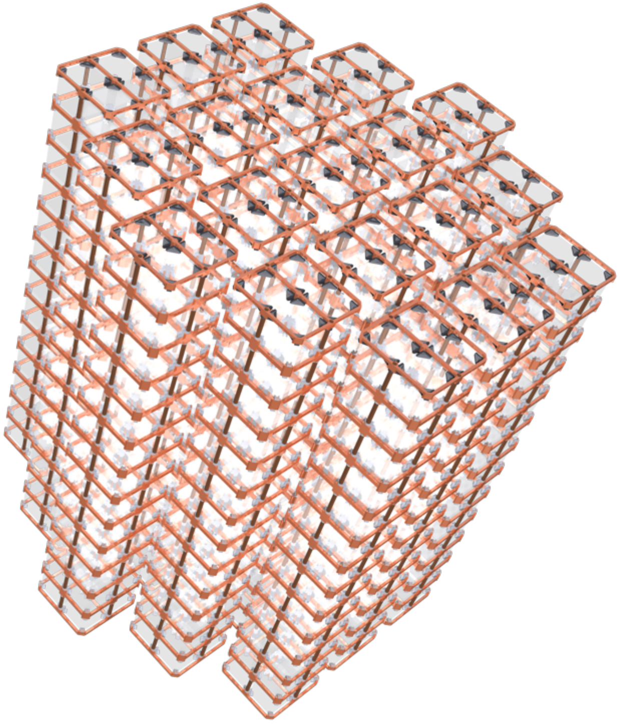
The CUORE Neutrinoless Double Beta Decay Experiment

Tom Banks, on behalf of the CUORE Collaboration
(UC Berkeley, LBNL, LNGS)



24th Rencontres de Blois
Particle Physics & Cosmology
Blois, France
30 May 2012

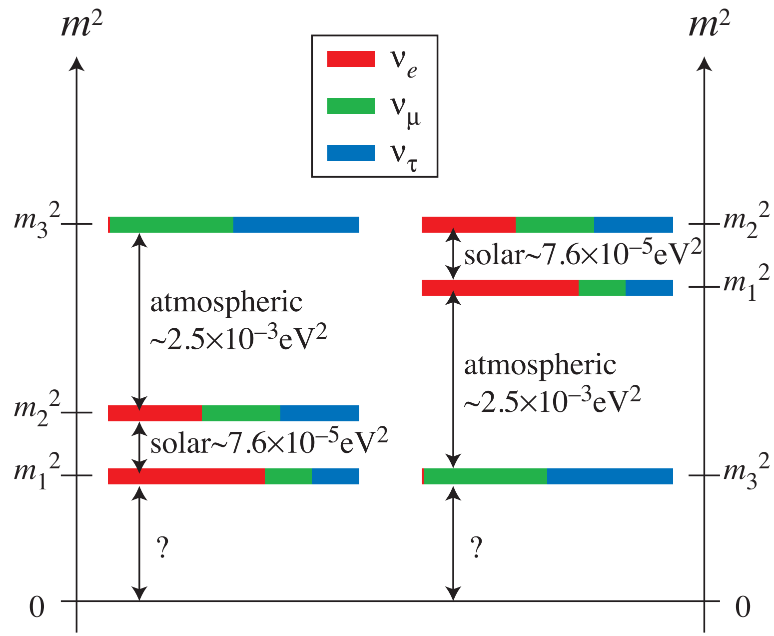
Physics motivation

- In the last decade, experiments convincingly established that neutrinos oscillate and therefore have mass

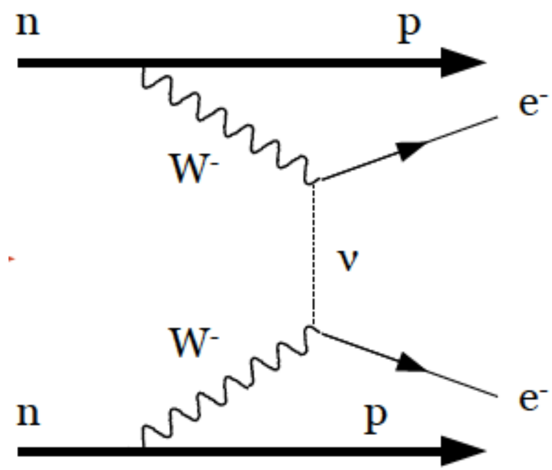
- However, oscillation experiments cannot determine the neutrino:

  1. Mass hierarchy
  2. Absolute mass scale
  3. Dirac or Majorana nature $(\nu = \bar{\nu}\,?)$

- $0\nu\beta\beta$ decay offers a unique means to probe these parameters

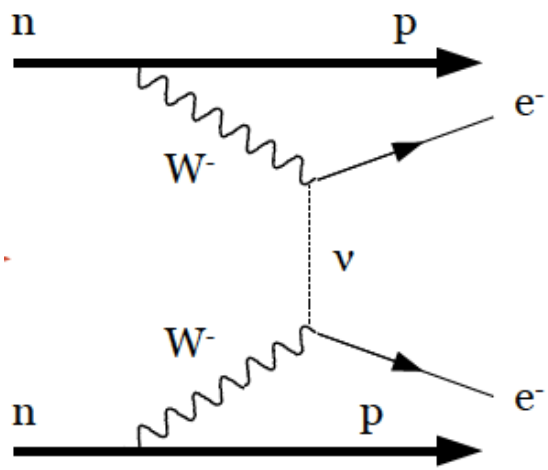


$0\nu\beta\beta$ decay



- Extremely rare process ($T_{1/2}$ > 10^{24} y), if it occurs at all
- Requires massive Majorana neutrinos $(\nu = \overline{\nu})$
- Violates lepton number = physics beyond SM

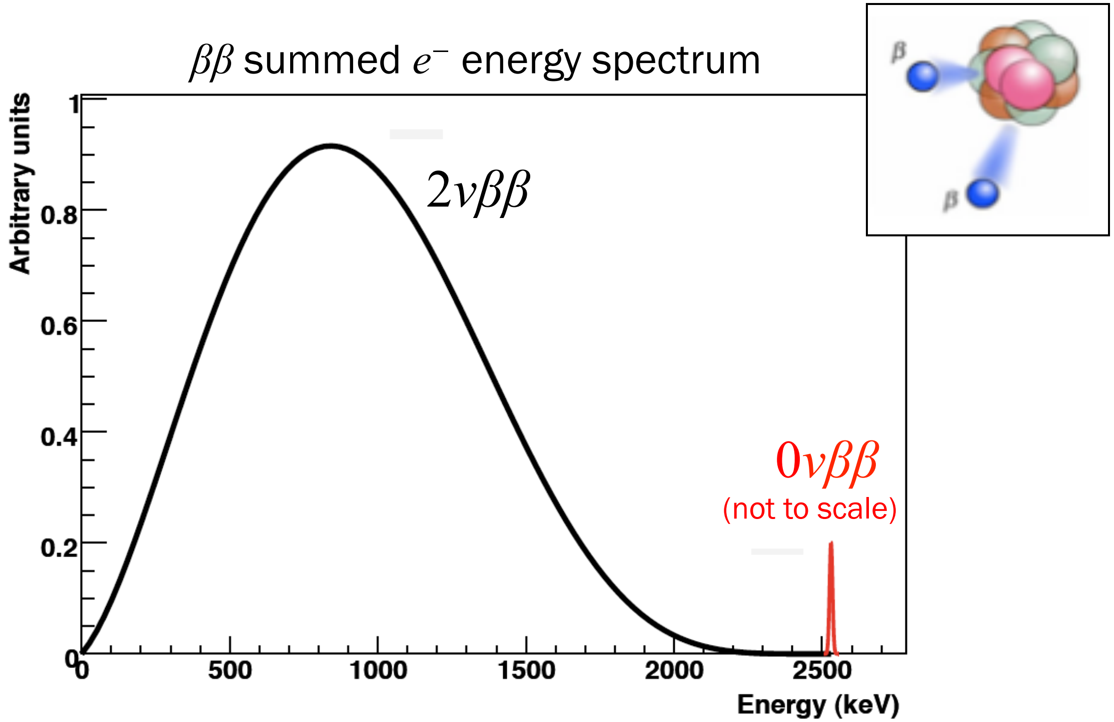
$0\nu\beta\beta$ decay



If $0\nu\beta\beta$ decay is observed, it would

1. confirm neutrinos are Majorana particles (i.e., $\nu = \overline{\nu}$);
2. set constraints on the effective Majorana mass $\langle m_{\beta\beta} \rangle$, providing information about the absolute ν mass scale;
3. provide information about the mass hierarchy.

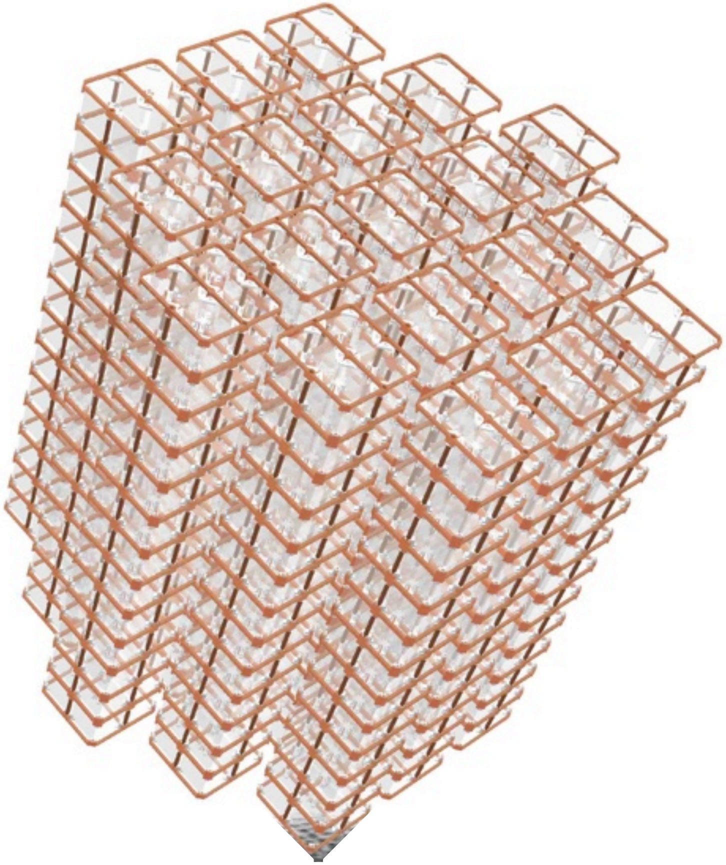
$0\nu\beta\beta$ decay signature



Two simultaneous electrons with summed energy equal to the Q-value for $\beta\beta$ decay in the isotope under study

CUORE

Cryogenic Undergound Observatory for Rare Events

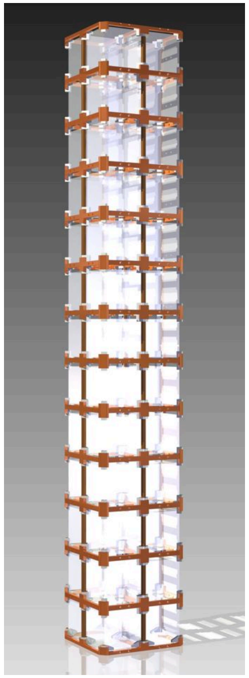


Primary objective is to search for $0\nu\beta\beta$ decay in ^{130}Te

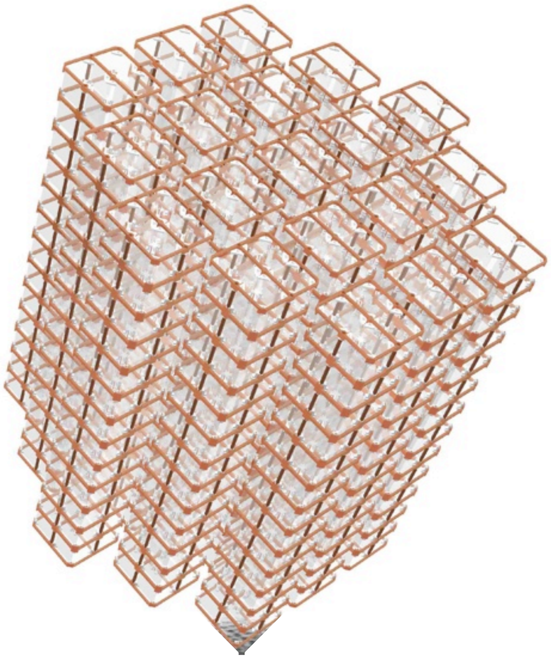
CUORE program

Cuoricino
2003–2008
11 kg ^{130}Te

COMPLETE



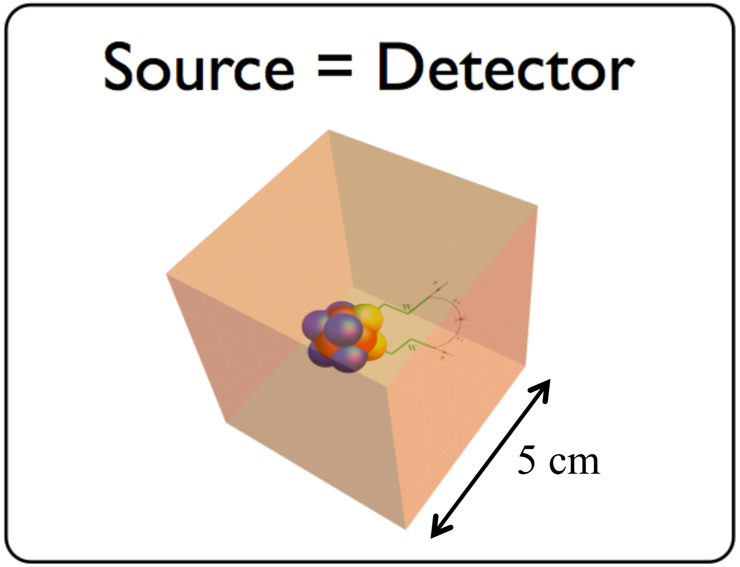
CUORE-0
2012–2014
11 kg ^{130}Te



CUORE
2014–2019
206 kg ^{130}Te

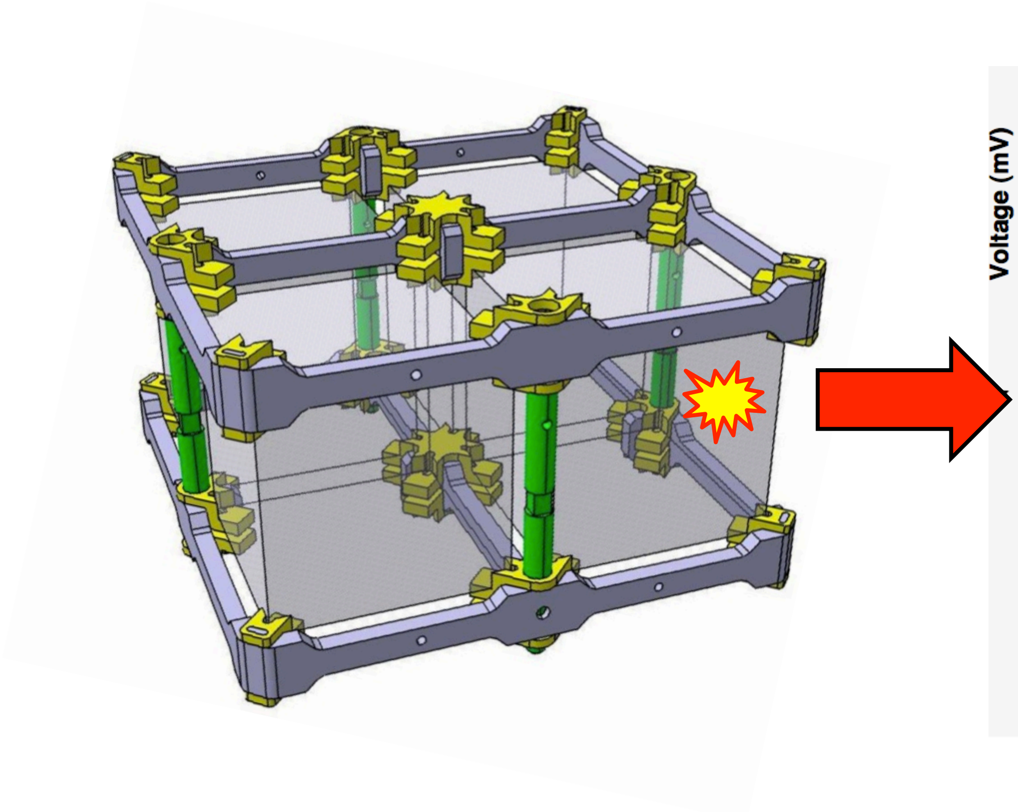
Cryogenic bolometers

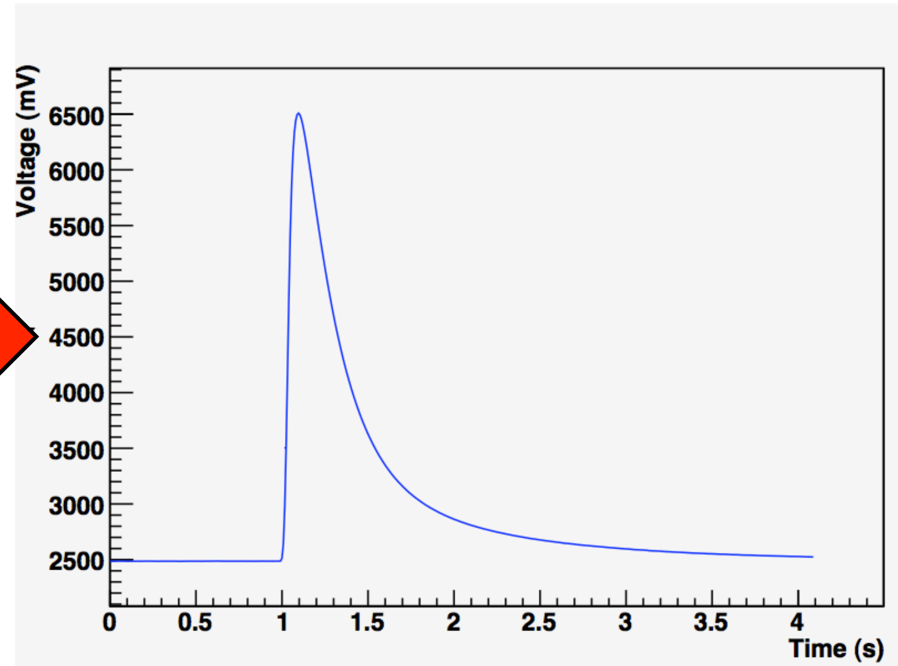
Ultracold TeO_2 crystals function as highly sensitive calorimeters



- Good energy resolution
- High efficiency
- Large source mass
- No particle identification
- Constraints on isotopes

Cryogenic bolometers

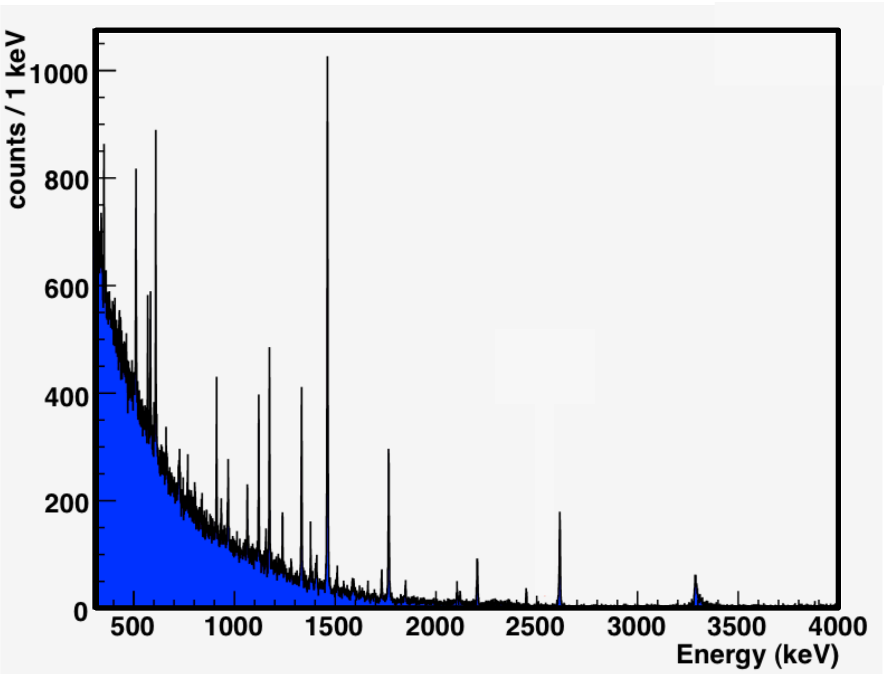




At T=10 mK, particle interactions produce produce measurable rises in crystal temperature

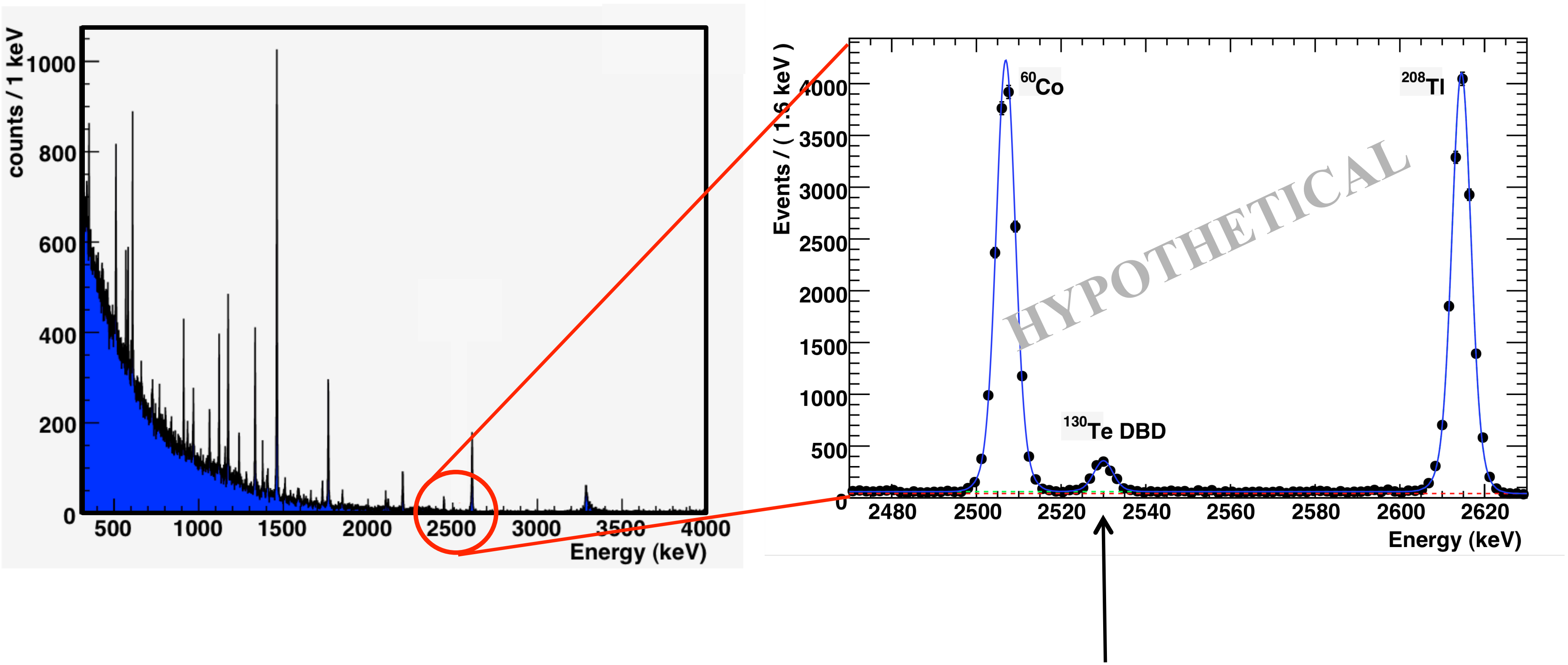
Amplitude of the temperature pulse is proportional to deposited energy

Experimental method



The energy spectrum of detected pulses is compiled...

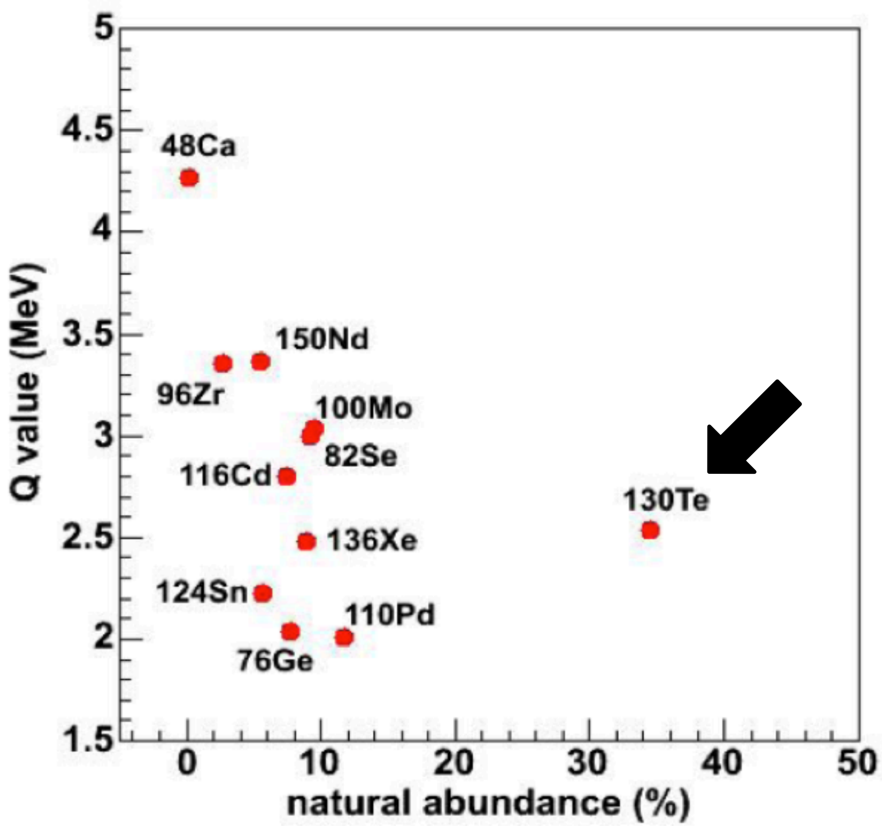
Experimental method



The energy spectrum of detected pulses is compiled...

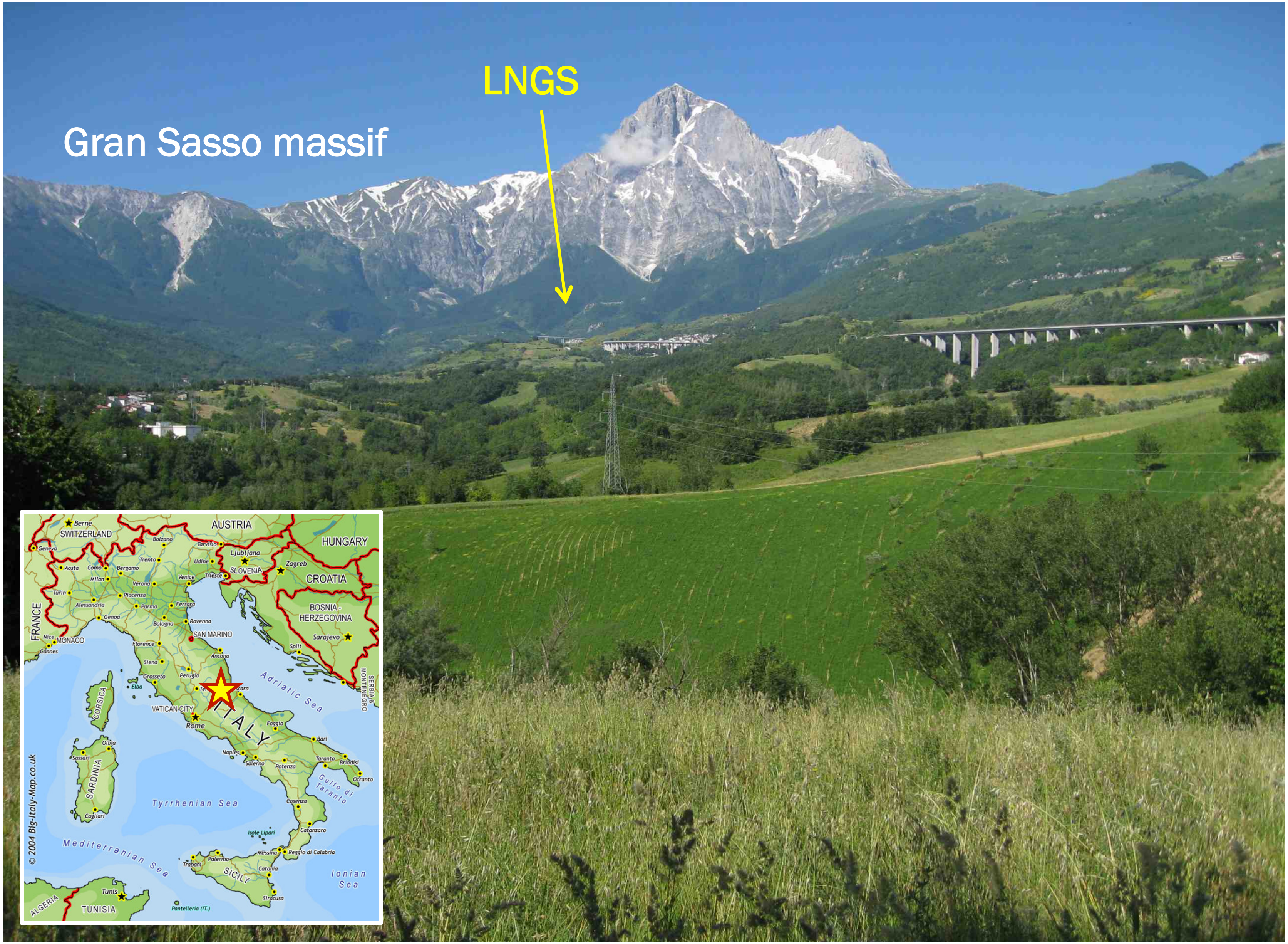
... and the signature of $0\nu\beta\beta$ in ^{130}Te would be a small peak at ~ 2527 keV.

^{130}Te as $0\nu\beta\beta$ decay isotope



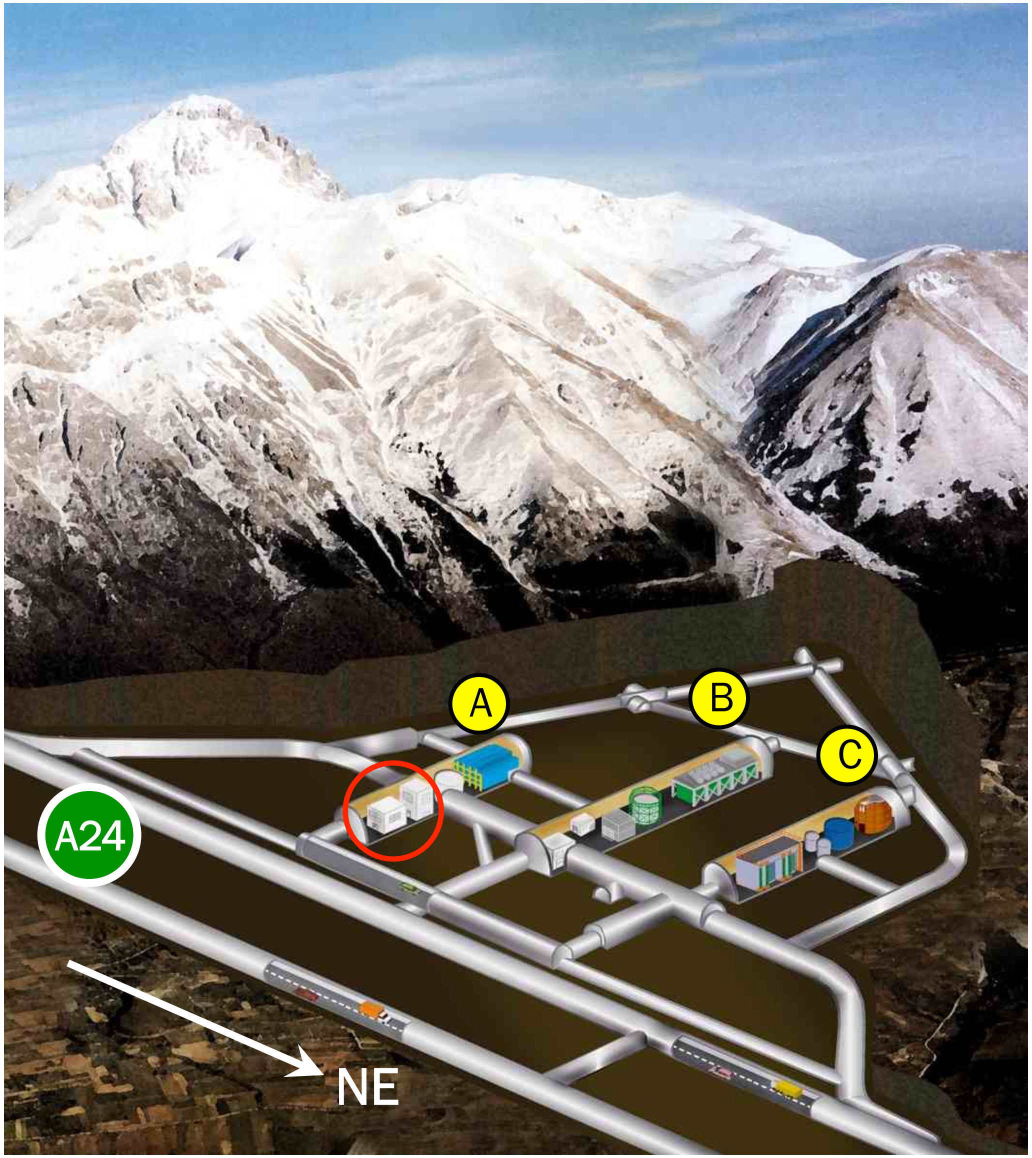
- ► High natural abundance → no enrichment necessary
- ► Good Q-value above natural γ energies + large phase space

Location: LNGS, Italy



LNGS underground lab

- Gran Sasso National Lab
- Built off highway tunnel through mountain
- 1.4-km rock overburden reduces muon flux by 10^6
- 3 experimental halls host 15+ experiments



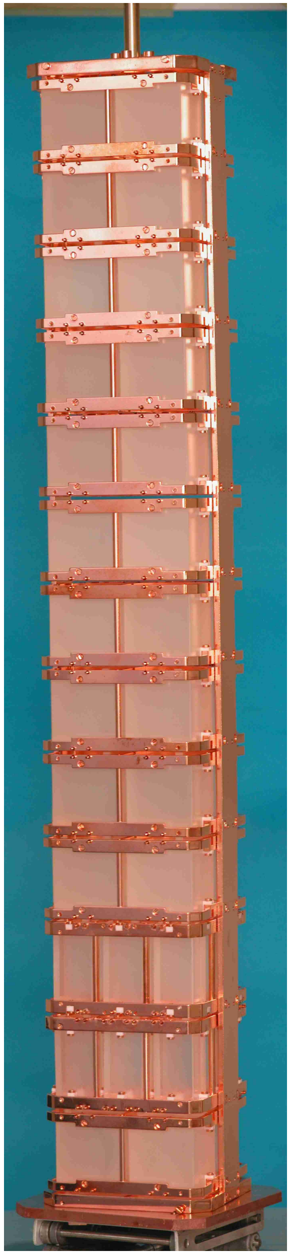
CUORE @ Hall A

CUORE hut

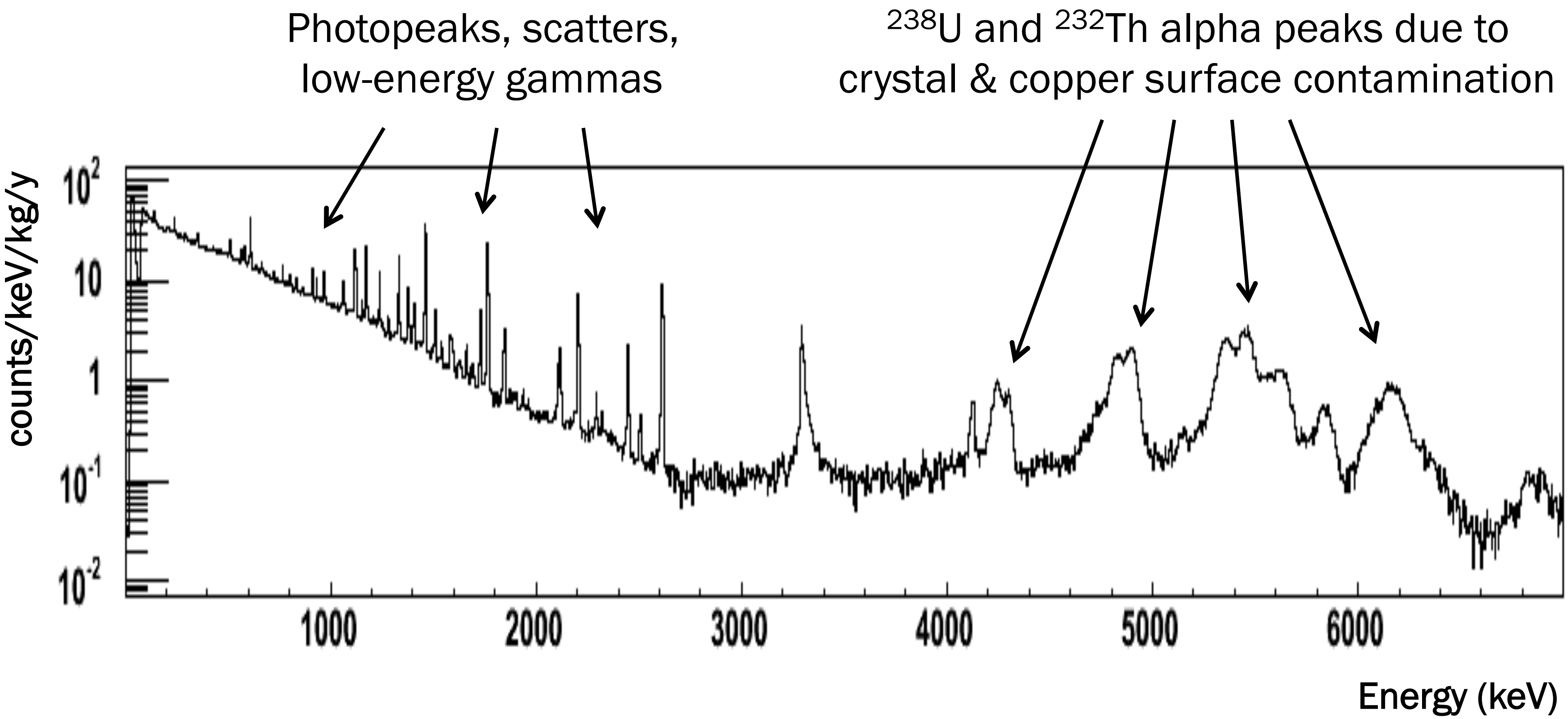
Cuoricino/
CUORE-0 hut

Cuoricino

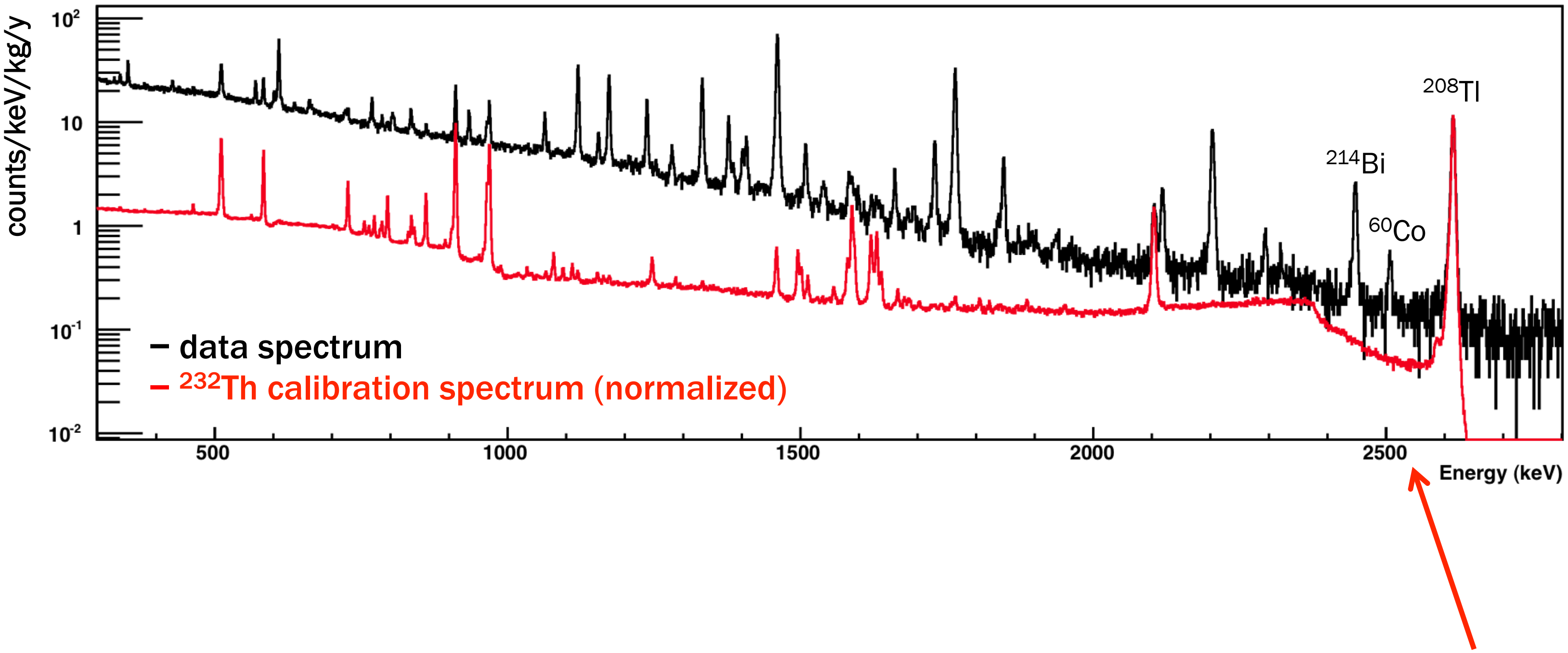
- Operated March 2003 – May 2008
- 62 TeO_2 crystal bolometers of different sizes; some enriched in ^{130}Te or ^{128}Te
- 40.7 kg TeO_2 $\longrightarrow$ **11.3 kg ^{130}Te**



Cuoricino energy spectrum



Cuoricino backgrounds

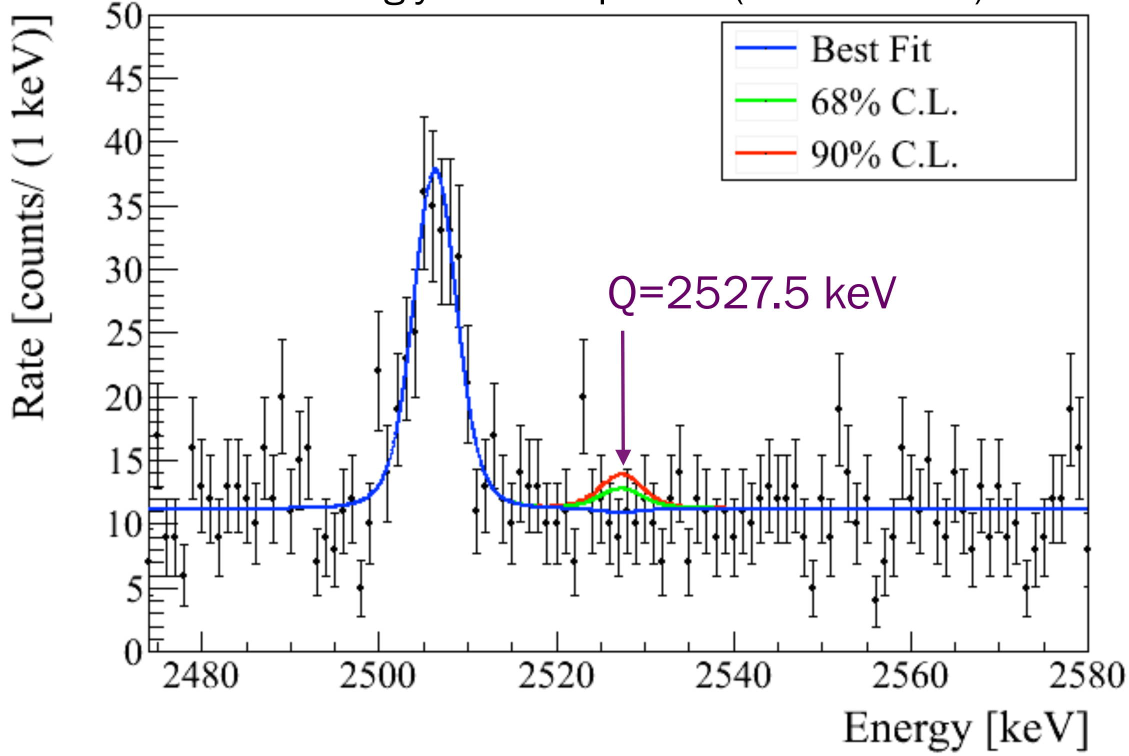


There are three main sources of background in the region around the Q value:

- (~35%) Compton gammas from ^{208}Tl, from ^{232}Th in cryostat
- (~55%) Degraded alphas from ^{238}U and ^{232}Th on copper surfaces
- (~10%) Degraded alphas from ^{238}U and ^{232}Th on crystal surfaces

Cuoricino results

19.75 kg-yr ^{130}Te exposure (2003–2008)



No evidence of $0\nu\beta\beta$ decay in ^{130}Te

E. Andreotti et al. (CUORICINO Collaboration), Astropart. Phys. 34: 822–831 (2011) [arXiv:nucl-ex/1012.3266].

Cuoricino ⟶ CUORE

Isotope mass fraction

Detector mass

Detector efficiency

Exposure time

$$\hat{T}_{1/2}^{0\nu\beta\beta}(n_\sigma) \propto \frac{\varepsilon \cdot a}{n_\sigma} \sqrt{\frac{M \cdot t}{B \cdot \delta E}}$$

Confidence level

Energy resolution

Background

- Half-life sensitivity depends on detector parameters
- Sensitivity is the max signal that could be hidden by a background fluctuation (at specified confidence level)

Cuoricino ⟶ CUORE

$$\hat{T}^{0\nu\beta\beta}_{1/2}(n_\sigma) \propto \frac{\varepsilon \cdot a}{n_\sigma}\sqrt{\frac{M \cdot t}{B \cdot \delta E}}$$

Isotope mass fraction

Detector mass (×19)

Detector efficiency

Exposure time (×2)

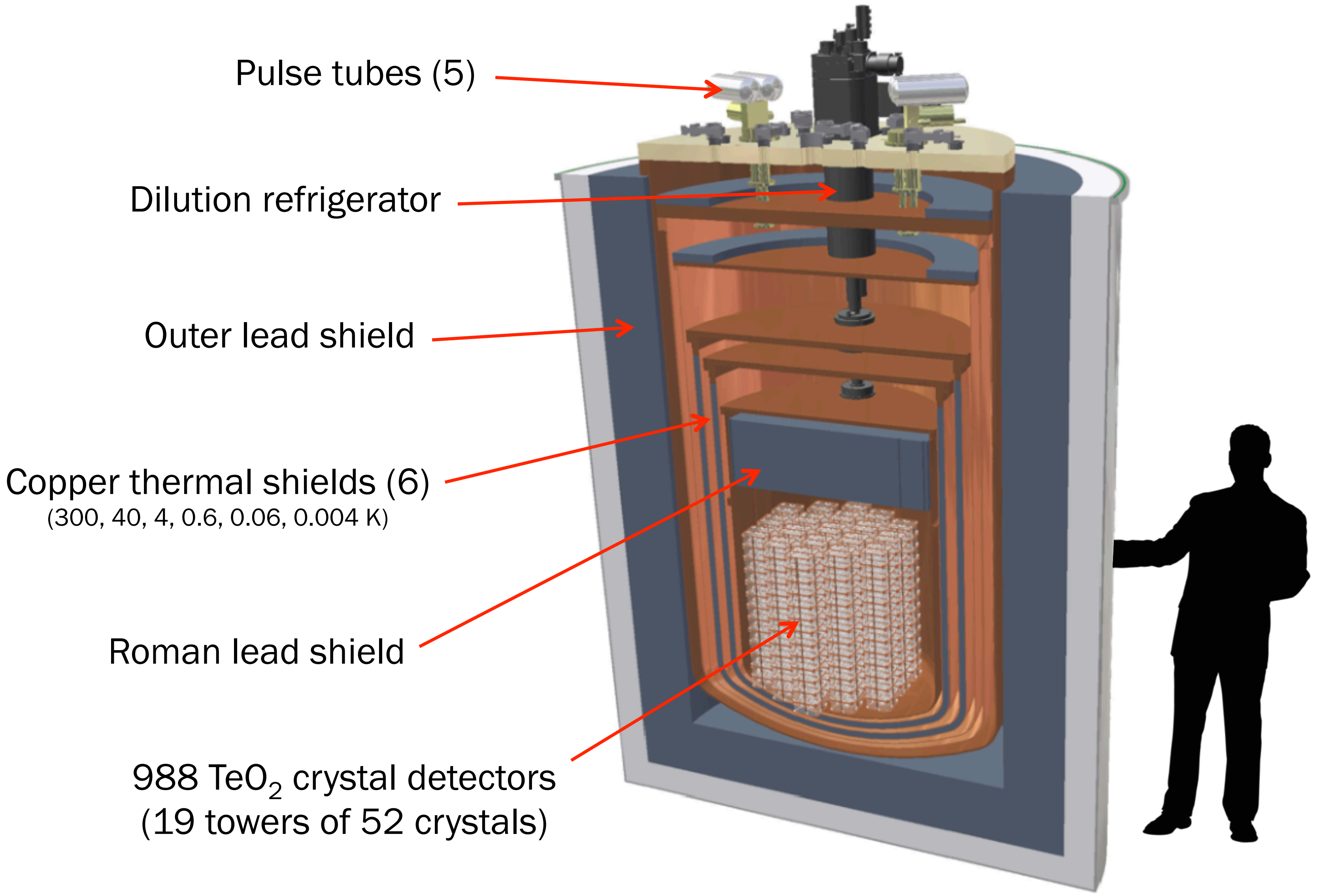
Confidence level

Energy resolution (÷1.6)

Background (÷18)

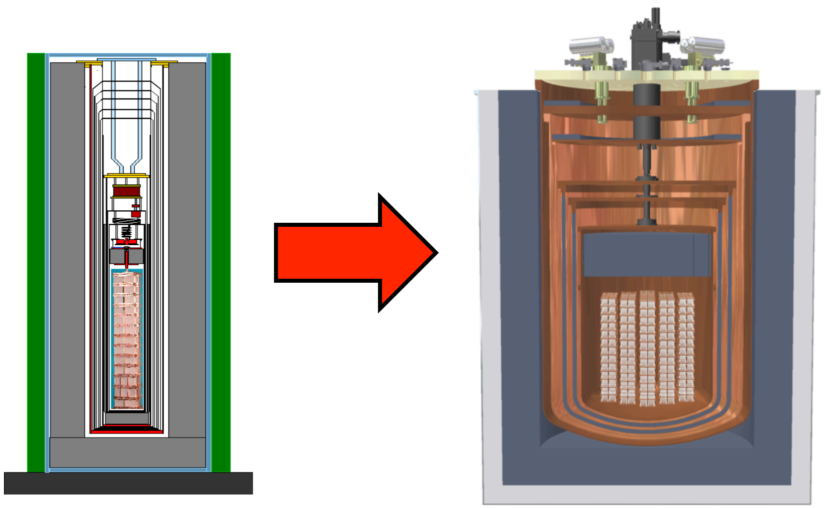
- Half-life sensitivity depends on detector parameters
- Sensitivity is the max signal that could be hidden by a background fluctuation (at specified confidence level)

CUORE


Pulse tubes (5)
Dilution refrigerator
Outer lead shield
Copper thermal shields (6)
(300, 40, 4, 0.6, 0.06, 0.004 K)
Roman lead shield
988 TeO_2 crystal detectors
(19 towers of 52 crystals)

Cryostat improvements

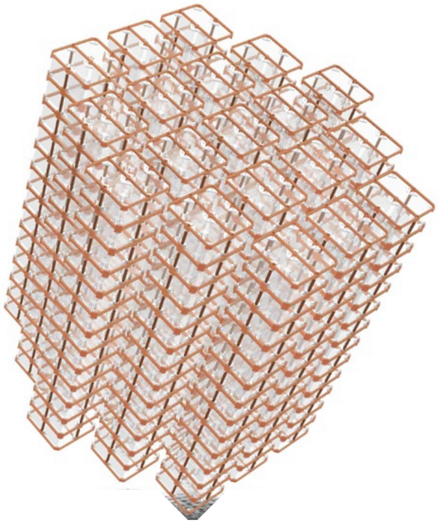
Cuoricino **CUORE**



- New custom dilution refrigerator
- Cryogen-free → more live time
- Better suspension → less vibration
- More Pb shielding
- Cleaner

Detector improvements

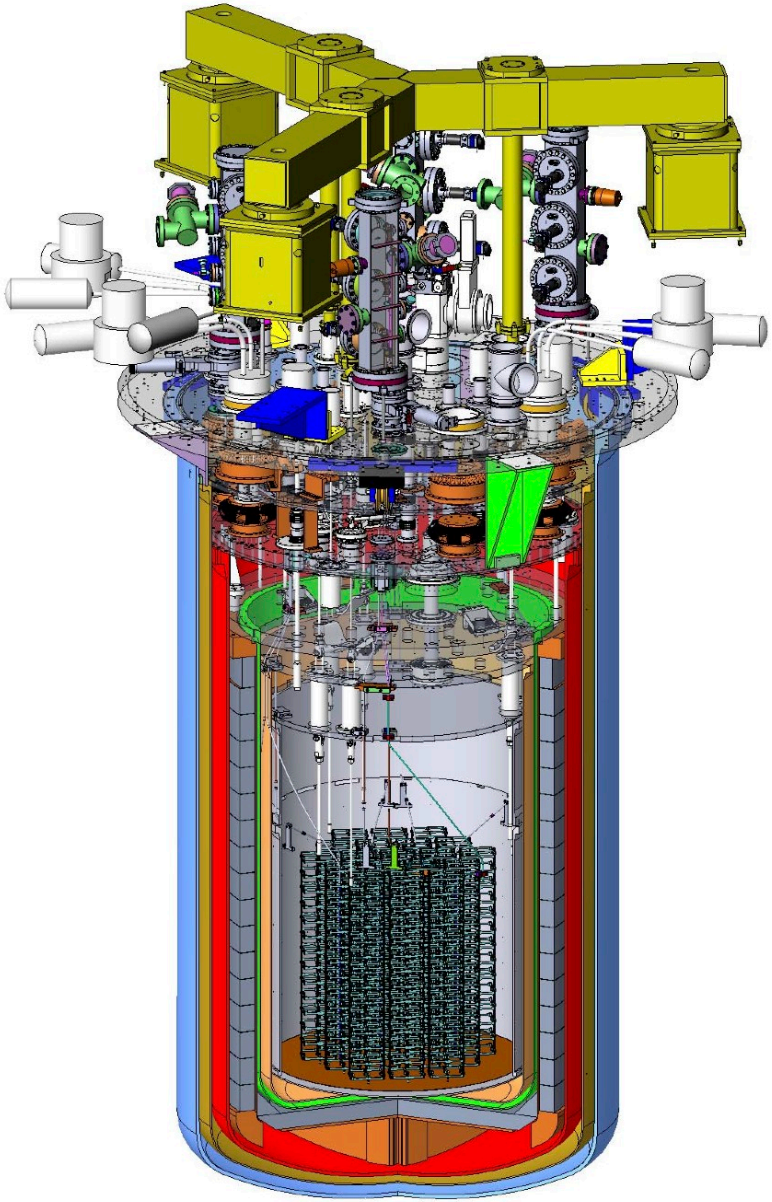
- Cleaner crystals
- Cleaner copper, and less per kg TeO_2
- Cleaner assembly environment
- Less vibration in copper frames
- Better self-shielding & anticoincidence coverage



	Cuoricino	CUORE-0	CUORE
^{130}Te mass (kg)	11	11	206
Background (c/keV/kg/y) @ 2528 keV	0.17	0.05	0.01
E resolution (keV) FWHM @ 2615 keV	7	5–6	5
$\langle m_{\beta\beta} \rangle$ (meV) @ 90% C.L.	300–710	200–500	40–90

Engineering & logistics

The primary experimental challenge is scaling up the bolometric apparatus…



CUORE status

Crystals in storage @ LNGS

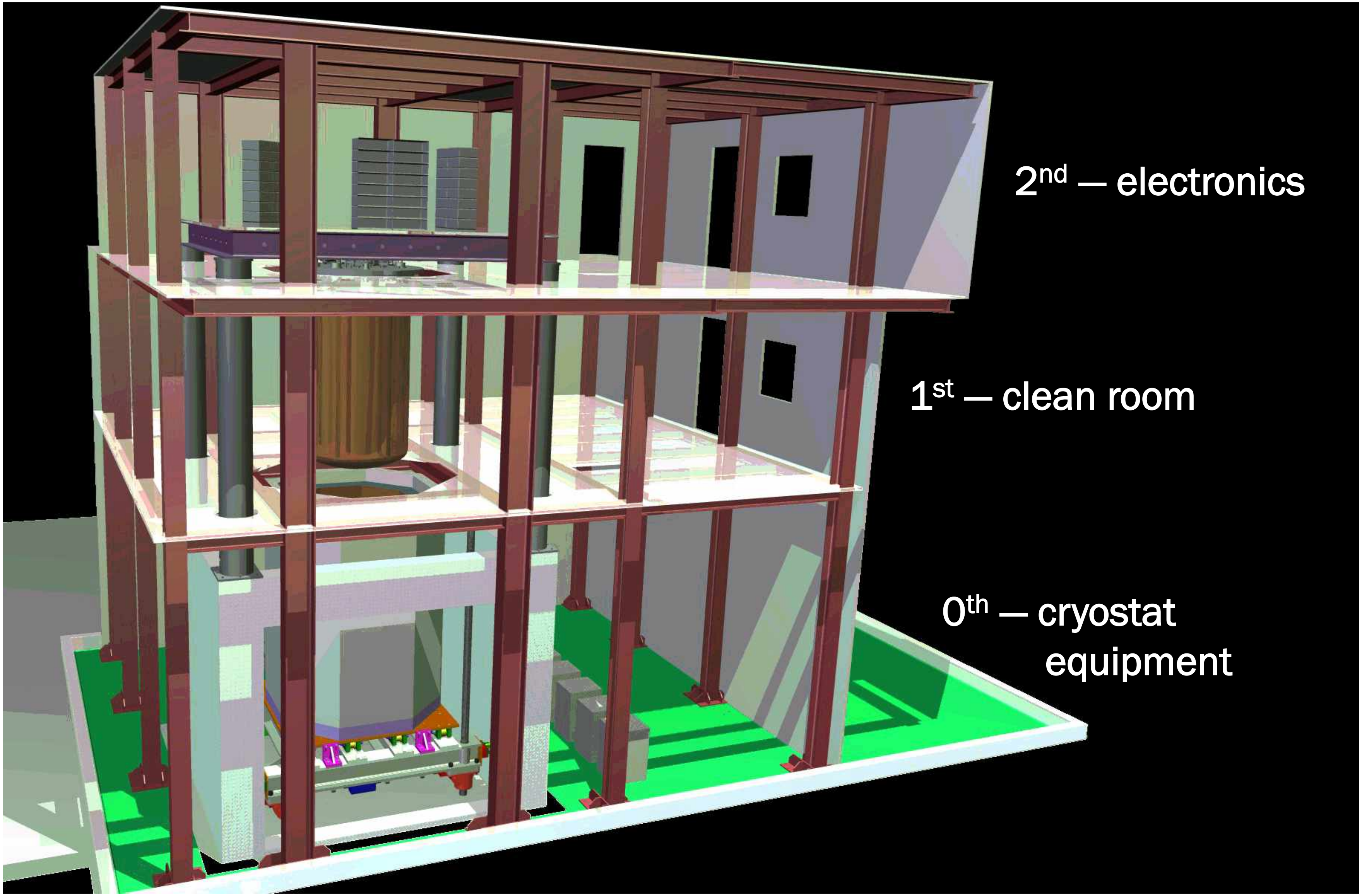
Cryostat shields @ factory

Dilution unit test setup
@ LNGS

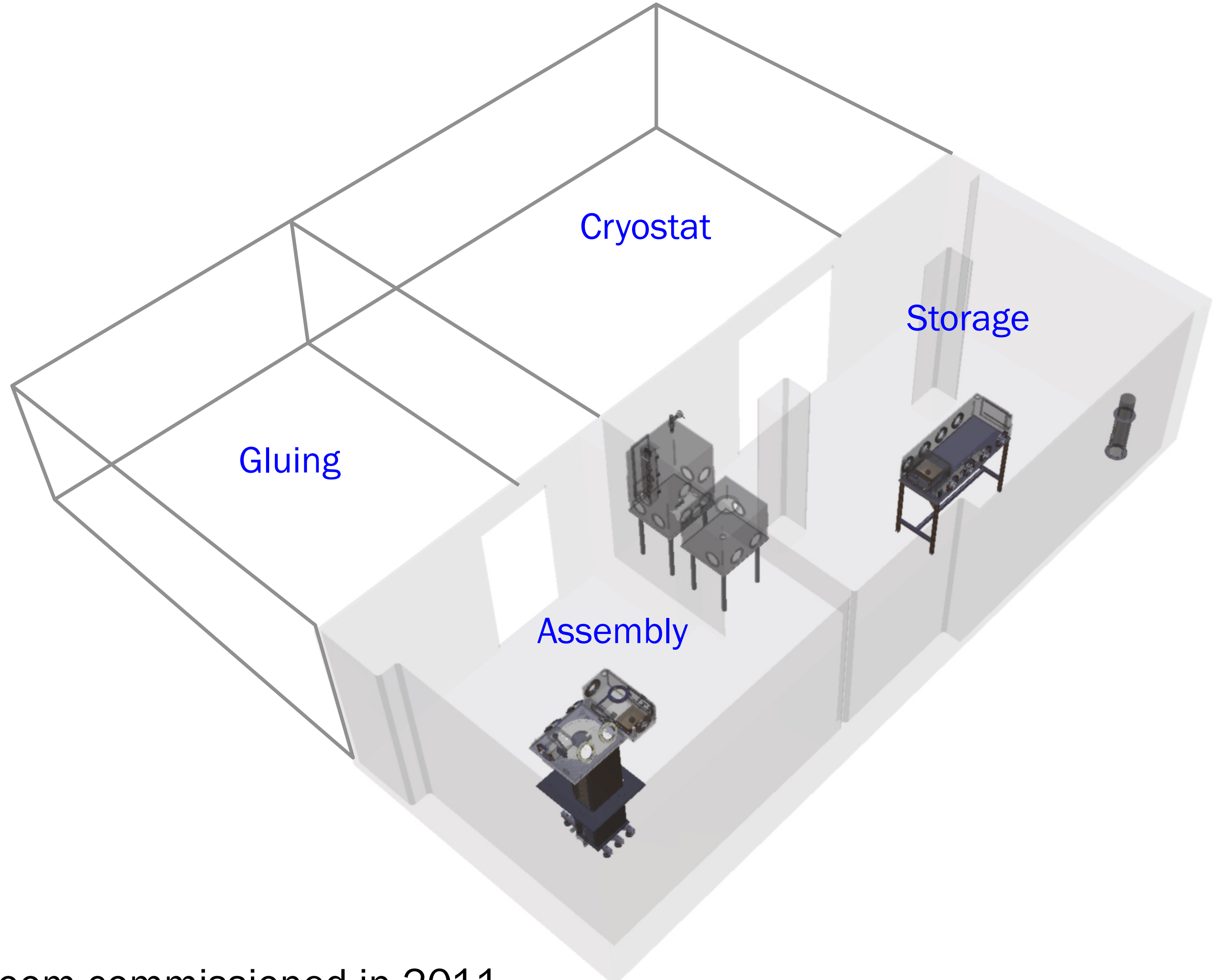
- 85% of crystals delivered so far (836/988)
- Copper parts are being machined and cleaned
- 3 (of 6) cryostat vessels to be delivered to LNGS soon
- Dilution refrigerator delivered to LNGS (though some repairs needed)

CUORE hut

CUORE hut

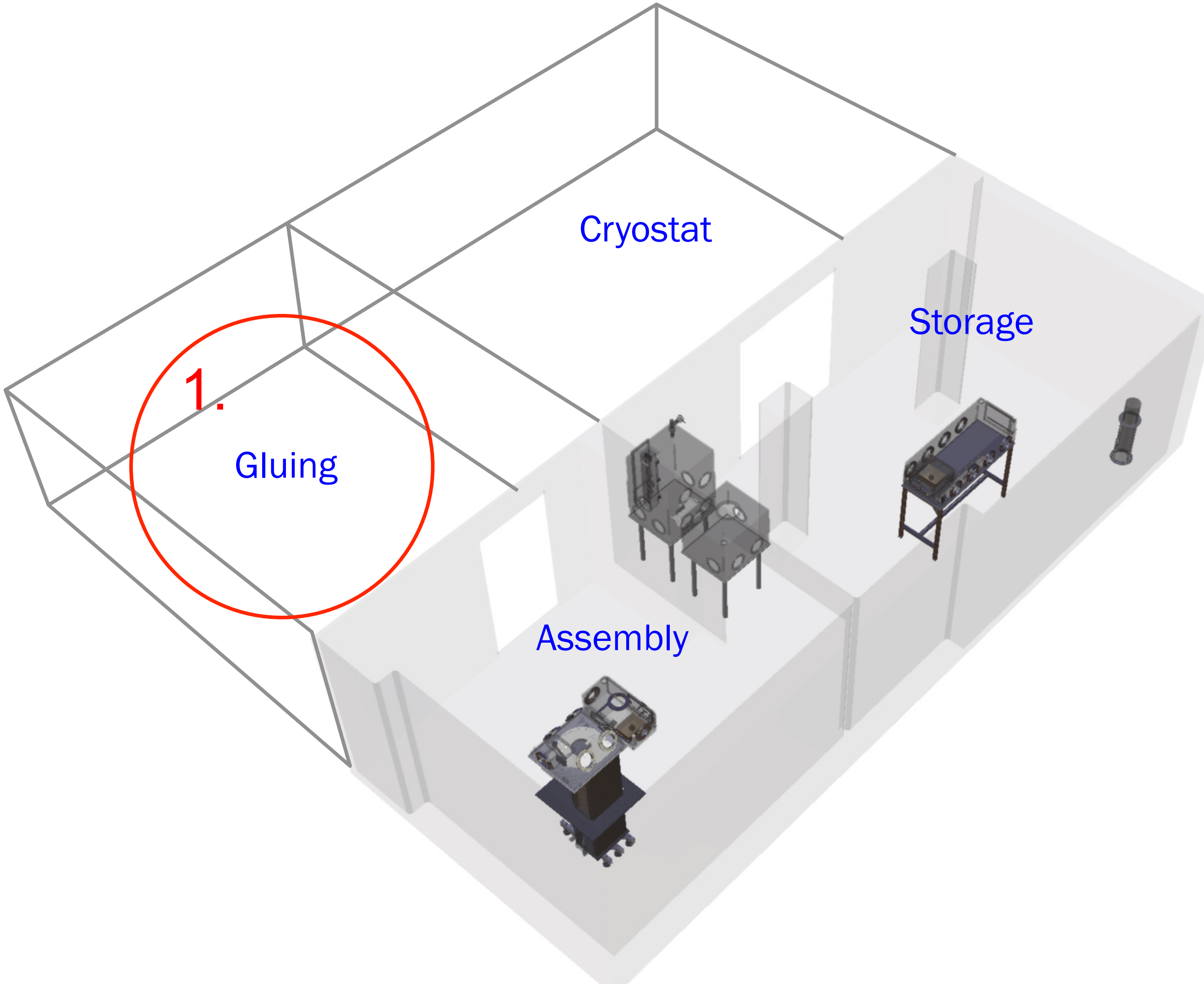


Detector assembly



- ▶ Clean room commissioned in 2011
- ▶ Crystals are prepared and assembled into towers inside N_2-filled glove boxes

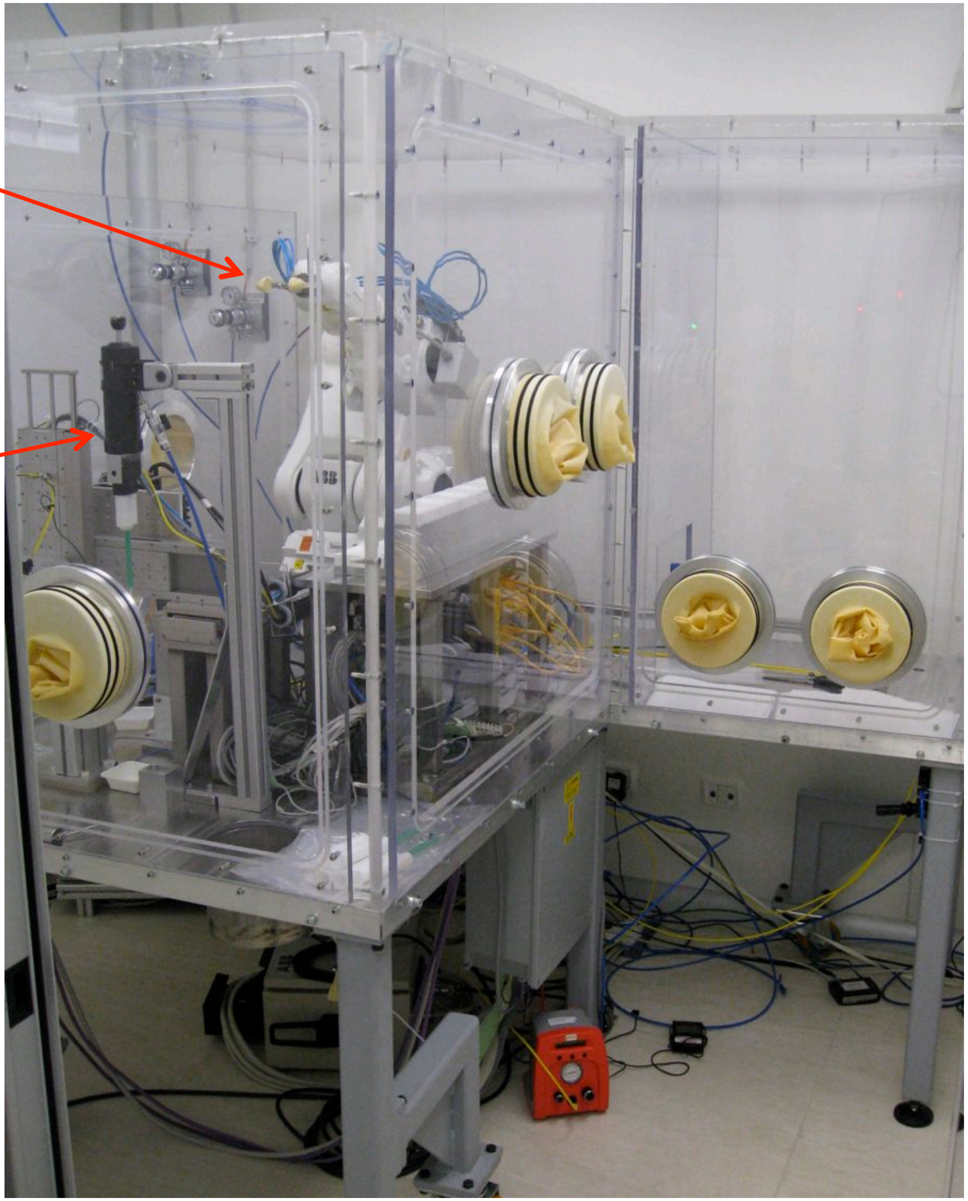
Crystal gluing

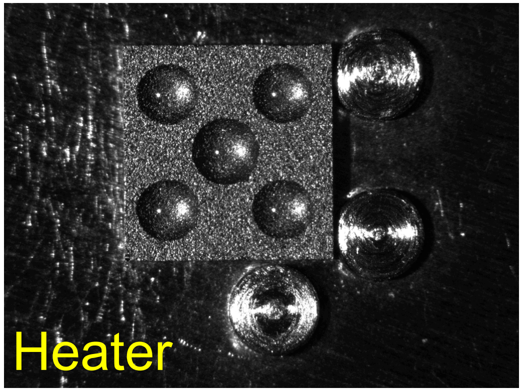


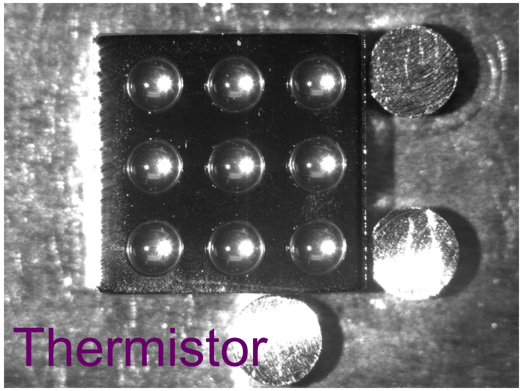
Crystal gluing

Robotic arm for handling crystals

Robot for mixing & dispensing glue

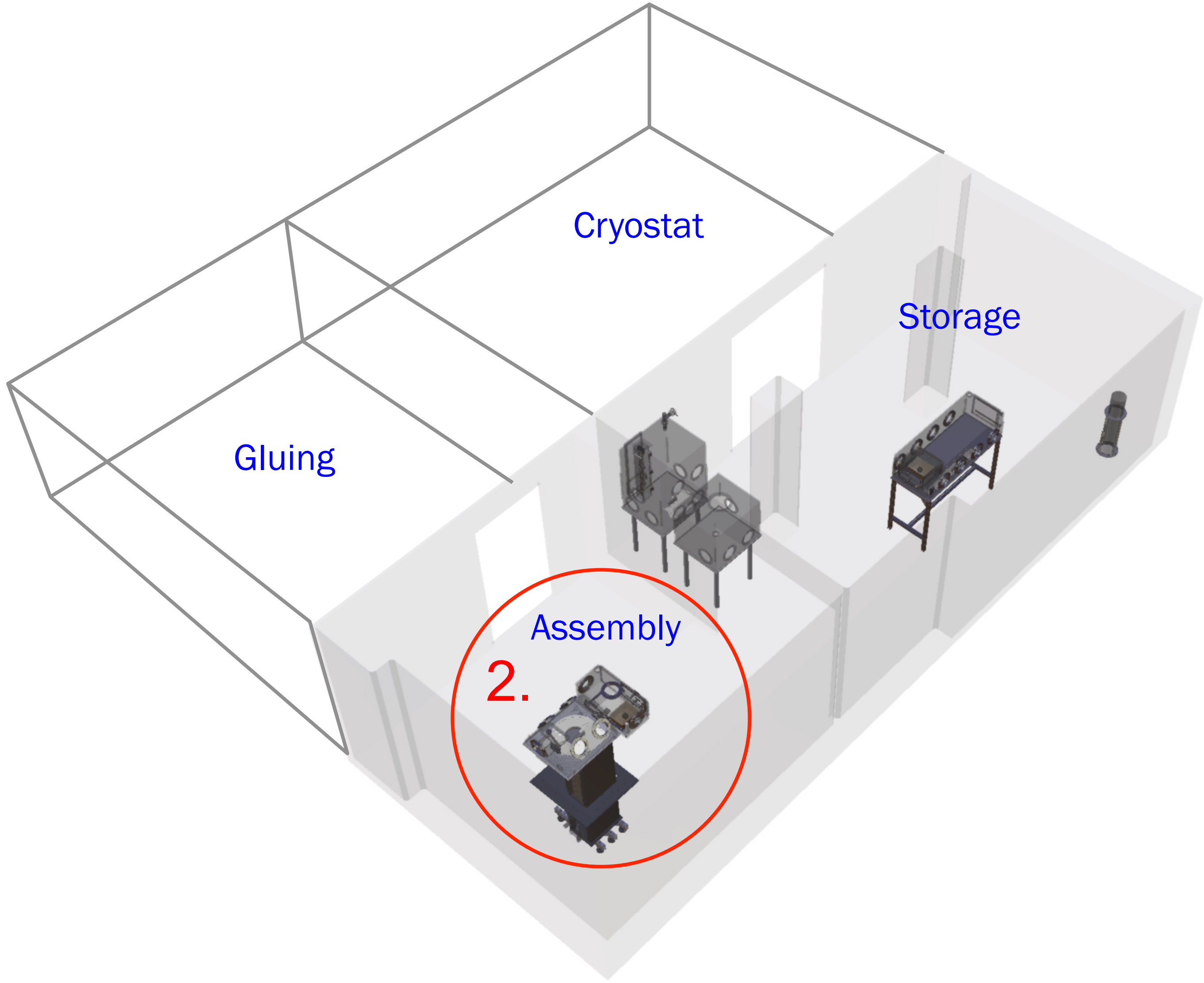




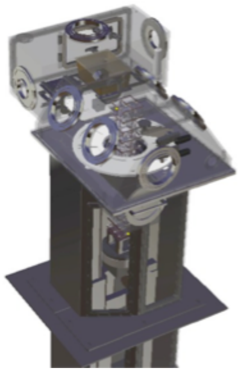


Semi-automated setup enables more precise & uniform gluing

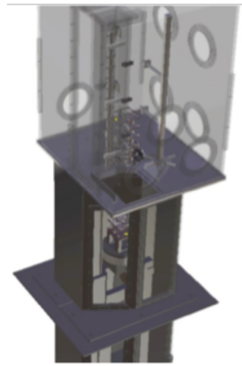
Tower assembly line



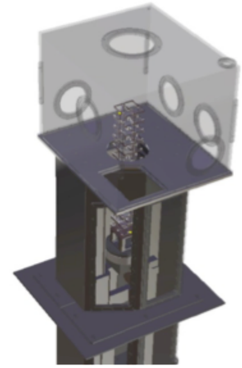
Tower assembly line



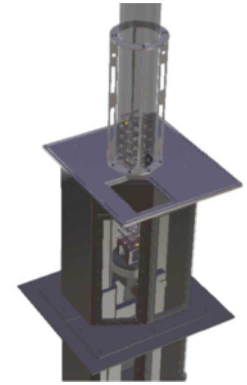
1. Assembly box



2. Cabling box



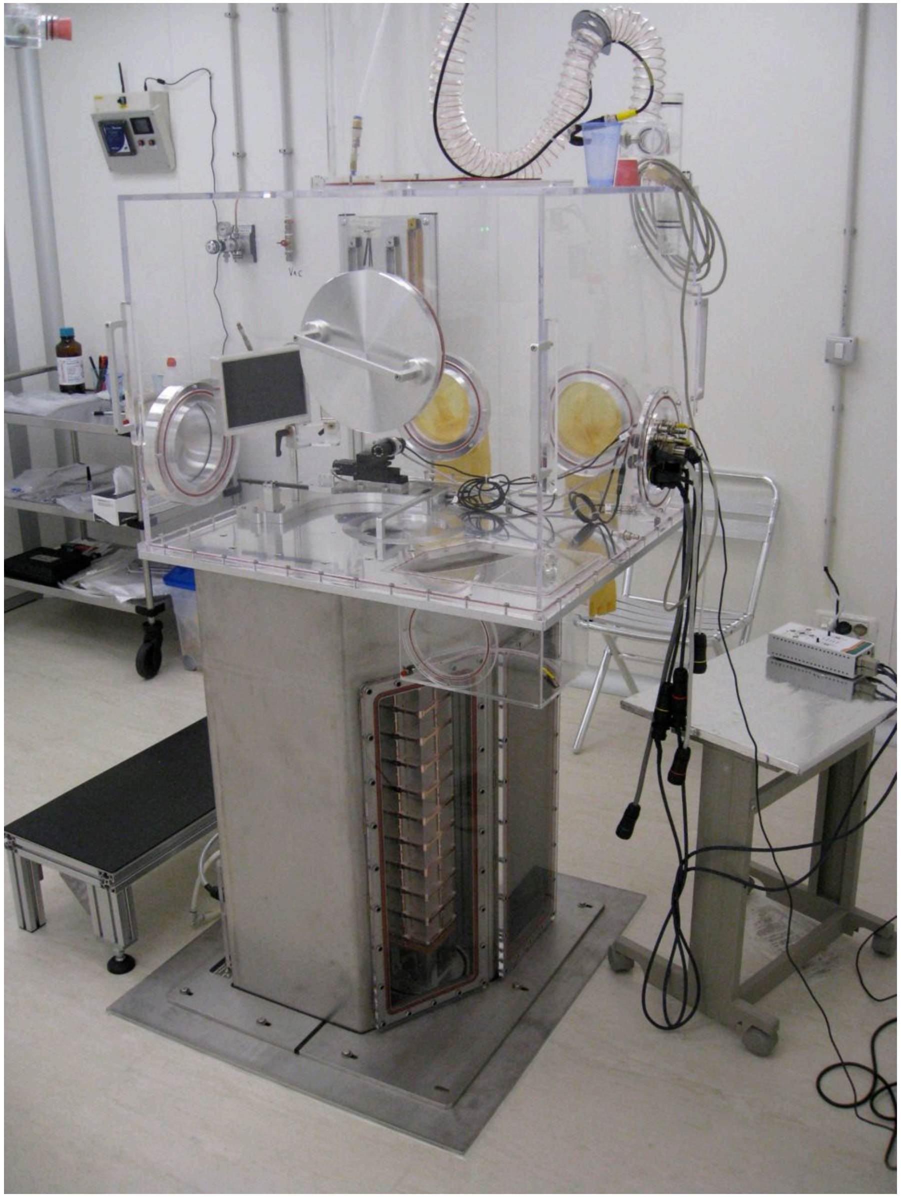
3. Bonding box



4. Storage box

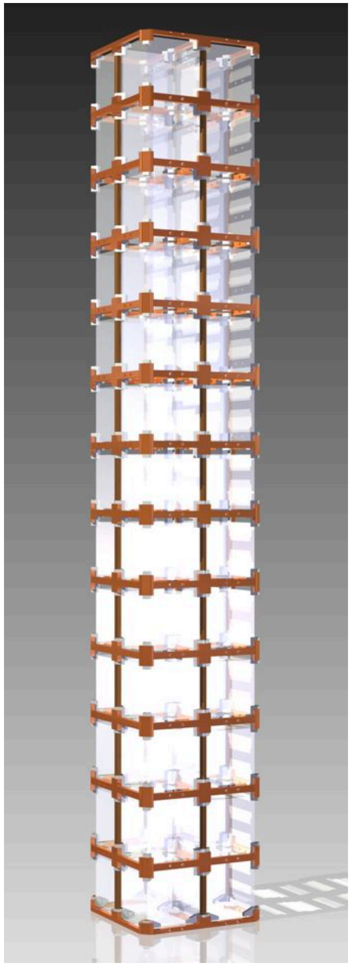
- Single station with 4 interchangeable glove boxes for specific tasks
- Must transform ~ 10,000 components (!) into 19 ultra-clean towers

Tower assembly line

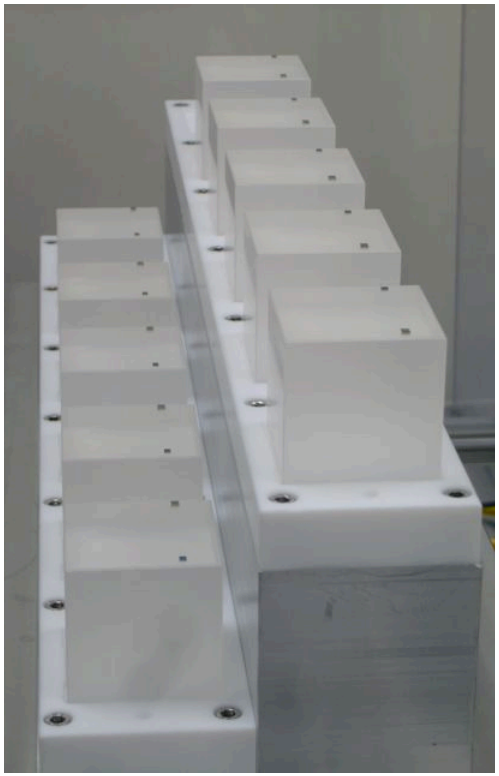


CUORE-0

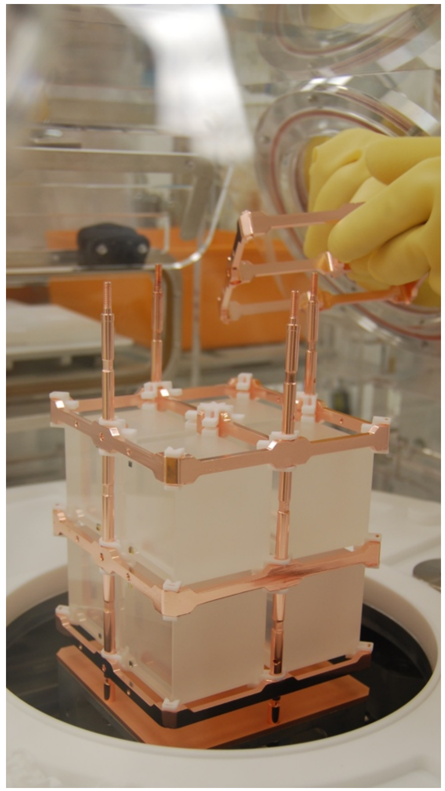
- First tower from CUORE assembly line
- Will be operated in former Cuoricino cryostat
- Purpose:
  1. Test CUORE assembly line
  2. Surpass Cuoricino while CUORE is being assembled



CUORE-0 saga



Gluing
(Oct 2011)



Assembly #1
(Oct 2011)

Found problems w/copper parts

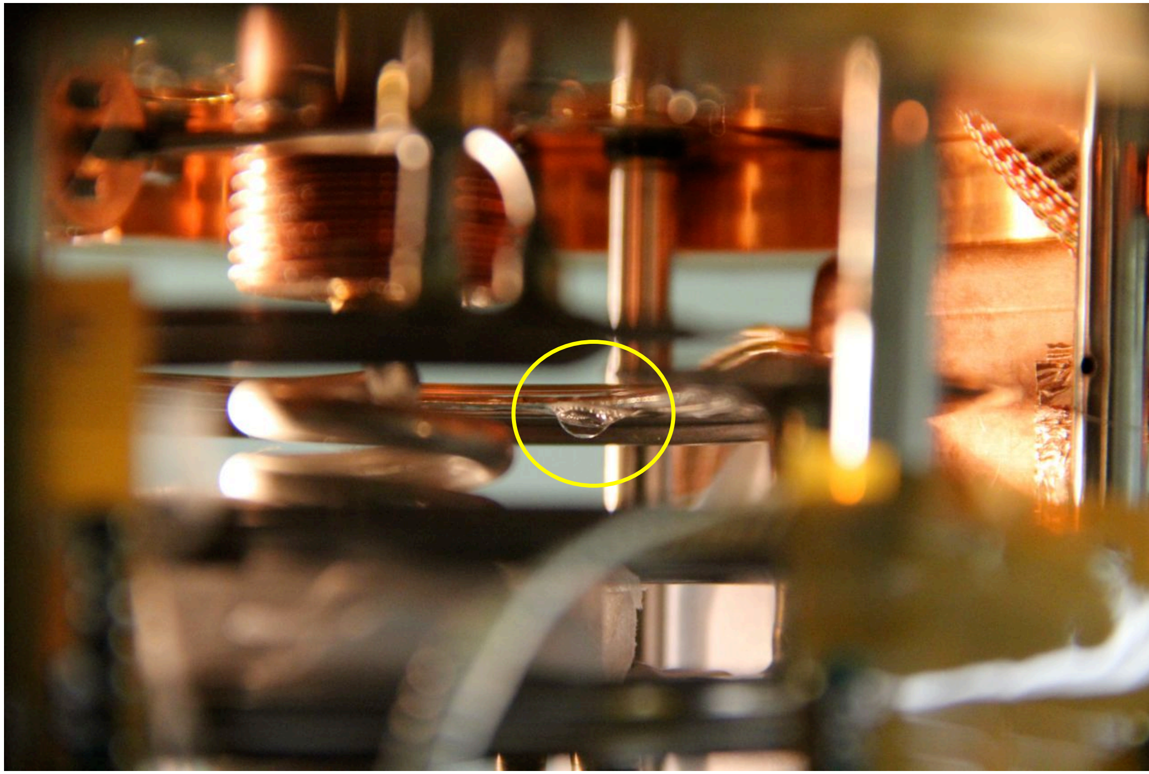
Assembly #2
(Apr 2012)

Success w/brand-new copper parts

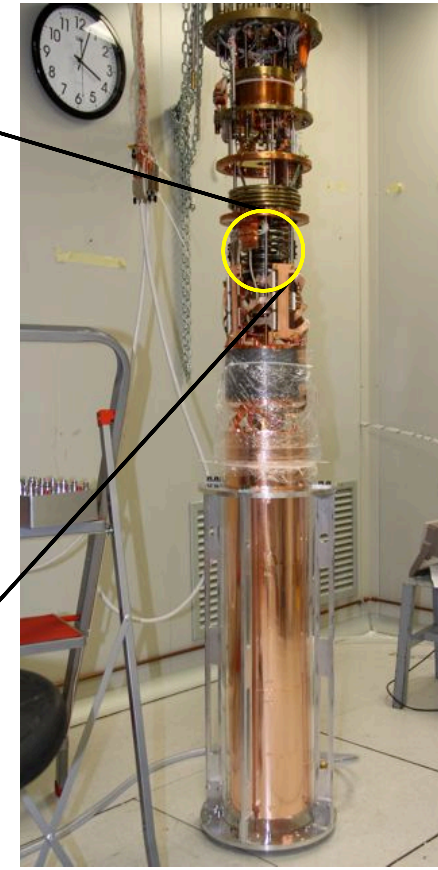
Cooldown #1
(Apr 2012)

Leak appeared in dilution refrigerator

CUORE-0 saga



Uppermost heat exchanger

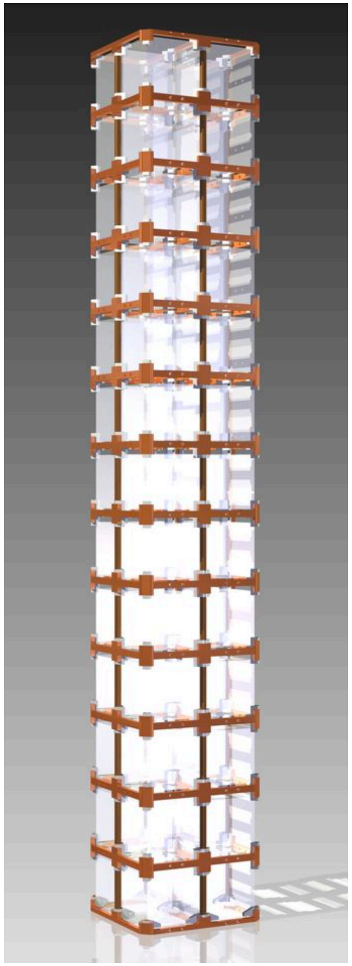


Cooldown #1
(Apr 2012)

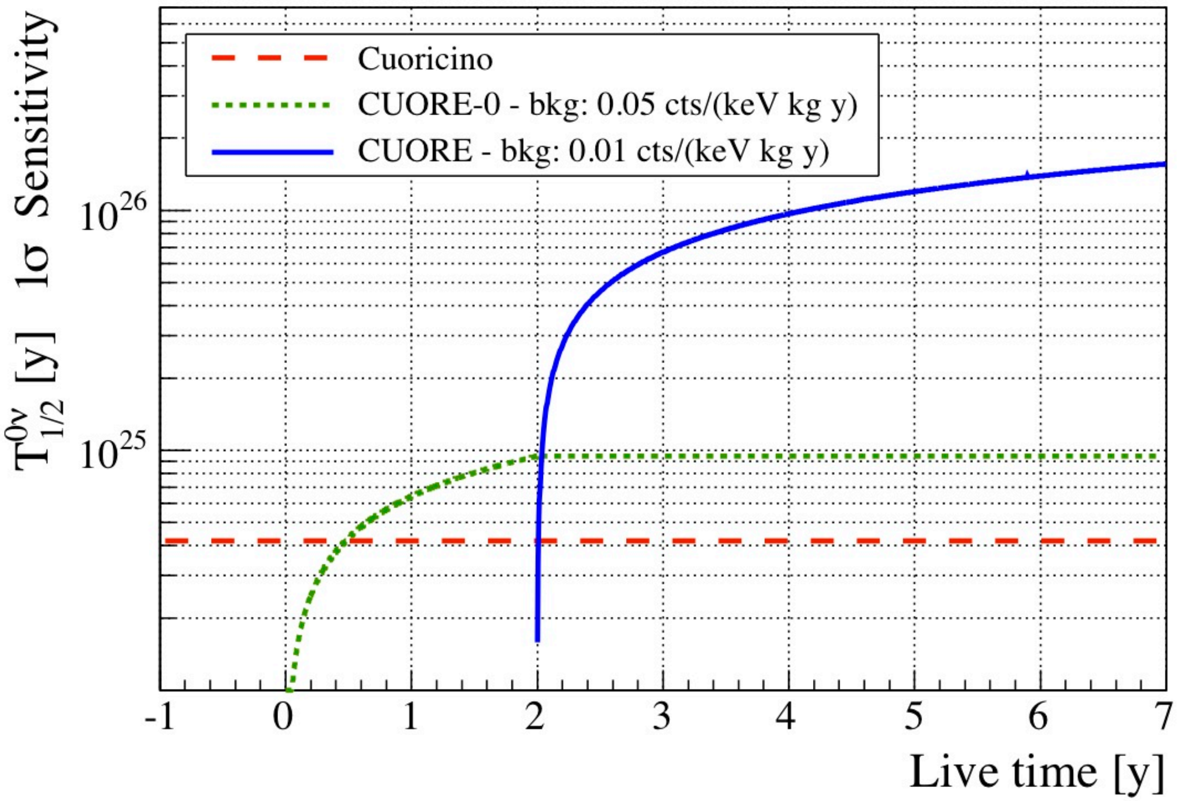
Leak appeared in dilution refrigerator

CUORE-0 schedule

- ☑ Gluing in October 2011
- ☑ Assembly in April 2012
- ☐ Cooldown in Summer 2012
- ☐ Data taking 2012—2014(?)



Experimental sensitivities



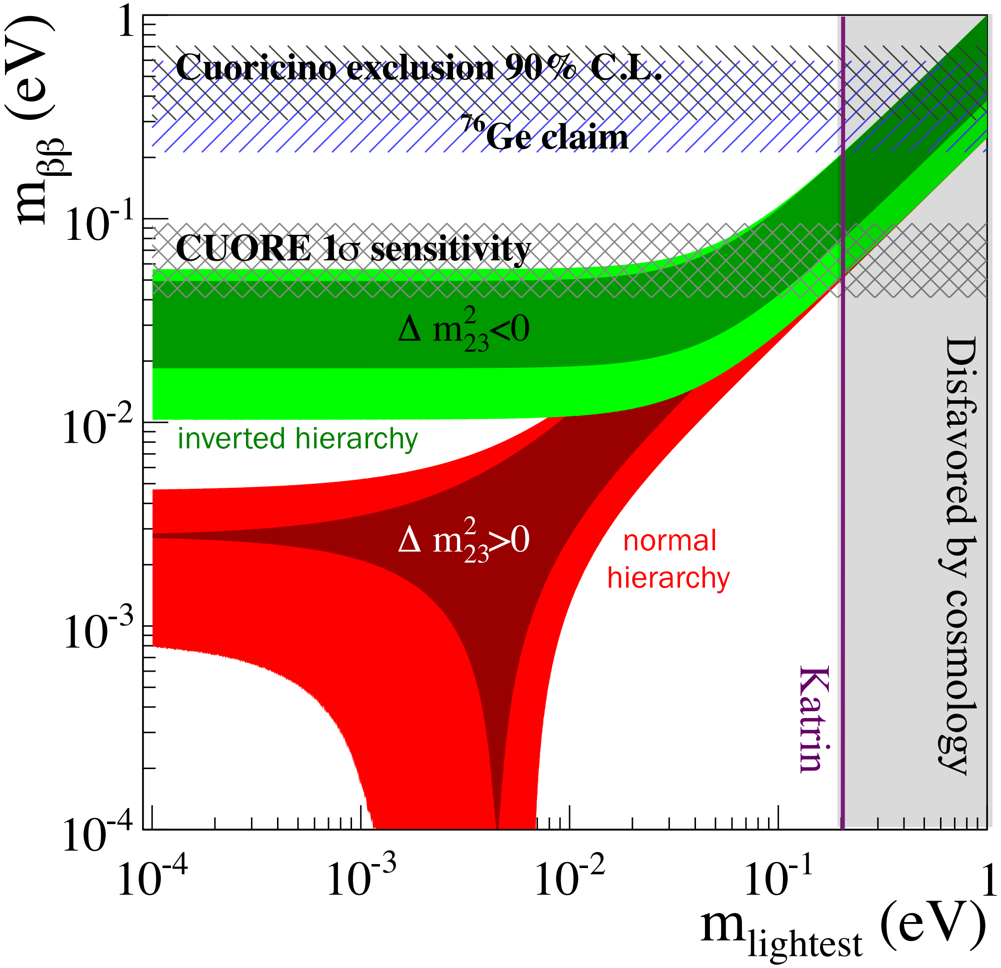
Cuoricino: $T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) \geq$ **4.2 × 10^{24} y** (1σ)

CUORE-0: $T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) \geq$ **9.4 × 10^{24} y** (1σ; 2 years)

CUORE: $T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) \geq$ **1.6 × 10^{26} y** (1σ; 5 years)

See "Sensitivity of CUORE to Neutrinoless Double-Beta Decay" [arXiv:nucl-ex/1109.0494v1]

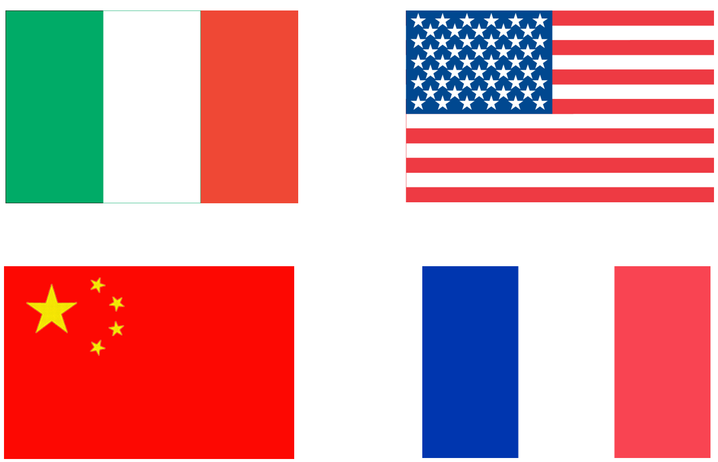
Experimental reach



Summary

- Cuoricino did not see evidence of $0\nu\beta\beta$ decay in TeO_2
- The CUORE-0 detector is ready to begin taking data as soon as its cryostat is repaired (this week?)
- Preparations for CUORE are ongoing and will continue for ~ 2 more years, with data taking in 2014(?)

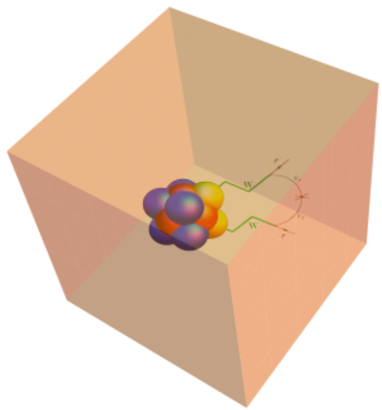
CUORE Collaboration



Fine

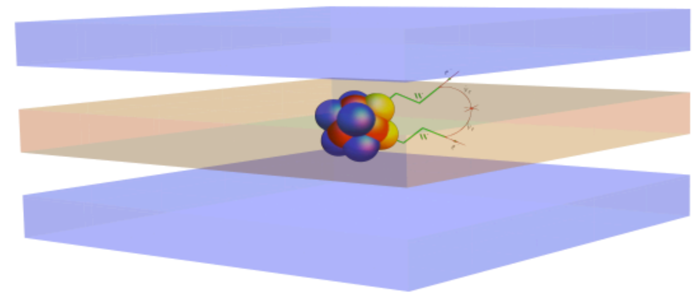
Experimental approaches

Source = Detector



Calorimeter for events of $E=Q_{\beta\beta}$

Source ≠ Detector

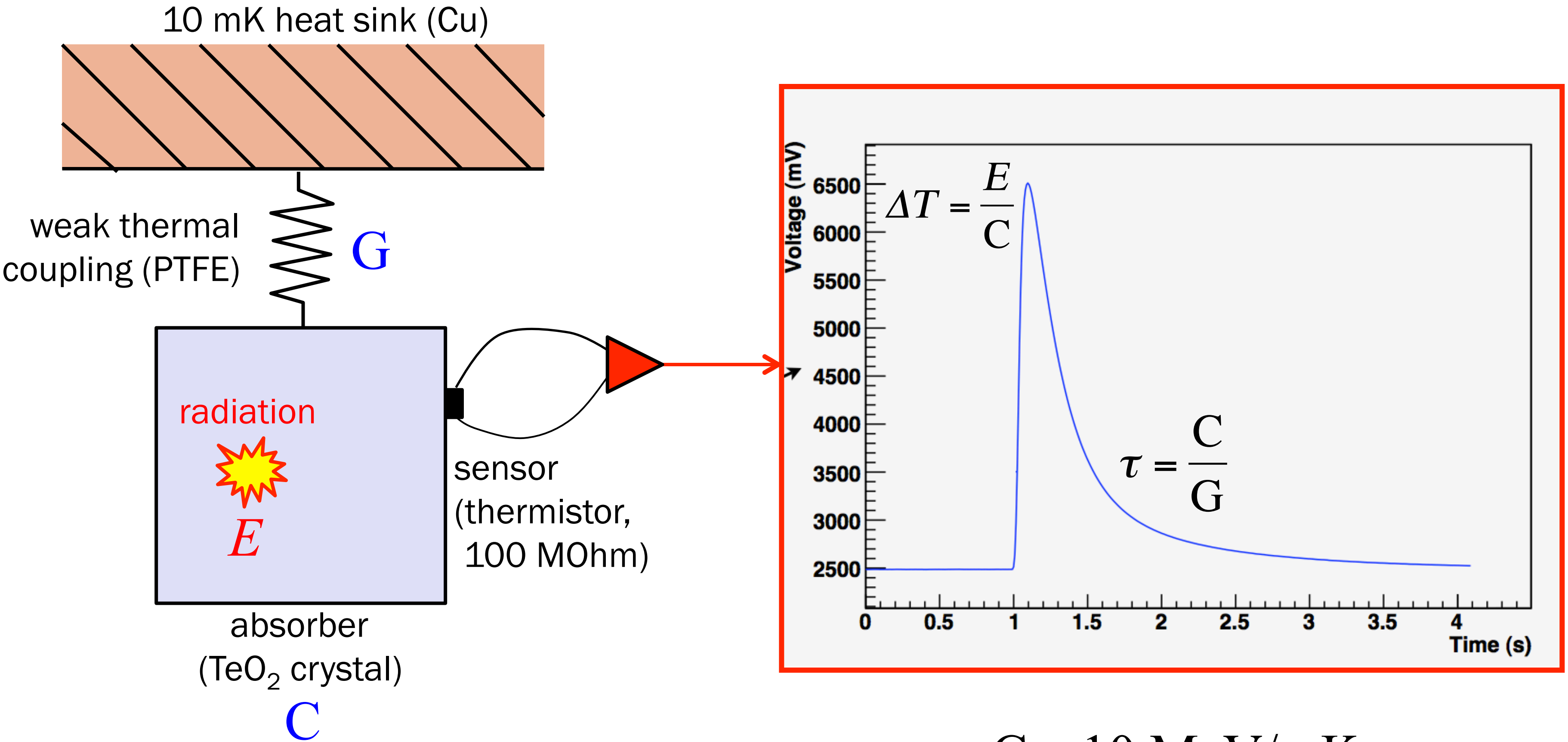


Track particles of $\Sigma E = Q_{\beta\beta}$

- Good energy resolution
- High efficiency
- Large source mass
- Constraints on possible sources
- No particle identification

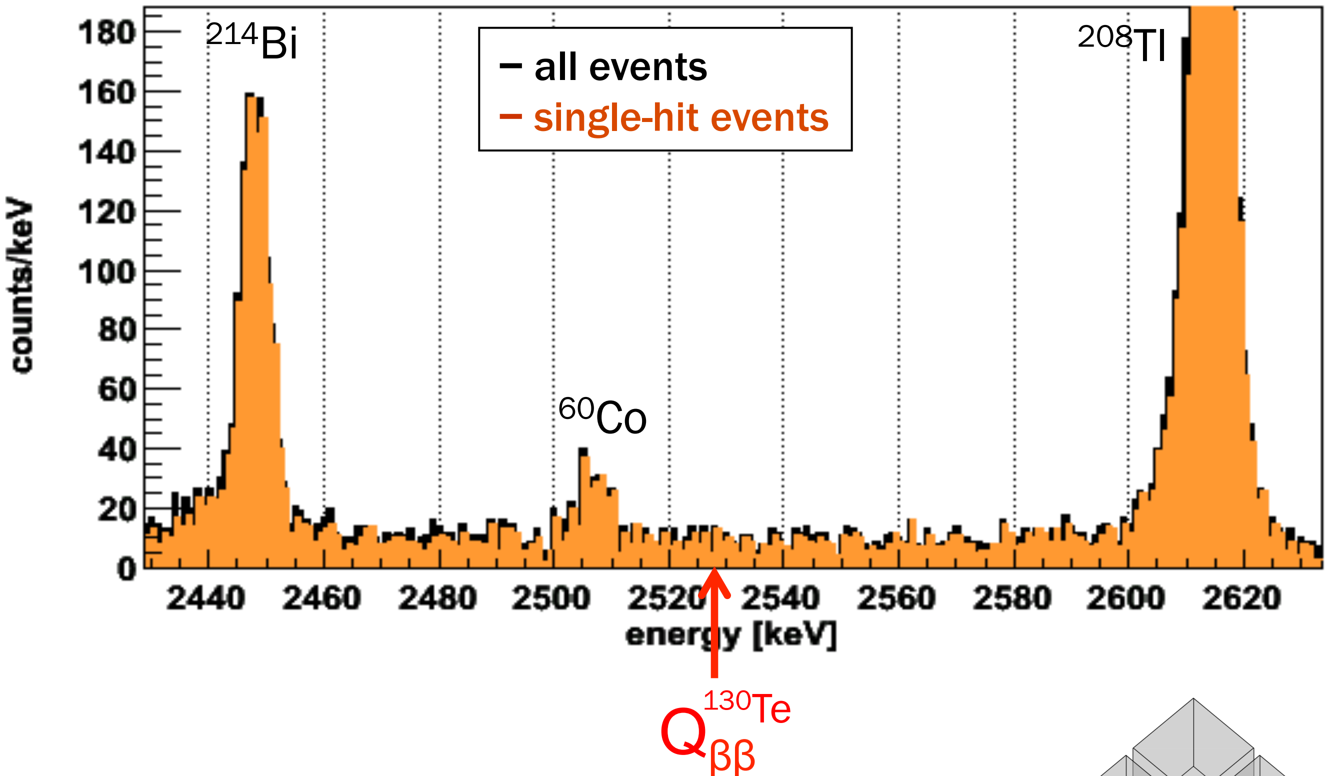
- Poor energy resolution
- Low efficiency
- Small source mass
- Study different sources
- Particle identification

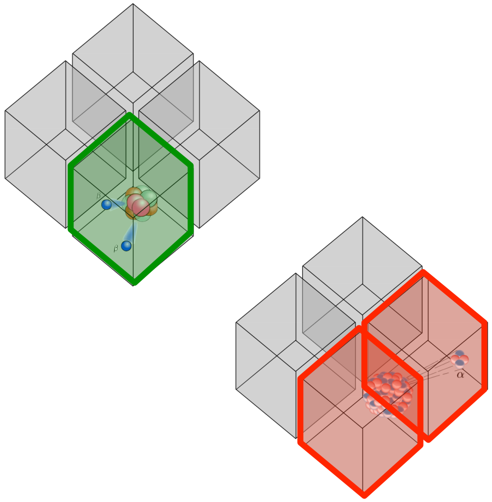
Cryogenic bolometers



$C \sim 10$ MeV/mK

Cuoricino coincidence veto

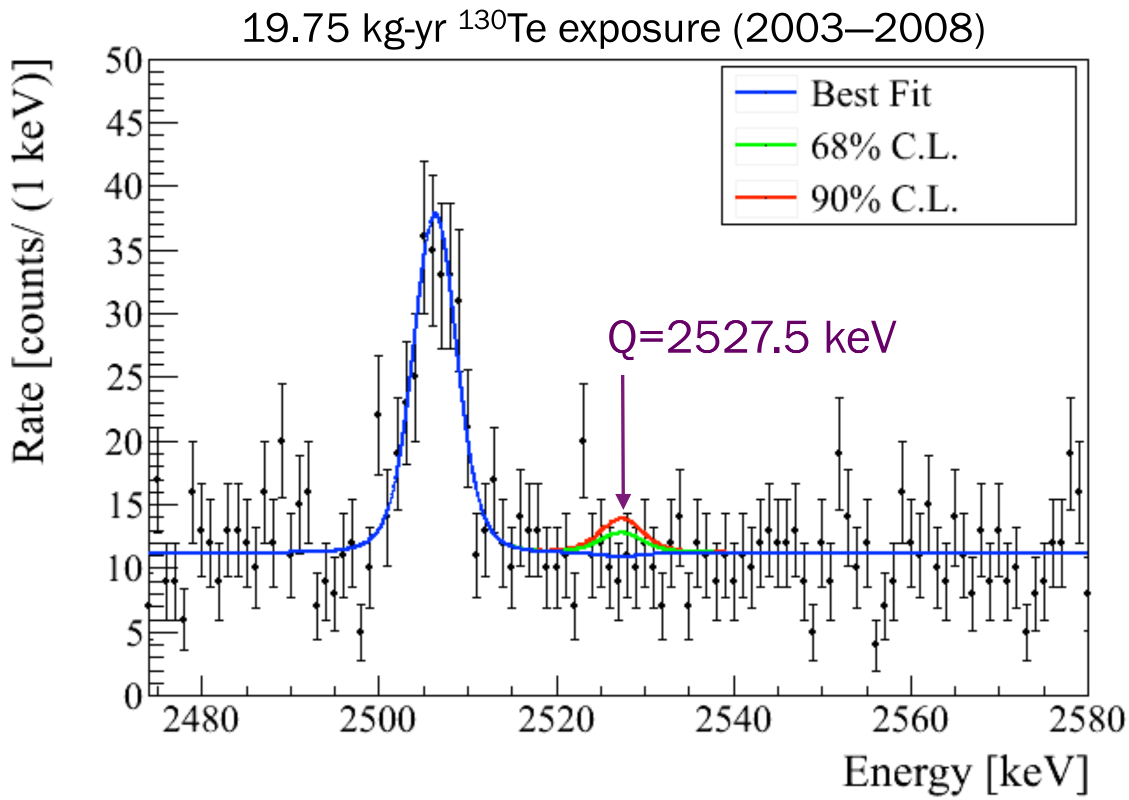




- $0\nu\beta\beta$ decay should produce a single-site event 85% of the time

- Excluding multi-site events reduces background by 15% in region of interest while retaining > 99% of signal

Cuoricino results (2010)



Background: 0.169 ± 0.006 counts/keV/kg/y (^{130}Te)

Lower limit, half-life: $T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) \geq 2.8 \times 10^{24}$ y (90% C.L.)

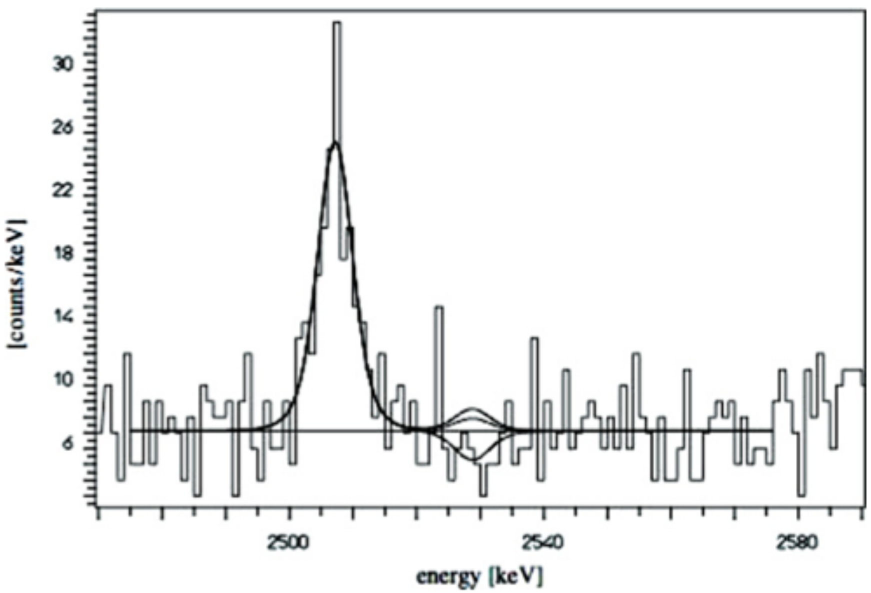
Upper limit, Majorana ν mass: $\langle m_{\beta\beta} \rangle < 300 - 710$ meV

E. Andreotti et al. (CUORICINO Collaboration), Astropart. Phys. 34: 822–831 (2011) [arXiv:nucl-ex/1012.3266].

Cuoricino results: comparison

2008 Result

data: 2003 – 2006
11.8 kg-yr ^{130}Te exposure

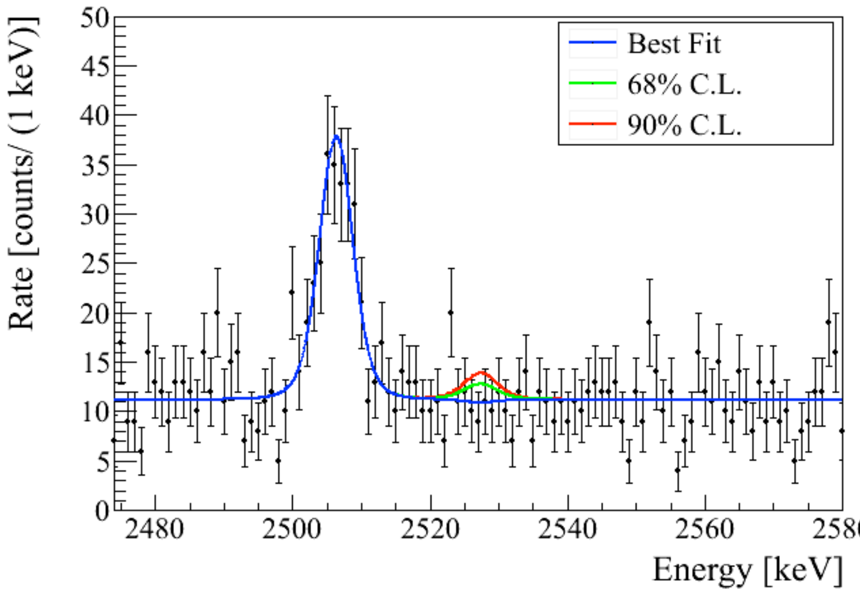


$$T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > 3.0 \times 10^{24}\ \mathrm{y}\ (90\%\ \mathrm{C.L.})$$

C. Arnaboldi et al. (CUORICINO Collaboration), Phys. Rev. C78, 035502 (2008) [arXiv:nucl-ex/0802.3439].

2010 Result

data: 2003 – 2008
19.8 kg-yr ^{130}Te exposure

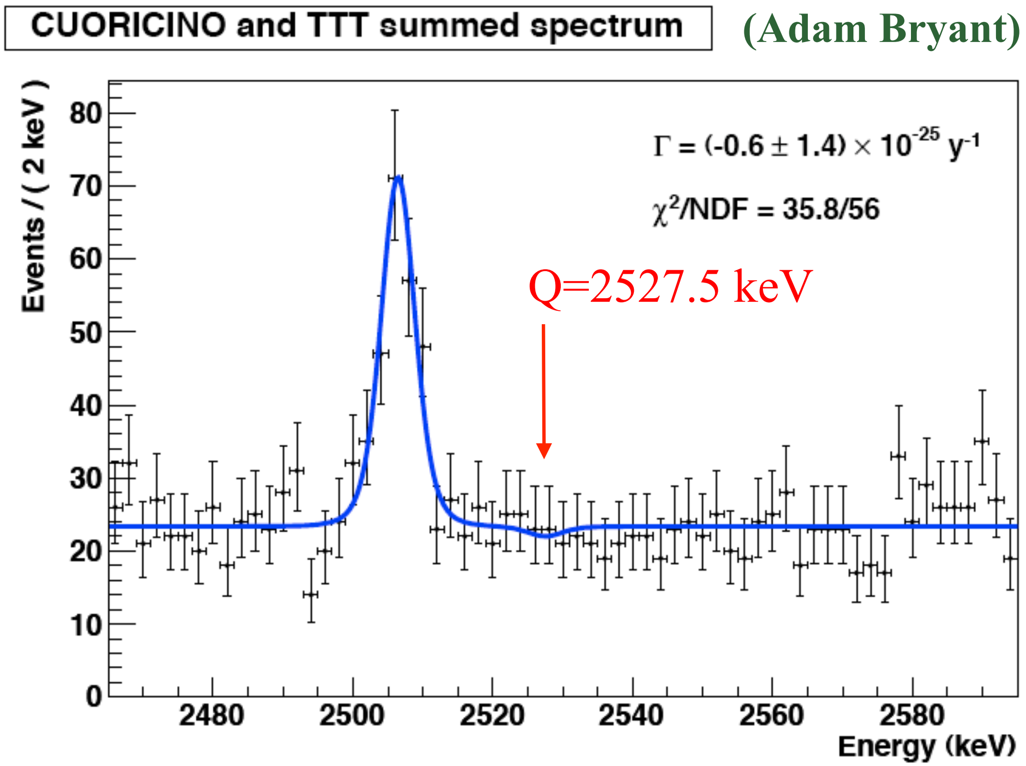


$$T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > 2.8 \times 10^{24}\ \mathrm{y}\ (90\%\ \mathrm{C.L.})$$

E. Andreotti et al. (CUORICINO Collaboration), Astropart. Phys. 34: 822–831 (2011) [arXiv:nucl-ex/1012.3266].

Cuoricino + TTT results (US analysis)

data: 2003 – 2010
19.9 kg-yr ^{130}Te exposure

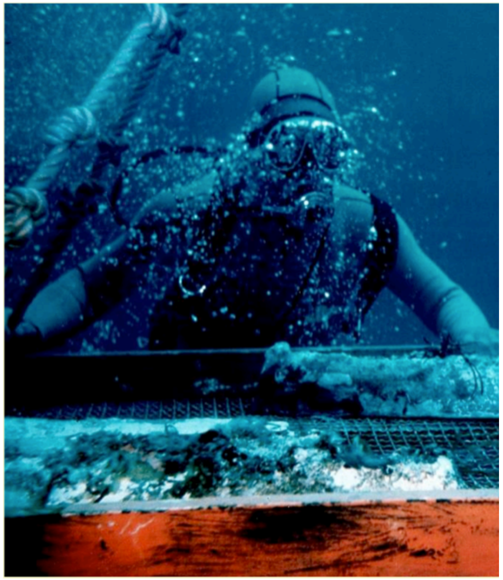


Background: ~ 0.16 counts/keV/kg/y

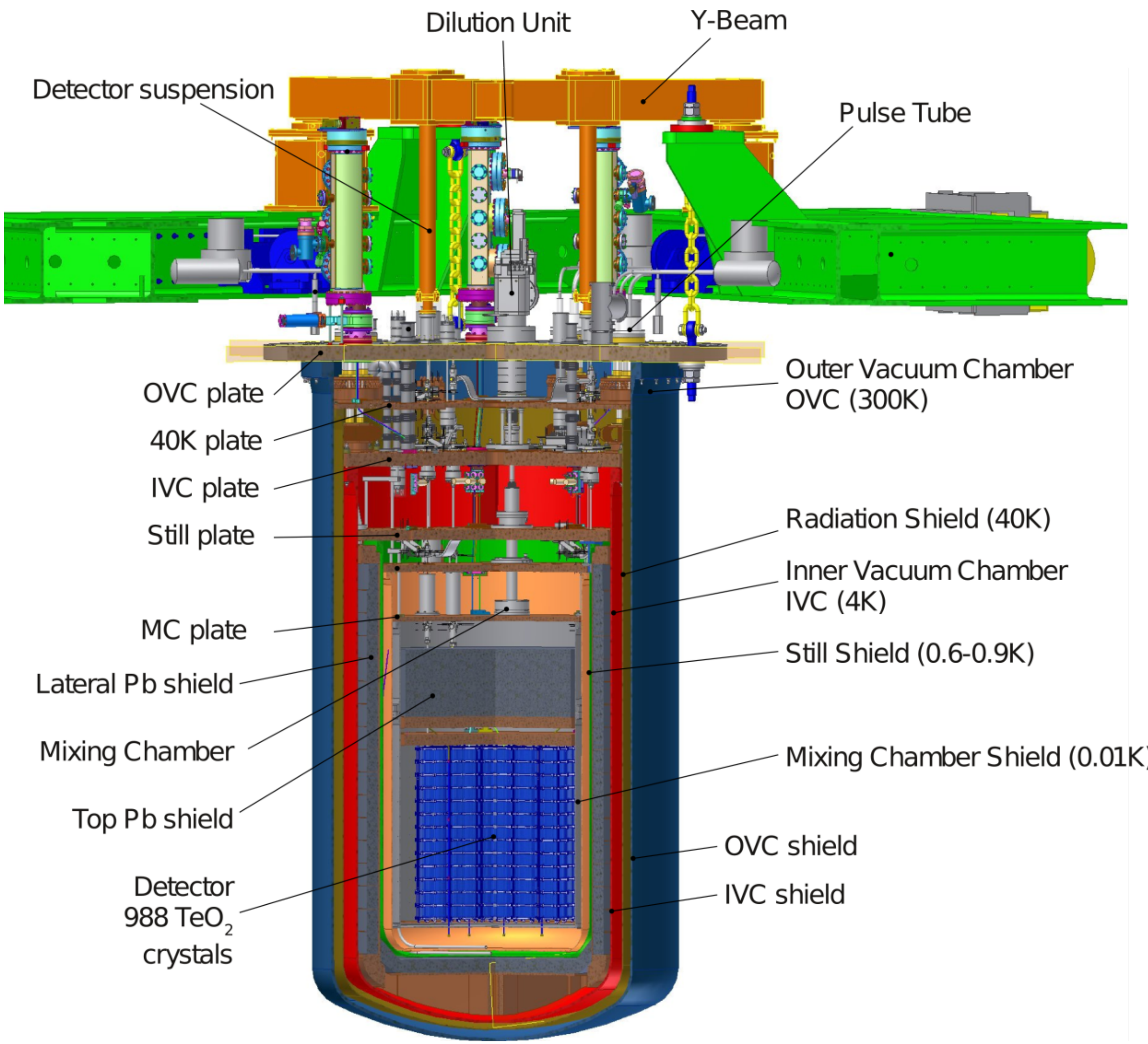
Lower limit, half-life: $T_{1/2}^{0\nu\beta\beta}\,(^{130}\mathrm{Te}) > \ 3.0 \times 10^{24}$ y (90% C.L.)

Roman lead shield

- Ancient Roman lead bricks for low-activity shielding
- Recovered in late ‘80s from shipwreck off Sardinian coast
- Obtained through agreement between INFN and Italian historical society
- 270 bricks, 33 kg each = 7 tons (after inscriptions removed)



CUORE cryostat



Calibration system

- **DCS** = **D**etector **C**alibration **S**ystem
  - 12 gamma source strings lowered in between crystal towers through guide tubes – no vertical access
  - strings are Kevlar with crimped ^{56}Co and/or ^{232}Th source capsules at intervals
  - thermalization requirements
  - integration with other systems