# Bolometric Search for Neutrinoless Bouble Beta Decay


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# OUTLINE

* Neutrino physics & DBD0v

* DBD0v sensitivity

* DBD0v bolometric detectors

  * CUORE & CUORICINO
  * Background studies

* Radon-induced surface contaminations

* Effects on large mass experiments & solutions

* Conclusions

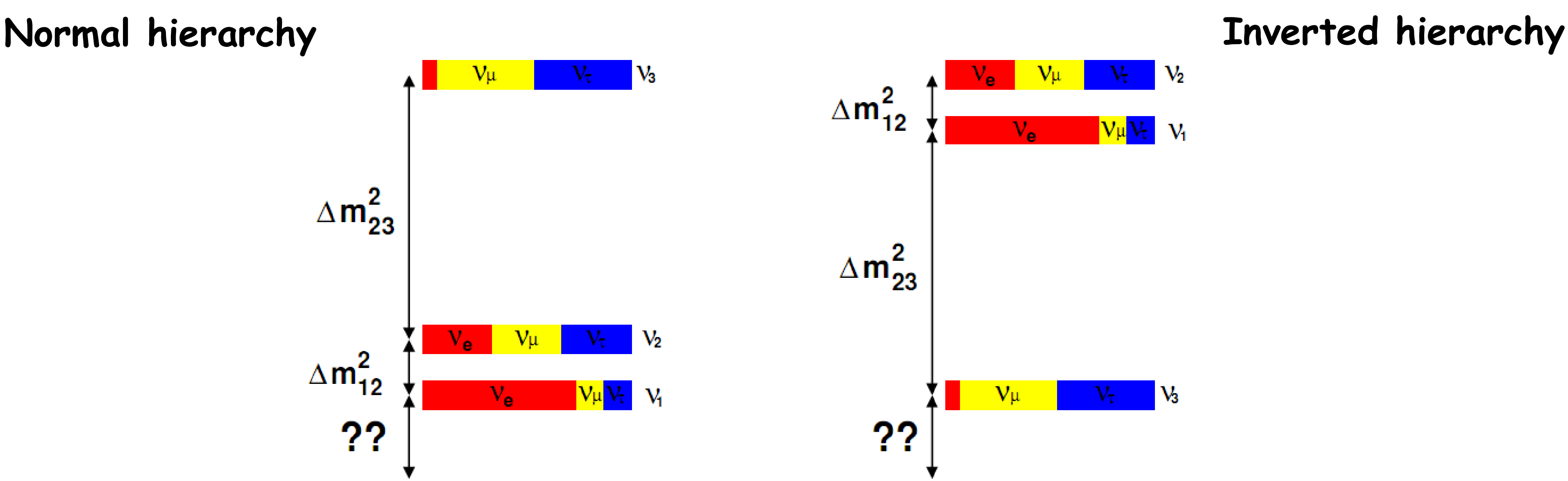
# Neutrino physics

## known

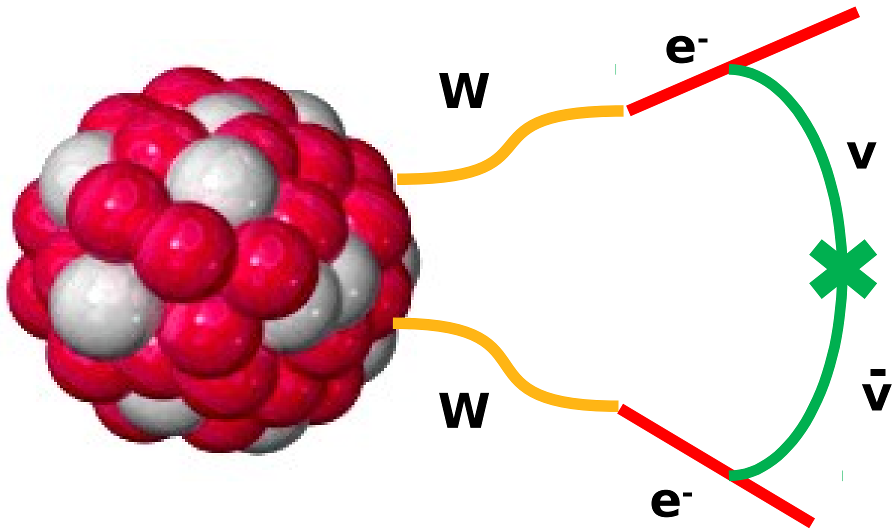
- Neutrinos oscillate =>Non-zero mass
- Some oscillation parameters are known

## unkown

- Mass hierarchy
- Absolute mass scale
- Dirac or Majorana particle



# DBD0ν

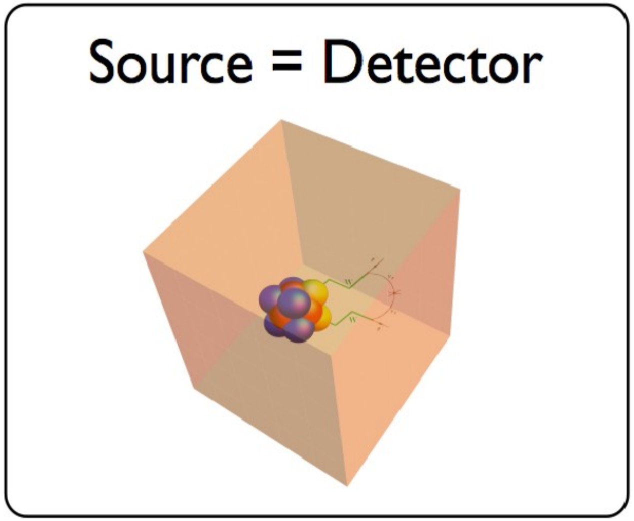



- $2^{nd}$ order nuclear weak decay
- not allowed in the SM
- $t_{1/2}$ expected > $10^{25}$ y

If observed:

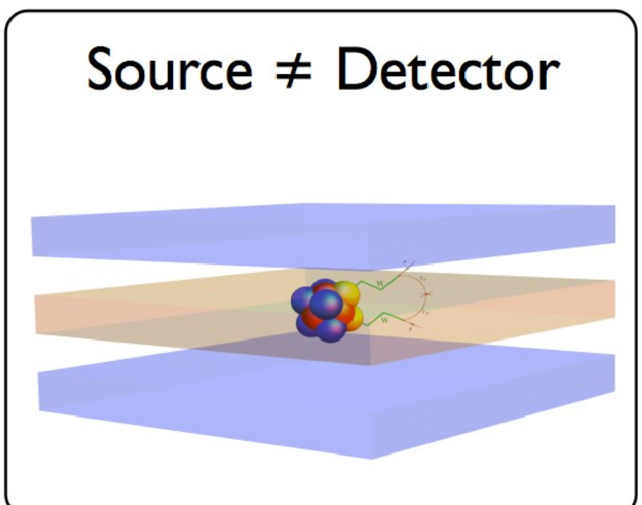
- the neutrino is a Majorana particle: $\nu_e \equiv \overline{\nu}_e$
- $\Delta L = 2$, lepton number violation
- ν mass measurement: $$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

# Design of a DBD0v experiment




Calorimetry

* High efficiency
* Good energy resolution
* Large mass source

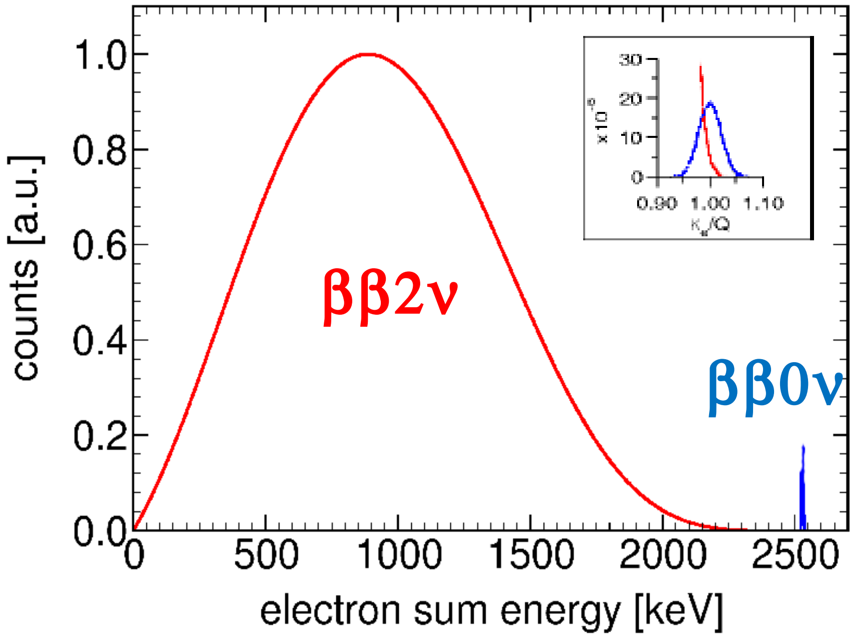



Scintillation

Tracking

* Large mass source
* Particle identification

# What are we looking for ??




**Monochromatic signal**
**@ Q-value (~ MeV range)**

$$\boxed{S_{0\nu} \propto \varepsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot T}{\Delta E \cdot b}}}$$

$b \neq 0$

**ε: efficiency**

**i.a.: isotopic abundance**

**A: atomic mass number**

**M: source mass**

**T: live time**

**ΔE: FWHM in the ROI**

**b: bkg in the ROI**

**...**

# DBD0v Sensitivity

$$S_{0\nu} \propto \varepsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot T}{\Delta E \cdot b}}$$

ε: efficiency => ~100% for bolometers

i.a.: isotopic abundance => Natural / Enrichment => $$$$ / radiopurity

M: detector mass [kg] => Next generation ~ 1 ton

T: time [y] => ~ 5 y

ΔE: energy resolution [keV] => ~ 5 keV for bolometers

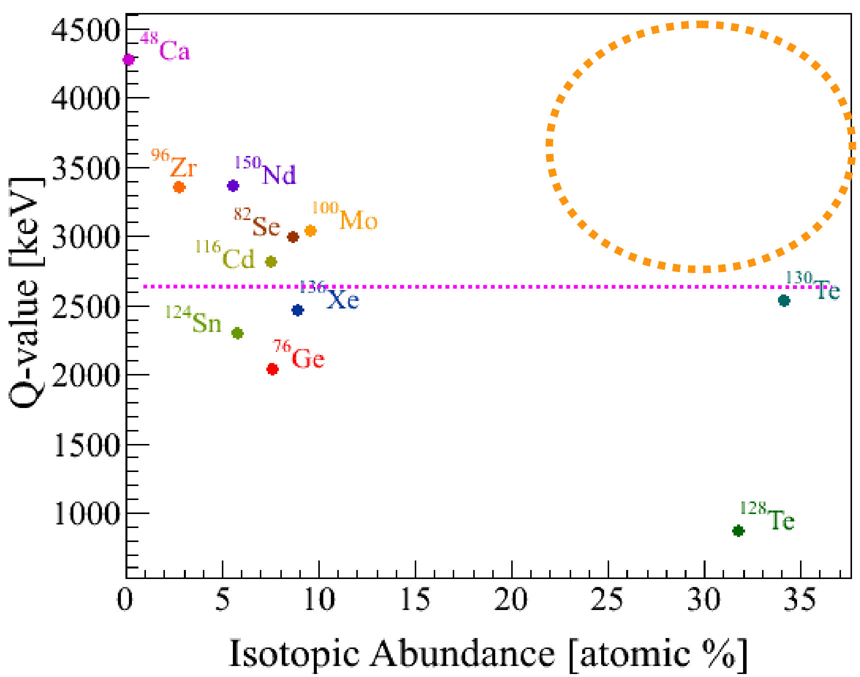
b: background [c/keV/kg/y] => ~ 0.01 c/keV/kg/y CHALLENGE

# Isotope choice

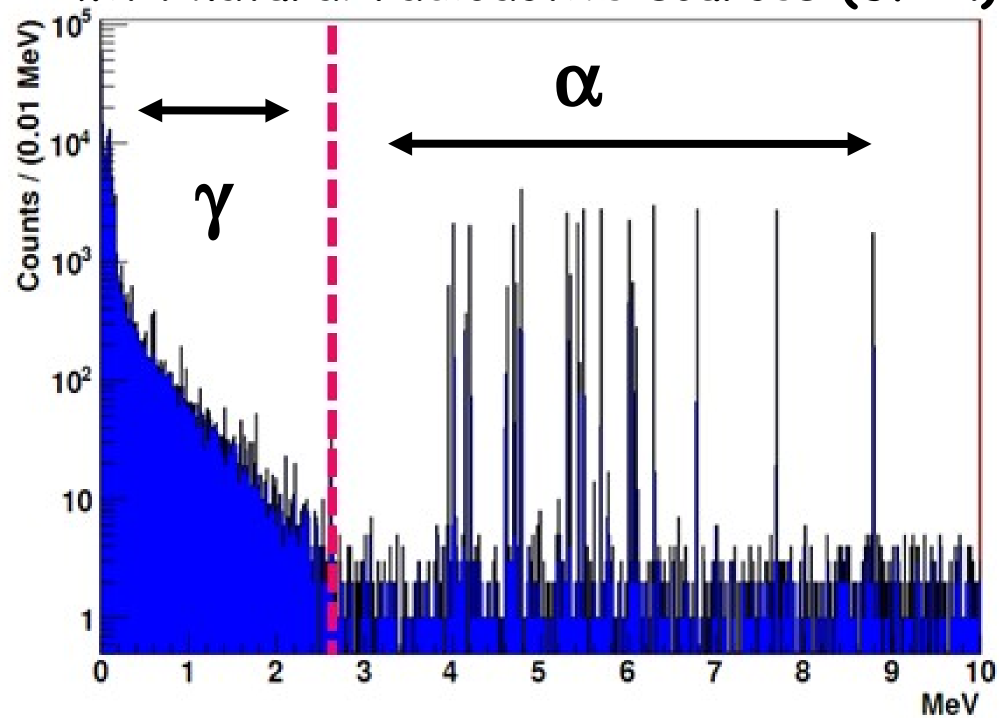
**The calorimetric technique allows a wide selection of possible DBD0v candidates:**

**No golden isotope: High Q-value & High i.a.**

$$S_{0\nu} \propto \varepsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot T}{\Delta E \cdot b}}$$




**Spectrum of a germanium bolometer calibrated with natural radioactive sources (U/Th)**




**$^{208}$Tl highest natural gamma line @ 2.6 MeV**

# Bolometer background sources

Due to the limited detector energy resolution and the fact that they are sensitive to all types of radiation, there are various background sources for DBD0v experiment:

**Neutrons** =>
- neutron activation: (n,g) reactions
- appropriate shielding for n moderation and absorption

**Muons** =>
- energy deposit in the ROI
- installation under a mountain or in a mine / coincidence

**Gammas**
**Betas** =>
- natural radioactivity / multiCompton events
- appropriate isotope choice / material selection

**Alphas** =>
- degraded alphas emitted by surfaces
- surface cleaning / particle discrimination

# CUORE & Cuoricino

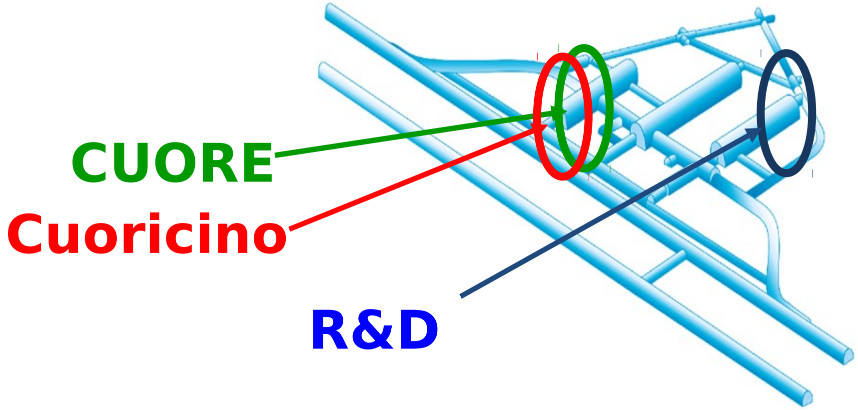
CUORE & Cuoricino use the bolometric technique to search for DBD0v in $^{130}Te$

CUORE will be able to span low neutrino mass region (tens of meV)

Cuoricino was a small CUORE prototype, about 5 years of data taking starting in 2003

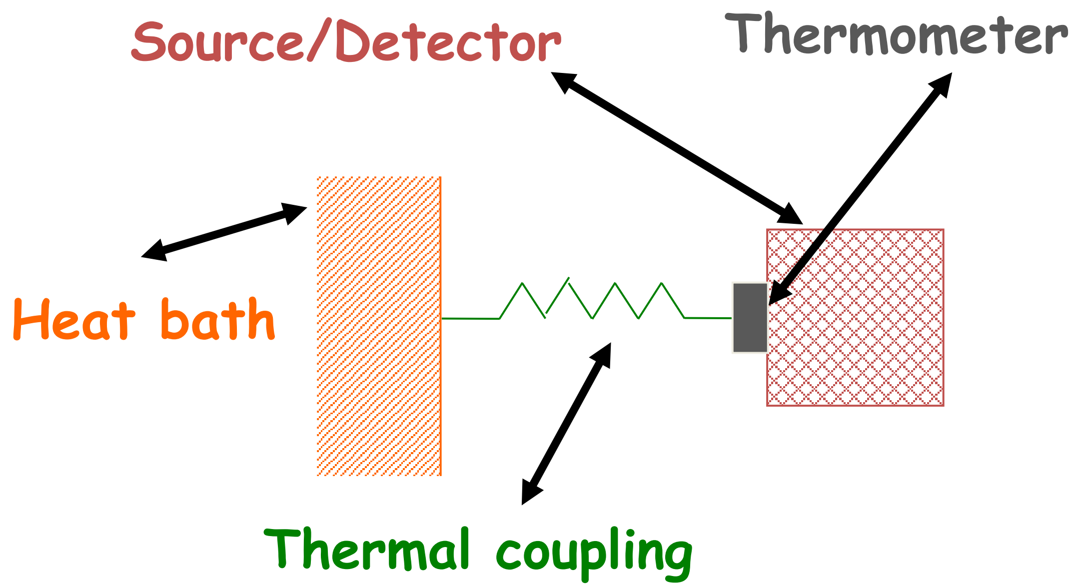
Experiments located underground in the Laboratori Nazionali del Gran Sasso @ 3400 m.w.e.

- Muon flux: $(3.2 \pm 0.2)\ 10^{-8}\ \mu/s/cm^2$
- Neutron flux: $10^{-6}$-$10^{-7}$ $n/s/cm^2$
- Rn level: 50-100 $Bq/m^3$



# Bolometric Technique

E. Fiorini and T. Niinikoski,
Nucl. Instrum. Methods 83 (1984) 224




e.g. $TeO_2$

$M = 750\ g$
$C \cong 2\ nJ/K$
@10mK
=> $1\ MeV / 100\ \mu K$

$R \cong 100\ M\Omega$
$dR/dT \cong 0.1\ M\Omega/\mu K$

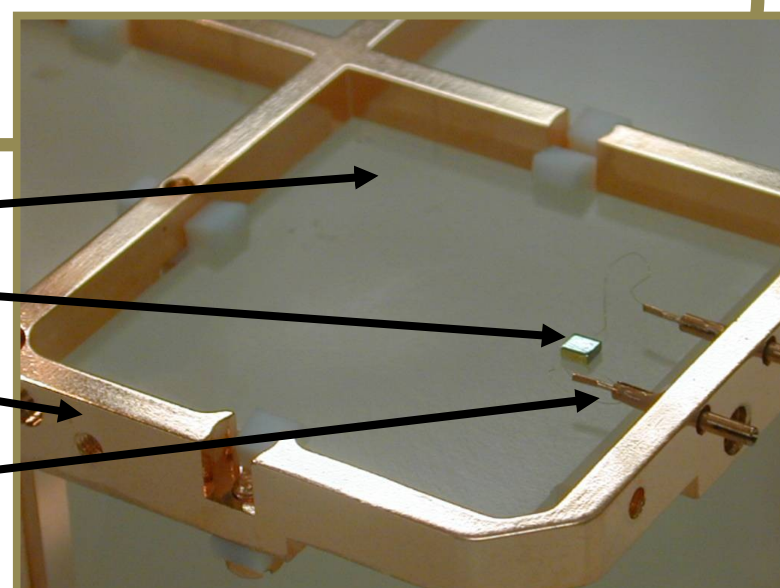
=> 1mV

$TeO_2$ -> Source/Detector

NTD-Ge -> Thermometer

Copper-> Heat bath

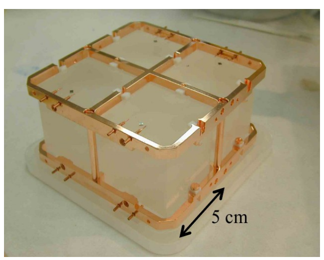
NTD-Ge gold wires -> Thermal coupling

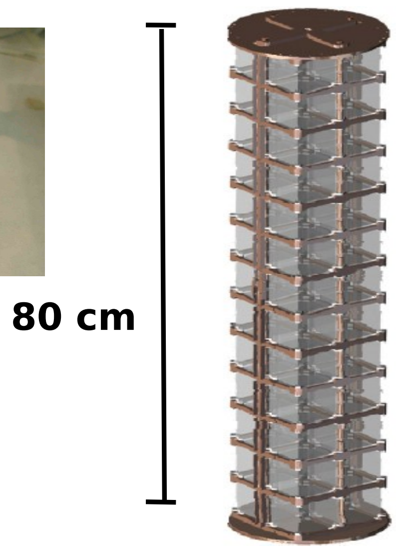


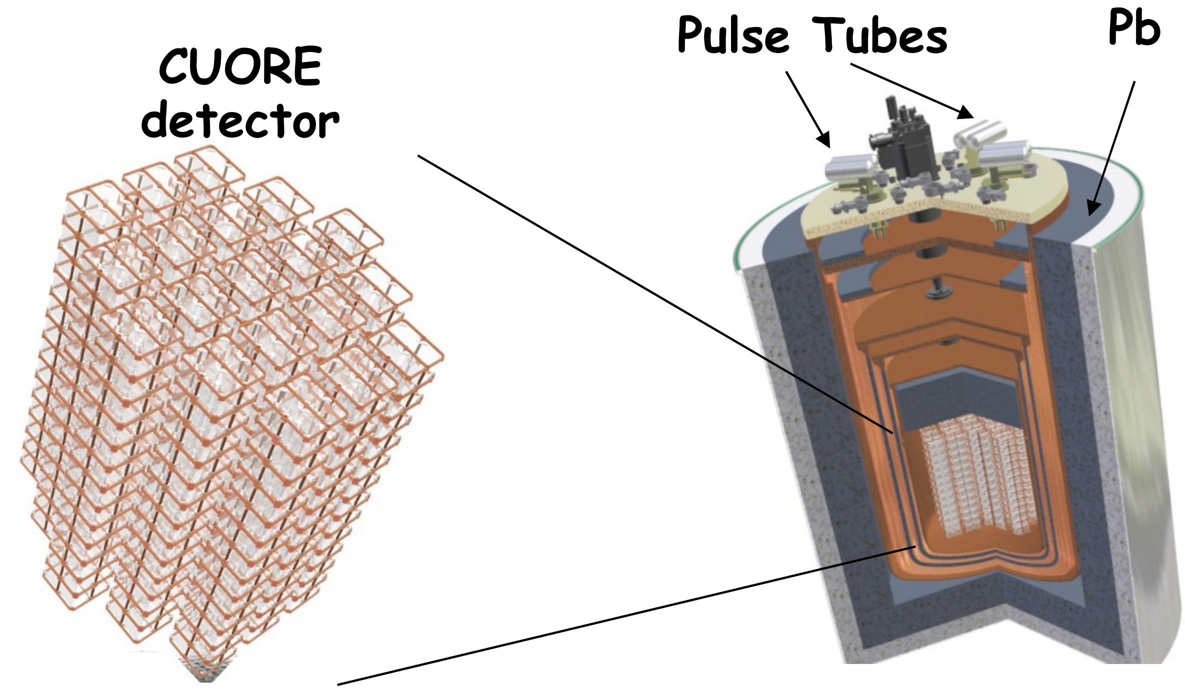
# The CUORE experiment

## Cryogenic Underground Observatory for Rare Events

**Array of 988 detectors. 19 CUORICINO-like towers M = 0.741 ton of $TeO_2$ (~200 kg $^{130}Te$) to measure DBD0ν of $^{130}Te$ with bolometric detector.**



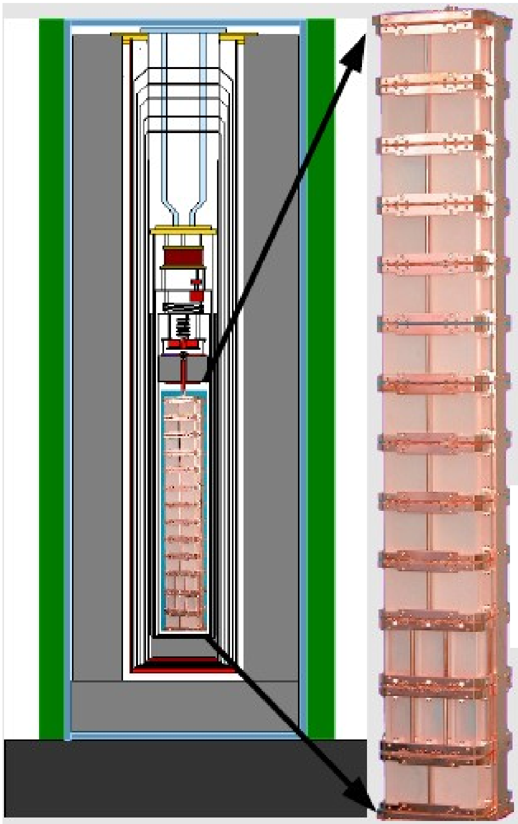




**Sensitivity: $1.6 \cdot 10^{26}$ y [T: 5y; ΔE: 5 keV; b: 0.01 c/keV/kg/y]**

**$m_{\beta\beta}$ = 35-82 meV** NME from F.Simkovic et al. Phys.Rev. C77 - J.Suhonen et al. Int.Jou.Mod.Phys. E17 - J.Menendez et al. Nucl. Phys. A818 - J.Barea et al. Phys. Rev. C79

**[arXiv:1109.0494] F. Alessandria et al. (LP) In press**

# Cuoricino



**Cuoricino results** :

- no evidence of DBD0v
- Statistics : ~ 19.75 kg*y of $^{130}Te$
- Bkg @ ROI: 0.18 ± 0.02 c/keV/kg/y
- *FWHM @ 2615 keV ($^{208}Tl$) → 6.3 keV

## Shieldings

### Internal:

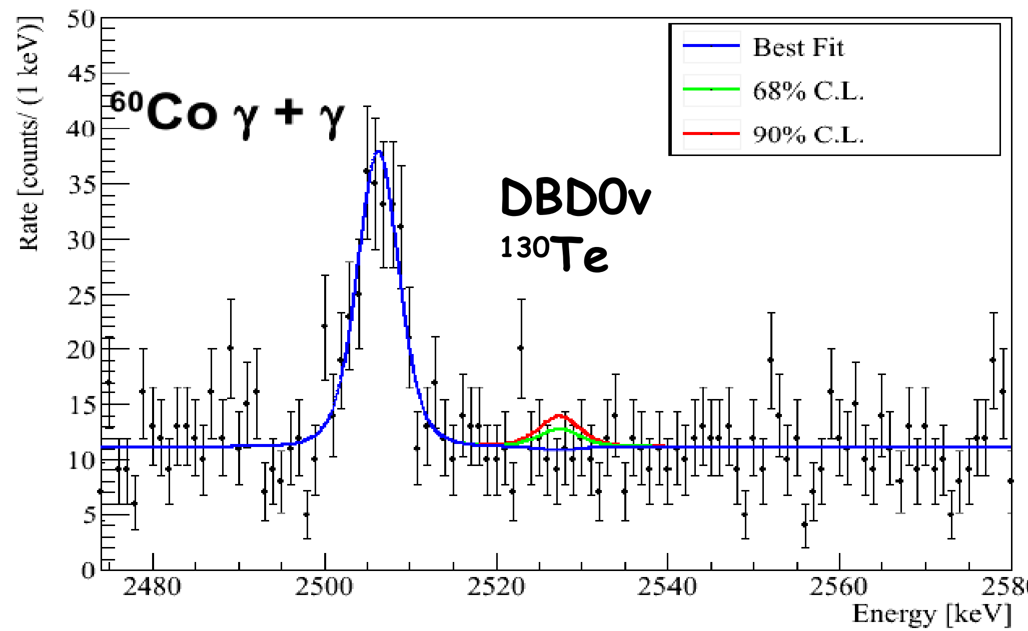
➔1cm low activity Pb (A < 4 mBq/Kg in $^{210}Pb$)

### External:

➔20cm Pb

➔20cm Borated Polyethylene

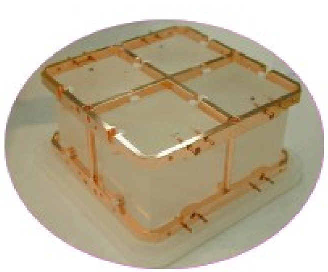
➔Anti-Rn box: Nitrogen overpressure

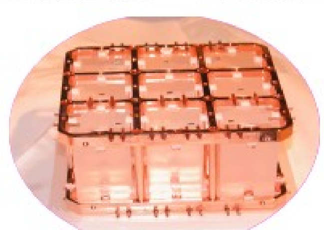



**A tower of 62 $TeO_2$ crystals**

11 floors made of 4 crystals:
- not enriched
- Mass: 790g
- Dimensions: 5x5x5 $cm^3$

2 floors made of 9 crystals:
- Mass: 330g
- Dimensions: 3x3x6 $cm^3$
- 2 enriched in $^{128}Te$ (82%)
- 2 enriched in $^{130}Te$ (75%)





**Total mass: 40.7 Kg (11.3 Kg in $^{130}Te$)**

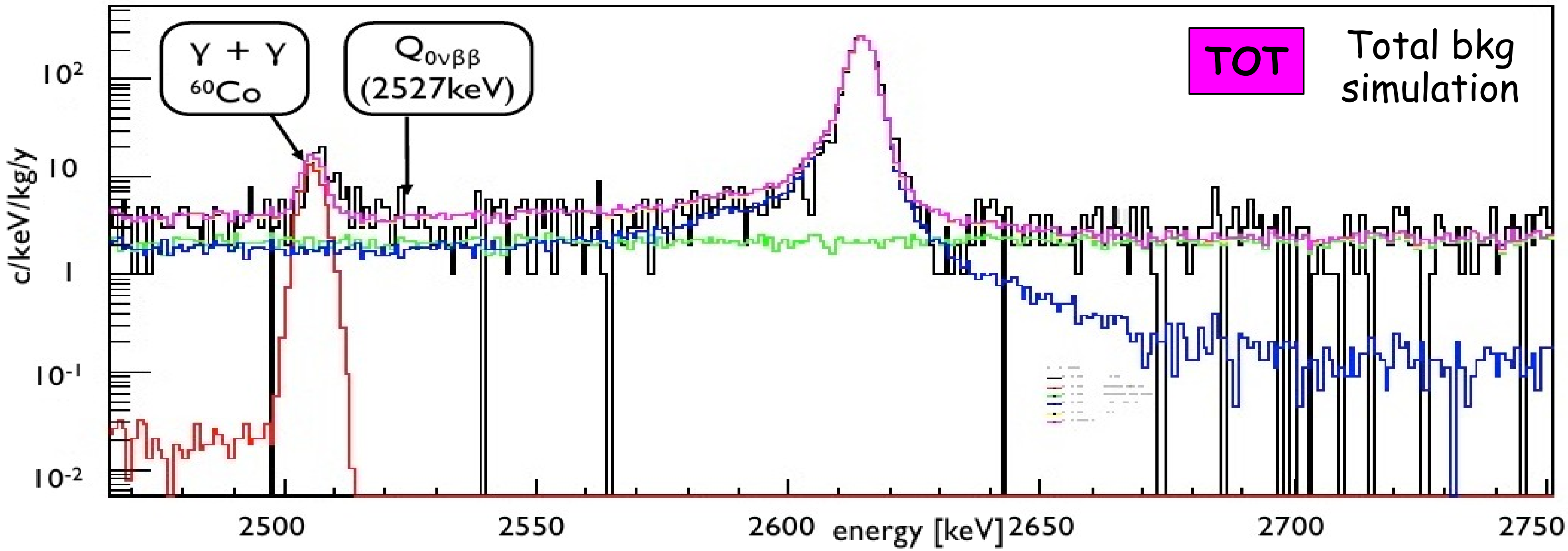
$$T^{0\nu}_{1/2} > 2.8 \times 10^{24}\ \mathrm{y} \ @\ 90\%\ \mathrm{C.L.}$$

Astropart. Phys. 34 (2011) 822–831 E. Andreotti et al. (LP)

$$m_{\beta\beta} \leq 0.3 - 0.7\ \mathrm{eV}$$

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

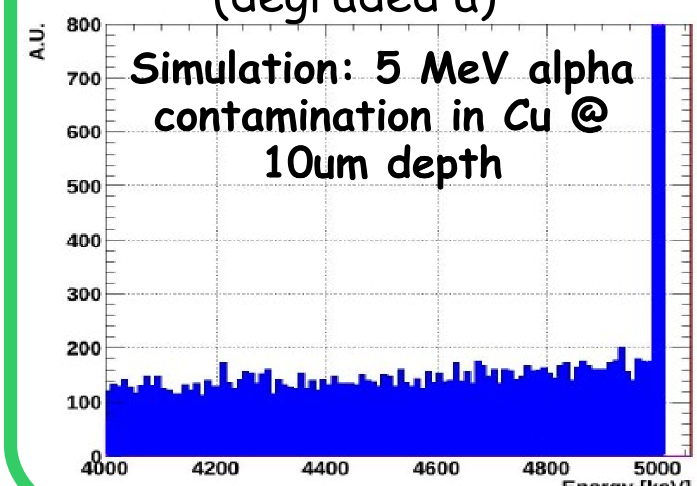
# Cuoricino




**35%** $^{232}$Th in cryostat (g/b)

$^{208}$Tl multiCompton + Thorium betas

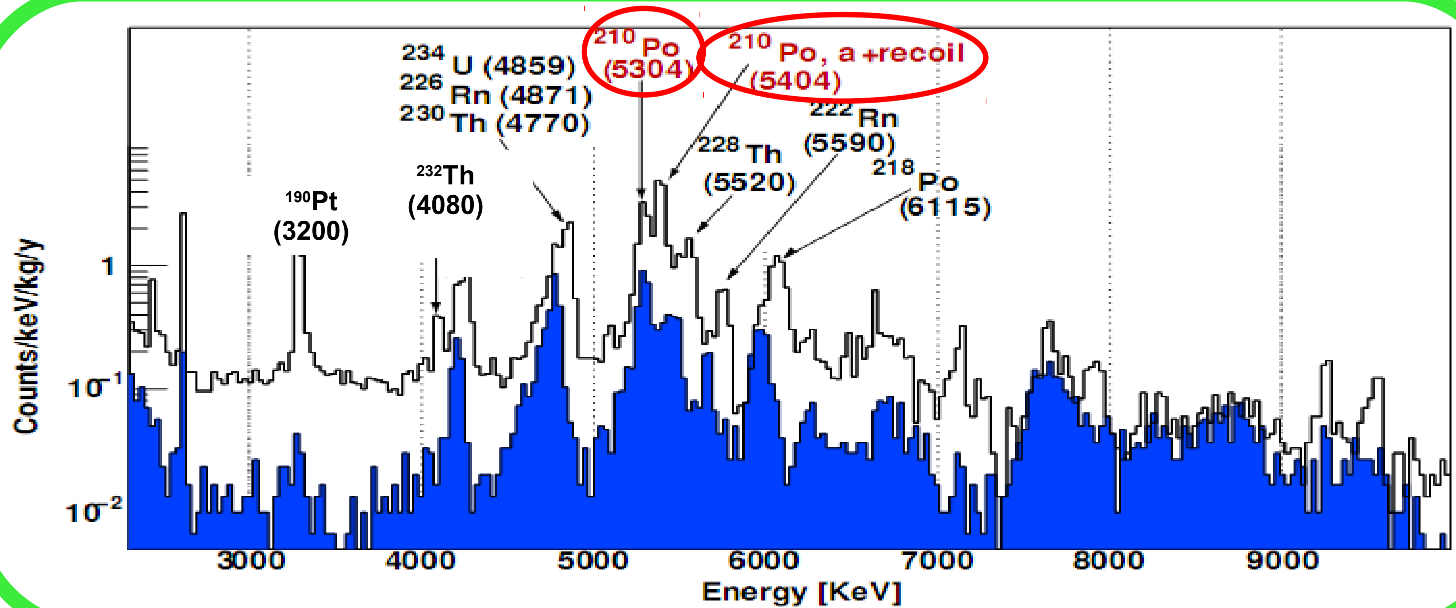
**65%** $^{232}$Th+$^{238}$U in Copper and $TeO_2$ surfaces (degraded a)




**0%** $^{60}$Co in Copper

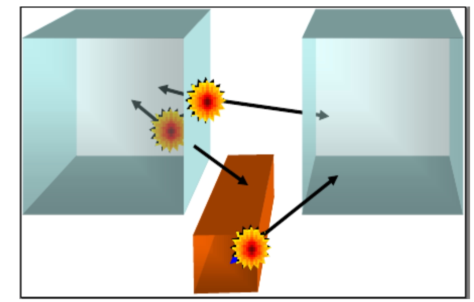
@ 2505 keV Cosmogenic activation

# Alpha contaminations in Cuoricino




Multiplicity 1 events

Multiplicity 2 events



Various and delocalized alpha contaminations

- Production
  - $^{190}$Pt
- Cleaning
- Recontaminations
  - $^{238}$U and daughters
  - $^{232}$Th and daughters

$^{210}$Po

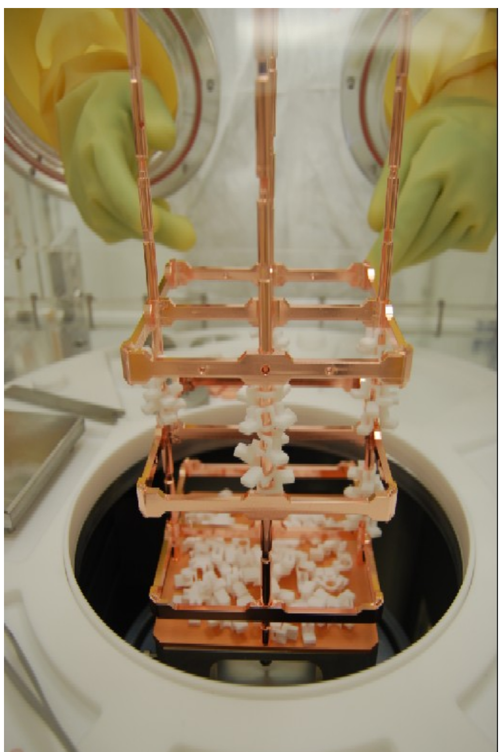
- Bulk of crystals
- Copper surfaces
- Crystal surfaces

# Surface contamination studies

## Copper cleaning R&D

**TTT**

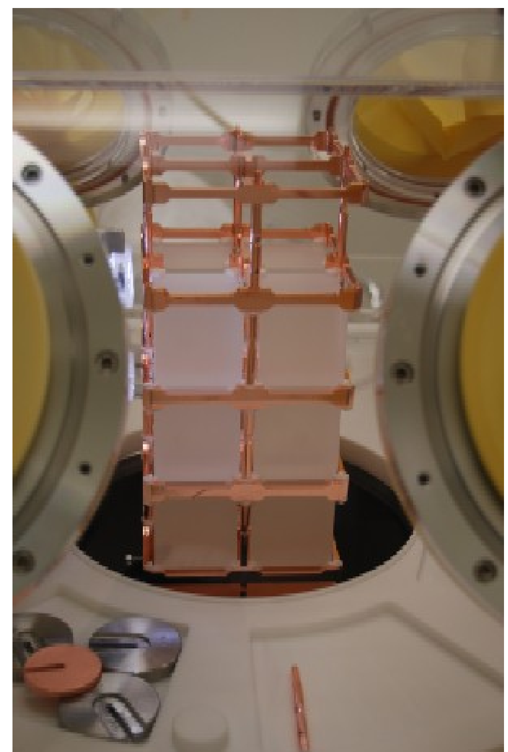
Specific measurements were performed in order to identify the best copper surface treatment for reducing the background in the ROI



## $TeO_2$ surface radiopurity studies

**CCVR**

Systematic control of bulk and surface contaminations of $TeO_2$ crystals



# TTT detector

**TTT (Three Tower Test):** large mass detector for testing Cu surface contaminations with 3 different cleaning procedures inside Cuoricino cryostat (same bkg and operational conditions and reprocessed Cuoricino crystals)


- Test the final design of the CUORE single module (reduction of inert material facing the crystals);

- Test the best Cu "cleaning recepies";

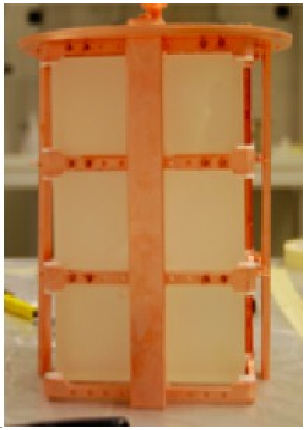
- Bkg study and abatement;

T1
Polyethylene
Cleaning:

* Soap
* Passivation
* 7 layers (70um)
Polyethelene complete
coverage

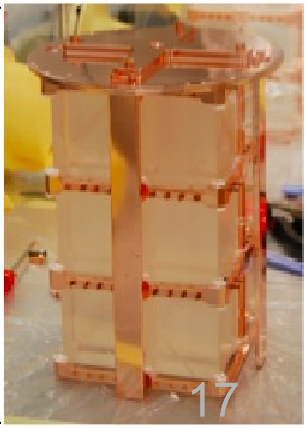
T2
Chemical New
Cleaning:

* Soap
* Acid electro erosion
* Etching
* Passivation



T3
Plasma
Cleaning:

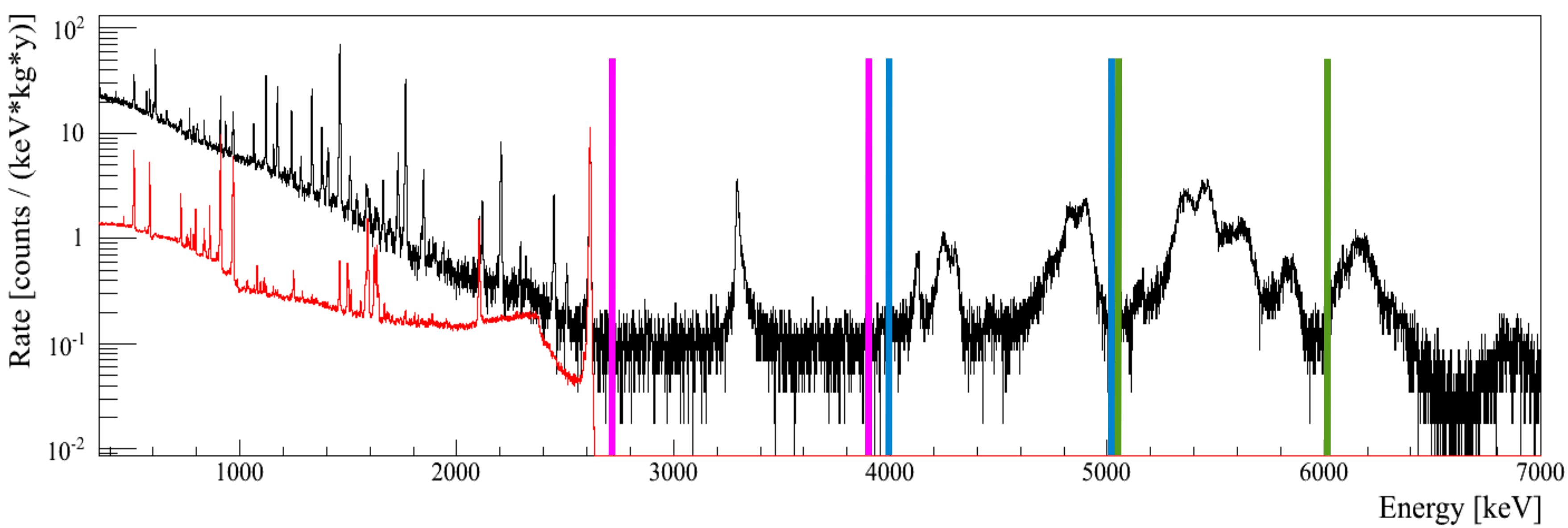
* Tumbling
* Chemical etching
* Electrochemical
etching
* Plasma



# TTT detector performances and results

| Tower | Live Time [day*crystal] | FWHM [keV] @ 2615 keV |
|---|---|---|
| T1 | 942.25 | 4.6 |
| T2 | 610.32 | 4.1 |
| T3 | 601.73 | 4.7 |

* [2.7-3.9] MeV : in between g and a region. Suitable region for degraded a studies
* [4-5] MeV : main a peaks of $^{232}Th+^{238}U$
* [5-6] MeV : $^{210}Po$ ($^{210}Pb$) contaminations



# TTT results

| Tower | continuum 2.7-3.9 MeV | U/Th 4-5 MeV | Po/Pb 5-6 MeV |
|---|---|---|---|
| T1 | 0.068 ± 0.006 | 0.27 ± 0.01 | 1.25 ± 0.04 |
| T2 | 0.120 ± 0.012 | 0.36 ± 0.03 | 1.82 ± 0.11 |
| T3 | 0.072 ± 0.008 | 0.25 ± 0.02 | 1.80 ± 0.09 |
| Cuoricino | 0.116 ± 0.002 | 0.576 ± 0.003 | 0.962 ± 0.004 |

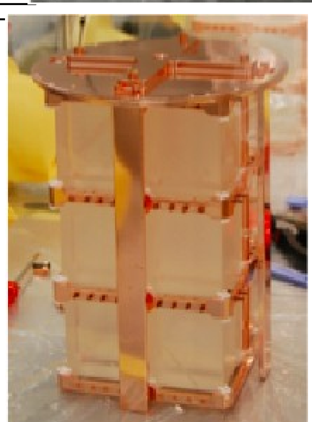
Rates [c/keV/kg/y] for the TTT and Qino, no coincidence cuts are applied on TTT

T1
Polyethylene Cleaning:

* Soap
* Passivation
* 7 layers (70um) Polyethelene complete coverage

T3
Plasma Cleaning:

* Tumblering
* Chemical etching
* Electrochemical etching
* Plasma

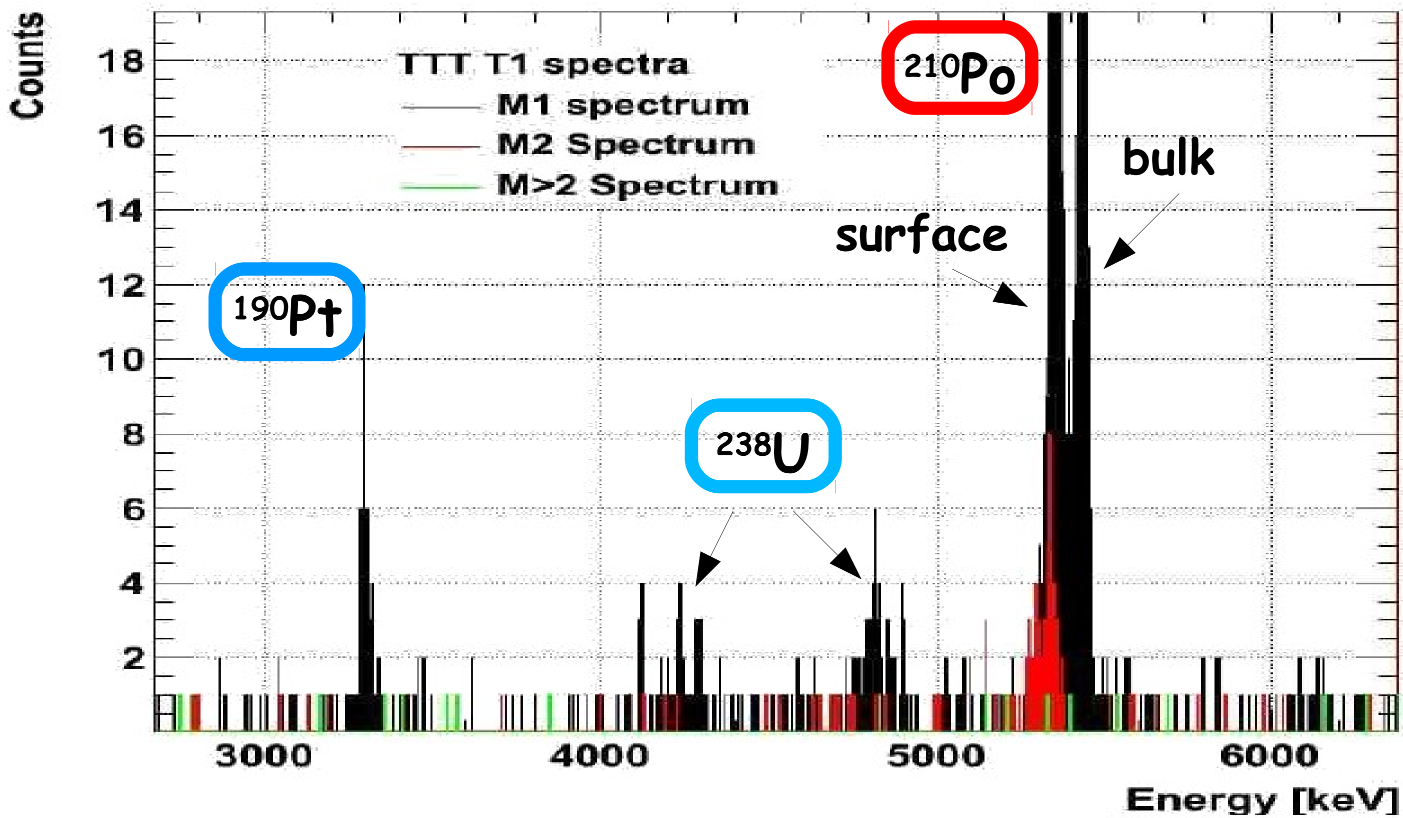


* T1 and T3 are compatible and show better bkgs compared to Cuoricino;

* Uranium and Thorium surface/bulk contaminations are reduced by a factor of ~2;

* No strong control of Polonium (Lead) re-contaminations

# TTT-T1 results




* M1 shows $^{210}$Po bulk crystal contaminations and surface contaminations (?crystals?, ?Copper/Polyethelene?)

* M2 tells us that crystals can explain a part of the overall $^{210}$Po contamination. By exclusion Copper/Polyethelene will explain the rest

$^{210}$Po

# CCVR: CUORE Crystals Validation Runs

The CCVRs are dedicated cryogenic set-ups planned to test the various batches of ready-to-use produced crystals.

CUORE crystal production started in 2008 in Jaiding (CHINA):

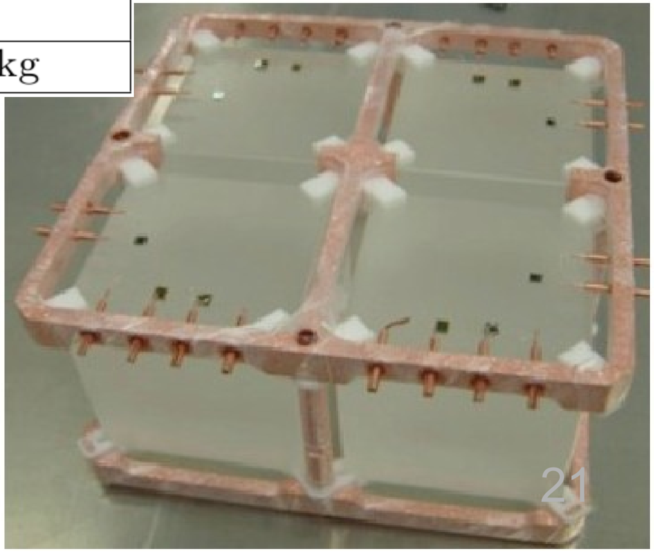
* ~30 crystals/month
* 700 crystals already delivered

* Bolometer performances: essentially energy resolution
* Bulk a contaminations
* Surface contaminations

| Isotope | Allowed Contamination |
|---|---|
| $^{238}$U | $< 3 \cdot 10^{-13}$ g/g |
| $^{232}$Th | $< 3 \cdot 10^{-13}$ g/g |
| $^{210}$Pb | $< 1 \cdot 10^{-5}$ Bq/kg |
| $^{210}$Po | $< 0.1$ Bq/kg |
| $^{40}$K | $< 1 \cdot 10^{-3}$ Bq/kg |

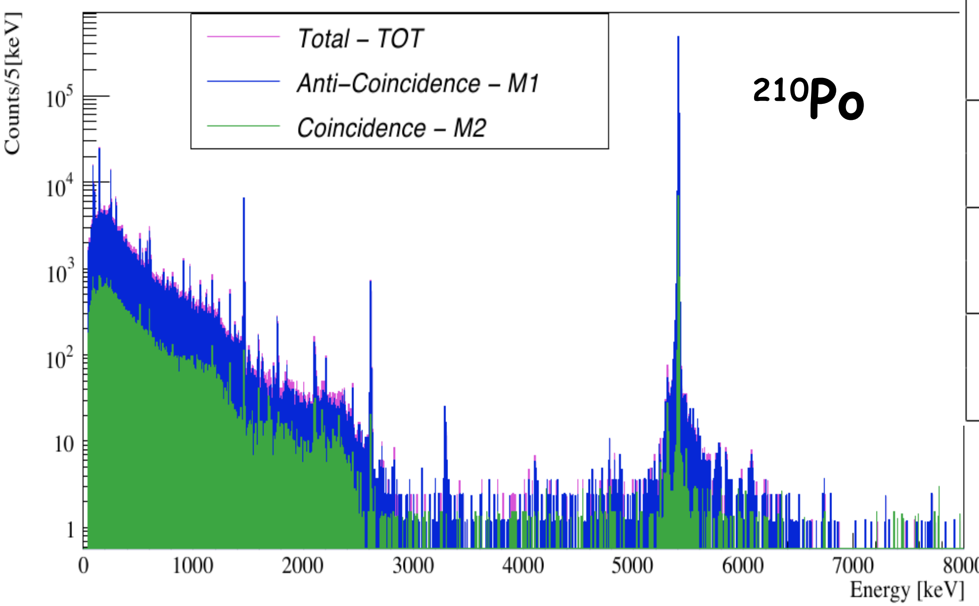
Up to now 7 CCVR tests were performed.

| Detector | Livetime [d] | Crystal tested |
|---|---|---|
| CCVR1 | 59.9 | 7, 11, 39, 41 |
| CCVR2 | 19.4 | 7, 11, 76, 97 |
| CCVR3 | 43.05 | 180, 190, 229, 236 |
| CCVR4 | 25.8 | 313, 340, 354, 380 |
| CCVR5 | 30.3 | 416, 421, 436, 455 |

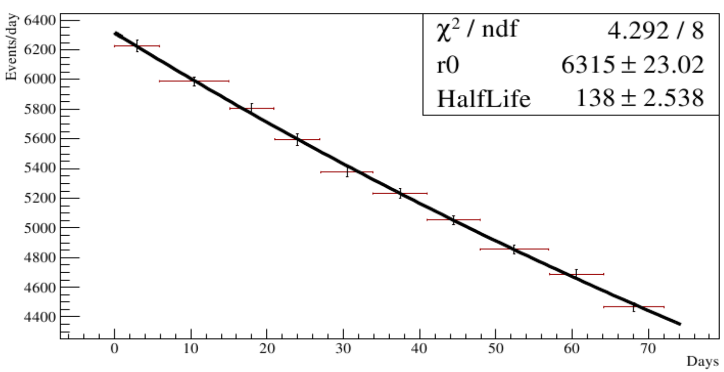


# CCVR results

Total Live Time: 713 days
Total Mass: 15 kg of $TeO_2$




| | | Continuum (2700, 3900) [keV] | U/Th (4000, 5000) [keV] | $^{210}$Po (5000, 6000) [keV] |
|---|---|---|---|---|
| CCVR | M1 | $0.09\pm0.02$ | $0.13\pm0.01$ | - |
| | M2 | $0.015\pm0.007$ | $0.014\pm0.003$ | - |
| TTT | M1 | $0.052\pm0.008$ | $0.28\pm0.02$ | $1.30\pm0.07$ |
| | M2 | $0.009\pm0.003$ | $0.0018\pm0.005$ | $0.09\pm0.01$ |
| Cuoricino | M1 | $0.104\pm0.002$ | $0.522\pm0.003$ | $0.846\pm0.004$ |
| | M2 | $0.009\pm 0.001$ | $0.084\pm0.001$ | $0.173\pm0.002$ |




* Continuum higher in CCVR-M1 because of $^{210}$Po tail (from MC simulation is 20%)

* CCVR has lower bulk and surface U/Th contaminations compared to Qino

* High $^{210}$Po contamination (vanishing). Po and Te are chemically affined;

[arXiv:1108.475] F. Alessandria et al. (LP) In press

# CCVR final results

**Total CCVR bulk contaminations**

| Chain | Nuclide | Upper limit [Bq/kg] | Upper limit [g/g] |
|---|---|---|---|
| $^{238}$U | $^{238}$U | 2.5E-07 | 2.0E-14 |
| | $^{234}$U | 4.7E-07 | 3.6E-14 |
| | $^{230}$Th | 5.7E-07 | 4.4E-14 |
| | $^{226}$Ra | 6.7E-07 | 5.3E-14 |
| | $^{218}$Po | 1.6E-07 | 1.3E-14 |
| $^{232}$Th | $^{232}$Th | 1.3E-07 | 3.1E-14 |
| | $^{212}$Bi | 8.4E-07 | 2.1E-13 |

**Total CCVR surface contaminations**

| Depth | Nuclide | Upper limit 90% C.L. [Bq/cm$^2$] |
|---|---|---|
| 1$\mu$m | $^{238}$U | 3.7E-09 |
| | $^{226}$Ra | 8.9E-09 |
| | $^{232}$Th | 1.9E-09 |

**Total $^{210}$Pb contamination:**
**Bulk 3.3E-6 Bq/kg**
**Surf @ 1um 9.2E-9 Bq/cm$^2$**

**(Qino reprocessed) TTT-T1 Surf @ 1um 6.1E-8 Bq/cm$^2$**

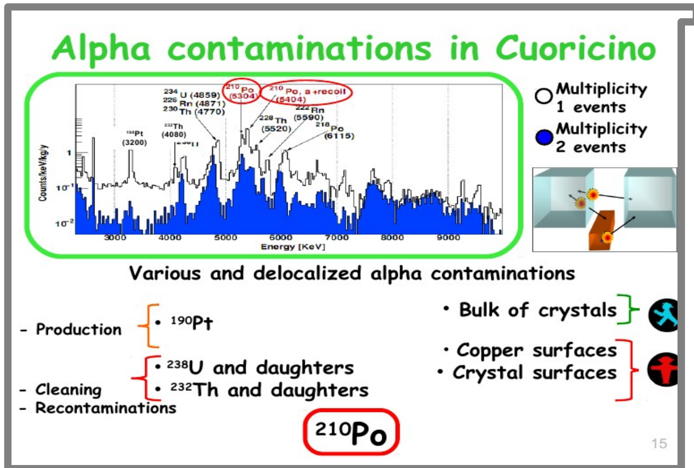
Qino: $\langle FWHM \rangle_{2615\ keV}$ = 6.3$\pm$2.5 keV

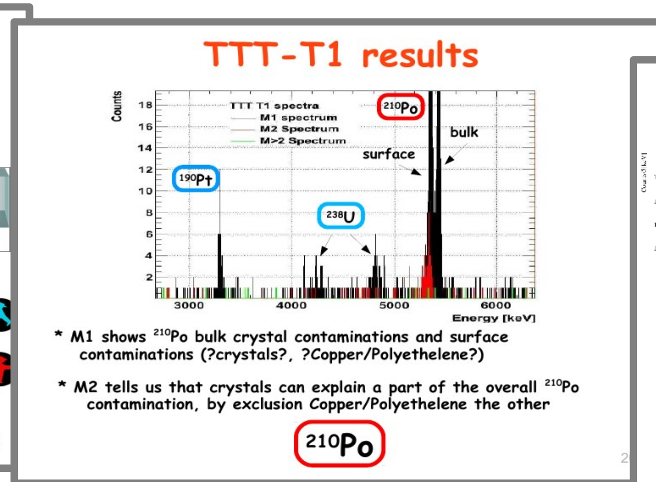
CCVR: $\langle FWHM \rangle_{2615\ keV}$ = 4.6$\pm$1.9 keV
CCVR: $\langle FWHM \rangle_{5.4\ MeV}$ = 5.6$\pm$2.1 keV

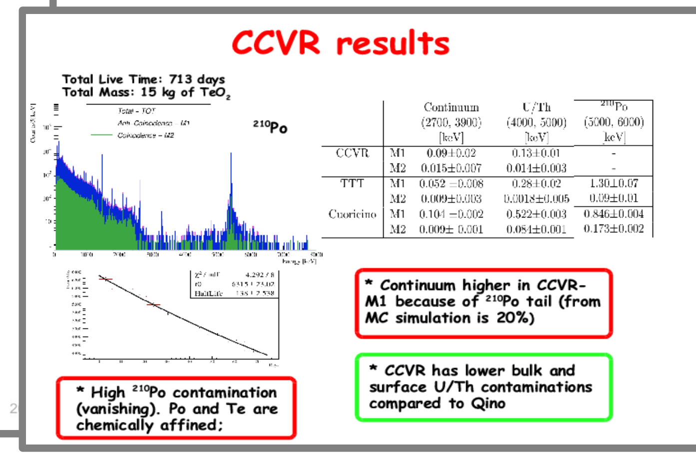
**Total contribution to CUORE in the ROI: 5.5*10-3 c/keV/kg/y**

[arXiv:1108.475] F. Alessandria et al. (LP) In press

# Qino + TTT + CCVR results



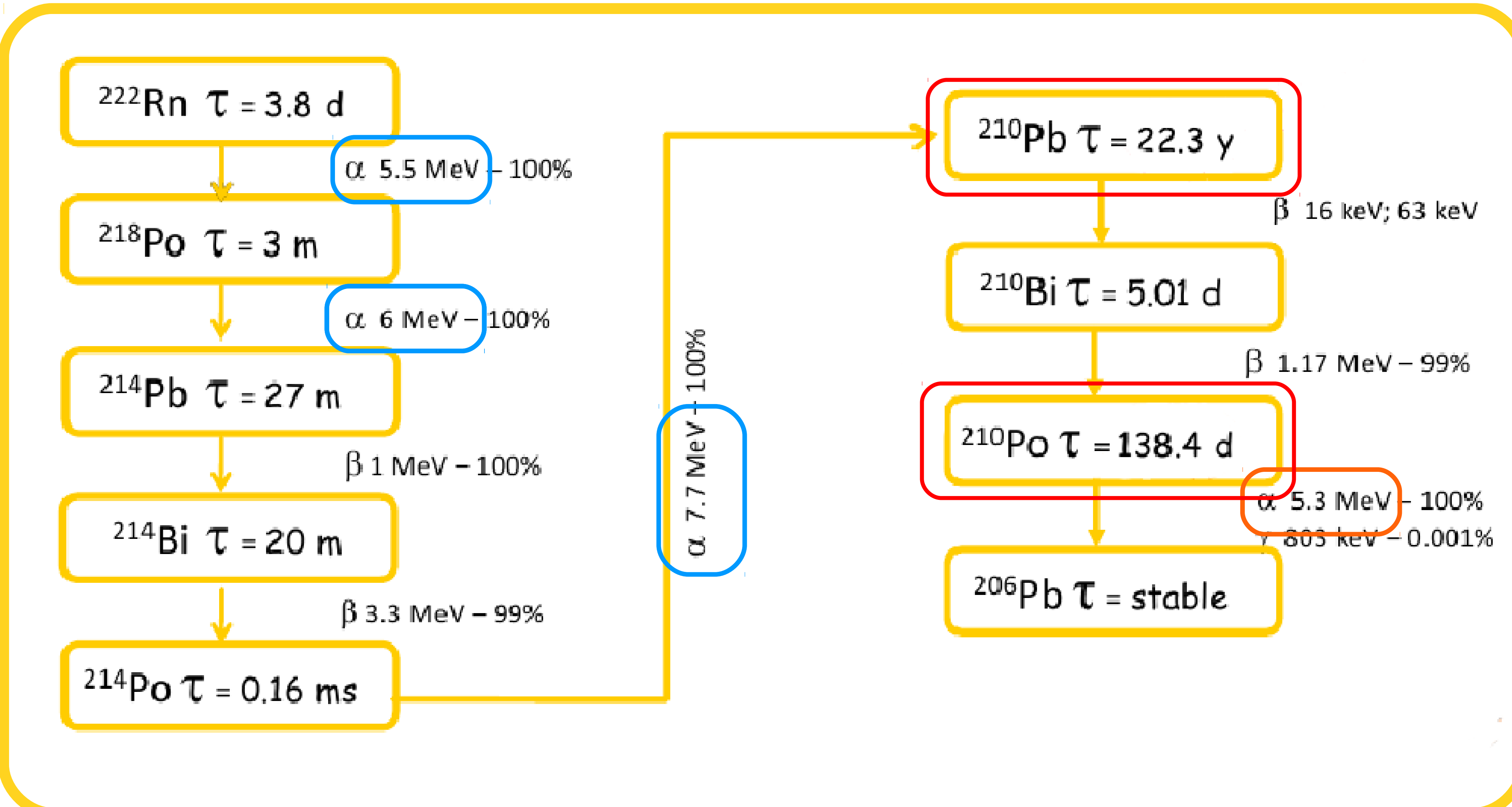




* Surface contaminations are a limitation to the sensitivity of low background experiments.

* The main source of re-contamination for Copper (TTT) and $TeO_2$ crystals (CCVR) seems to be induced by $^{210}Po$ ($^{210}Pb$ daughter).

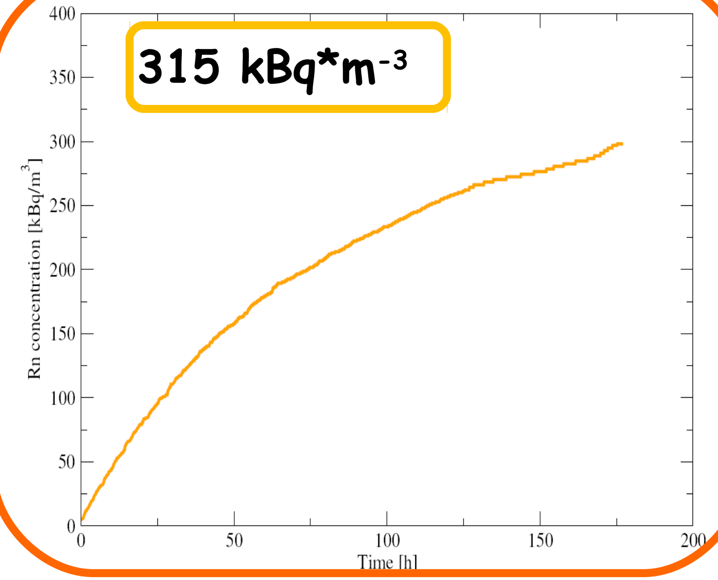
$^{210}Pb$ and $^{210}Po$ are produced by $^{222}Rn$ decay → Is $^{222}Rn$ a direct background source for DBD0v bolometric experiments ? → Can a detector exposed to $^{222}Rn$ be contaminated ?

# Radon decay chain

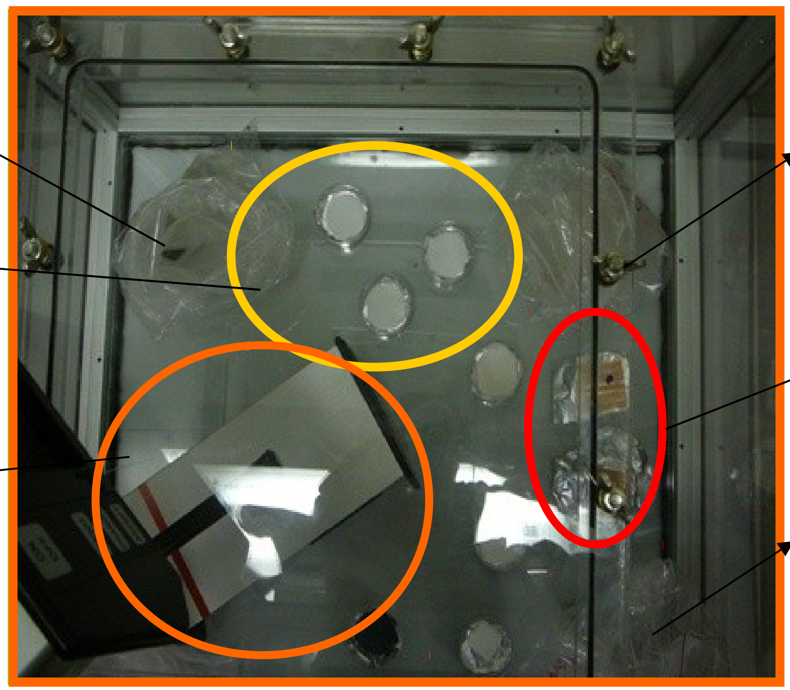


# Rn-induced contaminations (1)

Rn concentration in the radon-box




| Sample | Material | Exposure [d] |
|---|---|---|
| Cu_OFHC | Cu | 56 |
| Rame_BaseMen | Cu | 63 |
| TeO2_1Mis | $TeO_2$ | 49 |
| TeO2_2Mis | $TeO_2$ | 73 |
| Cu_OFHC_brv | Cu | 16 |
| TeO2_brv | $TeO_2$ | 14 |



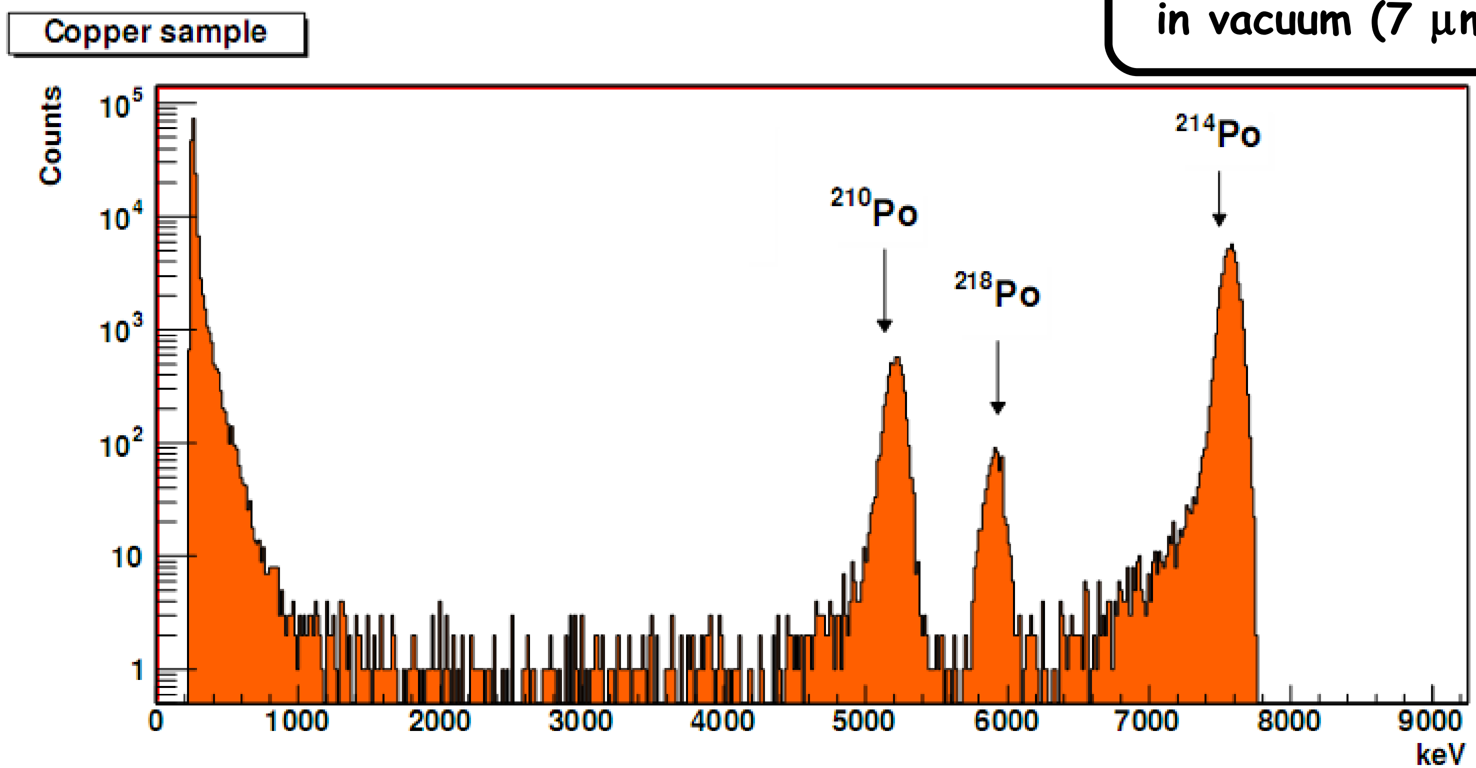
# Rn-induced contaminations (2)

Which contaminants?

Detector:

SBD of 1200 mm²

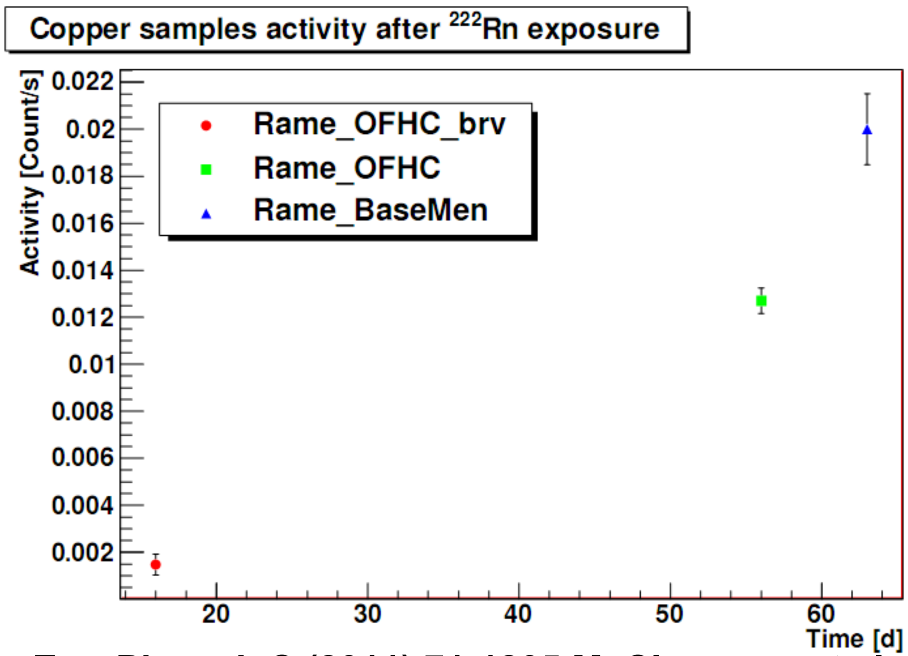
in vacuum (7 μm Hg)

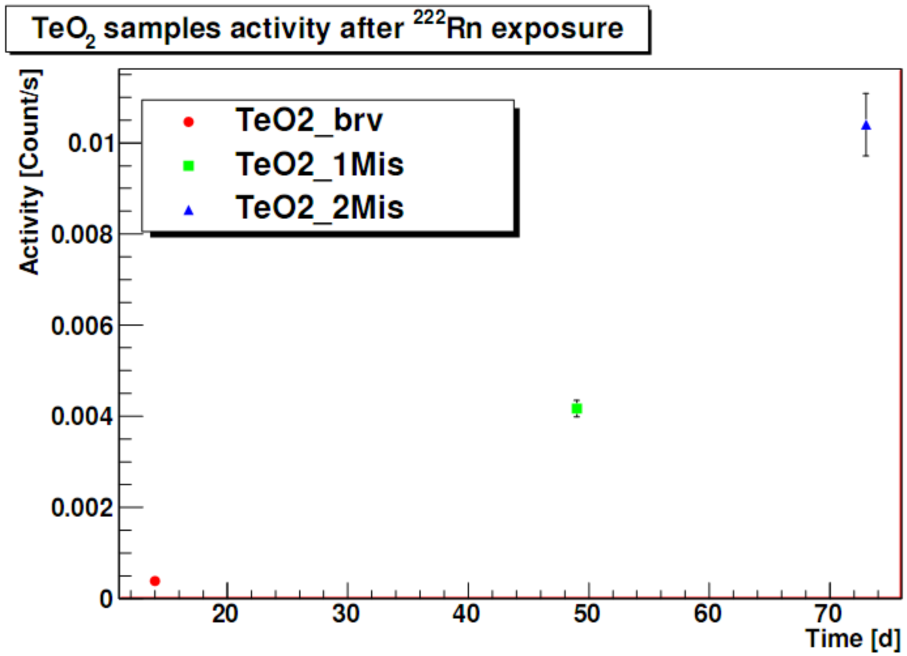



- Detector exposure to Rn directly induces Polonium contaminations
- Radon does not diffuse inside the sample

# Analysis of contaminants

## $^{210}Po$ activity evaluated under the peak

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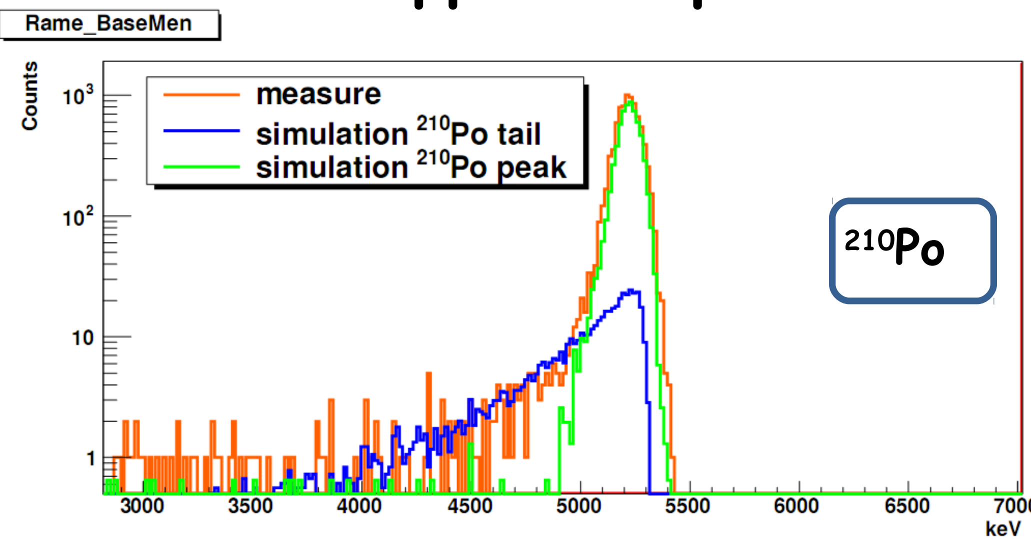
$^{210}Po$ contaminations are strictly releated to the time exposure of the samples (Cu & $TeO_2$) to Radon.

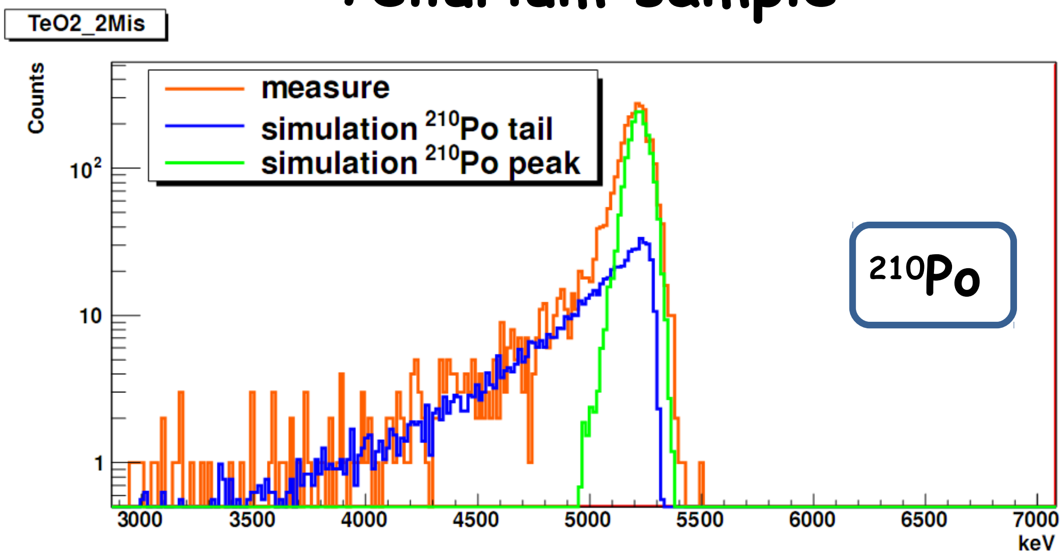
N.B.: $^{210}Po$ ($T_{1/2}$=138 d) is not in equilibrium with $^{210}Pb$ ($T_{1/2}$=22.4 y)

# $^{210}$Po diffusion

## Copper sample




## Tellurium sample




$$Y = A \cdot \exp(x \cdot \Lambda)$$

| Sample | Material | Exposure time | Diffusion depth |
|---|---|---|---|
| Rame_BaseMen | Copper | 63 days | 430±20 nm |
| Rame_OFHC | Copper | 56 days | 410±20 nm |
| Rame_OFHC_brv | Copper | 16 days | *** |
| TeO2_2Mis | Tellurium Oxide | 73 days | 940±20 nm |
| TeO2_1Mis | Tellurium Oxide | 49 days | 500±20 nm |
| TeO2_brv | Tellurium Oxide | 14 days | *** |

**$^{214}$Po and $^{210}$Po diffusion in $TeO_2$ and in Cu**



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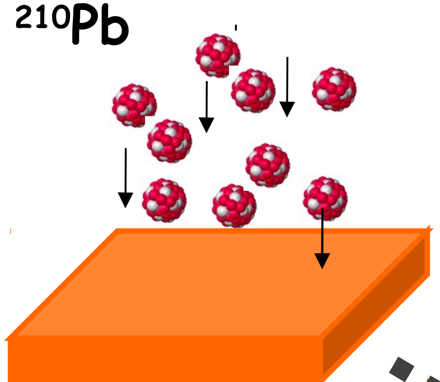
# Who produces $^{210}$Po ?

$$A = \frac{N_1}{\tau_1} = \frac{N_2}{\tau_2} = \frac{N_3}{\tau_3} = \ldots$$

**An element concentration in a closed system is proportional to its life-time**

Prompt Pb production mechanism

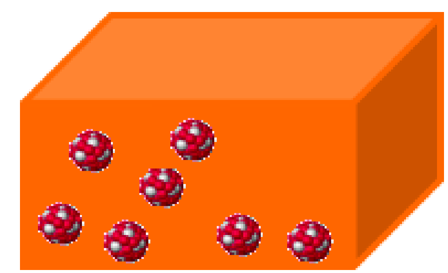
$^{210}$Pb



$^{210}$Pb is the element most concentrated in the Rn-box

Delayed Pb production mechanism

$^{218}$Po & $^{214}$Po



$^{210}$Po $\tau$ = 138.4 d

Detectable during the prompt $^{210}$Po decays

Detectable during the delayed $^{210}$Po decays

# $^{210}Pb$ contaminations

**$^{210}Pb$ evaluation starting from $^{210}Po$ contamination "prompt" (t ~ h) and "delayed" (t ~ 300 d)**

$$\boxed{A_{Po} = A^0_{Pb} \frac{\lambda_{Pb}}{\lambda_{Po} - \lambda_{Pb}} \left(e^{-\lambda_{Pb} t} - e^{-\lambda_{Po} t}\right)}$$

$$\boxed{\frac{\text{Delayed } A^0_{Pb}}{\text{Prompt } A^0_{Pb}} \sim 6}$$

**~ 85% of $^{210}Pb$ contamination is generated by delayed decays of Rn fast daughters ($^{218}Po$, $^{214}Po$).**

**=> Informations need for the design of a clean room**
**It is important to reduce Rn concentration more than the Pb one.**

# Sticking Factor

**The Rn sticking factor is evaluated on $^{210}Pb$ (starting from the $^{210}Po$ contaminations):**

$$\Sigma = \frac{A^0_{^{210}Pb} \cdot \tau_{^{210}Pb}}{\Gamma \cdot S \cdot t_{exp}}$$

**$\Gamma$: Rn nulei flux**
**S: sample surface**
**$t_{exp}$: time exposure to Rn**

| Sample | Material | Exposure time | $\Sigma_{Rn}$ |
|---|---|---|---|
| Rame_BaseMen | Copper | 63 days | $8.39 \cdot 10^{-9} \pm 4.53 \cdot 10^{-10}$ |
| Rame_OFHC | Copper | 56 days | $3.15 \cdot 10^{-9} \pm 3.15 \cdot 10^{-11}$ |
| Rame_OFHC_brv | Copper | 16 days | $2.32 \cdot 10^{-9} \pm 1.25 \cdot 10^{-10}$ |
| TeO2_2Mis | Tellurium Oxide | 73 days | $1.69 \cdot 10^{-9} \pm 5.36 \cdot 10^{-11}$ |
| TeO2_1Mis | Tellurium Oxide | 49 days | $1.41 \cdot 10^{-9} \pm 9.46 \cdot 10^{-11}$ |
| TeO2_brv | Tellurium Oxide | 14 days | $--$ |

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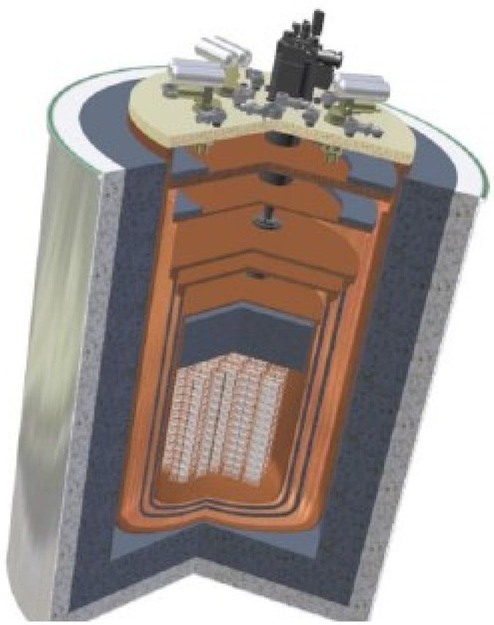
# Effects on CUORE

**Effects on CUORE sensitivity due to an exposure of Cu to Radon**

**Cu exposed for 1 year @ 100 $mBq/m^3$**

$\Sigma$ for Cu = $1.85 \times 10^{-4}$ @ 315 $kBq/m^3$

Hypothesys : Linearity @ 100 $mBq/m^3$



$A_{po\ Total} = 1.1 \times 10^{-7}\ Bq/cm^2$

Monte Carlo simulation

$B \leq 3.4 \times 10^{-3}$ counts/keV/kg/y

@ $10^{-3}$ Counts/keV/kg/y

# Is there a way out ?

Polonium (Pb) is one of the source of surface contaminations, but does not explain the background in the ROI.

Even if we completely understand the mechanisms inducing surface contaminations (degraded alpha), is it really possible to prevent re-contaminations of radiopure materials?

Will we ever have a 0 alpha background?

## SOLUTION

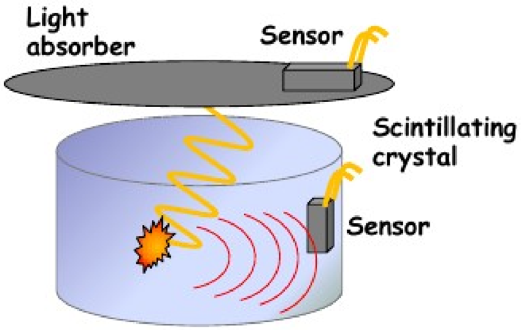
$\boxed{\alpha\ /\ \beta\ \text{discrimination}}$

Reduce the alpha background in the DBD0v ROI to a 0-level

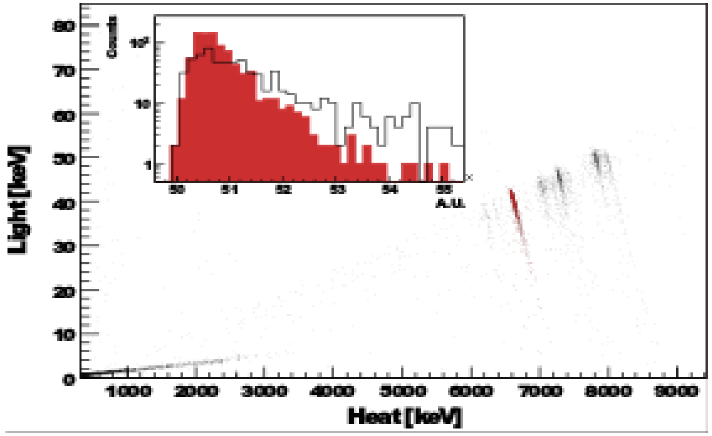
# α / β discrimination

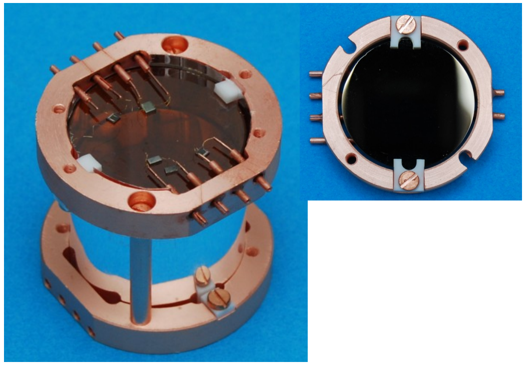
There are different proposed solutions:

* Scintillating bolometers: combination of heat and light for particle interaction discrimination:




LUCIFER experiment: DBD0v in $^{82}Se$ using ZnSe enriched crystals.



* Cherenkov light emission: [arXiv:1106.6286]: Discrimination of alpha and beta/gamma interactions in a $TeO_2$ bolometer.

* Pulse shape analysis: identification of a and b interaction in the detector through pulse shape analysis of signals.

ZnMoO4 bolometers allow a / b discrimination just on the heat signa

[arXiv:1011.5415] Gironi et al.

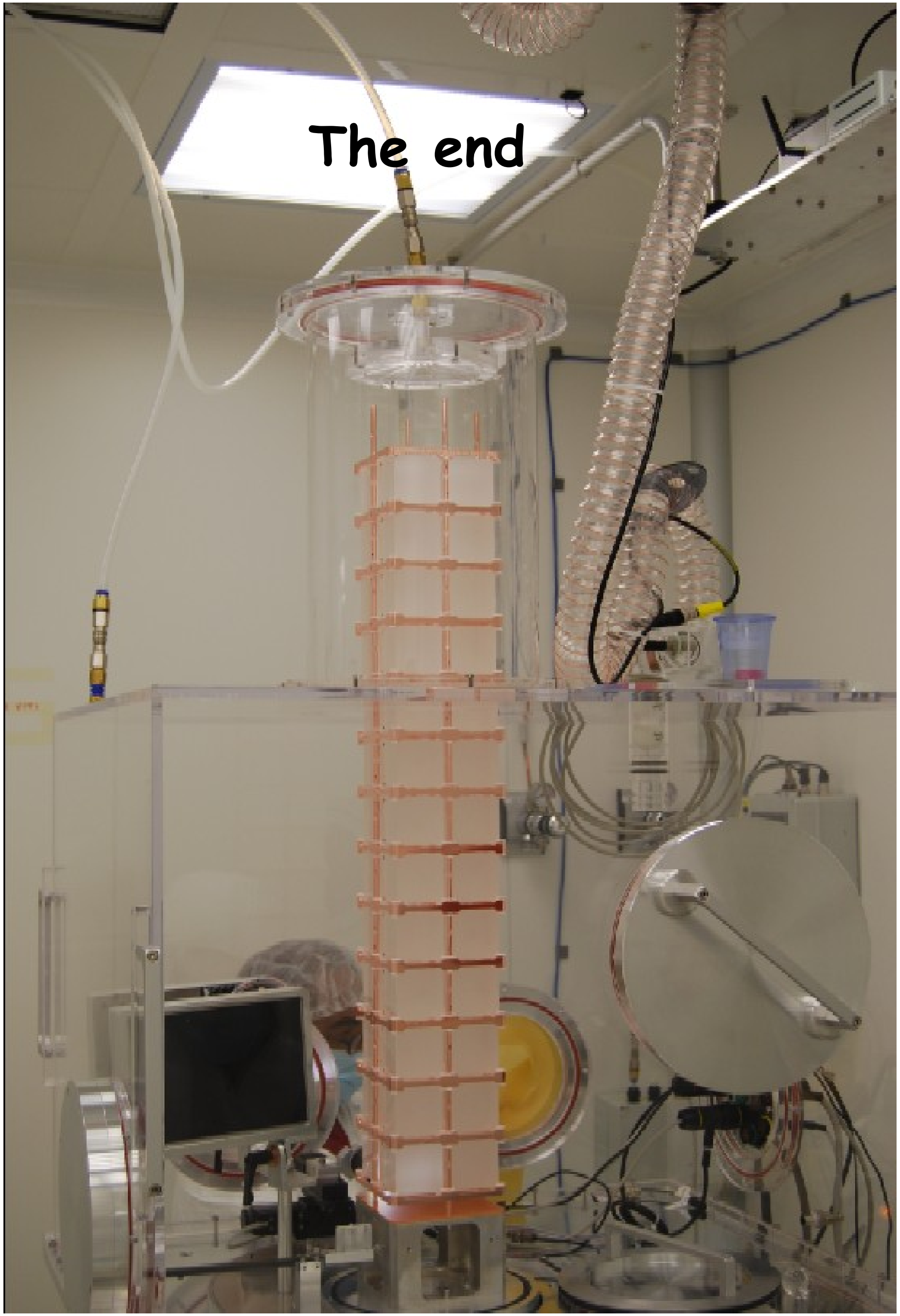
# Conclusions

* Polonium-210 (Lead-210) are the most intense source of surface contaminations for DBD0v bolometric experiments;

* Radon-induced contaminations are one mechanism of surface contaminations, but they do not explain the whole problem;

* $^{222}$Rn It is realldaughters, but they do not explain the whole problem;

* Particle discrimination seems to be a solution to the problem, but it still needs to be proved the scale to large mass detector;


The end