CUORE, CUPID and the Nature of Neutrino Mass

Pranava Teja Surukuchi
Yale University

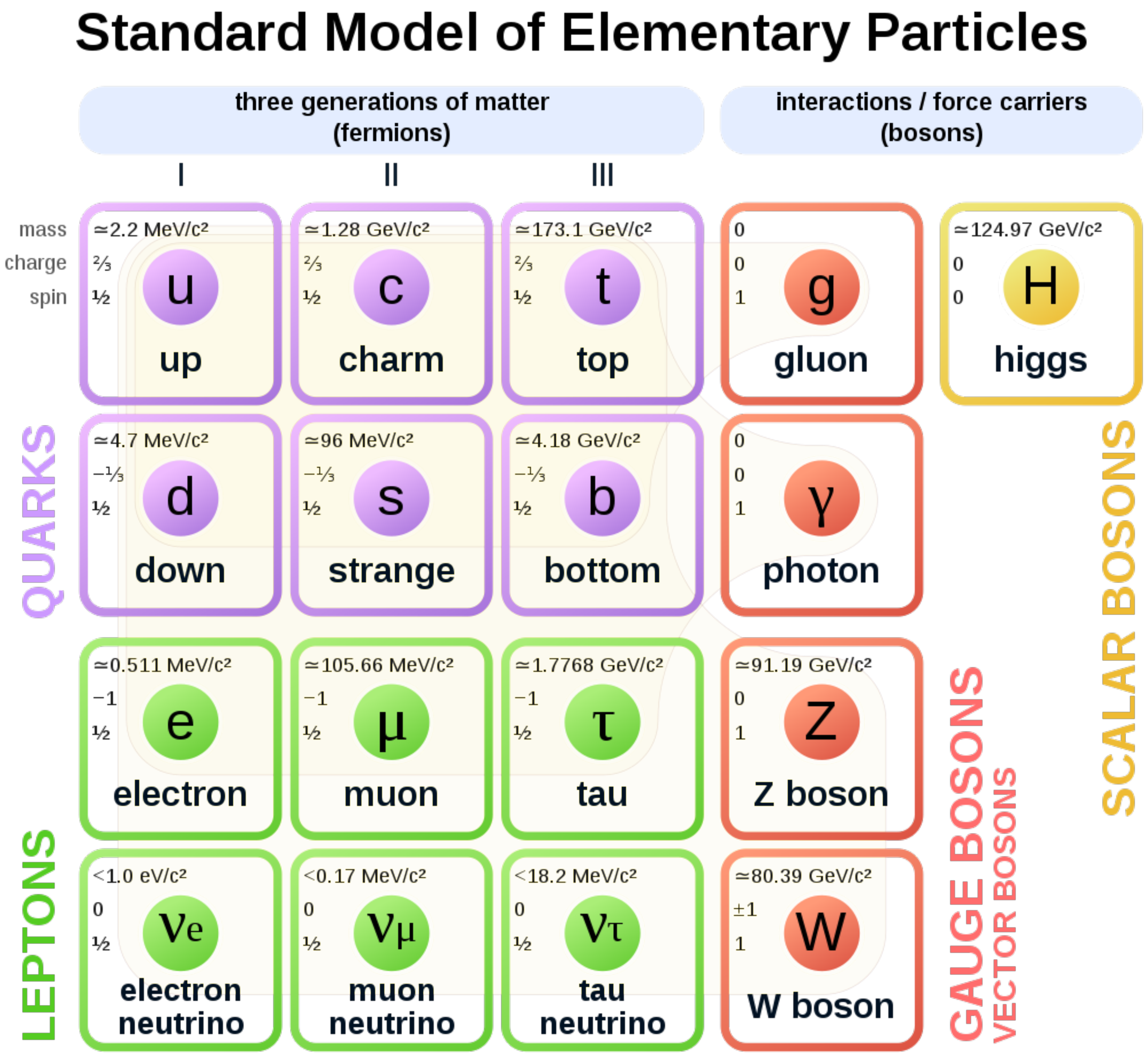
June 18, 2020

Yale

CUORE

BNL Seminar

Neutrinos: What We Know



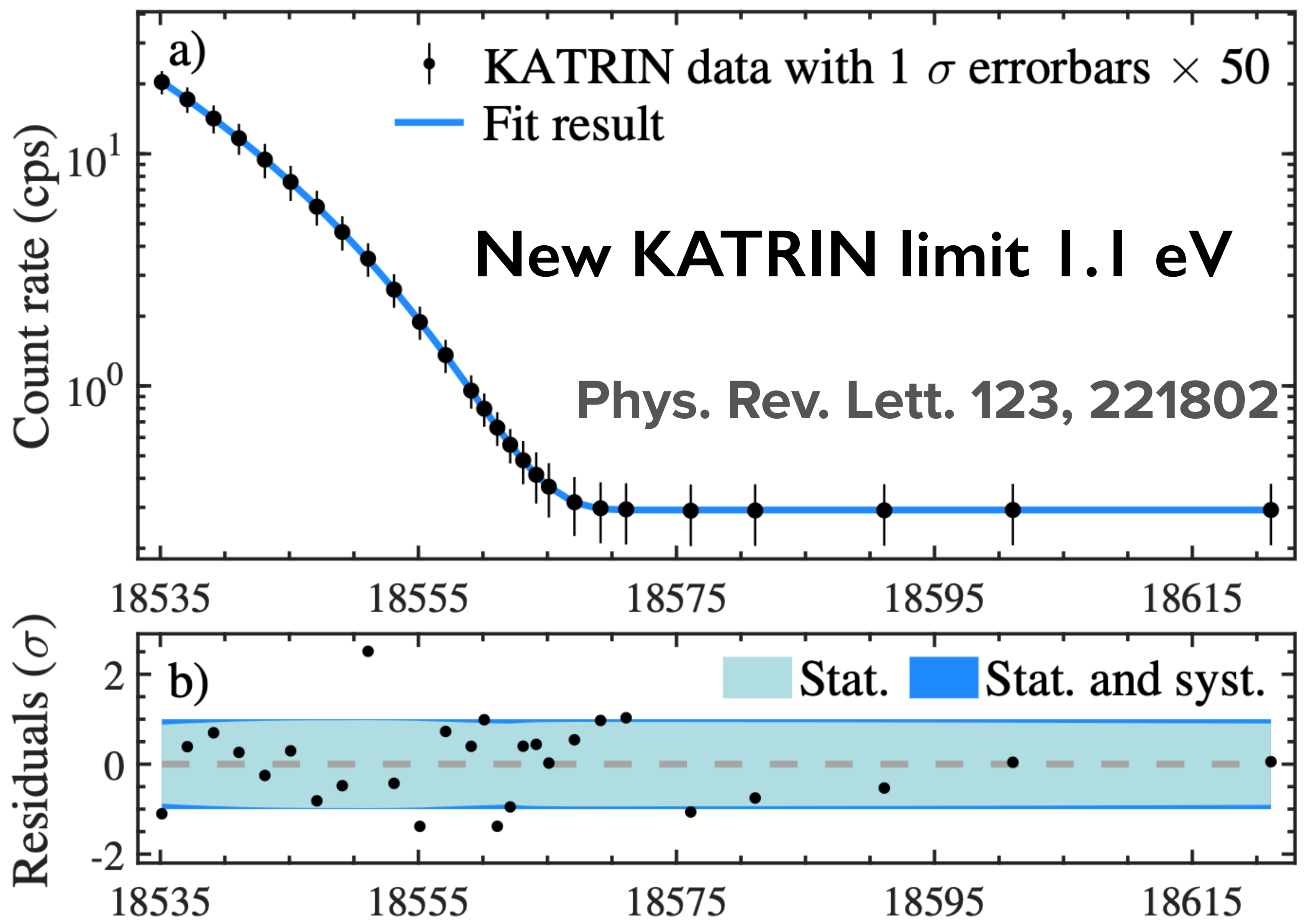
PBS NOVA [1], Fermilab, Office of Science, United States Department of Energy, Particle Data Group

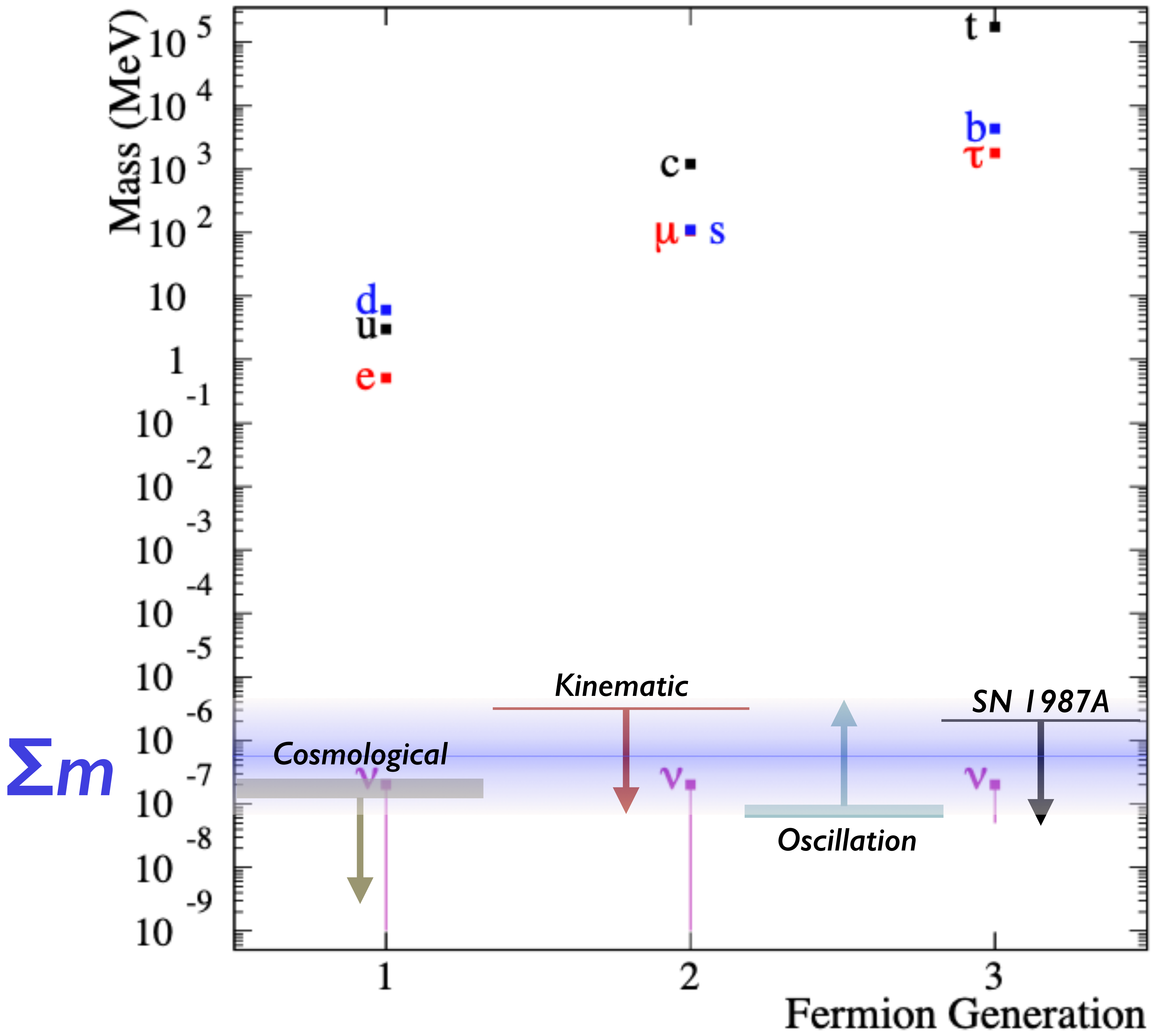
- Neutral fermions interacting via weak force
- Thought to be massless
- Oscillation experiments showed us that at least two of them are massive
- So far the absolute neutrino masses are not known

Neutrino Mass Measurements

Mass measurement paradigms:

- Neutrino oscillations
- Cosmological
- Beta decay measurements
- Neutrinoless double beta decay

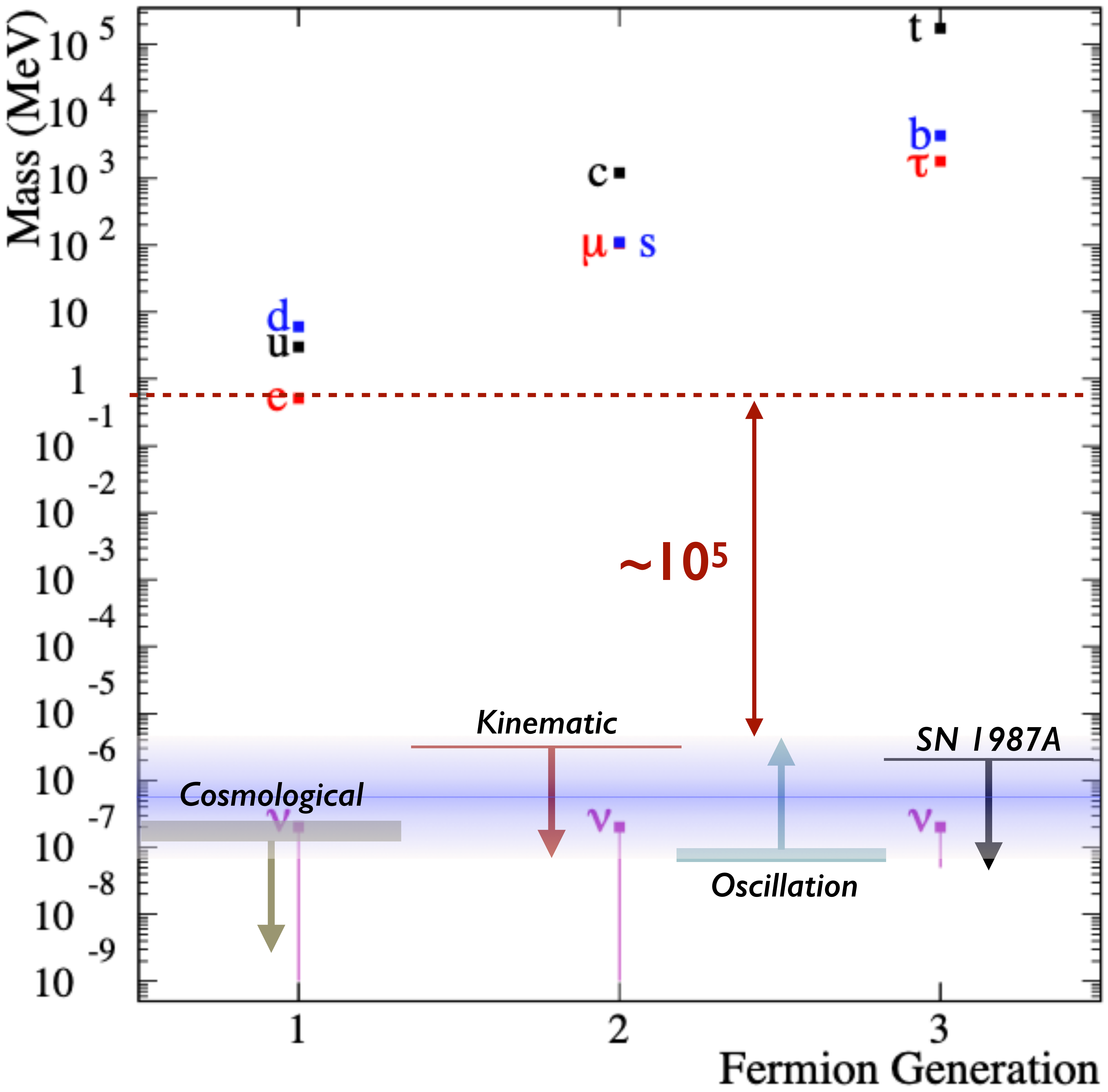




Adapted from arXiv:0604021

Nature of Neutrino Mass

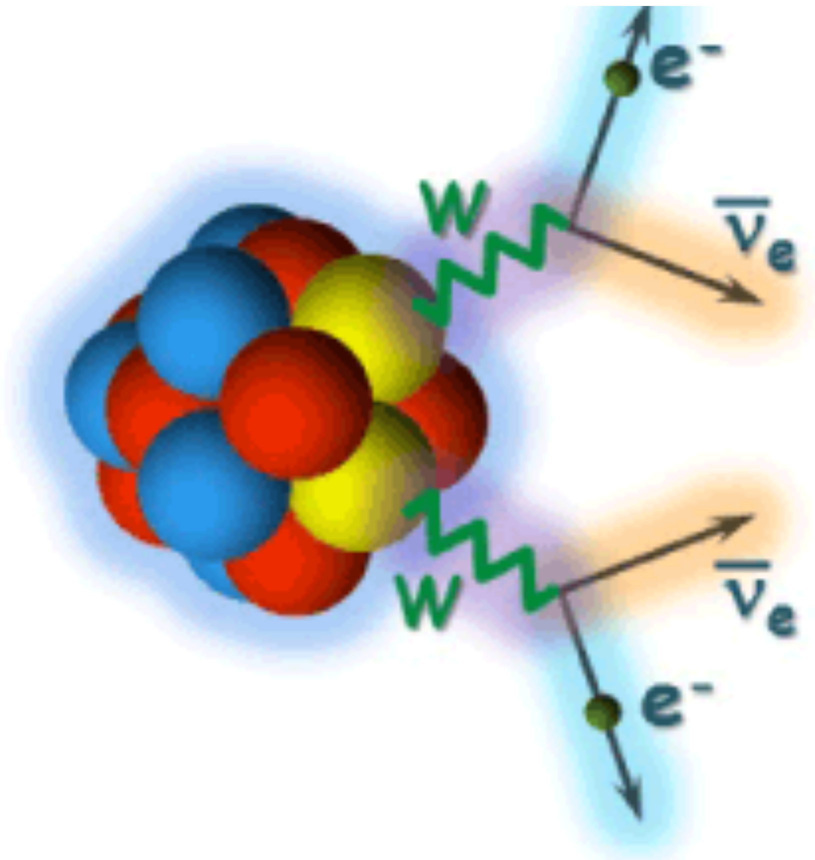
- Neutrino masses are at least 5 orders of magnitude smaller than other fundamental particles
- Nature of neutrino mass is unknown: Dirac vs Majorana
- The smallness of neutrino mass maybe tied to the Majorana nature of neutrino via See-saw mechanism
- Neutrinoless double beta decay experiments can help identify if neutrinos are Majorana type



Adapted from arXiv:0604021

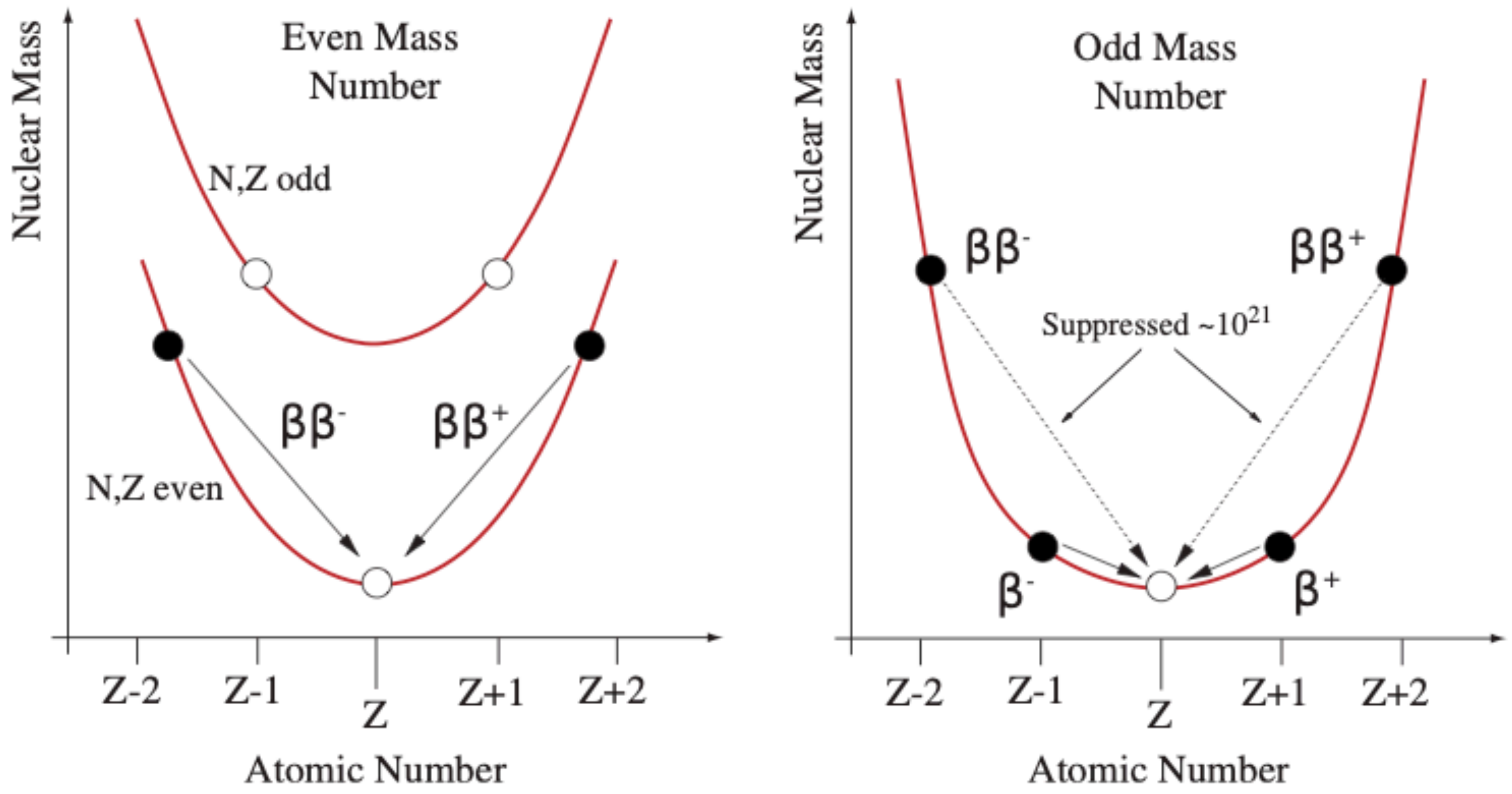
Double Beta Decay

- Two neutrons simultaneously convert to protons
- A few even-even nuclei can undergo double beta decay ($\nu\beta\beta$) when beta decay is energetically forbidden
- Half-life ($\sim 10^{20}$ yrs) >> age of universe
- 35 naturally occurring isotopes capable of $\nu\beta\beta$
- Already measured for several isotopes



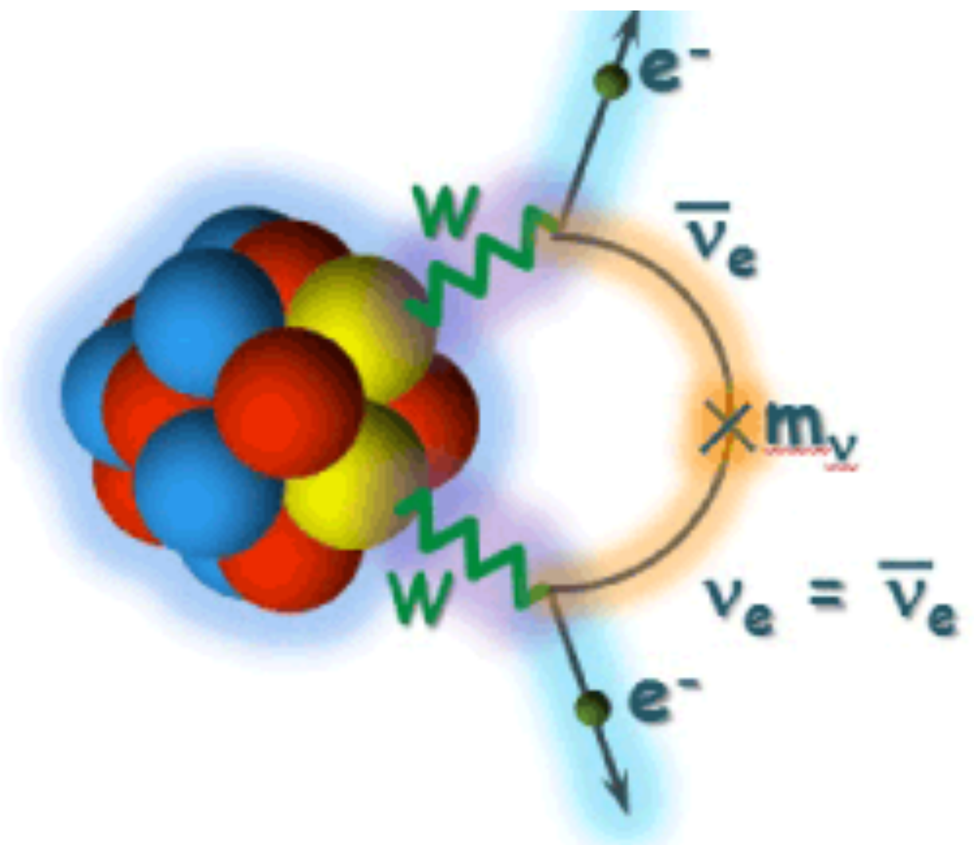
Double beta decay
which emits anti-neutrinos

-Osaka university



Neutrinoless Double Beta Decay (0νββ)

- Hypothesized nuclear process
- Implies:
  - ν has Majorana mass term
  - Lepton number violation
  - Hints to matter-antimatter asymmetry
- 0νββ experiments measure half-life (or decay rate)
- Constrain the ν mass and ordering



Neutrinoless double beta decay

-Osaka university

Nuclear Matrix elements

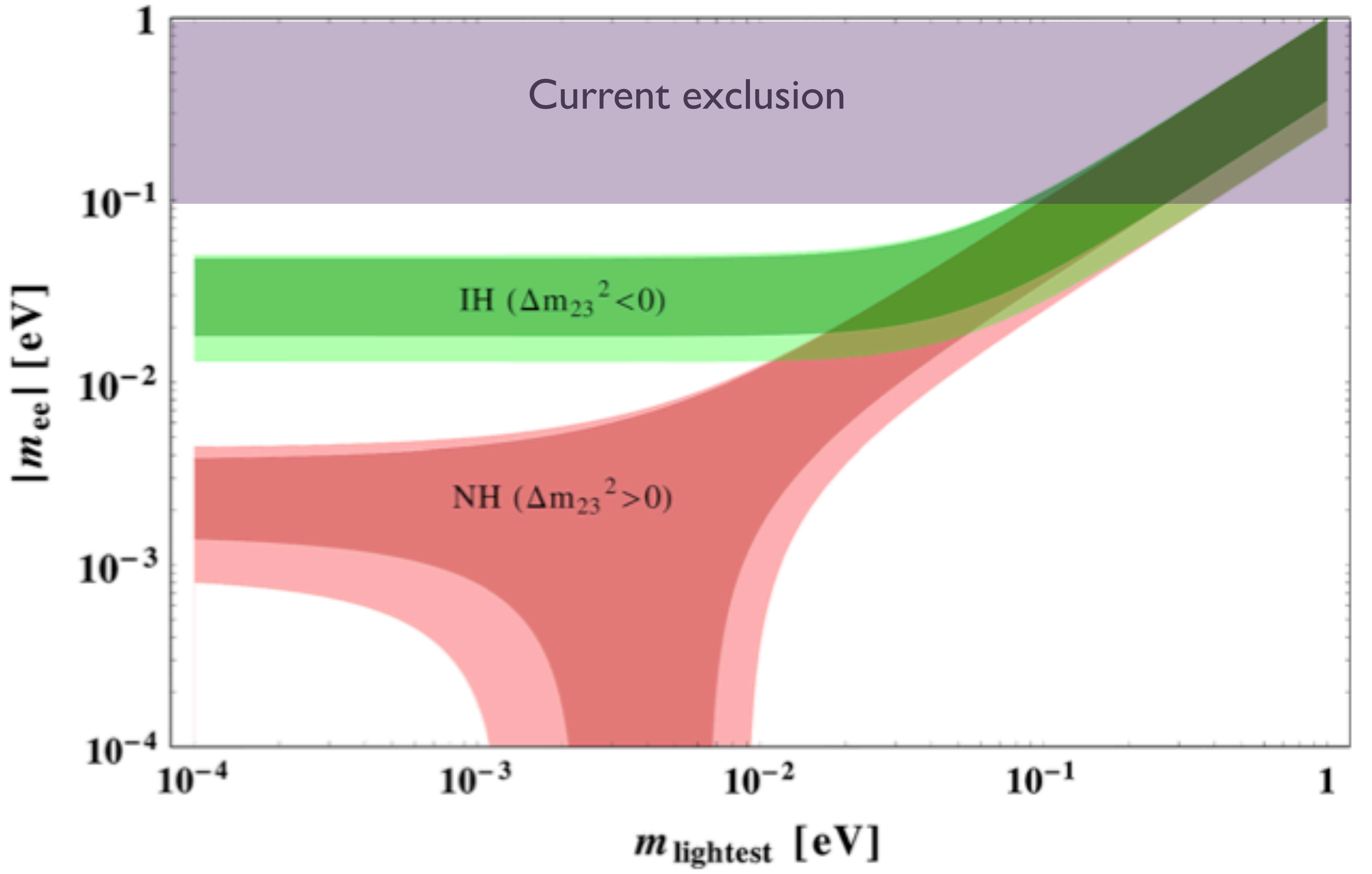
$$T_{1/2}^{0\nu} \propto \left(G\,|\mathcal{M}|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28}\left(\frac{0.01\,\mathrm{eV}}{\langle m_{\beta\beta}\rangle}\right)^2 \mathrm{y}$$

Phase space factor

Effective neutrino mass

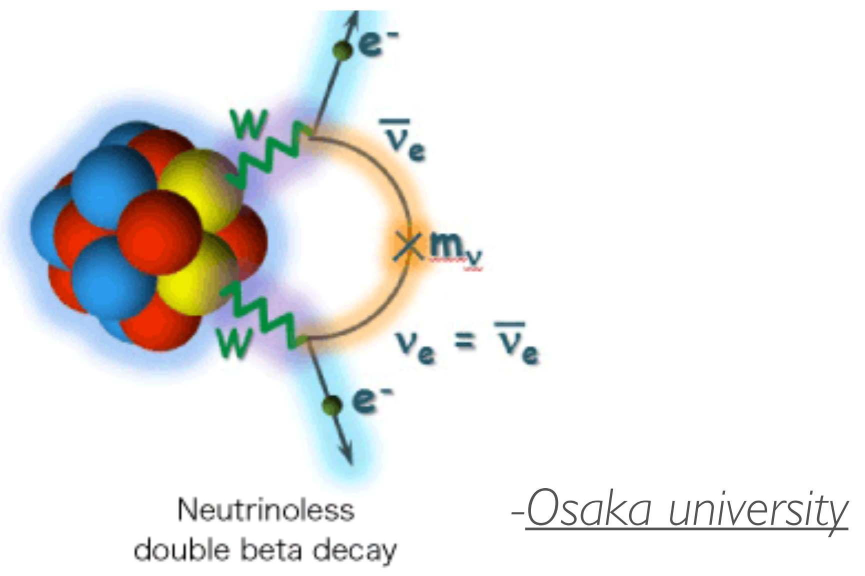
$$\langle m_{\beta\beta}\rangle = \left|\sum_j m_j U_{ej}^2\right|$$

Important to observe 0νββ in multiple isotopes



Searching for 0νββ

- Essentially a peak search at the Q value of the decay



Sensitivity in presence of BG:

$$S_{0\nu} \propto a\,\varepsilon \sqrt{\frac{M\,t}{B\,\Delta E}}$$

Efficiency

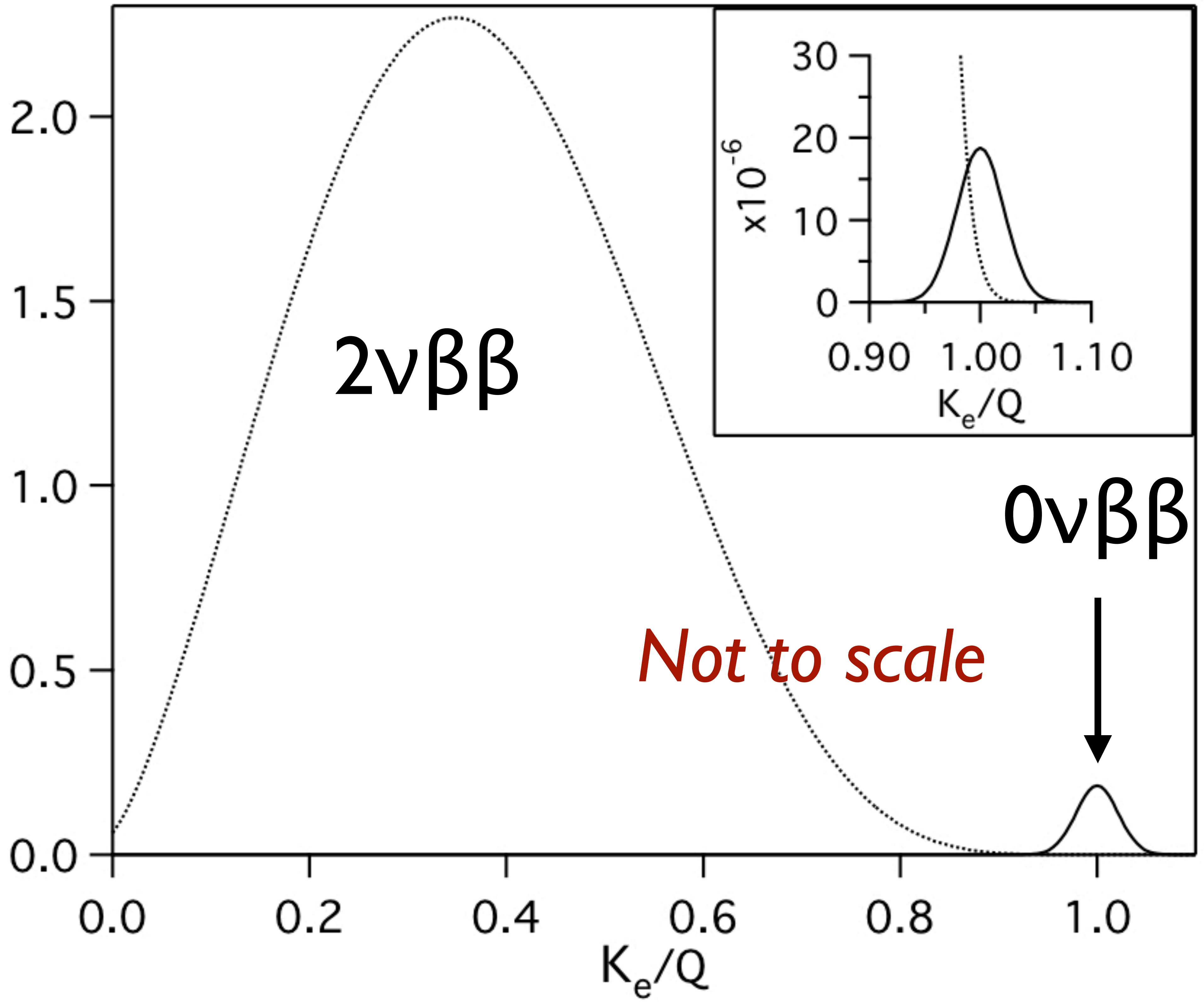
Mass

Runtime

Isotopic abundance

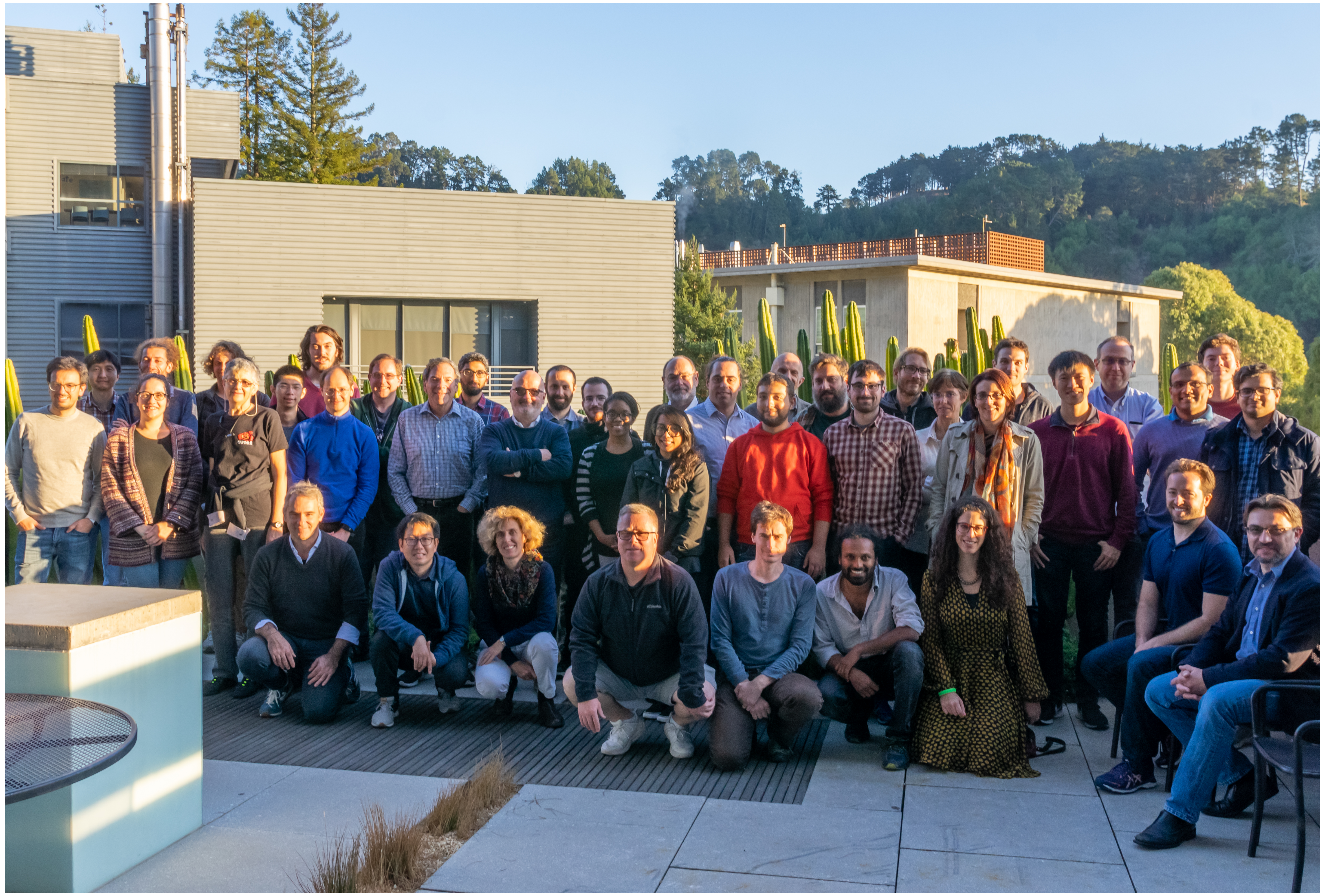
Background

Energy resolution



Resolution and backgrounds play important role in sensitivity

CUORE Experiment



CUORE

Cryogenic Underground Observatory for Rare Events

- **Primary Goal:** Search for $0\nu\beta\beta$ decay in ^{130}Te
- **Design:**
  - 19 towers (total of 988 TeO_2 crystals)

CUORE

Cryogenic Underground Observatory for Rare Events

- **Primary Goal:** Search for $0\nu\beta\beta$ decay in ^{130}Te
- **Design:**
  - 19 towers (total of 988 TeO_2 crystals)
  - *Large mass:* 742 kg of TeO_2 ,206 kg of ^{130}Te
  - *Low background goal:* 10^{-2} cts/(keV. kg. yr)
  - *Energy resolution:* Goal of 5 keV FWHM at $Q_{\beta\beta}$
  - High efficiency and duty cycle
- **Sensitivity:**
  - $T^{0\nu}_{1/2} \sim 9 \times 10^{25}$ yrs (90% C.L) in 5 yrs
  - $m_{\beta\beta} < 50\text{-}130$ meV

$$a\,\varepsilon\sqrt{\frac{M\,t}{B\,\Delta E}}$$

CUORE

Cryogenic Underground Observatory for Rare Events

- **Primary Goal:** Search for $0\nu\beta\beta$ decay in ^{130}Te
- **Design:**
  - 19 towers (total of 988 TeO_2 crystals)
  - *Large mass:* 742 kg of TeO_2 ,206 kg of ^{130}Te
  - *Low background goal:* 10^{-2} cts/(keV. kg. yr)
  - *Energy resolution:* Goal of 5 keV FWHM at $Q_{\beta\beta}$
  - High efficiency and duty cycle
- **Sensitivity:**
  - $T^{0\nu}_{1/2} \sim 9 \times 10^{25}$ yrs (90% C.L) in 5 yrs
  - $m_{\beta\beta} < 50\text{-}130$ meV

$$a\,\varepsilon\sqrt{\frac{M\,t}{\boxed{B}\,\Delta E}}$$

CUORE

Cryogenic Underground Observatory for Rare Events

- **Primary Goal:** Search for $0\nu\beta\beta$ decay in ^{130}Te
- **Design:**
  - 19 towers (total of 988 TeO_2 crystals)
  - *Large mass:* 742 kg of TeO_2 ,206 kg of ^{130}Te
  - *Low background goal:* 10^{-2} cts/(keV. kg. yr)
  - *Energy resolution:* Goal of 5 keV FWHM at $Q_{\beta\beta}$
  - High efficiency and duty cycle
- **Sensitivity:**
  - $T^{0\nu}_{1/2}$ ~ 9 x 10^{25} yrs (90% C.L) in 5 yrs
  - $m_{\beta\beta}$ < 50-130 meV

$$a\,\varepsilon\sqrt{\frac{M\,t}{B\,\boxed{\Delta E}}}$$

CUORE

Cryogenic Underground Observatory for Rare Events

- **Primary Goal:** Search for $0\nu\beta\beta$ decay in ^{130}Te
- **Design:**
  - 19 towers (total of 988 TeO_2 crystals)
  - *Large mass:* 742 kg of TeO_2 ,206 kg of ^{130}Te
  - *Low background goal:* 10^{-2} cts/(keV. kg. yr)
  - *Energy resolution:* Goal of 5 keV FWHM at $Q_{\beta\beta}$
  - High efficiency and duty cycle
- **Sensitivity:**
  - $T^{0\nu}_{1/2}$ ~ 9 x 10^{25} yrs (90% C.L) in 5 yrs
  - $m_{\beta\beta}$ < 50-130 meV

$$a\,\boxed{\varepsilon}\sqrt{\frac{M\,\boxed{t}}{B\,\Delta E}}$$

CUORE

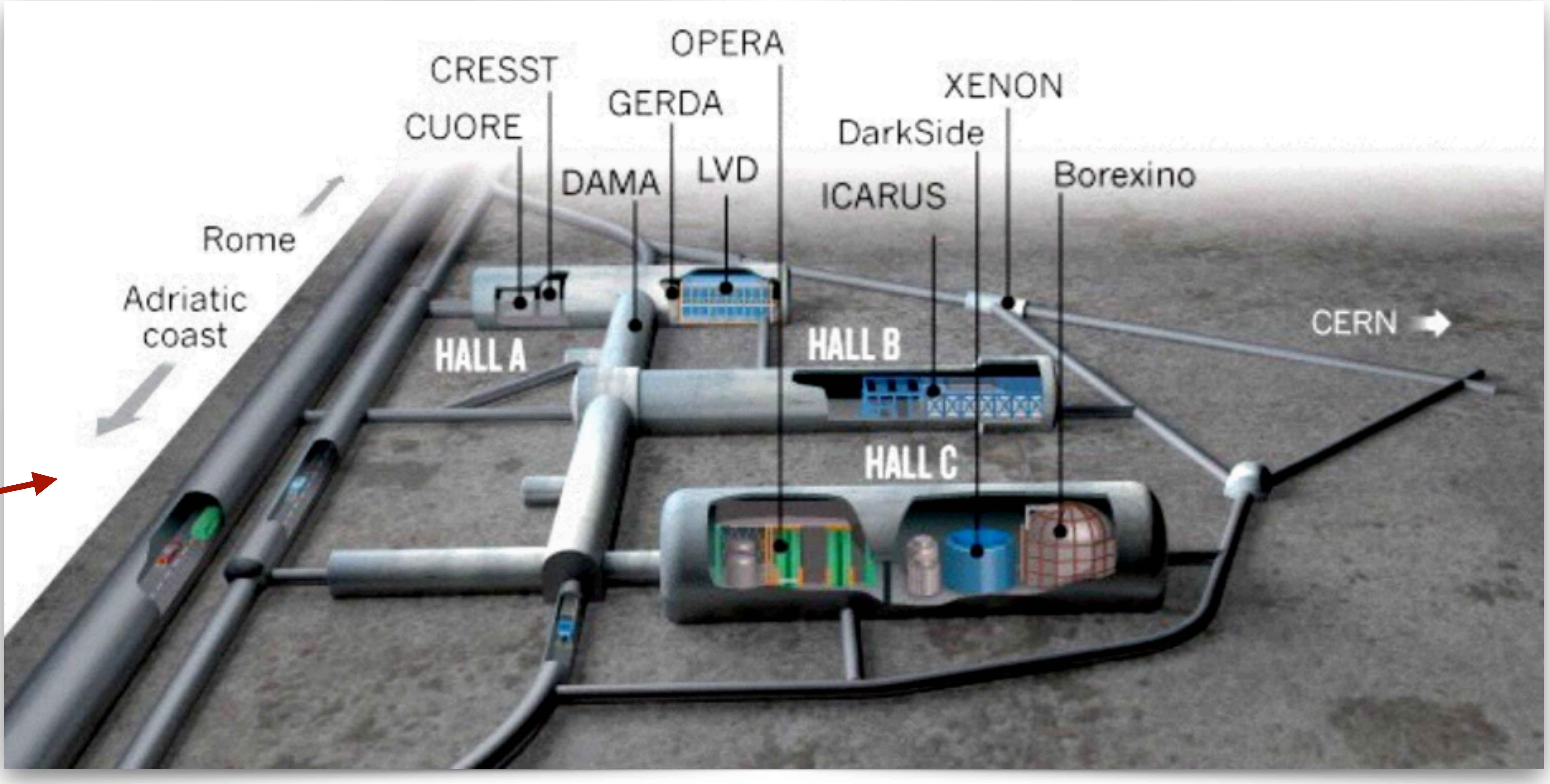
Cryogenic Underground Observatory for Rare Events

- **Primary Goal:** Search for $0\nu\beta\beta$ decay in ^{130}Te
- **Design:**
  - 19 towers (total of 988 TeO_2 crystals)
  - *Large mass:* 742 kg of TeO_2 ,206 kg of ^{130}Te
  - *Low background goal:* 10^{-2} cts/(keV. kg. yr)
  - *Energy resolution:* Goal of 5 keV FWHM at $Q_{\beta\beta}$
  - High efficiency and duty cycle
- **Sensitivity:**
  - $T^{0\nu}_{1/2} \sim 9 \times 10^{25}$ yrs (90% C.L) in 5 yrs
  - $m_{\beta\beta} < 50\text{-}130$ meV

$$a\,\varepsilon\sqrt{\frac{M\,t}{B\,\Delta E}}$$

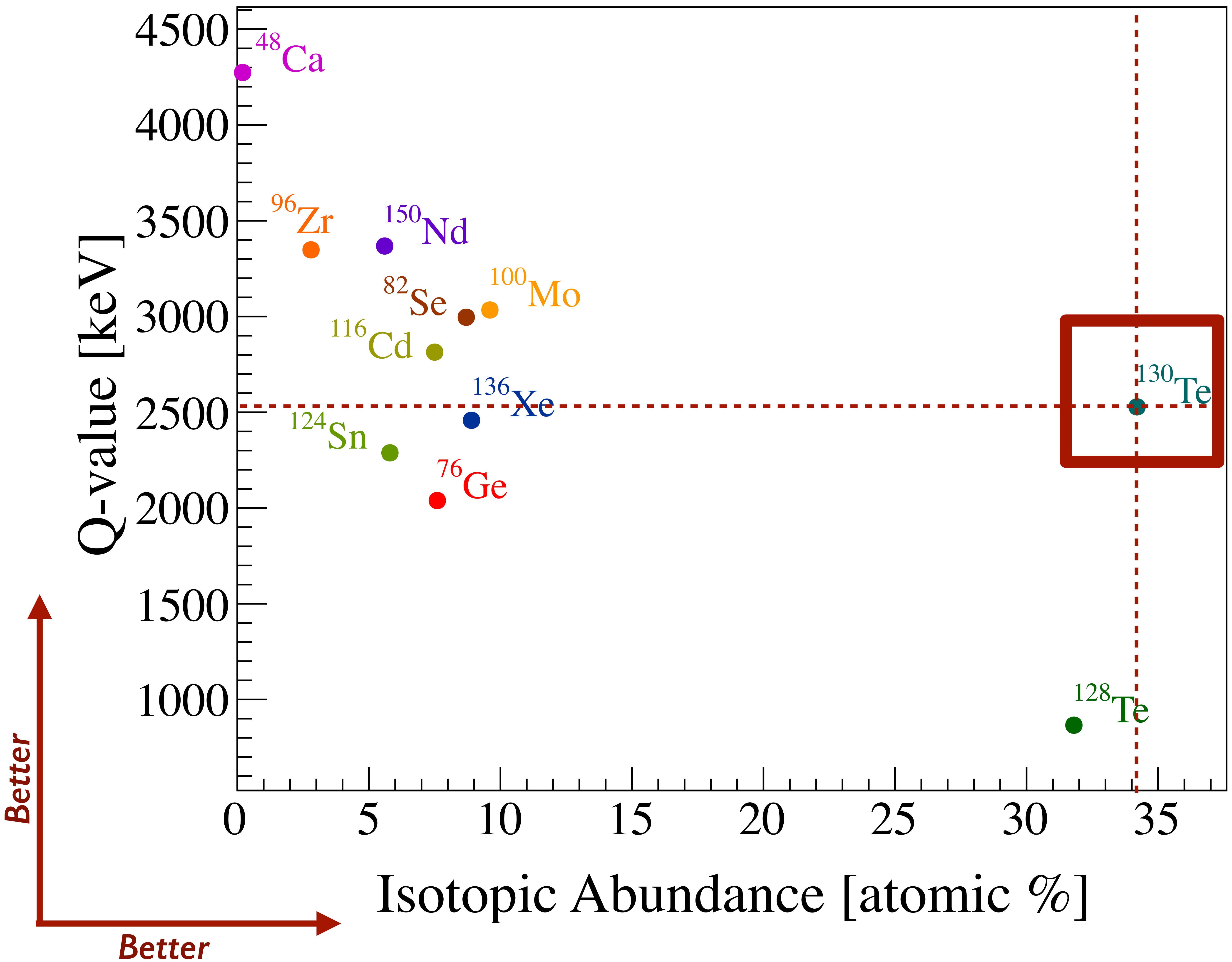
LNGS: Laboratori Nazionali del Gran Sasso

- Natural shielding from cosmic rays by a mountain of Gran Sasso
- 3600 meter water equivalent overburden



Isotope of Choice: ^{130}Te

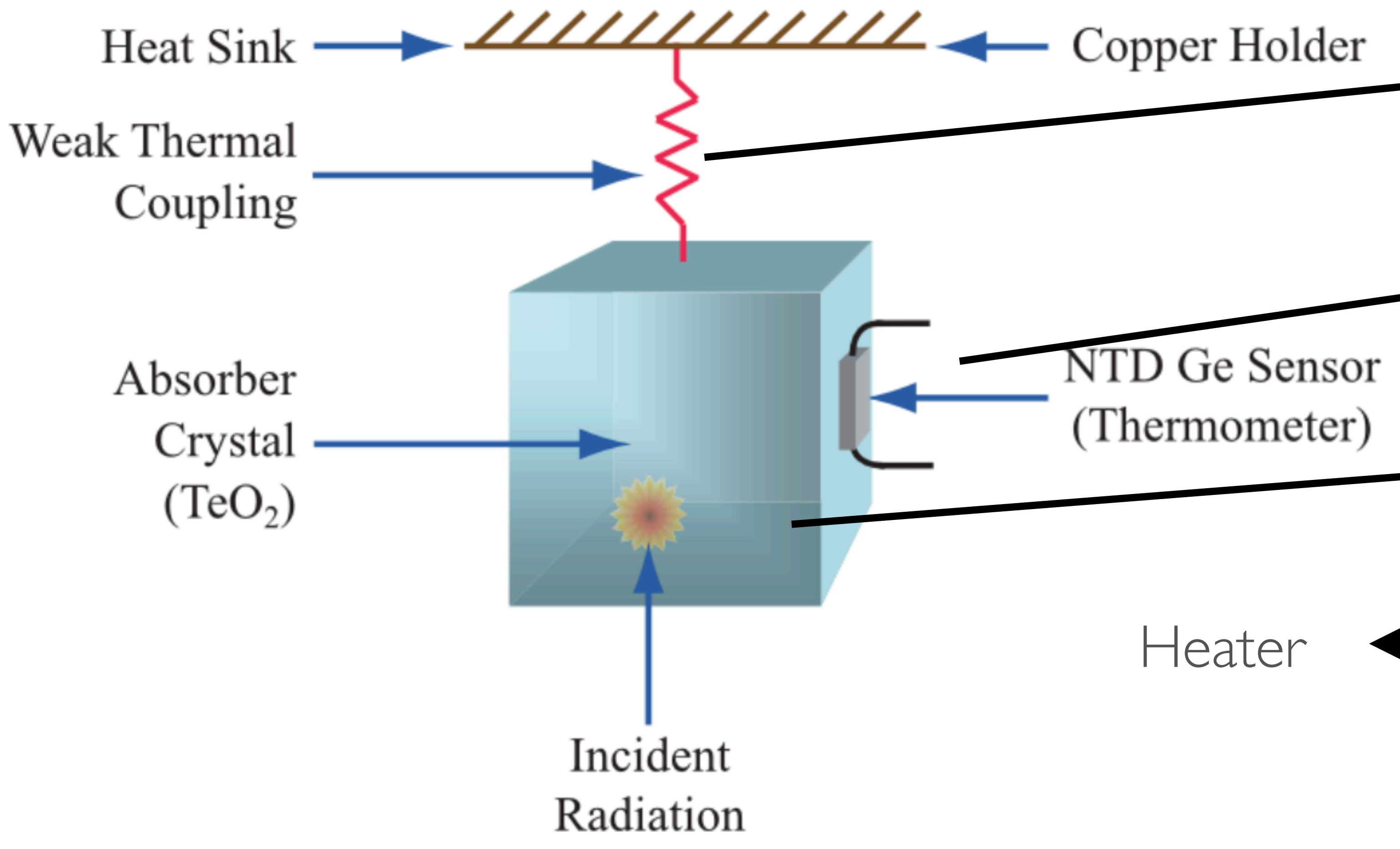
- 34 % natural isotopic abundance
- $Q_{\beta\beta}$ (2528 keV)
  - > most γ natural radioactivity
  - Background from 2νββ ~1/Q^5
- Isotope within the absorber
- Reproducible growth of high quality TeO_2 crystals with low contamination

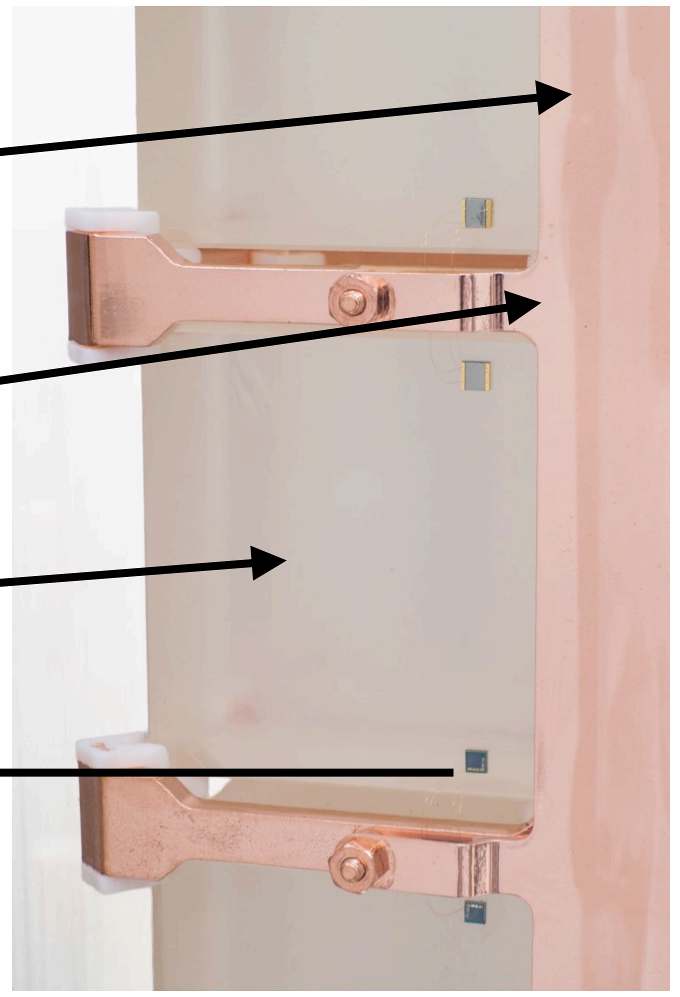


Calorimetric Technique

Crystal temperature rises when energy is deposited

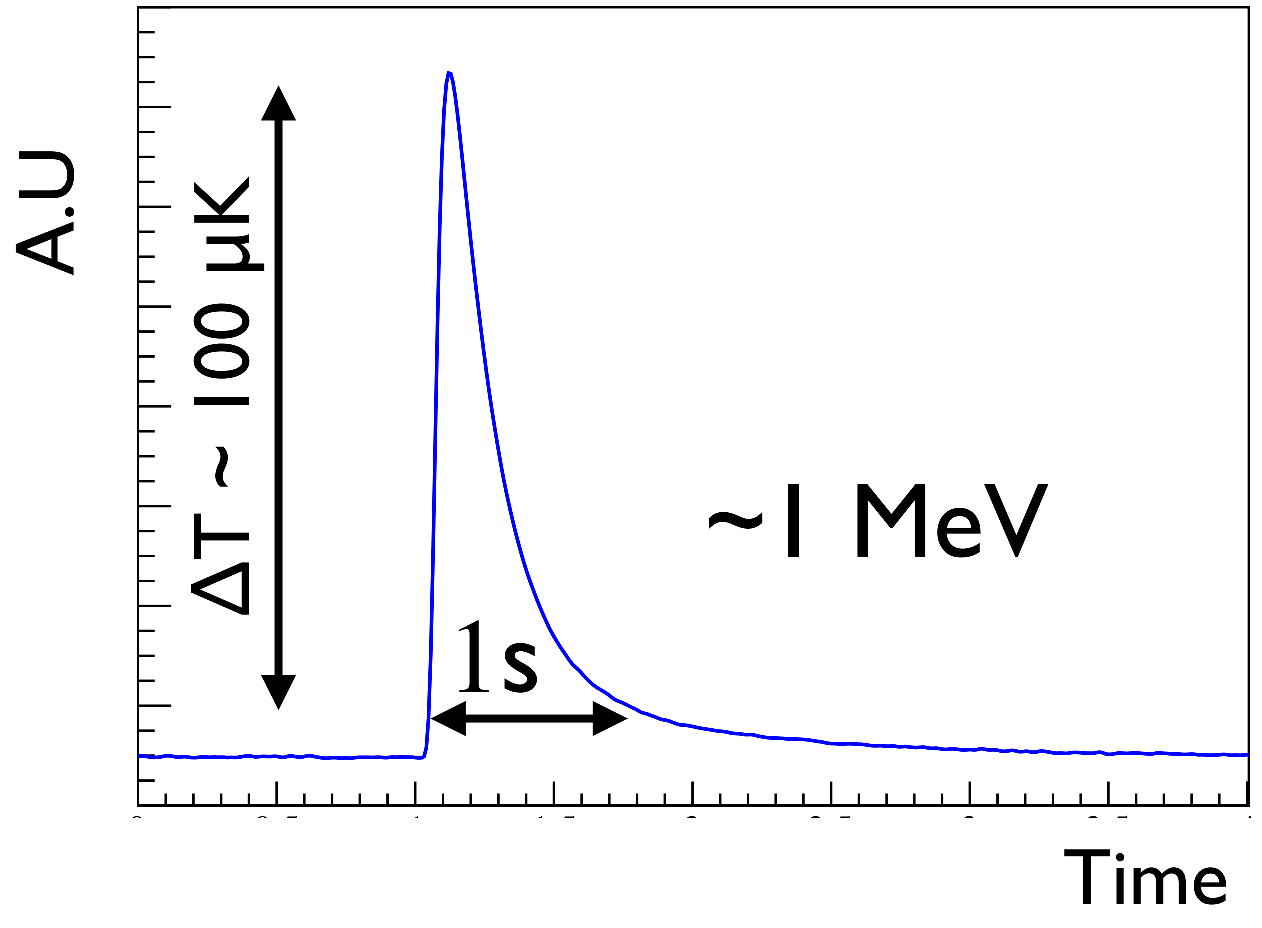
- Each crystal:
  - **Absorber:** 5x5x5 cm^3 TeO_2 crystal
  - **Operational temperature:** ~10 mK
  - **Thermal coupling:** PTFE holder
  - **Heater:** Gain calibration
  - **Sensor:** Ge neutron transmutation doped (NTD) thermistor





$\Delta T \propto E/C(T)$

$C(T) \propto T^3$

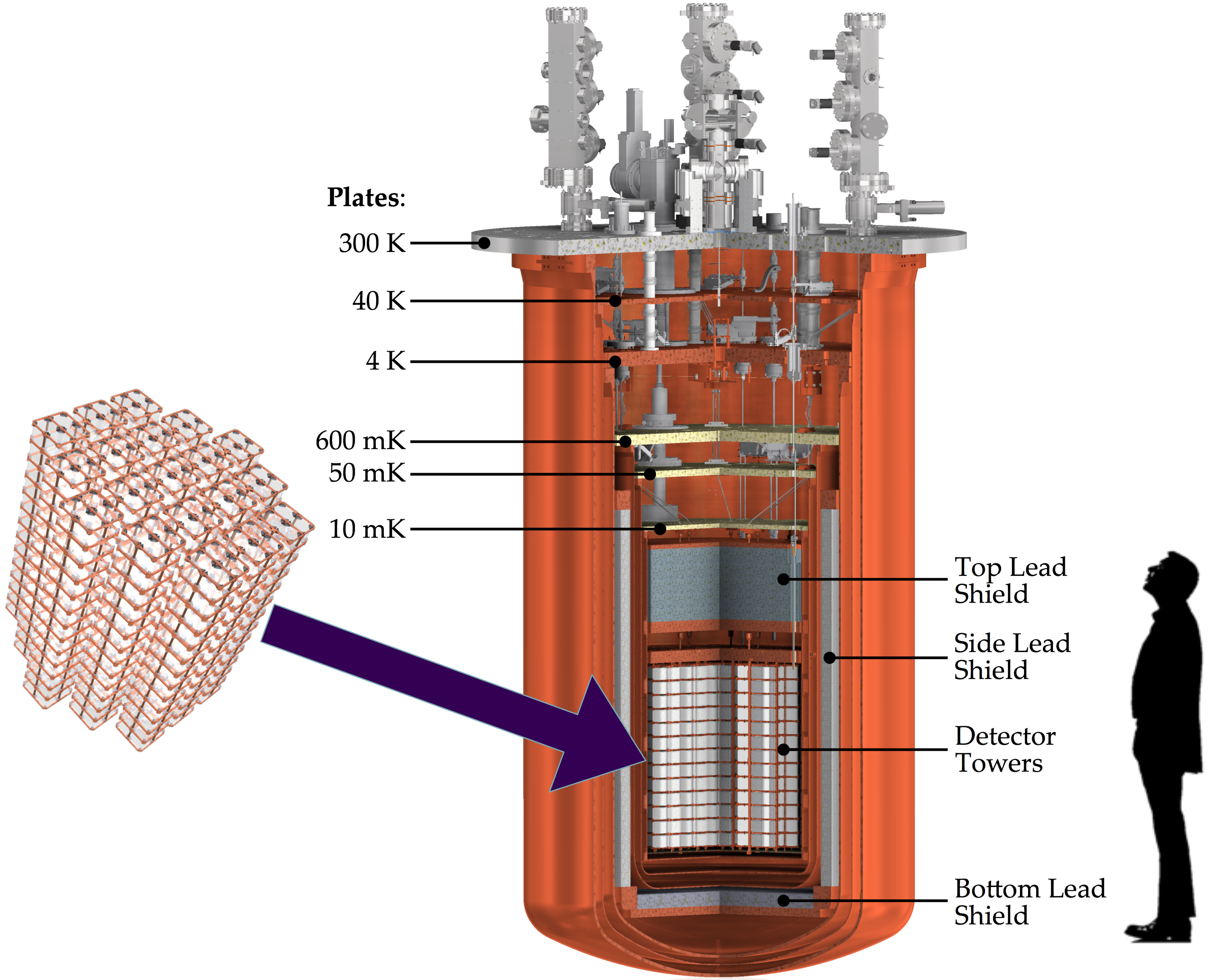


- Excellent energy resolution (~0.2% ΔE/E FWHM)
- Detector response independent of particle type
- Flexibility in 0νββ candidate choice

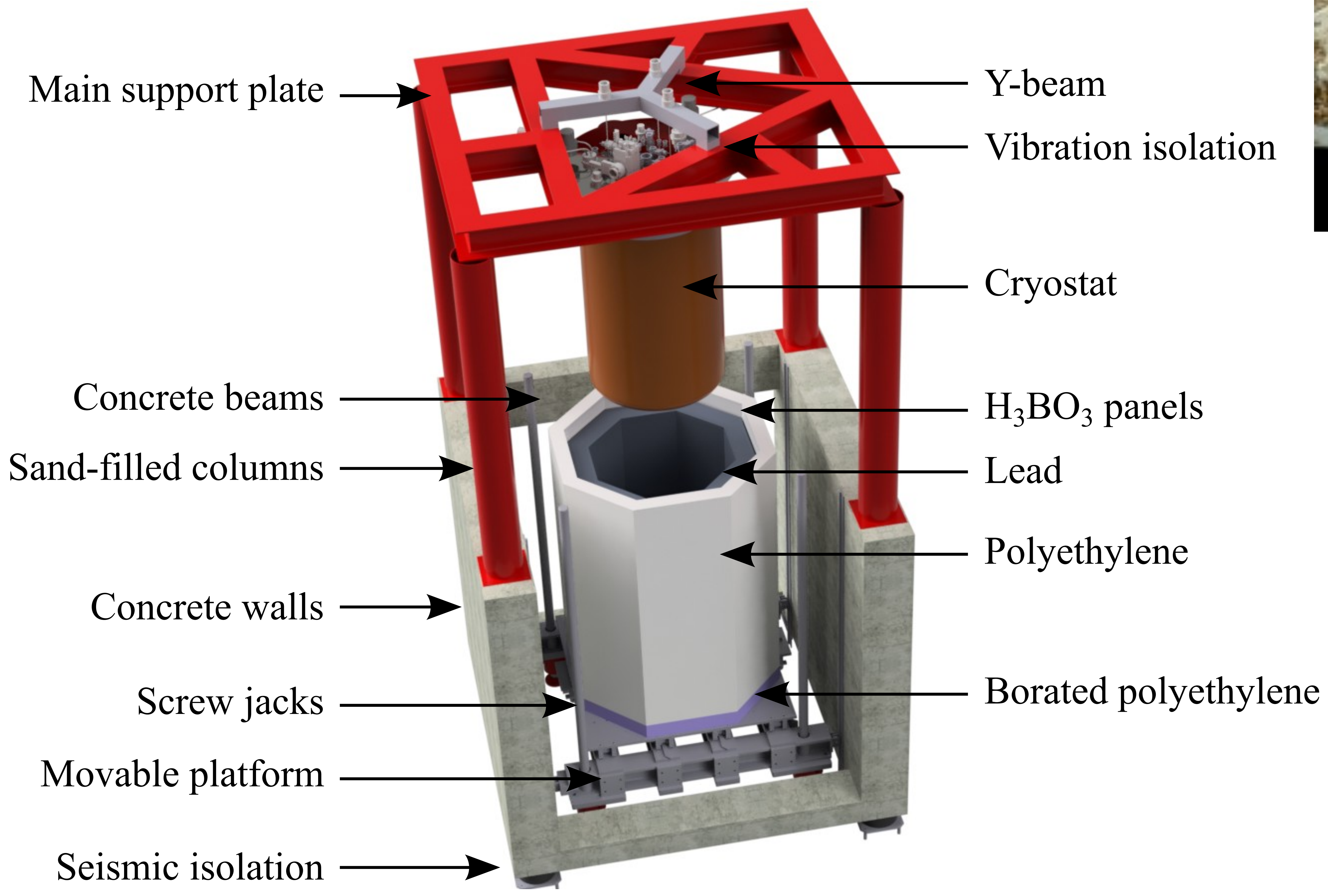
CUORE Cryostat

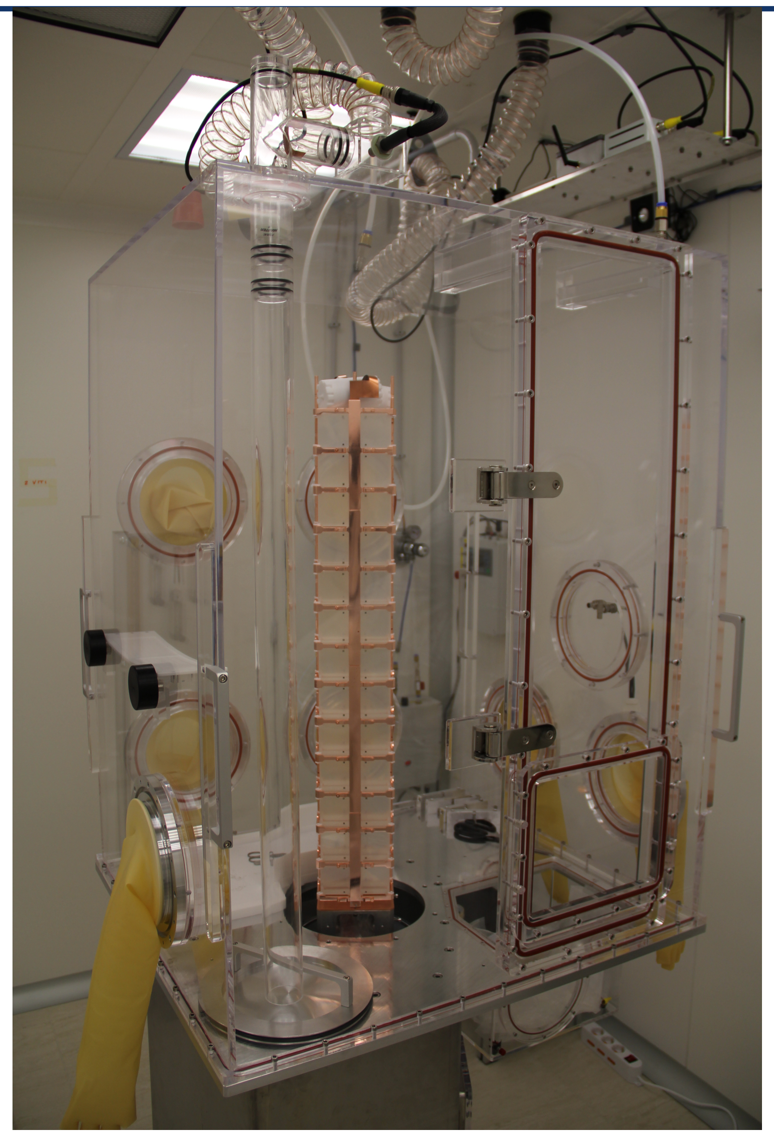
Low background cryostat needs to be maintained at low temperature with low vibrations

- Multiple stage cryogen-free cryostat:
  - Nested co-axial cylinders
  - Pulse Tubes for cooling **40 K** and **4 K** stages
  - Dilution Unit to cool rest of the stages
- Total mass: ~**30 ton**
  - 15 ton @ 4 K
  - 3 ton @ 50 mK
  - 1 ton @ 10 mK



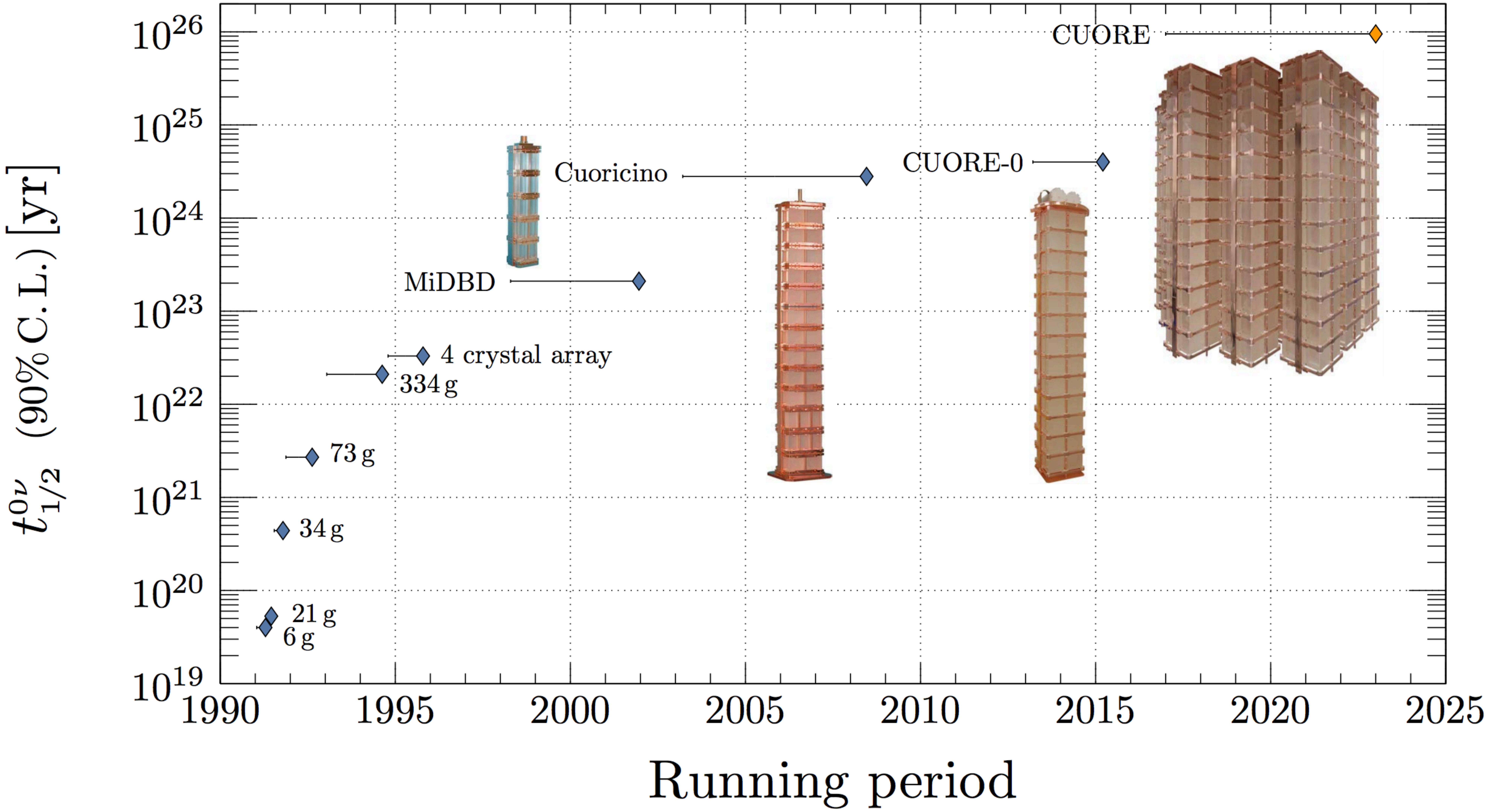
Low Background Experiment



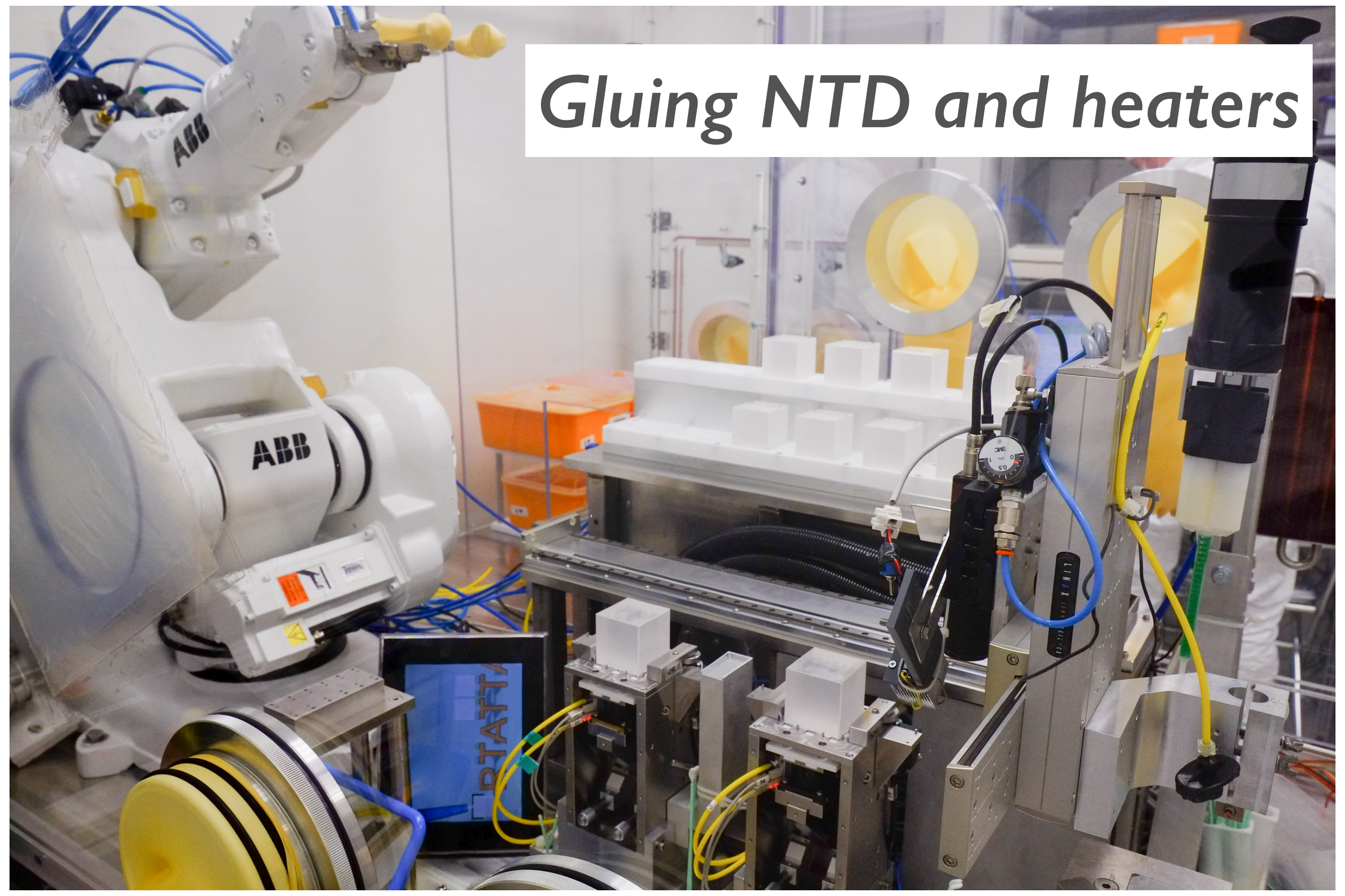


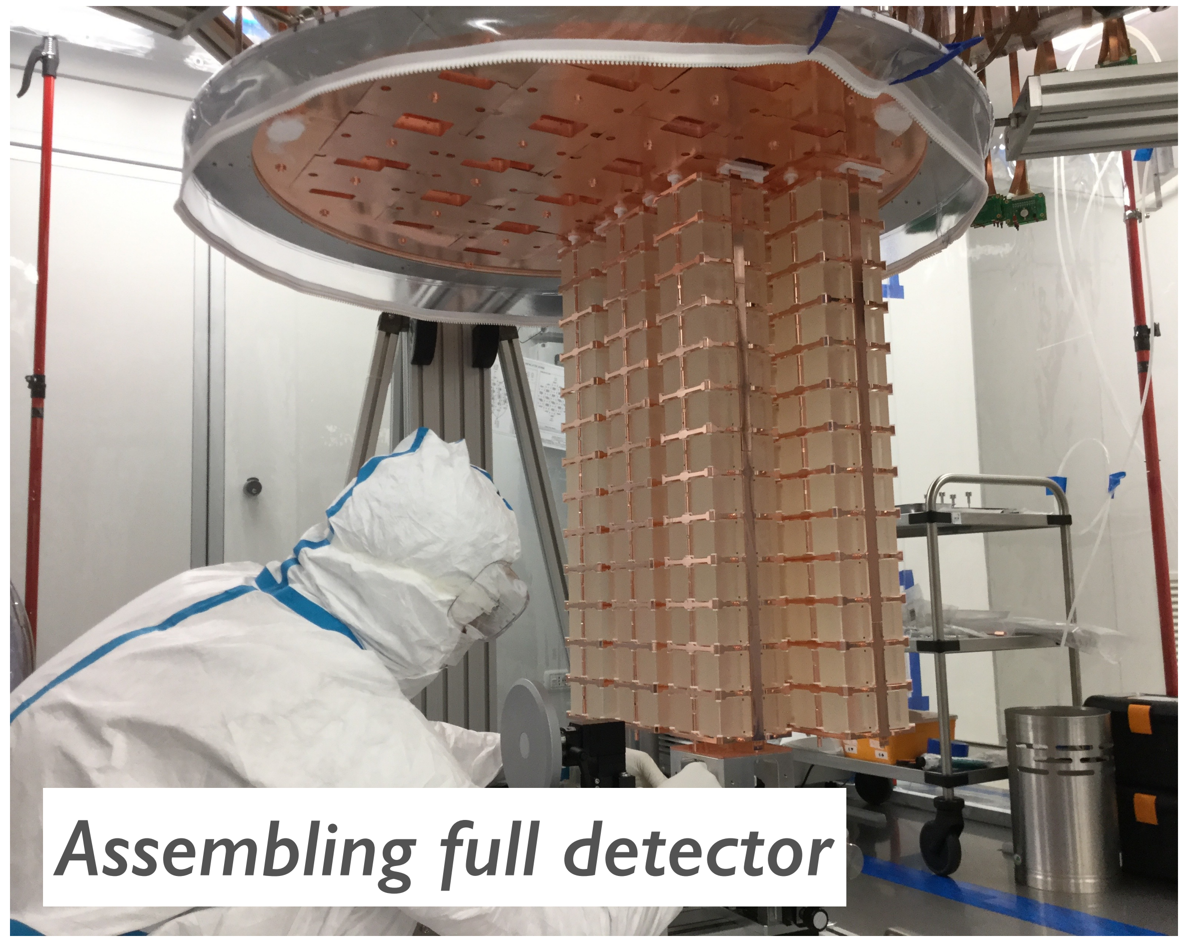
- In addition to natural shielding from rock
- Passive lead, polyethylene, and H_3BO_3 shielding
- 70 tonne of lead, 7 tonne of cold lead
- Careful material selection: Ancient Lead and low radioactive copper
- Strict radiopure controls
- Active background reduction from event selection

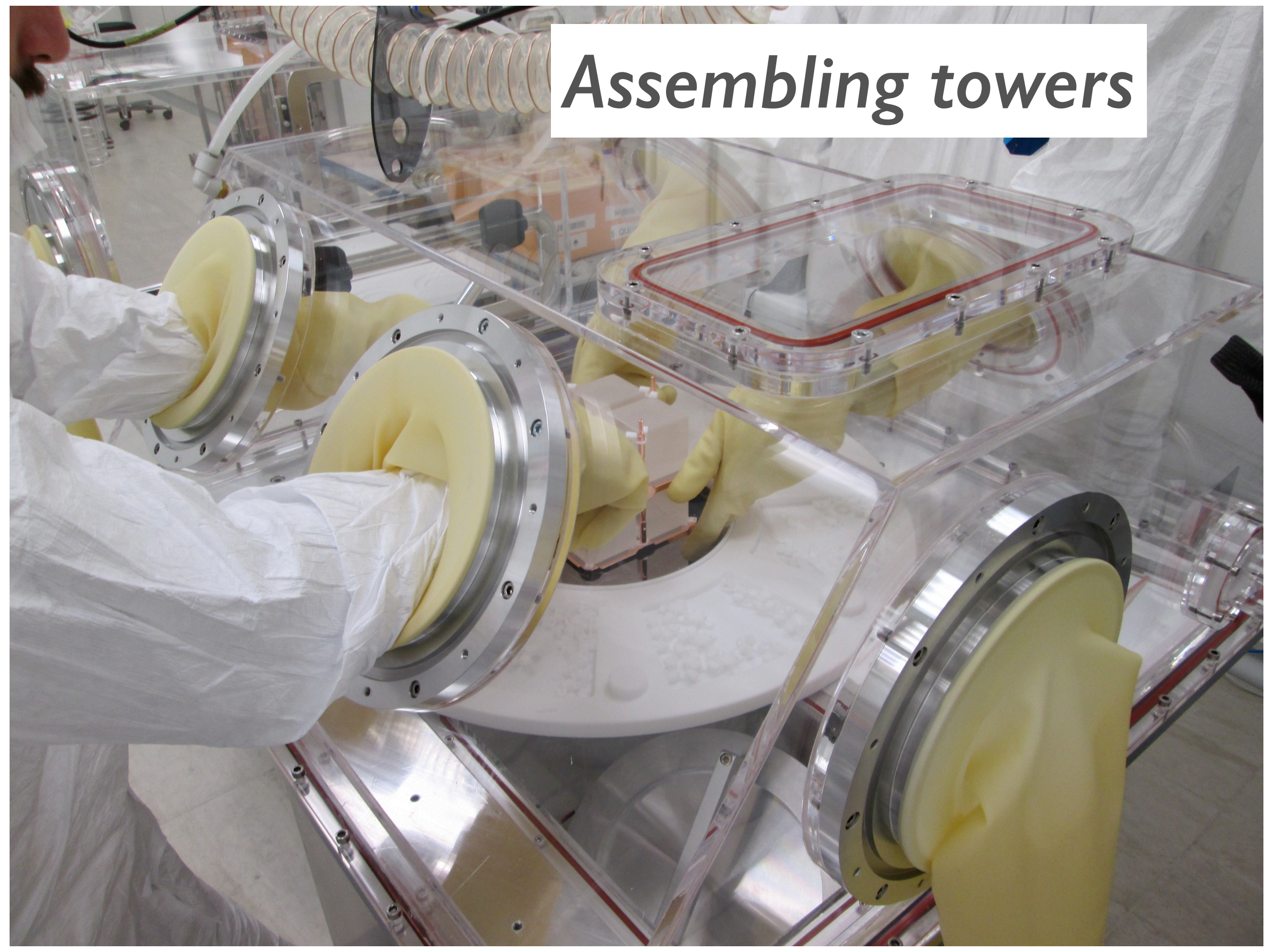
CUORE Development

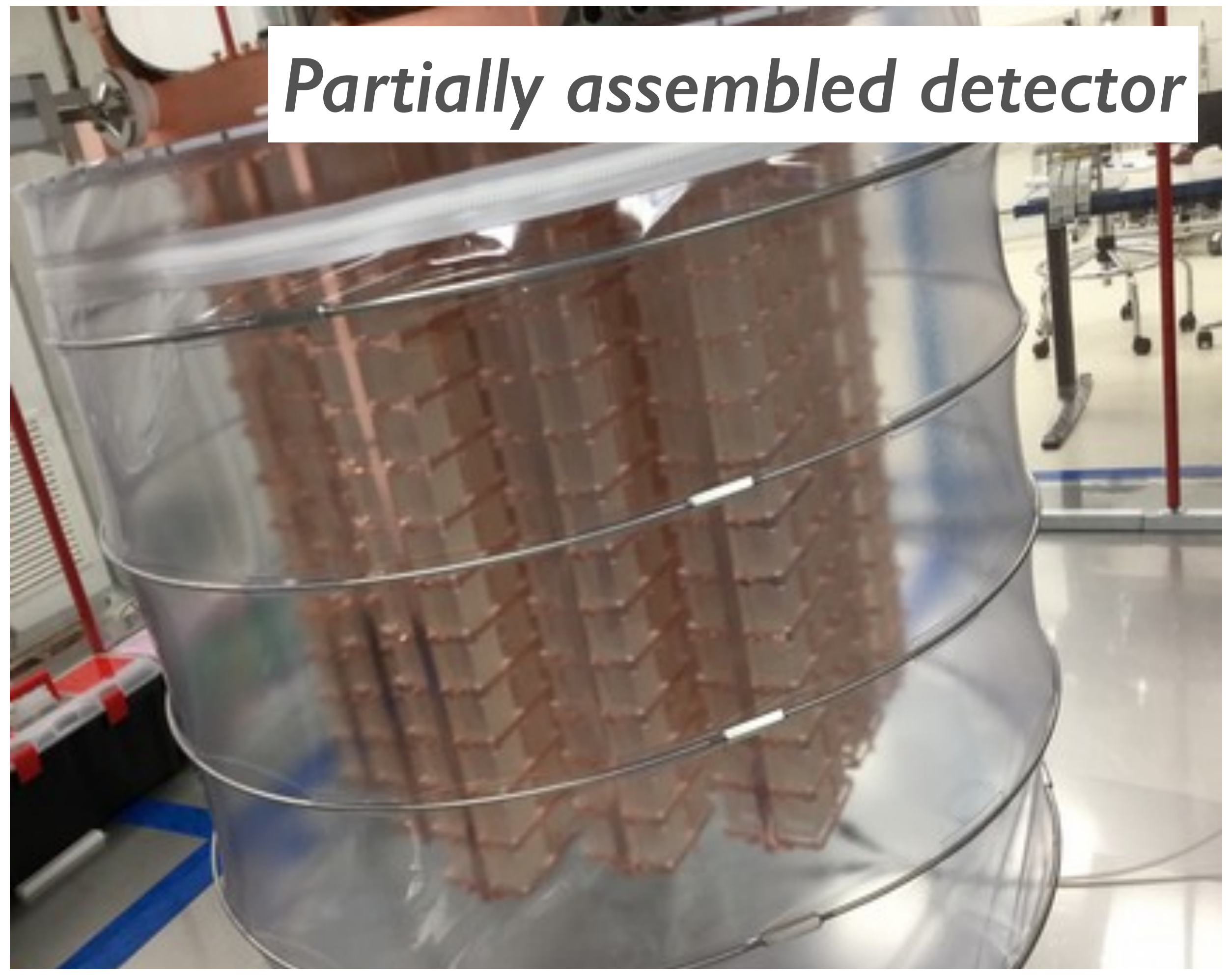


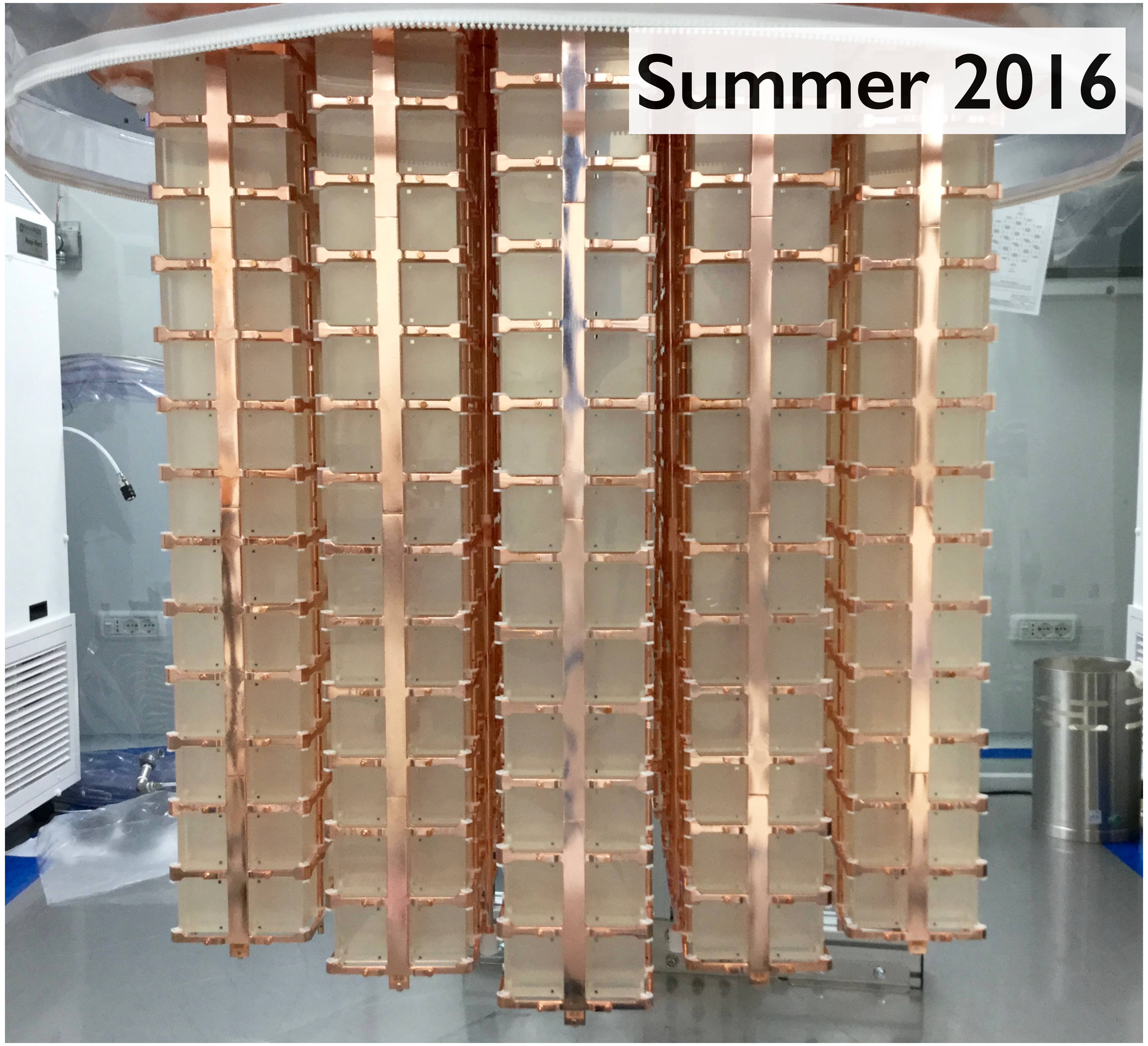
CUORE Installation





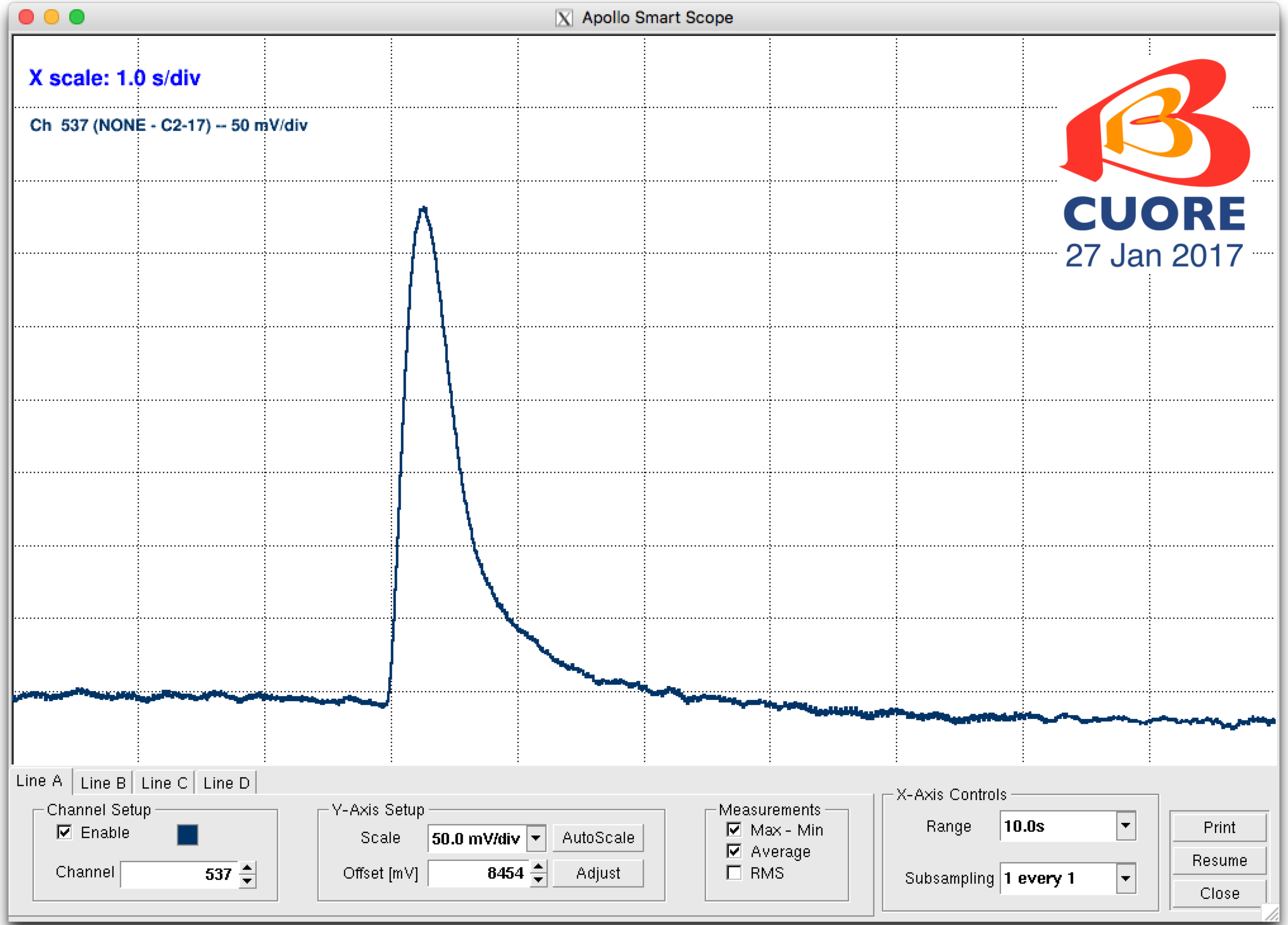






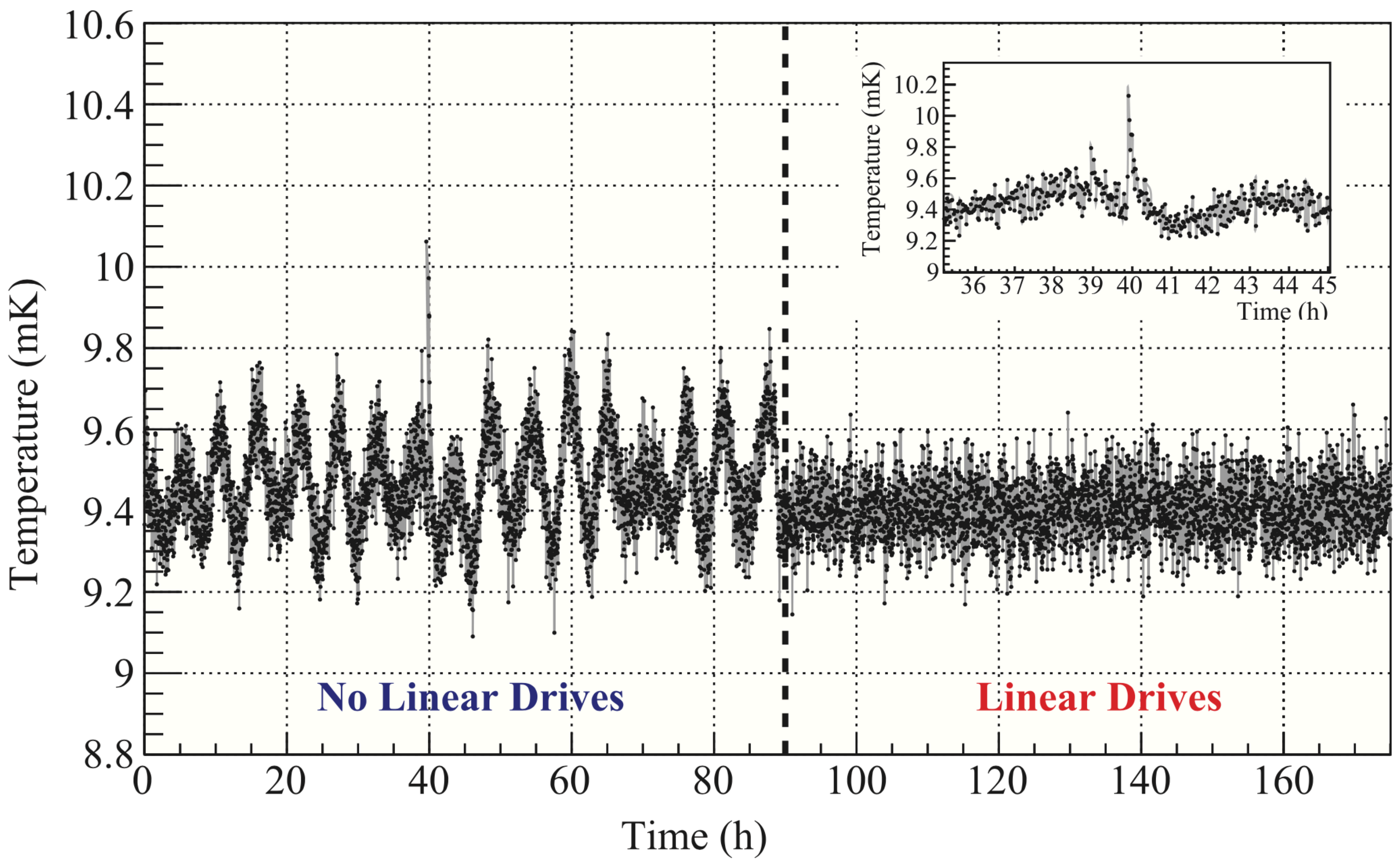
CUORE Commissioning

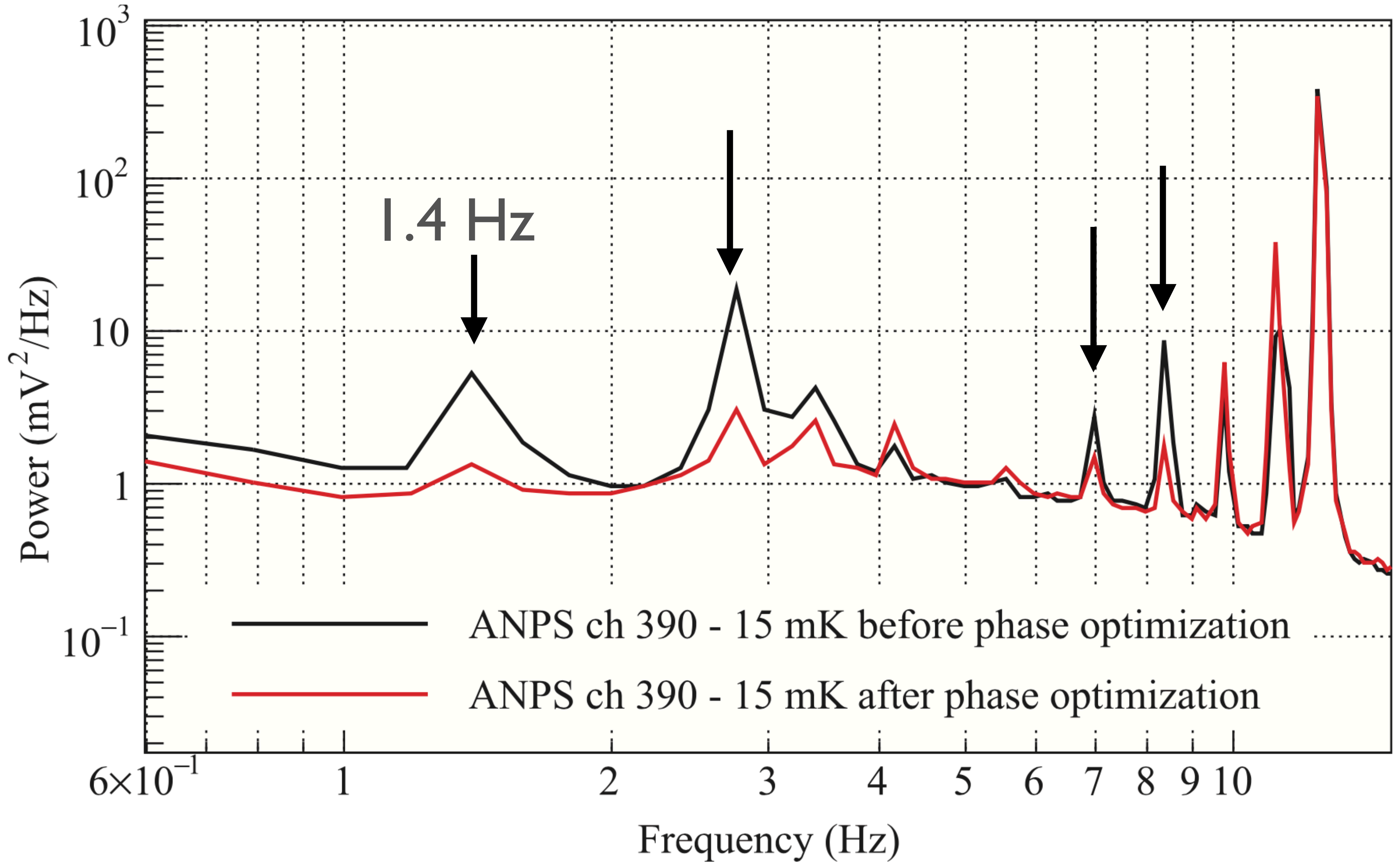
- Cooldown: Started in Dec 2016
- 1 Month cool down
- First data in Jan 2017



Early Detector Optimization

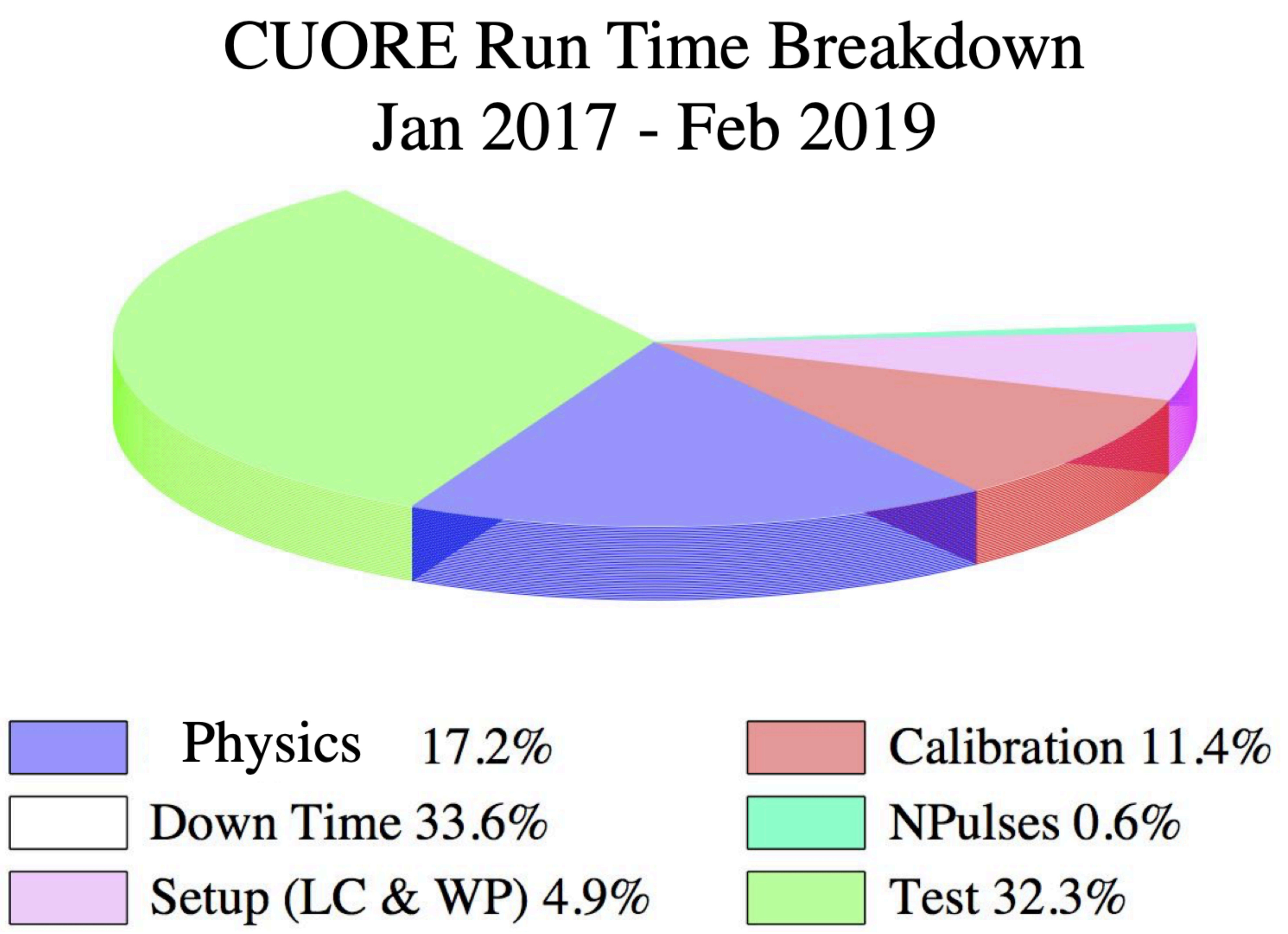
- Electronics and DAQ debugging
- Optimization of trigger thresholds
- Temperature scan
- Optimize thermal response of the detectors
- Noise and vibration control
  - Linear drives to control Pulse tubes
  - Pulse tube phase scans





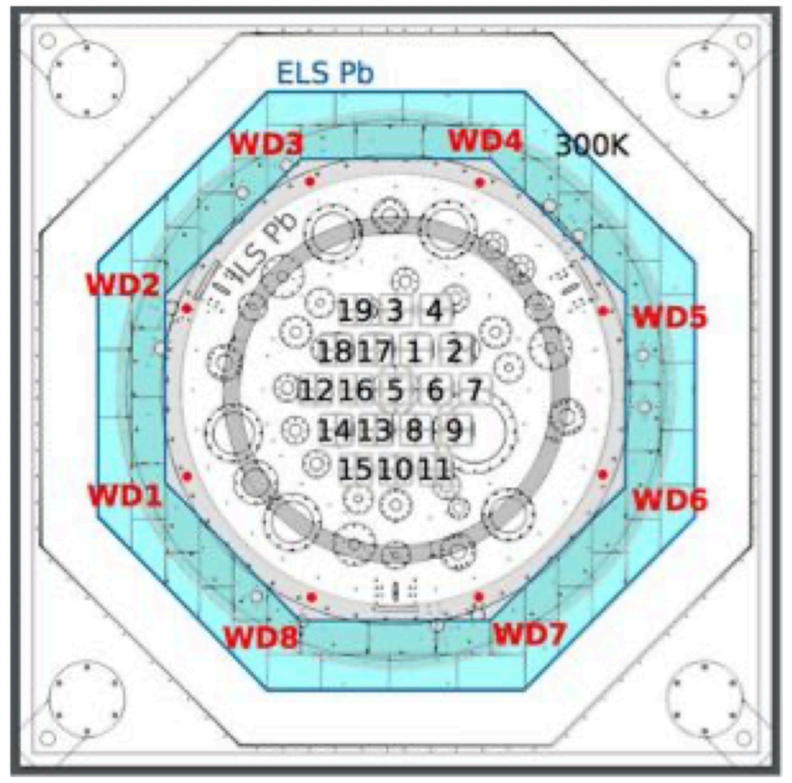
CUORE Data Taking

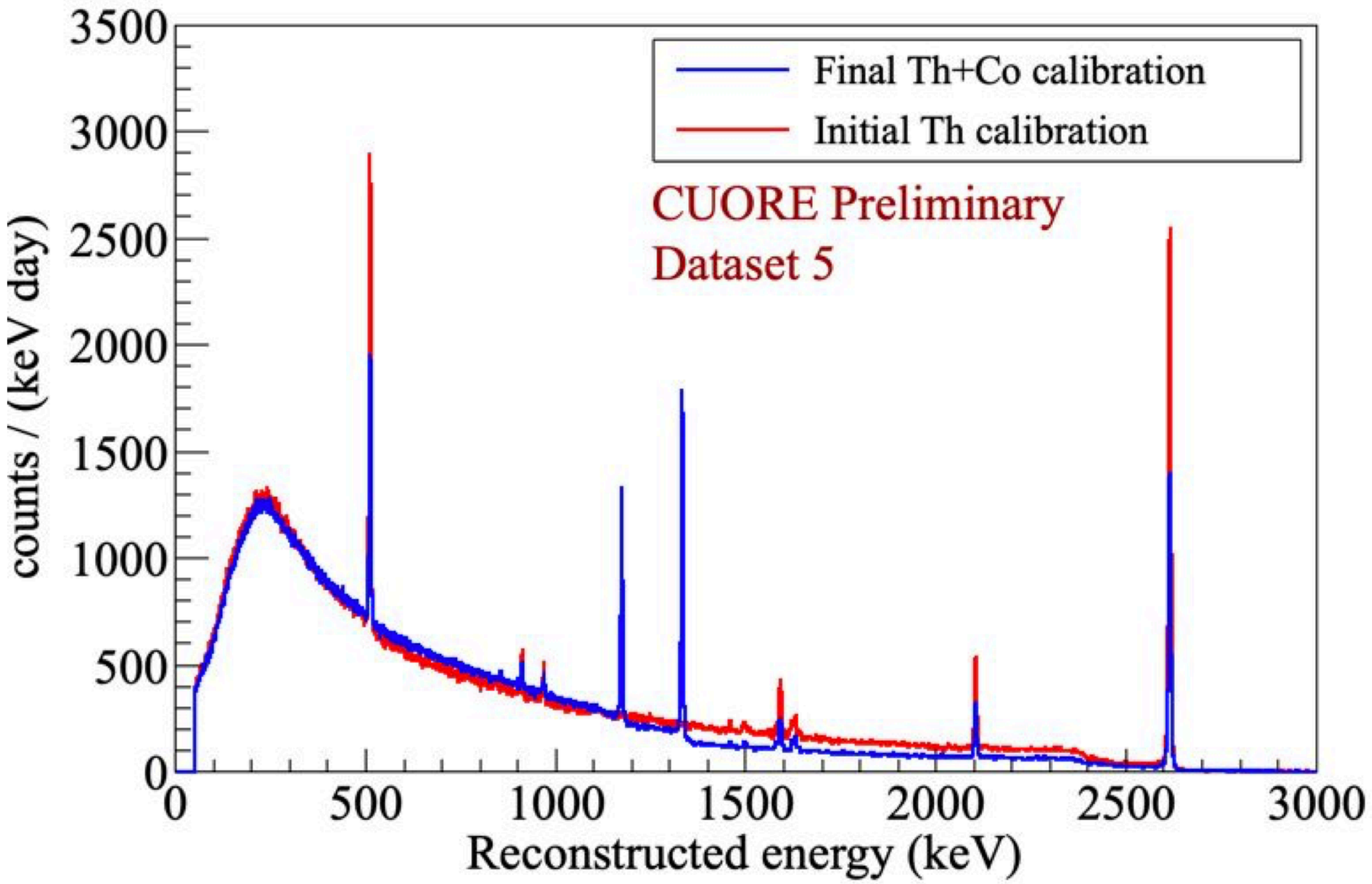
- First two years of data taking has seen a lot of downtime
  - Vacuum leak repair
  - Upgrades to dilution system
  - Install external calibration system
- Overall reduction in downtime: Continued stable data taking
- Enhanced several data analysis techniques



External Detector Calibration System (DCS)

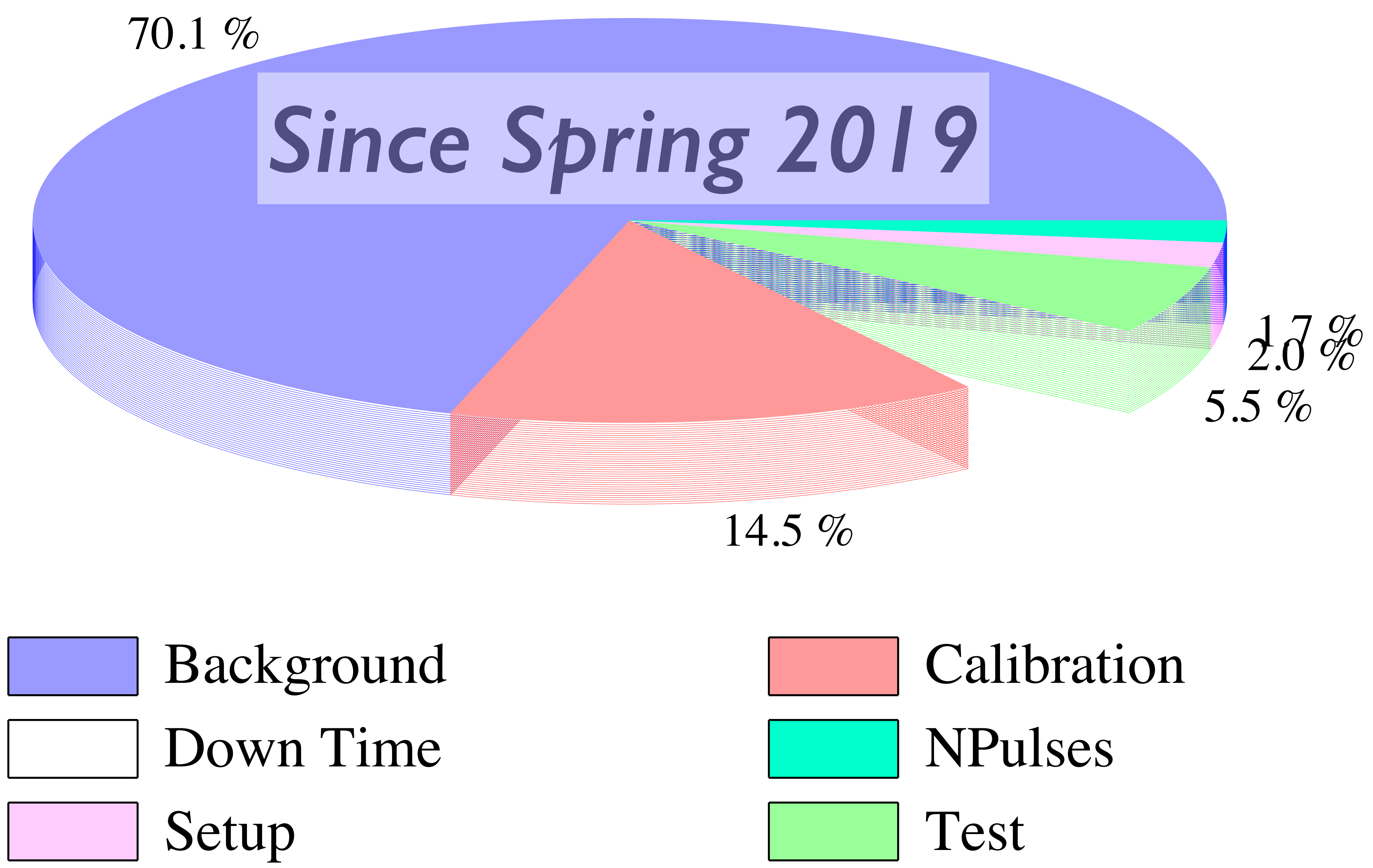
- Internal DCS:
  - ^{232}Th source
  - All the way down to 10 mK
  - Complicated deployment process
  - Interferes with cryogenic system
- External DCS:
  - Installed in summer 2018
  - ^{232}Th + ^{60}Co sources outside the 300 K vessel
- Short deployment periods helps to increase uptime



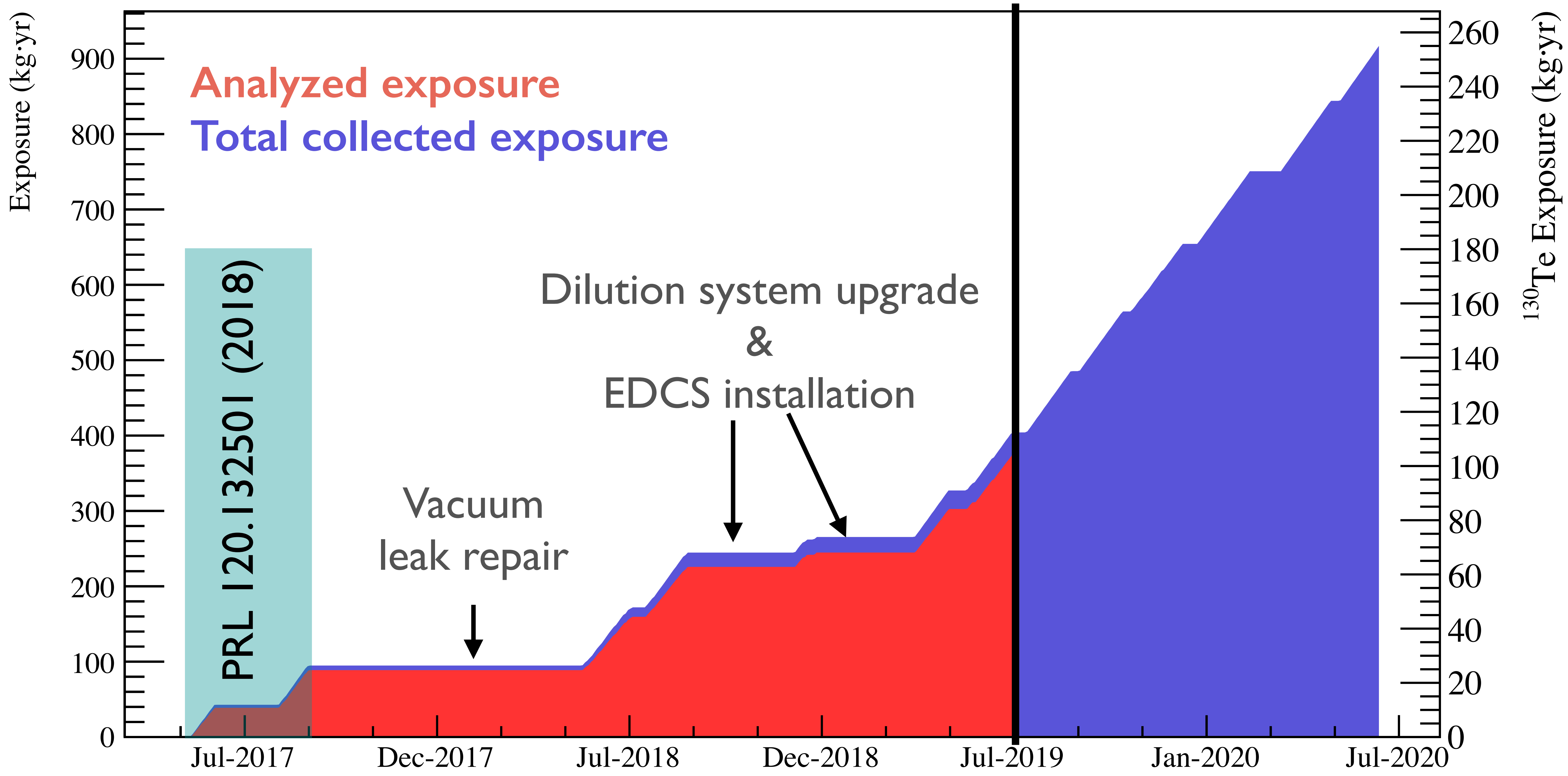


Data Taking

- After detector upgrades, continues low downtime data taking
- 12 datasets completed, each dataset ~1 month long (916.9 kg-yr data collected)
- 7 datasets analyzed (372.5 kg.yr)
- Plan for continued data taking

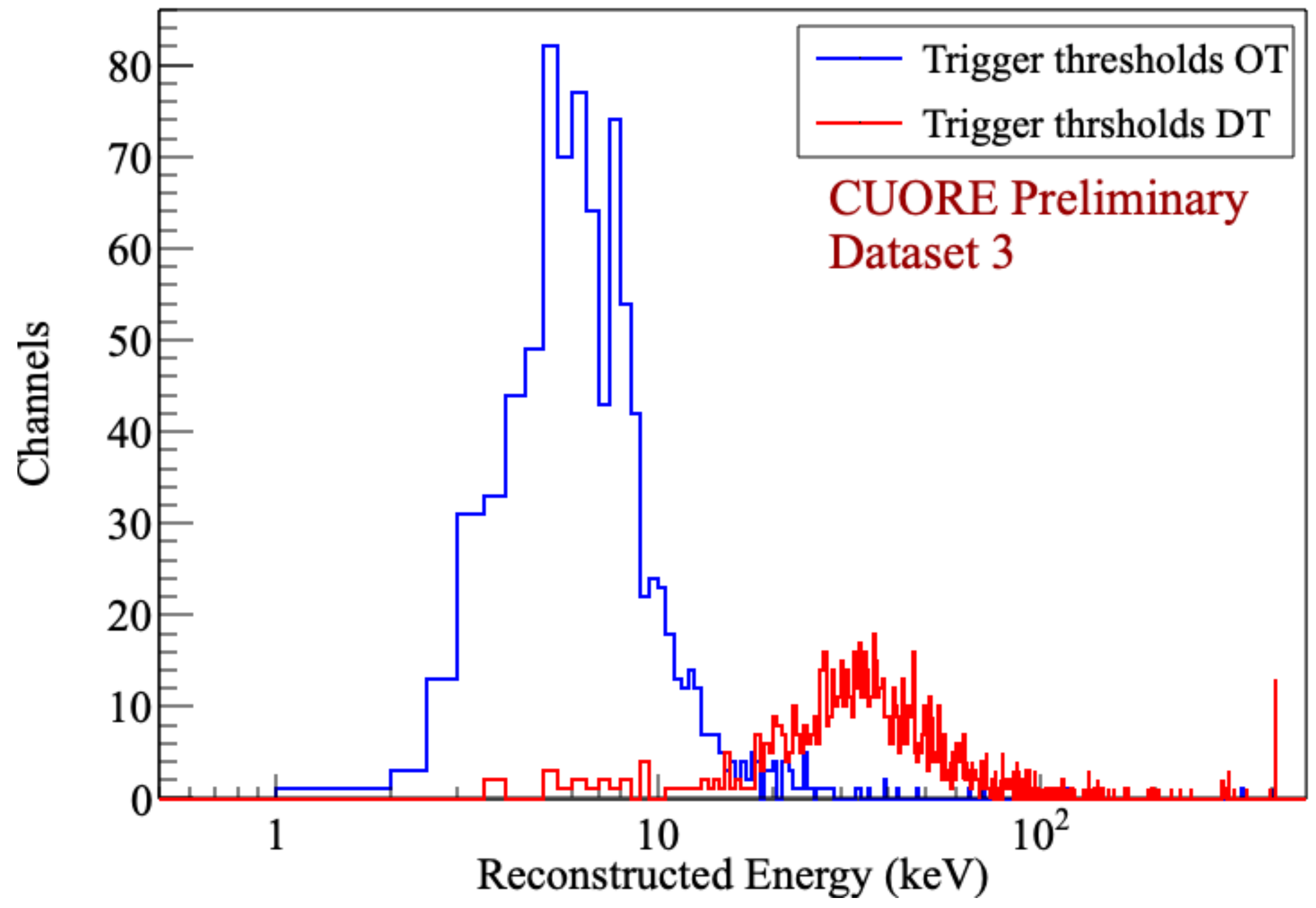


Stable data taking since Early 2019



Analysis Chain: Trigger

- **Trigger**
- Amplitude evaluation
- Gain stabilization
- Energy calibration
- Multiplicity cut
- PSA
- Blinding

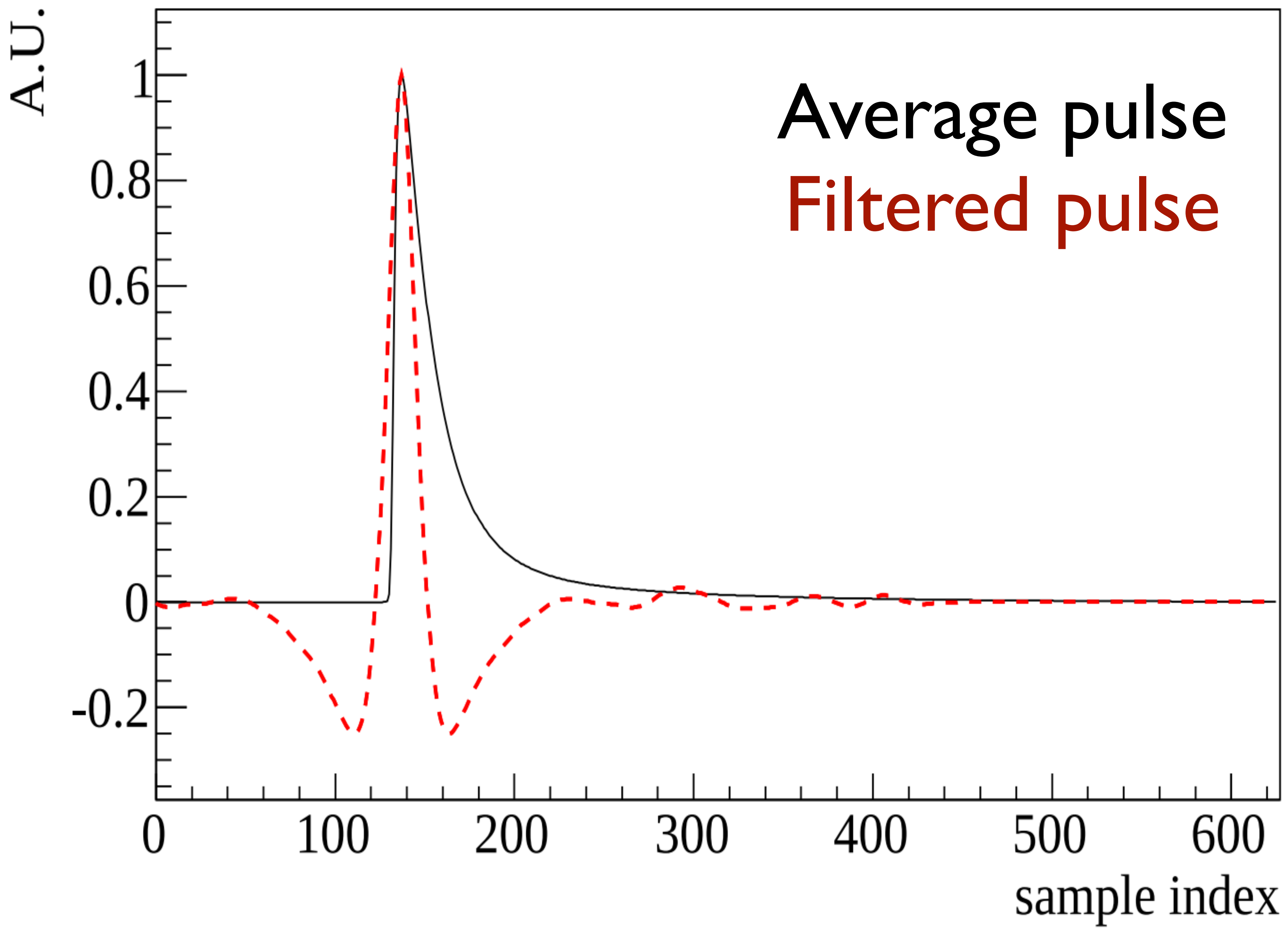


- Continuous data collected and saved
- Offline retriggering possible for all datasets
- Optimum Trigger (OT):
  - Triggered when optimum filter based amplitude crosses a threshold

Lower trigger thresholds achieved using optimum trigger

Analysis Chain: Amplitude

Trigger
↓
Amplitude evaluation
↓
Gain stabilization
↓
Energy calibration
↓
Multiplicity cut
↓
PSA
↓
Blinding

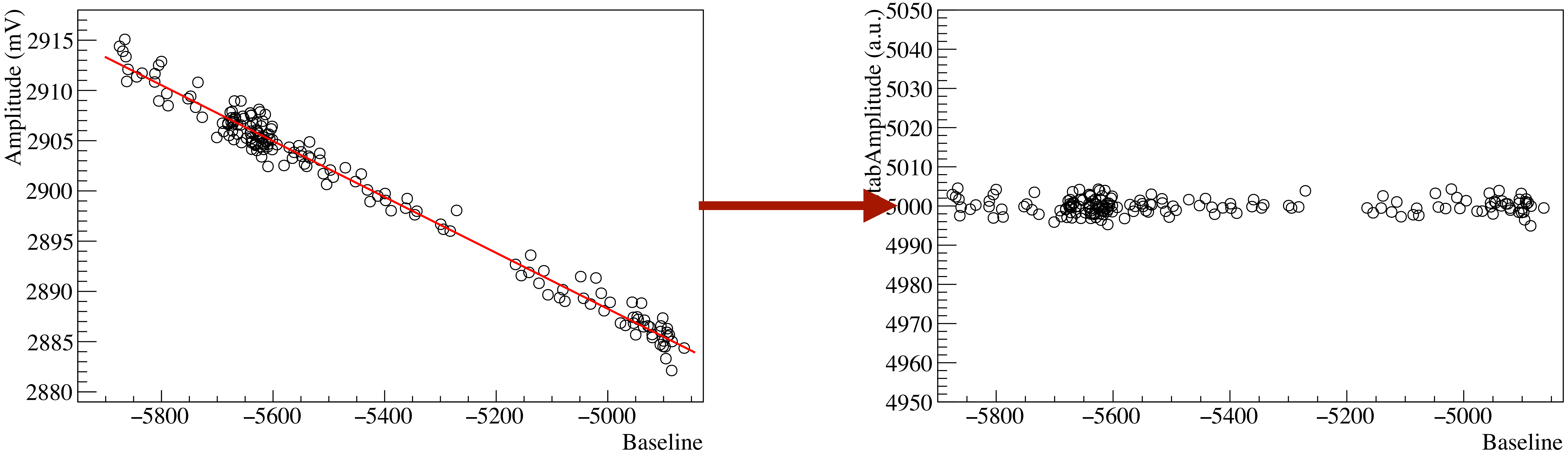


Amplitude α Energy

- Amplitude of the pulses are evaluated using matched filter that maximizes signal-to-noise ratio

Analysis Chain: Gain stabilization

Trigger
↓
Amplitude evaluation
↓
Gain stabilization
↓
Energy calibration
↓
Multiplicity cut
↓
PSA
↓
Blinding



Amplitude = Gain x Energy

- Gain is temperature dependent
- Stabilize the gain against temperature drifts
- Use fixed energy heater pulses to stabilize gain

Analysis Chain: Energy

Trigger

↓

Amplitude evaluation

↓

Gain stabilization

↓

Energy calibration

↓

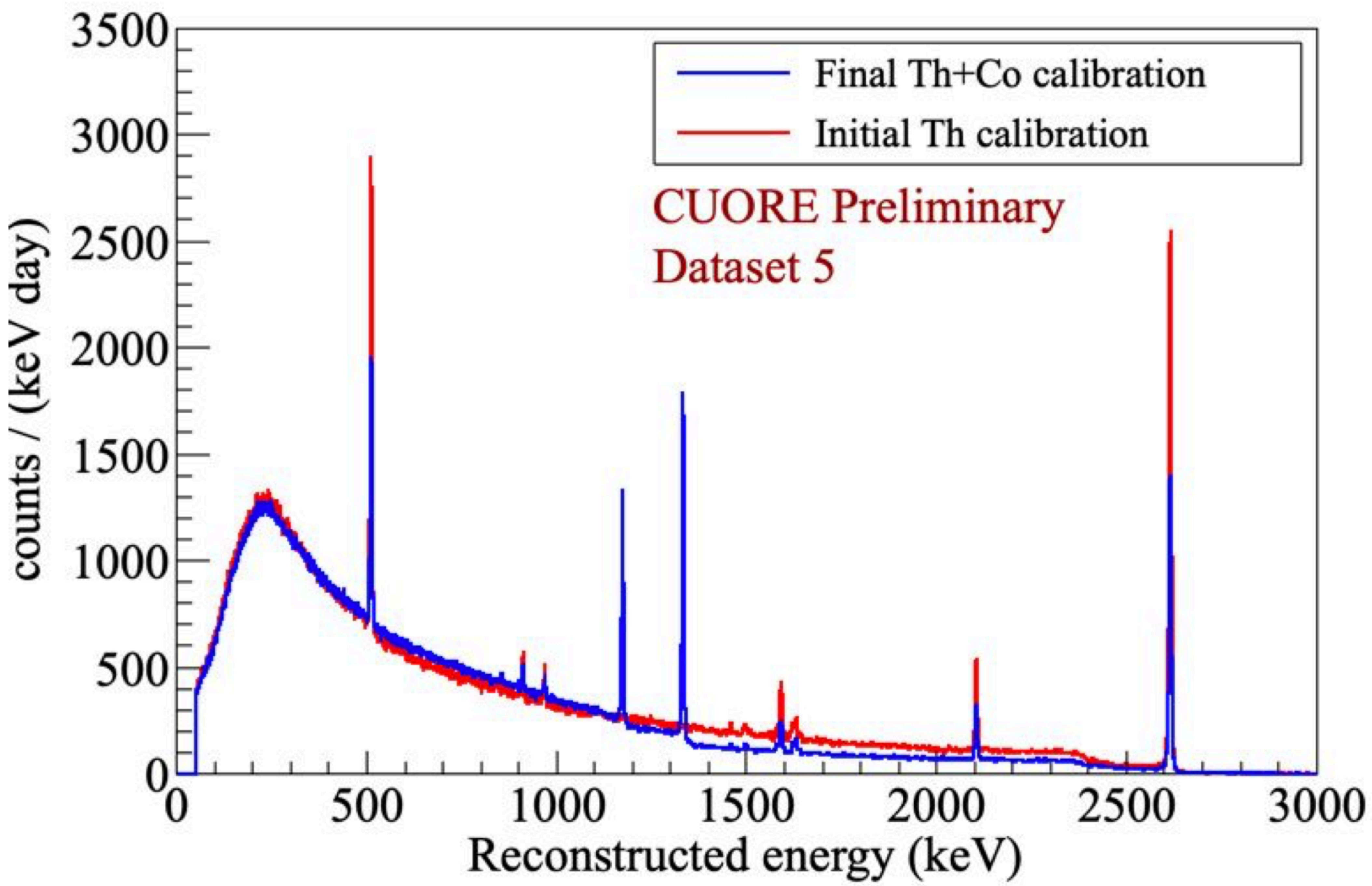
Multiplicity cut

↓

PSA

↓

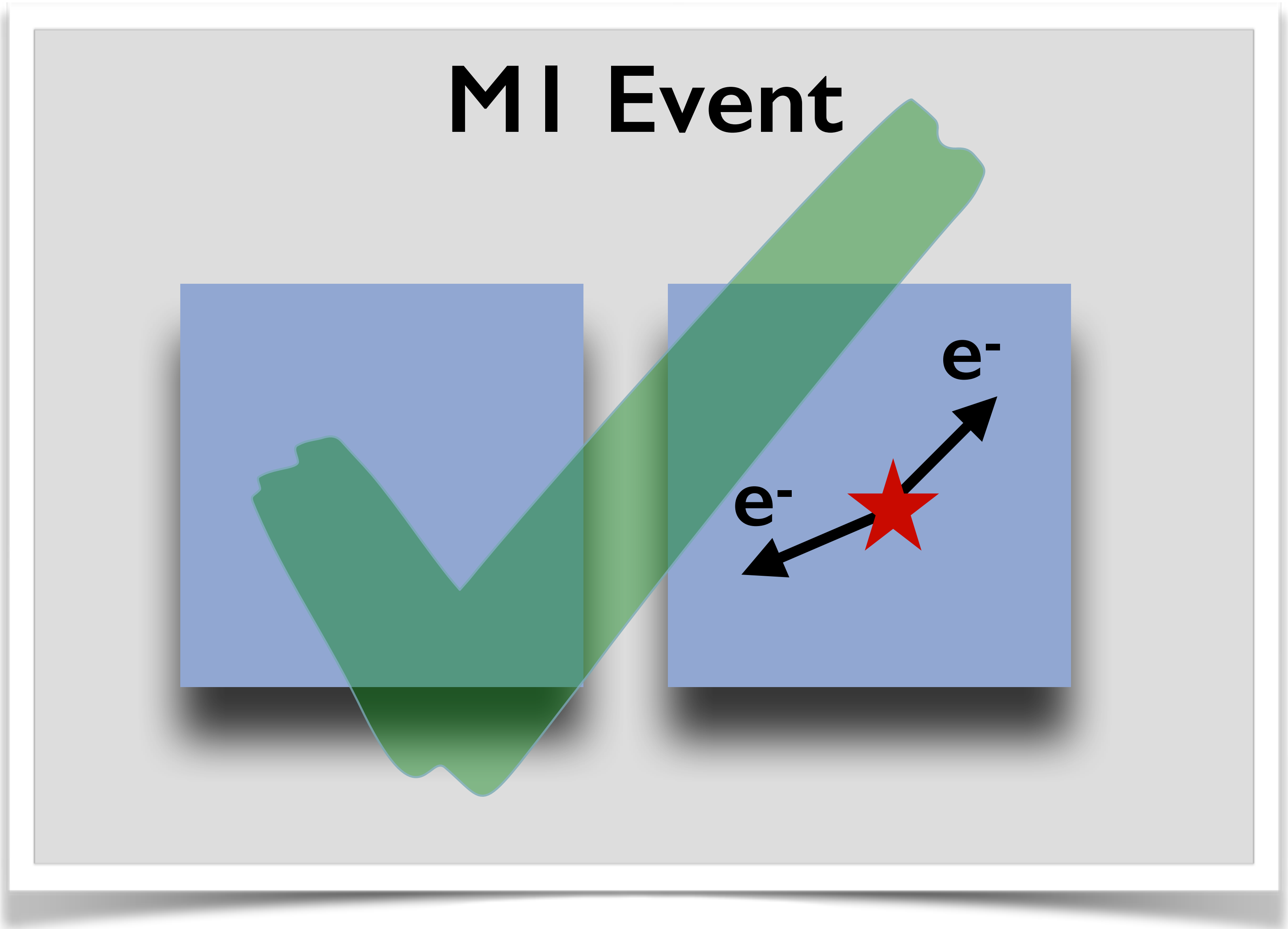
Blinding

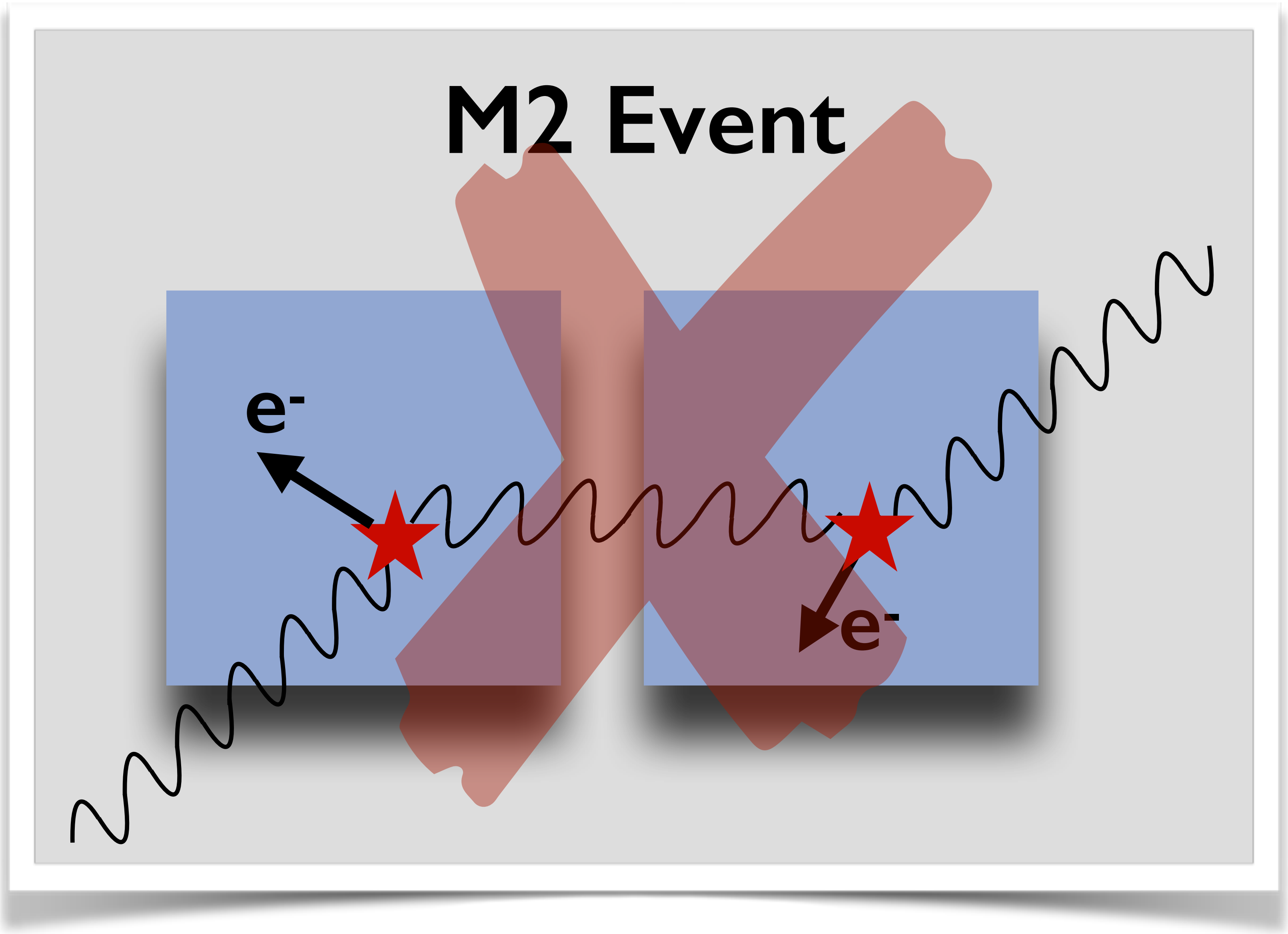


- Calibration data taken before and after each dataset
- Uses peaks from ^{232}Th+^{60}Co chain
- Each crystal independently calibrated

Analysis Chain: Multiplicity

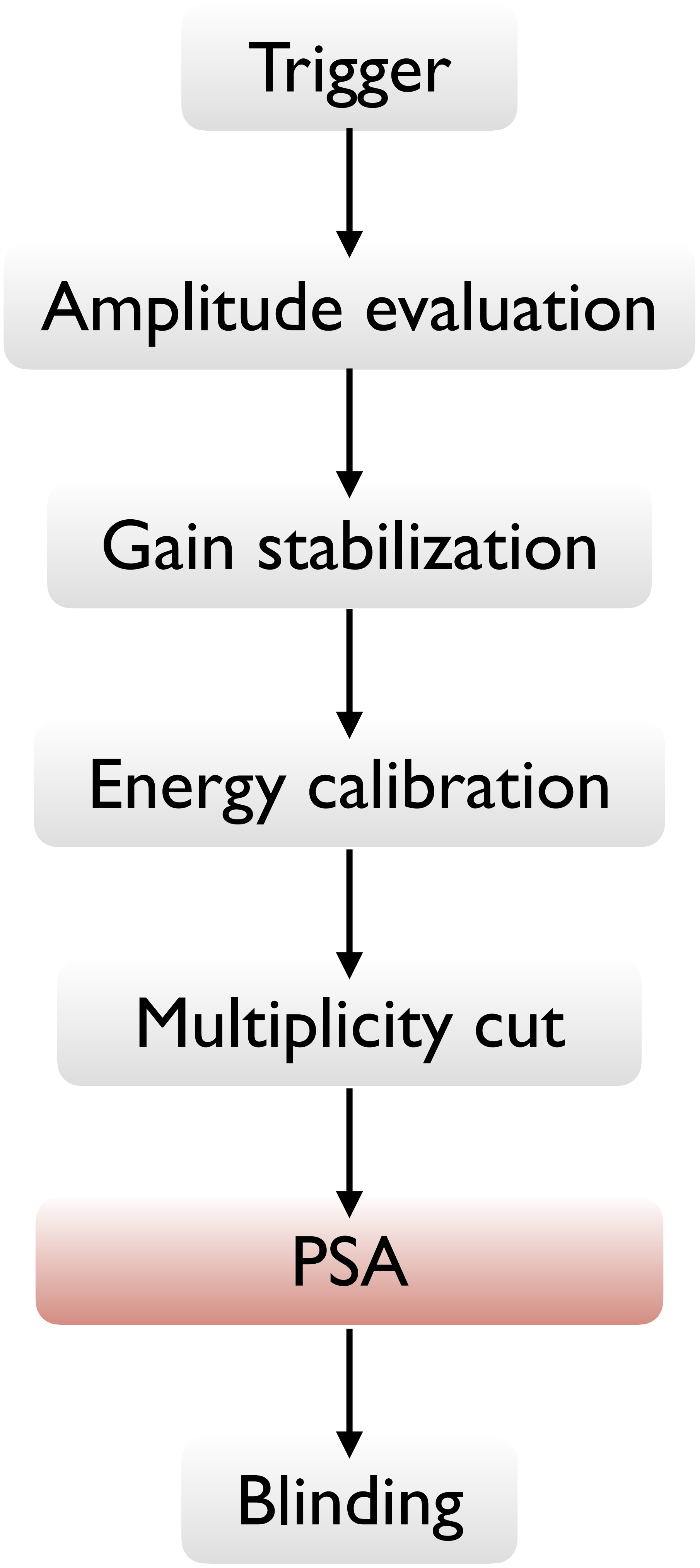
Trigger
↓
Amplitude evaluation
↓
Gain stabilization
↓
Energy calibration
↓
Multiplicity cut
↓
PSA
↓
Blinding

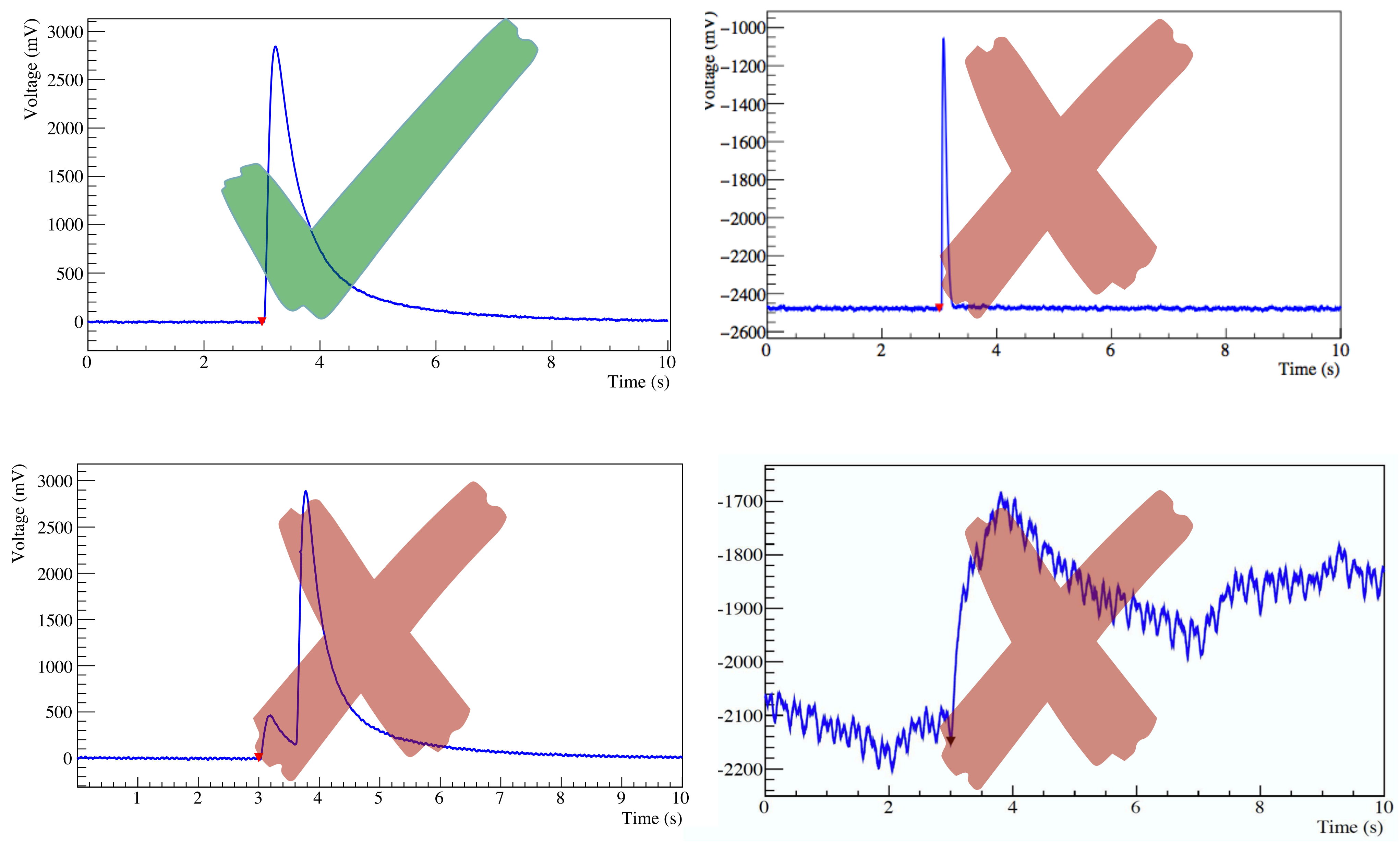


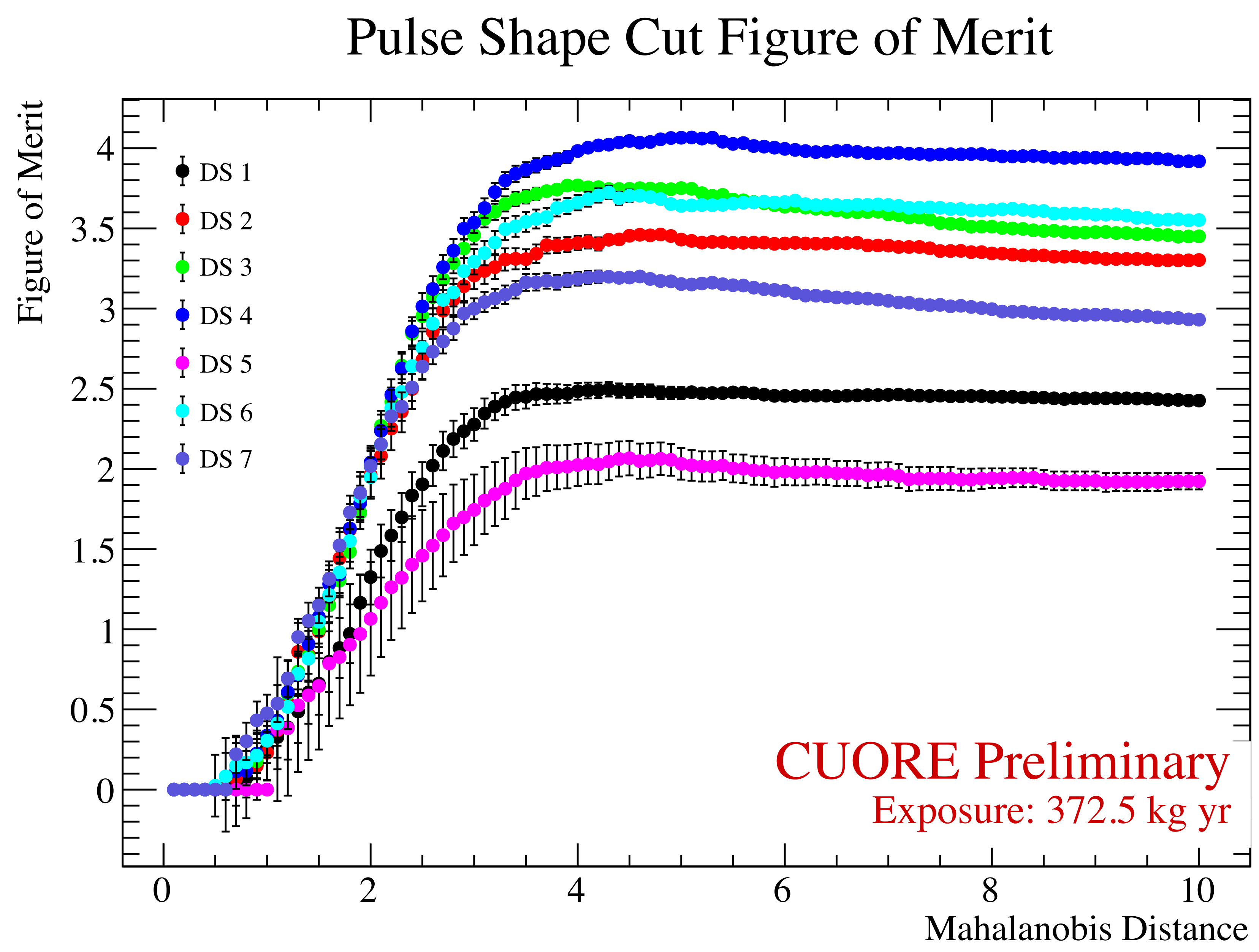


- Multi-site events typically come from radioactive contamination
- Select M1 events for $0\nu\beta\beta$ dataset
- Eliminate Compton scatters, surface alpha contamination, and muons

Analysis Chain: Pulse Shape Analysis



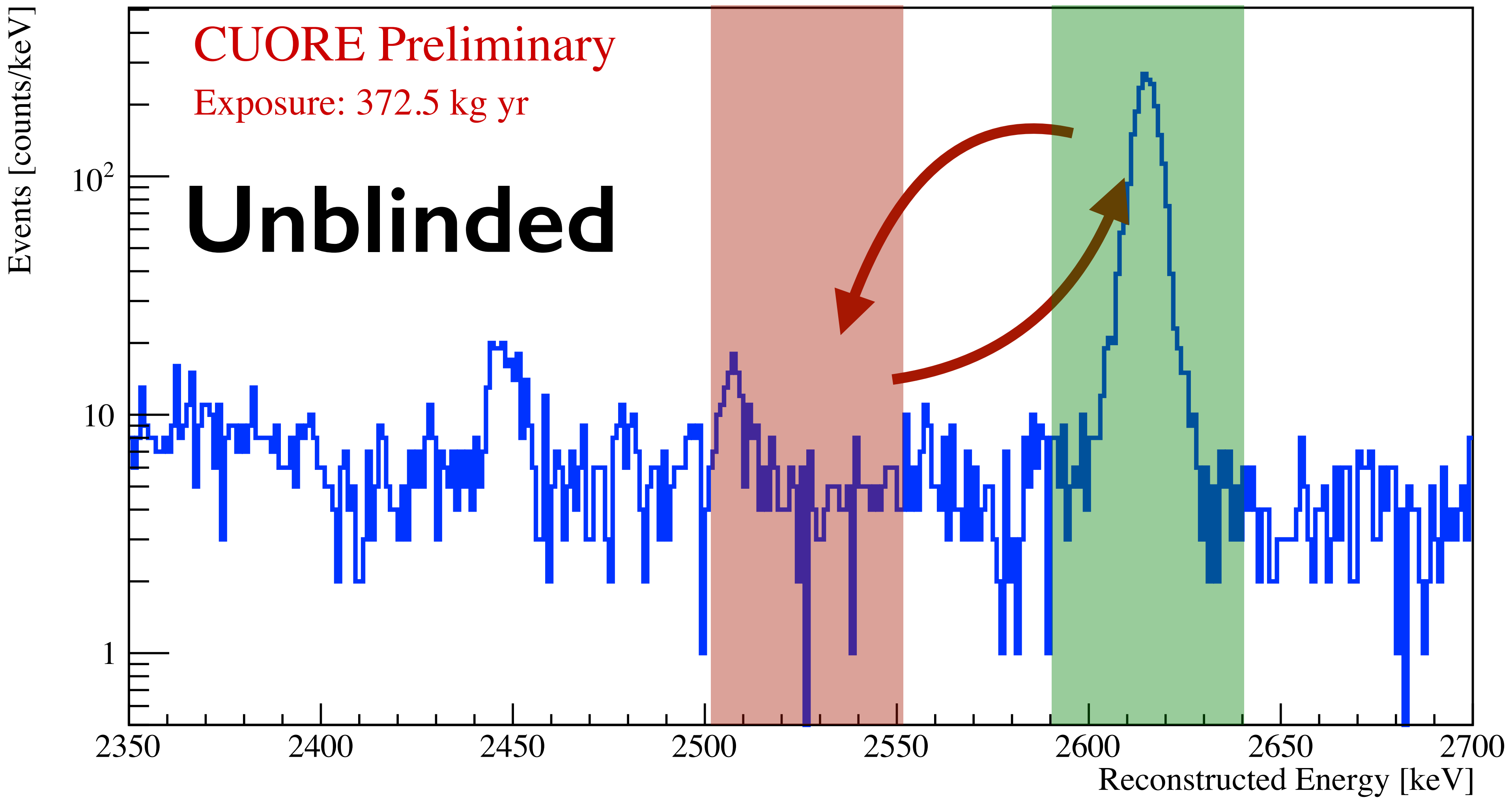


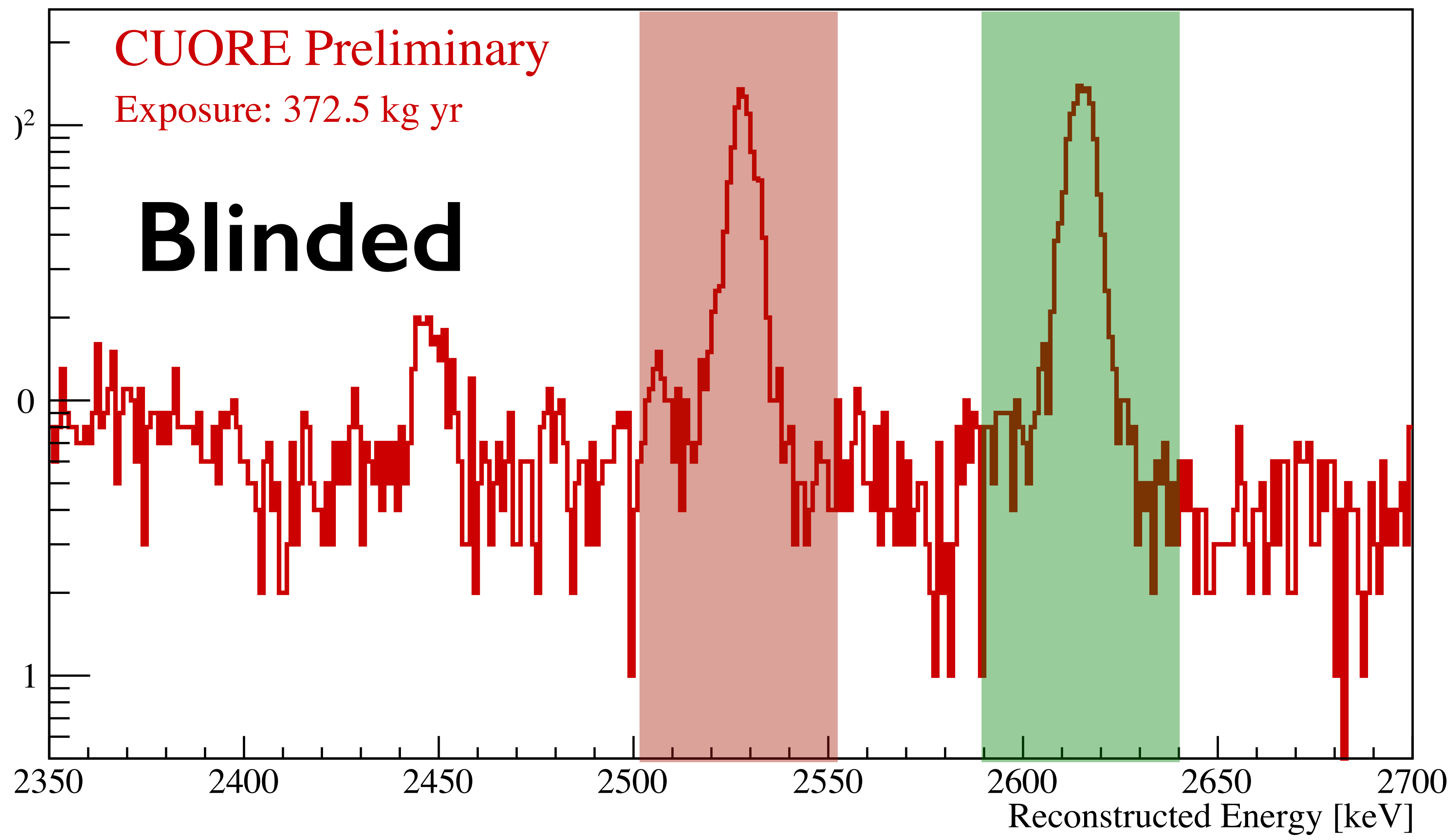


- Use the shape of the signal pulse to identify pulses that deviate from nominal pulse
- Multi-dimensional *distance* based on six pulse shape parameters is defined
- Acceptance criteria is defined by the *distance* of events from the centroid of distribution that maximizes experimental sensitivity

Analysis Chain: Blinding

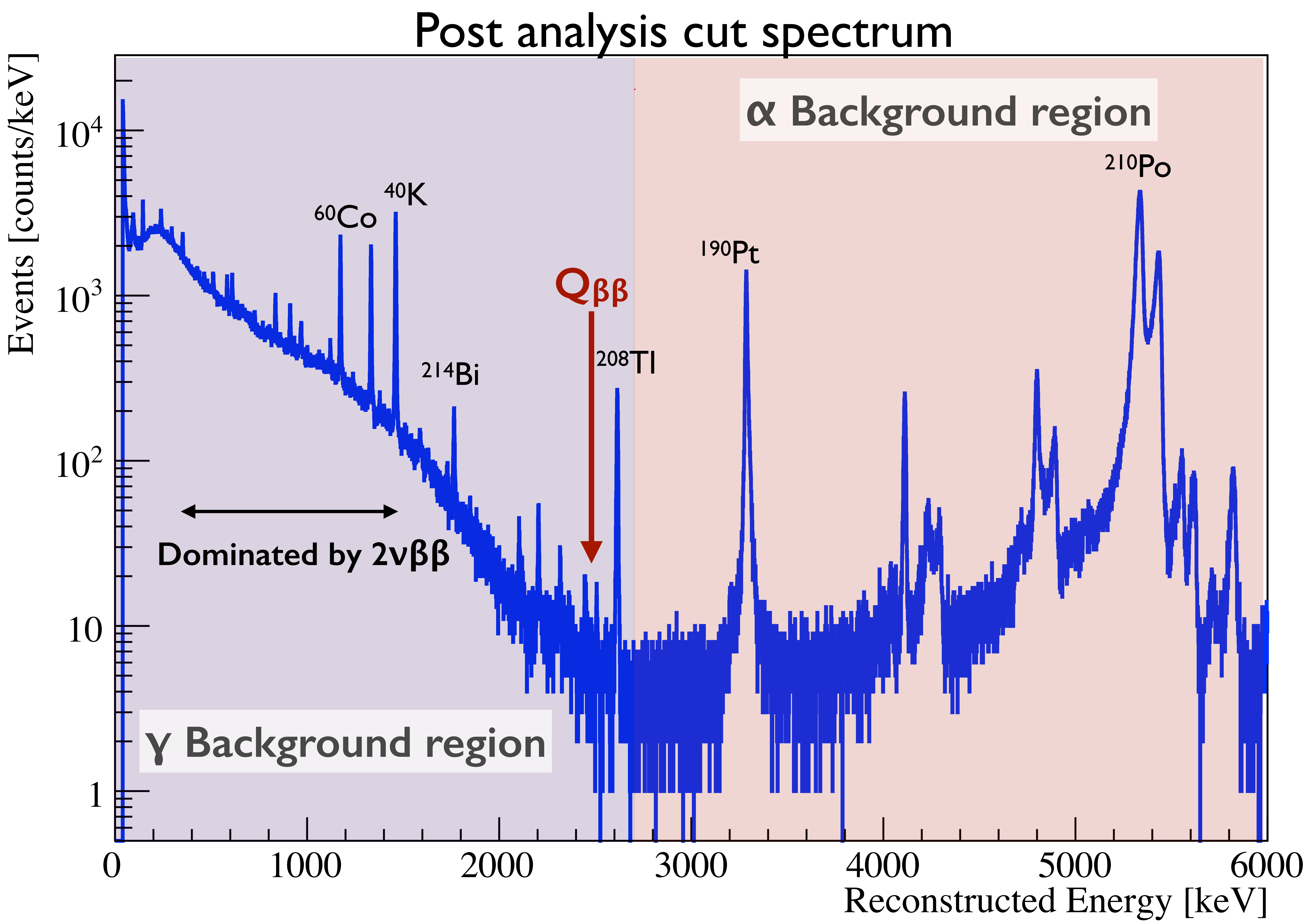
Trigger
↓
Amplitude evaluation
↓
Gain stabilization
↓
Energy calibration
↓
Multiplicity cut
↓
PSA
↓
Blinding





- Salting: Randomly move a fraction of events from ^{208}Tl at 2615 keV to $Q_{\beta\beta}$ region and vice versa
- Original event energies saved for unblinding
- Unblinding after the full analysis procedure is finalized

Spectrum



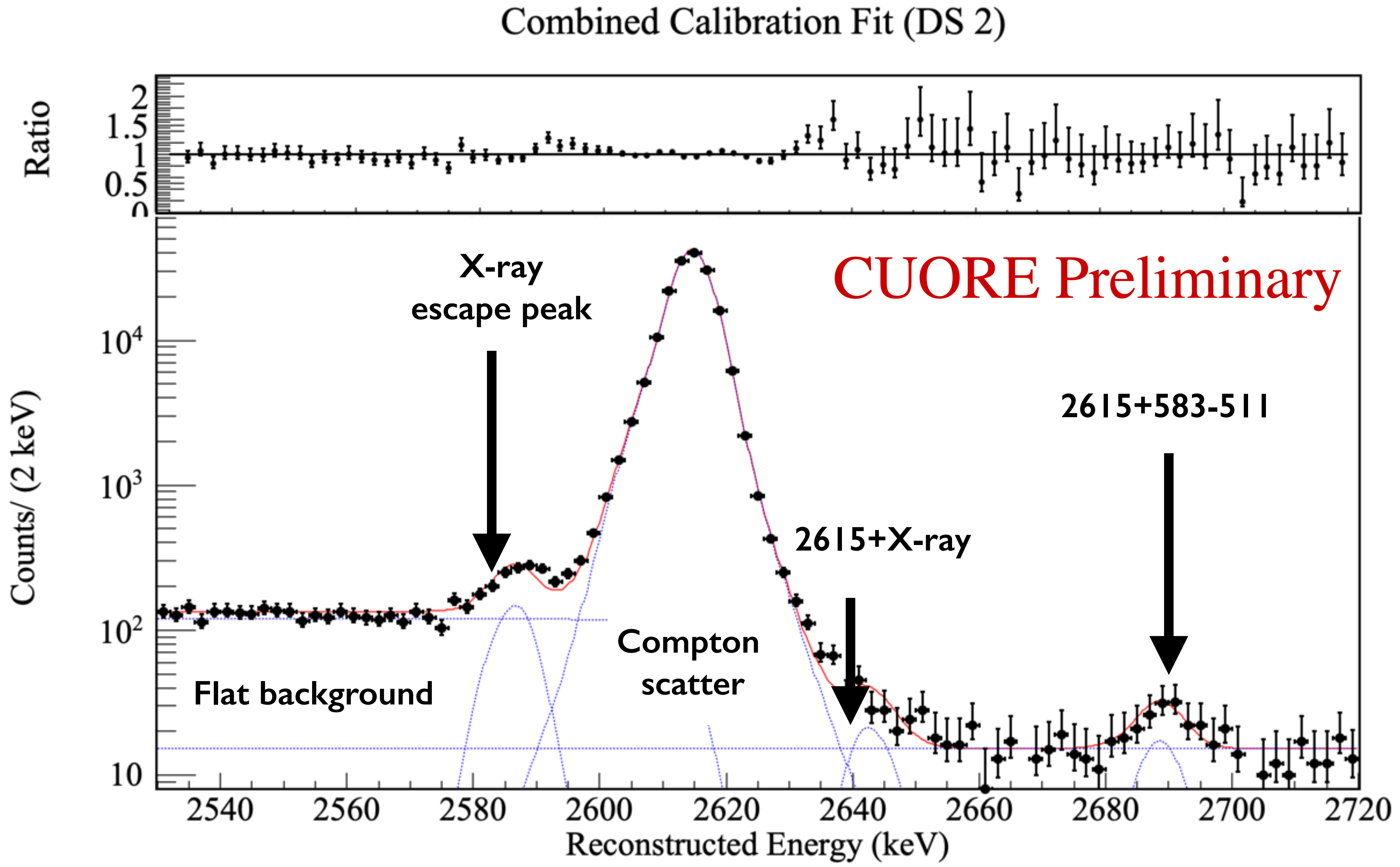
Total spectrum over 7 datasets

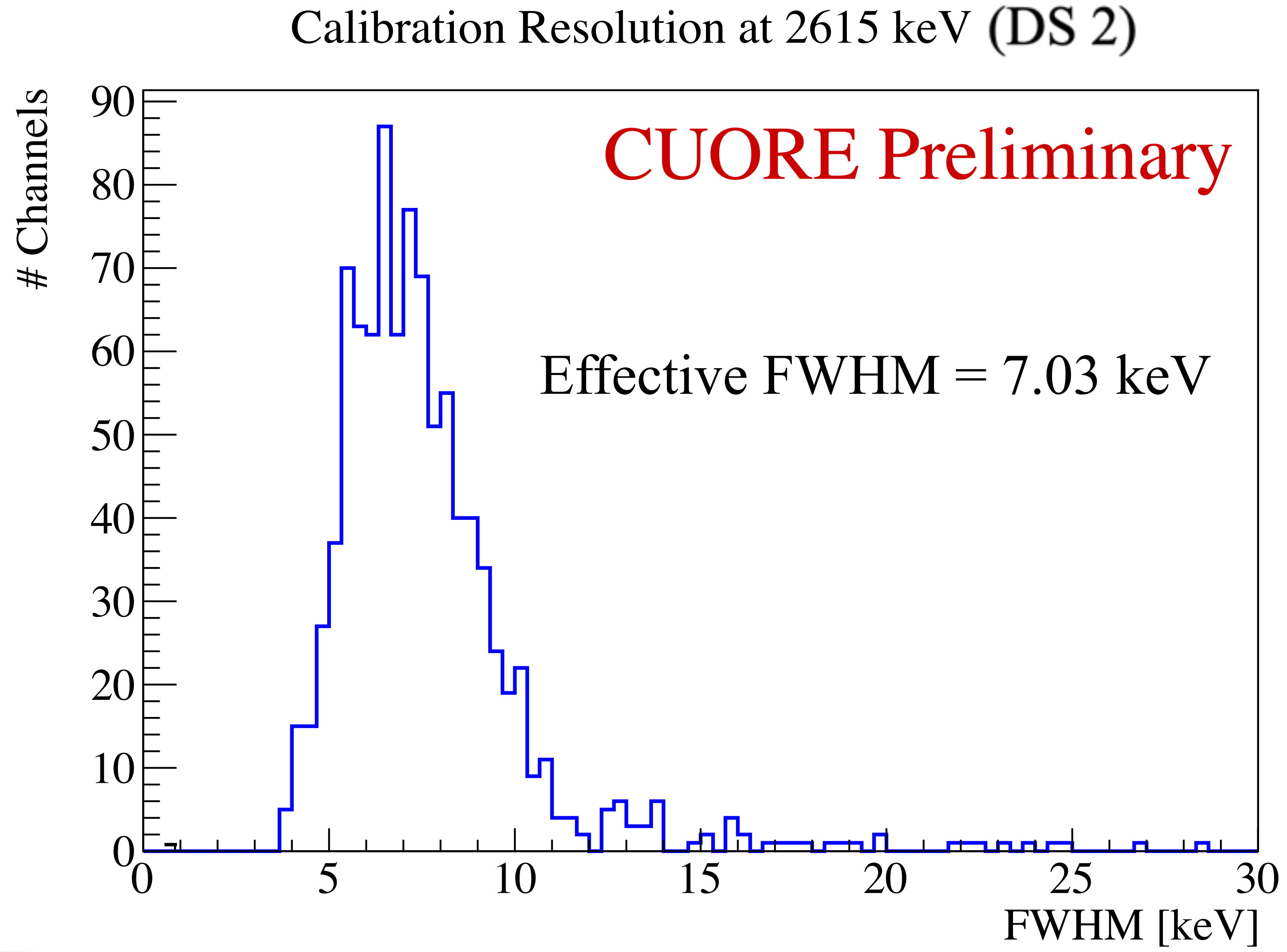
Detector Response

- Response modeled based on a fit to 2615 ^{208}Tl peak
- Main peak parametrized by 3 γ peaks, X-ray escape, flat background and Compton scatter distribution
- Fit performed over all channels in a tower
- Using the same line shape function, resolution and bias in energy extracted by fitting peaks in physics data
- Extrapolate to $Q_{\beta\beta}$

FWHM at 2615 keV in calibration data - 7.7 keV

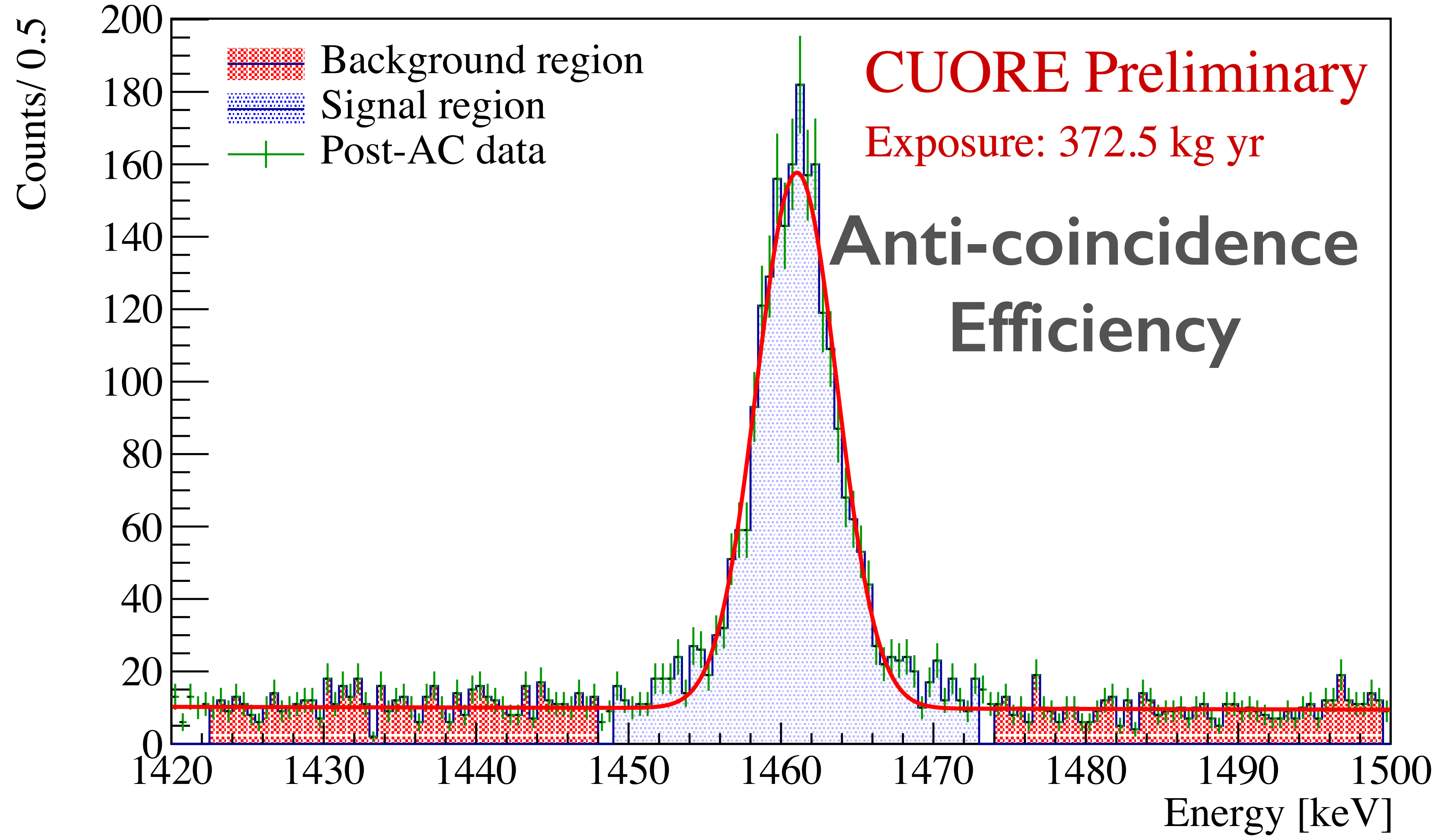
FWHM at $Q_{\beta\beta}$ in physics data - 7.0 keV

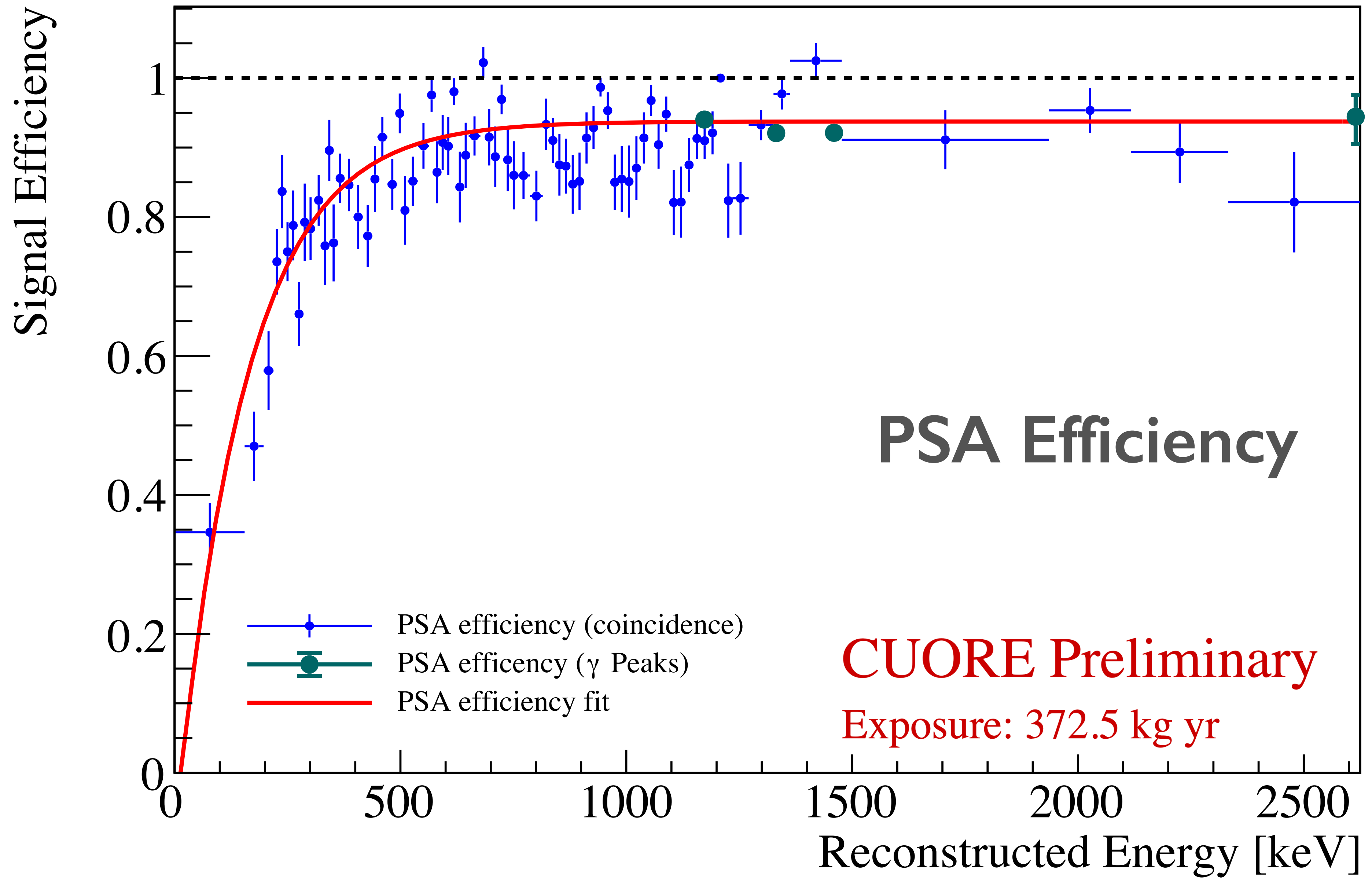




Efficiencies

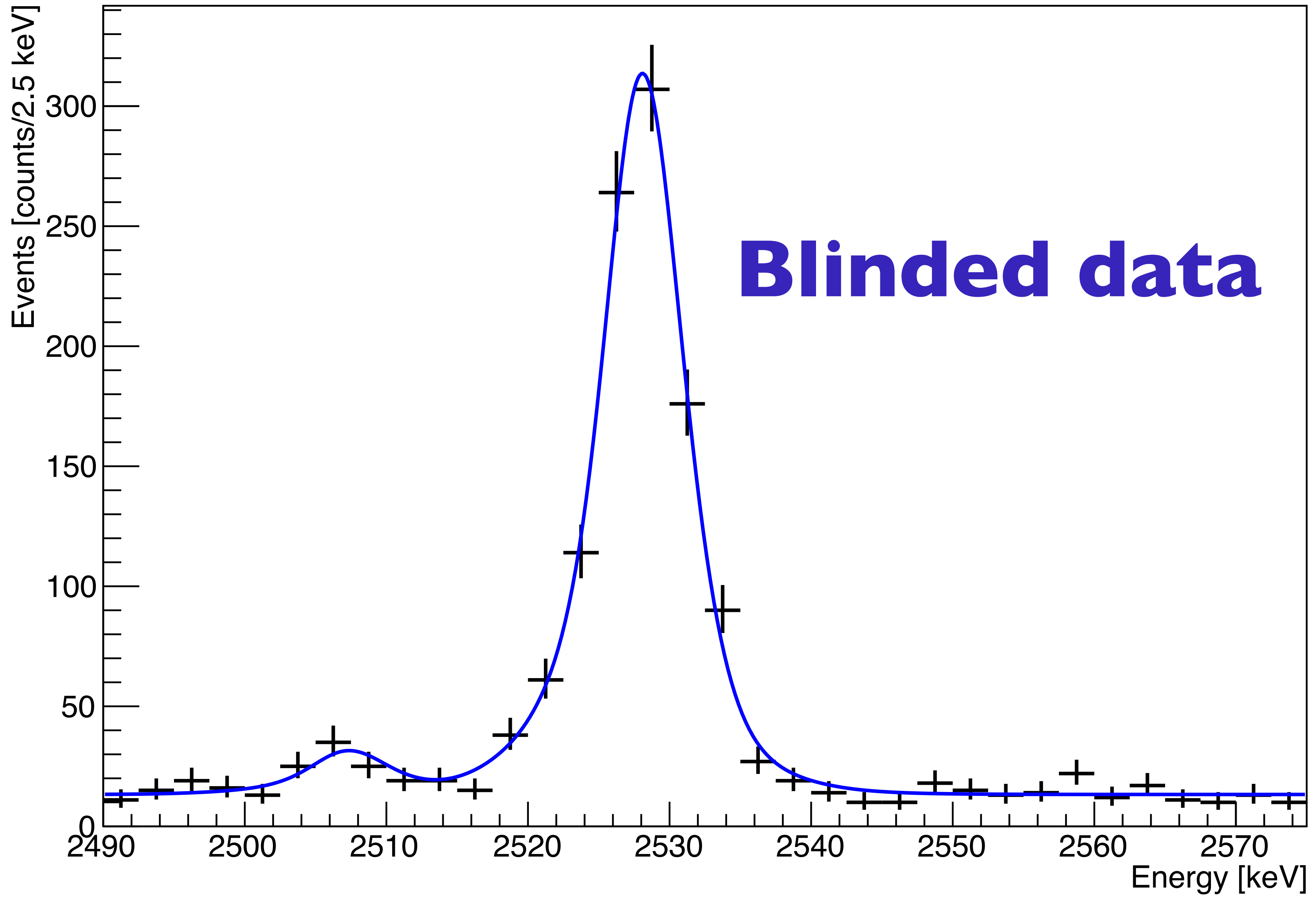
	Containment efficiency	Evaluated with MC simulations	MC	88.35(9) %
Crystal level	**Reconstruction efficiency**	Comprises: ➔ trigger ➔ event reconstruction ➔ pile-up identification	Heater	95.802(3) %
Dataset level	**Anti-coincidence efficiency**	Quantifies the probability of properly identifying a single-crystal event	^{40}K	98.7(1) %
Dataset level	**Pulse-shape analysis efficiency**	Fraction of events passing a multi-dimensional cut on 6 pulse-shape variables	M1 M2 ^{40}K 3x^{60}C ^{208}Tl	92.6(1) %





Fit Details

- Unbinned Bayesian fit over all datasets
- Uses Bayesian Analysis Toolkit (BAT)
- Fit region [2490, 2575] keV
- Systematics implemented as nuisance parameters
- Fits done separately on each dataset with and without systematics produces consistent results



Fit parameters:

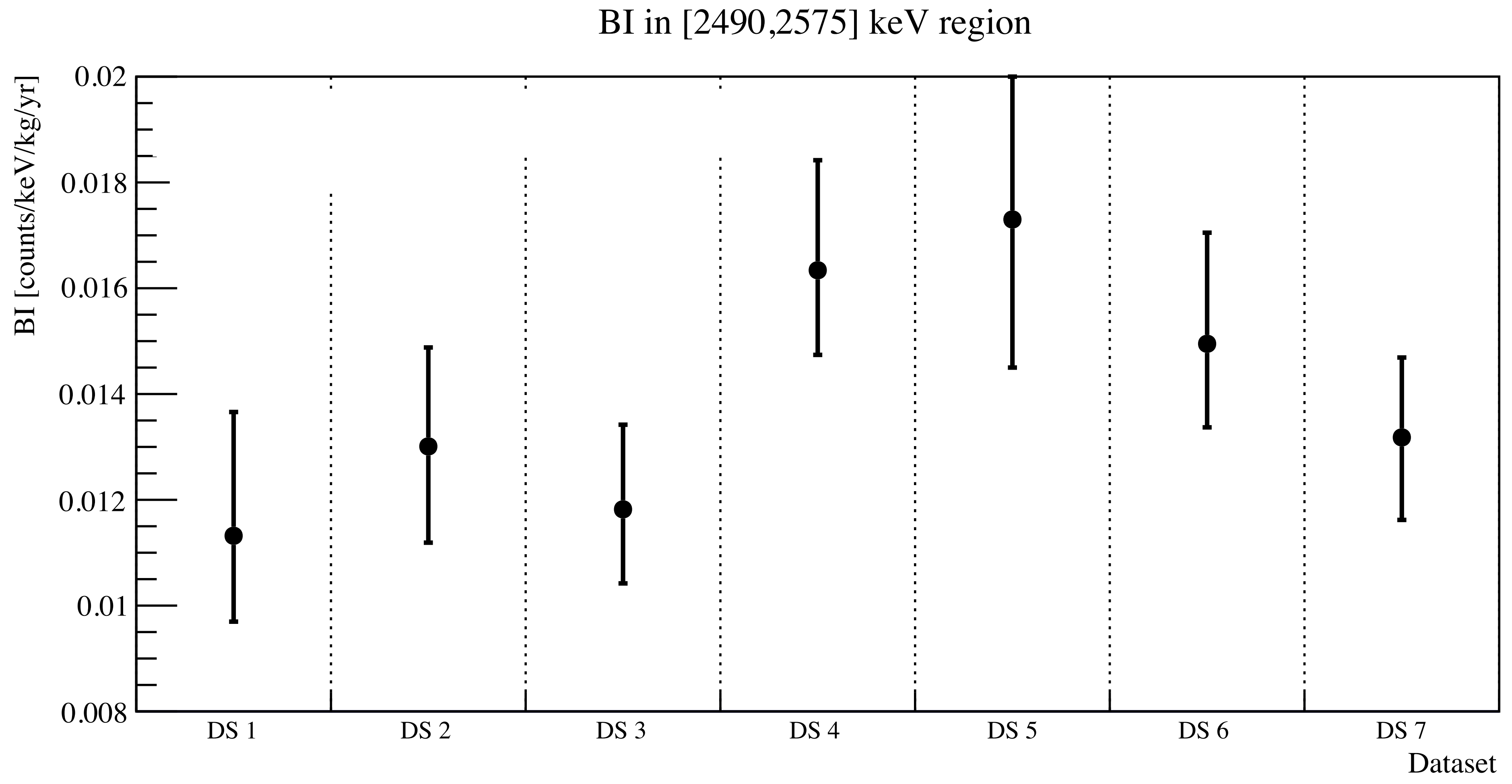
- $0\nu\beta\beta$ decay rate @ 2527.518 keV
- ^{60}Co sum peak amplitude
- ^{60}Co sum peak position
- Background index (flat)

Systematics:

- Analysis efficiencies
- Containment efficiency
- Energy scale
- Energy resolution
- $Q_{\beta\beta}$
- ^{130}Te abundance

Fit to ROI

Average BI from BG only fit = **(1.38±0.07).10^{-2}** counts/(keV · kg · yr)



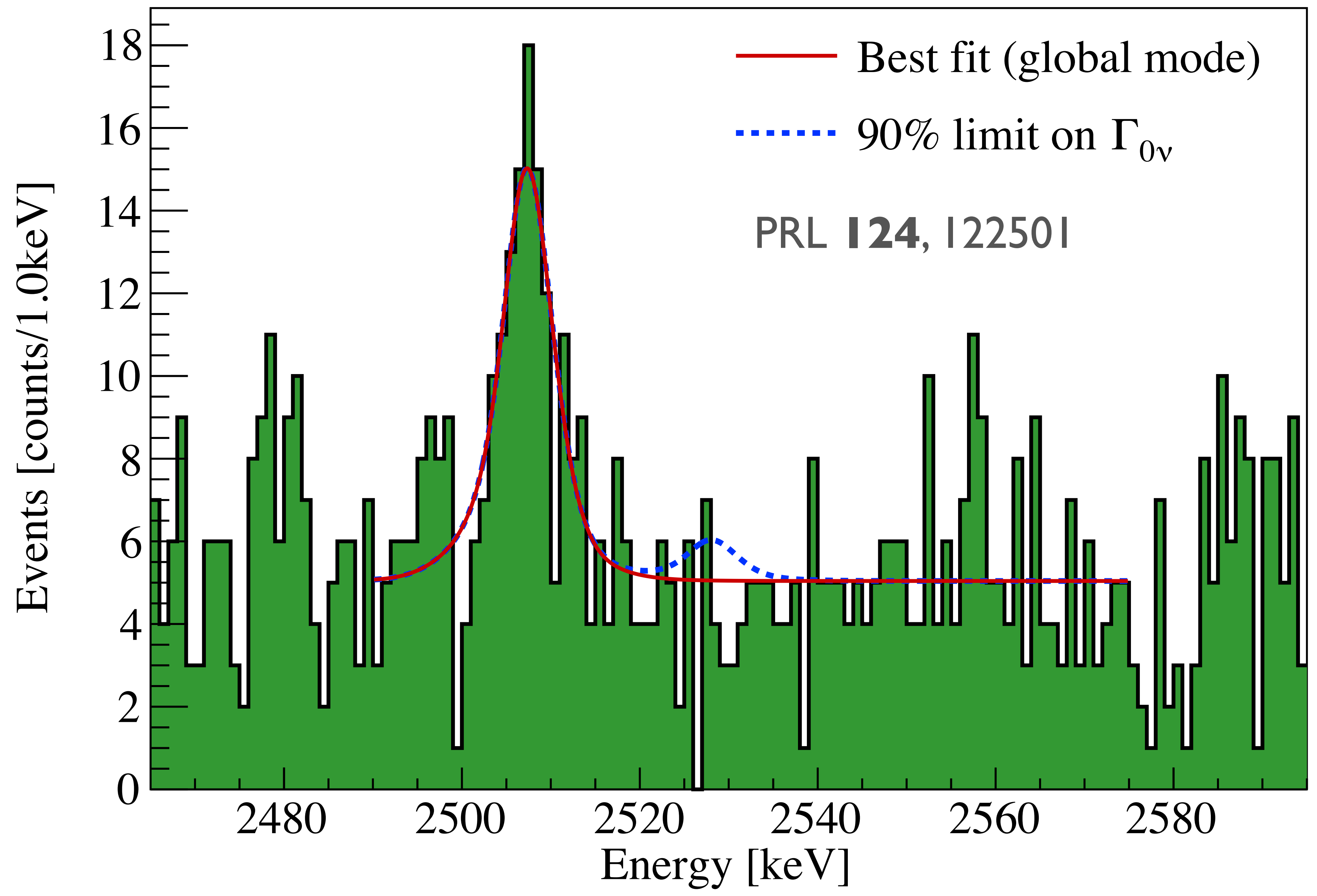
Sensitivity:

- Bkg-only model used to generate MC datasets and fit them to signal + bkg model
- Median exclusion sensitivity: $T^{0\nu}_{1/2}$ = **1.7 · 10^{25}** yr

Results:

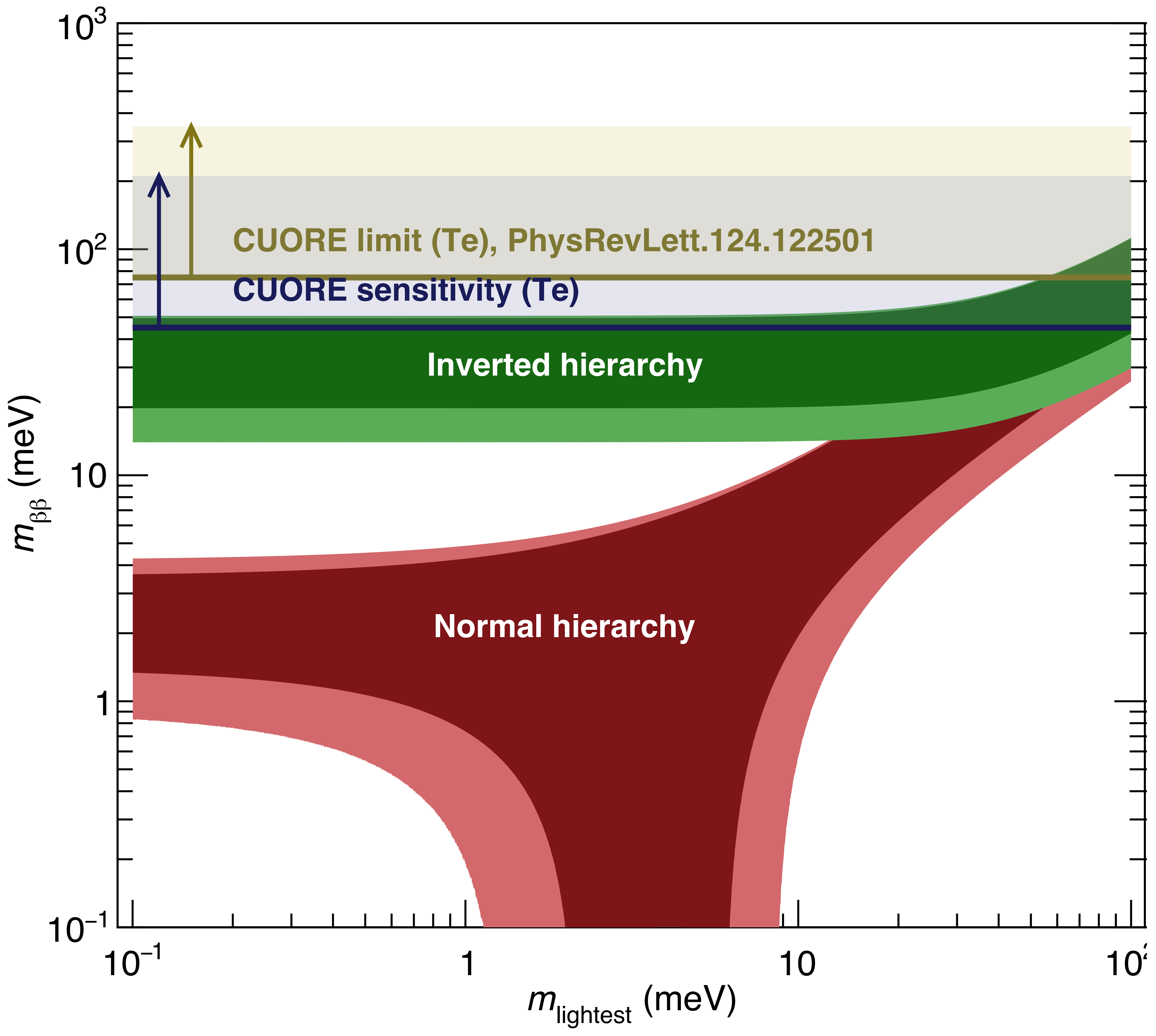
- No evidence of 0νββ Best fit decay = **0** yr^{-1}
- $T^{0\nu}_{1/2}$ > **3.2 x10^{25}** yr at 90% C.I

Phys. Rev. Lett. **124**, 122501



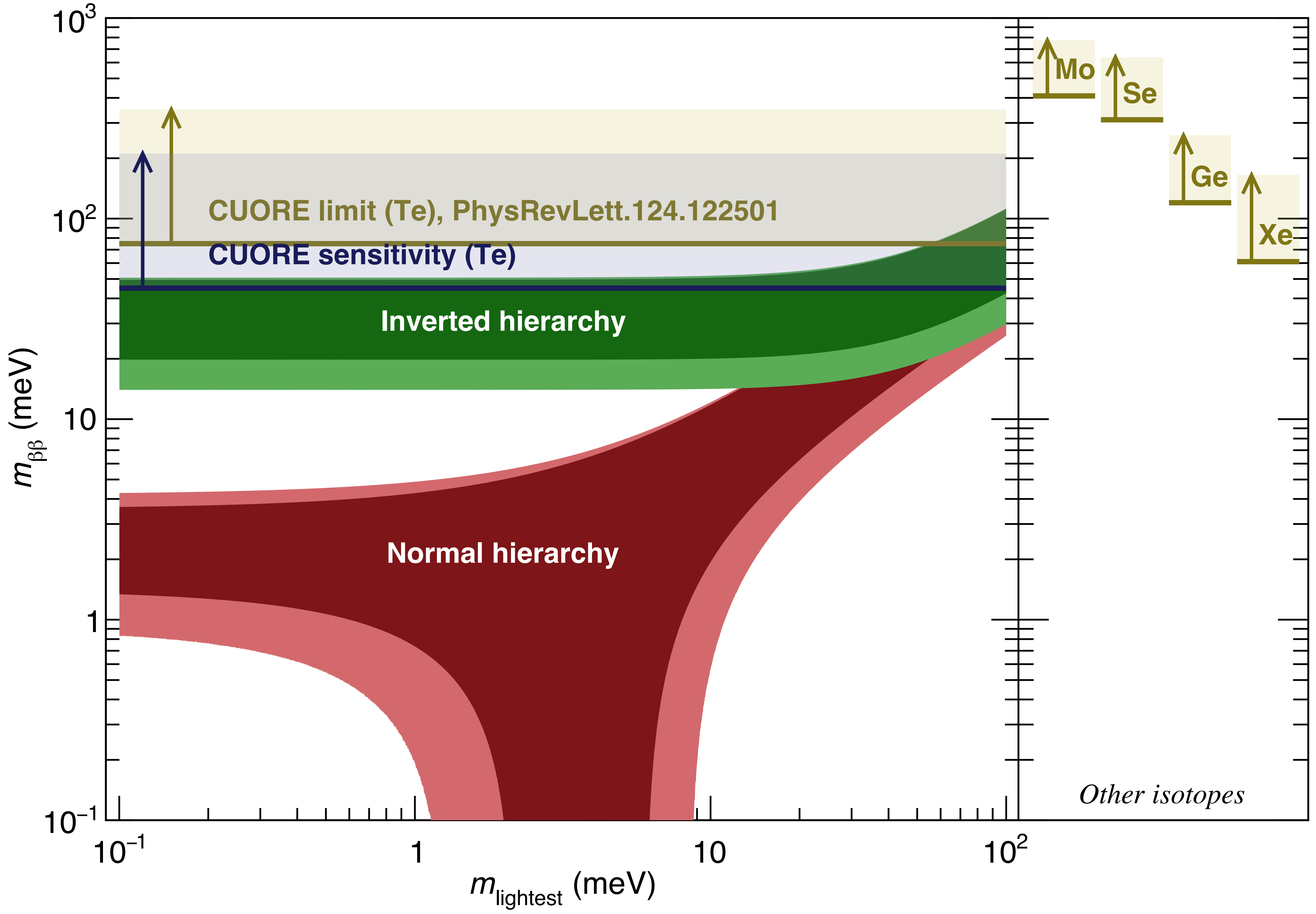
Limit on Effective Majorana Mass

- $T^{0\nu}_{1/2}$ > **3.2 x10²⁵** yr at 90% C.I
- Probability of getting a stronger limit is ~3 %
- Assuming light neutrino exchange: $m_{\beta\beta}$ < **75 - 350 meV**
- Uncertainities in nuclear matrix elements determines the range



CUORE Summary

- Calorimetric detector with excellent resolution
- CUORE started data taking in 2017
- Stable data taking since early 2019 at 50kg.yr/month
- >917 kg.yr data collected so far
- 372.5 kg.yr data analyzed
- Updated ^{130}Te $T^{0\nu}_{1/2}$ > **3.2 x10^{25}** yr and $m_{\beta\beta}$ < **75 - 350 meV**
- Sensitivity (5 yr data taking): ^{130}Te $T^{0\nu}_{1/2}$ > **9.0 x10^{25}** yr $m_{\beta\beta}$ < **50 - 130 meV**



Backgrounds in CUORE

$$a\,\varepsilon\sqrt{\frac{M\,t}{B\,\Delta E}}$$

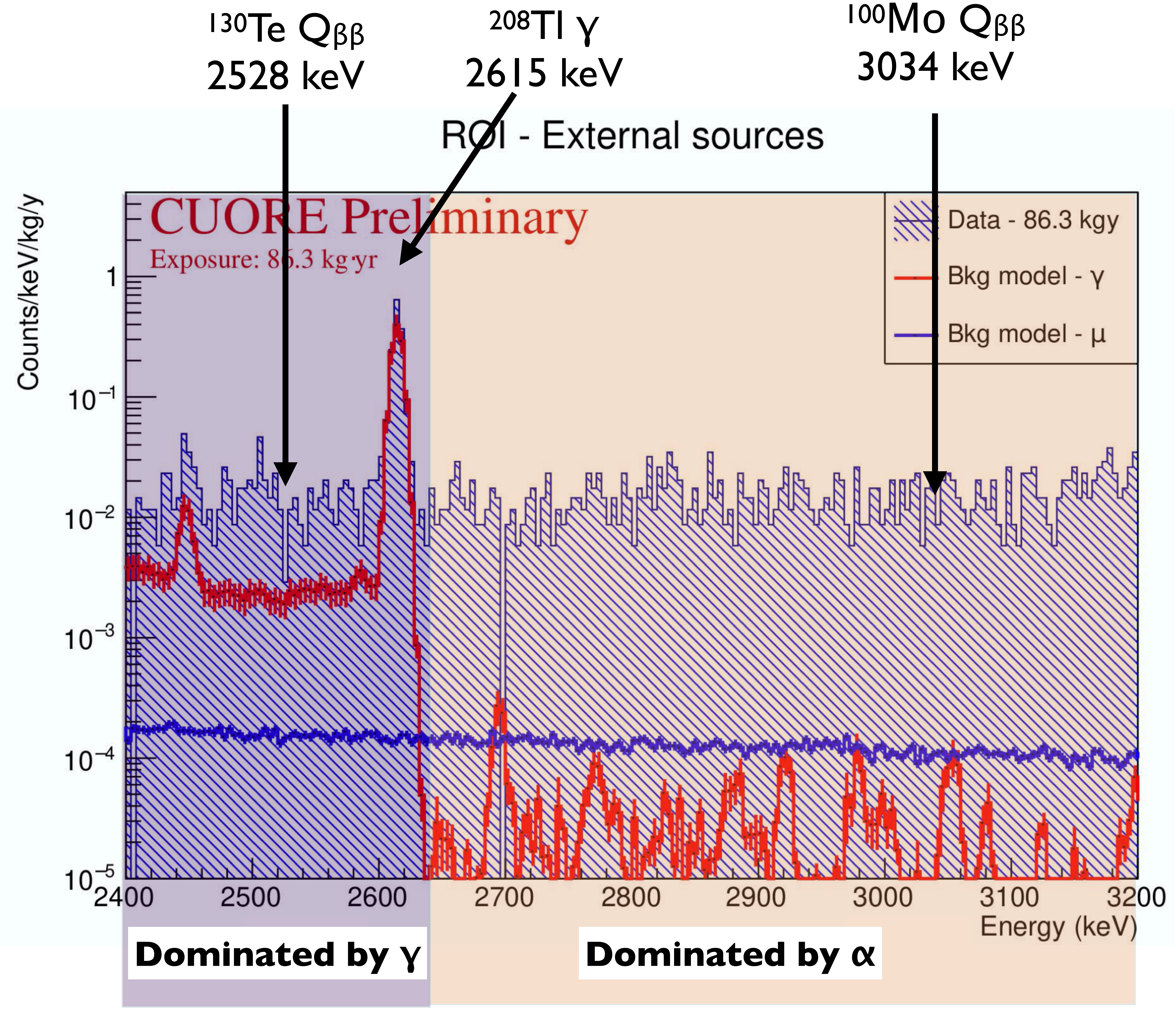
Reduce backgrounds to further improve sensitivity

<u>Backgrounds:</u>

- Below 2615 keV dominated by γ
- Above 2615 keV, primarily from αs (U/Th contamination)
- Next dominant background muons

<u>Reducing backgrounds:</u>

- Move to higher energy > 2615 keV
- Eliminate α backgrounds (By discrimination)
- Reduce muon backgrounds (Active veto)



CUPID

~170 authors
7 countries

CUPID pre-CDR
arXiv:1907.09376

INFN Sezione di Milano Bicocca and University of Milano Bicocca, Italy
M. Beretta, M. Biassoni, C. Brofferio, S. Capelli, P. Carniti, D. Chiesa, M. Clemenza, O. Cremonesi, M. Faverzani, E. Ferri, A. Giachero, L. Gironi, C. Gotti, M. Nastasi, A. Nucciotti, I. Nutini, L. Pagnanini, M. Pavan, G. Pessina, S. Pozzi, E. Previtali, A. Puiu, M. Sisti

INFN Sezione di Roma and Sapienza University of Rome, Italy
F. Bellini, L. Cardani, N. Casali, A. Cruciani, I. Dafinei, V. Pettinacci, C. Tomei, M. Vignati

INFN Sezione di Roma and Gran Sasso Science Institute, Italy
F. Ferroni

Universidad de Zaragoza, Spain
M. Martinez

INFN Laboratori Nazionali del Gran Sasso, Italy
C. Bucci, L. Canonica, V. Caracciolo, A. D'Addabbo, P. Gorla, S. Nisi, D. Orlandi, C. E. Pagliarone, L. Pattavina, S. Pirro, C. Rusconi, K. Schaffner

INFN Sezione di Bologna and University of Bologna, Italy
S. Zucchelli, N. Moggi

INFN Laboratori Nazionali di Frascati, Italy
A. Franceschi, T. Napolitano

INFN Laboratori Nazionali di Legnaro, Italy
G. Keppel, O. Azzolini

INFN Sezione di Padova, Italy
L. Taffarello

INFN Sezione di Genova and University of Genova, Italy
S. Di Domizio, M. Pallavicni

CSNSM Orsay, France
L. Bergé, M. Chapellier, L. Dumoulin, A. Giuliani, H. Khalife, P. de Marcillac, S. Marnieros, E. Olivieri, D. Poda, T. Redon, A. Zolotarova

CEA Saclay, France
E. Armengaud, N. Besson, M. de Combarieu, F. Ferri, M. Gros, X.F. Navick, C. Nones, P. Pari, B. Paul

IPNL Lyon, France
Q. Arnaud, C. Augier, J. Billard, A. Cazes, F. Charlieux, E. Elkhoury, J. Gascon, M. De Jesus, A. Juillard, D. Misiak, V. Sanglard, L. Vagneron

LAL Orsay, France
M. Brière, C. Bourgeois, E. Guerard, P. Loaiza

SIMAP Grenoble, France
M. Velazquez

Argonne National Laboratory, USA
W.R. Armstrong, C. Chang, V. Novosad, T. Polakovic, G. Wang, V. Yefremenko, J. Zhang

Lawrence Berkeley National Laboratory and University of California, Berkeley, USA
G. Benato, A. Drobizhev , B. K. Fujikawa, R. Huang, Yu. G. Kolomensky, L. Marini, E. Norman, M. Sakai, B. Schmidt, V. Singh, S. Wagaarachchi, J. Wallig, B. Welliver

Cal Poly, San Luis Obispo, USA
T. Gutierrez

Massachusetts Institute of Technology, USA
J. Johnston, J. Ouellet, J. Formaggio, L. Winslow

University of South Carolina, USA
F. Avignone, C. Rusconi, R. Creswick and K. Wilson

University of California Los Angeles, USA
K. Alfonso, H.Z. Huang

Virginia Tech, USA
S. Dell'Oro, T. O'Donnell

Yale University, USA
K. Heeger, R. Maruyama, J. Nikkel, D. Speller, P. T. Surukuchi

University of Science and Technology of China, China
H. Peng, M. Xue

Fudan University, China
L. Ma, Y. Shen, W. He

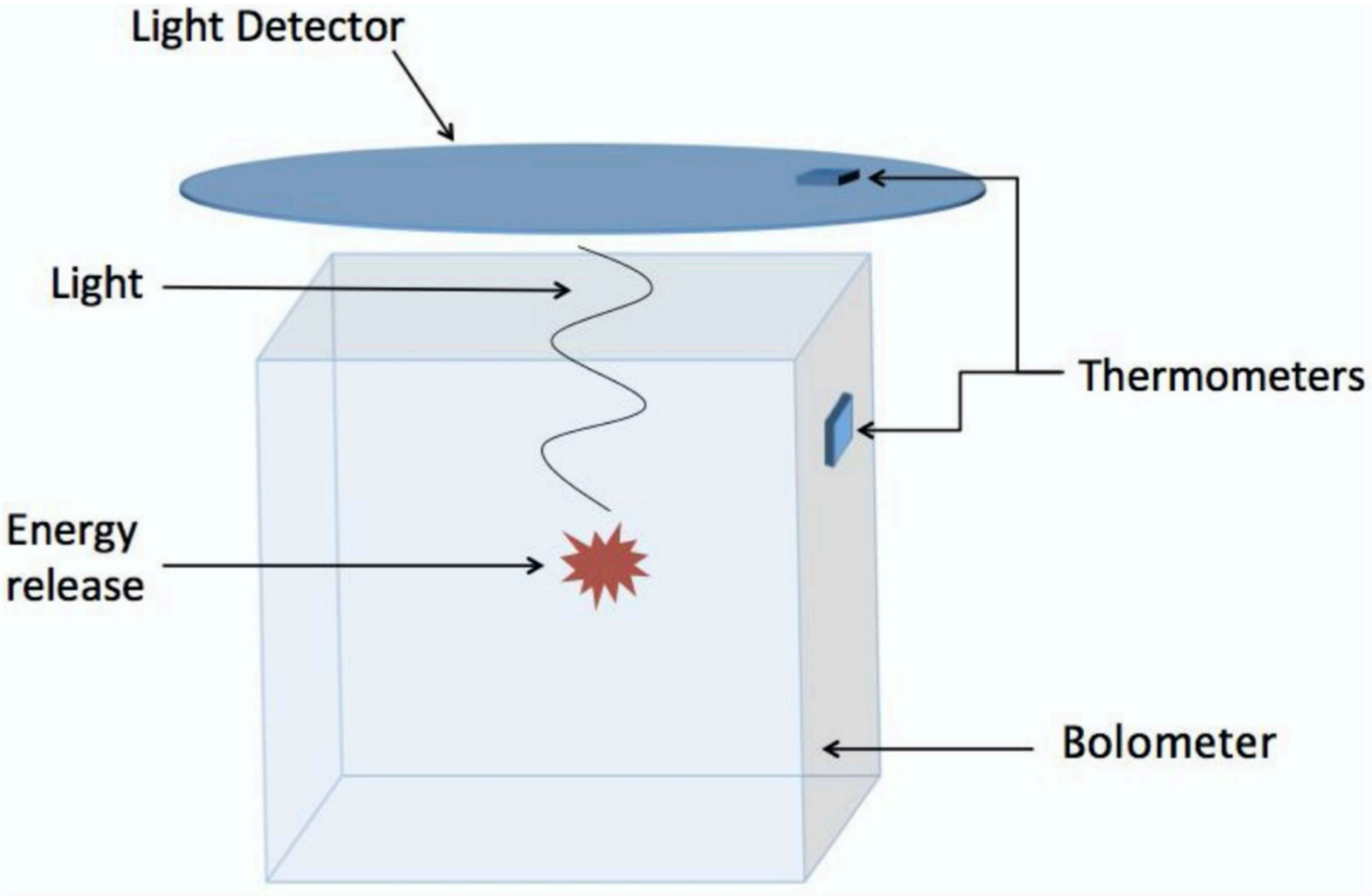
Shanghai Jiao Tong University, China
K. Han

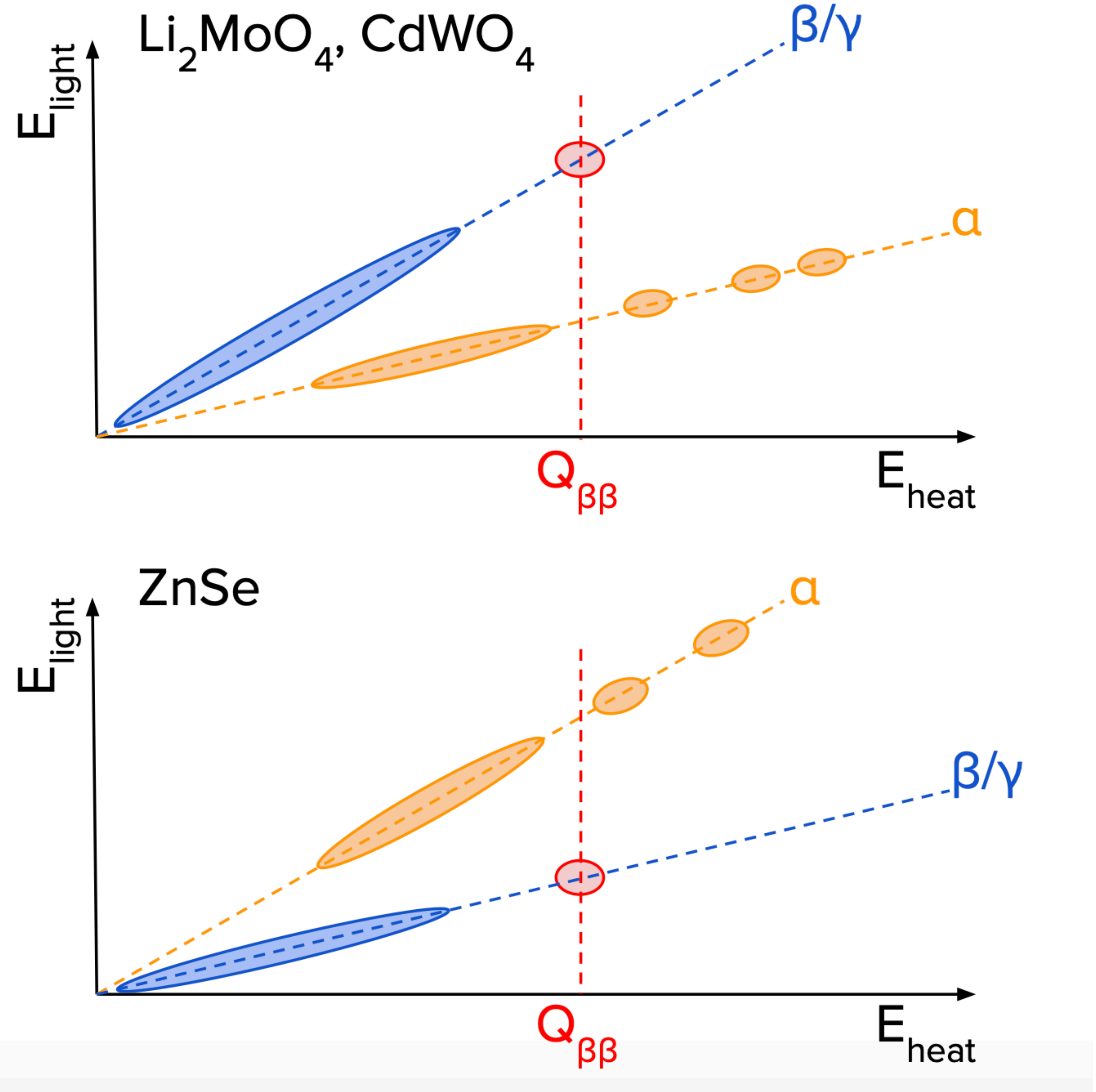
KINR Kiev, Ukraine
F. Danevich, V. Kobychev, O. Polischuk, V. Tretyak

ITEP Moscow, Russia
A. Barabash, S. Konovalov, V. Yumatov

NIIC Novosibirsk, Russia
V. Shlegel

CUPID: The Concept





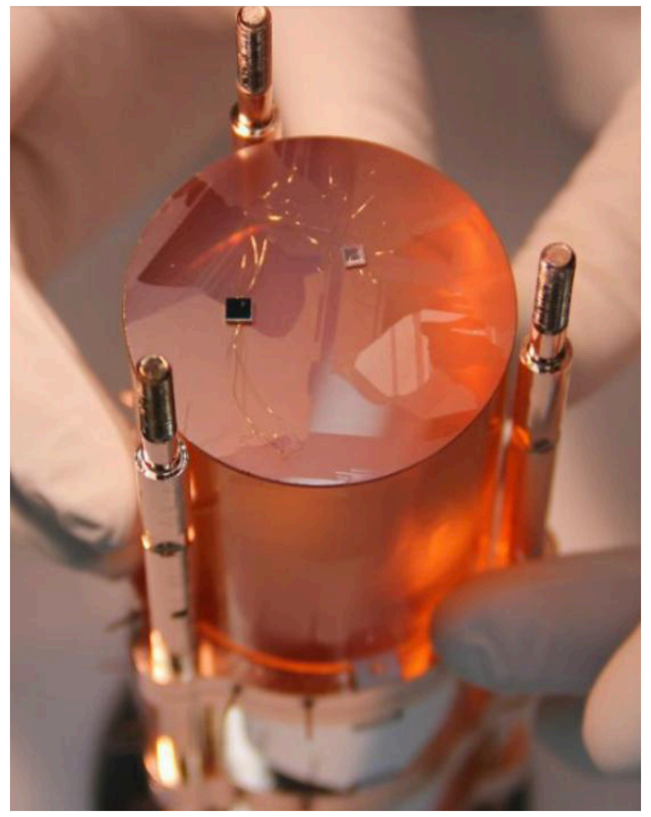
- Measure heat and light from energy deposition:
  Heat is particle independent, but light yield depends on particle type
- Add a light detector to crystal
- Actively discriminate using measured light yield

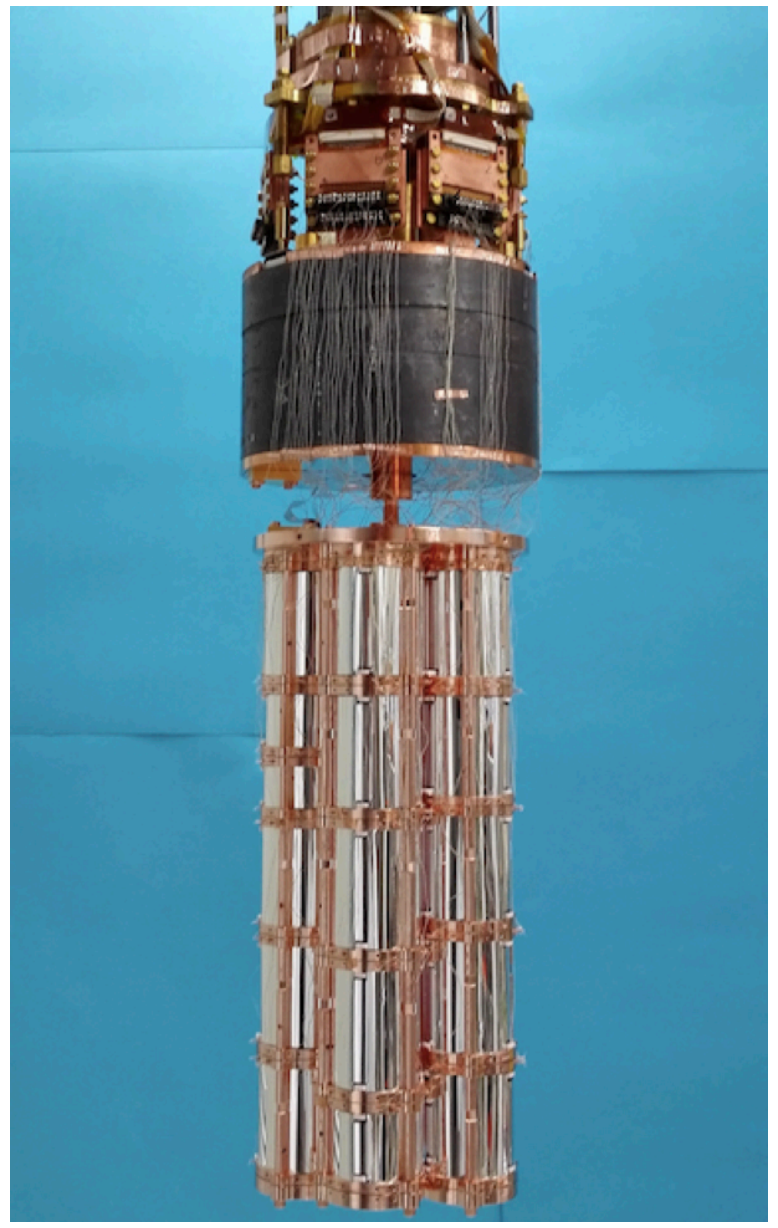
Prototype Demonstrators: Precursors to CUPID

CUPID-0:

- Located in the CUORE-0 cryostat at LNGS, Italy
- 24 $Zn^{82}Se$ (95% enrichement) +2 $Zn^{nat}Se$ crystals
  - 5.17 kg of ^{82}Se
- Ge light detectors and NTD thermistors

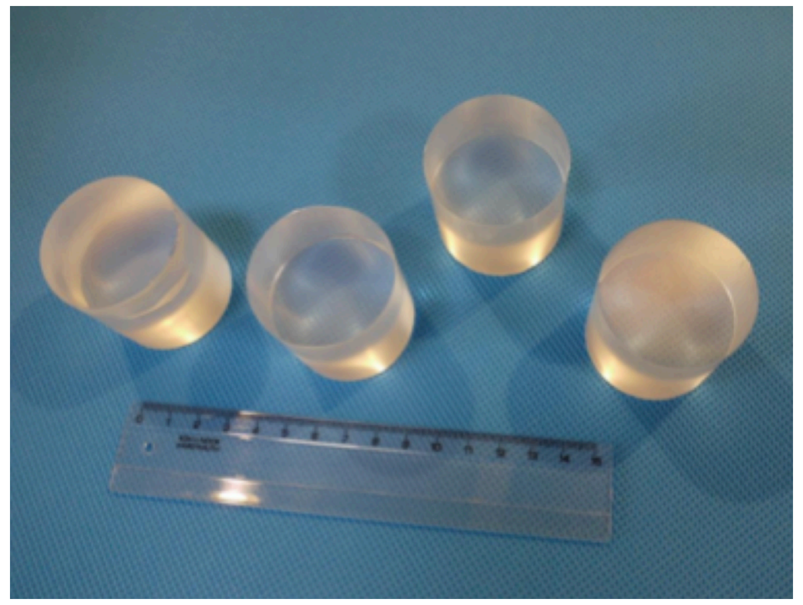
Phys. Rev. Lett. **123**, 032501

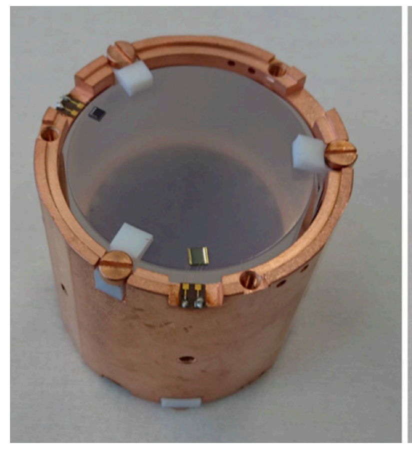


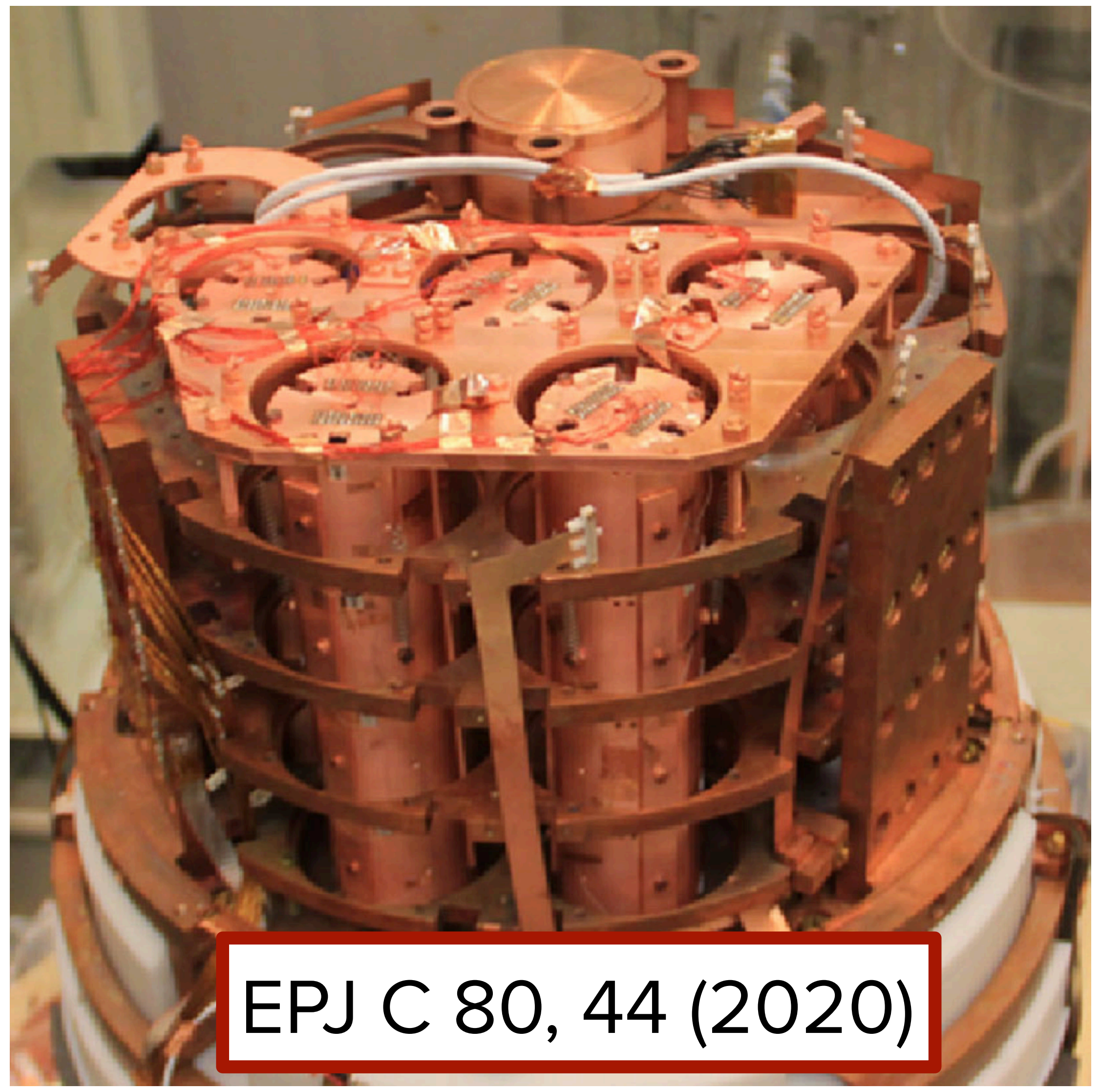


CUPID Mo:

- Located in the LSM, France
- 20 enriched $Li_2{}^{100}MoO_4$ (97% enrichement) crystals
  - 2.26 kg of ^{100}Mo
- Ge light detectors and NTD thermistors





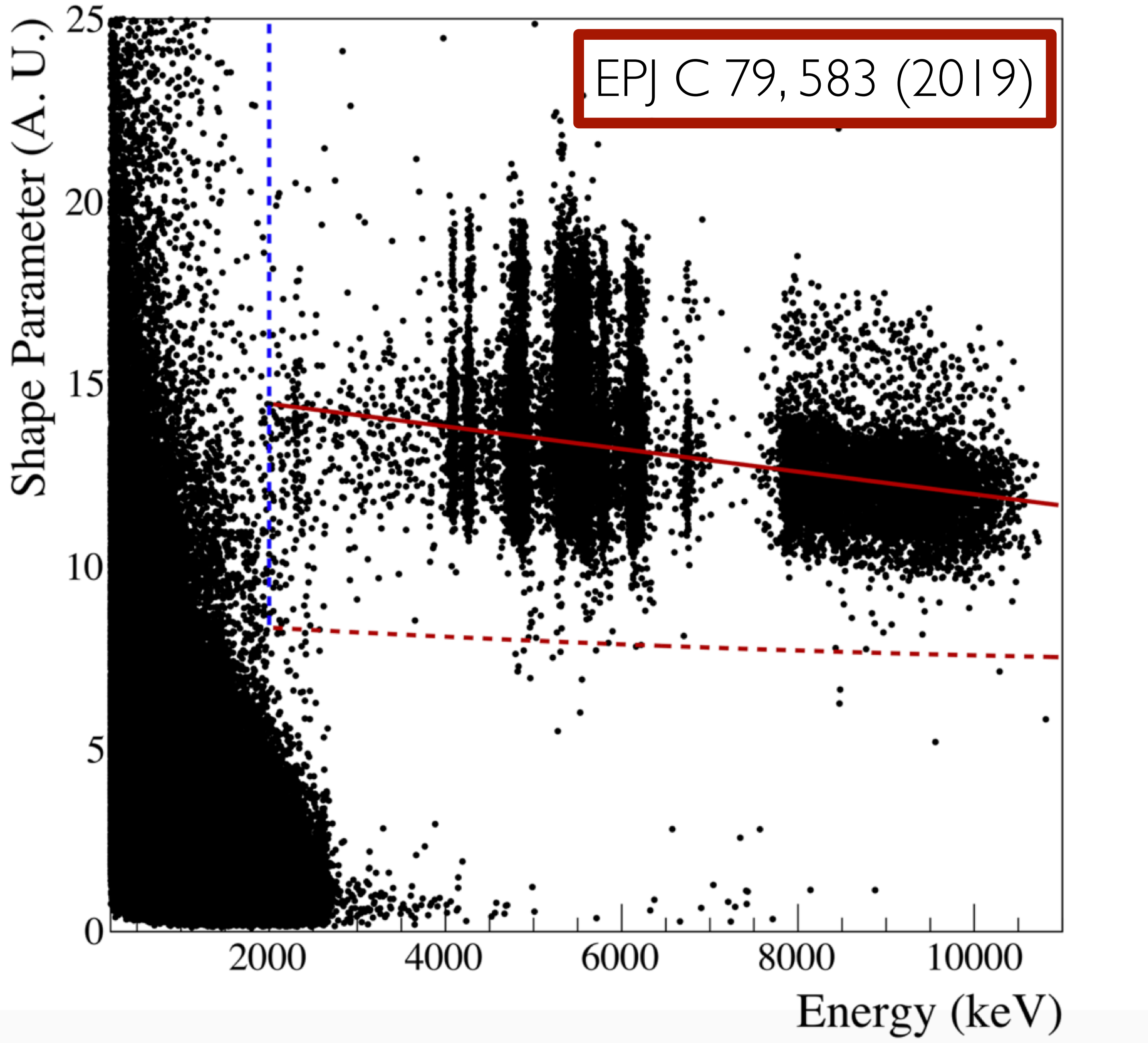


EPJ C 80, 44 (2020)

Prototype Demonstrators: Precursors to CUPID

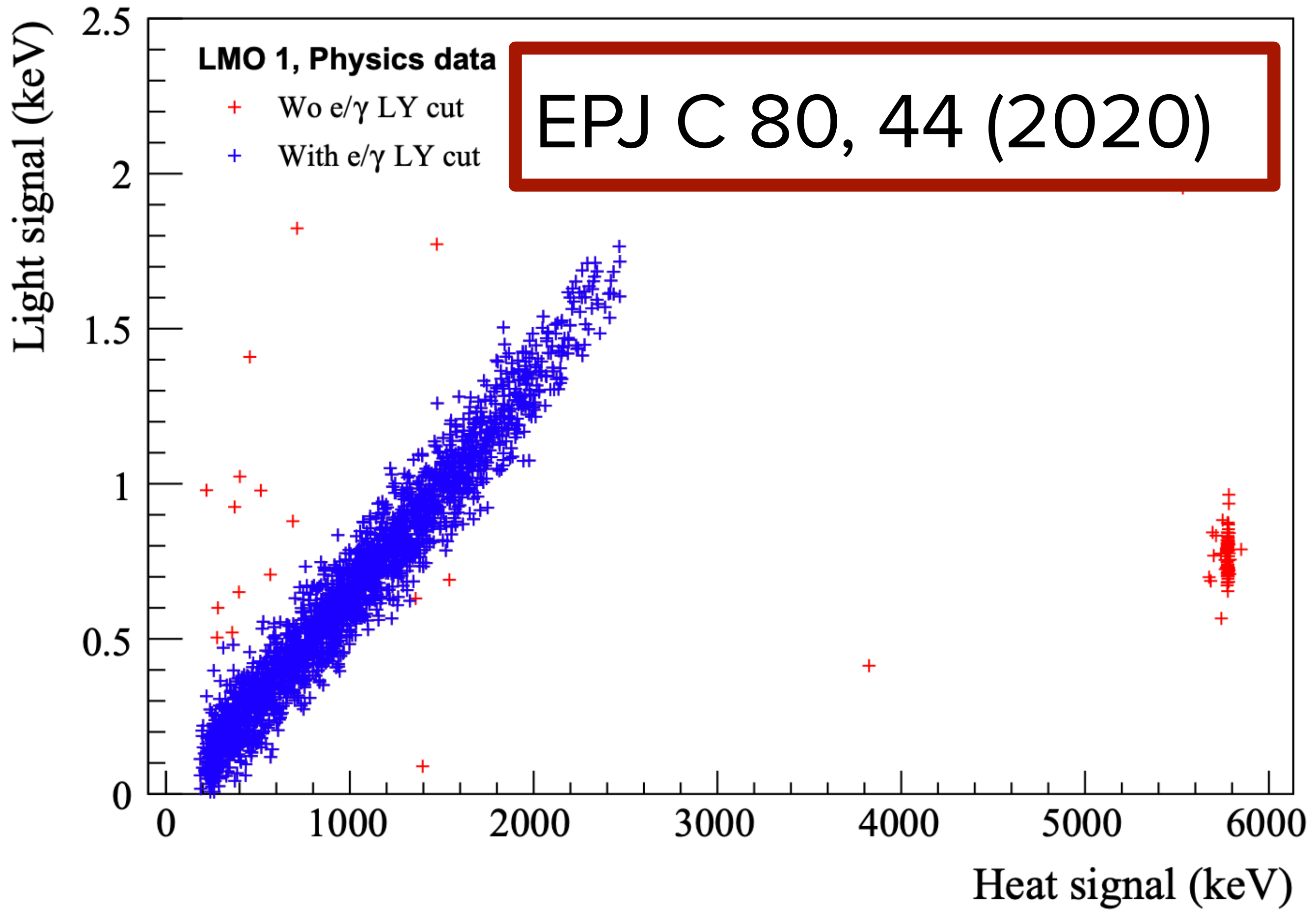
CUPID-0 (5.29 kg.yr):

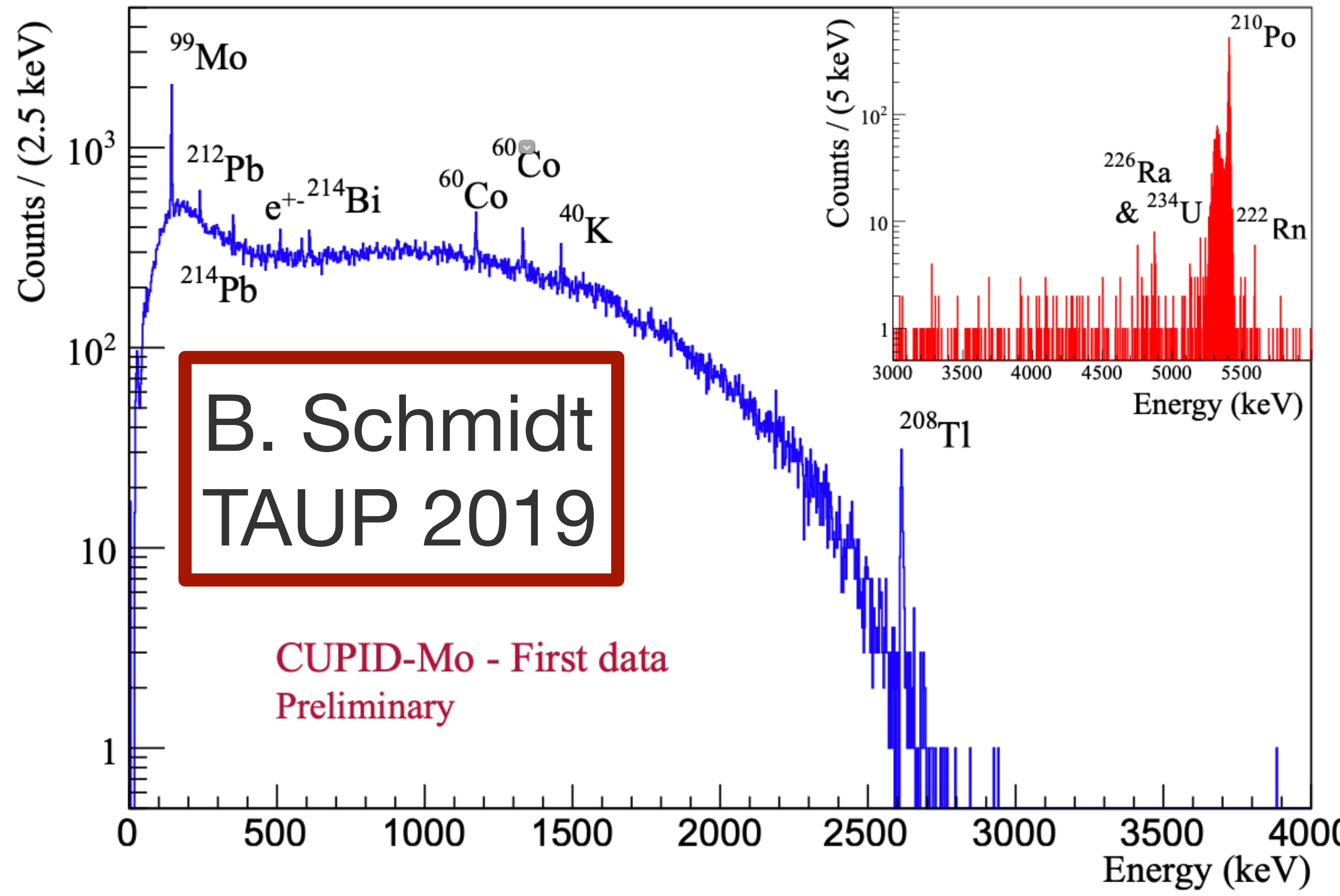
- Resolution of $Q_{\beta\beta}$ 20.05 ± 0.34 keV
- Background in ROI: 3.5×10^{-3} cts/(keV.kg .yr)
- $T_{1/2} > 3.5\times10^{24}$ yr and $m_{\beta\beta} <$ (311 - 638) meV



CUPID Mo (0.5 kg.yr):

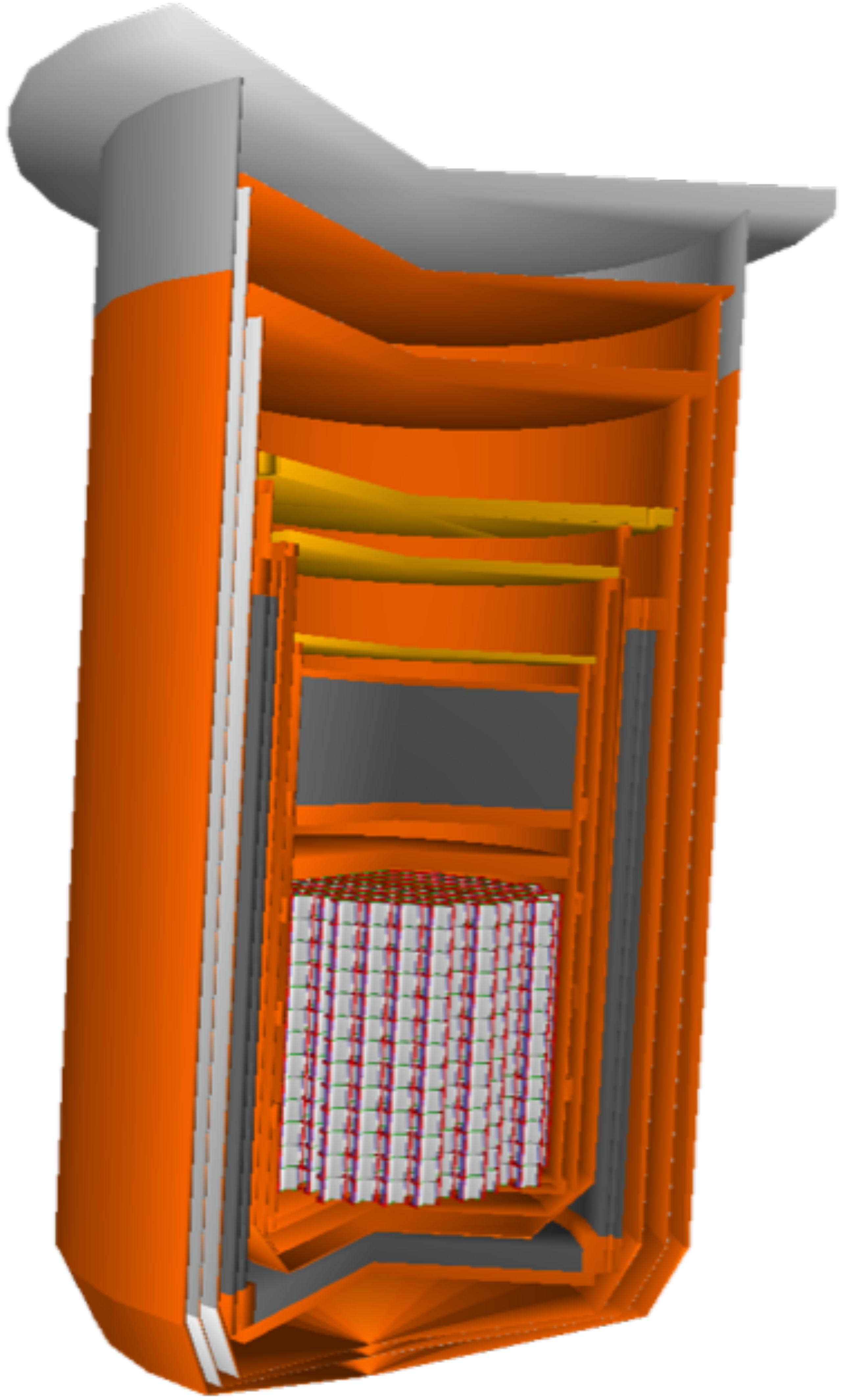
- Resolution of 6.5 keV @ 2615 keV
- No background events in ROI
- $T_{1/2} > 3.0\times10^{23}$ yr





CUPID Plans

- Use CUORE infrastructure
- $Li_2{}^{100}MoO_4$ scintillating crystals
- Opportunity to explore more isotopes
  - **Te**O_2
  - Zn**Se**
  - Li_2**Mo**O_4
  - **Cd**WO_4
- Modest cost compared to the other next generation experiments
- Schedule driven by ^{100}Mo enrichment (expected ~4 years)
- TDR and construction readiness for the end of 2021
- Pre-CDR available arXiv:1907.09376



CUPID Schematic

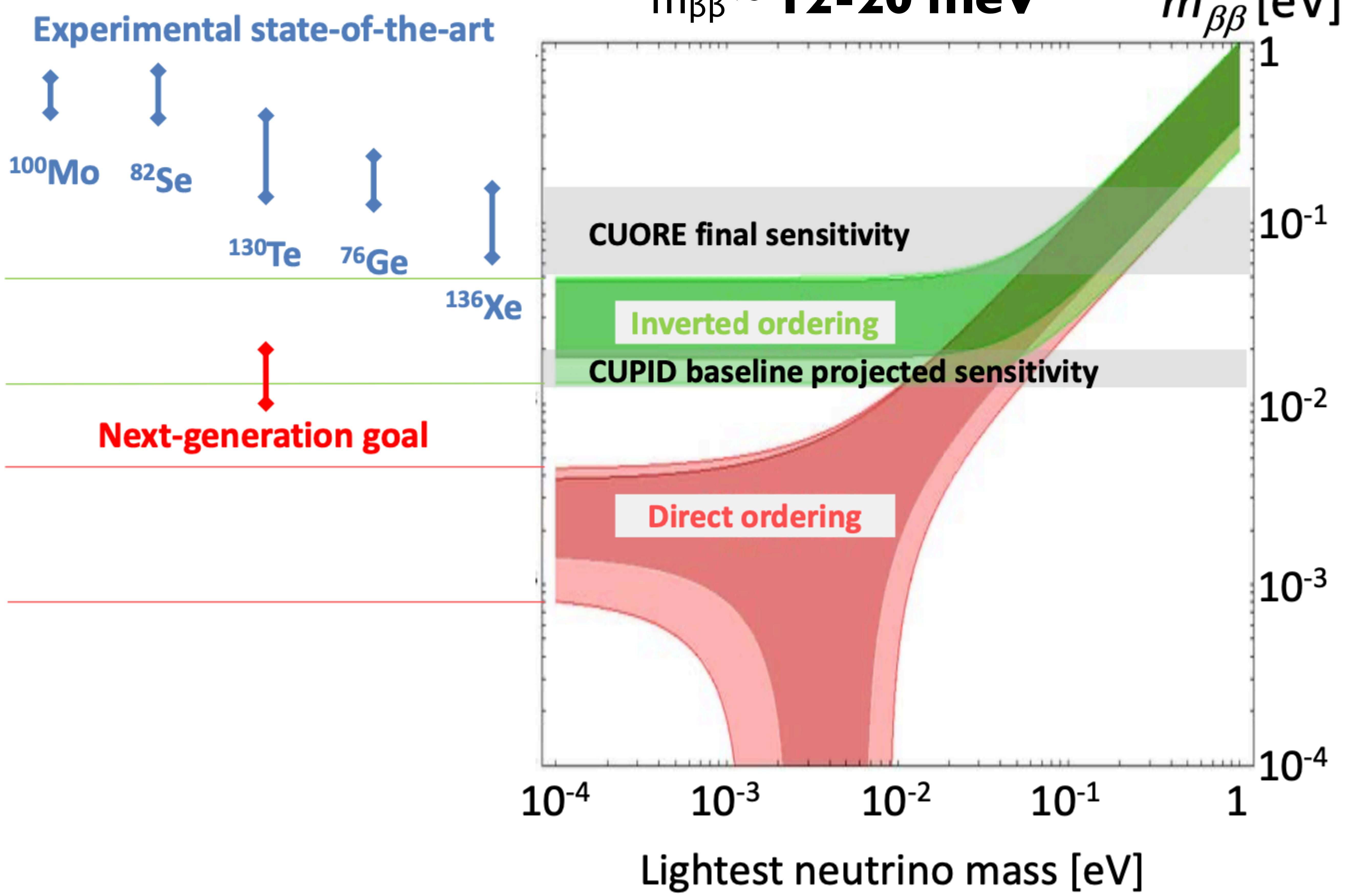
CUPID Sensitivity

CUPID Baseline:

- Mass: 472 kg (**253 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr

$T_{1/2}$ ~**10^{27} yrs**

$m_{\beta\beta}$ ~ **12-20 meV**



CUPID Sensitivity

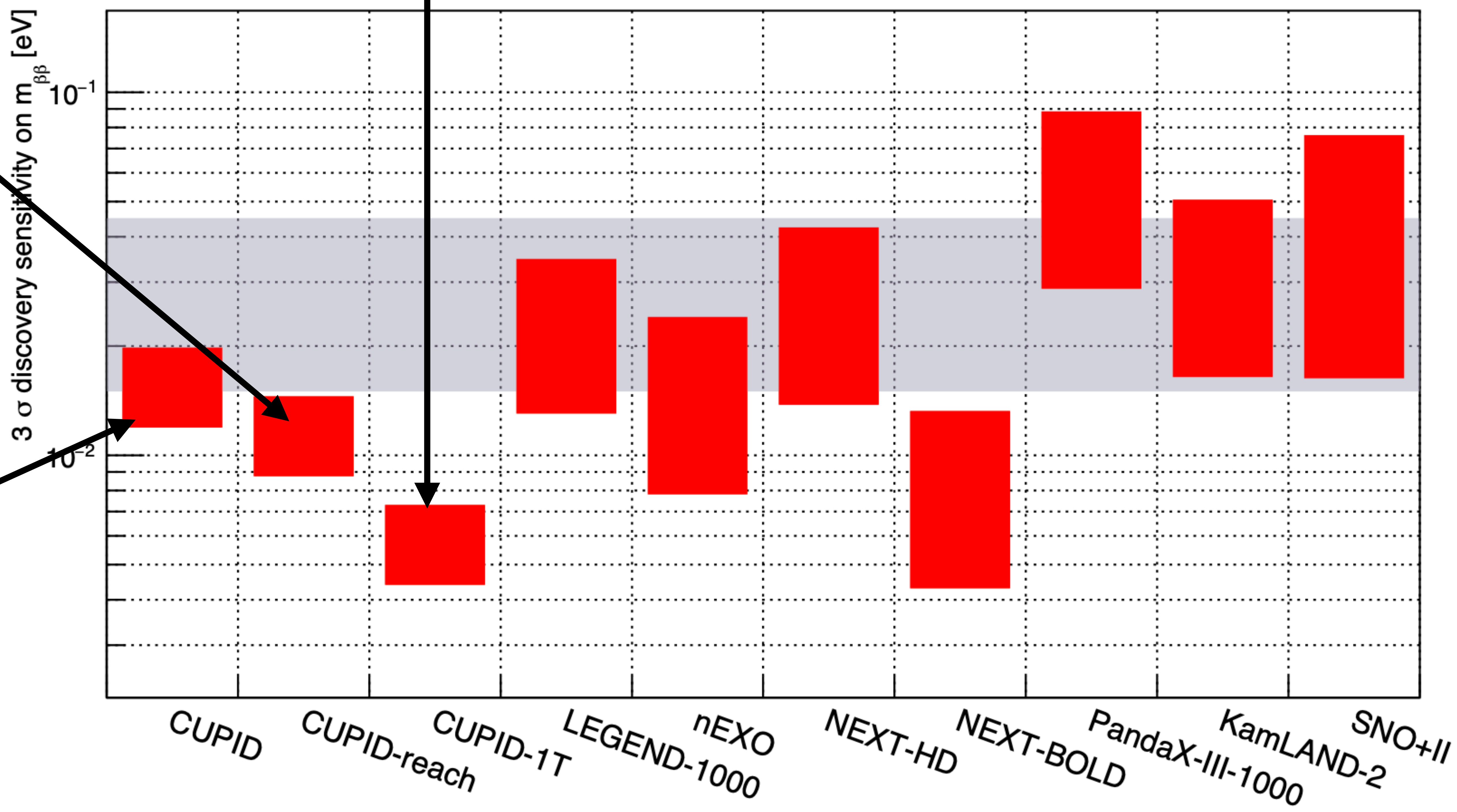
CUPID Baseline:

- Mass: 472 kg (**253 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr

Ultimate bolometer sensitivity:
1000 kg of ^{100}Mo
Discovery sensitivity $T_{1/2} > 8\times10^{27}$ yr (3σ)

More R&D for further background reduction by radio purity and higher bandwidth sensors
Discovery sensitivity $T_{1/2} > 2\times10^{27}$ yr (3σ)

Conservative (Can build today)
Discovery sensitivity $T_{1/2} > 1.1\times10^{27}$ yr (3σ)



Summary

- Large scale calorimetric approach to search for 0νββ demonstrated using CUORE
- Ton scale cryogenic infrastructure and instrumentation demonstrated
- Excellent energy resolution and background reduction demonstrated using CUORE
- CUPID will perform one of the most sensitive searches for 0νββ

CUORE Details

Bayes theorem: $P\left(\vec{\theta}|\vec{E}\right) = \dfrac{\mathcal{L}\left(\vec{E}|\vec{\theta}\right)\cdot\pi\left(\vec{\theta}\right)}{\int_\Omega \mathcal{L}\left(\vec{E}|\vec{\theta}\right)\cdot\pi\left(\vec{\theta}\right)d\vec{\theta}}$

Likelihood: $\mathcal{L}\left(\vec{E}|\vec{\theta}\right) = \prod_{dataset}\prod_{channel}\left[\frac{e^{-\lambda}\lambda^n}{n!}\prod_{event\ i}\left(\frac{s}{\lambda}pdf_{0\nu\beta\beta}\left(E_i|\vec{\theta}\right)+\frac{c}{\lambda}pdf_{^{60}Co}\left(E_i|\vec{\theta}\right)+\frac{b}{\lambda}\frac{1}{\Delta E}\right)\right]$

Expectation value: $\lambda = s + c + b$

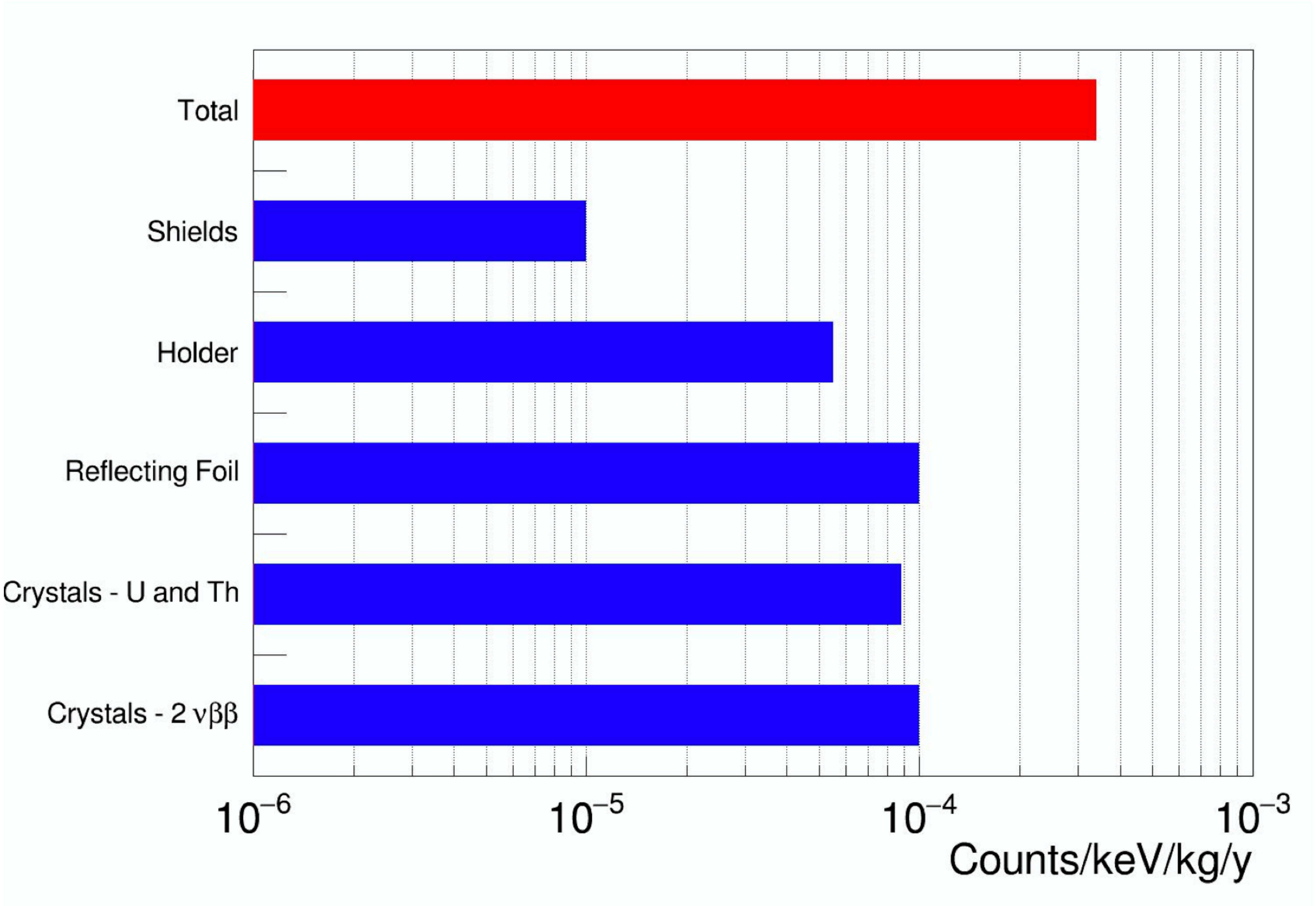
Width of fit region: ΔE

Systematics implemented as nuisance parameters

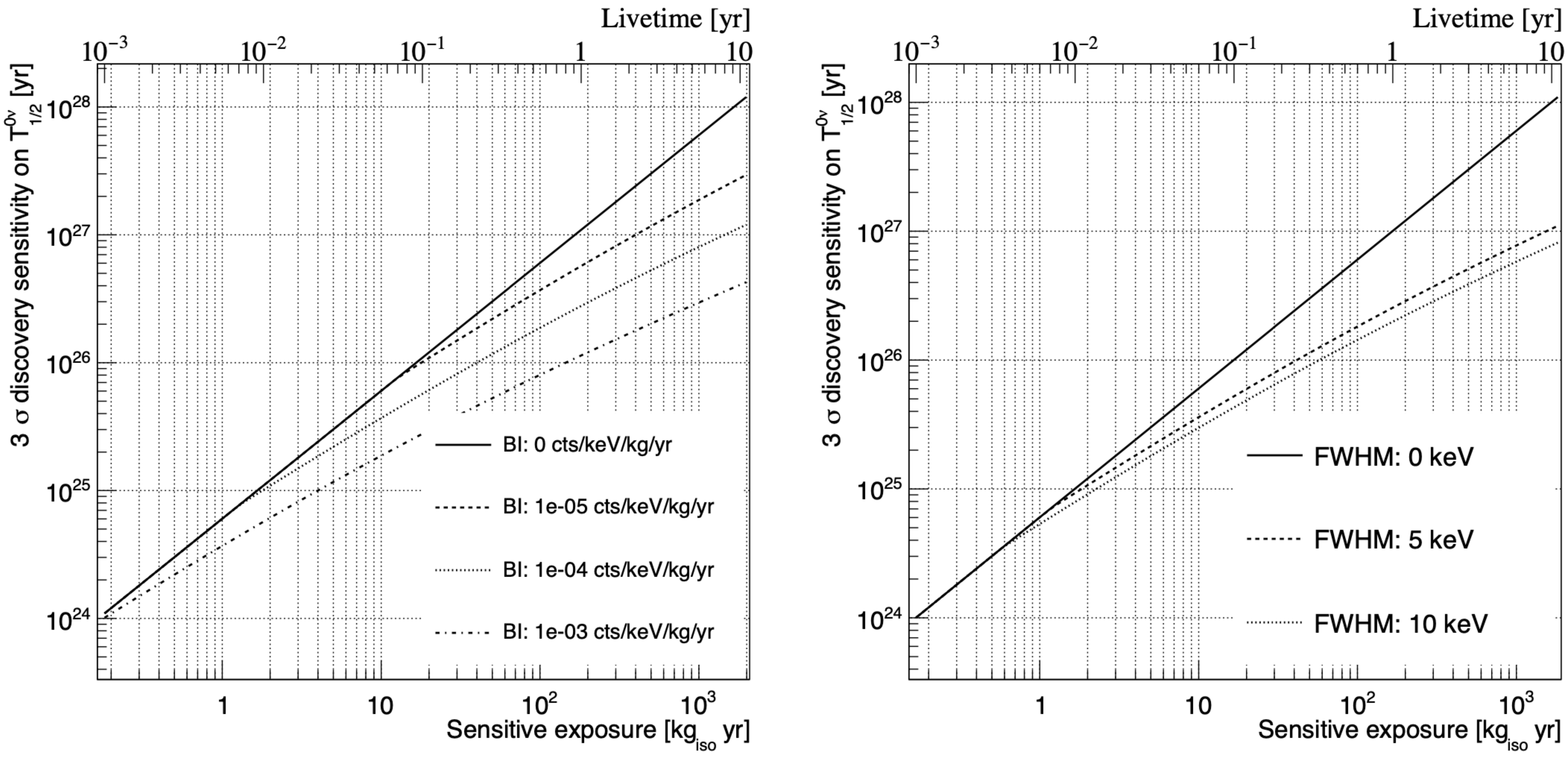
Parameter	Dependence	Method
Analysis efficiency I	Dataset	Gaussian
Analysis efficiency II	Global	Flat in [0.981, 1.021] range
Energy bias	Dataset	Fit residuals of peaks in physics spectrum from literature values with 2nd order polynomial
Energy resolution	Dataset	Fit ratio of FWHM in physics and calibration data with 2nd order polynomial
$Q_{\beta\beta}$	Global	Gaussian, 2527.518(13) keV
^{130}Te isotopic fraction	Global	Gaussian, 34.1668(16)%

Fit parameter systematics		
Systematic	Prior	Effect on $\hat{\Gamma}_{0\nu}$
Total analysis efficiency I	Gaussian	0.01%
Total analysis efficiency II	Uniform	0.04%
Containment efficiency	Gaussian	0.01%
Energy and resolution scaling	Multivariate	0.02%
$Q_{\beta\beta}$	Gaussian	0.02%
Isotopic fraction	Gaussian	0.02%

CUPID Background



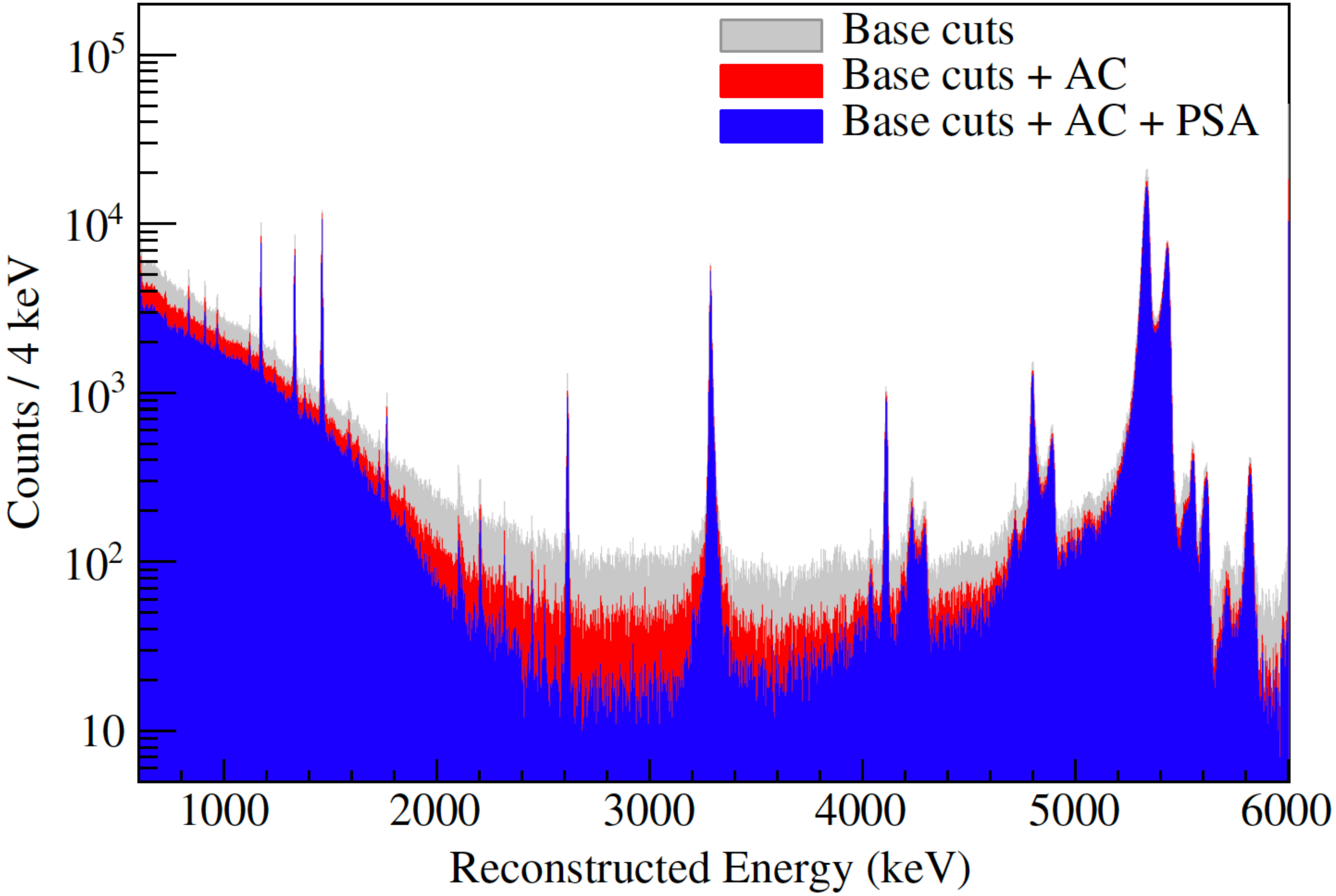
CUPID Sensitivity



Mass Measurement Paradigms: Summary

Method	Measurable mass term	Current limit
Neutrino oscillations	$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$	$\Sigma > 98$ meV(68meV) for IO(NO)
Beta decay measurements	$m_\beta = \sqrt{\|U_{ei}\|^2 m_i^2}$	$m_\beta < 1100$ meV $\Sigma < 3000$ meV
Cosmological models	$\Sigma = m_1 + m_2 + m_3$	$\Sigma < 120$ meV
Double beta decay	$\langle m_{\beta\beta} \rangle = \left\| \sum_j m_j U_{ej}^2 \right\|$	

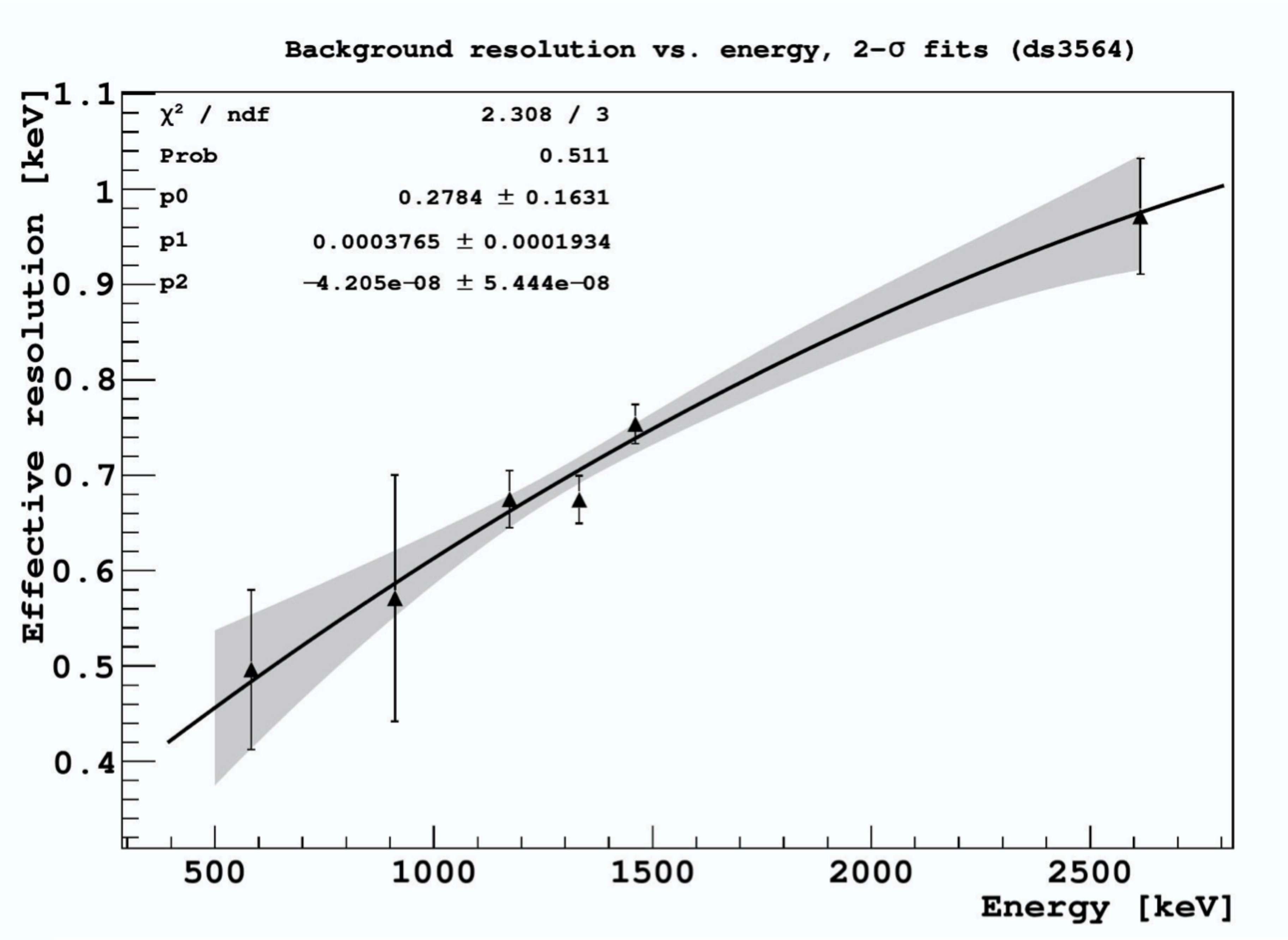
Spectrum

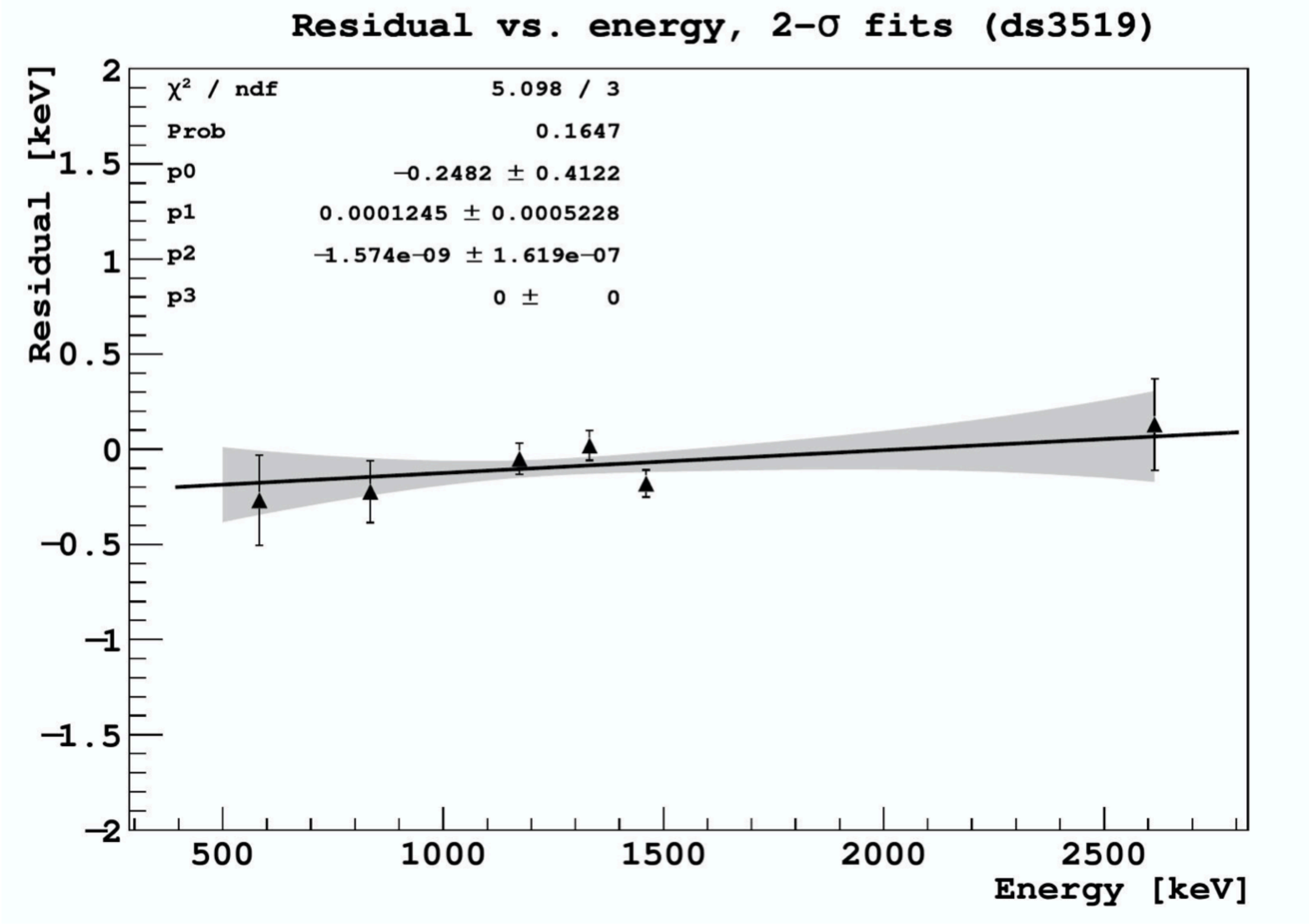


Base cuts
Base cuts + AC
Base cuts + AC + PSA
Counts / 4 keV
10^5
10^4
10^3
10^2
10
1000
2000
3000
4000
5000
6000
Reconstructed Energy (keV)

Line shape fit

Tower-Dataset Global Parameters	Channel-Dataset-Specific Parameters
Flat background size	Photopeak Q-value
Compton background size	Photopeak subpeak sizes and positions
X-ray Escape and Coincidence peak sizes	Peak resolution (σ used in each Gaussian)
2615 - 511 + 583 peak size and position	





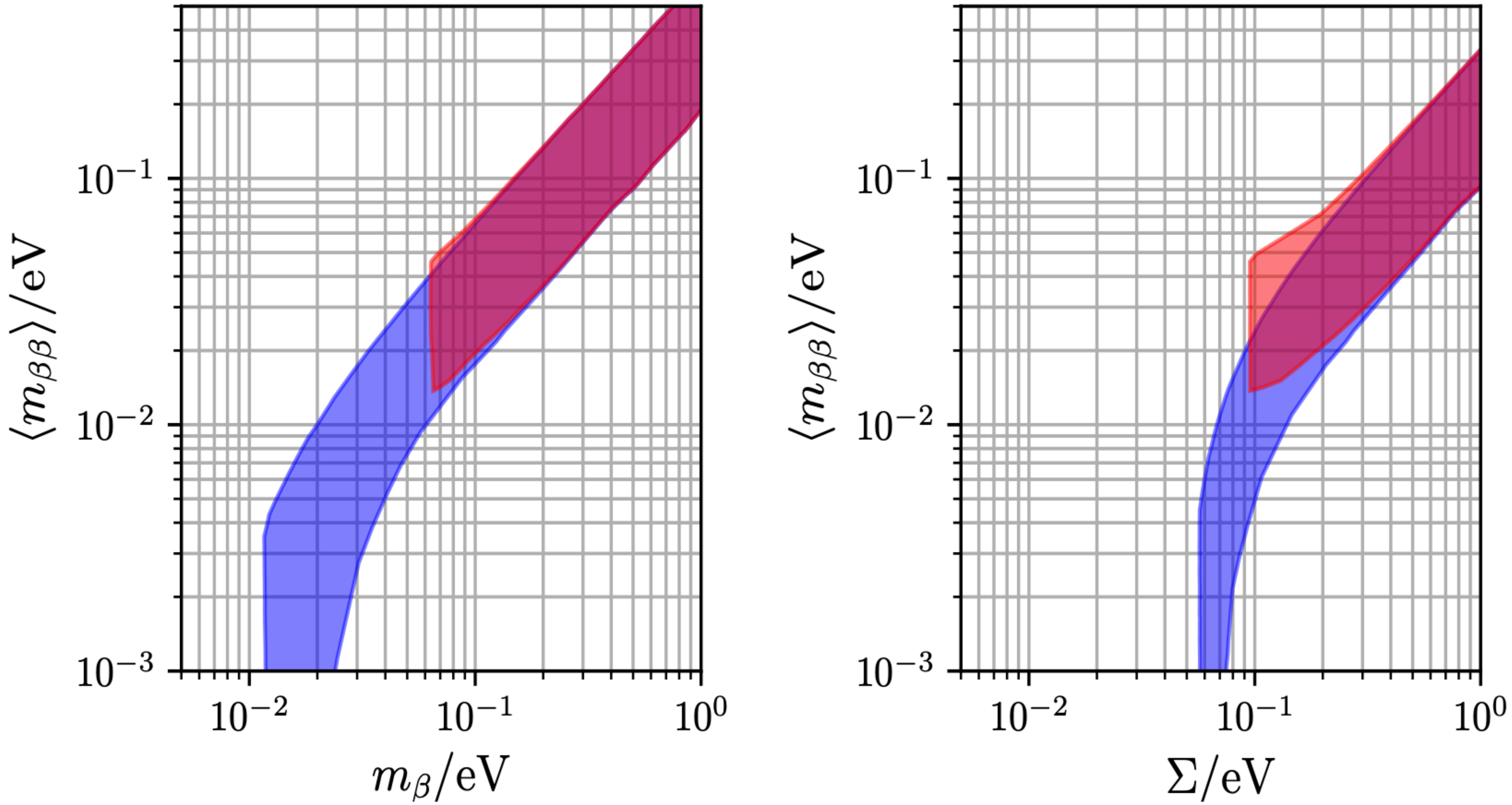
Cooling power

Table 1
Cooling power budgeted for the calibration system at all thermal stages of the cryostat.

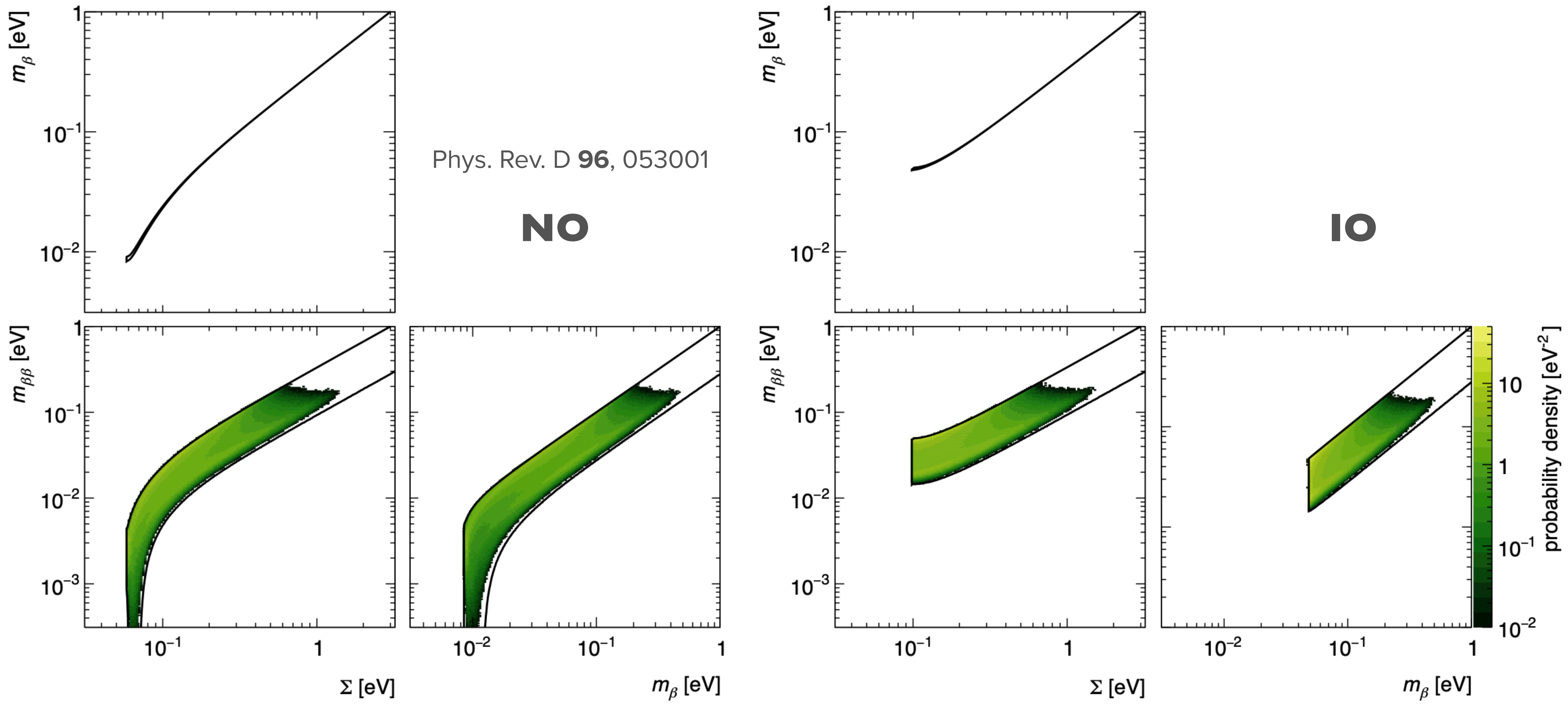
Thermal stage	Available cooling power
40 K	1 W
4 K	300 mW
600 mK	600 μW
50 mK	1 μW
10 mK	1 μW

Neutrino Masses

annurev-nucl-101918-023407



Neutrino Masses



Statistical Test

Statistical approach to 0νββ decay search

Bayes theorem: $P\left(\vec{\theta}|\vec{E}\right) = \frac{\mathcal{L}\left(\vec{E}|\vec{\theta}\right) \cdot \pi\left(\vec{\theta}\right)}{\int_{\Omega} \mathcal{L}\left(\vec{E}|\vec{\theta}\right) \cdot \pi\left(\vec{\theta}\right) d\vec{\theta}}$

Signal component

Background components

Likelihood: $\mathcal{L}\left(\vec{E}|\vec{\theta}\right) = \prod_{dataset} \prod_{channel} \left[\frac{e^{-\lambda}\lambda^{n}}{n!} \prod_{event\ i} \left(\frac{s}{\lambda} pdf_{0\nu\beta\beta}\left(E_i|\vec{\theta}\right) + \frac{c}{\lambda} pdf_{^{60}Co}\left(E_i|\vec{\theta}\right) + \frac{b}{\lambda}\frac{1}{\Delta E} \right) \right]$

Expectation value: λ=s+c+b

Width of fit region: ΔE

Systematics implemented as nuisance parameters

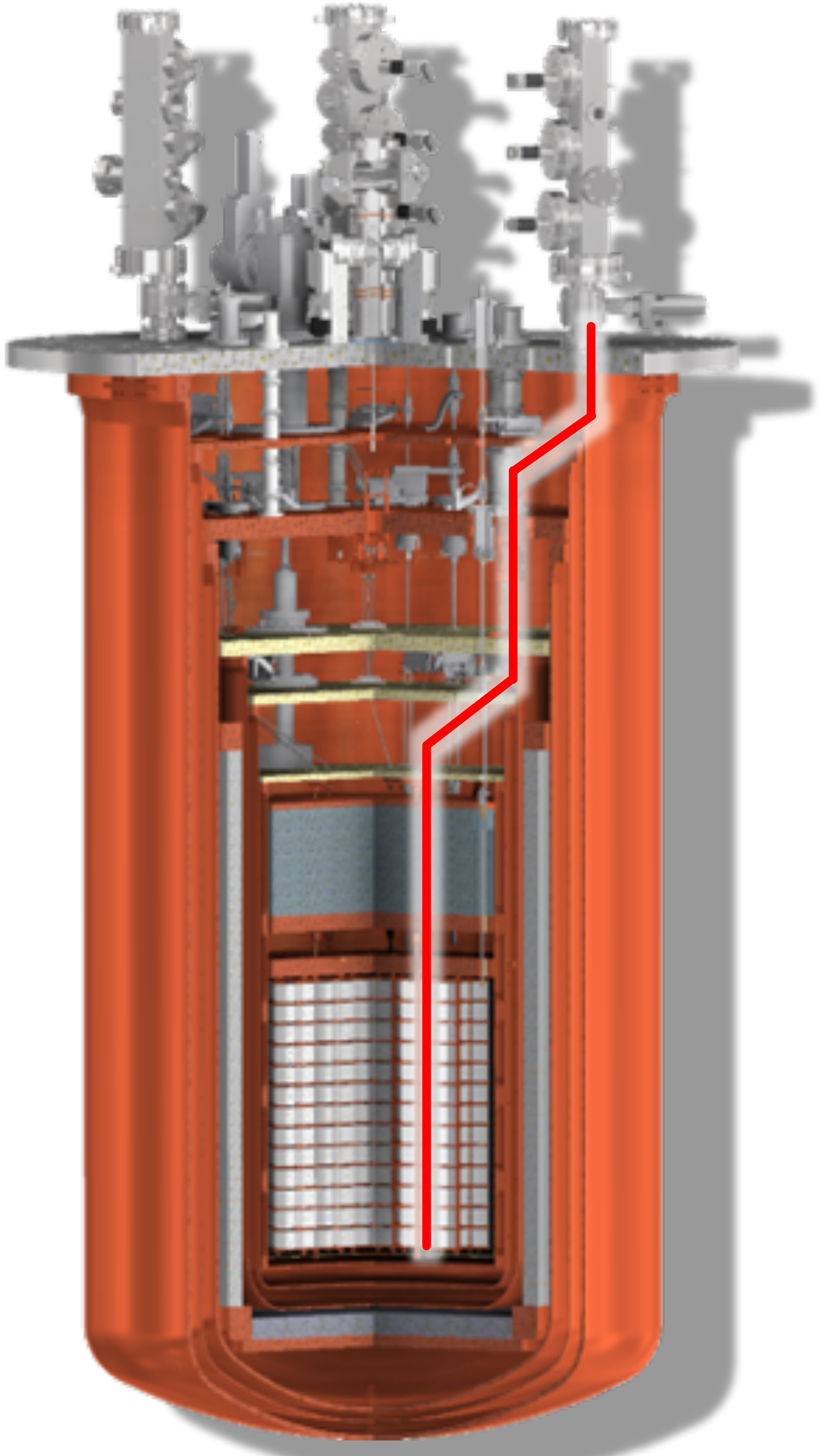
Parameter	Dependence	Method
Analysis efficiency I	Dataset	Gaussian
Analysis efficiency II	Global	Flat in [0.993, 1.007] range
Energy bias	Dataset	Fit residuals of peaks in physics spectrum from literature values with 2^{nd} order polynomial
Energy resolution	Dataset	Fit ratio of FWHM in physics and calibration data with 2^{nd} order polynomial
$Q_{\beta\beta}$	Global	Gaussian, 2527.518(13) keV
^{130}Te isotopic fraction	Global	Gaussian, 34.1668(16)%

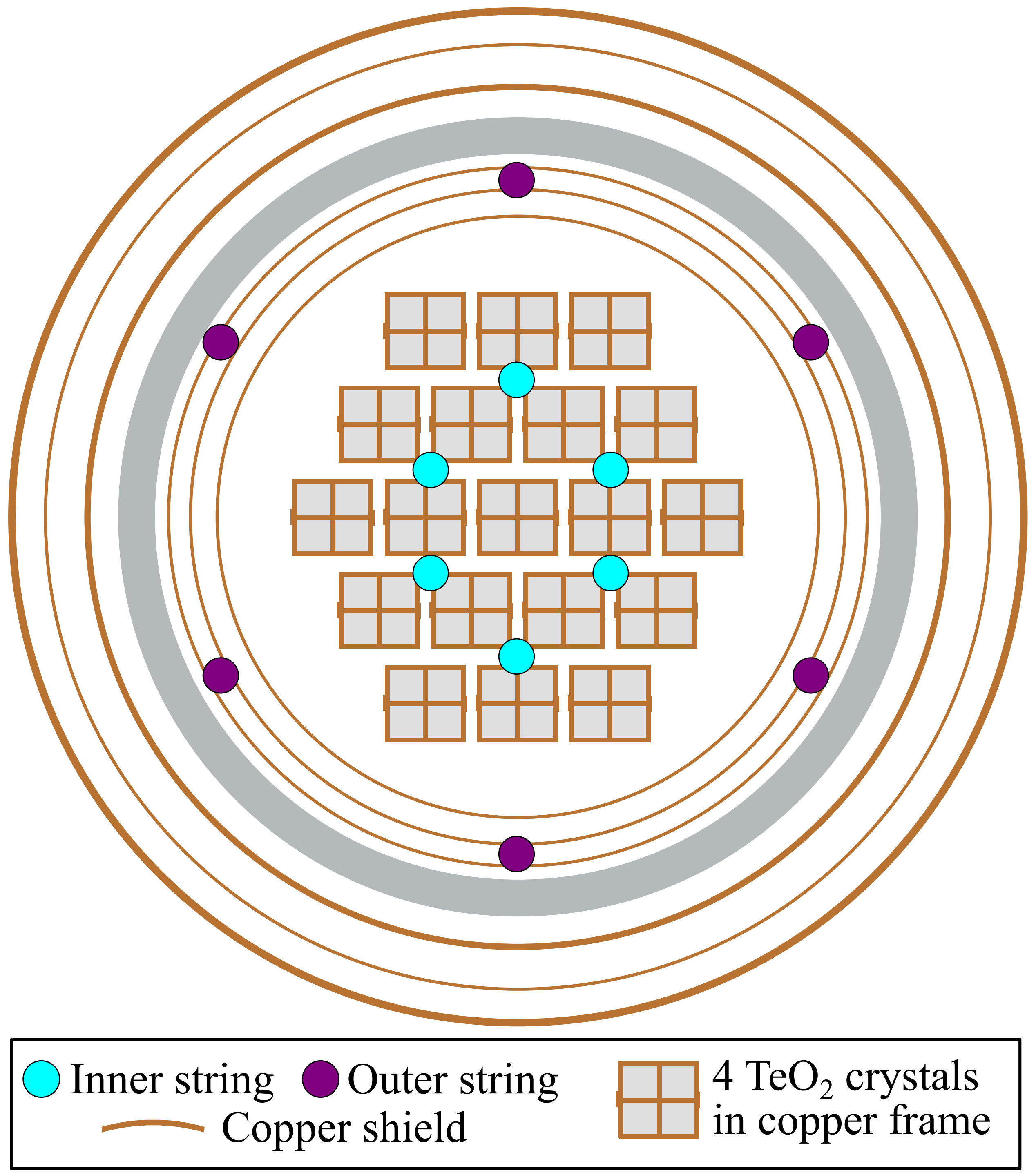
Contamination from tower components

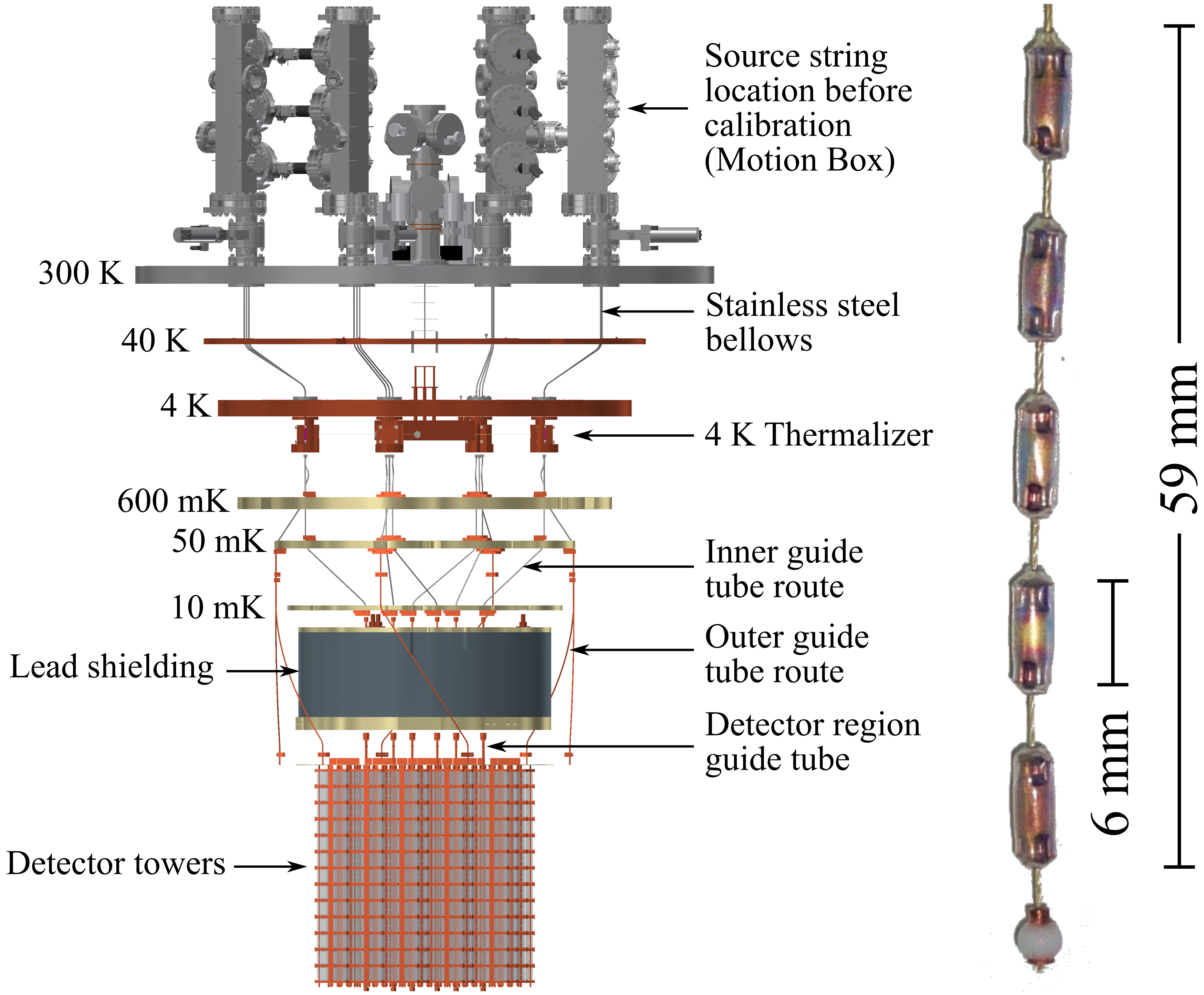
Component	Mass [g]	^{238}U contamination limit [g/g]	^{238}U contamination limit [bolo^{-1} yr^{-1}]	^{232}Th contamination limit [g/g]	^{232}Th contamination limit [bolo^{-1} yr^{-1}]
TeO_2 crystals	742 000	5×10^{-14}	10	2×10^{-13}	2000
Cu structure	70 000	5×10^{-12}	100	5×10^{-13}	500
PTFE holders	5500	2×10^{-12}	4	2×10^{-12}	100
Cu-PEN tape	3000	1×10^{-10}	100	4×10^{-10}	20 000
Ge thermistors	42	1×10^{-9}	20	1×10^{-9}	500
Si heaters	6.8	2×10^{-10}	0.5	8×10^{-11}	7
Au bonding wires	1.5	1×10^{-9}	0.6	1×10^{-8}	200
Glue	0.44	8×10^{-10}	0.1	2×10^{-10}	1

Table 3.1: Masses and upper limits on the bulk contamination levels of the CUORE detector tower components. All contamination data are limits at 90% C.L., expressed in grams of the contaminant per gram of the component and in decays per year per bolometer. Note that this is not a measure of the number of events actually recorded in the bolometers; it is just a metric to compare the magnitude of the possible contaminations, taking into account the different masses of the tower components and two different isotopes.

Detector Calibration System (DCS)

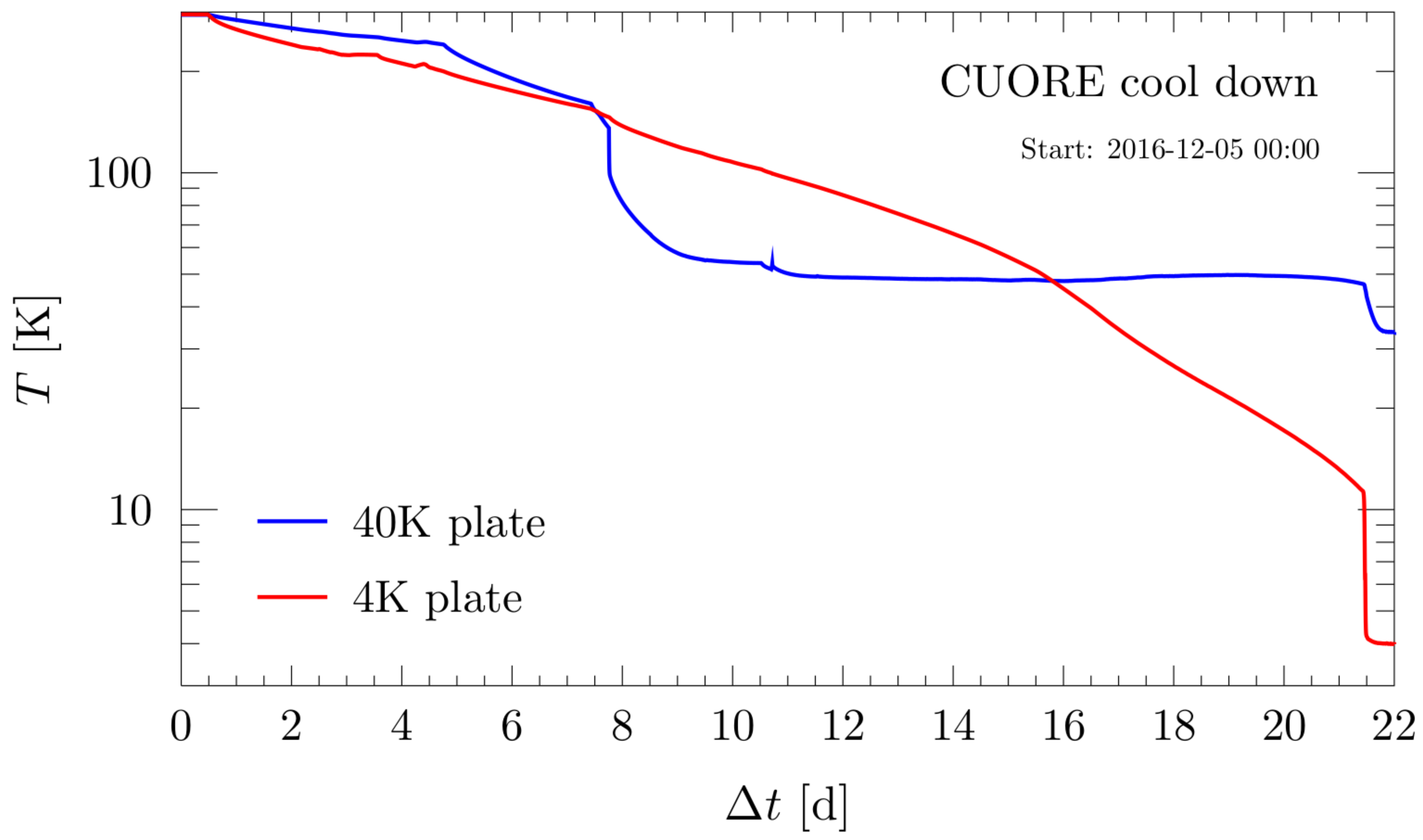


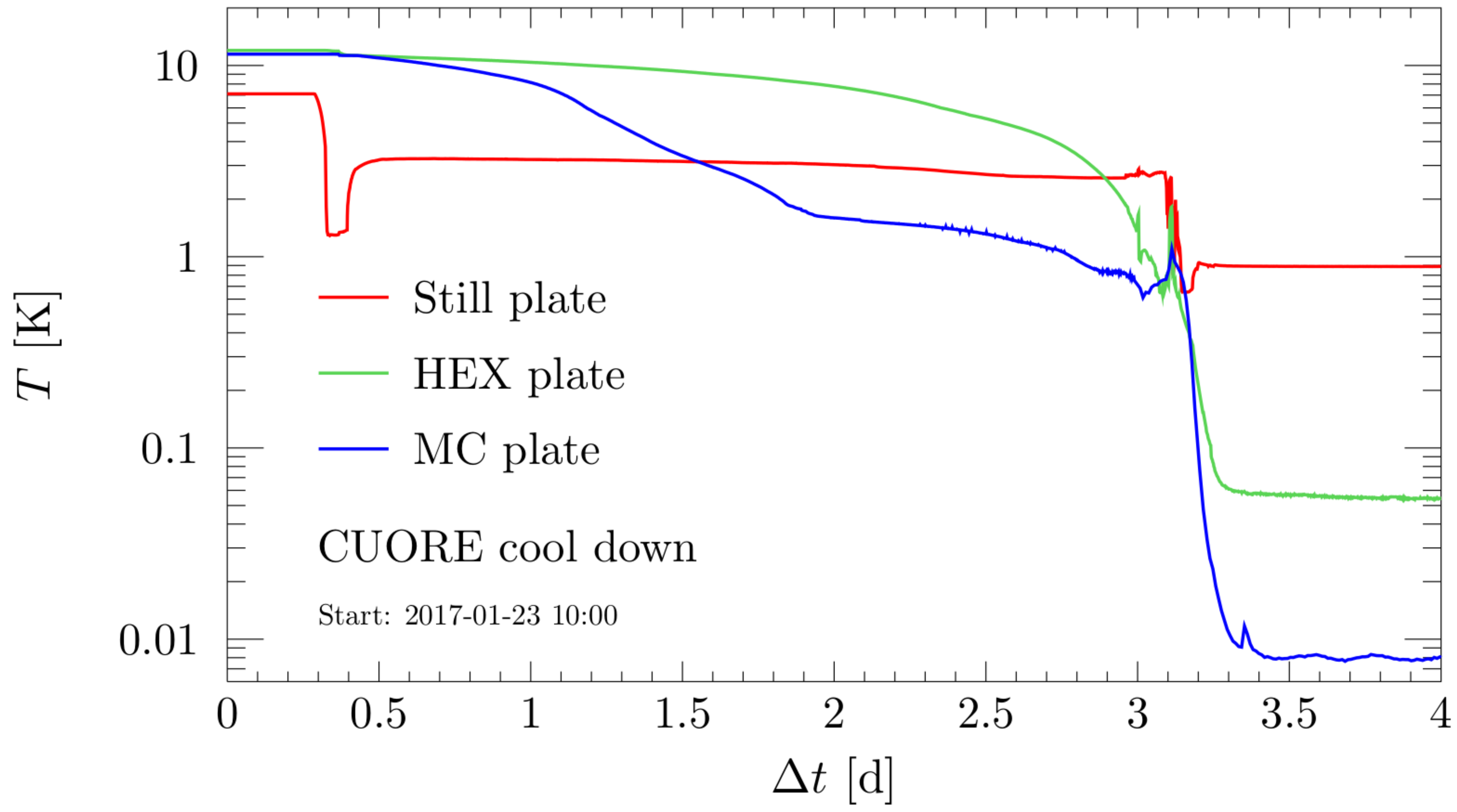




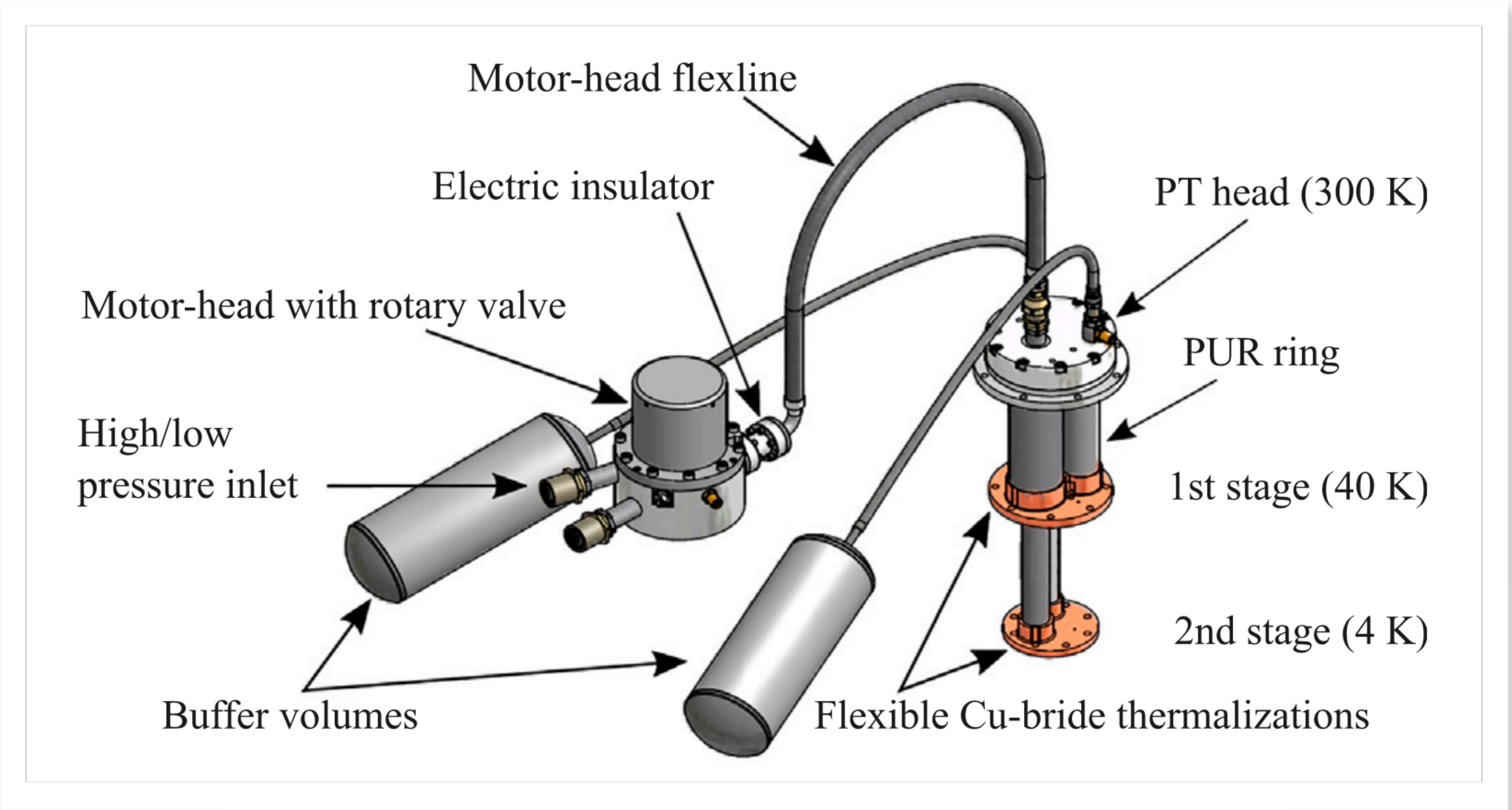
- Six ^{232}Th γ sources radioactive strings reaching down to 10 mK between detector towers

Cooling


CUORE cool down
Start: 2016-12-05 00:00
100
10
T [K]
40K plate
4K plate
0
2
4
6
8
10
12
14
16
18
20
22
Δt [d]


10
1
0.1
0.01
T [K]
Still plate
HEX plate
MC plate
CUORE cool down
Start: 2017-01-23 10:00
0
0.5
1
1.5
2
2.5
3
3.5
4
Δt [d]

Pulse tube


Motor-head flexline
Electric insulator
PT head (300 K)
Motor-head with rotary valve
PUR ring
High/low
pressure inlet
1st stage (40 K)
2nd stage (4 K)
Buffer volumes
Flexible Cu-bride thermalizations

Backgrounds in LNGS

- μ's: ~3 × 10-8 / (s·cm2)
- γ's: ~0.73 / (s·cm2)
- neutrons: 4 × 10^{-6} /(s·cm^2) below 10 MeV

Posterior