L’esperimento CUORE

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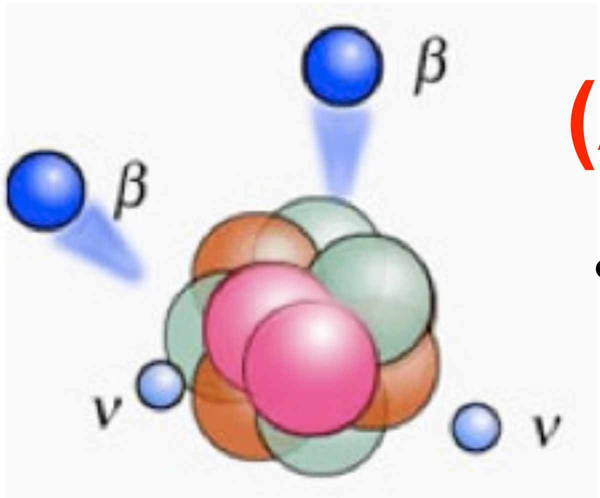
INFN – Sez. Milano Bicocca

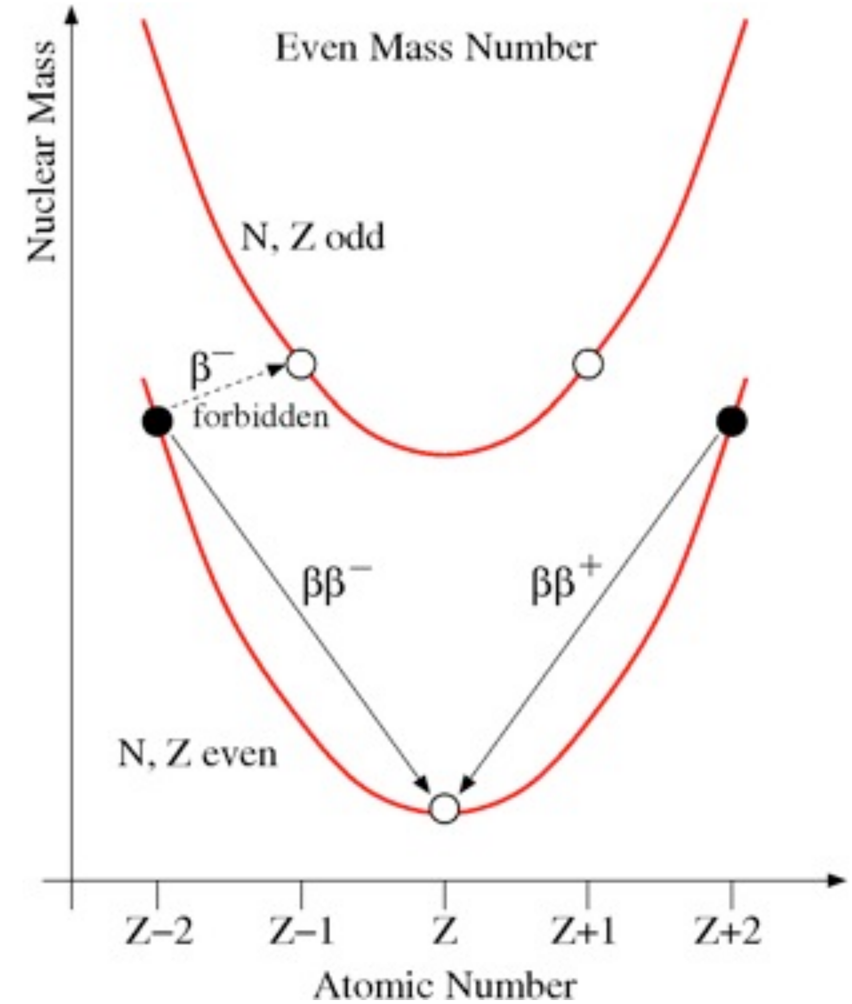
Il decadimento nucleare doppio beta

Transizione nucleare molto rara **(II ordine deboli interazioni)**

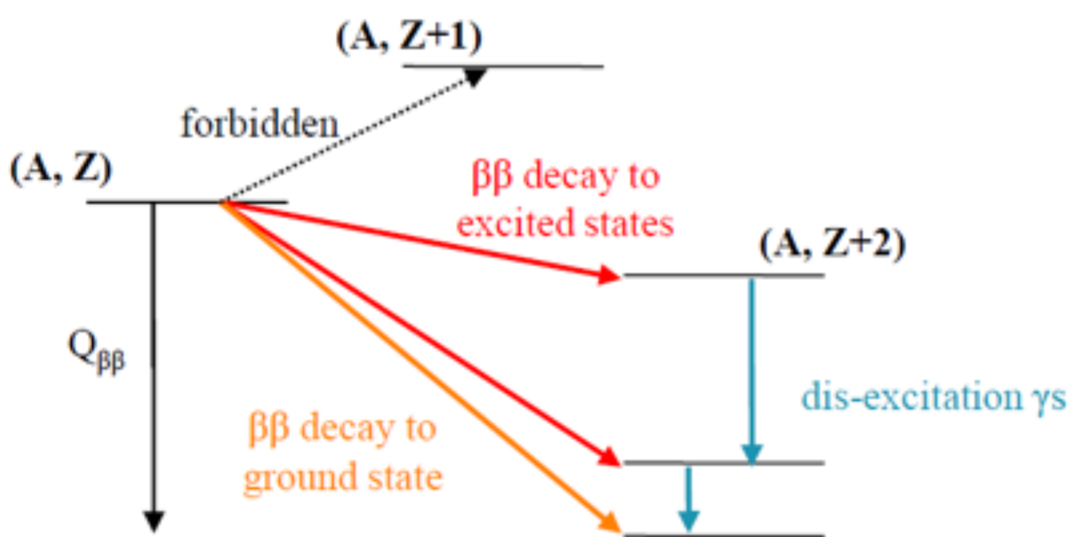


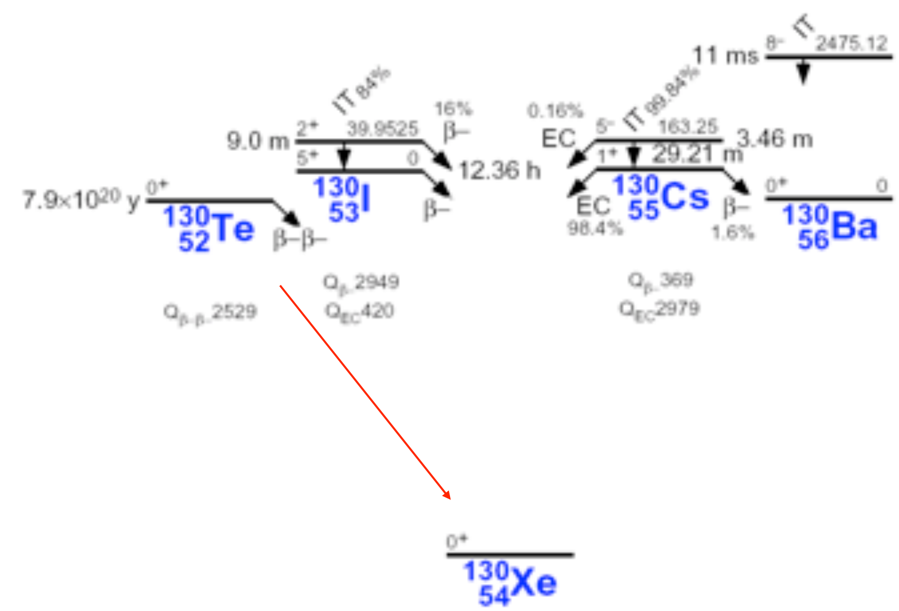
$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}$$

- favorita rispetto alla sequenza di due decadimenti singoli in numerosi **nuclei pari-pari**



- molti modi di decadimento:
  - $\beta^-\beta^-$, $\beta^+\beta^+$, $EC\beta^+$, ECEC
  - Stato fondamentale ed eccitati





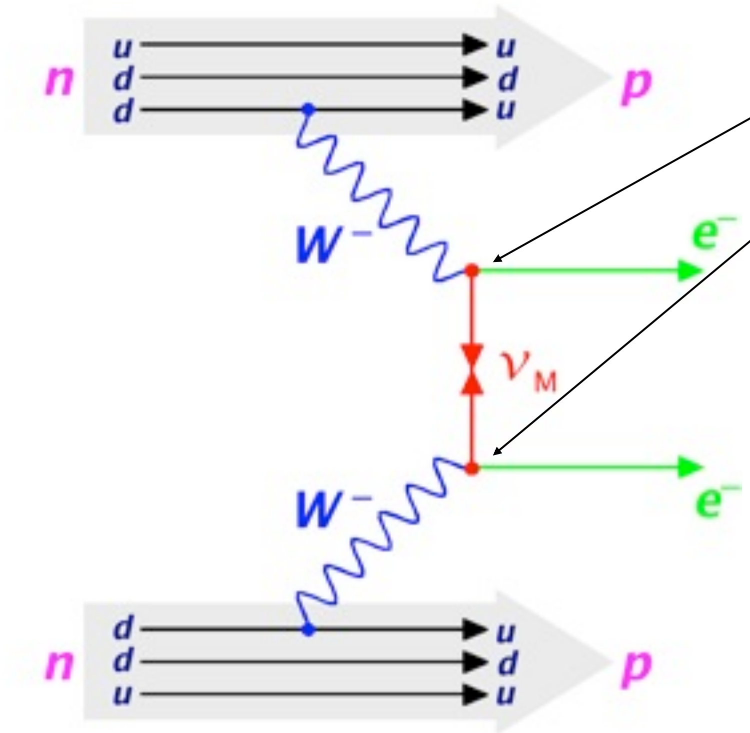
- **vite medie estremamente lunghe:** $\beta^-\beta^-$ osservato per 11 isotopi con $T_{1/2} \geq 10^{18}$ y

Il doppio beta senza neutrini

- Fin dalla sua proposta negli anni ’30 e’ stato considerato come strumento dalle caratteristiche uniche per verificare la
    - **natura del neutrino** (Dirac/Majorana)
- Nella versione originale procede attraverso lo scambio di un neutrino virtuale
- Garantisce quindi informazioni importanti (uniche) su
    - **Scala assoluta di massa del neutrino**
    - **Geararchia (ordinamento) delle masse**
    - **Violazione di CP nel settore leptonico**
- Tale missione è diventata particolarmente evidente dopo la coperta delle oscillazioni di neutrino.
- Il doppio beta ha così attratto l’interesse di molti fisici sperimentali
- Differenti tecniche ed approcci sperimentali sono stati così messi in campo per dare origine ad una vera e propria schieradi nuovi progetti.

Il meccanismo di massa per il ββ(0ν)

Scambio di un neutrino virtuale di Majorana



RH antineutrino (L=1) è emesso ad un vertice
LH neutrino (L=-1) è assorbito all'altro vertice

- **Particella di Majorana**
- **Inversione dell'Elicità**

Nel limite di piccole masse (del neutrino) la vita media può essere espressa come

$$\boxed{\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z)|M^{0\nu}|^2 < m_{ee} >}$$

SPAZIO DELLE FASI — NME — MASSA EFFICACE DI MAJORANA

$$< m_{ee} >= \sum_k U_{ek}^2 m_k$$

MATRICE DI MIXING DEL NEUTRINO\ — AUTOSTATI DI MASSA DEL NEUTRINO

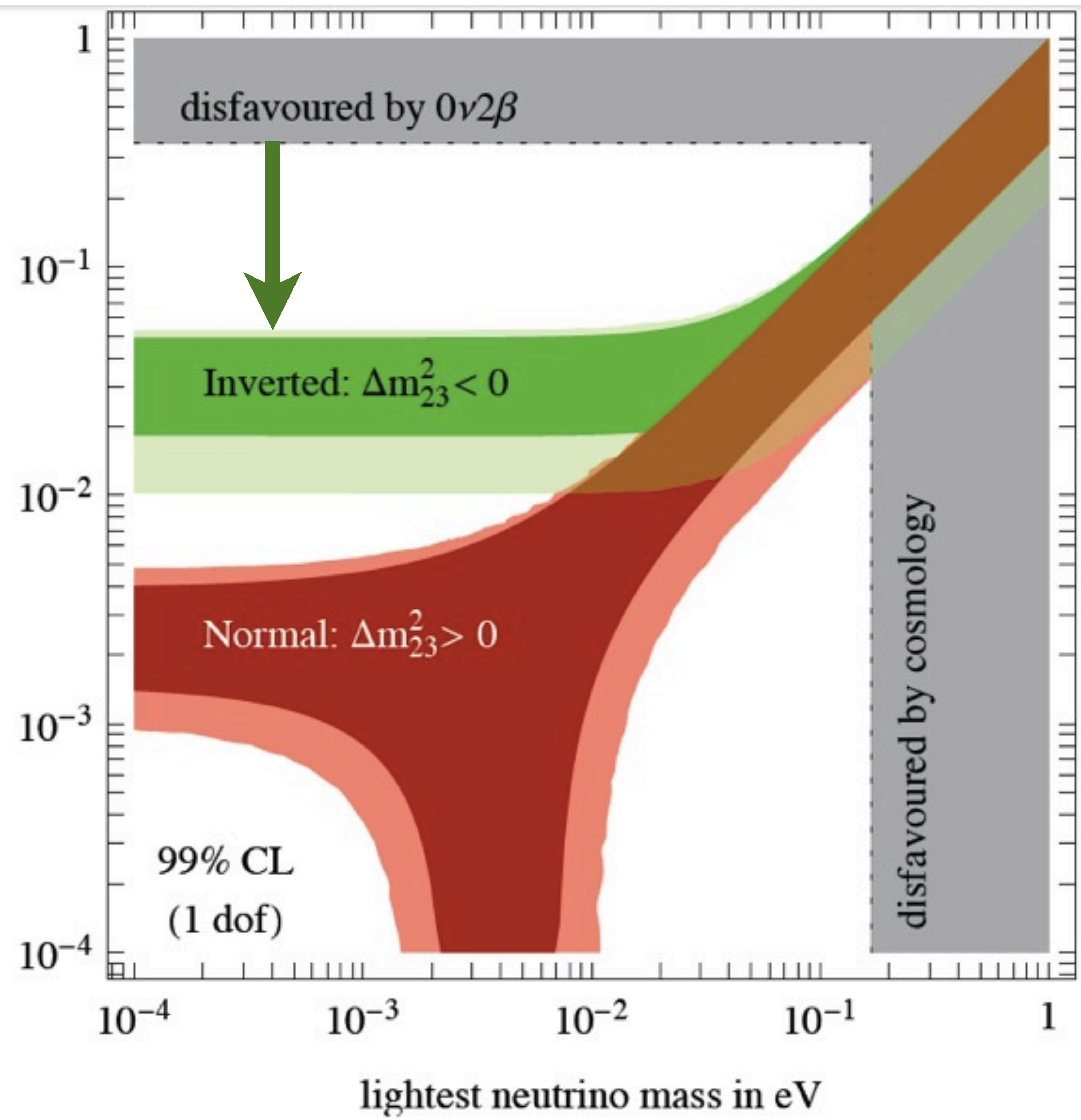
$$= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

SETTE incognite:
- 3 masse: m_k
- 2 angoli: θ_{12} e θ_{13}
- 2 fasi (Majorana): α and β

N.B.: Le fasi di Majorana rendono possibili le cancellazioni in m_{ee} (**m_{ee}** potrebbe quindi essere più piccolo di ciascun **m_i**).

Un Solo vincolo sperimentale
Necessità di misure complementari!

Oscillazioni di neutrino e ββ(0ν)

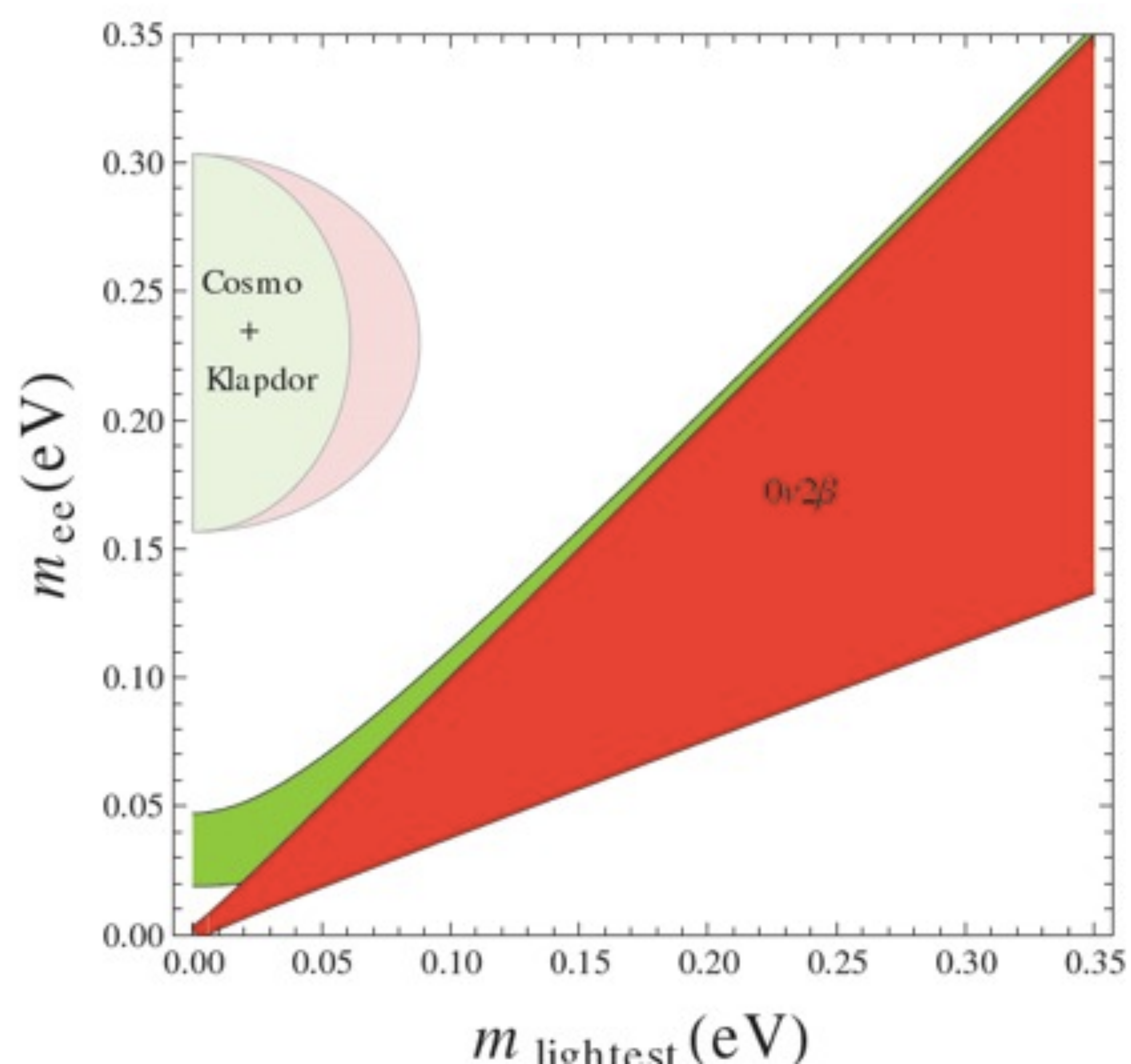


Grazie alle informazioni fornite dalle oscillazioni m_{ee} può essere espresso intermini di tre soli parametri:

- la scala di massa, rappresentata dall'autovalore più piccolo $\mathbf{m_{min}}$
- le fasi di Majorana.

Si distinguono allora tre possibilità (gerarchie):

- **normale (NH)**, dove $\mathbf{m_1 < m_2 < m_3}$
- **invertita (IH)** dove $\mathbf{m_3 < m_1 < m_2}$
- **quasi-degenere (QD)**, dove le differenze tra le masse sono piccole rispetto alla scala (m_{min})



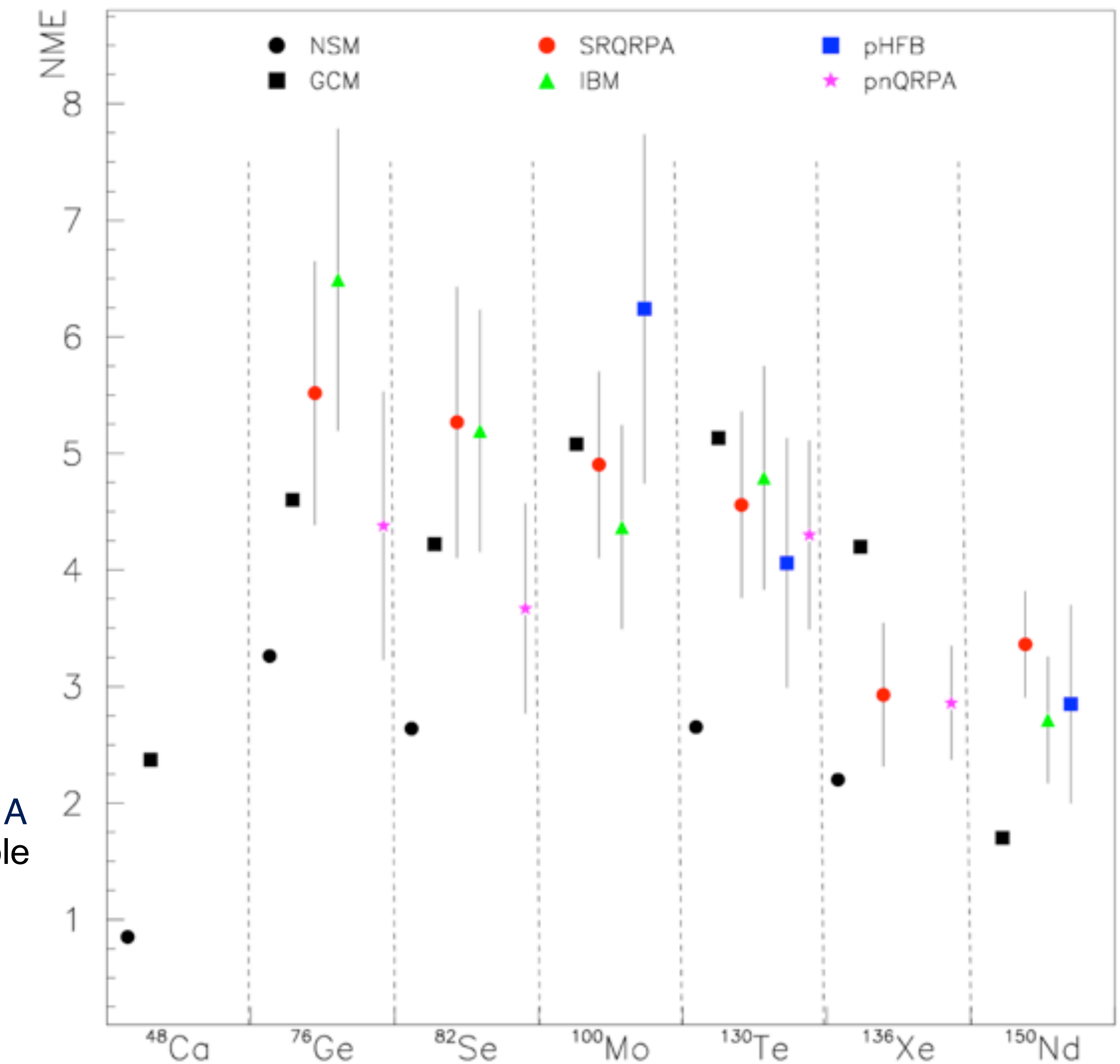
Elementi di matrice nucleare (NME)

Sononcalcolati sulla base di diversi modelli:

QRPA (RQRPA, SQRPA, …….), Shell model, IBM2 ...

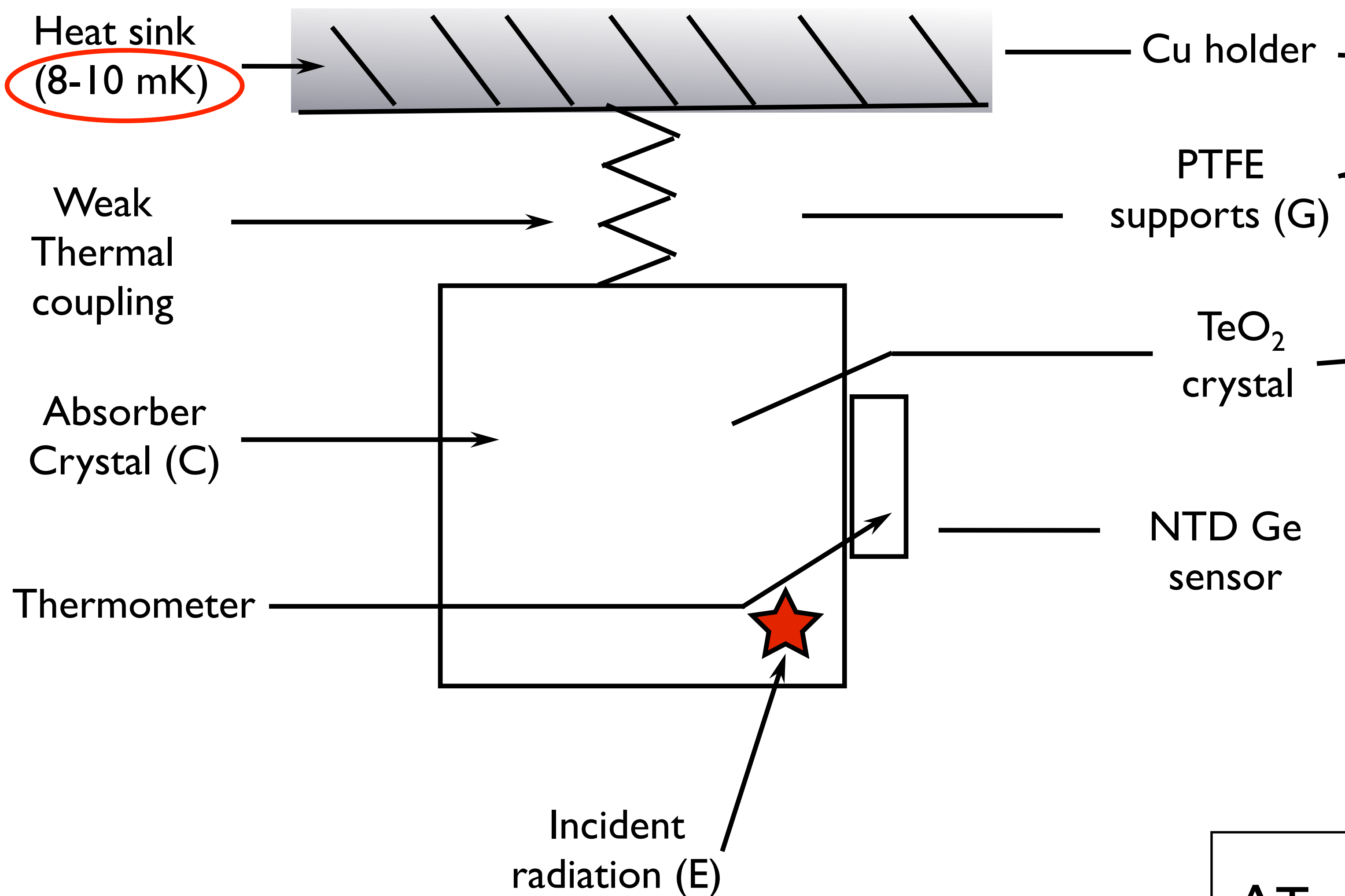
Le discrepanze sono una delle principali sorgenti di incertezza

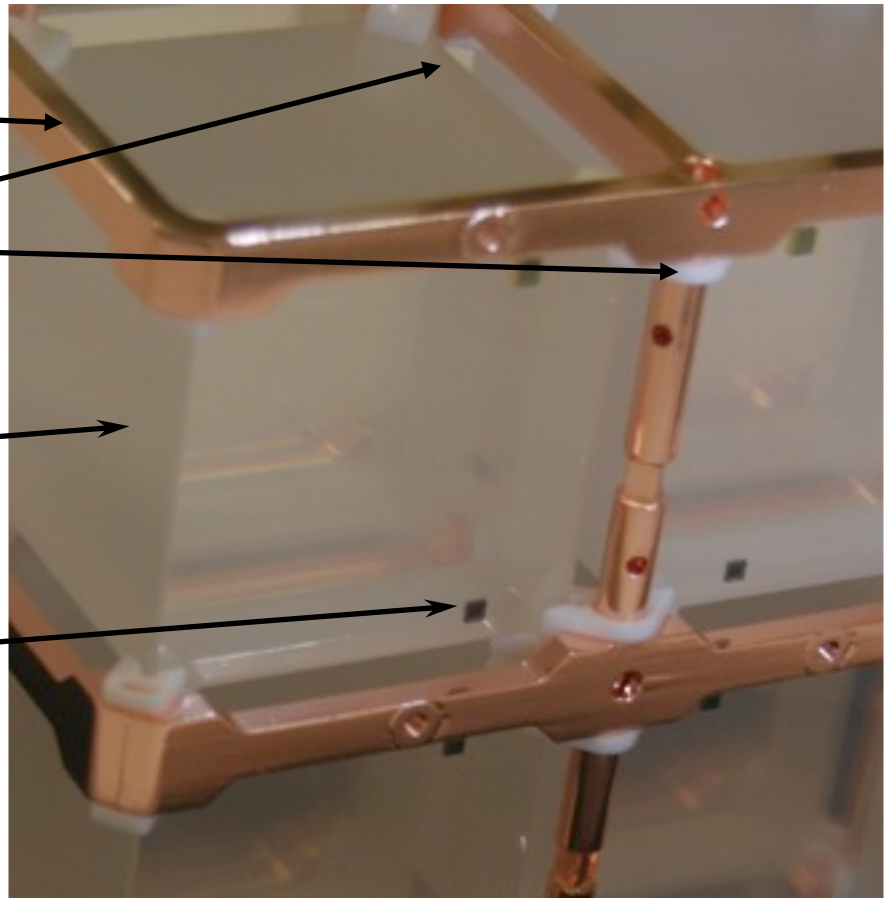
NSM nuclear shell model, Nucl. Phys. A 818 (2009) 139.Phys. Rev. C80 (2009) 048501(1)
SRQRPA self-consistent renormalized quasiparticle random phase approx.(2), Phys Rev D83 (2011) 113015, Phys Rev C79 (2009) 055501(1), Phys Rev C83 (2011) 034320
pnQRPA proton-neutron QRPA, Nucl Phys A847 (2010) 207
GCM generating coordinate method Phys. Rev. Lett. 105 (2010) 252503.
IBM interacting boson model(3), Phys Rev C79 (2009) 044301
pHFB projected Hartree-Fock-Bogoliubov Phys Rev C82 (2010) 064310



- più gruppi hanno calcolato i NME con metodi diversi
- NSM dà risultati piu' bassi
- NME variano in media di un fattore 2-3 su un dato nucleo
- le discrepanze sono fortemente correlate per diversi A
- nell'ambito dei calcoli QRPA le differenze sono piccole
- **nessun** "super" elemento

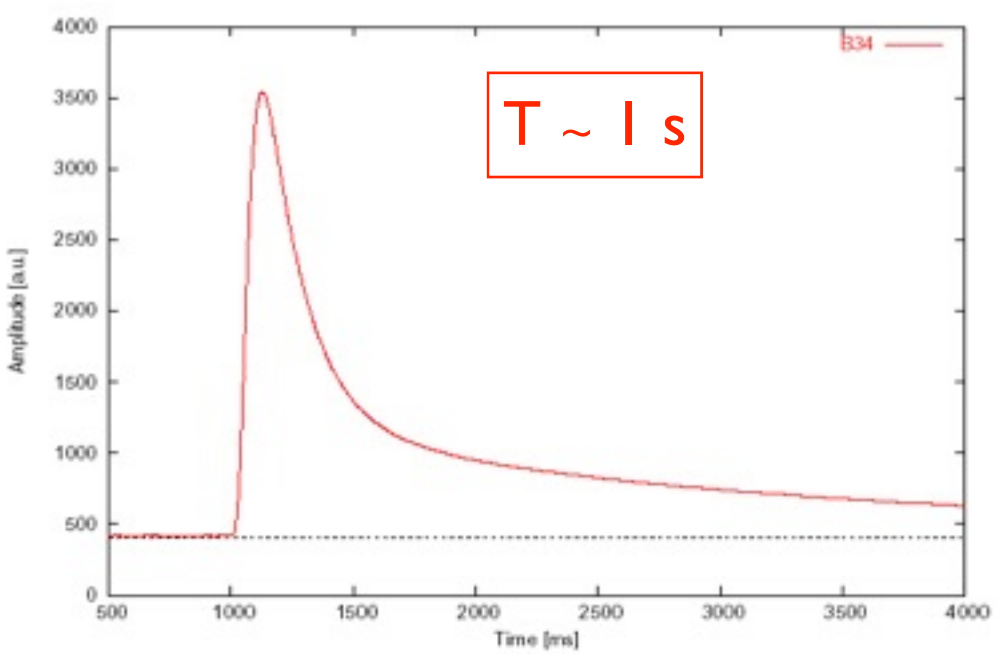
I bolometri di TeO_2





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

$$\tau = \frac{C}{G}$$



Pro: - buona risoluzione enrgetica
- versatilità (molti elementi diversi)
- elevata efficienza (sorgente=rivelatore)

Contro: - nessun spessore morto
- alta tecnologia (basse temperature)
- lentezza di risposta (impulsi)

Sensibilità sperimentale

$$S^{0\nu}_{1/2}(m_{ee}) \propto \epsilon \frac{i.a.}{A} \frac{1}{\sqrt{G^{0\nu}}|M^{0\nu}|} \sqrt[4]{\frac{bkg \cdot \Delta E}{M \cdot t_{meas}}}$$

- Isotopo

- Massa
- Risoluzione Energetica
- Background
- Tempo di misura

- ✣ Laboratori profondi
- ✣ Approccio bolometrico
- ✣ Grandi matrici di bolometri
- ✣ Selezione dei materiali
- ✣ Controllo delle procedure
- ✣ Condizioni stabili su scale di molti anni

BOLOMETRI

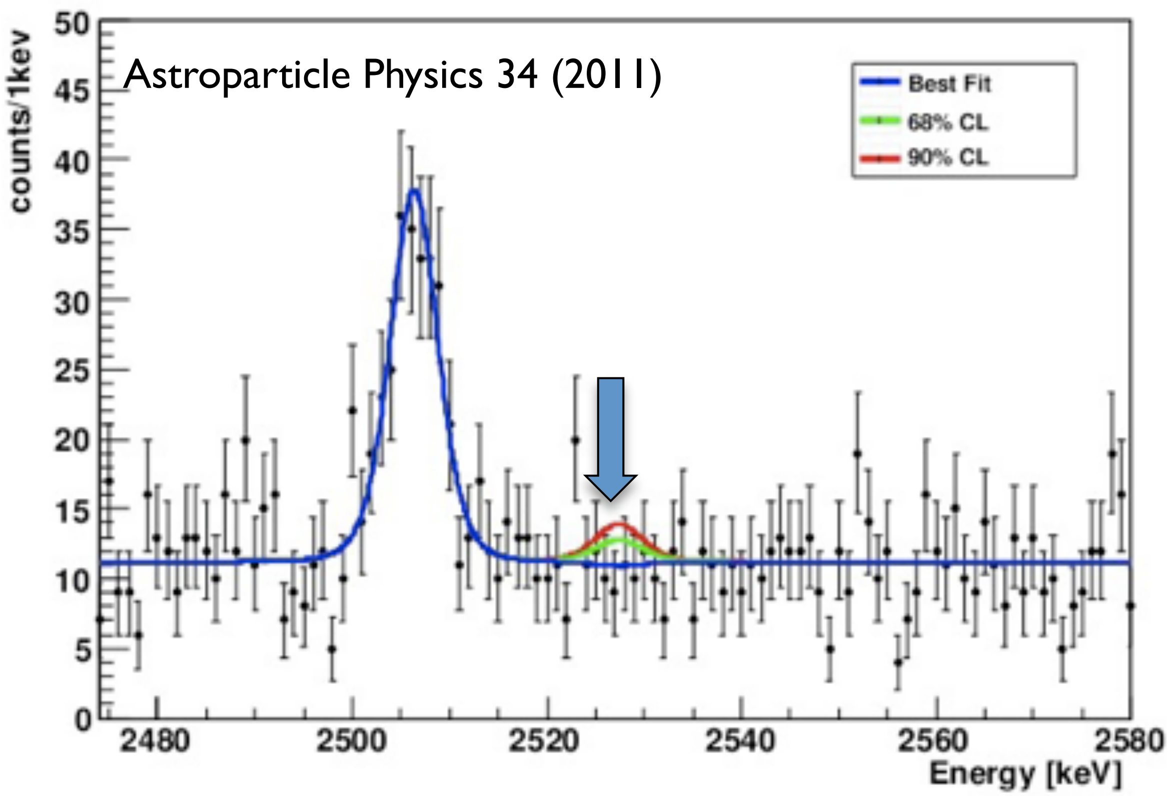
Candidato ββ: ^{130}Te **– Q** 2527.5 keV
Massa (isotopo): 206 kg ^{130}Te – **$N_{\beta\beta}$** 9.6 x10^{26}
Fondo atteso: 0.01 c/keV/kg/y
Risoluzione: ~ 5 keV @ROI
Sensibilità $T_{1/2}^{0\nu}$: 1.6x10^{26} y in 5 y
Sensibilità $<m_{ee}>$: $<m_{ee}>$ < 40 ÷ 94 meV in 5y (IH)

L'evoluzione dei bolometri di TeO_2

$\Delta E = 6.2 \pm 2.5$ keV (~0.3% FWHM)

Bkg = 0.169±0.006 c/keV/kg/y

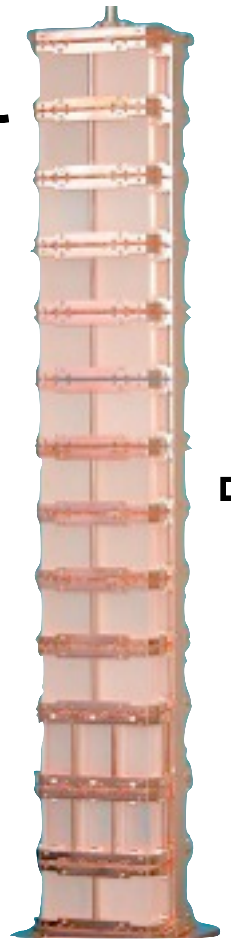
$T_{1/2}^{0\nu}$ (y) > 2.8×10^{24} y (90% CL)



$\langle M_{bb} \rangle < 0.3 - 0.7$ eV

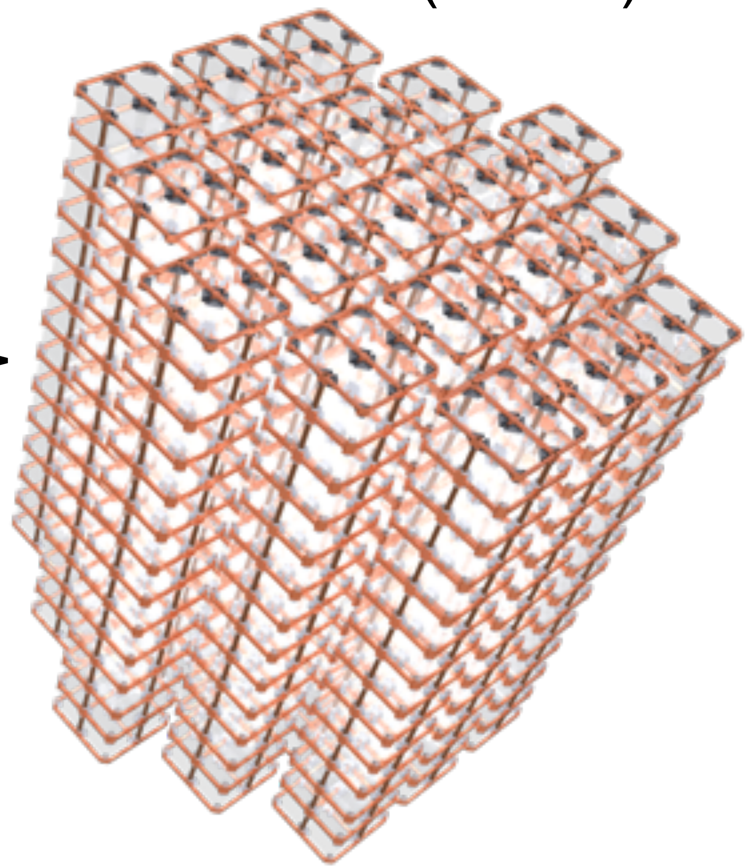
NME from F.Simkovic et al. Phys.Rev. C77
J.Suhonen et al. Int.Jou.Mod.Phys. E17
J.Menendez et al. Nucl. Phys. A818
J.Barea et al. Phys. Rev. C79

CUORICINO
40 kg
(2003-2008)



CUORE-0
(2012)

CUORE
1 ton
(~2014)



Studio sistematico delle sorgenti di fondo
Progettazione e realizzazione accurata delsetup

- Edificio ed infrastrutture
- Rivelatore
  - Cristalli
  - Struttura
  - Assemblaggio
- Sistema criogenico
- Sistema di calibrazione
- Elettronica e DAQ

CUORE

Cryogenic Underground Observatory for Rare Events

Closely packed array of 988 TeO_2 crystals 5×5×5 cm^3 (750 g)

741 kg TeO_2 granular calorimeter

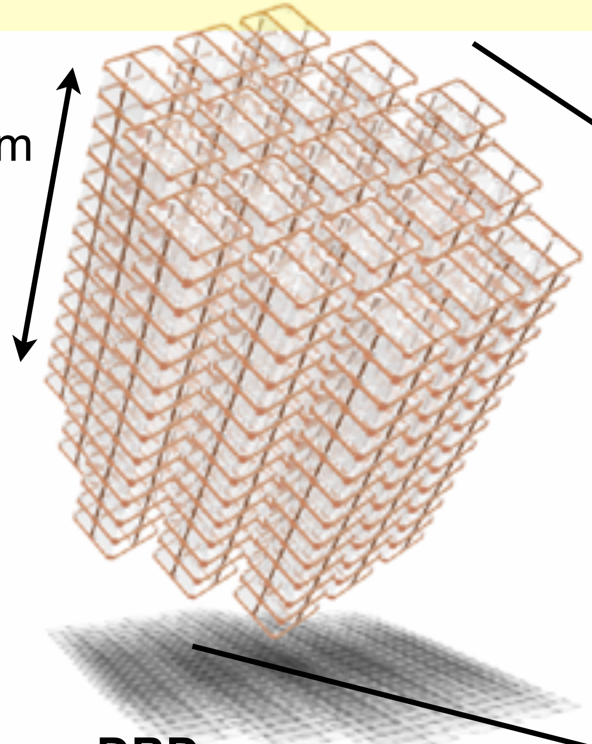
600 kg Te = 203 kg ^{130}Te

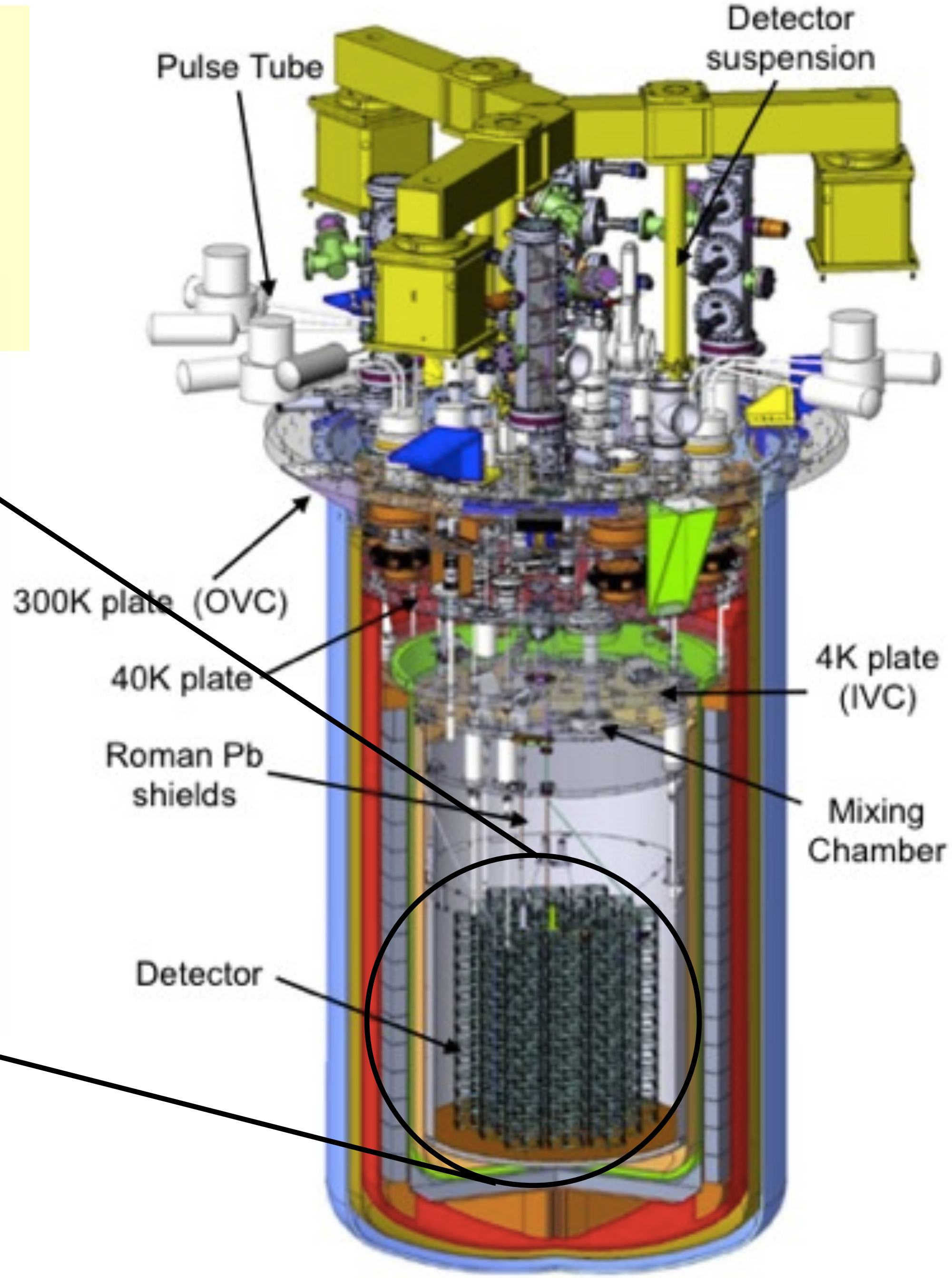
Single high granularity detector

19 torri

13 piani ciascuna

4 cristalli ciascuna





Calorimetric experiment on ^{130}Te neutrinoless DBD

Background	ΔE	$T_{1/2}$	$<m_{ee}>$			
c/kev/kg/y	keV	10^{26} y	R(QRPA)[1]	np(QRPA)	ISM[3]	IBM-2[4]
0.01	5	2.1	35-66	41-67	65-82	41
0.001	5	6.5	20-38	23-38	37-47	23

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

Singolo sistema criogenico (T_{work}=10-15mK)
Complesso sistema di schermi di radiazione
Disaccoppiamento meccanico
Sistema di calibrazione
Laboratorio sotterraneo (LNGS)

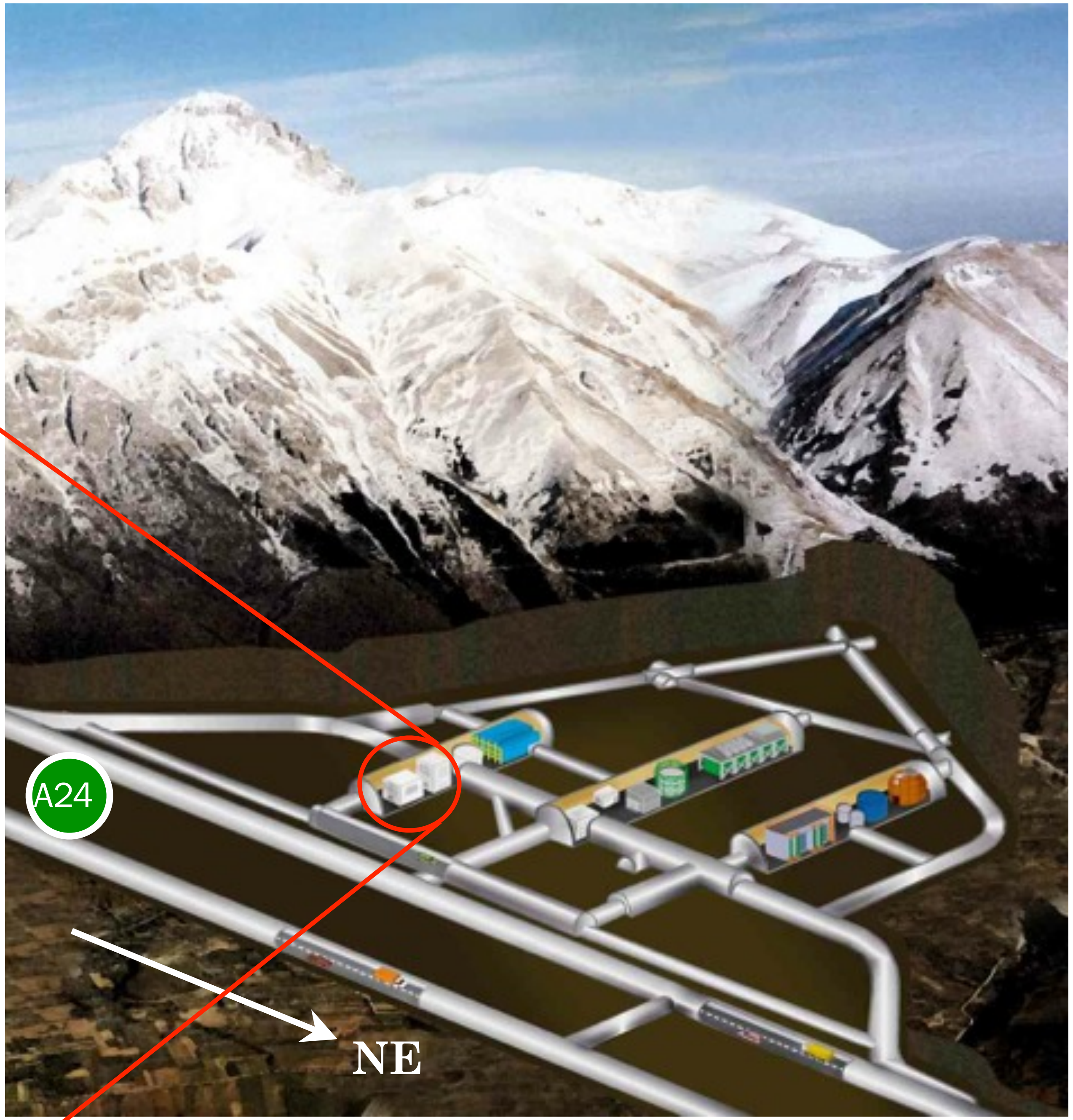
Dark Matter search potential

La Collaborazione CUORE

Il laboratorio sotterraneo LNGS

Edificio di CUORE

Edificio di Cuoricino/CUORE-0



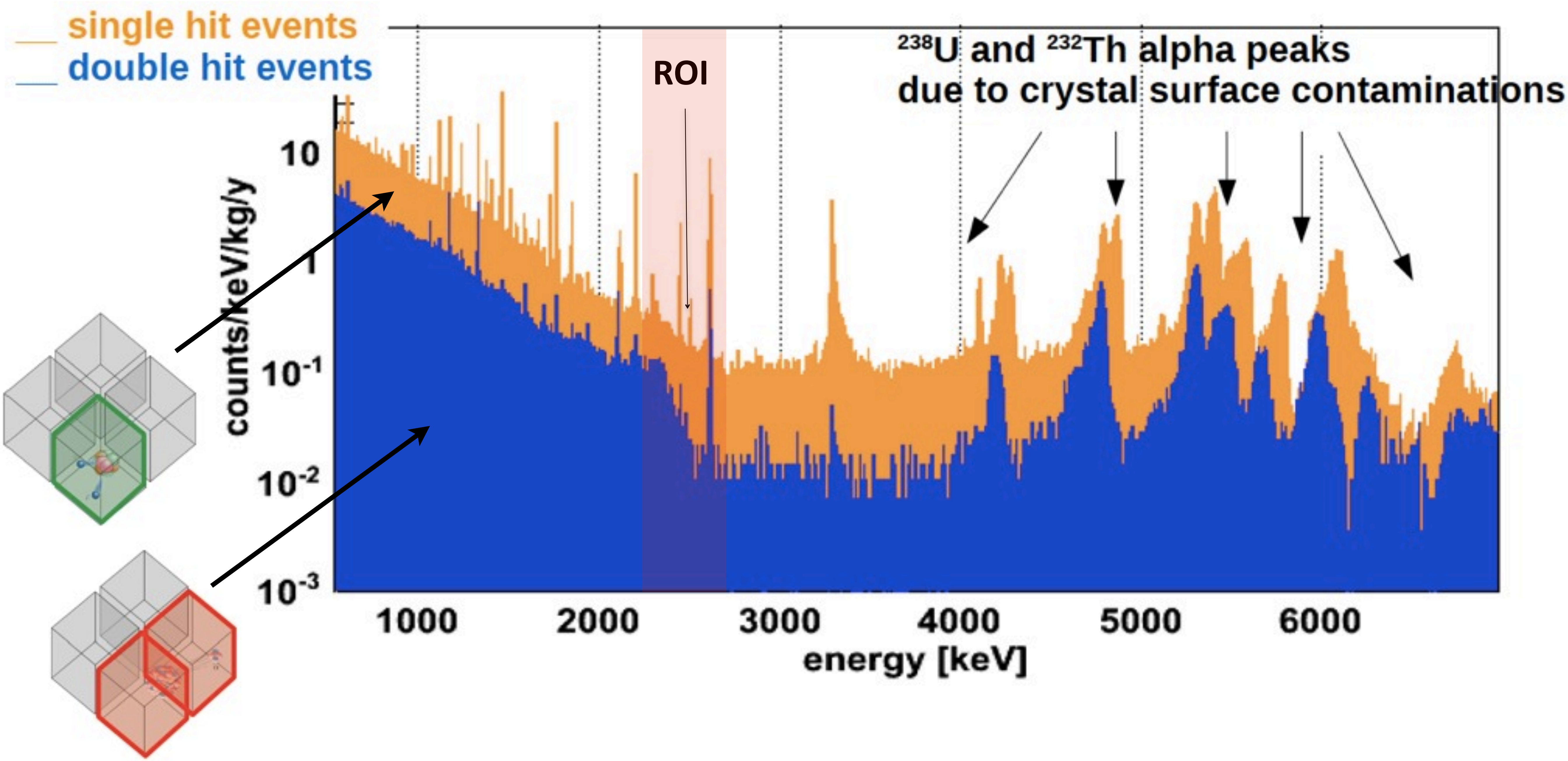
Underground facility

- Profondità media ~ 3650 m.w.e.
- Riduzione dei muoni di un fattore 10^6:

  $\sim 3\times10^{-8}\ \mu/(\mathrm{s\cdot cm^2})$

Il fondo

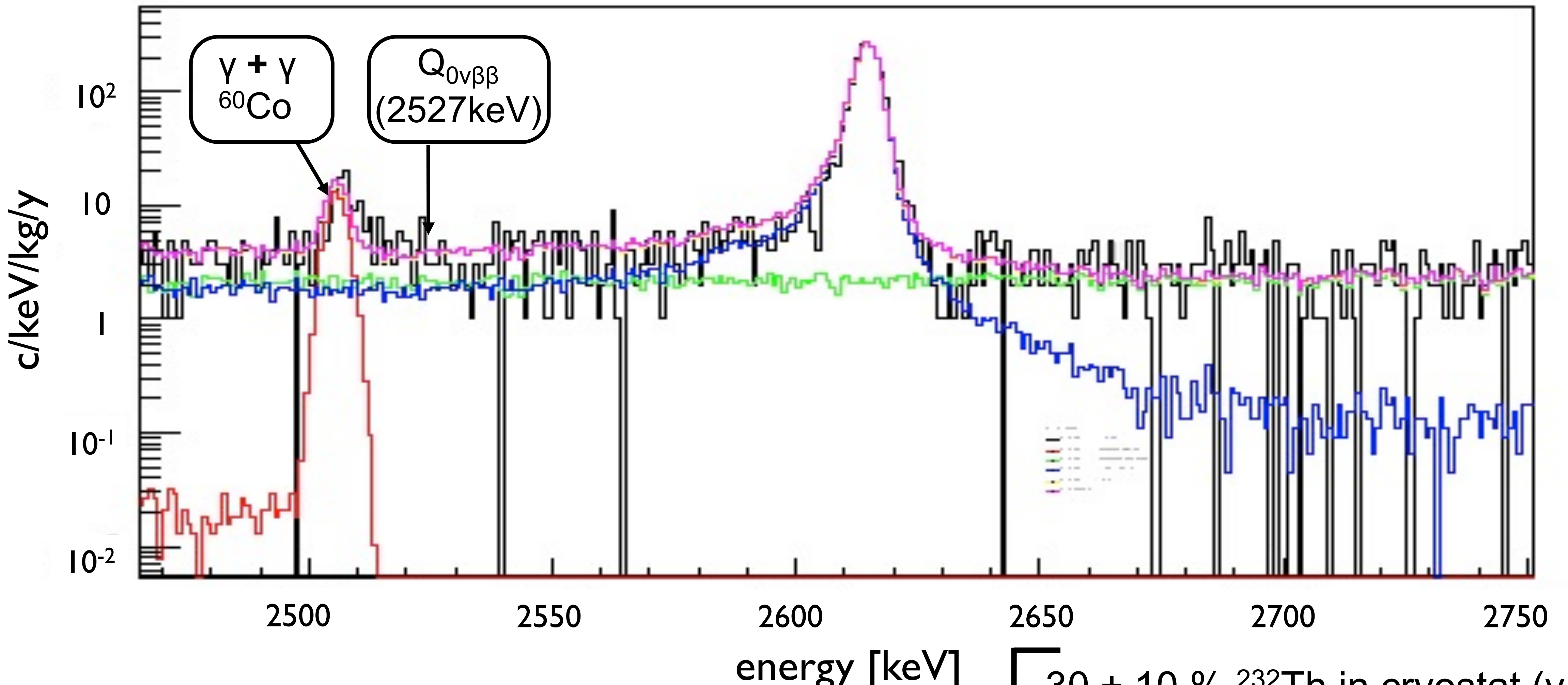
La maggior parte della statistica è data da Cuoricino ...



... ma molte informazioni sono state dedotte da numerose misure di R&D condotte presso il setup criogenico di sala C (LNGS)

Modello del fondo

MC: il fondo di CUORICINO è dominato da alfa degradate che rilasciano solo parte della loro energia nel rivelatore (contaminazioni superficiali)



30 ± 10 % ^{232}Th in cryostat (γ)

10 ± 5 % TeO_2 surface (α)

50 ± 20 % Cu surface (α)

BI @ 0vDBD ROI = 0.161 +/- 0.006 c/keV/kg/y
(spettro anticoincidenza, 5x5x5 cm^3 crystals)

C.Arnaboldi et al. http://arxiv.org/abs/hep-ex/0212053

C.Arnaboldi et al. Phys. Rev C 78 (2008) 035502

Bilancio

Source	CUORE in the ROI c/(keV kg y)	Source of data
Cosmogenic activation of crystals (bulk)	$\sim 1\ 10^{-3}$	NAA + MC
Gold wires (^{232}Th and ^{238}U) (bulk)	$< 1\ 10^{-3}$	Bolometric test + HPGe
Copper frames (^{232}Th) (bulk)	$< 1.5\ 10^{-3}$	HPGe + NAA + MC
^{232}Th in the Roman lead shield (bulk)	$< 4\ 10^{-3}$	Bolometric + HPGe
Muon interactions (bulk)	$\sim 1.8\ 10^{-3}$	Measured fluxes + MC
TeO_2 crystals surface activity	$< 4\ 10^{-3}$	Bolometric tests (CCVR) + MC
Surface activity of the mounting structure	$< 2\text{-}3\ 10^{-2}$	Test on small tower + MC

If contamination in the R&D run are due to surface contamination of copper structure

Conservative values

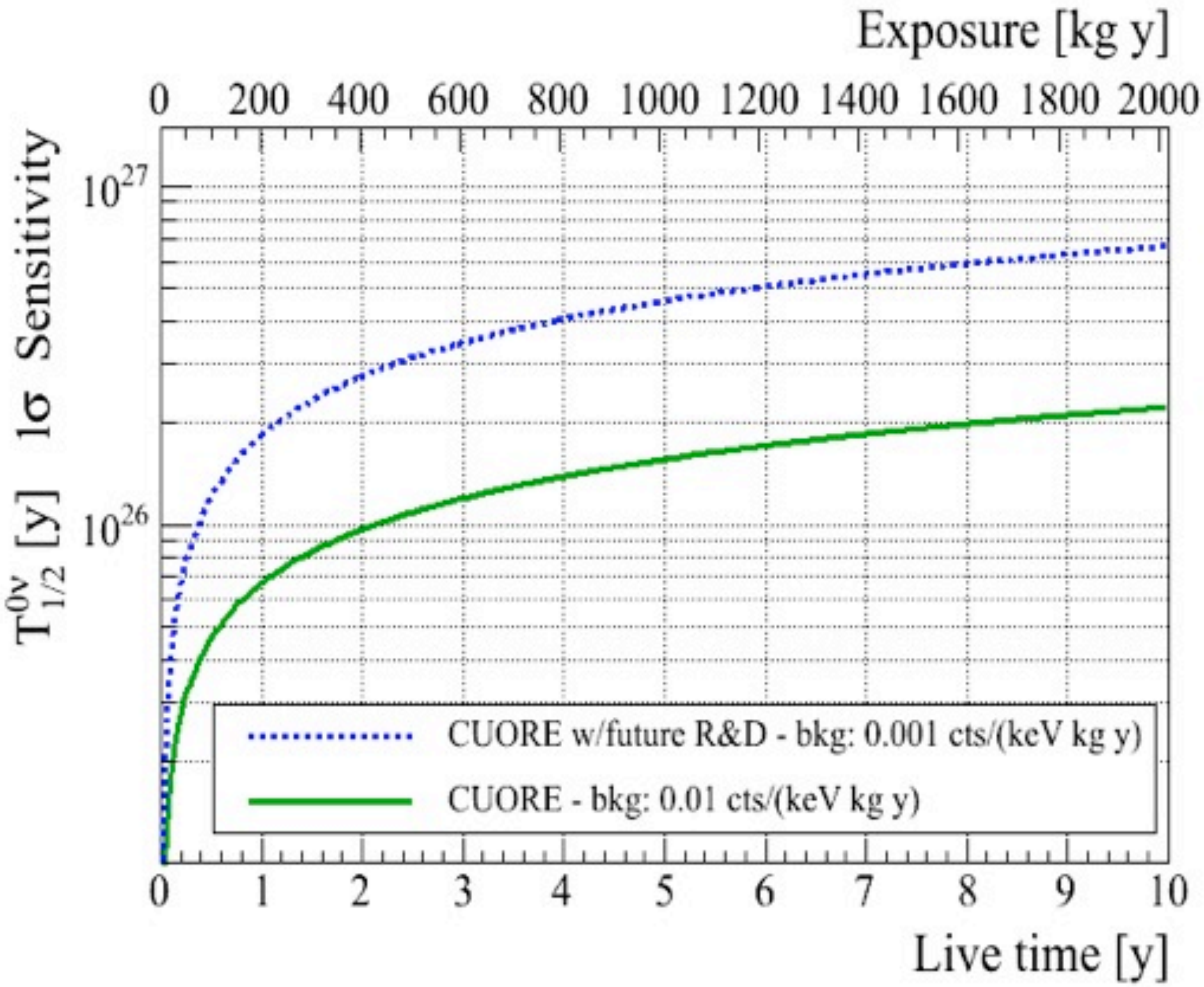
- Different depth profiles of surface contaminations compared and largest values quoted here

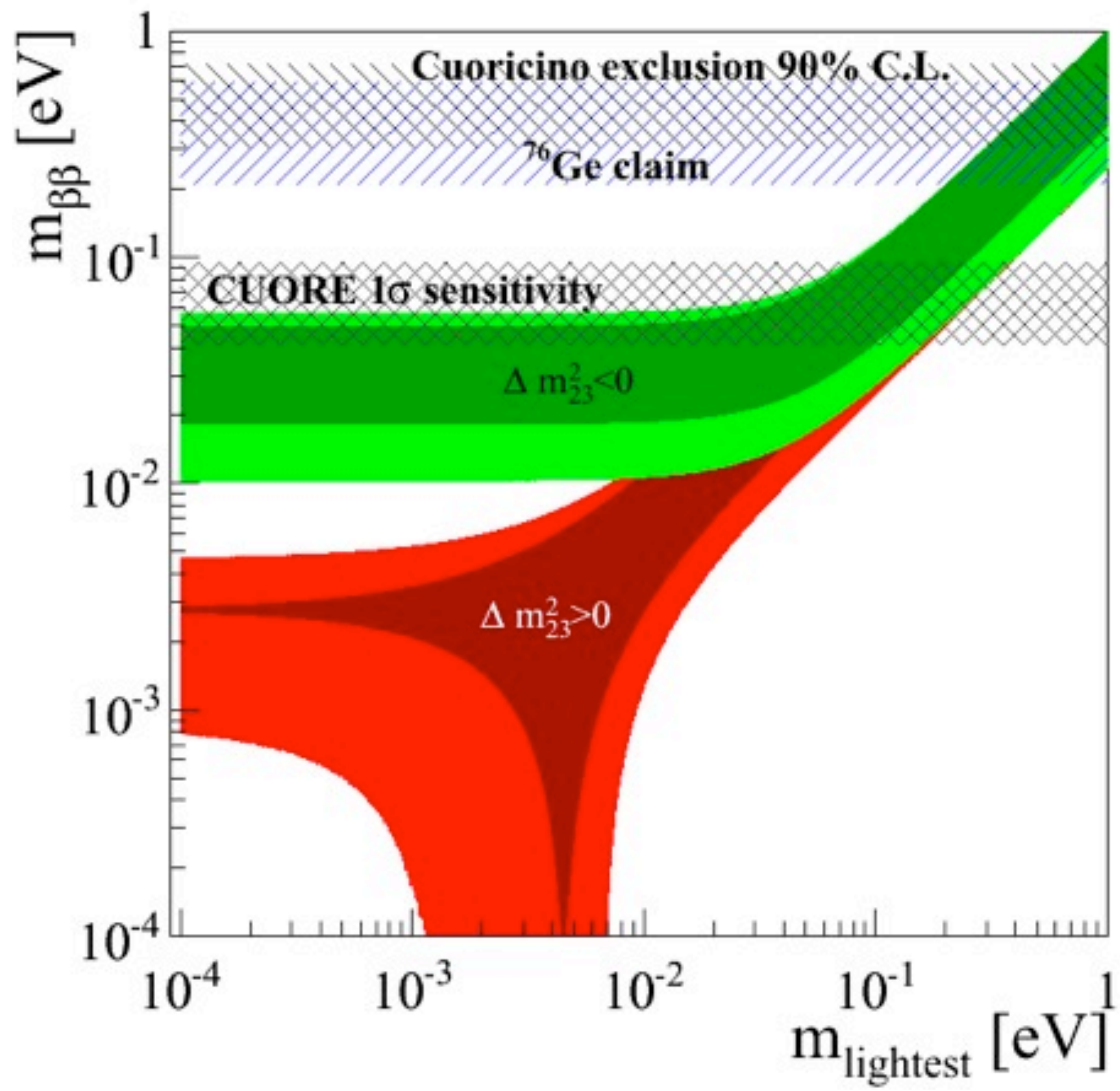
Upper limits

- Attribute all events in the target region as due solely from a certain source

F.Alessandria et al. [CUORE coll.] http://arxiv.org/abs/1109.0494v1
C.Arnaboldi et al. Phys. Rev. C 78 (2008) 035502
F.Bellini et al. Astr.Phys. 33 (2010) 169
F.Alessandria et al. [CUORE coll.] http://arxiv.org/abs/1108.4757v1

Sensibilità di CUORE





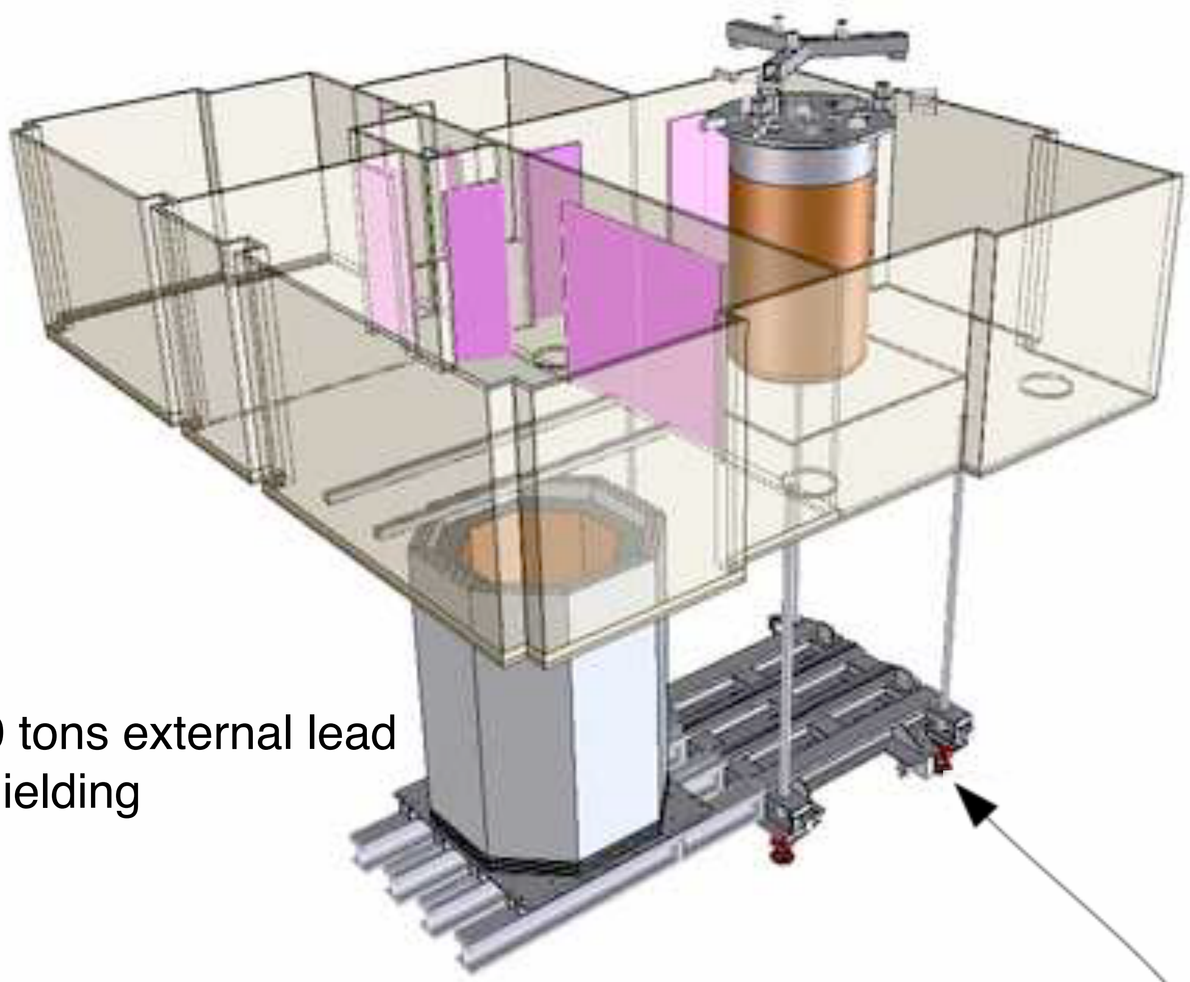
BI goal: 0.01 c/keV/kg/y

$T_{1/2}$ = 1.6 x 10^{26} y $\mathbf{m_{\beta\beta}}$ **= 41-95 meV**

L'elevata massa e la buona risoluzione energetica determinano la competitività di CUORE per sondare la regione IH: 41-95 meV

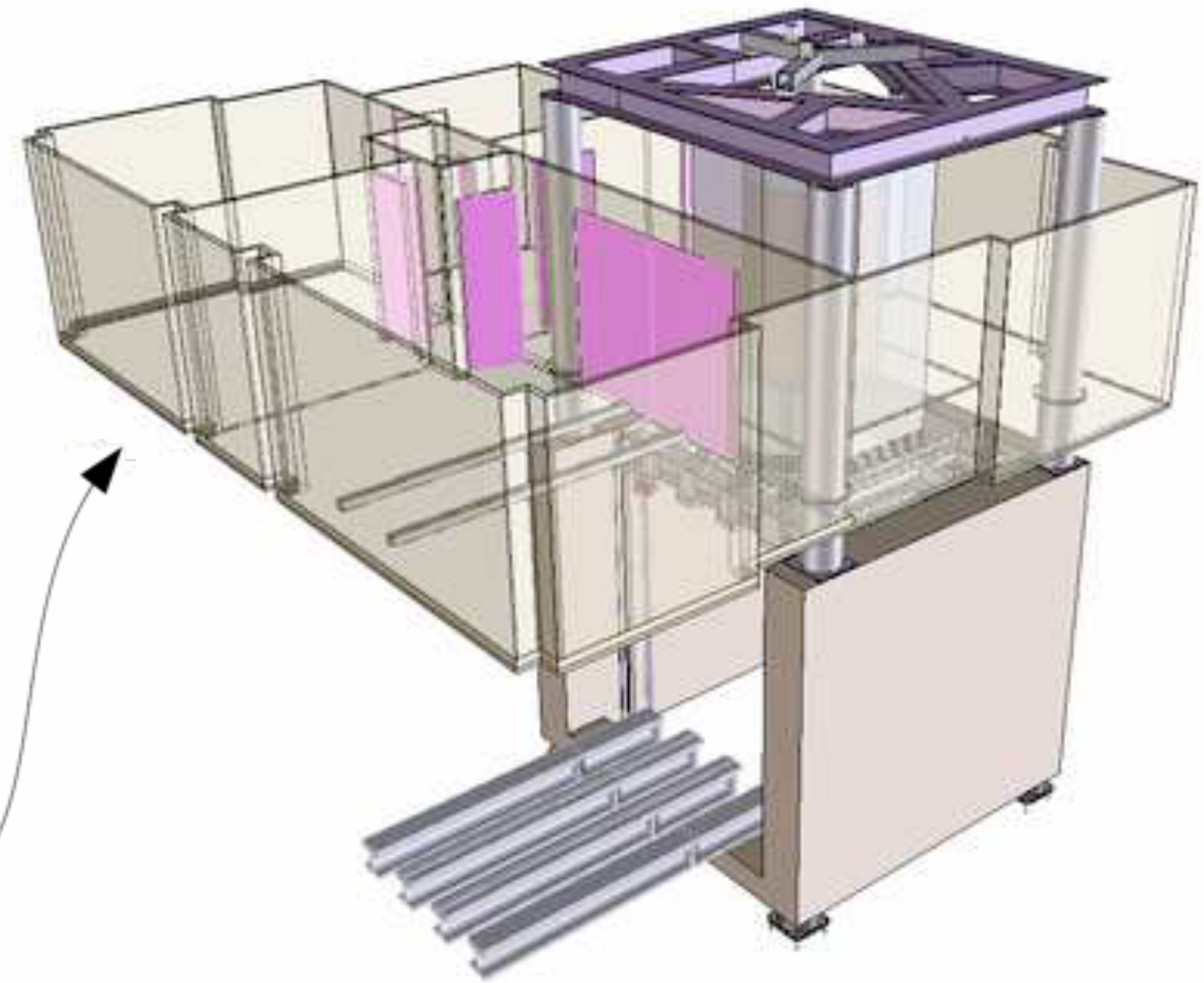
L’esperimento

L'edificio sotterraneo



20 tons external lead shielding

2nd Level
- Top flange access
- Suspension access
- Electronics & DAQ



1st Level
- Cryostat access
- Clean room

ground floor
- services (pumps, DU gas handling, compressors...)
- shields and screens storage

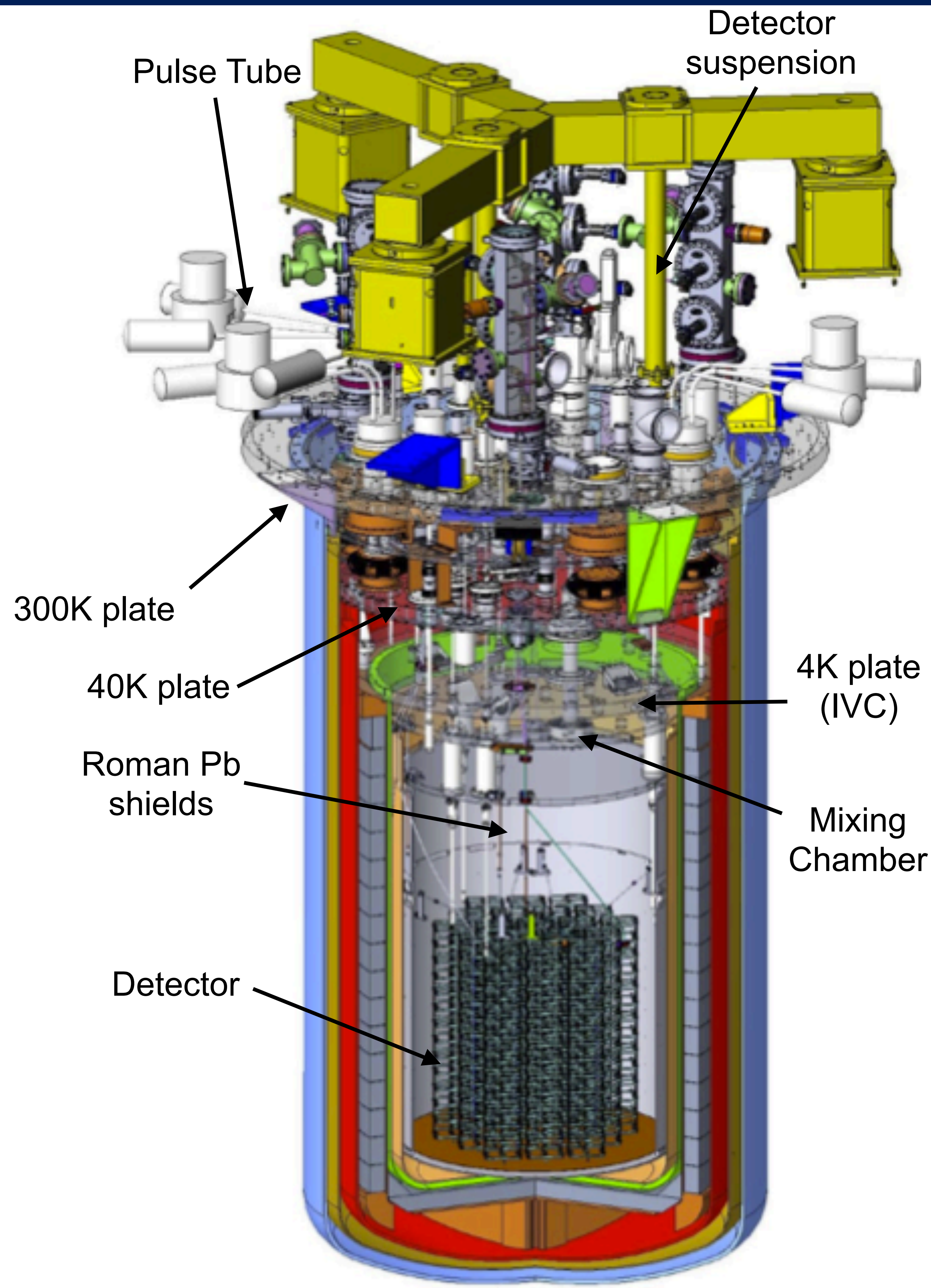
Il sistema criogenico

Custom cryogenic system @ LNGS.

- Improved shielding and material selection.
- High efficiency in background rejection, due to the packed geometry: minimum lead thickness surrounding the detector ~ 36 cm
- No cryogenics liquids: better duty cycle
- Mechanical suspension of the detector assembly completely independent from the refrigeretor structure: better control of noise induced by vibrations
- Severe control of the radioactivity of the set-up

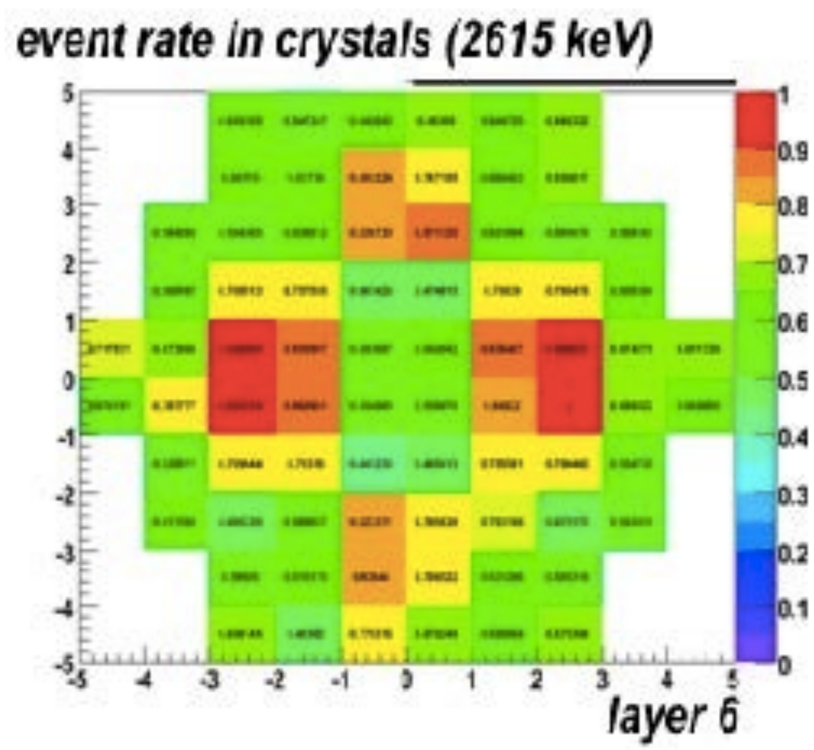
Embedded in the setup (after a severe control of the radioactivity of the materials):

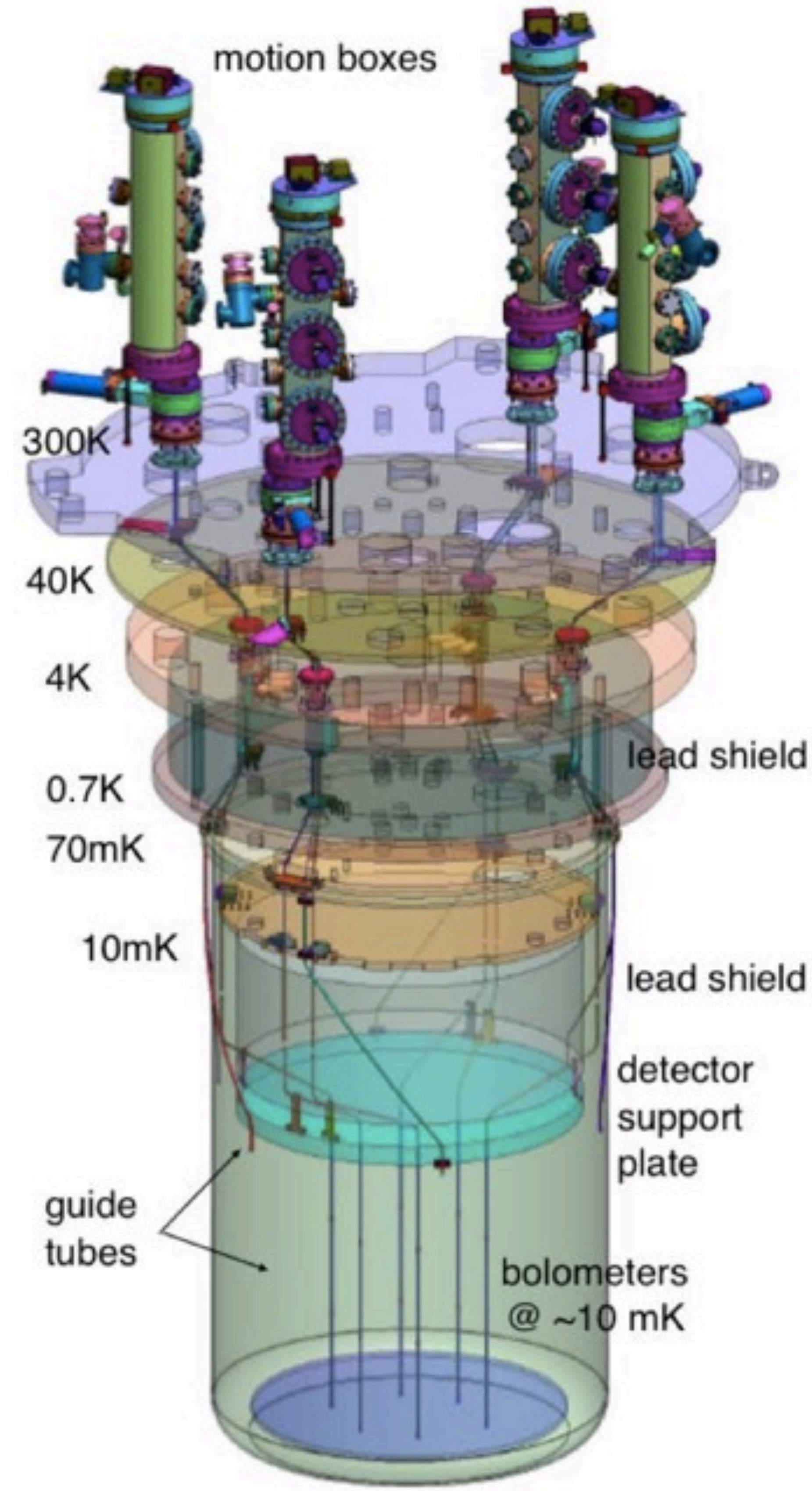
- Cryo-free dilution refrigerator (Leiden Cryogenics)
- Roman Lead (no 210Pb) cold shield
- Detector and Pd shiled suspension
- Calibration system



Il sistema di calibrazione

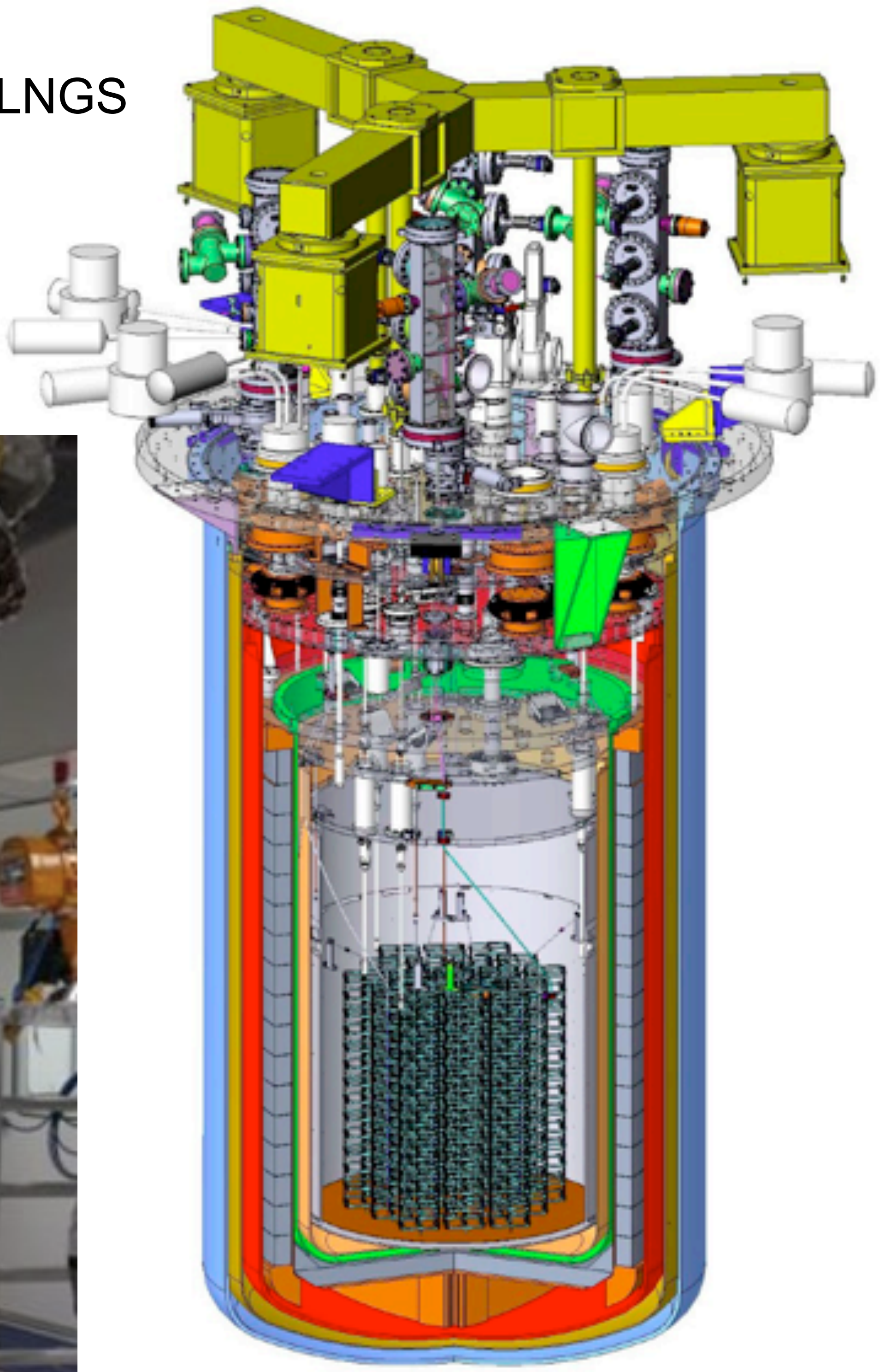
- 12 gamma source wires
  - ^{232}Th: thoriated tungsten wire
  - ^{56}Co: proton activated Fe wire
- Minimize down time but rate at each crystal not exceeding 150 mHz
- Stringent heat load requirement



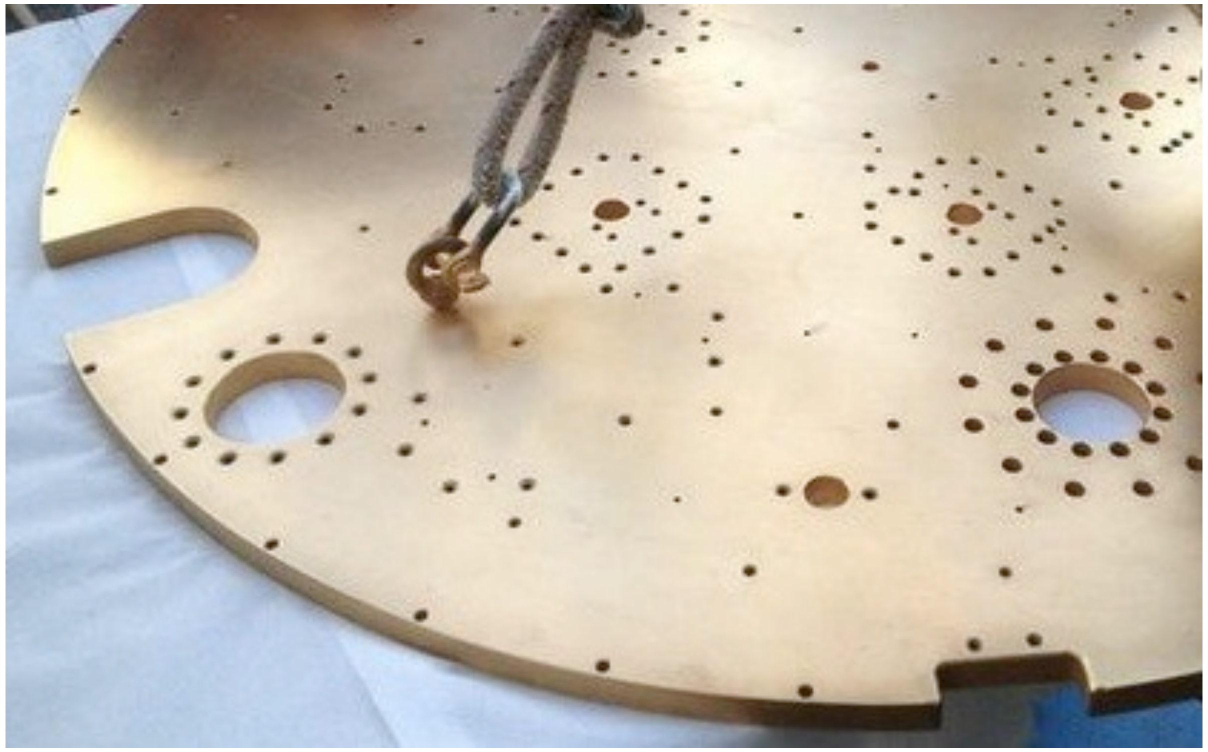


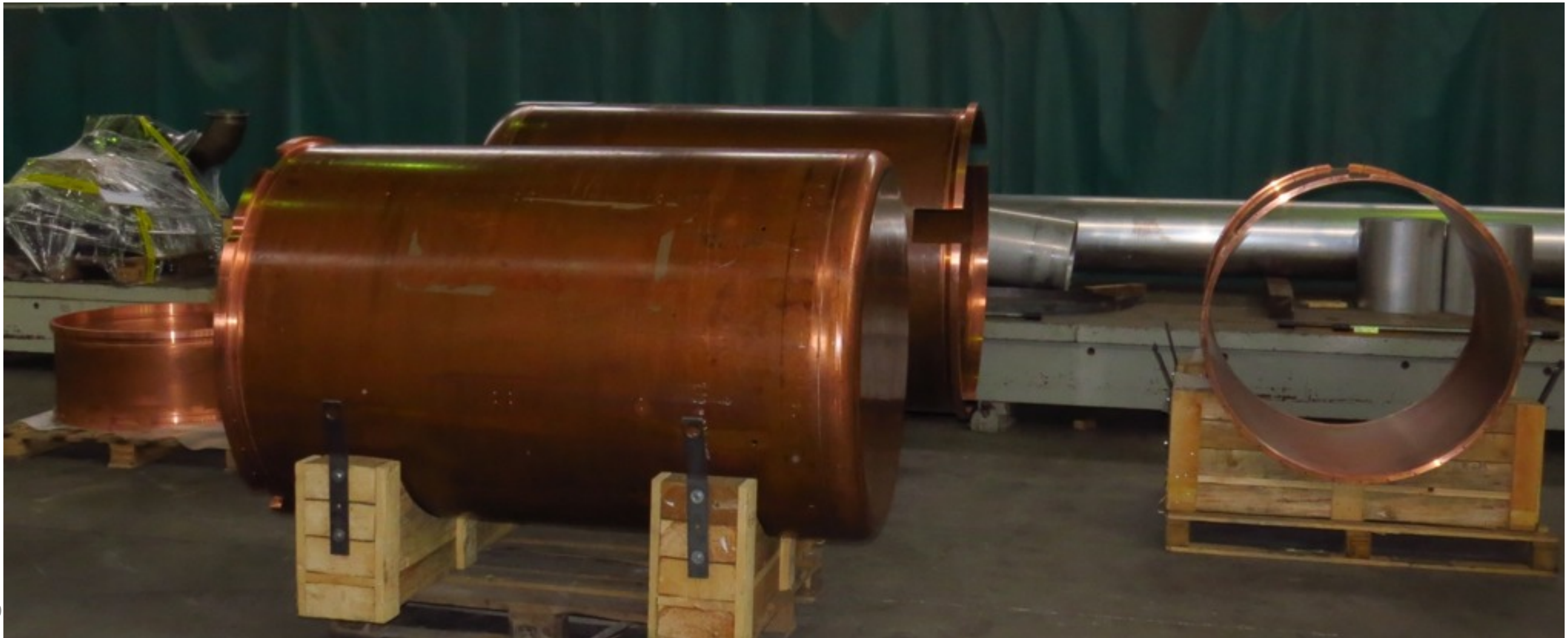
Criogenia

- Cryostat construction complete (delivered @ LNGS)
- Dilution unit performance better than expected. Delivered and tested @ LNGS
- CUORE building and infrastructures, ready
- Commissioning of the cryostat started on July 2012
  - 3 (of 6) cryostat chambers tested
  - System cooled to 4K



Criostato (600,50,10 mK)

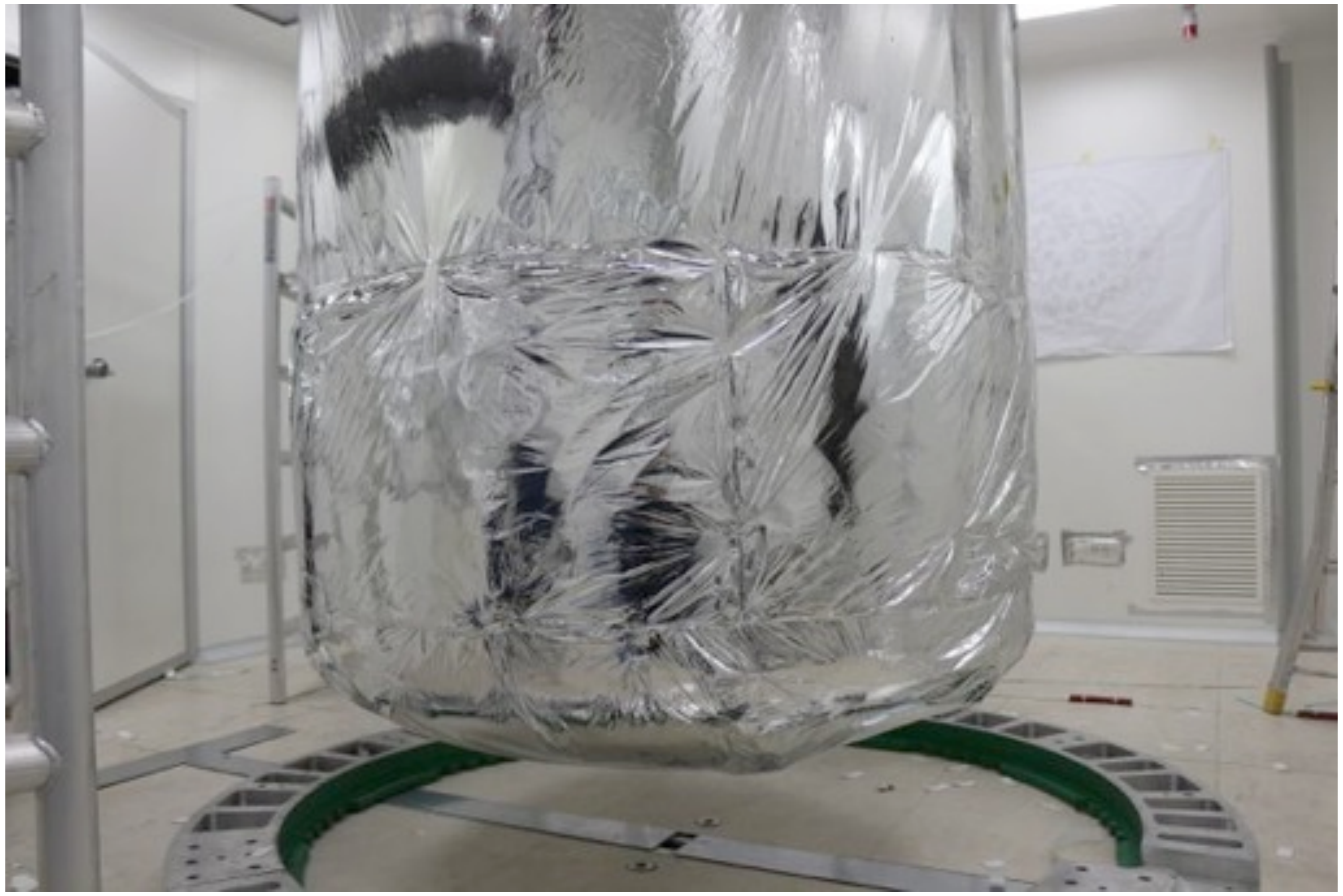




Commissioning

- commissioning @LNGS in progress
- 3 outer vessels assembled
- cooled to 4K in April 2013

Raffreddamento @ 4K



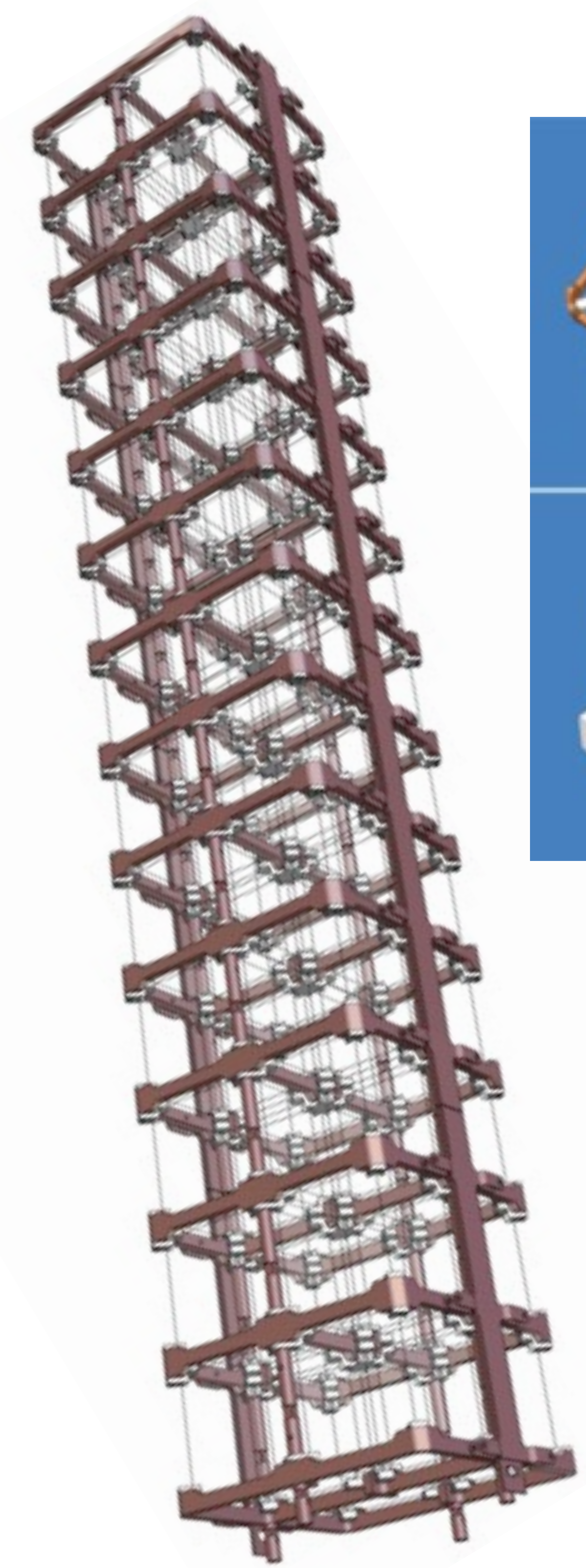
L’unità a diluizione

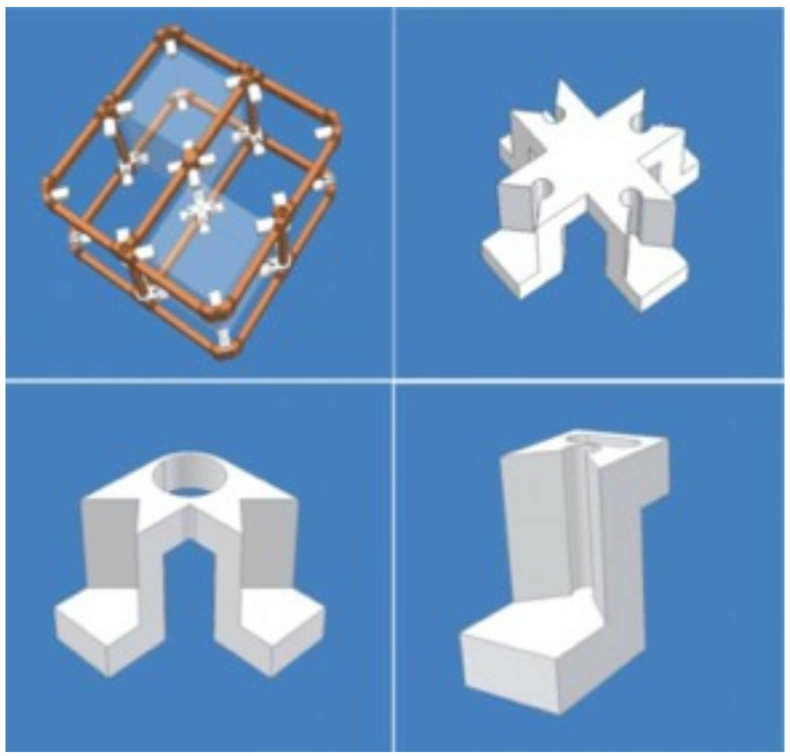
Tested on-site in a dedicated cryostat

- lowest **T**$_{\mathbf{base}}$ ≈ 4.95mK
- Cooling power (~10μW @ 12mK)

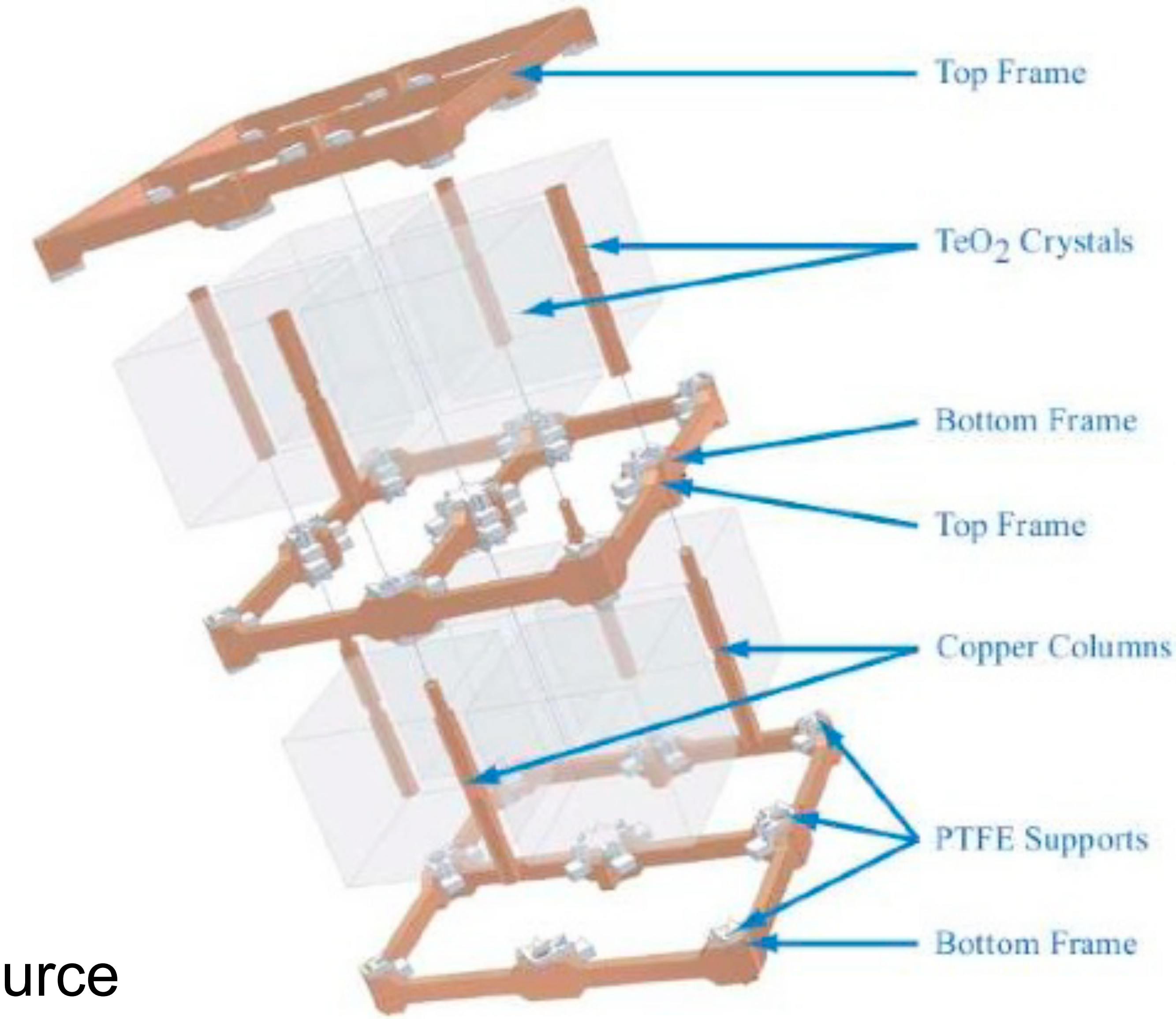
well within specifications

Una struttura migliorata

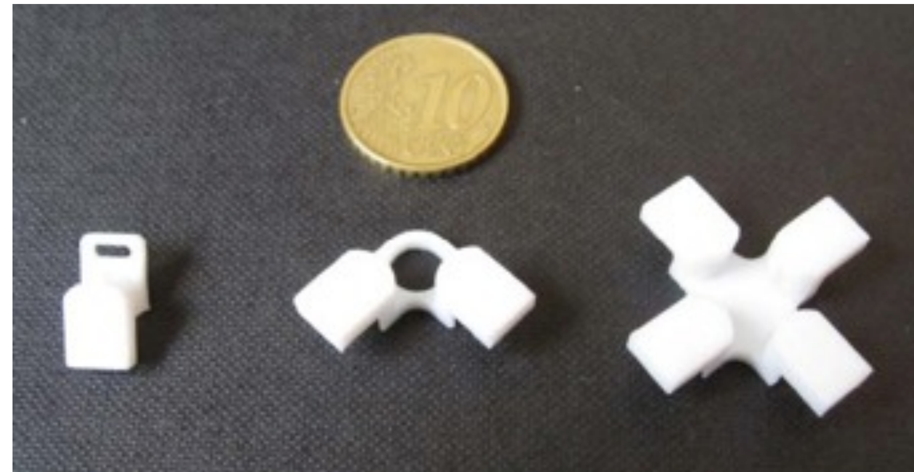


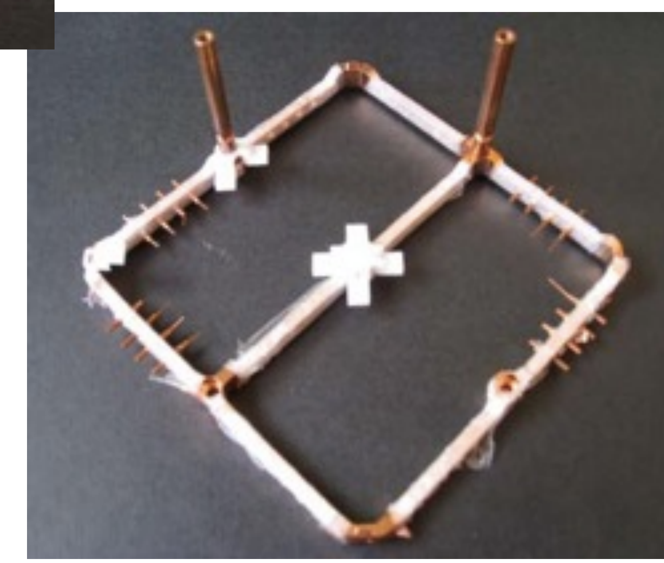


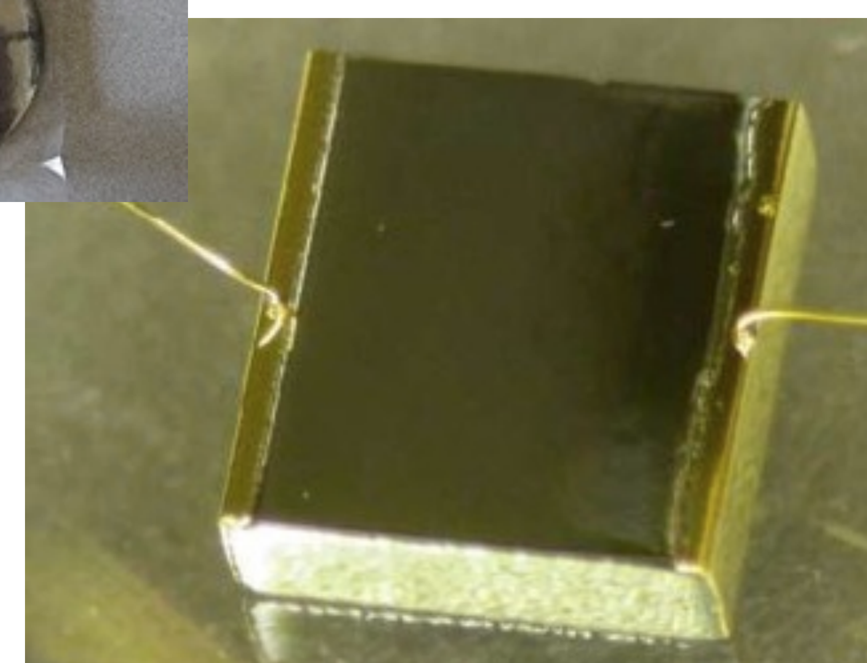
- Copper Frame:
  - Heat bath
  - Background source
- Teflon holders
  - The weak thermal link
  - Reduce vibration noise



Le parti del rivelatore





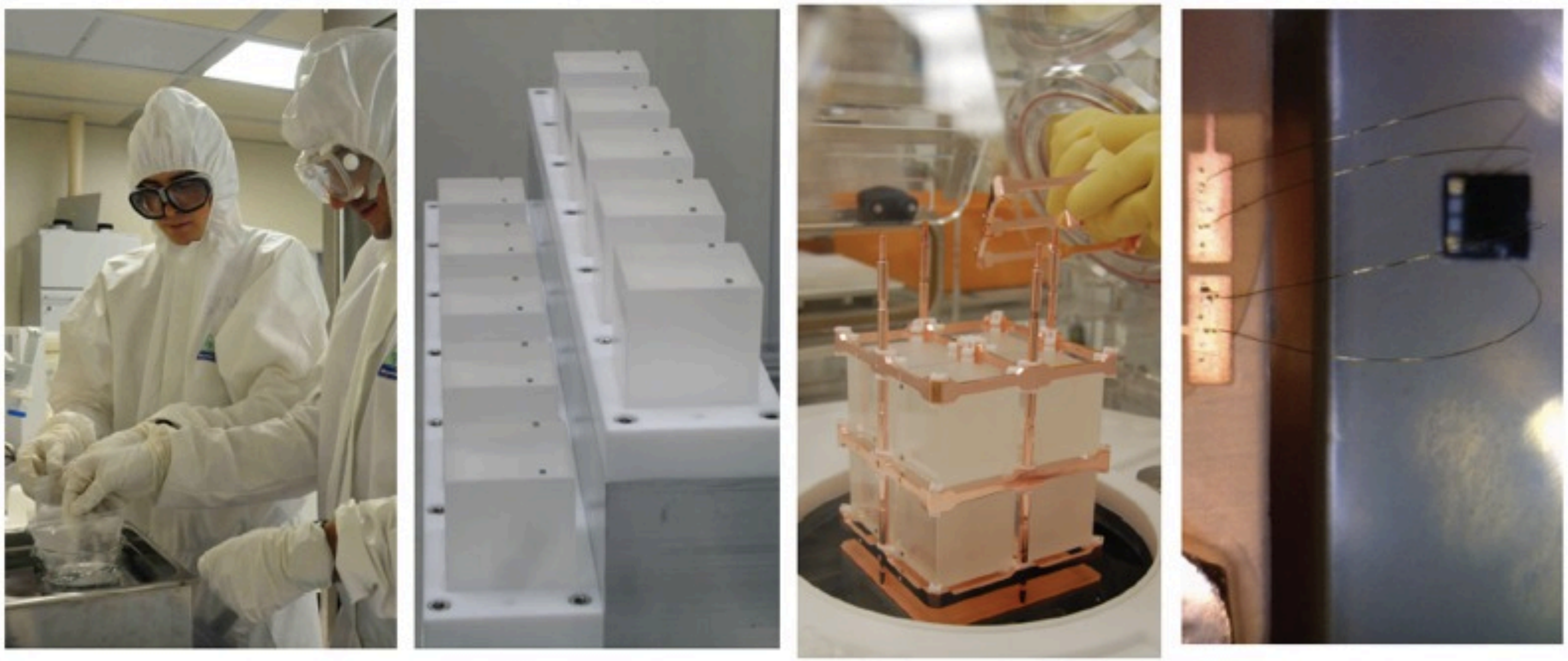


- TeO_2 production @ SICCS complete
- Teflon parts production complete
- Copper parts production complete in few months
- Copper cleaning progressing regularly (→ March 2014)
- Heaters production complete
- NTD production almost complete

NTD's: 695 of 1250 already delivered

Costruzione delle torri

CLEANING	GLUING	ASSEMBLY	BONDING



CLEANING	GLUING	ASSEMBLY	BONDING

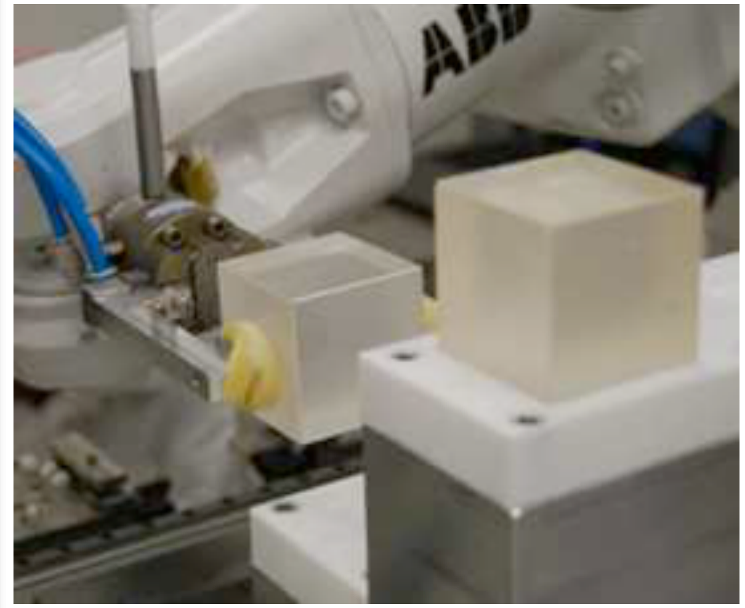
CLEANING
- Gluing consumables
- Periodic cleaning of glove boxes (every ~ 3 towers)

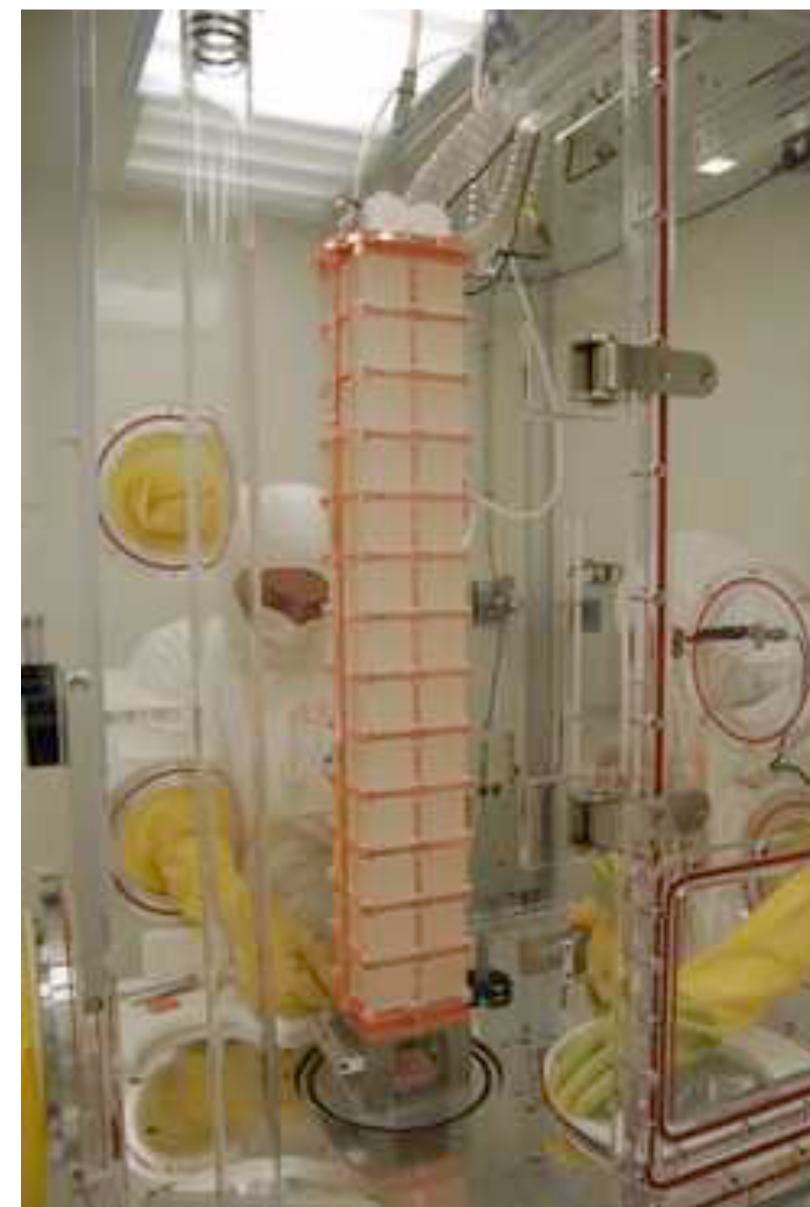
GLUING
- Attach NTDs & heaters to crystals

ASSEMBLY
- Mechanical assembly of crystals and copper into towers

BONDING
- Bond Au wires connecting NTDs & heaters to external traces

La linea di assemblaggio





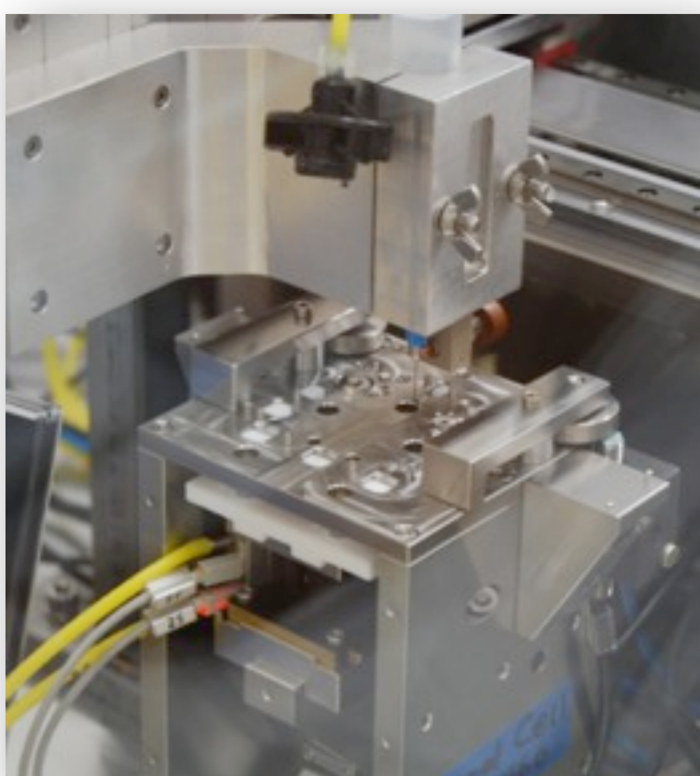
Single workstation with 4 interchangeable glove boxes for specific tasks

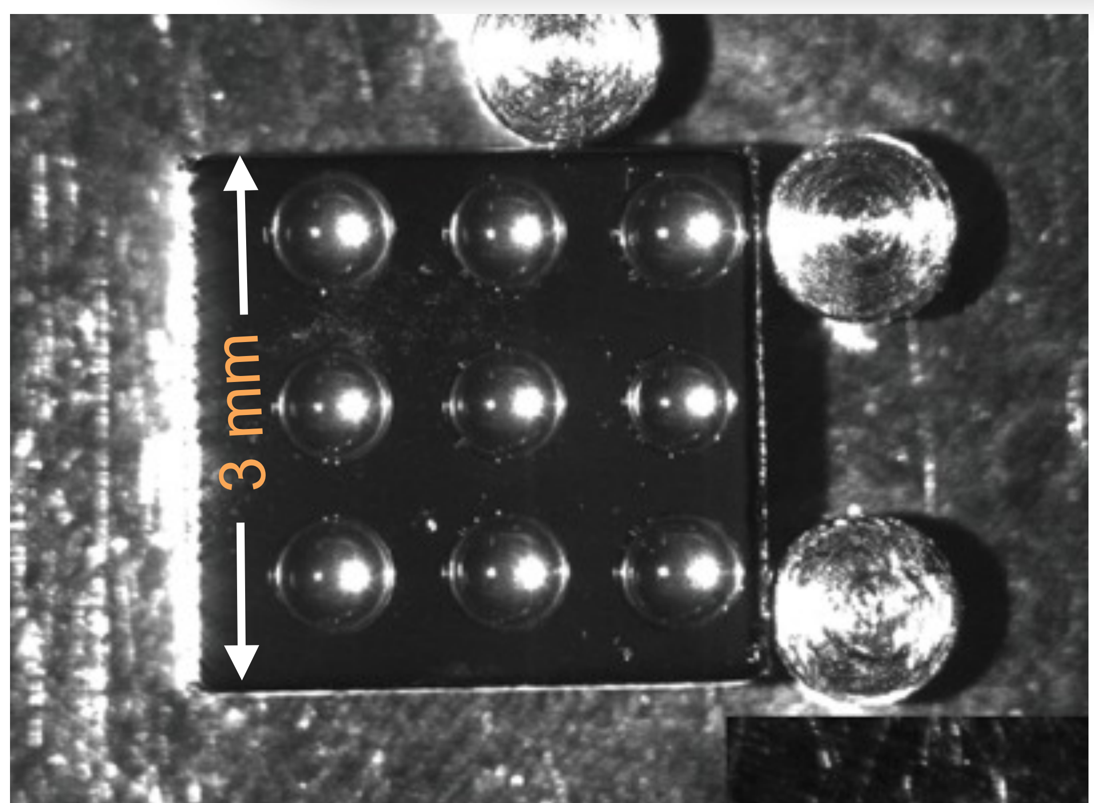
Mounting Box | Cabling Box | Bonding Box | Storage Box

Crystal-Sensor coupling

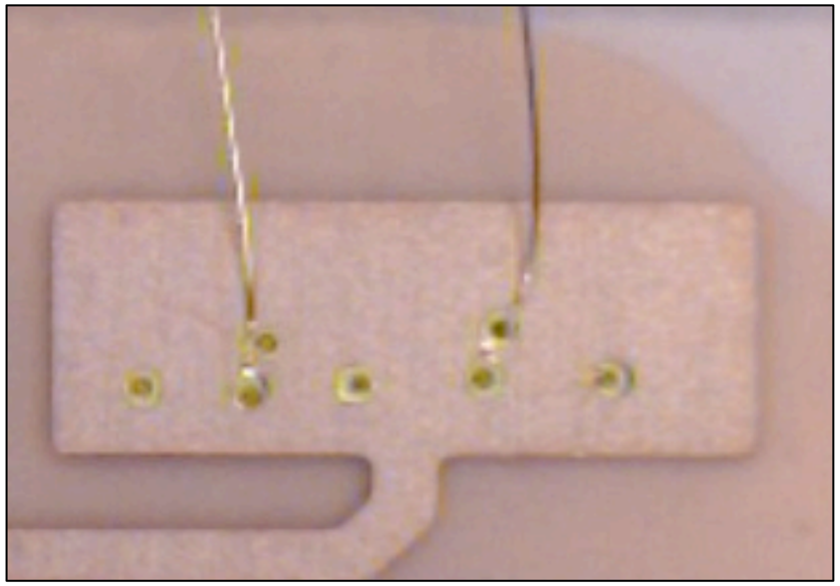
Robotic gluing for
- Uniformly sized
- Repeatable
- Controllable

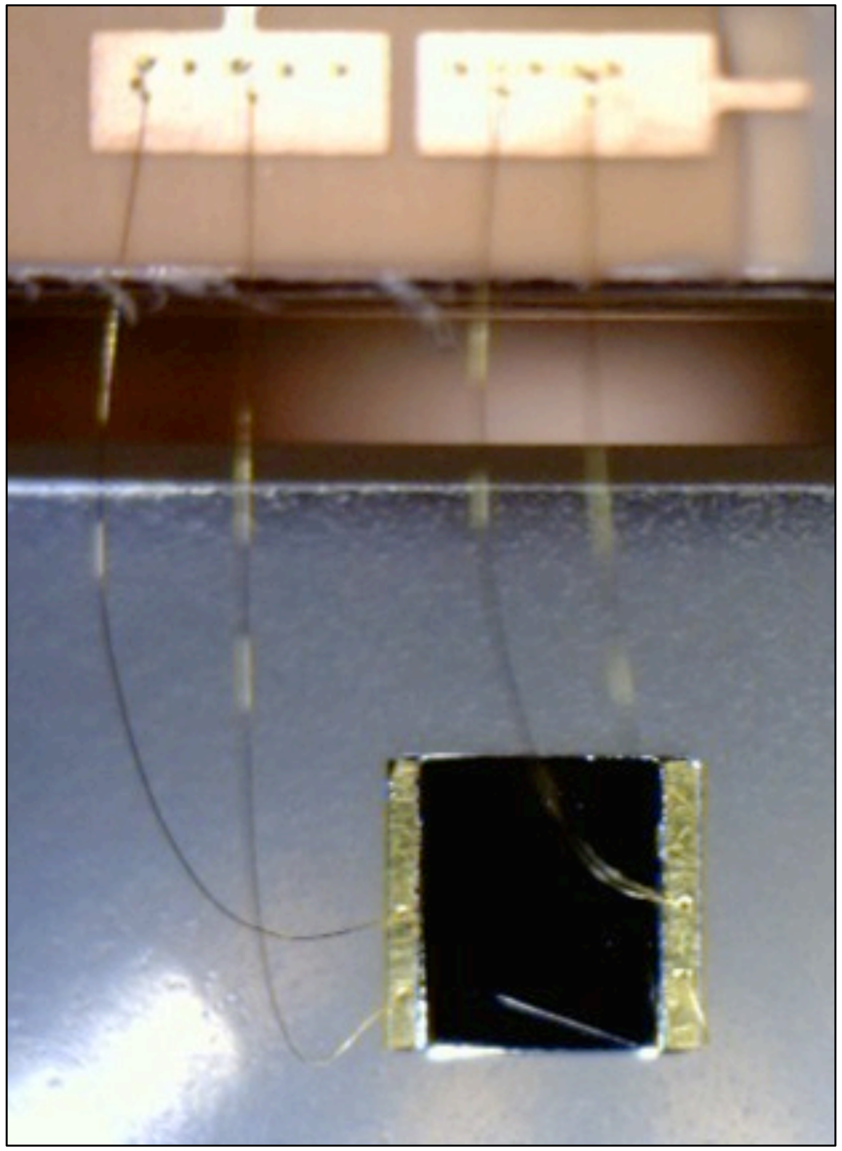
glue spots (and coupling)

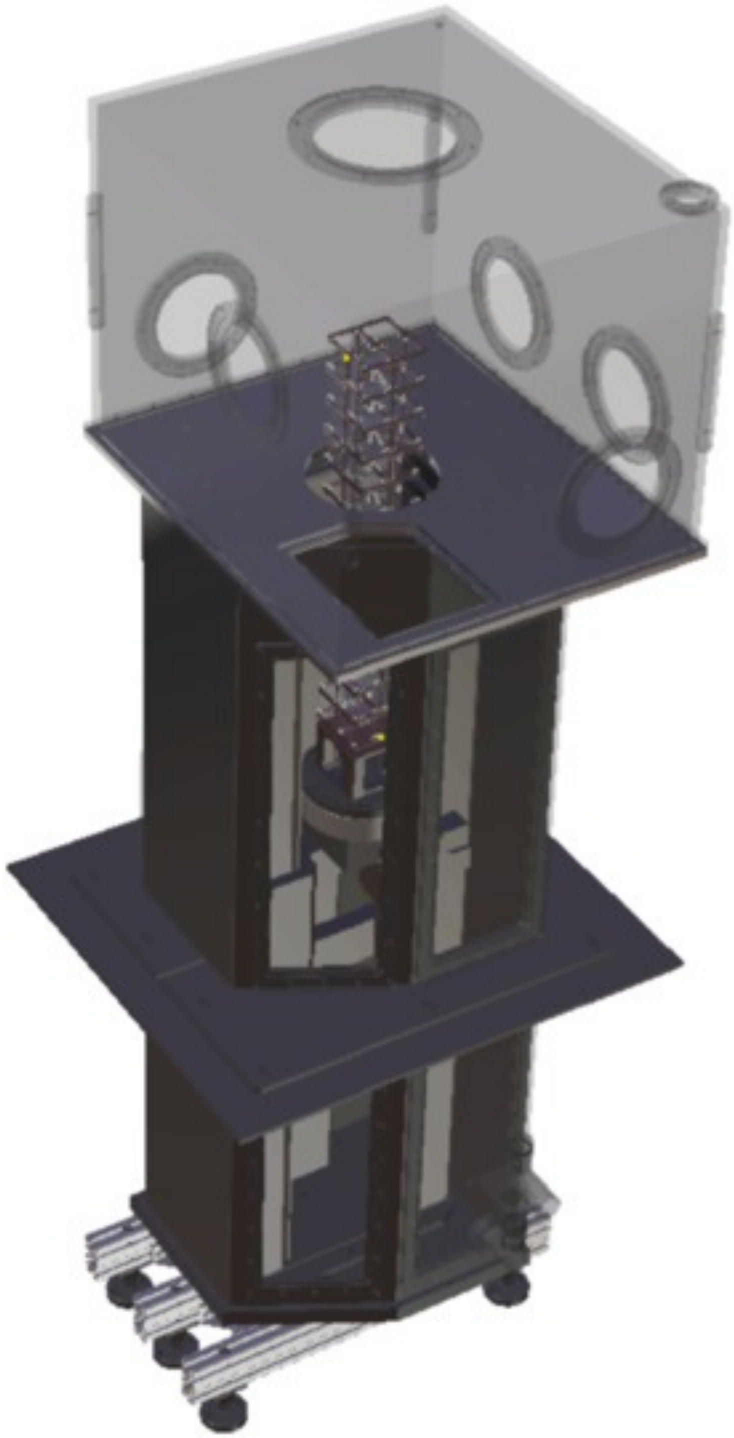


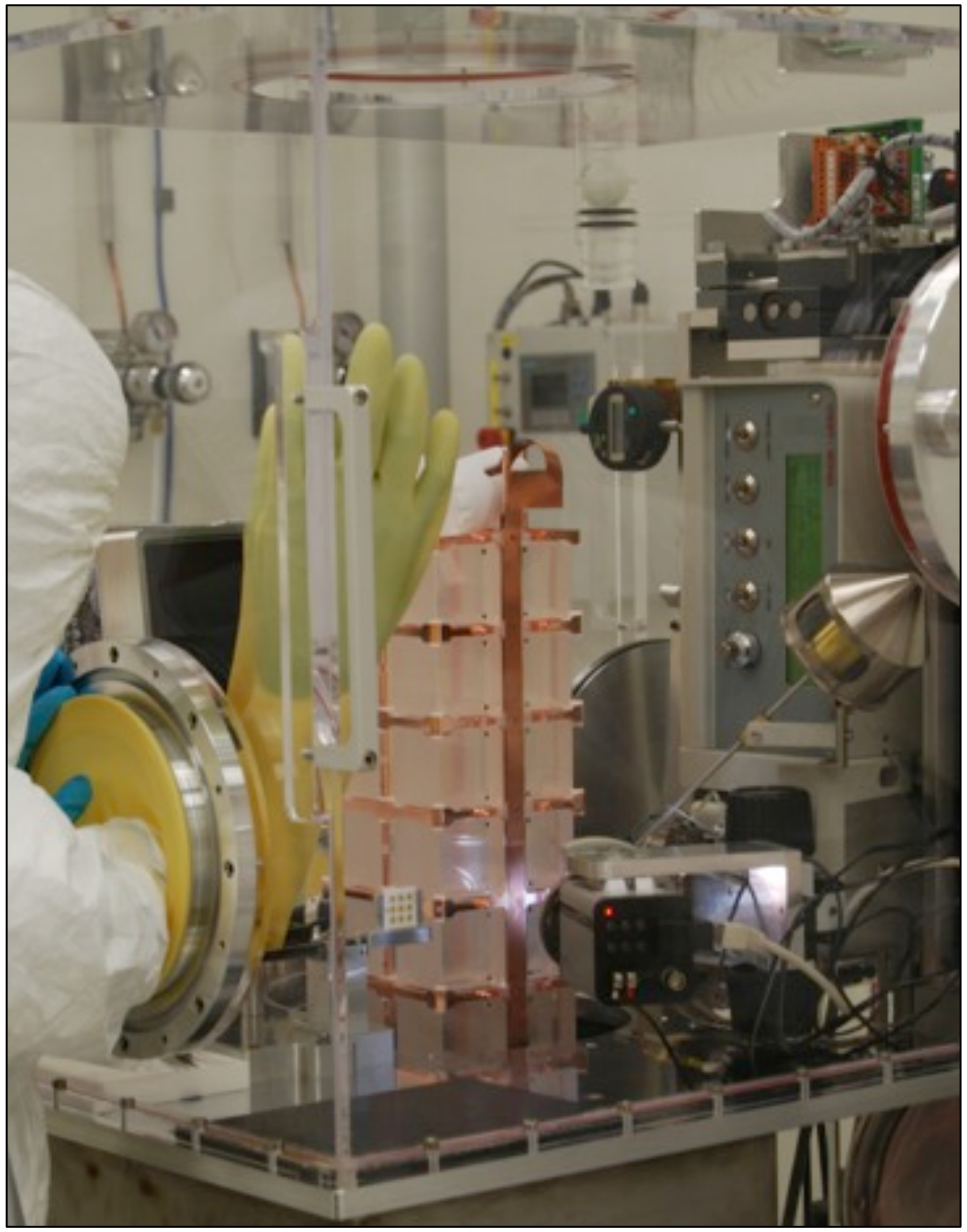


Bonding

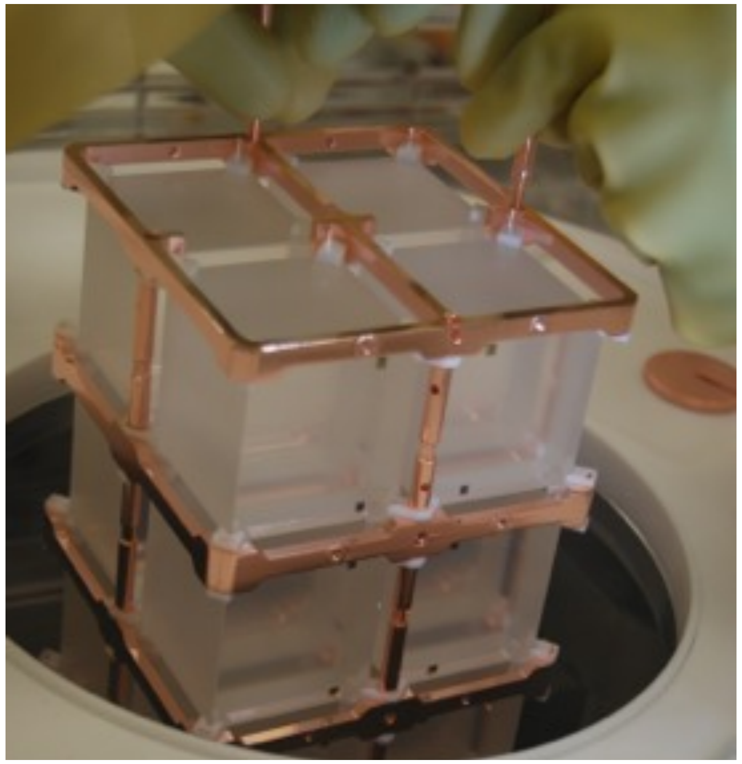


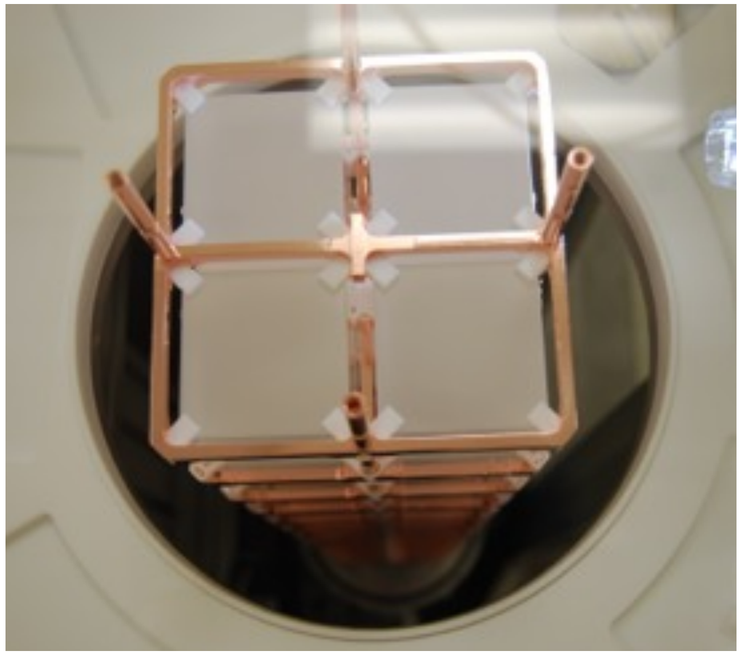


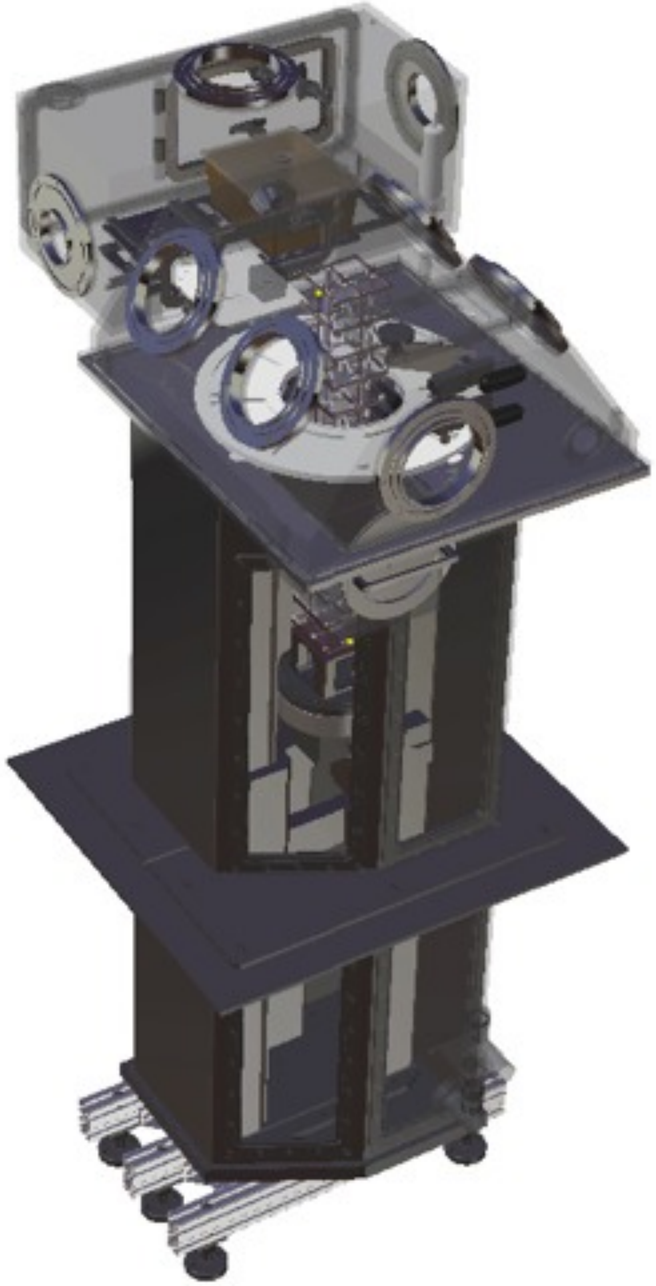


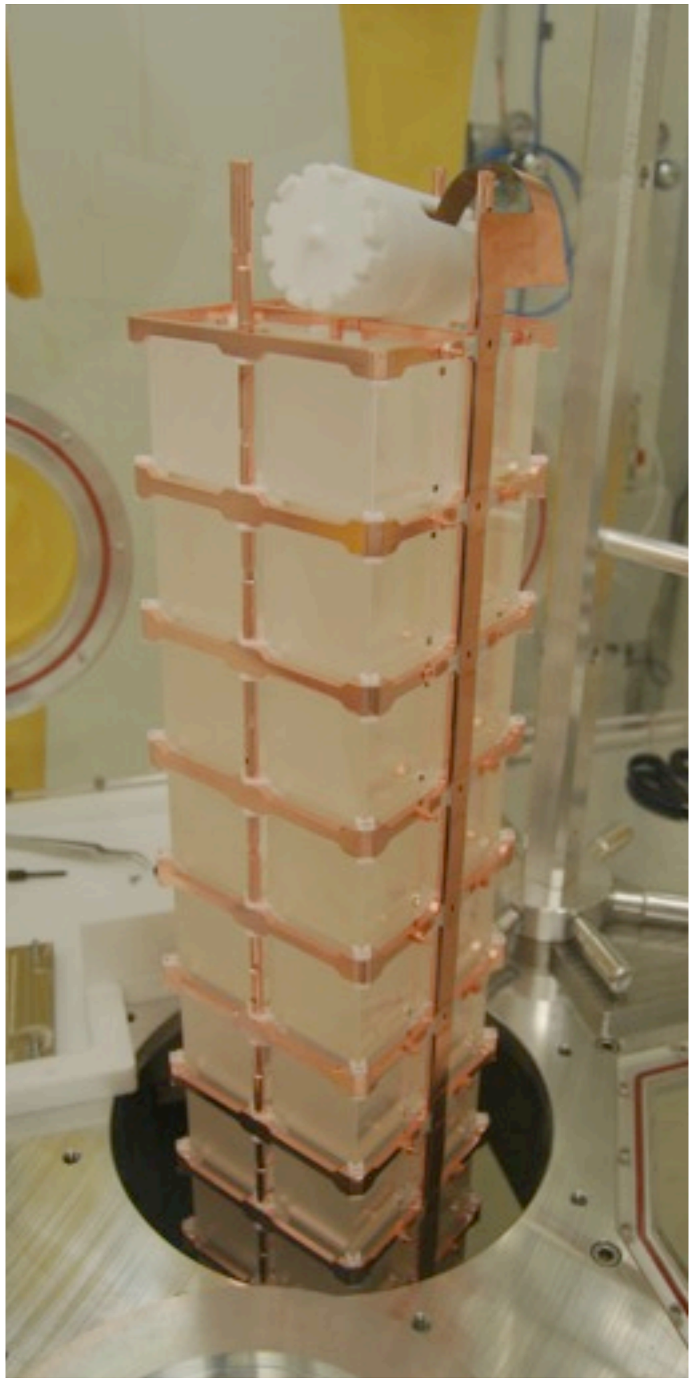


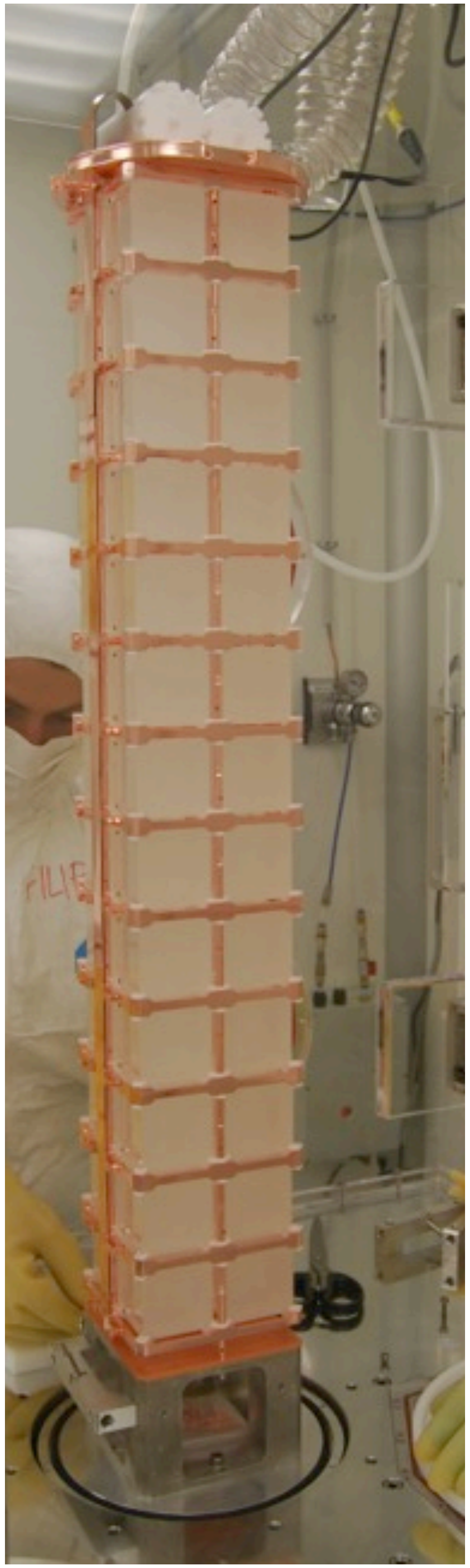
Mechanical assembly



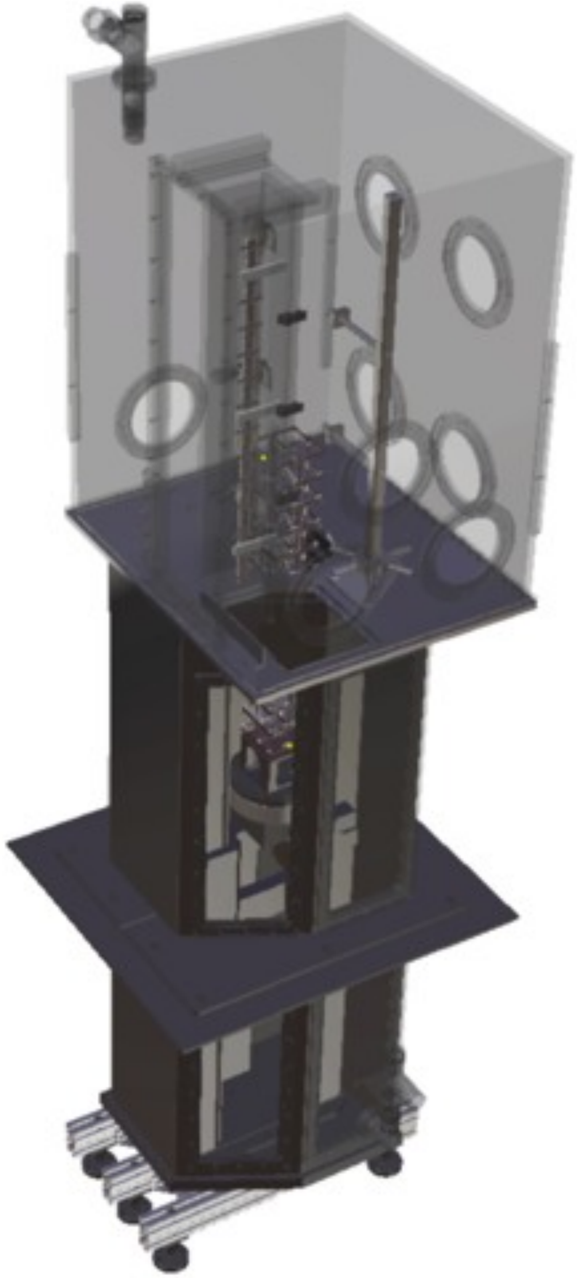


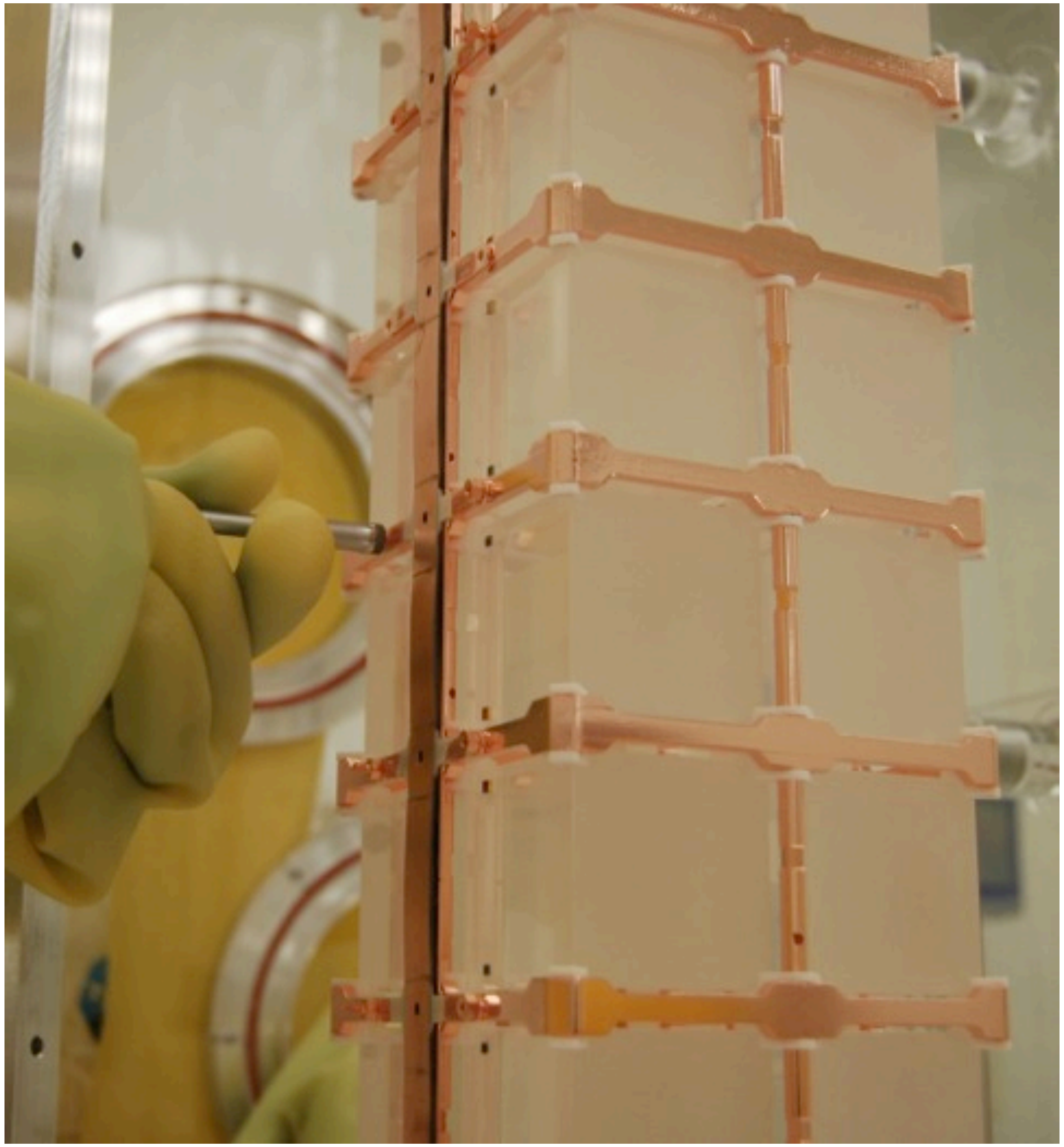




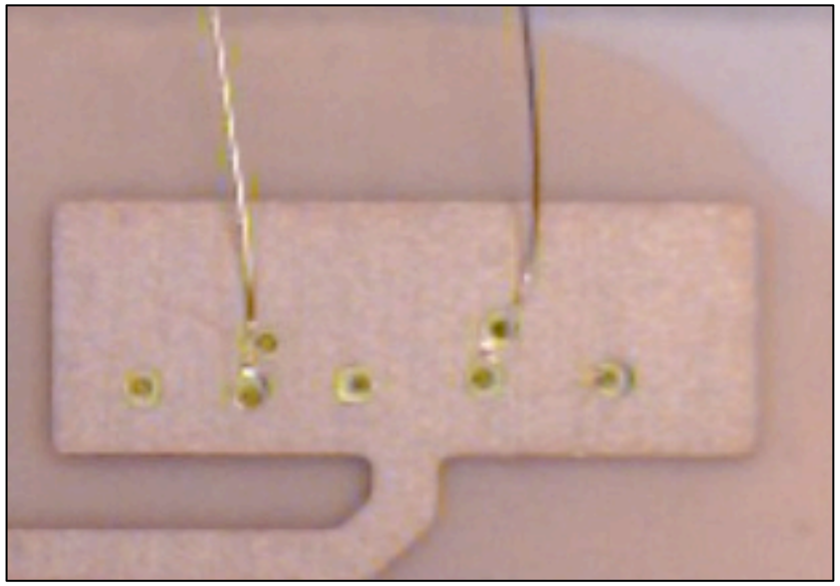


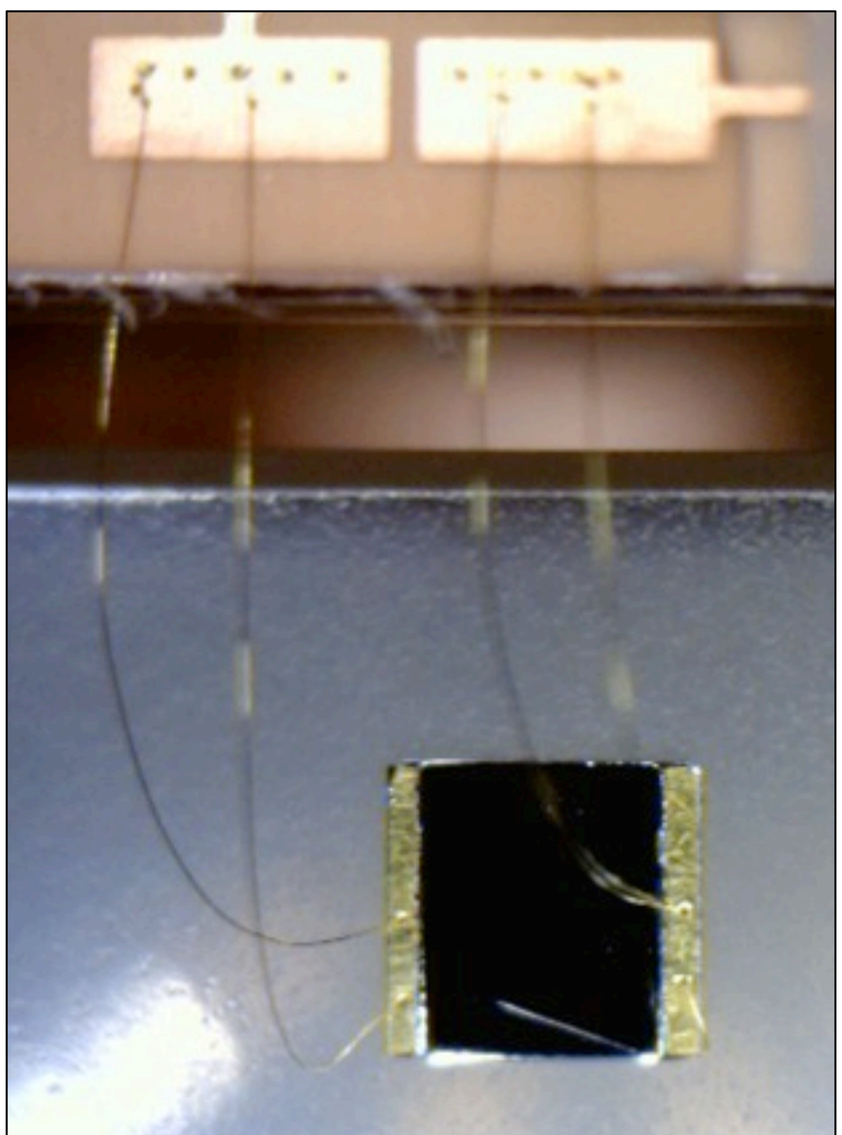
Cabling

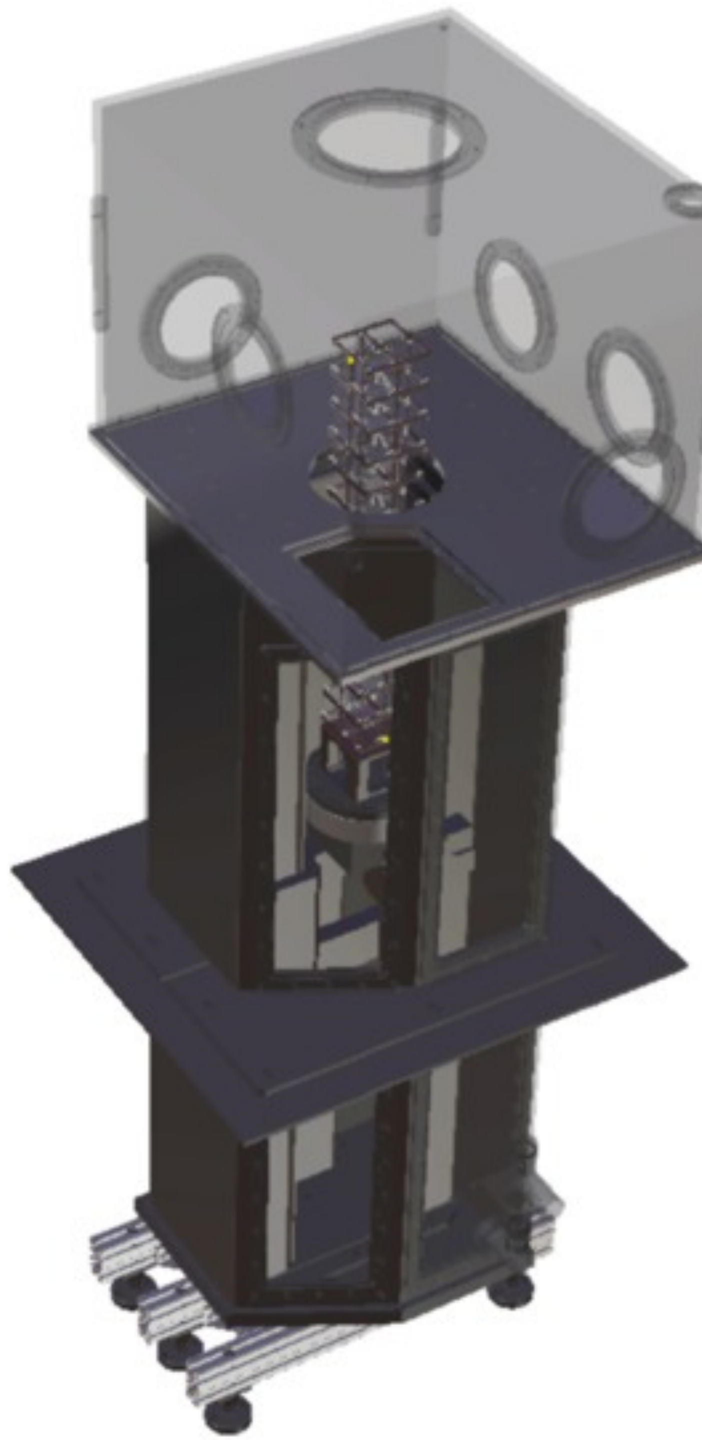


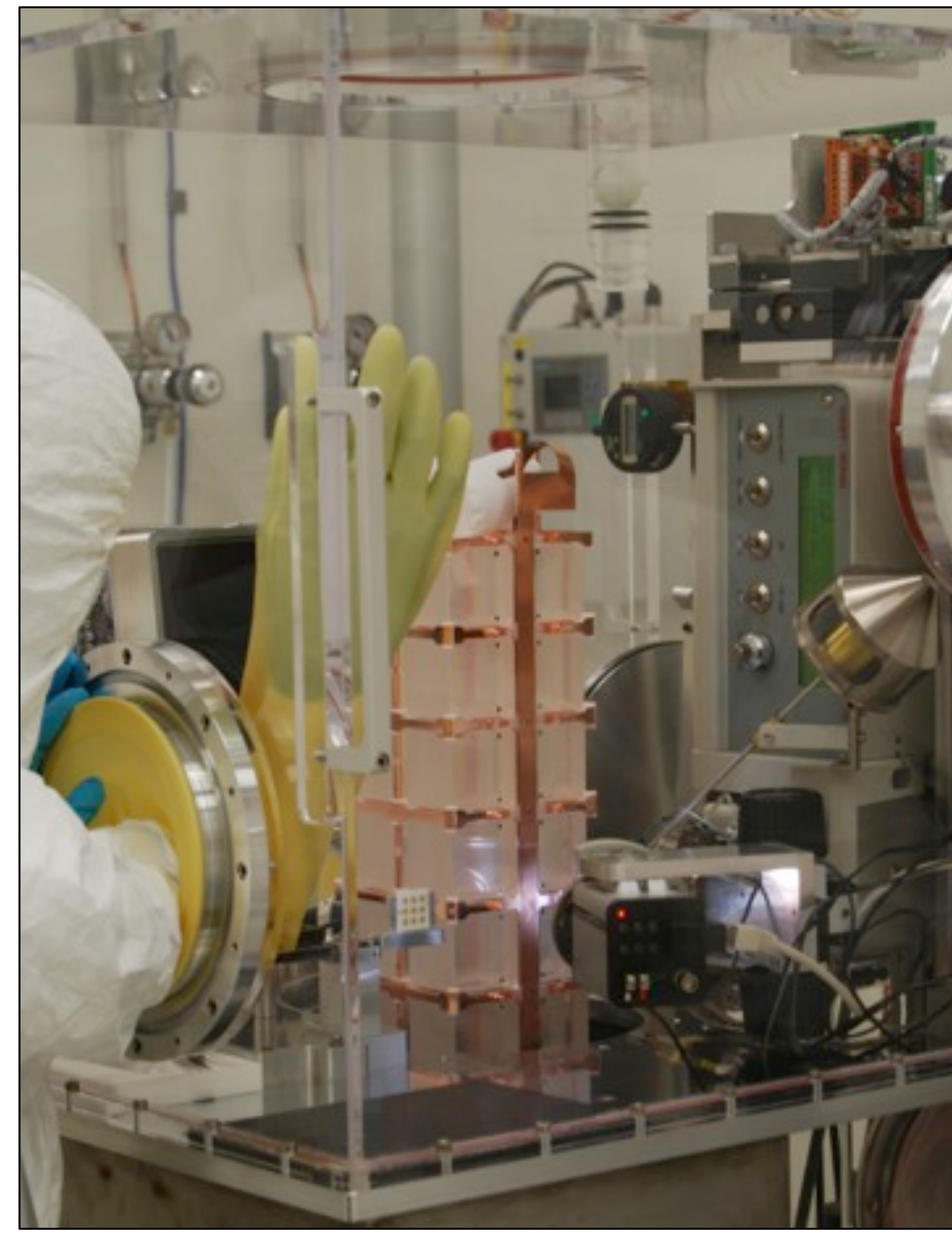


Wire bonding

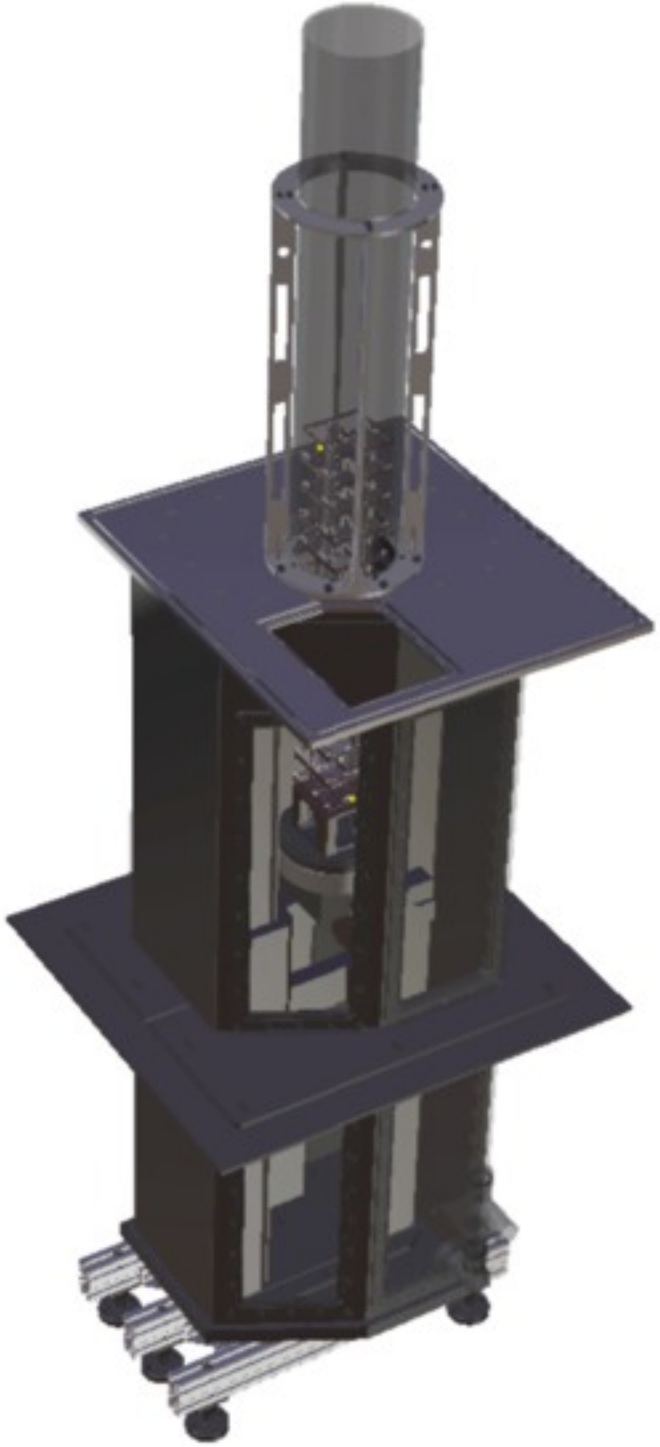








Storage

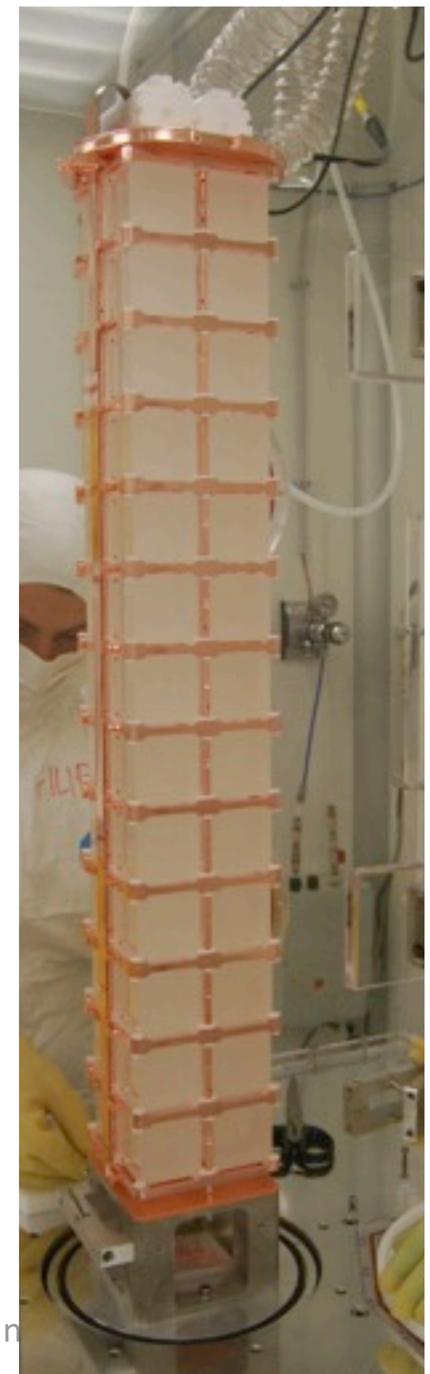


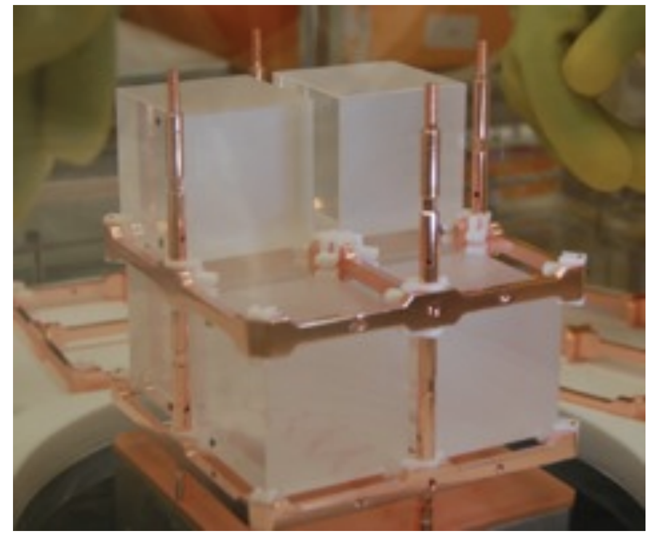
CUORE-0

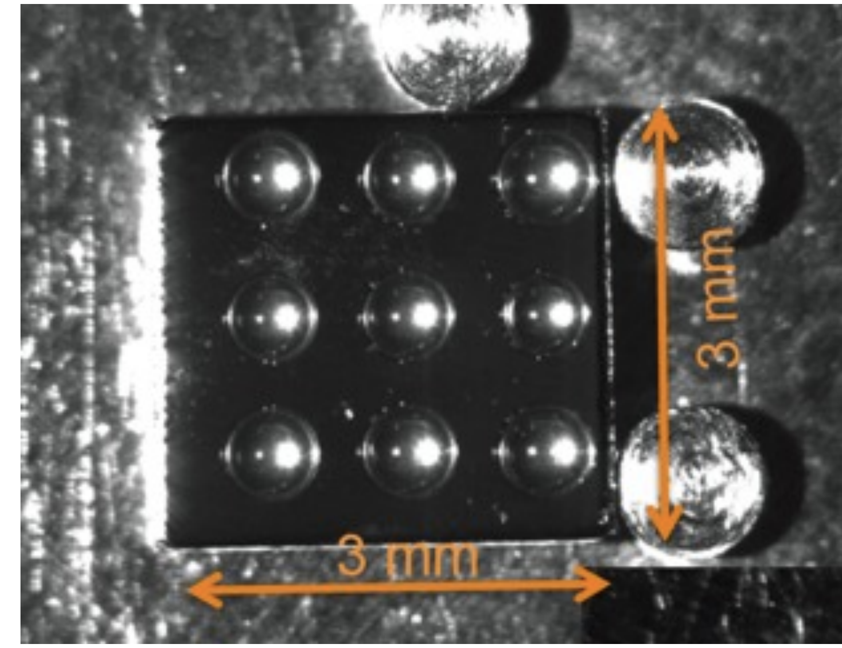
Goals:

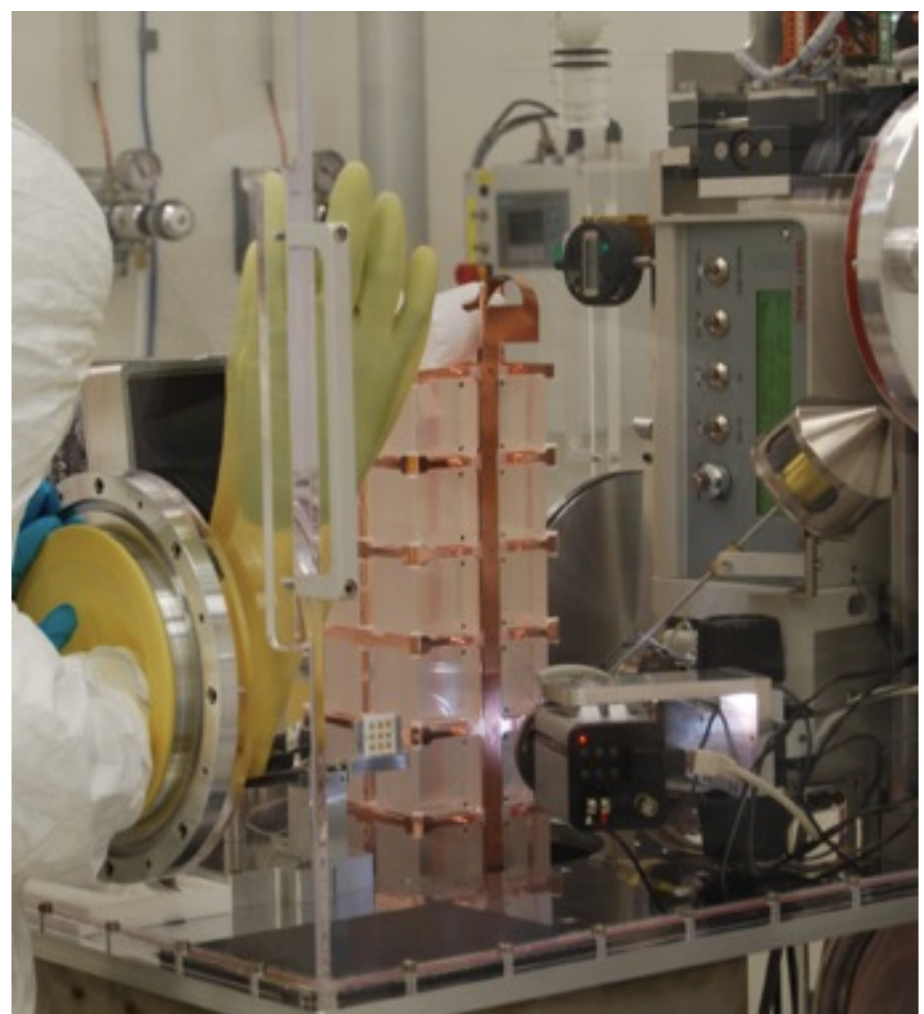
- full test and debug of the new CUORE assembly line
- high statistics check of the improved uniformity of bolometric response

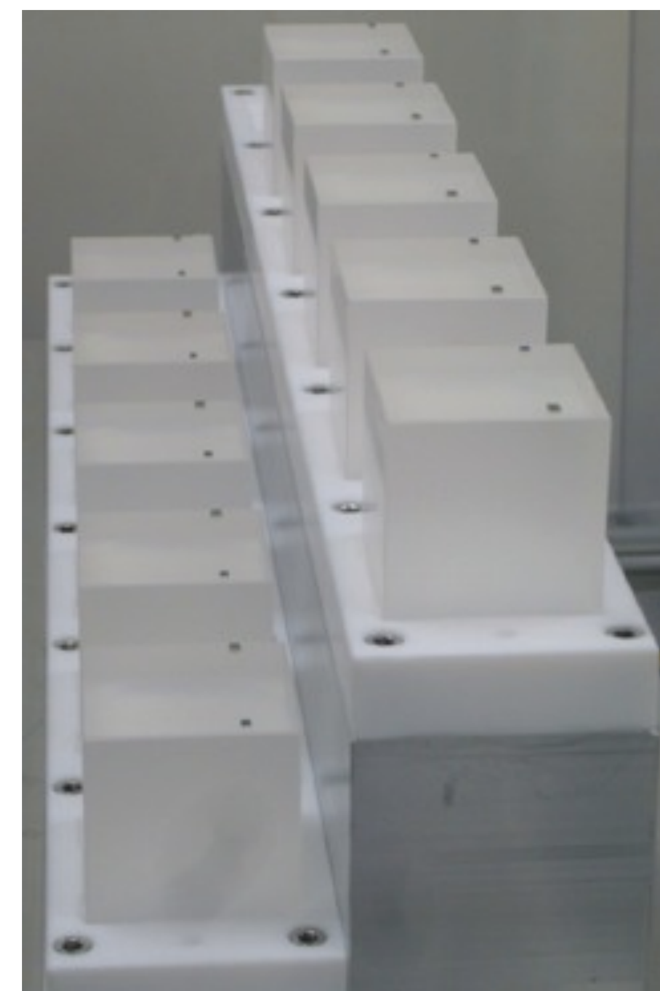
Background measurement started at the beginning of May 2013





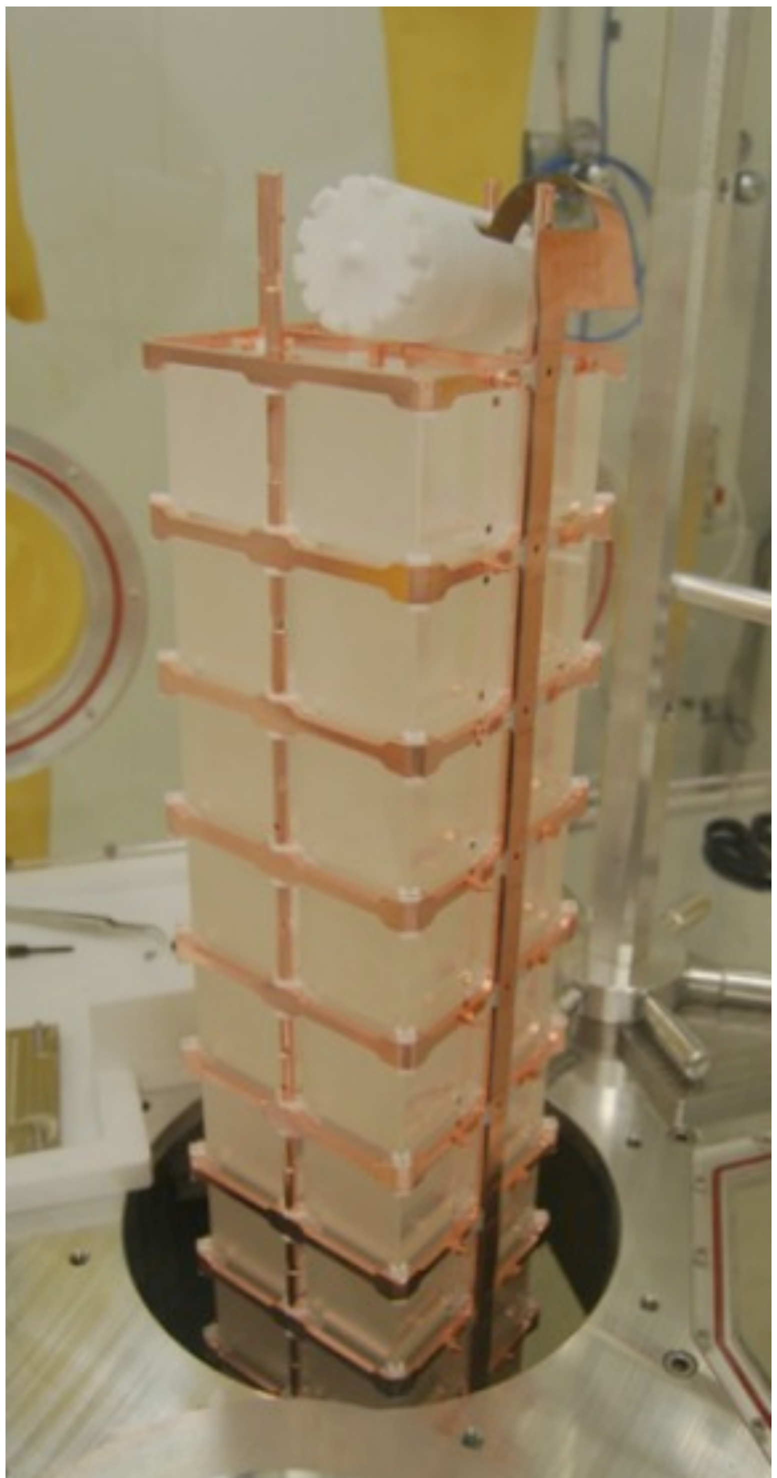




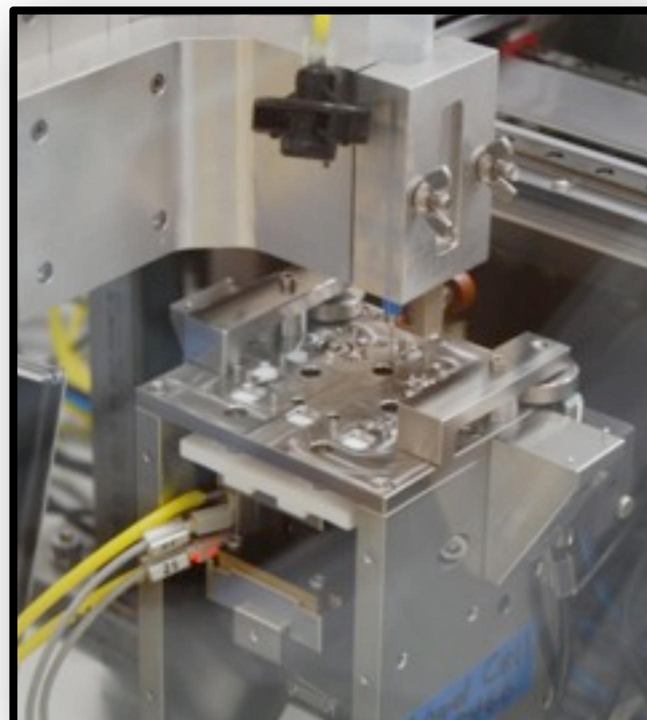


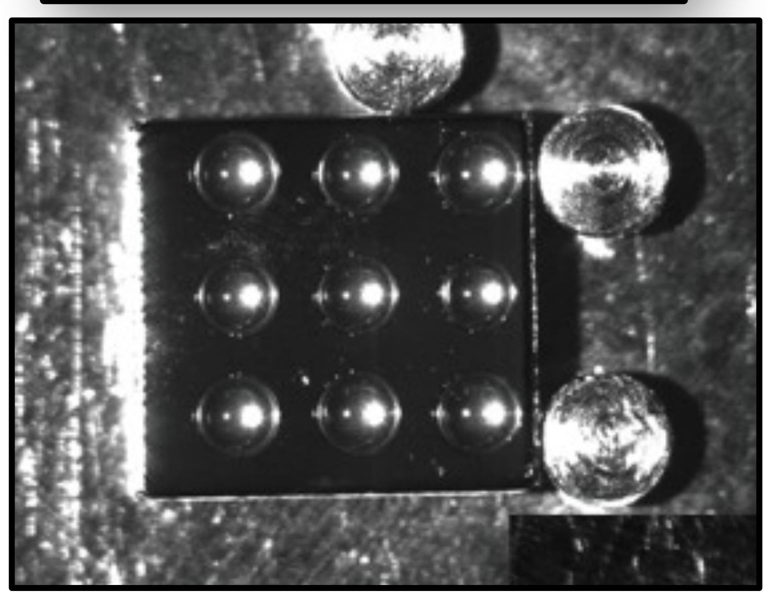
CUORE-0 construction

Mechanical assembly

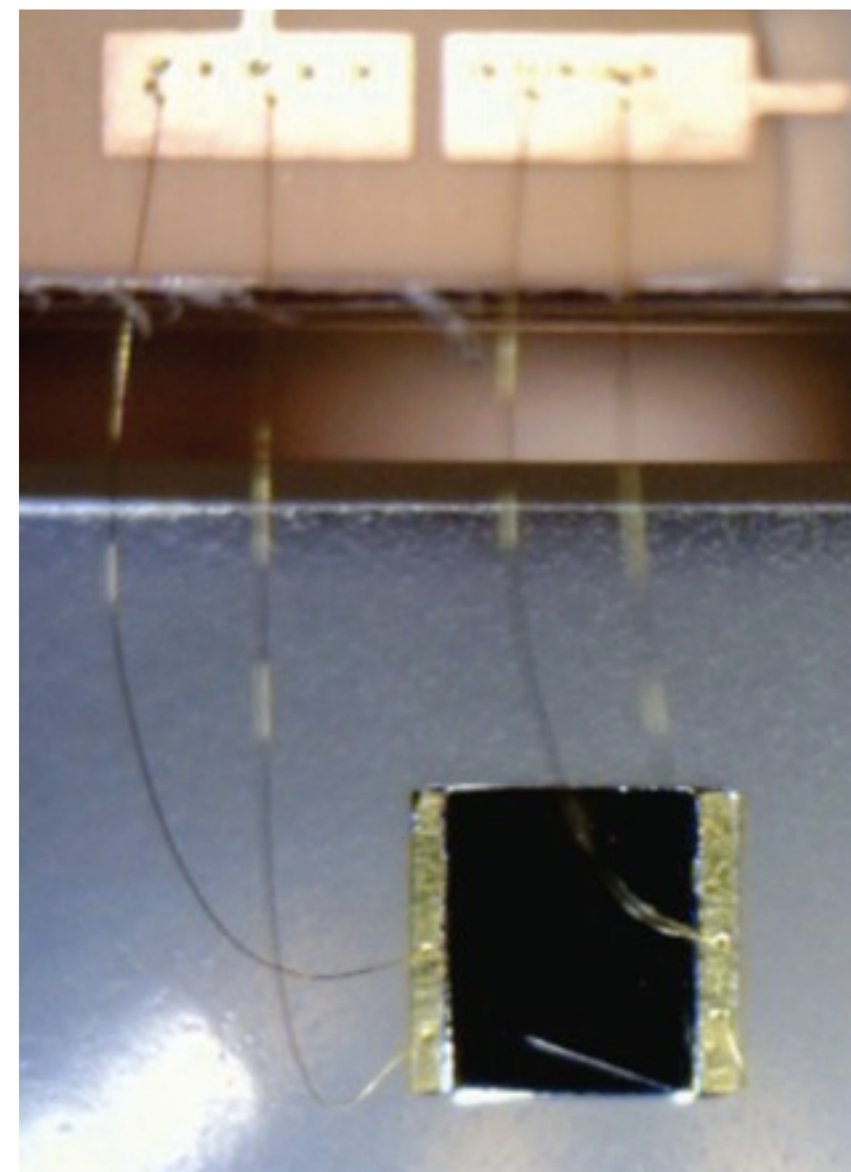


Sensors & heaters gluing
- semi-automated system





Sense wire (ball) bonding
- 50 μm gold wire
- direct bonding on final detector



CUORE-0 installation

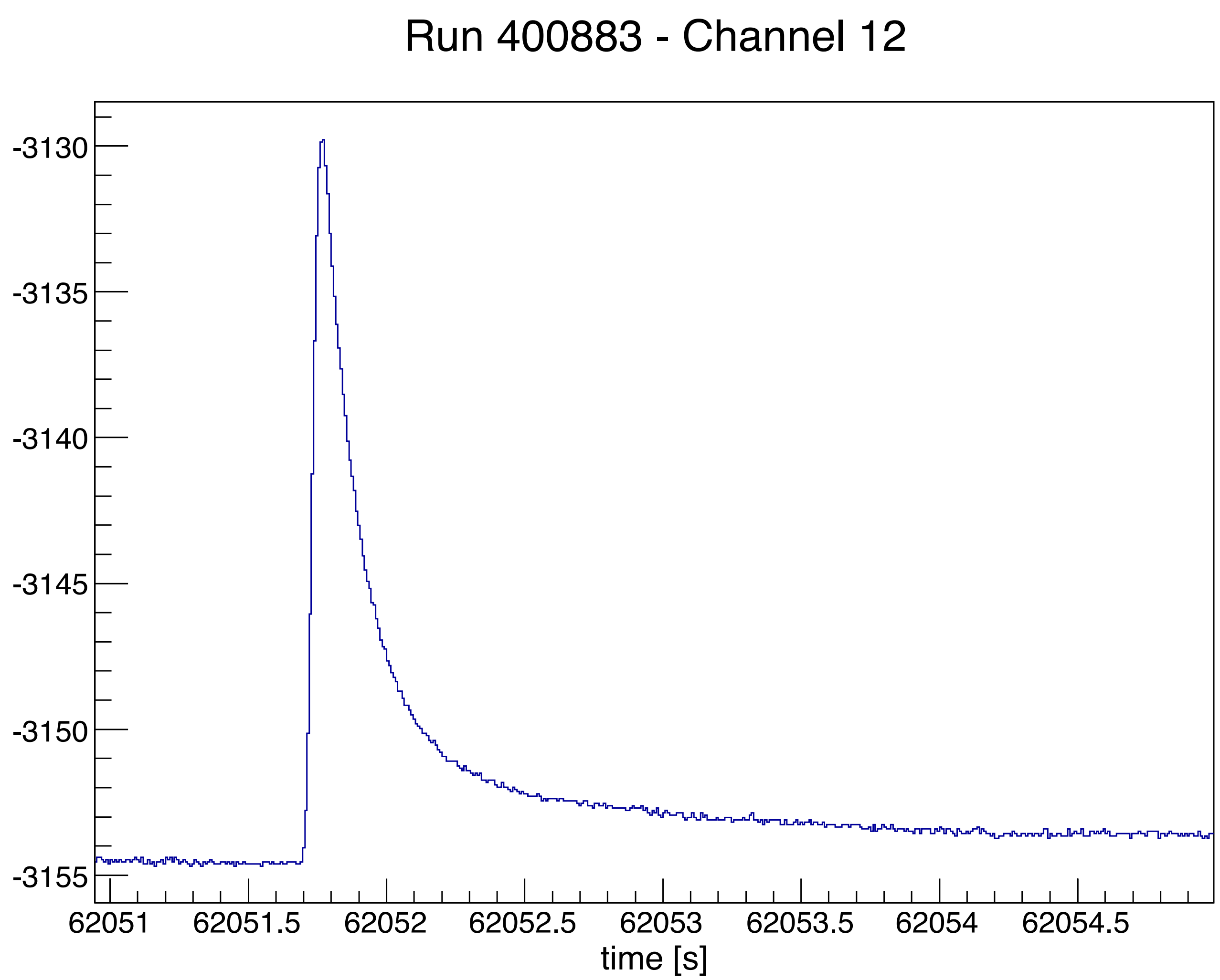
Installation of the CUORE-0 tower

CUORE-0: il run di novembre

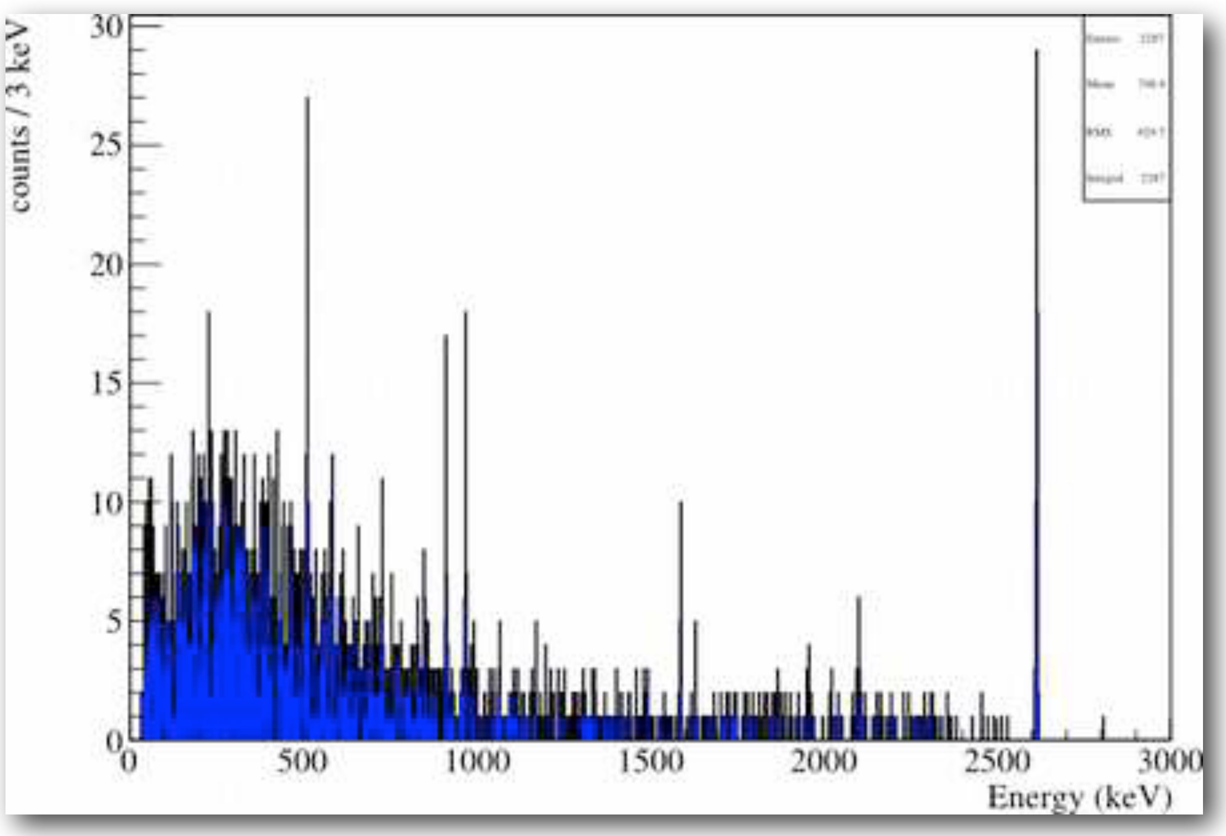
- Detectors can be maintained at base temperature in stable conditions only for only for few days.
- Short calibration measurement on few channels are carried out.
- The persistent leak prevents continuous data taking.

despite problems important informations are obtained:

- **the thermal contractions don’tcause problem to the tower wires**
- **the bonding connections survive to thermal cycles**
- **the thermal conduction of the new tower wires has to be taken into account for CUORE detector**
- **detectors are performing well**

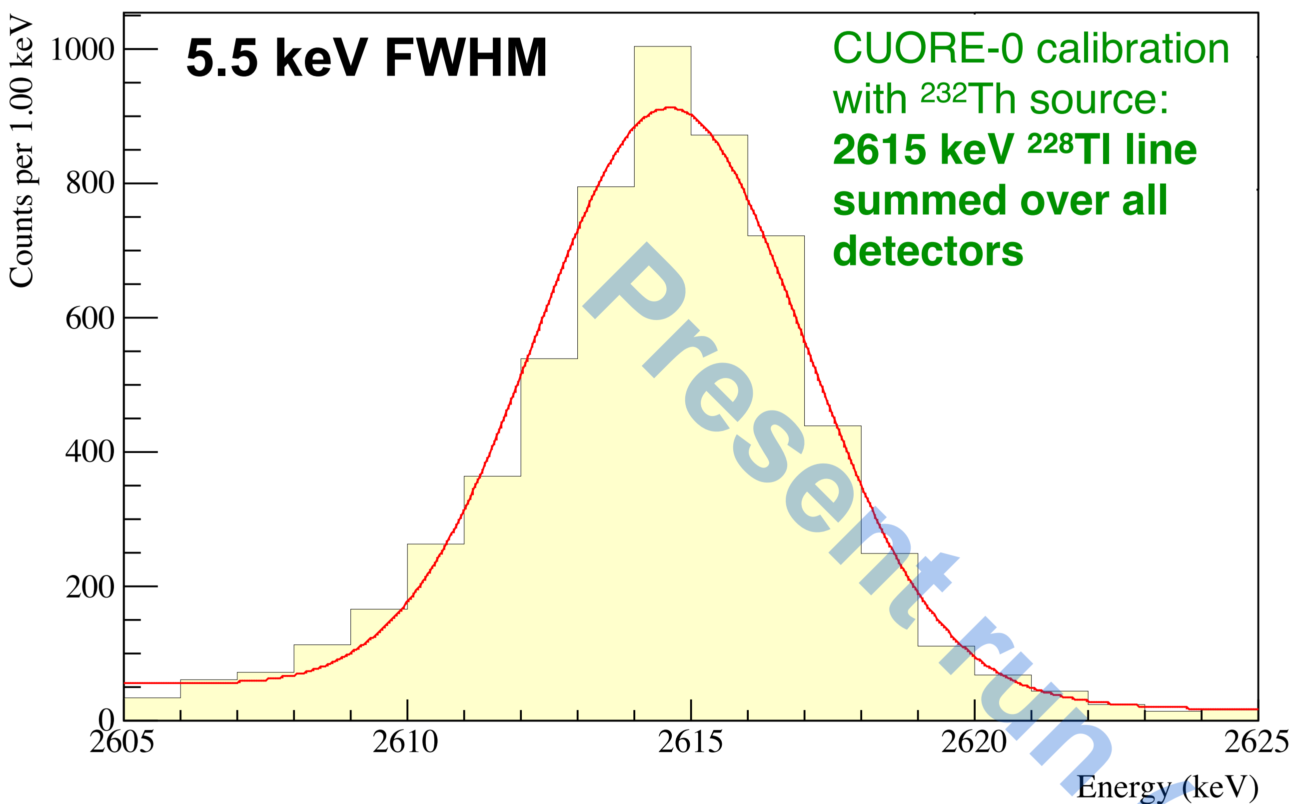


Ch. 45 calibration spectrum (^{232}Th source)



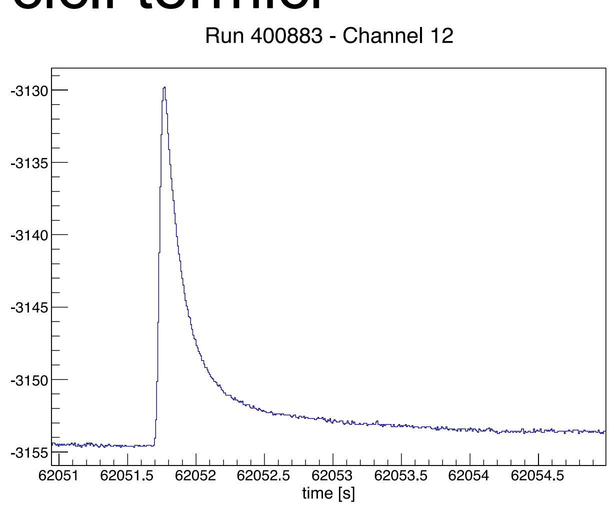
ΔE(FWHM) = 5.3 keV @ 2615 keV

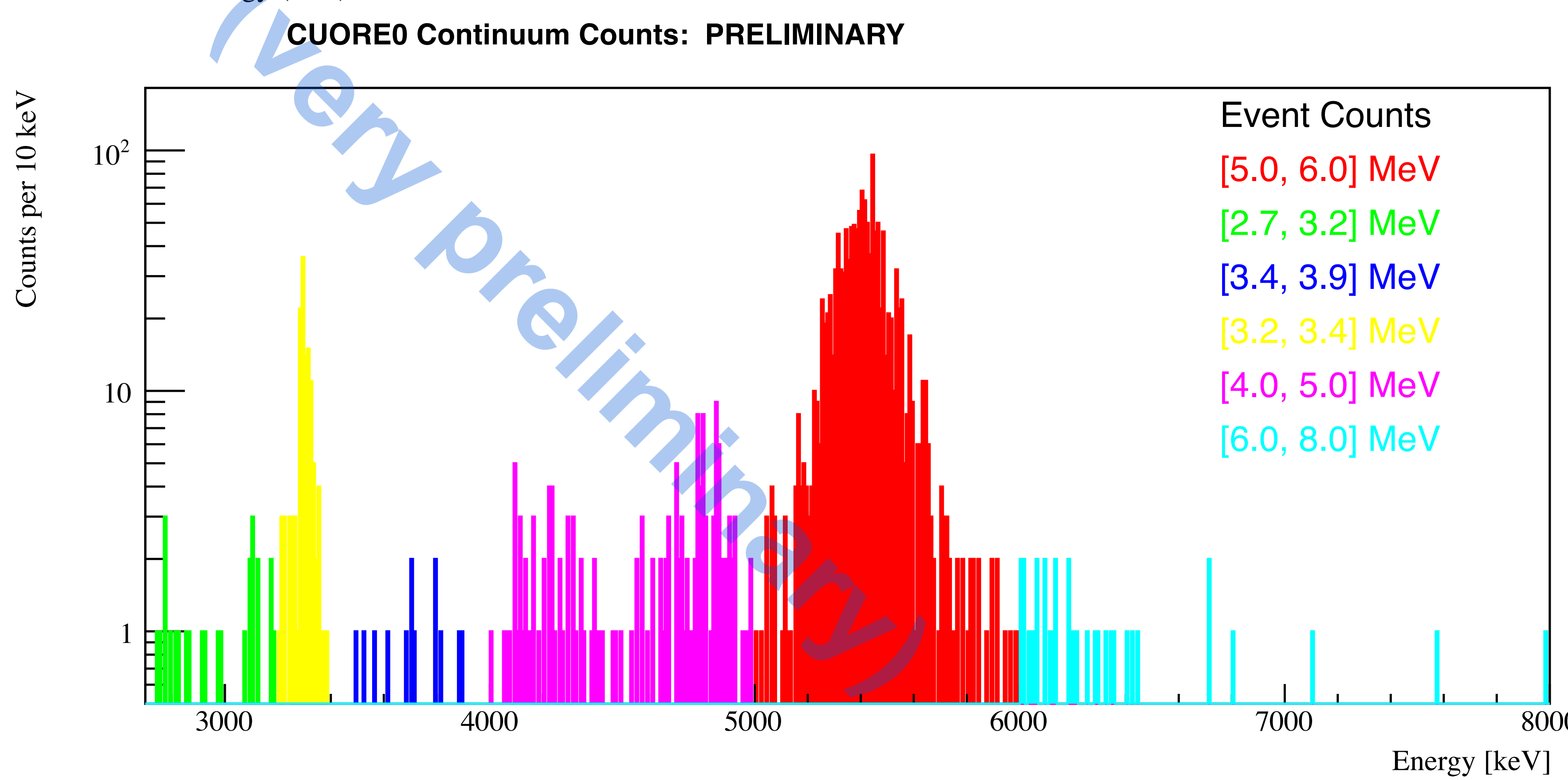
CUORE-0: il presente



- Dopo un po' di disavventure nel corso del 2012 (vecchio criostato del 1989) il sistema e' stato raffreddato definitivamente a febbraio 2013.
- Marzo ed Aprile sono stati dedicati ai run di ottimizzazione.
- La presa dati e' partita agli inizi di maggio

"Tutti" i rivelatori sono attivi e ben funzionanti ... nonostante i molti cicli termici

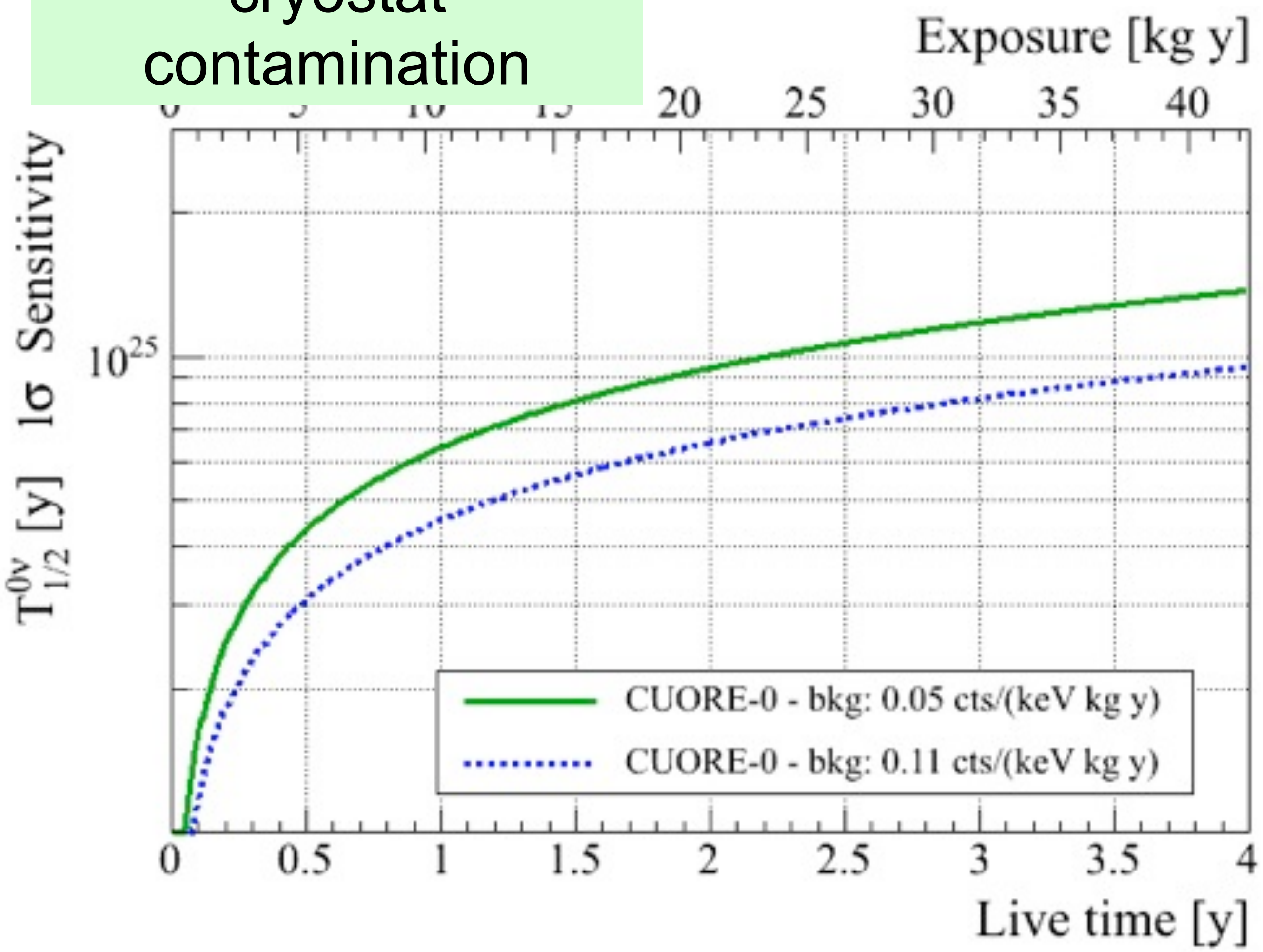




Sensibilità di CUORE0

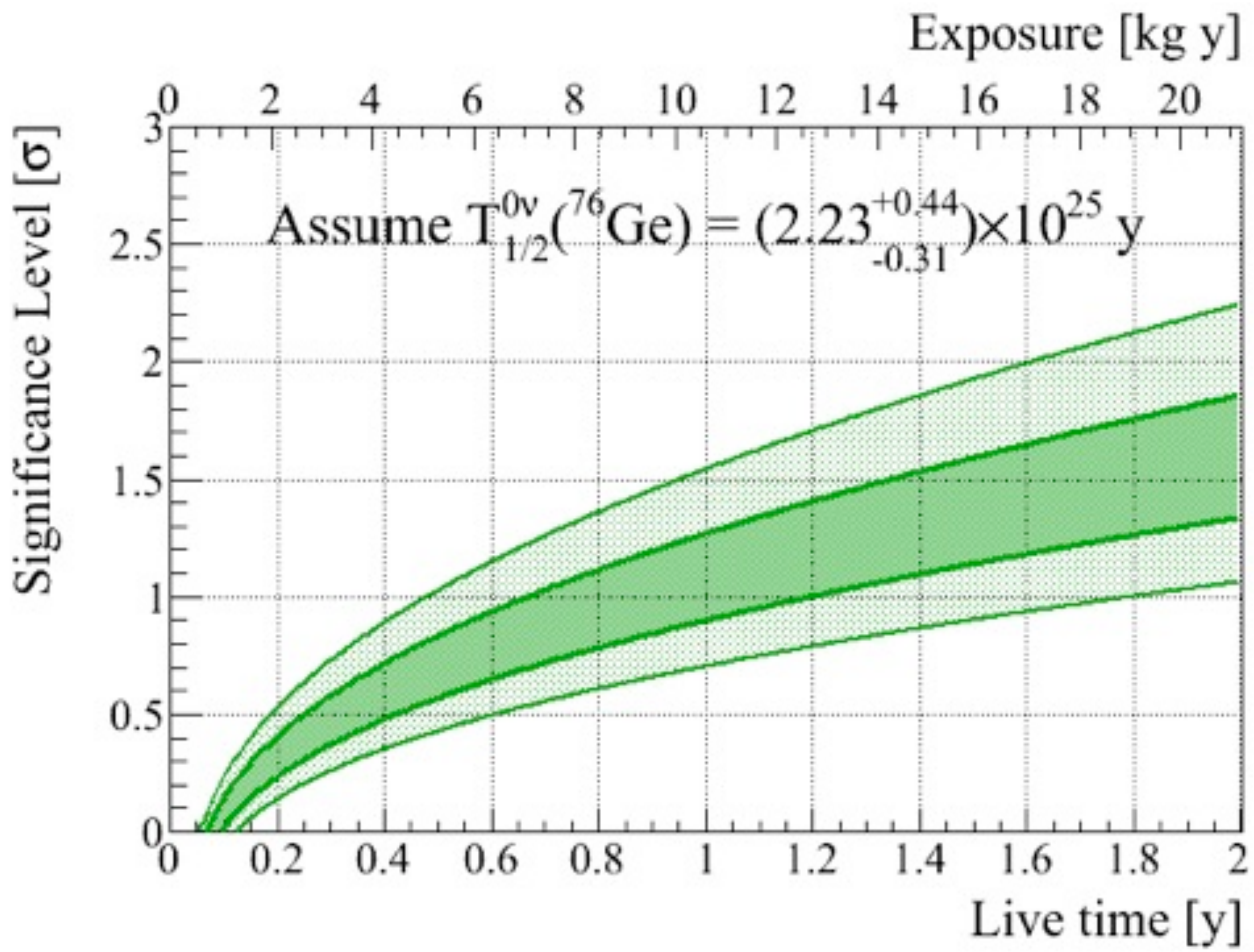
F. Alessandria et al. [CUORE coll.]
http://arxiv.org/abs/1109.0494v1

Limited by bkg from cryostat contamination



Background: 0.05-0.11 c/keV/kg/y range

If 0.05 c/(keV kg y), expected 2-year sensitivity is $T_{1/2}$ = 5.9 x 10^{24} y @ 90%CL

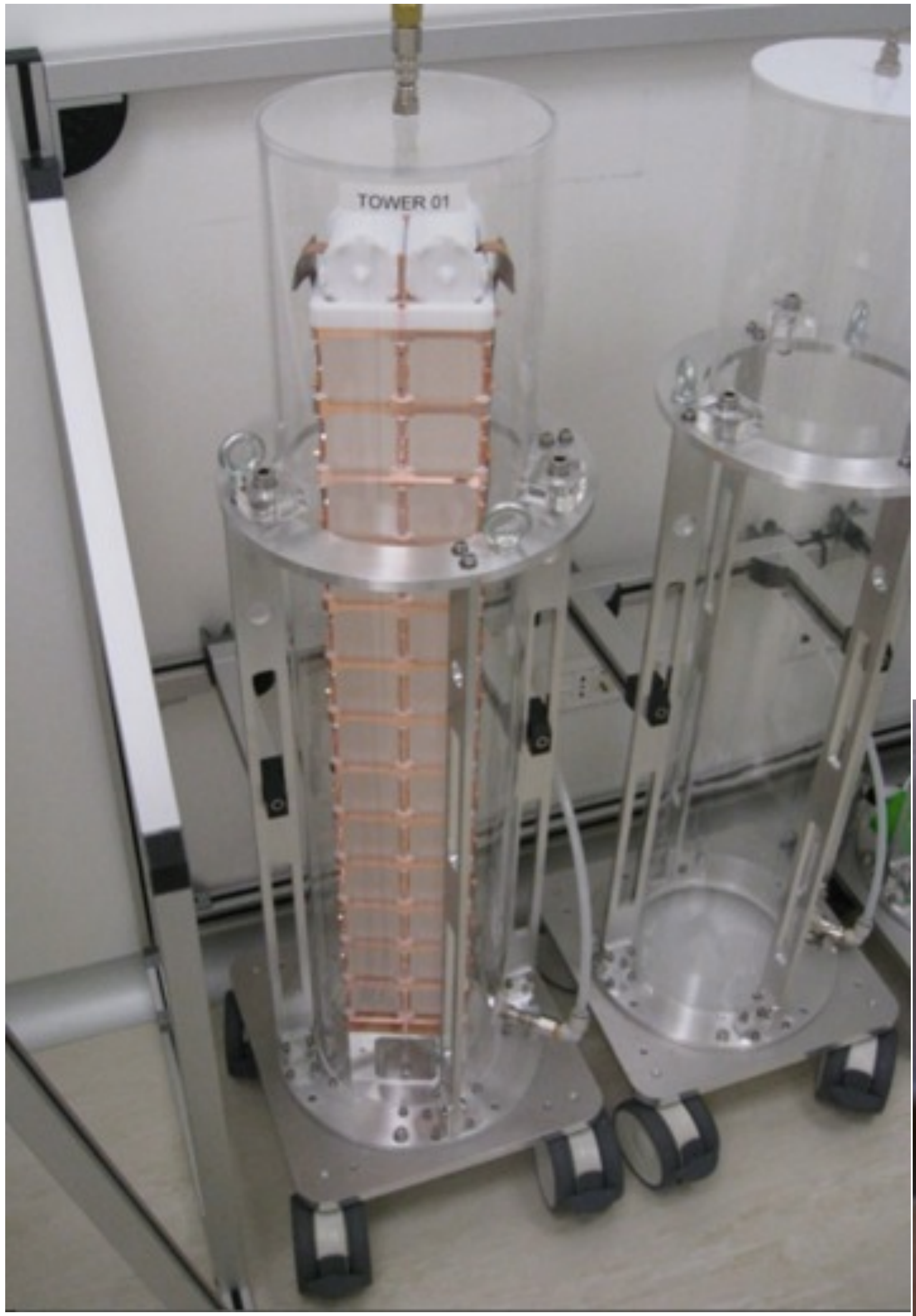


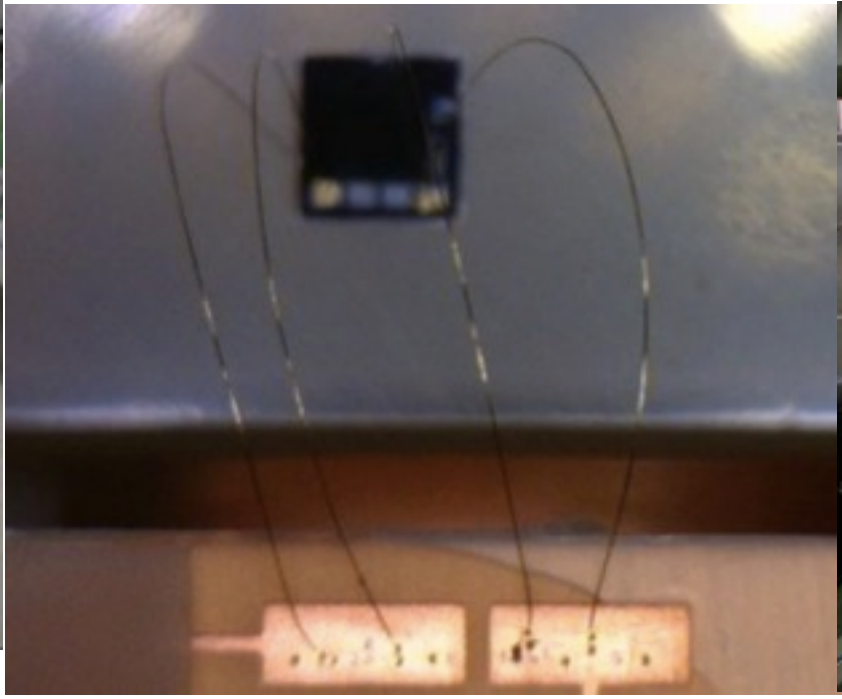
Significance level at which CUORE-0 can observe a DBD signal consistent with the claim in ^{76}Ge (KK-HK), assuming 0.05 c/keV/kg/y background

- 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

Le torri di CUORE

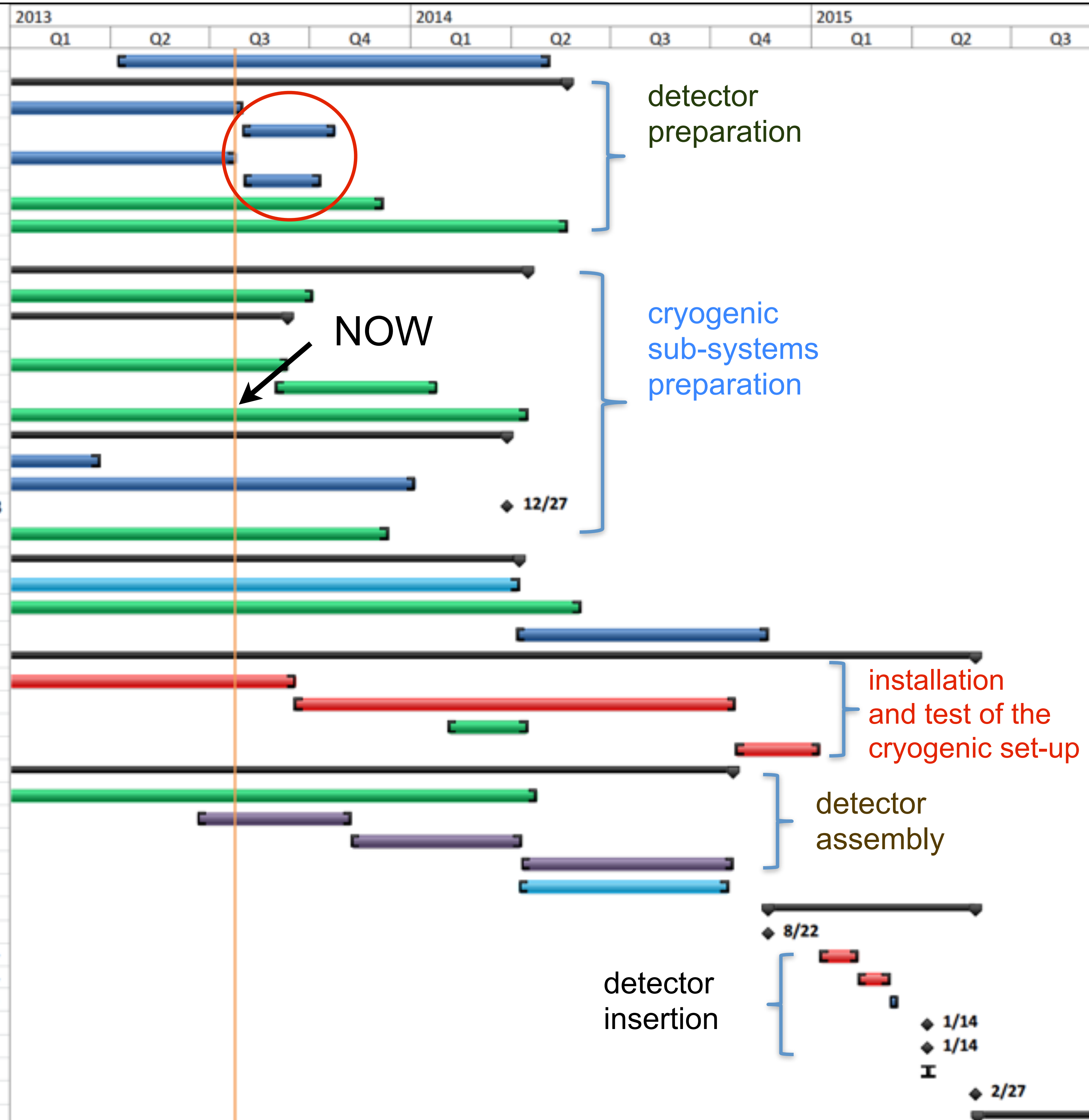
- TeO2 crystals delivery complete
- Parts production almost complete
- Radon abatement system installed
- Assembly program started and well performing
  - 2 CUORE towers ready





In volata ...

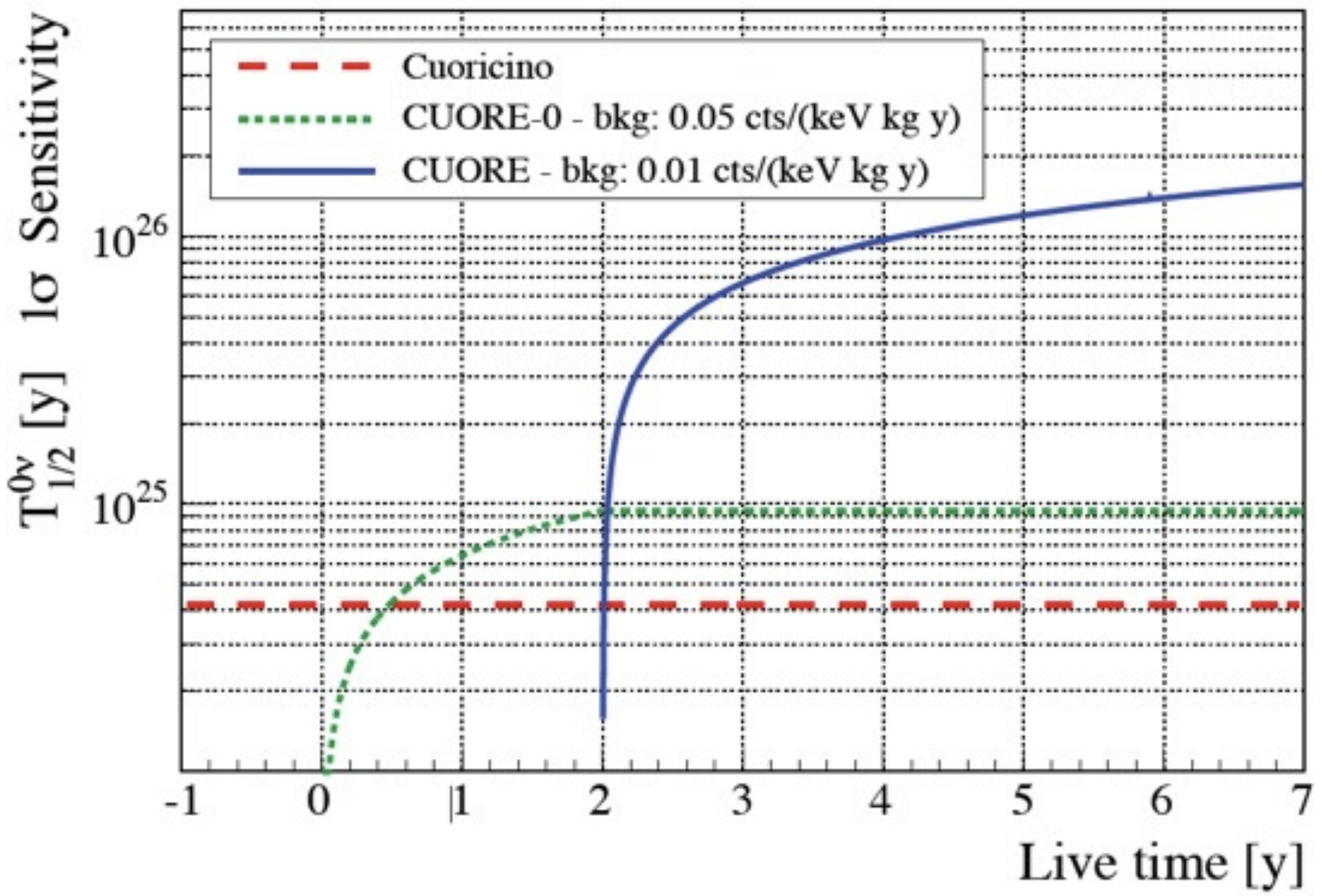
Task Name	Start	Finish
1.0 Hut (Faraday Cage)	**1/7/13**	**2/4/14**
2.0 Detector	**8/1/07**	**2/20/14**
Crystal Procurement	6/30/10	4/30/13
Crystal Refurbishment	5/1/13	7/23/13
Thermistors	3/16/11	4/24/13
Thermistors (spares)	5/2/13	7/10/13
Structure - Design, Prod.	8/1/07	9/5/13
Surface Cleaning	4/16/12	2/20/14
3.0 Cryogenics	**8/1/07**	**1/15/14**
3.1 Cryo Design & Construction	**8/1/07**	**1/15/14**
Cooling Units and Test Dewar	8/1/07	7/3/13
Cryostat Construction	**5/10/10**	**6/10/13**
300K - 4K Chamber Fab	5/10/10	7/23/12
600mK - MC Fab	8/17/12	6/10/13
Wiring for Commissioning	5/31/13	10/24/13
Internal Lead Shielding	12/1/08	1/15/14
3.2 Calibration System	**4/23/09**	**12/27/13**
Calibration Prototypes	4/23/09	12/21/12
Calibration Construction and Testing	7/2/12	10/4/13
Calibration System Fabrication Complete	12/27/13	12/27/13
3.3 Interfaces between Towers and Cryostat	6/20/11	9/10/13
4.0 Front End Electronics	**12/22/09**	**1/7/14**
Elec. Production & Testing	12/22/09	1/7/14
5.0 Data Acquisition Systems	1/9/12	3/4/14
6.0 Data Analysis Tools	**1/6/14**	**8/22/14**
7.0 Assembly Integration & Test	**5/7/12**	**2/27/15**
Initial Installation and 4K Tests - Commissioning Phase I	7/31/12	6/17/13
Base T no Load - Commissioning Phase II	6/17/13	7/23/14
Installation of external shield	11/4/13	1/15/14
Base T Full Load - Commissioning Phase III	7/24/14	10/8/14
7.3 Tower Assembly & Integration	**5/7/12**	**7/21/14**
Crystal Gluing	5/7/12	1/23/14
Assemble Towers 1 to 5	3/21/13	8/7/13
Assemble Towers 6 to 11	8/8/13	1/9/14
Assemble Towers 12 to 19	1/10/14	7/21/14
7.4 Electronics Install & Commissioning	**1/8/14**	**7/17/14**
7.5 Detector Insertion & Sys. Testing	**8/22/14**	**2/27/15**
US Scope Complete	8/22/14	8/22/14
Open and prepare for Installation	10/9/14	11/12/14
Installation of the 19 CUORE Towers	11/13/14	12/11/14
DCS Internal Guide Tube Installation and Connections	12/12/14	12/18/14
Detector Insertion Complete	**1/14/15**	**1/14/15**
System Closeout Complete	**1/14/15**	**1/14/15**
CD 4 Readiness Review	1/15/15	1/16/15
CD 4 - US Deliverables Complete	**2/27/15**	**2/27/15**
Pre-Ops	**3/2/15**	**8/14/15**



Conclusioni

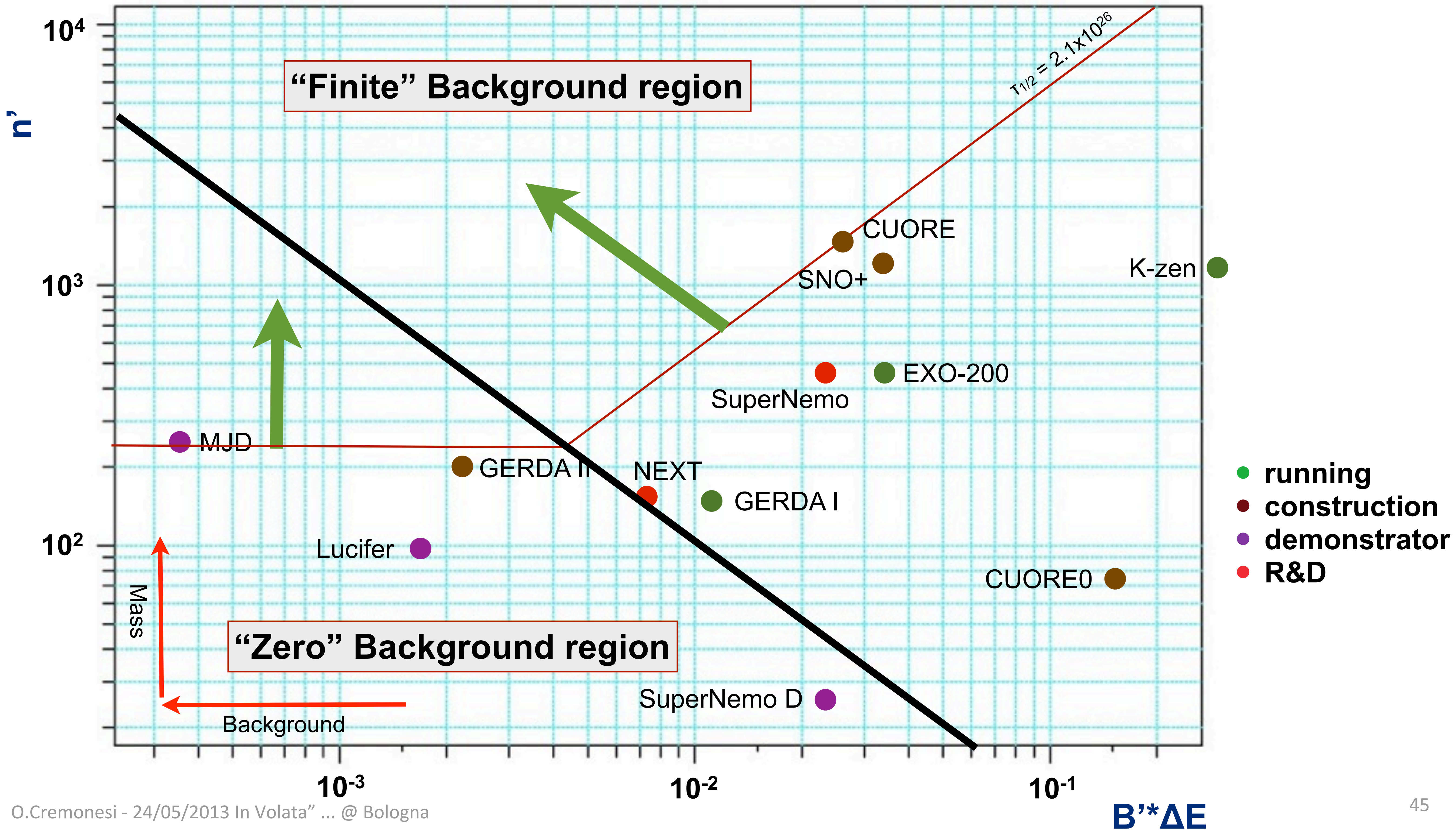
- With ~200 kg of 130Te and a resolution of 5 KeV FWHM, CUORE has the potential to explore the inverted mass hierarchy of neutrino mixing
- CUORE towers assembly started since February 2013.
- The construction of CUORE-0 and of the first CUORE towers has demonstrated that the collaboration can face the challenge of assembling the ~1000 CUORE bolometers (~10 k pieces) in extremely clean conditions
- Cryogenics commissioning started in July 2012 and is continuing regularly.

- CUORE operation will start in 2015
- CUORE-0 prototype has been successfully installed (in the CUORICINO cryostat) and is presently taking data.

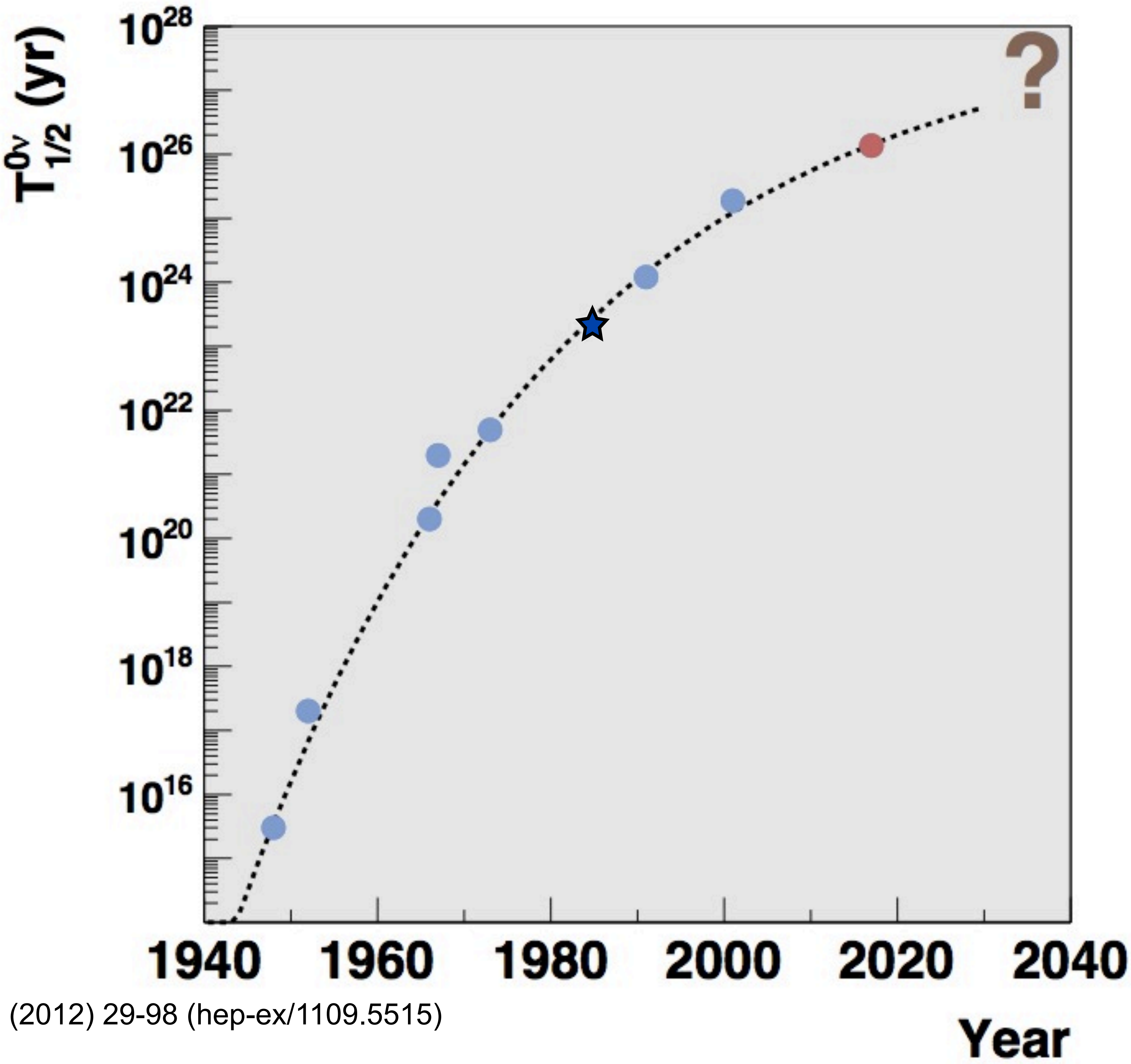


Experimental perspectives

n' = number of "effective" isotope moles
B = counts/keV/n'/yr



Next jump?



Riv. Nuovo Cim. 35 (2012) 29-98 (hep-ex/1109.5515)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