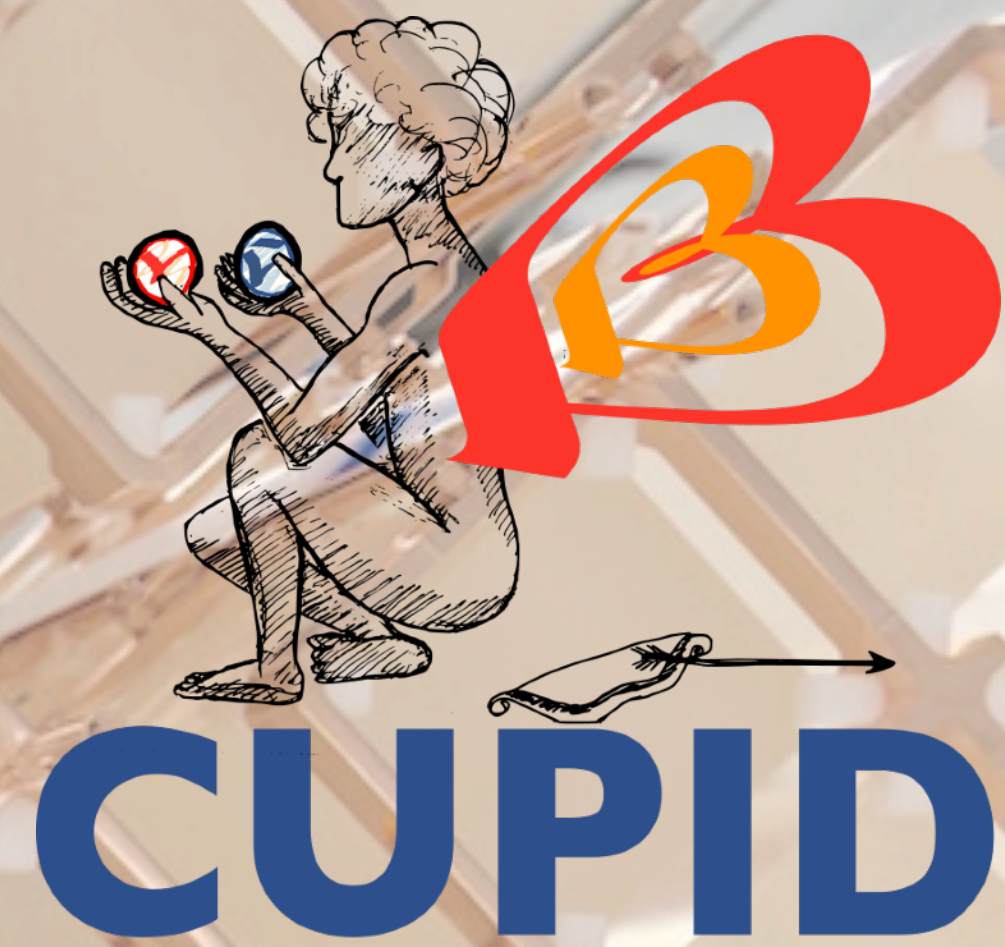




# Search for Neutrinoless Double Beta Decay with CUORE and CUPID



Pranava Teja Surukuchi  
(on behalf of the CUORE and CUPID collaborations)

21st Rencontres du Vietnam  
July 23, 2025

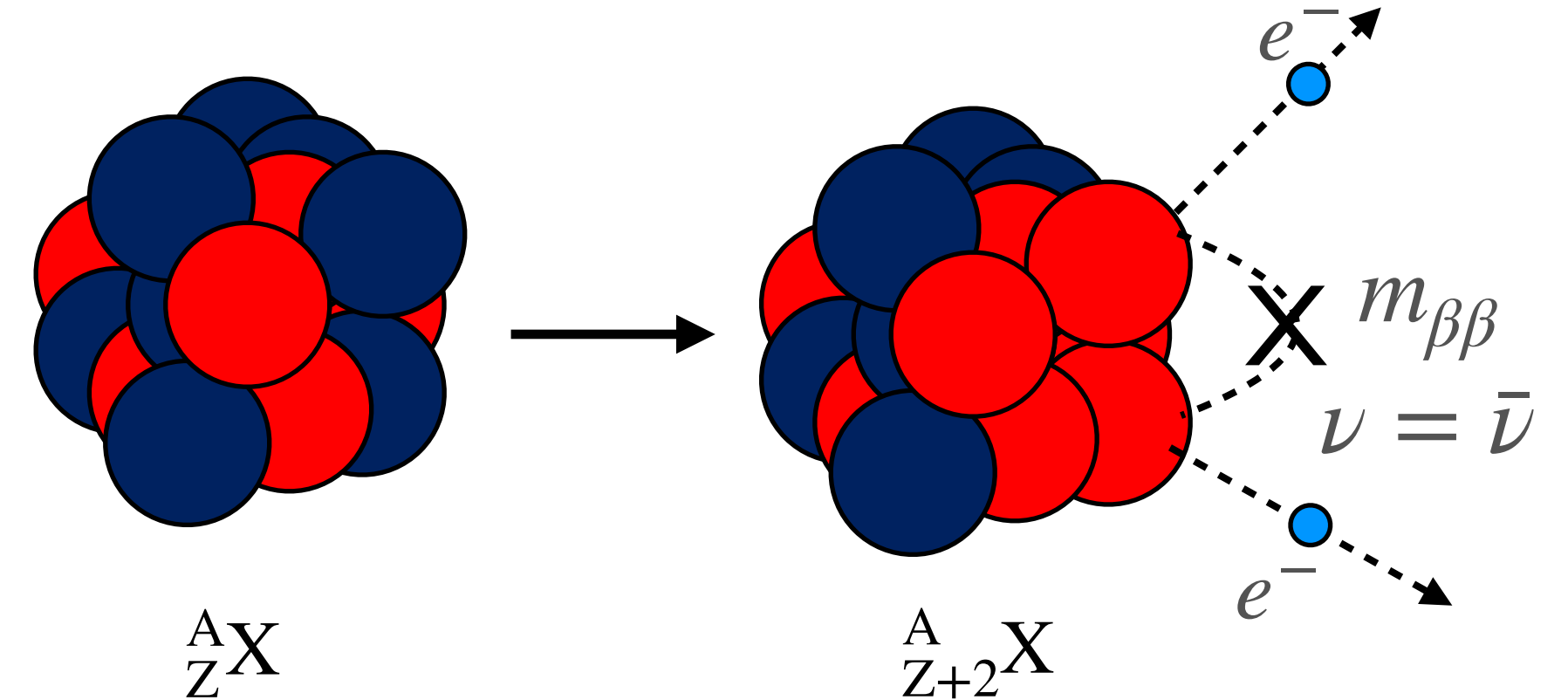


University of  
Pittsburgh



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

- If observed, it implies:
  - Neutrinos are Majorana particles
  - Could explain the smallness of neutrino mass
  - Lepton number violation ( $\Delta L = 2$ )
  - Hints to matter-antimatter asymmetry
- Measure/Constrain decay rate (or half-life)
- Can constrain the mass of neutrinos



Nuclear Matrix elements

$$T_{1/2}^{0\nu} \propto \left( \underset{\substack{\uparrow \\ \text{Phase space factor}}}{G} \underset{\substack{\uparrow \\ \text{Effective neutrino mass}}}{|\mathcal{M}|^2} \langle m_{\beta\beta} \rangle^2 \right)^{-1} \simeq 10^{27-28} \left( \frac{0.01}{\langle m_{\beta\beta} \rangle} \right)^2 \text{ yr}$$

Effective neutrino mass

$$\langle m_{\beta\beta} \rangle = \left| \sum_{j=1,2,3} m_j U_{ej}^2 \right|$$







## Cryogenic Underground Observatory for Rare Events

- Located in LNGS under the mountain of Gran Sasso
- **Primary Goal:** Search for  $0\nu\beta\beta$  decay of  $^{130}\text{Te}$
- **Design:**
  - 19 towers (total of 988  $\text{TeO}_2$  crystals)
  - 206 kg of  $^{130}\text{Te}$ :  $Q_{\beta\beta} \sim 2.5 \text{ MeV}$
  - *Low background:*  $\sim 10^{-2} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$
  - *Energy resolution:*  $\sim 8 \text{ keV FWHM}$  at  $Q_{\beta\beta}$



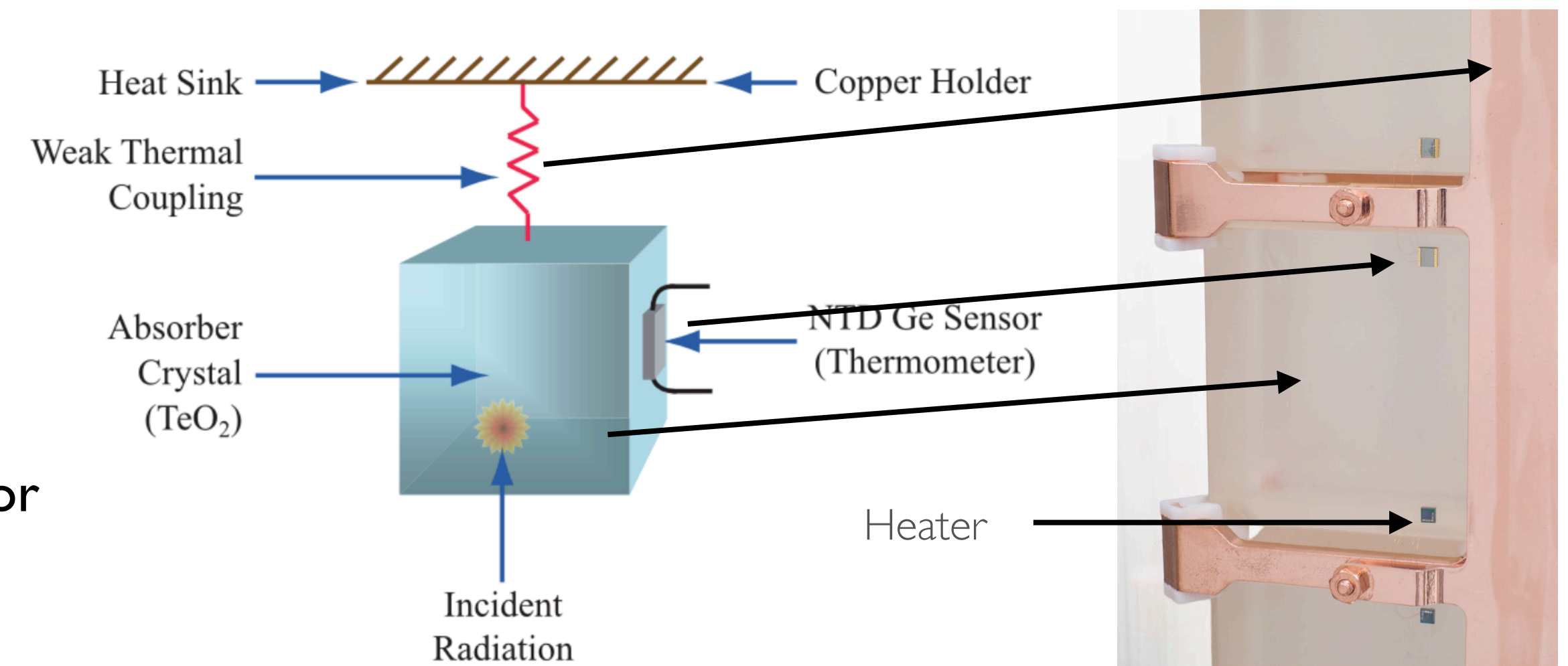
Wikimedia Commons





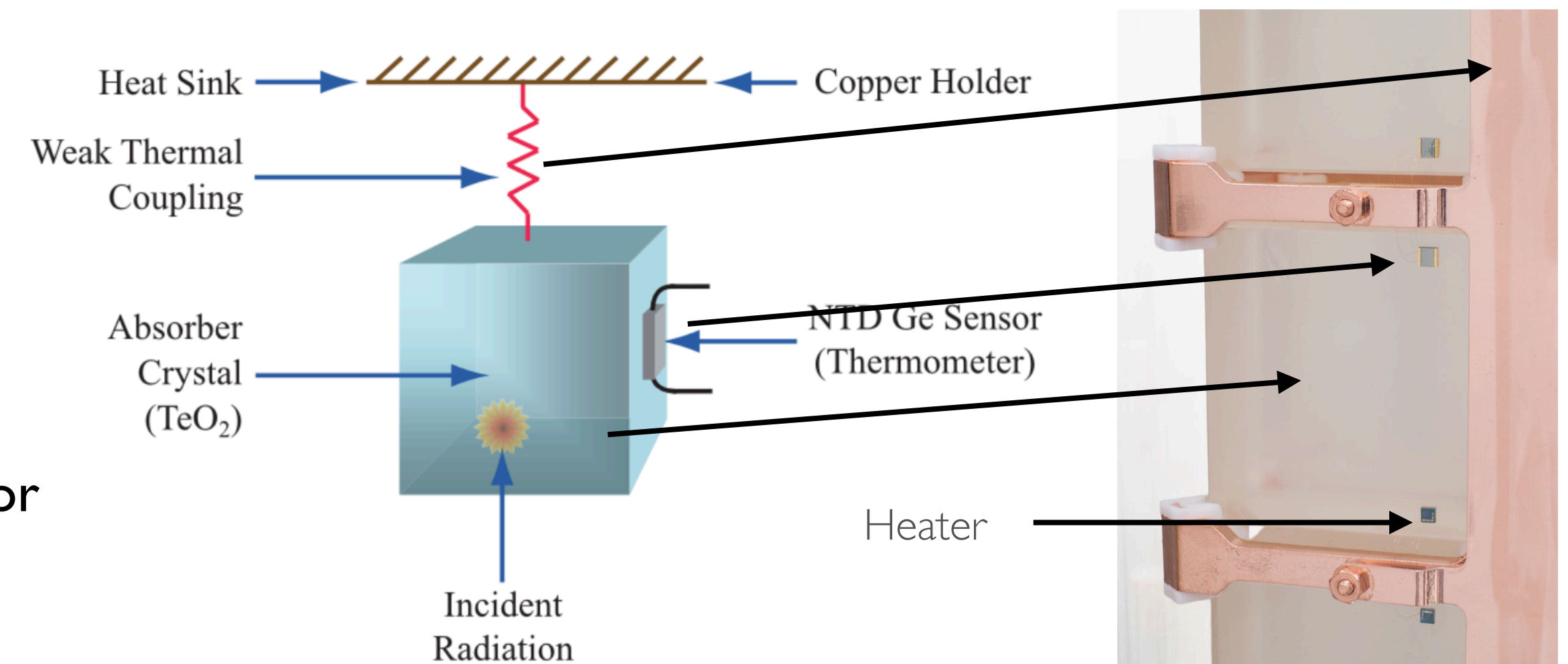
# Cryogenic Calorimetric Technique

- Each crystal:
  - **Absorber:** 5x5x5 cm<sup>3</sup> TeO<sub>2</sub> crystal
  - **Operational temperature:** ~10 mK
  - **Thermal coupling:** PTFE holder and gold wires
  - **Sensor:** Ge neutron transmutation doped (NTD-Ge) thermistor
  - **Heater:** Gain stabilization and calibration





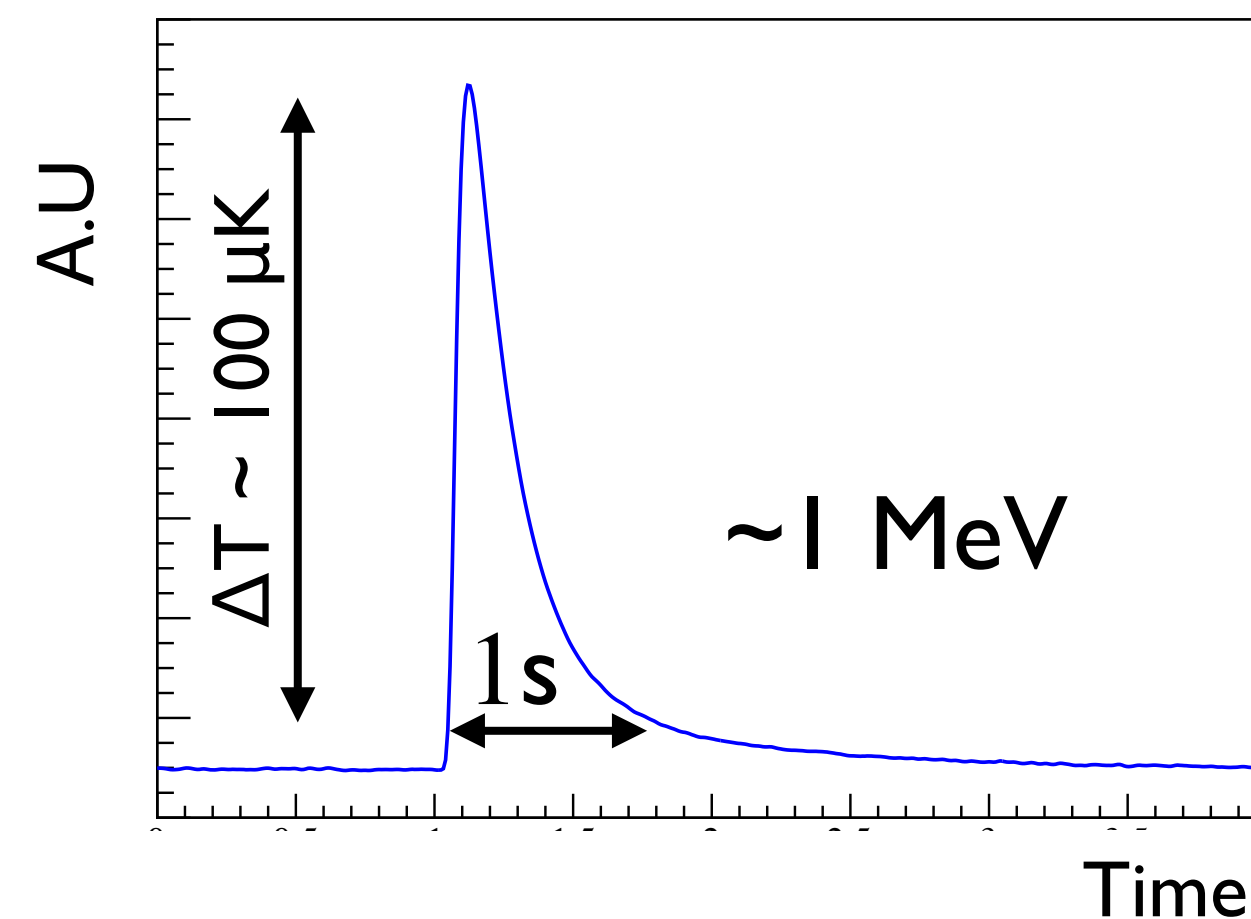
- Each crystal:
  - **Absorber:** 5x5x5 cm<sup>3</sup> TeO<sub>2</sub> crystal
  - **Operational temperature:** ~10 mK
  - **Thermal coupling:** PTFE holder and gold wires
  - **Sensor:** Ge neutron transmutation doped (NTD-Ge) thermistor
  - **Heater:** Gain stabilization and calibration



Crystal temperature rises when energy is deposited

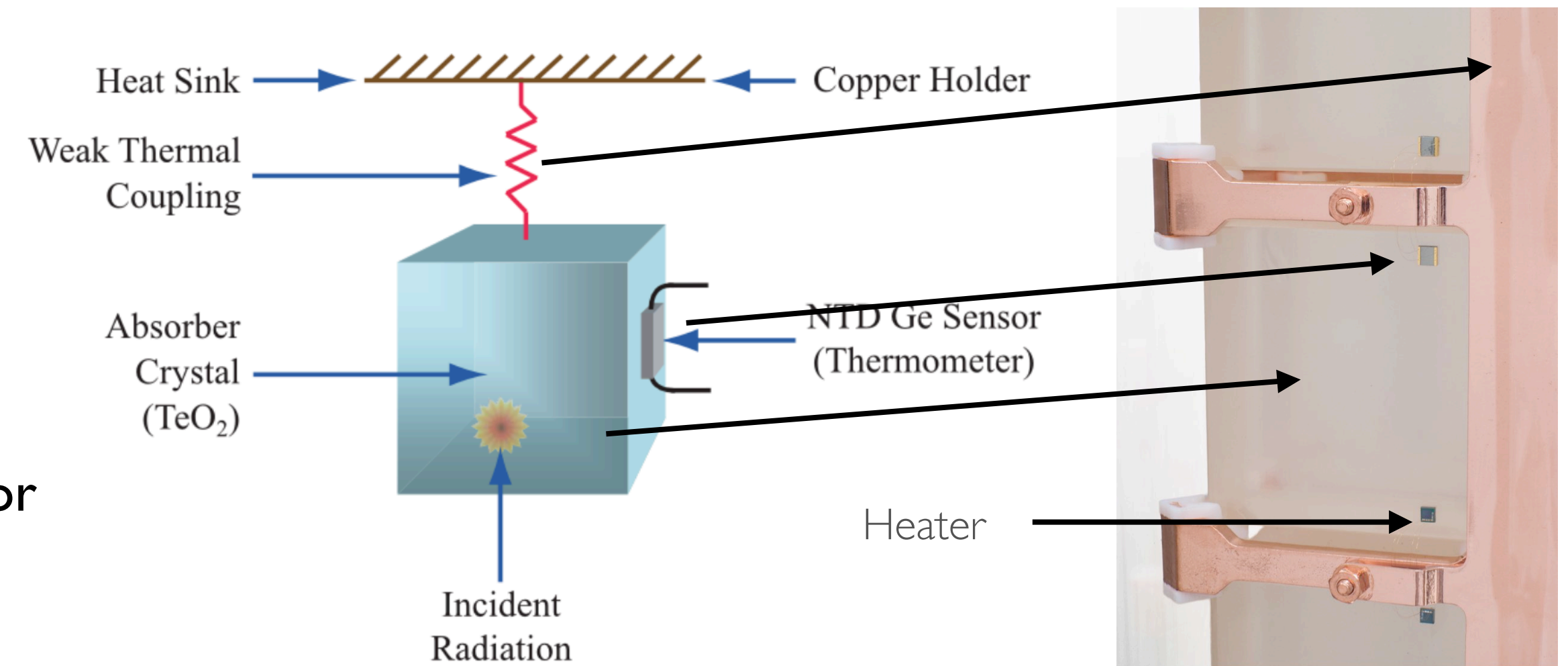
$$\Delta T \propto \frac{E}{C(T)}$$

$$C(T) \propto T^3$$





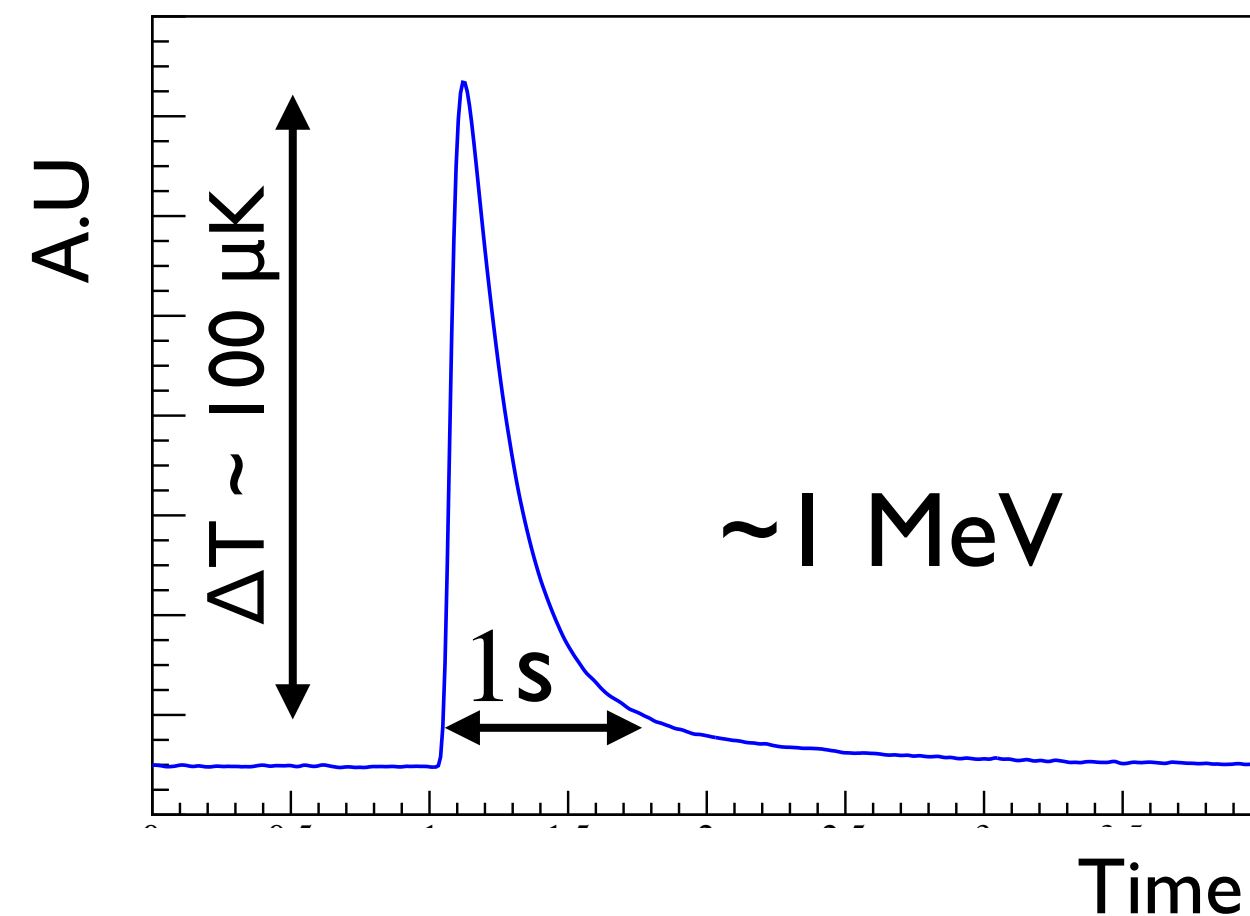
- Each crystal:
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$$\Delta T \propto \frac{E}{C(T)}$$

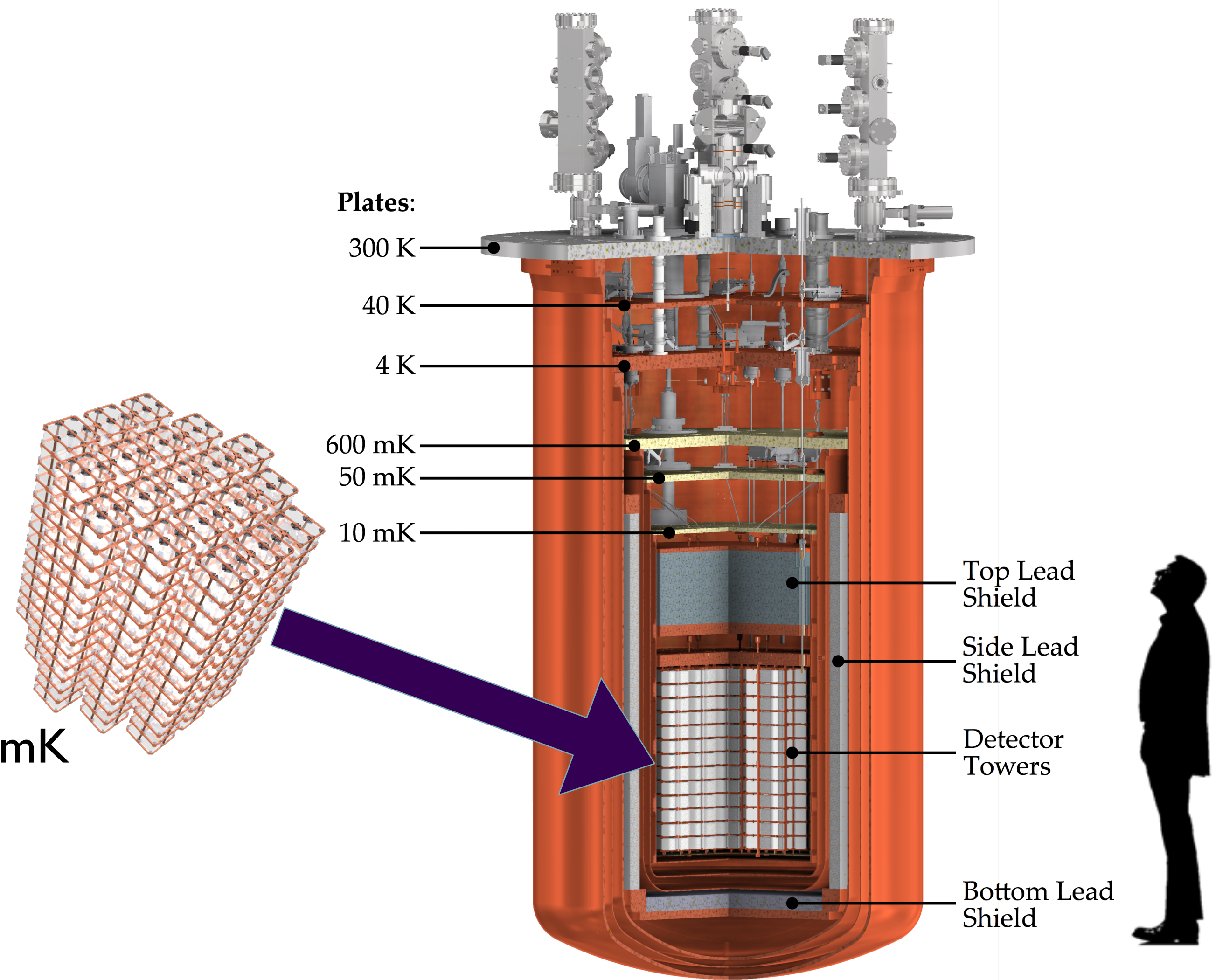
$$C(T) \propto T^3$$



- Excellent energy resolution ( $\sim 0.3\% \Delta E/E @ Q_{\beta\beta}$ )
- Detector response independent of particle type
- Flexibility in  $0\nu\beta\beta$  candidate choice



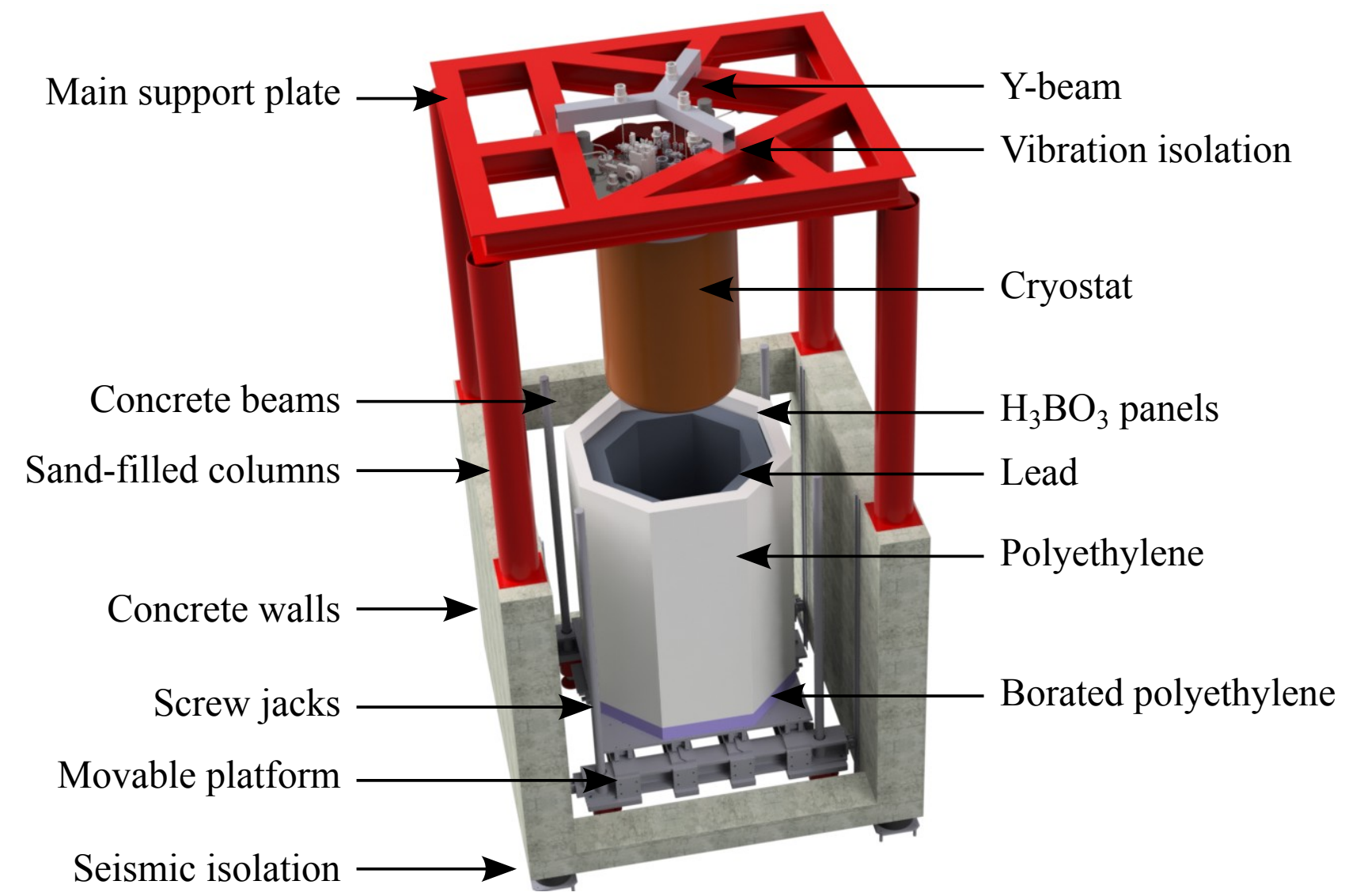
- Multiple stage cryogen-free cryostat:
  - Nested co-axial cylinders
  - Pulse Tubes for cooling **40 K** and **4 K** stages
  - Dilution Unit to cool rest of the stages
- Total cooled mass: ~**30 ton**
- First ever cryostat to have cooled ~1 tonne to 10 mK







# Mitigating Vibrations

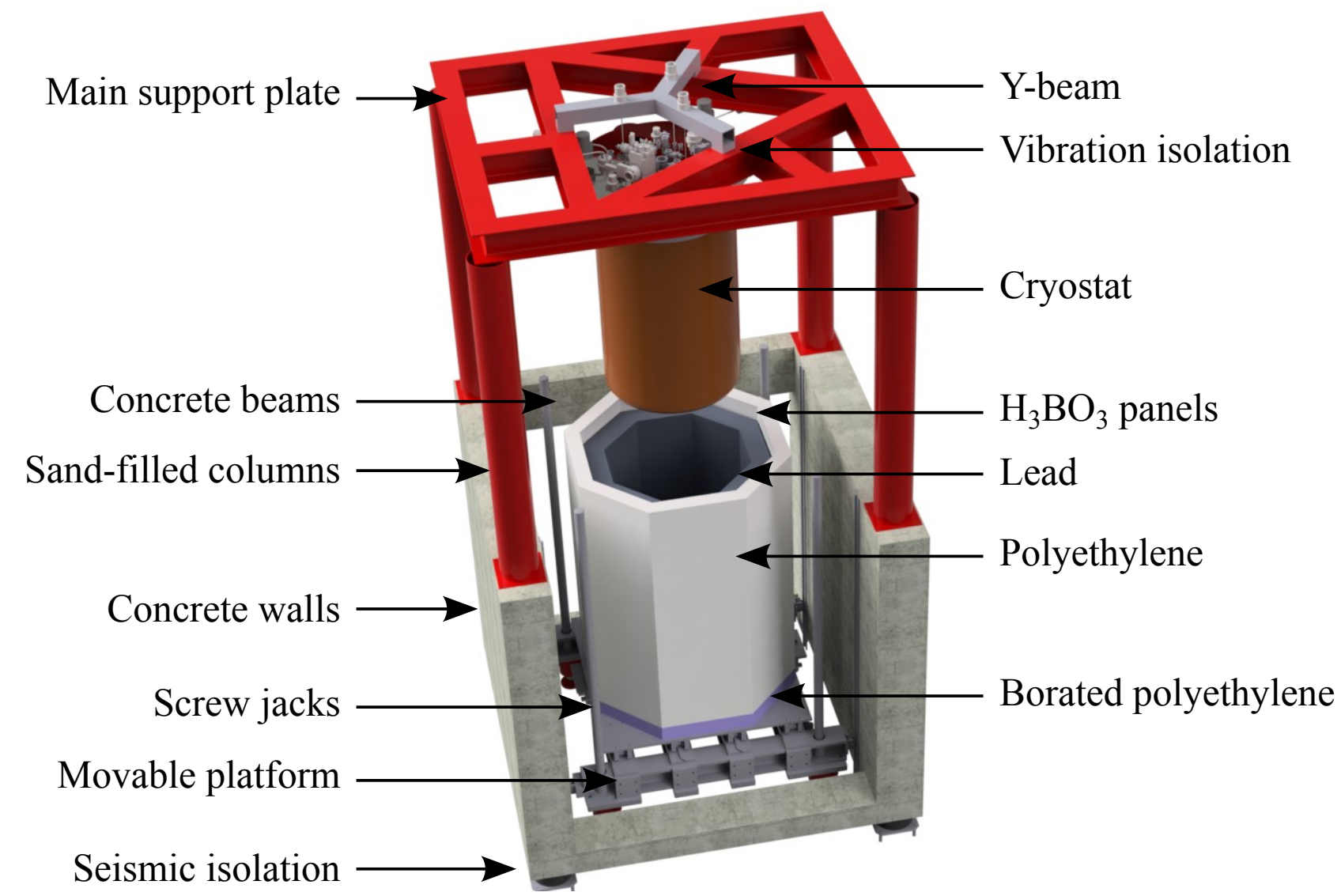


- Several levels of passive seismic isolation

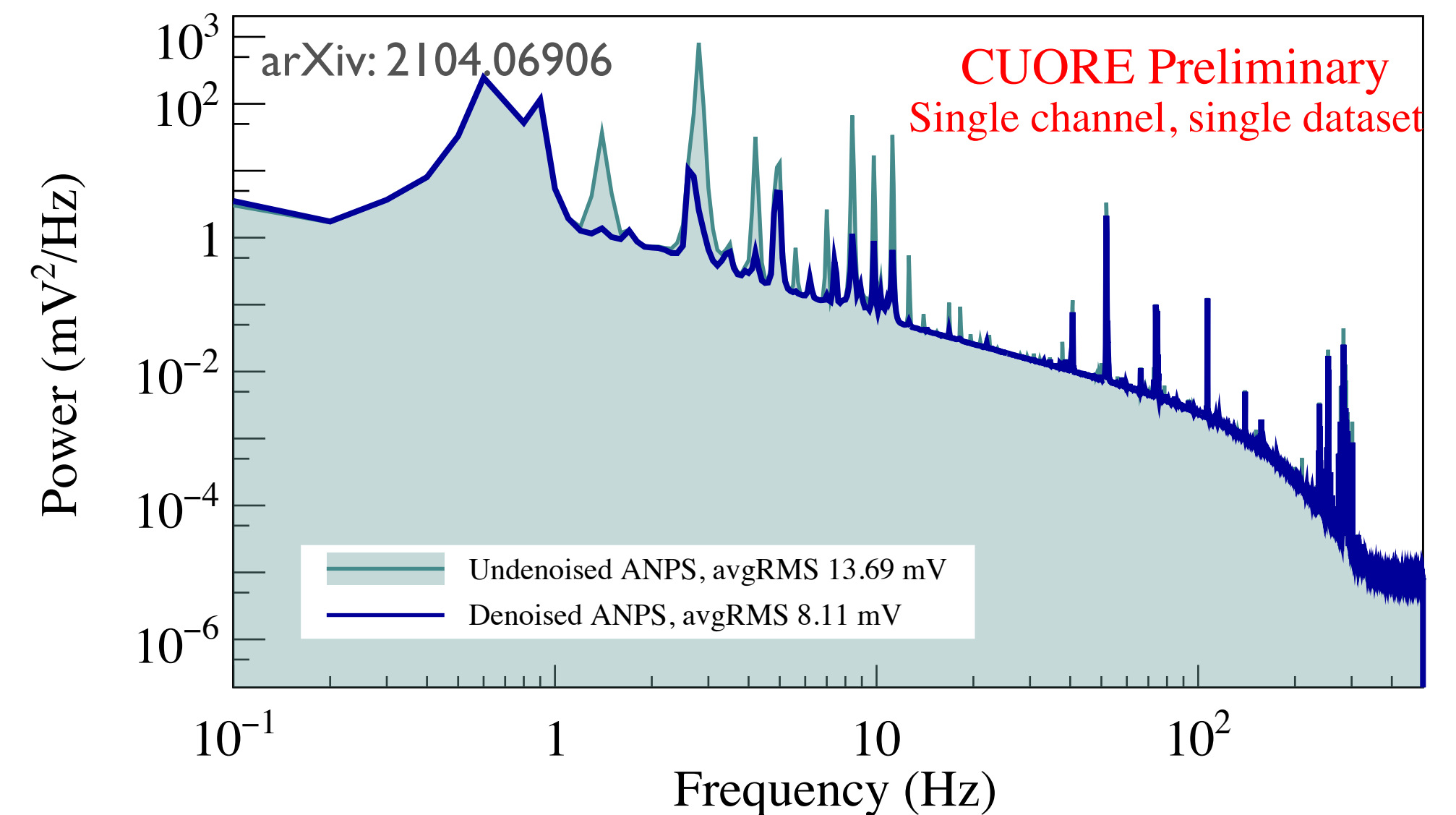
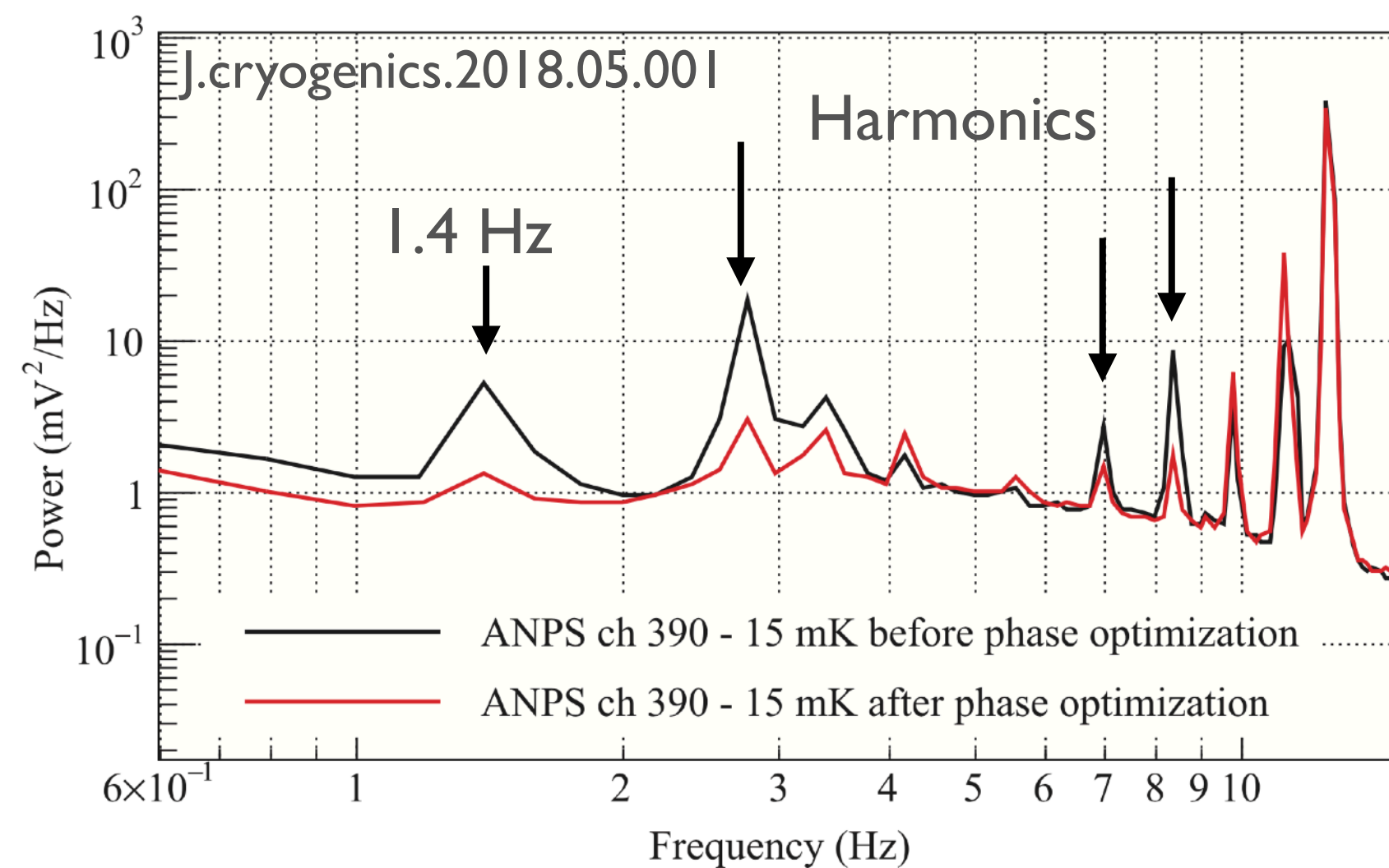




# Mitigating Vibrations



- Several levels of passive seismic isolation
- Active noise reduction:
  - Control relative pulse tube phases for destructive interference of vibrations
  - Using correlations between detectors and auxiliary devices for denoising
    - Seismometers, accelerometers, microphones, and antennas

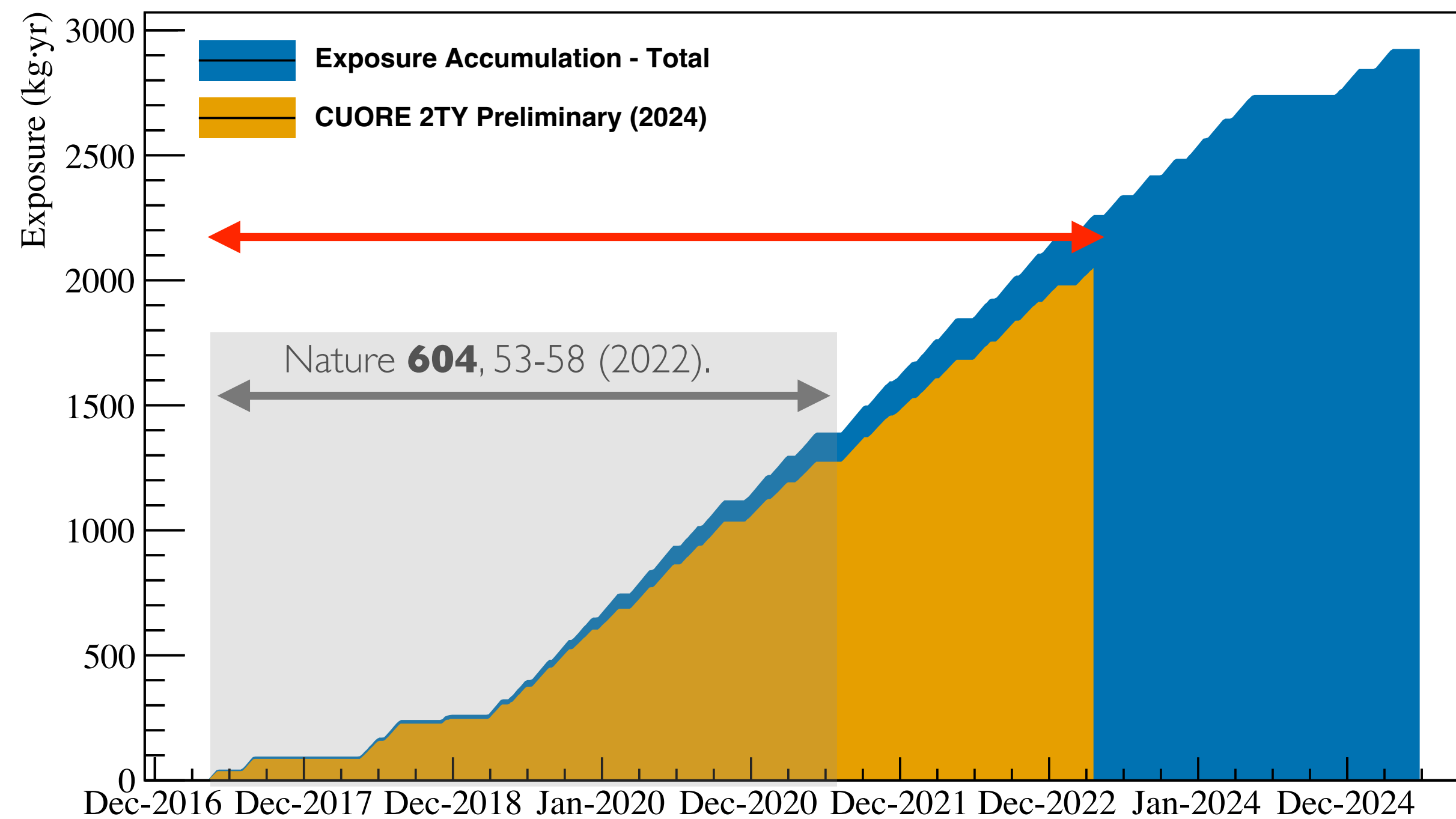






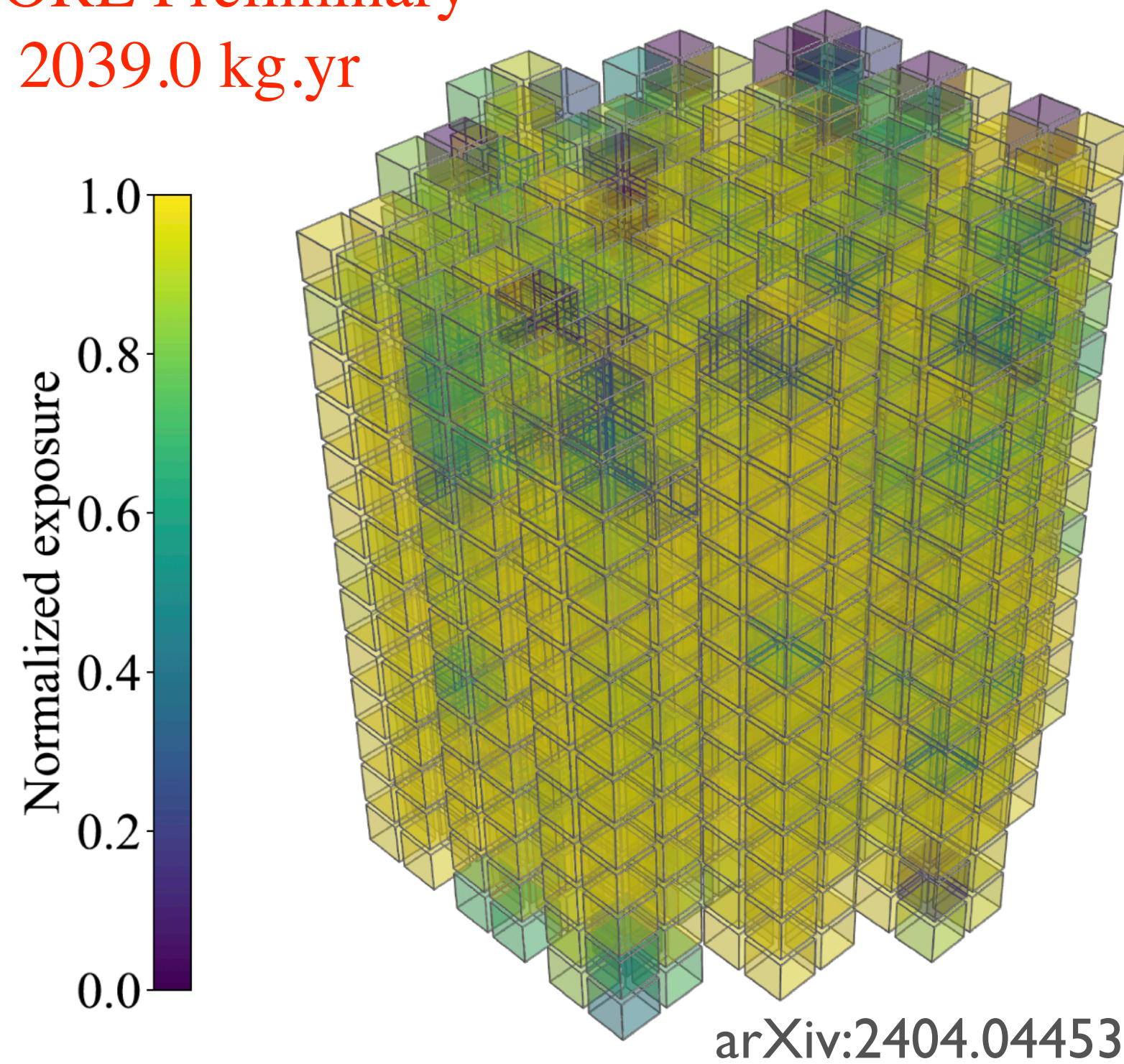
# Data Taking

- Pauses in data taking for detector optimization during early detector operations
- Since 2019 continuous data-taking with very little down time
- 34 datasets collected so far, each dataset  $\sim 1$  month long ( $\sim 50$  kg.yr/month)
- Published  $0\nu\beta\beta$  search results in 2022 for the data collected up to 2020
- Updated search with data collected up to 2023 ( $\sim 2$  tonne.yrs of  $\text{TeO}_2$  exposure)

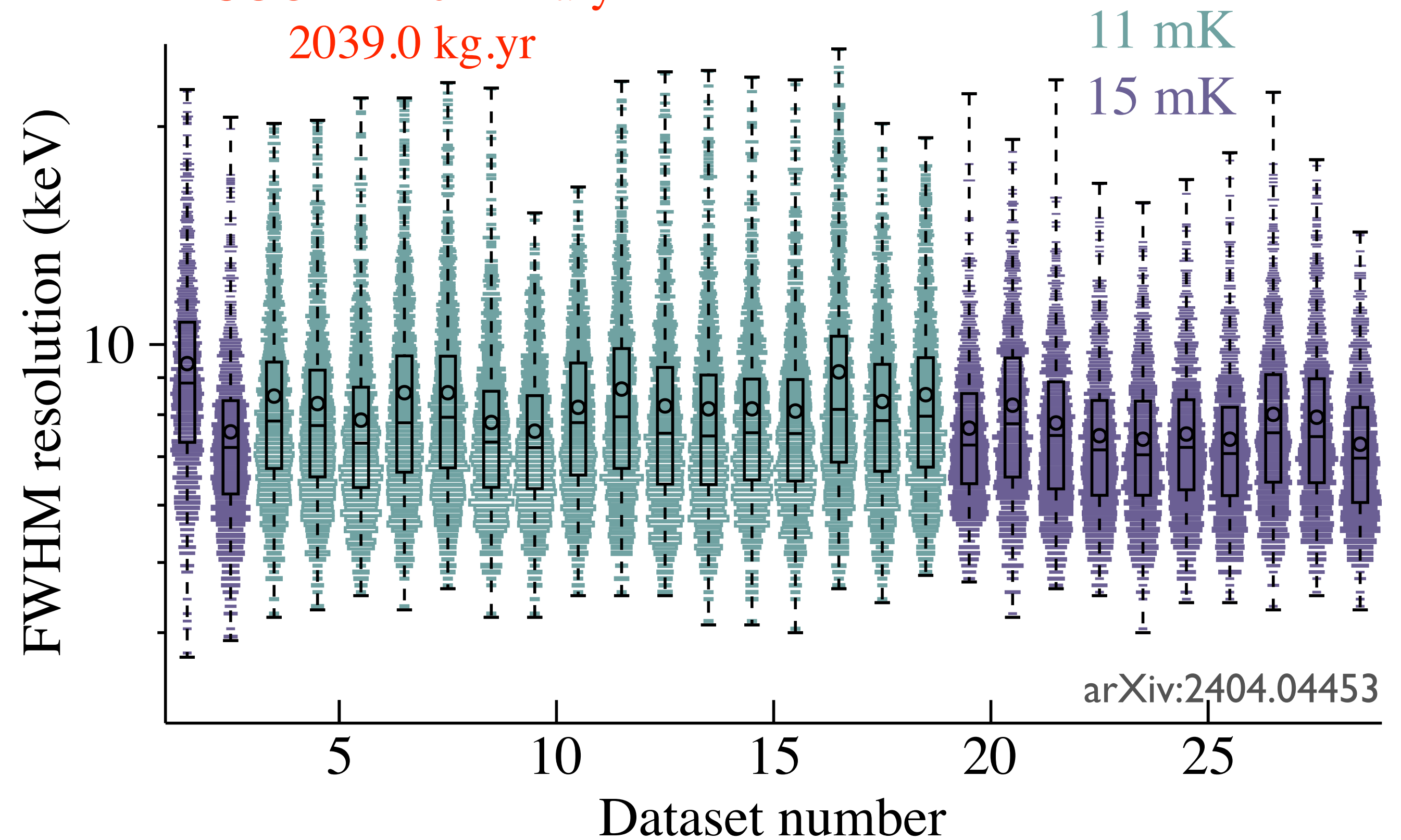




CUORE Preliminary  
2039.0 kg.yr



CUORE Preliminary  
2039.0 kg.yr

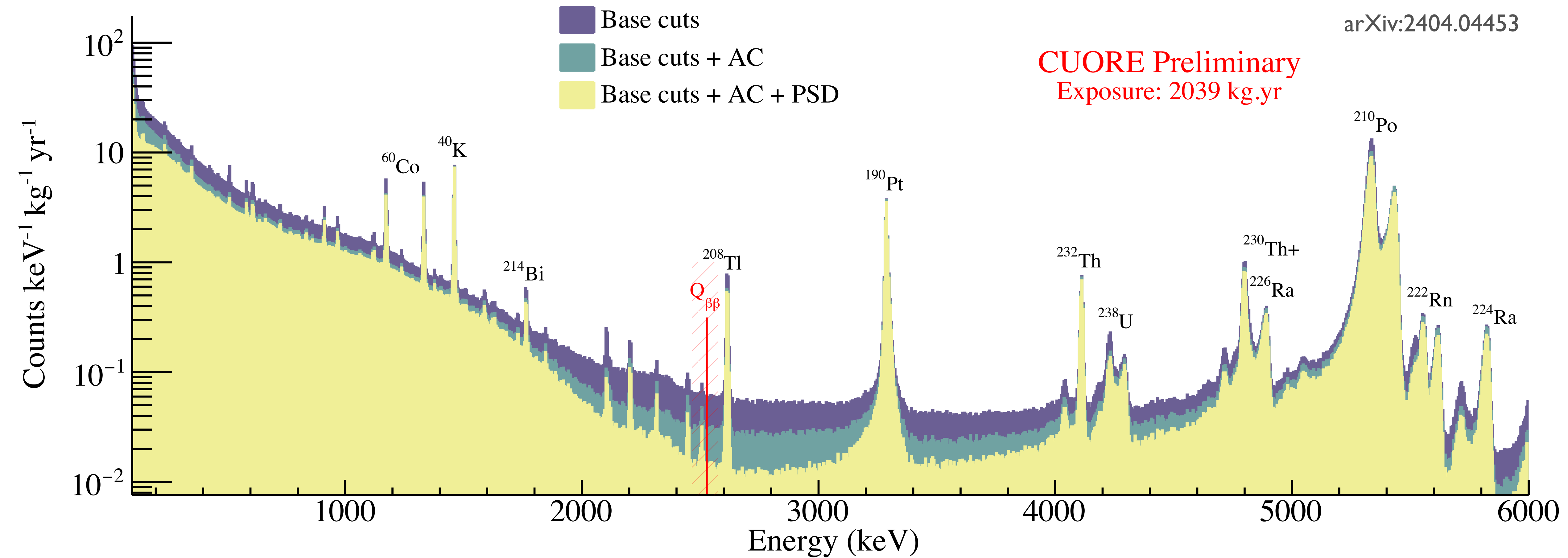


- 984 out of 988 channels active; ~914/984 channels surviving cuts
- Total analysis cut efficiency 93.4 %
- Robust analysis infrastructure that can handle ~1000 channels under varying conditions





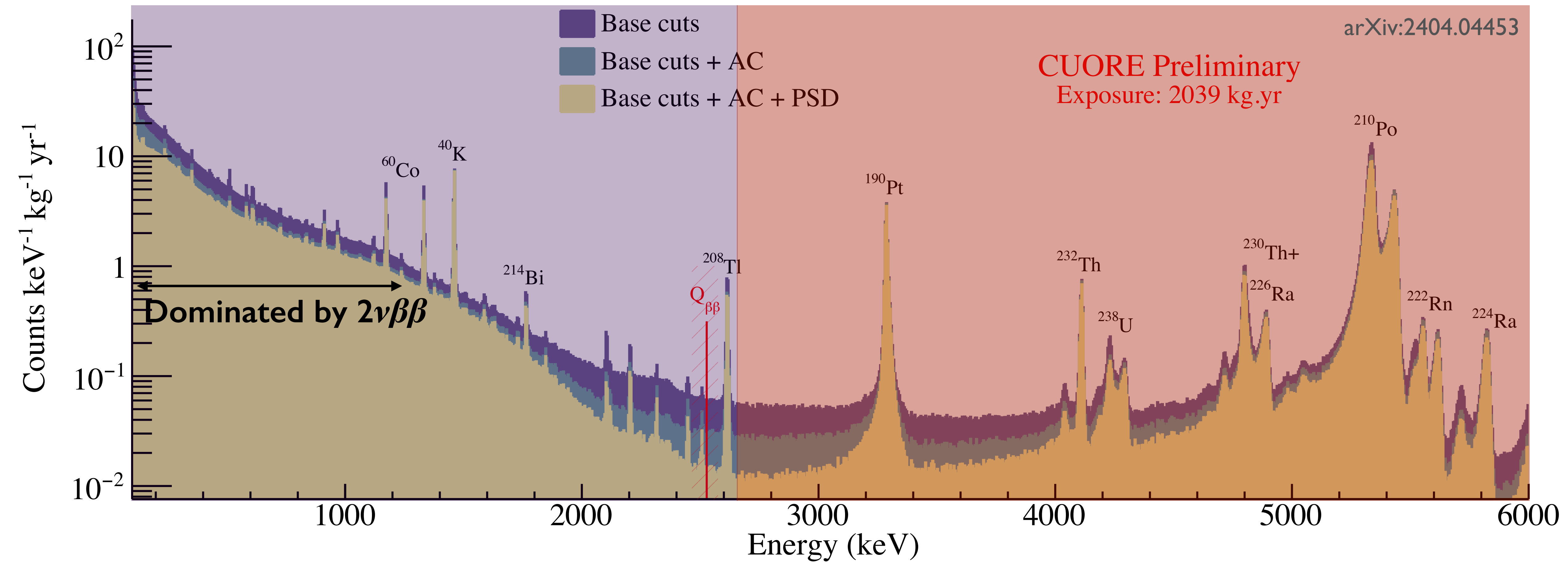
# Spectrum





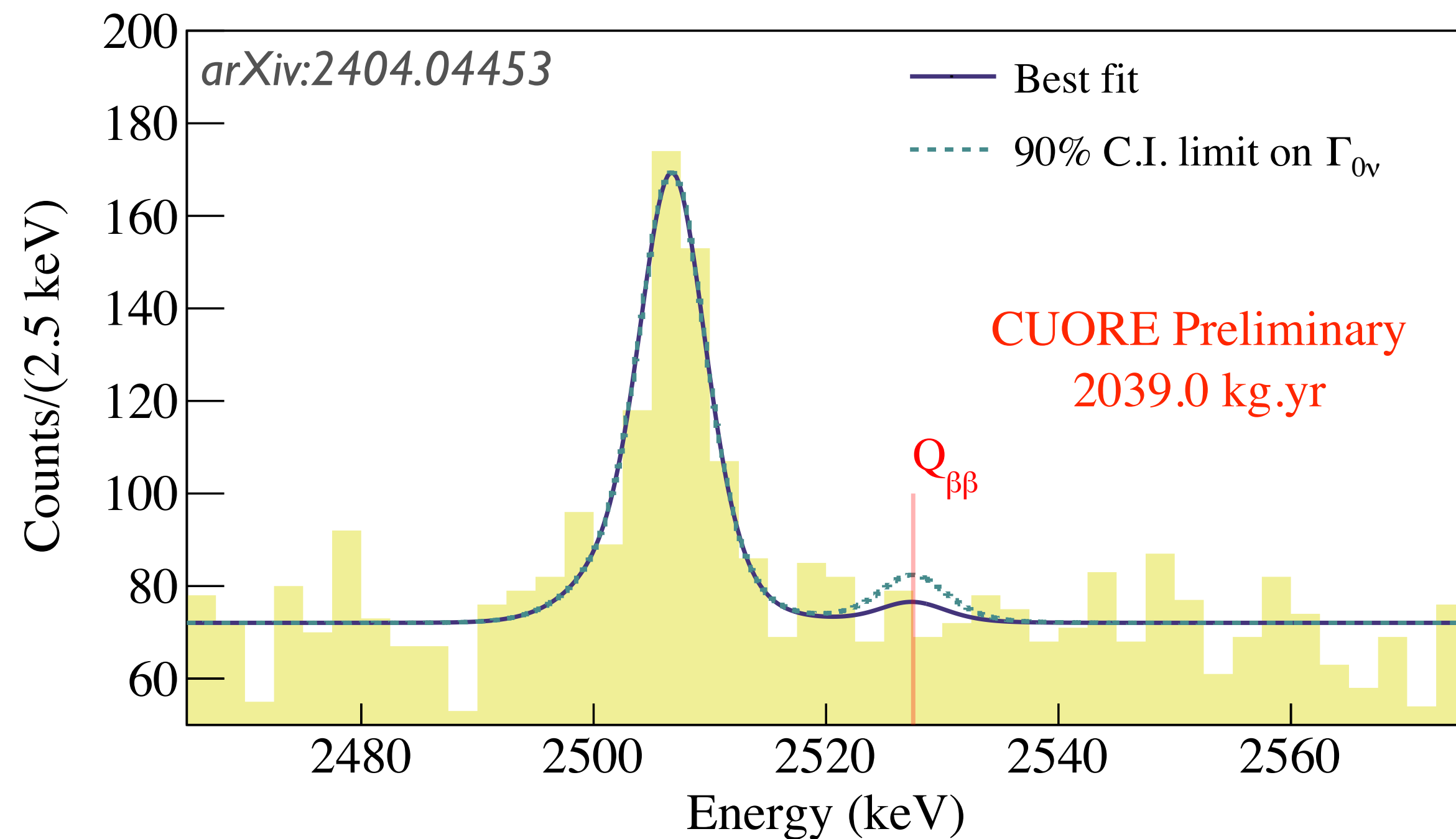


# Spectrum





- Fit performed over [2465, 2575] keV with fit parameters:
  - $0\nu\beta\beta$  decay rate @  $Q_{\beta\beta}$
  - $^{60}\text{Co}$  sum peak amplitude
  - Background (flat)
- No evidence of  $0\nu\beta\beta$
- $T_{1/2}^{0\nu} > 3.8 \times 10^{25}$  yr (90% C.I.)

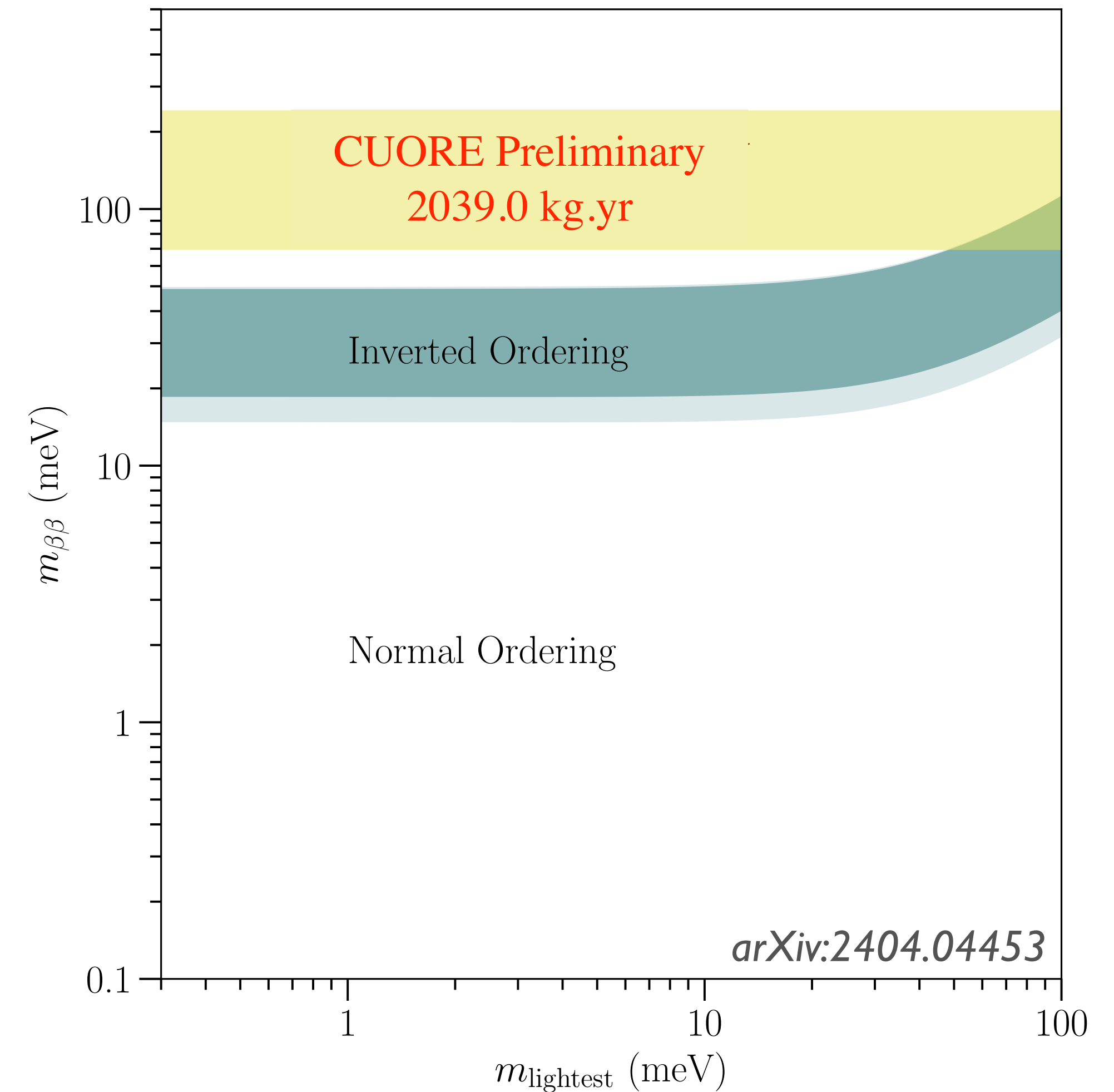
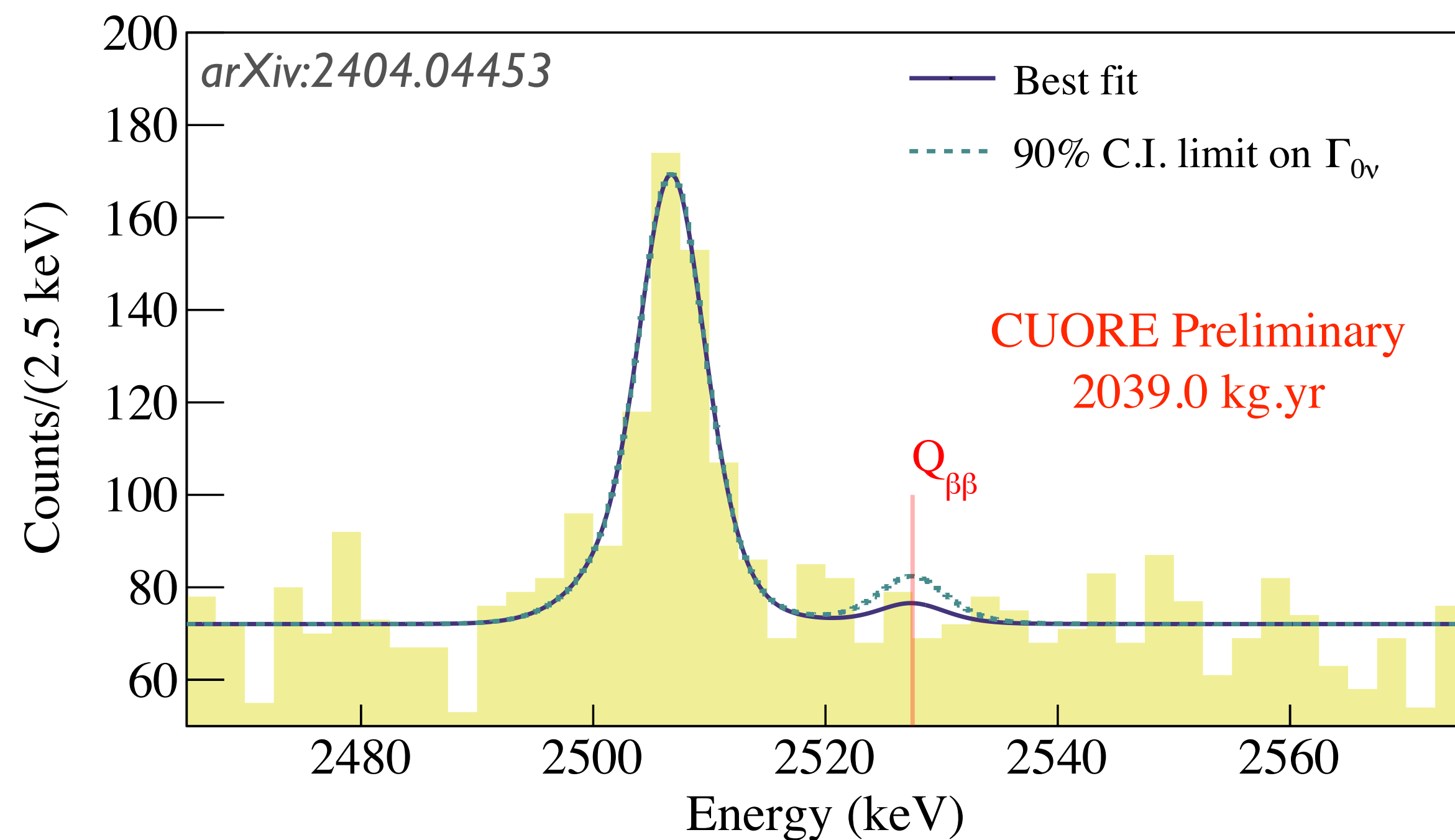






# Limit on Neutrino Mass

- Fit performed over [2465, 2575] keV with fit parameters:
  - $0\nu\beta\beta$  decay rate @  $Q_{\beta\beta}$
  - $^{60}\text{Co}$  sum peak amplitude
  - Background (flat)
- No evidence of  $0\nu\beta\beta$
- $T_{1/2}^{0\nu} > 3.8 \times 10^{25}$  yr (90% C.I.)



- Assuming light neutrino exchange:  
 $m_{\beta\beta} < \mathbf{70-240\ meV}$

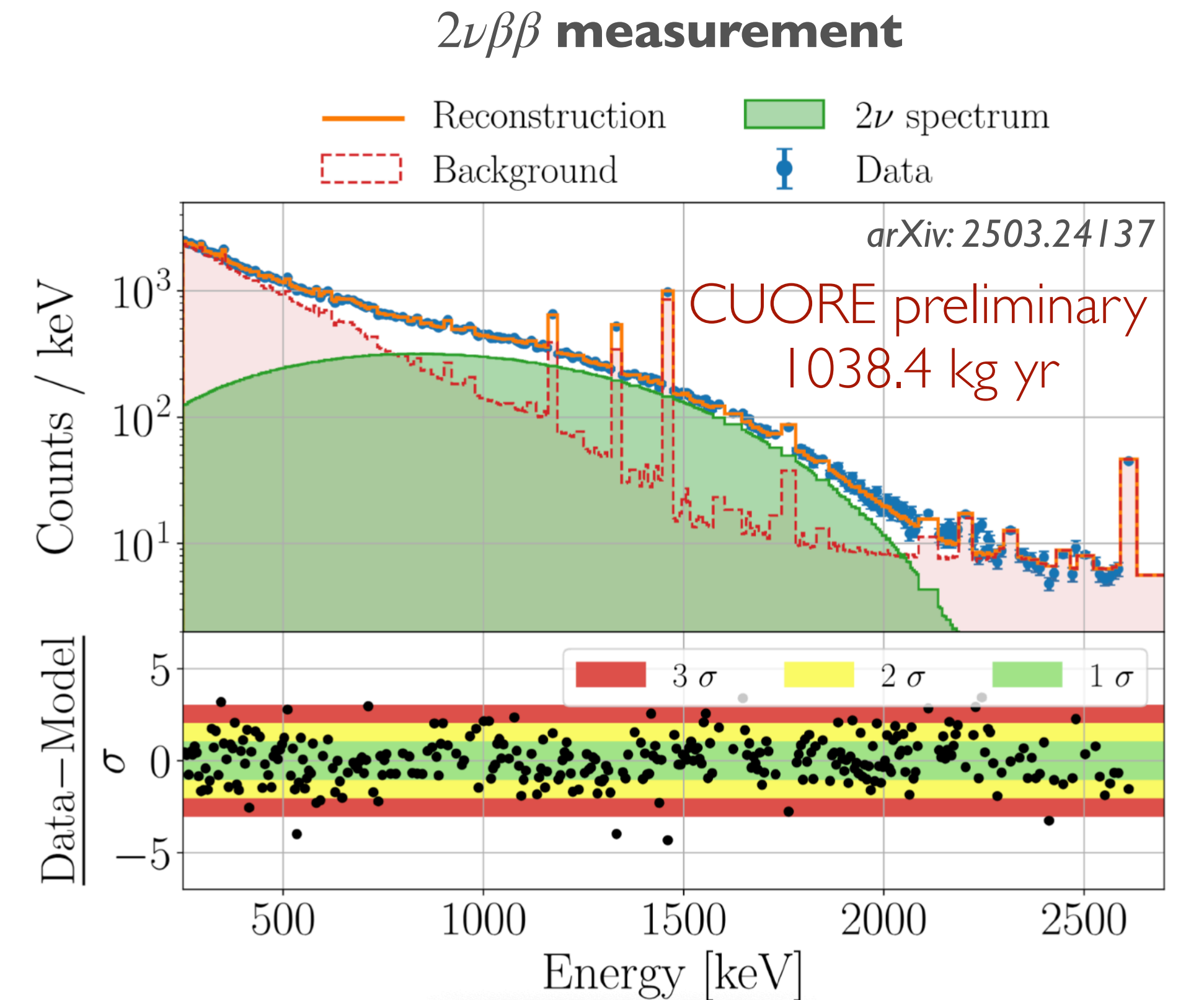
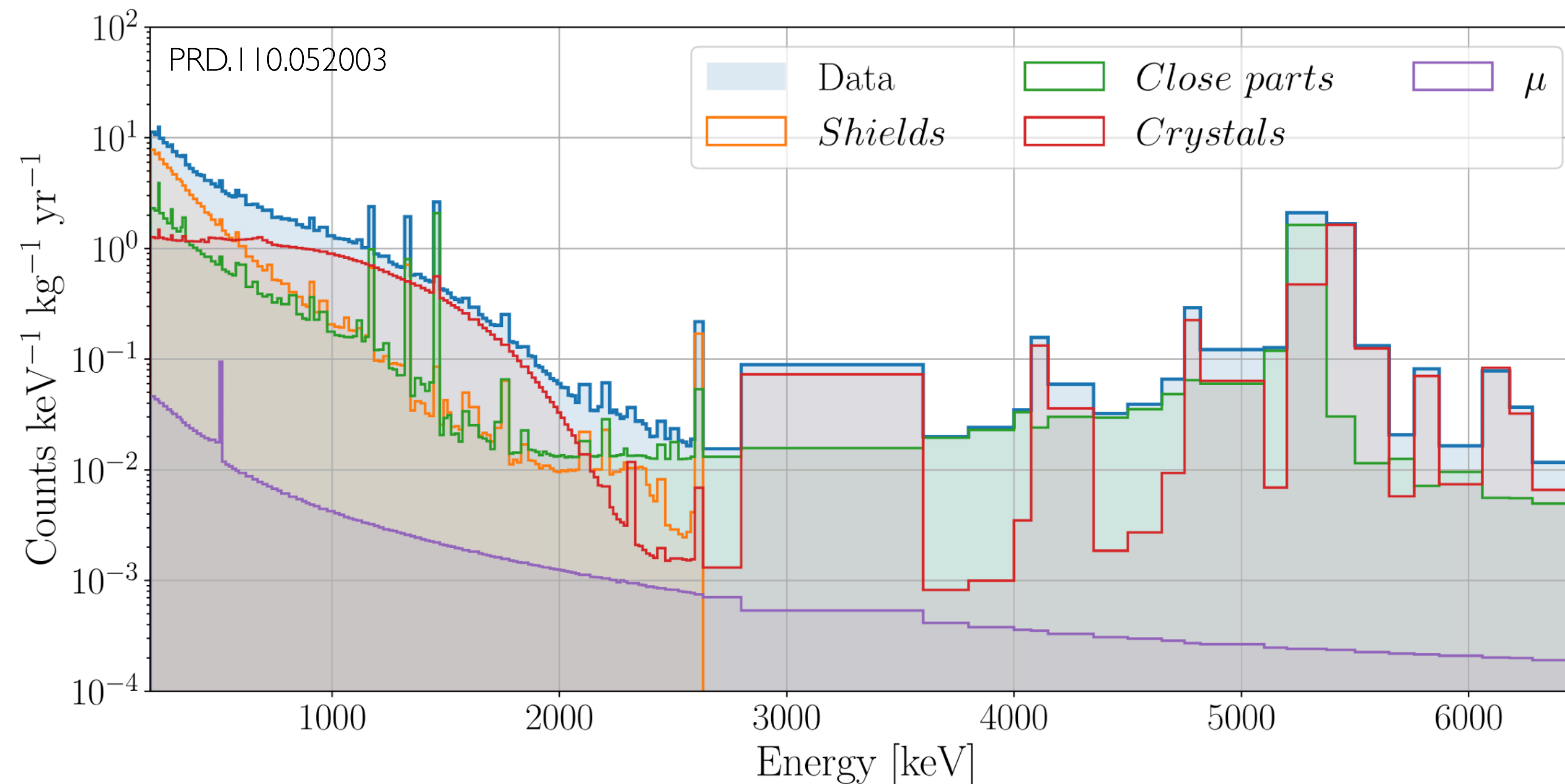






# Background Model and $2\nu\beta\beta$ decay of $^{130}\text{Te}$

- Background modeled using 80 source contributions
- Includes both surface and bulk contaminations
- 1038.4 kg.yr  $\text{TeO}_2$  exposure
- Model fits the data very well



$$T_{1/2}^{2\nu} = (9.32^{+0.05}_{-0.04} \text{ stat. } ^{+0.07}_{-0.07} \text{ syst.}) \times 10^{20} \text{ yr}$$

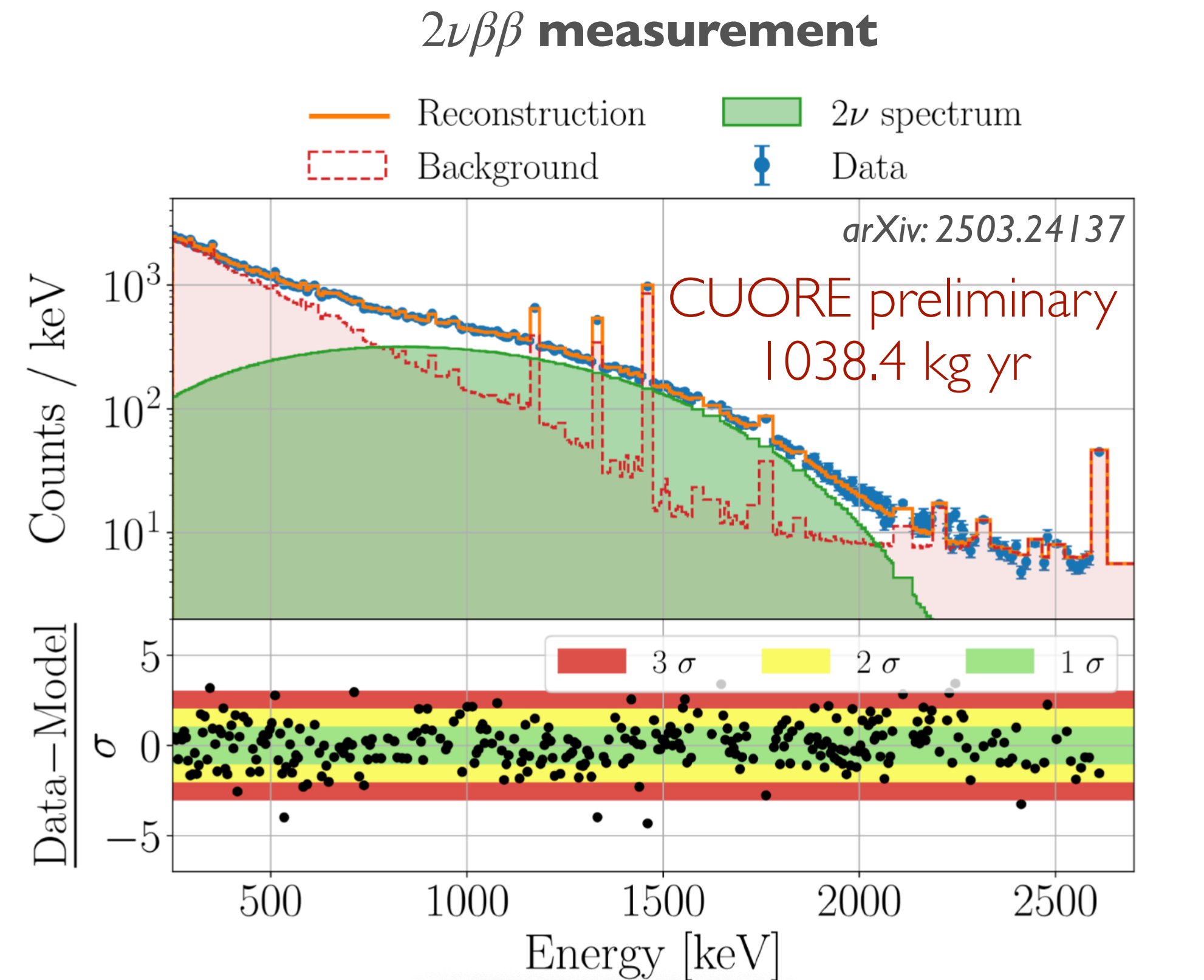
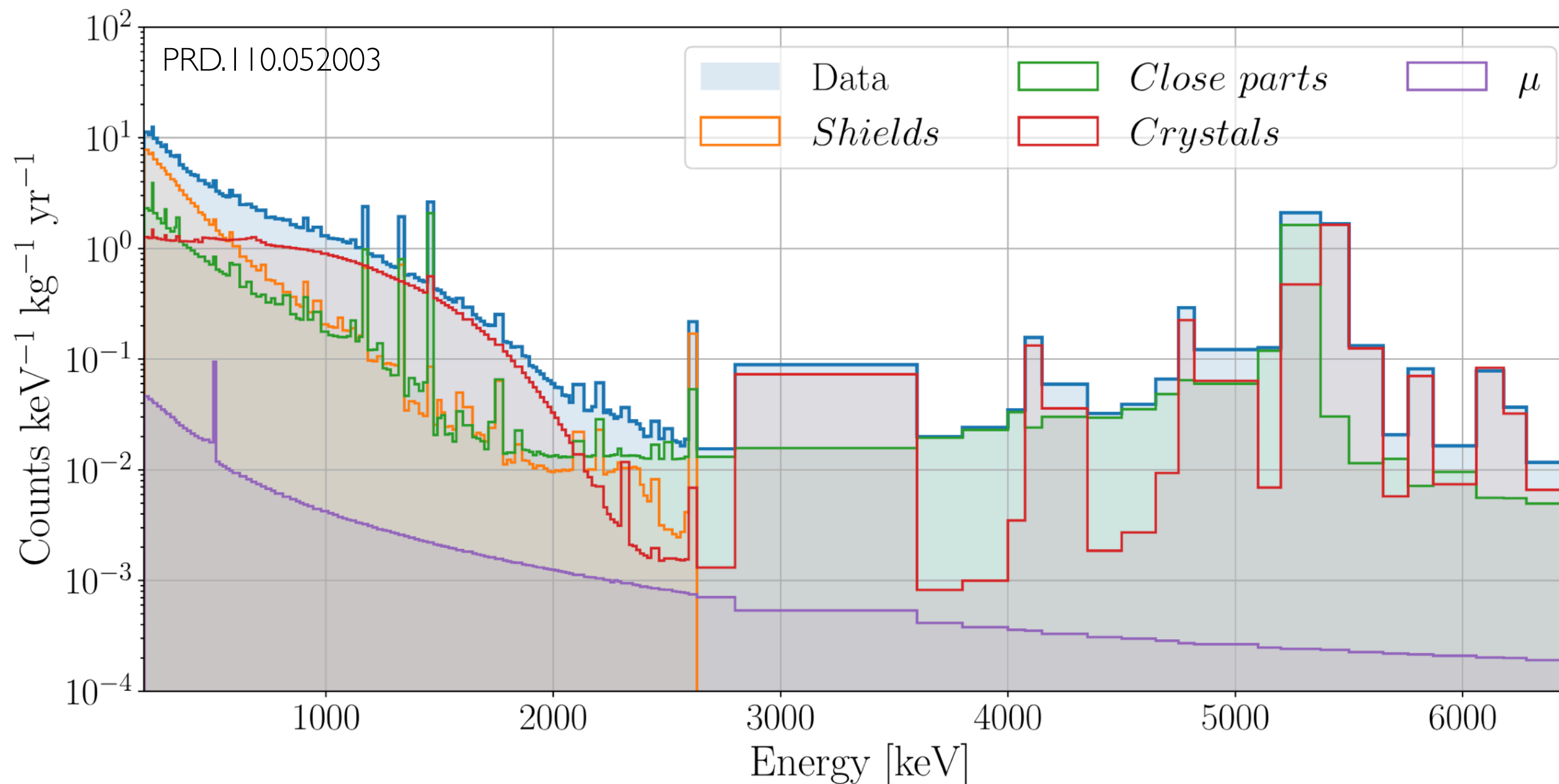






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- Background modeled using 80 source contributions
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- 1038.4 kg.yr  $\text{TeO}_2$  exposure
- Model fits the data very well
- $2\nu\beta\beta$  spectrum and half-life measured



$$T_{1/2}^{2\nu} = (9.32^{+0.05}_{-0.04} \text{ stat. } ^{+0.07}_{-0.07} \text{ syst.}) \times 10^{20} \text{ yr}$$

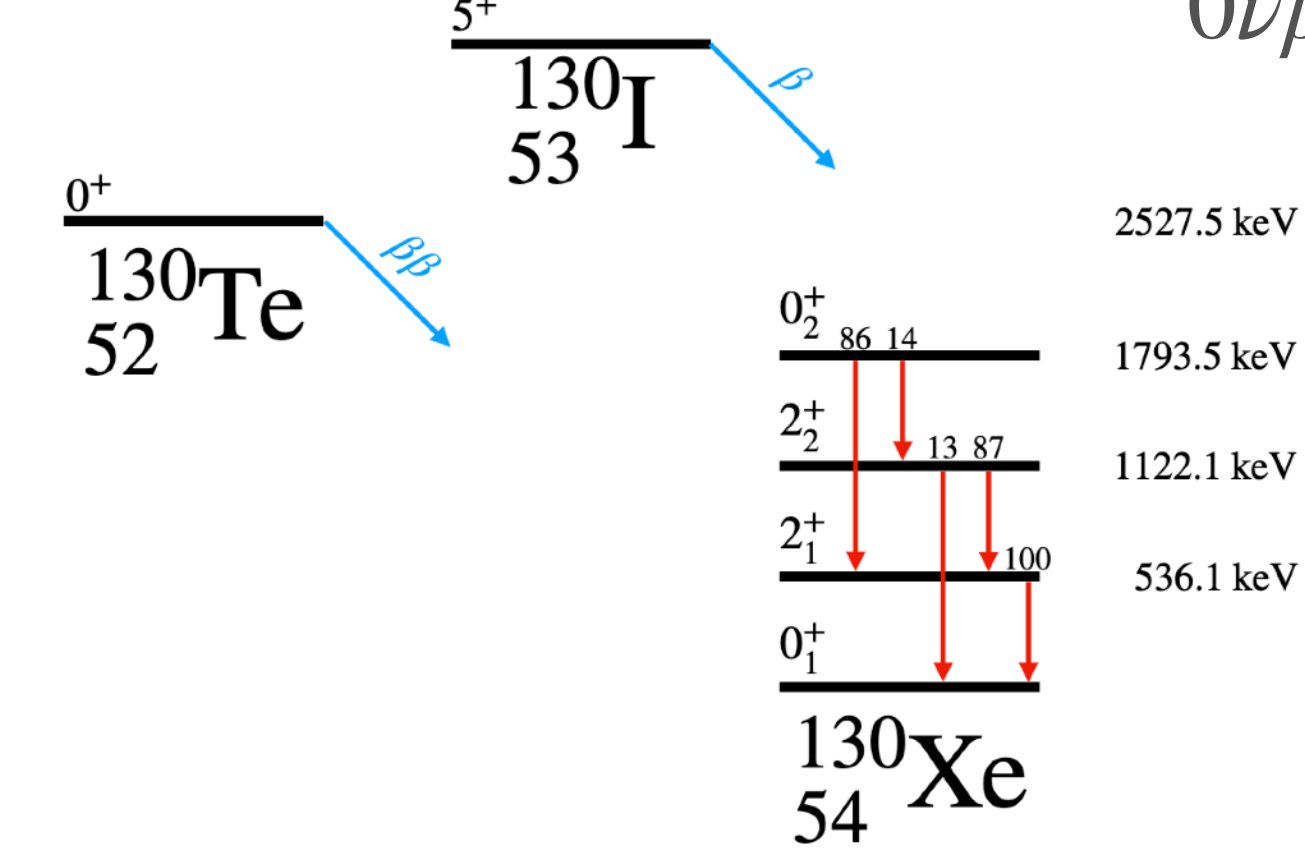






# Other Rare Searches in CUORE

epjc. 81, 567, (2021)



$0\nu\beta\beta$  and  $2\nu\beta\beta$  of  $^{130}\text{Te}$  to 1st  $0^+$  excited state

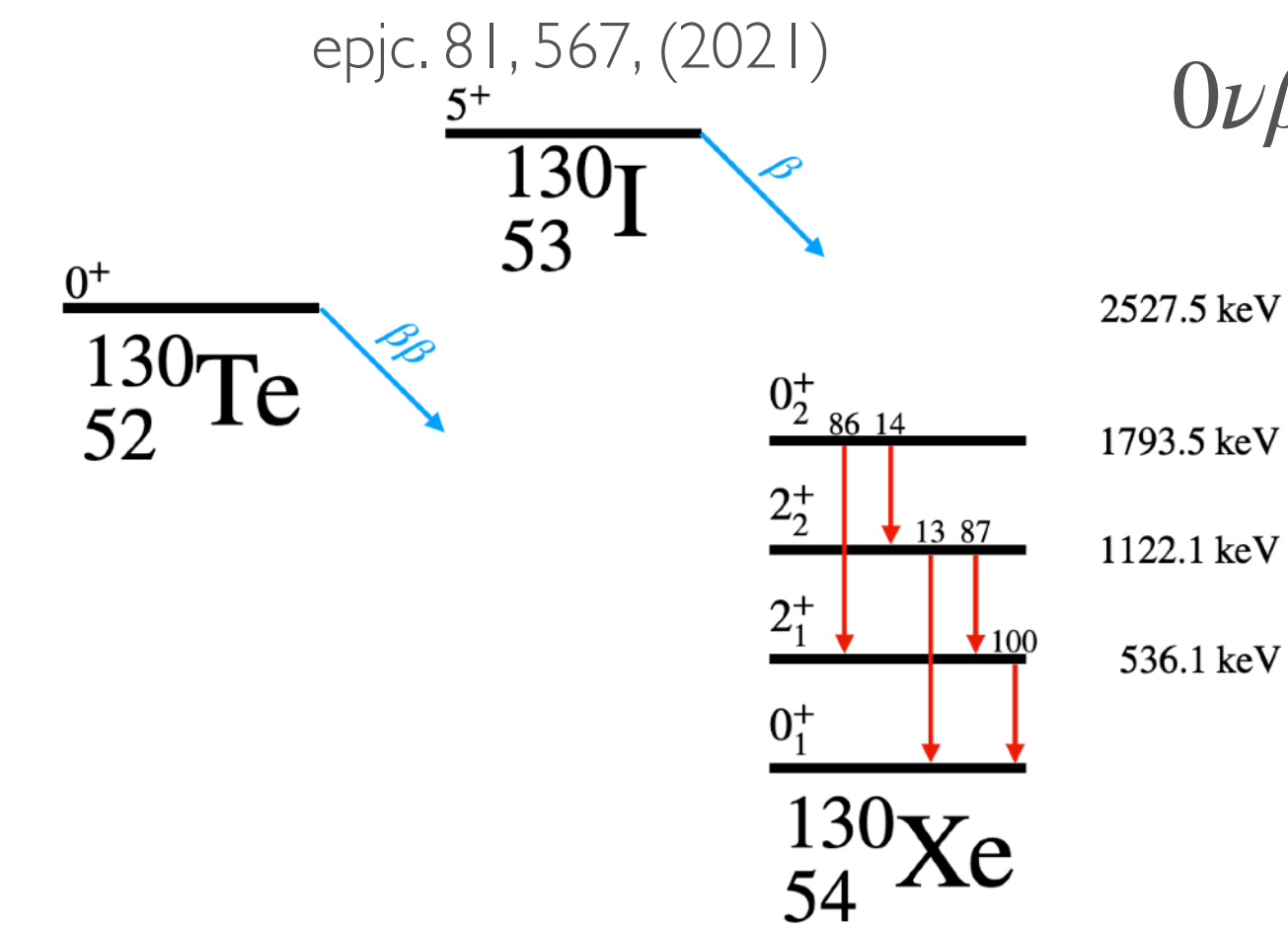
$$T_{1/2}^{0\nu} > 5.9 \times 10^{24} \text{ yr (90\% C.I.)}$$
$$T_{1/2}^{2\nu} > 1.3 \times 10^{24} \text{ yr (90\% C.I.)}$$







# Other Rare Searches in CUORE



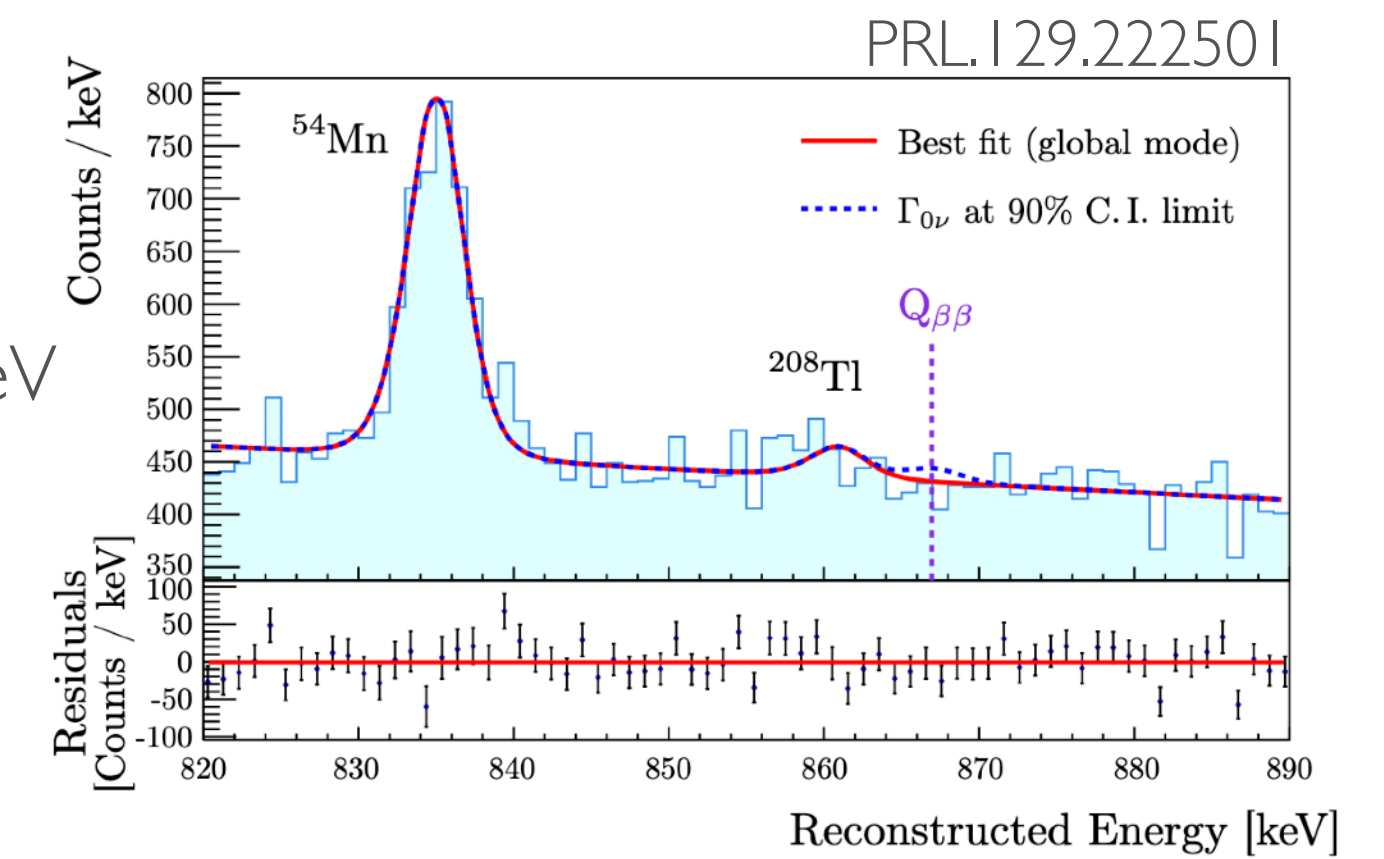
$0\nu\beta\beta$  and  $2\nu\beta\beta$  of  $^{130}\text{Te}$  to 1st  $0^+$  excited state

$$T_{1/2}^{0\nu} > 5.9 \times 10^{24} \text{ yr (90\% C.I.)}$$

$$T_{1/2}^{2\nu} > 1.3 \times 10^{24} \text{ yr (90\% C.I.)}$$

$$Q_{\beta\beta} = 866.7 \text{ keV}$$

$0\nu\beta\beta$  of  $^{128}\text{Te}$   
 $T_{1/2}^{0\nu} > 3.6 \times 10^{24} \text{ yr (90\% C.I.)}$

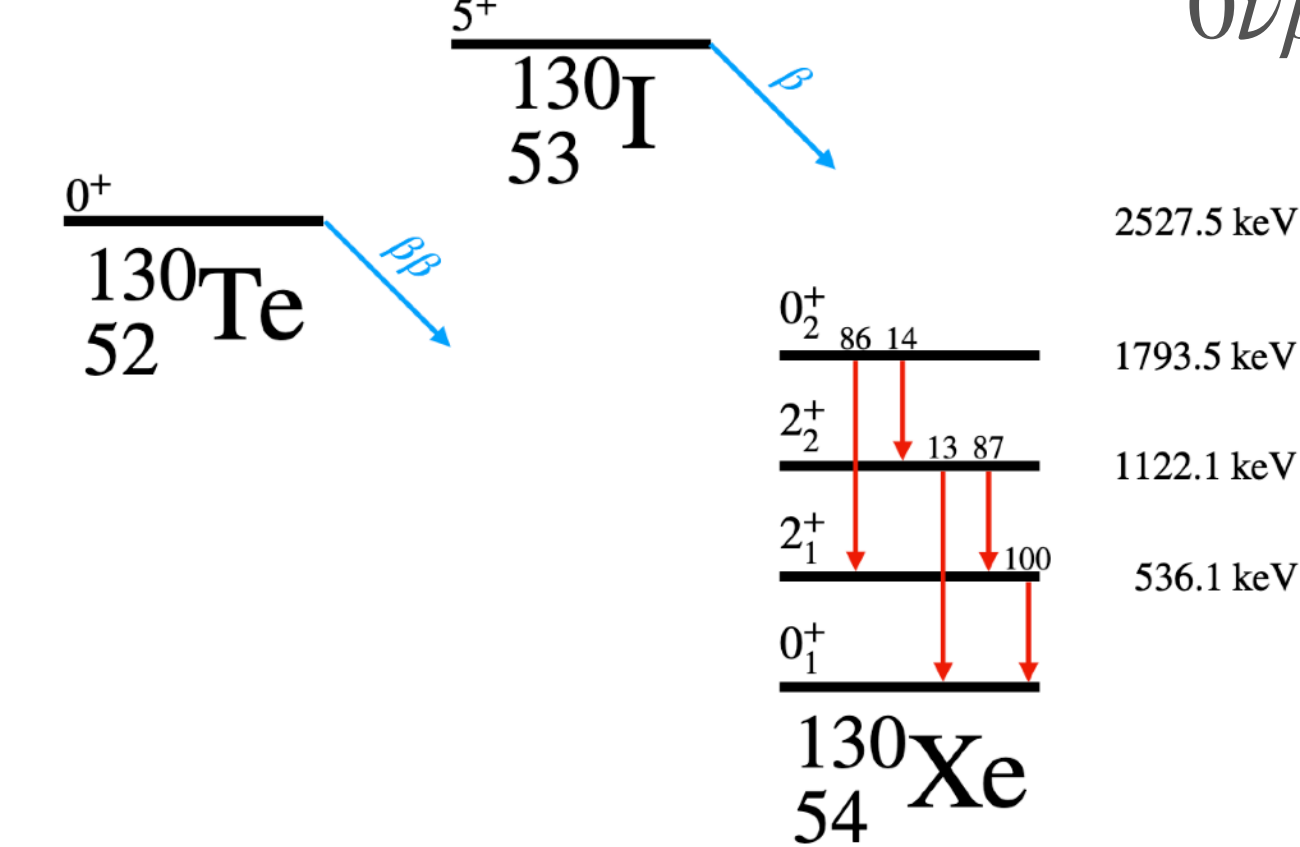






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epjc. 81, 567, (2021)



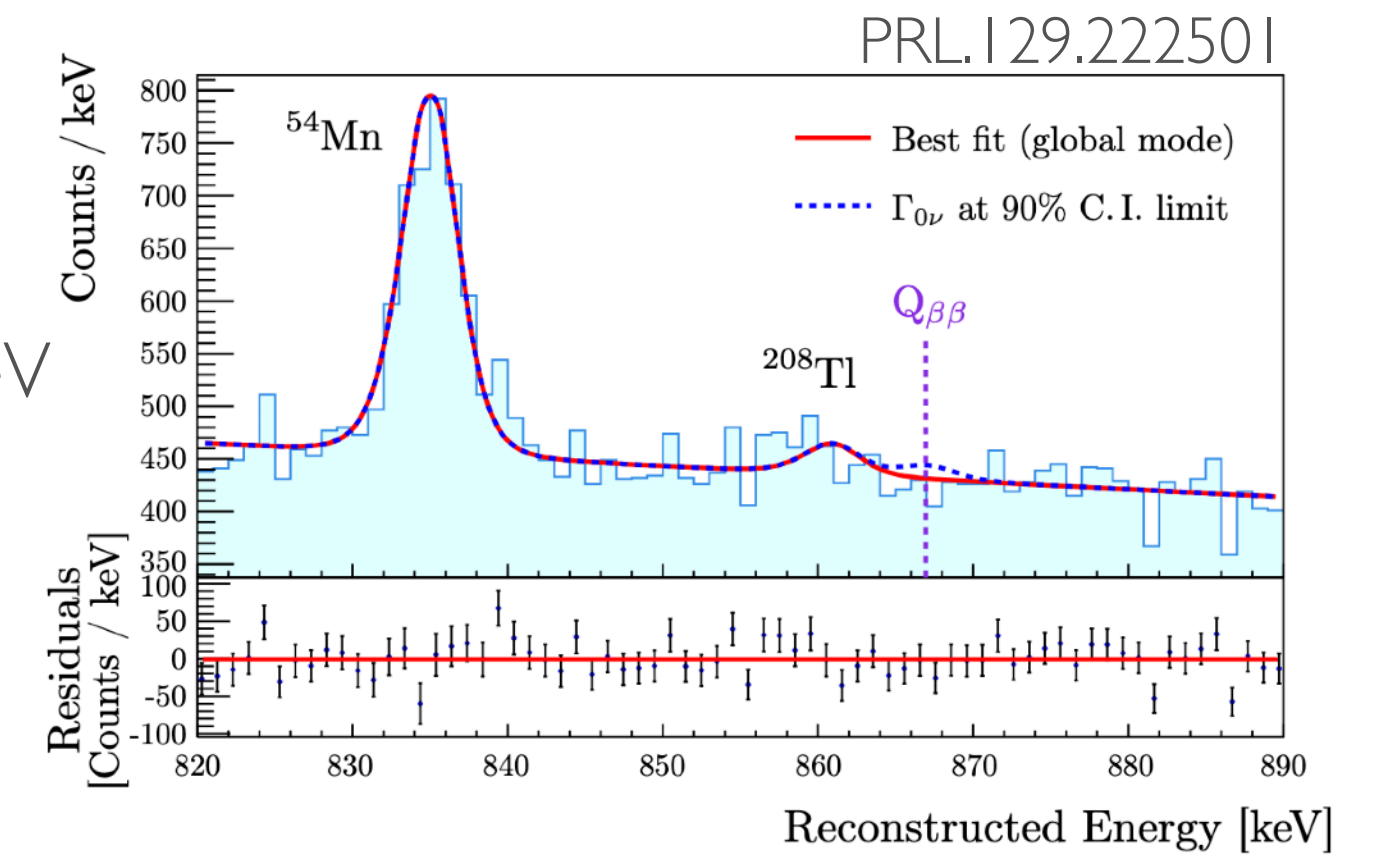
$0\nu\beta\beta$  and  $2\nu\beta\beta$  of  $^{130}\text{Te}$  to 1st  $0^+$  excited state

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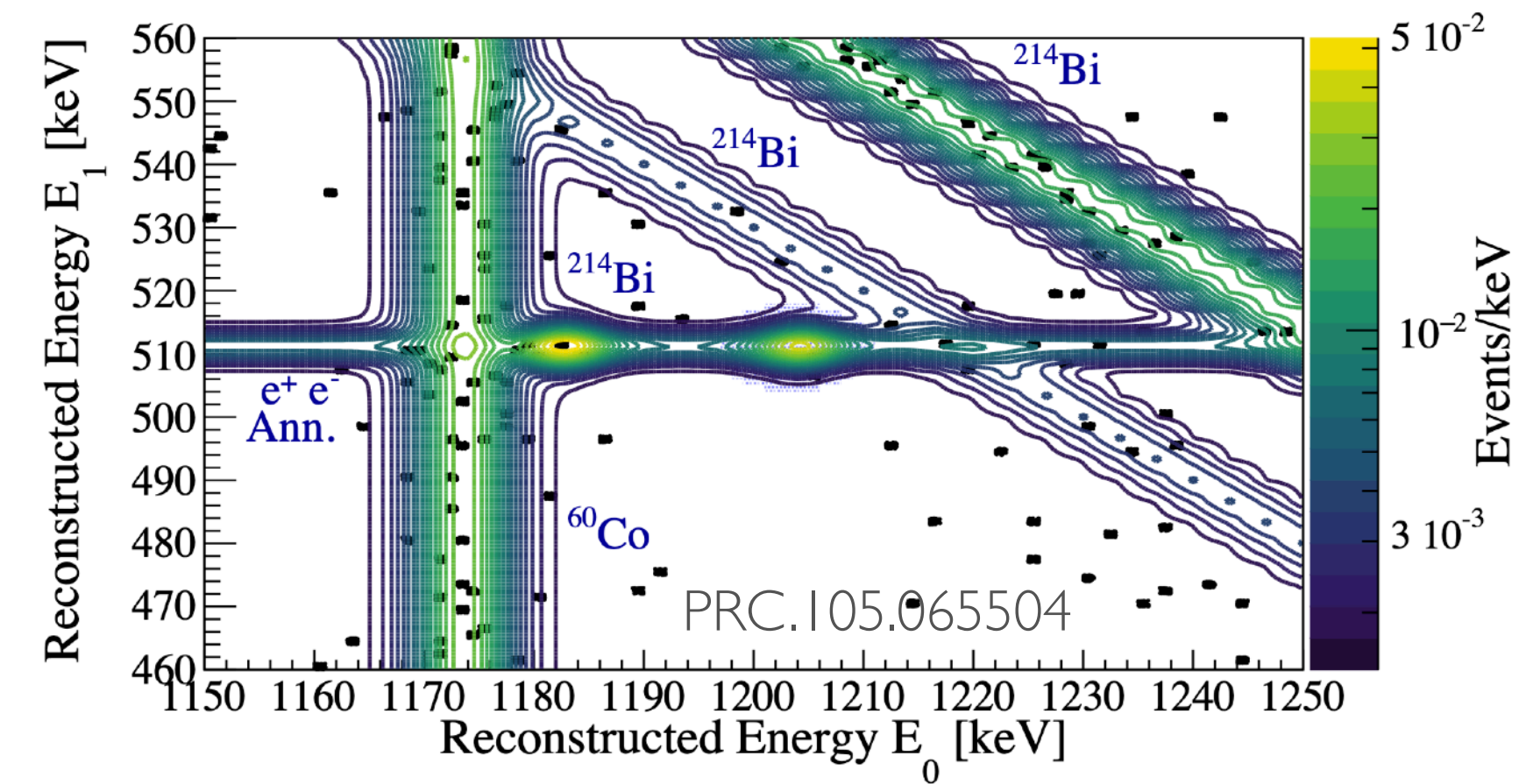
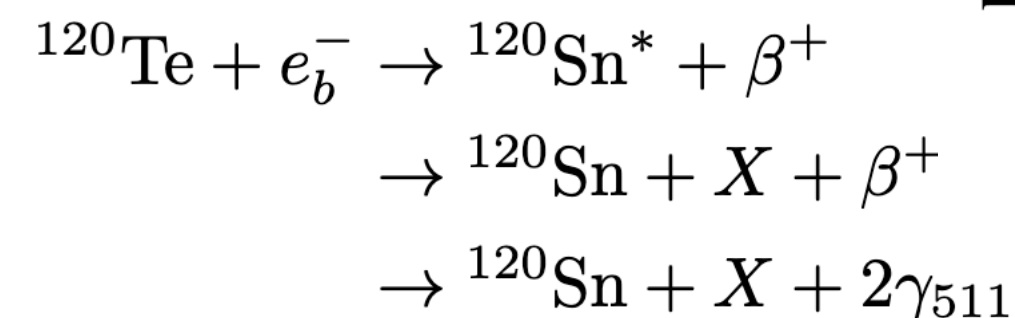
$$T_{1/2}^{2\nu} > 1.3 \times 10^{24} \text{ yr (90\% C.I.)}$$

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 $T_{1/2}^{0\nu} > 3.6 \times 10^{24} \text{ yr (90\% C.I.)}$



$$Q_{\beta\beta} = 1714.8 \text{ keV}$$



$0\nu\beta^+\text{EC}$  of  $^{120}\text{Te}$   
 $T_{1/2}^{0\nu} > 2.9 \times 10^{22} \text{ yr (90\% C.I.)}$

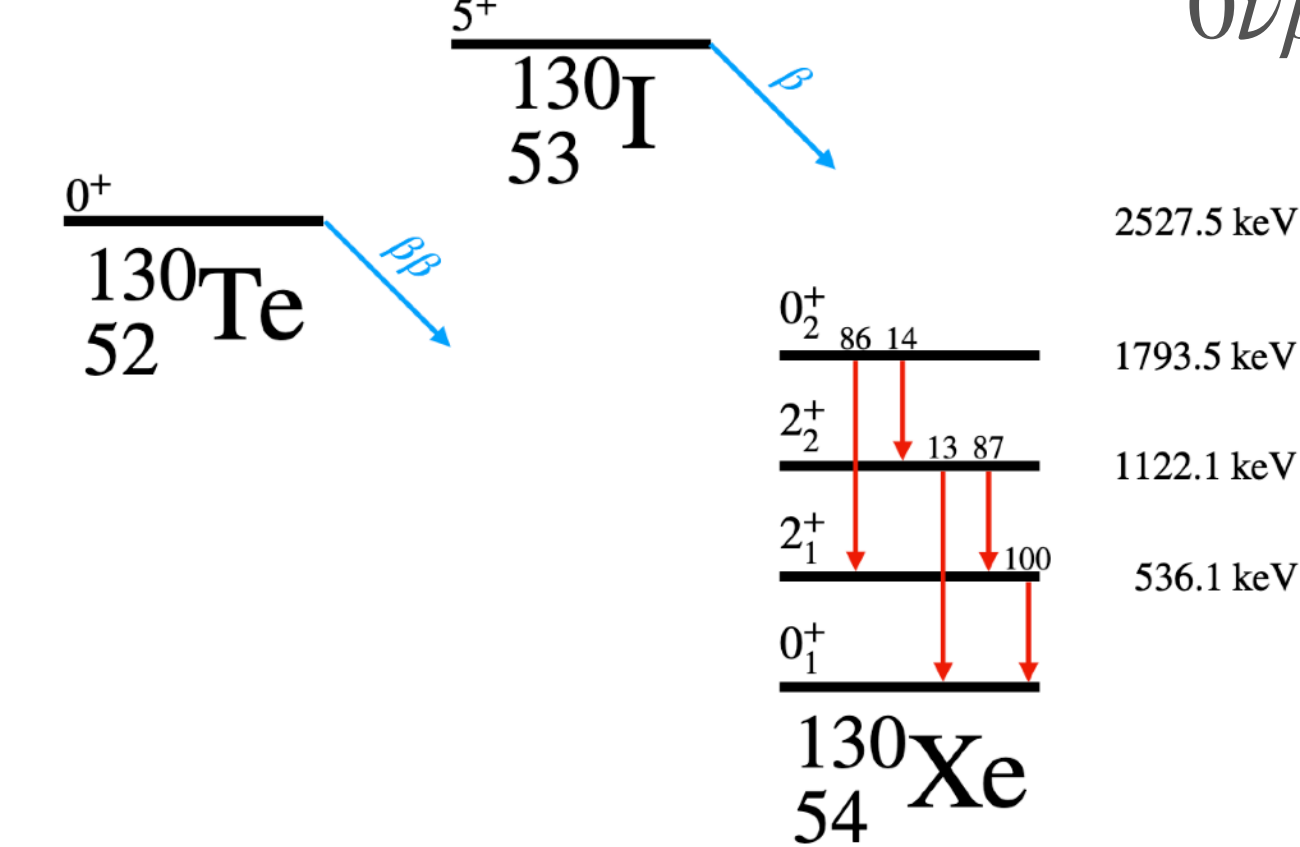






# Other Rare Searches in CUORE

epj.c. 81, 567, (2021)



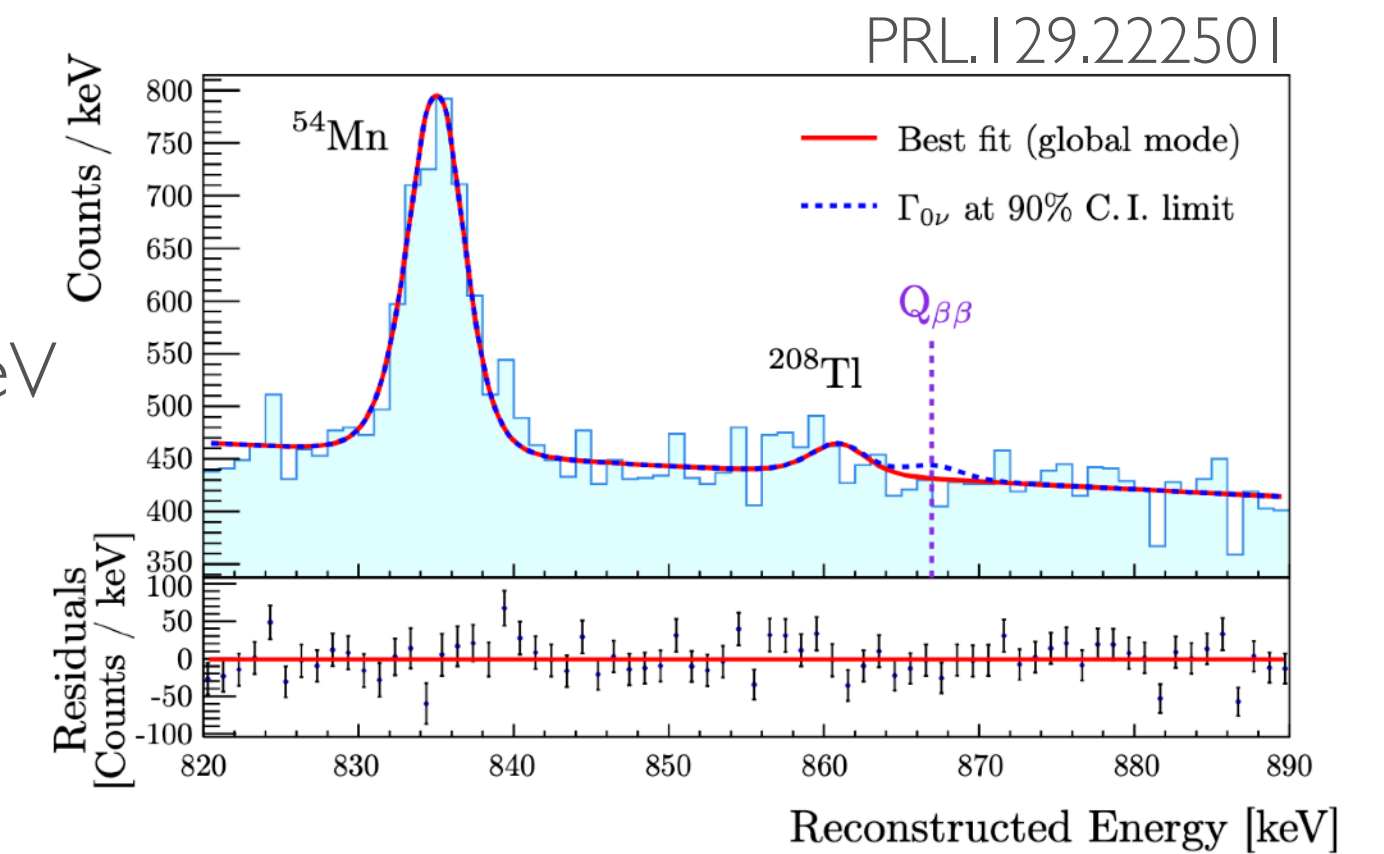
$0\nu\beta\beta$  and  $2\nu\beta\beta$  of  $^{130}\text{Te}$  to 1st  $0^+$  excited state

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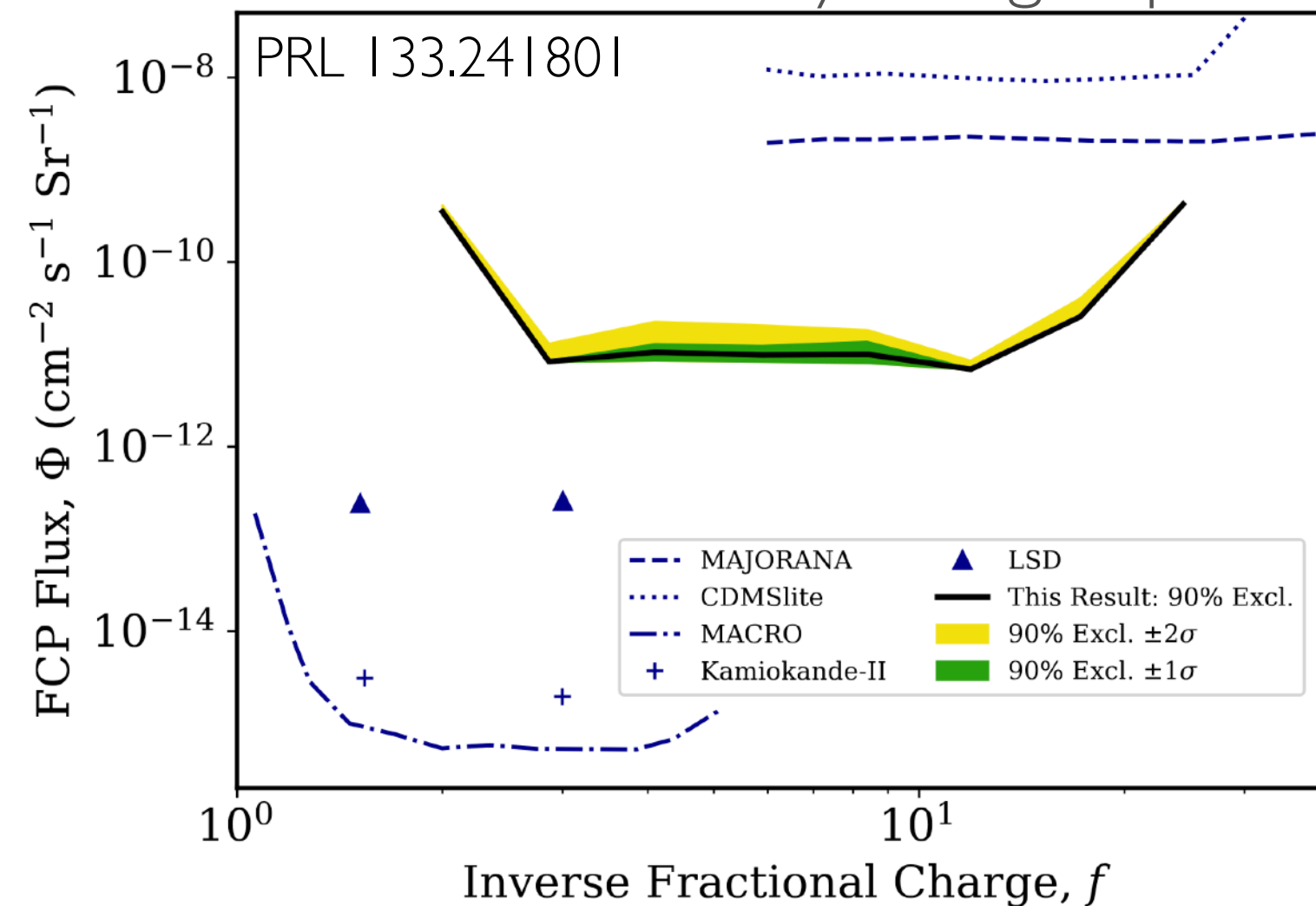
$$T_{1/2}^{2\nu} > 1.3 \times 10^{24} \text{ yr (90\% C.I.)}$$

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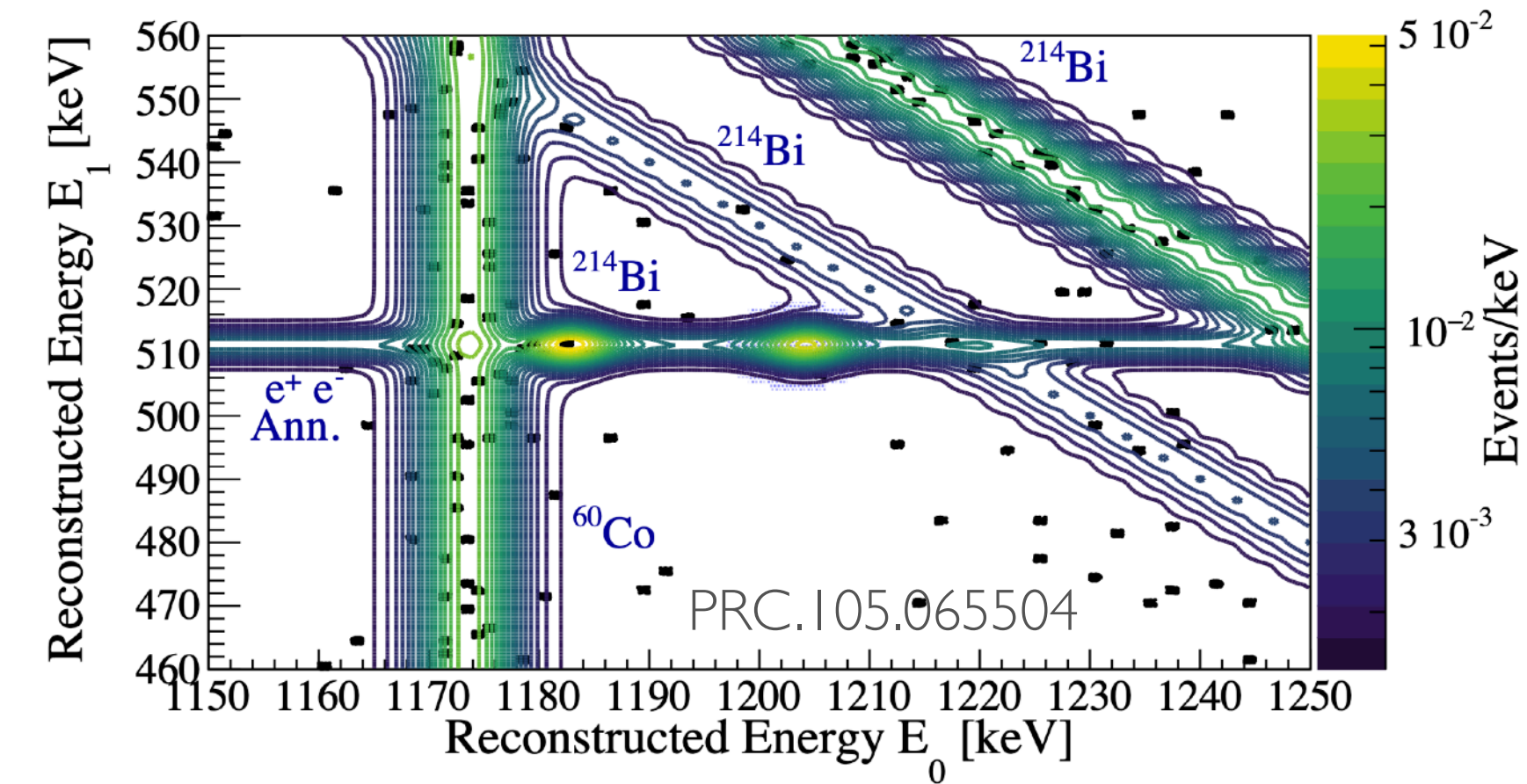
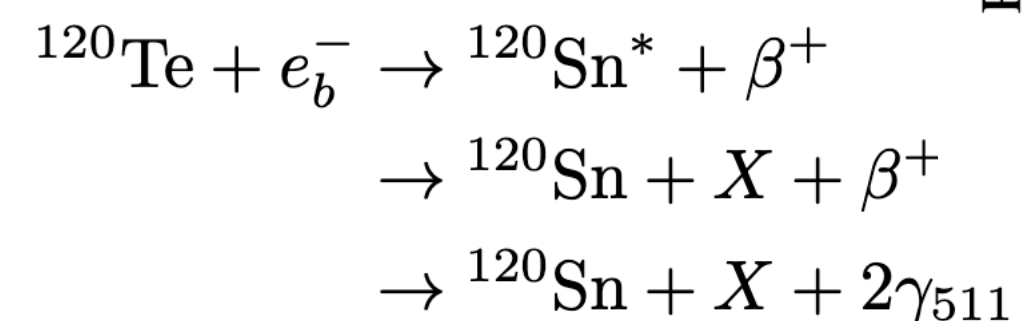
$0\nu\beta\beta$  of  $^{128}\text{Te}$   
 $T_{1/2}^{0\nu} > 3.6 \times 10^{24} \text{ yr (90\% C.I.)}$



Search for fractionally charged particles



$$Q_{\beta\beta} = 1714.8 \text{ keV}$$



$0\nu\beta^+\text{EC}$  of  $^{120}\text{Te}$   
 $T_{1/2}^{0\nu} > 2.9 \times 10^{22} \text{ yr (90\% C.I.)}$

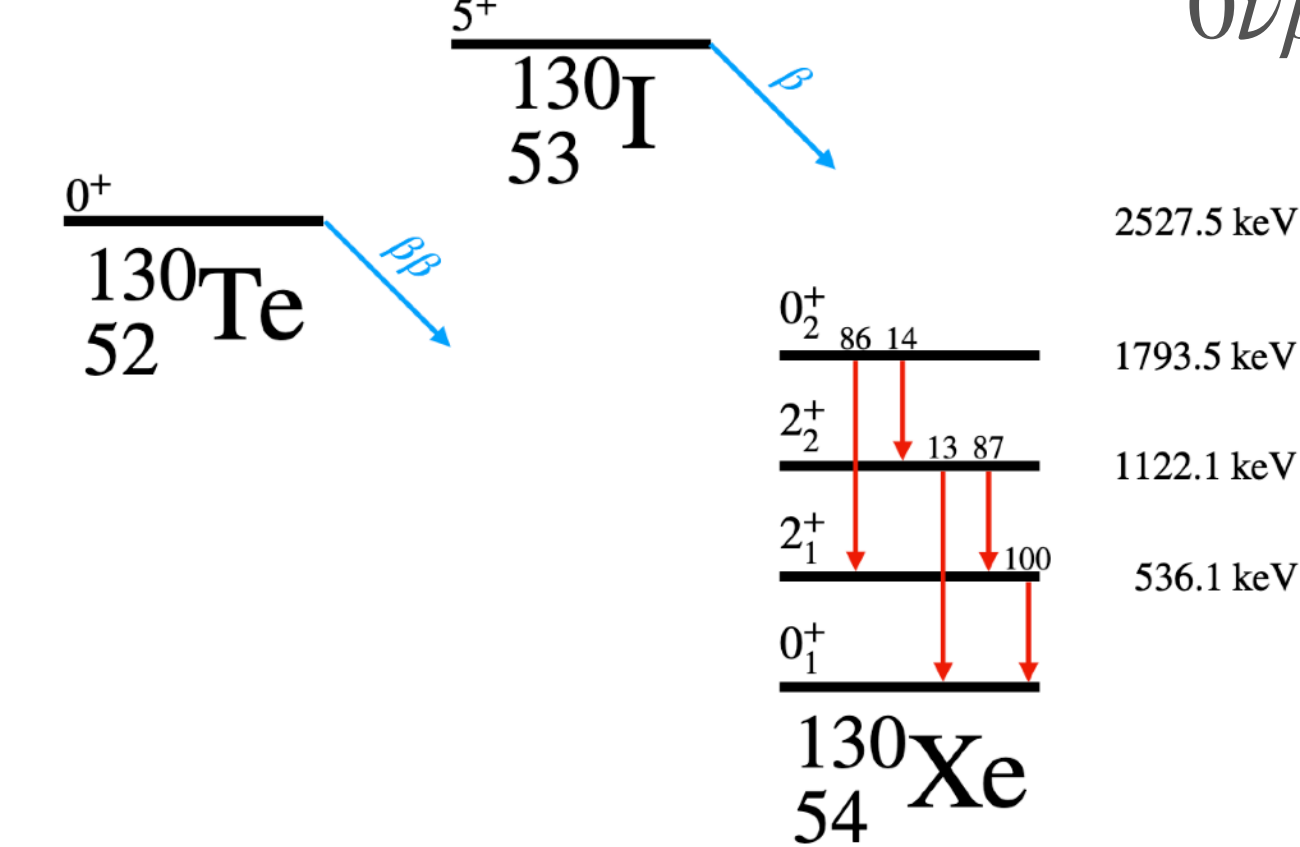






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epjc. 81, 567, (2021)



$0\nu\beta\beta$  and  $2\nu\beta\beta$  of  $^{130}\text{Te}$  to 1st  $0^+$  excited state

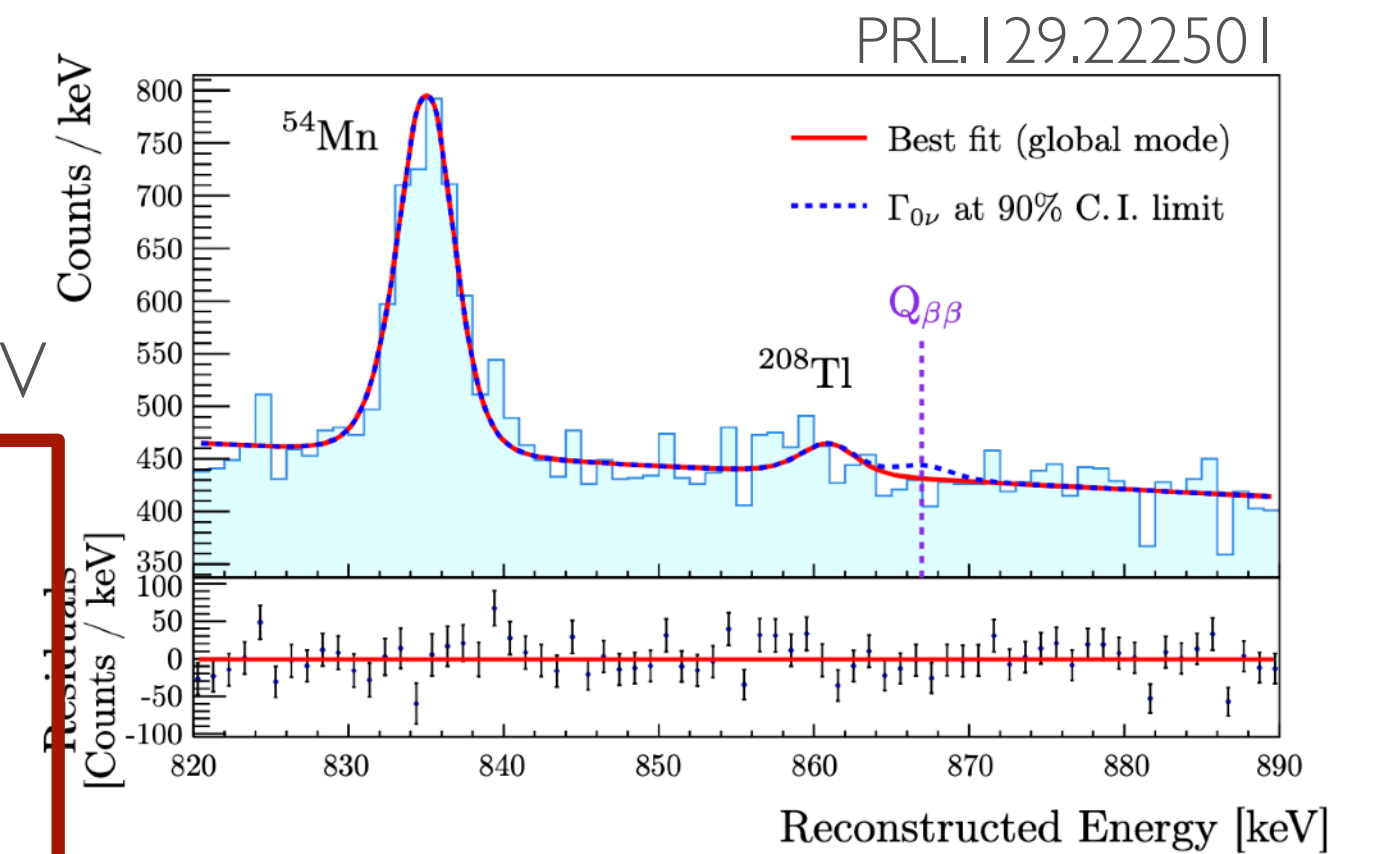
$$T_{1/2}^{0\nu} > 5.9 \times 10^{24} \text{ yr (90\% C.I.)}$$

$$T_{1/2}^{2\nu} > 1.3 \times 10^{24} \text{ yr (90\% C.I.)}$$

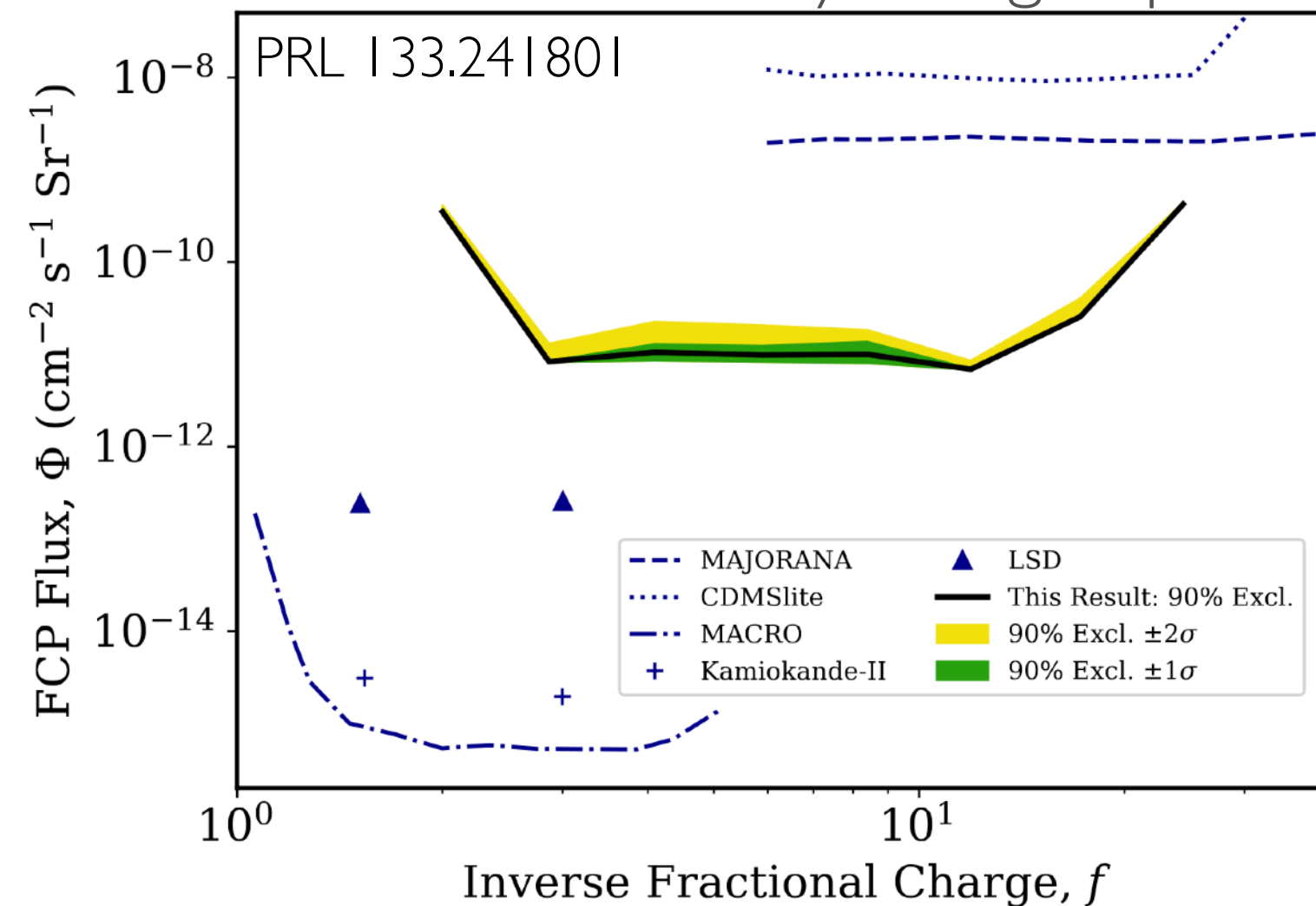
$$Q_{\beta\beta} = 866.7 \text{ keV}$$

Many more ongoing searches for physics beyond  $0\nu\beta\beta$  enabled by the improvements in analysis techniques

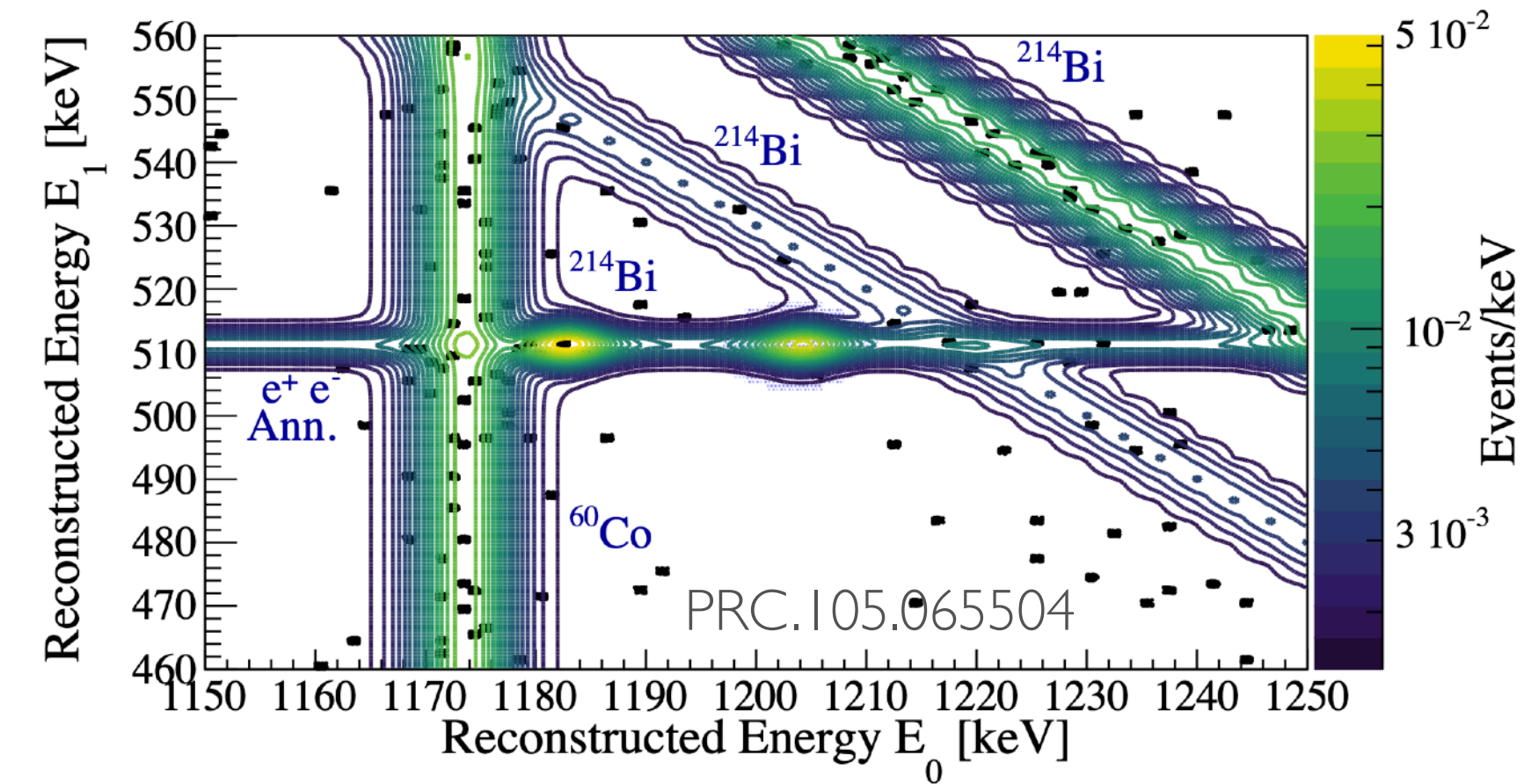
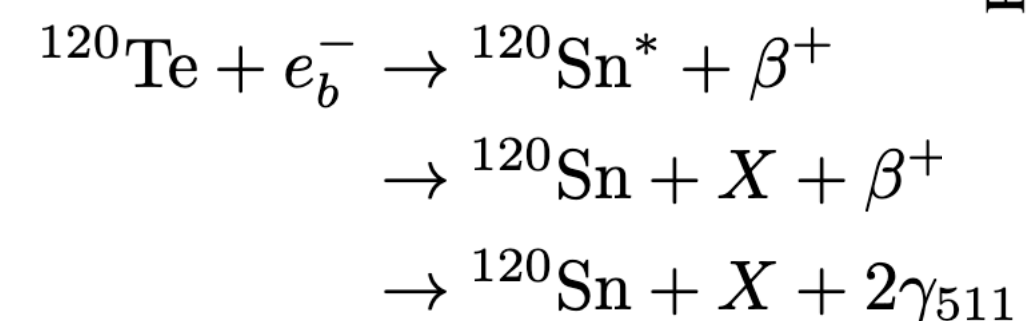
$0\nu\beta\beta$  of  $^{128}\text{Te}$   
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Search for fractionally charged particles



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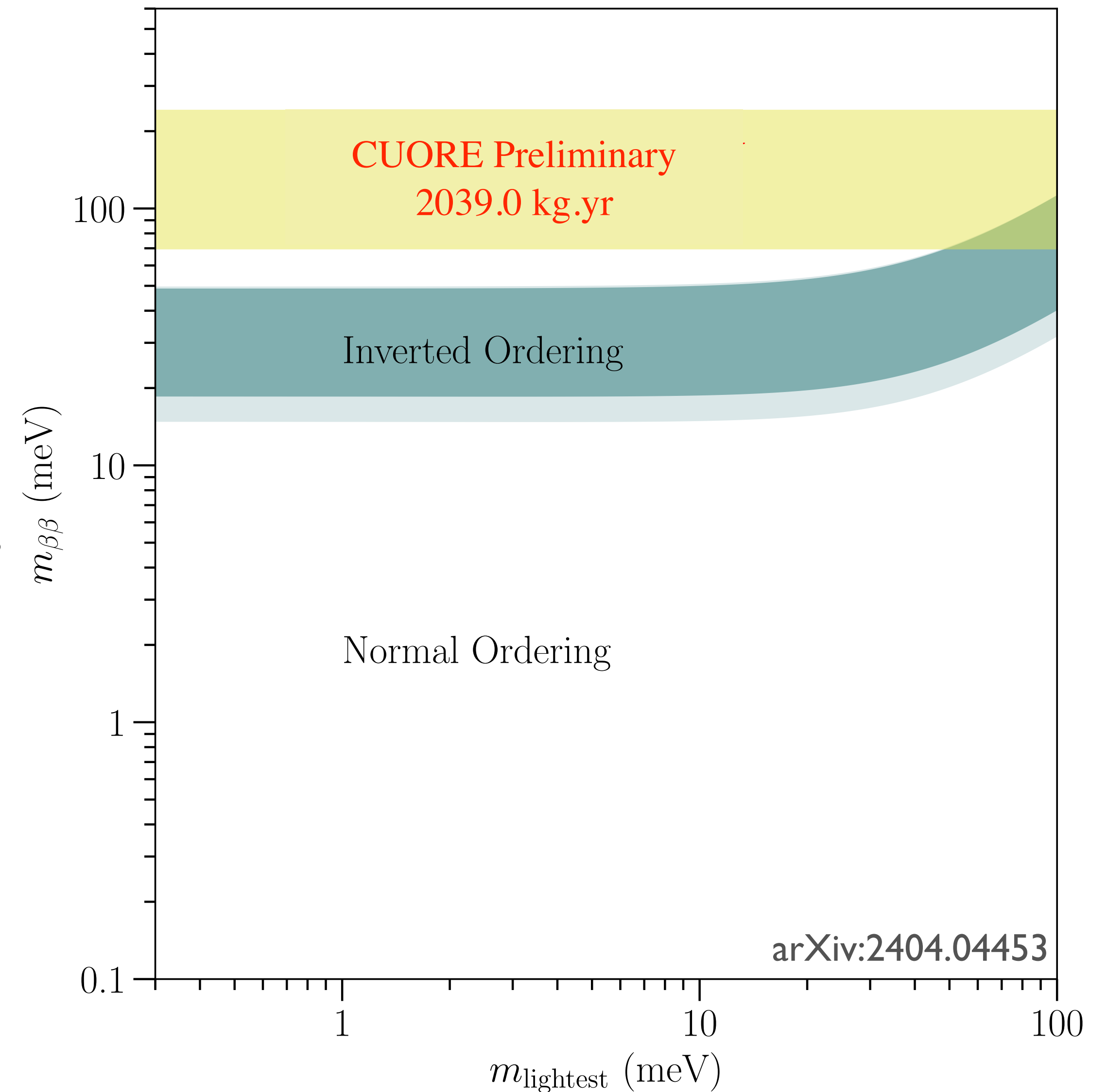






# CUORE Summary

- Calorimetric detector with excellent energy resolution
- Demonstrated continued data taking with minimum interventions
- Robust analysis chain to analyze  $\sim 1000$  detectors
- $T_{1/2}^{0\nu} > 3.8 \times 10^{25}$  yr (90% C.I.)
- Assuming light neutrino exchange:  
 $m_{\beta\beta} < \mathbf{70\text{--}240\text{ meV}}$

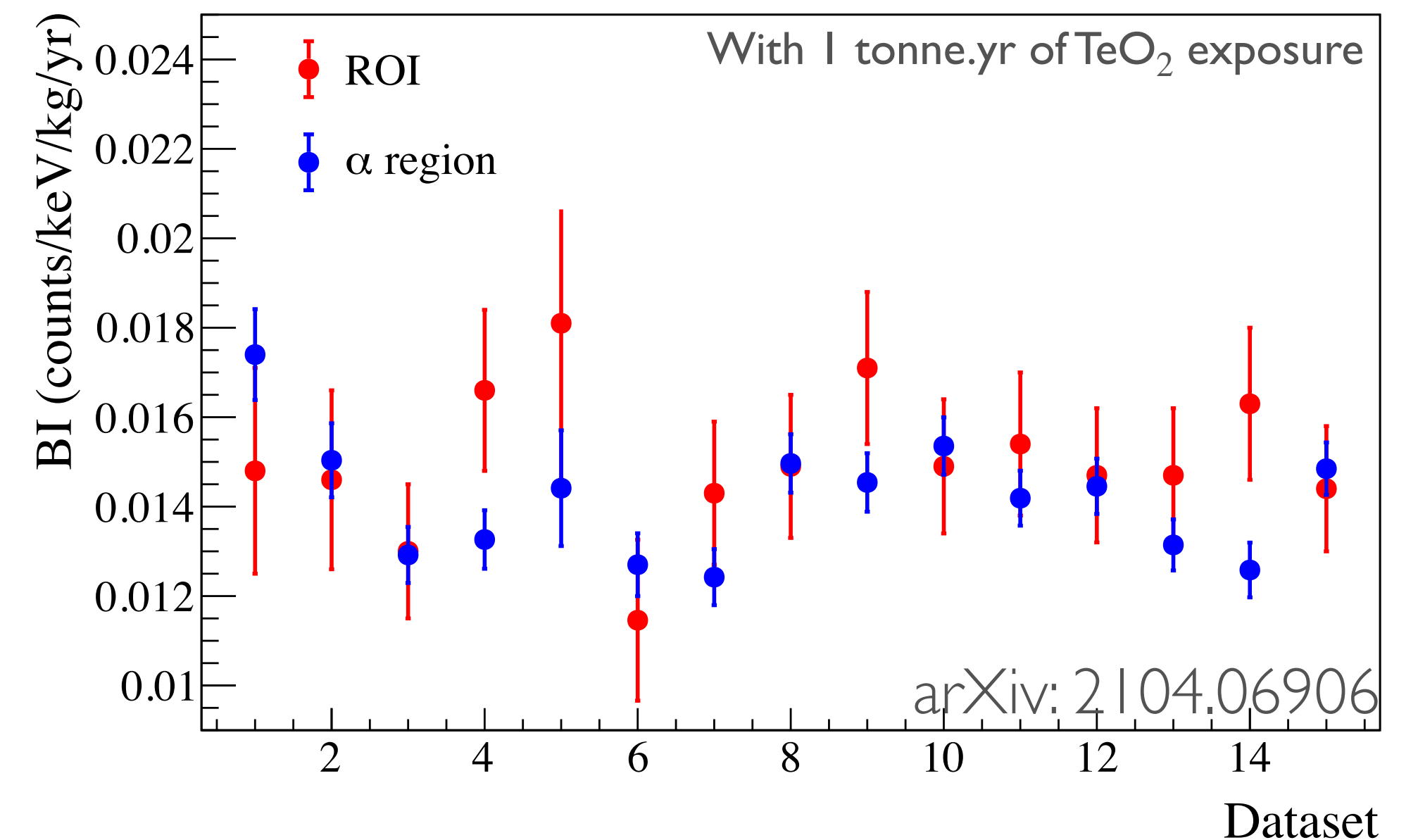
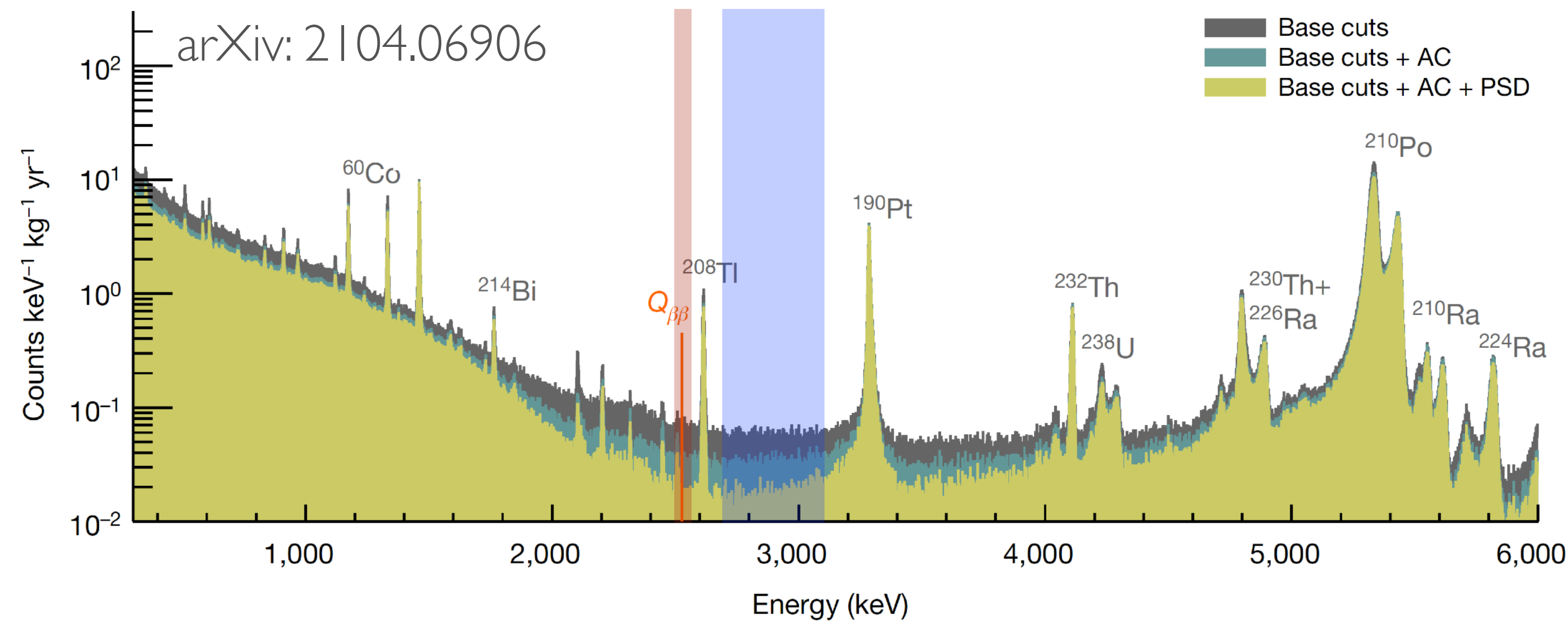






# CUORE Limits

- CUORE is background limited
- Dominated by  $\gamma/\beta + \alpha < 2615$  keV
- Above 2615 keV, primarily from  $\alpha$ s (U/Th contamination)
- BI in ROI:  **$1.49(4) \times 10^{-2}$  ckky**
- BI in Alpha region:  **$1.40(2) \times 10^{-2}$  ckky**
- Backgrounds in ROI are dominated by degraded alphas



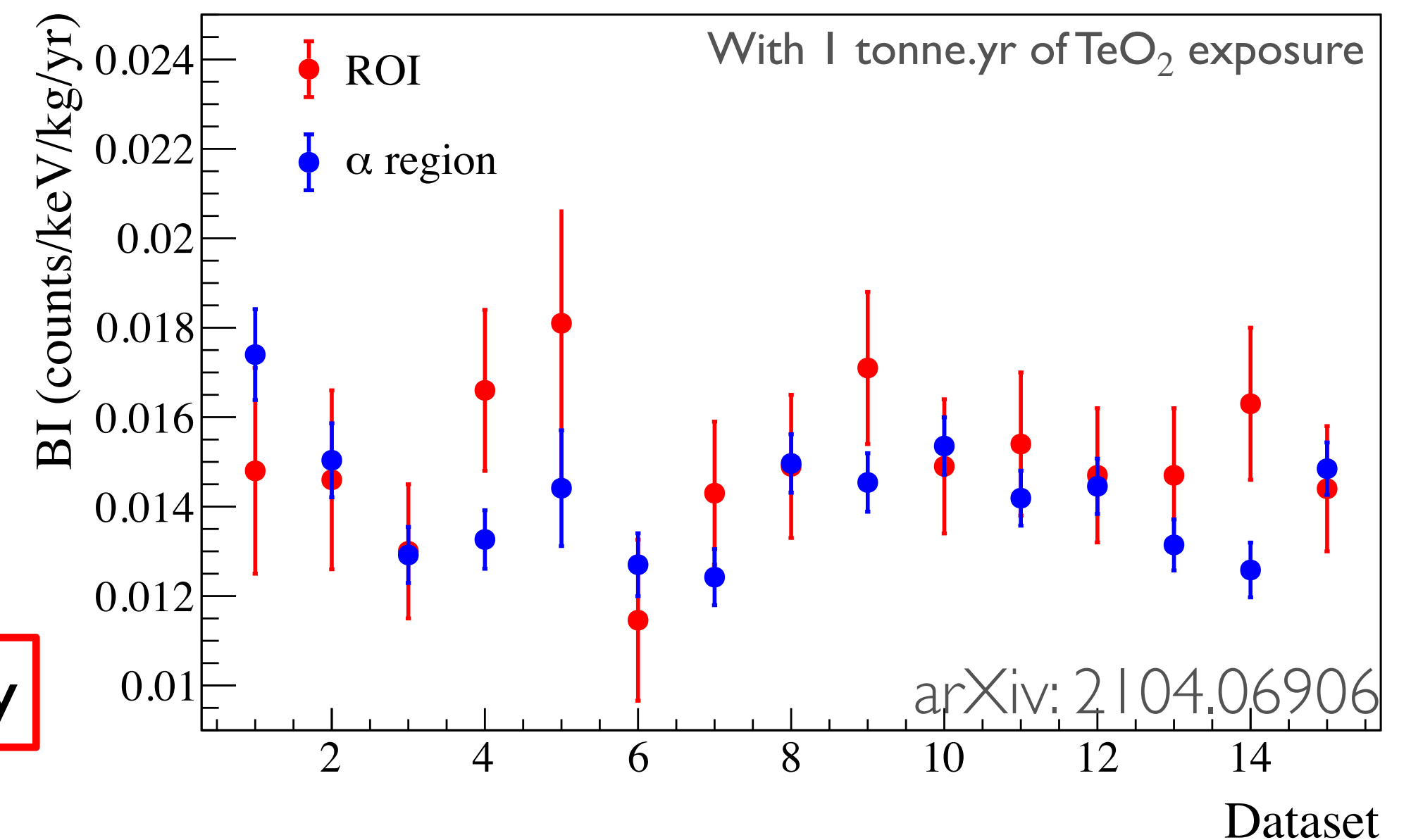
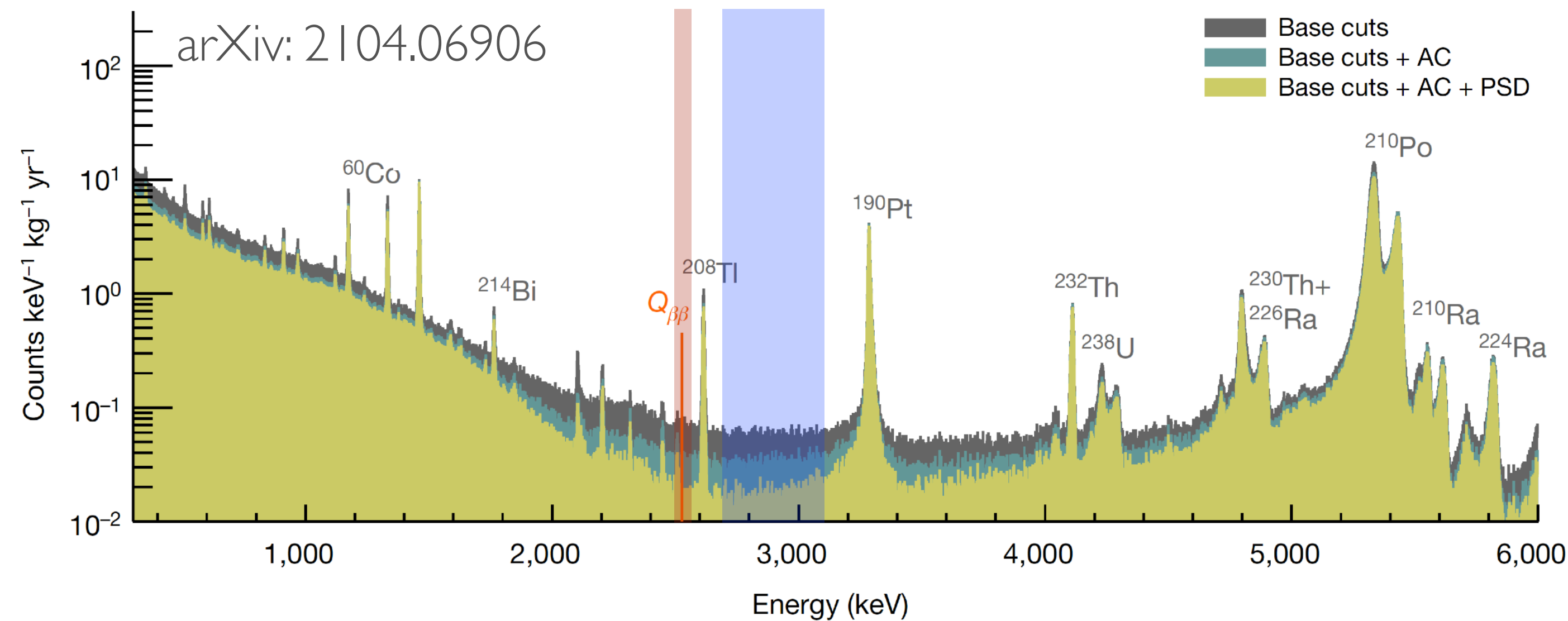




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- BI in Alpha region:  **$1.40(2) \times 10^{-2}$  ckky**
- Backgrounds in ROI are dominated by degraded alphas

Reduction of alpha backgrounds is crucial to improve sensitivity

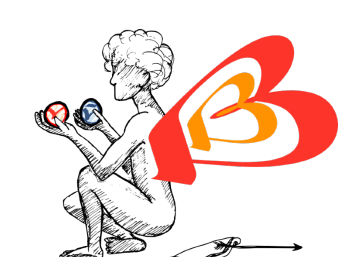




# CUORE Upgrade with Particle Identification

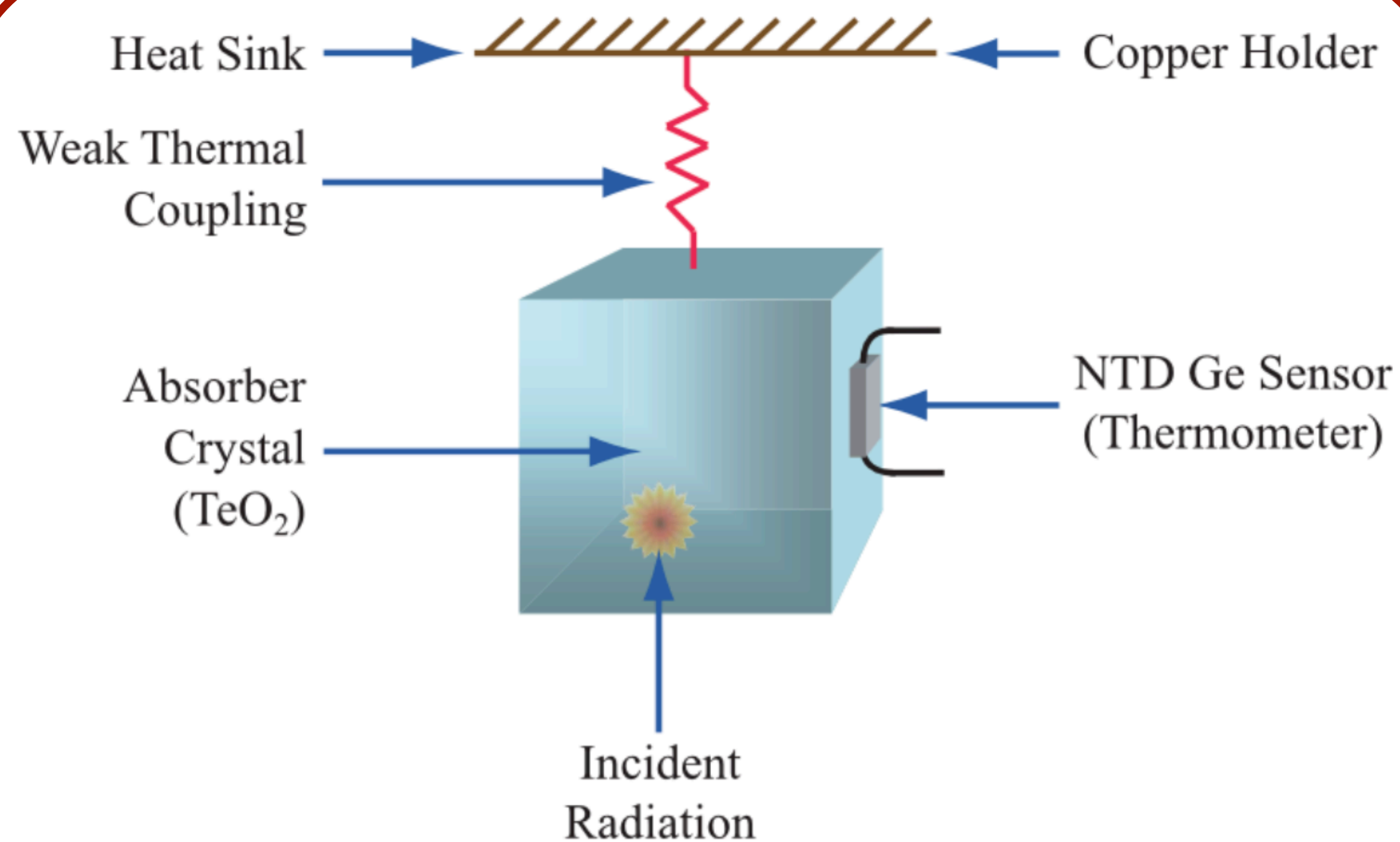




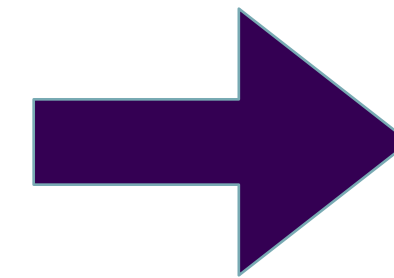


# CUPID Concept

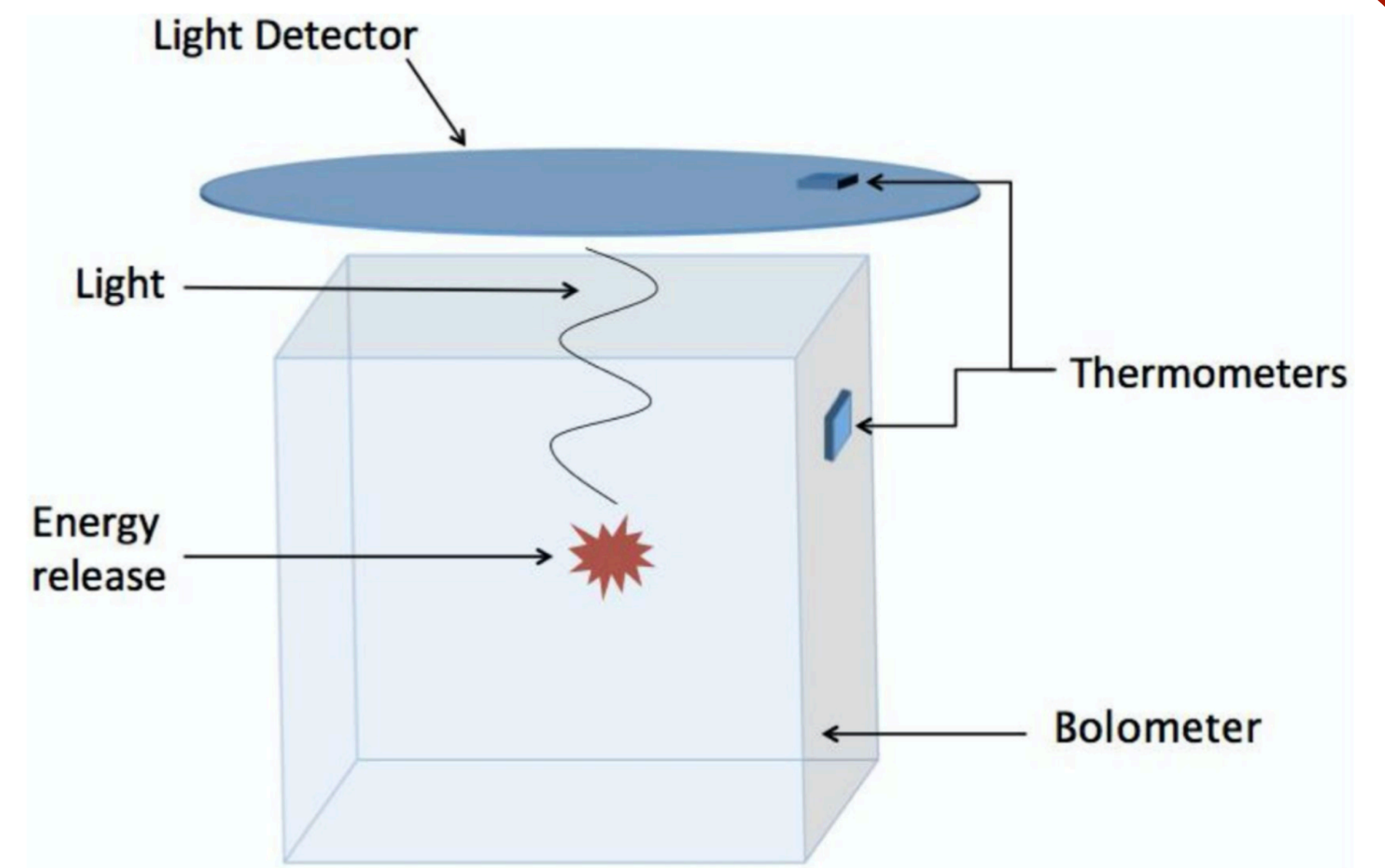
## CUORE: $^{130}\text{Te}$ crystal



$Q_{\beta\beta} = 2527 \text{ keV} < 2615 \text{ keV peak}$   
Measure only heat  
No particle ID

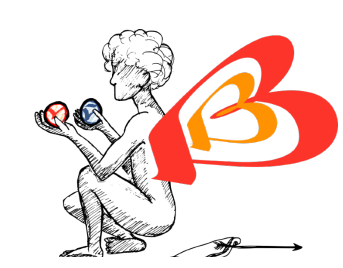


## CUPID: $^{100}\text{Mo}$ Scintillating Bolometer



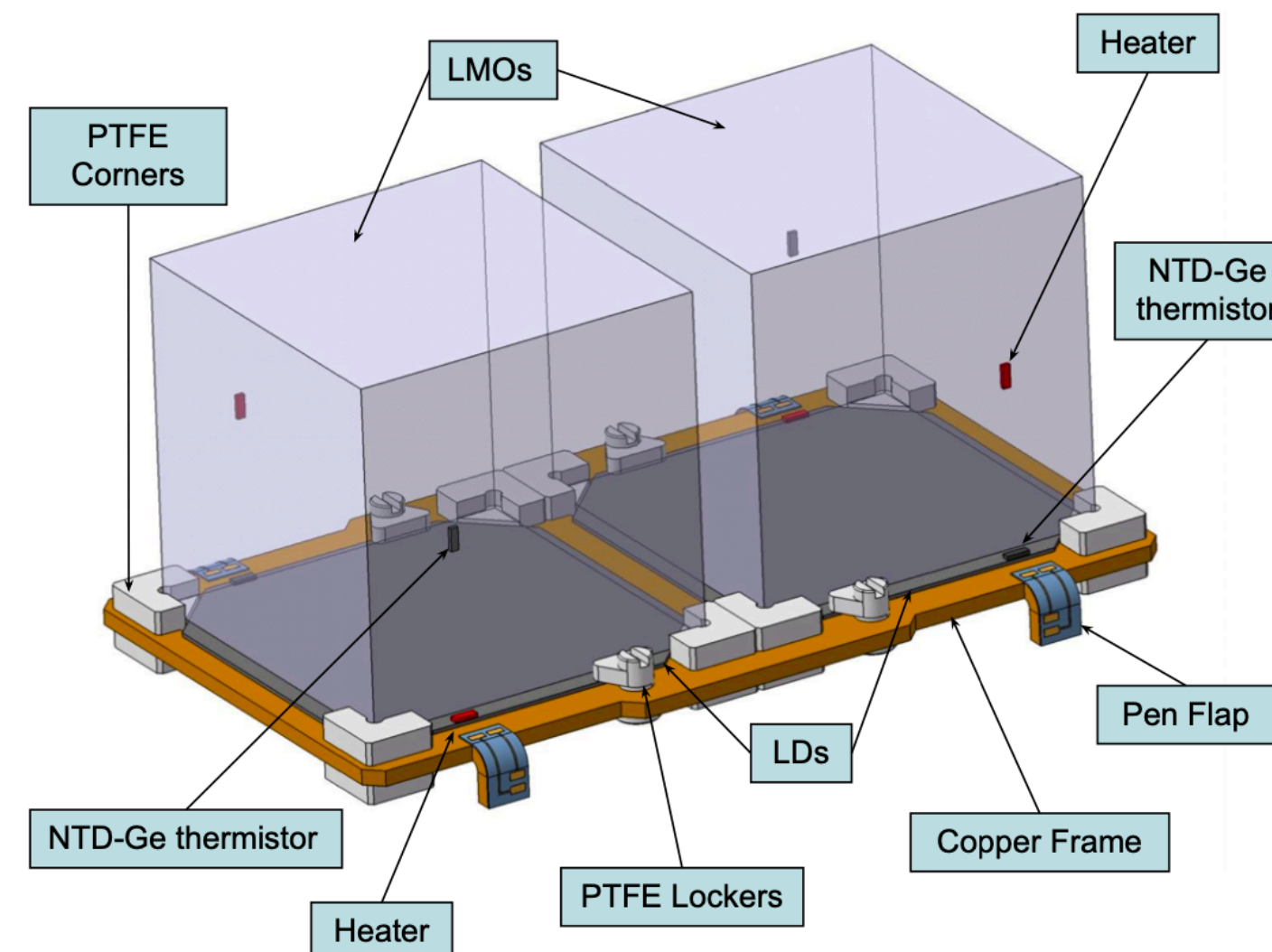
$Q_{\beta\beta} = 3034 \text{ keV}$ : Most  $\beta/\gamma$  backgrounds reduced  
Measure both heat + light  
Particle ID to actively discriminate  $\alpha$ s





# CUPID Design

- Evolutionary design based on CUORE and prototypes
- Single detector:
  - **Absorber:**  $4.5 \times 4.5 \times 4.5 \text{ cm}^3$   $\text{Li}_2^{100}\text{MoO}_4$  crystals ( $> 95\%$  enrichment)
  - **Operational temperature:**  $\sim 10 \text{ mK}$
  - **Thermal coupling:** PTFE holder
  - **Heater:** Gain calibration
  - **Light detector:** Ge light detector with Neganov-Trofimov-Luke amplification
  - **Sensors:** Ge neutron transmutation doped (NTD) thermistor

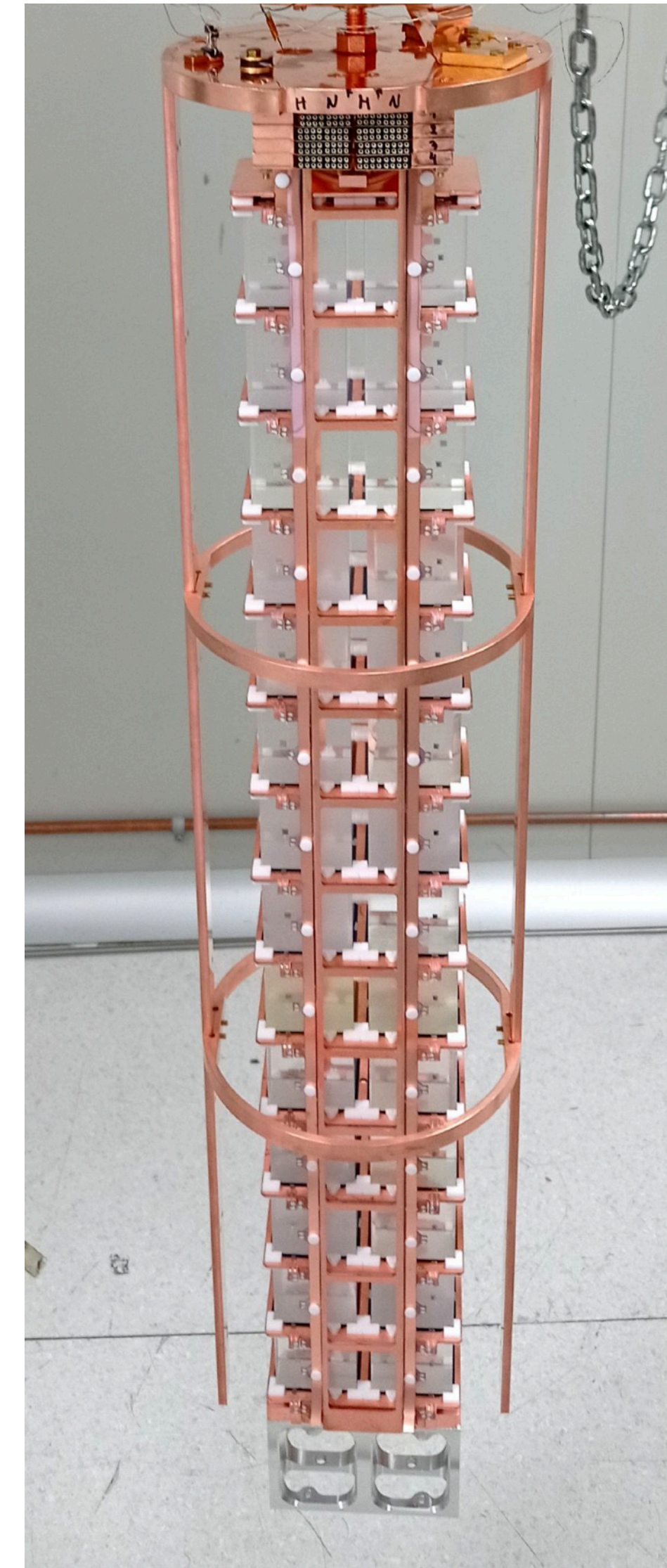
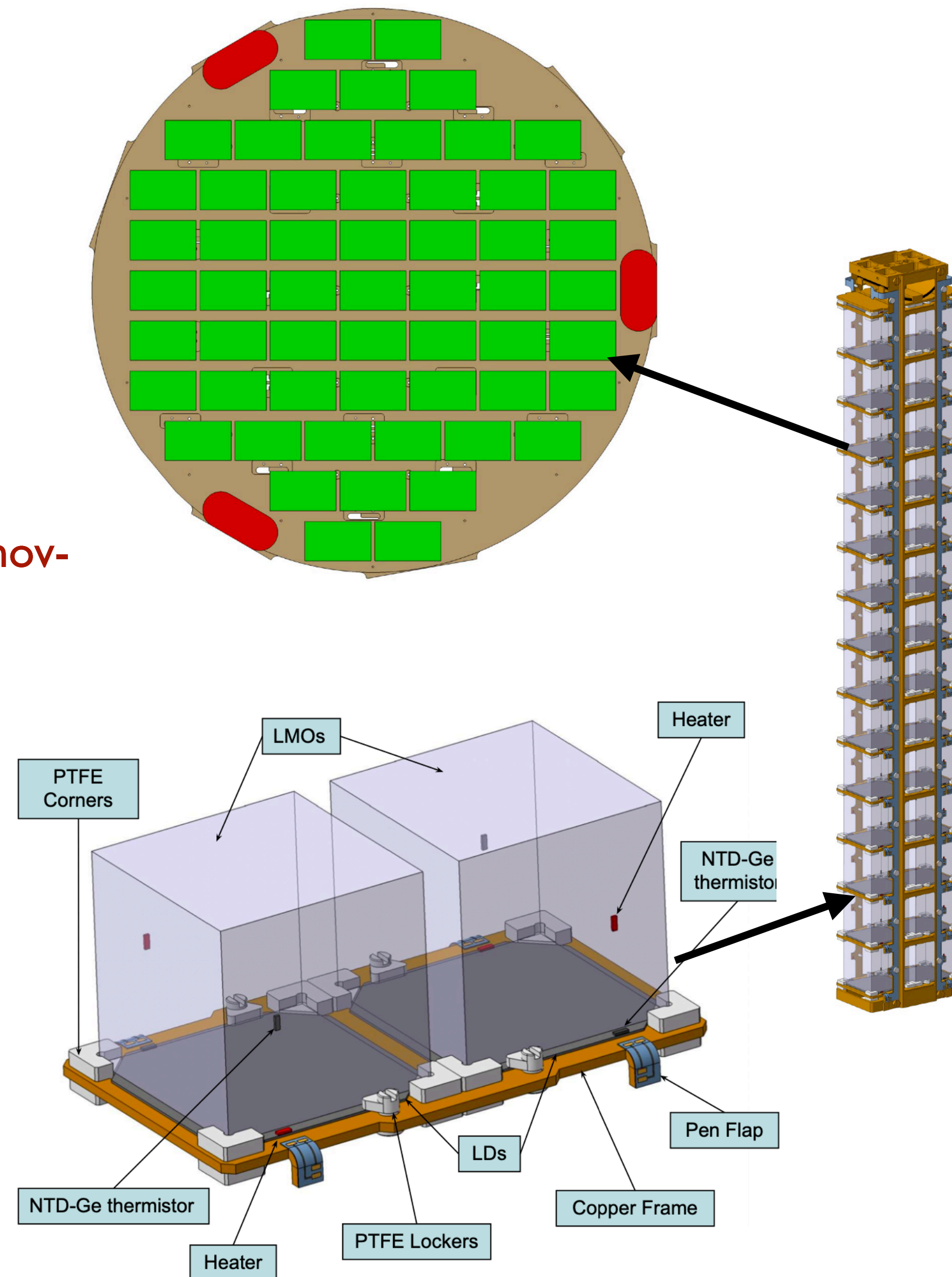




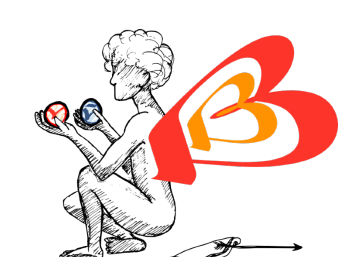


# CUPID Design

- Evolutionary design based on CUORE and prototypes
- Single detector:
  - **Absorber:**  $4.5 \times 4.5 \times 4.5 \text{ cm}^3$   $\text{Li}_2^{100}\text{MoO}_4$  crystals ( $> 95\%$  enrichment)
  - **Operational temperature:**  $\sim 10 \text{ mK}$
  - **Thermal coupling:** PTFE holder
  - **Heater:** Gain calibration
  - **Light detector:** Ge light detector with Neganov-Trofimov-Luke amplification
  - **Sensors:** Ge neutron transmutation doped (NTD) thermistor
- Detector array:
  - Modified detector array structure
  - 57 towers (total of 1596 crystals): Gravity-assisted design
  - 240 kg of  $^{100}\text{Mo}$
- Addition of **muon veto**
- Use well-characterized CUORE infrastructure

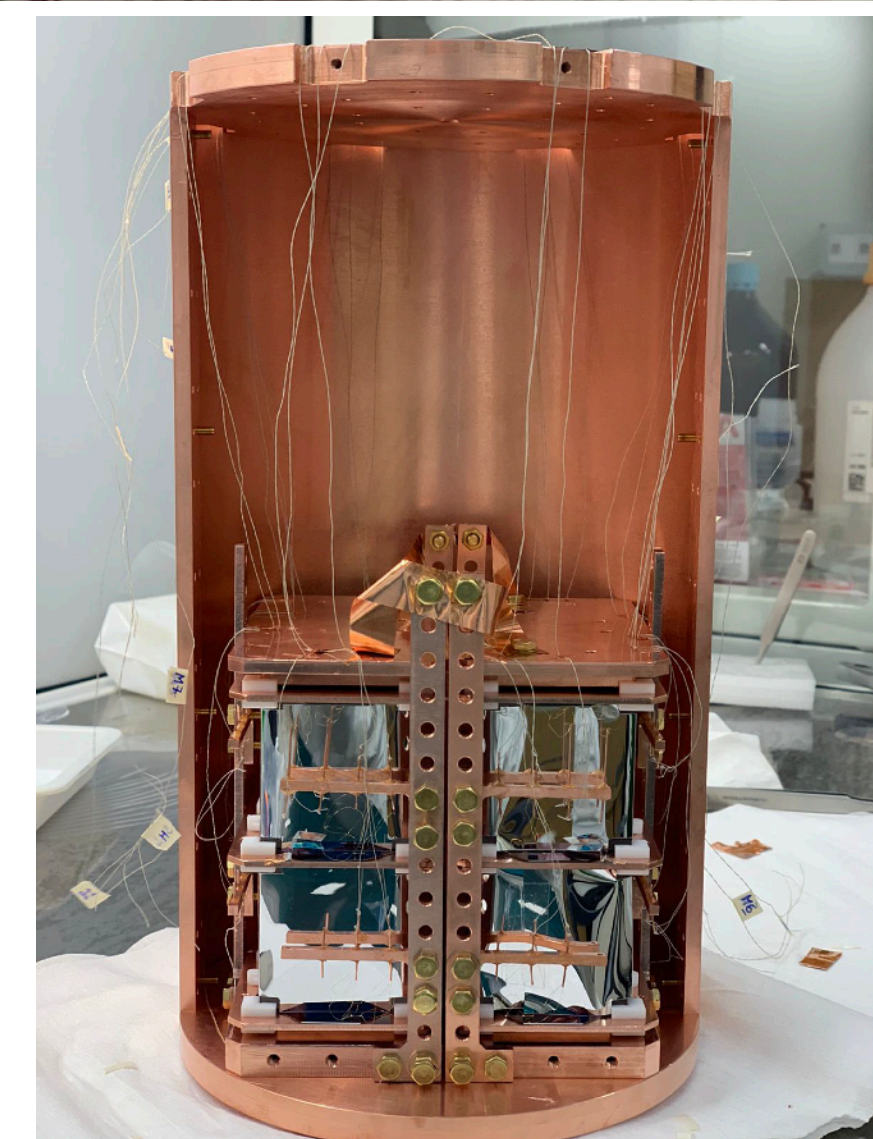
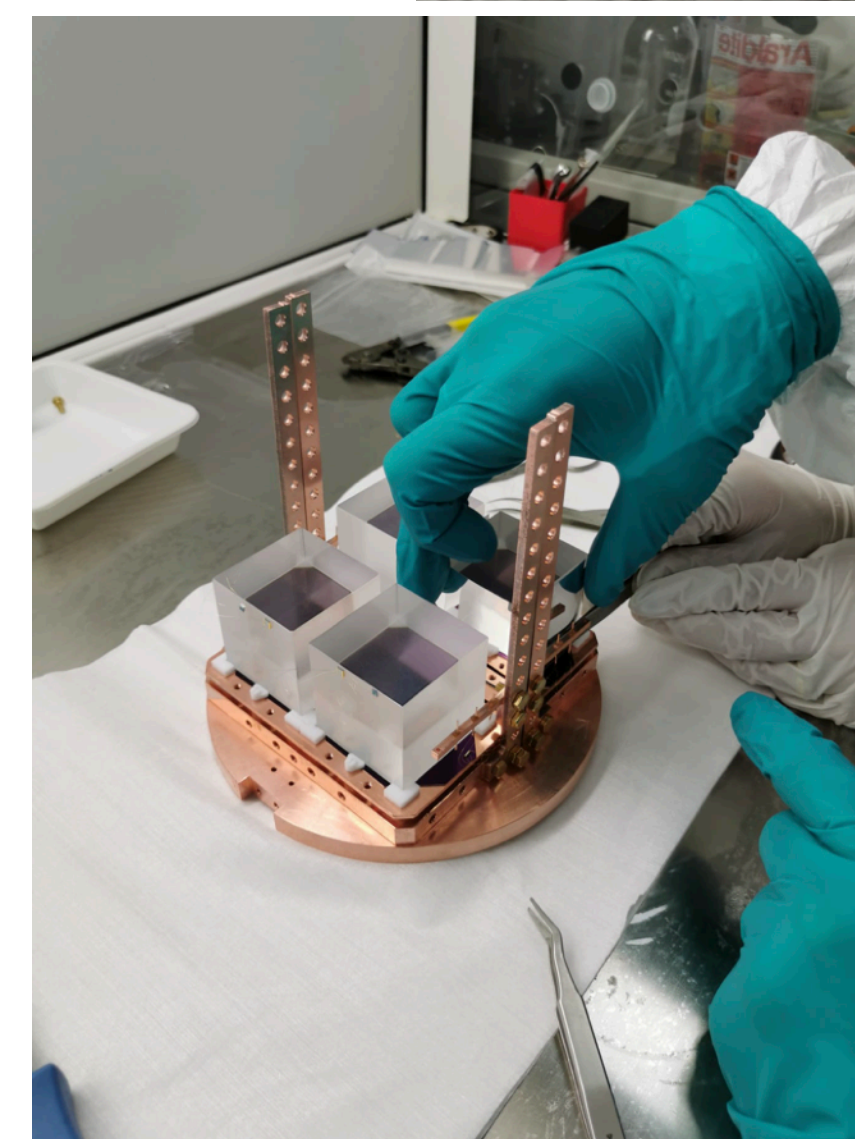
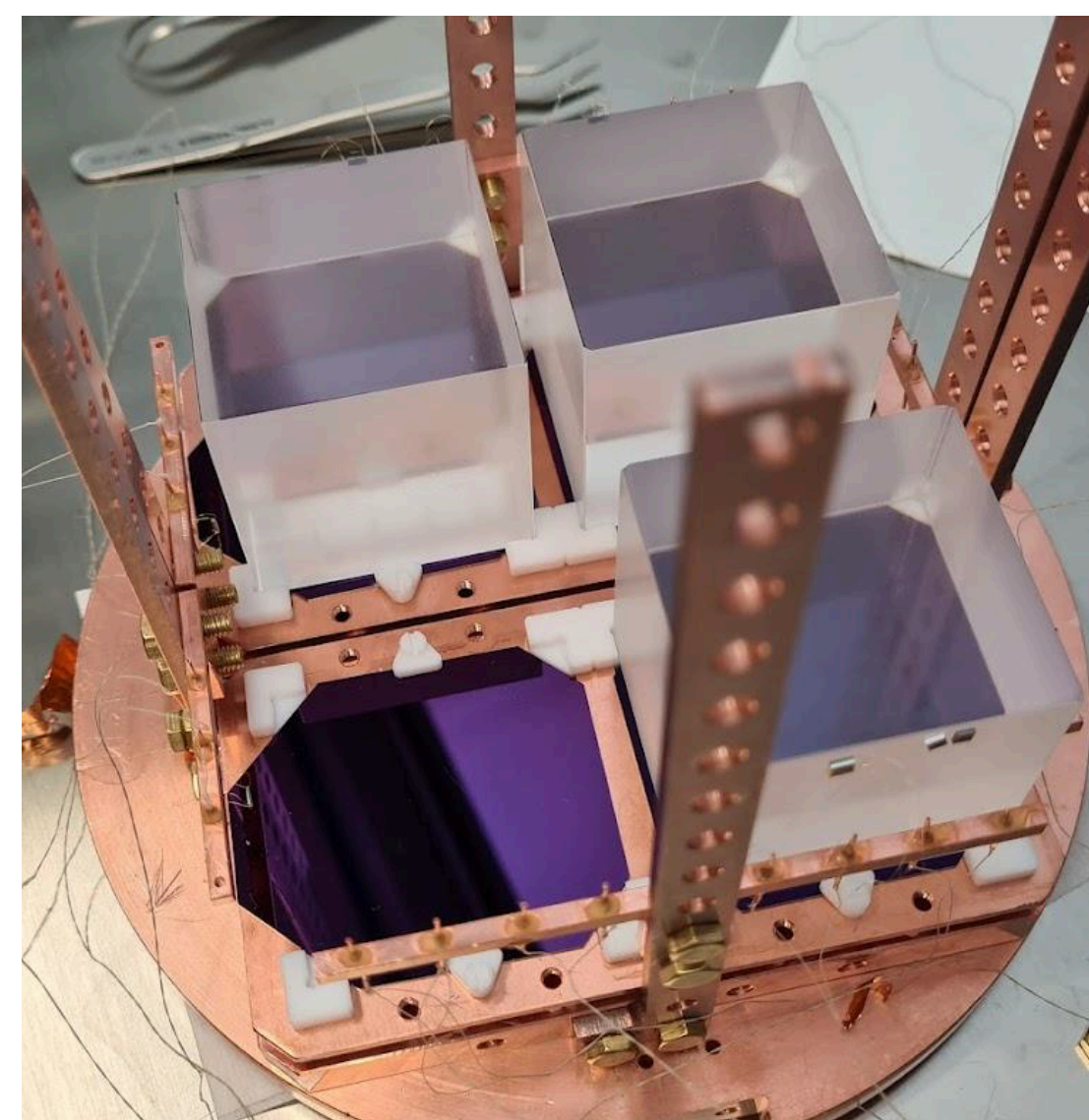
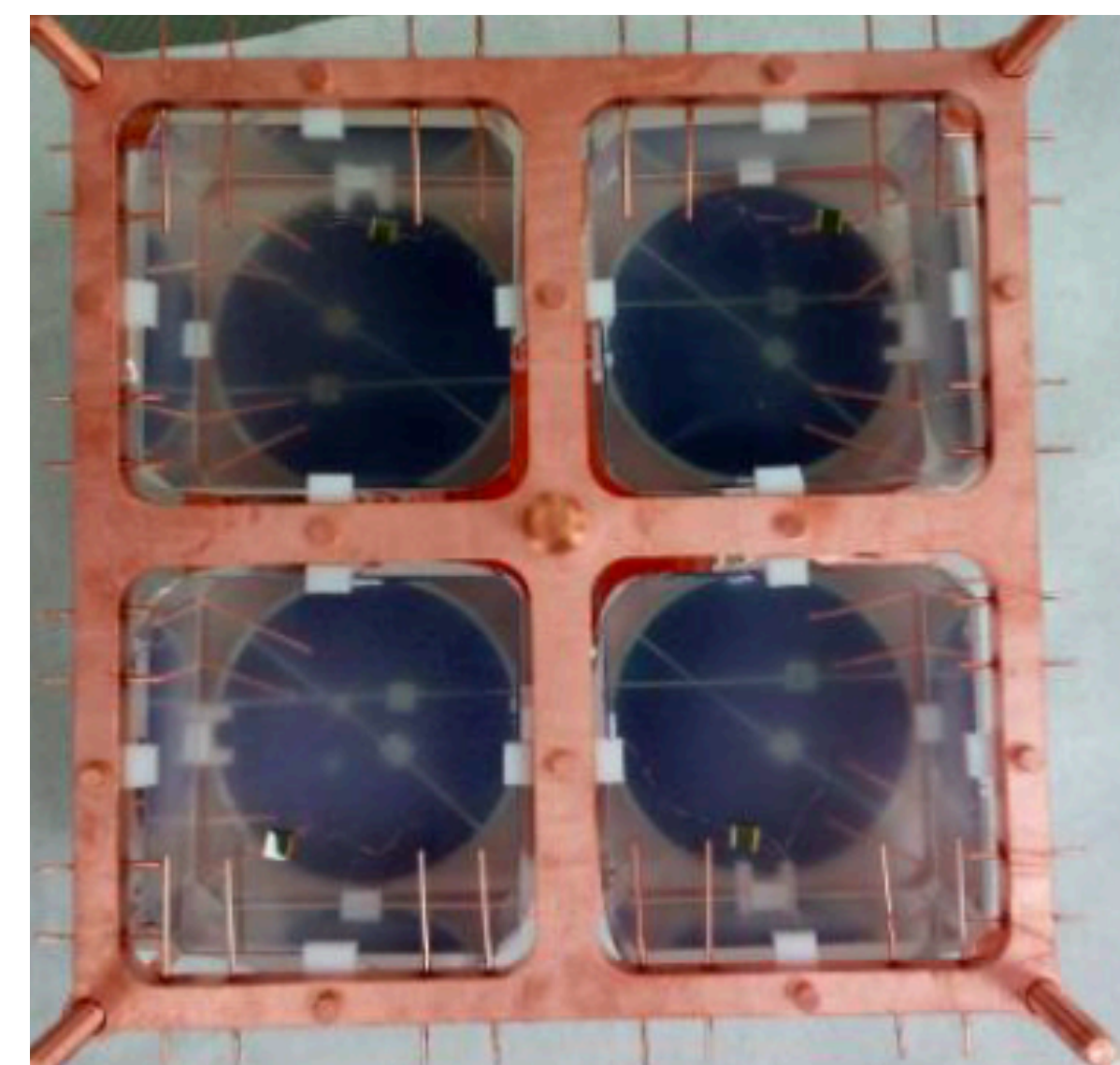
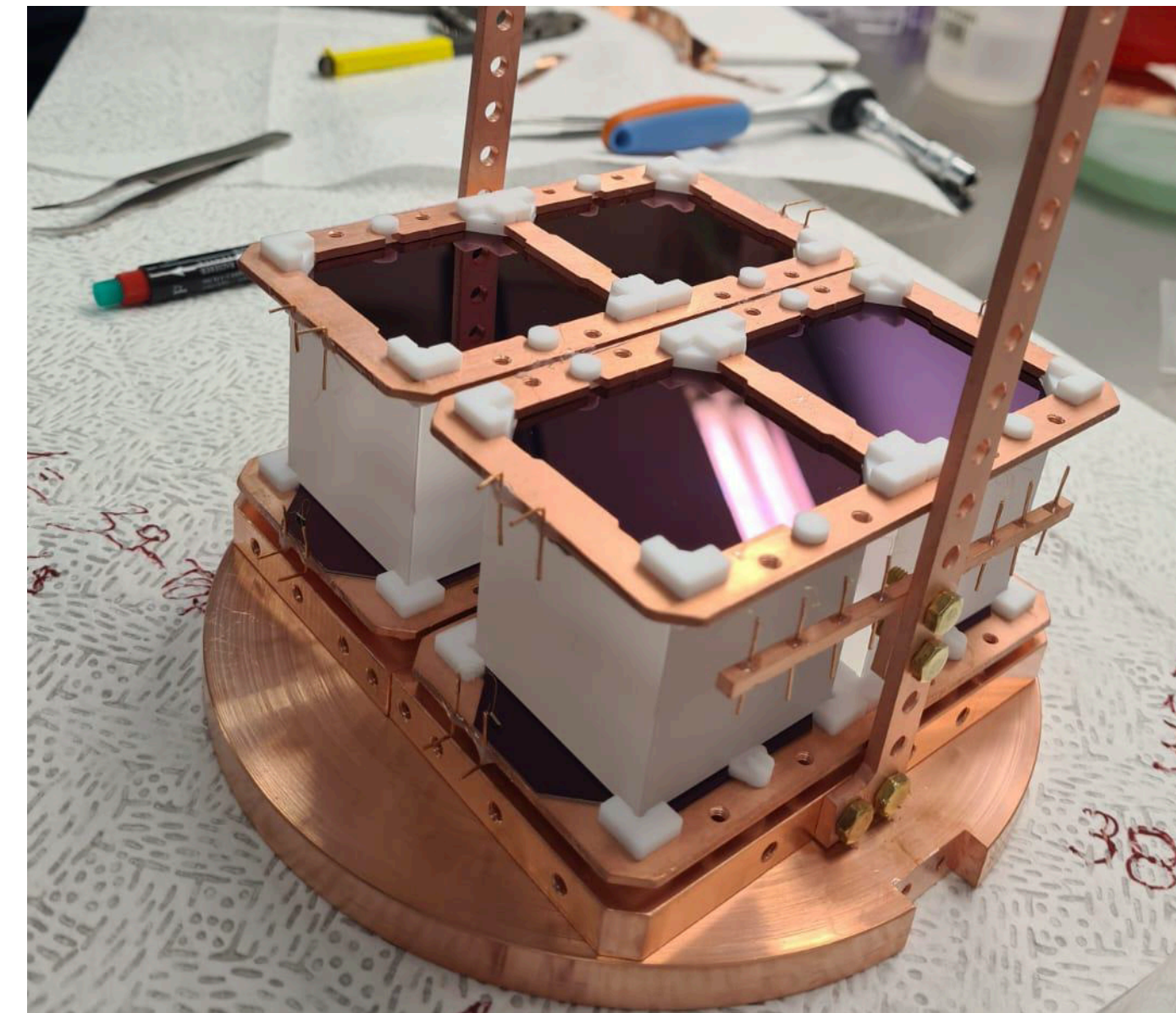




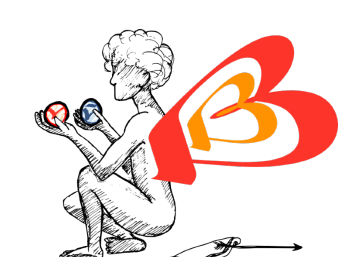


# Past and Ongoing R&D

- Final CUPID design based on several R&D tests

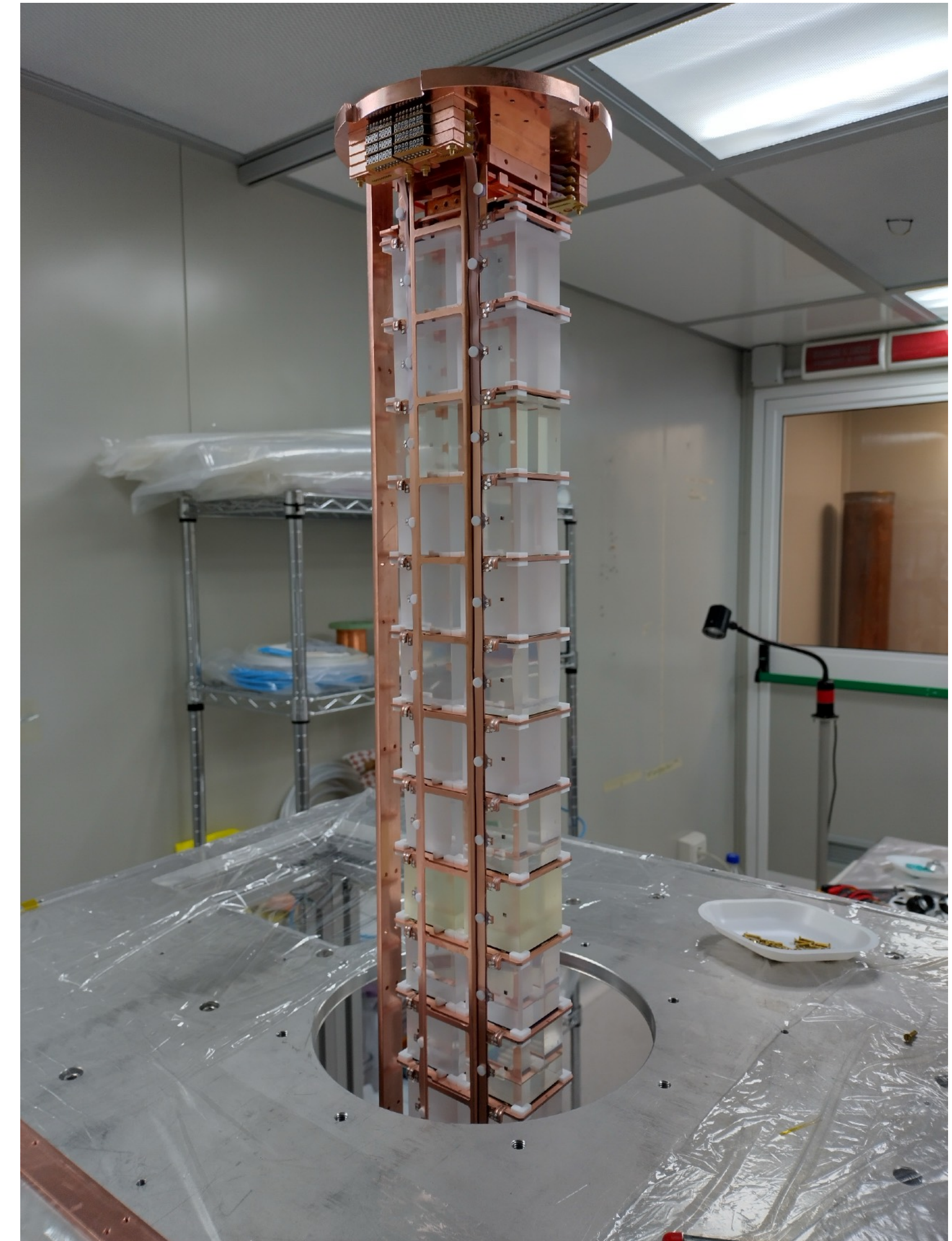
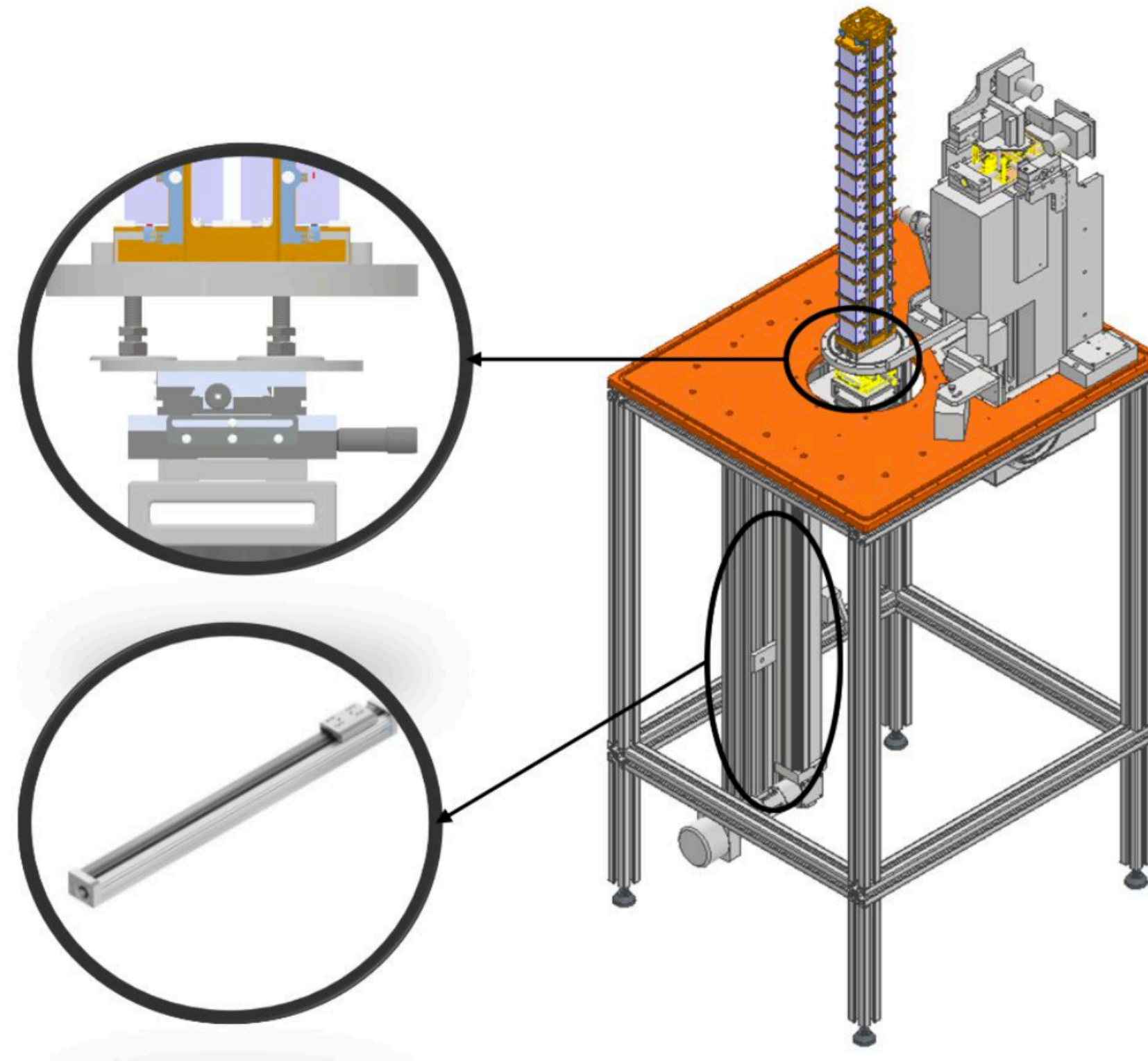




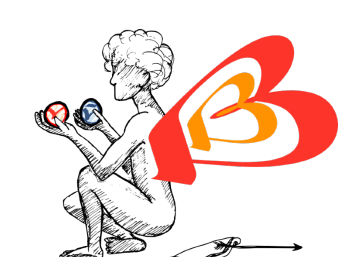


# Past and Ongoing R&D

- Final CUPID design based on several R&D tests
- Full CUPID baseline tower:
  - Mechanical, thermal, and vibrational characteristics
  - Assembly procedures
  - Quality of the crystals
- Secondary tests underway
  - Detector performance
  - Crystal radiopurity

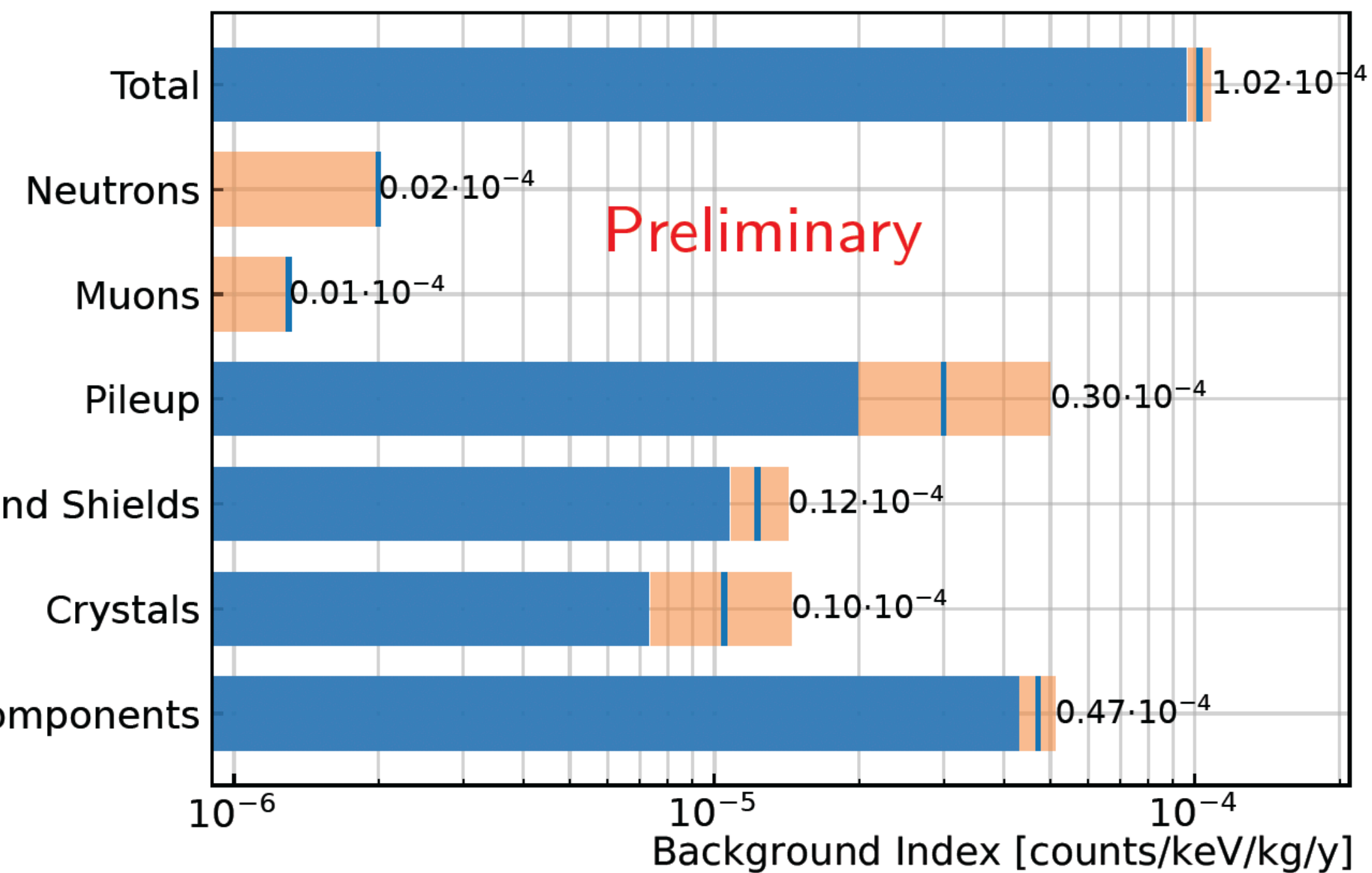






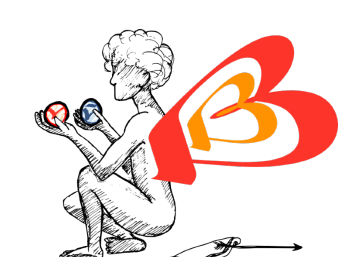
# CUPID Staged Deployment

- Data-driven simulations show that the background goal ( $10^{-4}$  cts/keV.kg.yr) can be reached



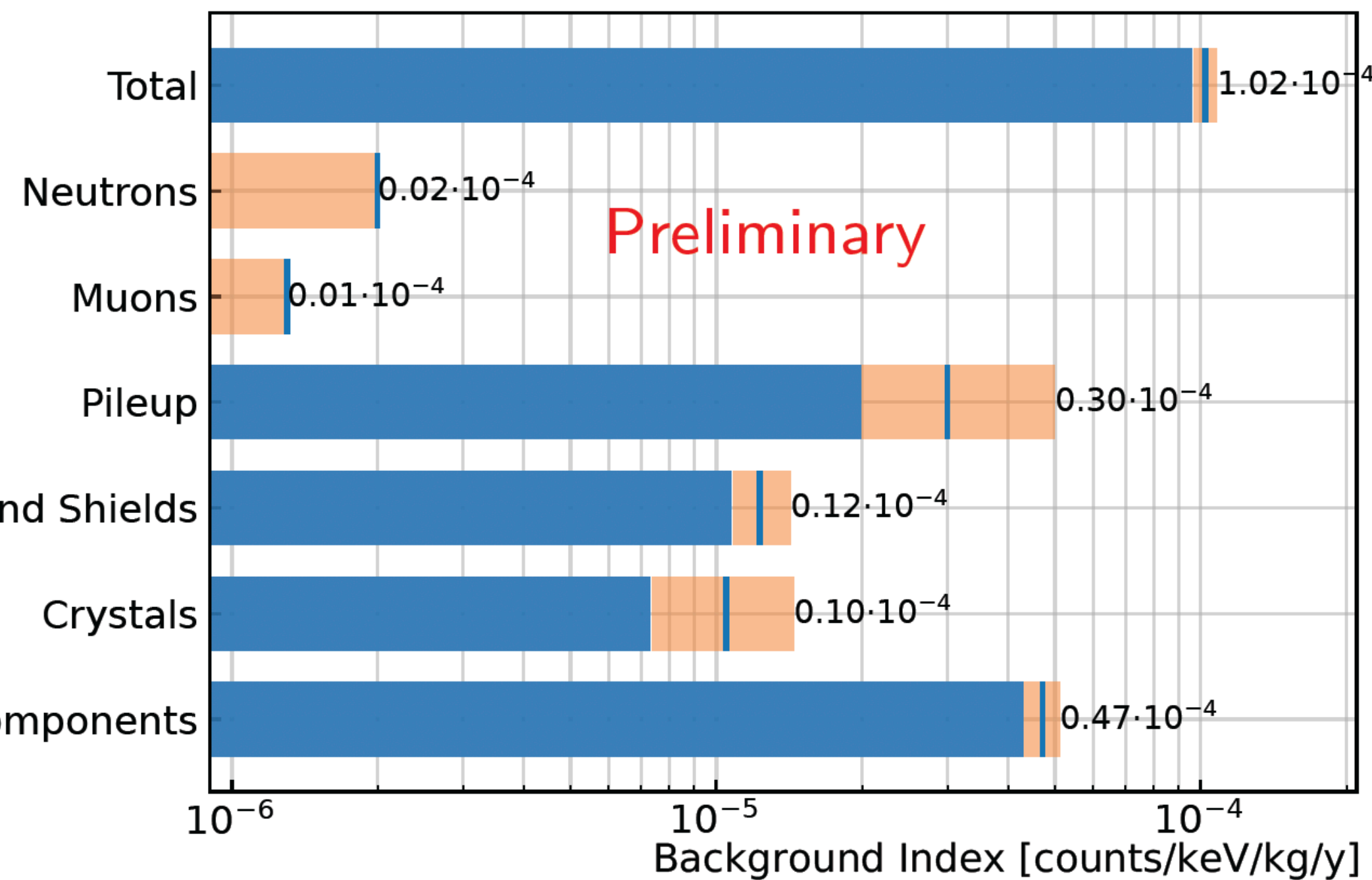
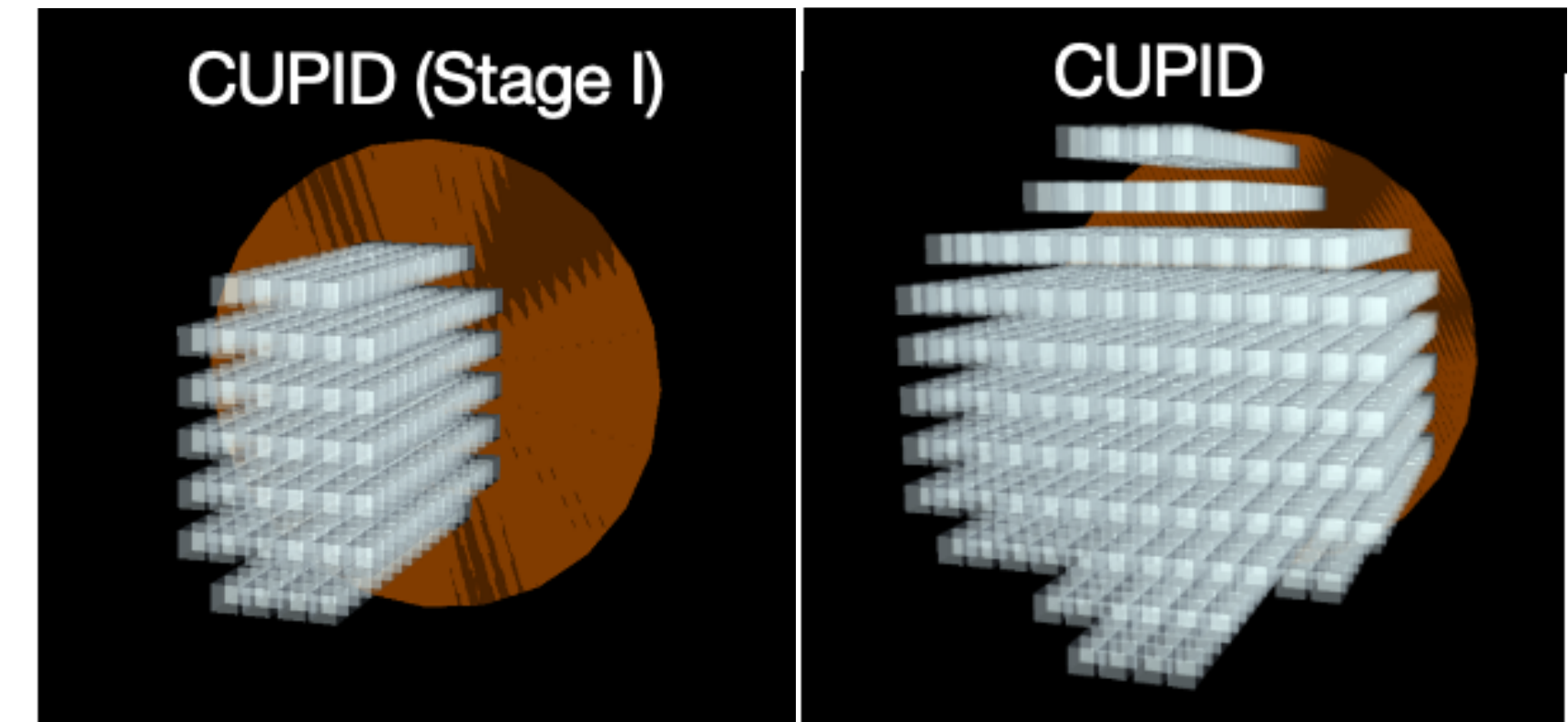
Vertical blue bar: mode of the pdf distribution.  
Orange band:  $\pm 1\sigma$  uncertainty



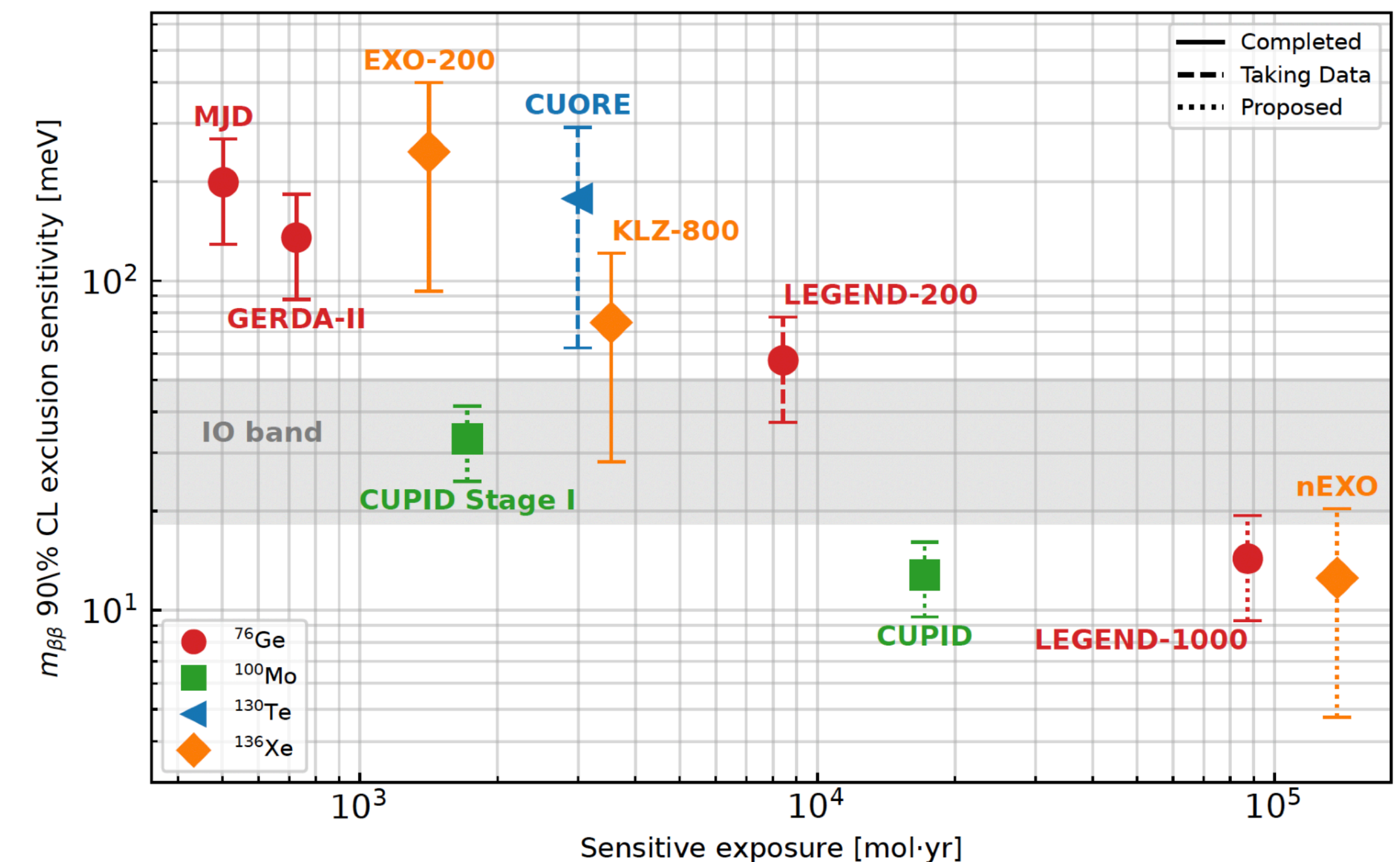


# CUPID Staged Deployment

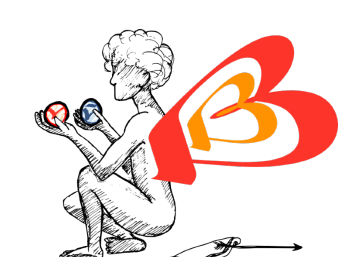
- Data-driven simulations show that the background goal ( $10^{-4}$  cts/keV.kg.yr) can be reached
- Staged deployment enables first science data by 2030 with CUPID Stage I
- CUPID Stage I has world-leading science reach
- Ton-scale experiment with competitive sensitivity



Vertical blue bar: mode of the pdf distribution.  
Orange band:  $\pm 1\sigma$  uncertainty







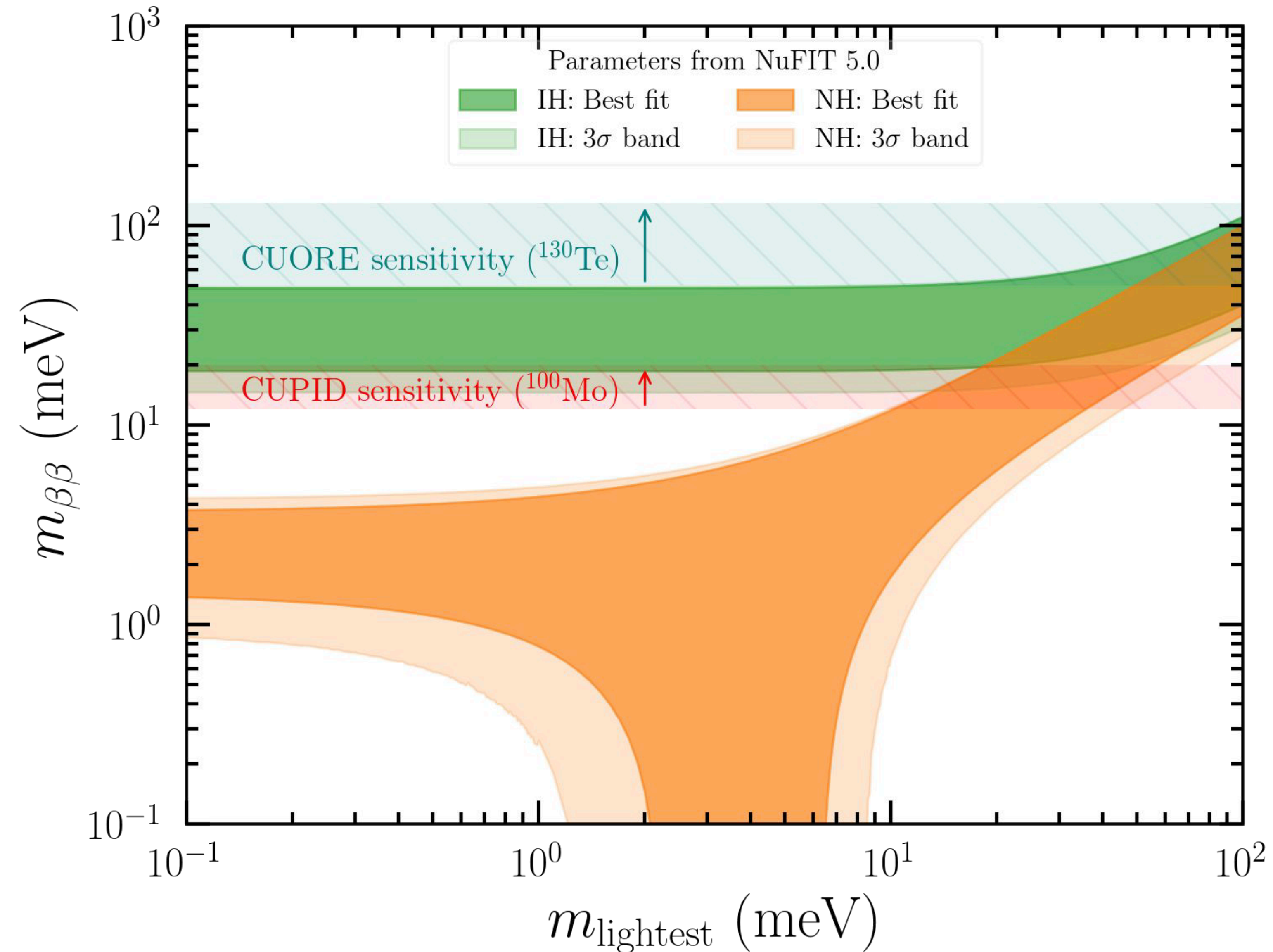
# CUPID Sensitivity

Discovery sensitivity:

$T_{1/2} \sim \mathbf{10^{27} \text{ yrs}} (3\sigma)$

$m_{\beta\beta} \sim \mathbf{12-20 \text{ meV}} (3\sigma)$

Fully probe the Inverted Ordering region







# CUPID Sensitivity

Discovery sensitivity:

$$T_{1/2} \sim \mathbf{10^{27} \text{ yrs}} (3\sigma)$$

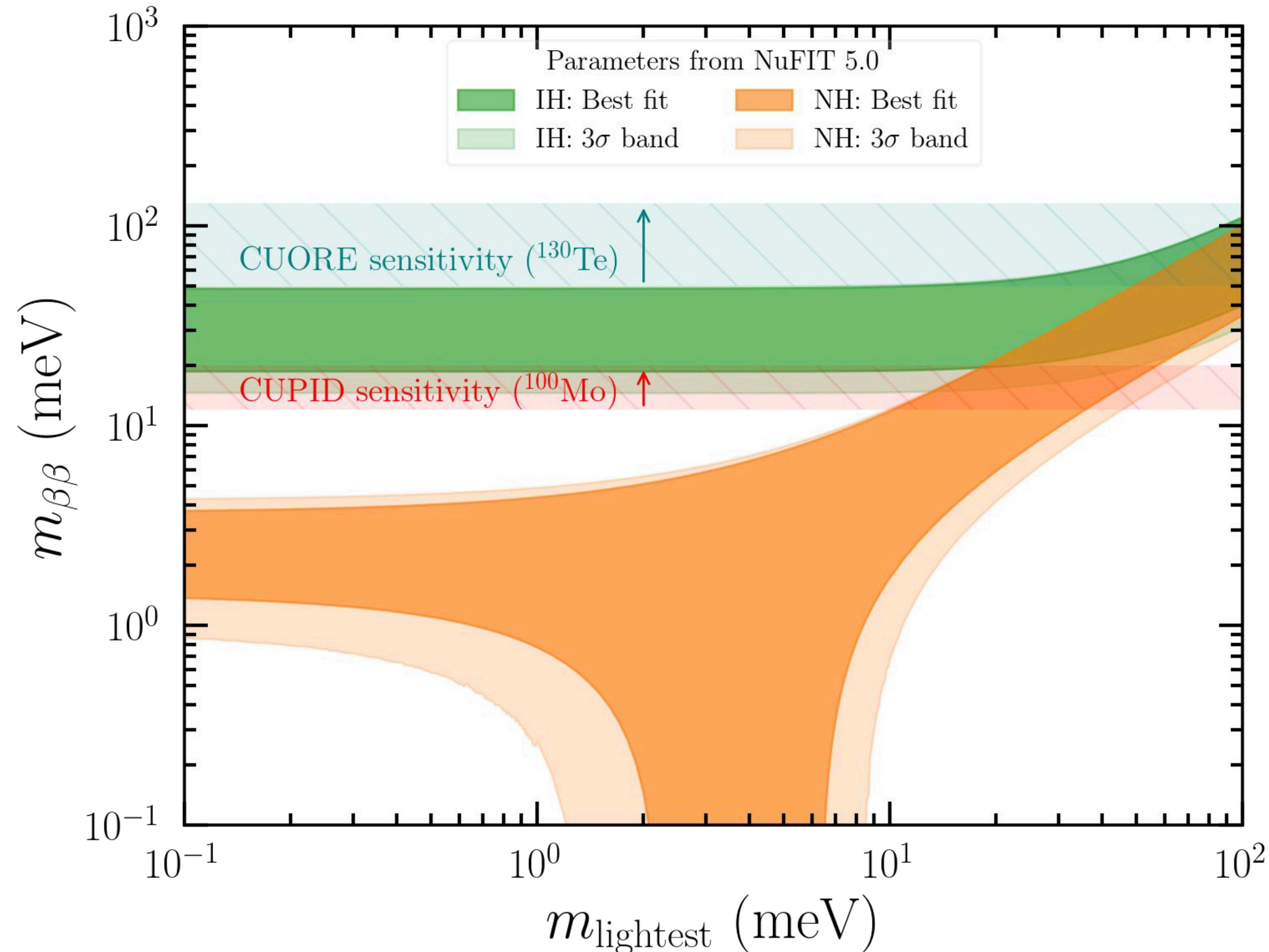
$$m_{\beta\beta} \sim \mathbf{12\text{--}20 \text{ meV}} (3\sigma)$$

Fully probe the Inverted Ordering region

Ongoing R&D to enable next-next bolometric detectors

In case of discovery, search for  $0\nu\beta\beta$  in other candidates ( $^{82}\text{Se}$ ,  $^{116}\text{Cd}$ ,  $^{130}\text{Te}$ ):

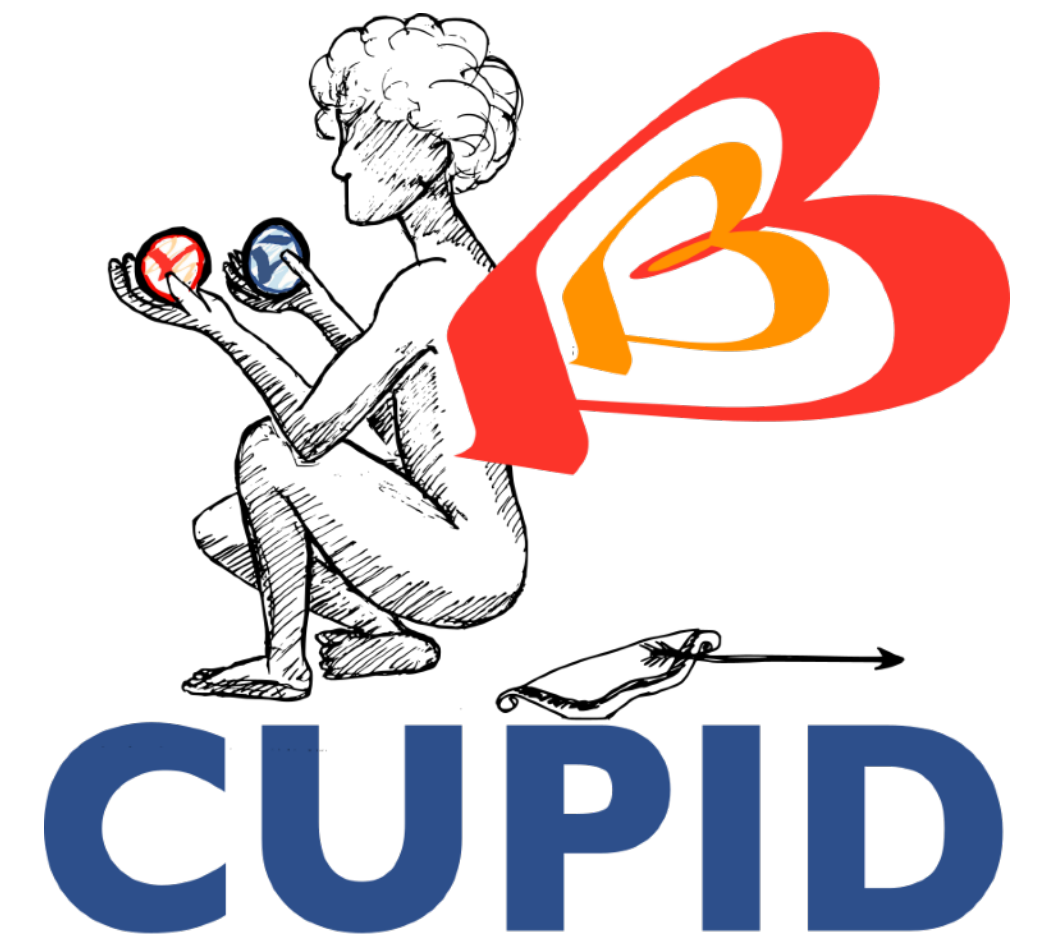
- Existing infrastructure
- Fully developed procedures
- Optimized analysis techniques





# Summary

- Neutrinoless double beta decay is one of the best probes to identify the nature of neutrinos
- CUORE successfully demonstrated  $0\nu\beta\beta$  search with large-scale calorimetric detector
- CUPID leveraging CUORE's expertise plans to perform one of the most sensitive  $0\nu\beta\beta$  searches to fully probe inverted hierarchy







Thank you!



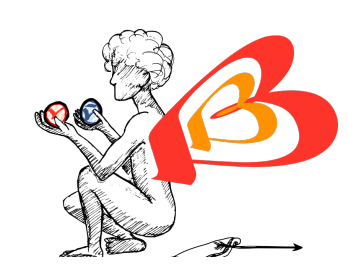
CUPID





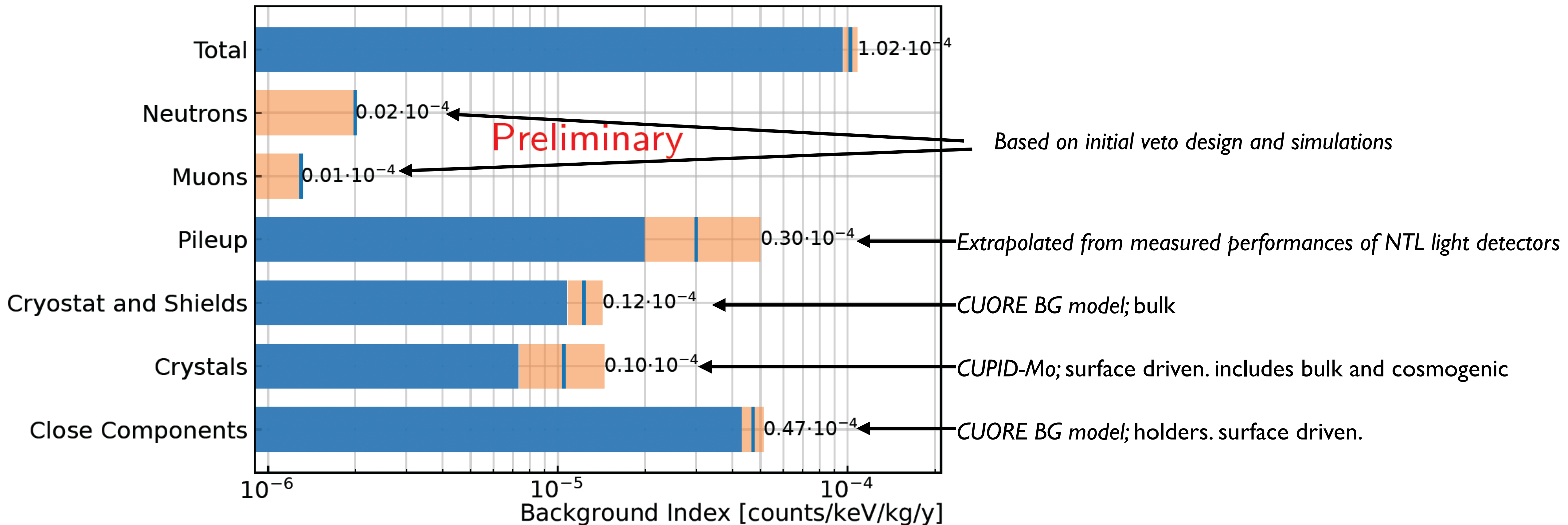






# CUPID Backgrounds

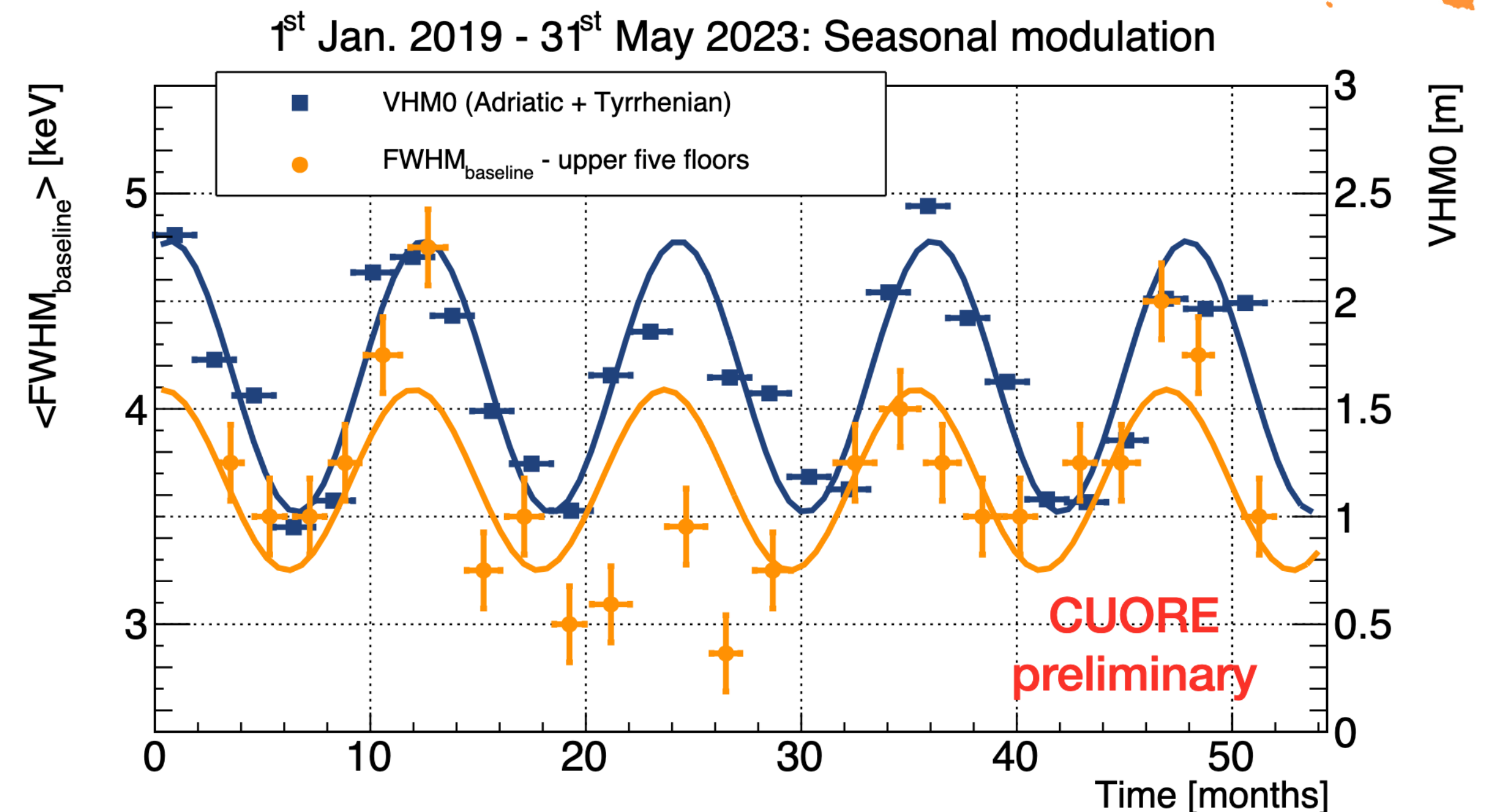
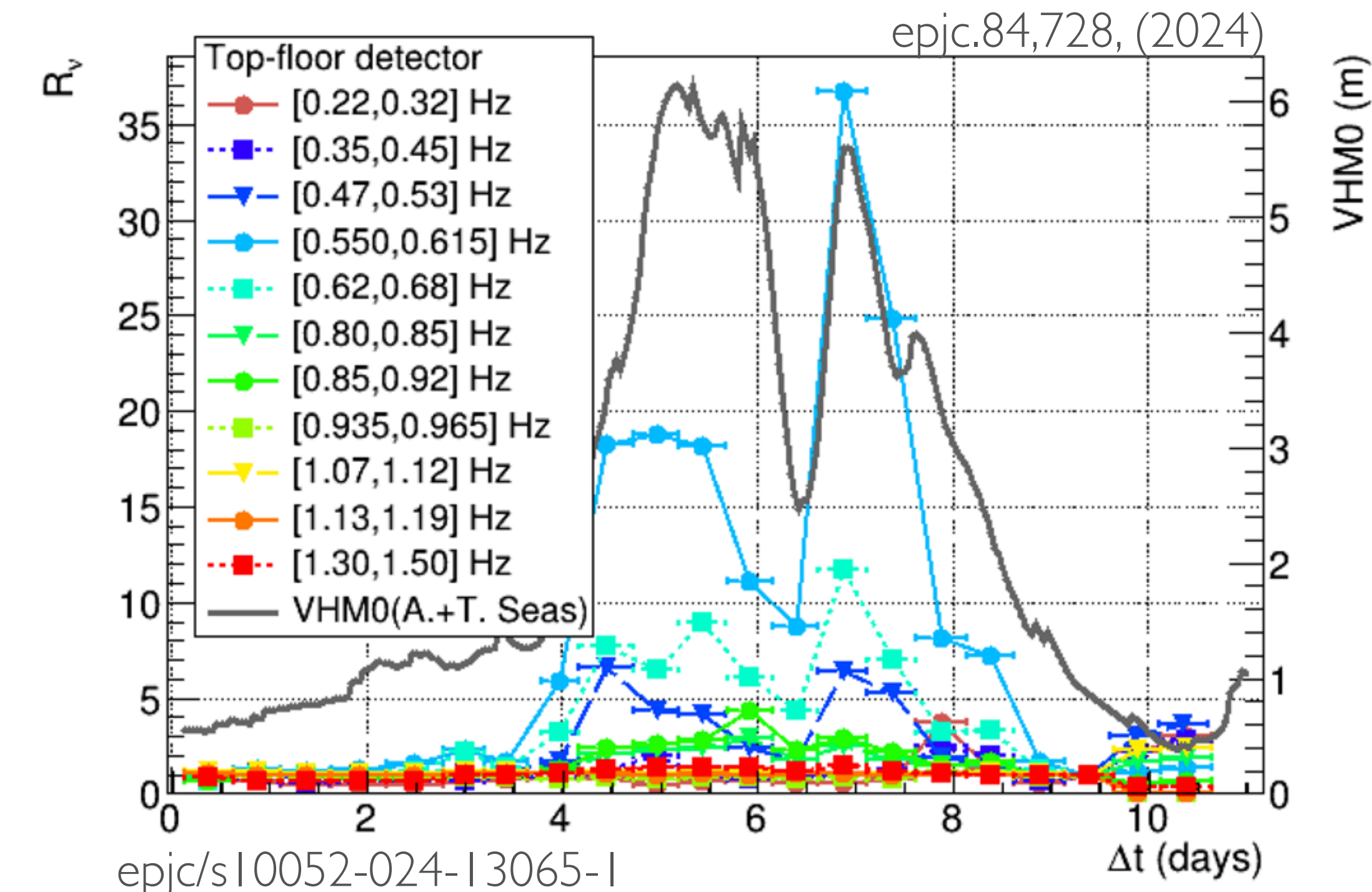
- Data-driven simulations show that the background goal ( $10^{-4}$  cts/keV.kg.yr) can be reached



Vertical blue bar: mode of the pdf distribution.  
Orange band:  $\pm 1\sigma$  uncertainty



- Few day-long surges in noise at low frequencies
- Correlations between CUORE low frequency noise and sea waves (Adriatic and Tyrrhenian)
- Correlated seasonal modulation of the detector resolution observed
- Studies underway for further active and passive noise reduction





# Enriched crystals procurement

- CUPID has established a supply chain for producing all the  $\text{Li}_2^{100}\text{MoO}_4$  crystals grown with  $\sim 95\%$  enriched  $^{100}\text{Mo}$
- SICCAS (Shanghai, China) has the capability to produce the enriched  $\text{Li}_2^{100}\text{MoO}_4$  crystals, procuring the isotope from a Chinese manufacturer.
- Pre-production is on-going, funded by INFN (Italy) and CNRS (France) with goals to:
  - Reduce to a minimum material (isotope) loss during growth and cut
  - Check and optimize radiopurity
  - Optimize light yield and transmission (surface quality)
- Radioassay of precursors done with multiple techniques and in different sites (China, Italy, US)
- Sequential crystal tests at LNGS CUPID facility to assess bolometric performances and analyse residual radioactivity

*SICCAS is the same company that produced all the CUORE  $\text{TeO}_2$  crystals with radiopurity similar to CUPID requirements for  $\text{Li}_2^{100}\text{MoO}_4$*



# CUPIID-1T: A Next-Next Generation Detector

## CUPIID-1T

- 4x scale up
- 1871 kg of  $\text{Li}_2^{100}\text{MoO}_4$  for 1000 kg of  $^{100}\text{Mo}$

## Cryogenics are achievable with current technology

- Distributed multi-cryostat setup
- Or single large cryostat and dilution refrigerator (comparable cooling power to CUORE)

## Quantum sensors

- Would require low-noise, high-bandwidth TES or mKIDs superconducting sensors
- Reasonable level of multiplexing
- Active R&D toward background reduction

## Background goal of $5 \times 10^{-6}$ counts/(keV·kg·yr)

- Reduce background  $\mu$ ,  $\beta/\gamma$ ,  $\alpha$  discrimination
- Consider pileup and subdominant backgrounds

CUPIID-1T is an Inverted Hierarchy precision measurement device across multiple isotopes or a Normal Hierarchy explorer

