CUORE

Latest Results from the CUORE Experiment

Pranava Teja Surukuchi
(for the CUORE collaboration)

May 11, 2022

Yale

CoSSURF 2022

Wright Laboratory

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

- Hypothesized nuclear process
- If observed, it 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

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

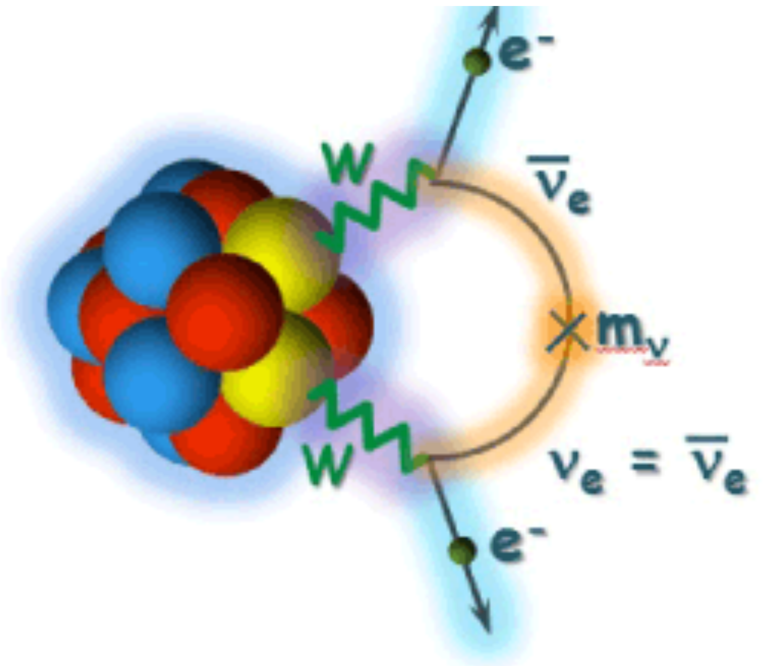
Nuclear Matrix elements

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

Phase space factor

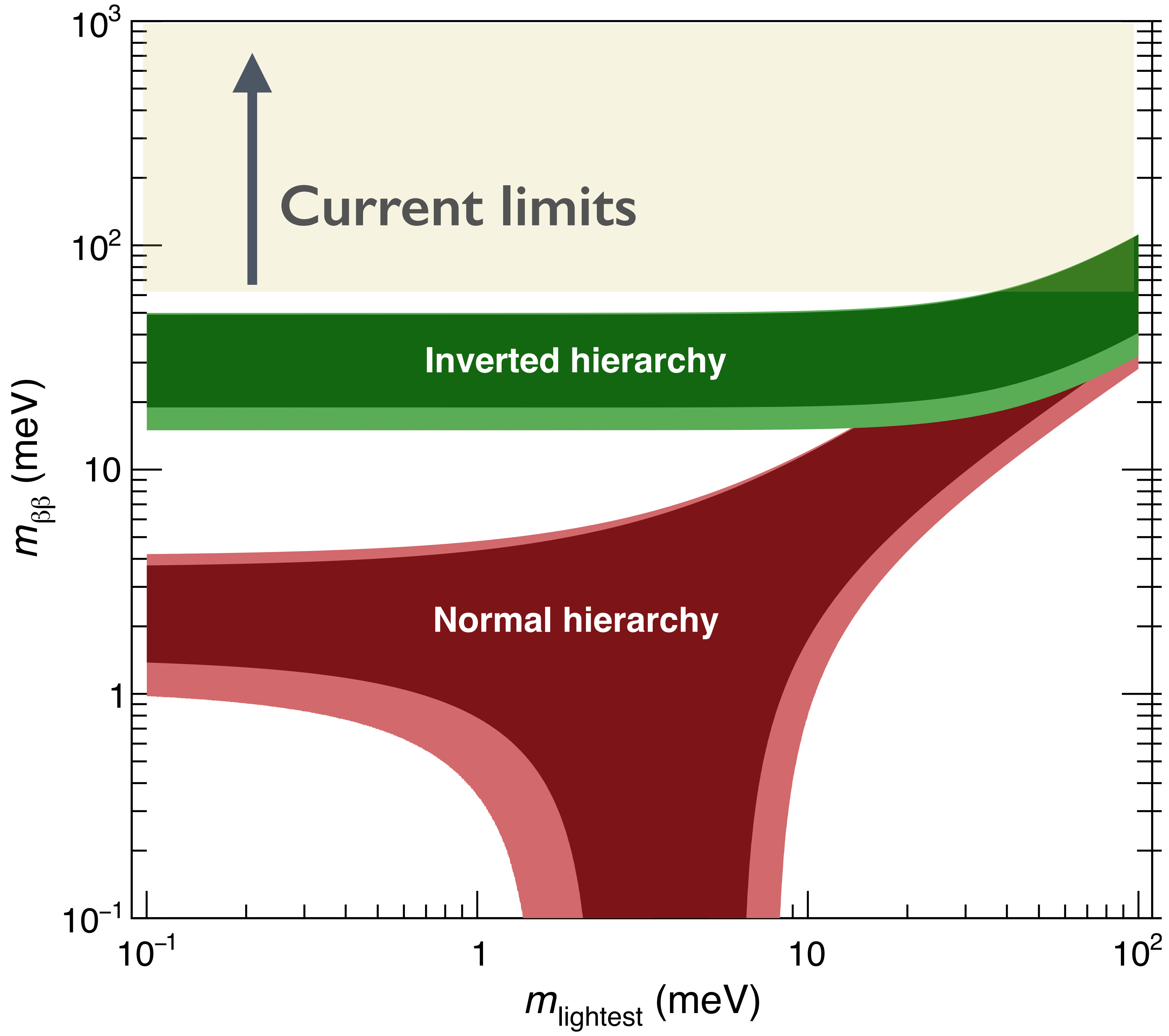
Effective neutrino mass

Important to observe $0\nu\beta\beta$ in multiple isotopes



Neutrinoless
double beta decay

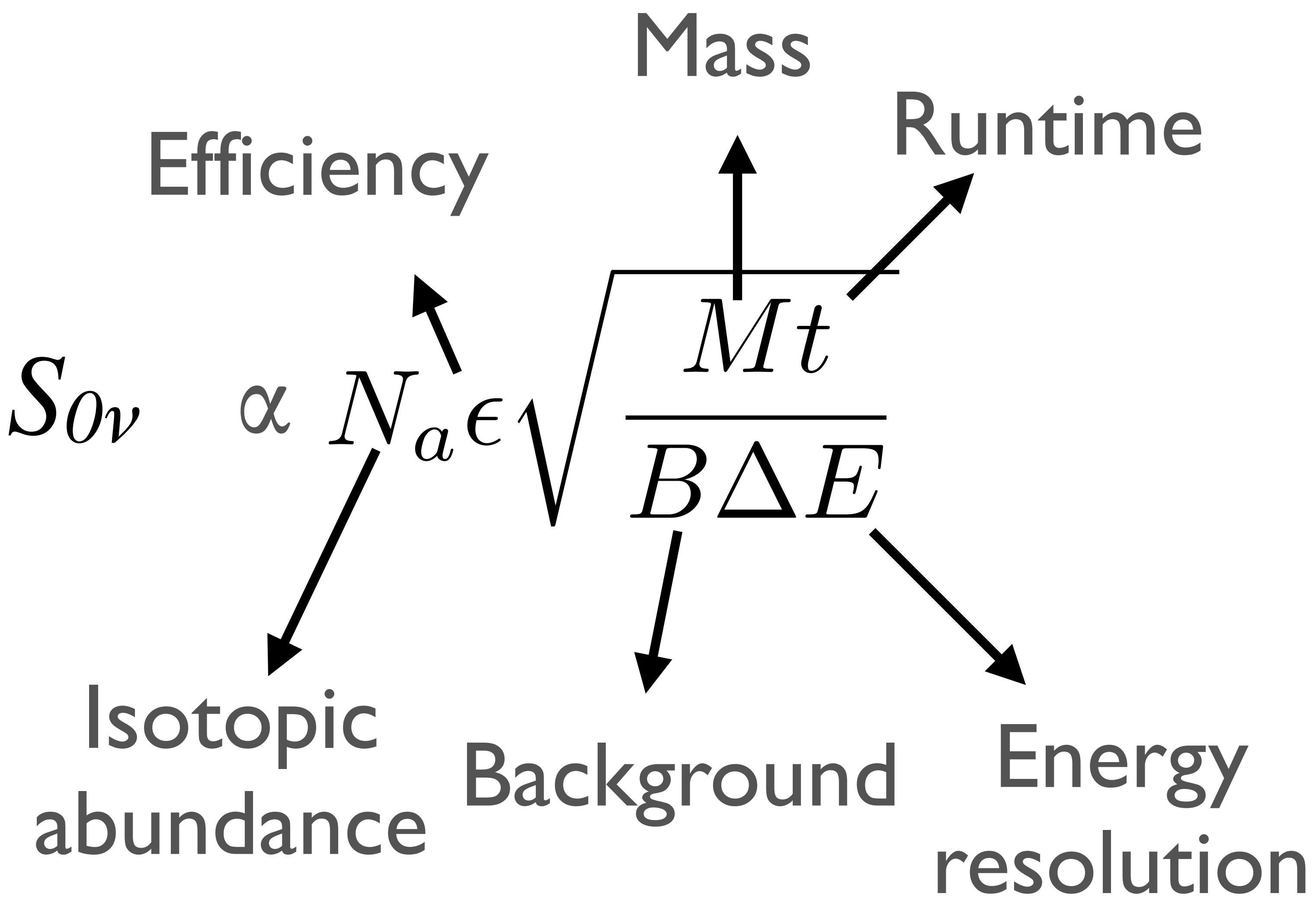
-Osaka university



Searching for $0\nu\beta\beta$

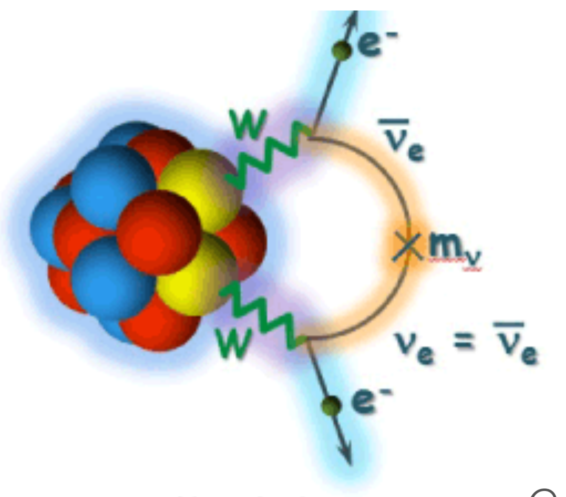
- A peak search at the Q value of the decay

Sensitivity in presence of BG:



$$S_{0\nu} \propto N_a \epsilon \sqrt{\frac{Mt}{B\Delta E}}$$

Resolution and backgrounds play important role in sensitivity



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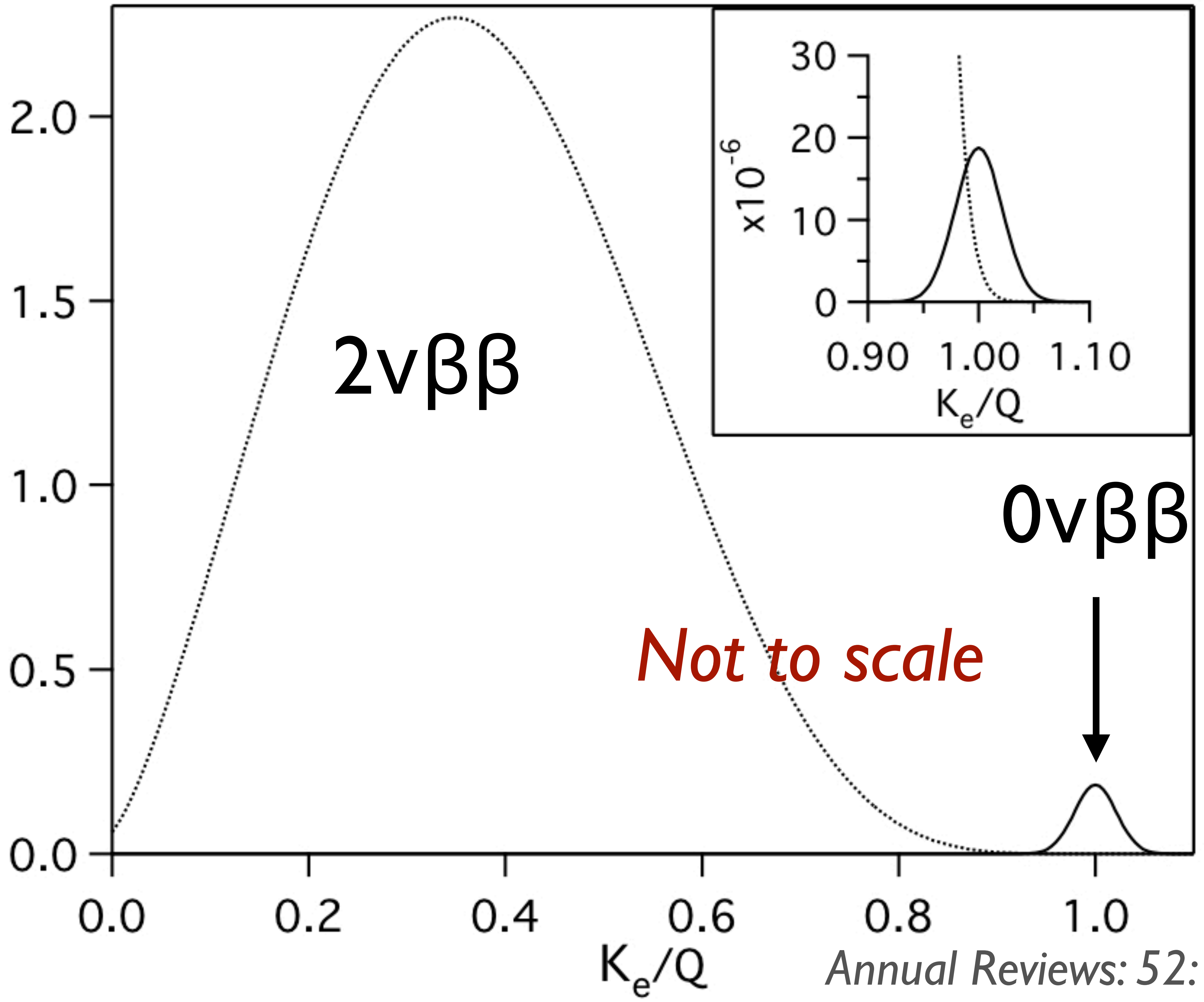
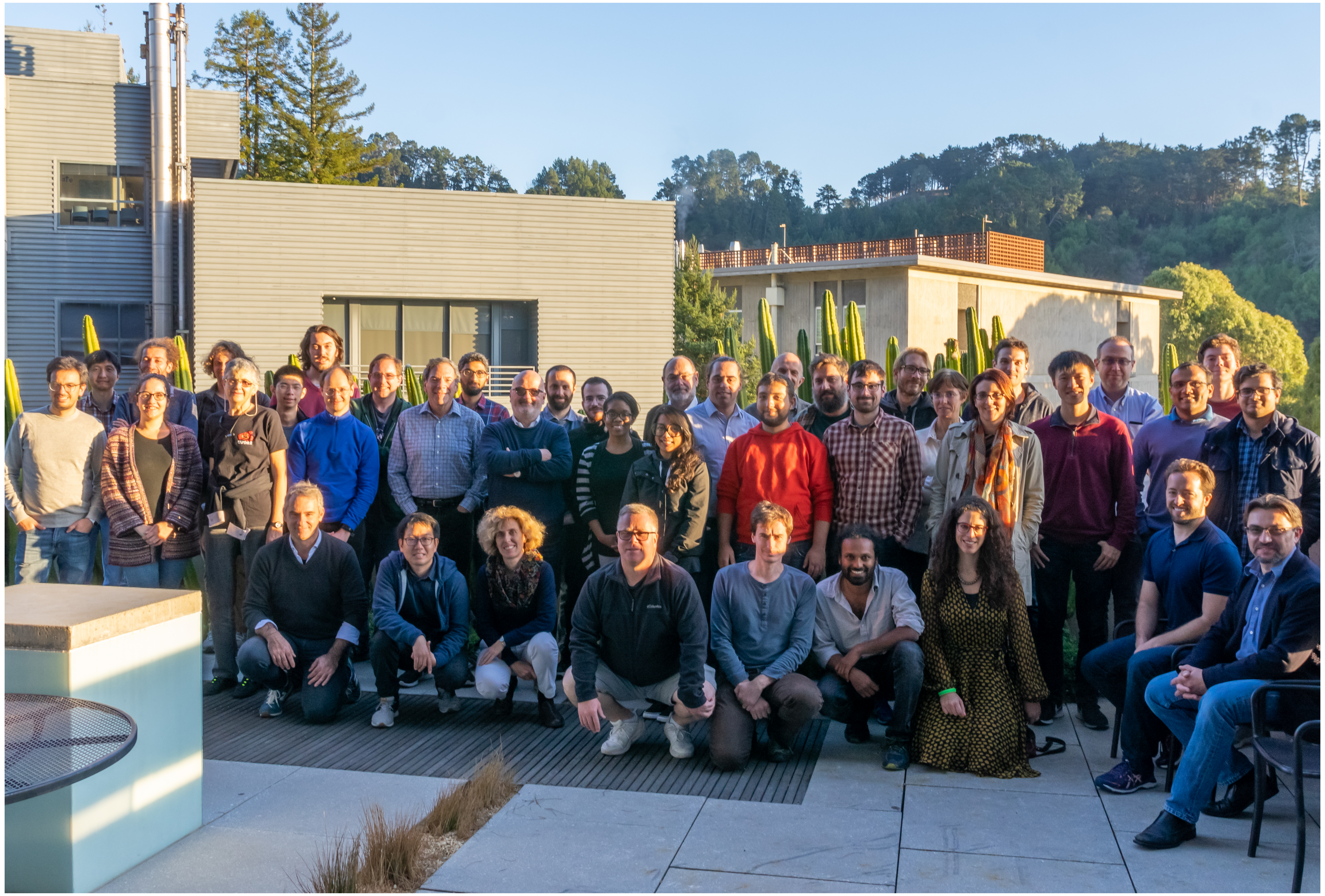


Not to scale

Annual Reviews: 52:115-151

CUORE Experiment



CUORE

Cryogenic Underground Observatory for Rare Events

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

$$N_a \epsilon \sqrt{\frac{Mt}{B \Delta E}}$$

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  - *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

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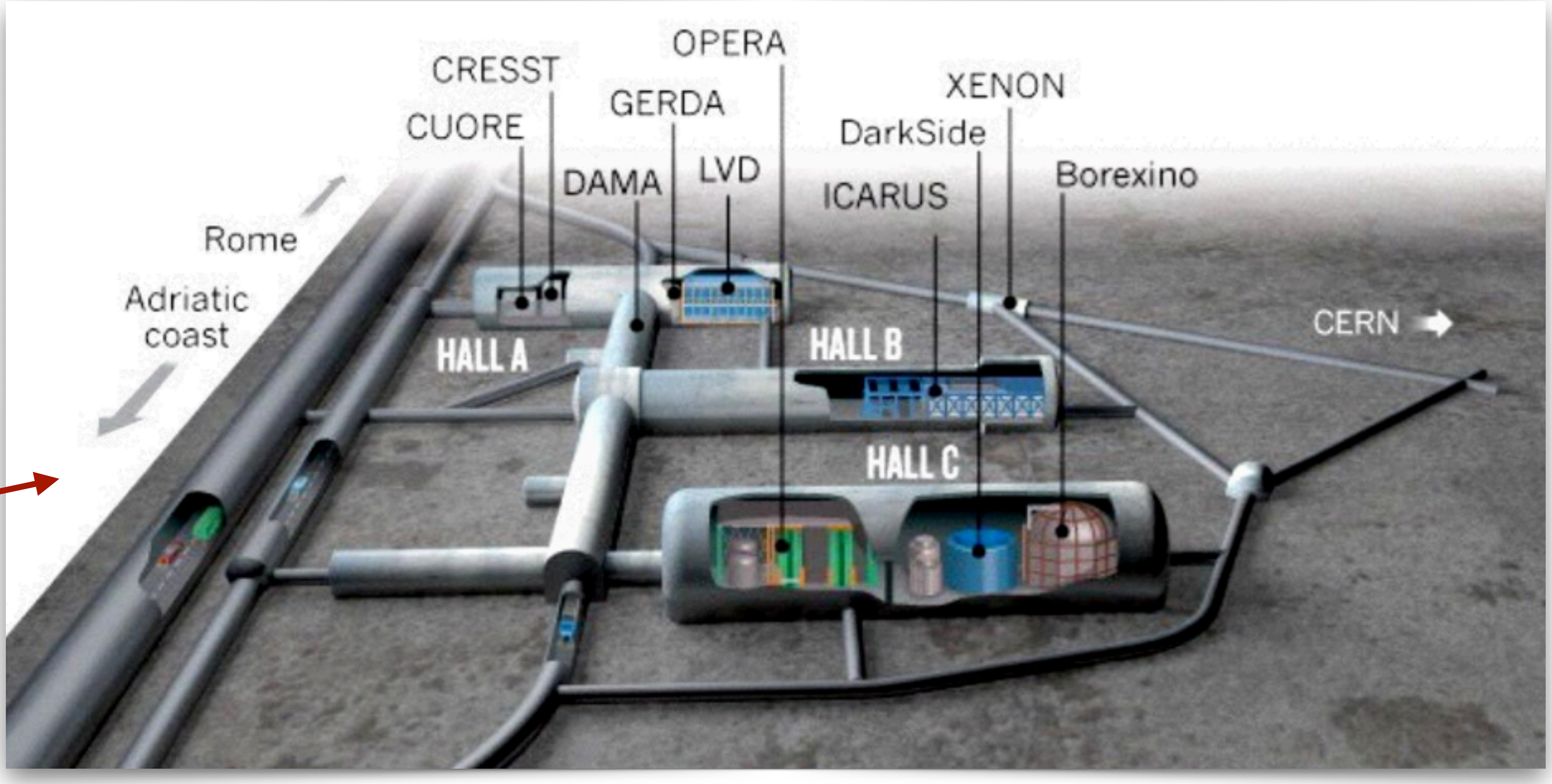
  - *Energy resolution:* Goal of 5 keV FWHM at $Q_{\beta\beta}$
  - High efficiency and duty cycle
- **Sensitivity:**
  - $T^{0\nu}_{1/2} \sim 9 \times 10^{25}$ yrs (90% C.L) in 5 yrs
  - $m_{\beta\beta} < 50\text{-}130$ meV

$$N_a \epsilon \sqrt{\frac{Mt}{B\Delta E}}$$

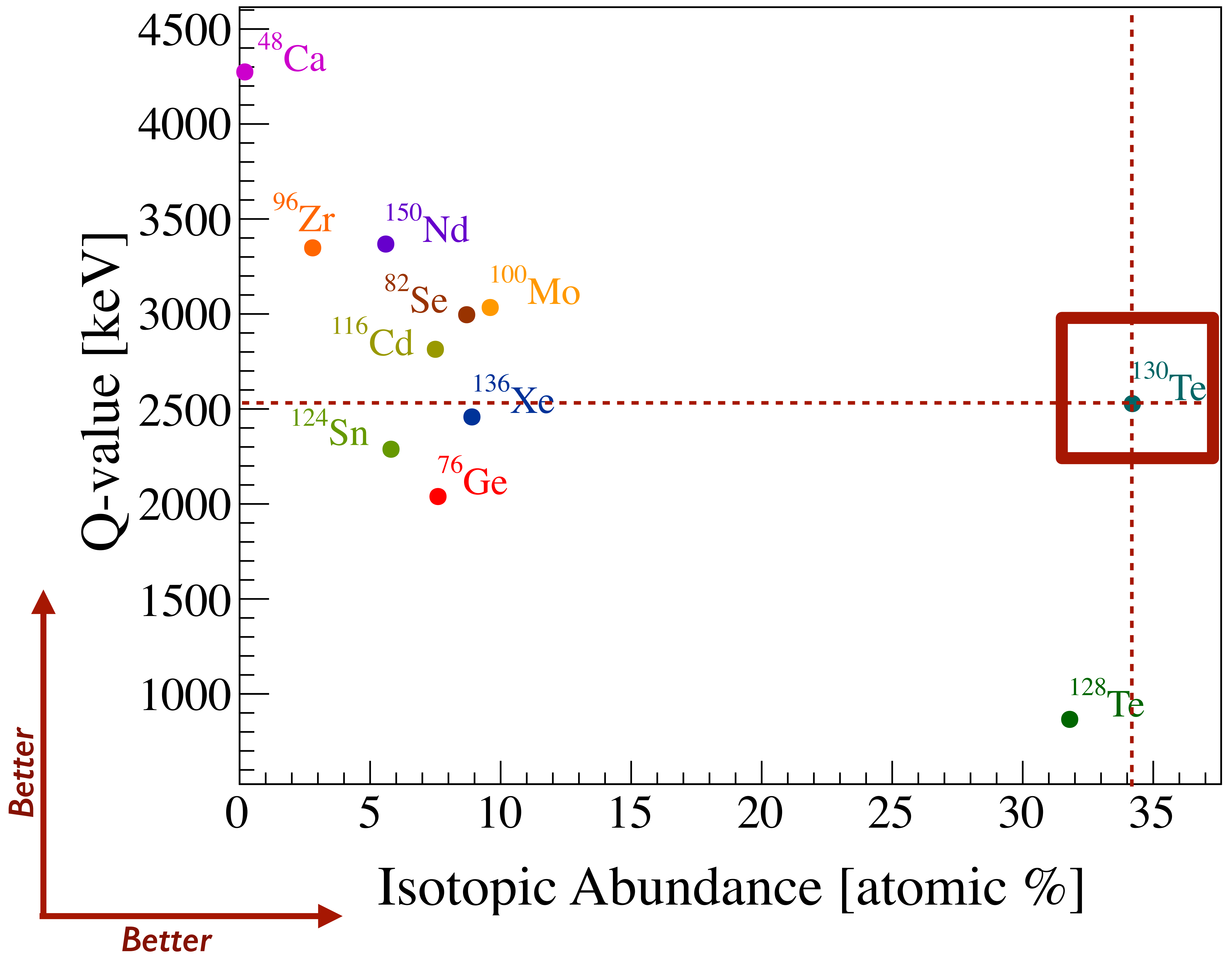
LNGS: Laboratori Nazionali del Gran Sasso

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



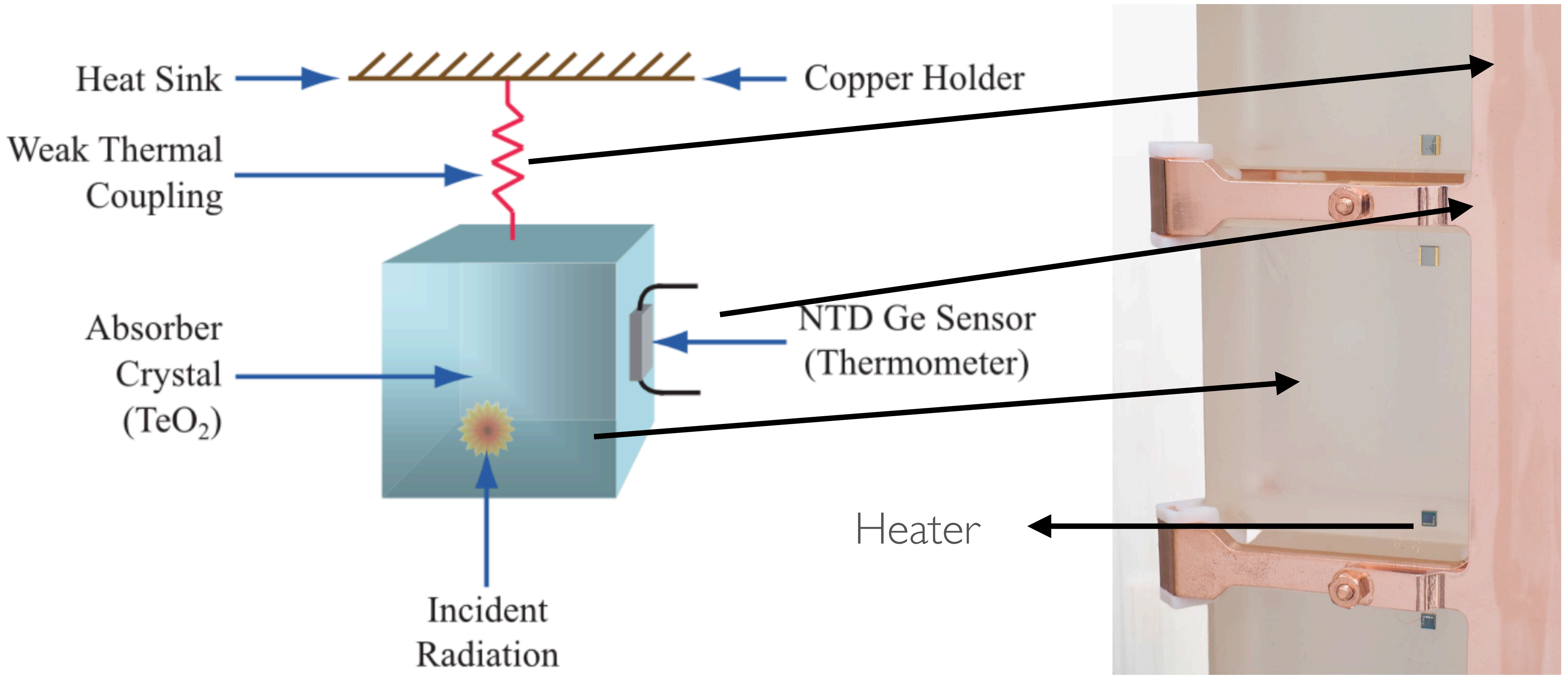
Isotope of Choice: ^{130}Te

- 34 % natural isotopic abundance
- $Q_{\beta\beta}$ (2528 keV)
  - Above most γ natural radioactivity
  - Low background from $2\nu\beta\beta$
- Isotope within the absorber
- Reproducible growth of high quality TeO_2 crystals with low contamination



Calorimetric Technique

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



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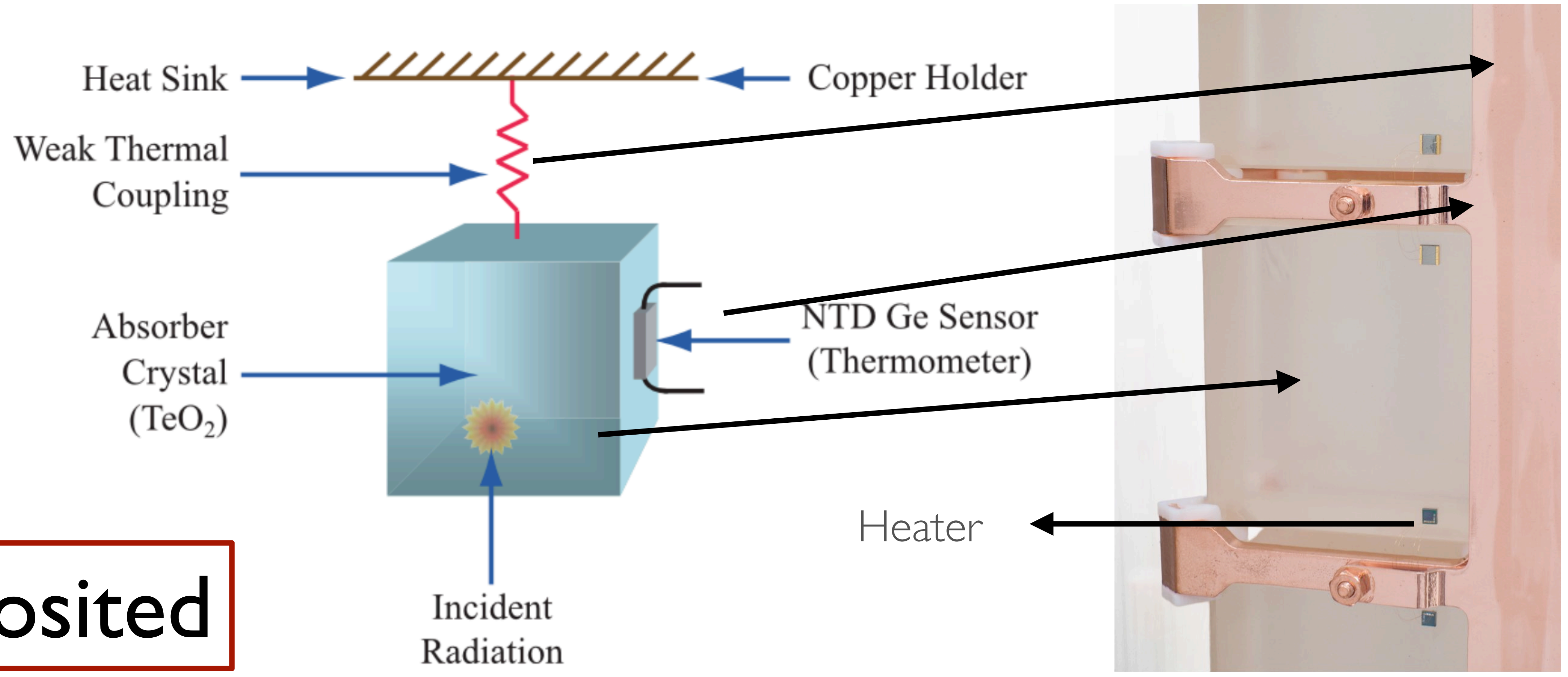
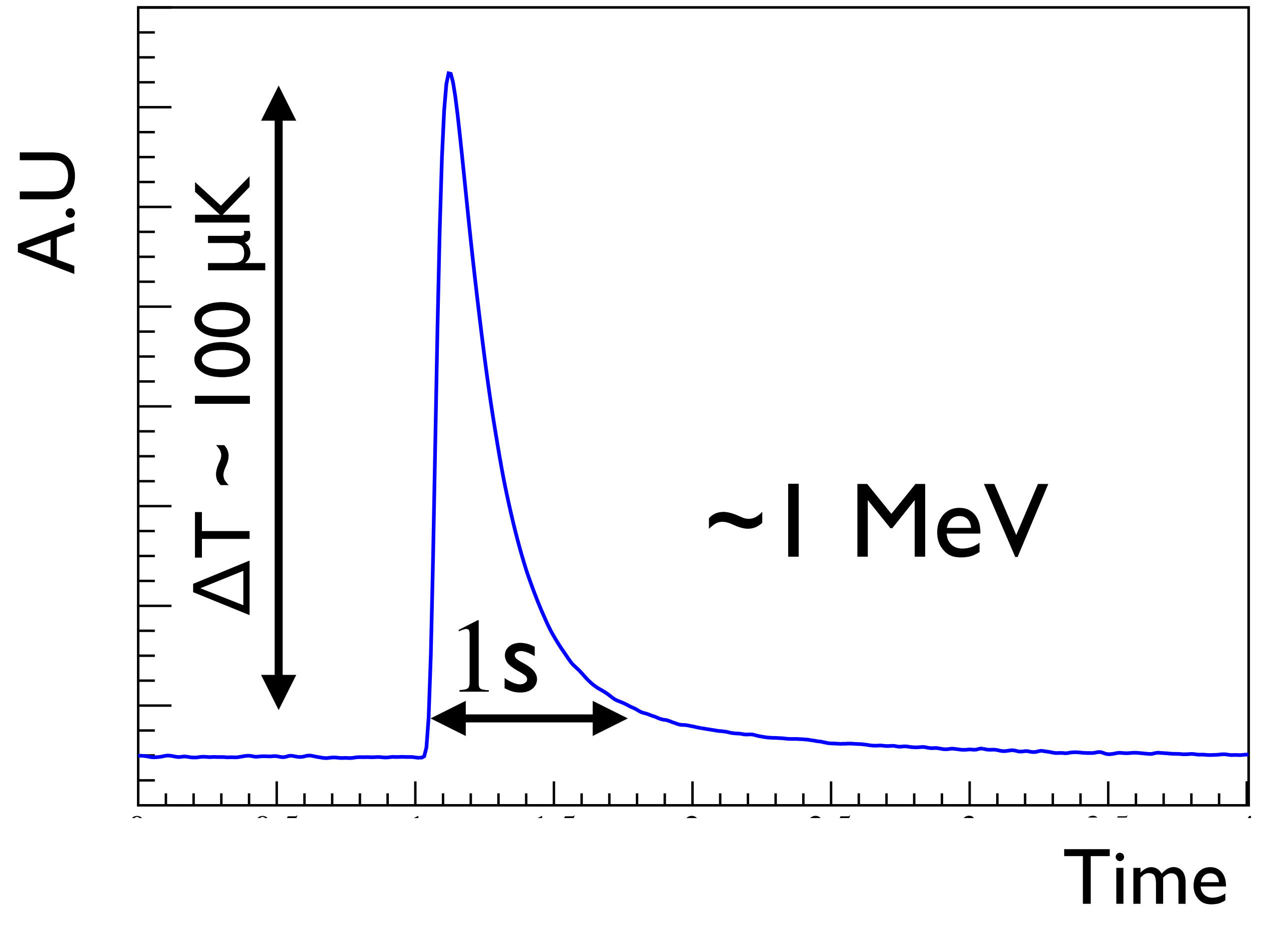


Crystal temperature rises when energy is deposited

$$\Delta T \ \alpha \ E/C(T)$$
$$C(T) \ \alpha \ T^3$$

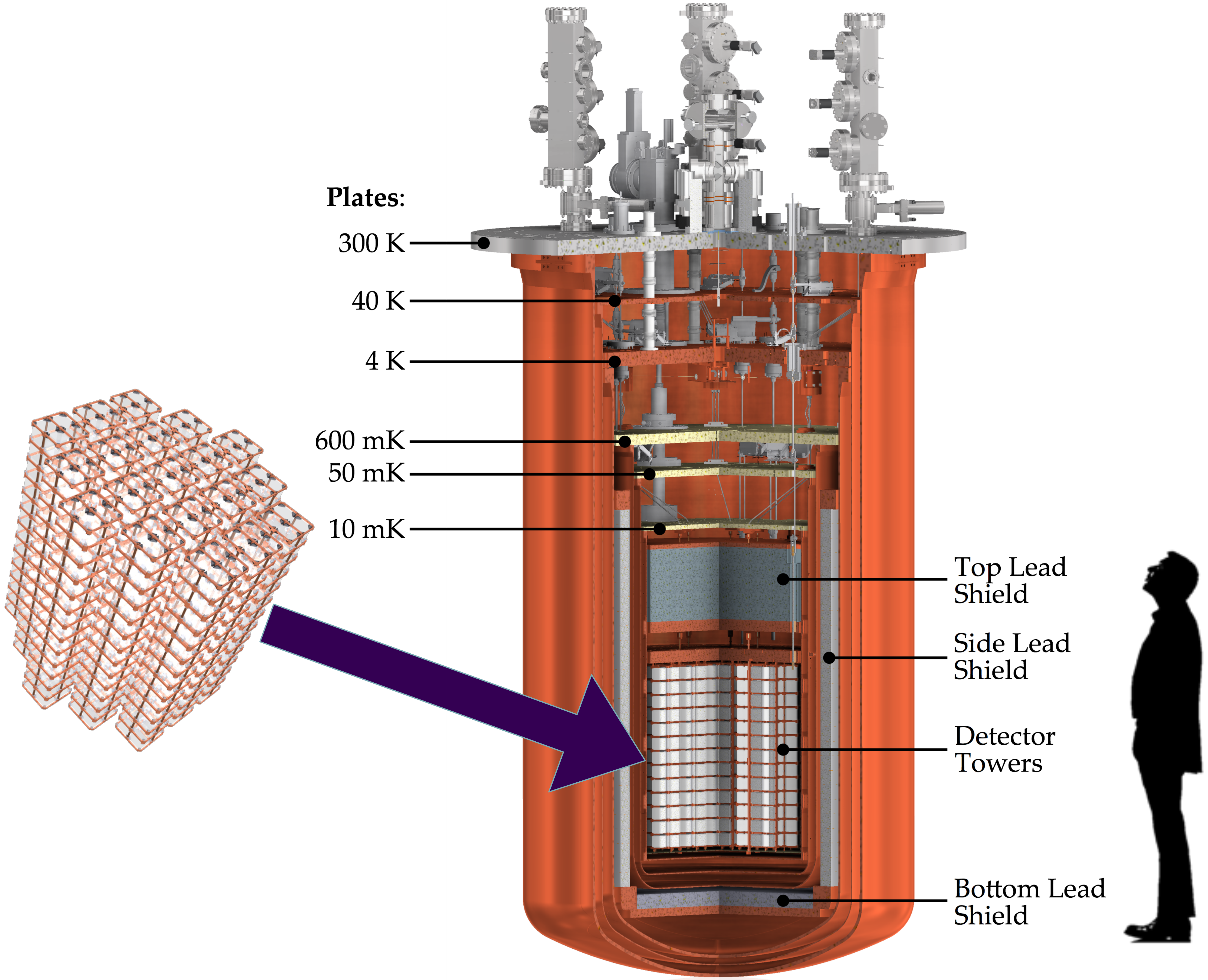


- Excellent energy resolution (~0.2% ΔE/E FWHM)
- Detector response independent of particle type
- Flexibility in $0\nu\beta\beta$ candidate choice

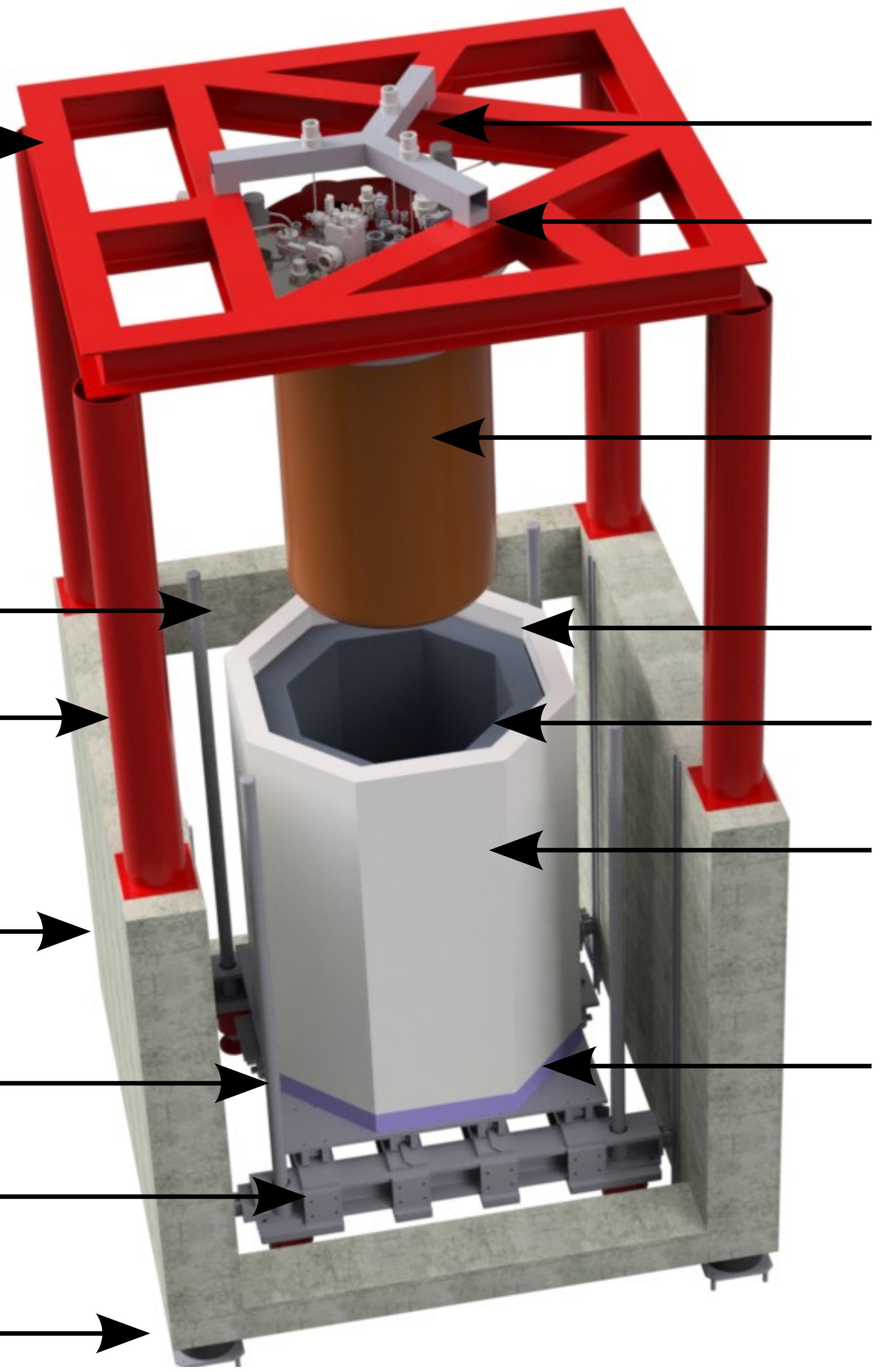
CUORE Cryostat

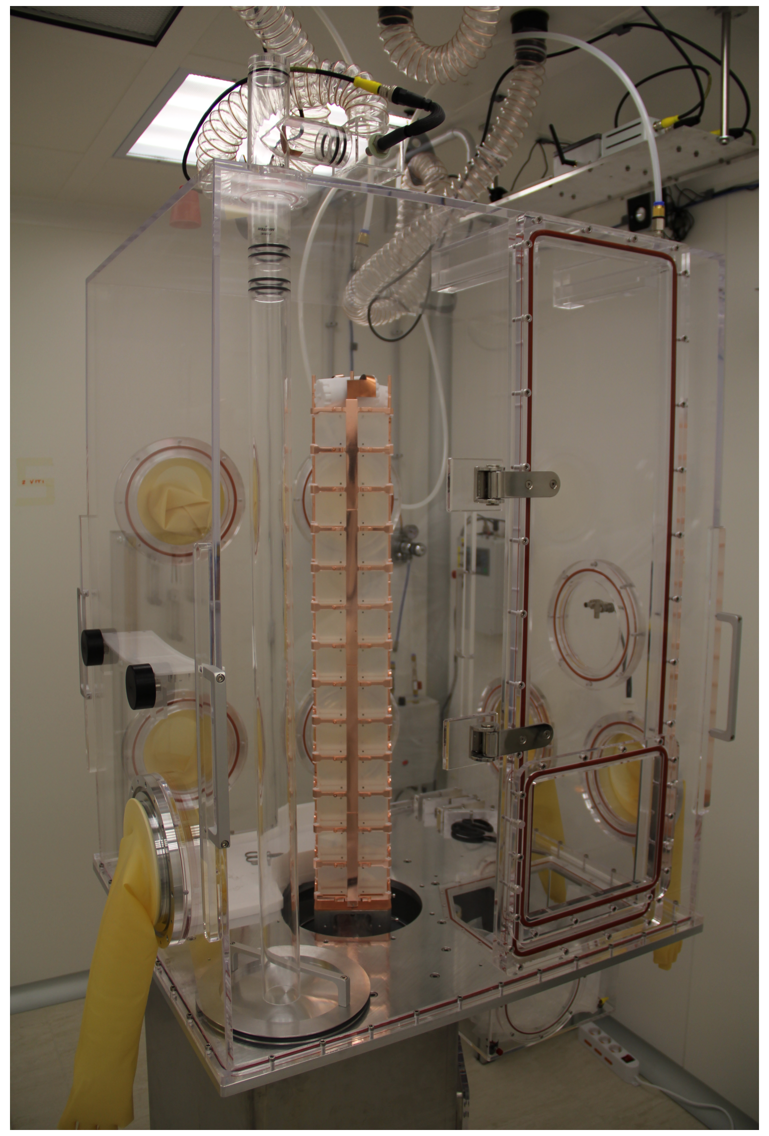
Low background cryostat needs to be maintained at low temperature with minimal vibrations

- 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

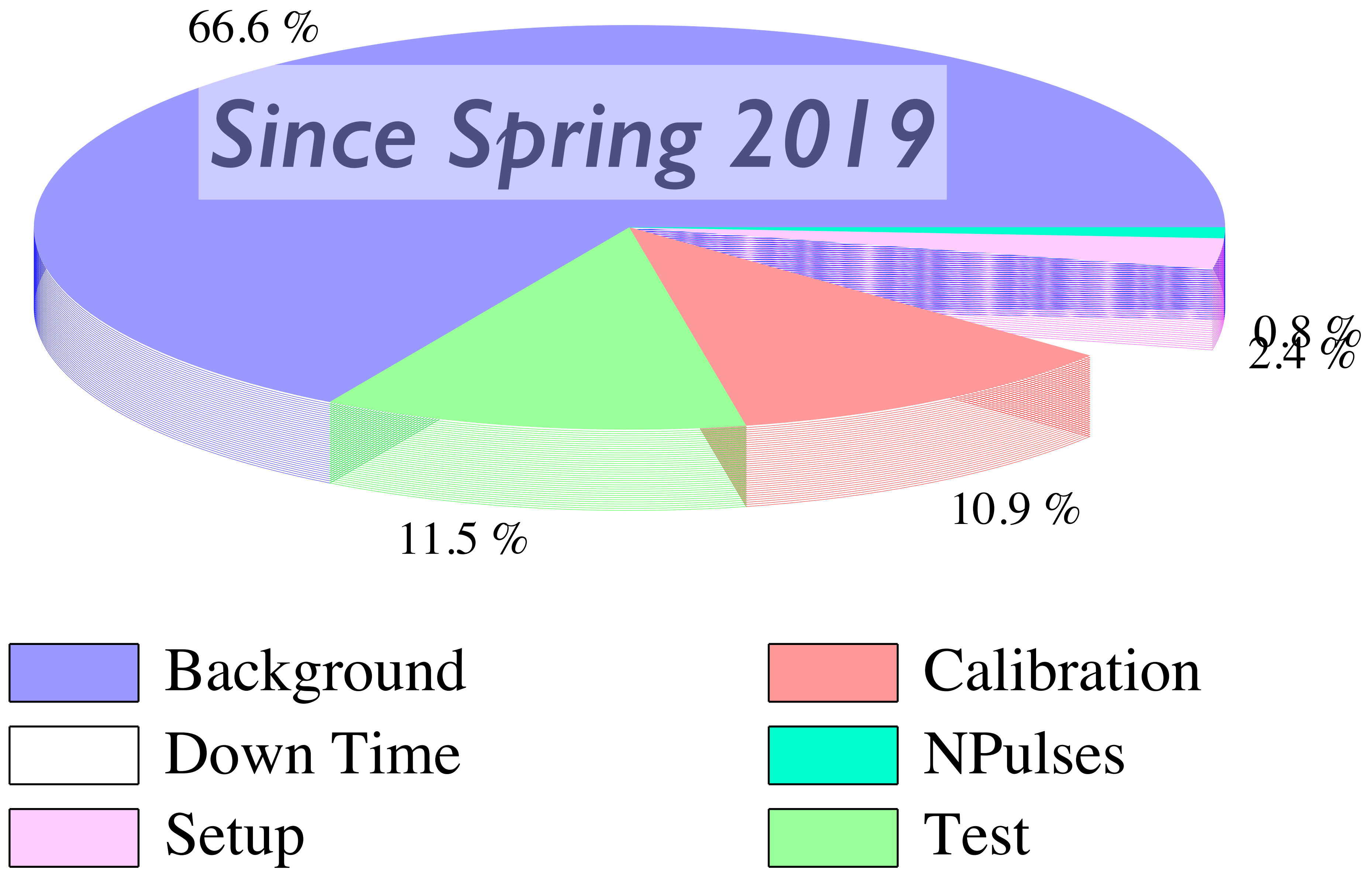

Main support plate
Concrete beams
Sand-filled columns
Concrete walls
Screw jacks
Movable platform
Seismic isolation
Y-beam
Vibration isolation
Cryostat
H_3BO_3 panels
Lead
Polyethylene
Borated polyethylene

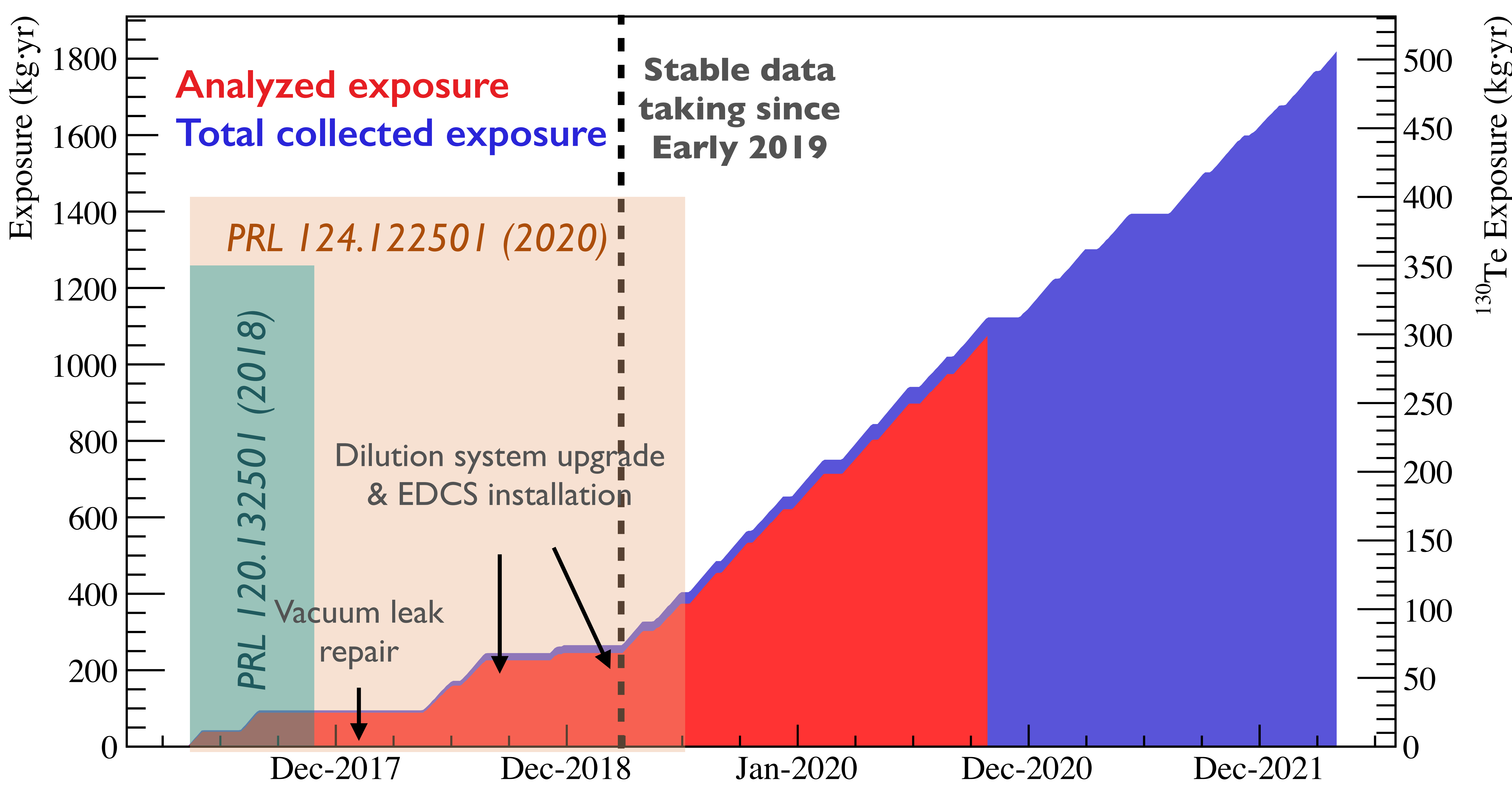


- Natural shielding from rock
- Passive lead, polyethylene, and H_3BO_3 shielding
- 70 tonne of lead, 7 tonne of cold lead
- Careful material selection: Ancient Lead and low radioactive copper
- Strict radiopure controls
- Active background reduction from event selection

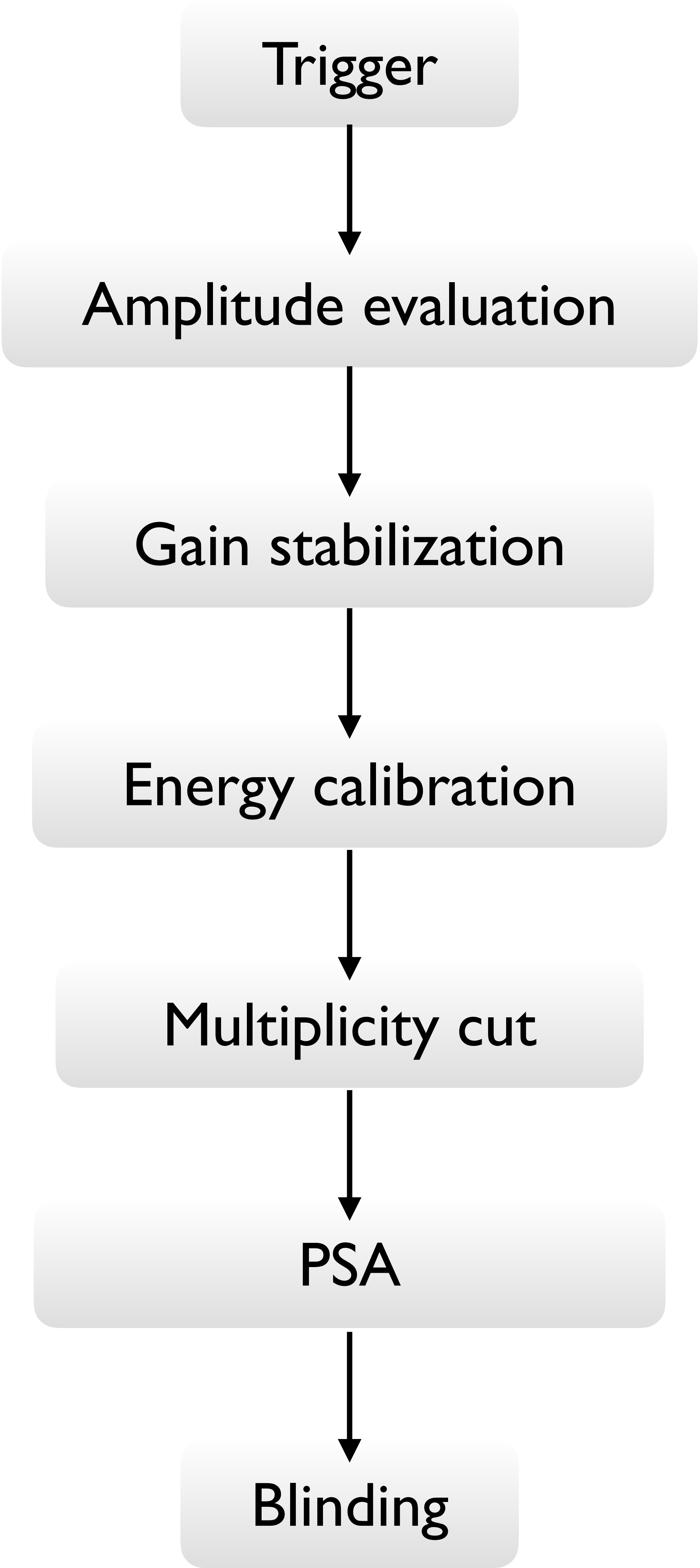
Data Taking

- High downtime from detector optimization and upgrades for first two years
- After detector upgrades, continues data taking with low downtime
- 22 datasets completed, each dataset ~1 month long (> **1800 kg.yr** data collected)
- 15 datasets analyzed (**1038.4** kg.yr)
- Continue to stably take data





Analysis Chain



Trigger

Amplitude evaluation

Gain stabilization

Energy calibration

Multiplicity cut

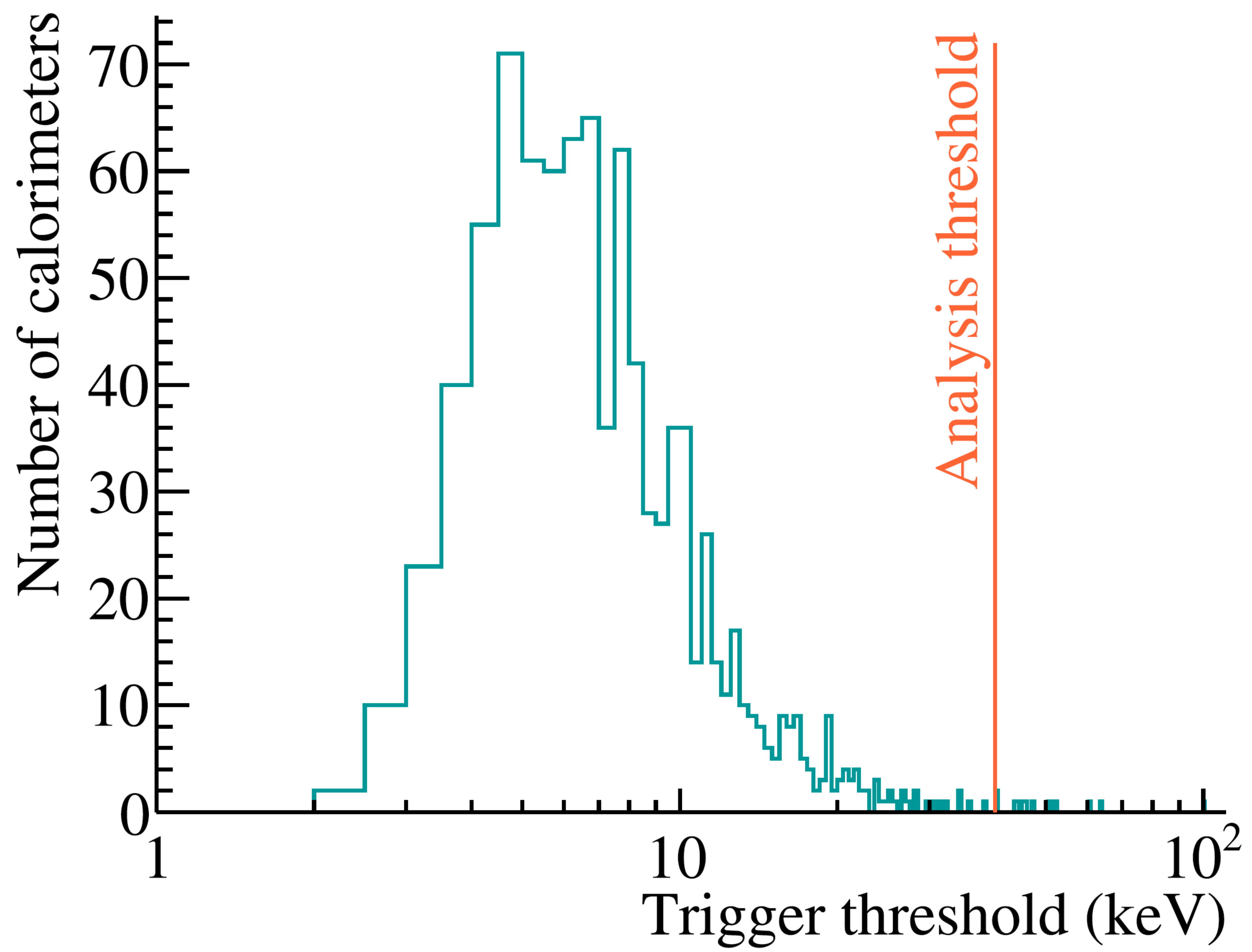
PSA

Blinding

Analysis Chain: Trigger

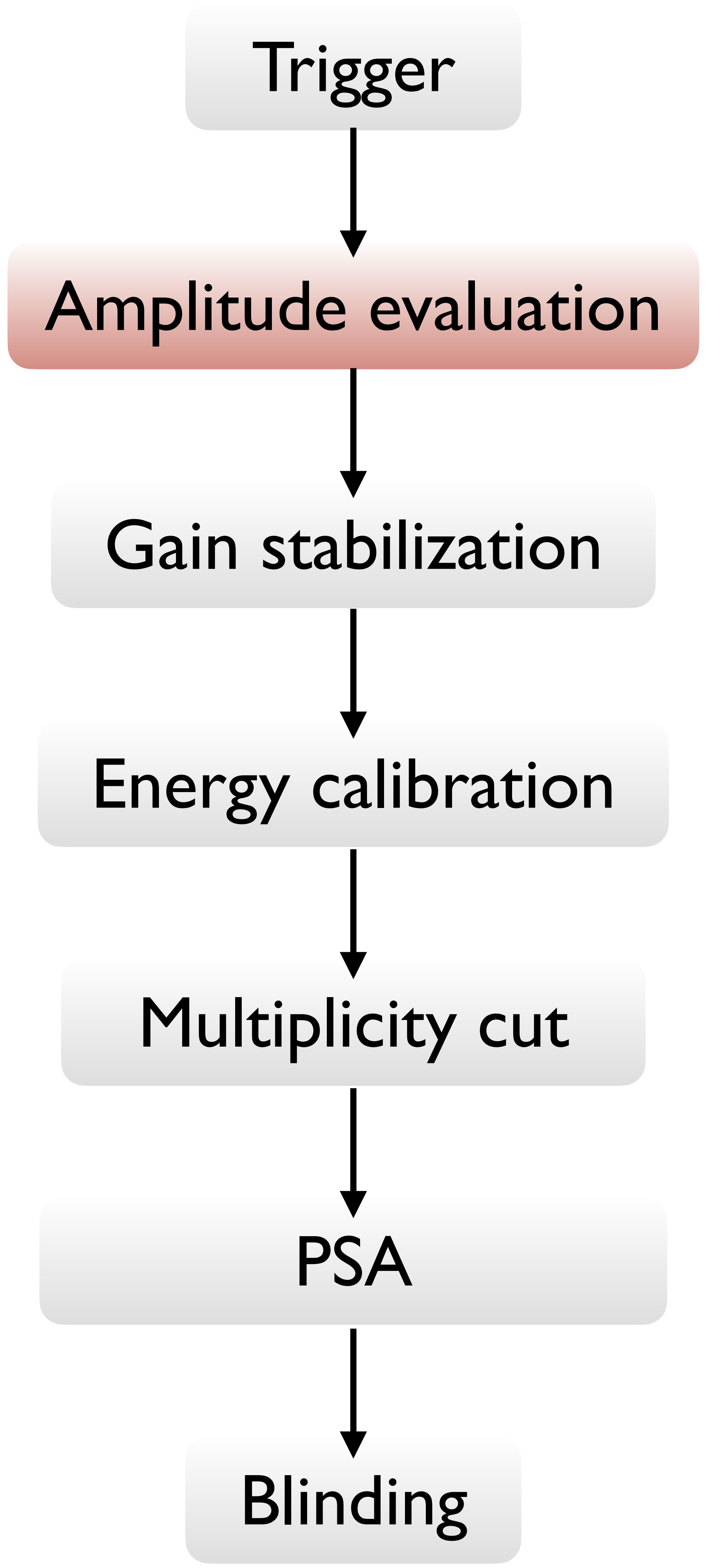
CUORE

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



- Continuous data collected and saved
- Offline retriggering for all datasets
- Optimum Trigger (OT):
  - Triggered when optimum filter based amplitude crosses a threshold
- 40 keV analysis threshold: 97% of channels have a trigger efficiency above 90%

Analysis Chain: Amplitude



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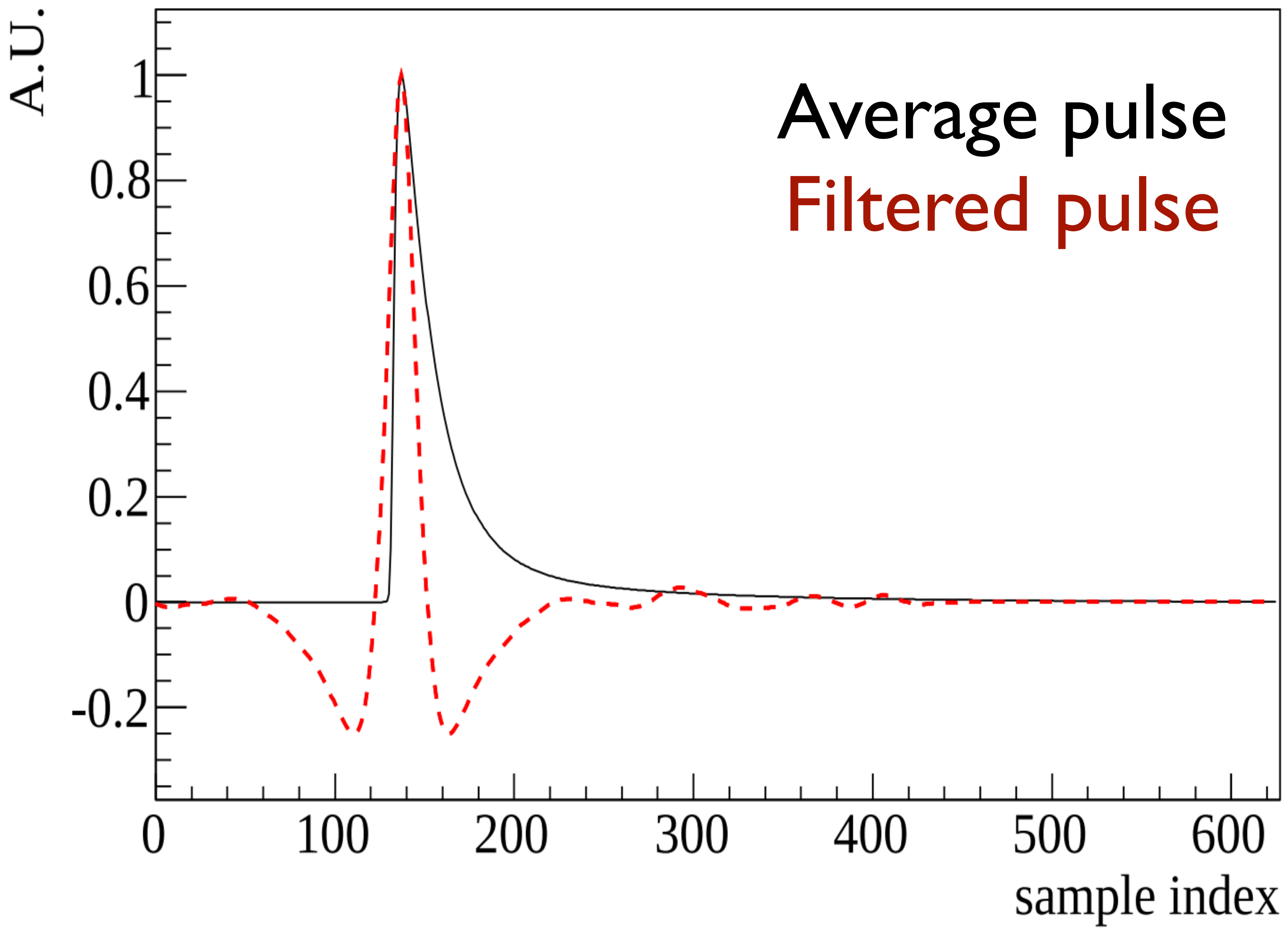

Amplitude $\propto$ Energy

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

Analysis Chain: Gain stabilization

Trigger

Amplitude evaluation

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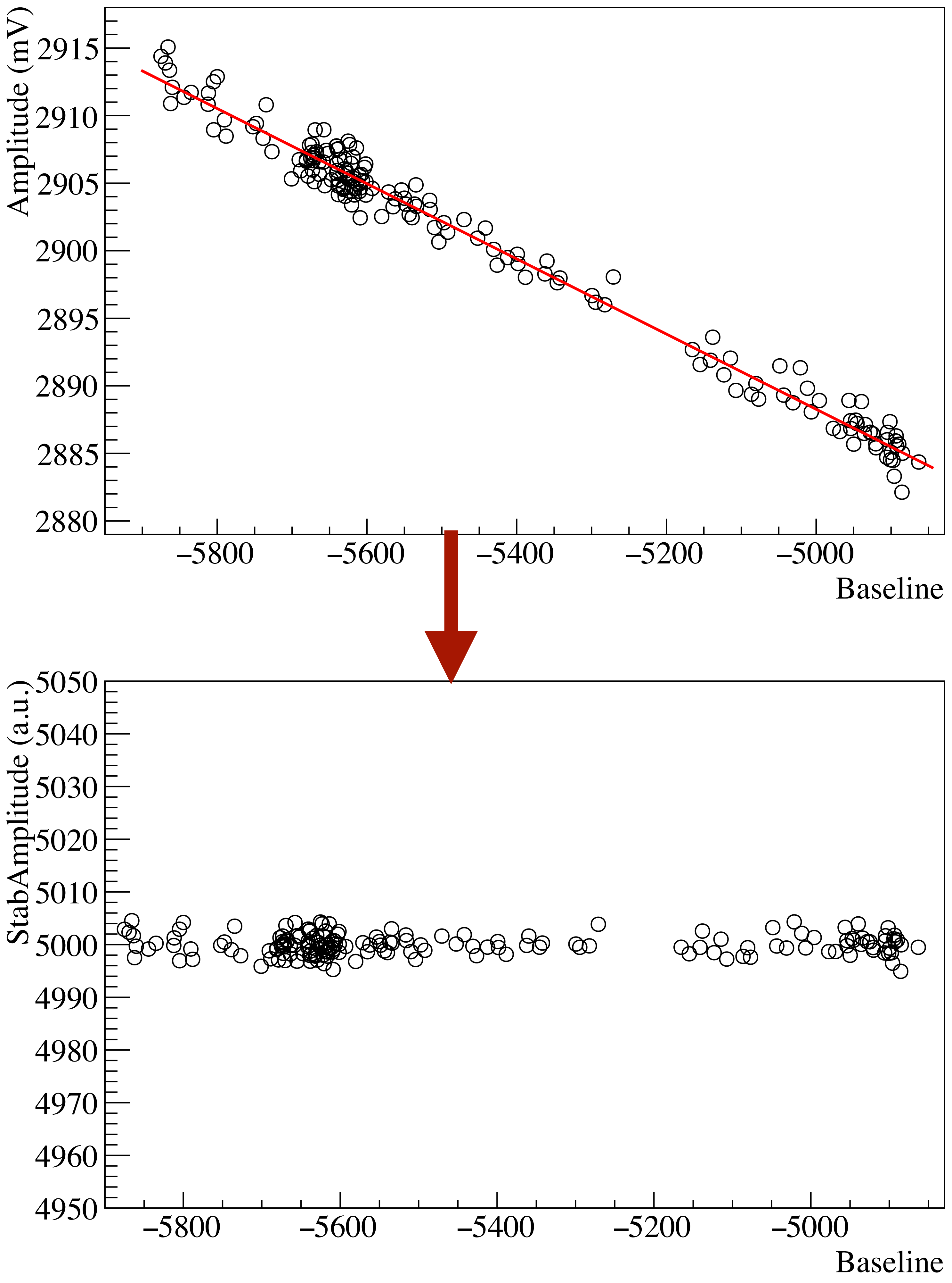
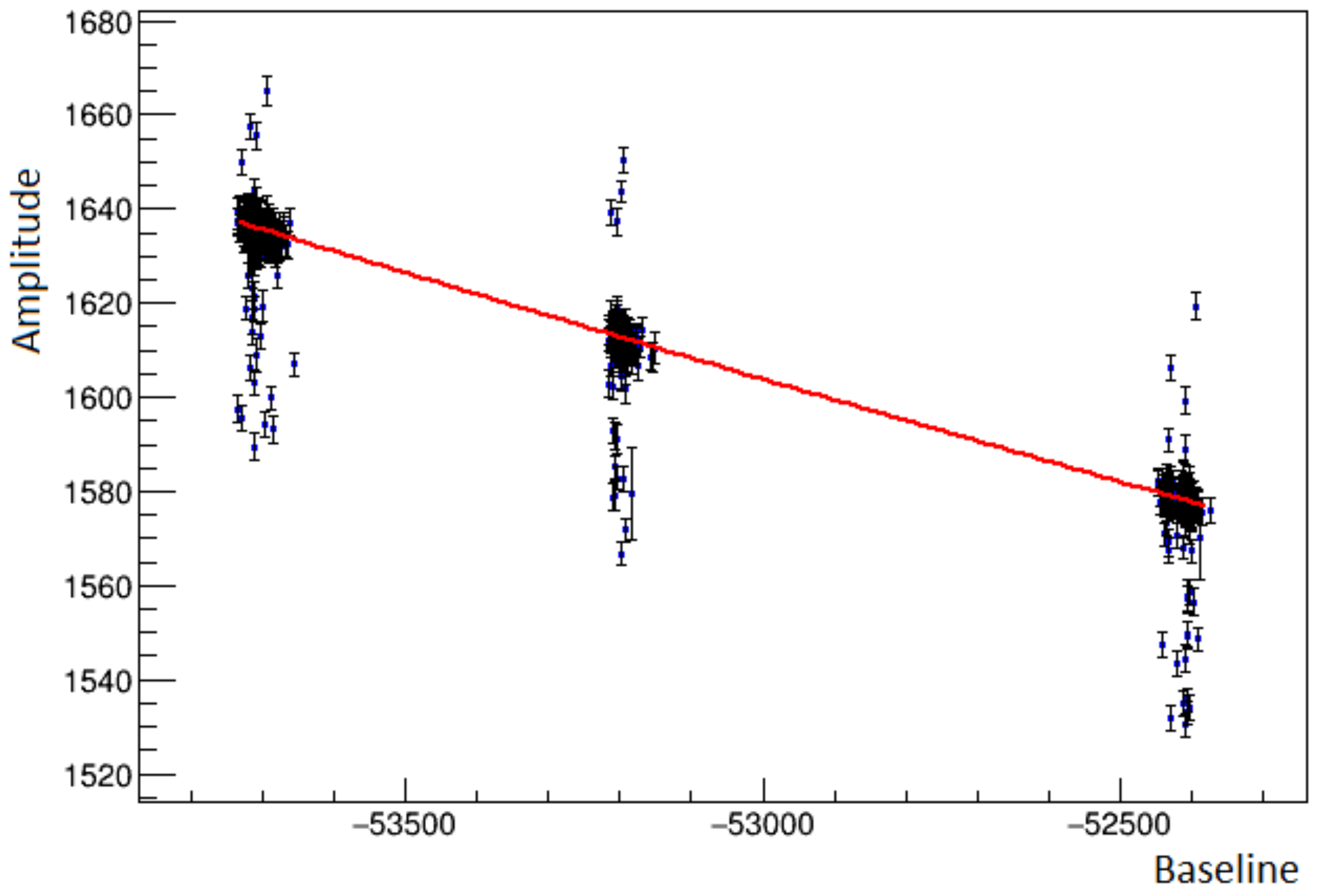
Heater Thermal Gain Stabilization



Amplitude = Gain x Energy

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

Calibration Thermal Gain Stabilization



Analysis Chain: Energy

Trigger

Amplitude evaluation

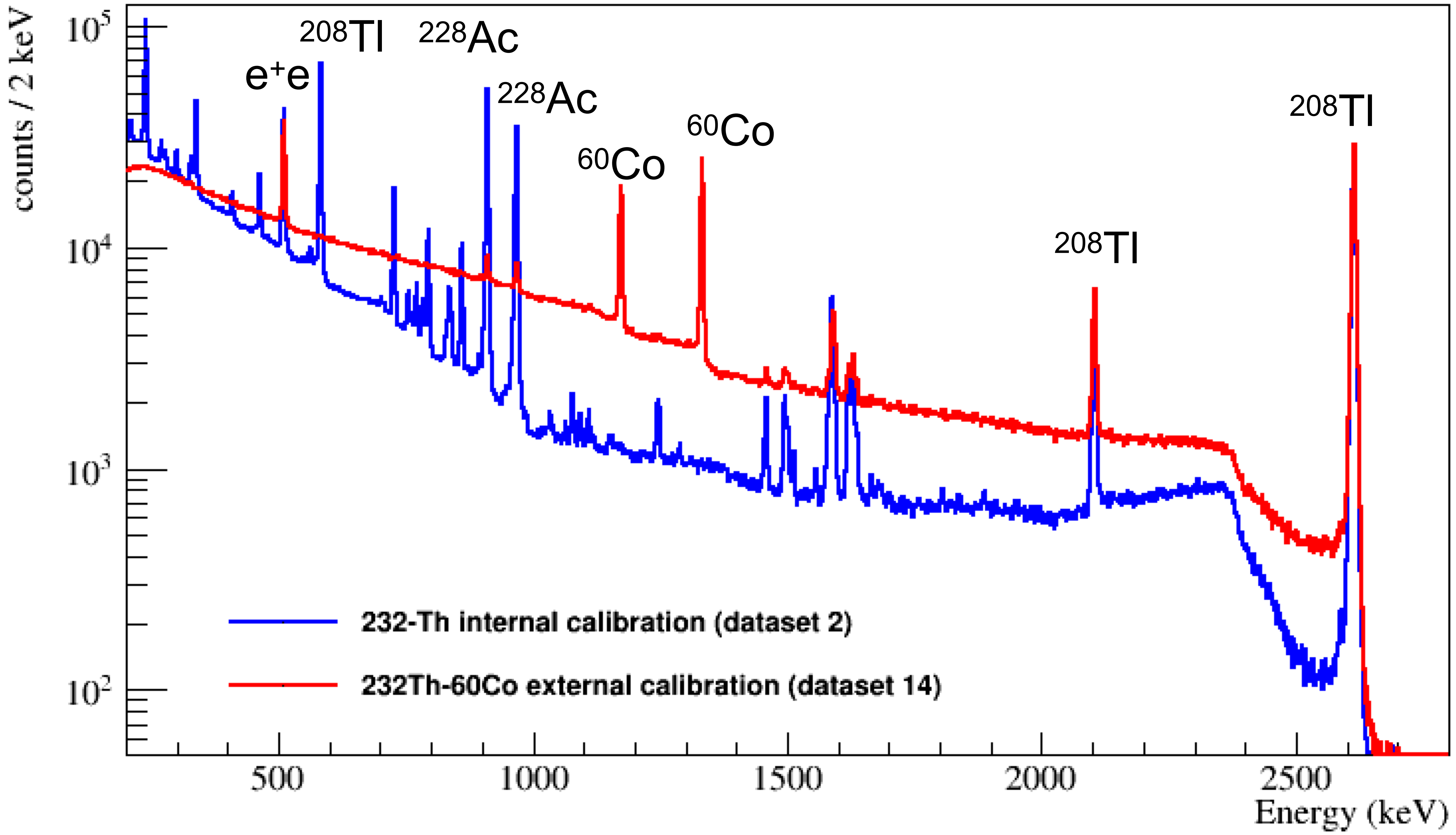
Gain stabilization

Energy calibration

Multiplicity cut

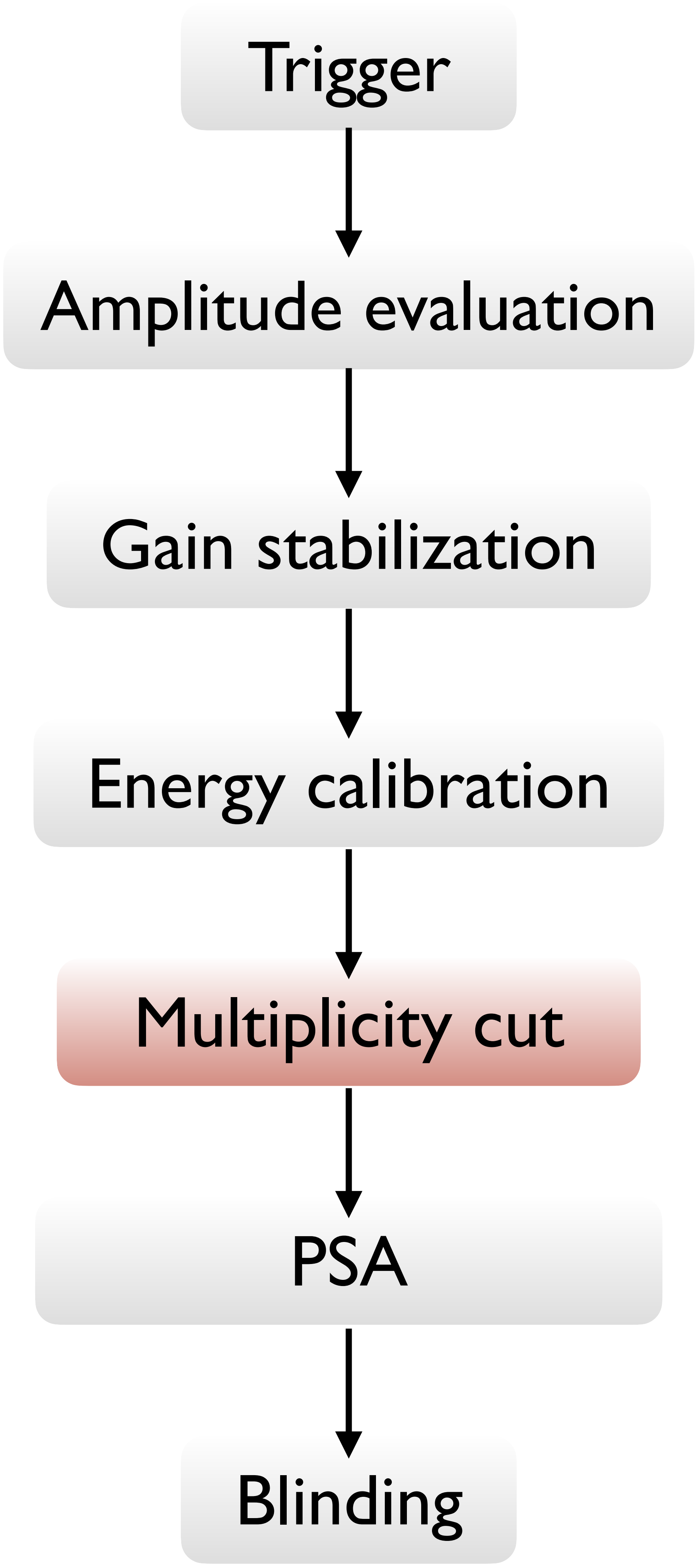
PSA

Blinding



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

Analysis Chain: Multiplicity


Trigger

Amplitude evaluation

Gain stabilization

Energy calibration

Multiplicity cut

PSA

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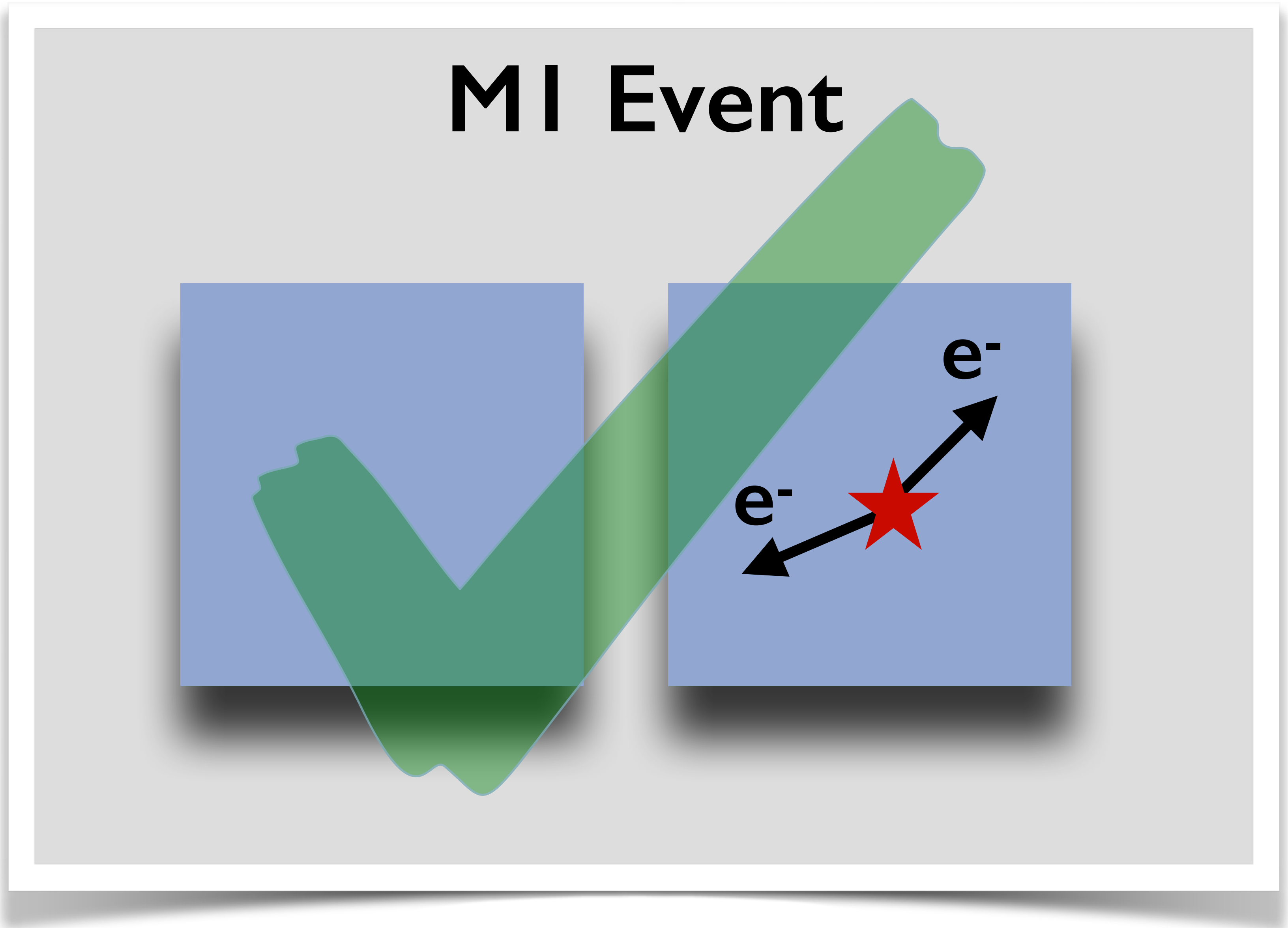
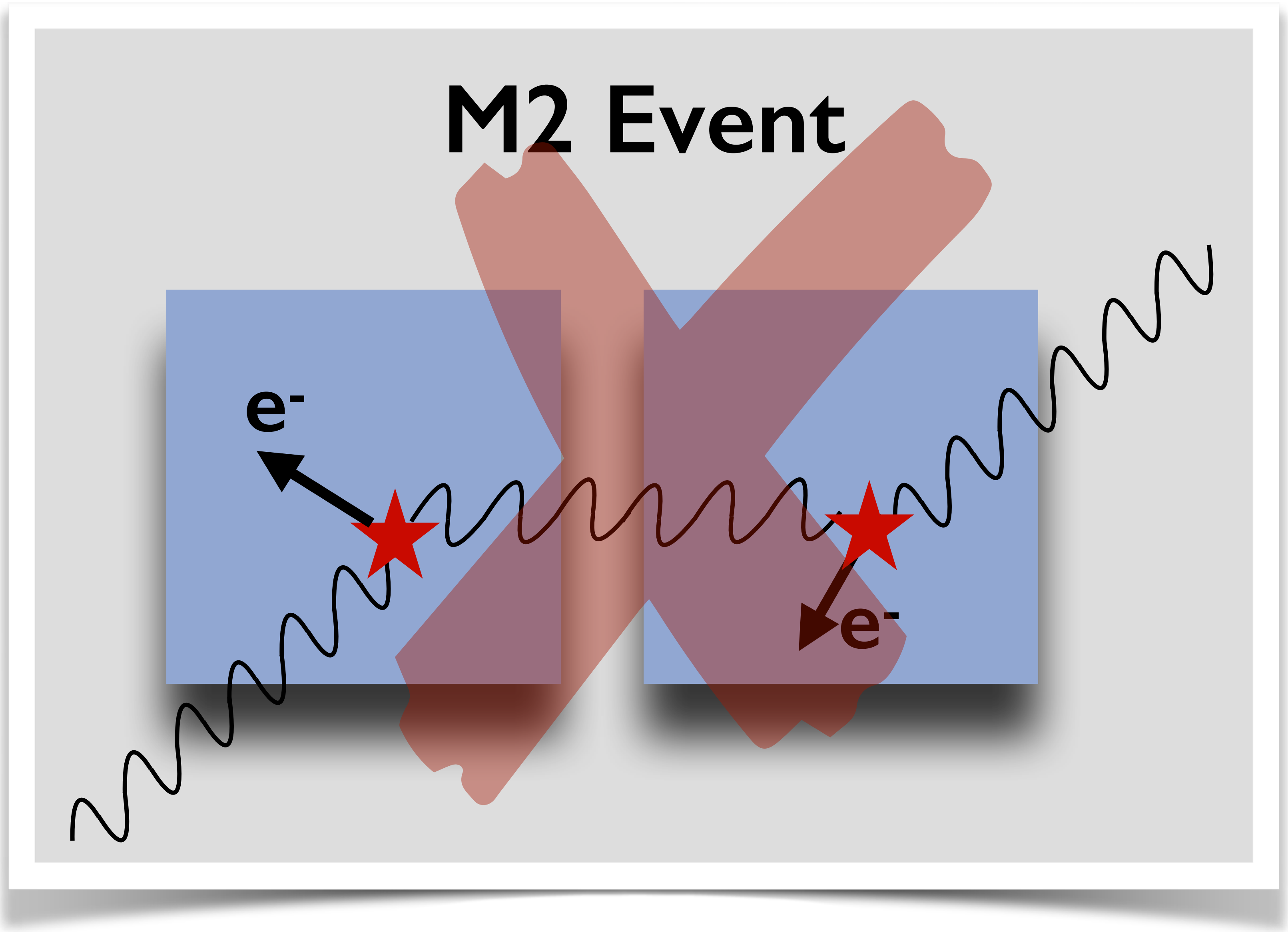
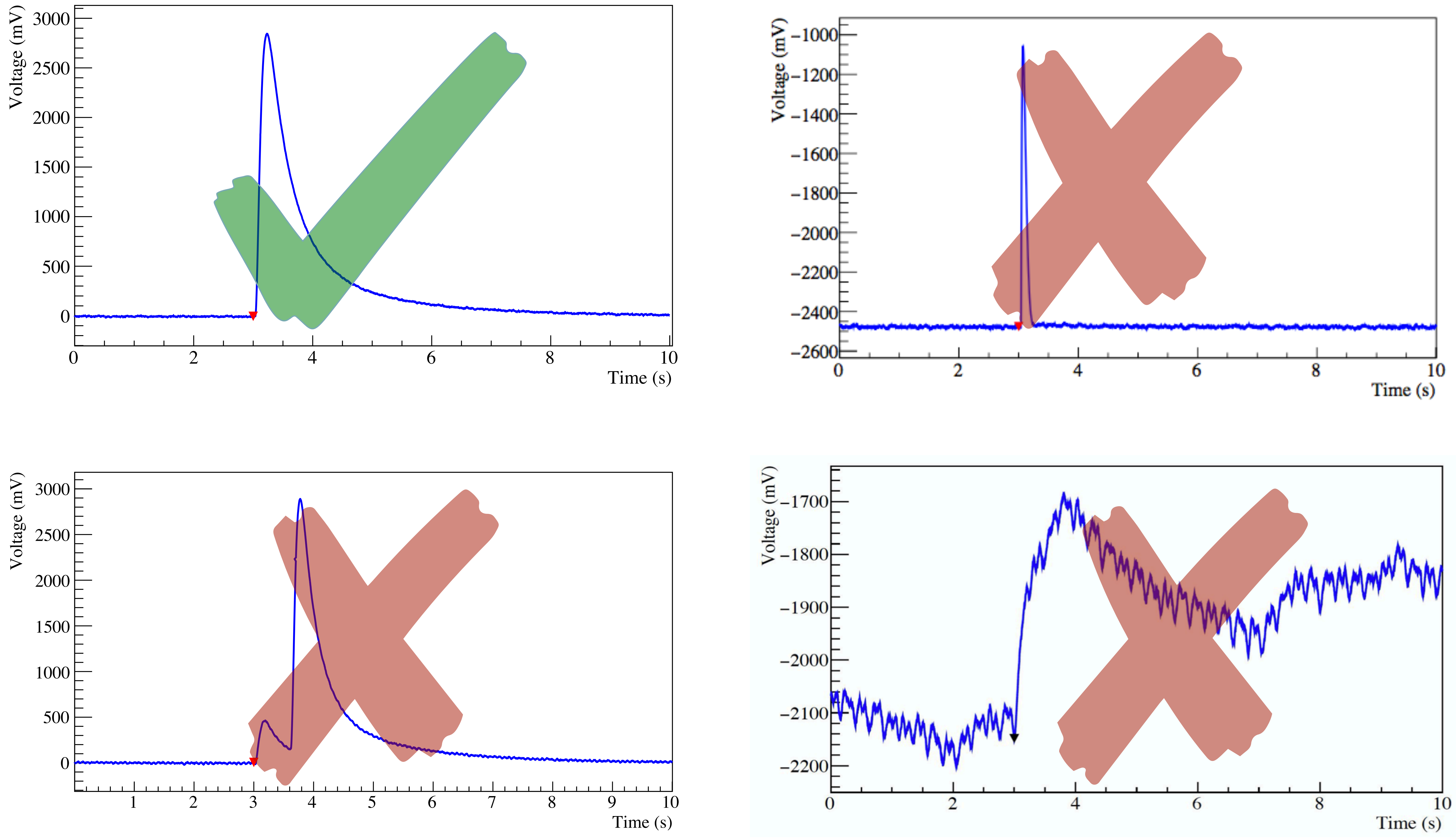




- Multi-site events typically come from radioactive contamination
- MC suggests 88% of $0\nu\beta\beta$ events are single-site
- Select M1 events for $0\nu\beta\beta$ dataset
- Eliminate Compton scatters, surface alpha contamination, and muons

Analysis Chain: Pulse Shape Discrimination

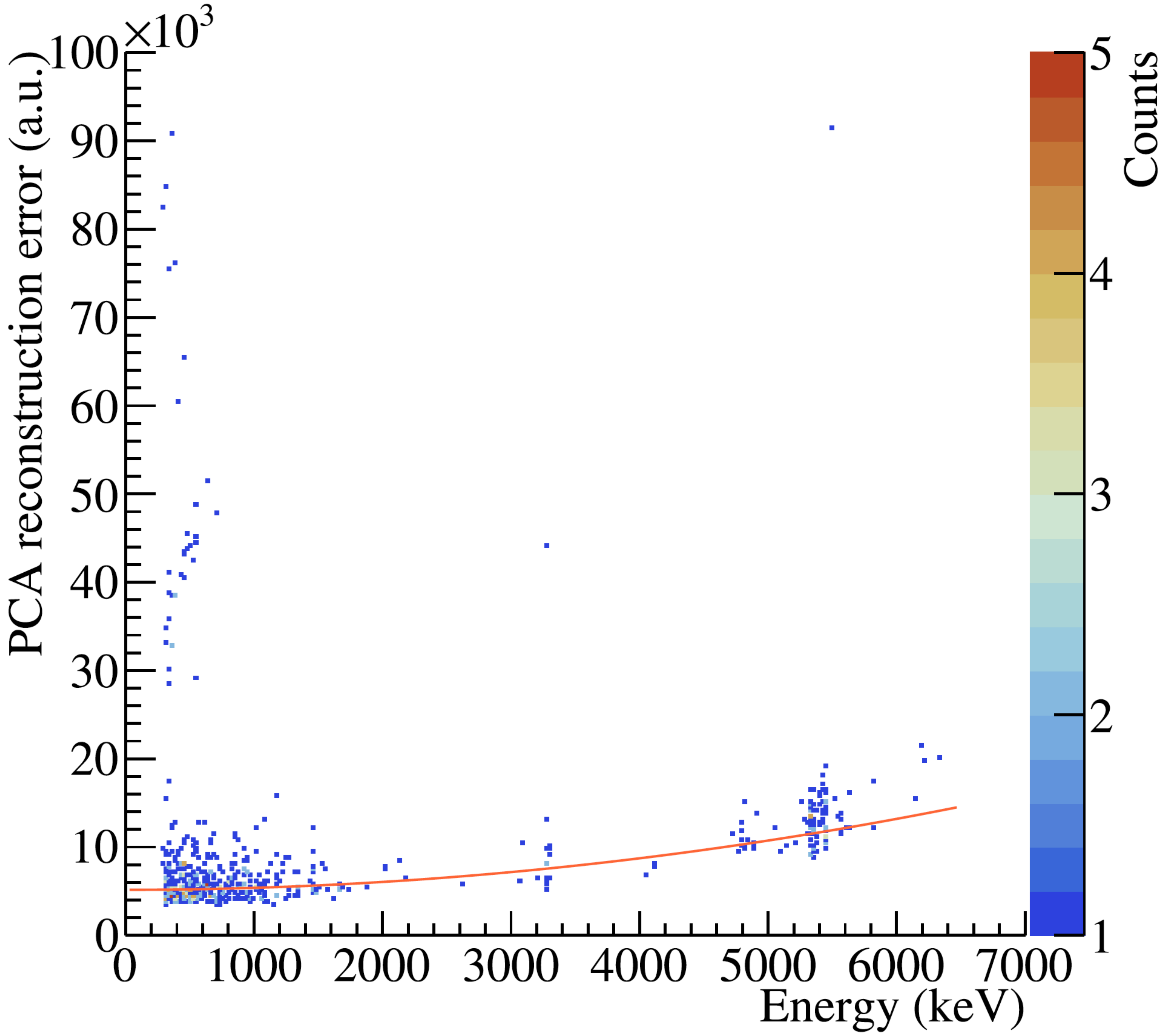
- Trigger
- Amplitude evaluation
- Gain stabilization
- Energy calibration
- Multiplicity cut
- **PSA**
- Blinding

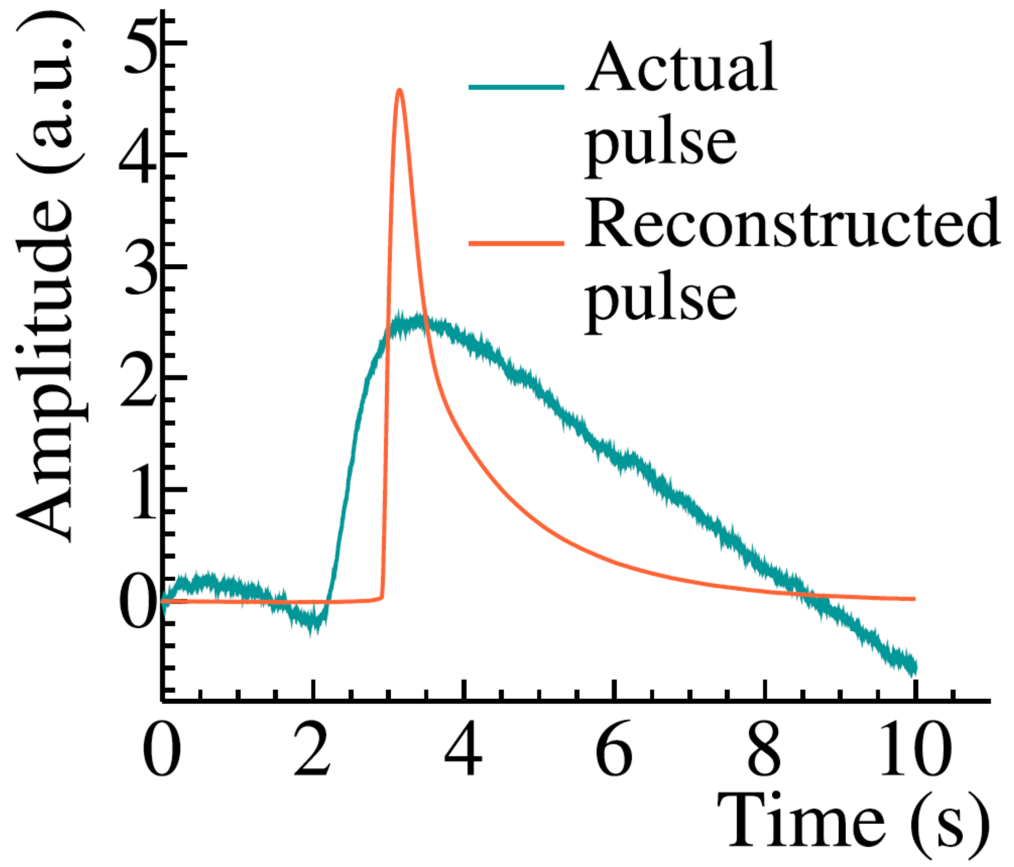


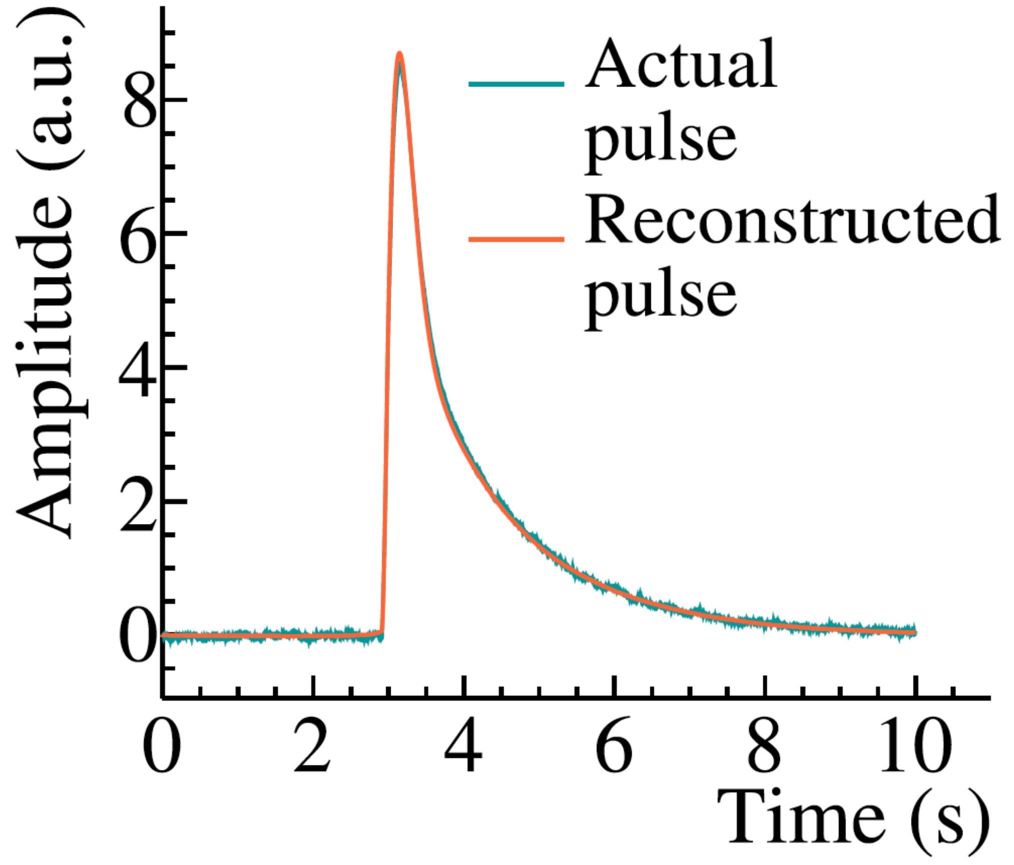
Analysis Chain: Pulse Shape Discrimination

Trigger
Amplitude evaluation
Gain stabilization
Energy calibration
Multiplicity cut
PSA
Blinding

- Use principal component analysis (PCA)
- For each channel and dataset, treat average pulse as the leading PCA component
- Remove unphysical pulses by looking at the deviation from nominal pulse

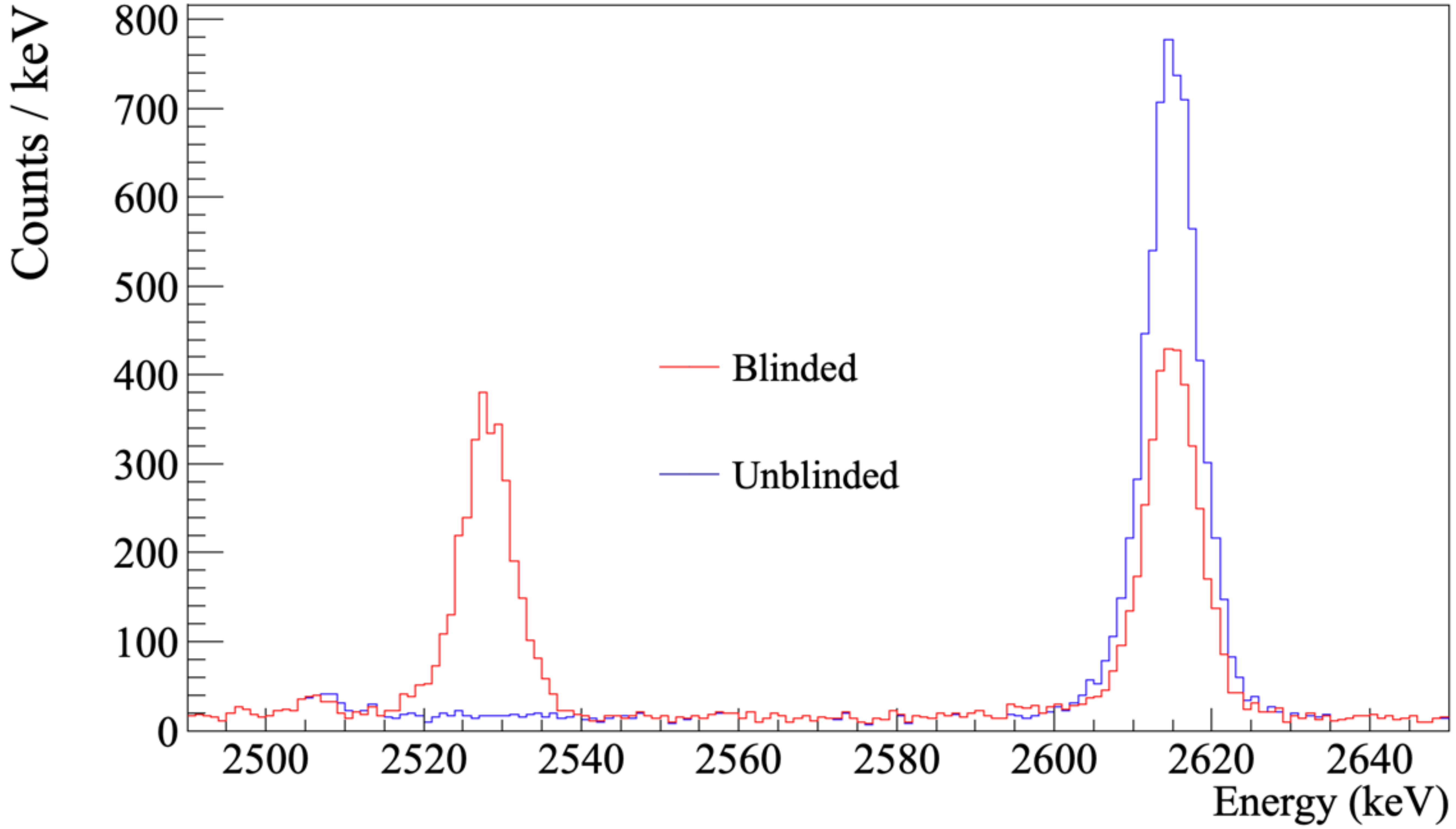






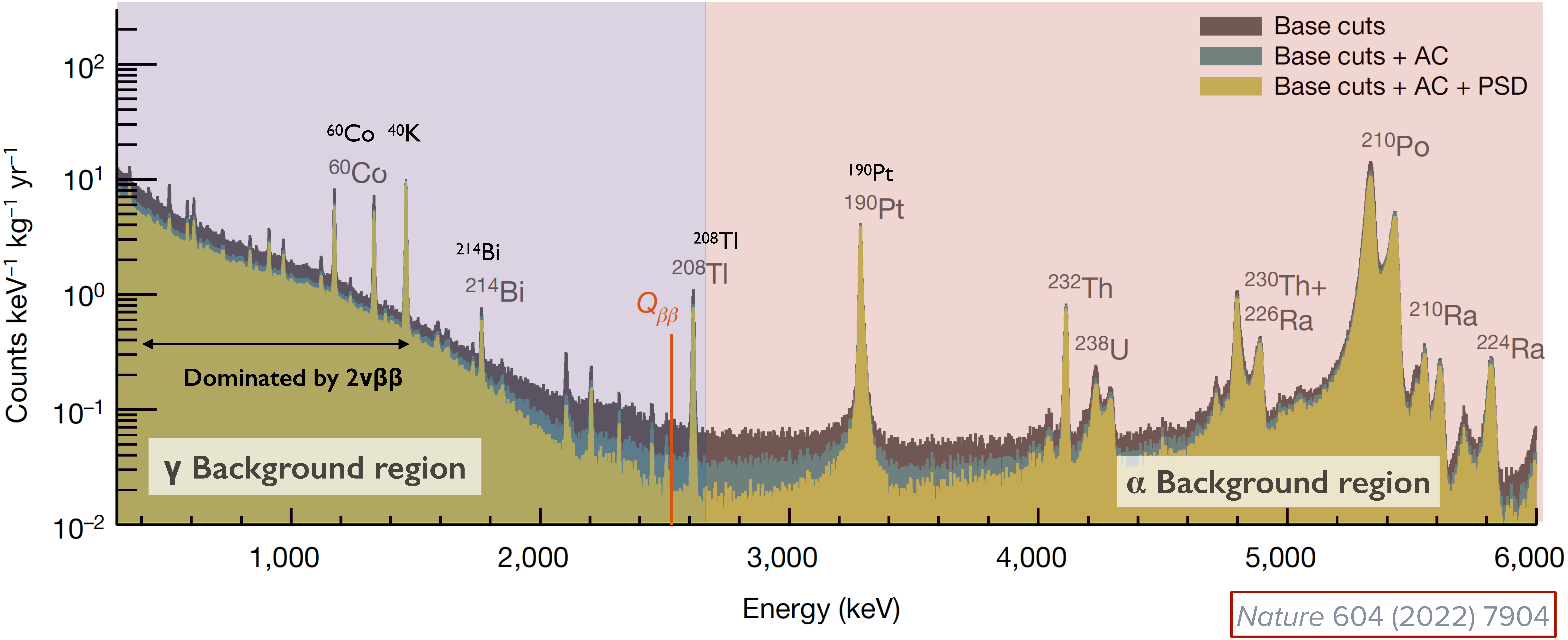
Analysis Chain: Blinding

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



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

Spectrum: All Datasets

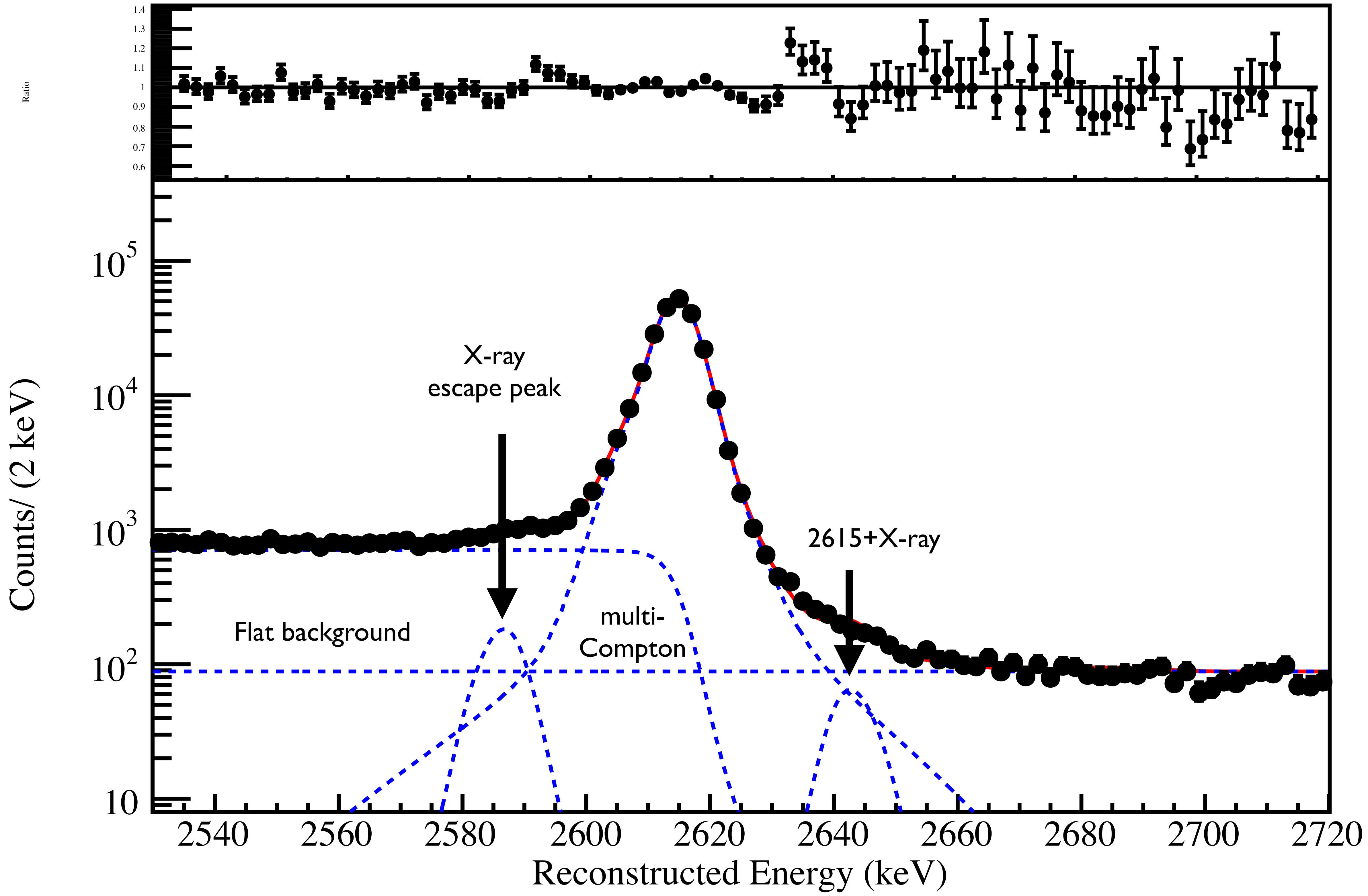


Nature 604 (2022) 7904

Pranava Teja Surukuchi, CoSSURF 2022

Detector Response

- Response modeled based on a fit to 2615 ^{208}Tl peak in calibration data
- Main peak parametrized by 3 Gaussian peaks: Detector response
- Additionally include flat background, X-ray escape, and multi-Compton
- Fit performed over all channels in a tower



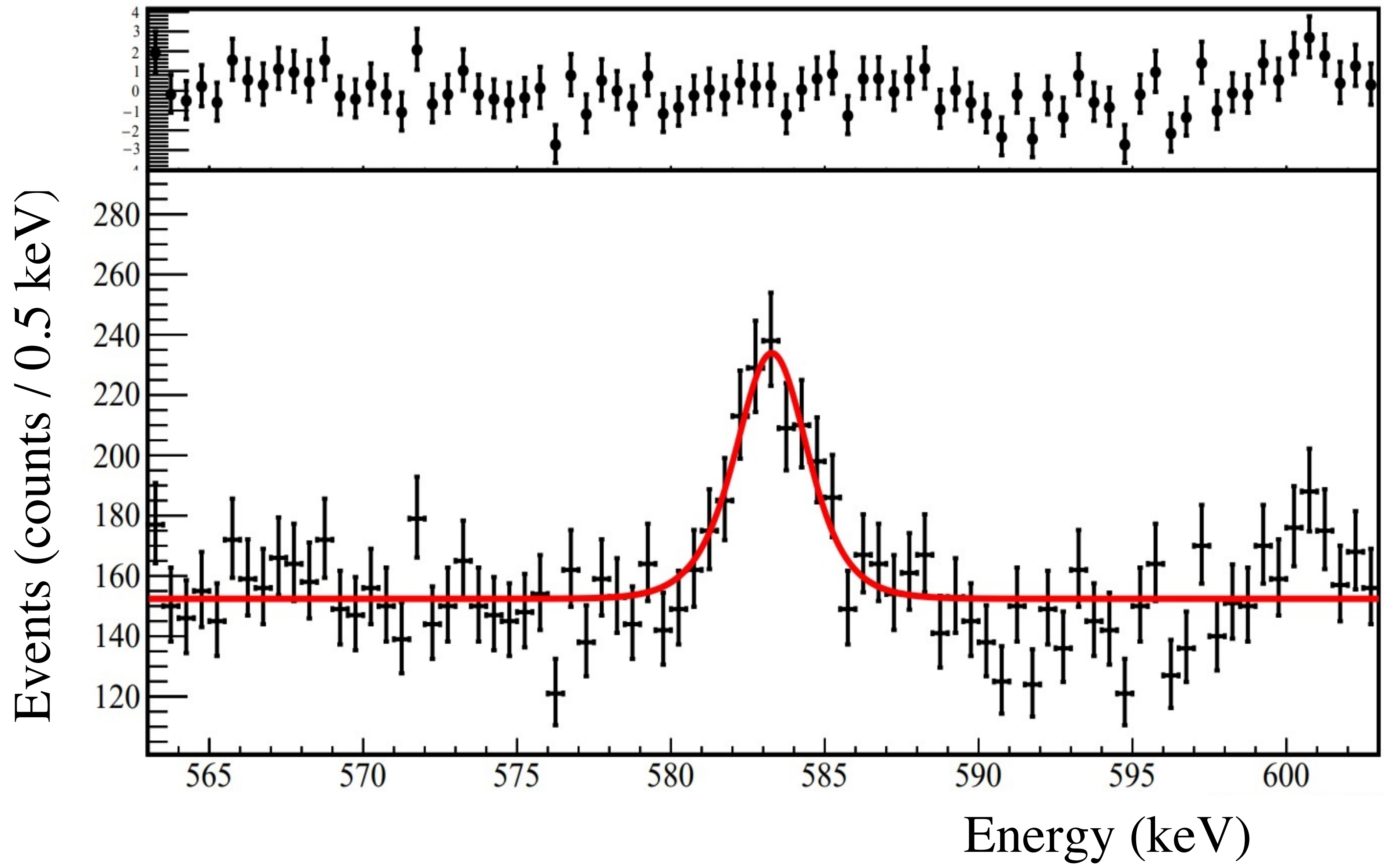
Detector Response

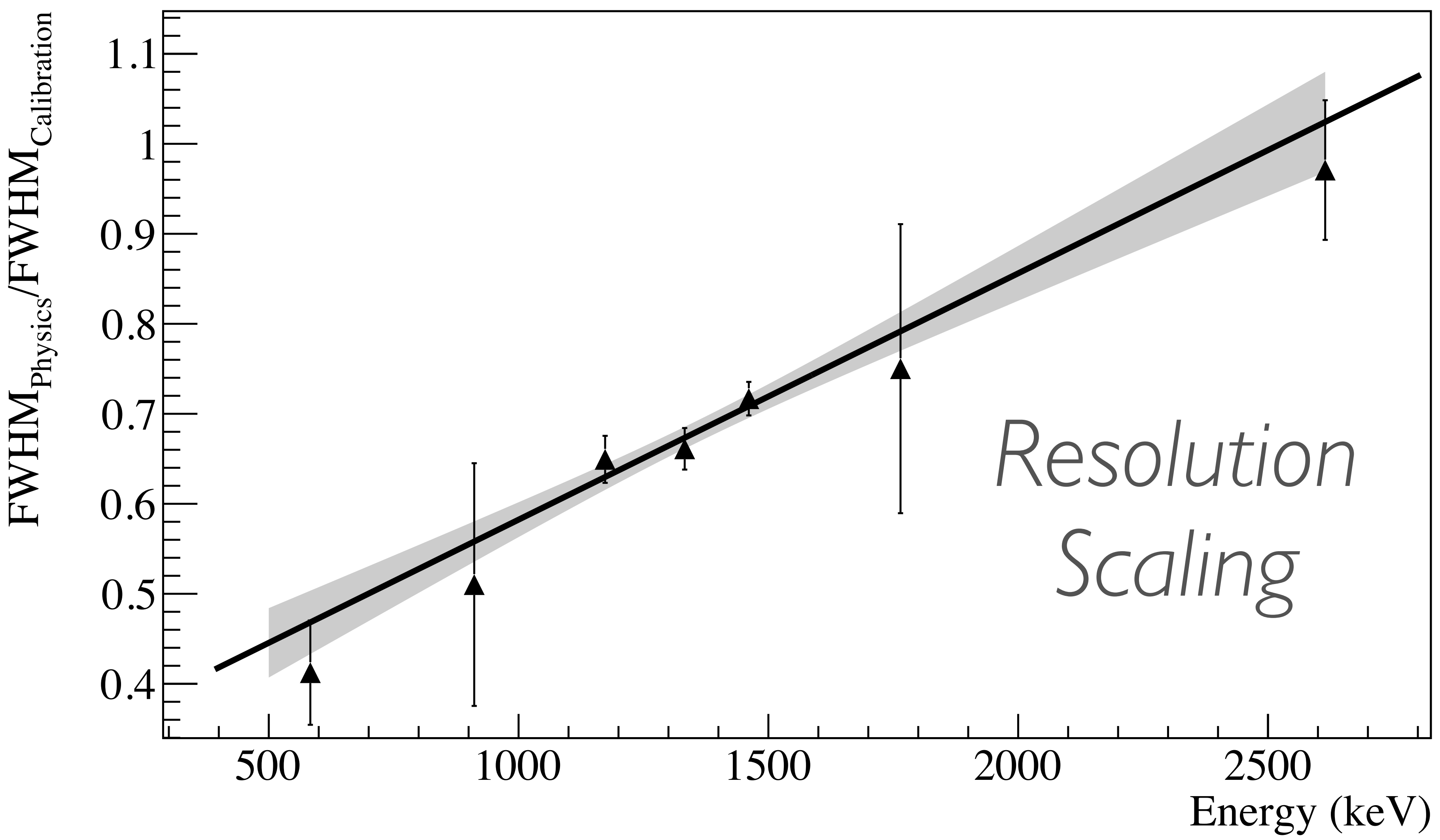
- Scale the detector response at 2615 ^{208}Tl peak to multiple peaks in physics data
- Based on this, determine energy bias and resolution scaling to $Q_{\beta\beta}$

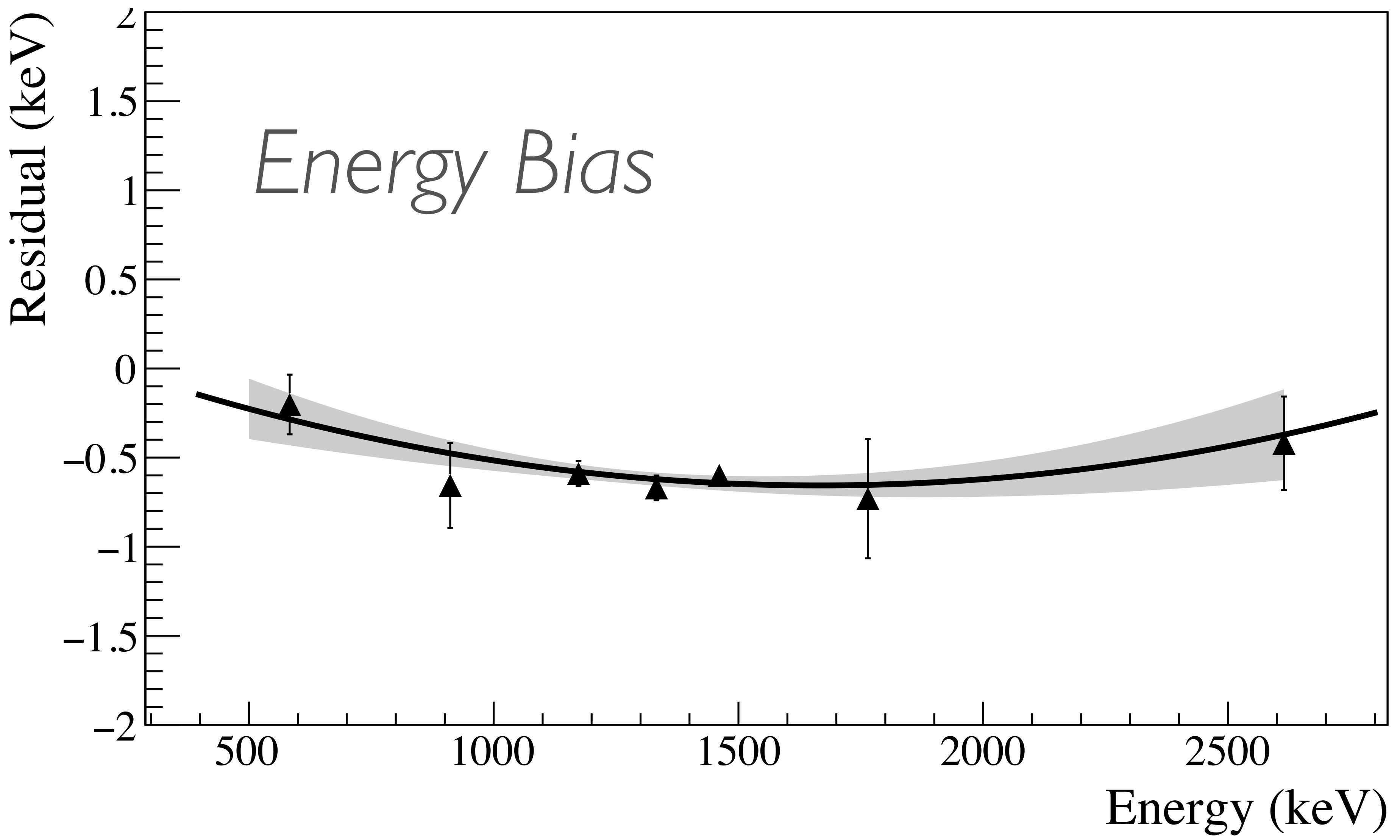
FWHM at 2615 keV in calibration data - 7.78(3) keV

FWHM at $Q_{\beta\beta}$ in physics data - 7.8(5) keV

Bias at $Q_{\beta\beta}$ < 0.7 keV







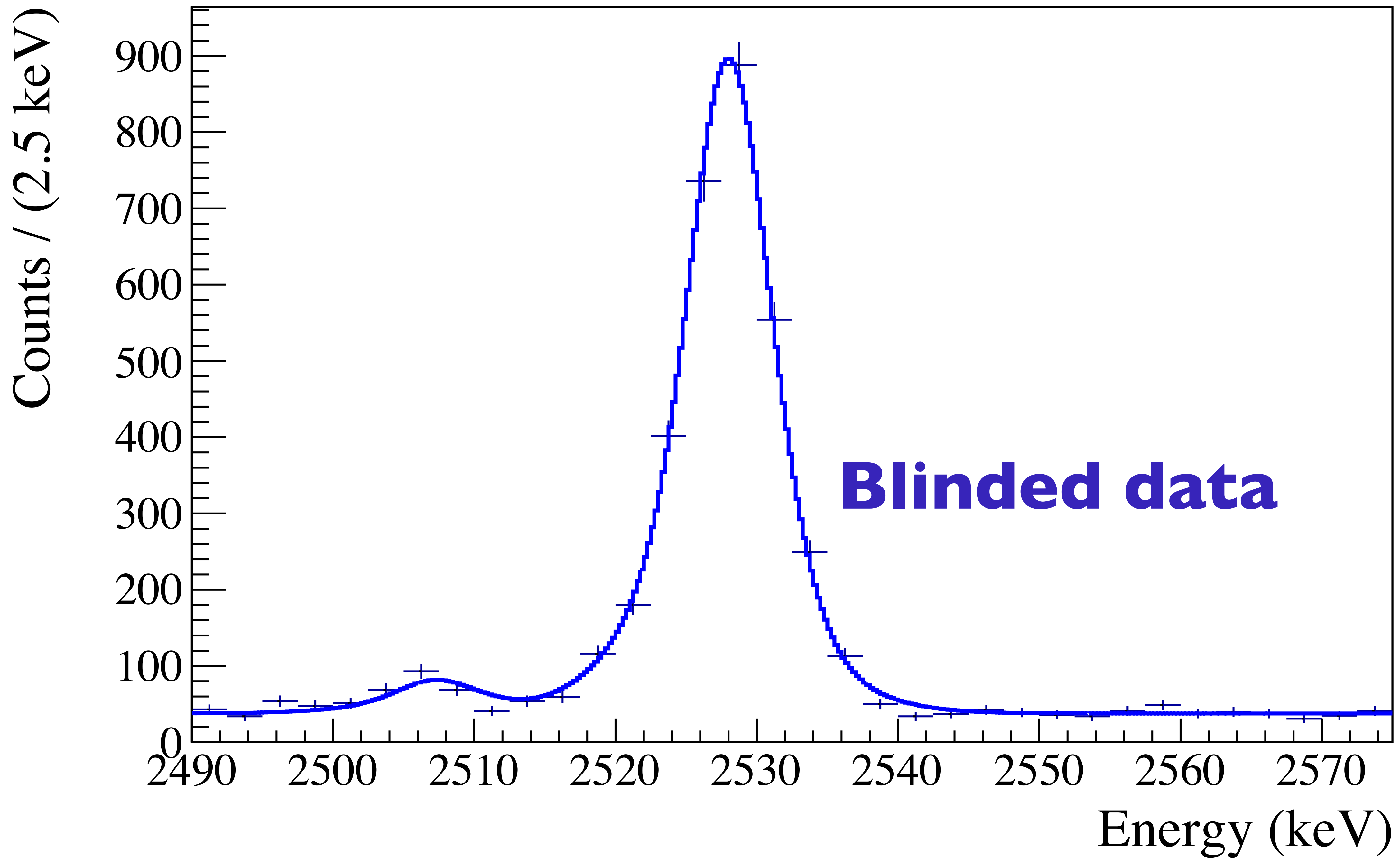
Efficiencies

Containment efficiency	Evaluated with MC simulations	MC	88.35 ± 0.09 %
Reconstruction efficiency	Comprises: ➜ trigger ➜ event reconstruction ➜ pile-up identification	Heater	96.418 ± 0.002 %
Anti-coincidence efficiency	Quantifies the probability of properly identifying a single-crystal event	^{40}K	99.3 ± 0.1 %
Pulse-shape discrimination efficiency	Fraction of events passing a multi-dimensional cut on 6 pulse-shape variables	M1 ^{40}K 2x^{60}C ^{208}Tl	96.4 ± 0.2 %

Total analysis efficiency **92.4 ± 0.2%**

Fit Details

- Unbinned Bayesian fit over all datasets
- Bayesian Analysis Toolkit (BAT)
- Fit region: [2490, 2575] keV
- Systematics implemented as nuisance parameters



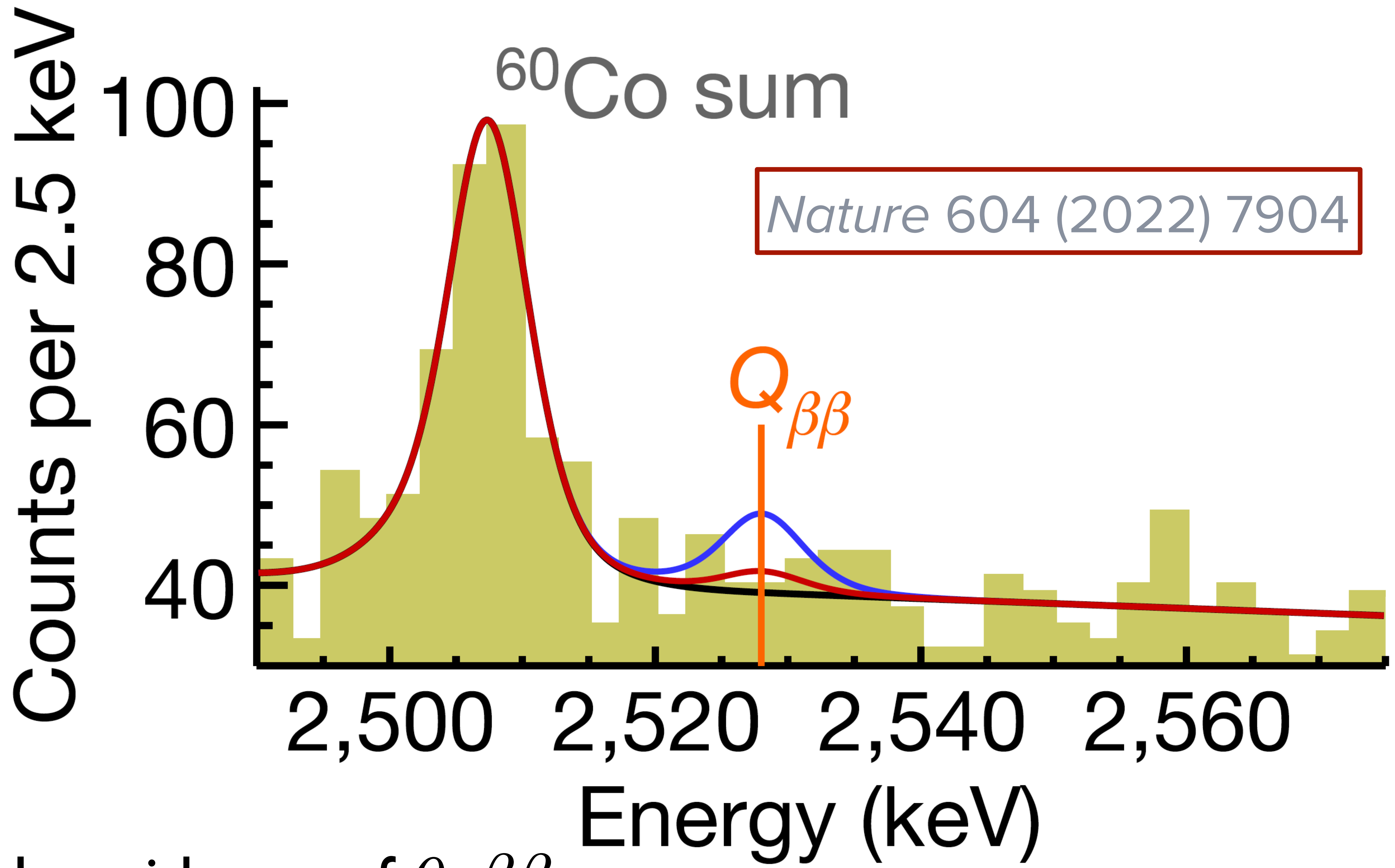
Fit parameters:

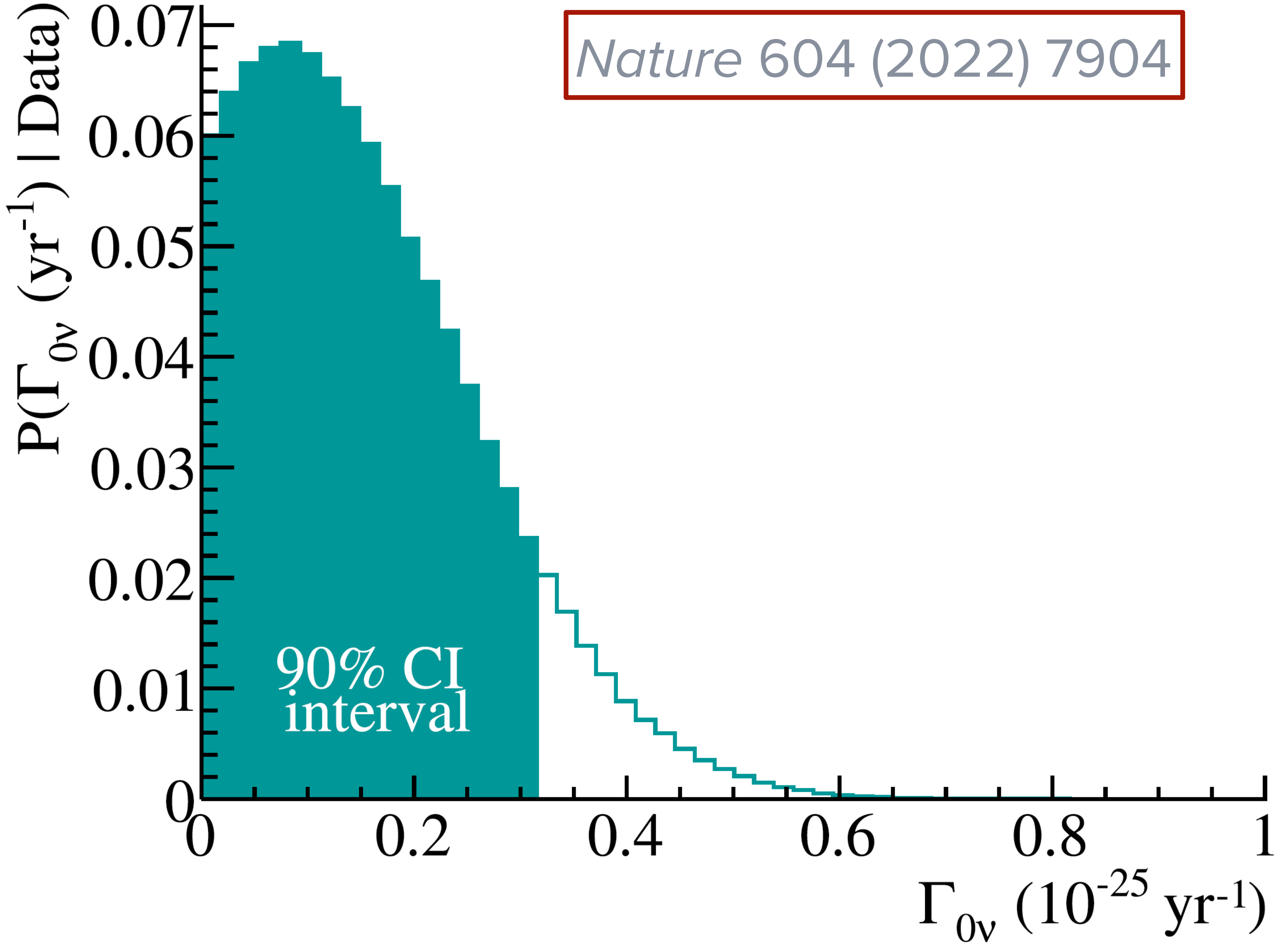
- $0\nu\beta\beta$ decay rate @ 2527.518 keV
- ^{60}Co sum peak amplitude
- Background index
- Background slope

Systematics:

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

Fit to ROI

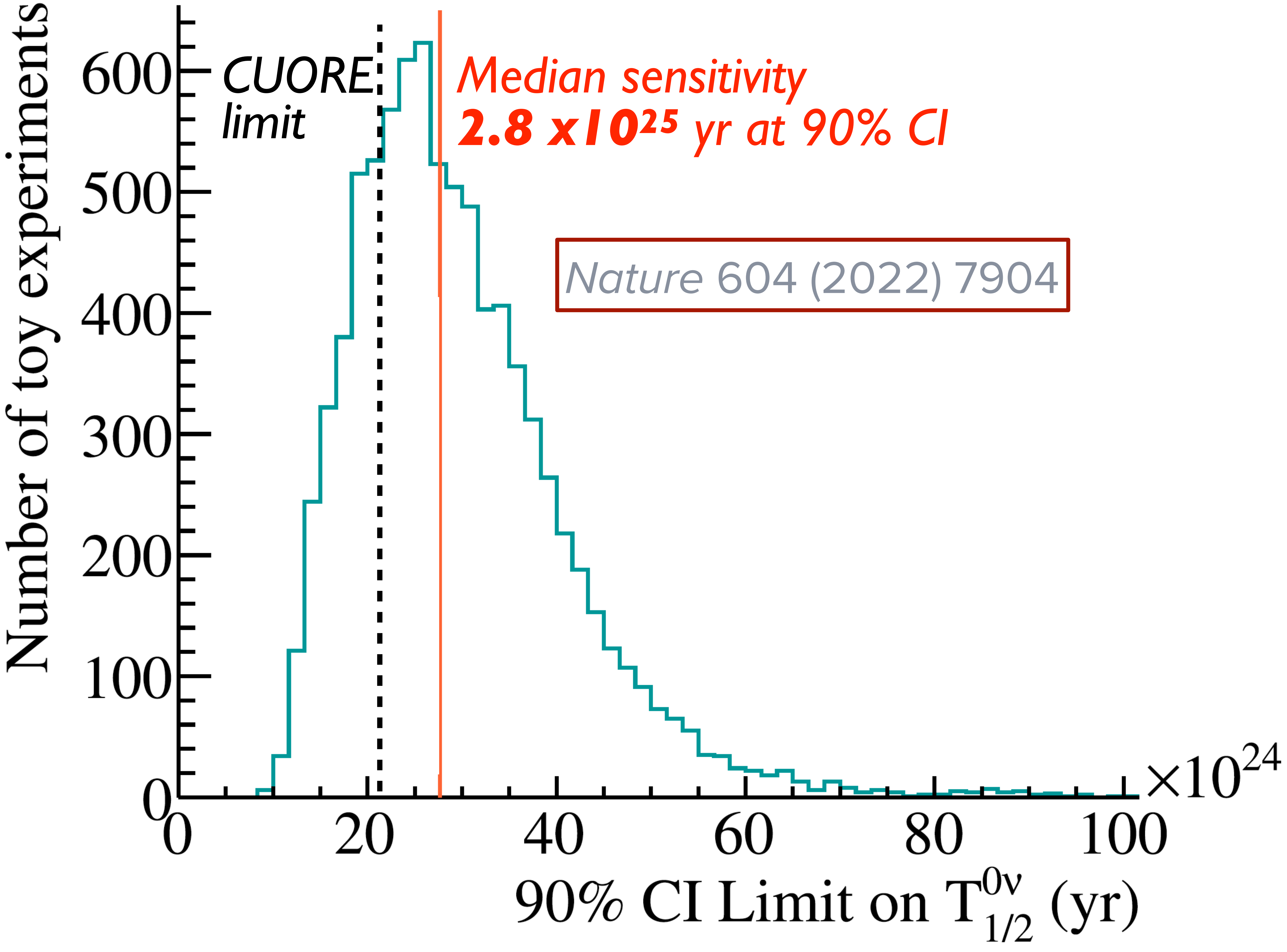




- No evidence of $0\nu\beta\beta$
- Best fit rate: **(0.9 ± 1.4)x10^{-26}** yr^{-1}
- Background index = **1.49(4)x10^{-2}** cts/keV/kg/yr
- $T^{0\nu}_{1/2}$ > **2.2 x10^{25}** yr at 90% C.I

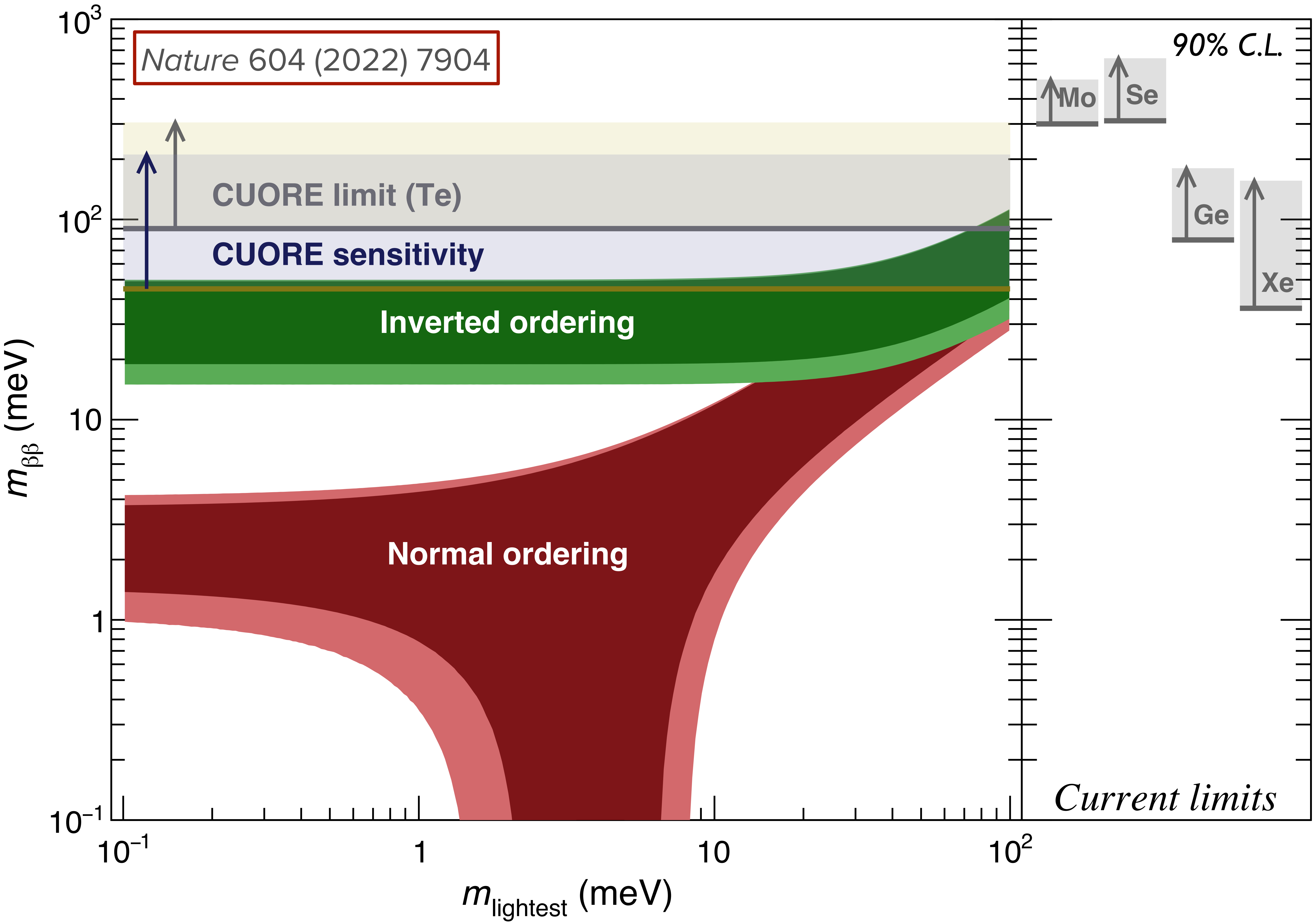
Sensitivity

- Sensitivity calculated by generating 10k toy experiments assuming no signal
  - Toys generated using linear background and ^{60}Co components
  - Fit with signal + background
- Median expected $T^{0\nu}_{1/2}$= **2.8 x10^{25}** yr at 90% CI
- Probability of getting a stronger limit is 72%



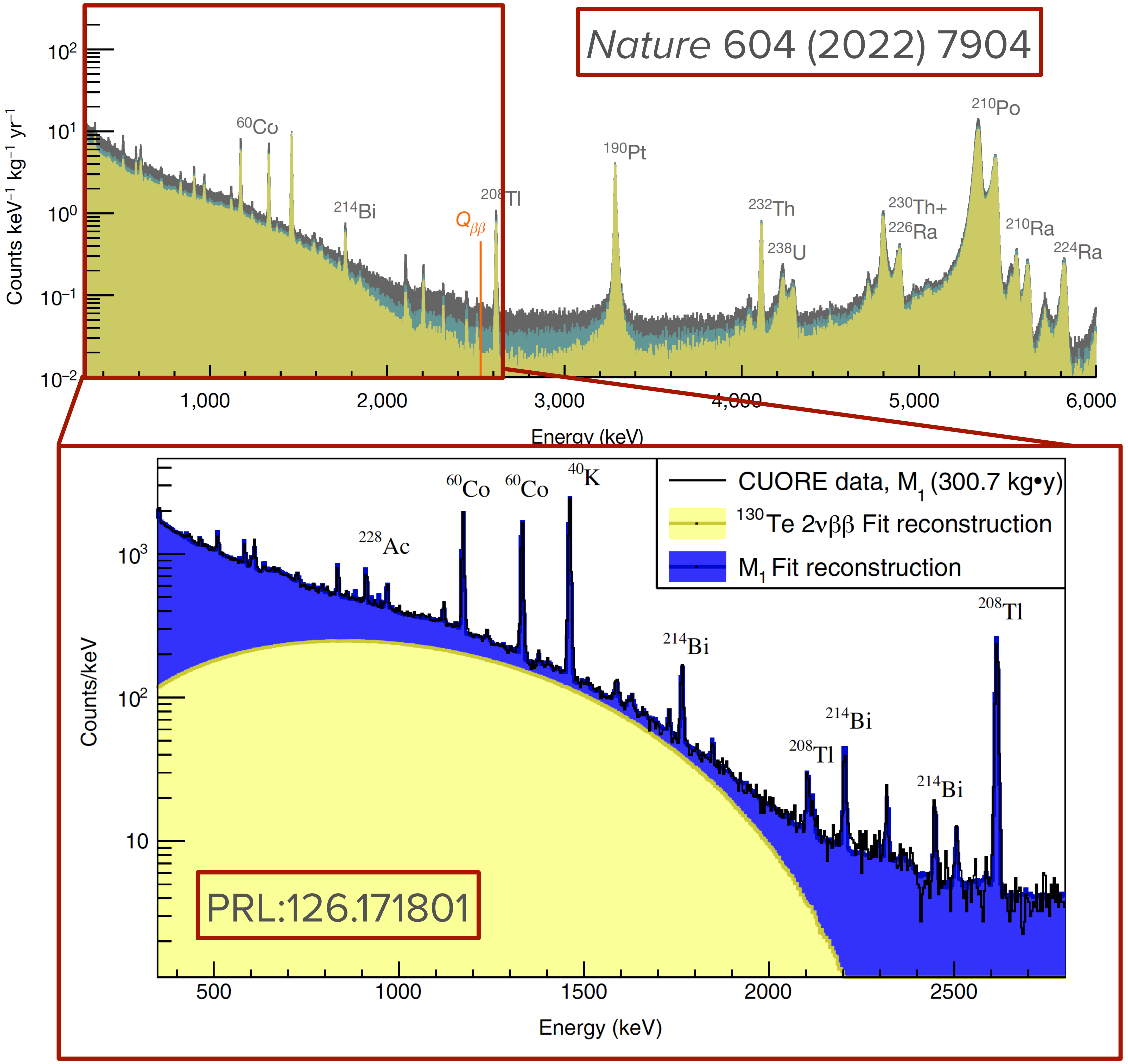
Limit on Effective Majorana Mass

- $T^{0\nu}_{1/2}$ > **2.2 x10^{25}** yr at 90% C.I
- Assuming light neutrino exchange: $m_{\beta\beta}$ < **90 - 305 meV**
- Uncertainities in nuclear matrix elements dominates the range
- Sensitivity (5 yr data taking): ^{130}Te $T^{0\nu}_{1/2}$ > **9.0 x10^{25}** yr $m_{\beta\beta}$ < **50 - 130 meV**



^{130}Te $2\nu\beta\beta$ Decay Half-life

- CUORE background model: 60 radioactive contaminants + muons + $2\nu\beta\beta$
- Perform simultaneous Bayesian fit to 62 MC simulated spectra
- $2\nu\beta\beta$ rate extracted as marginalized posterior PDF
- Most precise measurement of ^{130}Te half-life with exposure of **300.7** kg · yr
- Refined background model in preparation



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$$T^{2\nu}_{1/2}(^{130}Te) = 7.71^{+0.08+0.12}_{-0.06-0.15} \times 10^{20} yr$$

Conclusions

- CUORE is the largest ultra-cryogenic calorimeter searching for $0\nu\beta\beta$
- 5 years and running
- More than tonne.yr data analyzed and almost twice as much data collected
- Good energy resolution (**7.8 keV FWHM at $Q_{\beta\beta}$**) and low backgrounds (**1.4×10^{-2} cts/keV./kg./yr**) demonstrated
- Limits placed on ^{130}Te $T^{0\nu}_{1/2}$ > **2.2×10^{25}** yr and $m_{\beta\beta}$ < **90- 305 meV**
- CUPID plans to perform one of the most sensitive searches for $0\nu\beta\beta$

Thank you