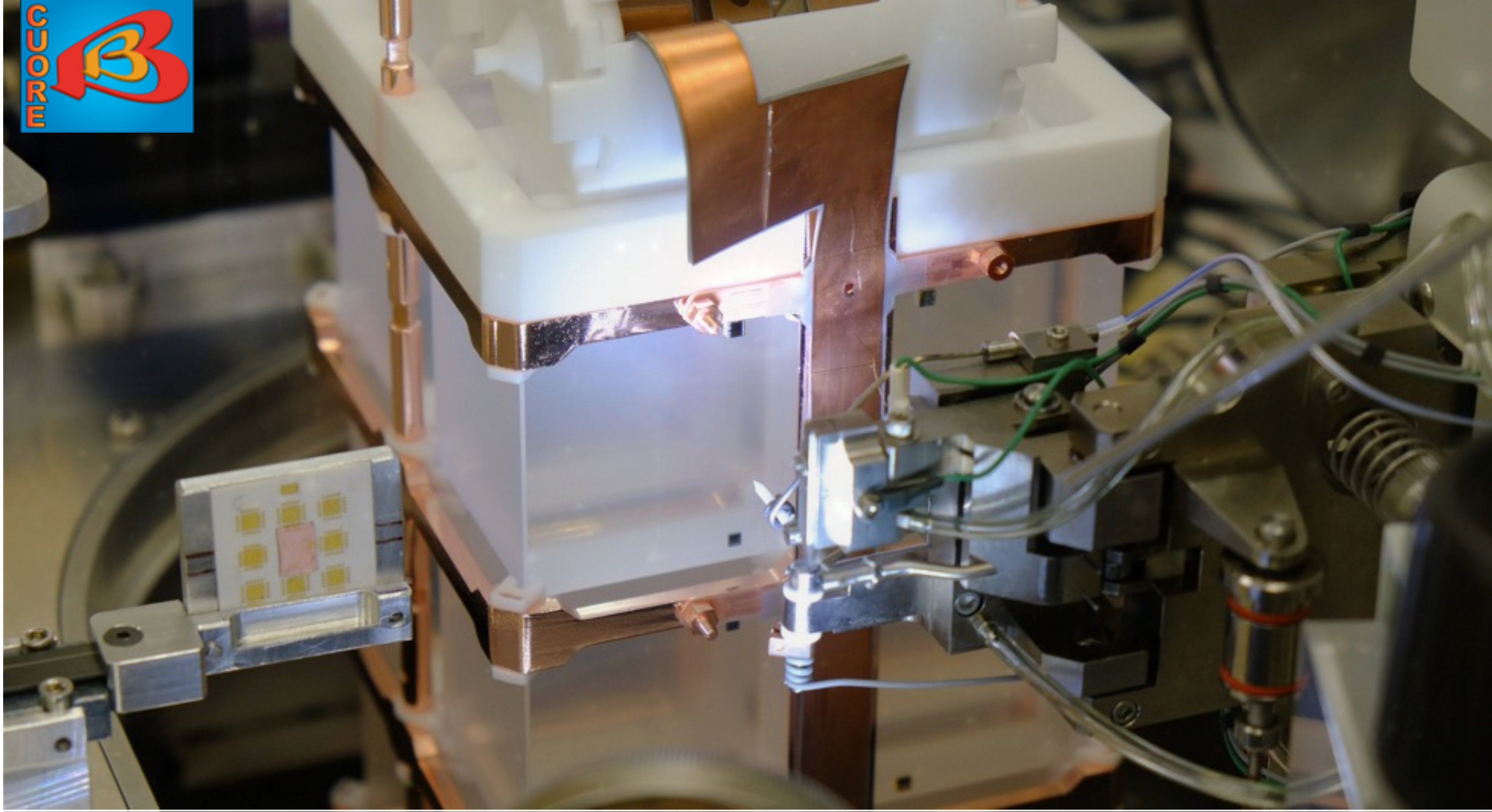


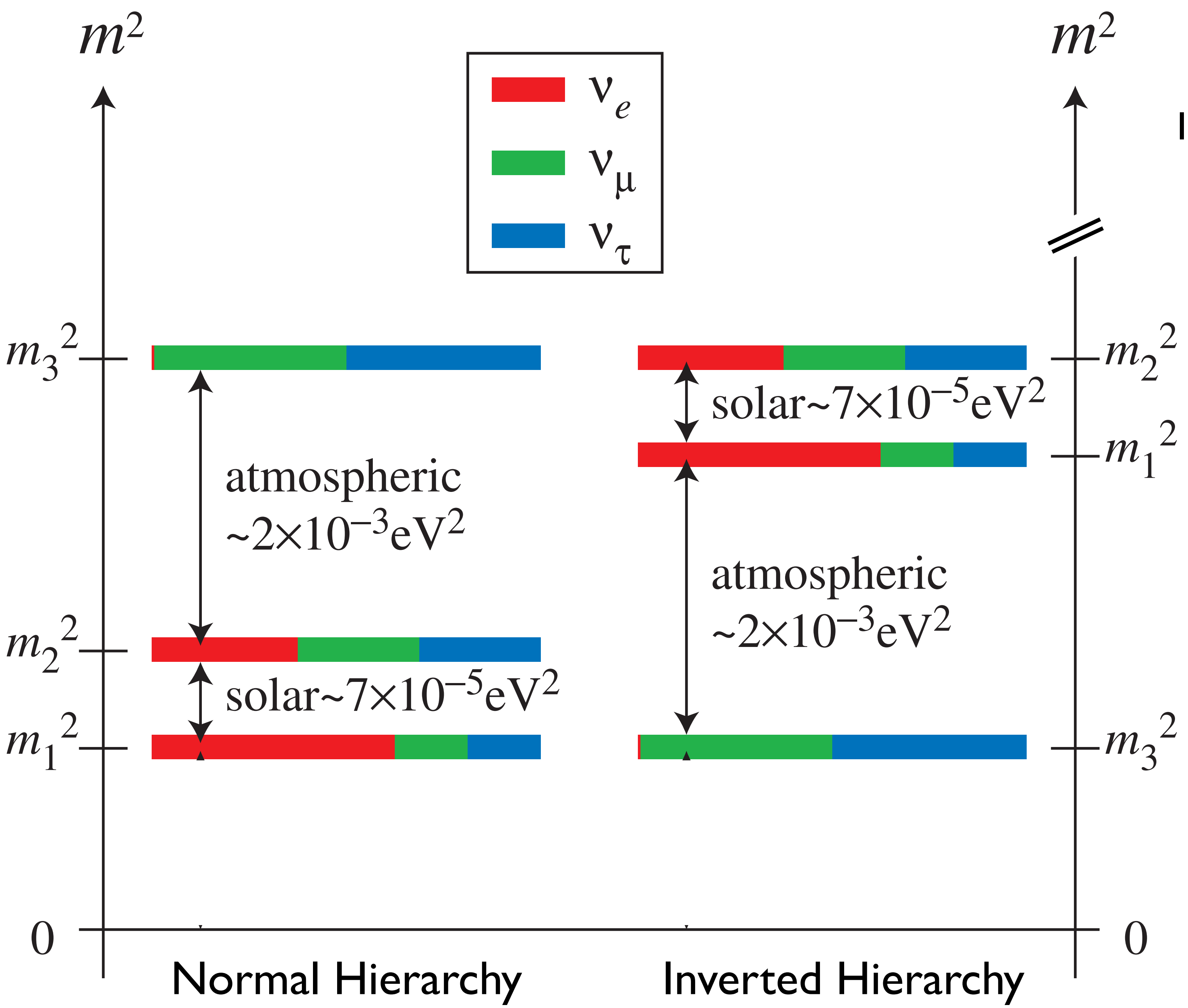
Results from the search for neutrinoless double-beta decay of Te-130 with CUORE-0

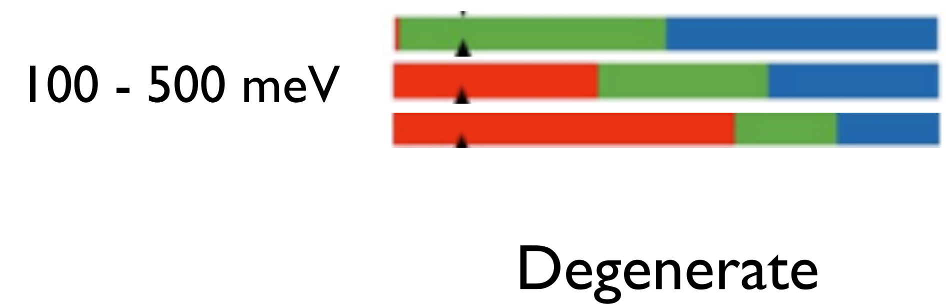
Kyungeun E. Lim (on behalf of the CUORE collaboration)

Apr. 14, 2015, LNS Seminar, MIT

What we know about Neutrinos

Neutrino Mass Splitting

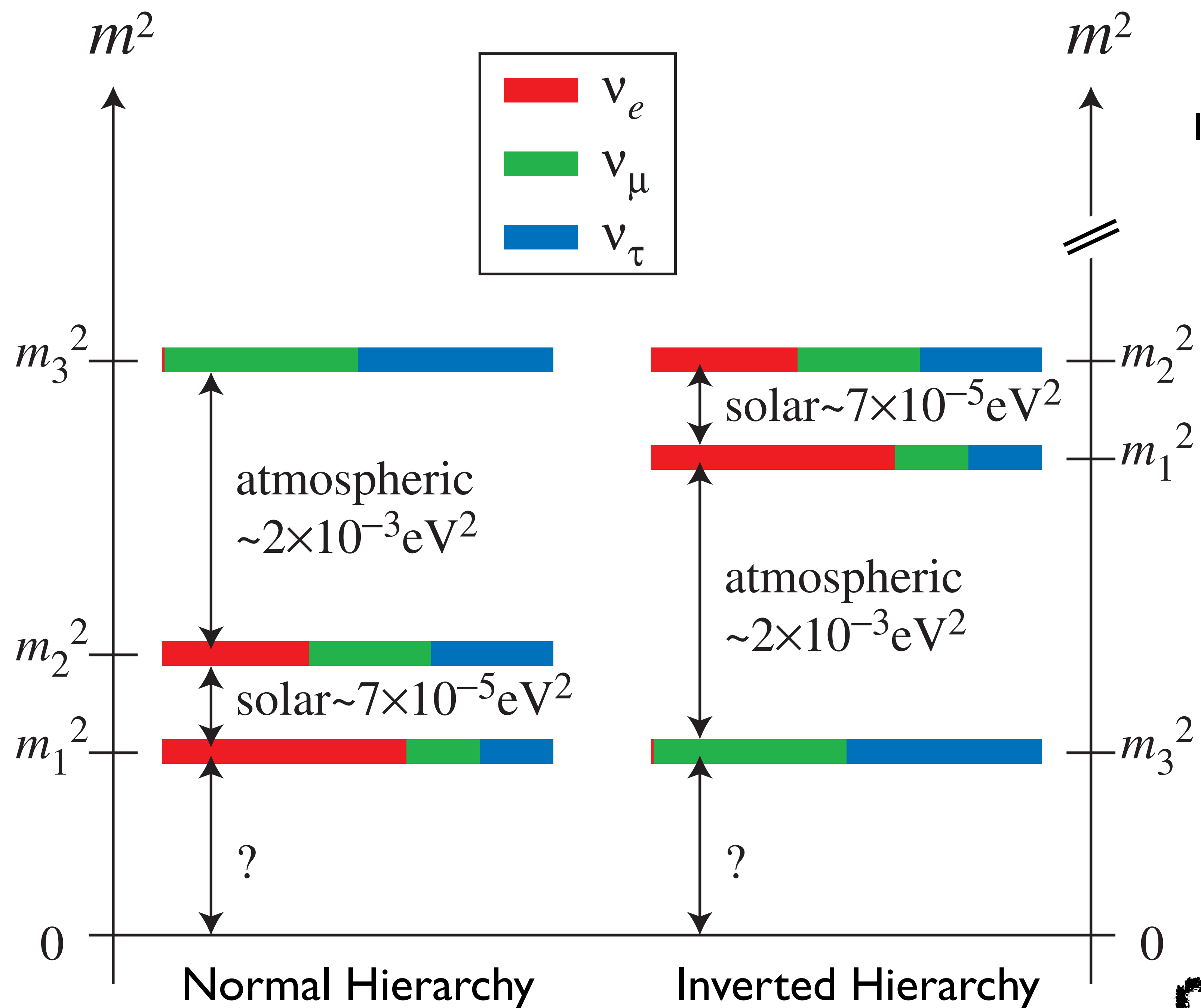


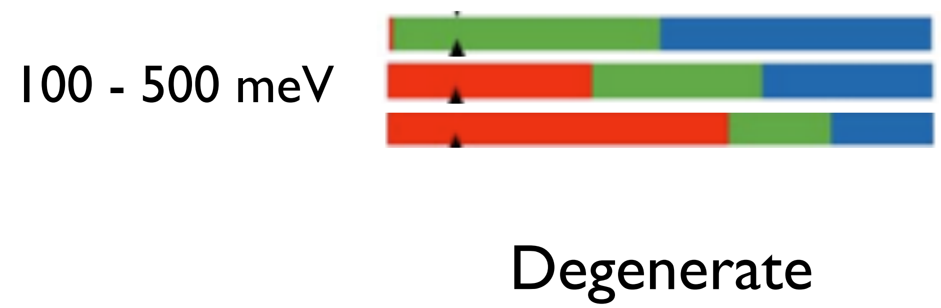


Rep. Prog. Phys. 76, 056201 (2013)

What we don't know about Neutrinos

Neutrino Mass Splitting





Rep. Prog. Phys. 76, 056201 (2013)

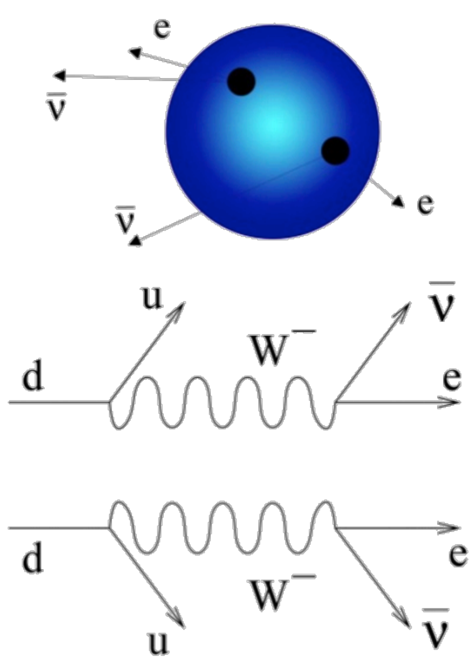
Is the neutrino its own antiparticle?

Outline

- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE : An array of TeO_2 bolometers
- CUORE-0 : $0\nu\beta\beta$ search w/ a single CUORE tower
    - CUORE-0 : Detector
    - CUORE-0 : Performance and Background
    - CUORE-0 : Results
- Summary

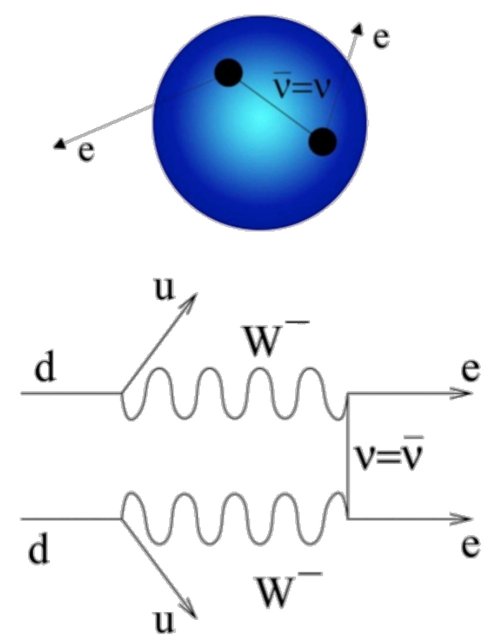
Neutrino(less) double-beta decay

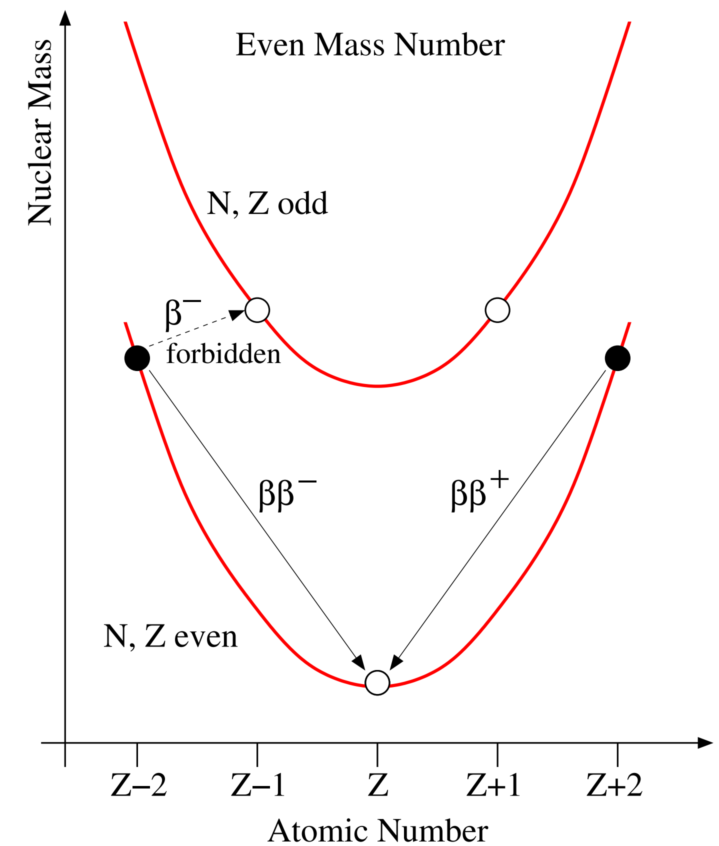
- $2\nu\beta\beta$



- Allowed in SM
- Observed in several nuclei ($T_{1/2}^{2\nu} \sim 10^{18}$-$10^{21}$ yr)

- $0\nu\beta\beta$





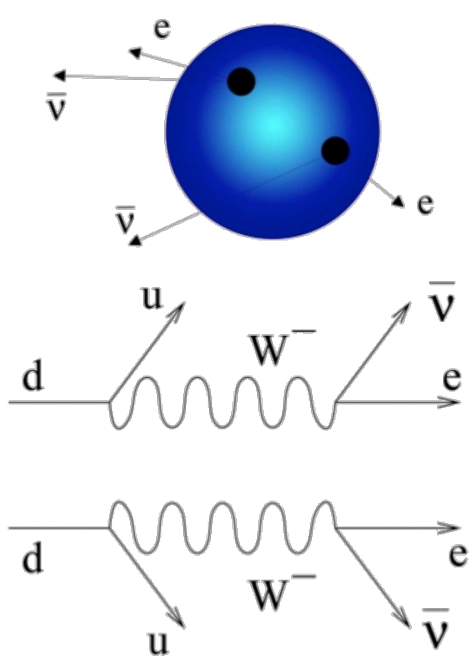
- Beyond SM
- Hypothetical process only if $\nu = \overline{\nu}$ and $m_\nu > 0$

Observation of 0νββ

1. will establish that neutrinos are Majorana Particles ($\nu = \overline{\nu}$)
2. demonstrate lepton number is not a symmetry of nature
3. will provide indirect info about the ν mass
4. may provide info about the mass hierarchy in combination with direct neutrino mass measurement

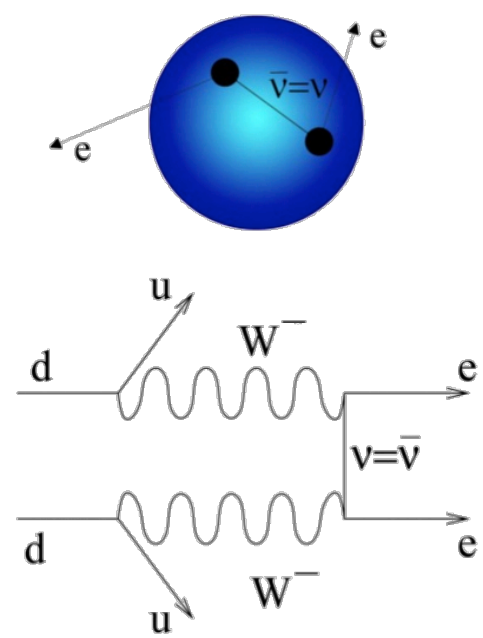
Neutrino(less) double-beta decay

- $2\nu\beta\beta$



- Allowed in SM
- Observed in several nuclei ($T_{1/2}^{2\nu} \sim 10^{18}$-$10^{21}$ yr)

- $0\nu\beta\beta$



- Beyond SM
- Hypothetical process only if $\nu = \bar{\nu}$ and $m_\nu > 0$

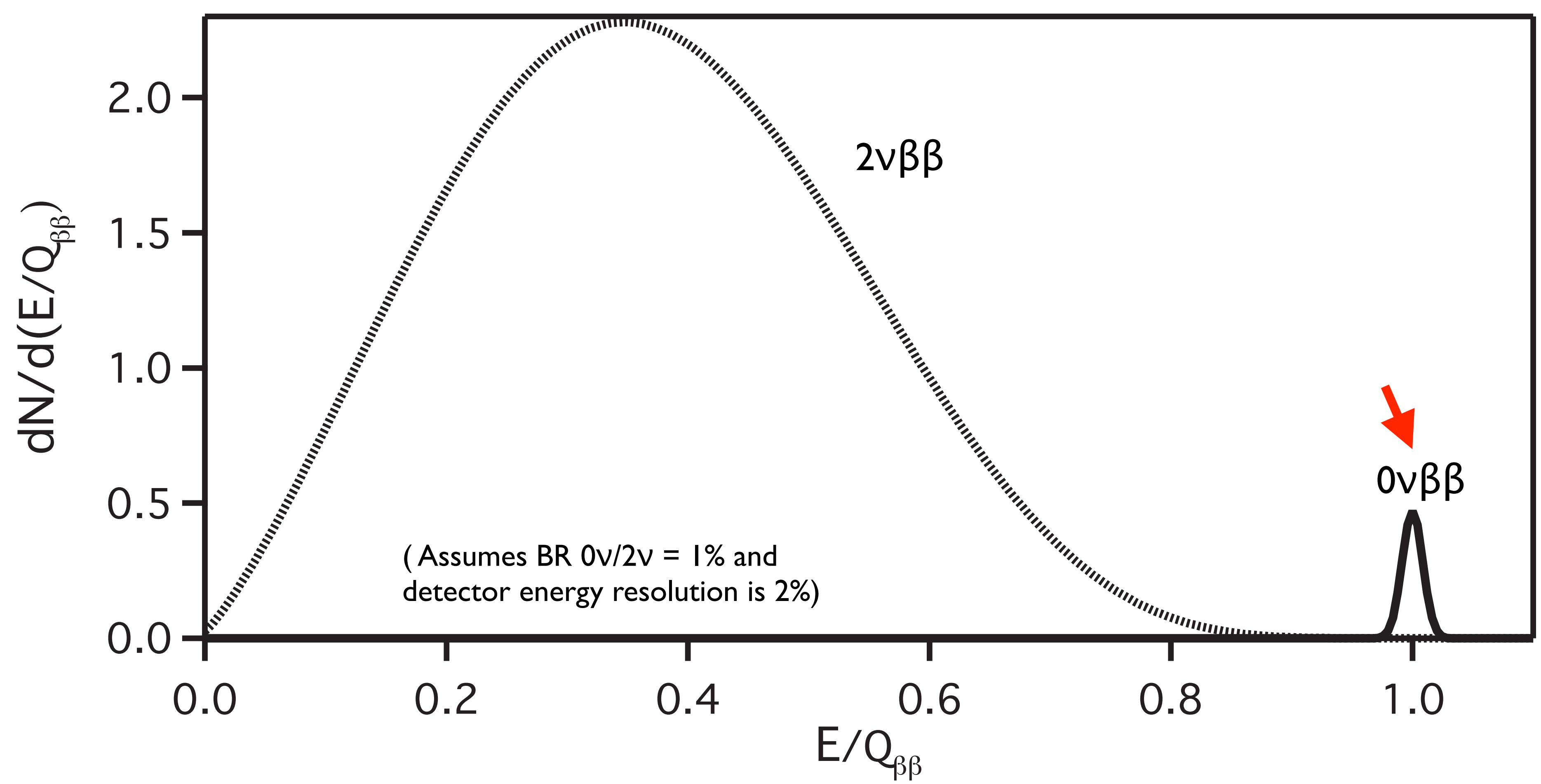
^{48}Ca, ^{150}Nd, ^{96}Zr, ^{100}Mo, ^{82}Se, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{76}Ge

Observation of 0νββ

1. will establish that neutrinos are Majorana Particles ($\nu = \bar{\nu}$)
2. demonstrate lepton number is not a symmetry of nature
3. will provide indirect info about the ν mass
4. may provide info about the mass hierarchy in combination with direct neutrino mass measurement

Signature of 0νββ

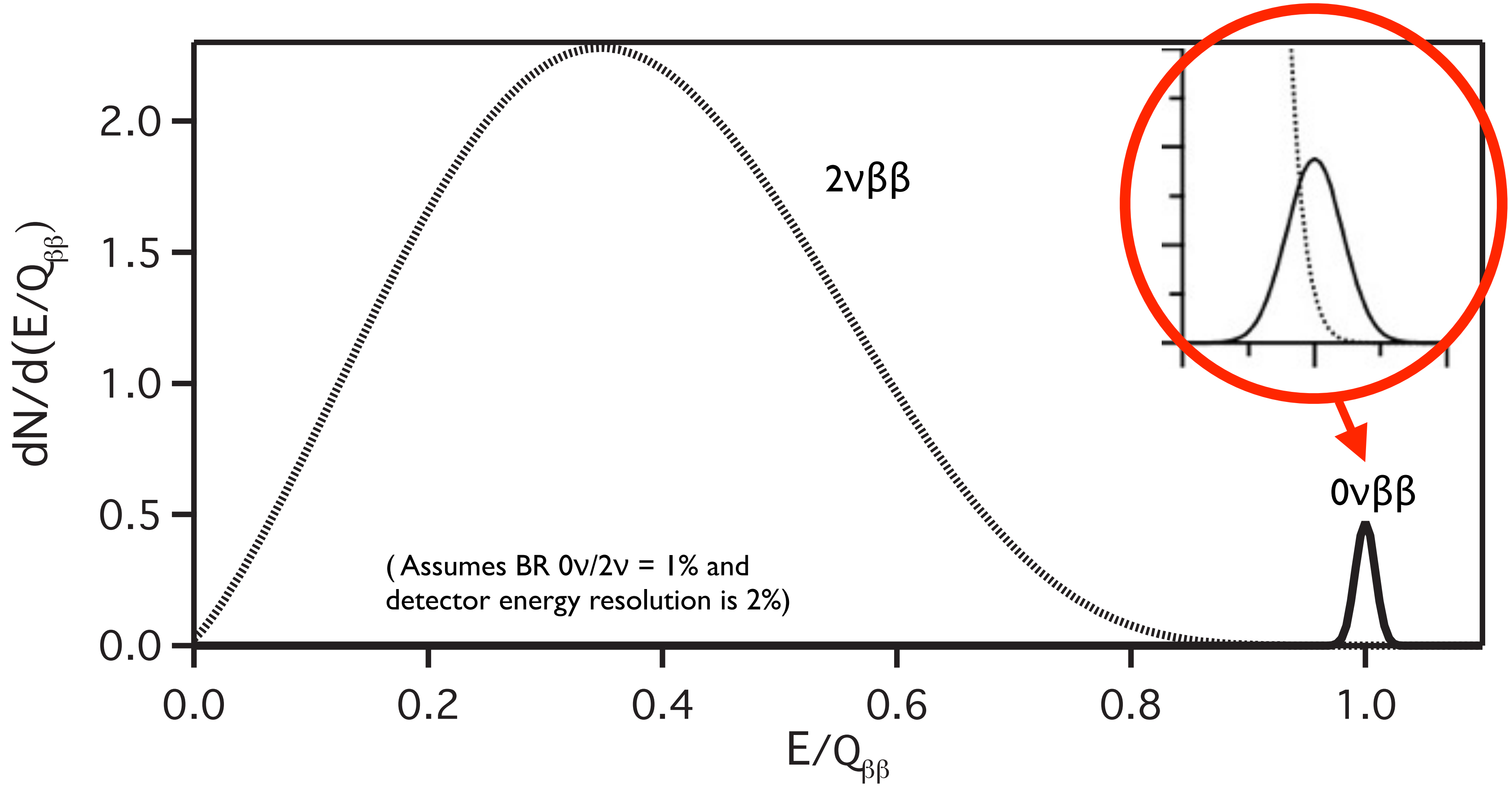
ββ summed e⁻ energy spectrum



- Look for peak in the detector at the Q-value of decay.
- Good energy resolution of a detector suppresses intrinsic background from 2νββ.

Signature of 0νββ

ββ summed e⁻ energy spectrum



- Look for peak in the detector at the Q-value of decay.
- Good energy resolution of a detector suppresses intrinsic background from 2νββ.

Search for 0νββ

Decay rate:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Well defined

Difficult to calculate

$$\langle m_{\beta\beta}\rangle \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

- Probes absolute mass scale
- Sensitive to hierarchy

$T_{1/2}^{0\nu}$	0νββ half-life
$G^{0\nu}$ (Q,Z)	phase space factor $(\propto Q^5)$
$M^{0\nu}$	Nuclear Matrix Element (NME)
$m_{\beta\beta}$	effective ββ neutrino mass
m_e	electron mass

Search for $0\nu\beta\beta$

Decay rate:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

$T_{1/2}^{0\nu}$ sensitivity $\propto a \cdot \epsilon \sqrt{\dfrac{M \cdot t}{b \cdot \delta E}}$

$T_{1/2}^{0\nu}$	$0\nu\beta\beta$ half-life
$G^{0\nu}$ (Q,Z)	phase space factor $(\propto Q^5)$
$M^{0\nu}$	Nuclear Matrix Element (NME)
$m_{\beta\beta}$	effective $\beta\beta$ neutrino mass
m_e	electron mass

a	isotopic abundance of source
ε	detection efficiency
M	total detector mass
b	background rate /mass/energy
t	exposure time
δE	energy resolution (spectral width)

Search for 0νββ

Decay rate:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

$T_{1/2}^{0\nu}$ sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

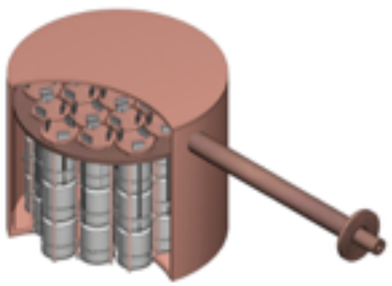
$T_{1/2}^{0\nu}$	0νββ half-life
$G^{0\nu}$ (Q,Z)	phase space factor $(\propto Q^5)$
$M^{0\nu}$	Nuclear Matrix Element (NME)
$m_{\beta\beta}$	effective ββ neutrino mass
m_e	electron mass

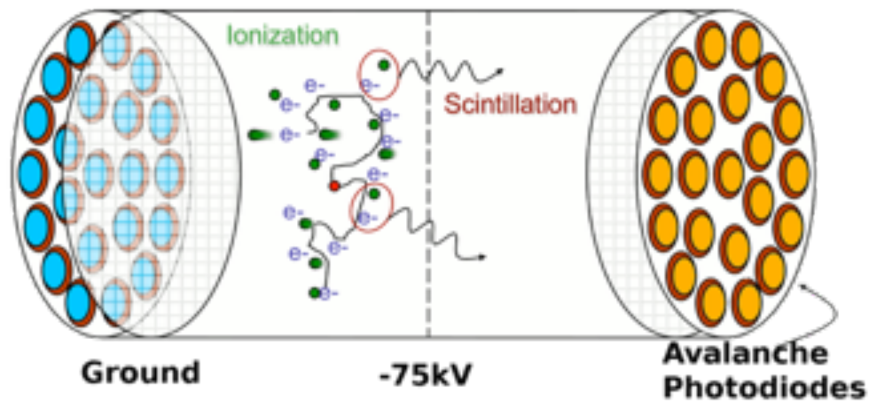
a	isotopic abundance of source
ε	detection efficiency
M	total detector mass
b	background rate /mass/energy
t	exposure time
δE	energy resolution (spectral width)

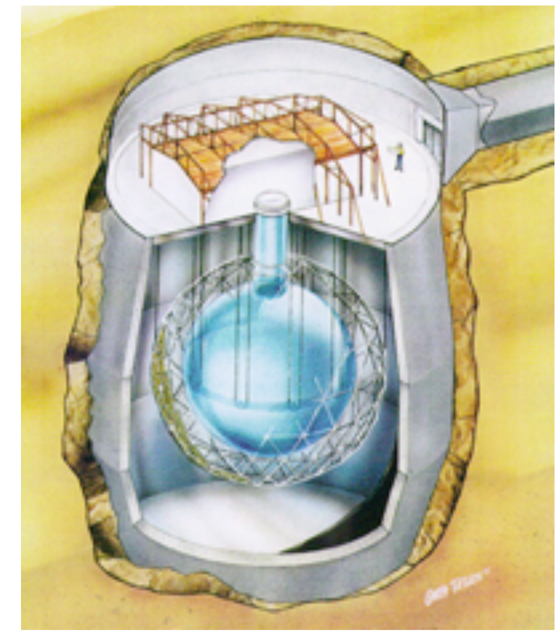
Source Selection/
Detector Building Strategies

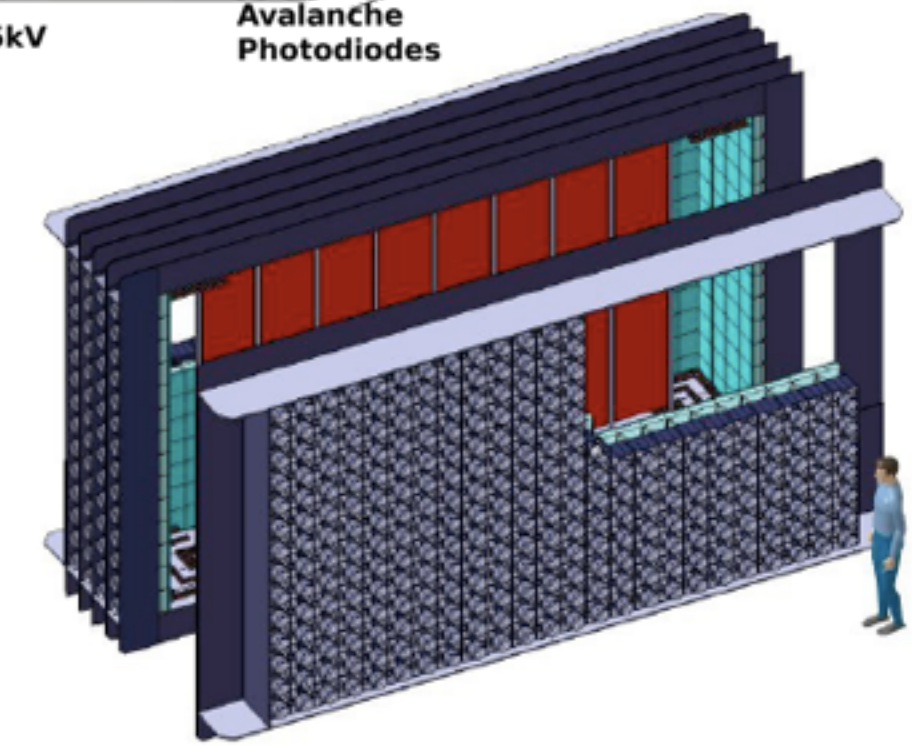
- Large total mass
- Ultra-low background
- Good energy resolution
- High Q-value
- High isotopic abundance
- NME

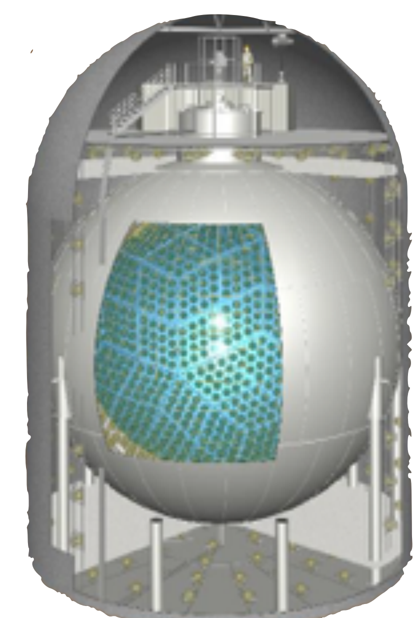
Search for 0νββ

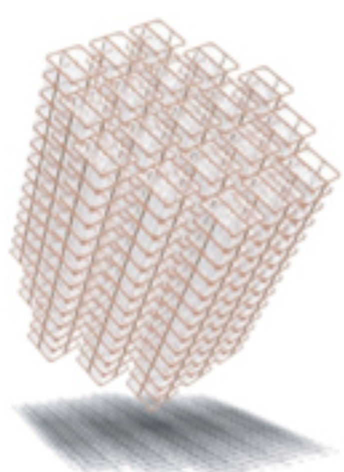


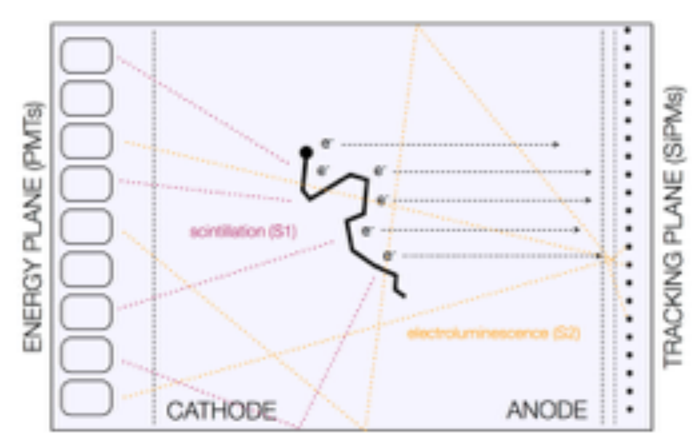




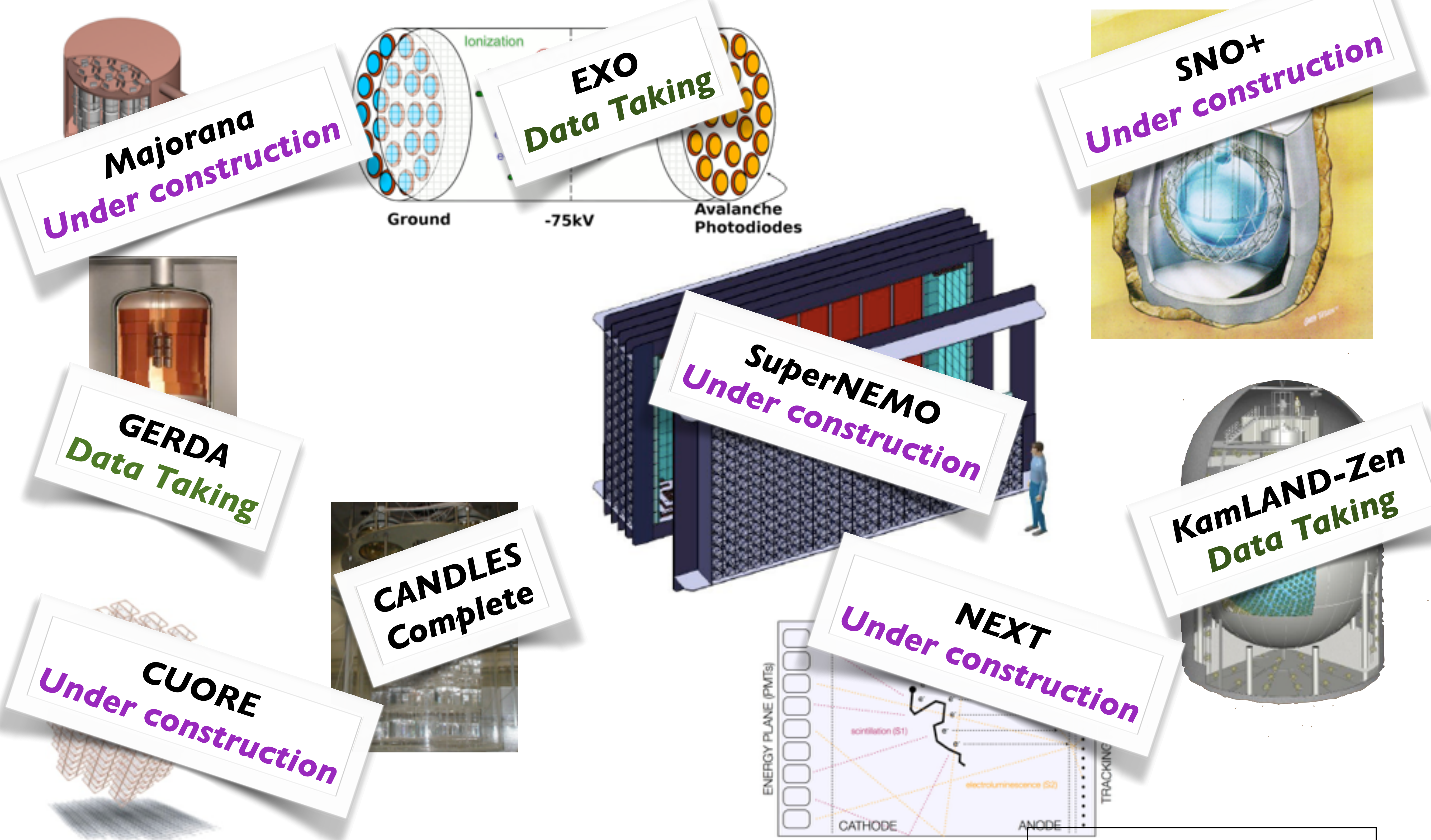








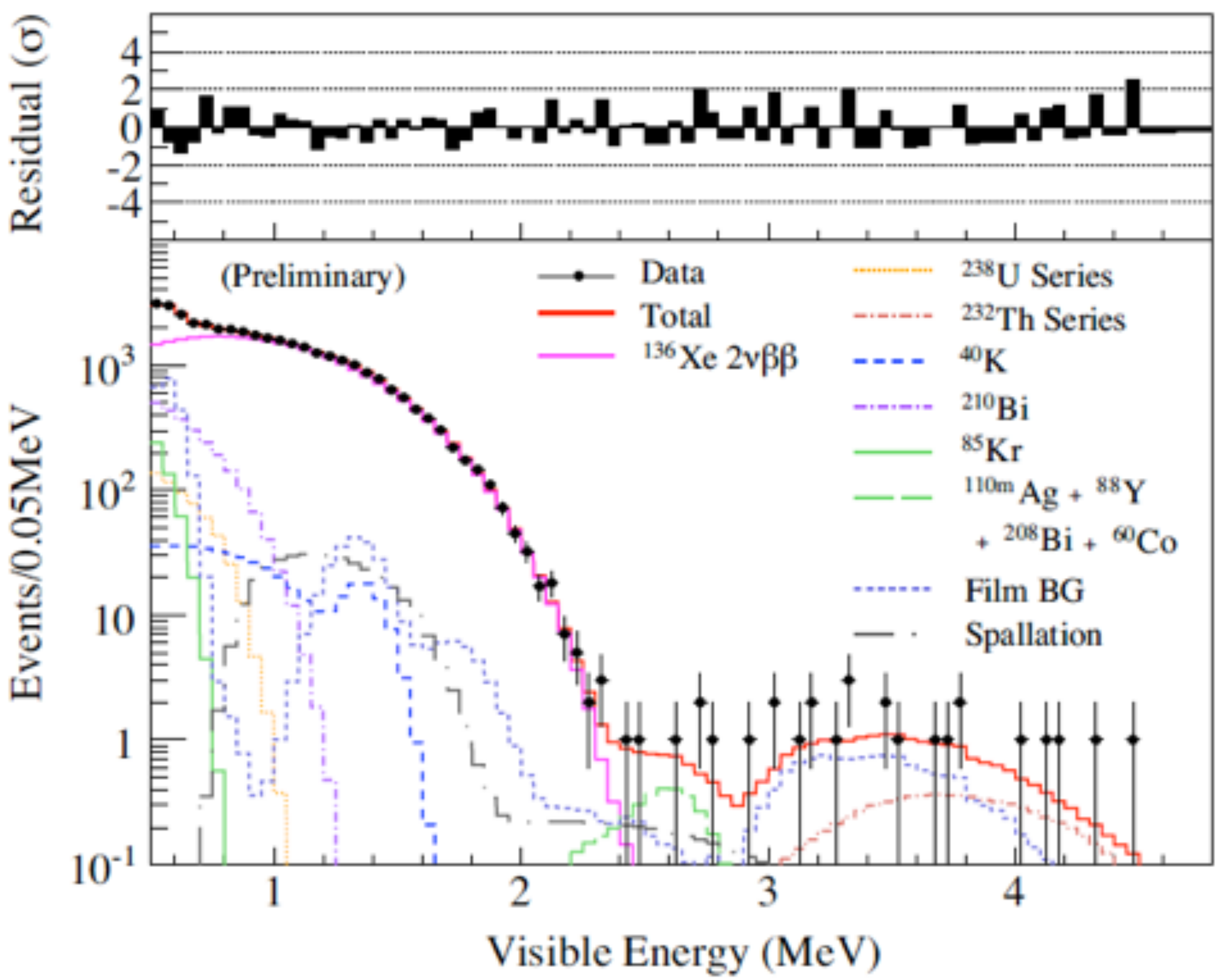
Search for 0νββ



L. Winslow, APS 2015

Search for 0νββ: ^{136}Xe

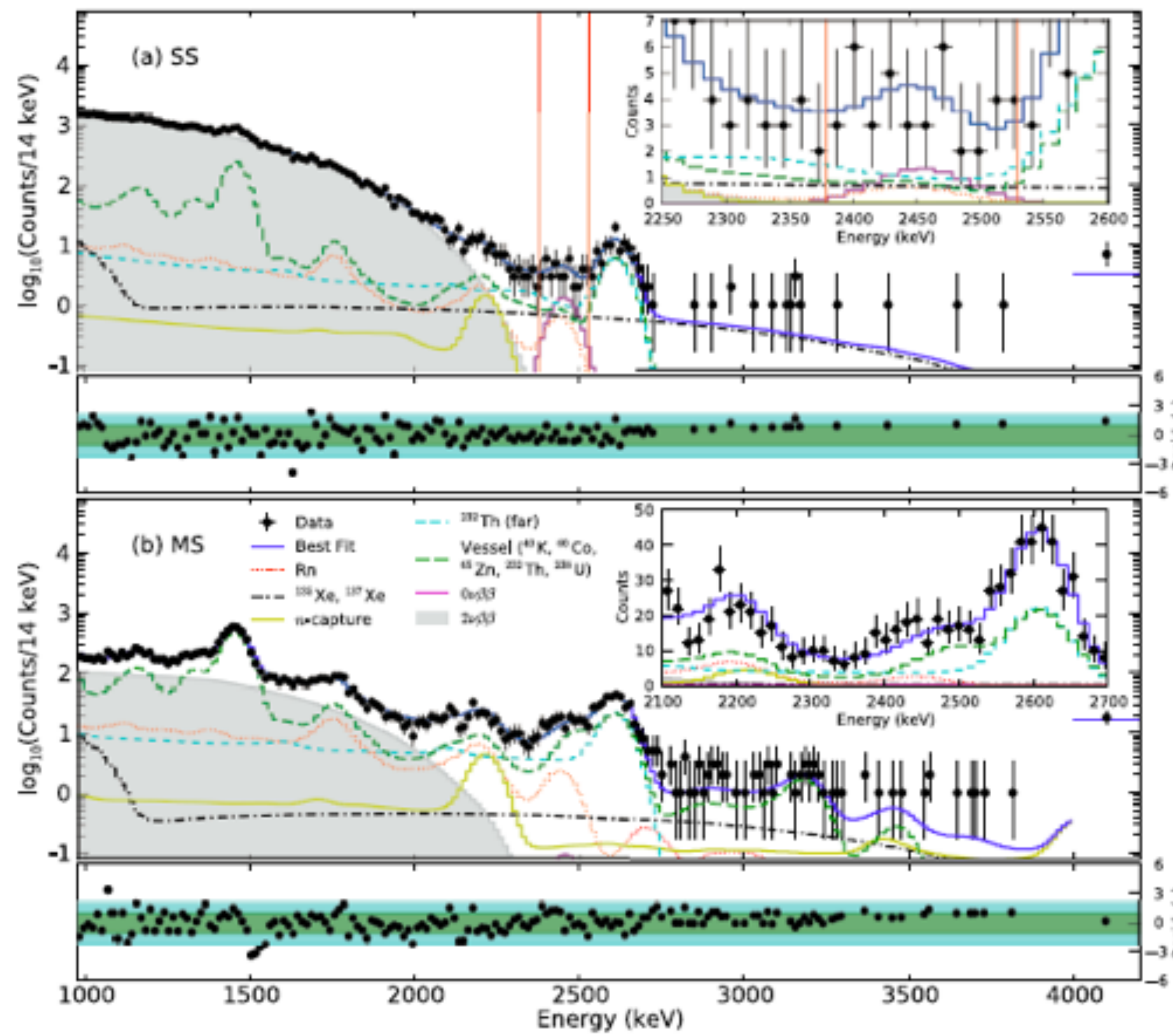
KamLAND-Zen



$T_{1/2} > 1.9\times10^{25}$ years

Phys.Rev.Lett. 111 (2013) 122503

EXO-200

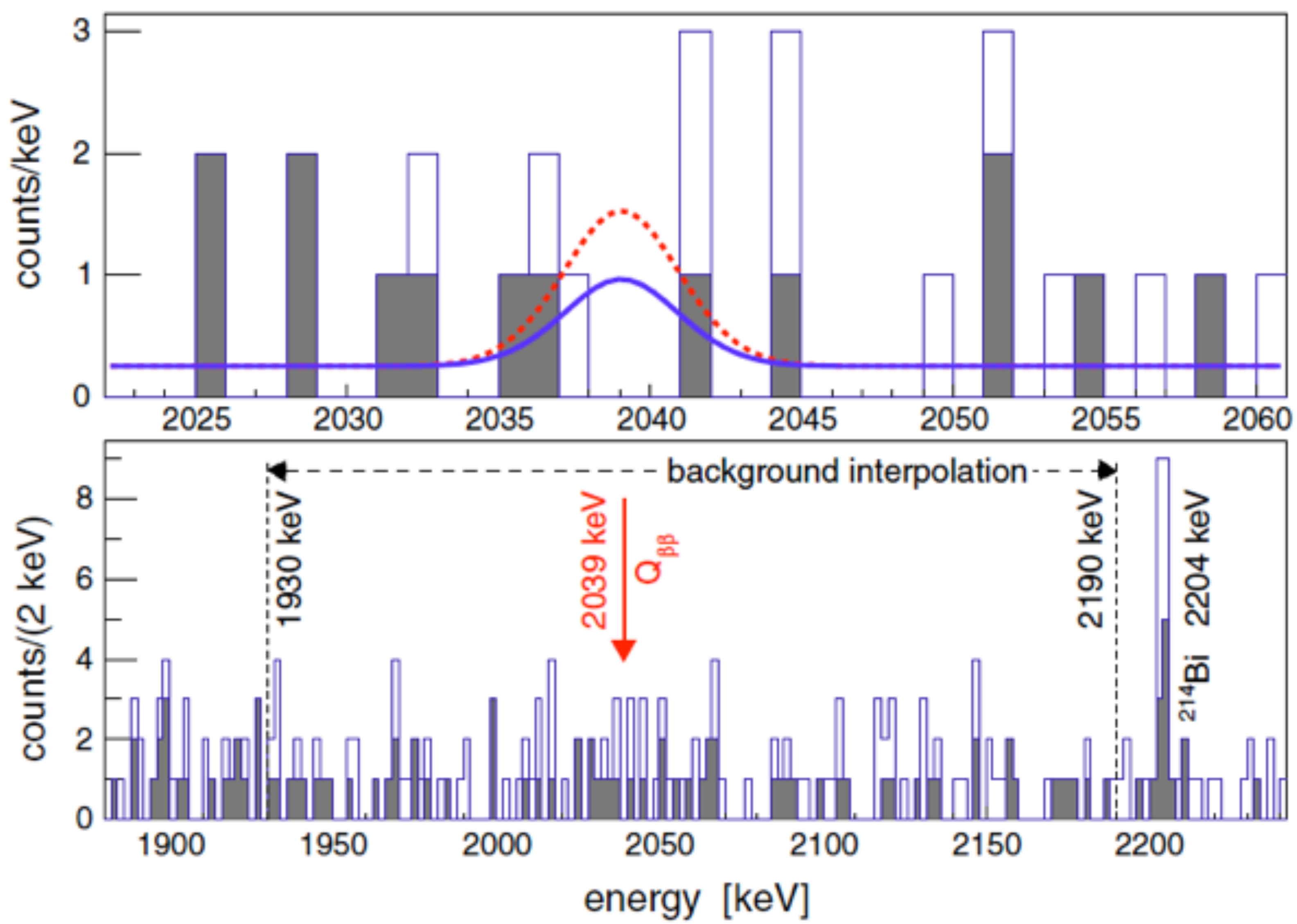


$T_{1/2} > 1.1\times10^{25}$ years

Nature 510 (2014) 229–234

Search for $0\nu\beta\beta$: ^{76}Ge

GERDA



Combined ^{76}Ge $T_{1/2} > 3.0\times10^{25}$ years

Phys.Rev.Lett. 110 (2013) 062502

Search for 0νββ: ^{130}Te

Decay rate:

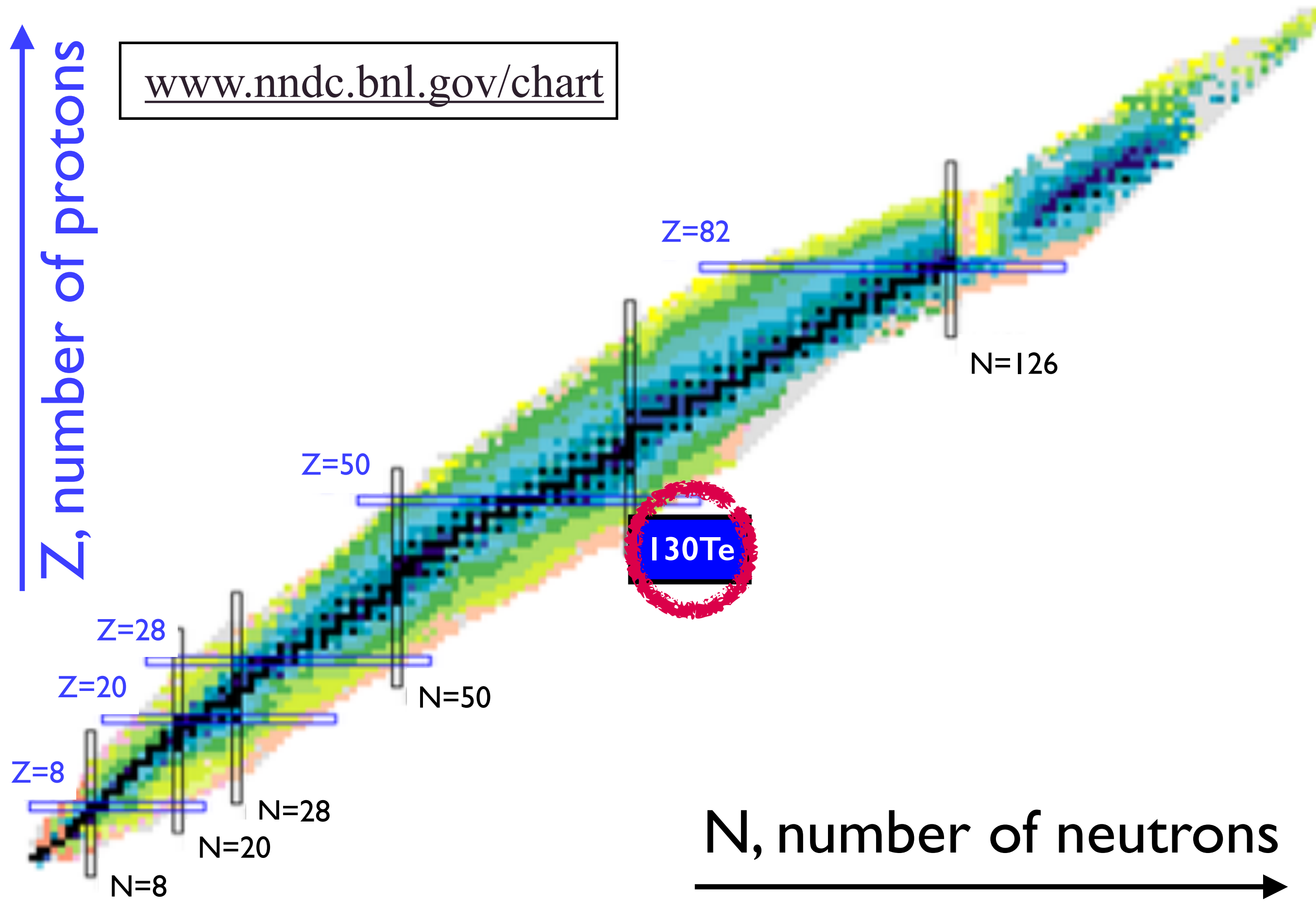
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

$T_{1/2}^{0\nu}$ sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

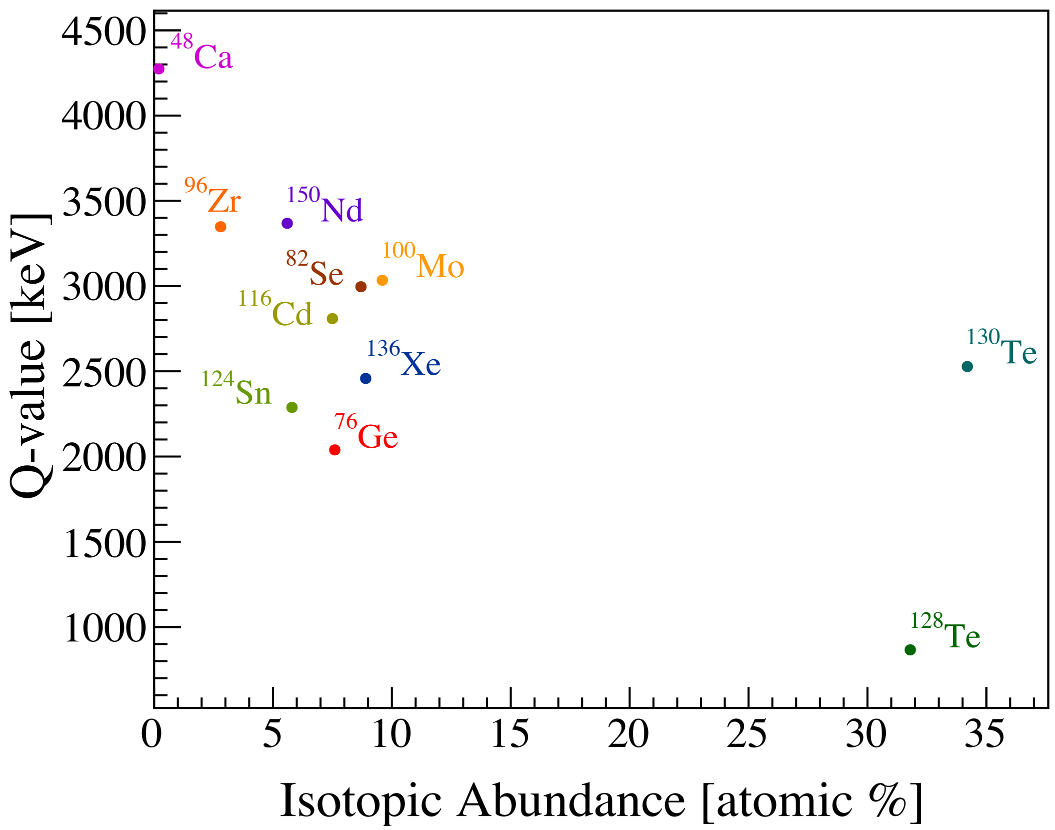
$T_{1/2}^{0\nu}$	0νββ half-life
$G^{0\nu}$ (Q,Z)	phase space factor $(\propto Q^5)$
$M^{0\nu}$	Nuclear Matrix Element (NME)
$m_{\beta\beta}$	effective ββ neutrino mass
m_e	electron mass

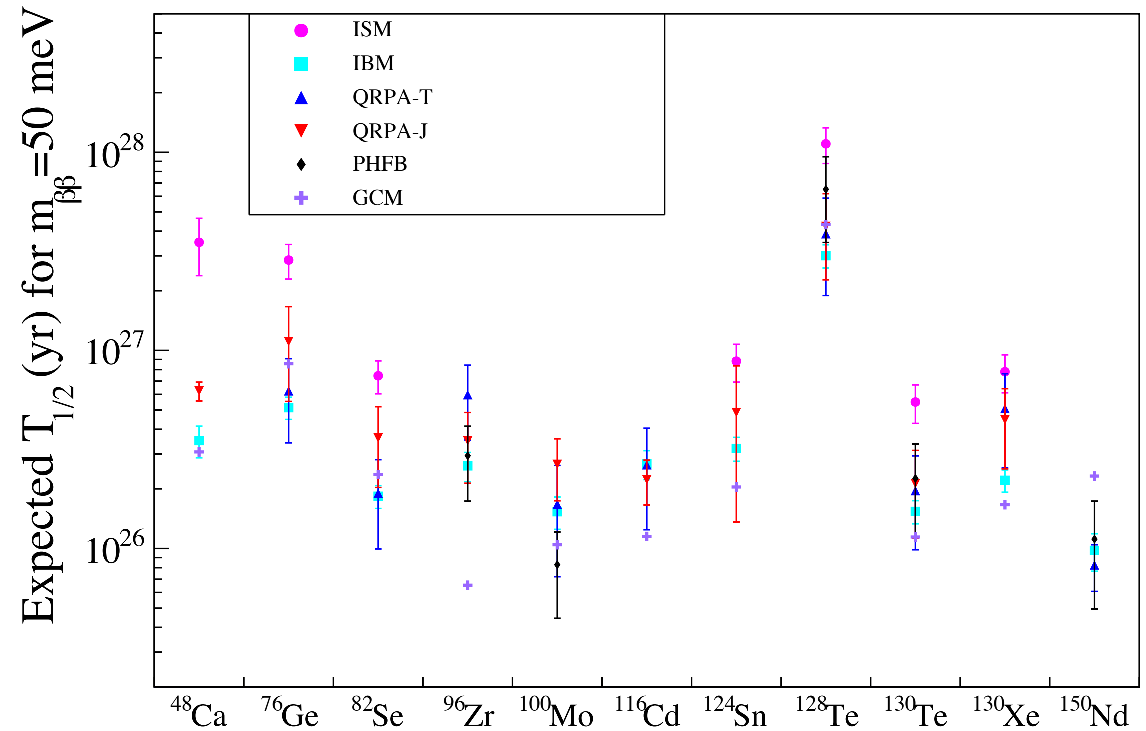
Source Selection/
Detector Building Strategies

- Large total mass
- Ultra-low background
- Good energy resolution
- High Q-value
- High isotopic abundance
- NME

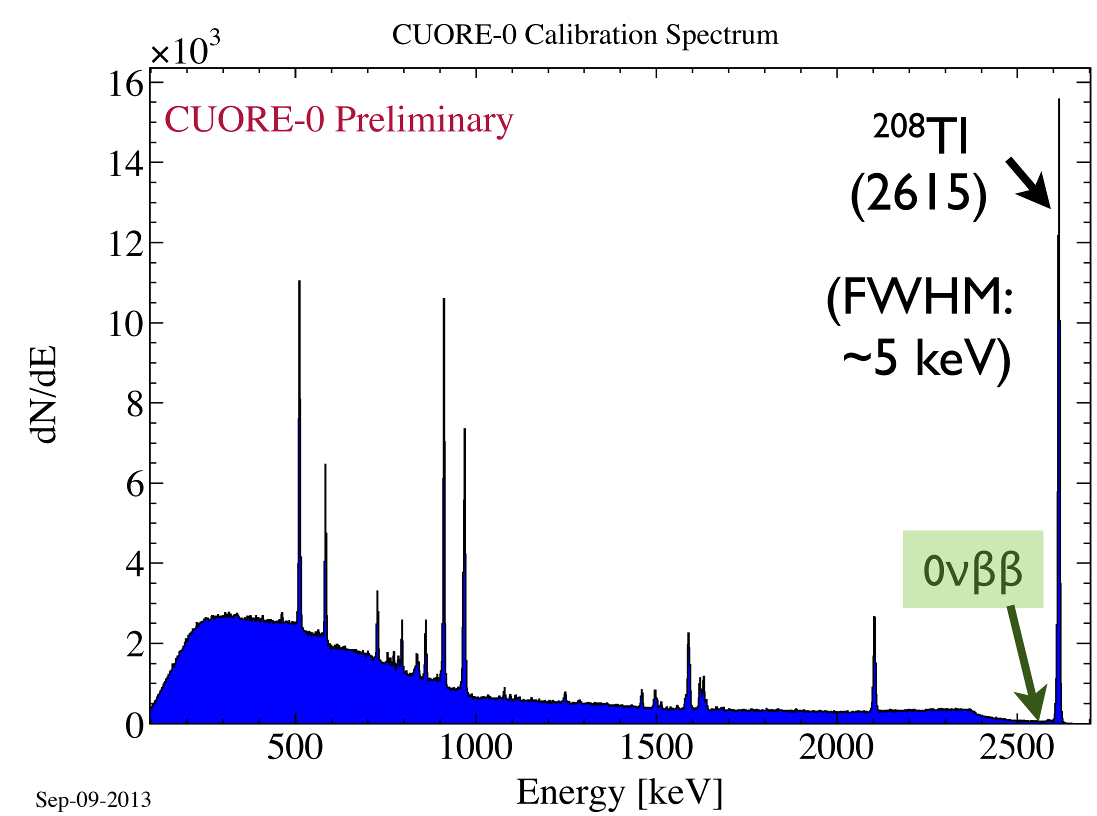


^{130}Te for $0\nu\beta\beta$

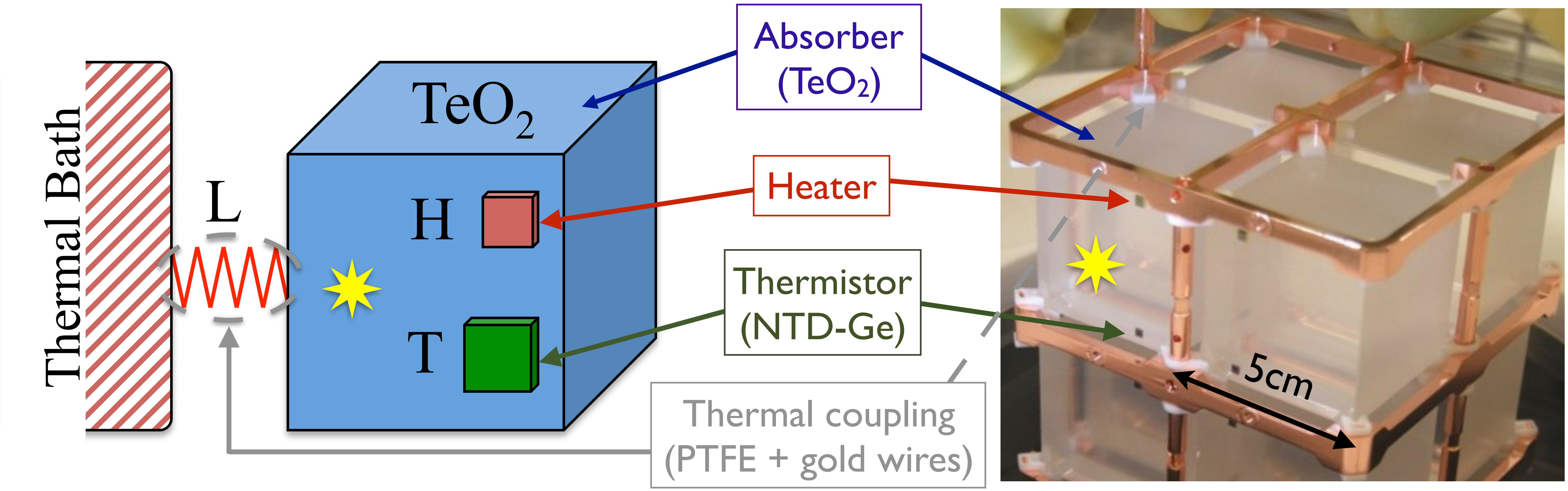




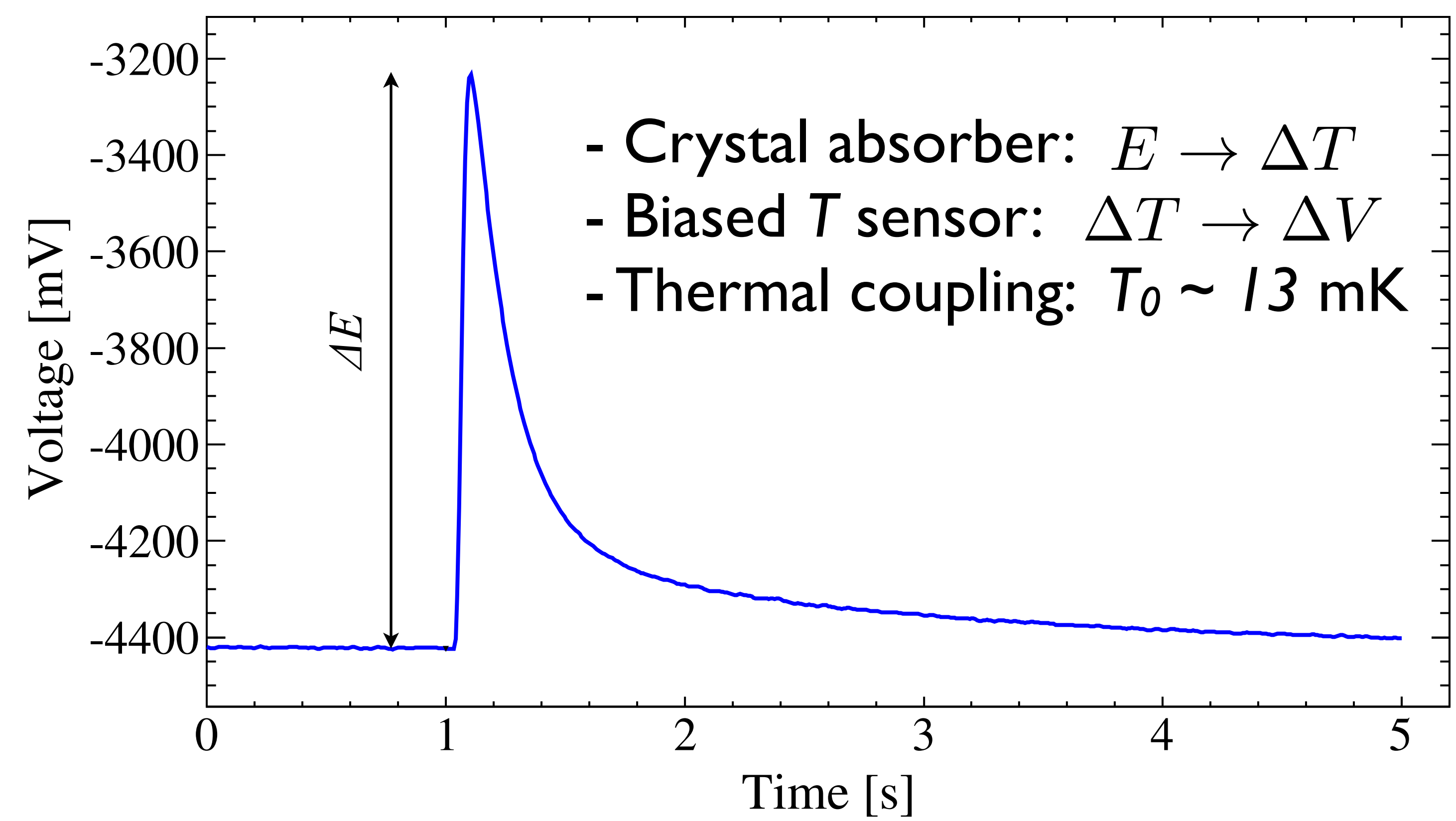
- High isotopic abundance, low background at the Q-value makes ^{130}Te appealing for $0\nu\beta\beta$ search.



TeO_2 Bolometers



- Measure energy deposition through temperature rise.
- Provides excellent energy resolution.



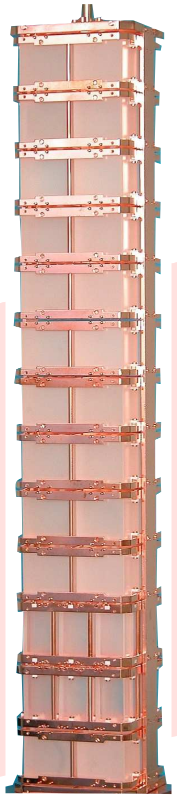
Outline

- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE : An array of TeO_2 bolometers
- CUORE-0 : $0\nu\beta\beta$ search w/ a single CUORE tower
  - CUORE-0 : Detector
  - CUORE-0 : Resolution and Background
  - CUORE-0 : Results
- Summary

The CUORE 0νββ Search

CUORE: Cryogenic Underground Observatory for Rare Events

Cuoricino (2003-2008)



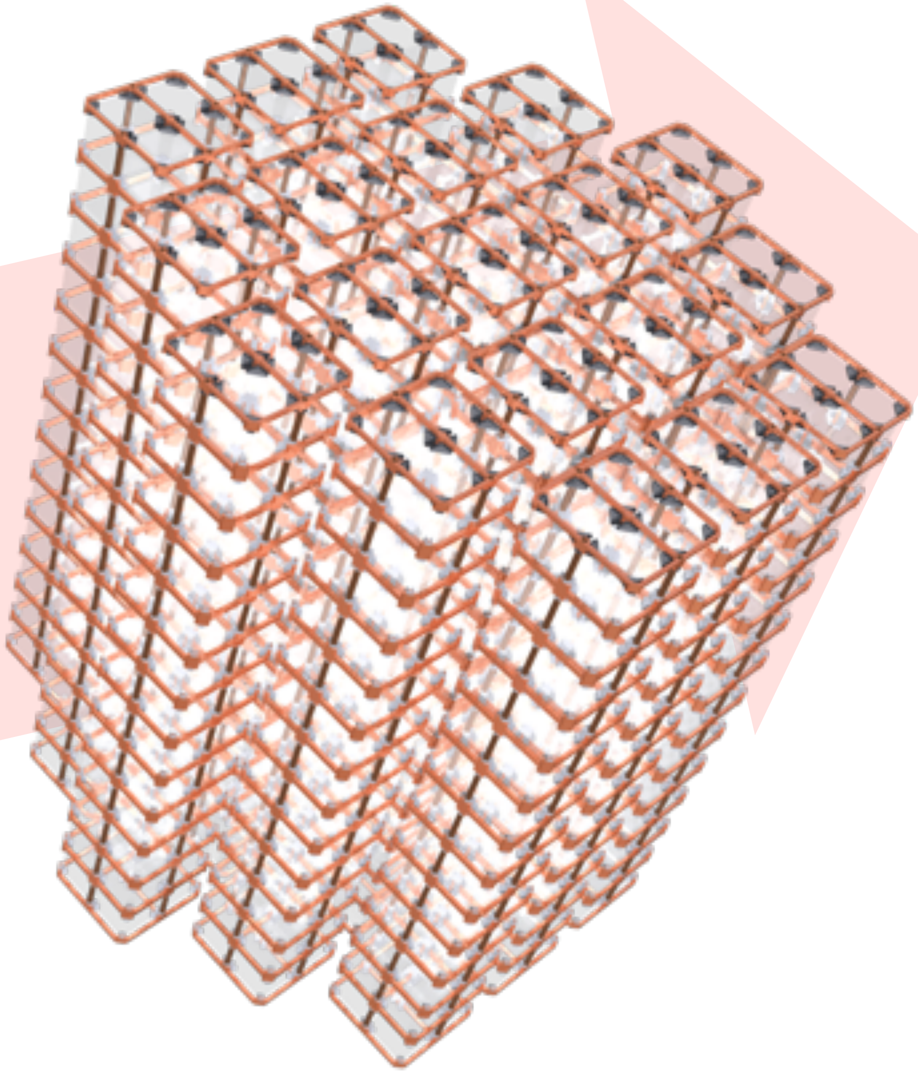
Achieved (2008)

$T_{1/2}^{0\nu}$ > 2.8x10^{24} yr (90% C.L.)

CUORE-0 (2013-2015)

Achieved (2015)

CUORE (2015-2020)



Projected (2020)

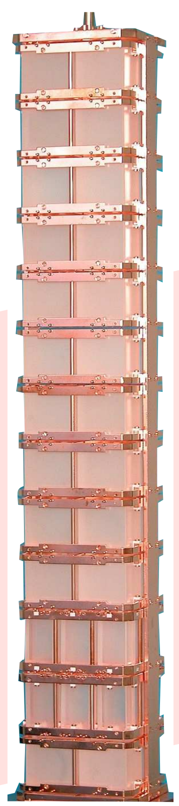
$T_{1/2}^{0\nu}$ > 9.5x10^{25} yr (90% C.L.)

Astroparticle Physics 34 (2011) 822

The CUORE 0νββ Search

CUORE: Cryogenic Underground Observatory for Rare Events

Cuoricino
(2003-2008)



Achieved (2008)

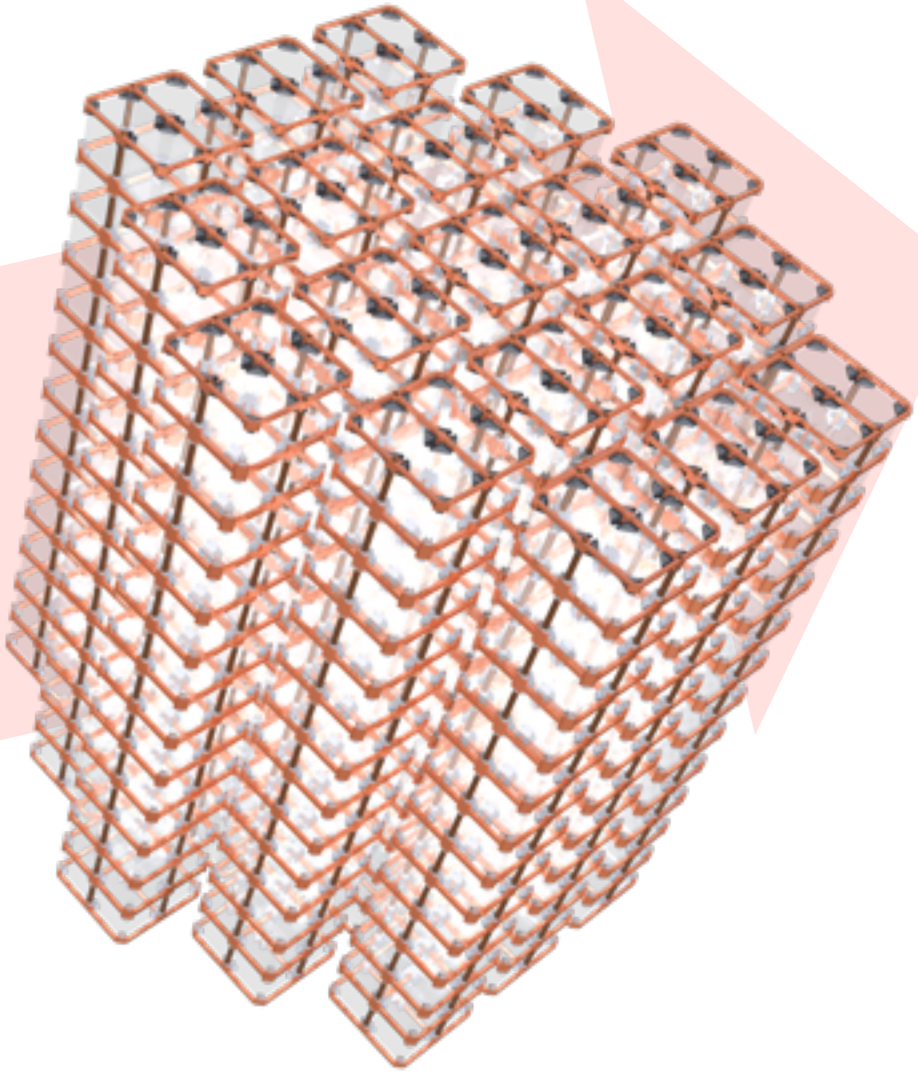
$T_{1/2}^{0\nu}$ > 2.8×10^{24} yr (90% C.L.)

Astroparticle Physics 34 (2011) 822

CUORE-0
(2013-2015)

Achieved (2015)

CUORE
(2015-2020)



Projected (2020)

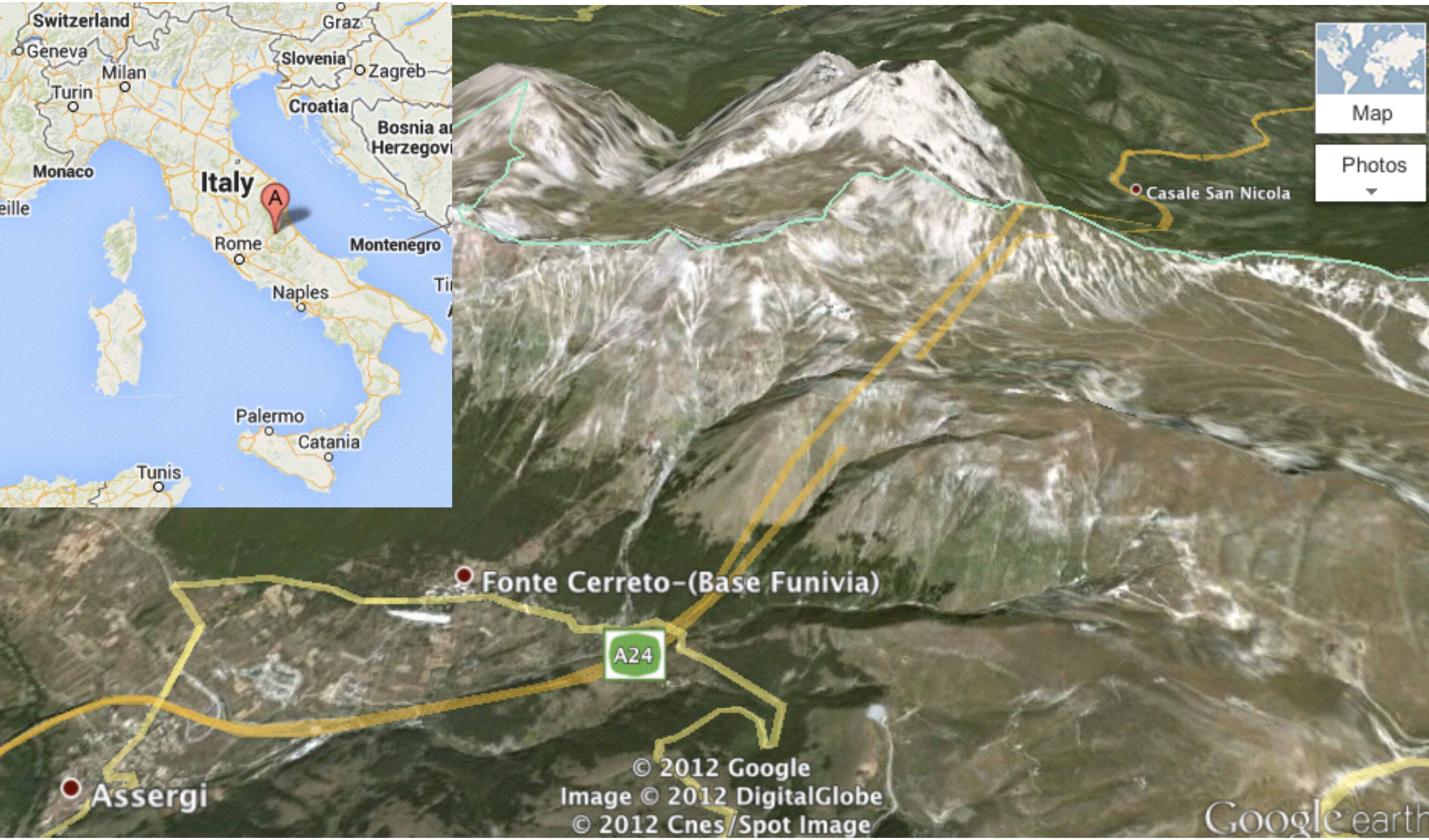
$T_{1/2}^{0\nu}$ > 9.5×10^{25} yr (90% C.L.)

CUORE Collaboration

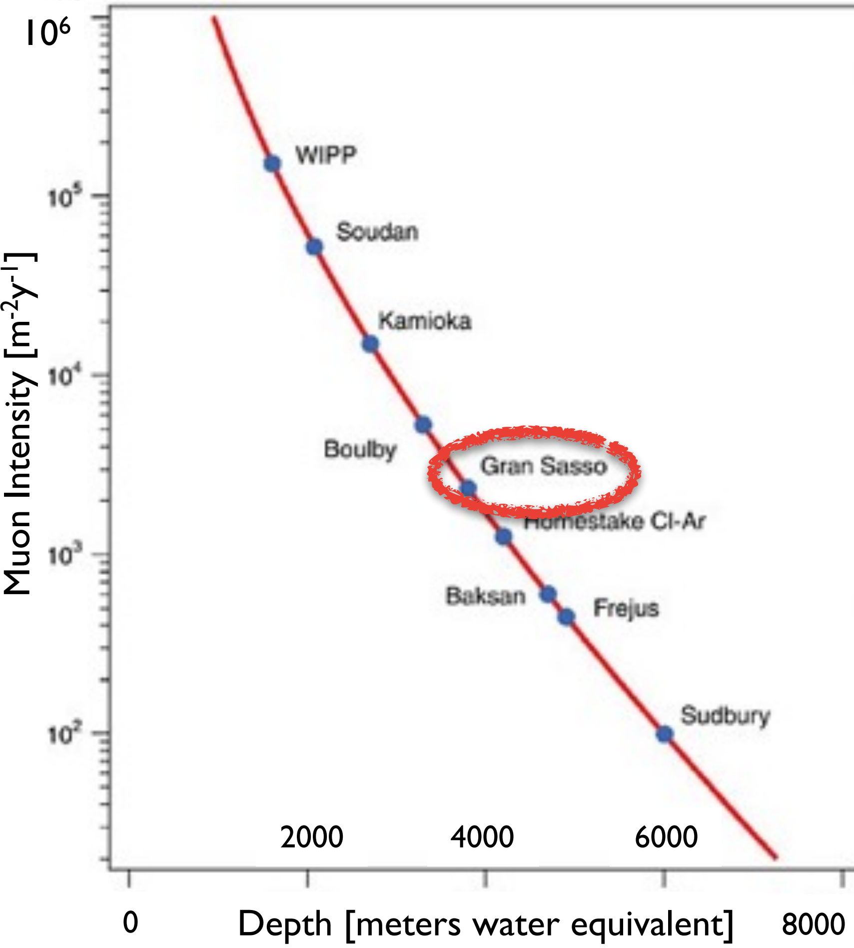
(Oct. 31, 2013 @ LNGS)

- 21 institutes (USA+Italy)
- 166 people

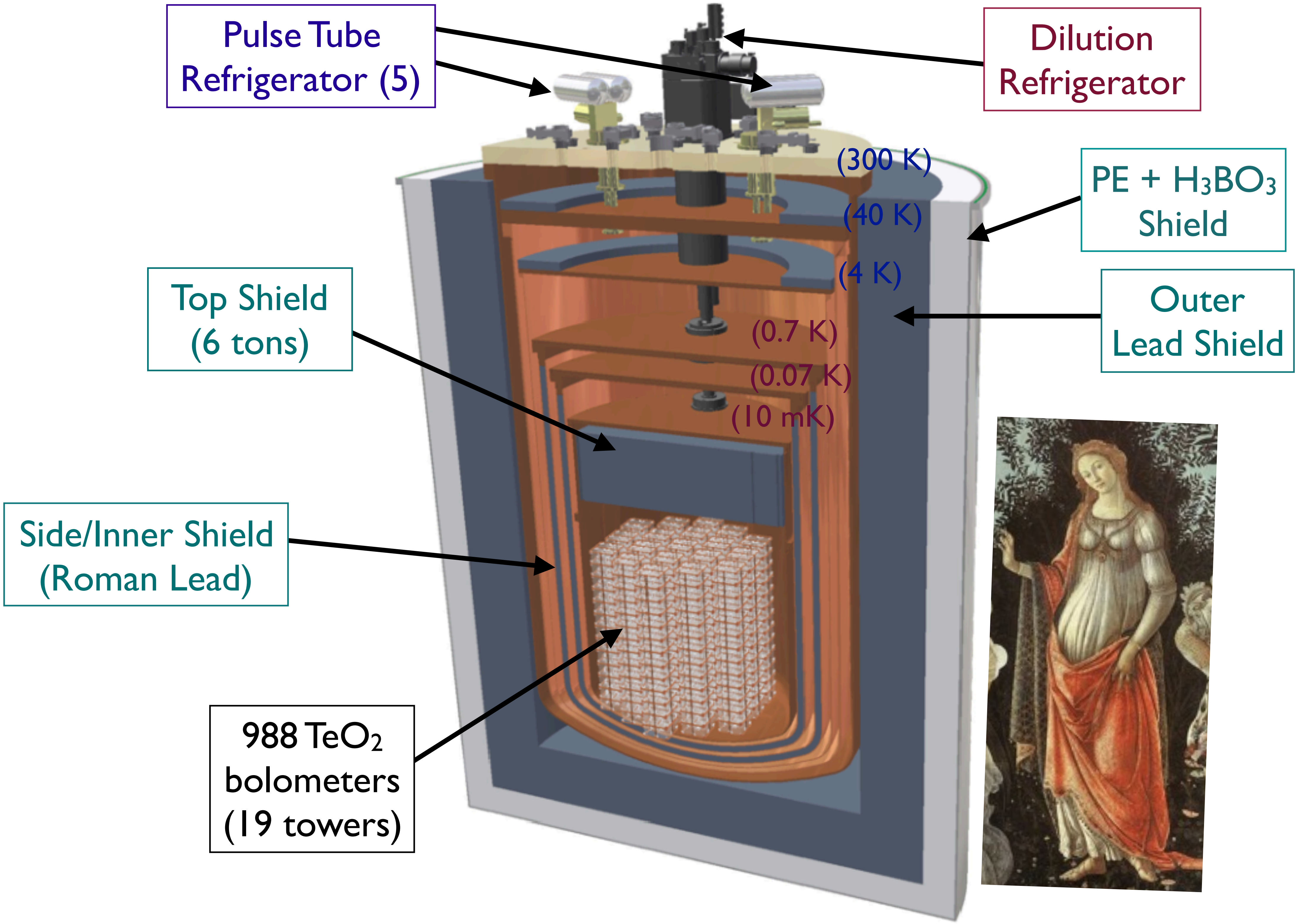
CUORE at LNGS



CUORE at LNGS

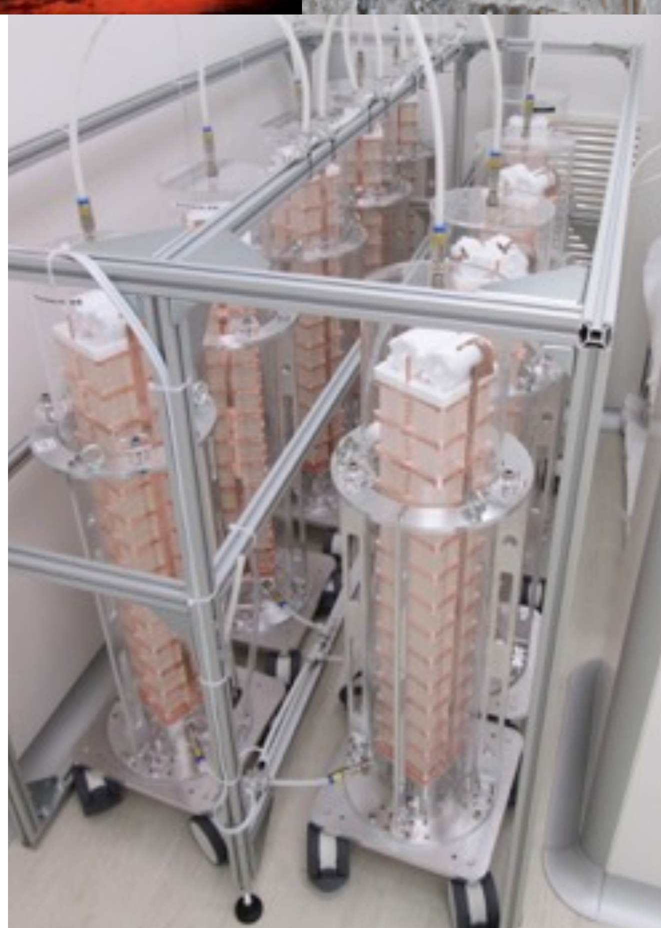


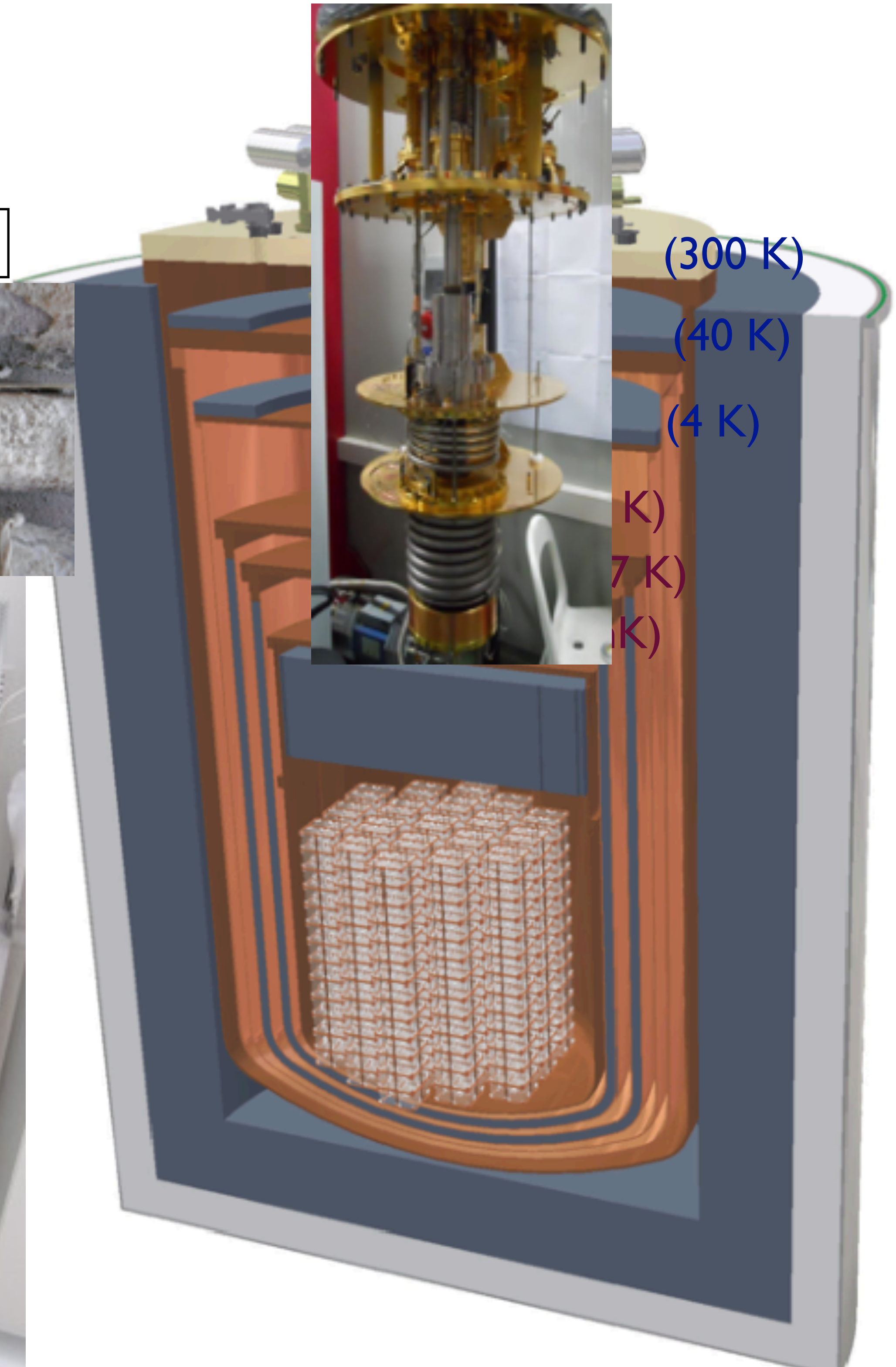
The CUORE Detector

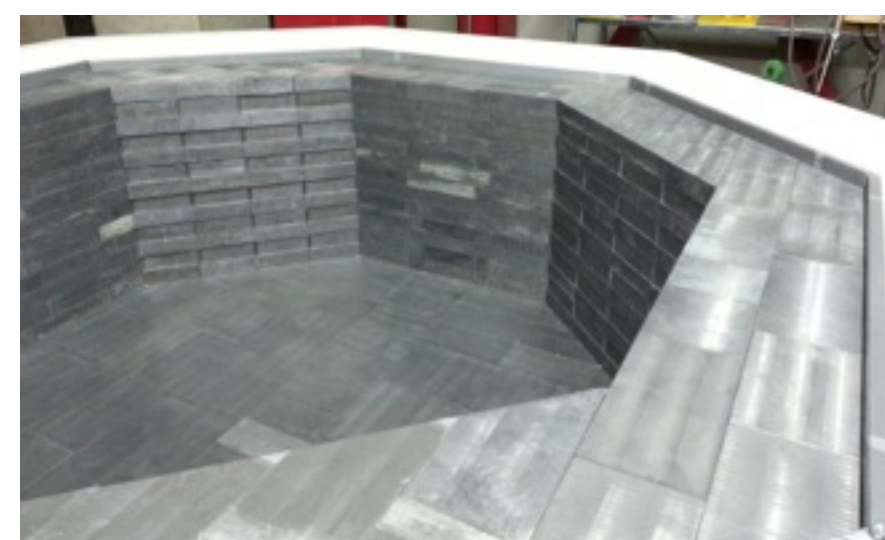


The CUORE Detector

doi:10.1038/news.2010.186 (nature)





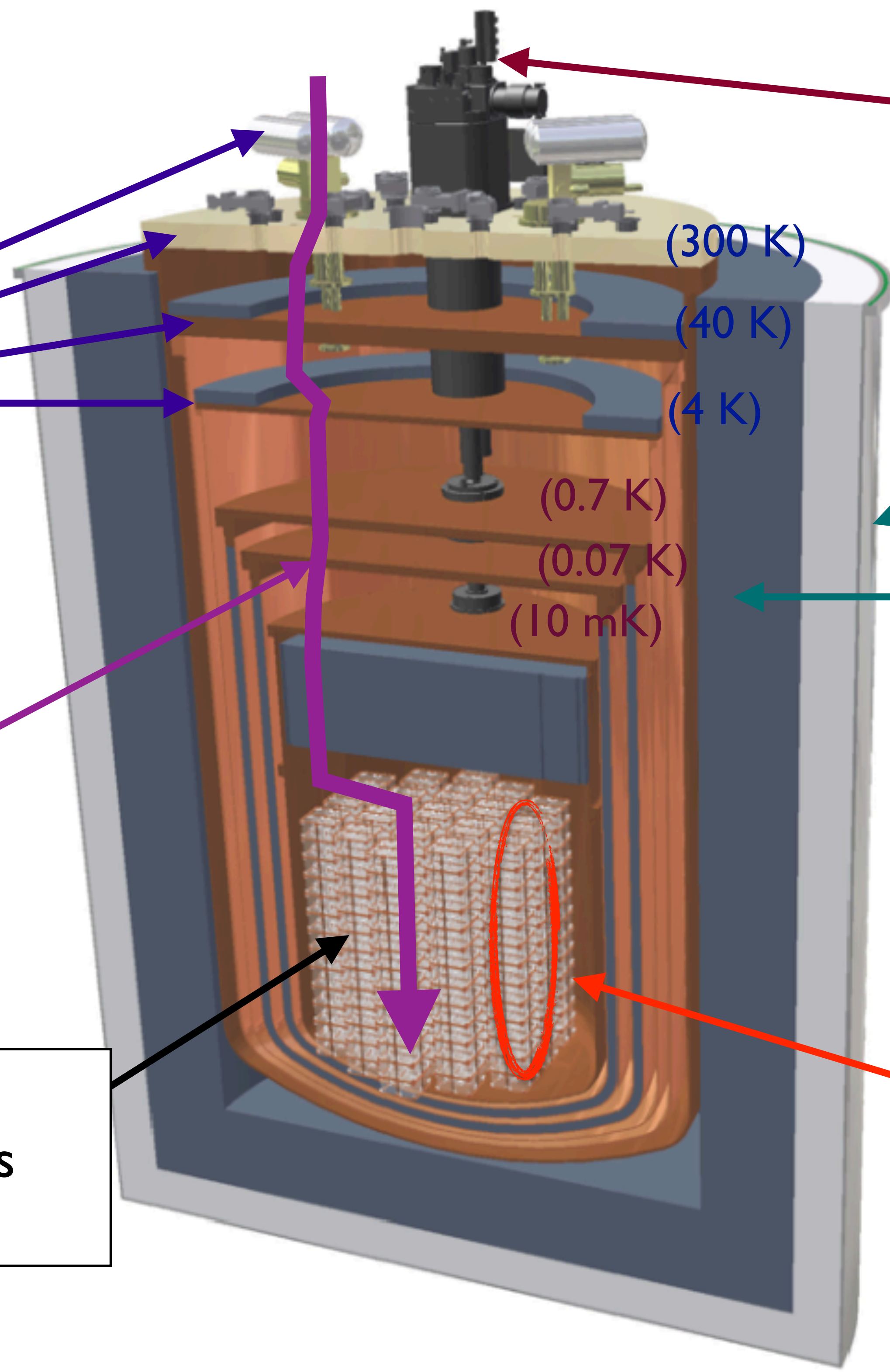


Progress towards CUORE

Cryostat assembled, commissioning, passed 4 K Test, reached 5.9 mK, wiring with mini-tower tested.

Detector calibration system well underway.

- 19 towers completed.
- Installation in the cryostat is anticipated in this summer.



Dilution Refrigerator reached 5 mK for the commissioning test, has been integrated in the cryostat.

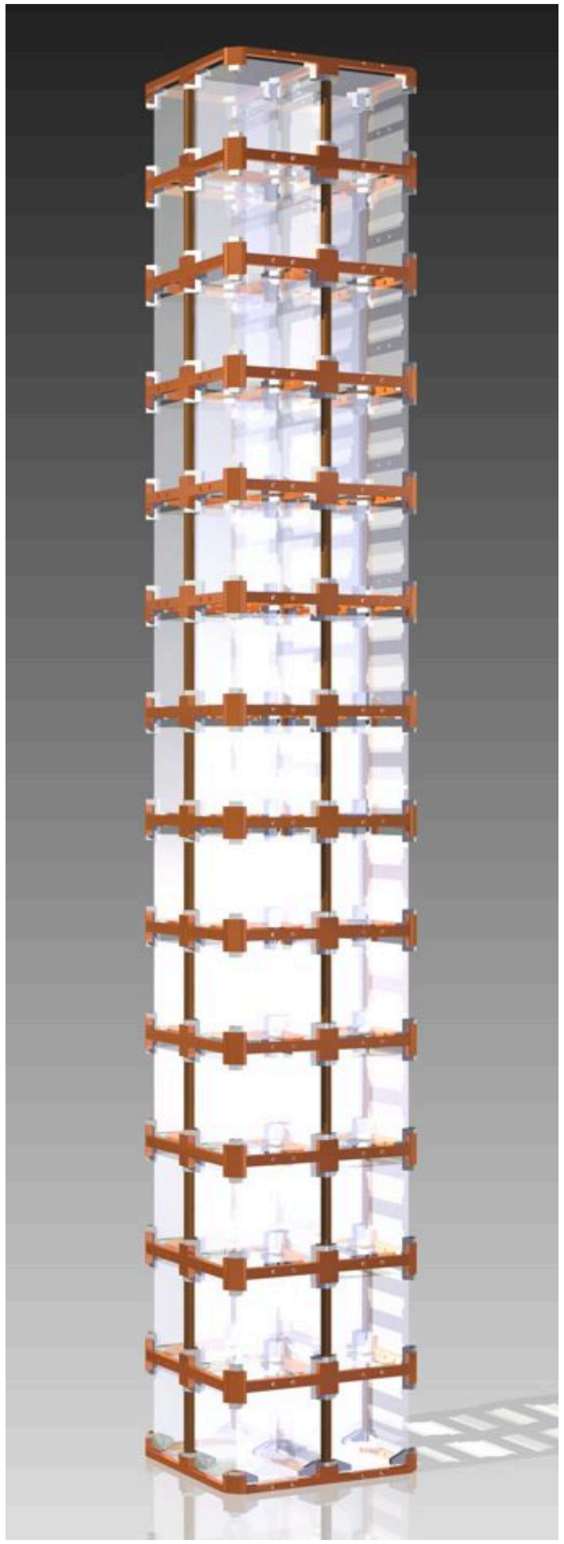
External shields installation finished.

CUORE-0, the first tower from CUORE assembly line has been running in the Cuoricino cryostat since March 2013.

Outline

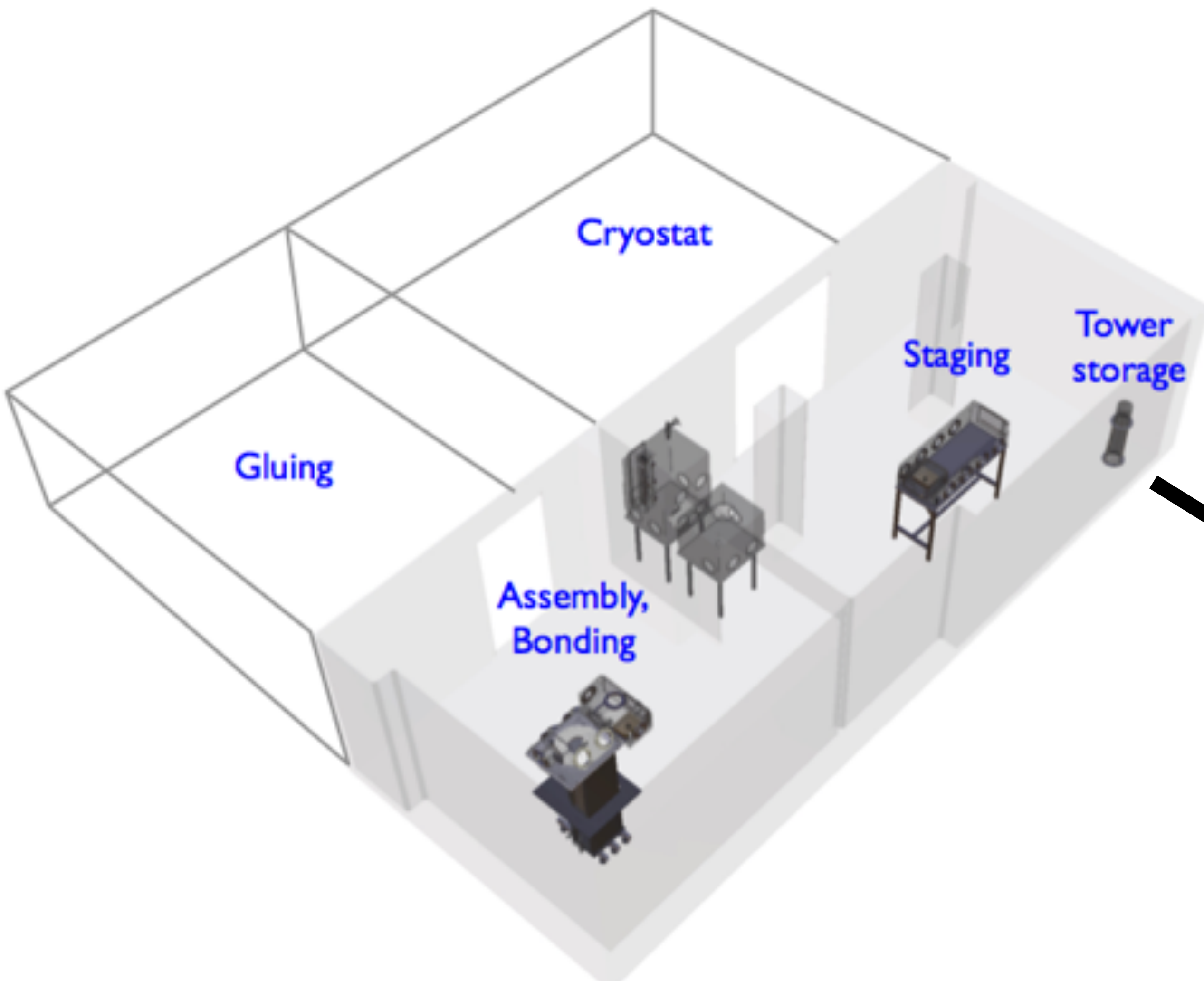
- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE : An array of TeO_2 bolometers
- CUORE-0 : $0\nu\beta\beta$ search w/ a single CUORE tower
  - CUORE-0 : *Detector*
  - CUORE-0 : Resolution and Background
  - CUORE-0 : Results
- Summary

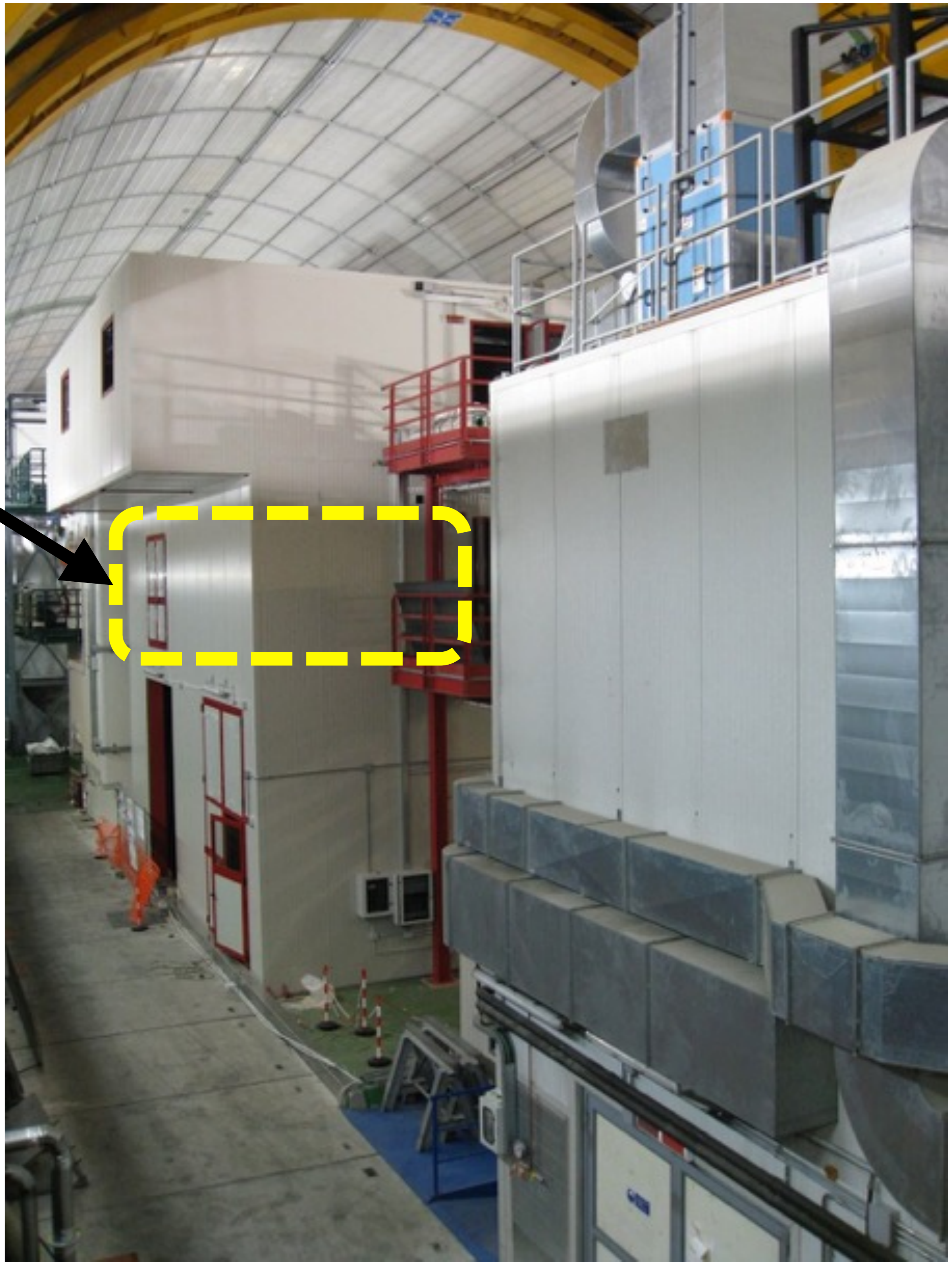
CUORE-0



- The first CUORE-like tower

Detector Assembly

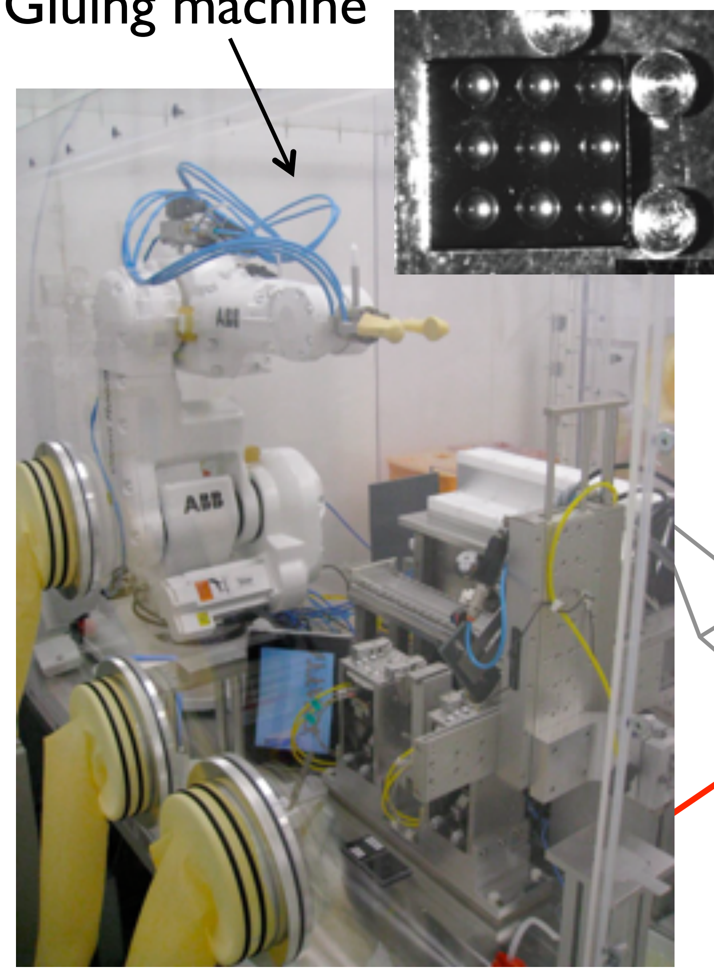


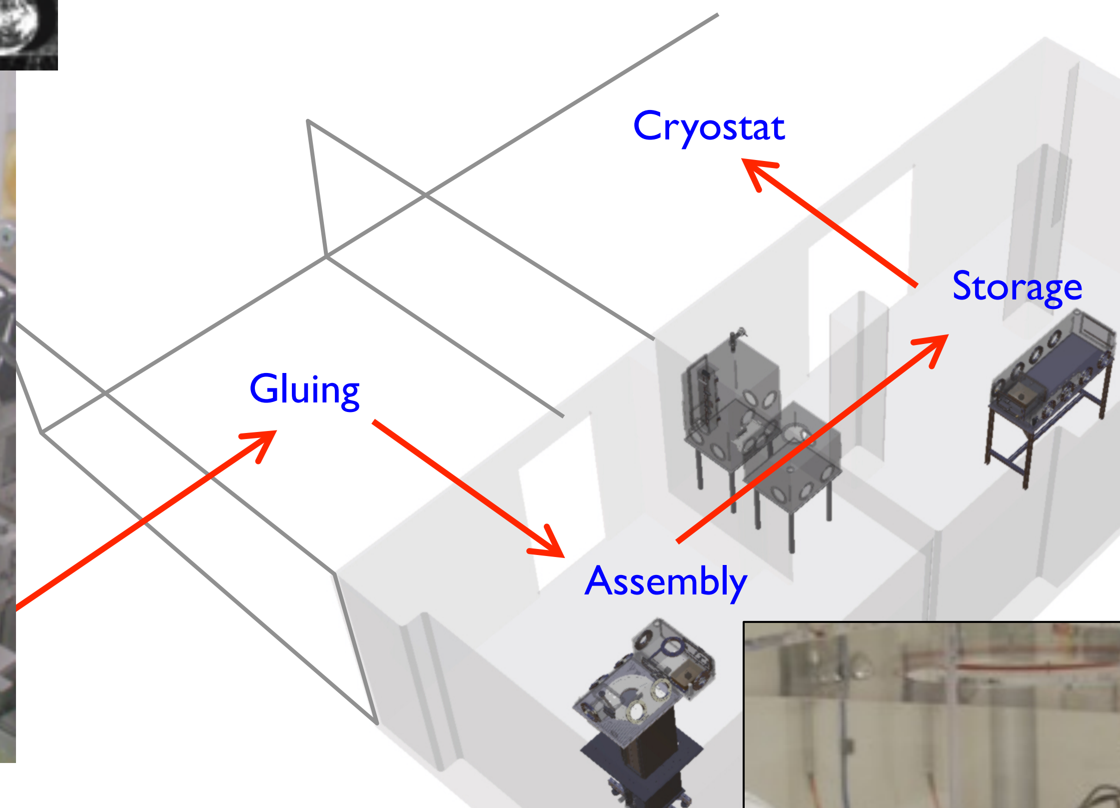


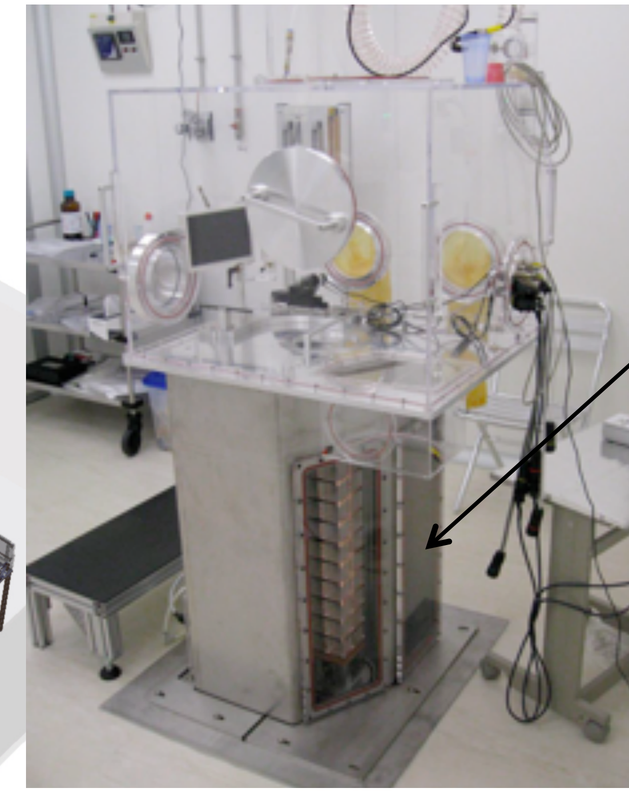
Crystals are prepared & assembled into towers inside N_2-fluxed glove boxes in a Class 1000 clean room.

Detector Assembly

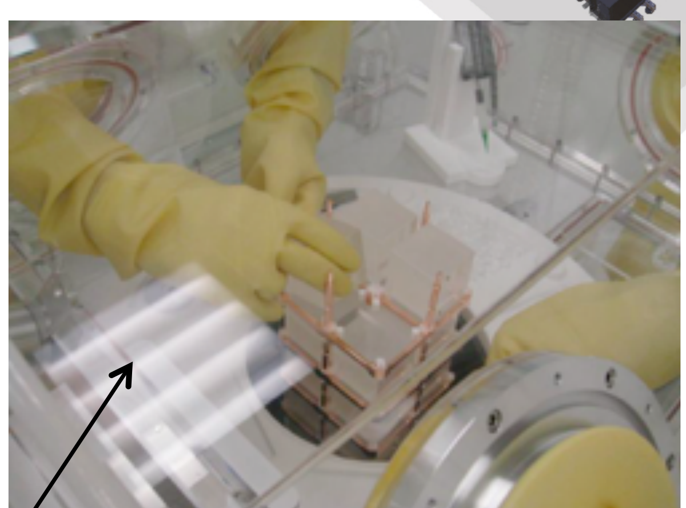
Gluing machine



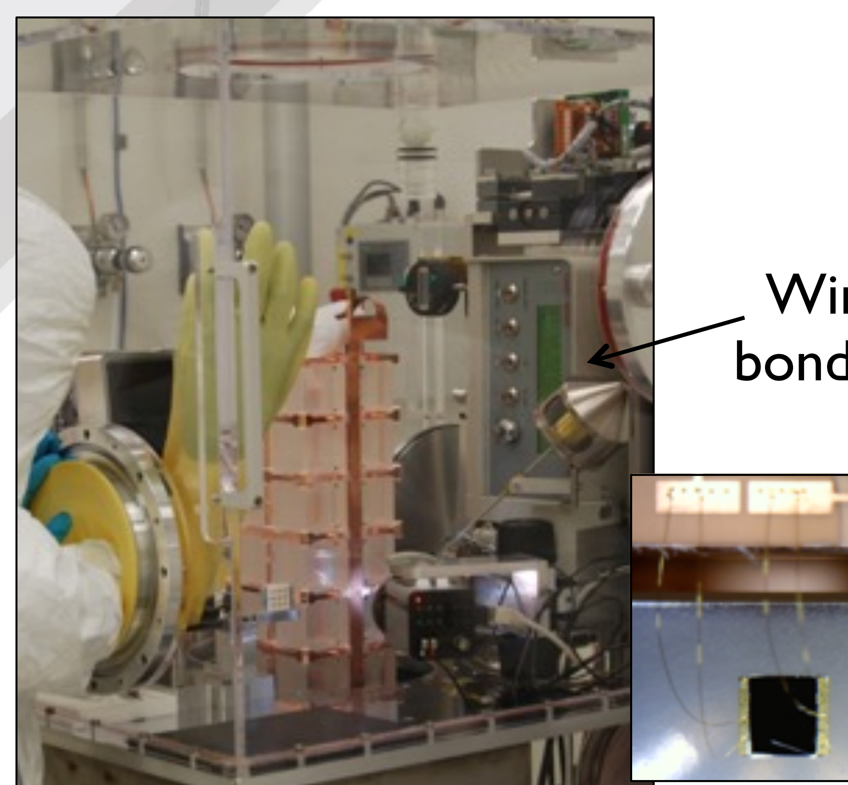




Tower garage

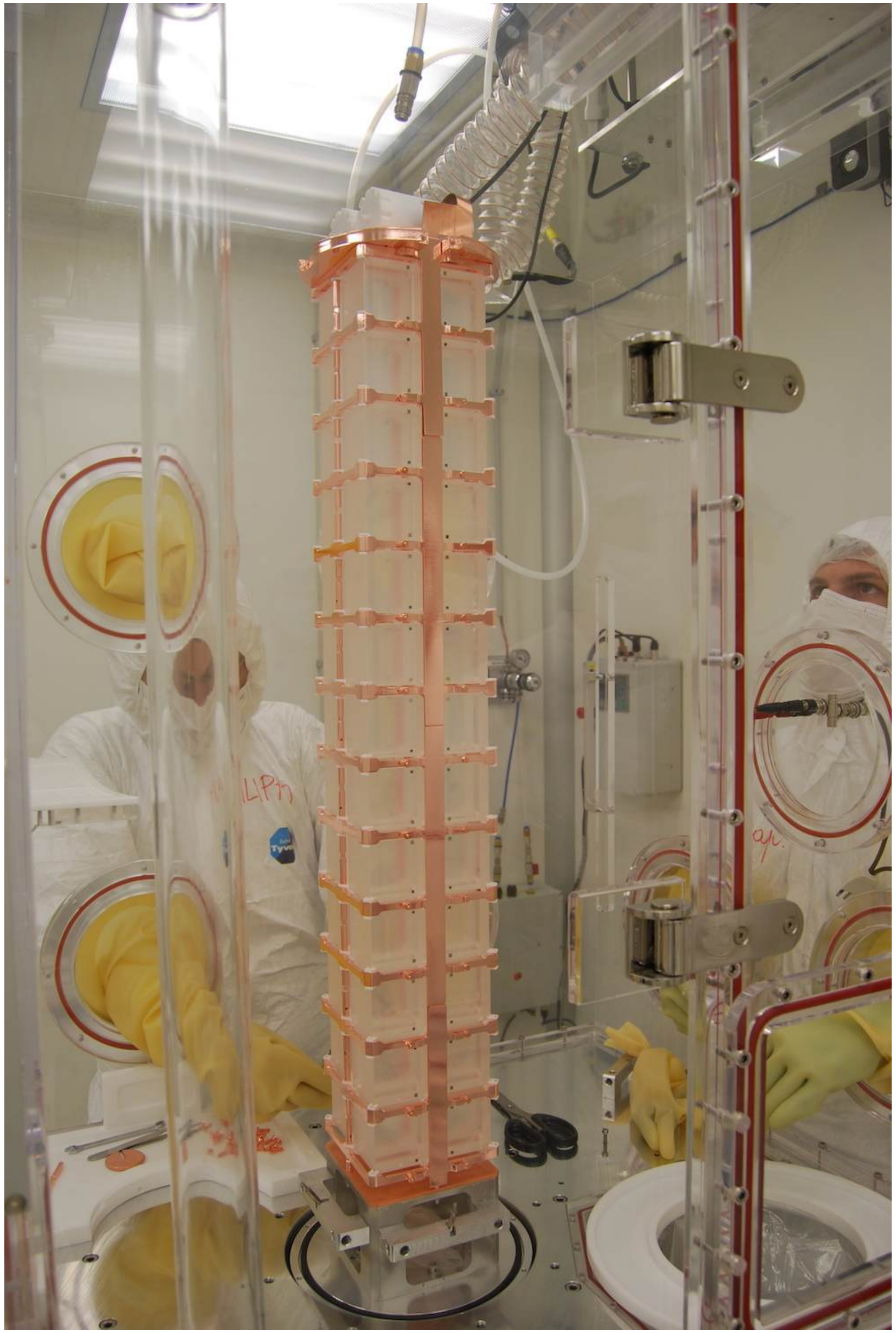


Mechanical assembly



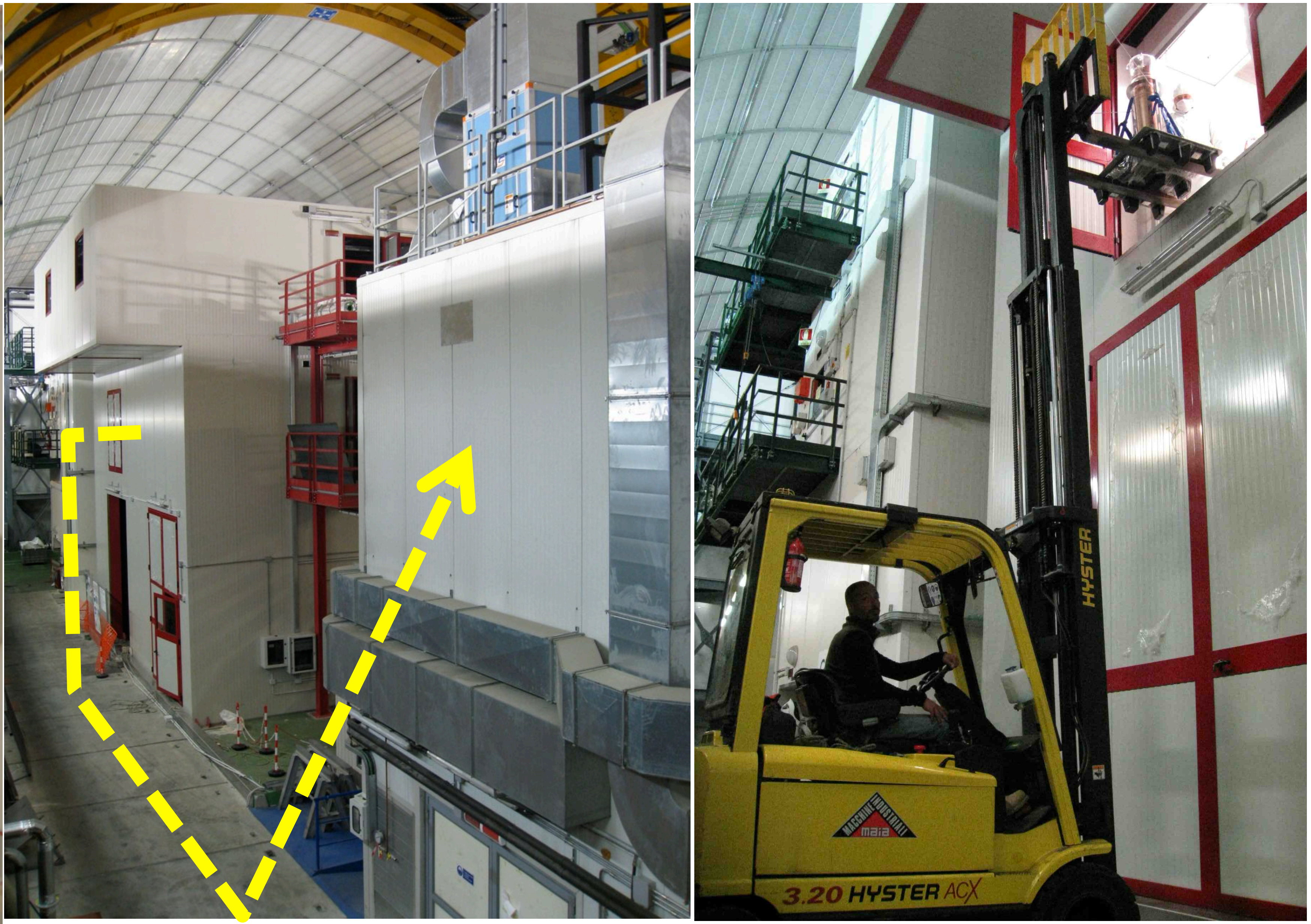
Wire bonding

Completed Tower



Tower Installation

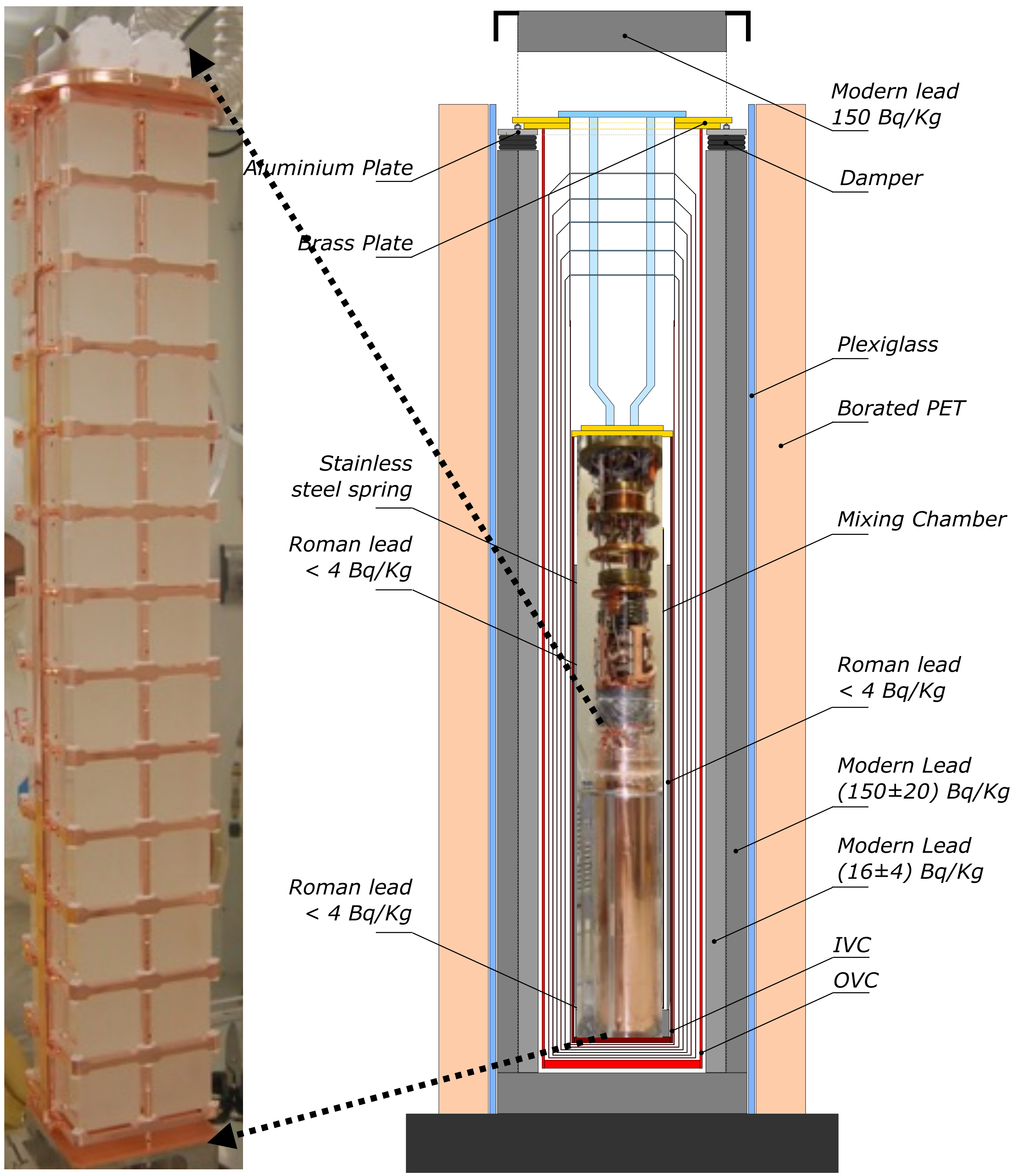
After assembly



Transported from CUORE cleanroom to Cuoricino cleanroom

Attached to Cuoricino dilution refrigerator

The CUORE-0 Experiment

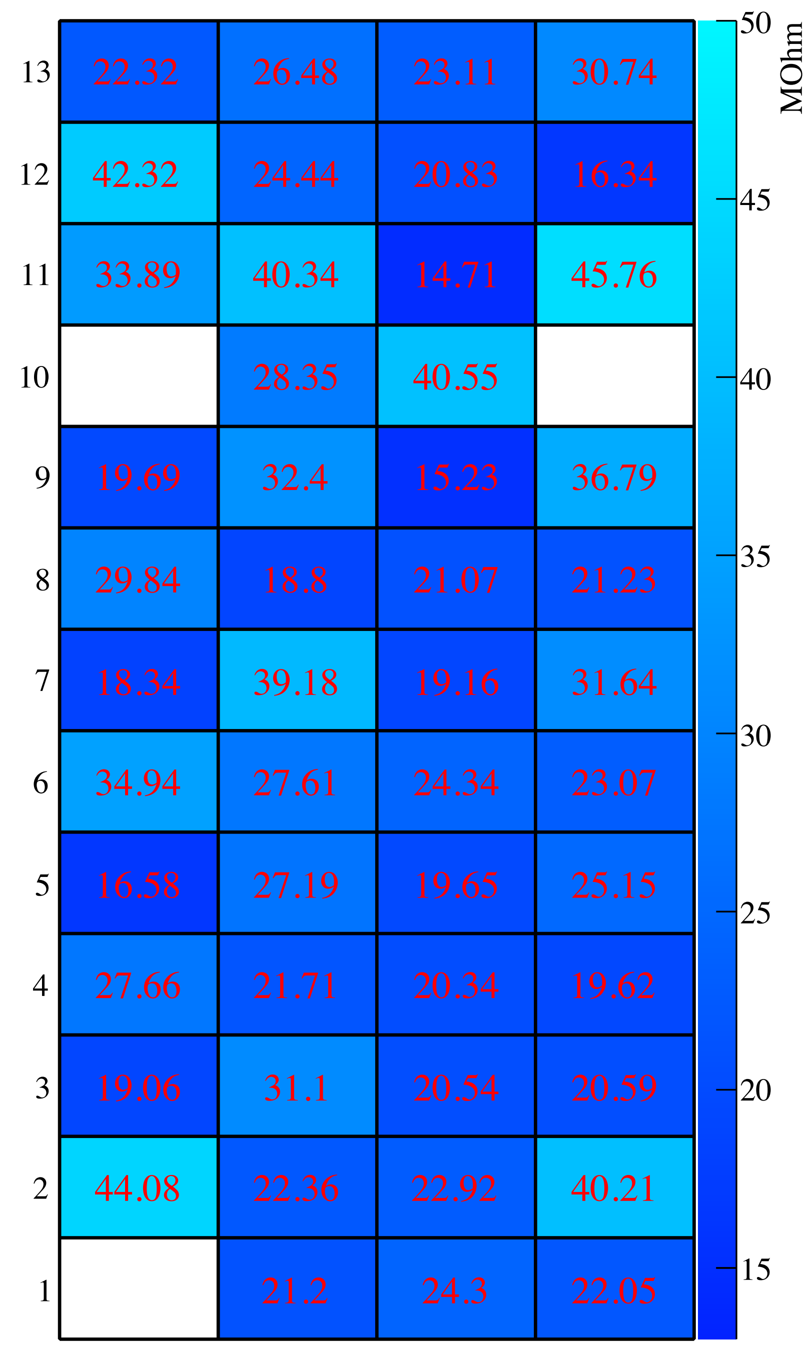


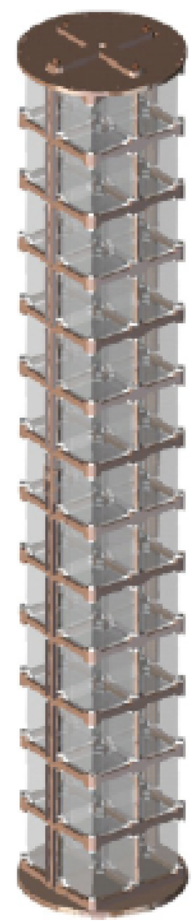
- 52 (13 x 4) crystals, 39 kg of TeO_2 (*11 kg of* ^{130}*Te*), 4 kg of copper structure.
- Validated new cleaning and assembly procedures for CUORE.
- Verified understanding on the background sources.

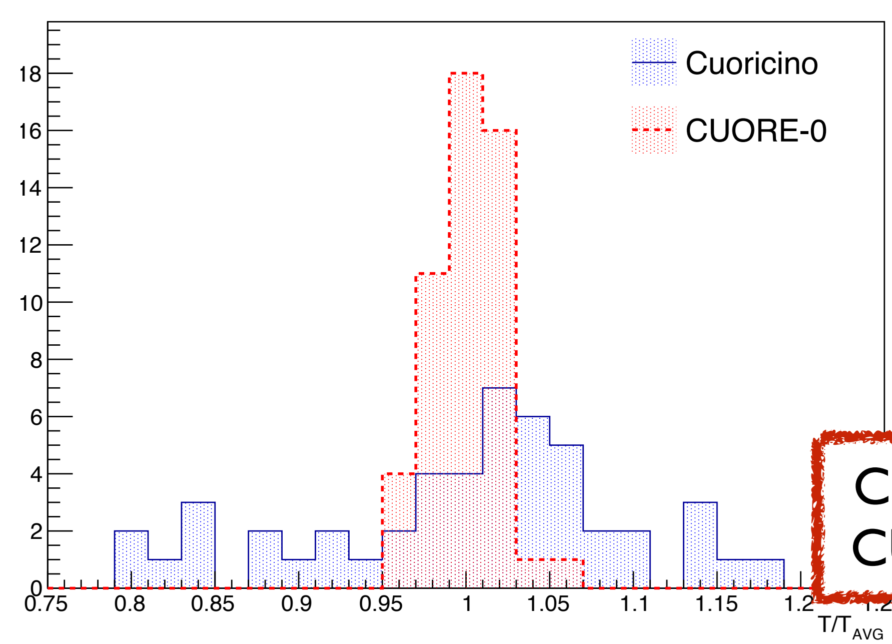
  Eur. Phys. J. C 74, 2956 (2014)
- Tested DAQ & Analysis framework for CUORE.
- Taking $0\nu\beta\beta$ data since March 2013 in former Cuoricino cryostat.

Tower Response

Run 201388 Working Resistances

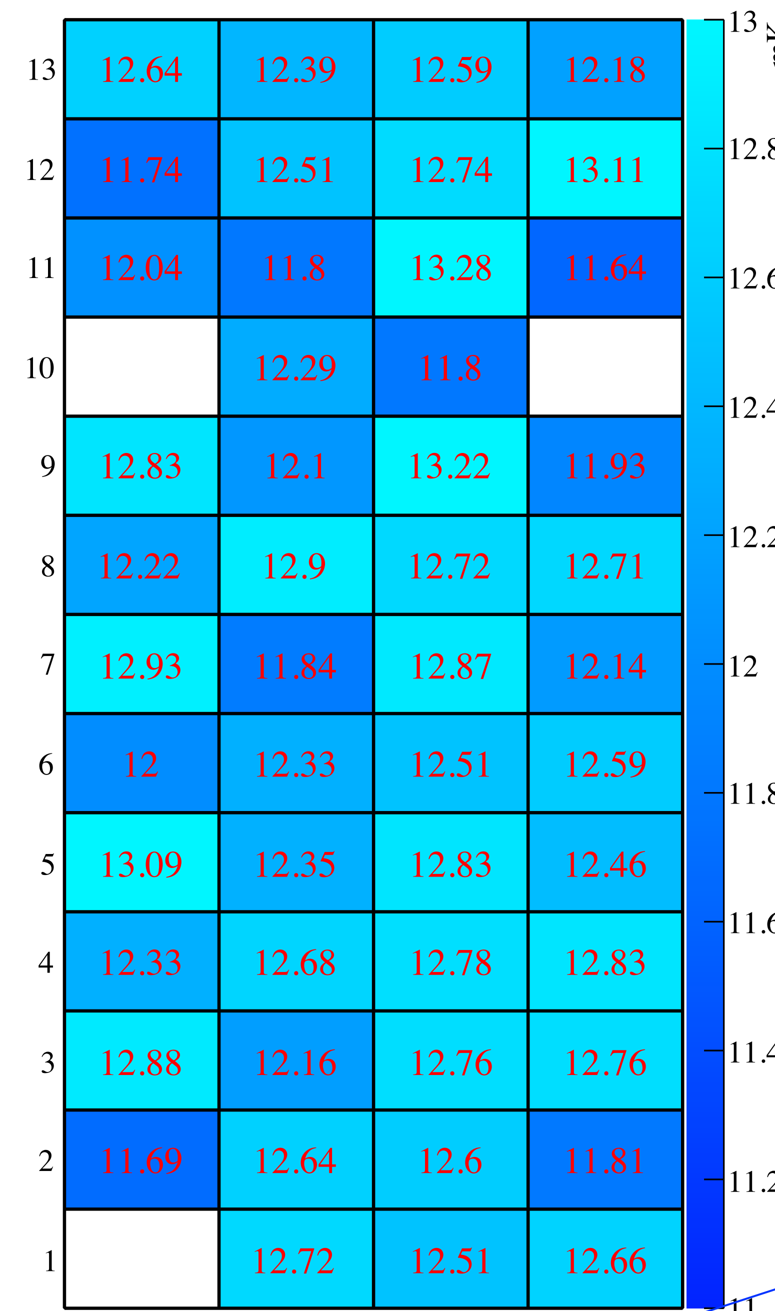






Cuoricino RMS: 9%
CUORE-0 RMS: 2%

Run 201388 Working Temperatures

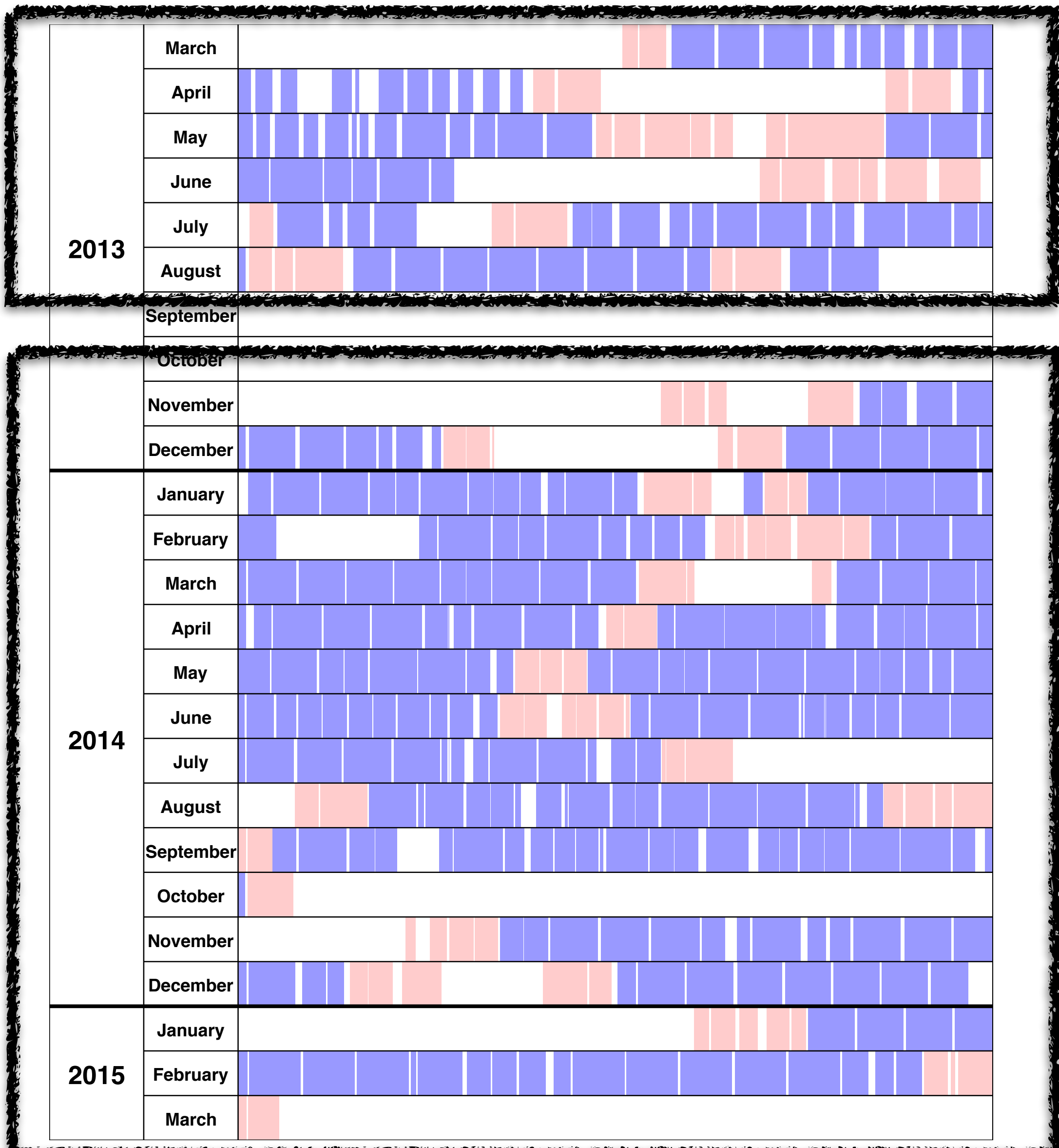


Detector paper in preparation!

Outline

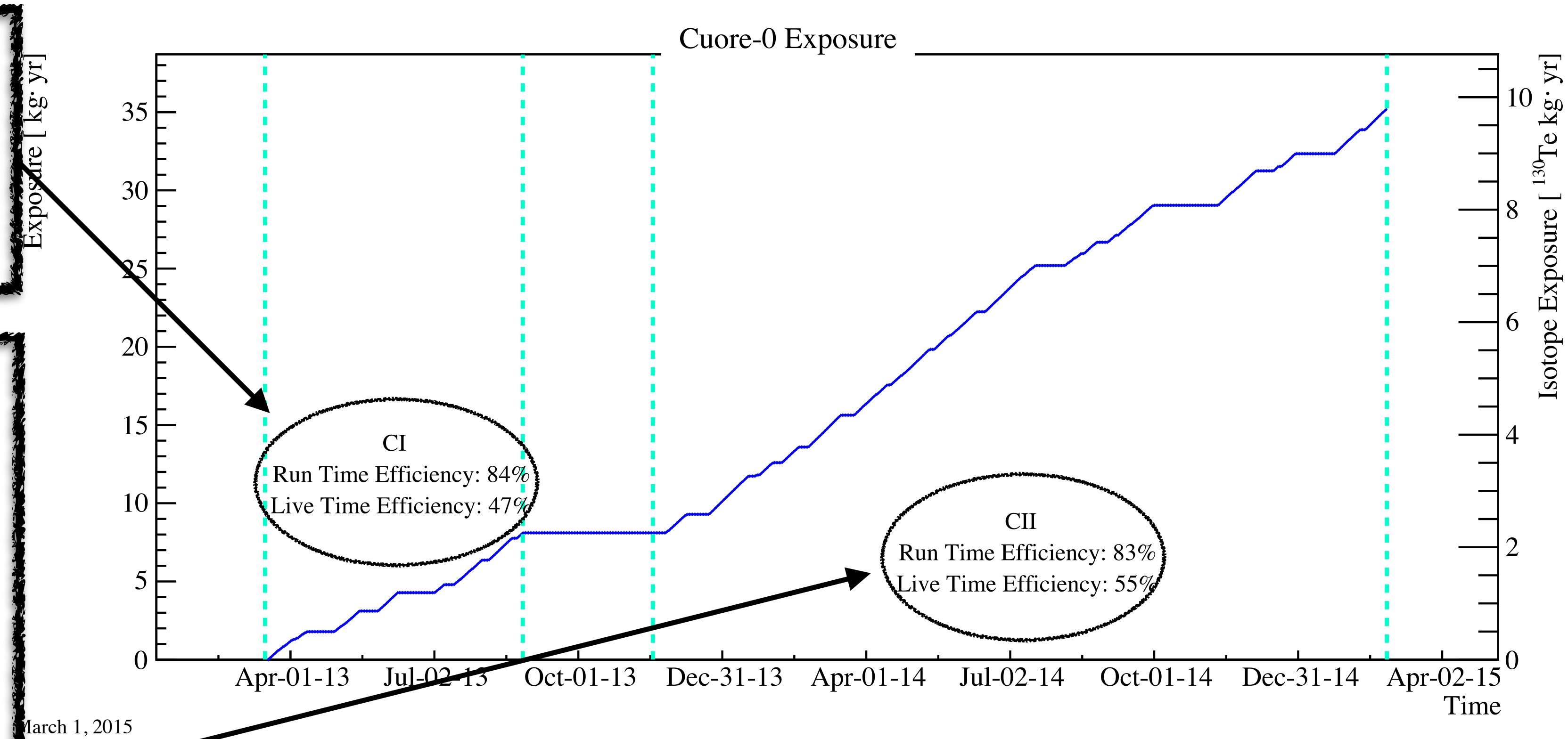
- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE : An array of TeO_2 bolometers
- CUORE-0 : $0\nu\beta\beta$ search w/ a single CUORE tower
  - CUORE-0 : Detector
  - CUORE-0 : *Resolution and Background*
  - CUORE-0 : Results
- Summary

Data Taking



Physics data

Calibration data

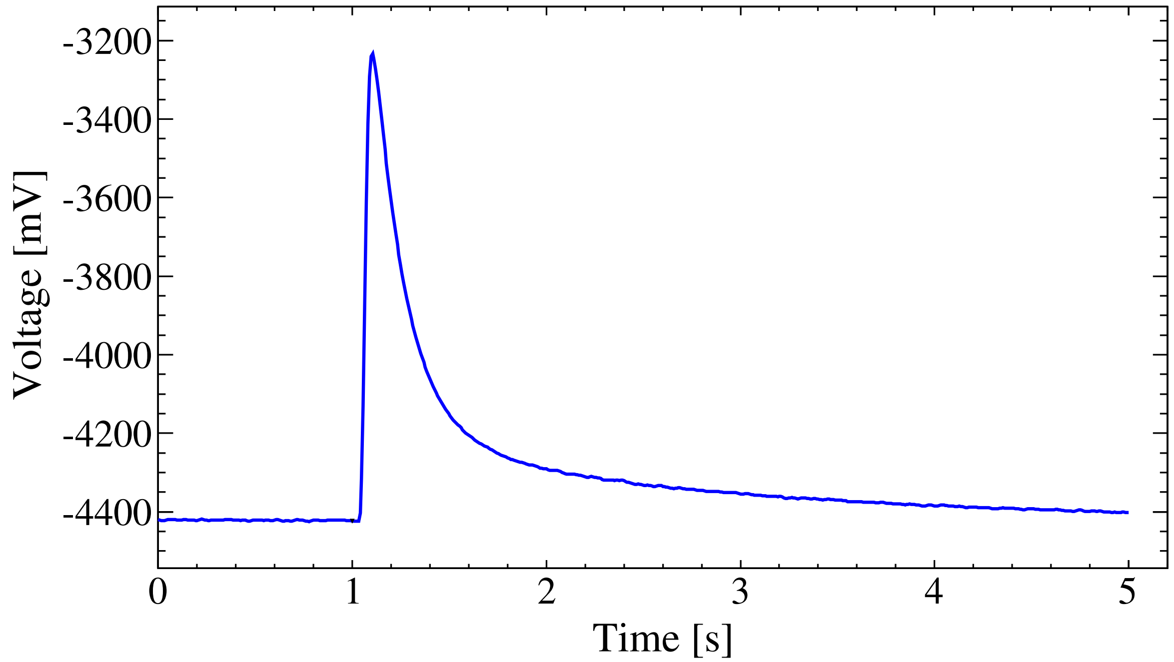


- Start data taking in March 2013
- Cryogenic maintenance between campaigns
- Acquired $0\nu\beta\beta$ data till March 2015
- 35.2 kg-yr of $^{nat}TeO_2$
- 9.8 kg-yr of ^{130}Te

Analysis Procedure: Experimental Input

Data Acquisition
continuously sample and record the bolometer signal @ 125 S/s

Bolometer Pulse



Raw Data Processing
- software trigger thresholds (30-120 keV)
- signal, noise, pulser events
- filter pulse to optimize energy resolution
- signal (thermal) gain correction
- energy calibration (V → keV)

Blinding

ROOT
Data Trees

Event Selection
- remove low quality events
- single pulse in 7.1s window
- require pulse shape to be expected signal
- no other pulse in coincidence in other bolometers

Analysis efficiency!

Reduced Data

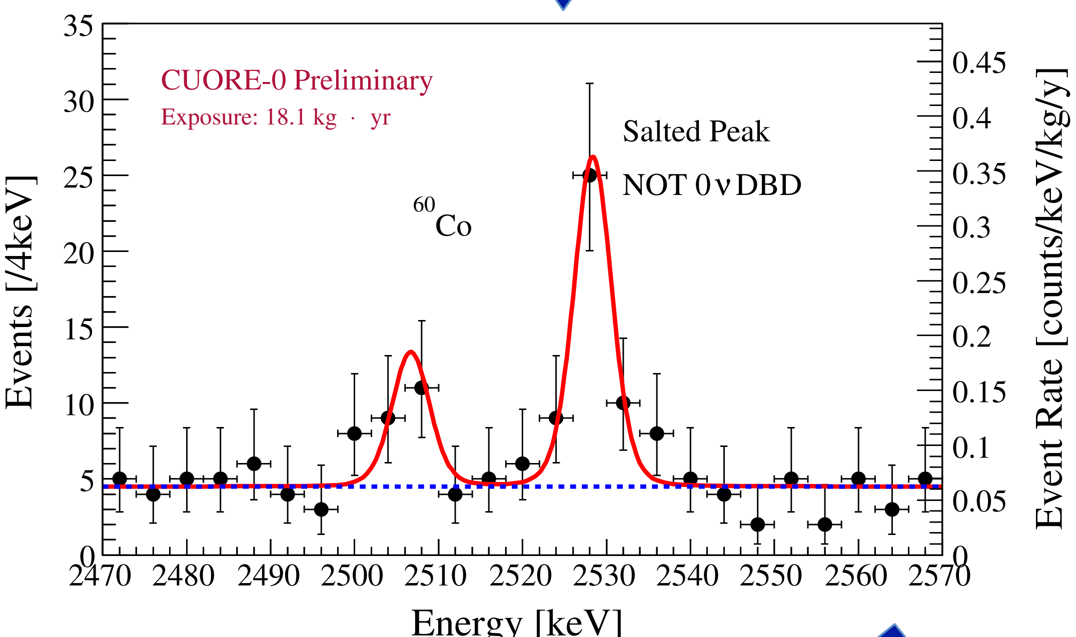
Experimental Input

calibration, $0\nu\beta\beta$ data

background estimation, energy resolution

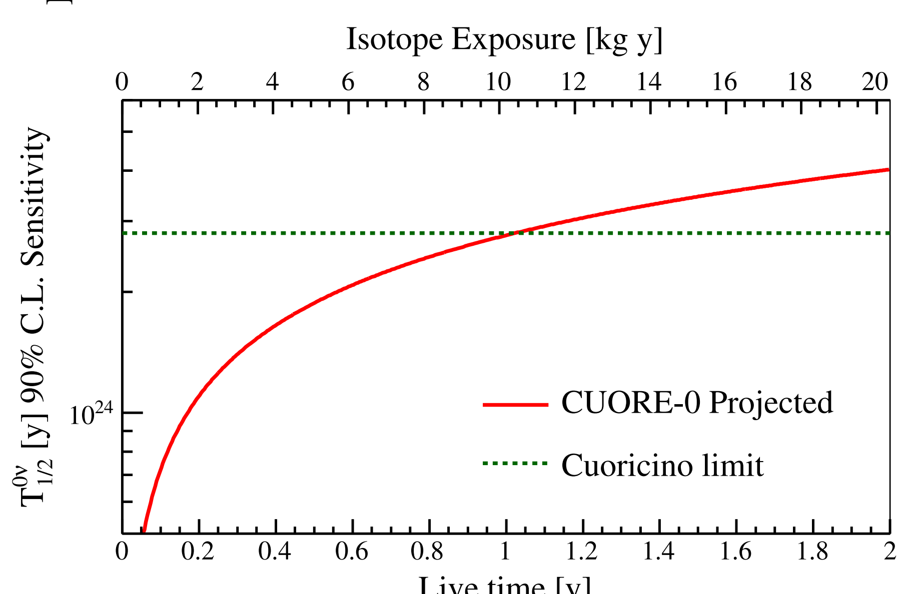
Analysis Procedure: Results & Interpretation

Data Acquisition → **Raw Data Processing** → **Event Selection** → **Experimental Input**

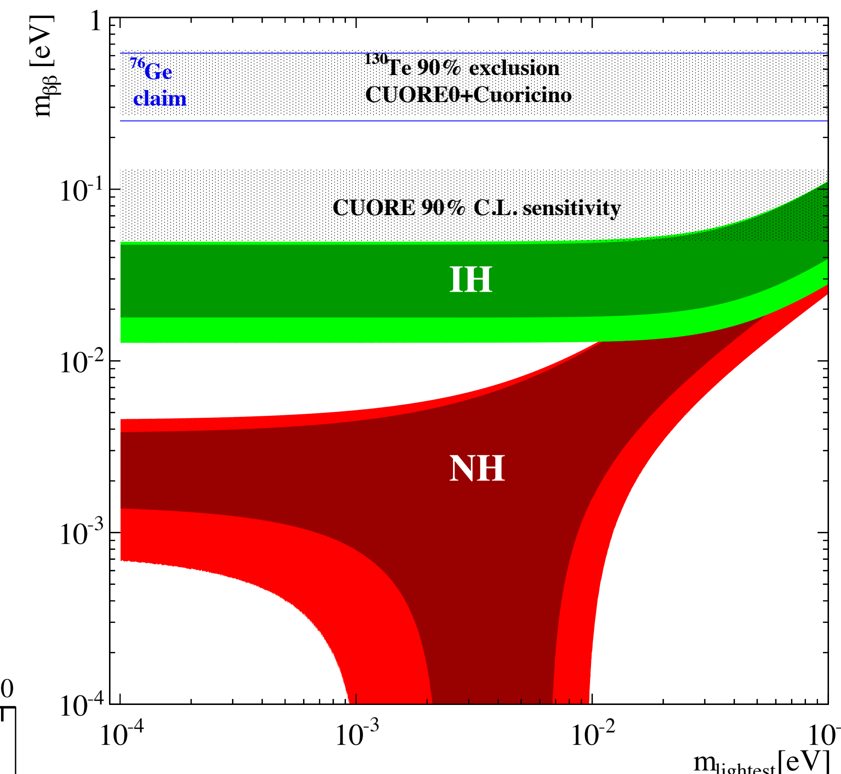


Statistical Treatment

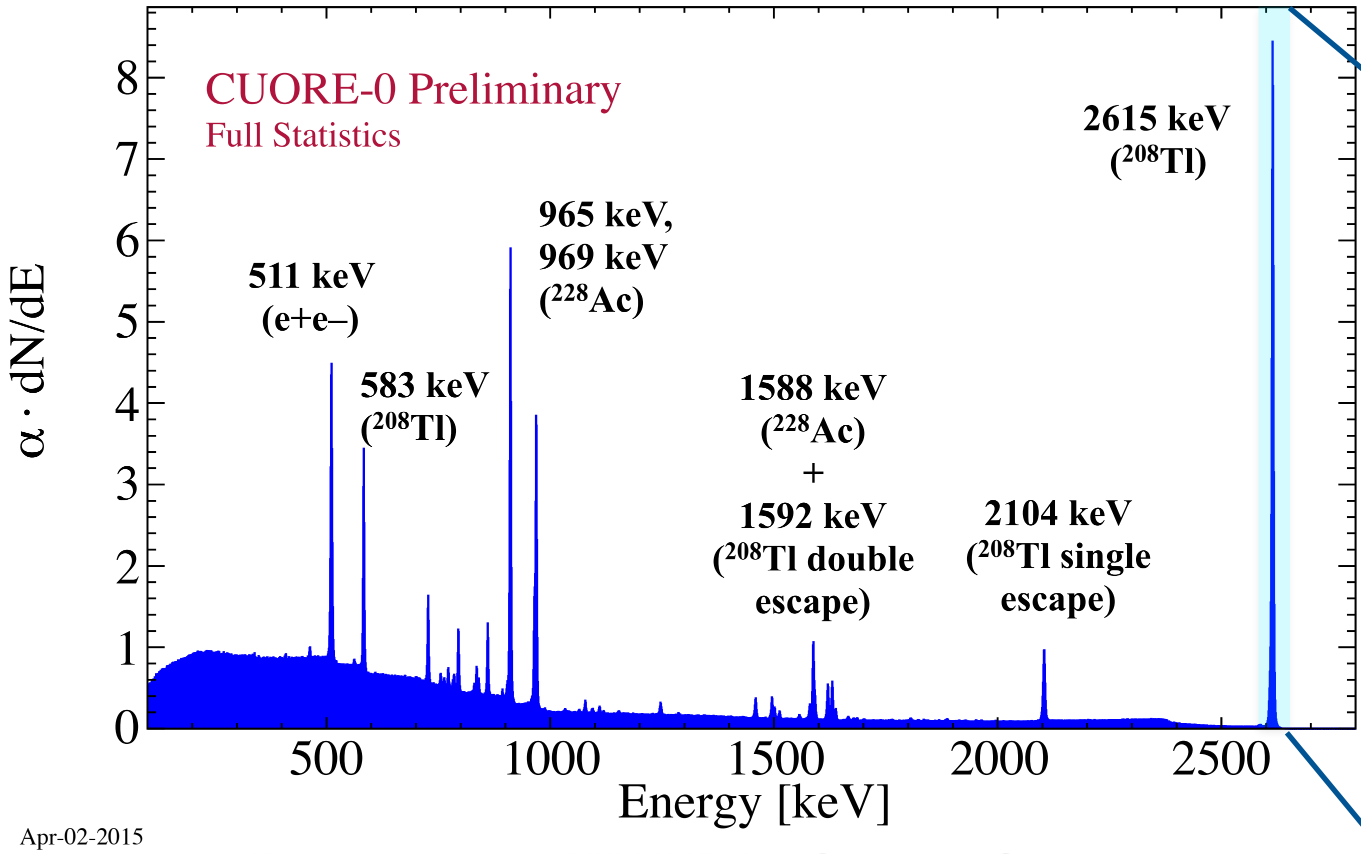
Unbinned likelihood (UEML) fit
Bayesian approach

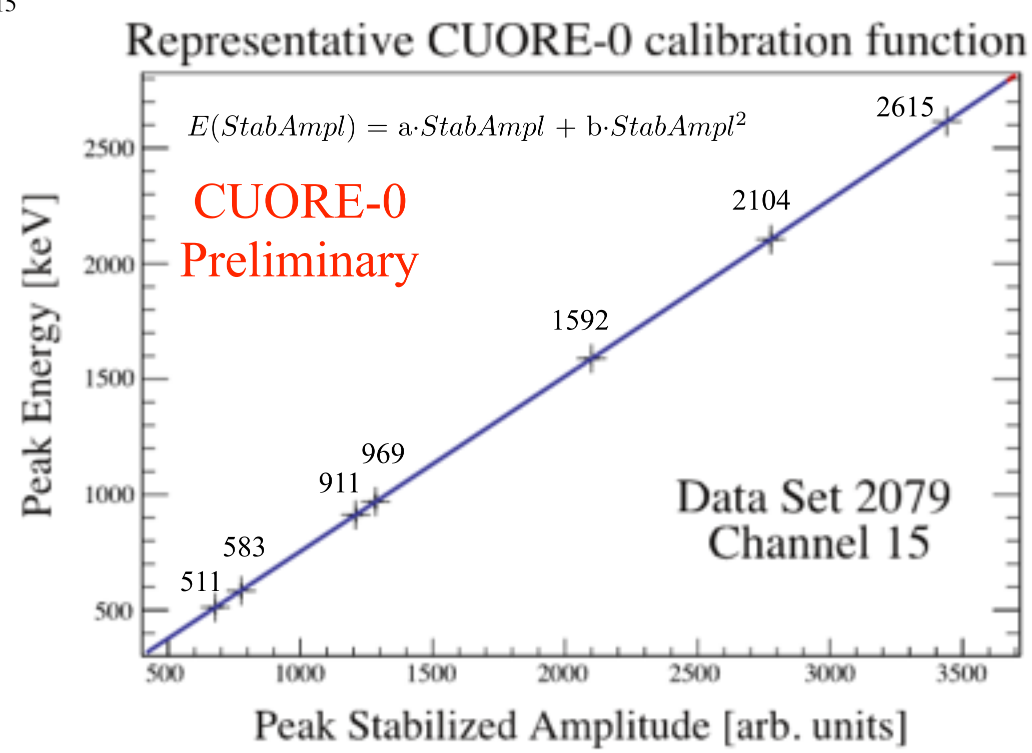


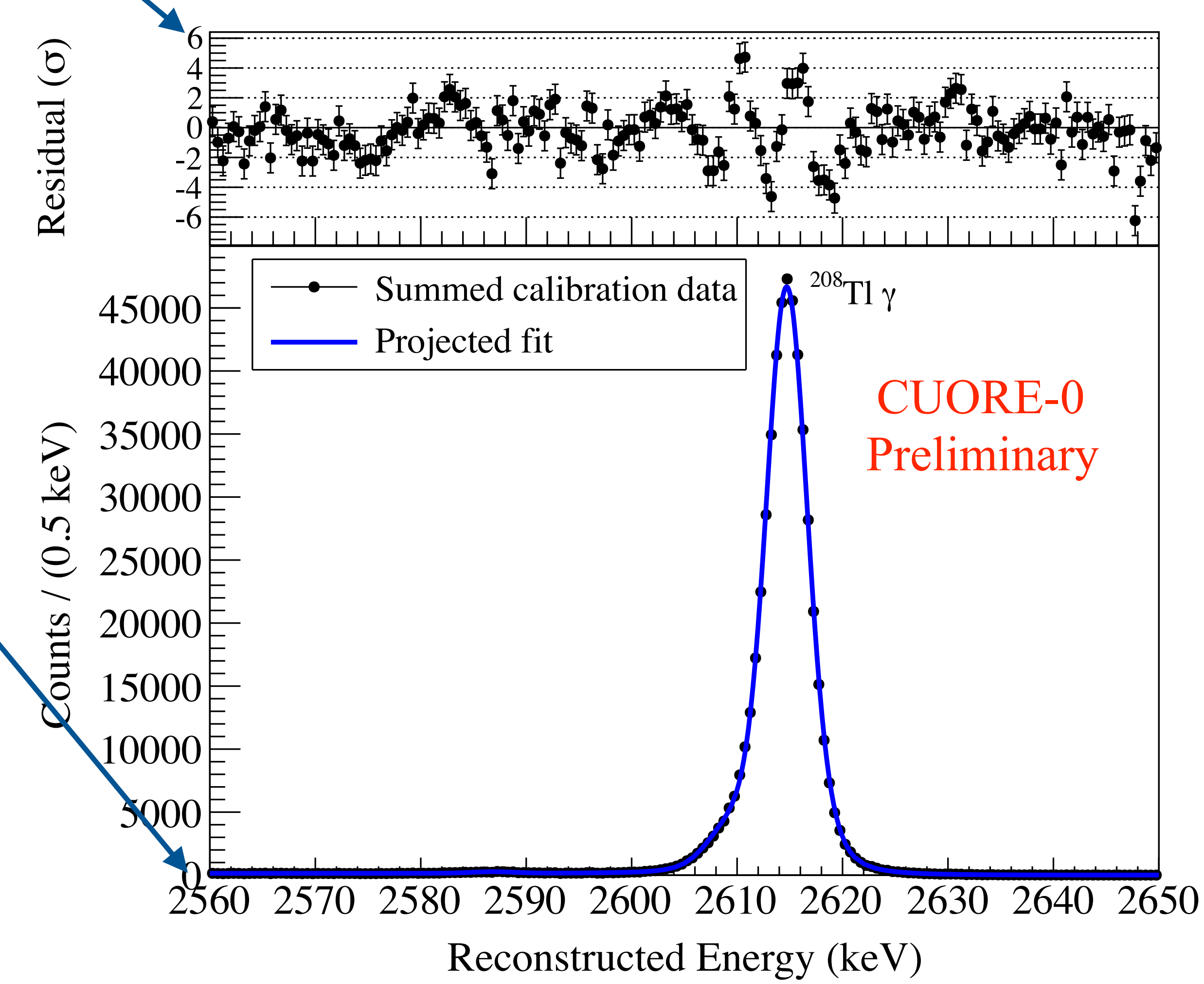
Nuclear Physics



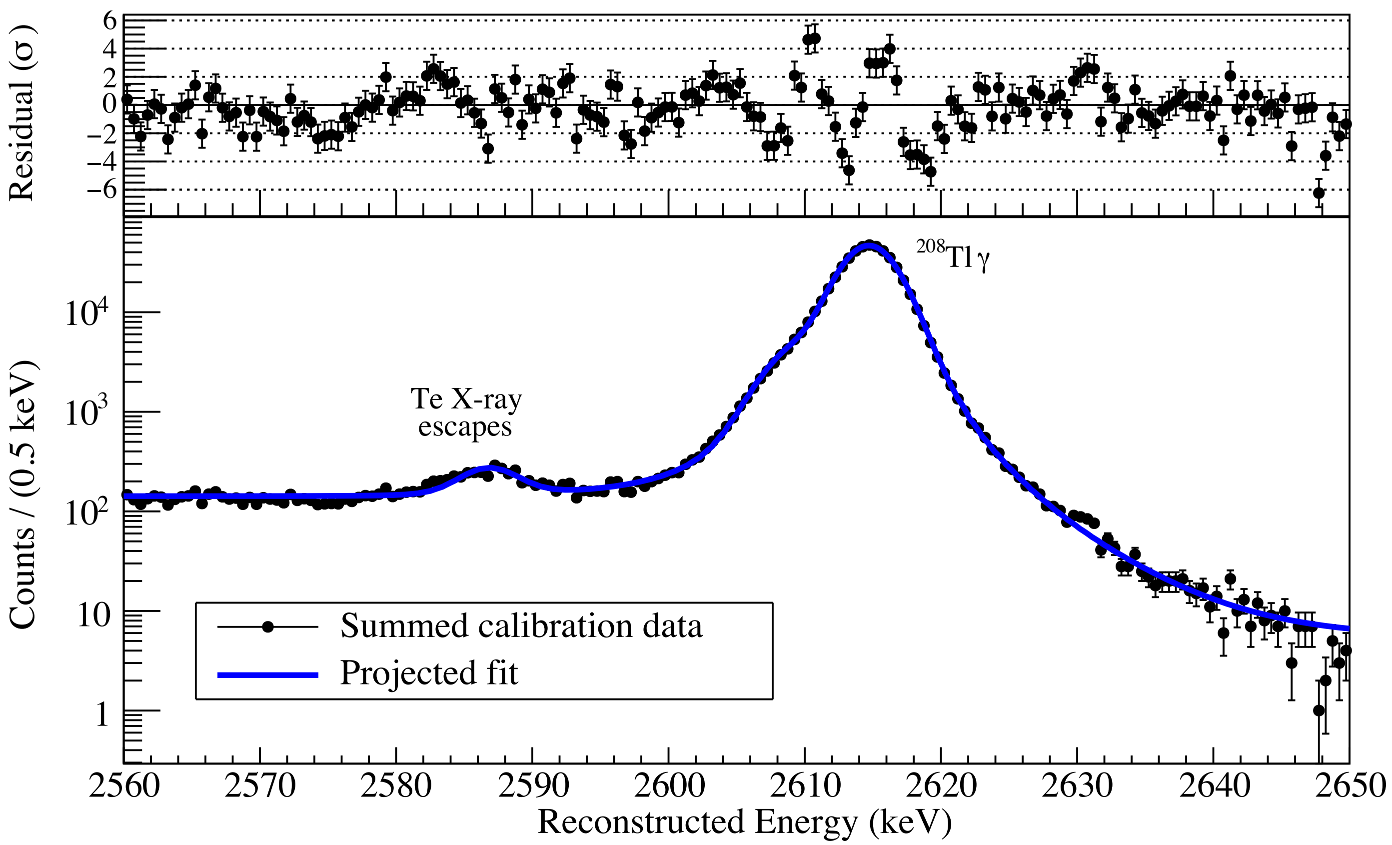
Calibration Spectrum

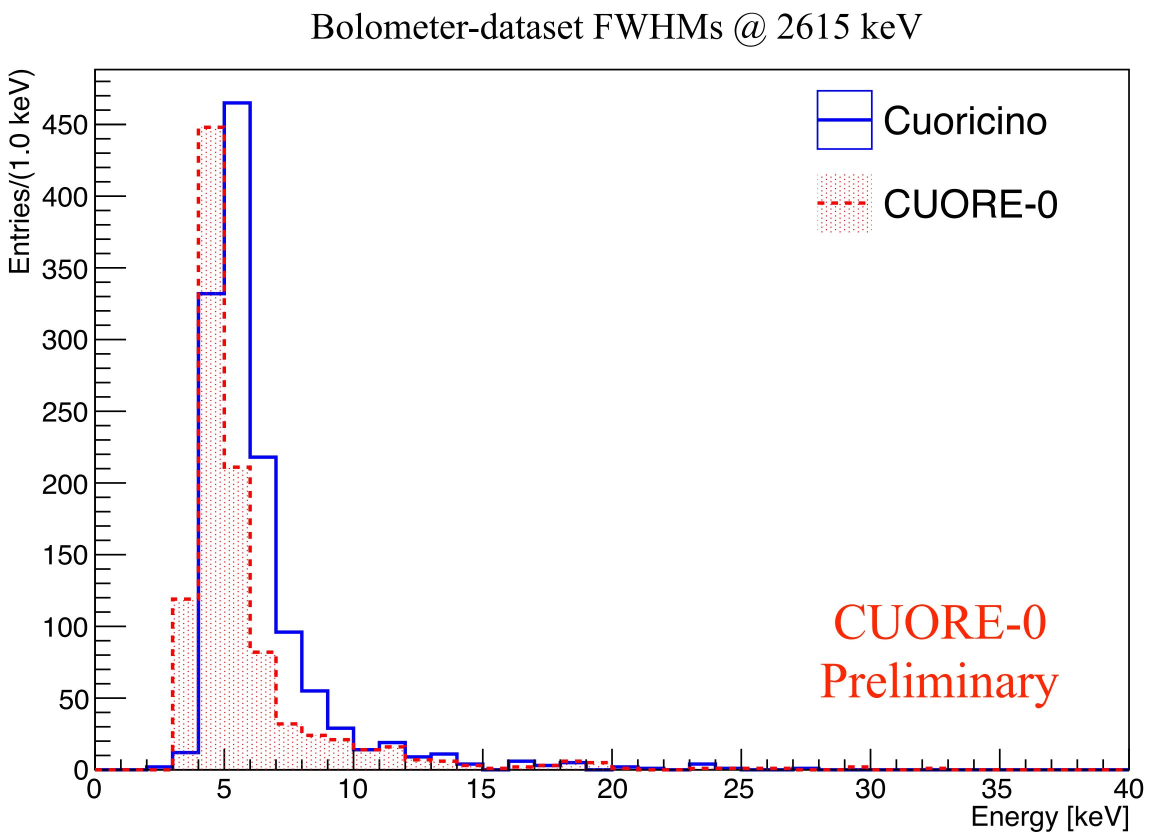






Energy Resolution



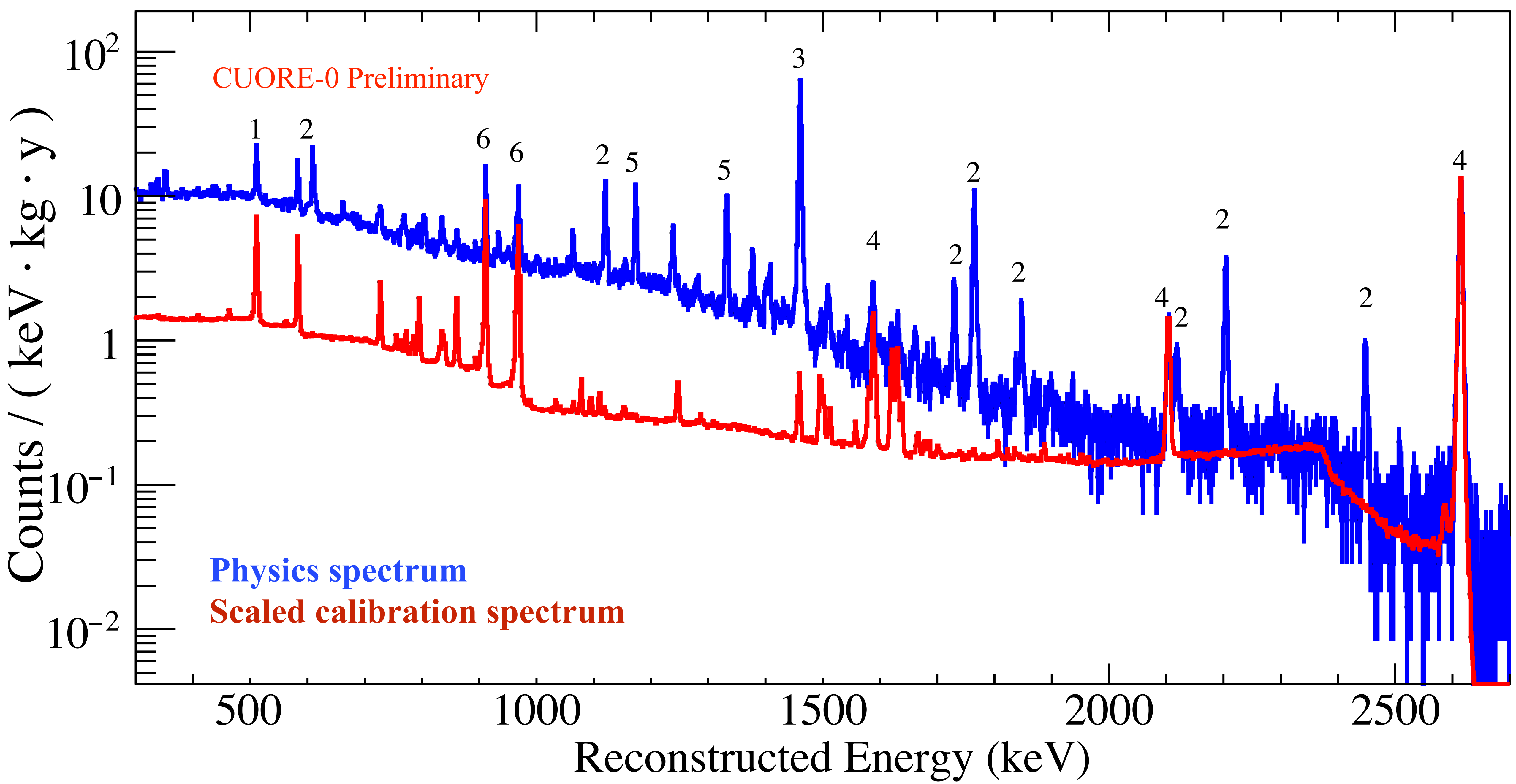


Weight FWHMs by corresponding exposure

	FWHM harmonic mean [keV]	FWHM dist RMS [keV]
Cuoricino	5.8	2.1
CUORE-0	4.9	2.9

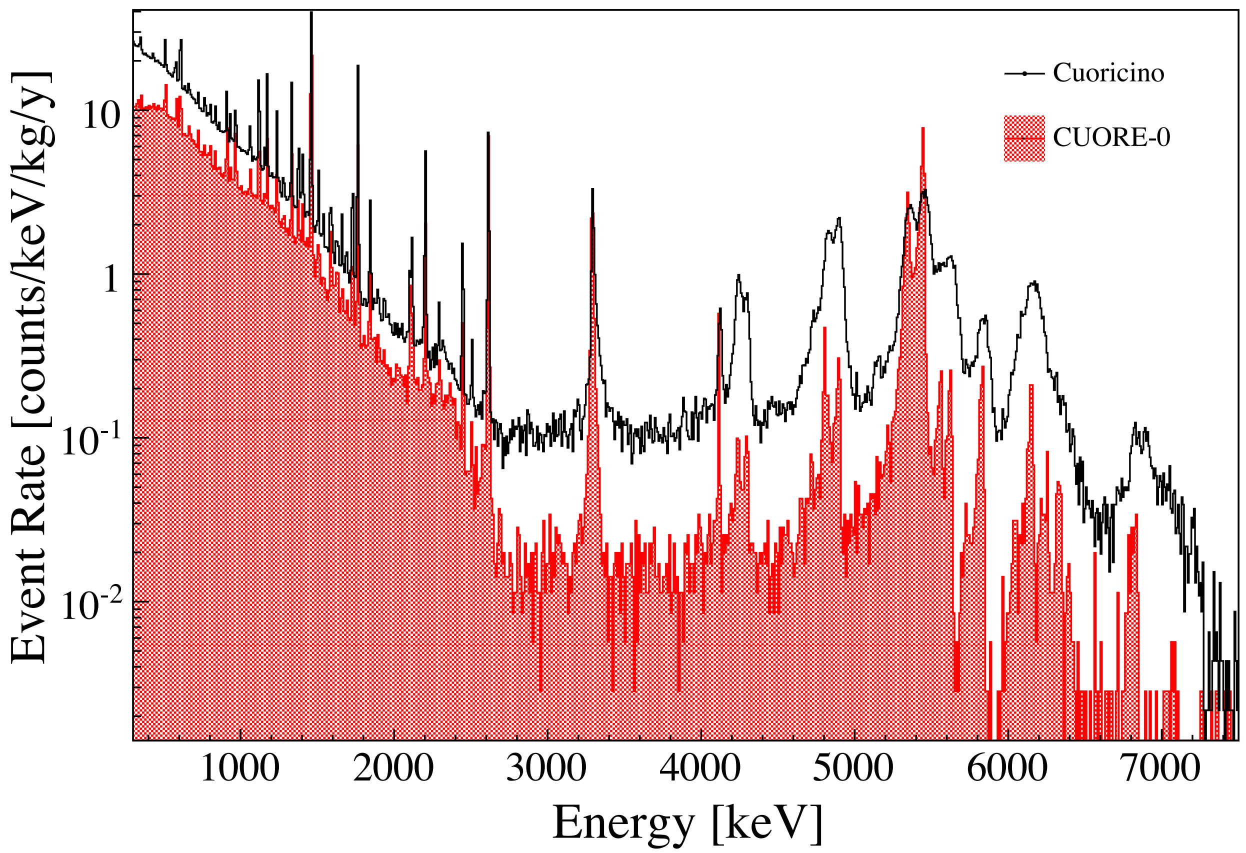
- Energy resolution is evaluated for each bolometer and dataset by fitting the 2615 keV peak from ^{208}Tl in the calibration data.
- The obtained resolution is < 5 keV, which is the CUORE goal.

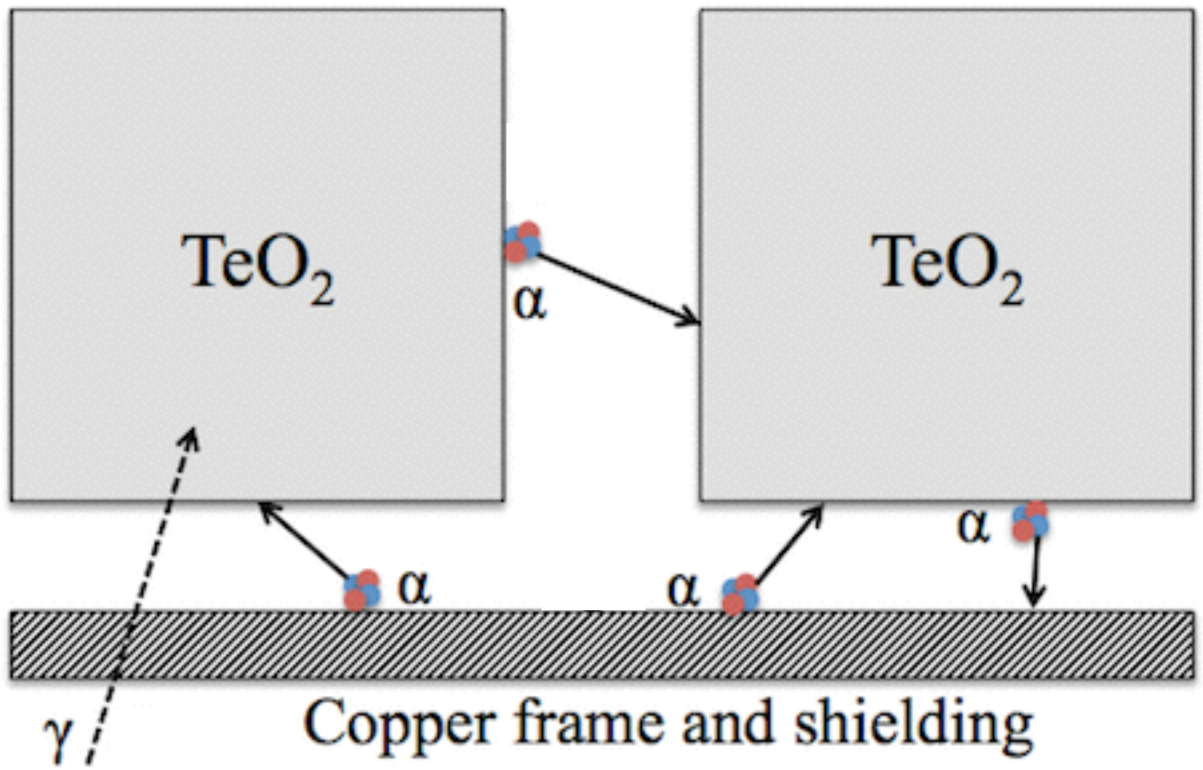
Background Spectrum



(1)e+e-, (2)^{214}Bi, (3)^{40}K, (4)^{208}Tl, (5)^{60}Co, (6)^{228}Ac

Background Comparison with Cuoricino

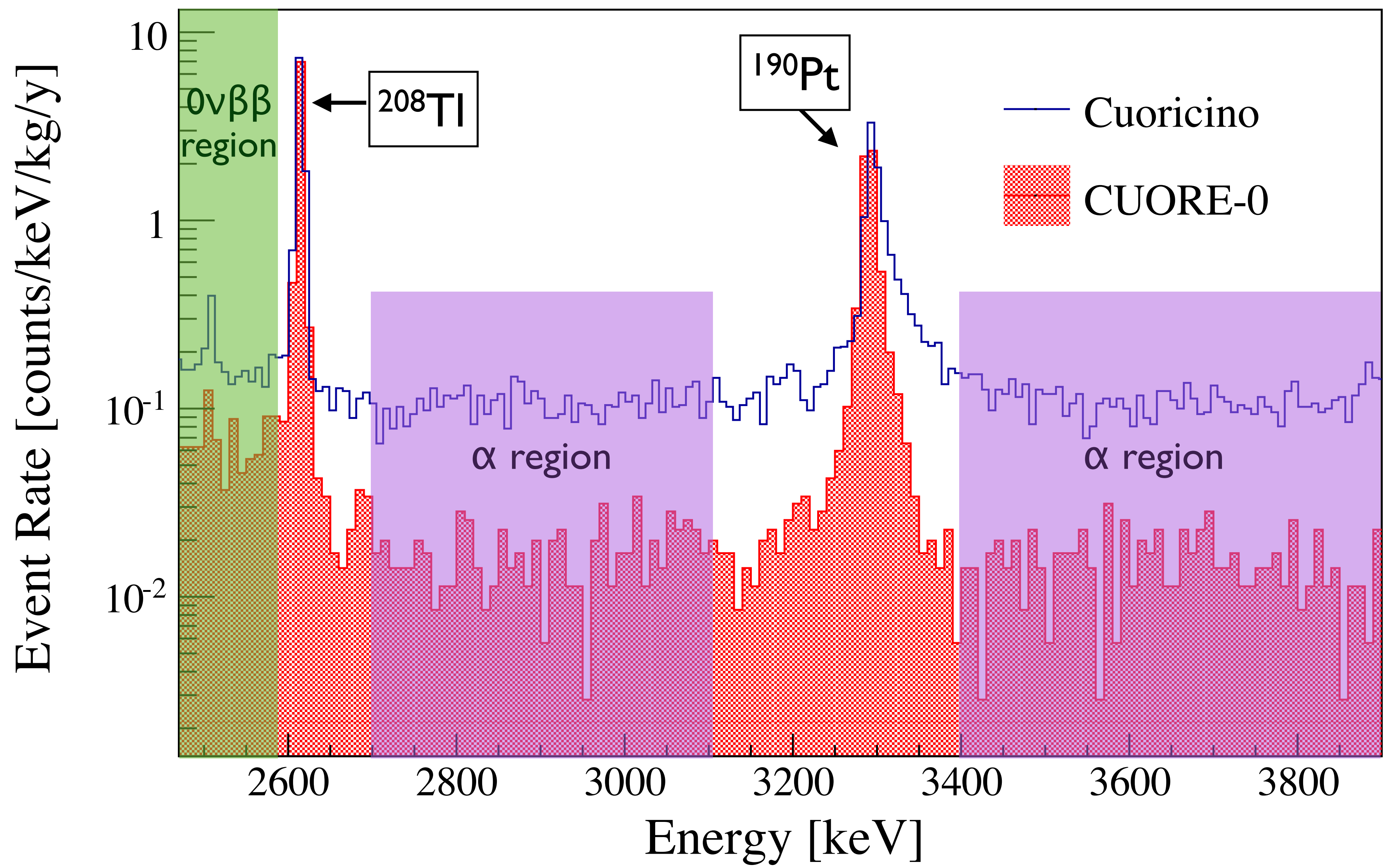




- γ background (from ^{232}Th) was not reduced since the cryostat remained the same.
- γ background (from ^{238}U chain) was reduced by a factor of 2.5 due to better radon control.
- α background from copper surface and crystal surface was reduced by a factor of 6.5 thanks to the new detector surface treatment.
- Demonstrate CUORE sensitivity goal is within reach.

Background paper in preparation!

Background Rate



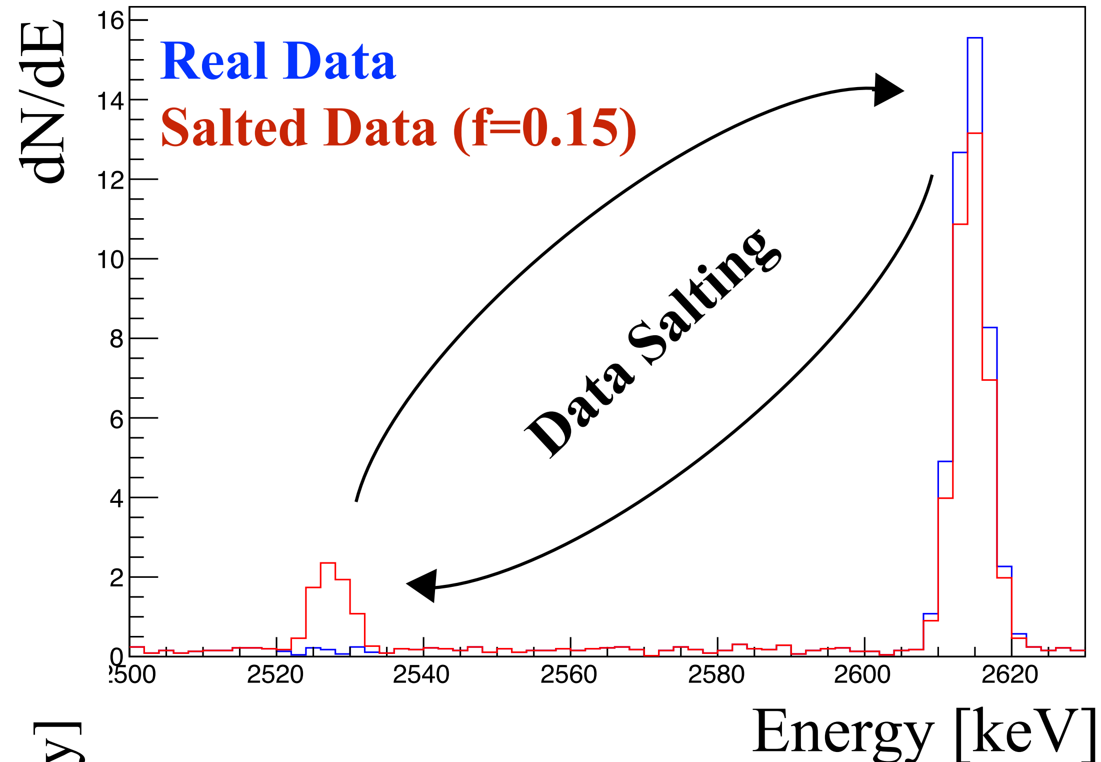
	Background rate [counts/keV/kg/y]		signal eff. [%] (detector+cuts)
	0νββ region	α region (excl. peak)	
Cuoricino	0.169 ± 0.006	0.110 ± 0.001	82.8±1.1
CUORE-0	0.058 ± 0.011	0.016 ± 0.001	81.3±0.6

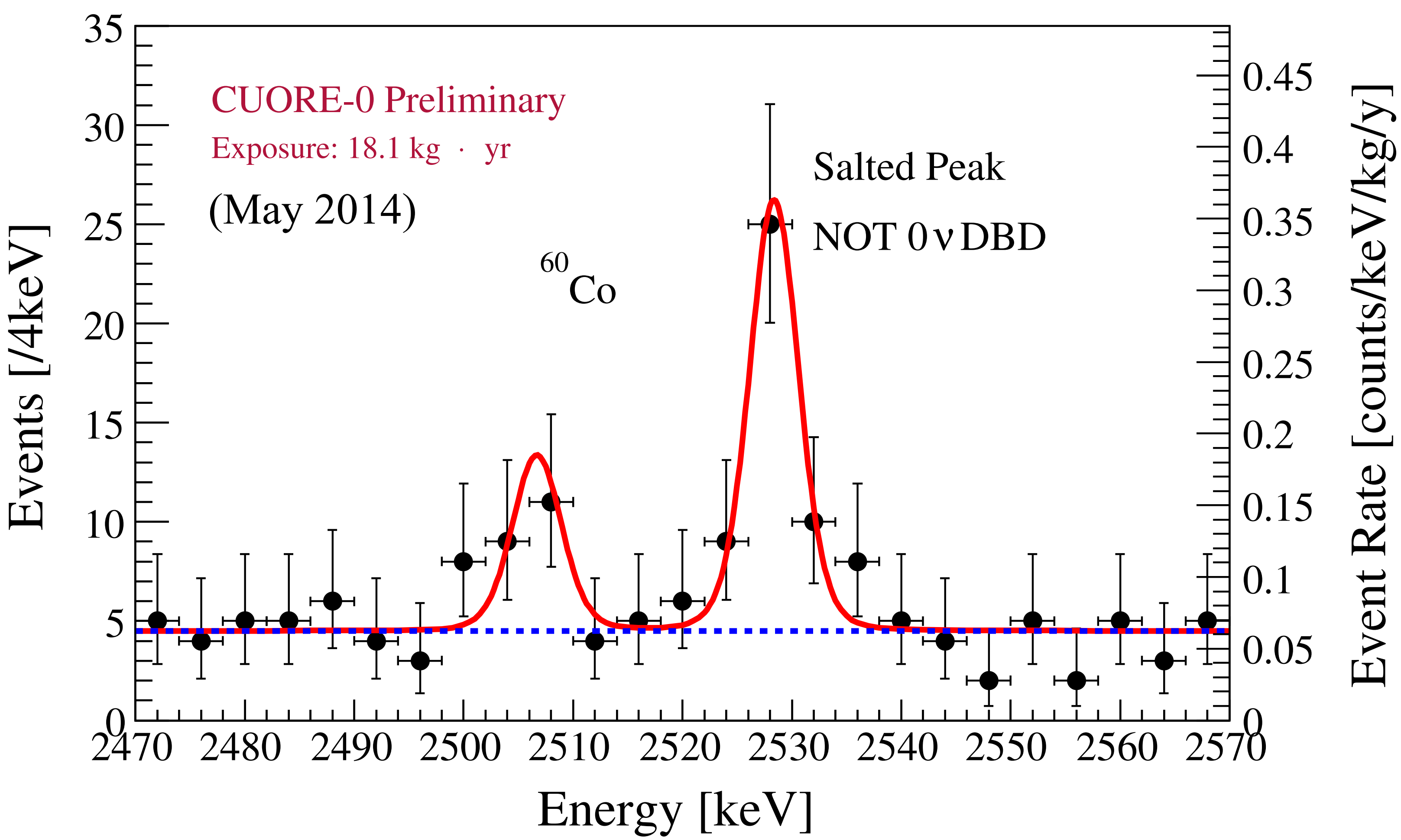
Outline

- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE : An array of TeO_2 bolometers
- CUORE-0 : $0\nu\beta\beta$ search w/ a single CUORE tower
  - CUORE-0 : Detector
  - CUORE-0 : Resolution and Background
  - CUORE-0 : *Results*
- Summary

Blinding 0νββ Region

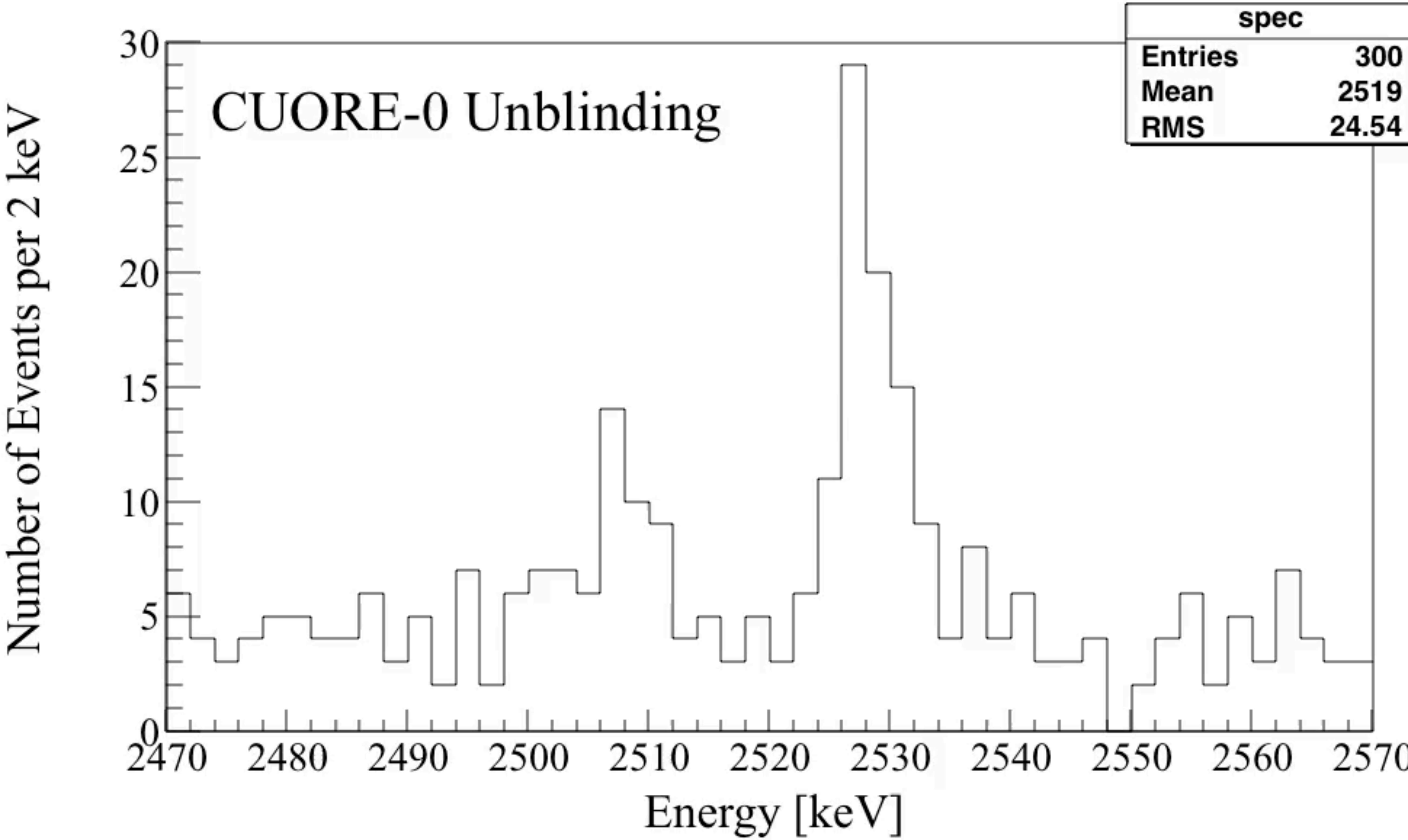
- Region of Interest was blinded by "salting" : A small (and ***blinded***) fraction of the events within ±10 keV in ^{208}Tl photopeak are exchanged with events within ±10 keV of the 0νββ Q-value to produce a ***fake*** peak.





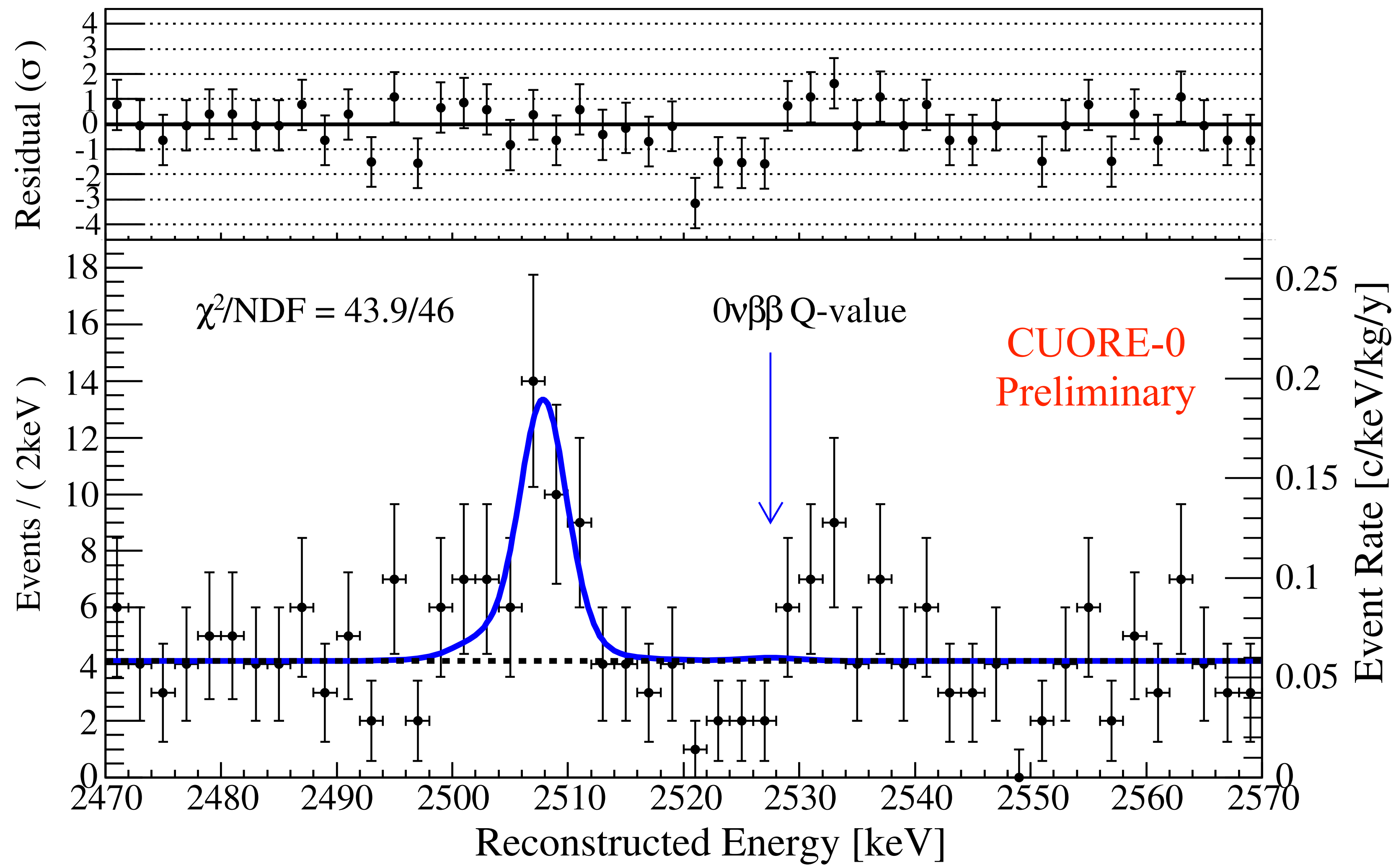
- Background at ROI can be characterized without biasing 0νββ analysis.

Unblinding



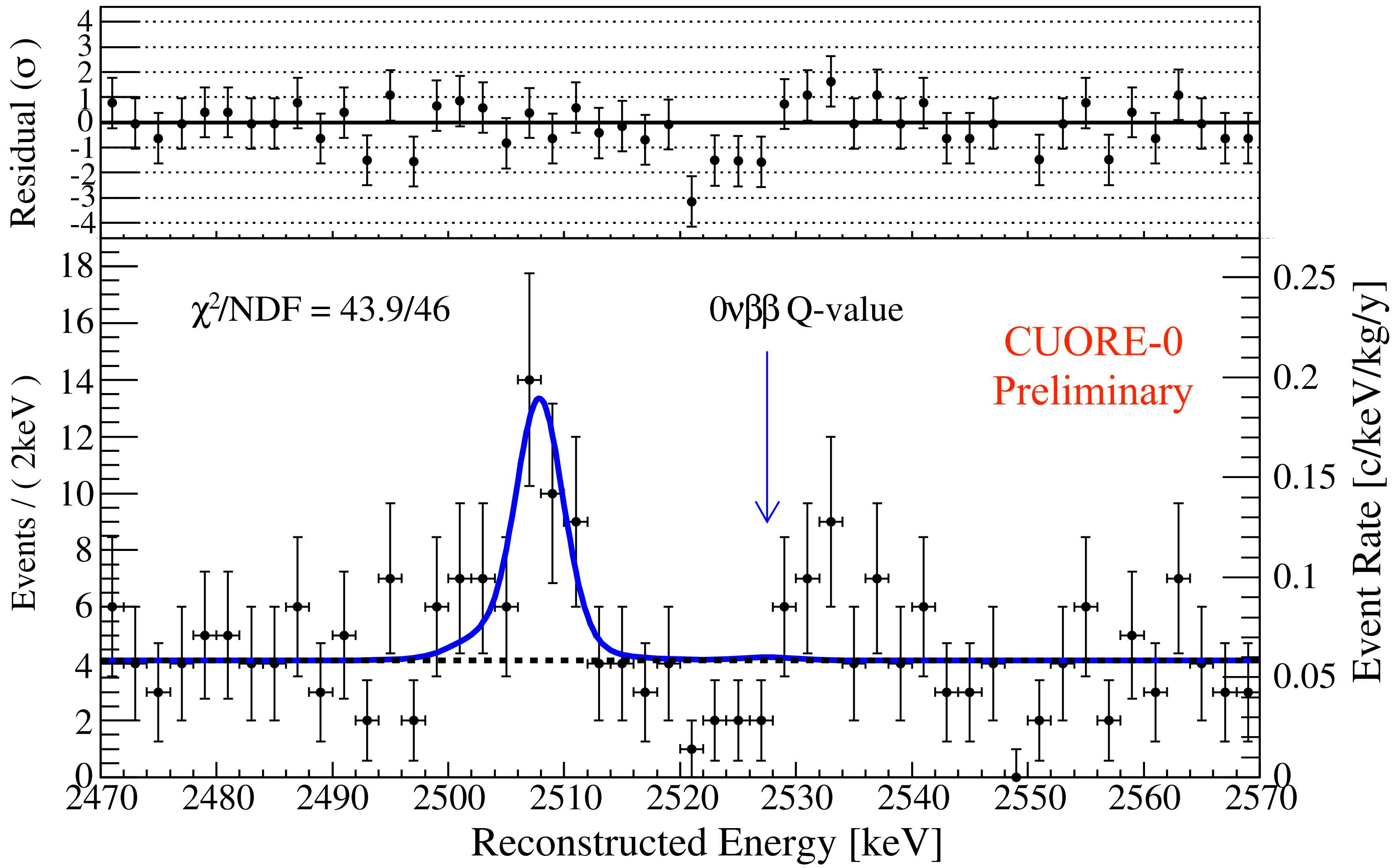
spec
Entries 300
Mean 2519
RMS 24.54
CUORE-0 Unblinding
Number of Events per 2 keV
Energy [keV]
0
5
10
15
20
25
30
2470
2480
2490
2500
2510
2520
2530
2540
2550
2560
2570

Fit to the Unblinded ROI



- Simultaneous unbinned extended ML fit to range [2470,2570] keV
- Fit function has 3 components:
  1. Calibration-derived lineshape modeling posited fixed at 2527.5 keV
  2. Calibration-derived lineshape modeling Co peak floated around 2505 keV
  3. Continuum background

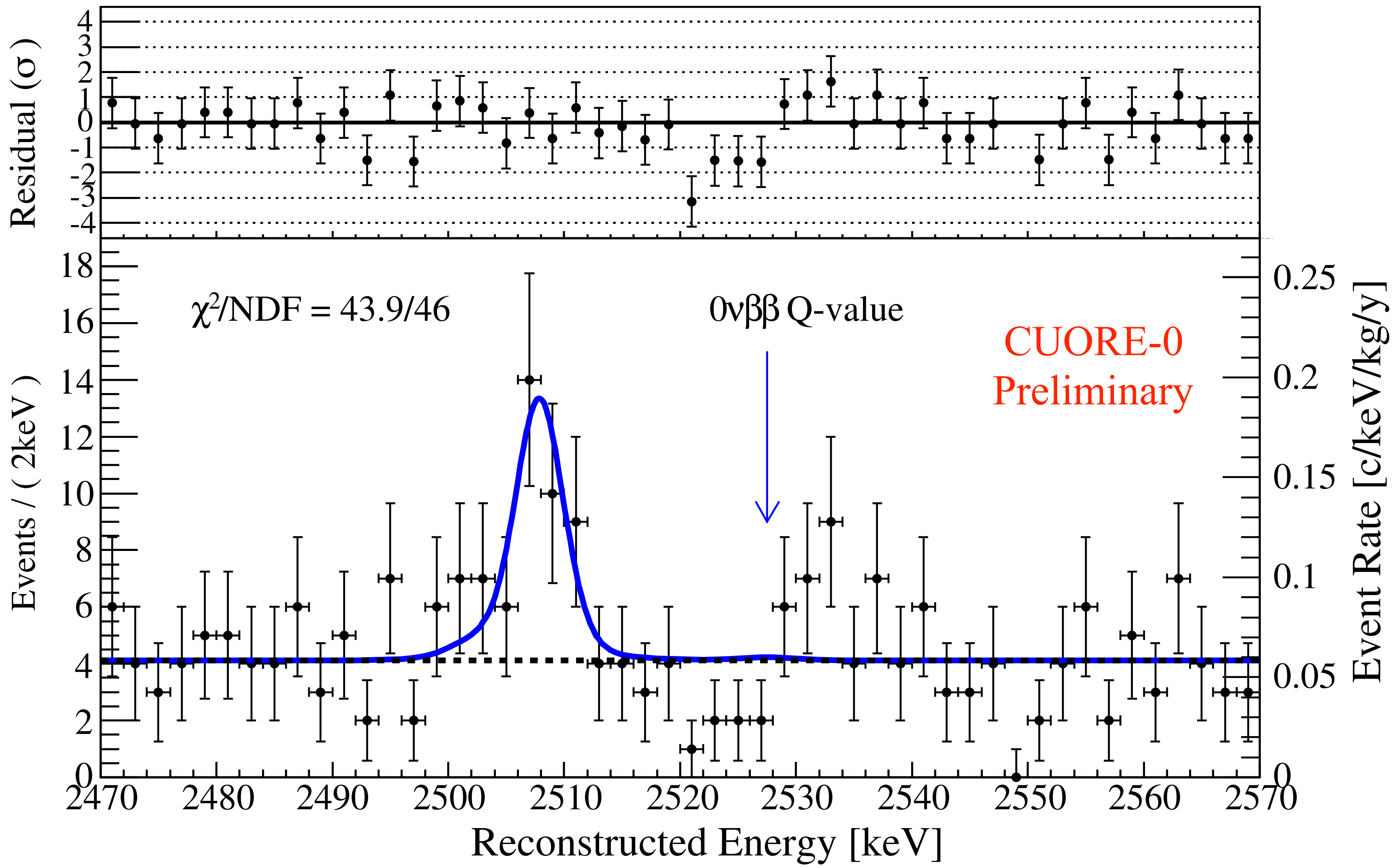
Fit to the Unblinded ROI



Fitted background: 0.058 ± 0.004 (stat.) $\pm\ 0.002$ (syst.) counts/keV/kg/yr

Best-fit decay rate: $\Gamma^{0\nu\beta\beta}(^{130}\mathrm{Te}) = 0.01 \pm 0.12\ (\mathrm{stat.}) \pm 0.01\ (\mathrm{syst.}) \times 10^{-24}\ \mathrm{yr}^{-1}$

Fit to the Unblinded ROI



$\Gamma^{0\nu\beta\beta}\,(^{130}\mathrm{Te}) < 0.25 \times 10^{-24}\ \mathrm{yr}^{-1}$ (90% C.L., statistics only)

$T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > 2.7 \times 10^{24}\ \mathrm{yr}$ (90% C.L., statistics only)

Systematics

TABLE I. Systematic uncertainties on $\Gamma_{0\nu}$ in the limit of zero signal (Additive) and as a percentage of nonzero signal (Scaling).

	Additive (10^{-24} y^{-1})	Scaling (%)
Lineshape	0.007	1.3
Energy resolution	0.006	2.3
Fit bias	0.006	0.15
Energy scale	0.005	0.4
Bkg function	0.004	0.8
Selection efficiency	0.7%	

- For each systematic, we run toy MC exps. to evaluate bias on fitted $0\nu\beta\beta$ rate.
- Bias is parameterized as p0 + p1xΓ, where p0 ="additive" and p1="scaling"
- *Signal lineshape*: Used variety of different line shapes to model signal
- *Energy resolution*: Apply 1.05 ± 0.05 correction to calibration-derived resolution
- *Fit bias*: Effect of using unbanned extended ML fit to extract values
- *Energy scale*: Assign 0.12 keV uncertainty derived from peak residuals in physics spectrum
- *Bkg function*: Choices of 0-,1-,2- order polynomial.

Systematics

TABLE I. Systematic uncertainties on $\Gamma_{0\nu}$ in the limit of zero signal (Additive) and as a percentage of nonzero signal (Scaling).

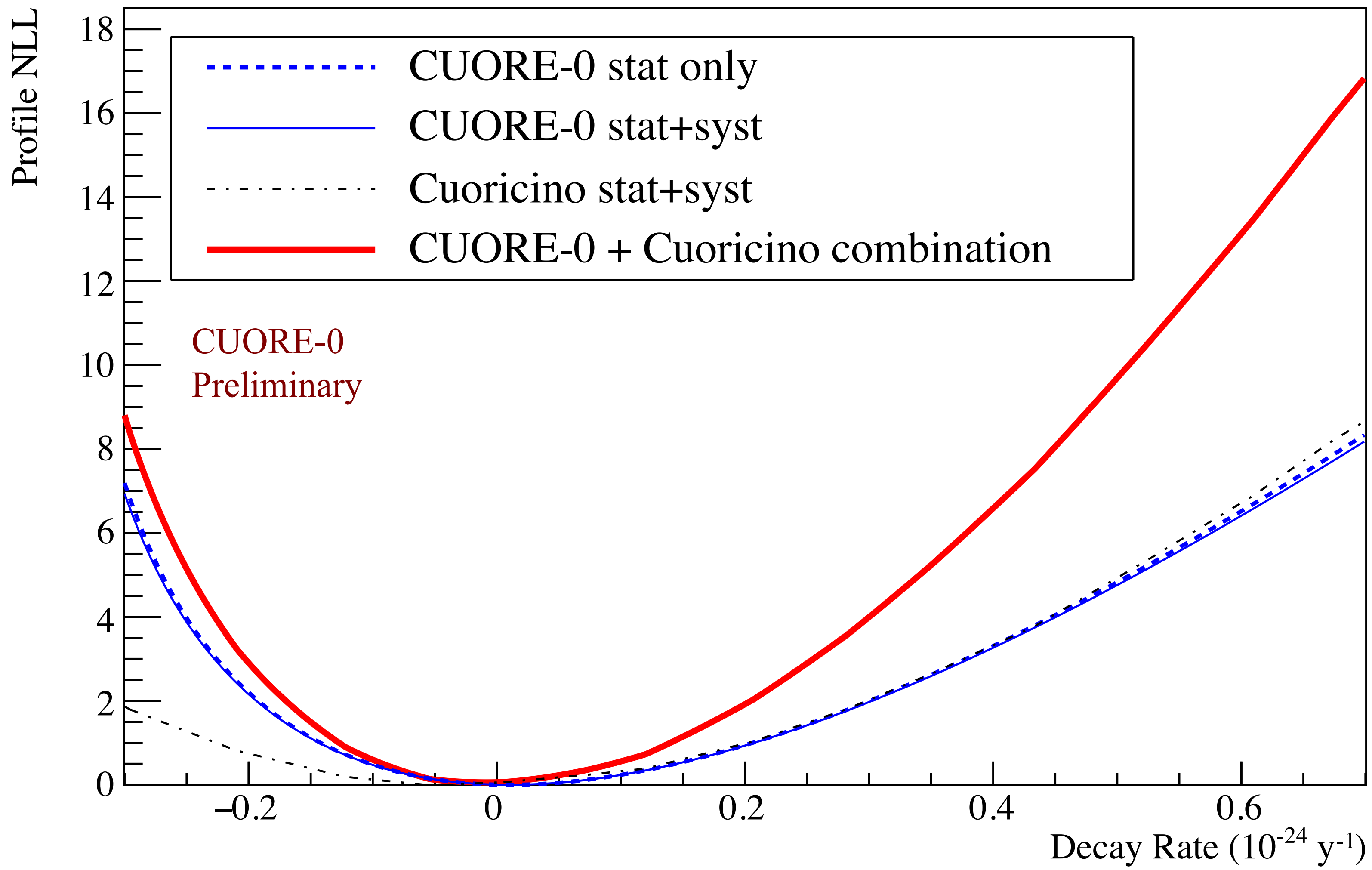
	Additive (10^{-24} y^{-1})	Scaling (%)
Lineshape	0.007	1.3
Energy resolution	0.006	2.3
Fit bias	0.006	0.15
Energy scale	0.005	0.4
Bkg function	0.004	0.8
Selection efficiency	0.7%	

We find **no evidence** for $0\nu\beta\beta$ of ^{130}Te (report the Bayesian limits)

$$\Gamma^{0\nu\beta\beta}(^{130}\mathrm{Te}) < 0.25 \times 10^{-24}\ \mathrm{yr}^{-1}\ (90\%\ \mathrm{C.L., stat.+sys.})$$

$$T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > 2.7 \times 10^{24}\ \mathrm{yr}\ (90\%\ \mathrm{C.L., stat.+sys.})$$

Combining Cuoricino & CUORE+0

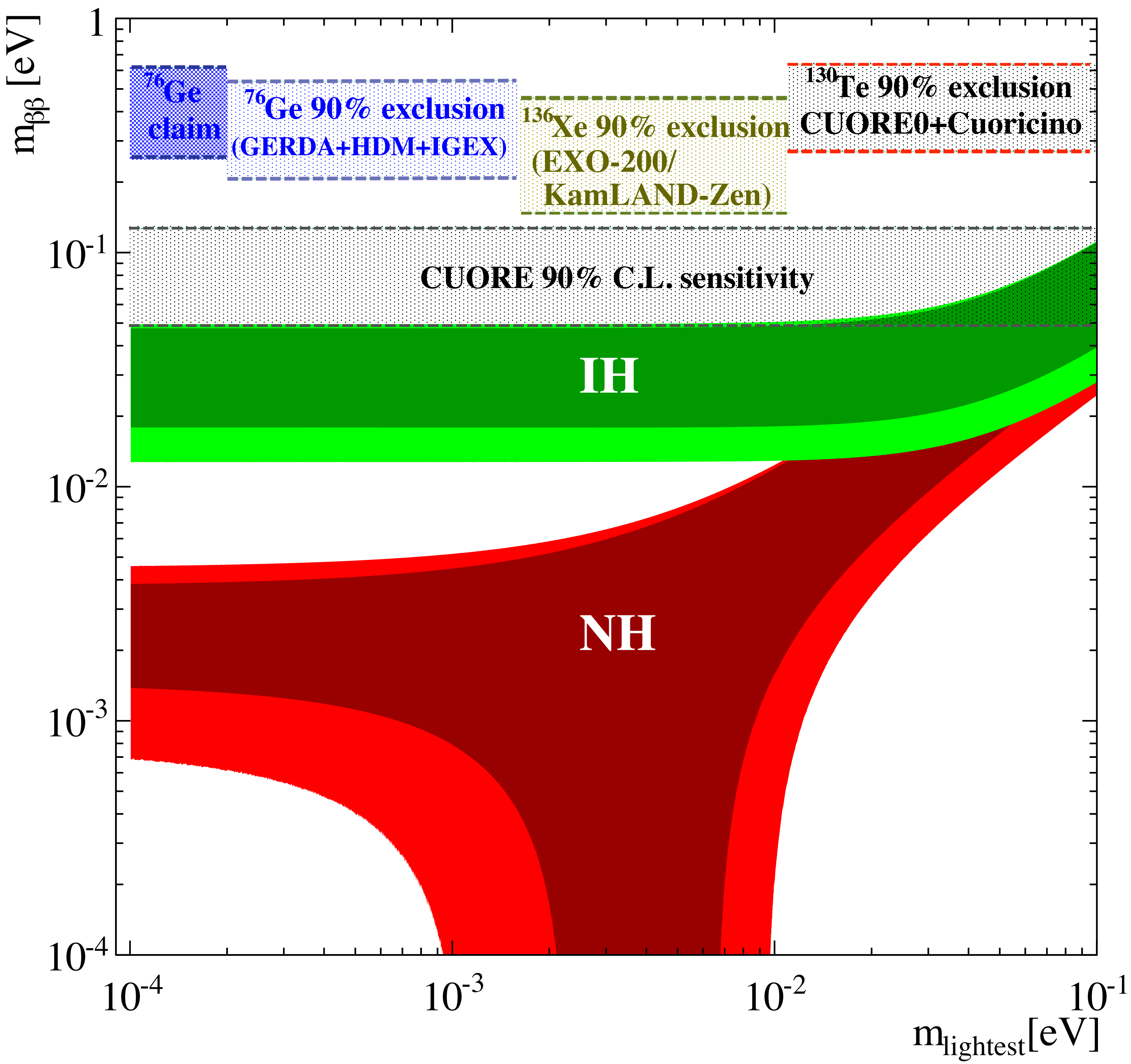


Combining the CUORE-0 result with the Cuoricino result from 19.75 kg-yr of ^{130}Te exposure yields the Bayesian lower limit:

$$T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > 4.0 \times 10^{24}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.,\ stat.+sys.})$$

arXiv:1504.02454
Submitted to PRL

Limits on Effective Majorana Mass



$\langle m_{\beta\beta} \rangle < 270 - 650$ meV

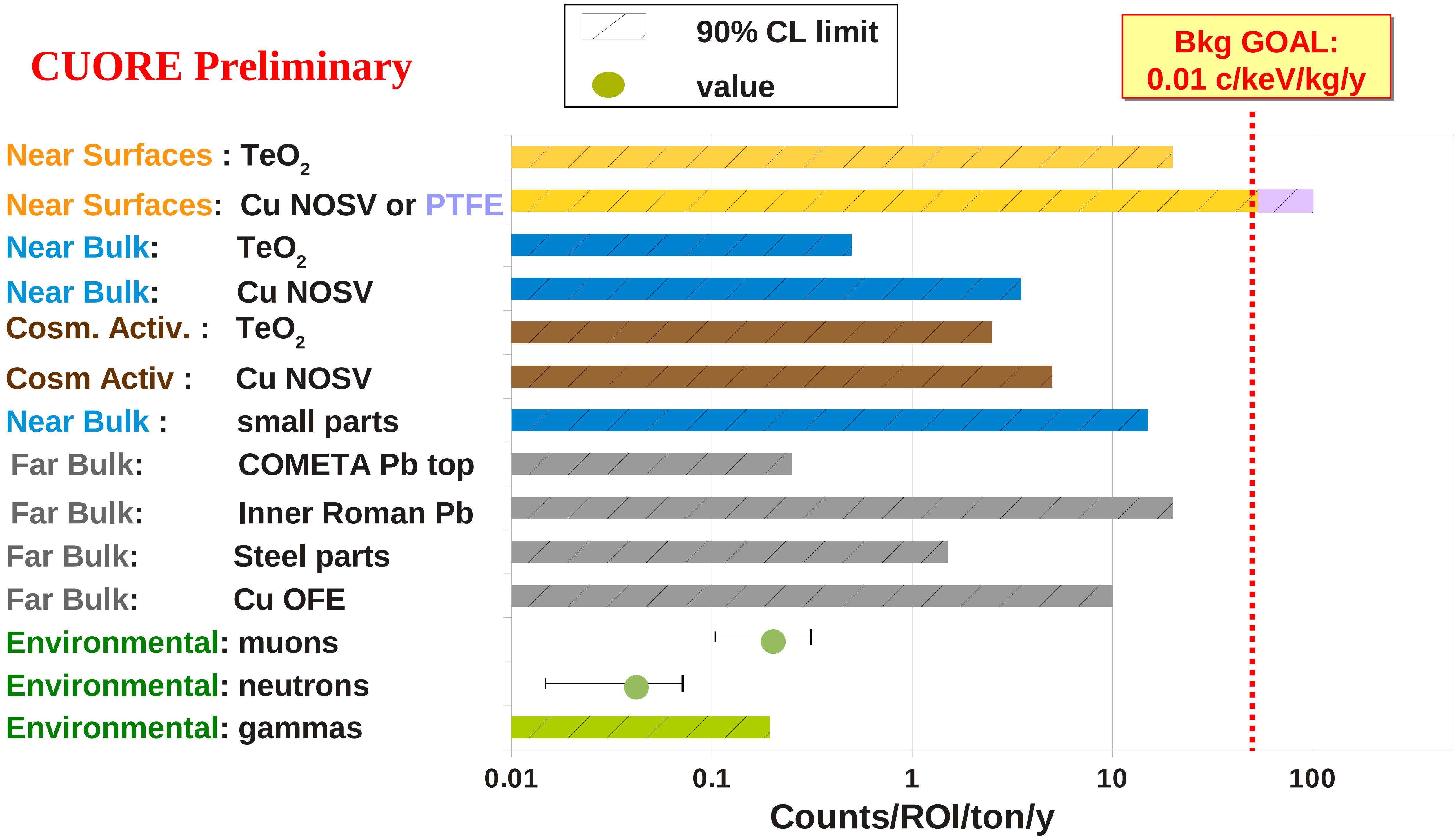
1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) ISM (NPA 818, 139 (2009))
5) EDF (PRL 105, 252503 (2010))

Including additional Shell-Model NME

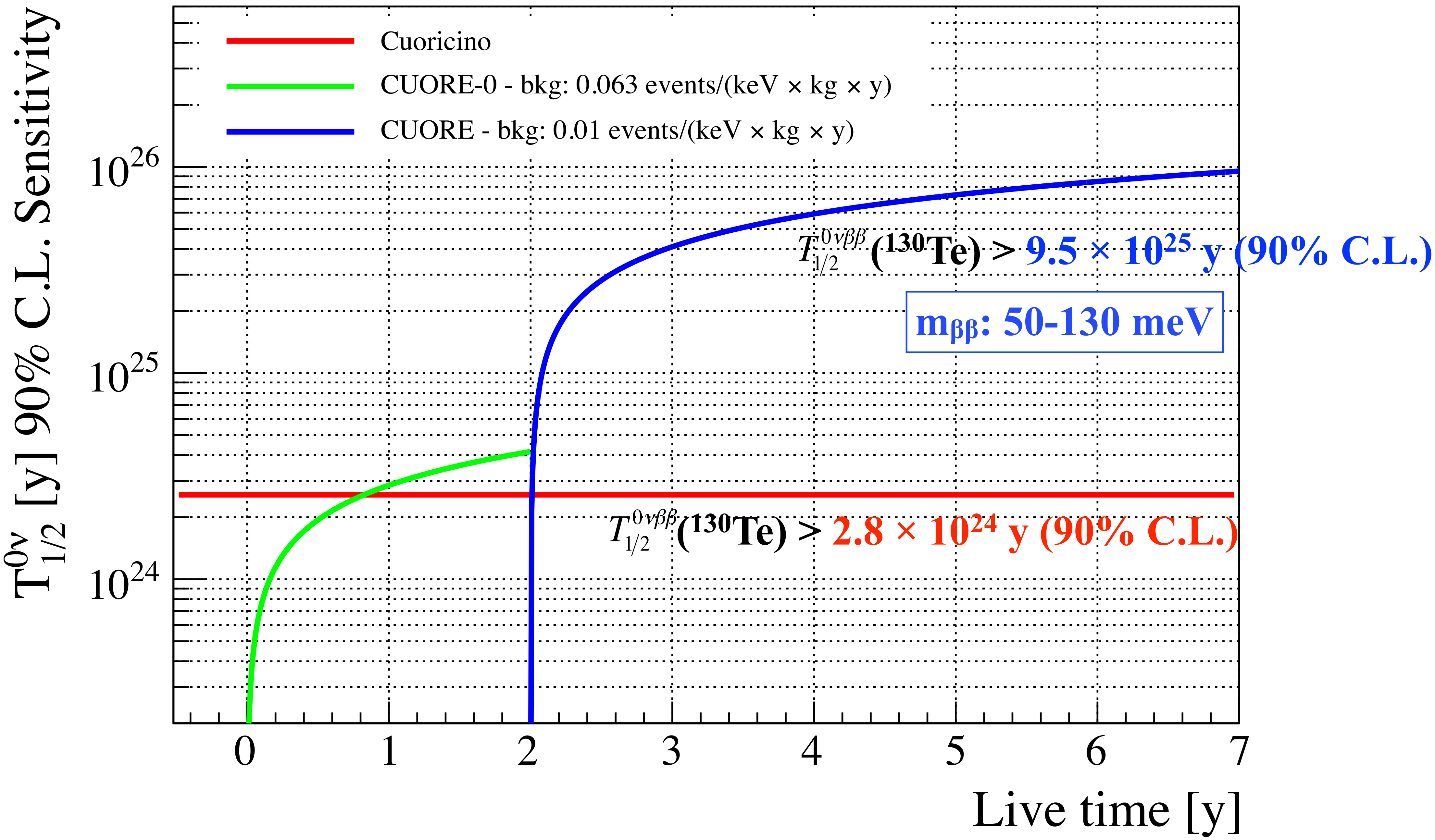
$\langle m_{\beta\beta} \rangle < 270 - 760$ meV

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))

CUORE: Background Budget



CUORE: Sensitivity



- Assumptions: 5 keV FWHM ROI resolution (δE), background rate (b) of 0.01 counts/(keV ·kg ·yr)
- 5 years of live time.

arXiv:1109.0494

Summary

- Observation of $0\nu\beta\beta$ will establish that neutrinos are Majorana particles.
- TeO_2 bolometers offer a well-established and competitive technique to search for $0\nu\beta\beta$.
- CUORE-0 and Cuoricino, the experiments on the way to CUORE, did not find evidence of $0\nu\beta\beta$ of ^{130}Te.
- CUORE-0, the first CUORE-like tower currently operating at LNGS, demonstrated background suppression and resolution improvements, i.e., achieved goals for CUORE.
- CUORE, the largest cryogenic detector using TeO_2 bolometers with 206 kg of ^{130}Te mass, completed detector construction and commissioning of the cryogenic system along with infrastructure is well underway.
- CUORE is scheduled to start data-taking in late 2015 and various R&D projects are on-going for searches beyond CUORE.