The CUORE experiment for $0\nu\beta\beta$ research: status and perspectives

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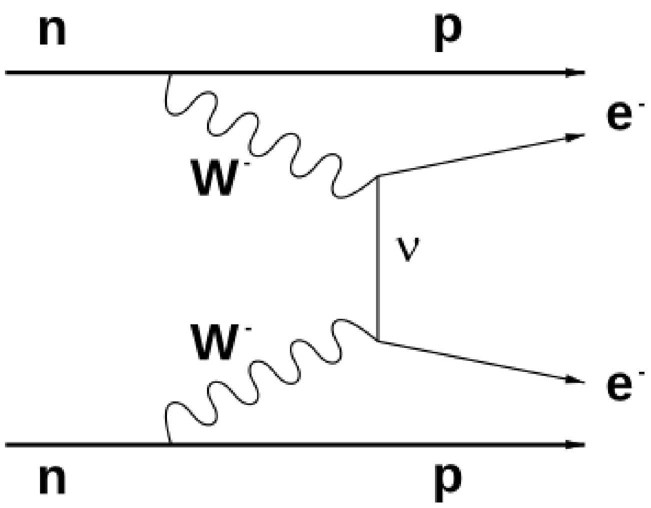
Outline

- Brief introduction to $0\nu\beta\beta$
- Experimental strategies
- Bolometric technique
- $0\nu\beta\beta$ with TeO_2 bolometers
- Cuoricino result
- CUORE project and status
- The background issue
- First CUORE phase: CUORE-0
- Conclusions

$0\nu\beta\beta$

- Channel for $\beta\beta$ decay **forbidden by SM ($\Delta L=2$)**
- Extremely **rare** process ($T_{1/2} > 10^{22} - 10^{24}$ y)
- **Never observed** (but Ge^{76} claim [1])
- It's observation would prove ν **Majorana nature**



For **light ν_M** exchange the **Decay Rate** is:

NME
NUCLEAR PHYS.

$$(T_{0\nu})^{-1} \propto G_{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee} \rangle^2$$

Phase Space Factor ATOMIC PHYS.

Effective Majorana mass PARTICLE PHYS.

Why 0νββ is important ?

$$\langle m_{ee}\rangle = \left|\sum |U_{ei}|^2 m_i e^{i\alpha_i}\right| = f(\theta_{12}, \theta_{23}, \theta_{13}, \Delta m_{12}, \pm\Delta m_{23}, m_0)$$

neutrino mixing matrix

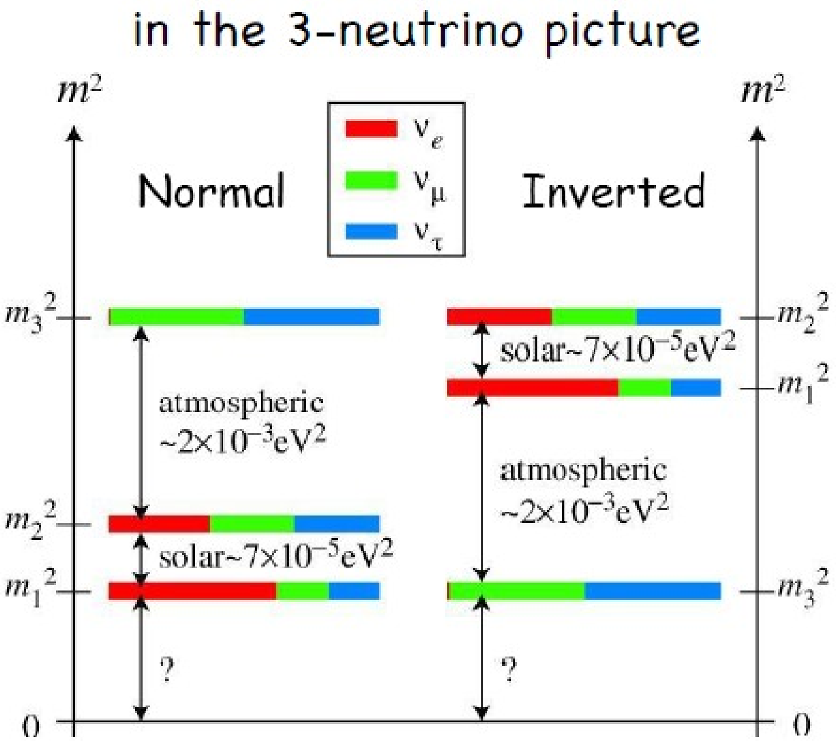
neutrino mass eigenstates

Majorana phases related to CP

Mixing angles

Mass hierarchy

Absolute mass scale



The observation of 0νββ:

Is currently the only feasible method to establish:

- **Majorana nature** of the neutrino
- **Lepton number** violation

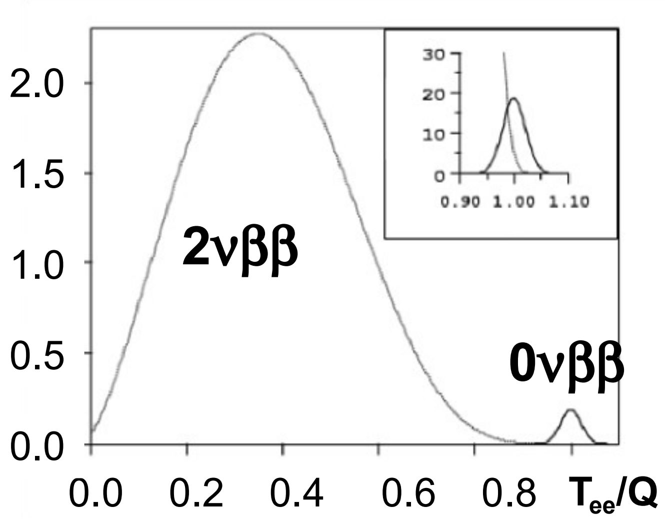
Can give important information about:

- Absolute neutrino **mass scale**
- Neutrino mass **hierarchy**
- **CP** Majorana phases

Experimental search

Main signature:

0νββ exhibits a **peak at Q** over 2νββ tail enlarged only by detector resolution



Defining the **experimental sensitivity $S^{0\nu}$** as the lifetime corresponding to the minimum detectable number of events over background at a given C.L.

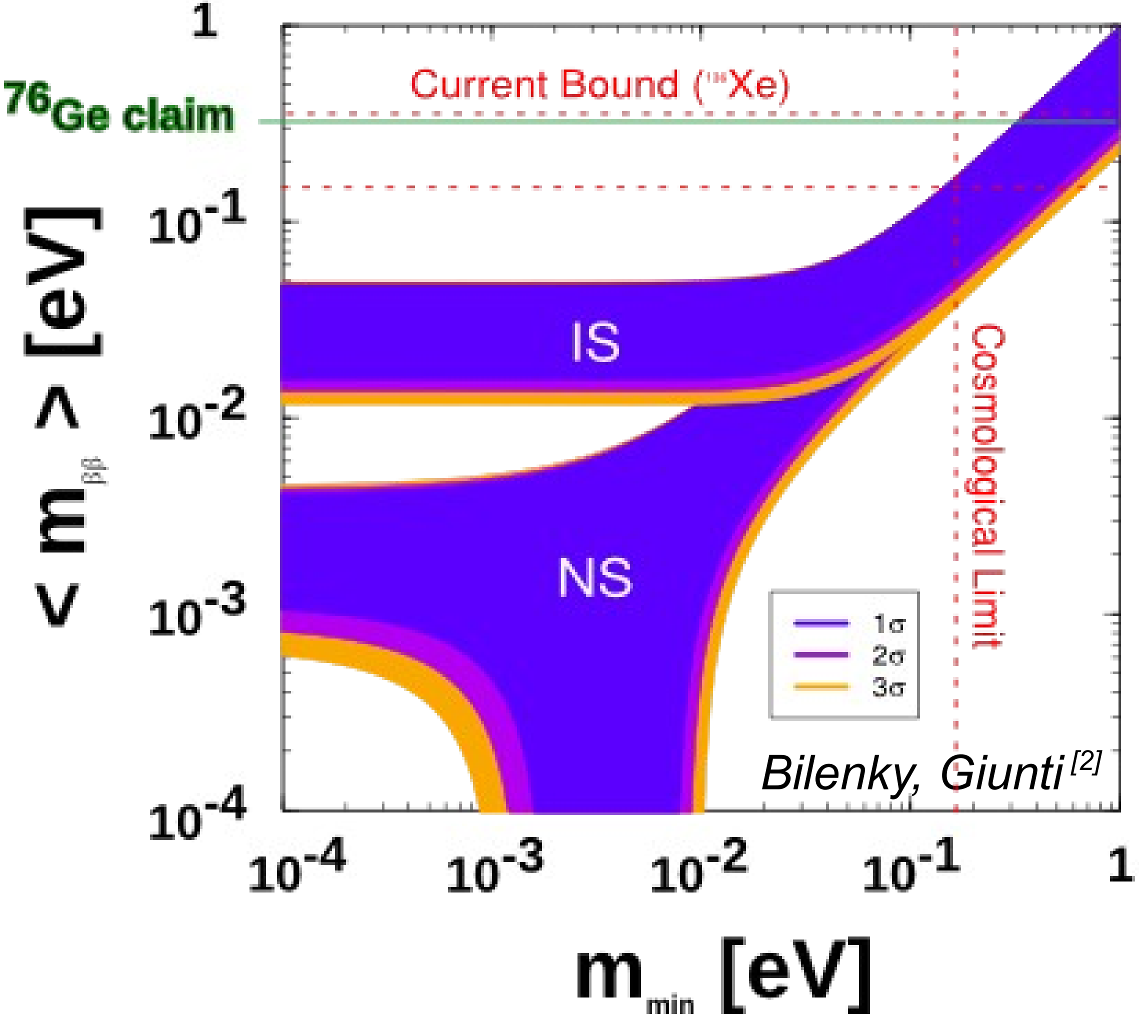
M : total active mass
ε : detector efficiency
a.i.: isotopic abundance
b: background in c/keV/kg/y
ΔE: detector resolution @ ROI
T: total live time

$$S^{0\nu} \propto \frac{\epsilon\, a.i.}{A}\left(\frac{M\,T}{b\,\Delta E}\right)^{1/2} \qquad b \neq 0$$

Qualitative expression in the Gaussian approximation
(not fully accurate for very low background experiments)

0νββ status of the art

After Daya-Bay



Most recent Results:

EXO-200: $<m_{\beta\beta}> < 0.15\text{-}0.36$ eV [3]

Kamland-Zen: $<m_{\beta\beta}> < 0.25\text{-}0.60$ eV [4]

Calculations are performed with QRPA and Shell Model

The range is due to NME uncertainties.

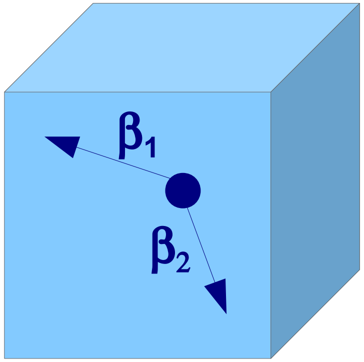
Experimental Strategies

Additional signatures can be looked for:

Single electron energy spectrum
Angular correlation between the two electrons
Track and event topology
Time Of Flight
Daughter nuclear specie

Two main approaches: **calorimetric** (source ≤ detector) or **external-source** detector

Calorimeters

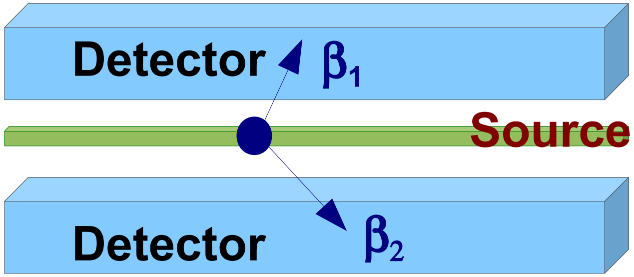


- *High M possibles*
- *High efficiency*
- *High resolution*
- *Event topology*

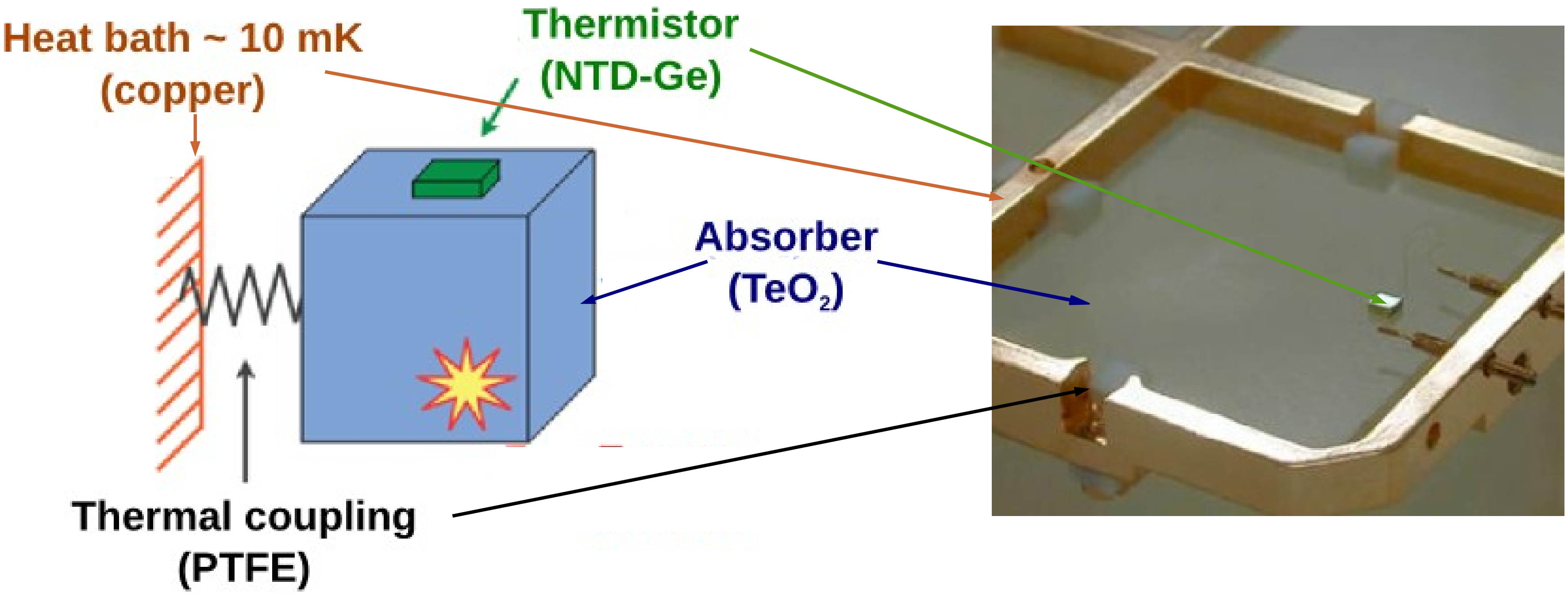
Xe detectors
pixellizations

External-source detectors

- *Event topology*
- *More $\beta\beta$ candidates in same det.*



Bolometric technique



Heat bath ~ 10 mK
(copper)

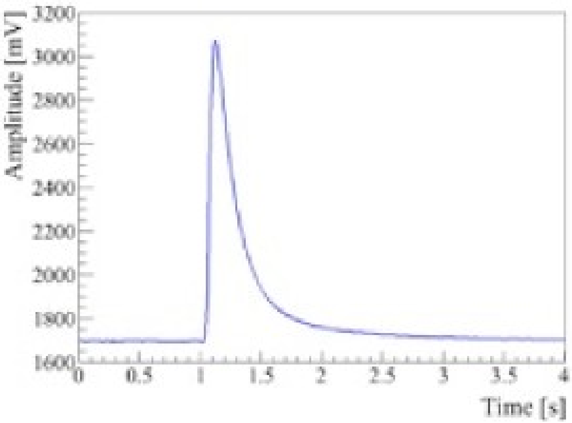
Thermistor
(NTD-Ge)

Absorber
(TeO_2)

Thermal coupling
(PTFE)

$$\Delta T = \frac{E}{C(T)}$$

$$\Delta t = \frac{C}{G}$$



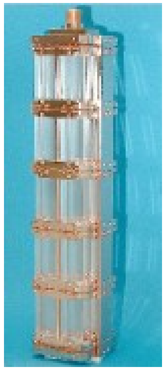
Particle energy is converted into phonons
by dielectric and diamagnetic absorbers
whose heat capacity ($C \div T^3$) is very low at low T.
(At T~10 mK ΔT ~300 μK @ 1 MeV)

- **Crystal Absorber (TeO_2): E --> ΔT**
- **Biased T sensor (NTD-Ge): ΔT --> ΔV**
- **Thermal link (PTFE+gold wires): T_0~10 mK**

$0\nu\beta\beta$ research with TeO_2

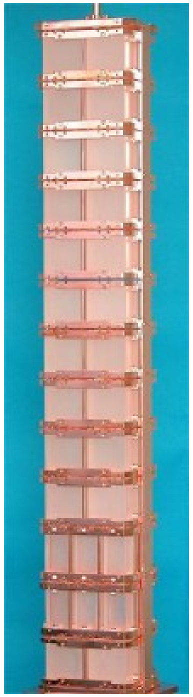
- ^{130}**Te** is a **good** DBD candidate (^{130}Te --> ^{130}Xe + 2e$^-$) with **high natural i.a.** (34.167%) and reasonably **high Q-value** (Q~2528 keV) leading to **high G(Q,Z)** and low background
- **TeO_2** is a compound with **good mechanical and thermal properties** containing ^{130}Te
- 5x5x5 cm^3 TeO_2 crystals have a high detection efficiency for $0\nu\beta\beta$ events: **ε~87.4%**

MiDBD
~ 6.8 kg



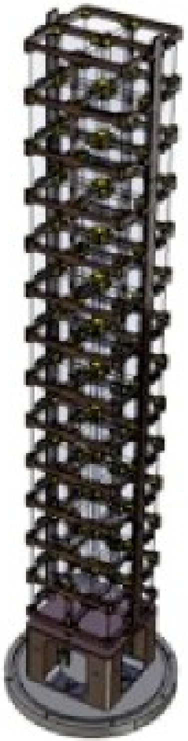
1997-2001

Cuoricino
~ 11 kg ^{130}Te



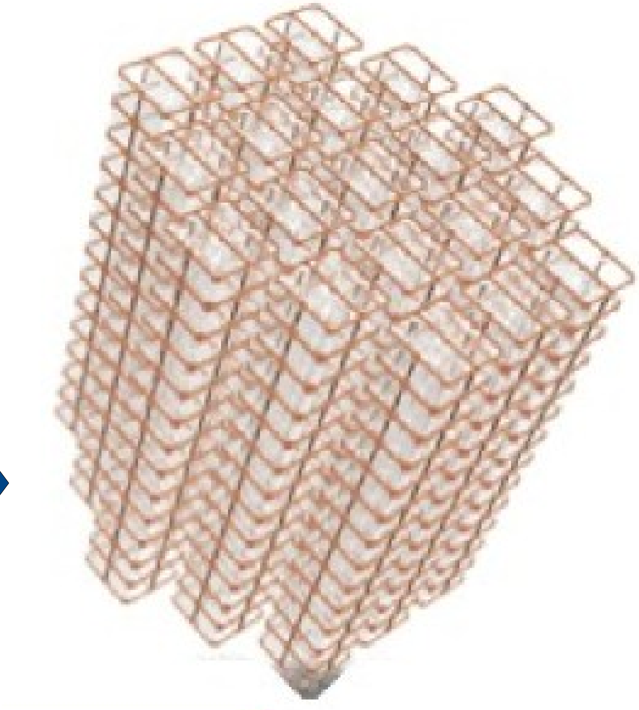
2003-2009

CUORE-0
~ 11 kg ^{130}Te



2012...2014

CUORE
~ 206 kg ^{130}Te



2014...

Cuoricino final 0νββ result

Statistics: **Mxt = 19.75 kg (130Te)xy**

Energy resolution: **ΔE = 6.3±2.5 keV FWHM**

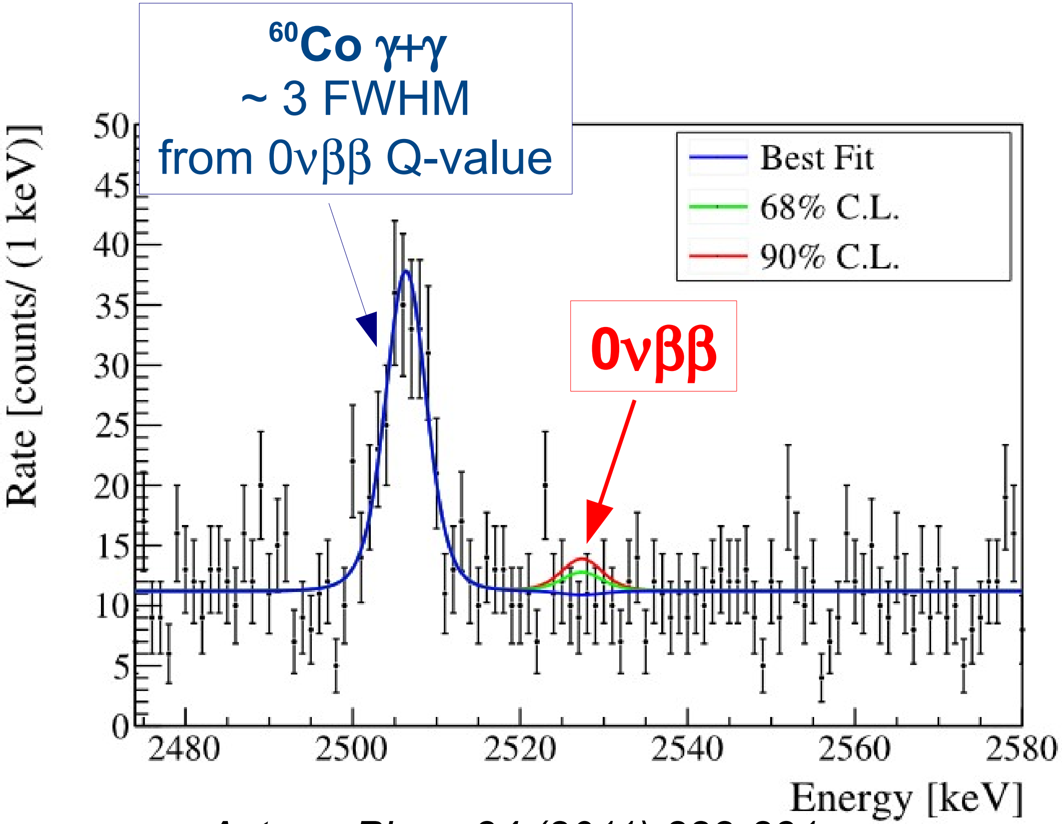
Background: **b = 0.169±0.006 c/keV/kg/y**

$T_{1/2}^{0\nu}$ > 2.8 x 10^{24} y [5]

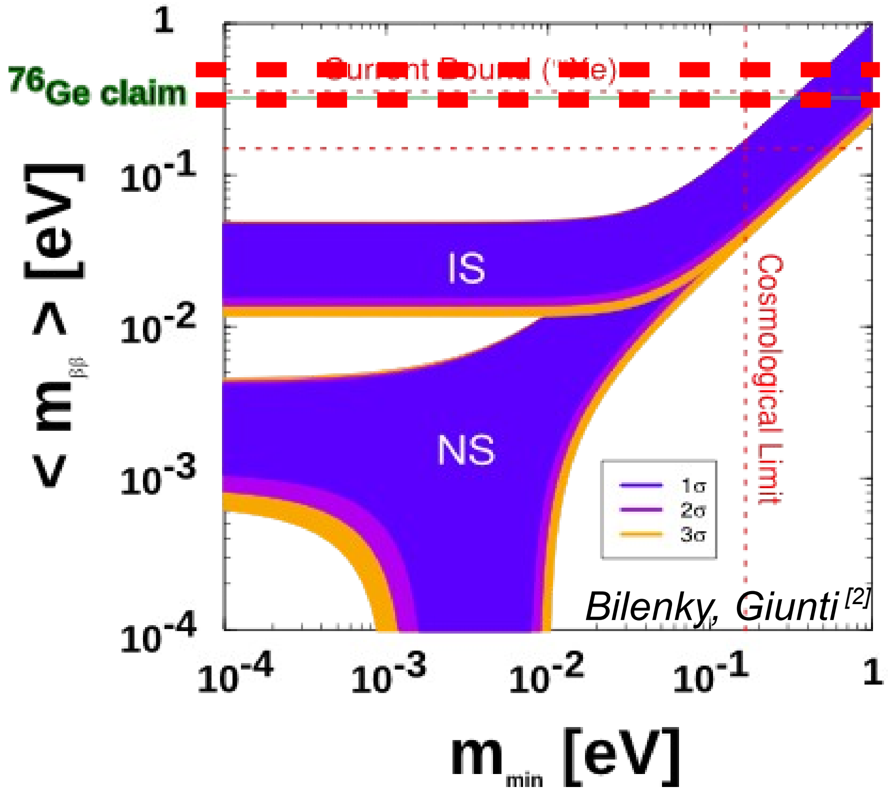
90% CL

$<m_{\beta\beta}>$ < 0.3÷0.7 eV [5]

NME from [6]

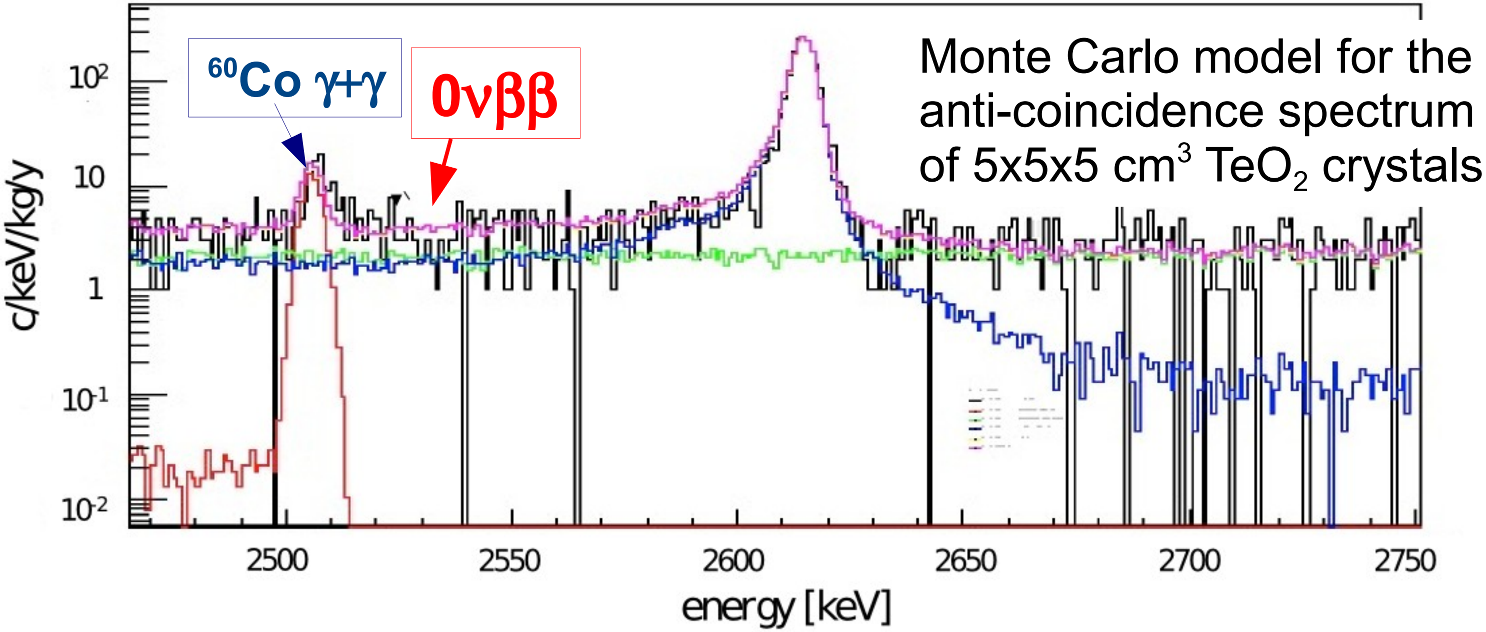


Astrop. Phys. 34 (2011) 822-831



Bilenky, Giunti [2]

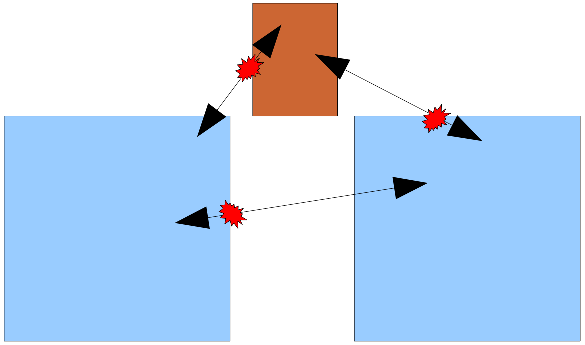
The Background in the Cuoricino ROI



Monte Carlo model for the anti-coincidence spectrum of 5x5x5 cm^3 TeO$_2$ crystals

b = 0.169±0.006 c/keV/kg/y

^{232}Th in the cryostat (γ) [7,8]	**30 ± 10 %**
Contamination on **crystal surface** [7,8]	**10 ± 5 %**
Contamination on **Cu surface** [7,8]	**50 ± 20 %**



The main issue are degraded α and β from crystal and copper surfaces

From Cuoricino to CUORE

988 TeO_2 5x5x5 cm^3 crystals (750 g each)

Detector Mass: ~741 kg TeO_2

^{130}Te mass (natural i.a.) : ~206 kg of ^{130}Te

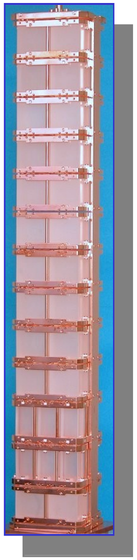
Array: 19 towers, each with 13 planes of 4 crystals each

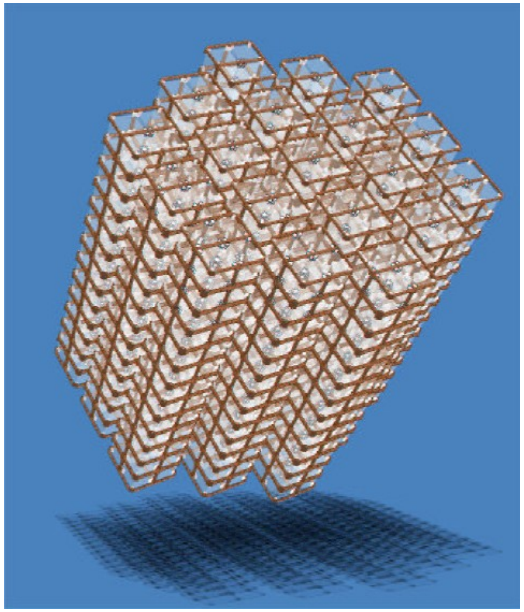
Sensitivity improvement:

$$S^{0\nu} \propto \frac{\epsilon\, a.i.}{A}\left(\frac{M\,T}{b\,\Delta E}\right)^{1/2}$$

(Mx20) + (ΔE/1.5) + (Tx2) + (b/20)

=> CUORE $S^{0\nu}$ ~ 35 Cuoricino $S^{0\nu}$





➡ the most challenging issue is background reduction

Background reduction

Passive methods adopted for CUORE while testing different active methods
(i.e. Surface sensitive bolometers, scintillating bolometers) for future improvements

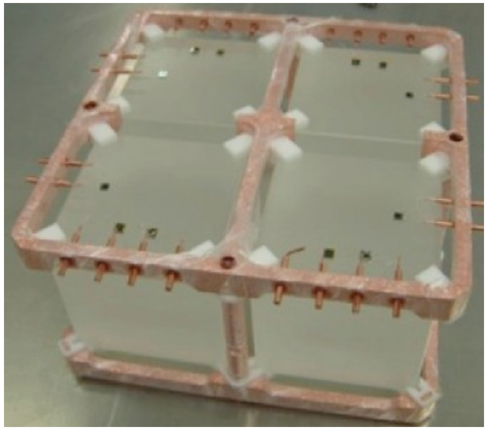
- **Shields design and materials selection**
- **New holder design** to reduce the amount of copper facing the crystals
- **TeO_2 crystals bulk contamination control**: strict protocol for TeO_2 production
- **Crystals surface contamination reduction**: new treatment developed

  => bolometric tests on 4 sample crystals from each batch: **CCVR [9] tests**
- **Surface contamination of the copper facing the crystals reduction**:

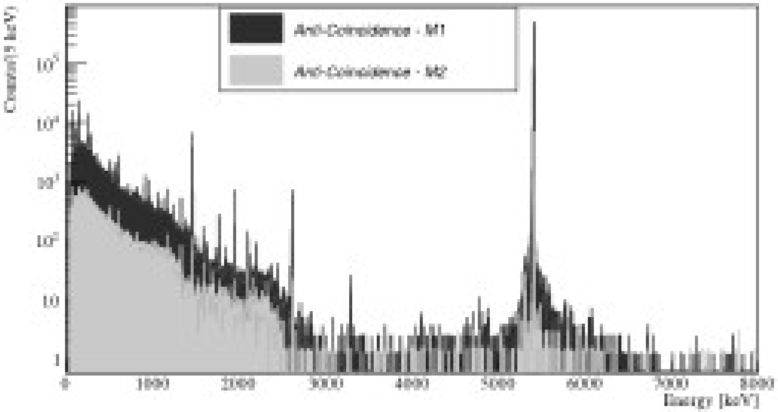
  => bolometric tests of three different surface treatments: **Three Tower Test (TTT)**
- Further improvement thanks to **detector granularity**

Background from TeO_2: CCVR test

CUORE Crystal Validation Run: a dedicated cryogenic setup in C Hall at LNGS to test crystal radioactivity and performances (4 crystal samples from each CUORE batch since 2008 – 8 runs)



CCVR 1-5 sum spectra [9]



- Improved performance with respect to CUORICINO: **ΔE FWHM @2615 = 4.6±1.2 keV**
- **Background** in the 2.7-3.9 MeV region **reduced by a factor of ~2** with respect to CUORICINO

Bulk/surface activities within contract specifications:

Bulk activity 90% C.L. upper limits:

8.4E-07 Bq/kg (^{232}Th), 6.7E-07 Bq/kg (^{238}U), 3.3E-06 Bq/kg (^{210}Po)

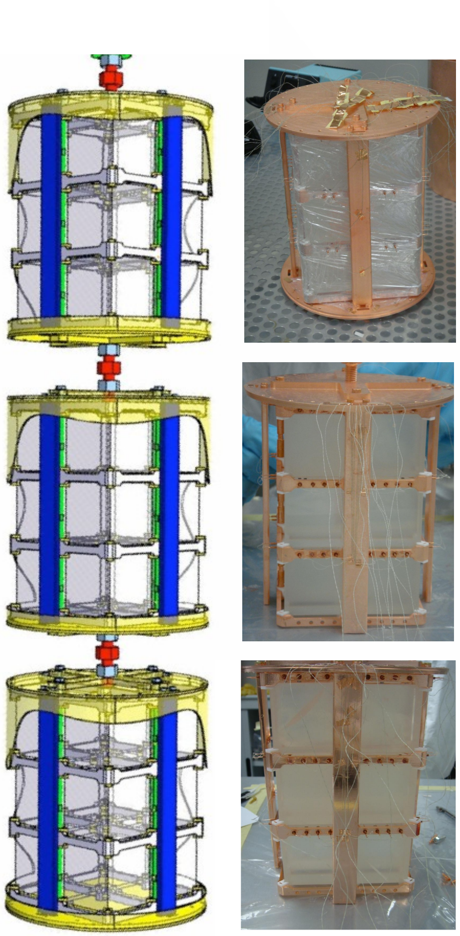
Surface activity 90% C.L. upper limits:

2E-09 Bq/cm^2 (^{232}Th), 1E-08 Bq/cm^2 (^{238}U), 1E-06 Bq/cm^2 (^{210}Po)

Background from Cu: TTT test

Bolometric test to compare the effect in the ROI of **3 different copper surface treatments**

Crystals from Cuoricino array **fully reprocessed** according to the new CUORE standards

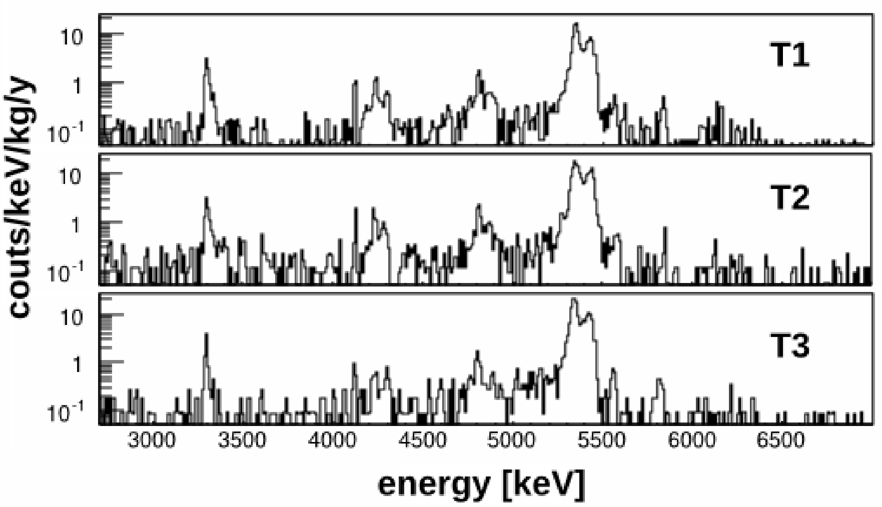


T1: Polyethylene
- Soap
- H_2O_2+ H_2O + citric acid
- 70 μm of polyethylene

T2: Chemical treatment
- Soap
- Electro-erosion
- Chemical etching
- H_2O_2+ H_2O + citric acid

T3: Plasma cleaning
- Tumbling
- Electro-polishing
- Chemical etching
- Magnetron Plasma etching

Total spectra (no anticoincidence applied)



Best result obtained for T1 and T3

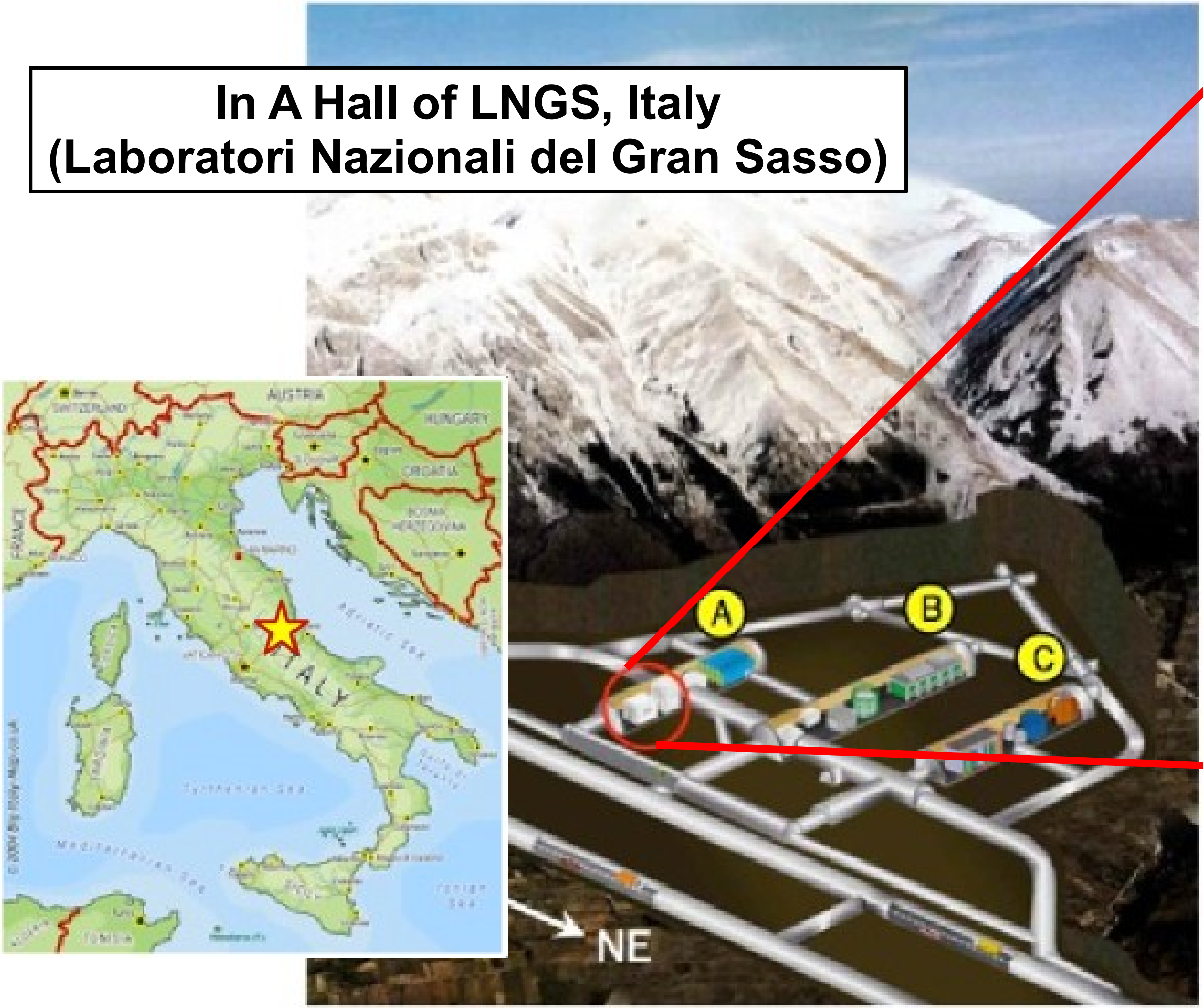
Bkg in the 2.7-3.9 MeV region after anti-coincidence cut:

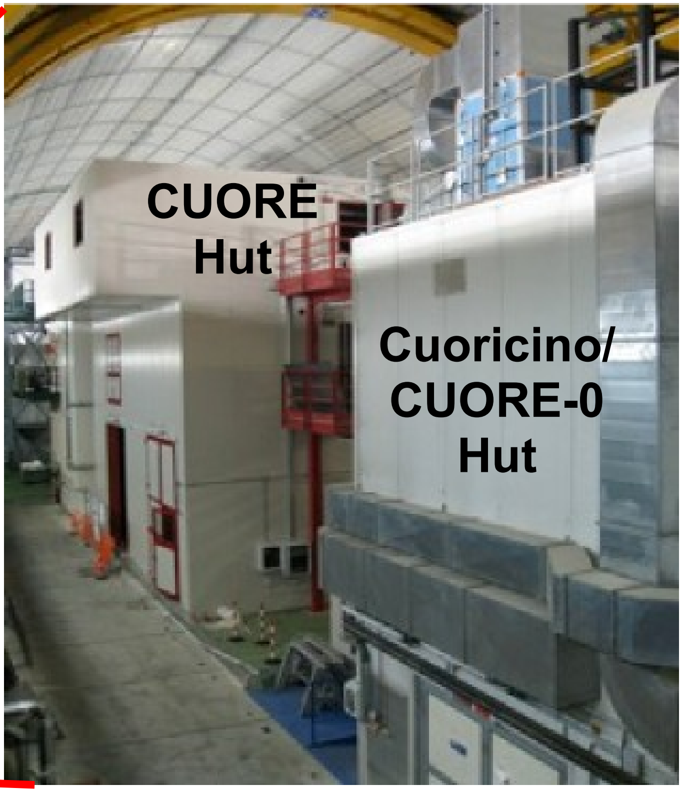
=> 0.052 ± 0.008 c/keV/kg/y

^{232}Th / ^{238}U on Cu: < 7E-08 Bq/cm^2

CUORE location

In A Hall of LNGS, Italy
(Laboratori Nazionali del Gran Sasso)





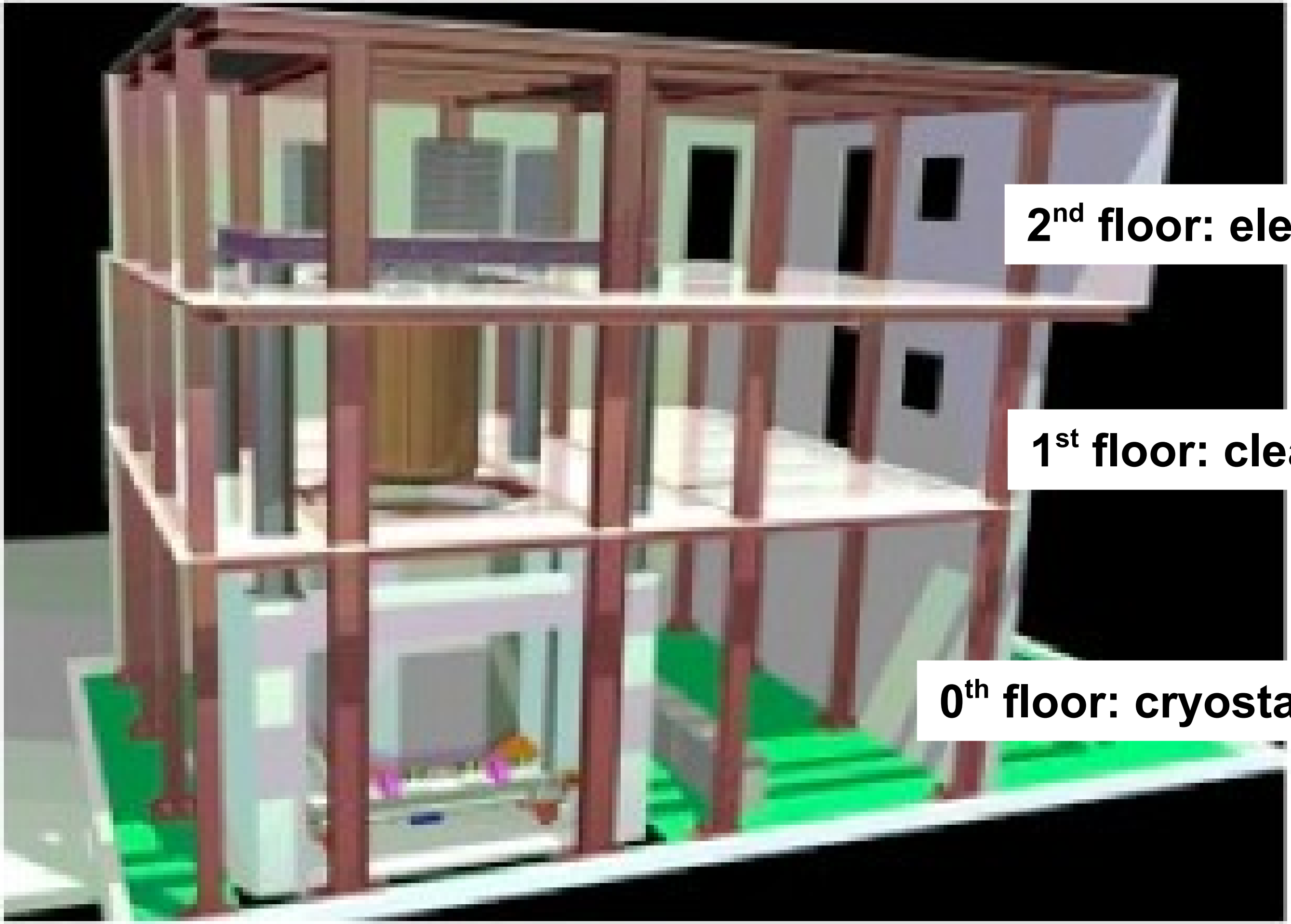
Average depth ~ 3650 m.w.e. [10]

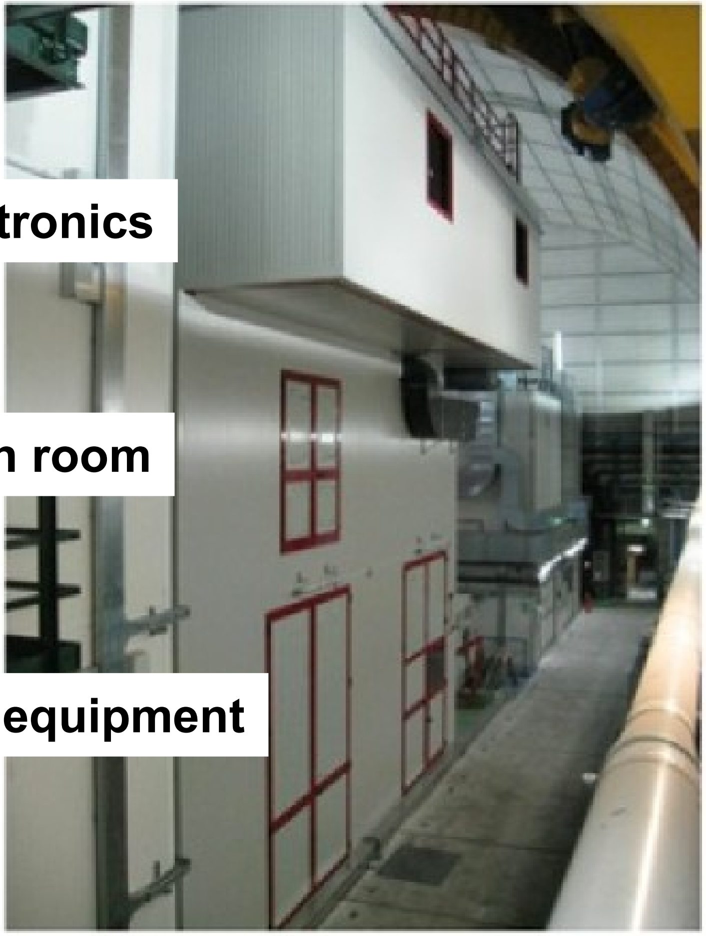
μ flux: $(2.58 \pm 0.3)\cdot10^{-8}$ μ/s/cm^2 [11]

n flux <10 MeV: 4×10^{-6} n/s/cm^2 [12,13]

γ flux < 3 MeV: 0.73 γ/s/cm^2 [14,15]

CUORE HUT





2^{nd} floor: electronics

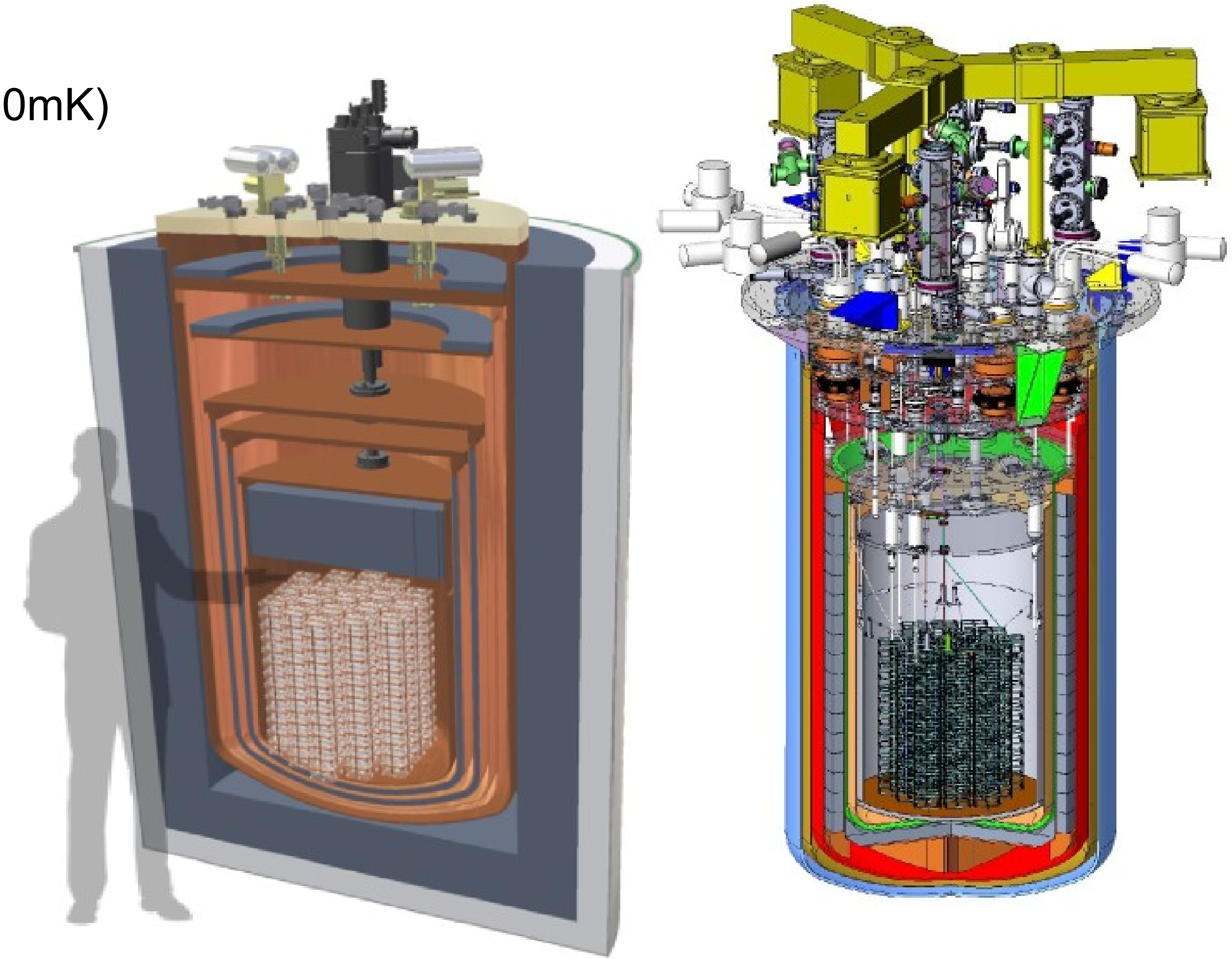
1^{st} floor: clean room

0^{th} floor: cryostat equipment

CUORE cryostat

Developed a low-noise, cryogen-free, low-radioactivity cryostat able to reach ~ 6 mK

- **6 nested copper vessels**
  (300K, 40K, 4K, 600mK, 50mK, 10mK)
- **Cryogen free**
  => better duty cycle
- **Detector suspensions indipendent of refrigerator**
  => less vibrational noise
- **Material selection**
  => low radioactivity
- **Shields for neutrons**
  (18cm PET + 2 cm H_3B0_3)
- **External+Internal Pb shields**
  (~35 cm minimum thickness)



CUORE background budget

Source Element	Contamination level Bulk [Bq/kg]; Surf [Bq/cm^2]	Source Data	c/keV/kg/y
Environmental γ	0.73 γ/s/cm^2	LNGS Meas. [14] [15]	< 3.9E-05 [15]
Environmental n	4E-06 n/s/cm^2	LNGS Meas. [12] [13]	(8.56±6.06)E-06 [15]
Environmental μ	3E-06 μ/s/cm^2	MACRO Meas. [11]	(1.04±0.22)E-04 [15]
Far bulk: Cu OFE and	<6.4E-5 (Th), <5.4E-5 (U)	HPGe	<2E-03
Far bulk: Steel parts	<1E-2 (Th), <5E-3 (U)	HPGe	<3E-04
Internal Roman Lead	Roman:<4.3E-5 (Th), <4.6E-5 (U)	HPGe	<4E-03
Internal Roman Lead	COMETA: <1.2E-4 (Th), <1.4E-4 (U)	HPGe	<5E-05
Small near parts	Depending on the material	HPGe, NAA, bolo	< 3E-03
Cosm. Activation: TeO_2	~ 1.5E-08 (^{60}Co) ~ 4E-07 (^{110}Ag, ^{110m}Ag)	Calculations	~ 1E-03
Cosm. Activation: Cu	< 5E-5 (^{60}Co)	Calculations	< 5E-04
Near bulk: Cu NOSV	< 2E-06 (Th), < 6.5E-05 (U)	NAA (Th), HPGe (U)	< 7E-04
Near bulk: TeO_2	< 8.4E-07 (Th),< 6.7E-07 (U) <3.3E-06 (Pb)	CCVR [9]	< 1E-04
Near Surface: Cu NOSV Or PTFE	Cu: <7E-08(Th / U), <7E-07(Pb) PTFE: <7E-06 (Pb)	From TTT 2.7-3.9 MeV rate	**< (2-3)E-02 if Cu** **<6E-02 if PTFE**
Near surface: TeO_2	<2E-09(Th),<1E-8 (U),<1E-06 (Pb)	CCVR [9]	< 4E-03

PRELIMINARY – GEOMETRY DETAILS NOT AT FINAL STAGE

CUORE Status

- **Hut and clean room**: fully equipped
- **Detector assembly line**: almost ready
- **Radon abatement system**: installed
- **Cryostat:** commissioning of first 3 shields will start soon at LNGS
- **Calibration system:** construction started
- **Copper parts:** are being machined and cleaned, delivered by end 2013
- **Crystals:** 90% stored underground at LNGS (100% by end 2012)
- **Thermistors:** production on-going, final delivering in early 2013

CUORE first phase: CUORE-0

1 CUORE-like tower of 13 planes - 4 crystals each

52 TeO_2 5x5x5 cm^3 crystals (750 g each)

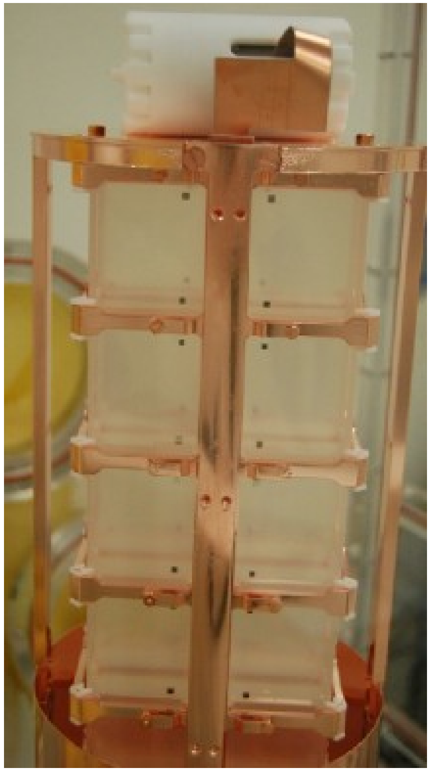
Detector Mass: ~39 kg TeO_2

^{130}Te mass (natural i.a.): ~11 kg of ^{130}Te

- All detector components manufactured, cleaned and stored with protocols defined for CUORE
- Assembled with the same procedures foreseen for CUORE
- In old CUORICINO cryostat

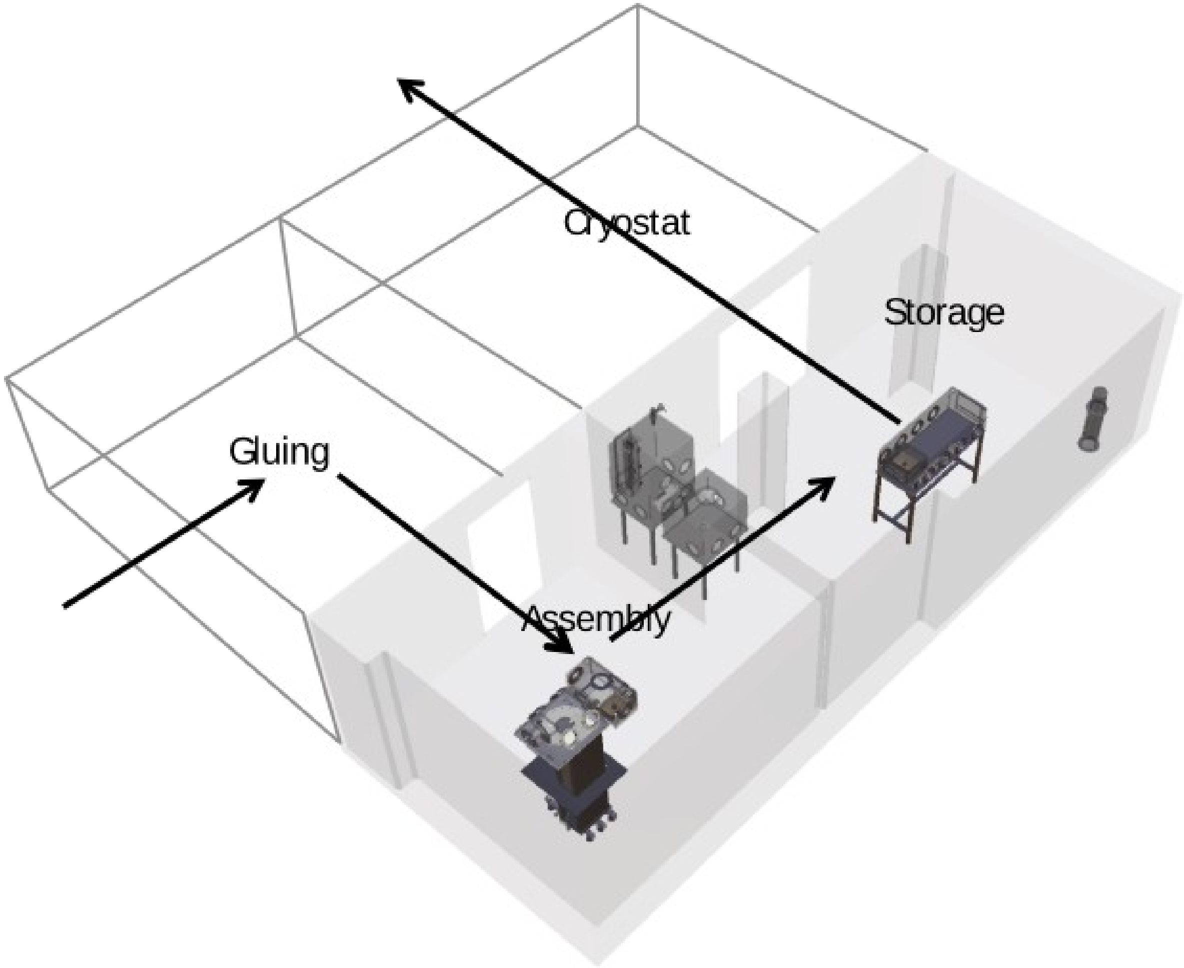
GOALS:

- Test of proof for CUORE at all stages
- Test and debug of the new CUORE assembly line
- Test of the whole new CUORE analysis framework
- Surpass CUORICINO in physics reach while CUORE is being assembled
- Demonstrate potential for DM and Axion detection (see S. Di Domizio talk in parallel session)



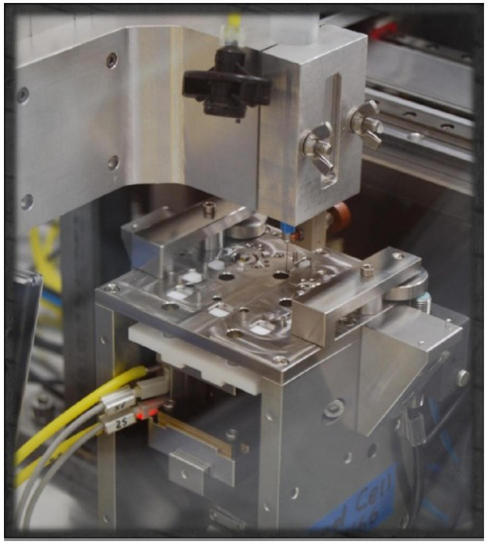
CUORE-0: assembly procedure

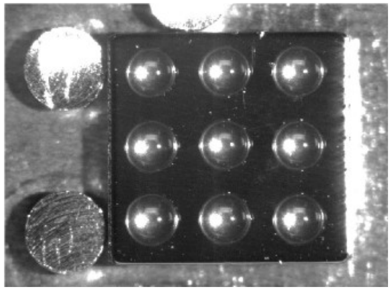
CUORE-0 assembly was performed in the new CUORE clean room following all the stages and using **all the equipment developed for CUORE**



CUORE-0: thermistor gluing

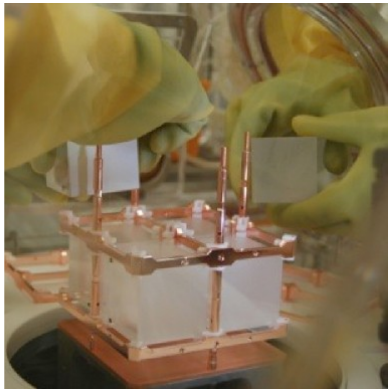
The gluing of CUORE-0 thermistor to crystals was performed with the **new CUORE gluing semi-automatic machine** (in a N_2 flushed glove box): fast, operator independent, minimizes radioactive contaminations, makes this stage more reproducible thus improving detector uniformity.

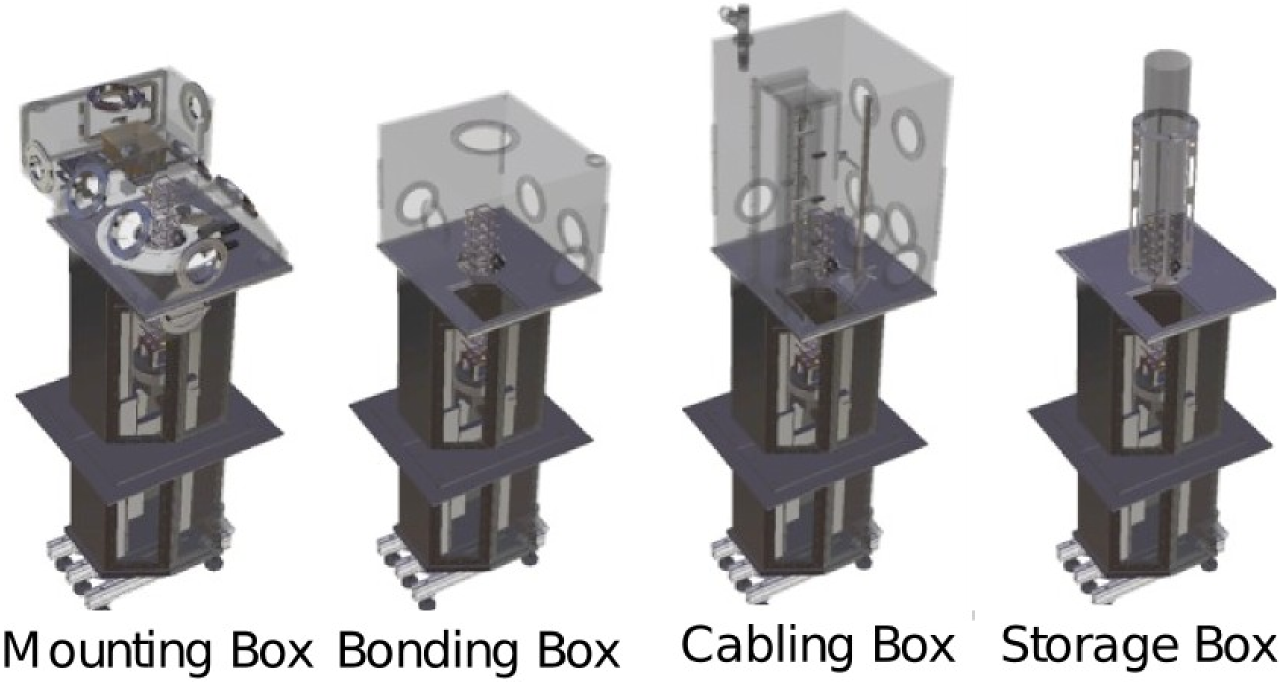


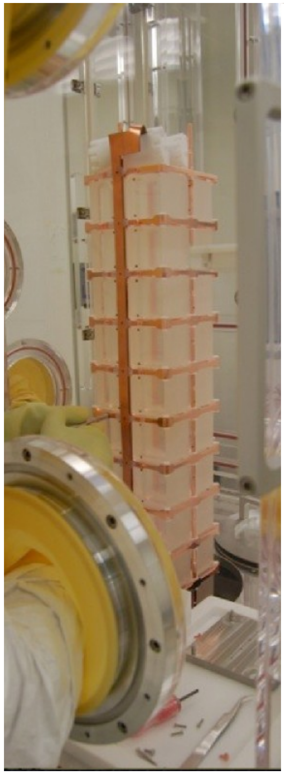


CUORE-0: tower assembly

The assembly of the tower was done with the **CTAL (CUORE Tower Assembly Line)** provided of a sealed and flushed stainless steel chamber (Garage) supporting a working plane where **4 different glove boxes switch** allowing 4 operations to be performed (mounting, bonding, cabling and tower storage) with radioactivity control and reproducible protocols







CUORE-0: shield installation and transportation

After shield installation the tower has been closed in a flushed Plexiglas box, then moved to the special opening door of the **CUORE clean room** with a trans-pallet. It has then been lifted with a fork-lift to the **CUORICINO clean room** where it has been joined to the cryostat dilution unit (operations not necessary for CUORE).

CUORE-0: status

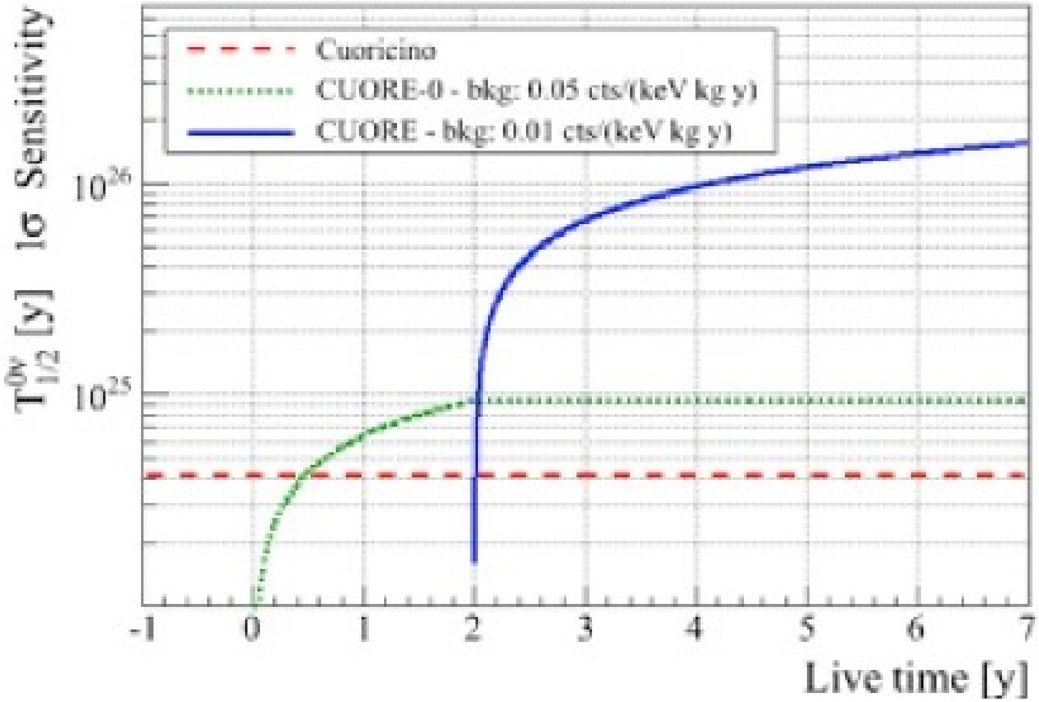
- The CUORE-0 cryostat and tower have been closed the first time on the 24th of April
- A leak in the dilution unit has then been discovered forcing to dismount and storage the tower
- The leak has been repaired by a technician from Oxford Instruments in the 1st week of June
- Cryostat was reassembled in mid-June
- Room temperature and low temperature tests on-going
- Data taking foreseen in middle August

CUORE-0 and CUORE sensitivity

	CUORE-0	CUORE	data
M [kg]	**39 (~11 of ^{130}Te)**	**741 (~206 of ^{130}Te)**	
ΔE [keV]	**~5**	**~5**	CCVR [9]
b [c/keV/kg/y]	**0.05**	**0.01**	Measured contaminations + bkg model
T [y]	**2**	**5**	

$$S^{0\nu} \propto \frac{\epsilon\, a.i.}{A}\left(\frac{M\,T}{b\,\Delta E}\right)^{1/2}$$

ε = 87.4%
i.a. (^{130}Te) = 34.167 %



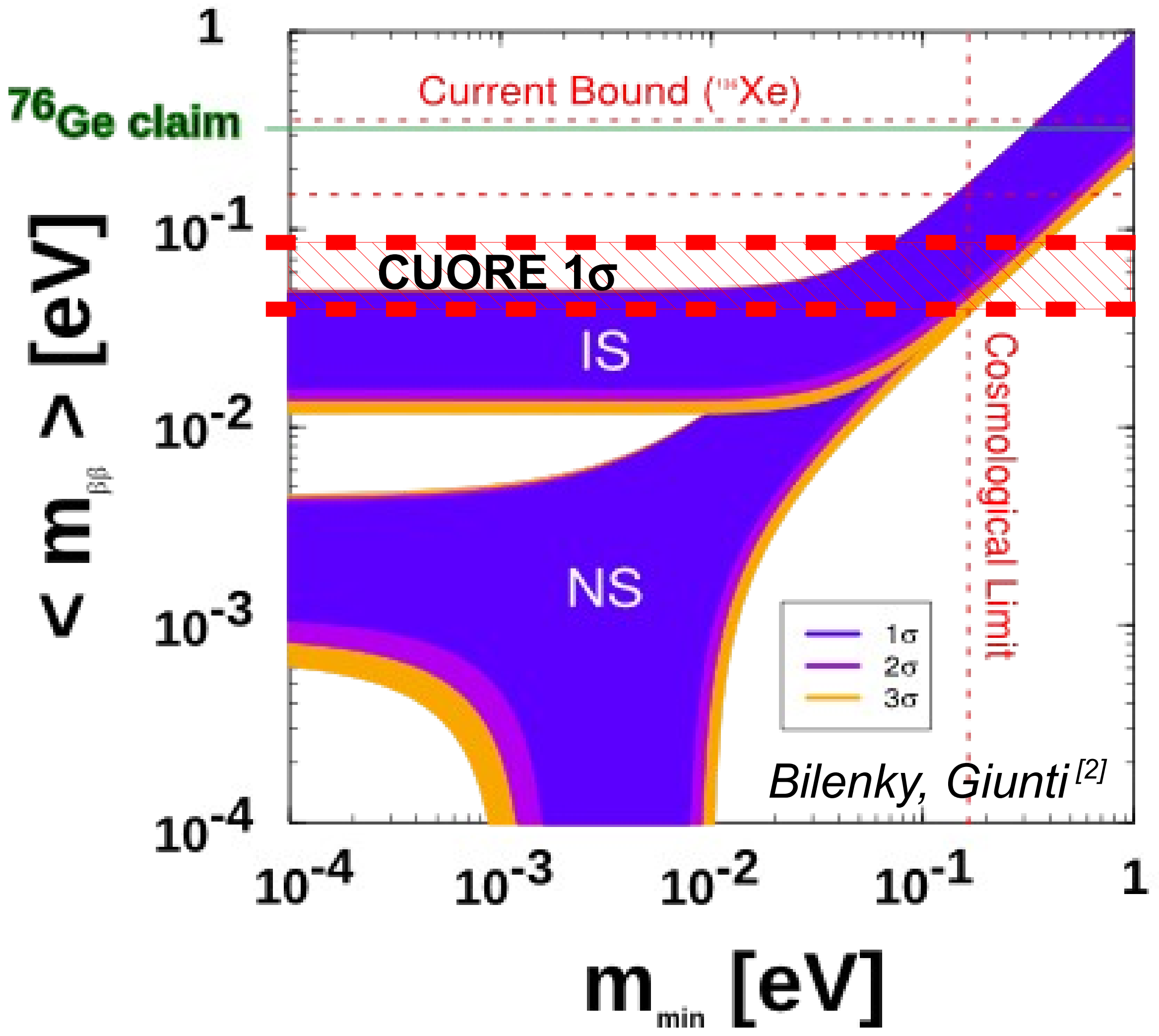
CUORE sentitivity to $<m_{\beta\beta}>$

b=0.01 c/keV/kg/y, T = 5 y

$T_{1/2}^{0\nu} > 1.6 \times 10^{26}$ y (1σ)
$T_{1/2}^{0\nu} > 9.5 \times 10^{25}$ y (90% CL)

$<m_{\beta\beta}> < 40 \div 90$ meV

NME from [6]



Conclusions

- TeO_2 bolometers represent since many years a competitive detector for $0\nu\beta\beta$ research
- After the CUORICINO lesson a strong R&D has been developed in order to reduce the background in the ROI (the main challenge being surface contaminations of detector and facing parts)
- Bolometric tests after improving surface treatments demonstrate that the CUORE goal of 0.01 c/keV/kg/y is just behind the corner. Copper/PTFE surface is the most crucial issue
- CUORE is under construction: LNGS hut and clean room ready, cryostat commissioning almost starting, crystal production and storage foreseen by 2012, other parts on schedule
- CUORE cool down foreseen for end 2014
- First CUORE tower, CUORE-0, will soon start data taking in the CUORICINO cryostat
- Positive result and optimization in view of CUORE of all production/cleaning and assembly stages

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The CUORE Collaboration

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- INFN & University Milano Bicocca
- INFN Roma & Sapienza University
- INFN Roma Tor Vergata
- INFN & University Genova
- INFN & University Firenze
- INFN LNL Laboratories
- INFN LNF Laboratories
- INFN Padova
- INFN and University Bologna

- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- University of California Berkeley
- University of Califoria Los Angeles
- University of South Carolina
- California Politechnic state University
- University of Wisconsin Madison
- CNRS – CSNSM Orsay
- Shanghai Institute of Applied Physics
- University of Zaragoza

Back-up slides

TeO_2 bolometer parameters

Detector working temperature: T ~ 10 mK

Mixing chamber temperature: T_{MC} ~ 5 mK

Heat capacity of crystal: C ~ 2 x 10-9J/K

Thermal conductance of thermal coupling to heat bath: G ~ 2 x 10-9 W/K

Time constant of bolometer: τ ~ C/G ~ 1 s

Rise time of pulse: ~ 50 ms

Decay time of pulse: ~ 200 ms

Resistance of thermistor: R ~ 100 MΩ

$R(T) = R_0 * \exp[(T_0/T)_\gamma]$

R_0: nominal values ~0.9-1.2 Ω
T_0: nominal values ~3-4 K
γ is considered to be = 0.5

A representative set of reasonable parameters that reproduces R ~ 100 MΩ is:
R_0 ~ 1.1 Ω, T_0 ~ 3.35 K, γ = 0.5

Detector Response:

ΔVthermistor ~ 0.3 mV/MeV

ΔRthermistor ~ 3 MΩ/MeV

ΔTthermistor ~ 0.03 mK/MeV

ΔTcrystal ~ 0.1 mK/MeV

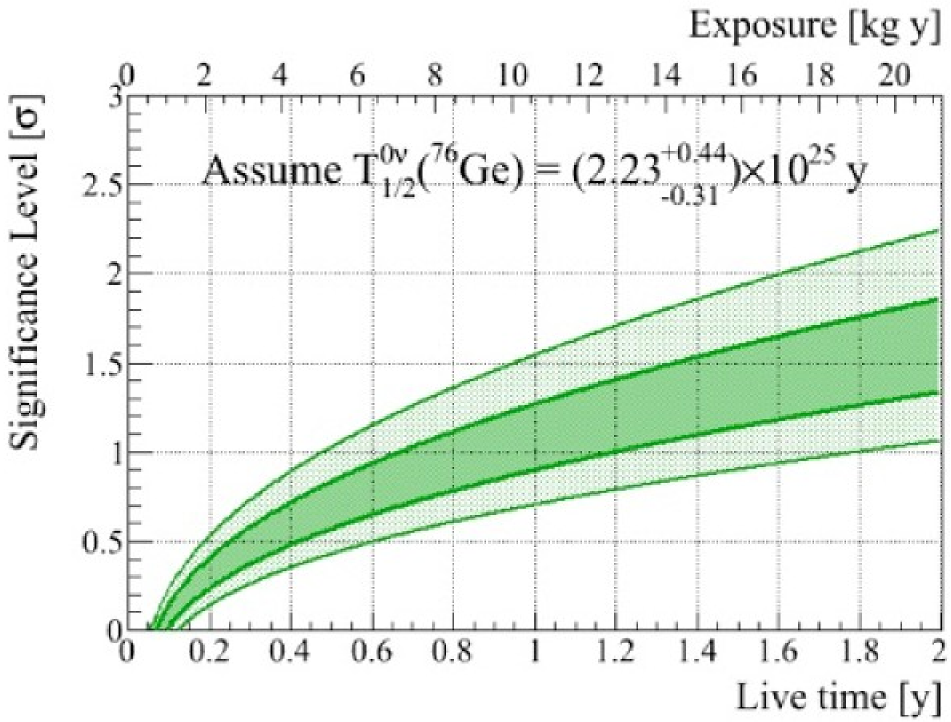
CUORE-0: Sensitivity to ^{76}Ge claim

b=0.05 c/keV/kg/y, T = 2 y

$T_{1/2}^{0\nu}$ > 5.9 x 10^{24} y (90% CL)
(CUORICINO: $T_{1/2}^{0\nu}$>2.8 x 10^{24} y)

$\langle m_{\beta\beta} \rangle$ < 0.17¸0.39 meV

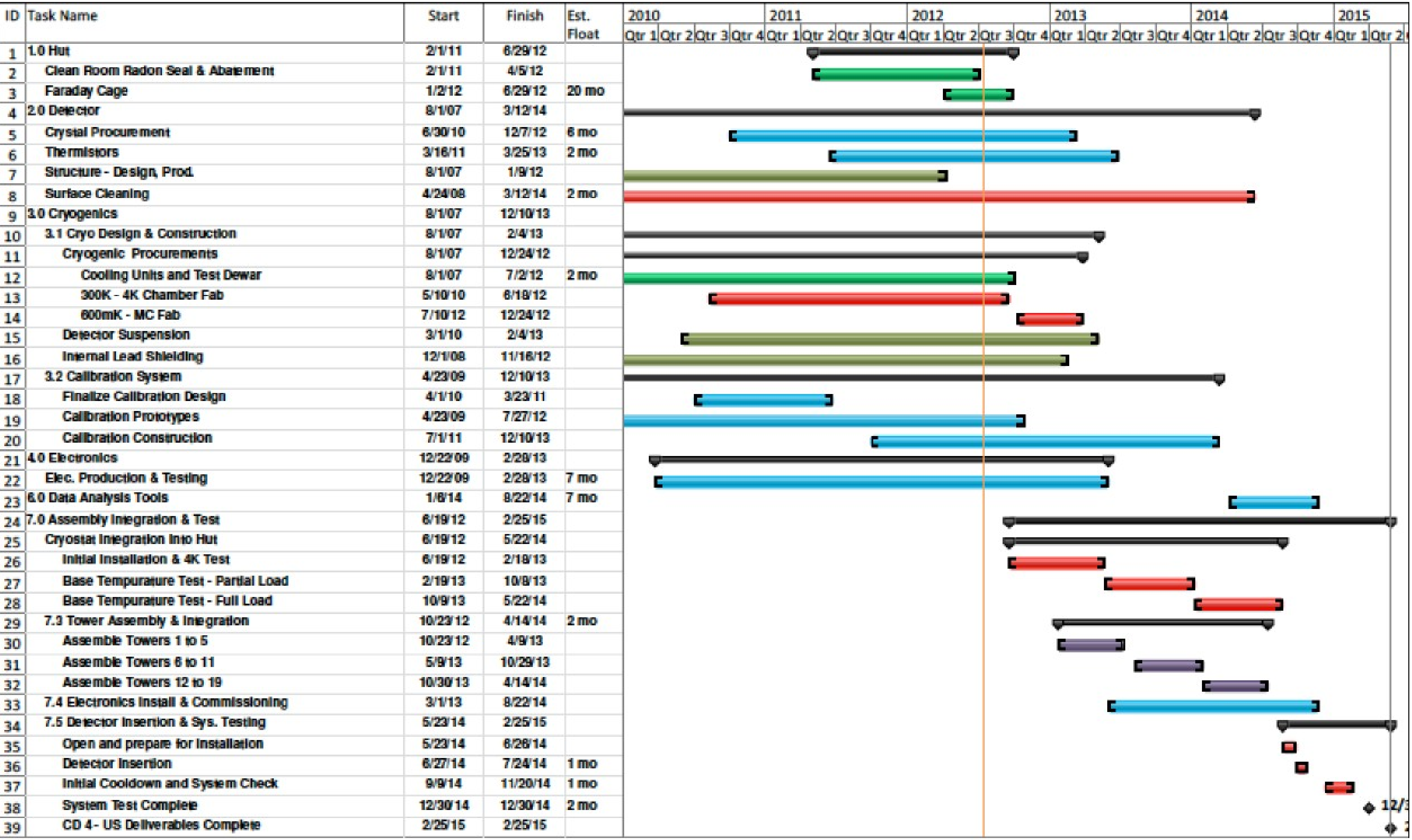
NME from [6]



Significance level at which CUORE-0 can observe a DBD signal consistent with the claim in ^{76}Ge (KK-HK), assuming 0.05 c/keV/kg/y background

- The inner band corresponds to the best-fit value of the claim; the range arises from the "1σ" range of QRPA NME calculations in A. Faessler et al., Phys. Rev. D79 (2009) 053001
- The outer band also includes the 1σ error on the ^{76} Ge claim

CUORE schedule



ID	Task Name	Start	Finish	Est. Float
1	1.0 Hut	2/1/11	6/29/12	
2	Clean Room Radon Seal & Abatement	2/1/11	4/5/12	
3	Faraday Cage	1/2/12	6/29/12	20 mo
4	2.0 Detector	8/1/07	3/12/14	
5	Crystal Procurement	6/30/10	12/7/12	6 mo
6	Thermistors	3/16/11	3/25/13	2 mo
7	Structure - Design, Prod.	8/1/07	1/9/12	
8	Surface Cleaning	4/24/08	3/12/14	2 mo
9	3.0 Cryogenics	8/1/07	12/10/13	
10	3.1 Cryo Design & Construction	8/1/07	2/4/13	
11	Cryogenic Procurements	8/1/07	12/24/12	
12	Cooling Units and Test Dewar	8/1/07	7/2/12	2 mo
13	300K - 4K Chamber Fab	5/10/10	6/19/12	
14	600mK - MC Fab	7/10/12	12/24/12	
15	Detector Suspension	3/1/10	2/4/13	
16	Internal Lead Shielding	12/1/08	11/16/12	
17	3.2 Calibration System	4/23/09	12/10/13	
18	Finalize Calibration Design	4/1/10	3/23/11	
19	Calibration Prototypes	4/23/09	7/27/12	
20	Calibration Construction	7/1/11	12/10/13	
21	4.0 Electronics	12/22/09	2/28/13	
22	Elec. Production & Testing	12/22/09	2/28/13	7 mo
23	6.0 Data Analysis Tools	1/6/14	8/22/14	7 mo
24	7.0 Assembly Integration & Test	6/19/12	2/25/15	
25	Cryostat Integration Into Hut	6/19/12	5/22/14	
26	Initial Installation & 4K Test	6/19/12	2/19/13	
27	Base Tempurature Test - Partial Load	2/19/13	10/9/13	
28	Base Tempurature Test - Full Load	10/9/13	5/22/14	
29	7.3 Tower Assembly & Integration	10/23/12	4/14/14	2 mo
30	Assemble Towers 1 to 5	10/23/12	4/9/13	
31	Assemble Towers 6 to 11	5/9/13	10/29/13	
32	Assemble Towers 12 to 19	10/30/13	4/14/14	
33	7.4 Electronics Install & Commissioning	3/1/13	8/22/14	
34	7.5 Detector Insertion & Sys. Testing	5/23/14	2/25/15	
35	Open and prepare for Installation	5/23/14	6/26/14	
36	Detector Insertion	6/27/14	7/24/14	1 mo
37	Initial Cooldown and System Check	9/9/14	11/20/14	1 mo
38	System Test Complete	12/30/14	12/30/14	2 mo
39	CD 4 - US Deliverables Complete	2/25/15	2/25/15	

No float left!

What beyond CUORE?

$$S^{0\nu} \propto \frac{\epsilon\, a.i.}{A} \left(\frac{M\, T}{b\, \Delta E} \right)^{1/2}$$

Extensions beyond CUORE are possible in order to increase sensitivity to cover the inverted hierarchy region of the neutrino mass spectrum

- **Relatively inexpensive isotopic enrichment of ^{130}Te**
- No change needed to the experimental infrastructure
- > 500 kg of ^{130}Te
- A factor 3 increase in i.a. **=> $S^{0\nu}_{enr} \sim 3\ S^{0\nu}_{nat}$**

- **Particle discrimination (R&D is being developed)**

signal shape, surface sensitive detectors [16] , Cherenkov light detection [17]

or scintillating bolometers (i.e. ZnSe, $CdWO_4$, $CdMoO_4$...)