Neutrinoless Double-Beta Decay: Status and Prospects of CUORE and KamLAND-Zen

T. O'Donnell
University of California, Berkeley
Lawrence Berkeley National Laboratory

IPA 2015

May 5 2015

Outline

$0\nu\beta\beta$: why do we care ?

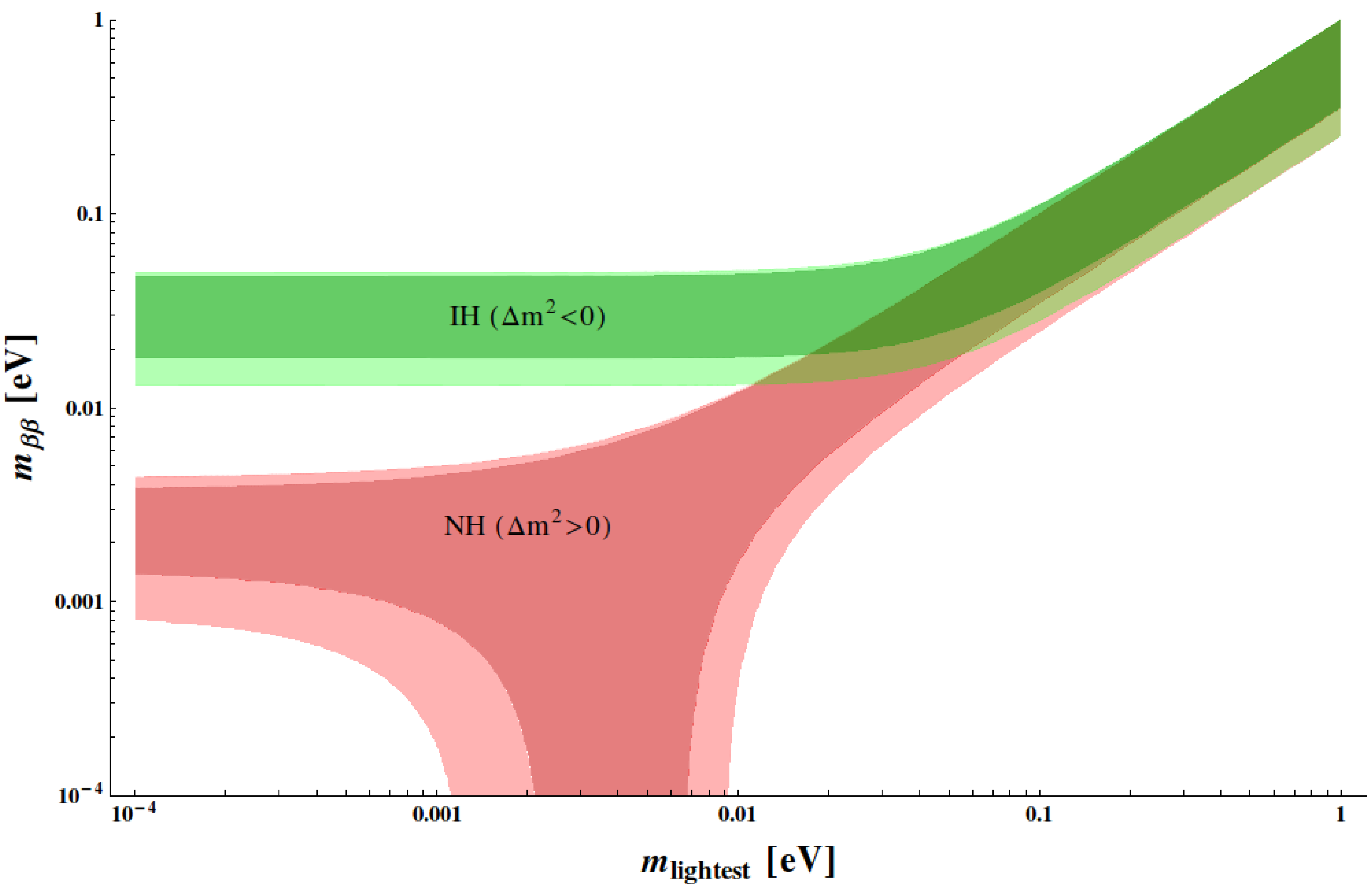
CUORE Program ($0\nu\beta\beta$ of ^{130}Te)

- CUORICINO
- CUORE-0
- CUORE

KamLAND-Zen($0\nu\beta\beta$ of ^{136}Xe)

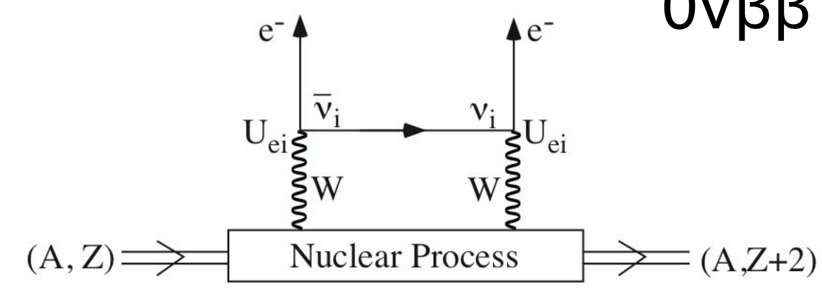
- KLZ Phase I
- KLZ Phase 2
- KLZ Phase 3

What might we learn from 0νββ??



- If $m_{\beta\beta}$ = 50 meV, $T_{1/2} \sim 10^{25} - 10^{27}$ years !

0νββ



half-life

Phase space factor

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2\frac{m_{\beta\beta}^2}{m_e^2}$$

Nuclear matrix element

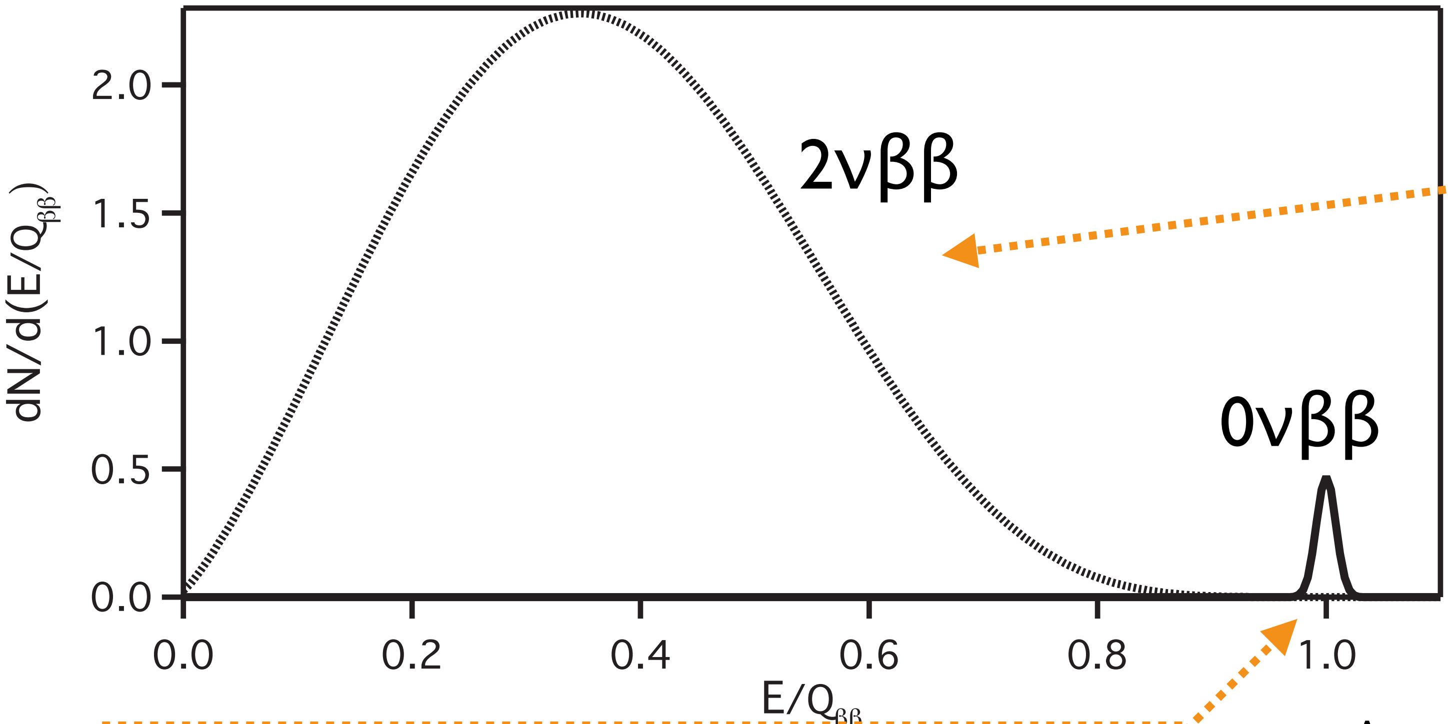
Effective Majorana neutrino mass: $m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2\, m_i\right|$

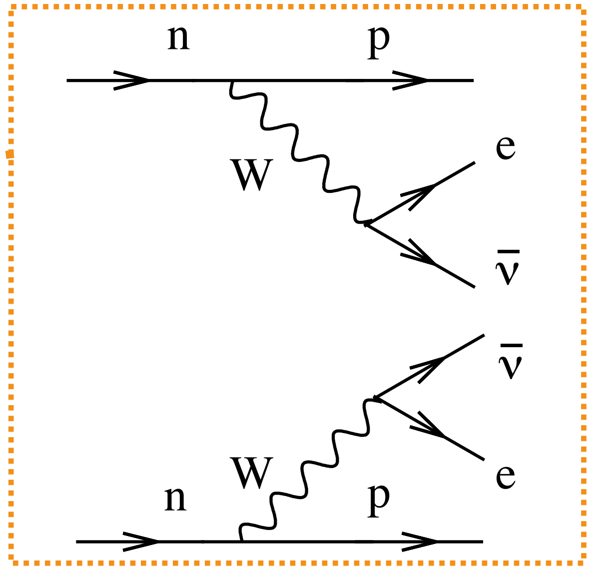
- If observed: learn neutrinos are **Majorana fermions**, **lepton number violation**; ***maybe*** the **mass hierarchy**, constraints on **absolute mass scale**

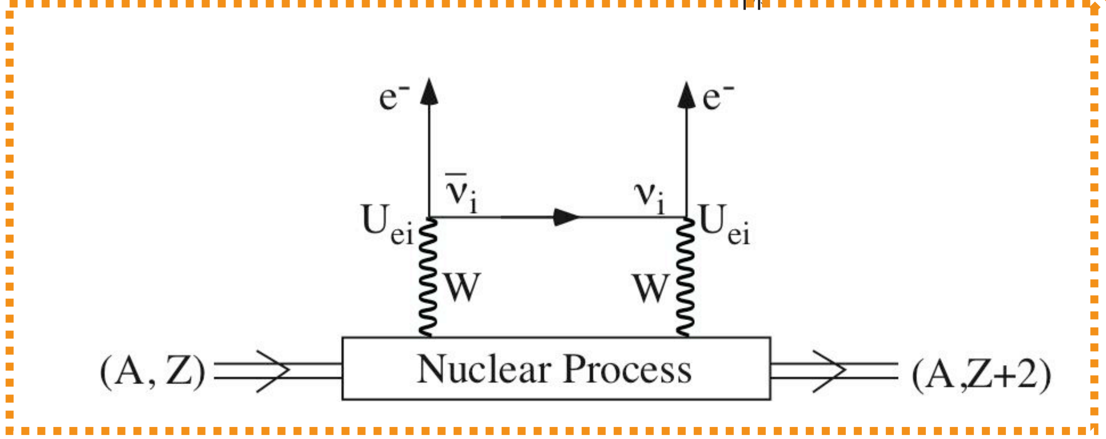
- If not observed: stringent limits help make the most of future neutrino data, maybe show neutrinos are not Majorana

Double-Beta Decay Signature

Summed-energy spectrum of final state electrons







Assumes BR 0v/2v = 1% and detector energy resolution is 2%

a	isotopic abundance of source
ε	detection efficiency
M	Total detector mass
b	bkg rate per unit mass per unit energy
t	exposure time
δE	energy resolution

Rule of thumb

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

Double Beta Decay - Searches

Candidate Isotope	Experiment
48Ca	Candles
76Ge	Gerda/Majorana
82Se	SuperNemo
100Mo	Moon
116Cd	Cobra
130Te	**CUORE-0/CUORE**/SNO+
136Xe	EXO, **KamLAND-Zen**

Outline

0νββ: why do we care ?

CUORE Program (0νββ of ^{130}Te)

- CUORICINO
- CUORE-0
- CUORE

KamLAND-Zen(0νββ of ^{136}Xe)

- KLZ Phase 1
- KLZ Phase 2
- KLZ Phase 3

The CUORE Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

SINAP

LUX ET VERITAS

INFN Istituto Nazionale di Fisica Nucleare

CAL POLY SAN LUIS OBISPO

Lawrence Livermore National Laboratory

Massachusetts Institute of Technology

UCLA

SAPIENZA UNIVERSITÀ DI ROMA

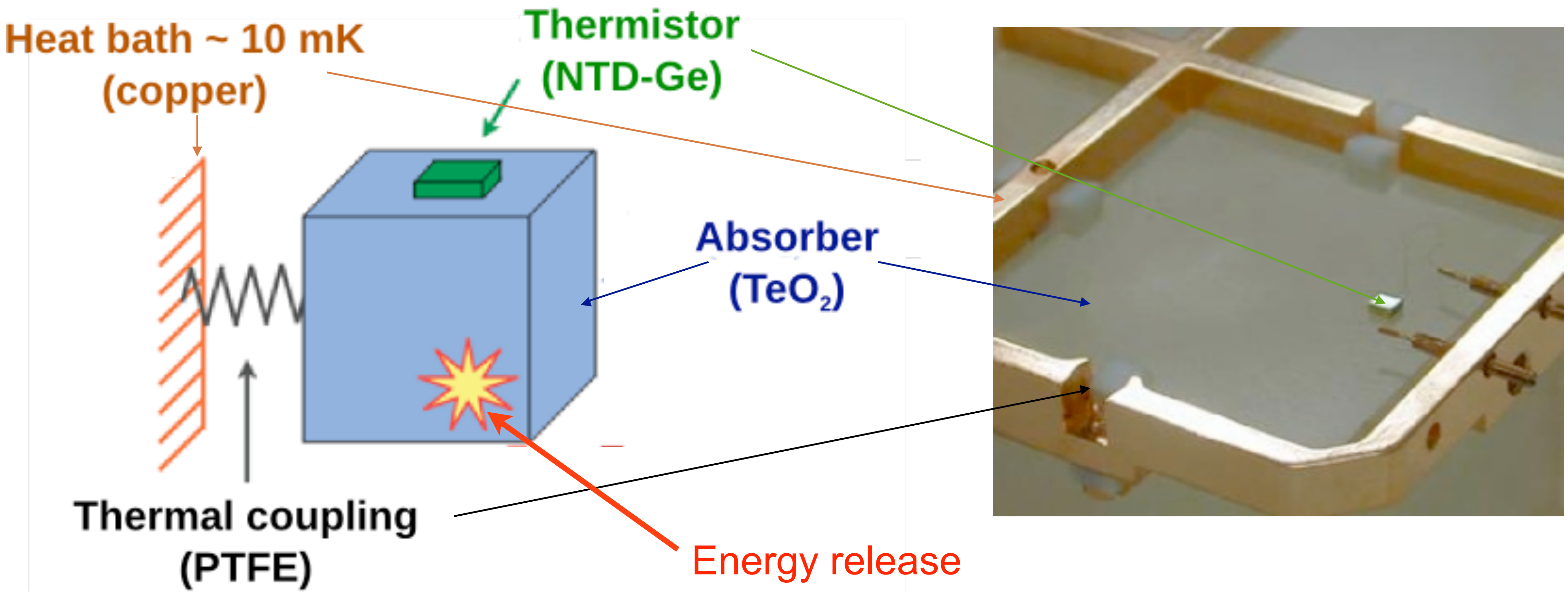
CSNSM

BERKELEY LAB

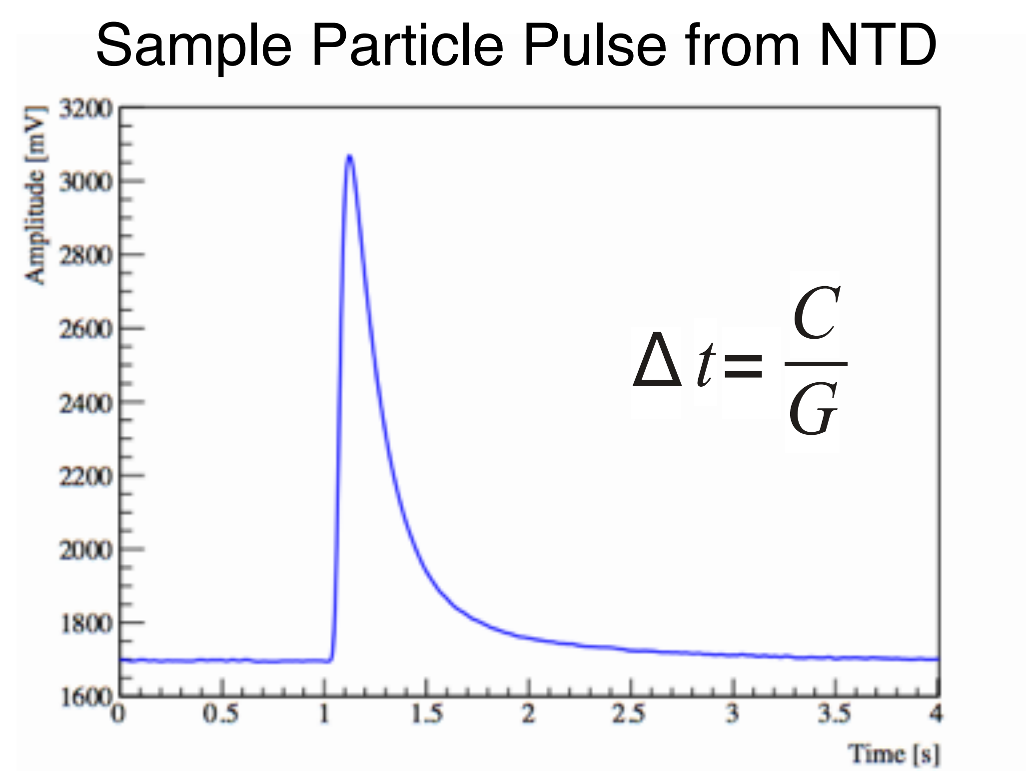
UNIVERSITY OF SOUTH CAROLINA

CUORE

A word about bolometer technique



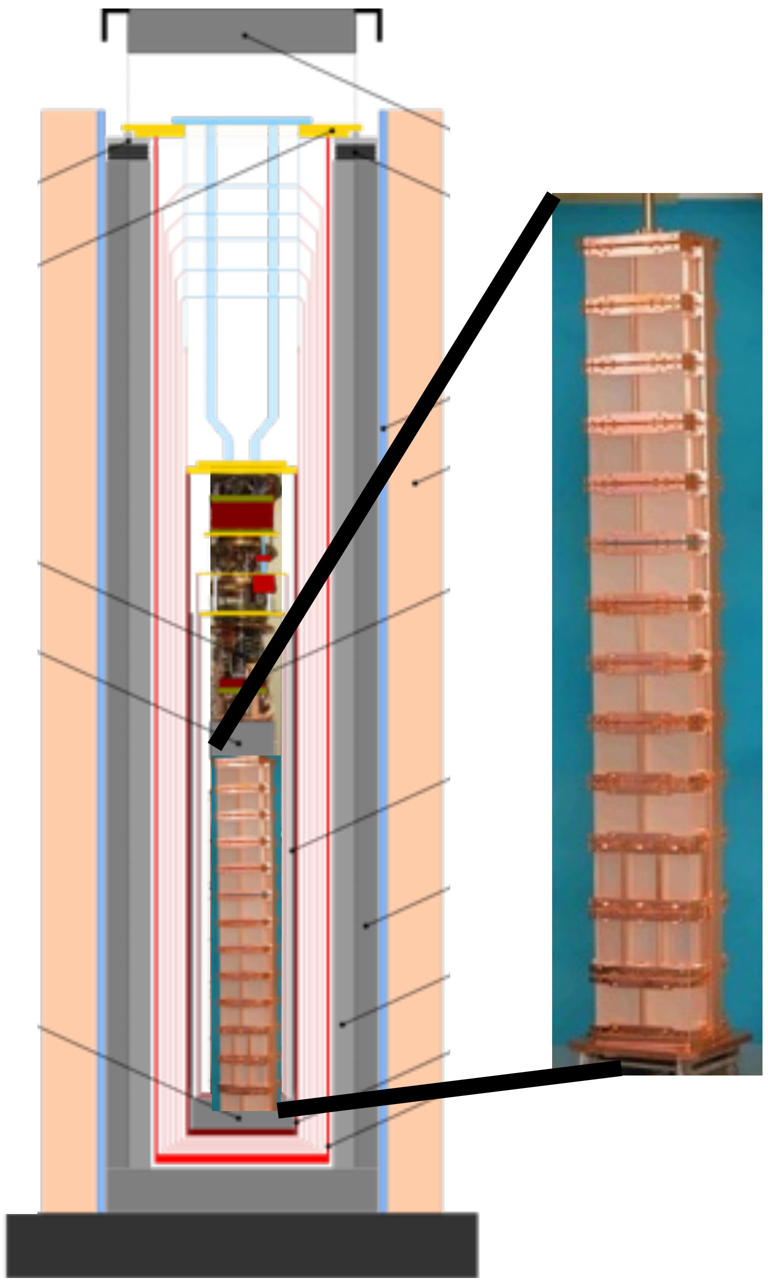
- Energy deposit in absorber results in temperature rise
- For TeO_2 crystals configured for CUORE at ~10mK, ΔT ~ 0.1mK per MeV
- Temperature change read out with Ge-NTD
- Energy response can be calibrated with sources



CUORICINO (2003 - 2008)

- 62 crystal TeO_2 bolometer array operated at Gran Sasso Lab, Italy

- ^{130}Te isotopic abundance: ~34%
- ^{130}Te Q-value: ~2528 keV

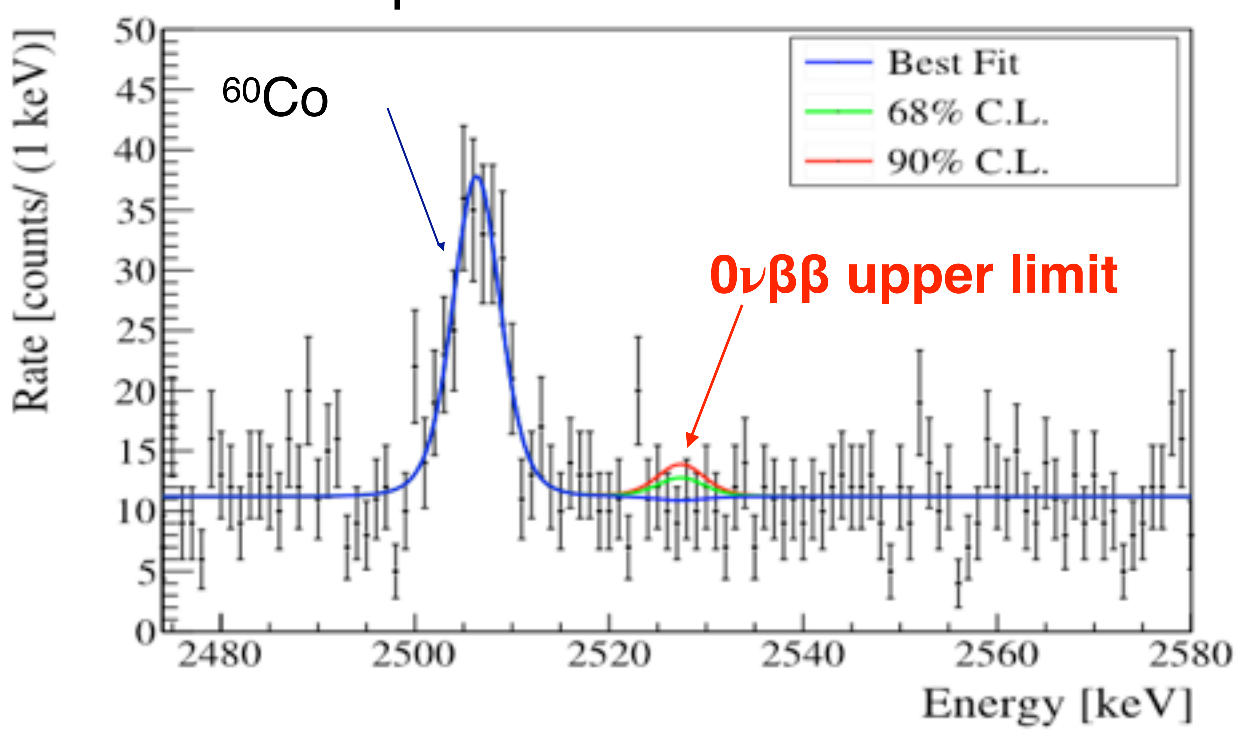


- Final results

$$T^{0\nu}_{1/2} > 2.8 \times 10^{24}\,\mathrm{yr} \quad (90\%\ \mathrm{C.L})$$
$$\langle m_{\beta\beta} \rangle < 0.3 - 0.7\,\mathrm{eV}$$

- M.t (^{130}Te): 19.75 kg.yr
- dE: 6.3 +/- 2.5 keV FWHM (mean +/- RMS)
- b: 0.169 +/- 0.006 c/keV/kg/yr

Final Spectrum of CUORICINO



CUORICINO (2003 - 2008)

CUORICINO

Background mainly from:

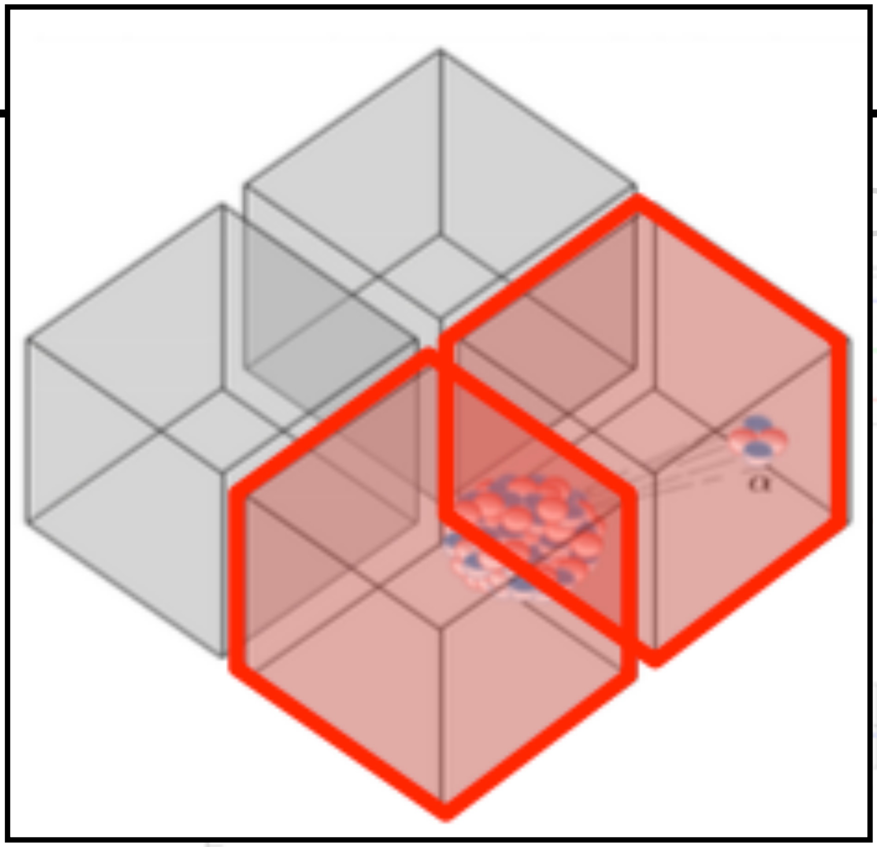
- ^{232}Th gammas from cryostat materials (a.k.a far sources)
- degraded α’s and β’s from crystals & Cu surfaces (a.k.a near sources)

CUORICINO (2003 - 2008)

CUORICINO

Background mainly from:

- ^{232}Th gammas from cryostat materials (a.k.a far sources)
- degraded α's and β's from crystals & Cu surfaces (a.k.a near sources)



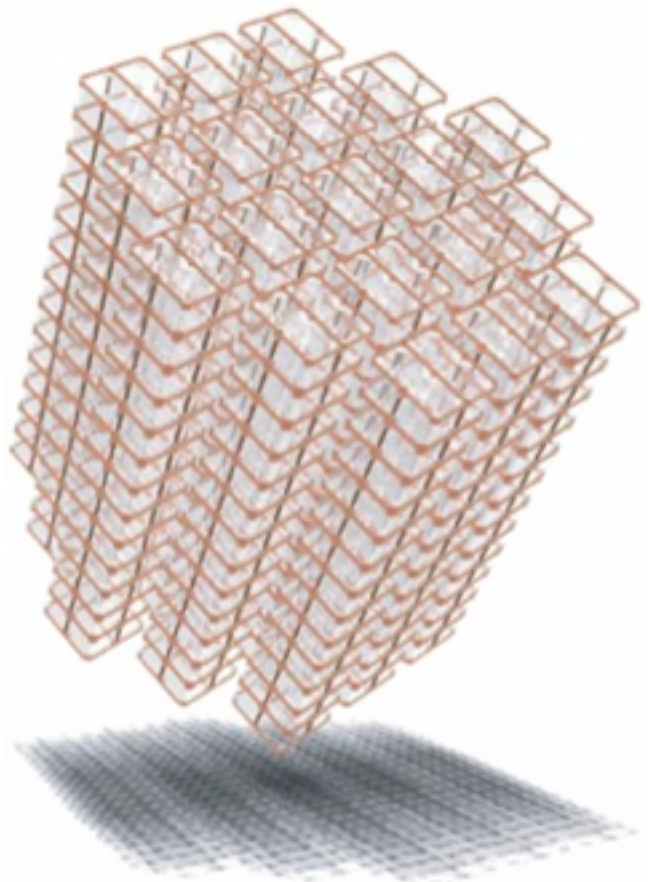
CUORICINO ➡ CUORE

- **M**: **Scale up mass of ^{130}Te (~20x)**
  - 988, 5x5x5 cm^3 $^{nat}TeO_2$ crystals
    - 741 kg of $^{nat}TeO_2$ or 206 kg of ^{130}Te
  - Assembled into 19 towers, 13 floors per tower, 4 crystals per floor

half-life sensitivity

$$\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

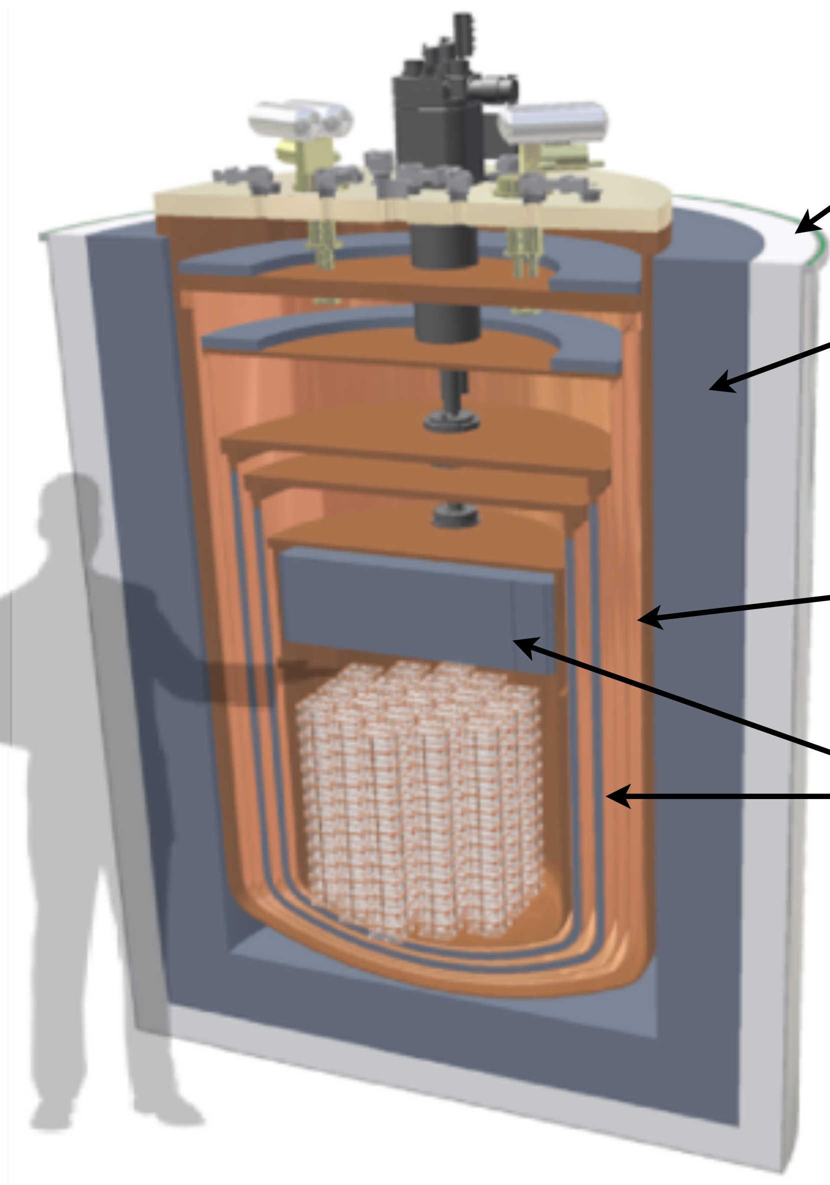
- **t**: **Cryogen-free dilution refrigerator**
  - ➡ Improves detector duty cycle
  - ➡ Improves stability



- **δE**: **Resolution**
  - Resolution of TeO_2 bolometers is excellent, 5keV @2615keV is demonstrated
- **b**: **Background**
  - Goal 0.01 counts/keV/ky/yr (~20x lower than CUORICINO)

Path to lower background (Far Sources)

- Improve shielding and radio-purity of cryostat materials

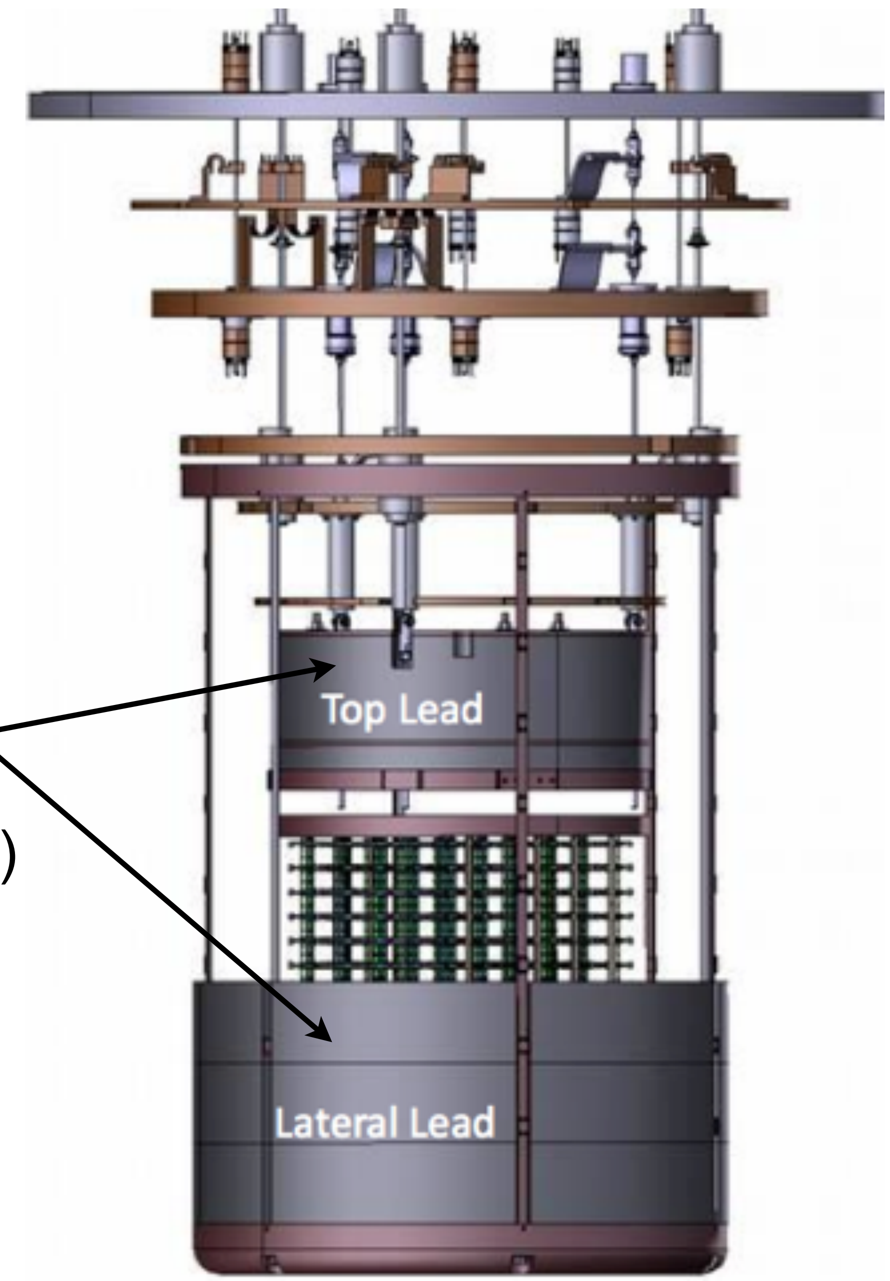


Neutron shield
(18 cm PET + 2cm of H_3BO_3)

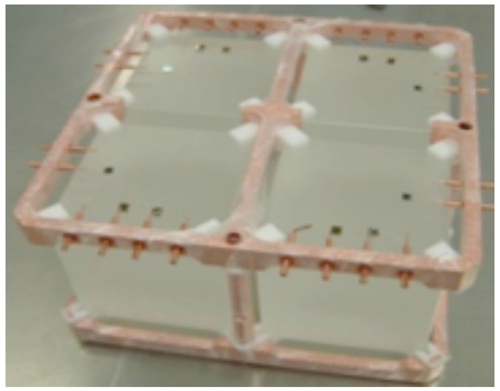
External lead shield
(thickness >35 cm)

Low-radioactivity copper for
cryostat vessels and flanges

Internal lead shield
(low-radioactivity/ancient lead)



Path to lower background (Near Sources)



Ultra-pure TeO2 crystal array

Bulk activity 90% C.L. upper limits:

$8.4 \cdot 10^{-7}$ Bq/kg (^{232}Th), $6.7 \cdot 10^{-7}$ Bq/kg (^{238}U), $3.3 \cdot 10^{-6}$ Bq/kg (^{210}Po)

Surface activity 90% C.L. upper limits:

$2 \cdot 10^{-9}$ Bq/cm^2 (^{232}Th), $1 \cdot 10^{-8}$ Bq/cm^2 (^{238}U), $1 \cdot 10^{-6}$ Bq/cm^2 (^{210}Po)

- Crystal holder design optimized to reduce passive surfaces (Cu) facing the crystals

- Developed ultra-cleaning process for all Cu components:
    - Tumbling
    - Electropolishing
    - Chemical etching
    - Magnetron plasma etching

T1 T2 T3

- Benchmarked in dedicated bolometer run at LNGS
    - Residual ^{232}Th / ^{238}U surface contamination of Cu: $< 7 \cdot 10^{-8}$ Bq/cm^2

- All parts stored underground, under nitrogen after cleaning

Path to lower background (Near Sources)

Ultra-pure TeO2 crystal array

Bulk activity 90% C.L. upper limits:

$8.4 \cdot 10^{-7}$ Bq/kg (^{232}Th), $6.7 \cdot 10^{-7}$ Bq/kg (^{238}U), $3.3 \cdot 10^{-6}$ Bq/kg (^{210}Po)

Surface activity 90% C.L. upper limits:

0Po)

Need to make sure parts remain clean and do not get 'recontaminated' !

- Crystal hol
  (Cu) facing

- Developed
  - Tun
  - Ele
  - Che
  - Magnetron plasma etching

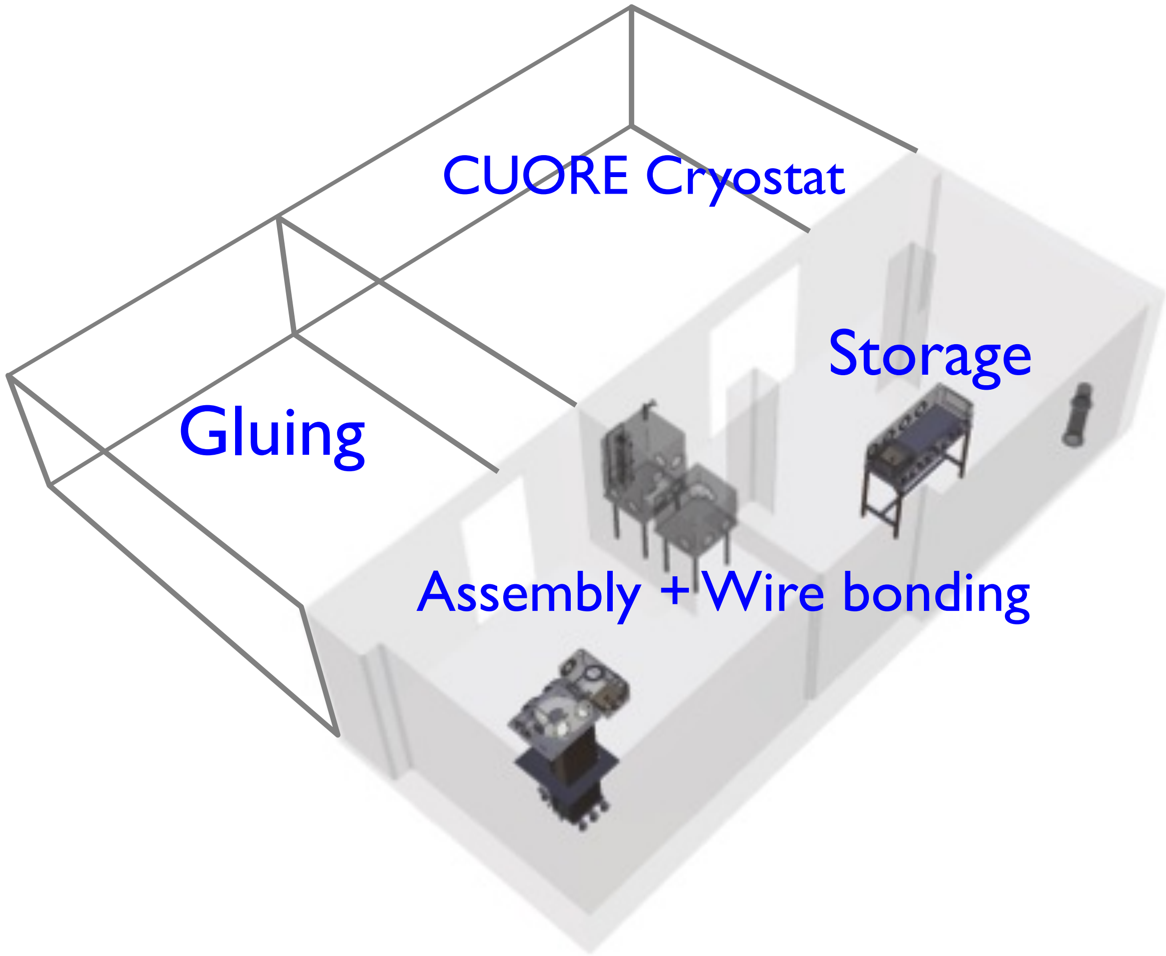
- Benchmarked in dedicated bolometer run at LNGS
  - Residual ^{232}Th / ^{238}U surface contamination of Cu: $< 7 \cdot 10^{-8}$ Bq/cm^2

- All parts stored underground, under nitrogen after cleaning

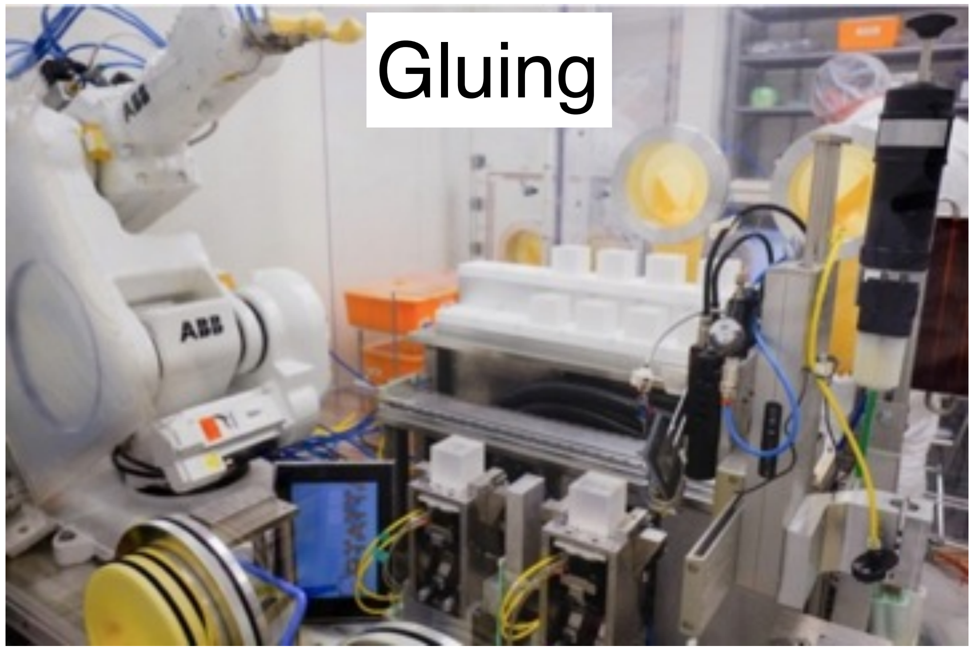
CUORE Assembly Line

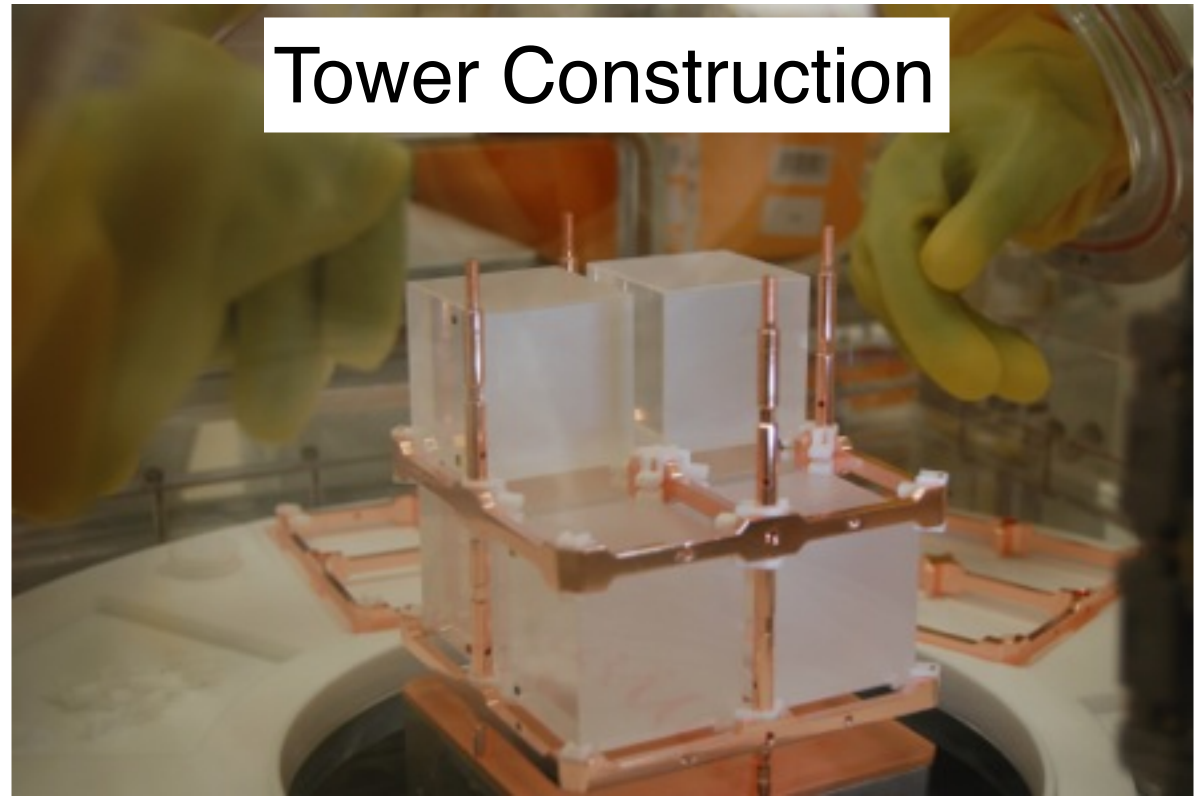
Class 1000 Clean Room for Detector Assembly and Storage

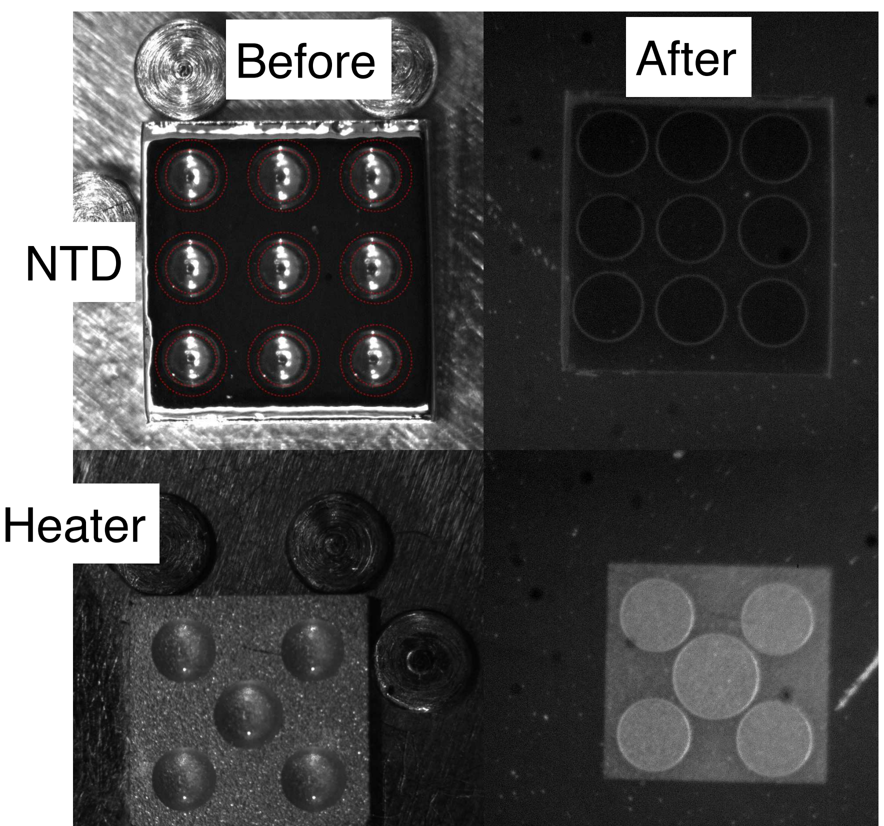
- All parts cleaned/screened according to CUORE protocol
- Stored underground at LNGS
- Assembly in underground clean room in N2 flushed glove boxes

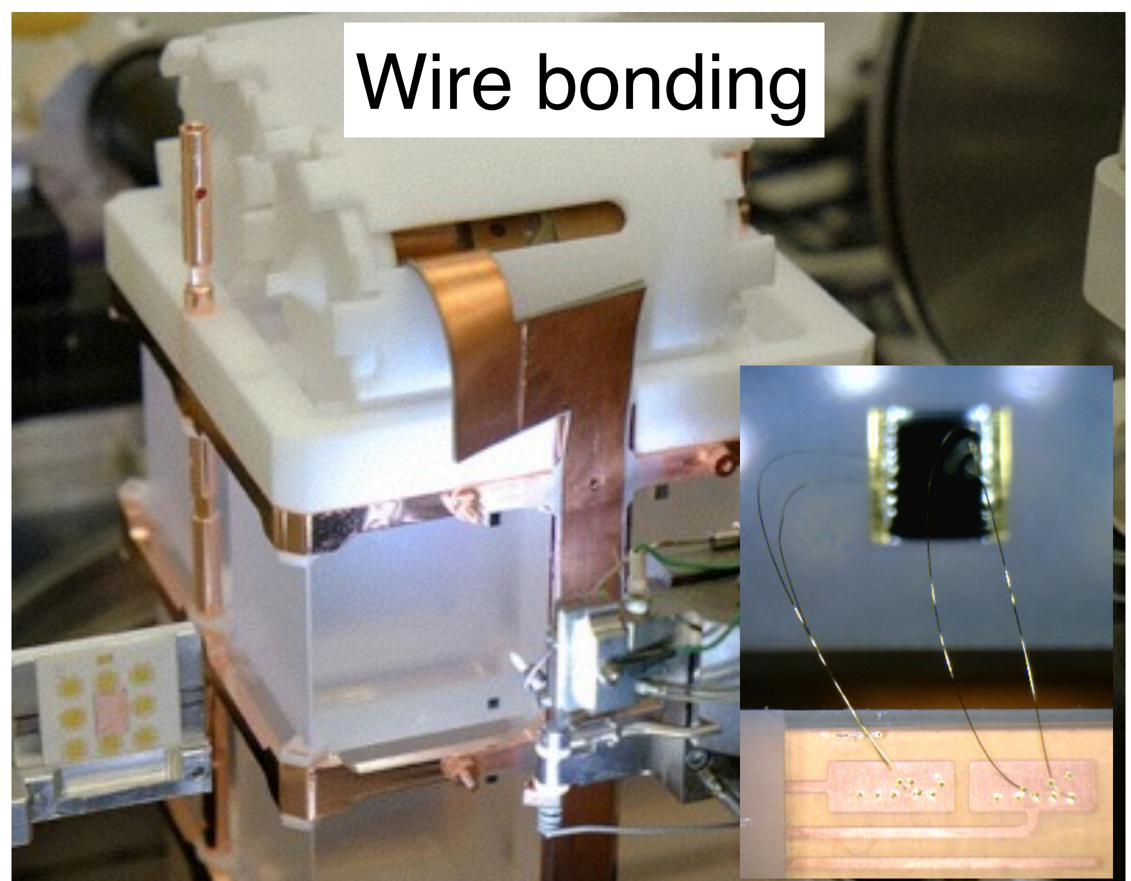


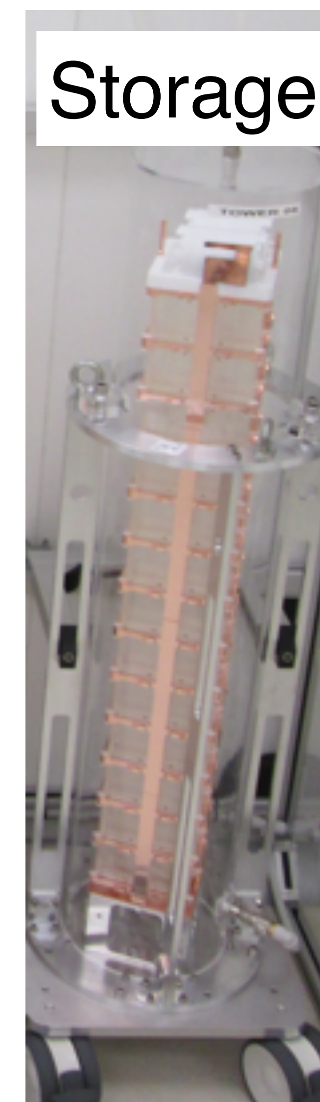
CUORE Assembly Line





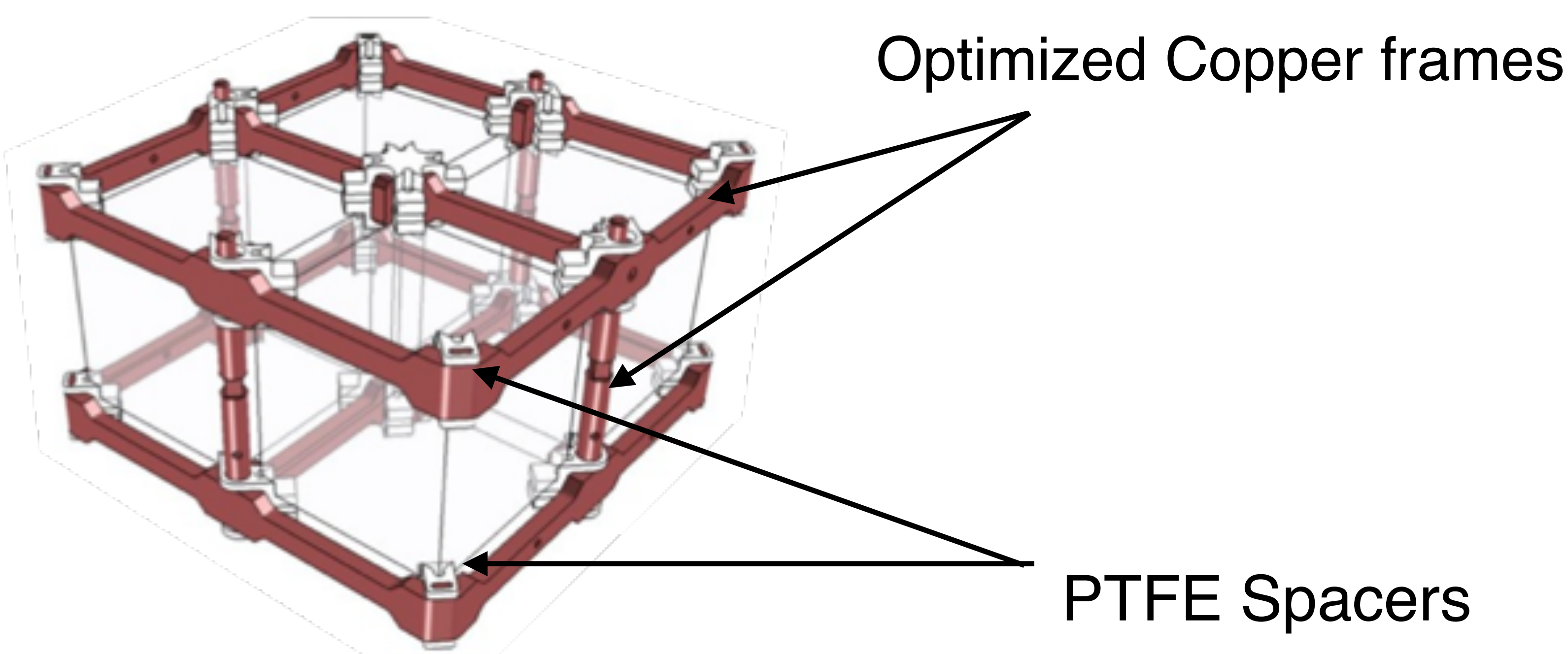




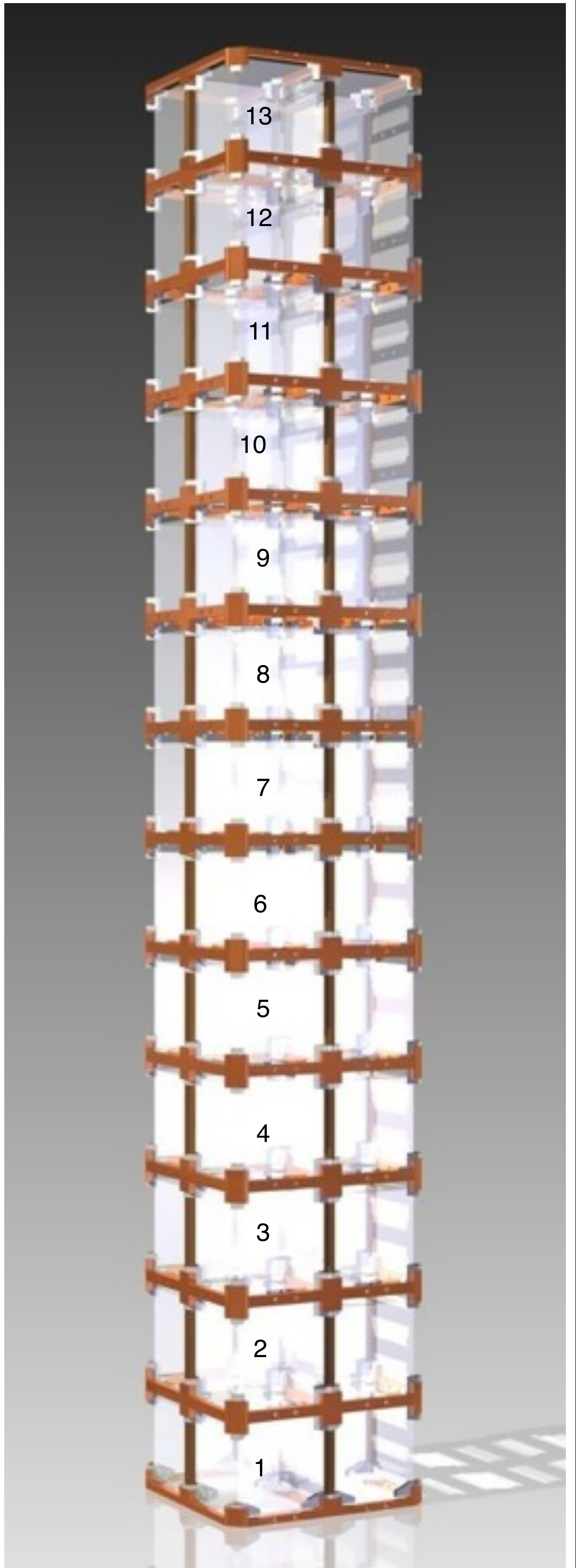


CUORE-0

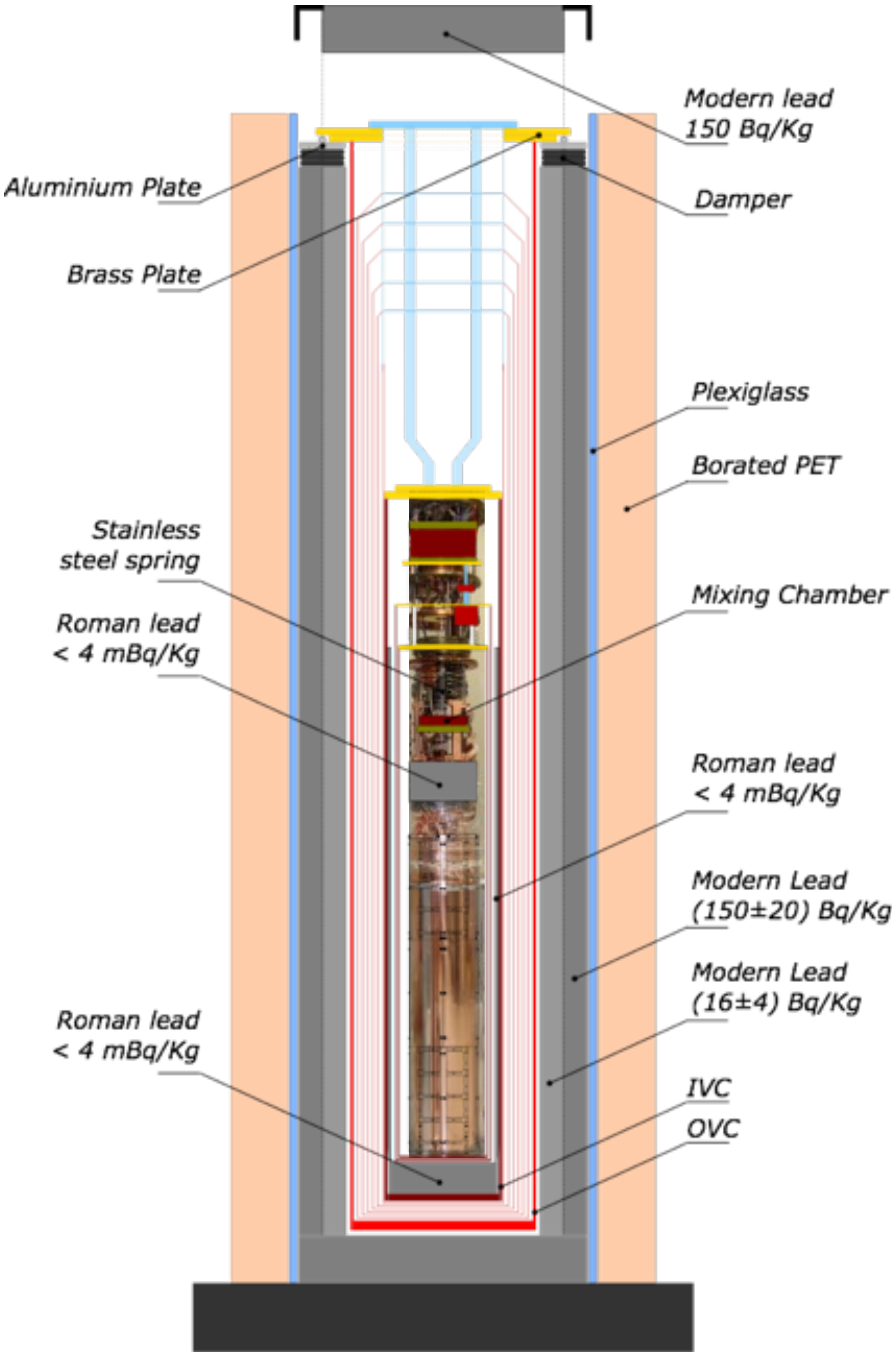
- A CUORE-style tower assembled between Fall 2011 - Spring 2012
  - 4 crystals per floor, 13 floors



  - 39 kg TeO_2 => 10.9 kg ^{130}Te



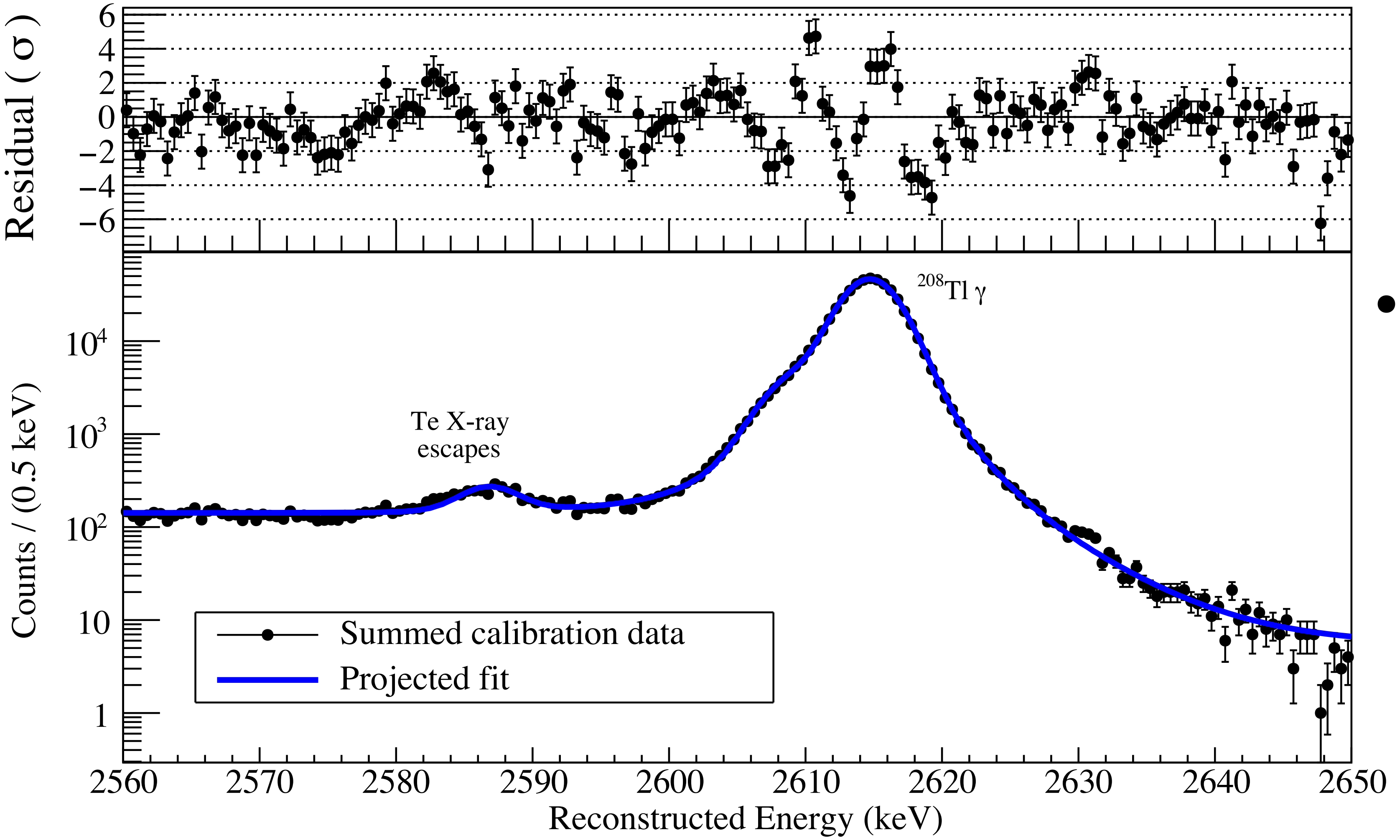
CUORE-0



- Uses the old CUORICINO cryostat
- Electronics from CUORICINO
- Shielding from CUORICINO
- Cooled to base T (~10 mK) Mar 2013
- Collected about 20 datasets so far
- 51 readable bolometers

➡ ~1000 bolometer-datasets

CUORE-0 Performance



Calibration Data

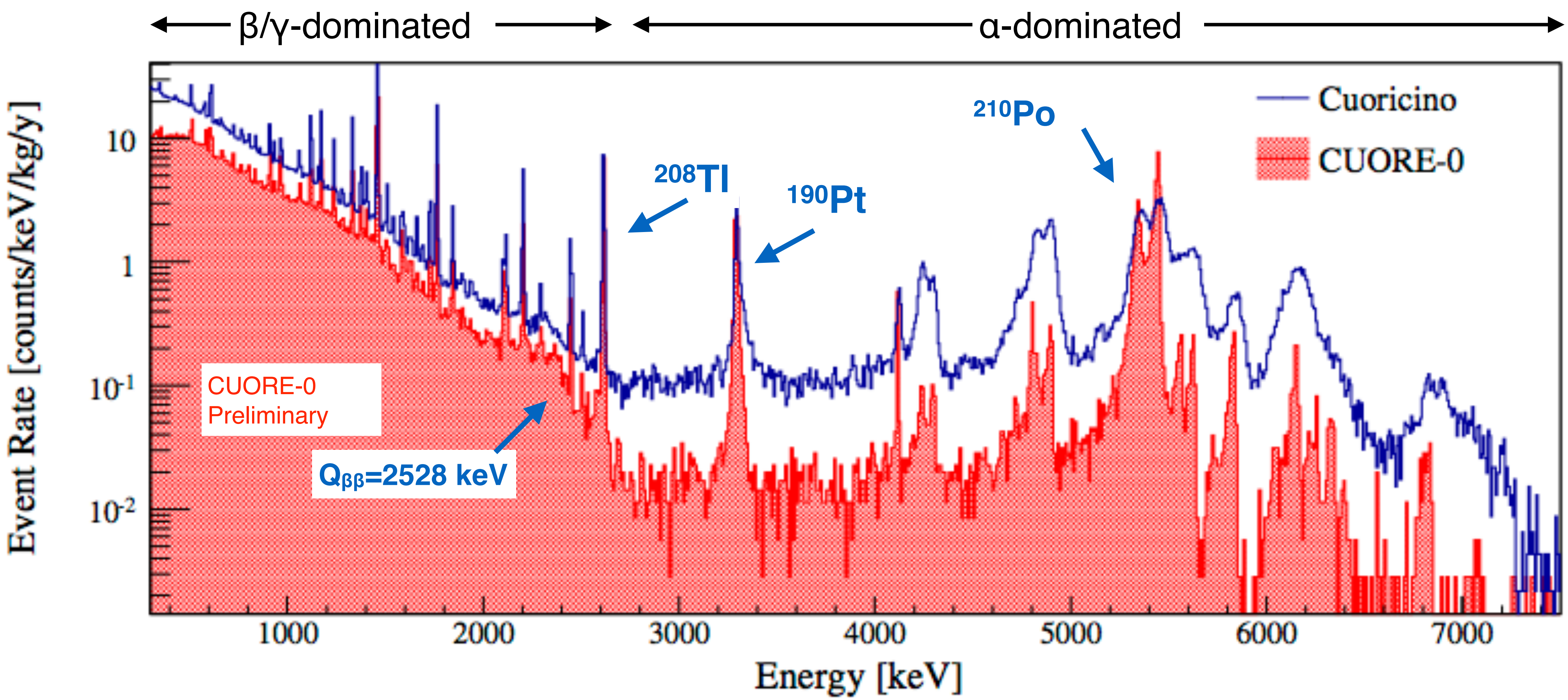
- Exposure weighted sum of the line-shapes of each bolometer-dataset overlaid on 2615 keV calibration data

- Characteristic value of the FWHMs of the bolometers = 4.9 keV

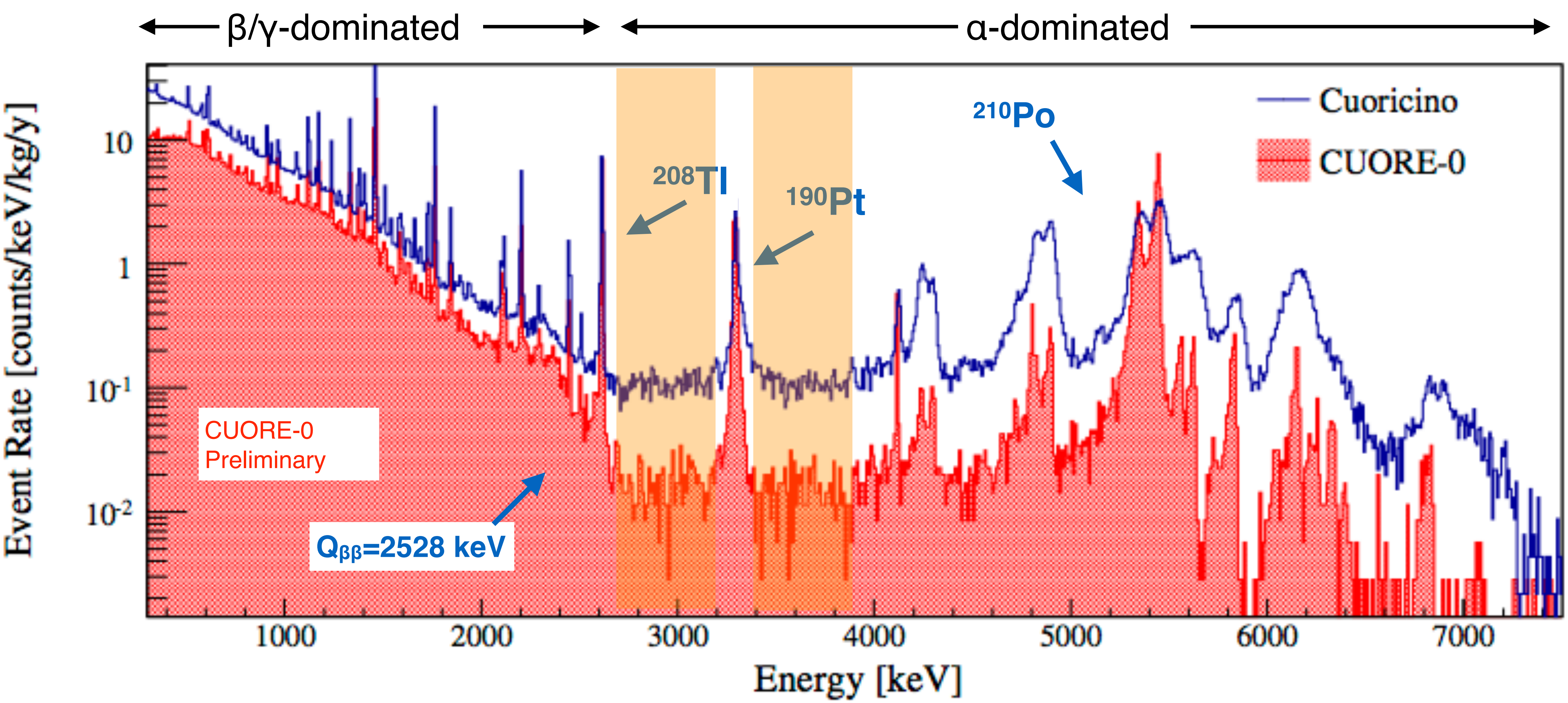
  ✓**Inline with CUORE goal of 5 keV**

- RMS of the FWHMs of the bolometers = 2.9 keV

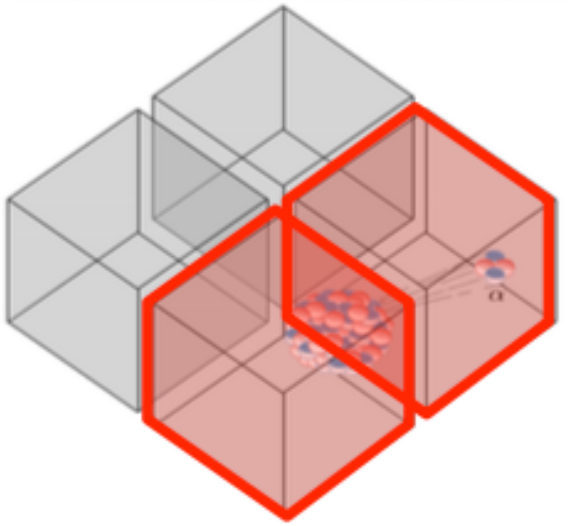
CUORE-0: Background measurement



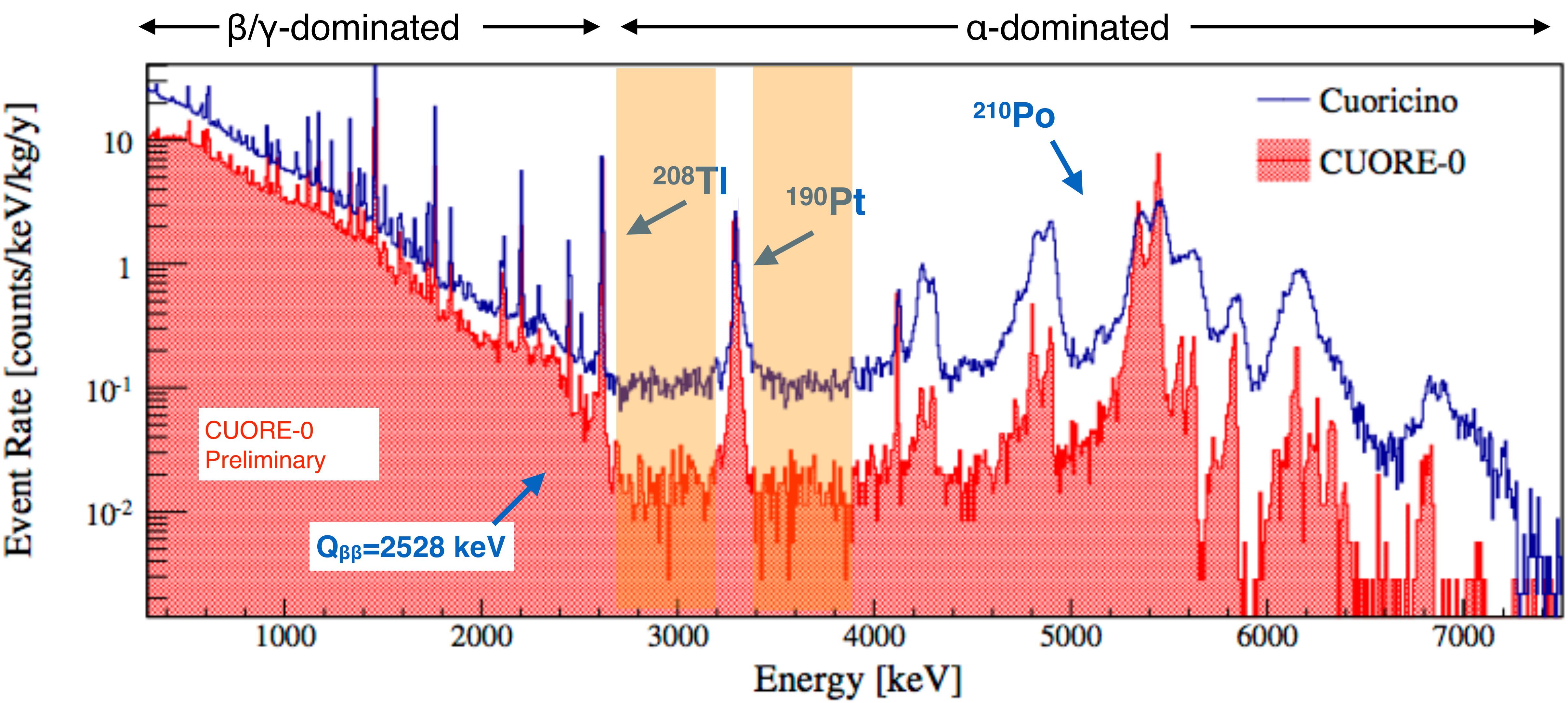
CUORE-0: Background measurement



- Use continuum in region 2700-3900 keV excluding (190Pt) to benchmark background from degraded alphas



CUORE-0: Background measurement



	0νββ region (c/keV/kg/yr)	2700-3900 keV * (c/keV/kg/yr)
CUORICINO ε = 83%	0.169 +/- 0.006	0.110 +/- 0.001
CUORE-0 ε = 81%	0.058 +/- 0.004	0.016 +/- 0.001

CUORE-0: Background measurement

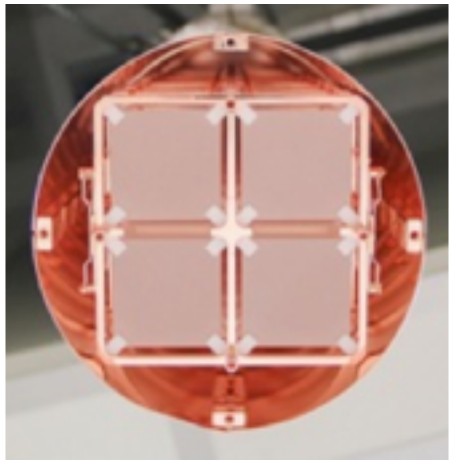
β/γ-dominated → ← α-dominated

- **In CUORE we expect ^{232}Th background from cryostat to be negligible**
- **The degraded alpha background measured with CUORE-0 is within a factor of 2 of CUORE goal**

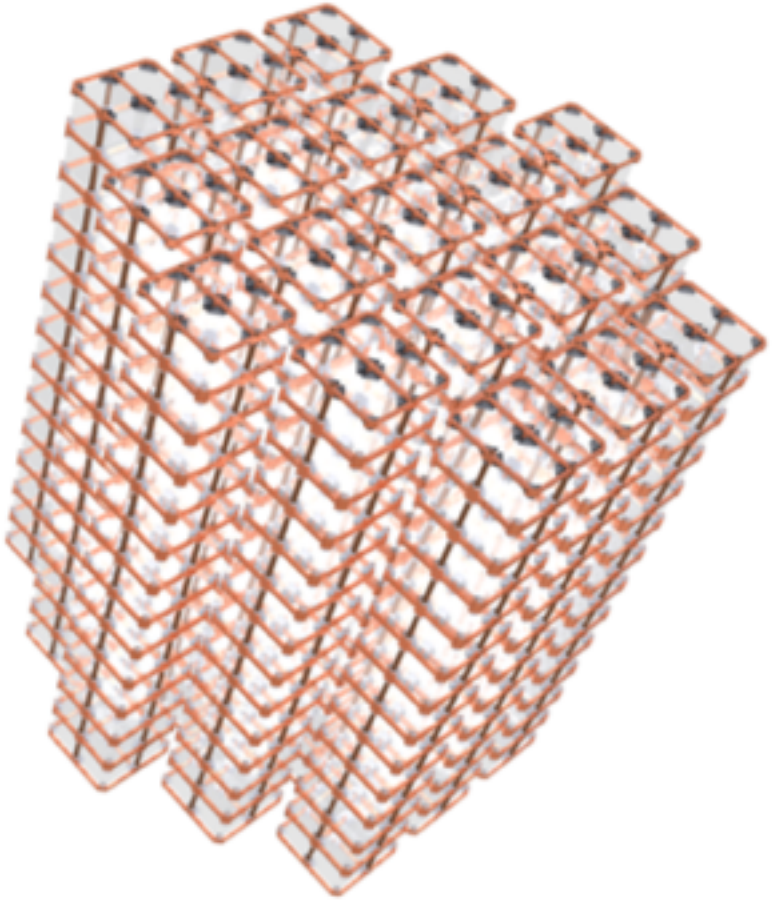
	0νββ region (c/keV/kg/yr)	2700-3900 keV * (c/keV/kg/yr)
CUORICINO ε = 83%	0.169 +/- 0.006	0.110 +/- 0.001
CUORE-0 ε = 81%	0.058 +/- 0.004	0.016 +/- 0.001

CUORE: Self Shielding

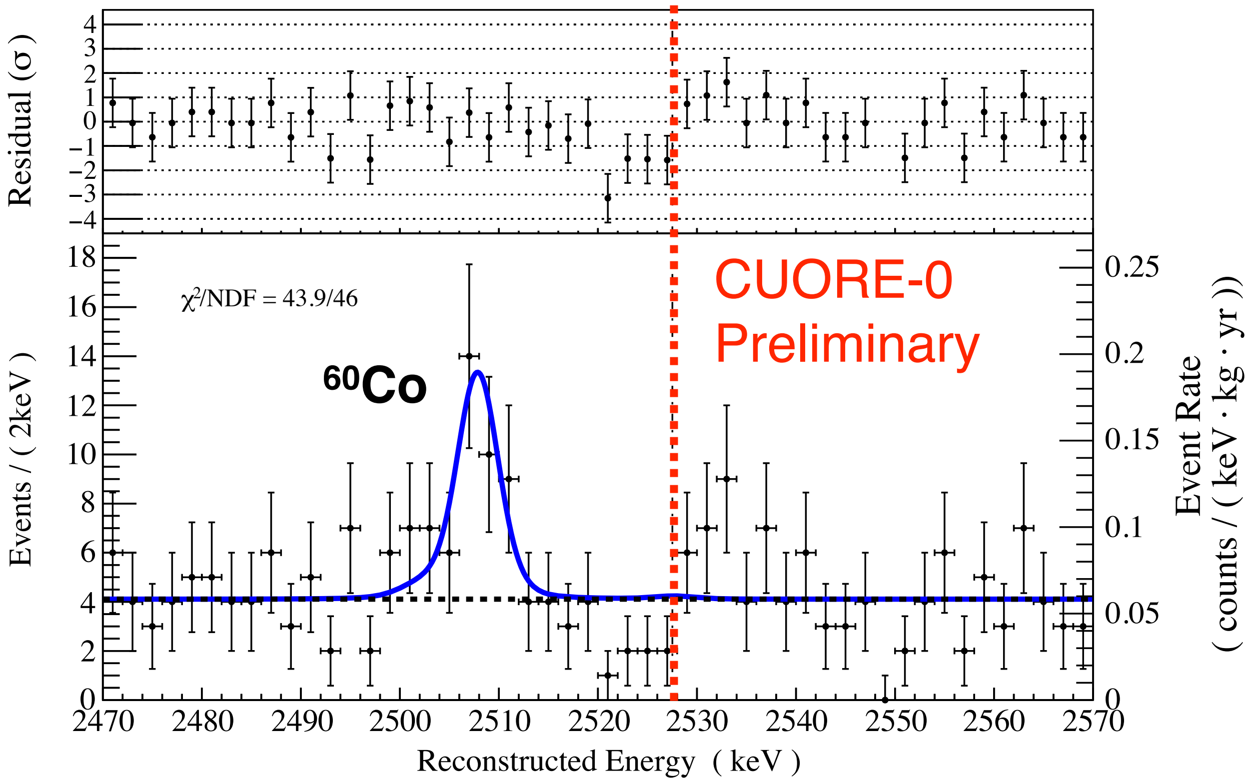
- CUORE-0 : All bolometers face 10 mk shield

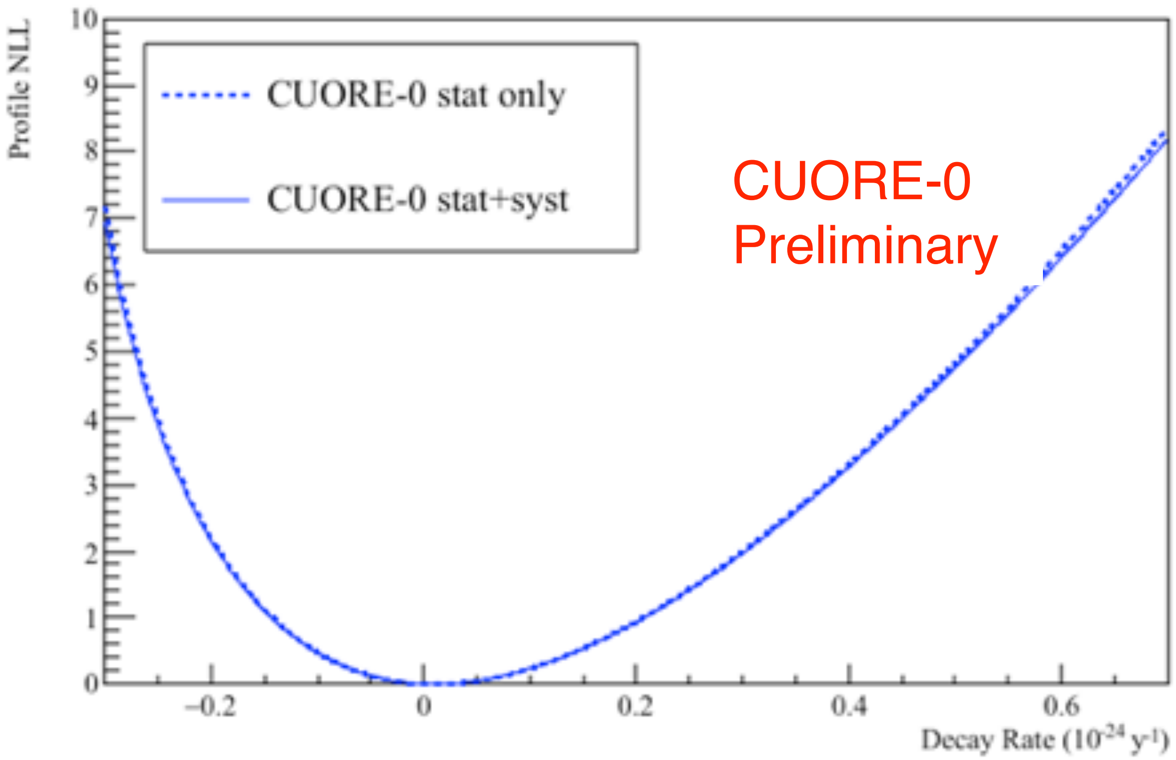


- CUORE: Only outermost crystals face 10mk shield



CUORE-0: $0\nu\beta\beta$ Search





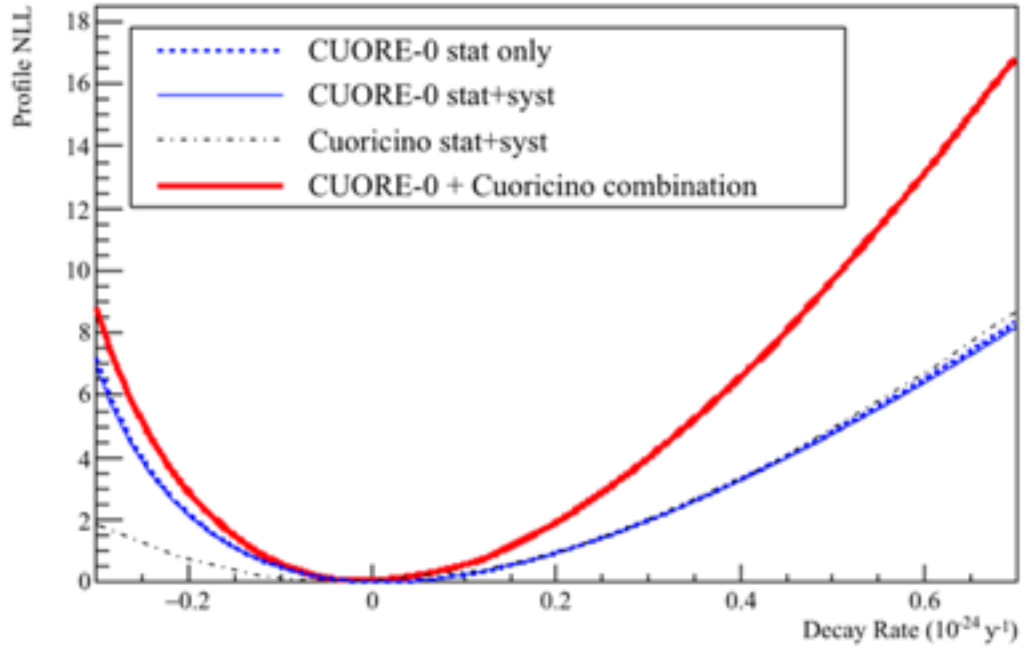
$Q_{\beta\beta}$ @ 2527.5 keV

- After all cuts: 233 events in 9.8 kg × yr exposure of ^{130}Te in ROI [2470-2570 keV]

$\Gamma_{0\nu}$	$0\nu\beta\beta$ decay rate	$0.01 \pm 0.12\,(\text{stat.}) \pm 0.01\,(\text{syst.}) \times 10^{-24}\ \text{yr}^{-1}$
Γ_B	Background rate	$0.058 \pm 0.004\,(\text{stat.}) \pm 0.002\,(\text{syst.})\ \text{counts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$

➡ Bayesian lower limit $\boxed{T^{0\nu}_{1/2} > 2.7 \times 10^{24}\ \text{yr} \quad \text{90\% C.L.}}$

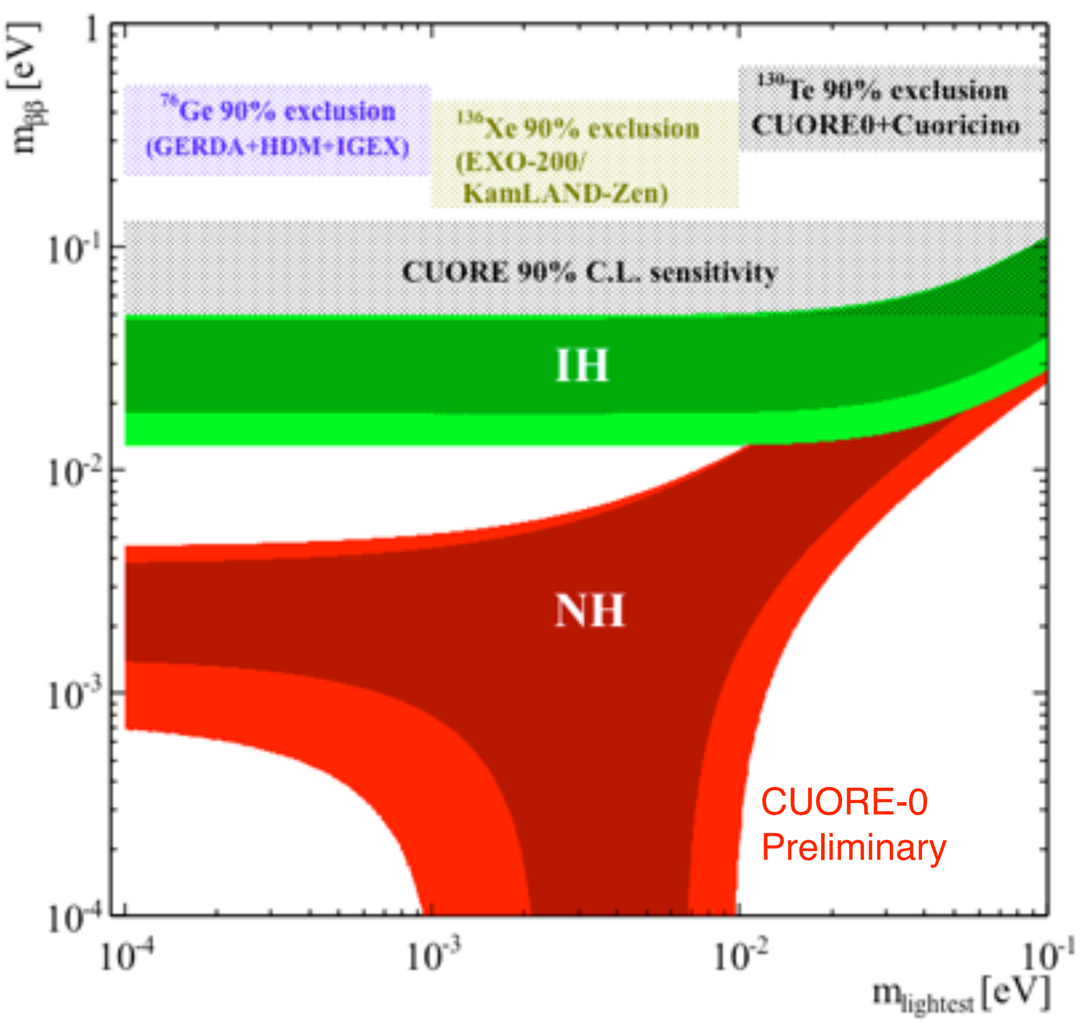
CUORE-0: Combination with CUORICINO



- The 90% C.L. (Bayesian) lower limit based on the combined profile function

$$T_{1/2}^{0\nu} > 4.0 \times 10^{24} \text{ yr}$$

- This is the most stringent limit to date on this half-life !

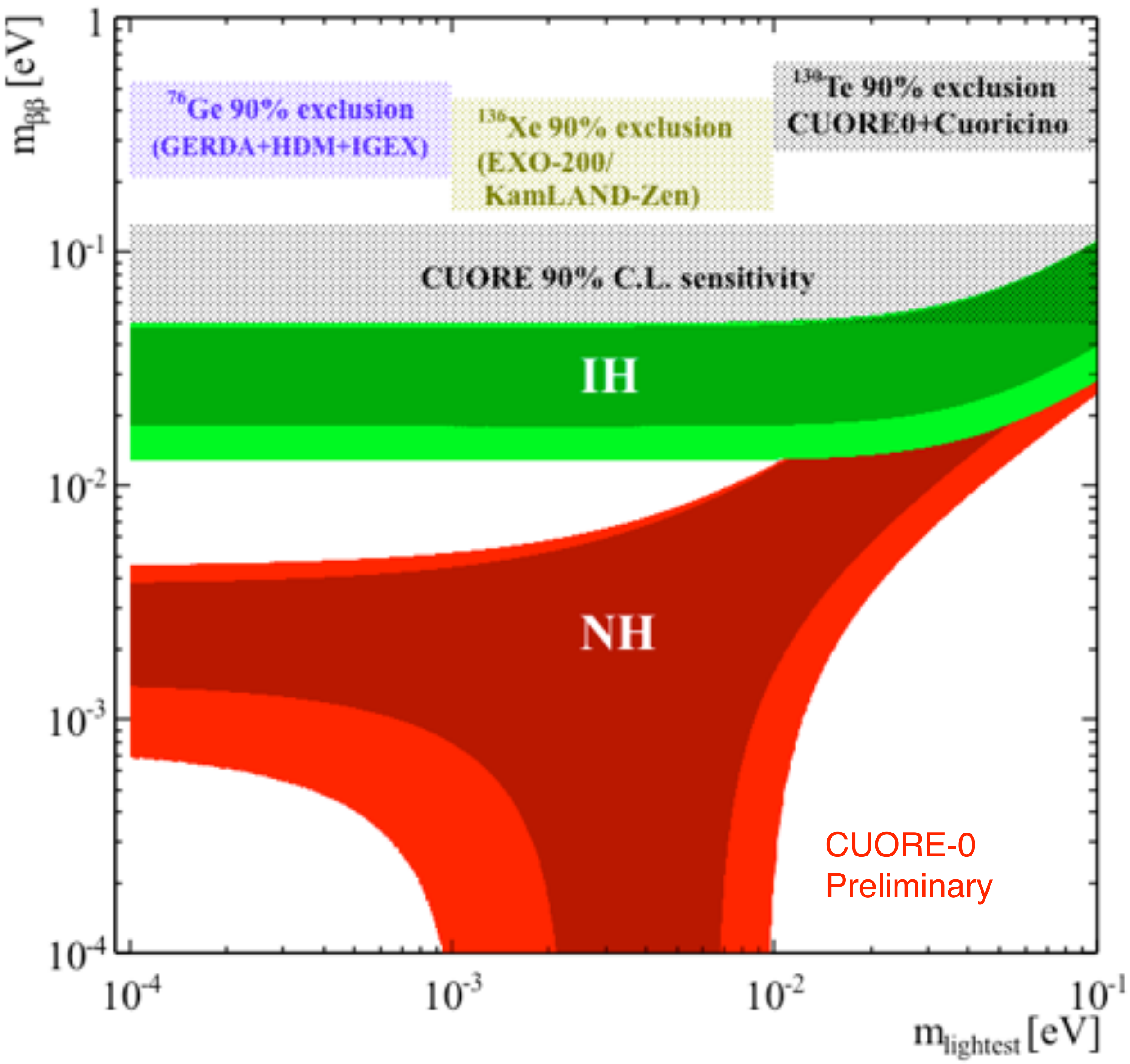


$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

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

The next ~5 years: CUORE Sensitivity



Assumptions:

- 988 bolometers
- 5 years of lifetime
- δE = 5 keV FWHM at 2615 keV
- b = 0.01 counts/(keV · kg · yr)

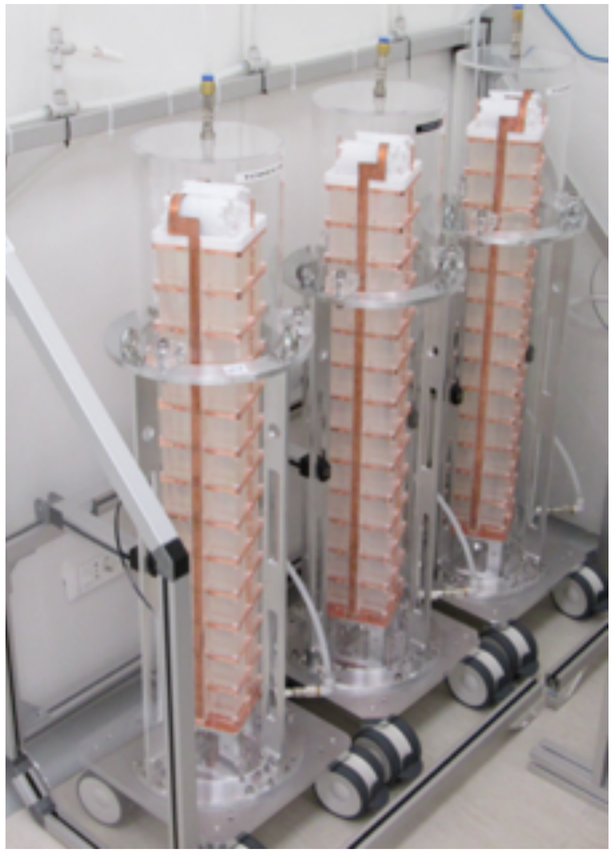
$$T^{0\nu}_{1/2} > 9.25 \times 10^{25}\ \mathrm{yr}\ (90\%\,\mathrm{C.L.})$$

$$m_{\beta\beta} < (50 - 130\,\mathrm{meV})$$

- May start to explore the inverted-hierarchy (depending on the NME)
- To improve sensitivity beyond CUORE needs active background suppression (e.g CUPID … **C**UORE **U**pgrade with **P**article **ID**)

Status of CUORE

- Assembly of all 19 towers now complete

- Cryogenic system is in the final stages of commissioning

- Expect to deploy the array in the cryostat later this year and begin operations

Outline

$0\nu\beta\beta$: why do we care ?

CUORE Program ($0\nu\beta\beta$ of ^{130}Te)

- CUORICINO
- CUORE-0
- CUORE

KamLAND-Zen($0\nu\beta\beta$ of ^{136}Xe)

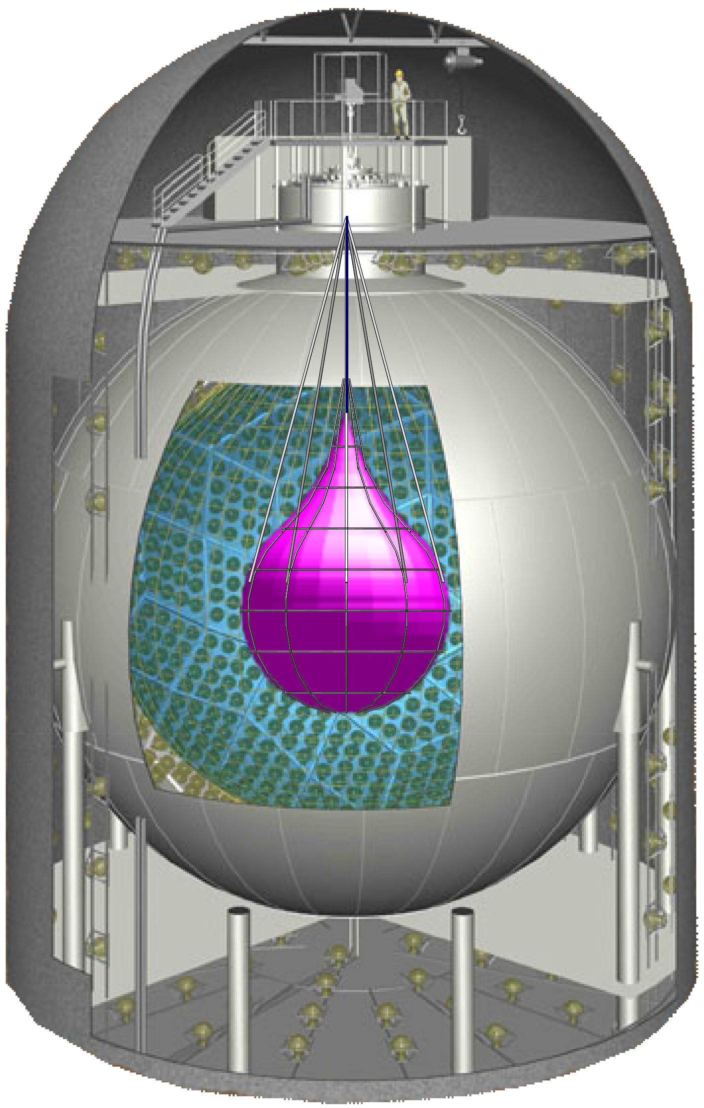
- KLZ Phase 1
- KLZ Phase 2
- KLZ Phase 3

KamLAND-Zen Collaboration

K. Asakura,[1] A. Gando,[1] Y. Gando,[1] T. Hachiya,[1] S. Hayashida,[1] H. Ikeda,[1] K. Inoue,[1, 2] K. Ishidoshiro,[1] T. Ishikawa,[1] S. Ishio,[1] M. Koga,[1, 2] R. Matsuda,[1] S. Matsuda,[1] T. Mitsui,[1] D. Motoki,[1] K. Nakamura,[1, 2] S. Obara,[1] Y. Oki,[1] M. Otani,[1] T. Oura,[1] I. Shimizu,[1] Y. Shirahata,[1] J. Shirai,[1] A. Suzuki,[1] H. Tachibana,[1] K. Tamae,[1] K. Ueshima,[1] H. Watanabe,[1] B.D. Xu,[1] Y. Yamauchi,[1] H. Yoshida,[1] A. Kozlov,[2] Y. Takemoto,[2] S. Yoshida,[3] K. Fushimi,[4] T.I. Banks,[5] S.J. Freedman,[2, 5†] B.K. Fujikawa,[2, 5] T. O'Donnell,[5] L.A. Winslow,[6] B.E. Berger,[7] Y. Efremenko,[2, 8] H.J. Karwowski,[9] D.M. Markoff,[9] W. Tornow,[2, 9] J.A. Detwiler,[10] S. Enomoto,[2, 10] and M.P. Decowski[2, 11]

1Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan
2Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa, 277-8583, Japan
3Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
4Faculty of Integrated Arts and Science, University of Tokushima, Tokushima, 770-8502, Japan
5Physics Department, University of California, Berkeley, and Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
6Department of Physics and Astronomy, University of California, Los Angels, Los Angels, California 90095, USA
7Department of Physics, Colorado State University, Fort Collins, Colorado 80523, USA
8Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA
9Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA; Physics Departments at Duke University, Durham, North Carolina 27705, USA; North Carolina Central University, Durham, North Carolina 27701, USA and the University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, USA
10Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, Washington 98195, USA
11Nikhef and the University of Amsterdam, Science Park, Amsterdam, the Netherlands

KamLAND-Zen

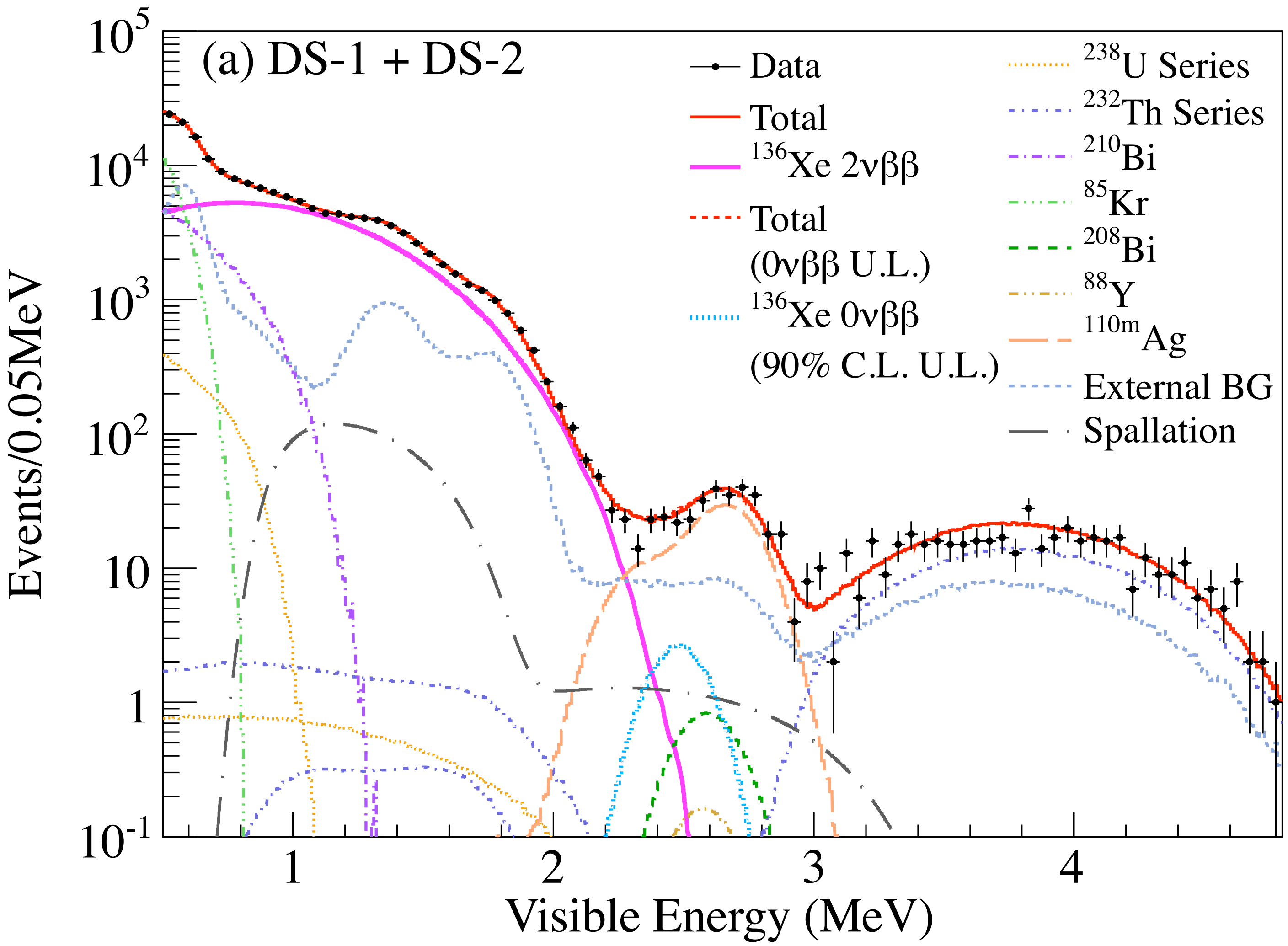


- Hosted in the KamLAND detector
- 3 m diameter mini-balloon at the center
- Loaded with 13 tons of Xe-loaded LS
  - ➡ ~2.5% by weight Xe
  - ➡ 90% ^{136}Xe (300 kg)
  - ➡ Q-value = 2458 keV
- KamLAND LS, 5m thick ultra-pure active shield
- KamLAND mineral oil buffer (2m thick)
- 3.2 kt water Cherenkov muon veto
- Scintillation light detected by array of ~2000 PMTs
- Energy resolution: $\sigma_E/E = 6.6\ \%/\sqrt{E}$ or 100 keV @ Q-value

KamLAND-Zen: Phase 1 Result

- Phase 1: Sept 2011-June 2012, 89.5 kg×yr exposure of ^{136}Xe

Candidate spectrum + Best-fit model



PRL **110** 062502 (2013)

- Two neutrino mode:

$$T^{2\nu}_{1/2} = 2.30 \pm 0.02(\text{stat}) \pm 0.12(\text{syst}) \times 10^{21}\text{yr}$$

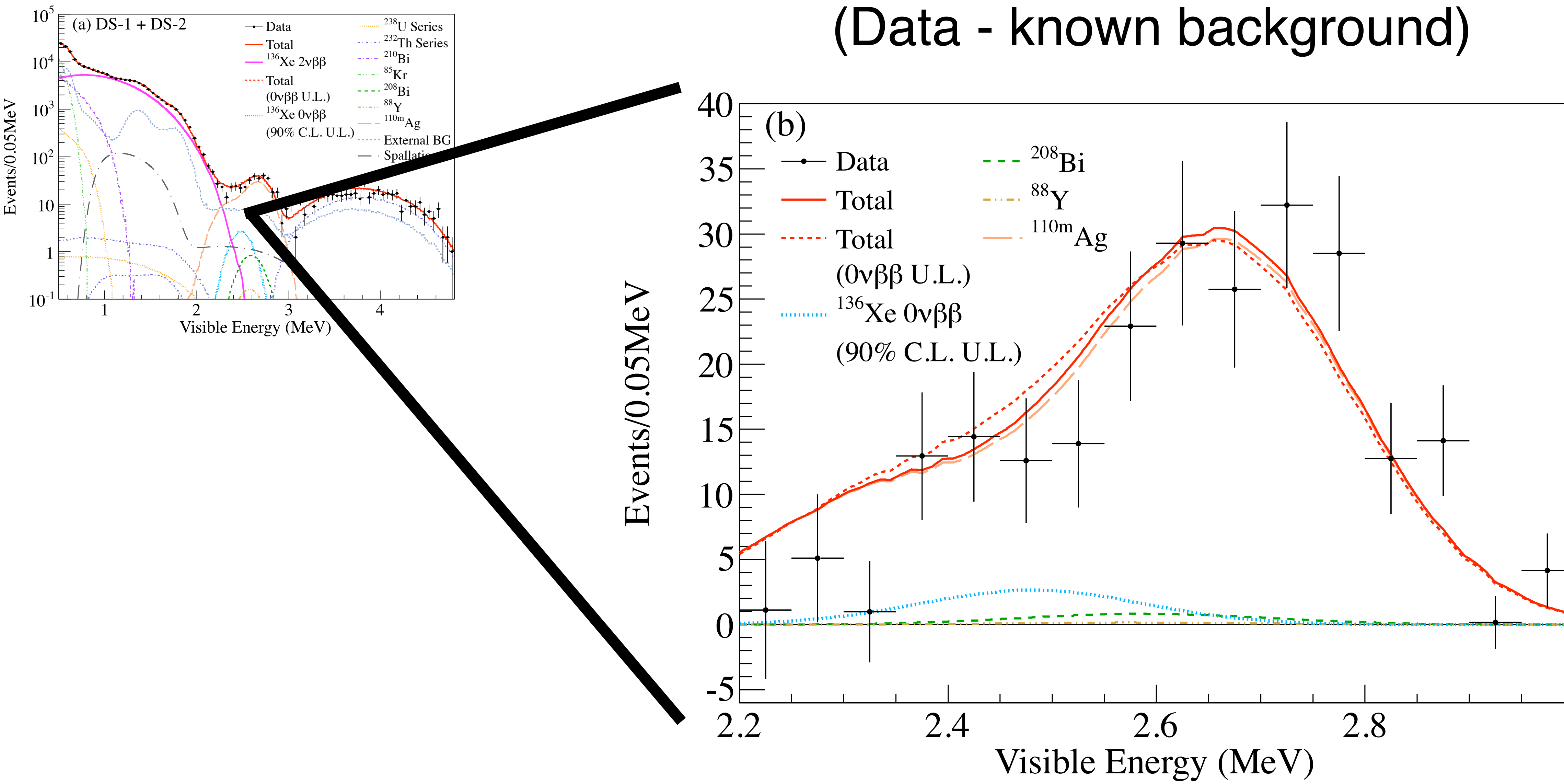
- Neutrinoless mode:

$$T^{0\nu}_{1/2} > 1.9 \times 10^{25}\ \text{yr} \quad (90\%\ \text{C.L})$$

KamLAND-Zen: Phase 1 -> Phase 2

Close up of 0vBB region

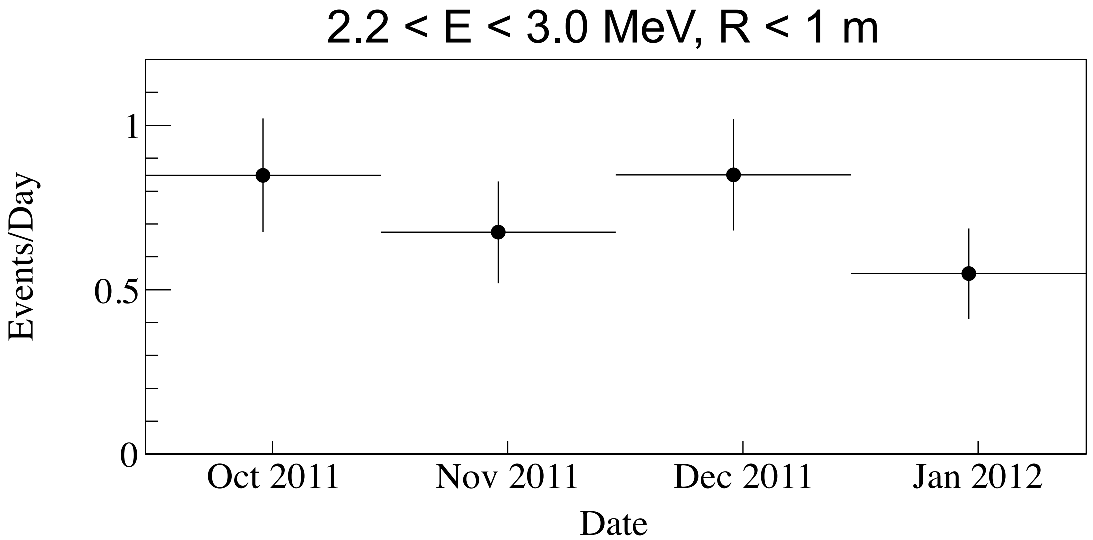
(Data - known background)



- Attributed to ^{110m}Ag … possibly fallout from the Fukushima nuclear accident
- At the end of Phase 1, the Xe and Xe-LS were purified to try to reduce the background

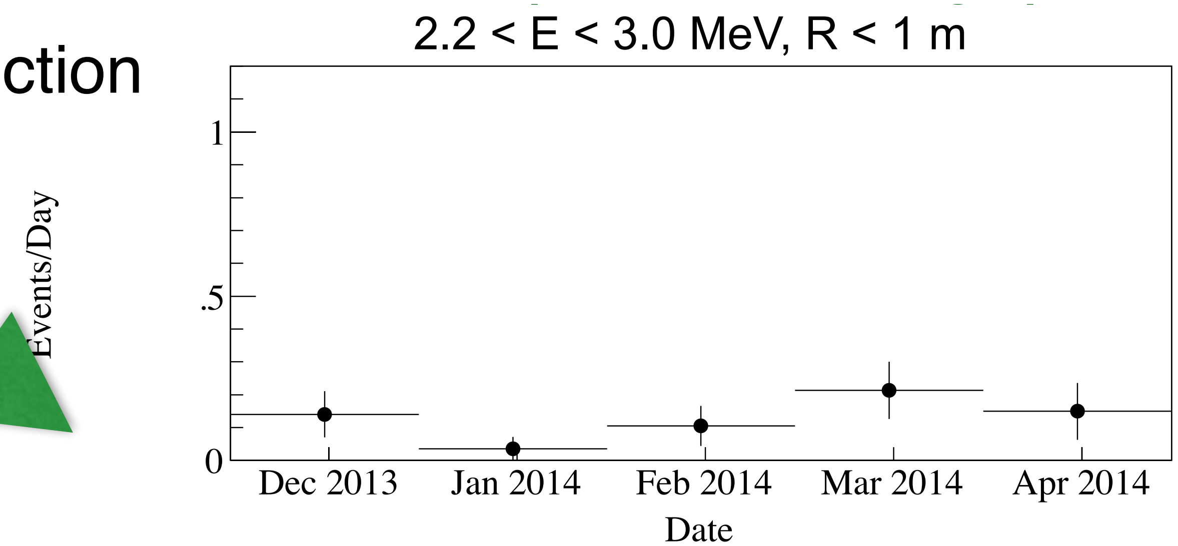
KamLAND-Zen: Phase 2

Phase1: First 112 days

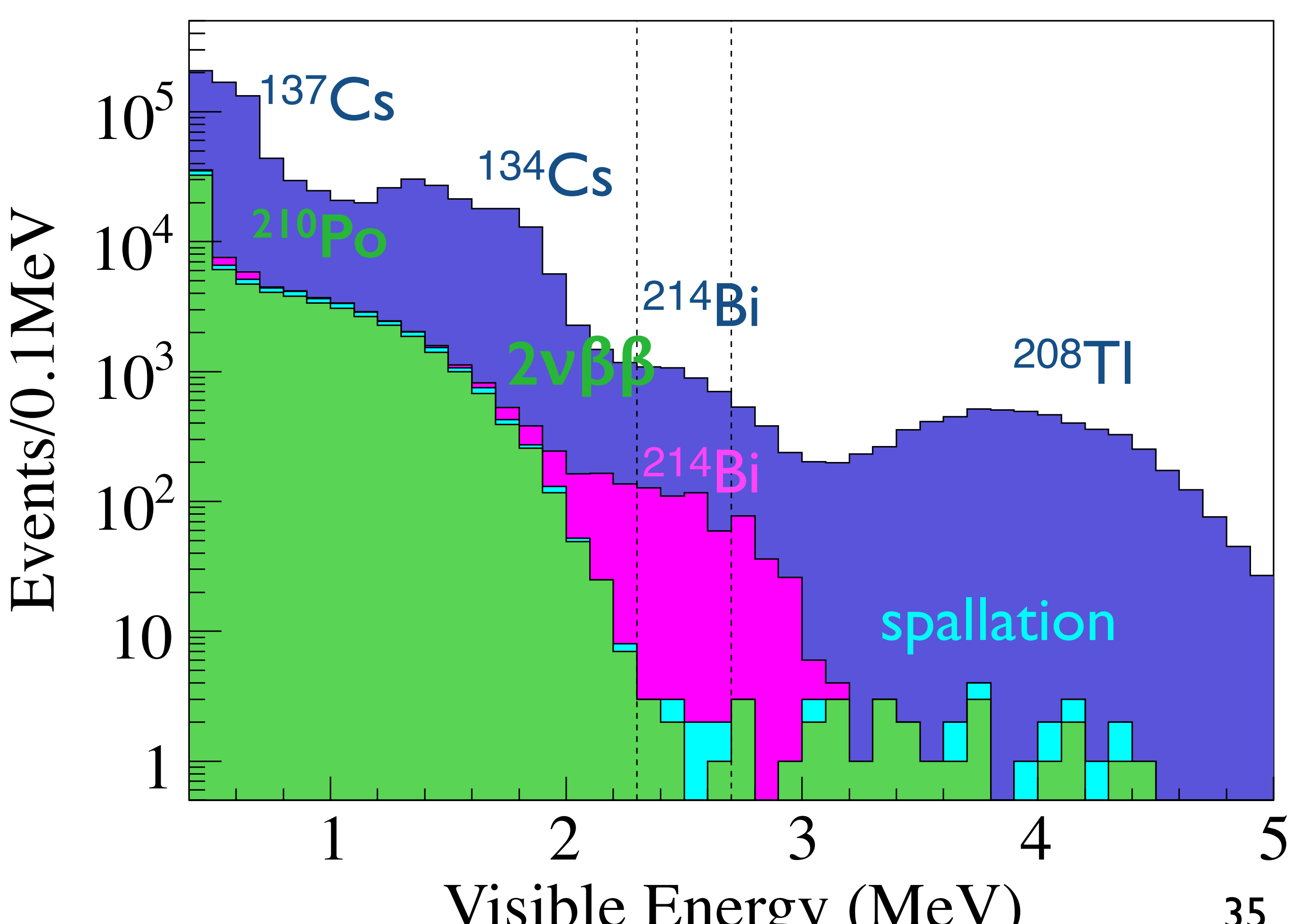


~10x reduction

Phase 2: First 114 days



0ν ROI: 2.3 MeV < E < 2.7 MeV



- 383 kg of ^{136}Xe loaded in Xe-LS
- ~27 kg×yr exposure of ^{136}Xe

Candidates remaining after:

R<2.0m + 2ms post μ veto

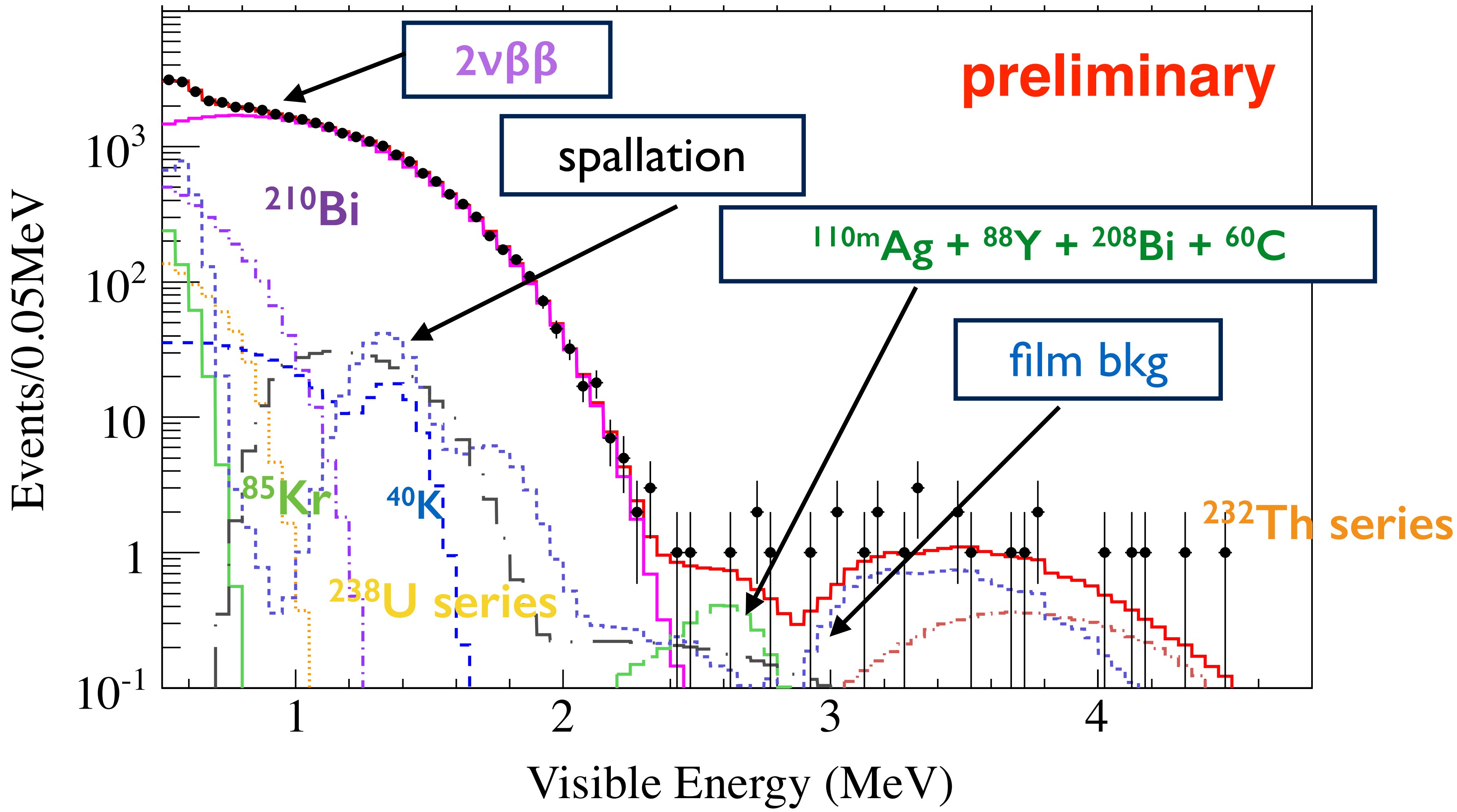
R<1.0m (Xe-LS) cut

Delayed Coincidence cut

Spallation cut

6 events in 0ν ROI

KamLAND-Zen: Phase 2 Fit

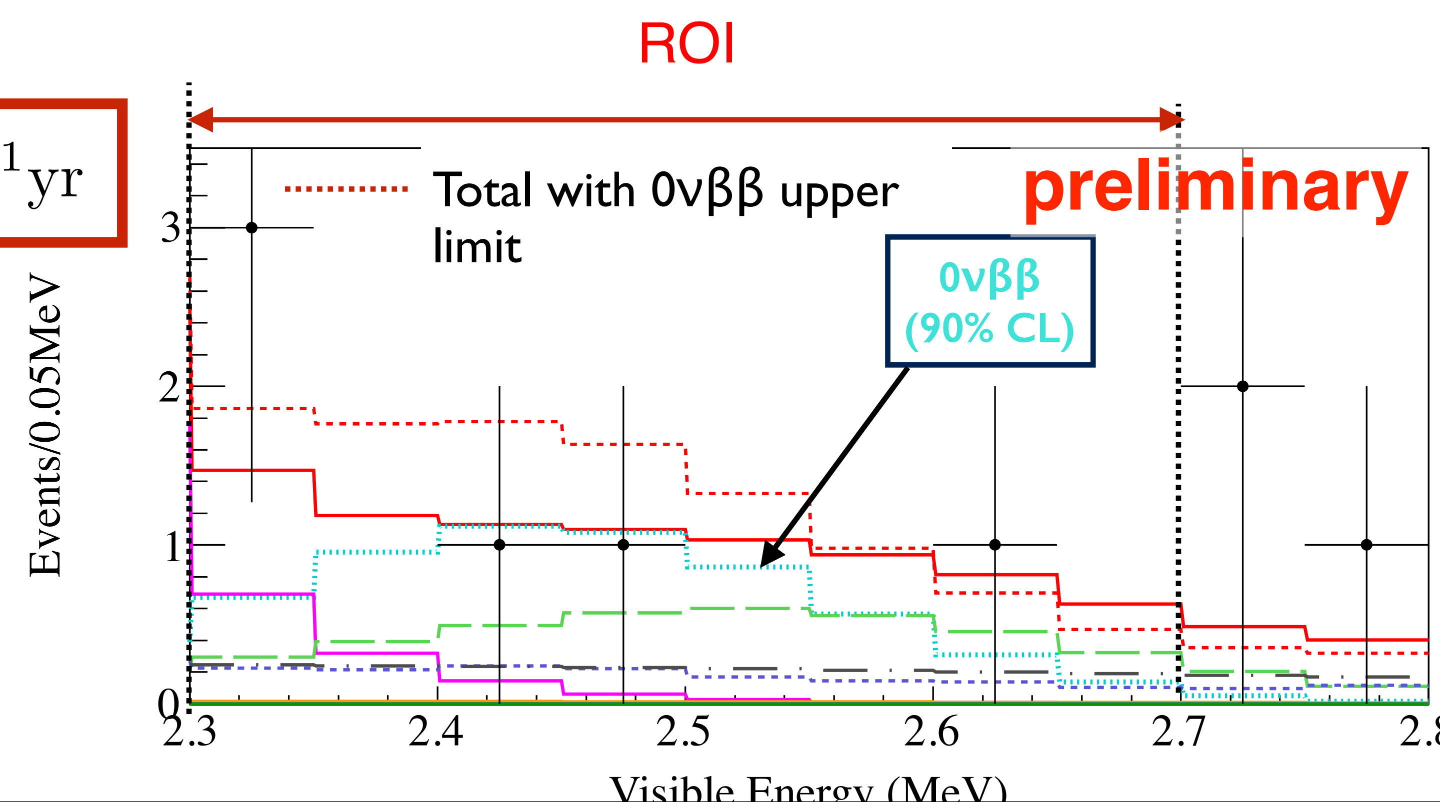


- R < 1.0 m

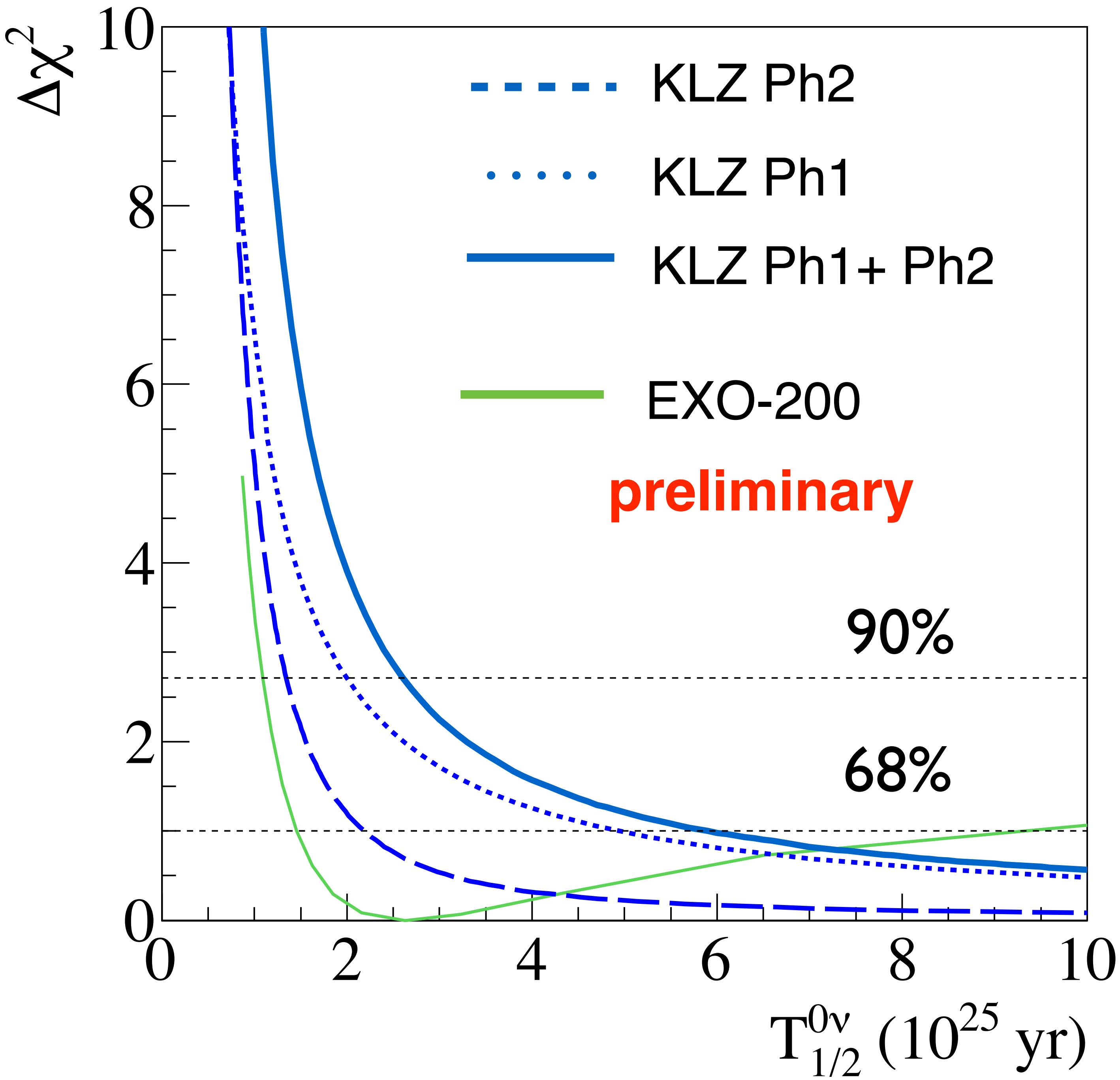
$$T^{2\nu}_{1/2} = 2.32 \pm 0.05(\mathrm{stat}) \pm 0.08(\mathrm{syst}) \times 10^{21}\,\mathrm{yr}$$

preliminary

$$T^{0\nu}_{1/2} > 1.3 \times 10^{25}\,\mathrm{yr}$$ 90% C.L.



KamLAND-Zen: Phase 2 Fit



All limits at 90% CL

KLZ Phase 2

$$T^{0\nu}_{1/2} > 1.3 \times 10^{25}\ \mathrm{yr}$$

KLZ Phase 1

$$T^{0\nu}_{1/2} > 1.9 \times 10^{25}\ \mathrm{yr}$$

KLZ Phase 1 + 2

$$T^{0\nu}_{1/2} > 2.6 \times 10^{25}\ \mathrm{yr}$$

preliminary

$$\langle m_{\beta\beta} \rangle < 180 - 300\ \mathrm{meV}$$

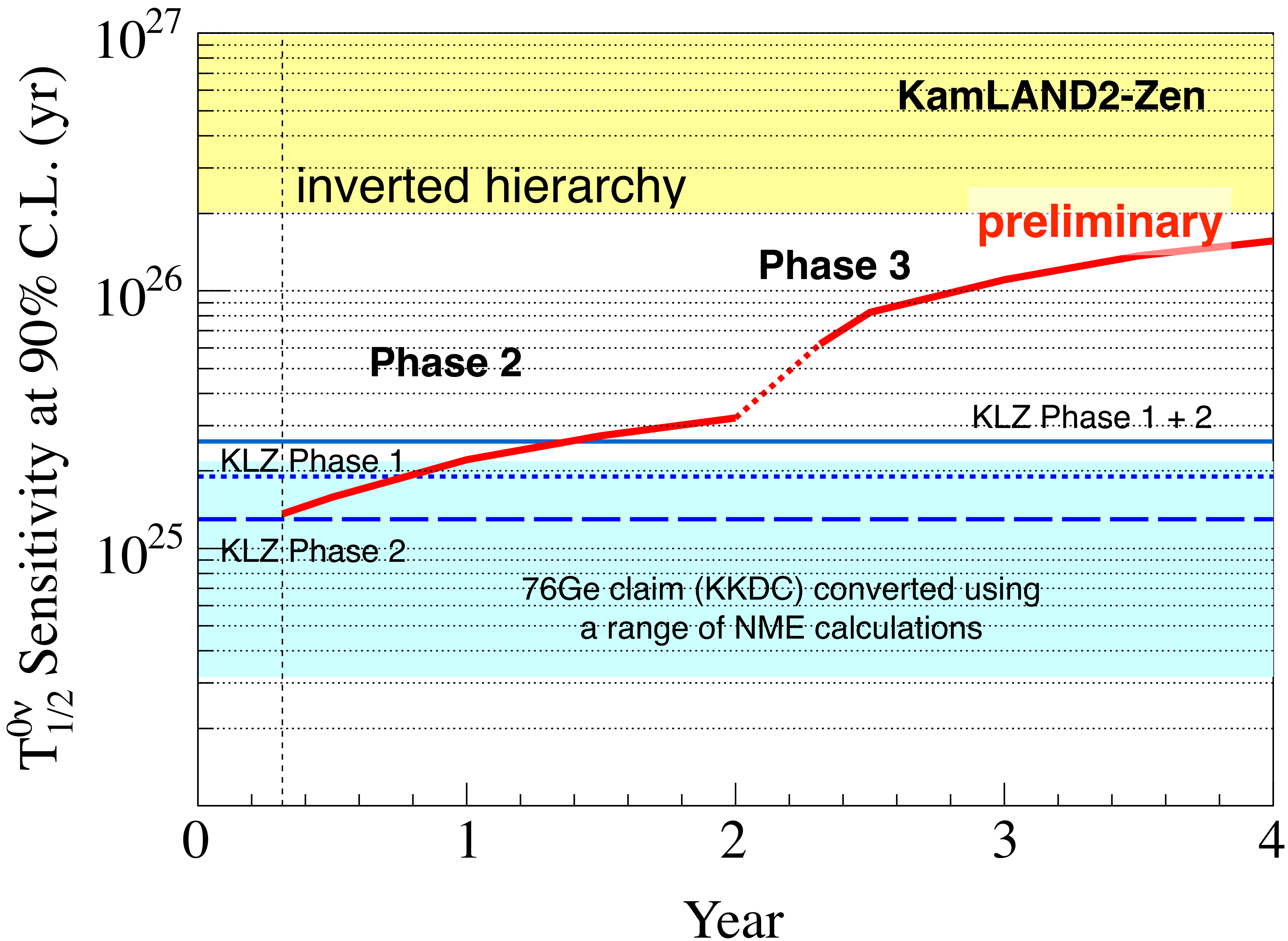
QRPA NME Model
J. Phys. G 39 124006 (2012)

KamLAND-Zen Plans

- Plan to continue Phase 2 until late 2015
  - About 350 days lifetime accumulate already

- Preparations for next phase underway
  - About 600 kg of 136Xe has been prepared
  - New inner balloon is being prepared this summer
    - Goal to remove ^{110m}Ag
    - Goal to reduce ^{214}Bi contamination in balloon 10x
  - Expect to install at the end of this year
  - Begin Phase 2 operations in early 2016

KamLAND-Zen Plans



Summary

- Data from CUORE-0 verifies the new assembly line, materials selection, and ultra-cleaning protocols reduce pernicious surface backgrounds
- CUORE-0 combined with CUORICINO provides the most stringent limit to date on $0\nu\beta\beta$ decay of ^{130}Te

http://arxiv.org/abs/1504.02454
Submitted to PRL

$T^{0\nu}_{1/2} > 4.0 \times 10^{24}$ yr (90% C.L.) $\langle m_{\beta\beta} \rangle < 270 - 650$ meV

- KamLAND-Zen capitalized on existing infrastructure to quickly realize competitive double beta decay search
- Preliminary results from Phase 1+ 2 of KamLAND-Zen

$T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr (90% C.L.) $\langle m_{\beta\beta} \rangle < 180 - 300$ meV

- Both KLZ Phase 3 and CUORE expect to approach IH in the next few years