From CUORICINO to CUORE: investigating neutrino properties with double beta decay

Monica Sisti

Università and INFN – Milano Bicocca

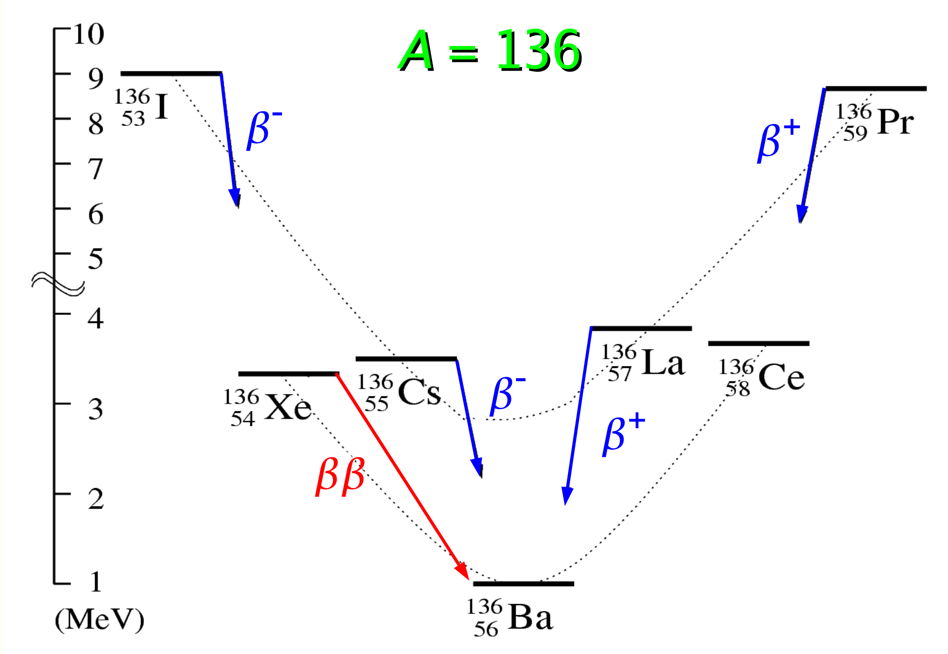
DAPNIA/SPP CEA — Saclay - June 16th, 2008

Outlook

- The importance of neutrinoless double beta decay
- Experimental search with cryogenic detectors
- Recent results from CUORICINO experiment
- From CUORICINO to CUORE
- Background model and predictions for CUORE
- Present status of CUORE

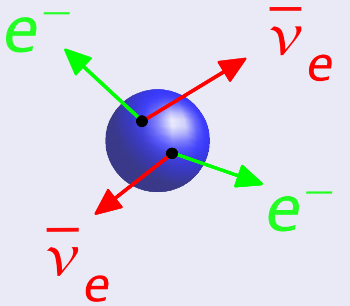
Double beta decay

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



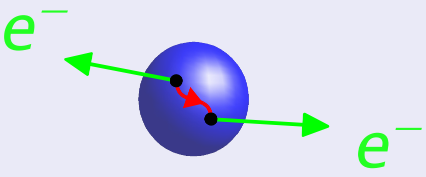
$\beta\beta$-2ν: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

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



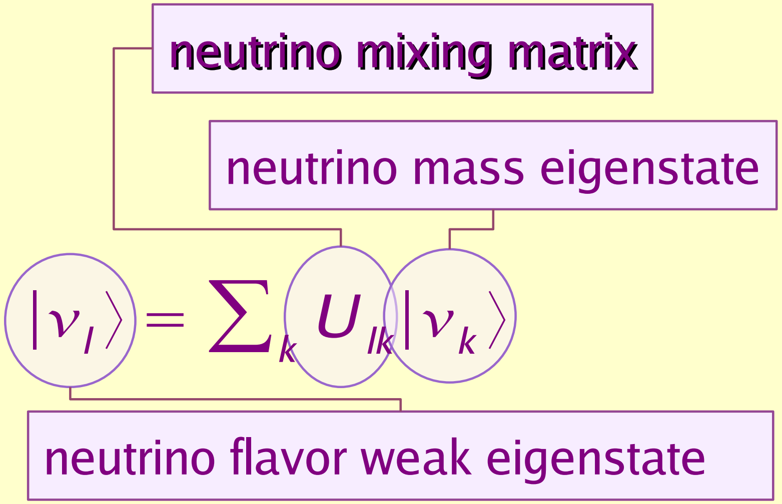
$\beta\beta$-0ν: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

- not allowed in Standard Model (ΔL=2)
- expected $\tau_{1/2} > 10^{25}$ years
- only one *criticized* evidence to date



Present knowledge about neutrino properties

- **neutrinos have mass and mix!**
- **from neutrino oscillation experiments:**
  $\Delta m_{ik}^2 = |m_i^2 - m_k^2|$ and $\sin^2 2\vartheta_{ik} = f(|U_{lk}|^2)$

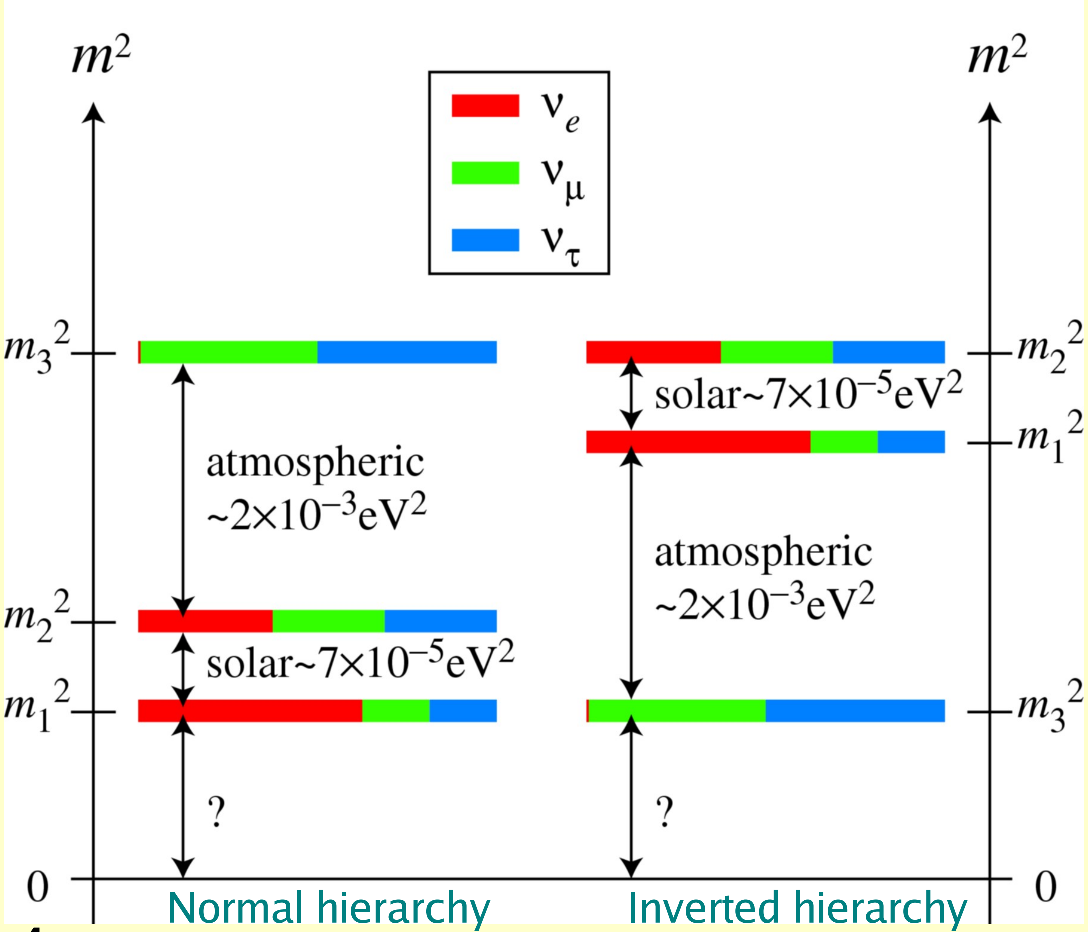


neutrino mixing matrix

neutrino mass eigenstate

$$|\nu_l\rangle = \sum_k U_{lk} |\nu_k\rangle$$

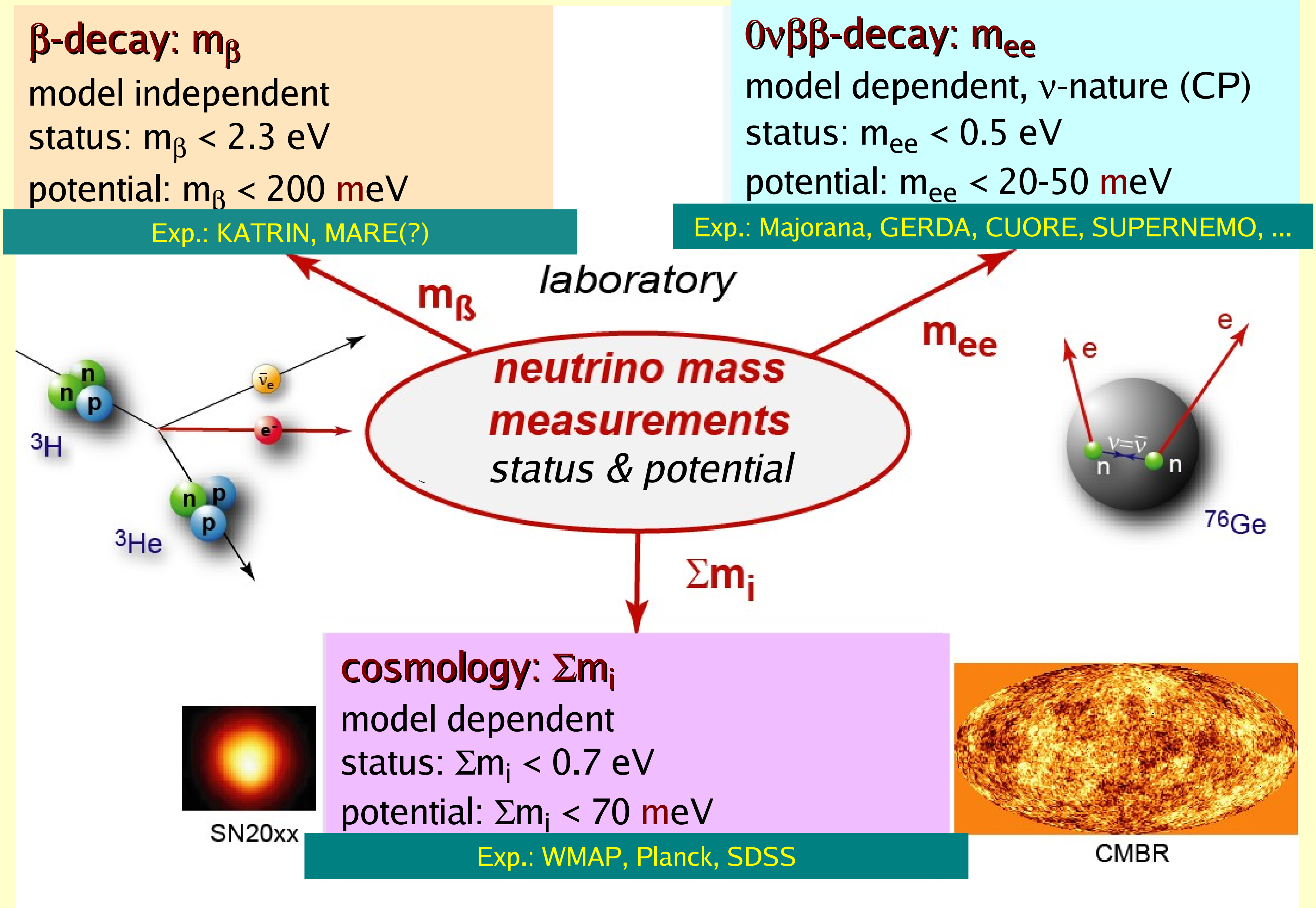
neutrino flavor weak eigenstate



still missing

- ▶ mass scale (i.e. mass of the lightest ν)
- ▶ hierarchy
  - $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$?
- ▶ Dirac or Majorana particle?
- ▶ CP violation in the lepton sector

Measurement of mass scale



β-decay: m_β

model independent

status: $m_\beta < 2.3$ eV

potential: $m_\beta < 200$ meV

Exp.: KATRIN, MARE(?)

0νββ-decay: m_{ee}

model dependent, ν-nature (CP)

status: $m_{ee} < 0.5$ eV

potential: $m_{ee} < 20\text{-}50$ meV

Exp.: Majorana, GERDA, CUORE, SUPERNEMO, ...

cosmology: Σm_i

model dependent

status: $\Sigma m_i < 0.7$ eV

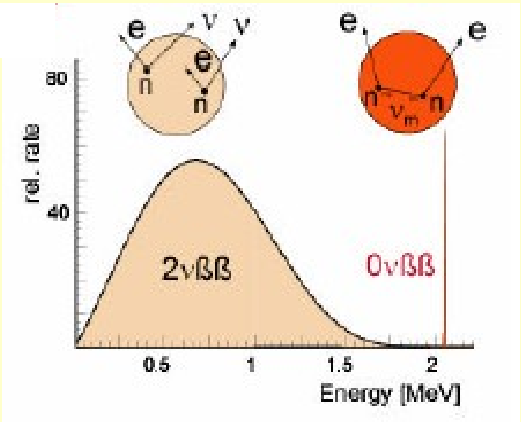
potential: $\Sigma m_i < 70$ meV

Exp.: WMAP, Planck, SDSS

$\beta\beta$-0ν: a unique tool to investigate neutrinos

ββ -0ν decay

$$m_{ee} = \left| \sum U_{ei}^2 \ m_i \right|$$



✔ **The decay occurs only if neutrinos are Majorana particles**

✔ The decay rate depends on the "**effective Majorana mass**":

$$m_{ee} = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 \ e^{i\alpha_{21}} + m_3 |U_{e3}|^2 \ e^{i\alpha_{31}} \right|$$

α_{ij} are Majorana CP-phases (= ±1 for CP conservation)

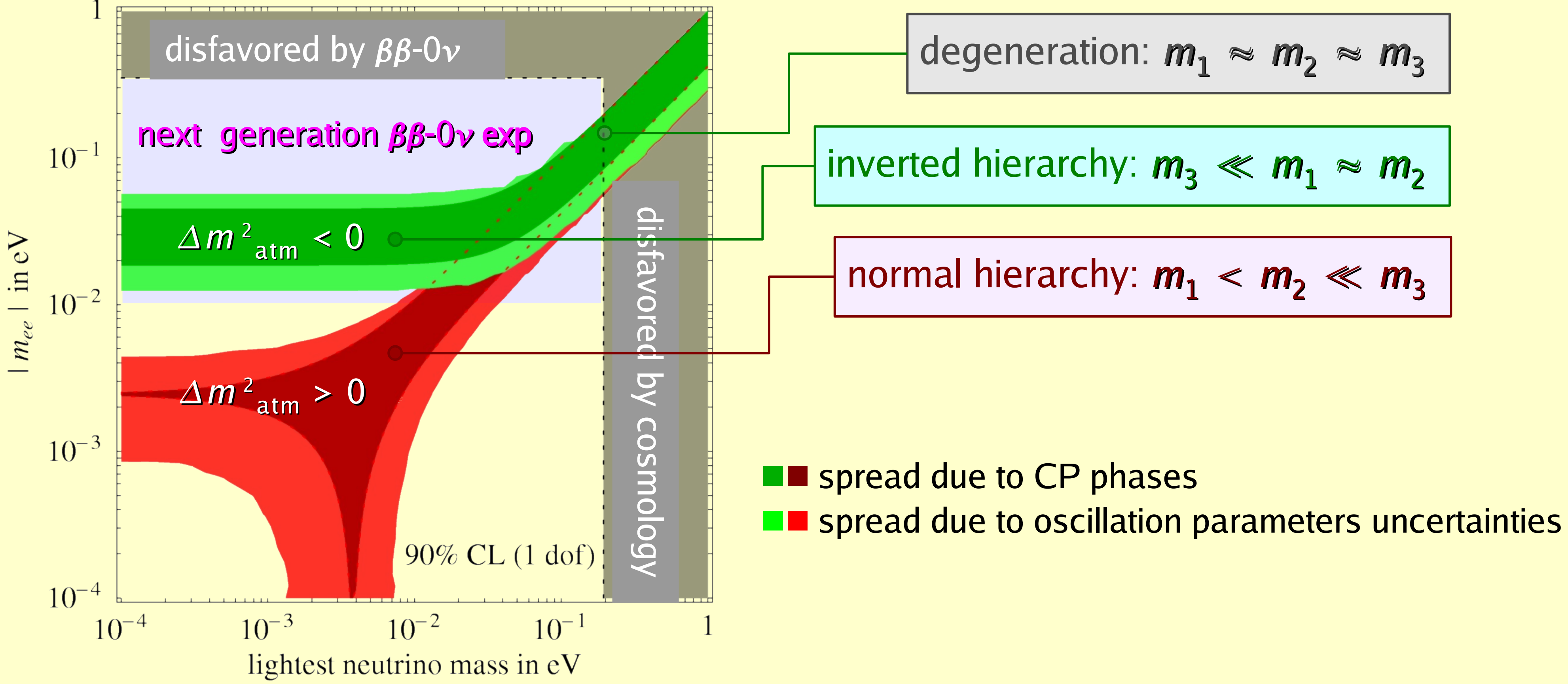
Next generation experiments will give informations on:

✔ **neutrino mass scale**

✔ **neutrino mass hierarchy**

ββ-0ν future sensitivity

- **next generation experiments aim at $|m_{ee}| \approx 10$ meV**



degeneration: $m_1 \approx m_2 \approx m_3$

inverted hierarchy: $m_3 \ll m_1 \approx m_2$

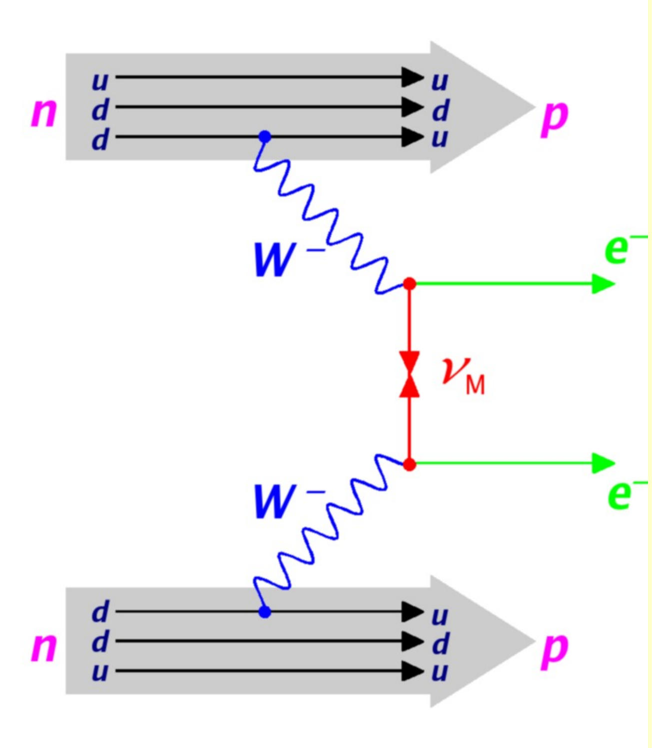
normal hierarchy: $m_1 < m_2 \ll m_3$

🟩🟥 spread due to CP phases

🟩🟥 spread due to oscillation parameters uncertainties

- discovery with $|m_{ee}| \geqslant 10$ meV
  - the neutrino is a **Majorana particle**
  - $|m_{ee}| \geqslant \approx 50$ meV ⇒ **degeneration** and **absolute ν mass scale** fixed
- upper limit with $|m_{ee}| < 10$ meV
  - **if** neutrinos are Majorana particles ⇒ normal hierarchy

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



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

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

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

light Majorana ν mediated $\beta\beta$-0ν decay rate

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

nuclear structure factor

$$F_N \equiv \underbrace{G^{0\nu}}_{\text{phase space}}(Q_{\beta\beta}, Z)|\underbrace{M^{0\nu}}_{\text{matrix element}}|^2$$

- phase space $G^{0\nu}(Q_{\beta\beta}, Z) \propto Q_{\beta\beta}^5$ can be precisely evaluated
- matrix element $|M^{0\nu}|$ contains details of **nuclear physics** source of uncertainties
  - $|m_{ee}|$ is affected by large uncertainties (a factor ≈3)

Experimental sensitivity for ββ-0ν

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

Experimental ββ-0ν rate

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

number of active nuclei N_{nuclei}= $i.a.\ \mathcal{N}_A M/A$

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

measuring time [y]

Experimental sensitivity to $\tau_{½}^{0\nu}$

- with no decay observed
  - $N_{\beta\beta} \leqslant (bkg \cdot \Delta E \cdot M \cdot t_{meas})^{½}$ at 1σ

detector mass [kg]

detector efficiency

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

isotopic abundance
atomic number

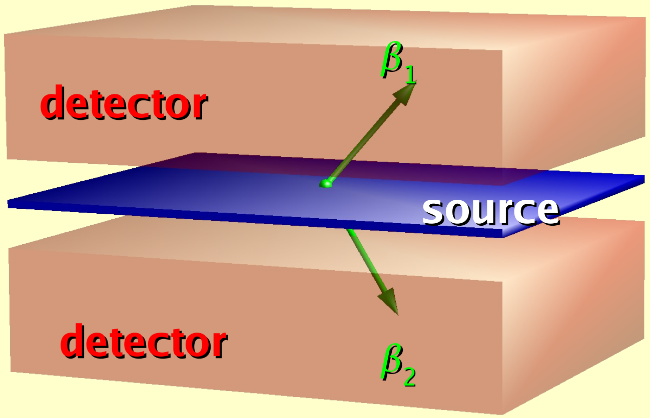
energy resolution [keV]

specific background [c/keV/kg/y]

- for $bkg = 0 \Rightarrow N_{\beta\beta} \leqslant 3$ at 2σ

$$\sum(\tau^{0\nu}_{1/2}) \propto \frac{\epsilon\, i.a.}{A} M\, t_{meas}$$

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

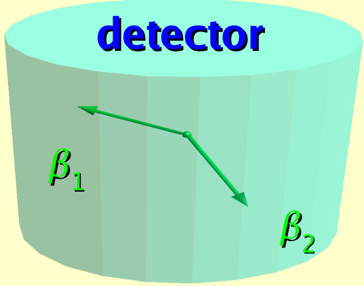


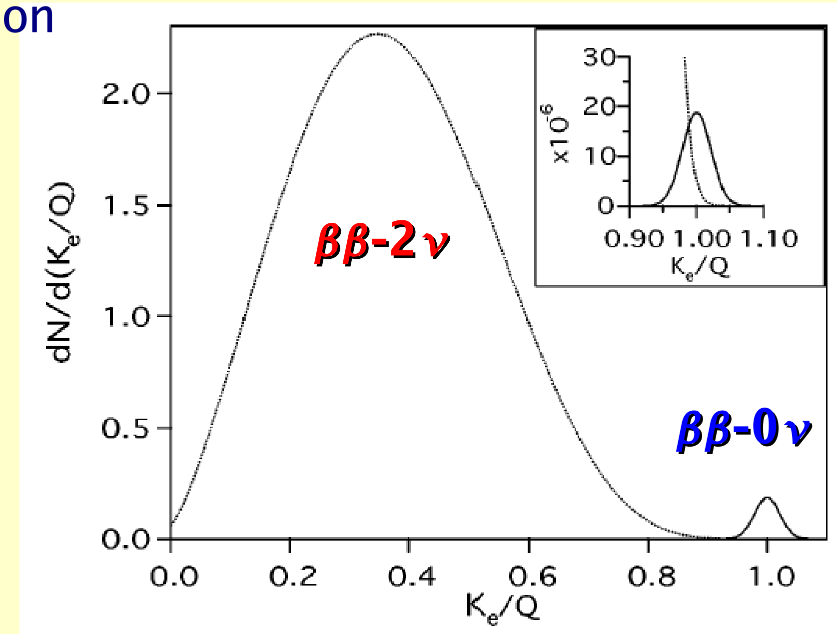
Source ≠ detector

- source in foils
- electrons analyzed by TPCs, scintillators, drift chambers,...
  - ▲ background rejection by event topology
  - ▲ angular correlation gives signature of mass mechanism
  - ▲ any isotopes with solid form possible
  - ▼ small amount of material
  - ▼ poor efficiency
  - ▼ poor energy resolution

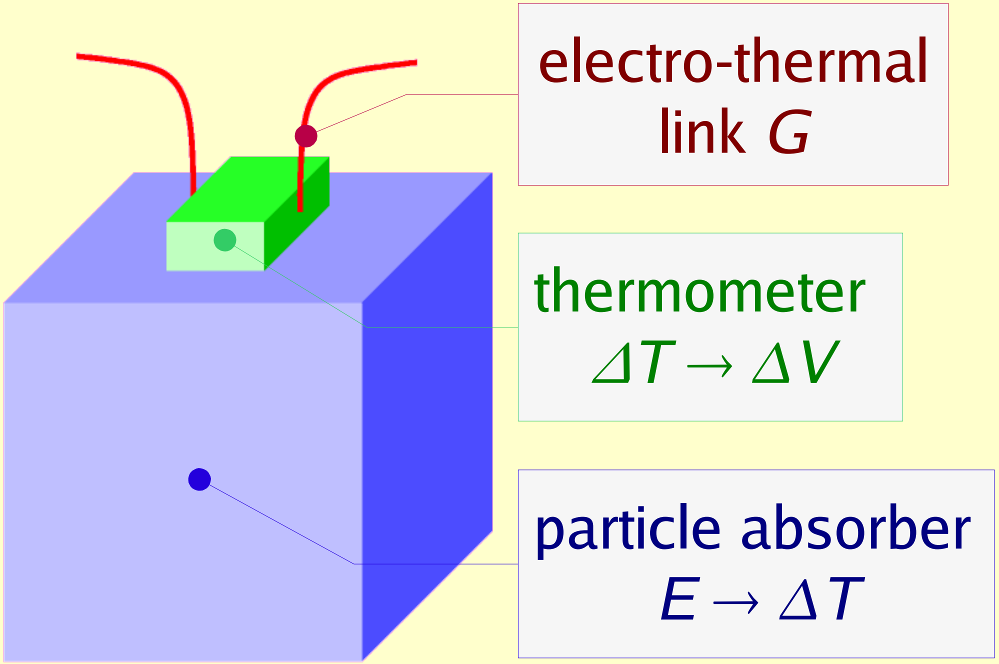
Source ⊆ detector (calorimetry)

- detector measures sum energy $E = E_{\beta_1} + E_{\beta_2}$
  - ▶ $\beta\beta$-0ν signature: a peak at $Q_{\beta\beta}$
- 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)





Calorimetric approach with cryogenic detectors



electro-thermal link *G*

thermometer $\Delta T \rightarrow \Delta V$

particle absorber $E \rightarrow \Delta T$

Properties

- ▲ high energy resolution
- ▲ large choice of absorber materials
- ▲ true calorimeters
- ▼ only energy and time informations
- ▼ slow time response $\tau = C/G \sim 1$ s

TeO_2 Absorbers

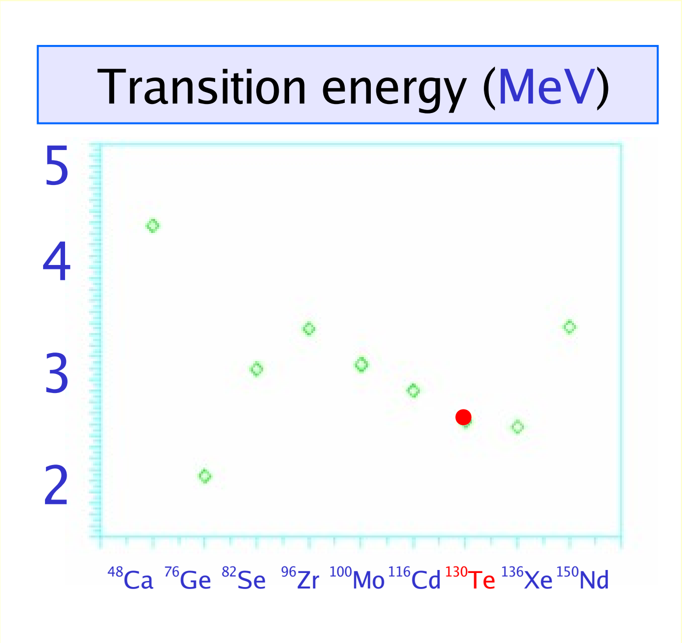
- ▲ low specific heat
- ▲ large crystals available
- ▲ radiopure

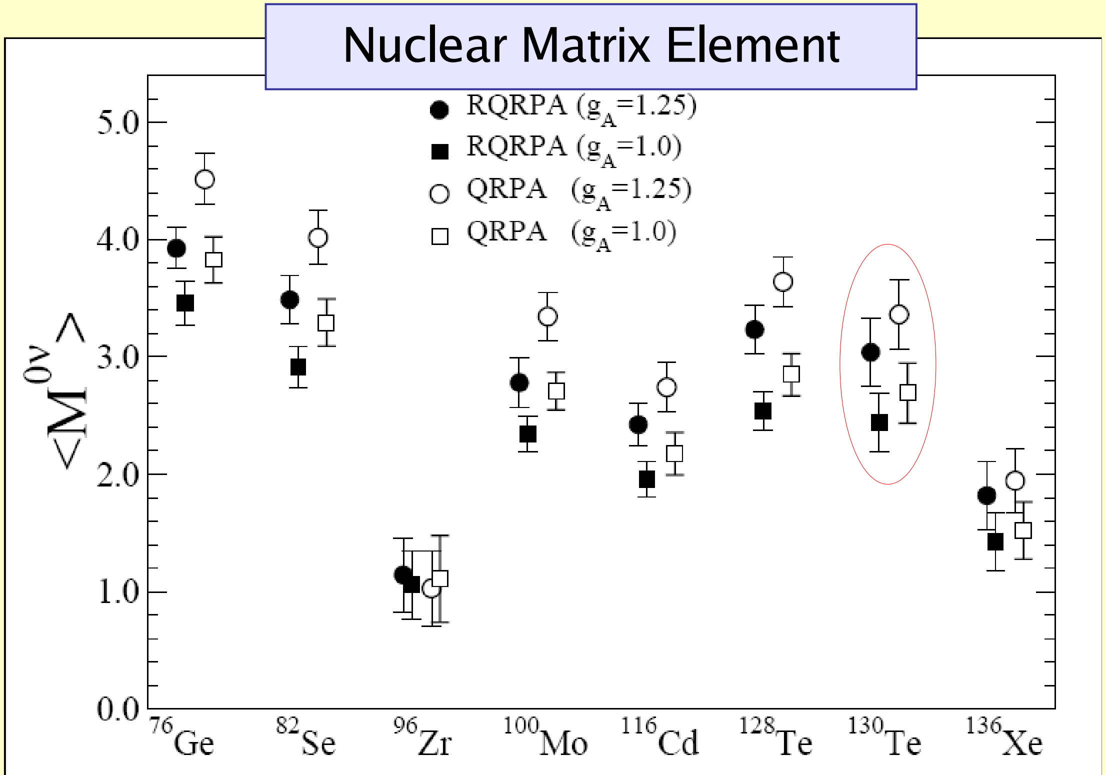
- **All the deposited energy is measured**
- **The detector is fully sensitive**

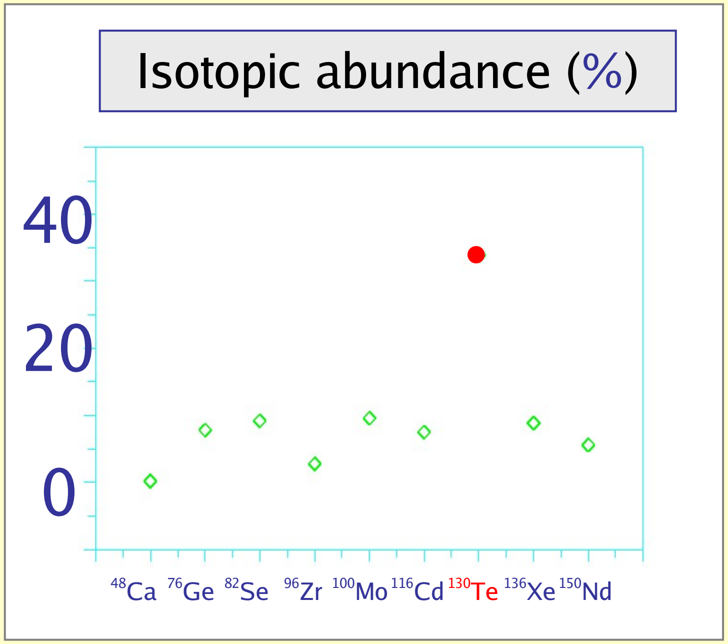
The bolometric technique for the study of $\beta\beta$-0ν was proposed by E. Fiorini and T.O. Niinikoski in 1983

Properties of ^{130}Te as $\beta\beta$-0ν candidate

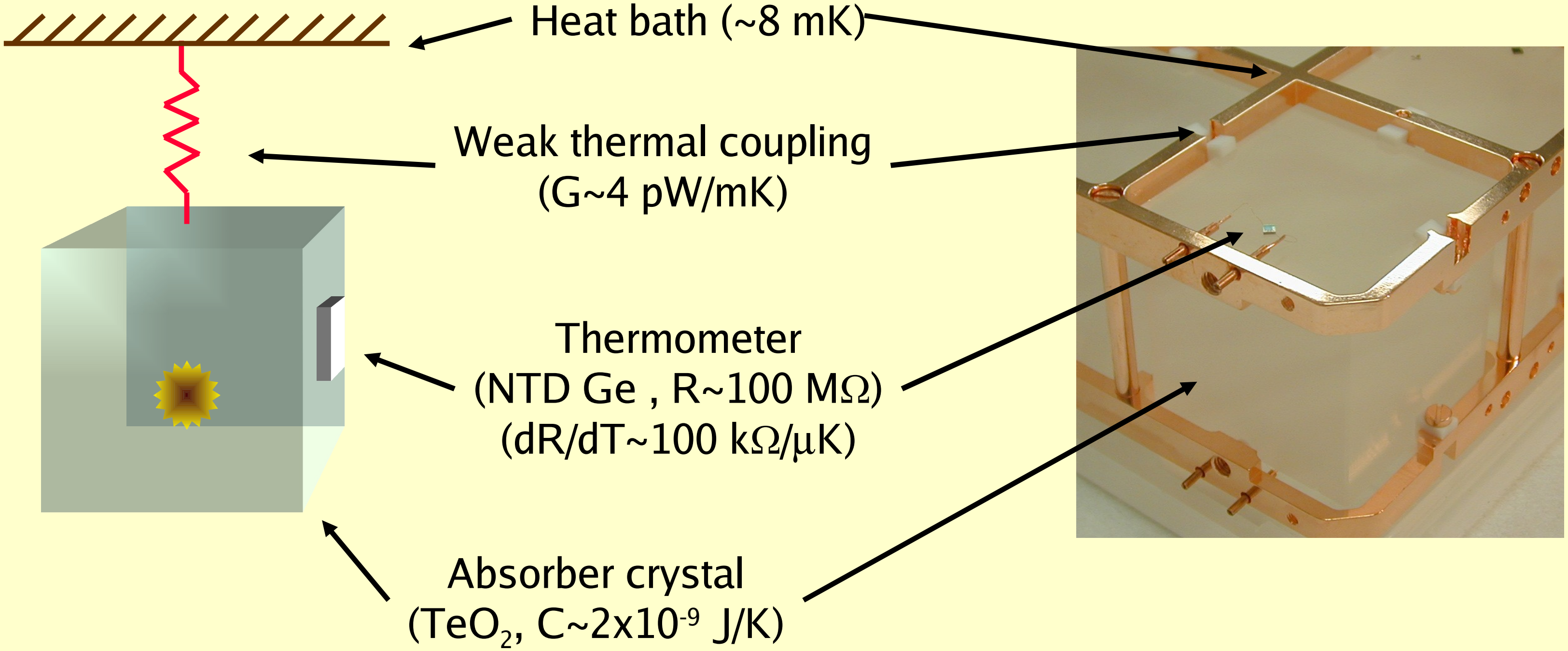
- **high natural isotopic abundance: I.A. = 33.8 %**
- **transition energy: Q = 2530 keV**
- **encouraging nuclear matrix element calculations**
- **$\beta\beta$-2ν already observed by a precursor experiment (MIBETA) and by NEMO3 at the level $\tau_{1/2}$ = (5-7)×10^{20} y**


Transition energy (MeV)


Nuclear Matrix Element


Isotopic abundance (%)

TeO_2 cryogenic detectors



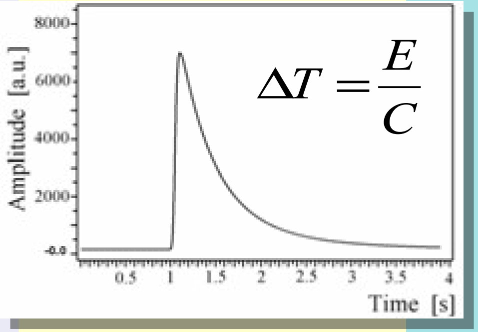
Heat bath (~8 mK)

Weak thermal coupling
(G~4 pW/mK)

Thermometer
(NTD Ge , R~100 MΩ)
(dR/dT~100 kΩ/μK)

Absorber crystal
(TeO_2, C~$2x10^{-9}$ J/K)

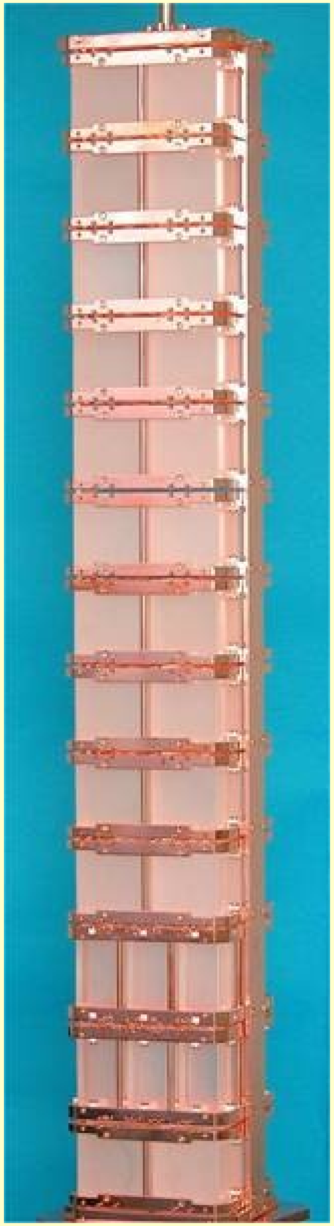
- $\Delta T = E/C$ C thermal capacity
  - ⇨ low C
    - ⇨ low T (i.e. $T \ll 1$K)
    - ⇨ dielectrics, superconductors
- $\tau = C/G$ signal recovery time
- ultimate limit to sensitivity: statistical fluctuations of internal energy U
  $\langle \Delta U^2 \rangle = k_B T^2 C$



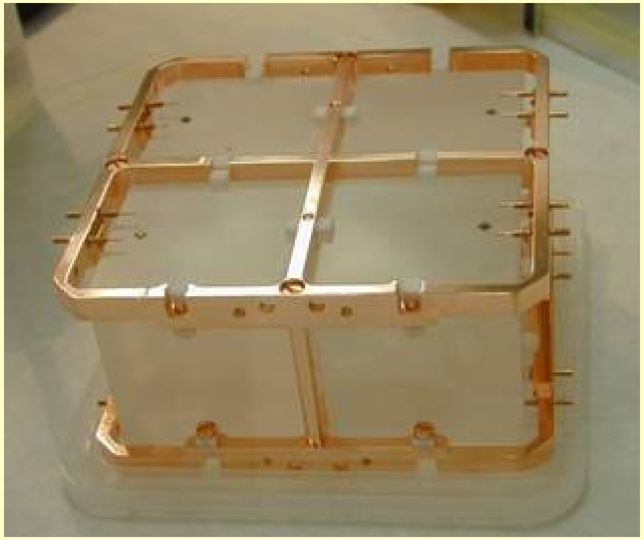
- example: 760 g of TeO_2 @ 10 mK

$C \sim T^3$ (Debye) $\Rightarrow C \sim 2 \times 10^{-9}$ J/K
1 MeV γ-ray $\Rightarrow \Delta T \sim 80\ \mu$K
$\Rightarrow \Delta U \sim 10$ eV
$G \sim 4 \times 10^{-9}$ W/K
$\Rightarrow \tau = C/G \sim 0.5$ s

CUORICINO ^{130}Te $\beta\beta$-0ν search



11 modules
4 detectors each
Dimension: 5x5x5 cm^3
TeO_2 crystal mass: 790 g

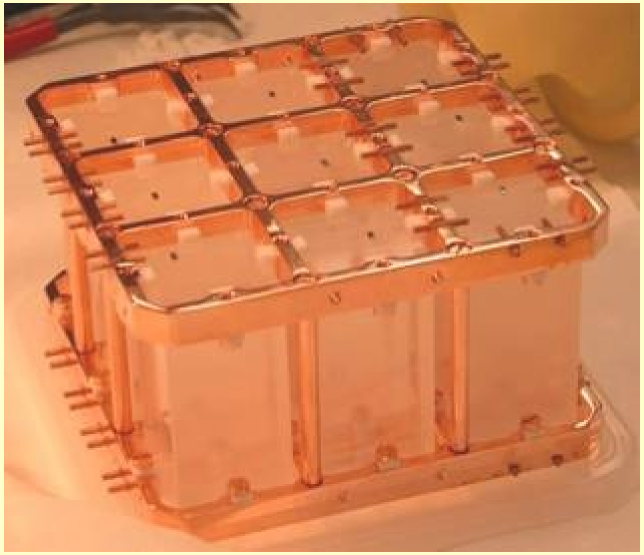


Total mass
40.7 kg

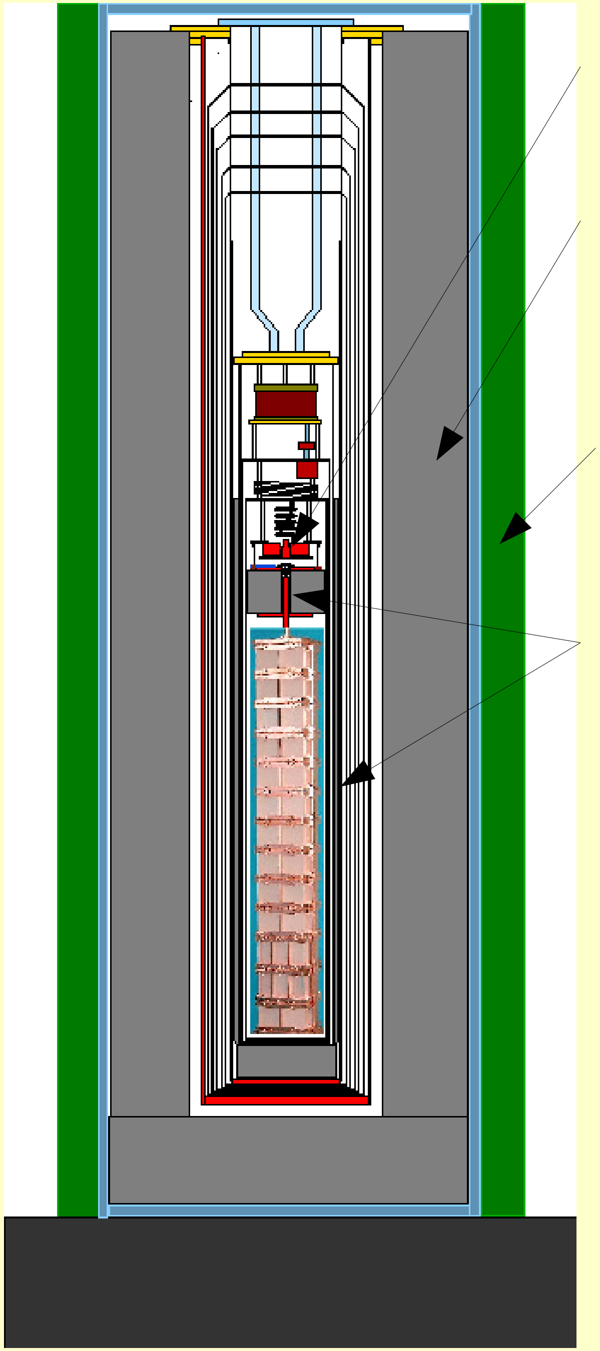
^{130}Te mass
11 kg

~ 5×10^{25}
^{130}Te nuclei

2 modules
9 detectors each,
Dimension: 3x3x6 cm^3
TeO_2 crystal mass: 330 g



CUORICINO experimental set-up



heat bath

external
lead shield
(20 cm)

neutron
shield
(10 cm)

Roman lead
shield
(10 cm top,
1.2 cm around)

Run I

Cooldown: February 2003

29 big + 15 small detectors

^{130}Te active mass: 7.95 kg

Upgrade: October 2003
- Wiring
- DAQ
- Temperature feedback
- Cryogenics (20 years old cryostat)

Run II

Cooldown: May 2004

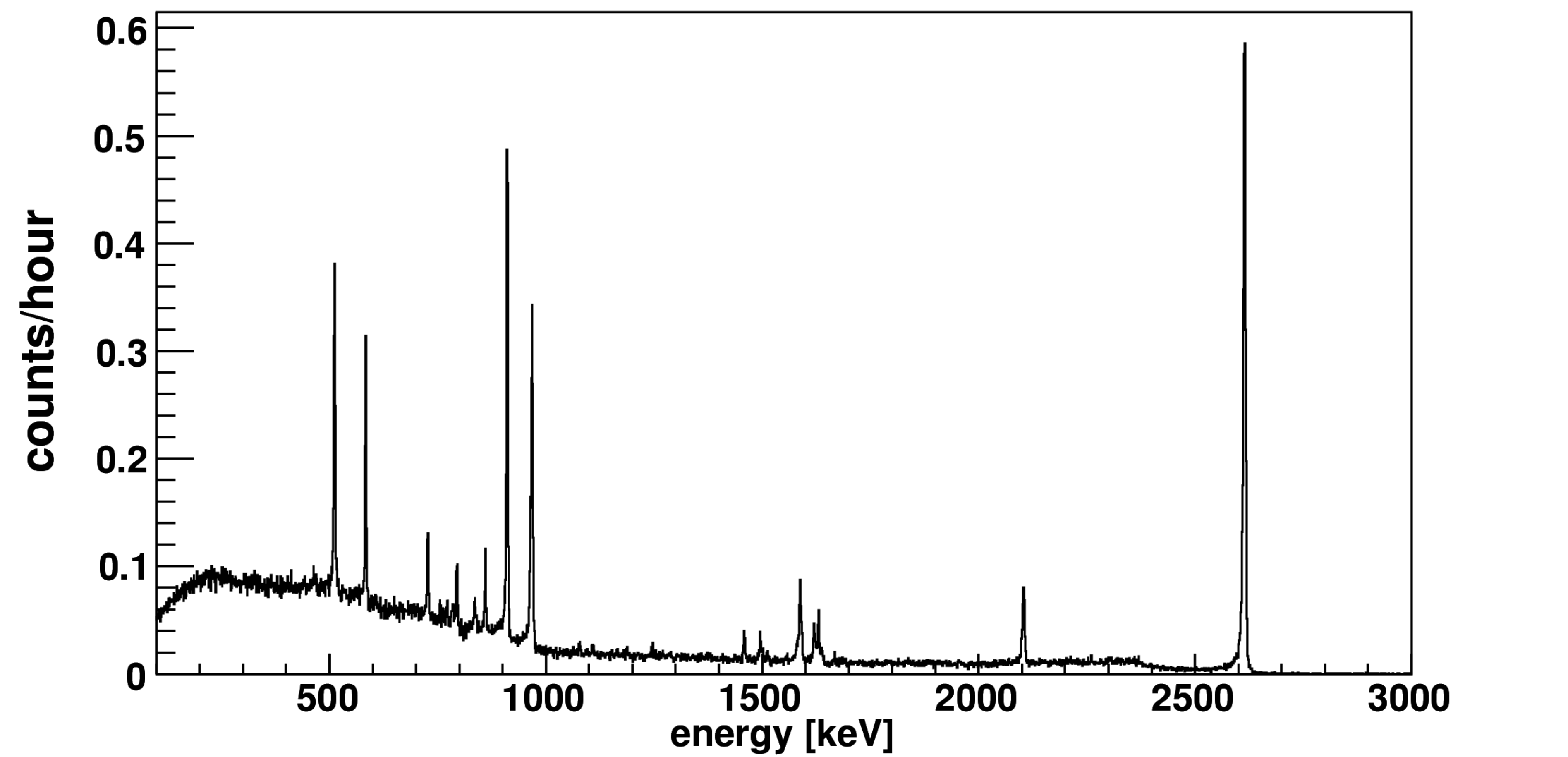
40 big + 15 small detectors

^{130}Te active mass: 10.37 kg

Run II live time ~ 55%

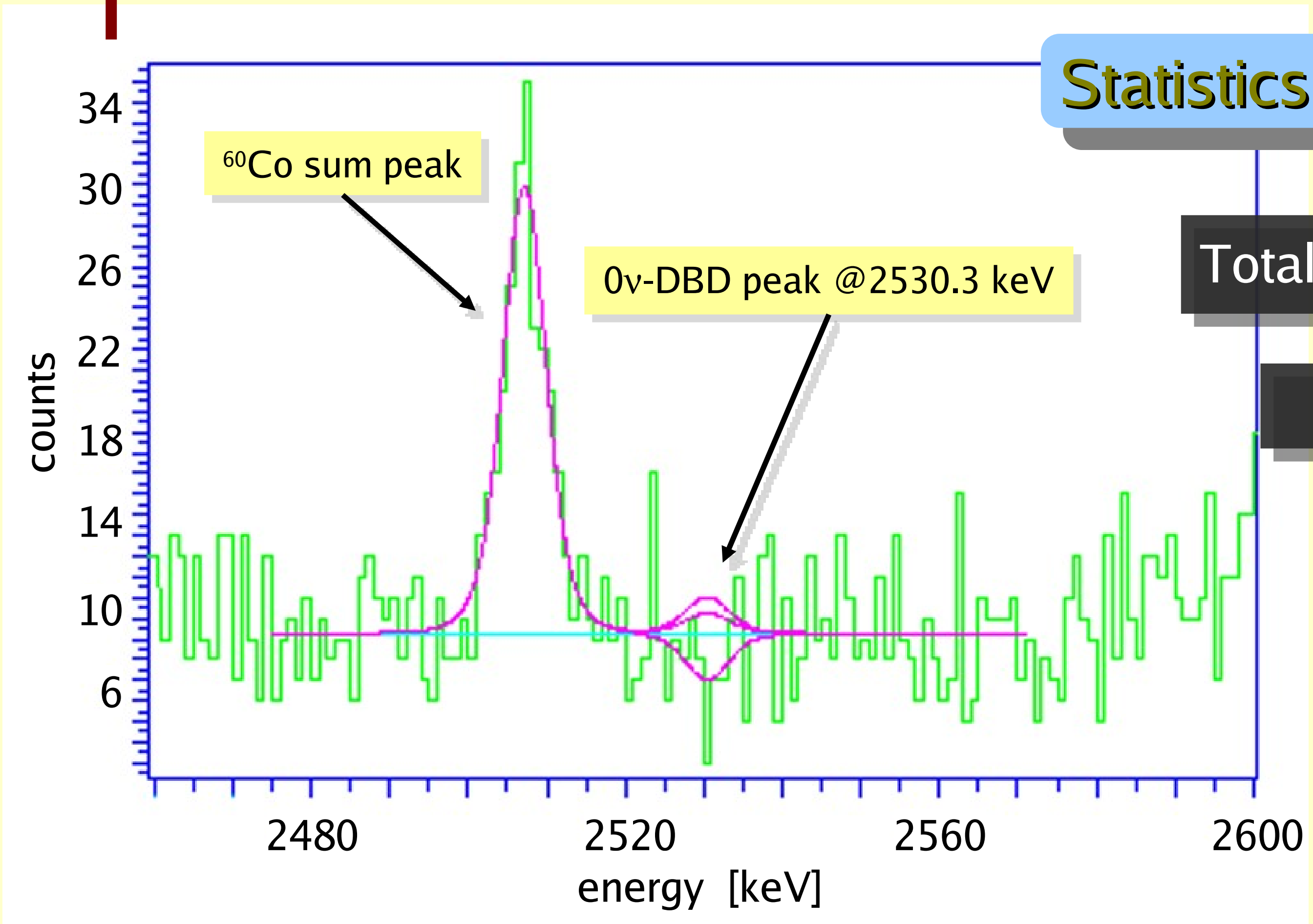
CUORICINO performance

Run II - sum calibration spectrum with ^{232}Th source of 5x5x5 cm^3 detectors



Average FWHM @ 2.6 MeV: 7 keV (5x5x5 cm^3)
9 keV (3x3x6 cm^3)

CUORICINO results



Anticoincidence background spectrum the ββ–0ν *region*

Statistics updated to August 2007

Total statistic ~ 15.53 kg (^{130}Te) × y

b = 0.18 ± 0.01 c/keV/kg/y

Maximum Likelihood
flat background + fit of 2505 peak

ΔE_{FWHM} ~ 8 keV @ 2615 keV

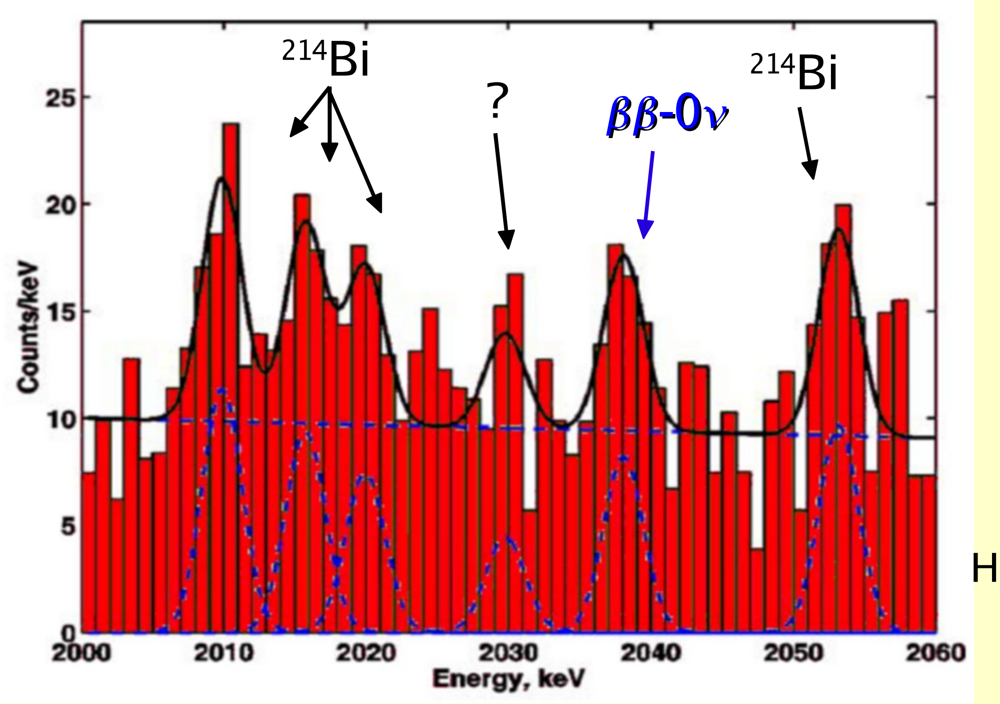
$$\tau^{0\nu}_{1/2} \geq 3.1\times10^{24}\,y\ \ (90\%\ \mathrm{C.L.}) \quad \Rightarrow \quad m_{ee} \leq 200-684\ \ meV^{*}$$

*Depending on nuclear matrix element values
Rodin et al., Nucl. Phys. A766 (2006) 107 + erratum arXiv:nucl-th/0706.4304v1

Heidelberg-Moscow ^{76}Ge $\beta\beta$-0ν claim

- calorimetric experiment with 5 HP-Ge semiconductor detectors enriched to 87% in ^{76}Ge ➡ total active mass of 10.96 kg ⇒ 125.5 moles of ^{76}Ge

- best exploitation of the Ge detector technique proposed by E. Fiorini in 1960
  - longest running experiment (13 years) with largest exposure (71.7 kg×y)
  - Status-of-the-art for low background techniques and for enriched Ge detectors
  - reference for all last generation $\beta\beta$-0ν experiments



1990 –2003 data, all 5 detectors

exposure = 71.7 kg×y

$\tau_{1/2}^{0\nu}$ = 1.2×10^{25} years

m_{ee} = 0.44 eV

H.V.Klapdor-Kleingrothaus *et al.*, Phys. Lett. B 586 (2004) 198

... still controversial result ...

CUORICINO and the HM claim of evidence

Comparison is complicated by nuclear matrix elements uncertainties

For the nuclear models, consider three active schools of thoughts:

- QRPA Tübingen: Rodin et al., erratum arXiv:nucl-th/0706.4304v1
- QRPA Jyväskylä: Civitarese et al, Nucl. Phys. A761 (2005) 313
- Shell Model: Caurier et al., arXiv:nucl-th/0801.3760v1

$$|m_{ee}| = \frac{m_e}{\left(F_N \tau_{1/2}^{0\nu}\right)^{1/2}}$$

HM ^{76}Ge

$\tau_{½}^{0\nu} = (0.69 - 4.18) \times 10^{25}$ years

$m_{ee}^{Rod} = 0.22 \div 0.58$ meV

$m_{ee}^{Civ} = 0.38 \div 0.94$ meV

$m_{ee}^{Cau} = 0.30 \div 0.73$ meV

CUORICINO ^{130}Te

$\tau_{½}^{0\nu} > 3.1 \times 10^{24}$ years

$m_{ee}^{Rod} < 0.45$ meV

$m_{ee}^{Civ} < 0.57$ meV

$m_{ee}^{Cau} < 0.41$ meV

Arnaboldi et al., arXiv:hep-ex/0802.3439v1

How to improve the sensitivity?

increase isotopic abundance by enrichment

→ money and R&D efforts needed

→ option for a second phase

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

and

$$m_{ee} \propto \left(\frac{1}{\tau^{0\nu}_{1/2}}\right)^{1/2}$$

!!!

increase experimental mass and measuring time

the crucial issue!!!! ➡

reduce background by:

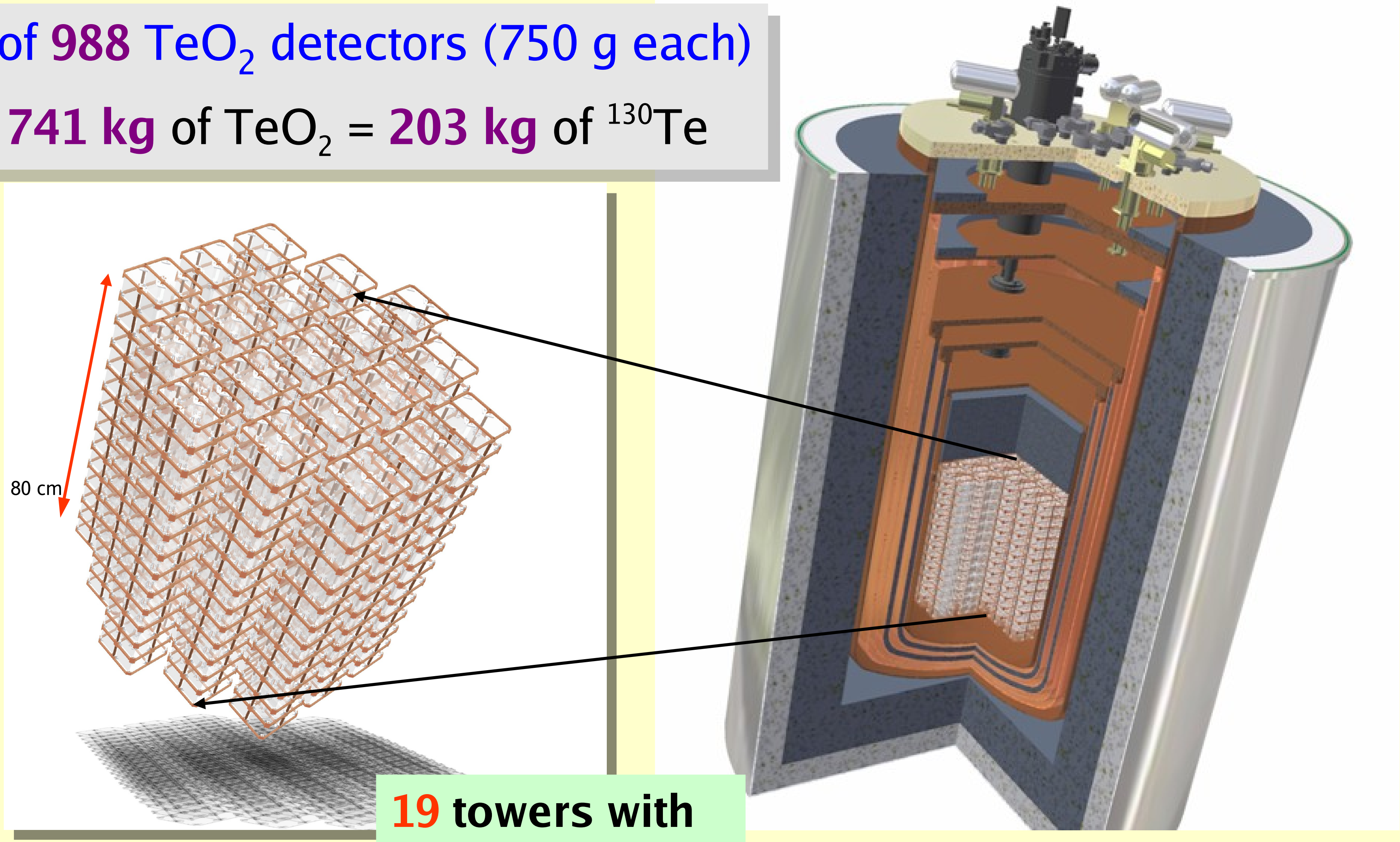
- material selection and proper handling
- shielding
- surface cleaning
- avoid recontamination

CUORE: the challenge!

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

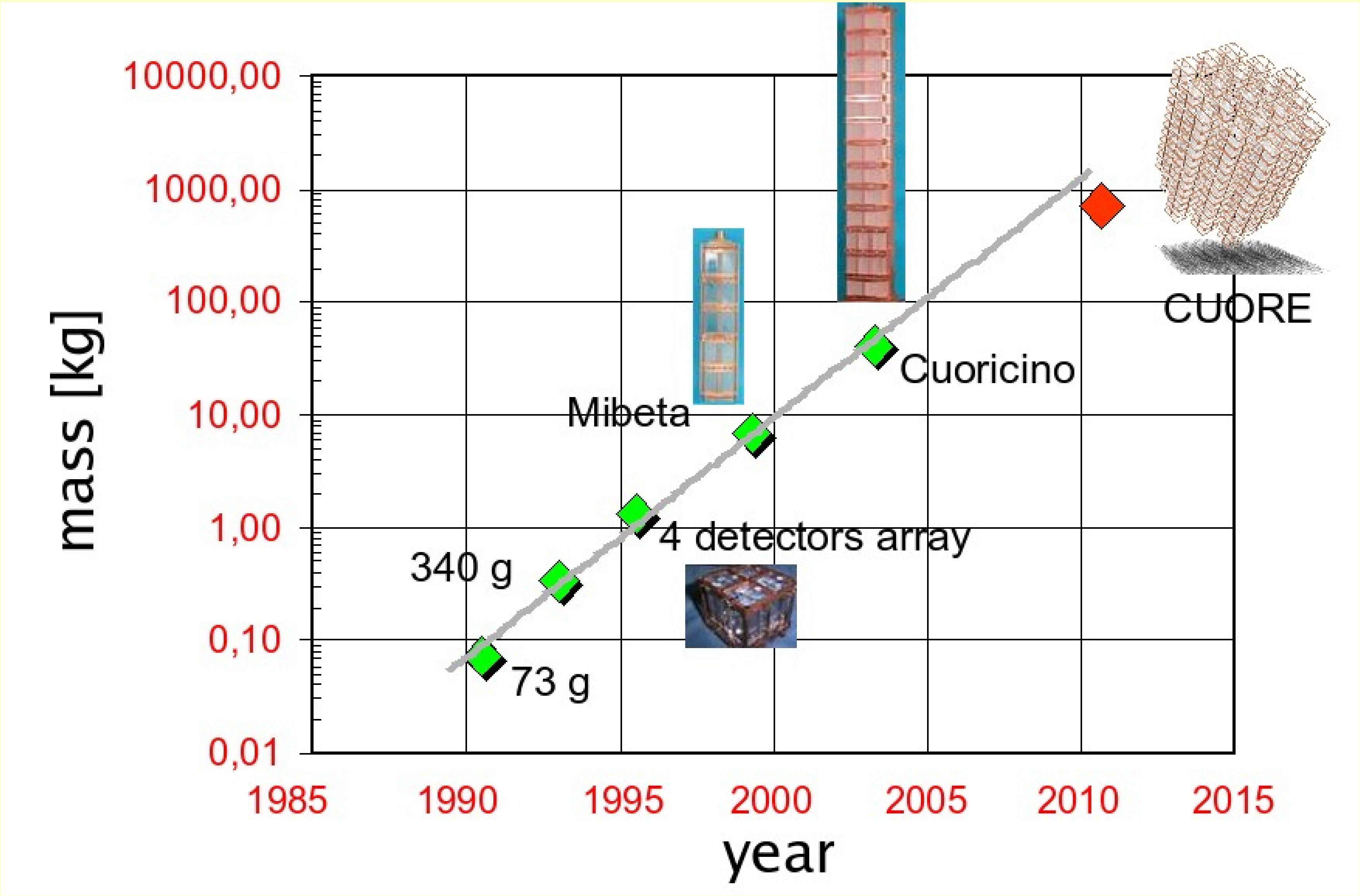
Array of **988** TeO_2 detectors (750 g each)

M = **741 kg** of TeO_2 = **203 kg** of ^{130}Te



19 towers with
13 planes of
4 crystals each

History of TeO_2 detectors: Moore's law



CUORE: the collaboration

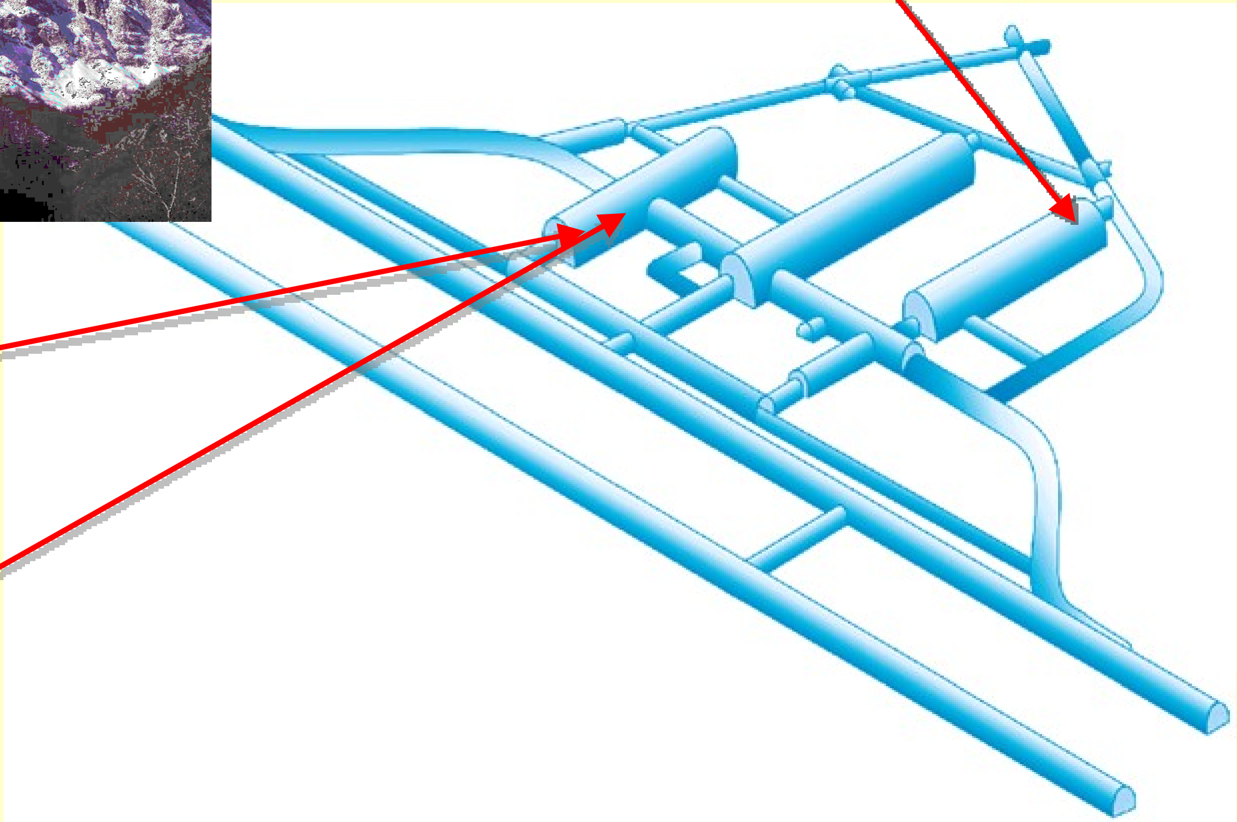
Present Collaboration

63 European collaborators

35 US collaborators

CUORE @ Laboratori Nazionali del Gran Sasso

3200 m.w.e. overburden



CUORE R&D (Hall C)

Cuoricino (Hall A)

CUORE (Hall A)

CUORE sensitivity

CUORE $\beta\beta$-0ν sensitivity will depend strongly on the background level.

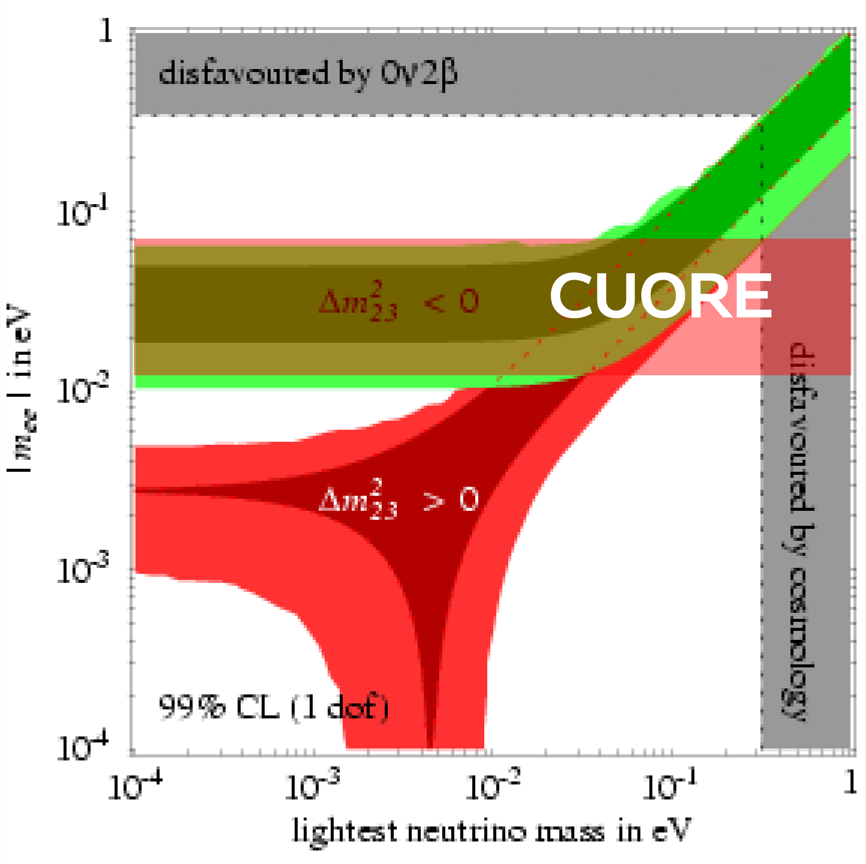
In five years:

Background [c/keV/kg/y]	ΔE [keV]	a	$\tau_{1/2}^{0\nu}$ [y]	a	m_{ee} [meV]
0.01	5		2.1×10^{26}		$24 \div 83$
0.001	5		6.5×10^{26}		$14 \div 47$

— conservative

— optimistic

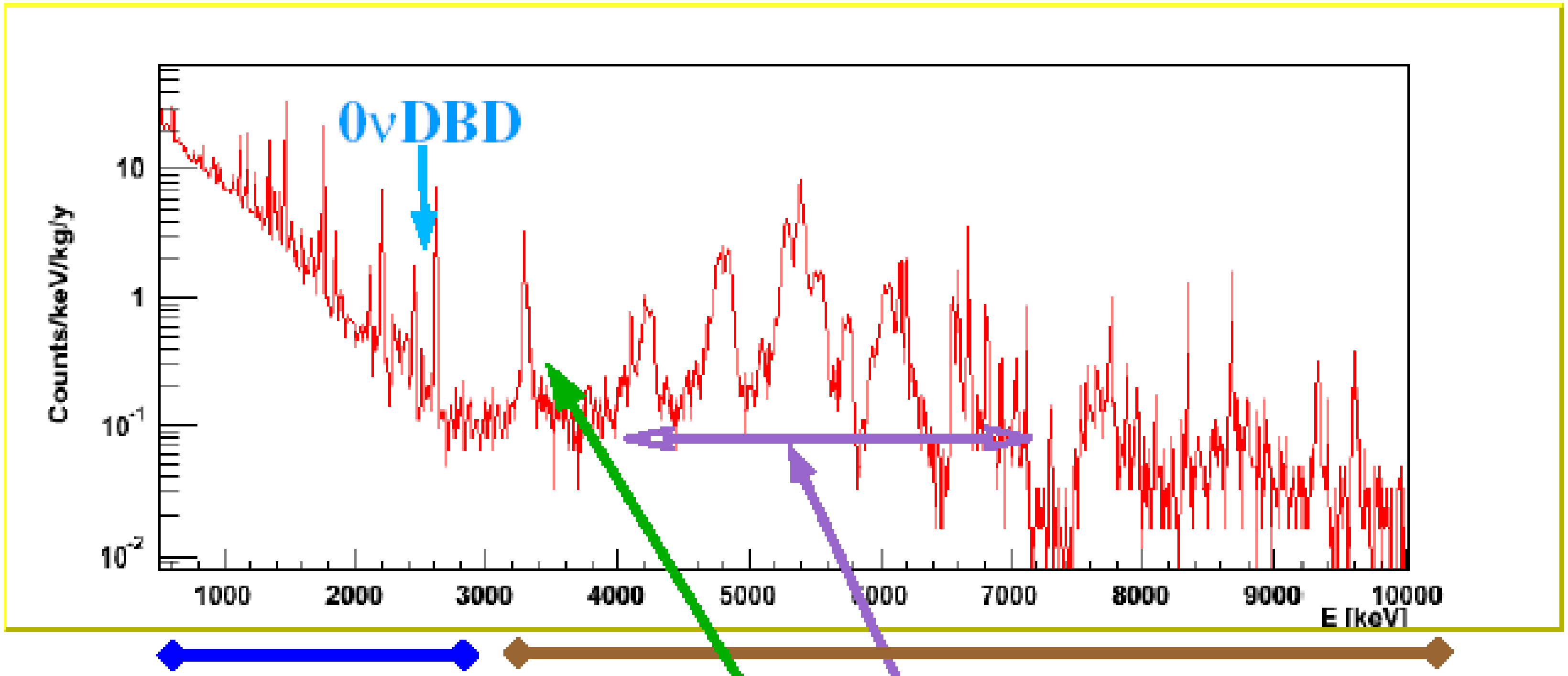
A.Strumia and F.Vissani.: hep-ph/0503246



Spread in $\langle m_\nu \rangle$ from **nuclear matrix element uncertainty**

The crucial point: background

CUORICINO measured background



Gamma region, dominated by gamma and beta events, highest gamma line = 2615 keV ^{208}Tl line (from ^{232}Th chain)

Alpha region, dominated by alpha peaks (internal or surface contaminations)

Understanding CUORICINO background

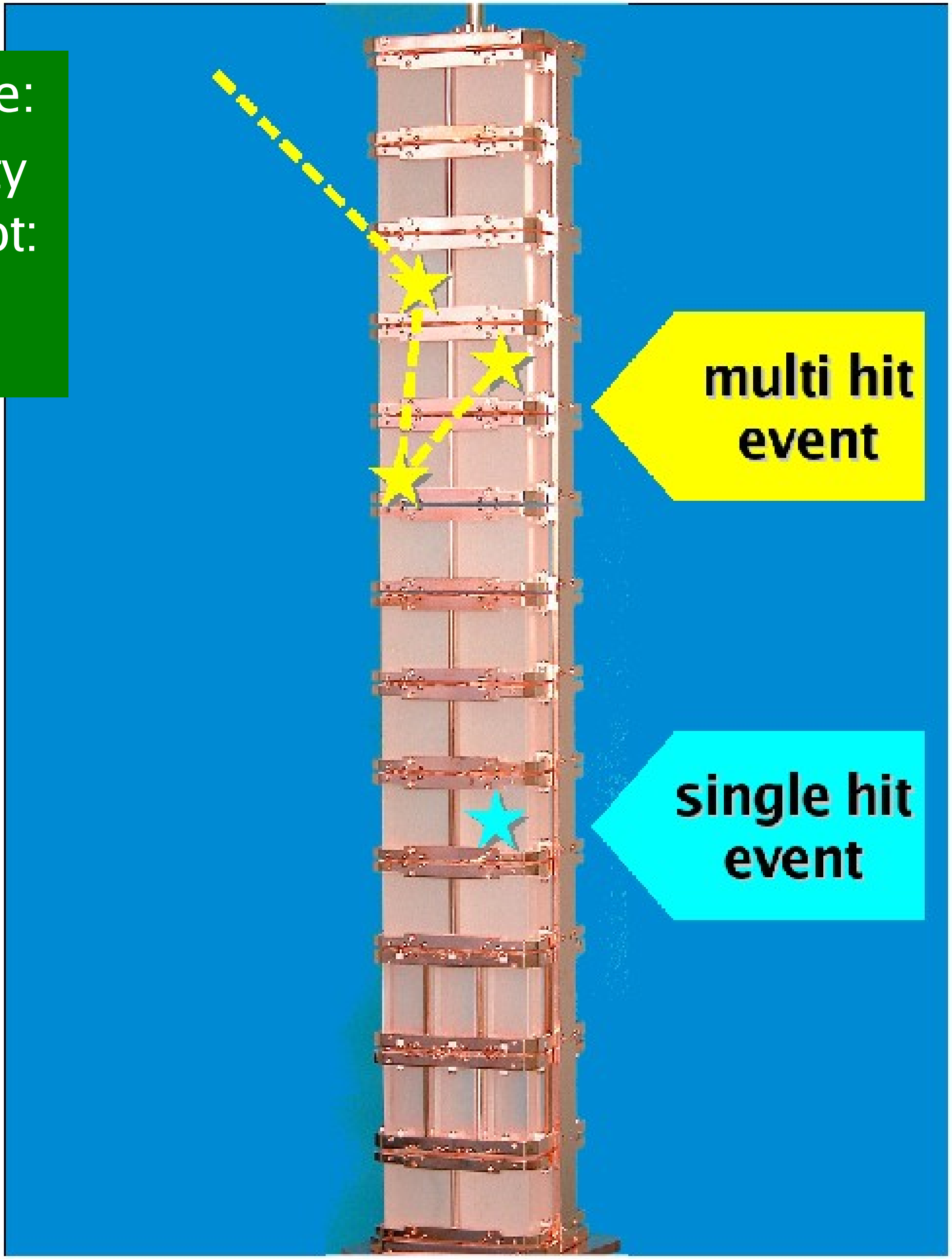
Each TeO_2 crystal is an independent device: event selection according to their multiplicity (number of contemporary hits) allows to plot:

anticoincidence spectra (single hit)
coincidence spectra (multiple hits)

background reduction & infos on background origin!

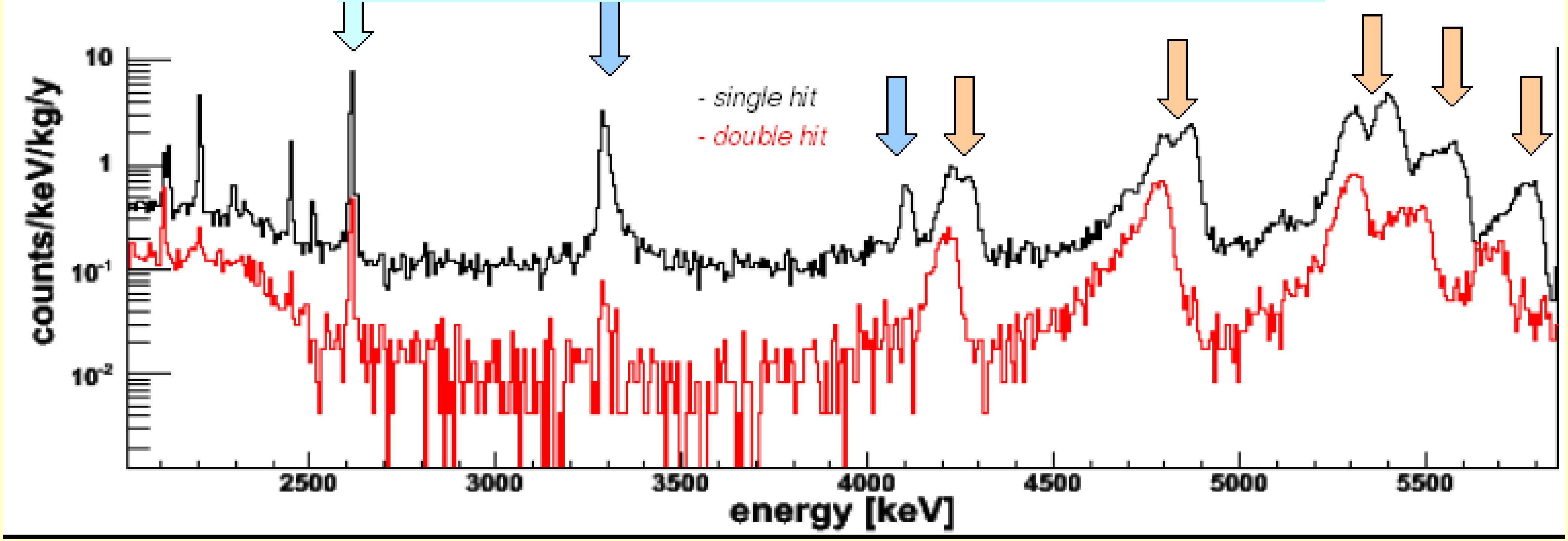
The probability for a double beta decay event to be fully contained within the crystal is 86%: anticoincidence cut reduces background by ~20%

The high granularity of CUORE will improve the anticoincidence efficiency



Understanding CUORICINO background

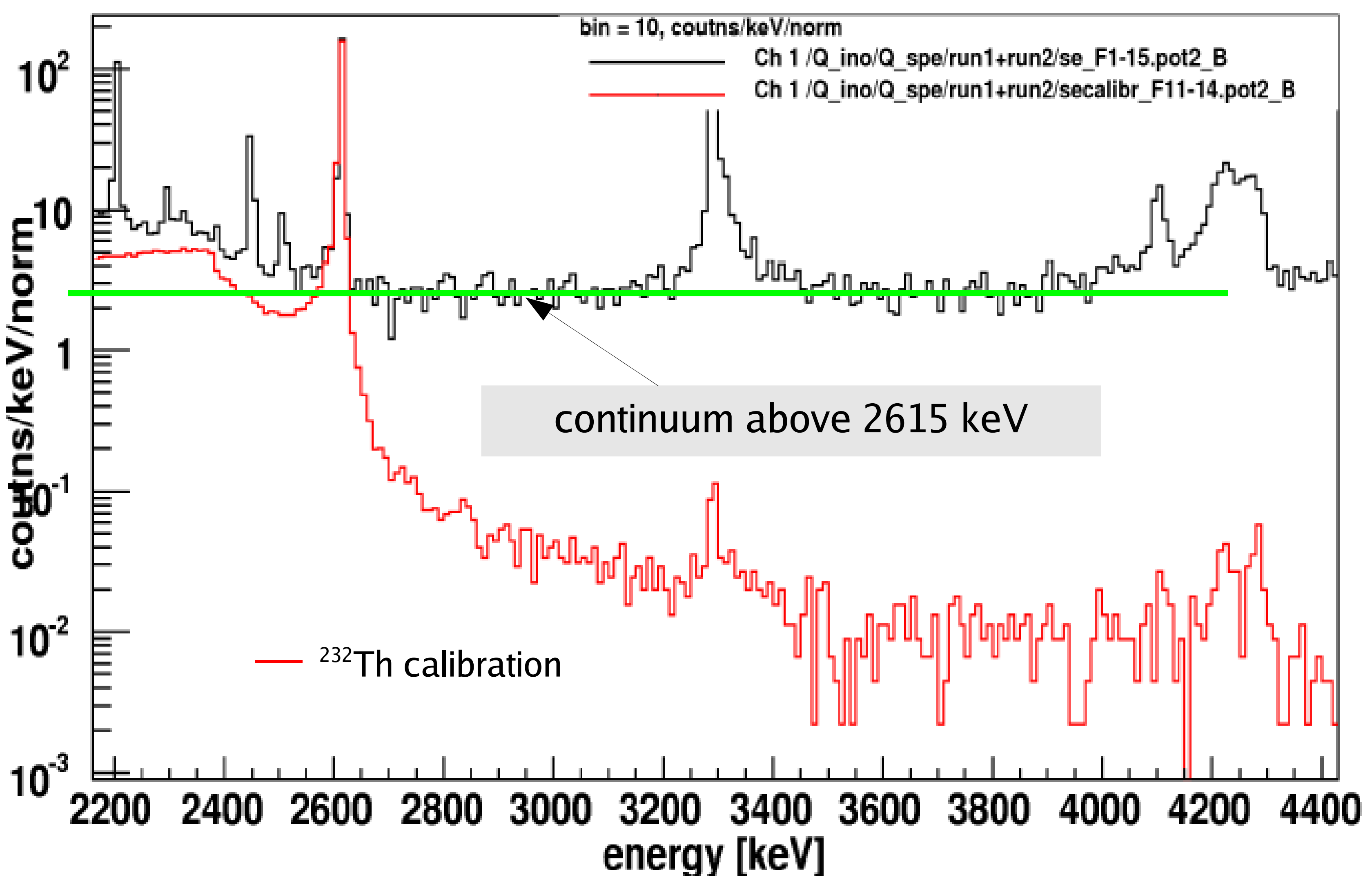
contamination type	location	contribution to
α	crystal bulk	single hit spectra
α	crystal surface	double hit spectra
α	external surface	single hit spectra
γ	external bulk	single + double hit spectra



Background informations from peak shape and coincidence study

Background sources @ 2530 keV

Gamma background (^{232}Th) from external sources



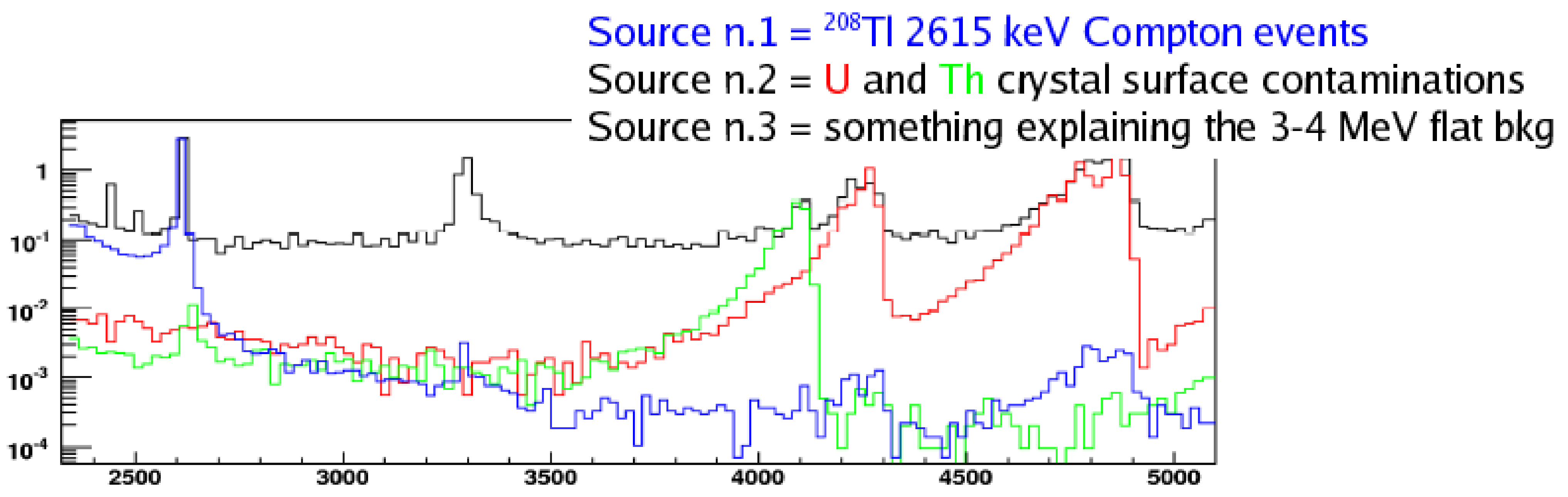
continuum above 2615 keV

^{232}Th calibration

no other gamma peak identified above ^{208}Tl

Background @2.5 MeV relative contributions

2 clearly identified sources + 1 unknown source
(copper is the most probable candidate)



Source n.1 = ^{208}Tl 2615 keV Compton events

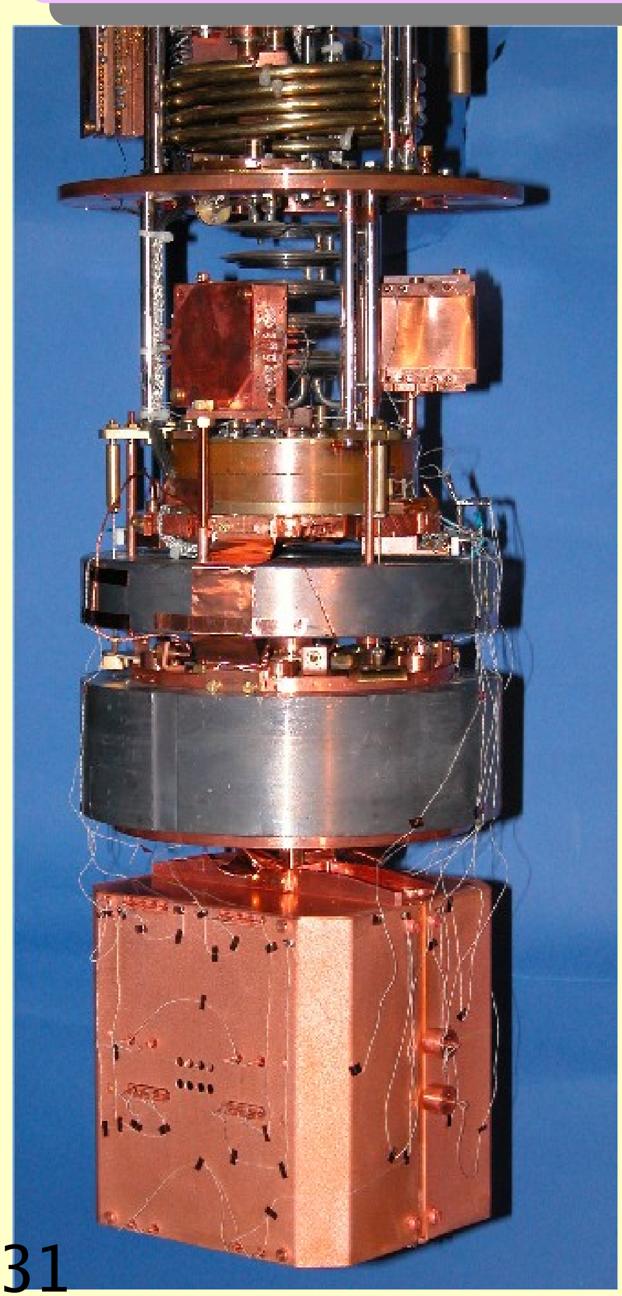
Source n.2 = U and Th crystal surface contaminations

Source n.3 = something explaining the 3-4 MeV flat bkg

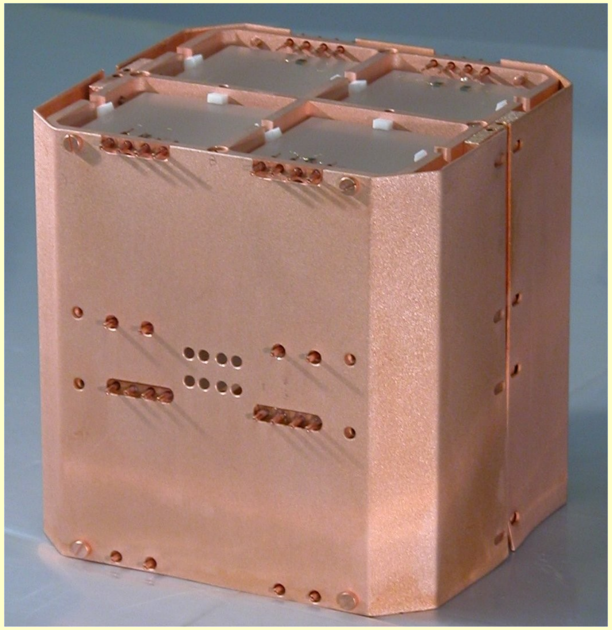
Source	^{208}Tl	$\beta\beta(0\nu)$	3-4 MeV
TeO$_2$ ^{238}U and ^{232}Th surf. contam.	-	10± 5%	20± 10%
Cu ^{238}U and ^{232}Th surf. contam.	~15%	50± 20%	80± 10%
^{232}Th contam. of cryostat Cu shields	~85%	30± 10%	-

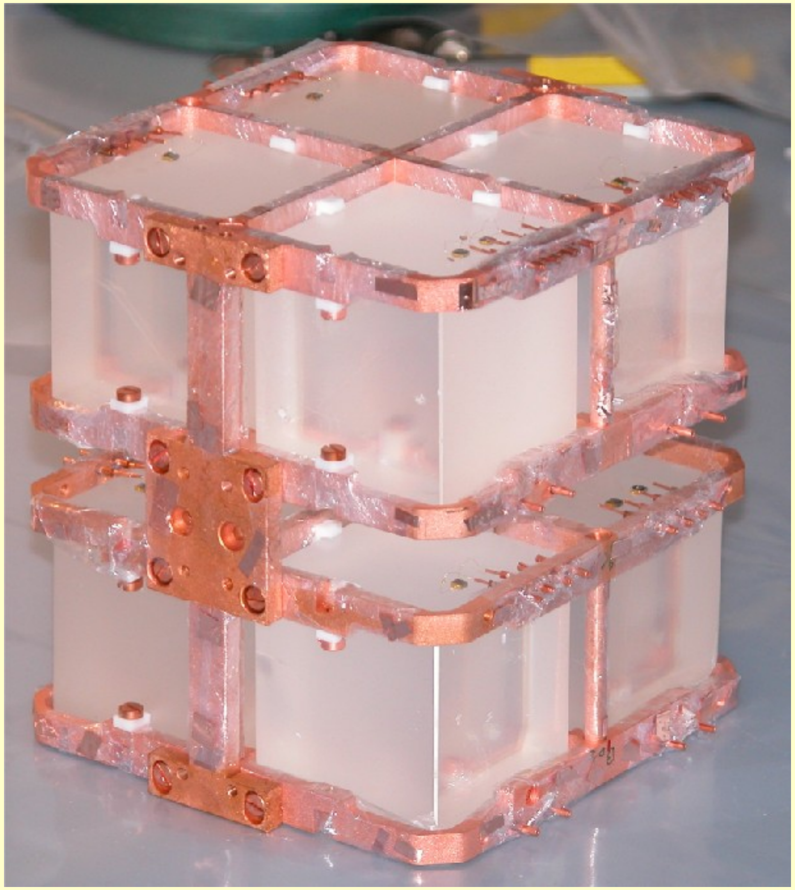
CUORE R&D: the RAD detector

A dedicated array for background study in the Hall C facility (LNGS)



RAD: Radioactivity Array Detector

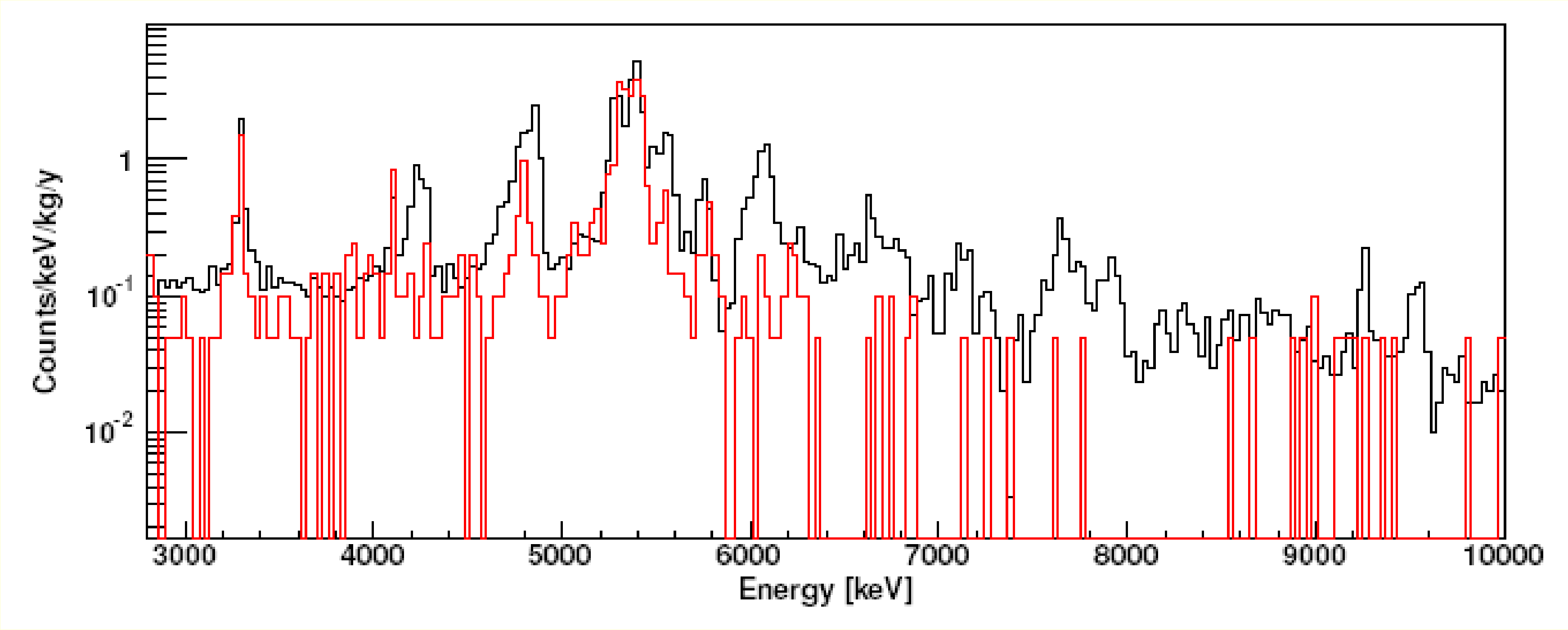




RAD detector results

After cleaning crystals and copper surfaces:

- reduction of crystal surface contamination of a factor ~5
- reduction of continuum background in 3-4 MeV region of a factor ~2



Comparison between CUORICINO (black) and RAD (red) spectra

CUORE background prediction

Measured contaminations projected (Montecarlo) on CUORE

SOURCE	**BACKGROUND @ 2.5 MeV (10^{-3} counts/keV/kg/y)**
TeO_2 crystal bulk	< ~1.3
TeO_2 crystal surface	< ~7
Detector mounting bulk	< ~1
Detector mounting surface	< ~25
Experimental set-up gamma	~ 2
Environmental gamma	~ 0.002
Environmental neutrons	< ~0.1
Environmental muons (no veto)	~ 0.4

... STILL WORKING TO IMPROVE THESE NUMBERS!

→ special efforts devoted to crystal production and copper surface cleaning

TeO_2 crystal production

CUORE dedicated crystal growth facility @ SICCAS (China)

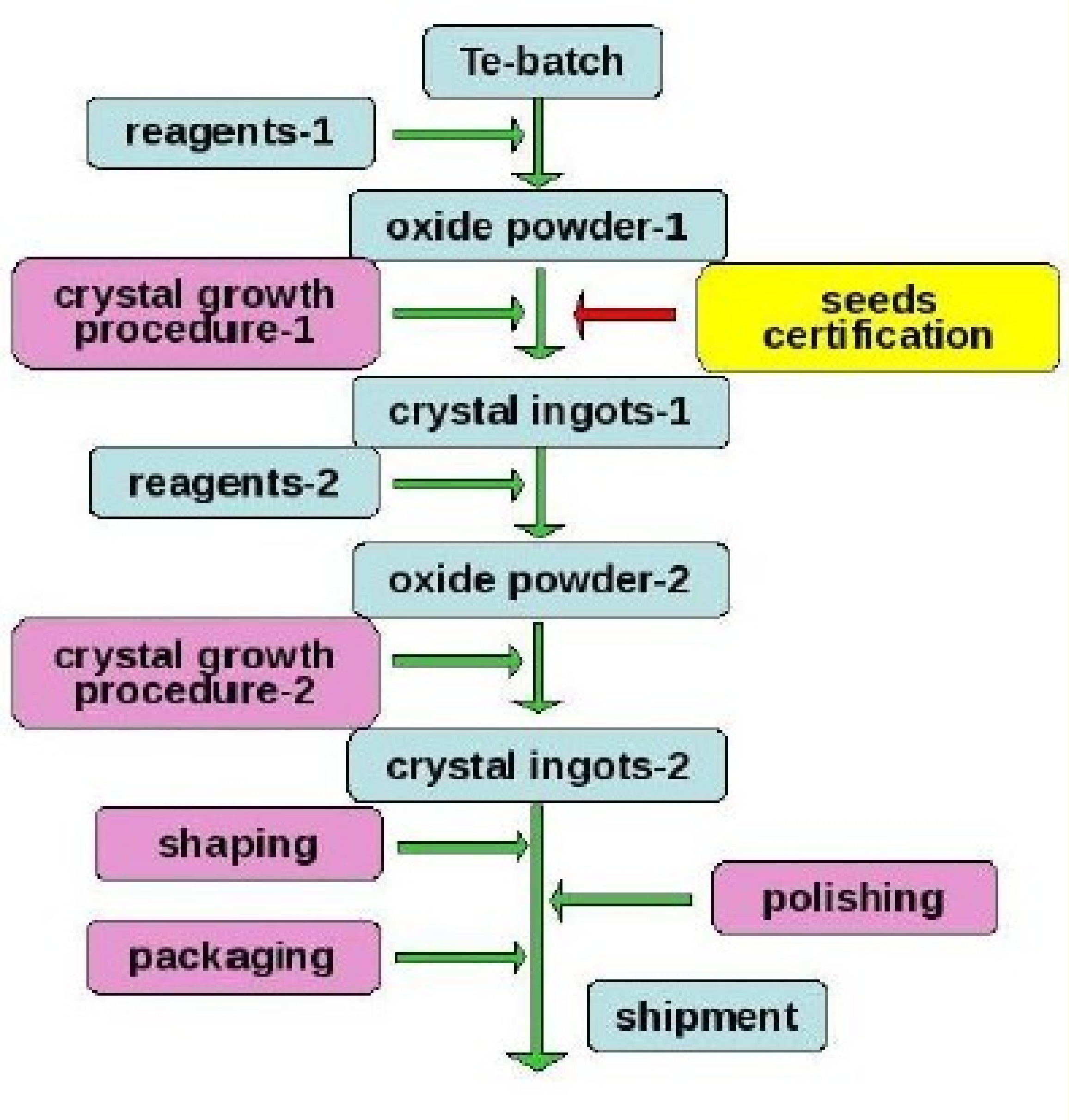
1) Kushan Jincheng Chemical Reagent Co. Ltd

high purity grade TeO2 powder production unit

QUALITY MANAGEMENT SYSTEM
CERTIFICATION OF CONFORMITY

high purity water and reagents production units

TeO_2 crystal production



Kunshan chemical plant

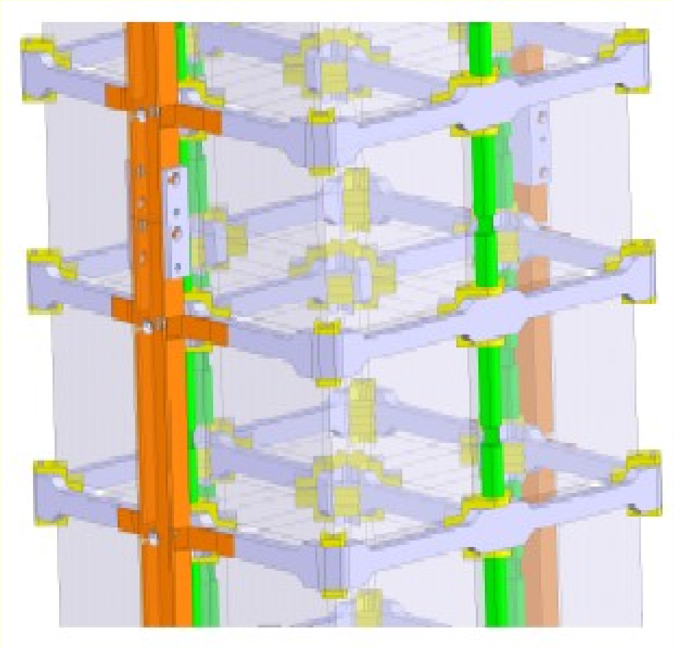
TeO$_2$ crystal production

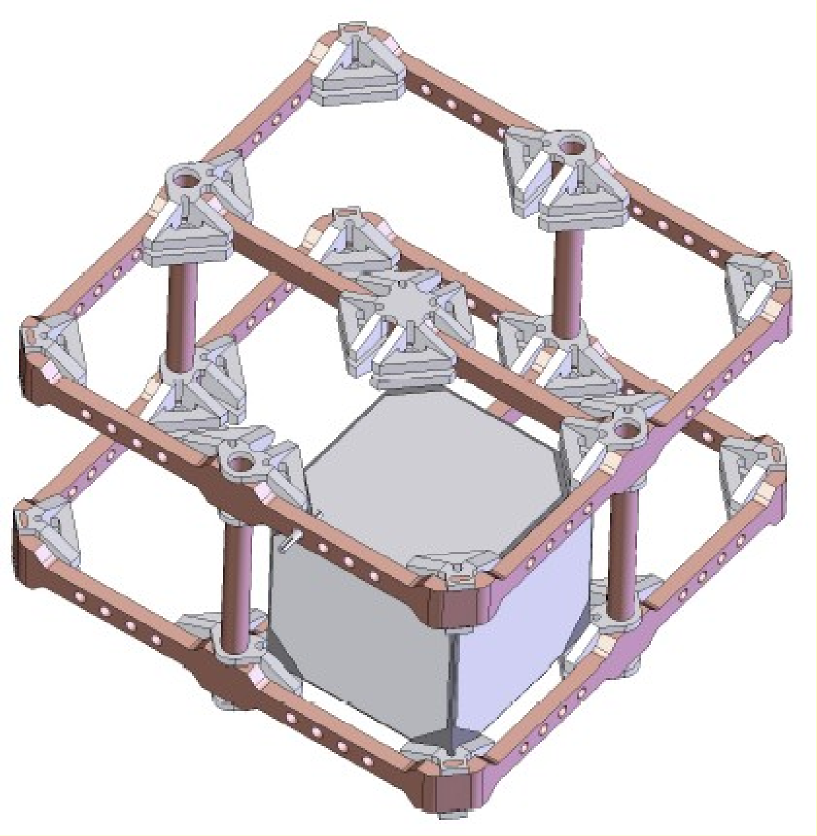
Crystals will be delivered to Gran Sasso by ship to reduce cosmic ray exposure
(~ 45 days trip)

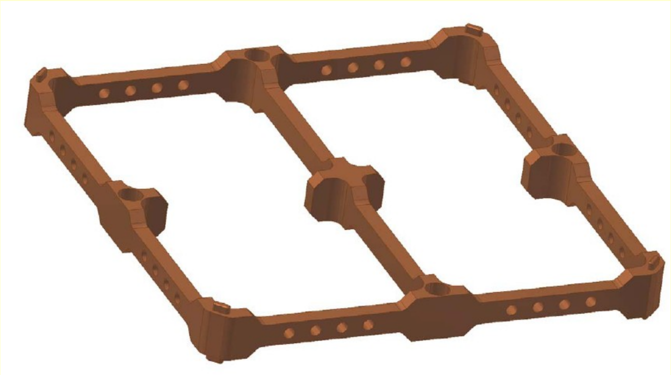
First crystals
will arrive
this summer!

Detector mounting production

CUORE detector will be compact and granular
➪ self shielding detector







New holder design to reduce Cu among crystals
Frames will be produced by EDM machining

Copper surface cleaning

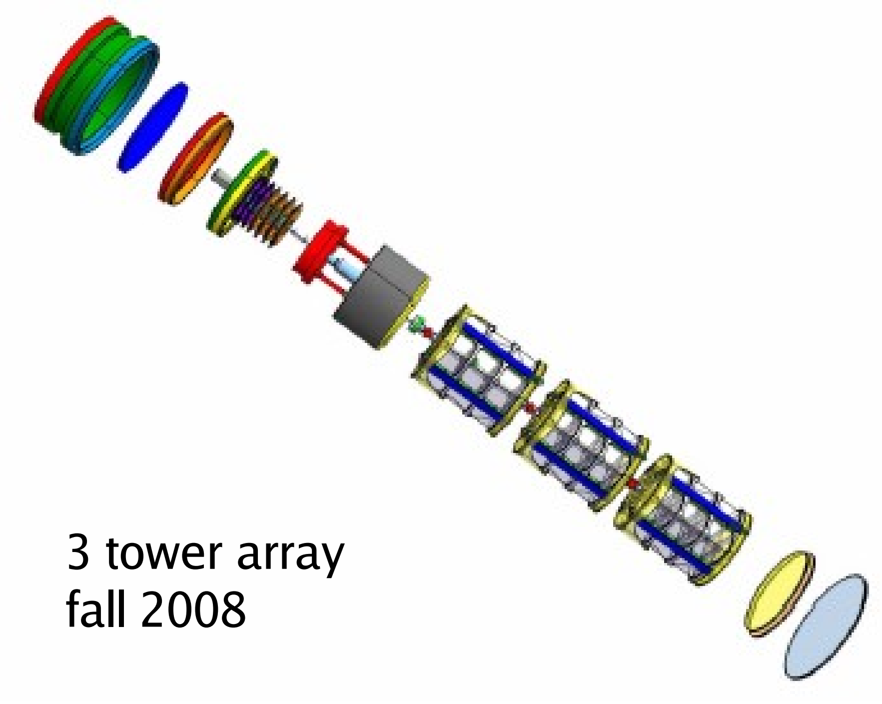
Dedicated cleaning facility @
INFN-Laboratori Nazionali di Legnaro (PD)

All copper surfaces in the detector area will undergo the following cleaning procedure:

Tumbling
Electrochemical
Chemical
Magnetron sputtering
+ UltraSonic cleaning between each step

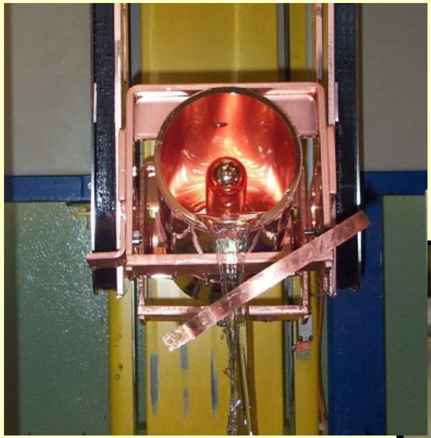
First measurements with Silicon Barrier detectors on small copper samples show a reduction of ^{210}Po surface contamination!

Bolometric test this fall! ➡


3 tower array
fall 2008

Copper surface cleaning

Legnaro chemical facility



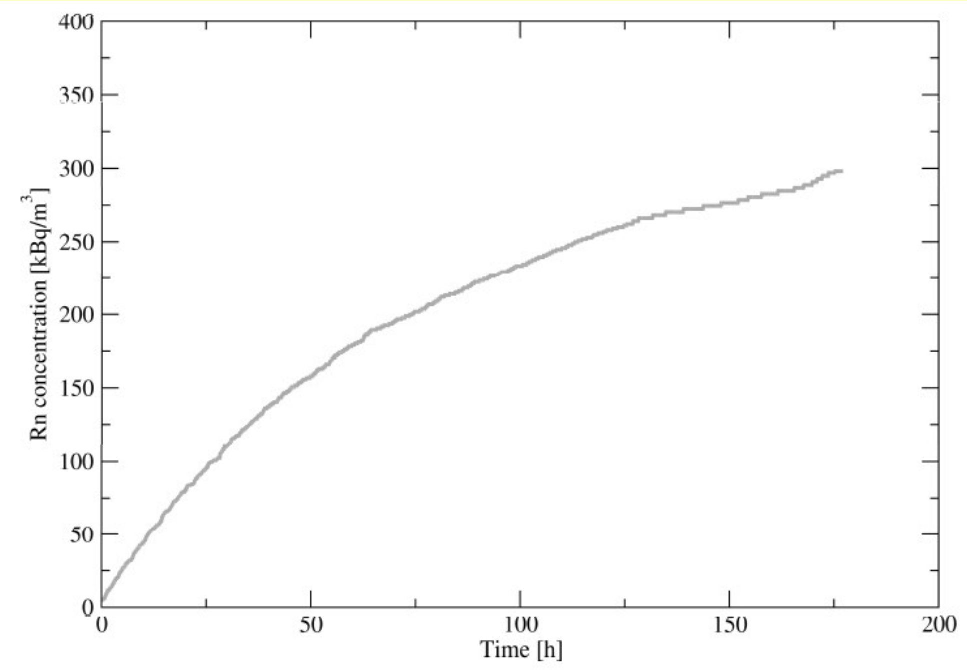
Legnaro UHV Plasma etching

Tumbler

Radon

NEW!!!

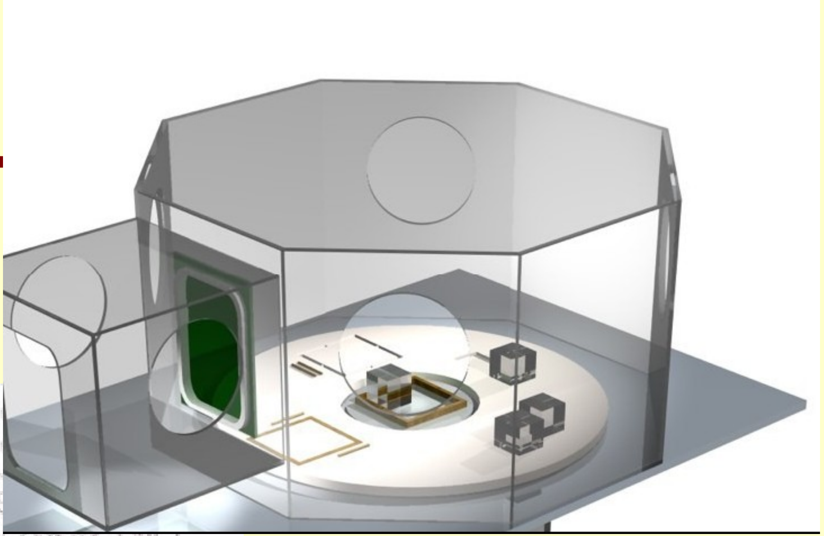
Experimental set-up to measure the sticking factor of Radon on critical surfaces (copper, teflon, TeO_2, ...)

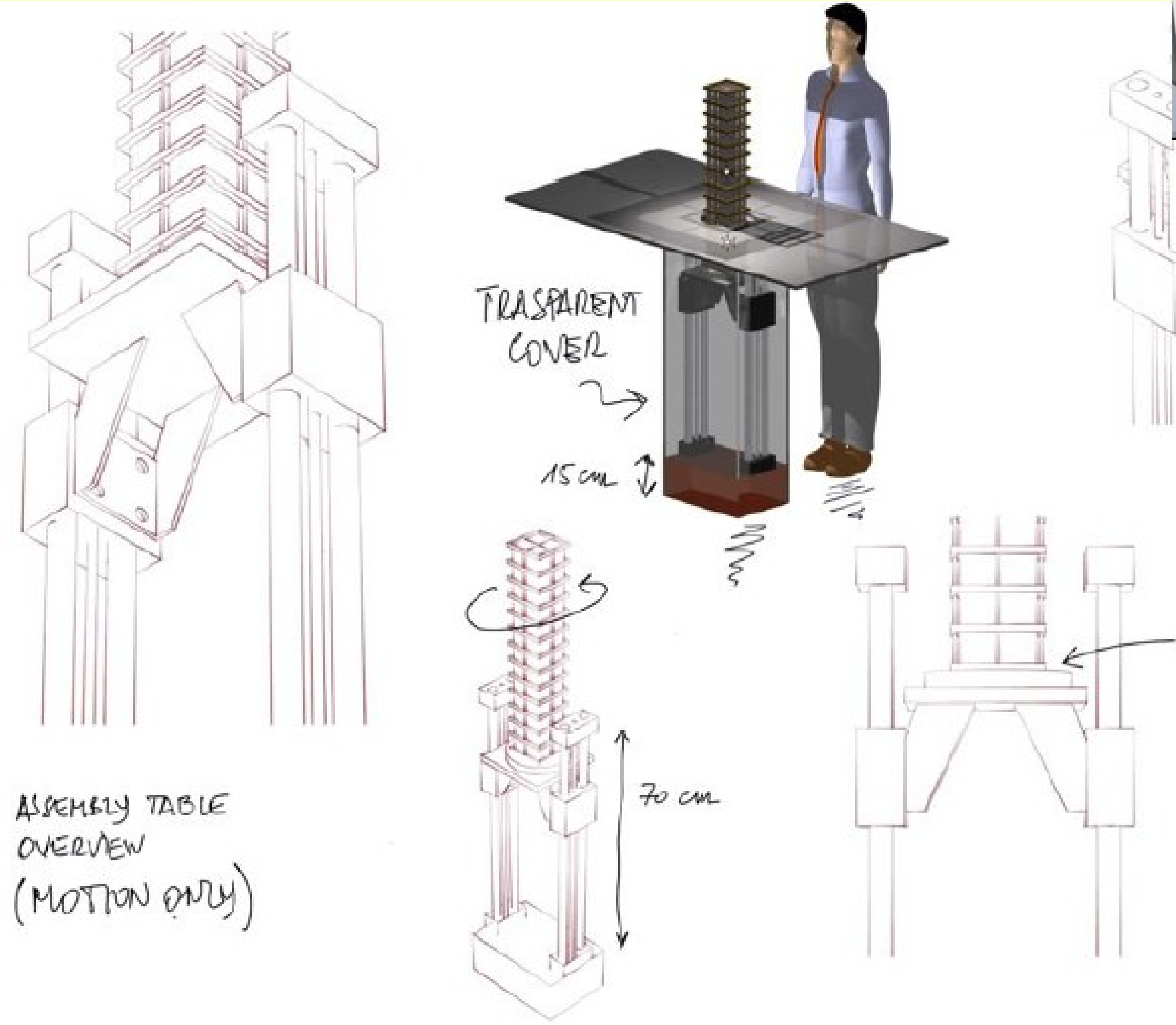


Detailed analysis on the way

!!! Preliminary results on copper and TeO_2 samples show that the Radon sticking factor is small: $\sim 10^{-10}$!!!

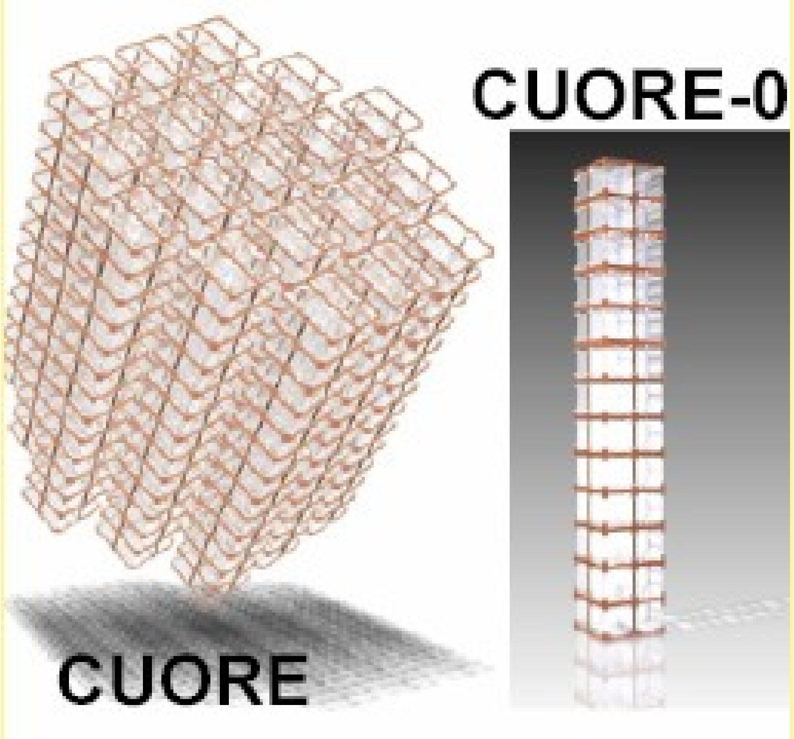
Tower assembly





CUORE-0

CUORE-0 will be the first CUORE tower
It will be operated in Hall A dilution refrigerator
(CUORICINO experimental set-up)



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

MOTIVATIONS:

- Test of the assembly procedure
- Test of background achievements

CUORE-0 will be a powerful experiment that will soon overtake CUORICINO sensitivity

CUORICINO will be stopped at the end of June

CUORE-0 vs CUORICINO