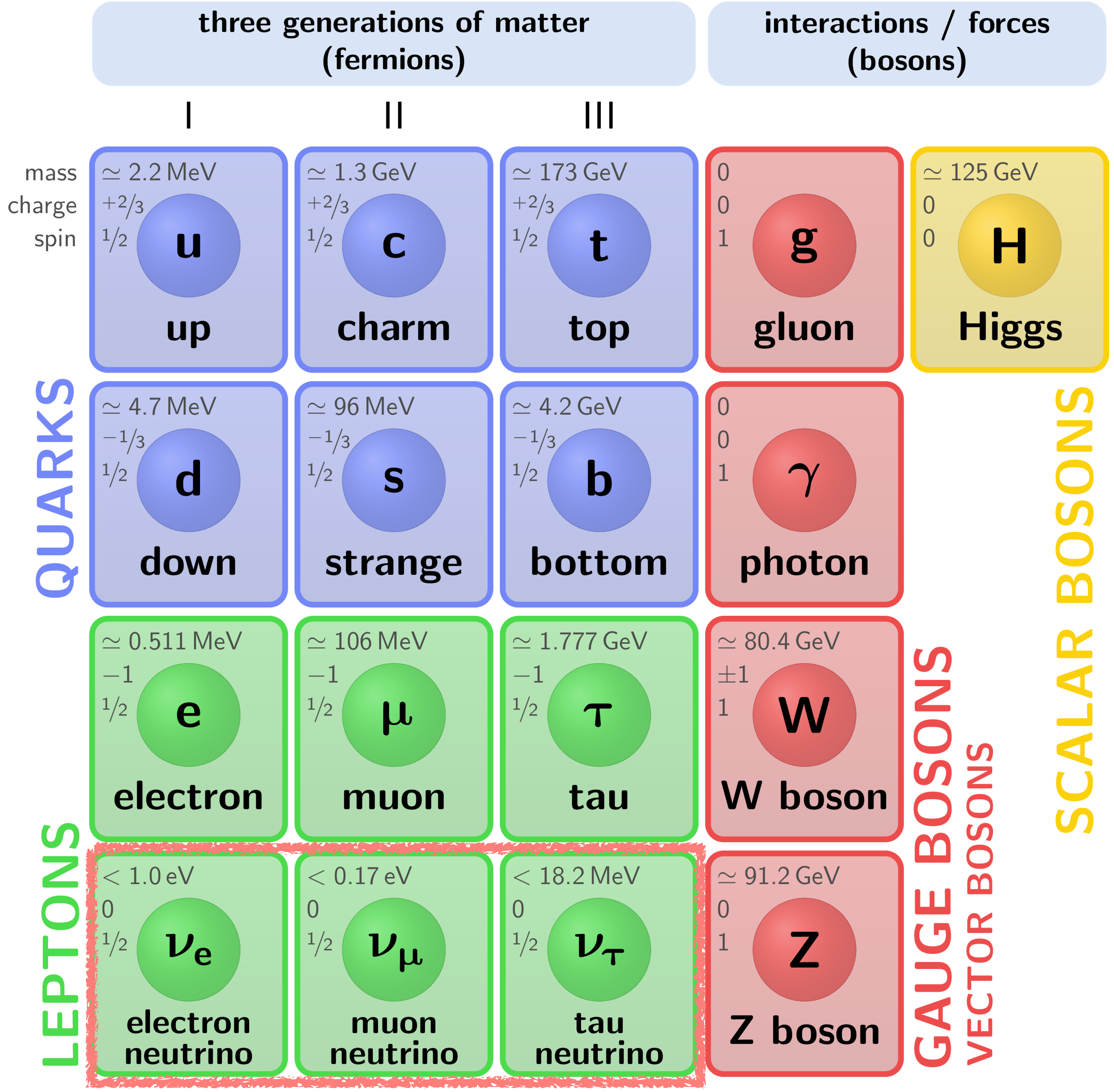
Searching for $0\nu\beta\beta$ decay with CUORE and CUPID

Jorge Torres, for the CUORE/CUPID collaborations
Oct 21, 2025 (Mexican Workshop on Particles and Fields)

Neutrinos

- Neutrinos are neutral leptons that only interact via the weak force.
- They come in three "flavors": electron, muon, and tau neutrinos.
- They have 3 mass eigenstates that oscillate as neutrinos travel.
- Neutrinos have a non-zero mass, which is not explained by the Standard Model.
- Massive efforts to try and understand the mass nature of neutrinos!



Status quo of neutrino physics

Parameter	Main method(s)	Source(s)	Status
θ_{12}	Oscillations	solar, reactor	✅
θ_{23}	Oscillations	atmospheric, accelerator	✅
θ_{13}	Oscillations	reactor, accelerator	✅
Δm^2_{21}	Oscillations	reactor, solar	✅
$\|\Delta m^2_{31}\|$	Oscillations	reactor, accelerator, atmospheric	✅
Ordering (sgn Δm^2_{31})	Oscillations	reactor, accelerator, atmospheric	🤔 (hints)
$m_{1,2,3}$	Kinematics	β decay, cosmology	🤔 (limits)
δ_{CP}	Oscillations	accelerator	🤔 (hints)
α, β	Rare processes	double beta decay	❌

Table: Adapted from arXiv:2111.07586

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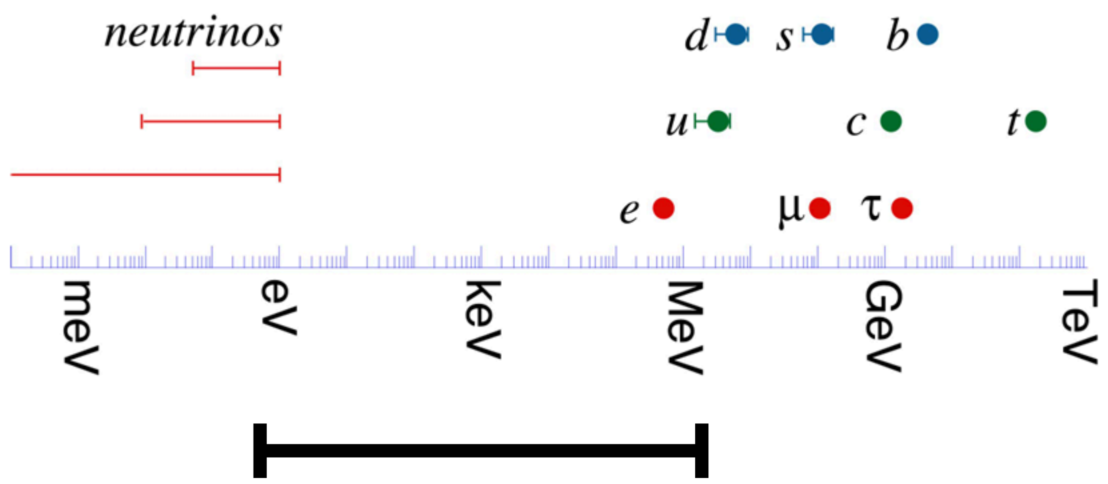
The particle nature of neutrinos

Dirac neutrinos

- Neutrino and antineutrino are different.
- Requires introducing two non-interacting leptonic fields (ν_R and $\bar{\nu}_L$) for mass generation.
- Leads to "hierarchy problem"



Why >6 orders of magnitude smaller Yukawa coupling…?

Majorana neutrinos

- Neutrino = antineutrino.
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- "Natural" neutrino mass by introducing GUT-scale physics.
- Could explain matter-antimatter asymmetry.

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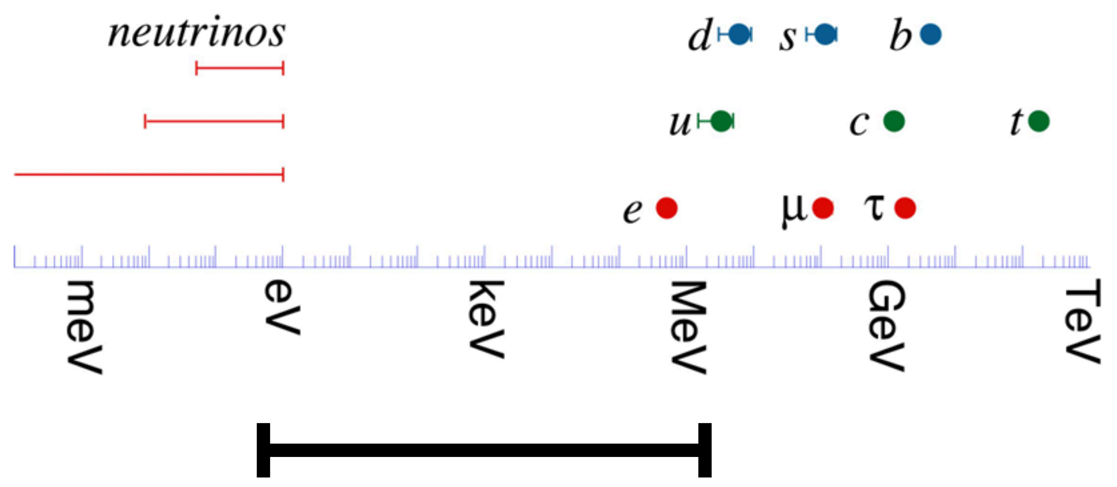

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Matter-antimatter asymmetry

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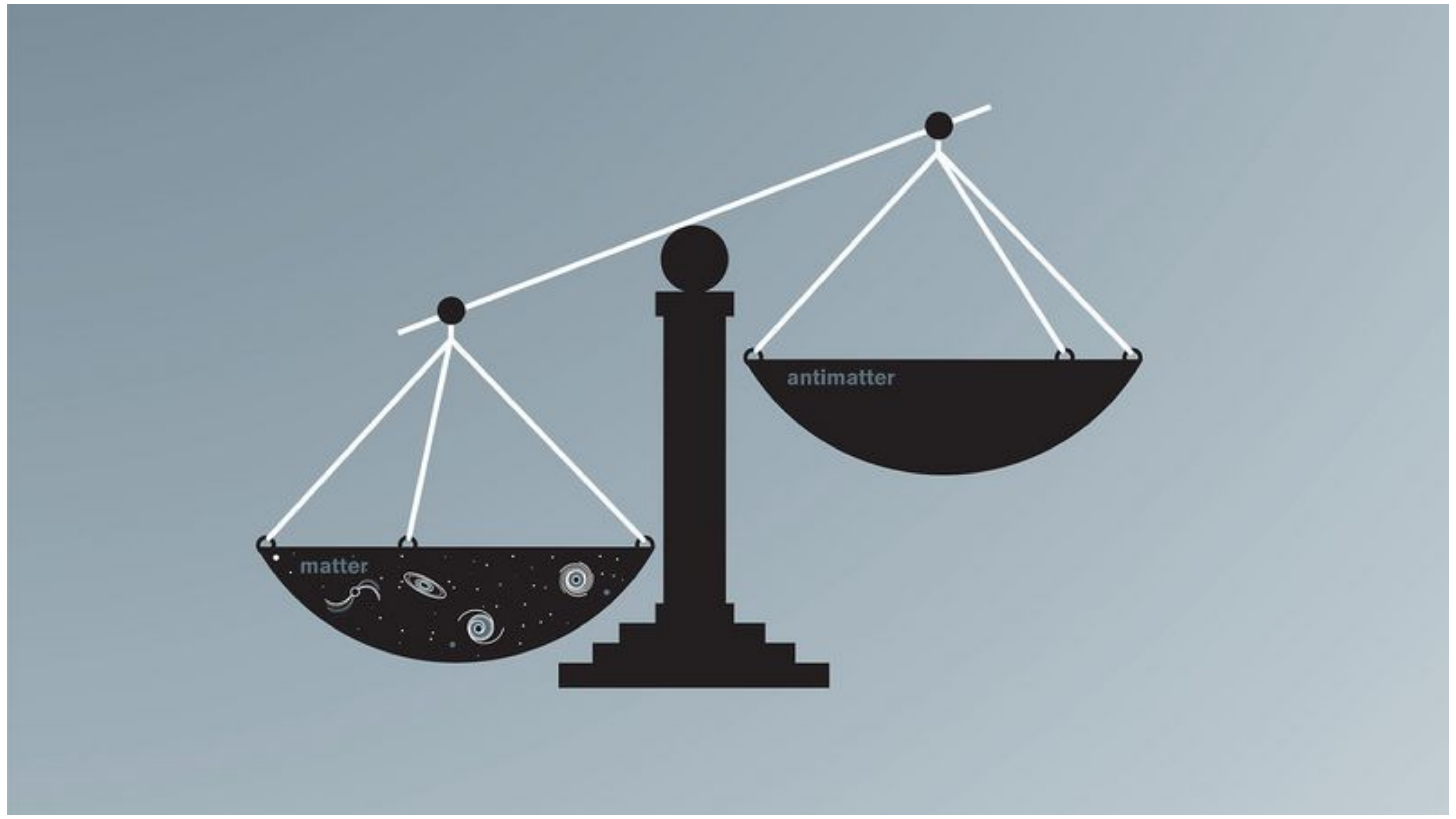
- Leading theory is that this asymmetry was dynamically produced, not as initial condition. Then:
  - Matter-generating process dominates.
  - Or, matter and antimatter created equally, but there's an antimatter-annihilating process that dominates
- Lepton number violation is a crucial ingredient
- (baryo-) Leptogenesis via Majorana neutrinos could explain matter-antimatter asymmetry.



Credit: Symmetry Magazine

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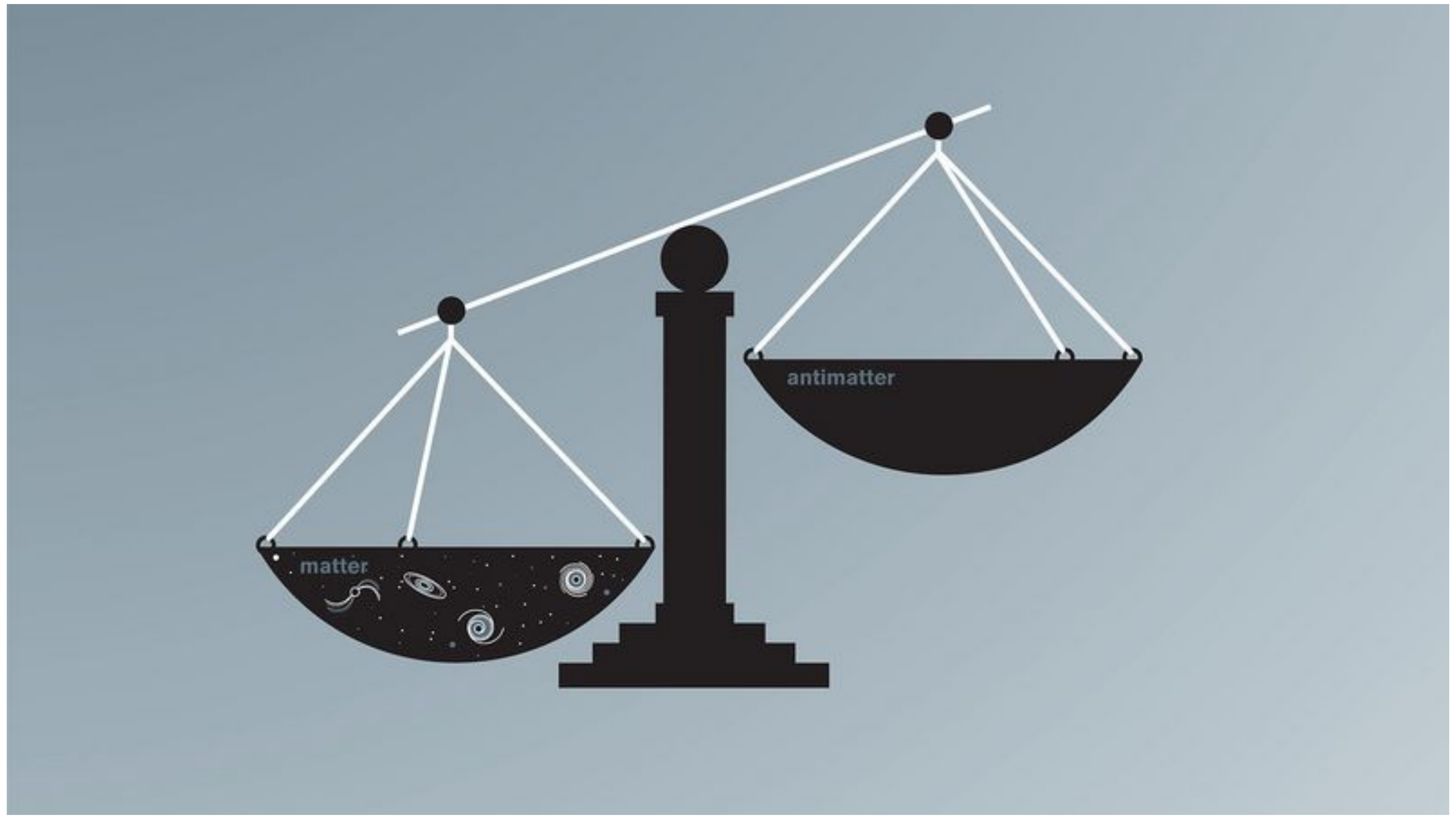

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→ $0\nu\beta\beta$

A matter creating process

Neutrinoless double beta ($0\nu\beta\beta$) decay

- $2\nu\beta\beta$ can occur in ~35 isotopes. Observed.
- If neutrinos are Majorana, virtual creation and annihilation of Majorana neutrino occurs: $0\nu\beta\beta$ decay **may** happen (not observed yet).
- Observation of $0\nu\beta\beta$ decay would imply that:
    - Neutrinos are Majorana particles.
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    - If light-neutrino mediated process (simplest model), constraints on neutrino mass nature.

$$\Delta L = 0$$

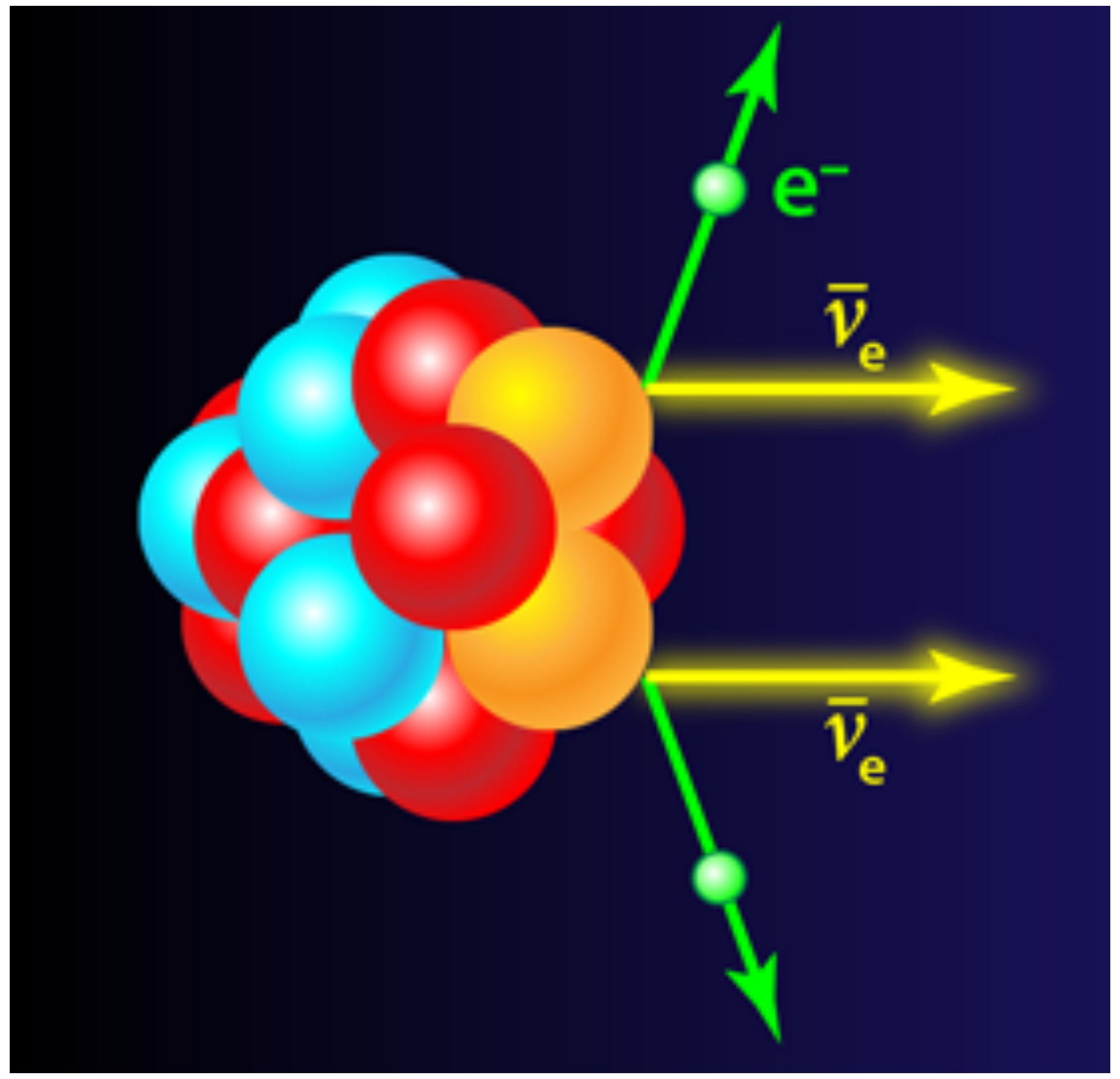

Image credits: APS/Alan Stonebraker

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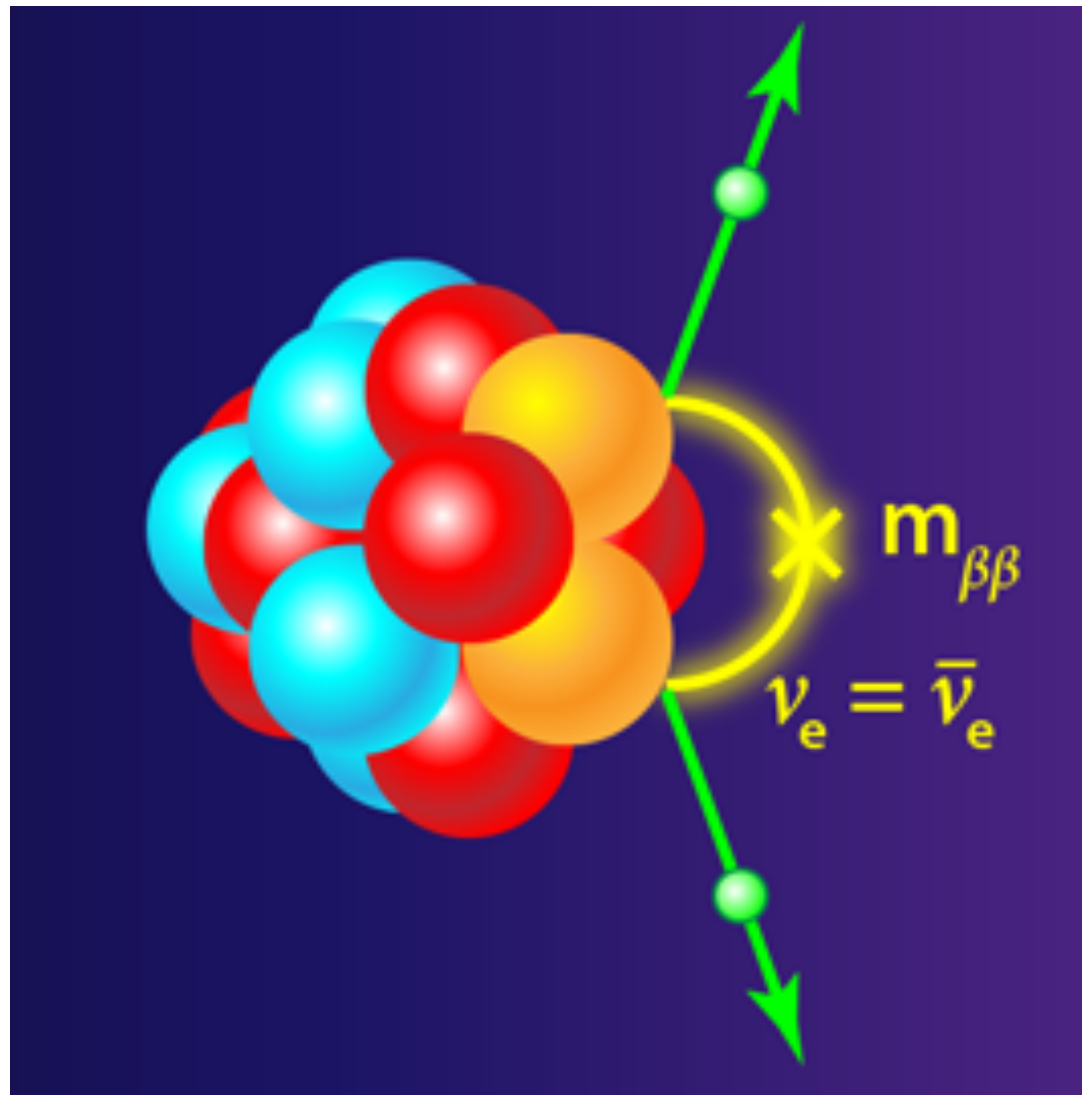

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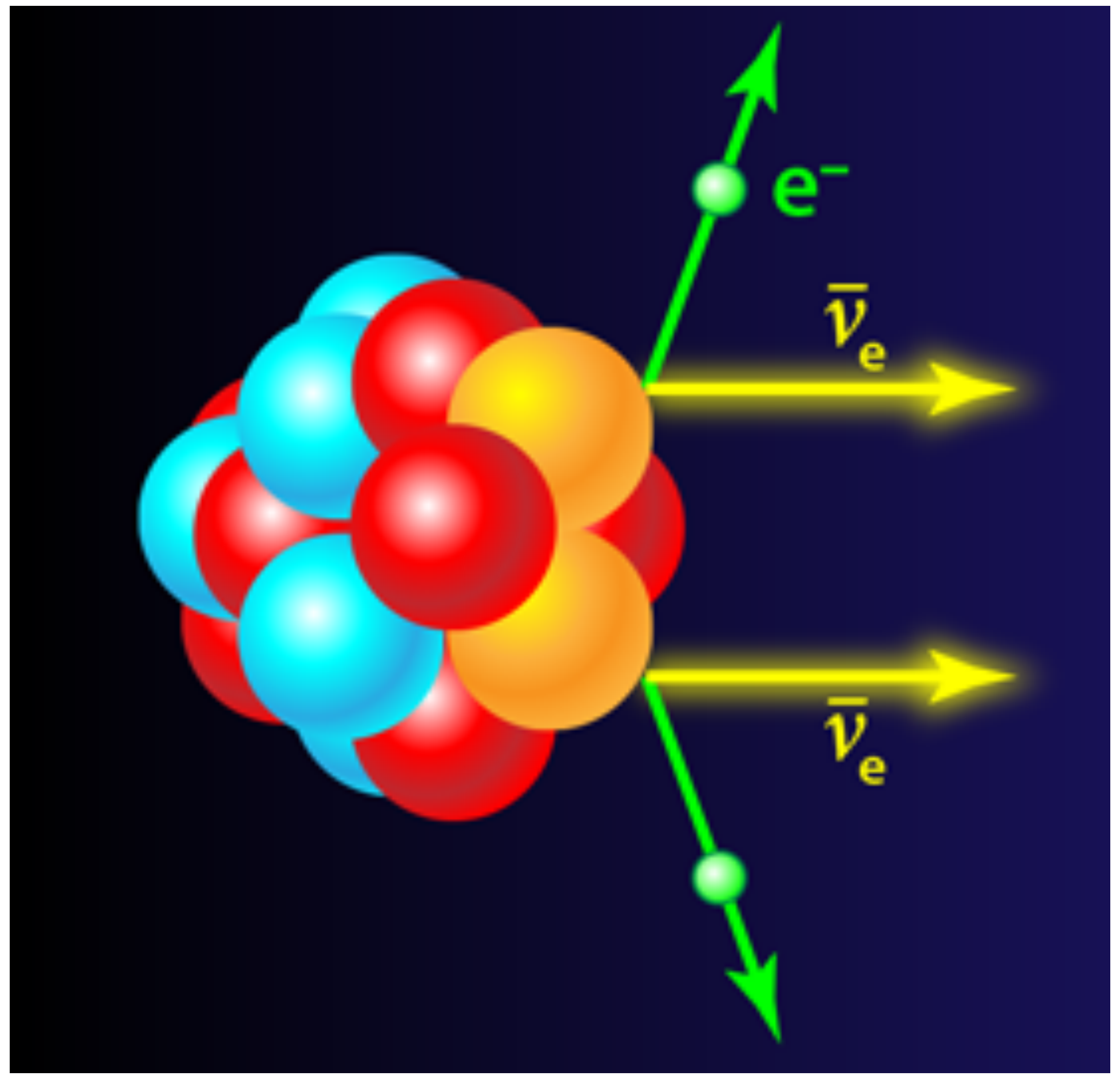

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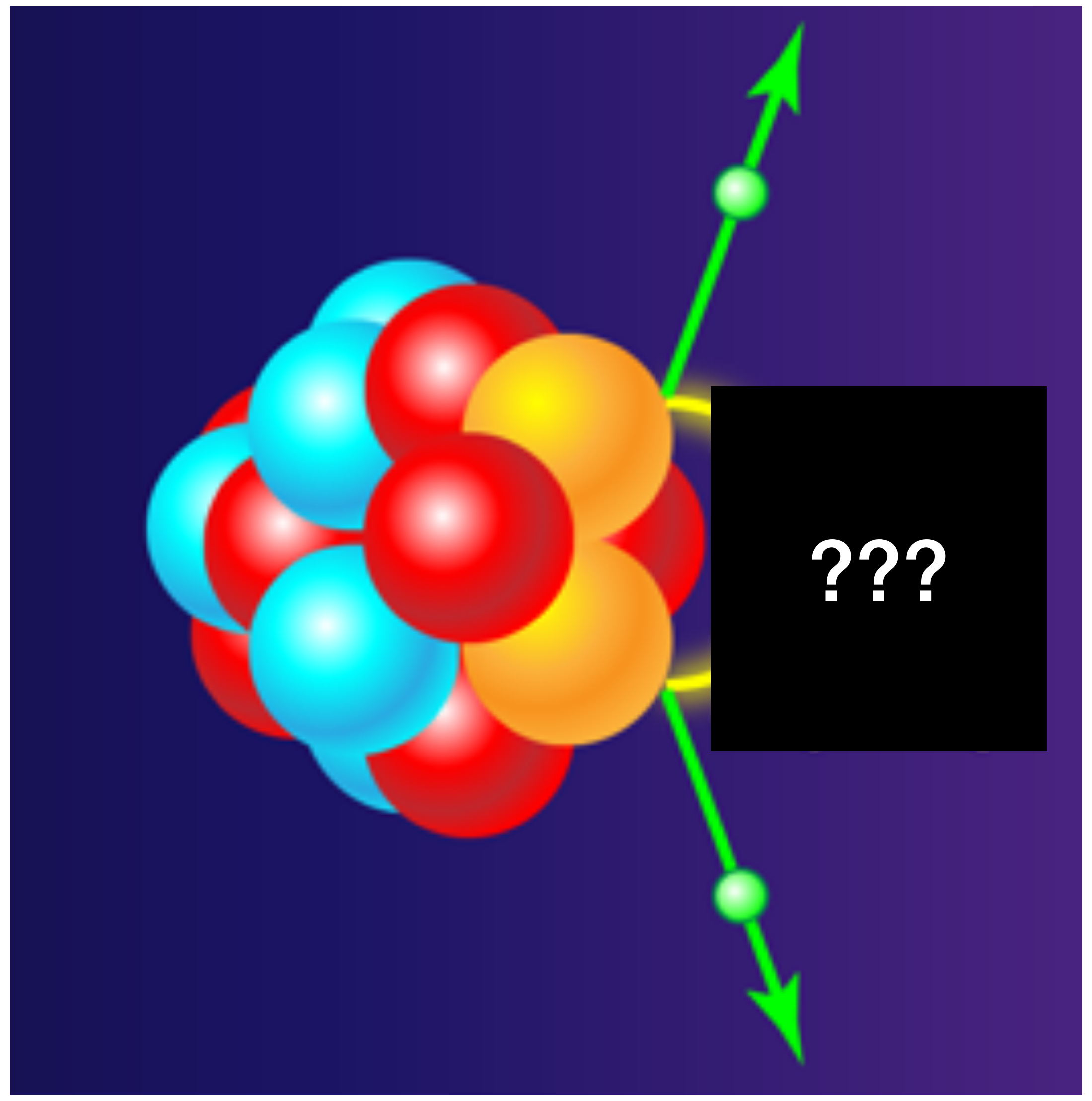
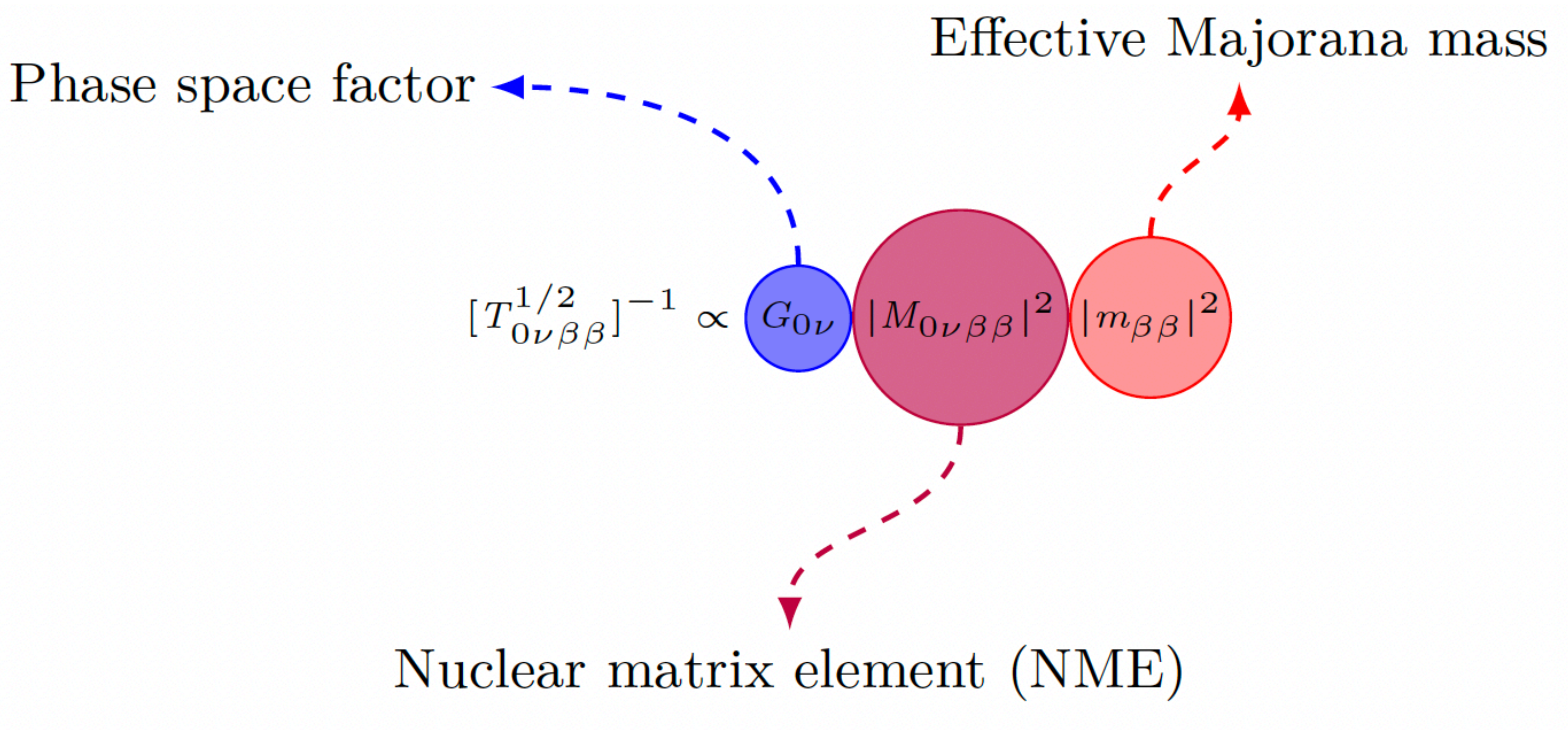
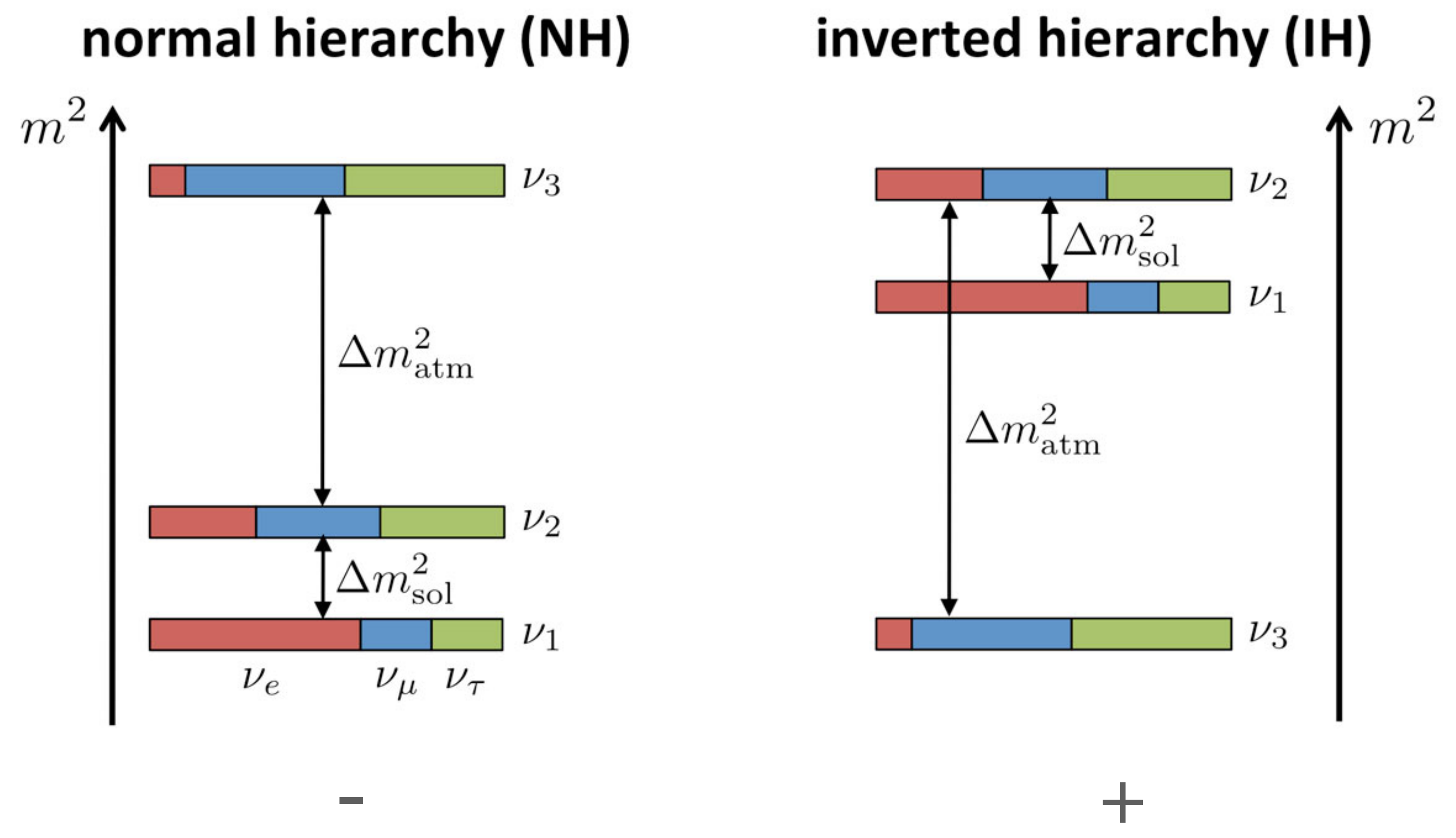


How is this connected to neutrino physics?

- Assuming exchange of light neutrinos
- $G_{0\nu}$: relatively easy to compute.
- $M_{0\nu\beta\beta}$: hard to calculate. Current calculations agree within a factor of 2-3.
- $m_{\beta\beta} = \sum_i (U_{ei})^2 m_i$: weighted sum of 3 neutrino flavors. We want to infer this!

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_1 e^{2i\alpha} + s_{12}^2 c_{13}^2 e^{2i\beta}\sqrt{m_1^2 + \Delta m_{12}^2} + s_{13}^2\sqrt{m_1^2 \pm |\Delta m_{23}^2|}$$





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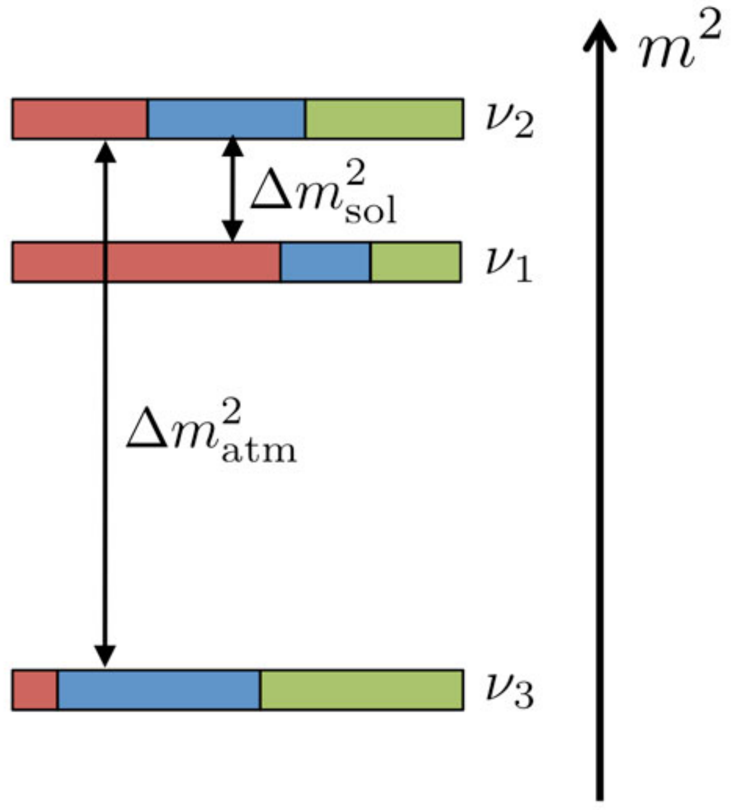
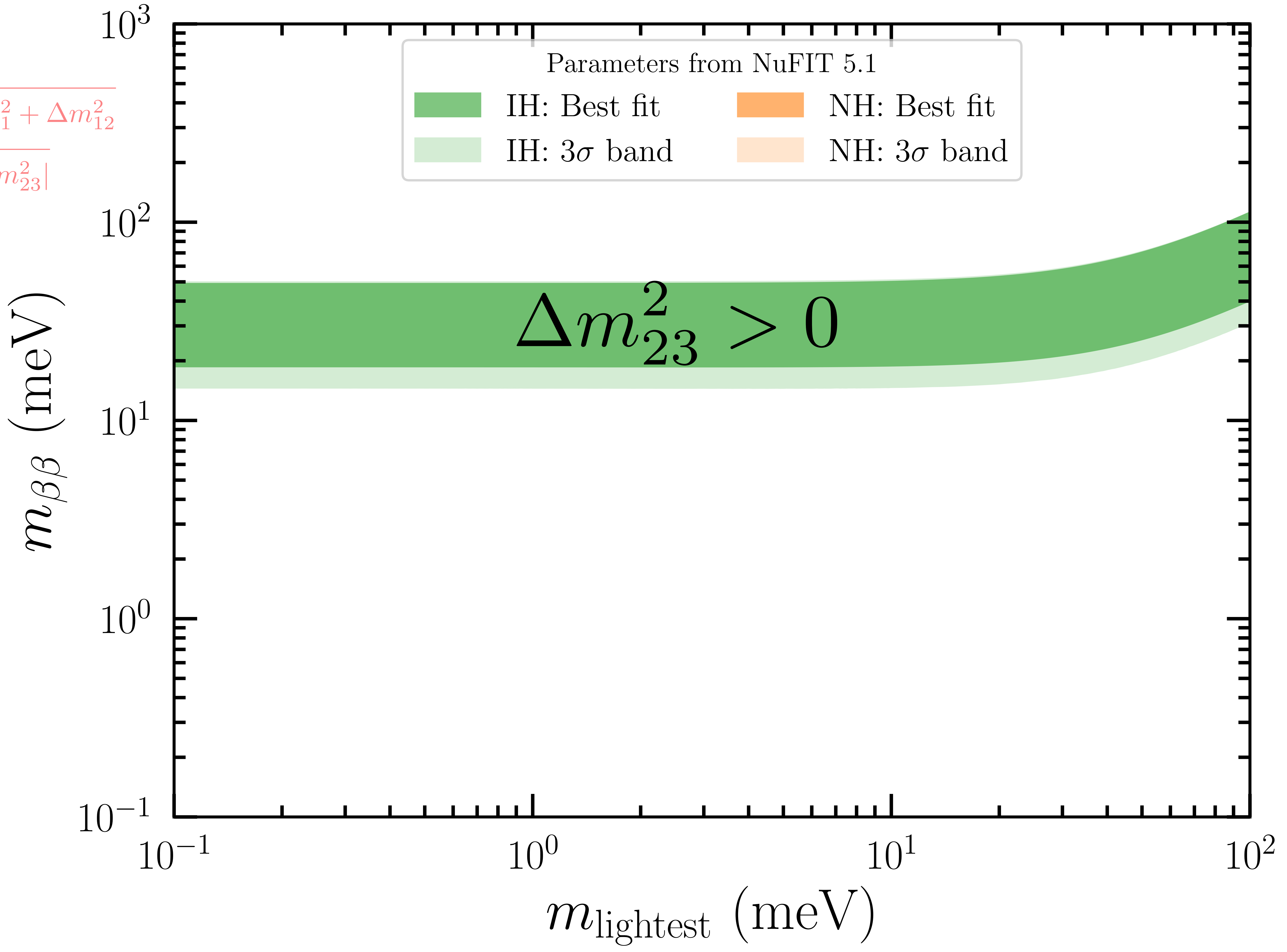
inverted hierarchy (IH)





"Islands" with discovery potential

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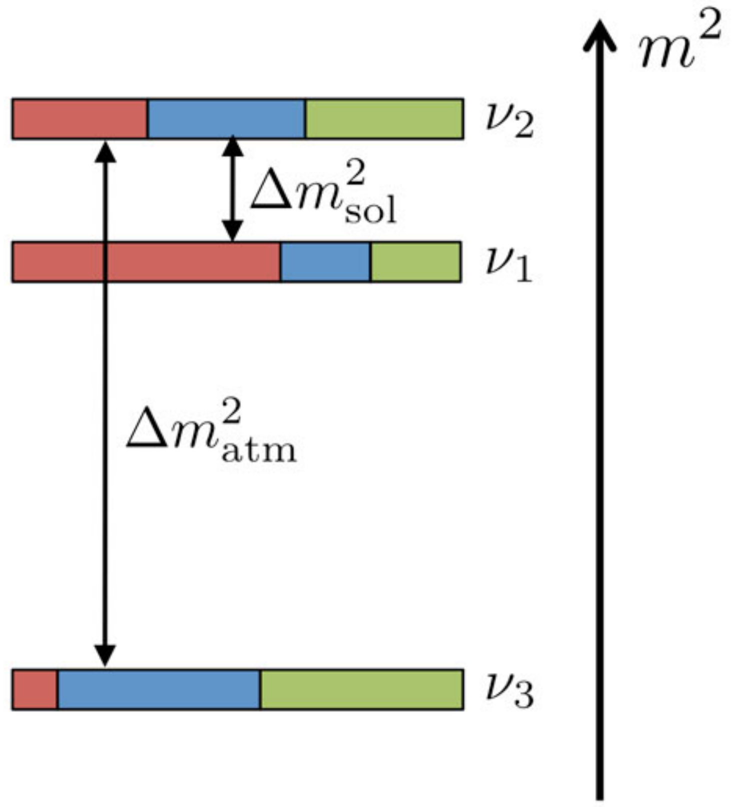

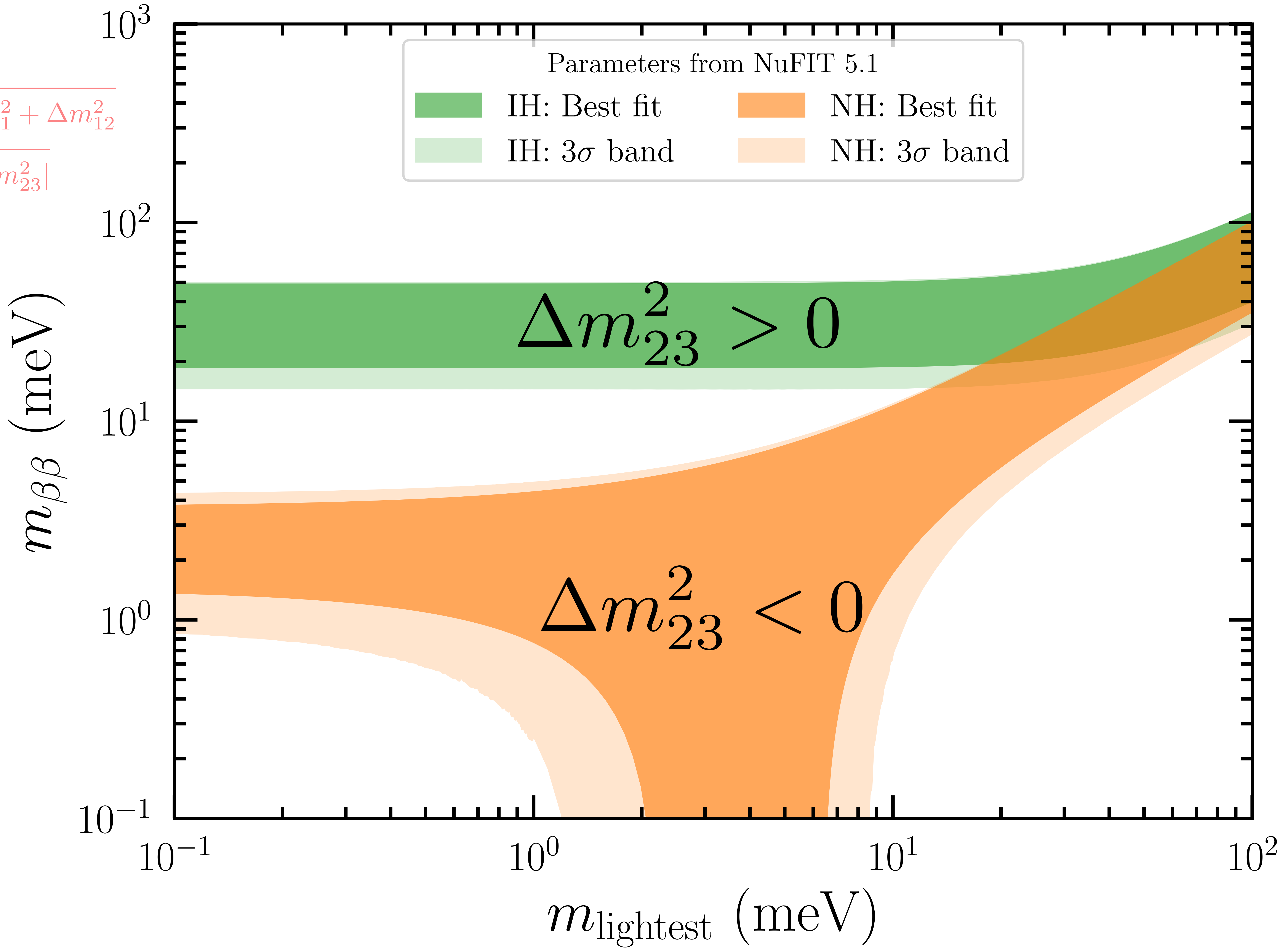

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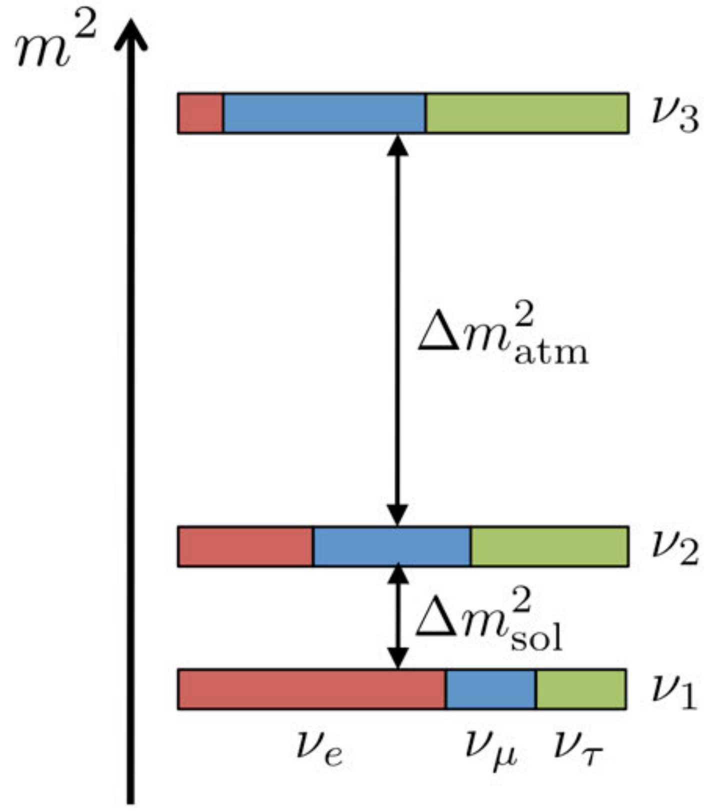
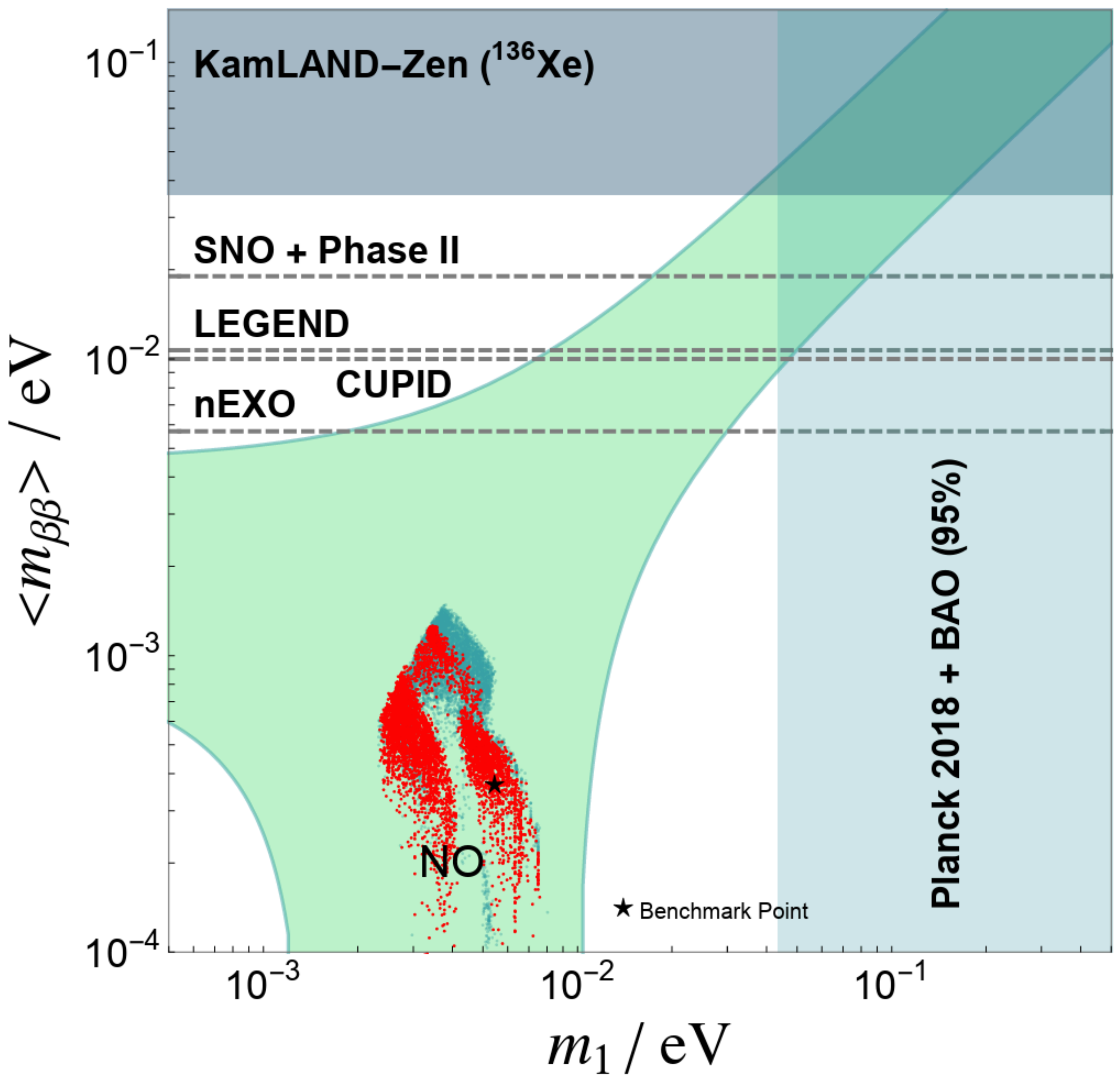


How to connect this to BSM theories?

- Your model has to predict a constraint/value of either or both:
  - Effective Majorana mass
  - Lightest neutrino mass
- The shape of the lobster plot could be changed by the addition of new neutrino species, e.g. sterile neutrinos.
- Shape distortion also could come from e.g.:
  - left-right symmetric models (JHEP 10 (2015) 077)
  - Additional higher-dim operators (JHEP (2017) 82)
- Models can be ruled out as experiments take more data.



Bonilla et al, JHEP 06 (2023) 078

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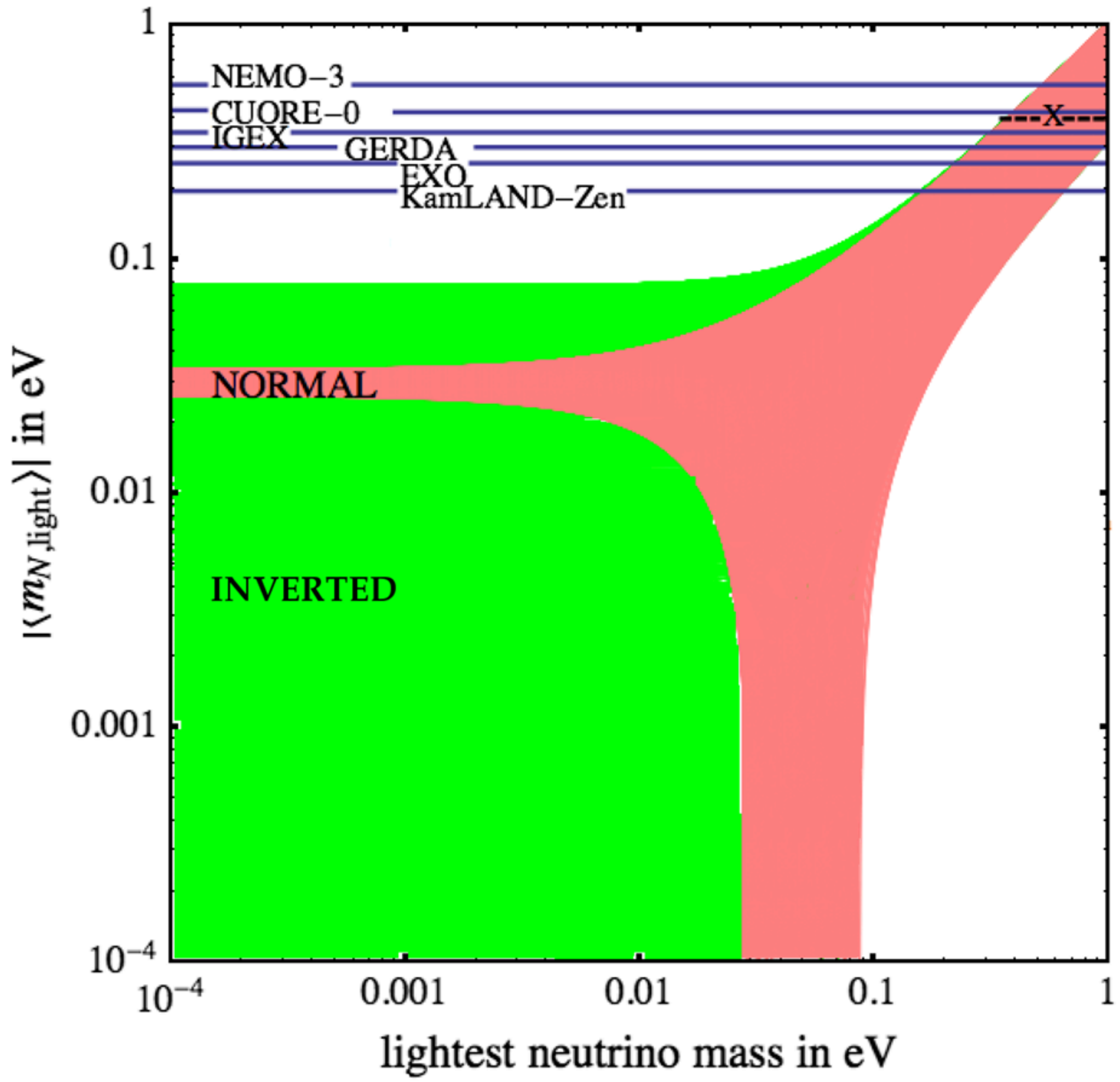
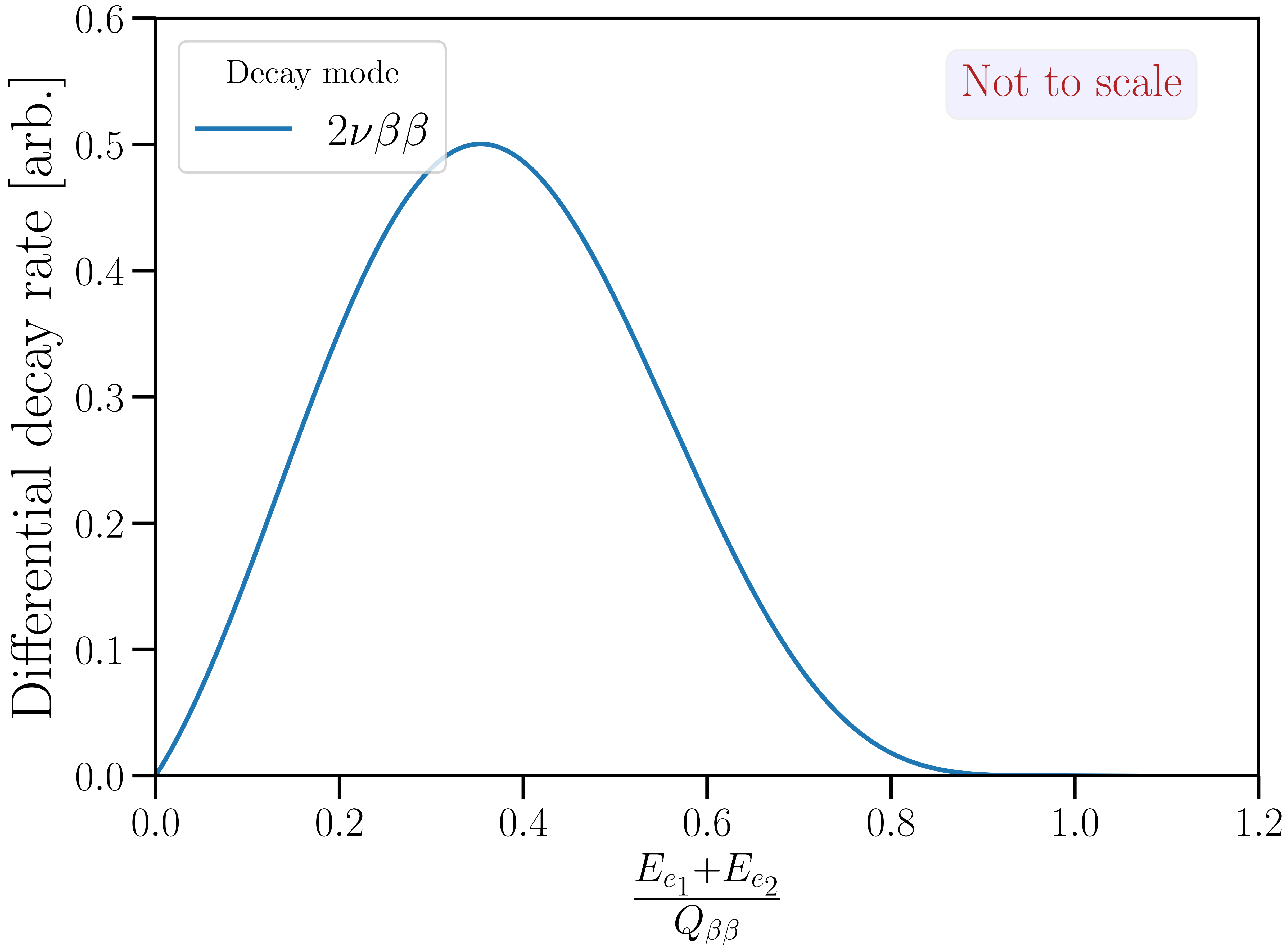


Barea et al, Phys. Rev. D **92**, 093001 (2015)

Experimental signature

- $2\nu\beta\beta$ decay produces a distribution due to shared energies of decay products.
- $0\nu\beta\beta$ decay will produce a peak at E=$Q_{\beta\beta}$ ("q-value", available kinetic energy)
- The width of the peak will be determined by the energy resolution of the detector.
- Good resolution needed to reject $2\nu\beta\beta$ decay events.
- Measure/constraint half-life of process: $T^{1/2}_{0\nu}$, infer neutrino physics.



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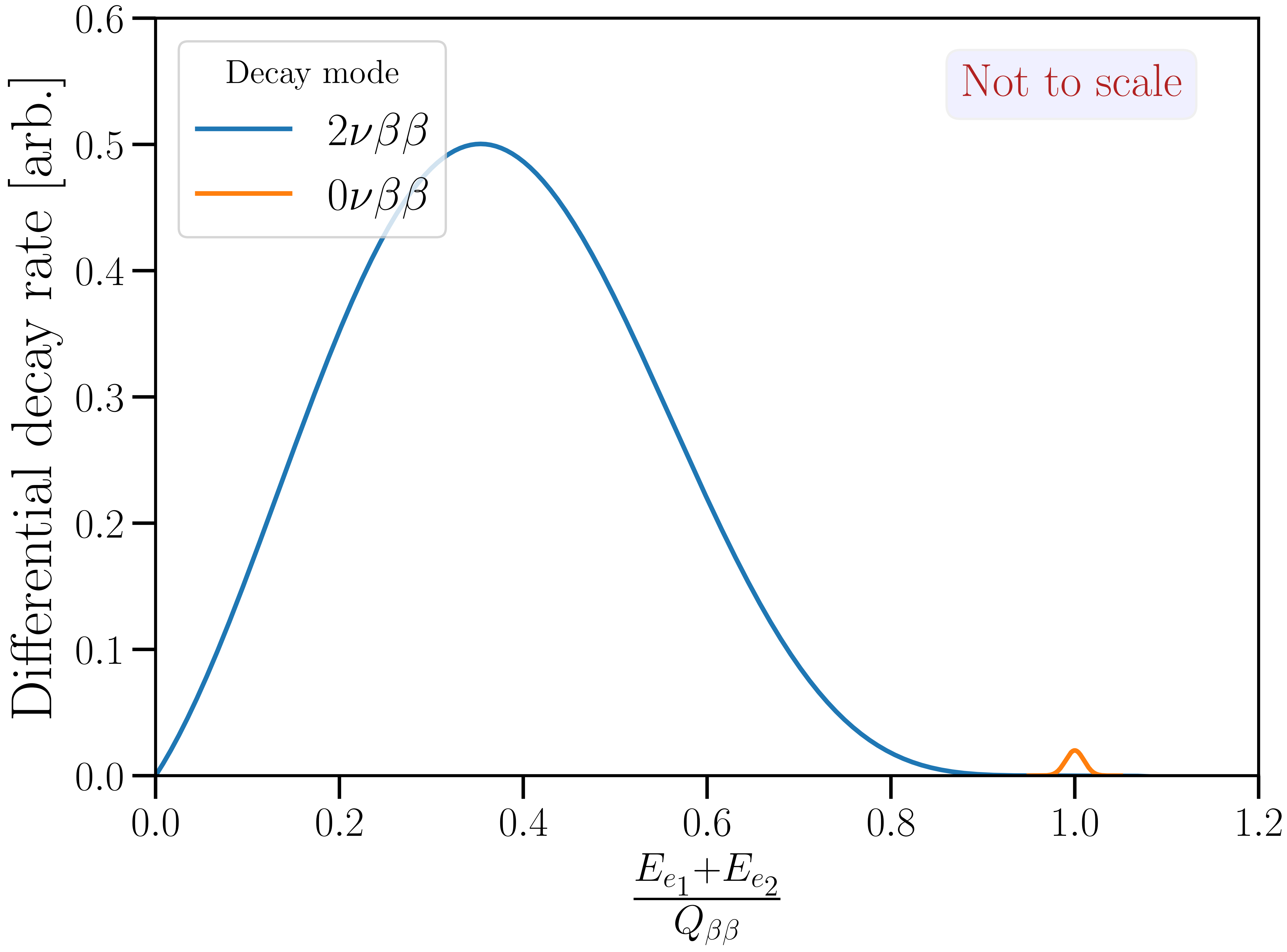

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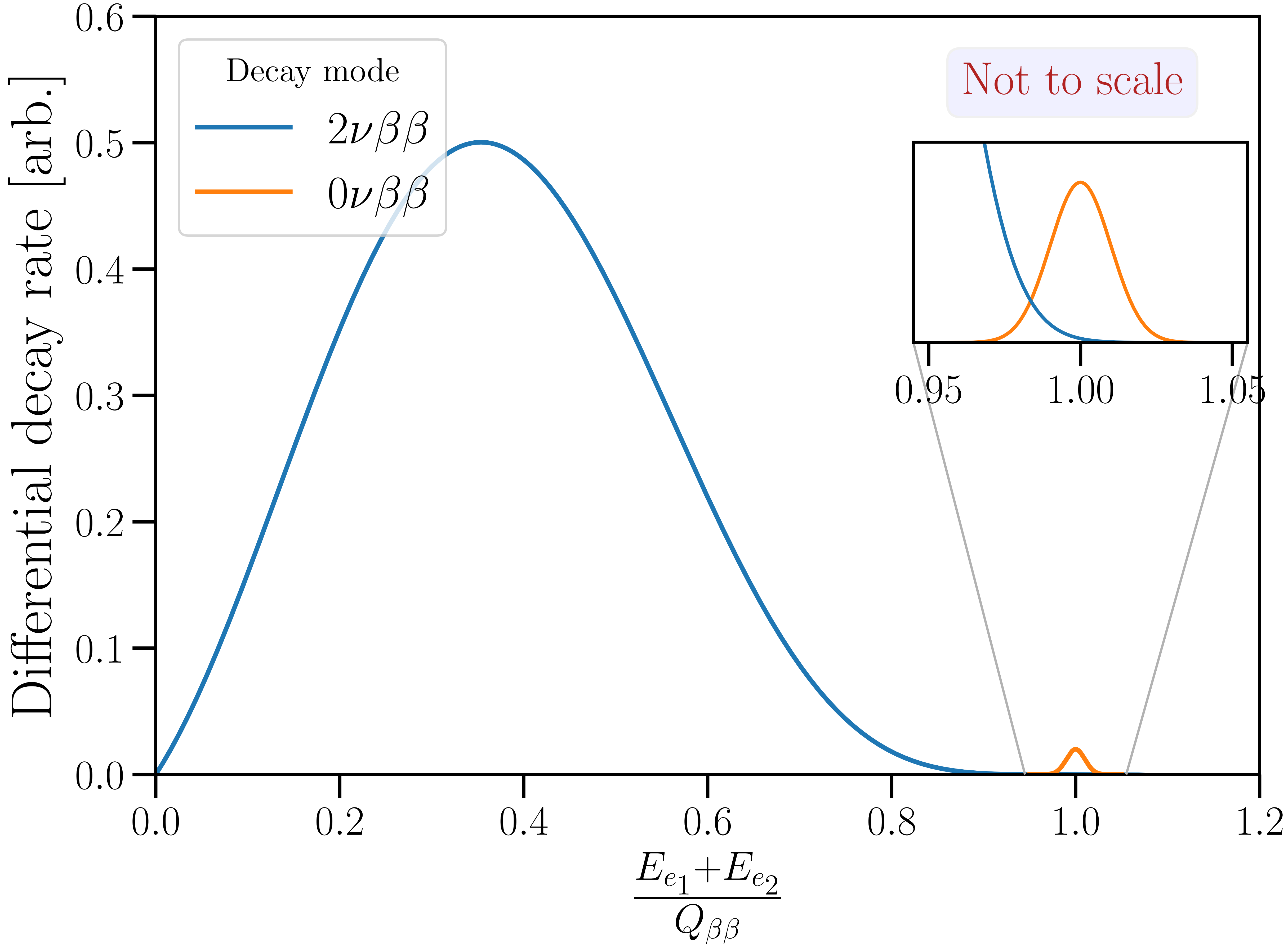

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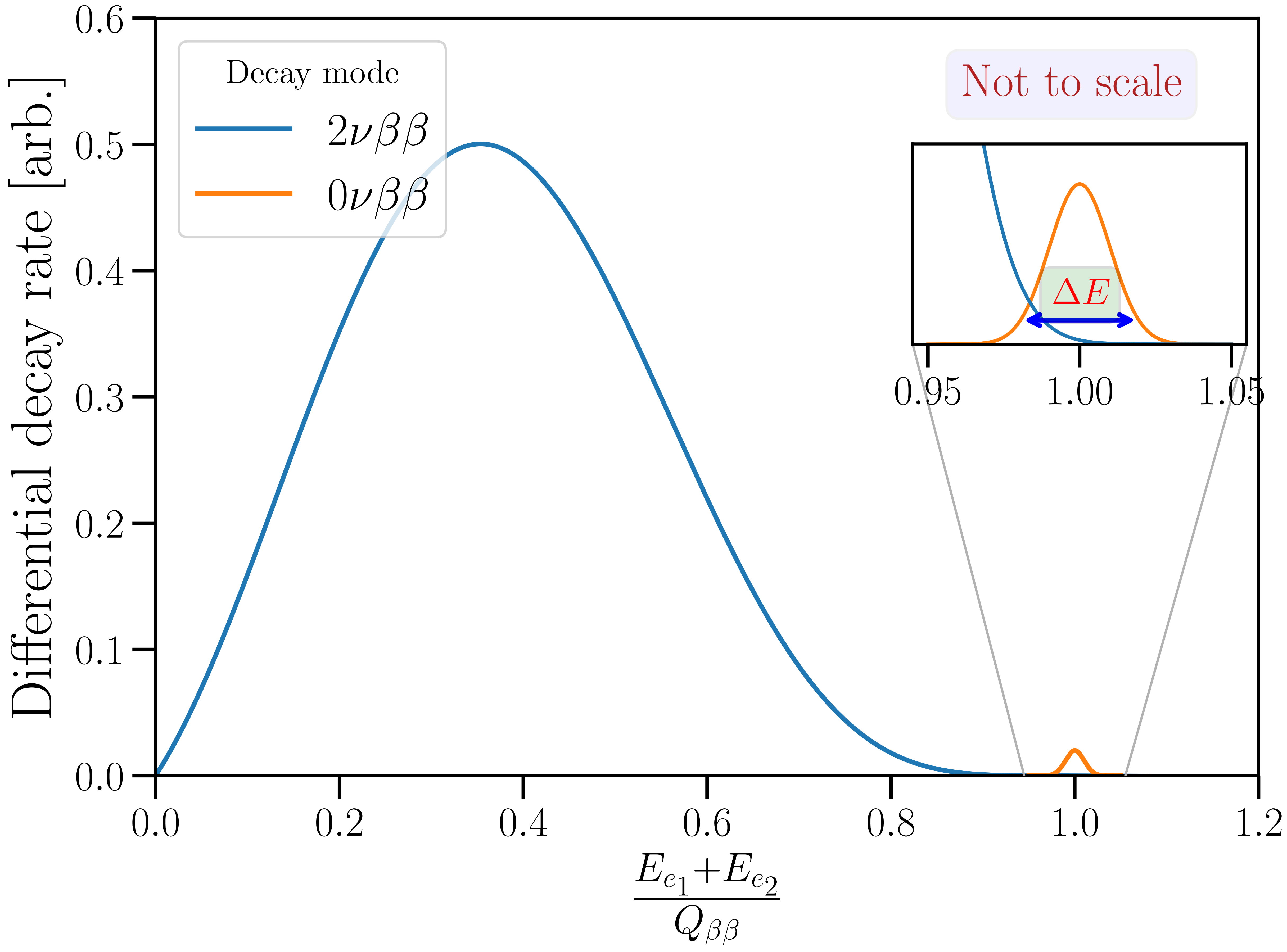
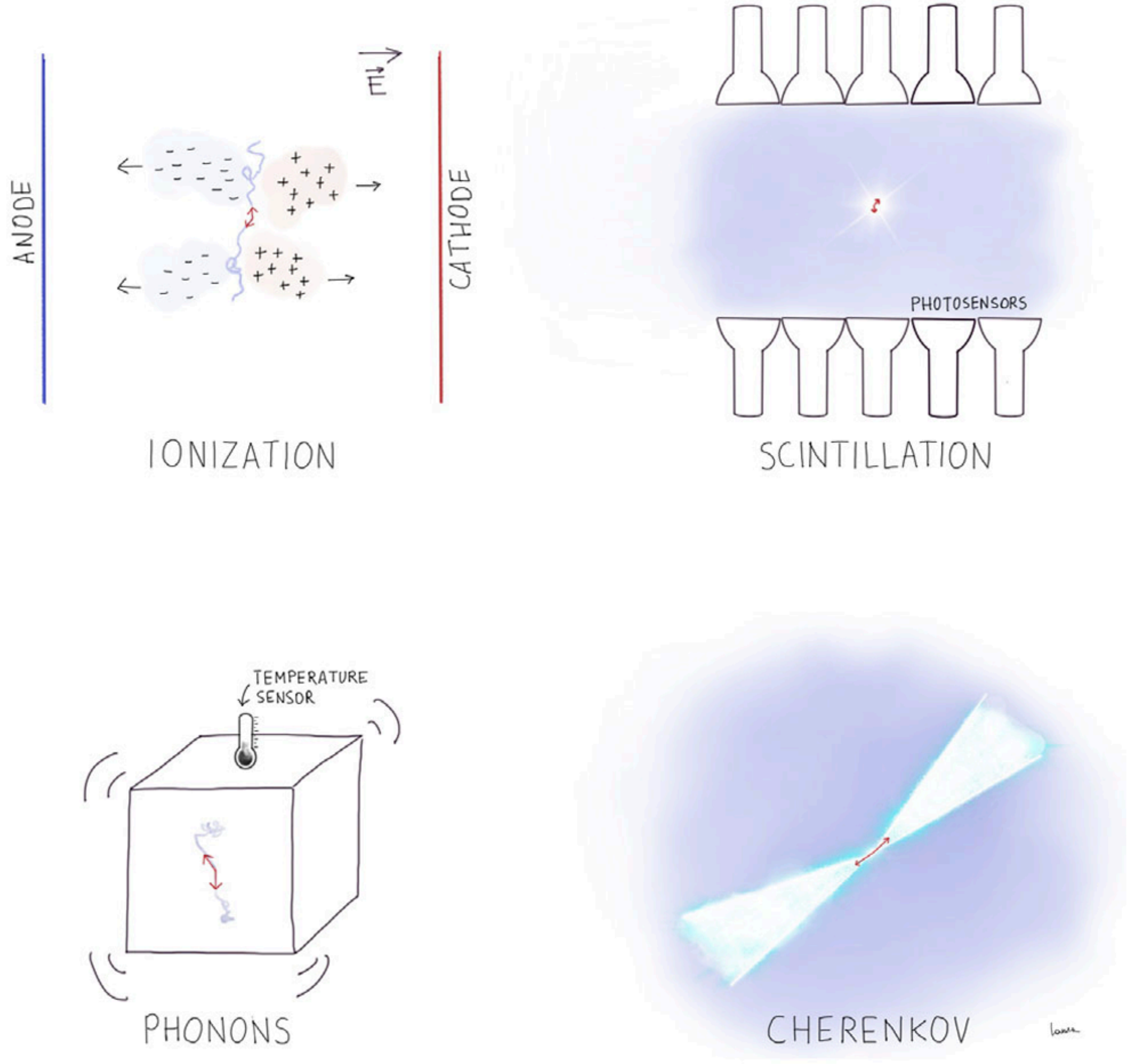


How to build a $0\nu\beta\beta$ decay experiment: detection method

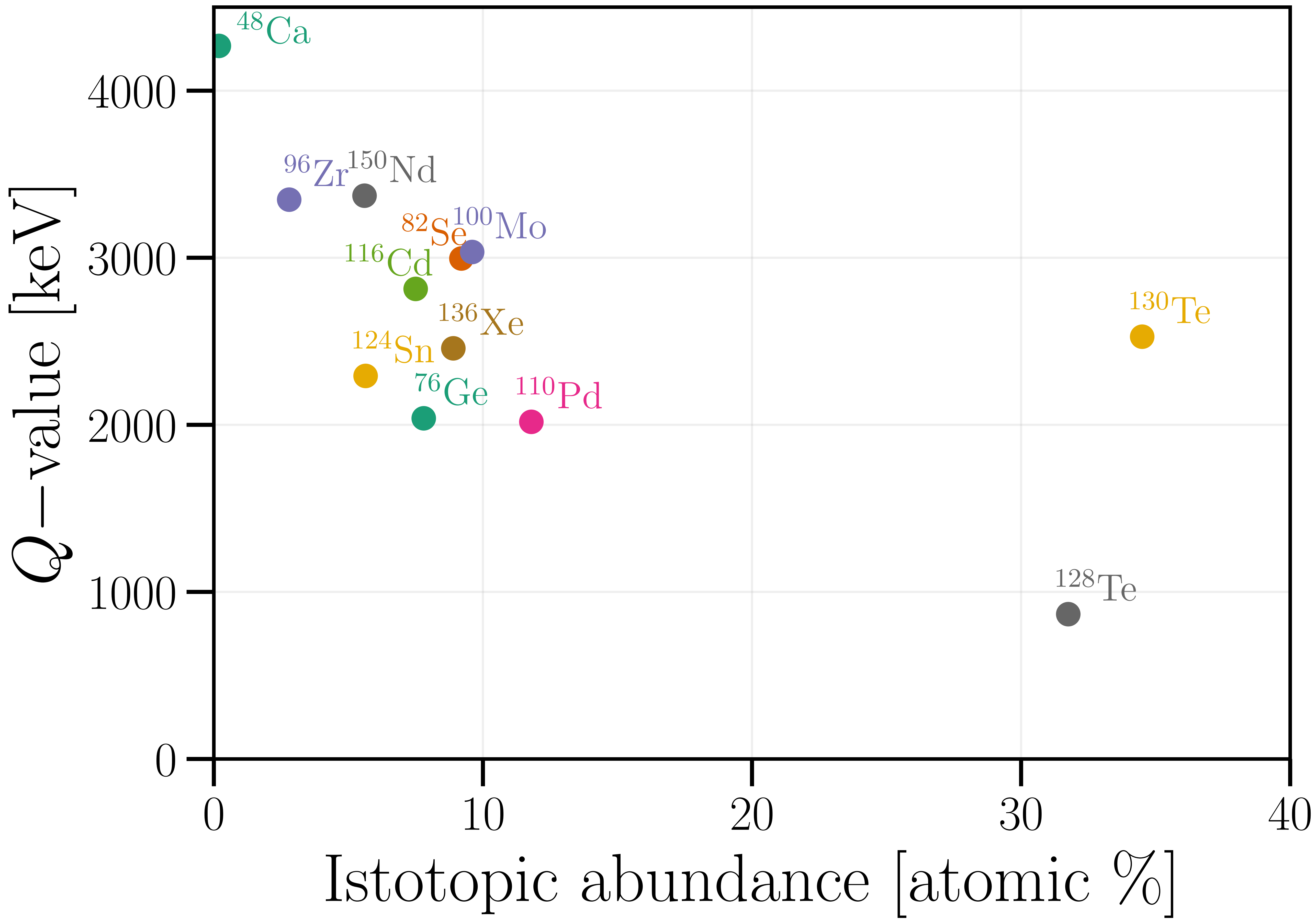
- Goal: reconstruct energy with good resolution while rejecting most backgrounds.
- Different methods with different advantages/disadvantages:
  - Scalability.
  - Energy resolution
  - Topology reconstruction for particle ID
- Some experiments use more than one method



L. Maneti, from Agostini et al., Rev. Mod. Phys. 95 (2023)

How to build a $0\nu\beta\beta$ decay experiment: isotope choice

- Preferably an isotope with high natural abundance
- Higher $Q_{\beta\beta}$ is better:
  - Less β/γ bkgs from natural radioactivity
  - $2\nu\beta\beta$ rate suppressed as $\sim \frac{1}{Q_{\beta\beta}^5}$
- Isotope can be incorporated into a material that can also serve as the detection medium.



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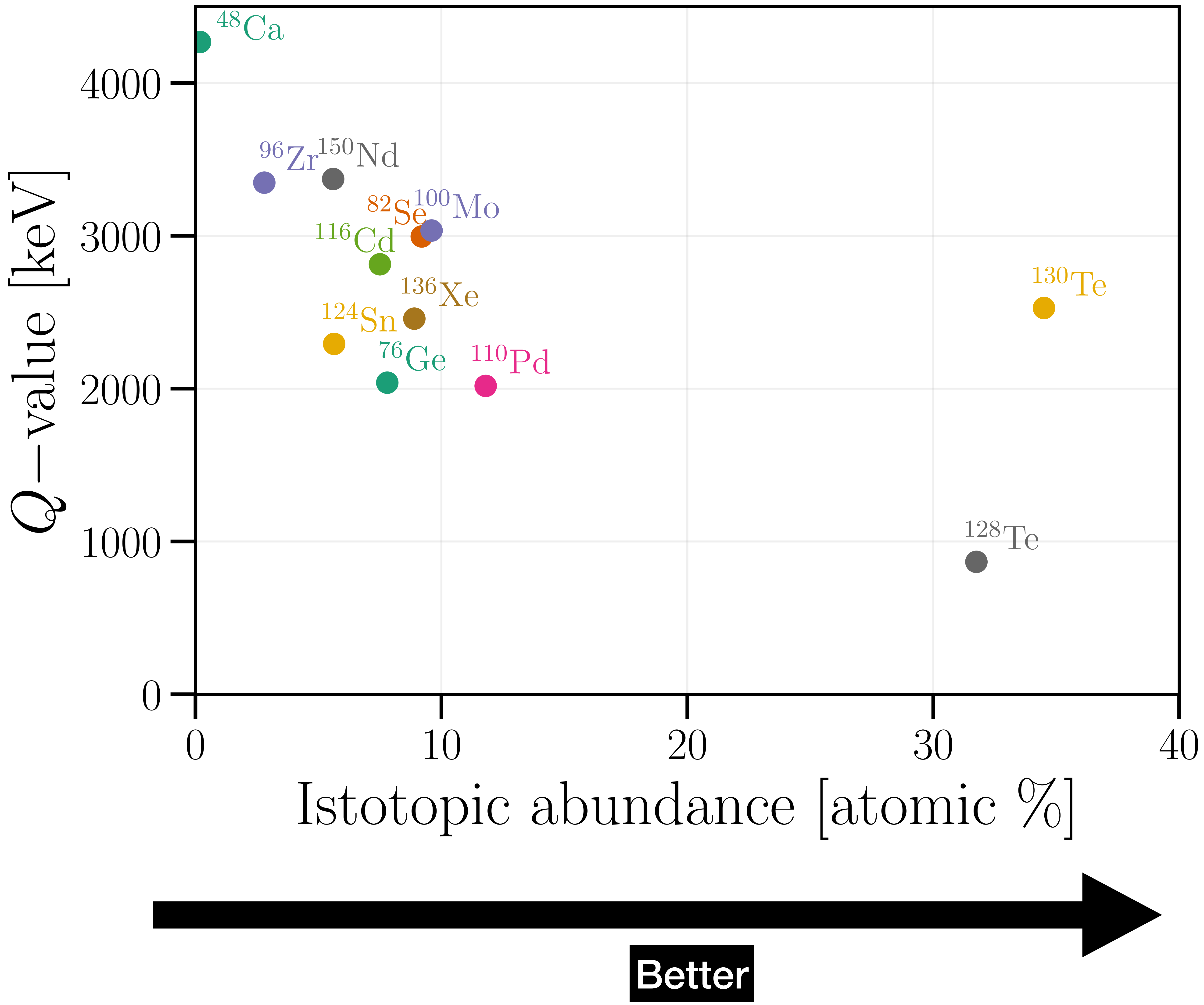

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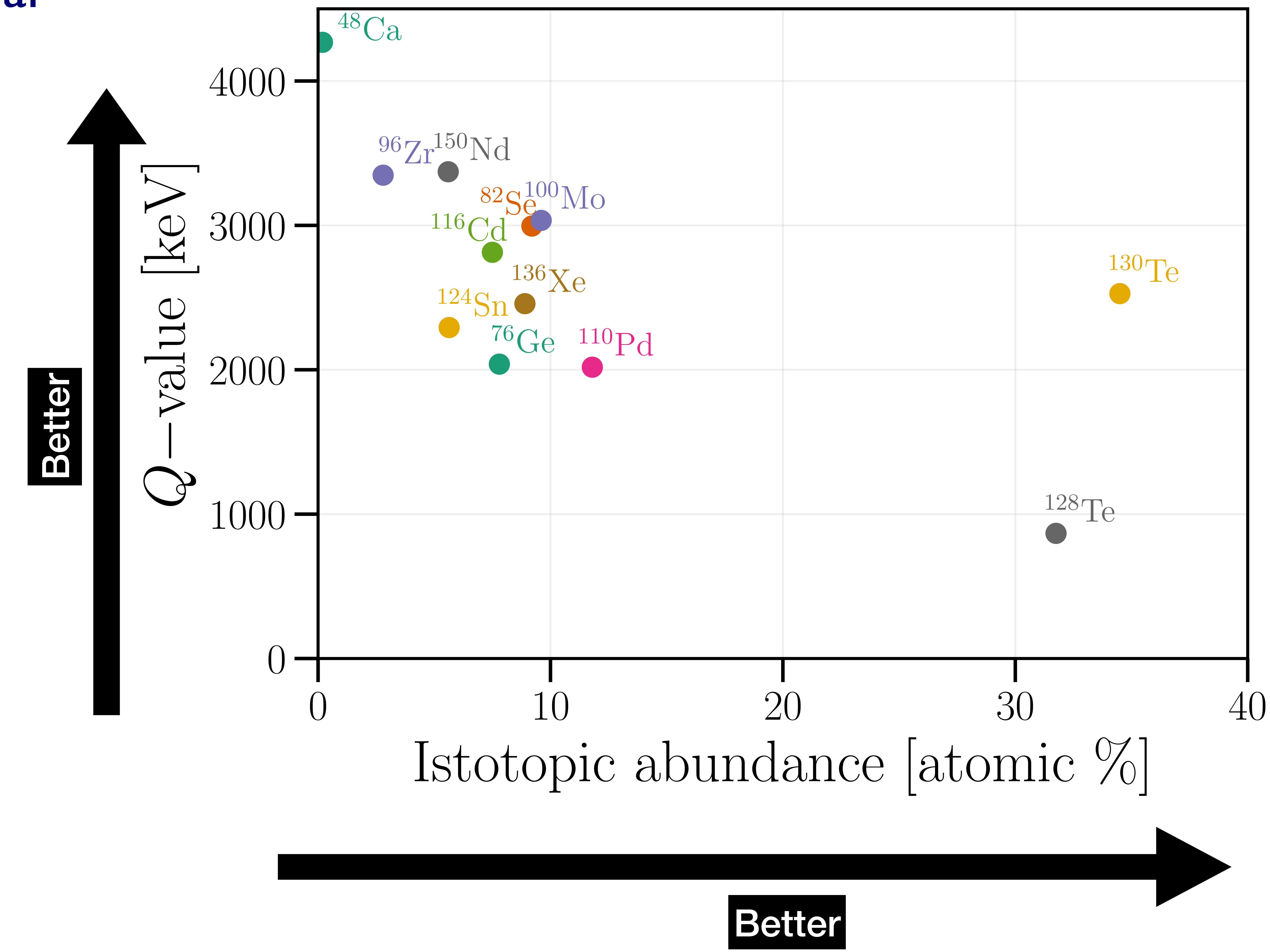

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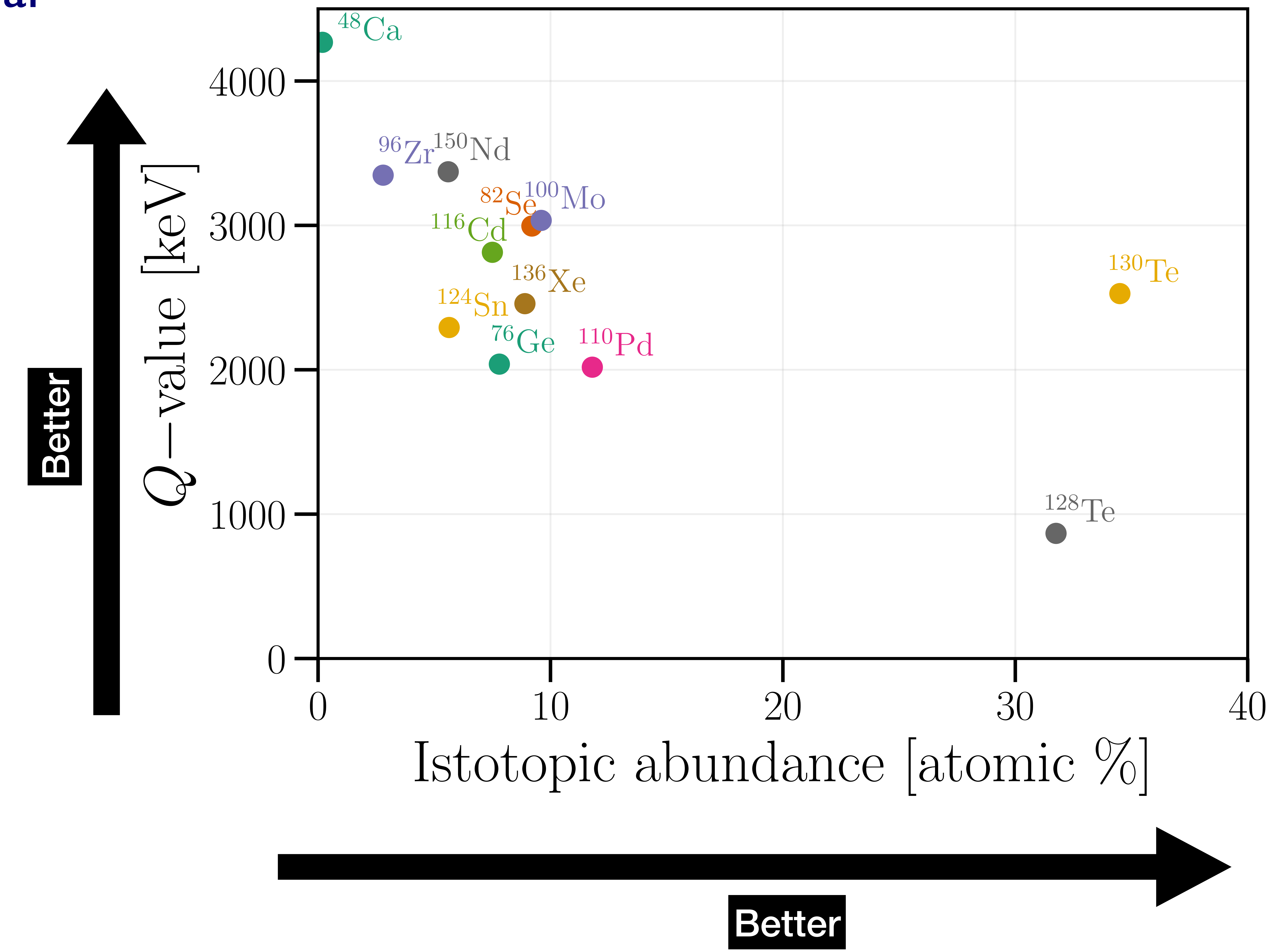
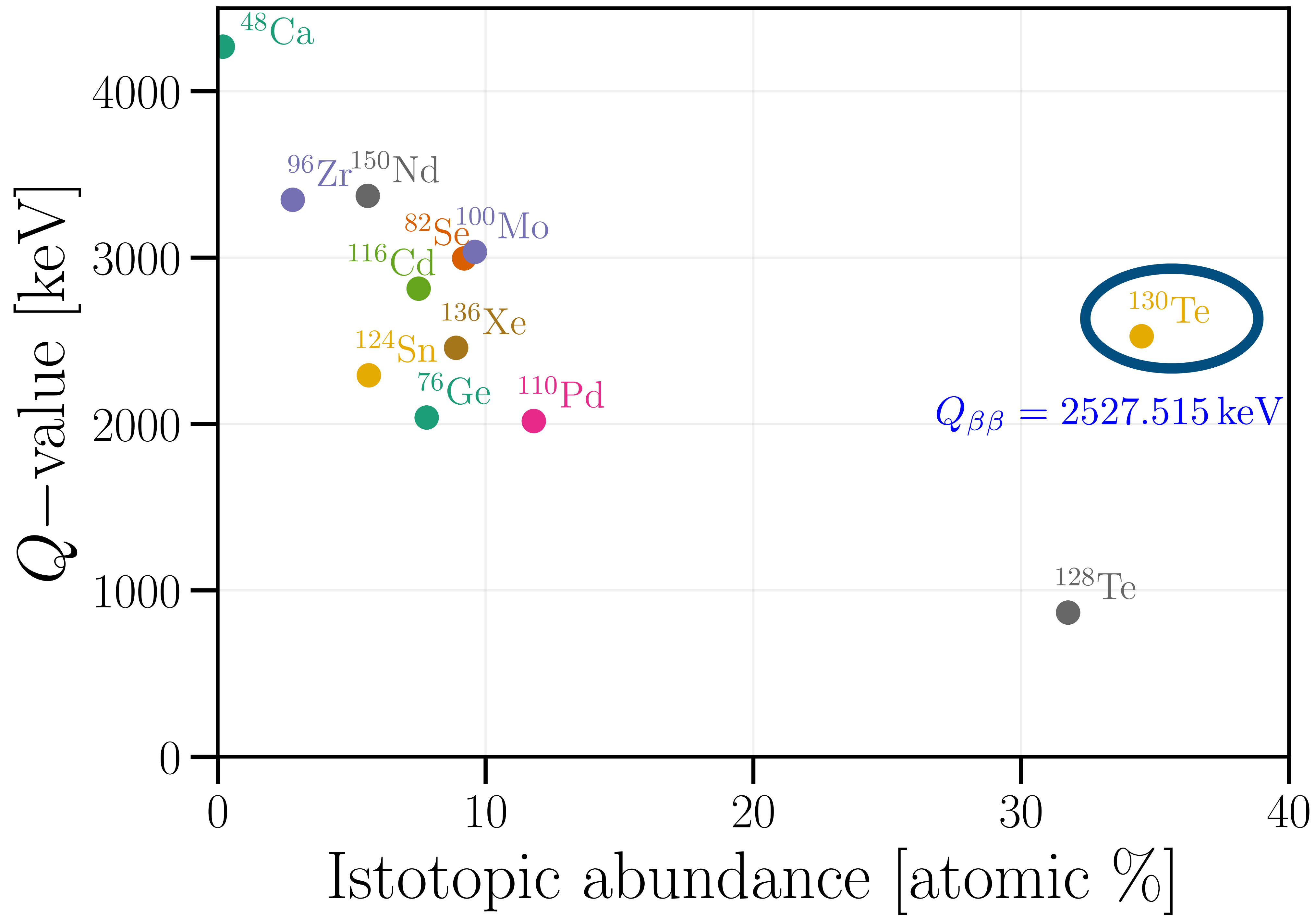
CUORE



Cryogenic Underground Observatory for Rare Events (CUORE)



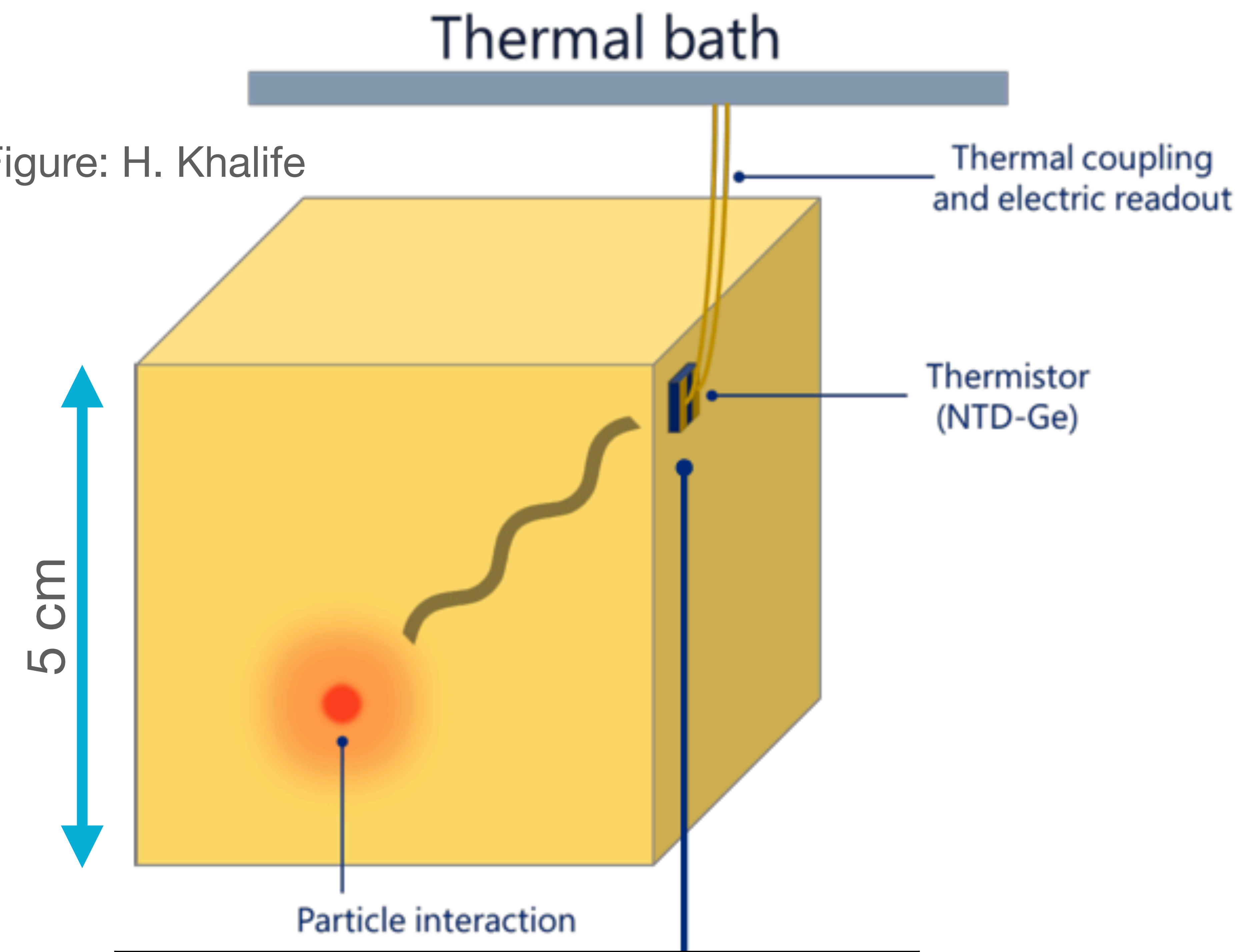
- First milli-K cryo-calorimeter $0\nu\beta\beta$ decay experiment reaching one-tonne scale.
- CUORE is located in Hall A of LNGS.
- ~3600 m.w.e of overburden—> muon flux reduced by ~6 orders of magnitude

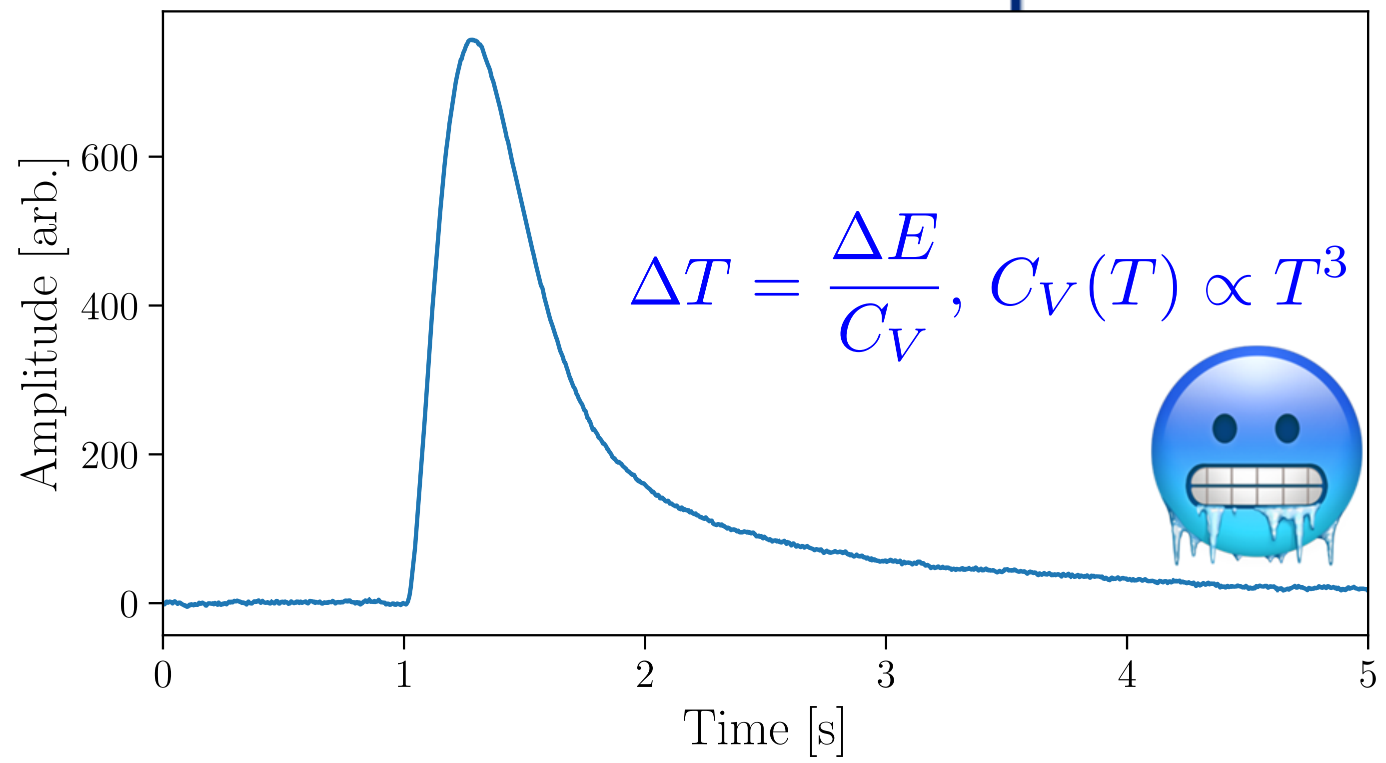
- Search for $0\nu\beta\beta$ in ^{130}Te (TeO_2 crystals).
- High natural abundance, adequate $Q_{\beta\beta}$ (~2.5 MeV)

CUORE's operation principle

CUORE bolometer

Figure: H. Khalife





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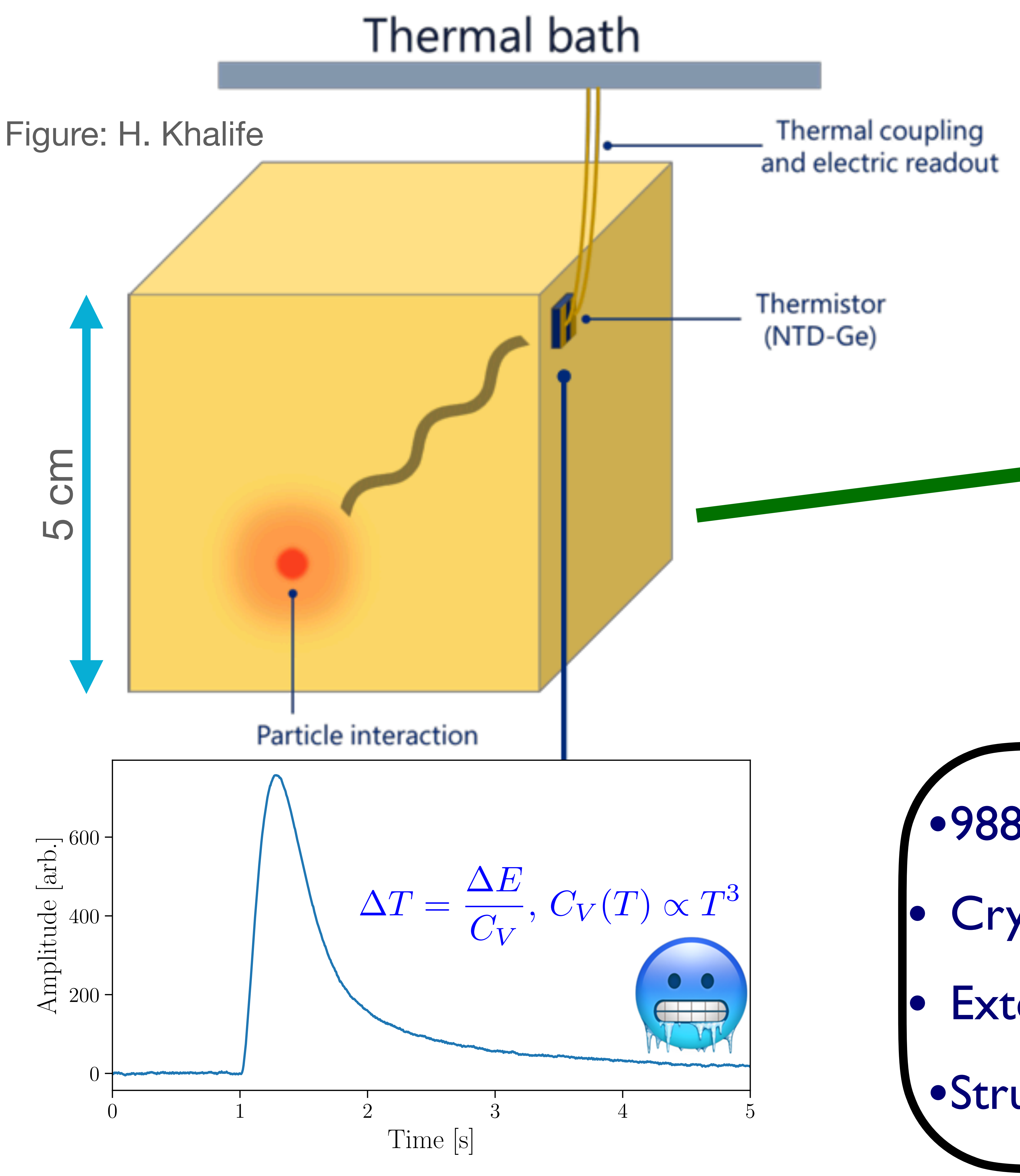

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- Cryostat cools detectors at ~10 mK
- External and internal shields to reduce backgrounds
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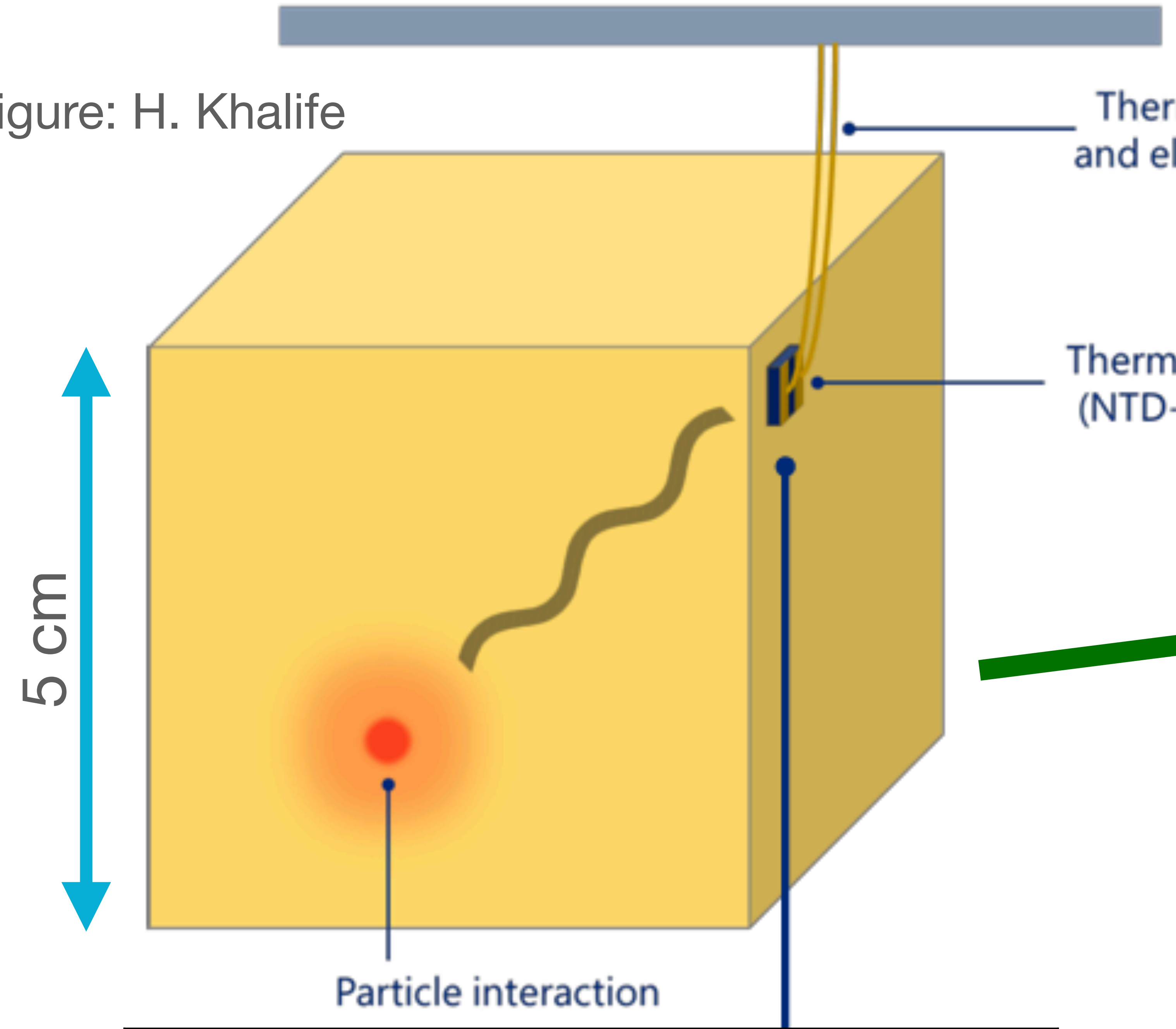

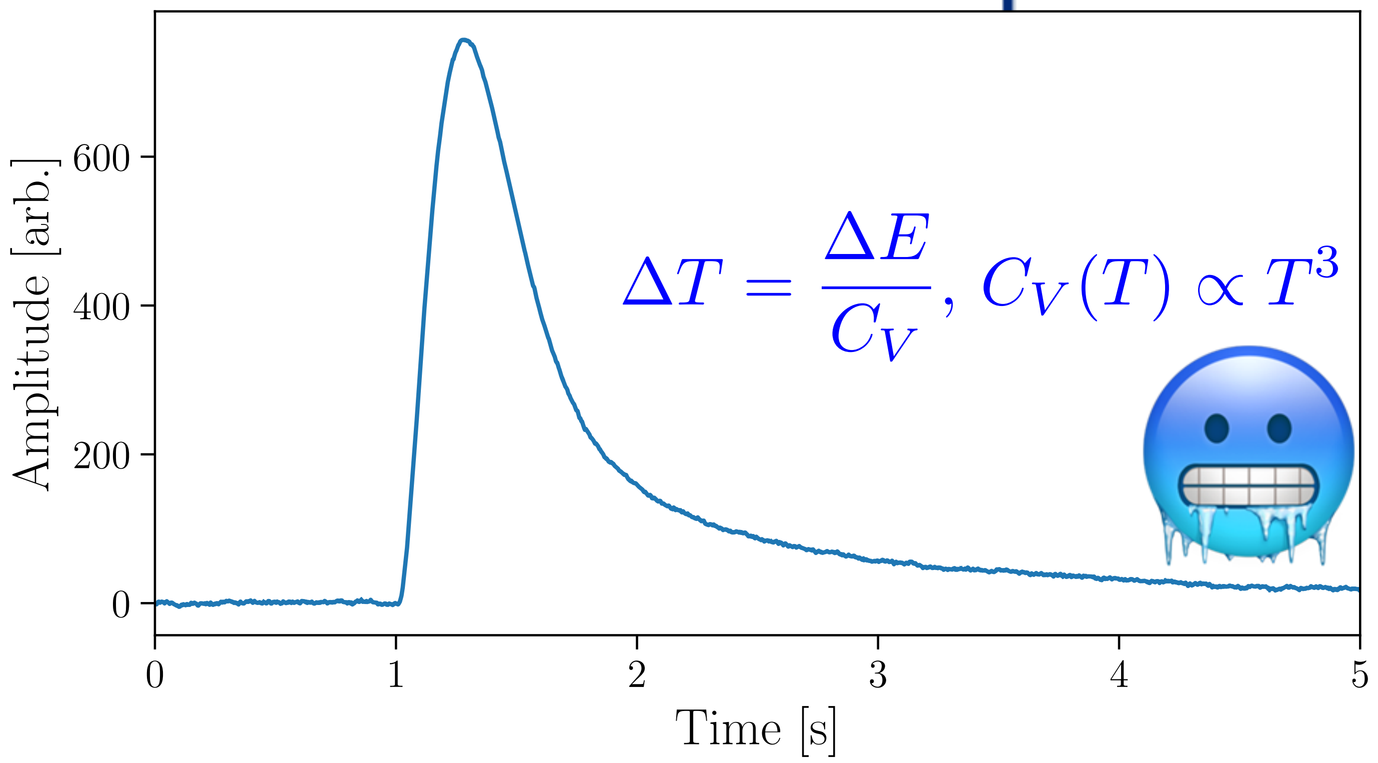

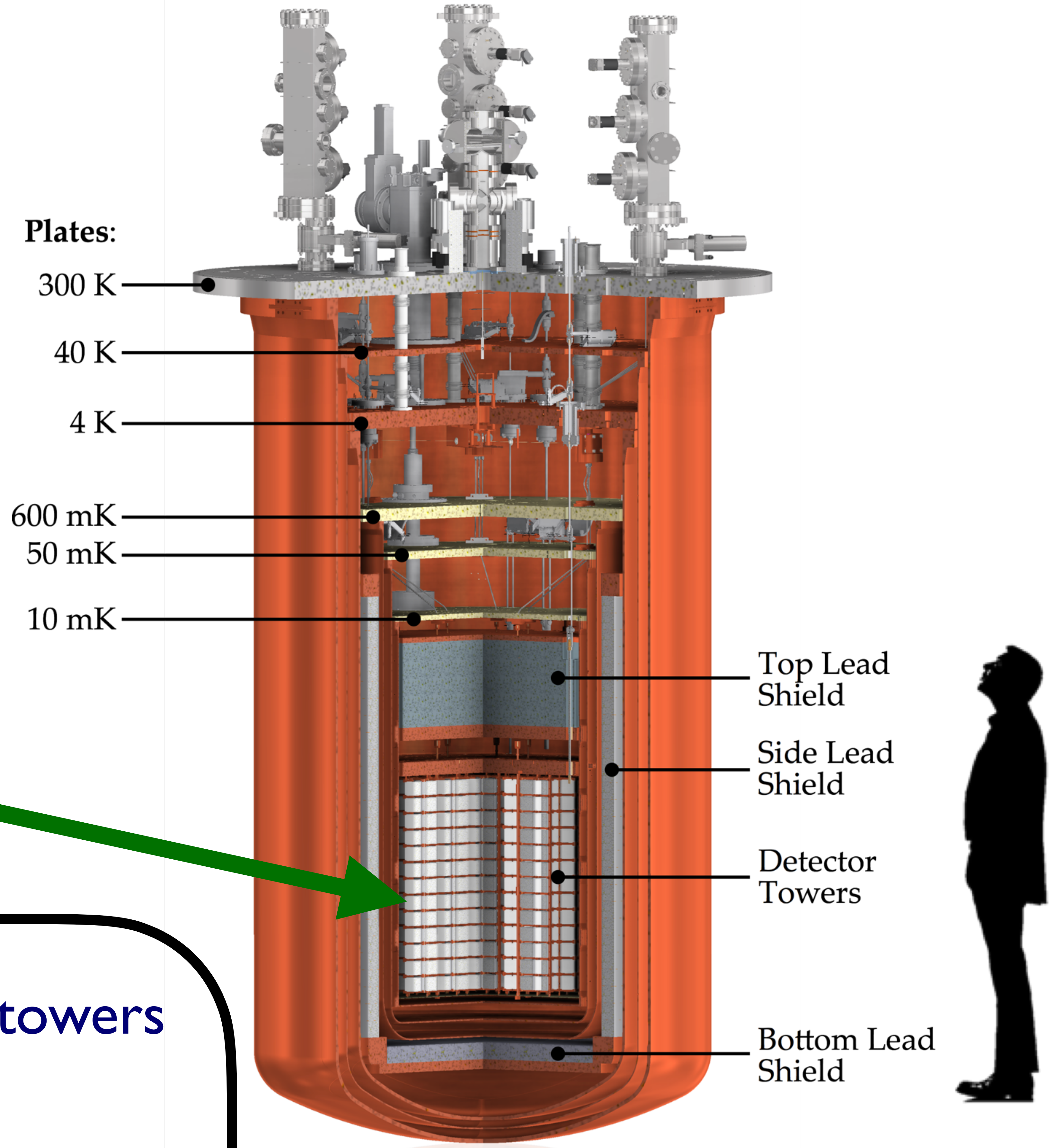

J. Phys.: Conf. Ser. **969** 012087

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- Steady collection since 2019 @ ~50 kg·yr per month
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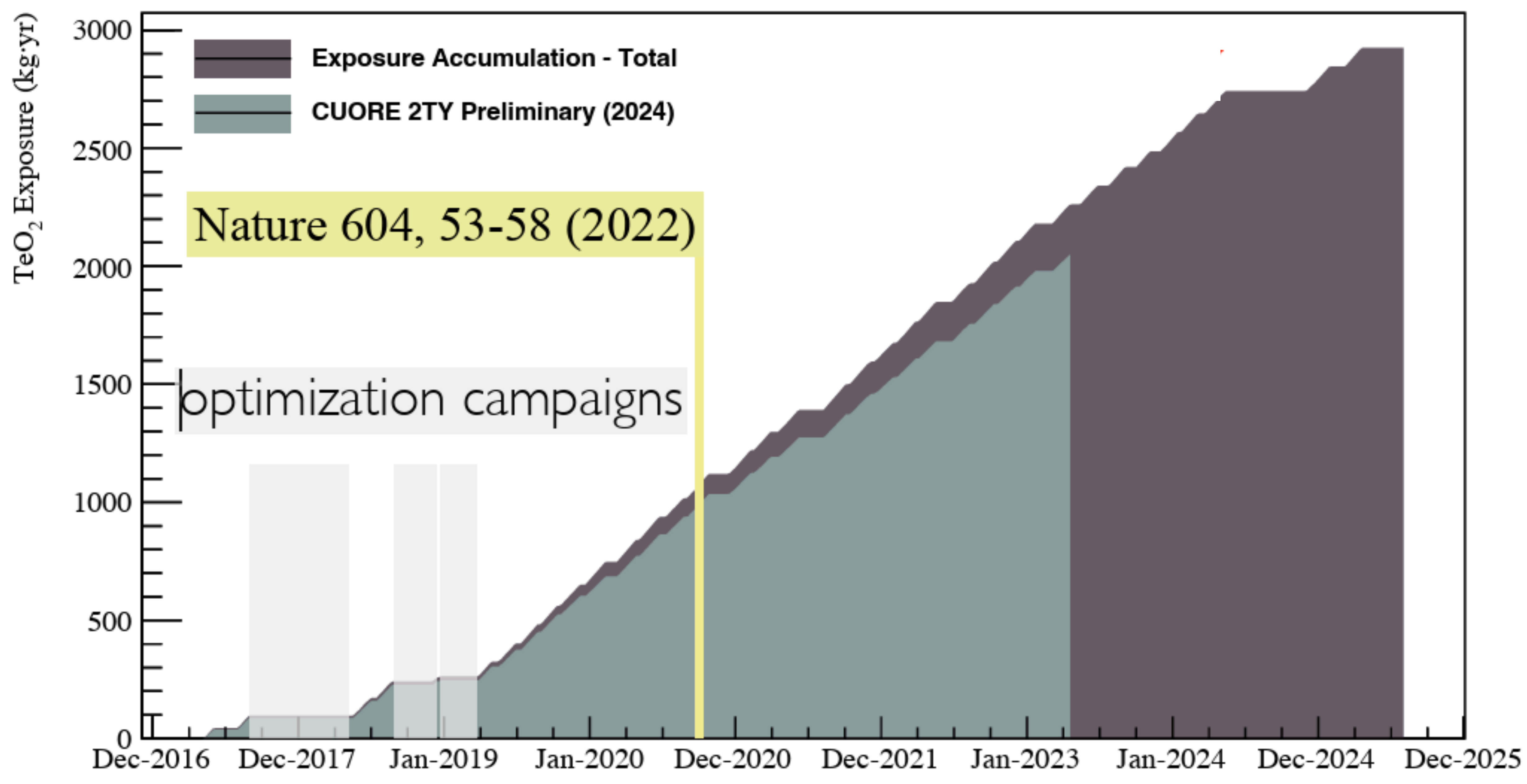
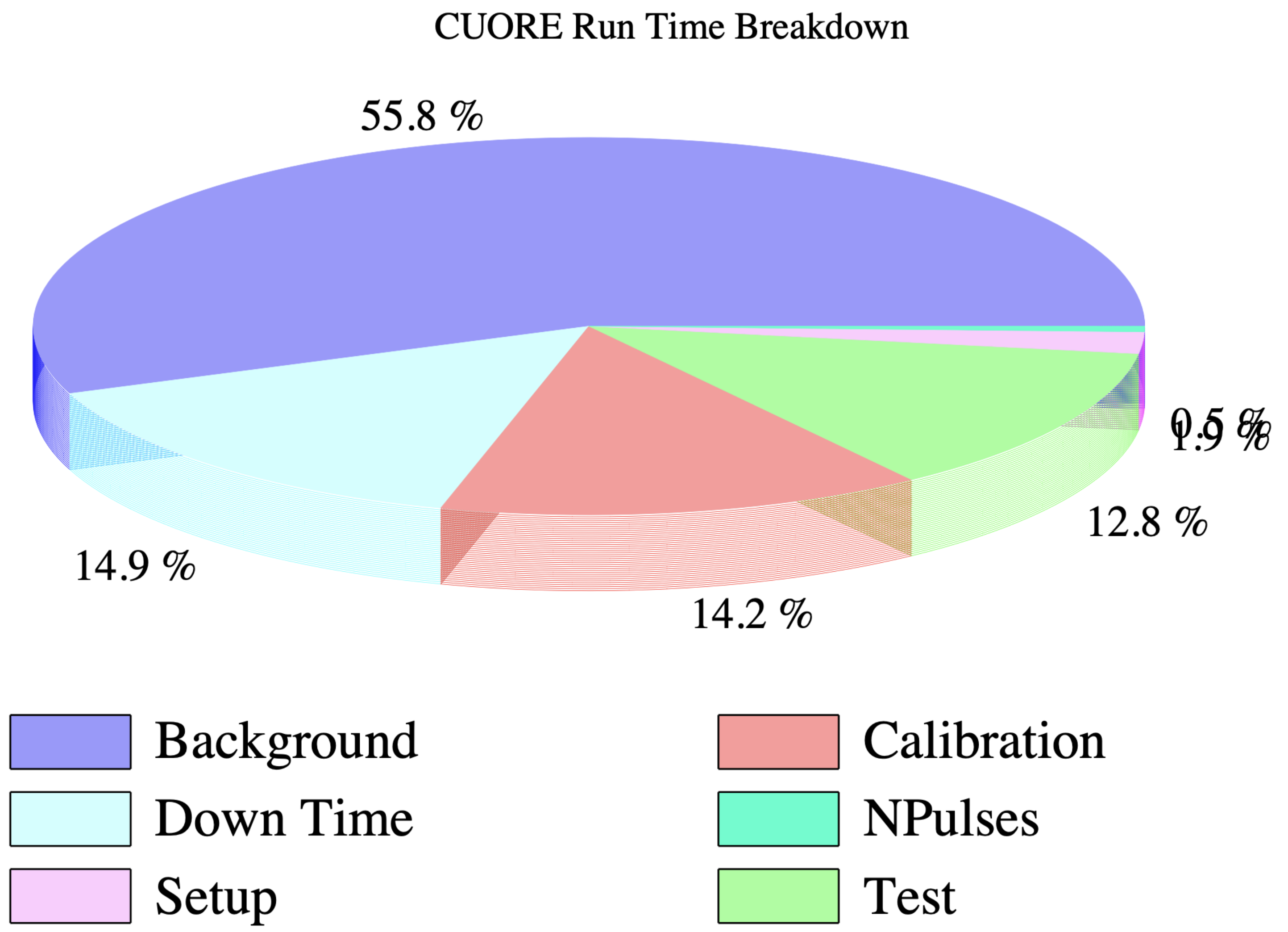
- Goal: 3 tonne-yr of TeO_2 (~1 tonne-yr of ^{130}Te)





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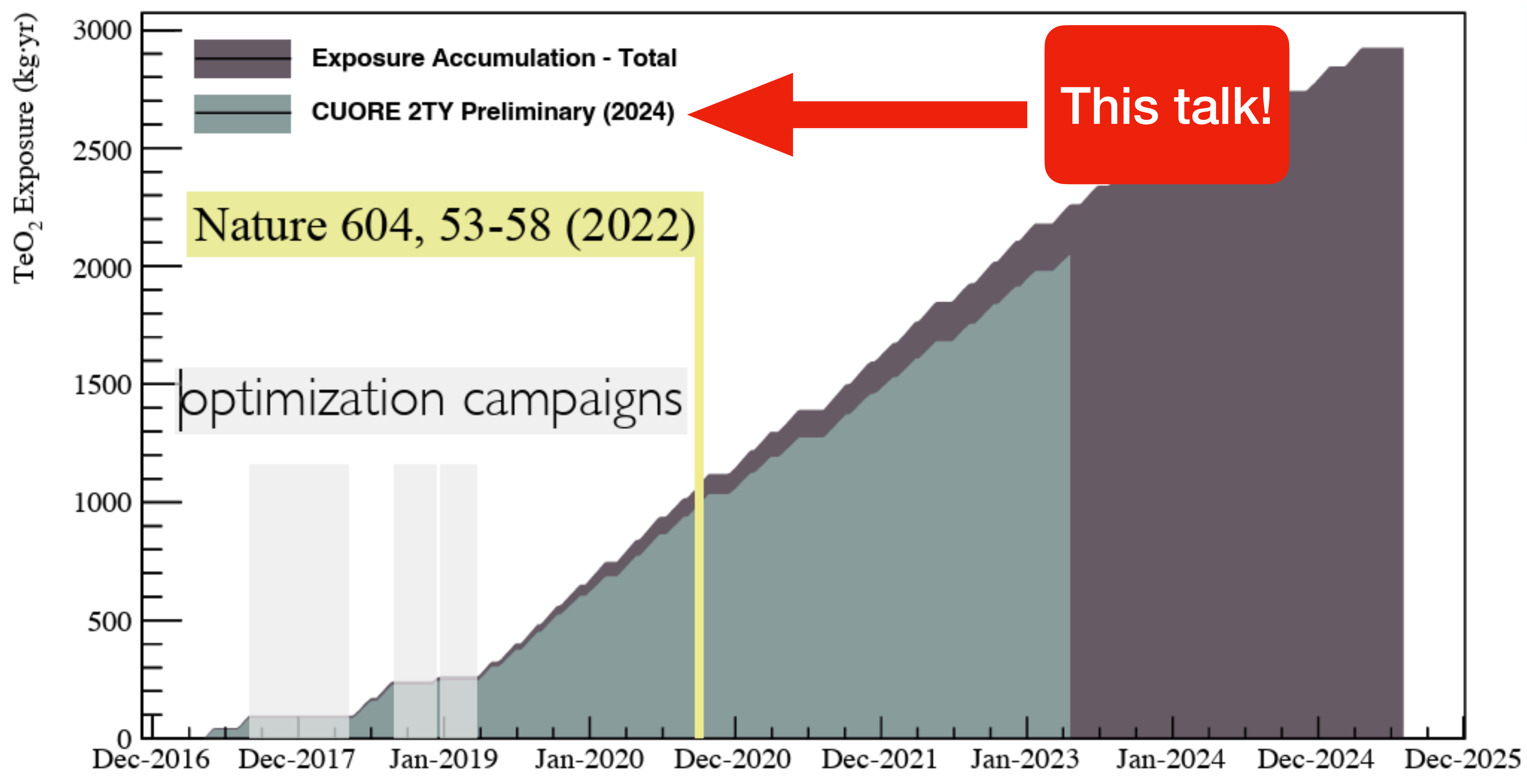

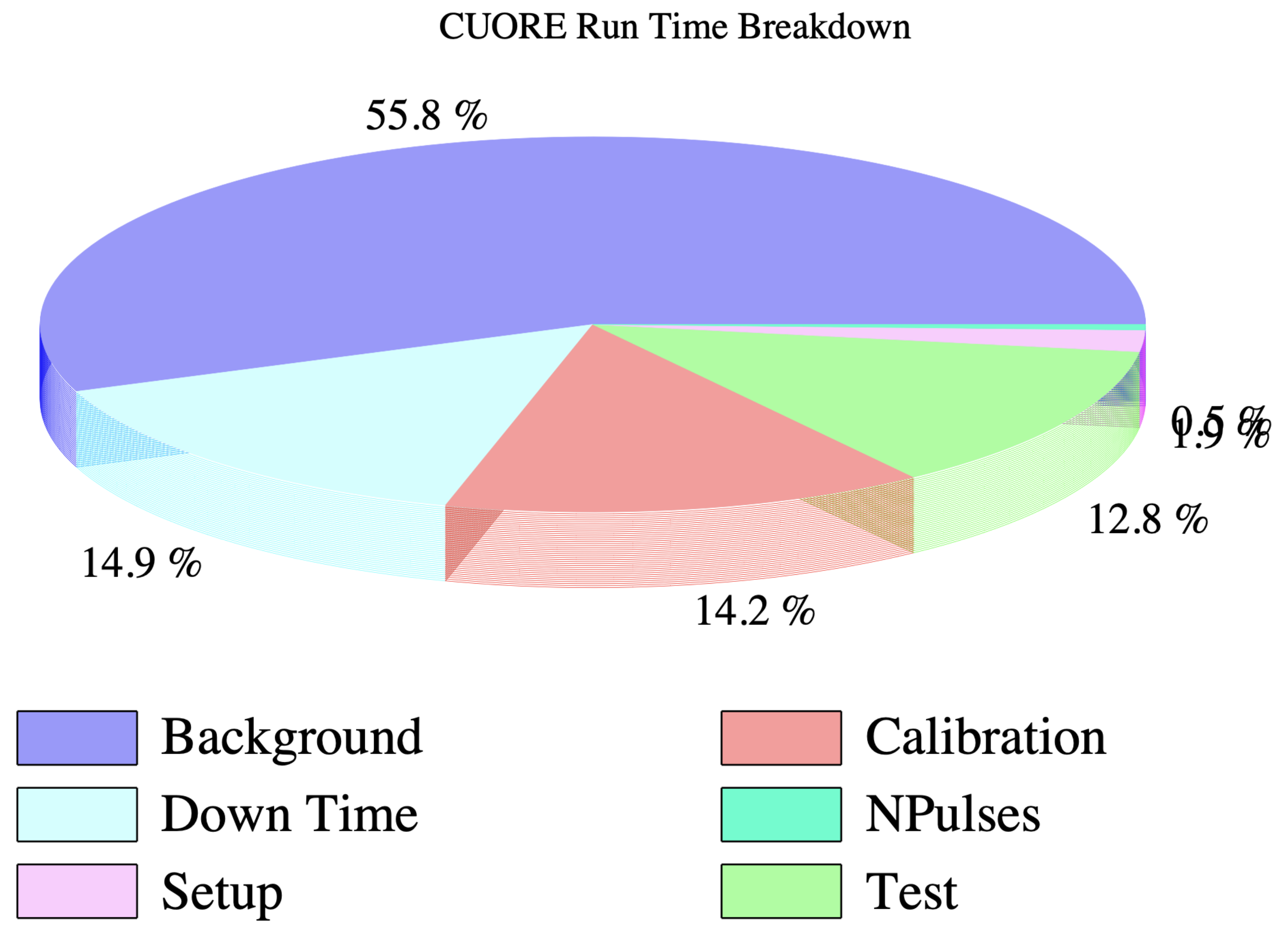

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Just published on Oct 16 2025

Science

RESEARCH ARTICLES

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Constraints on lepton number violation with the 2 tonne · year CUORE Dataset

CUORE Collaboration*†

†CUORE Collaboration authors and affiliations are listed in the supplementary materials.

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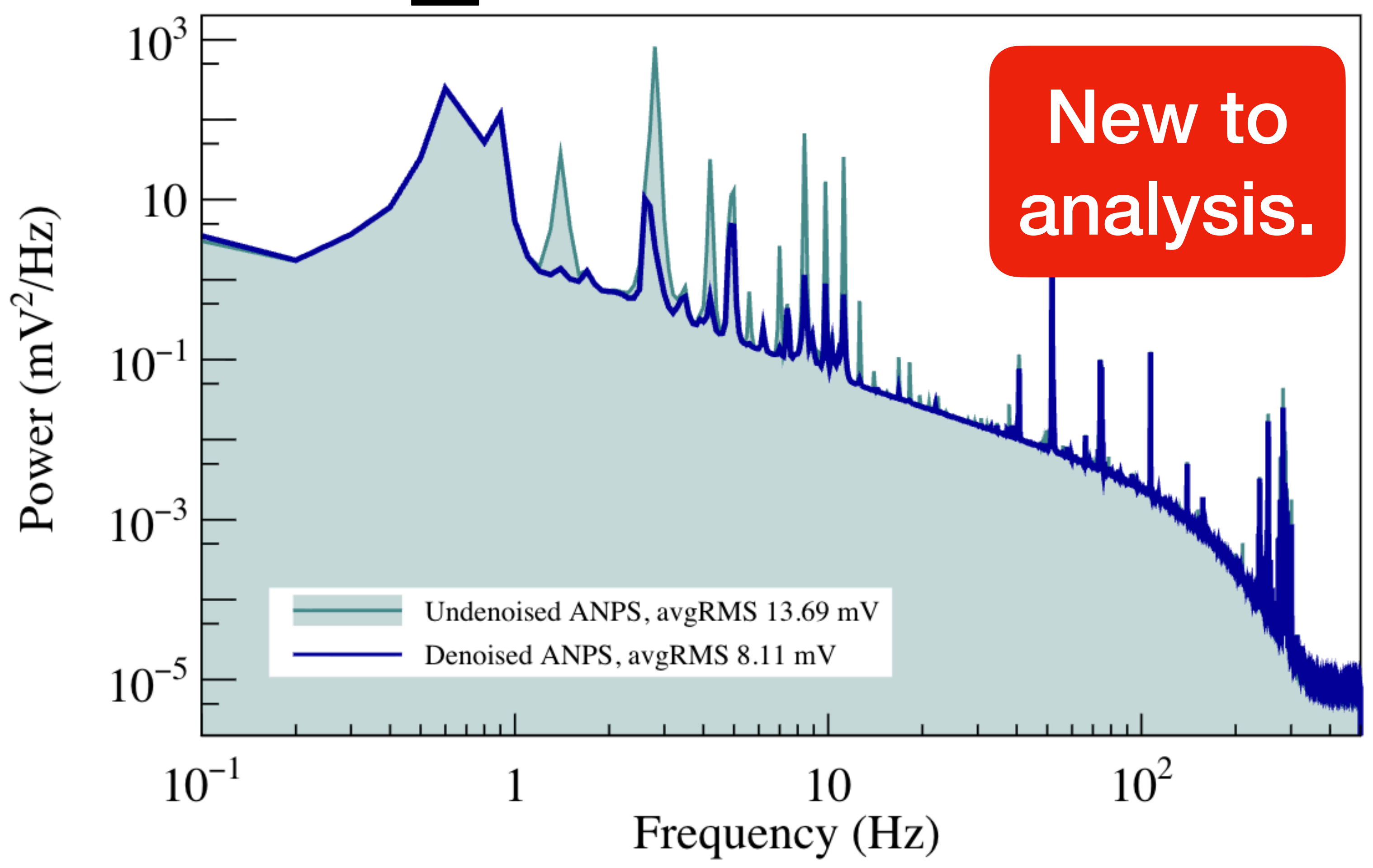
Matter-antimatter asymmetry underlines the incompleteness of the current understanding of particle physics. Neutrinoless double-beta decay ($0\nu\beta\beta$) may help explain this asymmetry, while unveiling the Majorana nature of the neutrino. The CUORE experiment searches for $0\nu\beta\beta$ of ^{130}Te using a tonne-scale cryogenic calorimeter operated at milli-kelvin temperatures. We report no evidence of $0\nu\beta\beta$ and place a lower limit on the half-life of $T_{1/2} > 3.5 \times 10^{25}$ years (90% C.I.) with over 2 tonne · year TeO_2 exposure. The tools and techniques developed for this result and the 5 year stable operation of nearly 1000 detectors demonstrate crucial infrastructure for a future-generation experiment capable of searching for $0\nu\beta\beta$ across multiple isotopes.

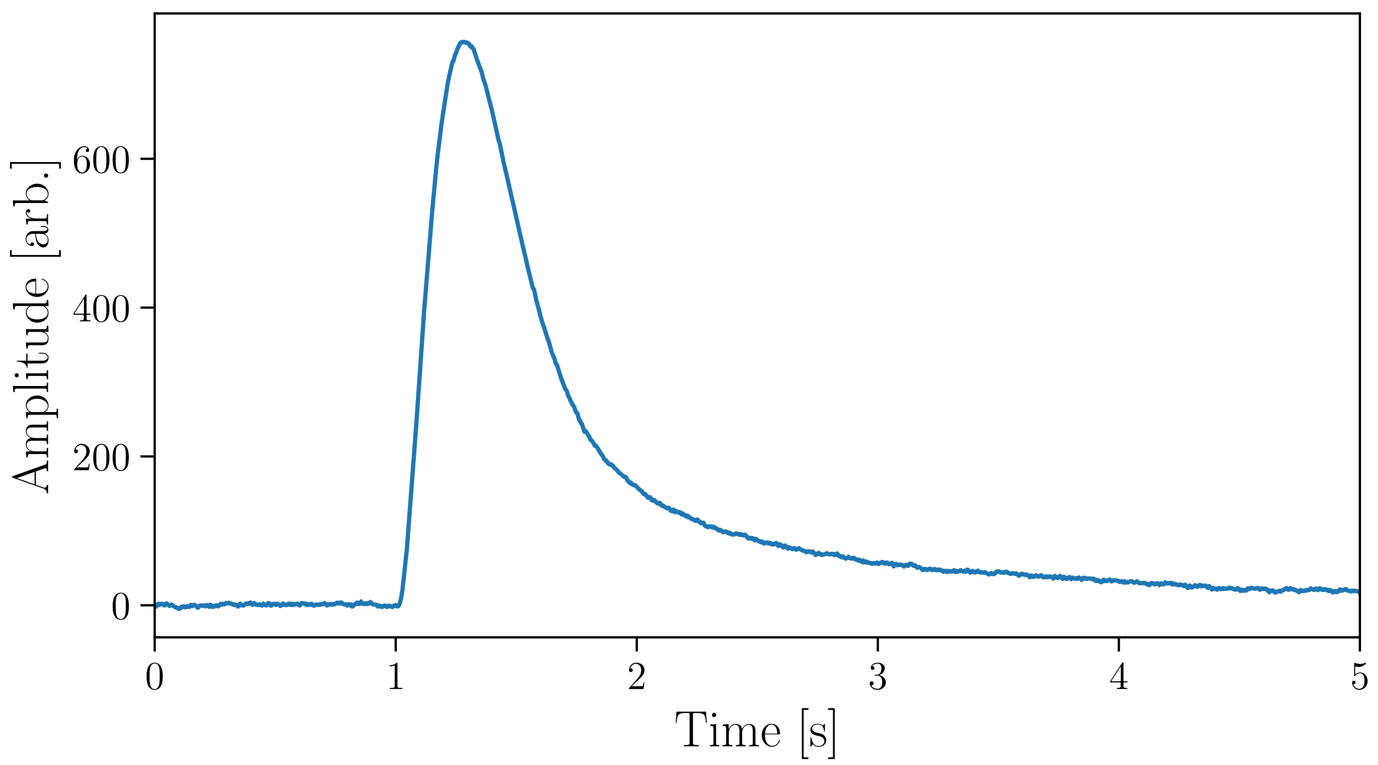
Science 10.1126/science.adp6474 (2025)

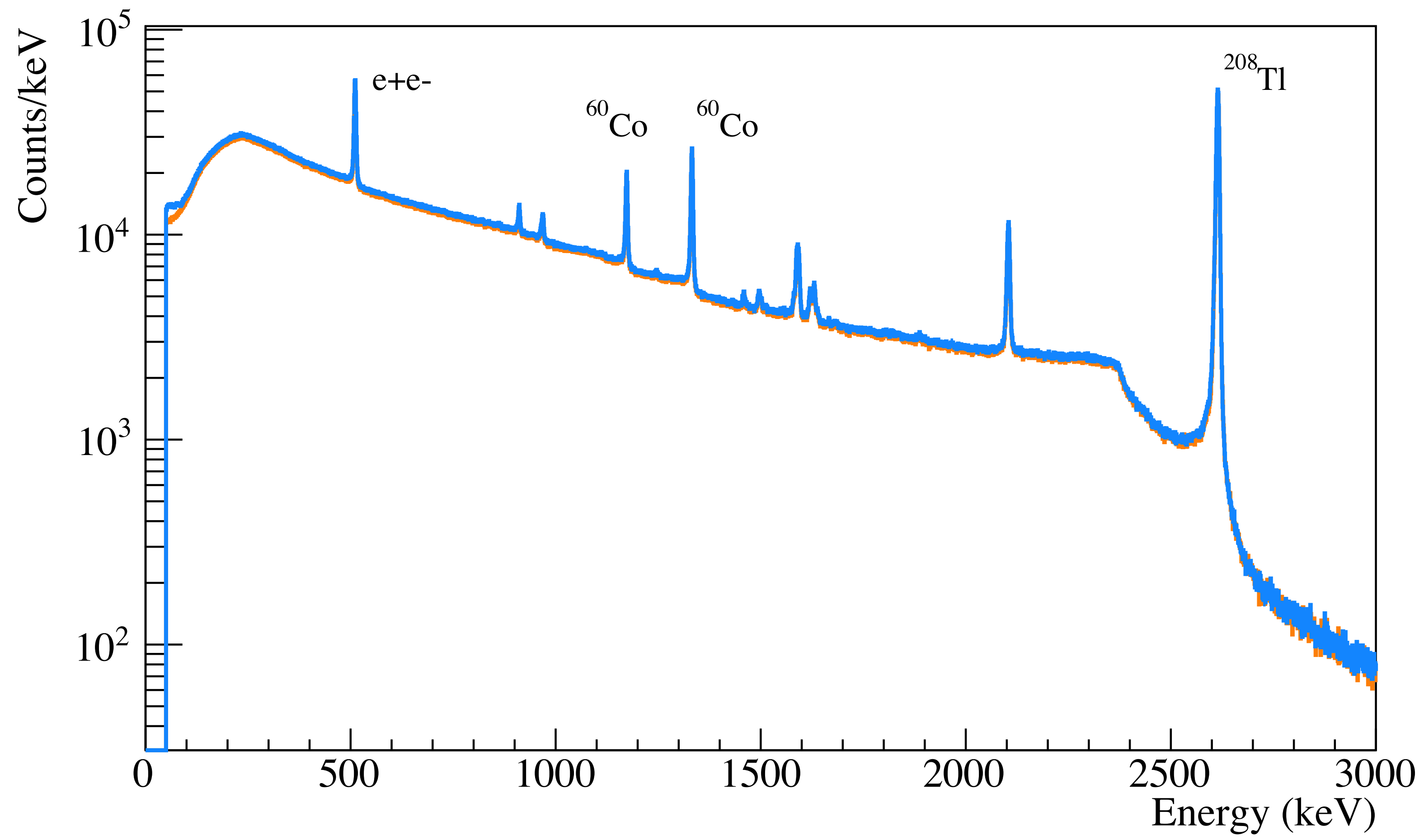
Signal and data processing

- Data undergoes through a noise-mitigation process, and through matched-filter that increases signal-to-noise ratio.
- Denoised pulse then further corrected for temperature effects from the detector, and then converted to units of energy.
- Energy calibration done using calibration runs.

Science 10.1126/science.adp6474 (2025)







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

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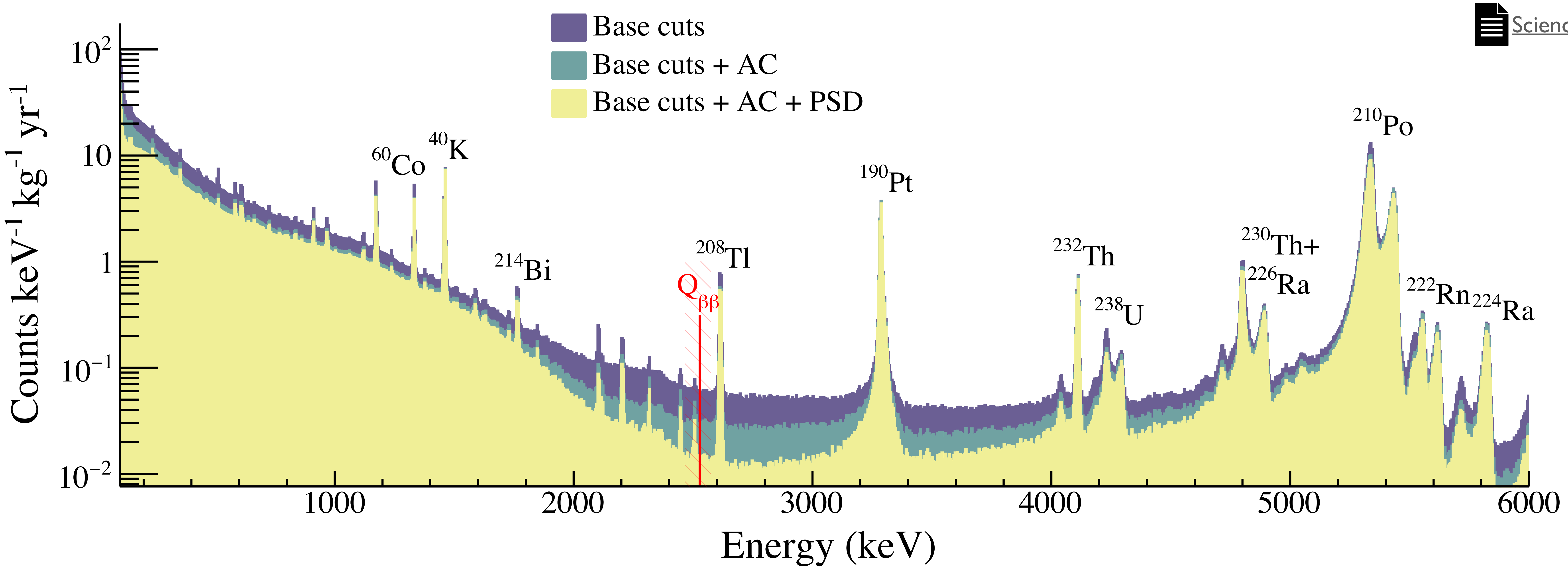
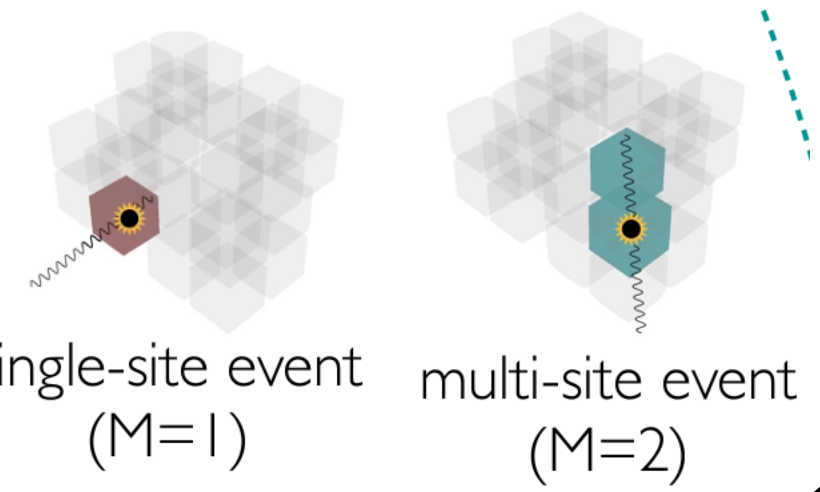


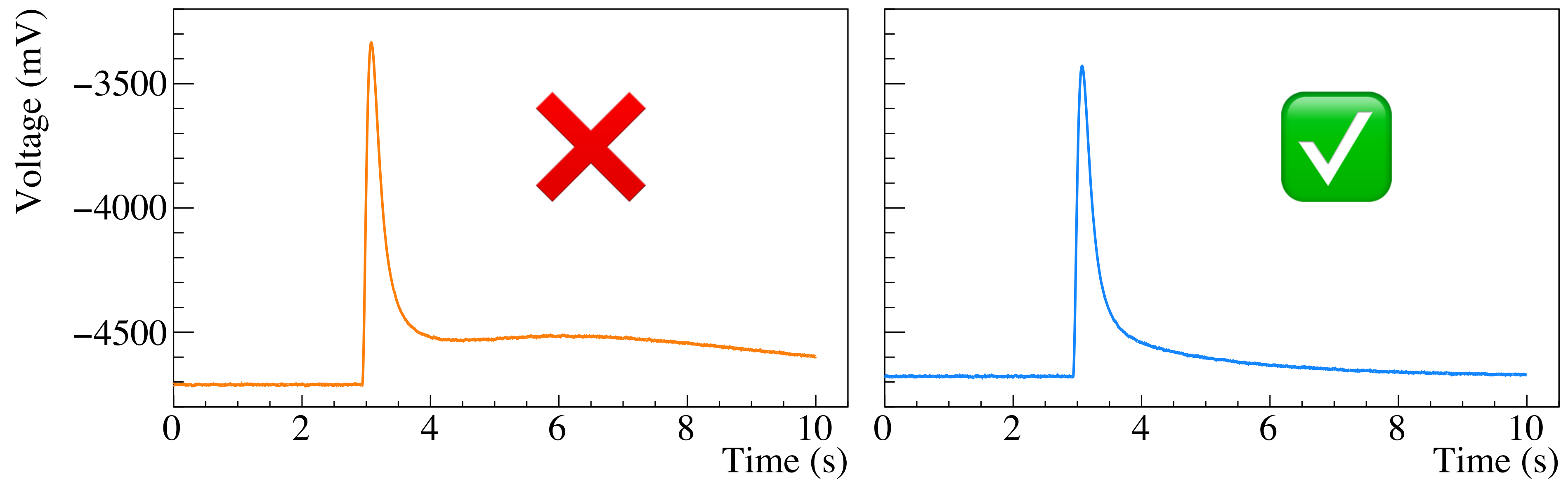
Anti-coincidence (AC) selection

Only keep single-site events, as we expect ~90% containment of $0\nu\beta\beta$ events



Pulse Shape Discrimination (PSD)

Reject spurious events, non-signal events by virtue of Principal Component Analysis (PCA)



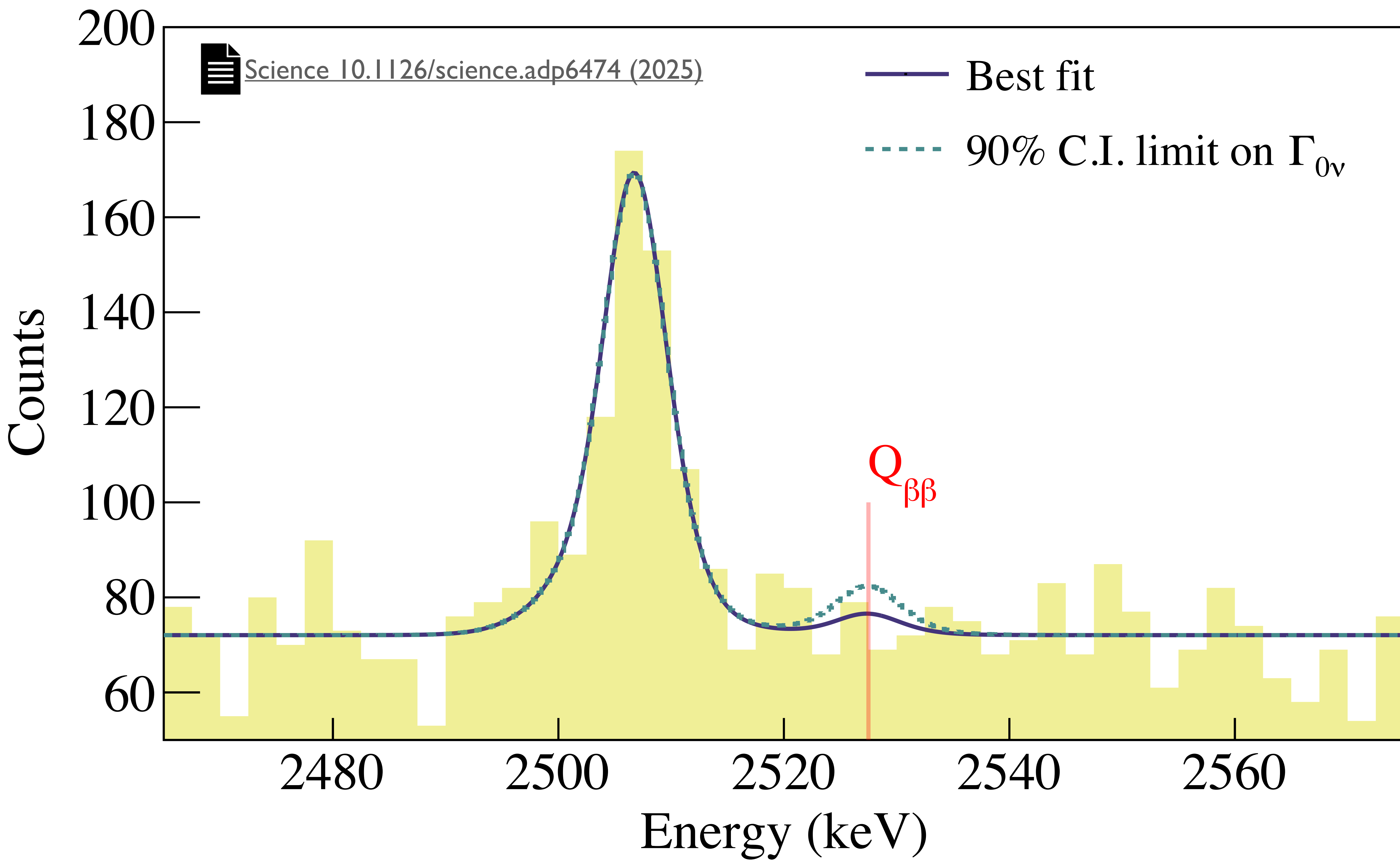
2 tonne-year results

- After applying detector effects:
  - Bayesian fit in ROI [2465 keV, 2575 keV], with systematics as nuisance parameters.
- **No evidence** of $0\nu\beta\beta$ decay

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

Systematics:

- Efficiencies (~93%)
- Energy bias an resolution
- Value of $Q_{\beta\beta}$
- Abundance of Te-130



- Decay rate: $\Gamma^{0\nu} < 2.0 \times 10^{-26}$ yr^{-1} (90 C.I.)
- Half-life limit: $T^{0\nu}_{1/2} > 3.5 \times 10^{25}$ yr (90% C.I.)

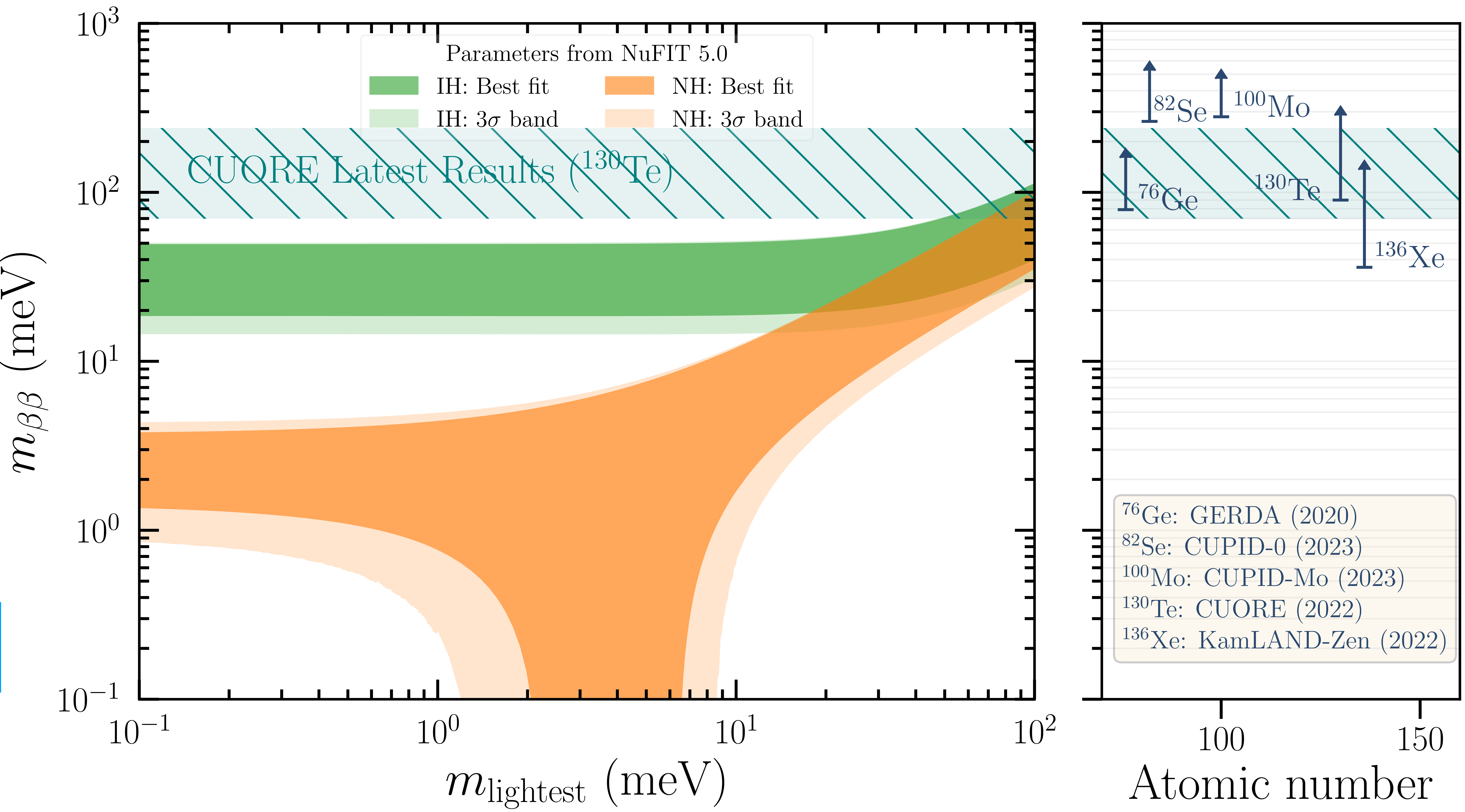
Limit on $m_{\beta\beta}$ from CUORE's latest results

Assuming light neutrino exchange:

$m_{\beta\beta} < [70, 250]\ \text{meV}$

A range, because of NMEs

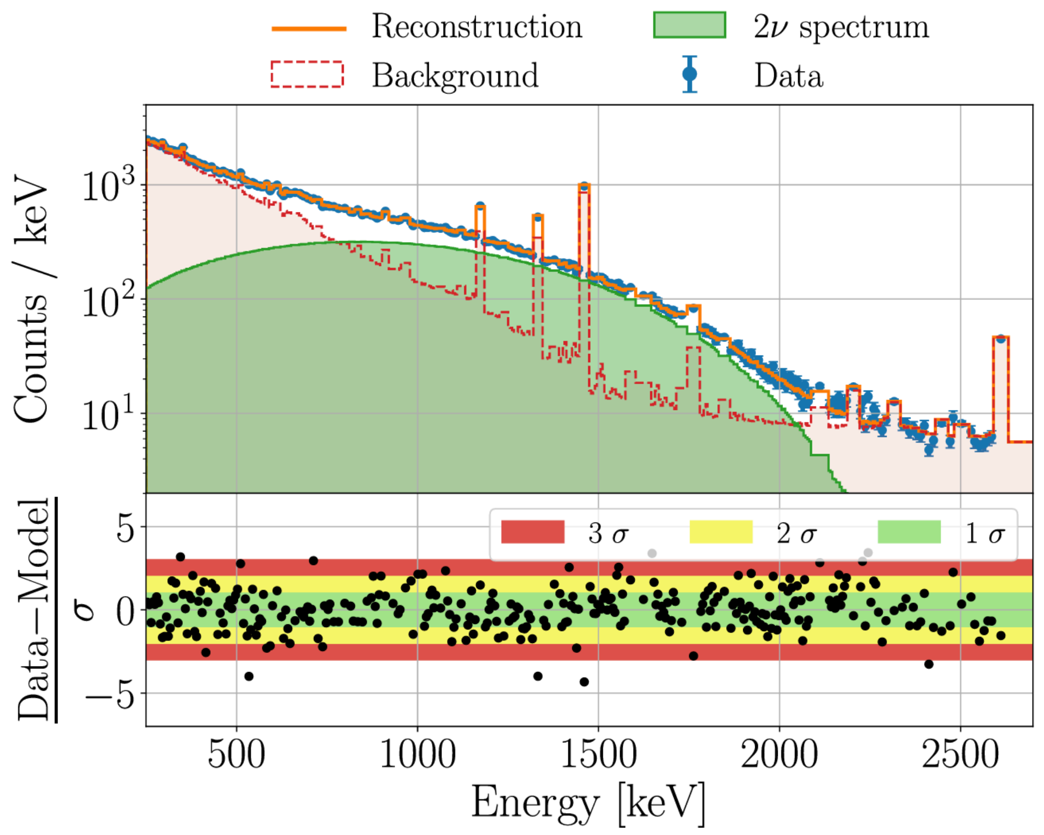
https://www.science.org/doi/10.1126/science.adp6474



Other analyses

Other analyses

Other double beta decay searches



Studies of SM-allowed and BSM processes.

- Eur. Phys. J. C 81, 567
- Phys. Rev. C, 105 065504
- Phys. Rev. Lett. 129, 222501
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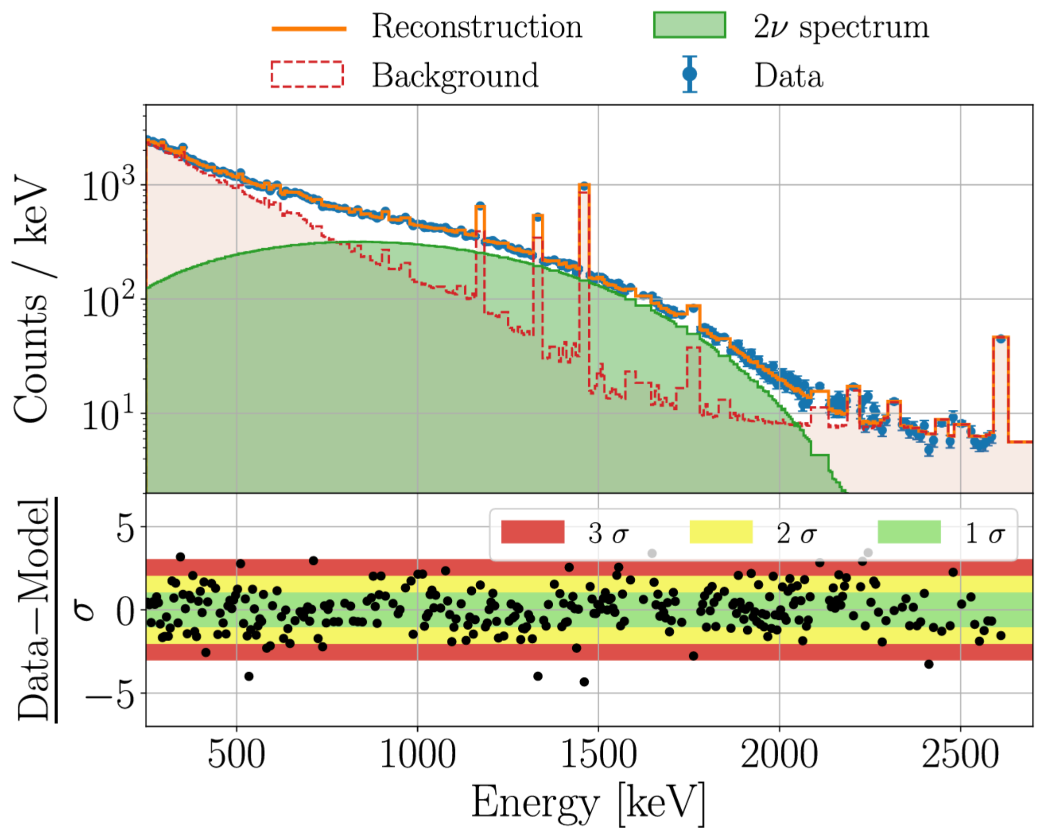

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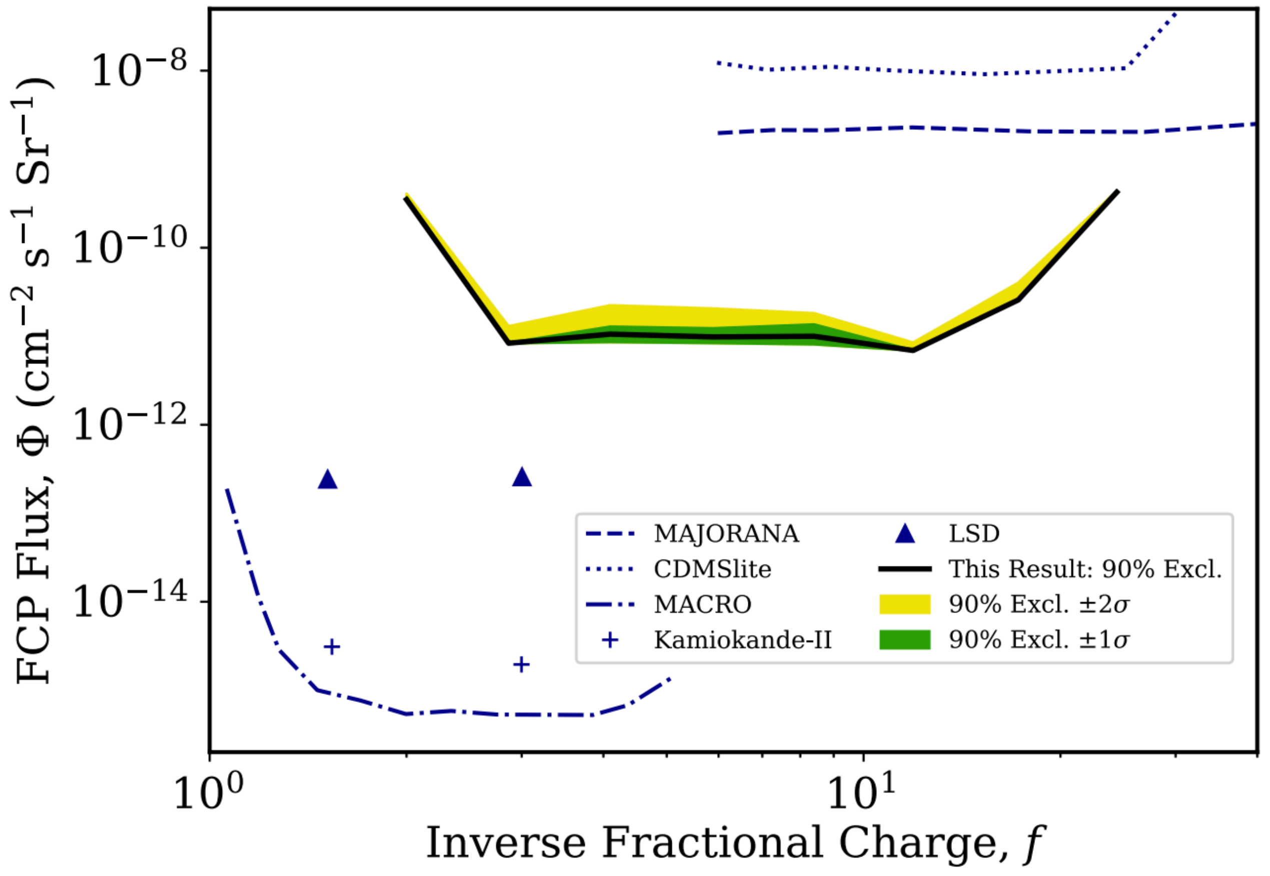
Search for fractionally charged particles (FCPs)



World-leading limits on FCPs, demonstrating CUORE's sensitivity to track-like exotic phenomena.

- Phys. Rev. Lett. 133, 241801

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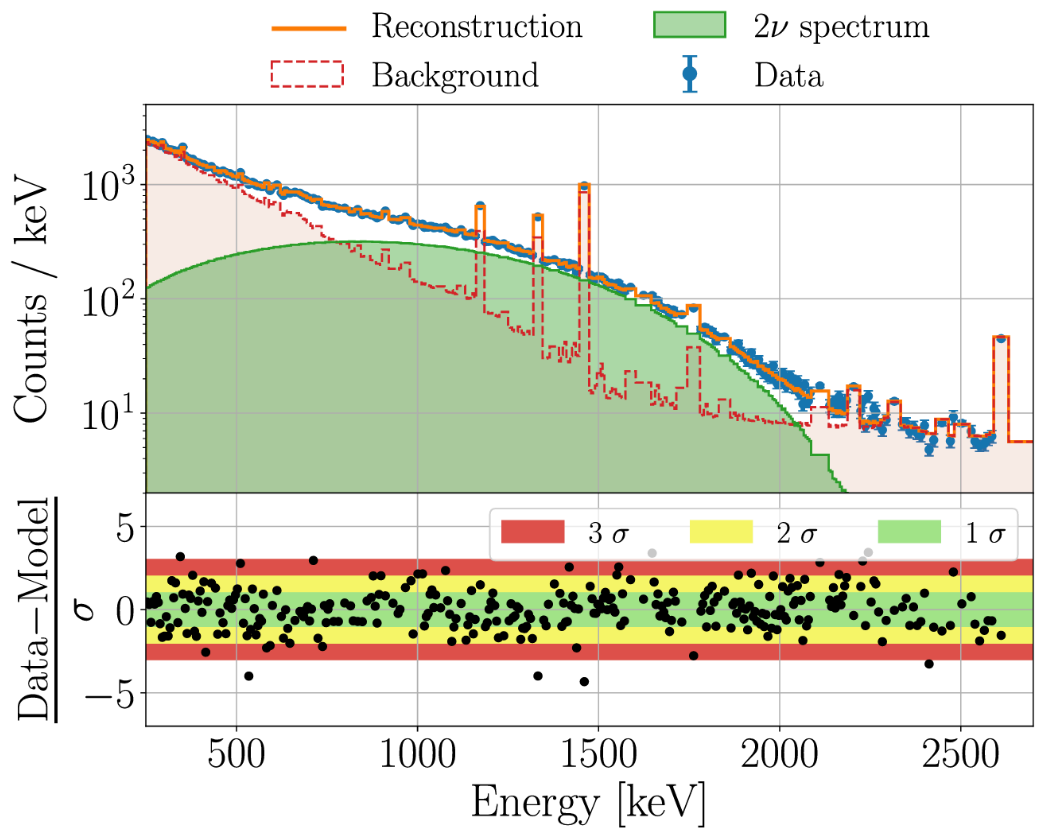

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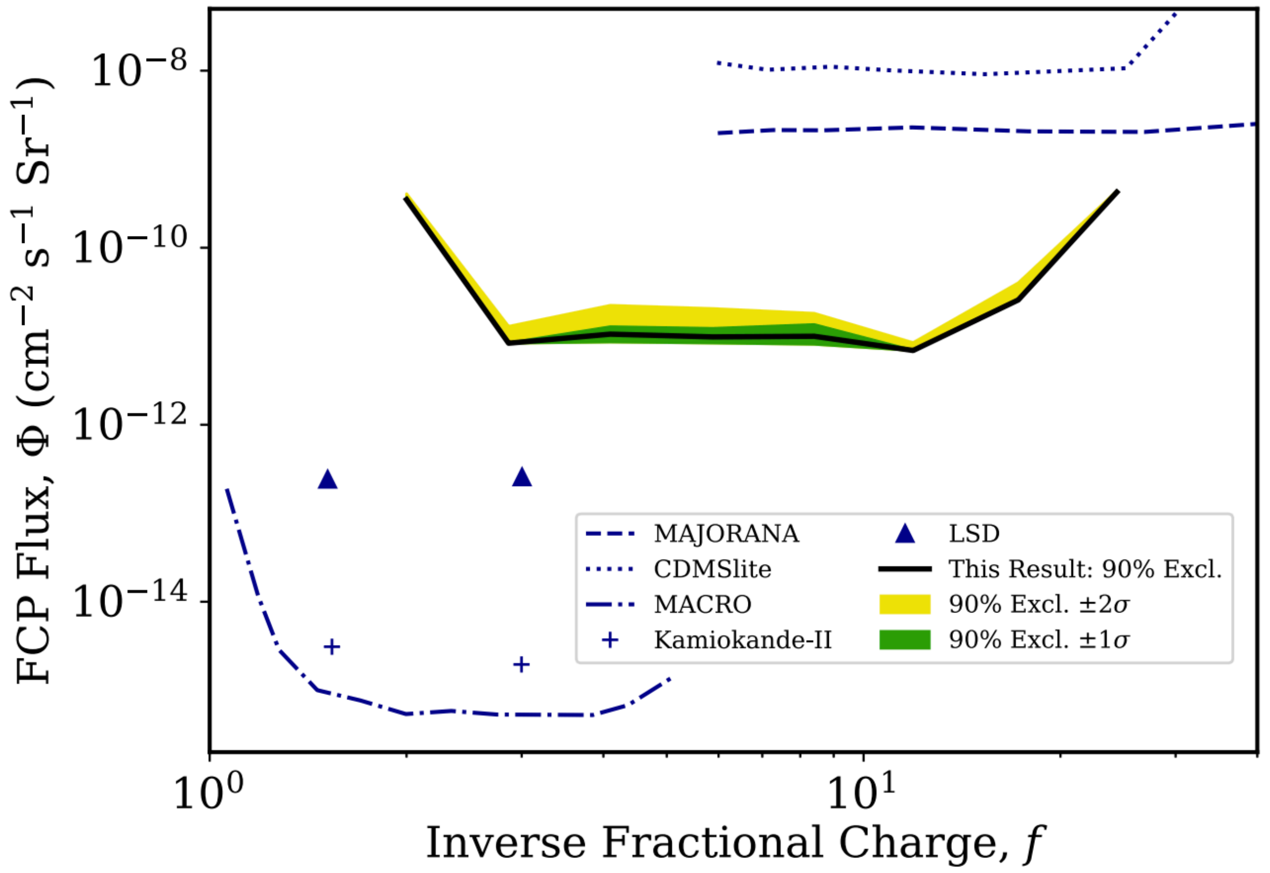

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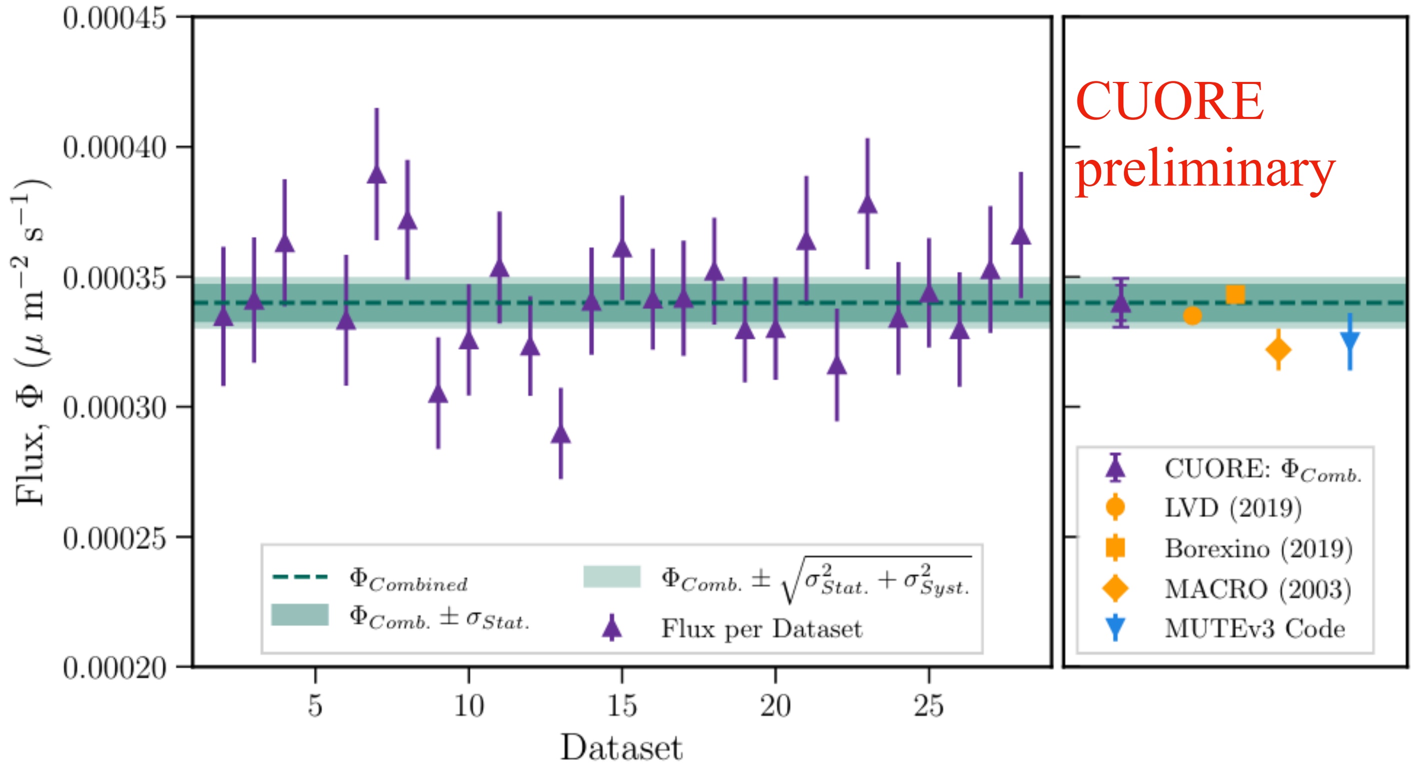
Reconstruction of cosmic-ray muon events



Leveraging CUORE's segmentation for measuring the LNGS muon flux with through-going muons.

- arXiv:2509.05528

Other analyses

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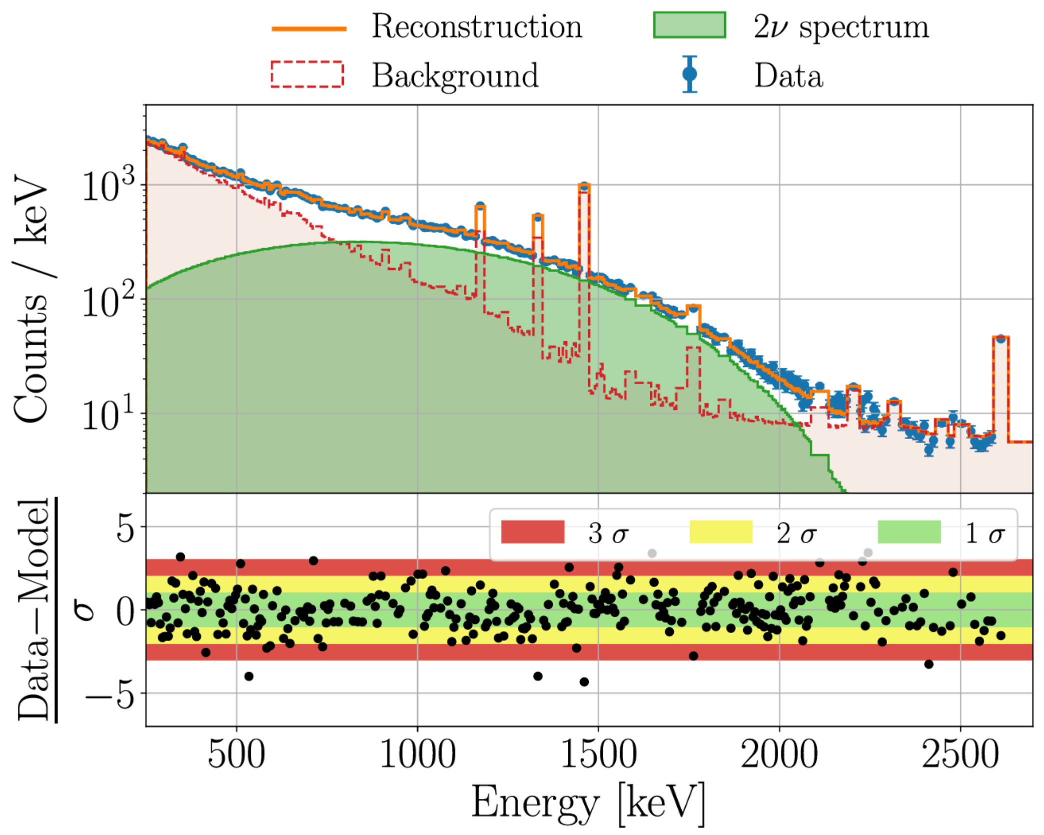

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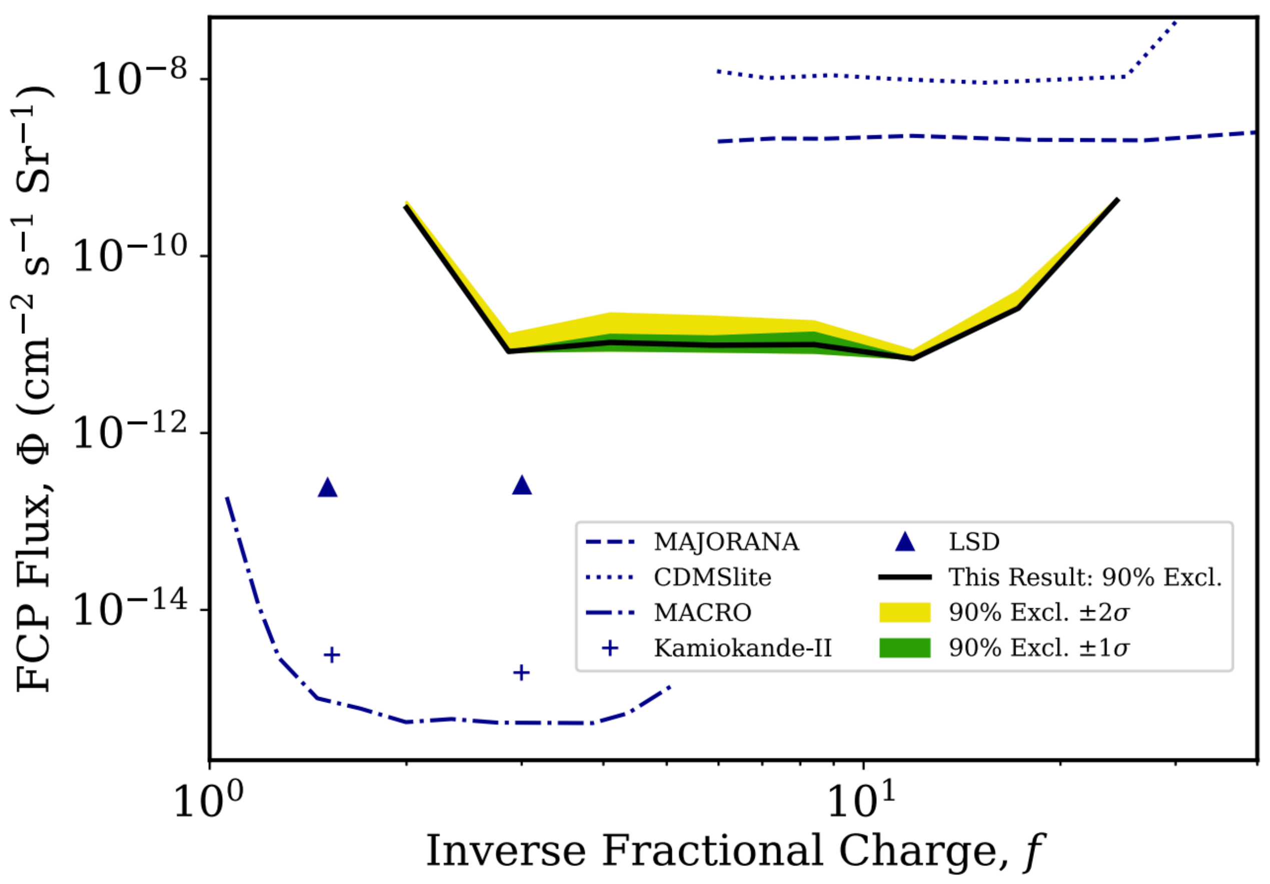

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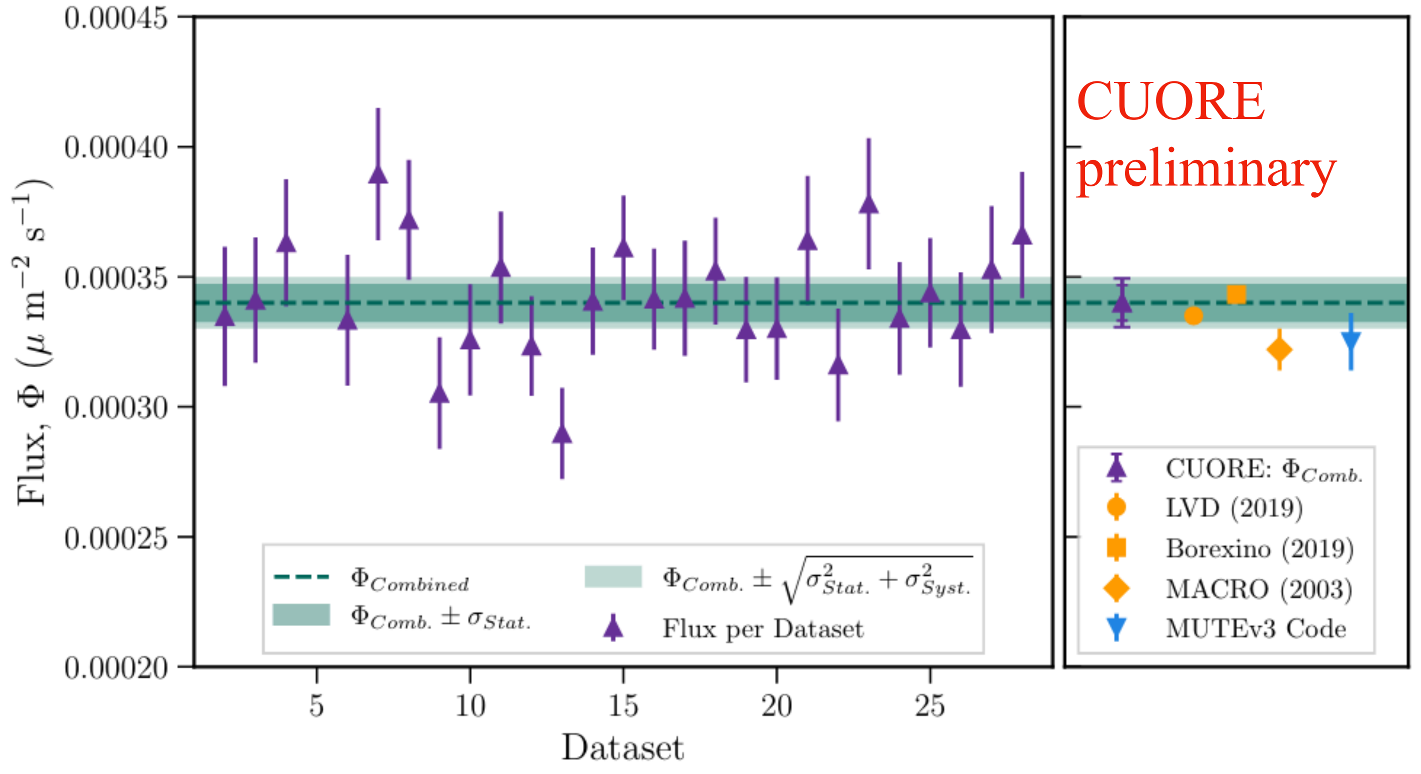

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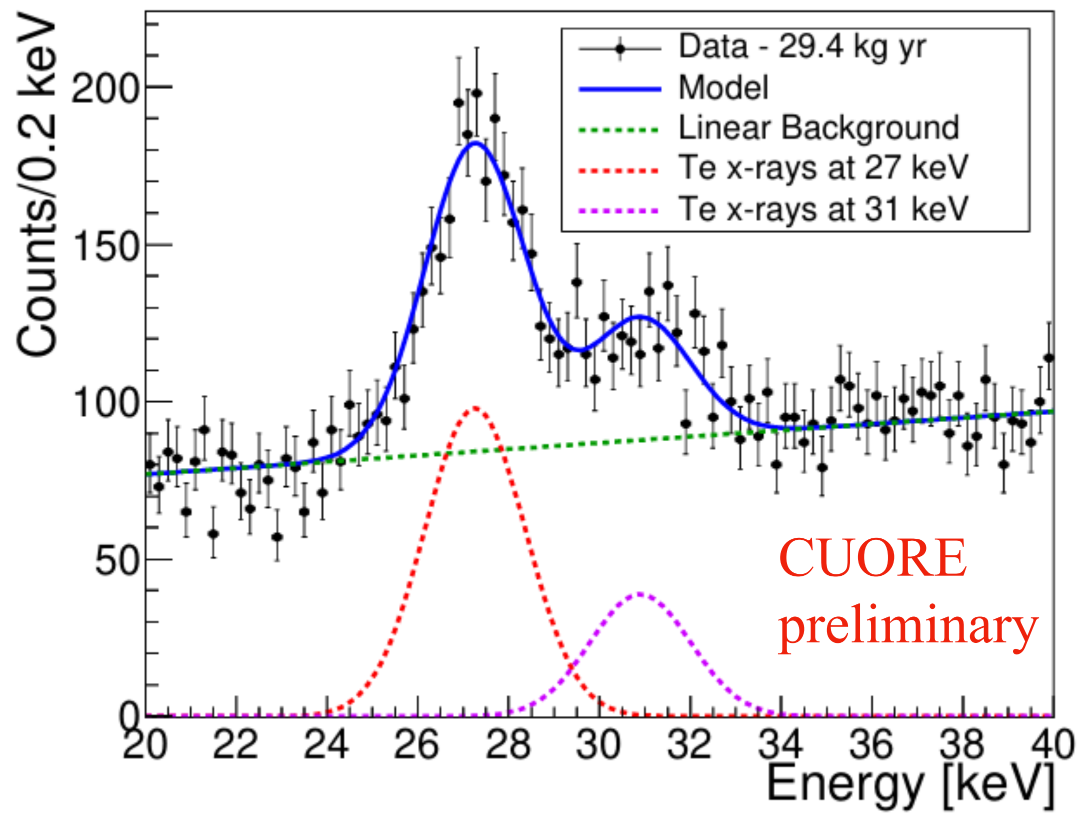
Low energy characterization and studies



Exploring the keV-scale capabilities of CUORE to solar axions, WIMP and other low-energy searches.

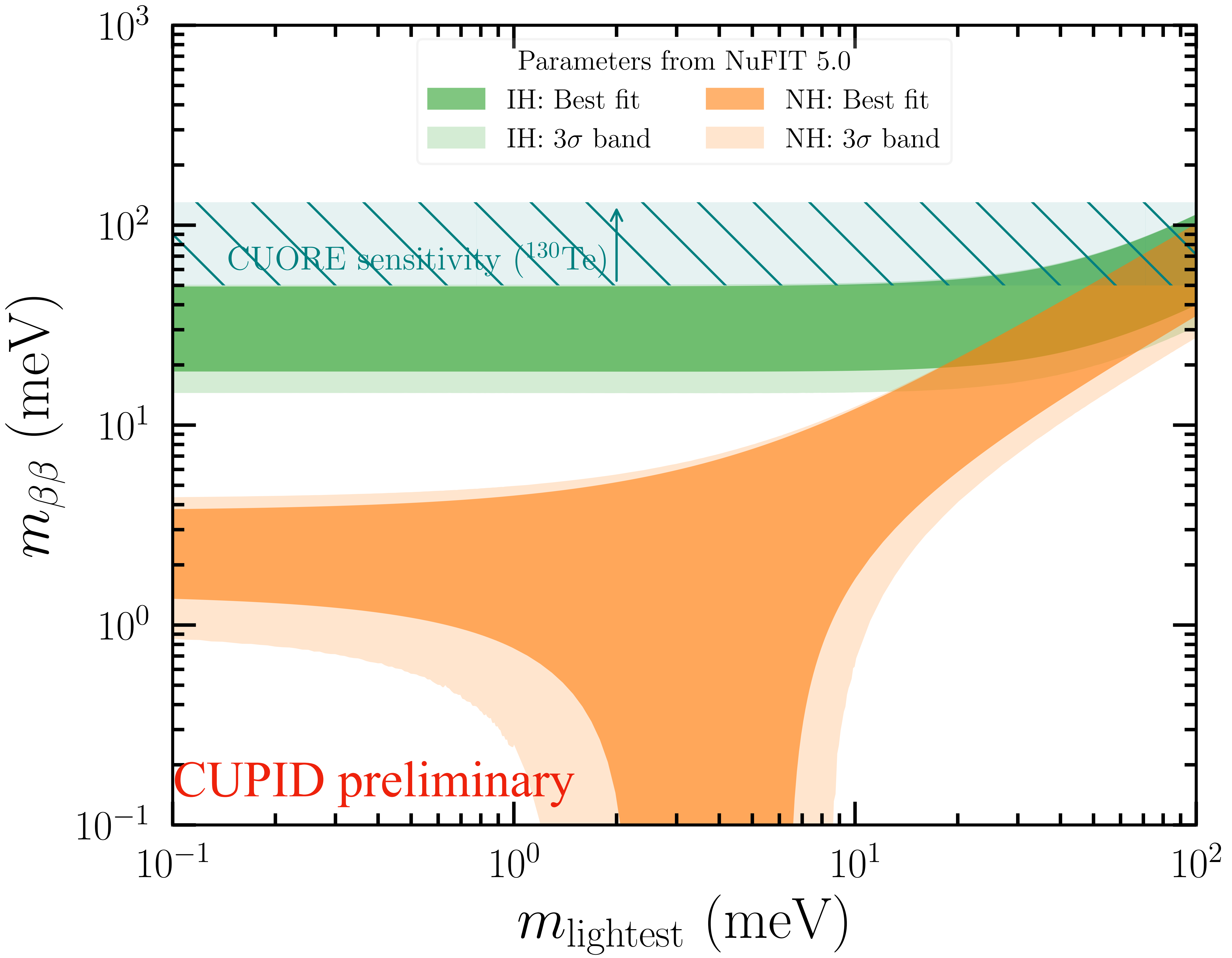
- arXiv:2505.23955

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):
  - $T^{0\nu}_{1/2} > 1.0 \times 10^{27}$ yrs
  - $m_{\beta\beta} = (12.2 - 20.6)$ meV
- CUPID can probe the IH region.
- New technology can decrease backgrounds and increase sensitivity.



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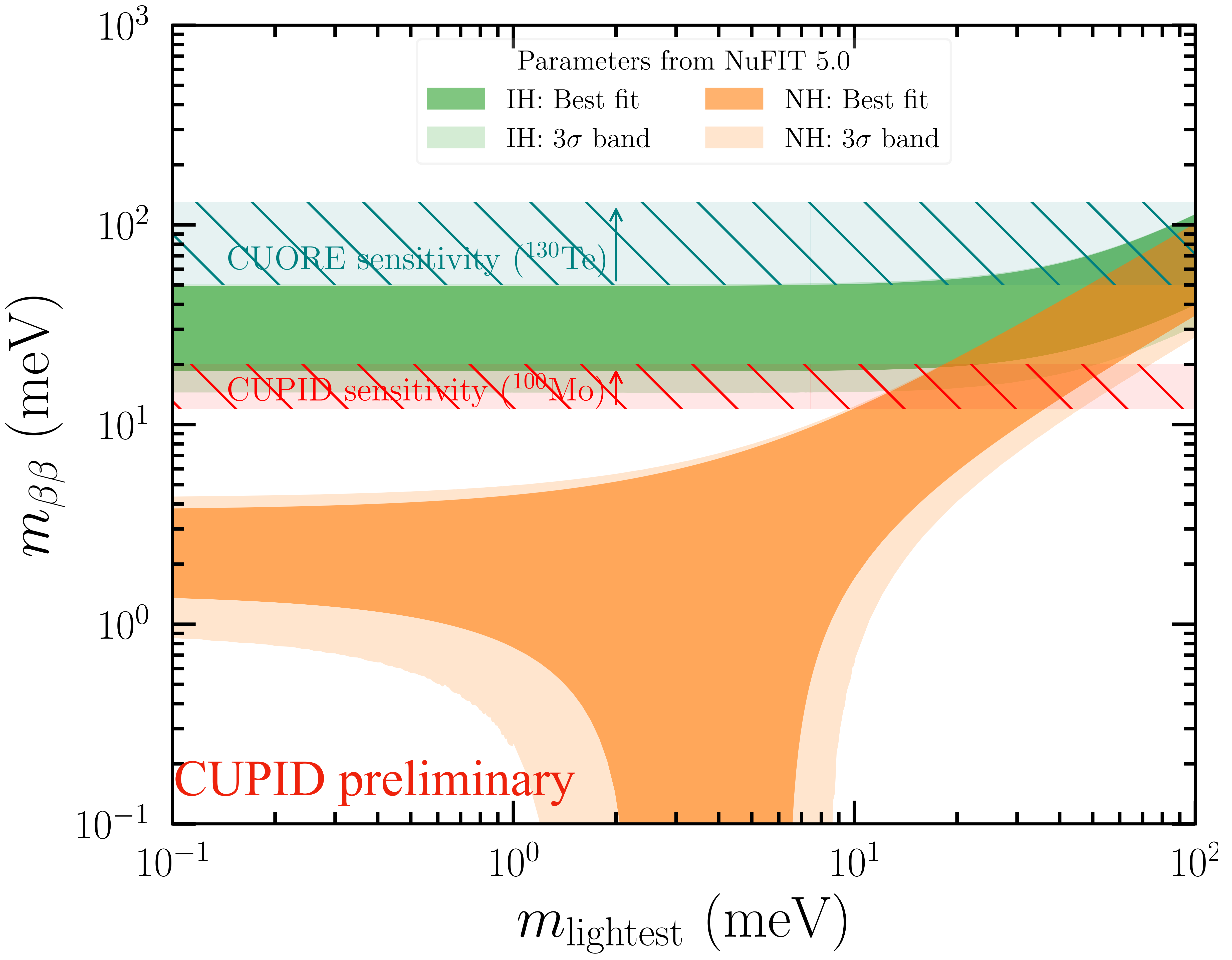

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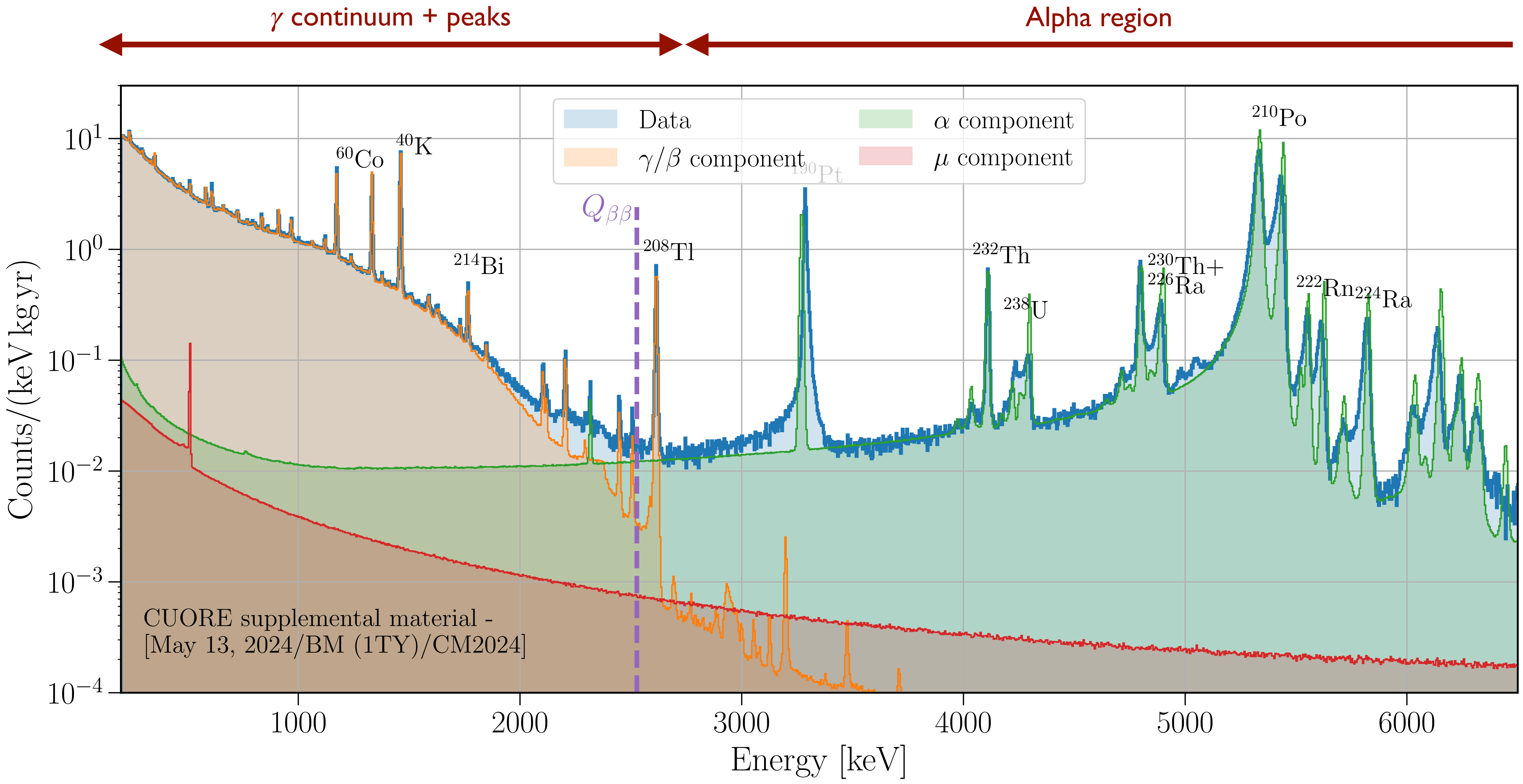
Lessons for CUPID from CUORE's background



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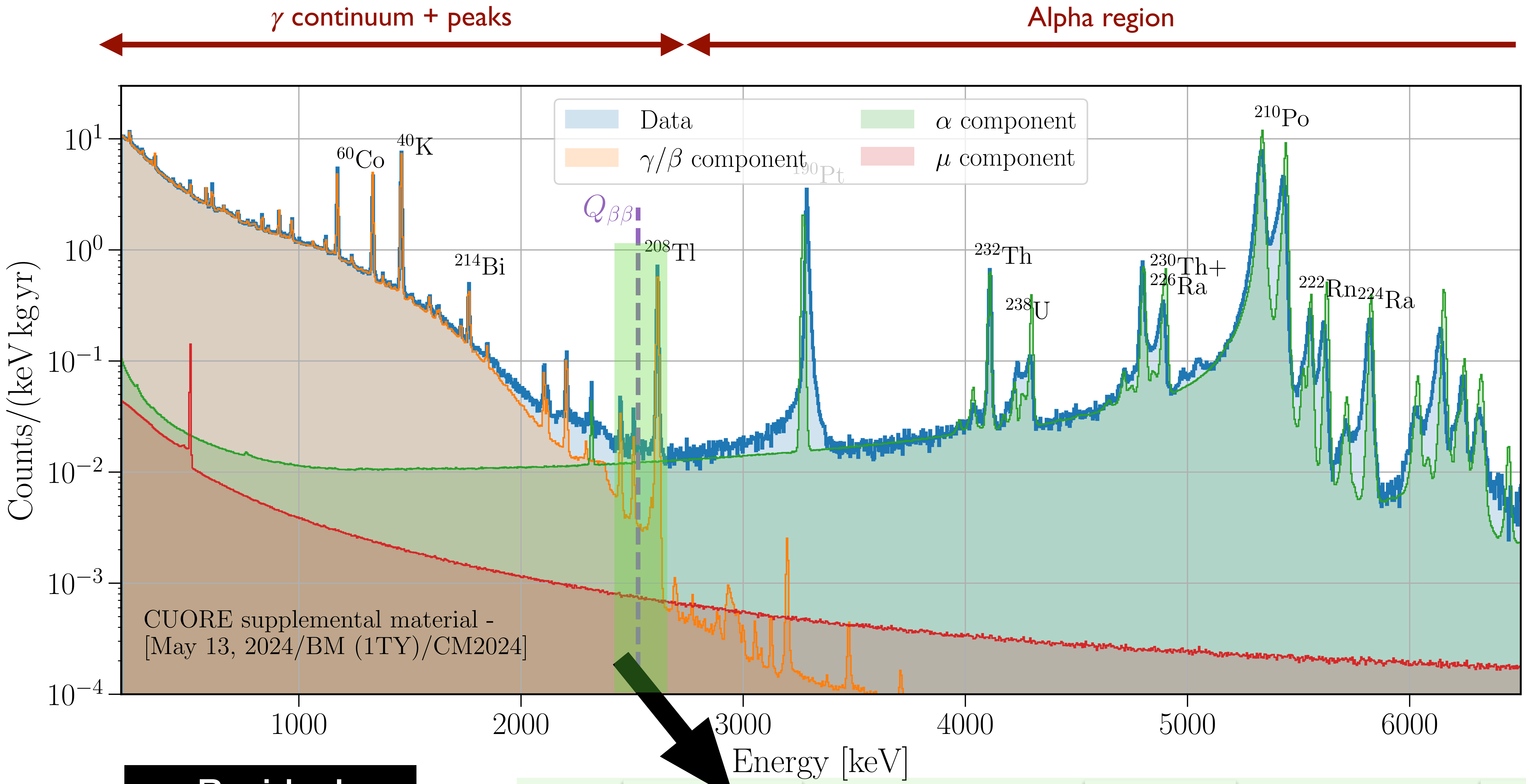

Residual backgrounds in the region of interest

β/γ — ~10% β/γ radioactivity

α — ~90% degraded alphas (U/Th)

μ — $\lesssim$1% muons

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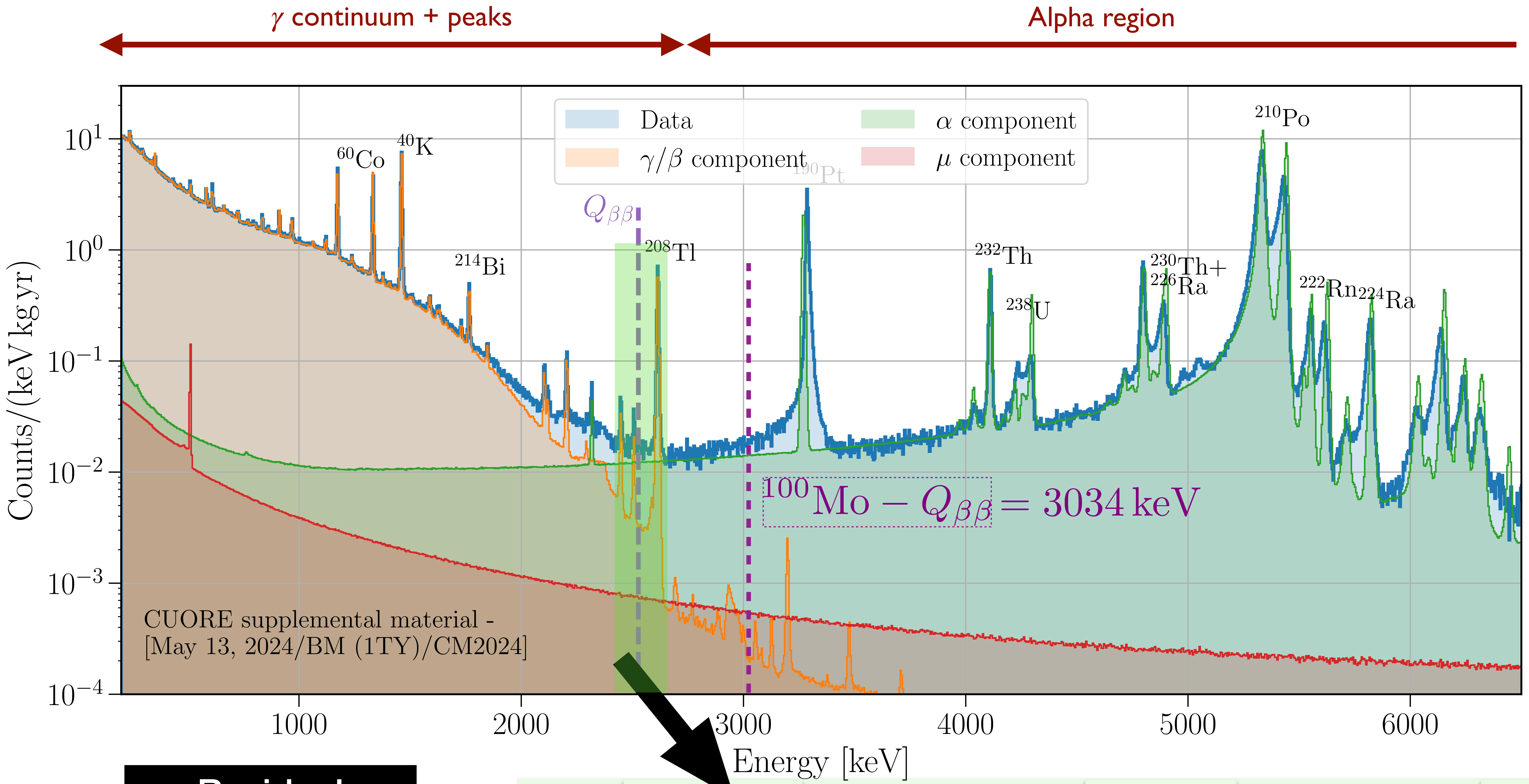


Residual backgrounds in the region of interest

β/γ	α	μ
~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:
  - Cryogenic-calorimeter 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.
- New technology validated by two demonstrators:
  - CUPID-0 — Phys. Rev. Lett. 129, 111801
  - CUPID-Mo — Eur. Phys. J. C 82, 1033 (2022)

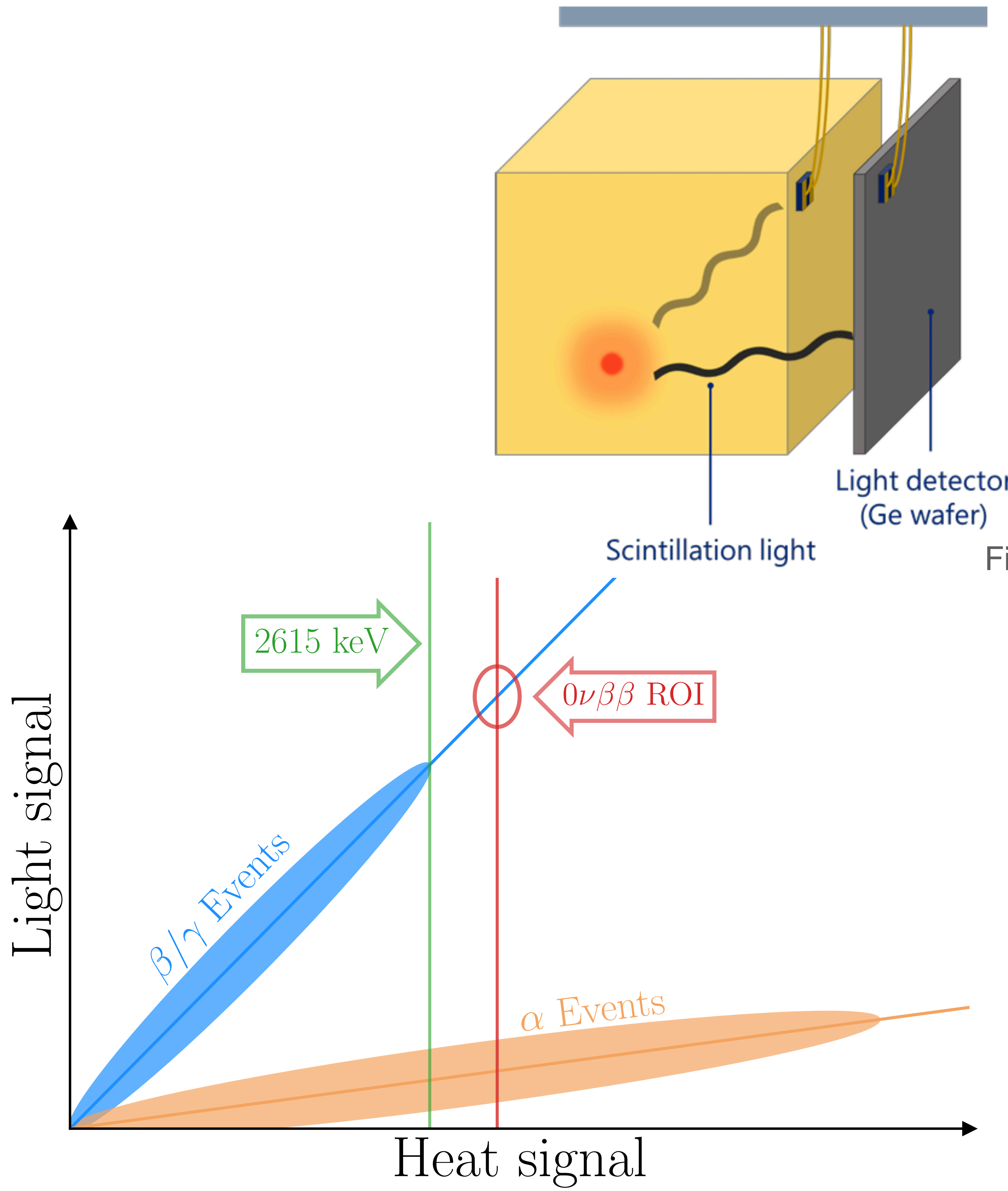
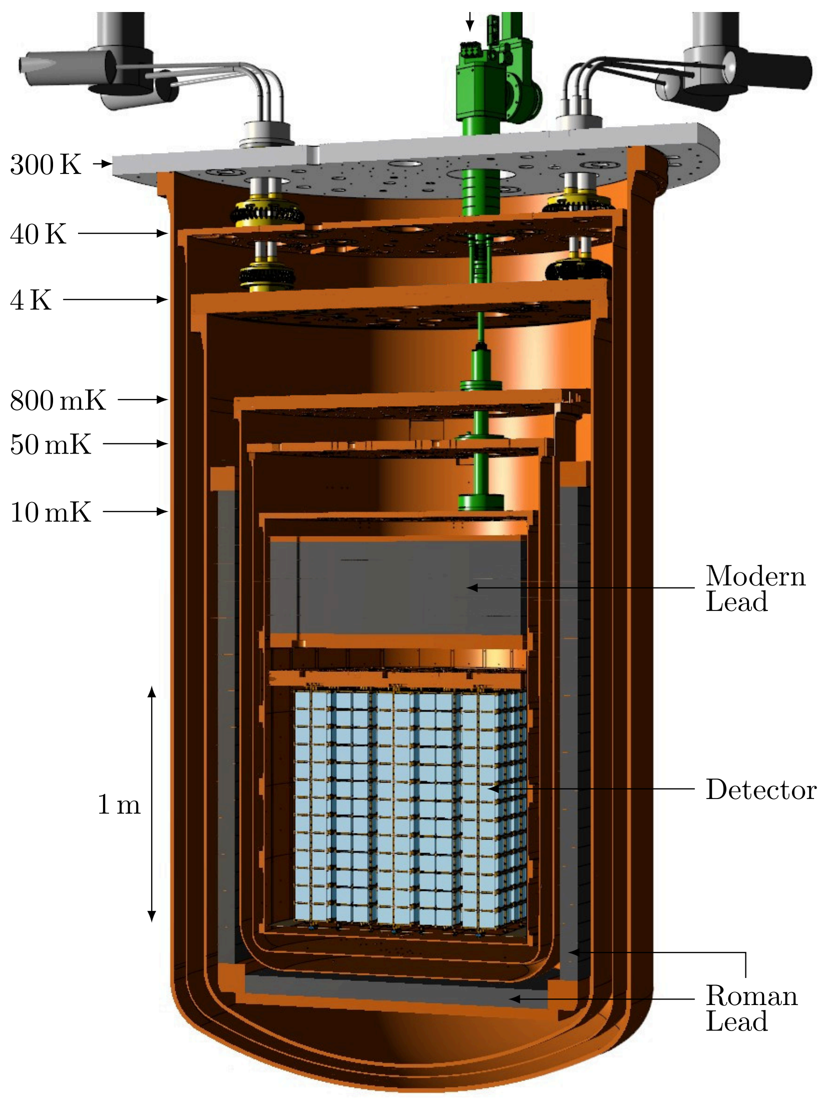


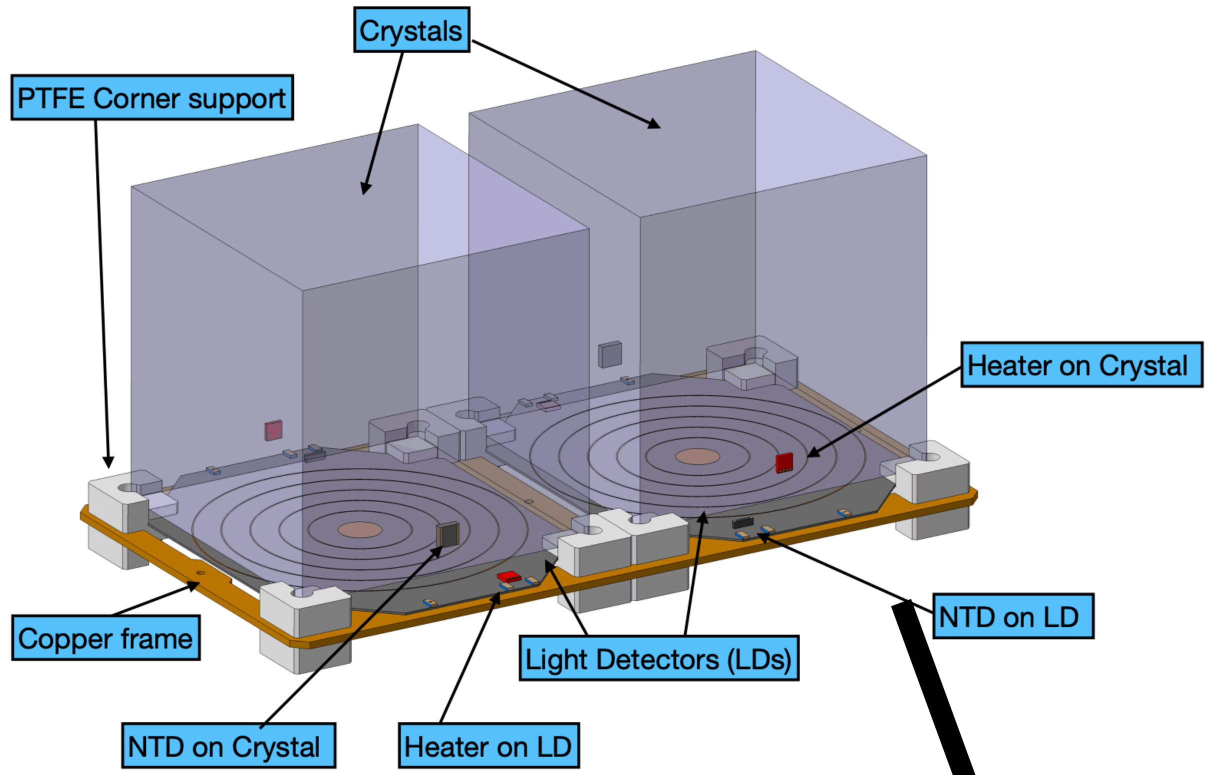
Figure: H. Khalife

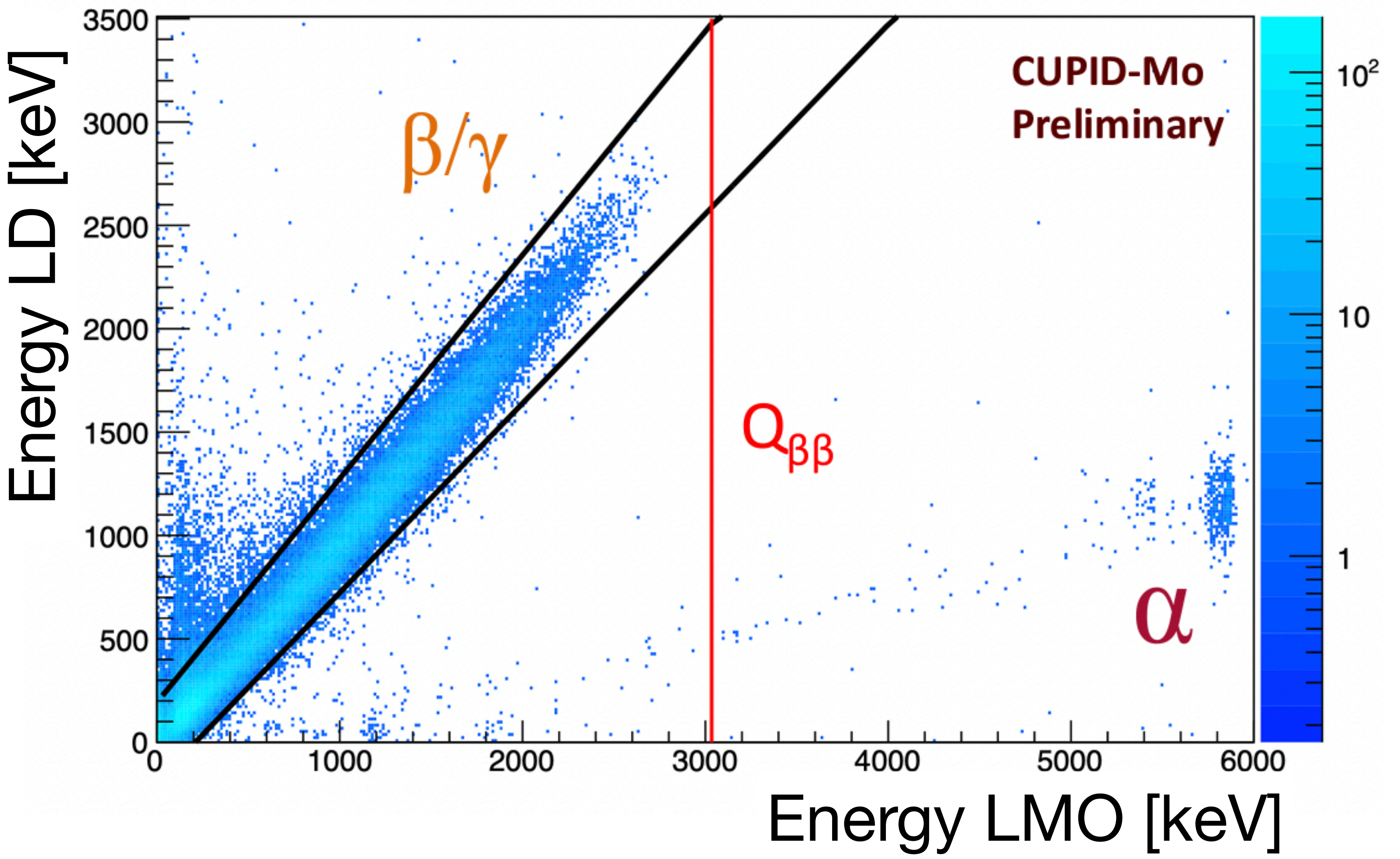
The CUPID Experiment

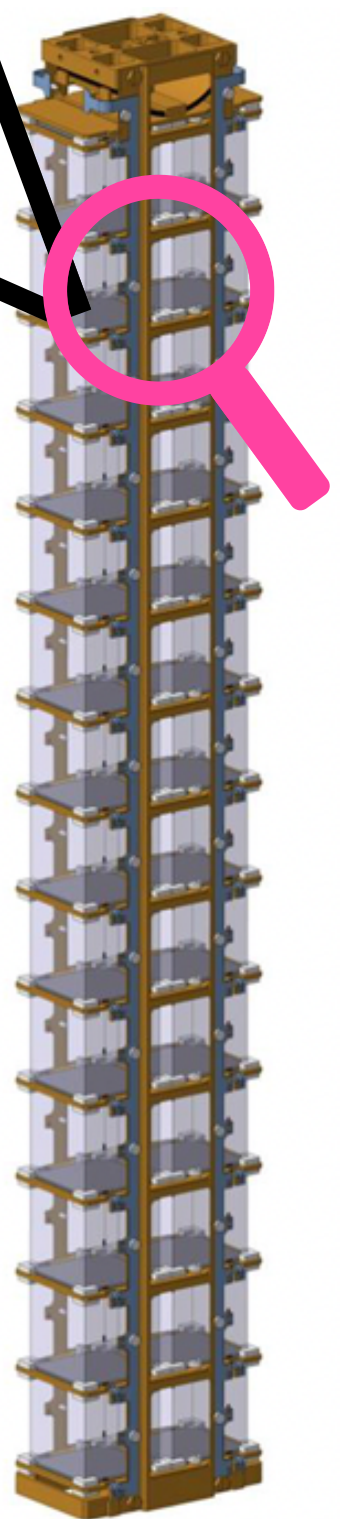
Eur. Phys. J. C 85, 737 (2025)

- 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 $Q_{\beta\beta}$
- Expected to start data-taking early in the next decade.

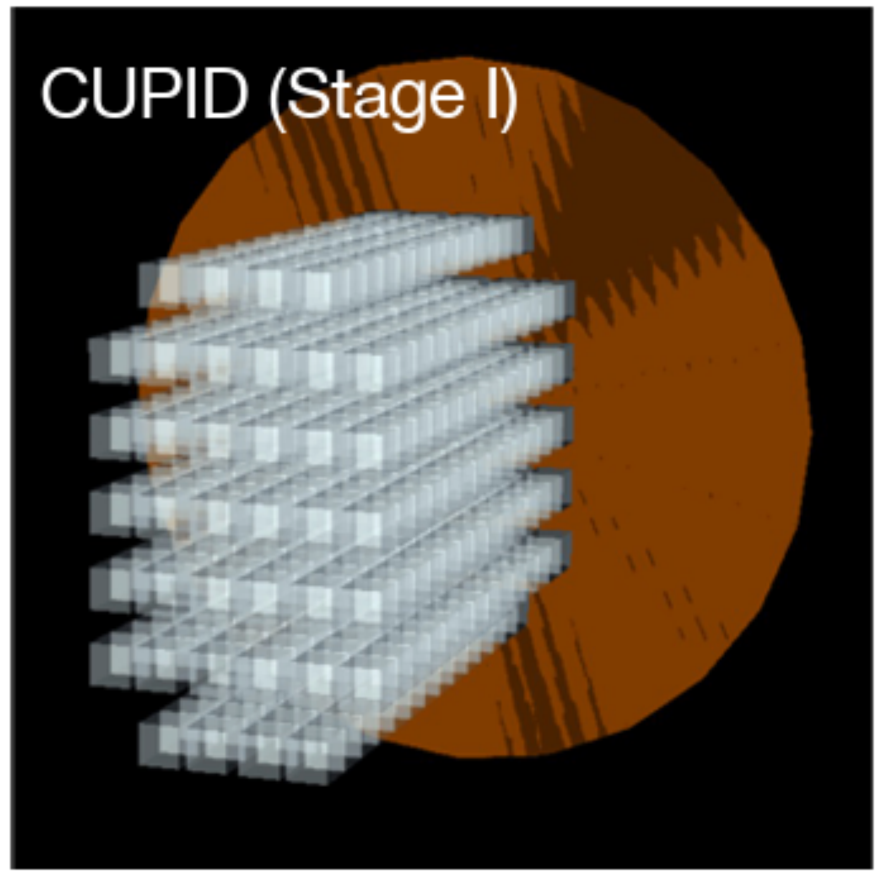




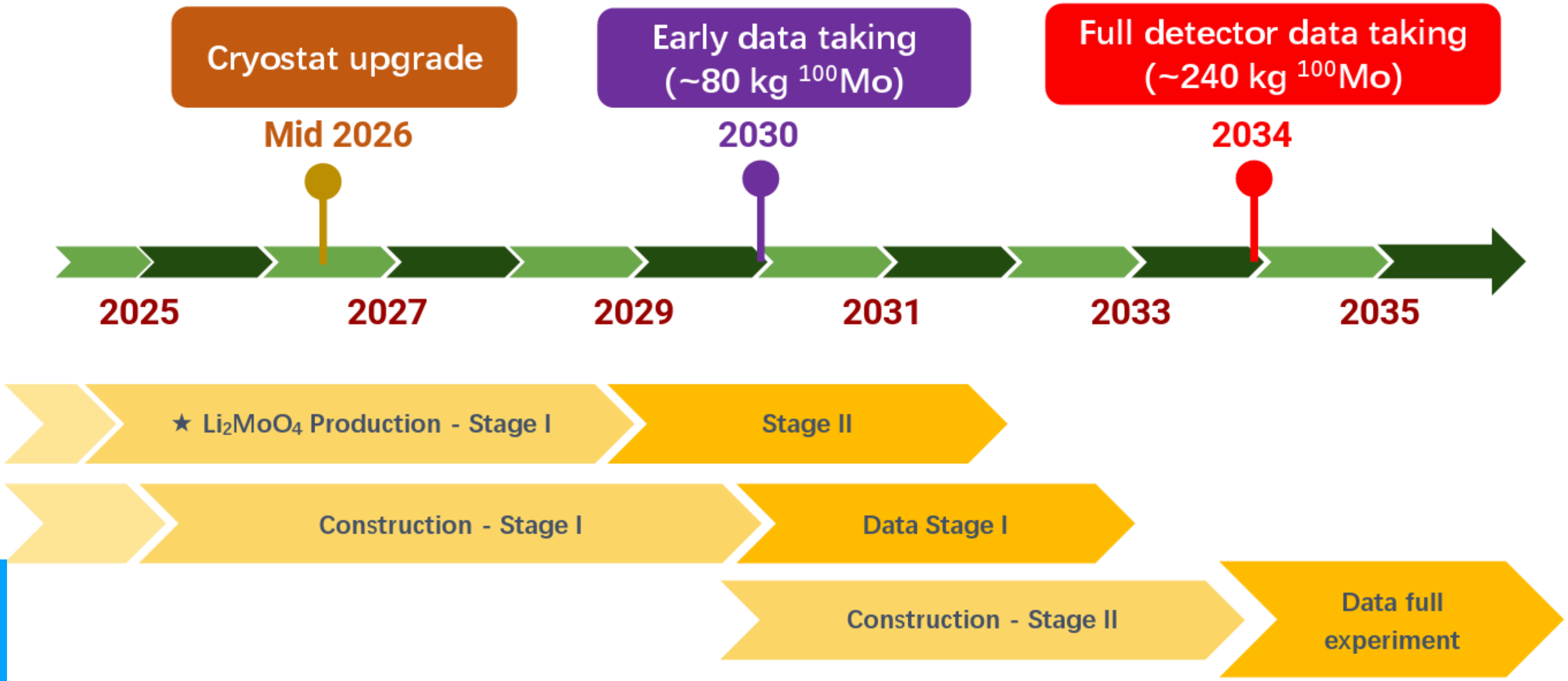


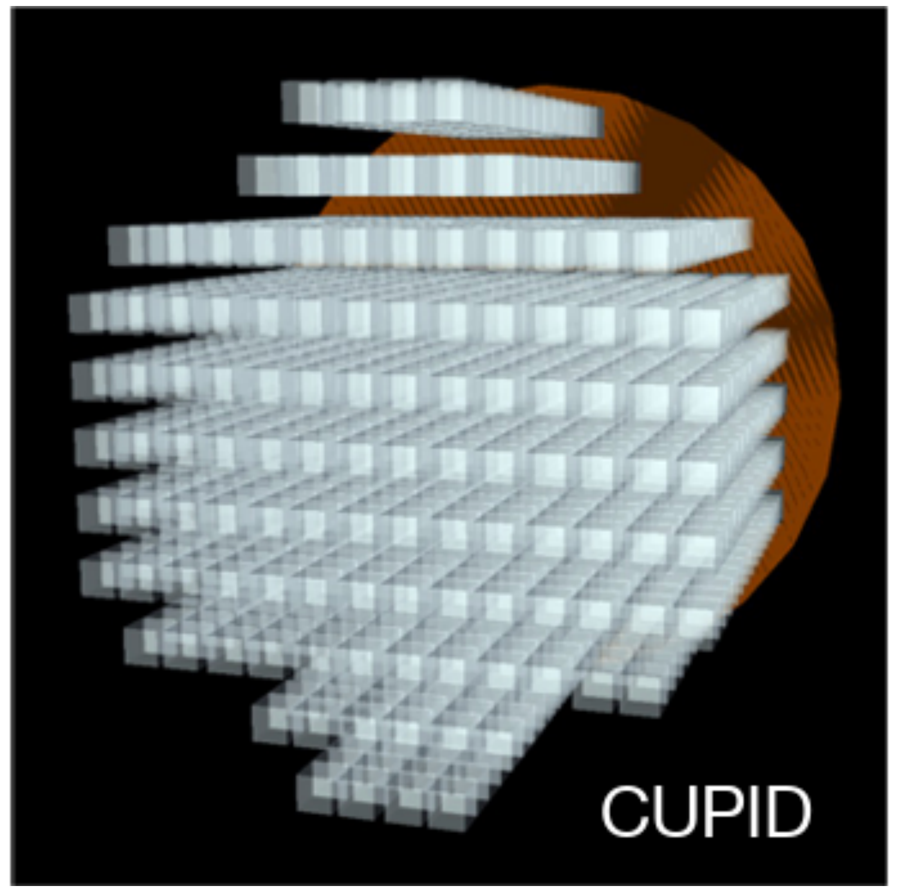


CUPID timeline



- 1/3 of total mass
- 3 years of data taking



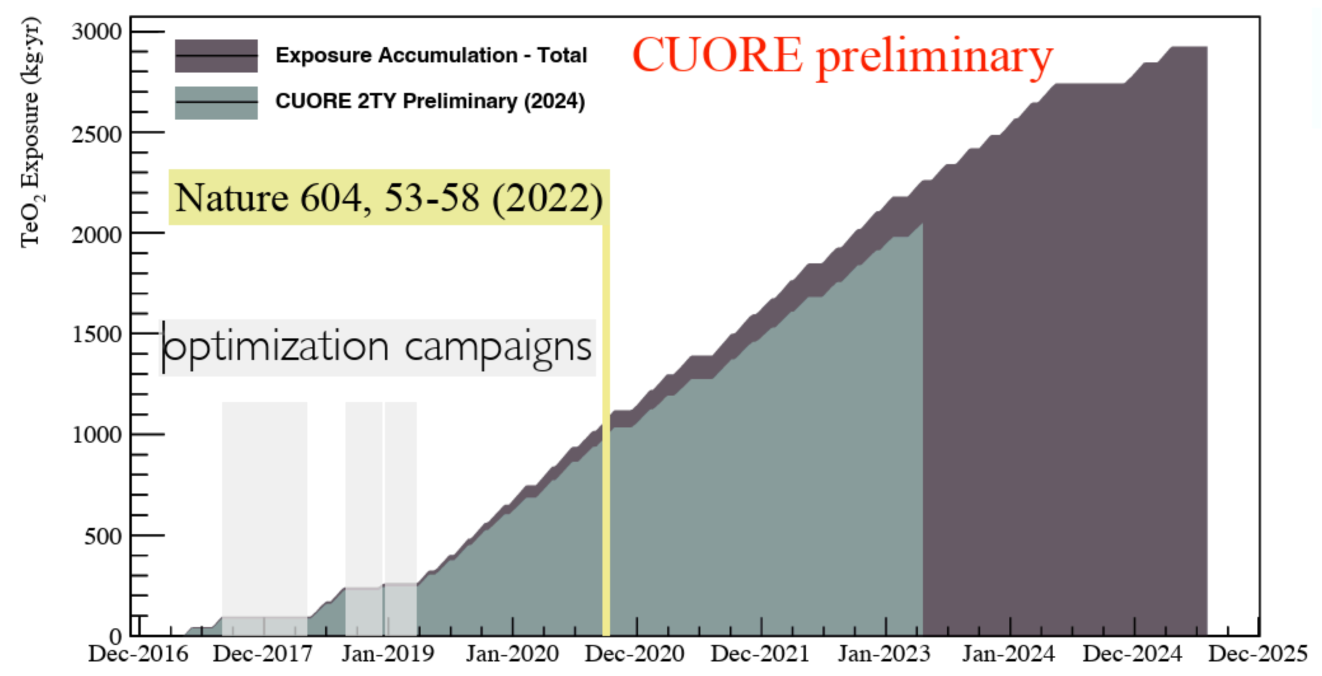


- Full mass (240 kg of ^{100}Mo)
- Rest of data taking

Summary

Summary

- $0\nu\beta\beta$ is a physically motivated process with major implications
- CUORE has been successfully operating ~1000 cryogenic-detectors since 2017.
- Relevant physics results



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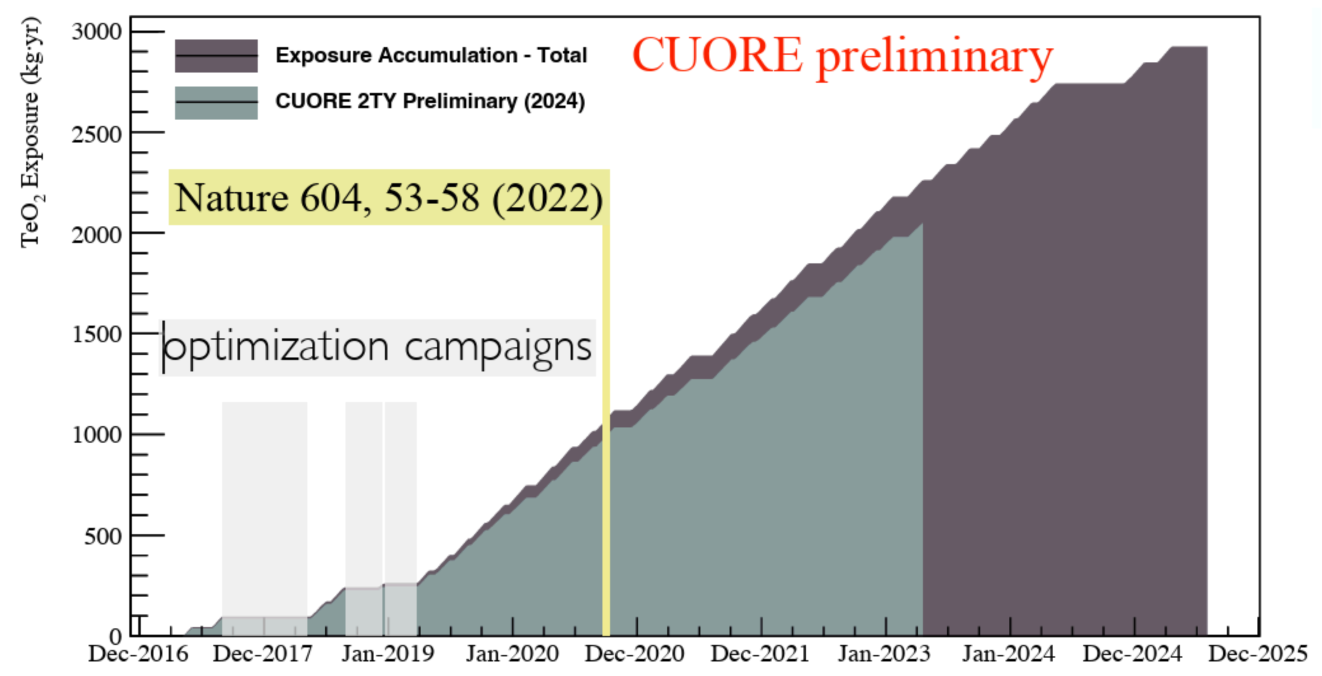
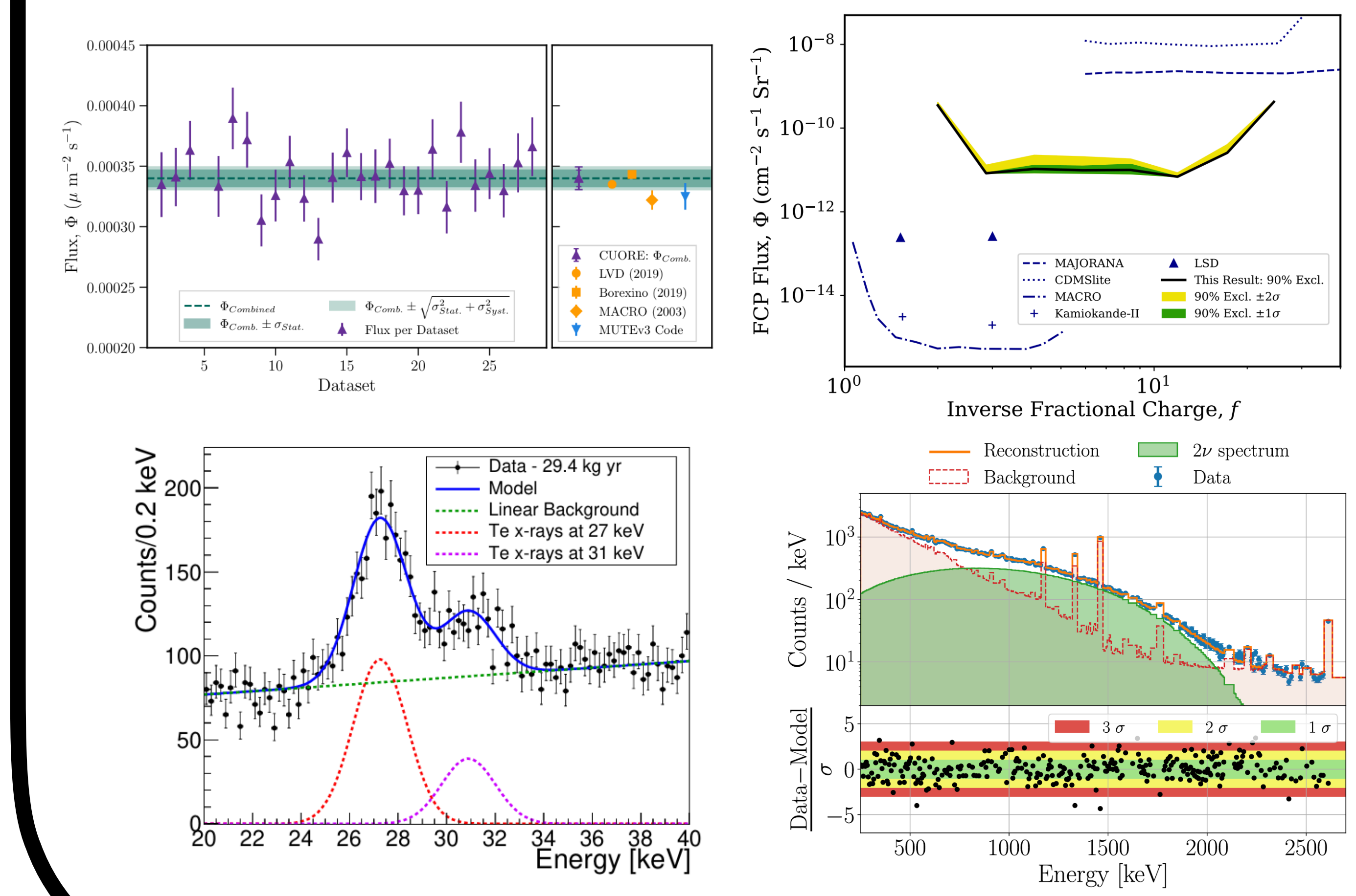


- Several physics analyses beyond flagship analysis
- Important feedback for future experiment CUPID.



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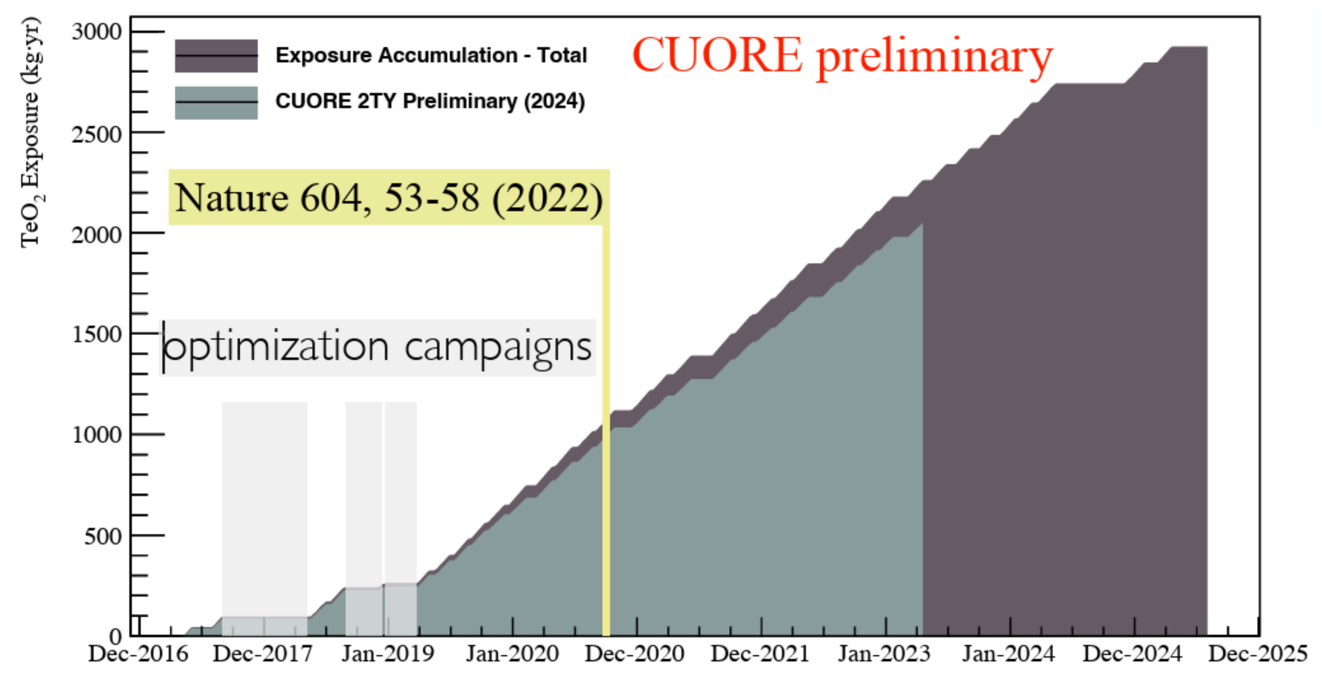

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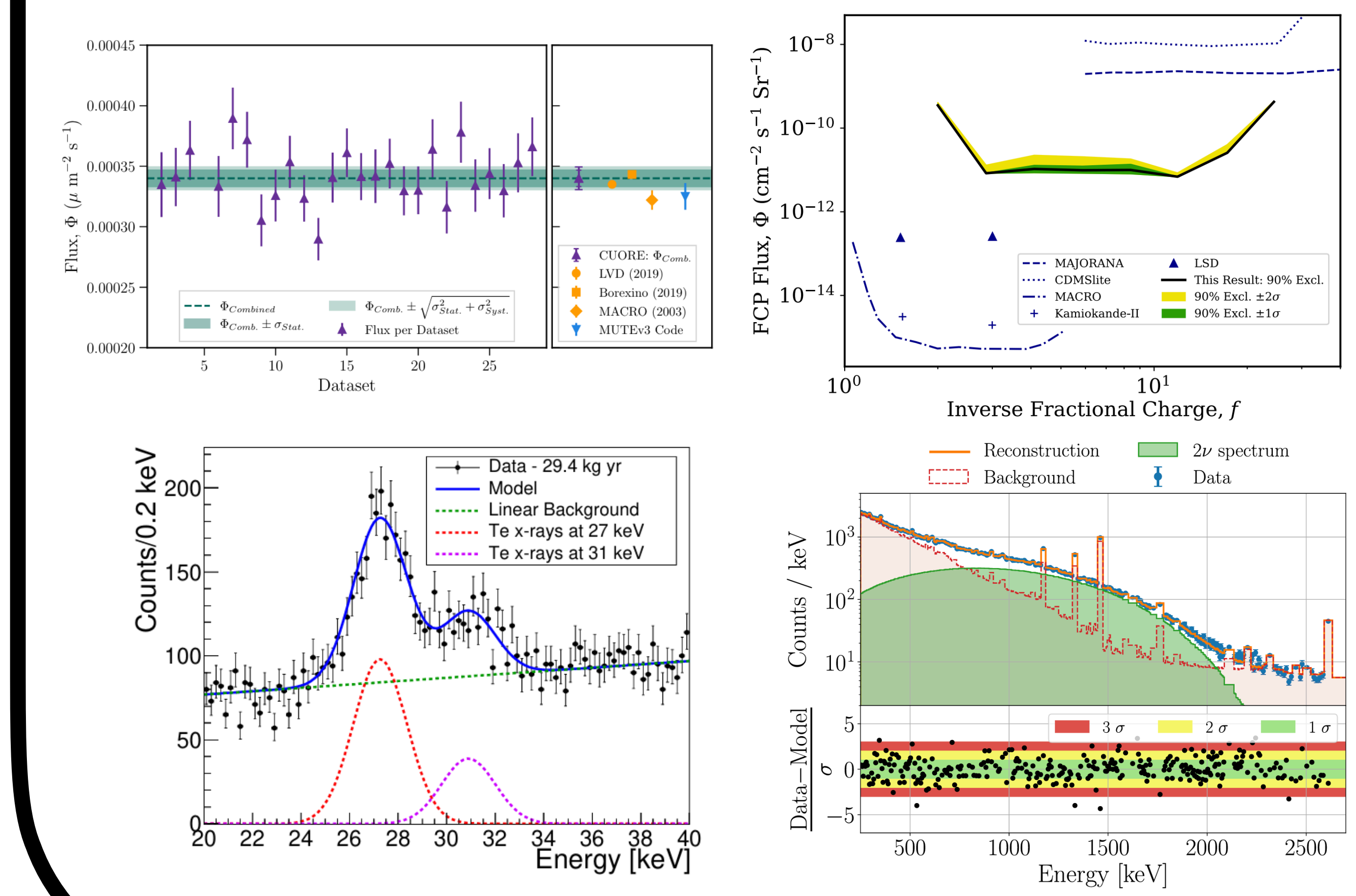
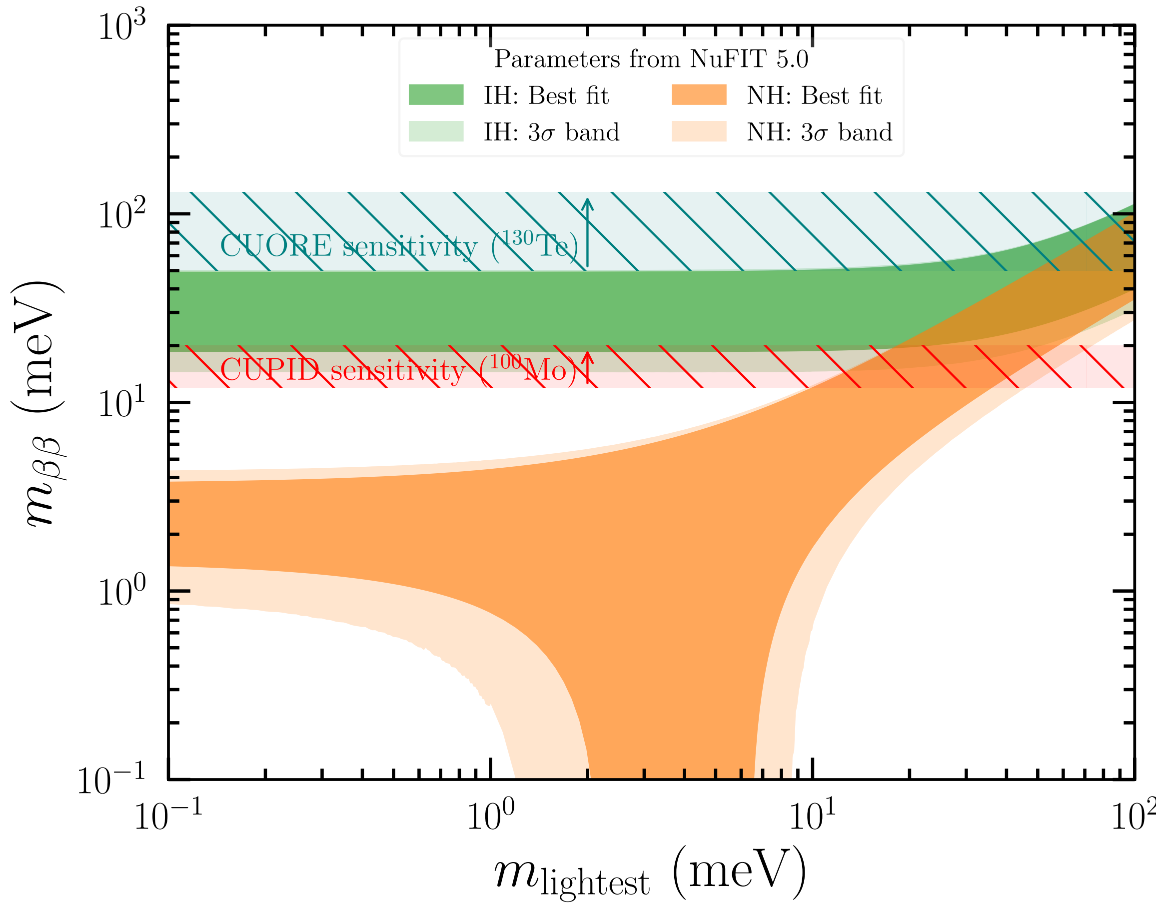


- CUPID moving forward.
- Planning to take data by beginning of next decade.
- CUPID will be among the world-wide suite of $0\nu\beta\beta$ decay experiments with discovery potential.



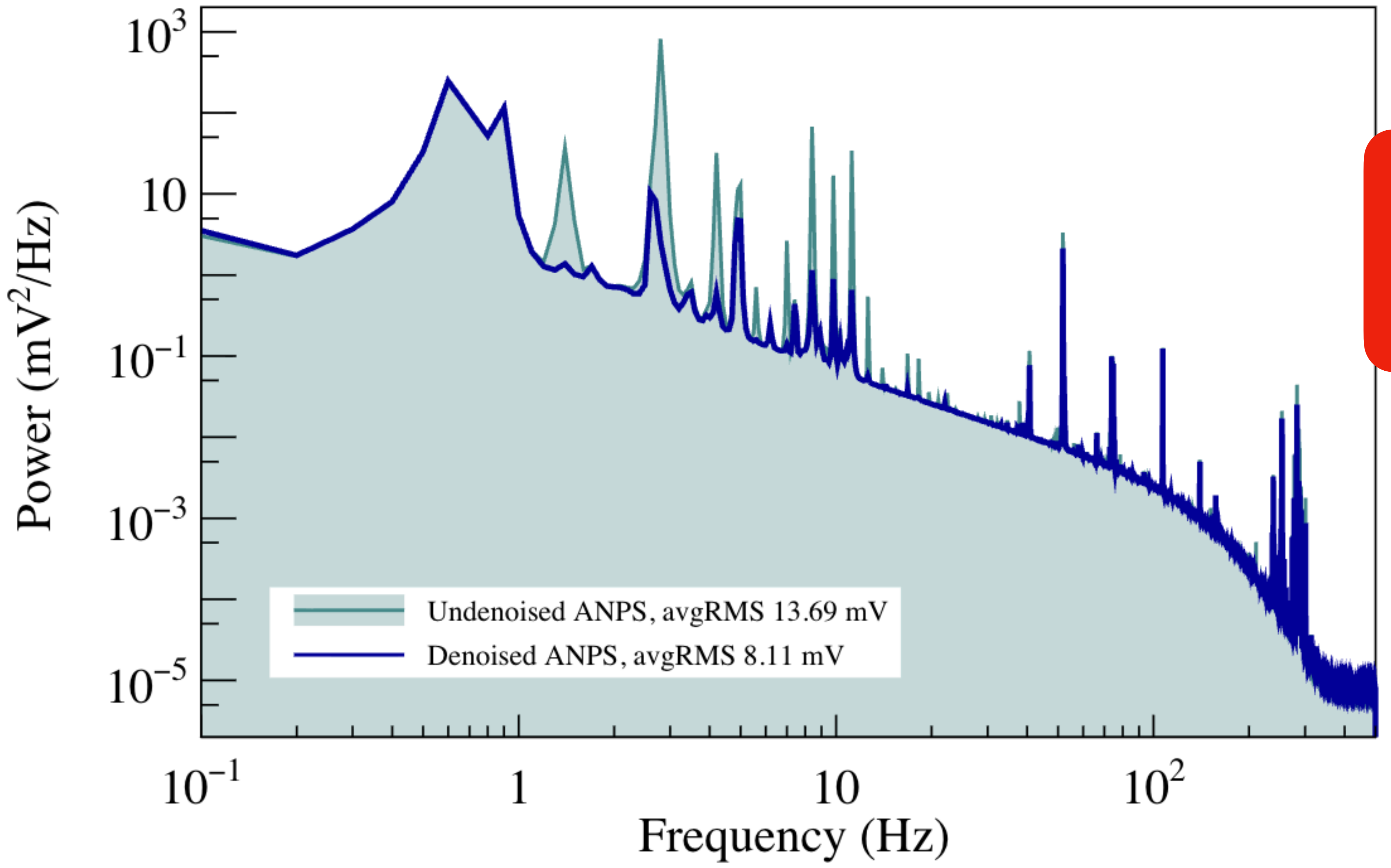
Thanks!


INFN
NSF
CUPID
UCLA
CAL POLY
IMM BOLOGNA UNIT
Irfu
BICOCCA
VirginiaTech
Argonne
BERKELEY LAB
UNIVERSITÉ DE LYON
SOUTH CAROLINA
SAPIENZA
UGA Université Grenoble Alpes
Massachusetts Institute of Technology
Northwestern
araid
Yale
CAPA
BOSTON UNIVERSITY
Drexel
G S S I

Backup slides

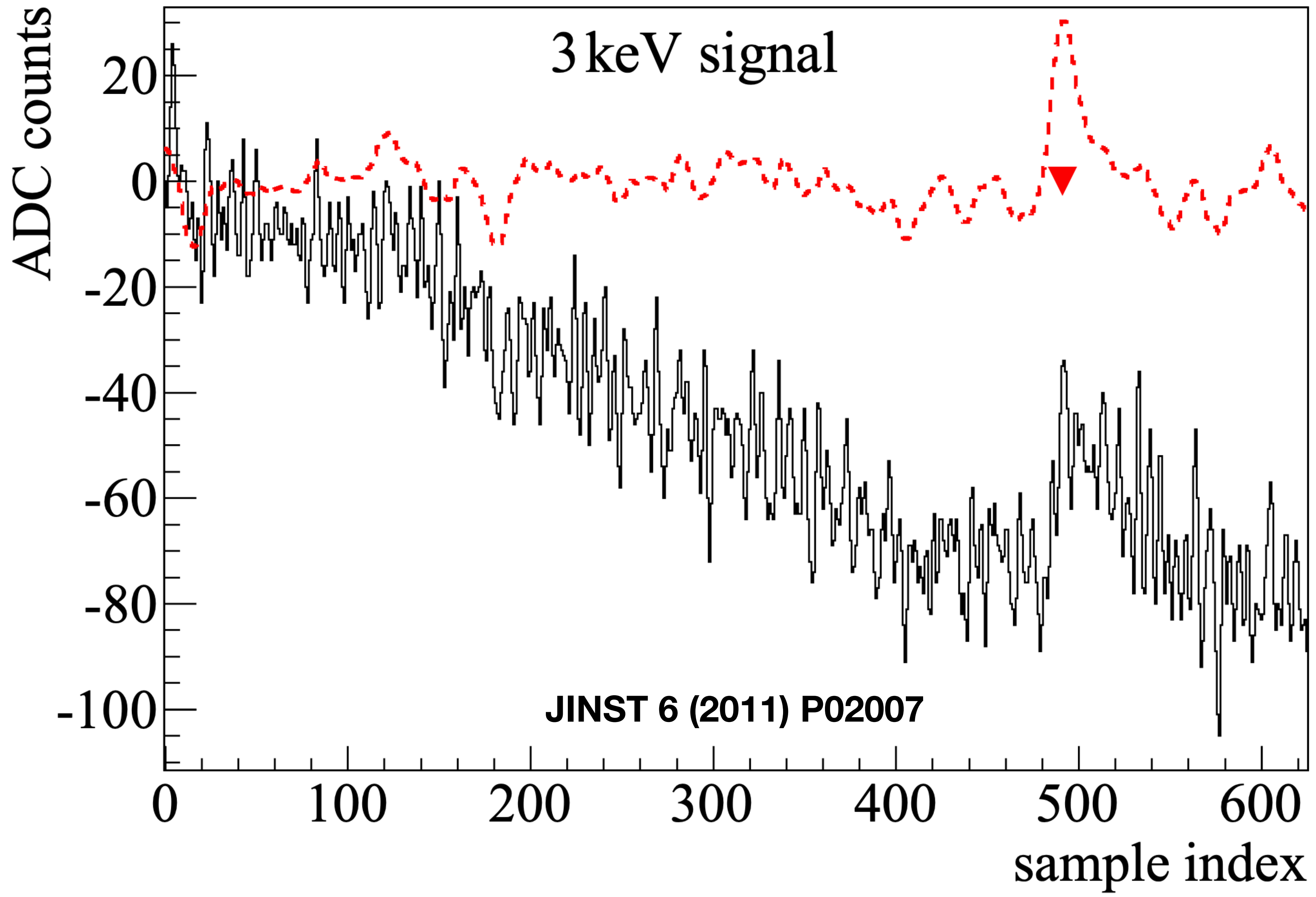
Signal processing

Denoising algorithm



New to analysis.

Optimum trigger algorithm

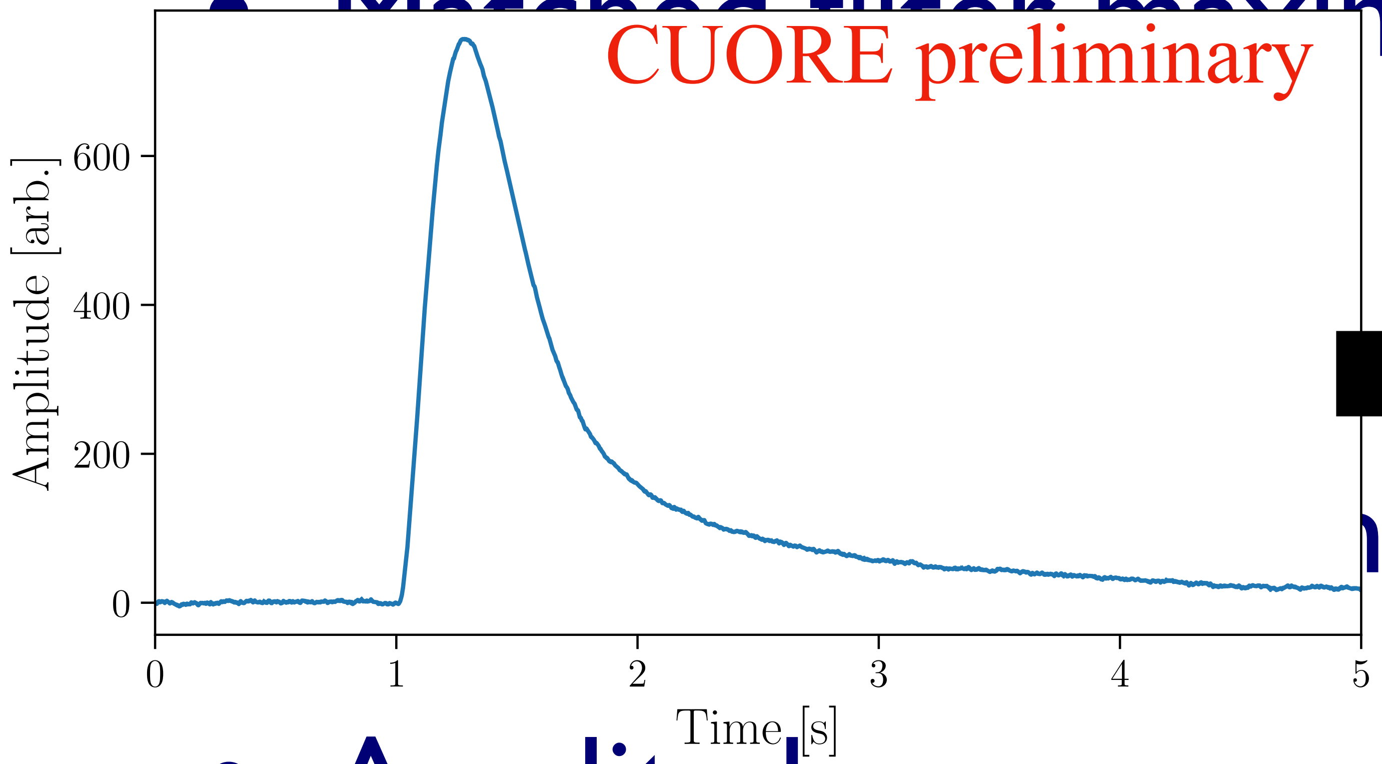


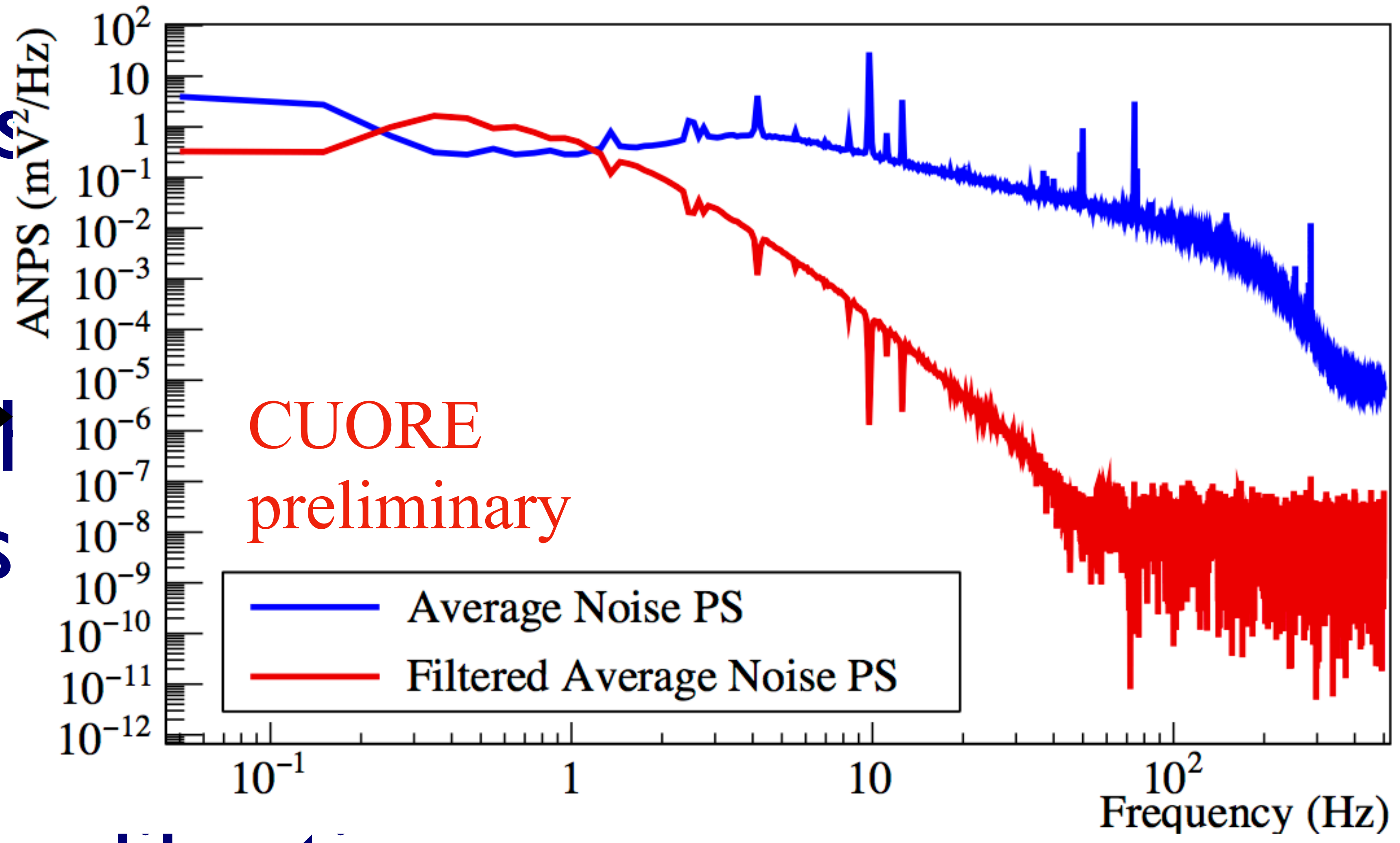
- Mitigation of noise by correlating vibrations with aux. devices (accelerometers, microphones, …)

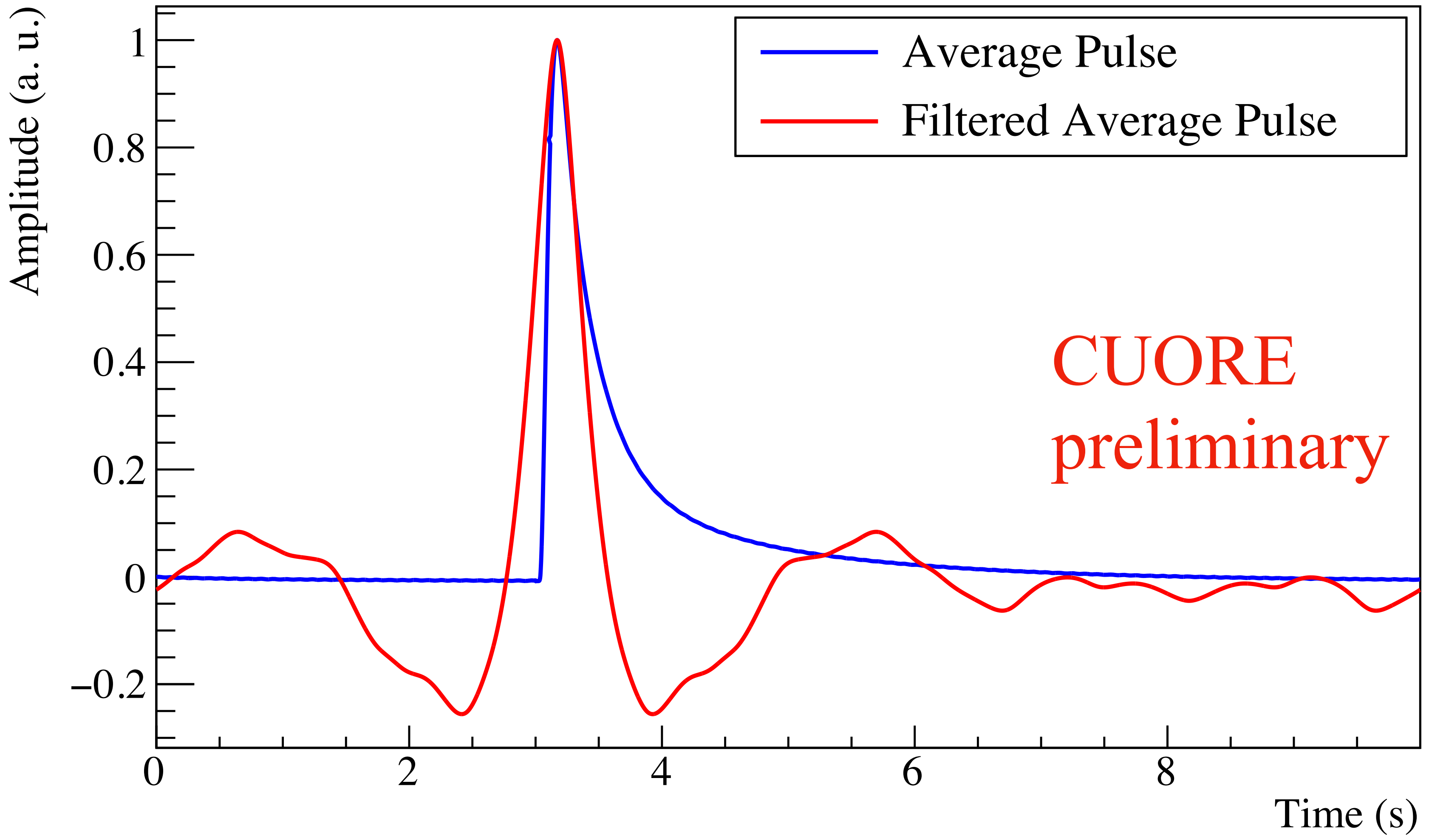
- Application of filter that optimizes SNR using template.
- Identification of pulses and lowering energy thresholds.

Energy reconstruction

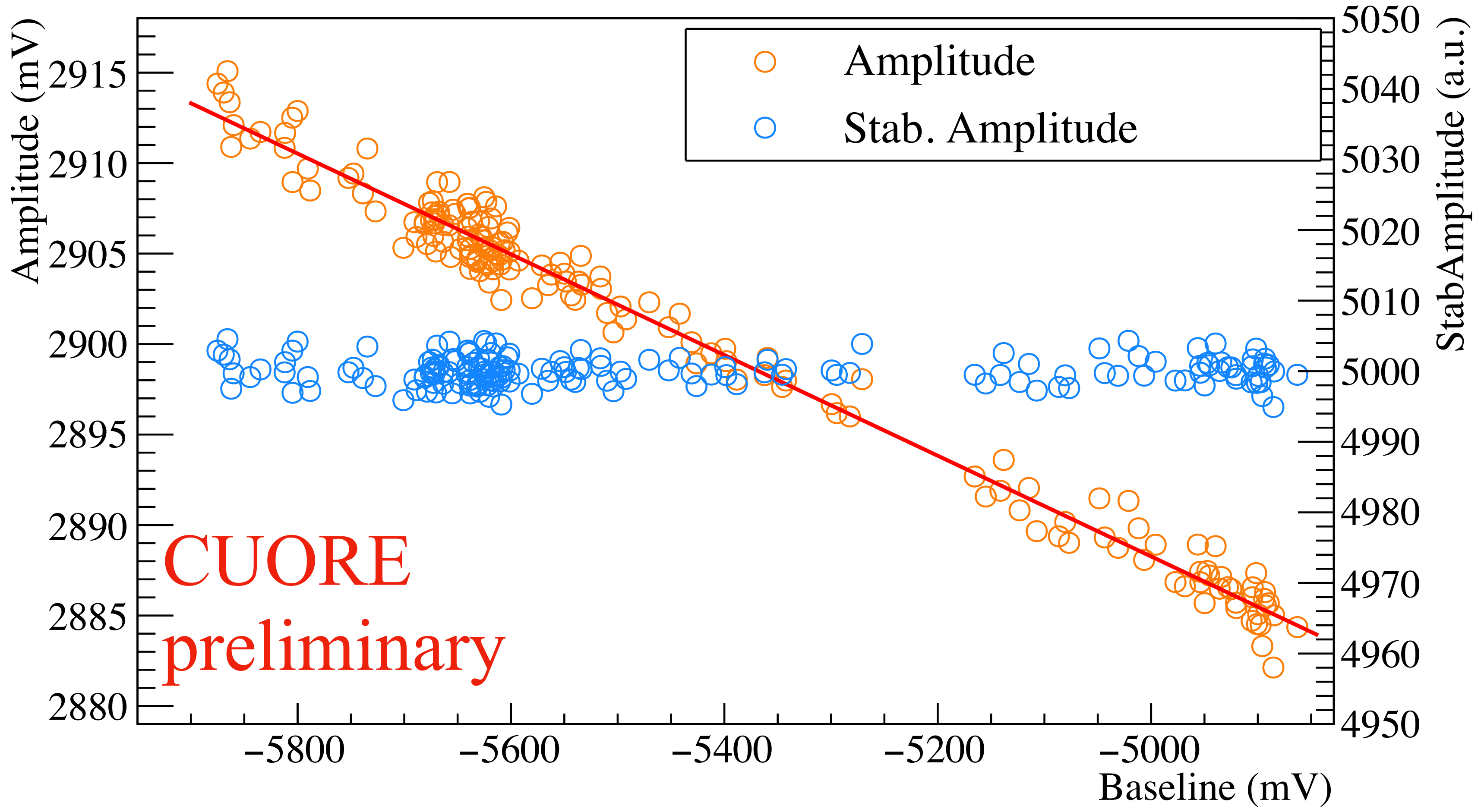
- Matched filter maximizes s… … drifts

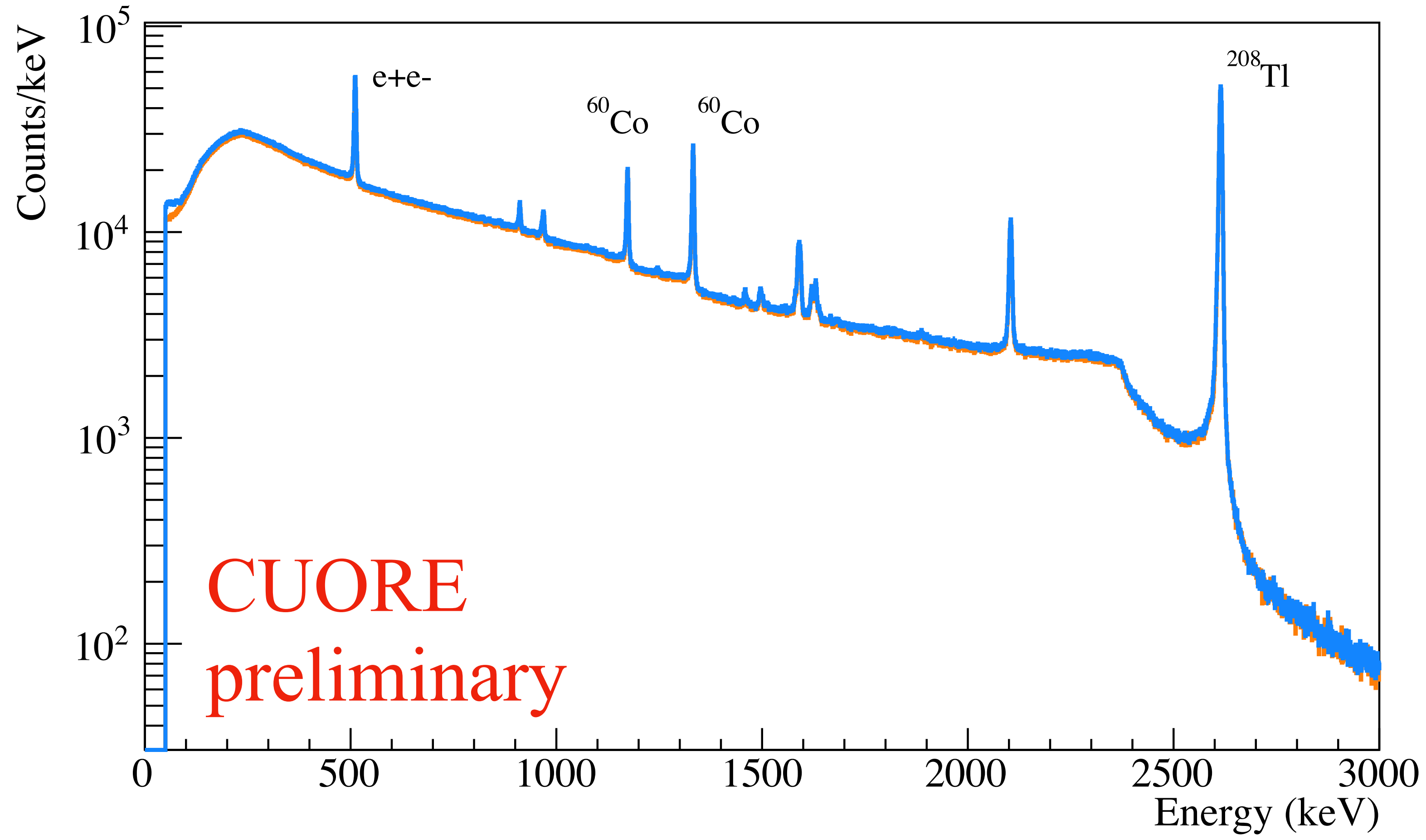






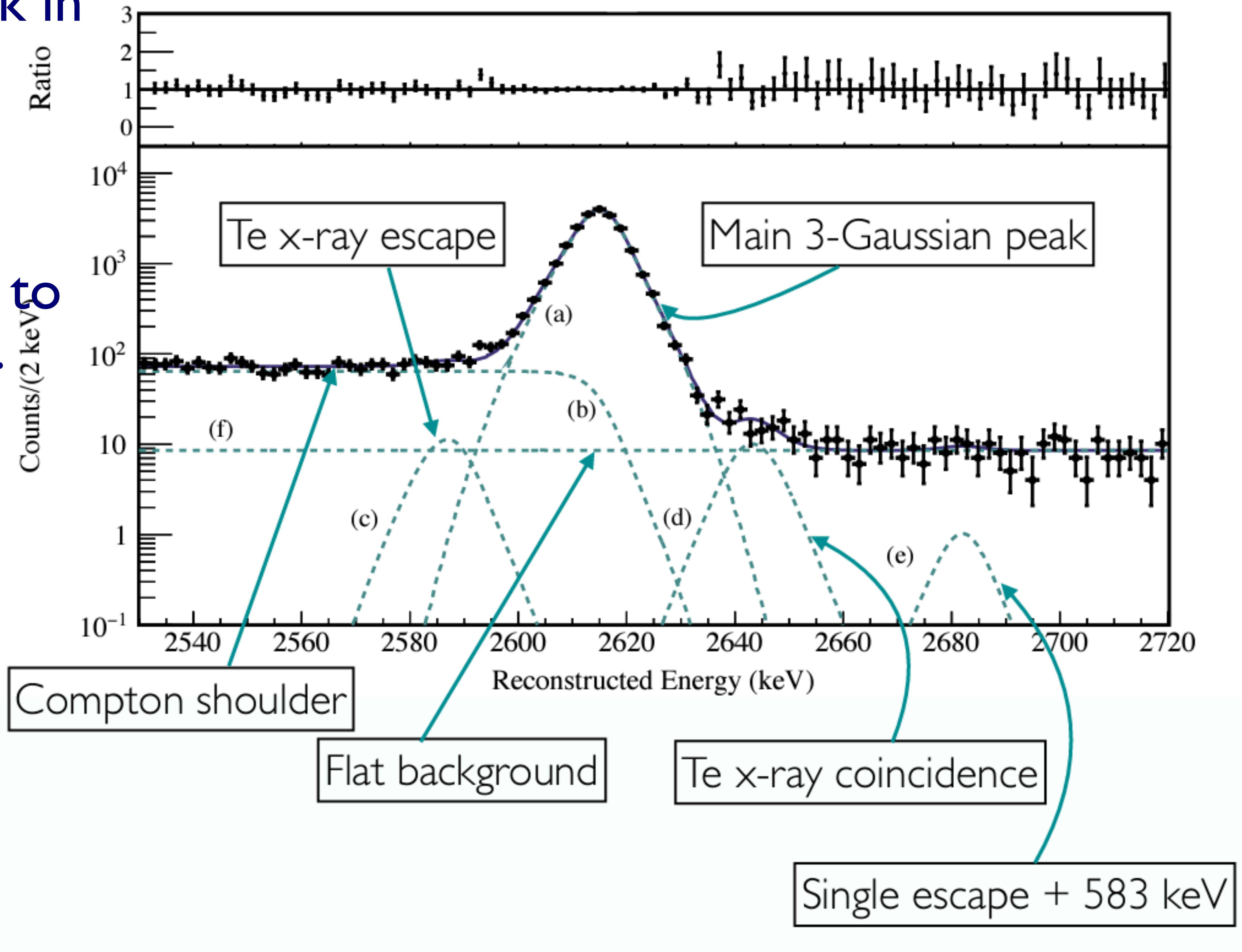
- Amplitudes are converted using peaks from external calibration system (^{232}Th+^{60}Co).





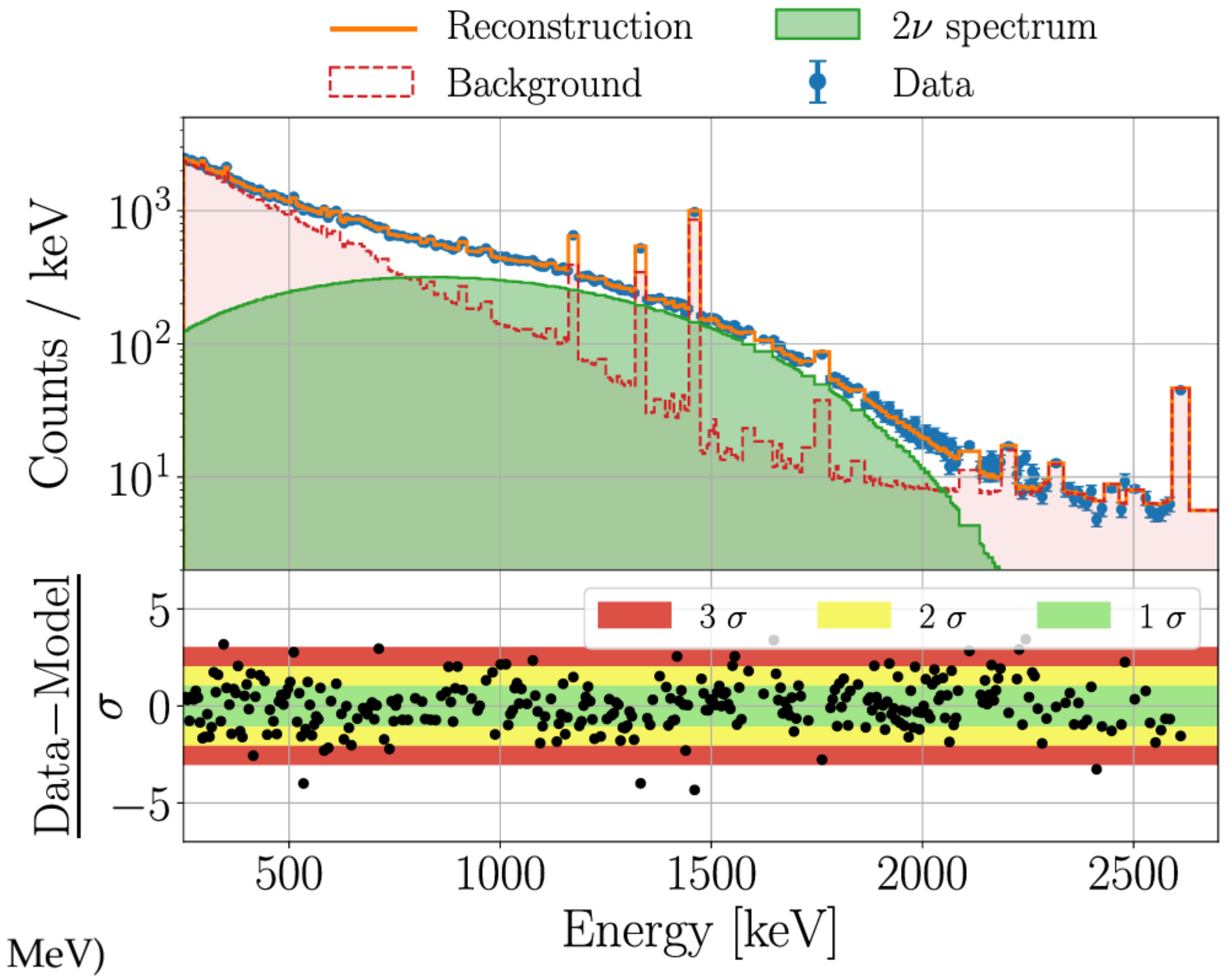
Detector response

- 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 $Q_{\beta\beta}$:
  - $\text{FWHM}\left(Q_{\beta\beta}\right) = 7.310 \pm 0.024\,\text{keV}$
  - $E_{\text{bias}}\left(Q_{\beta\beta}\right) = 0.40^{+0.21}_{-0.44}\,\text{keV}$

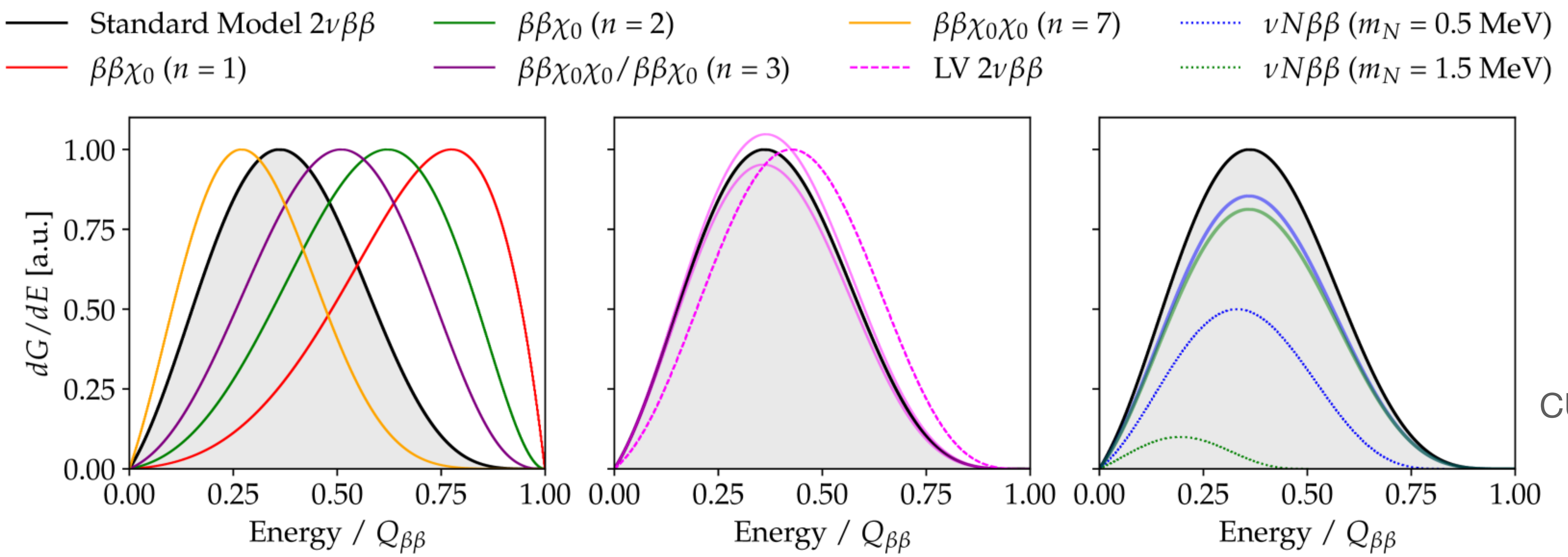


Energy spectrum variations

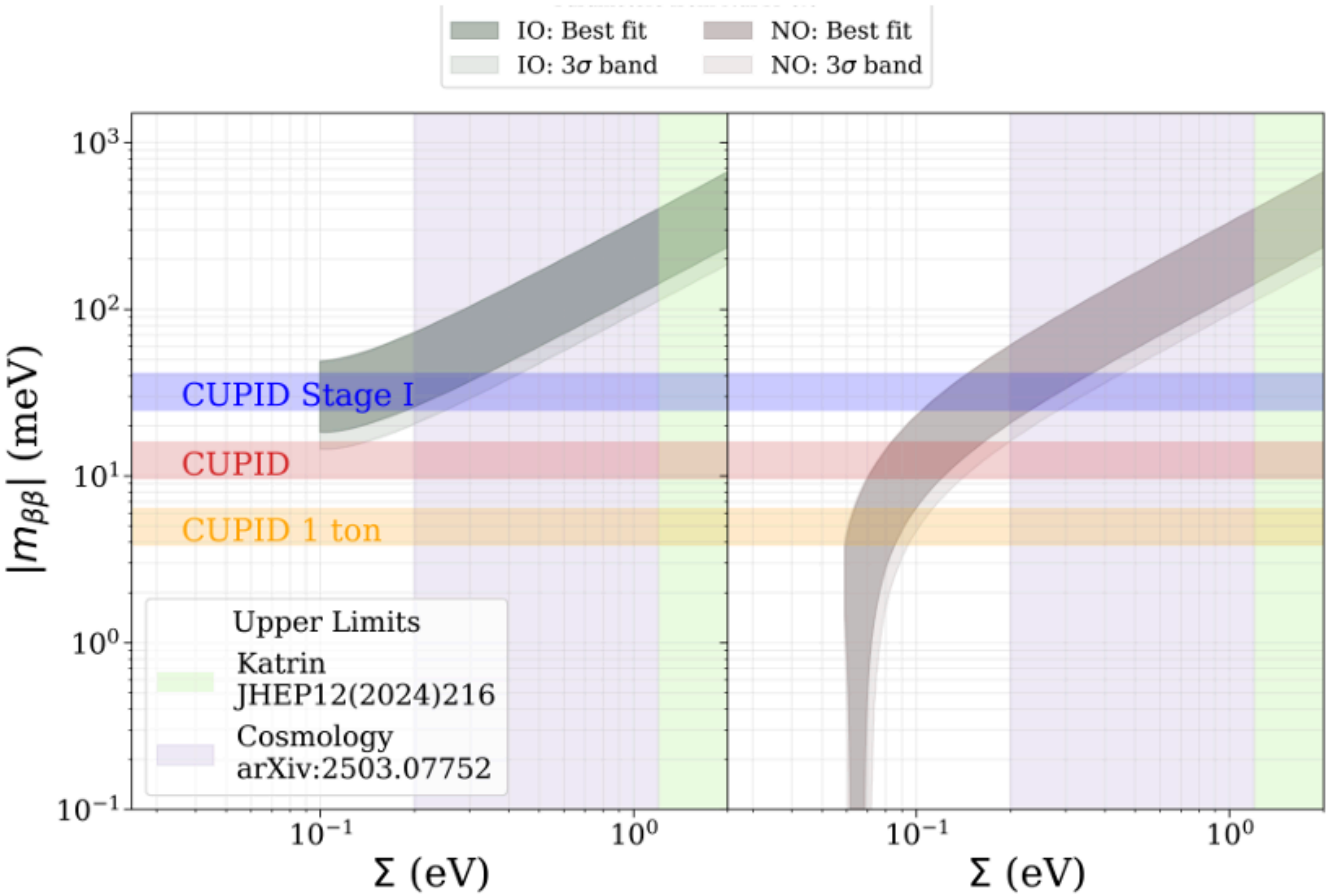
- We have a precise understanding of our spectral shape of the $2\nu\beta\beta$ for Te-130.
- Some BSM processes could have an effect on the energy spectrum of the $2\nu\beta\beta$ decay mode.
- We can study different models with our data



CUORE collab, arXiv:2503.24137v1

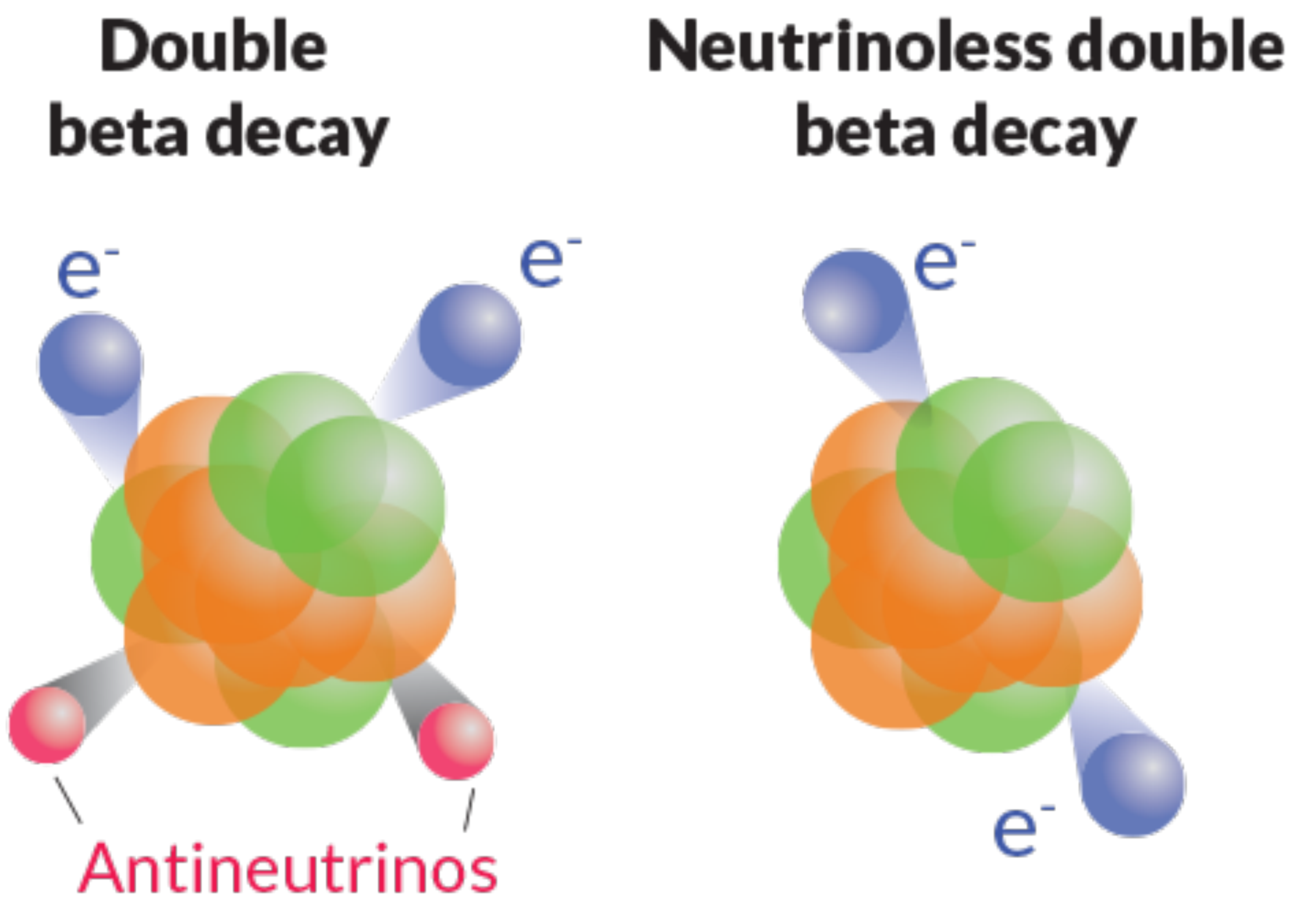


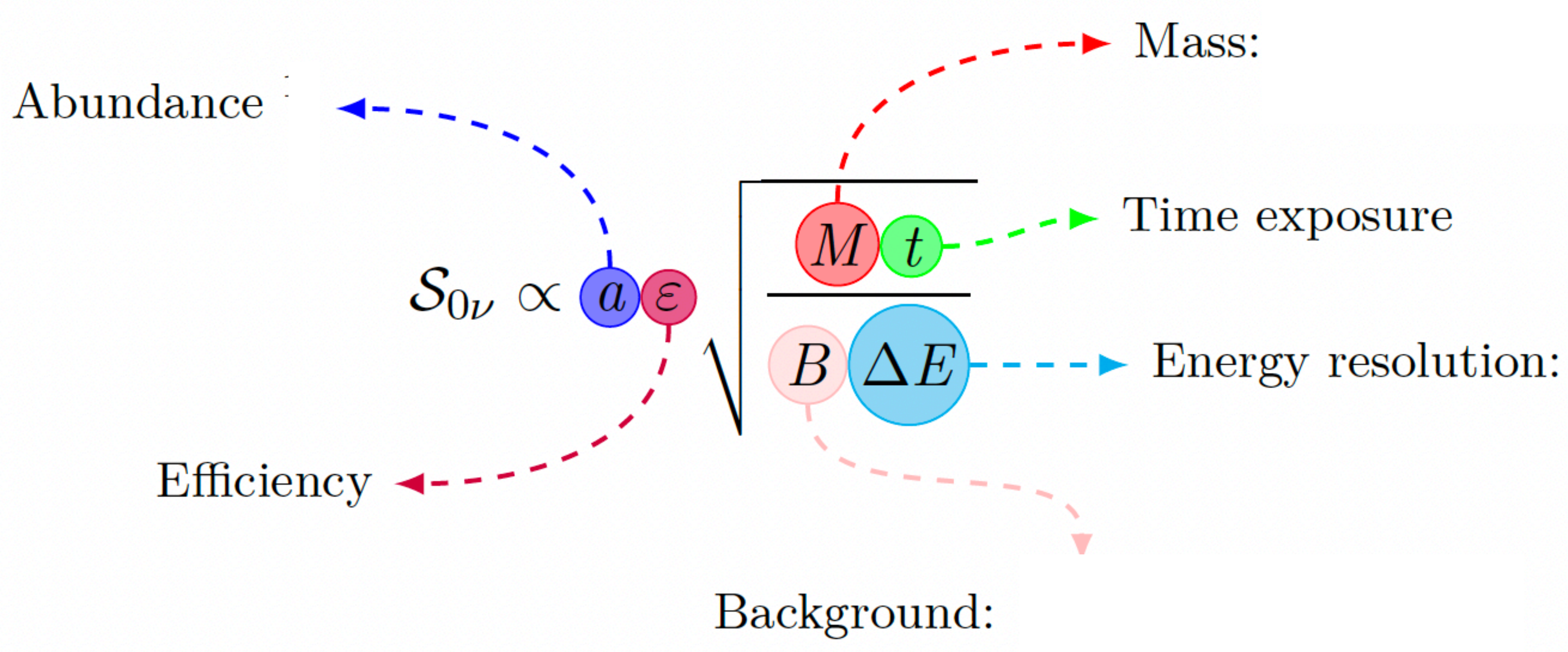
CUPID-Mo, arXiv:2405.10766v2


IO: Best fit
IO: 3σ band
NO: Best fit
NO: 3σ band
$|m_{\beta\beta}|$ (meV)
CUPID Stage I
CUPID
CUPID 1 ton
Upper Limits
Katrin
JHEP12(2024)216
Cosmology
arXiv:2503.07752
Σ (eV)
Σ (eV)

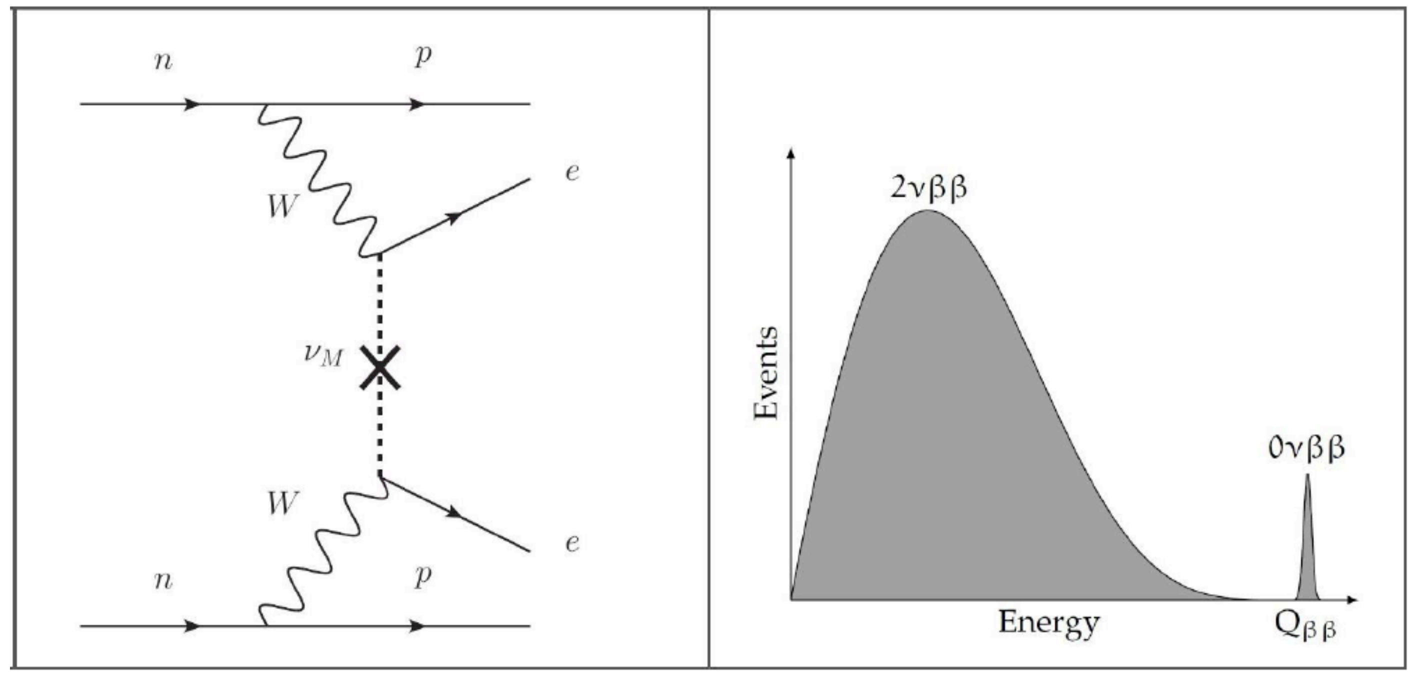
Neutrinoless double beta ($0\nu\beta\beta$) decay

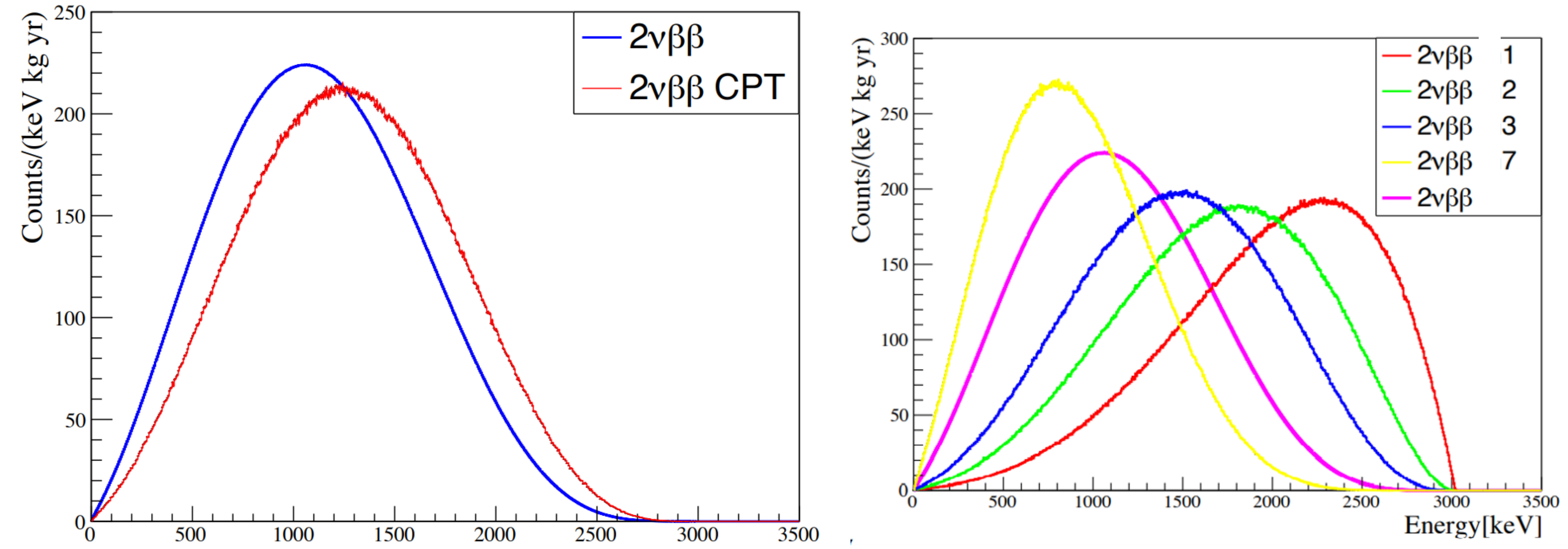
- Observation of $0\nu\beta\beta$ decay implies that neutrinos are Majorana.
- Decay rate proportional to effective Majorana mass
- $0\nu\beta\beta$ signal is a peak at Q-value.
- Sensitivity limited by backgrounds (inverse square root).
- Experiments currently taking data, next generation being planned

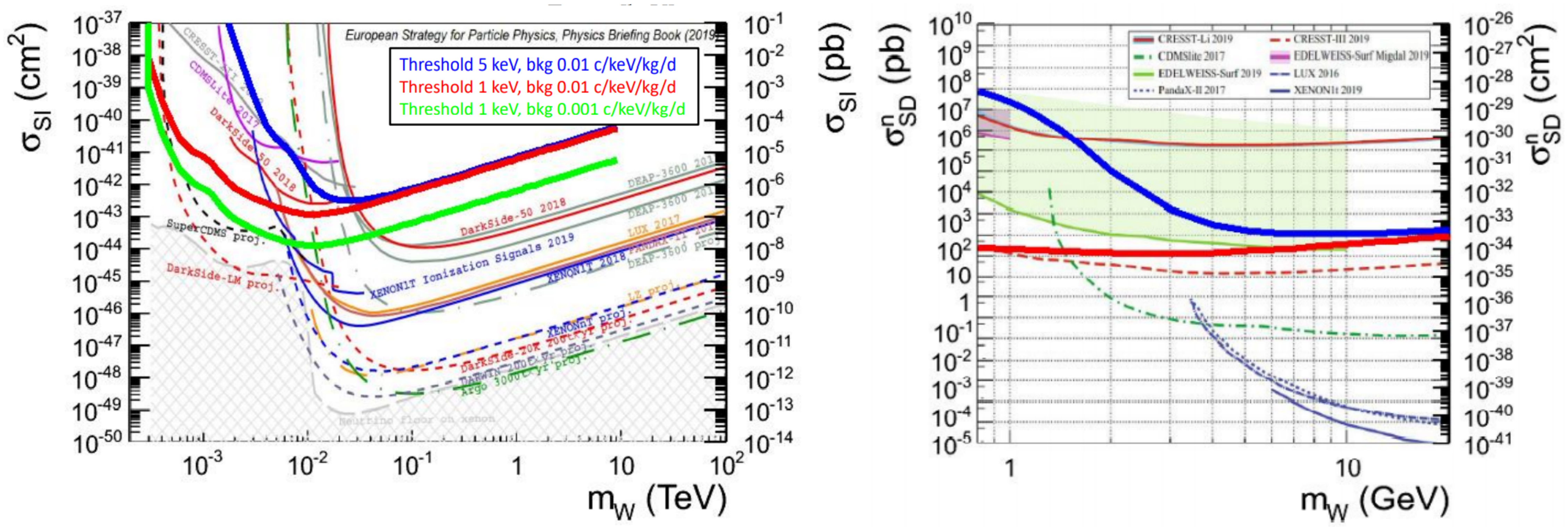




CUPID science program







Search for 0vββ decay

Precision two-neutrino double beta decay

$2\nu\beta\beta$ and $0\nu\beta\beta$ decays to excited states

Majoron-emitting decays

Tests of Lorentz invariance and CPT violation

Tests of fundamental principles

- Electric charge conservation
- Verification of the Pauli exclusion principles

Tri-nucleon decay and baryon number conservation

Light dark matter searches

Supernova neutrino searches

Solar axion searches

Millicharged particles

Neutrinos as backgrounds

- Neutrino Charged Current Interaction

$$\nu + {}^{100}\mathrm{Mo} \rightarrow {}^{100}\mathrm{Tc} + e^- + \gamma(\mathrm{s}) \qquad (1)$$

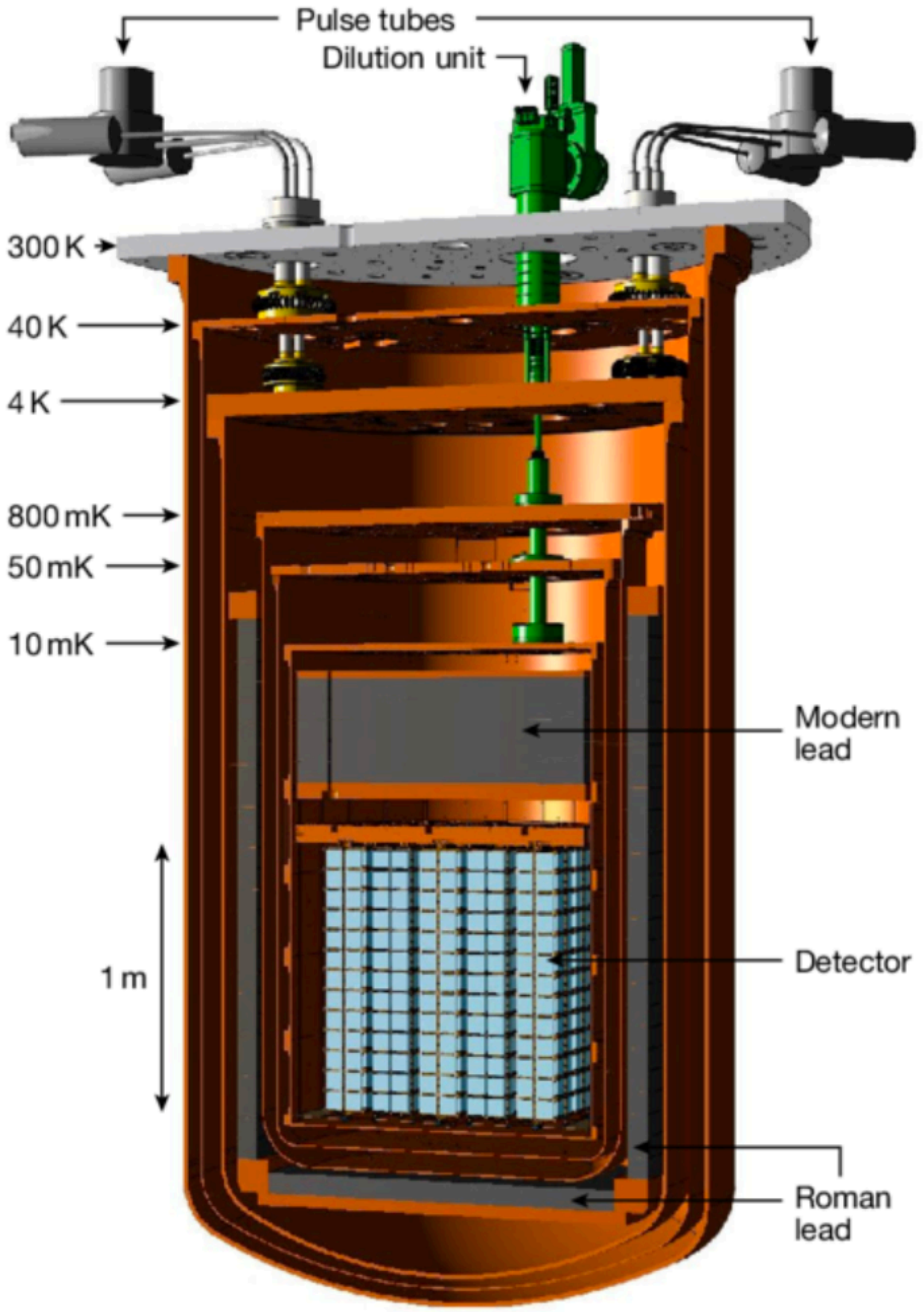
$$ {}^{100}\mathrm{Tc} \rightarrow {}^{100}\mathrm{Ru} + e^- + \bar{\nu} \quad (Q = 3.2\,\mathrm{MeV}, t_{1/2} = 15s) \qquad (2)$$

  – Ejiri and Elliott (2017) use a similar procedure as de Barros & Zuber to estimate the rates for all solar ν sources:
    - Backgrounds from (2) contribute ~1×10^{-6} counts/(keV · kg · yr)
    - Backgrounds from (1) are 2-3 orders of magnitude below (2)

  – Delayed coincidence cuts to reduce this further

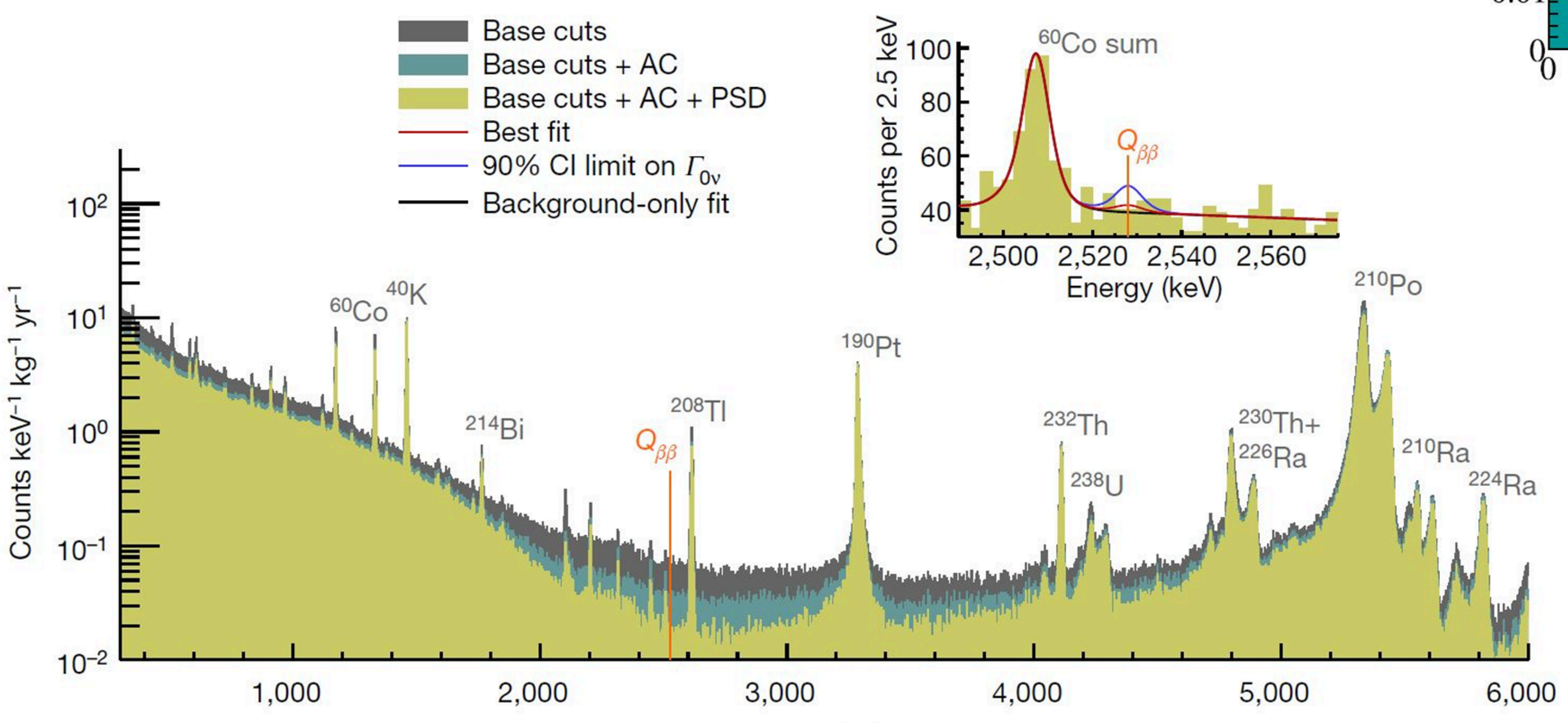
Cryostat

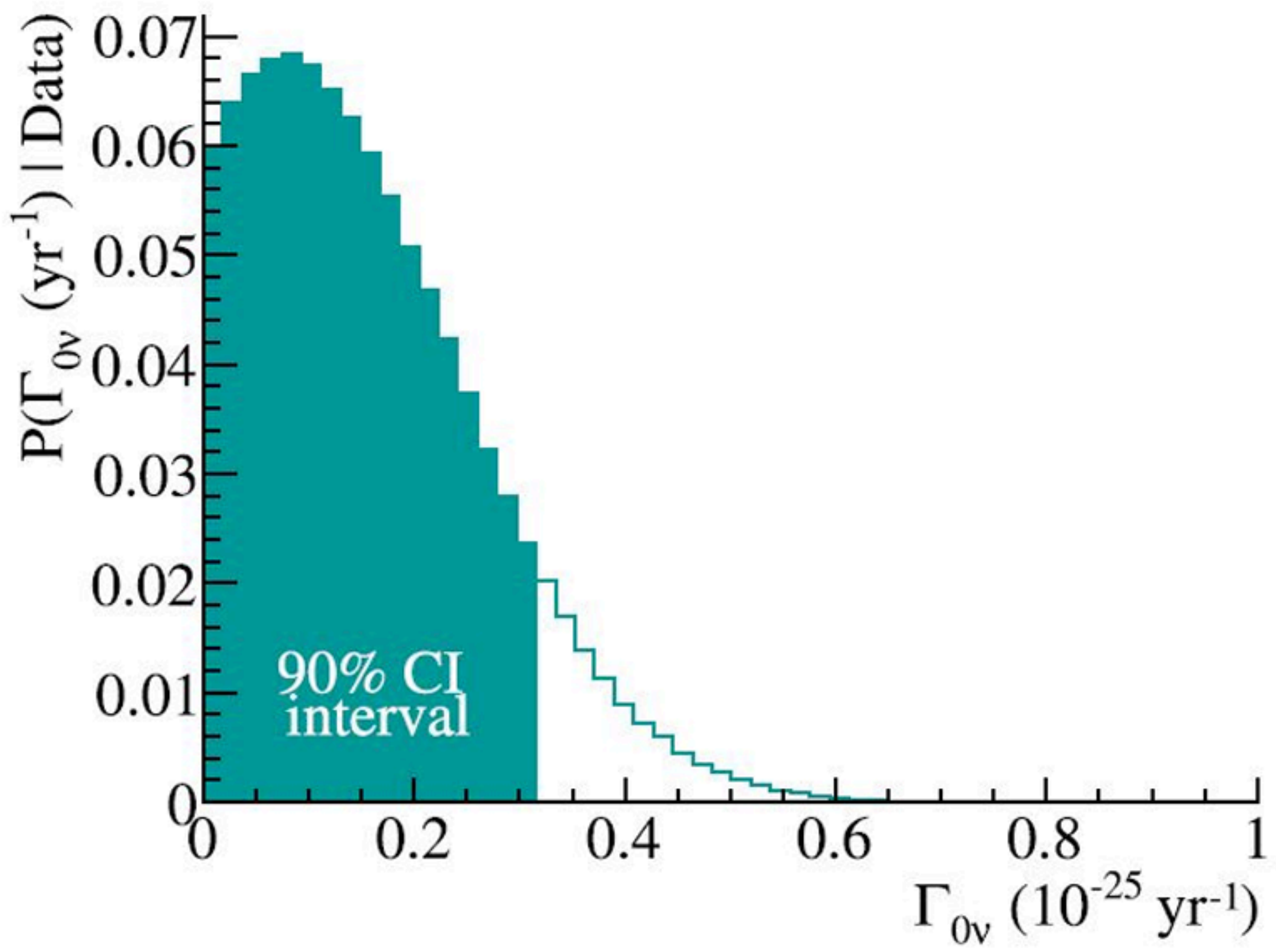
- Cryogen-free cryostat
- Cools down ~1 ton detector to ~10 mK
- Mechanically decoupled for extremely low vibrations
- PT to cool down to ~4K
- Dilution refrigerator down to operating temperature ~10 mK
- Nominal cooling power: 4 μW @ 10mK
- Cryostat total mass ~30 tons
- Mass at T < 4K: ~15 tons
- Mass at T < 50 mK: ~3 tons (Pb, Cu and TeO2)



The CUORE 1TY Result

See: *Nature* **604,** 53–58 (2022)





Best Fit Value:

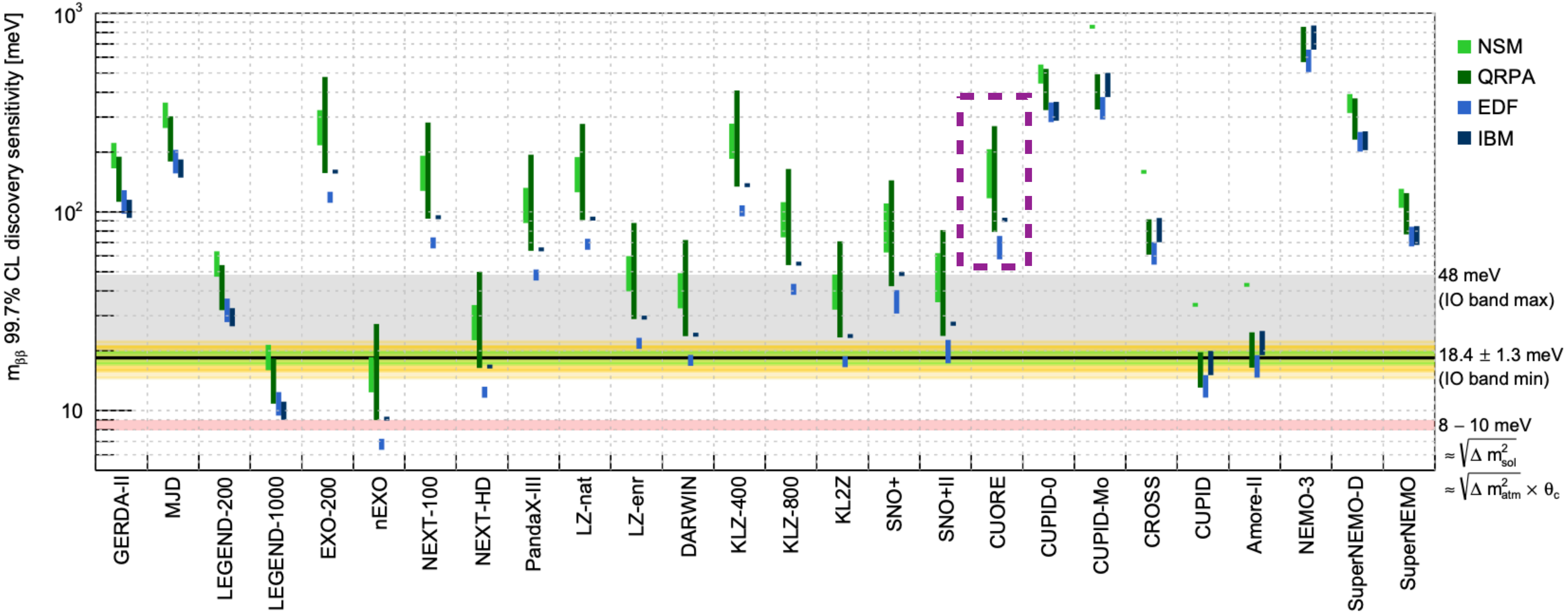
$\Gamma_{0\nu} = (0.9 \pm 1.4) \times 10^{-26}$ / yr

Bayesian 90% CI Limit:

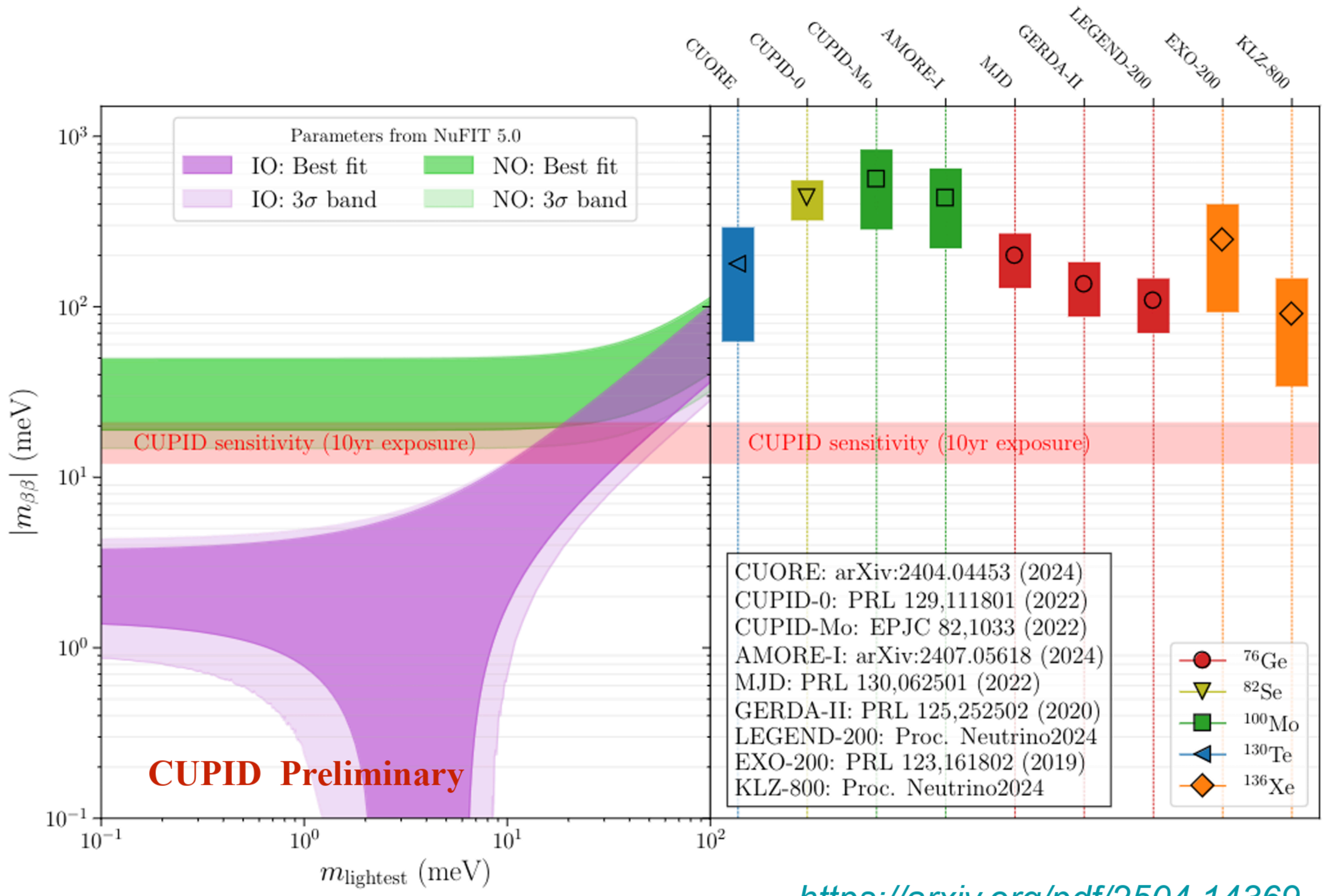
$T_{1/2} > 2.2 \times 10^{25}$ yr

Frequentist 90% CI Limit:

$T_{1/2} > 2.6 \times 10^{25}$ yr



$m_{\beta\beta}$ 99.7% CL discovery sensitivity [meV]
10^3
10^2
10
NSM
QRPA
EDF
IBM
48 meV
(IO band max)
18.4 ± 1.3 meV
(IO band min)
8 – 10 meV
$\approx \sqrt{\Delta m^2_{sol}}$
$\approx \sqrt{\Delta m^2_{atm}} \times \theta_c$
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
PandaX-III
LZ-nat
LZ-enr
DARWIN
KLZ-400
KLZ-800
KL2Z
SNO+
SNO+II
CUORE
CUPID-0
CUPID-Mo
CROSS
CUPID
Amore-II
NEMO-3
SuperNEMO-D
SuperNEMO

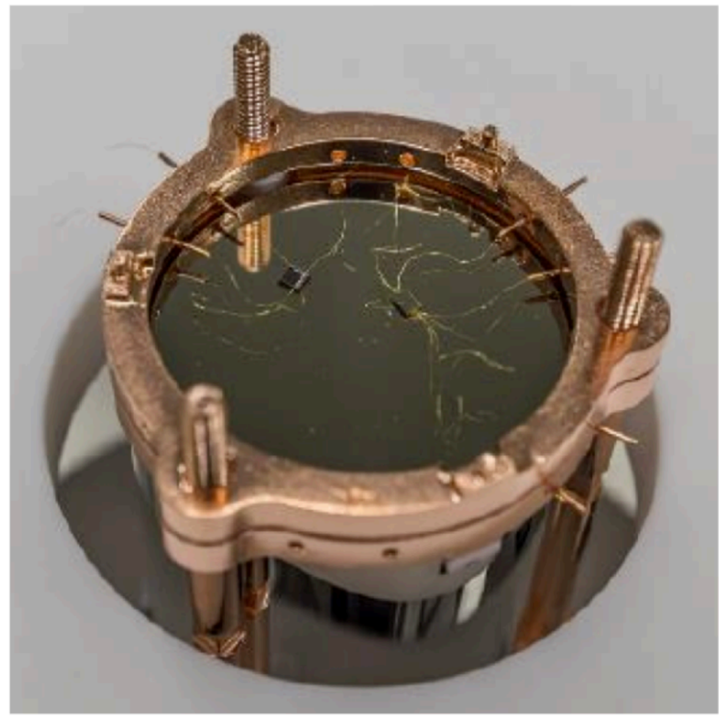


https://arxiv.org/pdf/2504.14369

10 kg-scale demonstrators

CUPID-0

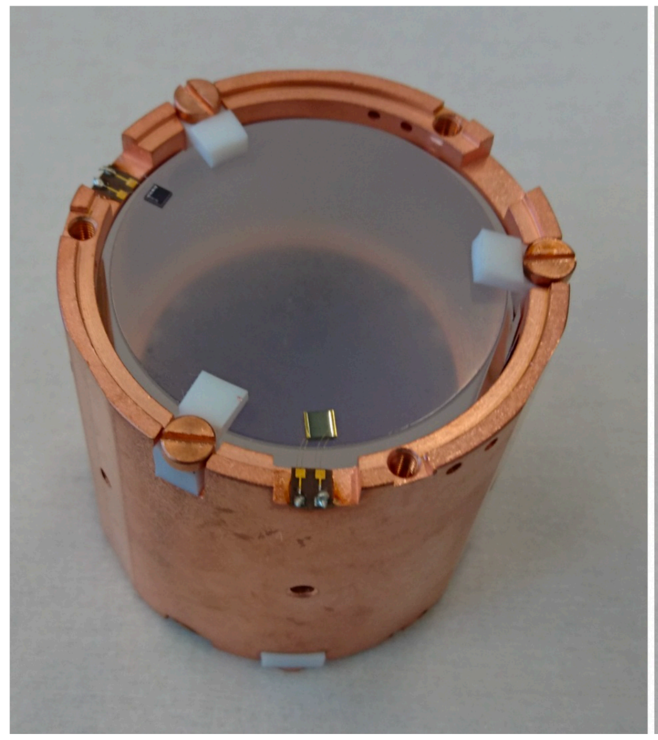
- $Zn^{82}Se$ crysta … chment ^{82}Se (5.17 kg) at LNGS (Italy)
- α-rejection efficiency > 99.9%
- Background index: 3.5×10^{-3} ccky
- $\Delta E = 21.8$ keV @ $Q_{\beta\beta}$ (2998 keV)
- Physics results
- Bkg studies

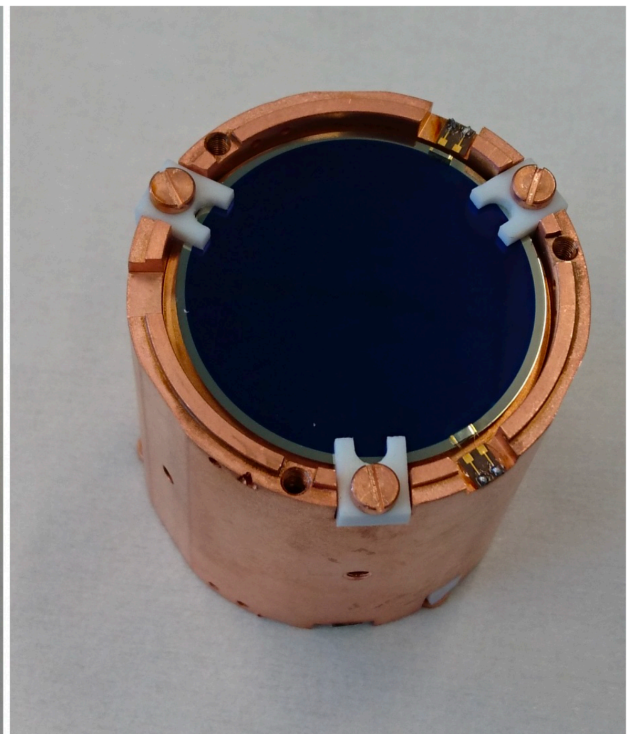


Phys. Rev. Lett. 129, 111801

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)
- Physics results
- Bkg studies

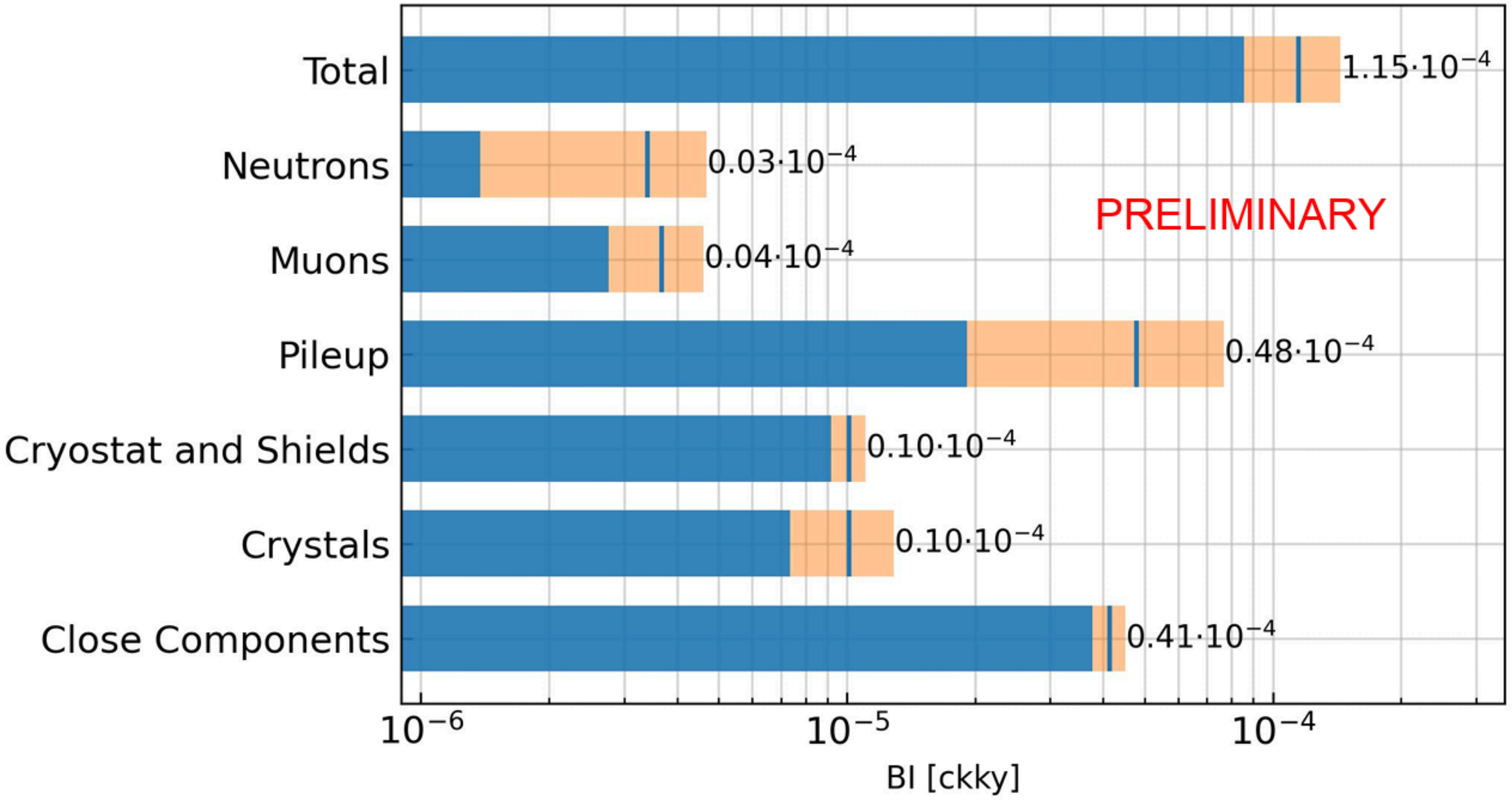




Eur. Phys. J. C 82, 1033 (2022)

CUPID's projected background index

- ROI Background Index (B.I.) goal: $< 10^{-4}$ cts/(keV kg yr) [vs. CUORE's 10^{-2} ckk
- 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



P. Loaiza, TAUP 2025 talk