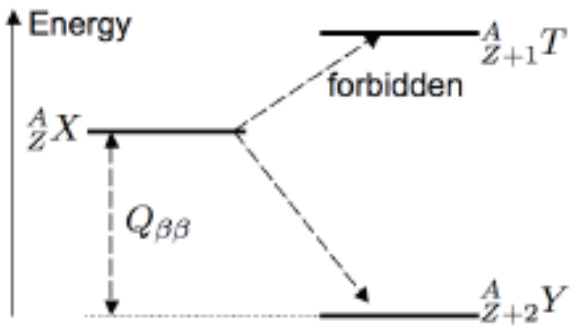
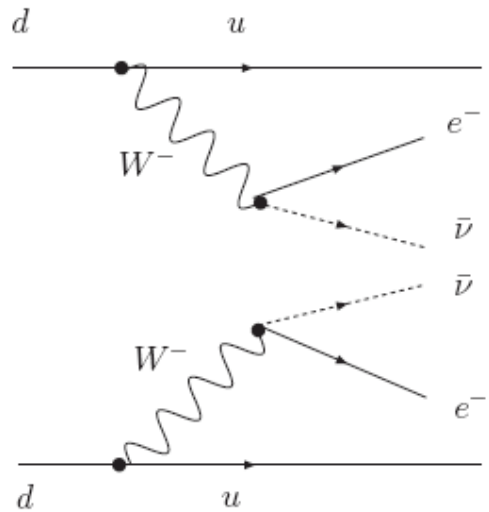
Status of CUORE

Fundamental Symmetries Workshop
August 10, 2012

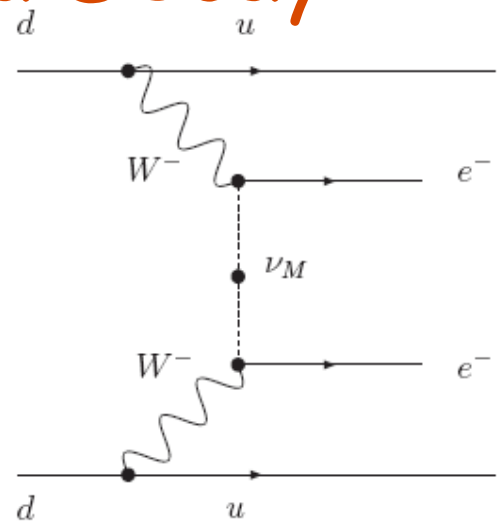
Yury Kolomensky
UC Berkeley/LBNL

Neutrinoless Double-Beta Decay





Standard Model 2νββ decay
$\tau \geq 10^{19}$ y



0νββ $\tau \geq 10^{25}$ y

- Observation of 0νββ would mean
  - Lepton number violation
  - Neutrinos are Majorana particles
  - Rate measures (effective) electron neutrino mass

$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

0νββ Rate and Neutrino Mass

0νββ rate

Phase space $\propto Q^5$

Nuclear matrix element

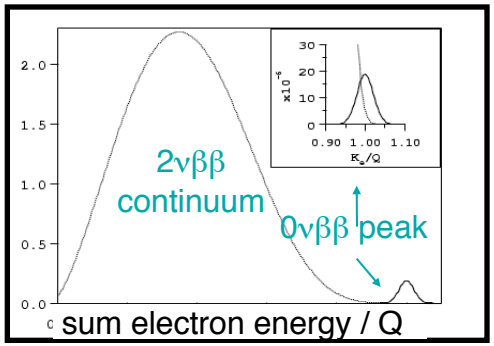
Effective neutrino mass

$$\Gamma = 1/\tau = G_F^2 \Phi(Q,Z)\, |M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$

high Q candidates preferred

large phase space

low background



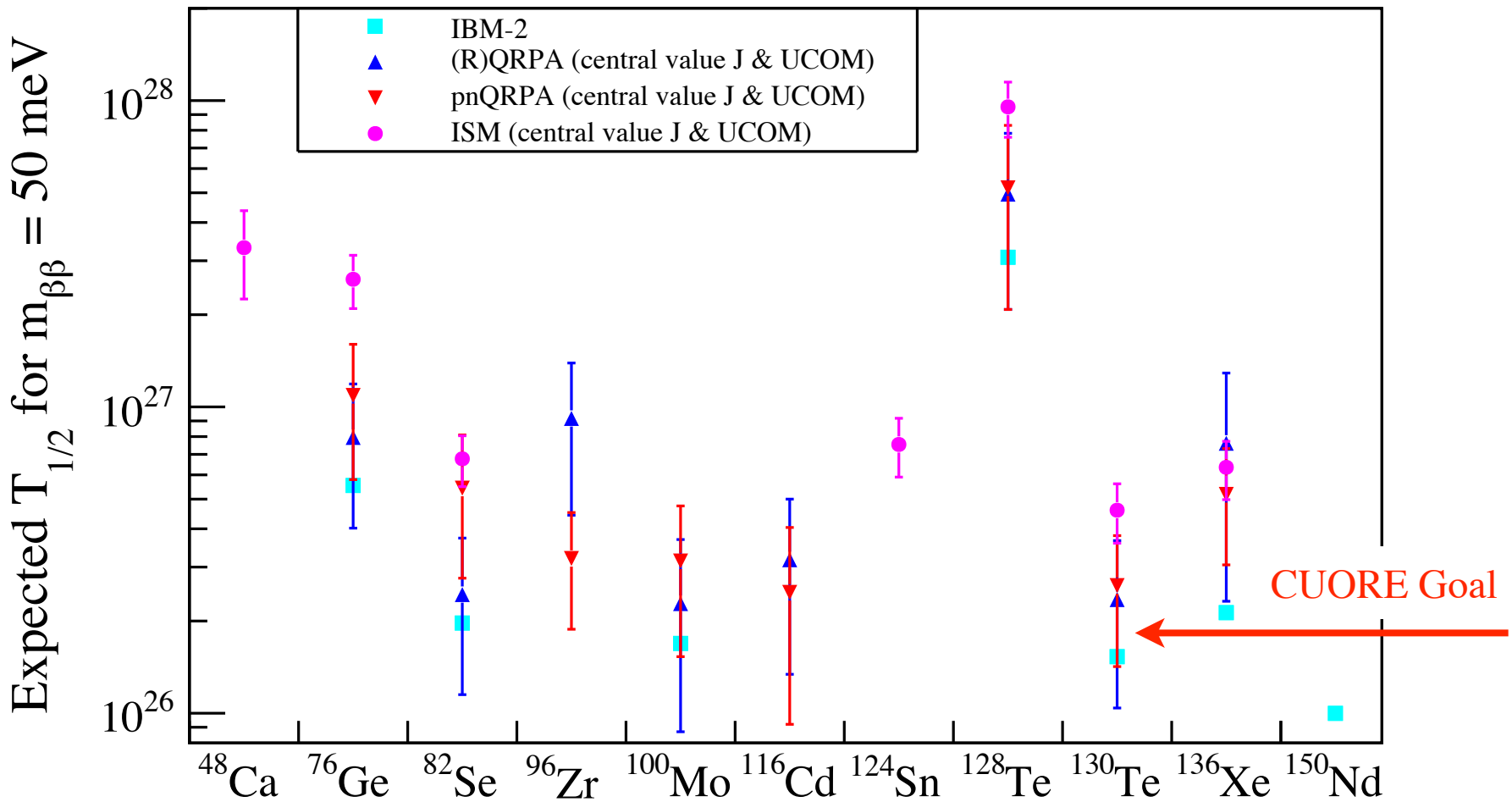
^{238}U γ end at 2.4 MeV

^{232}Th γ end at 2.6 MeV

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

$\tau^{0\nu} \sim 10^{24}$–10^{26} years: large mass and extremely low backgrounds needed (underground labs, ultra purity materials, active rejection of backgrounds)

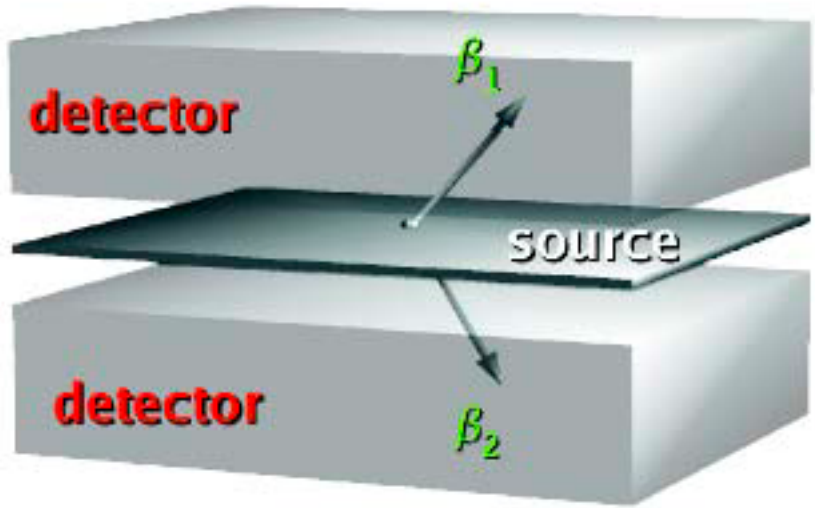
0νββ Isotopes: Required Sensitivity



Two Experimental Techniques

Source external to detector

Ex: NEMO, SuperNEMO, others



+: event topology, background rejection, multiple isotopes possible

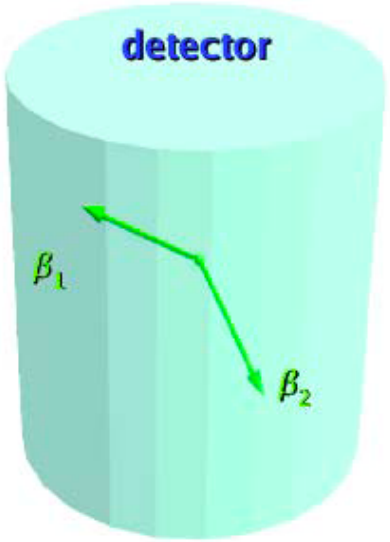
–: detector mass, resolution, acceptance

Technology: typically tracking detectors

May prove invaluable to test models once 0νββ is discovered

Source internal to detector

Ex: Gerda, Majorana, EXO, CUORE, SNO+, KamLAND-Zen, and others



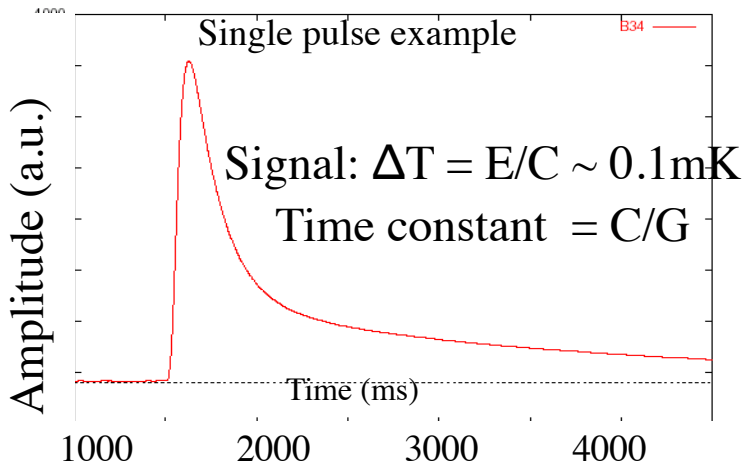
+: detector mass, resolution, acceptance

–: event topology, background rejection

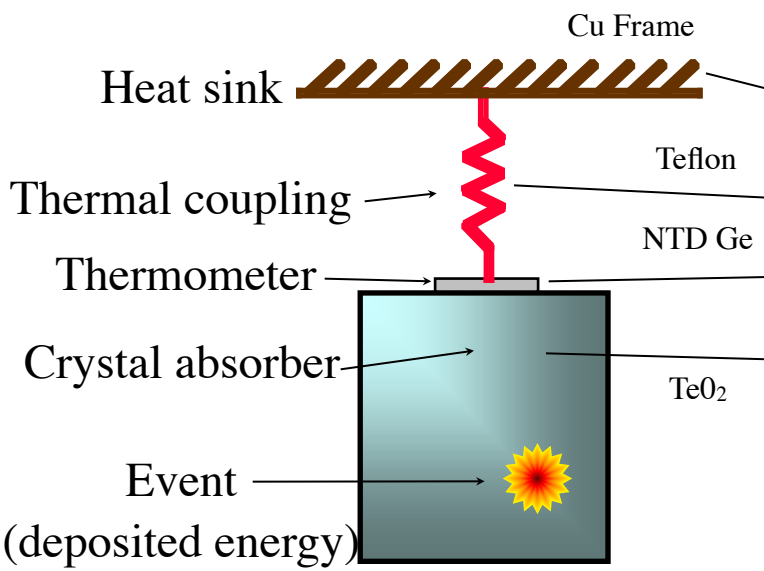
Technology: calorimeters (bolometers, ionization, scintillation), tracking

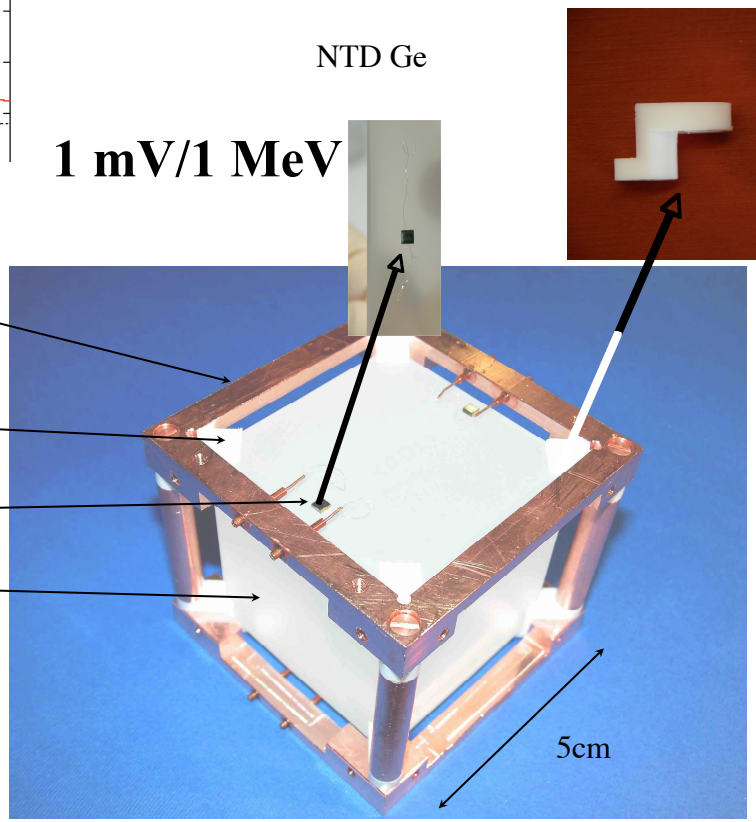
Typically aimed at 0νββ discovery

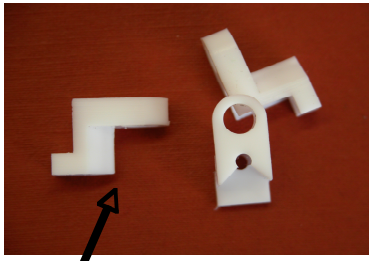
Cryogenic Bolometers



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

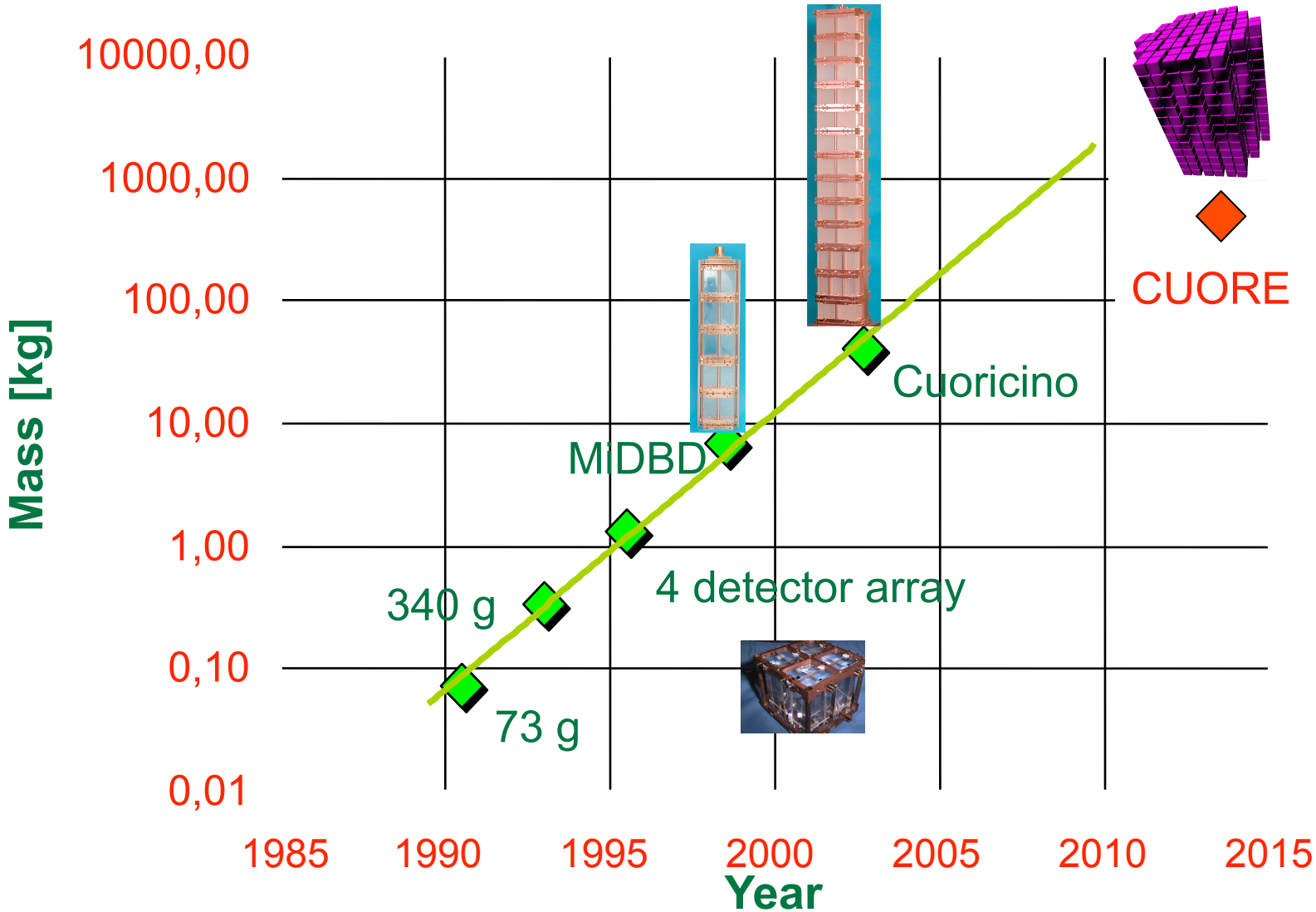






G = 4 pW/mK

TeO_2 Experiments

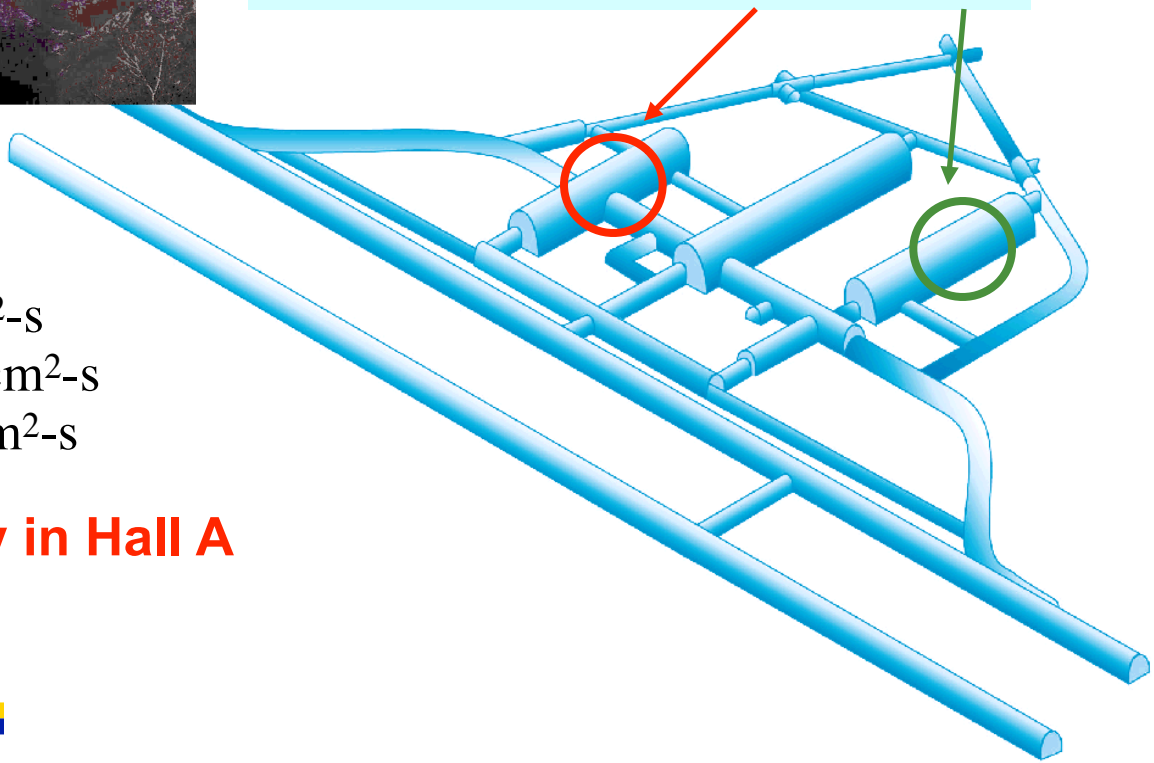


The CUORE Collaboration

SAPIENZA
UNIVERSITÀ DI ROMA

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 ready in Hall A

See B. Plaster's talk on facilities

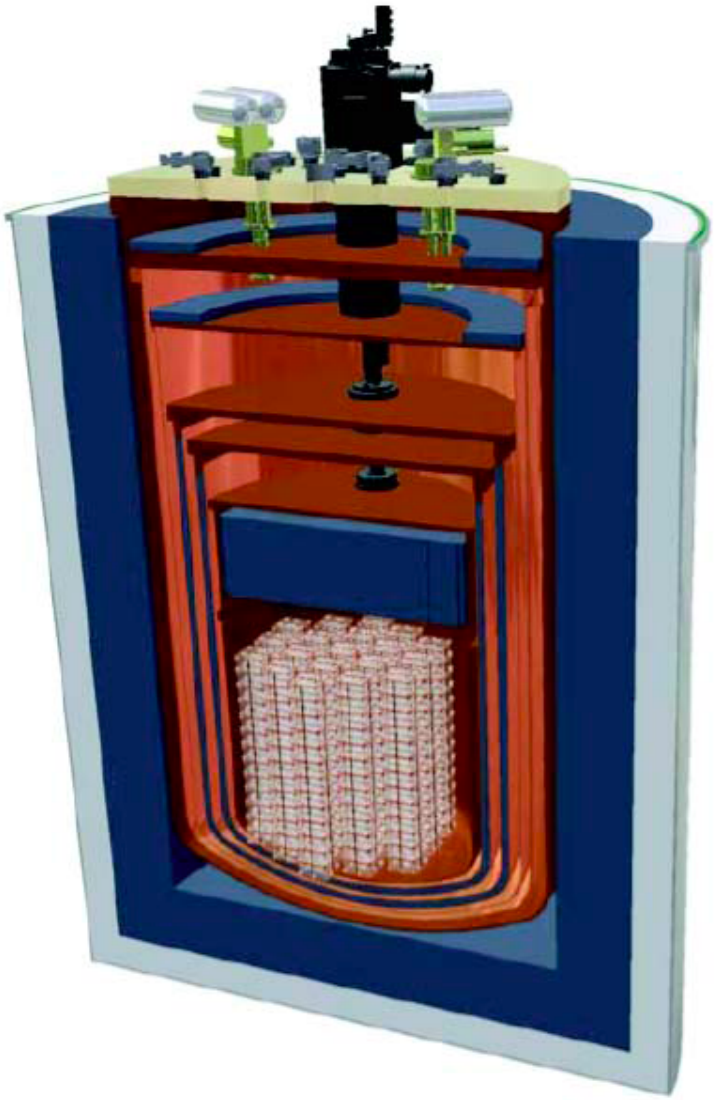
CUORE

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% natural isotope abundance

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

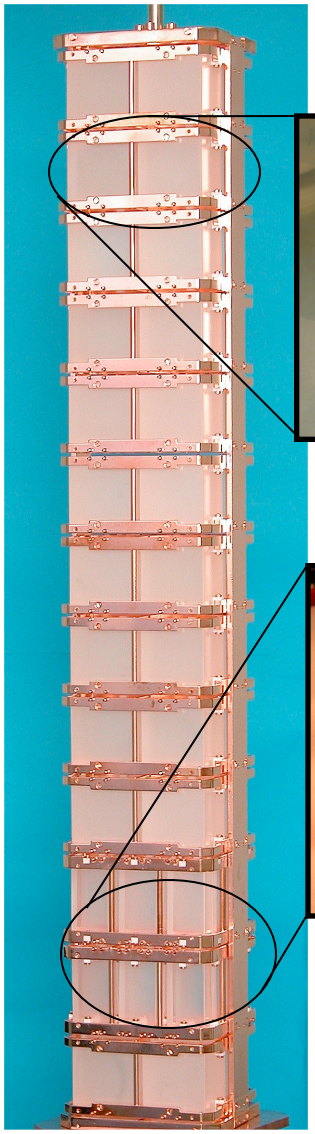
- New pulse tube refrigerator and cryostat
- Radio-purity techniques and high resolution achieve low backgrounds
- Joint venture between Italy (INFN) and US (DOE, NSF)
- Under construction (expected operations by end of 2014)
- Inexpensive ($10M US contribution); opportunities to probe multiple isotopes & upgrade to 1 ton scale

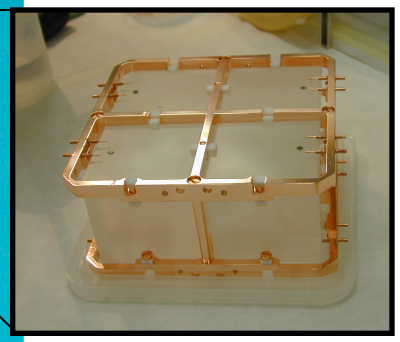


Cuoricino, the prototype for CUORE

Gran Sasso National Lab (Italy)

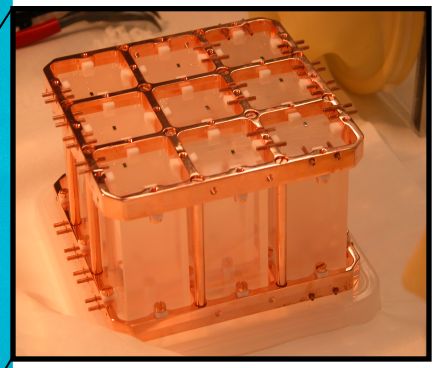
Bolometer detectors
Cooled to 10mK





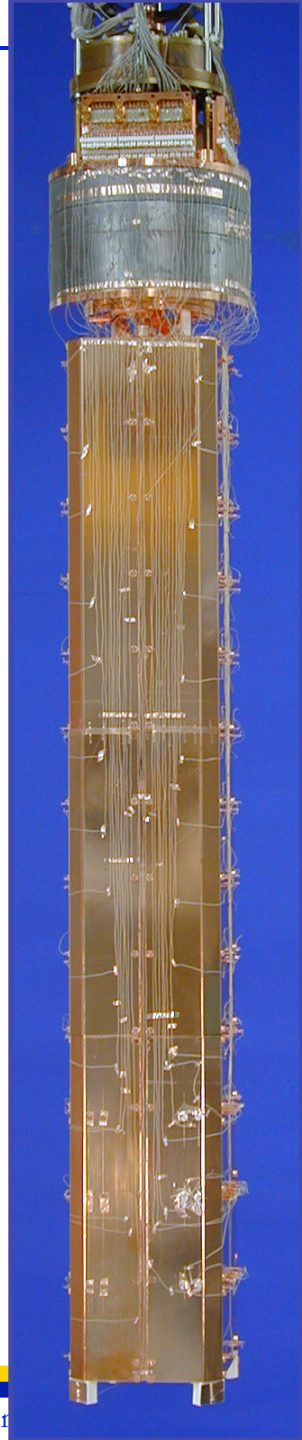
11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 790 g
44 x 0.79 = 34.76 kg of TeO_2

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**

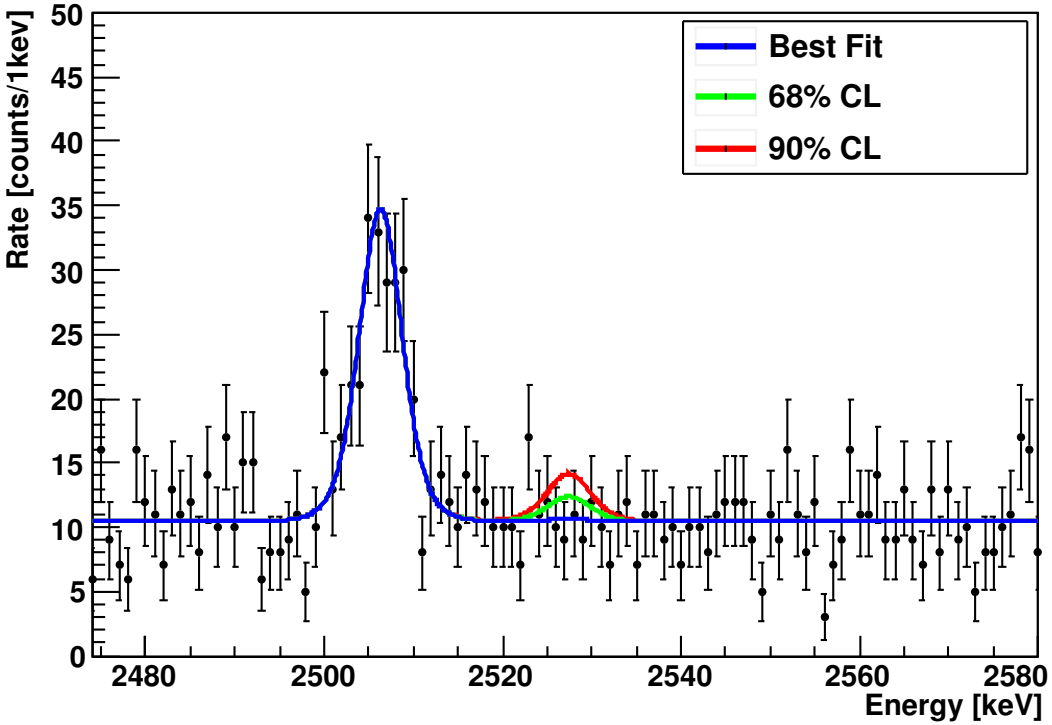


Cuoricino Results (2010)

Exposure
= 19.6 kg y

Resolution:
FWHM at 2615 keV ~7 keV

Background:
In the ββ0ν region (large crystals)
= 0.153 ± 0.006 counts /(keV kg y)



E. Andreotti et al., Astr. Phys. **34**, 822 (2011)

No peak found

$\tau^{0\nu}_{1/2} > 2.8\times10^{24}$ y at 90% C.L.

$m_{\beta\beta} < 0.3 - 0.7$ eV

Spread is due to a range of published matrix elements

From Cuoricino to CUORE

Standard sensitivity for a counting analysis:

Efficiency

Detector mass (kg)

Isotopic abundance

Exposure time (y)

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

Desired sensitivity

Atomic weight

SNR

ROI (keV)

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)
- ✓ Most improvements demonstrated in dedicated R&D

Background Reduction

Background model: CUORICINO

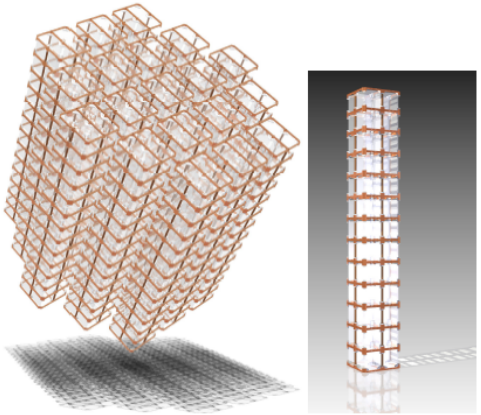
- (40±10)% in ββ0ν region from ^{208}Tl at 2615 keV
- α and β from inert material facing detector (e.g. Cu): (50±20)%
- α and β from surface contamination of crystals: (10±5)%
- Negligible contributions from neutrons and ^{60}Co at 2505 keV

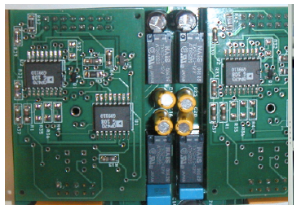
CUORE strategy:

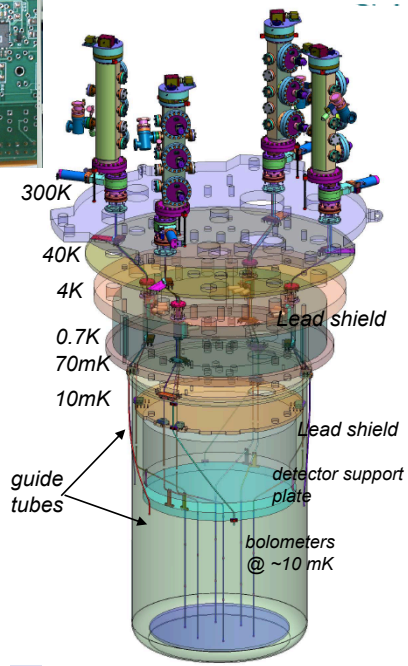
- improve shields & material quality
- improve bulk contamination in TeO_2 (SICCAS)
- reduce surface contribution from
  - TeO_2 crystals
  - components facing TeO_2 crystals (mainly copper)
- increased coincidence efficiency to reject surface background events
- Overall goal: 0.01 c/y/kg/keV

US Contributions to CUORE

- DOE-NP + NSF
- Detector
  - 500 TeO_2 crystals procured @ SICCAS (China)
  - 1200 NTD thermistors
  - Detector assembly and integration
- Electronics (NSF contribution)
- Calibration system
  - Internal to cryostat: careful cryogenic design
  - Energy scale uncertainty goal < 0.05 keV in $0\nu\beta\beta$ region
- Anti-radon system
- DAQ and analysis tools, farm
- Data analysis

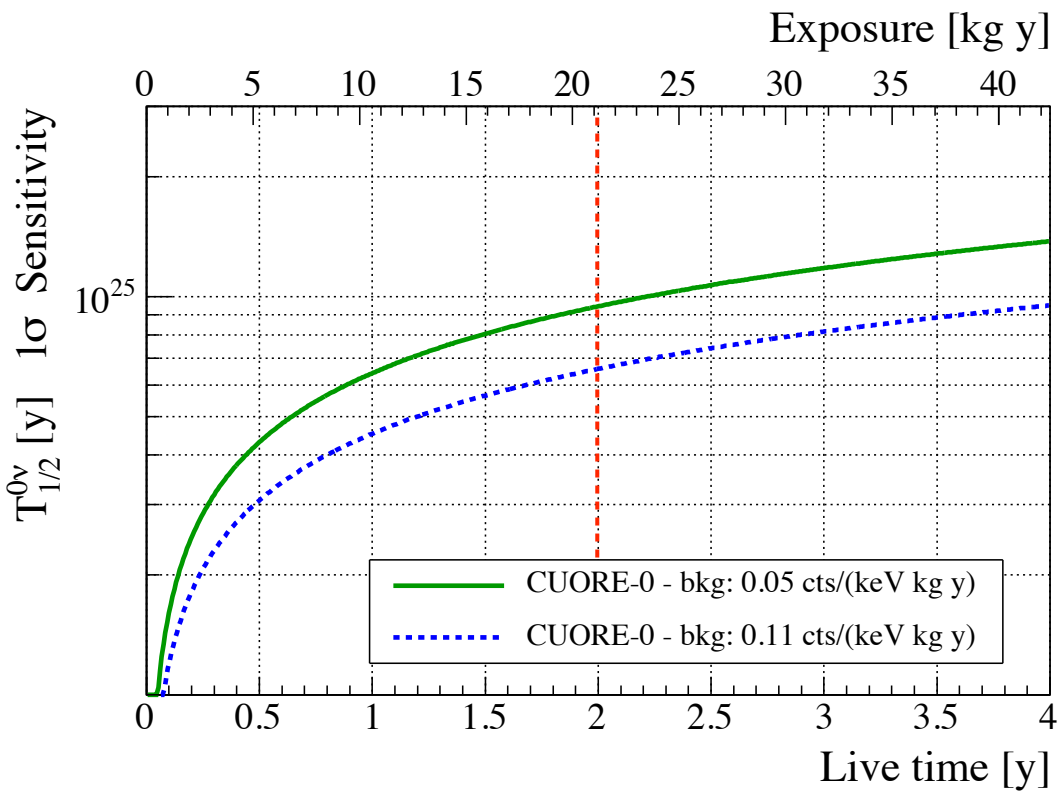


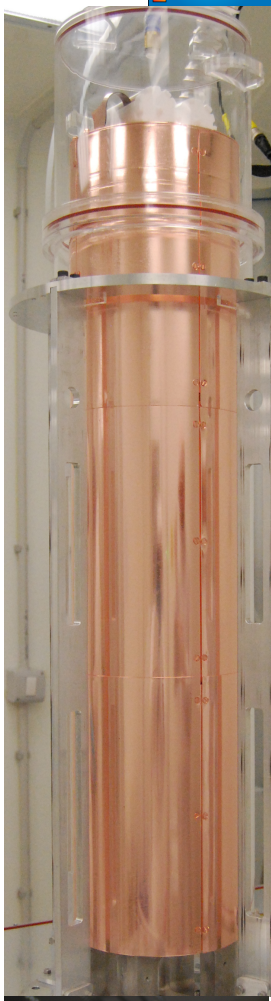




CUORE-0

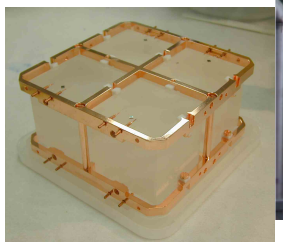
- 1 full tower of CUORE (52 crystals), to be operated in Cuoricino cryostat starting ~now
  - Final "dry run" for cleaning, assembly procedures
  - Bonus: better science reach than Cuoricino
    - ☞ Status: assembled, installed, and cooling down

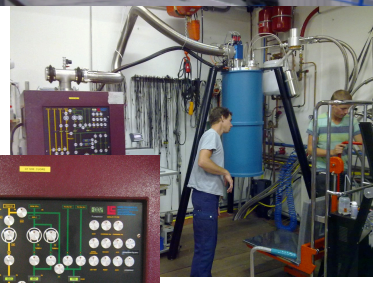


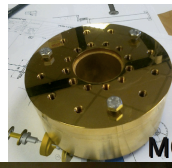


CUORE Status

- Dedicated site in Hall A
  - ☞ Detector assembly in a clean room above cryostat to start in Fall 2012
- Cryostat delivered
  - ☞ Dilution unit designed in Leiden and meets specs, testing at LNGS in progress
- Crystal delivery on schedule
  - ☞ From SICCAS (China)
- NTD production on schedule
  - ☞ Irradiation complete, 1200 NTDs being produced
- Electronics designed and being procured
  - ☞ Testing at UCLA







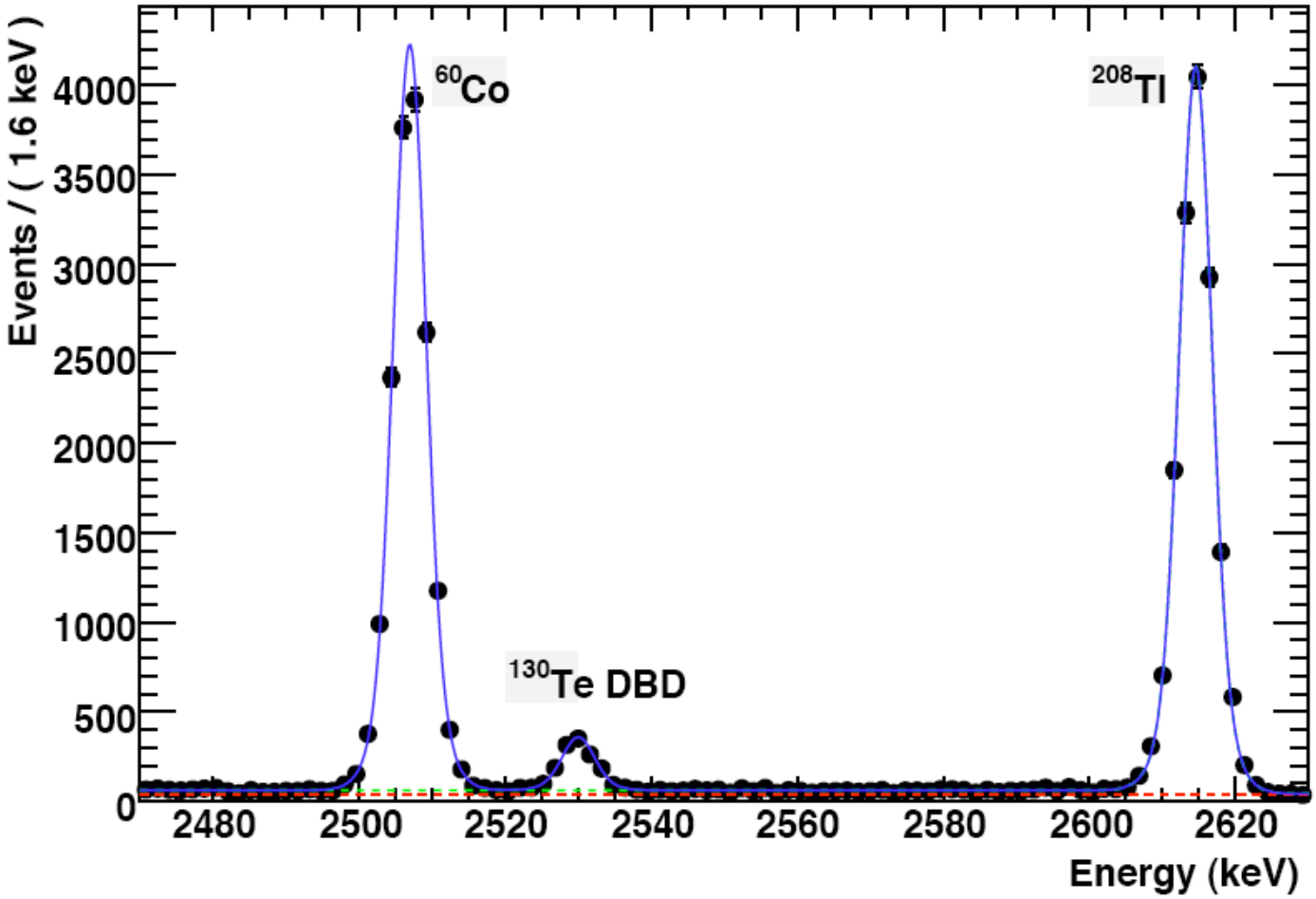
CUORE Discovery Potential

Assume KKDC result: $T_{1/2}=25\times10^{23}$ 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

One possible outcome:



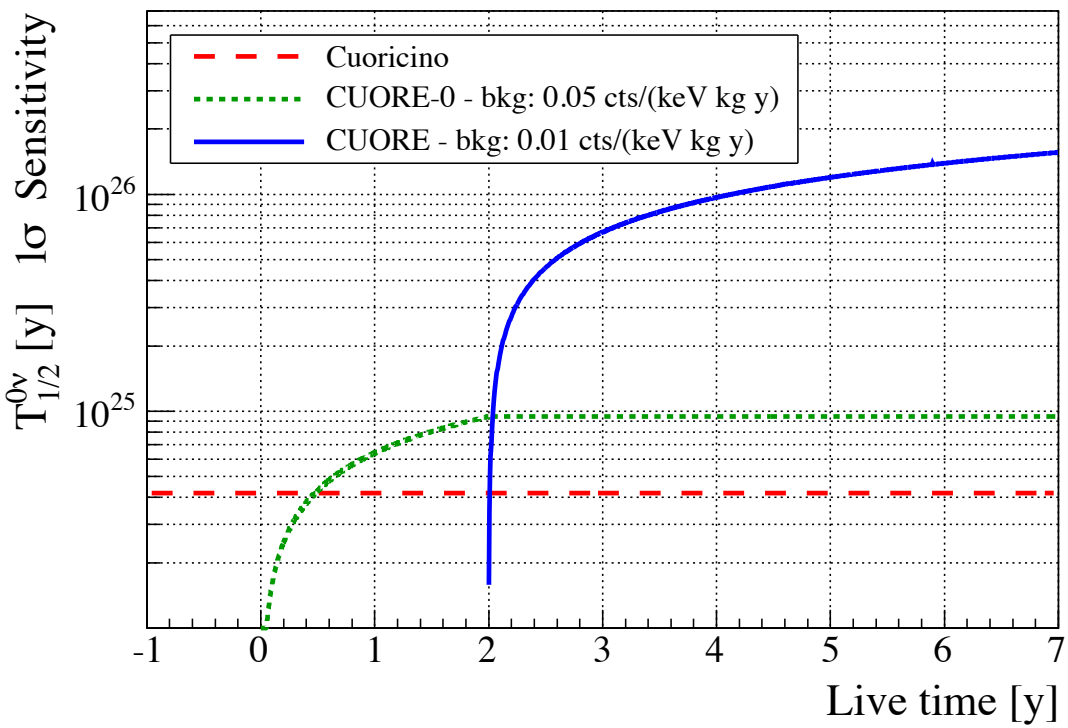
CUORE Sensitivity

5 year sensitivity

Setup	t (y)	b (cts/(keV kg y))	$\widehat{T^{0\nu}_{1/2}}(1\sigma)$ (y)	$m_{\beta\beta}$ (meV) QRPA-F	QRPA-S	ISM	IBM
CUORE-0	2	0.05	9.4×10^{24}	170–310	190–320	310–390	200
	zero-bkg. case at 68% C.L.:		5.3×10^{25}	*70–130*	*81–130*	*130–160*	*85*
CUORE baseline	5	0.01	1.6×10^{26}	41–77	48–78	76–95	50
	zero-bkg. case at 68% C.L.:		2.5×10^{27}	*10–19*	*12–19*	*19–24*	*12*

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

First tower (CUORE-0) to be operated until the start of CUORE.

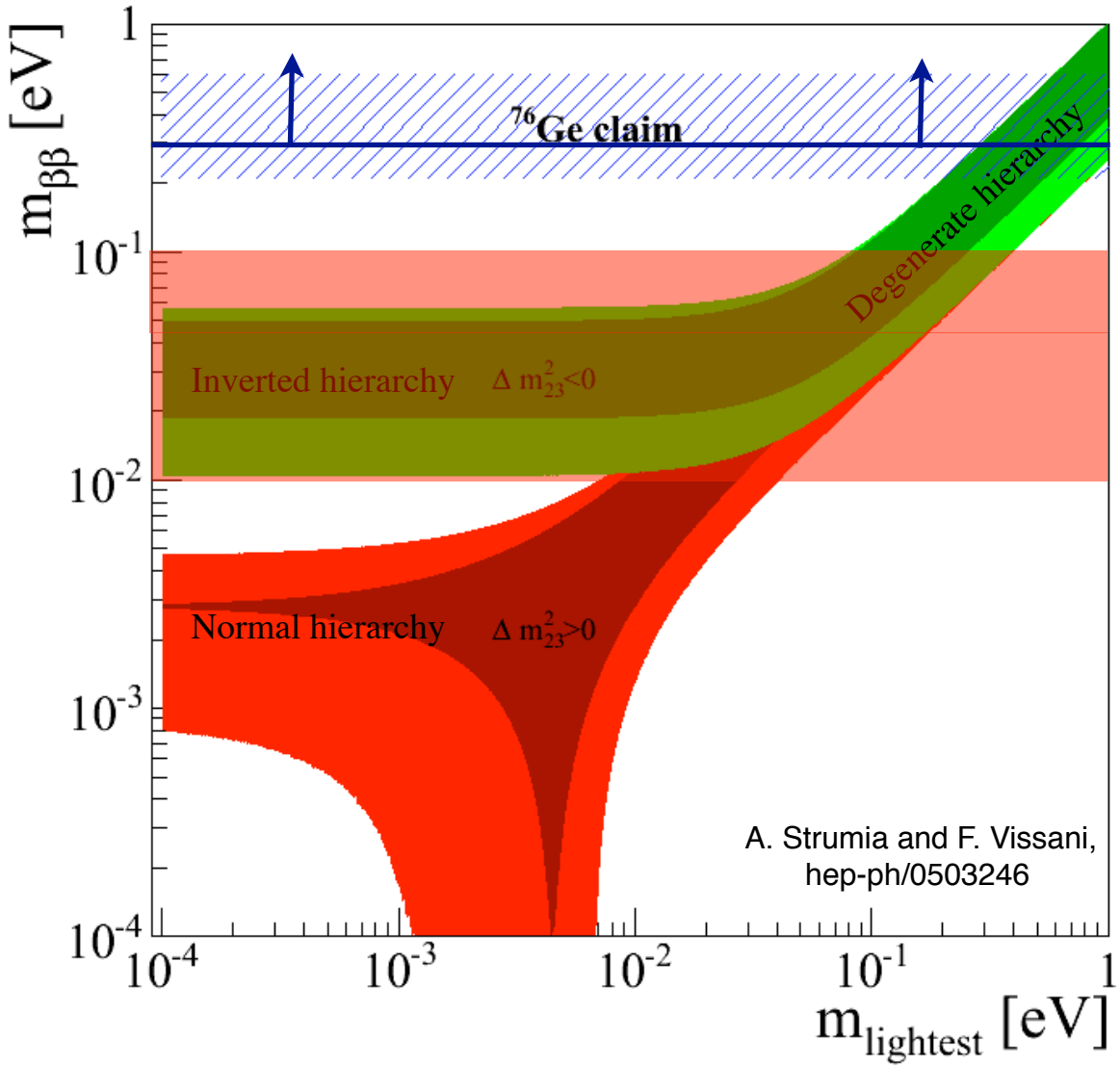


Beyond CUORE

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

- 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
  - Ionization measurements
  - Surface-sensitive bolometers
  - Pulse shape discrimination through non-equilibrium phonons
- Important direction for future R&D
  - Efforts in the US and Italy underway

DBD and Neutrino Mass



Recent constraints (CUORICINO, NEMO-3, KamLand-Zen, EXO)

CUORE goal

SuperCUORE ?

$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

Other Measurements with CUORE

- Reduction in the background levels, especially at low energy, make other physics measurements possible
  - 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
  - Supernova watch
  - Rare nuclear transitions

0νββ: one of the top priorities in neutrino physics

- Probe Majorana nature of neutrinos and the absolute scale of neutrino mass
- CUORE: one of the leading DBD experiments in near future; to start operations in 2014
- Will start probing inverted hierarchy
- Upgrade path to 1 ton scale experiment to cover the inverted hierarchy

→ Stay tuned !

Backup

Experimental Sensitivity

Standard sensitivity for a counting analysis (nonzero background):

Efficiency

Detector mass (kg)

Isotopic abundance

Exposure time (y)

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

Desired sensitivity in σ

ROI (keV)

Atomic weight

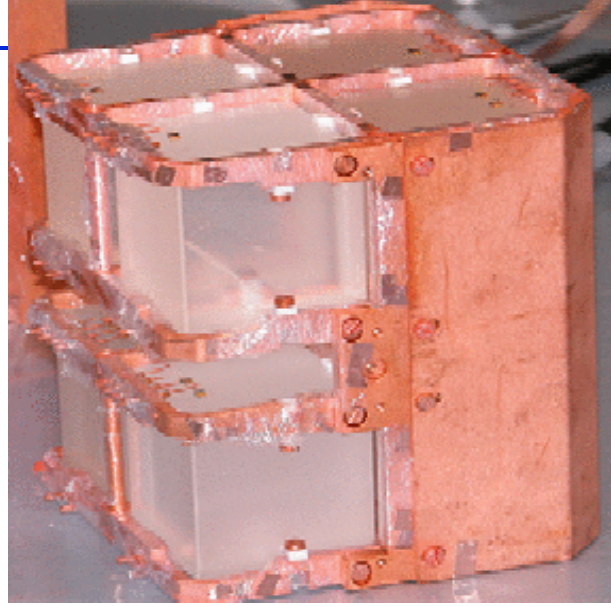
SNR (assume 0)

Background (c/kg/y/keV)

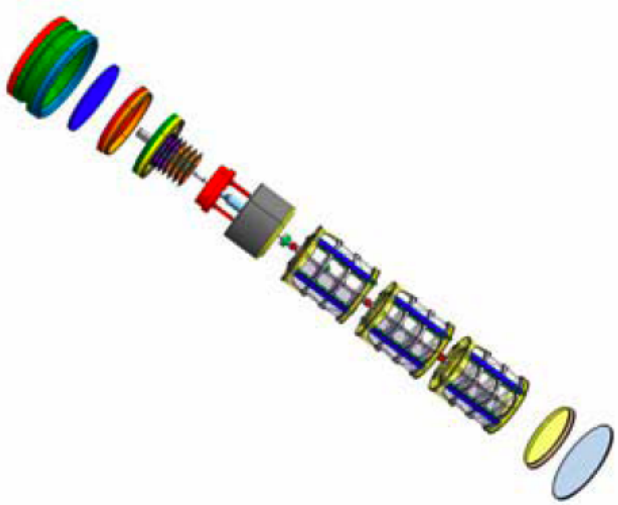
Experimental challenge:

- ✓ Increase *M* as high as possible (200-1000 kg for current experiments): $$, R&D
- ✓ Increase *a*: $$
- ✓ Decrease *b* as much as possible (to 2νββ limit): radio purity, active rejection
- ✓ Decrease δ (highest resolution possible): technology choice

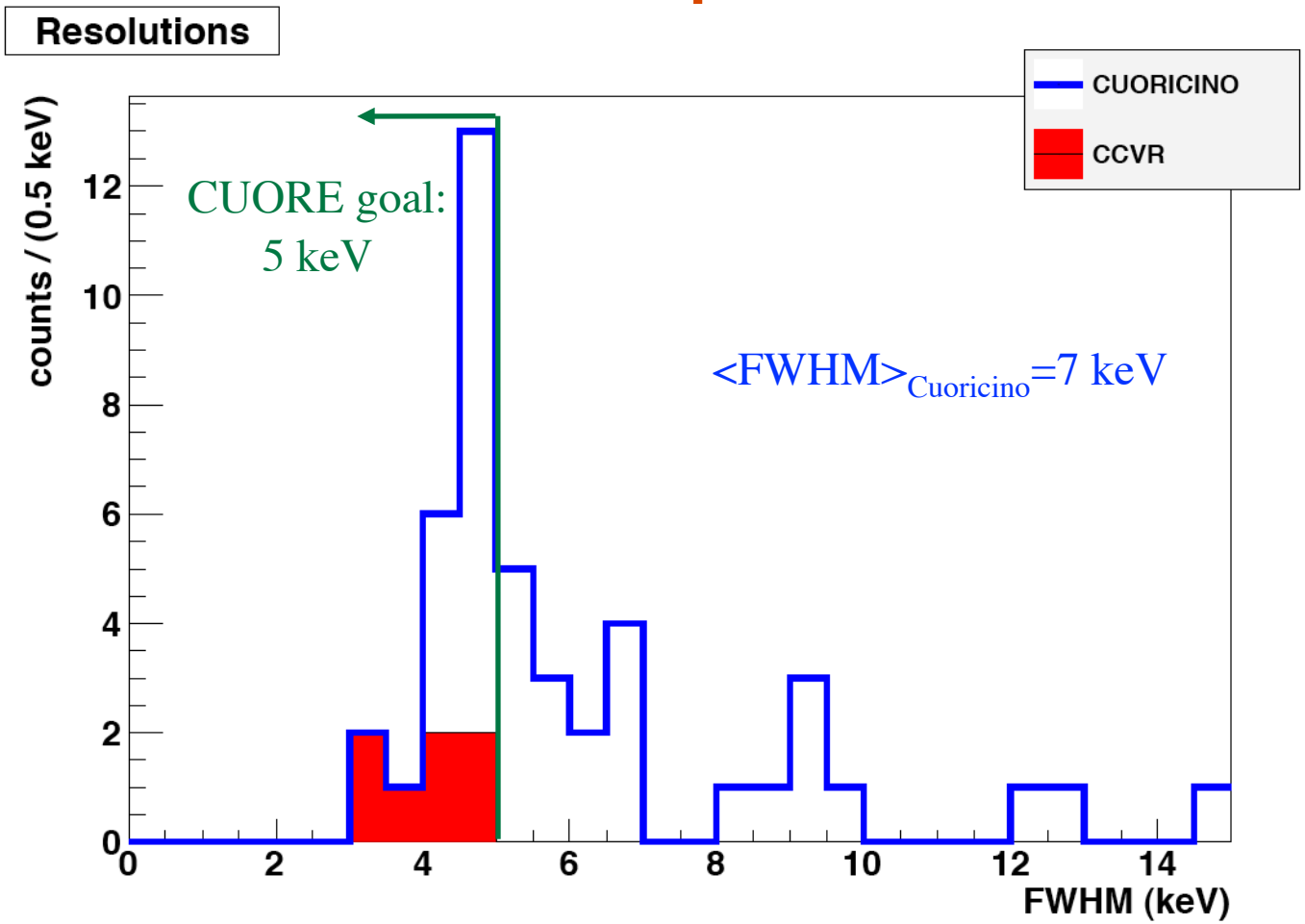
Test Facilities



- 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)



Resolution Improvements



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