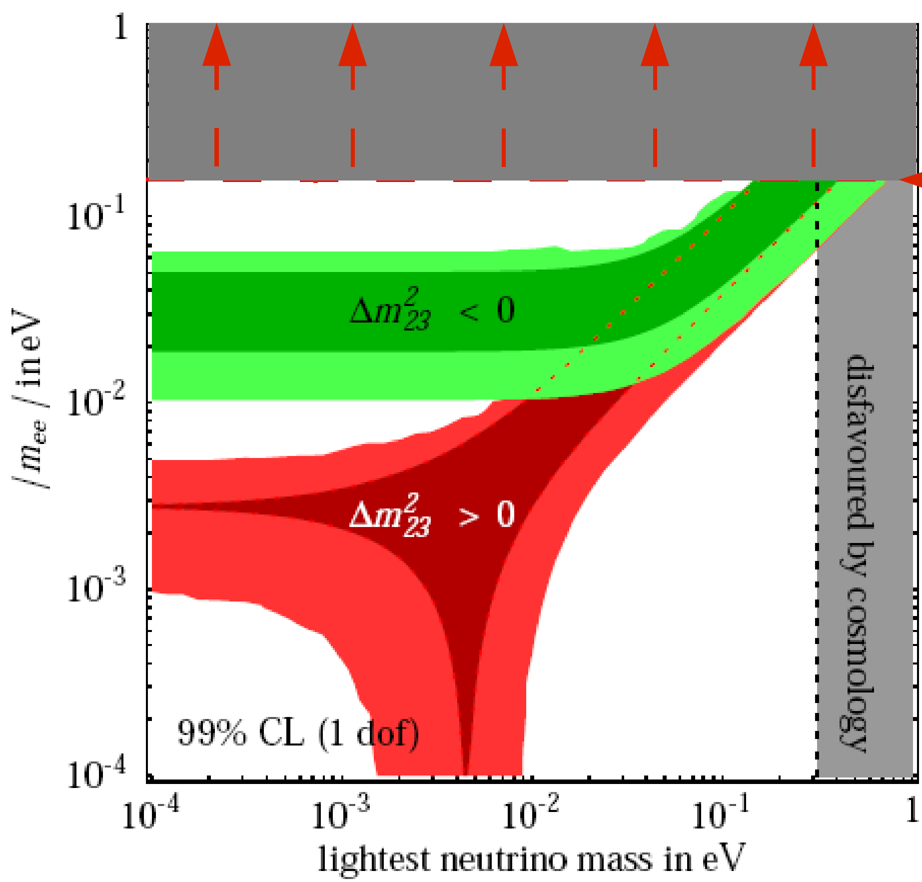
$$\tau_{1/2}^{0\nu\beta\beta} > 2.4\cdot 10^{24}\, y\ @\ 90\, C.L. \quad \Rightarrow \quad \langle m_{\beta\beta}\rangle < [0.18 \div 0.94]\, eV$$

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

In the parameter space

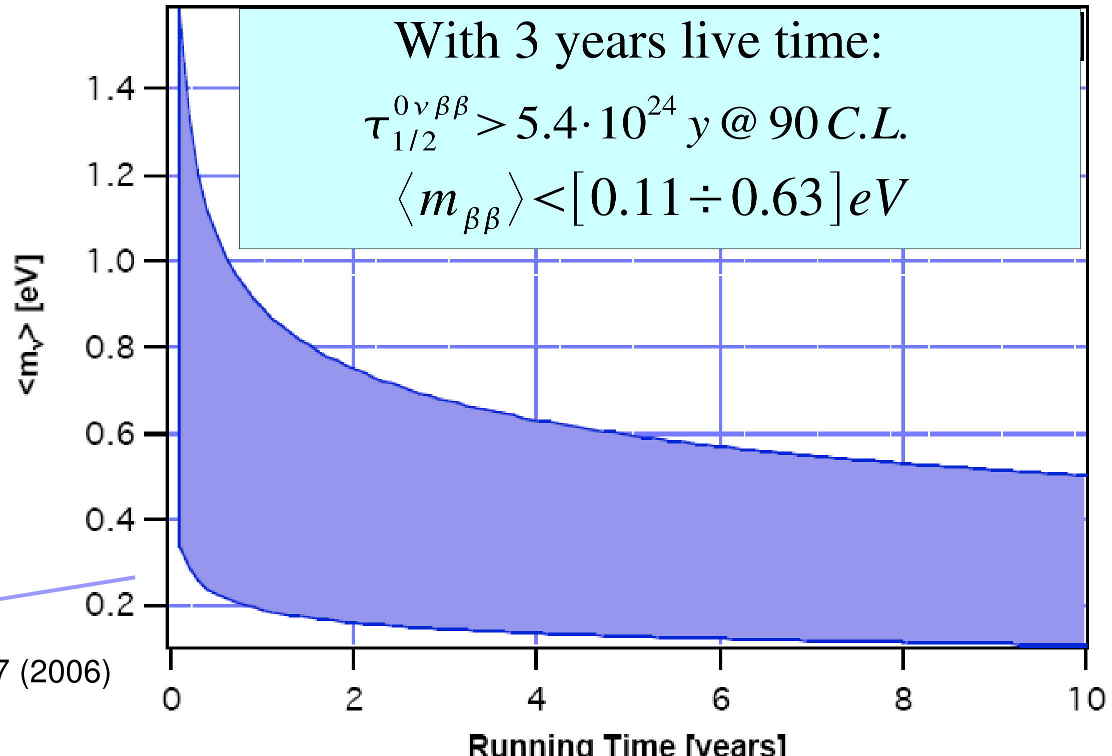
KK: $0.24\,eV < m_{\beta\beta} < 0.58\,eV \Leftrightarrow m_{\beta\beta}^{best} = 0.44\,eV$

Klapdor-Kleingrothaus et al. Phys. Lett. B 586, 198-212



CUORICINO:

$$m_{\beta\beta} < [0.18 - 0.94]\,eV$$



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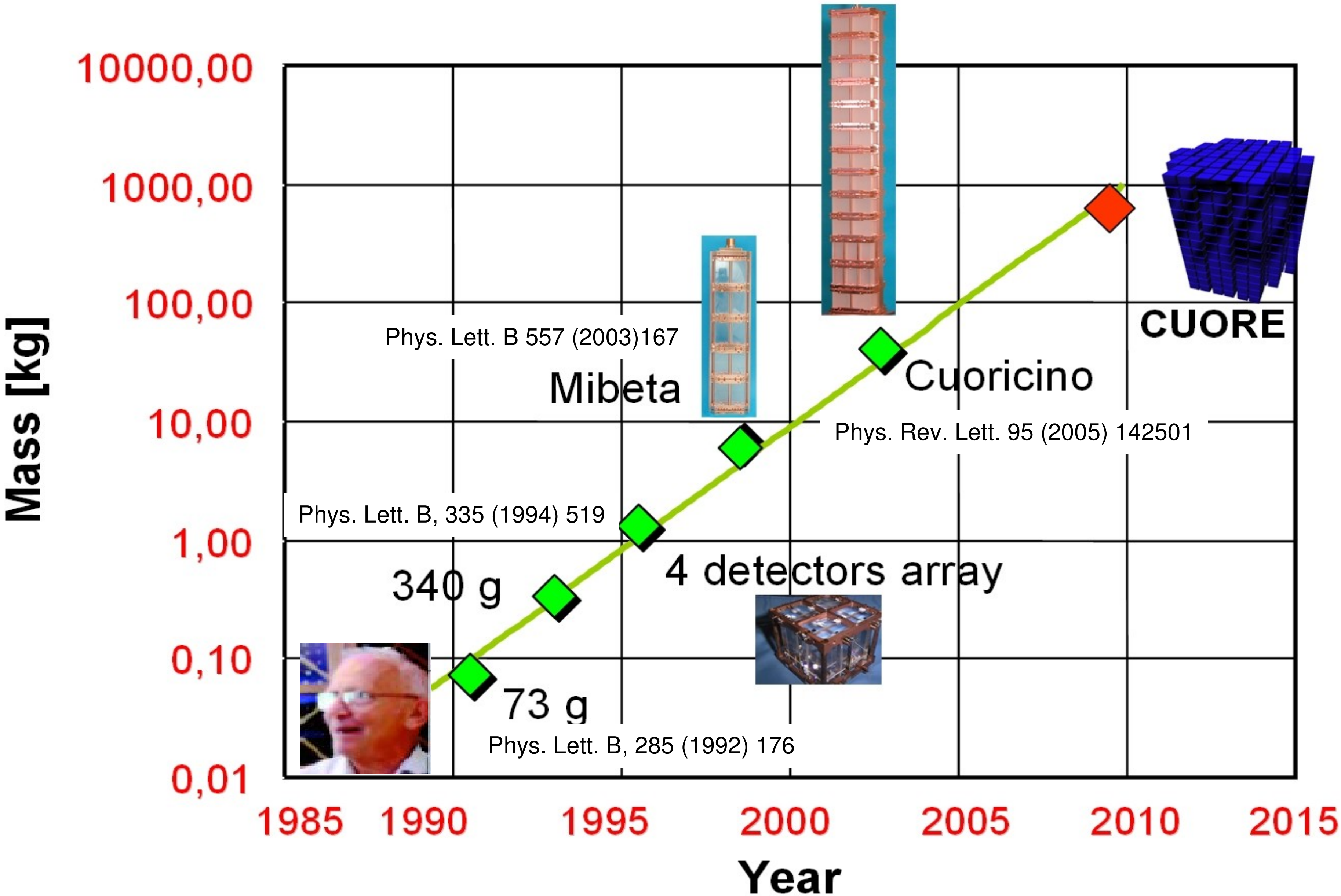
The Moore's Law of Bolometry

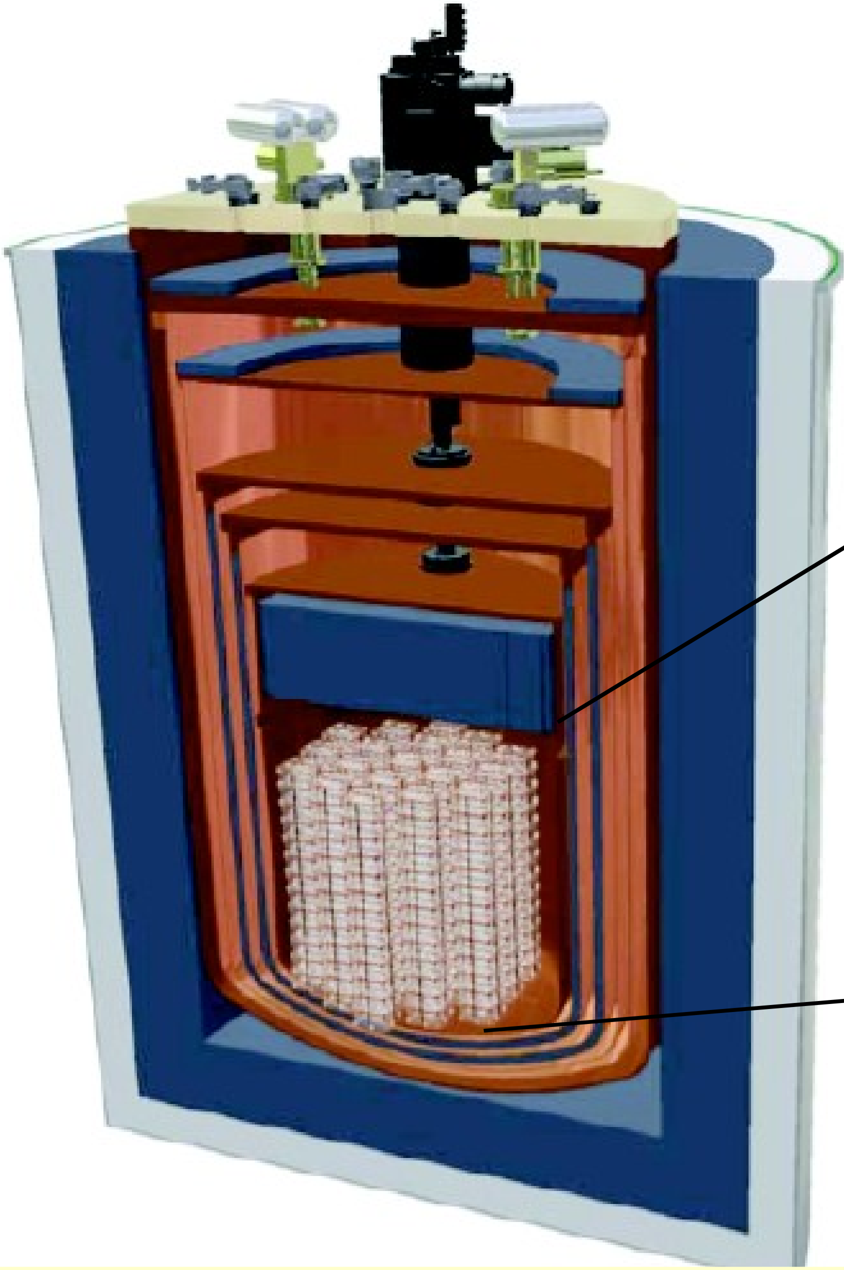


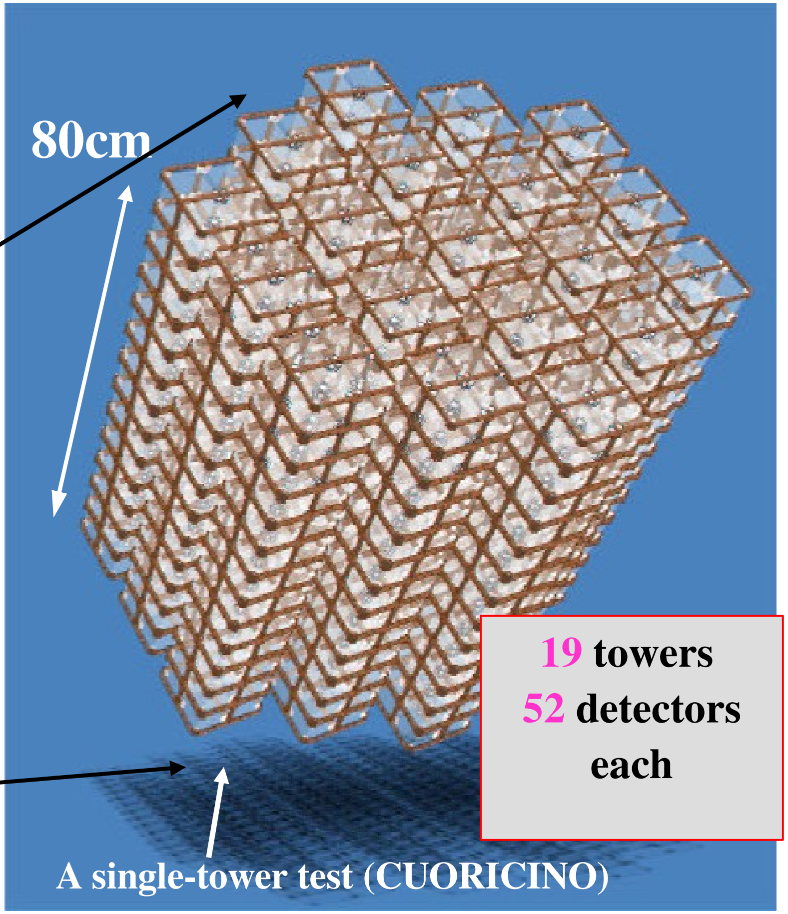
Cryogenic Underground Observatory for Rare Events

Single dilution refrigerator ~10 mk

- $\beta\beta0\nu$, Cold Dark Matter, Axion searches

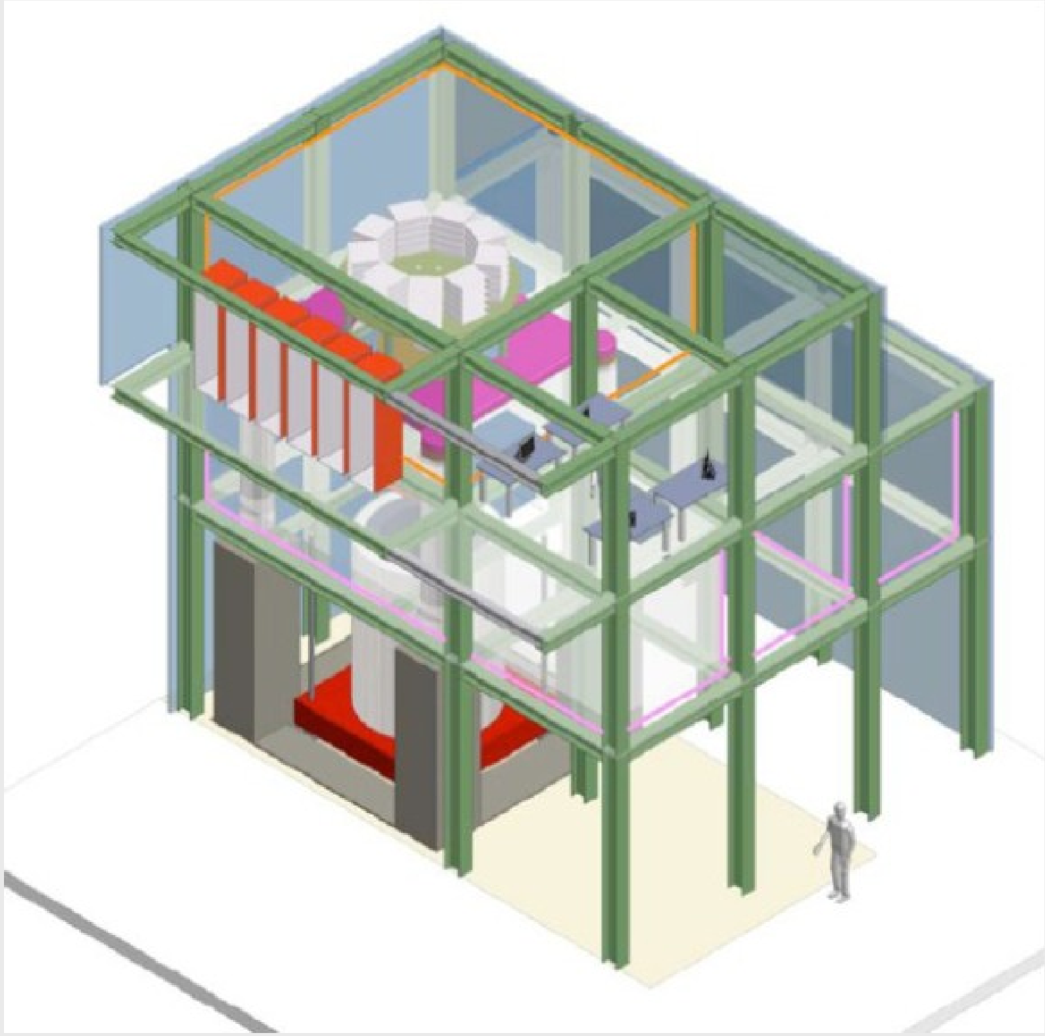
  proposal hep/ph 0501010

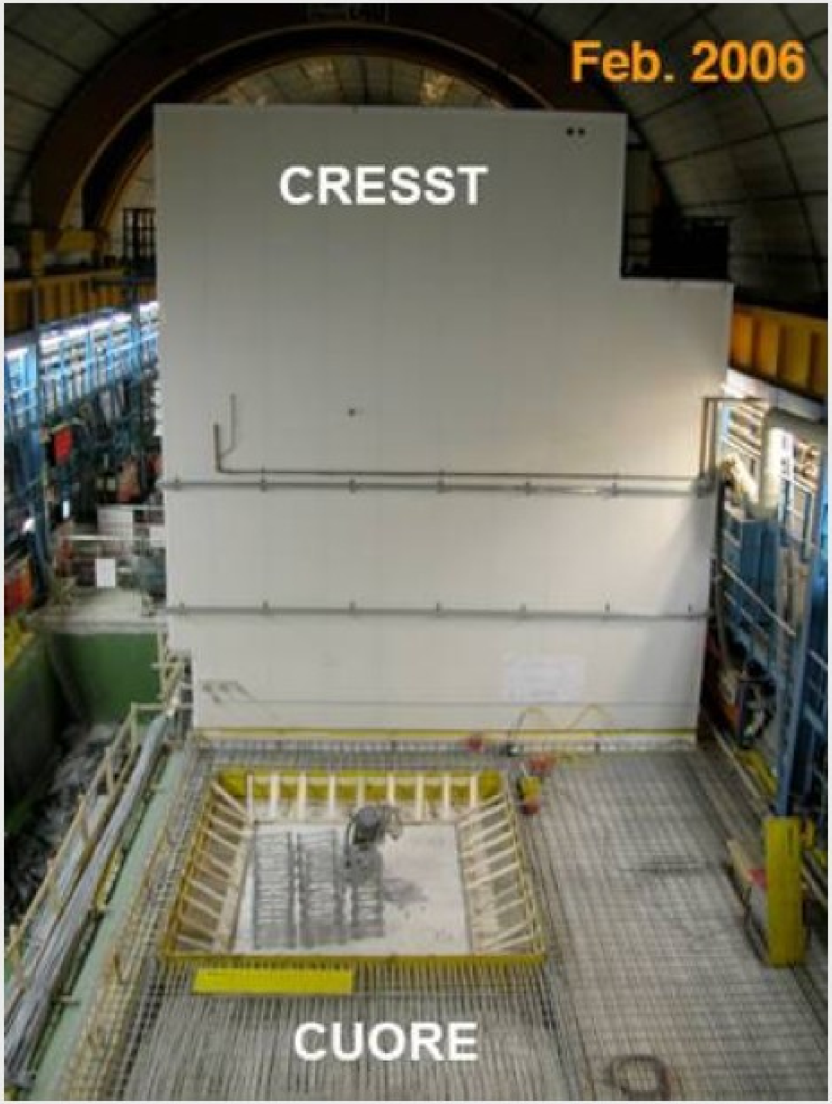




Closed packed array of 988 TeO_2 5x5x5 cm^3 crystals ⇒741 kg TeO_2 ⇒ 204kg ^{130}Te

CUORE Housing





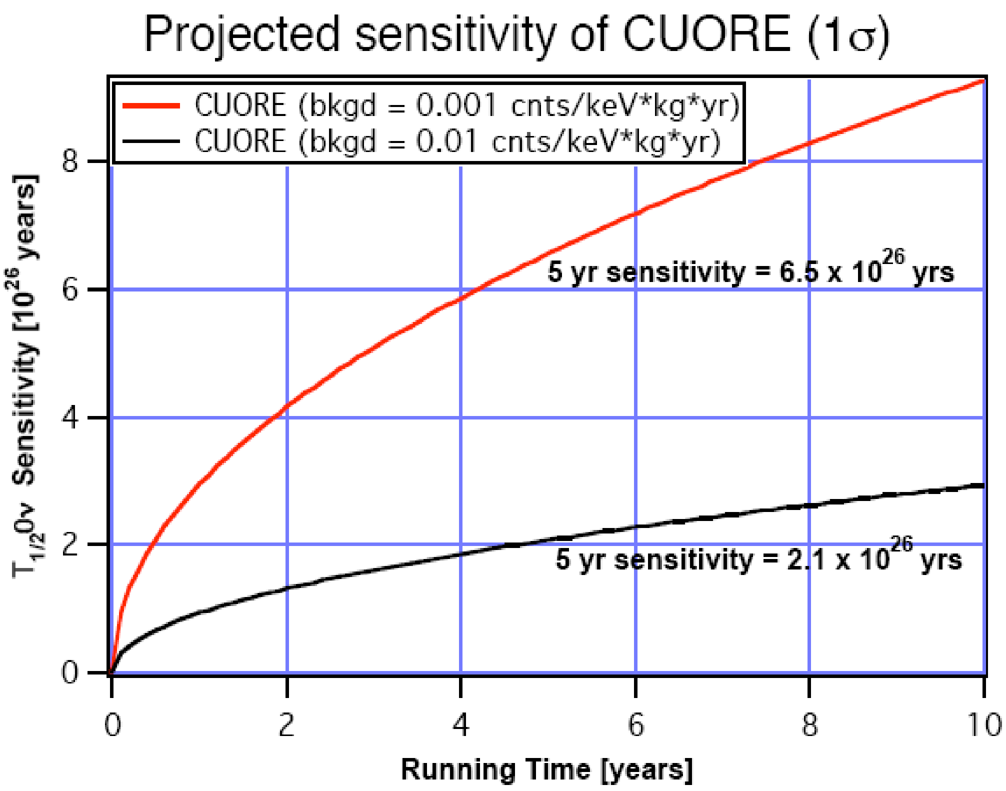
Basement already completed ... the rest is coming

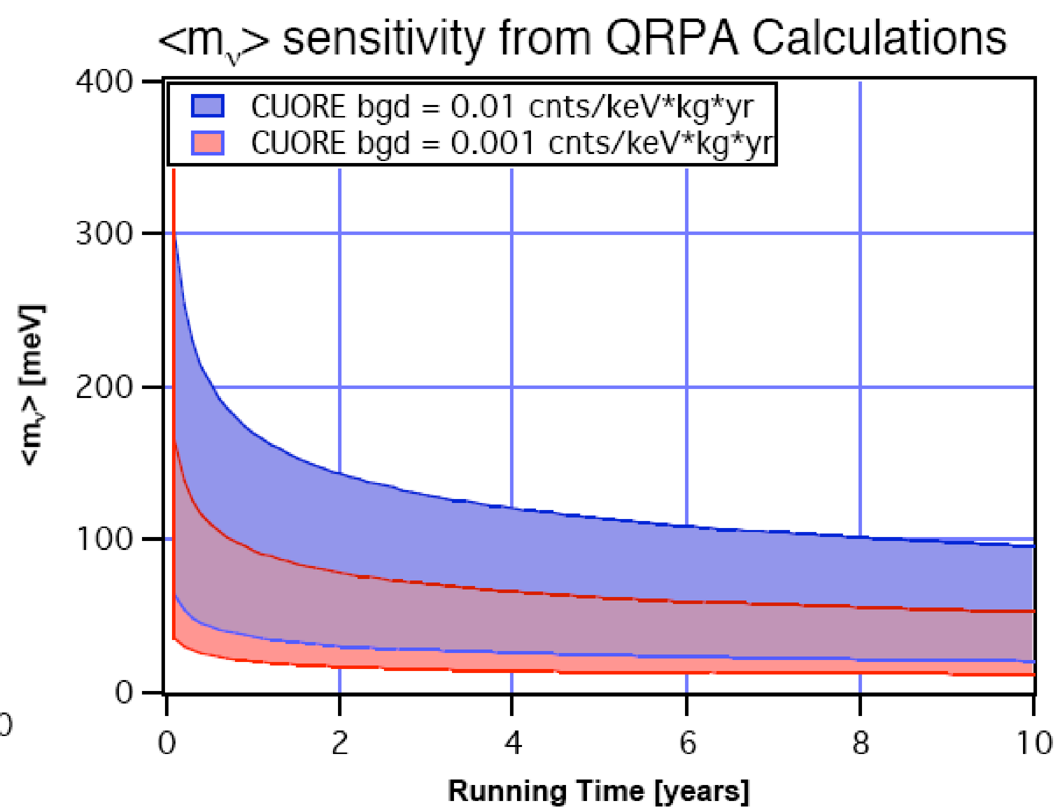
CUORE sensitivity

CUORE 0νββ sensitivity will depend strongly on the bkg level and detector performance

1st generation exp: proof of technology
2nd generation exp: explore inverted hierarchy

CUORE GOAL:
test inverse hierarchy: 19-50 meV



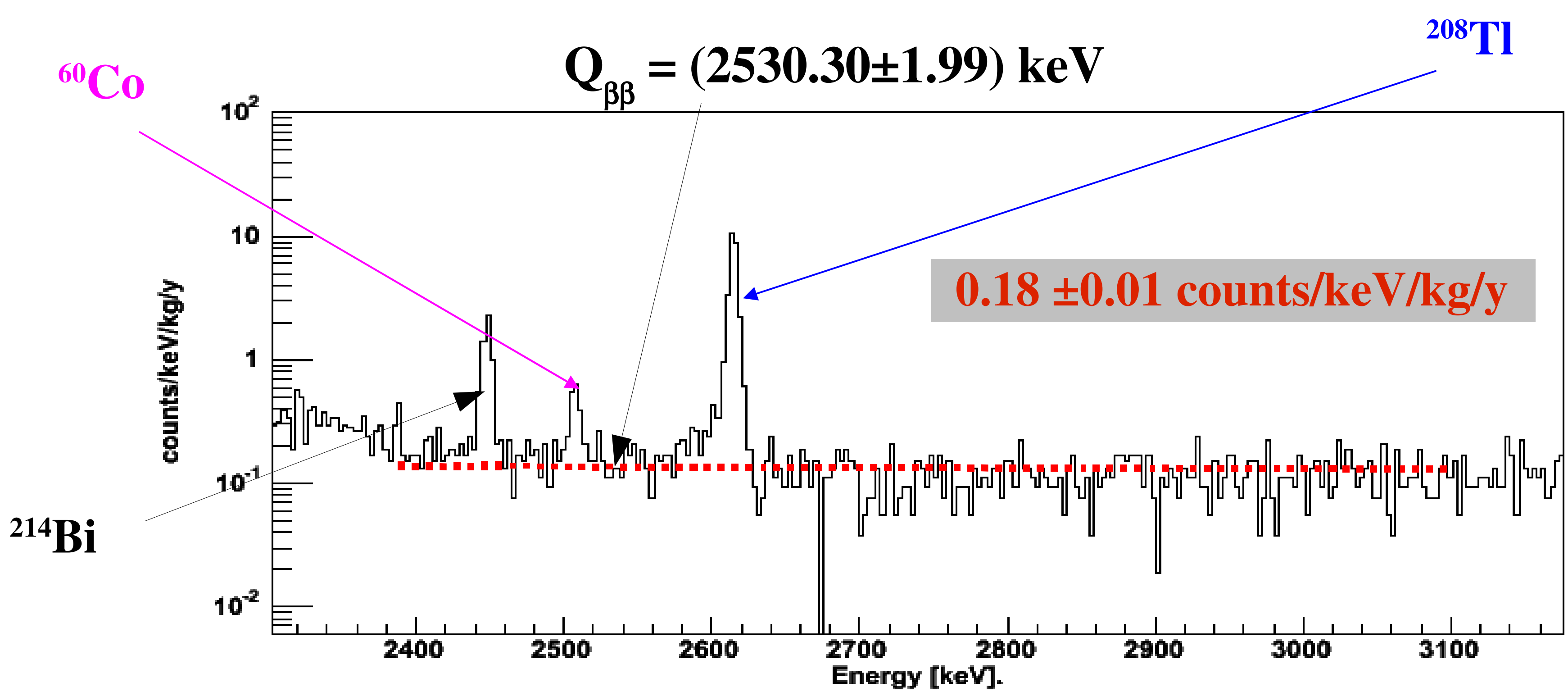


Spread due to NME uncertainties: main obstacle to answer ν mass question

CUORICINO bkg in the 0νββ region

- ***All lines identified all over the whole spectrum***: U & Th chains, ^{40}K, ^{207}Bi, ^{60}Co

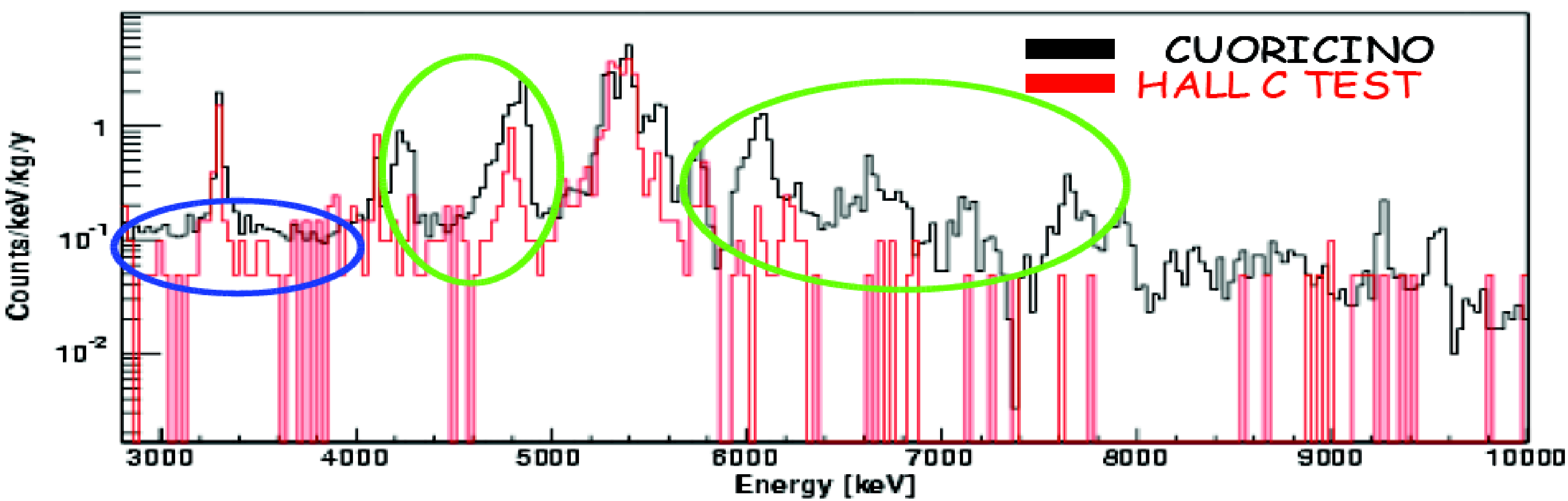
- **In 0νββ region:**
  - **30 ± 10% ^{208}Tl (2614.5 keV line) via multi-Compton events from *^{232}Th* in *cryostat shields***
  - **10 ± 5% from crystals surface *^{238}U and ^{232}Th contamination***
  - **50 ± 20% from degraded α produced by ^{238}U and ^{232}Th contaminations of *mounting structure*** **main candidate the *copper surface***
  - **negligible contribution from 2505 (1173γ+1332γ) keV ^{60}Co tail due *Cu cosmogenic activation***



Background reduction

- Cryostat ^{232}Th bulk contamination contribution reduced by properly shielding in CUORE cryostat + selection of construction materials: bkg= < 10^{-3} c/keV/kg/y
- Cosmogenic Cu and Te activation reduced by underground storage of materials

- Surface contribution:
  - test wih new crystals surface cleaning (etching, lapping with 2μm SiO_2 clean powder)
    reduction of a factor 4
  - test wih new Cu cleaning (etching, electro-polishing, passivation) and complete coverage of Cu facing the crystal with ~50μm PET film
    reduction of ~40% of flat continuum background



Hall C cryostat has different shields than CUORICINO resulting in higher rates < 2.6 MeV. Possible to study α bkg only

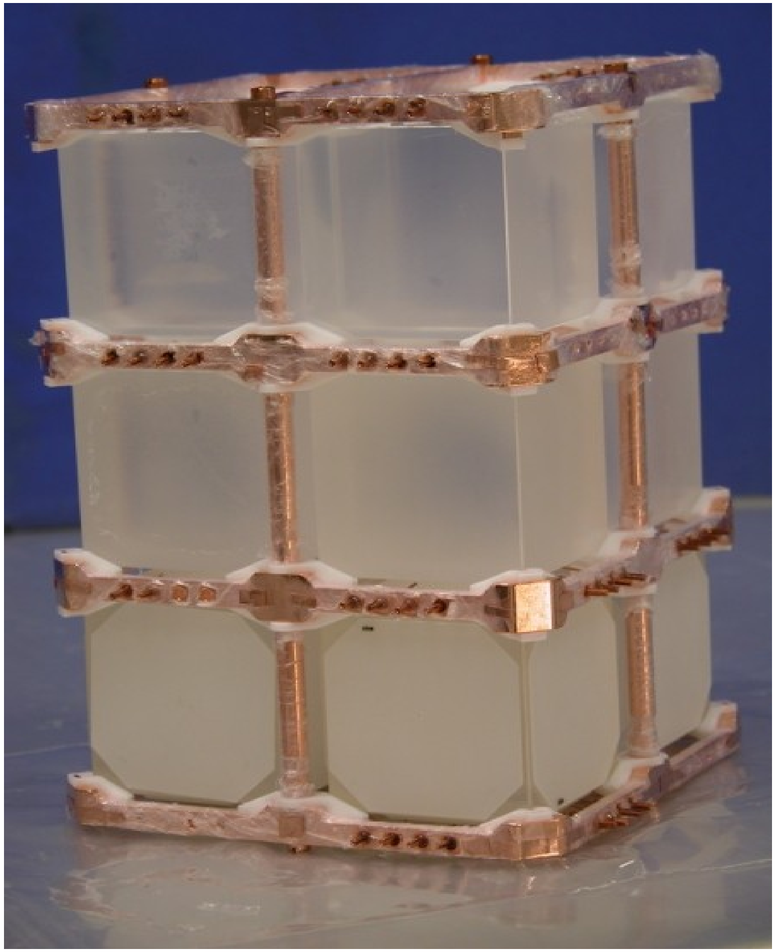
The fight is not over yet

The extrapolated contribution to CUORE are

- Crystal Surface contamination contribution $<3\bullet 10^{-3}$ counts/keV/kg/y
- Copper Surface contamination contribution $<5\bullet 10^{-2}$ counts/keV/kg/y
- New structure with reduced Cu amount is being tested right now

  MC simulation Cu contribution $< 2.5\bullet 10^{-2}$ counts/keV/kg/y

still a factor no less than 2.5 to go



New passive procedure (plasma cleaning) under test

most exp. efforts now concentrated in the

reduction of surface impurities

alternative viable way:

adopt a smarter, yet more complex, bkg recejction system:

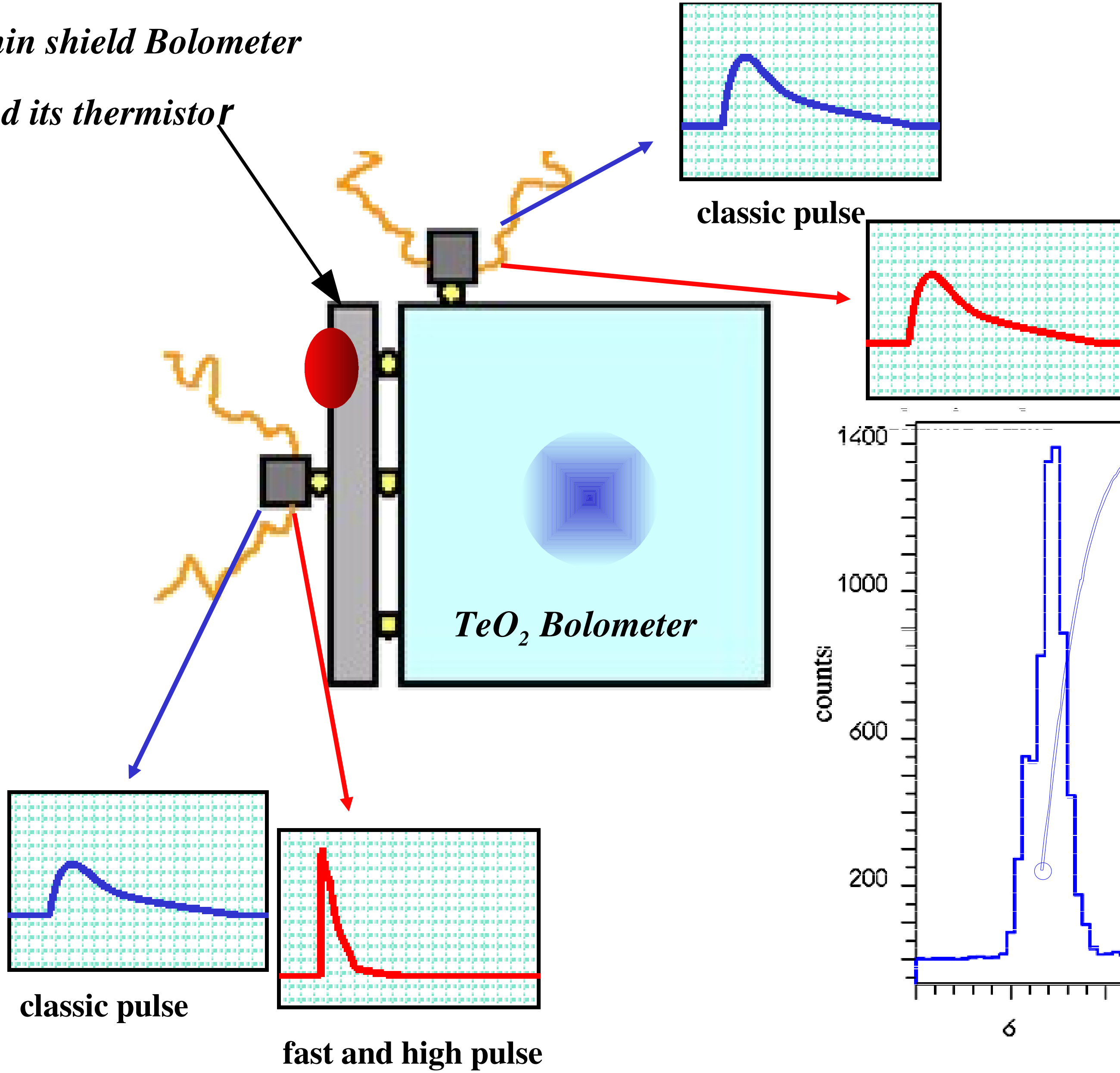
Surface Sensitive Bolometers

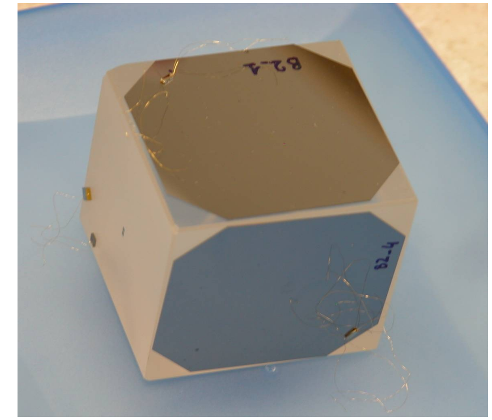
CUORE R&D:active bkg rejection

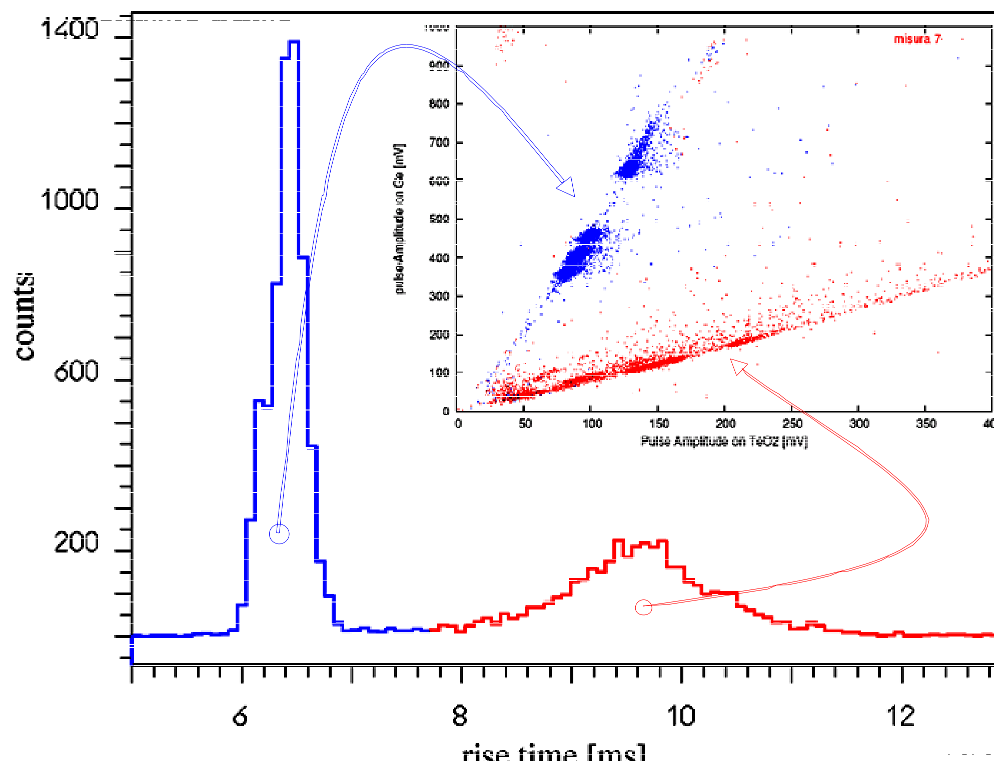
Surface sensitive detectors: ***composite bolometer with a thin Ge, Si, TeO_2 crystal***

Thin shield Bolometer

and its thermistor







Conclusion

- Dirac or Majorana neutrino nature is a fundamental question that needs to be answered at (almost) all cost(s)
- Neutrino-less DBD might be the sole chance to give a measure of neutrino mass

- CUORICINO:
  - The most sensitive 0νββ decay running experiment:

$$\tau_{1/2}^{0\nu\beta\beta} > 2.4 \cdot 10^{24}\, y \,@\, 90\, C.L. \quad \Rightarrow \quad \langle m_{\beta\beta} \rangle < [0.18 \div 0.94]\, eV$$

  - Good chances to confirm Klapdor-Kleingrothaus claim
  - CUORICINO proved the feasibility of CUORE
  - Crucial informations for background identification

- CUORE:
  - Hut construction already started
  - Intense R&D activity to reduce background and optimize construction
  - Enrichment or alternative options (^{48}Ca, ^{100}Mo, ^{116}Cd, ^{150}Nd) still open

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neutron & γ background

- **External neutron flux:**
  - **Φ=3.7•10^{-6} n/s/cm^2 (measurement E<10MeV + μ-induced neutrons simulation in the rock)**
  - **Total anti-coicidence bkg~10^{-5} counts/keV/kg/y**

- **Muon-induced neutrons in the shieldings**
  - **muon flux Φ = (3.2+0.2) •10^{-4} μ/s/m^2, induced neutron flux on detector Φ~10^{-7} n/s/cm^2**
  - **total anti-coincidence bkg= (3.0±0.3)•10^{-4} counts/keV/kg/y**

- **External radiation: Φ=7.7•10^6 γ /d/cm^2 measured with Ge detector**
  bkg= 1.5•10^{-5} counts/kg/keV/y with 24 cm external Pb shield

- **External Pb shield contamination: 100 μBq/kg**
  bkg = 2.4•10^{-4} counts/kg/keV/y

- **Internal shield**
  - **Roman lead contamination (6cm Pb):**
    60±17 μBq/kg bkg = 6•10^{-3} counts/keV/kg/y
  - **DownRun Pb <22 μBq/kg bkg < 2•10^{-3} counts/keV/kg/y**
    (but ^{60}Co contamination & 27 Bq/kg ^{210}Pb)

  - **Cu shield contamination : <12 μBq**
    bkg <2.4•10^{-3} counts/keV/kg/y
    (better for Th contamination.. worse for ^{60}Co contamination and neutron activation)