Searching for $0\nu\beta\beta$ decay with CUORE and CUPID

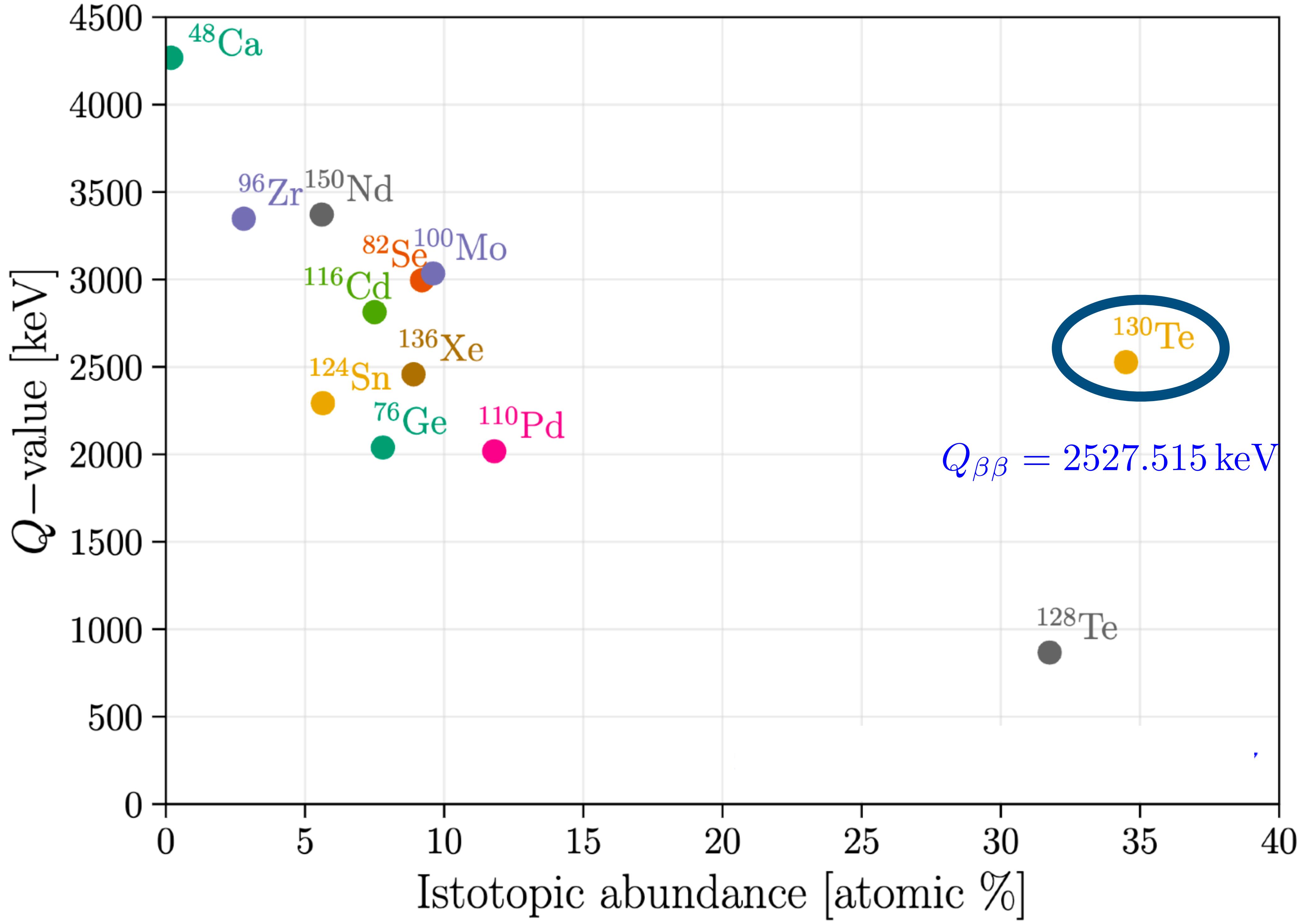
Jorge Torres (Yale), for the CUORE/CUPID collaborations
Dec 1, 2023 (DNP/DBD Meeting, Hawaii)

Wright Laboratory

Yale

CUORE CUPID

Cryogenic Underground Observatory for Rare Events (CUORE)



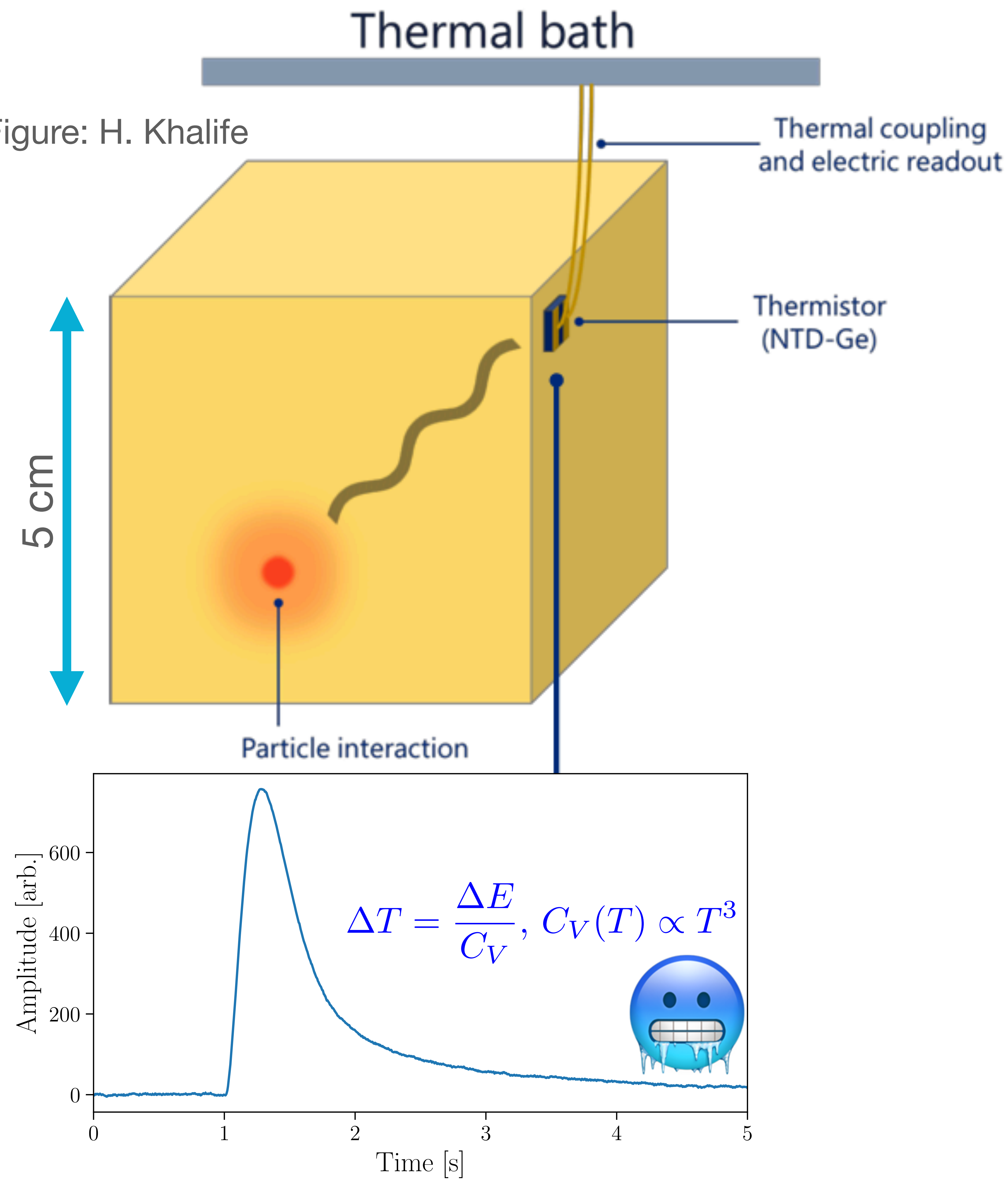
- First milli-K bolometric $0\nu\beta\beta$ decay experiment reaching one-tonne scale.
- CUORE is located in Hall A of LNGS.
- 3600 m.w.e of overburden

- Search for $0\nu\beta\beta$ in ^{130}Te (TeO_2 crystals).
- High natural abundance, adequate $Q_{\beta\beta}$, good quality of crystals.

CUORE's operation principle

CUORE bolometer

Figure: H. Khalife



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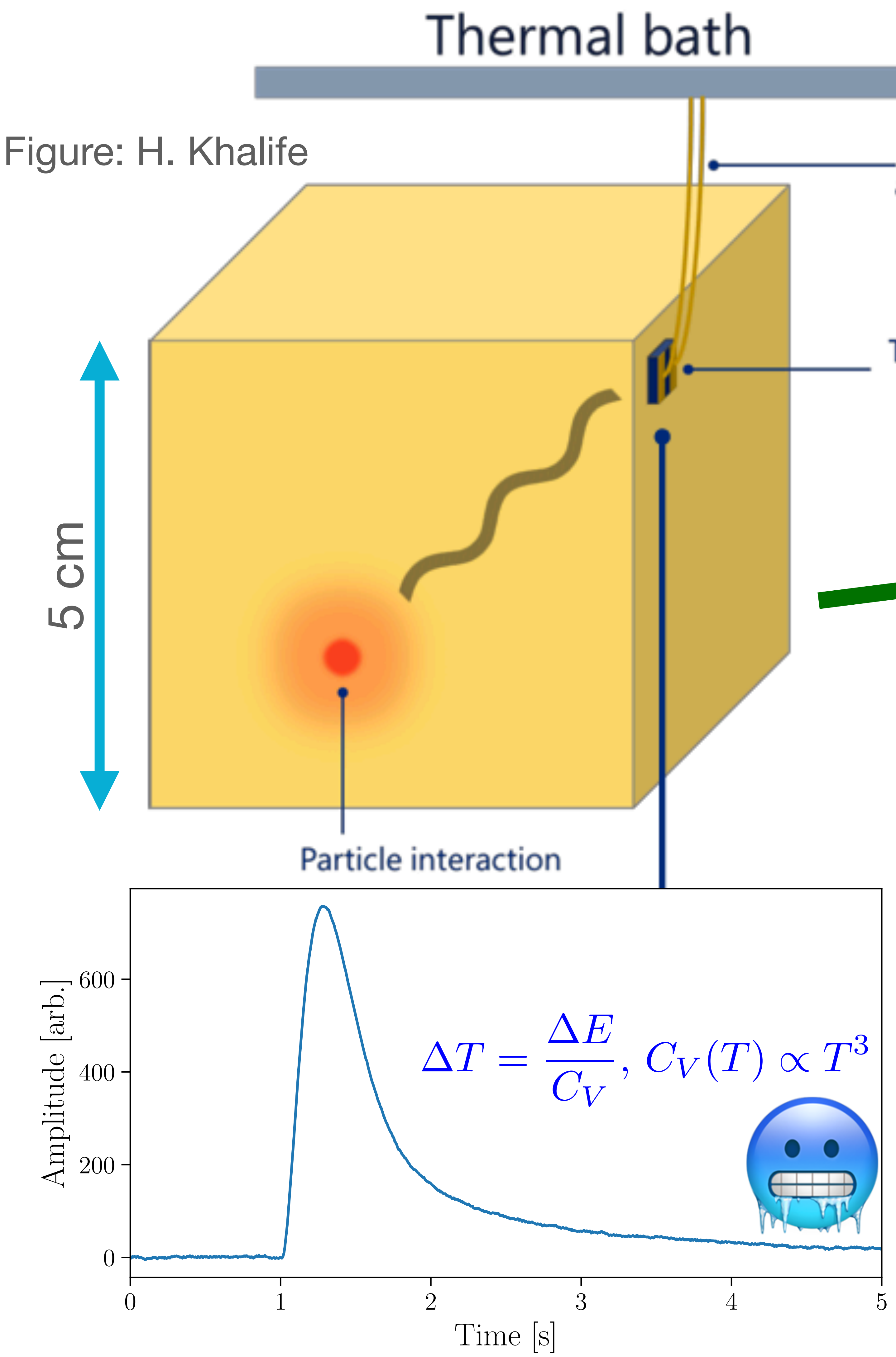

- 988 bolometers arranged in 19 towers
- Cryostat cools detectors at ~10 mK
- External and internal shields to reduce backgrounds
- Structure to minimize mechanical-induced noise.

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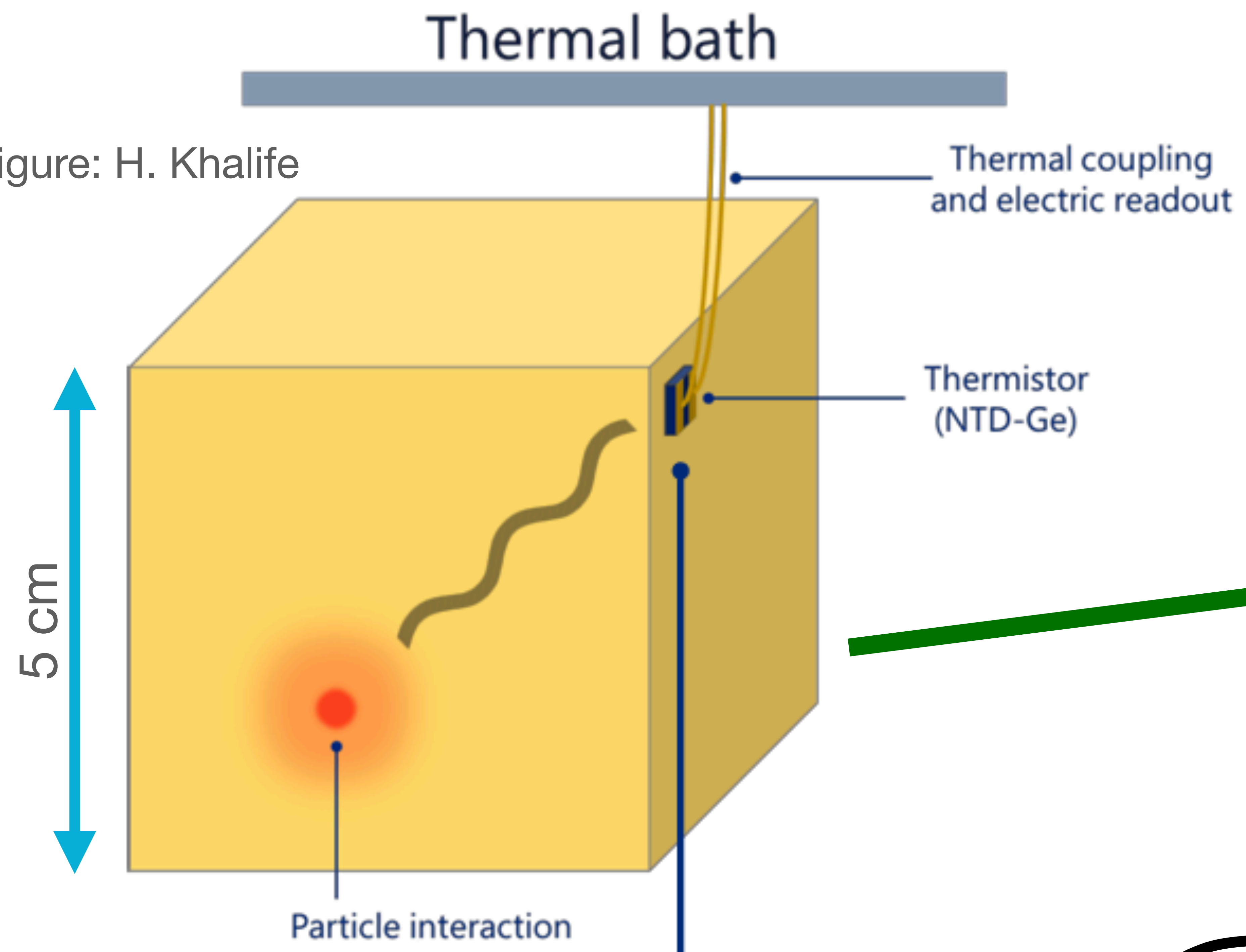

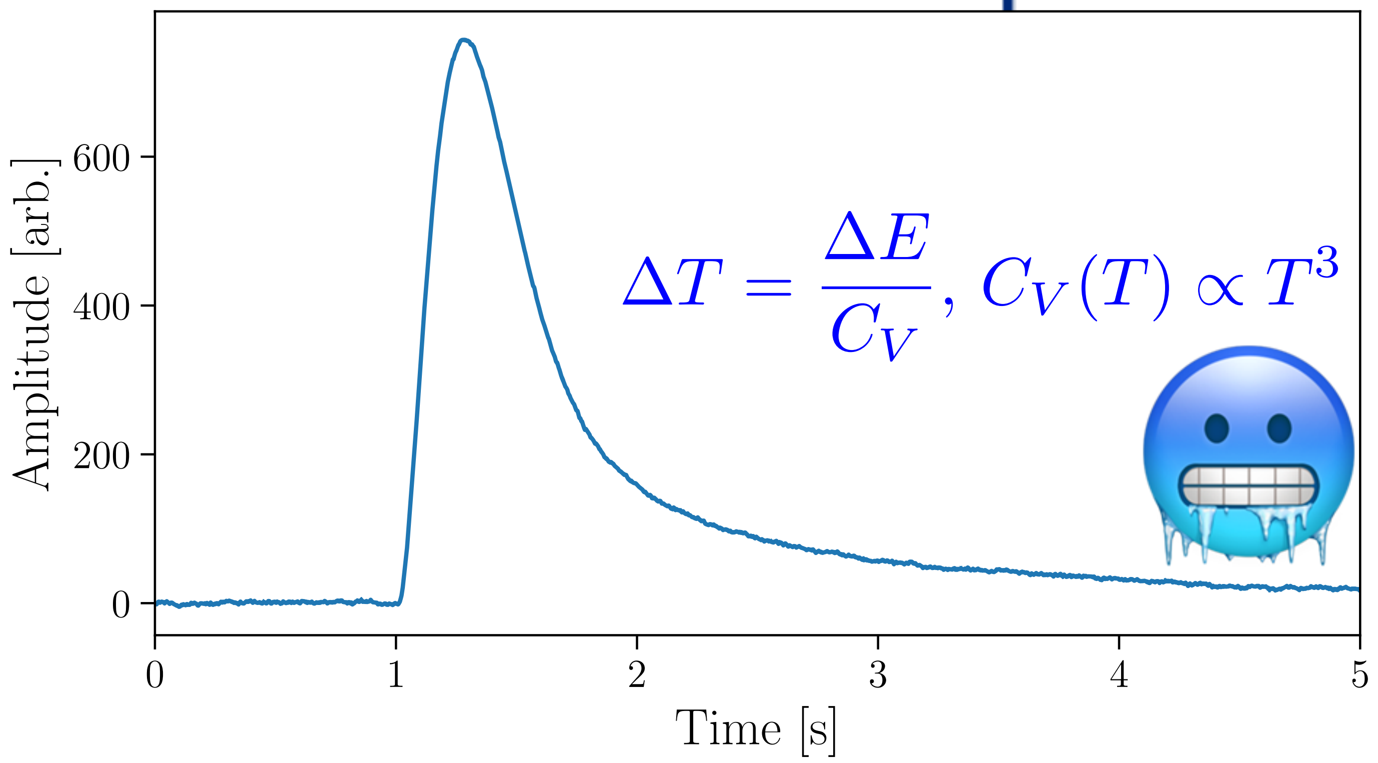

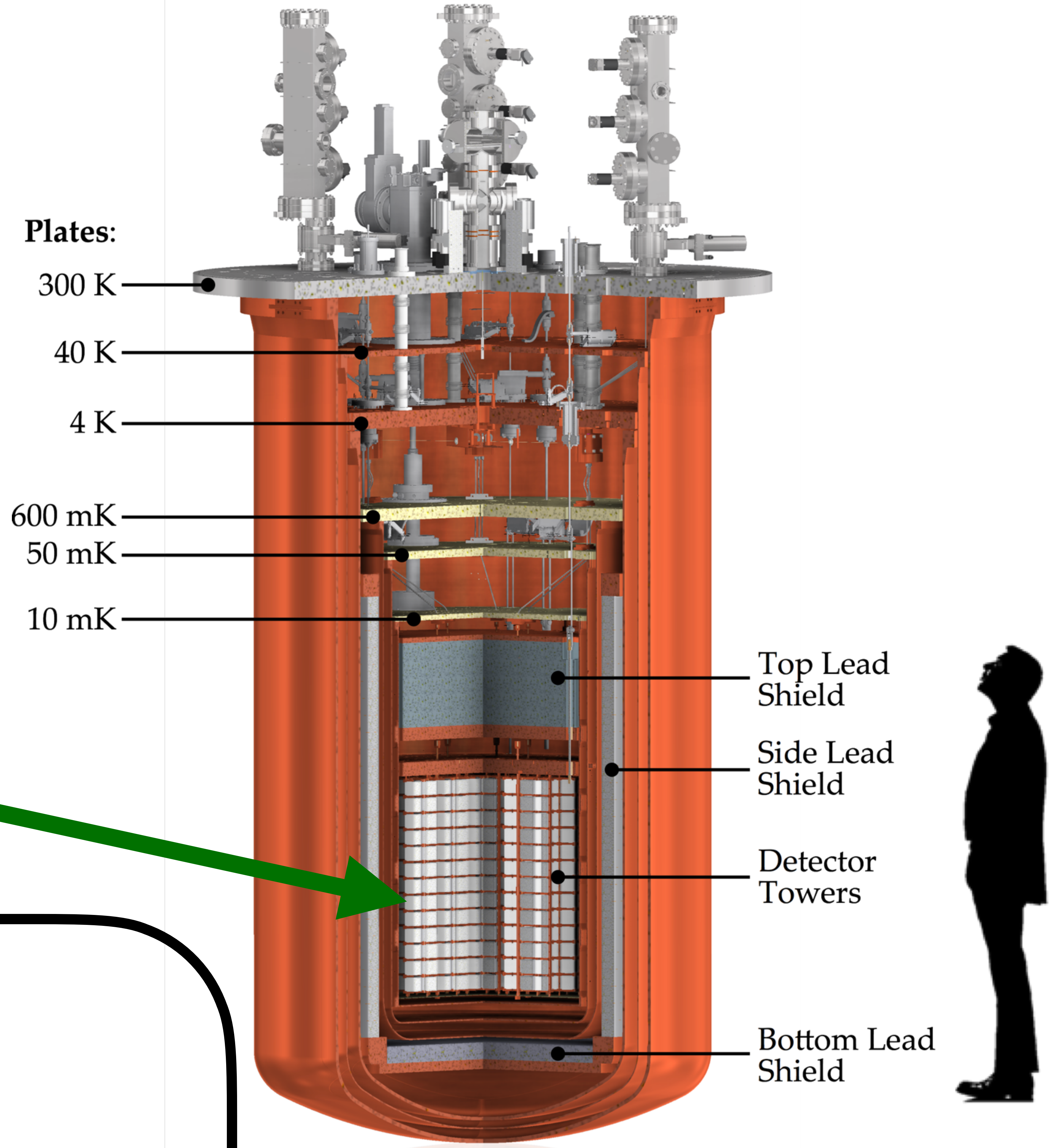

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CUORE in numbers

Mass: 742 kg of TeO_2, 206 kg of ^{130}Te

Abundance ^{130}Te: 34%

$$\mathcal{S}_{0\nu} \propto a \sqrt{\frac{M\,t}{B\,\Delta E}}$$

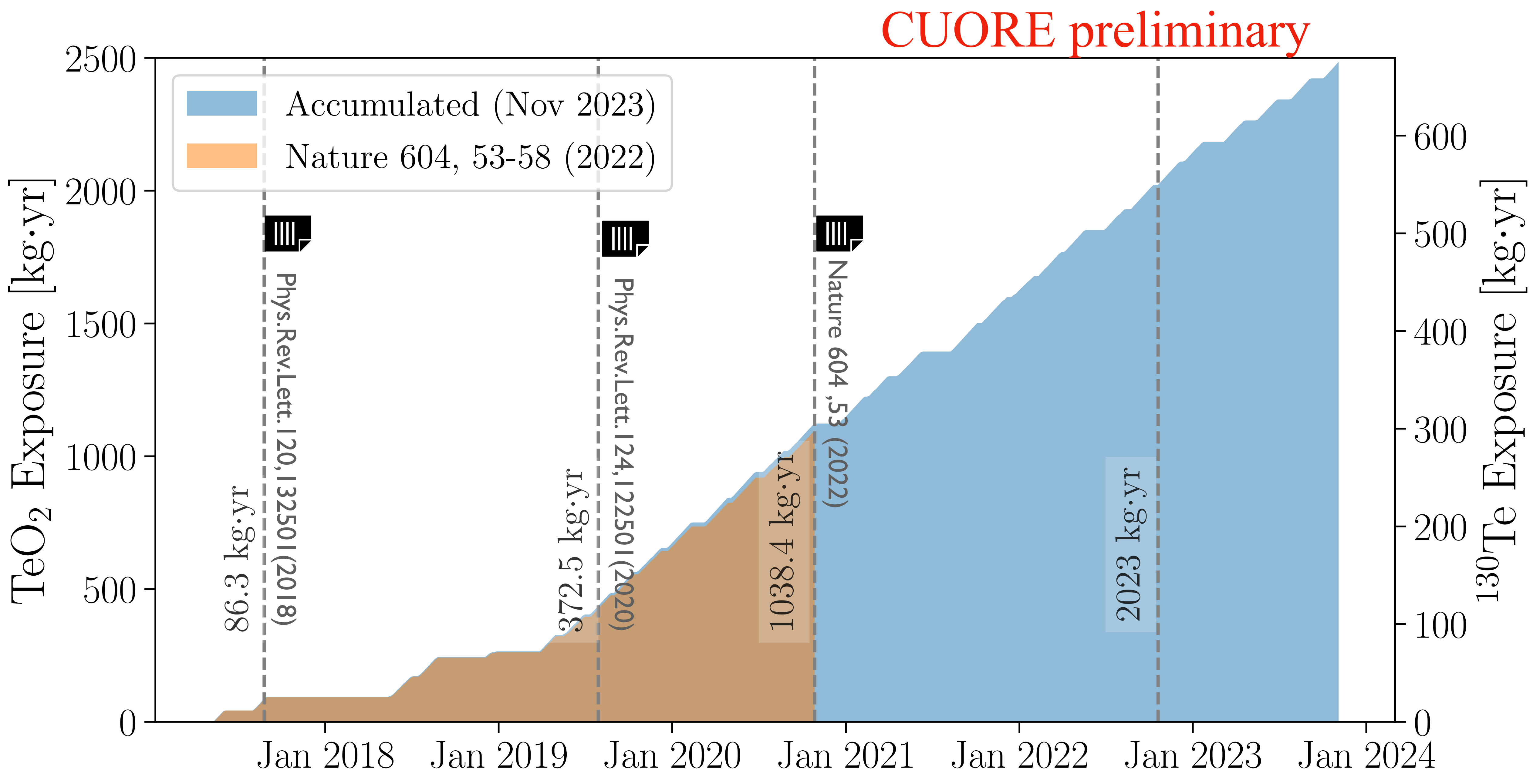
~ 50 kg·yr/month @ $> 90\%$ duty cycle

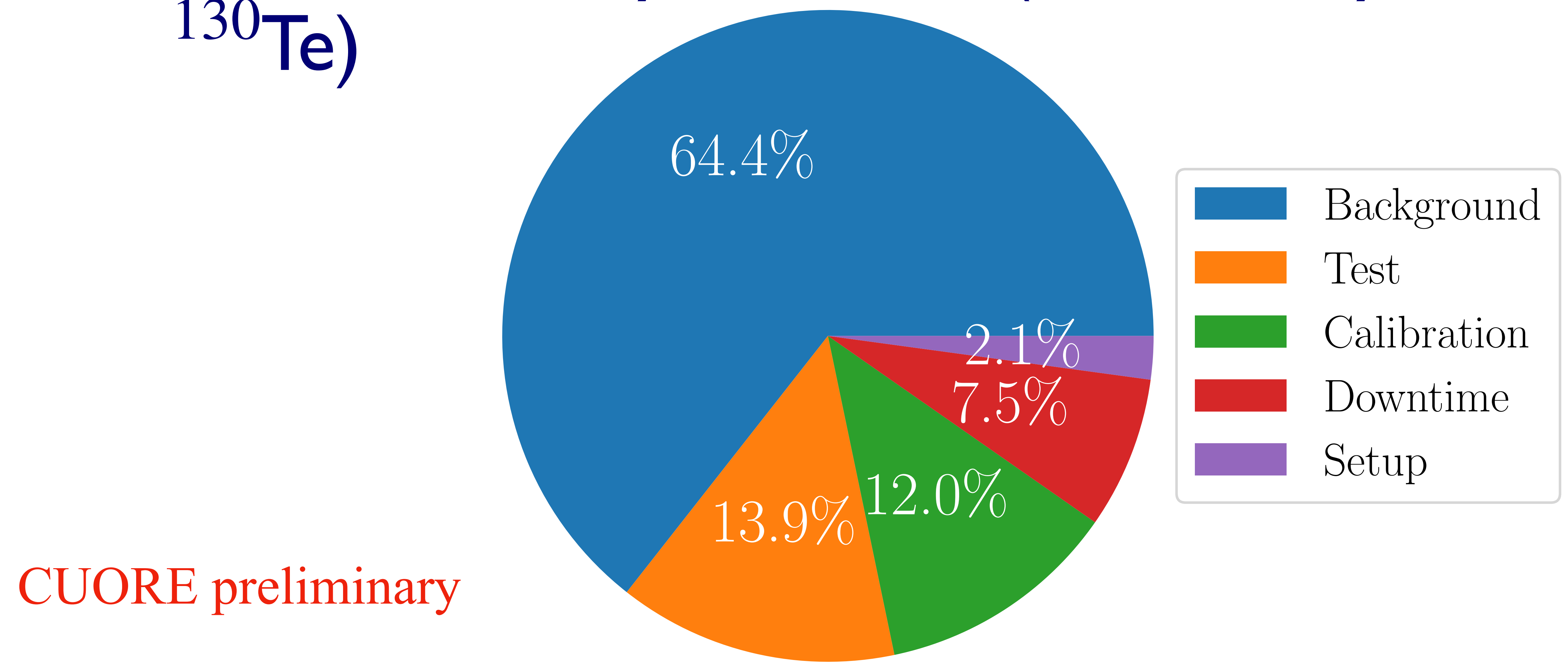
Energy resolution: $\sim 0.3\%$ at $Q_{\beta\beta}$

Background: $\sim 10^{-2}$ cts/(keV· kg·yr)

Data-taking and collected exposure

- Start of data-taking in April of 2017
- Steady collection since 2019 @ ~50 kg·yr per month
- 2 Tonne·yr (TY) exposure achieved in late 2022
- Goal: 3 tonne-yr of TeO_2 (~1 tonne-yr of ^{130}Te)





- Datasets ~1 month long.
- Calibration runs at start/end of dataset.
- Uptime close to 90%.

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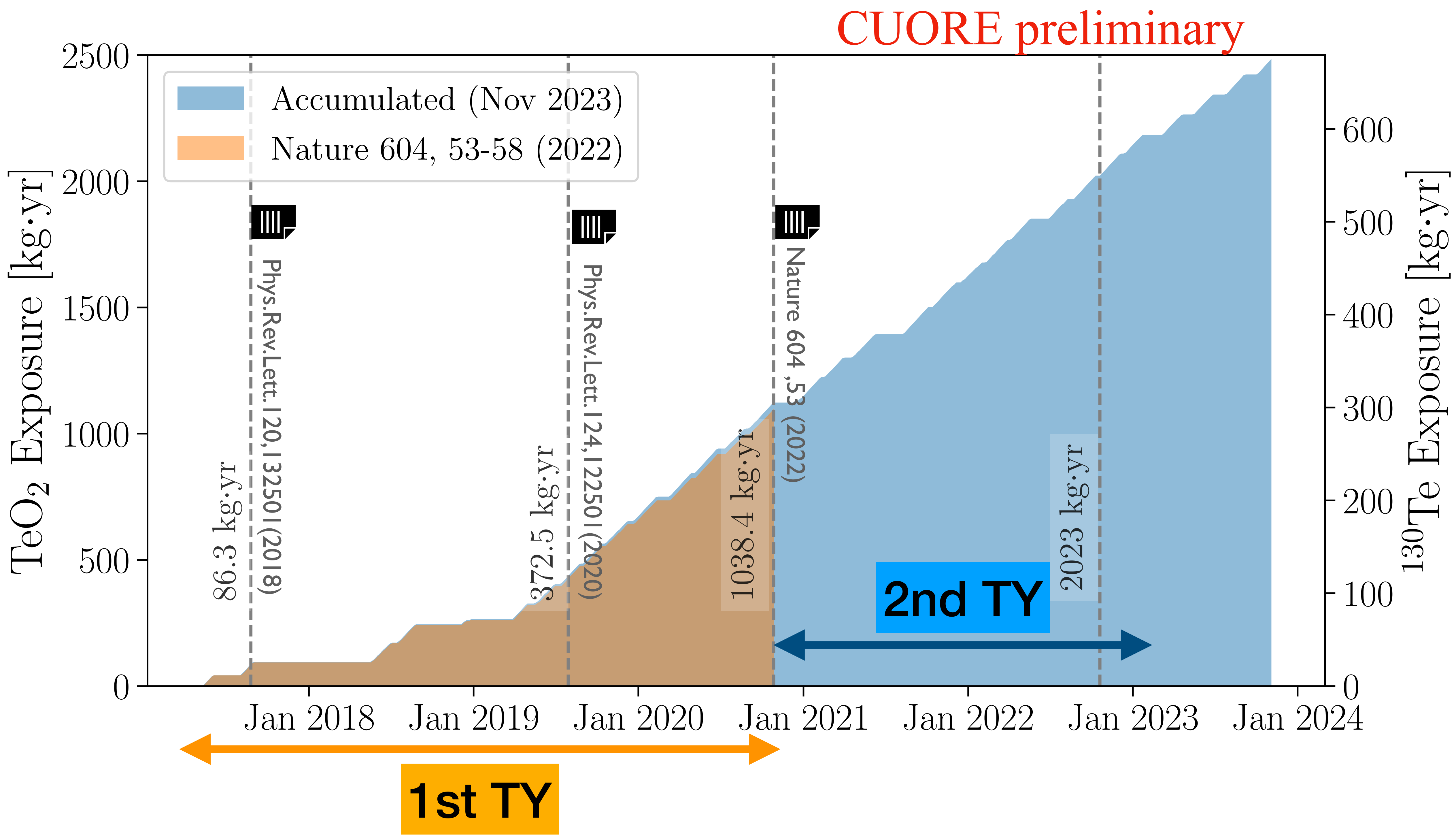

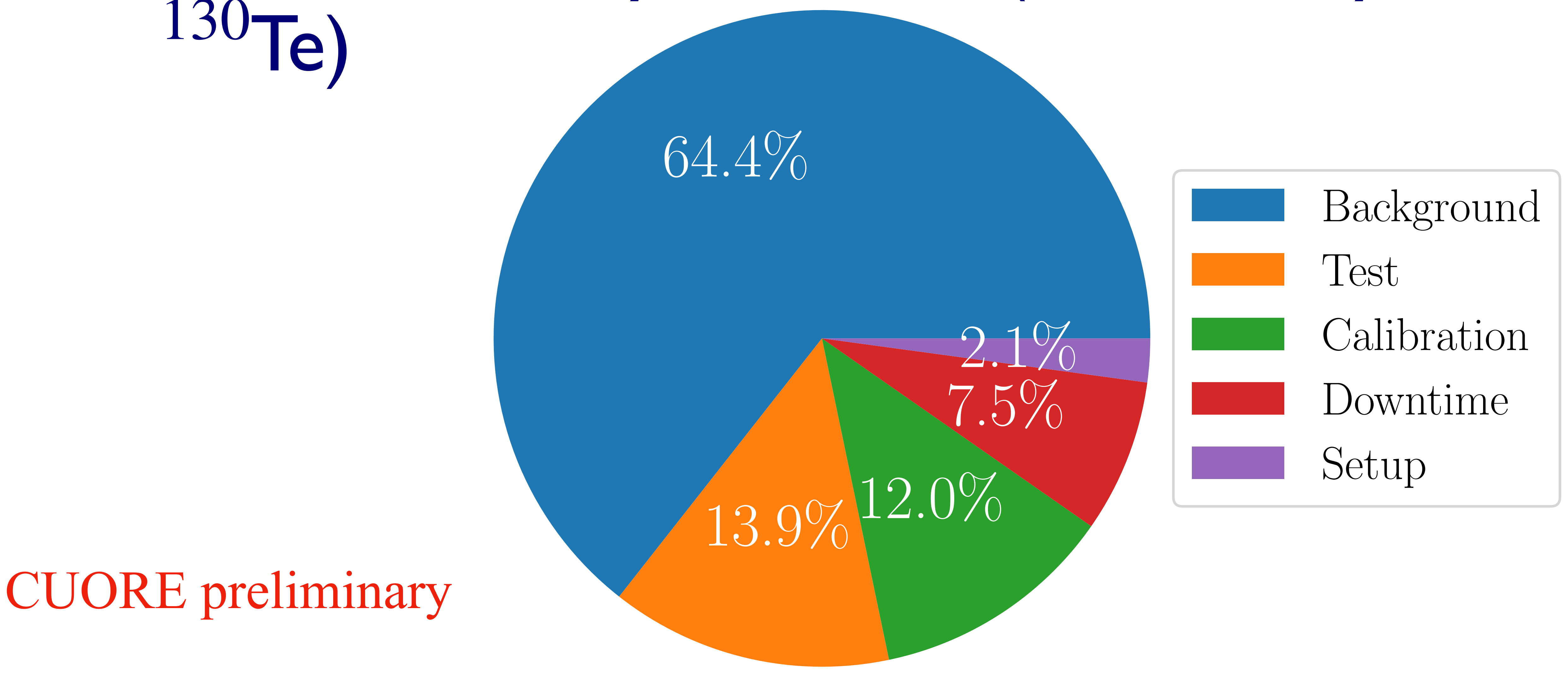

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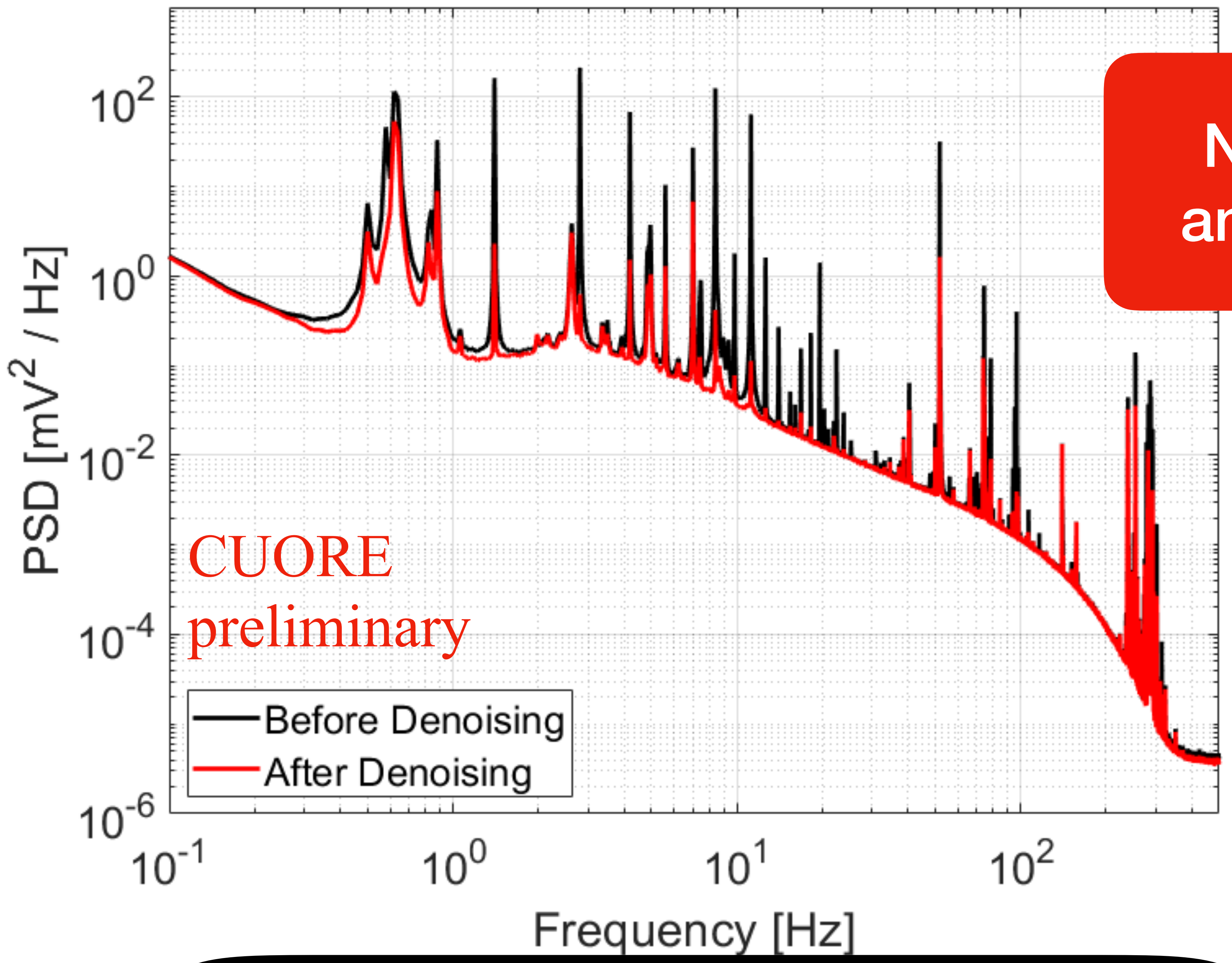
Signal processing

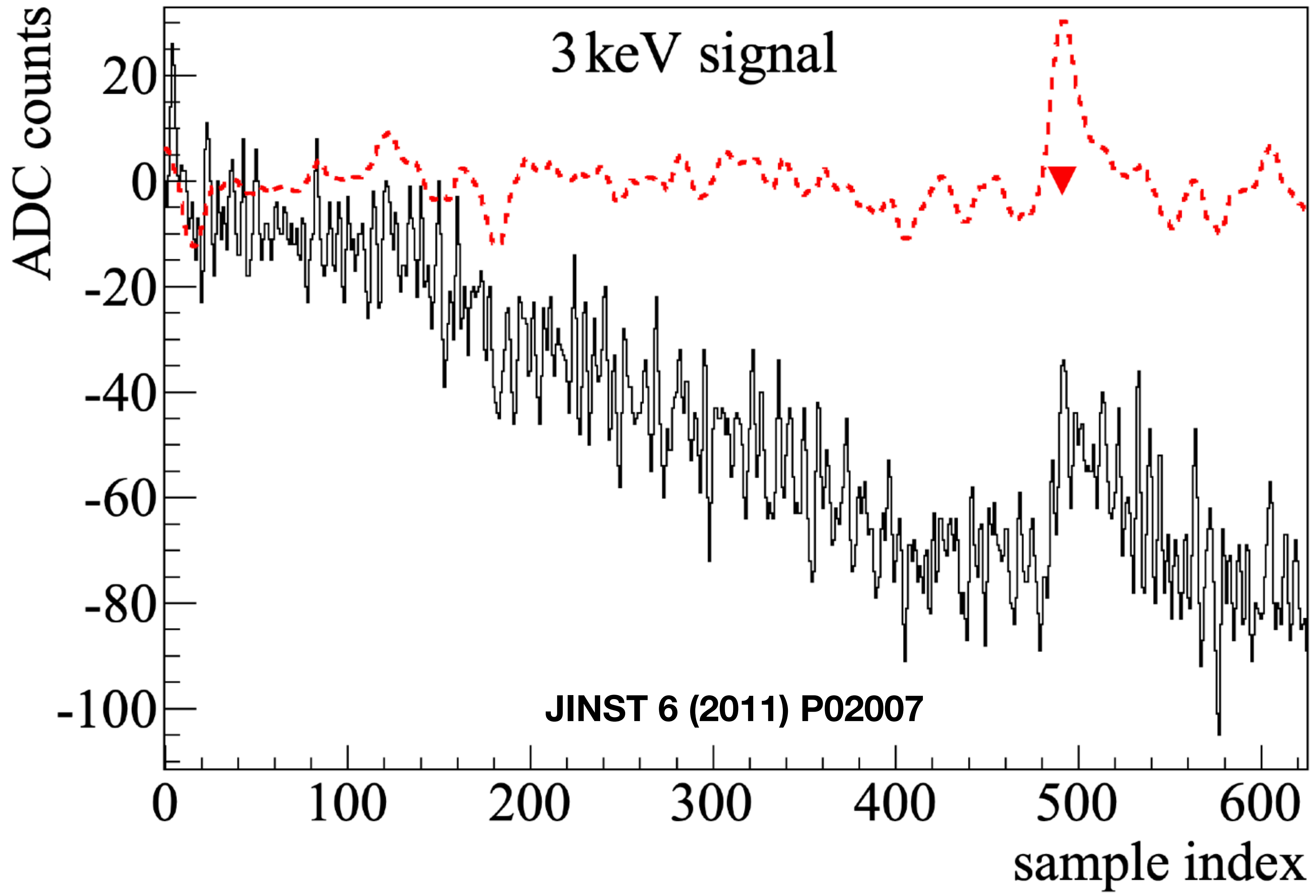
Denoising algorithm



New to analysis.

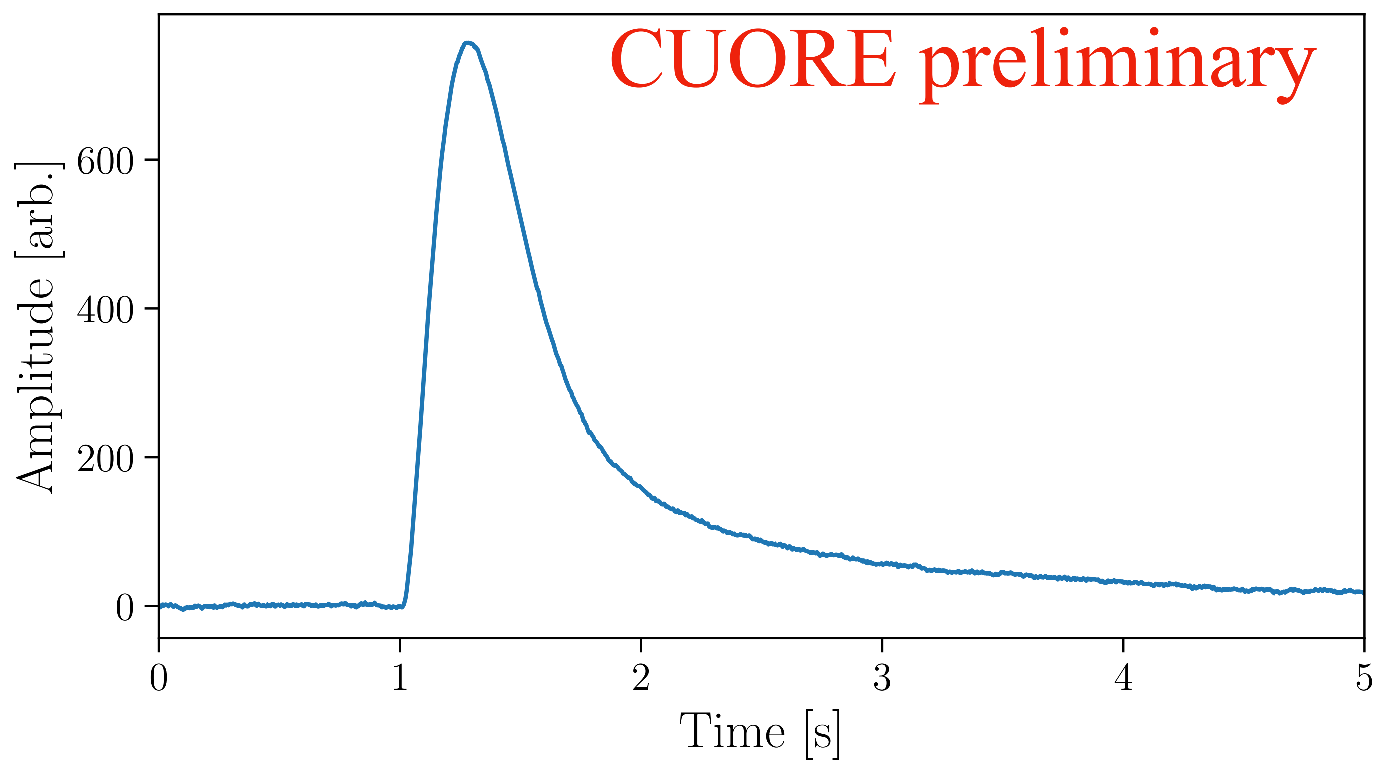
- Mitigation of noise by correlating vibrations with aux. devices (accelerometers, microphones, …)

Optimum trigger algorithm



- Application of filter that optimizes SNR using template.
- Identification of pulses and lowering energy thresholds.

Energy reconstruction



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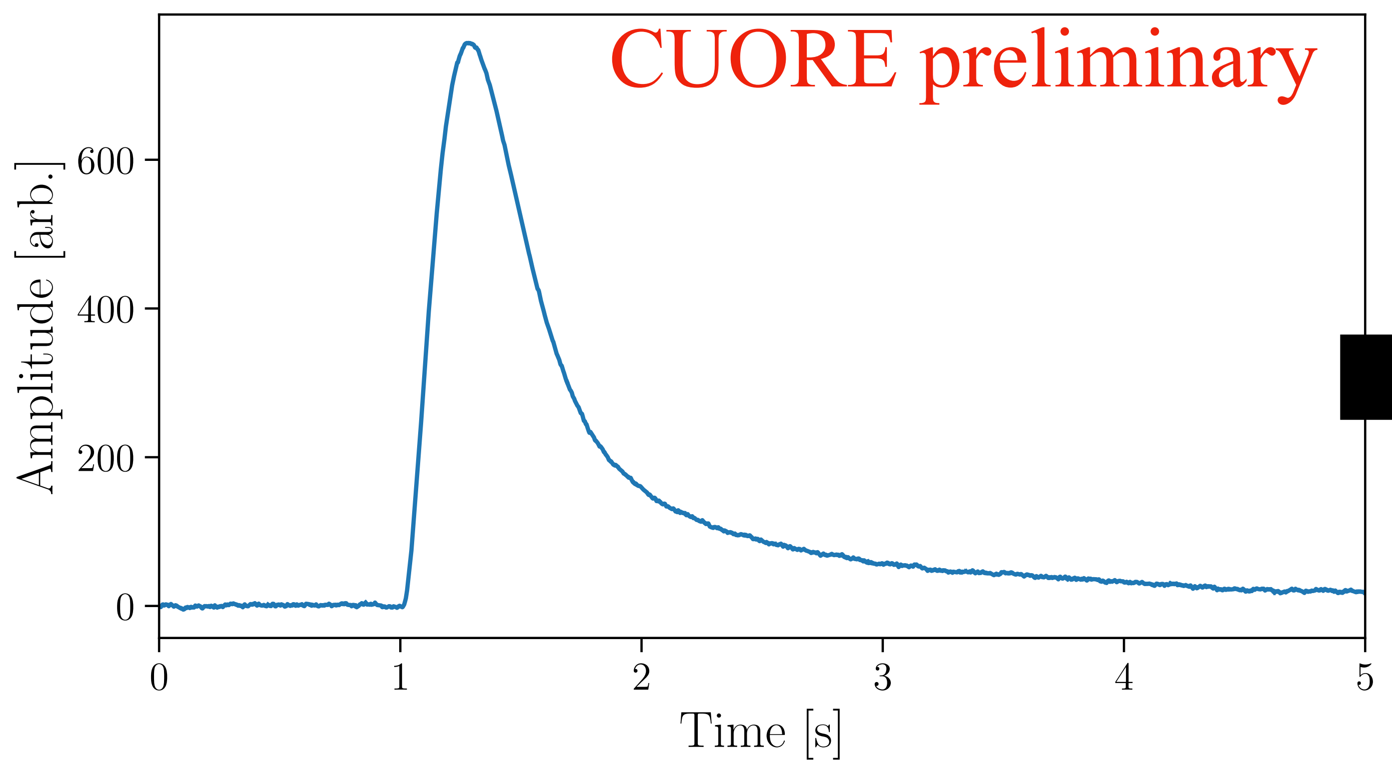
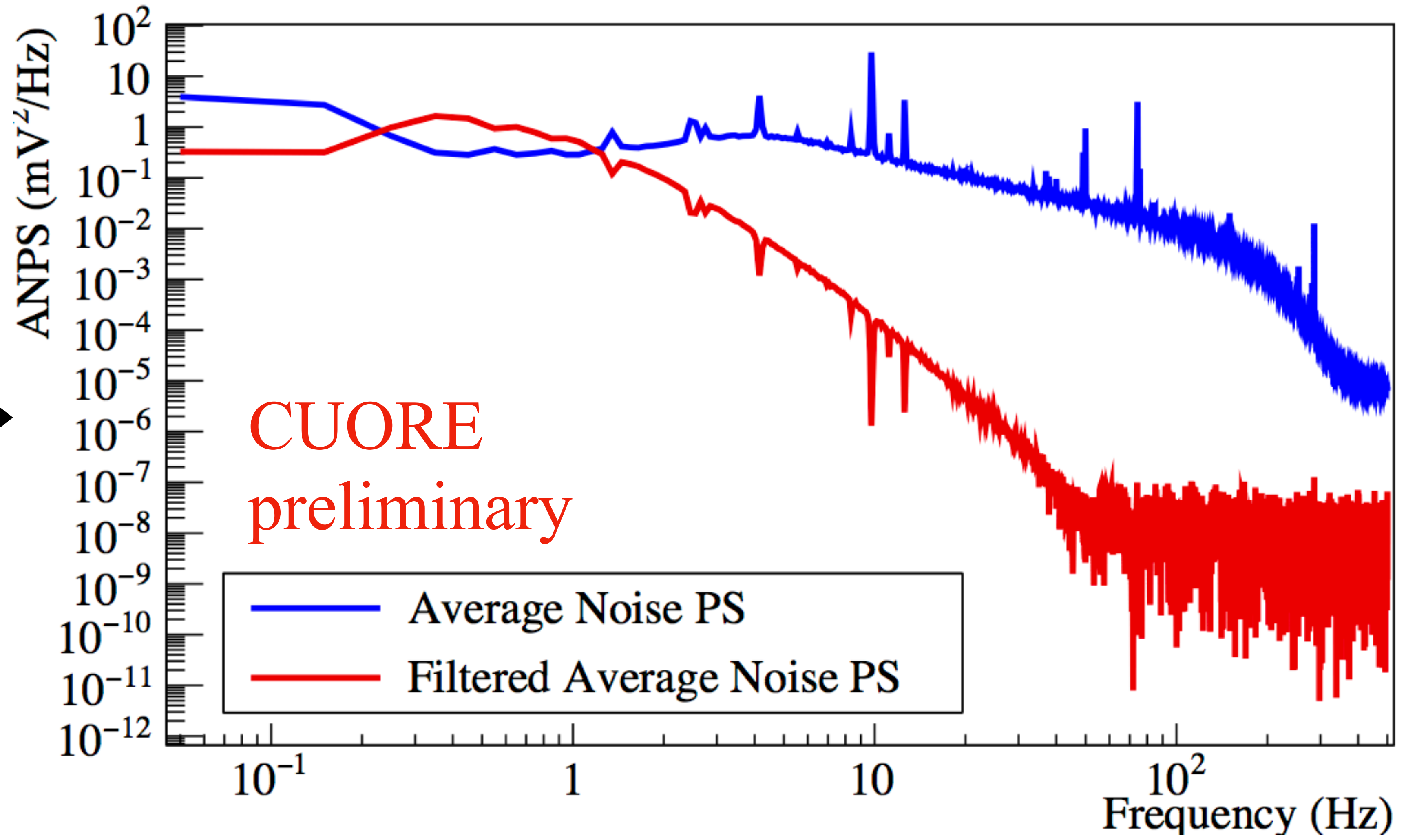
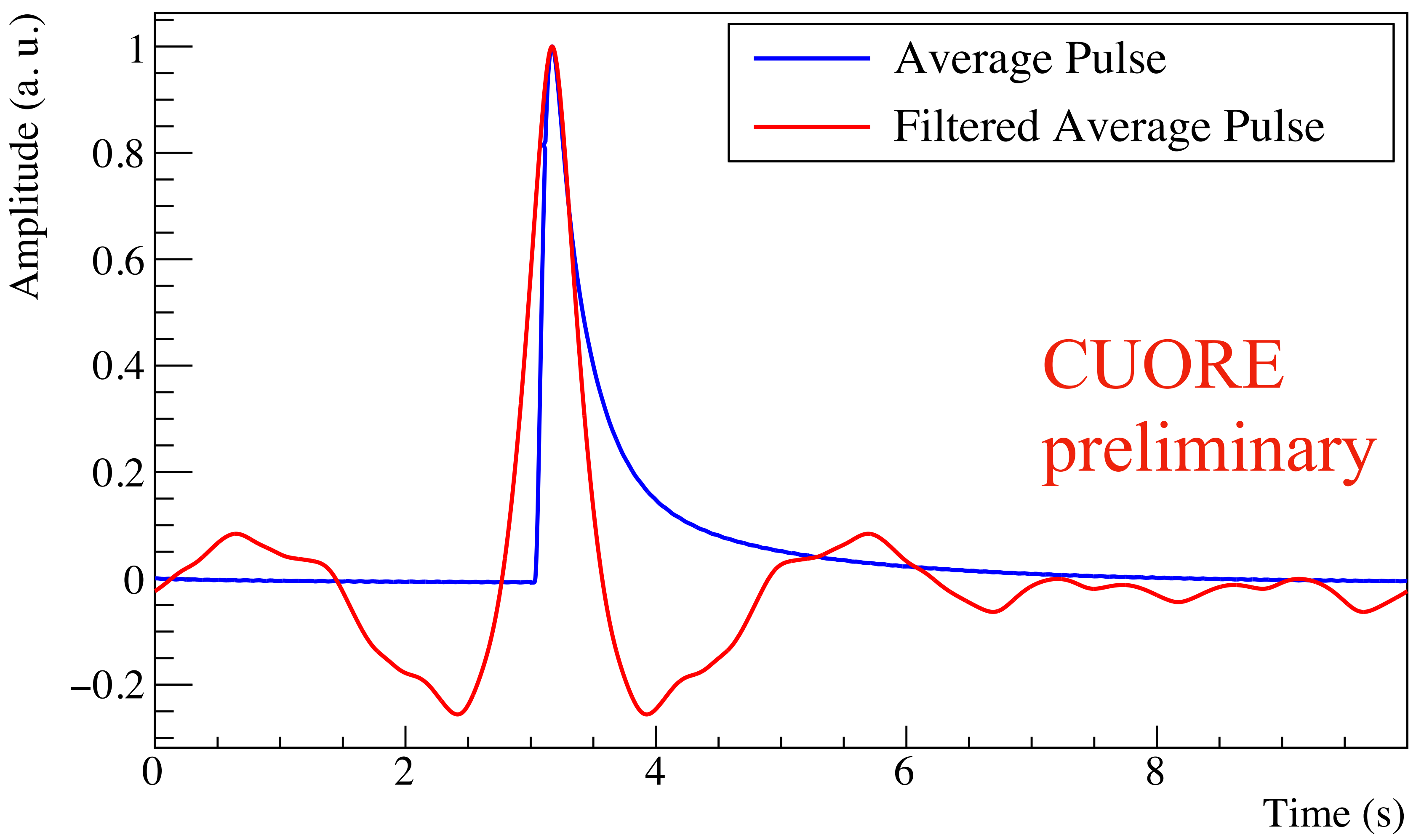


- Matched filter maximizes singnal-to-noise ratio.





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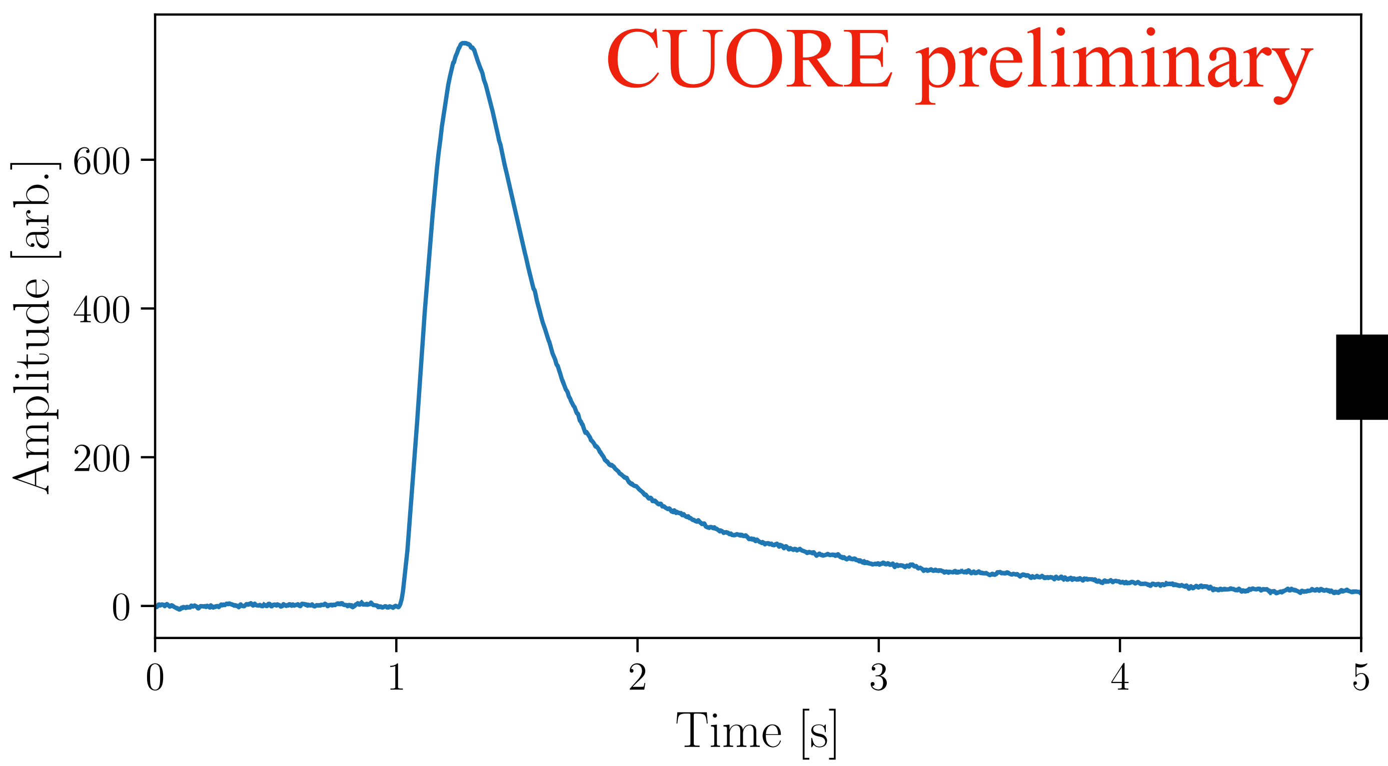
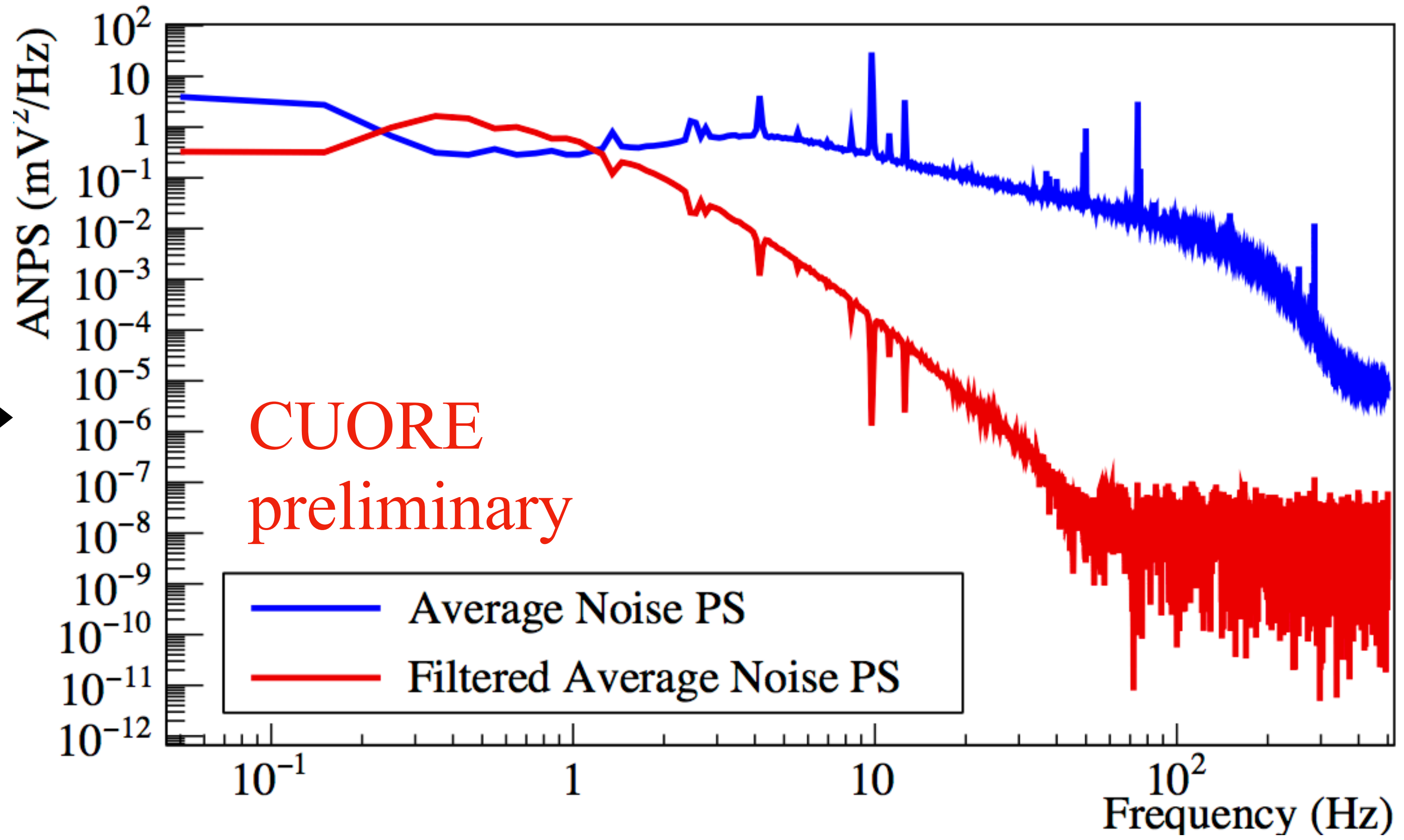
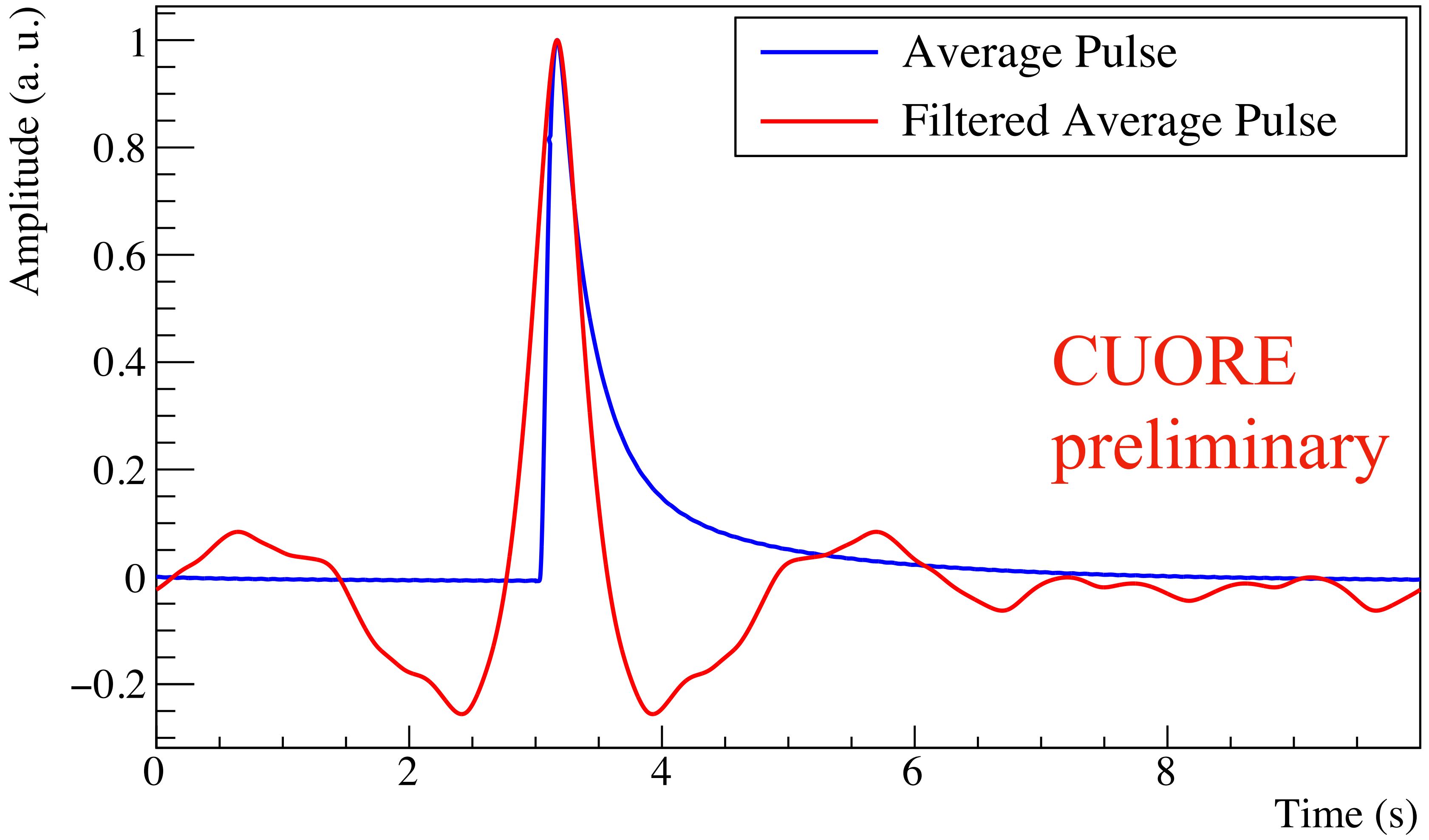
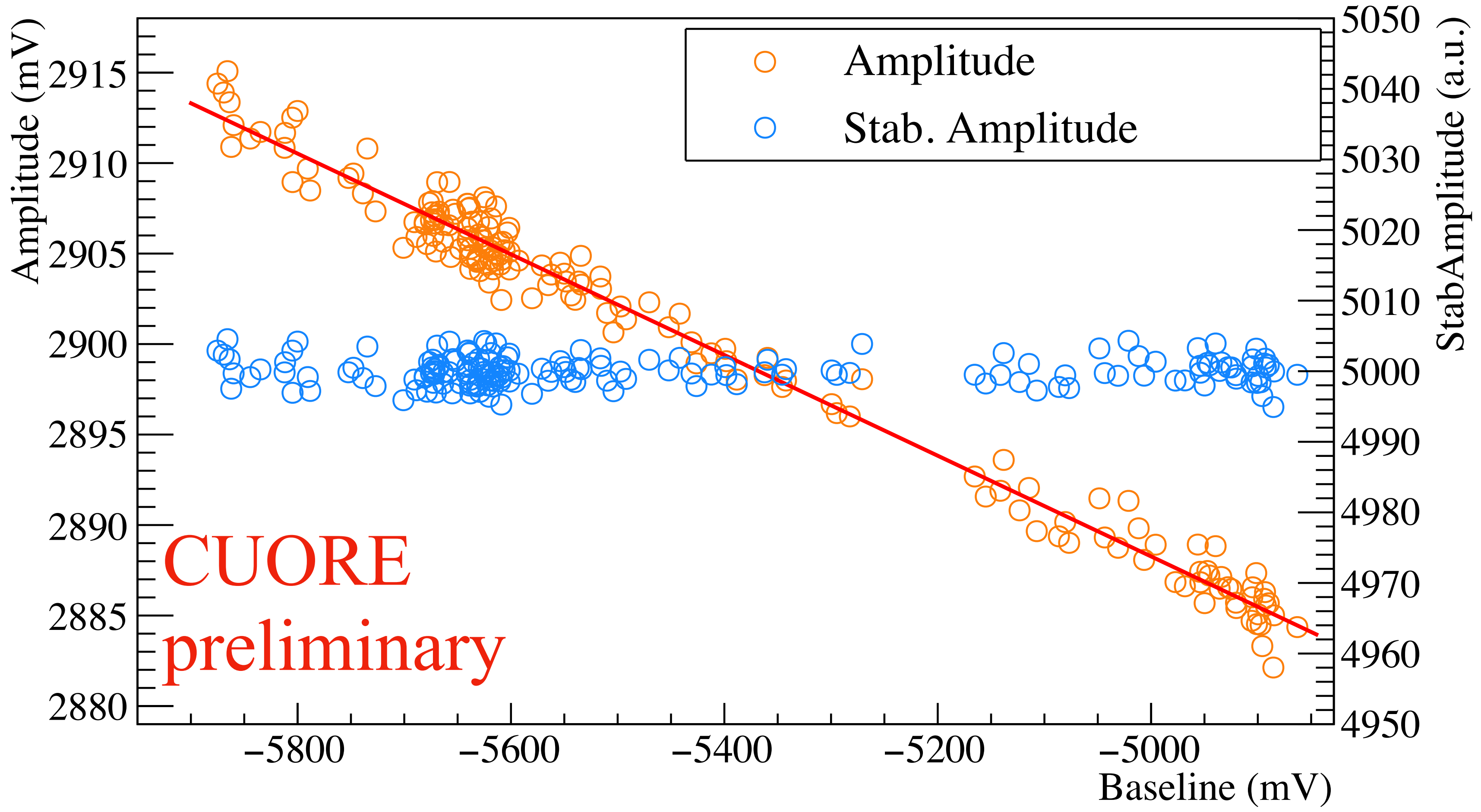






- Matched filter maximizes singnal-to-noise ratio.
- Fixed-energy pulses from heaters to correct thermal gain drifts.



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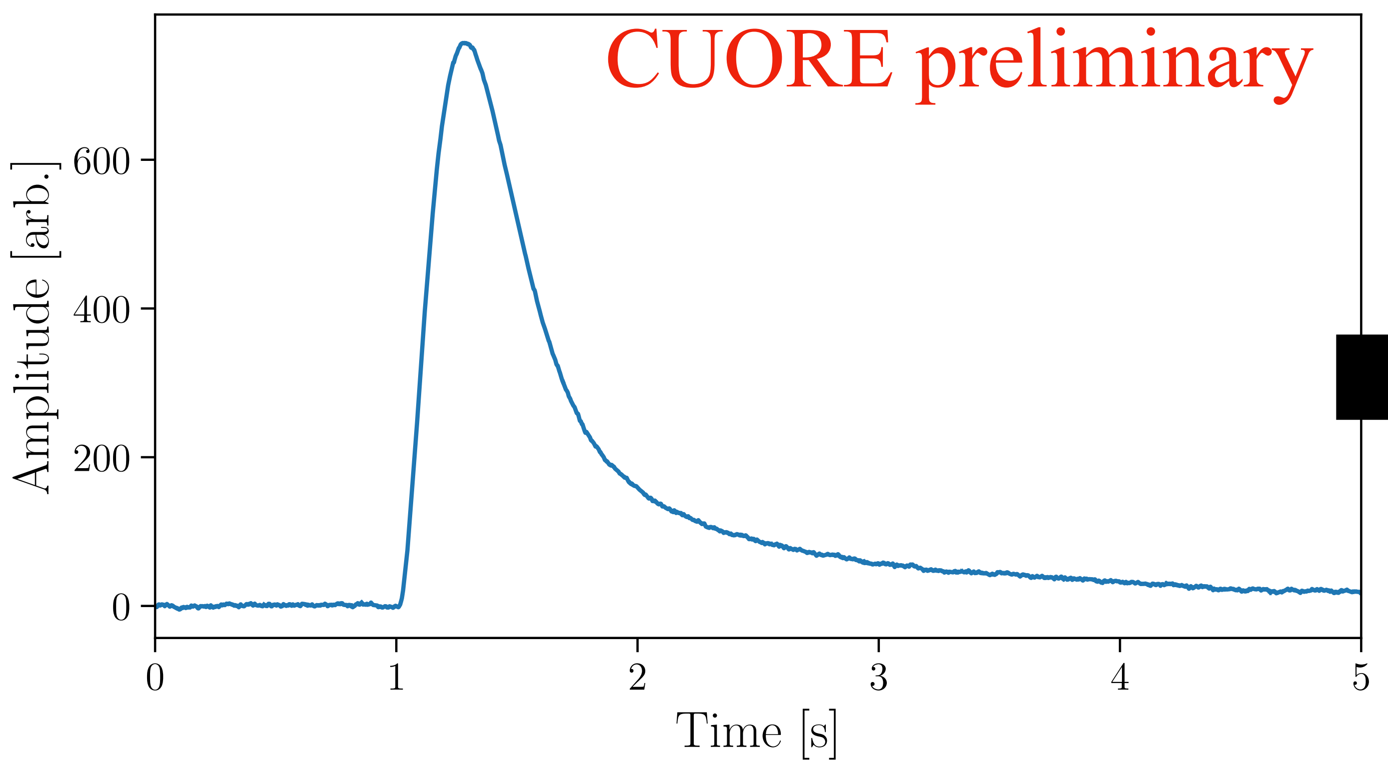
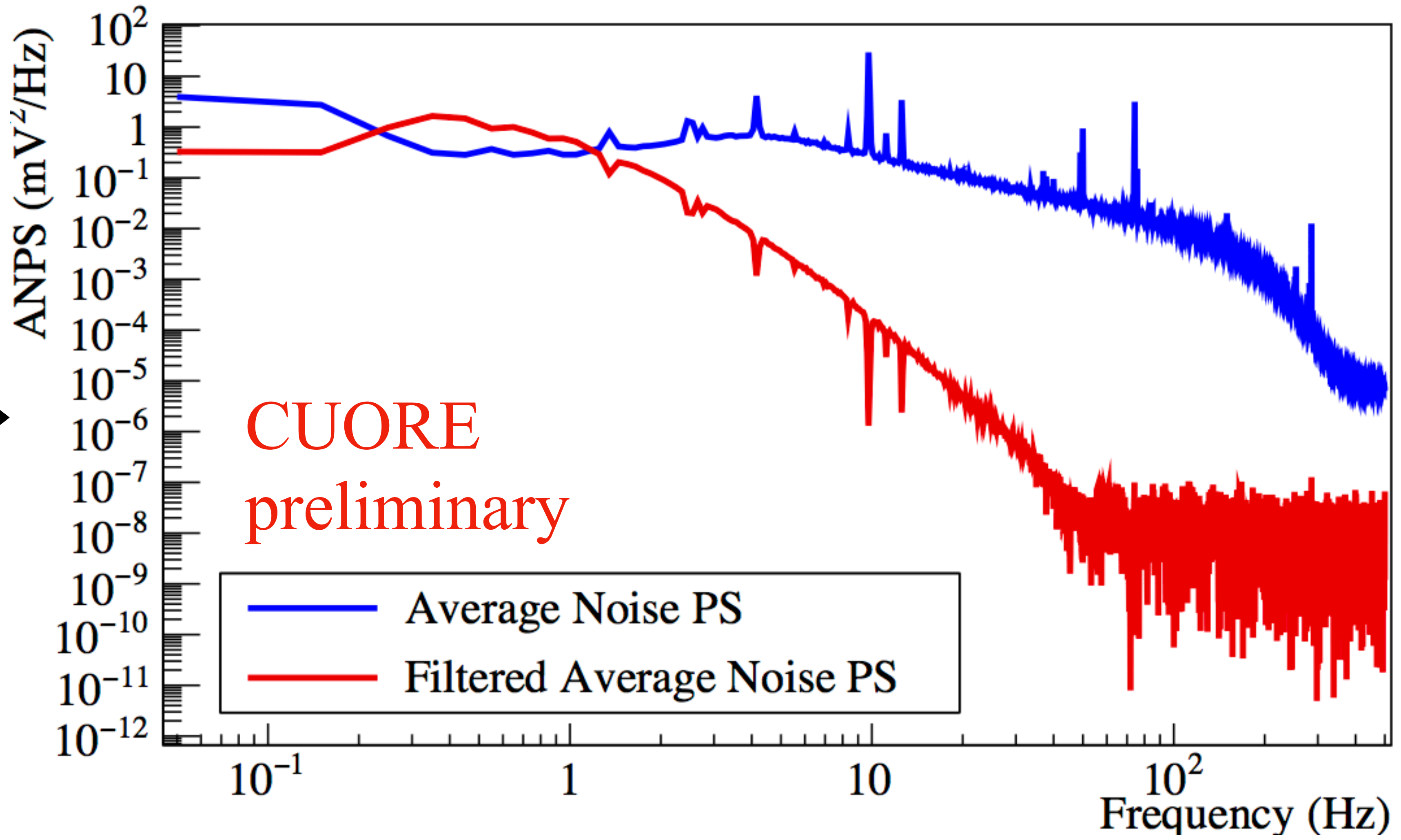
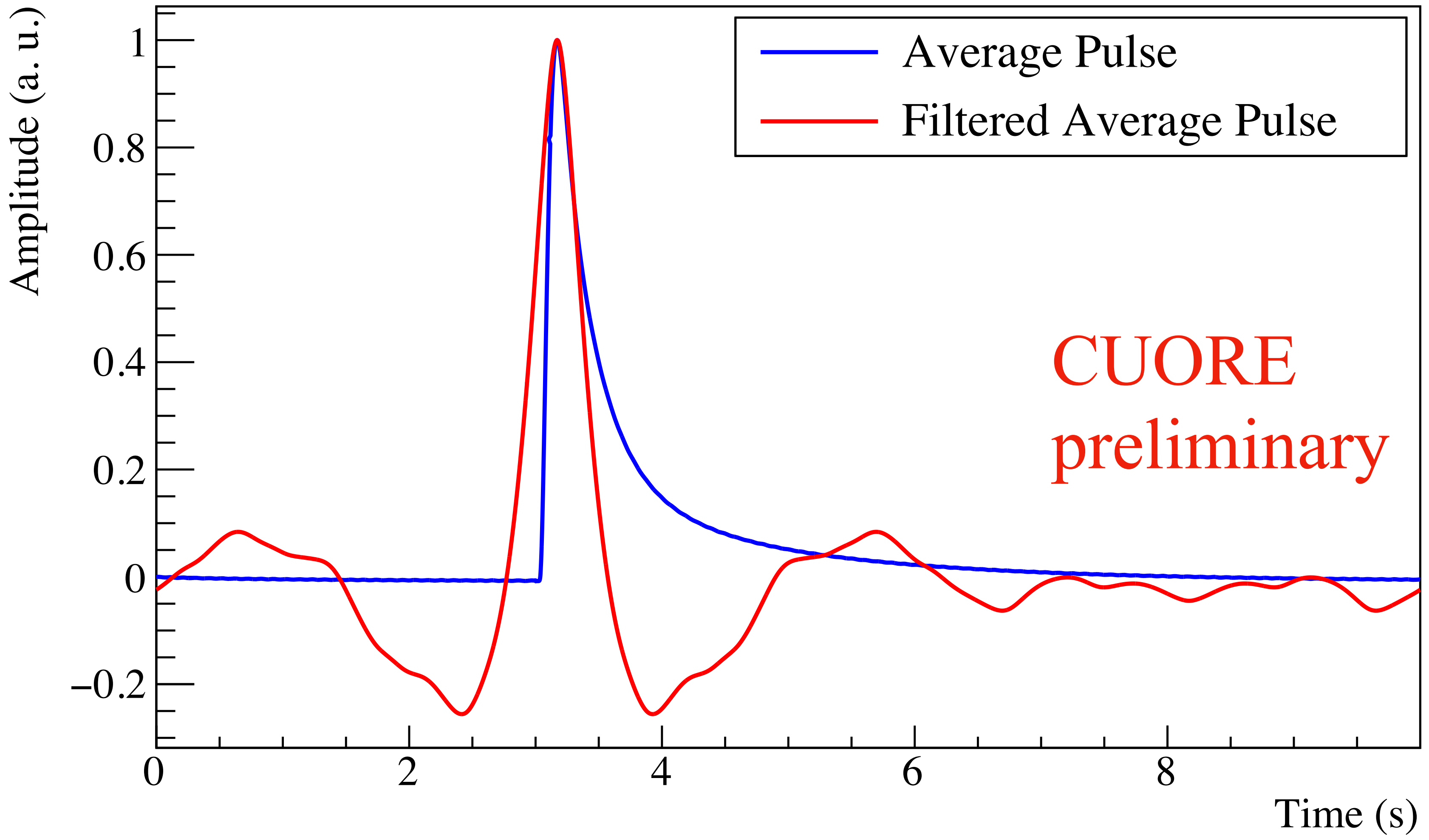
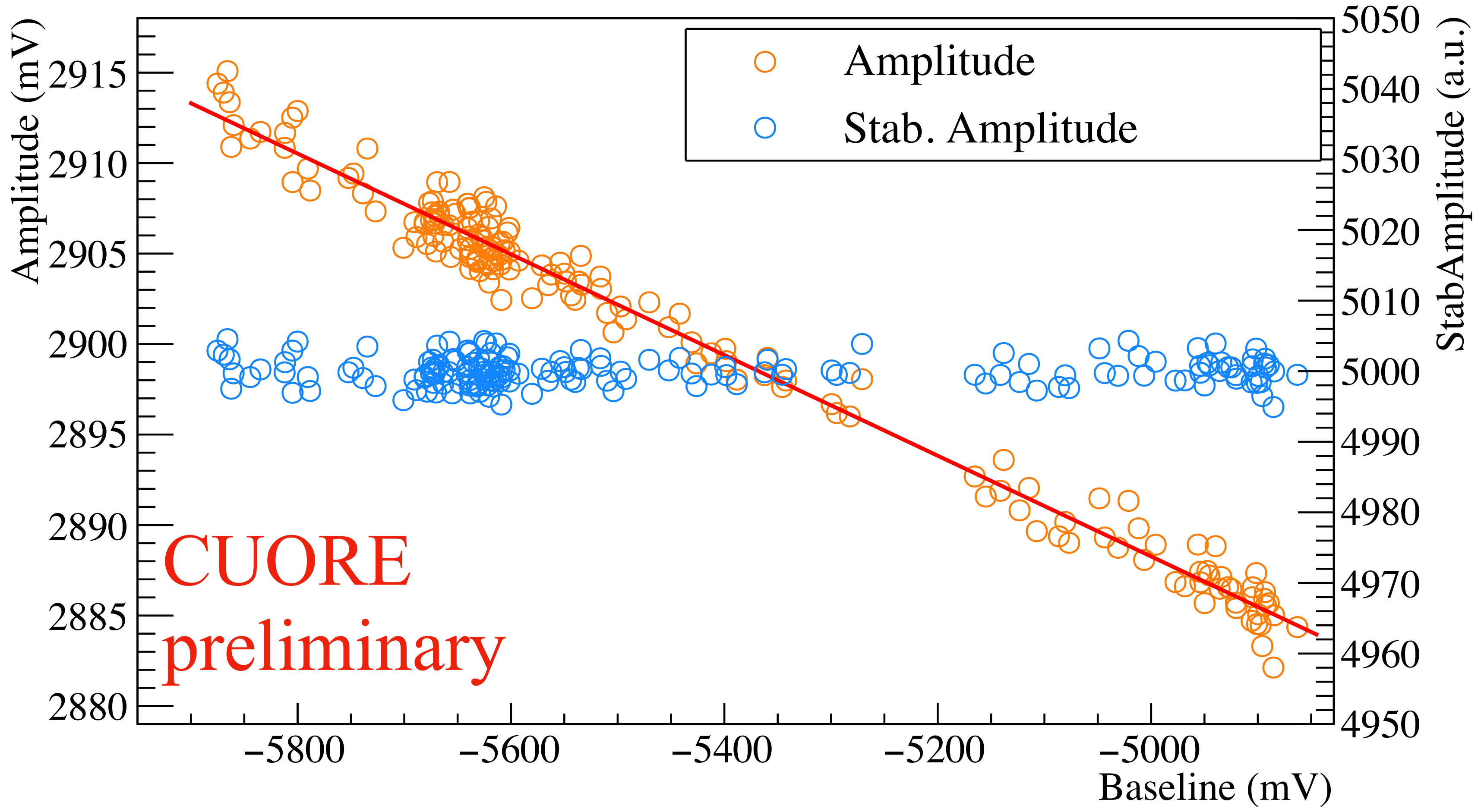
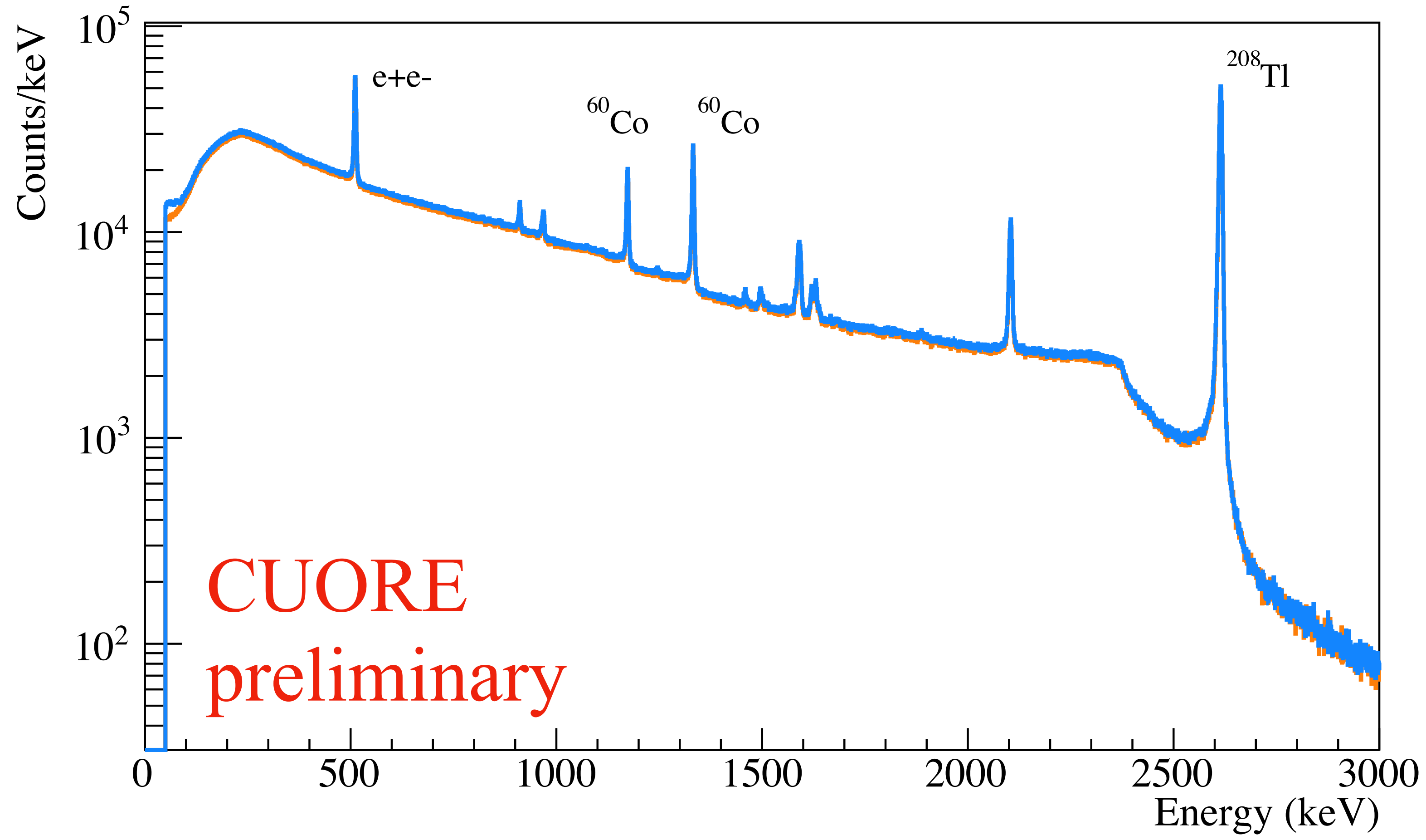




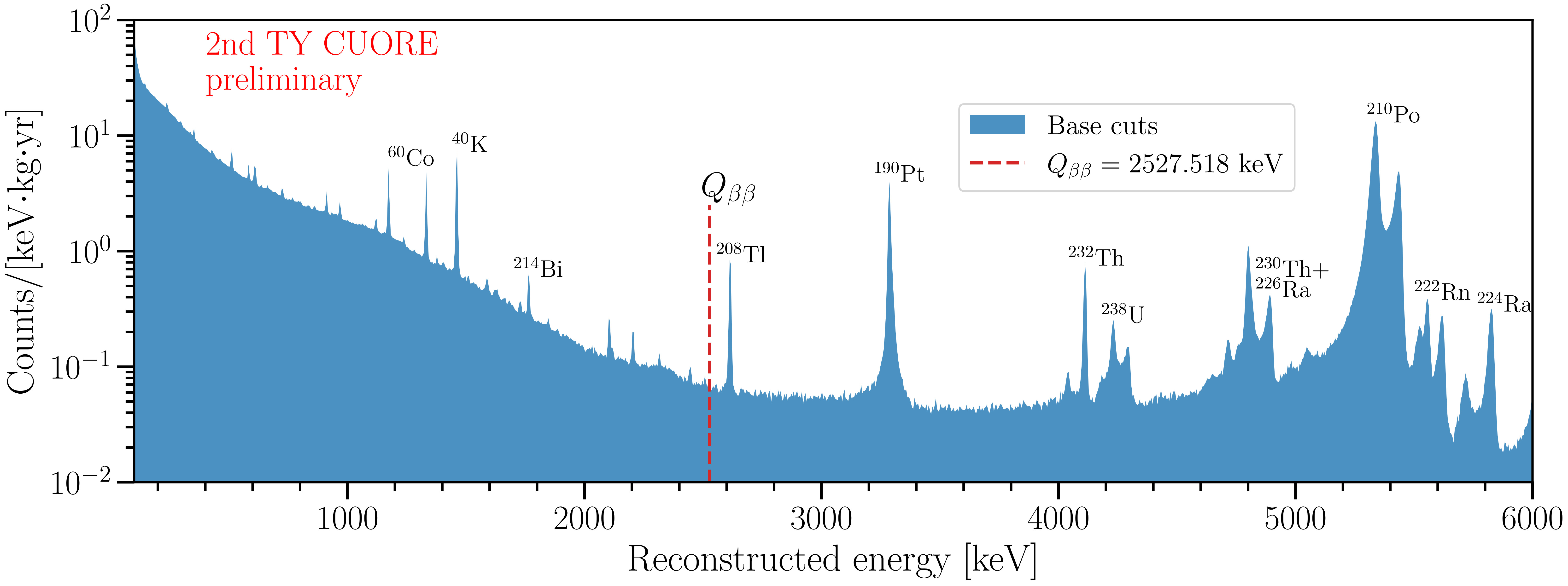


- Matched filter maximizes singnal-to-noise ratio.
- Fixed-energy pulses from heaters to correct thermal gain drifts.
- Amplitudes are converted to energy by using peaks from external calibration system (^{232}Th+^{60}Co).





Event selection for $0\nu\beta\beta$ decay search



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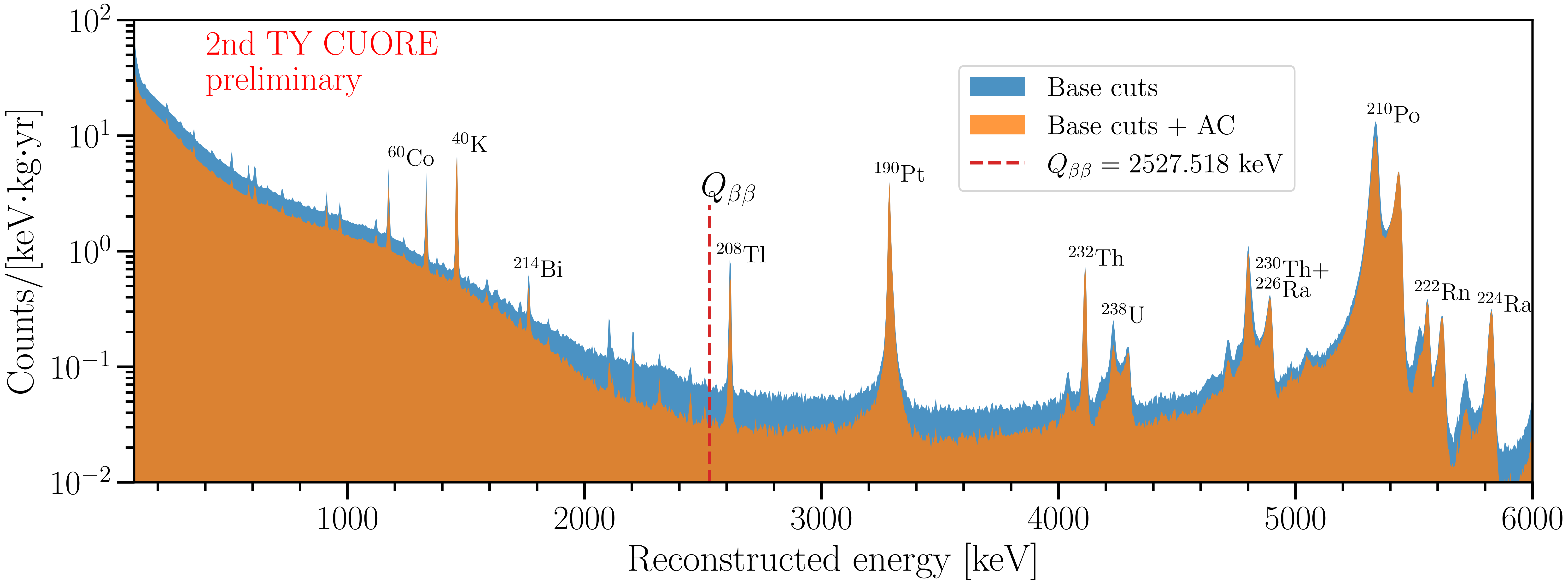
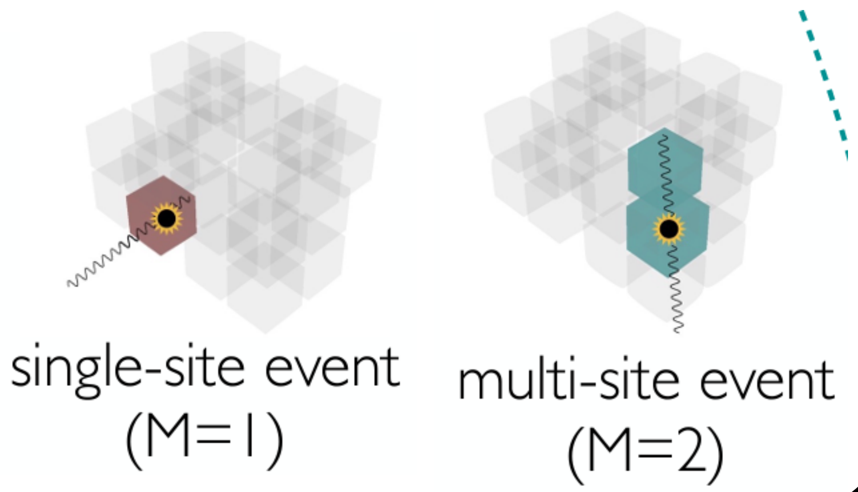


Anti-coincidence (AC) selection

Reject M>1 events, as we expect ~90% containment of $0\nu\beta\beta$ events



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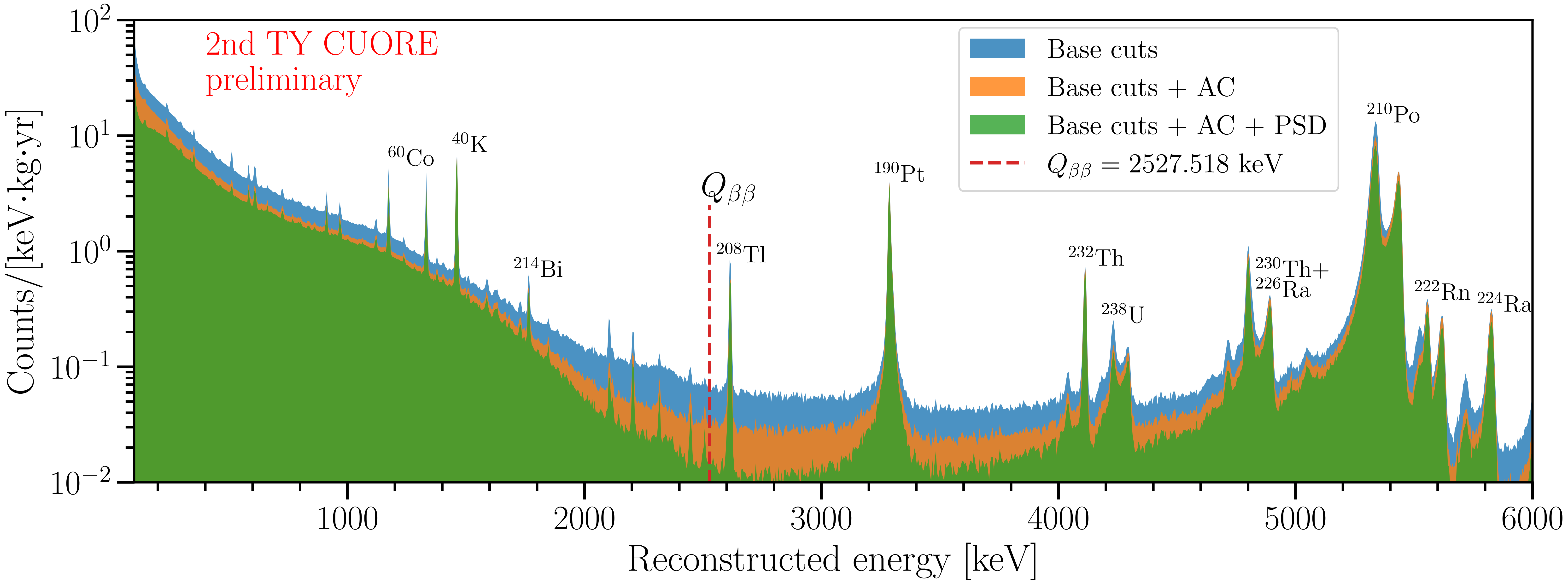

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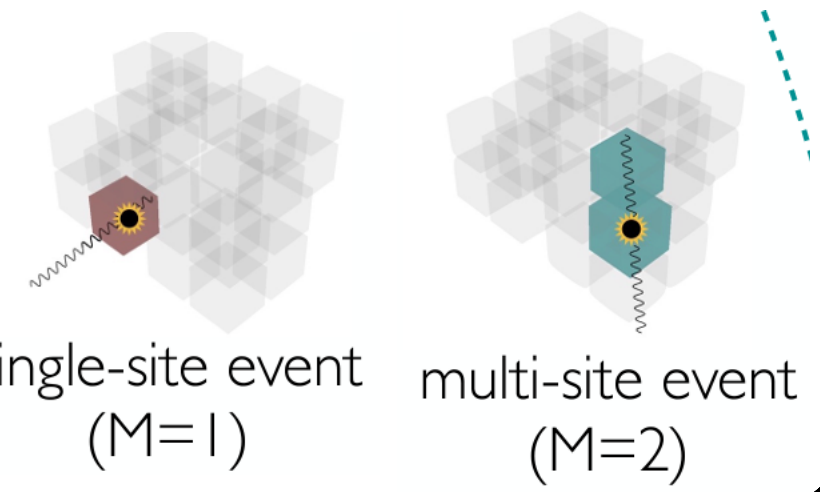
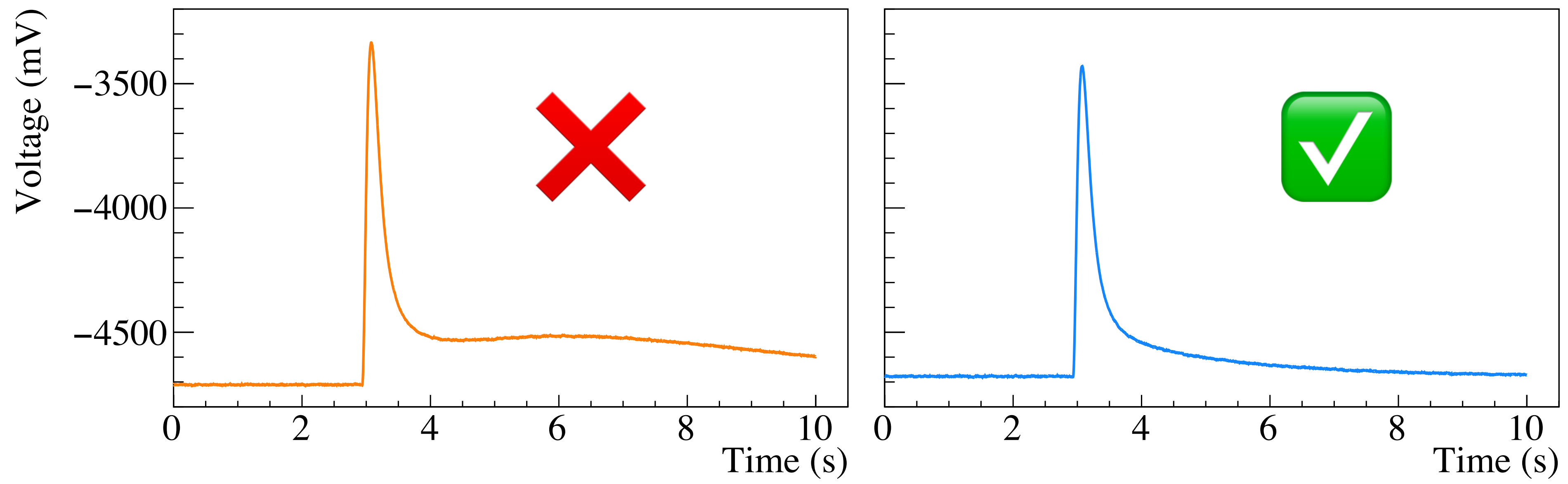


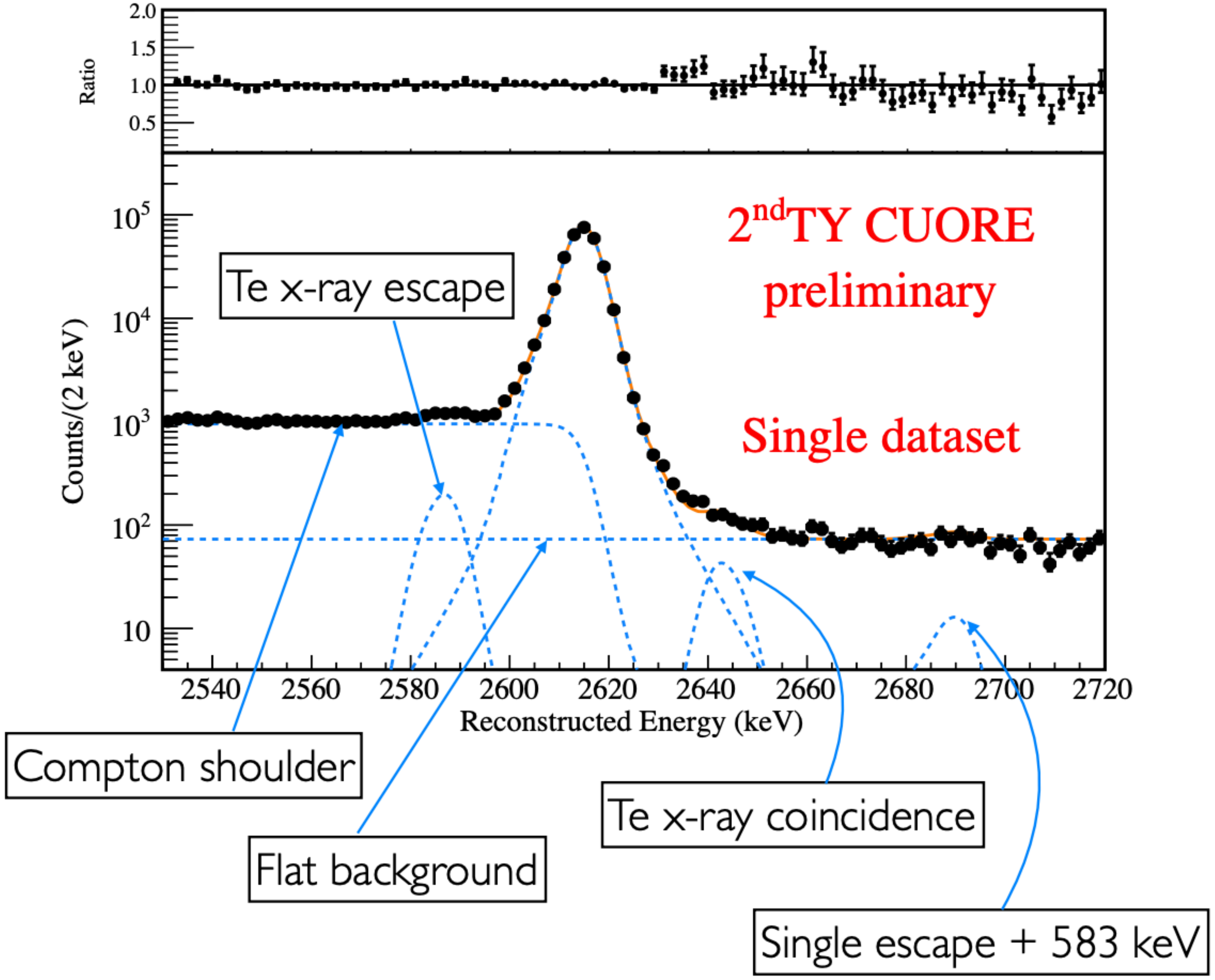
Pulse Shape Discrimination (PSD)

Reject spurious events by virtue of Principal Component Analysis (PCA)



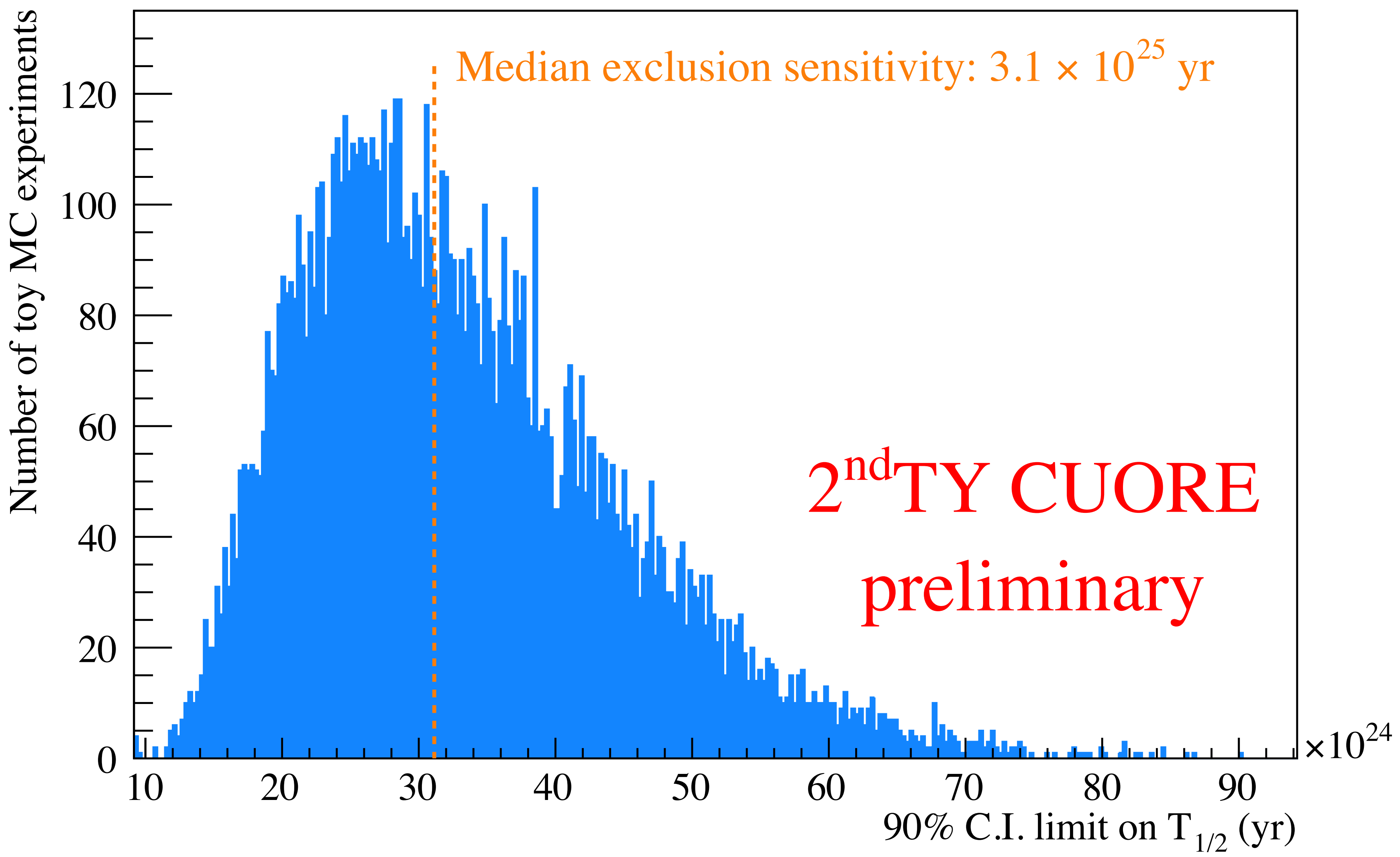
Detector response

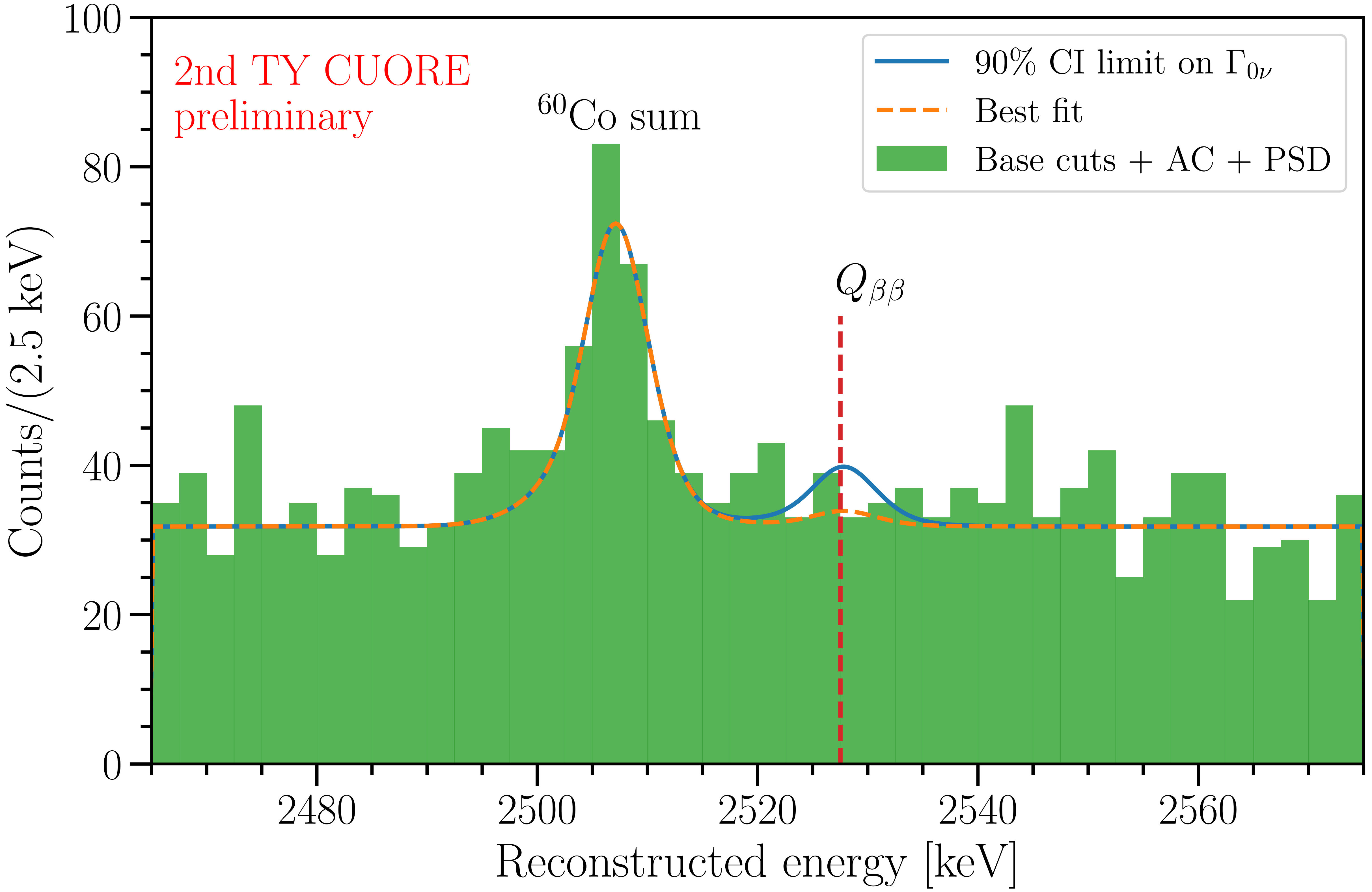
- Fit to prominent Tl-208 calibration peak in our detector.
- Modeled by sum of three gaussians.
- Detector response from extrapolation to physics data (prominent gamma peaks).
- Energy resolution and bias at $Q_{\beta\beta}$:
  - $\mathrm{FWHM}_{\text{2nd TY}}\left(Q_{\beta\beta}\right) = 7.26^{+0.43}_{-0.47}\,\text{keV}$
  - $E_{\text{bias, 2nd TY}}\left(Q_{\beta\beta}\right) = -0.11^{+0.19}_{-0.25}\,\text{keV}$



2nd tonne-year results

- Bayesian fit in ROI [2465 keV, 2575 keV], with systematics as nuisance parameters.
- **No evidence** of $0\nu\beta\beta$ decay
- Median exclusion sensitivity: 3.1×10^{25} yr (90% C.I.)
- Half-life limit: $T_{1/2}^{0\nu} > 2.7 \times 10^{25}$ yr (90% C.I.)

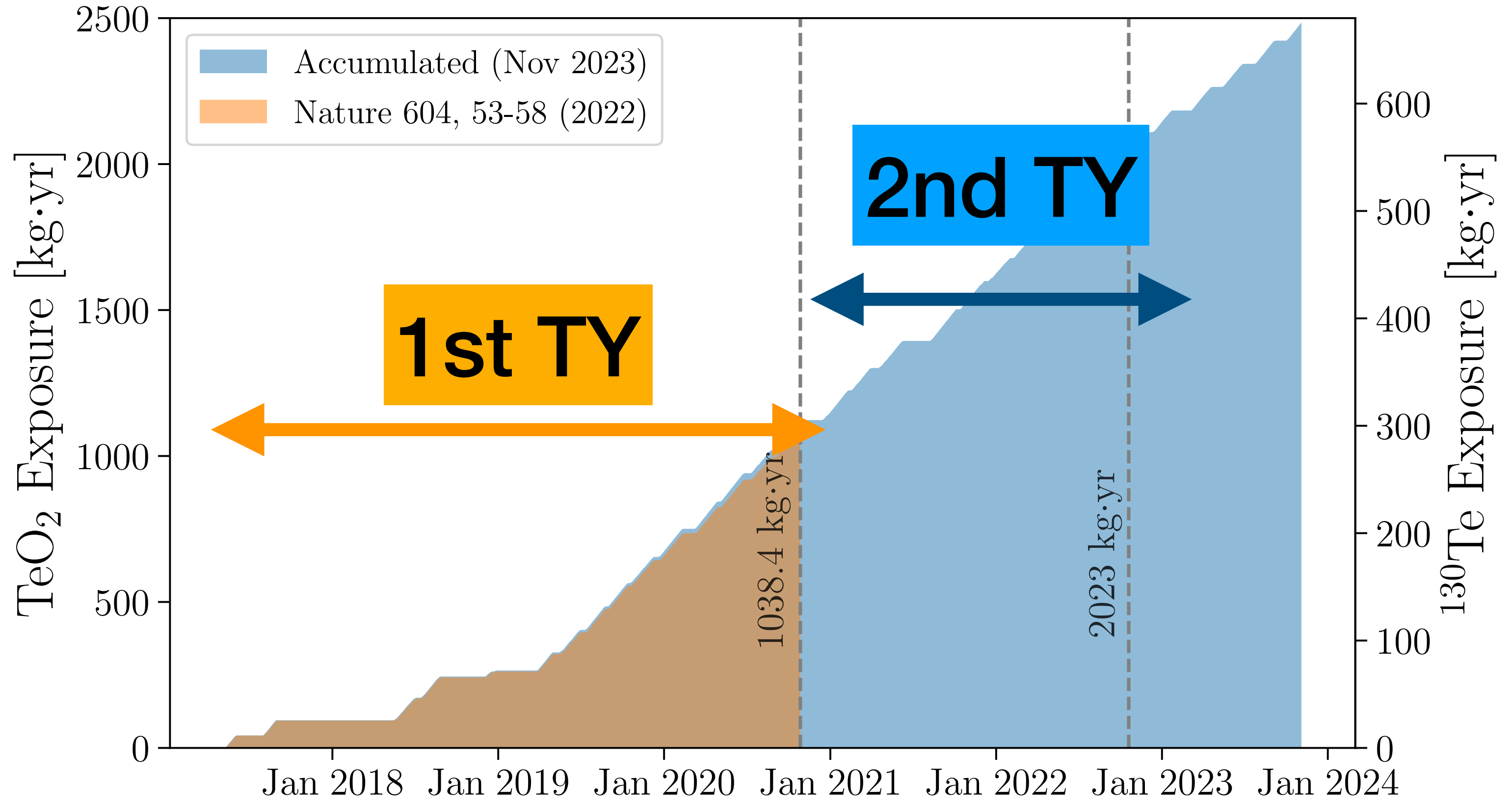


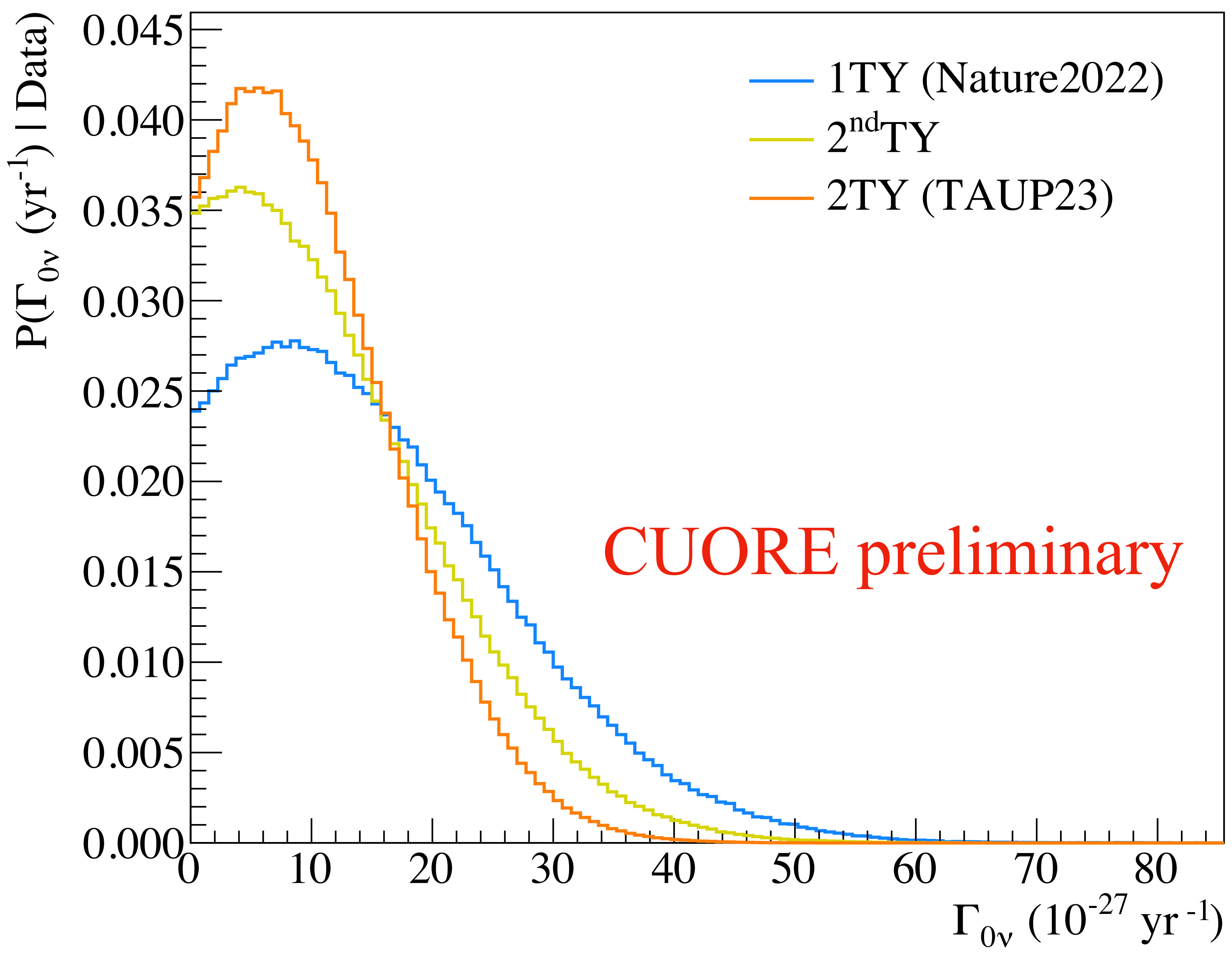


- Model ROI with ^{60}Co sum peak + linear bkg + peak at $Q_{\beta\beta}$
- Unbinned fit with $\Gamma_{0\nu\beta\beta} > 0$

2 ton-year (TY) results

- Combination of 1st TY (Nature) and 2nd TY limits
- Analyzed exposure: 2023 kg·yr
- **No evidence** of $0\nu\beta\beta$.
- Can set following limits:
  - $\Gamma_{0\nu} < 2.1 \times 10^{-26}$ yr^{-1} (90% C.I.)
  - $T^{0\nu}_{1/2} > 3.3 \times 10^{25}$ yr (90% C.I.)
  - $m_{\beta\beta}$ < 75-255 meV
- Final study including reprocessed (new analysis chain) 1st TY to follow.





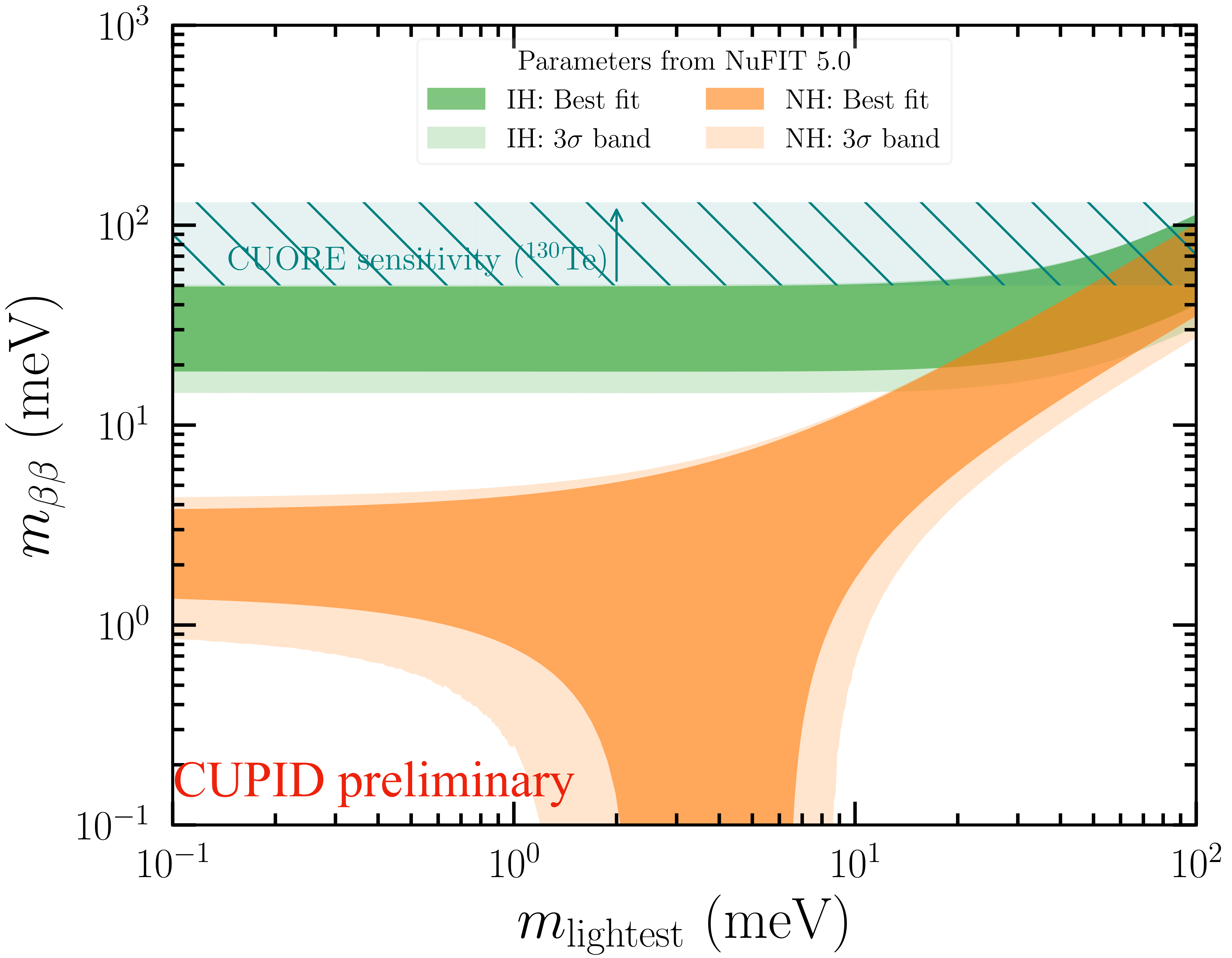
limit from integrating marginalized posterior

Quo vadis?

- CUORE will continue to take data until it collects 3 tonne-year (1 tonne-year) of TeO_2 (^{130}Te).
- CUORE's sensitivity limited by backgrounds in the ROI.
- Enter CUPID…

The case for CUPID (**C**UORE **U**pgrade with **P**article **ID**)

- CUPID is an upgrade to the successful CUORE experiment.
- Discovery sensitivity (3σ):
  - $T_{1/2}^{0\nu} > 1.0 \times 10^{27}$ yrs
  - $m_{\beta\beta} = (13 - 21)$ meV
- CUPID can probe the IH region.
- New technology can decrease backgrounds and increase sensitivity.



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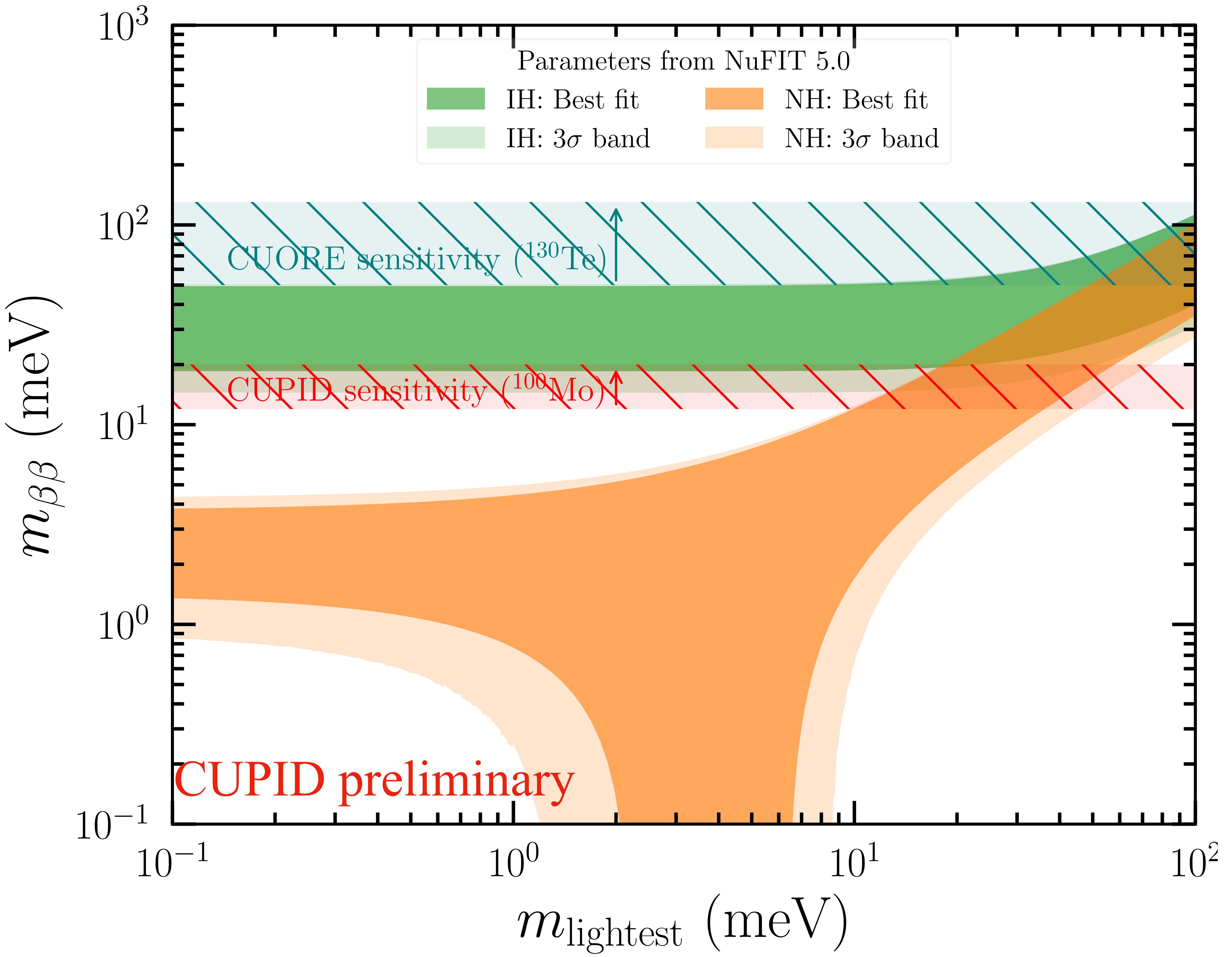
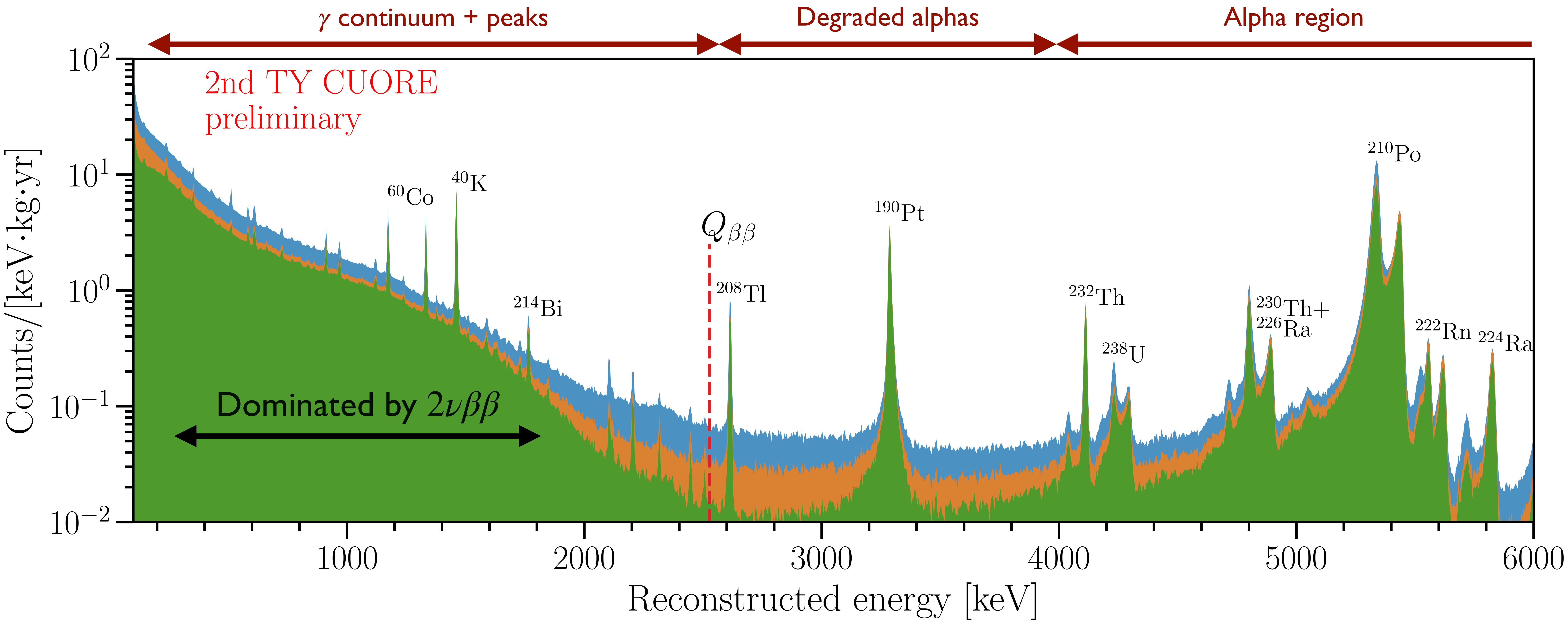


Lessons for CUPID from CUORE's background



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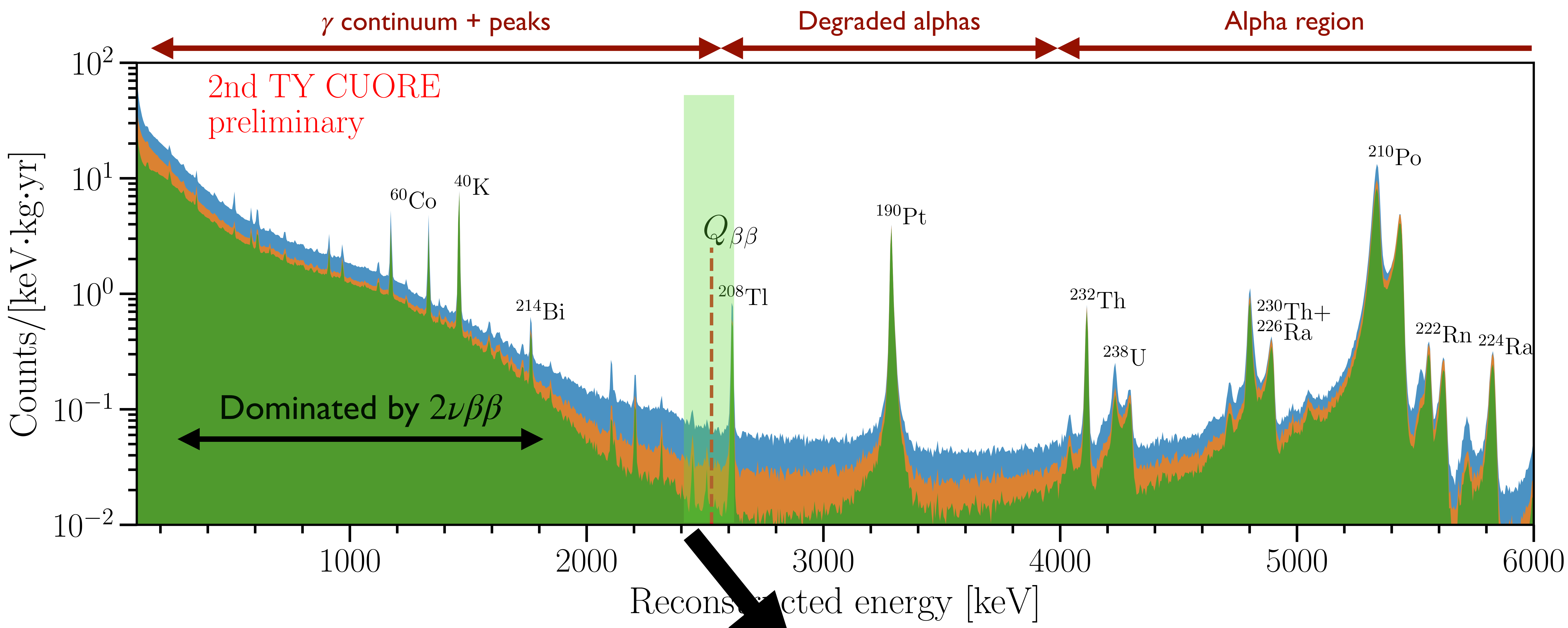

Residual backgrounds in the ROI

β/γ — ~10% β/γ radioactivity

α — ~90% degraded alphas (U/Th)

μ — $\lesssim$1% muons

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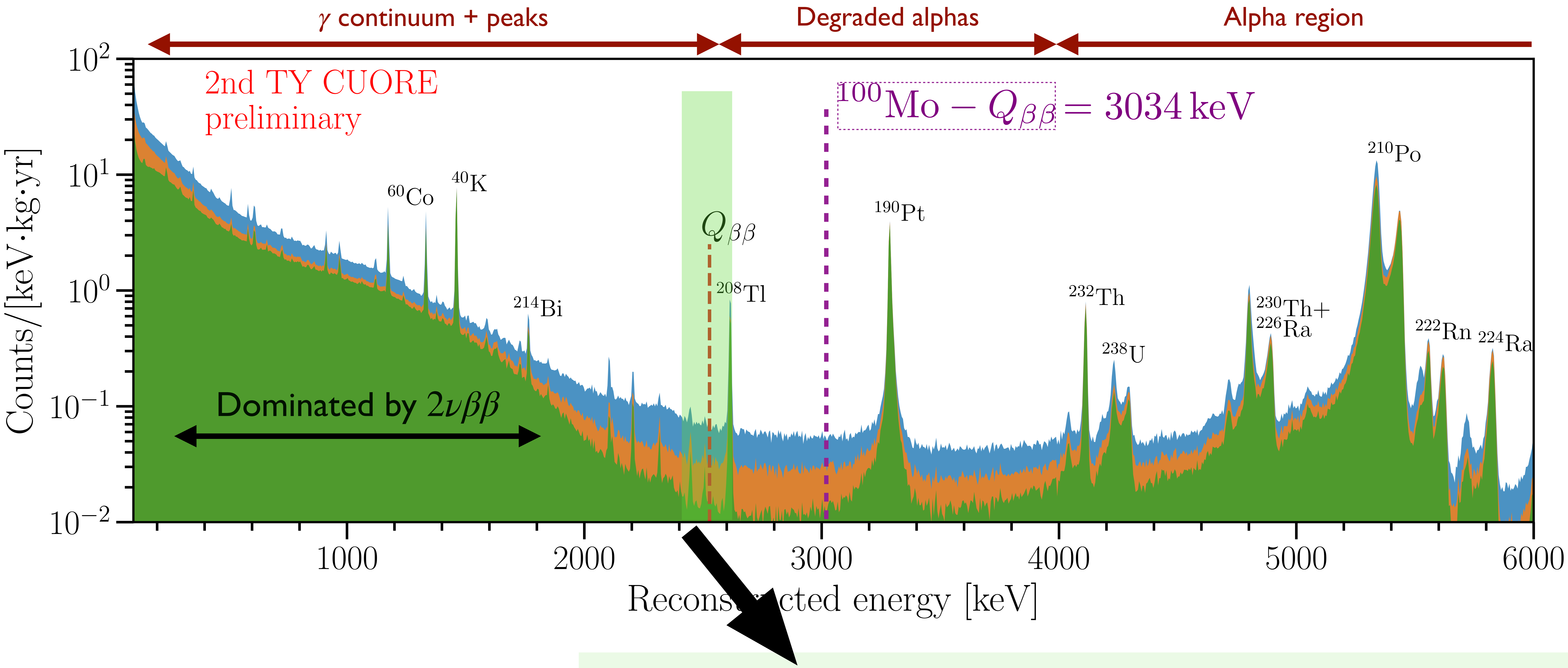

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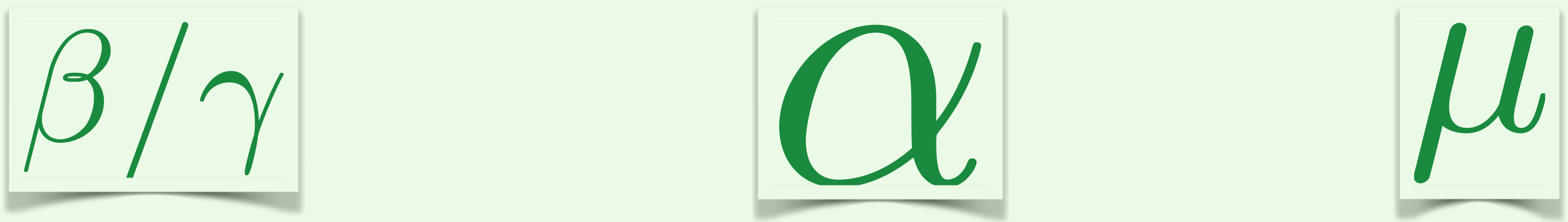


~10% β/γ radioactivity

~90% degraded alphas (U/Th)

$\lesssim$1% muons

Mitigating alpha backgrounds

- Exploit the scintillating nature of crystals.
- Exploration of dual readout for heat and light signals:
  - Bolometer coupled to light detector (Ge wafer linked to thermometer)
  - Different light-yield for alphas and betas
- Discrimination based on bivariate cut on light and heat signals.
- Build demonstrators to validate new technology.

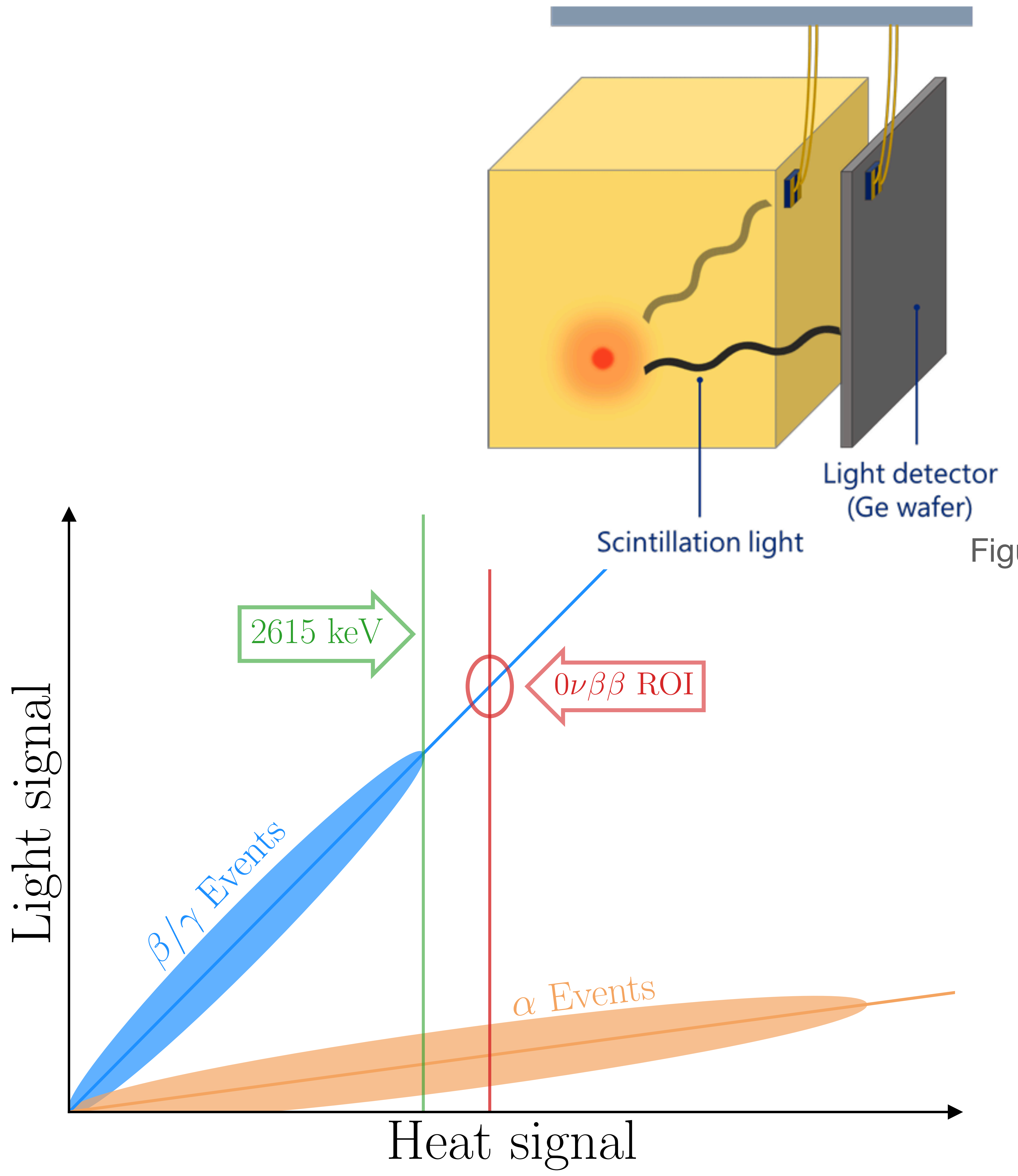
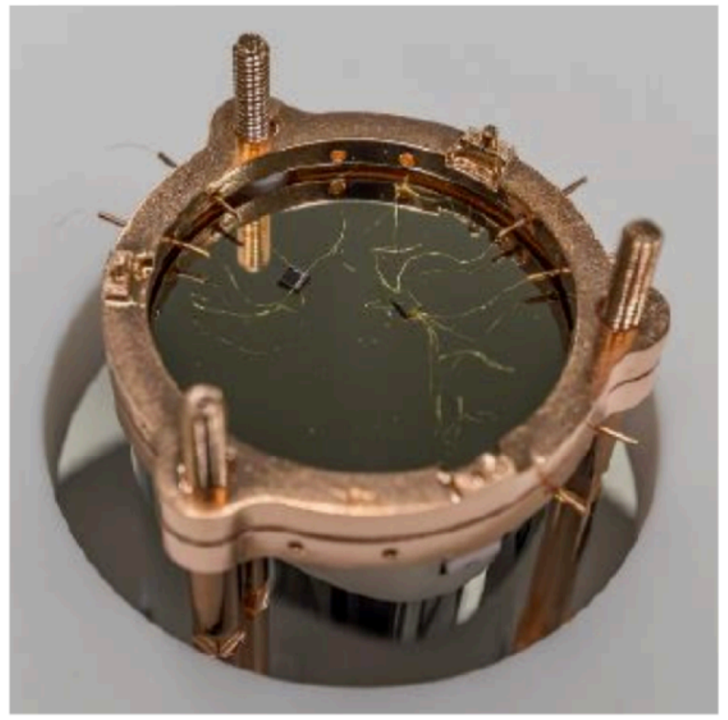


Figure: H. Khalife

10 kg-scale demonstrators

CUPID-0

- $Zn^{82}Se$ crystals, 95% enrichment ^{82}Se (5.17 kg) at LNGS (Italy)
- α-rejection efficiency > 99.9%
- Background index: 3.5×10^{-3} ccky
- $\Delta E = 21.8$ keV @ $Q_{\beta\beta}$ (2998 keV)
- Physics results
- Bkg studies




CUPID-Mo

- $Li_2^{100}MoO_4$ crystals, 95% enrichment ^{100}Mo (2.34 kg) at LMS (France)
- α-rejection efficiency > 99.9%
- Background index: 2.7×10^{-3} ccky
- $\Delta E = 7.4$ keV @ $Q_{\beta\beta}$ (3034 keV) 👑👑👑
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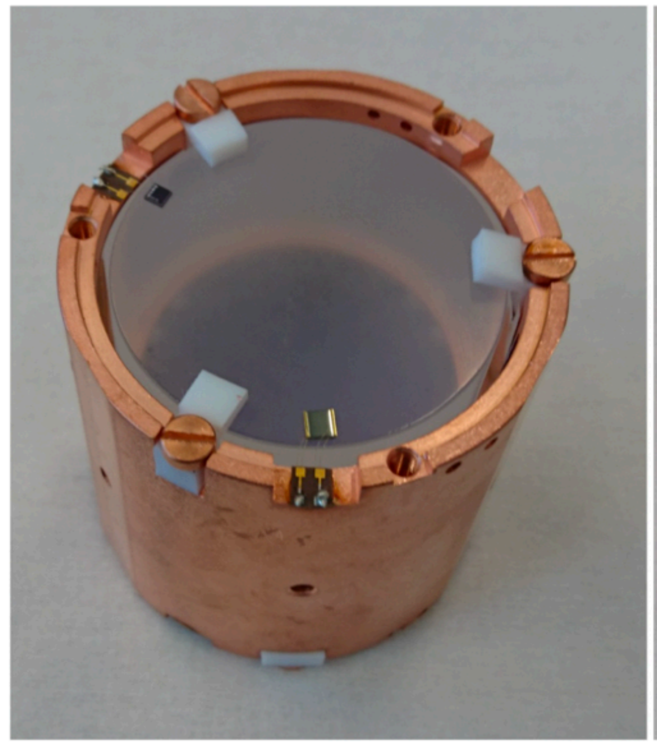
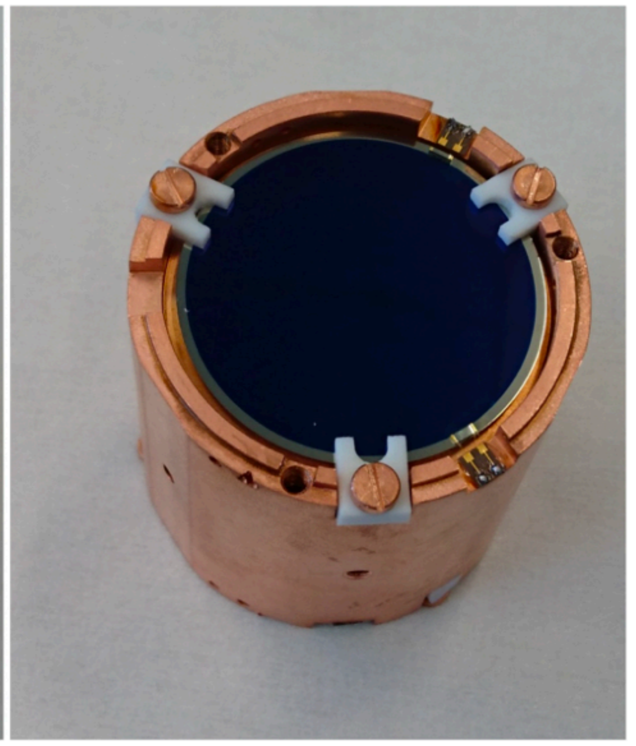

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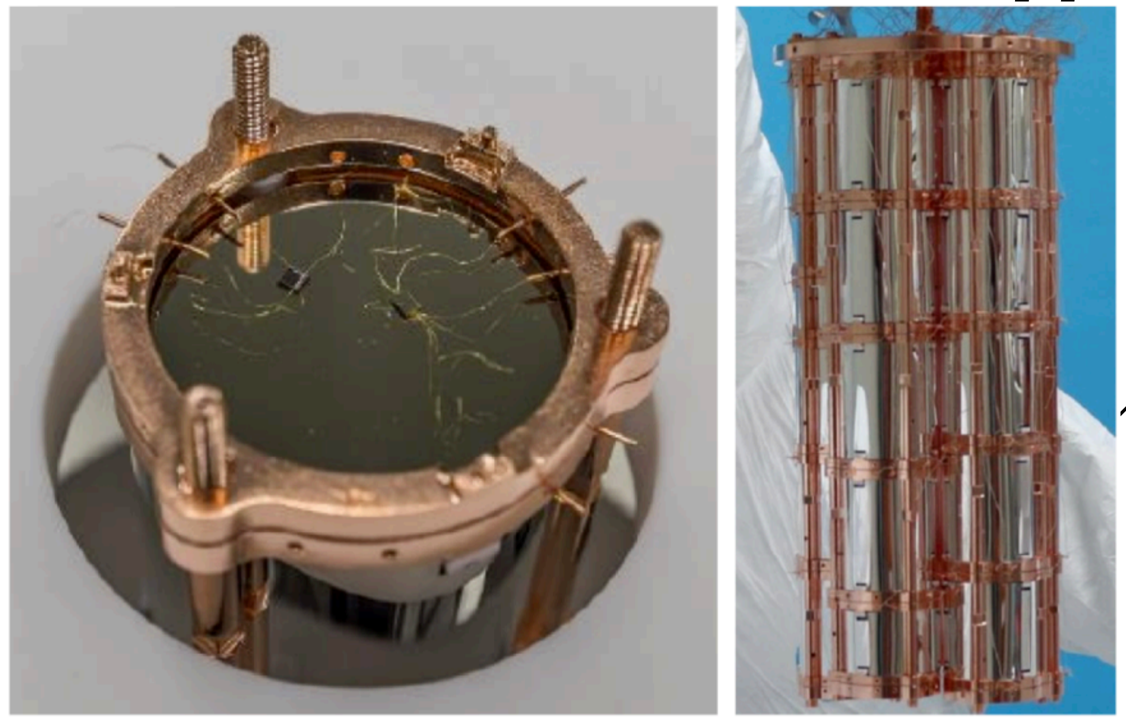

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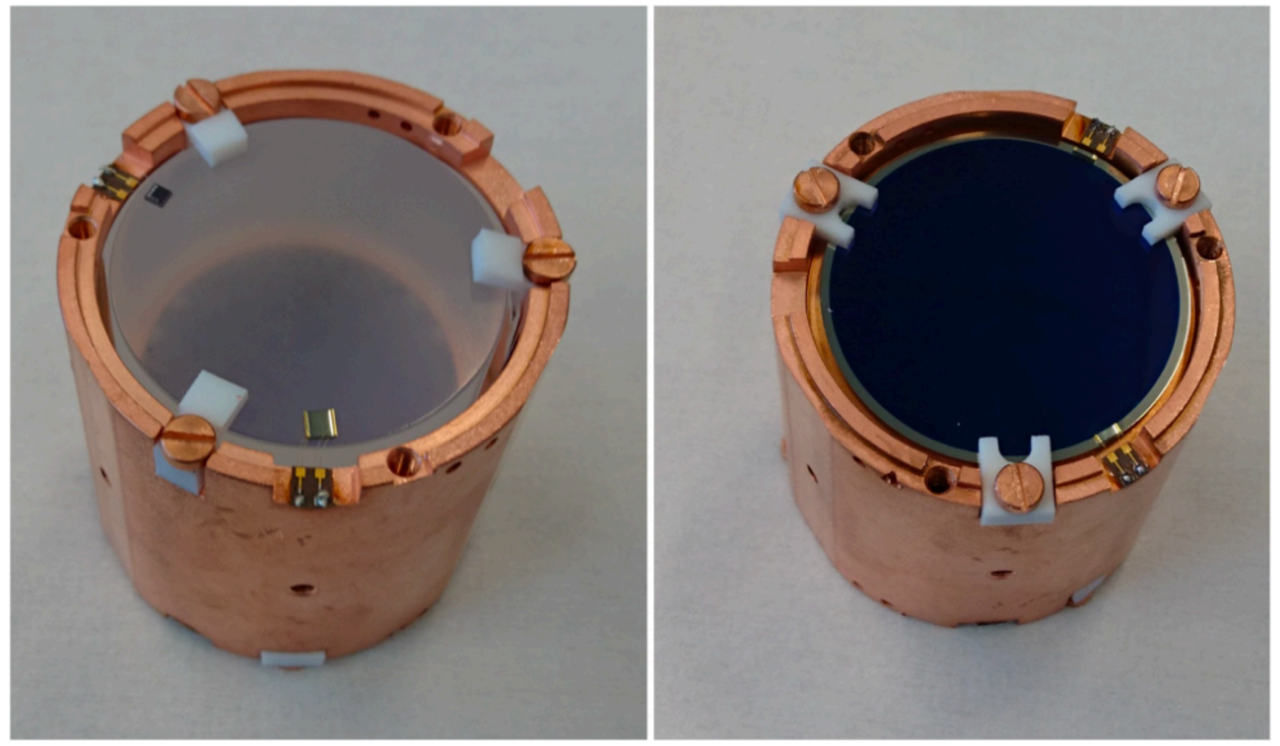
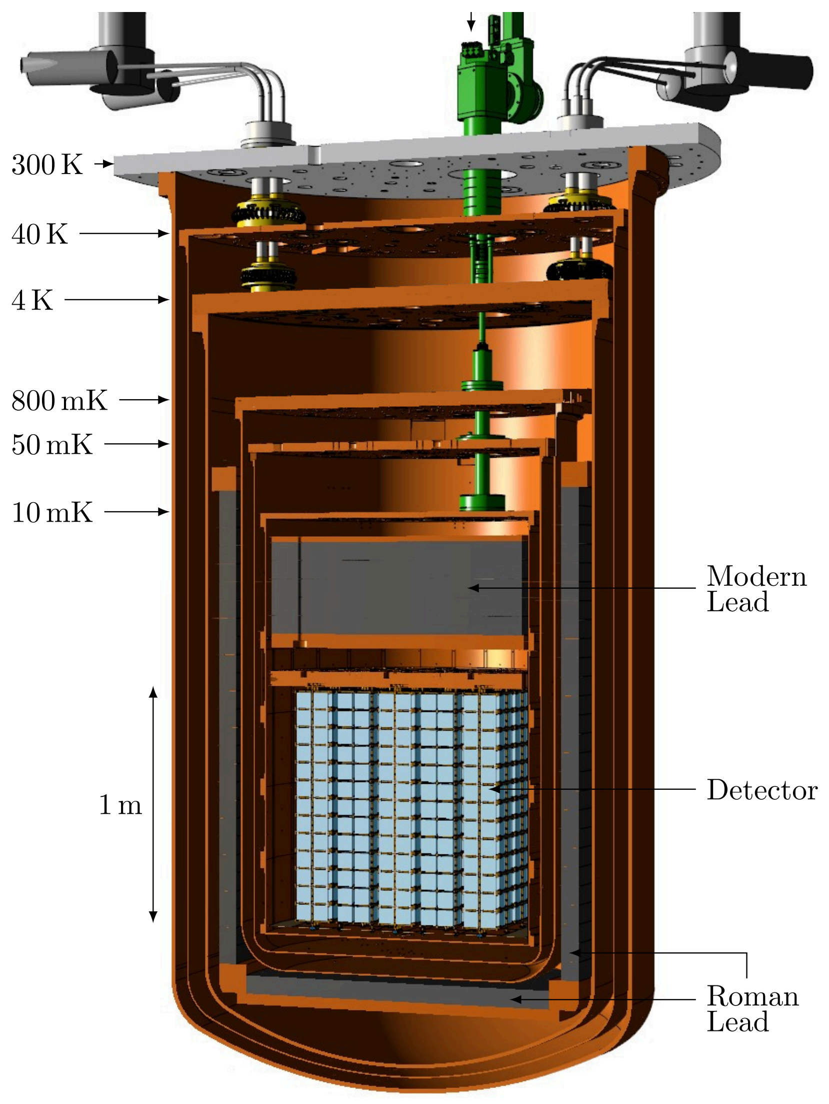
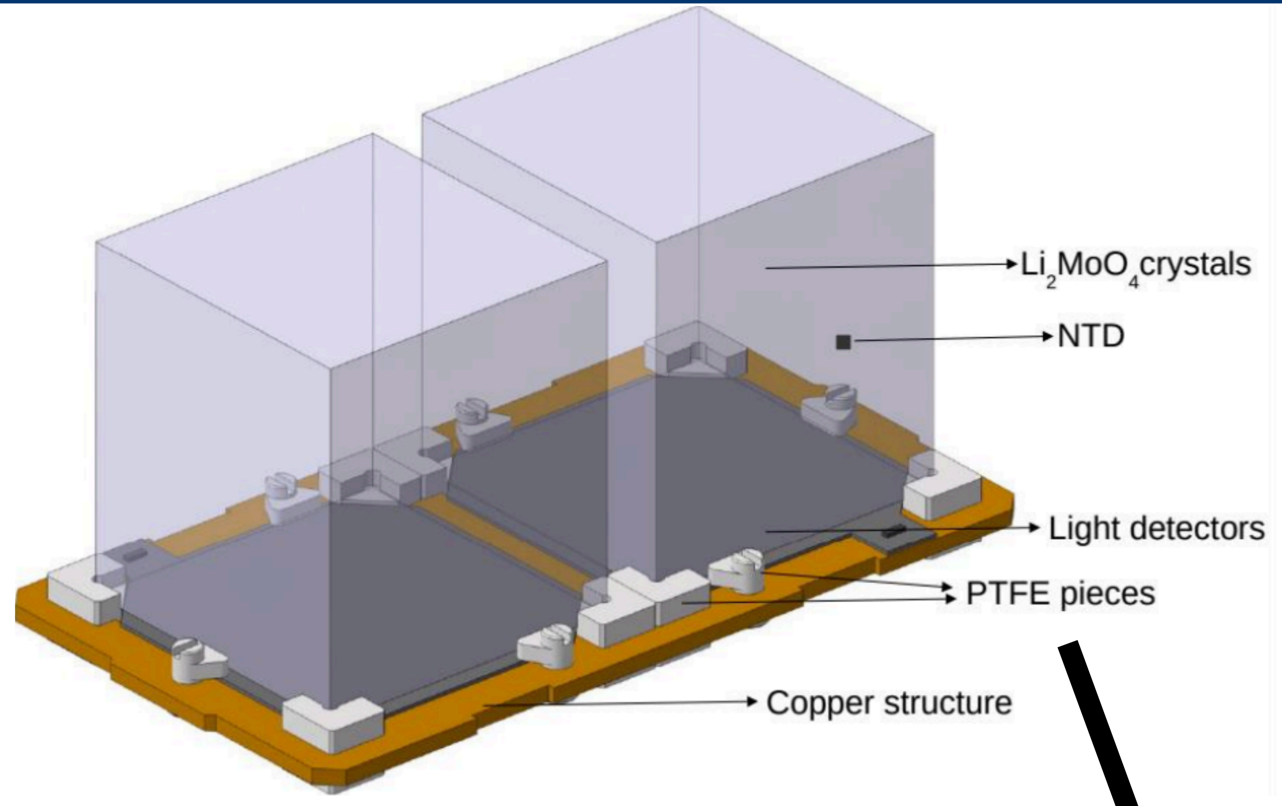
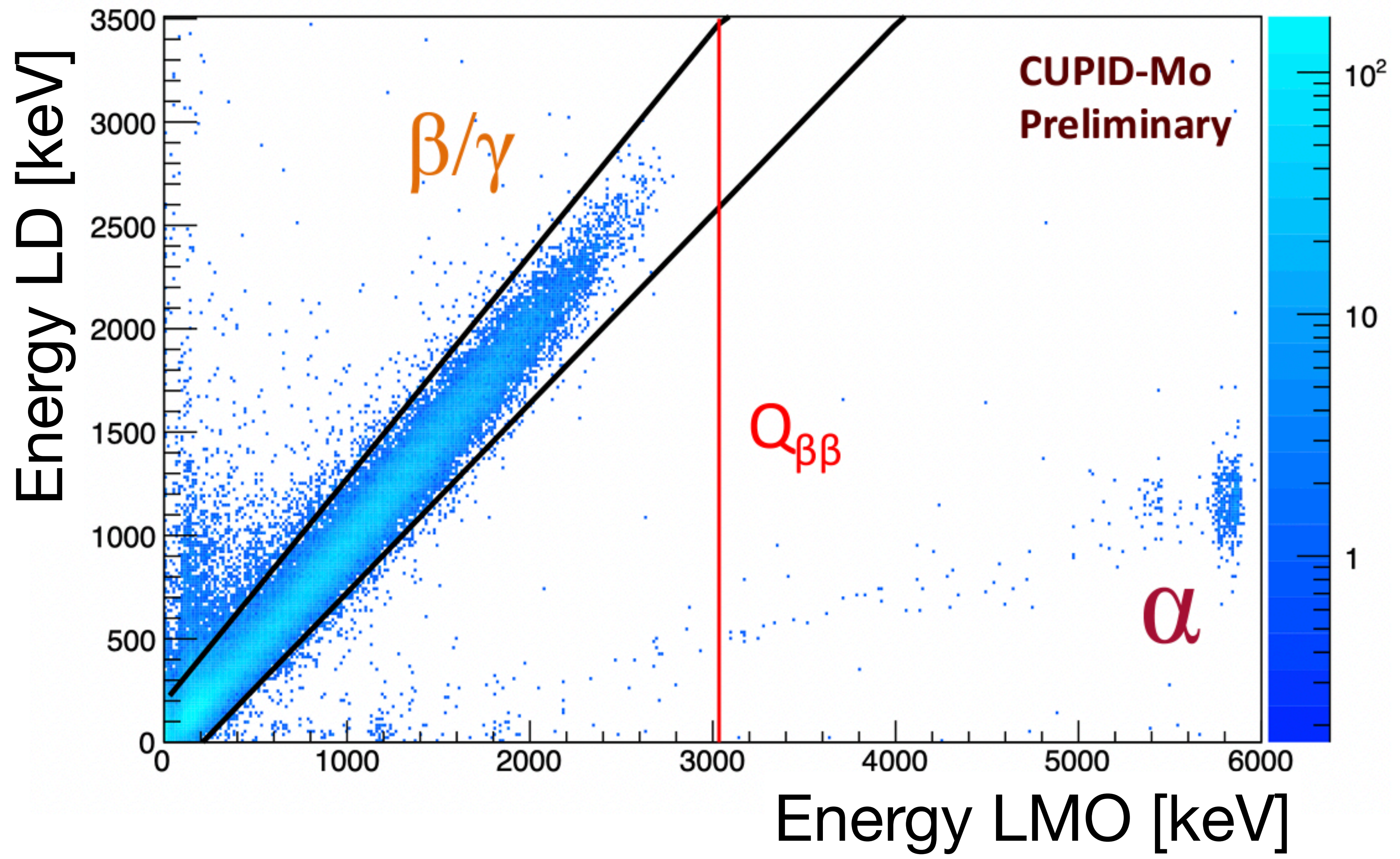


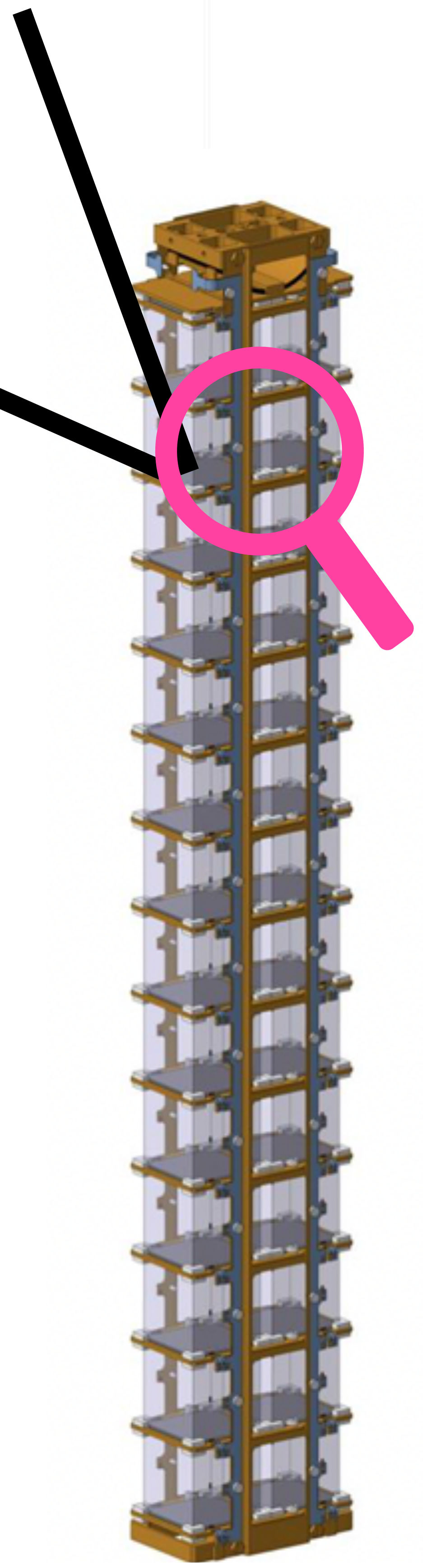
The CUPID Experiment

- Use CUORE's infrastructure
- 1596 $Li_2^{100}MoO_4$ crystals (45x45x45 mm^3)
- 240 kg of ^{100}Mo (enrichment > 95%)
- 1710 Ge wafer light detectors
- $\alpha-$rejection efficiency demonstrated to be > 99.9%
- Energy resolution: FWHM < 5 keV at $Q_{\beta\beta}$
- LD baseline resolution < 100 eV RMS
- Light yield: 0.3 keV/MeV





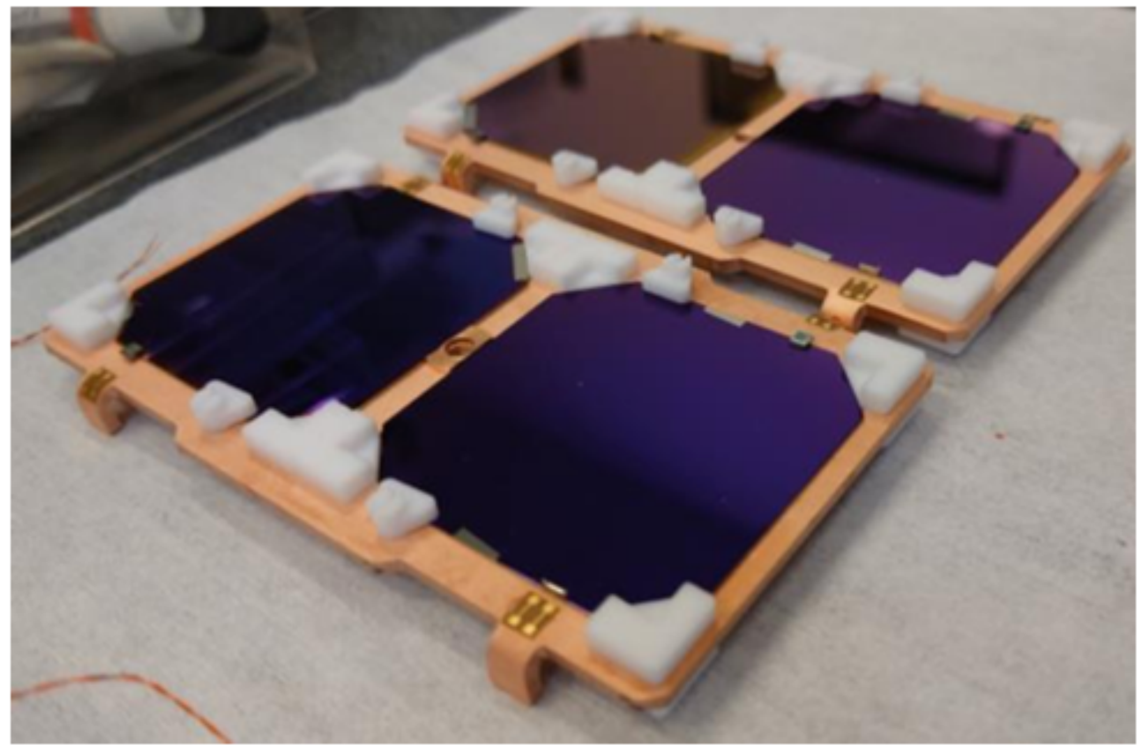


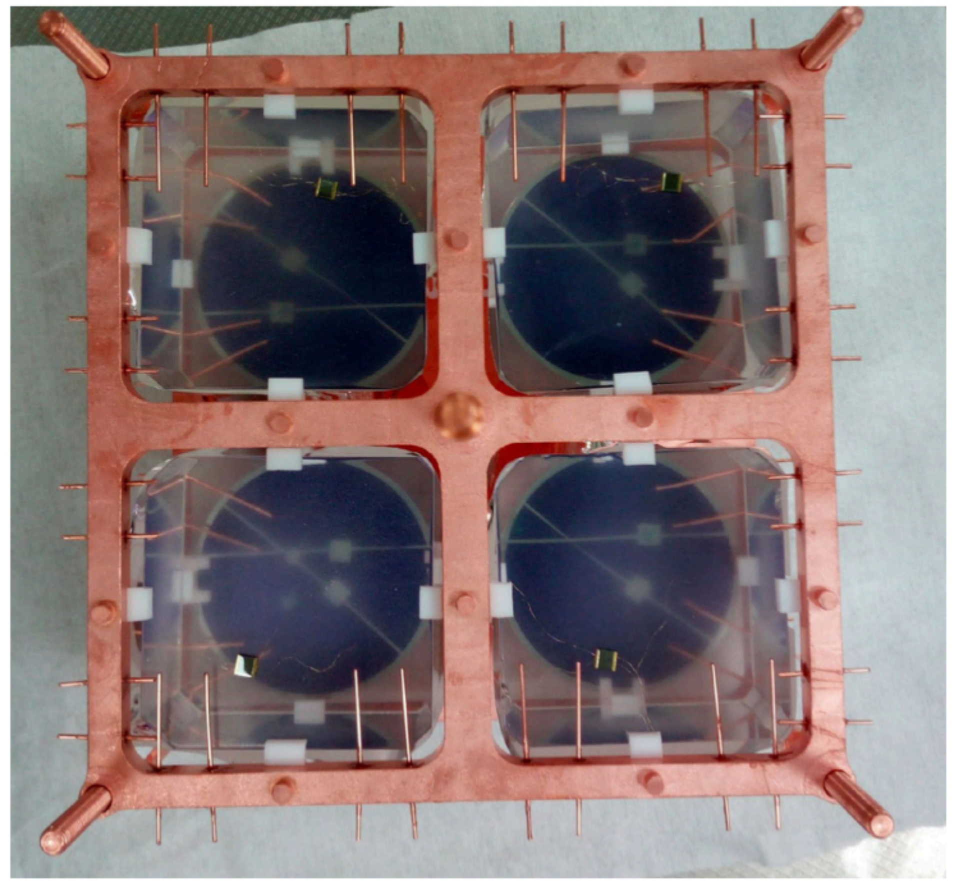


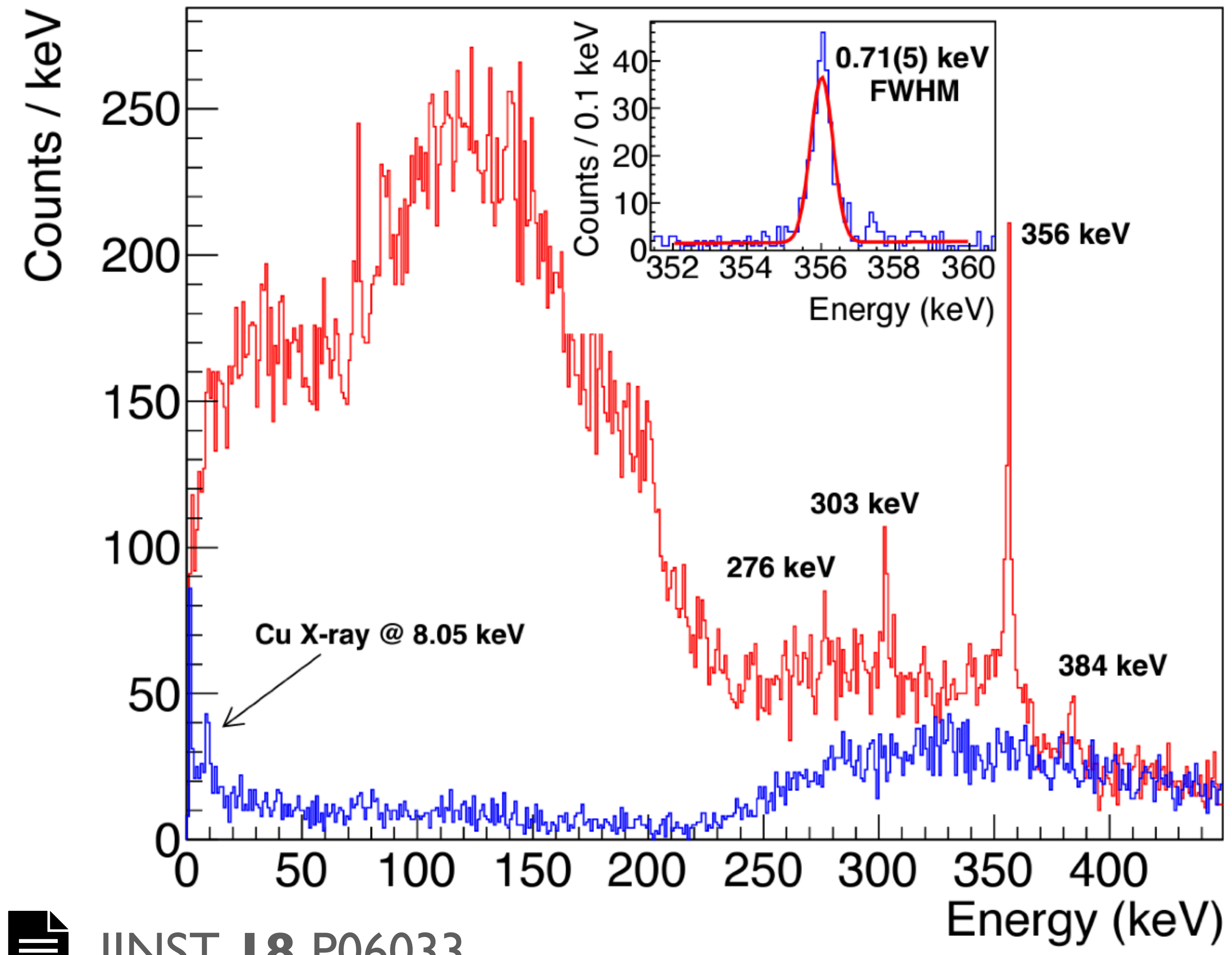
Light collection optimization and detector validation

- Performed studies with Ge wafer with anti-reflective SiO coating and NTD readout for CUPID baseline.
- Performed in a pulsetube cryostat at IJCLab.
- Reflecting foil and light detector position optimization.
- Baseline energy resolution 70-90 eV RMS.
- Results show that CUPID baseline **meets necessary α-rejection capabilities**, but saturates pile-up bkg constraint.

Eur. Phys. J. C (2022) 81:104
Eur. Phys. J. C (2022) 82:810





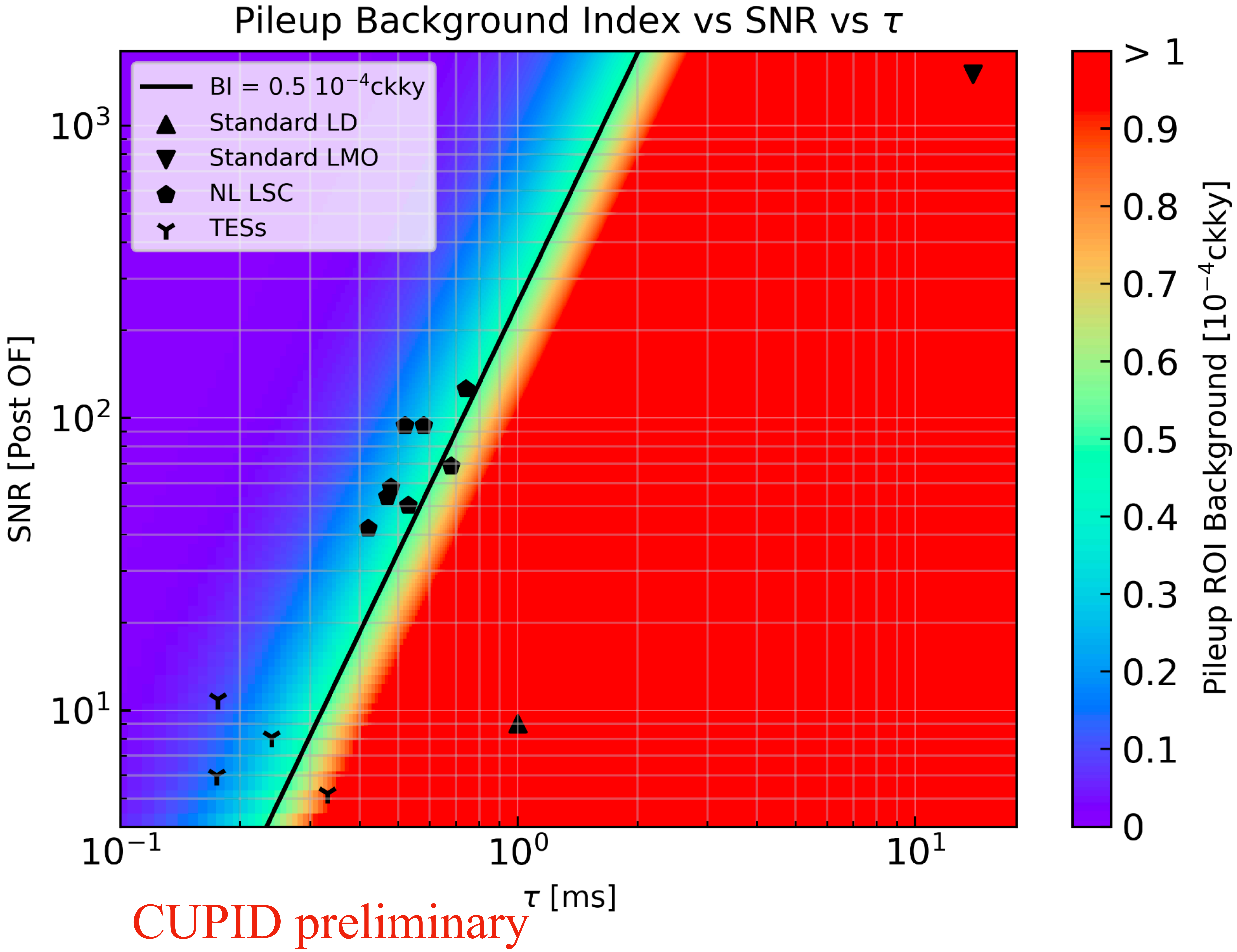


JINST **18** P06033

- ^{133}Ba source calibration.
- $\Delta E = 0.71$ keV FWHM @ 356 keV.

Studies on pile-up

- Relatively fast $2\nu\beta\beta$ decay of ^{100}Mo: $T_{1/2}^{2\nu} = 8.1 \times 10^{18}$ yr
- Slow pulses from heat readout cause random bkg coincidences in ROI.
- Goal: 0.5×10^{-4} ckky, rely on light detectors
- Ways to address this issue:
  - Shorten rise-time: Transition edge sensors (TES)
  - Increase SNR: NTDs with Neganov-Trofimov-Luke (NLT) effect. (**Baseline**)
- New technologies demonstrated to reach needed B.I. level goals.



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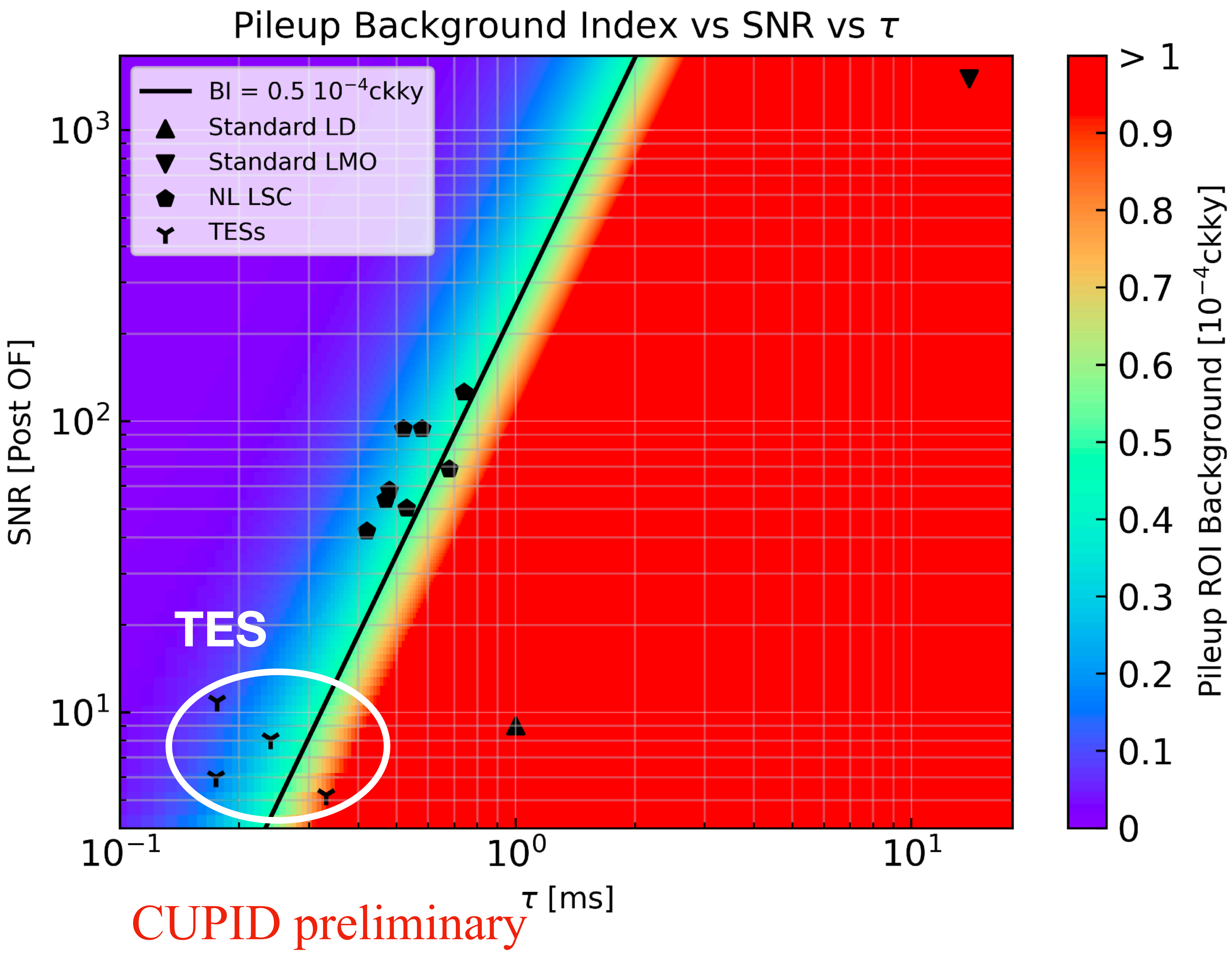

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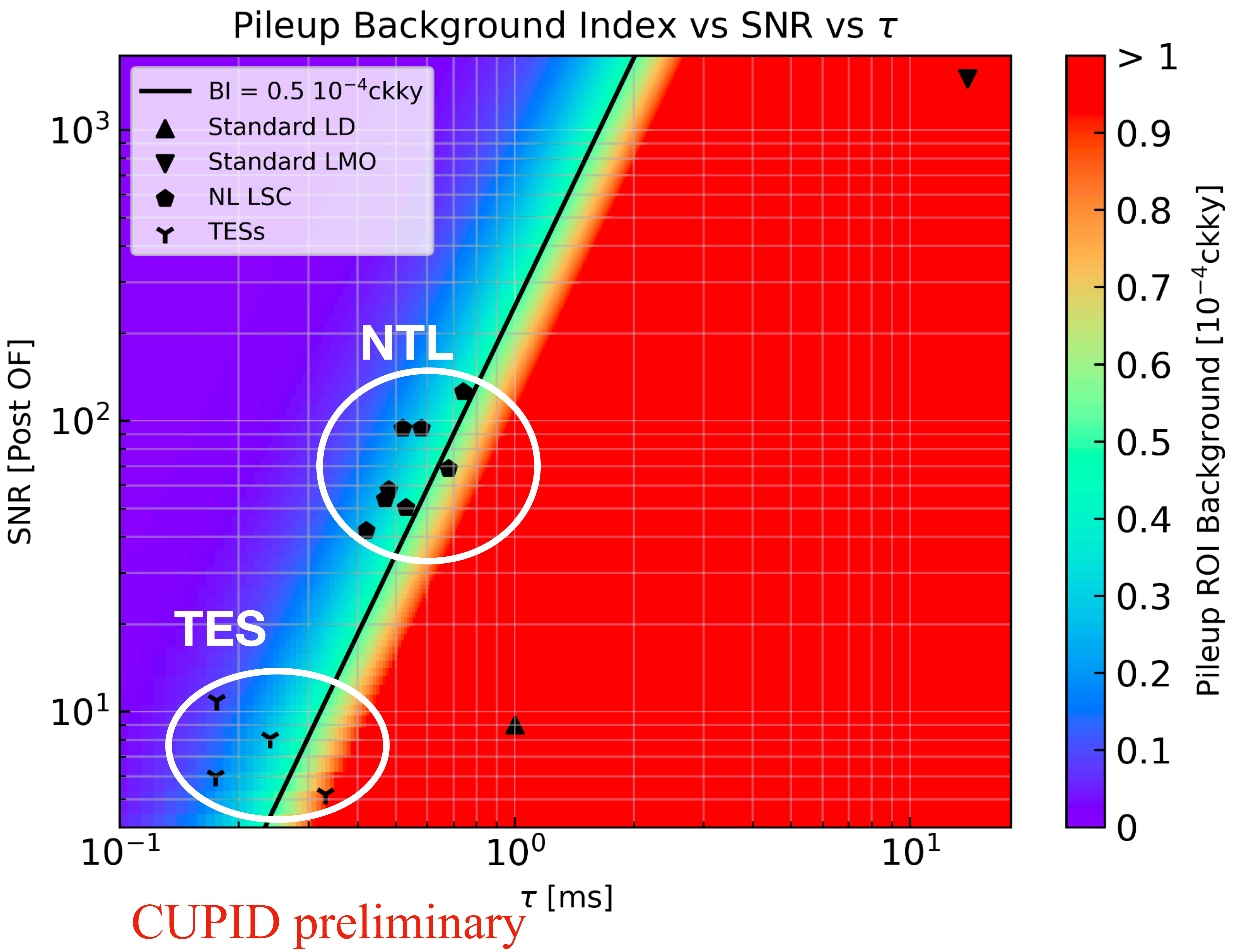
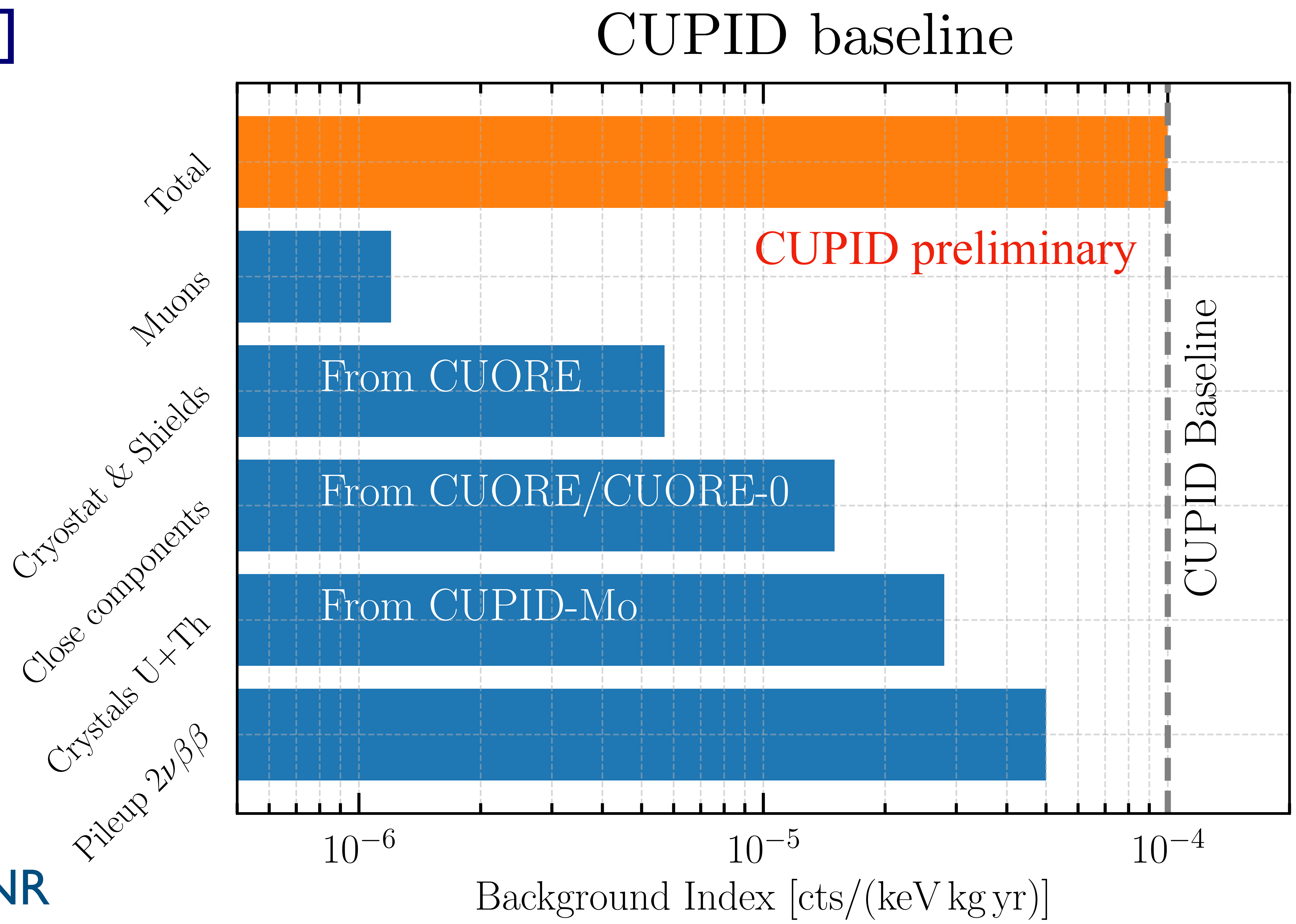


Tower optimization/validation

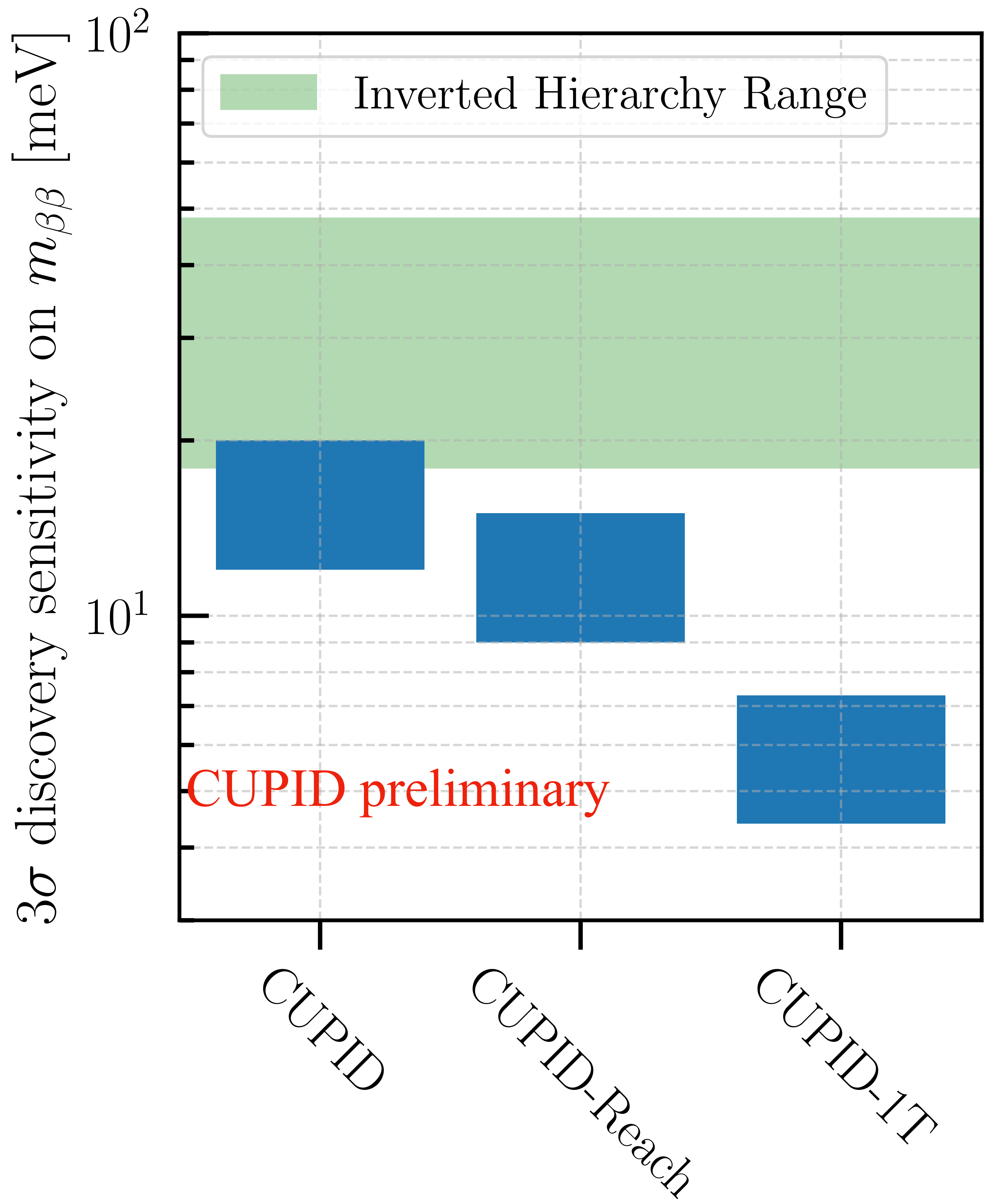
- Goals:
  - Validate assembly procedure, thermalization, and mechanical structure
  - Study of glue type effects on NTD thermistor
  - Validate performance of LMOs and light-detectors
  - Tests on vibrations
- 14 floors, 28 crystals, 30 LDs, 2 runs so far.
- Future tests in 2024:
  - Tests with NTL LDs
  - Reduction of copper

CUPID's projected background index

- ROI Background Index (B.I.) goal: $< 10^{-4}$ cts/(keV kg yr) [vs. CUORE's 10^{-2} ckky]
- Upper limits and measurements from predecessor experiments.
- Well-defined mitigation strategies:
  - Muon veto.
  - Material selection, cleaning, shielding.
  - Delayed coincidence cuts (U/Th chains).
  - Lower noise, higher bandwidth electronics.
  - Improved light-detector timing resolution/SNR

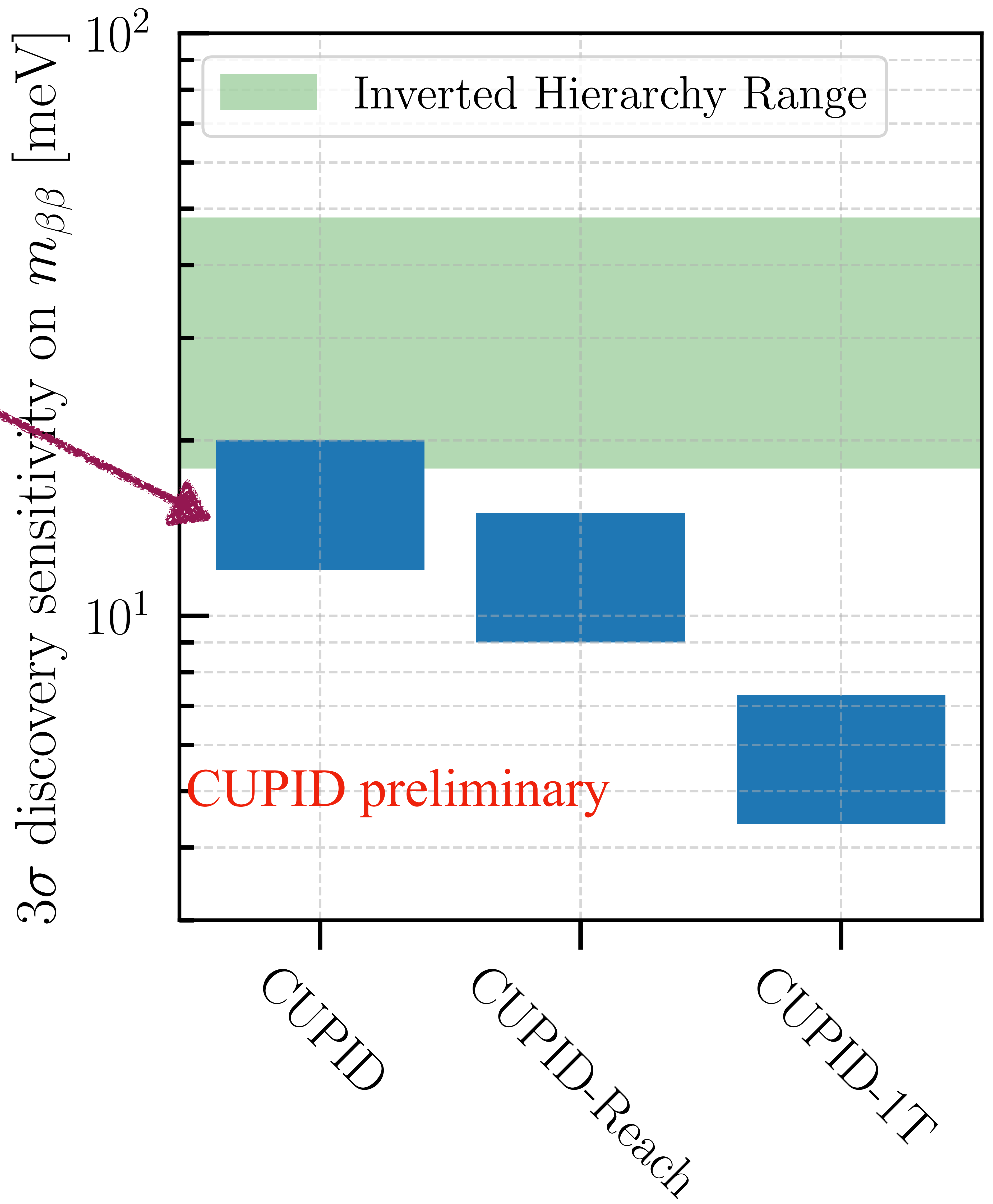


Projected Sensitivity



Projected Sensitivity

CUPID = baseline, what we know we can build now



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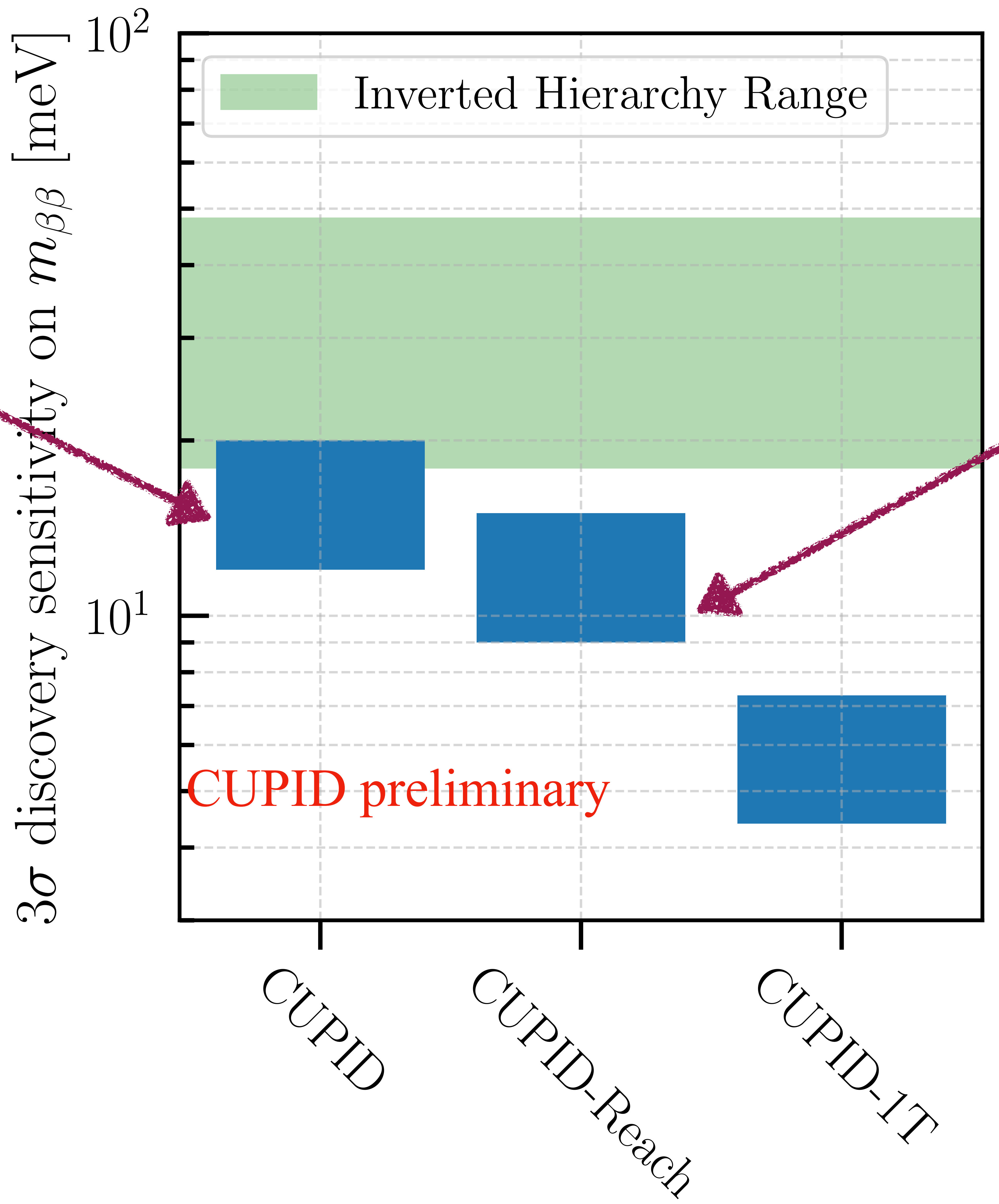

CUPID-Reach = B.I. reduced to $< 2 \times 10^{-5}$ cts/(keV kg yr)

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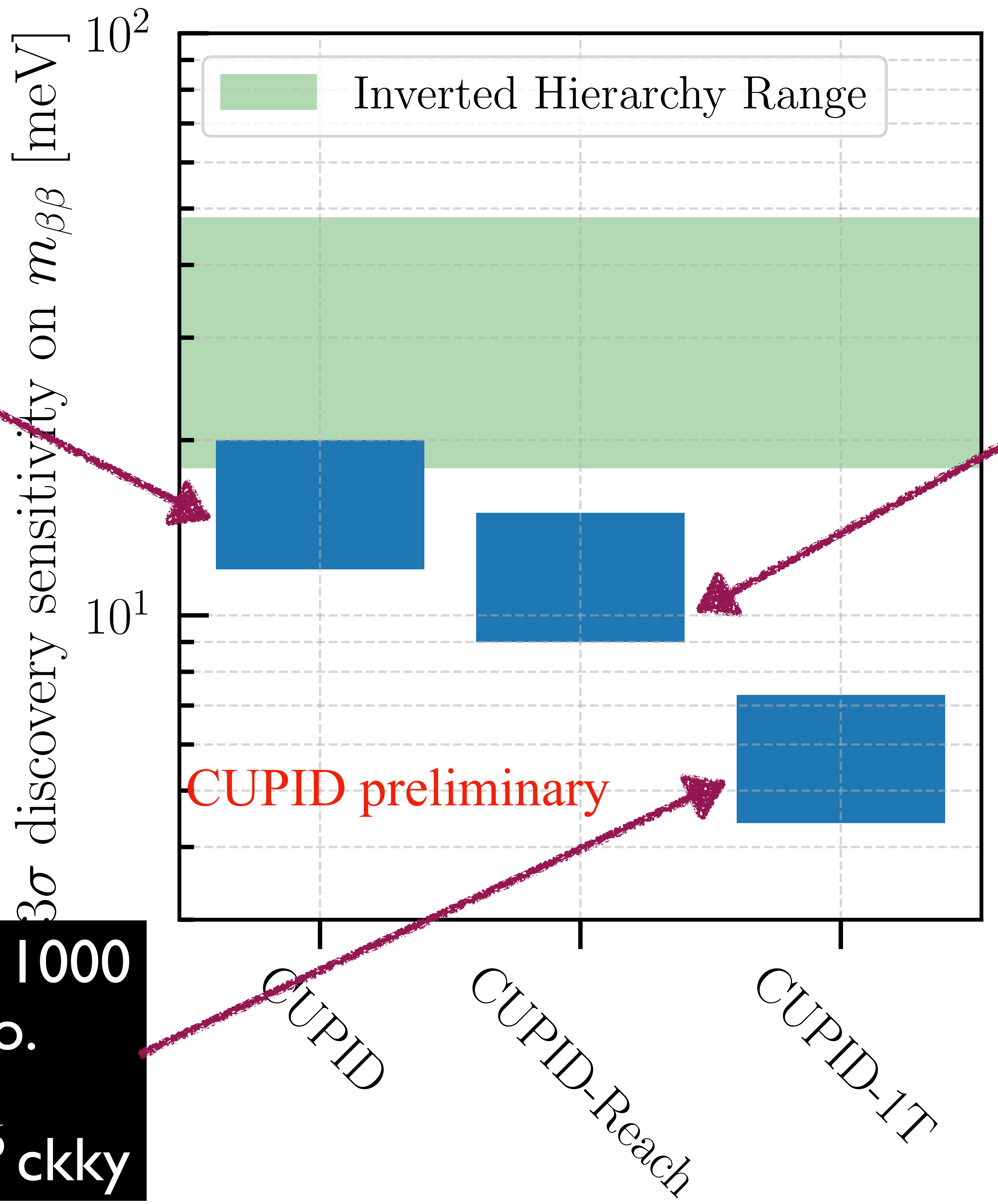

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CUPID 1-Ton: 1000 kg of ^{100}Mo.

B.I. $< 5 \times 10^{-6}$ ckky

Summary

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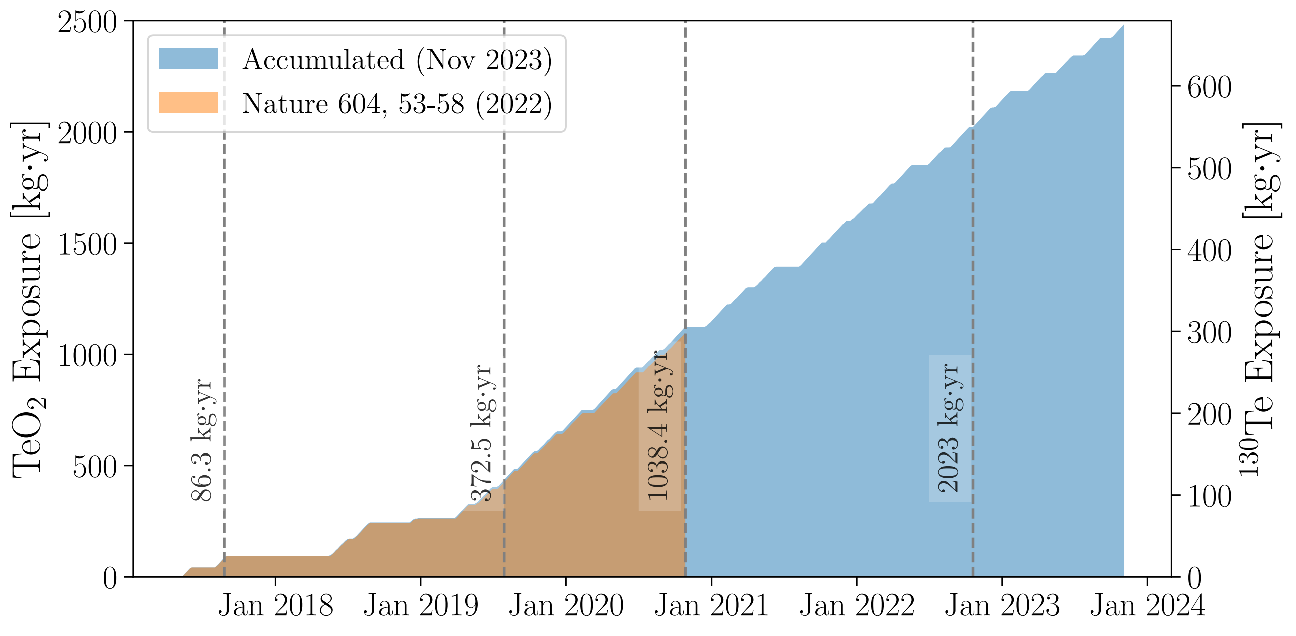
- CUORE has achieved 2 ton-year exposure.
- Full analysis being finished.
- CUORE will finish taking data after achieving 3 tonne-years of TeO_2 exposure



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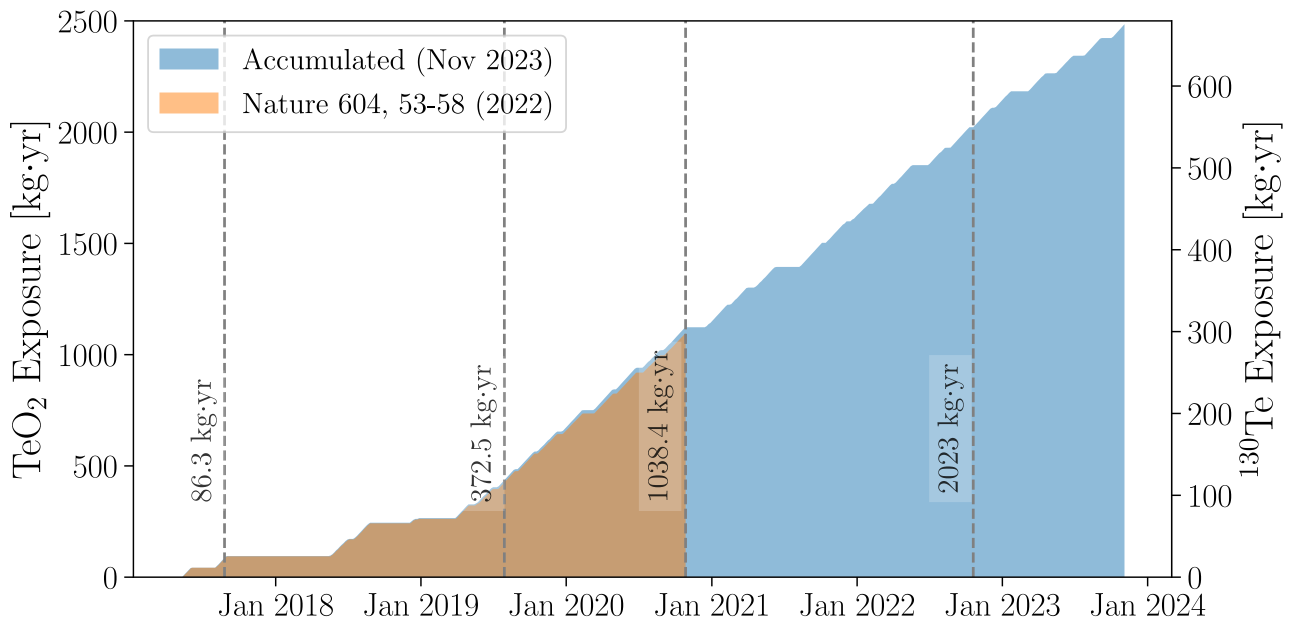
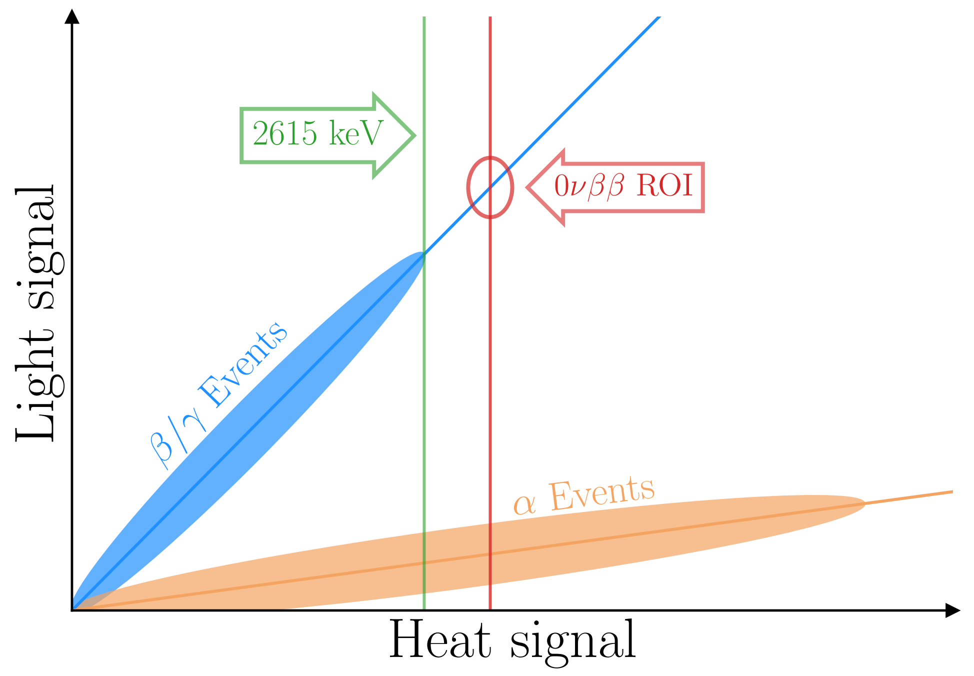


- CUPID will build upon previous experiments knowledge/ infrastructure.
- Adding particle ID + other techniques to reduce B.I.



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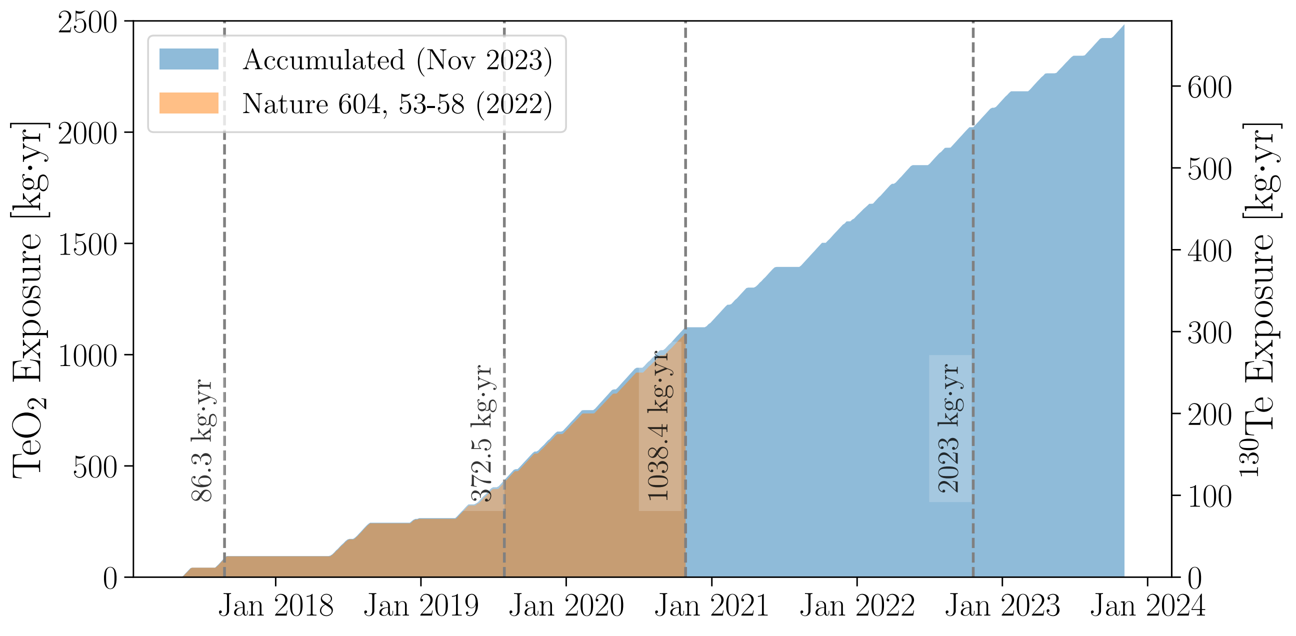

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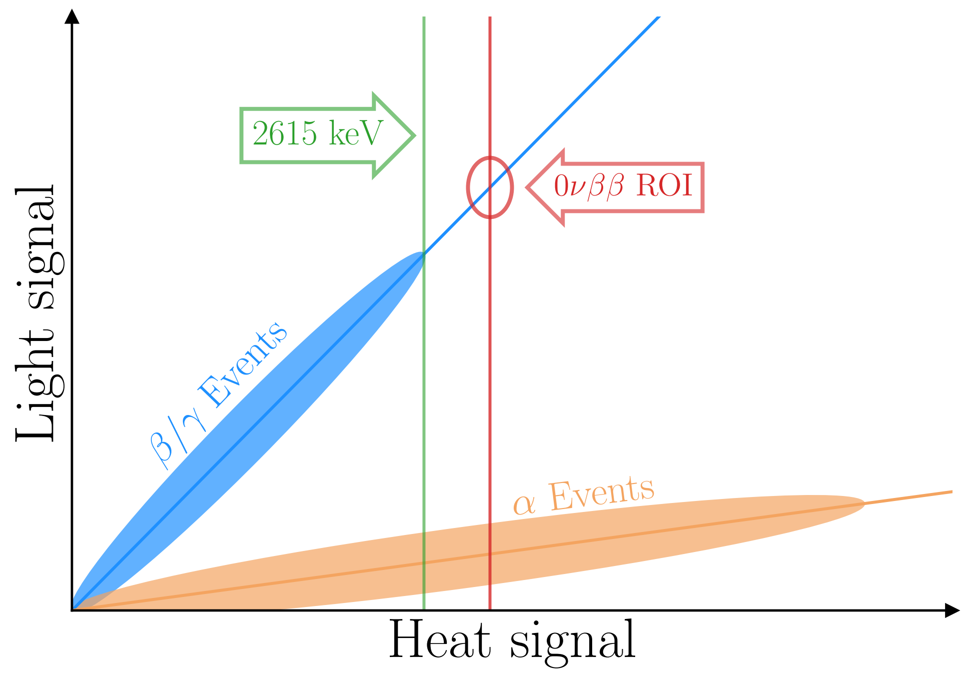
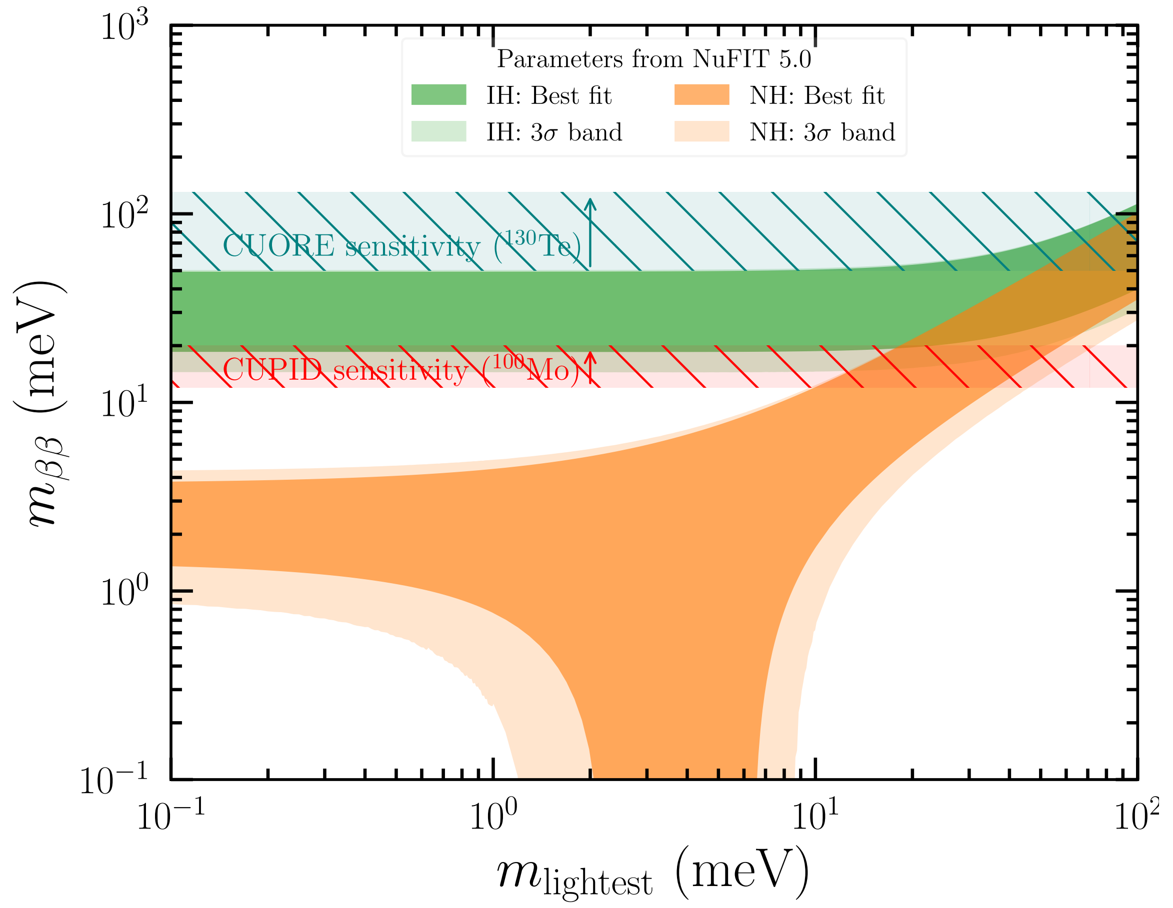


- Experiment moving forward.
- Planning to take data by end of decade.
- CUPID will be among the world-wide suite of $0\nu\beta\beta$ decay experiments with discovery potential.



Thanks!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Universidad Zaragoza
BOSTON UNIVERSITY
Drexel UNIVERSITY
G S S I

CUORE/CUPID talks

- C12.00003: K. Vetter, Denoising Algorithms for the CUORE Experiment
- C12.00004: D. Mayer, Studying Track-Like Events with CUORE
- C12.00005 : S. Pagan, A search for solar axions with CUORE and other low-energy analyses
- D12.00007 : J. Camilleri, ^{100}Mo Neutron Activation Background Measurement for CUPID
- DB02.00106: S. Puranam, Improving CUORE Energy Reconstruction Using Principal Component Analysis
- E12.00001: V. Singh, Suppression of $2\nu\beta\beta$ pile-up events in CUPID using light detectors.
- E12.00002: C. Capelli, Transition-edge sensors with multiplexing readout for the CUPID experiment
- E12.00003: A. Drobizhev, Neutron Transmutation Doped (NTD) Germanium Thermistors for CUPID
- M11.00003: V. Sharma, Tri-nucleon decay in ^{130}Te with CUORE
- MW01.00005: J. Torres, Searching for $0\nu\beta\beta$ decay with CUORE and CUPID