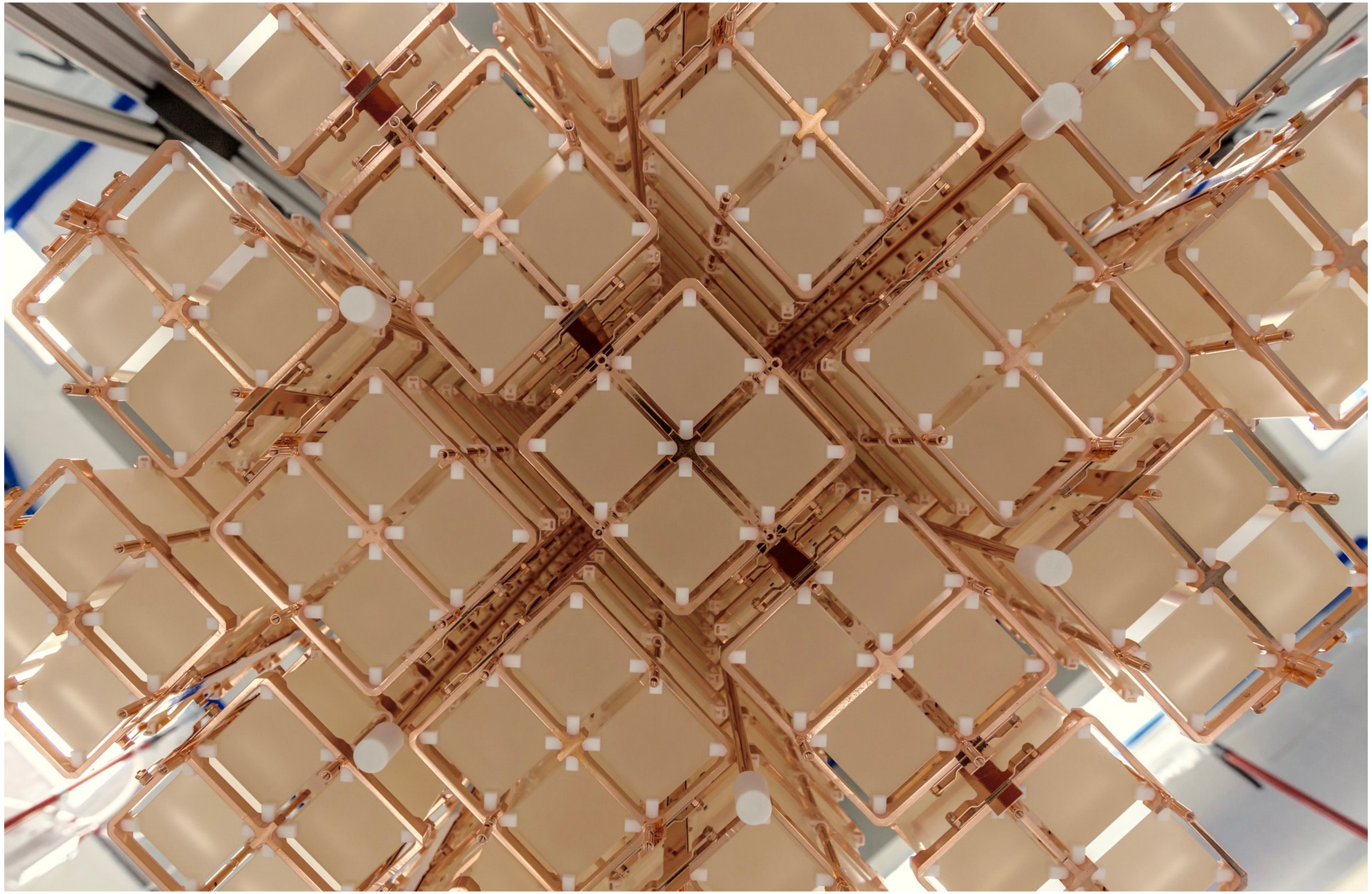
Probing the Nature of Neutrino Mass with Neutrinoless Double Beta Decay



Karsten Heeger
Yale University

October 24, 2025

Yale

Neutrinos and Beta Decay

1930, Pauli

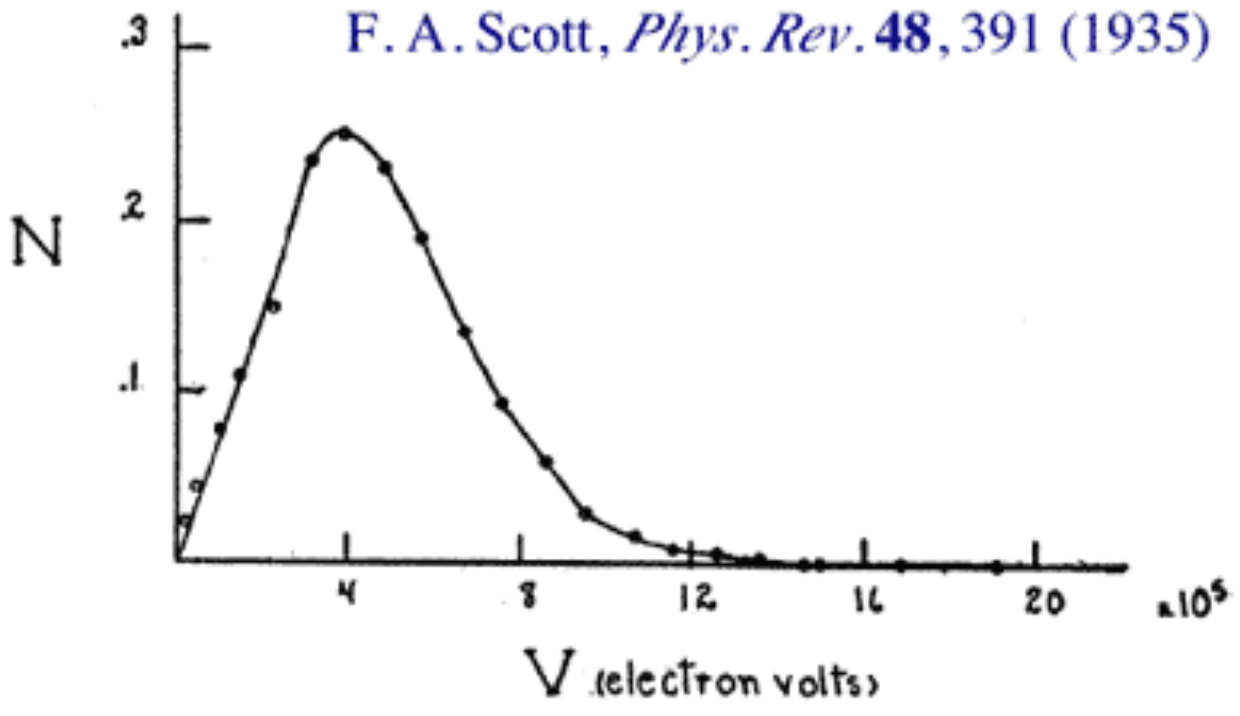
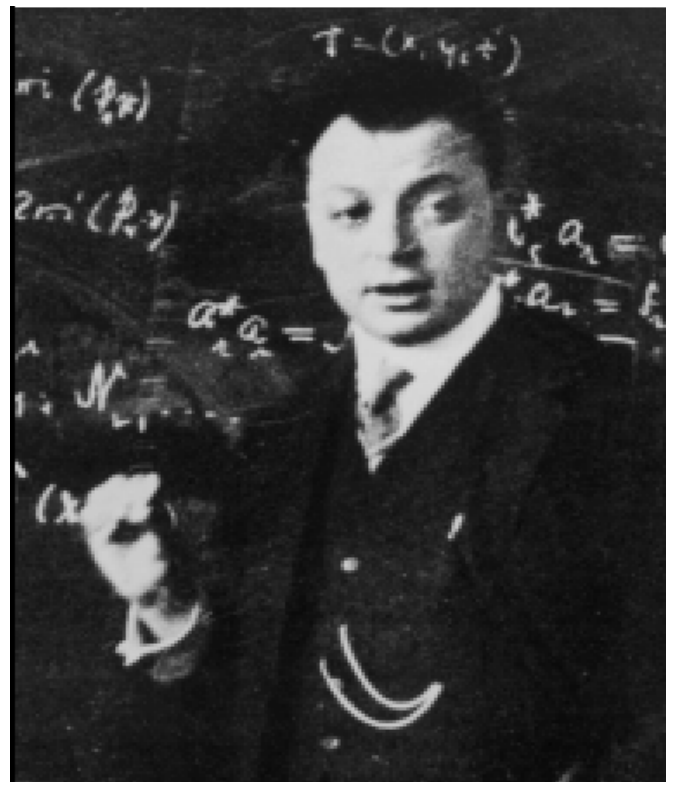
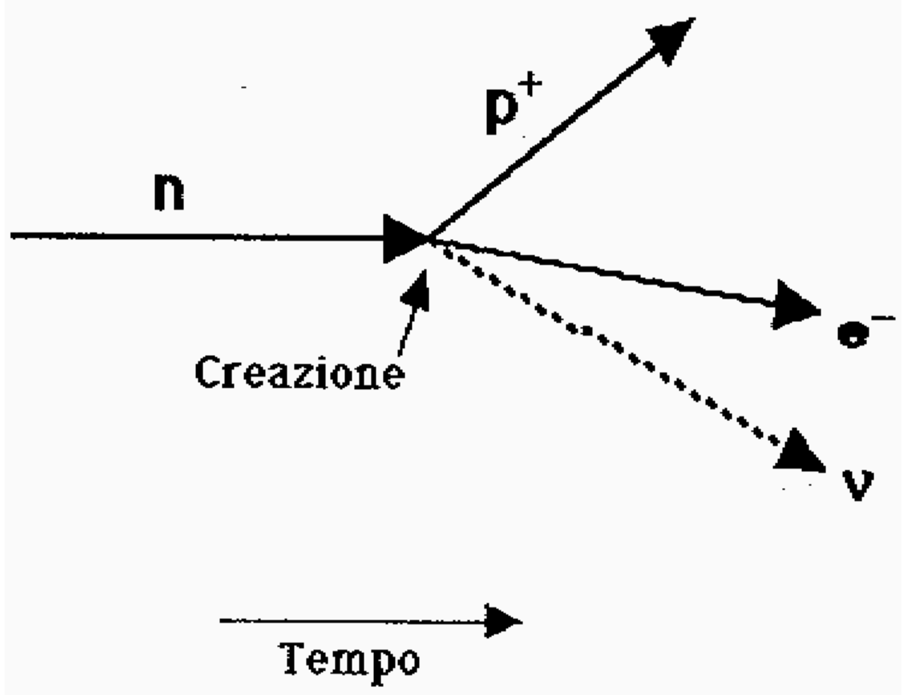
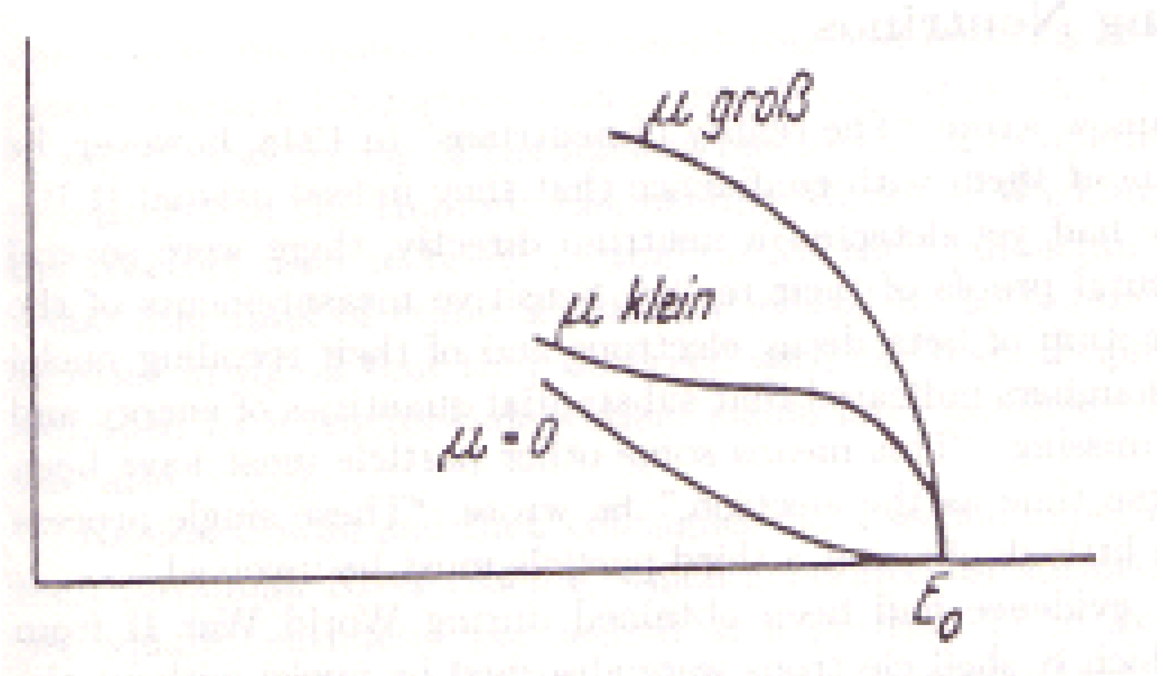


FIG. 5. Energy distribution curve of the beta-rays.

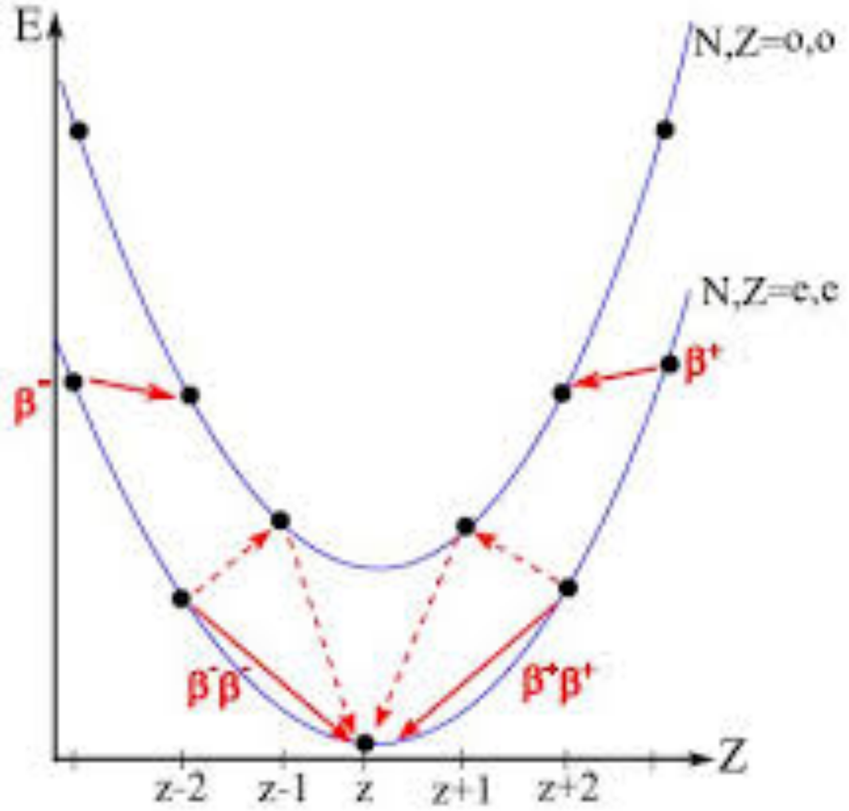


1932, Fermi

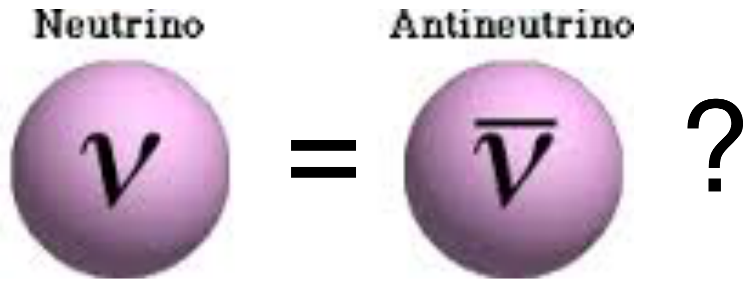


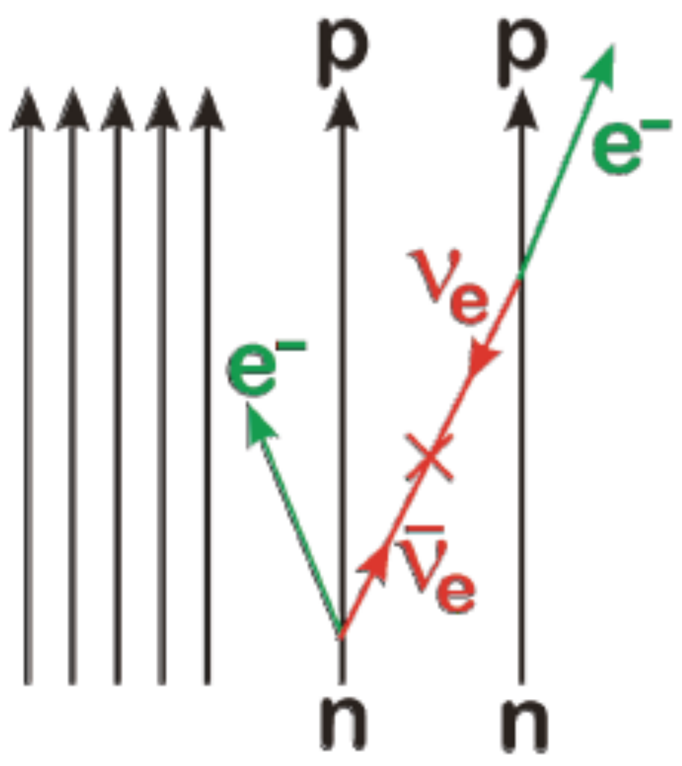


1935, Goeppert Mayer

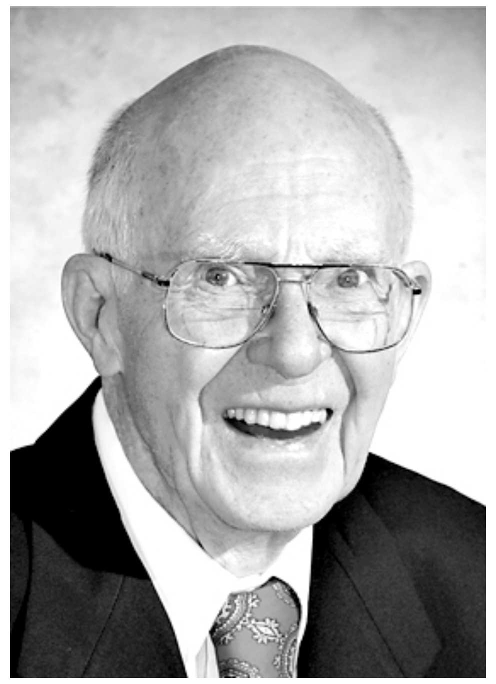


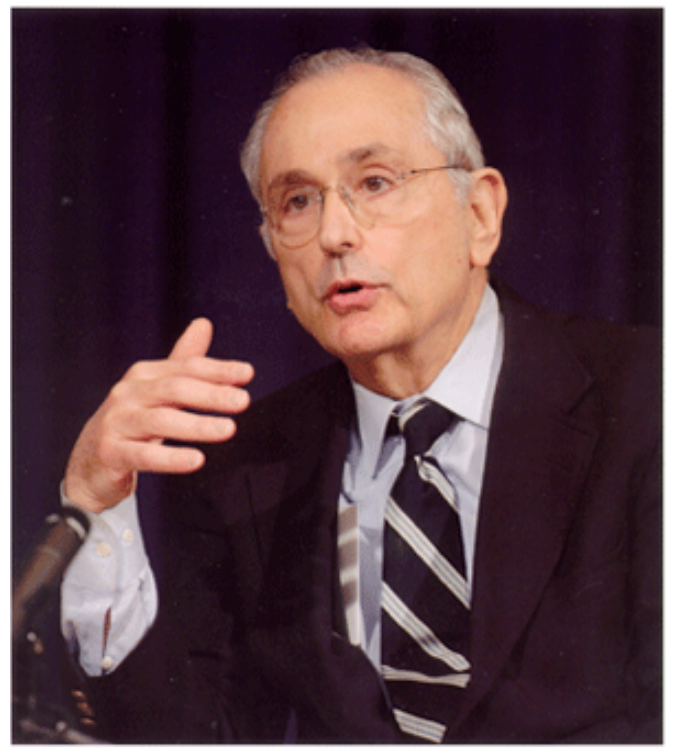
1937, Majorana





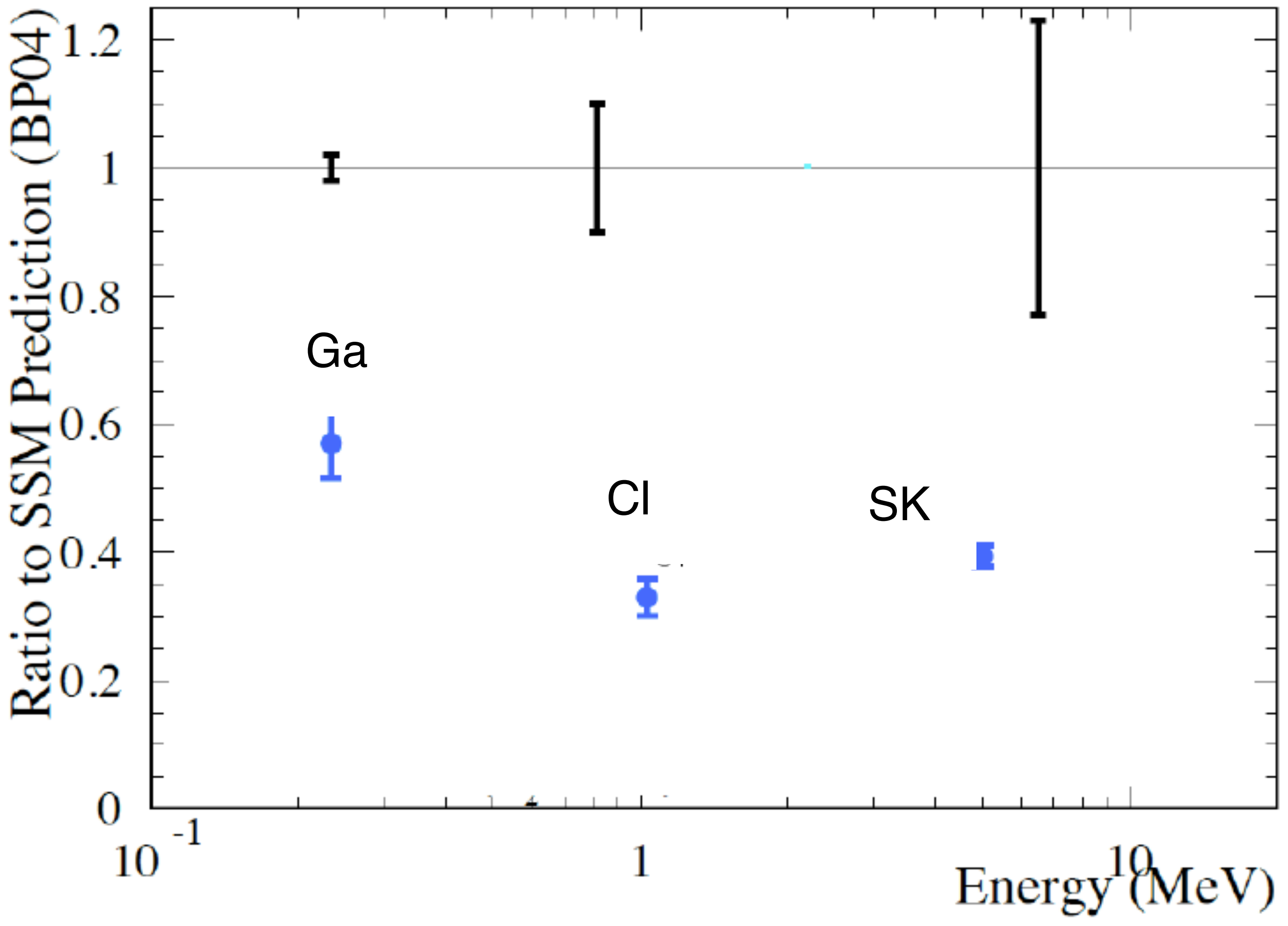
From Anomalies to Precision Oscillation Physics





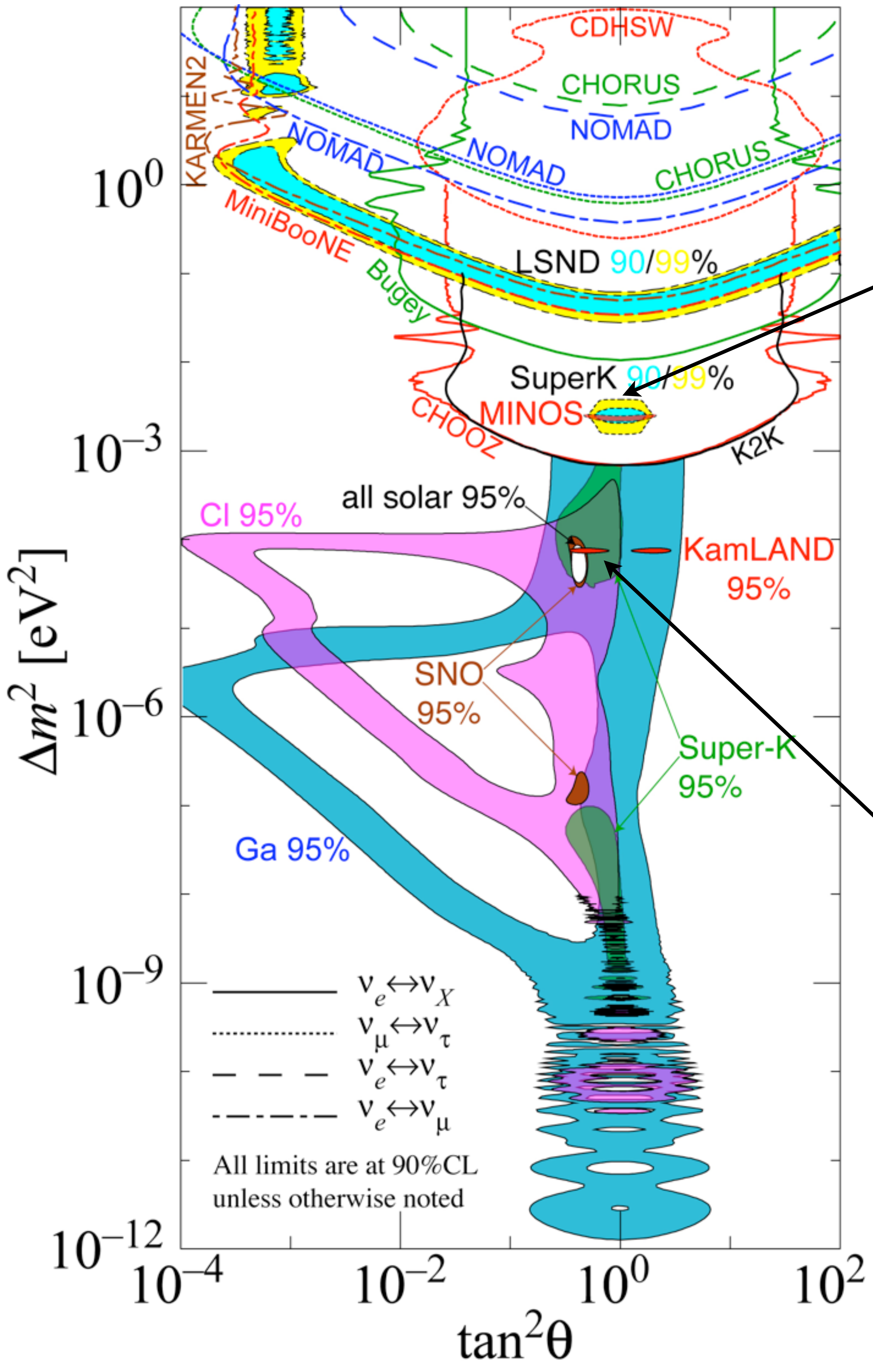
1960 -1990

solar neutrino problem



1990 - 2000

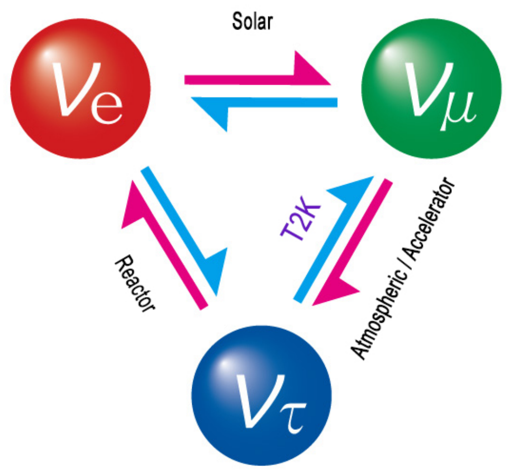
oscillation searches



http://hitoshi.berkeley.edu/neutrino

atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}



solar/reactor neutrinos

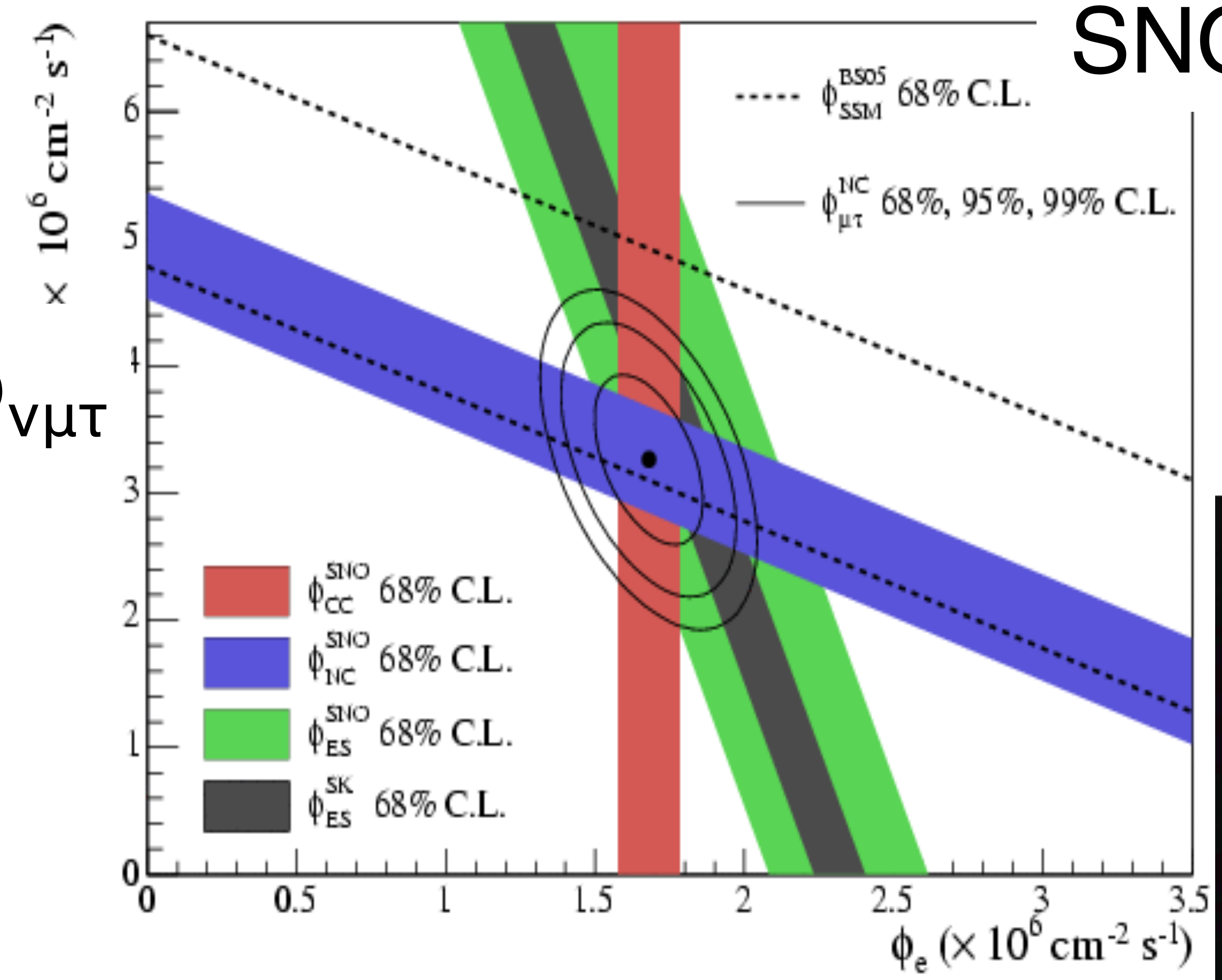
θ_{12}, Δm^2_{12}

Discovery of Neutrino Flavor Change and Oscillation

Solar ν_e

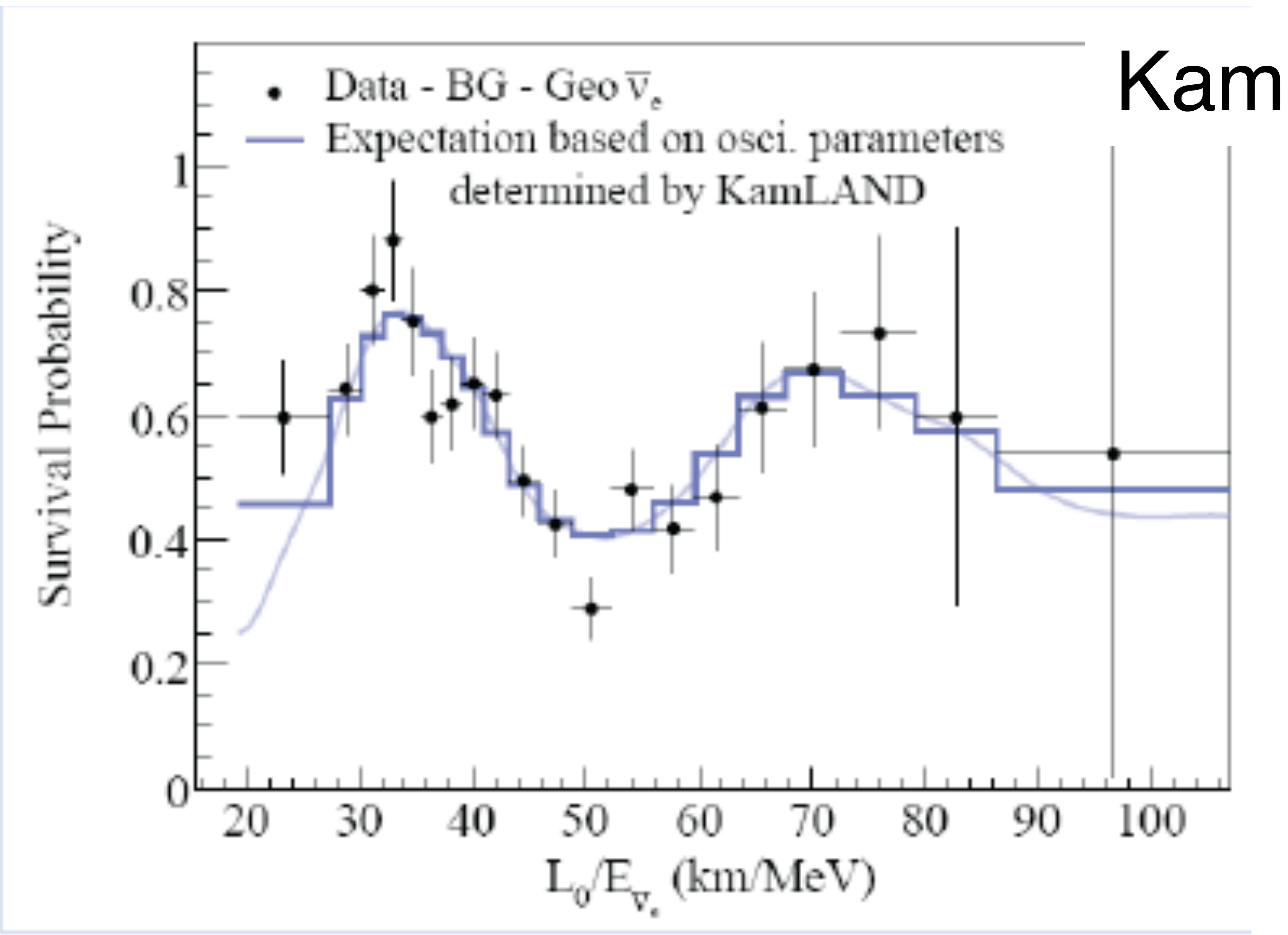
SNO

$\Phi_{\nu\mu\tau}$

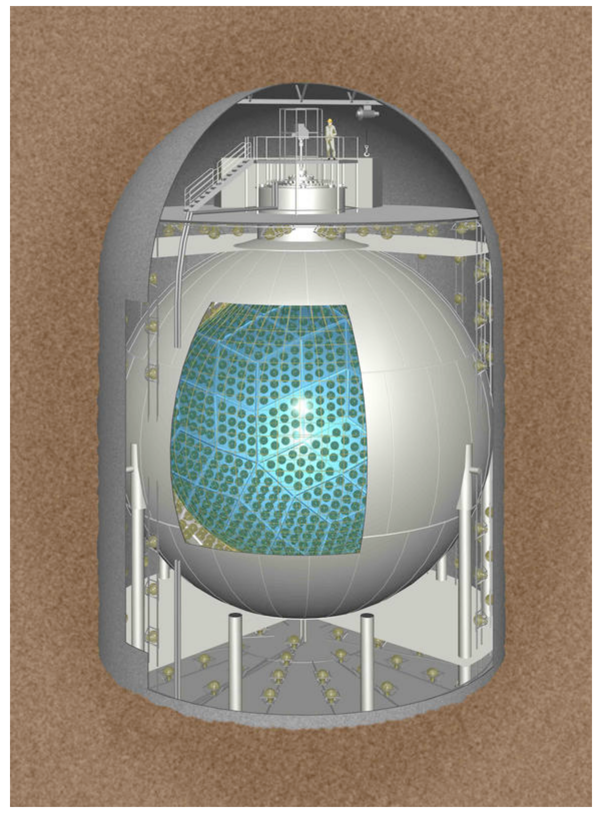


$\Phi_{\nu e}$

Reactor $\overline{\nu}_e$



KamLAND



L/E

Neutrino oscillations imply that neutrinos have mass and mix.

Neutrino Mixing

Evidence for neutrino oscillations in many sources

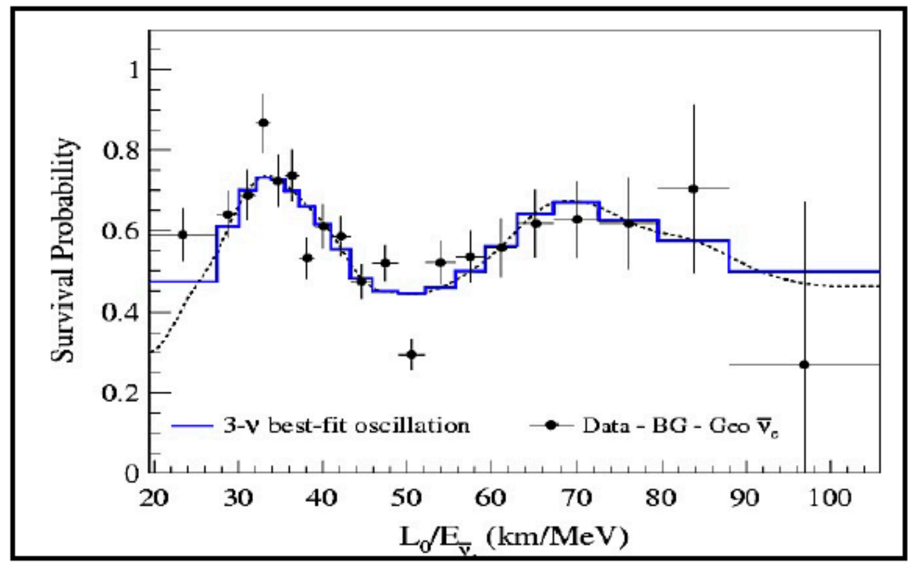
reactor

solar

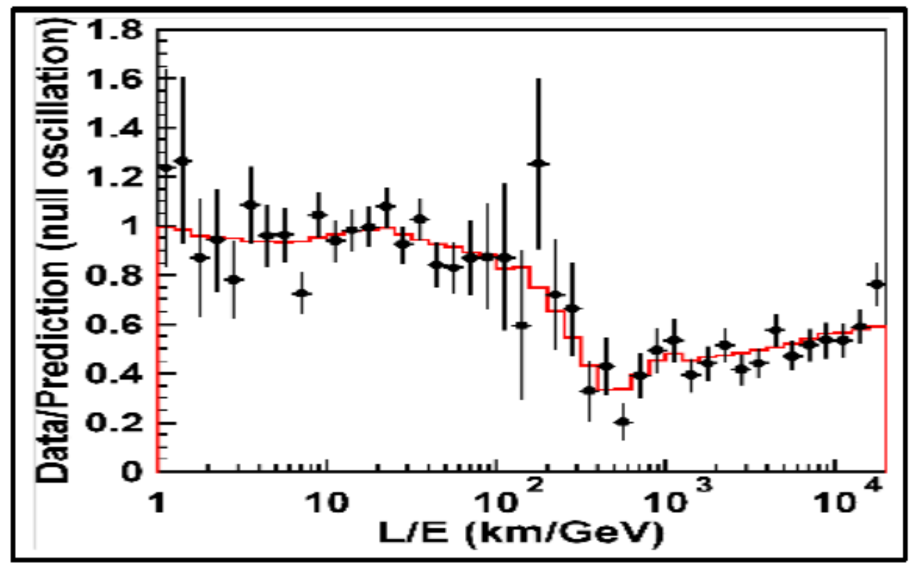
long baseline

atmospheric

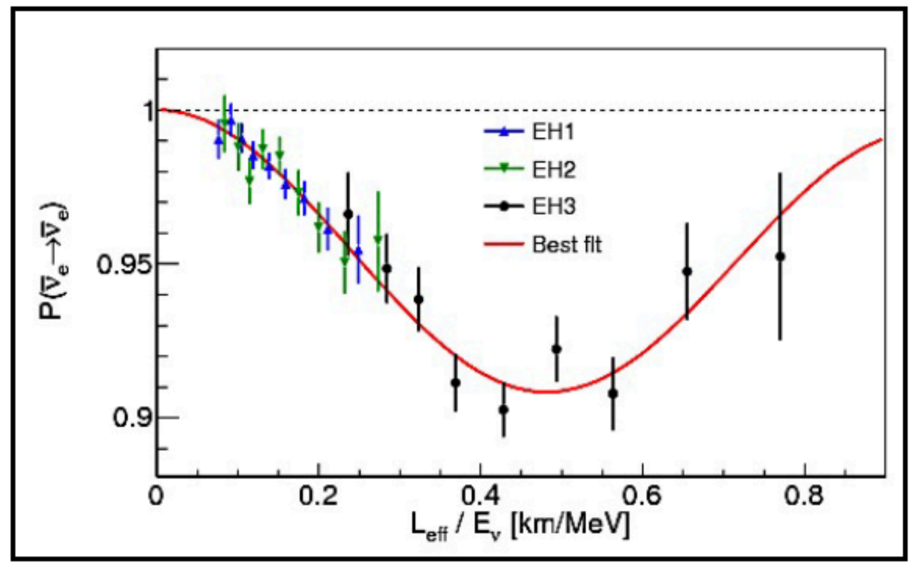
$e \rightarrow e$ $(\delta m^2, \theta_{12})$



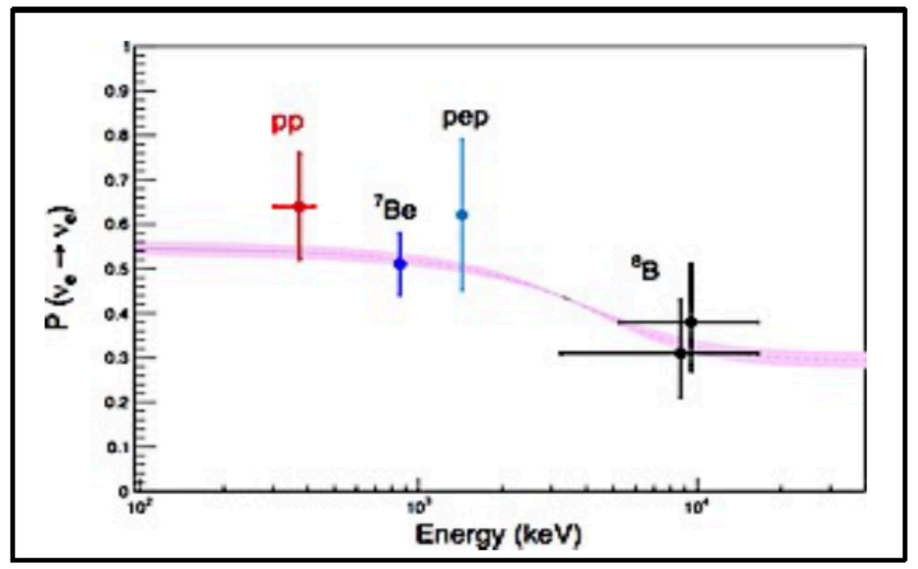
$\mu \rightarrow \mu$ $(\Delta m^2, \theta_{23})$



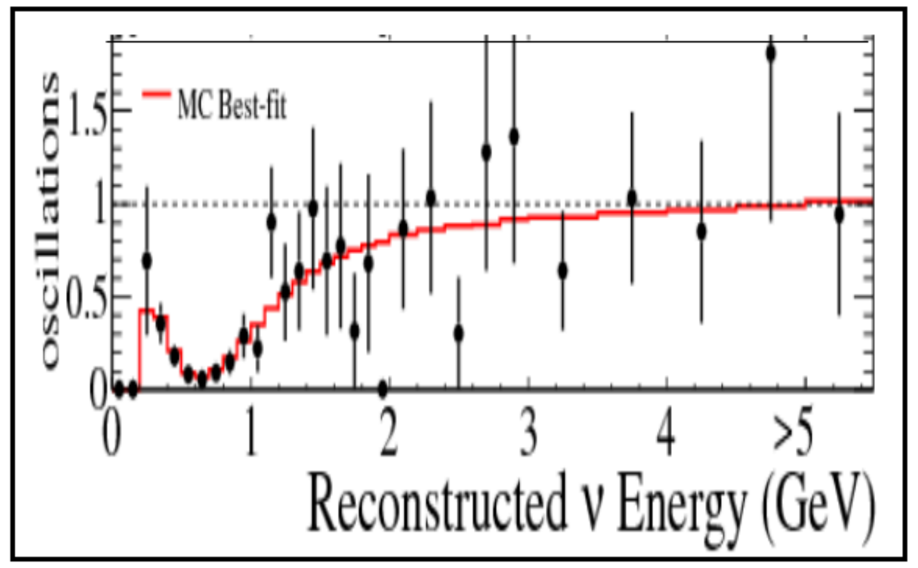
$e \rightarrow e$ $(\Delta m^2, \theta_{13})$



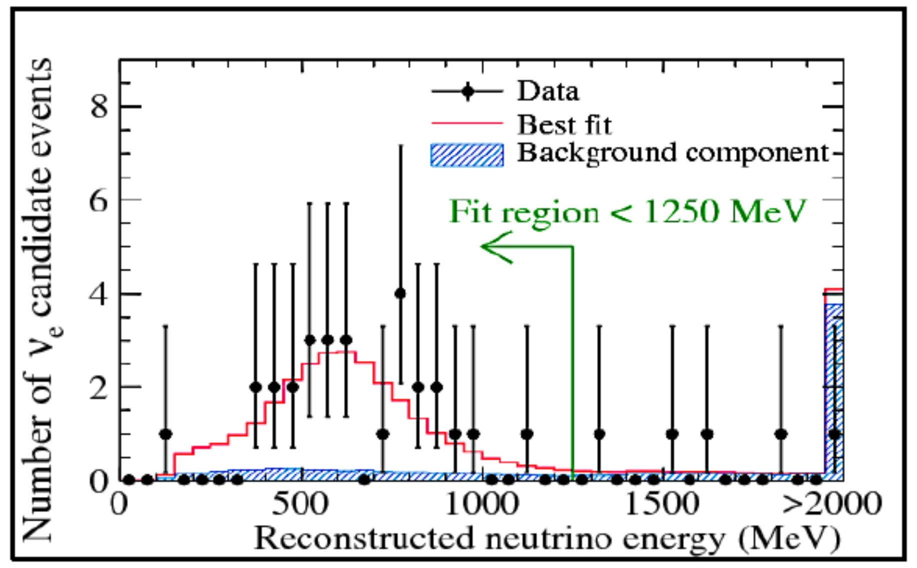
$e \rightarrow e$ $(\delta m^2, \theta_{12})$



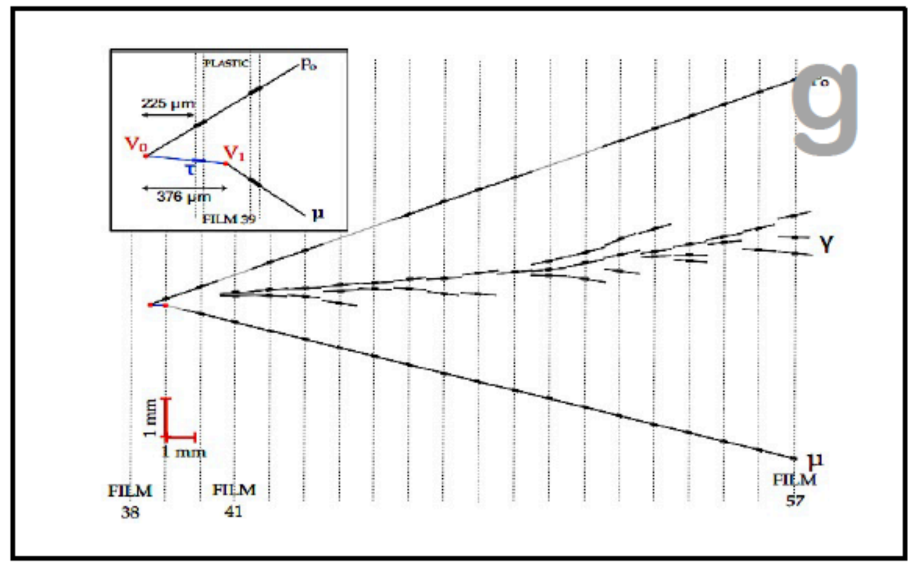
$\mu \rightarrow \mu$ $(\Delta m^2, \theta_{23})$

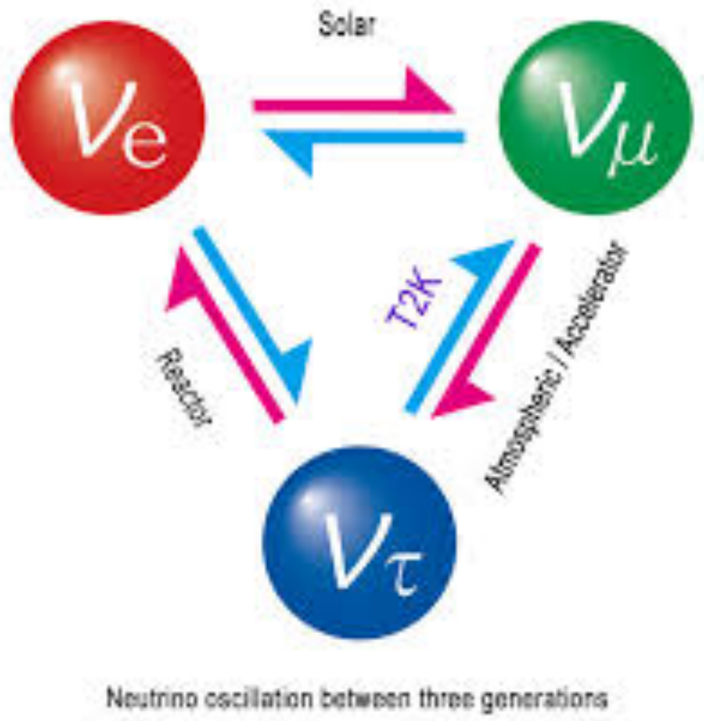


$\mu \rightarrow e$ $(\Delta m^2, \theta_{13}, \theta_{23})$



$\mu \rightarrow \tau$ $(\Delta m^2, \theta_{23})$

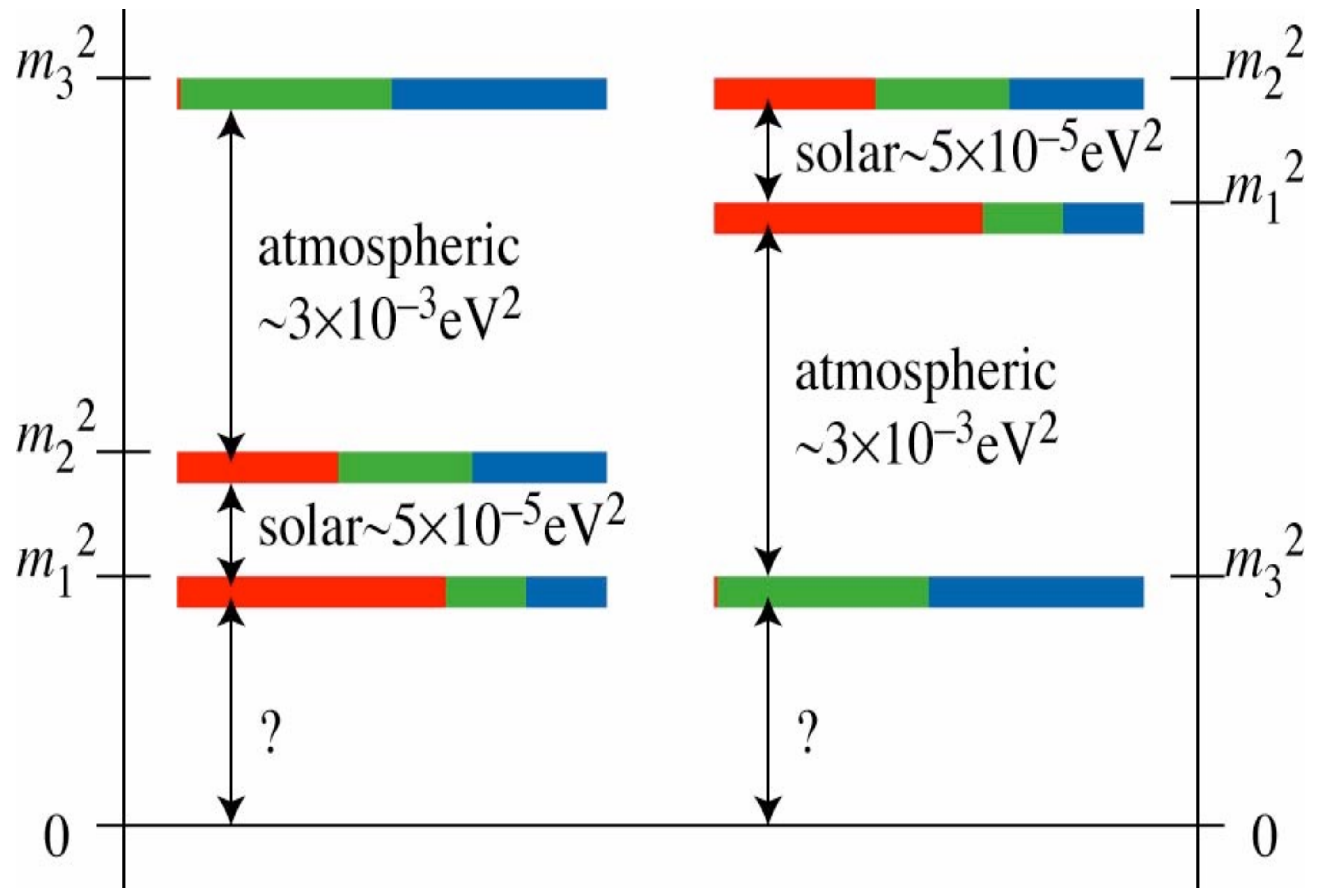




3-flavor picture fits data pretty well

E. Lisi

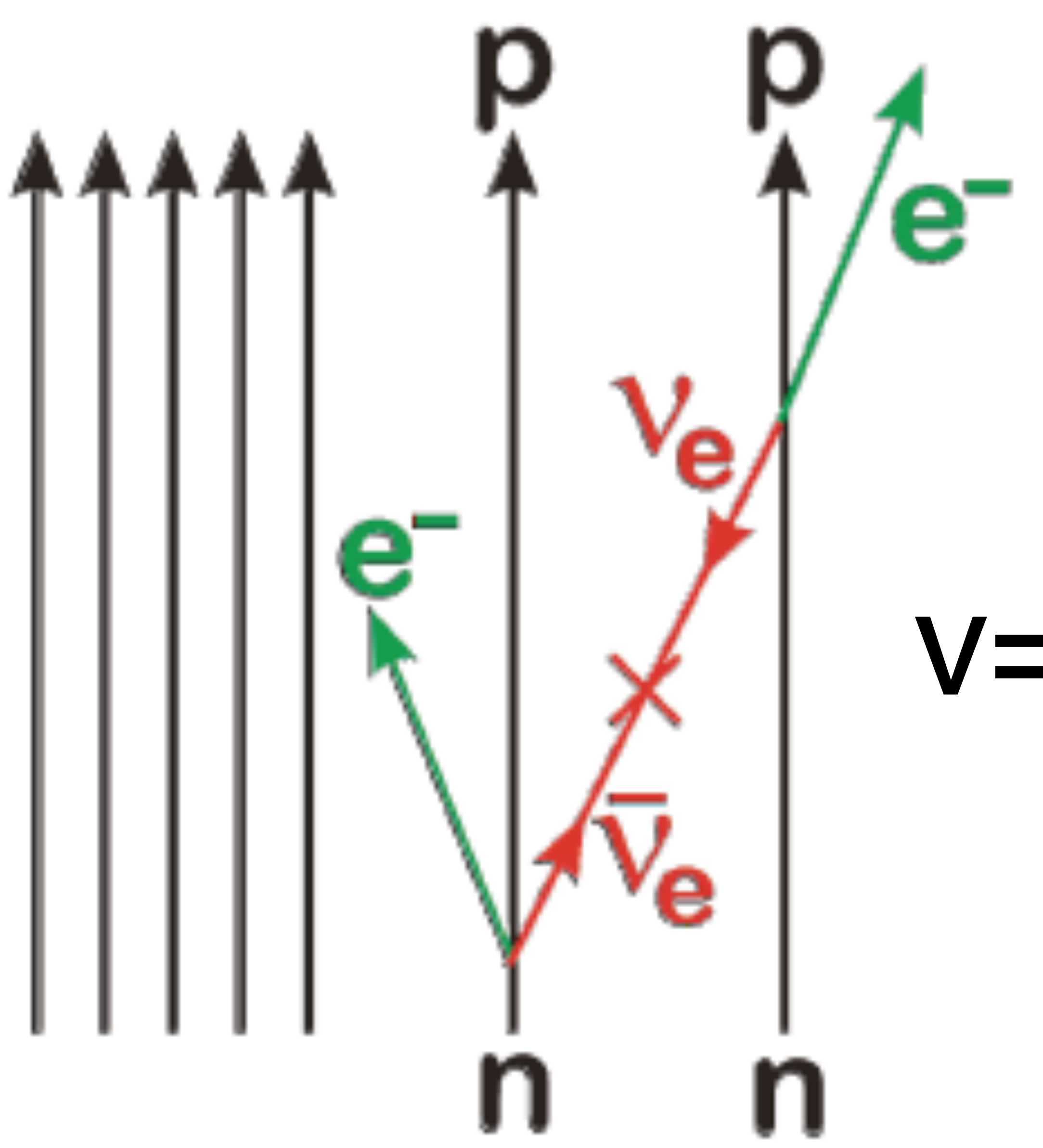
Neutrino Mass - Open Questions



What is the ordering of the neutrino states?

What is their mass?

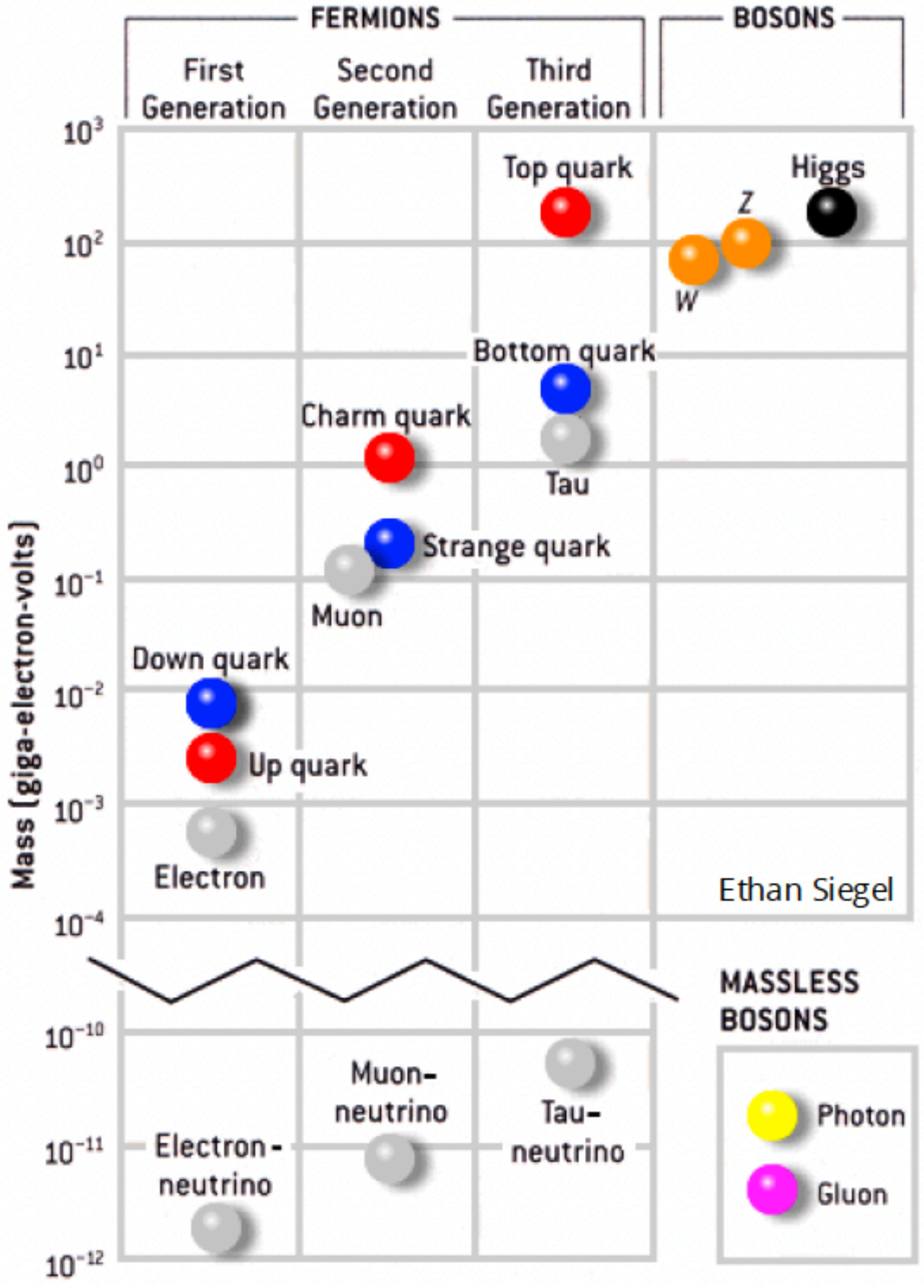
Are neutrinos Majorana particles?



$\nu=\bar{\nu}$?

Neutrino Mass

- Neutrinos are only Standard Model fundamental fermions with unmeasured mass
- Scale of neutrino mass sets them apart from all other particles of Standard Model
- Physics behind neutrino mass linked to many interesting questions in nuclear, particle, and astro physics
- Direct and model independent measurement of neutrino mass possible from beta decay

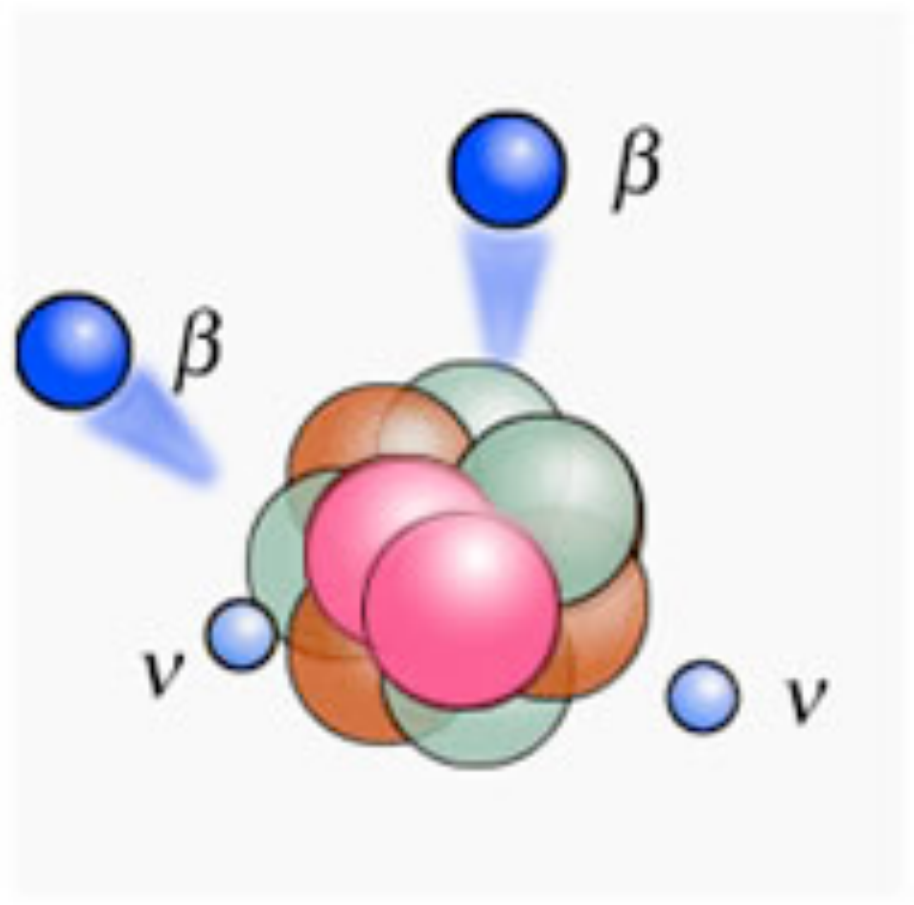


Understanding Neutrino Mass from Beta Decays

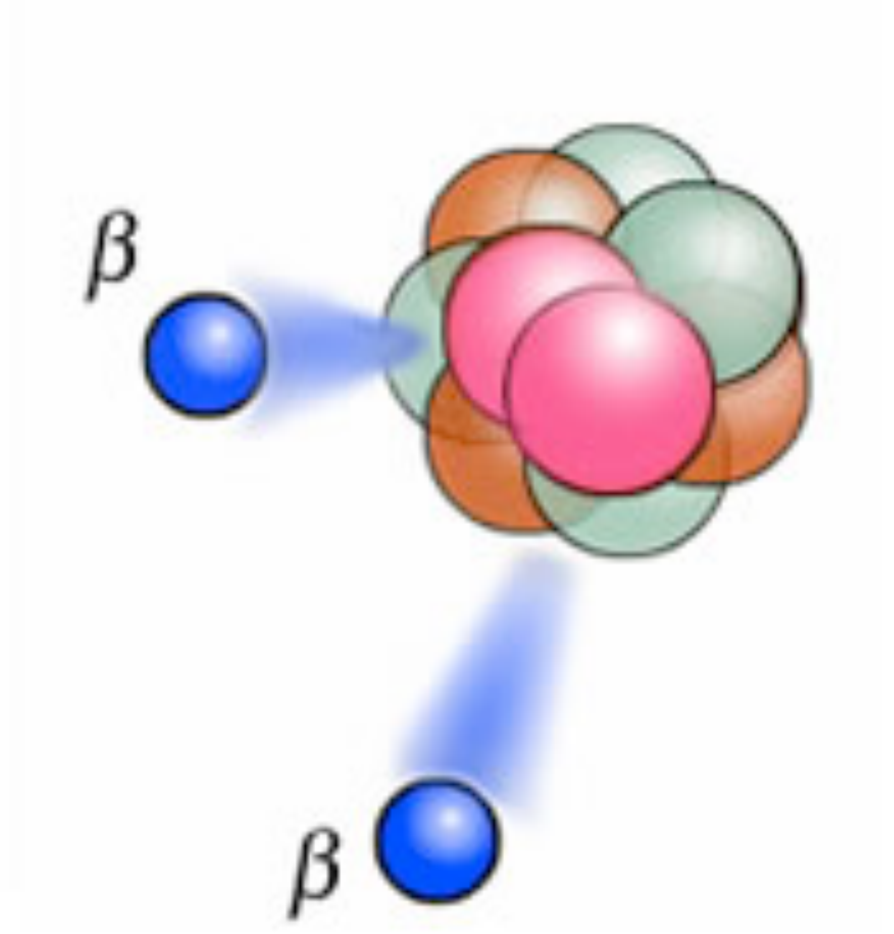
Single Beta Decay

Nuclei as a laboratory for understanding neutrino mass.

Double Beta Decay

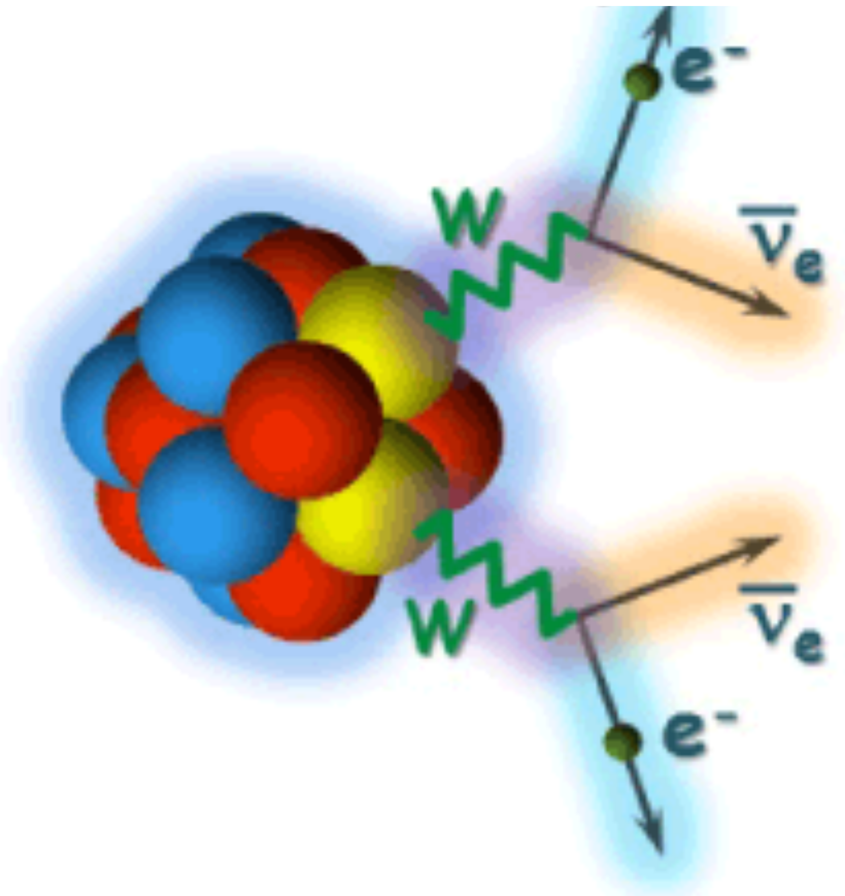


2νββ

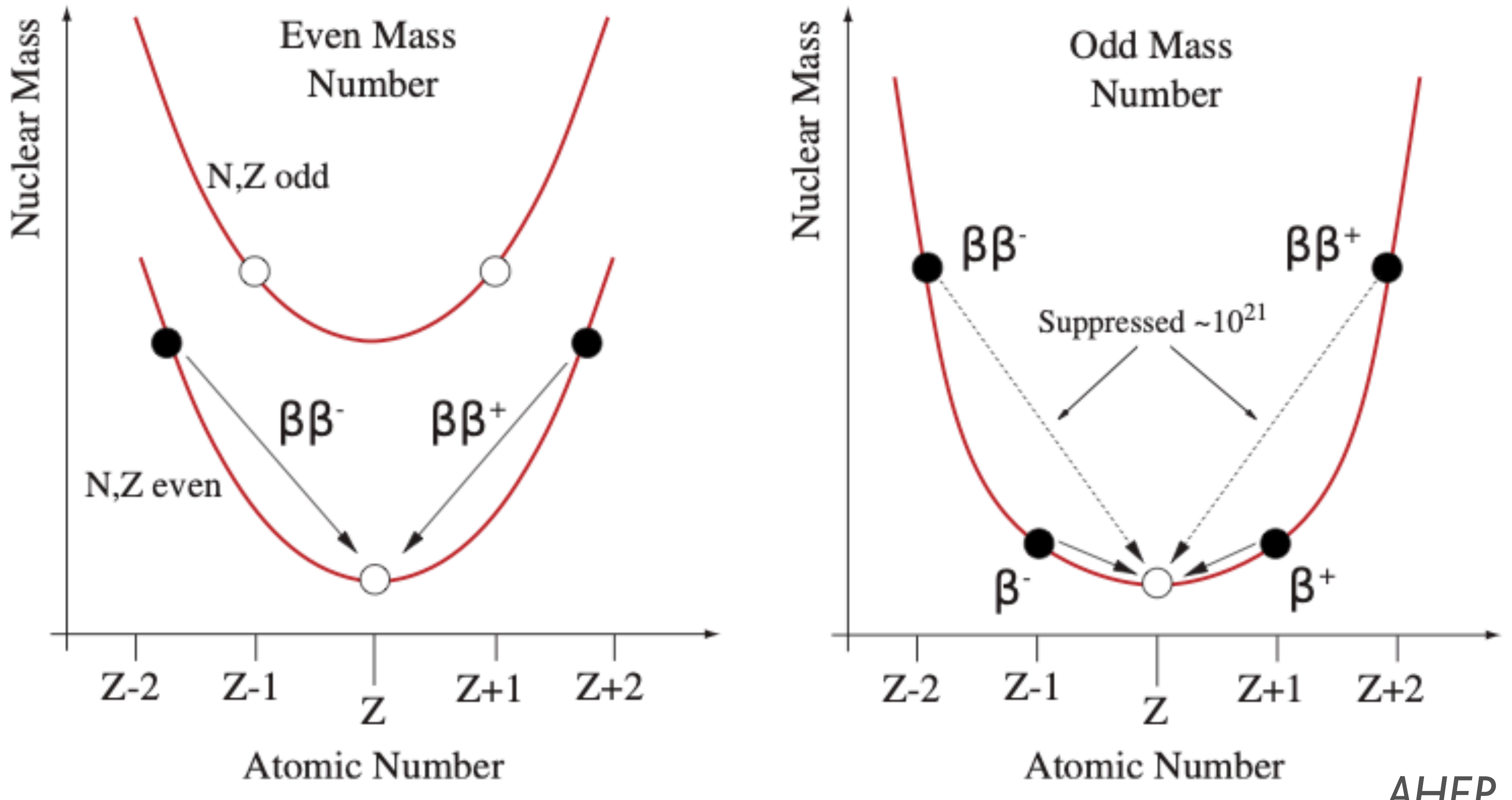


0νββ

Double Beta Decay



Double beta decay
which emits anti-neutrinos



AHEP, 2016-2162659

Two neutrons simultaneously convert to protons

Possible in few even-even nuclei

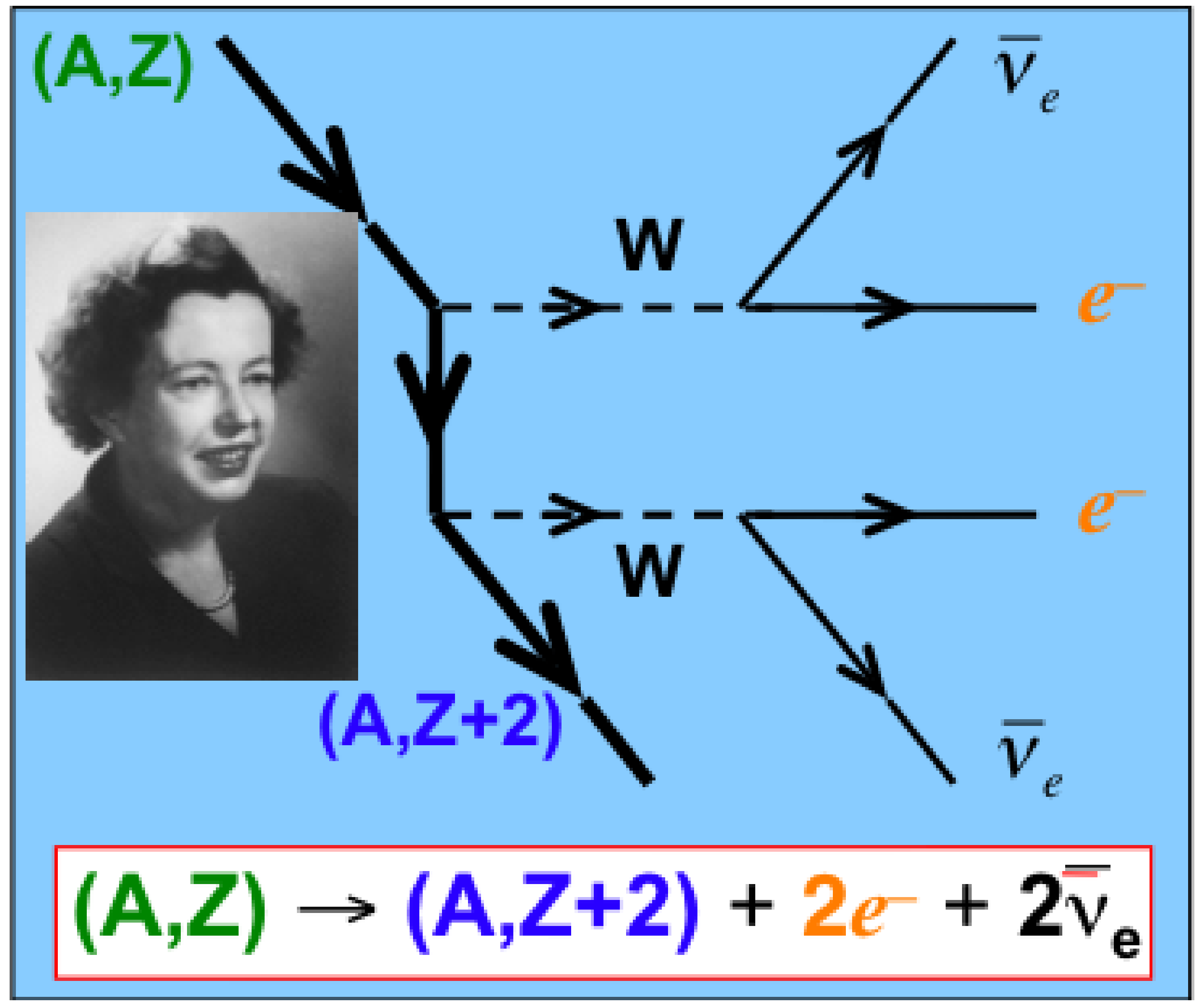
Half-life (~10^{20} yrs)

35 naturally occurring isotopes capable of 2νββ

Already measured for several isotopes

Probing Neutrino Mass with Double Beta Decay

$2\nu\beta\beta$



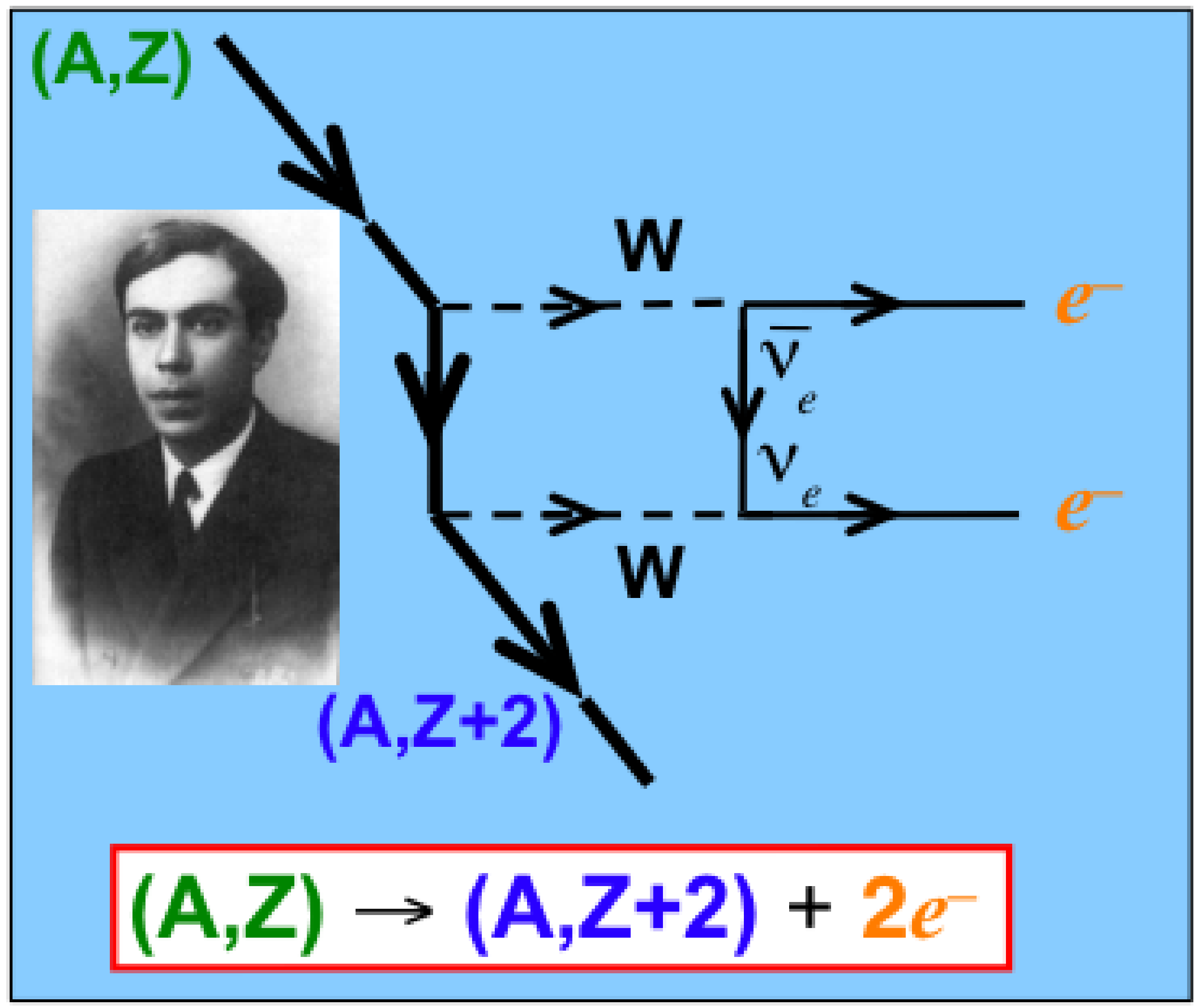
Proposed in 1935 by Maria Goeppert-Mayer

Observed in several nuclei

$T_{1/2} \sim 10^{19} – 10^{21}$ yrs

$$\Gamma_{2\nu} = G_{2\nu} \,|\, M_{2\nu} \,|^2$$

$0\nu\beta\beta$



Proposed in 1937 by Ettore Majorana

Not observed yet

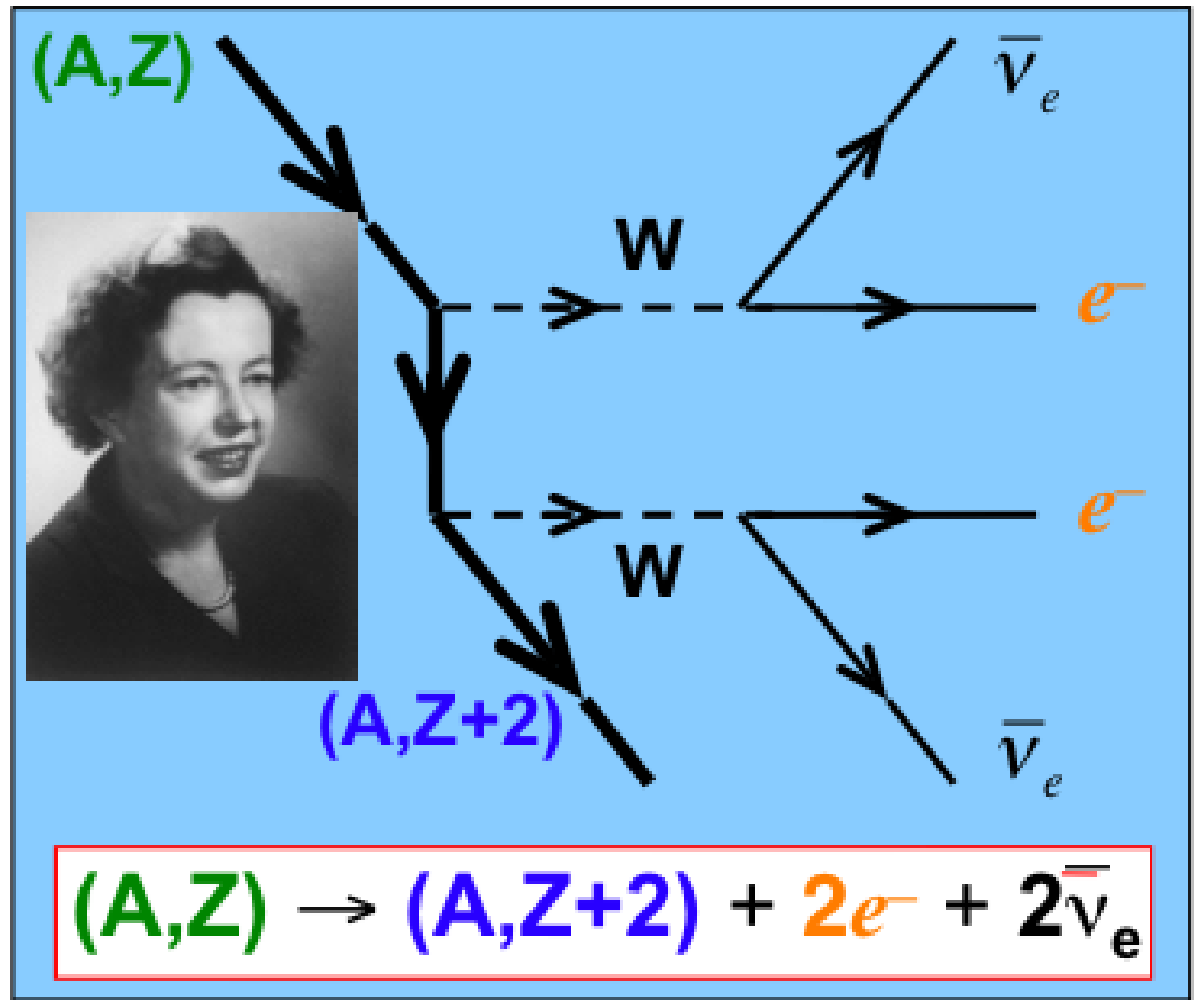
$T_{1/2} \geq 10^{25}$ y

$$\Gamma_{0\nu} = G_{0\nu} \,|\, M_{0\nu} \,|^2 \left\langle m_{\beta\beta} \right\rangle^2$$

Nuclei as a laboratory to study lepton number violation at low energies

Probing Neutrino Mass with Double Beta Decay

$2\nu\beta\beta$



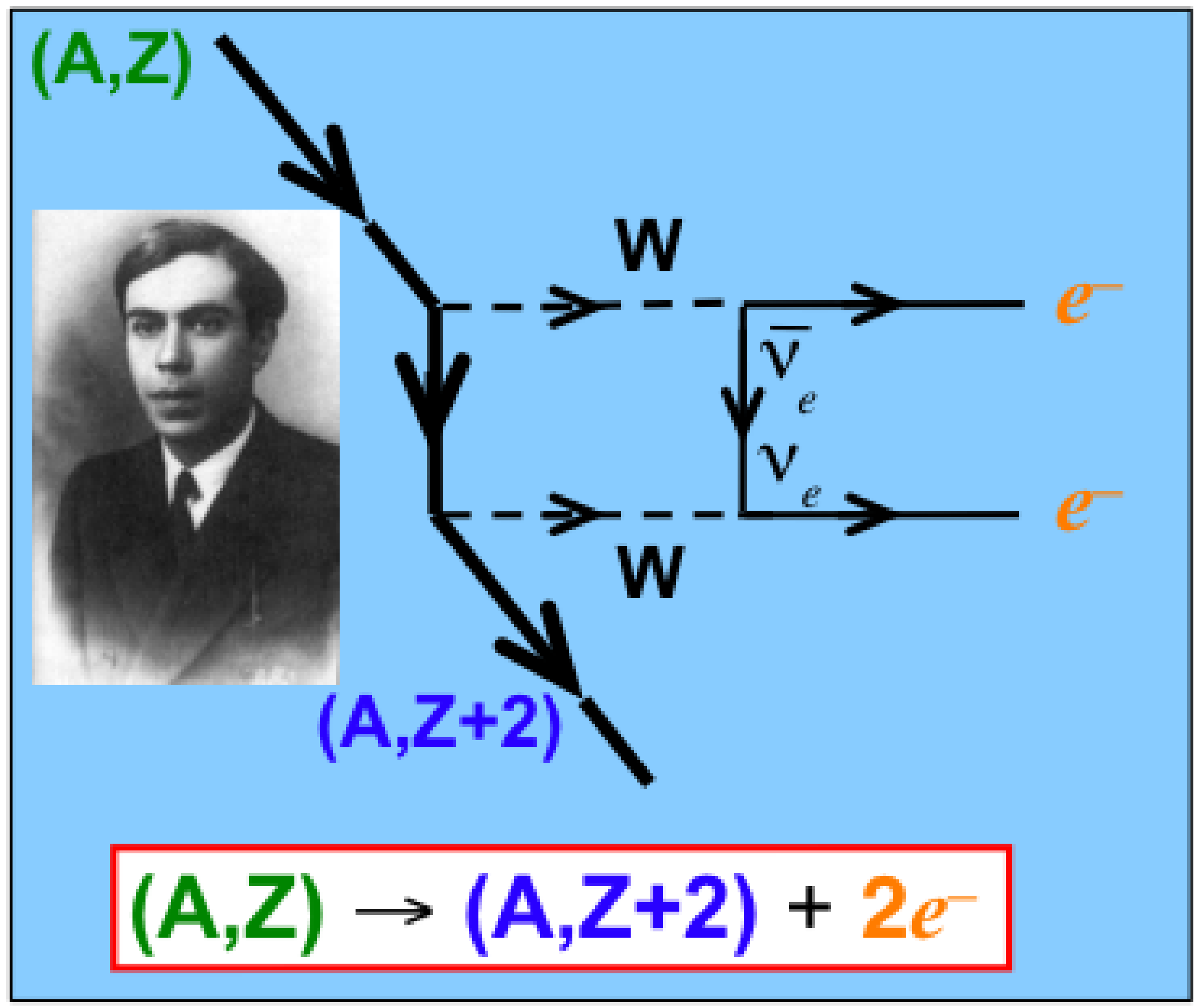
Proposed in 1935 by Maria Goeppert-Mayer

Observed in several nuclei

$T_{1/2} \sim 10^{19} – 10^{21}$ yrs

$$\Gamma_{2\nu} = G_{2\nu} \, |M_{2\nu}|^2$$

$0\nu\beta\beta$



Proposed in 1937 by Ettore Majorana

Not observed yet

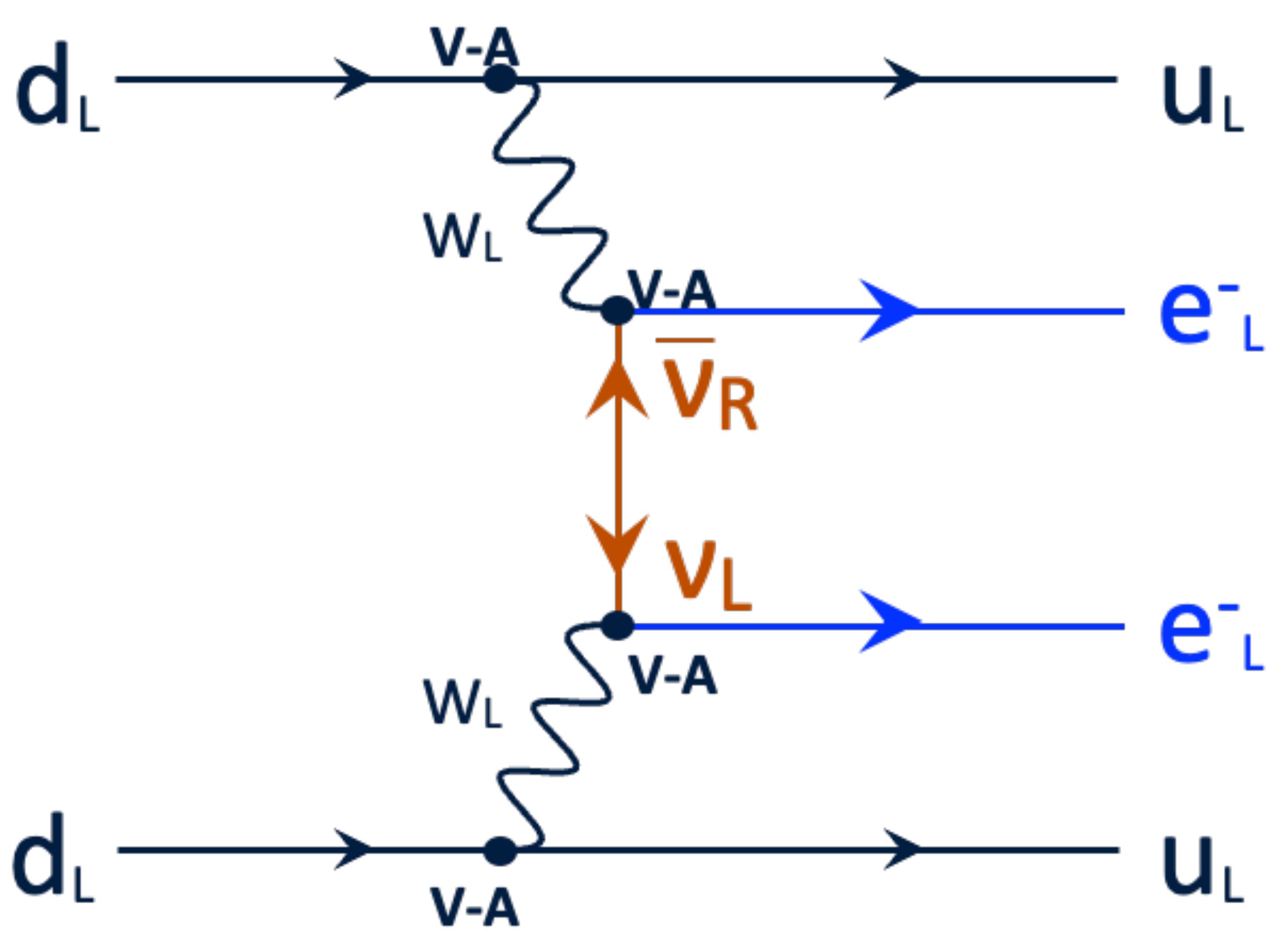
$T_{1/2} \geq 10^{25}$ y

$$\Gamma_{0\nu} = G_{0\nu} \, |M_{0\nu}|^2 \left\langle m_{\beta\beta} \right\rangle^2$$

Observation of 0$\nu\beta\beta$ would establish

- lepton number non-conservation
- Majorana mass
- effective neutrino mass

Neutrinoless Double Beta Decay (0νββ)



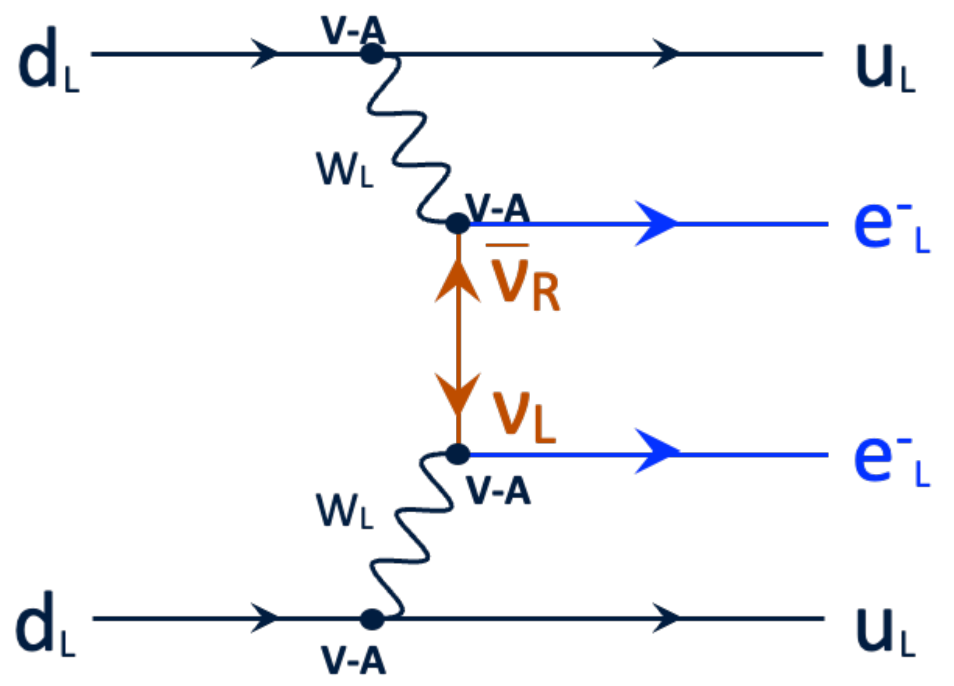
Light neutrino Exchange
(V-A)

Commonly considered by all experiments
→ effective $\langle m_{\beta\beta} \rangle$

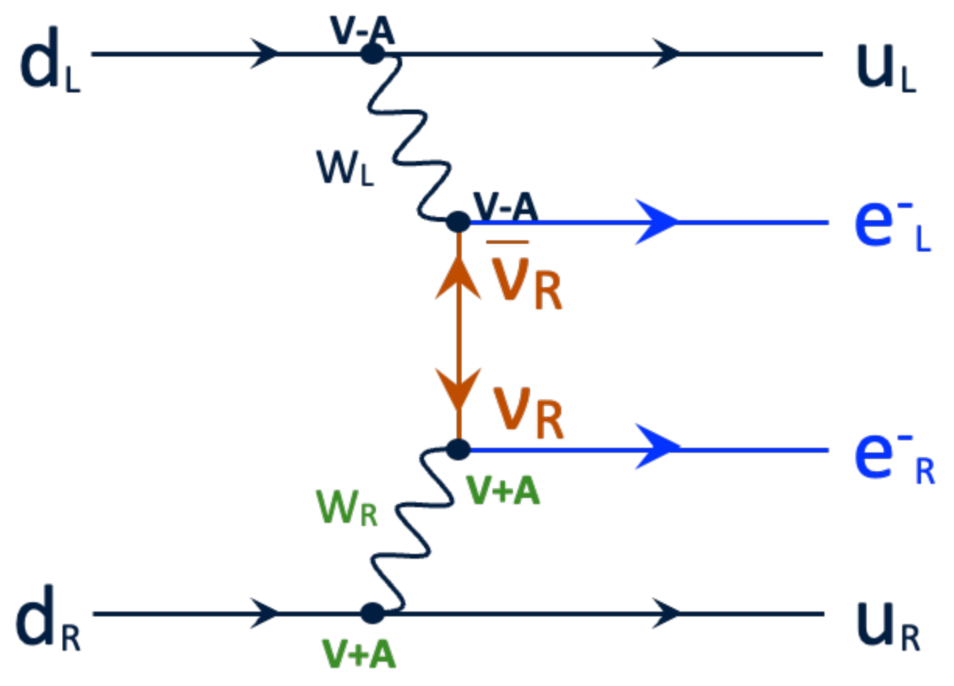
Neutrinoless Double-Beta Decay

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

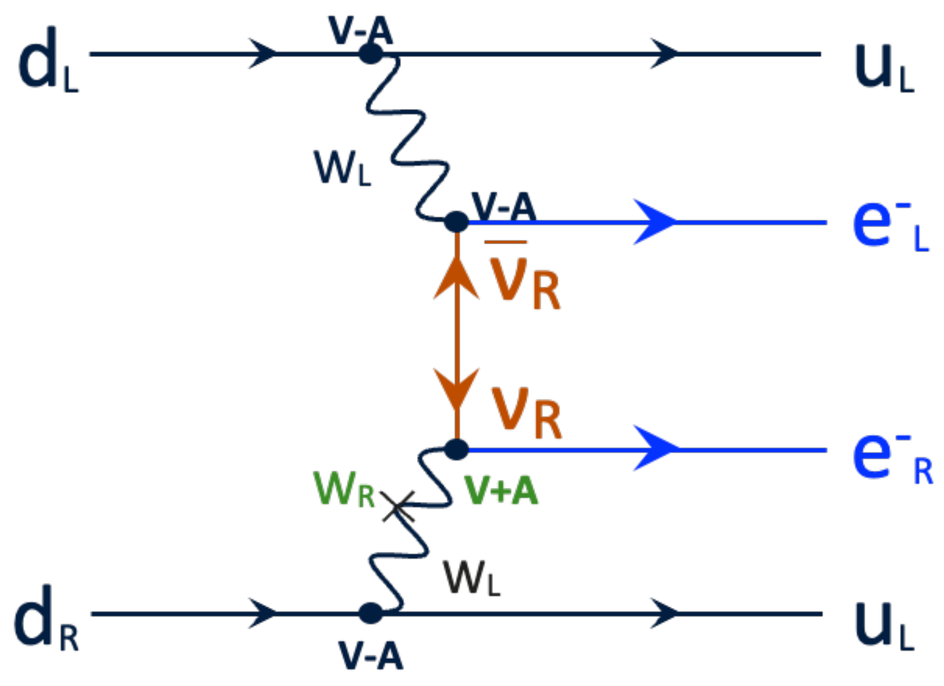
Neutrinoless Double Beta Decay (0νββ)



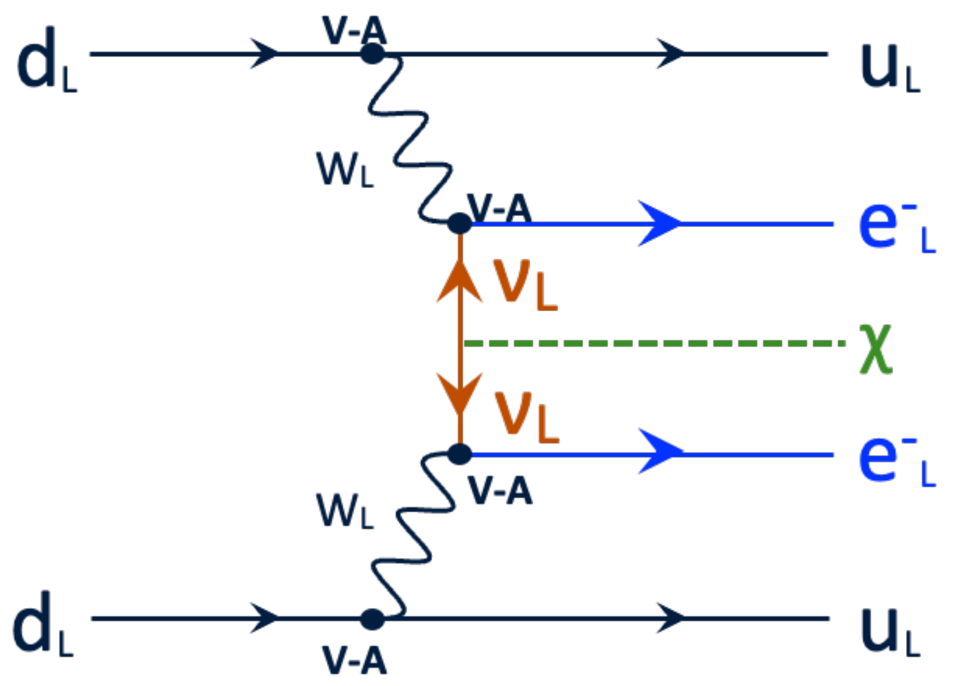
Light neutrino Exchange
(V-A)



Left-Right Symmetry (λ)
$(V+A)_l + (V+A)_h$



Left-Right Symmetry (η)
$(V+A)_l$



Majoron emission

etc…

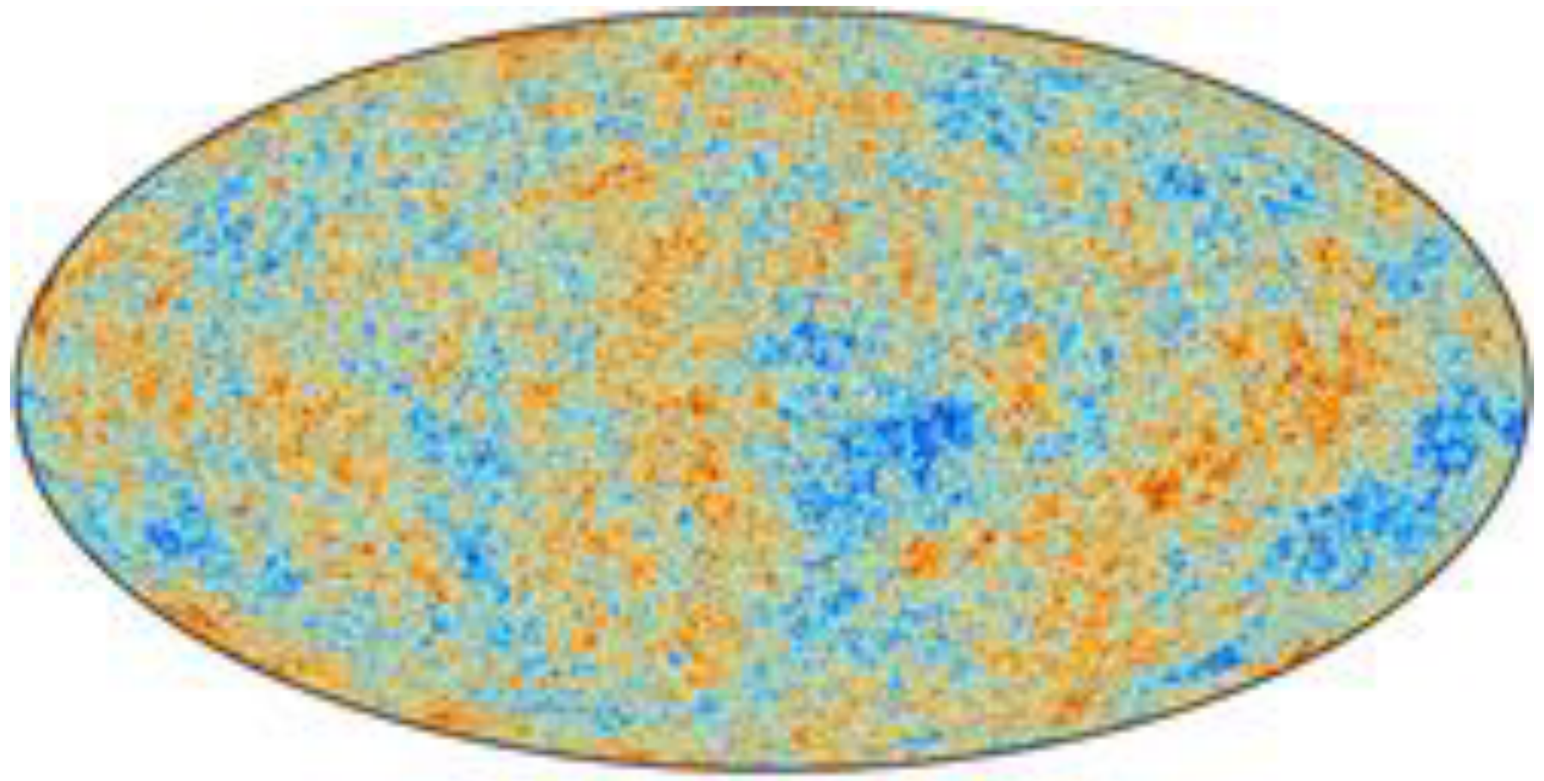
Underlying mechanism is not known …

Commonly considered by all experiments
→ effective $\langle m_{\beta\beta} \rangle$

Neutrinoless Double-Beta Decay

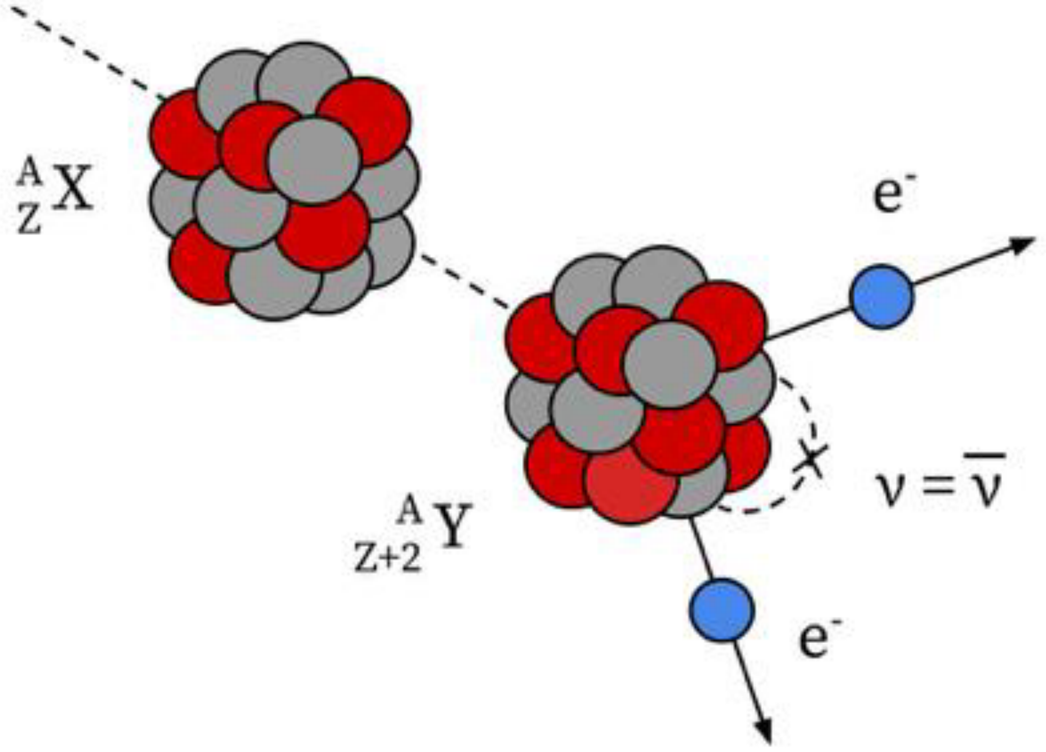
$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

Probing the Neutrino Mass Scale



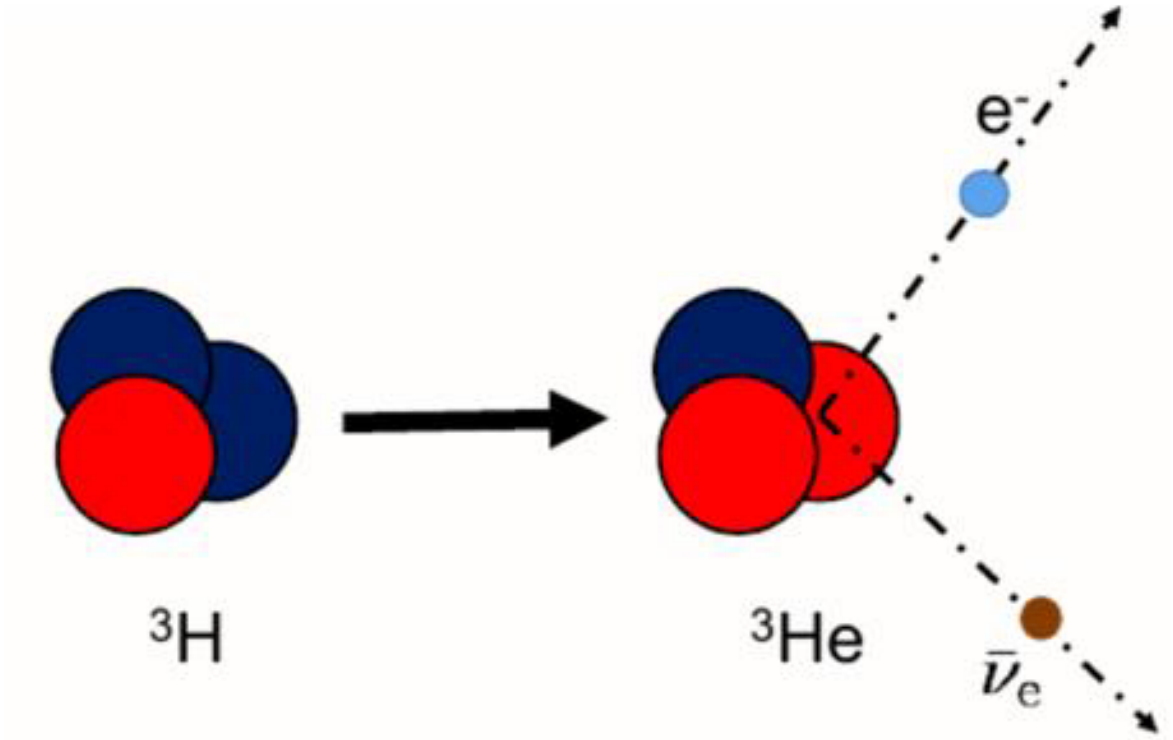
Cosmology

$$\sum m_\nu = \sum_{i=1}^{3} m_i$$



Neutrinoless Double-Beta Decay

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

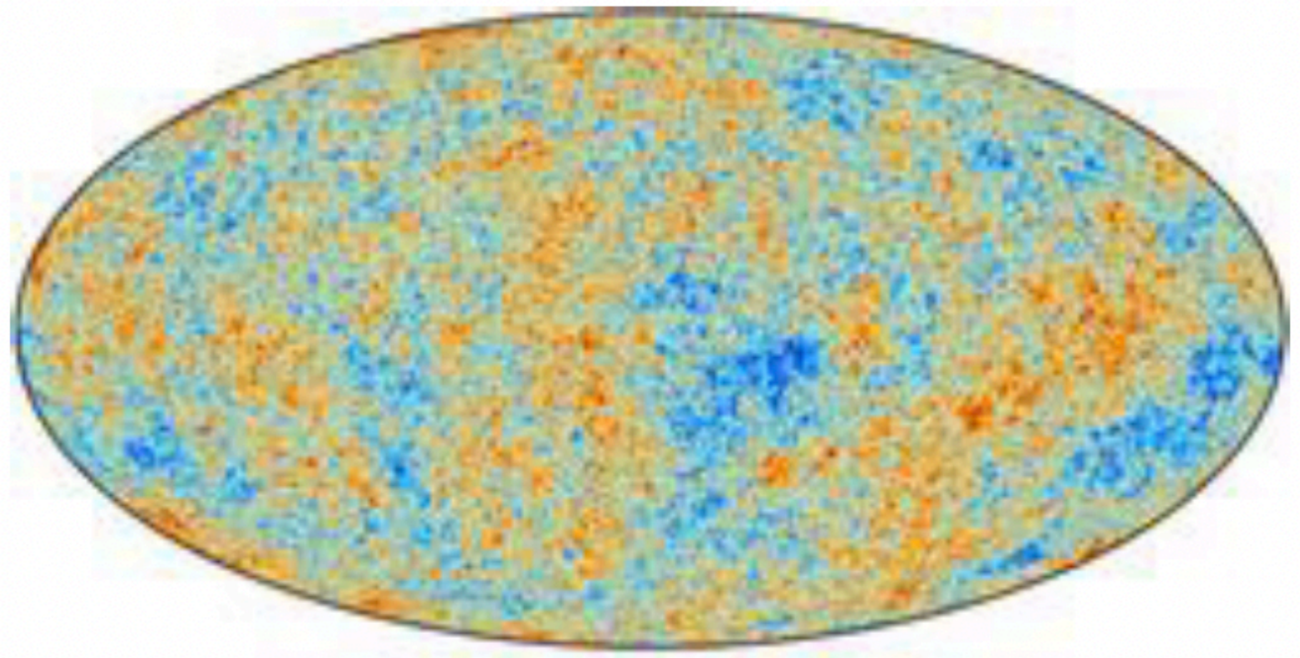


Endpoint Measurements (β-decay and EC)

$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

Probing the Neutrino Mass Scale

W. Elbers *Neutrino 2024*
arXiv:2503.14744



Cosmology

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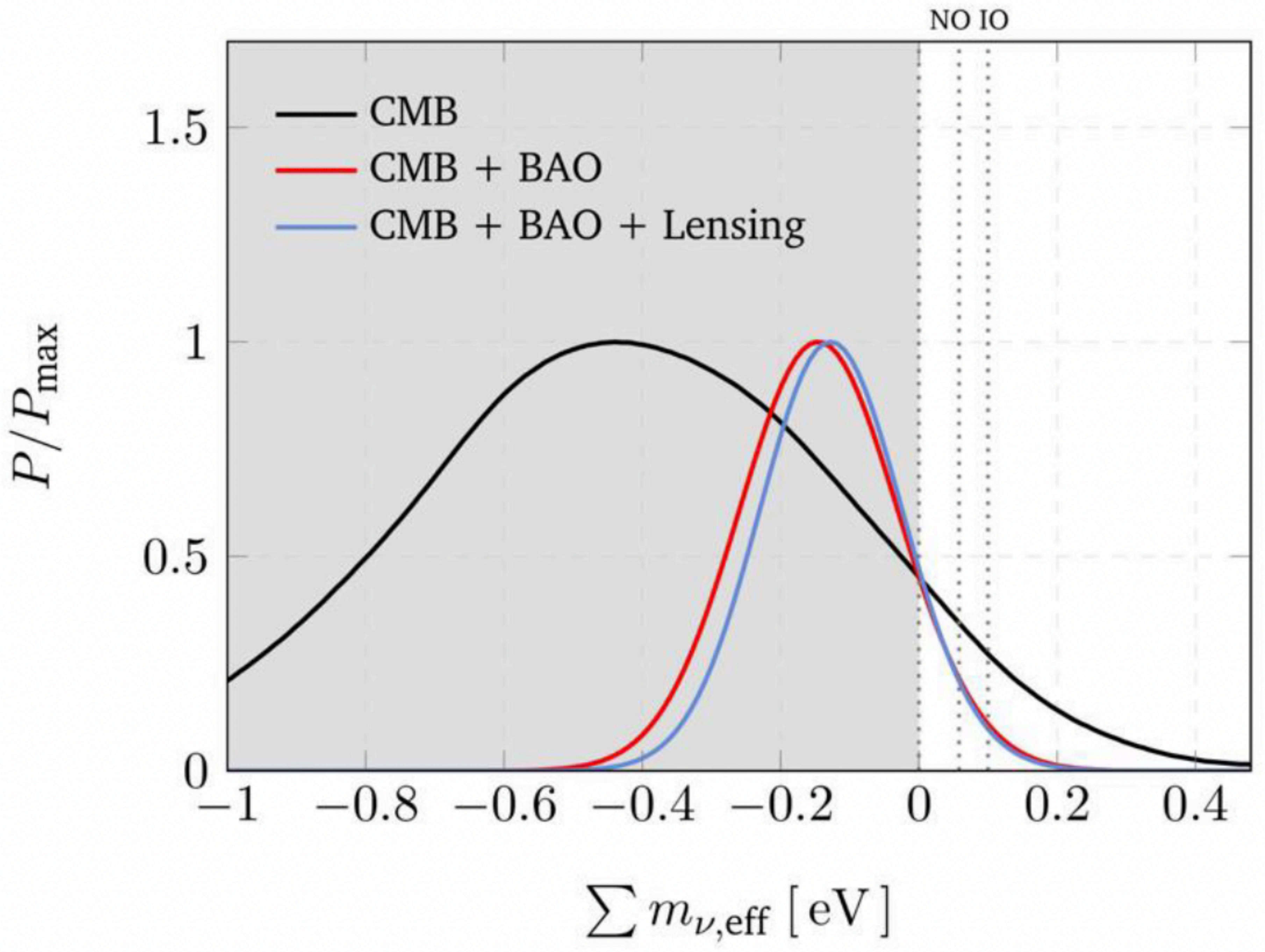
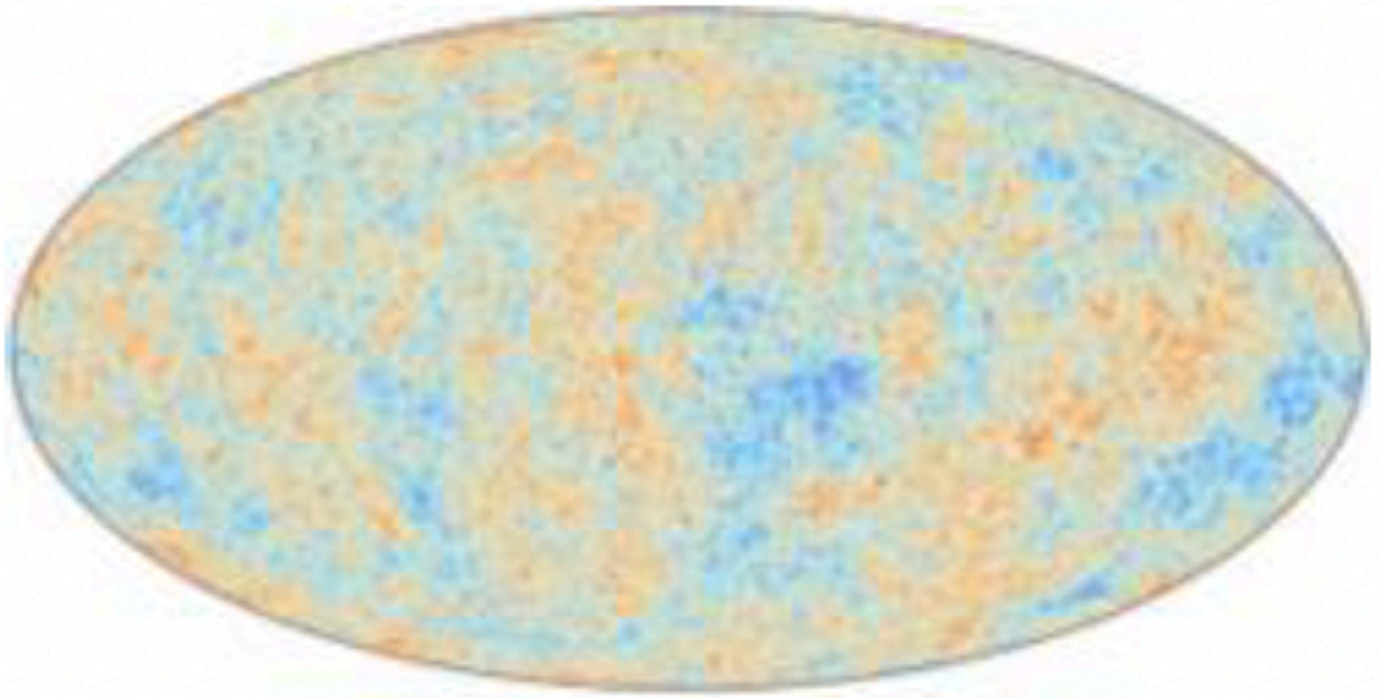


- Most stringent neutrino mass limits currently derived from cosmology
- Rely on 7+ parameter fits to extended ΛCDM model
- Fits increasingly prefer *negative* neutrino mass

DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

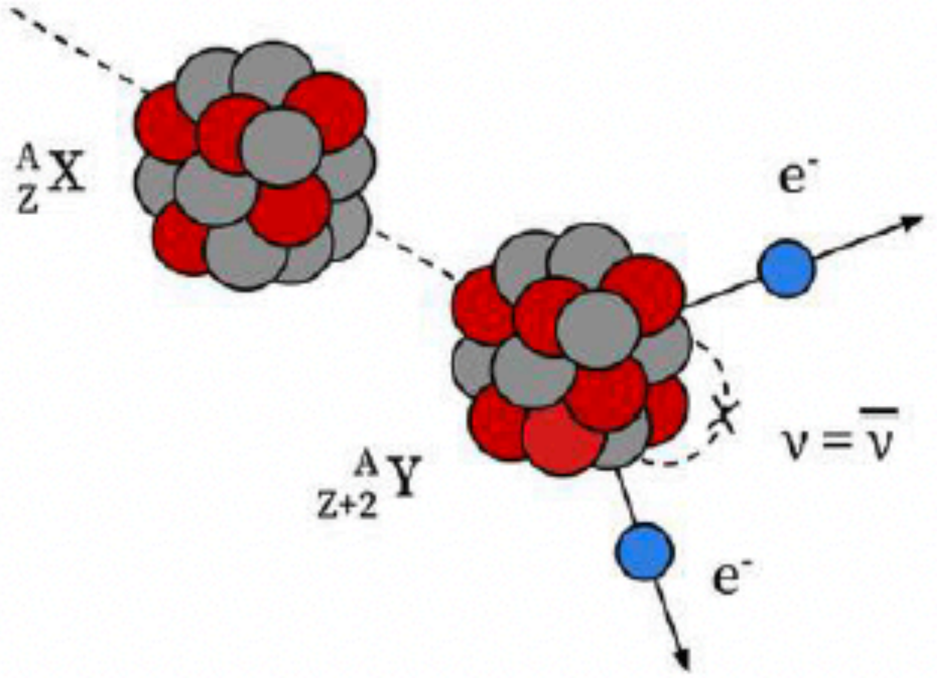
U.S. Department of Energy Office of Science

Probing the Neutrino Mass Scale



Cosmology

$$\sum m_\nu = \sum_{i=1}^{3} m_i$$



Neutrinoless Double-Beta Decay

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

- Capable of probing Majorana nature of neutrino
  - Model dependent sensitivity to neutrino mass with explanation of disparate mass scale
- Tonne-scale program is top experiment recommendation of 2023 NSAC LRP

Neutrino Mass Constraints

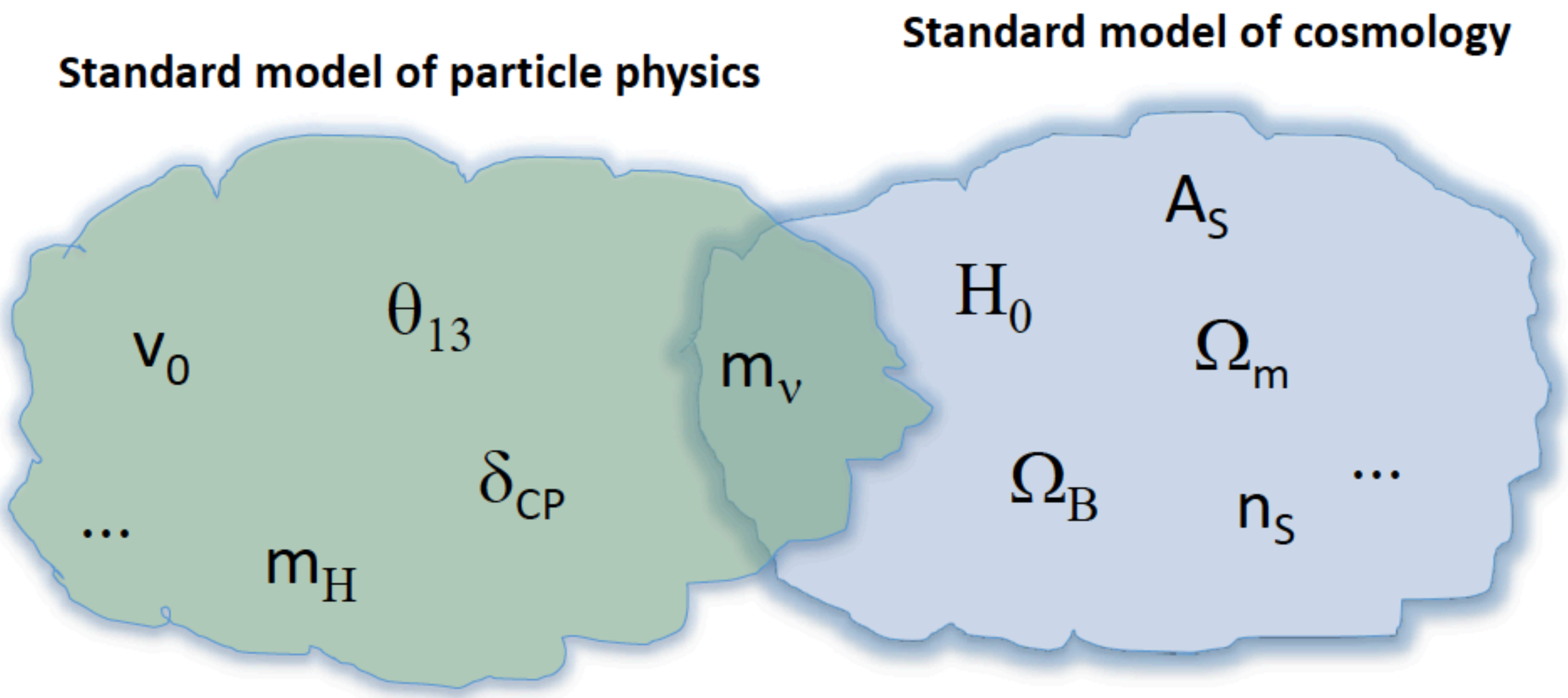
Cosmology measures $\sum_i m_i$

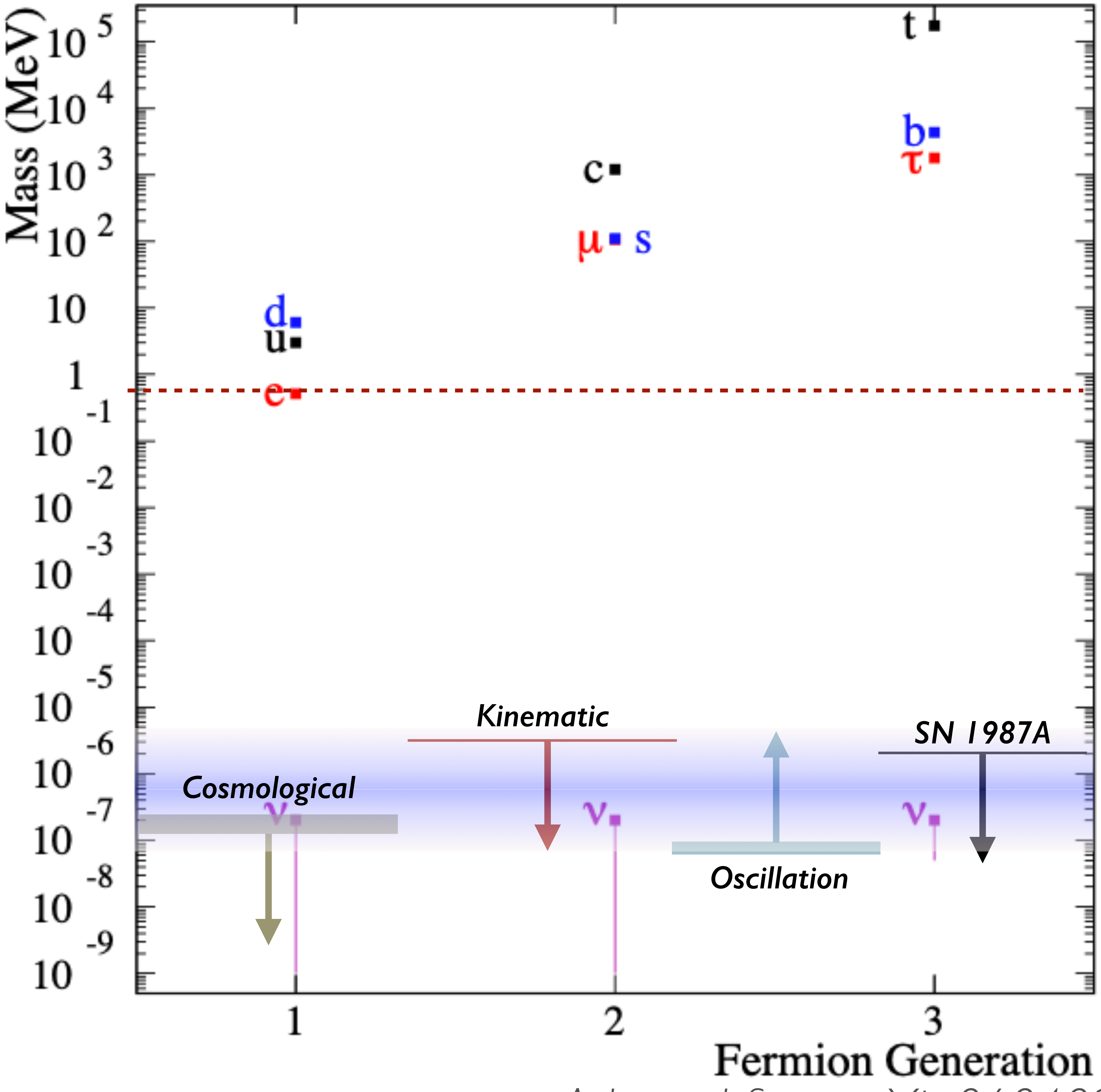
Double beta decay measures $\left|\sum_i U_{ei}^2\, m_i\right|$

Direct searches measure $\left(\sum_i |U_{ei}^2|\, m_i^2\right)^{1/2}$

m_ν measurable both by laboratory experiments and cosmology

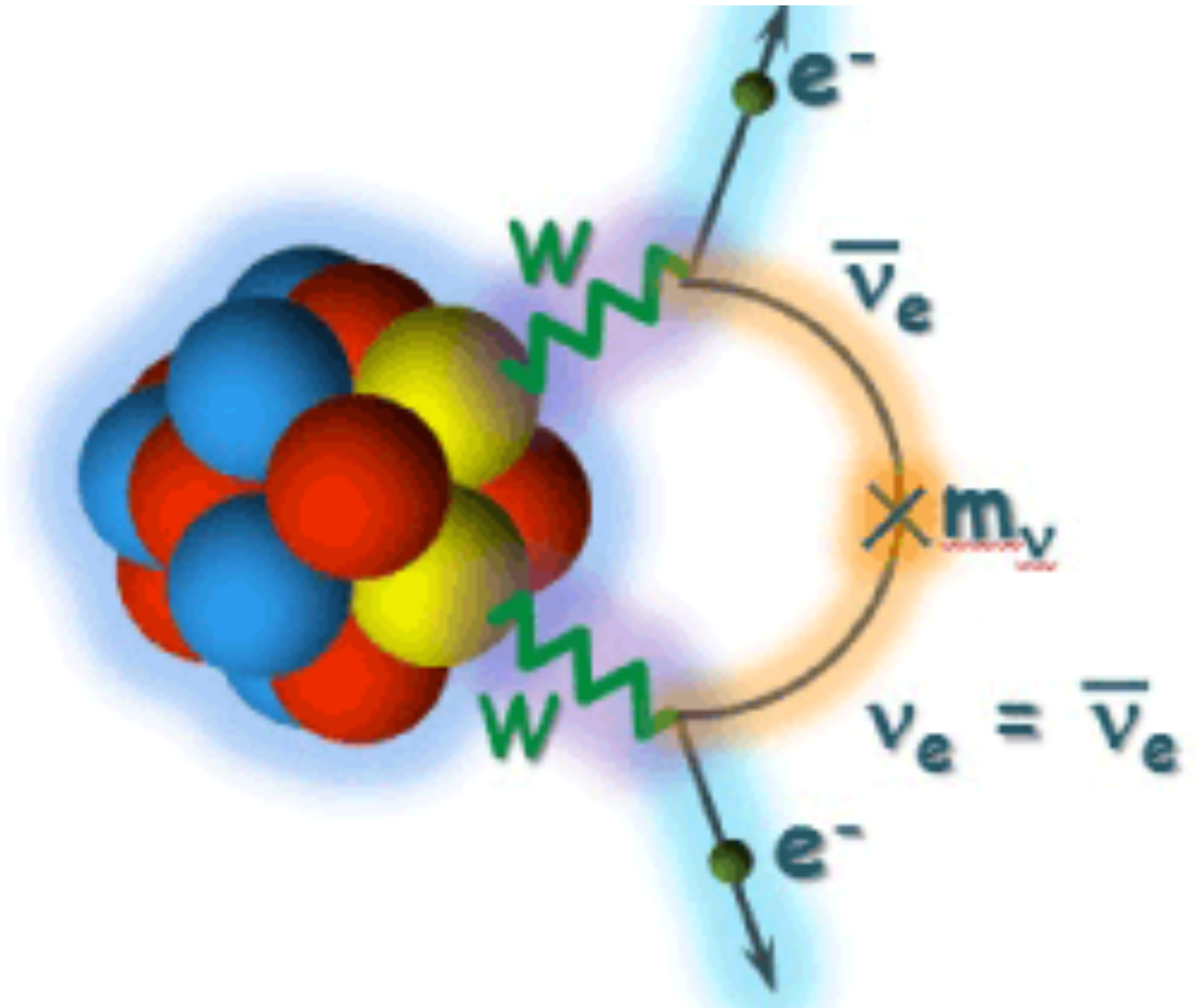
a critical test of consistency



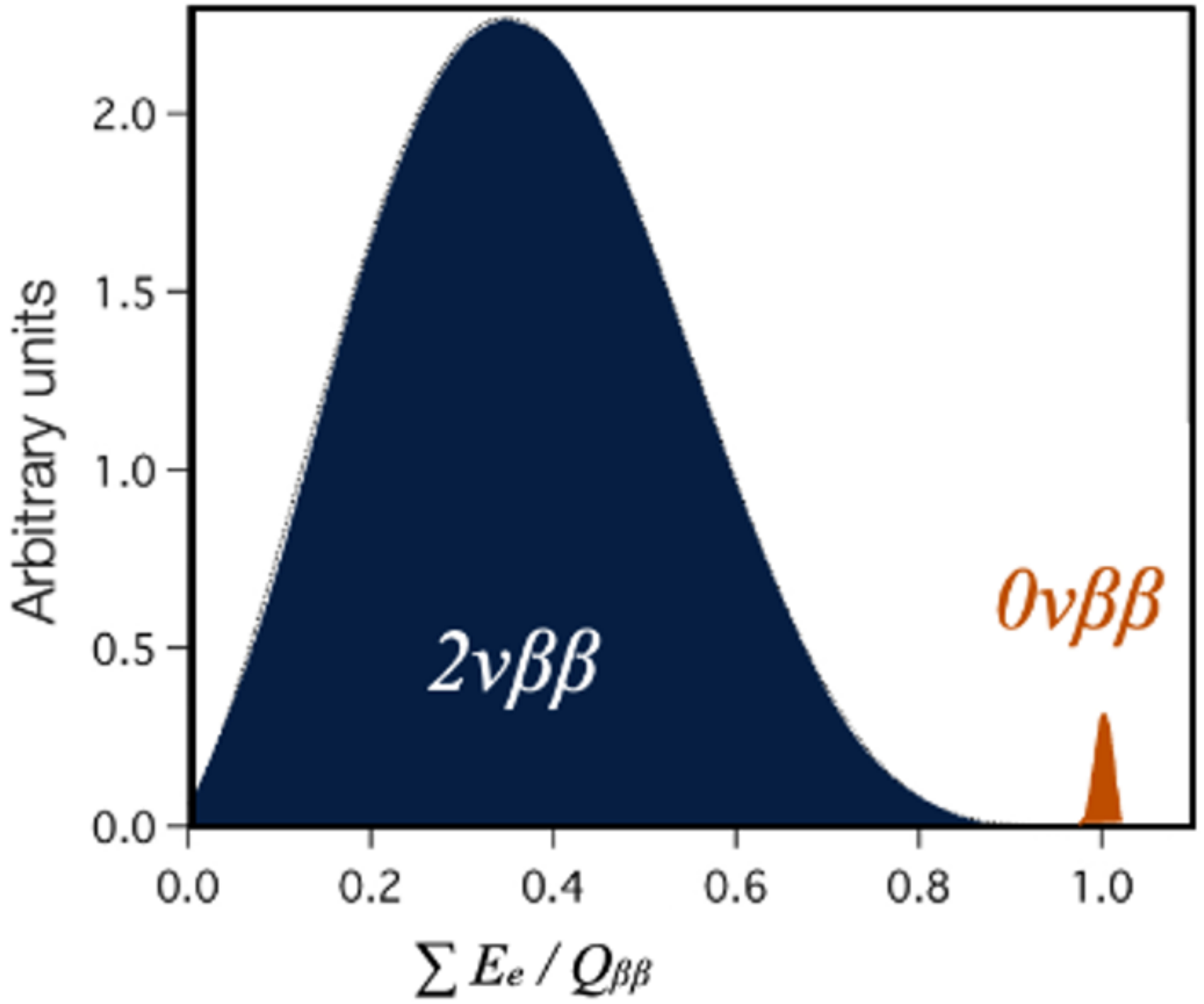


Adapted from arXiv:0604021

Neutrinoless Double Beta Decay (0νββ)



Neutrinoless double beta decay

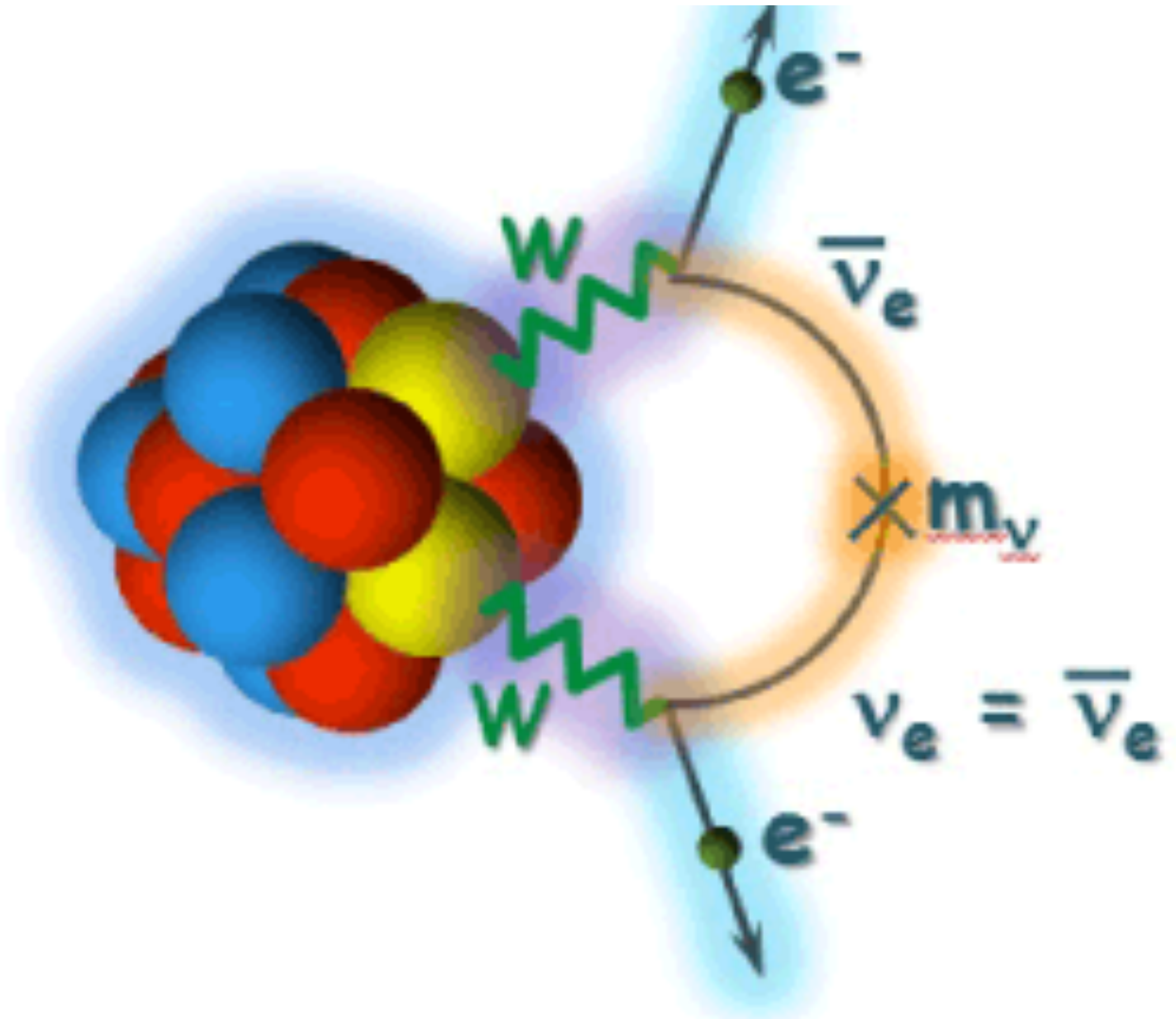


Search for peak search at the Q value of the 0νββ decay

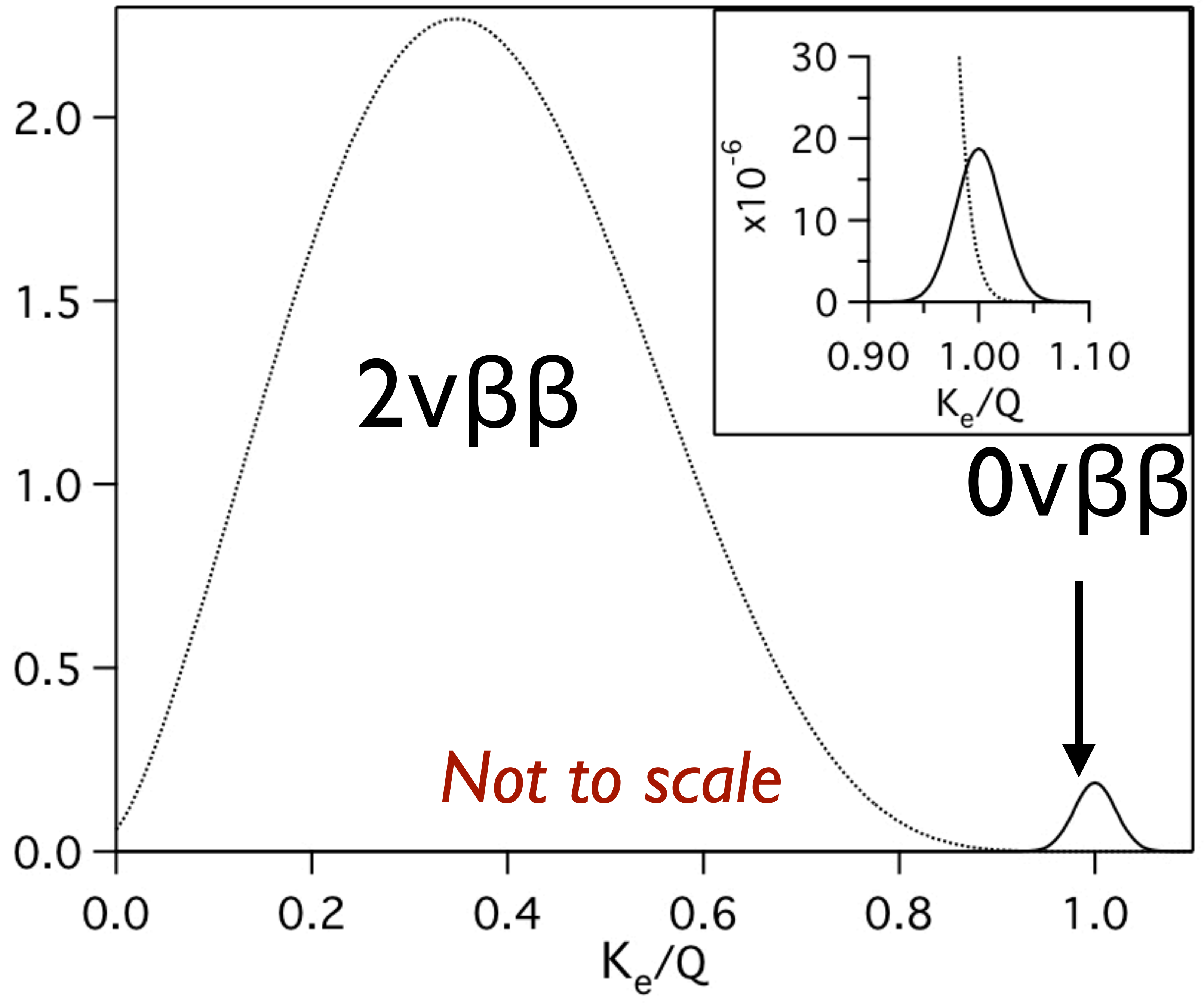
Energy peak is necessary and sufficient signature to claim a discovery.

Additional signatures from signal topology etc

Neutrinoless Double Beta Decay (0νββ)

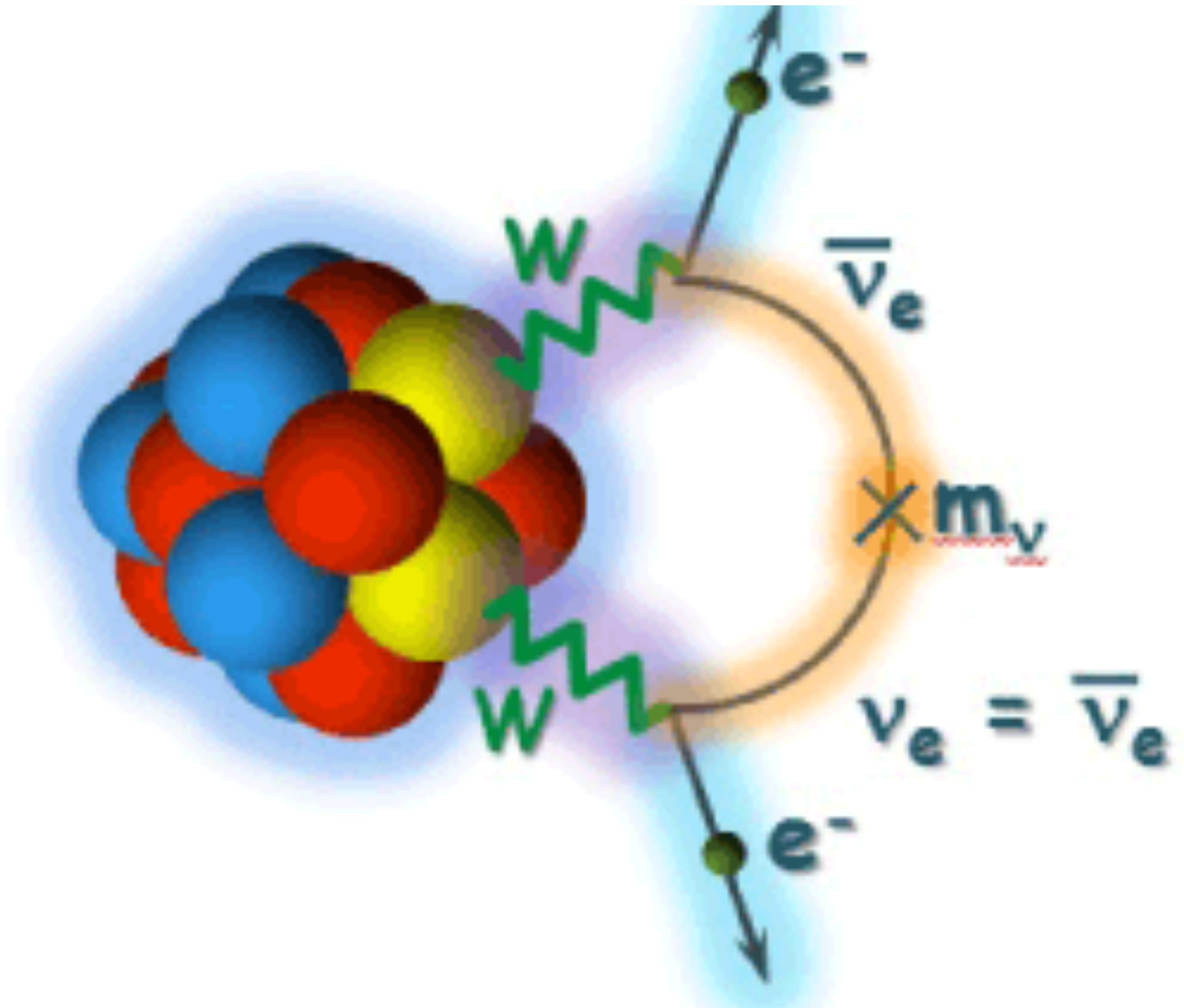


Neutrinoless double beta decay

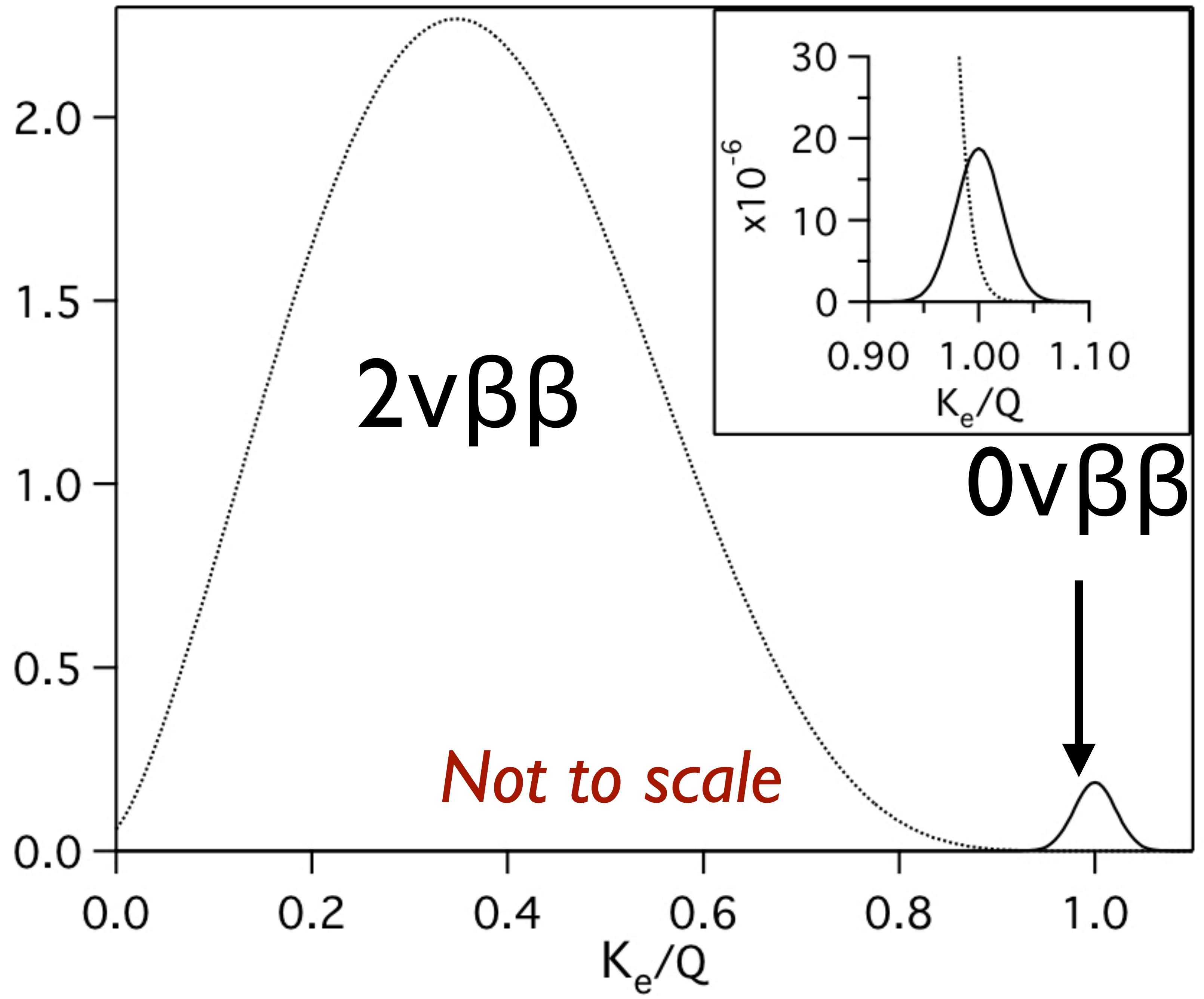


Detector energy resolution and backgrounds are key to sensitivity.

Neutrinoless Double Beta Decay (0νββ)



Neutrinoless double beta decay



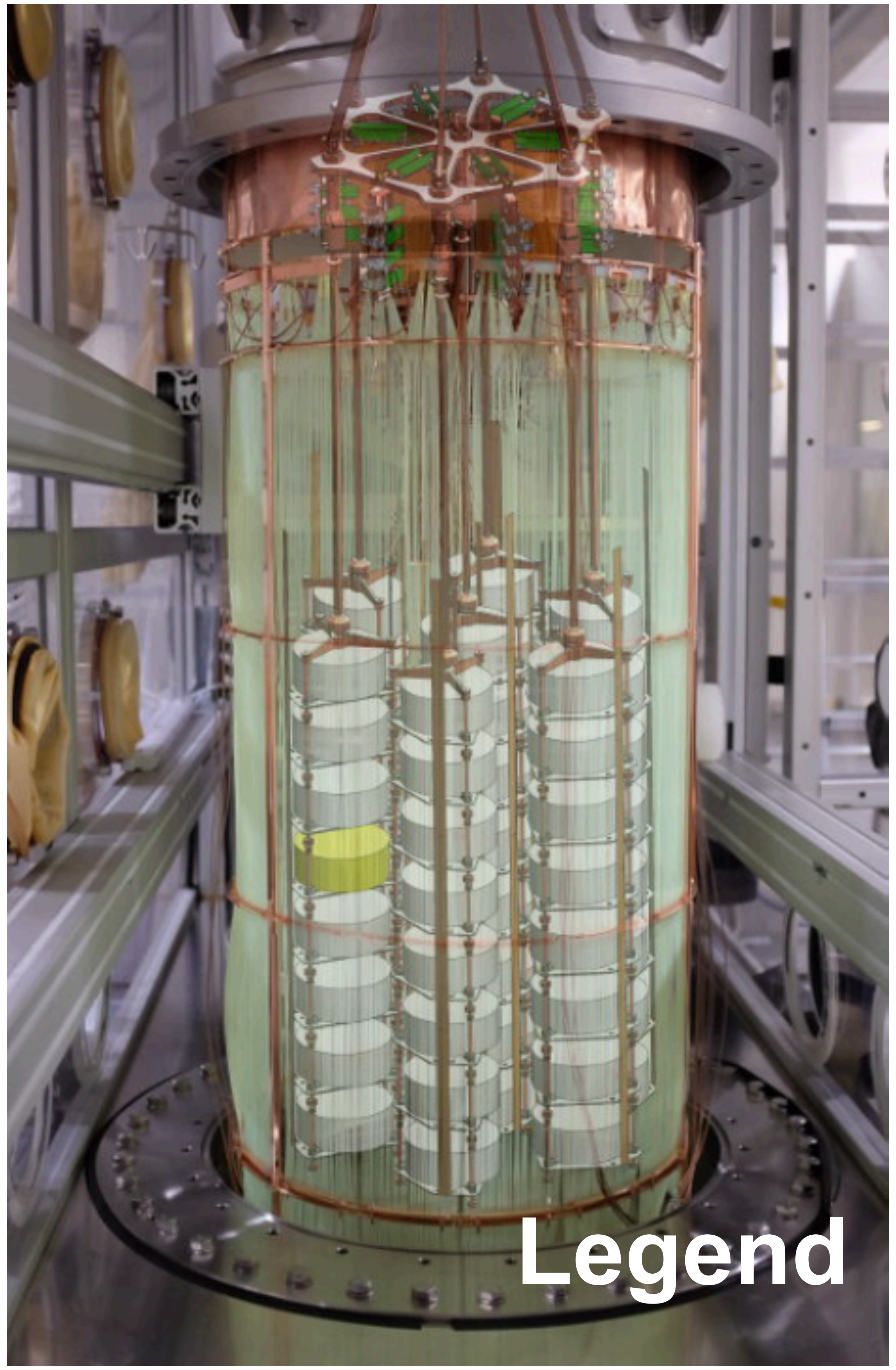
Sensitivity

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

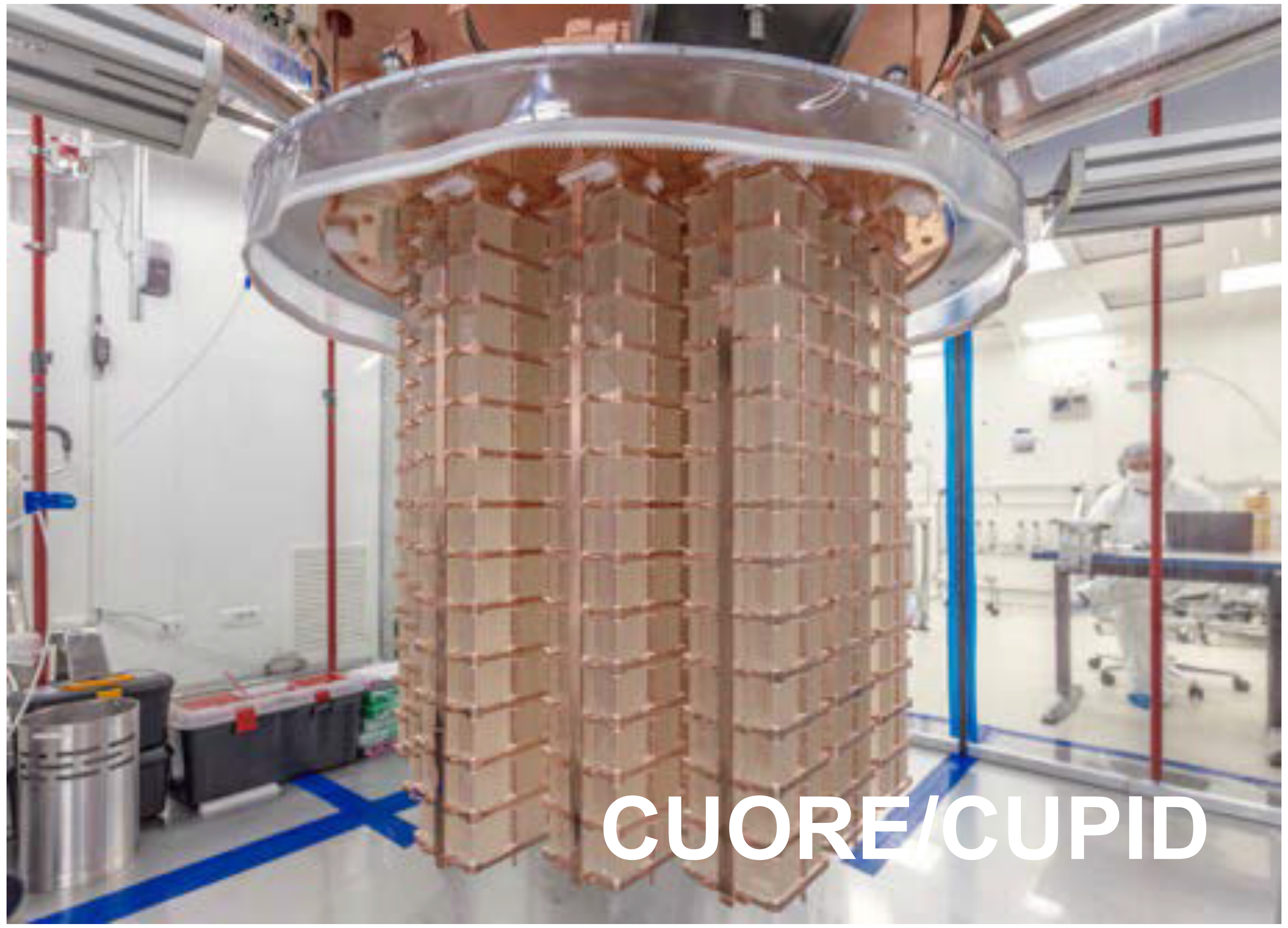
Efficiency, Mass, Runtime, Isotopic abundance, Background, Energy resolution

Detector energy resolution and backgrounds are key to sensitivity.

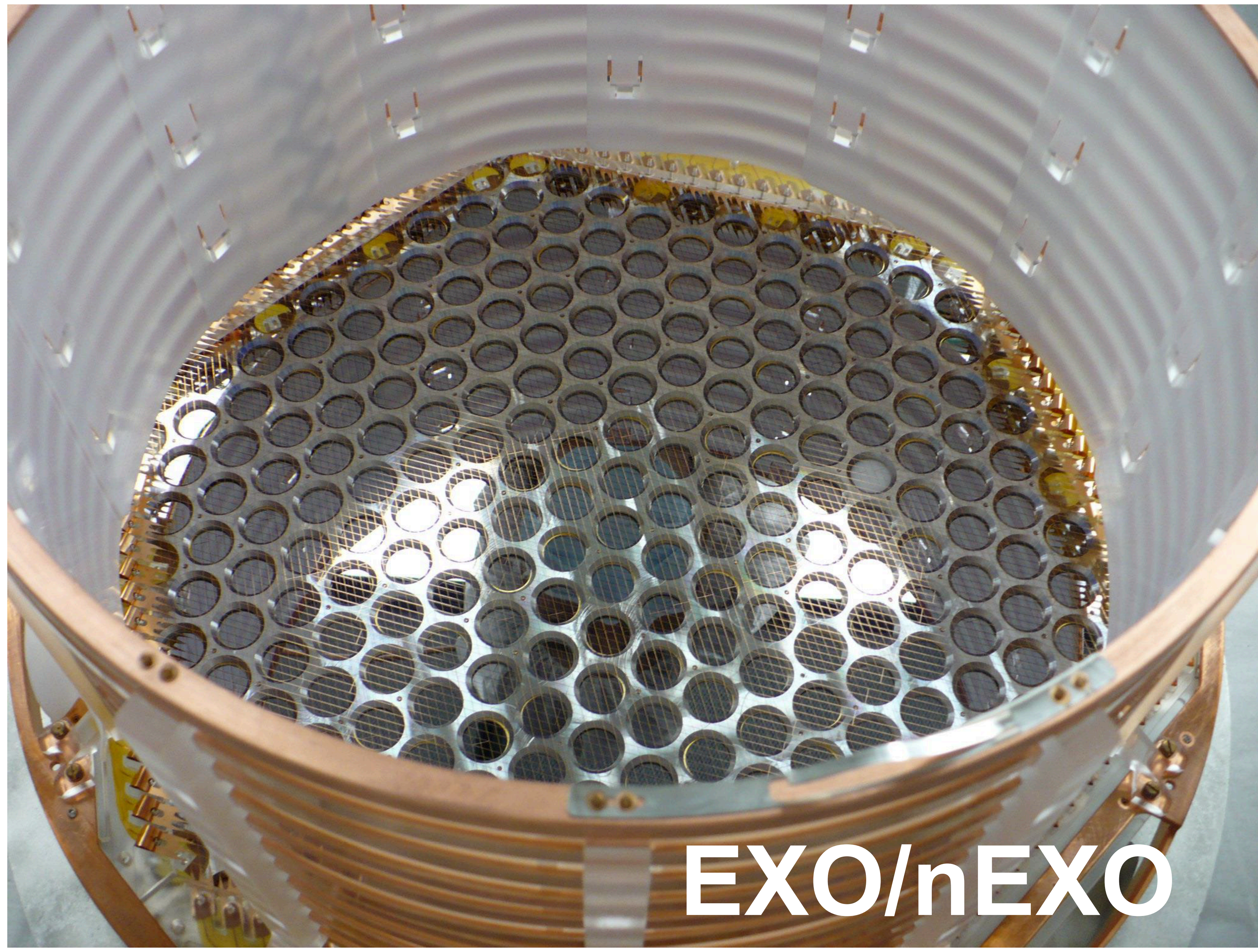
0νββ Searches - Different Isotopes and Technologies



Ge detectors



Te/Mo bolometers

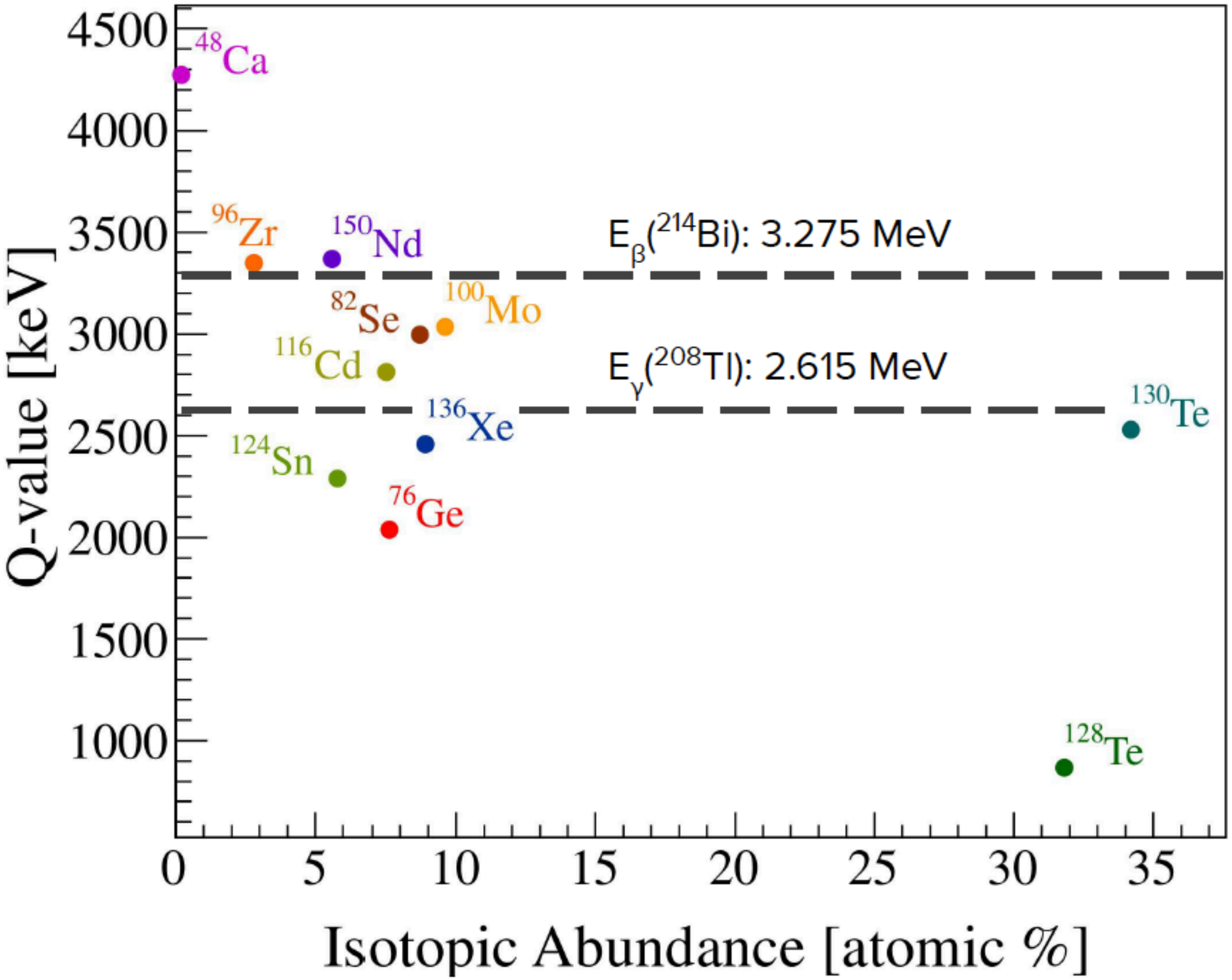


Xe TPC

Isotope Choice

Desired Characteristics

- High isotopic abundance
- Qββ above end point of β or γ radiation
- Large-scale production possible
- Enrichment possible

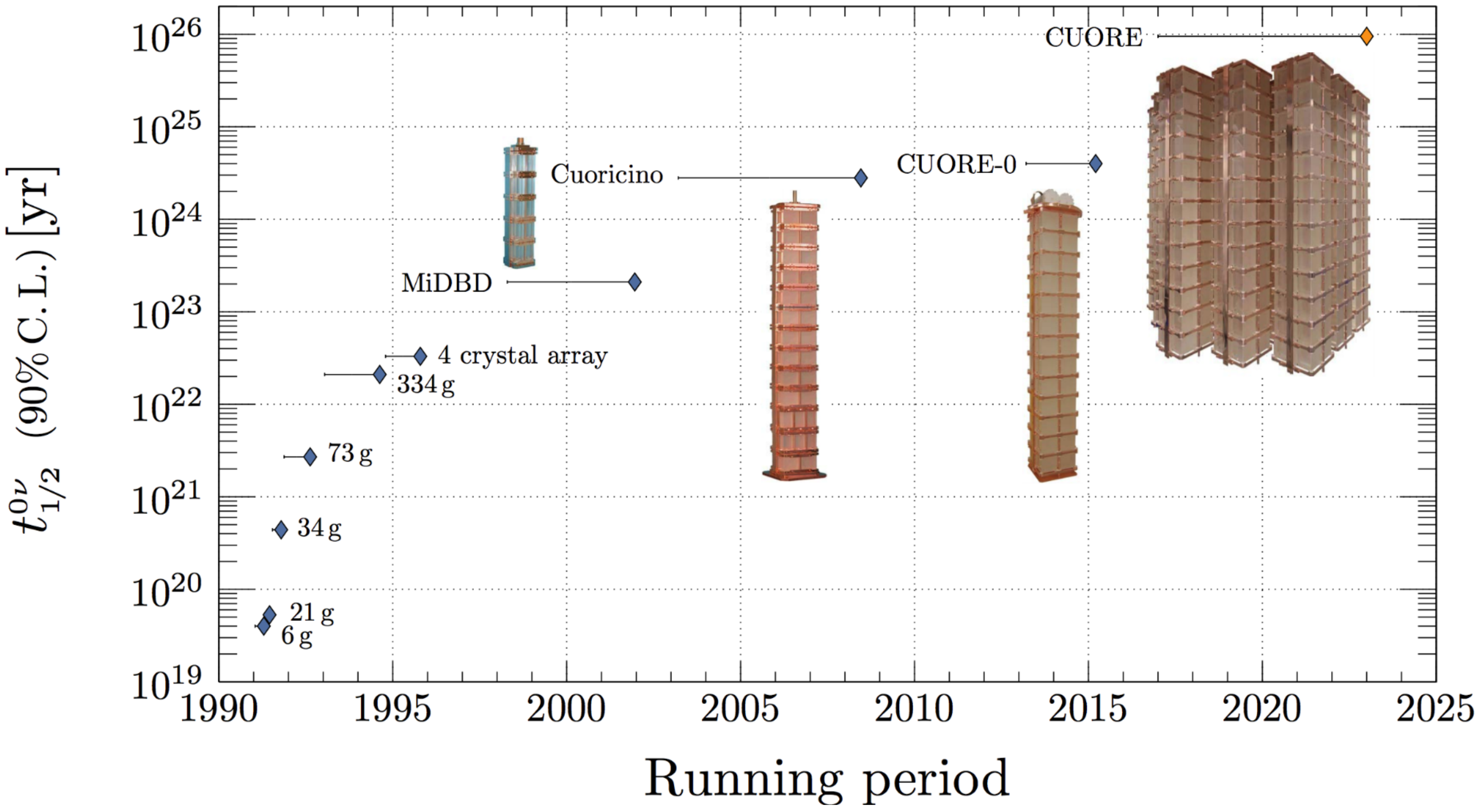


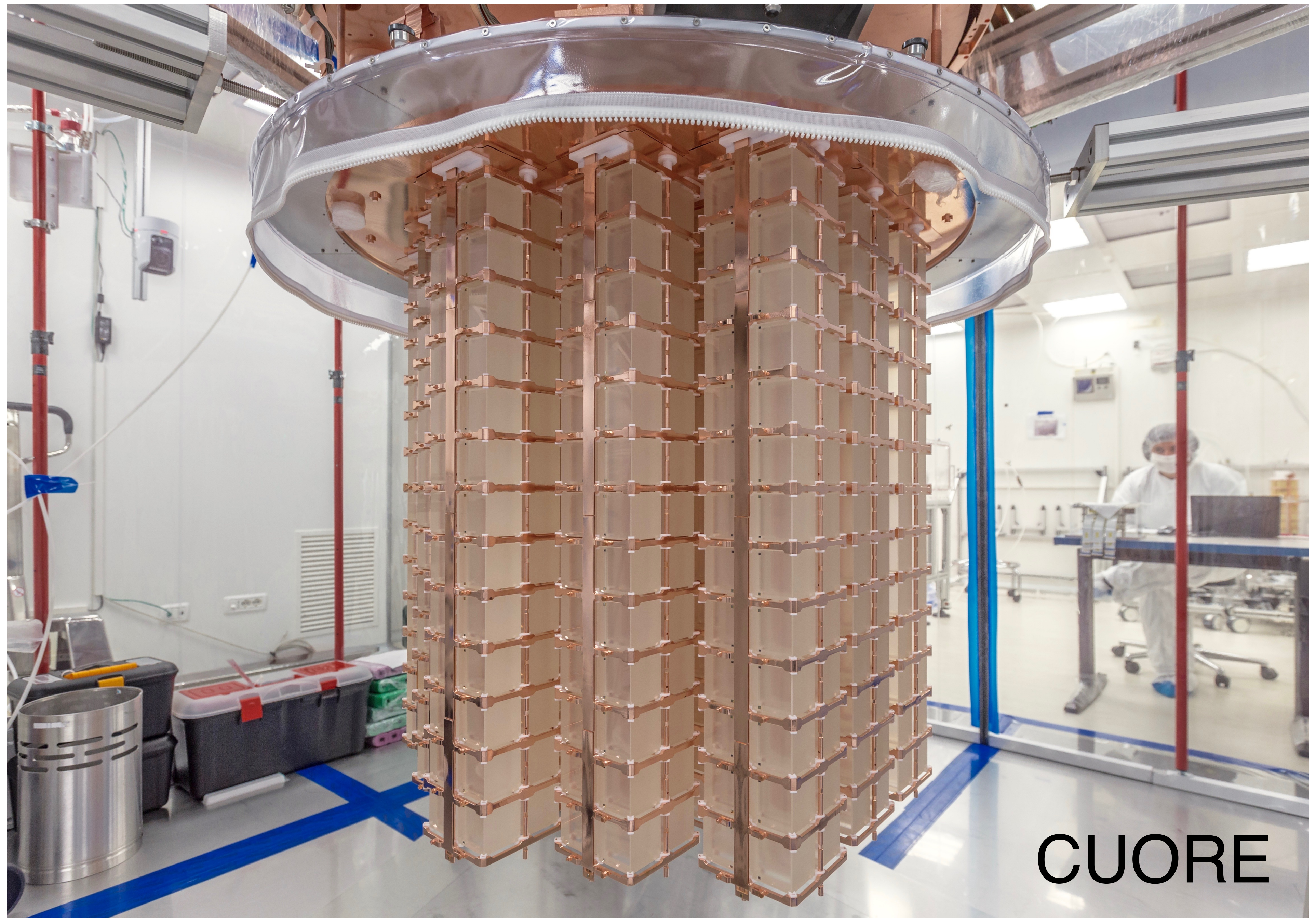
History of Bolometer Experiments for Rare Events

30 years of experience in searching for 0νββ with cryogenic bolometers

CUORE and CUPID folow a long series of experiments, from few grams to 742 kg of detector material

First tonne-scale bolometric experiment in the world





Brofferio, C. and Dell'Oro, S., Rev. Sci. Inst. 89, 121501 (2018)

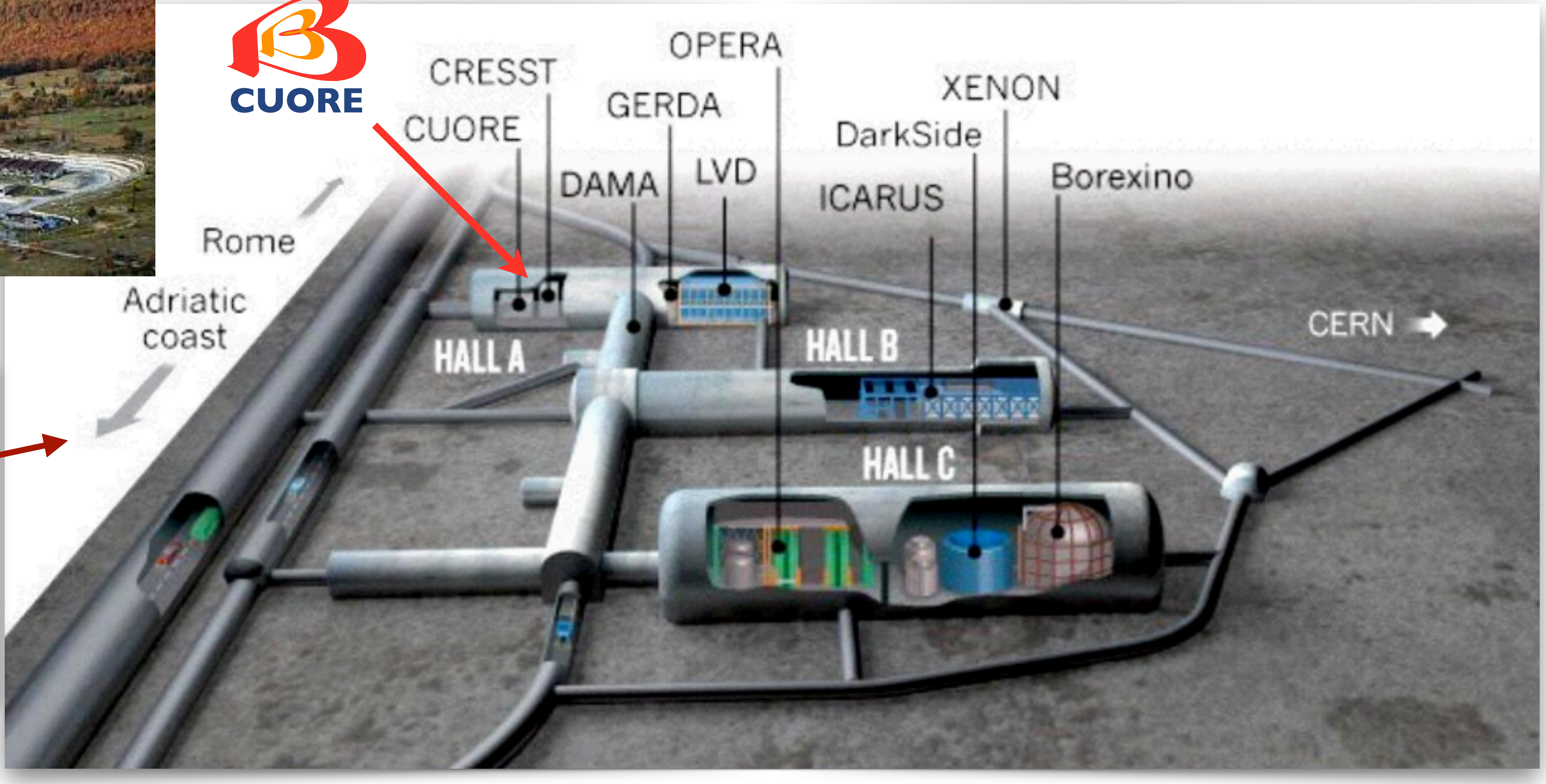
LNGS: Laboratori Nazionali del Gran Sasso

Natural shielding from cosmic rays by the mountain of Gran Sasso

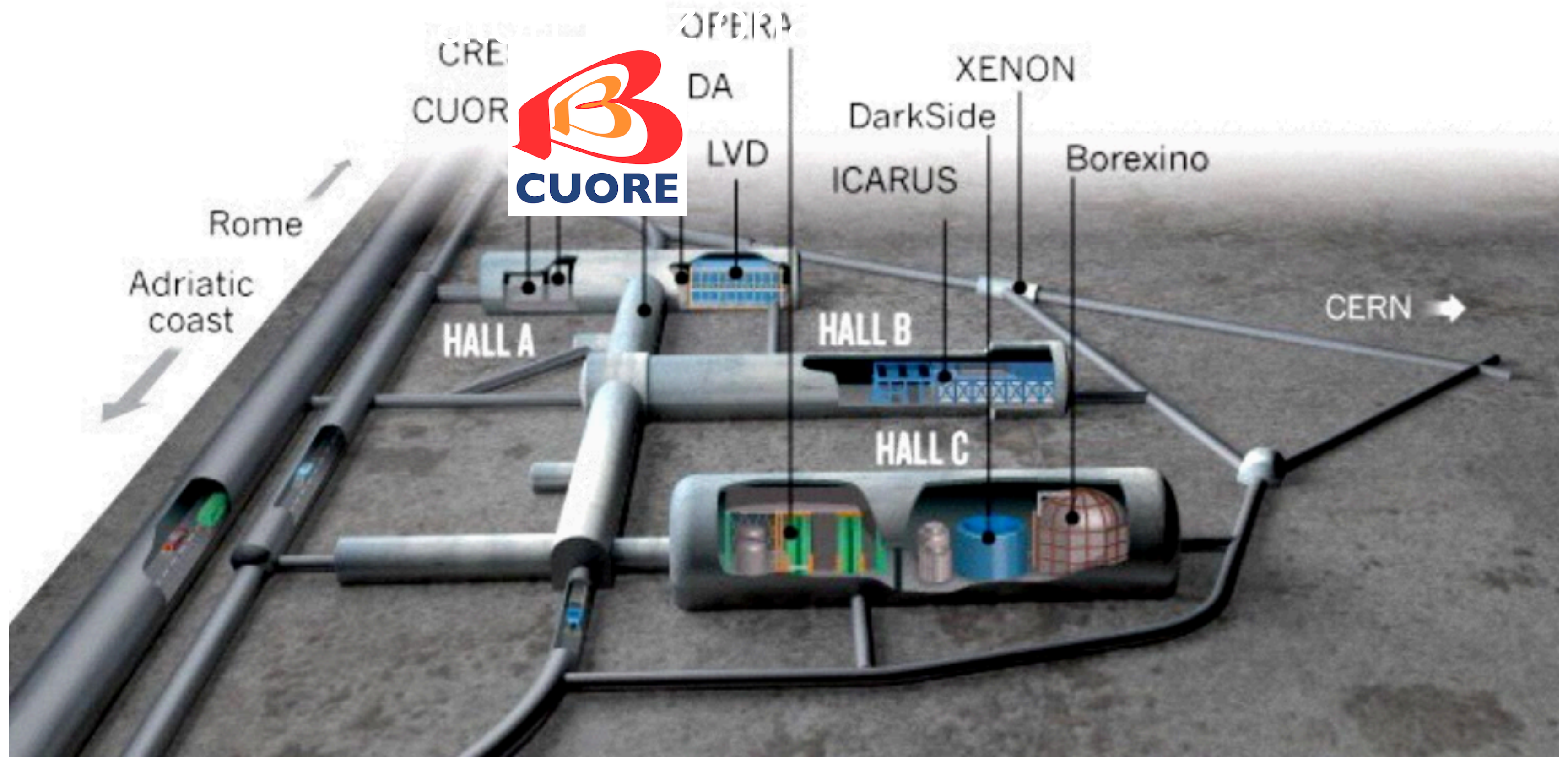
3600 meter water equivalent overburden

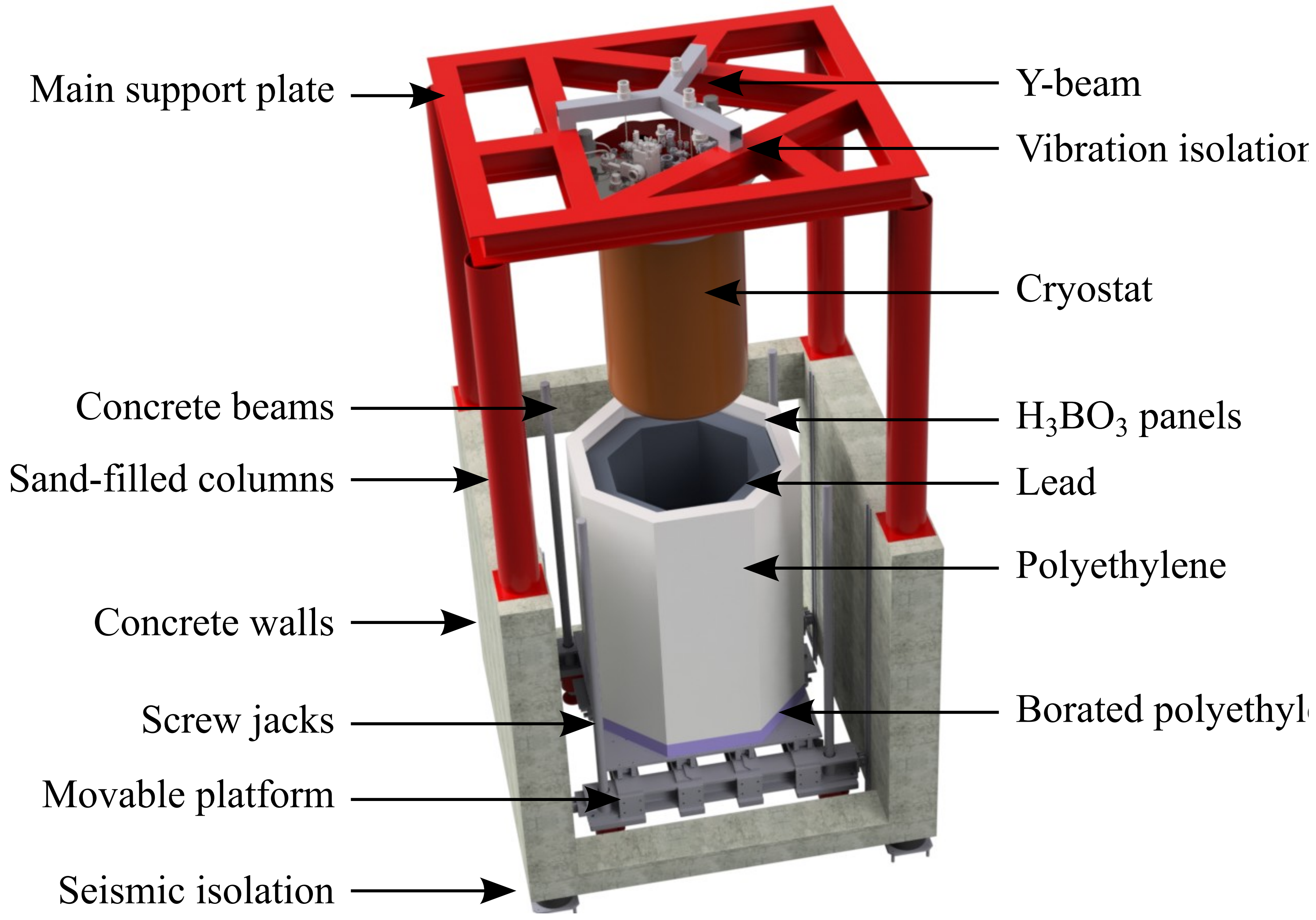
Well-established support for experiments and user access

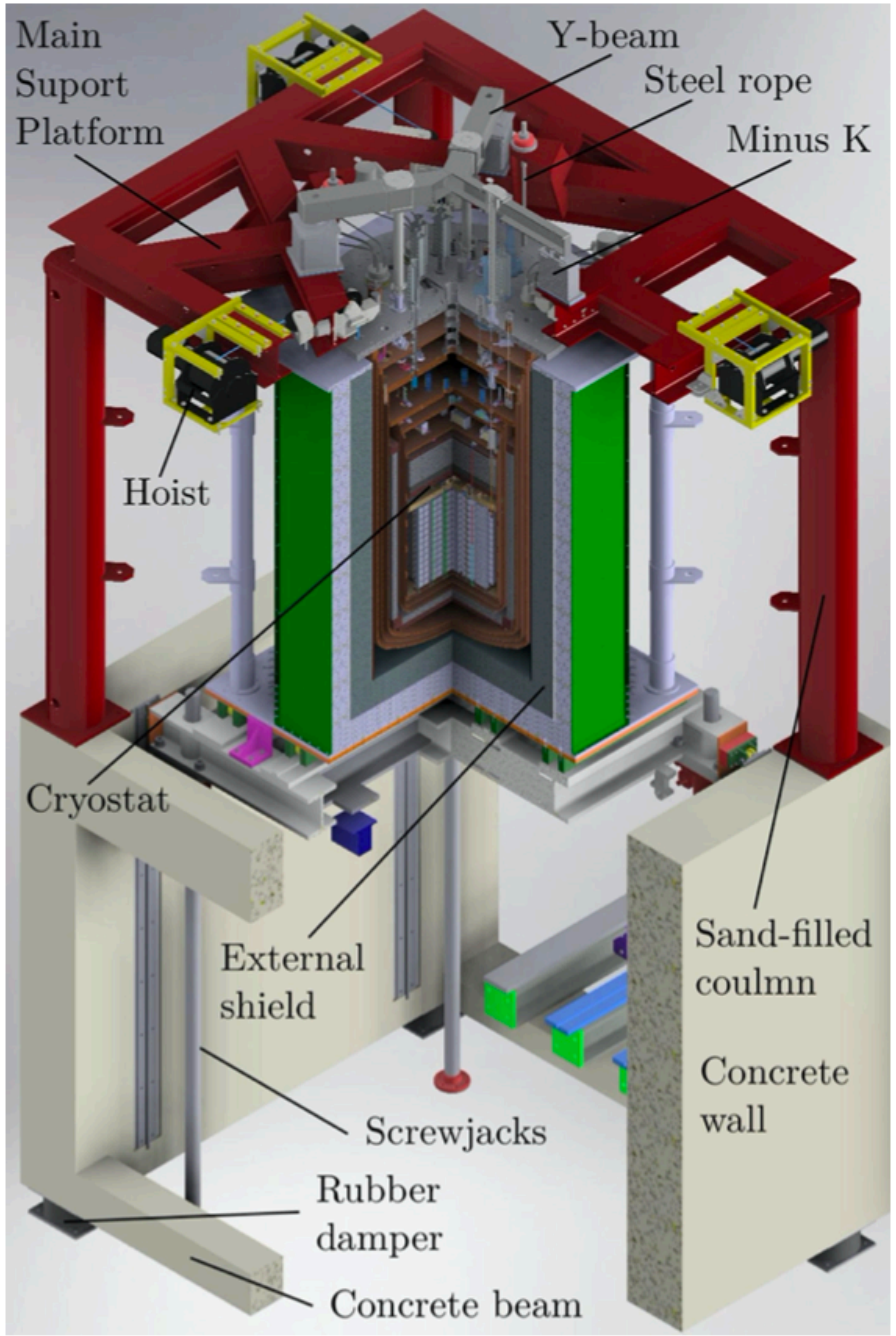
CUORE



Experimental Site







Unique cryogenic infrastructure.

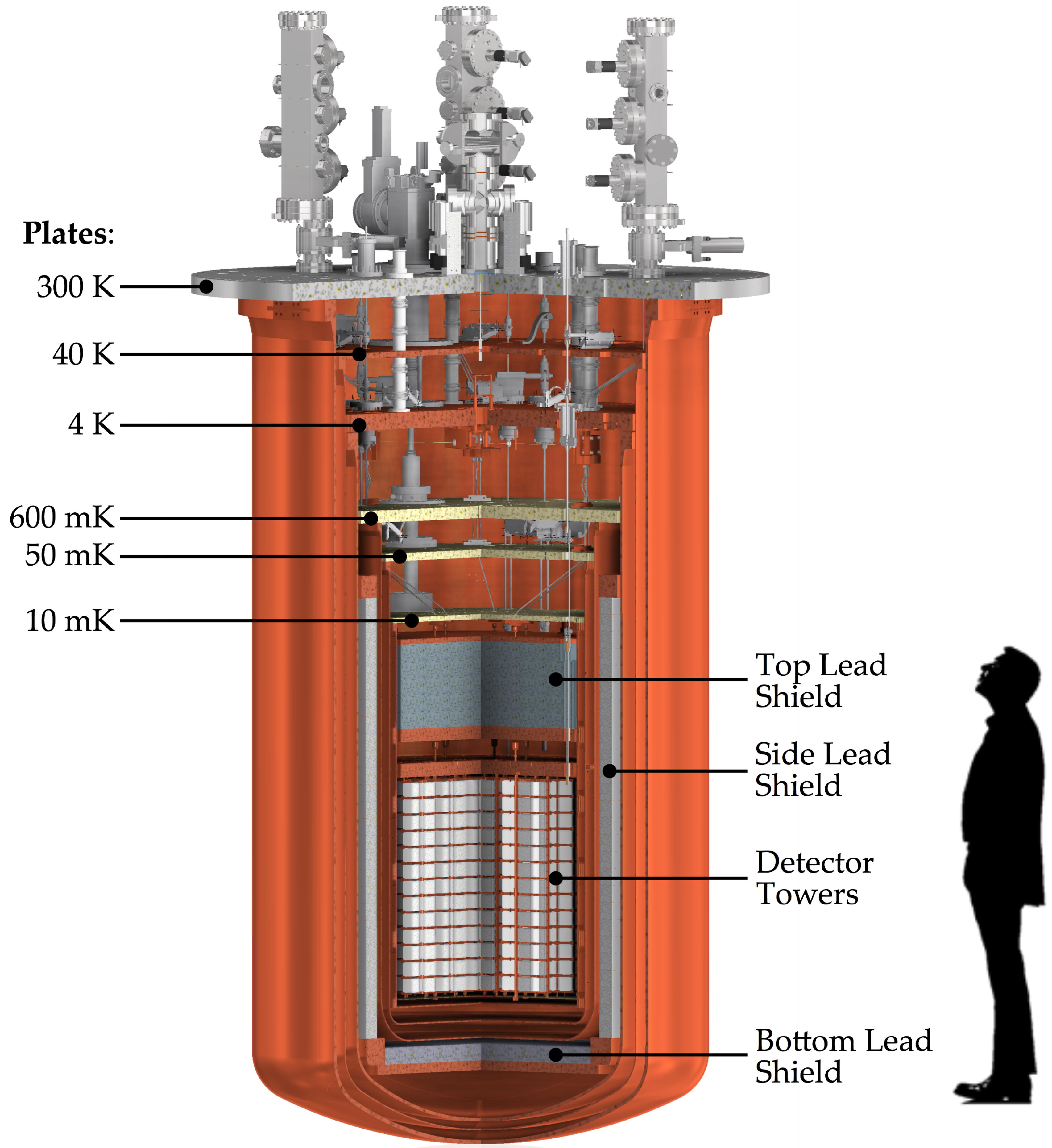
CUORE - *Coldest Cubic Meter in the Known Universe*

CUORE cryostat

- Multistage cryogen-free
- cryostat
- Cooling systems: fast cooling
- system, Pulse Tubes (PTs), and
- Dilution Unit (DU)
- ~15 tons @ < 4 K
- ~ 3 tons @ < 50 mK
- Mechanical vibration isolation
- Active noise cancelling

CUORE (passive) shielding

- Roman Pb shielding in cryostat
- External Pb shielding
- H_3BO_3 panels + polyethylene



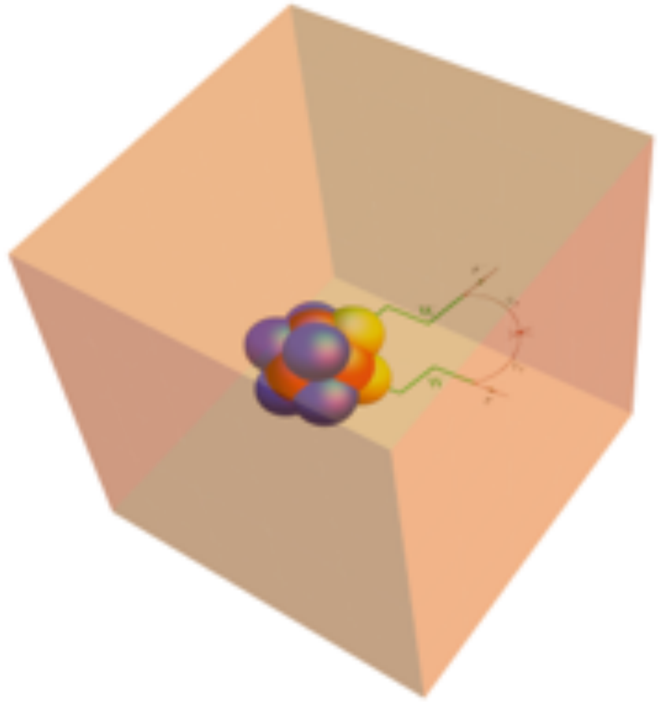

Roman lead ingots

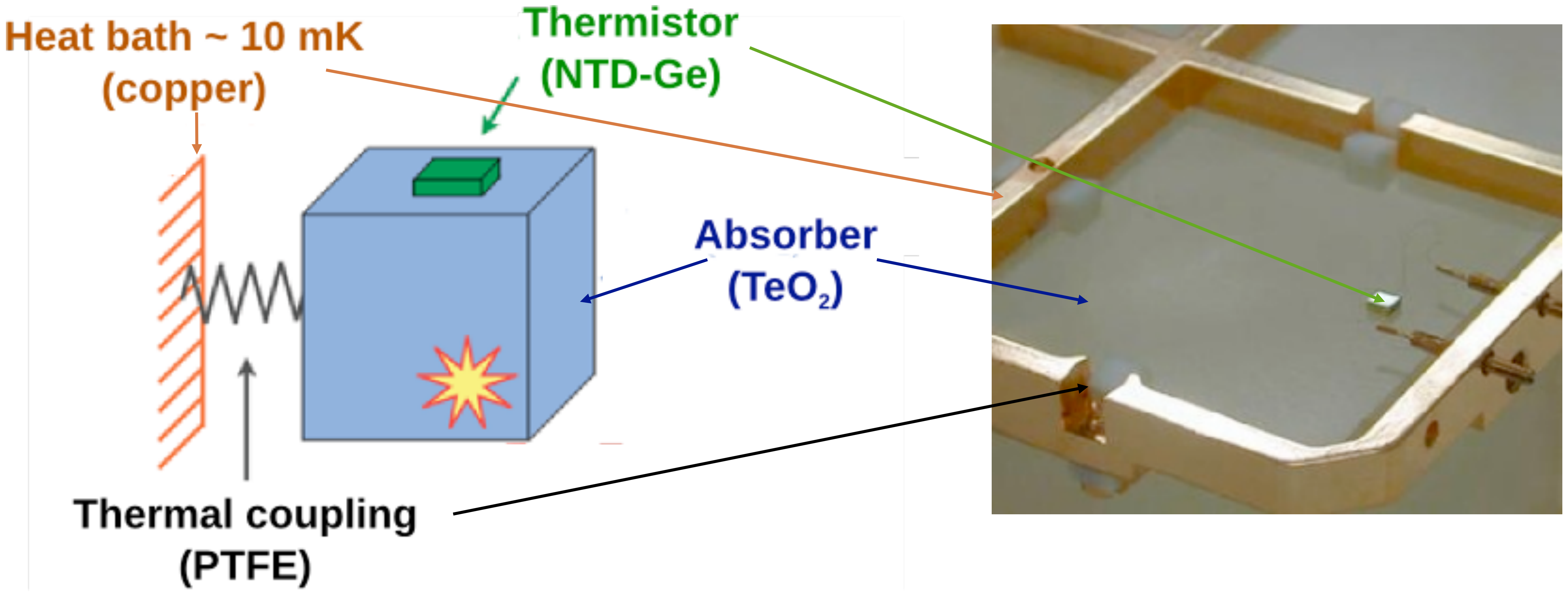
70 tonne of lead, 7 tonne of cold lead

Careful material selection: Ancient Lead and low radioactive copper

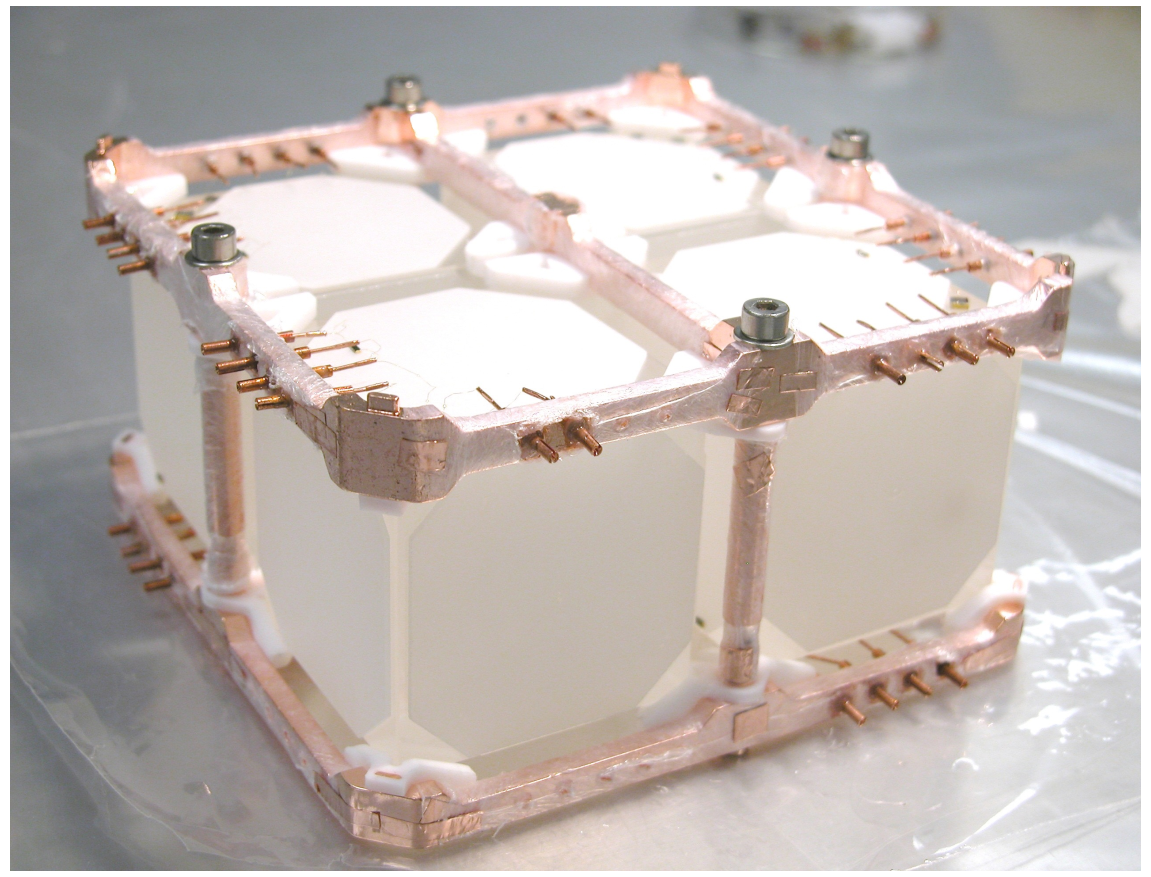
Bolometric Search for 0νββ

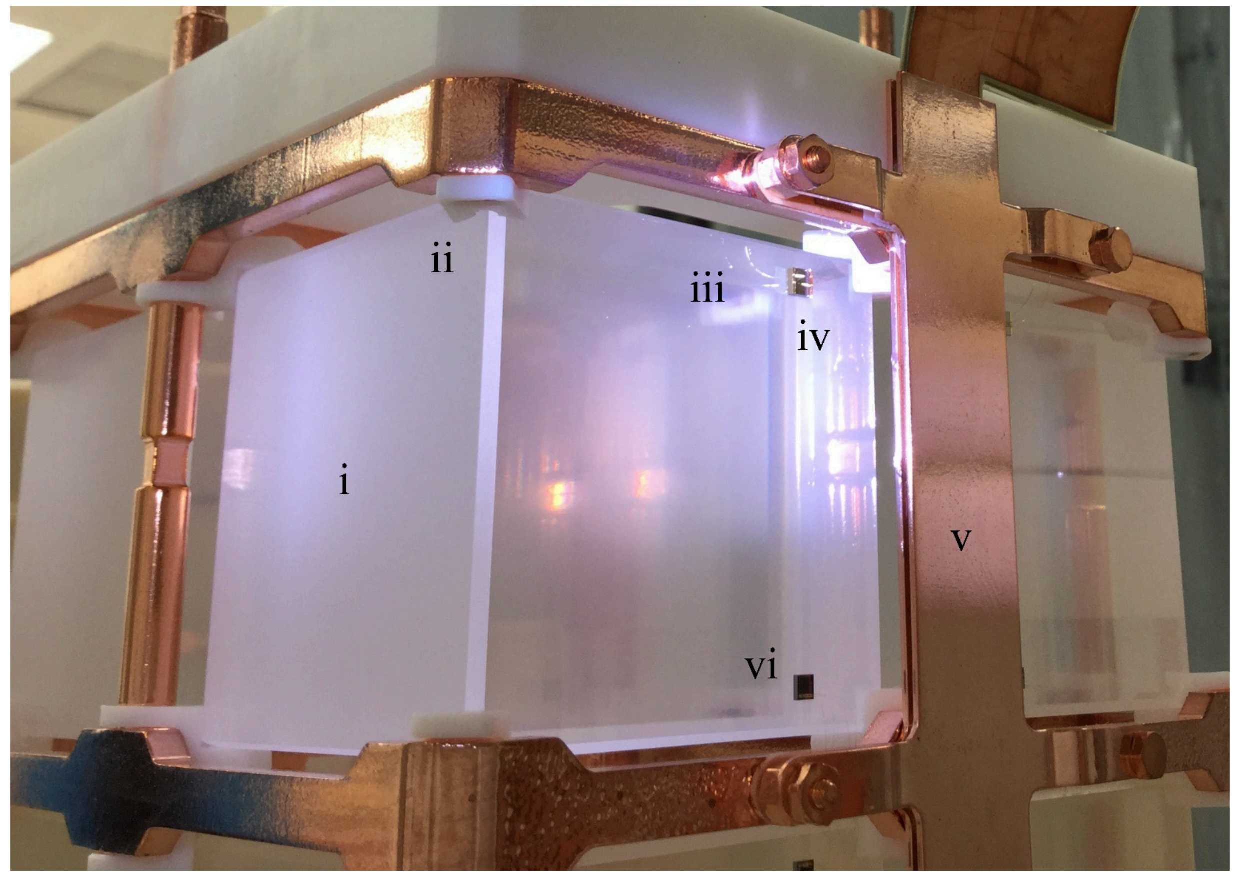
Source = Detector



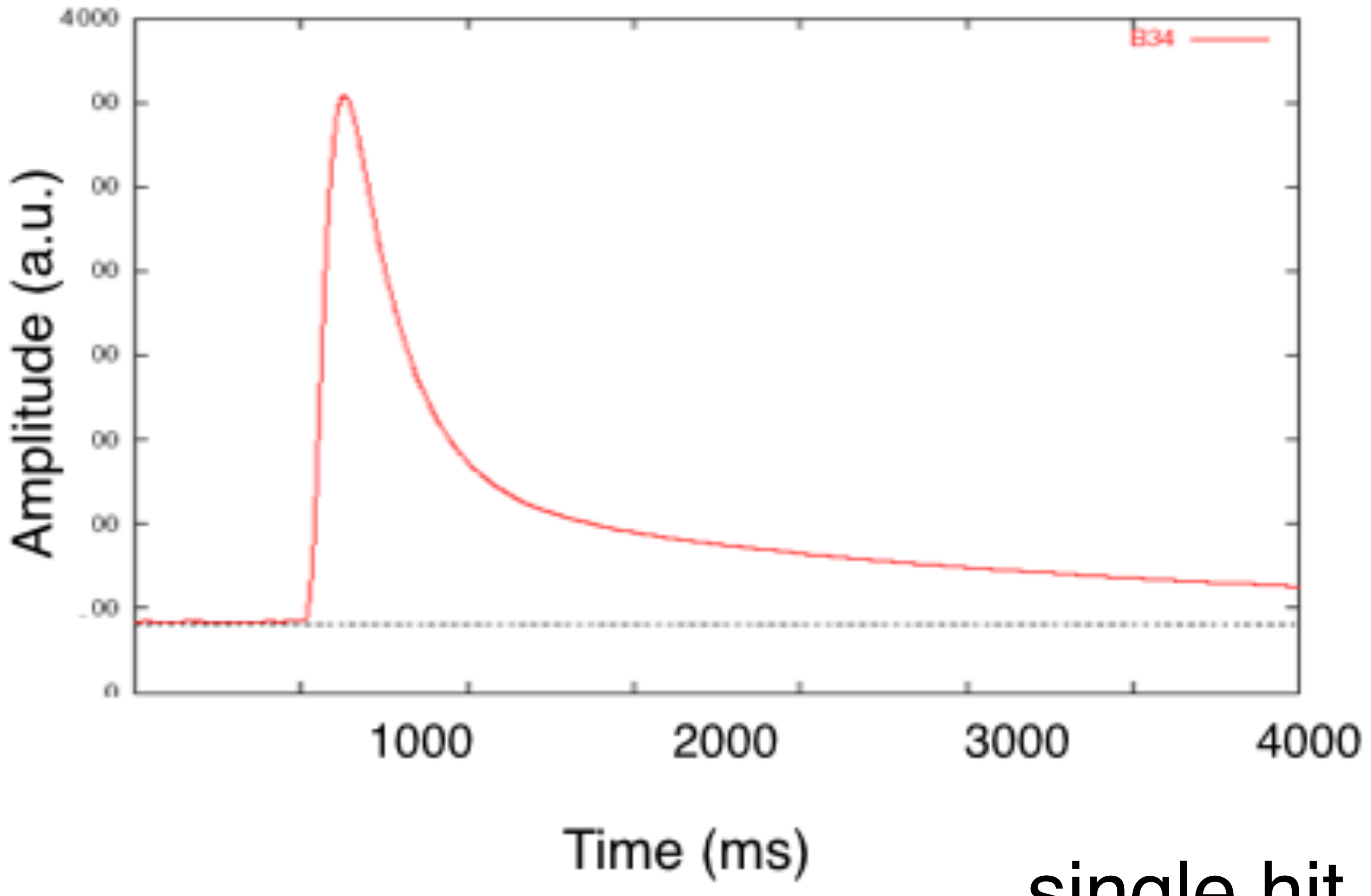


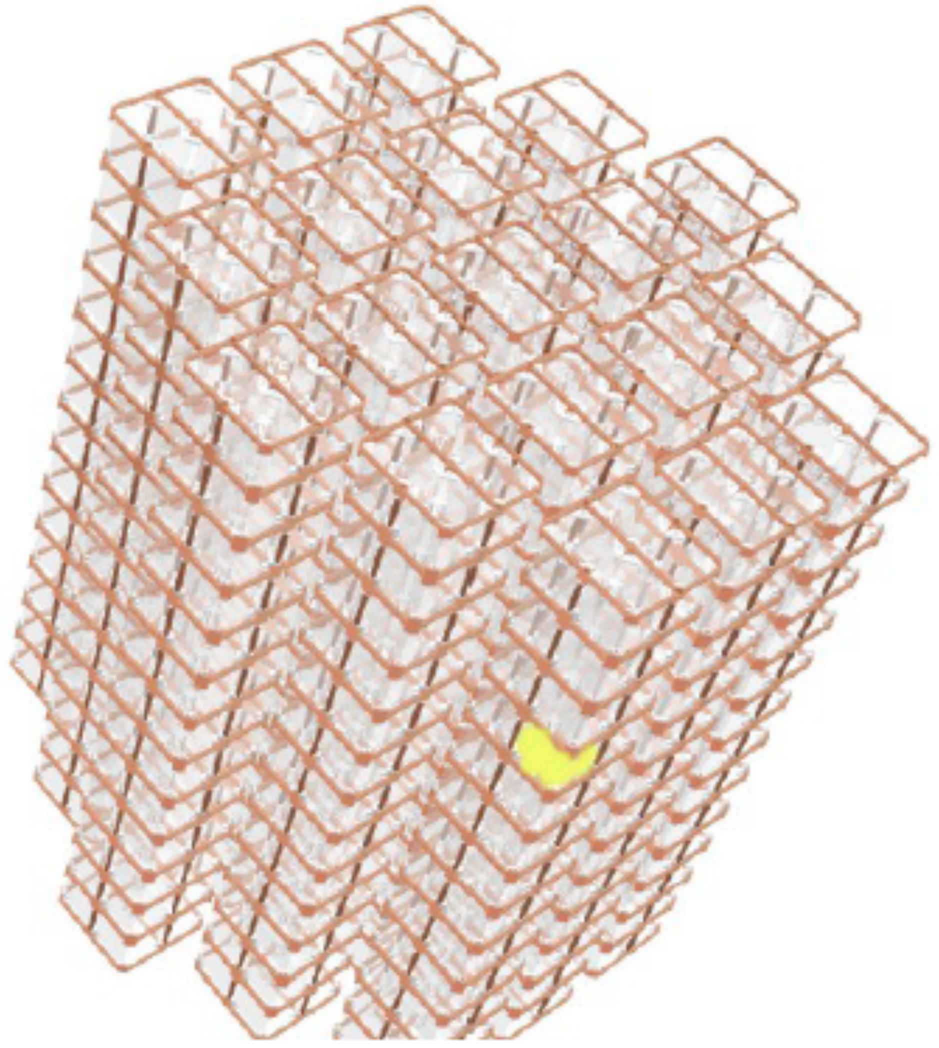
$^{130}Te \rightarrow {}^{130}Xe + 2e^-$ Q = (2527.518 +/- 0.013) keV





Single pulse example



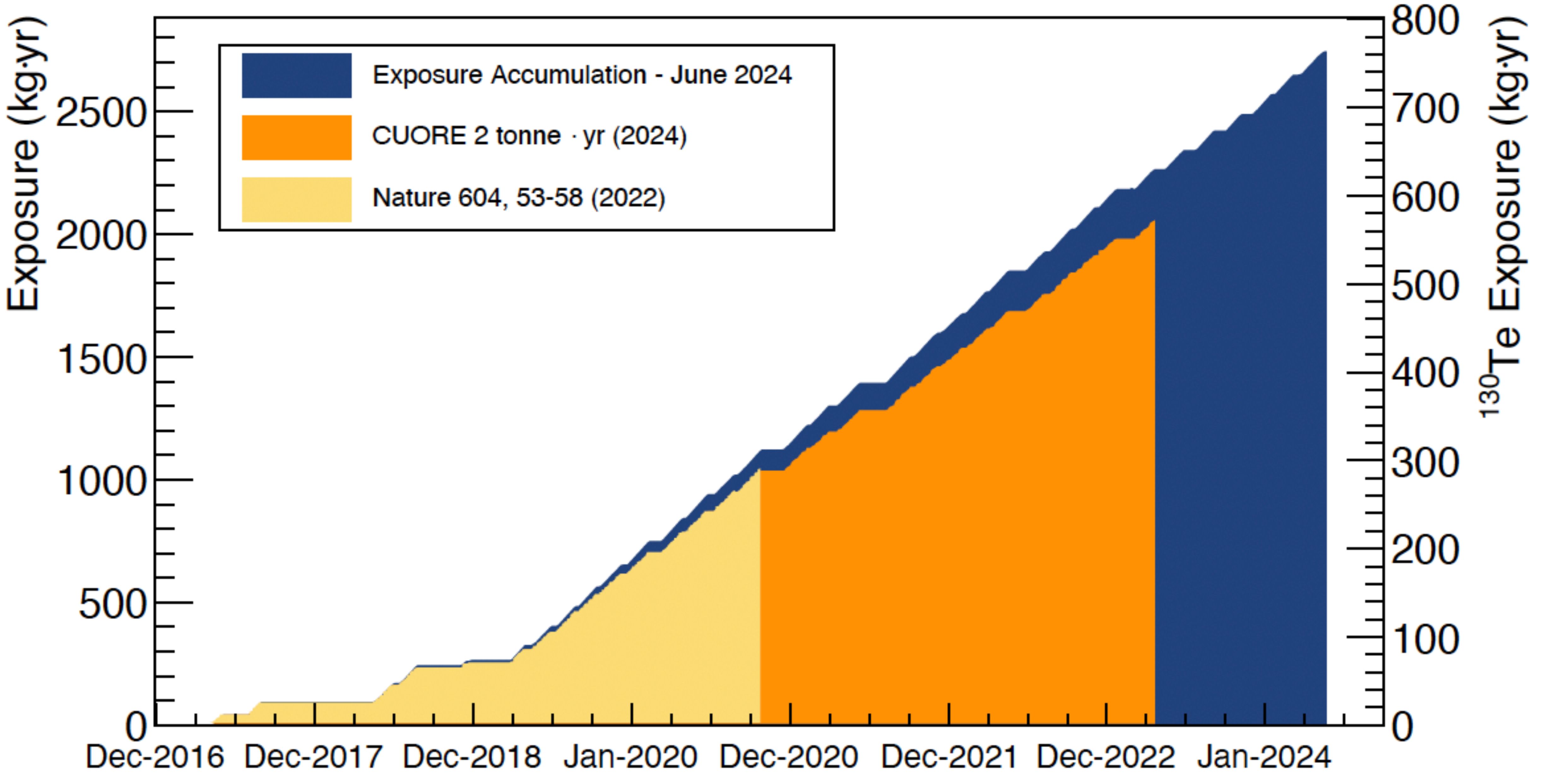


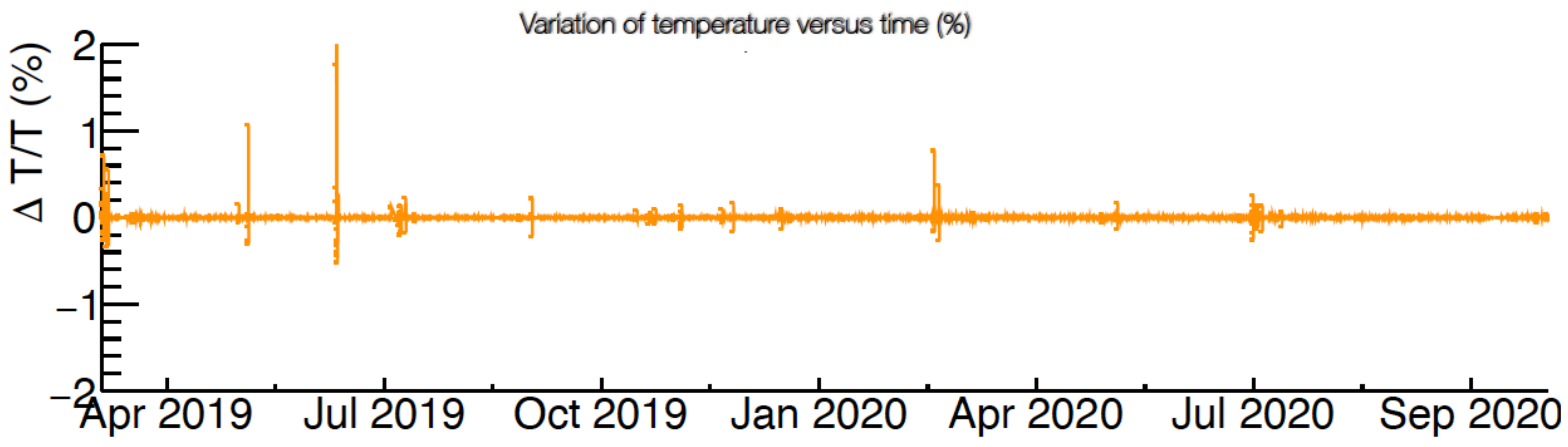
single hit, monochromatic event

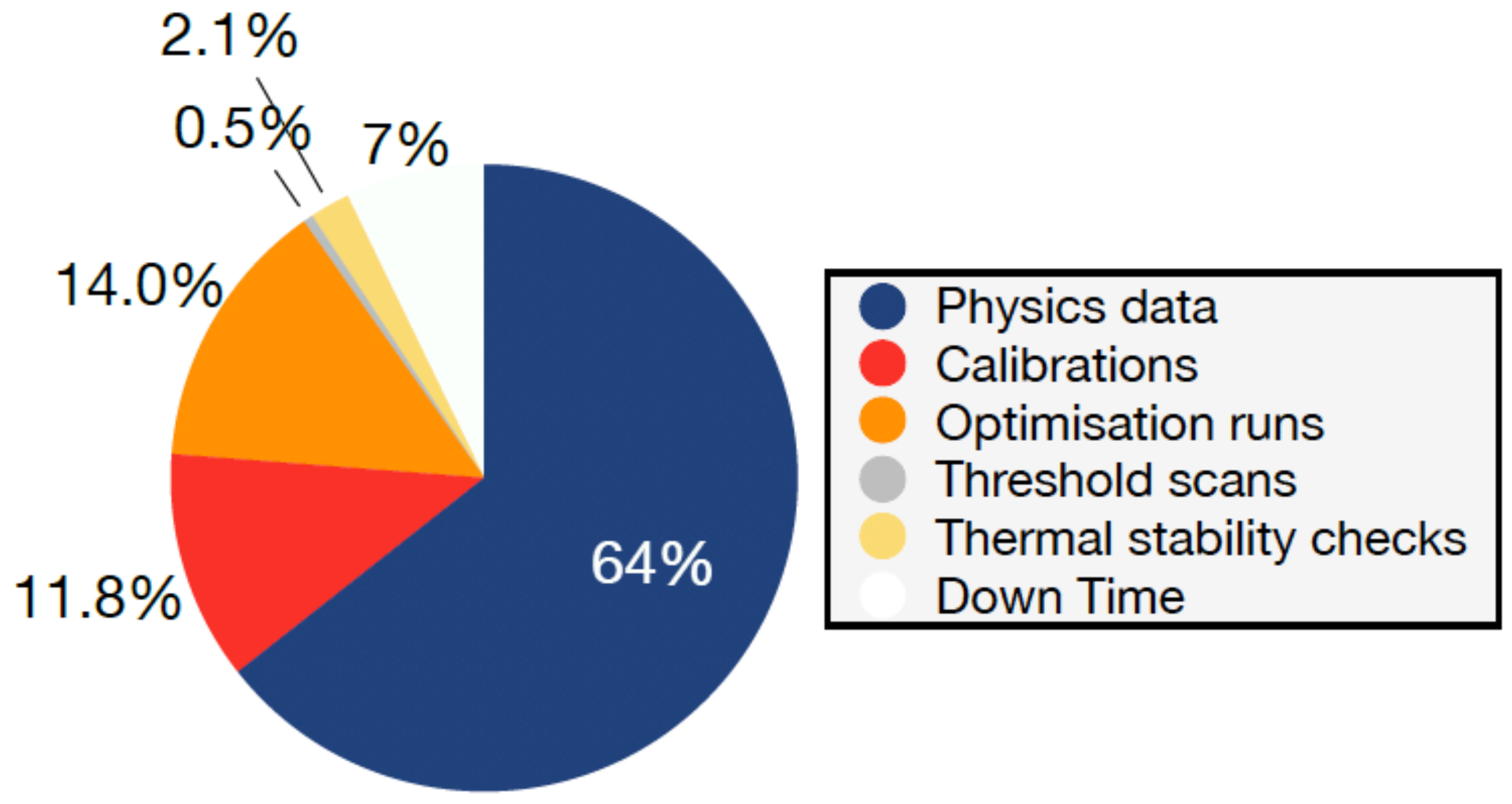
CUORE Detector

CUORE Data Taking

- Data taking started in Spring 2017
  - In the first two years we learned how to operate the cryogenic system at its best and optimised the performances
  - Datasets (~ 2 months long) interleaved by routine maintenances
- Continuous physics data taking at mK temperature since March 2019
  - Uptime > 90%
  - Data taking rate ~ 50 kg·yr/month



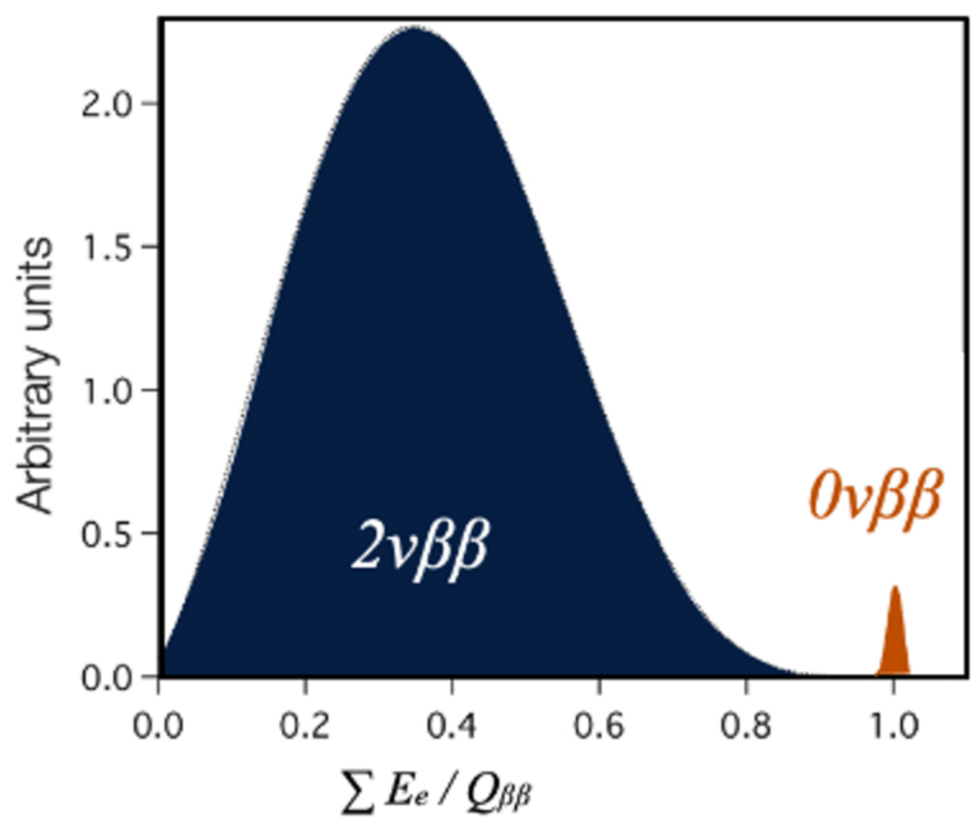




11

Karsten Heeger, Yale University

CUORE 2-tonne Year Spectrum

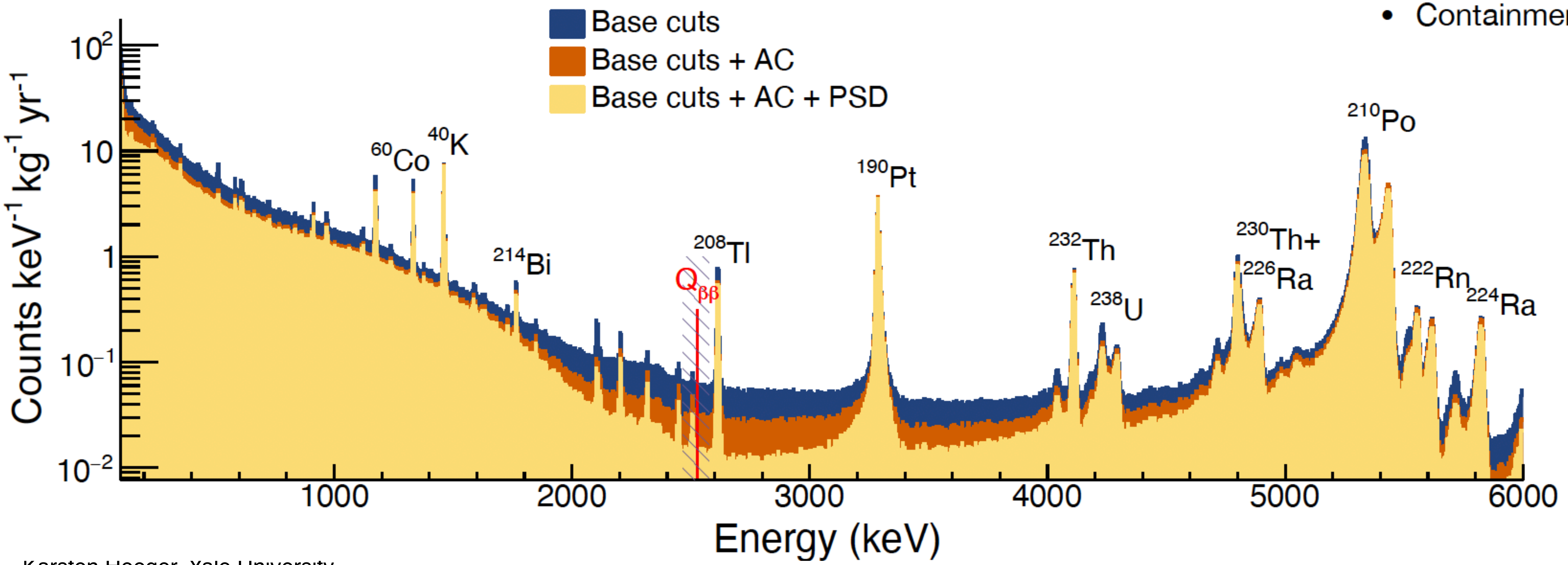


Latest results on the ^{130}Te 0νββ search

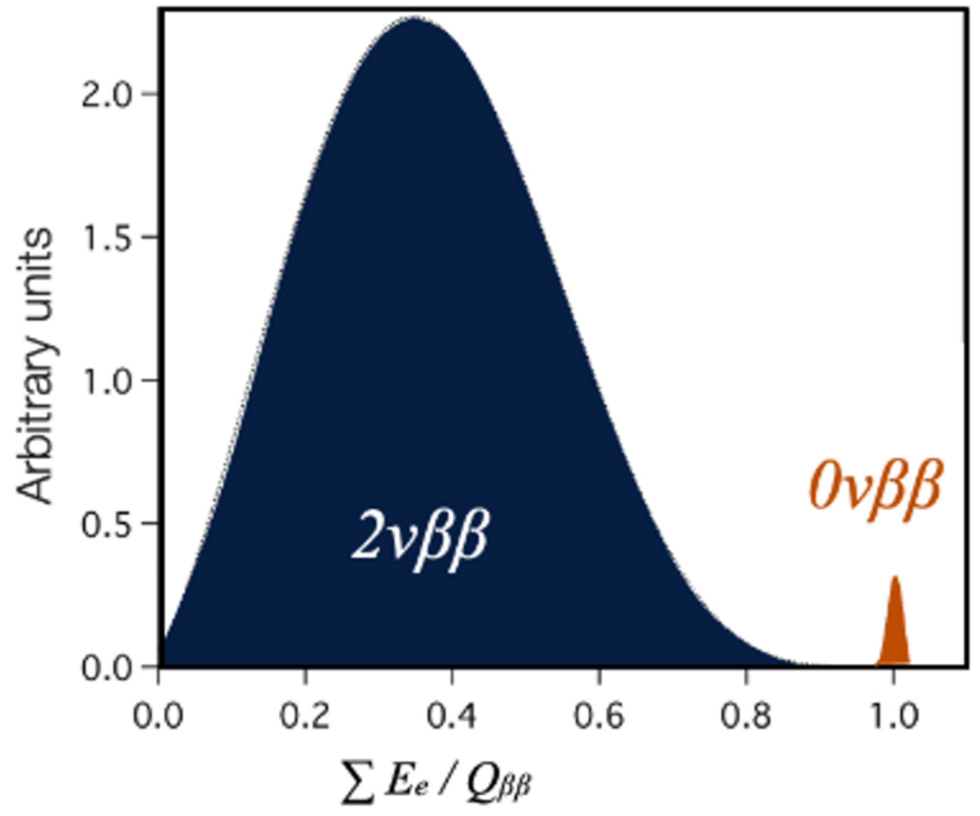
- 28 datasets analyzed from May 2017 to April 2023
- Total analysed exposure: 2039.0 kg·yr TeO_2 (567.0 kg·yr ^{130}Te)

Efficiencies

- Total analysis efficiency 93.4 %
  - Reconstruction: 95.6 %
  - Anti-coincidence (M1): 99.8 %
  - PSD: 97.9 %
- Containment efficiency: 88.4 %



CUORE 2-tonne Year Spectrum



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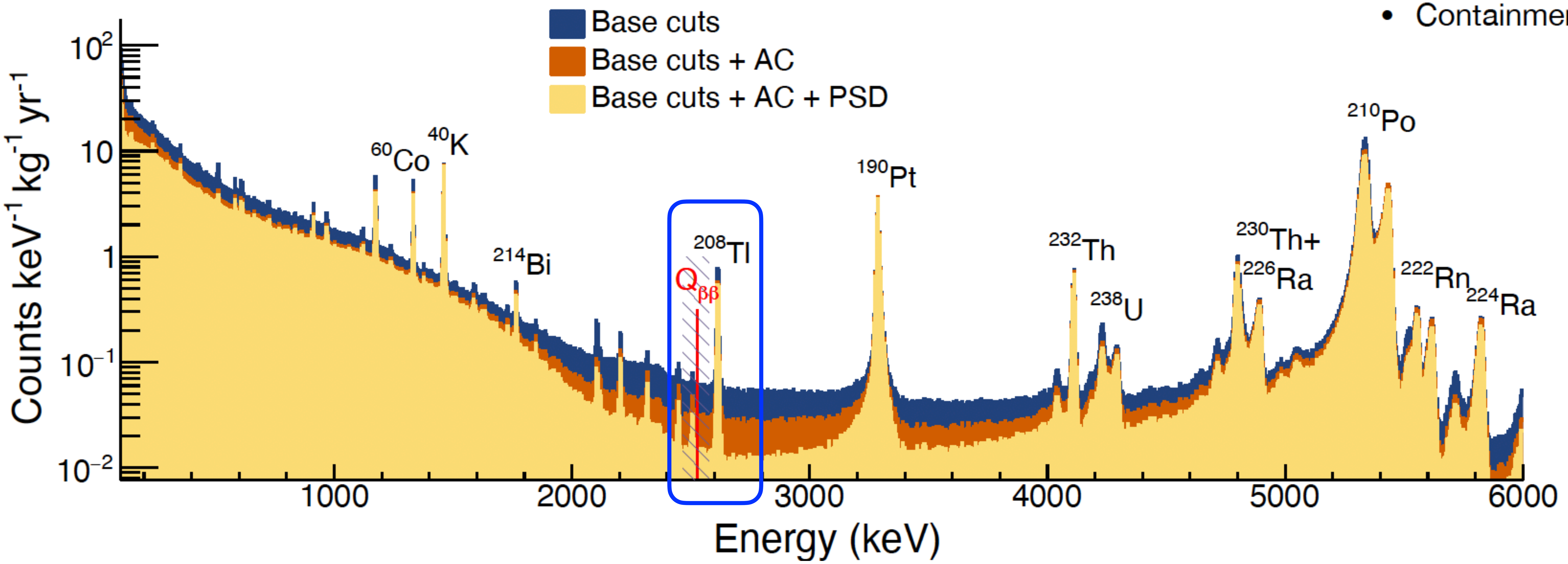
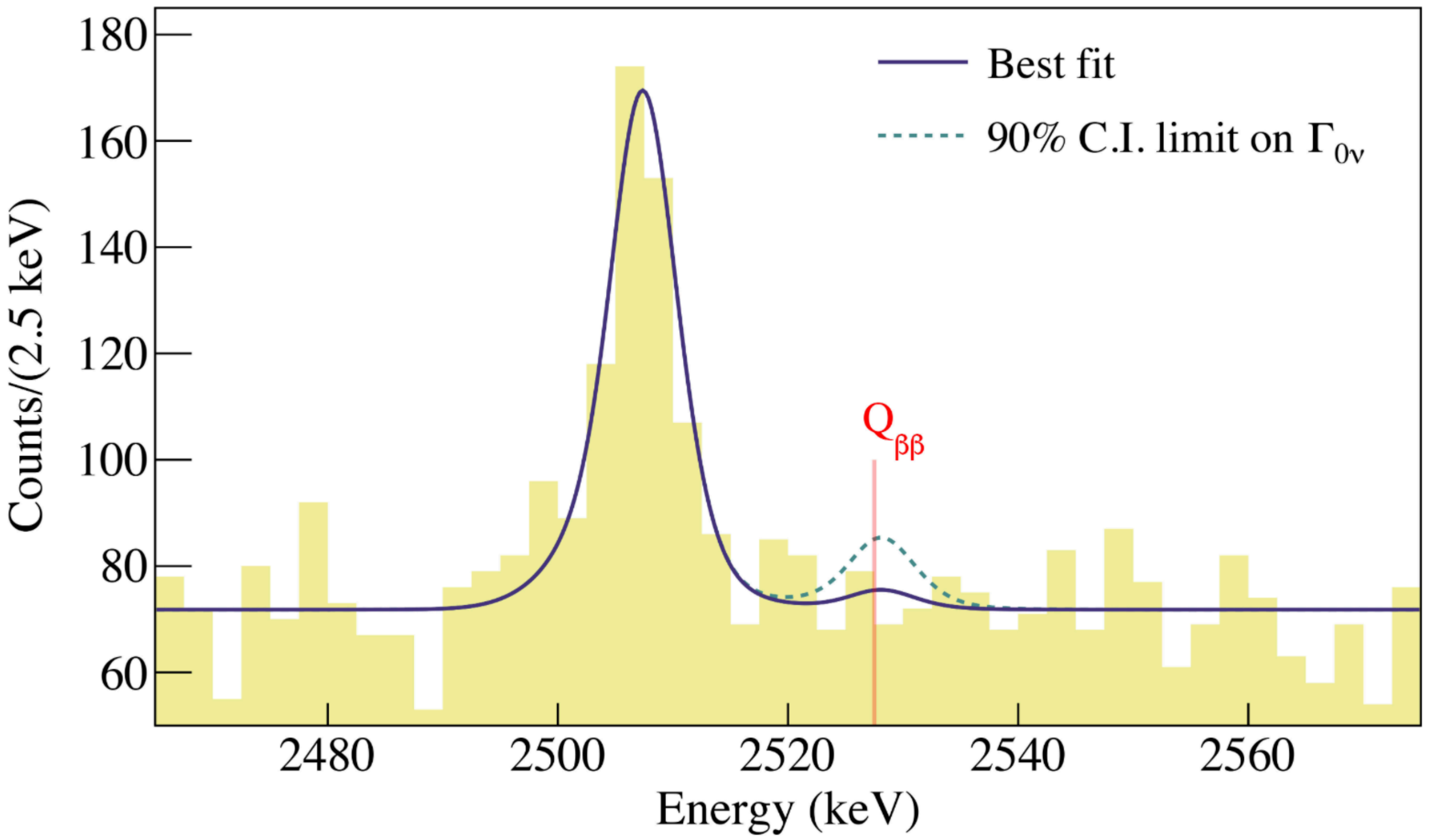


CUORE 2-tonne Year Spectrum

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



Bayesian and Frequentist Analysis

- Unbinned fit in ROI: [2465, 2575] keV
- Flat-background dataset-dependent
- $0\nu\beta\beta$ posited peak
- time-dependent ^{60}Co-sum peak
- Energy resolution channel and dataset dependent

Average background index: $1.42(2) \times 10^{-2}$ count/ keV kg yr

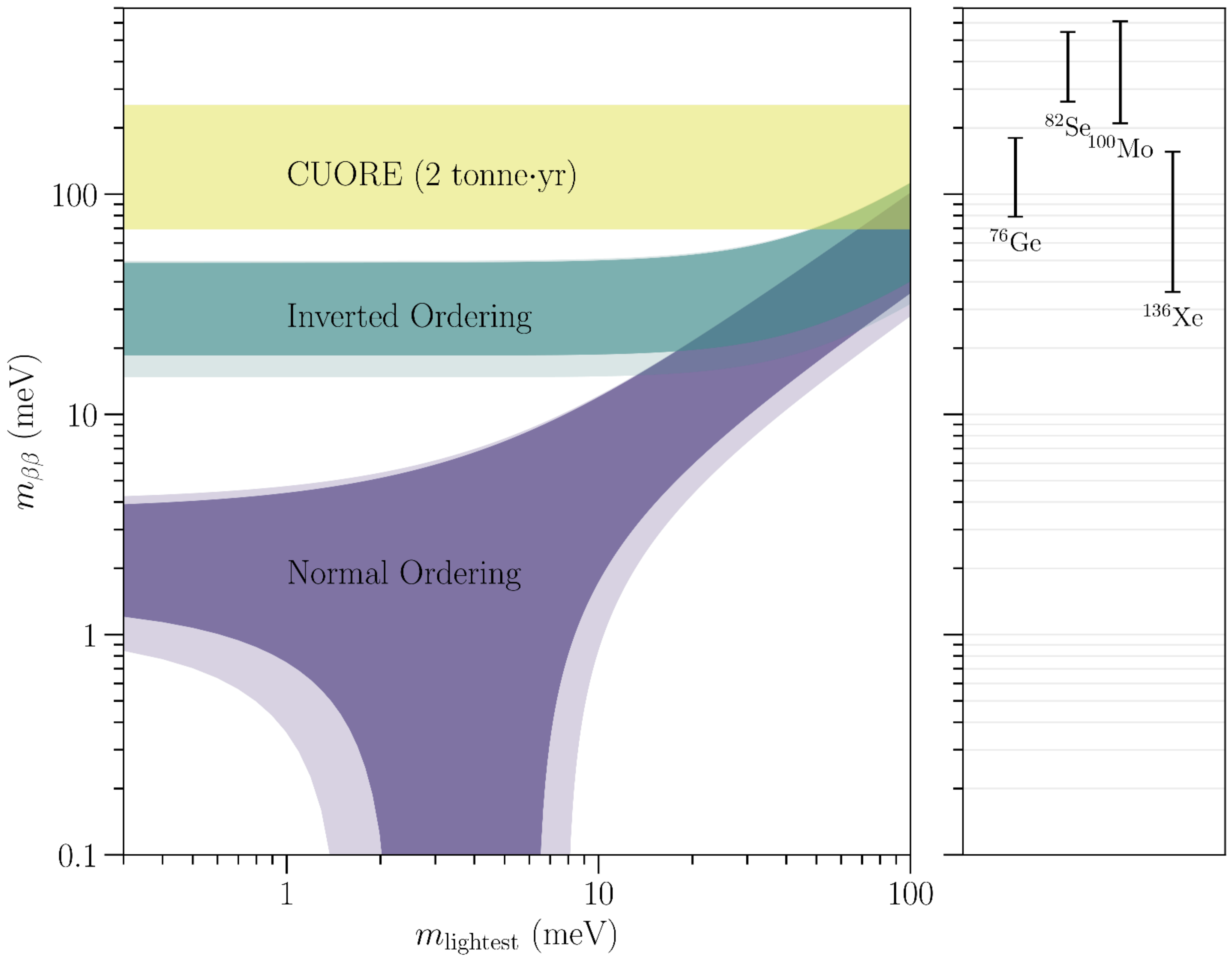
Half-life limit $T_{1/2}^{0\nu} > 3.5 \times 10^{25}$ yr (90% C.I.)

Frequentist: $T_{1/2}^{0\nu} > 3.4 \times 10^{25}$ yr

Science

DOI: 10.1126/science.adp6474
16 October 2025

CUORE 2-tonne Year Results



Median exclusion sensitvity

4.4×10^{25} yr (90% C.I.)

Compared to this value, the probability of obtaining a stronger limit is 74%.

Limit on the effective Majorana mass (assuming lihht Majorana neutrino exchange)

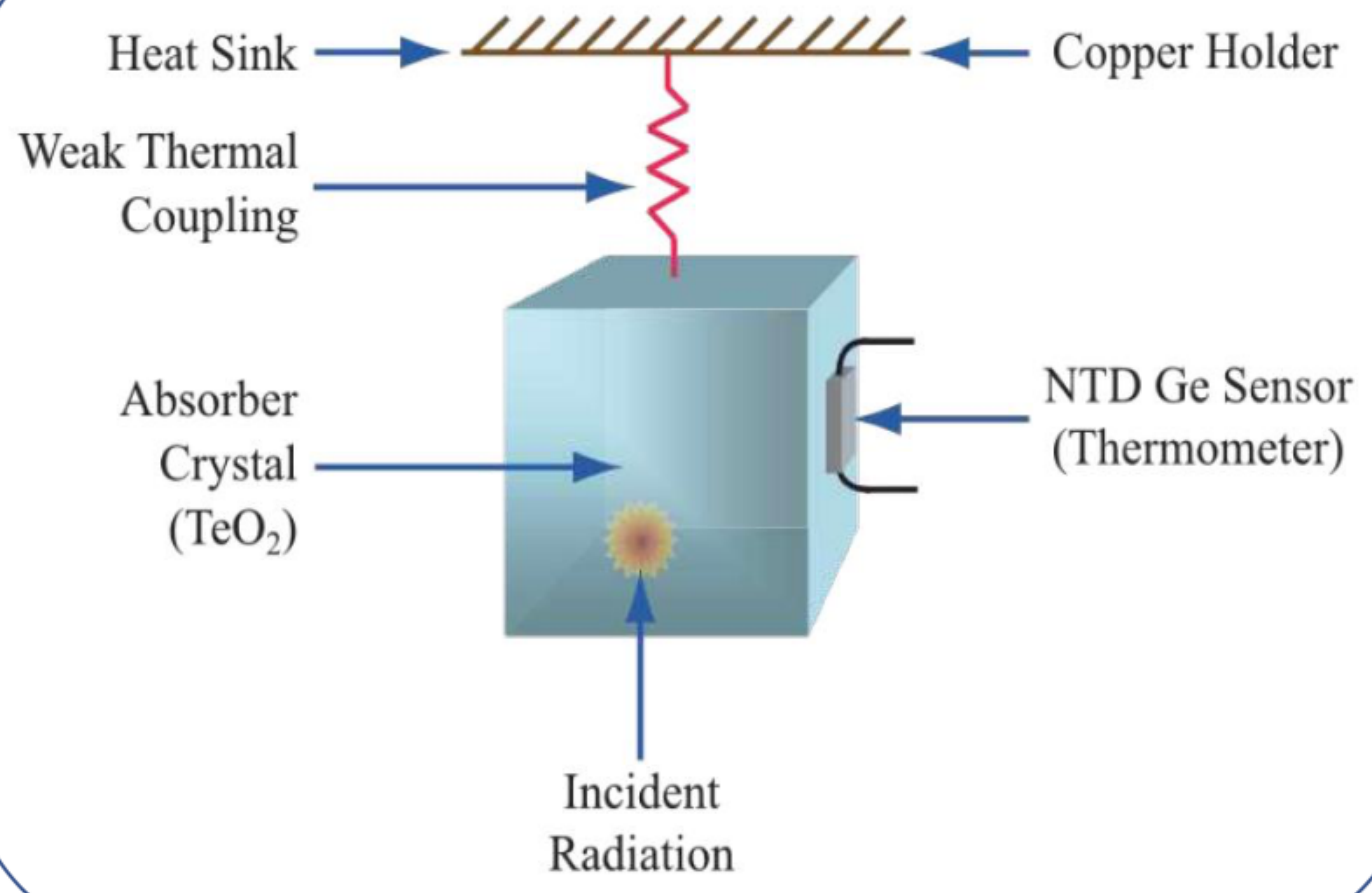
$$m_{\beta\beta} < 70 - 250\ meV$$

Science

DOI: 10.1126/science.adp6474
16 October 2025

CUPID: CUORE Upgrade with Particle Identification

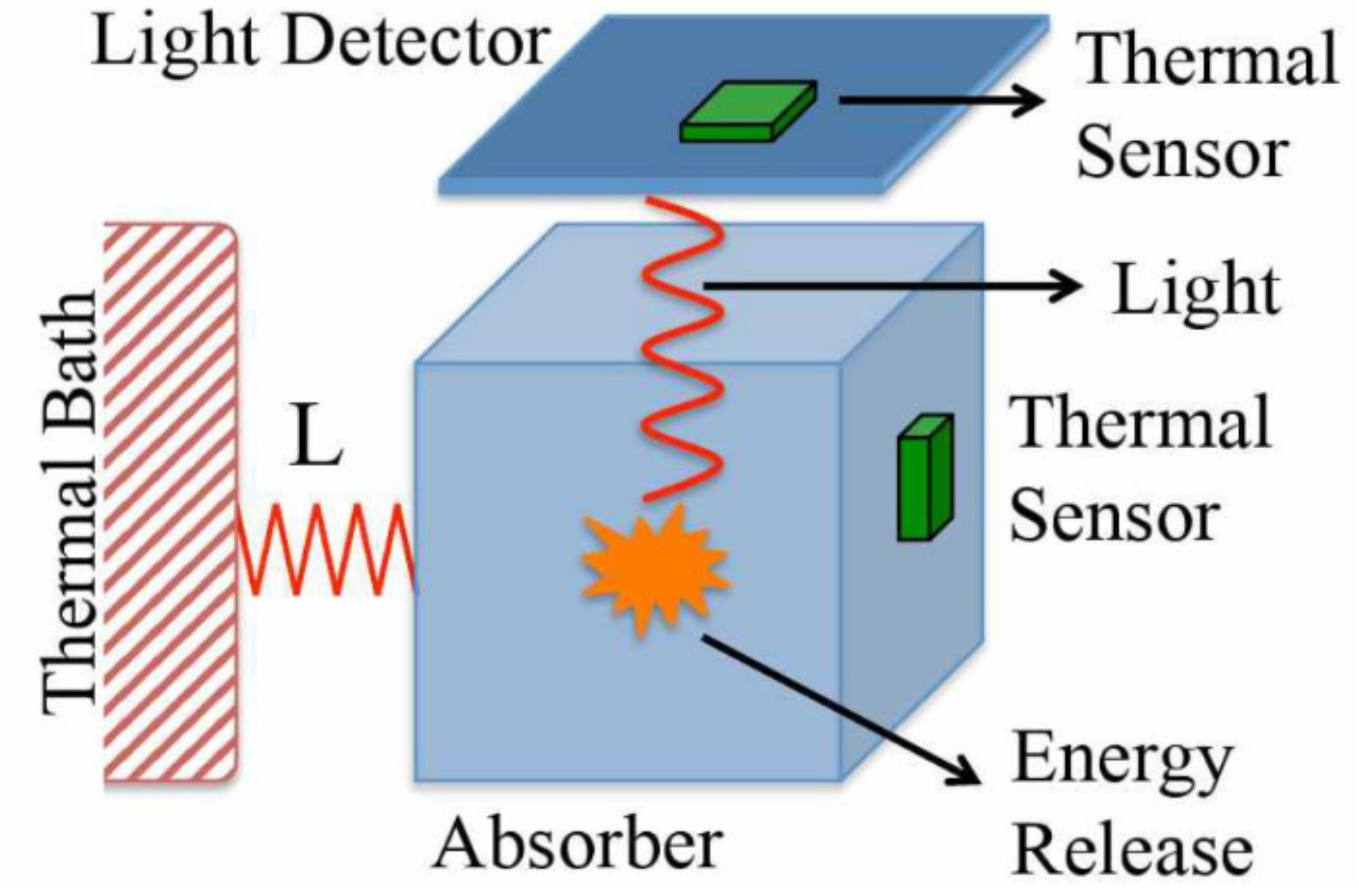
CUORE ^{130}Te
pure thermal detector
(bolometer)



PID → remove α

high Q → remove γ

CUPID ^{100}Mo
heat + light
(scintillating bolometer)



No PID
Q = 2527 keV **< 2615 keV**

^{100}Mo **Q-value: 3034 keV**: β/γ background significantly reduced

CUPID: CUORE Upgrade with Particle Identification

Single Detector

$Li_2{}^{100}MoO_4$, 45x45x45 mm, 280 g

Ge light detector as in CUPID-Mo, CUPID-0

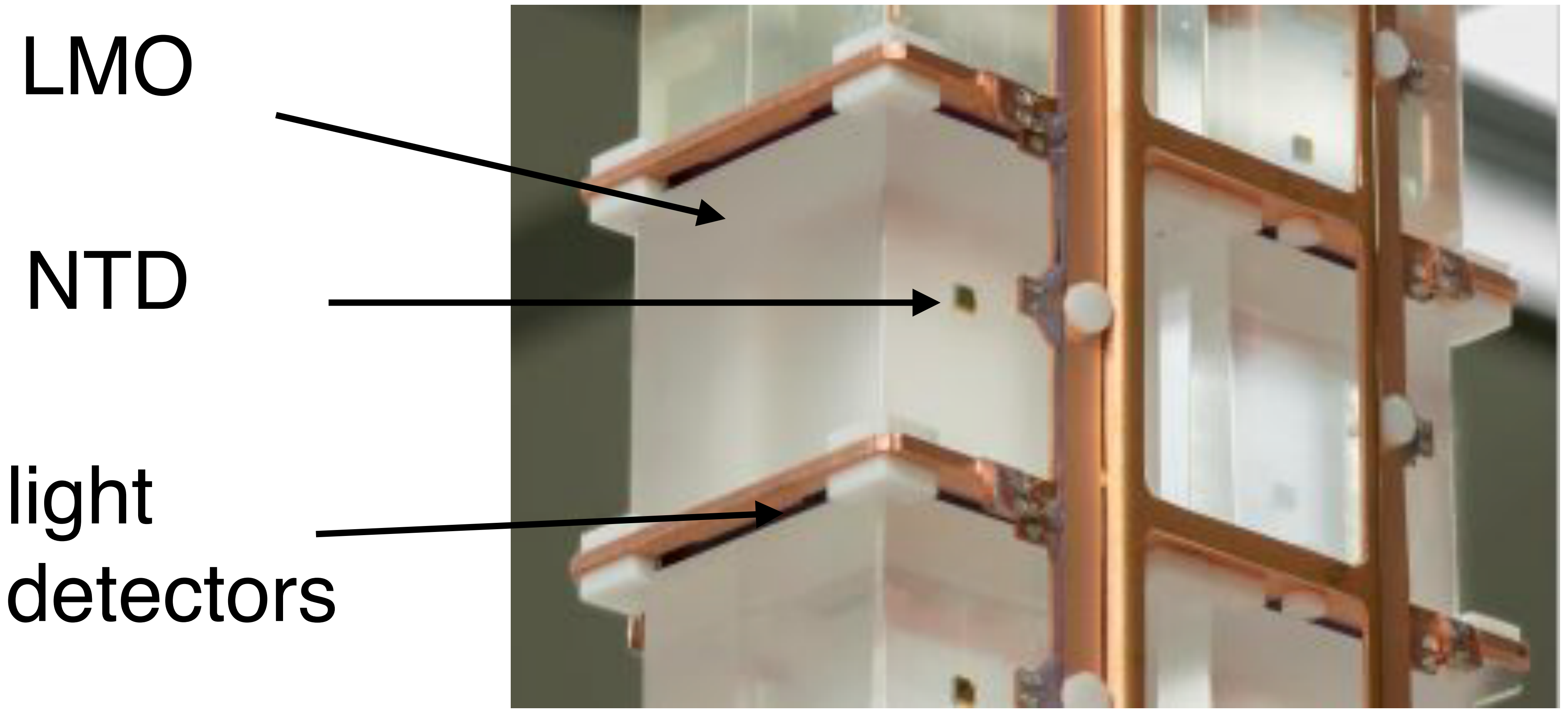
Detector Array

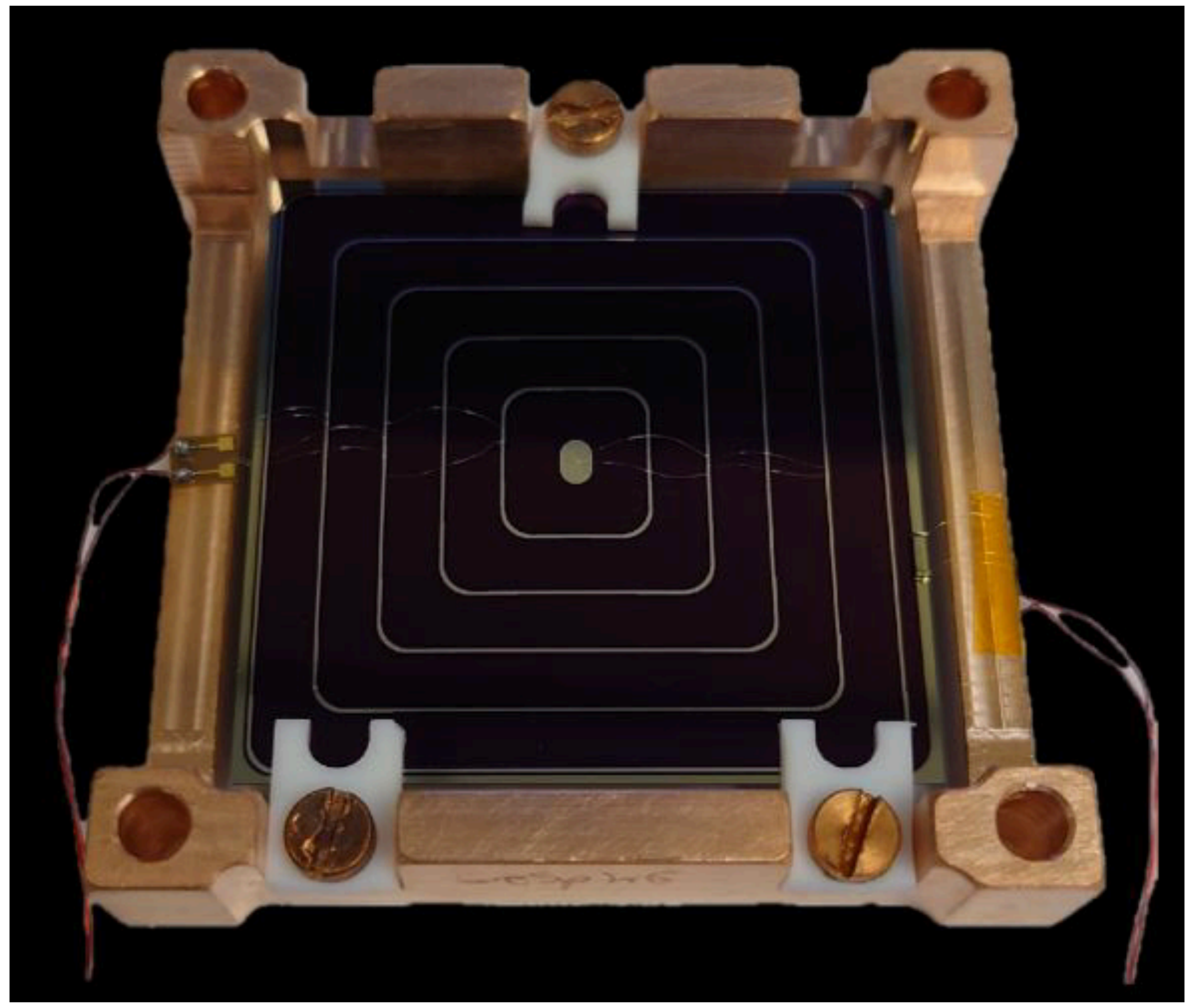
~240 kg of ^{100}Mo with >95% enrichment

~$1.6 \cdot 10^{27}$ ^{100}Mo atoms

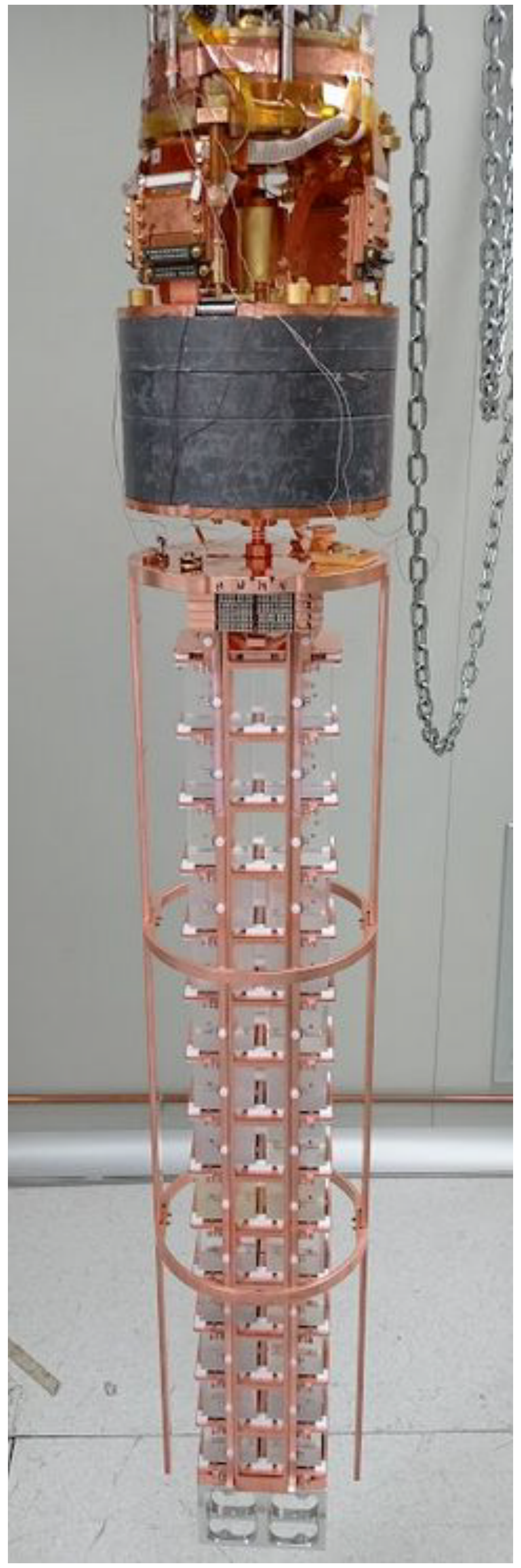
57 towers of 14 floors with 2 crystals each, 1596 crystals

Opportunity to deploy multiple isotopes, phased deployment



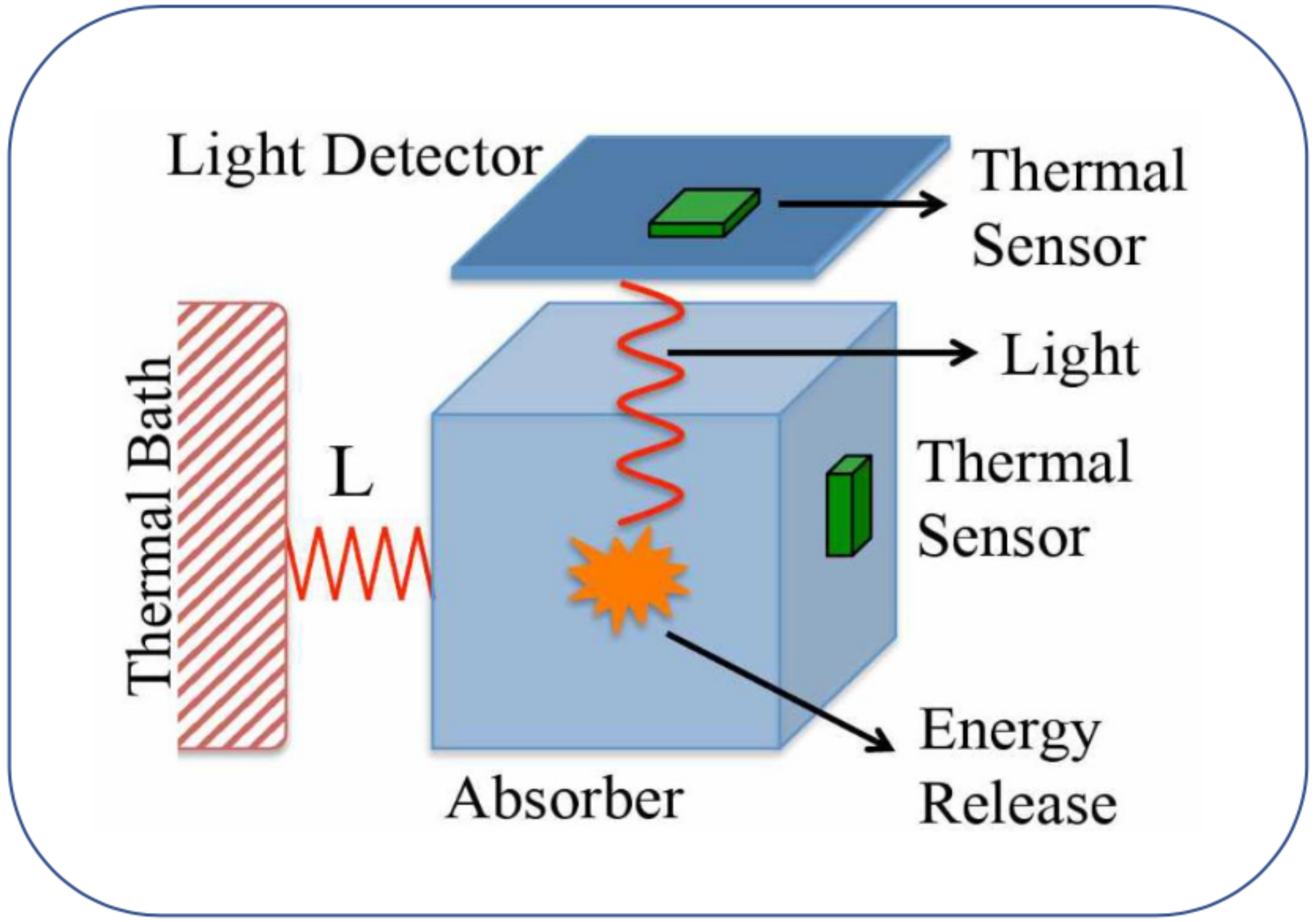


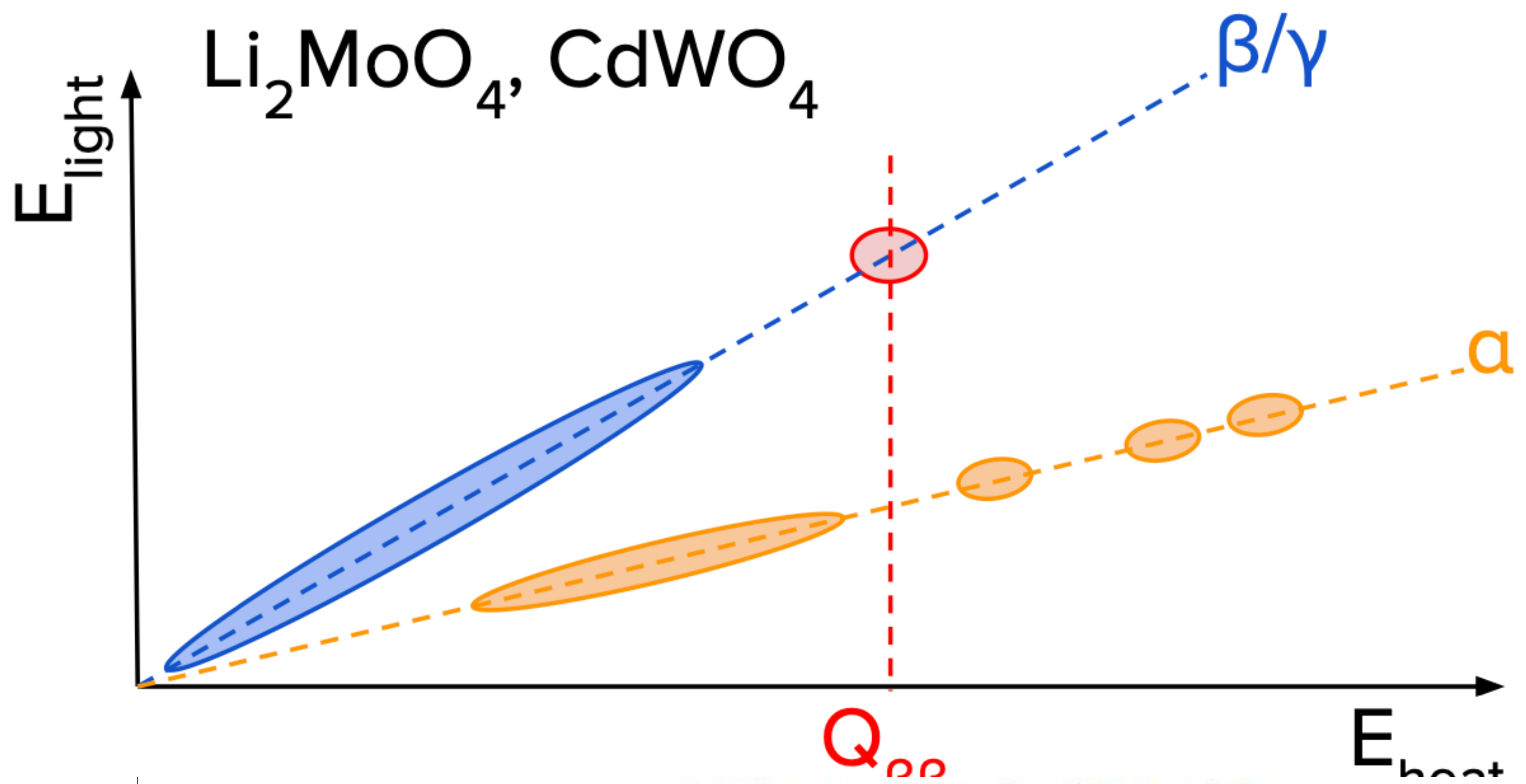
single tower

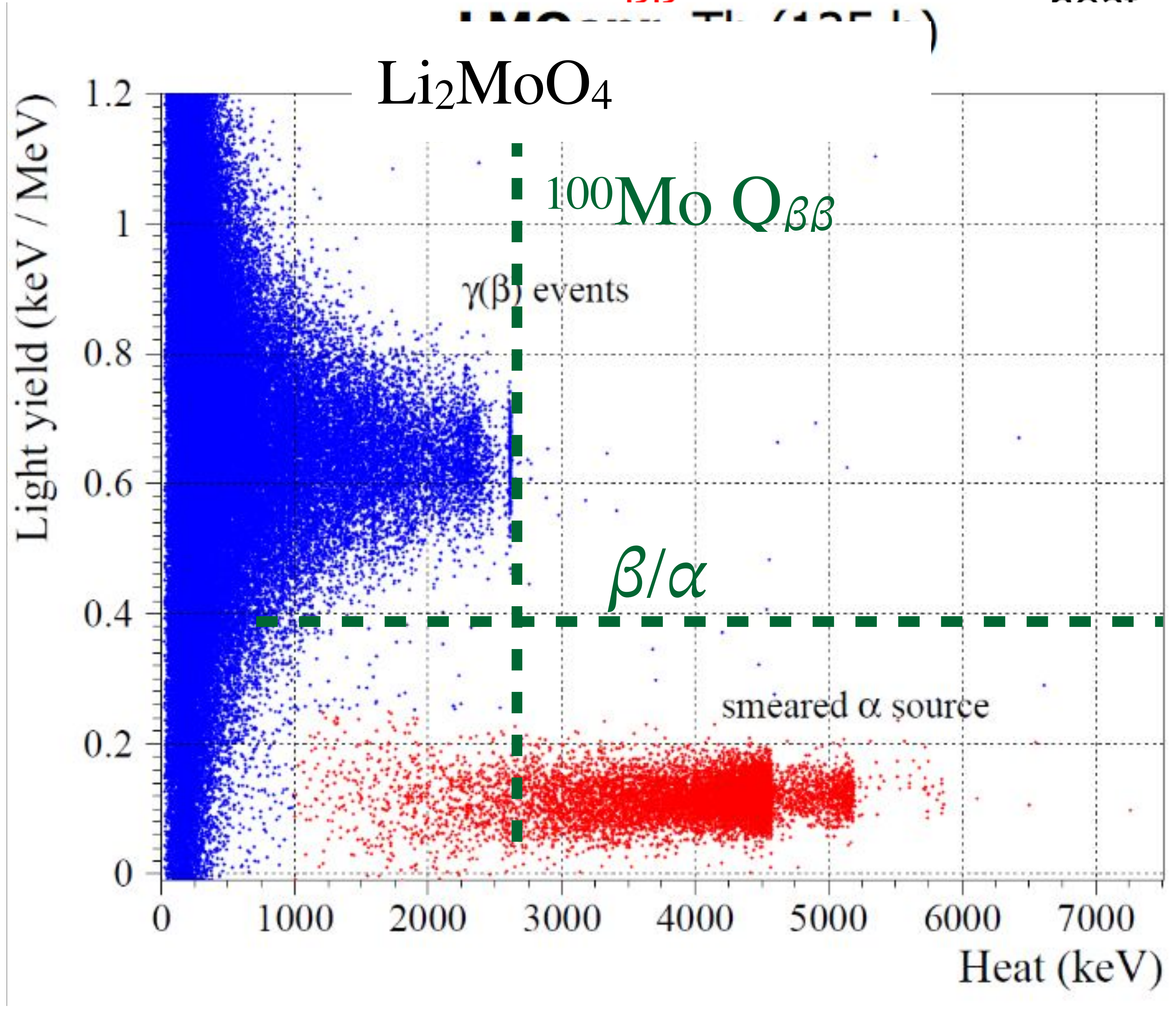


CUPID Concept

CUPID ^{100}Mo
heat + light
(scintillating bolometer)





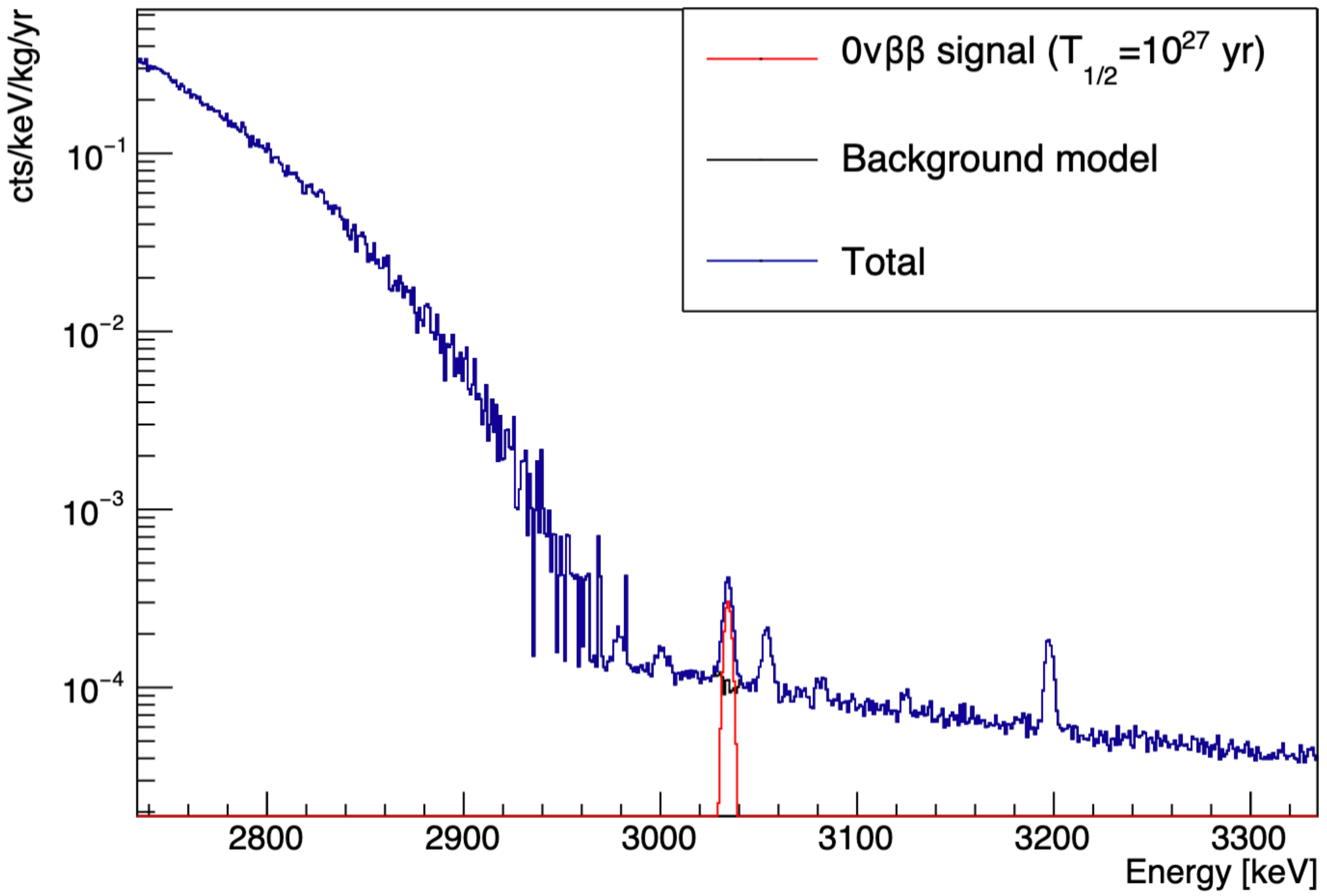


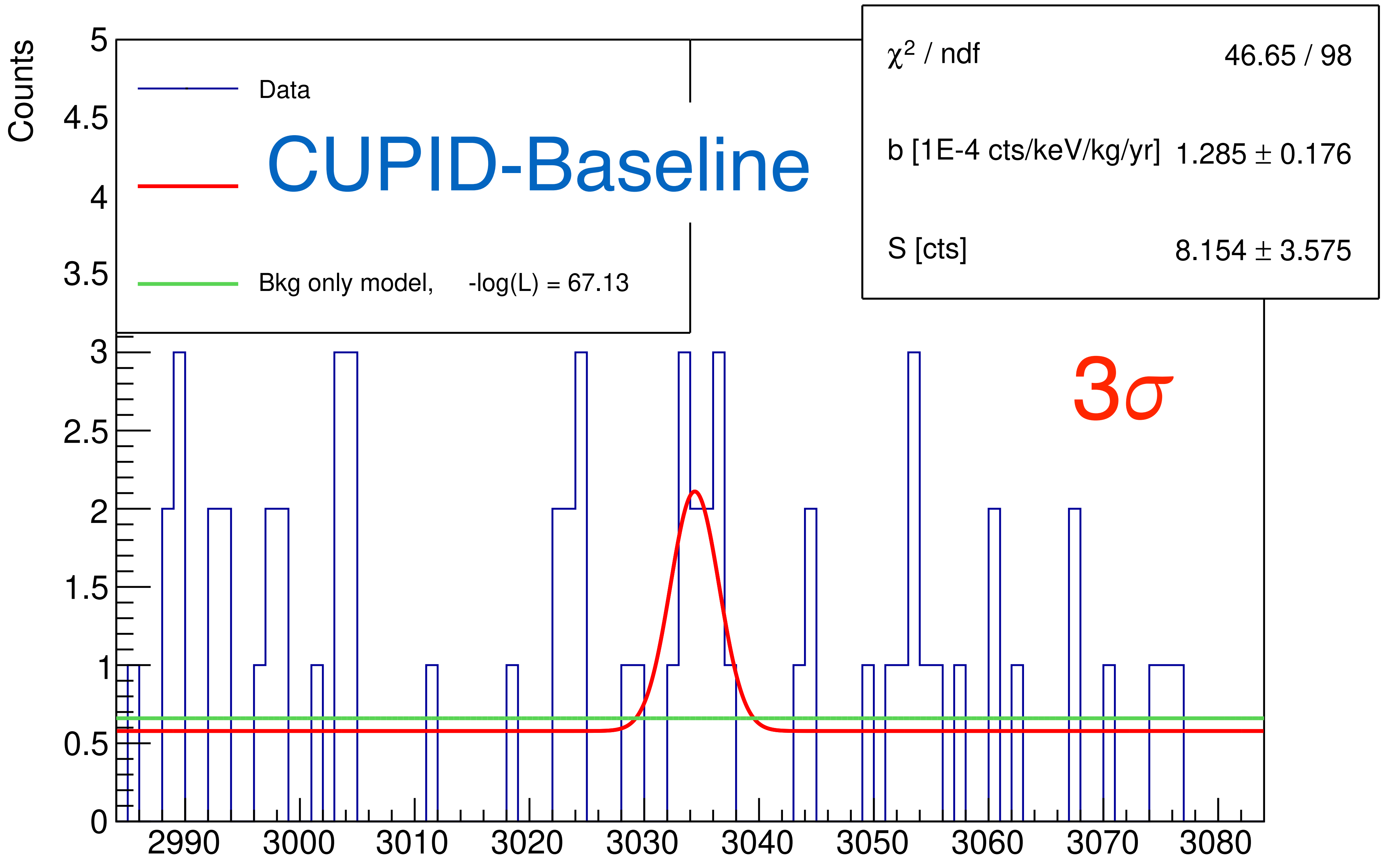
Measure heat and light from energy deposition

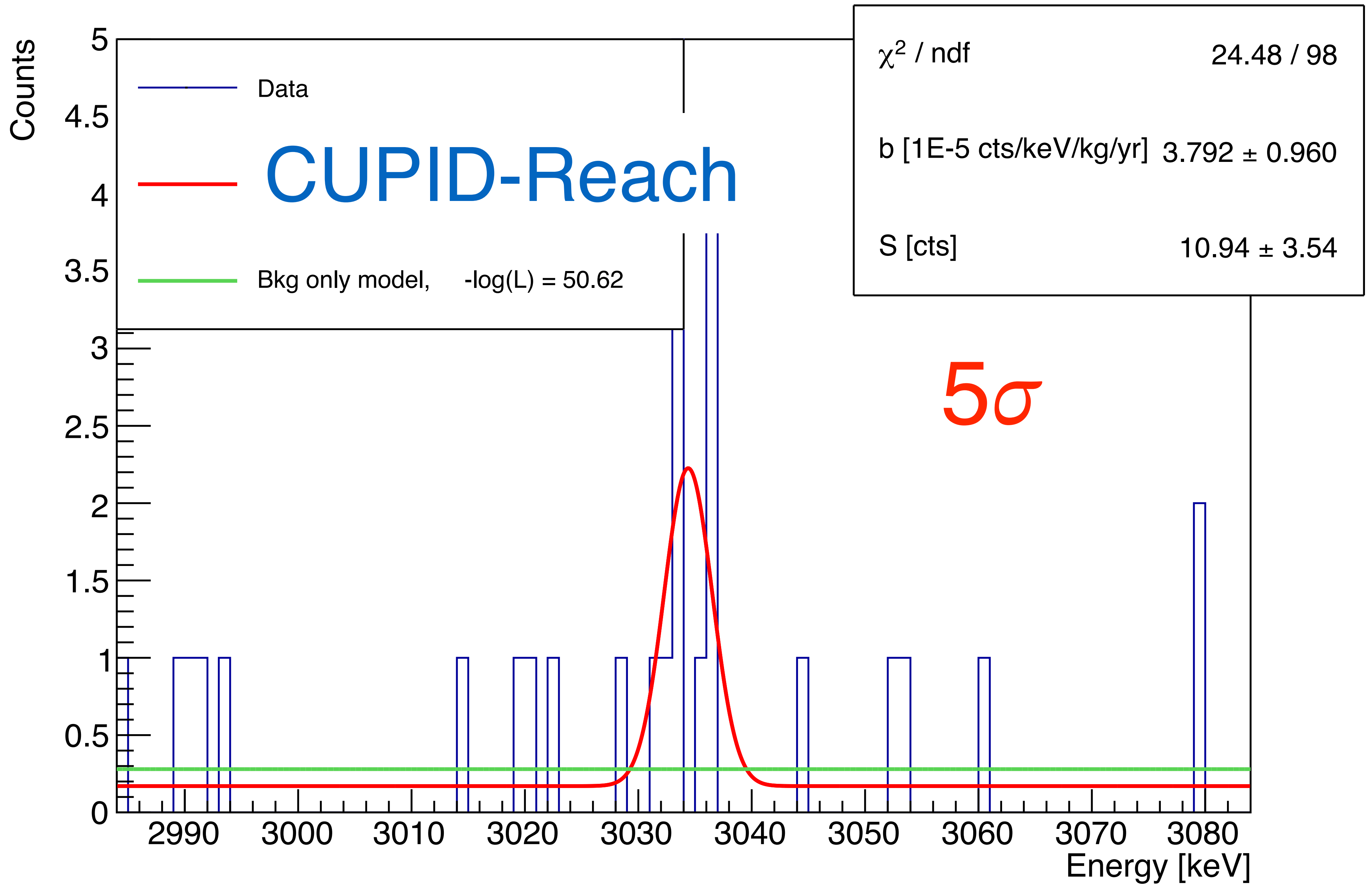
Heat is particle independent, but light yield depends on particle type

Actively discriminate α using measured light yield

CUPID Signal: Preparing for Discovery







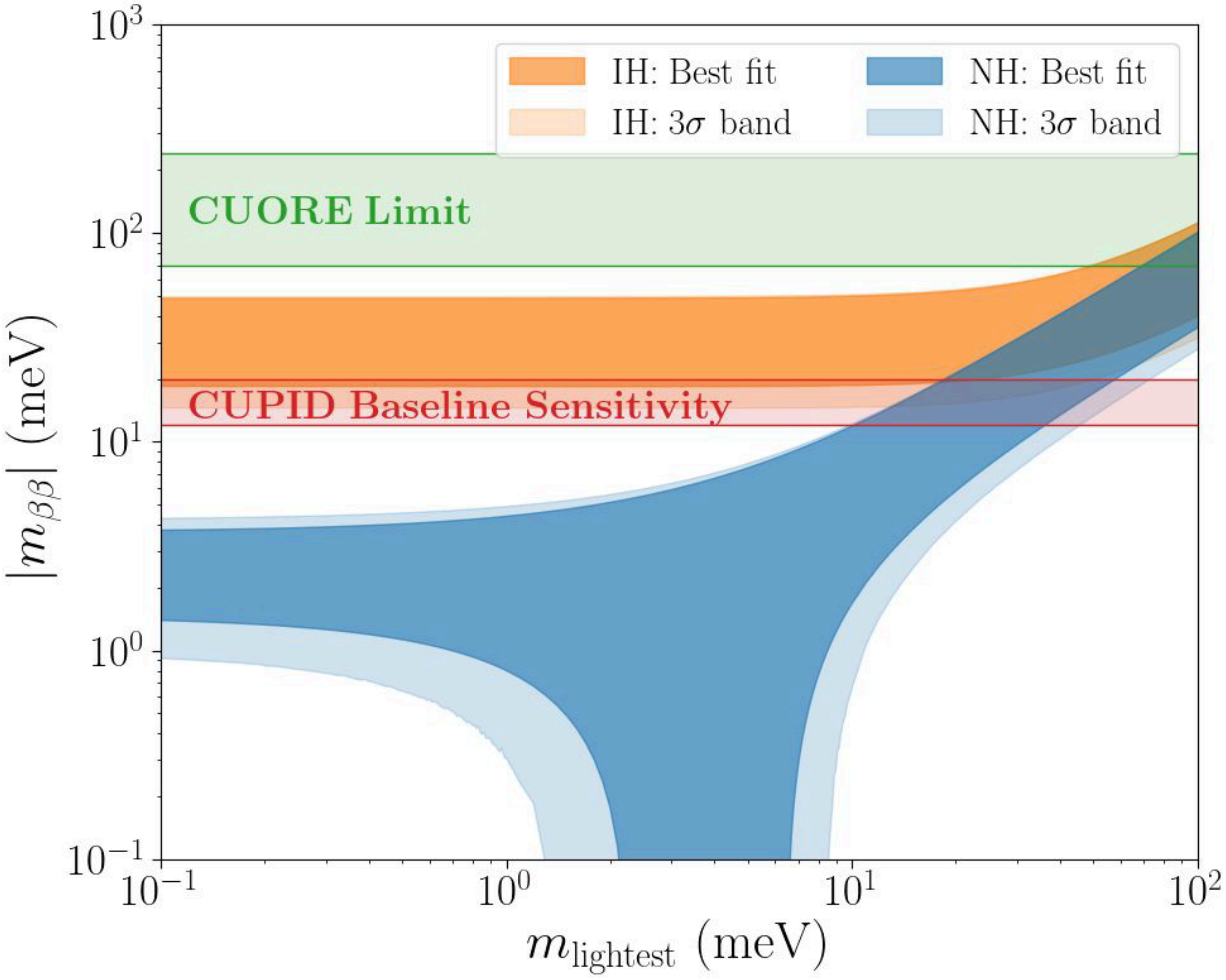
Example of toy experiments simulated for 10-year exposure and $T_{1/2}(^{100}Mo)=10^{27}$ years.

If signal is seen, modular detector allows data taking with different isotopes.

CUPID Sensitivity to 0νββ

CUPID Baseline

- Mass: 472 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo)
- **10** yr runtime
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr



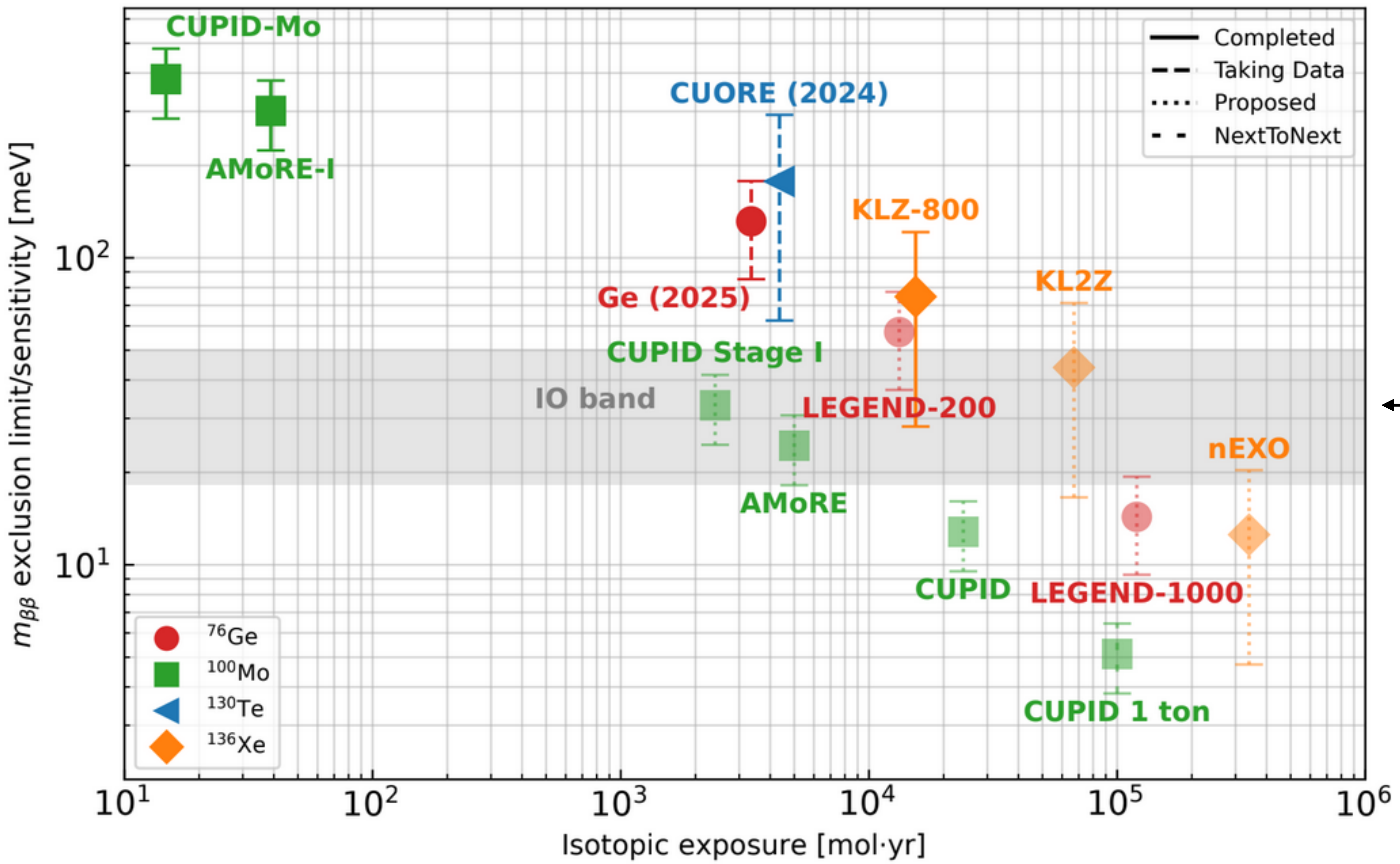
CUPID Baseline Discovery Sensitivity

$T_{1/2}$ > **1.1x10^{27} yrs (3σ)**

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

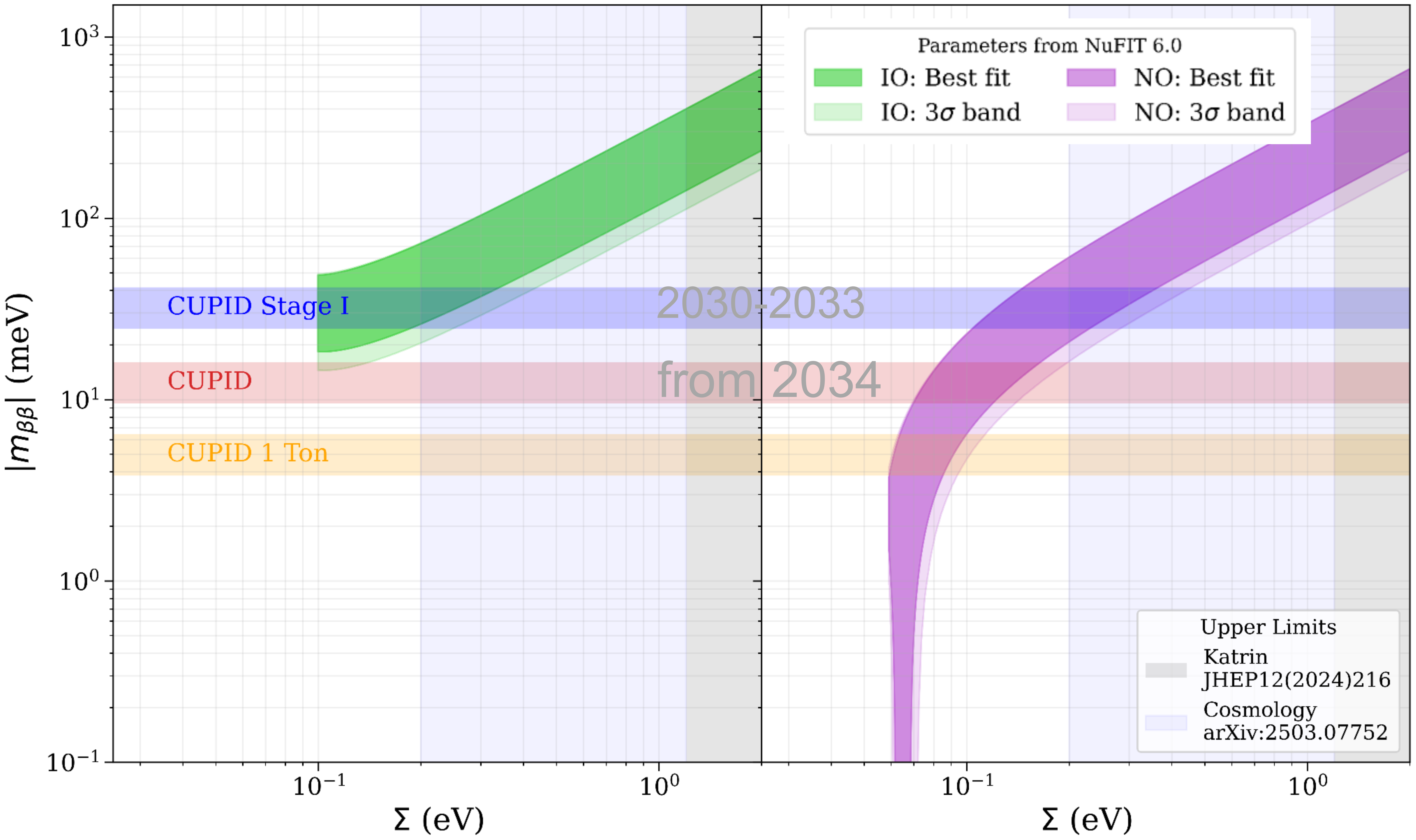
CUPID aims to cover the inverted hierarchy and a fraction of normal ordering

Sensitivity and Isotopic Exposure of 0νββ Experiments



Inverted ordering

CUPID Sensitivity: Stage I and Beyond



interplay with other mass measurements:

- Katrin
- cosmology
- ordering from oscillations

technology scalable to 1 ton and beyond

CUORE/CUPID Collaborations

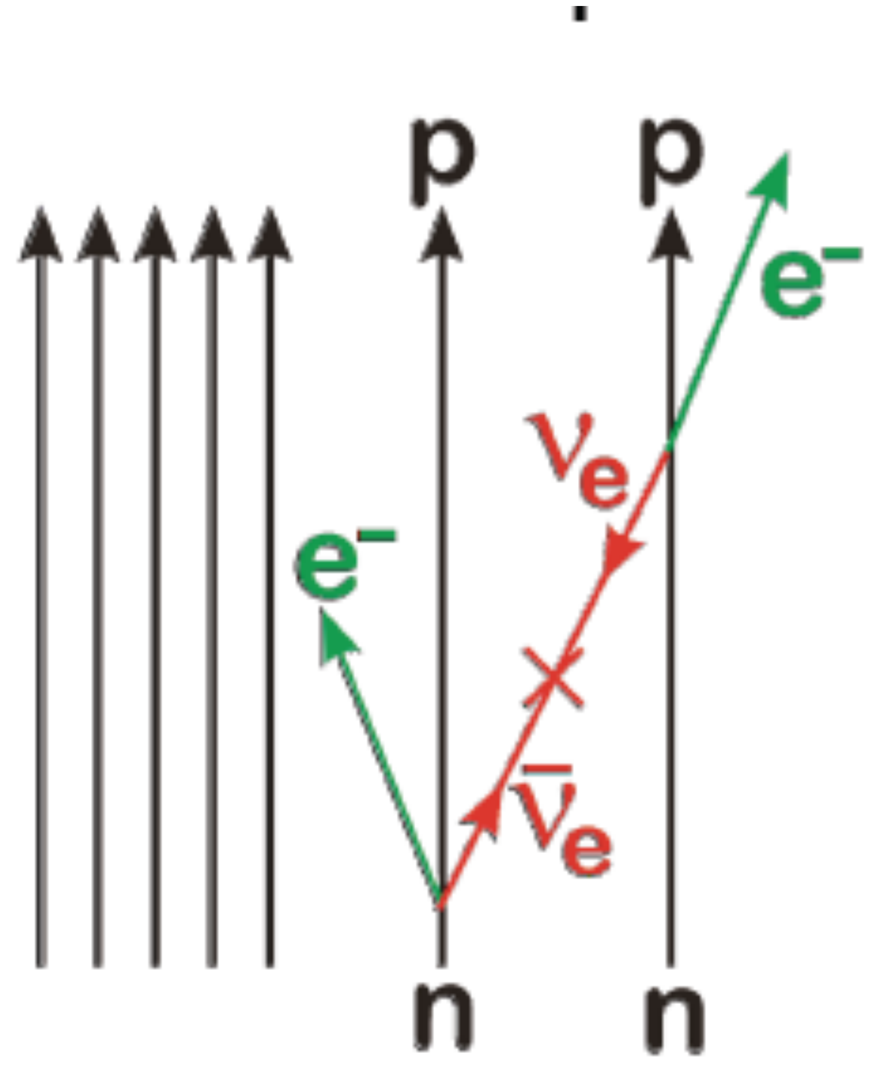
Thanks to the CUORE and CUPID collaborations

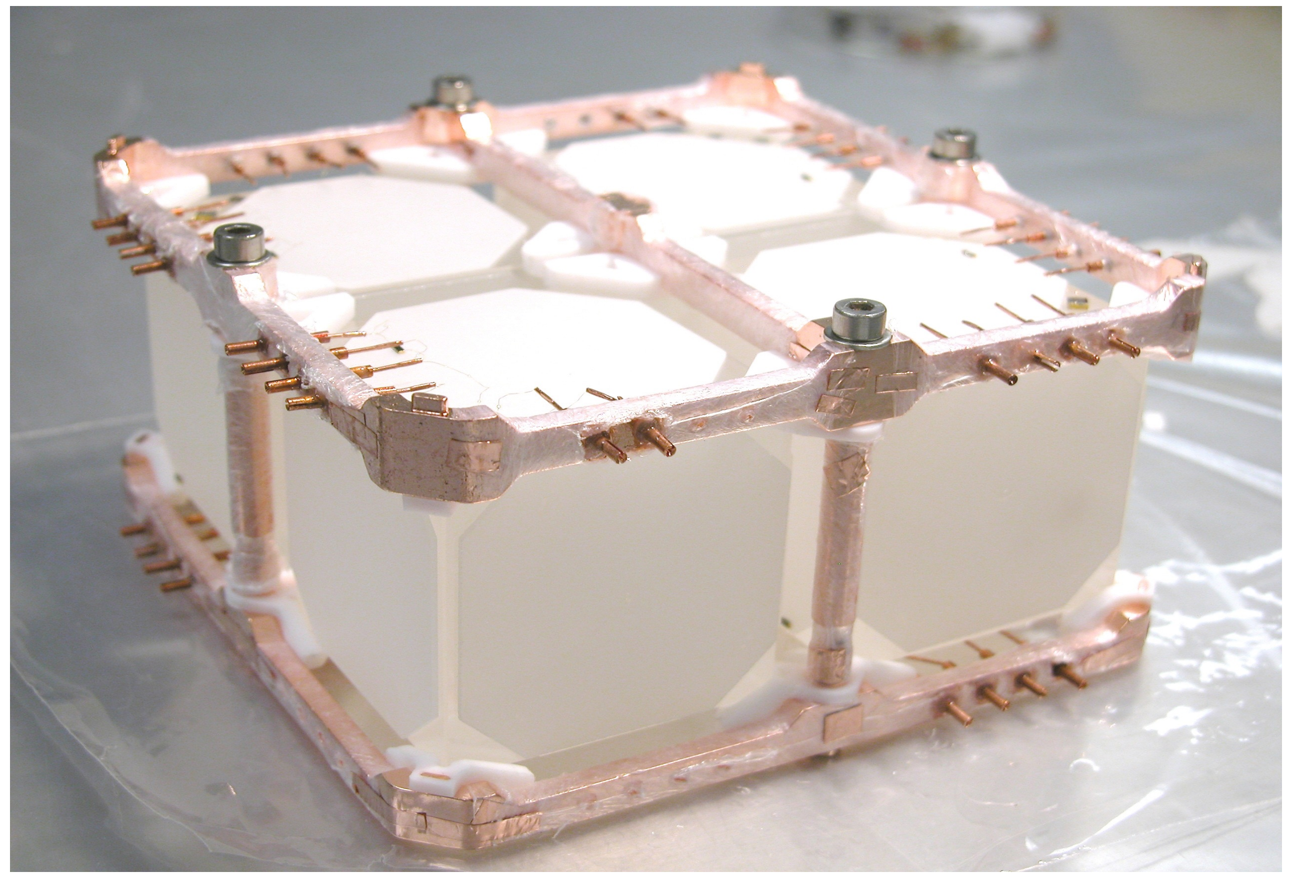
US funding provided by U.S. DEPARTMENT OF ENERGY, National Science Foundation

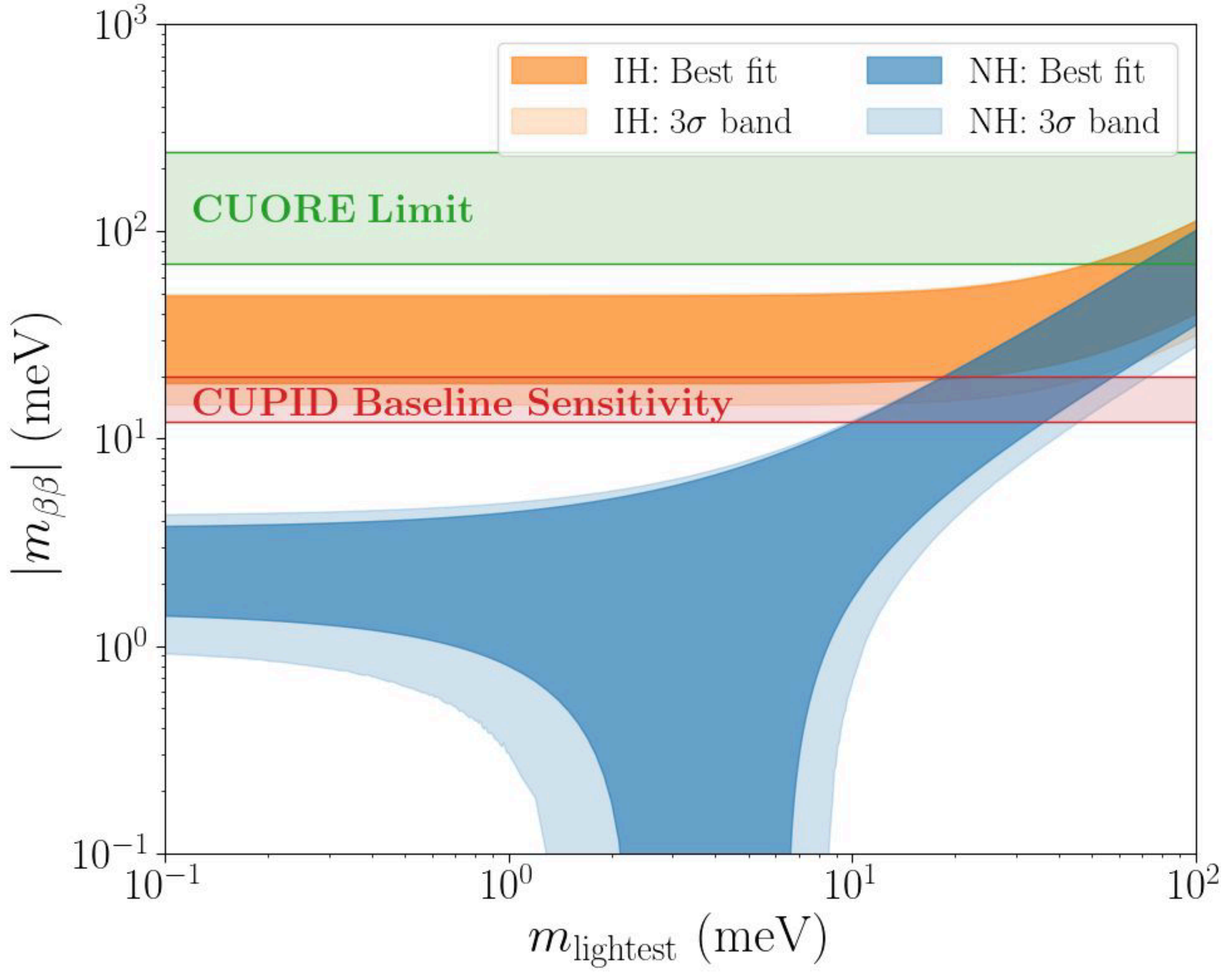
Summary and Outlook

Low-energy ν experiments provide key insight into the nature of neutrinos, synergies with dark matter experiments. Instrumentation development and novel detectors open new frontiers.

Neutrinoless double beta (0νββ) is powerful and comprehensive probe of lepton number violation (ΔL=2).







Neutrinoless Double-Beta Decay

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

$$m_{\beta\beta} < 70 - 250\ meV$$

Science

DOI: 10.1126/science.adp6474

Exciting years ahead!