CUORICINO and CUORE: present and future of ^{130}Te neutrinoless double beta decay searches

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on behalf of the CUORE collaboration

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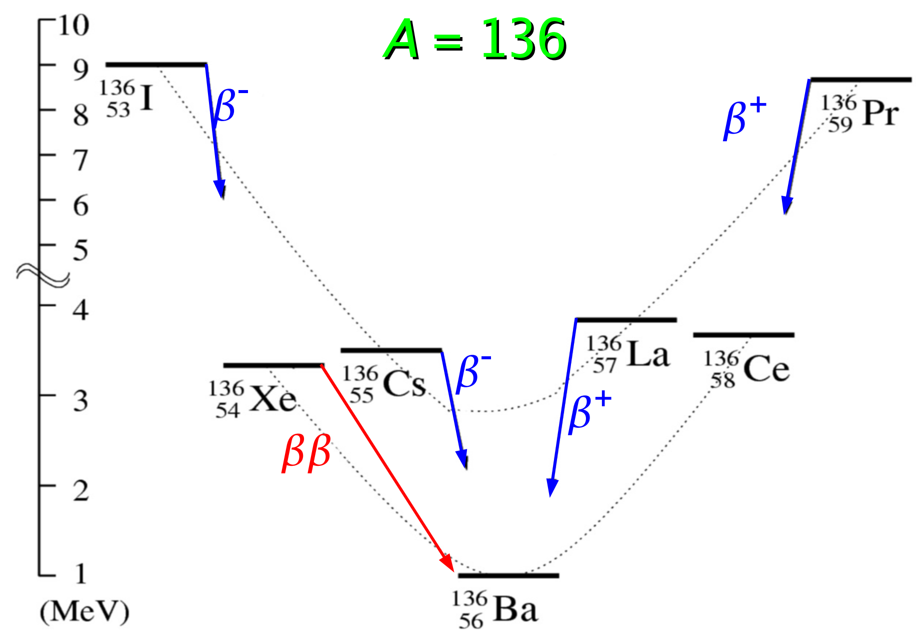
Outline

- Neutrinoless double beta decay and neutrino properties
- Calorimetric searches with thermal detectors
- Cuoricino search for ^{130}Te neutrinoless double beta decay
  - ► understanding Cuoricino background
- CUORE
  - ► background reduction assessment: the Three Tower Test (TTT)
  - ► first step towards CUORE: the CUORE-0 experiment
  - ► CUORE sensitivity expectations
  - ► CUORE construction status

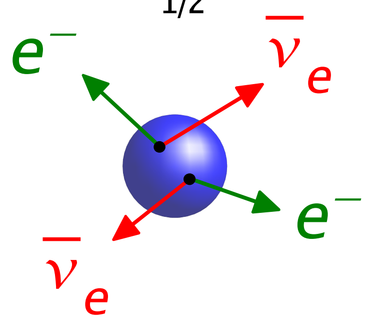
Introduction: double beta decay

second order **nuclear weak decay**
of even-even nuclei
in *A* even multiplets:
^{48}Ca, ^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe ...



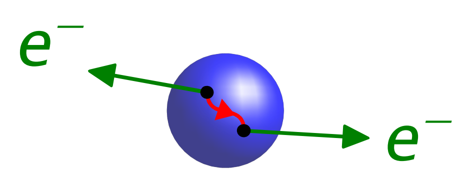
$\beta\beta$-2ν: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

- allowed in Standard Model
- observed with $\tau_{1/2} > 10^{19}$ years

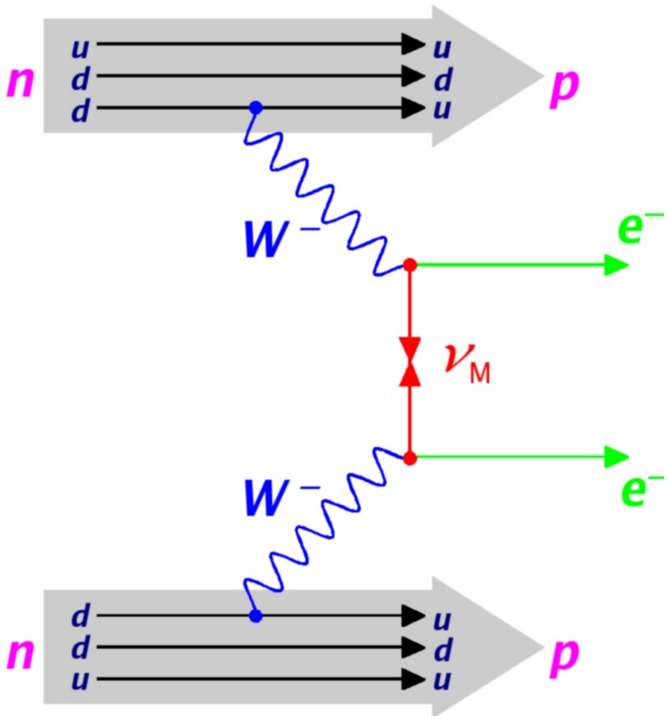


$\beta\beta$-0ν: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

- not allowed in Standard Model
- expected $\tau_{1/2} > 10^{25}$ years
- one *controversial* claim to be checked



$\beta\beta$-0ν and neutrino properties



- a virtual neutrino is exchanged
  - neutrino must have **mass** to allow helicity non conservation $\Rightarrow \Delta H=2$
  - neutrino must be a **Majorana particle** to allow lepton number non conservation $\Rightarrow \Delta L=2$

$$\beta\beta\text{-}0\nu \;\Leftrightarrow\; \begin{matrix} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{matrix}$$

▲ these conditions hold even if other mechanisms are possible and may dominate

light Majorana ν mediated $\beta\beta$-0ν decay rate $$\frac{1}{\tau^{0\nu}_{1/2}} = \frac{\langle m_\nu \rangle^2}{m_e^2} \cdot F_N$$

nuclear structure factor

$$F_N \equiv G^{0\nu}(Q_{\beta\beta}, Z)\,|M^{0\nu}|^2$$

phase space (for $G^{0\nu}$) — nuclear matrix element (for $M^{0\nu}$)

effective neutrino Majorana mass

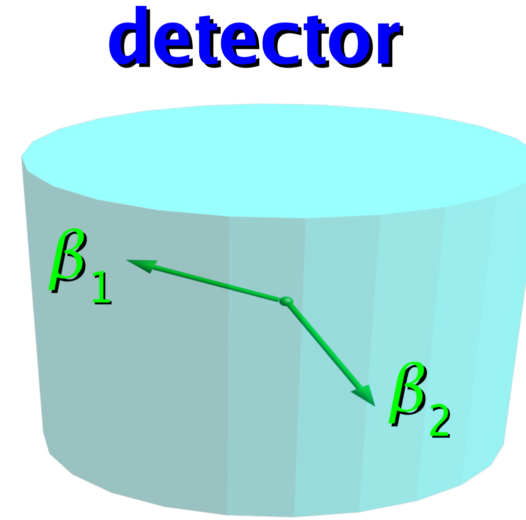
$$\langle m_\nu \rangle = \left| \sum_k m_{\nu_k} \eta_k |U_{ek}|^2 \right|$$

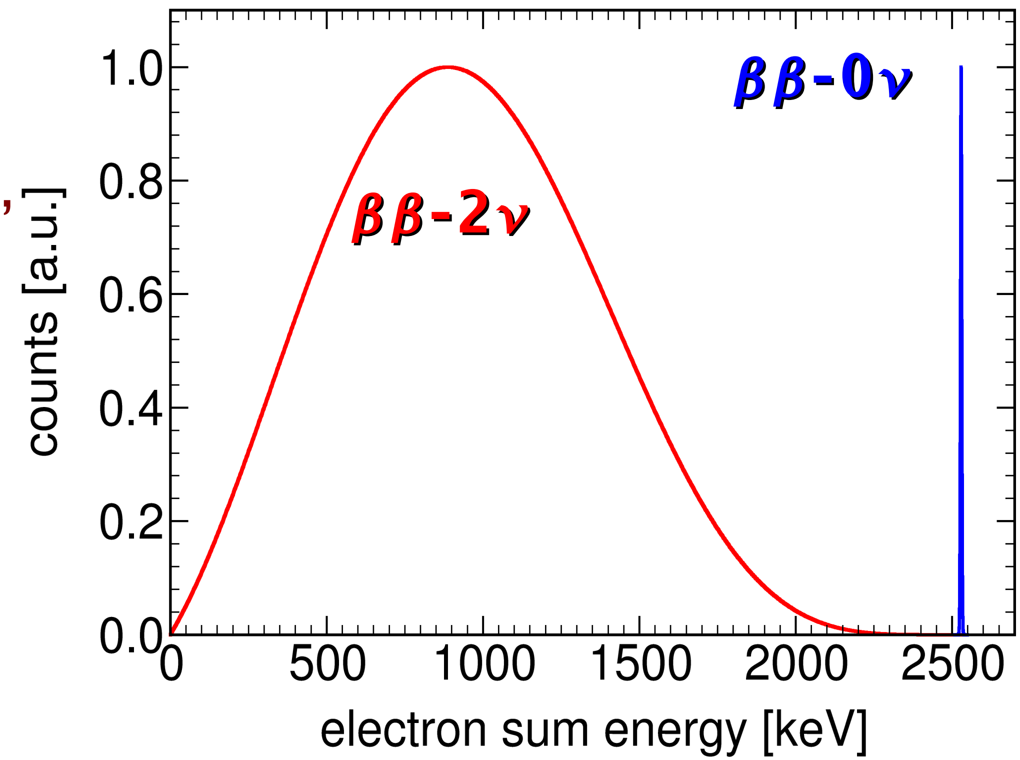
CP phases* (for η_k) — neutrino mixing matrix (for U_{ek})

Experimental approaches for $\beta\beta$-0ν

Source ⊆ detector (calorimetry)

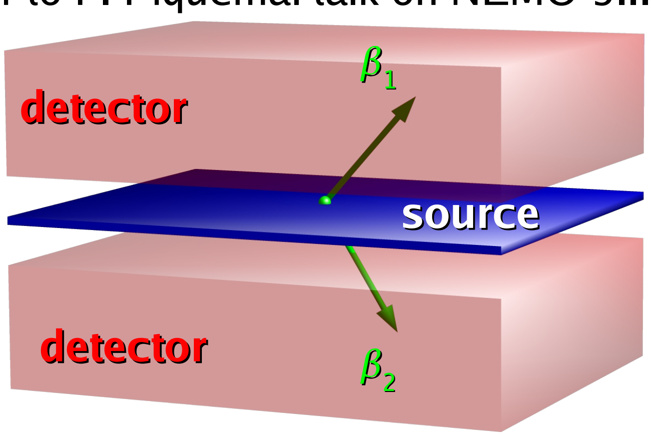
- detector measures sum energy $E = E_{\beta_1} + E_{\beta_2}$
  - ▶ $\beta\beta$-0ν signature: a peak at transition energy $Q_{\beta\beta}$
- scintillators, **bolometers**, semiconductor diodes, gas chambers
  - ▲ large masses
  - ▲ high efficiency
  - ▲ many isotopes possible
- depending on technique
  - high energy resolution (bolometers, semiconductors)
  - moderate topology recognition (Xe TPC, semiconductors)



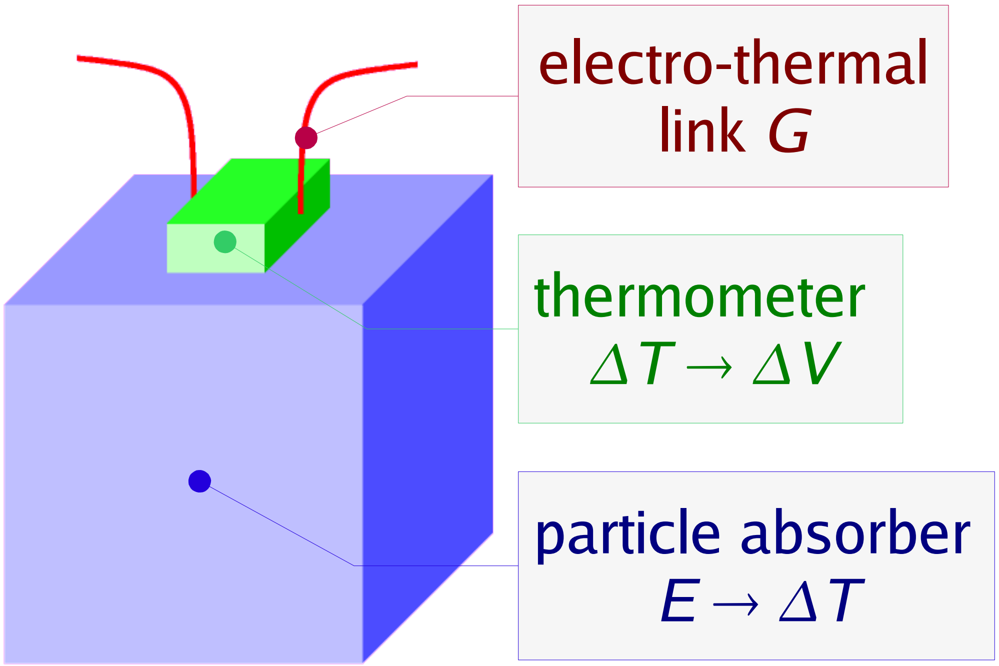


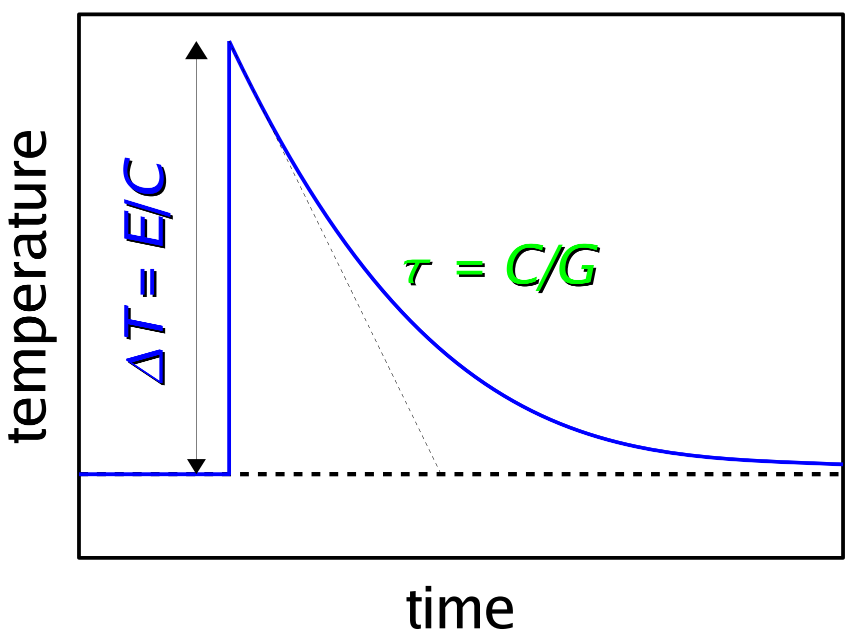
Source ≠ detector ...

(refer to F. Piquemal talk on NEMO-3...)



Cryogenic detectors as calorimeters





- complete energy *thermalization*
  - ▶ calorimetry
- $\Delta T = E/C$ (C thermal capacity)
  - ▶ low C
    - ▷ low T (i.e. $T \ll 1K$)
    - ▷ dielectrics, superconductors
- **Pros and cons**
  - ▲ high energy resolution
  - ▲ large choice of absorber materials
  - ▲ true calorimeters
  - ▼ only energy and time informations
  - ▼ slow time response

- **750 g of TeO_2 @ 10 mK**

  $C \sim T^3$ (Debye) $\Rightarrow C \sim 2\times10^{-9}$ J/K

  1 MeV γ-ray $\Rightarrow \Delta T \sim 80\ \mu K$

  $G \sim 4\times10^{-9}$ W/K $\Rightarrow \tau = C/G \sim 0.5$ s

Experimental sensitivity for $\beta\beta$-0ν

$$\langle m_\nu \rangle \propto \sqrt{1/\tau_{1/2}^{0\nu}}$$

Experimental $\beta\beta$-0ν rate

- with $N_{\beta\beta}$ decays observed

$$\tau_{1/2}^{0\nu} = \ln 2 \frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

- number of active nuclei $N_{nuclei} = i.a.\, \mathcal{N}_A M/A$
- measuring time [y]

Experimental sensitivity to $\tau_{1/2}^{0\nu}$

- with **no** decay observed
  - $N_{\beta\beta} \leqslant (bkg \cdot \Delta E \cdot M \cdot t_{meas})^{1/2}$ at 1σ

$$\sum(\tau_{1/2}^{0\nu}) \propto \epsilon \cdot \frac{i.a.}{A} \sqrt{\frac{M t_{meas}}{\Delta E \cdot bkg}}$$

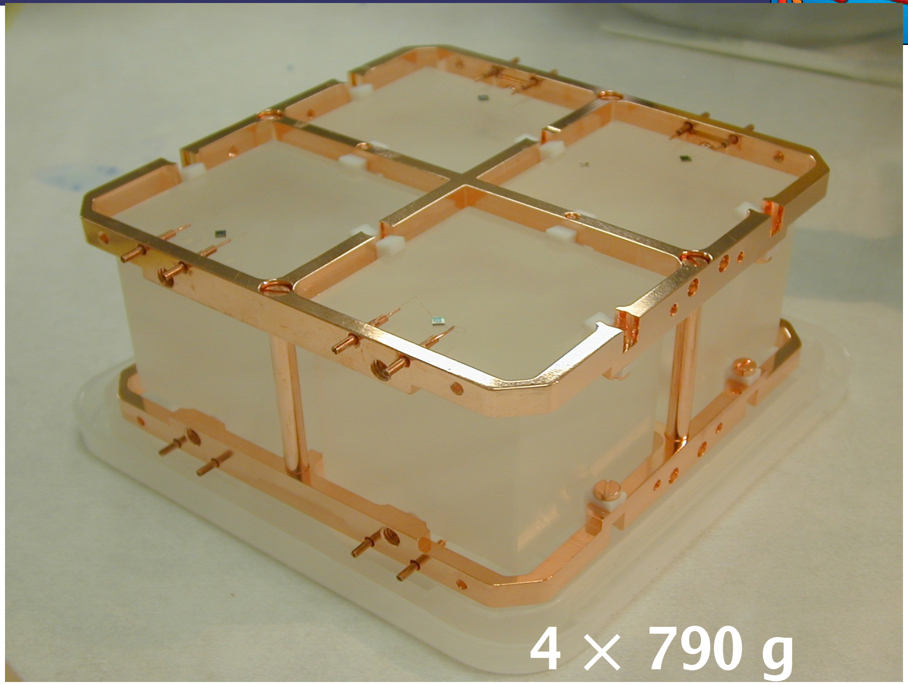
- detector efficiency
- detector mass [kg]
- isotopic abundance, atomic number
- energy resolution [keV]
- specific background [c/keV/kg/y]

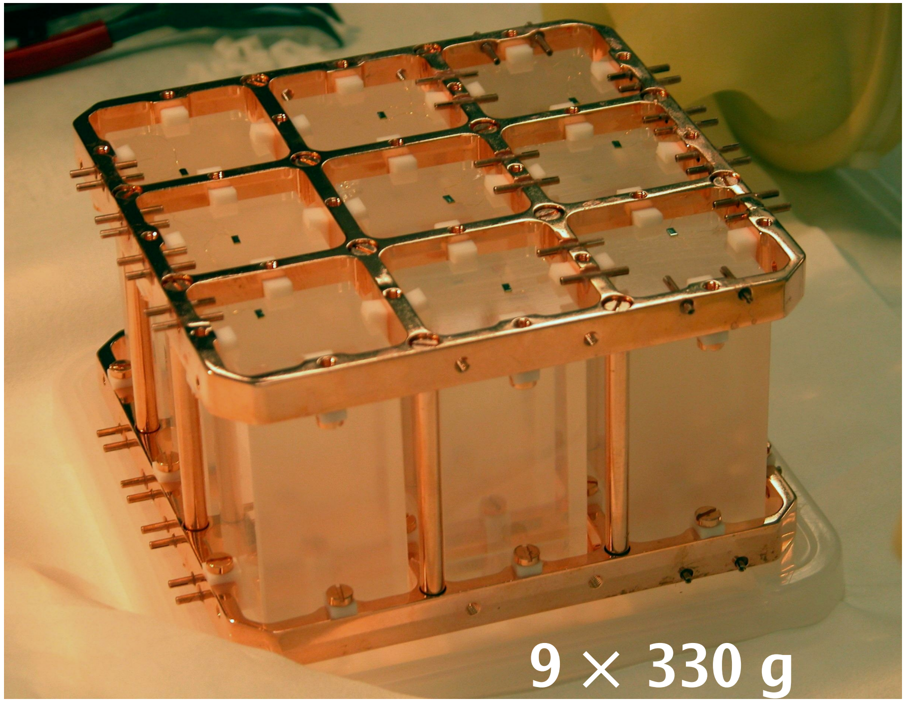
> - for $bkg = 0 \Rightarrow N_{\beta\beta} \leqslant 3$ at 2σ
>
> $$\sum(\tau_{1/2}^{0\nu}) \propto \frac{\epsilon\, i.a.}{A} M t_{meas}$$

The CUORICINO experiment

TeO_2 thermal calorimeters

- **Active isotope ^{130}Te**
  - natural abundance: a.i. = 33.8%
  - transition energy: $Q_{\beta\beta}$ = 2527.52 keV
  - *short* expected half life
    $\langle m_\nu \rangle \approx 50$ meV $\Leftrightarrow$ $\tau_{1/2}^{0\nu} \approx 1 \div 6 \times 10^{26}$ y
- **Absorber material TeO_2**
  - low heat capacity
  - large crystals available
  - radiopure

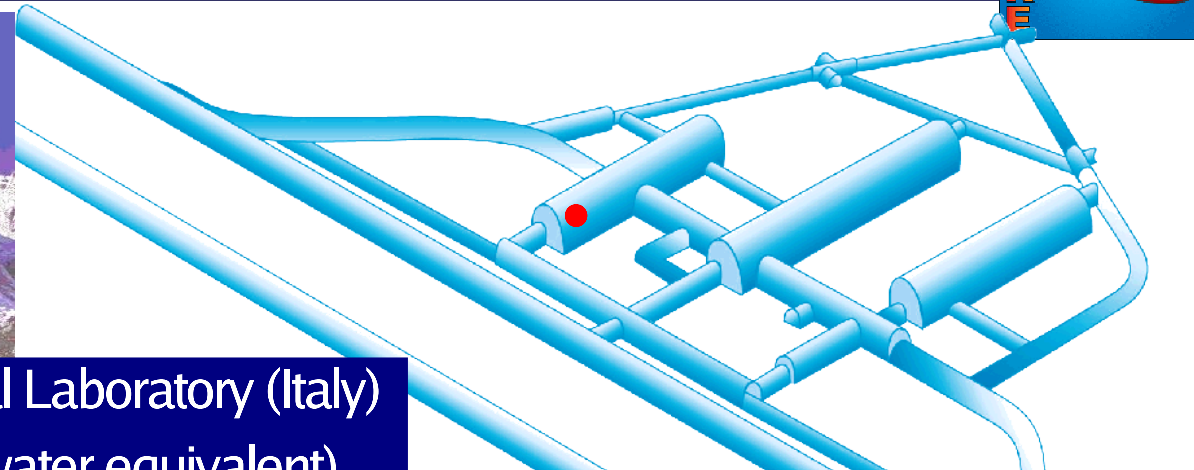




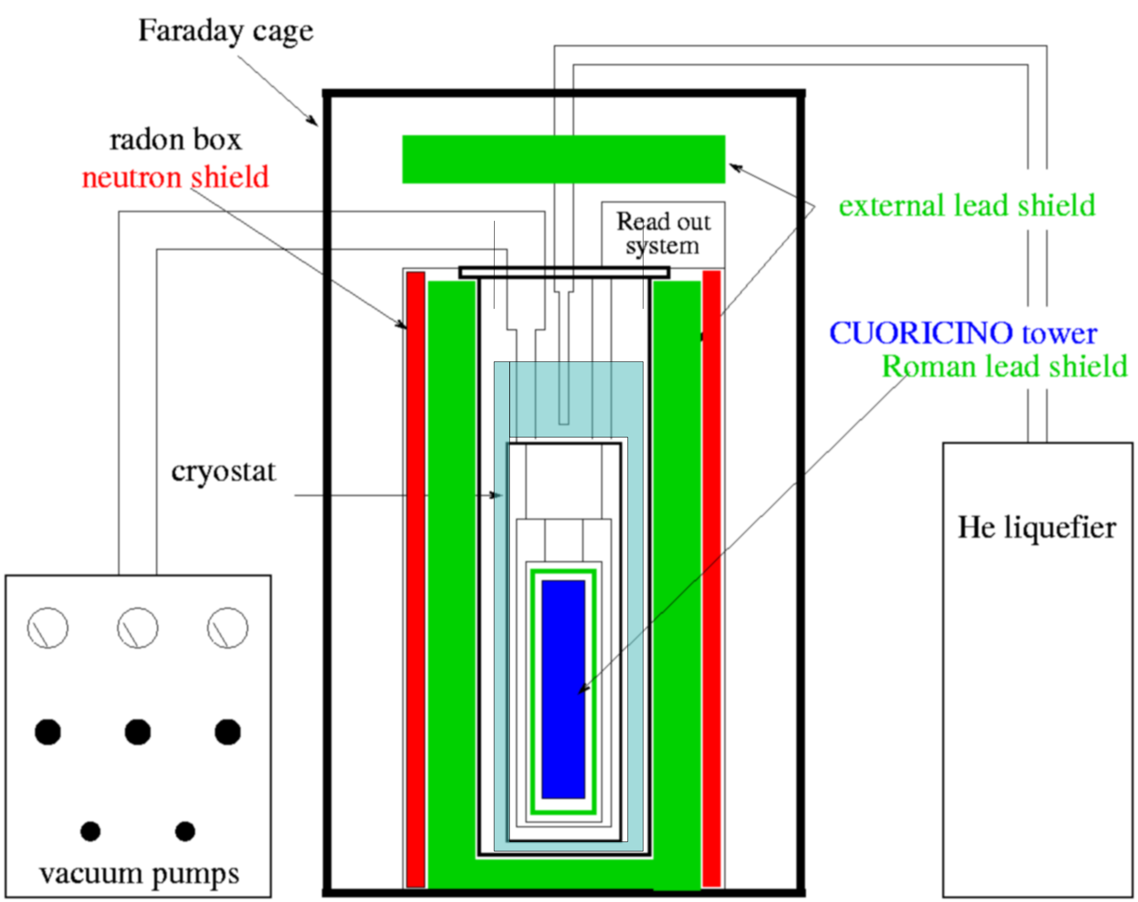
CUORICINO experiment @ LNGS

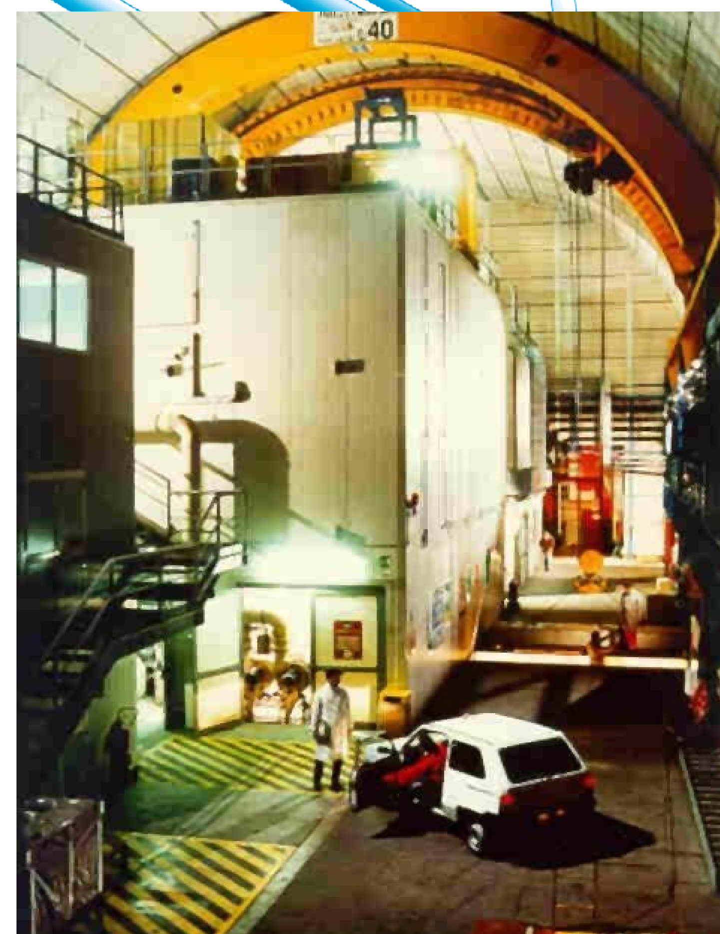
- 62 TeO_2 detectors in the ***tower*-like structure** foreseen for **CUORE**
- 11 modules: 4 × **790 g** crystals
- 2 modules: 9 × **330 g** crystals
- **total mass 41 kg (~11 kg ^{130}Te)**
  - **intermediate size $\beta\beta$ experiment**
  - **test for radioactivity**

CUORICINO site at LNGS



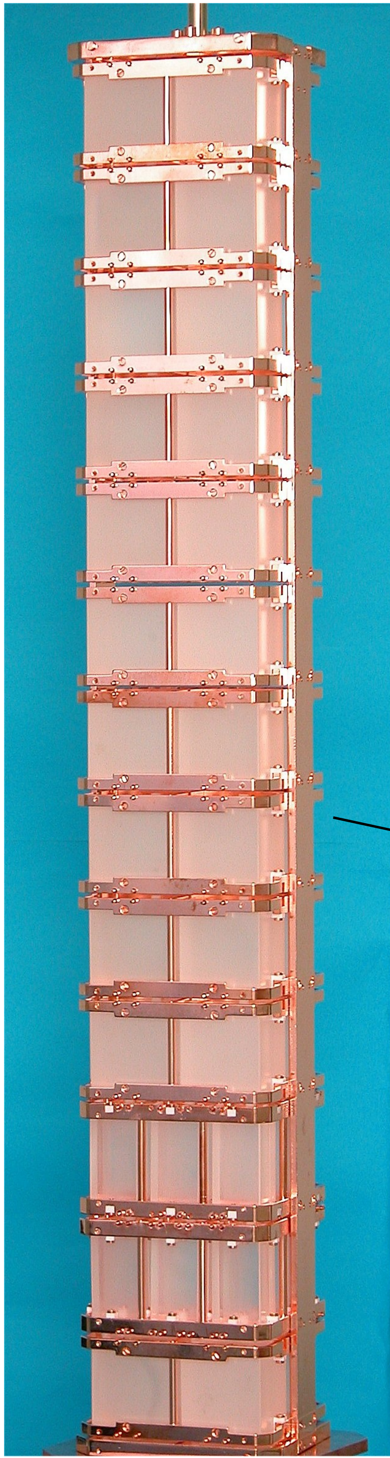
underground in Gran Sasso National Laboratory (Italy)
under 1400 m of rock (≈3600 m water equivalent)



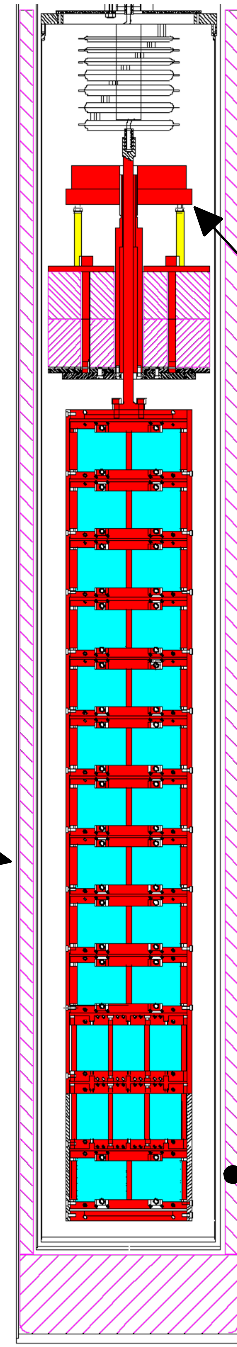


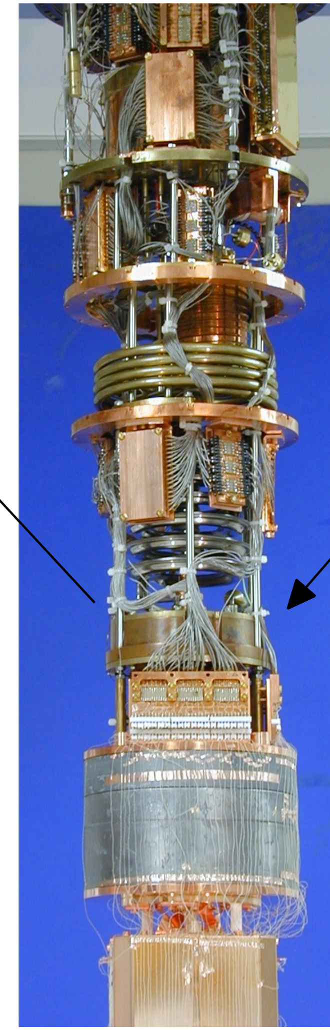
The CUORICINO set-up

Cuoricino *tower*: 62 TeO_2 crystals



~70 cm





roman Pb shielding (1 cm lateral)

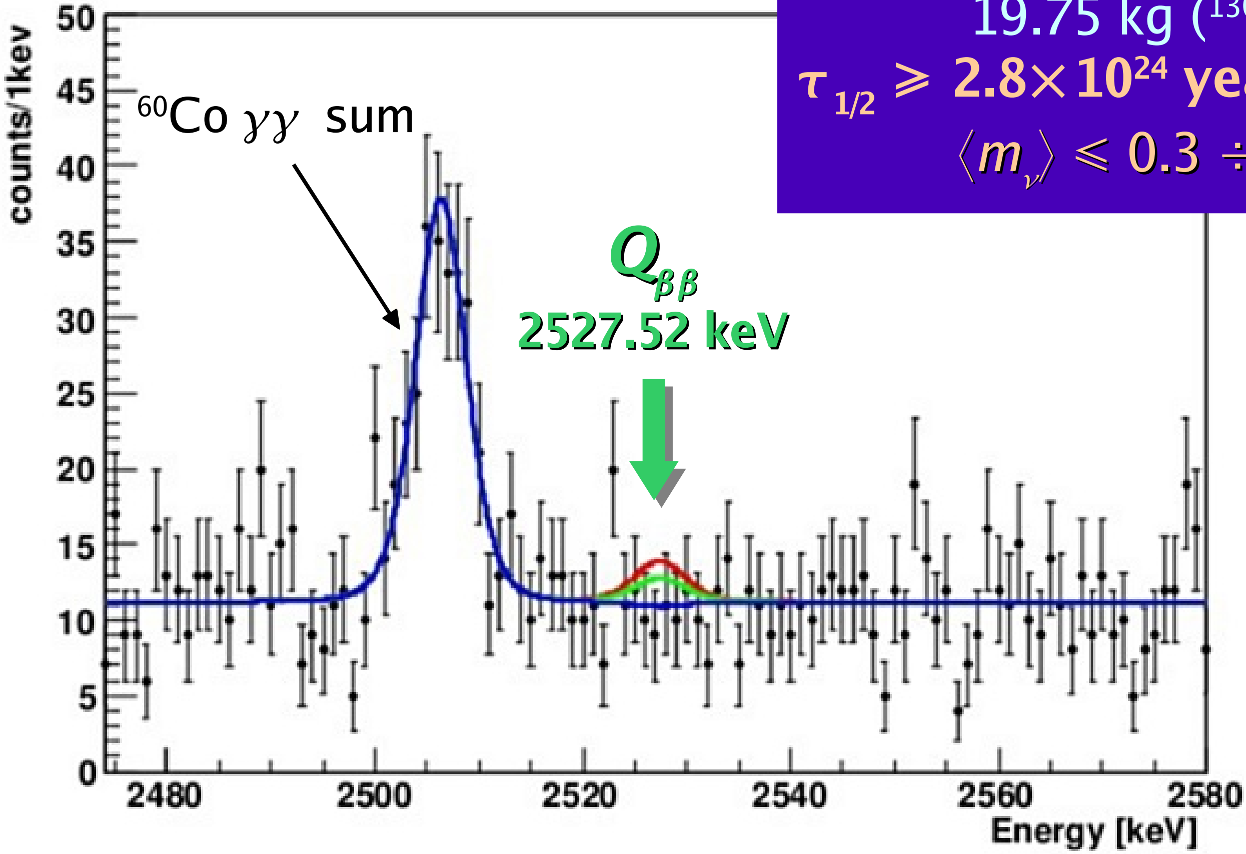
external shields:

- 10 cm Pb + 10 cm low act Pb
- neutron shield: B-polyethylene
- nitrogen flushed anti-radon box

CUORICINO final results

- run from April 2003 to June 2008 (RUN II 05/2004-06/2008: duty cycle ~45%)
- total exposure **19.75 kg (^{130}Te) × years**
- energy resolution FWHM ΔE = 8 keV at $Q_{\beta\beta}$ (σ_E=1.3‰)
- anti-coincidence applied to reduce surface U/Th background and external γs
- background mainly from U/Th on Cu and TeO_2 surfaces (α and β)
  - $b \approx 0.169$ c/keV/kg/y at $Q_{\beta\beta}$

anti-coincidence sum spectrum
19.75 kg (^{130}Te) × y
$\tau_{1/2} \geqslant 2.8 \times 10^{24}$ years at 90% C.L.
$\langle m_\nu \rangle \leqslant 0.3 \div 0.7$ eV *



* Nuclear Matrix Elements from
1 Šimkovic et al., PRC 77 (2008) 045503
2 Civitarese et al., JoP:Conference series 173 (2009) 012012
3 Menéndez et al., NPA 818 (2009) 139
4 Barea and Iachello, PRC 79 (2009) 044301

How to improve CUORICINO sensitivity on $\beta\beta$-0ν

Isotope and material composition
Detector design and optimization
System design and optimization

Single crystal size
Number of crystals
→ detector mass [kg]

Isotopic enrichment → isotopic abundance

System reliability
Duty cycle
→ measuring time [y]

$$\sum(\tau_{1/2}^{0\nu}) \propto i.a. \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

System stability
Vibration control
New crystal material
→ energy resolution [keV]

specific background [c/keV/kg/y]
← Material selection
Surface cleaning
Passive shielding
Detector segmentation
Active rejection
Higher Q (above 2.615 keV)

$$\langle m_\nu \rangle^2 = \frac{1}{F_N} \cdot \frac{m_e^2}{\tau_{1/2}^{0\nu}}$$

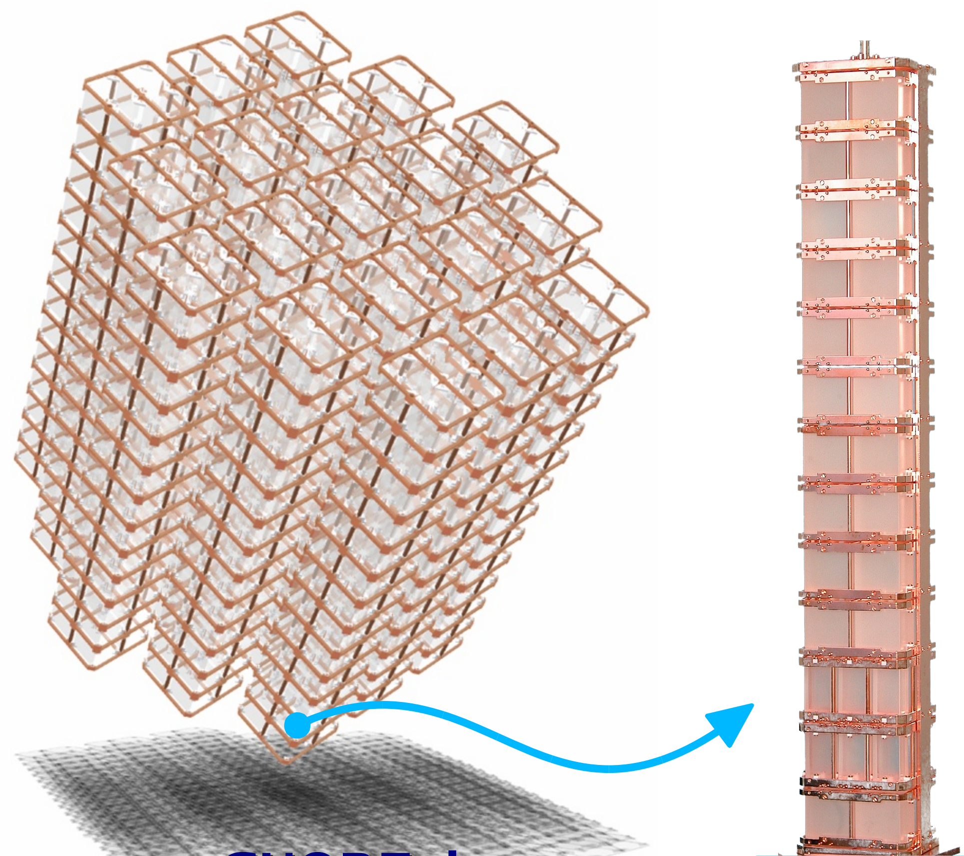
nuclear matrix element ← Isotope choice

CUORE

- **CUORE**: **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents
- improve $\times 10$ the Cuoricino sensitivity on $\langle m_\nu \rangle$
- i.e. improve $\times 100$ the Cuoricino sensitivity on $\tau_{1/2}$

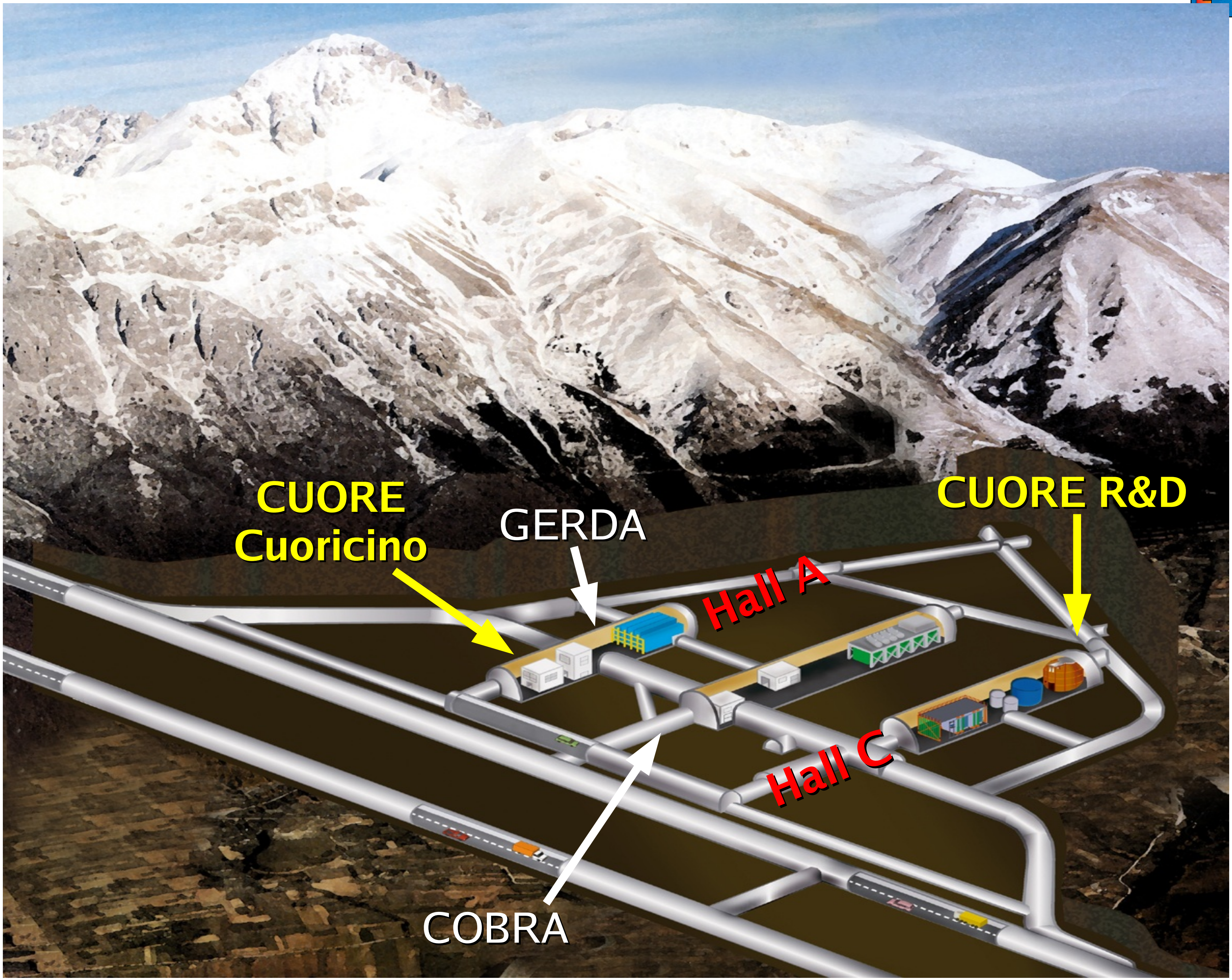
$$\sum (\tau_{1/2}^{0\nu}) \propto \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

  - increase total detector mass $M \times 18$
    - 988 crystal natural **TeO_2** 750 g crystals ⇒ total mass **740 kg TeO_2** ⇒ **200 kg of ^{130}Te**
  - increase measuring time t_{meas} $\times 5$
    - improve duty cycle
  - reduce background bkg $\div 100$
    - improve shielding and material selection
    - better surface cleaning
    - improve detector design
    - use coincidence cuts



CUORE detector
19 *towers* – 52 detectors each

CUORE site at LNGS



CUORE sensitivity potential

- sensitivity depends strongly on **background** level
- **NME uncertainties** broaden the sensitivity expectations *

CUORE 1σ sensitivity in 5 years			
bkg [c/keV/kg/y]	ΔE [keV]	$\tau_{1/2}^{0\nu}$ [y]	$\langle m_\nu \rangle$ [meV]
0.01	5	2.1×10^{26}	35 ÷ 82
0.001	5	6.5×10^{26}	20 ÷ 47

Nuclear Matrix Elements from
1 Šimkovic et al., PRC 77 (2008) 045503
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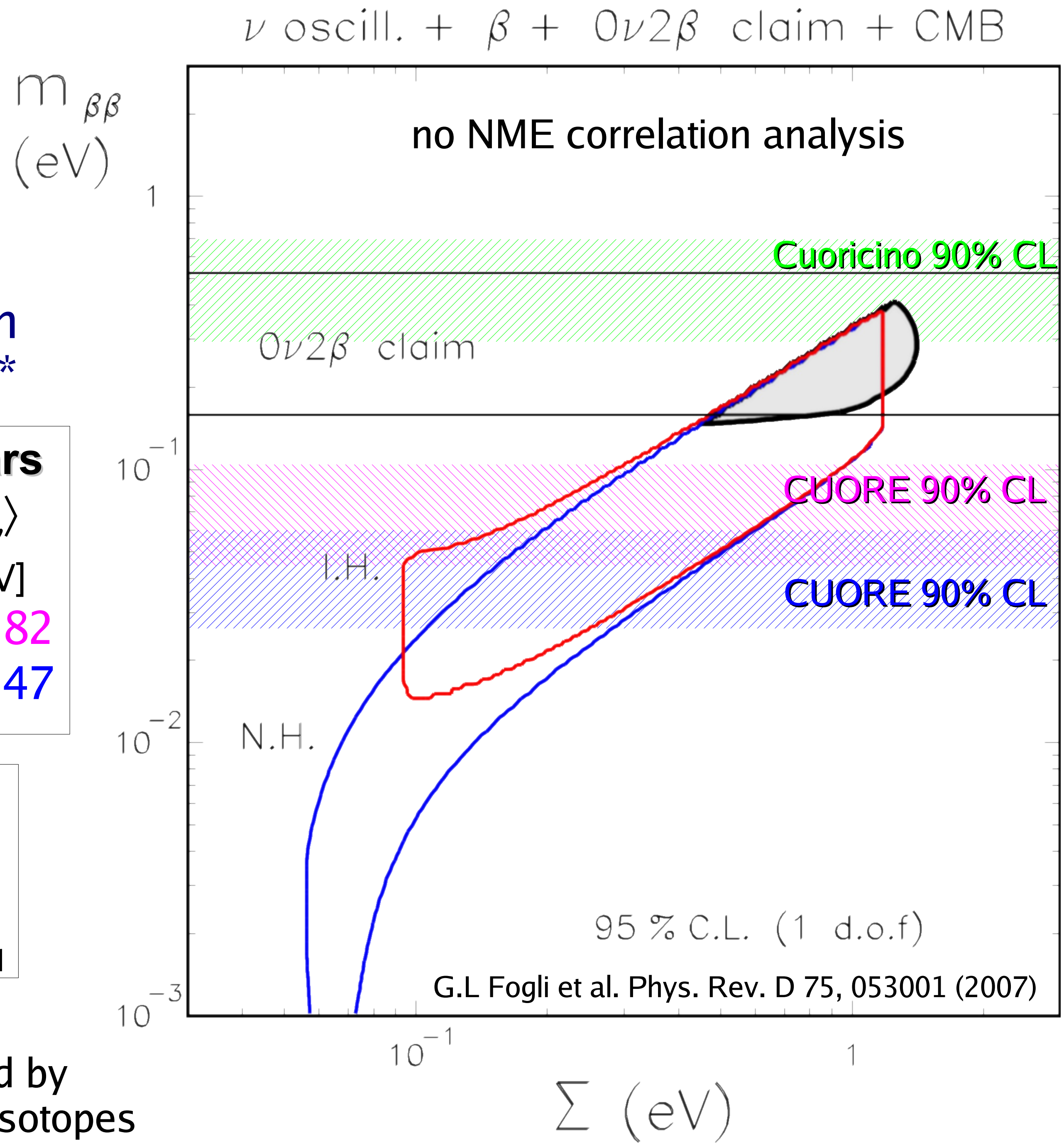
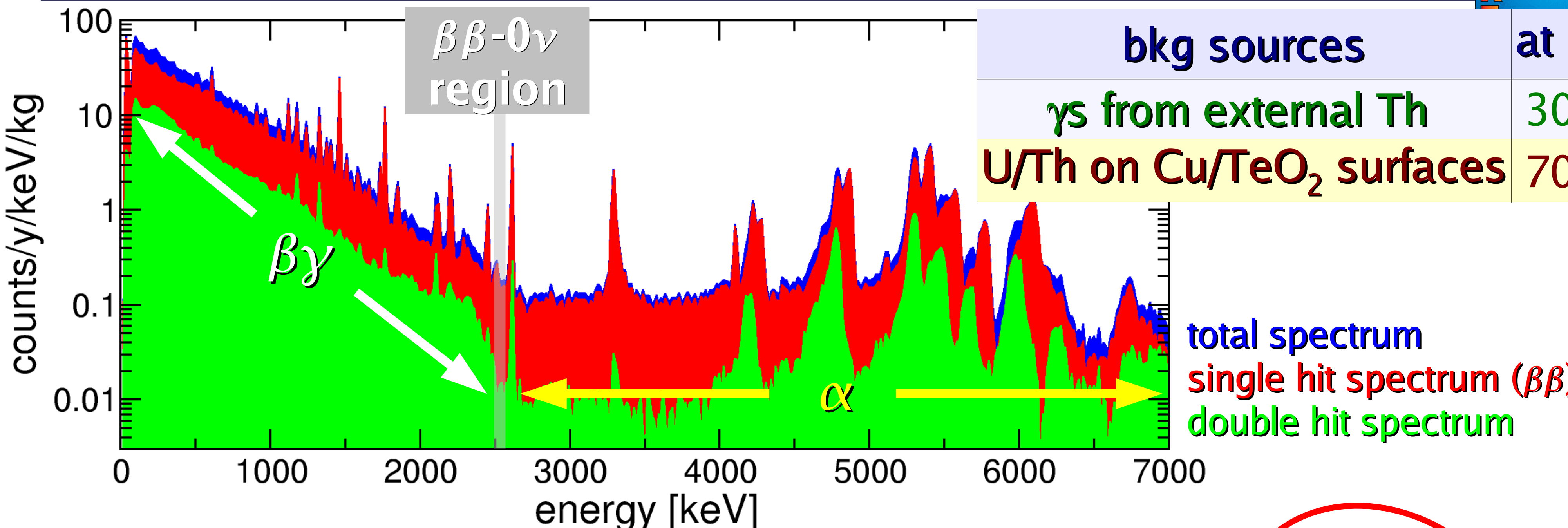


* **NME uncertainties** can be reduced by observing $\beta\beta$-0ν in many different isotopes

Understanding CUORICINO background

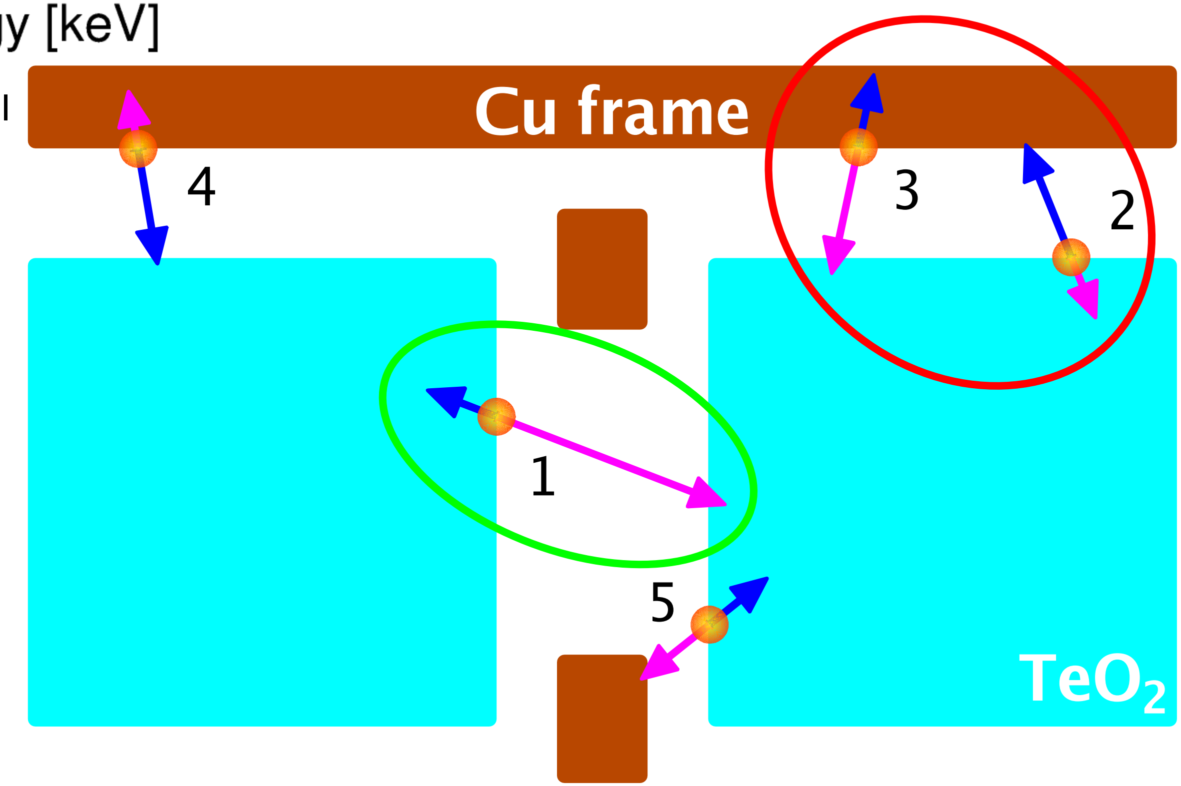


bkg sources	at $Q_{\beta\beta}$
γs from external Th	30%
U/Th on Cu/TeO_2 surfaces	70%

- recoiling daughter nucleus; E_{recoil}
- parent nucleus
- α; E_α

1 discarded by coincidence cut
2 peak with tail at E_α
3 broad distribution up to E_α
4 broad distribution up to E_{recoil}
5 broad peak around E_{recoil}

$E_{recoil} \approx 0.02 E_\alpha \approx 100$ keV

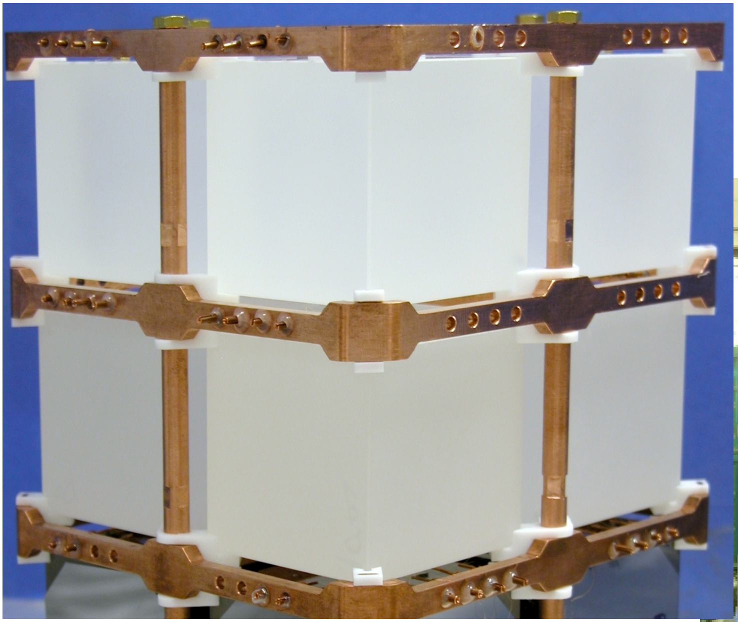


α radioactivity: copper surface cleaning

- detector design minimizes the amount of copper between crystals
- copper machining by EDM
- advanced surface cleaning @ Legnaro
- detector assembly in clean-room and anti-radon box

cleaning procedure for Copper pieces facing the detectors (TECM)

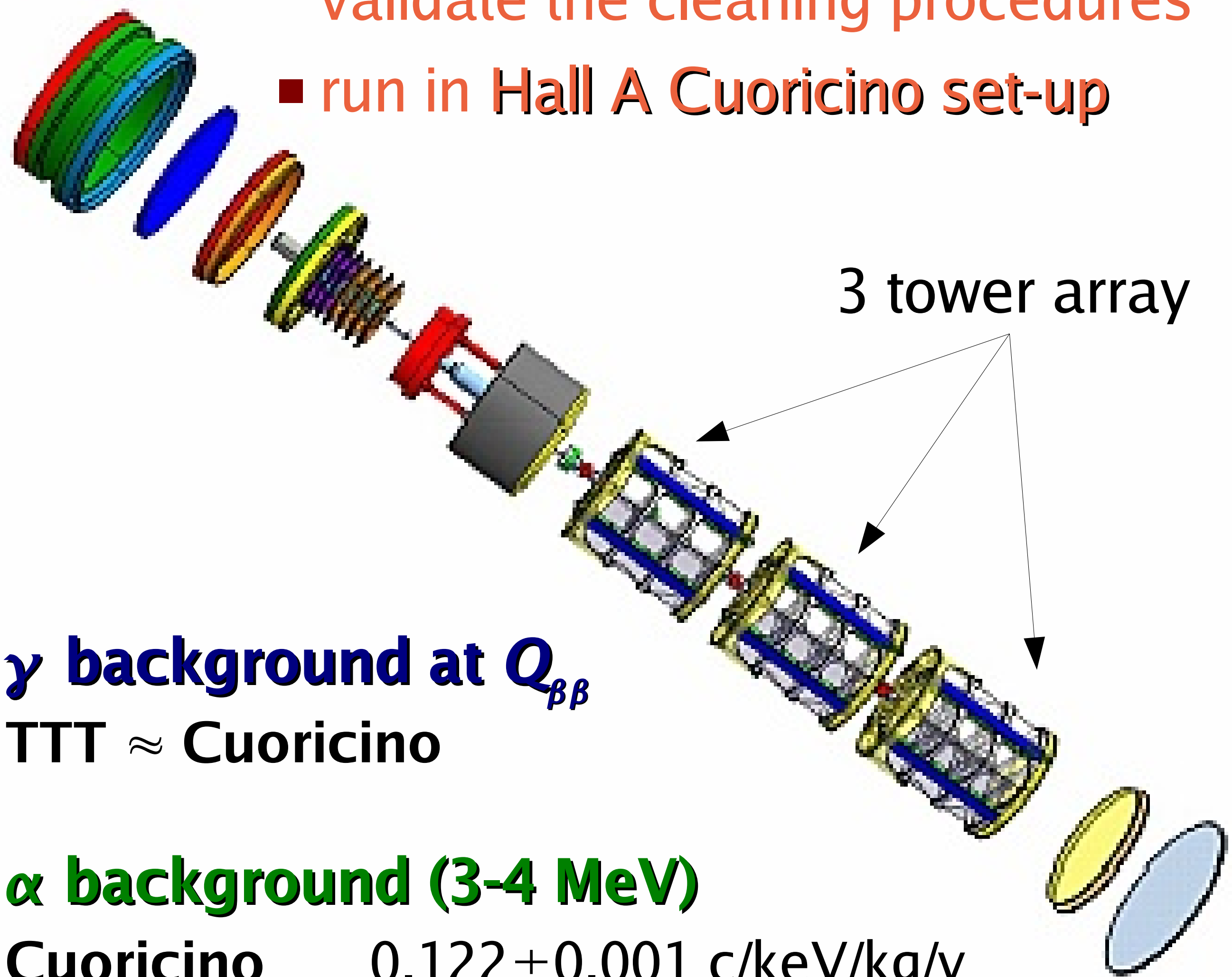
- Tumbling
- Electrochemical
- Chemical
- Magnetron sputtering
- U/S cleaning between each step



Surface cleaning procedure validation

Three Tower Test (TTT)

- bolometric test to compare and validate the cleaning procedures
- run in Hall A Cuoricino set-up



γ background at $Q_{\beta\beta}$

TTT ≈ Cuoricino

α background (3-4 MeV)

Cuoricino	0.122±0.001 c/keV/kg/y
TTT	0.048±0.007 c/keV/kg/y

CUORE background expectations

- from tests (Hall C and TTT) on **crystals and copper surfaces cleaning**
  - reduction of **crystal surface** contamination of a factor **~5**
  - reduction of **continuum background** in 3-4 MeV region of a factor **~2**
- from strict **material selection**
- from improved **detector geometry** (→ better coincidence cuts)
- from improved **lead passive shielding** against environmental γs

presently MC projected bkg [10^{-3} c/kg/kev/y]:

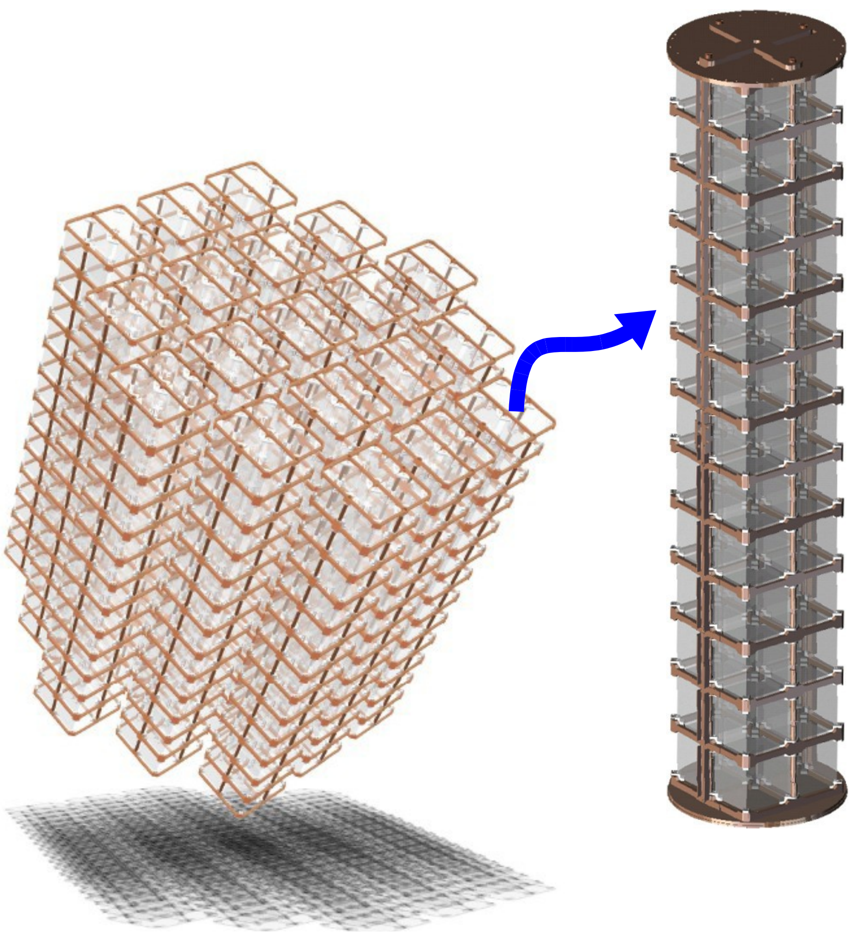
20÷40 from copper surface (α)
< 3 from crystal surface (α, β, γ)
< 2 from detector bulk contaminations (γ, β)
< 10 from experimental set-up (γ)
< 0.5 from environment (γ, n, μ)

within a factor **2÷4** from the
CUORE target background **< 0.01 c/kg/kev/y**

- more **work is in progress to further improve** the CUORE expected background
  - control of **crystal surface and bulk contamination**
  - improve **copper surface cleaning**

CUORE-0

- **CUORE-0 will be the first CUORE tower**
  - it will be operated in the CUORICINO experimental set-up
  - assembly procedure test
  - cleaning procedure and radioactivity achievement test
  - sensitivity will soon overtake CUORICINO



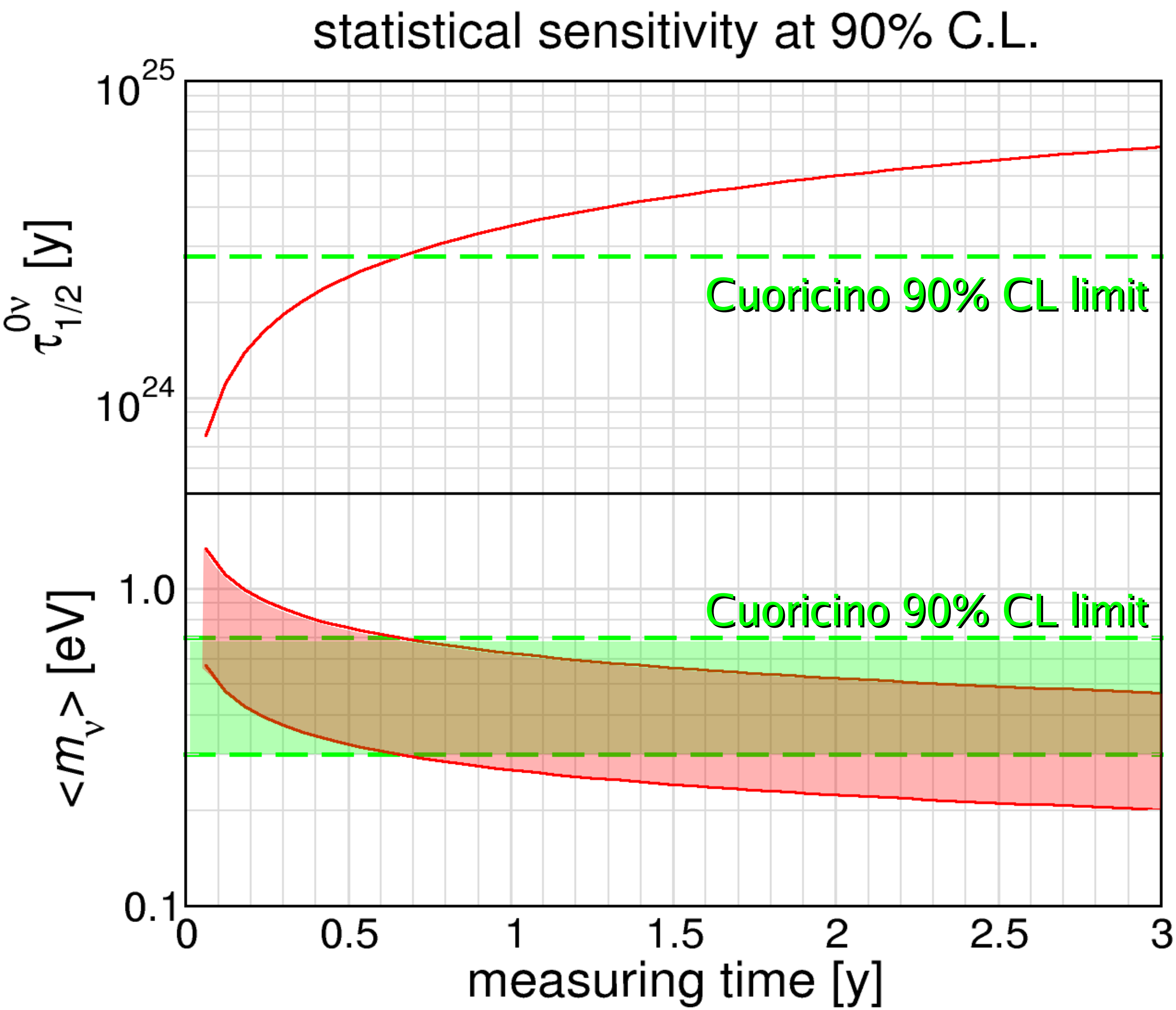
52 TeO_2 crystals
750 g each
5×10^{25} ^{130}Te nuclei

MC extrapolated background at $Q_{\beta\beta}$

γ (Hall A set-up)	0.048±0.005 c/keV/kg/y
surface (from TTT)	0.048±0.009 c/keV/kg/y

total bkg ≤ **0.12 c/keV/kg/y** at 2σ

CUORE-0 sensitivity potential



$$\sum\left(\tau^{0\nu}_{1/2}\right) \propto \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

$$\langle m_\nu \rangle \propto \sqrt{1/\tau^{0\nu}_{1/2}}$$

CUORE-0
bkg = 0.12 c/keV/kg/y
M = 39 kg
ΔE = 5 keV

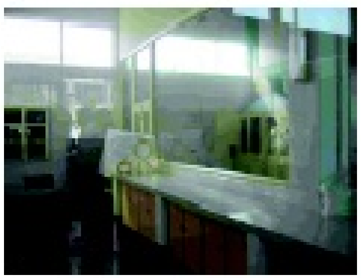
TeO_2 crystal production / 1

SICCAS (Shangai, China)

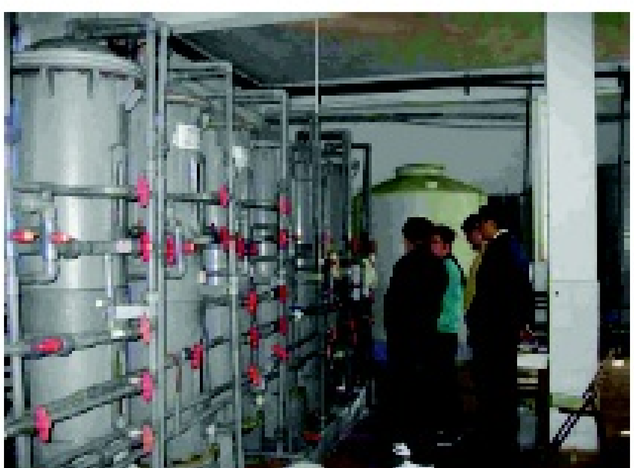
- CUORE dedicated crystal growth facility
- CUORE dedicate Clean Room for
  - cutting, grinding, shaping, orienting, lapping
  - final surface processing and packaging

1) Kushan Jincheng Chemical Reagent Co. Ltd

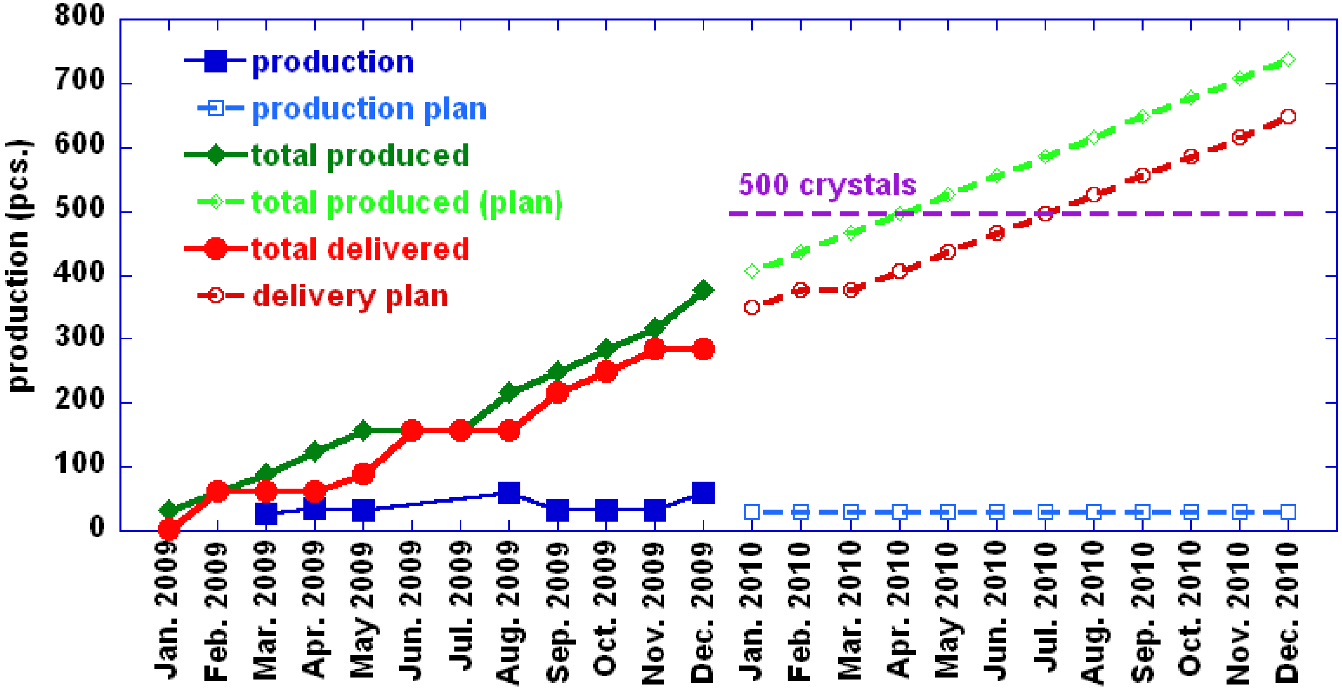
high purity grade TeO2 powder production unit



high purity water and reagents production units



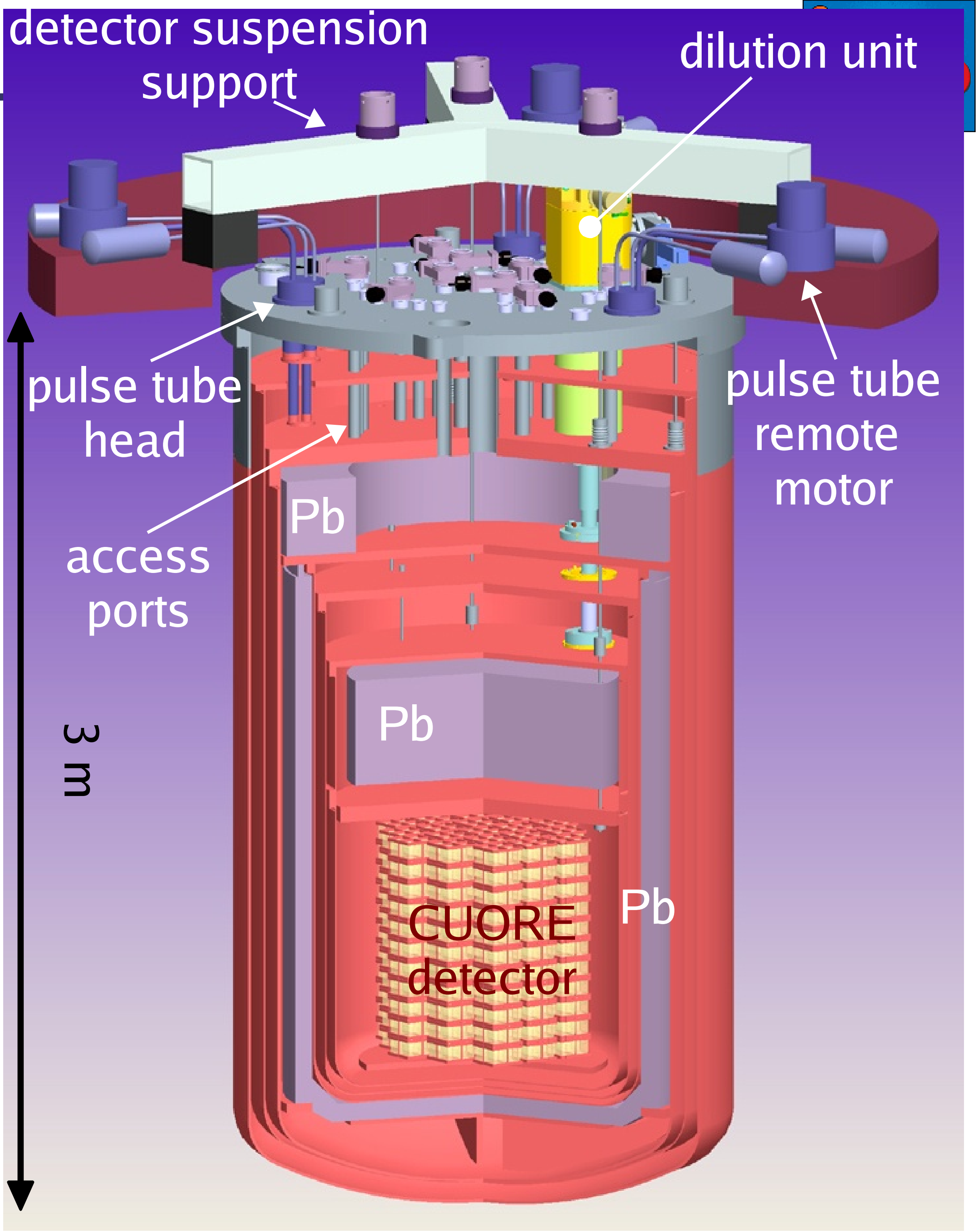
TeO_2 crystal production / 2



- delivery to LNGS by ship to reduce cosmic ray exposure (~ 45 days trip)
- 441 crystals already arrived and safely stored @ LNGS (06/2010)
- delivered crystal are randomly tested at low temperature for purity and bolometric performances

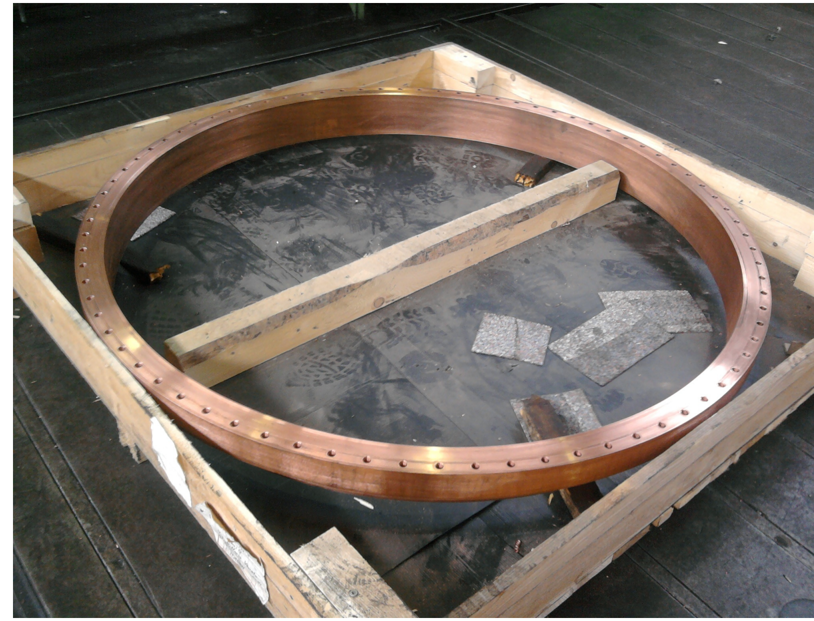
CUORE cryostat

- **cryogen free**
- **base temperature < 10mK**
- **low radioactivity**
  - only selected pure copper
  - other selected materials only in small amounts (SS, TiAlSn...)
- **heavy load support**
  - detector total mass ~1 ton
  - lead shielding total mass ~10 ton
- **low mechanical vibration**
  - independent detector suspension
- **dimensions**
  - external: ⊘ ≤ 1687, *h* ≤ 3100
  - exp. space: ⊘ ≥ 900, *h* ≥ 1385

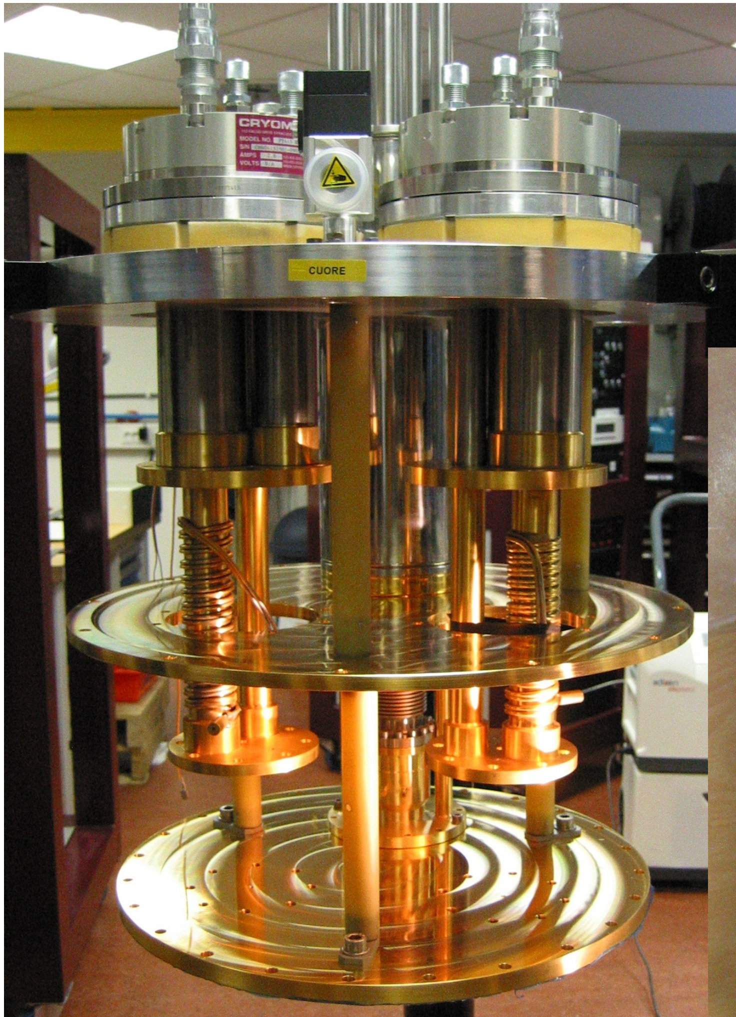


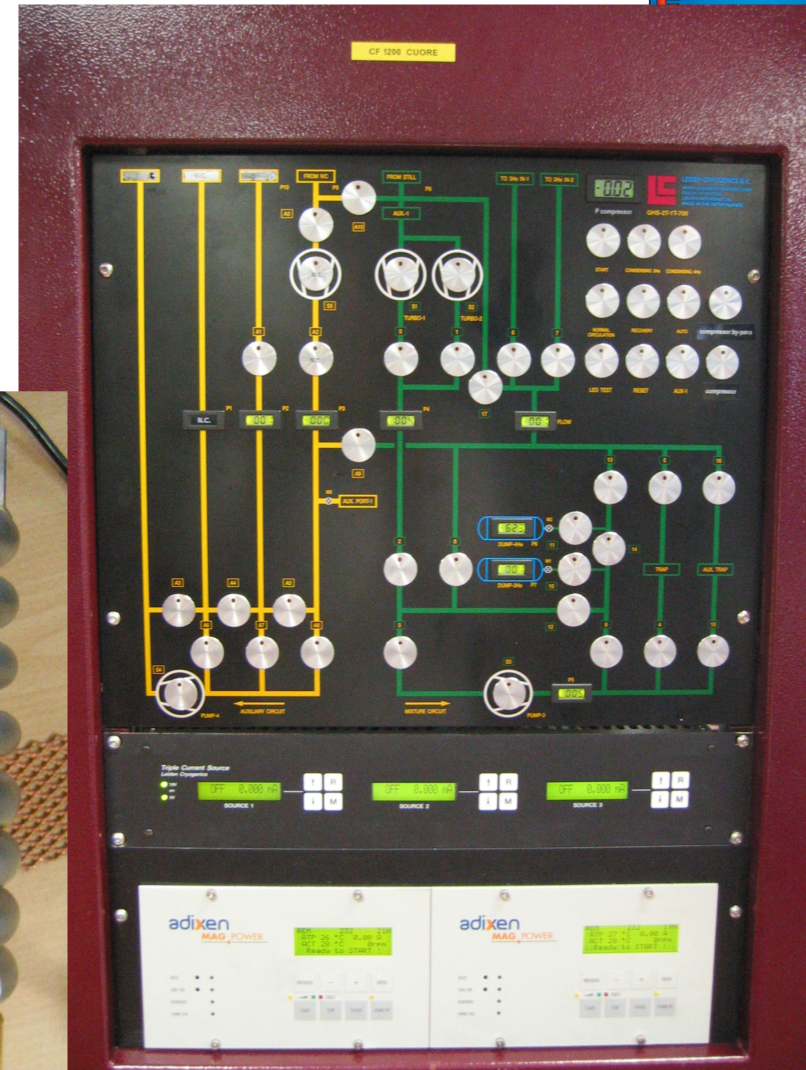
- ► under construction
- ► commissioning 2011

CUORE cryostat / 2



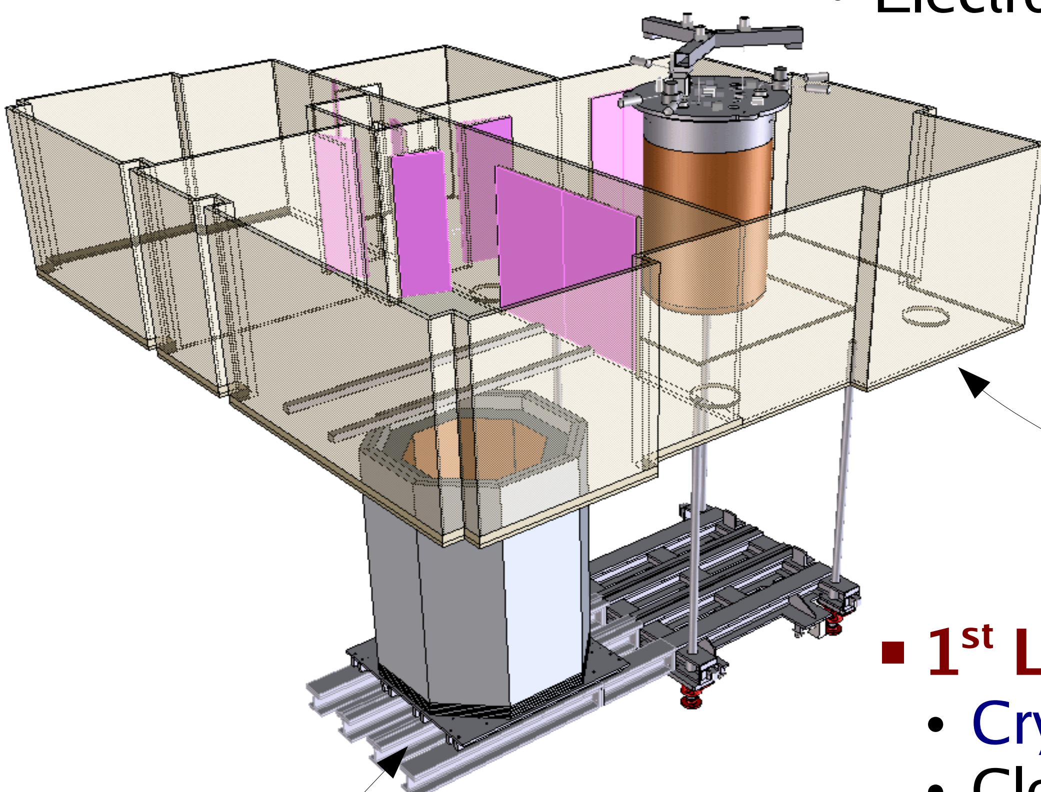
CUORE Dilution Unit

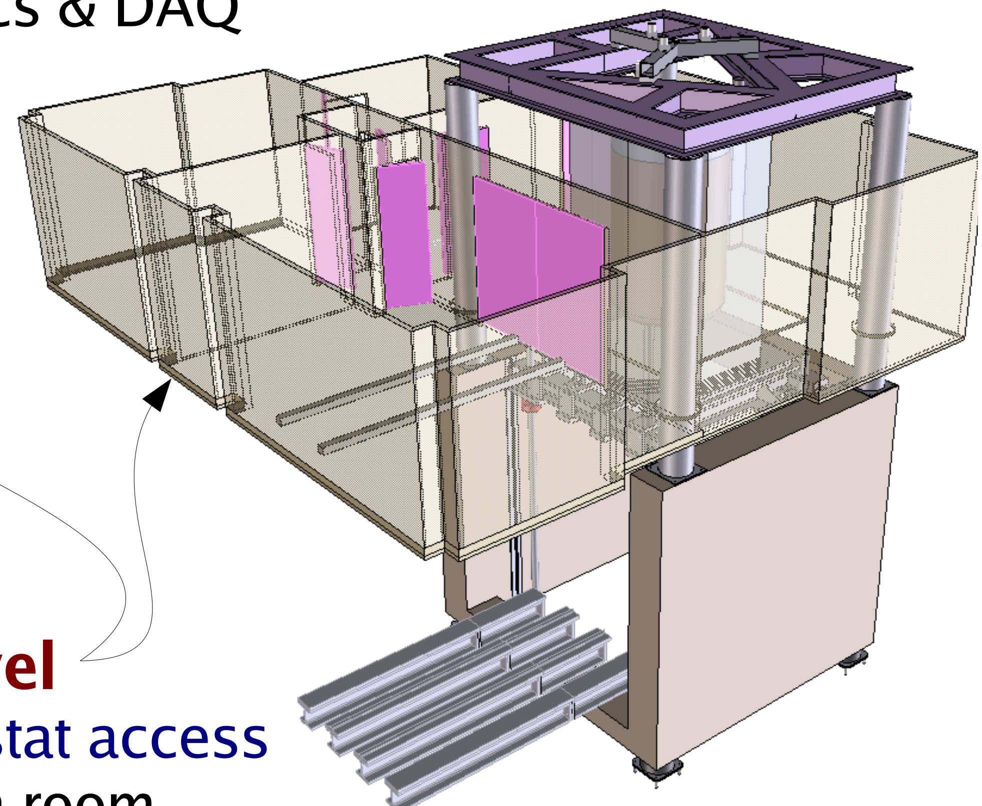




CUORE Hut: external shielding and clean room

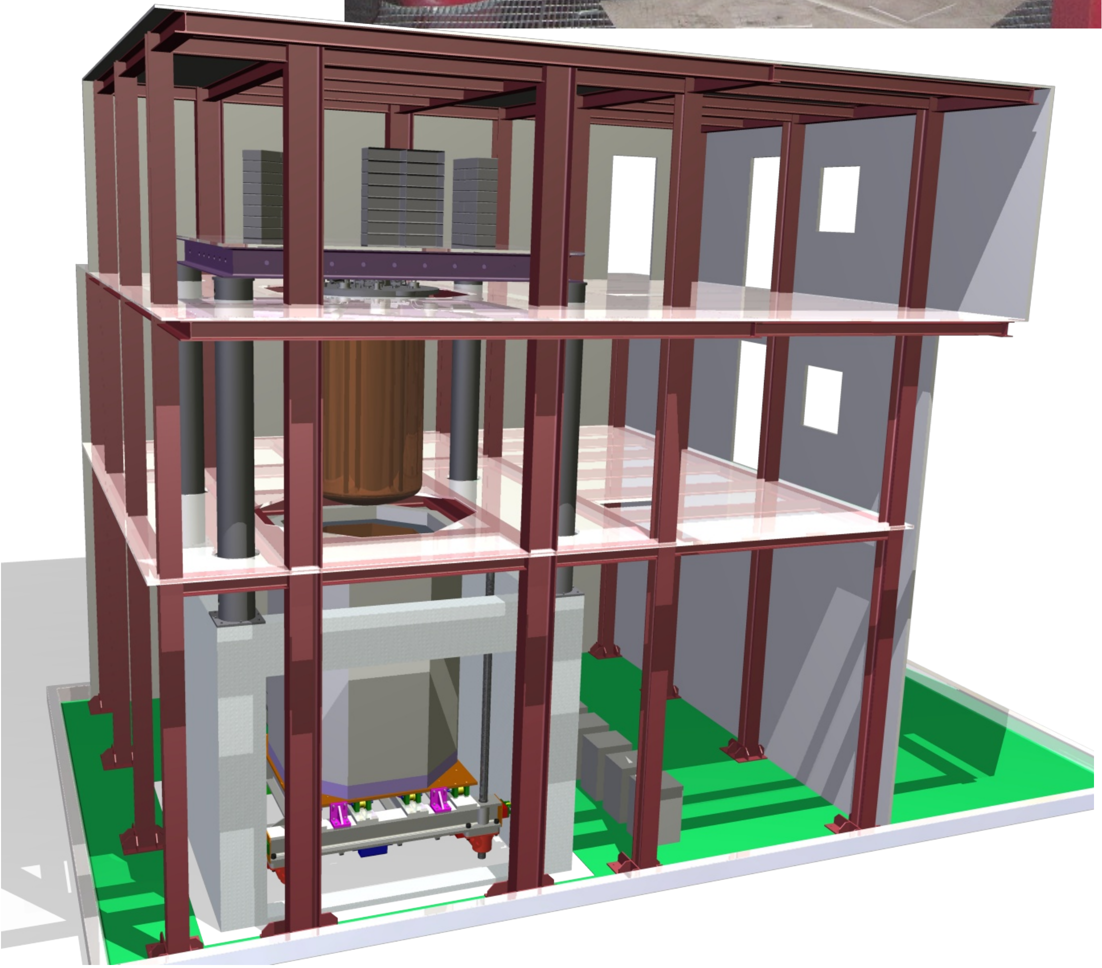
- **2nd Level**
  - Top flange access
  - Suspension access
  - DU Gas Handling
  - Electronics & DAQ



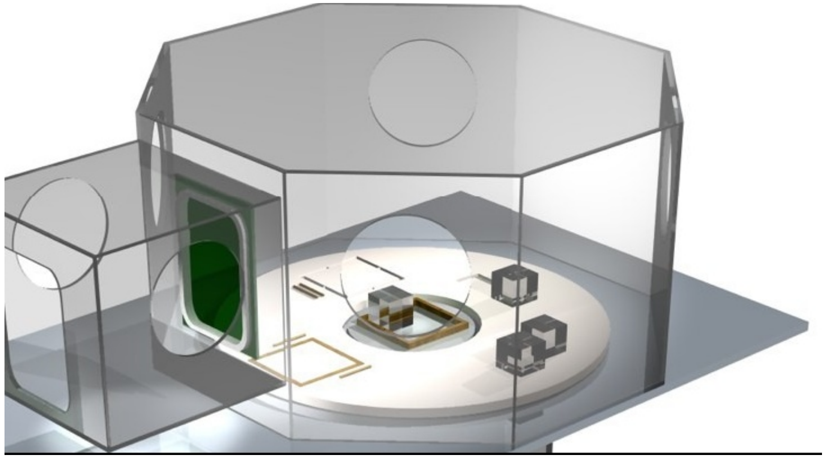


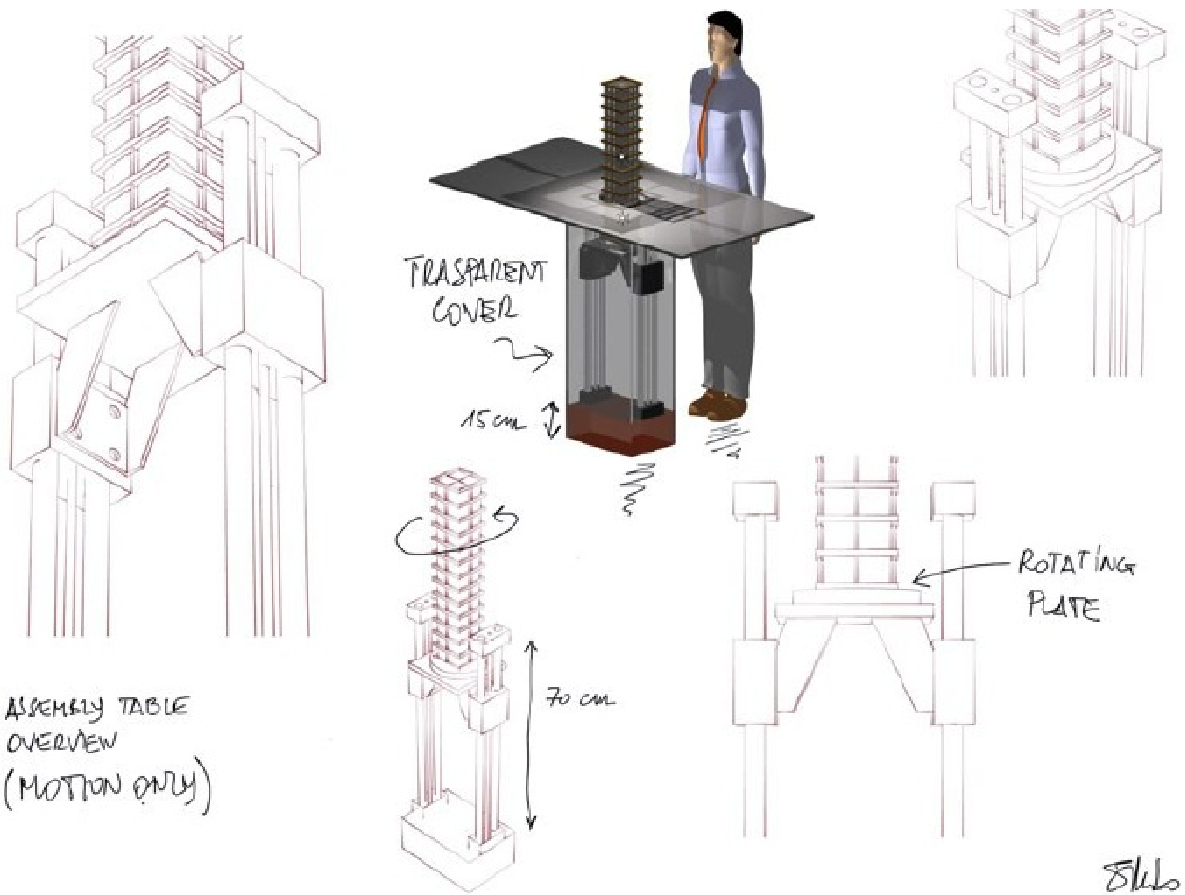
- **1st Level**
  - Cryostat access
  - Clean room
- **ground floor**
  - services (pumps,...)
  - shields and screens storage

CUORE Hut



CUORE schedule





2008-2009:
- Hut construction
- Crystals production
- Utilities

2010-2011:
- Clean room
- External Shielding
- Cryogenics
- CUORE-0

2012:
- Internal Shielding
- Faraday Cage
- Detector assembly
- Front-end & DAQ

2013:
- Data taking

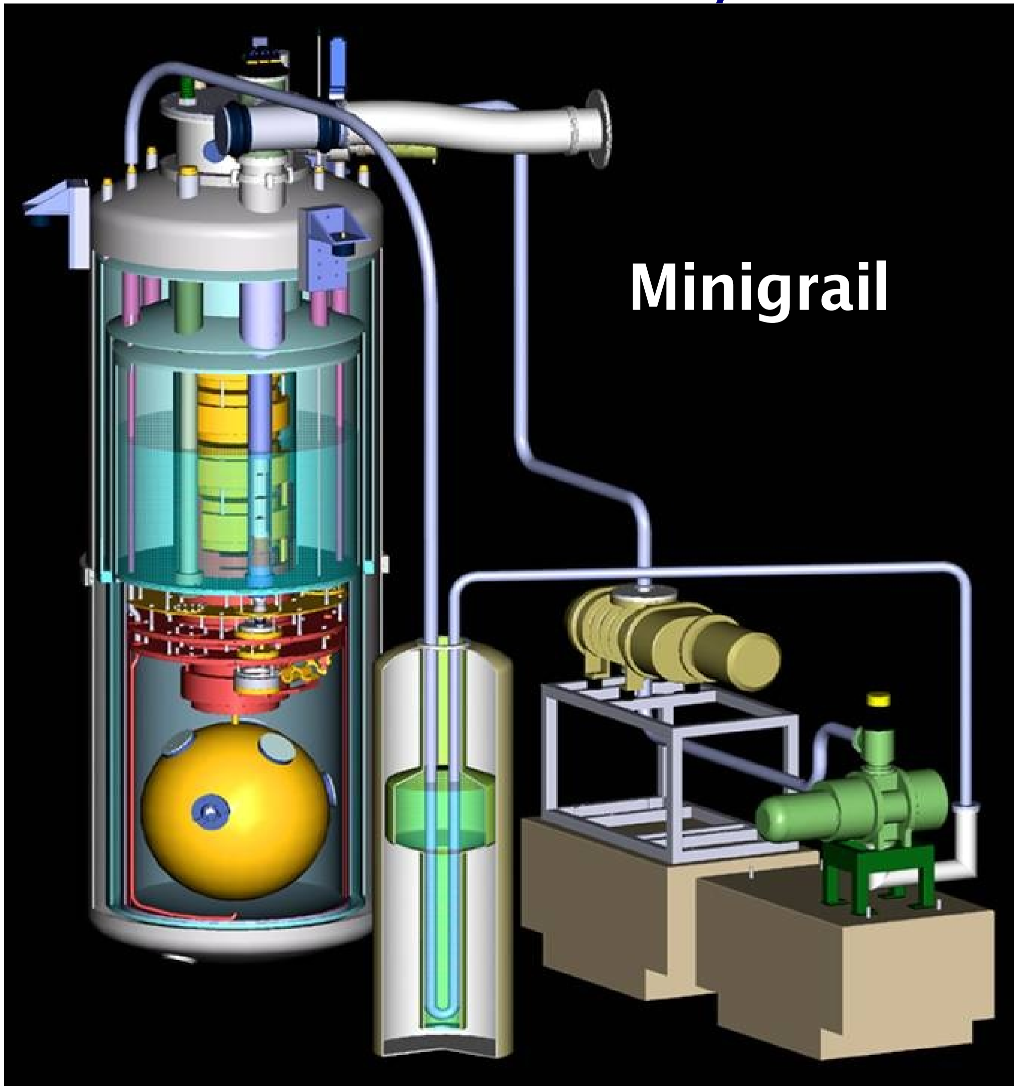
Conclusions

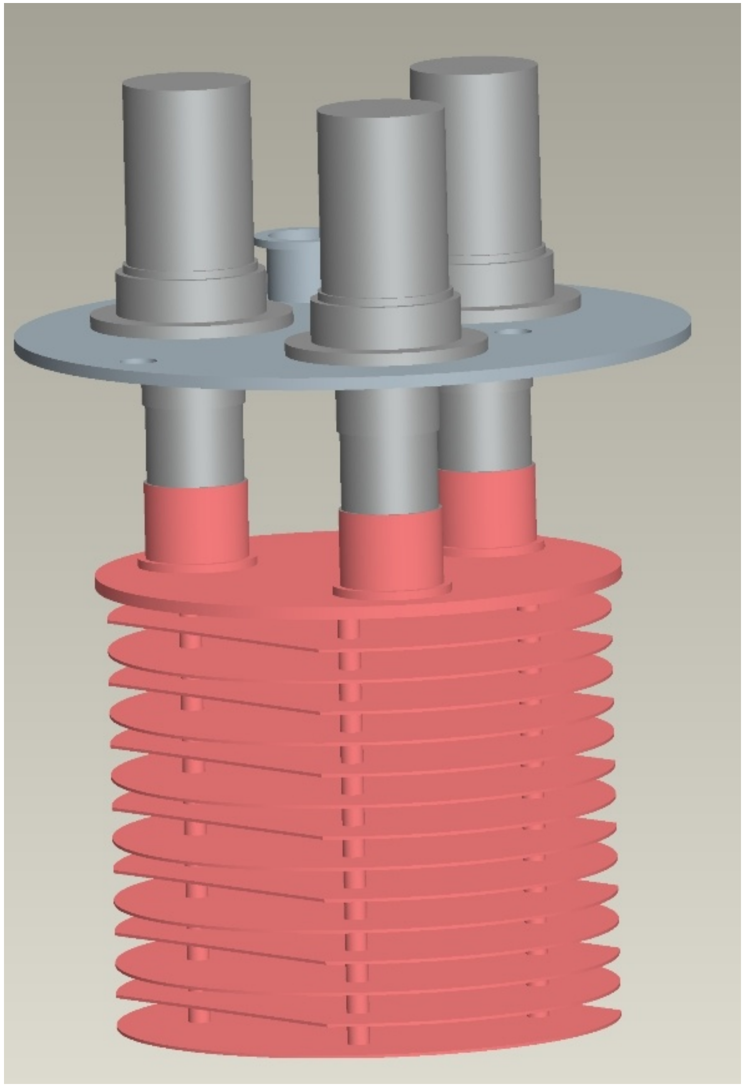
- Cryogenic detectors represent a well established technique, very competitive for neutrinoless double beta decay search
- CUORICINO demonstrated the feasibility of CUORE, a next generation calorimeter with high energy resolution and improved background
- CUORE is presently being built at LNGS
  - it will explore the inverse hierarchy mass region
- CUORE-0 will start in 2011
  - it will improve CUORICINO limit
  - it will give important information on the achieved background reduction
- CUORE is planned to start data taking in 2013

Backups...

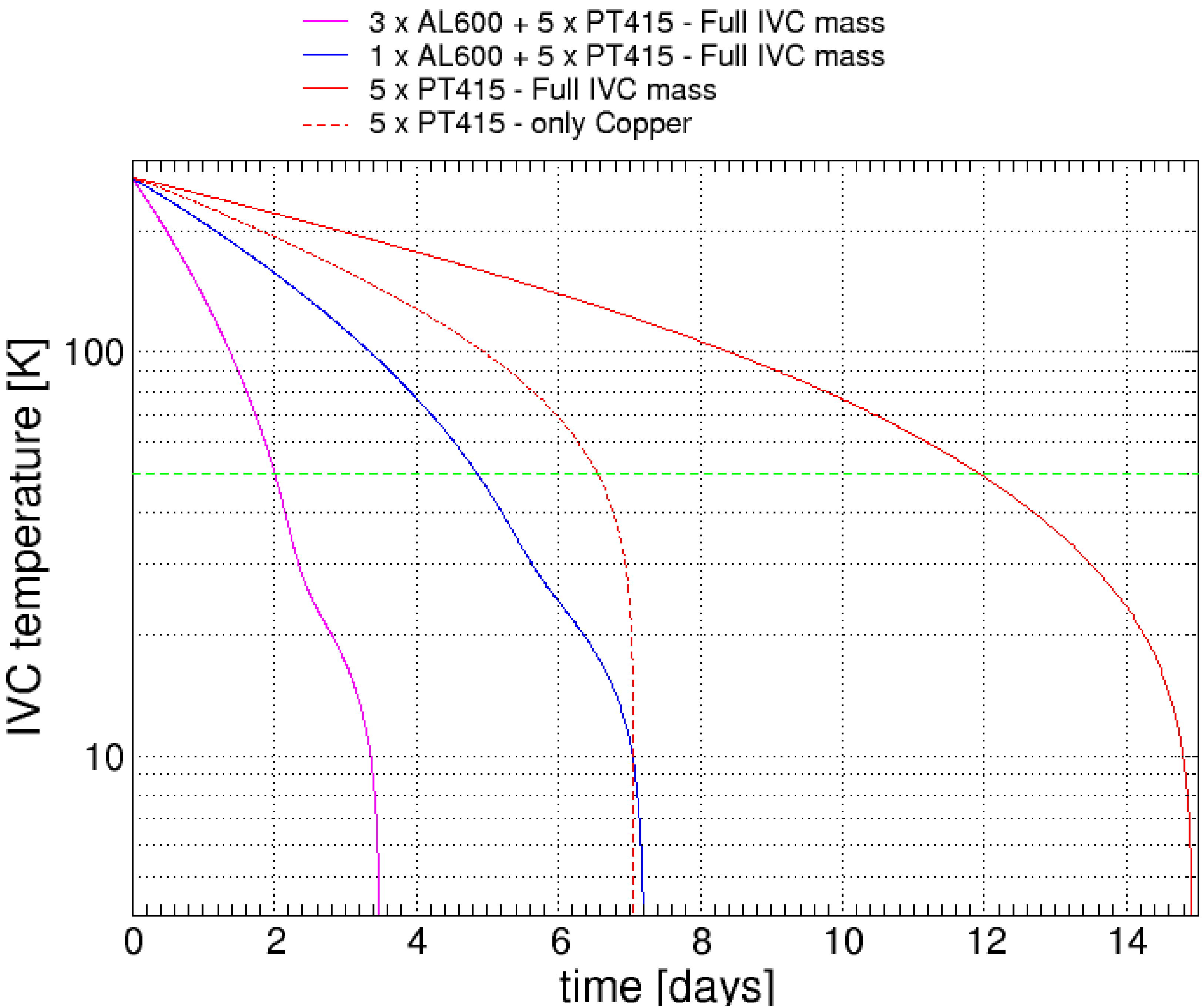
Cooling down: 300K - 4K

- 40K shield cooled by the 5 PT415
- IVC cooled by forced helium flow and the 5 PT415
- helium cooled by **up to 3 GM AL600** (600W@77K)
- helium circulated by 2 roots



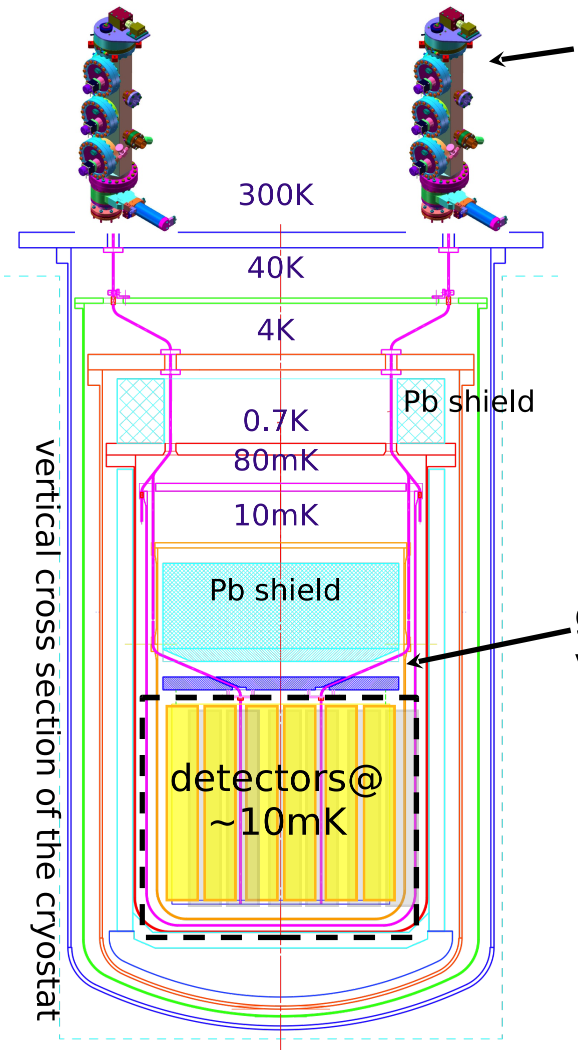


Cooling down: 300K - 4K

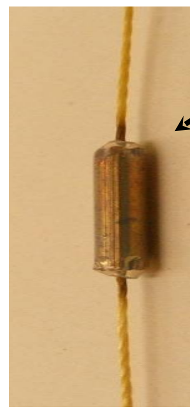


Cryogenics: detector calibration system

Individual energy calibration of all 988 bolometers

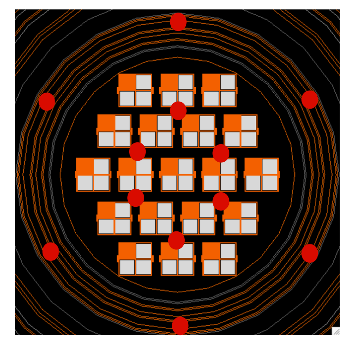


motion system: insertion/extraction of sources in and out of cryostat

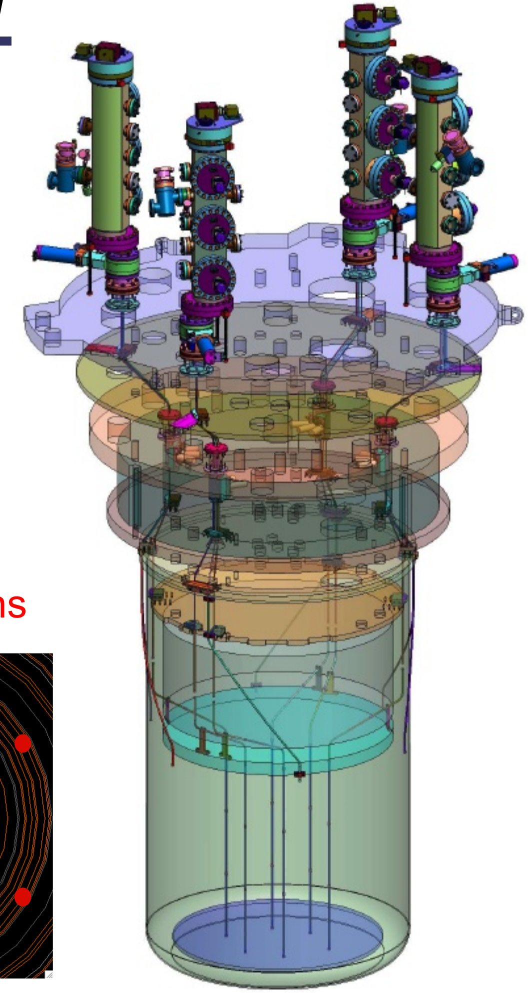


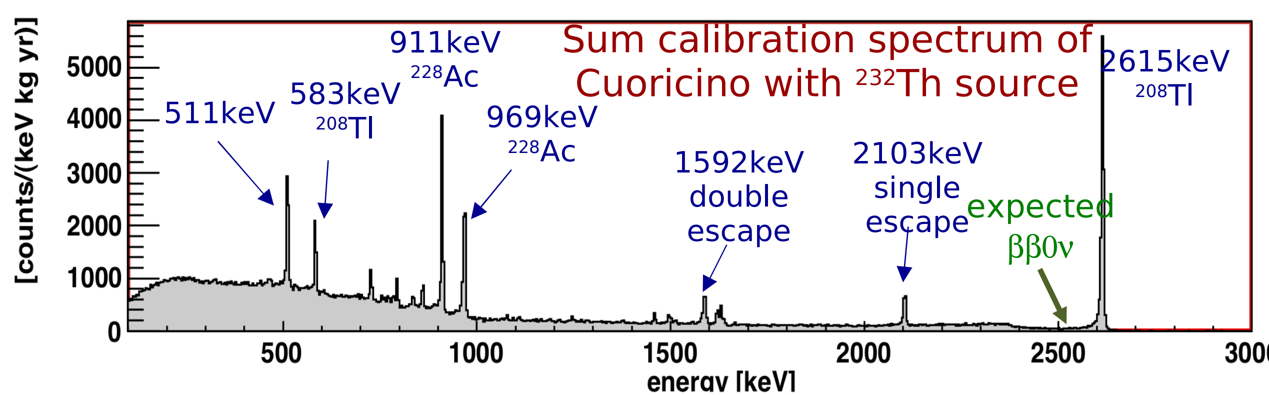
^{232}Th source strings: move under own weight

source locations



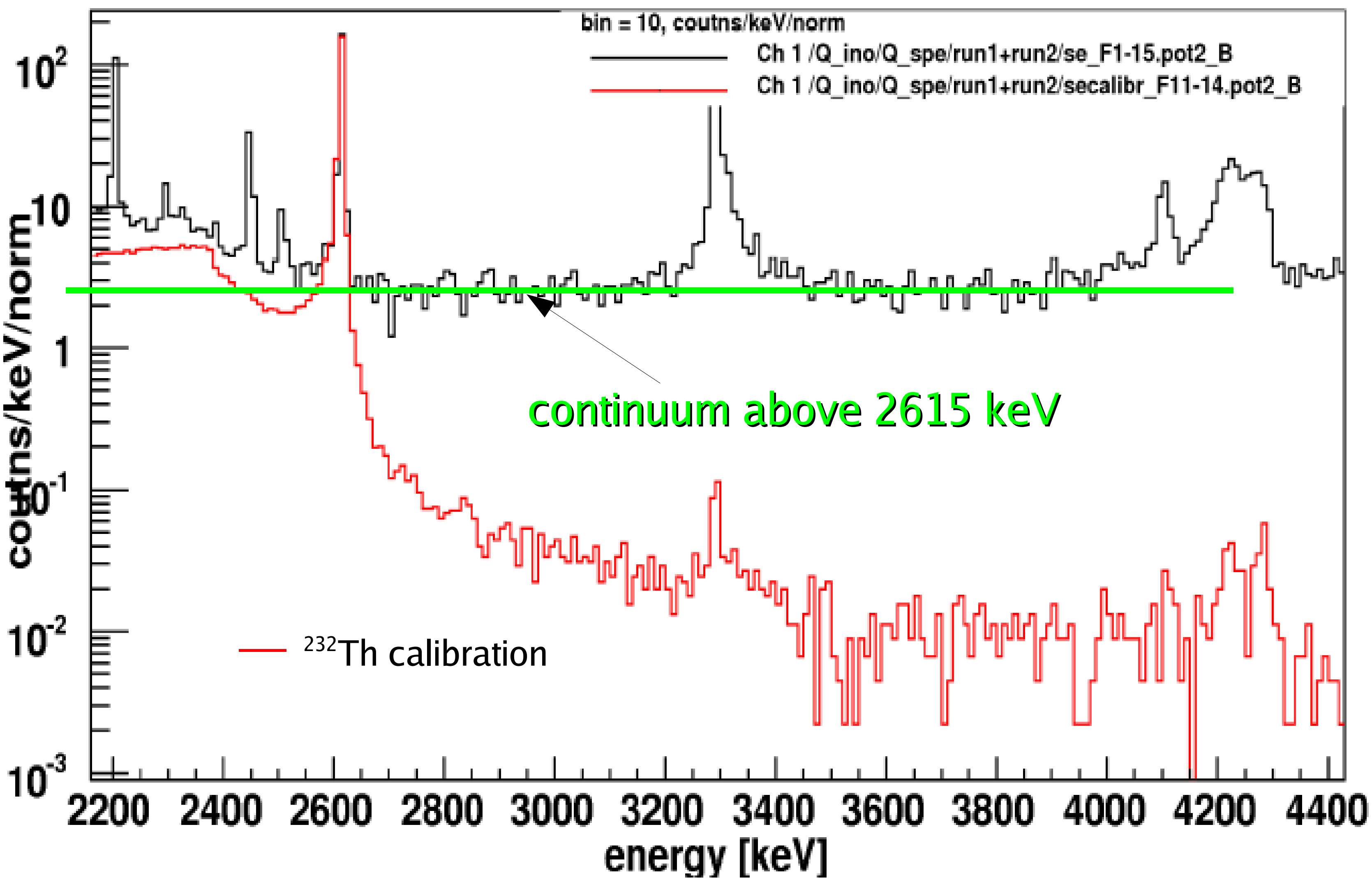
guide tubes: no straight vertical access





The main issue: background / 1

- Cuoricino background spectrum
- γ background from external sources (^{232}Th)

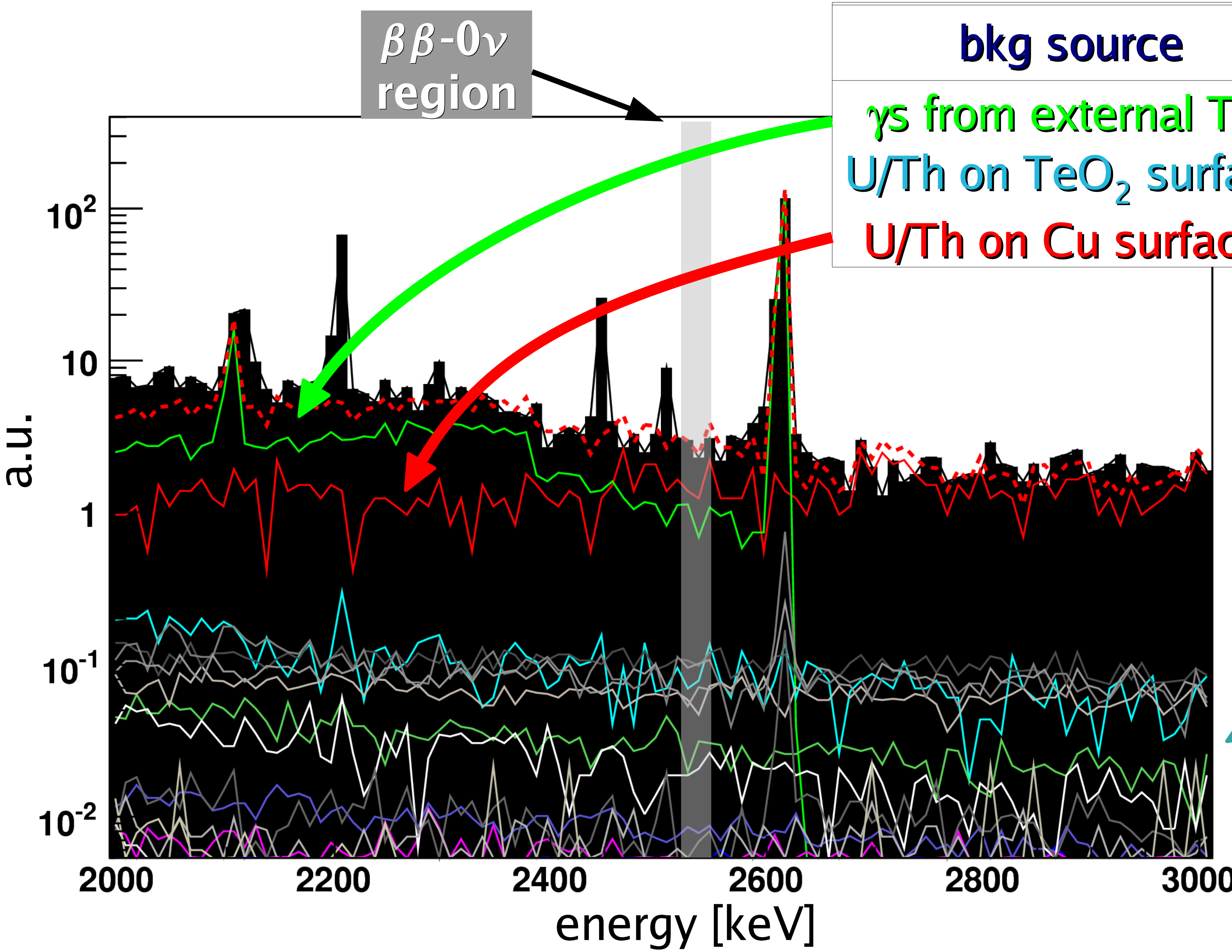


no γ peak identified above ^{208}Tl line at 2615 keV

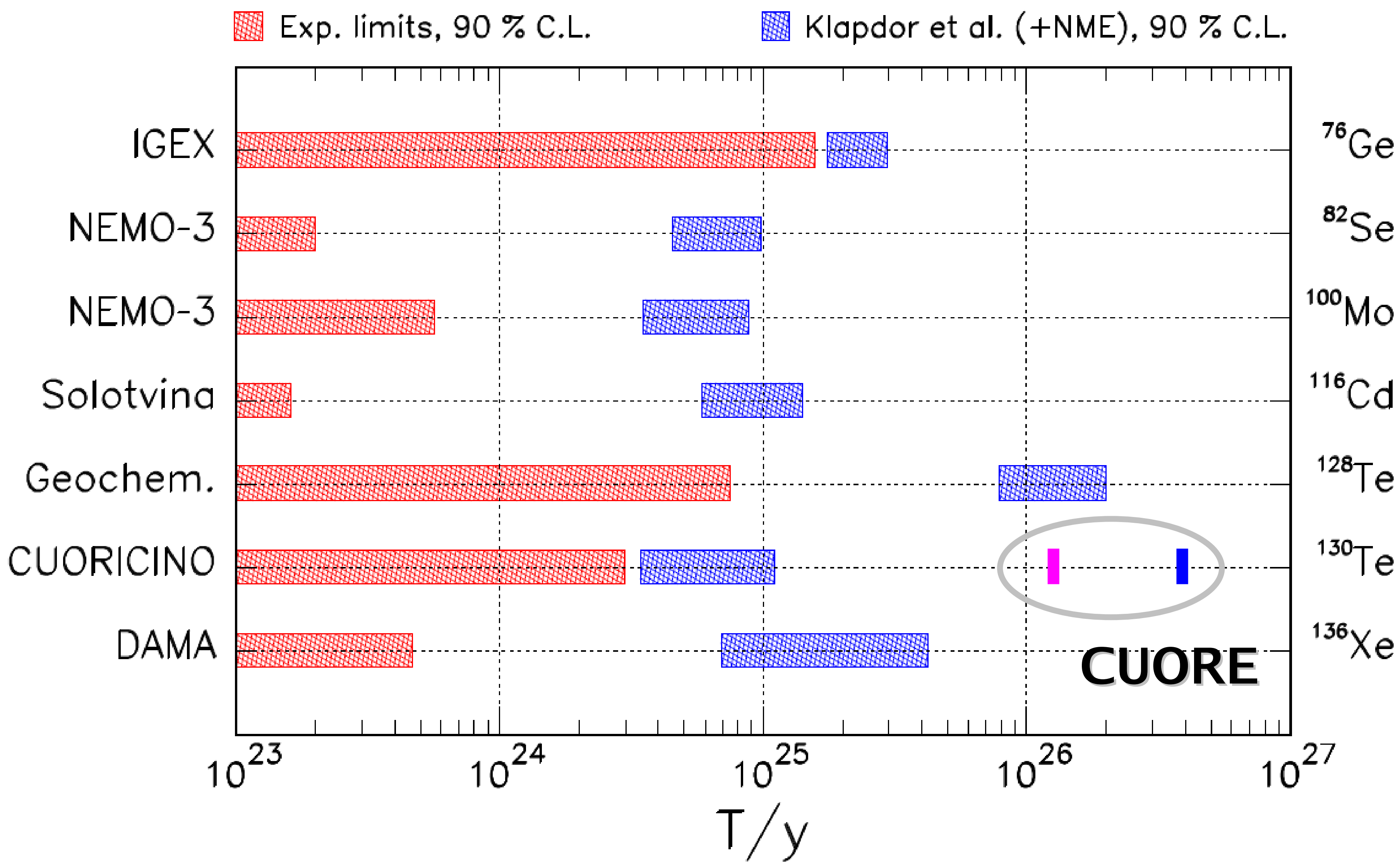
The main issue: background / 2

CUORICINO background MC reconstruction - - - - - - -

bkg source	at $Q_{\beta\beta}$
γs from external Th	30%
U/Th on TeO_2 surface	20%
U/Th on Cu surface	50%



NME correlation analysis



A. Faessler et al.: arXiv 0810.5733