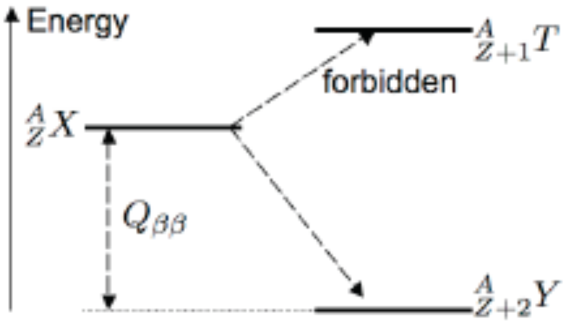
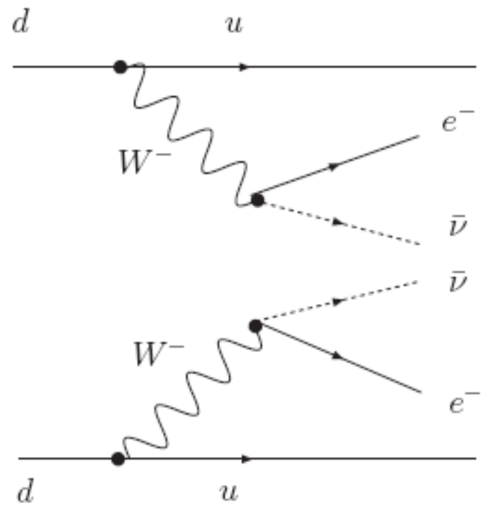
Status of CUORE

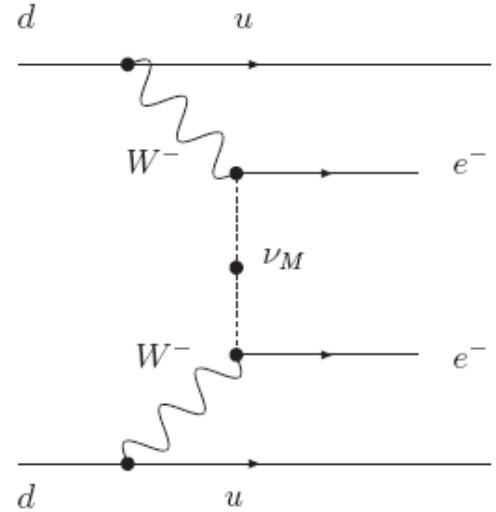
Yury Kolomensky
LBNL/UC Berkeley
2009 Joint APS/JPS Meeting
For the CUORE Collaboration

Neutrinoless Double-Beta Decay





$2\nu\beta\beta$ decay $\tau \geq 10^{19}$ y



$0\nu\beta\beta$ $\tau \geq 10^{25}$ y

- Observation of $\beta\beta 0\nu$ would mean
  - Lepton number violation
  - Neutrinos are Majorana particles
  - Rate measures electron neutrino mass

(See Boris' talk for more profound implications)

ββ0ν Rate and Neutrino Mass

ββ0ν rate

Phase space $\propto Q^5$

Nuclear matrix element

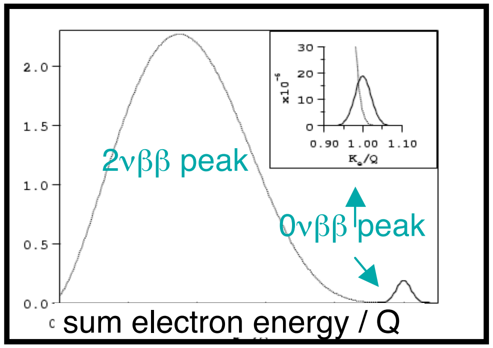
Effective neutrino mass

$$\Gamma = 1/\tau = G_F^2 \Phi(Q,Z)\, |M_{nucl}|^2 <m_{\beta\beta}>^2$$

high Q candidates preferred

large phase space

low background

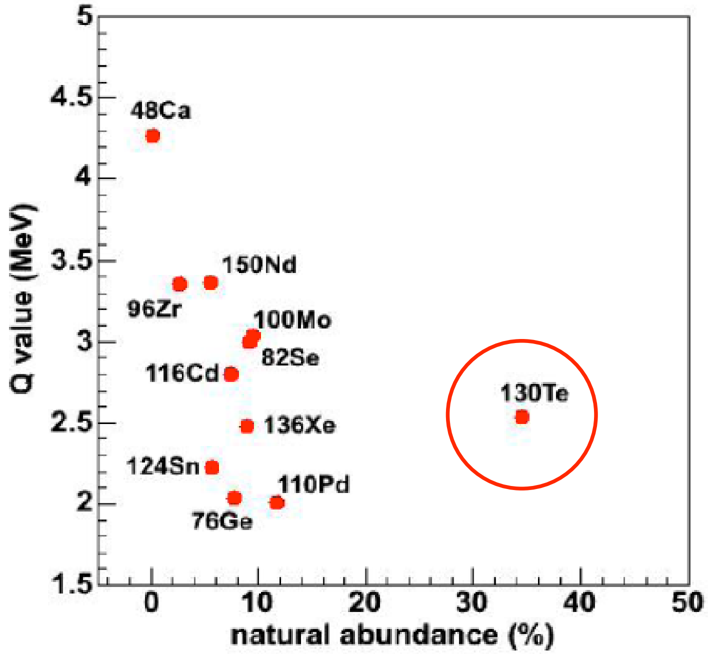


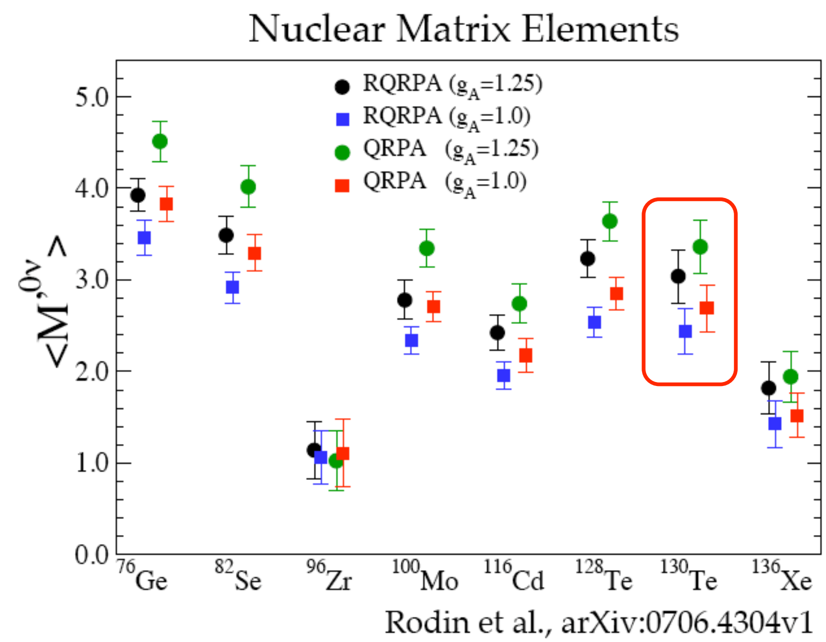
^{238}U γ end at 2.4 MeV

^{232}Th γ end at 2.6 MeV

[2039 keV (^{76}Ge) ⇔ 4271 keV (^{48}Ca)]

Tellurium as DBD Isotope



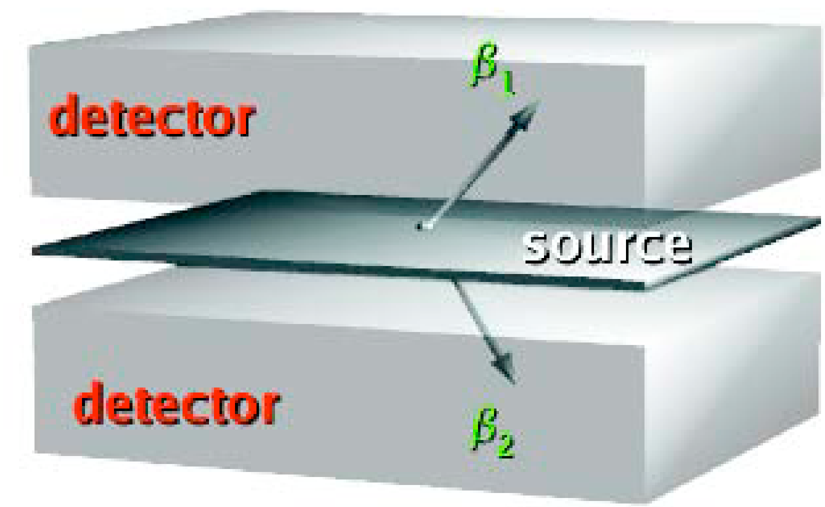


- Cost effective: Enrichment not *required*
  - Natural abundance 33.87%
- High Q = 2527.5 keV
  - Large phase space
  - Low gamma background: ROE between the Compton edge (2360 keV) and full ^{208}Tl energy (2615 keV)
- 2νββ observed with geochemical, bolometric, and tracking techniques
- Extensive existing R&D with TeO_2 bolometers

Two Experimental Techniques

Source external to detector

Ex: NEMO, Super-NEMO



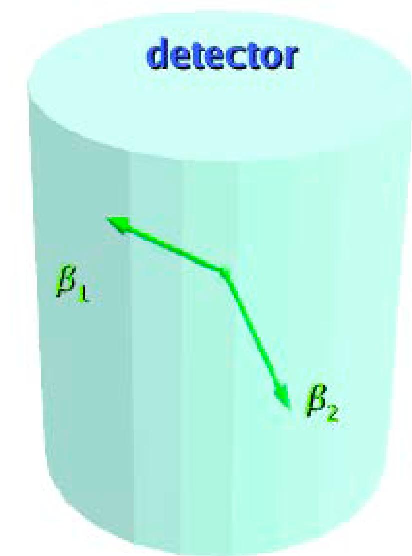
+: event topology, background rejection

–: detector mass, resolution, acceptance

Technology: typically tracking detectors

Source internal to detector

Ex: Gerda, EXO, CUORE and others

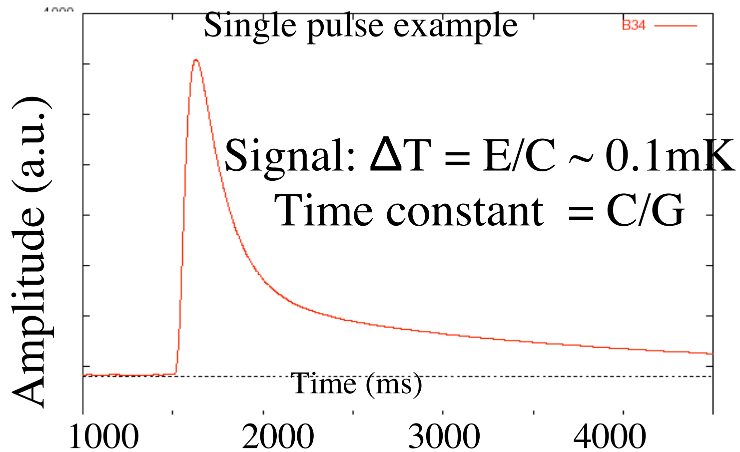


+: detector mass, resolution, acceptance

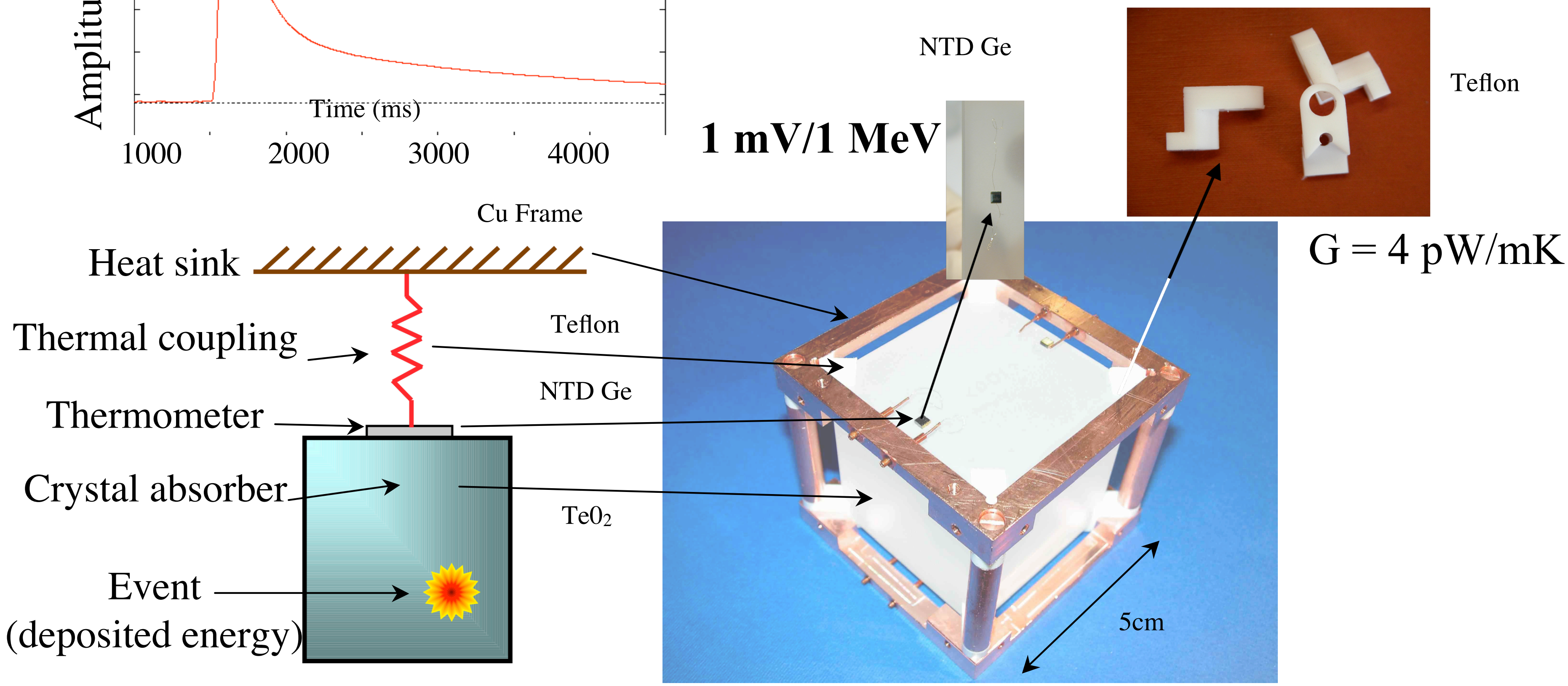
–: event topology, background rejection

Technology: calorimeters (bolometers, ionization, scintillation), tracking

Cryogenic Bolometers

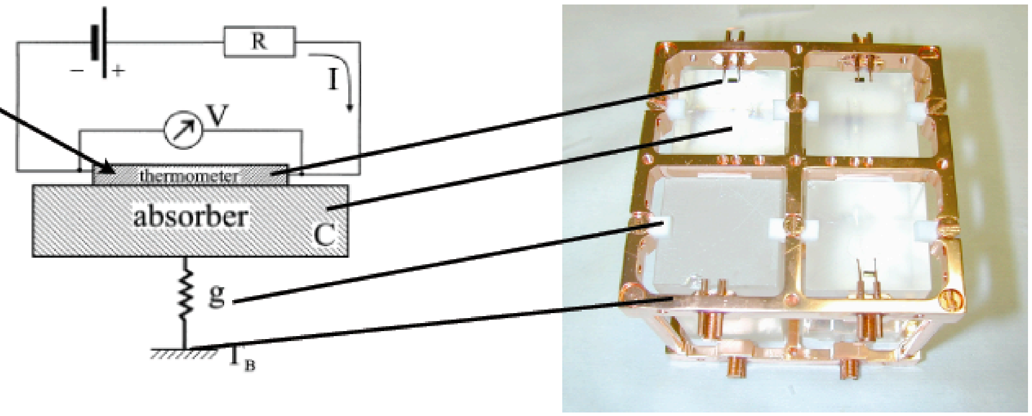


- Dielectric diamagnetic materials
- Low temperatures (~10mK)
- Low heat capacity
  - C~2 nJ/K = 1 MeV / 0.1 mK



Thermometer of Choice

Neutron-transmutation doped (NTD) Ge thermistor

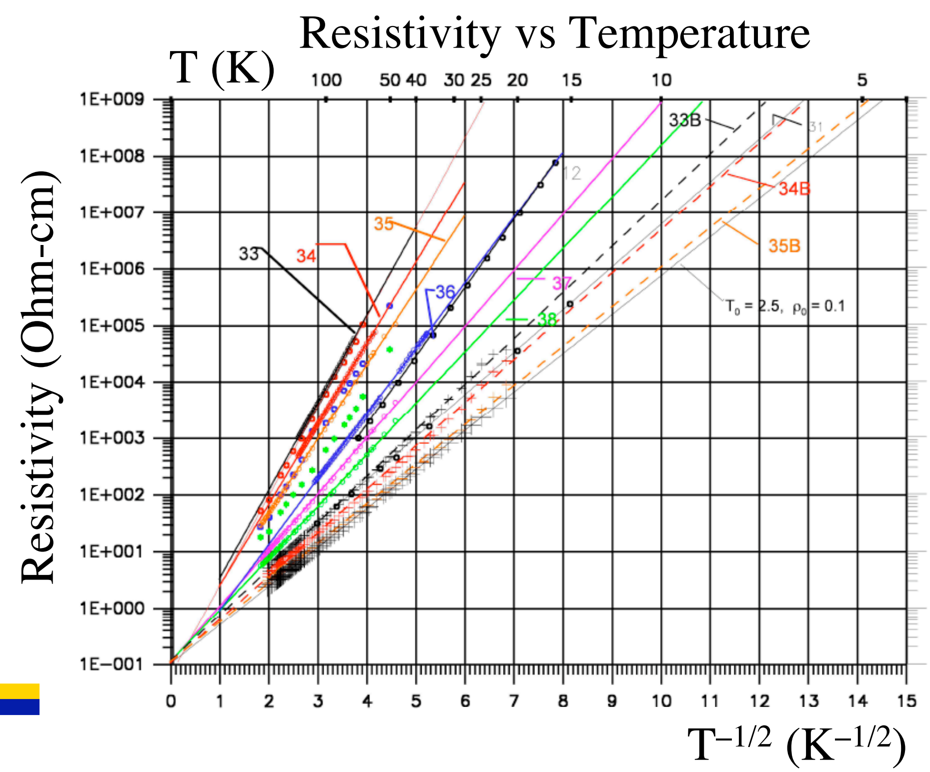


NTD resistivity after doping:

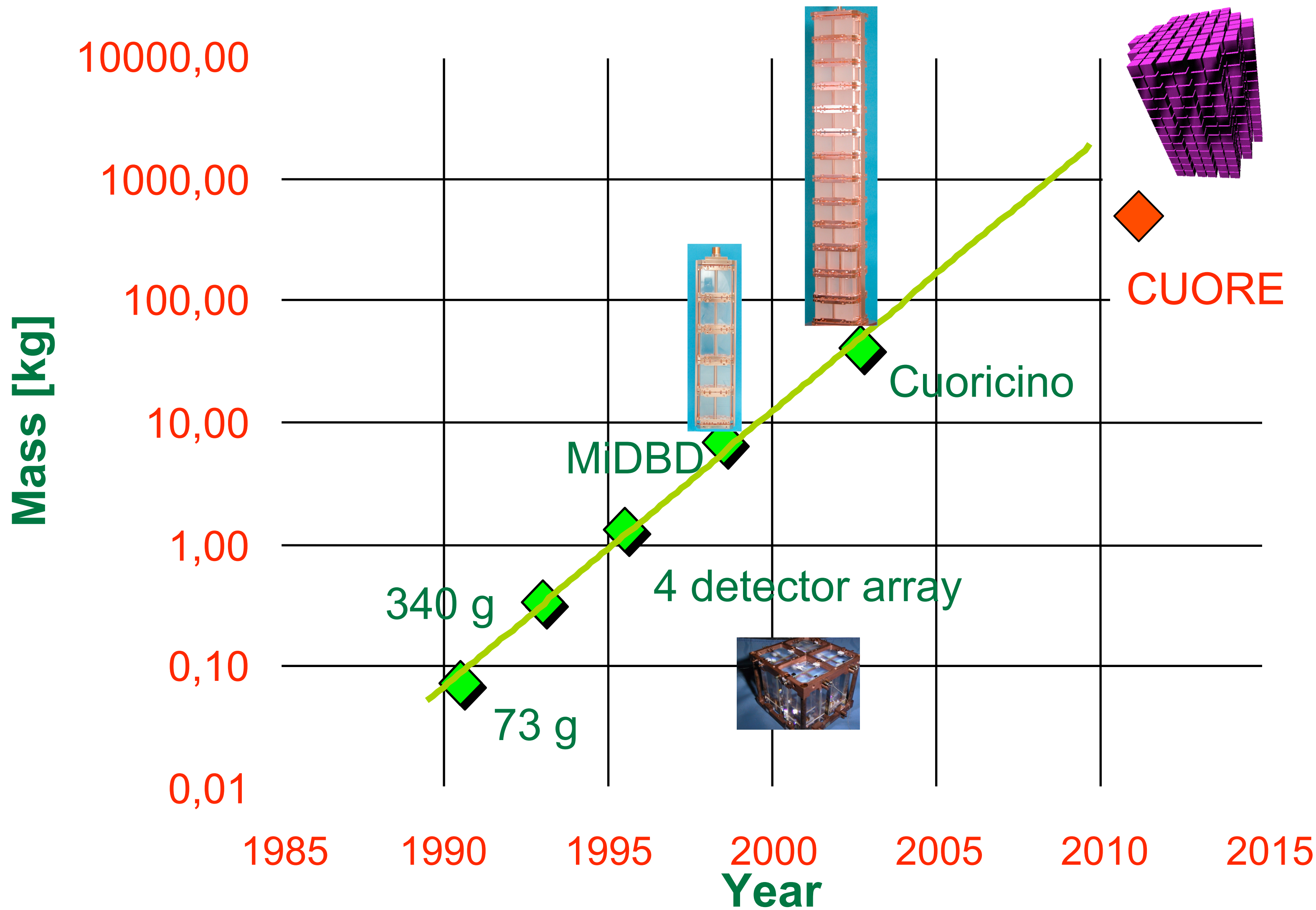
$$\rho(T) = \rho_0 \exp\left(\frac{T_0}{T}\right)^{1/2}$$

Typical values: ρ_0=1 Ohm-mm, T_0=3.1 K, neutron fluence ~3.6×10^{18} cm^{-2}

CUORE will use 1x1x3 mm^3 thermistors with flat contacts to facilitate machine wire bonding. Irradiated at MIT NRL



TeO_2 Experiments



The CUORE Collaboration

unige

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di Fisica Nucleare

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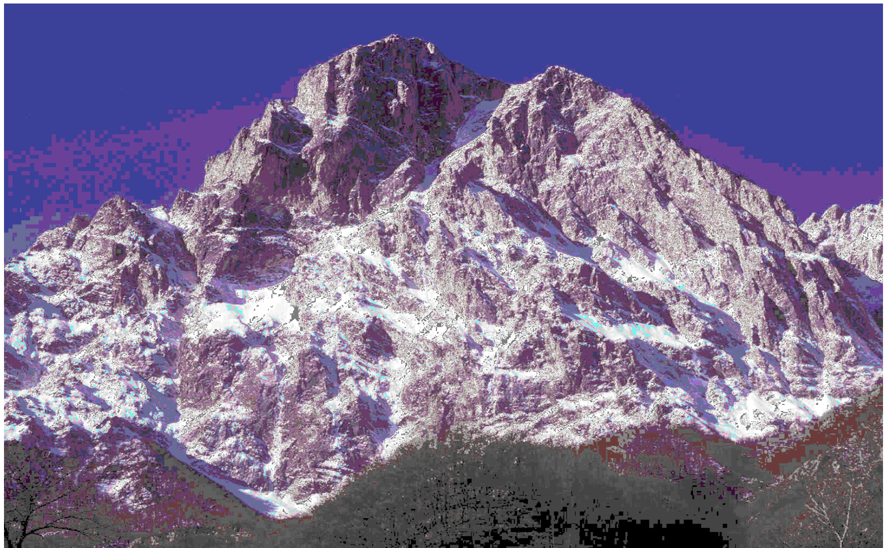
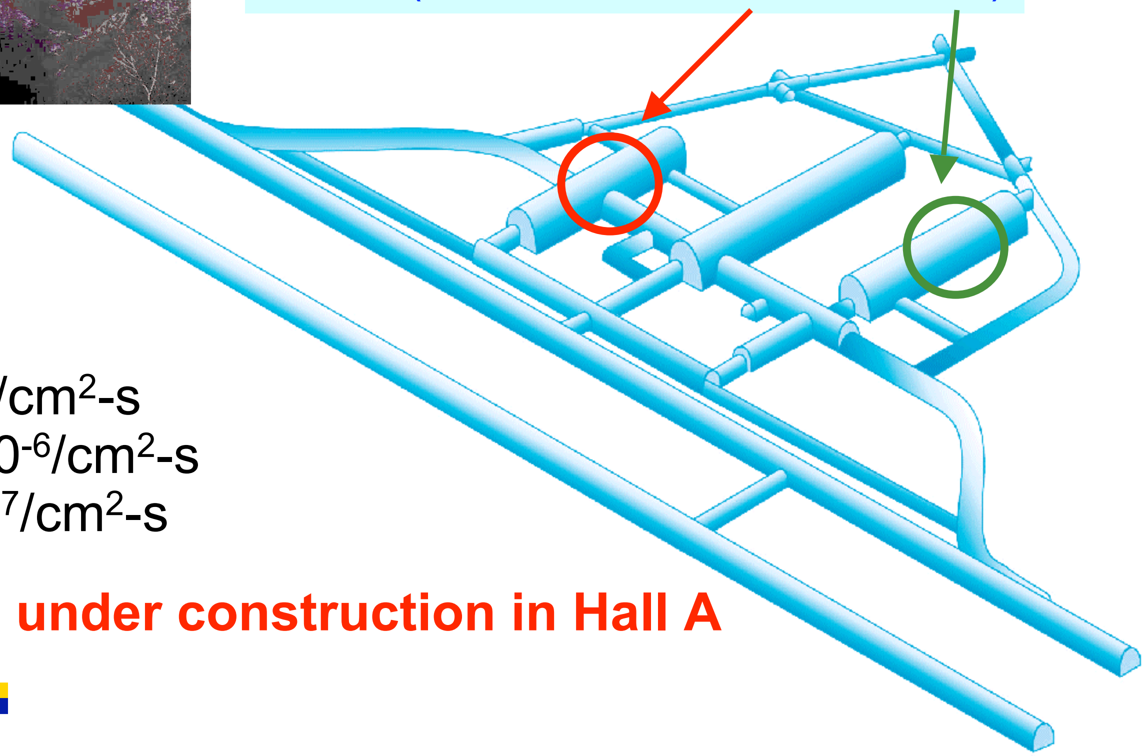
THE UNIVERSITY of WISCONSIN MADISON

UNIVERSITY OF SOUTH CAROLINA

Gran Sasso Laboratory



Two locations:
Hall A (Cuoricino/CUORE)
Hall C (R&D final tests for CUORE)



Shielding: 3500 m.w.e.
Muons: ~2 x 10^{-8}/cm^{2}-s
Thermal neutrons: ~1 x 10^{-6}/cm^{2}-s
Epithermal neutrons: ~2 x 10^{-6}/cm^{2}-s
> 2.5 MeV Neutrons: 2 x 10^{-7}/cm^{2}-s

Site for CUORE under construction in Hall A

The CUORE Project

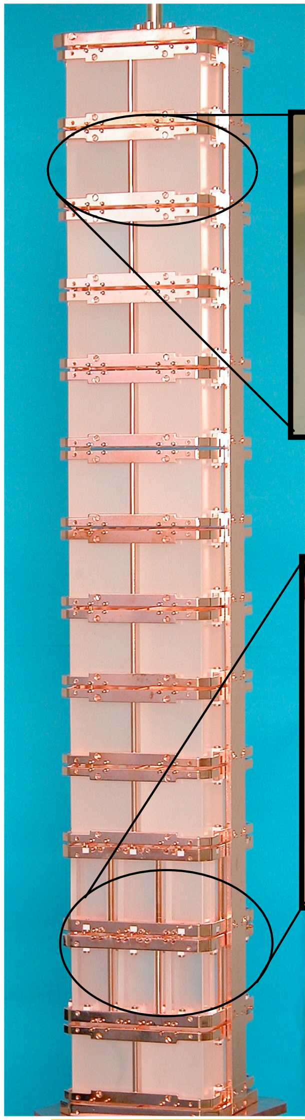
Array of 988 TeO_2 crystals

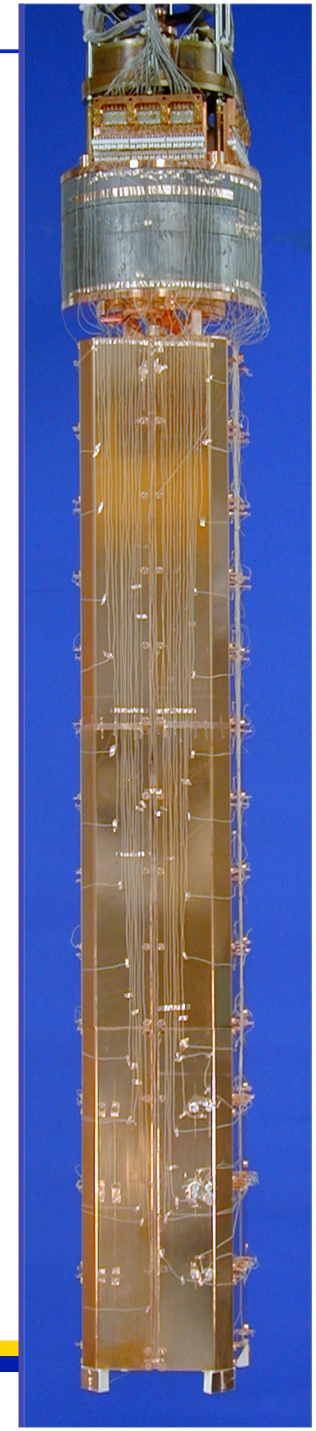
- **19** towers suspended in a cylindrical structure
- **13** levels, **4** crystals each
- 5x5x5 cm^3 (750g each)
- ^{130}Te: 33.8% isotope abundance

750 kg TeO_2 => 200 kg ^{130}Te

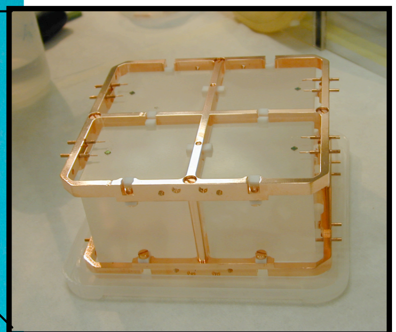
- New pulse tube refrigerator and cryostat
- Joint venture between Italy (INFN) and US (DOE, NSF)
- Under construction (past CD2/3 in the US)

Cuoricino, the prototype for CUORE



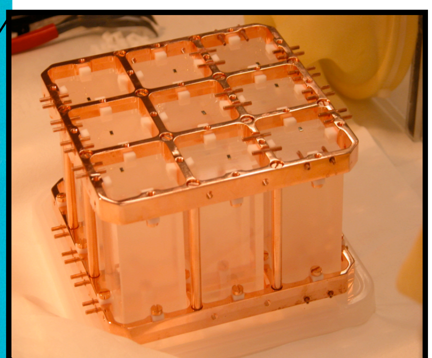


Cooled to 8-10mK



11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 790 g
44 x 0.79 = 34.76 kg of TeO_2

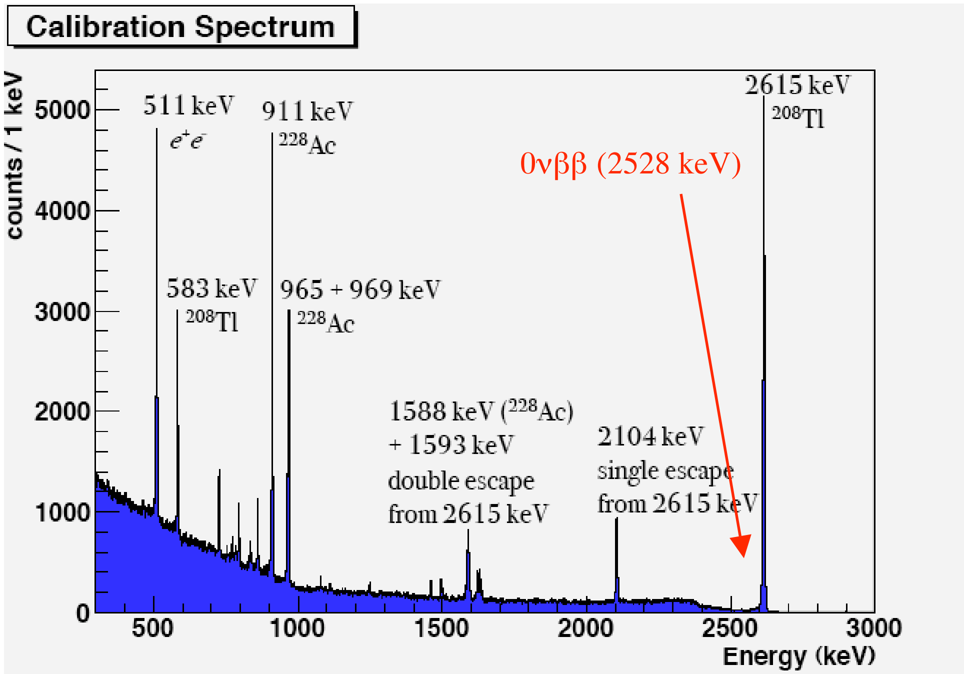
Encased in a cryostat, lead shield, nitrogen box, neutron shield, and Faraday cage



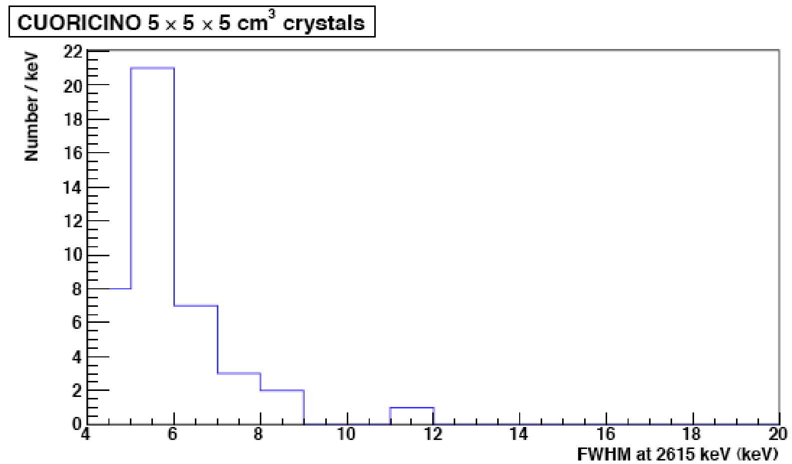
2 modules x 9 crystals each
crystal dimension: 3x3x6 cm^3
crystal mass: 330 g
18 x 0.33 = 5.94 kg of TeO_2

Total detector mass: 40.7 kg TeO_2 ⇒ **11.34 kg ^{130}Te**
Final dataset: **18 kg-y**

Cuoricino Performance



Energy Resolution



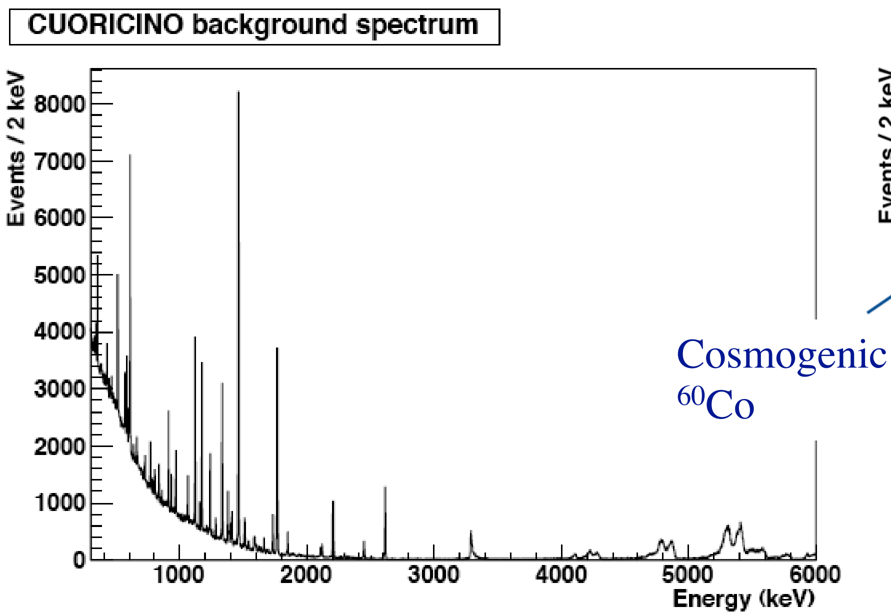
- ✓ Relative calibration and stabilization of detector response with electronic heaters
- ✓ Absolute calibration every 1-2 months with external Th source

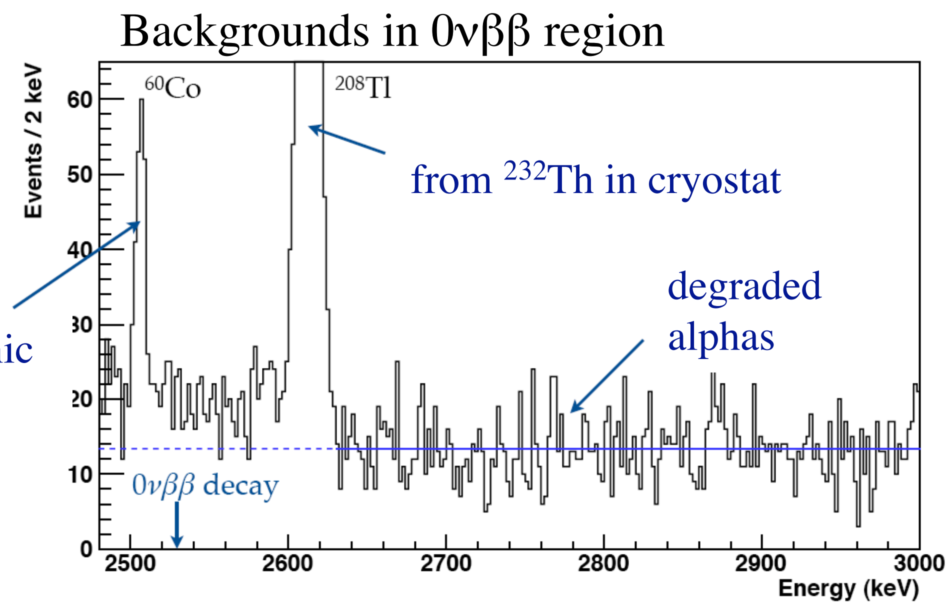
Resolution contributions

- Thermal/Phononic (σ ~ eV)
- Electronic noise (σ ≤ 1 keV)
- Microphonics (σ ~ keV)
- Detector response σ ~ keV

A. Bryant

Cuoricino Backgrounds



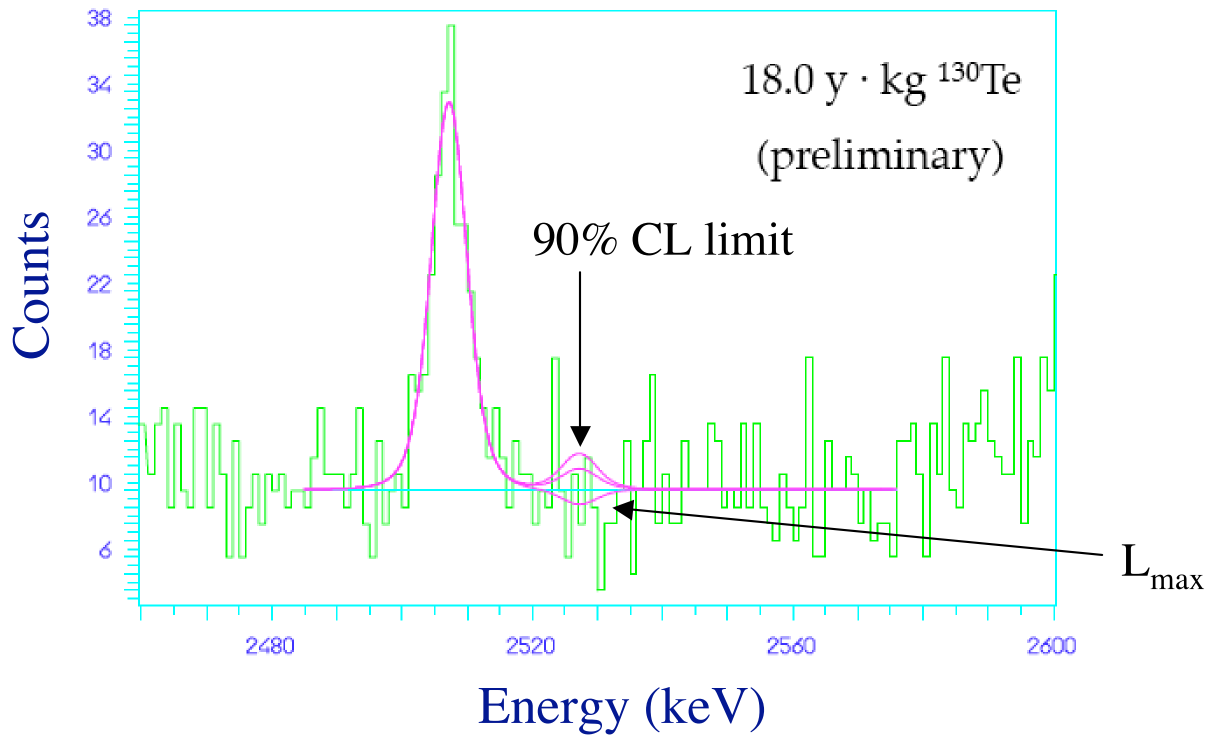


- (40±10)% in ββ0ν region from ^{208}Tl at 2615 keV
- α and β from inert material facing detector (e.g. Cu): (50±20)%
- α and β from surface contamination of crystals: (10±5)%
- Negligible contributions from neutrons and ^{60}Co at 2505 keV

Total background level in 0νββ region 0.18±0.01 counts/(keV kg y)

A. Bryant

Cuoricino Results



<u>No peak found</u>

$\tau^{0\nu}_{1/2} > 2.9 \times 10^{24}$ y at 90% C.L.

$m_{ee} < (0.20 - 0.69)$ eV

Spread is due to a range of published matrix elements

A. Bryant

From Cuoricino to CUORE

Standard sensitivity for a counting analysis:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.17\times 10^{26}}{n_\sigma}\left(\frac{a\varepsilon}{W}\right)\sqrt{\frac{Mt}{(1+\zeta)b\delta(E)}}$$

Efficiency
Detector mass (kg)
Isotopic abundance
Exposure time (y)
Desired sensitivity
ROI (keV)
Atomic weight
SNR
Background (c/kg/y/keV)

Cuoricino to CUORE:

- ✓ Increase M by a factor of 19
- ✓ Decrease b by a factor of 18
- ✓ Decrease δ by 40%
- ✓ Improve livetime (increase t)

Background Reduction

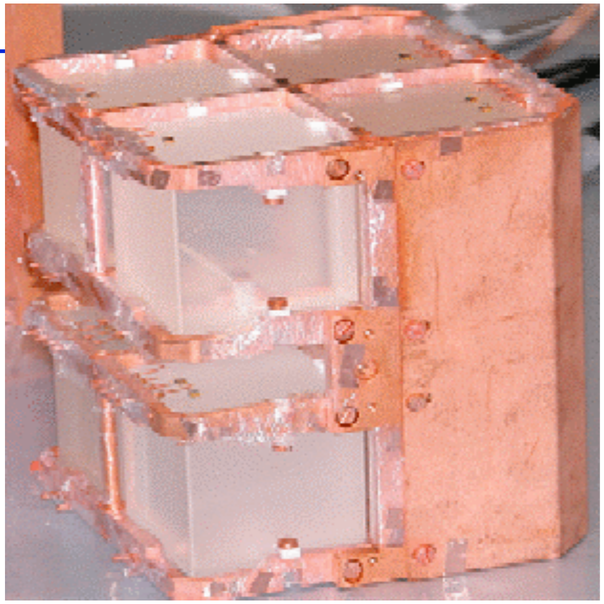
Background model: CUORICINO

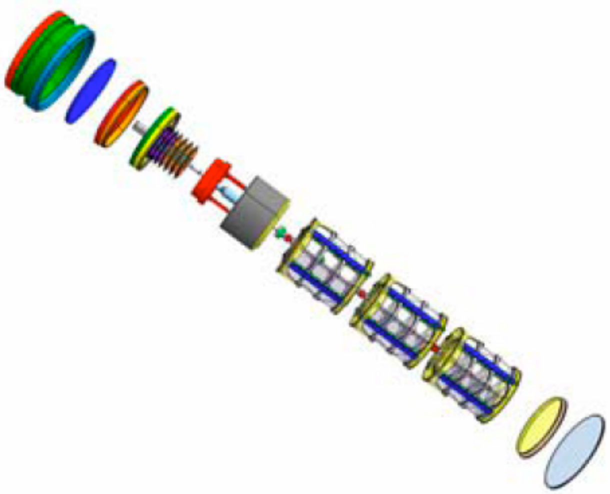
- $(40\pm10)\%$ in $\beta\beta0\nu$ region from ^{208}Tl at 2615 keV
- α and β from inert material facing detector (e.g. Cu): $(50\pm20)\%$
- α and β from surface contamination of crystals: $(10\pm5)\%$
- Negligible contributions from neutrons and ^{60}Co at 2505 keV

CUORE strategy:

- improve shields & material quality
- improve bulk contamination in TeO_2 (SICCAS)
- reduce surface contribution from
  - TeO_2 crystals
  - components facing TeO_2 crystals (mainly copper)
- increased coincidence efficiency to reject surface background events
- Overall goal: 0.01 c/y/kg/keV

Test Facilities





- Dedicated test facility in Hall C
  - Extensive R&D on material characterization (bulk, surface contaminations) during Cuoricino
- Cuoricino cryostat in Hall A
  - Final high-statistics tests of surface cleaning technologies
- Low-counting facilities @ LNGS and LBNL
- All results cross-checked against Cuoricino data and scaled to CUORE with MC
  - E.g. benefits of increased coverage for multi-site event veto (anti-coincidence)

Bulk Contamination

Measured limits (10^{-12} g/g)

Contaminant	Method	^{232}Th	^{238}U	^{40}K	^{210}Pb	^{60}Co
TeO_2	bolometric	0.2*	0.1*	1	10 μBq/kg	1 μBq/kg
Copper	Ge detectors	2.4	1.3	0.3	-	10 μBq/kg
Roman lead	Ge detectors	15	4	2	4 mBq/kg	10 μBq/kg
Low act. lead	Ge detectors	5.4	2.3	1.6*	27 Bq/kg*	180 μBq/kg*

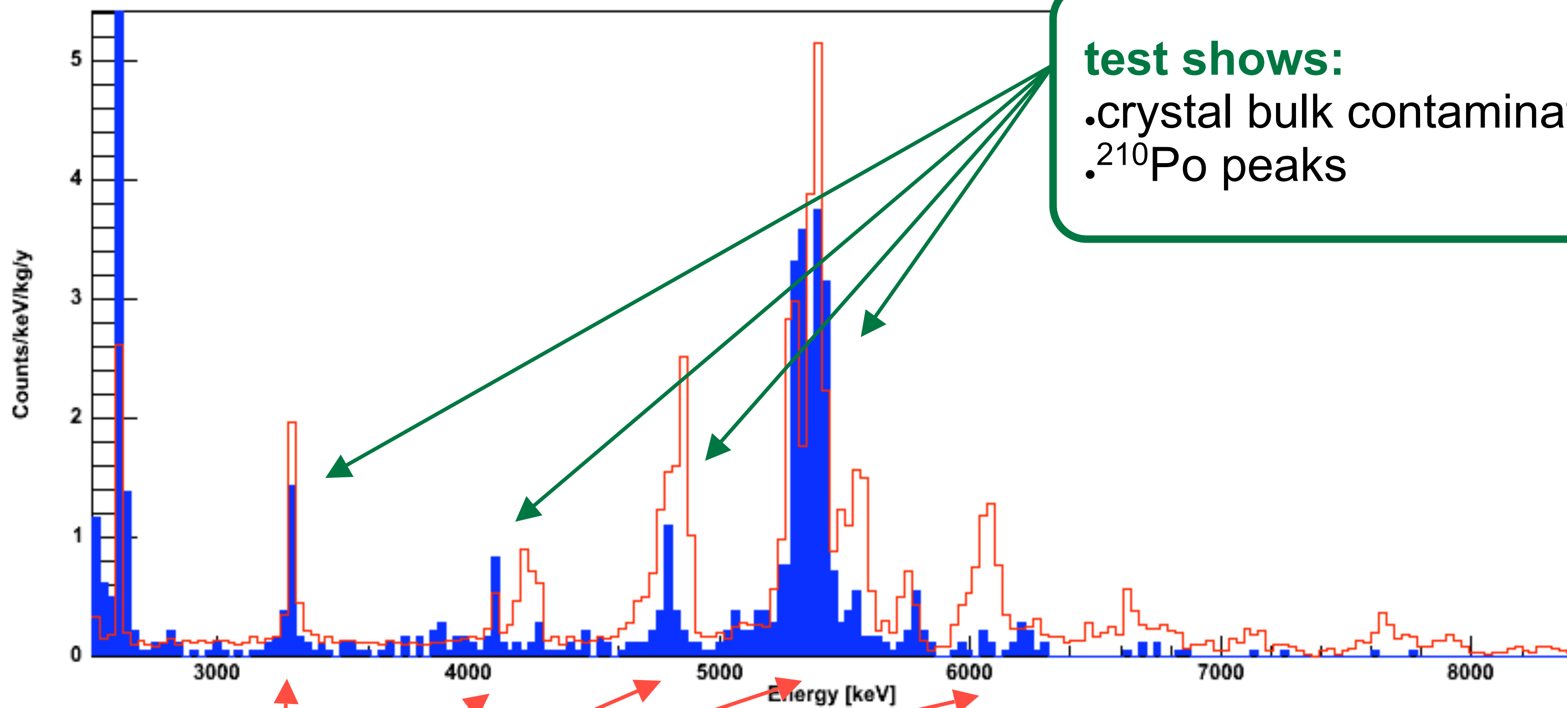
*: measured values; others are 90% CL limits.

Scaling to CUORE

Simulated element	TeO_2 crystals	Cu structure	Pb shields	Total
$0\nu\beta\beta$ decay region (counts/keV·kg·yr)	0.7×10^{-3}	0.6×10^{-3}	2.0×10^{-3}	3.3×10^{-3}
Dark matter region (counts/keV·kg·day)	2.3×10^{-2}	3.6×10^{-4}	0.3	0.3

Reduction in TeO_2 Surface Background

Etch crystals in dilute HNO_3 then polish with clean SiO_2 slurry



test shows:
- crystal bulk contamination
- ^{210}Po peaks

Cuoricino crystal surface contamination has disappeared: **reduction by ~ 4**

Copper Surface Contamination

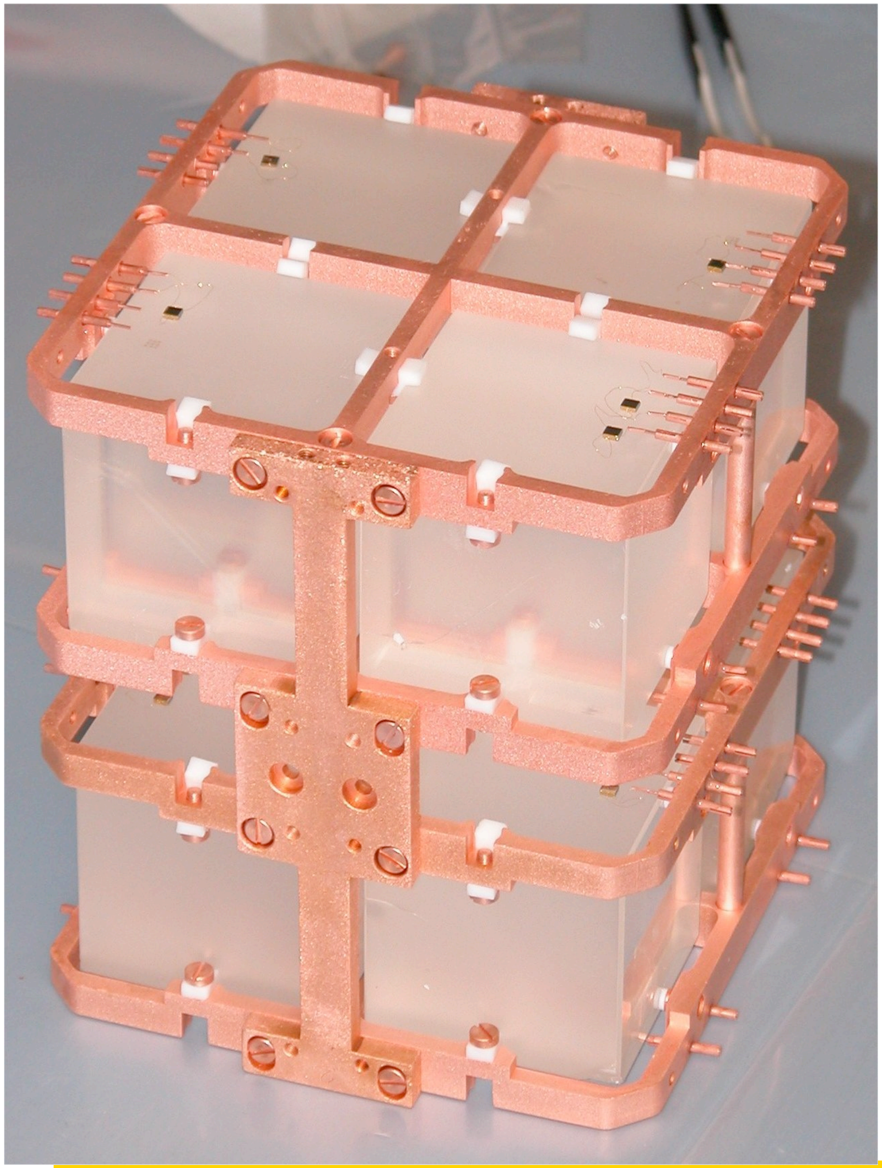
- Improve surface cleaning techniques
  - Chemical
  - Plasma cleaning
- Alpha suppression
  - Polyethylene wrapping
    - ☞ Final test running now in Hall A

Best results so far

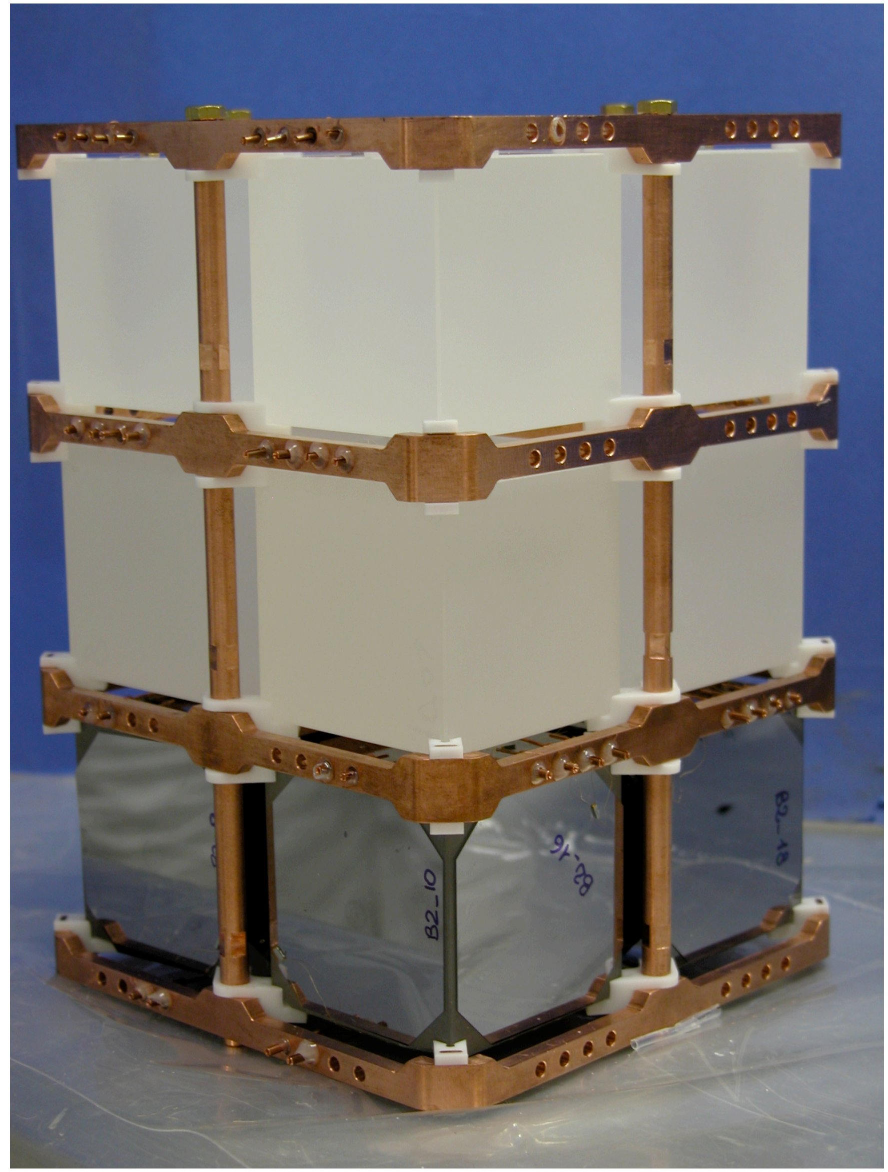
Element	Contamination Bq/cm^2	Contribution to the $0\nu\beta\beta$ region counts/keV·kg·yr
TeO_2	3×10^{-8}	0.5×10^{-2}
Copper	4.4×10^{-7}	3.5×10^{-2}
Total	-	4.0×10^{-2}

Additional factor of 2 from reduction of Cu surface area

CUORICINO-like



CUORE-like



Background Summary

Cuoricino bkgd ($0\nu\beta\beta$) = 0.18 c/keV/kg/y

(a) Cryostat internal Cu shields (bulk) - 0.072 c/keV/kg/y

(b) TeO_2 surfaces – 0.018 c/keV/kg/y

(c) Cu surfaces – 0.09 c/keV/kg/y

negligible contribution from neutrons

CUORE current estimate:

cleaner Cu shields and thicker internal Pb shield reduces

(a) to <0.004 c/keV/kg/y

etching and polishing crystals reduces

(b) to <0.004 c/keV/kg/y

clean or wrap Cu surfaces reduces

(c) to <0.034 c/keV/kg/y

reduce Cu surface area by ~ 2 reduces

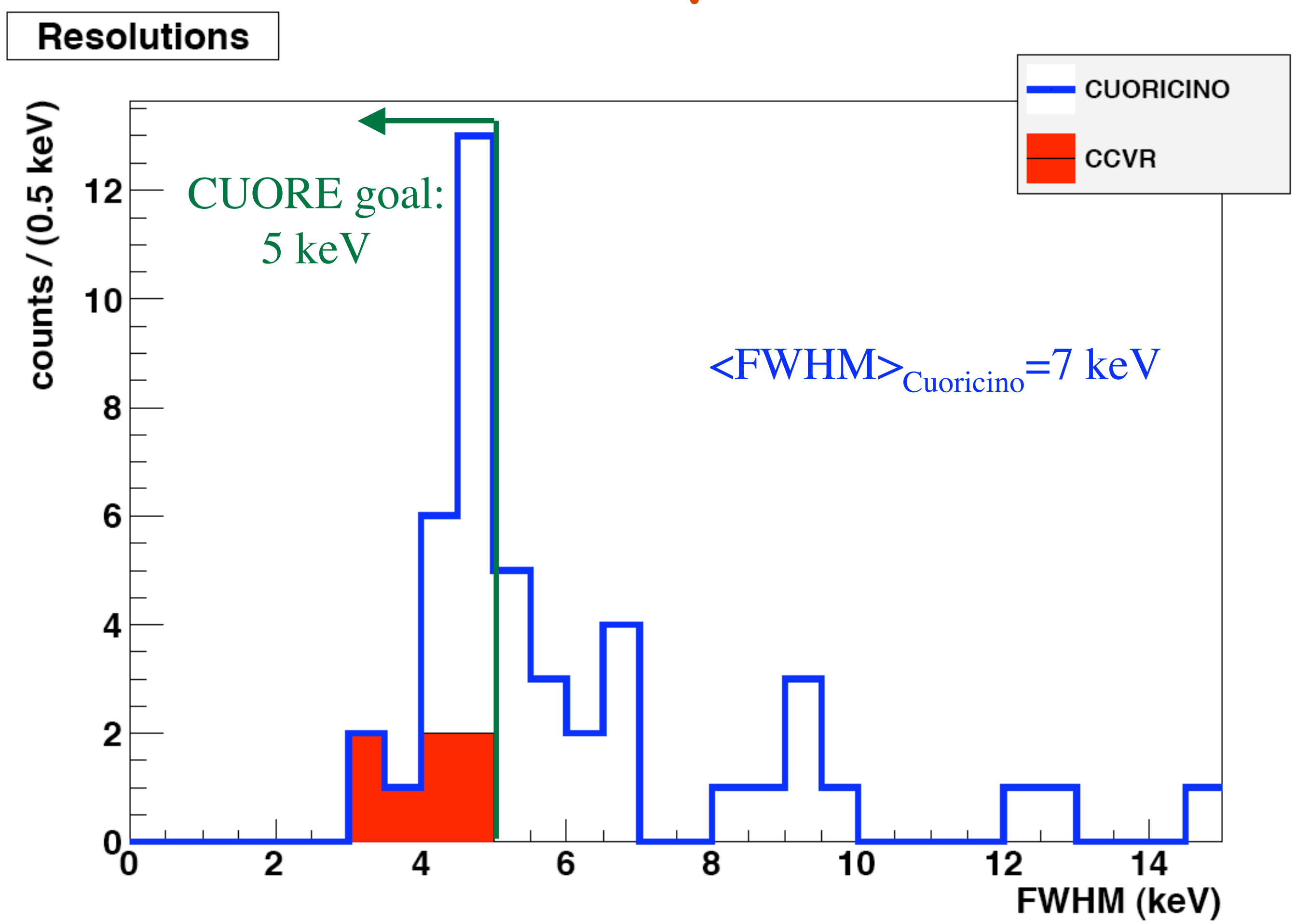
(c) to <0.017 c/keV/kg/y

Total bkgd ~ < 0.025 c/keV/kg/y

Somewhat larger than the goal, however:

- ✓ Some numbers are upper limits; c.f. recent Hall C estimate 0.016±0.003 c/keV/kg/year
- ✓ Higher efficiency of anti-coincidence not yet accounted

Resolution Improvements



All delivered crystals so far are safely within specs. Resolution improvements due to improved mechanical tolerances (vibrations) and crystal quality (impurities)

Additional Challenges

Cryogenics

- 10 mK base temperature
- >1600 kg total mass @ 10 mK
- 5 μW power @ 10 mK
- 20 t total mass inside cryostat

Detector Calibration System

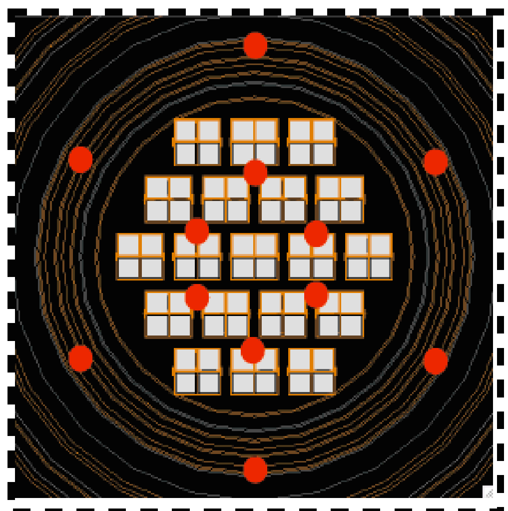
- Internal to cryostat
- Minimize heat load
- Calibration time < 1 week while avoiding event pileup
- Energy scale uncertainty goal < 0.05 keV in 0νββ region

motion system:
insertion and extraction of sources in and out of cryostat

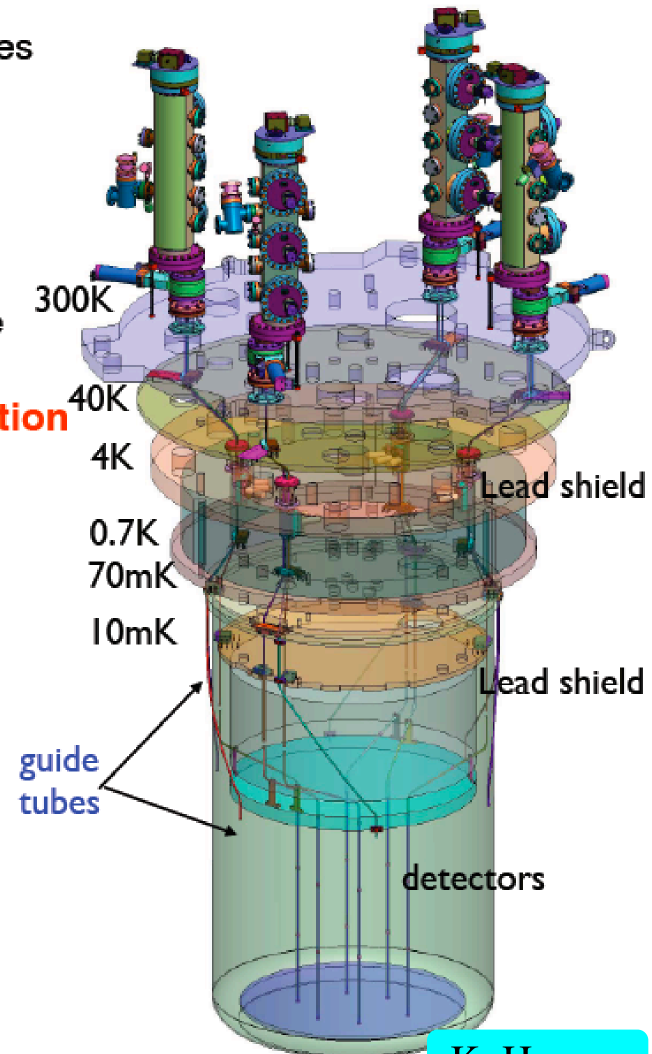
guide tubes:
no straight vertical access

source strings:
move under own weight in guide tubes

source location



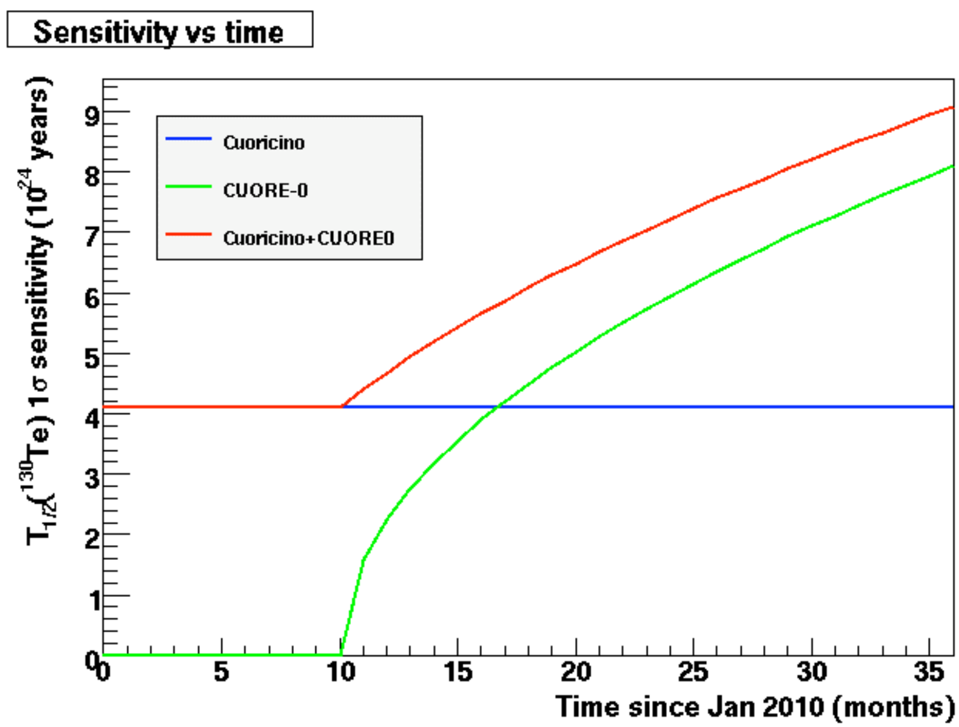
top view of detector array with source positions



K. Heeger

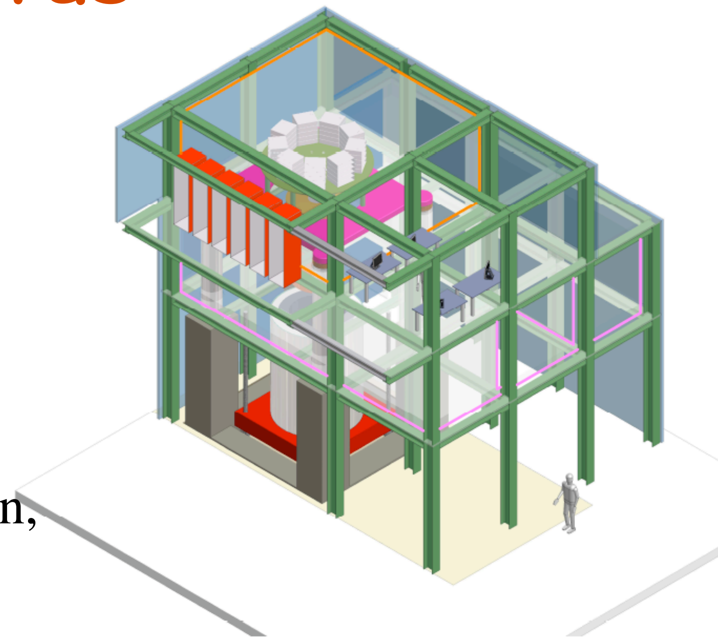
CUORE-0

- 1 full tower of CUORE (52 crystals), installed in Cuoricino cryostat by October 2010
  - Verify cleaning, assembly procedures
  - Bonus: better science reach than Cuoricino



CUORE Status

- Dedicated site in Hall A
  - Detector assembly in a clean room above cryostat
    - ☞ Detector hut and cryo support structures completed
- Cryostat purchased
    - ☞ Dilution unit being designed in Leiden, to be delivered by end of 2010
- Crystal delivery on schedule
    - ☞ 3 shipments of 60 crystals SICCAS
- NTD production on schedule
    - ☞ Irradiation complete, 1200 NTDs being produced
- Electronics designed and is being procured



CUORE Schedule

2009 2010 2011 2012

R&D

3-tower test → CUORE-0 construction → CUORE-0 data taking

background R&D

assembly tests

single tower assembly (in Cuoricino cryostat)

CUORE

CUORE construction → CUORE data taking

Planned physics operations by end of 2012

5 year data taking period

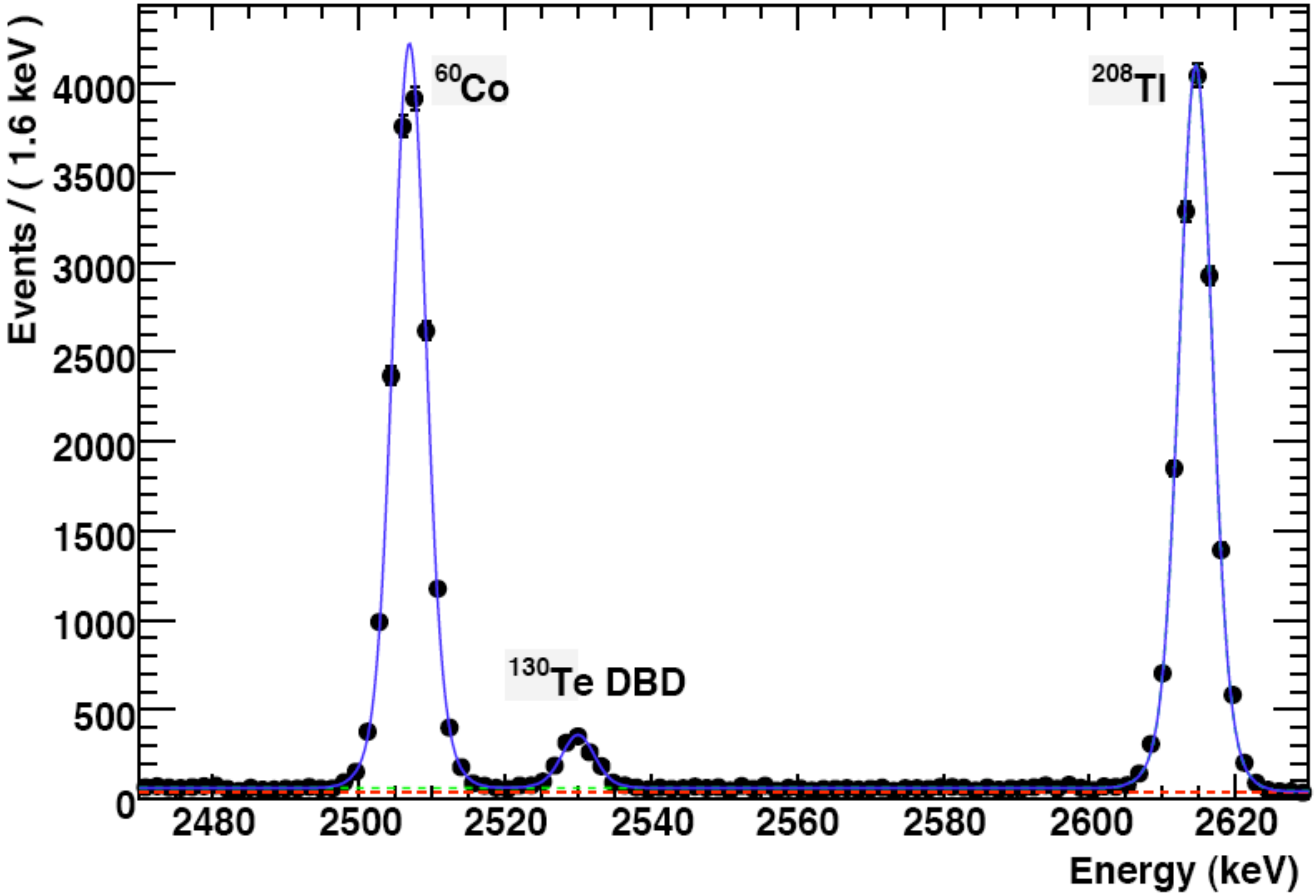
CUORE Sensitivity

Assume KKDC result: $T_{1/2}$=25x10^{23} y (also near Cuoricino limit)

Background 0.01 c/keV/kg/year, 5 keV FWHM resolution, 5 years of running

Assume conservative scaling of Co and Tl peaks

Outcome of one possible experiment:

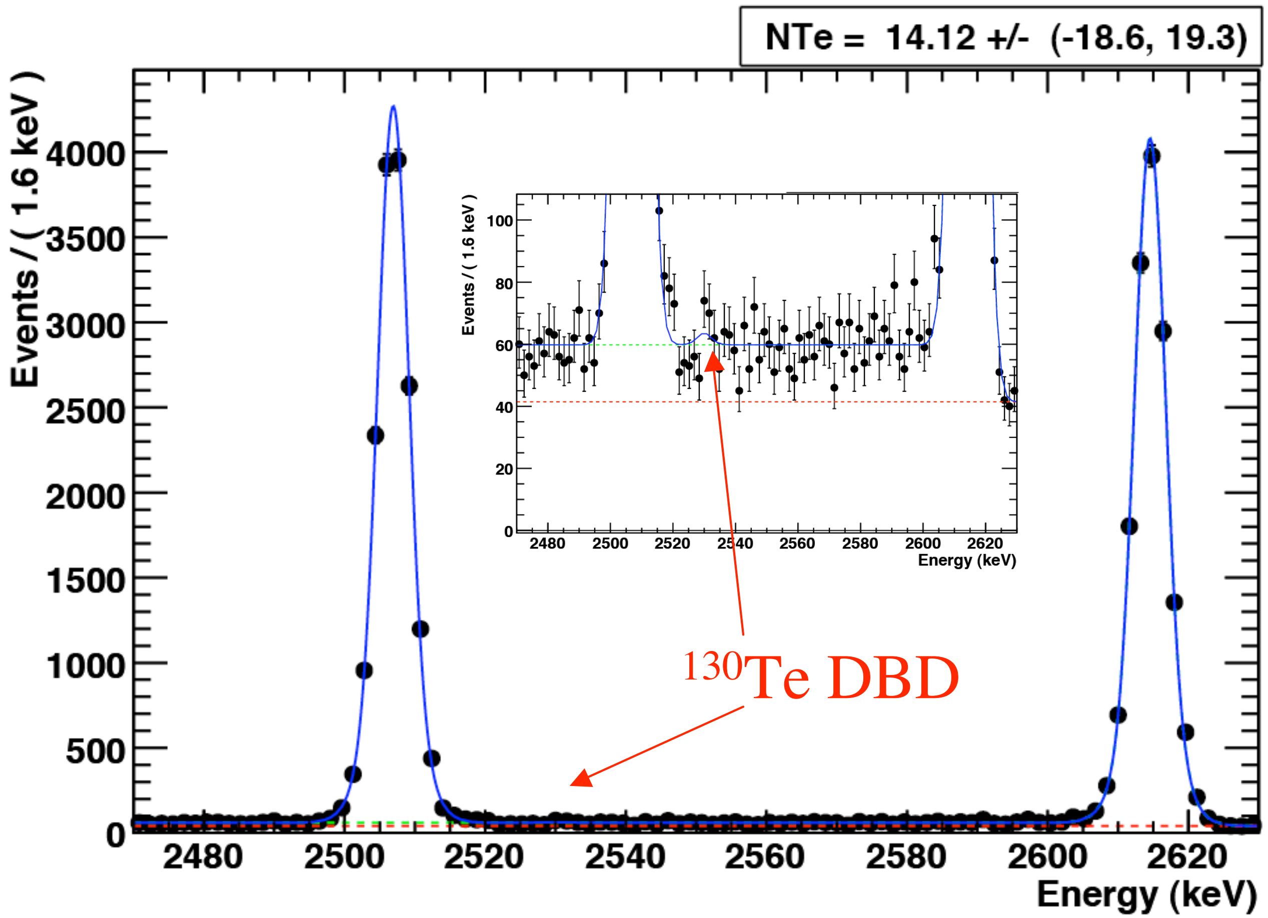


CUORE Sensitivity

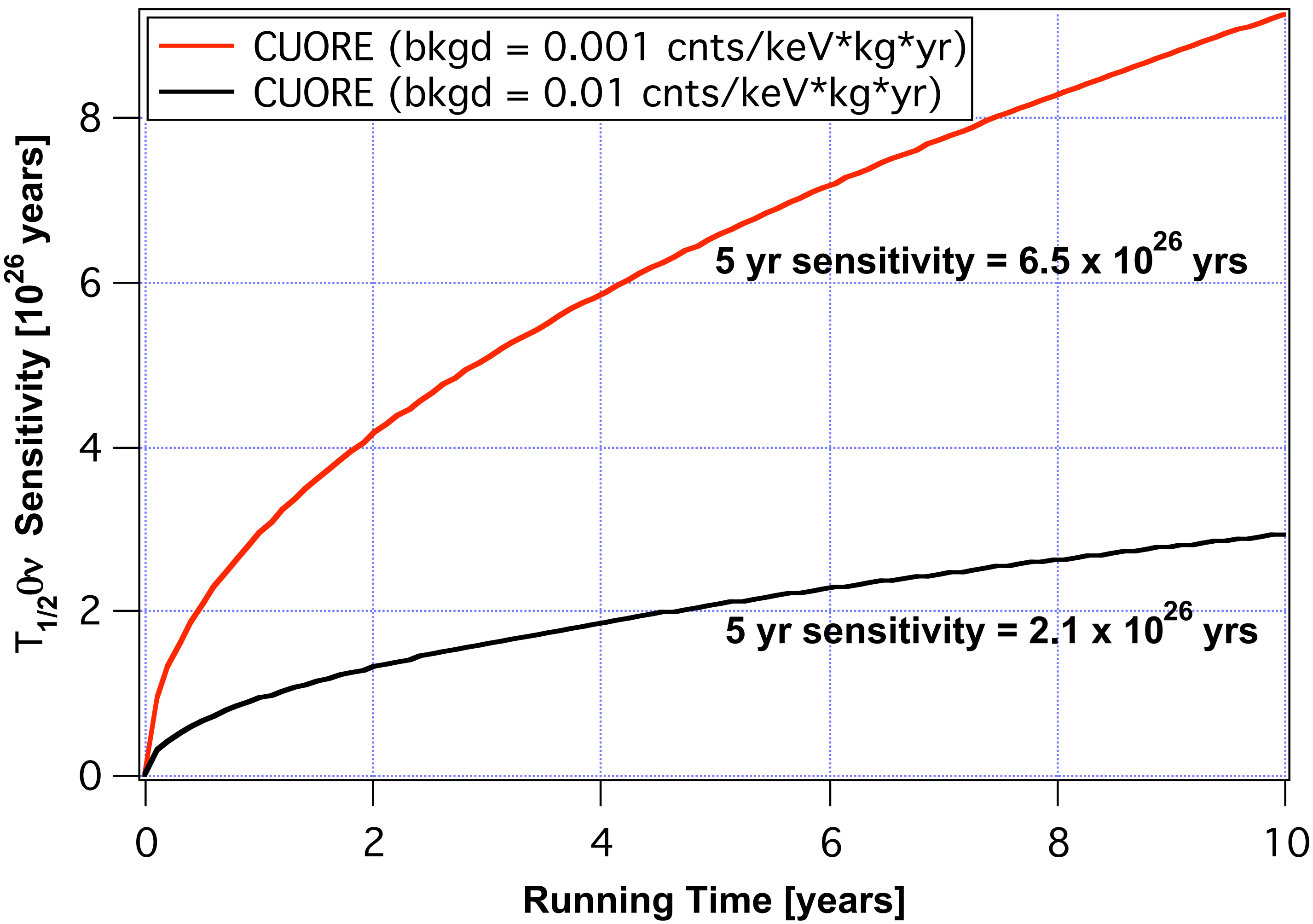
1σ limit: $T_{1/2}=2x10^{26}$ y (=$2000x10^{23}$ y)

Background 0.01 c/keV/kg/year, 5 keV FWHM resolution, 5 years

One possible outcome:



CUORE Sensitivity

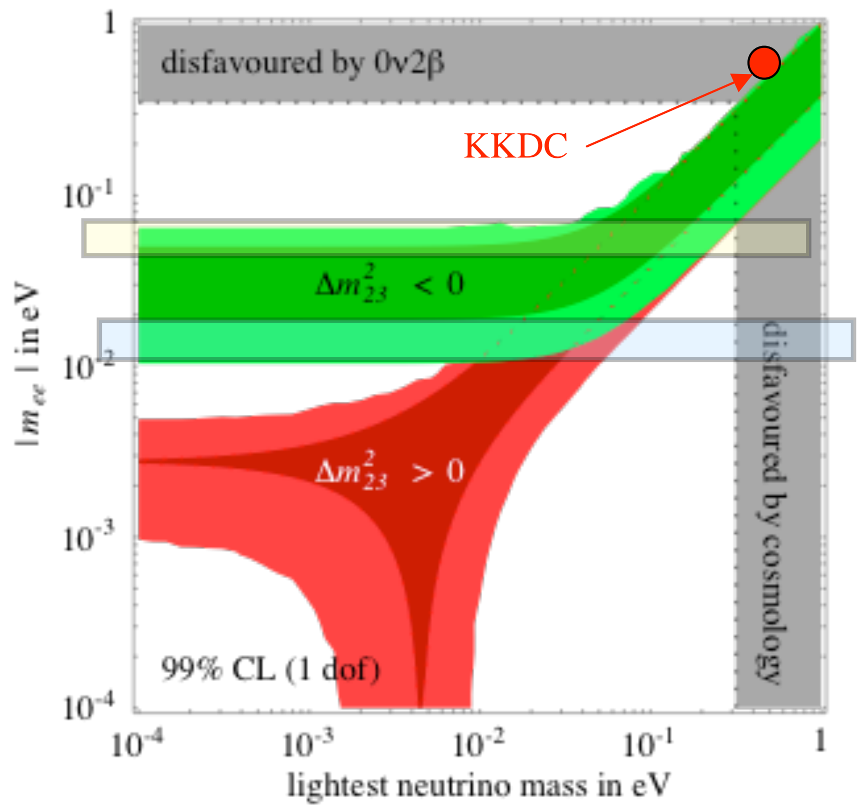


CUORE Sensitivity

Five year 1σ sensitivity based on detector resolution of 5 keV (FWHM), background, and matrix element spread

Background (c/kg/keV/y)	$T_{1/2}$(y)	$\lvert m_\nu \rvert$ (meV)
0.01	2×10^{26}	45…70
0.001	7×10^{26}	14…22

A. Strumia and F. Vissani, hep-ph/0503246



Other Potential Measurements

- Reduction in the background levels, especially at low energy, make other physics measurements possible
  - $2\nu\beta\beta$ in Te (see L.Kogler's talk)
  - Dark matter search a la DAMA
    - Quenching factor of O(1) for bolometers
    - Look for annual modulation of detector rates
    - Requires low energy threshold (10 keV) and energy resolution of 1 keV at low energy
  - Solar axions through Bragg conversion
  - Rare nuclear transitions

Beyond CUORE

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.17\times10^{26}}{n_\sigma}\left(\frac{a\varepsilon}{W}\right)\sqrt{\frac{Mt}{(1+\zeta)b\delta(E)}}$$

- CUORE design is scalable to O(1 ton) detector
  - Relatively inexpensive isotopic enrichment of ^{130}Te
    - > 500 kg of ^{130}Te
    - A factor of 3 increase in *a*
  - Other DBD isotopes can also be used bolometrically
- Additional background suppression
  - Scintillating bolometers
    - See S.Pirro's talk
  - Ionization measurements
  - Surface-sensitive bolometers
  - Pulse shape discrimination through non-equilibrium phonons
- Important direction for future R&D

Conclusions

<u>CUORE</u>

- One of the largest mid-range experiments under construction
- Excellent physics potential
- Construction in progress: expect physics in 2013