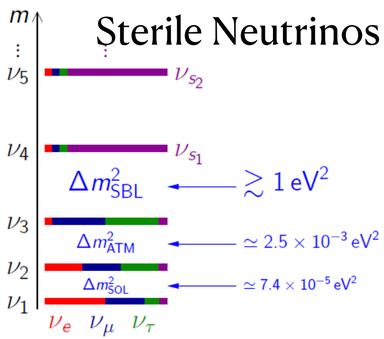
Latest Results from the CUORE Experiment

QNP 2022

Samantha Pagan on behalf of the CUORE Collaboration

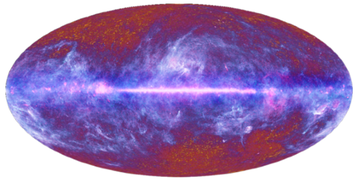
Unanswered questions about neutrinos

of neutrinos species



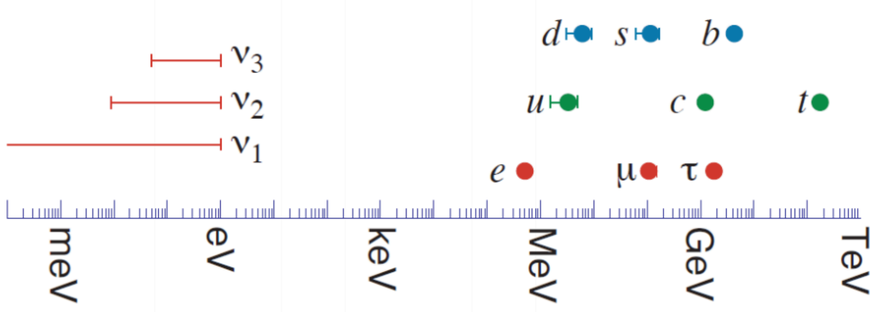
https://www.nevis.columbia.edu/daedalus/motiv/sterile.html

Cosmological Models



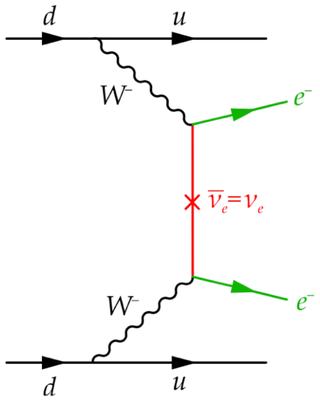
https://plancksatellite.org.uk/results/first-full-sky-image/

Neutrino Mass Scale



2013 Snowmass Neutrino report: https://arxiv.org/pdf/1310.4340.pdf

Majorana or Dirac

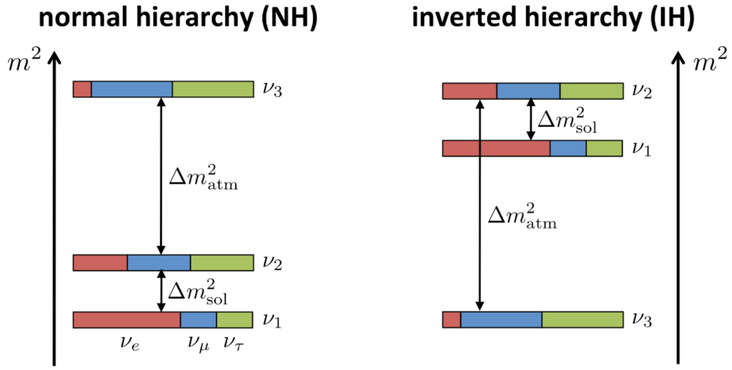


Neutrinoless Double Beta Decay

Could explain matter anti matter asymmetry

https://cuore.lngs.infn.it/en/about/physics

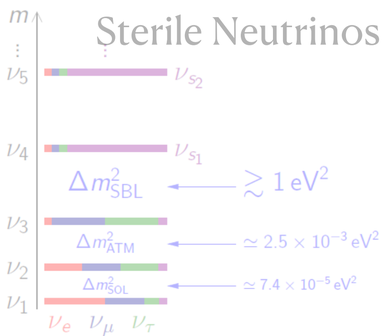
Mass Hierarchy



Credit: JUNO Collaboration / JGU-Mainz

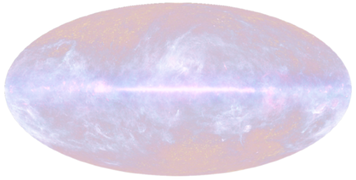
Unsolved questions about neutrinos

of neutrinos species



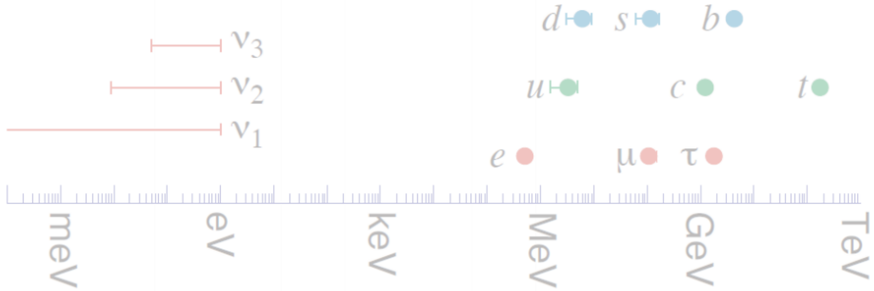
https://www.nevis.columbia.edu/daedalus/motiv/sterile.html

Cosmological Models



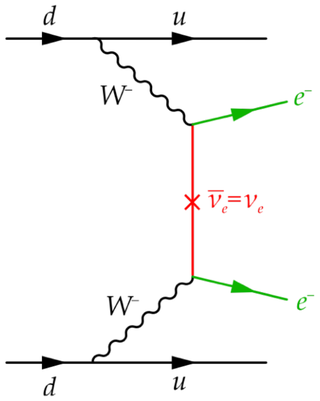
https://plancksatellite.org.uk/results/first-full-sky-image/

Neutrino Mass Scale



2013 Snowmass Neutrino report: https://arxiv.org/pdf/1310.4340.pdf

Majorana or Dirac

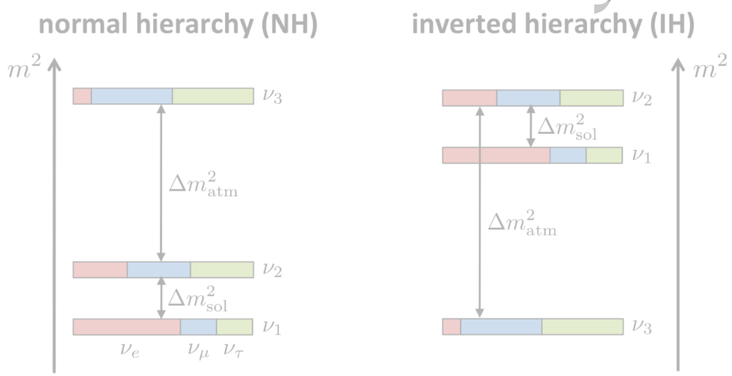


Neutrinoless Double Beta Decay

Could explain matter anti matter asymmetry

https://cuore.lngs.infn.it/en/about/physics

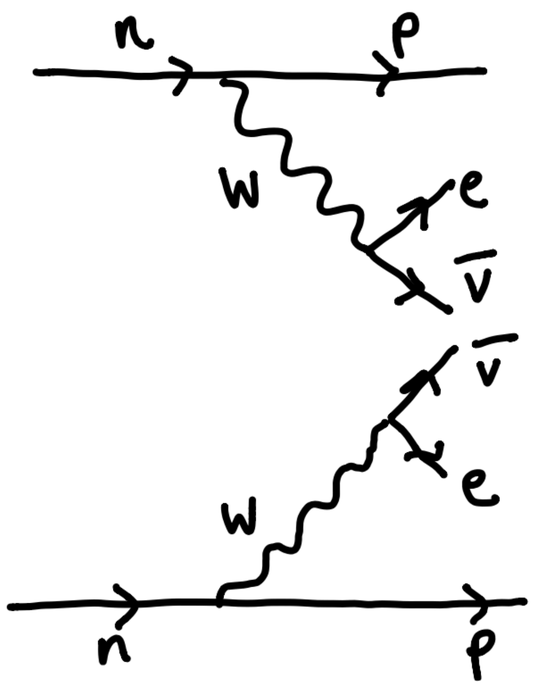
Mass Hierarchy



Credit: JUNO Collaboration / JGU-Mainz

Double Beta Decay (2νββ)

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$



Standard model process

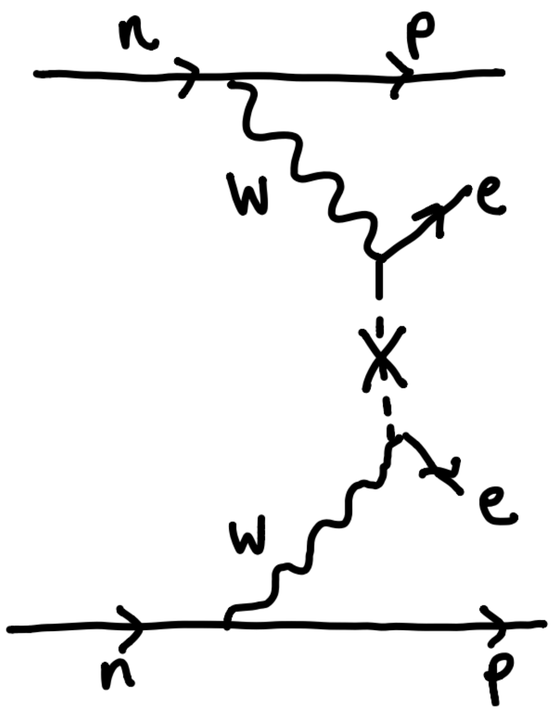
Precise measurement and spectral shape inform nuclear models

Example Isotopes: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{128}Te, ^{130}Te, ^{136}Xe (even mass number)

Measured Half-life: **~10^{17}-10^{22}** yrs

Neutrinoless Double Beta Decay(0νββ)

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + \cancel{2\bar{\nu}_e}$$



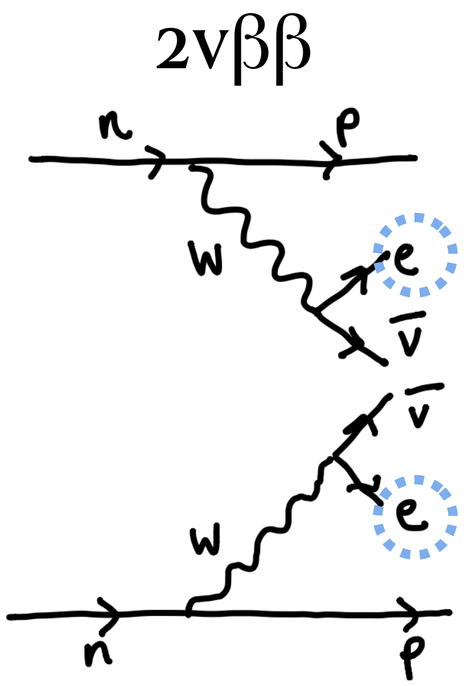
Violates the conservation of total lepton number, Beyond the SM process

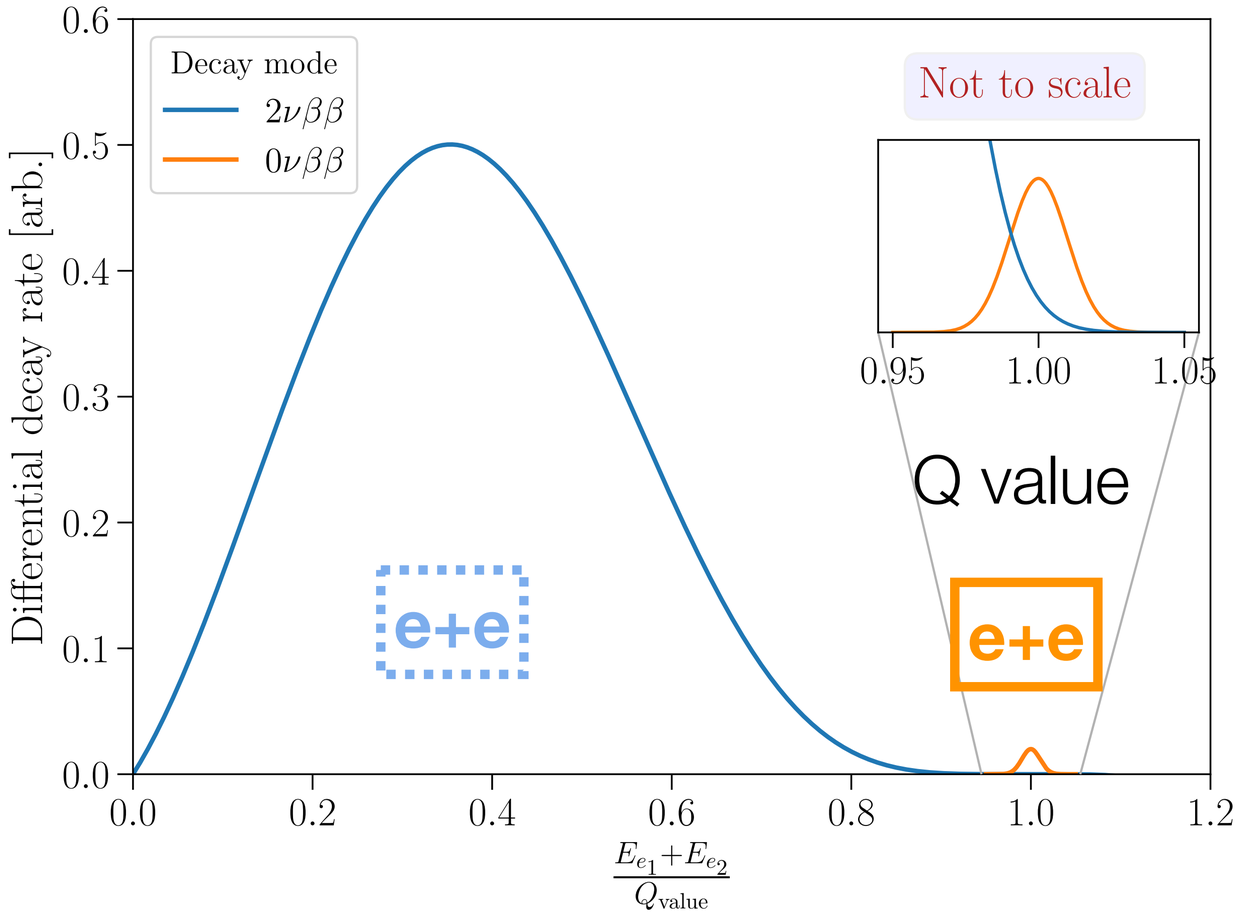
Implies a Majorana neutrino

Example Isotopes: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe

Half life limits: ~**10^{25}-10^{26}** years

Neutrinoless Double Beta Decay: Signal





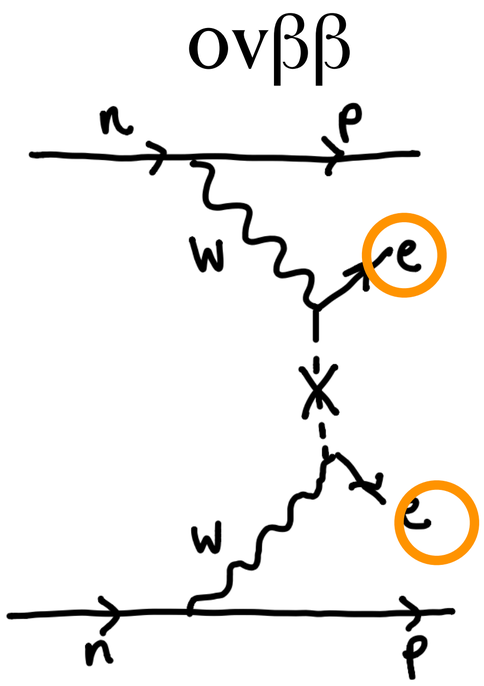


Image Credit: J. Torres

0νββ Half Life

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot \frac{|<m_{\beta\beta}>|^2}{m_e}$$

Phase space factor

Nuclear Matrix element

Effective Majorana mass

$$m^2_{\beta\beta} = |\sum_i U^2_{ei} m_{\nu_i}|^2$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

https://www.particlebites.com/?m=201609

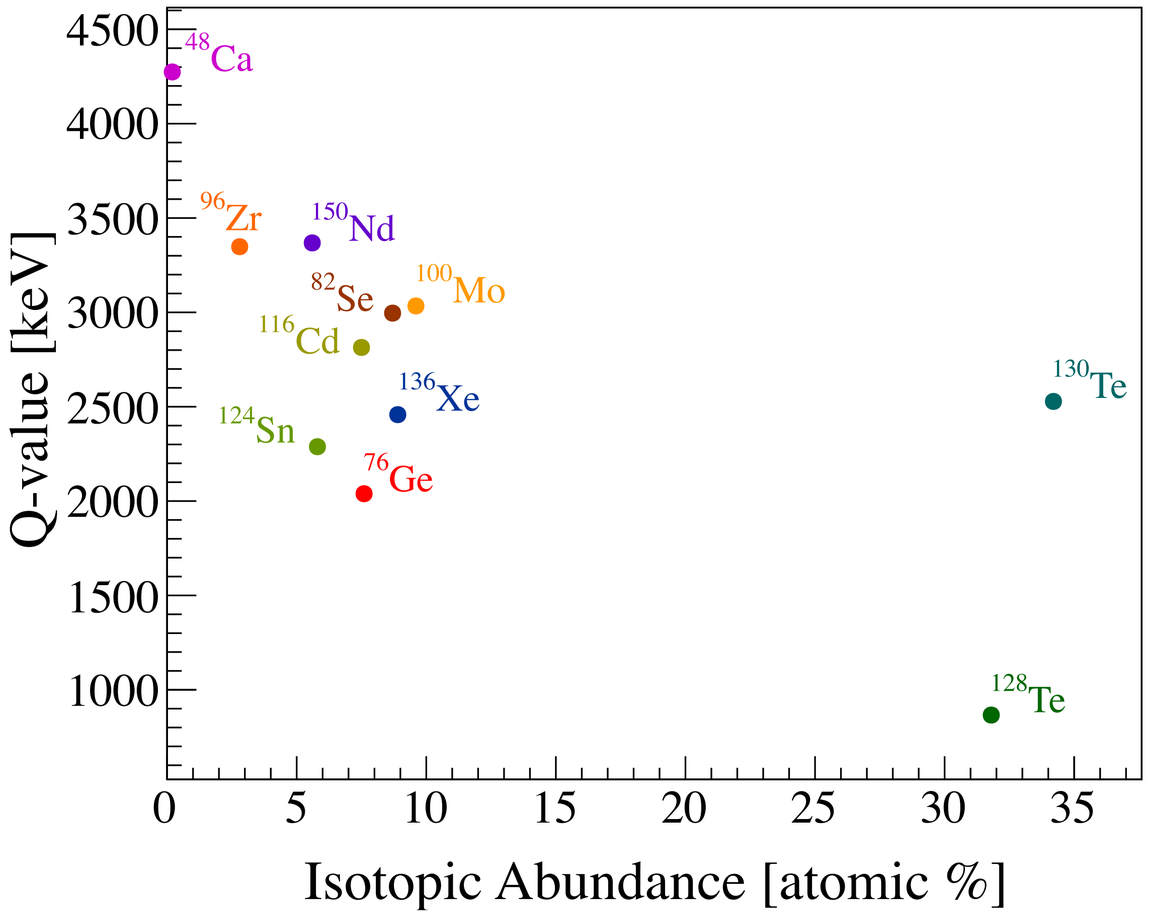
ββ Isotopes

Experiments using various isotopes:
^{76}Ge, ^{130}Te, ^{136}Xe, ^{82}Se, ^{100}Mo,

Q-value:
Higher is preferable

$$2\nu\beta\beta \text{ background } \propto \frac{1}{Q_{\beta\beta}^5}$$

Isotopic abundance:
Higher is preferable



Zuber, J.Phys.Conf.Ser. 578 (2015) 1, 012007

ββ Isotopes

Experiments using various isotopes:
^{76}Ge, ^{130}Te, ^{136}Xe, ^{82}Se, ^{100}Mo,

Q-value:
Higher is preferable

$$2\nu\beta\beta \text{ background } \propto \frac{1}{Q_{\beta\beta}^5}$$

Isotopic abundance:
Higher is preferable

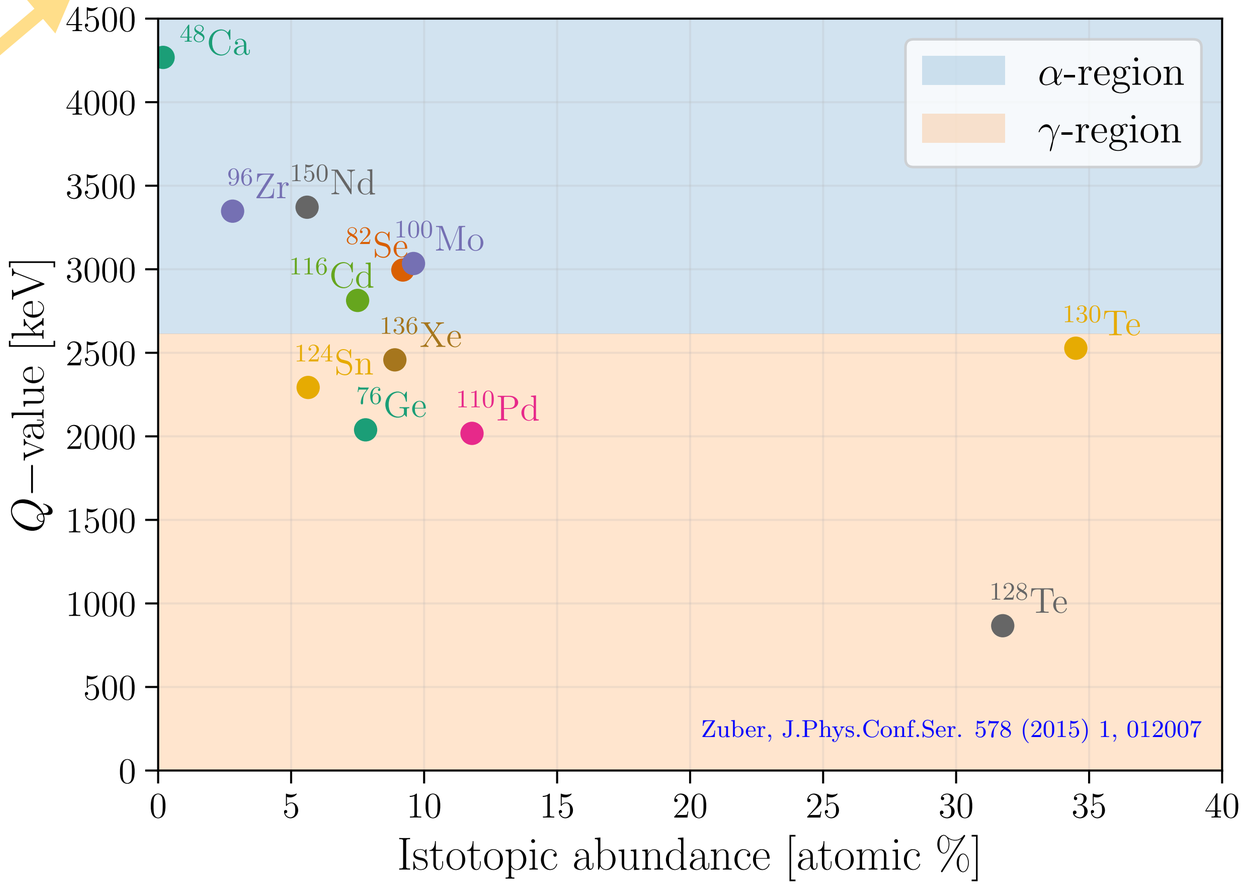


Image credits: J. Torres

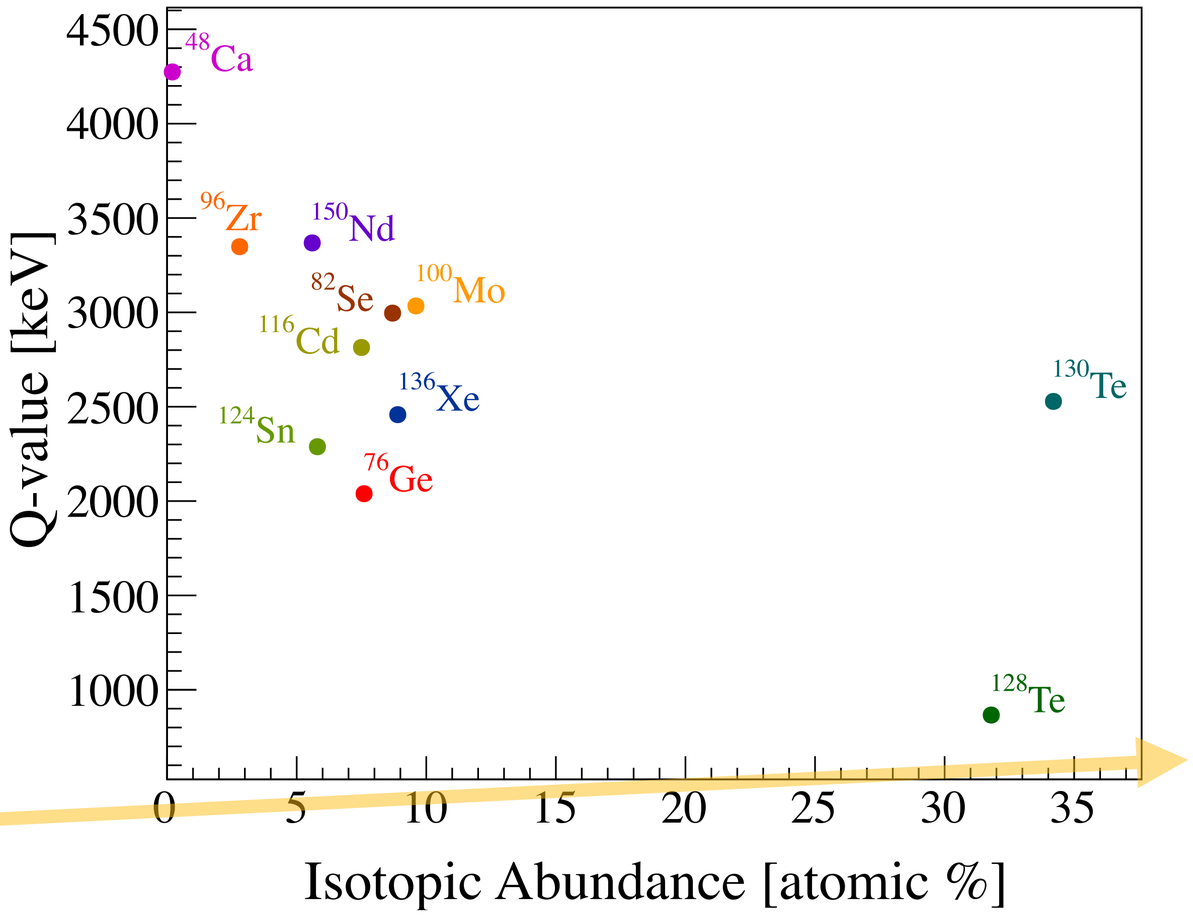
ββ Isotopes

Experiments using various isotopes:
^{76}Ge, ^{130}Te, ^{136}Xe, ^{82}Se, ^{100}Mo,

Q-value:
Higher is preferable

$$2\nu\beta\beta \text{ background } \propto \frac{1}{Q_{\beta\beta}^5}$$

Isotopic abundance:
Higher is preferable



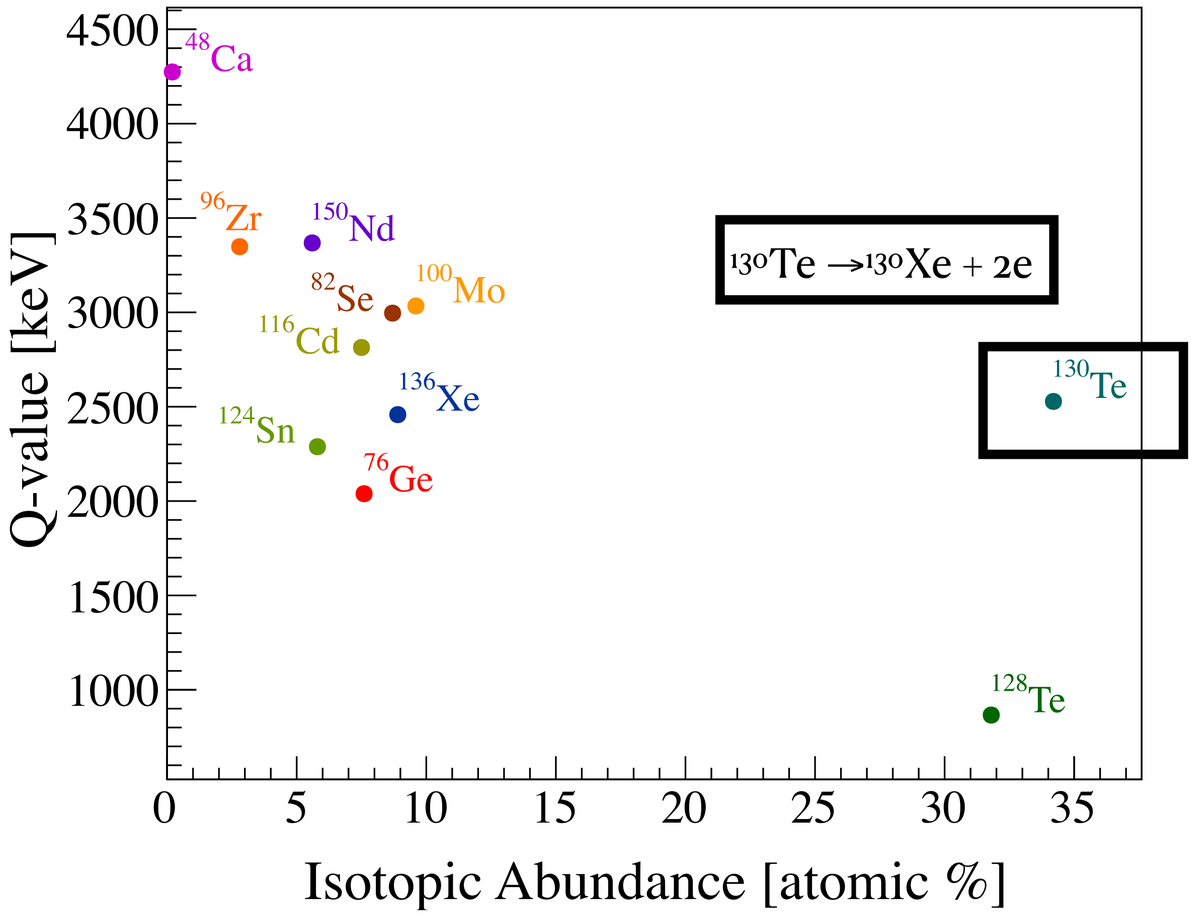
Zuber, J.Phys.Conf.Ser. 578 (2015) 1, 012007

ββ Isotopes

^{130}Te

Q-value: 2528 keV

High isotopic abundance of 33.8%
can use natural crystals



Zuber, J.Phys.Conf.Ser. 578 (2015) 1, 012007

CUORE Collaboration and Acknowledgments

We would like to acknowledge support from the U.S. Department of Energy Office of Science contract No. DE-SC0019368 and DE-SC0012654 and the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1752134.

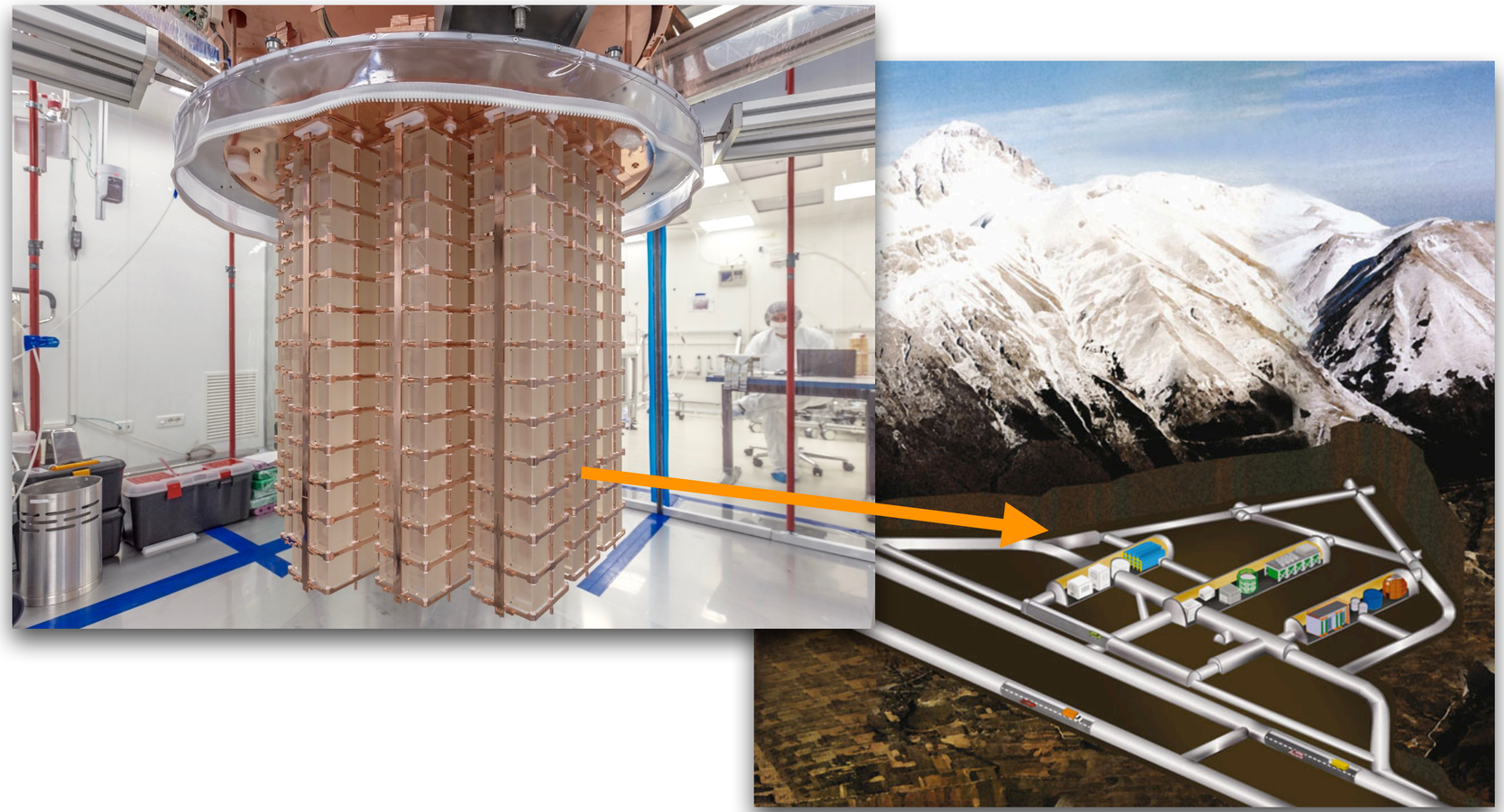
CUORE: The Cryogenic Underground Observatory for Rare Events

Source/detector: ^{130}Te

988 TeO_2 crystals

Gran Sasso National Laboratory(LNGS), L'Aquila, Italy
Average depth: ~3600 m.w.e.

Cryogenic calorimeters-bolometers



CUORE: The Cryogenic Underground Observatory for Rare Events

19 towers with 13 floors of 4 crystals each

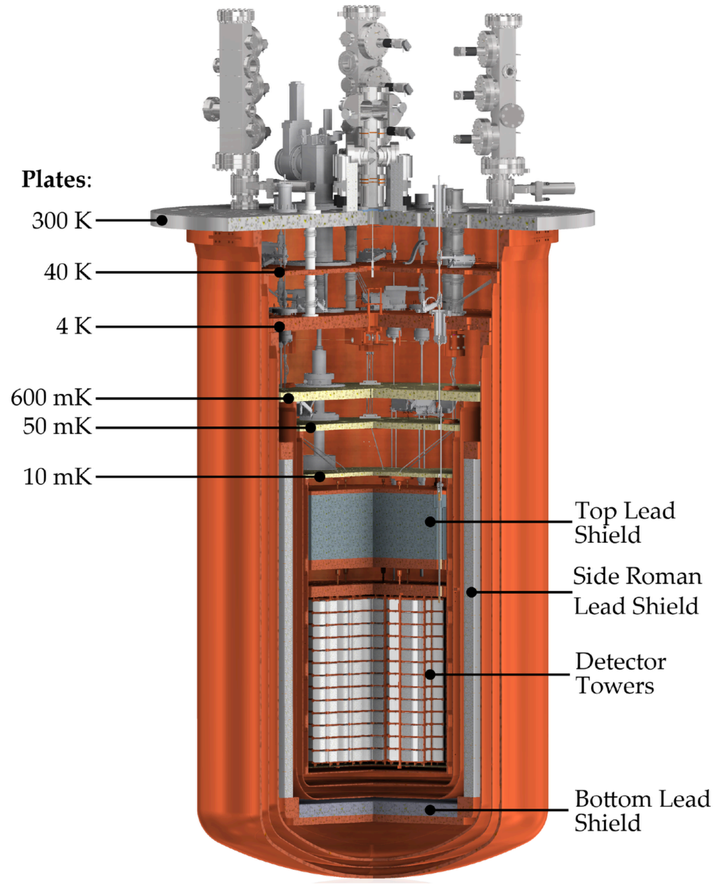
TeO_2 natural abundance crystal
5.00×5.00×5.00 cm^3, 750 g each

Total ^{130}Te mass: 206 kg

Custom dilution refrigerator, nested vessels, and 5 pulse tubes

Operated at ~10 mK

Surrounding lead, and roman lead shielding



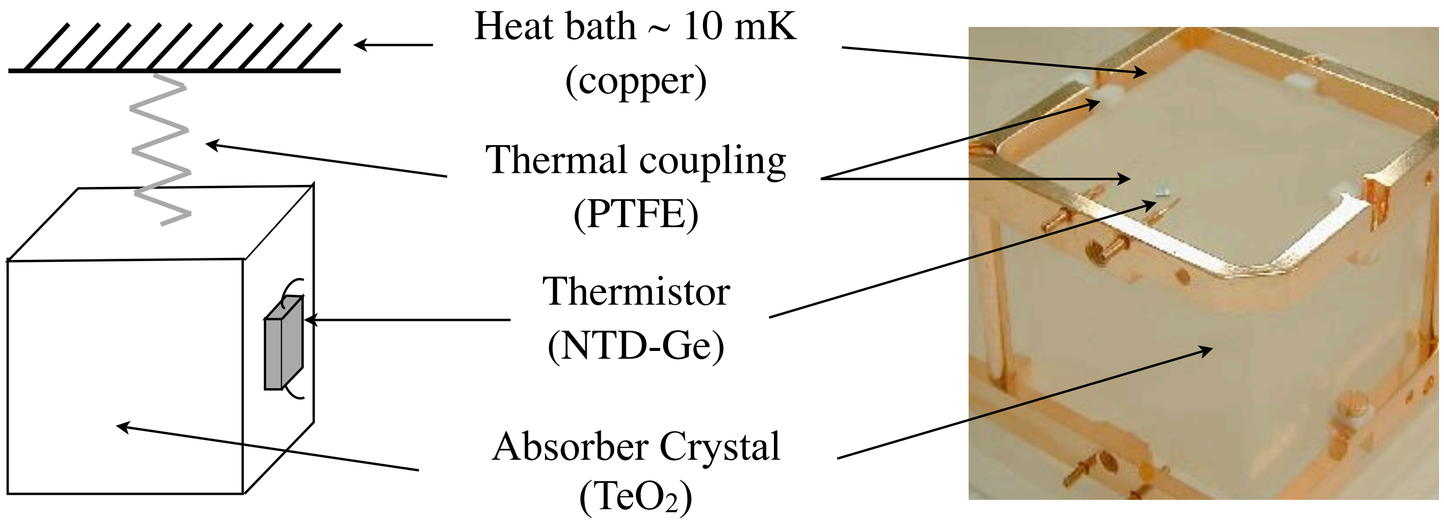
Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

Bolometers: Operating Principle

Particle interaction increase crystal temperature

Thermal coupling to 10 mK heat bath

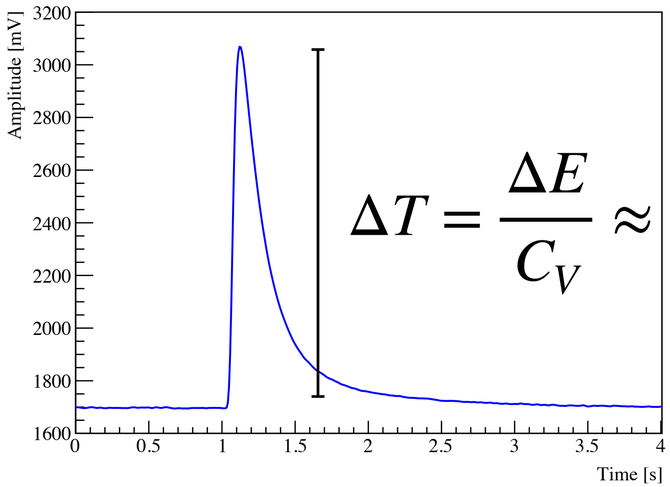
Neutron Transmutation Doped (NTD) Ge thermistors



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

$$R(T) = R_0 e^{\sqrt{\frac{T_0}{T}}}$$

E. E. Haller, J. Appl. Phys. 77, 2857-2878 (1995)



$$\Delta T = \frac{\Delta E}{C_V} \approx 100 \frac{\mu K}{MeV}$$

CUORE Sensitivity

$$s \propto a_I \sqrt{\frac{mt}{B\Delta E}}$$

mass

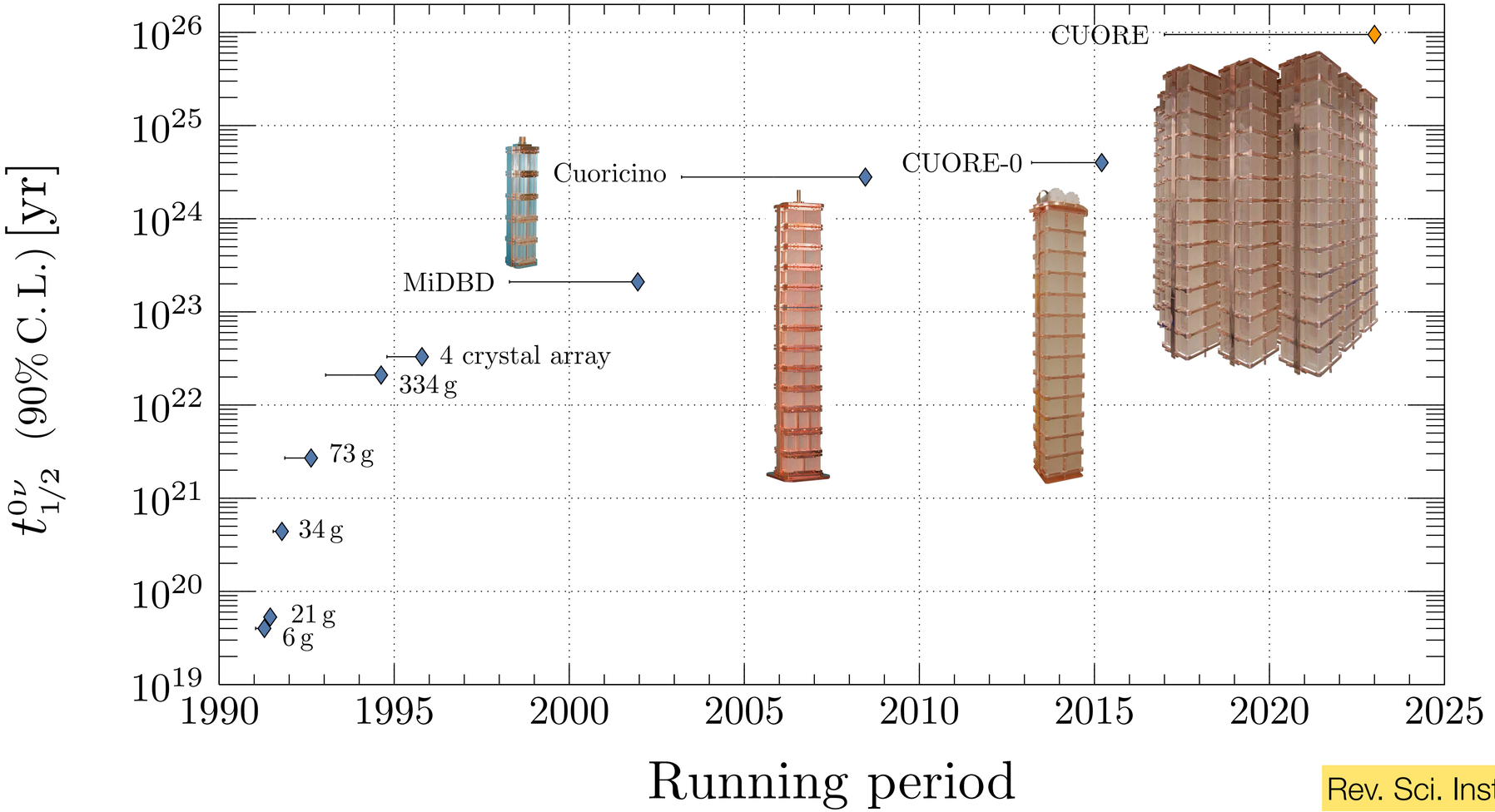
time

Isotopic abundance

Backgrounds
10^{-2} cts/(KeV·kg ·y)

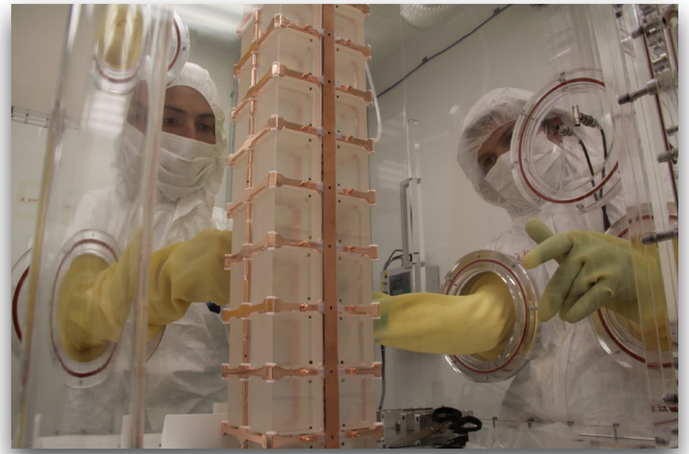
Energy
Resolution
~ 1% at $Q_{\beta\beta}$

Evolution of cryogenic 0νββ bolometers



Rev. Sci. Instrum. 89, 121502 (2018)

CUORE Construction Photos



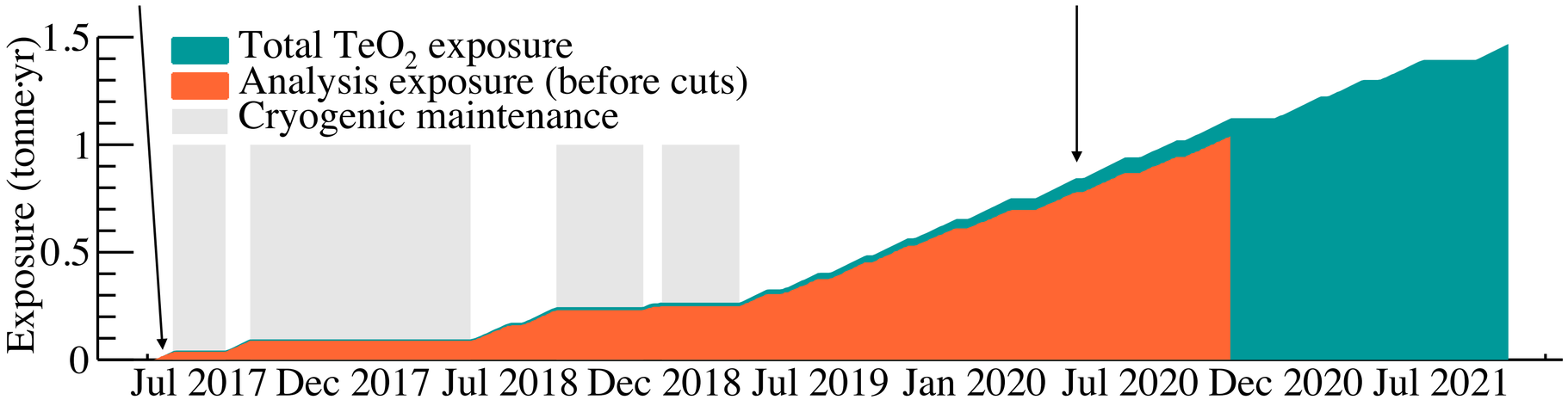
CUORE 1 Tonne·Year Results

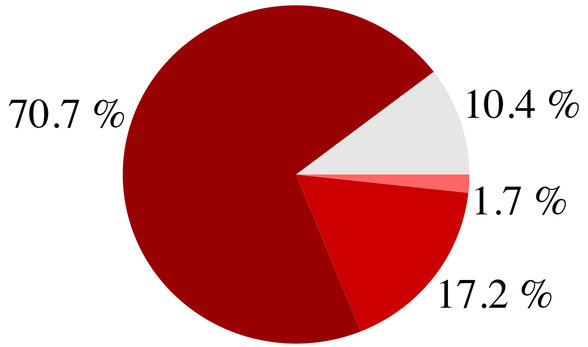
CUORE Data Taking: 1 Tonne·Year Results

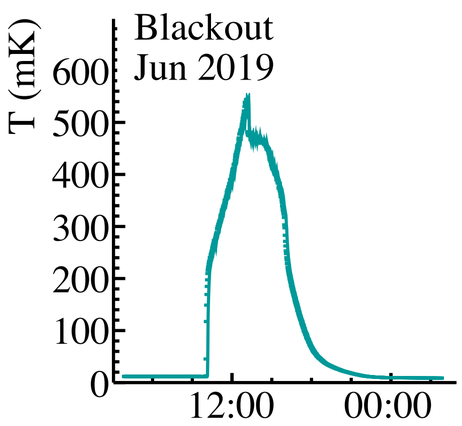
Began data taking in 2017

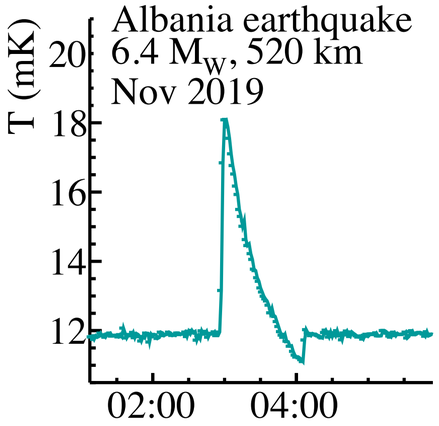
Stable operations, ~ 50kg·yr/month

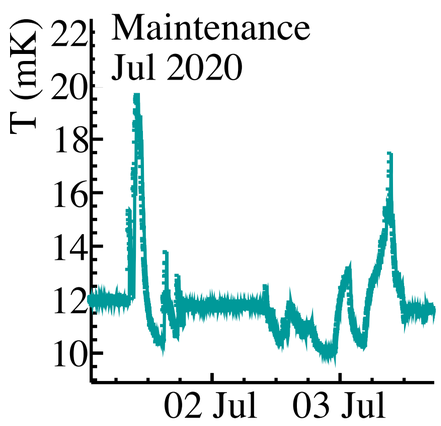
Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

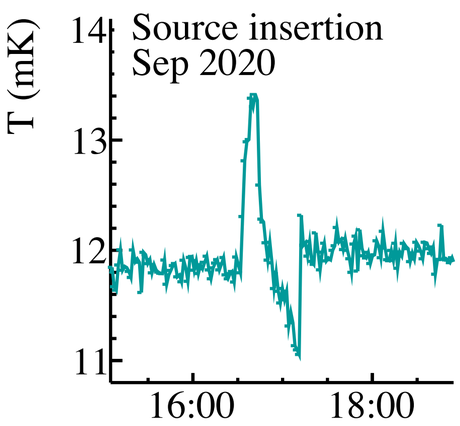








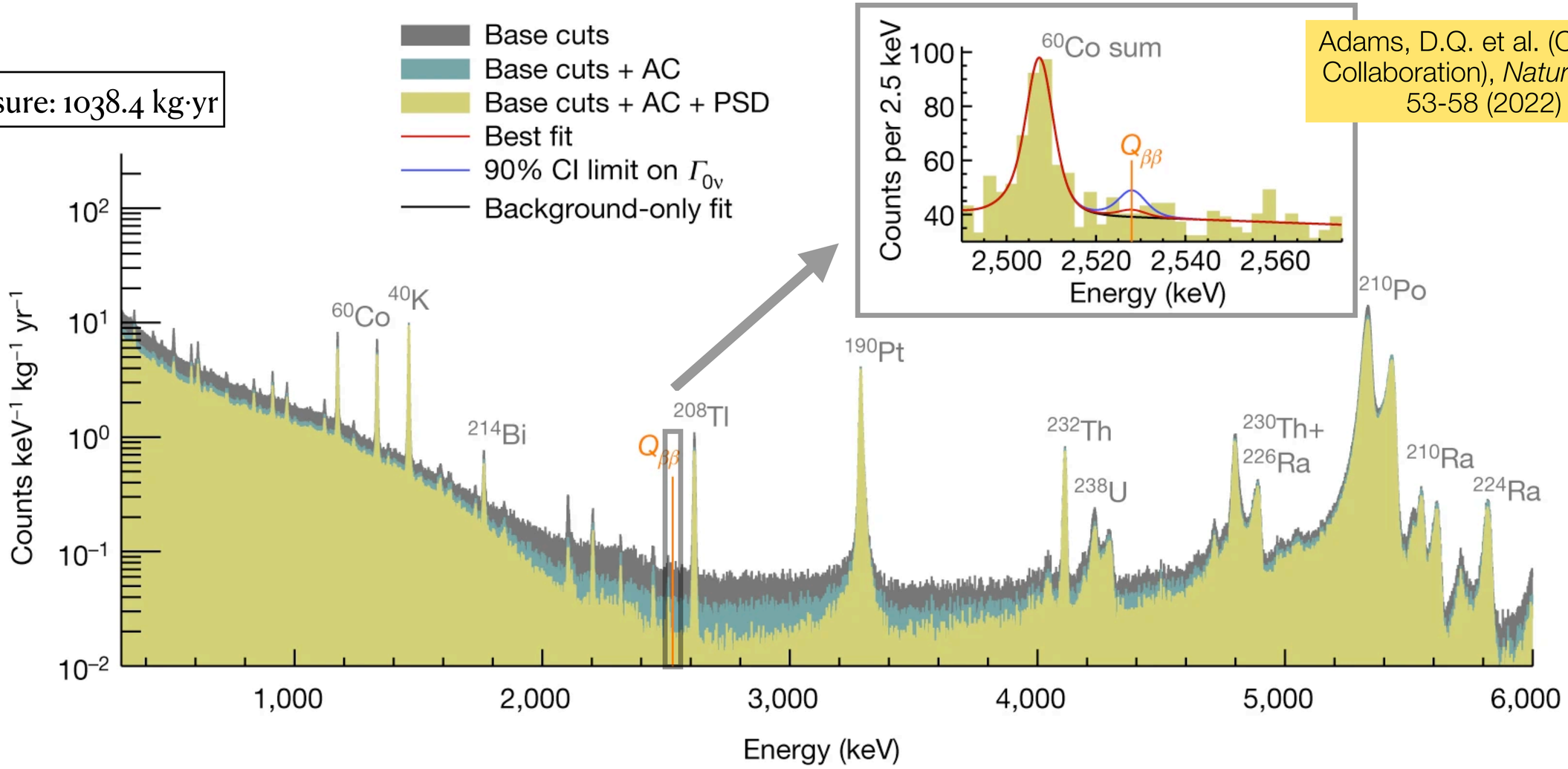




Downtime
Physics
Calibration
Setup

1 Tonne·Year Energy Spectrum

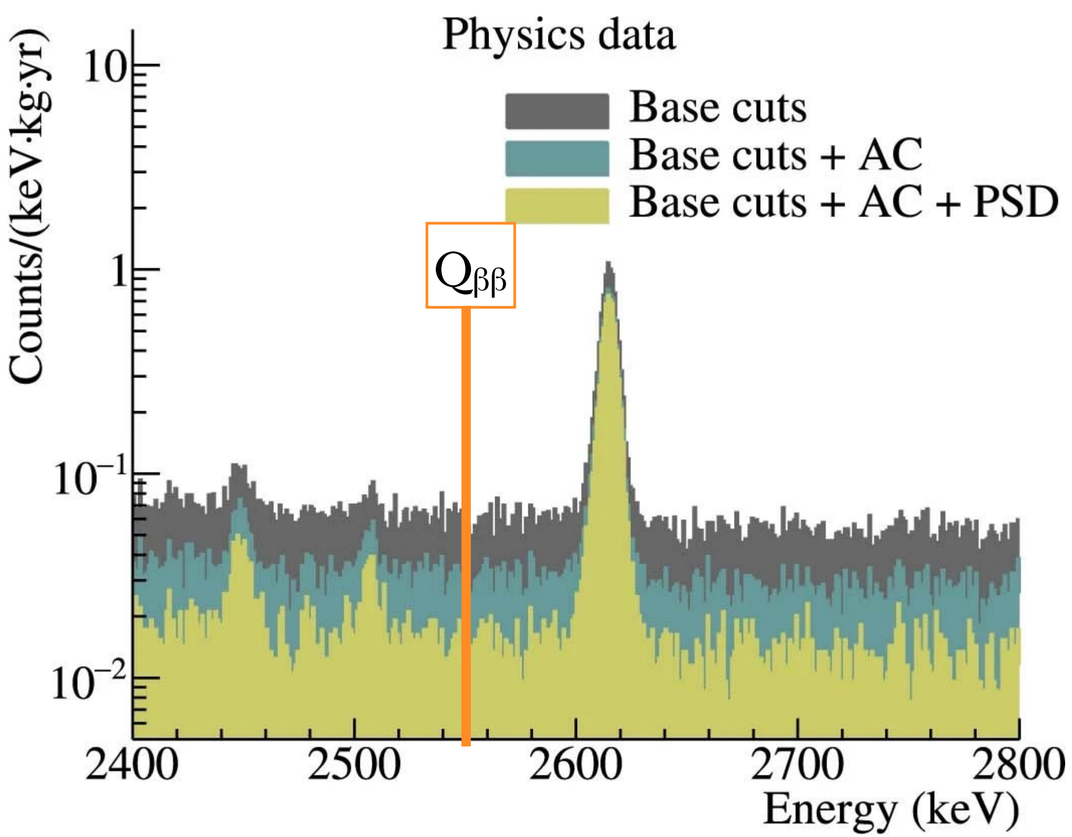
TeO_2 exposure: 1038.4 kg·yr



Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

1 Tonne·Year Backgrounds

Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)



Near sources: Crystals, copper holders, foil, 2νββ, crystal impurities, ^{238}U ^{232}Th chains
Far Sources: Shields, Cryostat, Decays in ^{238}U and ^{232}Th chains
Externals Sources: Environmental muons, γs, and neutrons

1 Tonne·Year Background Fit Results

Nuisance Parameters: Analysis efficiency, energy bias, energy resolution, $Q_{\beta\beta}$, ^{130}Te abundance

Fit Parameters: $\Gamma_{0\nu}$, background index, background slope, ^{60}Co rate

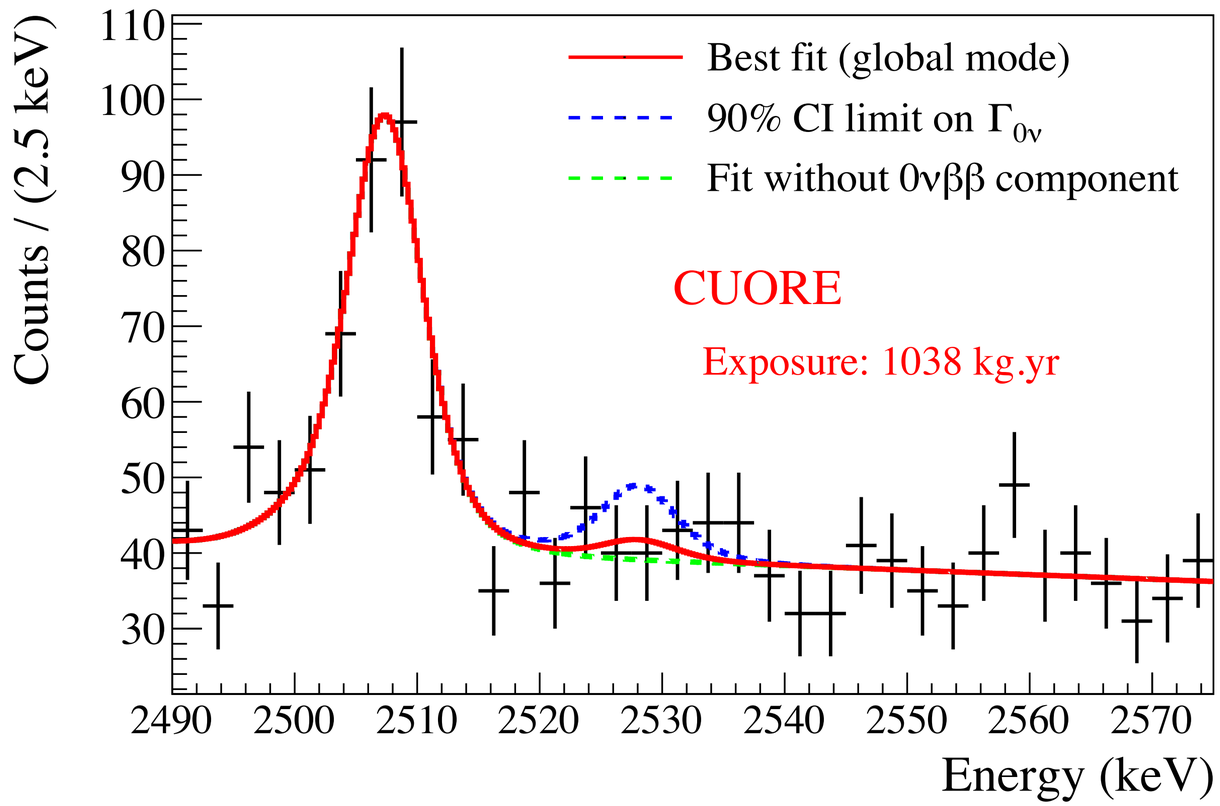
Best fit to [2490,2575] keV

Unbinned Bayesian analysis using Bayesian Analysis Toolkit (BAT)

No evidence of $0\nu\beta\beta$

Background-only model:
$b = 1.49(4) \times 10^{-2}$ counts/(keV·kg·yr) (90 % C. I.)

Best fit signal-plus-background model:
$\Gamma_{0\nu} = (0.9 \pm 1.4) \times 10^{-26}\ yr^{-1}$



Bayesian Median Exclusion Sensitivity

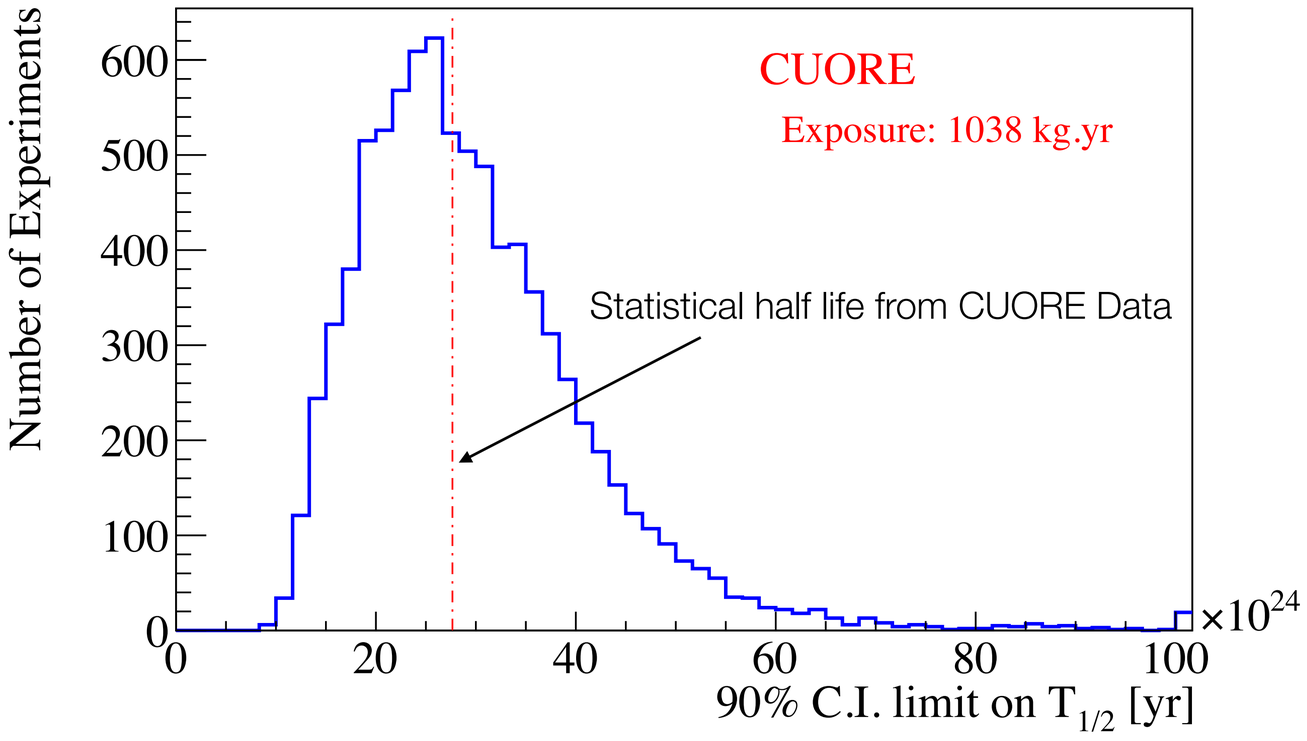
Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

10^4 toy-MC spectra with background only model

Fit spectra with signal+bkg model and extract 90% C.I. limit

Median exclusion sensitivity
$T_{1/2}$ = **2.8 x 10^{25} yr** (90% C.I.)

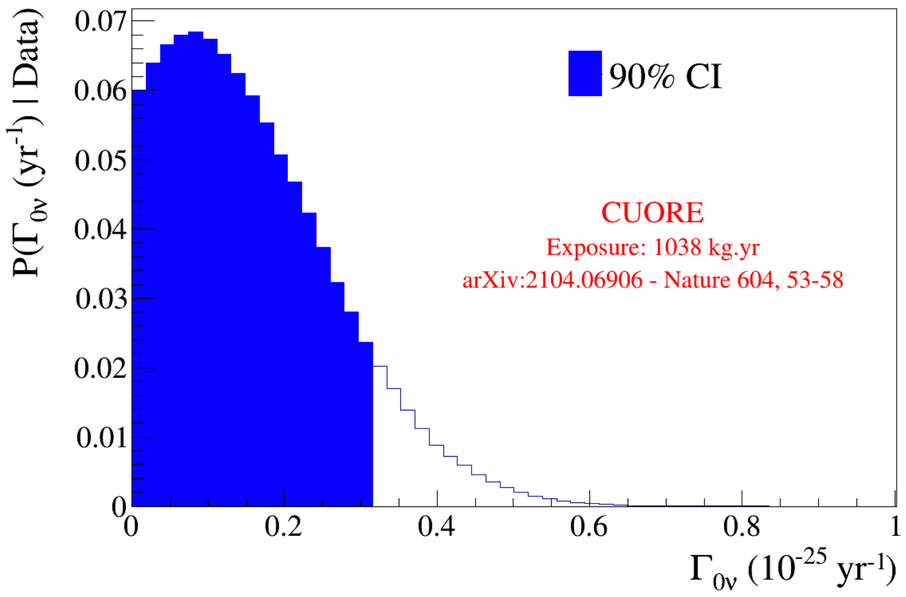
72% Probability to get a more stringent limit given current sensitivity



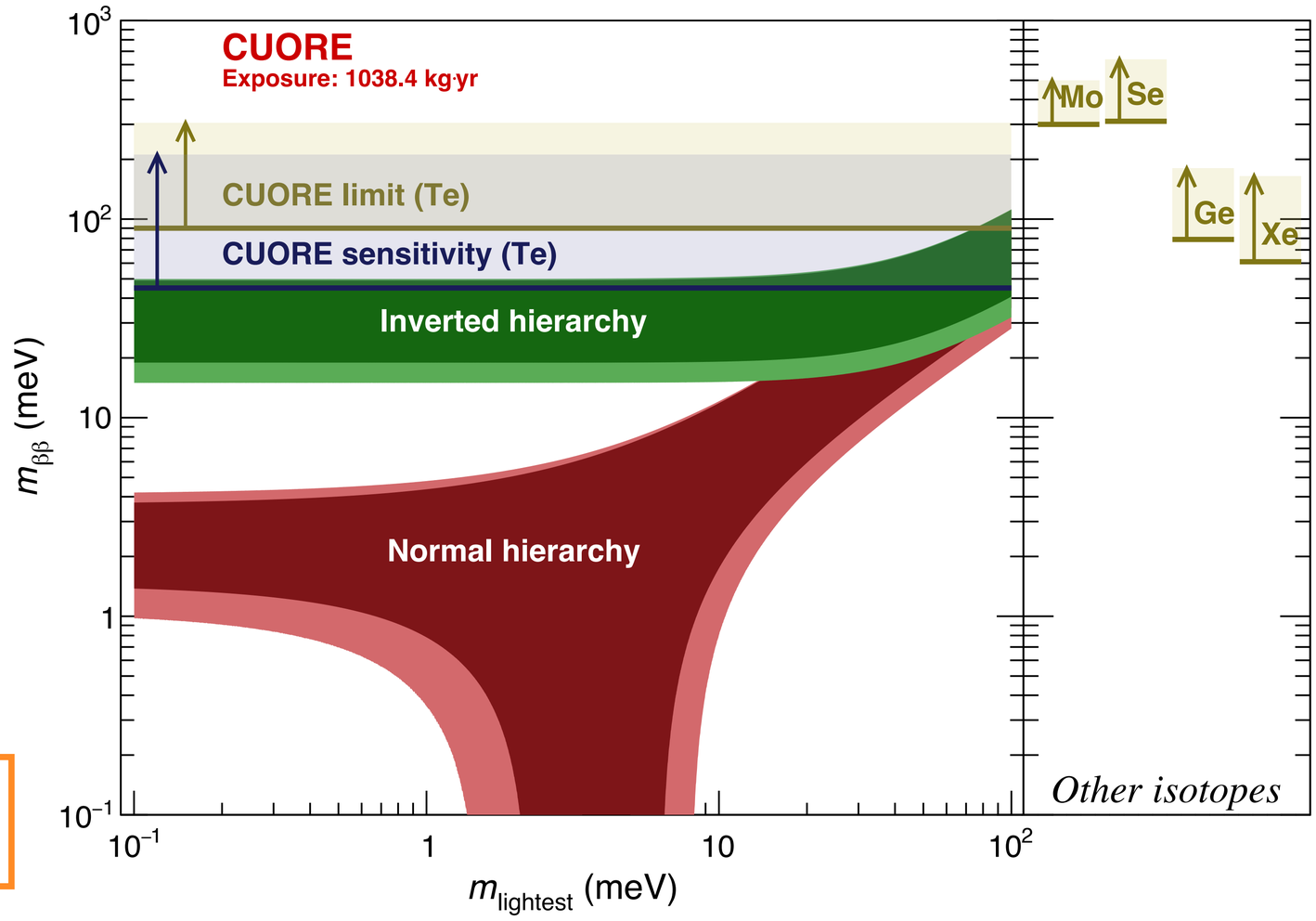
Distribution of 90% C.L. half-lives from Toy MC experiments

CUORE 1 Tonne·Year 0νββ Limit

Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)



$T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ yr (90% C.I.)



CUORE 0νββ Limit and Sensitivity

Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

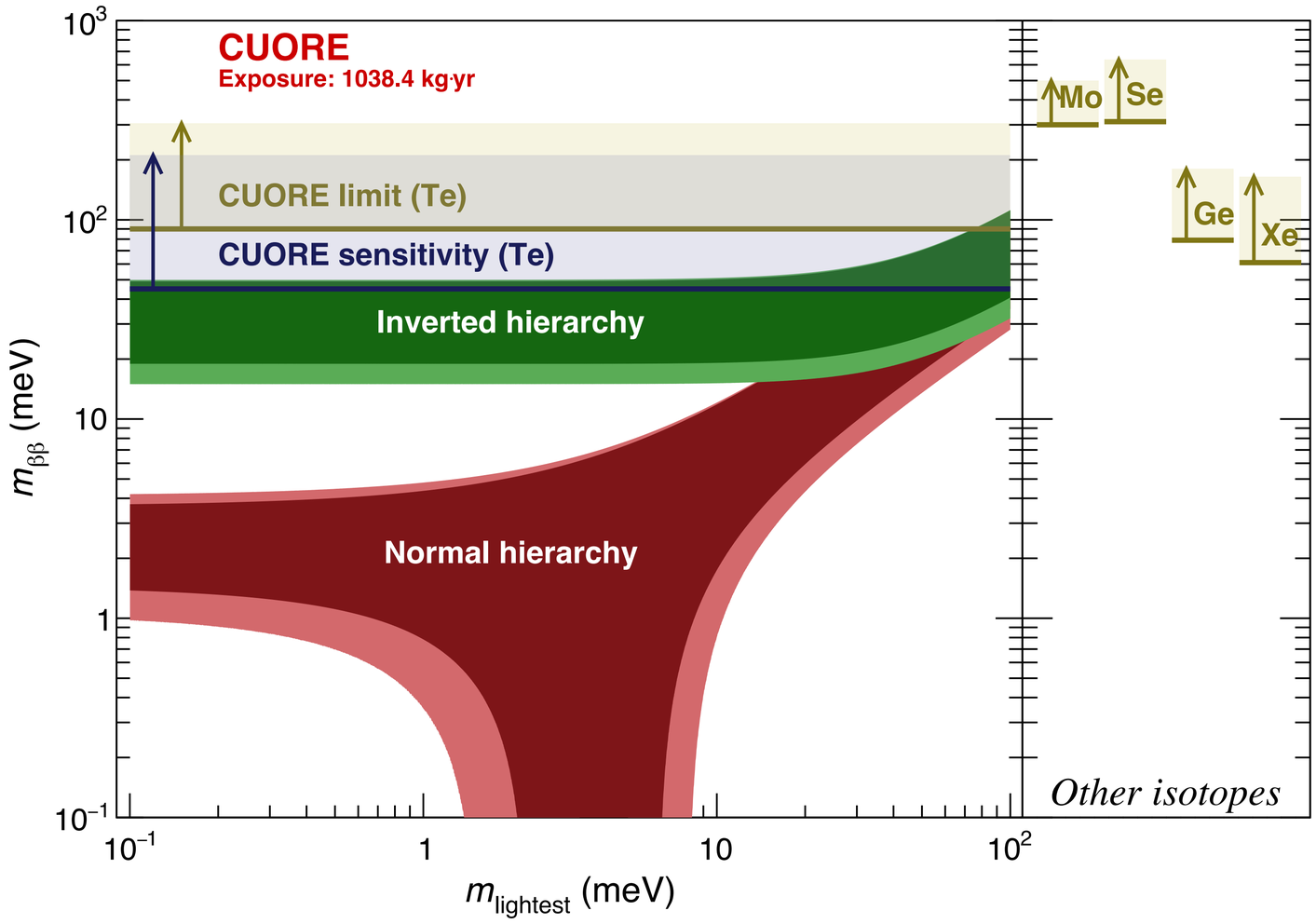
CUORE 1 Tonne Limit:

$m_{\beta\beta} < 90\text{-}305$ meV

CUORE Sensitivity (5 yrs)

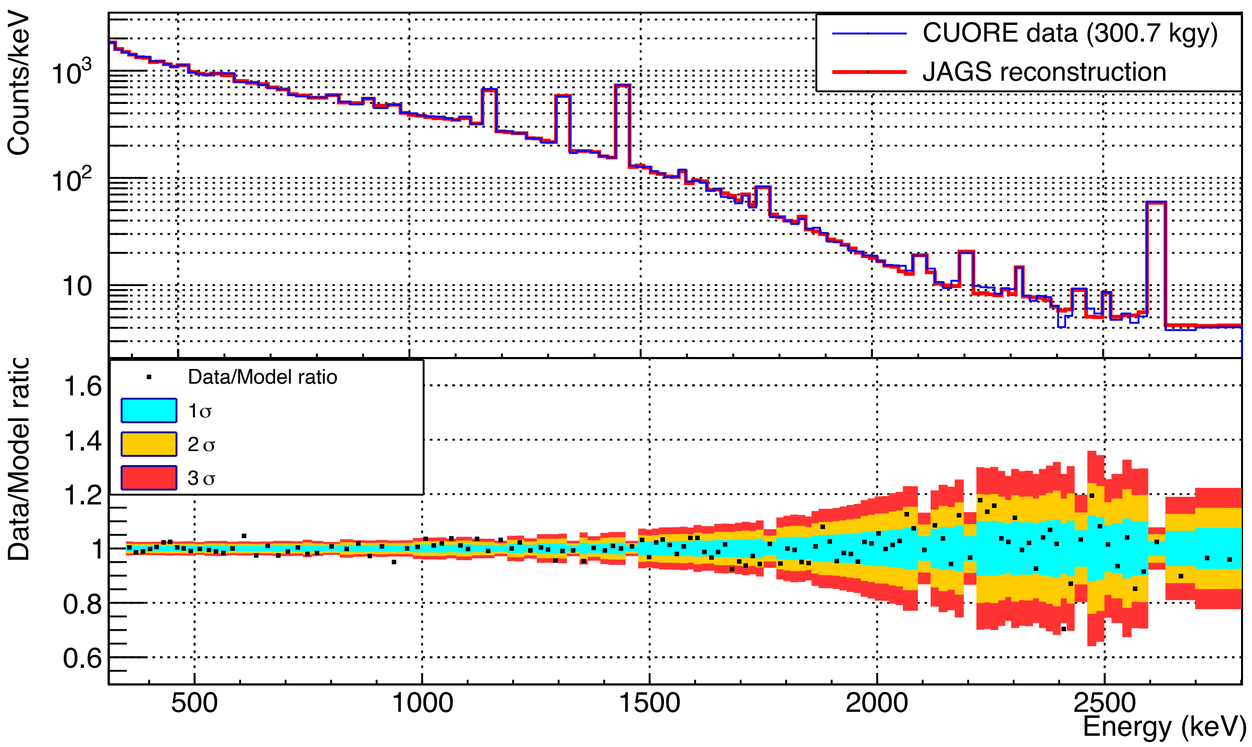
$m_{\beta\beta} < 50 - 130$ meV

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot \frac{|<m_{\beta\beta}>|^2}{m_e}$$



Other rare decay searches

2νββ Decay Measurement



The CUORE Collaboration. *Phys. Rev. Lett.* 126:171801 (2021)

CUORE Background Model

Geant 4 simulation combined with CUORE detector response

62 simulated sources: Including 2νββ decay in the crystals and contaminants

Produces multiplicity, time resolution, energy dependent trigger efficiencies

^{130}Te 2νββ Decay

TeO_2 Exposure: 300.7 kg·yr

Bayesian analysis

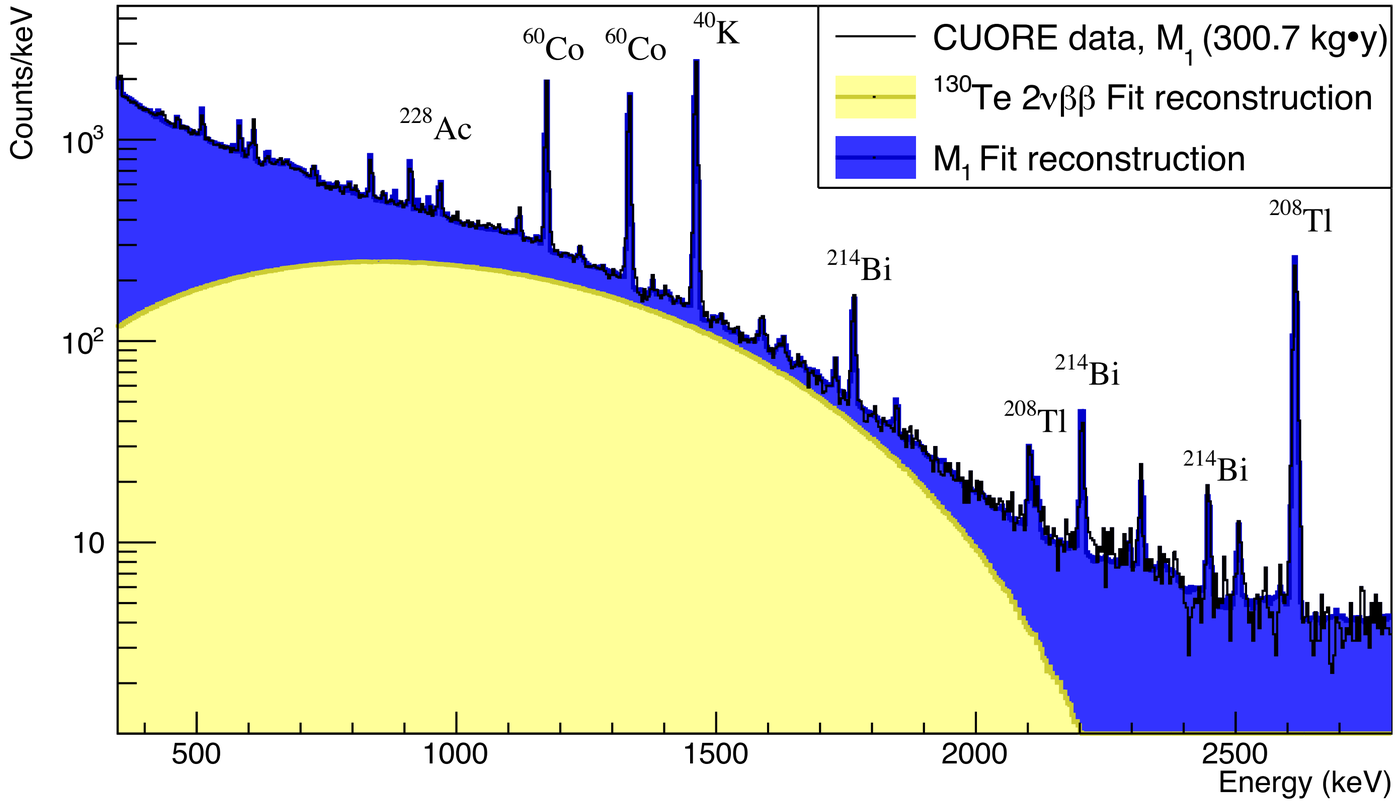
Performed on single crystal events

Uses background model and MC

Spectral fit from 350 keV to 2.8 MeV

$$T^{2\nu}_{1/2} = 7.71^{+0.08}_{-0.06}(\text{stat.})^{+0.12}_{-0.15}(\text{syst.}) \times 10^{20}\ \text{yr}$$

The most precise determination ^{130}Te 2νββ decay half-life

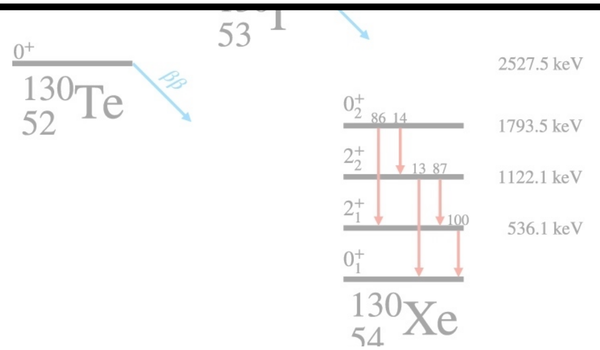


The CUORE Collaboration. *Phys. Rev. Lett.* 126:171801 (2021)

Other Recent CUORE Results

All results are the most stringent limits on these searches in Te

Double beta decay of ^{130}Te to the first 0+ excited state of ^{130}Xe



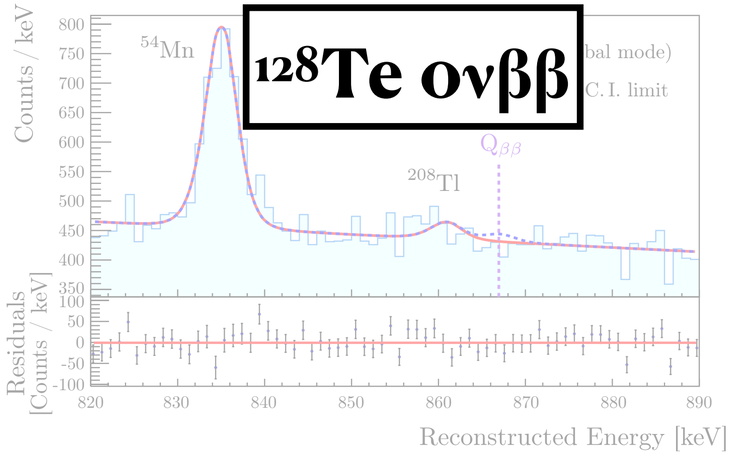
Unique signature, test of nuclear physics

$0\nu\beta\beta$: $(T_{1/2})^{0\nu}_{0^+_2} > 5.9 \times 10^{24}$ yr (90% C.I.)

$2\nu\beta\beta$: $(T_{1/2})^{2\nu}_{0^+_2} > 1.3 \times 10^{24}$ yr (90% C.I.)

Adams, D.Q. et al. (CUORE Collaboration) *Eur. Phys. J. C* **81**, 567 (2021) https://doi.org/10.1140/epjc/s10052-021-09317-z

^{128}Te $0\nu\beta\beta$

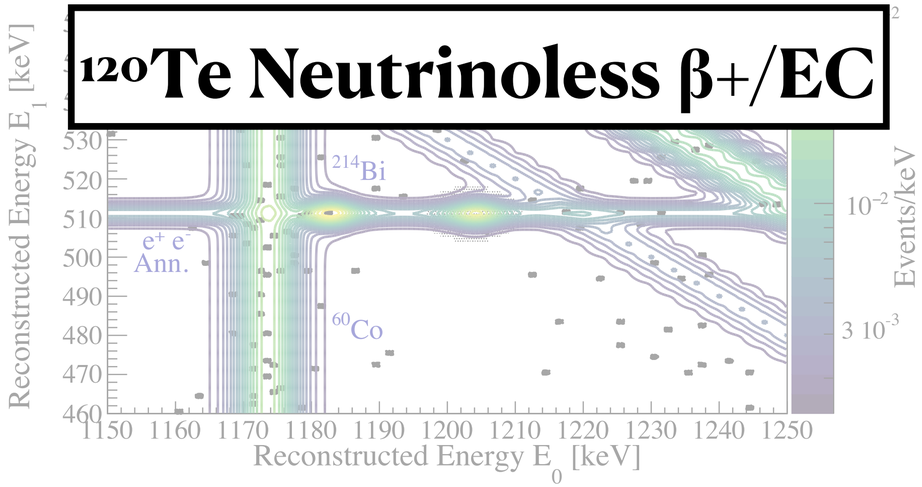


$0\nu\beta\beta$ decay in an additional Te isotope of high isotopic abundance

$(T_{1/2}) > 3.6 \times 10^{24}$ yr (90% CI).

Adams, D.Q. et al. (CUORE Collaboration) https://doi.org/10.48550/arXiv.2205.03132

^{120}Te Neutrinoless β+/EC



Additional mechanism of ββ

^{120}Te β+/EC: $T_{1/2} > 2.9 \times 10^{22}$ yr (90% C.I.)

Adams, D.Q. et al. (CUORE Collaboration) Phys.Rev.C 105 (2022) 065504 https://doi.org/10.1103/PhysRevC.105.065504

What comes after CUORE?

CUORE → CUPID

CUPID and 0νββ

CUPID: CUORE Upgrade with Particle IDentification

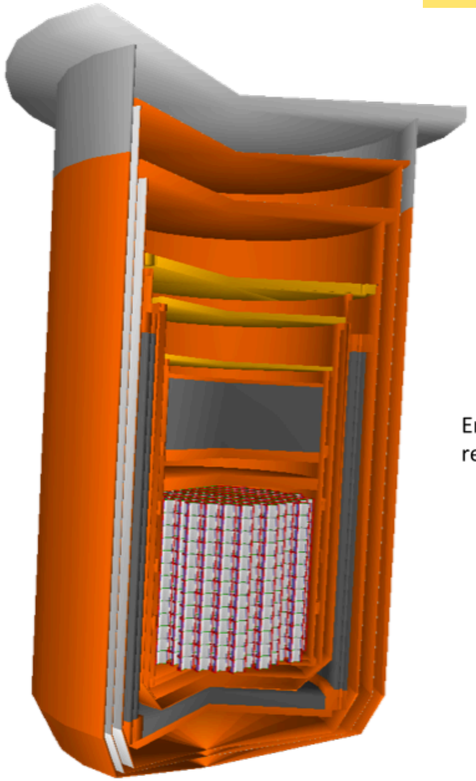
LNGS Gran Sasso National Laboratory

Source/detector: ^{100}Mo
Signal: Peak at 3035 KeV

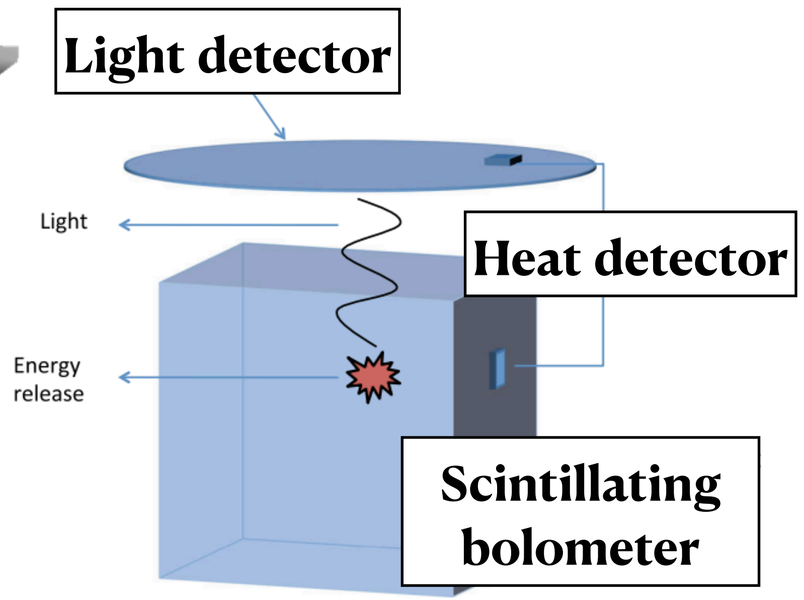
Upgraded Technology/Systems:
Scintillating Bolometers
Particle Identification
Muon Veto
Baseline Background: 10^{-4} cts/(keV·kg·yr)

Baseline Sensitivity: $m_{\beta\beta} < 10\text{-}17$ meV

CUPID Pre-CDR: ArXiv:1907.09376



CUPID Cryostat

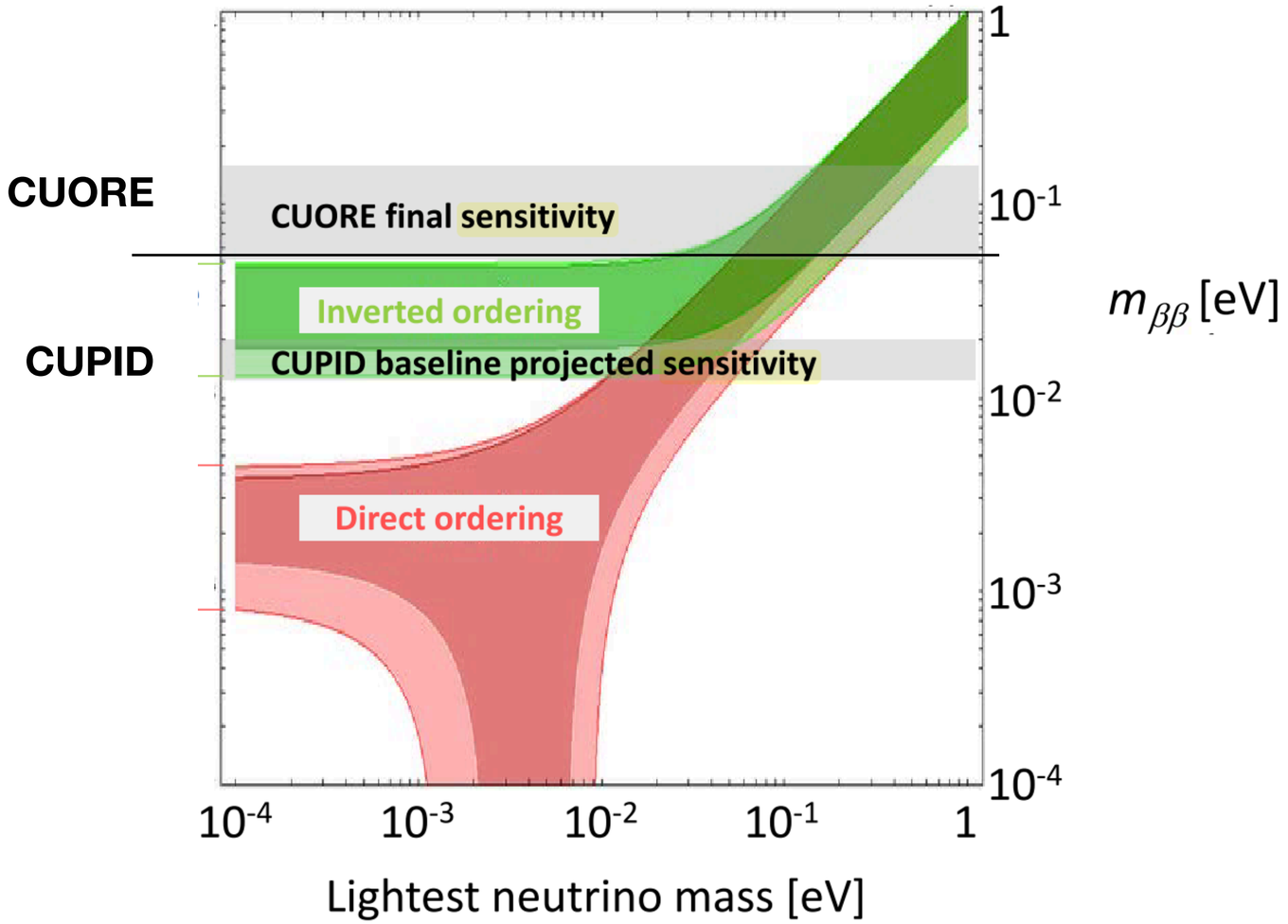


0νββ Sensitivity from CUORE to CUPID

Baseline projected sensitivity covers the inverted ordering region

CUPID Baseline Sensitivity:
$m_{\beta\beta}$ <10-17 MeV

CUPID Pre-CDR: ArXiv:1907.09376



Summary

- CUORE is the first tonne-scale operating cryogenic $0\nu\beta\beta$ decay experiment
- CUORE is stably operating and aims to collect 5 yr of livetime data
- 1 tonne·yr of CUORE data has been analyzed for $0\nu\beta\beta$ decay
- CUORE has the leading limit on $2\nu\beta\beta$ of ^{130}Te
- CUORE's science program includes multiple rare events searches
- CUPID will build off of the CUORE technology and infrastructure to reach greater sensitivity and cover the inverted ordering region for the $0\nu\beta\beta$

Thank you!

Visit https://cuore.lngs.infn.it/en/about/physics for more information!

Back up slides

1 Tonne·Year Parameters and Efficiencies

Parameter	Value
Number of datasets	15
Dead channels	4
Active channels	~934
TeO_2 exposure	1038.4 kg·yr
^{130}Te exposure	288 kg·yr
FWHM at $Q_{\beta\beta}$	7.8(5) keV
Trigger threshold	~10 keV
Analysis threshold	40 keV

Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

Efficiency name	% efficiency	Description
$0\nu\beta\beta$ containment	(88.350 ± 0.090)%	Probability for a $0\nu\beta\beta$ event to be M1 and fully contained in the ROI. From MC.
Trigger and energy reconstruction	96.418(2)%	Includes: trigger, event reconstruction, and pile up
Multiplicity/ Anticoincidence	99.3(1)%	Correctly tagging a single crystal event
Pulse shape analysis	96.4(2)%	Efficiency for a good physical pulse to pass pulse shape discrimination cuts
All cuts except containment	92.4(2)%	Products of the terms above, propagated in quadrature

Systematics

Implemented as additional nuisance parameters to the fit

Parameter	Dependence	Method/Prior
Analysis efficiency I	Dataset	Gaussian
Analysis efficiency II	Global	Gaussian
Energy bias	Dataset	Fit residual peaks in physics spectrum from literature value with 2nd order polynomial
Energy resolution	Dataset	Fit ratio of FWHM in physics and calibration data with 1st order polynomial
Qbb	Global	Gaussian
130Te isotopic fraction	Global	Gaussian