Probing the Majorana Nature of the Neutrino with CUORE and CUPID

Tyler Johnson

Yale

CUORE

CUPID

The Standard Model of Particle Physics

Neutrinos have a lot of interesting quirks

- ❖ Neutrinos are massive (despite prediction they aren't), but much smaller than their peers
- ❖ Might be their own anti-particle
- ❖ They rarely interact with matter, thus measurements are often sparse

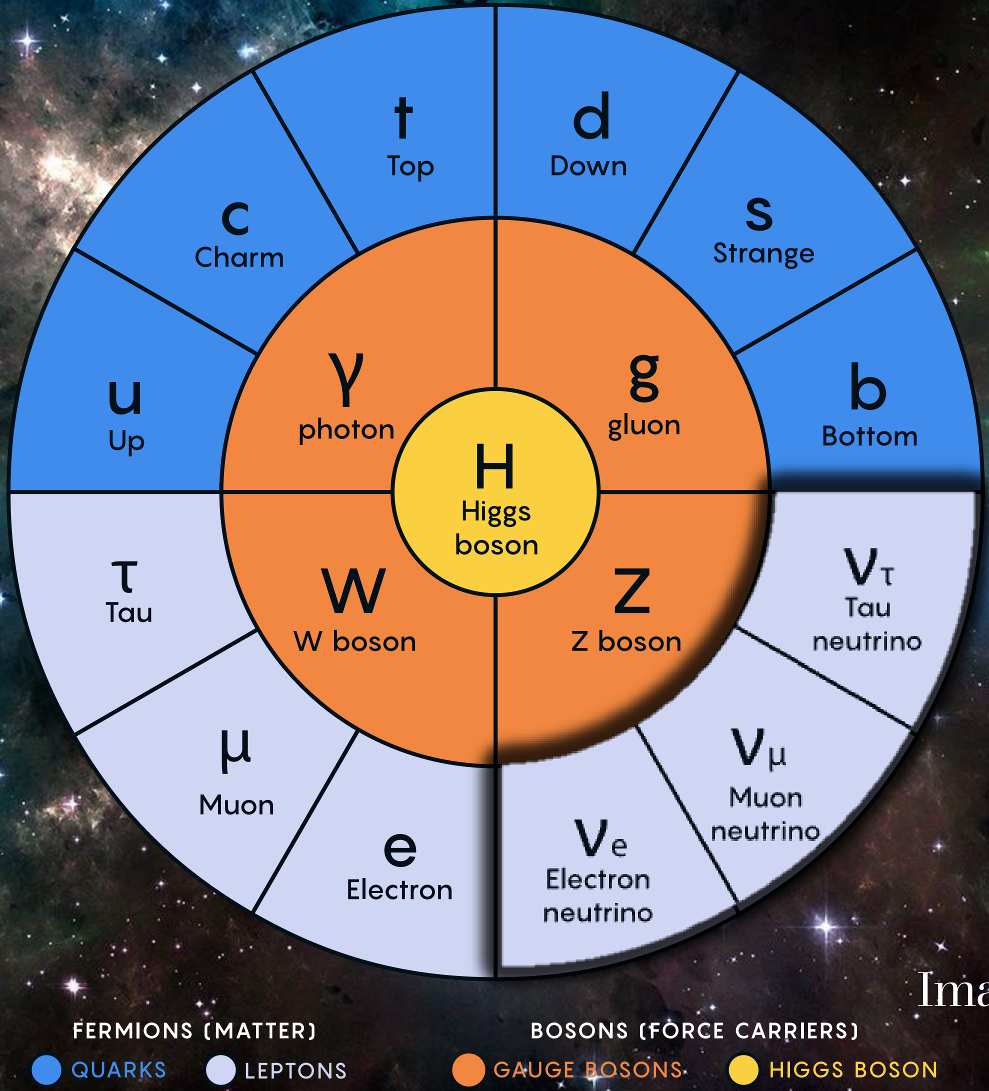
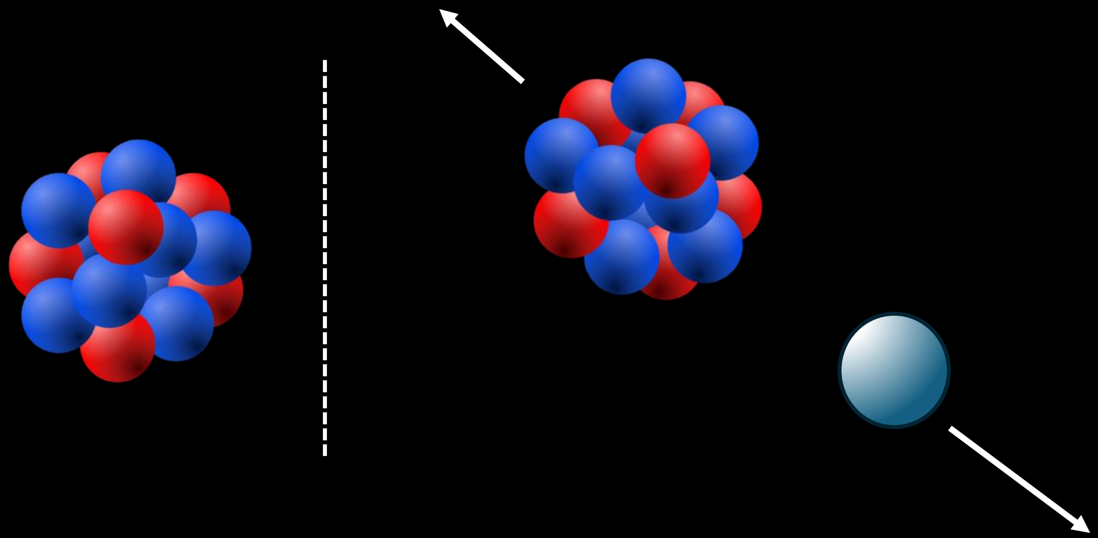
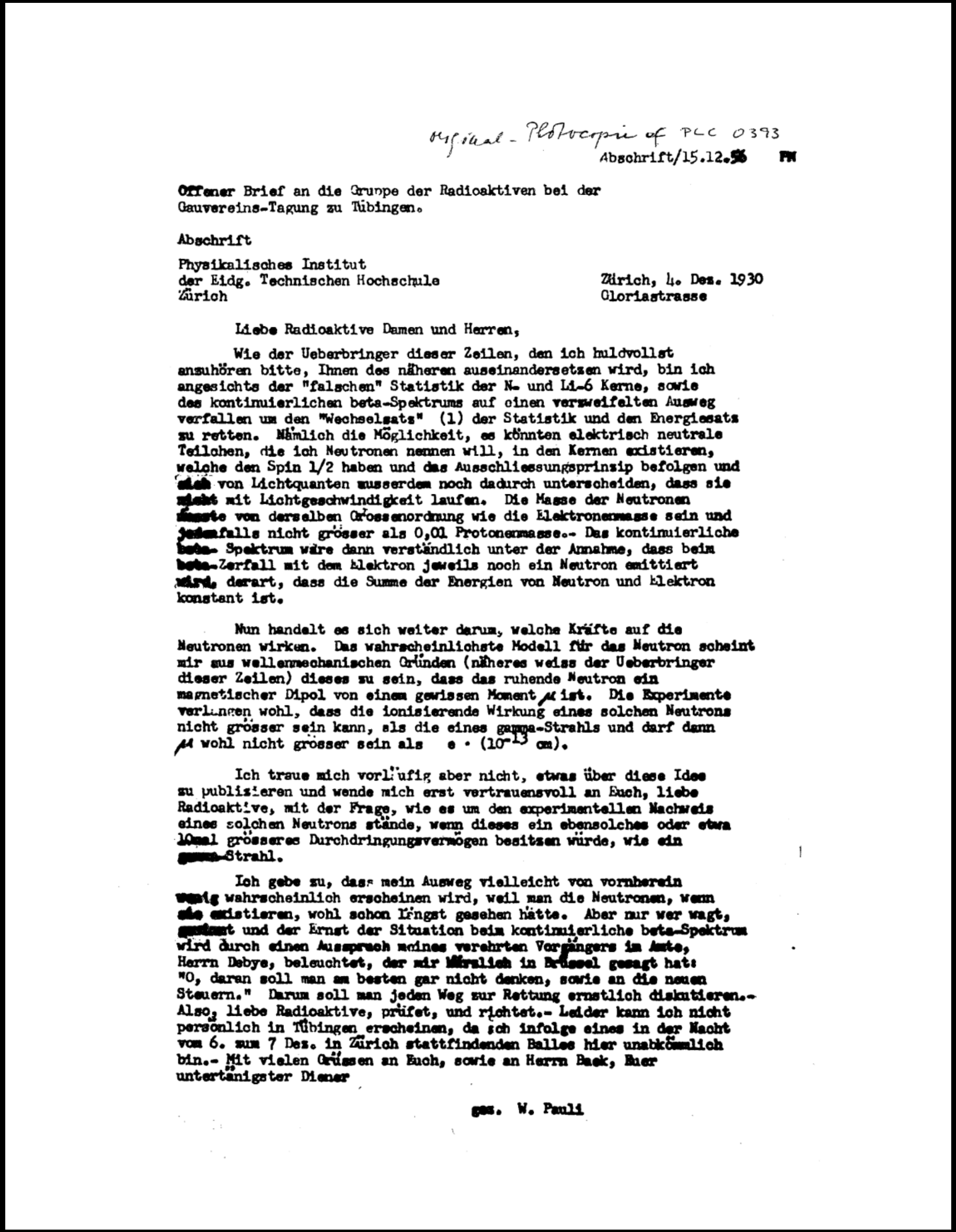


Image from Quanta Magazine

“Dear Radioactive Ladies and Gentlemen…”

- Beta decay (as it was then understood) posed a grave threat to the Conservation of Energy





Original - Photocopie of PLC 0393

Abschrift/15.12.56 FN

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

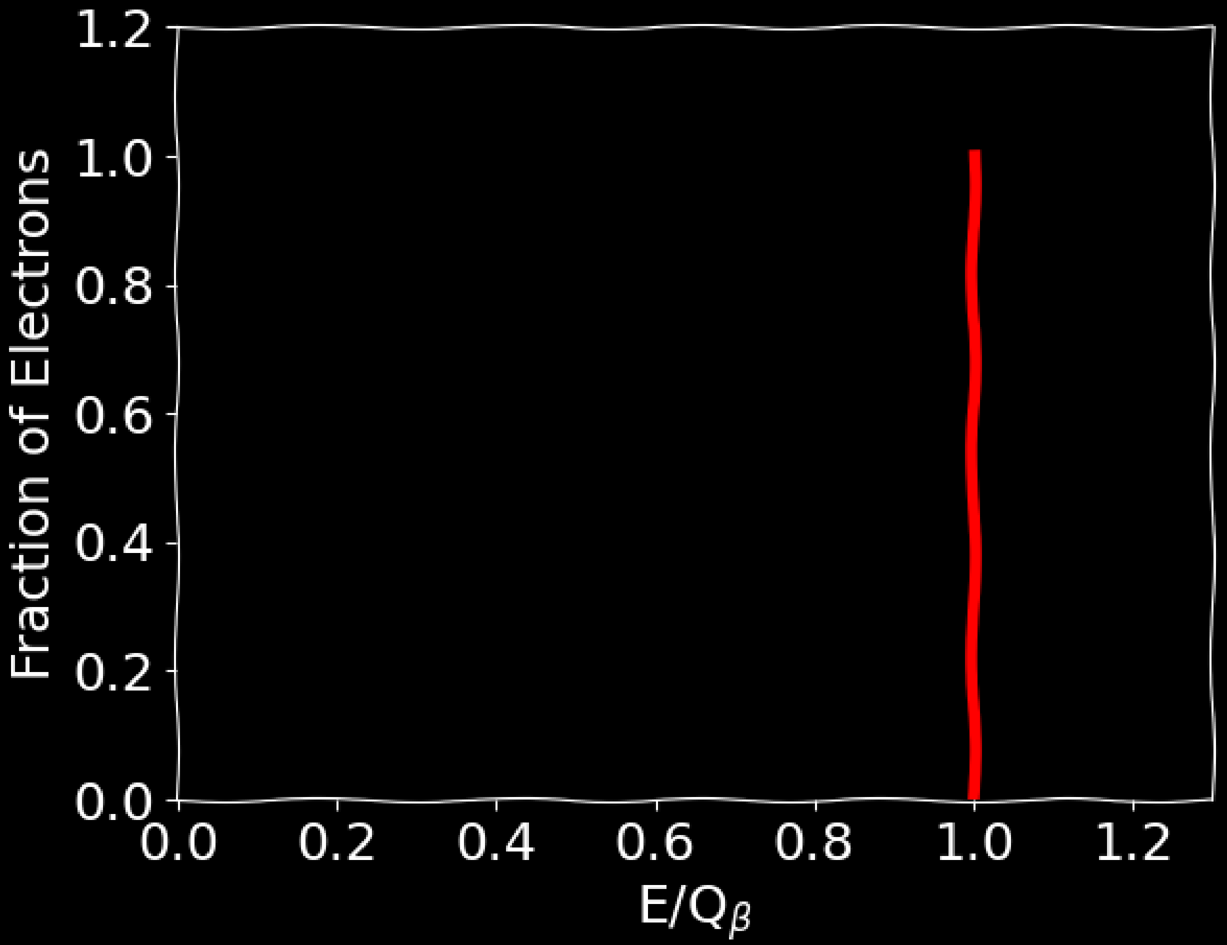
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

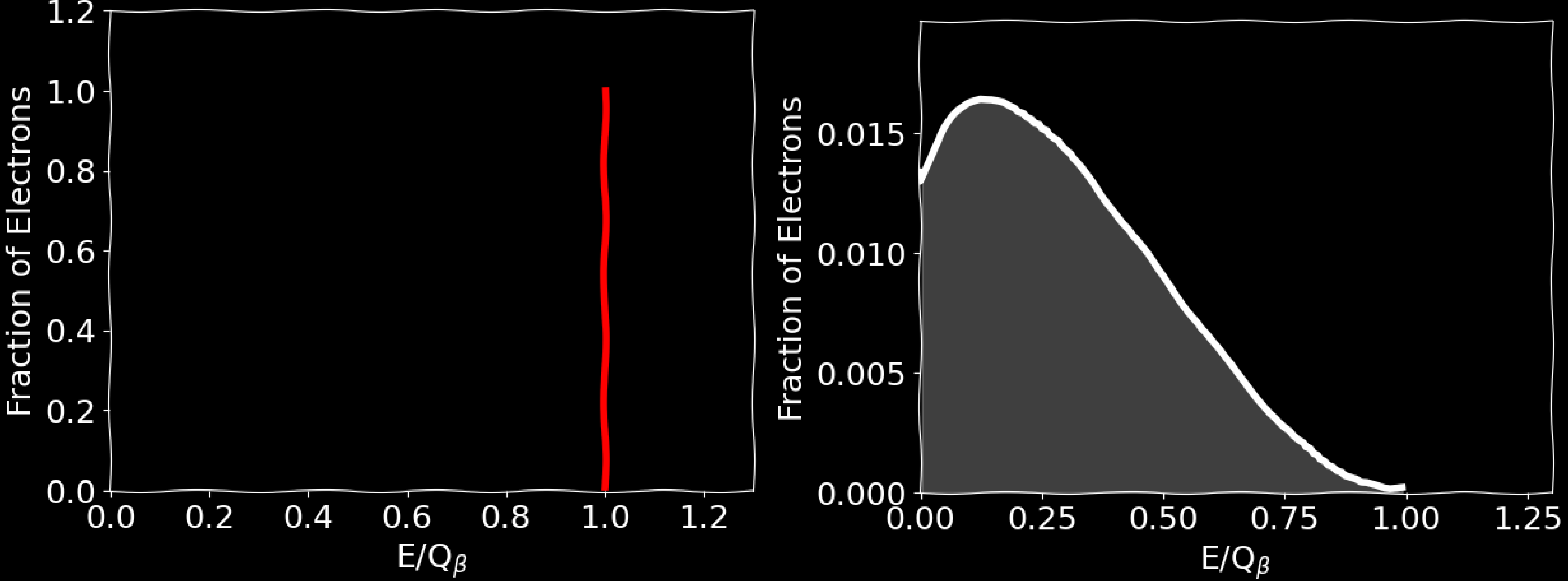
Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

ges. W. Pauli

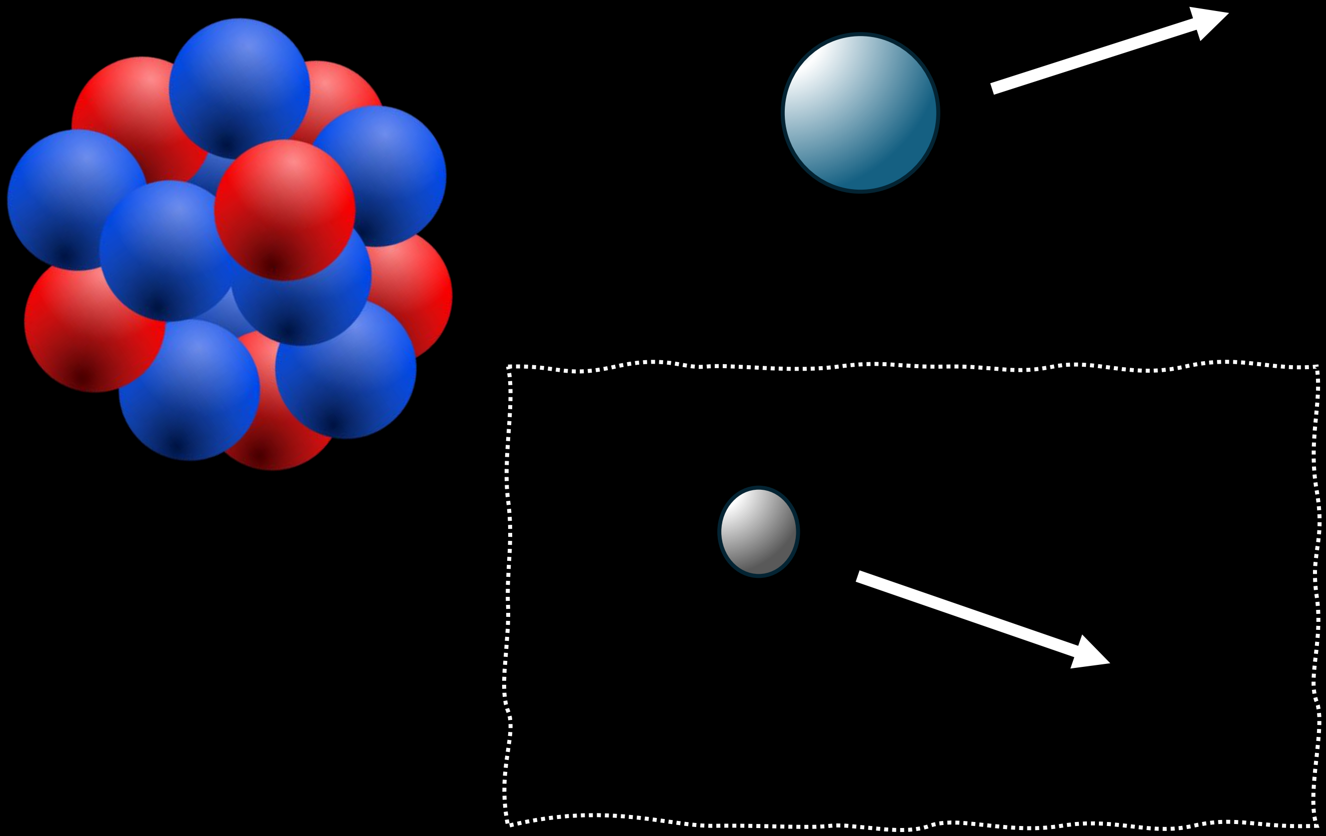
Expected Mono-energetic Electrons



Found a Continuum!



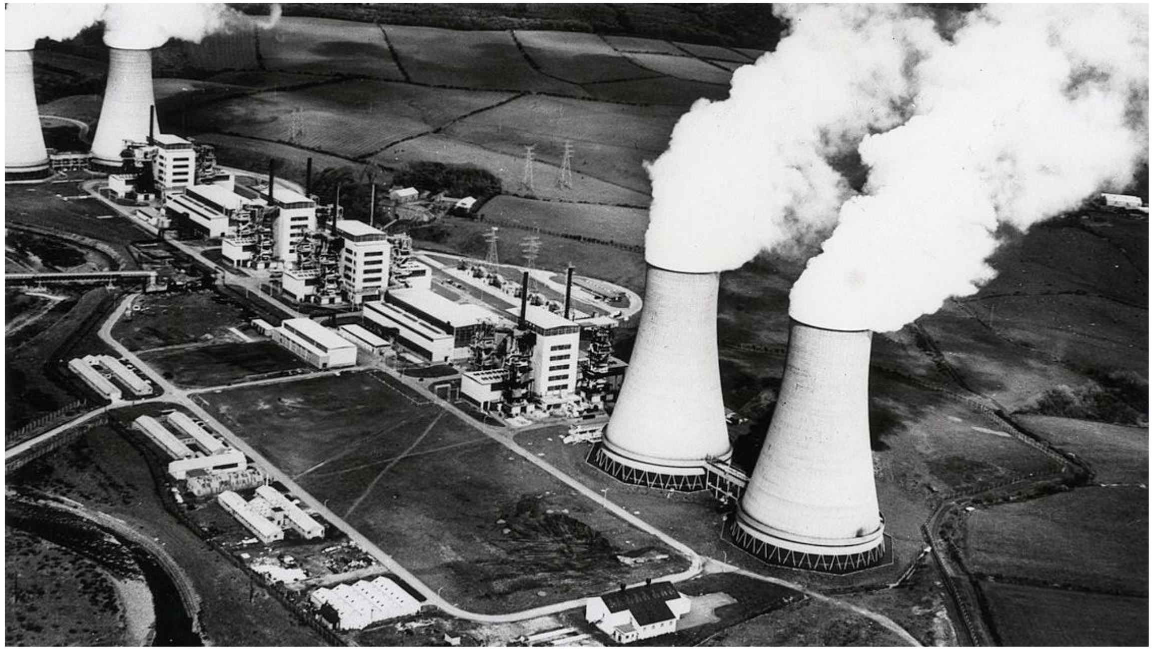
Implies the Existence of a Neutrino

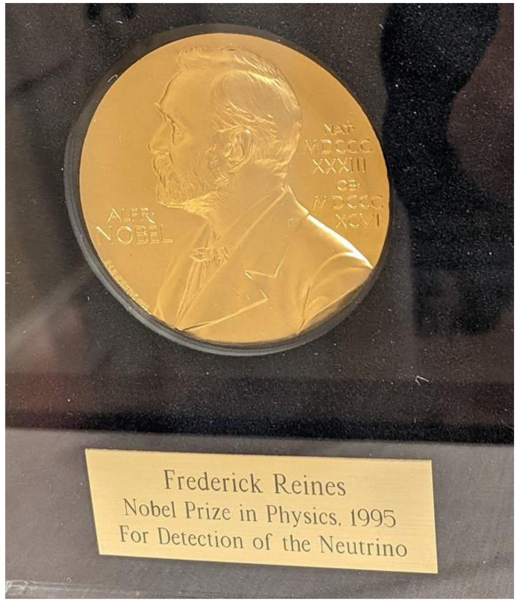


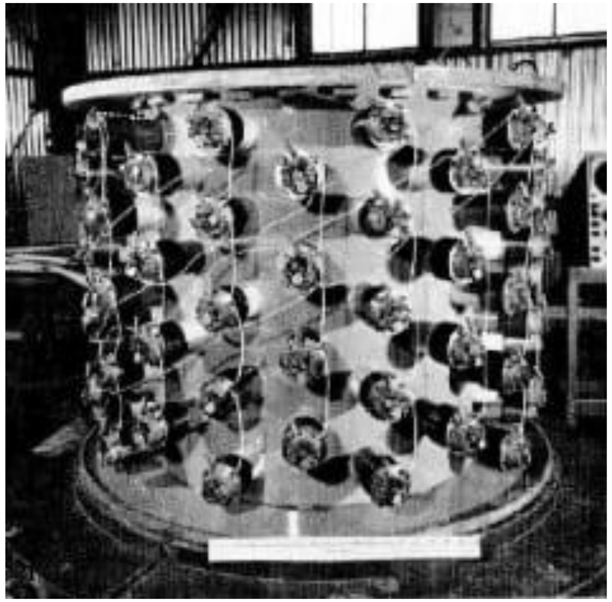
A Neutrino!

Neutrinos Discovered

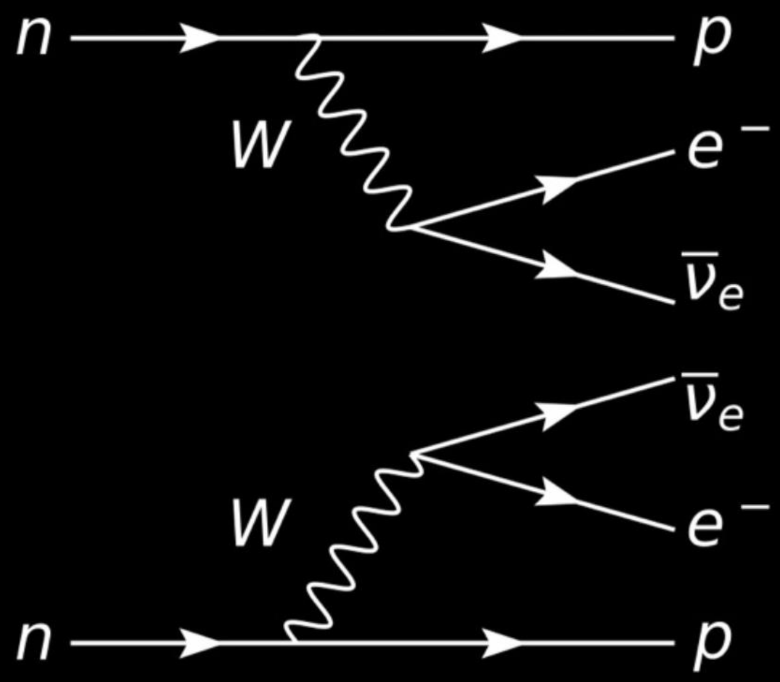
Neutrino discovered at a nuclear reactor at Savannah River by Reines and Cowan in 1957

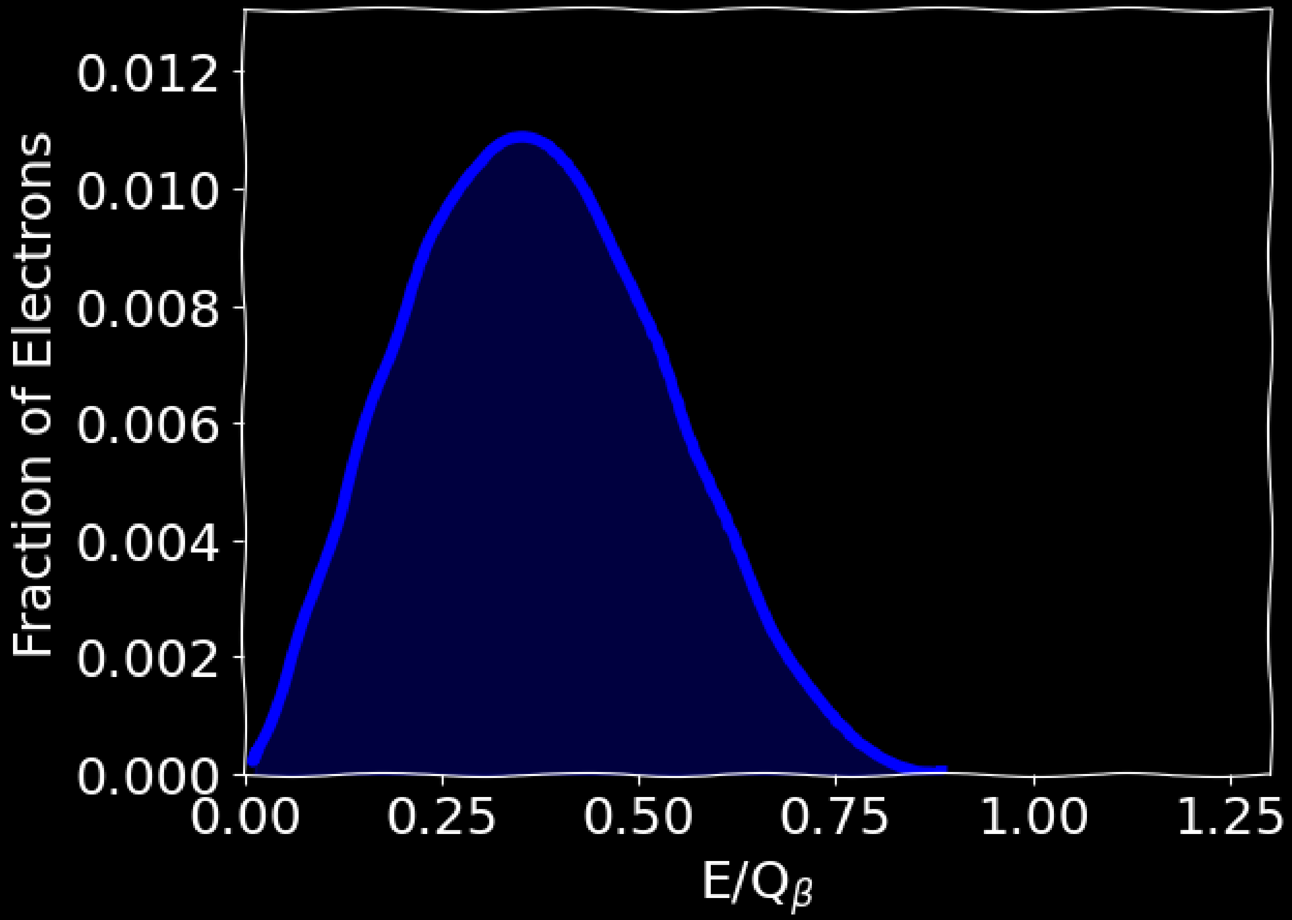




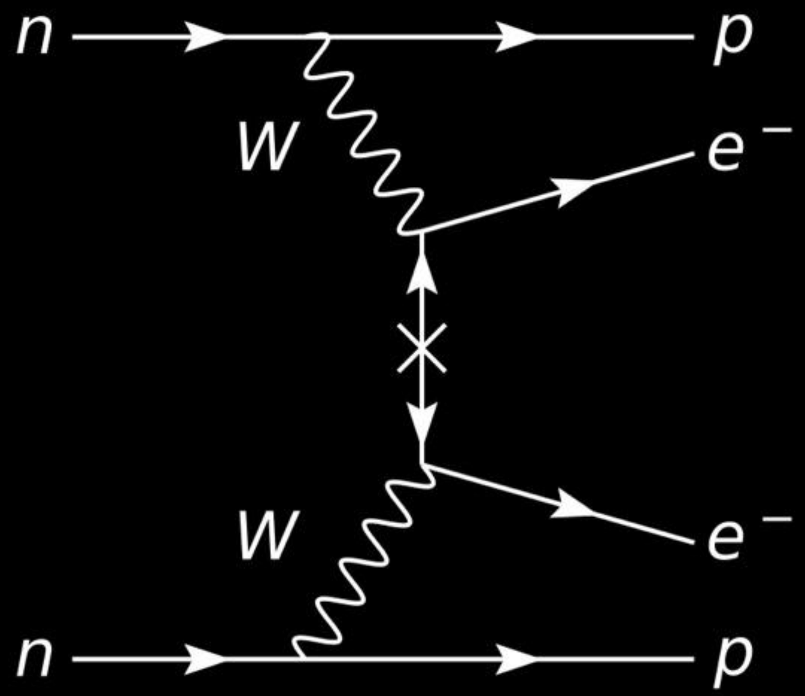


Two Neutrino Beta Decay





Neutrino-less Double Beta Decay (0νββ)



Required the violation of lepton number conservation

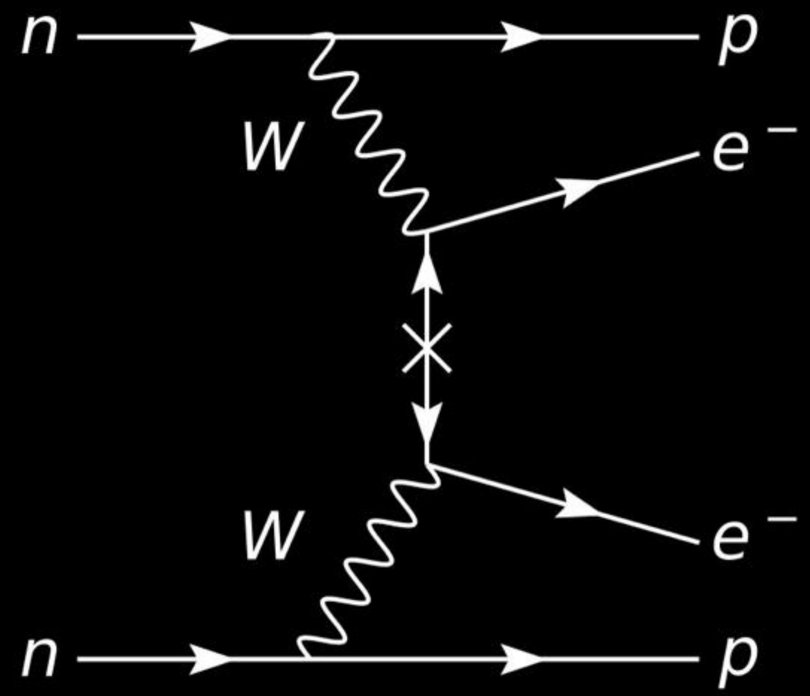
Second order weak transition

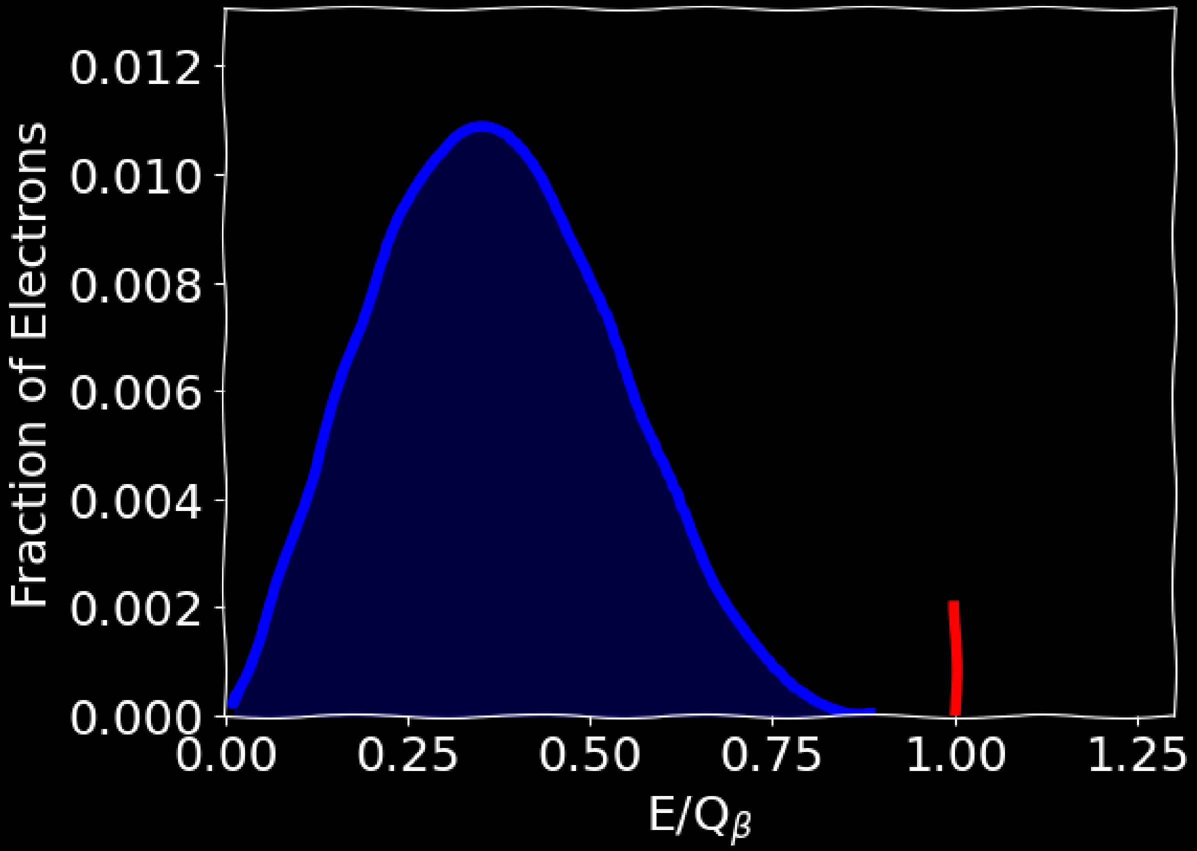
Beyond the Standard Model process

Ultra rare

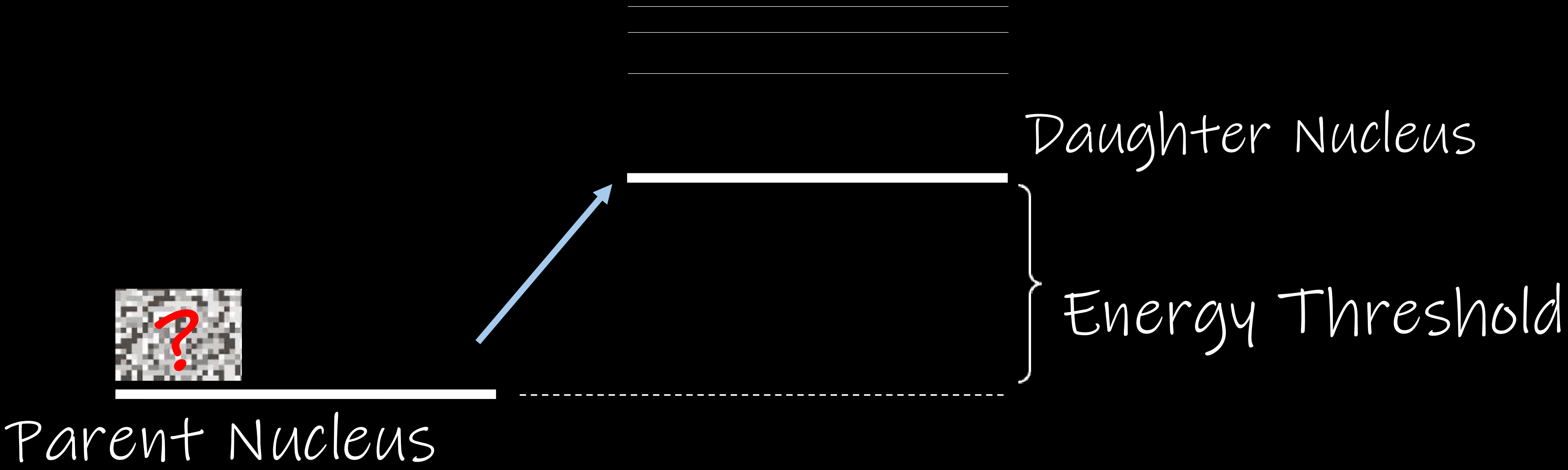
Can only happen in neutrinos are Majorana

Neutrino-less Double Beta Decay (0νββ)

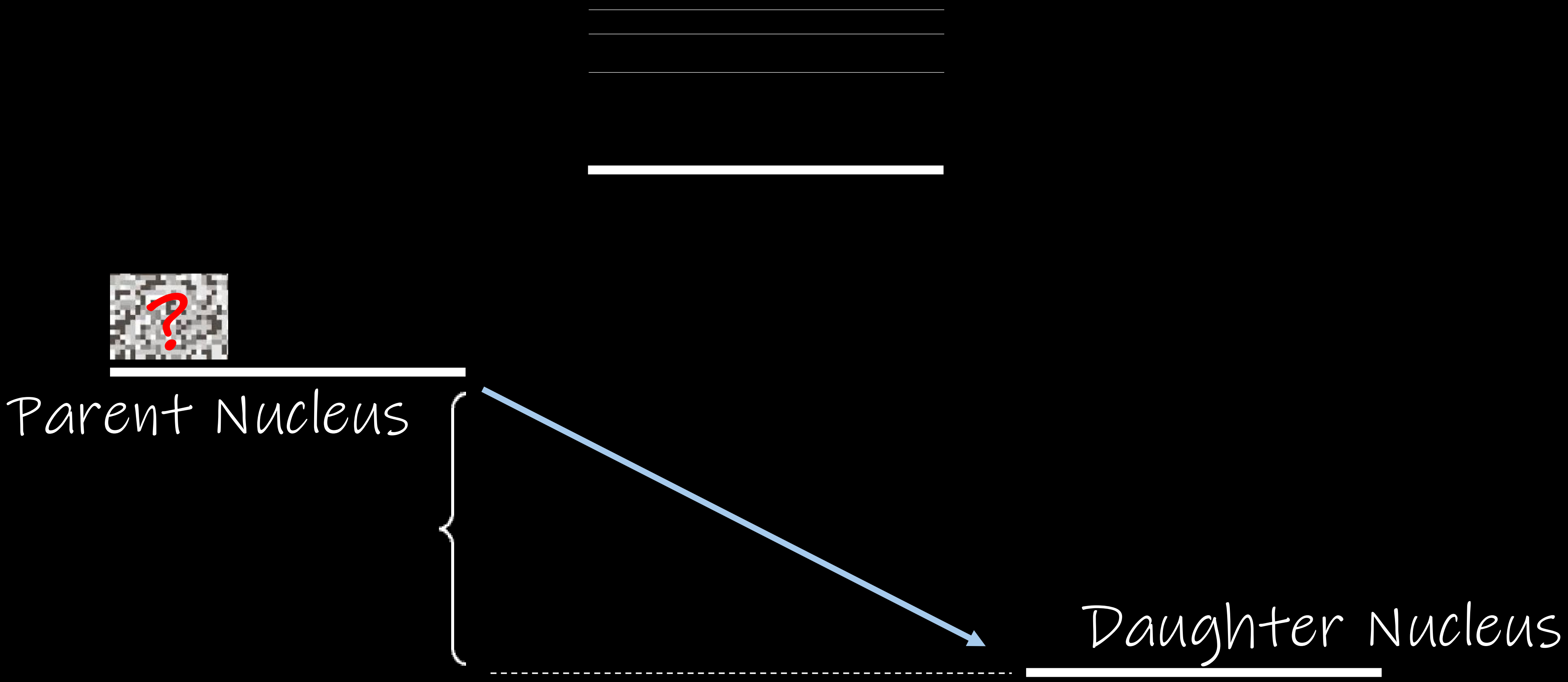




Isotope Selection



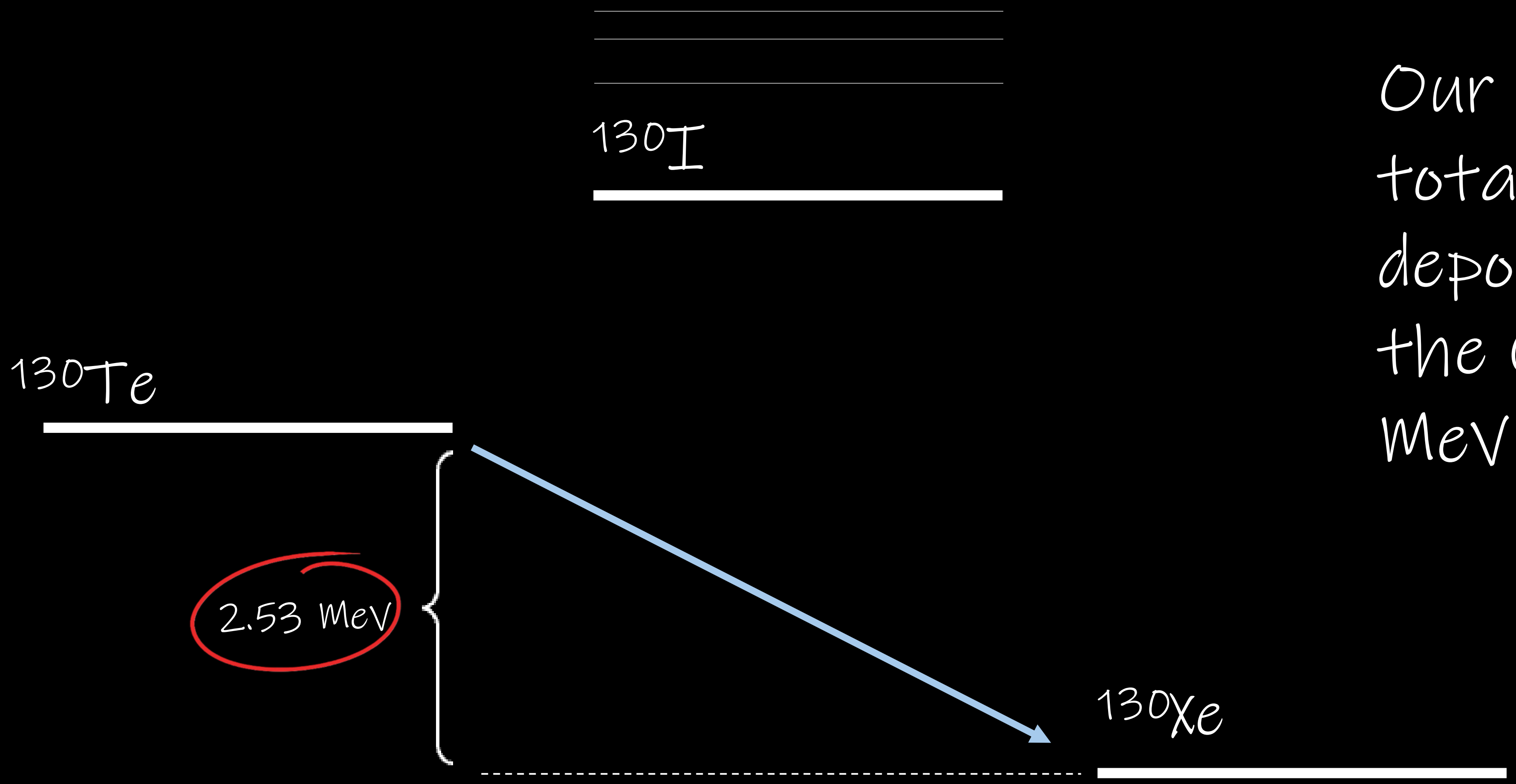
Isotope Selection



Parent Nucleus

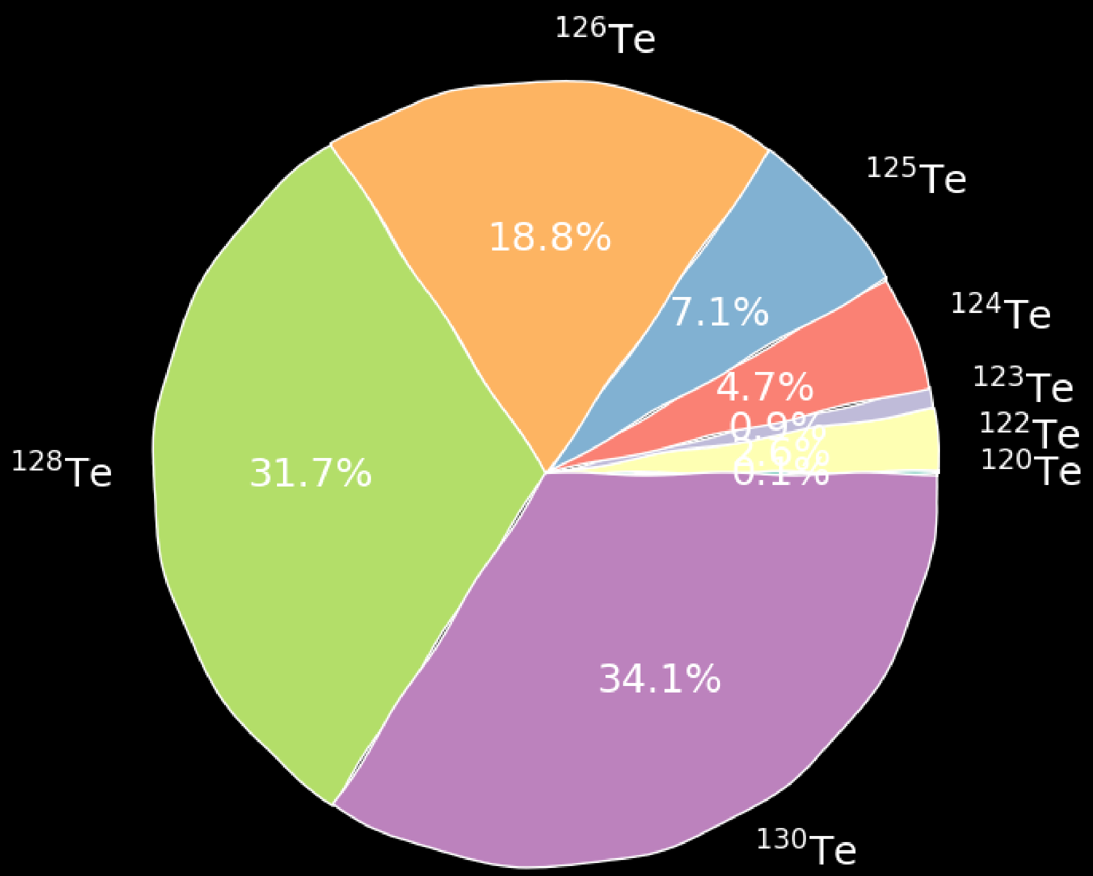
Daughter Nucleus

Isotope Selection



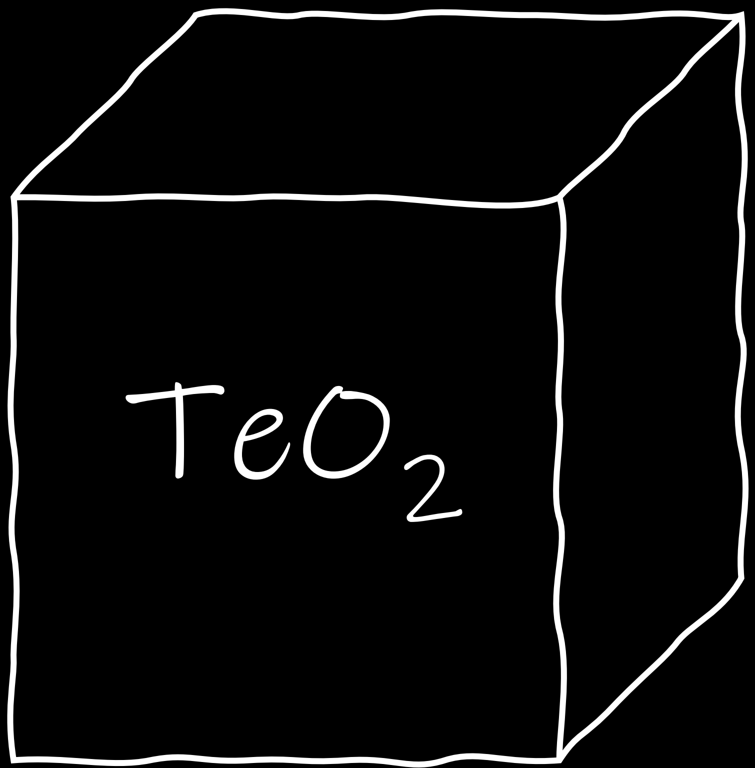
Our signal is a total energy deposition around the Q-value, 2.53 MeV

The Detector: Tellurium


Natural Abundances of Tellurium Isotopes

34.1% of
natural Te is
the 130
isotope

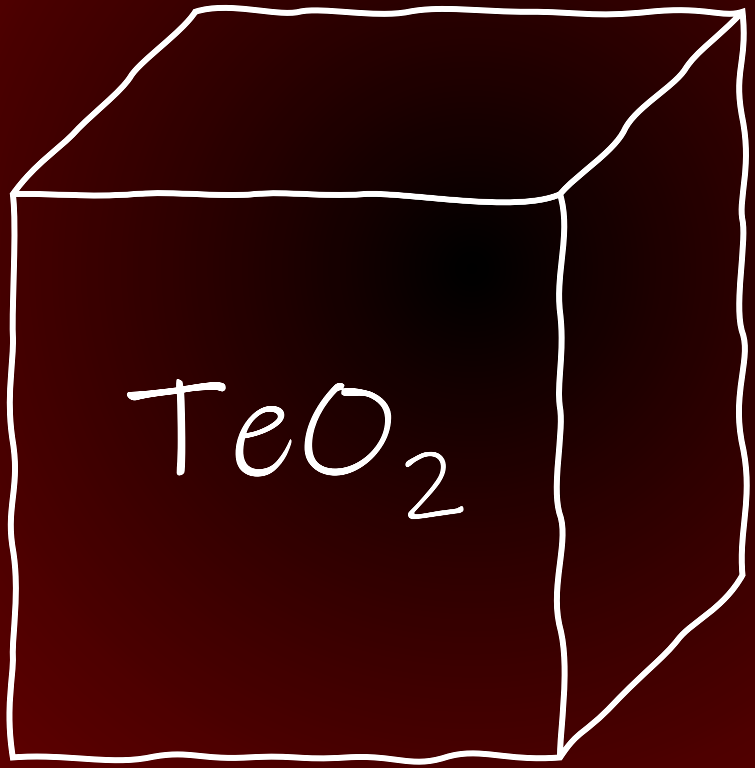
Source = Detector



A bulk material is well poised for high exposures needed
Of this search

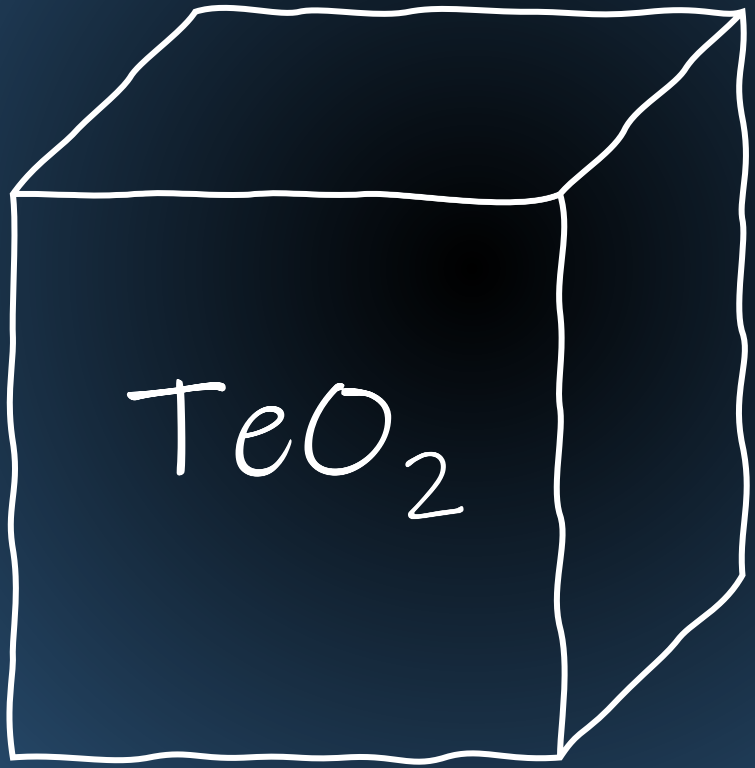
How how to "detector-ize" the crystal?

Make a Bolometer



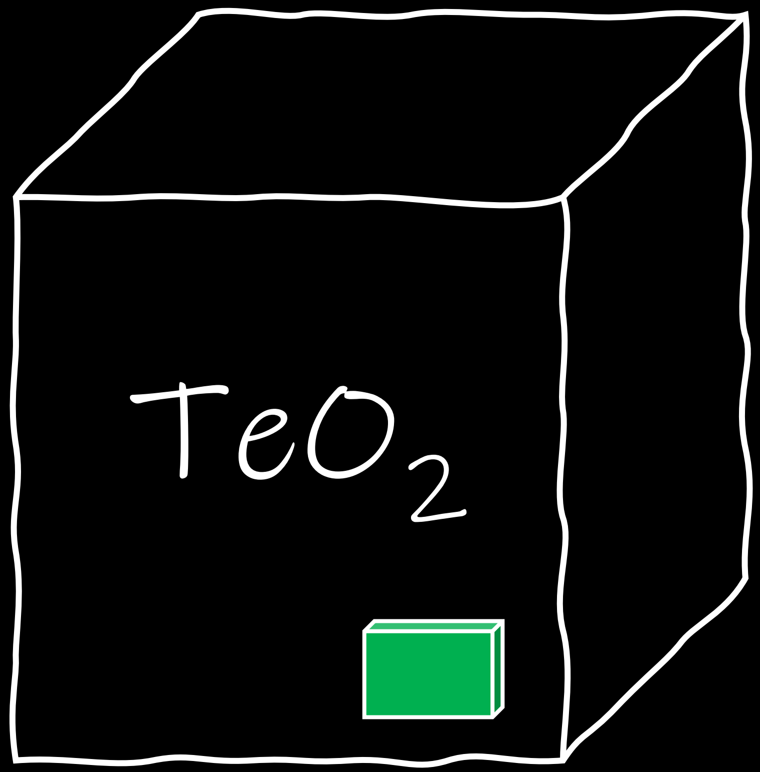
Make a Bolometer

~ 10 mK



Make a Bolometer

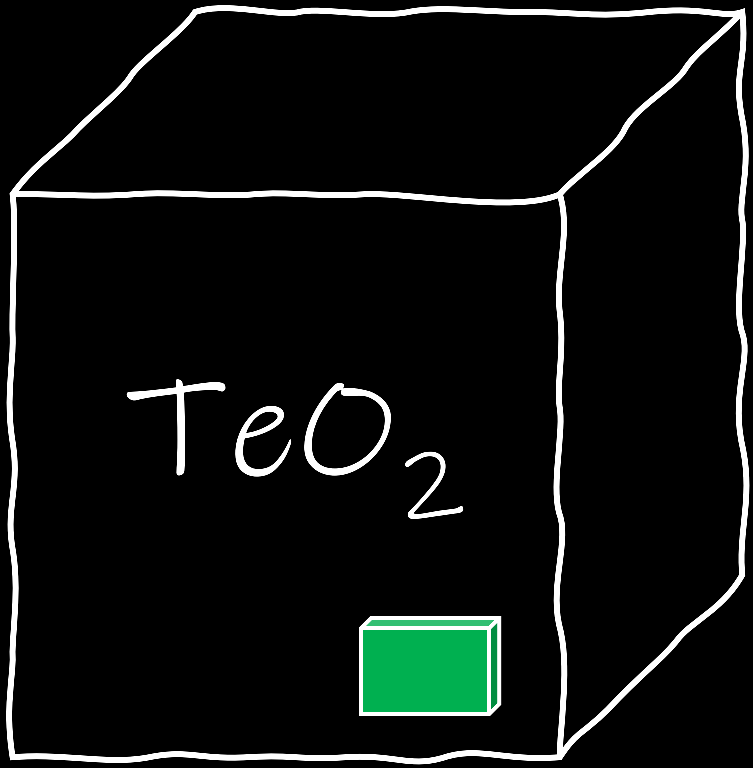
~10 mK

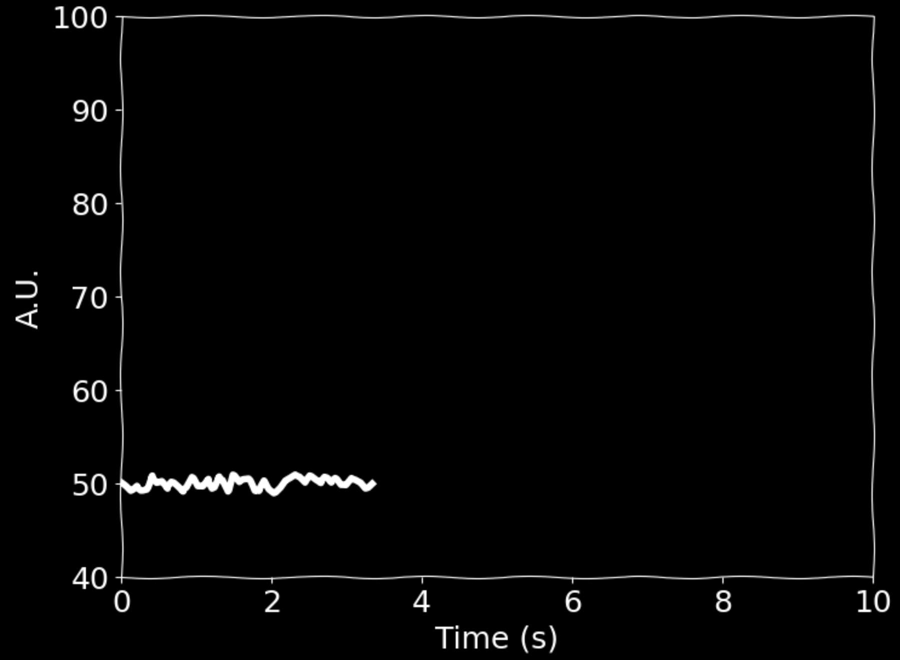


NTD-Ge Thermistor

Make a Bolometer

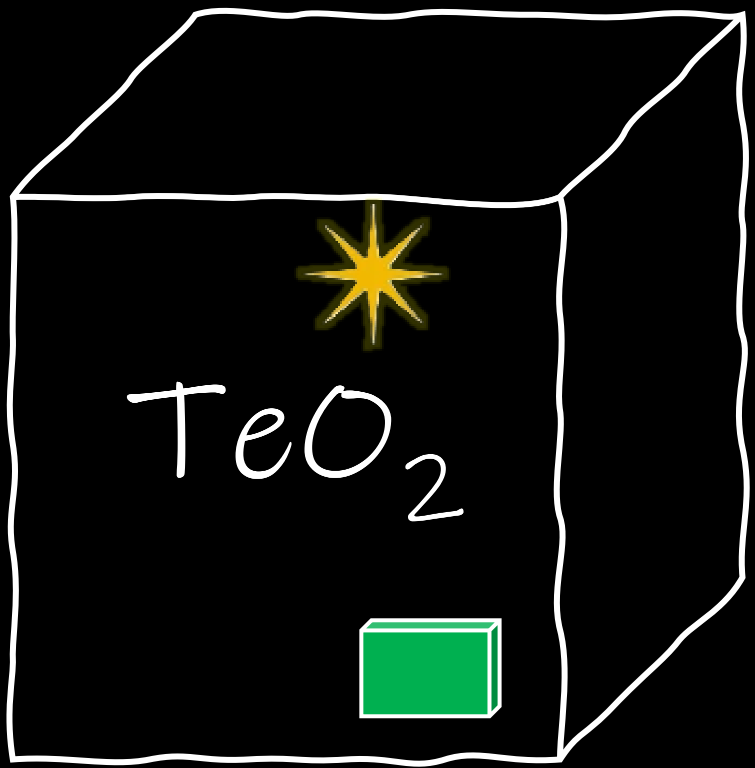
~10 mK

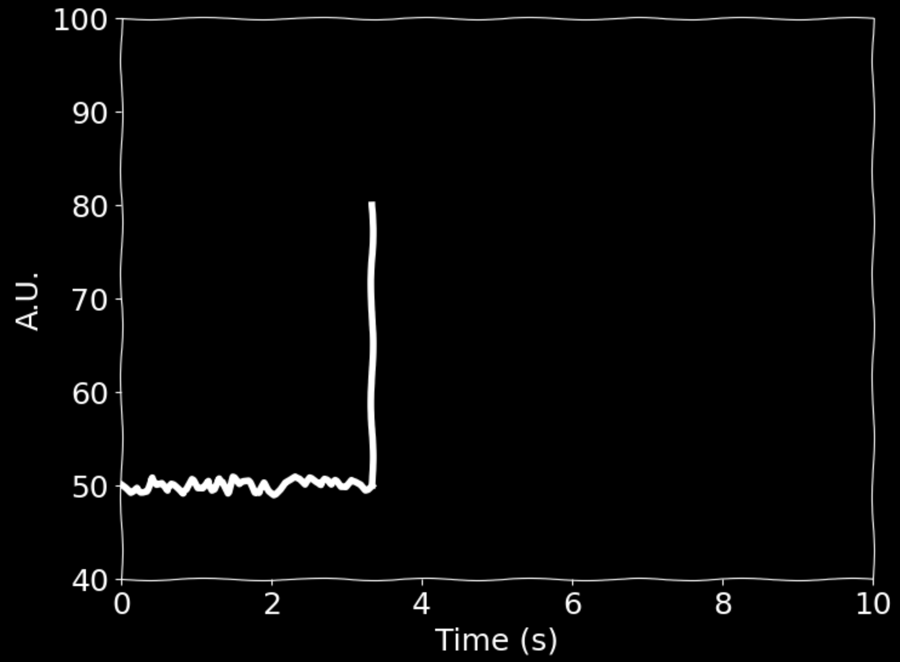




NTD-Ge Thermistor

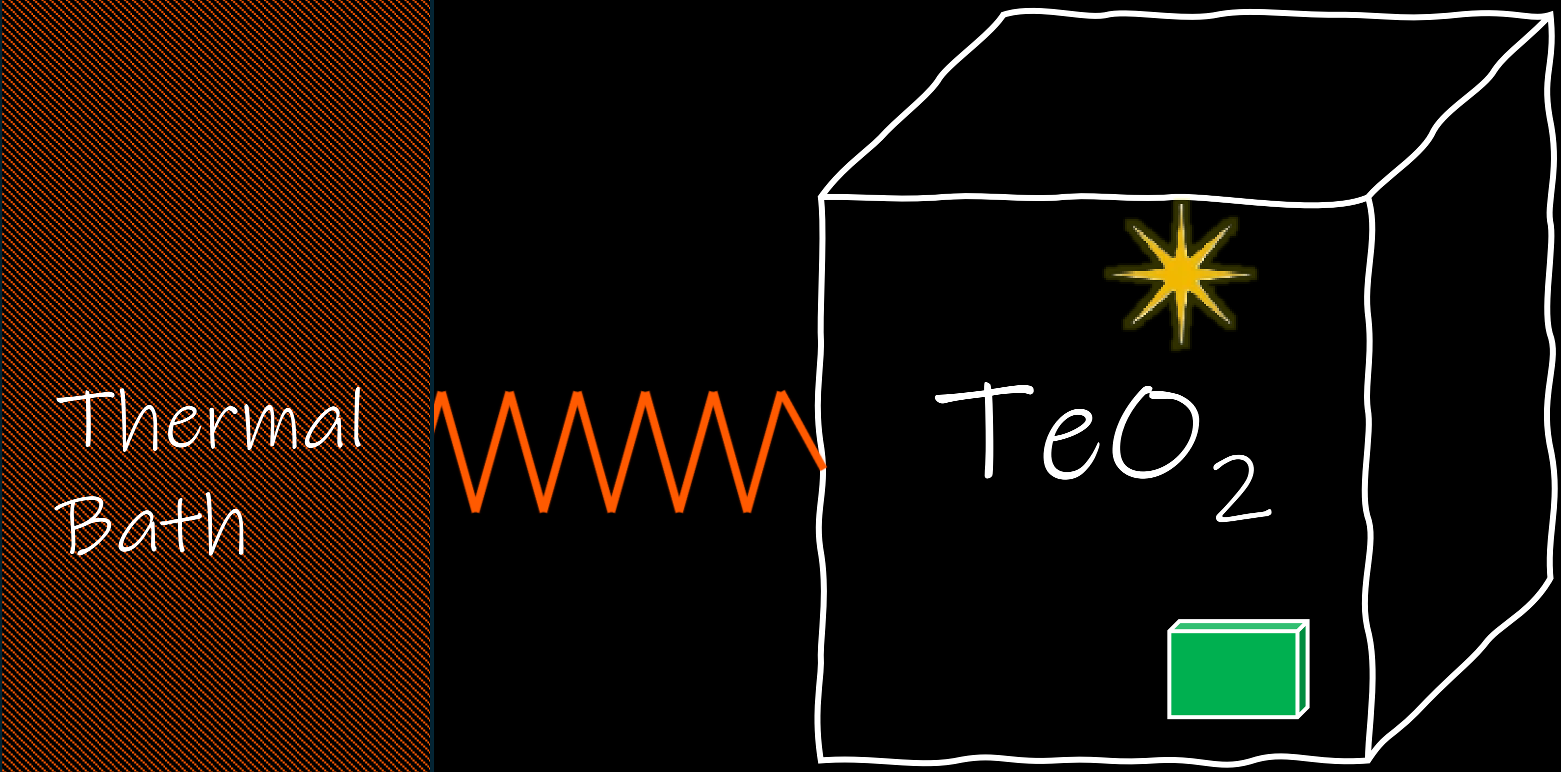
Make a Bolometer
~10 mK

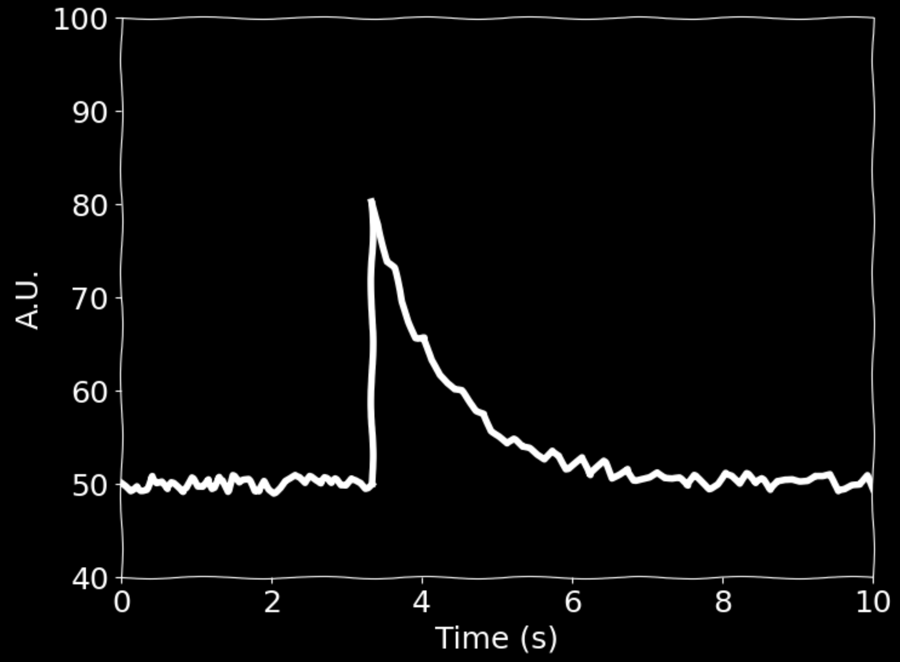




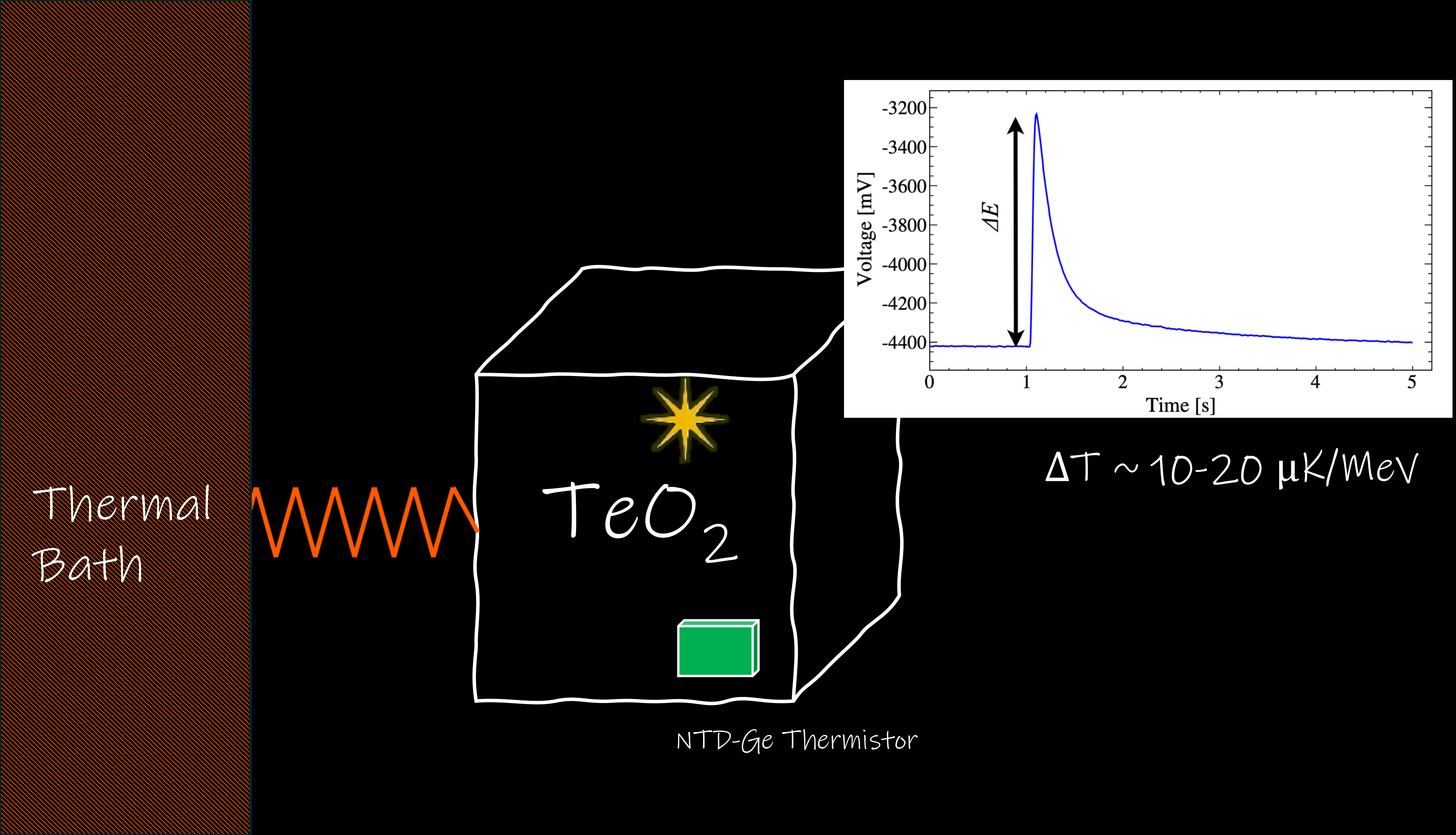
NTD-Ge Thermistor

Make a Bolometer



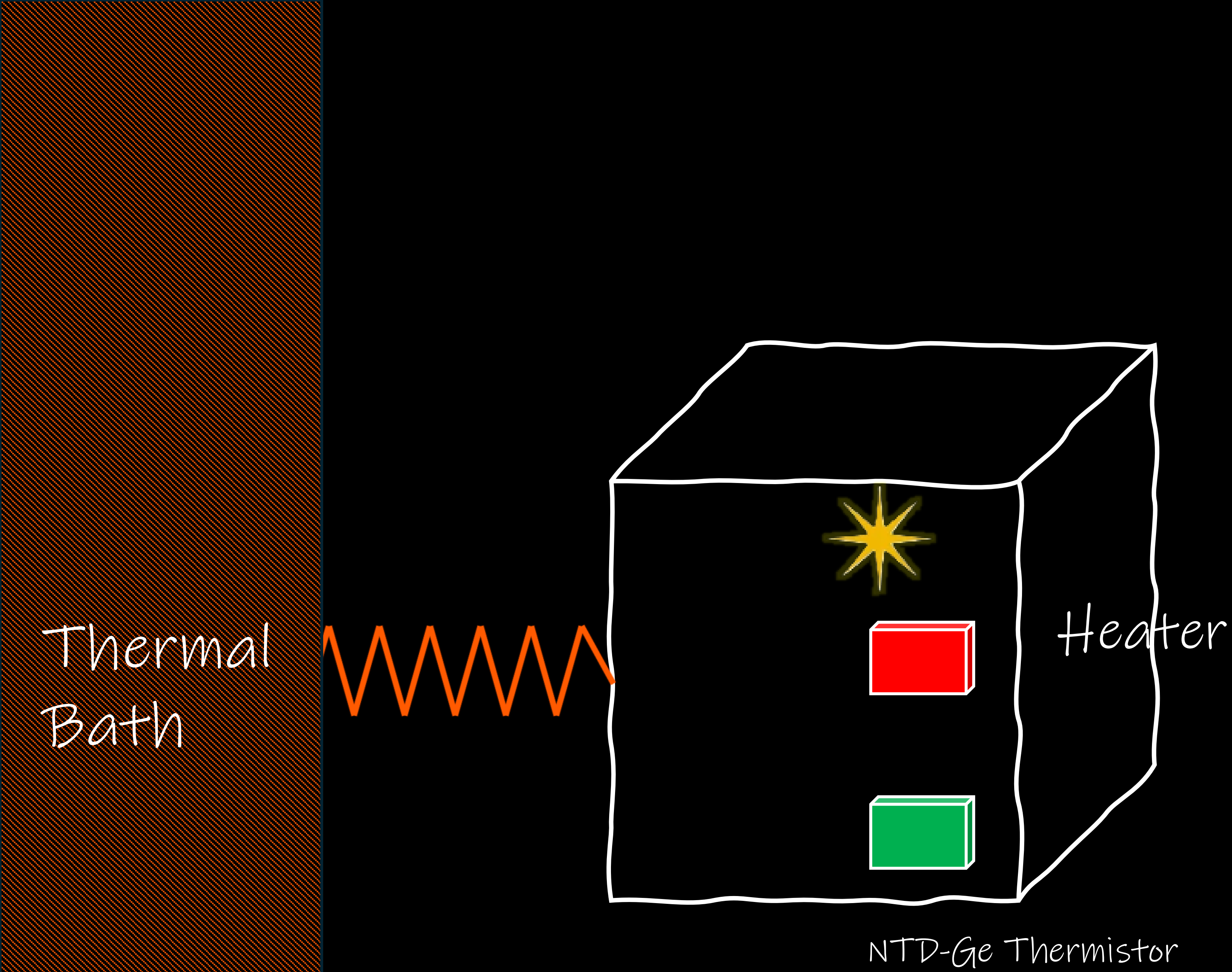


NTD-Ge Thermistor



$\Delta T \sim$ 10-20 μK/MeV

NTD-Ge Thermistor


Thermal
Bath
Heater
NTD-Ge Thermistor

CUORE

Cryogenic Underground Observatory
for Rare Events

Università degli Studi di Cassino e del Lazio Meridionale

Universitas Studii Paduani

University of Pittsburgh

Fudan University 1905

G S
S I

INFN
Istituto Nazionale di Fisica Nucleare

Johns Hopkins University

Massachusetts Institute of Technology

Sapienza Università di Roma

Università degli Studi di Milano Bicocca

UCLA

Virginia Tech

SINAP

Yale

CSNSM
Centre de Sciences Nucléaires et de Sciences de la Matière

Alma Mater Studiorum A.D. 1088

Shanghai Jiao Tong University 1896

Learn by Doing
Cal Poly

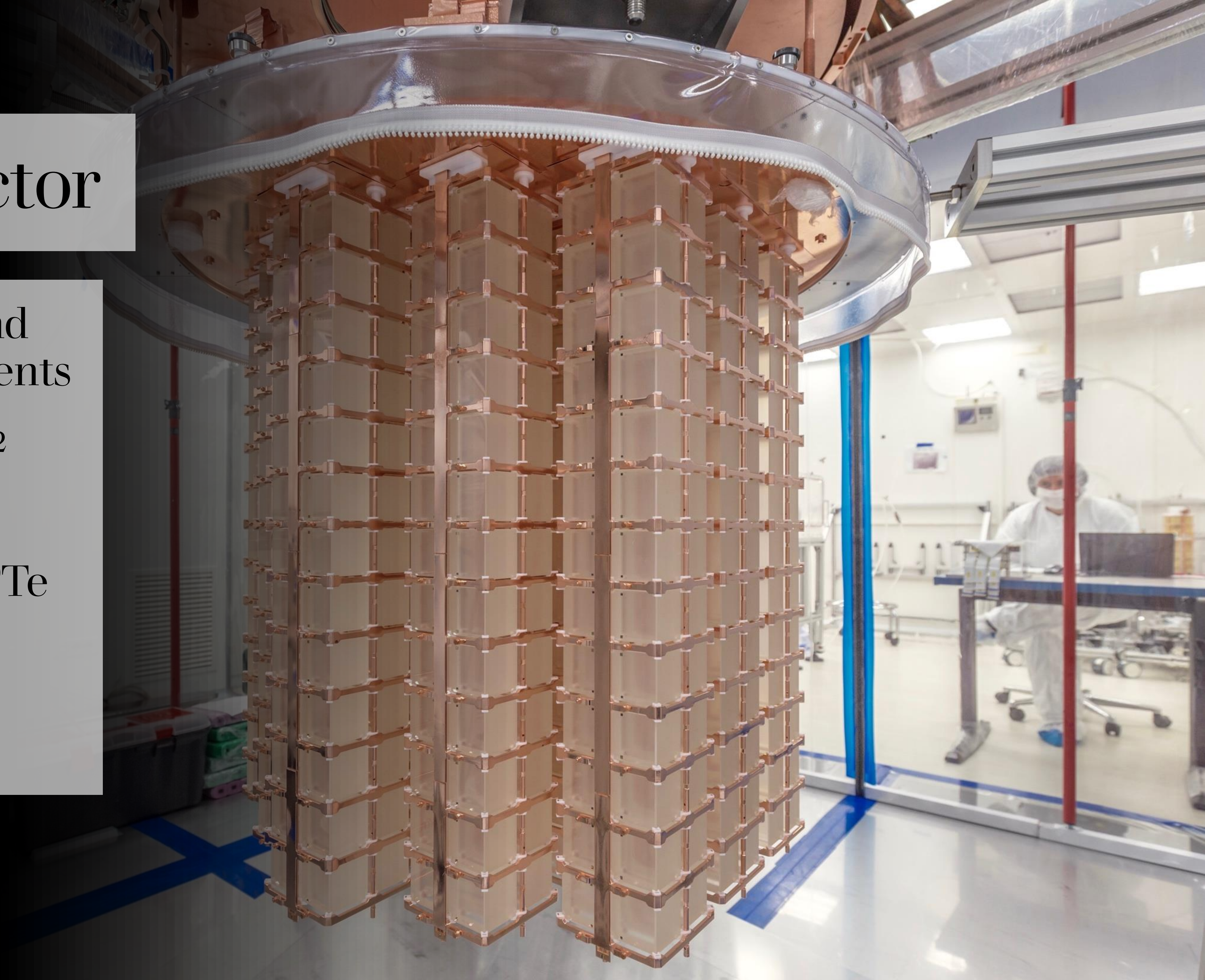
The University of California 1868 Berkeley

Berkeley Lab

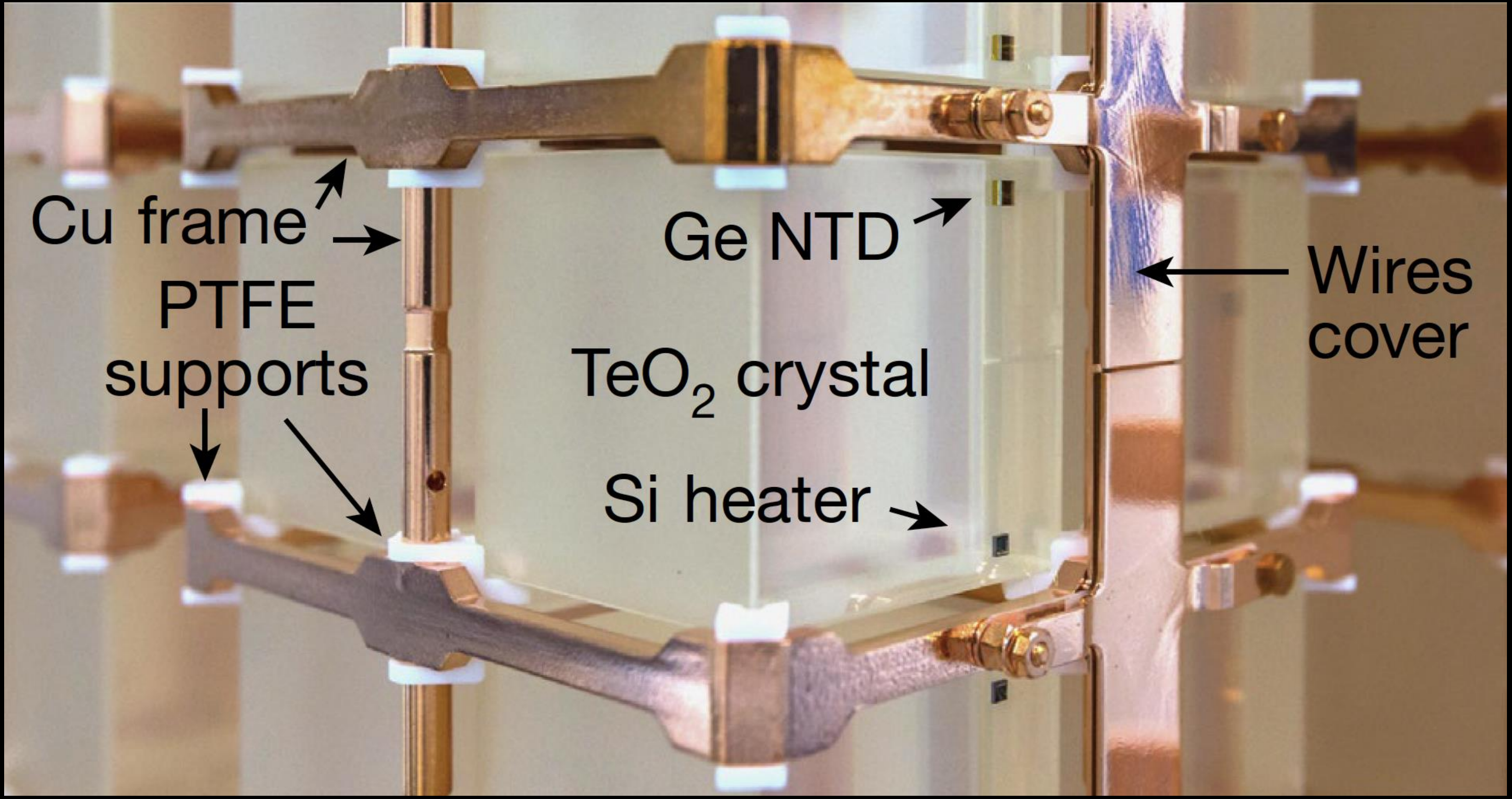
University of South Carolina

CUORE Detector

- Cryogenic Underground Observatory for Rare Events
- Composed of 988 TeO_2 crystals organized in 19 towers
- 742 kg TeO_2, 206 kg ^{130}Te
- Q-value of 2527.5 keV



CUORE Crystal Configuration



https://www.nature.com/articles/s41586-022-04497-4

TeO_2 crystal
Detector/absorber
750 grams
ΔT ~100 µK/MeV
τ ~1 second

Weak thermal links to the PTFE supports

Copper Frame
~10 mK heat sink

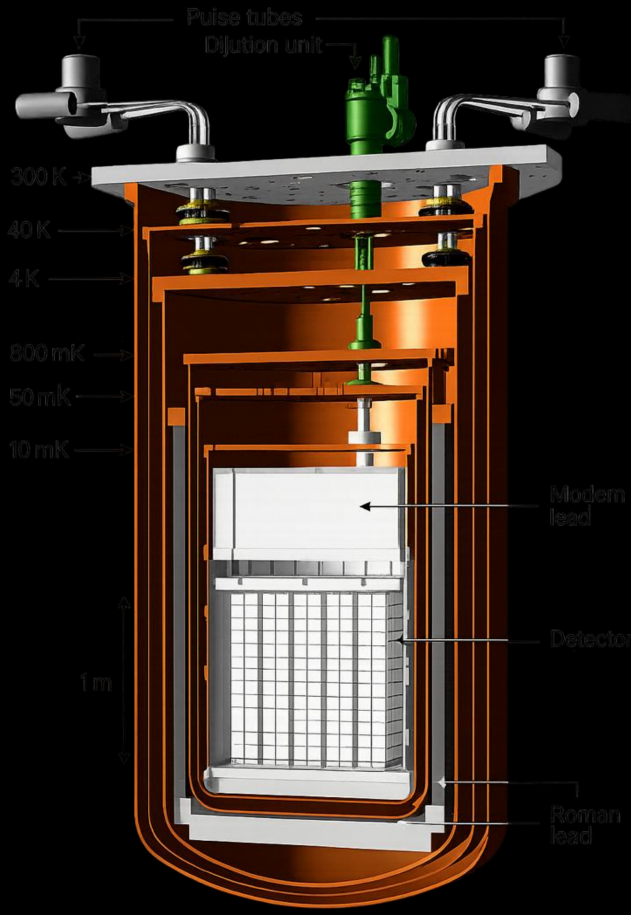
Ge NTD sensor

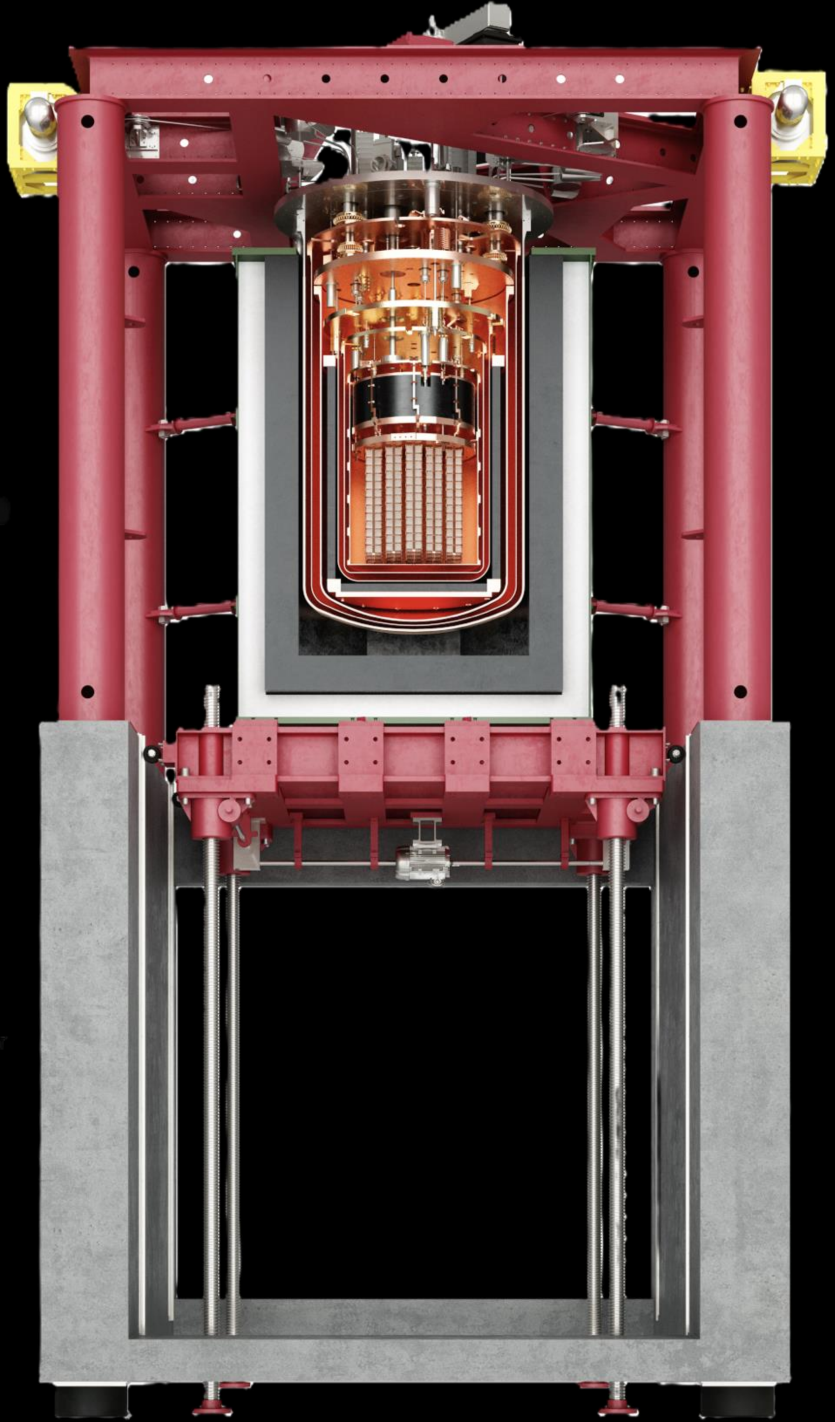
Si Joule Heater
Inject reference pulses for stabilization of baseline temperature

Gold wires providing electrical connection from sensors

Detector Infrastructure

- Large cryostat
- Pulse Tube cooled
- Vibration Damping System



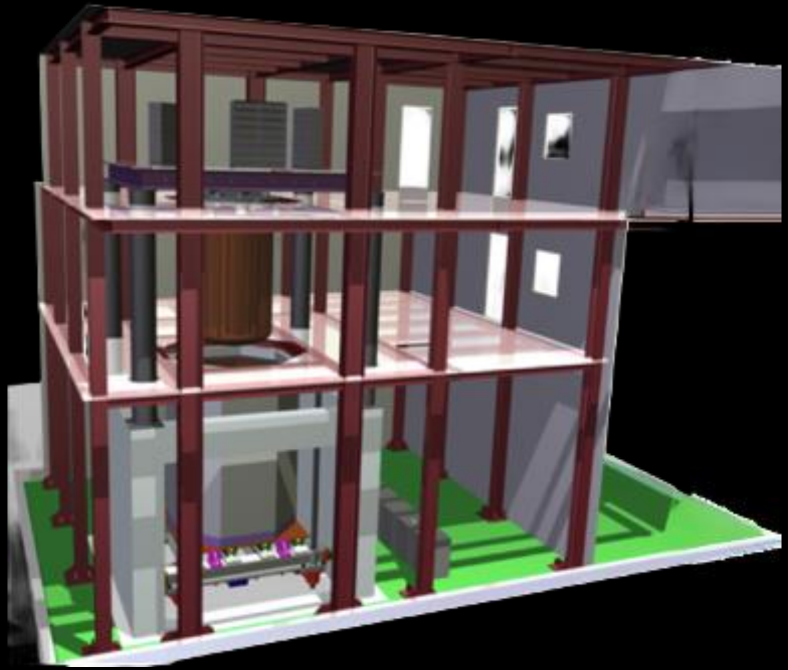


Shielding

- 18 cm of polyethylene
- 2 cm of Borated Poly
- >35 cm modern lead shielding
- Copper cryostat vessels
- Internal ancient lead

CUORE @ Gran Sasso

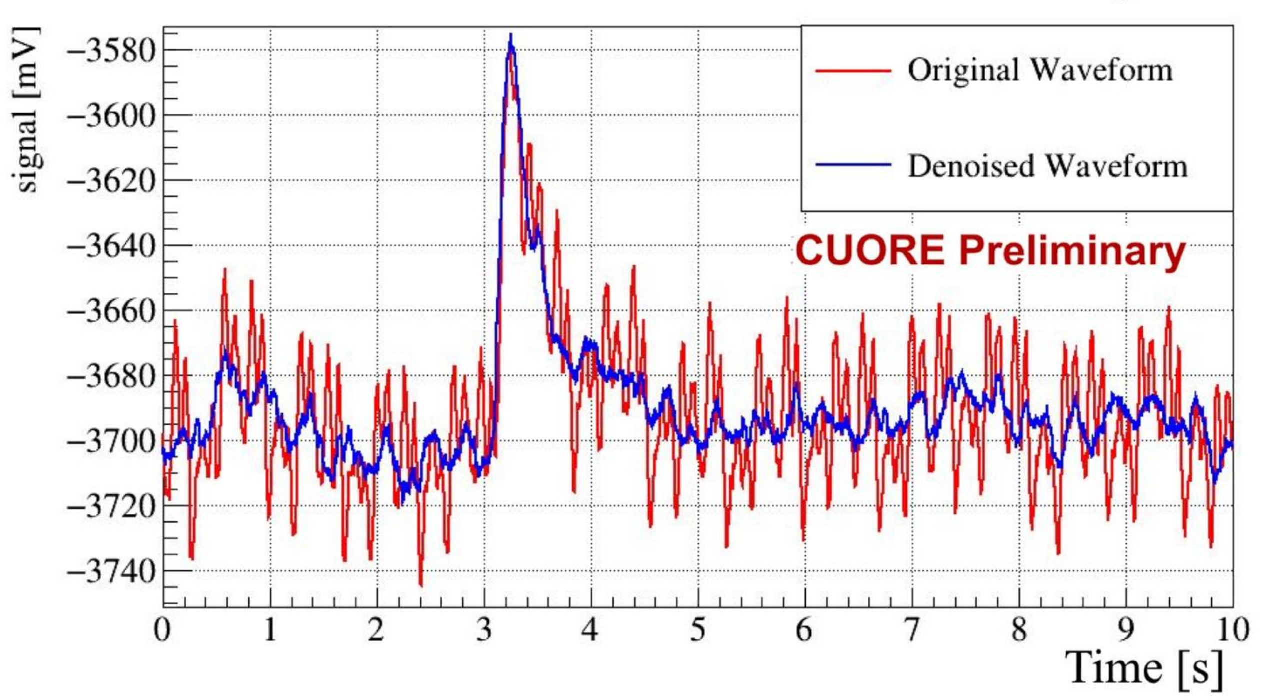
- Under ~3,600 m.w.e rock overburden
- 6 orders of magnitude reduction in muon flux
- Muons: 3 x 10^{-8} /sec/cm^2
- Neutrons: 4 x 10^{-6} /sec/cm^2 (below 10 MeV)
- Design background goal: 10^{-2} ckkyr

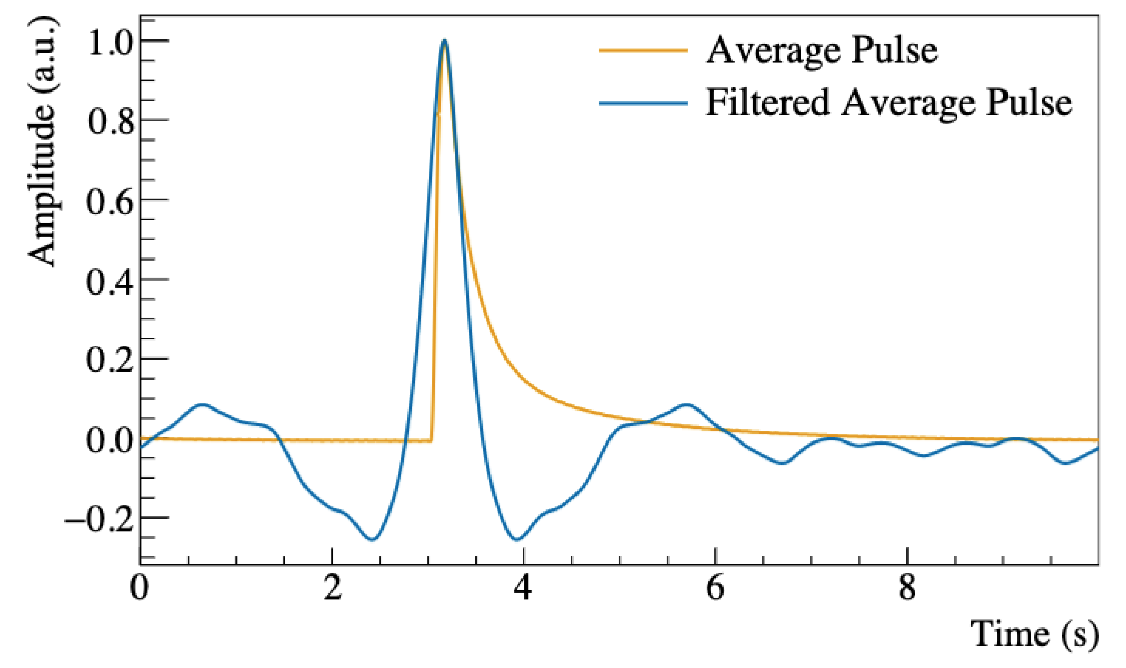


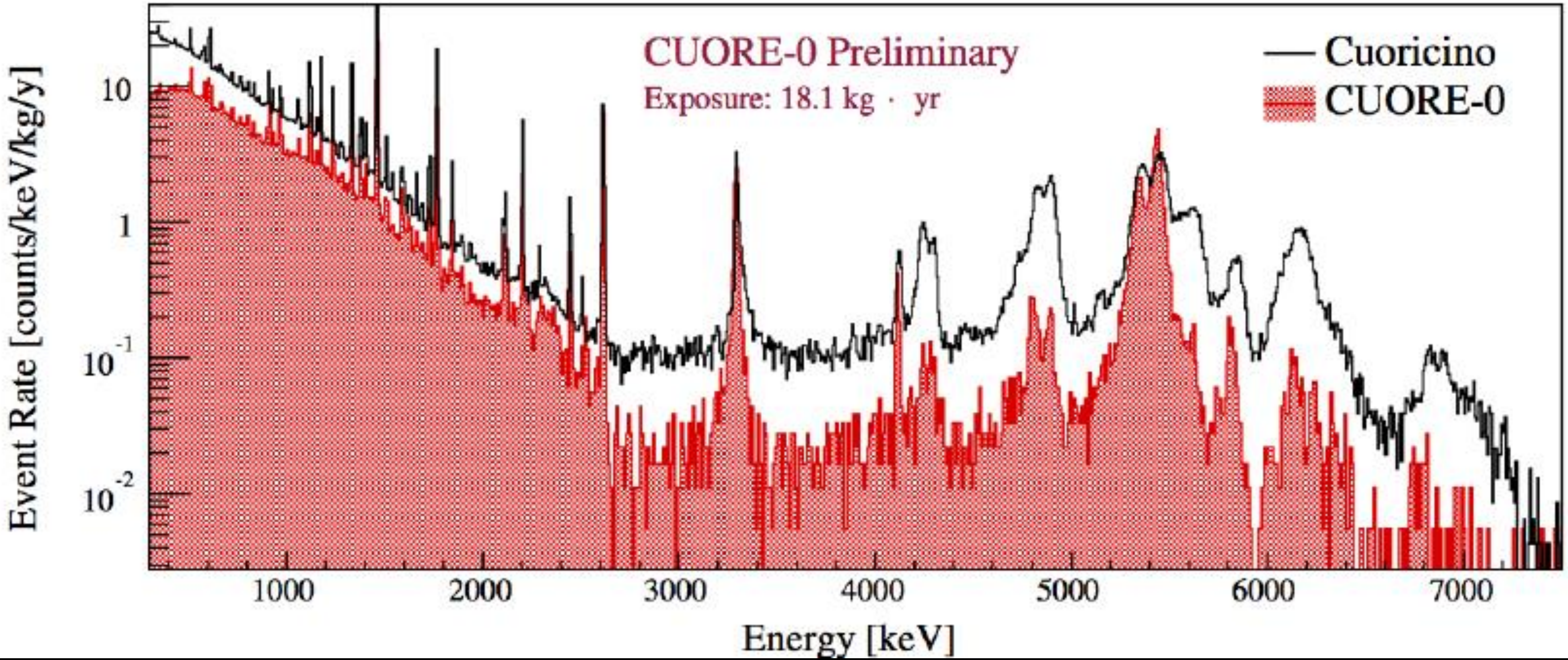
Analysis: Noise Reduction & Filtering

Denoising using auxiliary devices
(microphones, seismometers,
accelerometers)

Optimal Filter






CUORE-0 Preliminary
Exposure: 18.1 kg · yr
Cuoricino
CUORE-0
Event Rate [counts/keV/kg/y]
10
1
10^{-1}
10^{-2}
1000
2000
3000
4000
5000
6000
7000
Energy [keV]

Experimental Sensitivity

$$T^{0\nu} \propto \sqrt{\frac{M \cdot t}{B \cdot E}}$$

$M \cdot T$

Large Exposure

B

Low Background in ROI

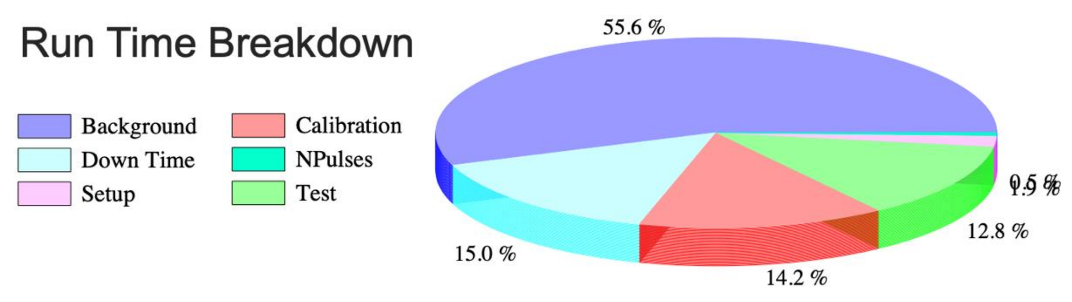
E

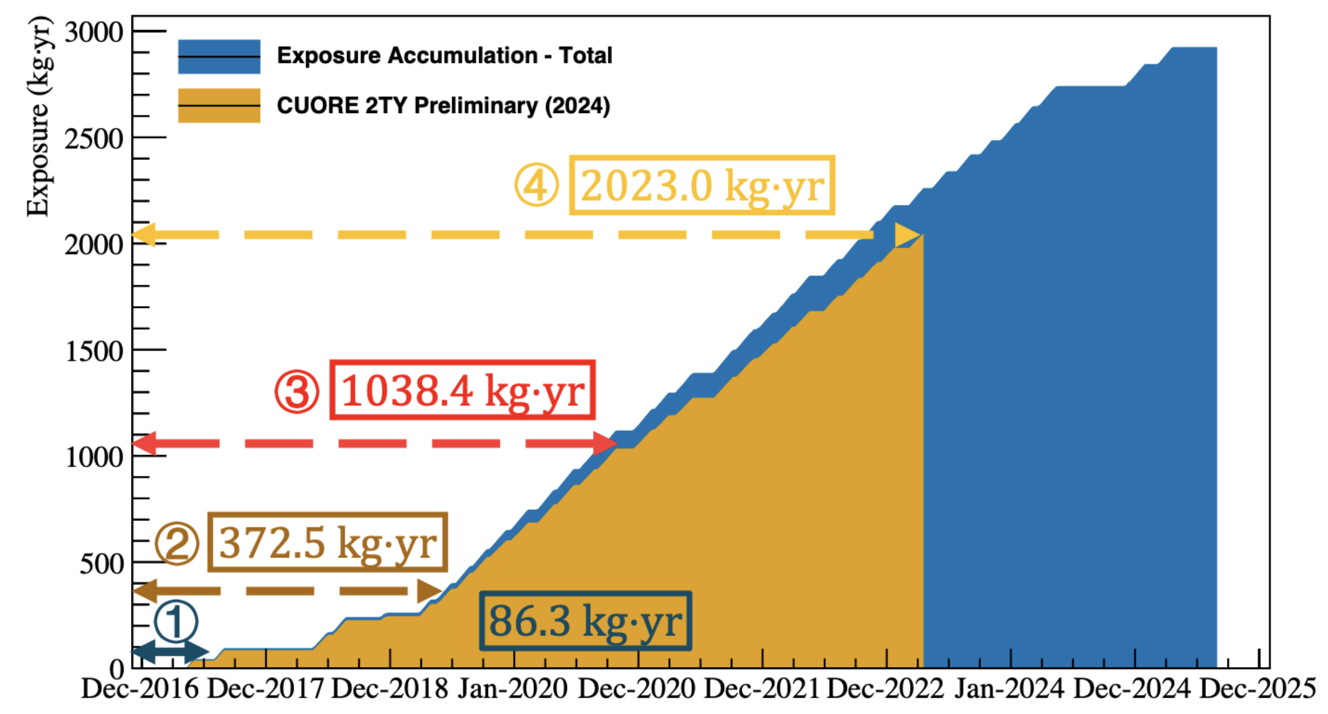
High Energy Resolution

Exposure

Stable data collection since 2019, with ≳ 85% uptime

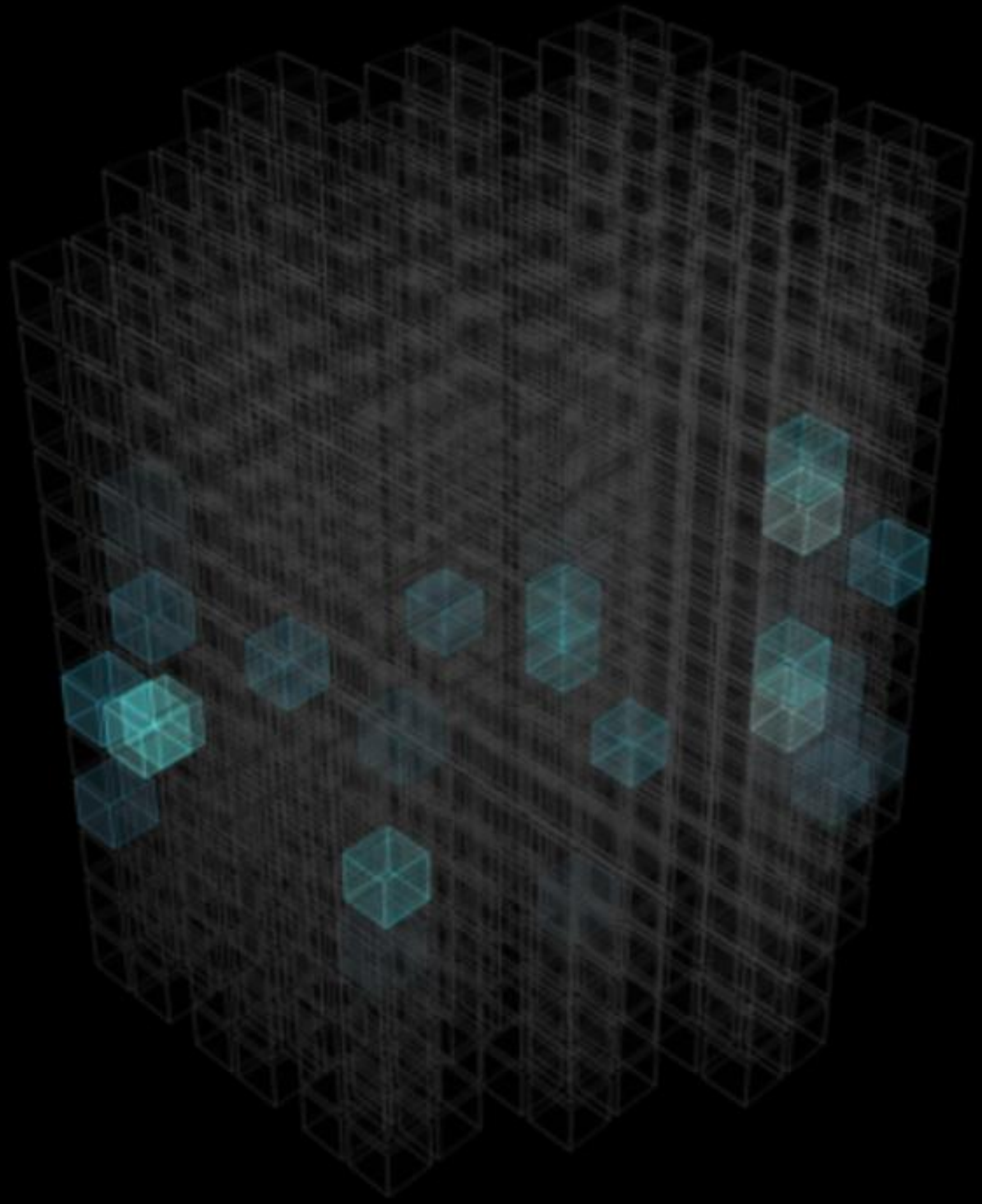
Data collection to continue into the summer of 2026



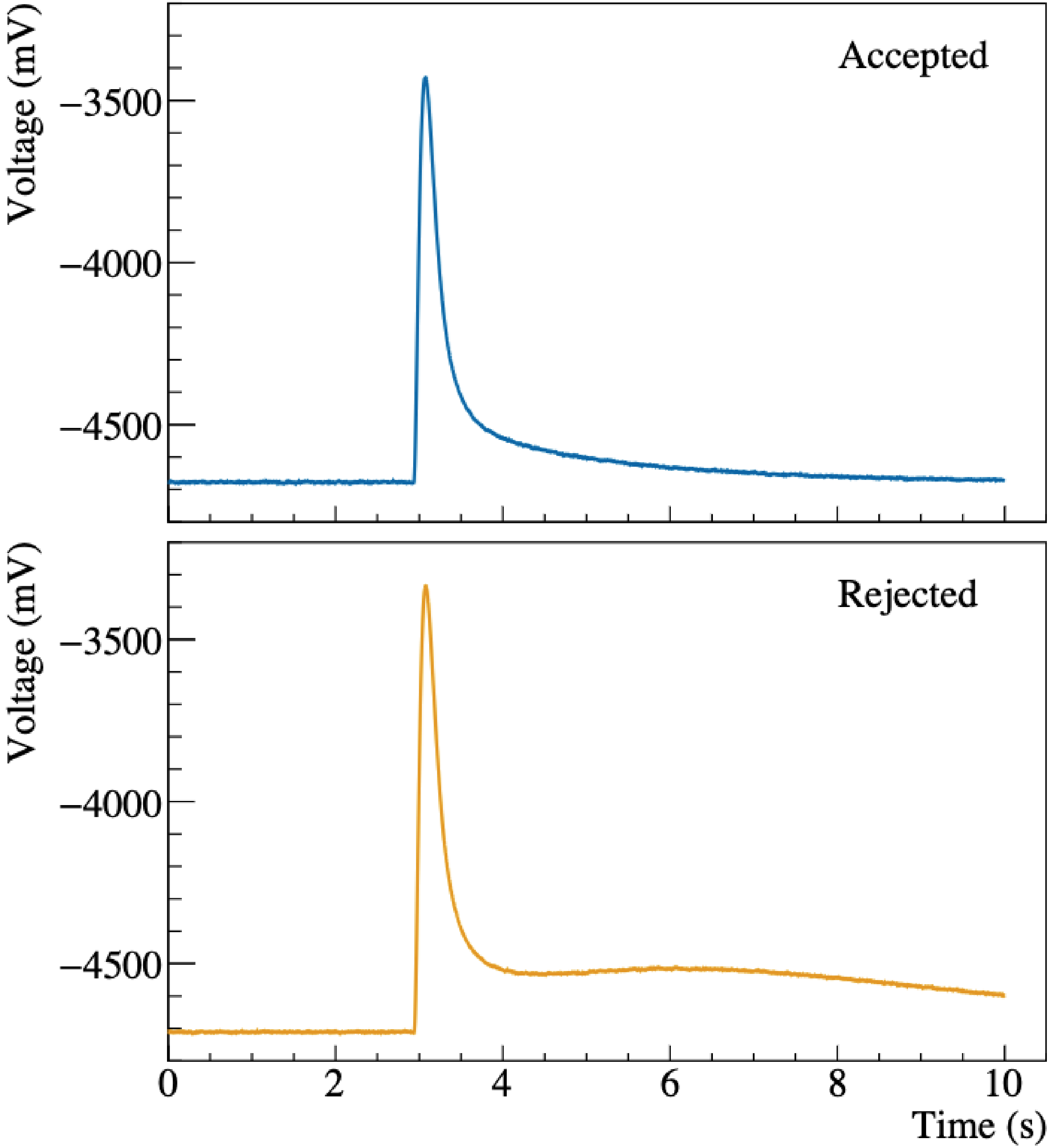


Anti-coincidence Cut

- 88% of signal events are contained within one crystal

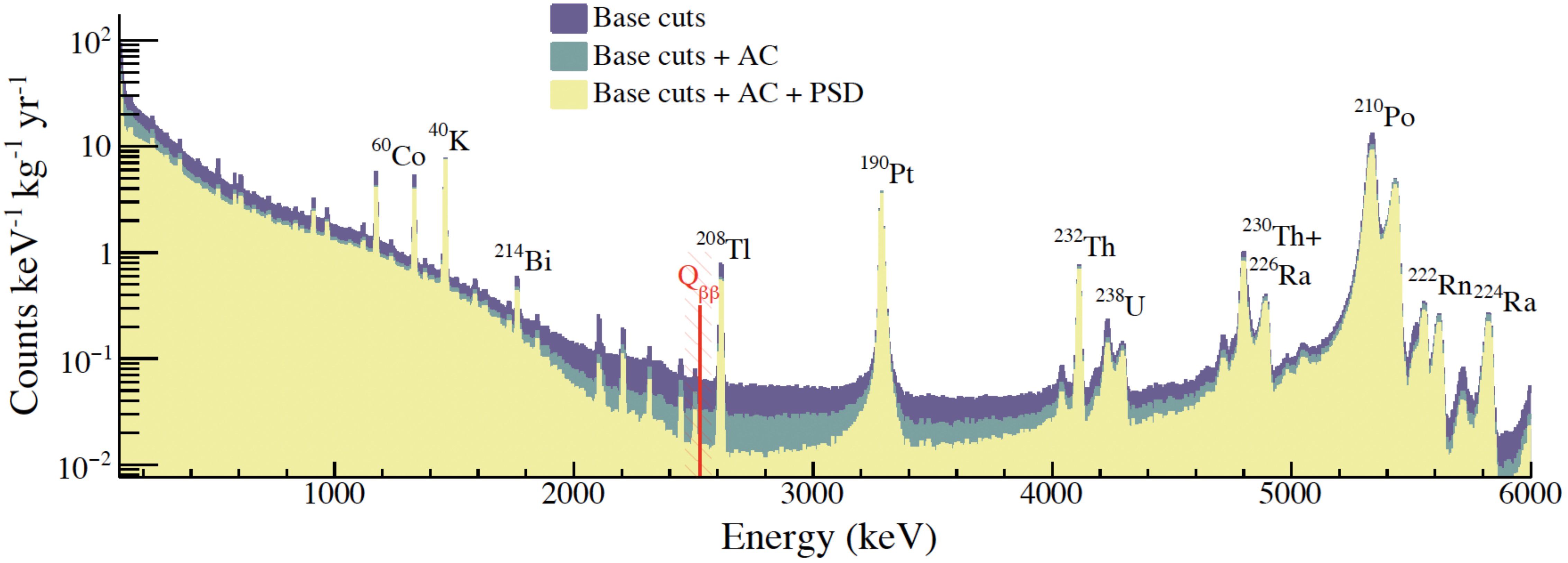


Pulse Shape


Accepted
Rejected
Voltage (mV)
−3500
−4000
−4500
Voltage (mV)
−3500
−4000
−4500
0
2
4
6
8
10
Time (s)

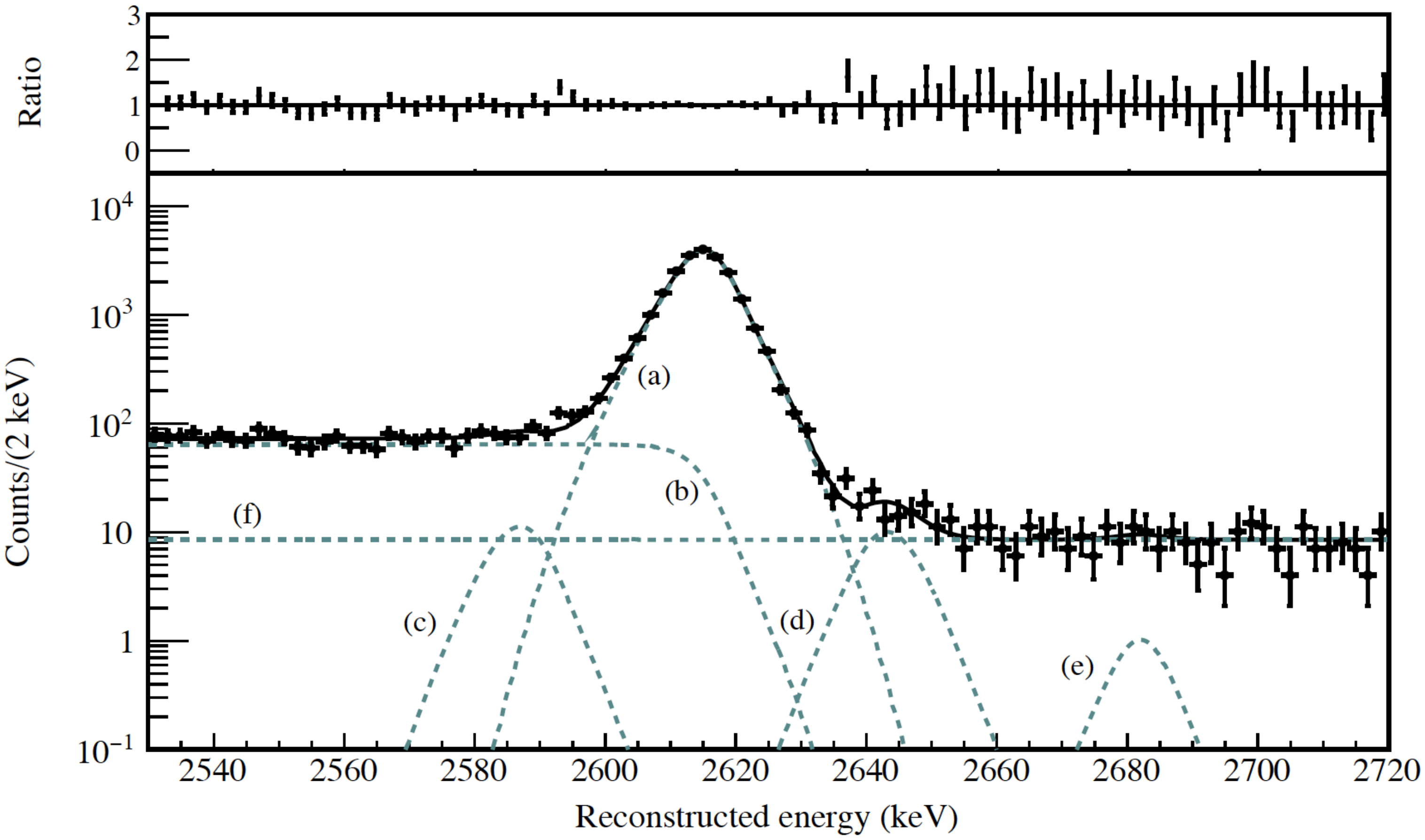
Final Spectrum

Exposure: 2039.0 kg yr TeO_2, 567.0 kg yr ^{130}Te
Total Analysis Cut Efficiency is 93.4(18)%



From Science Paper

Detector Response, Lineshape

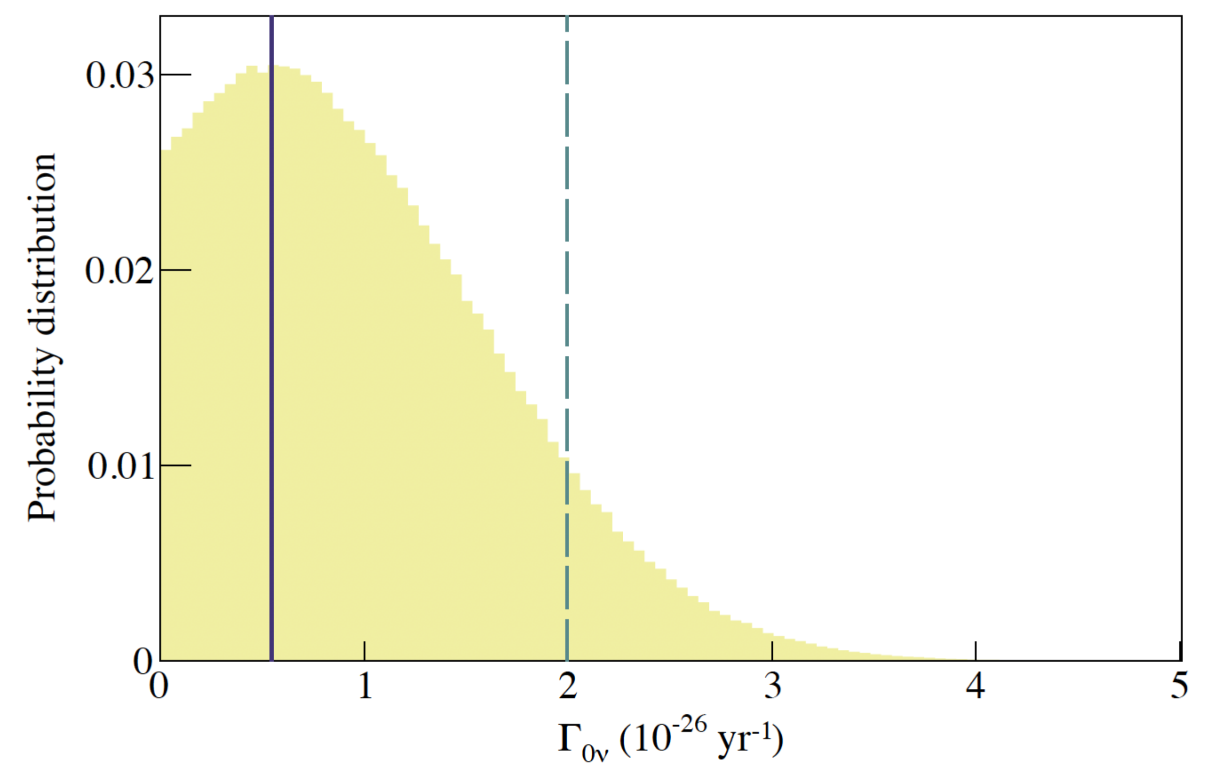


From Science Paper

Fitting Procedure

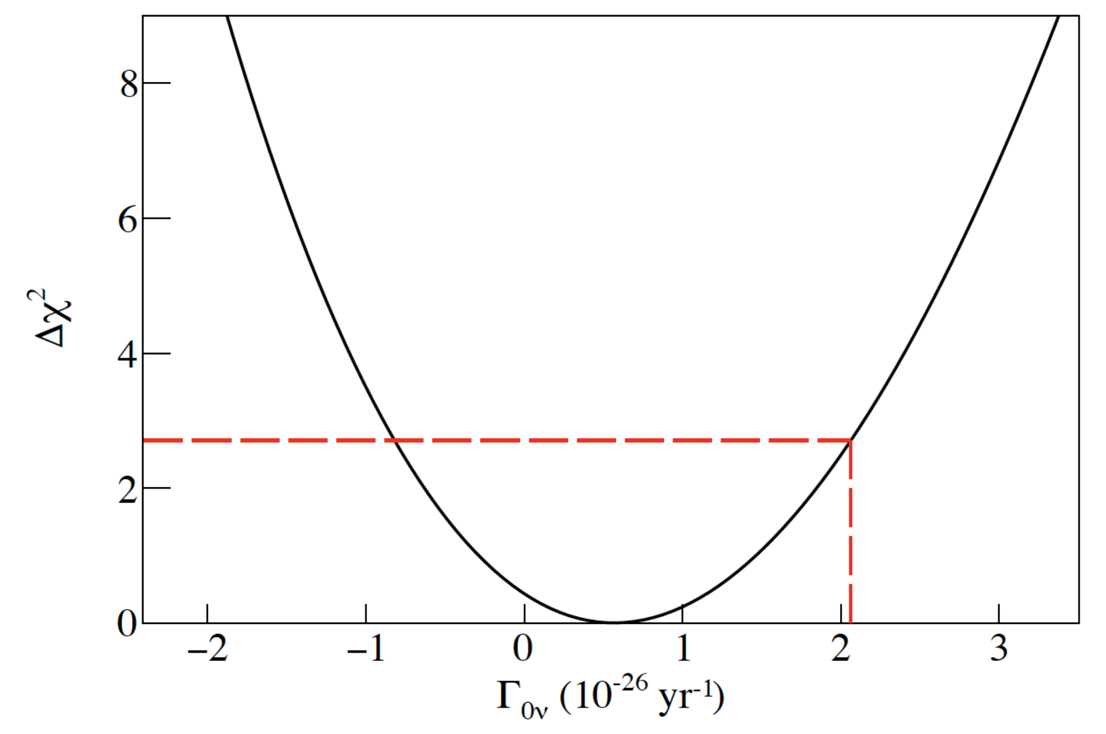
Bayesian Analysis

$$T^{0\nu} > 3.8 \cdot 10^{25}\text{yr (90\% C.I.)}$$

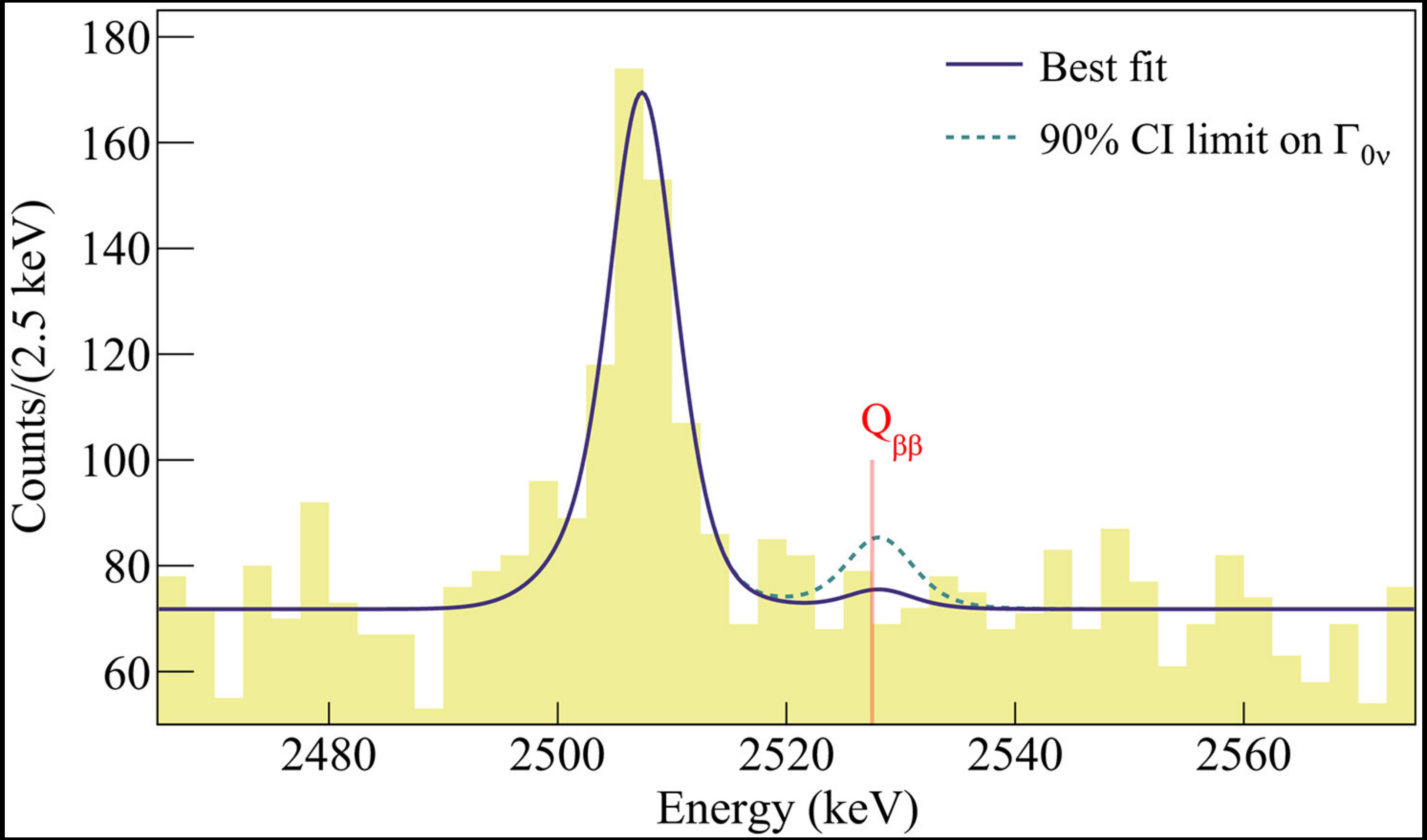


Frequentist Analysis

$$T^{0\nu} > 3.7 \cdot 10^{25}\text{yr (90\% C.L.)}$$



Fit Result 2TY

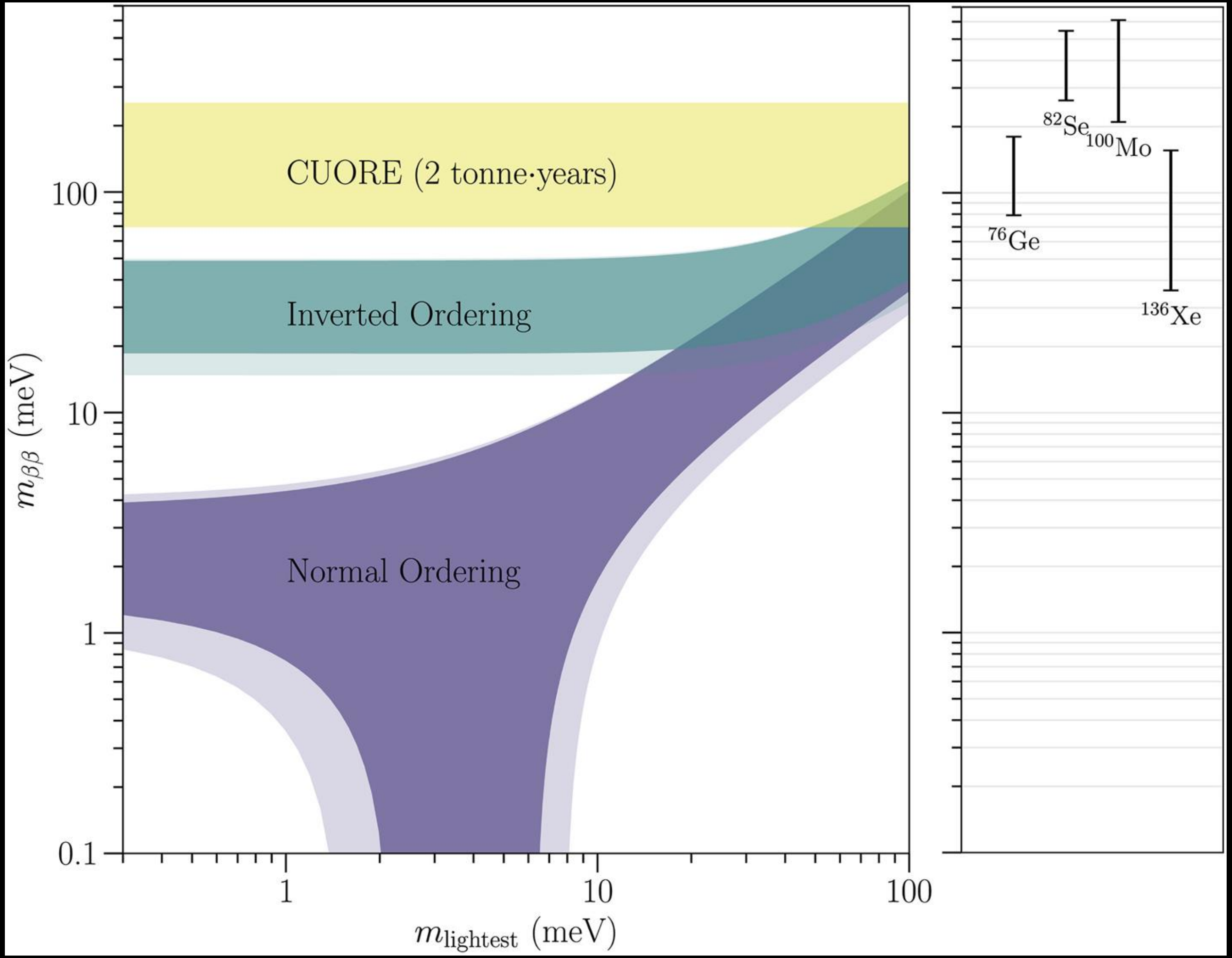


Science Paper

$M_{\beta\beta}$ Limit

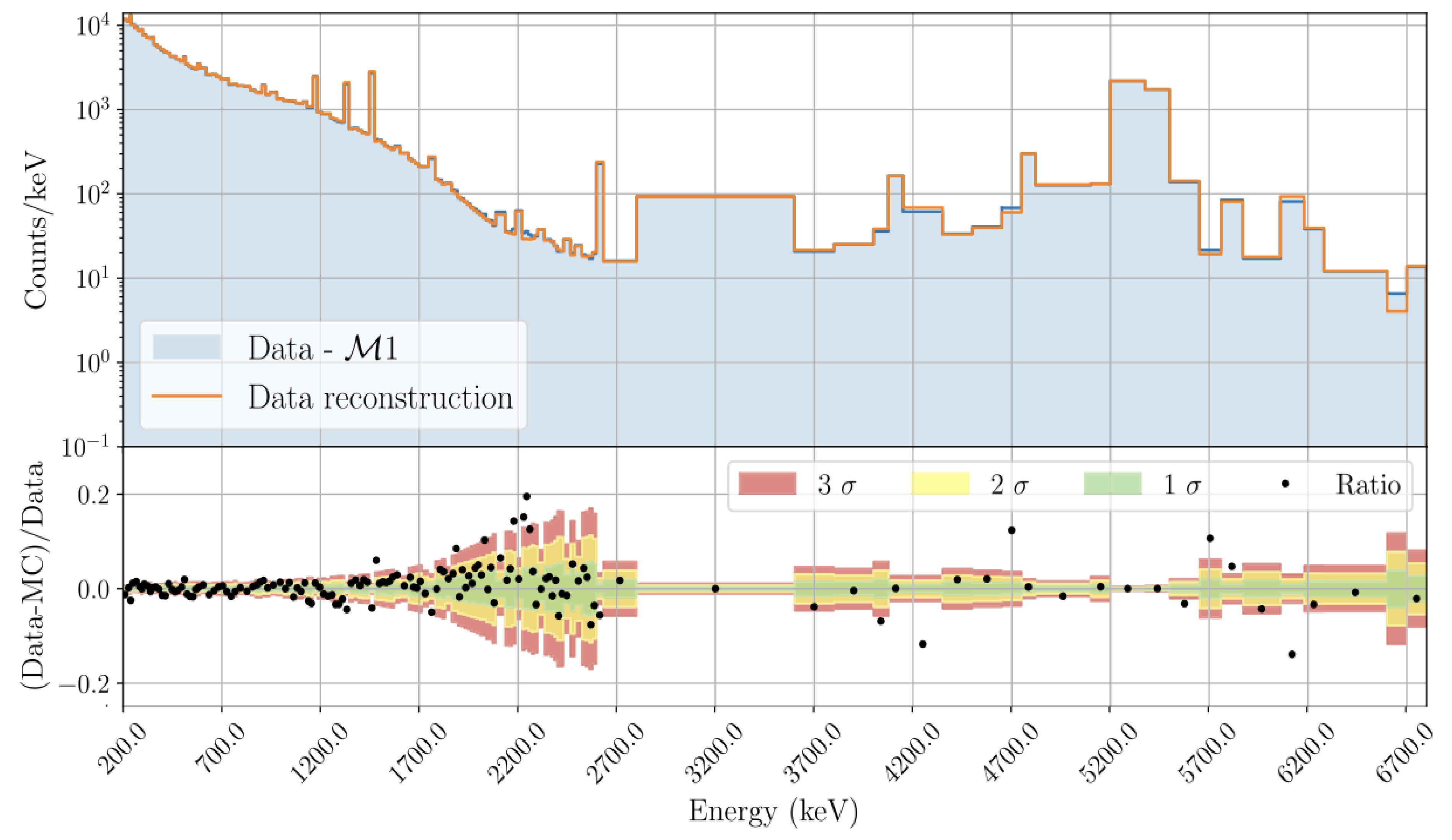
$$1/\tau = G^{0\nu} g_A^4 |M^{0\nu}| m_{\beta\beta}^2$$

Contours illustrating the 3sigma regions given
By neutrino oscillation measurements

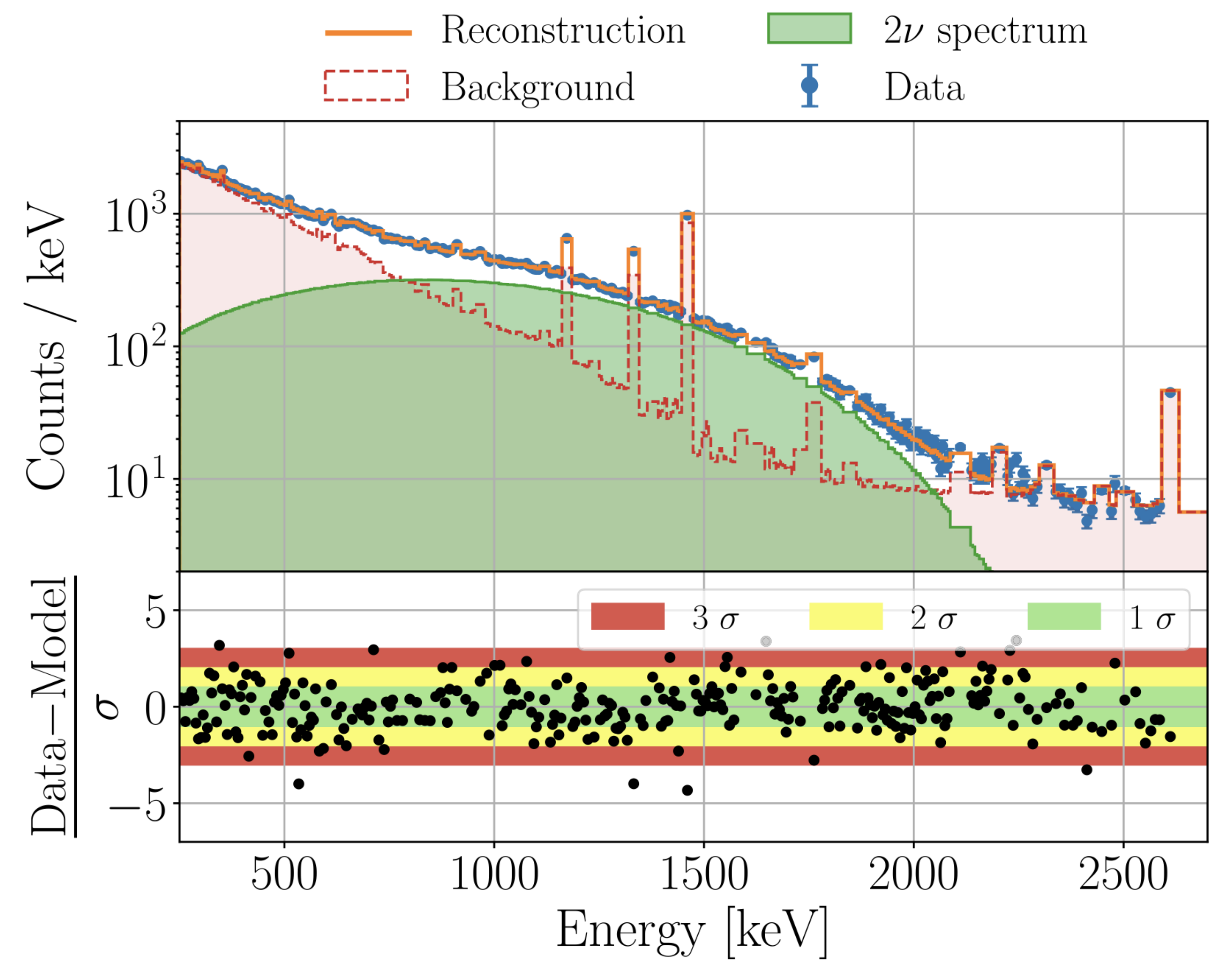


Science Paper

Background Model



2νββ Rate



$$T^{2\nu}_{1/2} = 8.76^{+0.09}_{-0.07}(\text{stat})^{+0.14}_{-0.17}(\text{sys}) \times 10^{20}\text{yr}$$

CUPID

CUORE Upgrade with Particle IDentification

JOHNS HOPKINS UNIVERSITY

VirginiaTech
Invent the Future®

UNIVERSITÉ DE LYON

IJCLab
Irène Joliot-Curie

BEIJING NORMAL UNIVERSITY 1902

cnrs
IN2P3

LEARN BY DOING
CAL POLY

BERKELEY LAB

INFN

NRC KI-ITEP

UNIVERSITA' DEGLI STUDI DI MILANO
BICOCCA

SAPIENZA
UNIVERSITÀ DI ROMA

University of Pittsburgh

cea

Irfu

НАЦІОНАЛЬНА АКАДЕМІЯ НАУК УКРАЇНИ 1918

UGA
Université Grenoble Alpes

Argonne
NATIONAL LABORATORY

Massachusetts Institute of Technology

UNIVERSITY OF SOUTH CAROLINA

université PARIS-SACLAY

IMM
BOLOGNA UNIT

THE UNIVERSITY OF CALIFORNIA 1868

UCLA

SHANGHAI JIAO TONG UNIVERSITY 1896

Yale

NIKOLAEV INSTITUTE OF INORGANIC CHEMISTRY
SIBERIAN BRANCH OF RUSSIAN ACADEMY OF SCIENCES

CAPA
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Northwestern

BOSTON UNIVERSITY

Drexel UNIVERSITY

University of Science and Technology of China 1958

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088

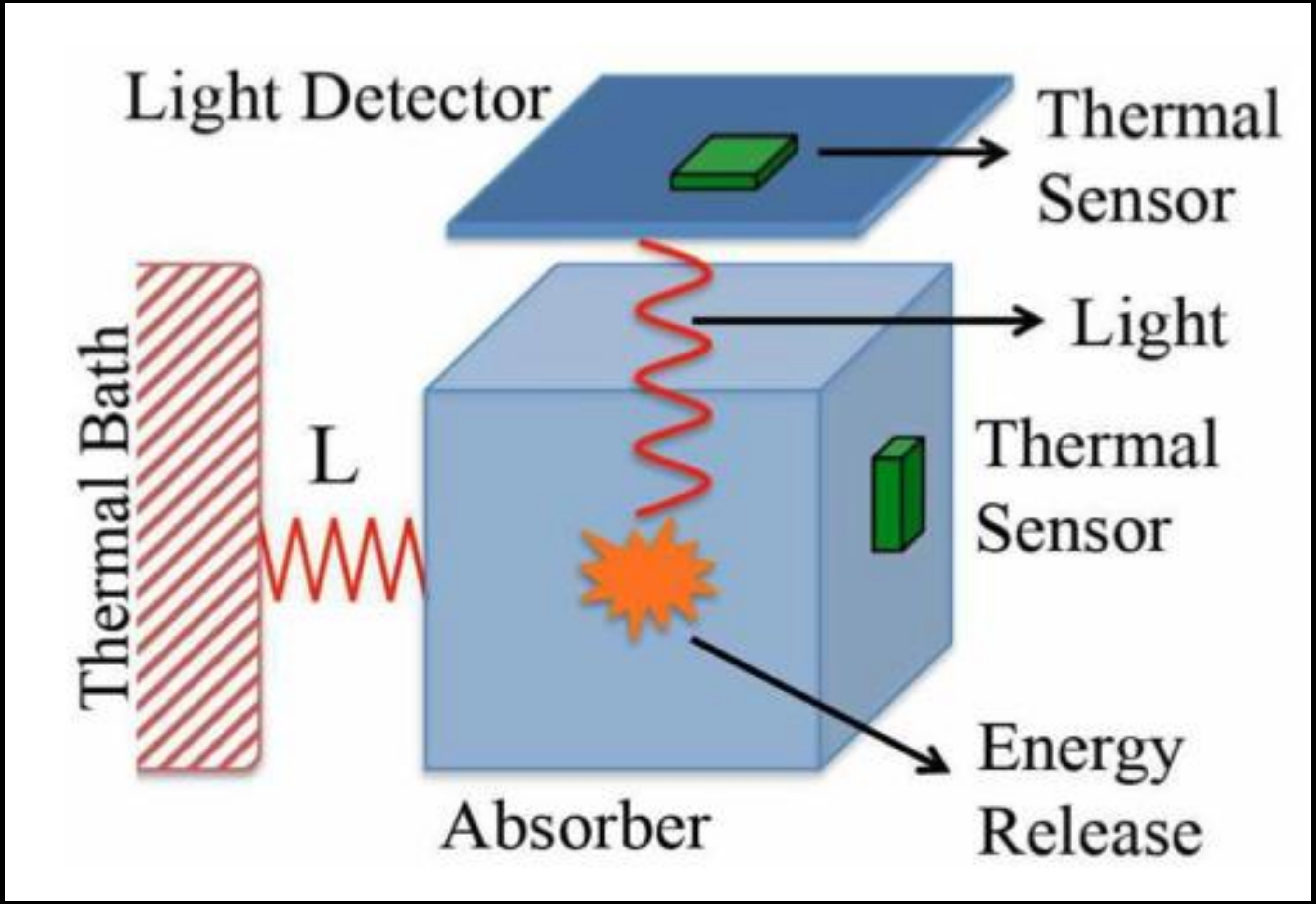
FUDAN UNIVERSITY 1905

araid
FUNDACIÓN AGENCIA ARAGONESA PARA LA INVESTIGACIÓN Y EL DESARROLLO

iP2i
LES 2 INFINIS LYON

G S
S I

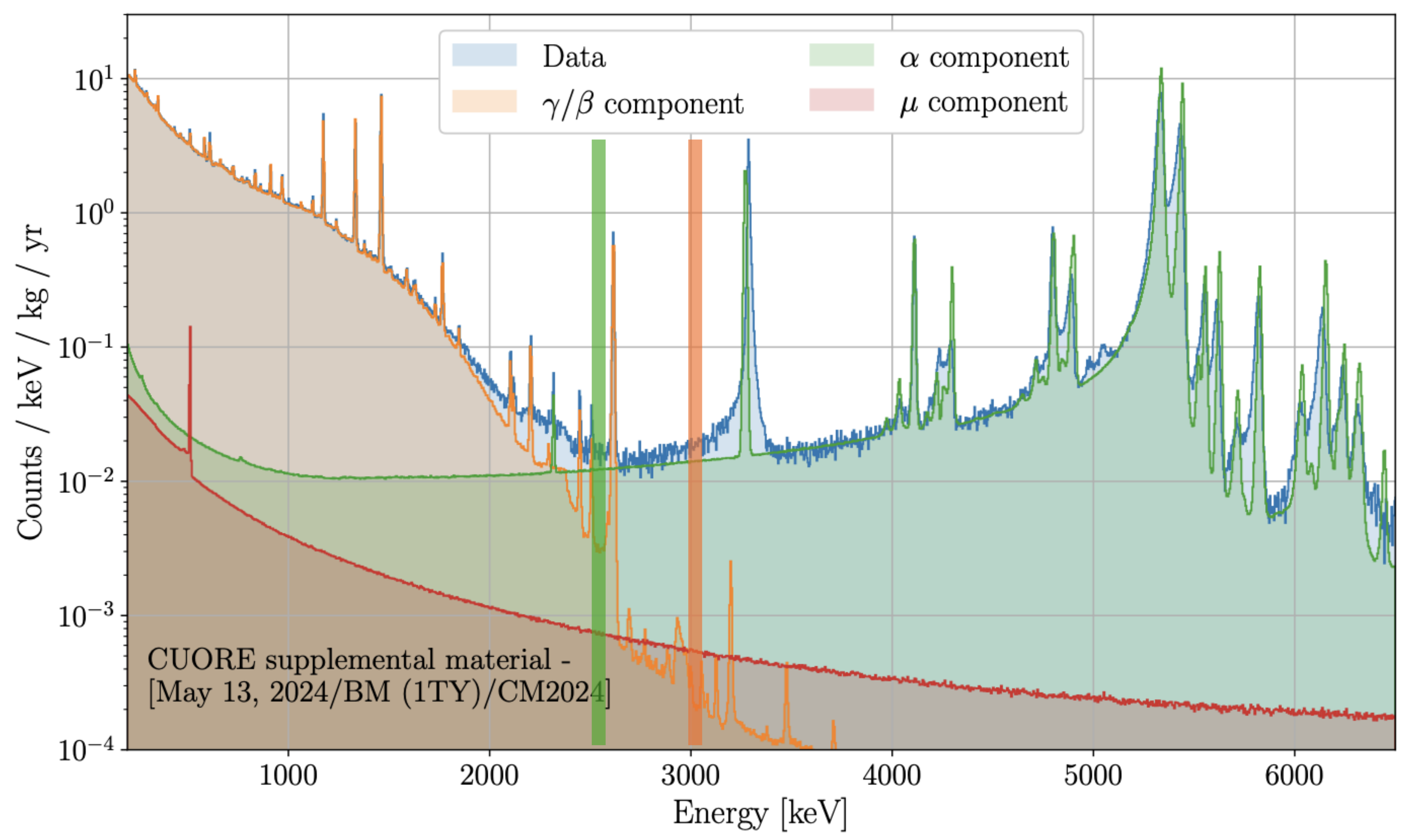
CUPID Concept



Several upgrades made to the CUORE design

Switch from TeO_2 to $L_{i2}MoO_4$

Lessons Learned from CUORE



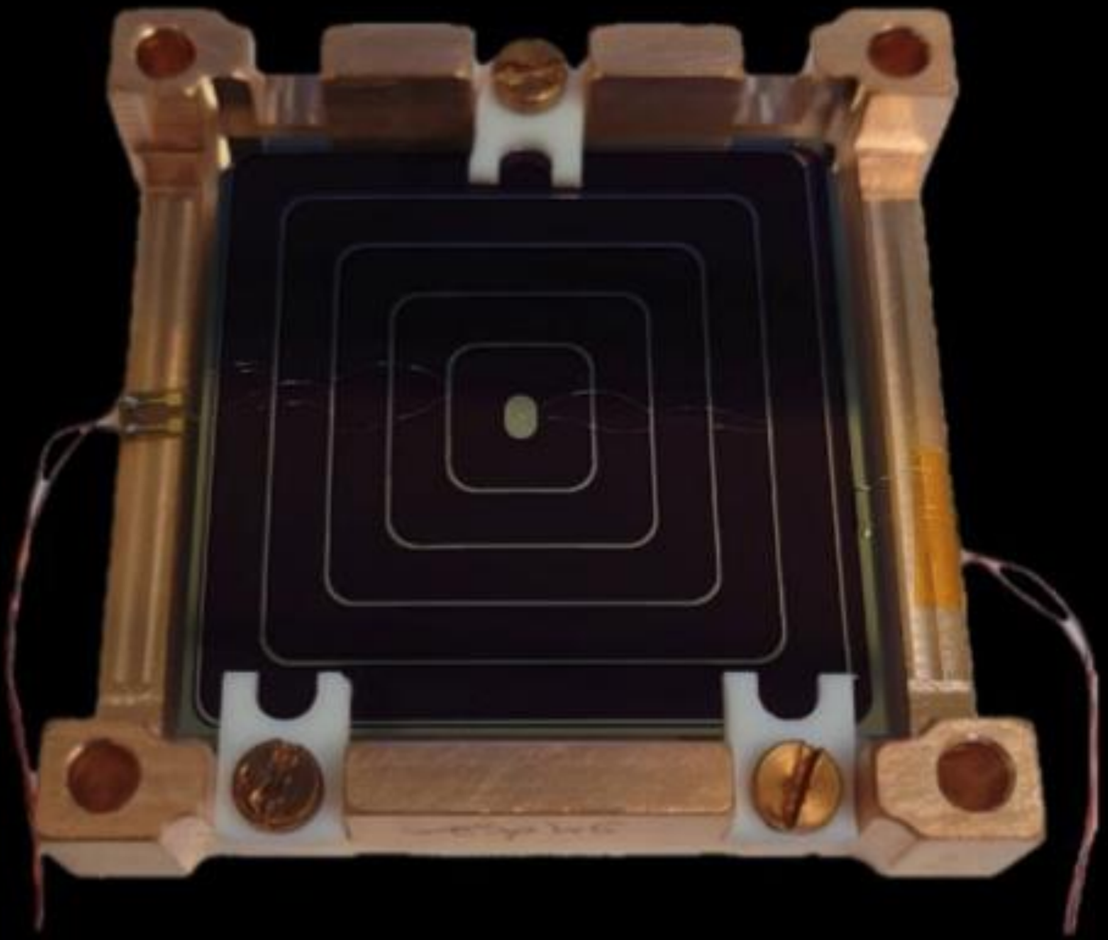
CUORE supplemental material -
[May 13, 2024/BM (1TY)/CM2024]

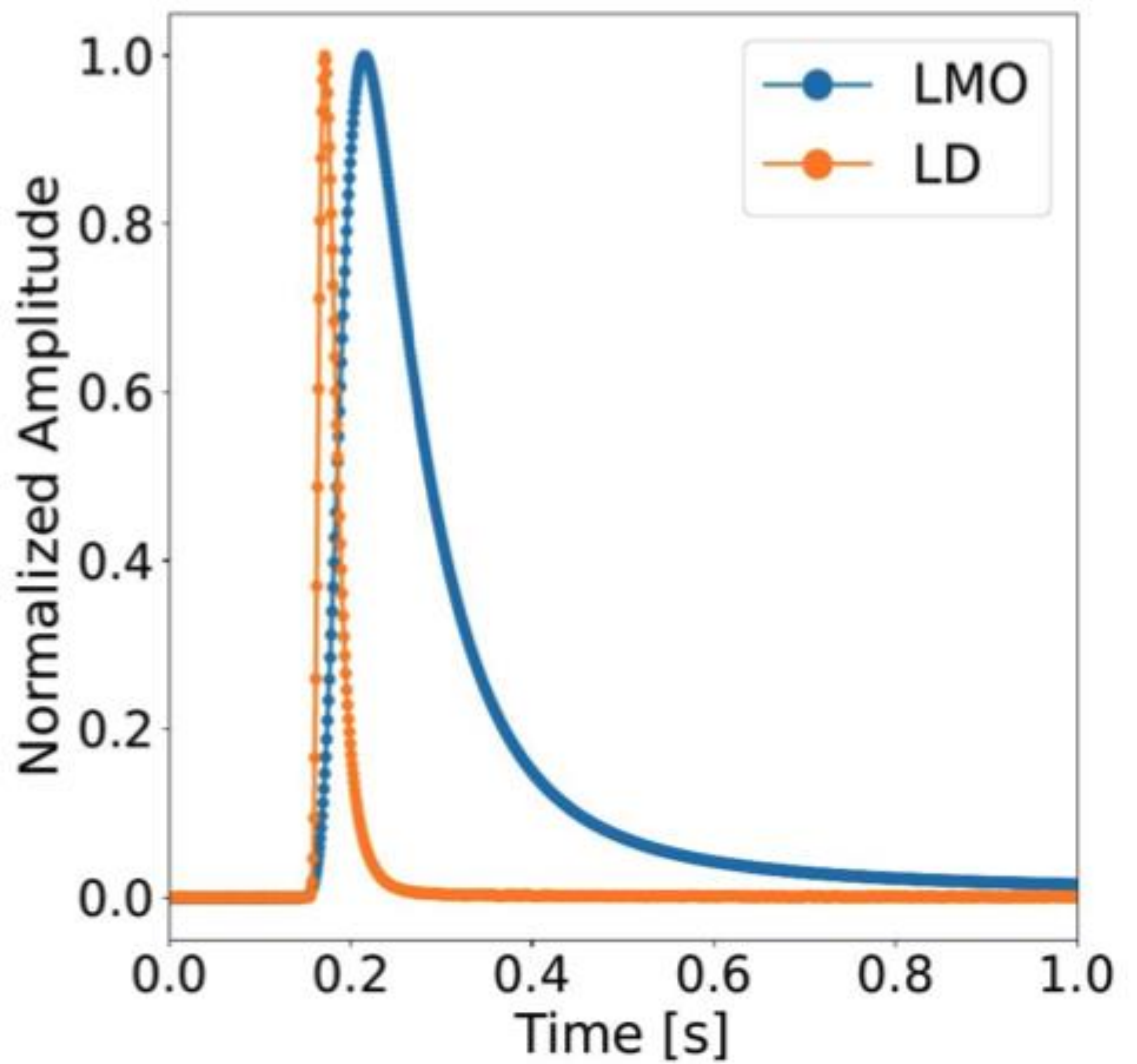
A 99%+ efficient muon veto &
a 98%+ alpha rejection scheme
paves the way to a background rate
Of 10^{-4} counts/kg/keV/year

$Q_{\beta\beta}$ now above the 2.615 keV
Tl-208 line

CUORE background rate is
(1.42+/-0.01)x10^{-2} ckkyr

Upgrades: Light Detectors

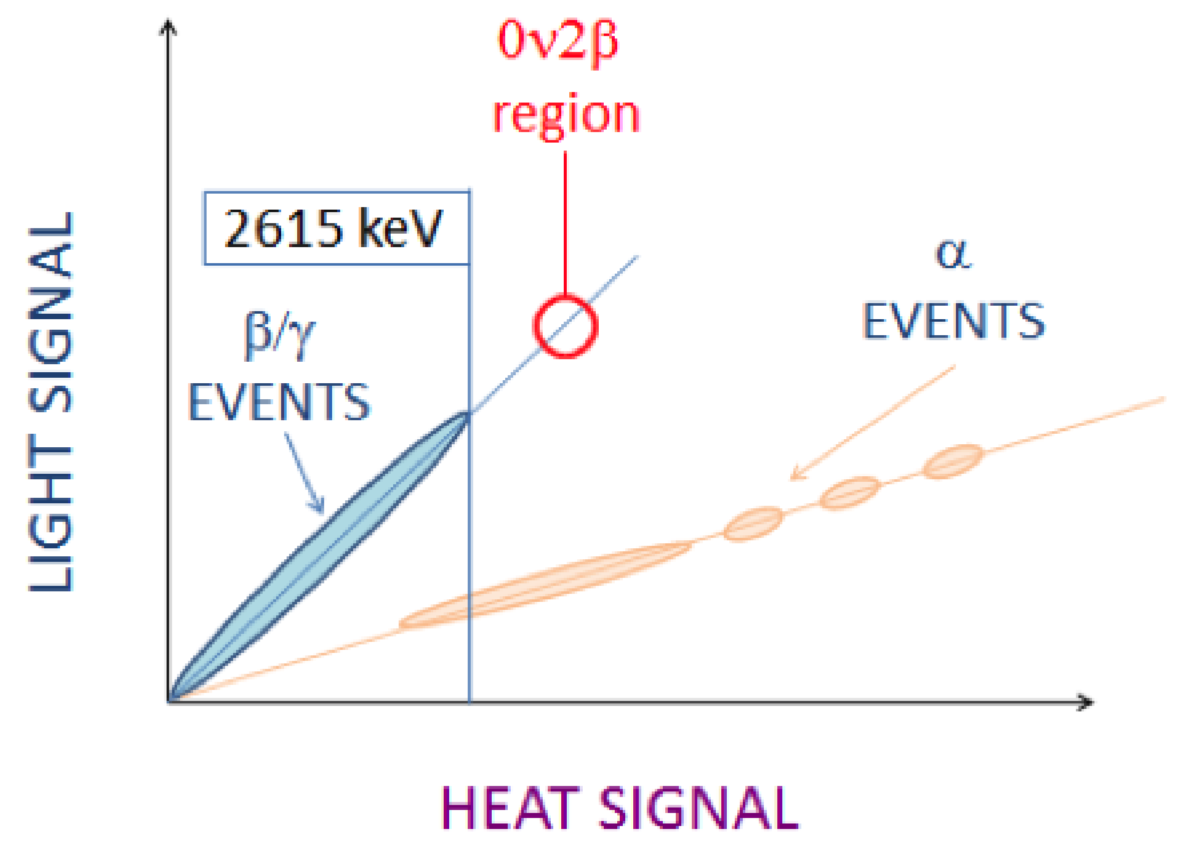




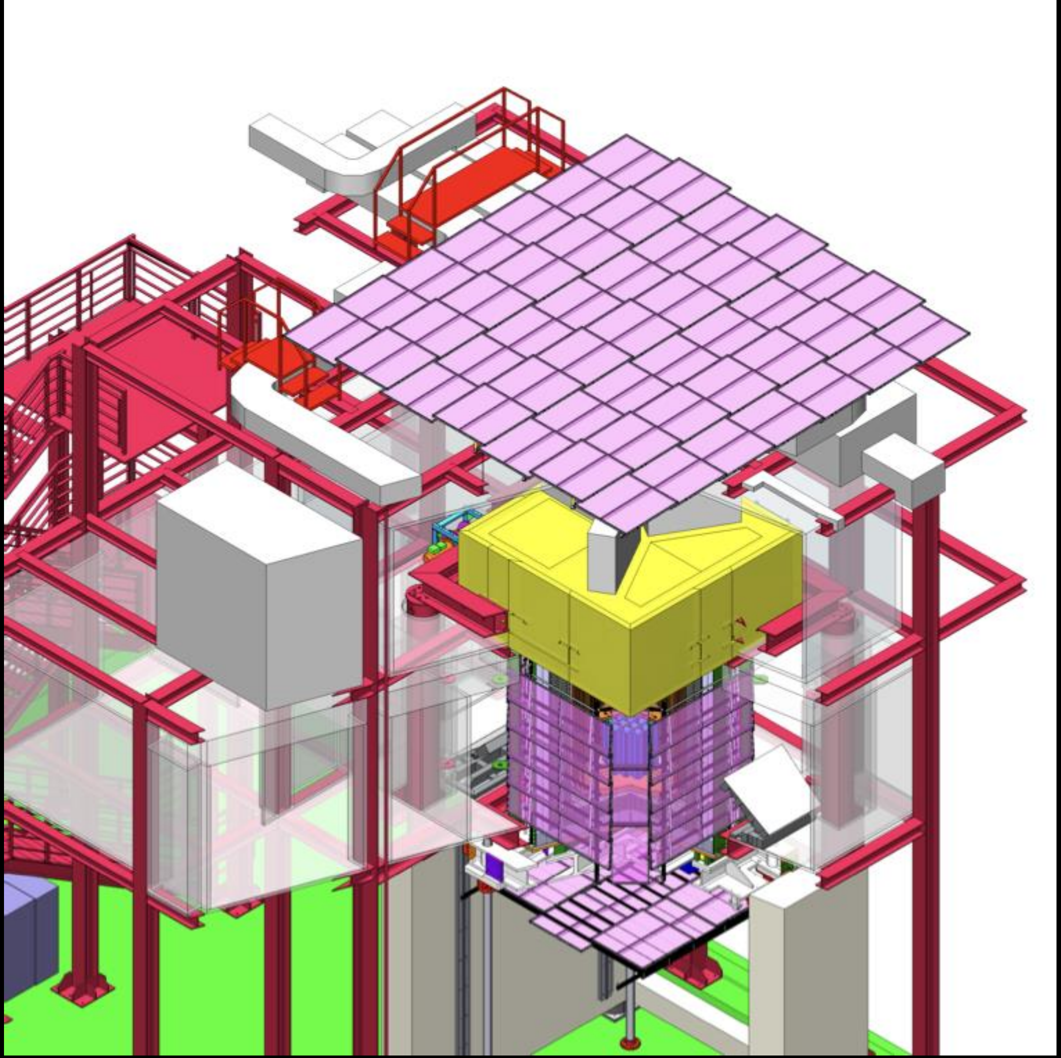
Particle ID

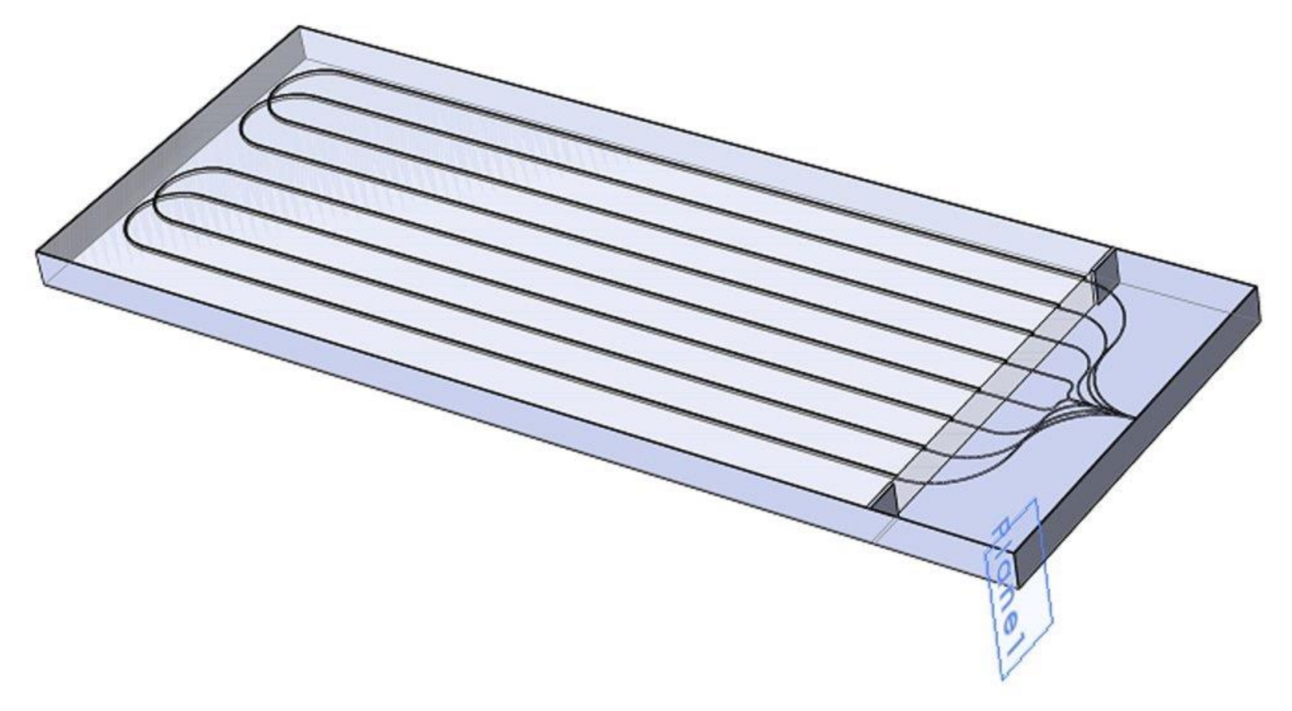
A primary advantage of the detectors is the ability to discriminate alpha events

Nominally achieve 98%+ rejection

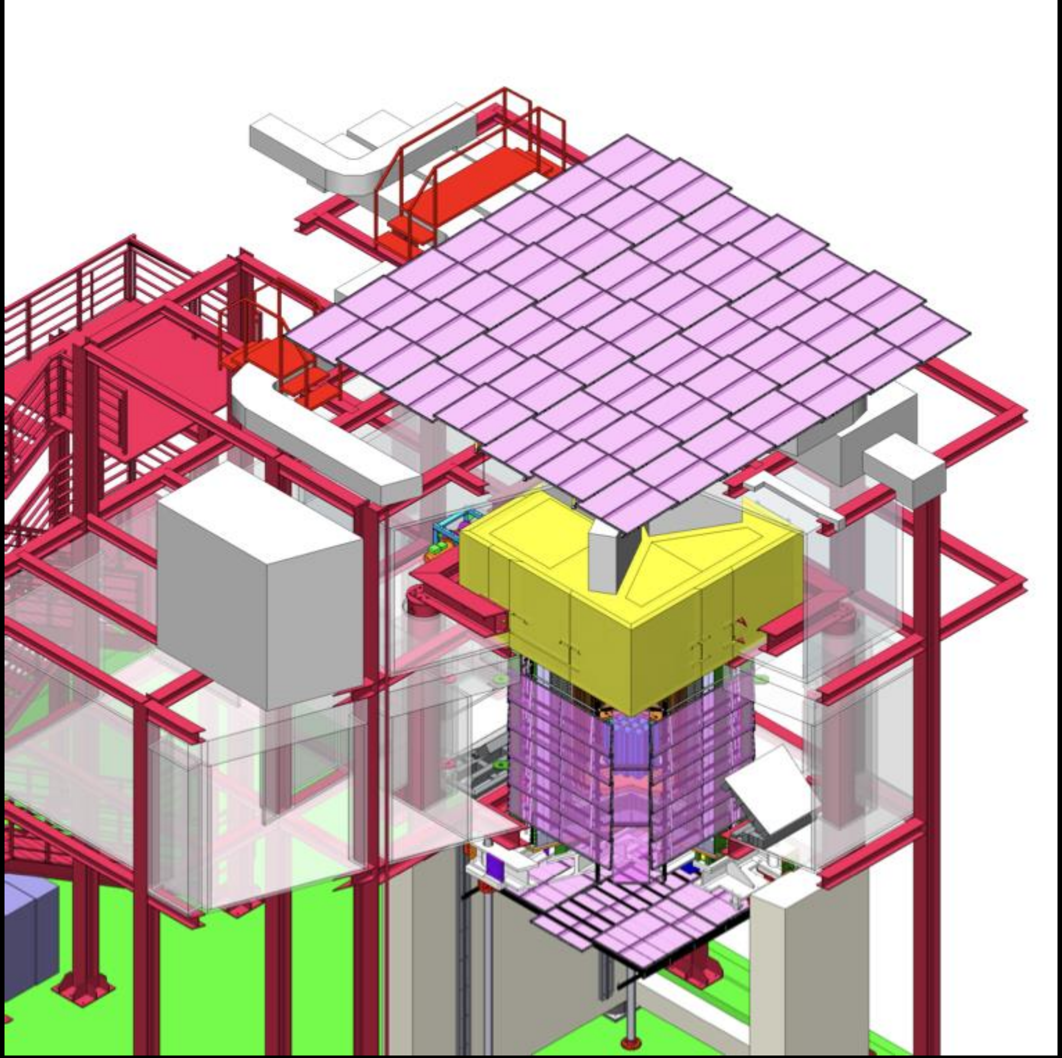


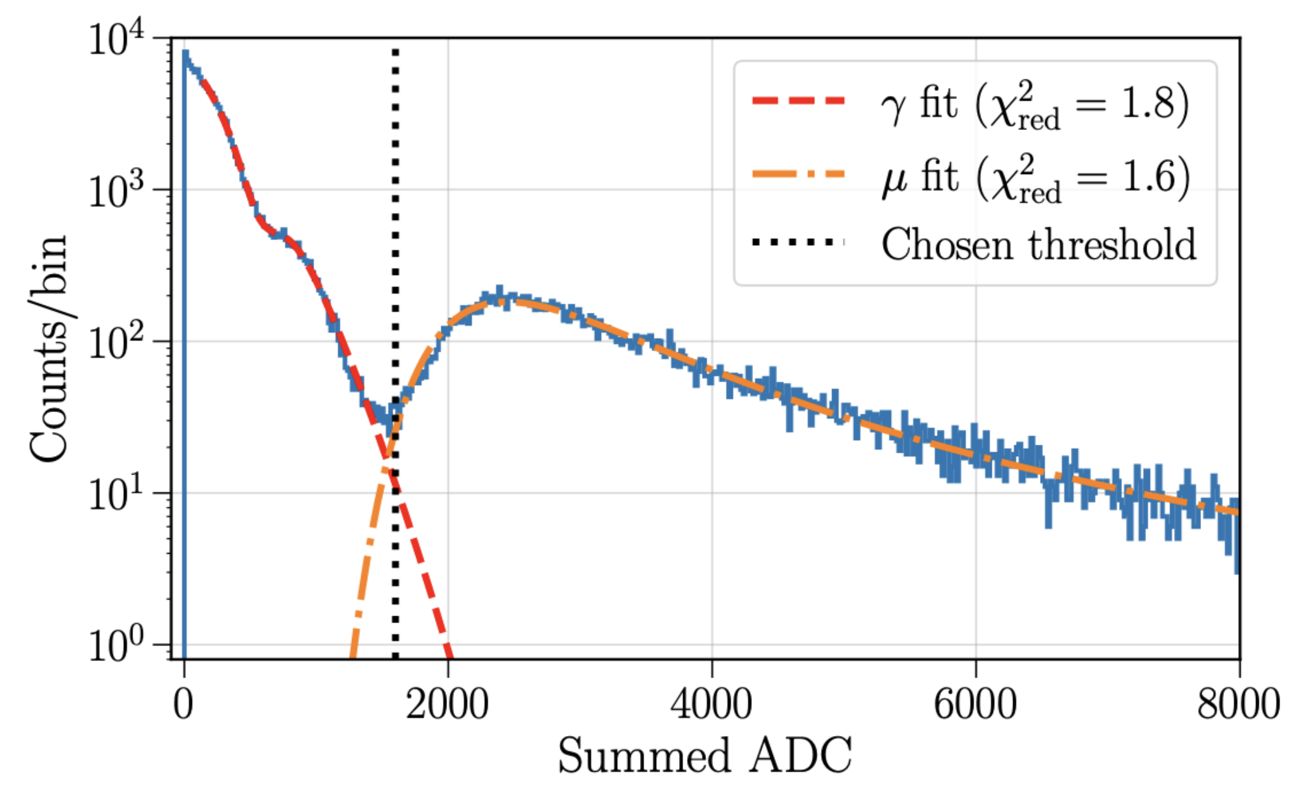
Upgrades: Muon Veto



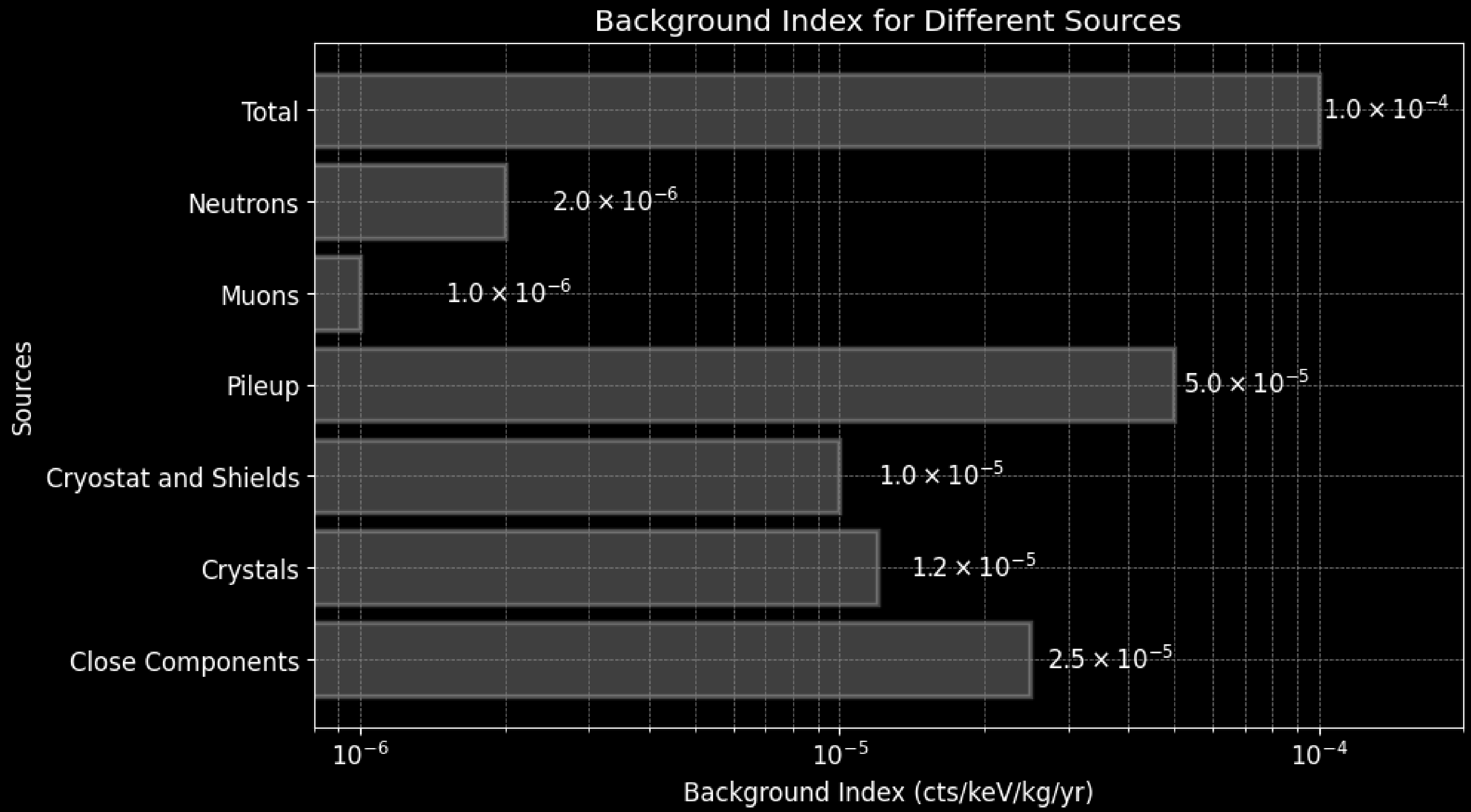


Upgrades: Muon Veto

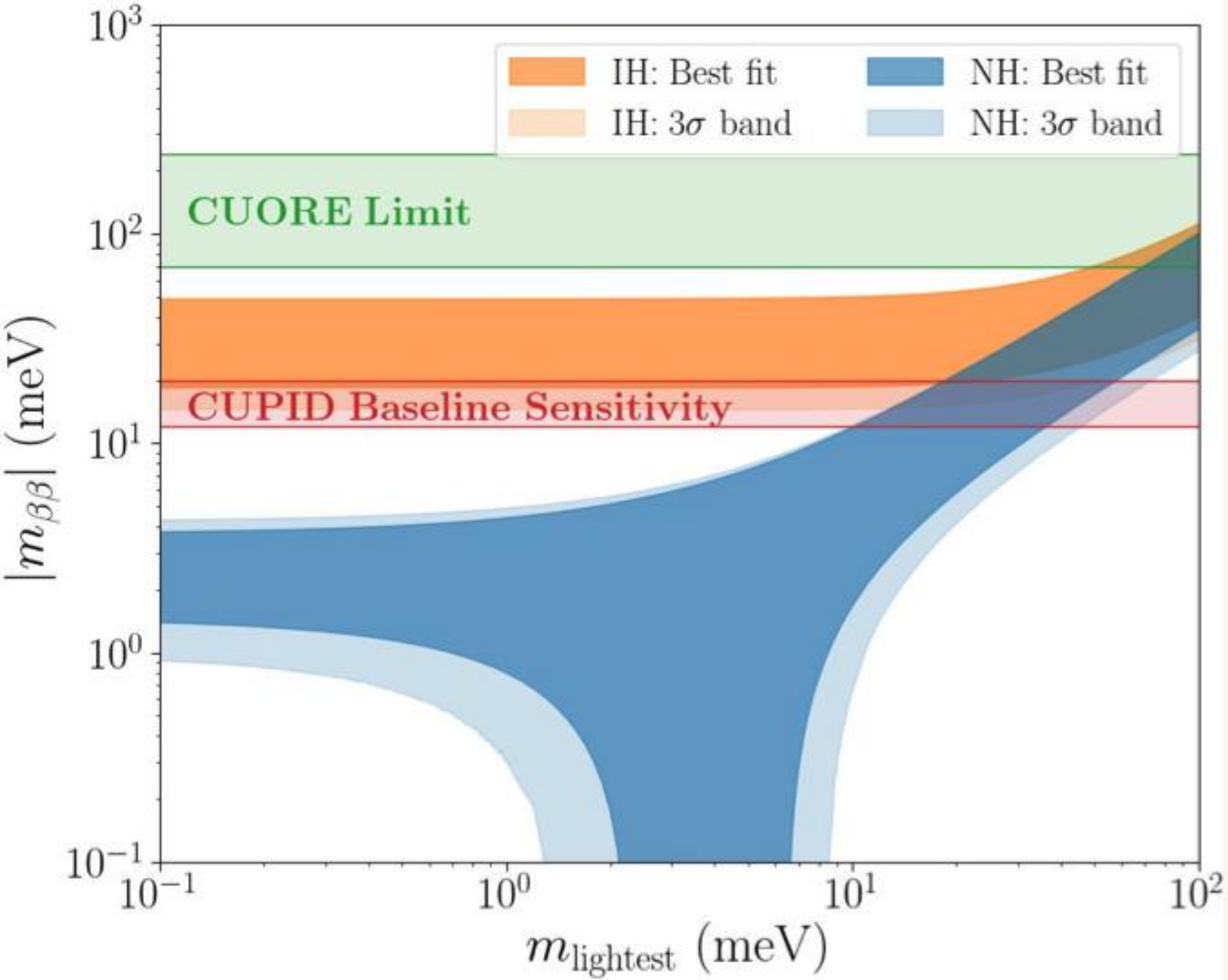




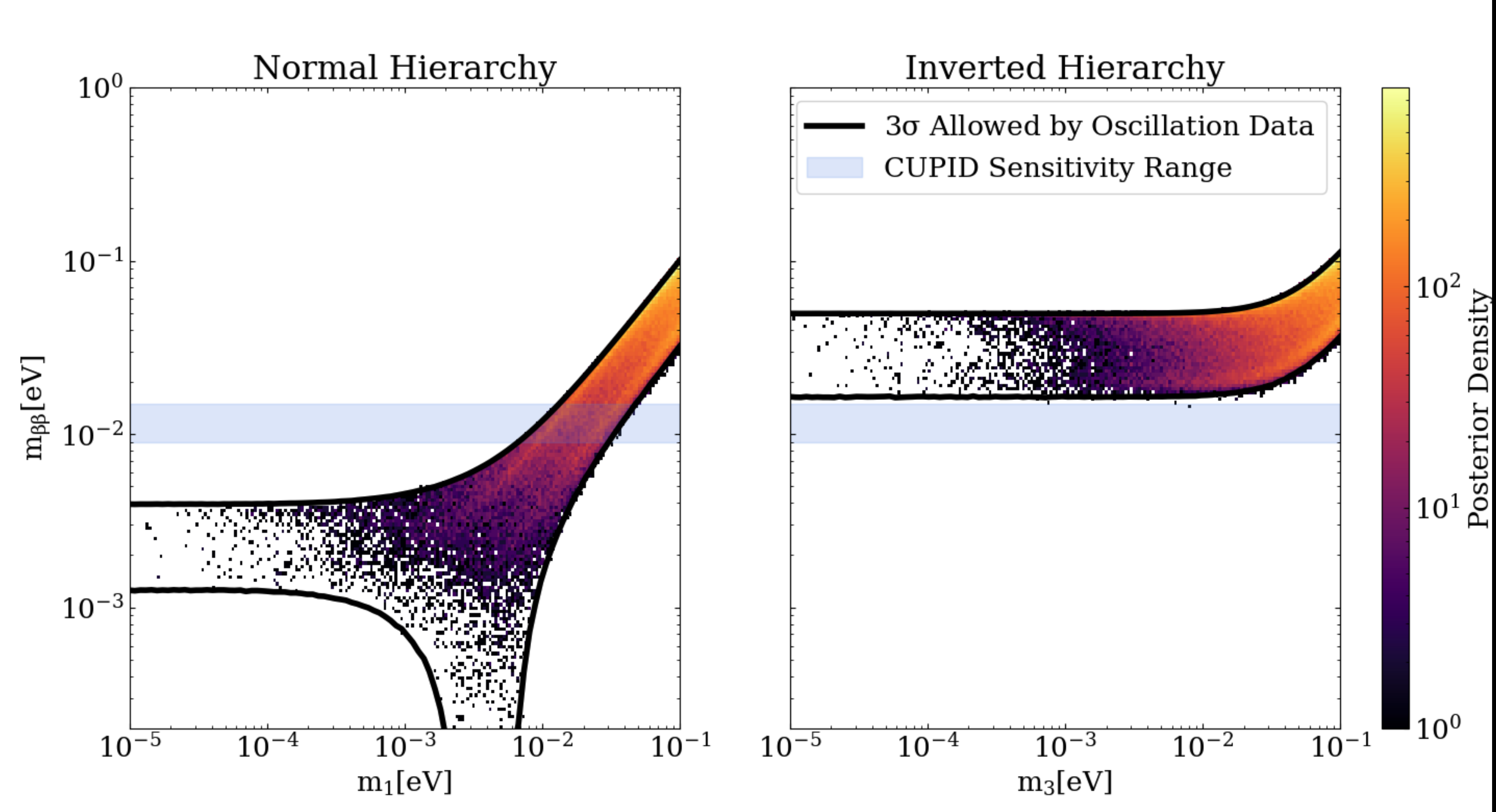
Background Goals



Projected Sensitivity



Projected Sensitivity



Near Future

CUORE will begin to transition to CUPID in a phased approach

2030: CUPID Stage-I: 1/3 of the crystals & 3 year data-taking

2034: CUPID full array: Add the remaining 2/3 of the crystals & full data-taking