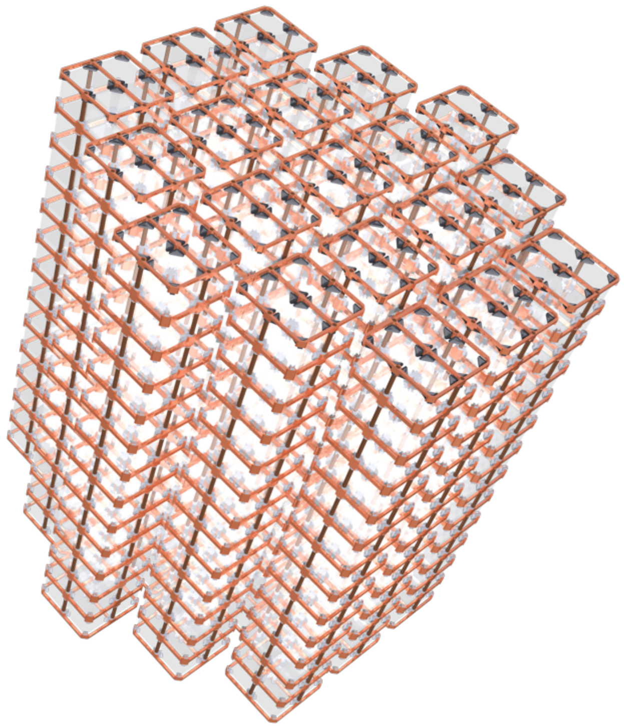
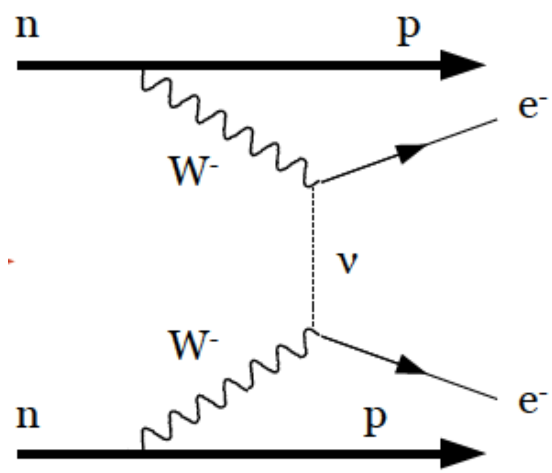
The CUORE Neutrinoless Double Beta Decay Experiment

Tom Banks (UC Berkeley, LBNL, & LNGS)
DBD11 Workshop, Osaka, JP
15 Nov 2011

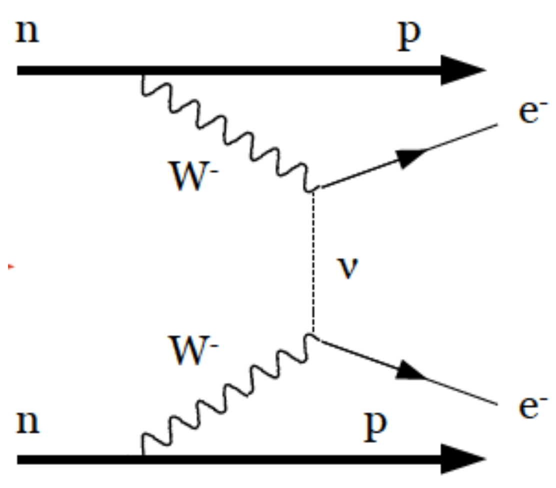


Neutrinoless double beta ($0\nu\beta\beta$) decay



- Extremely rare process ($T_{½}$ > 10^{24} y), if it occurs at all
- Requires massive, Majorana neutrinos $(\nu = \overline{\nu})$
- Violates lepton number = physics beyond SM

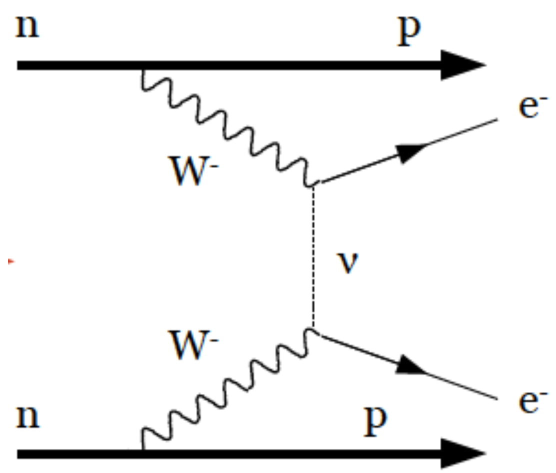
Neutrinoless double beta ($0\nu\beta\beta$) decay



If $0\nu\beta\beta$ 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. possibly provide information about the mass hierarchy.

Neutrinoless double beta ($0\nu\beta\beta$) decay



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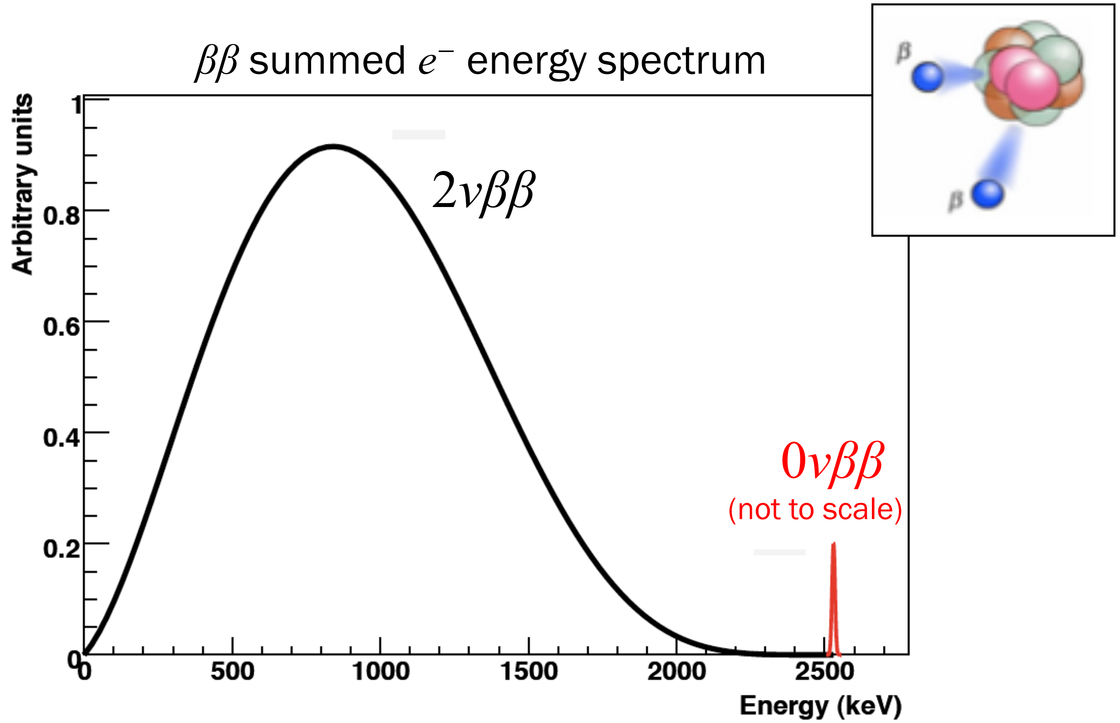
$0\nu\beta\beta$ decay offers unique potential to probe unknown neutrino parameters

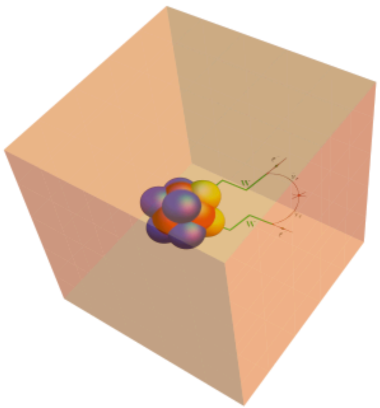
Detecting $0\nu\beta\beta$ decay



- **General approach:** Detect the two decay electrons
- **Signature:** Two simultaneous electrons with summed energy $Q_{\beta\beta}$, the Q-value for $\beta\beta$ in the isotope under study
- Energy resolution is critical to discriminating a tiny endpoint peak

Established experimental approaches

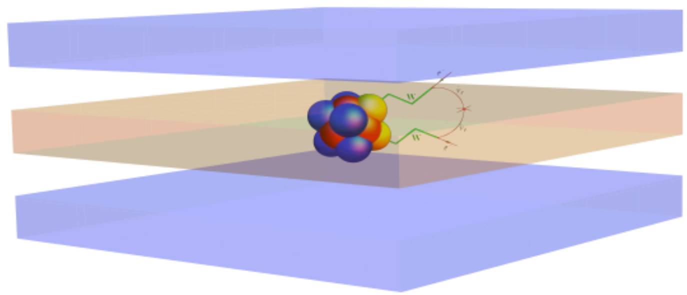
Source = Detector



Use as calorimeter to watch for events of energy $E=Q_{\beta\beta}$

- 👍 Good energy resolution
- 👍 Large source mass
- 👍 High efficiency
- 👎 No particle identification

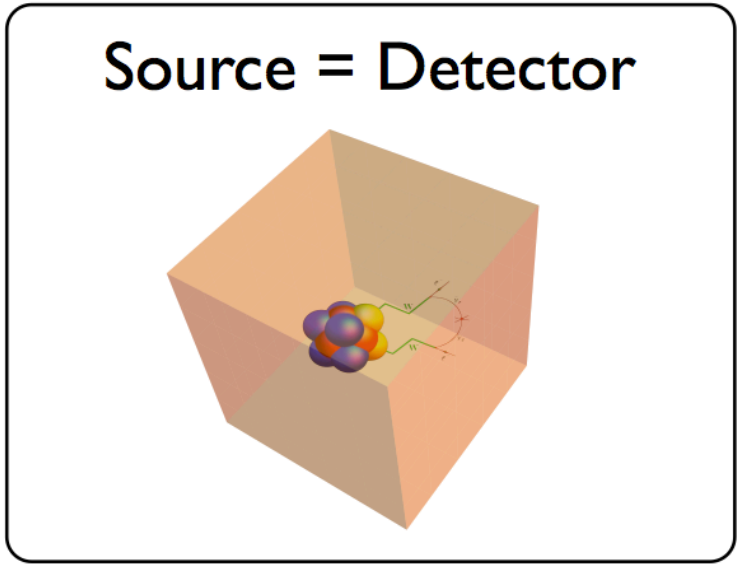
Source ≠ Detector

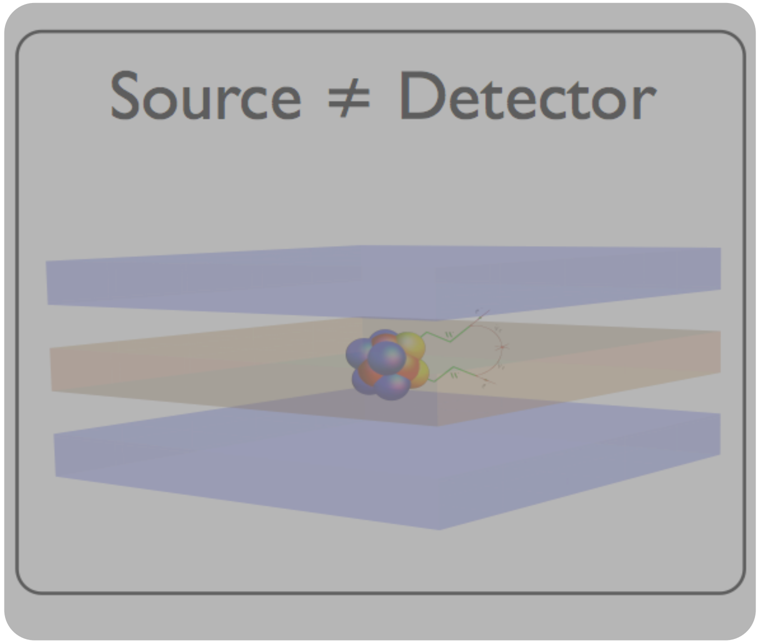


Use tracking detectors to watch for 2 β's emitted from foil with energy $\Sigma E_{\beta} = Q_{\beta\beta}$

- 👎 Poor energy resolution
- 👎 Small source mass
- 👎 Low efficiency
- 👍 Particle identification

Established experimental approaches

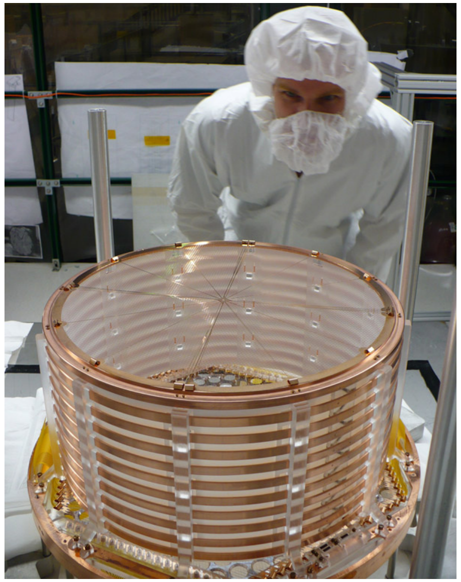




CUORE

Nascent experimental approaches

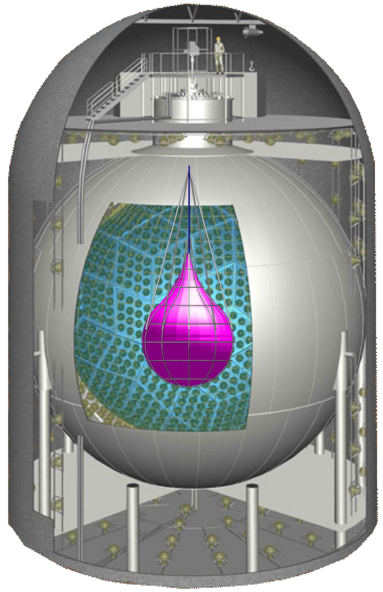
Source = Detector
Xe-filled TPCs



EXO

- Particle identification
- Technically complex

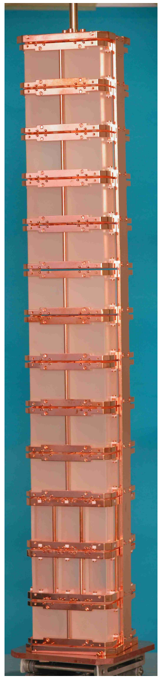
Source = Detector
Loaded scintillator



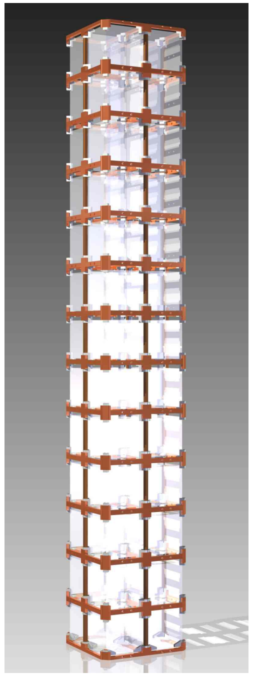
KamLAND-Zen

- Repurpose existing experiments
- Large source mass
- Poor energy resolution
- No particle identification

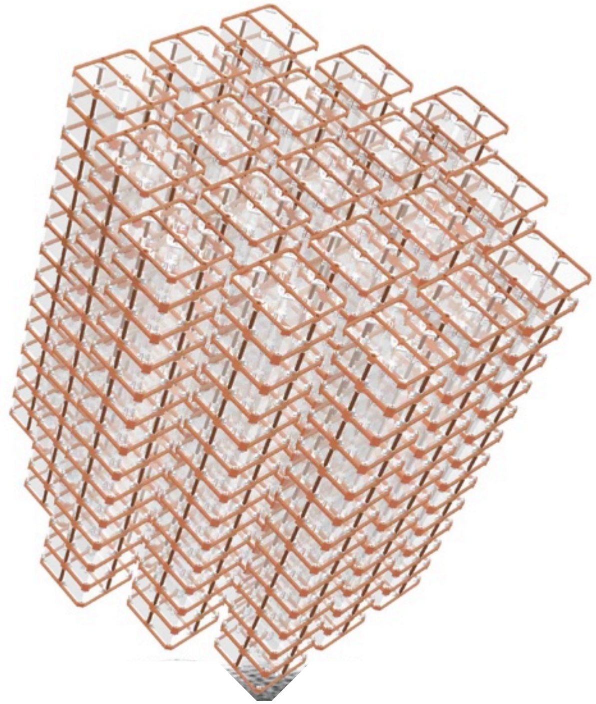
Cuoricino/CUORE program



Cuoricino
2003–2008
11 kg ^{130}Te



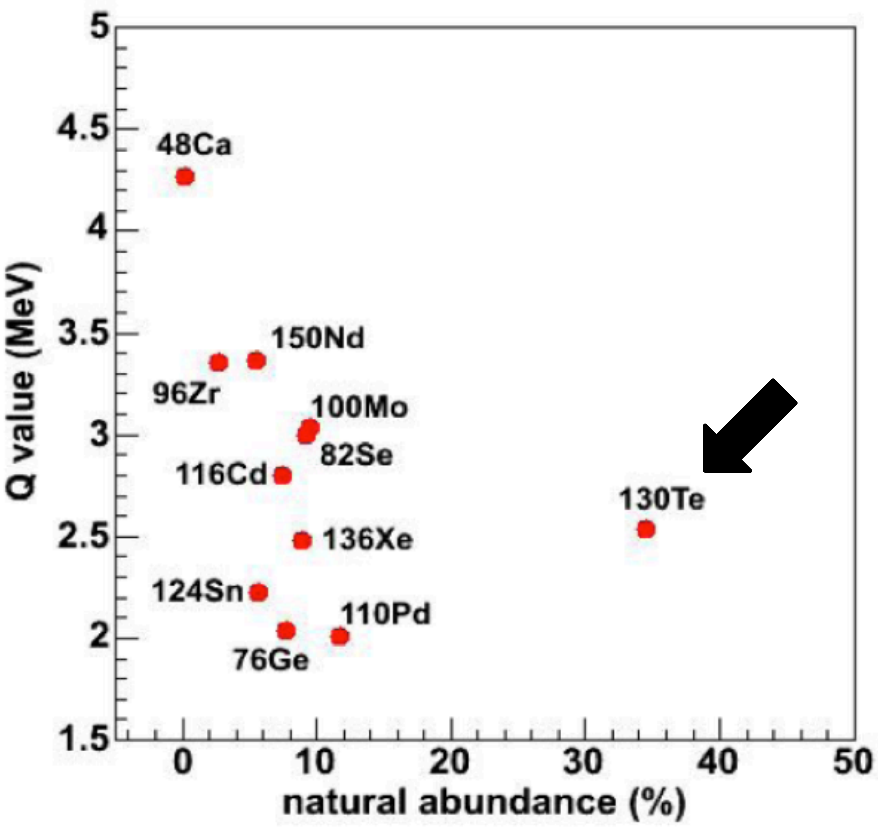
CUORE-0
2012–2014
11 kg ^{130}Te



CUORE
2013–2018
206 kg ^{130}Te

- CUORE: Cryogenic Undergound Observatory for Rare Events
- All cryogenic bolometer experiments searching for $0\nu\beta\beta$ decay in ^{130}Te

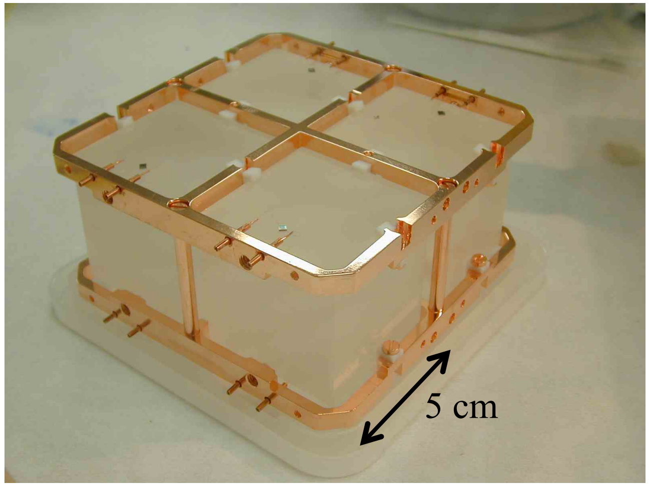
^{130}Te as $0\nu\beta\beta$ candidate



- ► High natural abundance (~ 34%), so enrichment isn't necessary
- ► Good Q-value @ 2528 keV: (1) above natural γ energies, (2) large phase space

Cryogenic bolometers

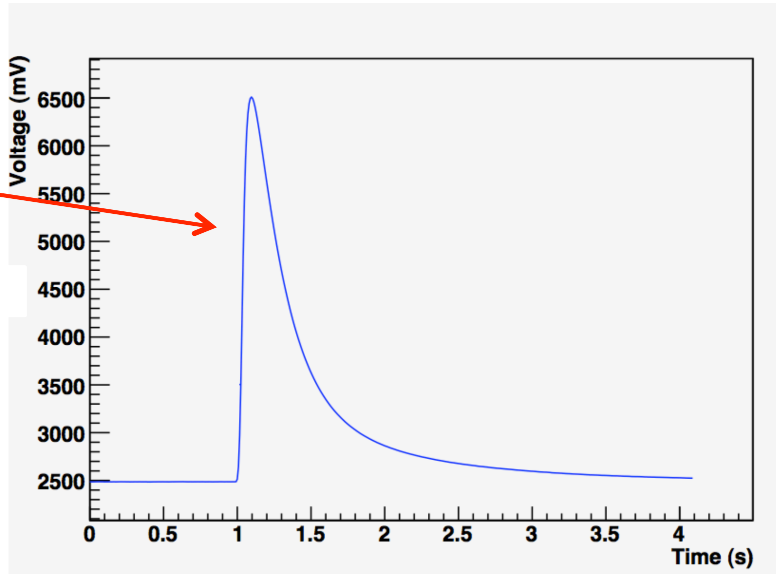
- Crystals of TeO_2 are cooled to ~ 10 mK inside a dilution-refrigerator cryostat



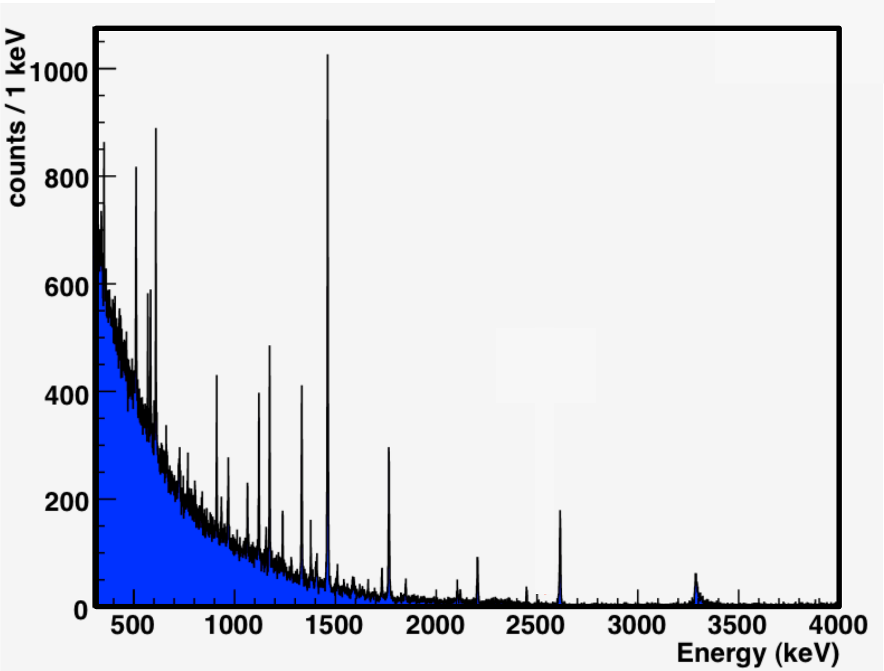
- Cold crystals have such small heat capacities that single interactions produce measurable rises in temperature

- Temperature pulses are measured by thermistors glued to the crystals

- A pulse's amplitude is proportional to the energy deposited in the crystal

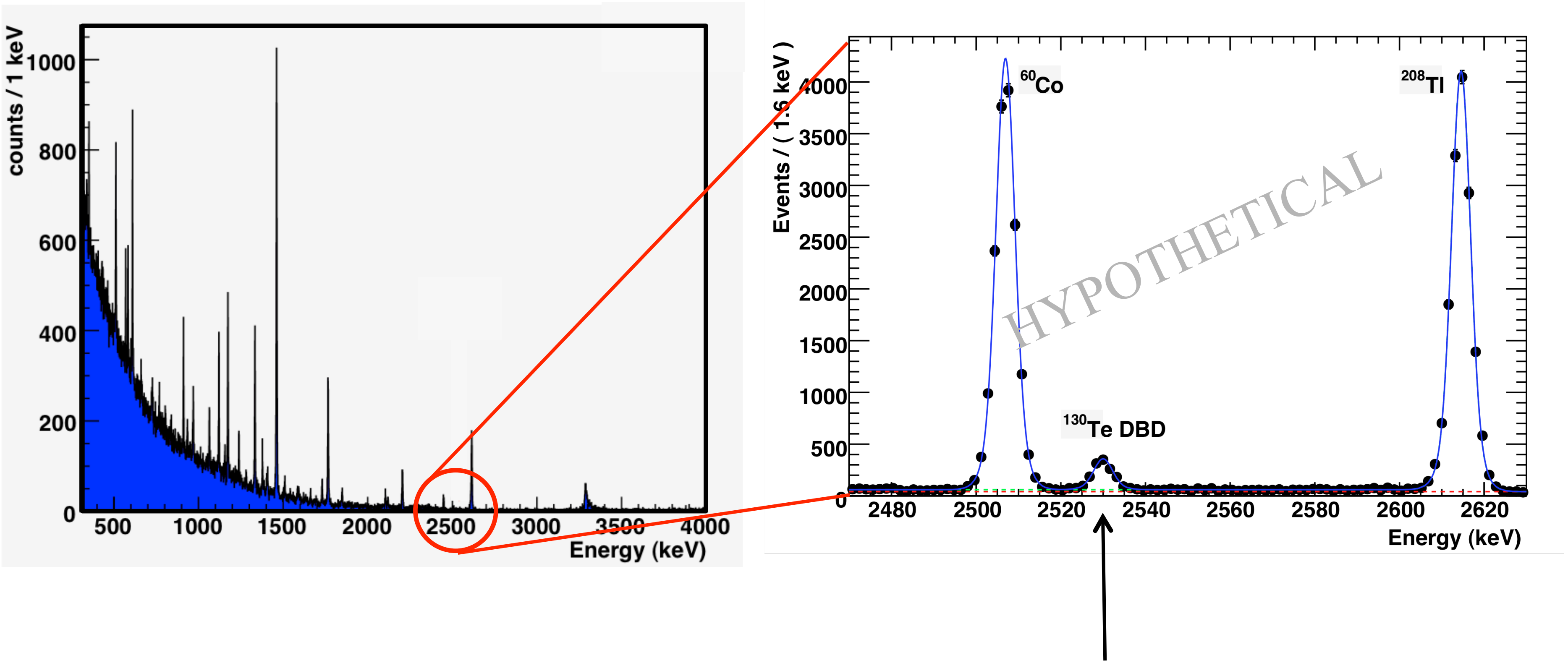


Cuoricino/CUORE method



The energy spectrum of detected pulses is compiled...

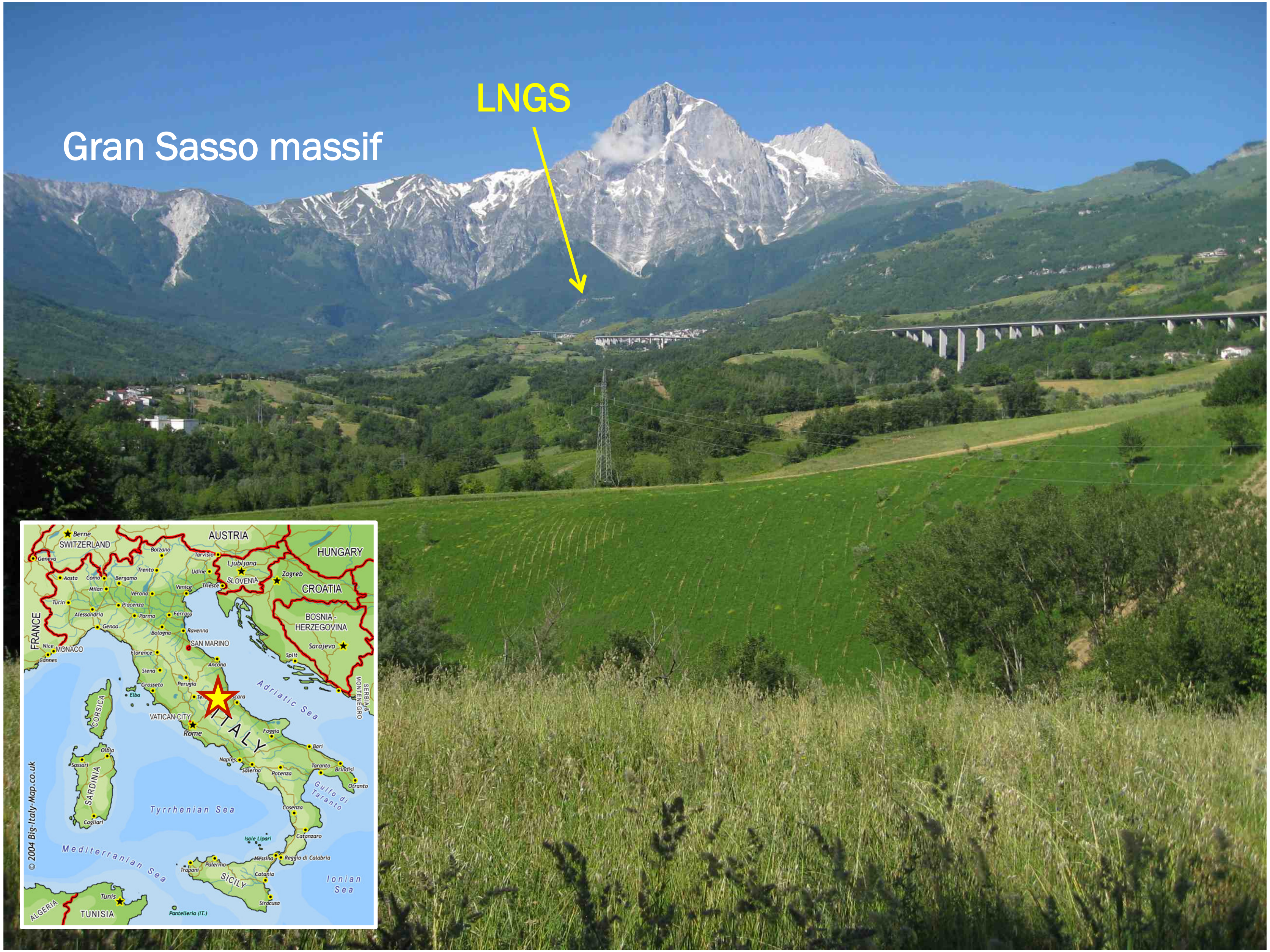
Cuoricino/CUORE method



The energy spectrum of detected pulses is compiled…

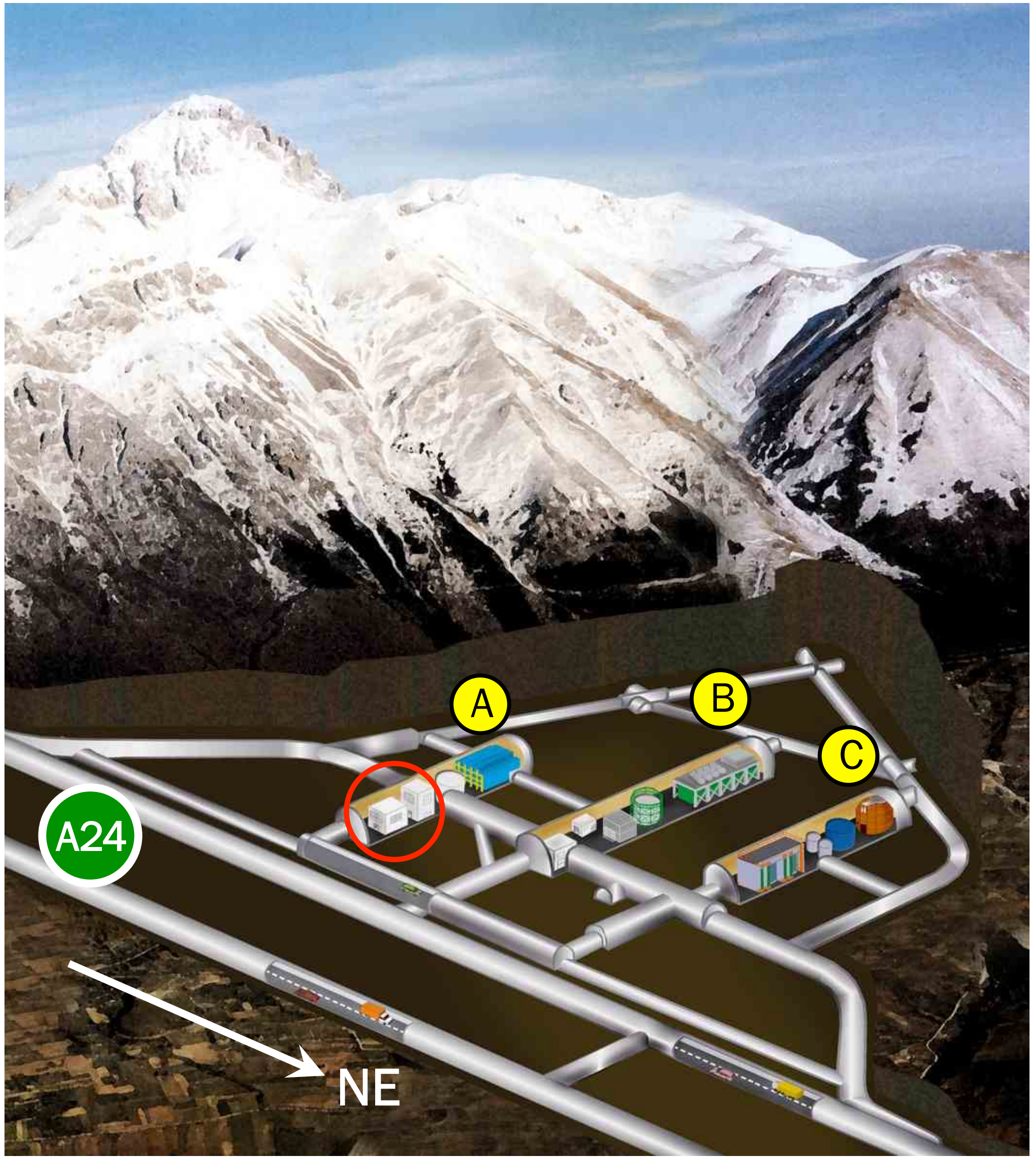
… and the signature of $0\nu\beta\beta$ in ^{130}Te would be a small peak at 2528 keV.

Experiment location: LNGS, Italy



LNGS underground facility

- Gran Sasso National Lab (LNGS), managed by INFN, Italy's nuclear physics agency
- Branches off highway tunnel through mountain
- 1.4-km avg. rock overburden
  = 3100 m.w.e. flat overburden
  → factor 10^6 reduction in muon flux to ~ $3\times10^{-8}\ \mu/(\text{s cm}^2)$
- 3 experimental halls (A, B, C)
- Hosts 15+ experiments



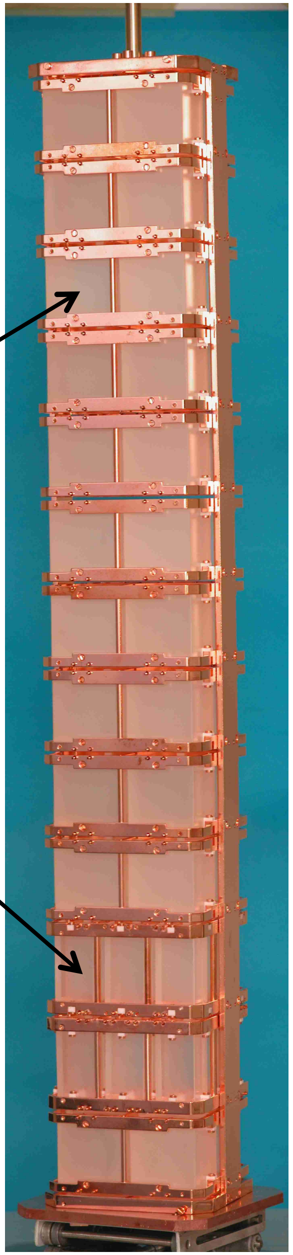
Cuoricino/CUORE facilities @ LNGS

CUORE hut

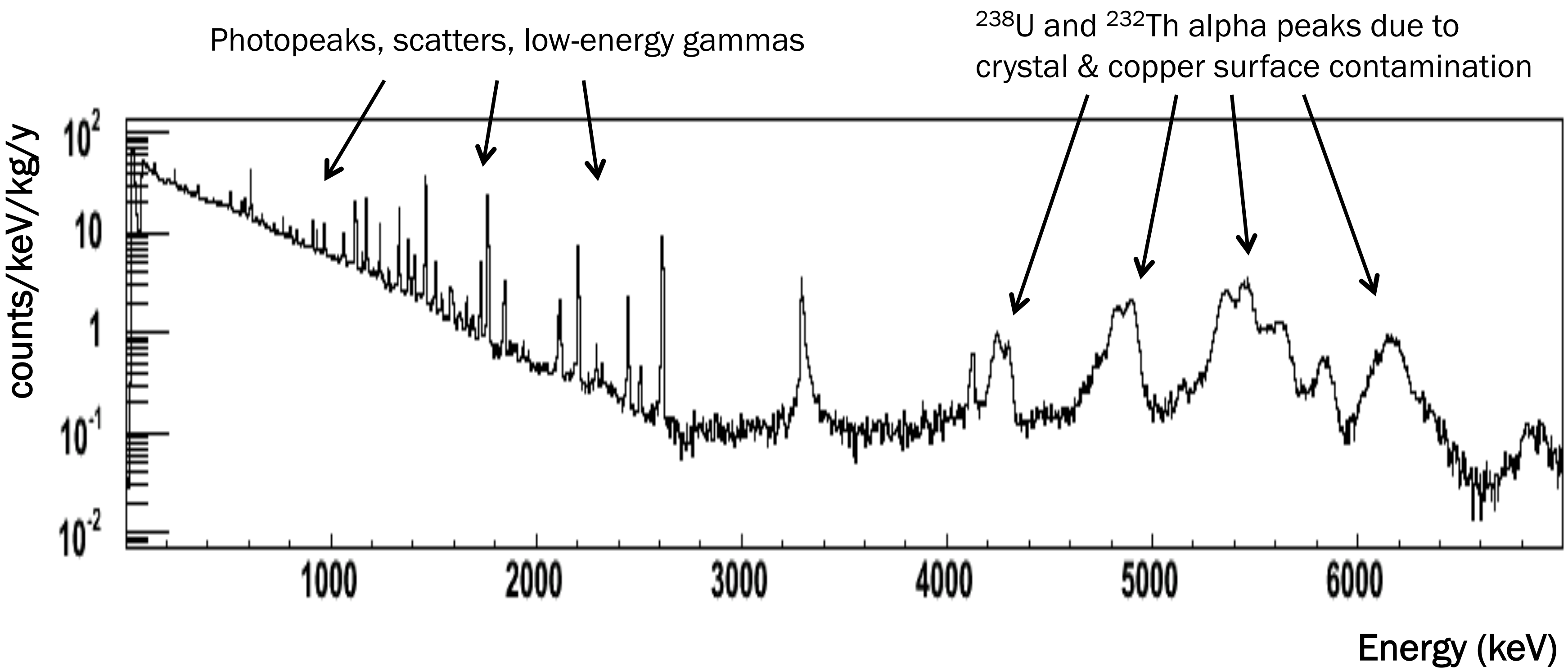
Cuoricino/
CUORE-0 hut

Cuoricino experiment

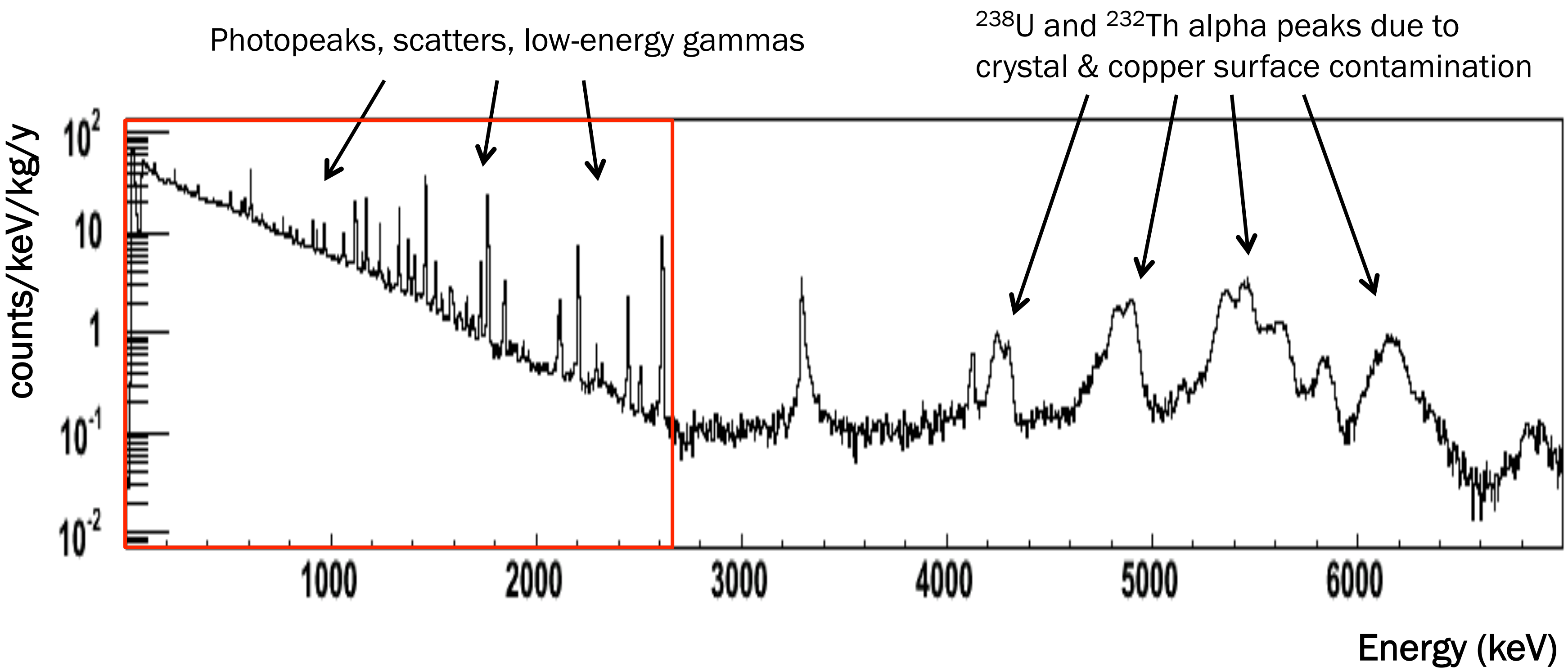
- CUORE predecessor
- Operated March 2003 – May 2008
- 62 TeO_2 crystal bolometers:
  - 44 "large" crystals (5x5x5 cm^3, 790 g)
  - 18 "small" crystals: (3x3x6 cm^3, 330 g)
  - 58 crystals made of natural 27% ^{130}Te
  - 2 small crystals enriched to 75% in ^{130}Te
  - 2 small crystals enriched to 82% in ^{128}Te
- 40.7 kg TeO_2 → 11.3 kg ^{130}Te



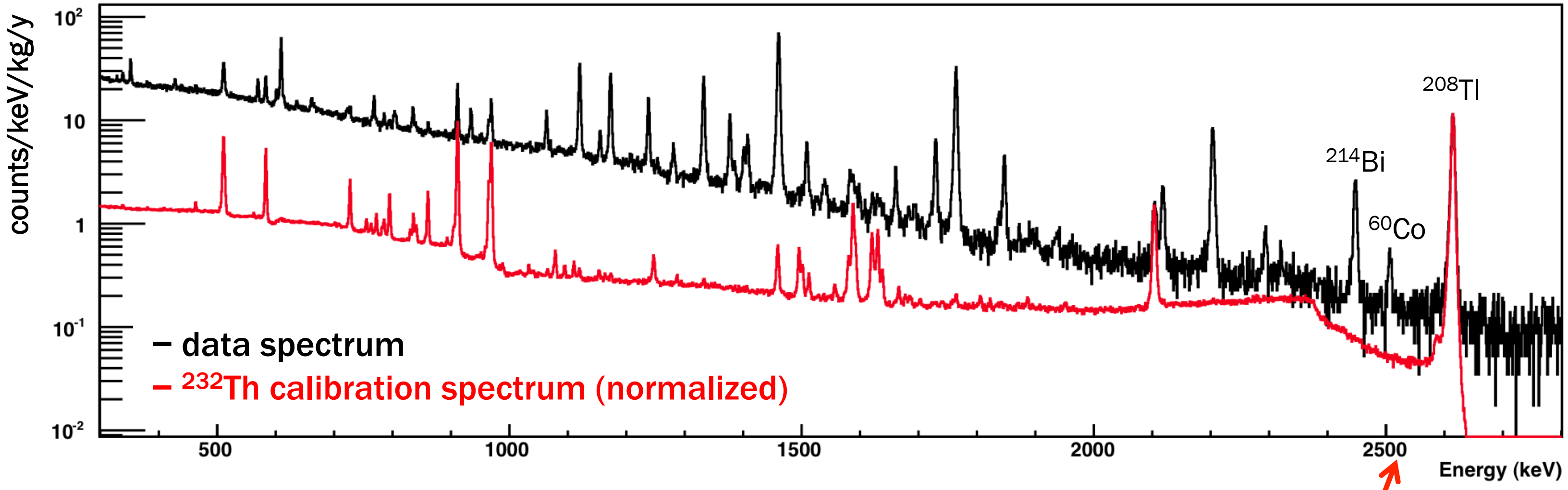
Cuoricino energy spectrum



Cuoricino energy spectrum

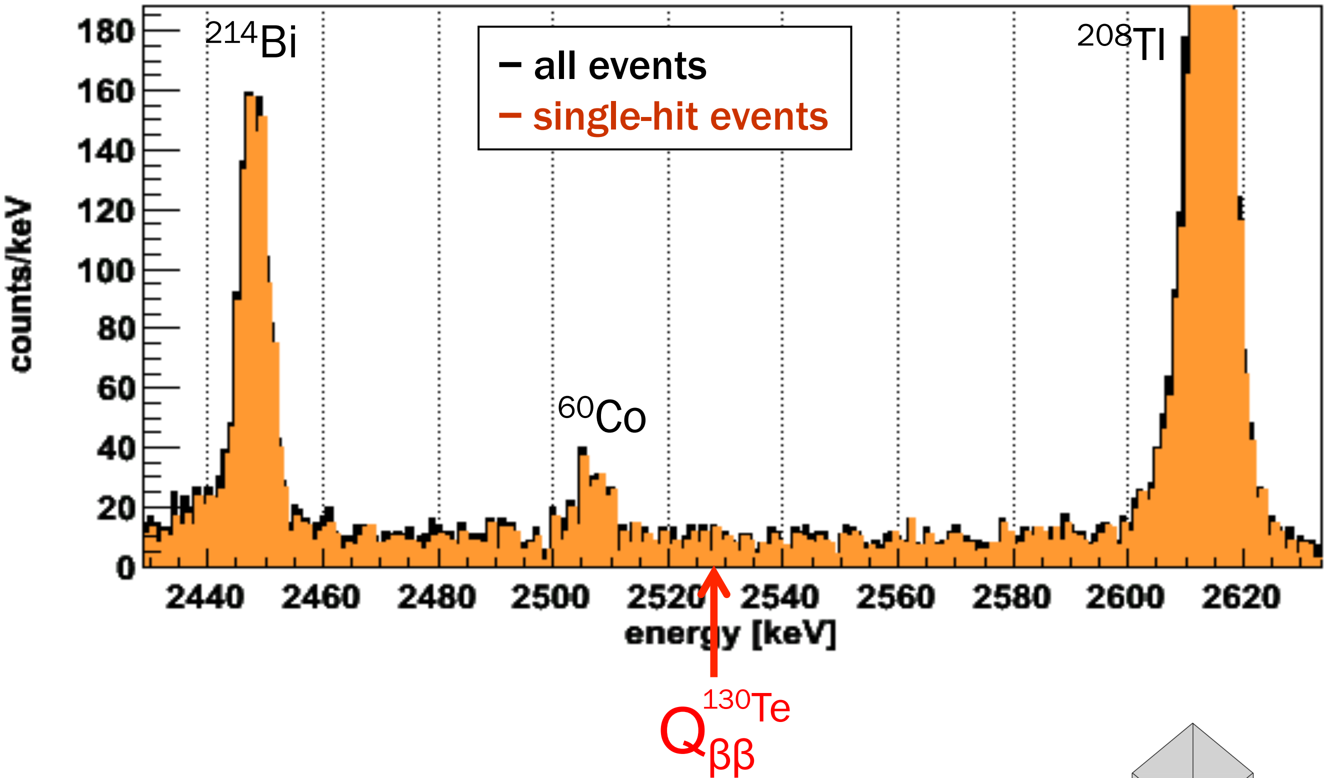


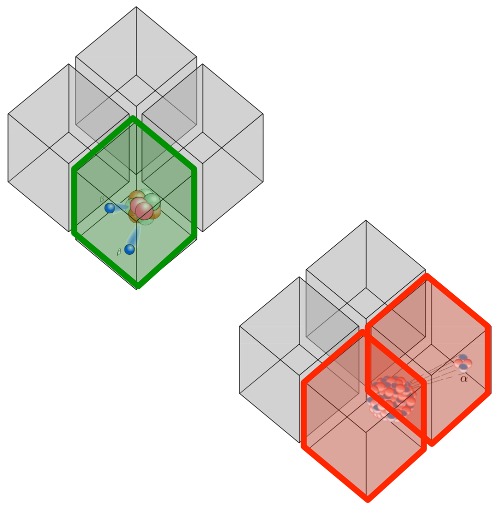
Cuoricino backgrounds



- There are three main sources of background in the region around the Q value:
  - (~35%) Compton events from ^{208}Tl gammas, from ^{232}Th contamination in the cryostat (i.e., inside the lead shield)
  - (~55%) Degraded alphas from ^{238}U and ^{232}Th on copper surfaces
  - (~10%) Degraded alphas from ^{238}U and ^{232}Th on crystal surfaces
- The 2506 keV ^{60}Co peak is likely due to cosmic-ray activation of the copper

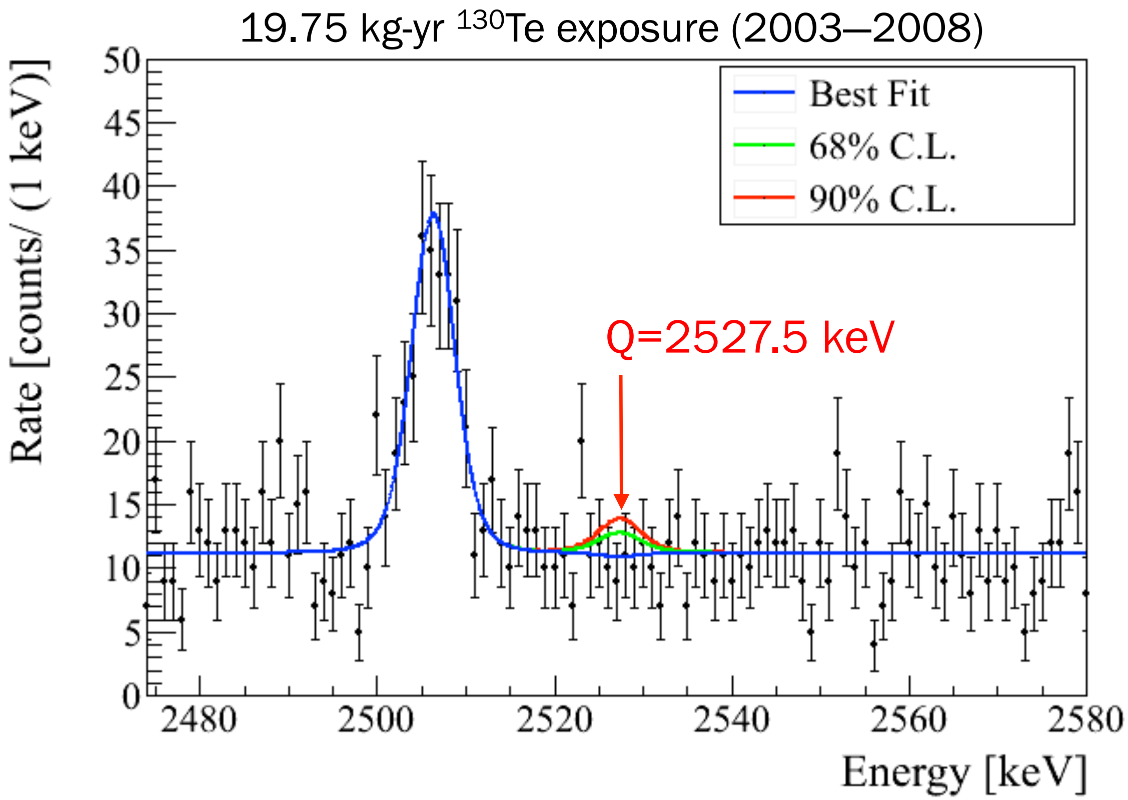
Cuoricino coincidence veto





- ► $0\nu\beta\beta$ 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)

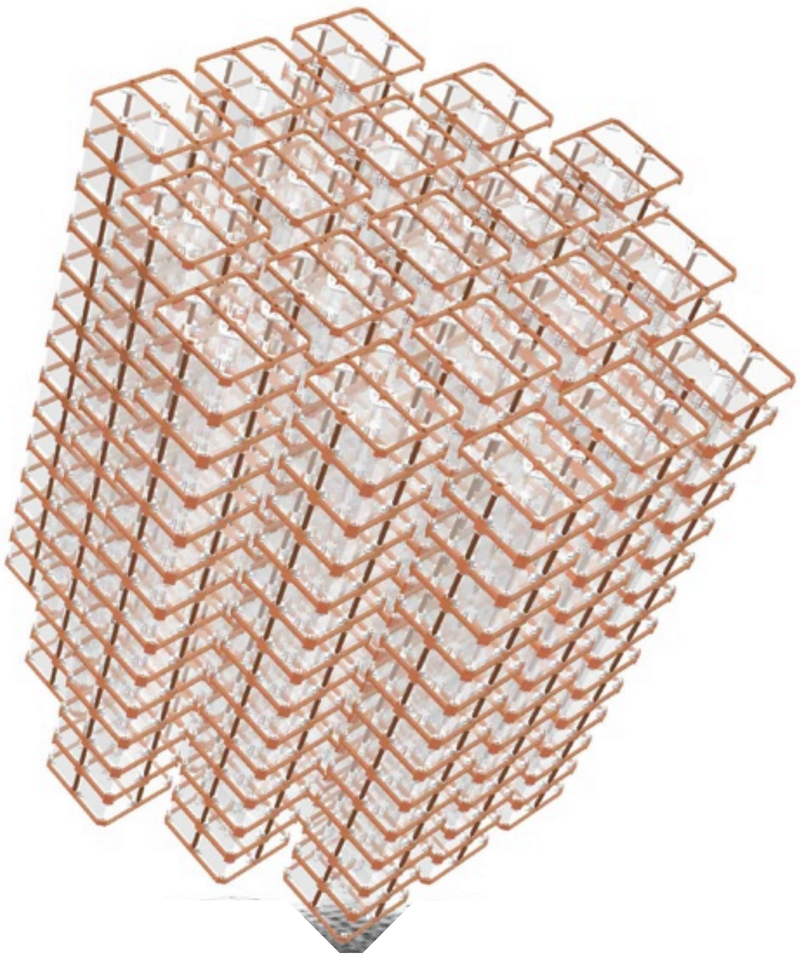


Background: 0.169 ± 0.006 counts/keV/kg/y

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].



CUORE

From Cuoricino to CUORE

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

Isotope mass fraction
Detector mass
Detector efficiency
Exposure time
Confidence level
Energy resolution
Background

- “Factor of Merit” formula assumes a Gaussian background
- Illustrates relationship between half-life sensitivity and detector parameters
- Sensitivity is the maximum decay signal that could be hidden by a background fluctuation at specified confidence level

From Cuoricino to CUORE

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

Detector efficiency

Isotope mass fraction

Detector mass (×19)

Exposure time (×2)

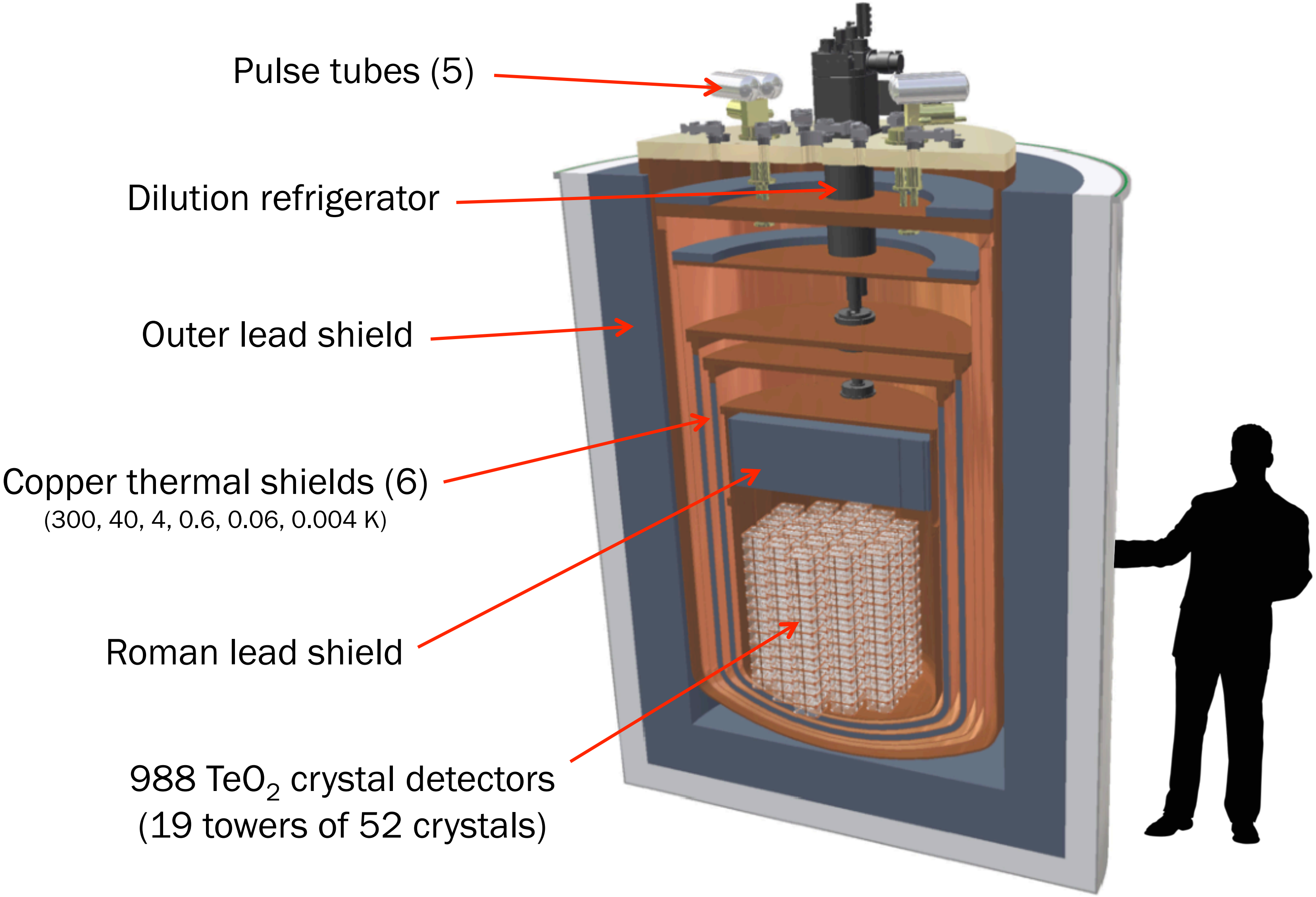
Confidence level

Background (÷18)

Energy resolution (÷1.6)

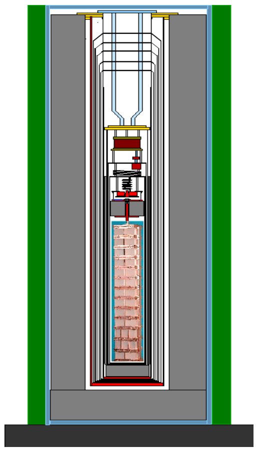
- “Factor of Merit” formula assumes a Gaussian background
- Illustrates relationship between half-life sensitivity and detector parameters
- Sensitivity is the maximum decay signal that could be hidden by a background fluctuation at specified confidence level

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)

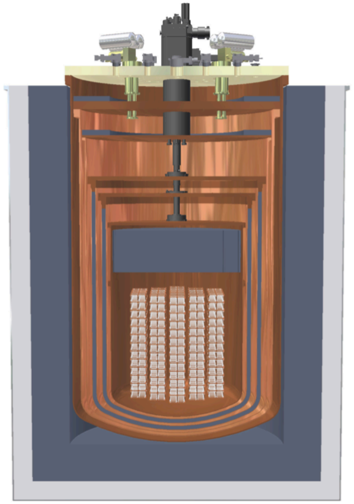
Cryostat improvements



Cuoricino

- 20-year-old Oxford dilution refrigerator
- Periodic refilling of cryogens (LHe) causes dead time and thermal fluctuations
- Poor mechanical decoupling from detectors generates vibrational noise
- Minimum lead thickess ≈ 22 cm
- ^{232}Th contamination generates irreducible background in ROI of ~ 0.05 c/keV/kg/y

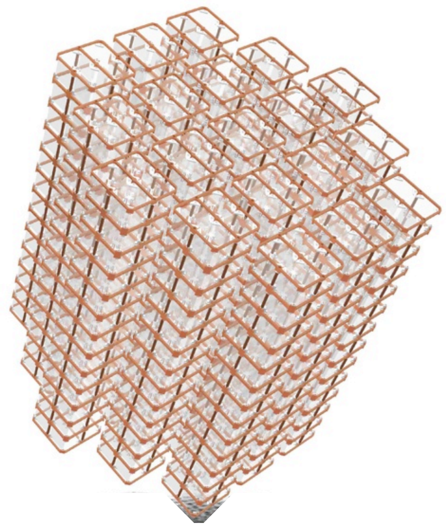
CUORE



- New, custom dilution refrigerator
- Cryogen-free (during operation) → better duty cycle
- Detector suspension independent of refrigerator apparatus
- Minimum lead thickess ≈ 36 cm
- Stringent radiopurity controls on materials and assembly

Detector improvements

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

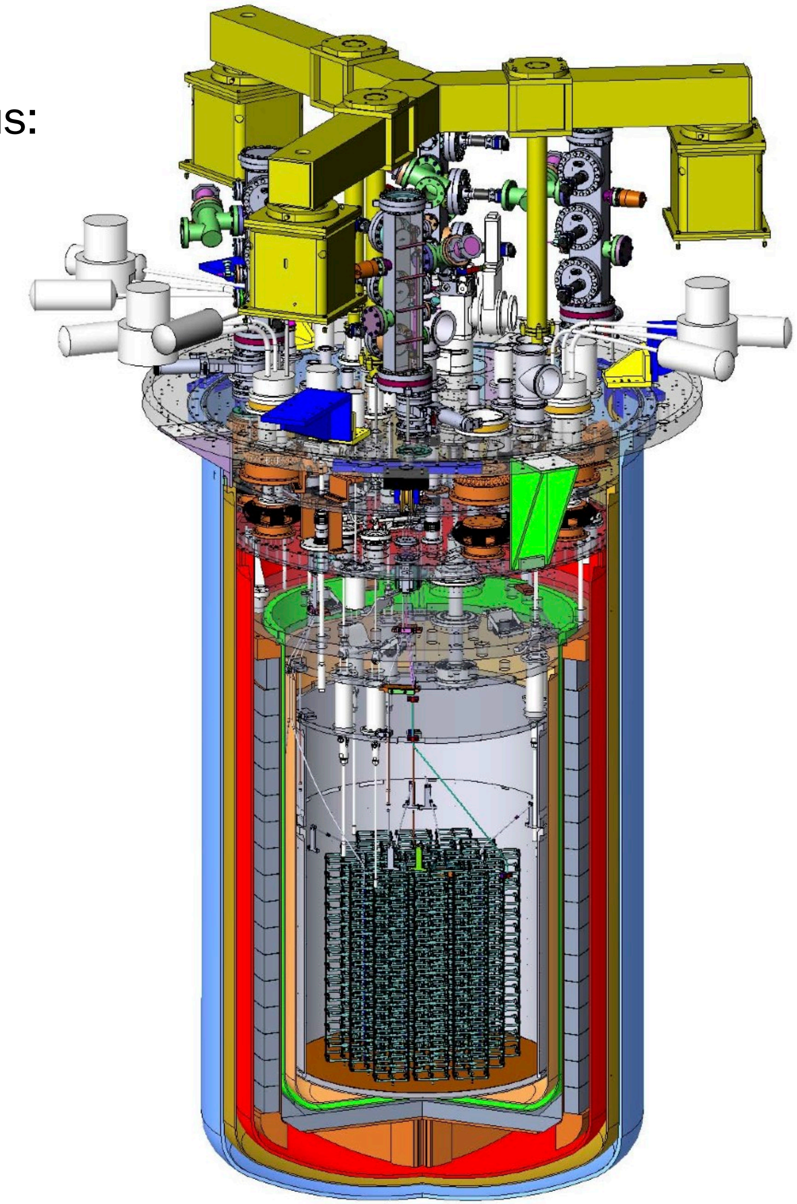


	Cuoricino	CUORE-0	CUORE
^{130}Te mass (kg)	11	11	206
Background (c/keV/kg/y) @ 2528 keV	0.17	0.05	0.01
E resolution (keV) FWHM @ 2615 keV	7	5–6	5
$\langle m_{\beta\beta} \rangle$ (meV) @ 90% C.L.	300–710	200–500	40–90

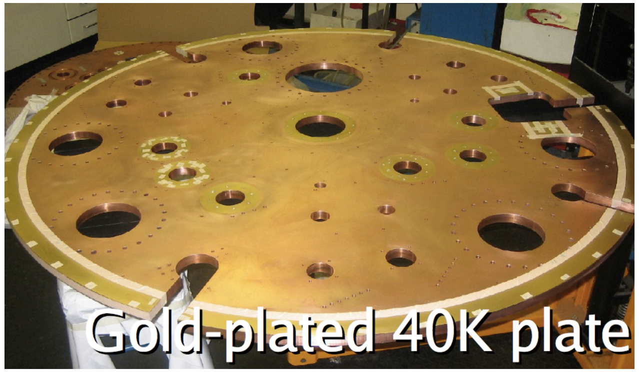
Engineering

Challenge is in scaling up the bolometric apparatus:

- Mass production of 988 ultra-radiopure crystal detectors
- Instrumentation of 988 detectors in close-packed, 13-tower array
- Complex, nested cryostat
- Multiple interconnected systems sharing tight space under very cold conditions
- Long cooldown time (~ 1 month) necessitates careful planning and robust systems



Cryostat



- 4 companies to pour, work, and form low-rad copper into 6 vessels + flanges
- Outer 3 vessels (300, 40, 4 K) are electron-beam welded
- Delivery scheduled for February 2012
- More delicate inner 3 vessels (600, 50, 10 mK) will be manufactured next year

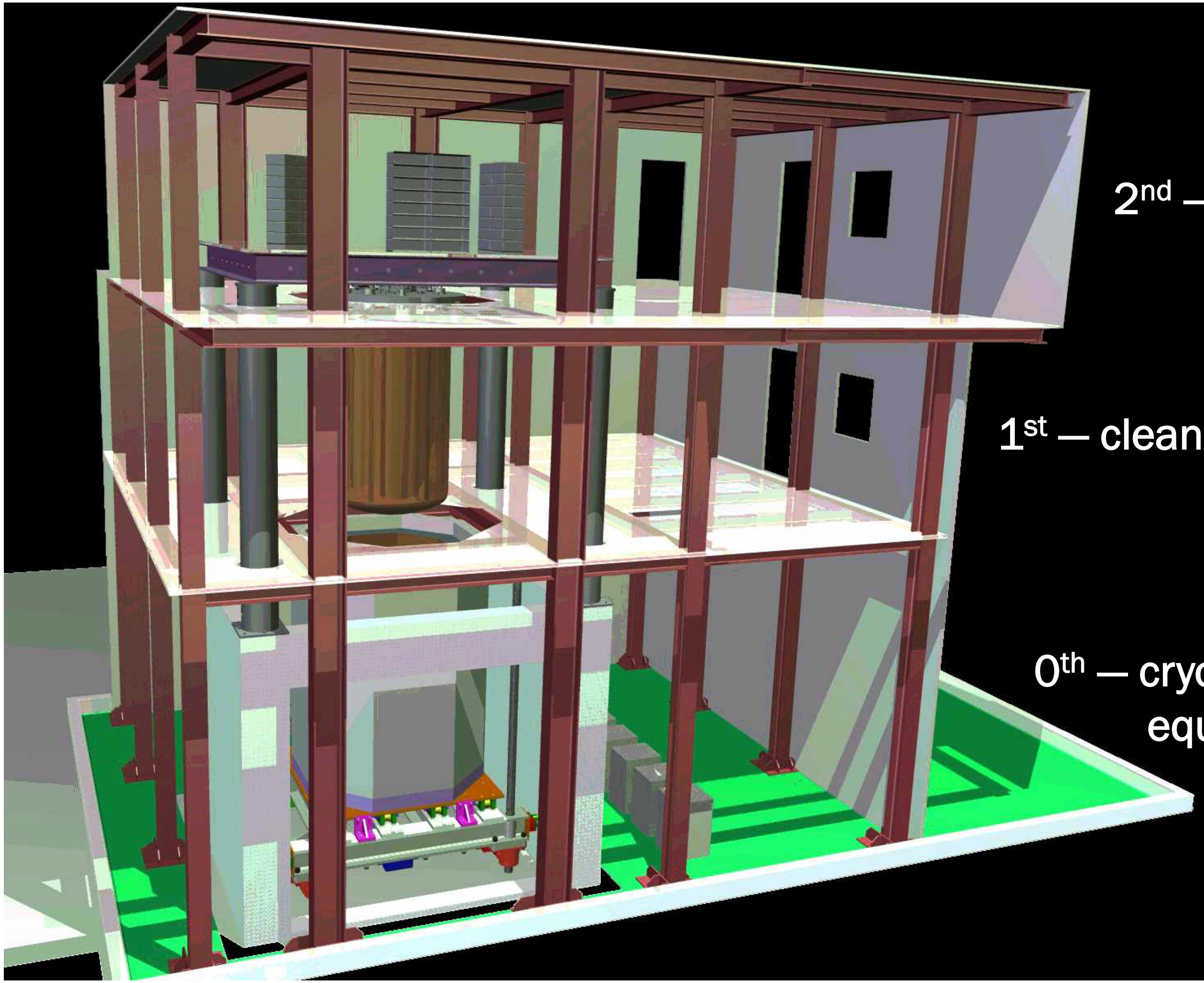
Dilution refrigerator

- Custom made by Leiden Cryogenics in The Netherlands
- Cooled down to 5.26 mK in test setup in Leiden
- 5 μW cooling power at 10 mK
- Complete, but delivery depends on vessel schedules

Hut

Nov 2011

Hut

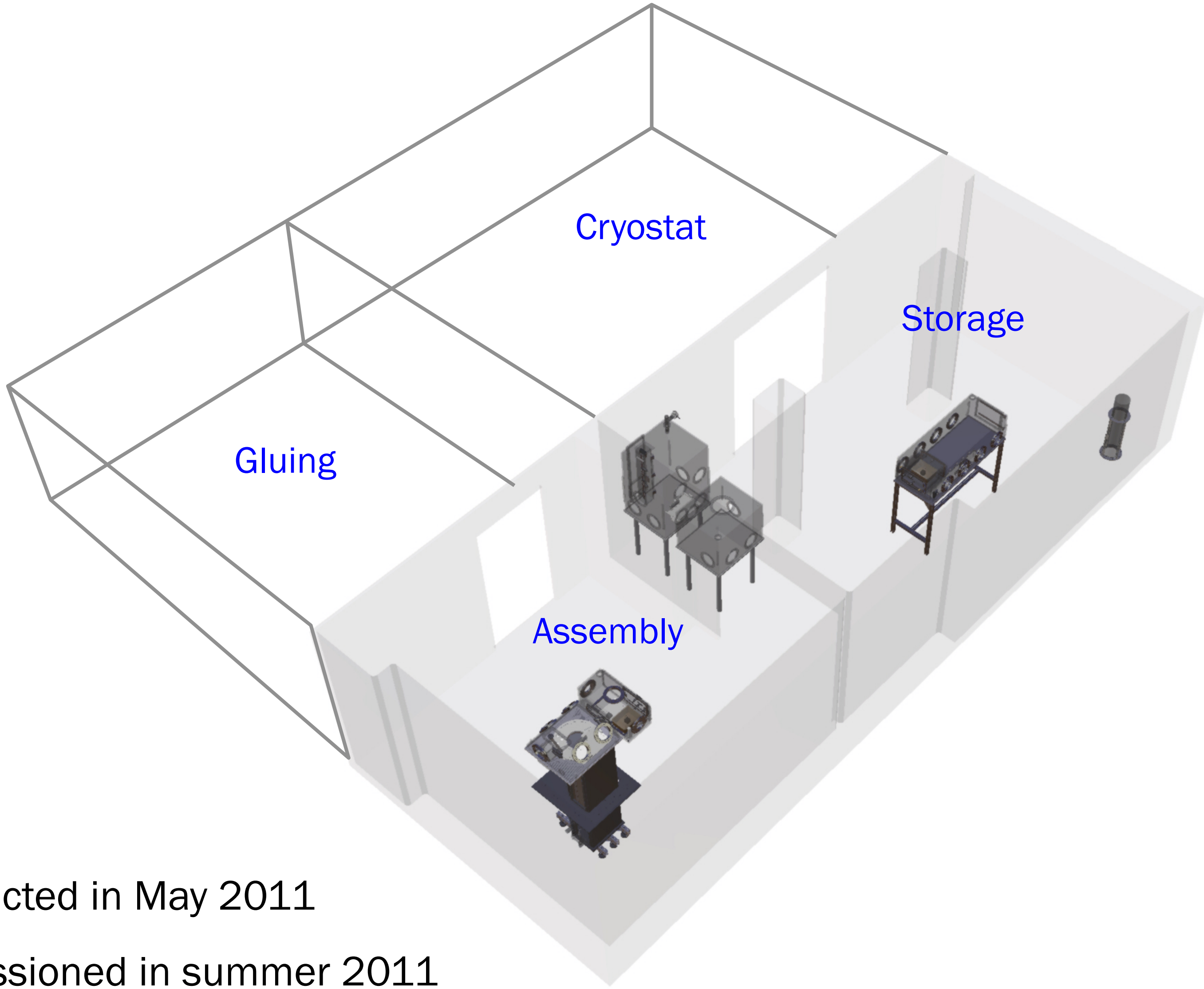


2nd — electronics

1st — clean room

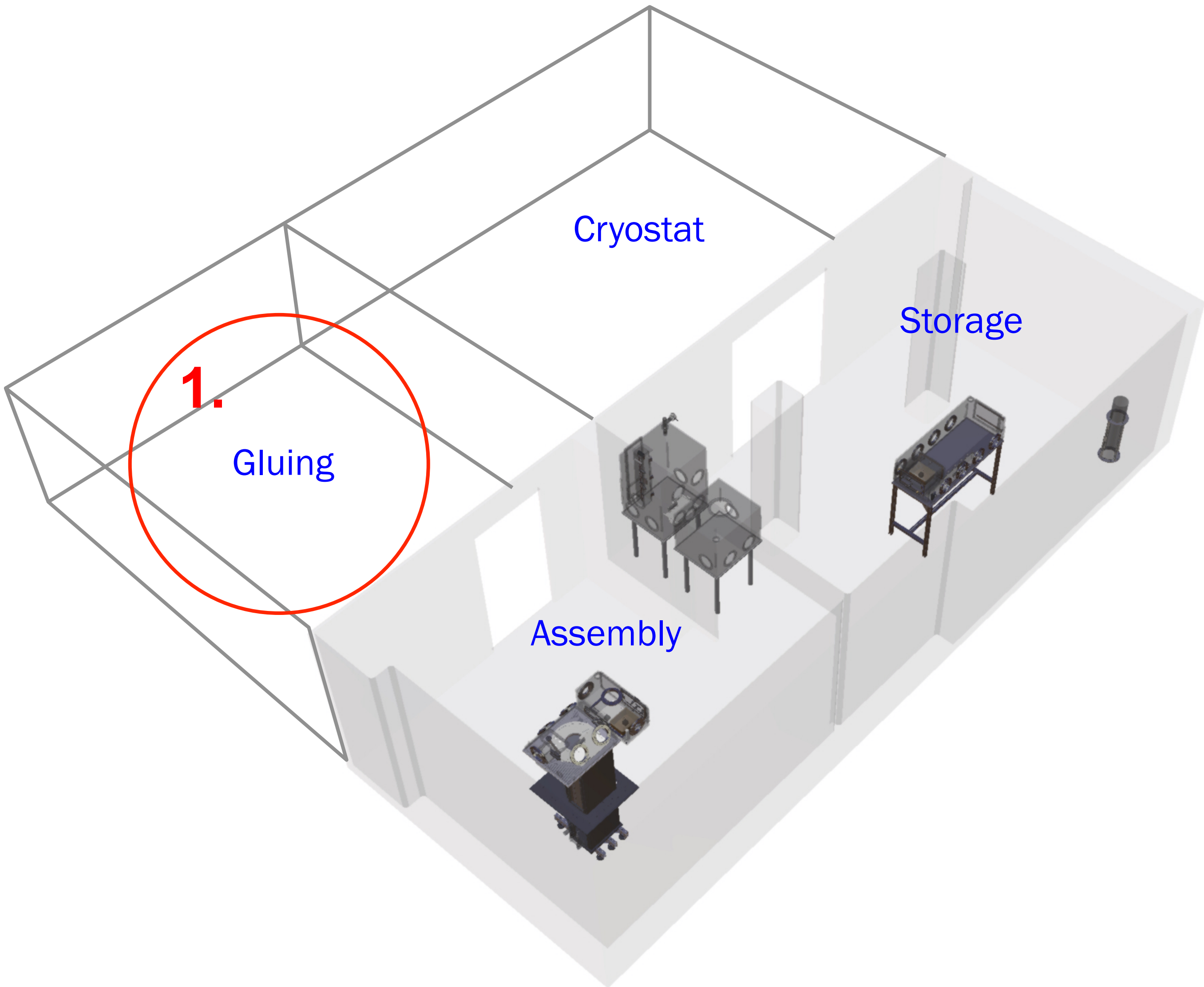
0th — cryostat equipment

Clean rooms



- Constructed in May 2011
- Commissioned in summer 2011
- Crystals are glued and assembled into towers inside N_2-filled glove boxes

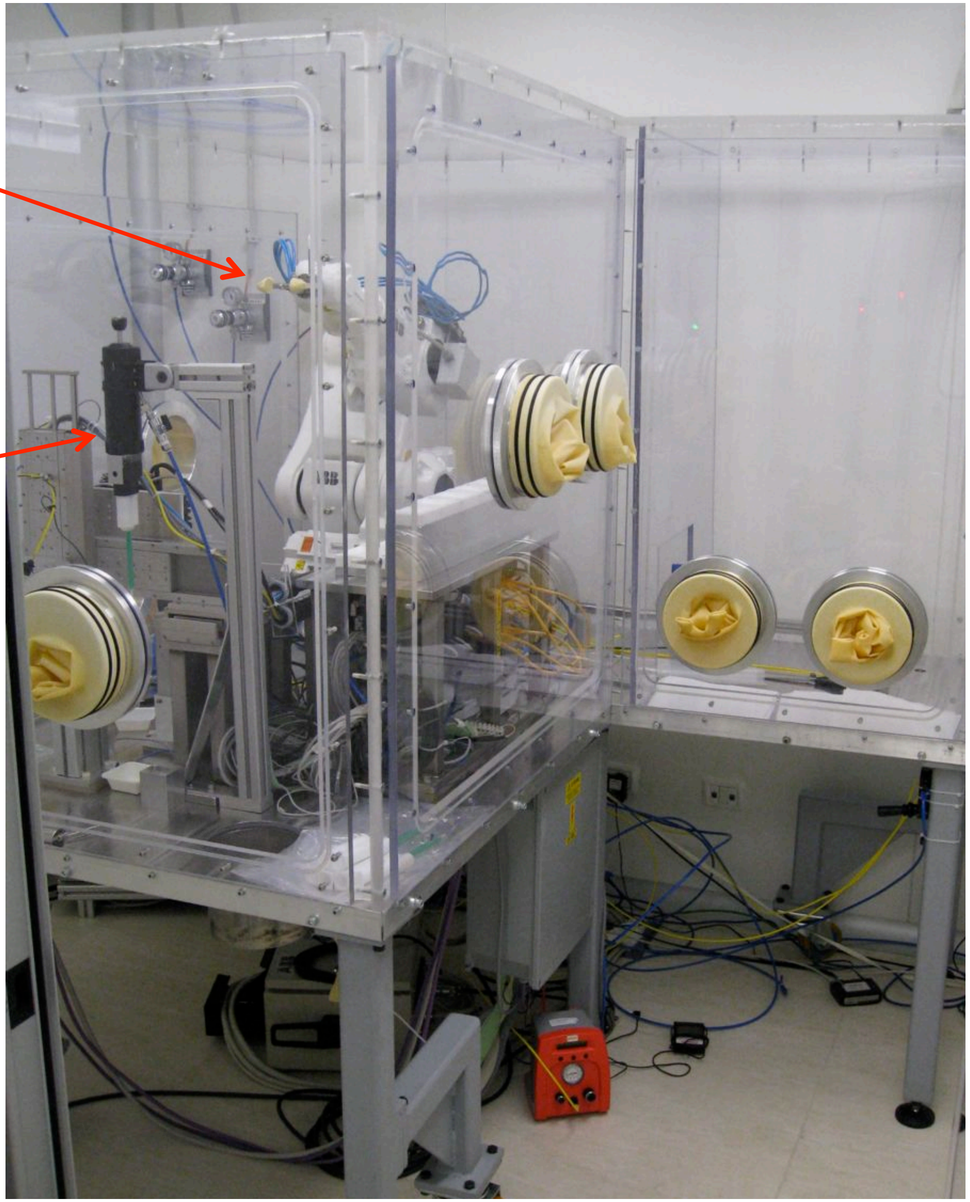
Clean rooms

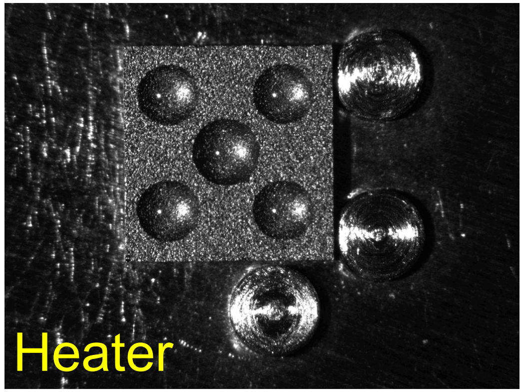


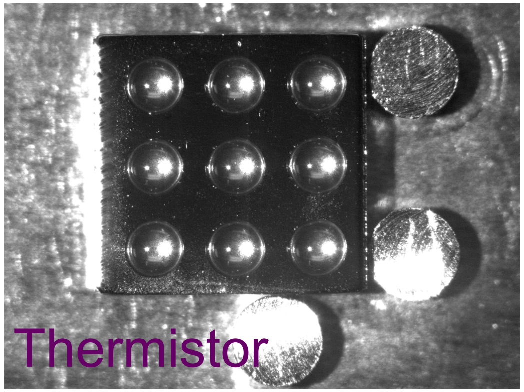
Gluing station

Robotic arm for handling crystals

Robot for mixing & dispensing glue

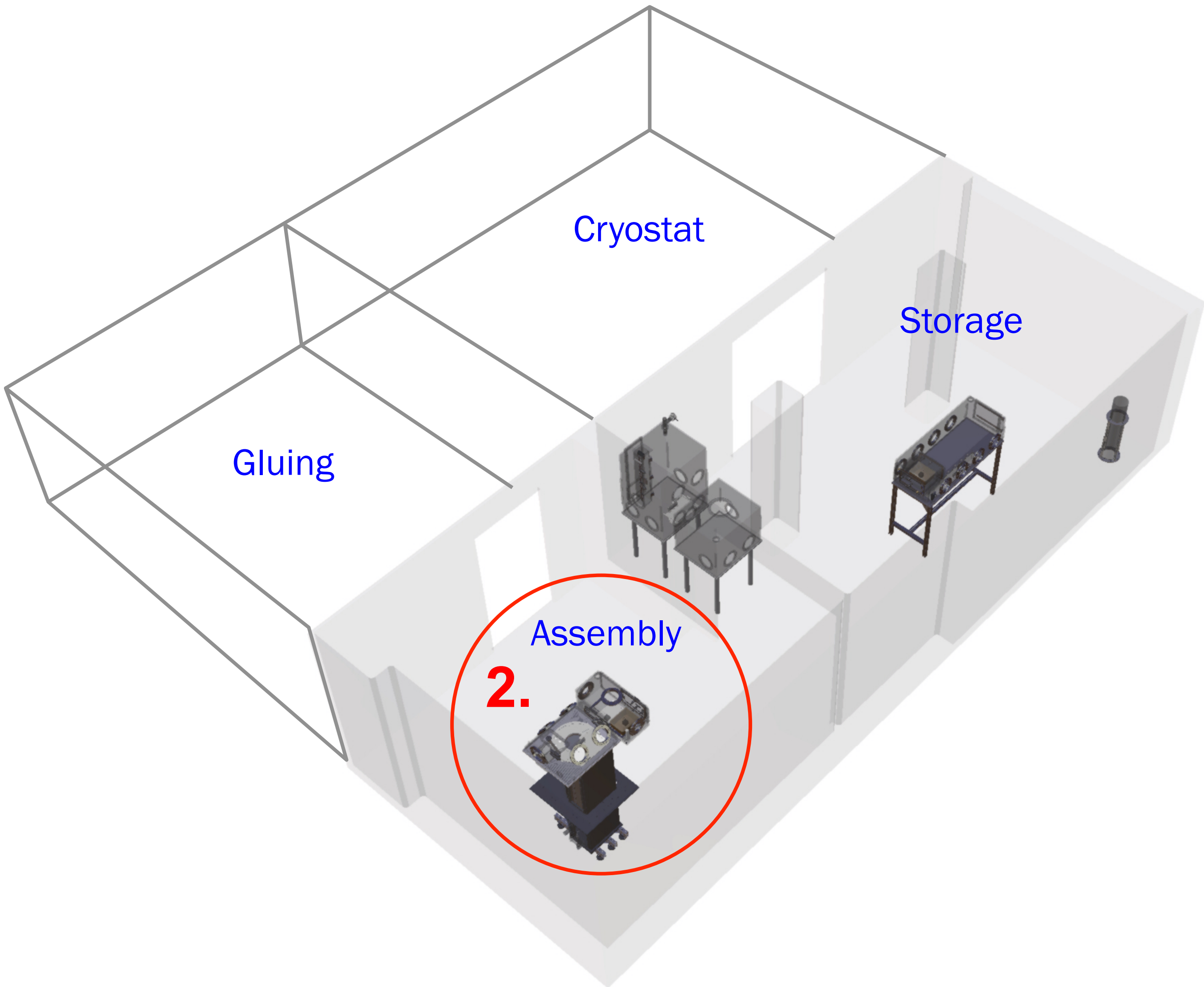




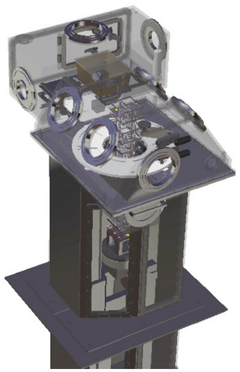


Semi-automated setup enables more precise & uniform gluing

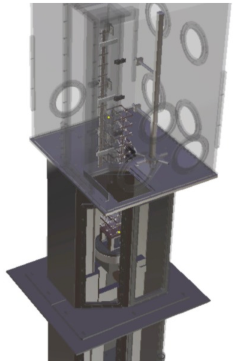
Clean rooms



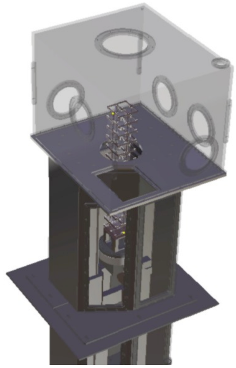
CUORE tower assembly line (CTAL)



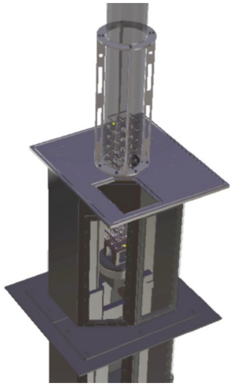
1. Assembly box



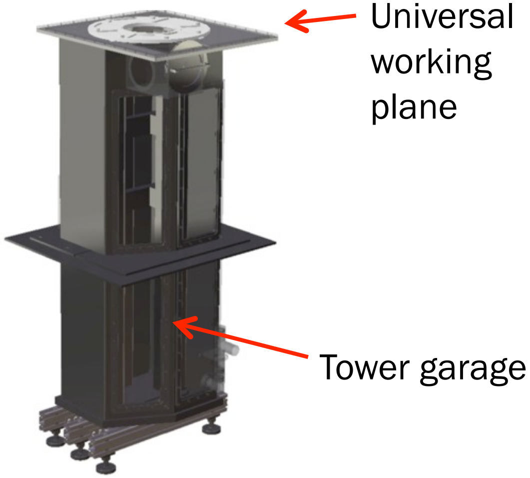
2. Cabling box



3. Bonding box

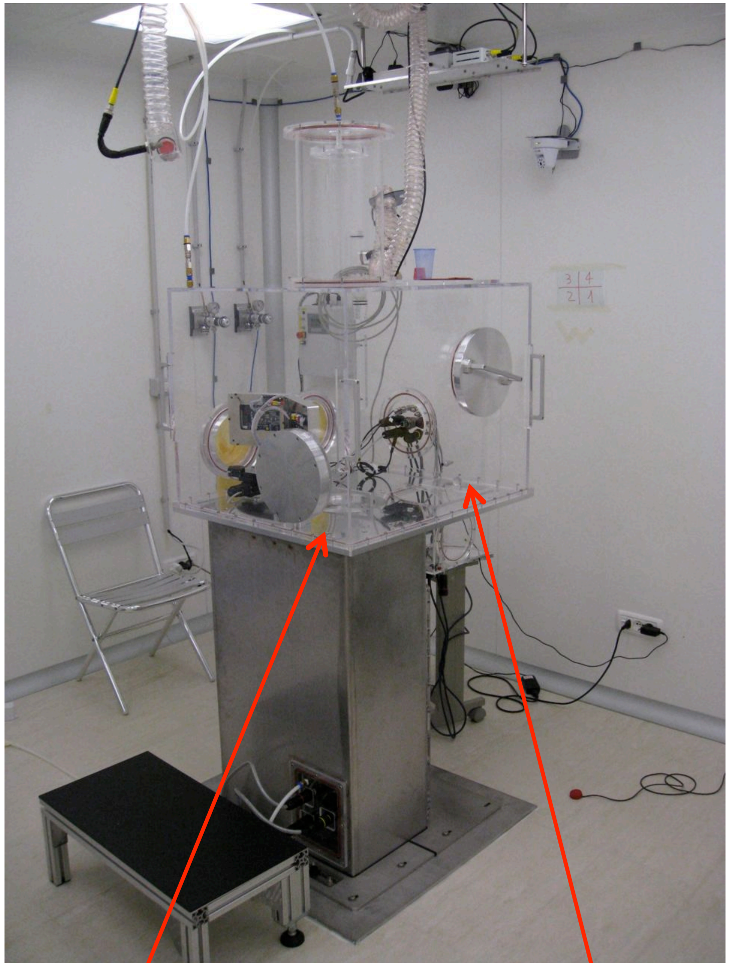


4. Storage box



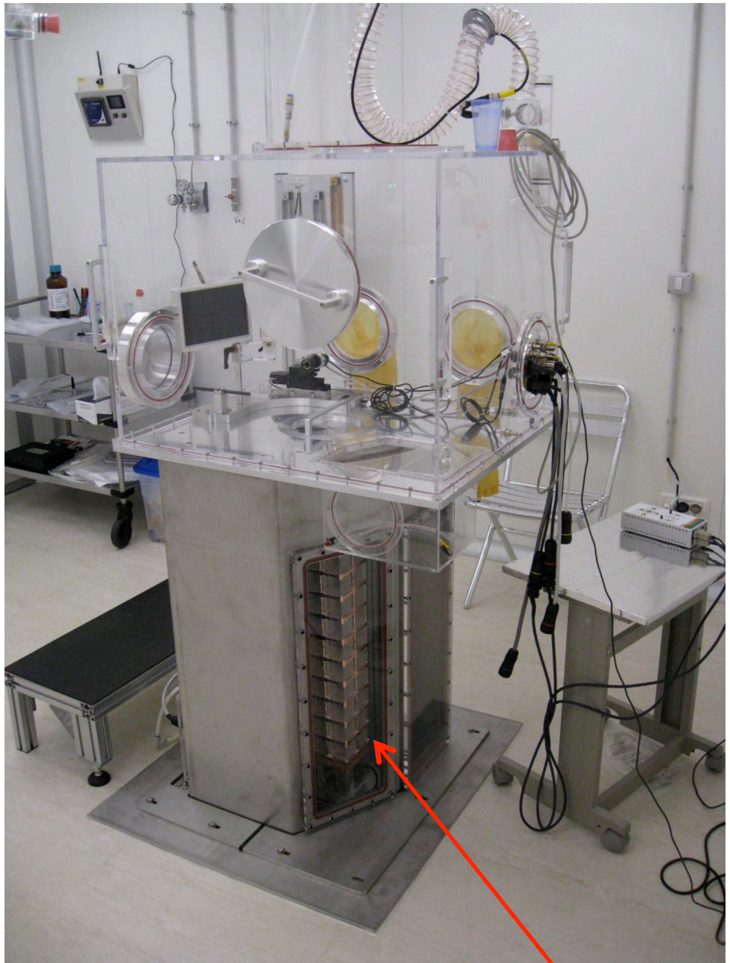
- The CTAL must transform 9994 separate pieces into 19 ultra-clean towers
- Approach: A single assembly station with 4 interchangeable glove boxes for specific tasks

CTAL working plane & tower garage



Universal Working Plane

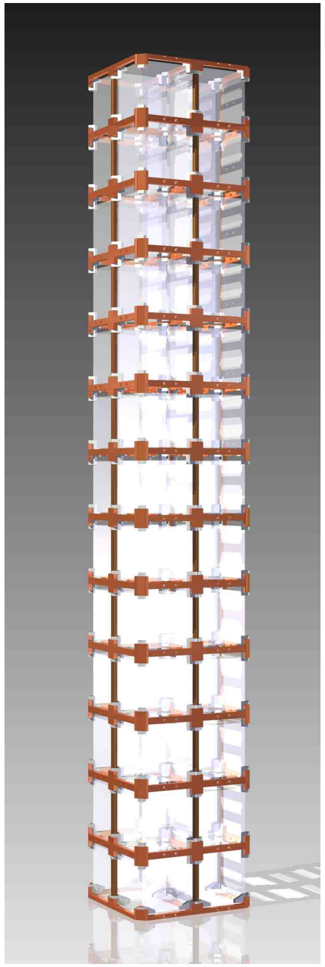
Glove box (bonding)



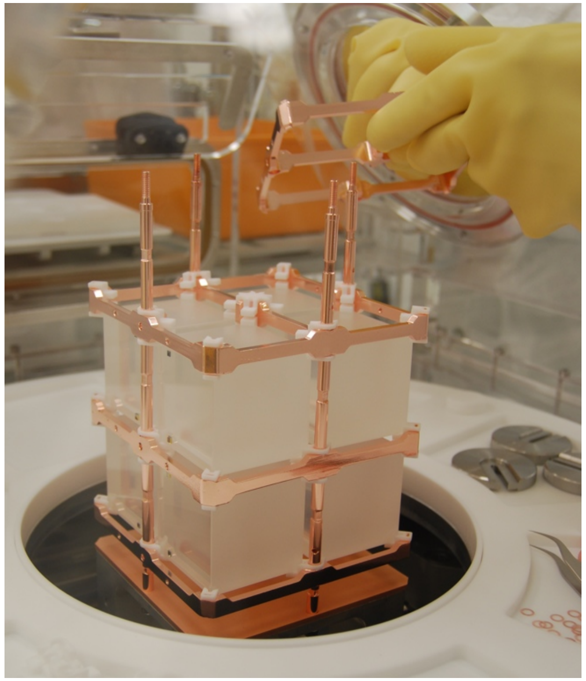
Tower garage

CUORE-0

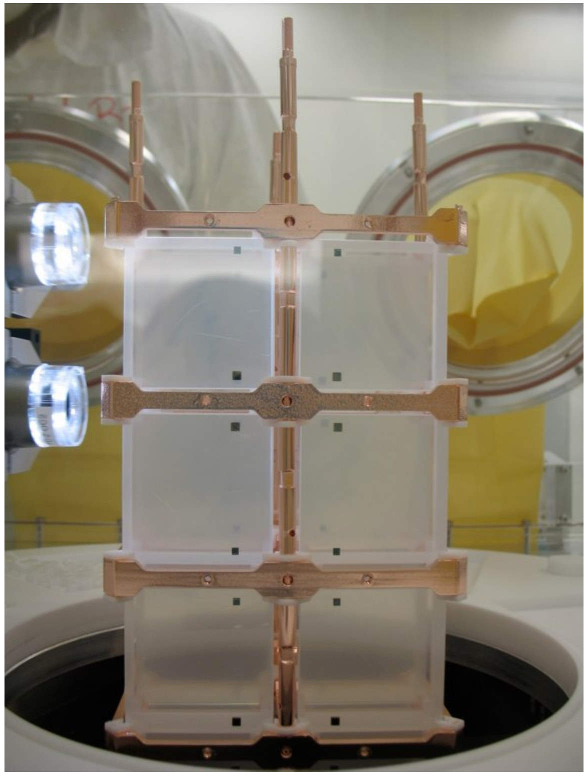
- First tower from CUORE assembly line
- Purpose
  1. Test of assembly-line procedures
  2. Should surpass Cuoricino in physics reach while CUORE detector is being assembled



CUORE-0: 1st assembly attempt



October 2011

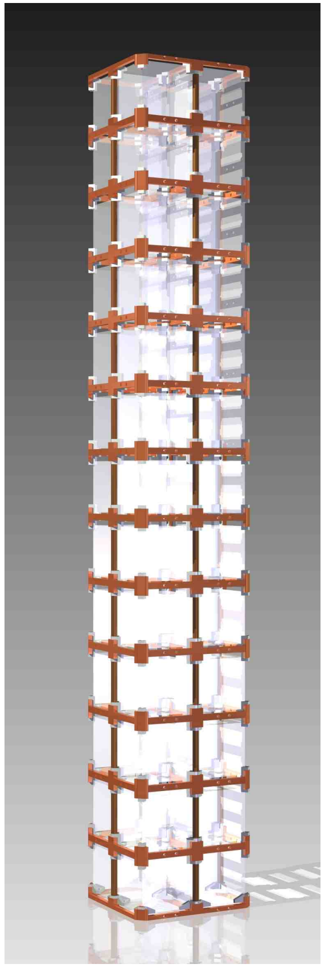


CUORE-0

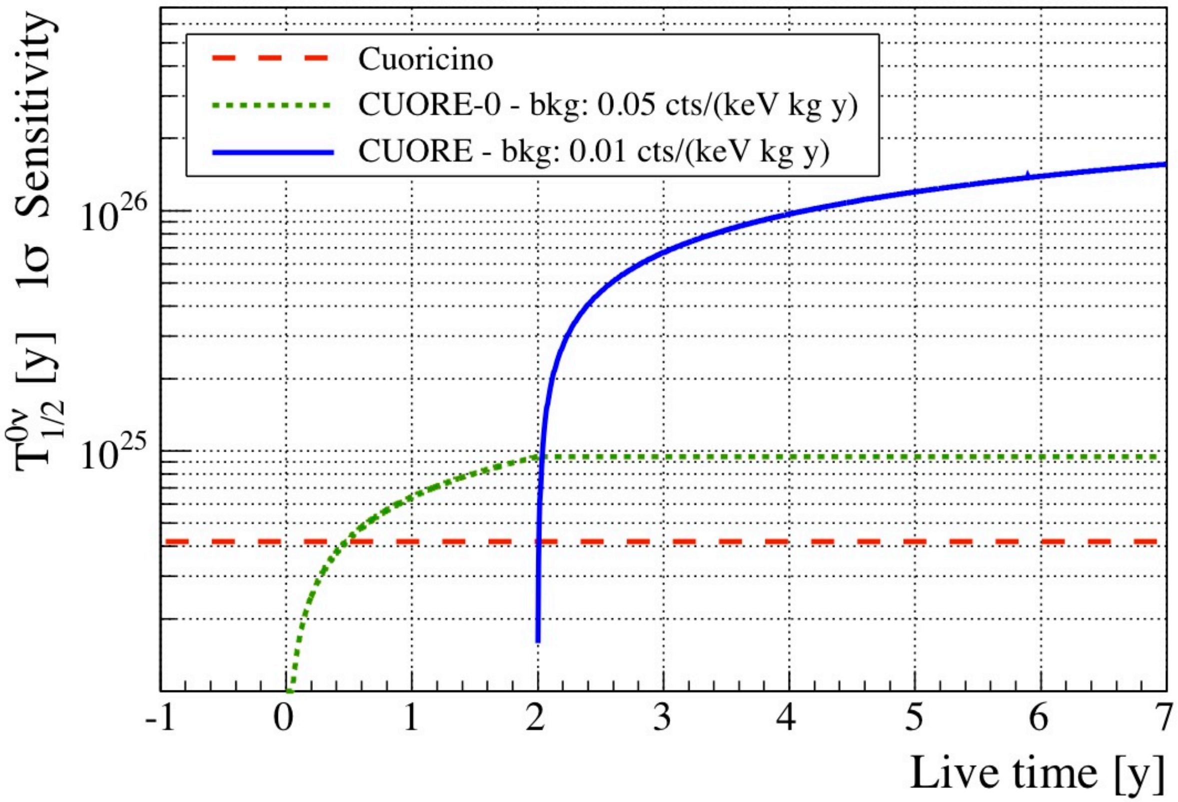
- First tower from CUORE assembly line

- Purpose
  1. Test of assembly-line procedures
  2. Should surpass Cuoricino in physics reach while CUORE detector is being assembled

- Schedule:
  - ☑ Gluing in October 2011
  - ☐ Assembly in February 2012
  - ☐ Installation in former Cuoricino cryostat in March 2012
  - ☐ Data taking 2012—2014



Experiment sensitivities



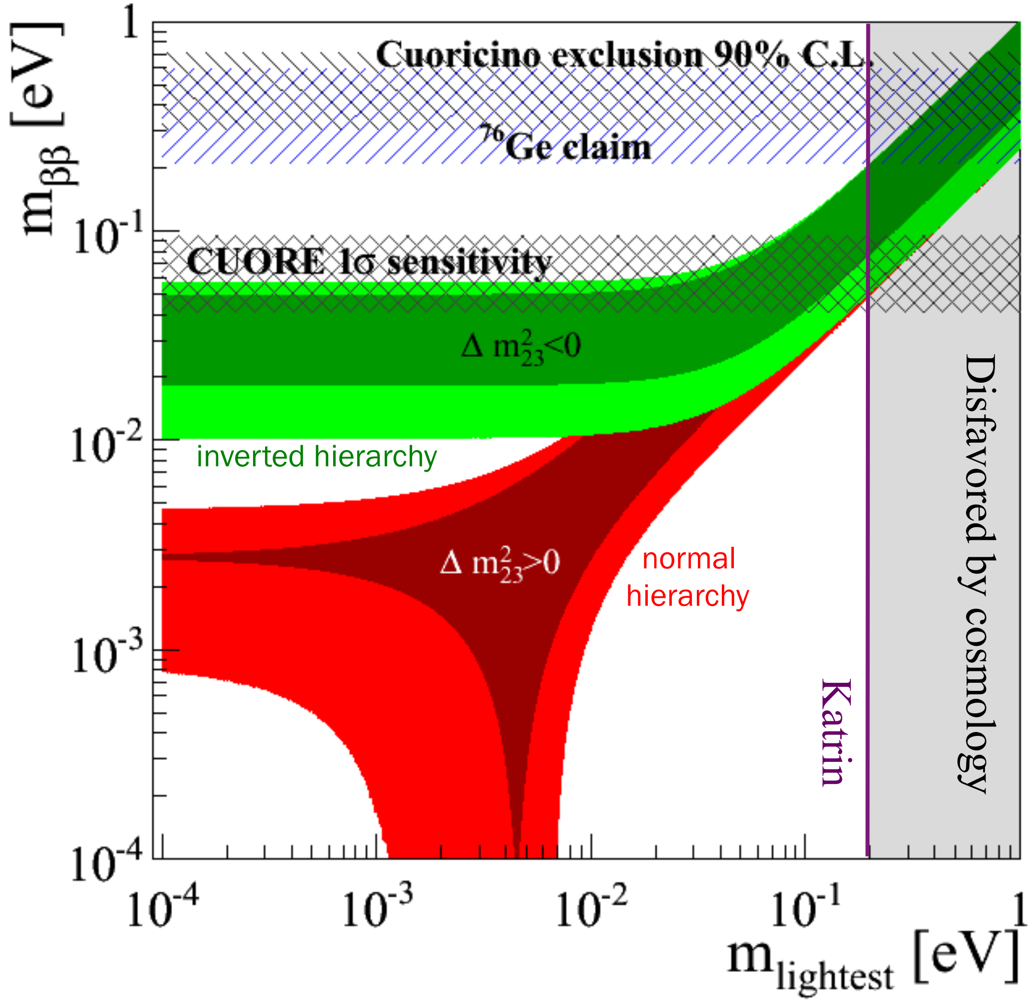
Cuoricino: $T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) \geq 4.2 \times 10^{24}$ y (1σ)

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

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

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

Experiment reach



Schedule

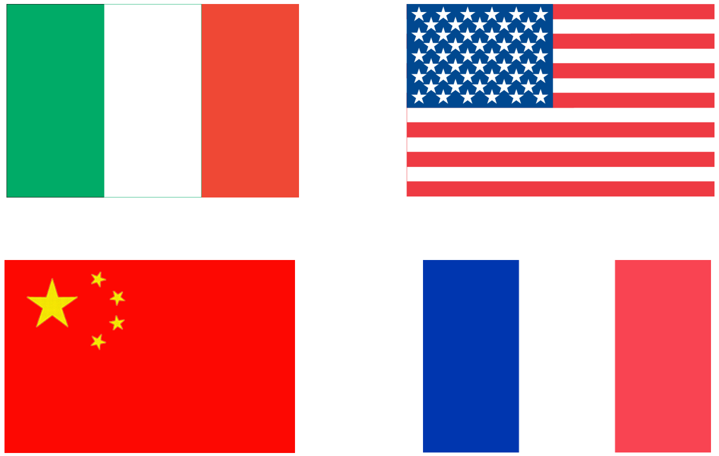
2008: Hut construction
Crystal production

2009–2010:
Crystal production
Engineering/design/fabrication

2011–2014:
Crystal production
Clean room commissioning
CUORE-0
CUORE detector assembly
CUORE cryogenics
CUORE electronics & DAQ

2015: Data taking!

CUORE Collaboration



Fine