Latest results from the CUORE experiment

Mattia Beretta on behalf of the CUORE collaboration

University of California Berkeley

12/07/2023 – ICNFP 2023

Physics focus: double beta decay

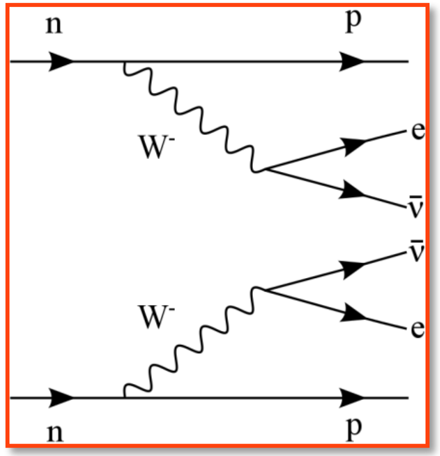
Second order weak process: (A,Z) → (A,Z+2)

2νββ:

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

Predicted and measured

$T^{2\nu}_{1/2}$: $10^{19} - 10^{22}$ y

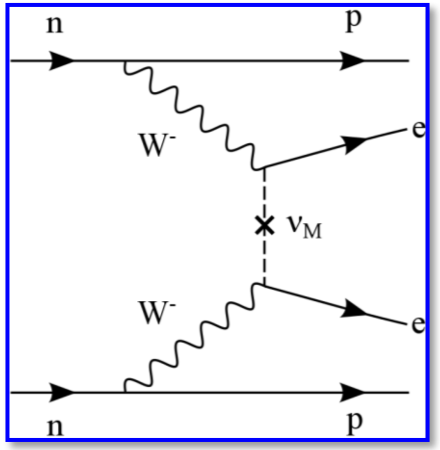


0νββ:

$$(\mathrm{A,Z}) \rightarrow (\mathrm{A,Z+2}) + 2\mathrm{e}^-$$

Prohibited in SM (ΔL = 2)

Limits: $T^{2\nu}_{1/2} > 10^{24} - 10^{26}$ y



$$m_\nu \neq 0$$
$$\nu \equiv \overline{\nu}$$

Main goal for the CUORE experiment

Physics focus: double beta decay

Second order weak process: (A,Z) → (A,Z+2)

Searched in double electron spectra

2νββ:

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

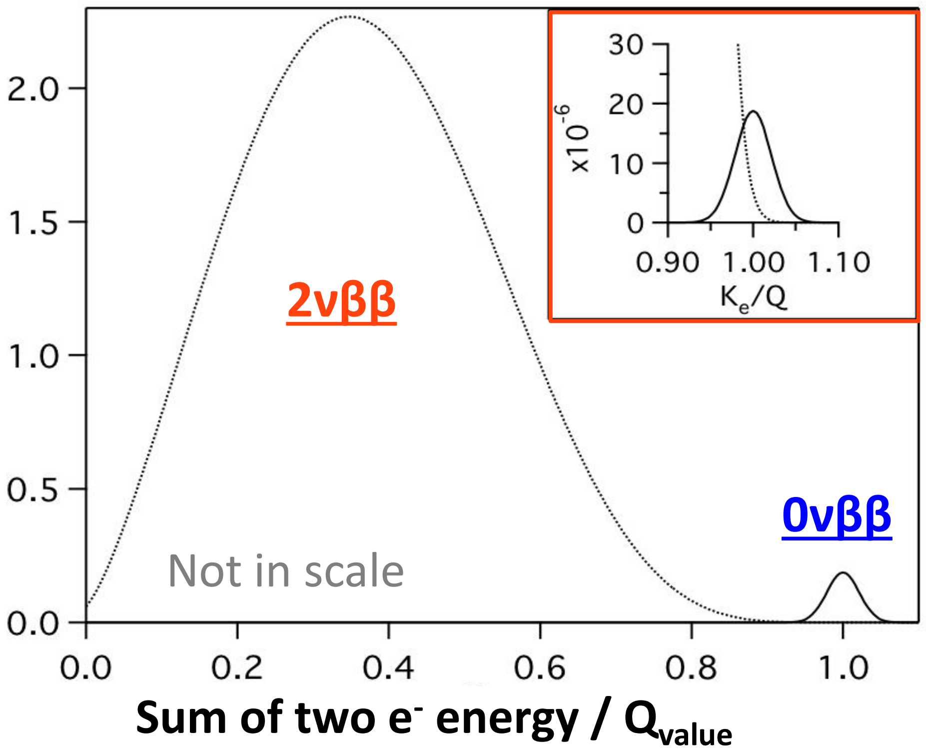
0νββ:

$$(\mathrm{A,Z}) \rightarrow (\mathrm{A,Z+2}) + 2\mathrm{e}^{-}$$

Energy resolution

At the Q_{value}

Total energy of the transition

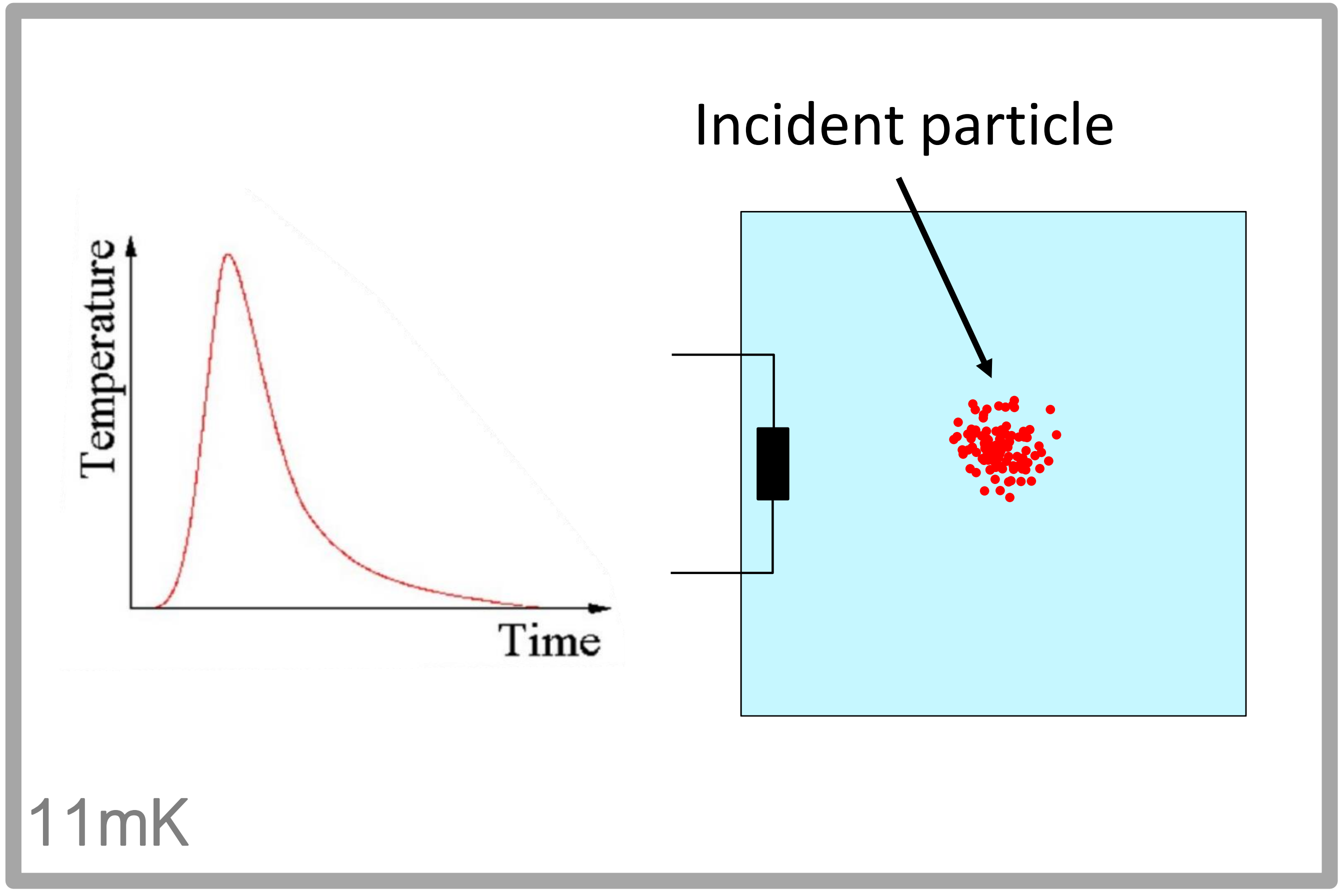


Low Background

Few counts expected

Cryogenic calorimeters: detector concept

Detecting energy as temperature increase



Crystal (TeO_2) containing 0νββ candidate (^{130}Te)

Kept at ~ 10mK

Energy deposition increases temperature

Detected with resistive thermometer

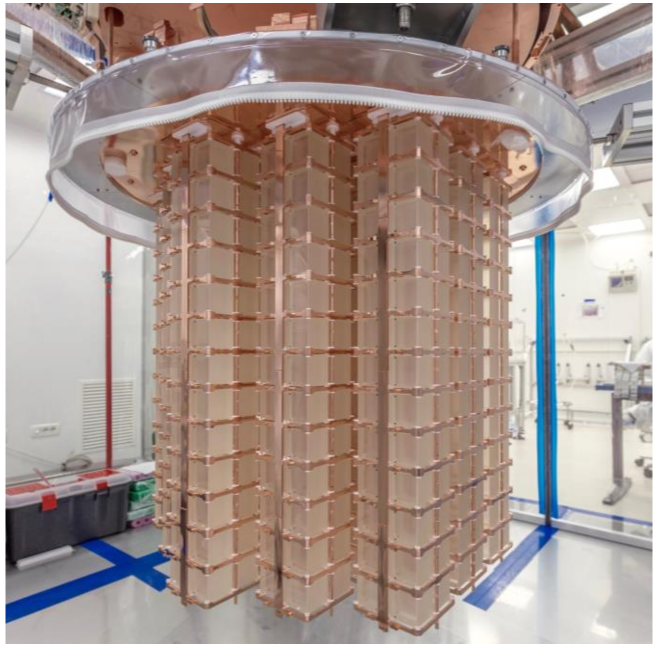
µK sensitivity

Thermometer is made of neutron transmutation doped germanium

CUORE detector: 988 crystals simultaneously operated

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

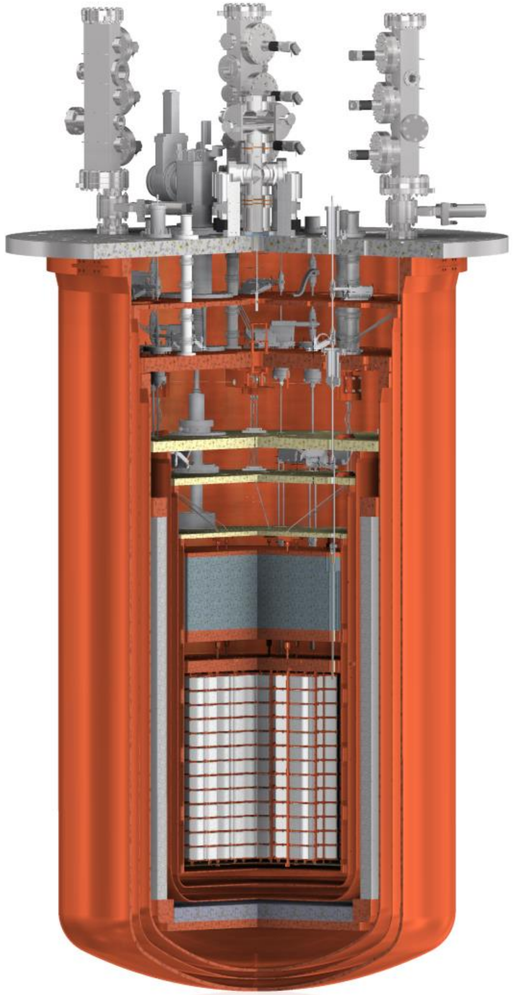
The first tonne-scale operating cryogenic 0νββ decay experiment



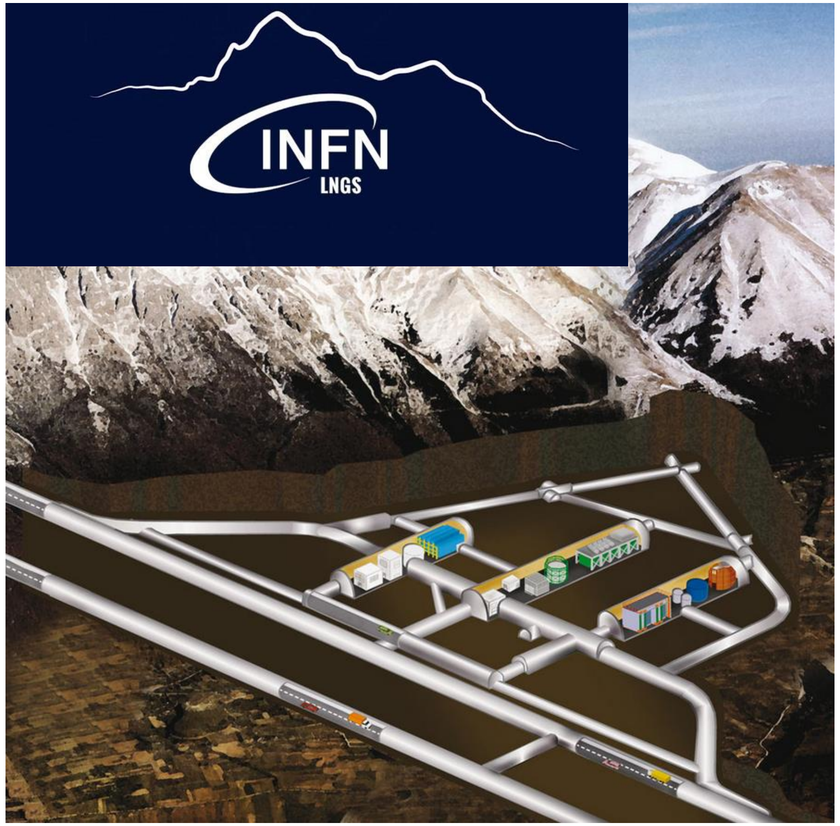
19 towers
→ 13 floors
→ 4 crystals

Controlled materials
Clean environment

Cryogenics 102, 9-21 (2019)



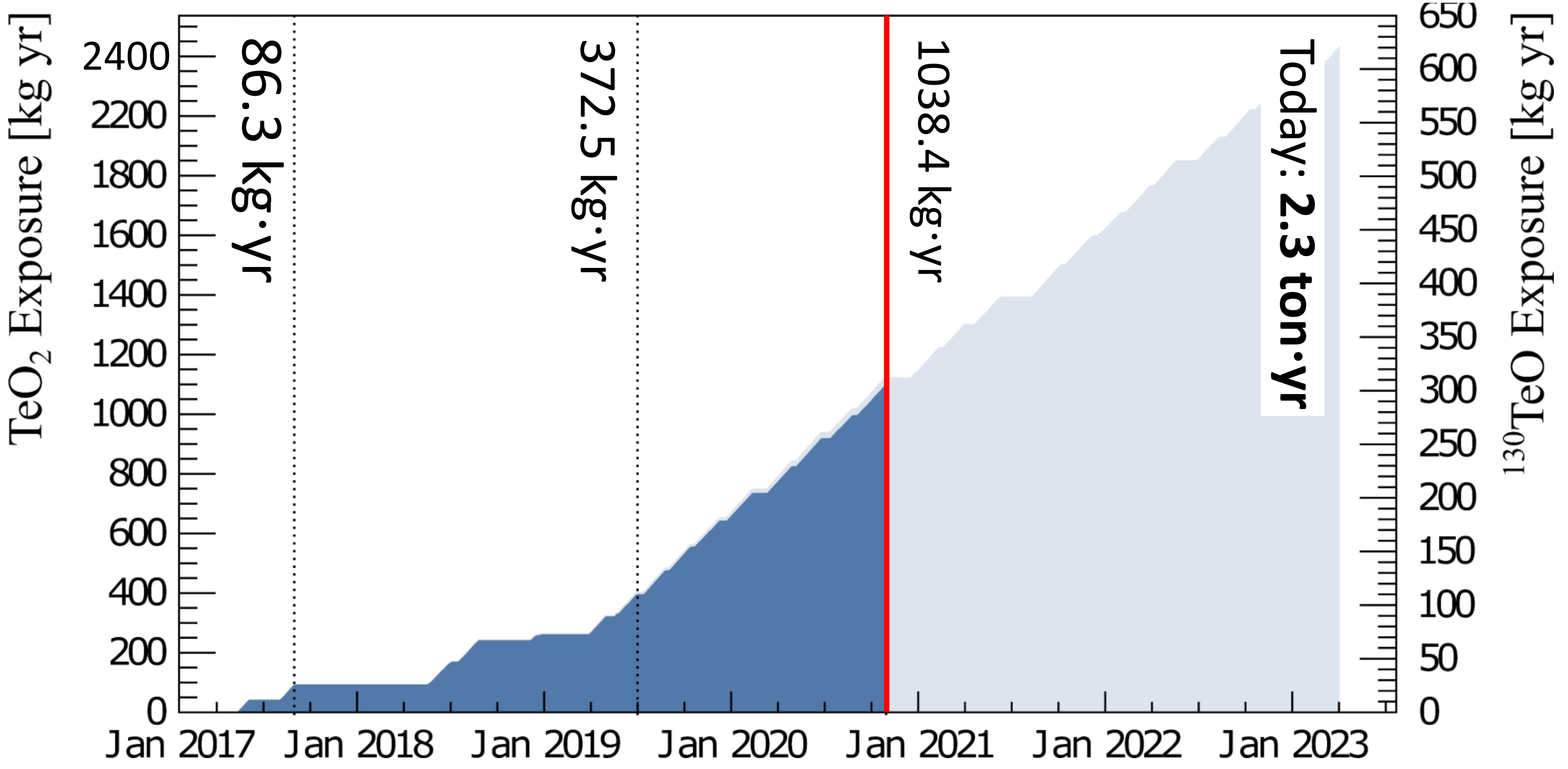
Custom cryostat for cryogenic operation



Hosted in Gran Sasso underground laboratory
Shielding from cosmic rays

Data taking and duty cycle

Nature 604, 53–58 (2022)

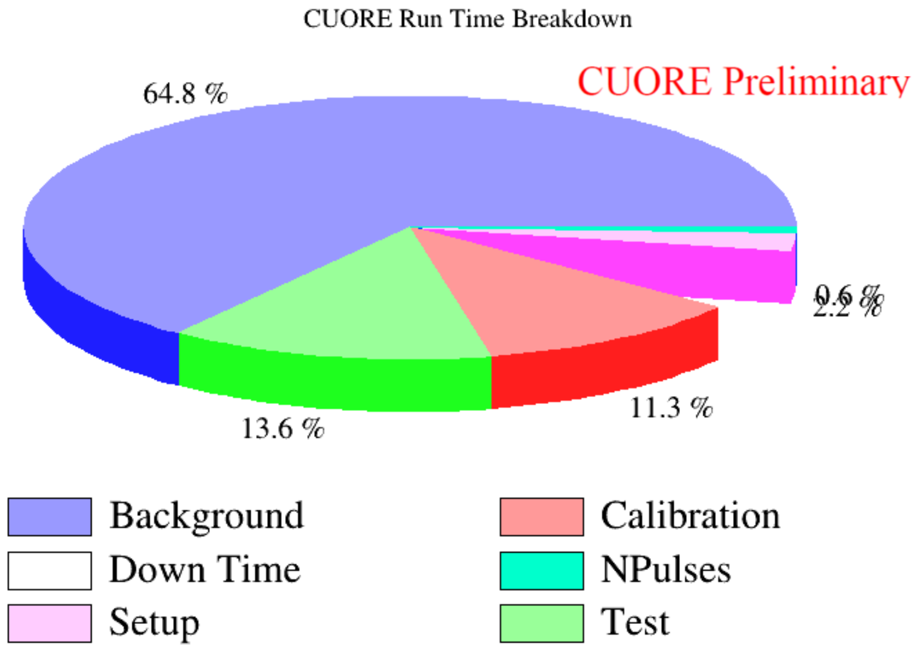


CUORE is taking data stably

Aim: 3 ton·yr exposure

CUORE has analyzed 1 ton·yr of data

best limit on 0νββ of ^{130}Te



The cryogenic system is controlled and functioning

Only 9.7% down time (mostly before 2019) → 90.3% live time

64.8% of total time is **live physics time**

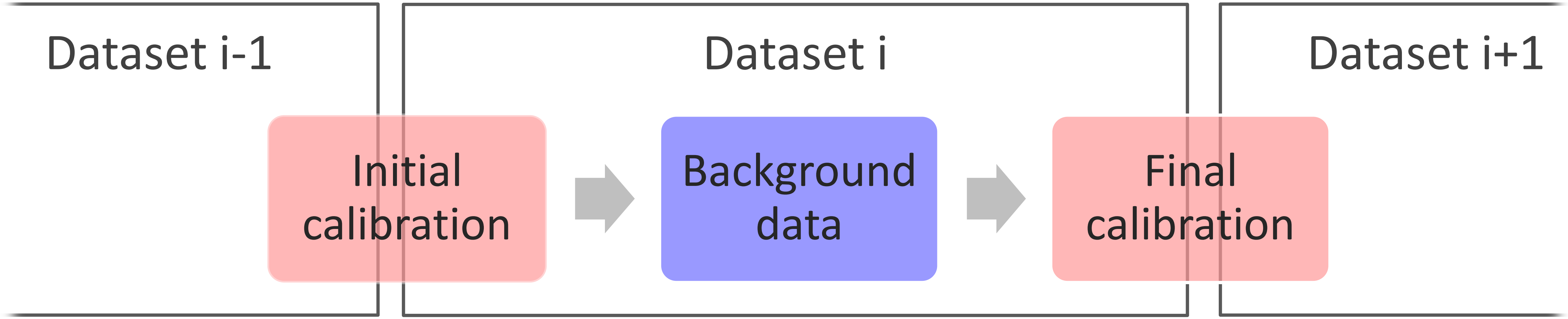
Not including calibration and periodic tests

Structure of the acquired data

Nature 604, 53–58 (2022)

Data organized in subsequent datasets - O(month)

Delimited by calibrations with ^{232}Th+^{60}Co



15 datasets included in the analysis

934/988 (94.5%) channels included on average in the analysis

TeO_2 exposure = 1038.4 kg·y

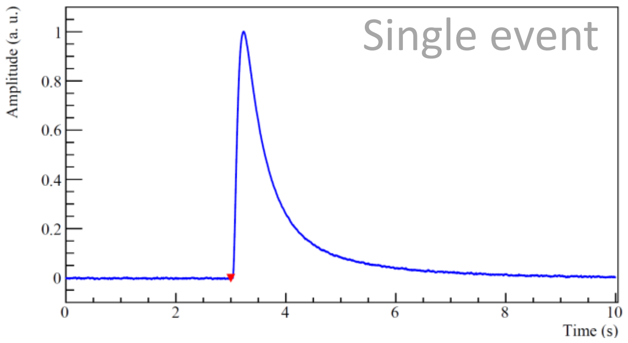
^{130}Te exposure = 288 kg·y

Offline data analysis procedure – for each dataset

Nature 604, 53–58 (2022)

Continuous data → Derivative triggering → Optimum filter → Digital filter deconvolving the noise

First processing

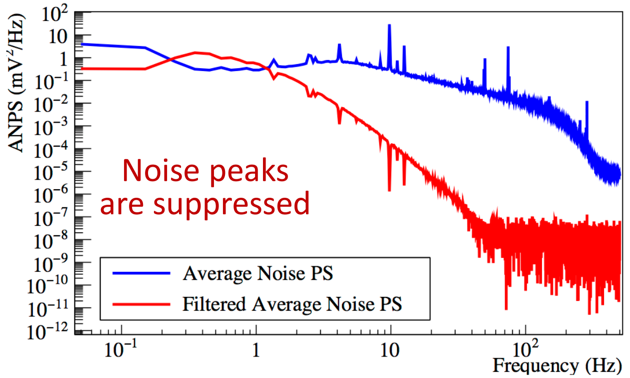


$$H(\omega) \sim \frac{S(\omega)}{N(\omega)}$$

Average signal

Average noise

Higher weight to signal frequencies



Lower threshold

Better efficiency

Re-trigger with optimum filter

↓

New Optimum filter → **Variables used for the physics analyses**

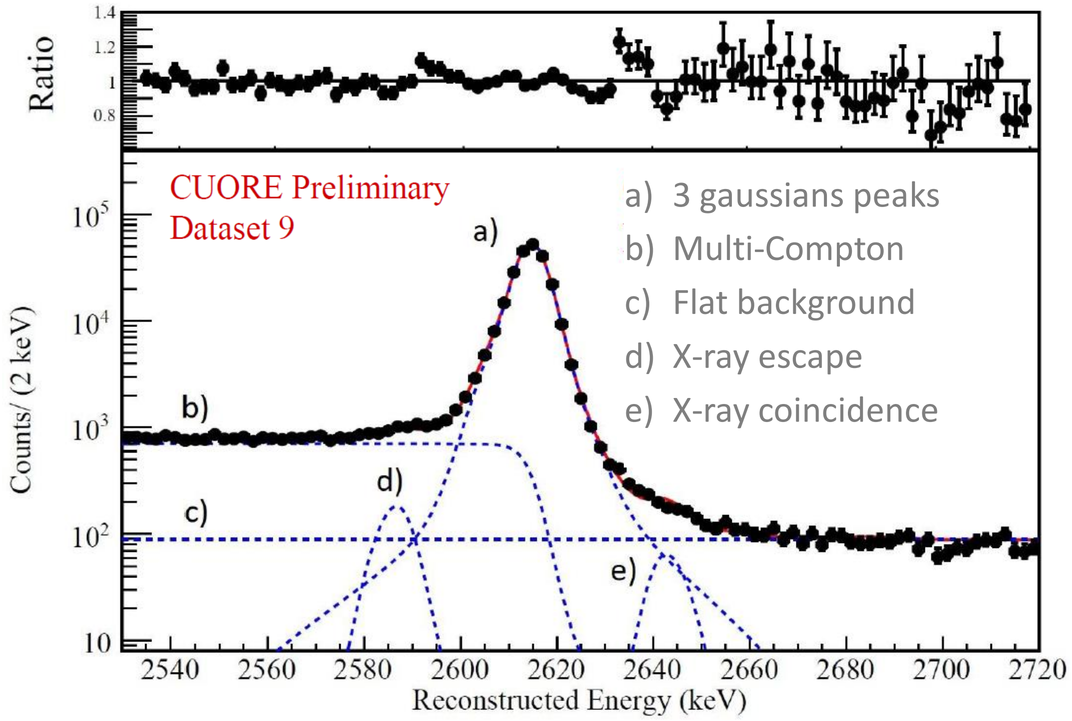
Re - processing

Energy, shape variables, timing …

Base cut Efficiency = 96.4%

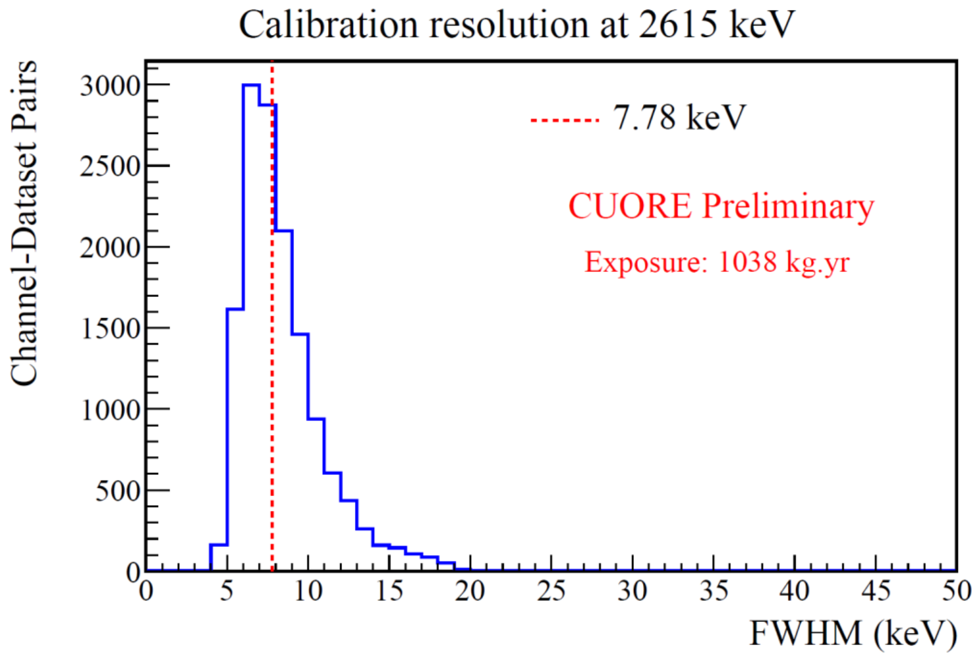
Calibration data: detector response and energy resolution

Nature 604, 53–58 (2022)



Response modelled on the 2615 keV line from ^{232}Th chain

Accounts for non idealities



Calibration FWHM resolution:

(7.78 ± 0.03) keV at 2615 keV

Background resolution rescaled to the Q_{value}:

(7.8 ± 0.5) keV at 2527 keV

Techniques for event selection

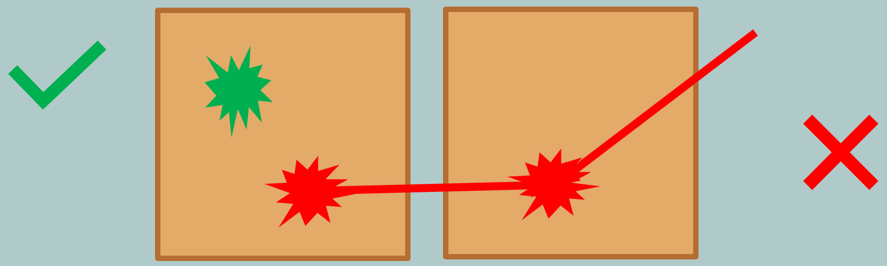
Nature 604, 53–58 (2022)

Preserve only 0νββ candidate events with best possible efficiency

Anticoincidence cut (AC)

0νββ leaves all energy in a crystal

Select events accordingly



Time resolution is ±5ms

Efficiency = 99.3%

Combined with the probability of a 0νββ event in a single crystal

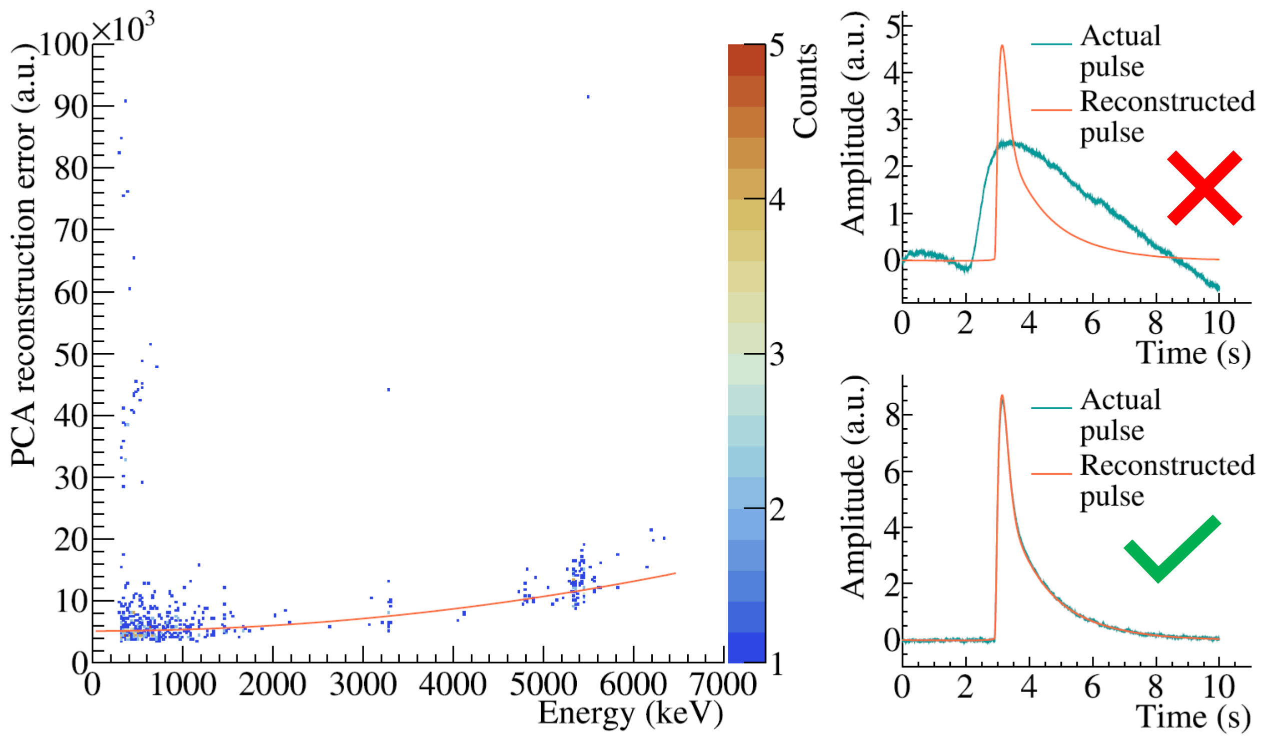
Containment probability = 88.3%

from MonteCarlo simulations

Pulse shape discrimination (PSD)

Reconstruct the pulse with single PCA component

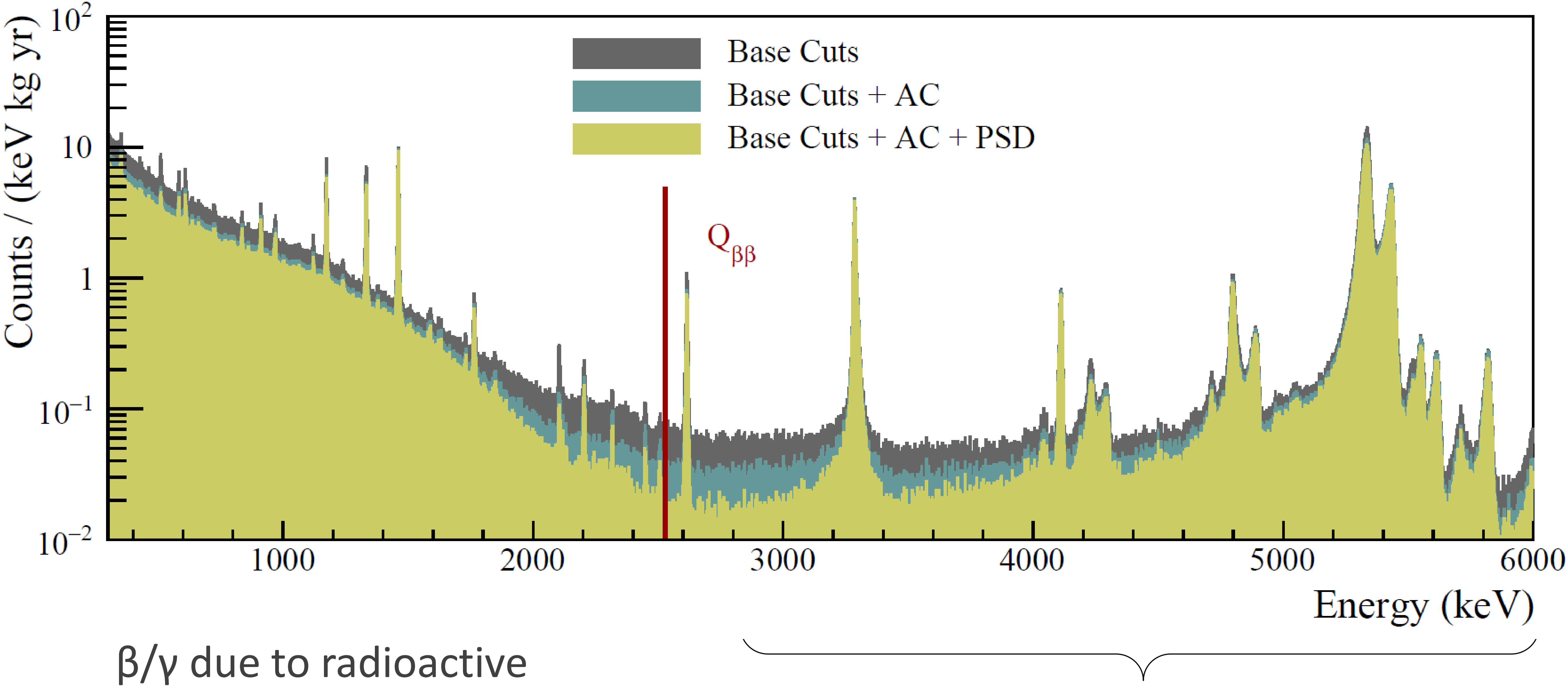
Difference is discrimination metric



Efficiency = 96.4%

Unblinded background data

Nature 604, 53–58 (2022)

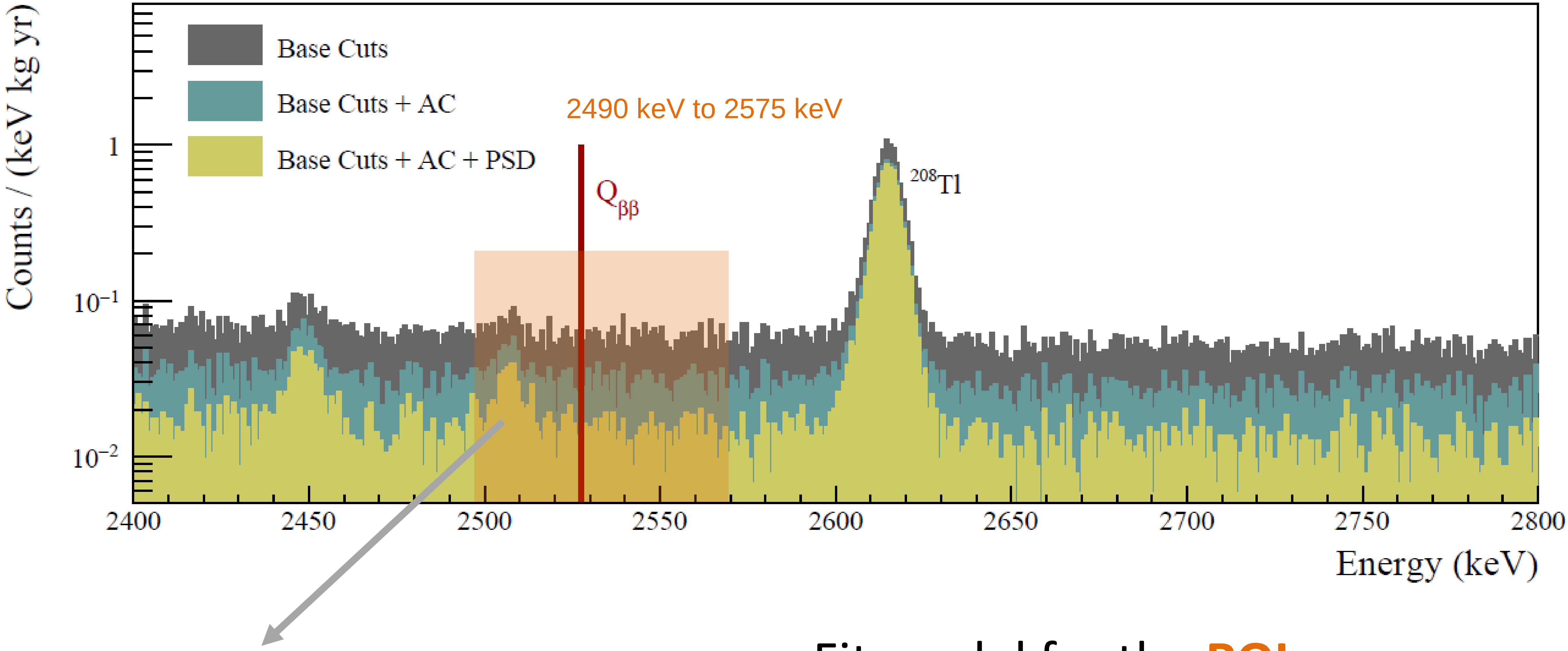


β/γ due to radioactive contaminations and ^{130}Te 2νββ

α events due to close contaminations

Unblinded background data – region of interest (ROI)

Nature 604, 53–58 (2022)



^{60}Co sum line

1173 keV+1333 keV

Fit model for the **ROI**:

$\Gamma^{0\nu}$ + ^{60}Co rate + linear background

0νββ results

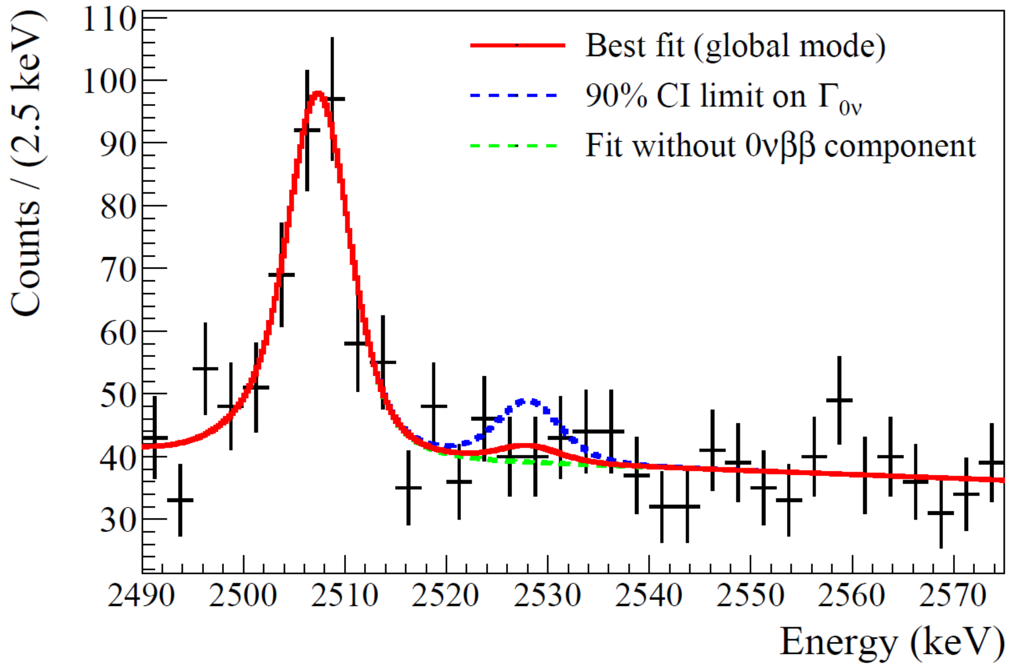
Nature 604, 53–58 (2022)

Unbinned Bayesian fit

Simultaneous on all datasets

Nuisance parameters as systematics

Includes uncertainties on efficiencies



Best fit value:

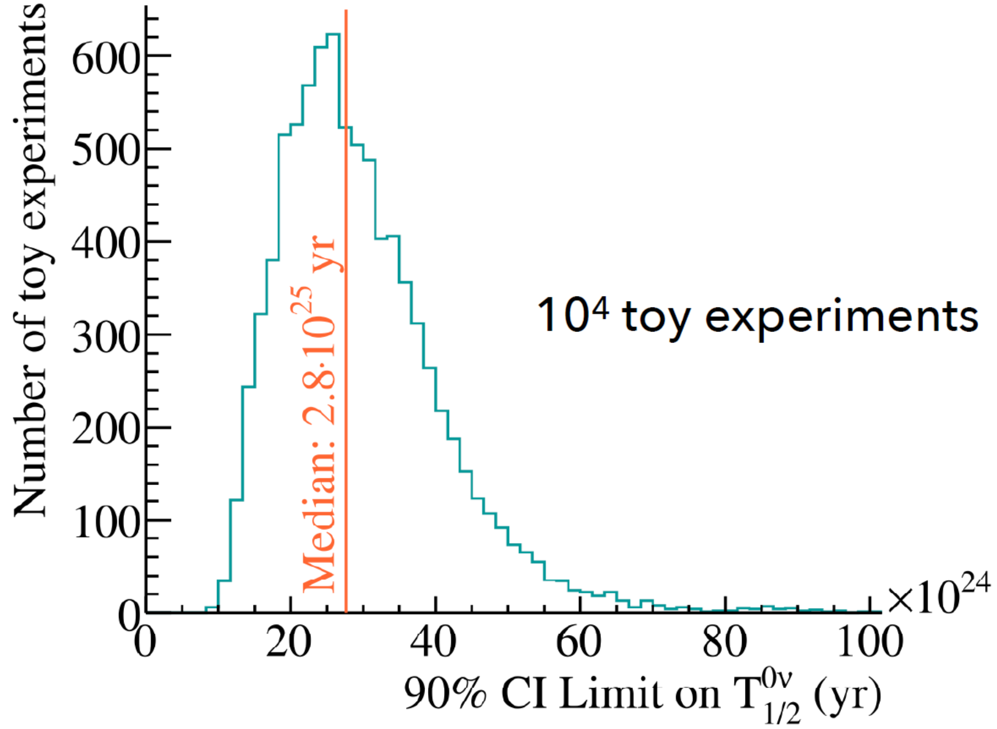
$\Gamma^{0\nu} = (0.9 \pm 1.4) \cdot 10^{-26}\ \mathrm{yr}^{-1}$

No evidence of the decay

Bayesian limit (90% C.I.):

$T^{0\nu}_{1/2} > 2.2 \cdot 10^{25}$ yr

Corresponding half-life limit



Median sensitivity:

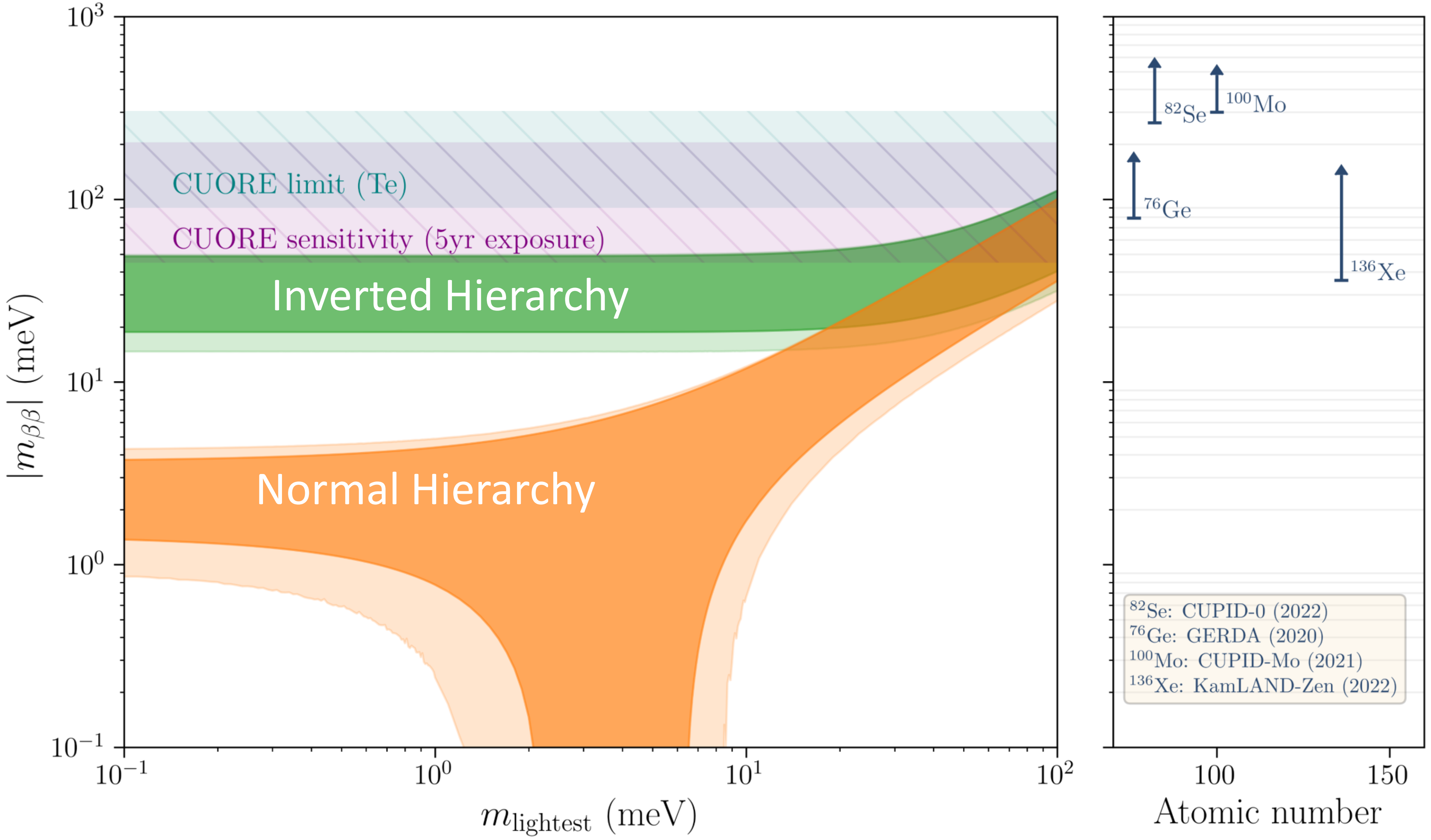
$T^{0\nu}_{1/2} > 2.8 \cdot 10^{25}$ yr

Evaluated from toy Monte Carlo

We had a background over fluctuation

Corresponding limits on $m_{\beta\beta}$

Nature 604, 53–58 (2022)



Bayesian limit
(90% C.L.):

$T^{0\nu}_{1/2} > 2.2\cdot10^{25}$ yr

+

Most recent NME

↓

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

Oscillation parameters from NUFIT 2020 are used. All limits are at 90% C.L. and 3σ uncertainty is shown on the inverted and normal hierarchy bands.

CUORE searches beyond $0\nu\beta\beta$

High mass

Stable data-taking

Low background

Granular detector

Ideal detector for multiple rare processes

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

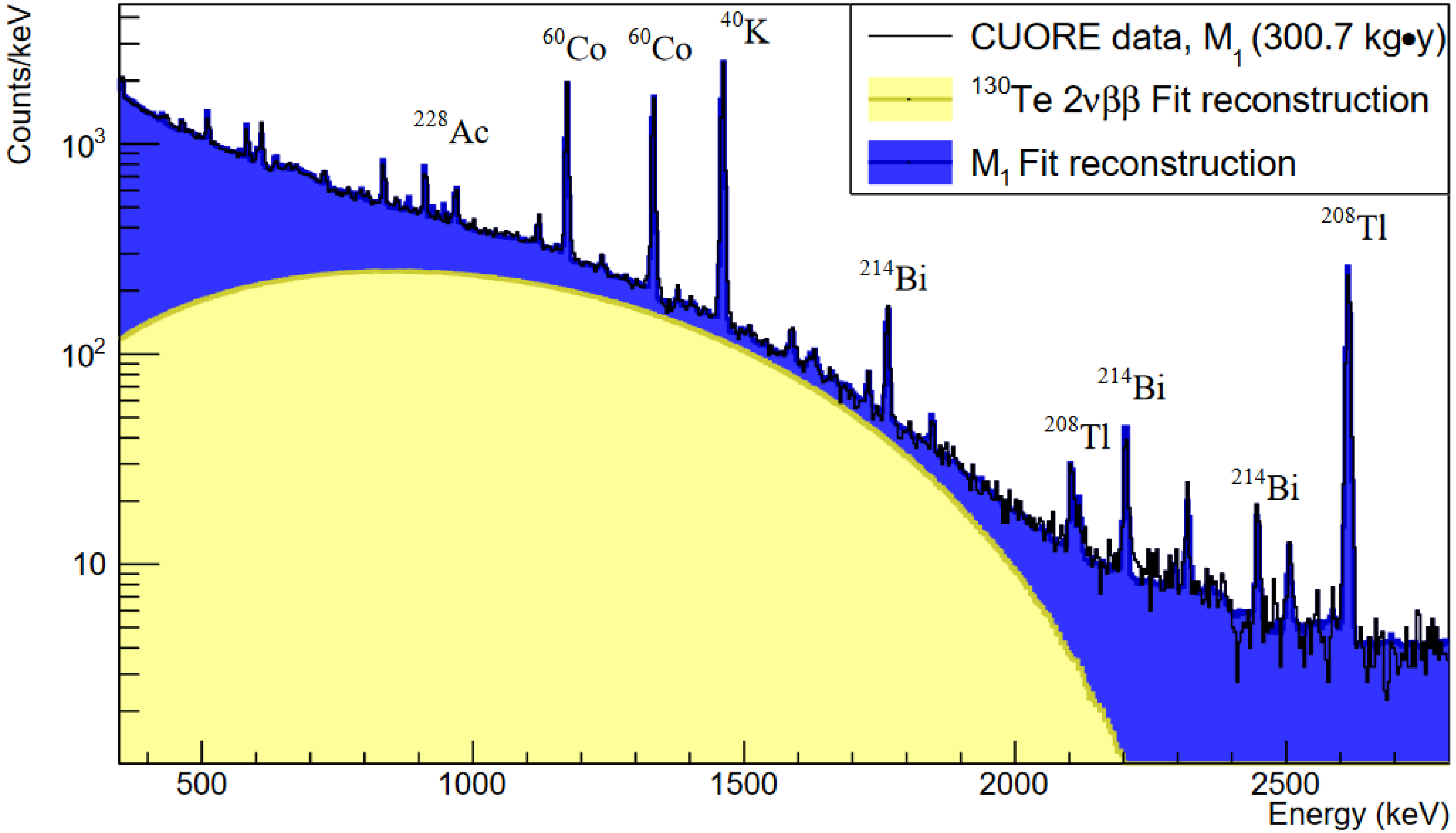
^{120}Te β^{+}EC

^{130}Te excited $0\nu\beta\beta$

^{130}Te $2\nu\beta\beta$

2νββ results – from 300.7 kg·y

10.1103/PhysRevLett.126.171801

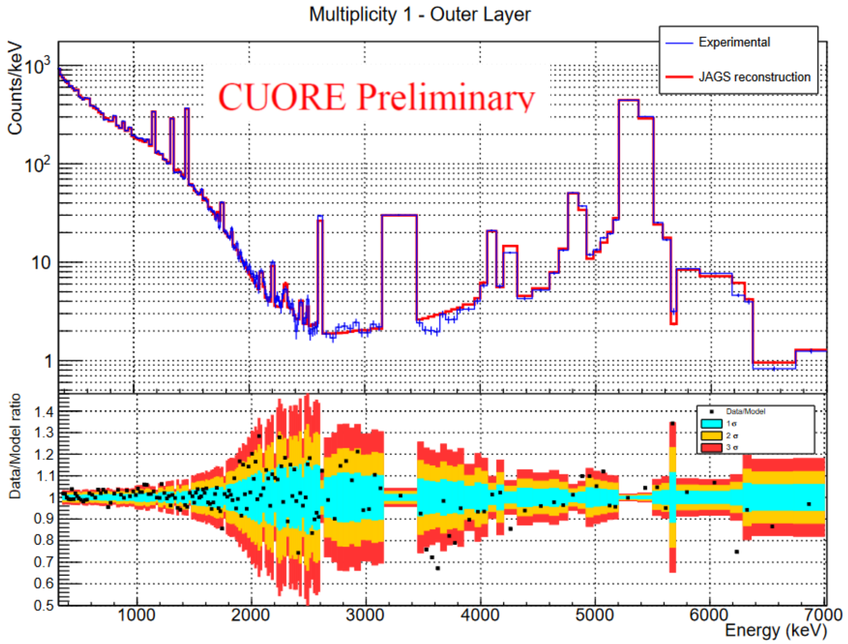


$$T_{1/2}^{2\nu} = (\,7.71^{+0.08}_{-0.06}(\mathrm{stat})^{+0.12}_{-0.15}(\mathrm{syst})\,)\cdot 10^{20}yr$$

Best measurement for ^{130}Te 2νββ

Fit of Monte Carlo simulations to the background spectrum

Reconstruct and disentangle the contributions



Different rare decays

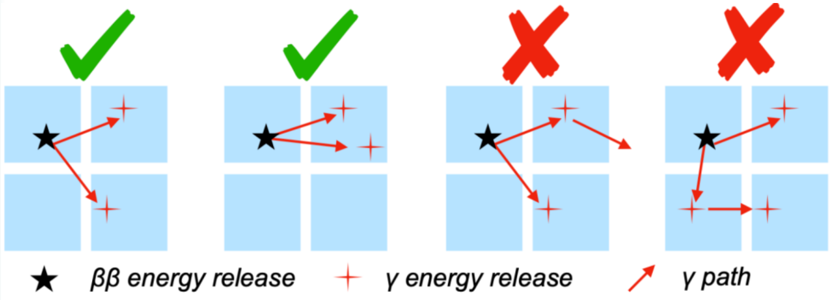
0νββ to excited states

372.5 kg·yr

Multiplicity-based selection

β and de excitation γs

M2 or M3 channels



$$T_{1/2}^{0\nu} > 5.9 \cdot 10^{24} yr\ (90\%\ \mathrm{C.L.})$$

Eur. Phys. J. C **81**, 567 (2021)

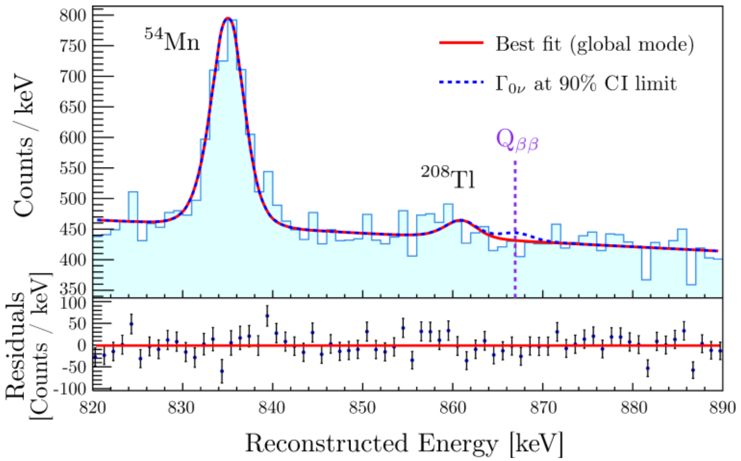
0νββ of ^{128}Te

309.33 kg·yr

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

2ν and βγ background

Direct search with M1 events



$$T_{1/2}^{0\nu} > 3.6 \cdot 10^{24} yr\ (90\%\ \mathrm{C.L.})$$

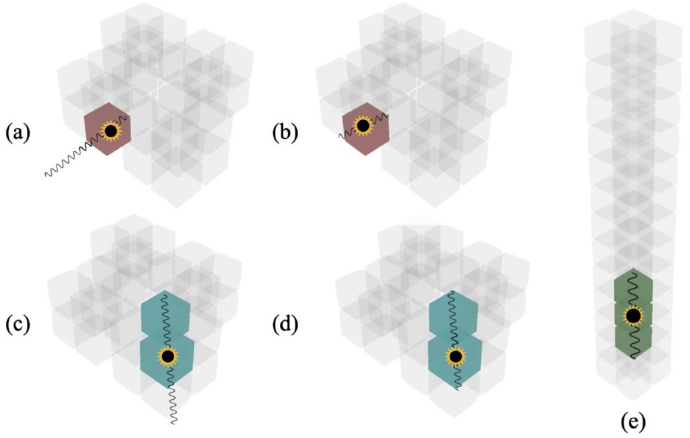
Phys. Rev. Lett. 129, 222501

0ν β^+EC of ^{120}Te

355.7 kg·yr

$$^{120}\mathrm{Te} + e^- \rightarrow {}^{120}\mathrm{Sn} + X + 2\,\gamma_{511\mathrm{keV}}$$

M1 to M3 signatures



$$T_{1/2}^{0\nu} > 2.9 \cdot 10^{22} yr\ (90\%\ \mathrm{C.L.})$$

Phys. Rev. C 105, 065504

Summary

CUORE is the first tonne-scale operating cryogenic 0νββ decay experiment

Stable data taking increasing towards 3 ton·yr

CUORE has analyzed 1 ton·yr of data

Best limit on ^{130}Te 0νββ

Initial background model defined

Best measurement of ^{130}Te 2νββ

Next steps

Background model on the full statistics, update of 0ν results with increased statistics

Other physics analyses

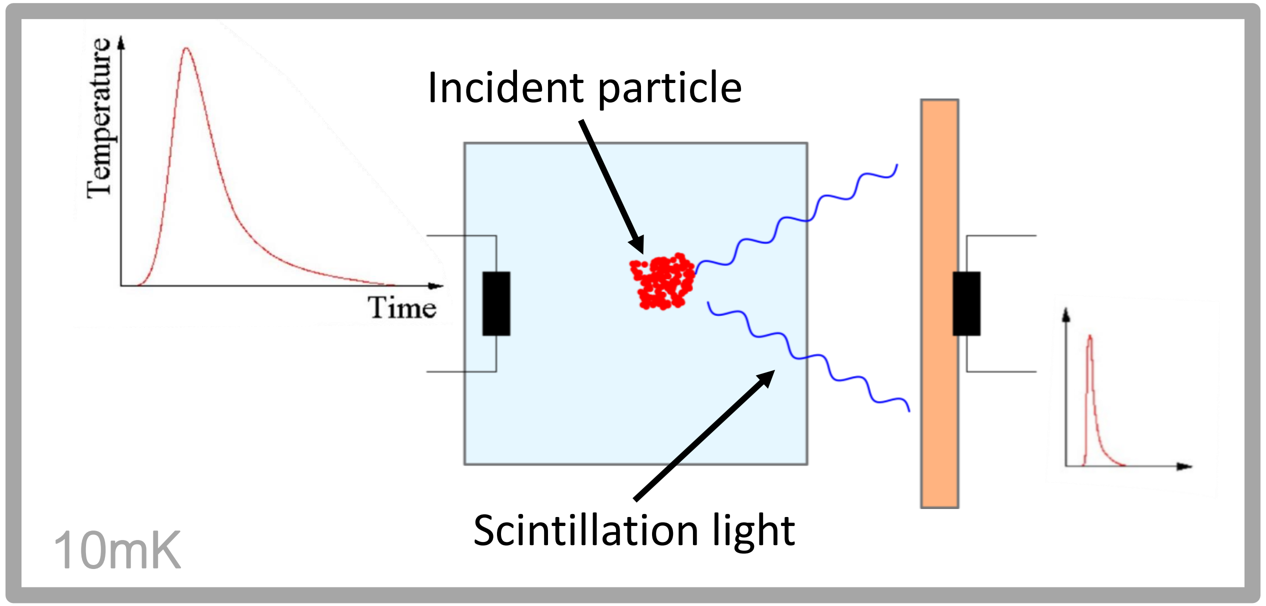
… while working on the next generation 0νββ experiment

The CUORE Upgrade with Particle IDentification (CUPID)

arXiv:1907.09376

Scintillating crystal
(Li_2MoO_4) enriched in
0νββ candidate (^{100}Mo)

Operated as a cryogenic calorimeter



Cryogenic calorimeter used as light detector

Particle identification with pulse shape and light output

Discrimination of degraded α particles

Main residual background in CUORE

Physics goal: $T^{0\nu}_{1/2} > 10^{27}$ yr

CUORE experience: ton scale cryogenic bolometer

CUPID-Mo and CUPID-0 experience with cryogenic scintillators

Thank you for your attention from all the CUORE collaboration

>110 scientists from 27 institutions in 4 countries

Constantly improving towards the next generation experiments

Backup slides

Necessary qualities of a 0νββ detector

Experimental sensitivity

Maximum measurable half-life at a given C.L.

$$S_{0\nu} \propto \sqrt{\frac{M \cdot T}{B \cdot \Delta}}$$

Isotope Mass

Mass scalability

High isotopic abundance

Energy resolution

$\Delta \sim$ ‰ at Q_{value}

↕

2νββ induced background

Background

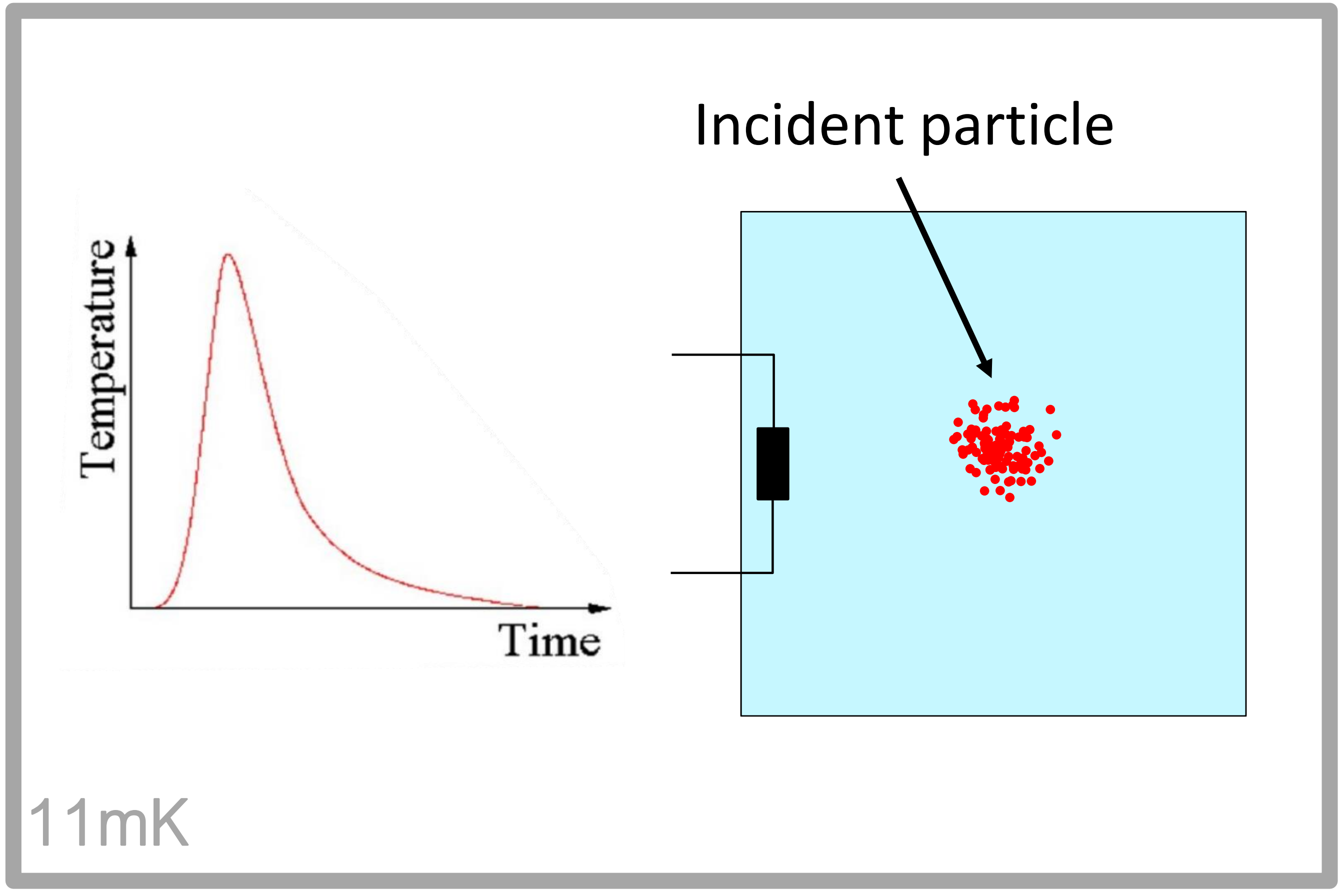
High purity materials

Rejection techniques

Maximized through cryogenic calorimeters

Cryogenic calorimeters: detector concept

Detecting energy as temperature increase



Thermometer is made of neutron transmutation doped germanium

Energy resolution

Provided by the technique

Background

Control of materials

Isotope Mass

^{130}Te has ~30% natural istotopic abundance

Multiple modules

Optimum filter – more in depth

Digital filter deconvolving the noise

Transfer function that maximizes SNR

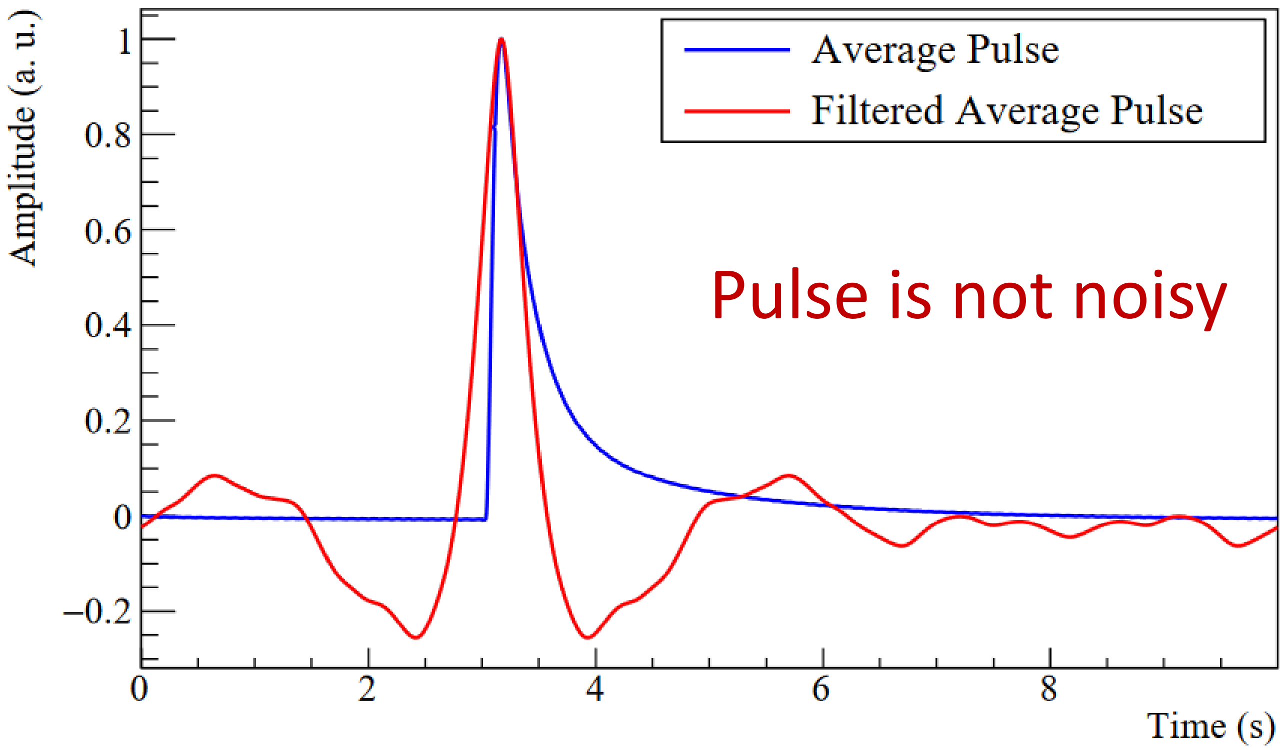
$$H(\omega) \sim \frac{S(\omega)}{N(\omega)}$$

Template signal

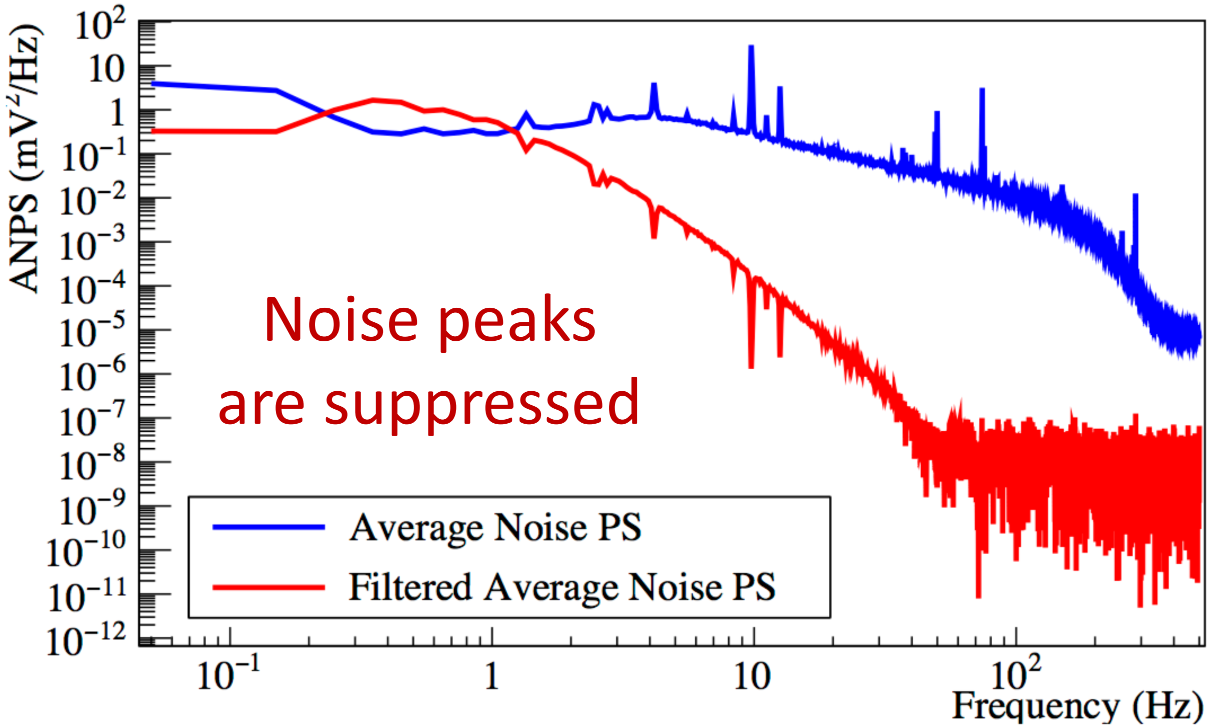
Modelled with average signal

Noise of the system

Modelled with average noise power spectrum



Pulse is not noisy



Noise peaks are suppressed

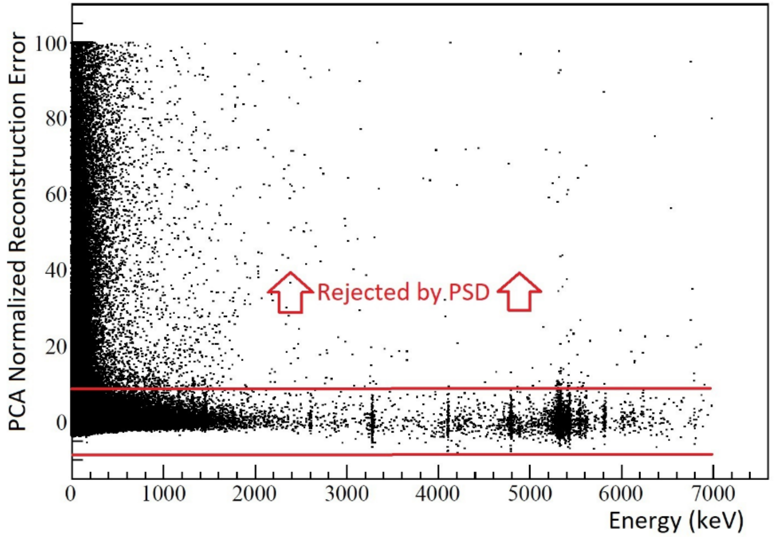
PSD trough PCA

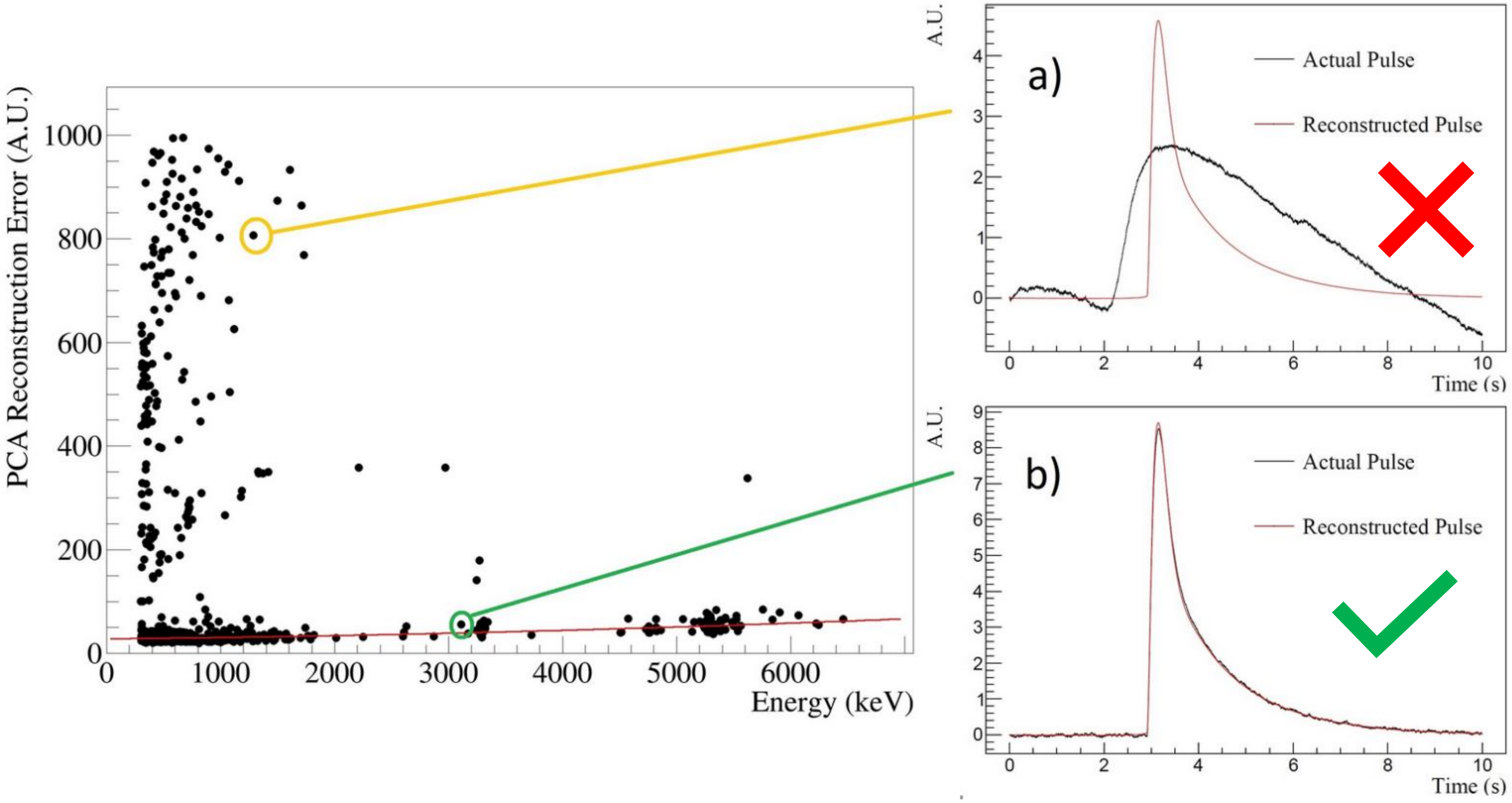
PCA says that the average pulse is the main component

Using a single component to reconstruct the pulse

Error given by the difference with rescaling

$$RE = \sqrt{\sum_{i=1}^{n} \left(\mathbf{x}_i - (\mathbf{x} \cdot \mathbf{w})\mathbf{w}_i\right)^2}$$



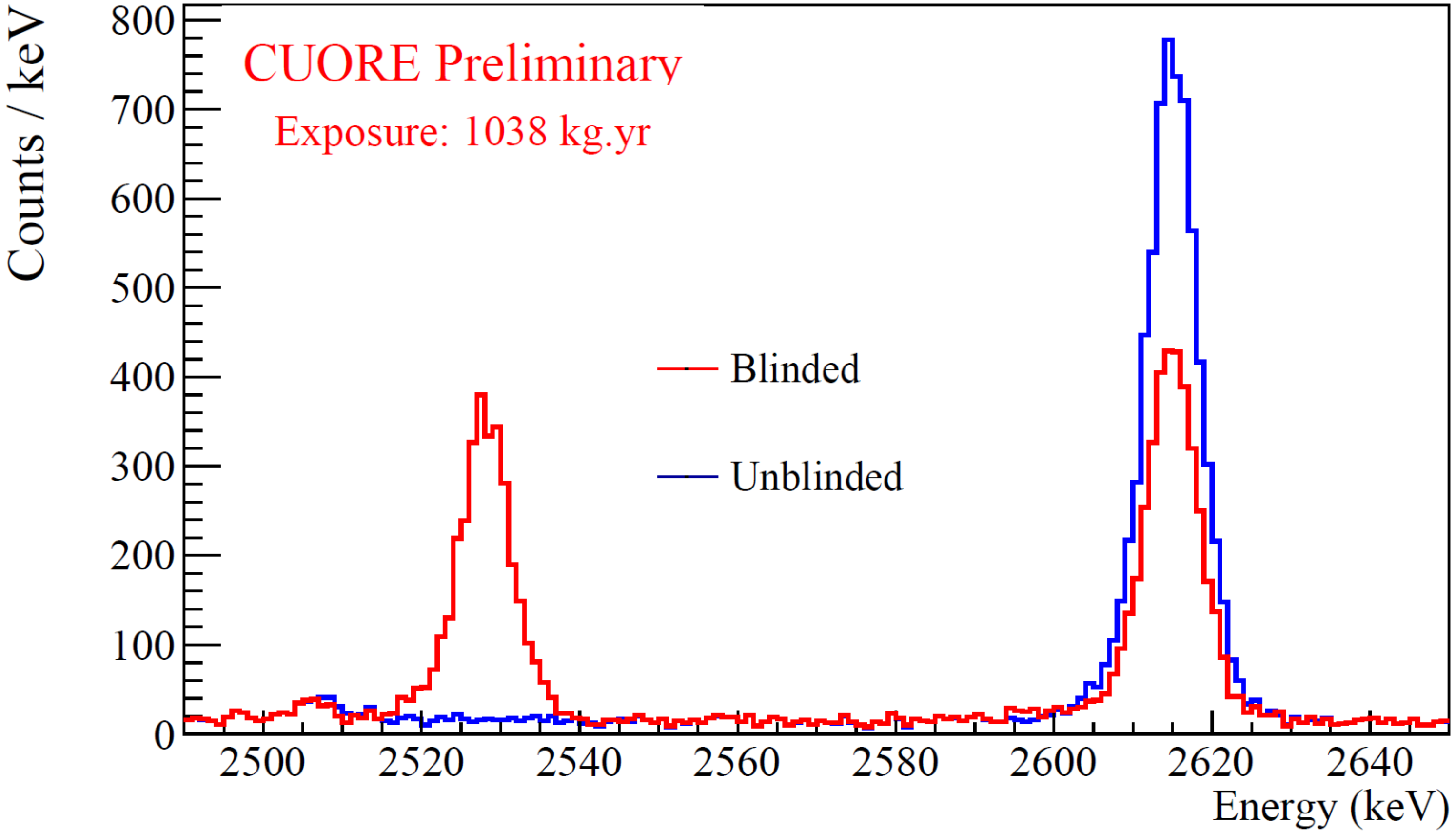


Error is normalized with respect to energy

Blinding of the background data

Nature 604, 53–58 (2022)

Goal: cover the region where 0νββ is expected



Random fraction of 2615keV events moved around the Qvalue

Encryption of the original event energies

Events are decrypted after the analysis is fixed

How 0νββ fit is performed

Fit model parameters:

$\Gamma^{0\nu} + {}^{60}\mathrm{Co}$ rate + linear background

Common to all datasets

Common and rescaled for decay

Rate is dataset dependent, slope is constant

↓

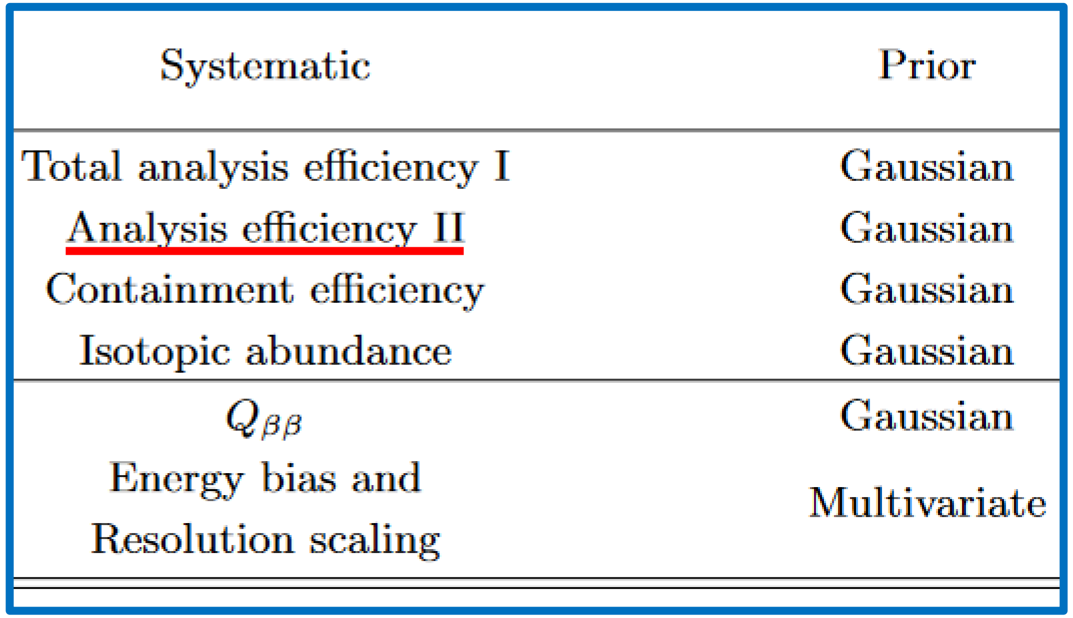
Bayesian fit with BAT software

Using non-negative uninformative priors for the rates

How 0νββ systematics are treated

Systematic uncertainties due to the variation of nuisance parameters

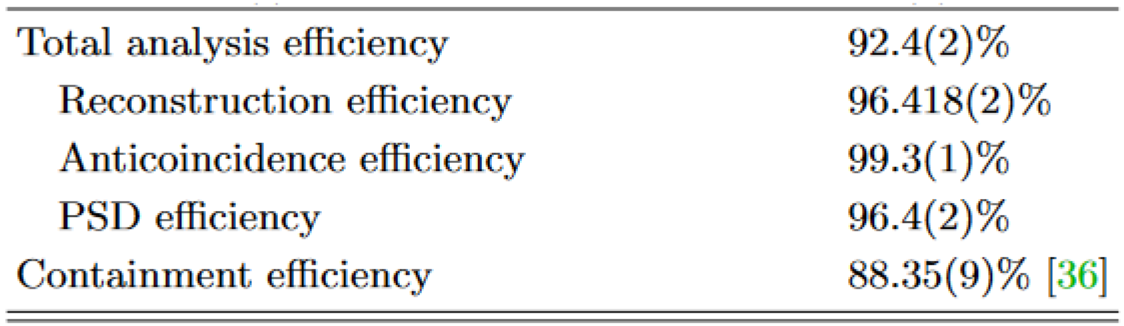
Included one by one in the fit, checking effects on the outcome



Systematic	Prior
Total analysis efficiency I	Gaussian
Analysis efficiency II	Gaussian
Containment efficiency	Gaussian
Isotopic abundance	Gaussian
$Q_{\beta\beta}$	Gaussian
Energy bias and Resolution scaling	Multivariate

Discrepancies of the PSD efficiency between single calorimeters

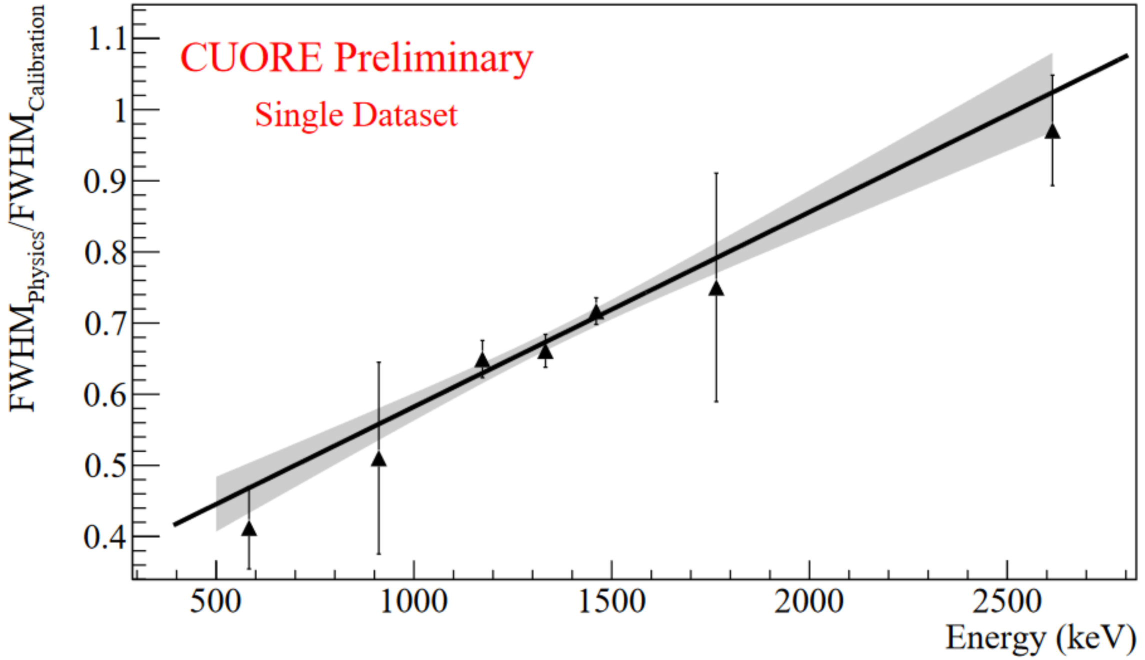
Efficiencies in the analysis and relative uncertainties



Total analysis efficiency	92.4(2)%
Reconstruction efficiency	96.418(2)%
Anticoincidence efficiency	99.3(1)%
PSD efficiency	96.4(2)%
Containment efficiency	88.35(9)% [36]

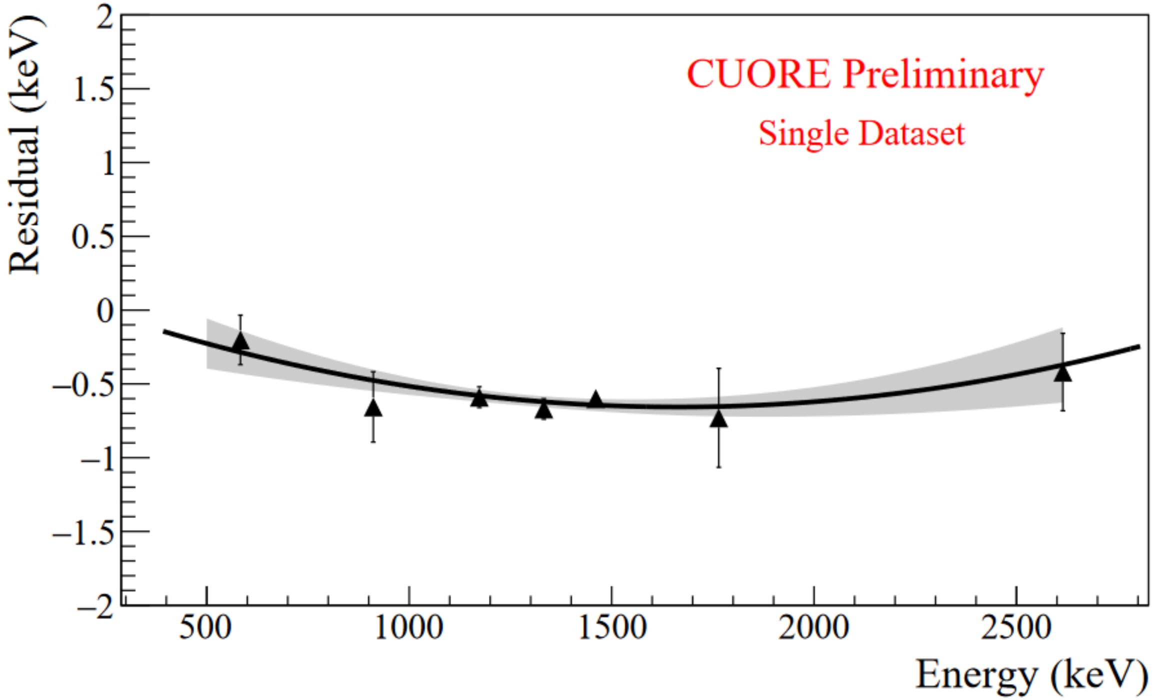
[36] C. Alduino et al. (CUORE), Phys. Rev. C 93, 045503 (2016), arXiv:1601.01334 [nucl-ex].

Resolution scaling and energy bias → included as nuisances in the 0νββ fit



Energy resolution scales with energy

Used to get the resolution at QValue

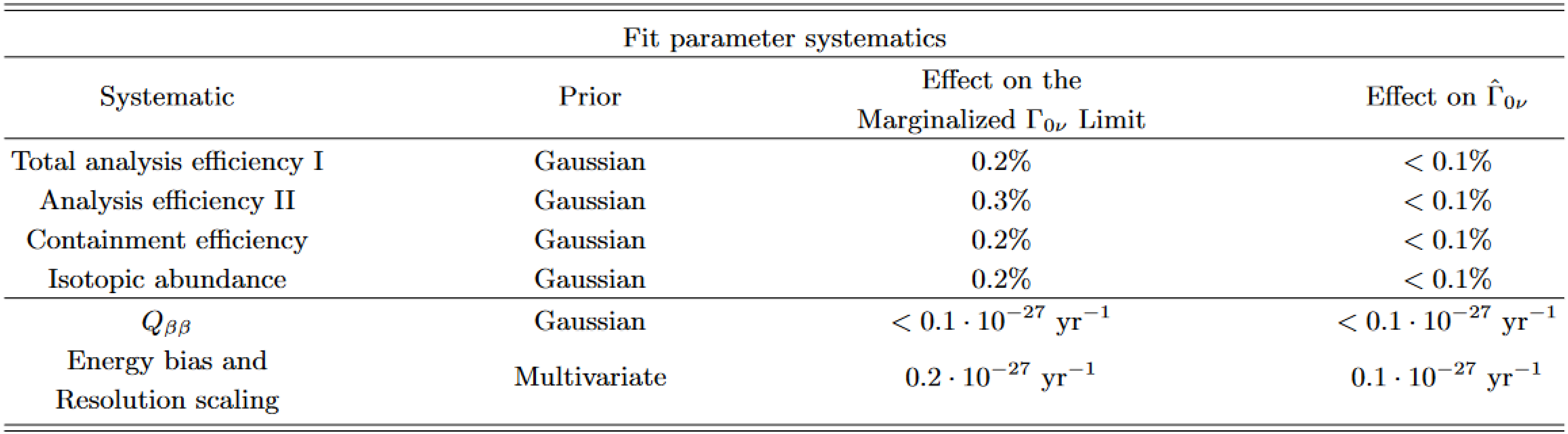


Energy bias due to imperfect calibration

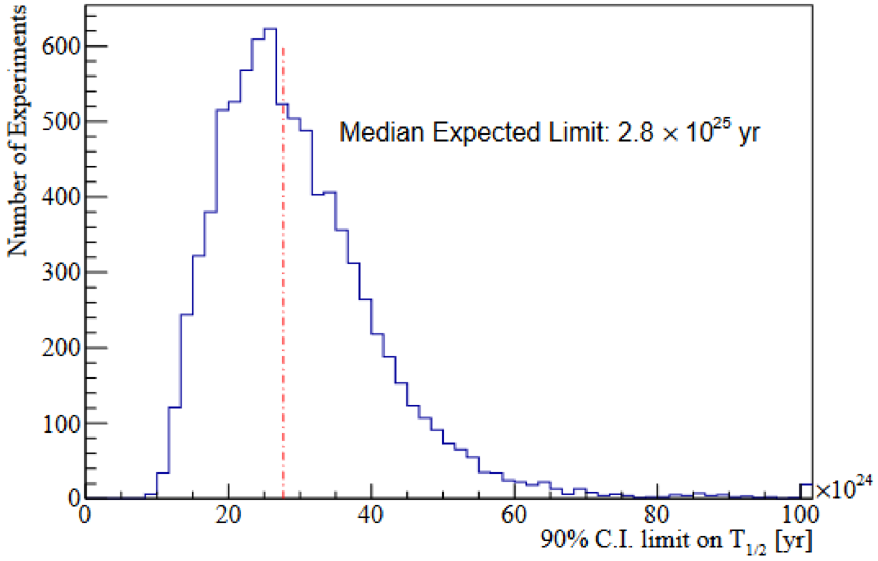
Fed to the fit as nuisance parameter

Both dataset dependent

Systematic uncertainties effect on the 0νββ result



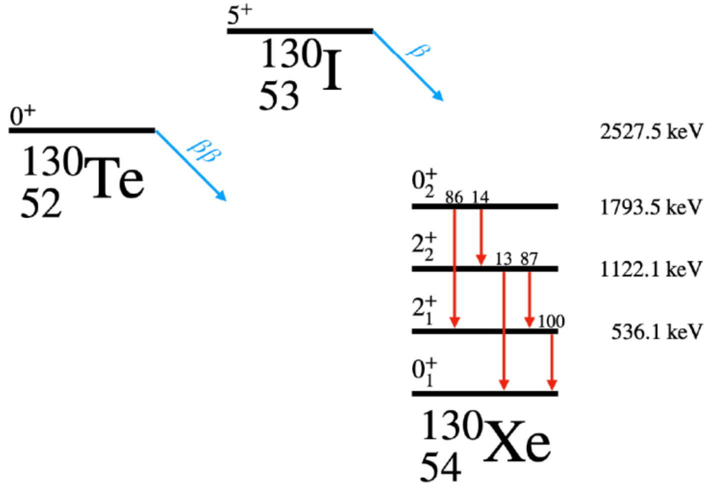
Fit parameter systematics			
Systematic	Prior	Effect on the Marginalized $\Gamma_{0\nu}$ Limit	Effect on $\hat{\Gamma}_{0\nu}$
Total analysis efficiency I	Gaussian	0.2%	$< 0.1\%$
Analysis efficiency II	Gaussian	0.3%	$< 0.1\%$
Containment efficiency	Gaussian	0.2%	$< 0.1\%$
Isotopic abundance	Gaussian	0.2%	$< 0.1\%$
$Q_{\beta\beta}$	Gaussian	$< 0.1 \cdot 10^{-27}$ yr^{-1}	$< 0.1 \cdot 10^{-27}$ yr^{-1}
Energy bias and Resolution scaling	Multivariate	$0.2 \cdot 10^{-27}$ yr^{-1}	$0.1 \cdot 10^{-27}$ yr^{-1}



Effects evaluated with toy experiments

0νββ to excited states – 372.5 kg·y

Eur. Phys. J. C **81**, 567 (2021)



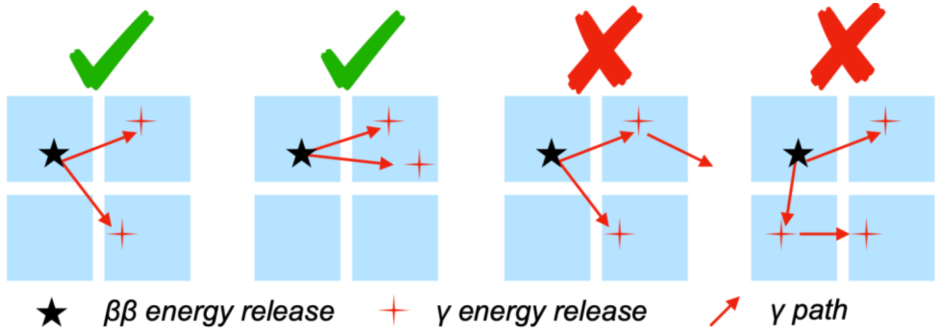
Exploit multiplicity to access specific signatures

β and de excitation γs

M2 or M3 channels

Improved previous result by factor 5

$$T_{1/2}^{0\nu} > 5.9 \cdot 10^{24} yr \; (90\% \, \mathrm{C.L.})$$



Neutrinoless β^+EC decay of ^{120}Te - 355.7 kg·y of TeO_2

Phys. Rev. C 105, 065504

Clear process under study:

$$^{120}\mathrm{Te} + e^- \rightarrow {}^{120}\mathrm{Sn} + X + 2\,\gamma_{511\mathrm{keV}}$$

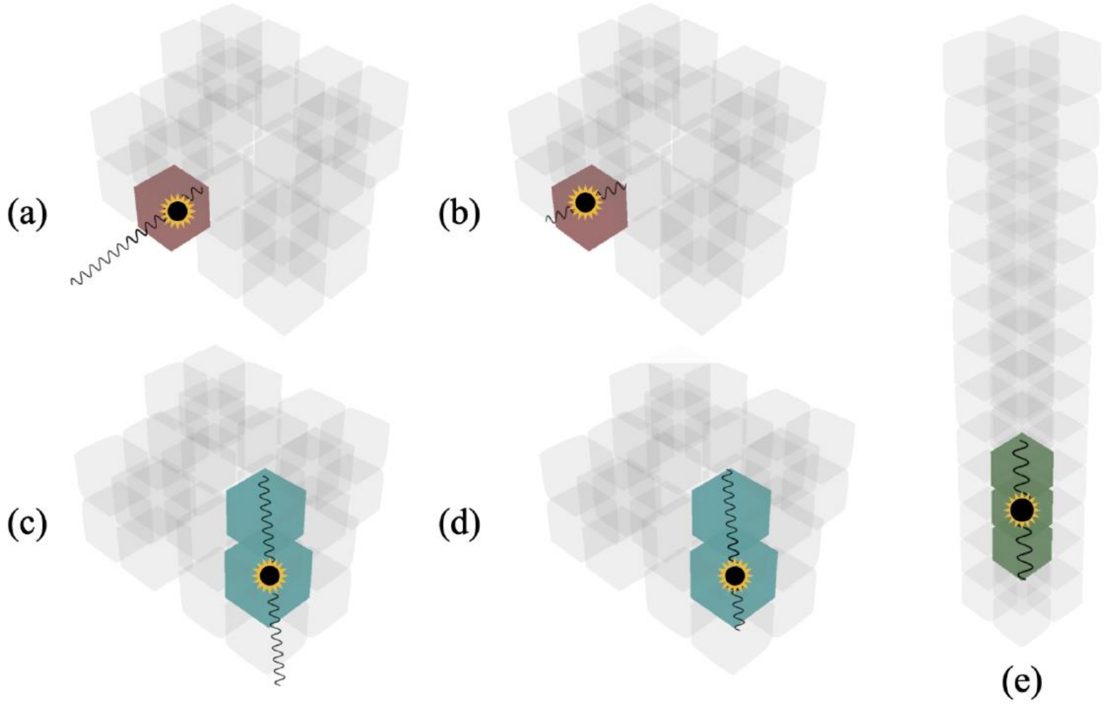
Isotopic abundance 0.09%

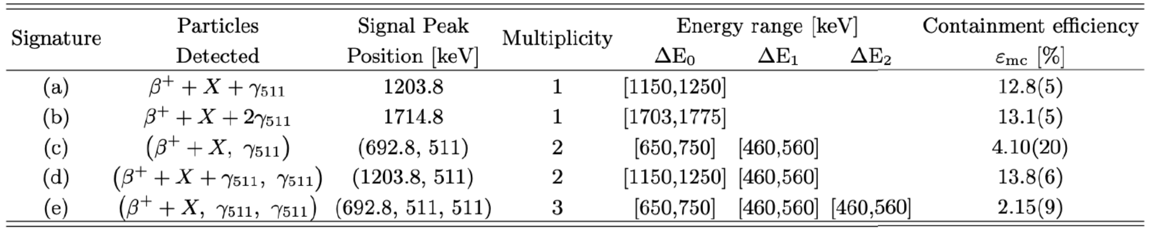
0.24 kg·yr of ^{120}Te

Multiple M1 to M3 signatures

10 times better than previous studies

$$T_{1/2}^{0\nu} > \; 2.9 \cdot 10^{22} yr \; (90\% \; \mathrm{C.L.})$$





Signature	Particles Detected	Signal Peak Position [keV]	Multiplicity	Energy range [keV] ΔE_0	ΔE_1	ΔE_2	Containment efficiency ε_{mc} [%]
(a)	$\beta^+ + X + \gamma_{511}$	1203.8	1	[1150,1250]			12.8(5)
(b)	$\beta^+ + X + 2\gamma_{511}$	1714.8	1	[1703,1775]			13.1(5)
(c)	$(\beta^+ + X,\ \gamma_{511})$	(692.8, 511)	2	[650,750]	[460,560]		4.10(20)
(d)	$(\beta^+ + X + \gamma_{511},\ \gamma_{511})$	(1203.8, 511)	2	[1150,1250]	[460,560]		13.8(6)
(e)	$(\beta^+ + X,\ \gamma_{511},\ \gamma_{511})$	(692.8, 511, 511)	3	[650,750]	[460,560]	[460,560]	2.15(9)

0νββ decay of ^{128}Te - 309.33 kg·y of TeO$_2$

Phys. Rev. Lett. 129, 222501

Second most abundant isotope

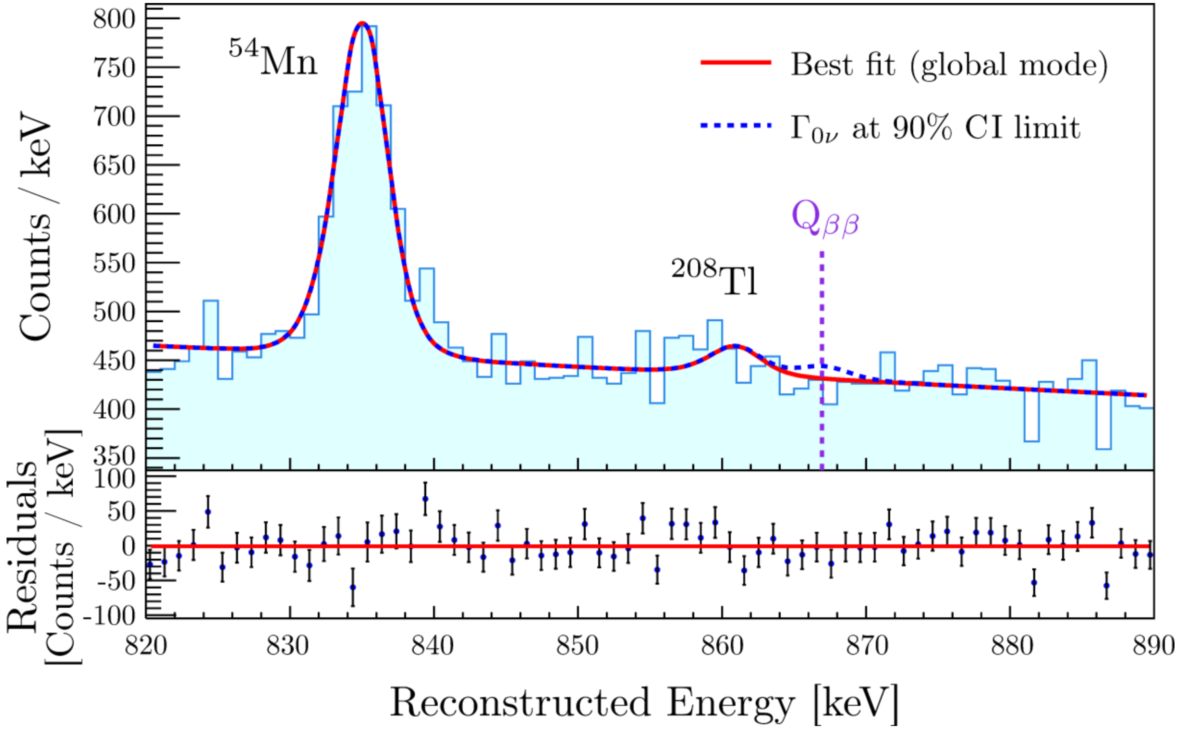
i.a. 31.7% → 188 kg·yr of ^{128}Te

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

2ν and βγ background

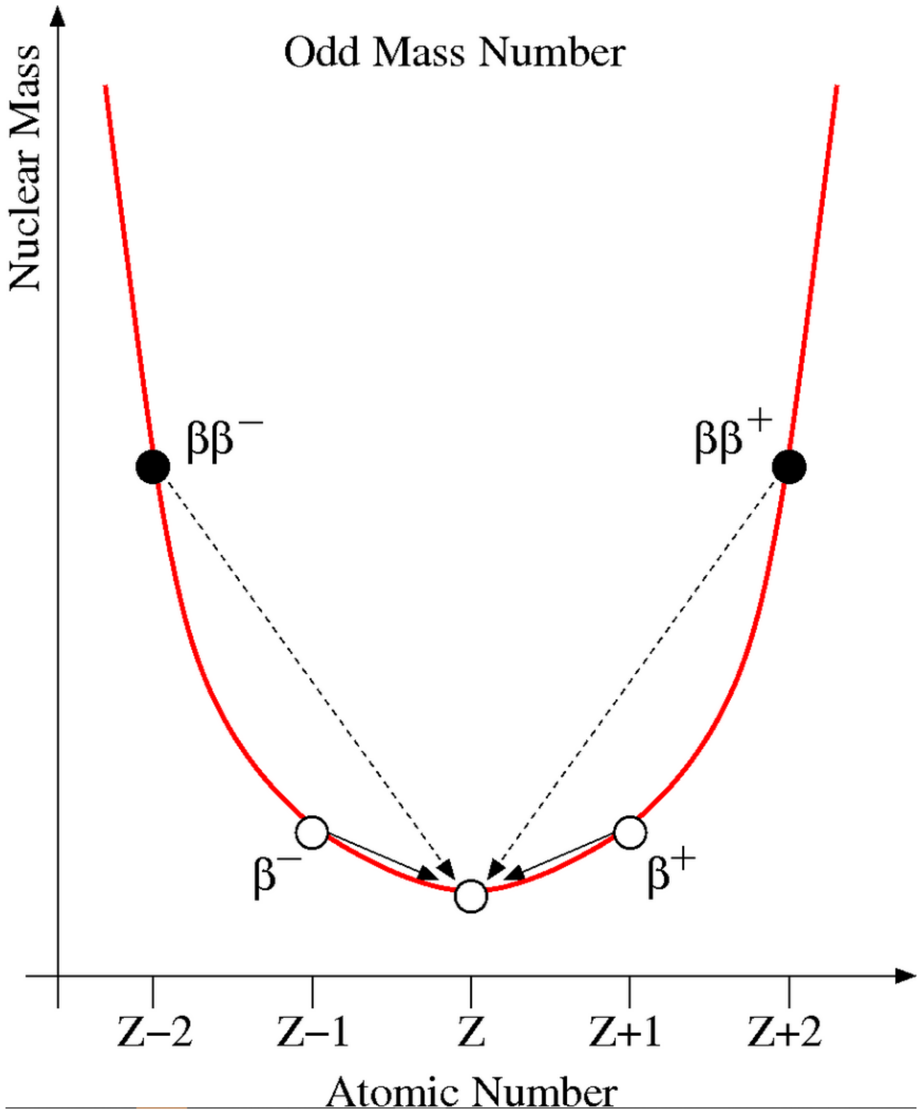
Selecting M1 events in the region of interest

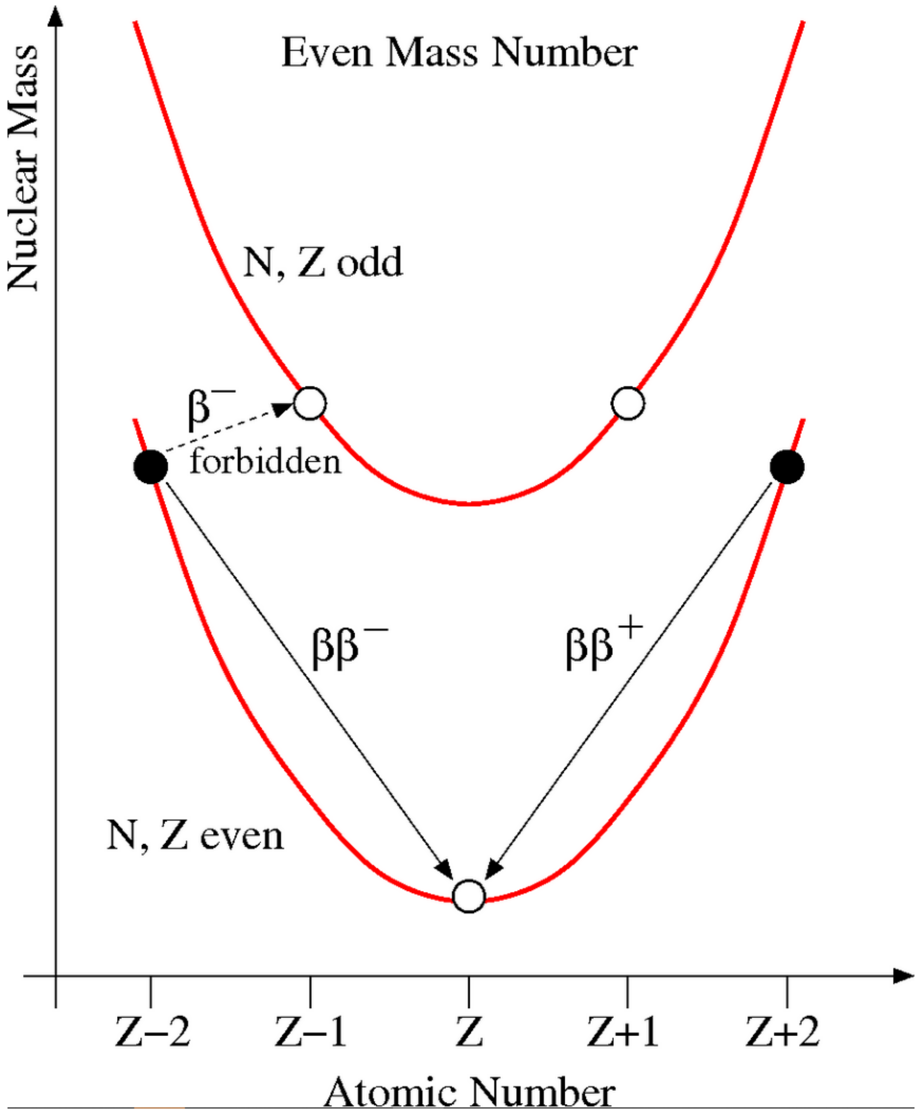
30 times better than previous direct limit



$$\boxed{T_{1/2}^{0\nu} > \ 3.6 \cdot 10^{24} yr \ (90\% \ \mathrm{C.L.})}$$

Double beta decay and nuclear structure





ββ decay is suppressed with respect to β decay, and it is therefore difficult or impossible to observe

β decay is forbidden for certain even-even nuclei, so ββ decay may be seen

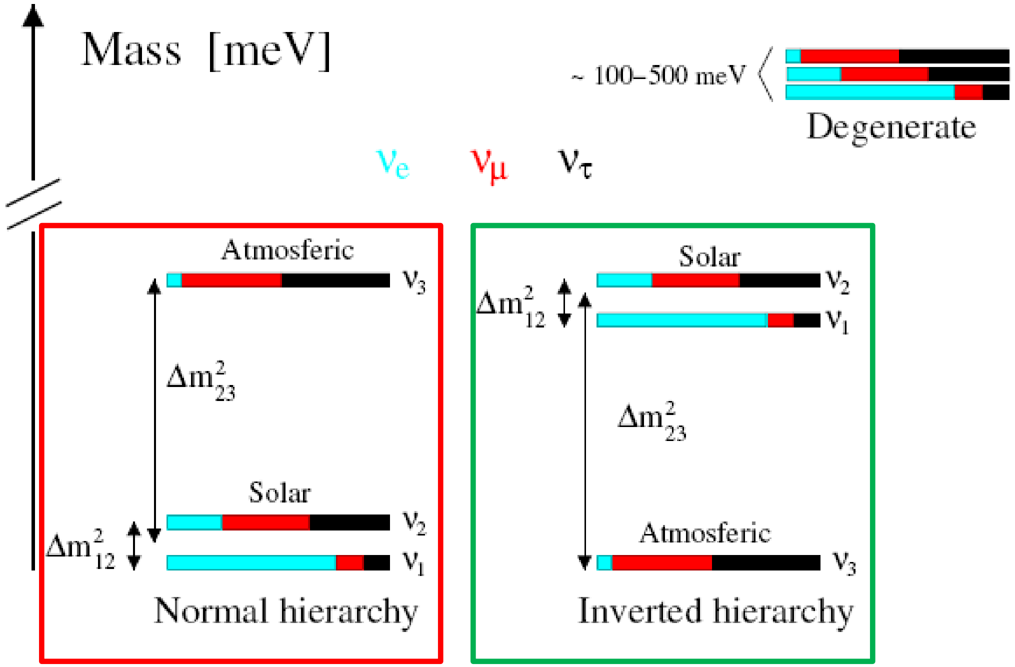
0νββ formulas and theoretical references

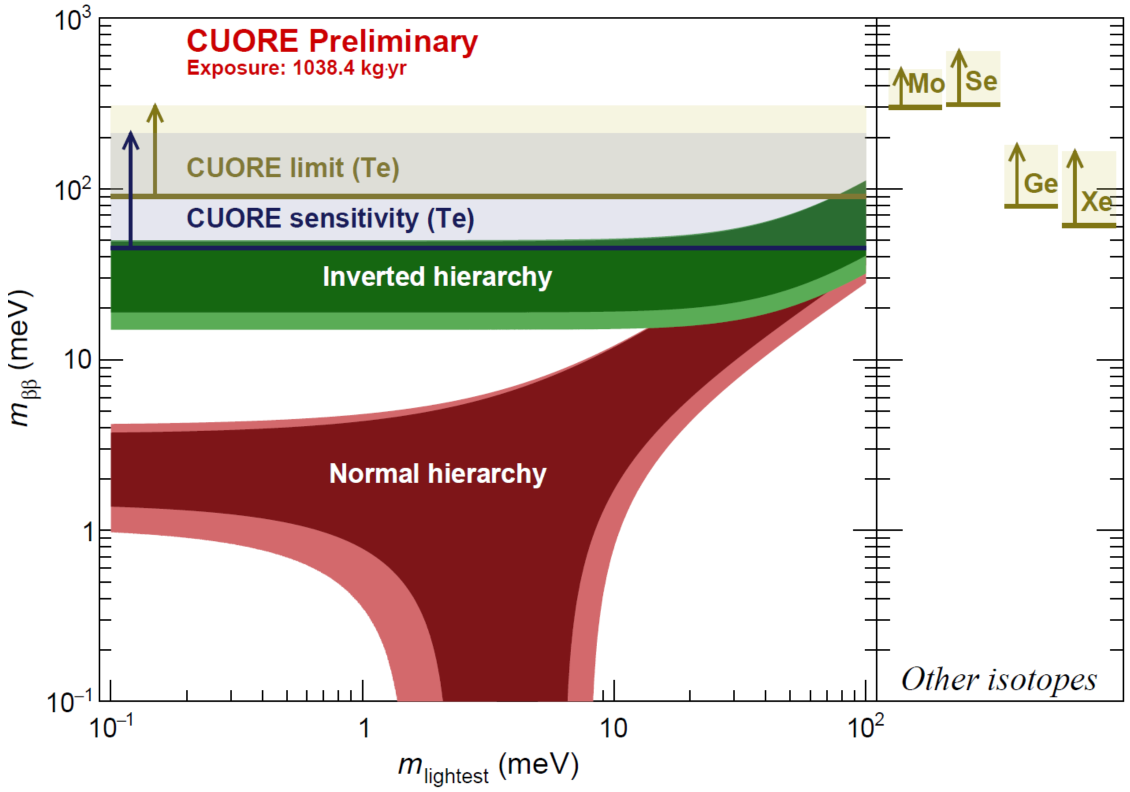
$$\Gamma^{0\nu} \propto G^{0\nu}(Q,Z)\ \ |M^{0\nu}|^2\ \ |\langle m_{\beta\beta}\rangle|^2$$

Phase space factor

Nuclear matrix element

Majorana mass





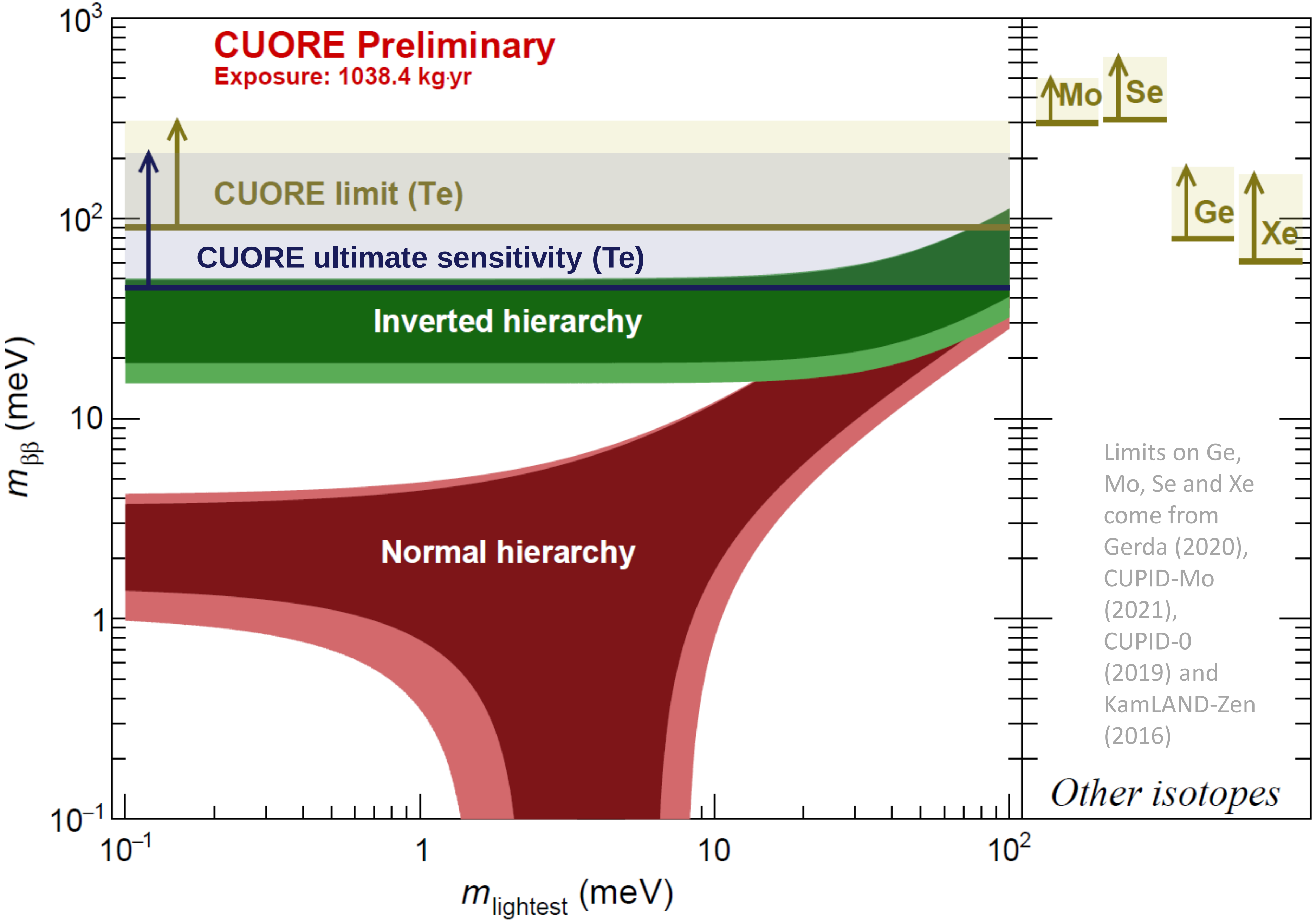
$$N_{Ev} = M\frac{\chi\cdot N_{Av}}{M_{mol}}\eta\frac{T}{\tau^{0\nu}}$$

χ = stechyiometric coeff.

η = isotopic abundance

Corresponding limits on $m_{\beta\beta}$

Nature 604, 53–58 (2022)



Limits on Ge, Mo, Se and Xe come from Gerda (2020), CUPID-Mo (2021), CUPID-0 (2019) and KamLAND-Zen (2016)

Oscillation parameters from NUFIT 2020 are used. All limits are at 90% C.L. and 3σ uncertainty is shown on the inverted and normal hierarchy bands.

Bayesian limit (90% C.L.):

$T^{0\nu}_{1/2} > 2.2 \cdot 10^{25}$ yr

+

Most recent NME

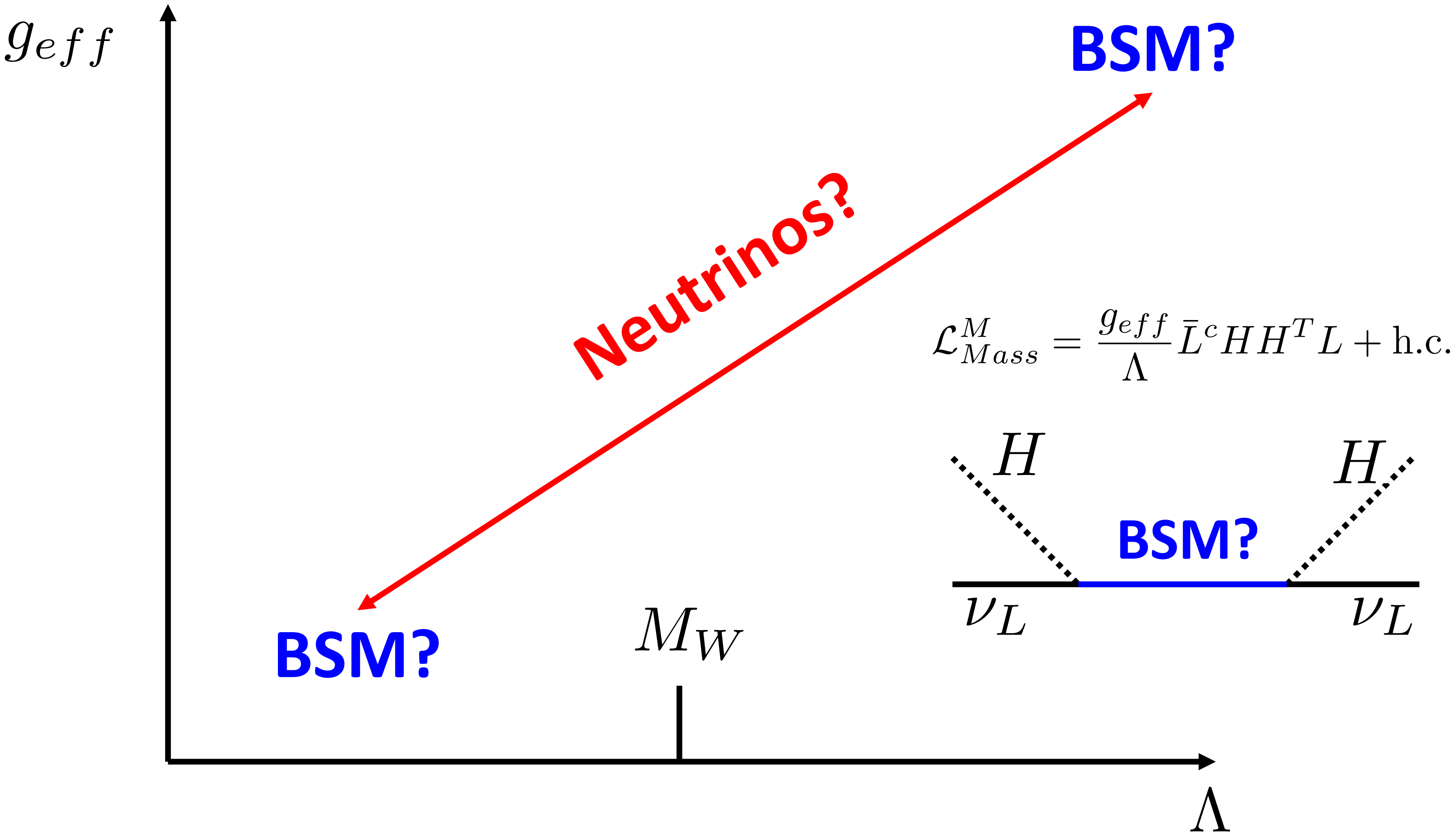
↓

$m_{\beta\beta} <$ (90-305) meV

Theoretical importance of 0νββ searches

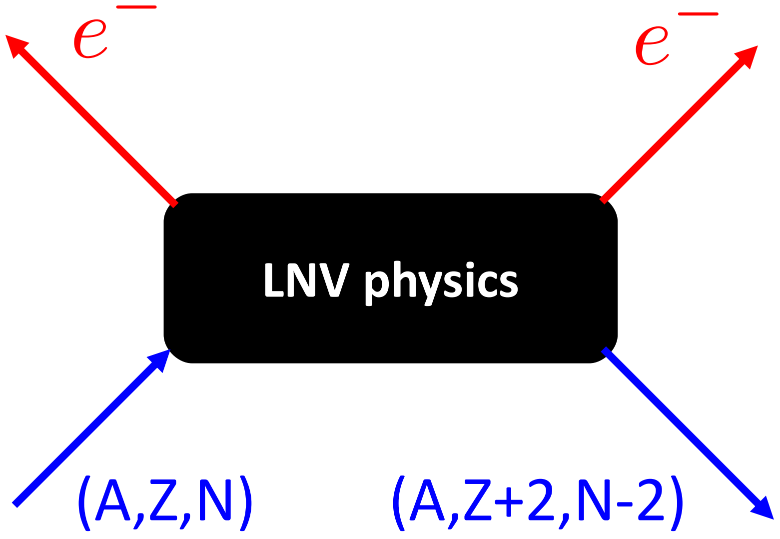
Different possible generator masses and couplings to neutrinos

- All BSM features → **new phenomenologies**



$$\mathcal{L}^{M}_{Mass} = \frac{g_{eff}}{\Lambda} \bar{L}^c H H^T L + \text{h.c.}$$

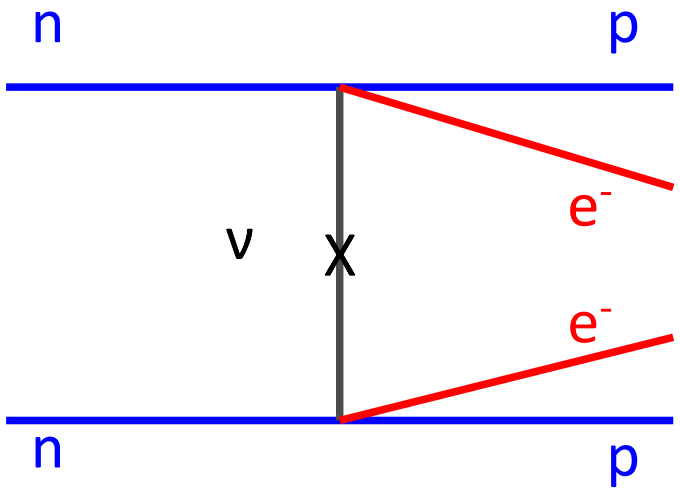
Theoretical importance of 0νββ searches

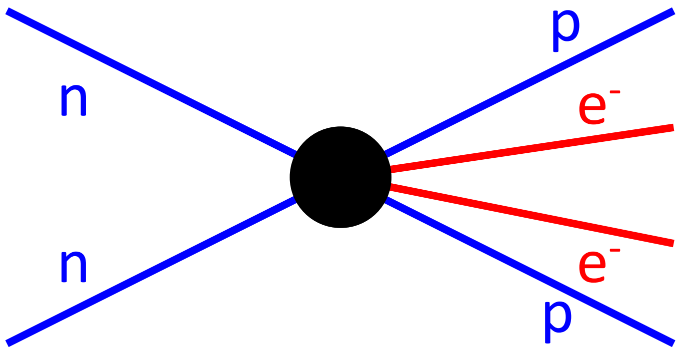


Black Box

- Unpacked differently by different mass models
- Independent by the model chosen

- Each model leads to **different predictions** with respect to the physics of 0νββ
- Two different main scenarios:





Techniques for event selection

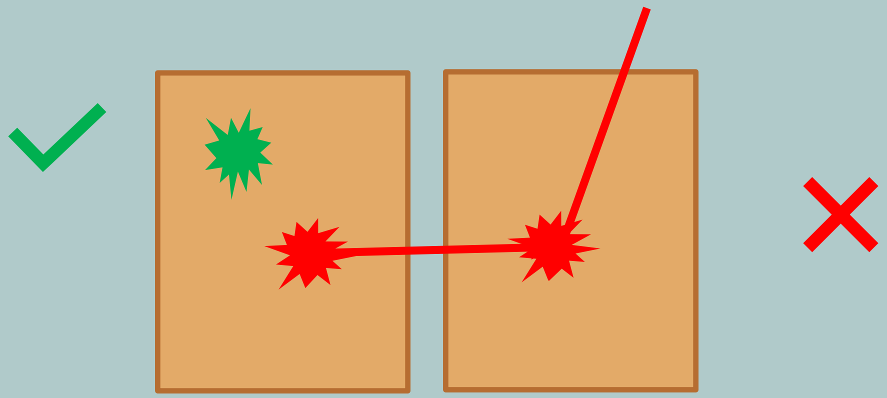
Nature 604, 53–58 (2022)

Preserve only 0νββ candidate events with best possible efficiency

Anticoincidence cut (AC)

0νββ leaves all energy in a crystal

Select events accordingly



Time resolution is ±5ms

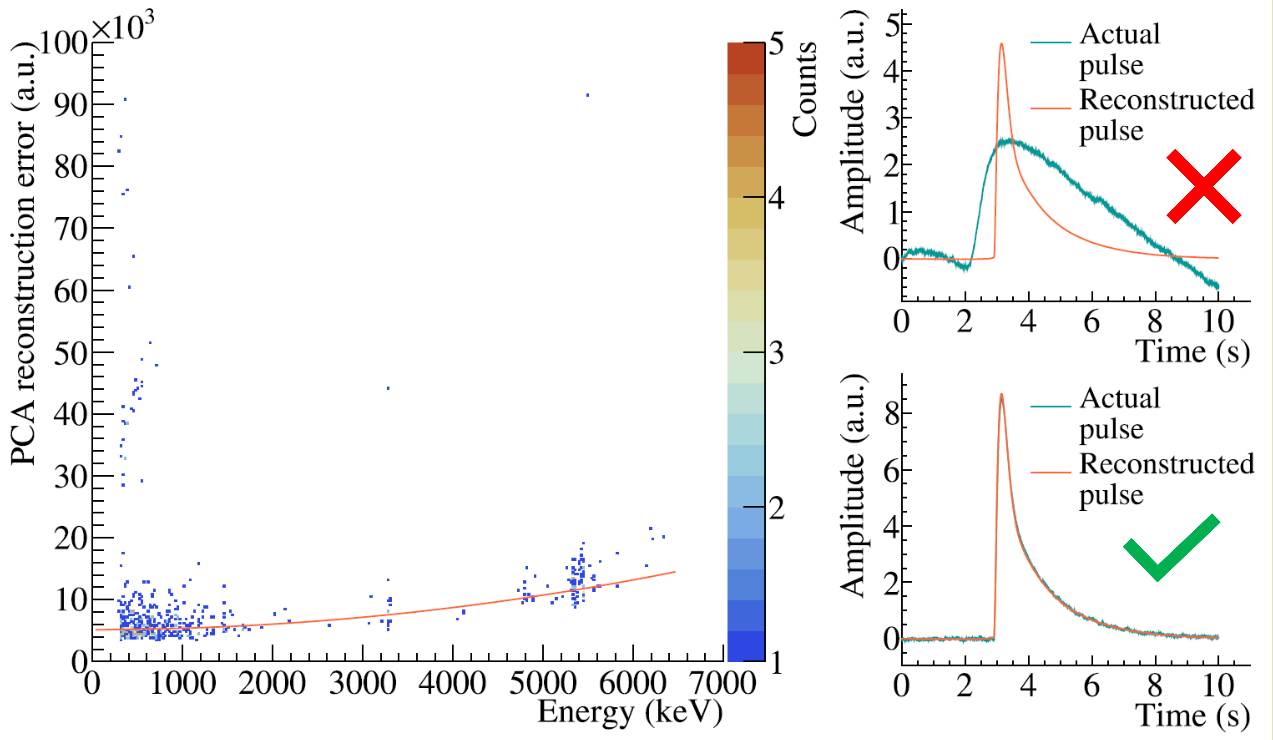
Efficiency = $99.3\%_{\text{Anticoincidence}} \cdot 88.3\%_{\text{containment}}$

Efficiency uncertainties included in the final fit

Pulse shape discrimination (PSD)

Reconstruct the pulse with single PCA component

Difference is discrimination metric



Efficiency = 96.4%

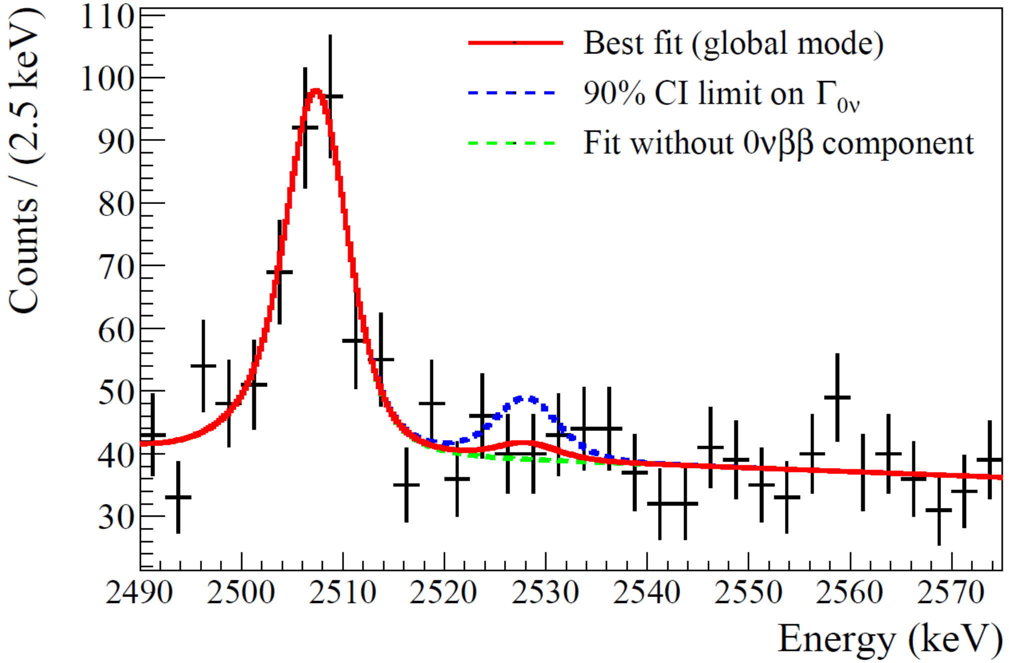
0νββ results

Nature 604, 53–58 (2022)

Unbinned Bayesian fit

Simultaneous on all datasets

Nuisance parameters as systematics



Best fit value:

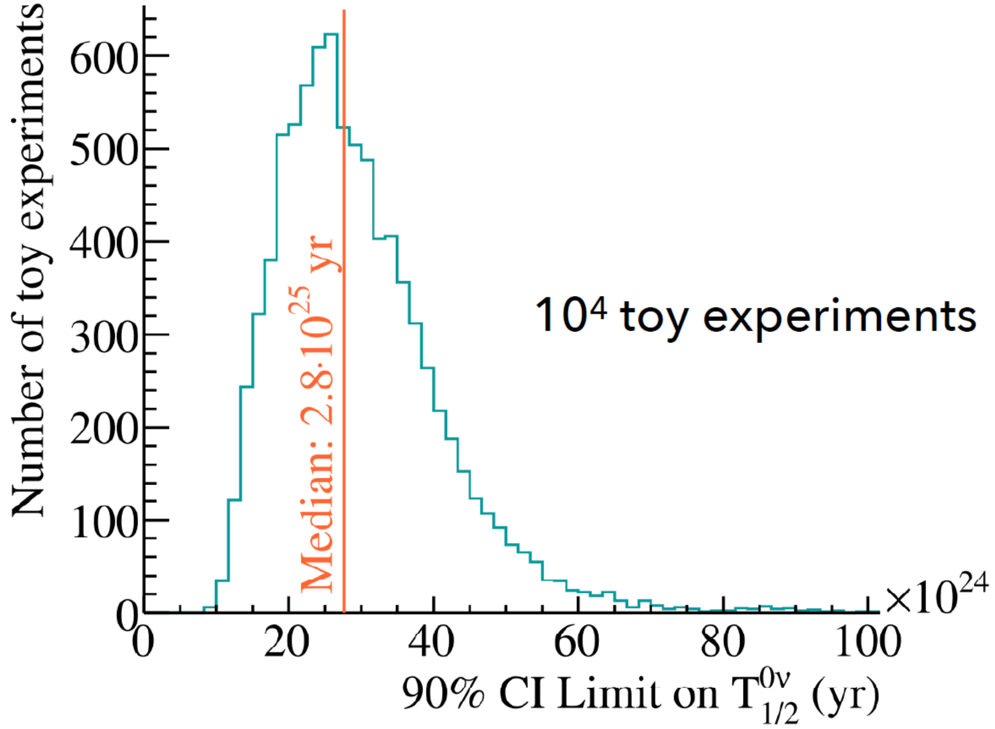
$\Gamma^{0\nu} = (0.9 \pm 1.4) \cdot 10^{-26}\ \mathrm{yr}^{-1}$

No evidence of the decay

Bayesian limit (90% C.I.):

$T^{0\nu}_{1/2} > 2.2 \cdot 10^{25}$ yr

Corresponding half-life limit



10^4 toy experiments

Median sensitivity:

$T^{0\nu}_{1/2} > 2.8 \cdot 10^{25}$ yr

Evaluated from toy Monte Carlo

We had a background over fluctuation