ICHEP 2022 BOLOGNA

CUPID-0

Latest results from CUPID-0

Sapienza Università di Roma

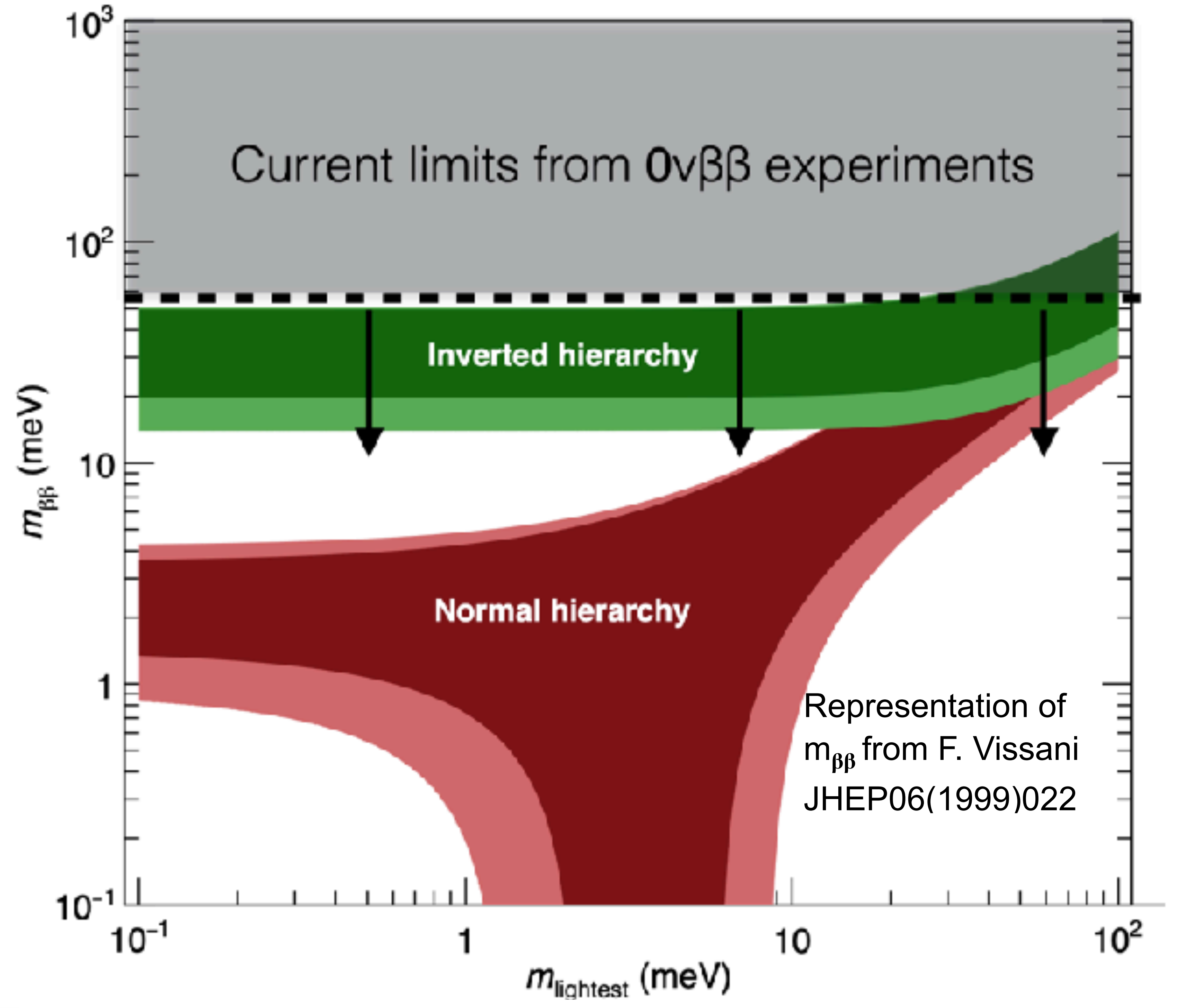
INFN Istituto Nazionale di Fisica Nucleare

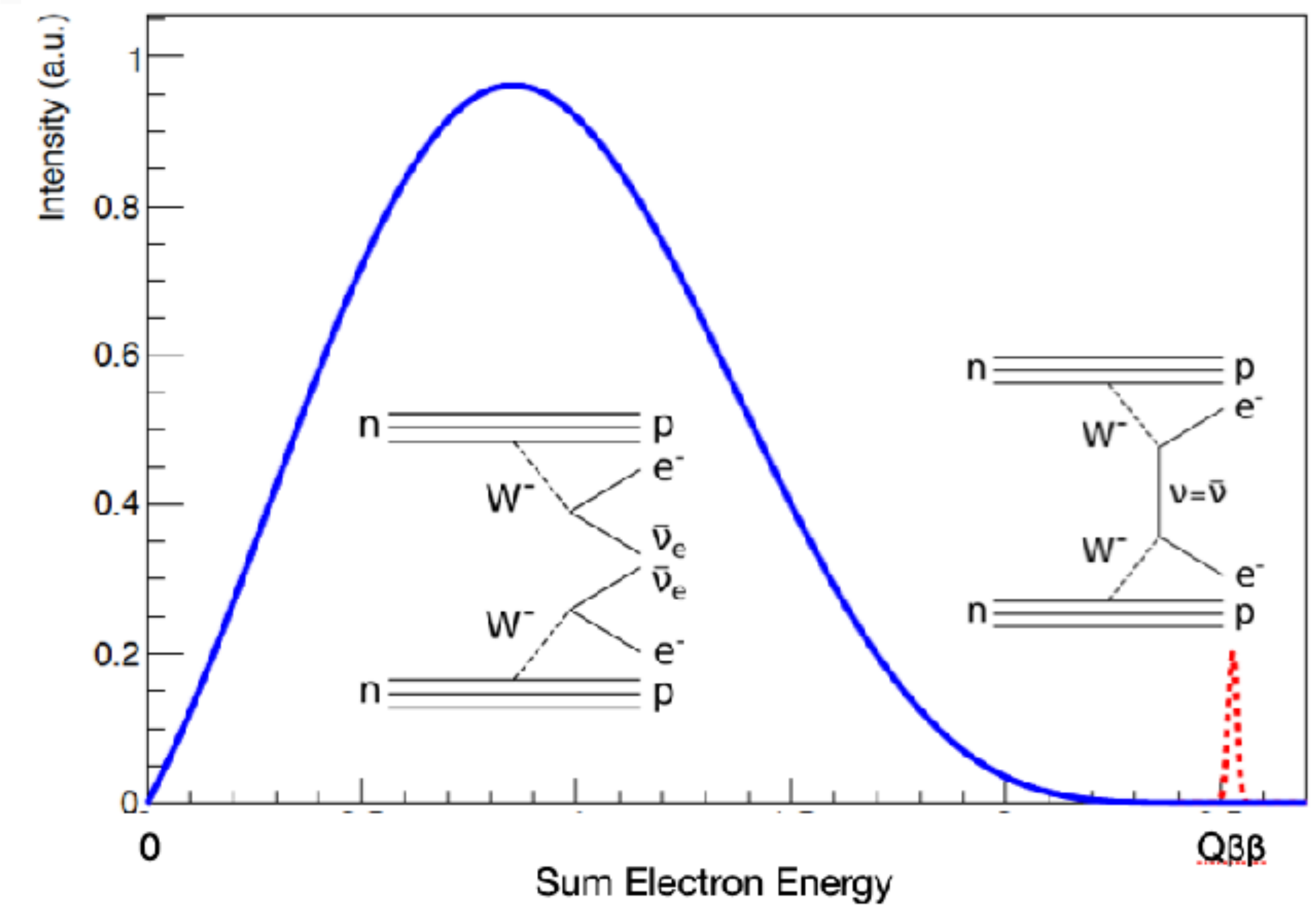
Guido Fantini on behalf of the CUPID-0 Collaboration

Physics case

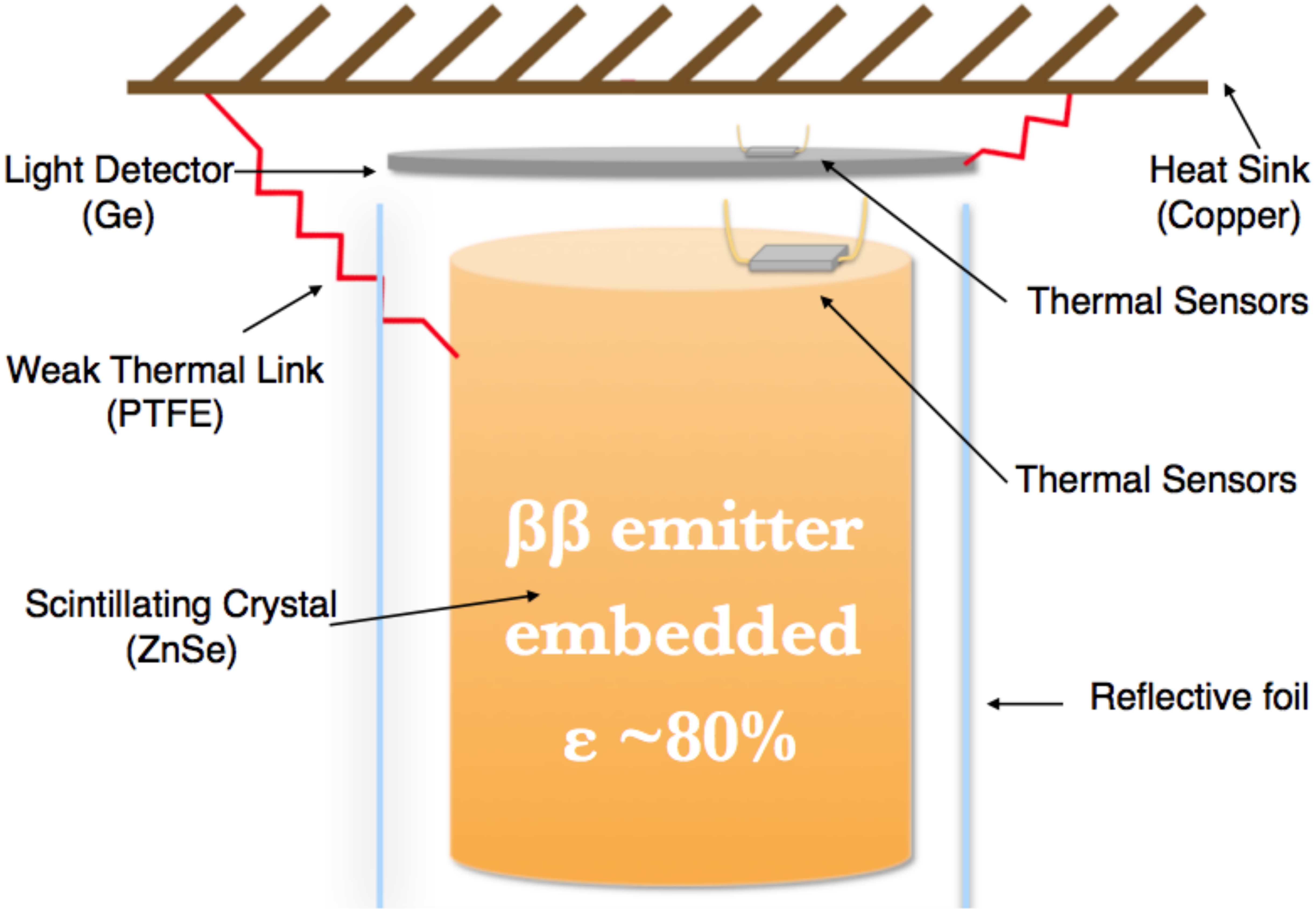
- lepton number violation (ΔL=+2)
- neutrino mass hierarchy, absolute scale, Majorana mass component
- matter anti-matter asymmetry in the Universe (matter creation in the lab)
- peak at 2νββ spectral endpoint

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





Scintillating bolometers



Eur. Phys. J. C (2018) 78:428
10.1140/epjc/s10052-018-5896-8

- T~10 mK temperature makes heat capacity very low
- ββ decays heat the crystal
- temperature pulse readout via NTD thermistor as voltage pulse
- scintillation light heats Ge light detector (same readout)
- weak thermal link to heat bath brings detector back to base T

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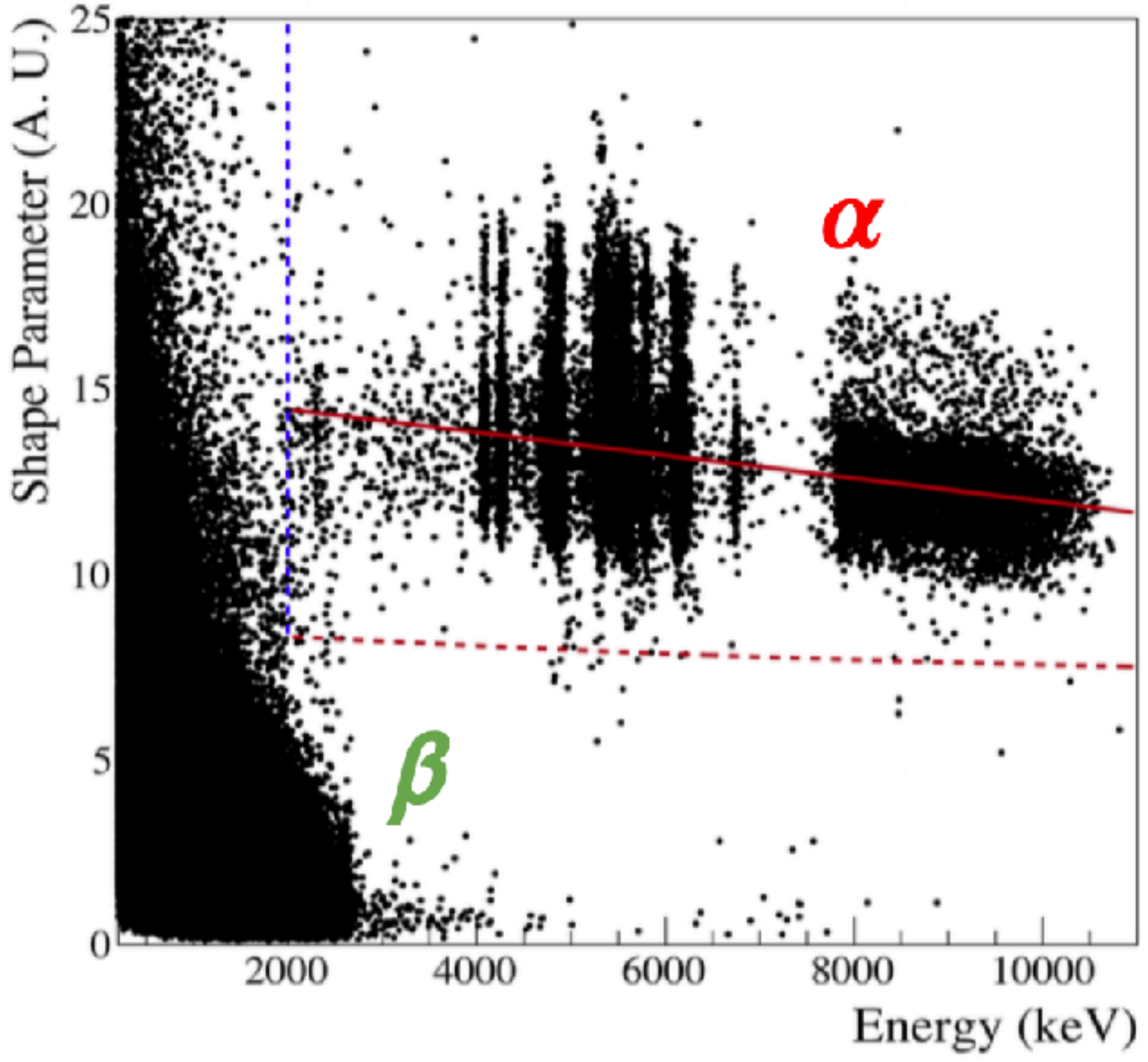
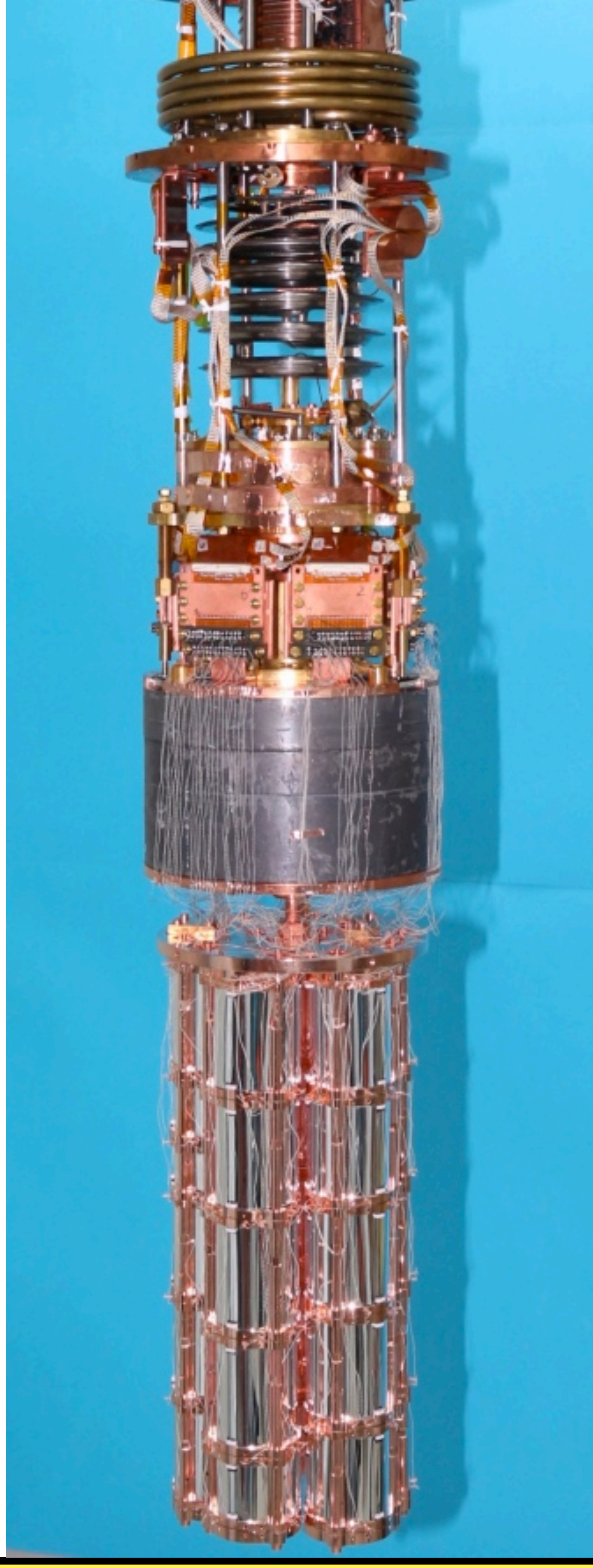
10.1140/epjc/s10052-018-5896-8

The CUPID-0 experiment



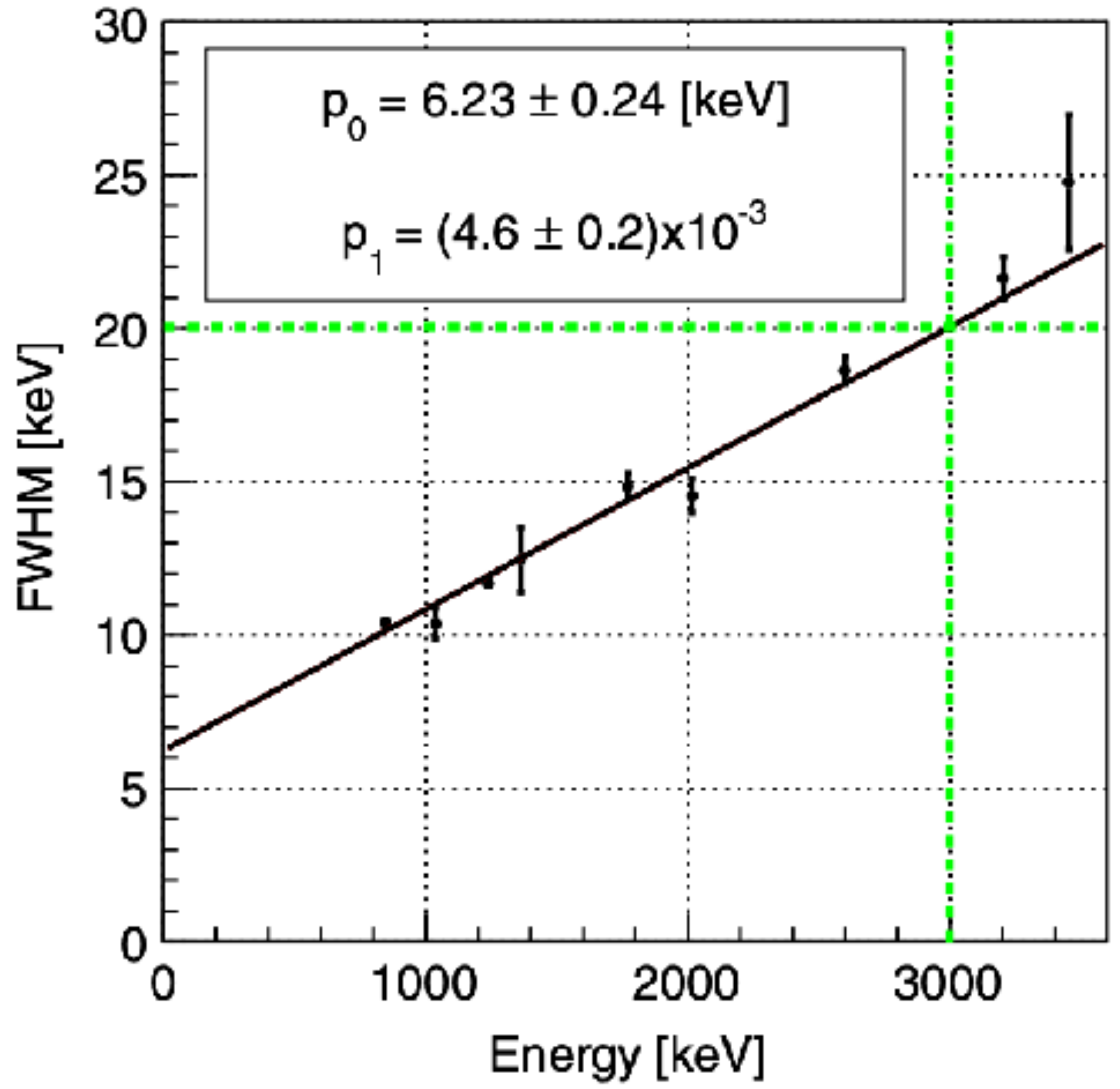
- 26 ZnSe cylindric scintillating bolometer crystals, 2 natural + 24 95% enriched in ^{86}Se
- surrounded by VIKUITI (3M) reflective foil
- installed underground in the INFN LNGS lab to shield from cosmic radiation
- achieve full α/βγ discrimination with dual heat/light readout
- operation phase I (3/2017-12/2018) with reflective foil
- operation phase II (6/2019-2/2020) w/o reflective foil

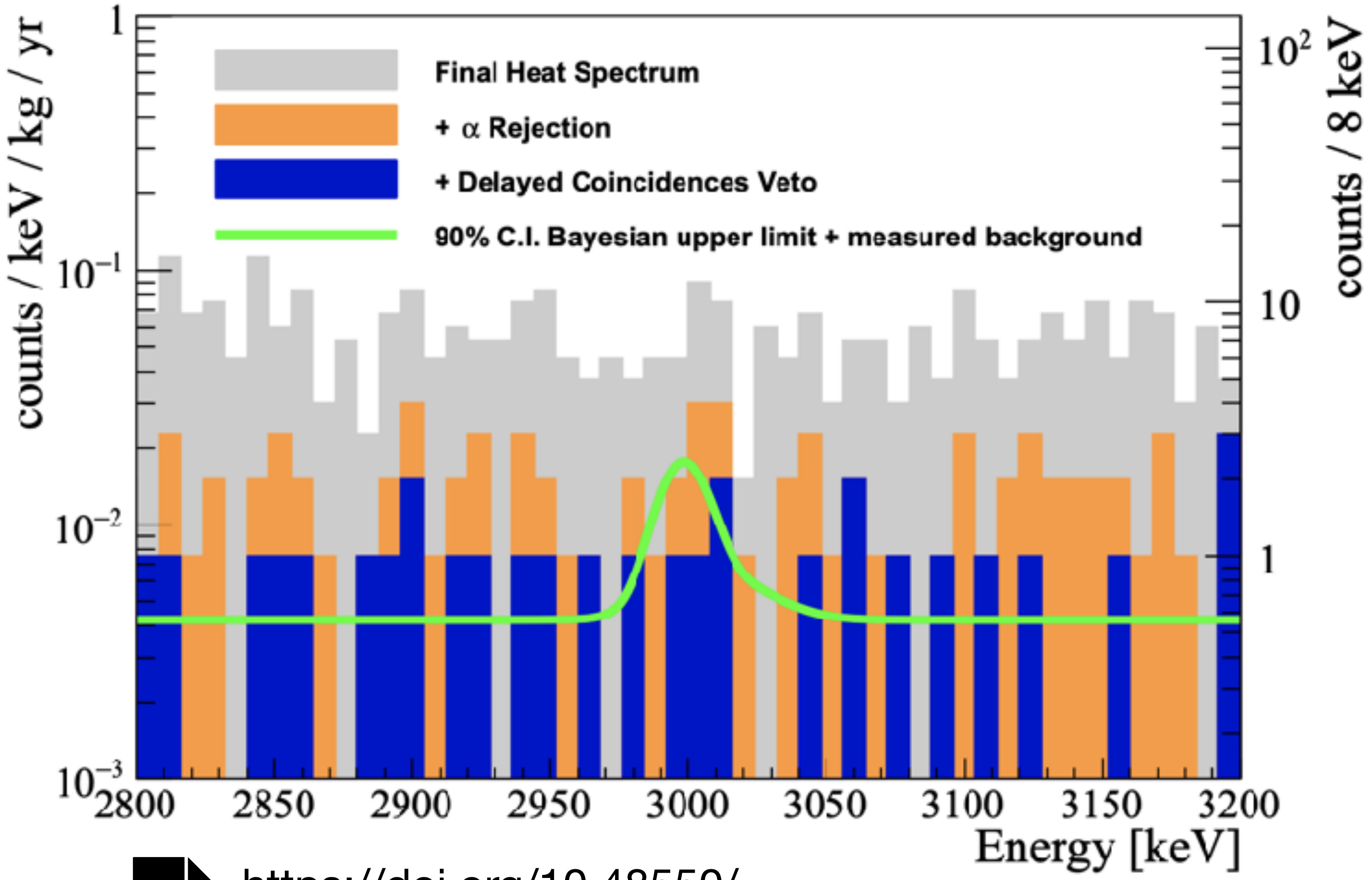


0νββ results

- 8.82 kg.yr ^{82}Se exposure (phase I + II)
- energy resolution (20.05 ± 0.34) keV at ~3 MeV
- background index
  $(3.5 \pm 1.0)\ 10^{-3}$ cts/(keV kg yr) phase I
  $(5.5 \pm 1.5)\ 10^{-3}$ cts/(keV kg yr) phase II
- no evidence found, Bayesian 90% C.I. set
  $T^{0\nu}_{1/2} > 4.6 \times 10^{23}$ yr
  $m_{\beta\beta} < (263 - 545)$ meV

Phys. Rev. Lett 123, 032501 (2019)
10.1103/PhysRevLett.123.032501





https://doi.org/10.48550/arXiv.2206.05130

Background Model

From here on: Results from Phase I only!

Eur. Phys. J. C (2019) 79:583
10.1140/epjc/s10052-019-7078-8

Component	Mass (kg)	Source	Index	Activity (Bq/kg)
Crystals	10.5	$2\nu\beta\beta$	1	$(9.96 \pm 0.03) \times 10^{-4}$
		^{65}Zn	2	$(3.52 \pm 0.06) \times 10^{-4}$
		^{40}K	3	$(8.5 \pm 0.4) \times 10^{-5}$
		^{60}Co	4	$(1.4 \pm 0.3) \times 10^{-5}$
		^{147}Sm	5	$(1.6 \pm 0.3) \times 10^{-7}$
		^{238}U–^{226}Ra	6	$(5.51 \pm 0.10) \times 10^{-6}$
		^{226}Ra–^{210}Pb	7	$(1.54 \pm 0.02) \times 10^{-5}$
		^{210}Pb–^{206}Pb	8	$(7.05 \pm 0.16) \times 10^{-6}$
		^{232}Th–^{228}Ra	9	$(2.74 \pm 0.10) \times 10^{-6}$
		^{228}Ra–^{208}Pb	10	$(1.20 \pm 0.03) \times 10^{-5}$
		^{235}U–^{231}Pa	11	$(5.3 \pm 0.7) \times 10^{-7}$
		^{231}Pa–^{207}Pb	12	$(7.8 \pm 0.4) \times 10^{-7}$
Holder	3.10	^{54}Mn	13	$(2.2 \pm 0.3) \times 10^{-4}$
CryoInt ([a])	36.9	^{232}Th	14	$< 4.5 \times 10^{-5}$
		^{238}U	15	$(7 \pm 3) \times 10^{-5}$
		^{40}K	16	$(3.0 \pm 0.6) \times 10^{-3}$
		^{60}Co	17	$(6.8 \pm 1.3) \times 10^{-5}$
IntPb	202	^{232}Th	18	$< 6.3 \times 10^{-5}$
		^{238}U	19	$< 7.3 \times 10^{-5}$
CryoExt	832	^{60}Co	20	$(2.6 \pm 0.9) \times 10^{-5}$
ExtPb ([b])	24694	^{232}Th	21	$(4.3 \pm 0.6) \times 10^{-4}$
		^{238}U	22	$(2.5 \pm 1.2) \times 10^{-4}$
		^{40}K	23	$(2.8 \pm 0.8) \times 10^{-3}$
		^{210}Pb	24	7.8 ± 0.3
Component	Surface (cm^2)	Source	Index	Activity (Bq/cm^2)
Crystals	2574	^{226}Ra–^{210}Pb–0.01μm	25	$(2.63 \pm 0.15) \times 10^{-8}$
		^{228}Ra–^{208}Pb–0.01μm	26	$(6.5 \pm 1.1) \times 10^{-9}$
		^{226}Ra–^{210}Pb–10μm	27	$< 2.3 \times 10^{-9}$
		^{228}Ra–^{208}Pb–10μm	28	$(4.2 \pm 1.6) \times 10^{-9}$
Reflectors ([c])	2100	^{232}Th–10μm	29	$< 7.3 \times 10^{-10}$
		^{226}Ra–^{210}Pb–10μm	30	$(8.7 \pm 1.3) \times 10^{-9}$
		^{210}Pb–^{206}Pb–10μm	31	$(1.0 \pm 0.5) \times 10^{-8}$
		^{210}Pb–^{206}Pb–0.01μm	32	$(1.43 \pm 0.02) \times 10^{-7}$
Muons	Flux in units of $\mu/(\mathrm{cm}^2\mathrm{s})$		33	$(3.7 \pm 0.2) \times 10^{-8}$

ZnSe

Cryostat and Shields

Reflecting foil

Muons

Bulk

Surface

Aim at reproducing the energy spectrum with a weighted sum of different sources

Source selection based on data (prominent lines)

Each source is a MC simulation, the activity is fit to the data

Background Model

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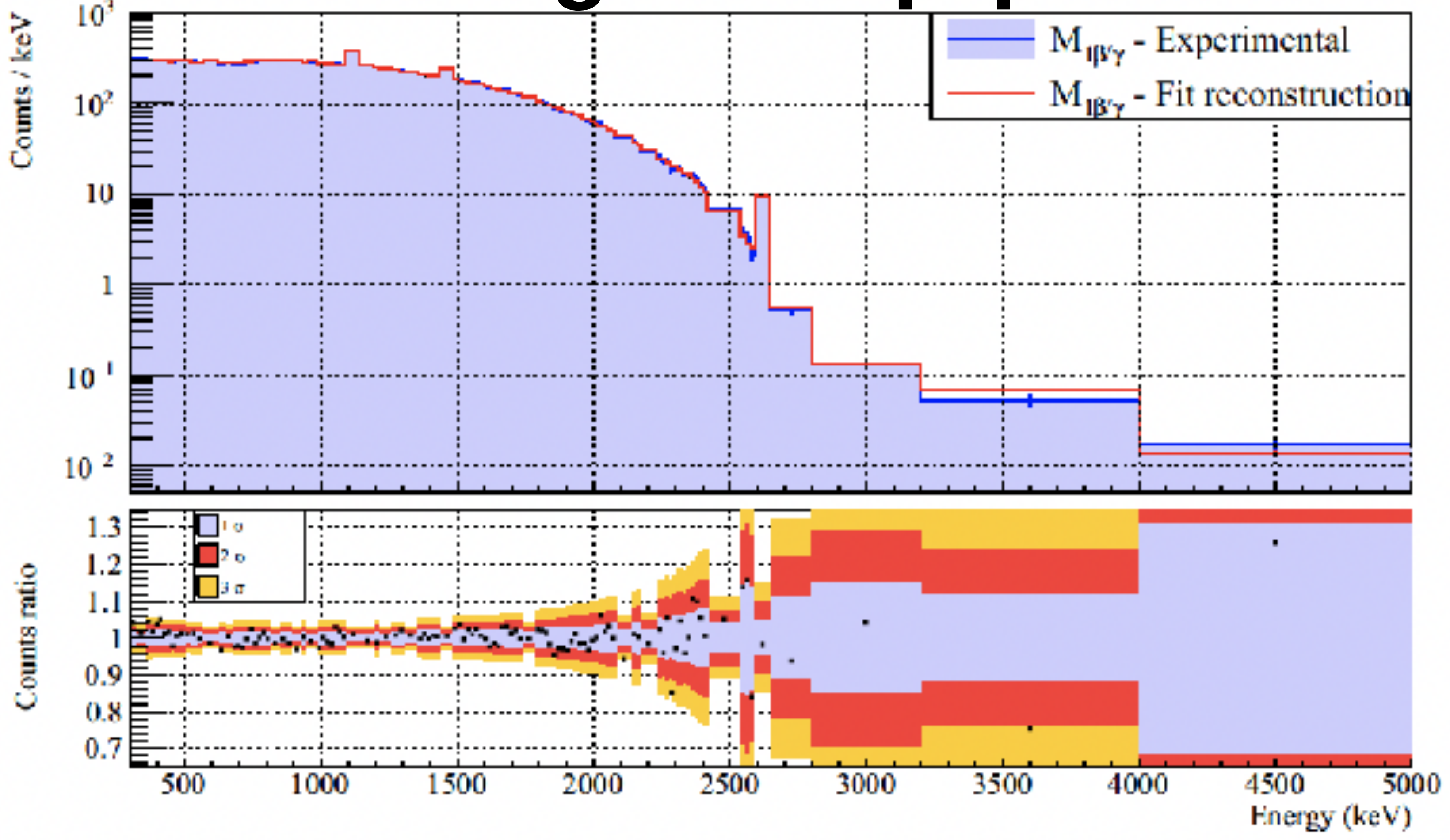
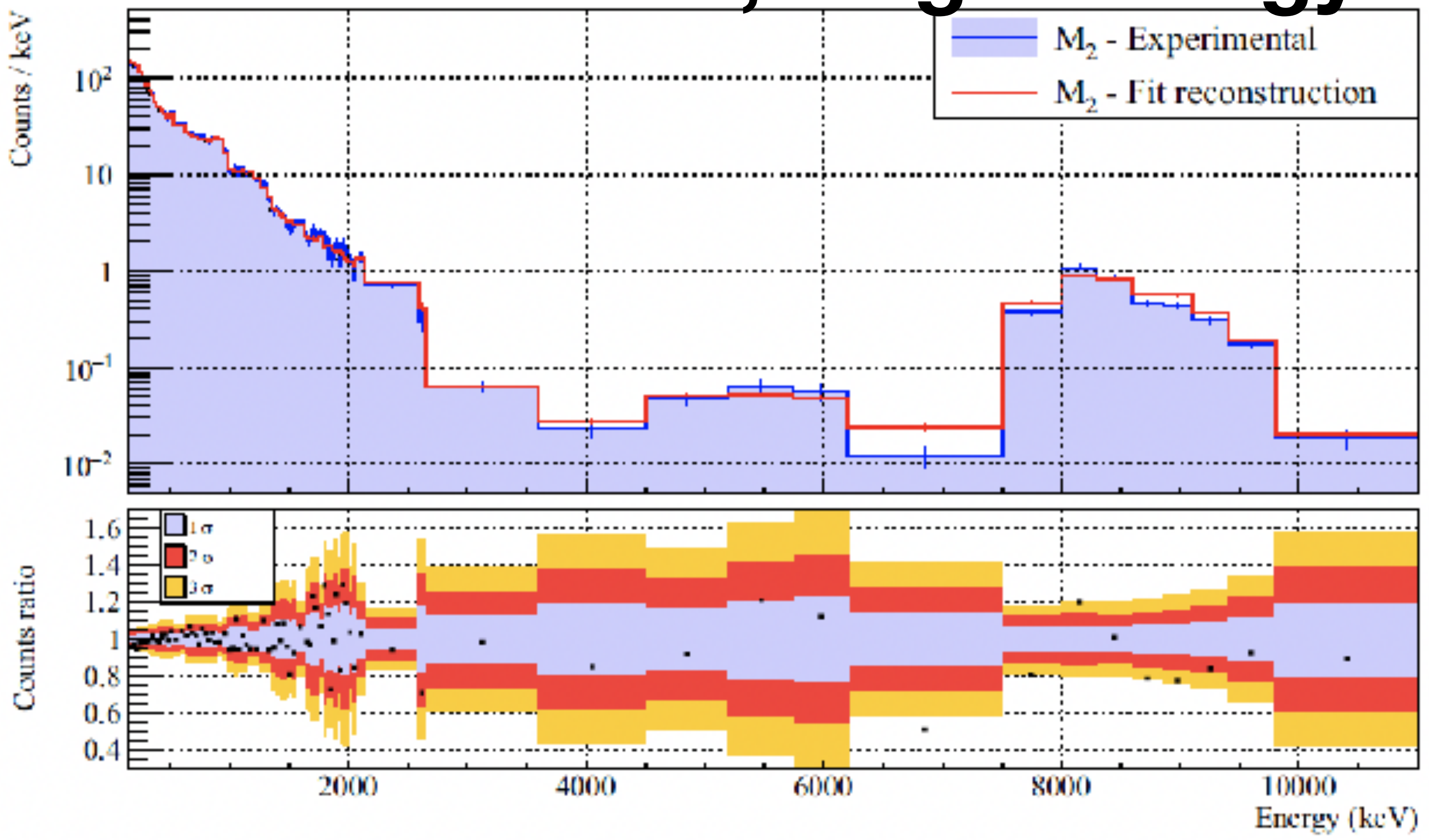
10.1140/epjc/s10052-019-7078-8

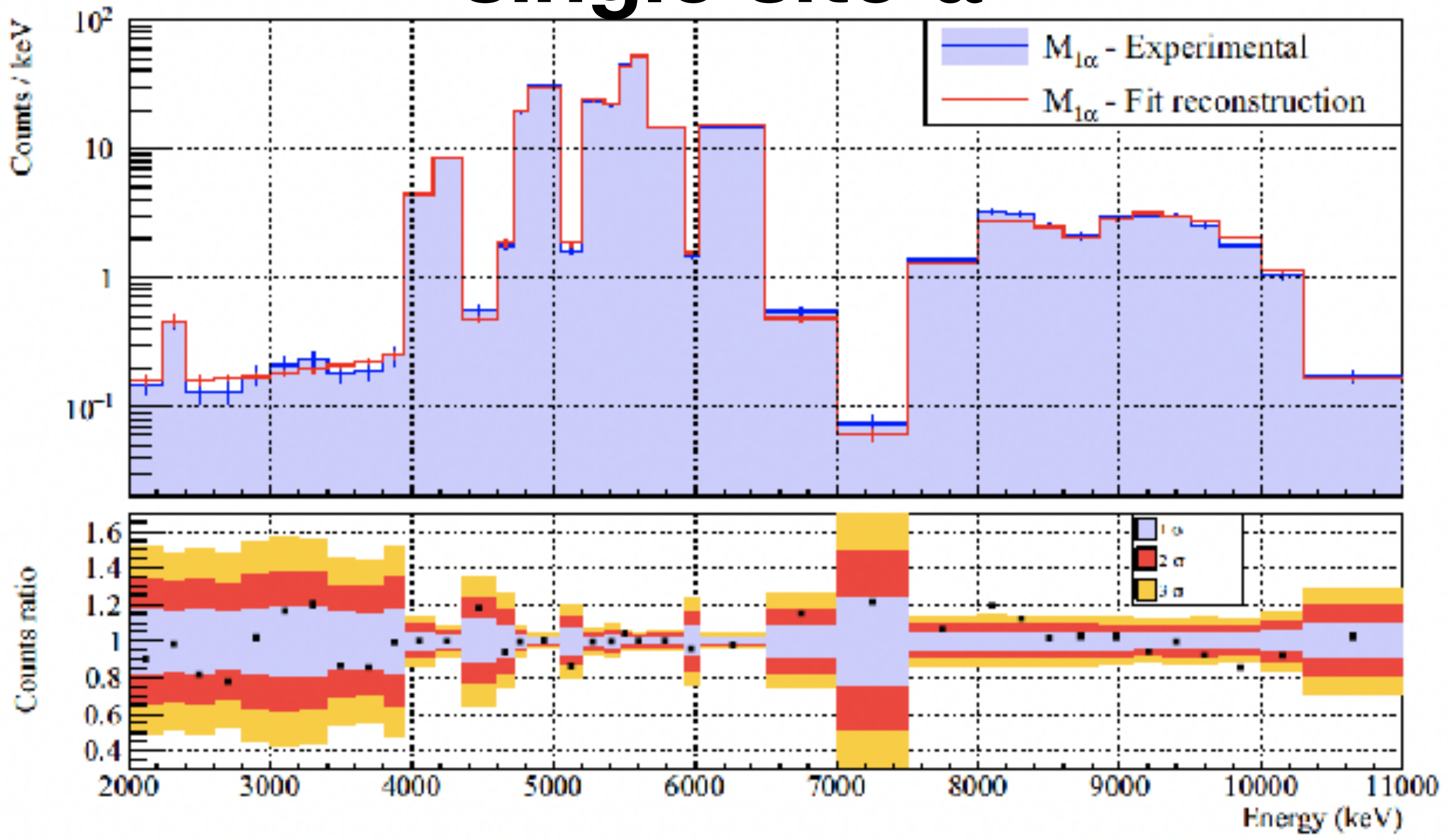
single site β/γ



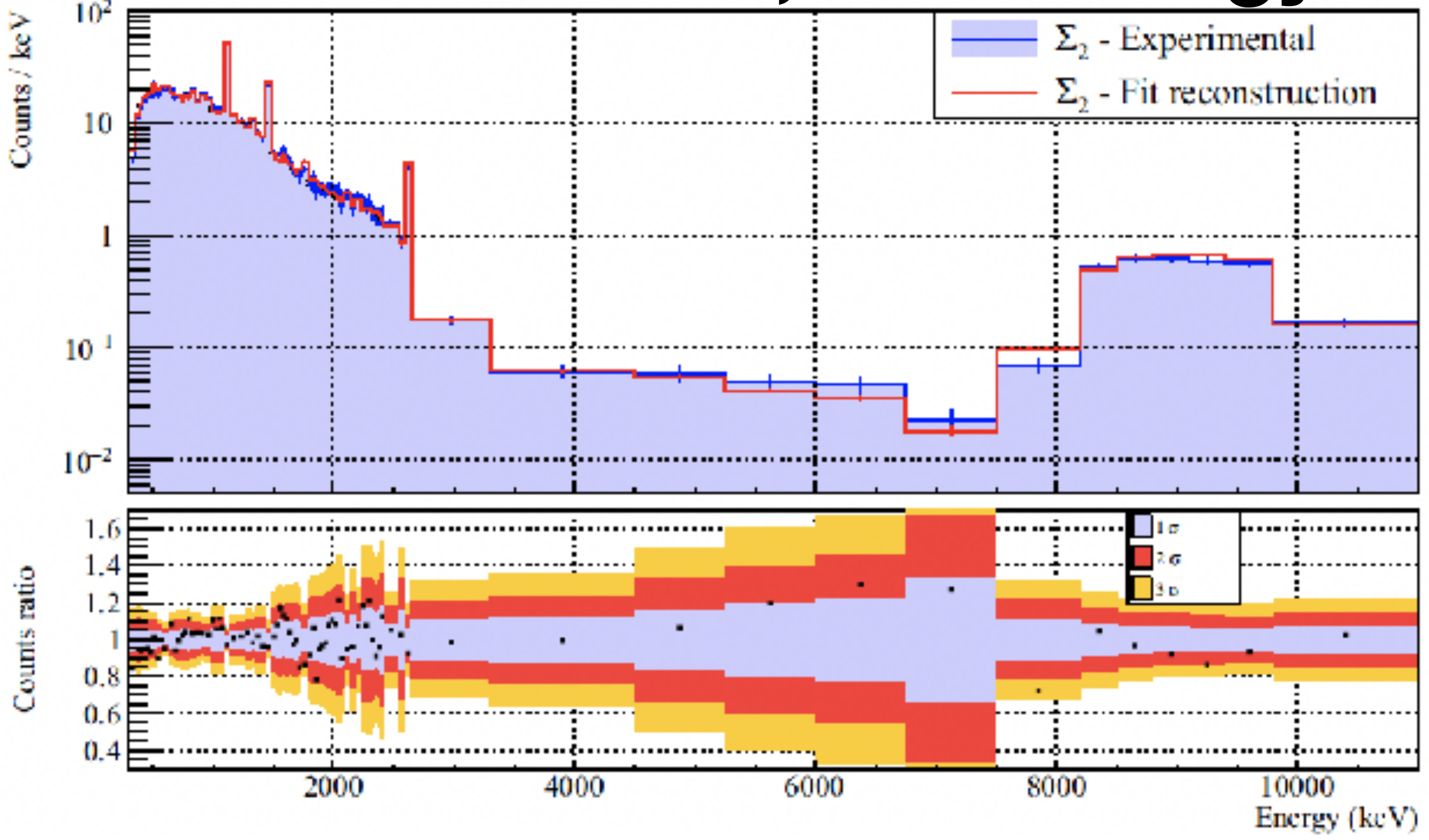
double site, single energy



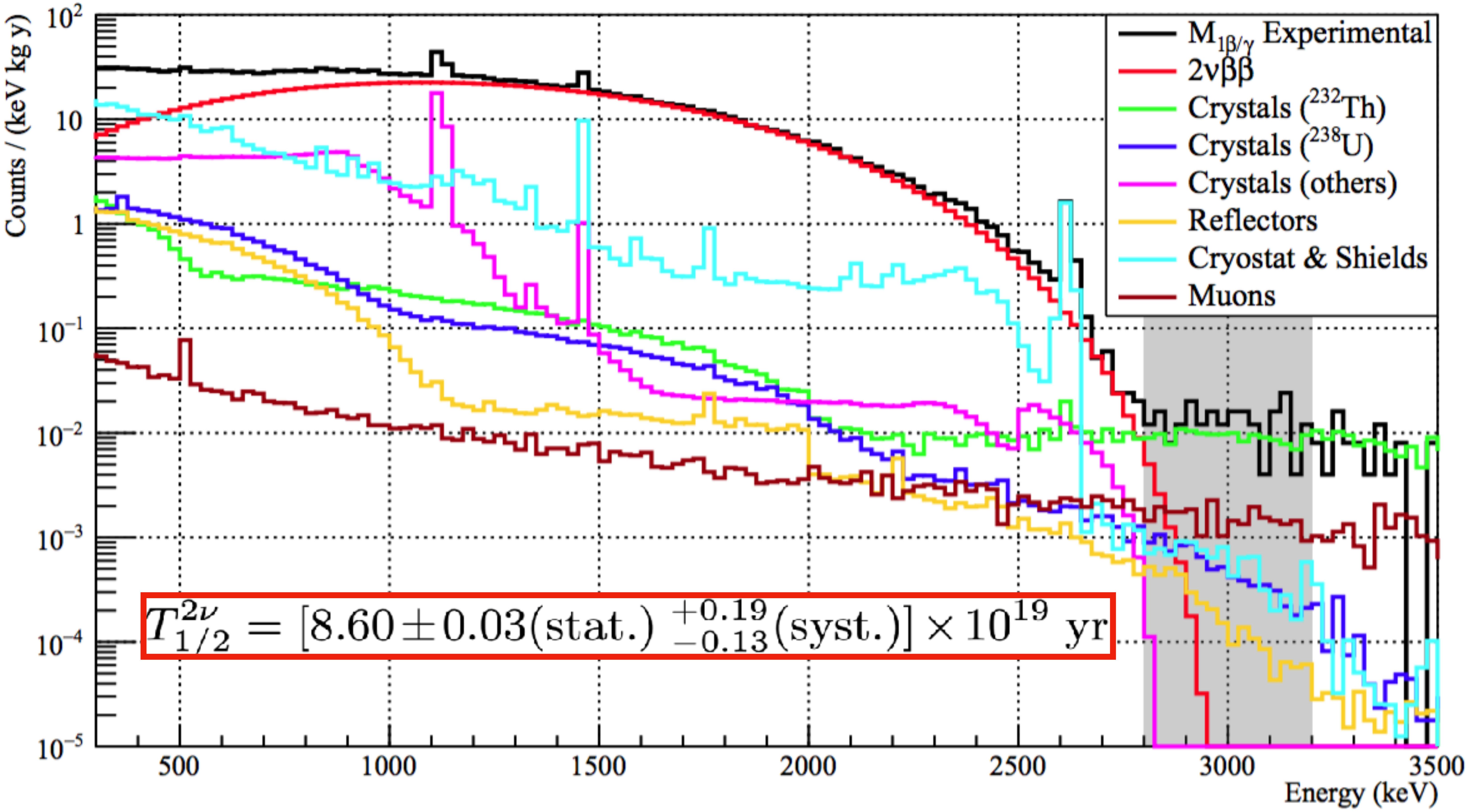
single site α



double site, sum energy



2νββ results



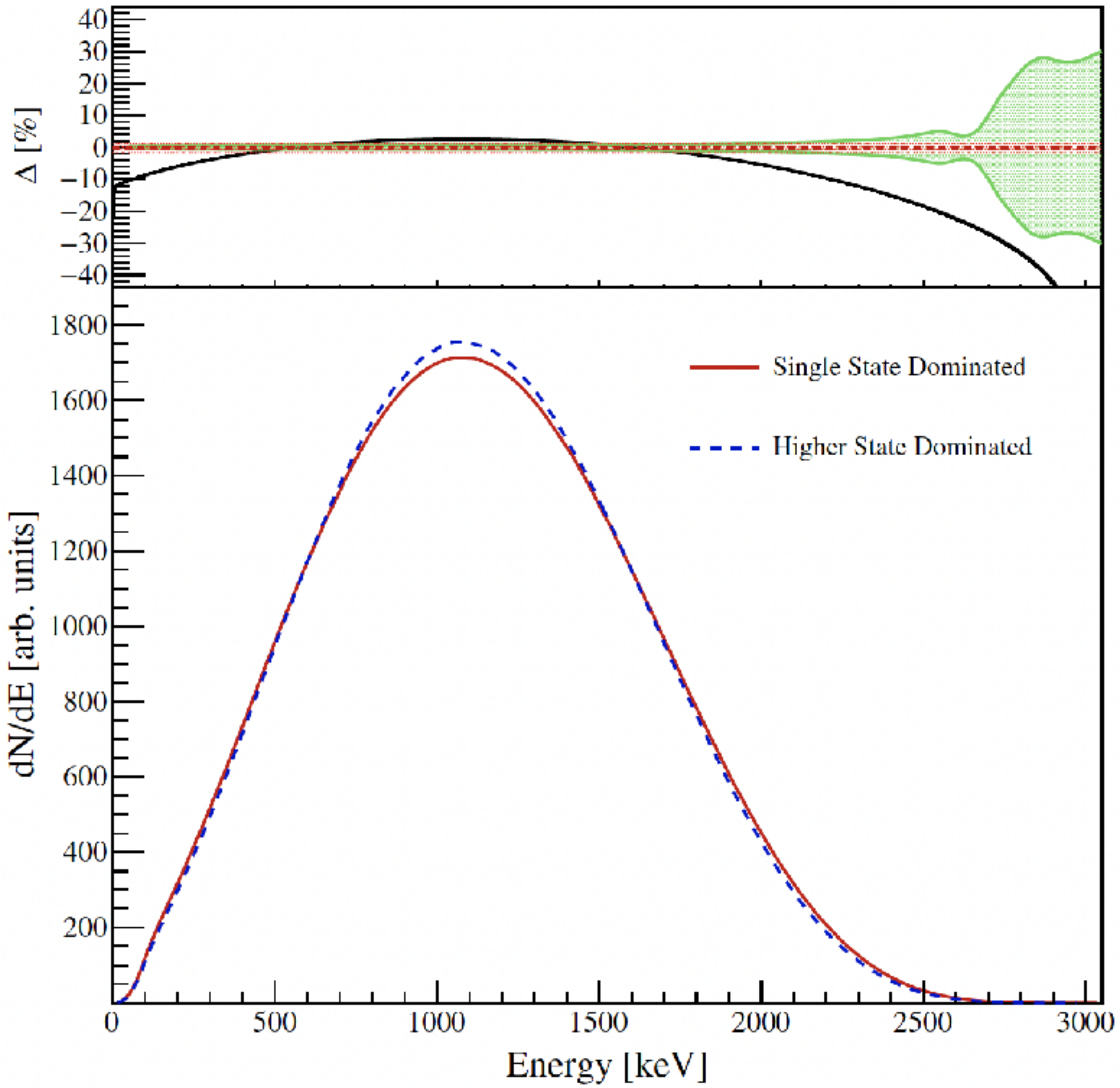
(the time veto for ^{208}Tl events is not included in the plot)

The dominant contribution < 2.5 MeV is 2νββ of ^{82}Se

Eur. Phys. J. C (2019) 79:583
10.1140/epjc/s10052-019-7078-8

Phys. Rev. Lett 123, 262501 (2019)
10.1103/PhysRevLett.123.262501

2νββ results - spectral shape sensitivity



- High statistics and signal purity can be used to disentangle tiny spectral shape differences in 2νββ events
- CUPID-0 provided evidence for Single State Dominance of 2νββ transition in ^{82}Se over Higher State Dominance
- Many exotic processes have their signature as a distortion of the 2νββ energy spectrum

Phys. Rev. Lett 123, 262501 (2019)
10.1103/PhysRevLett.123.262501

Lorentz violation

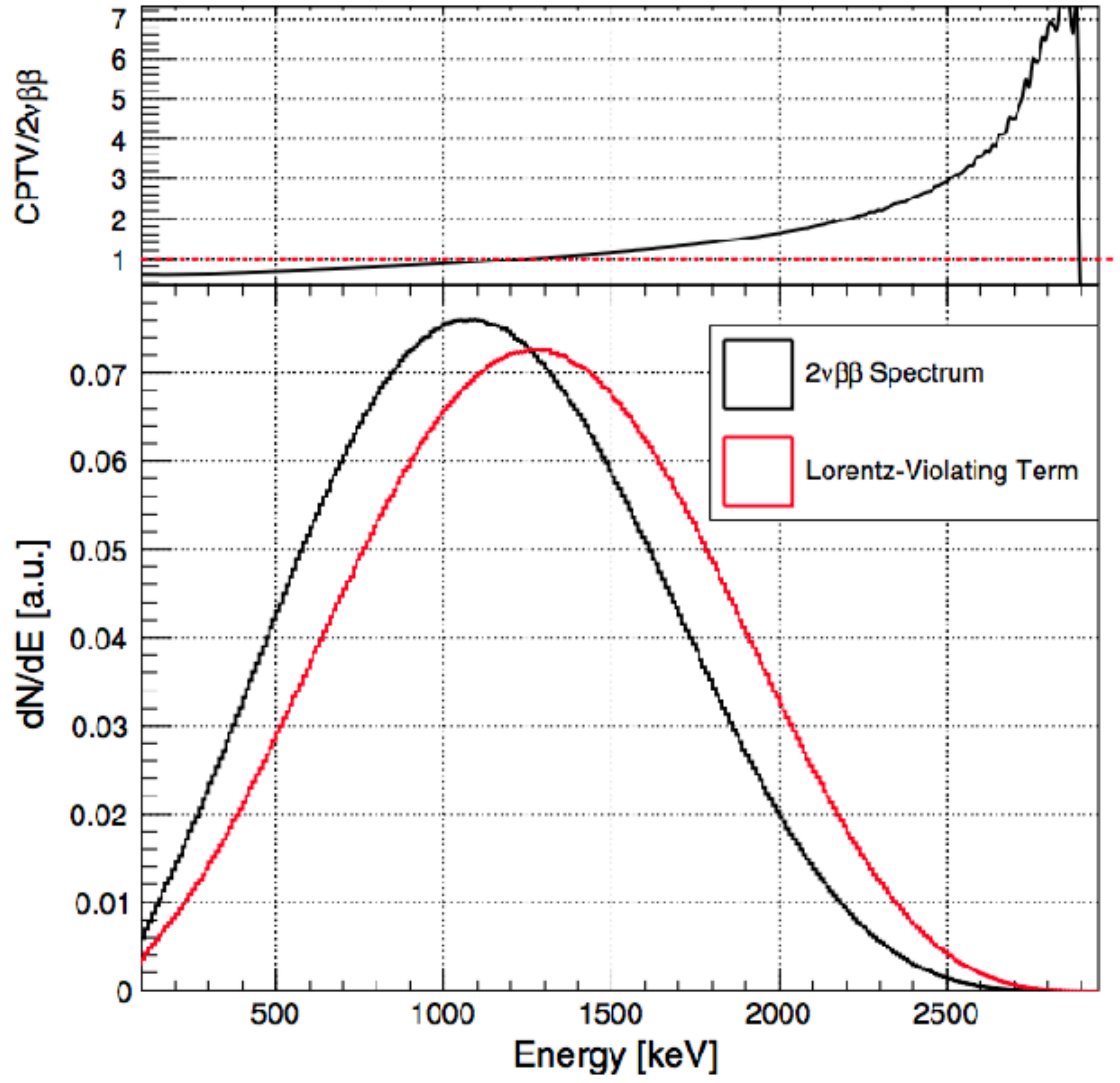
The introduction of a consistent quantum gravity theory predicts new physics at the Planck scale, that has a low energy counterpart in the SME as Lorentz-violating operators.

Coefficient controlling CPT-odd operators

$$\frac{d\Gamma_{2\nu\beta\beta}}{dE} \sim (Q_{\beta\beta} - E)^5 + 10\,\mathring{a}^{(3)}_{of}\,(Q_{\beta\beta} - E)^4$$

Standard Model $2\nu\beta\beta$
n = 5

Lorentz Violating $2\nu\beta\beta$
n = 4



Phys. Rev. D 100, 092002
10.1103/PhysRevD.100.092002

Phys. Rev. D 100, 092002
10.1103/PhysRevD.100.092002

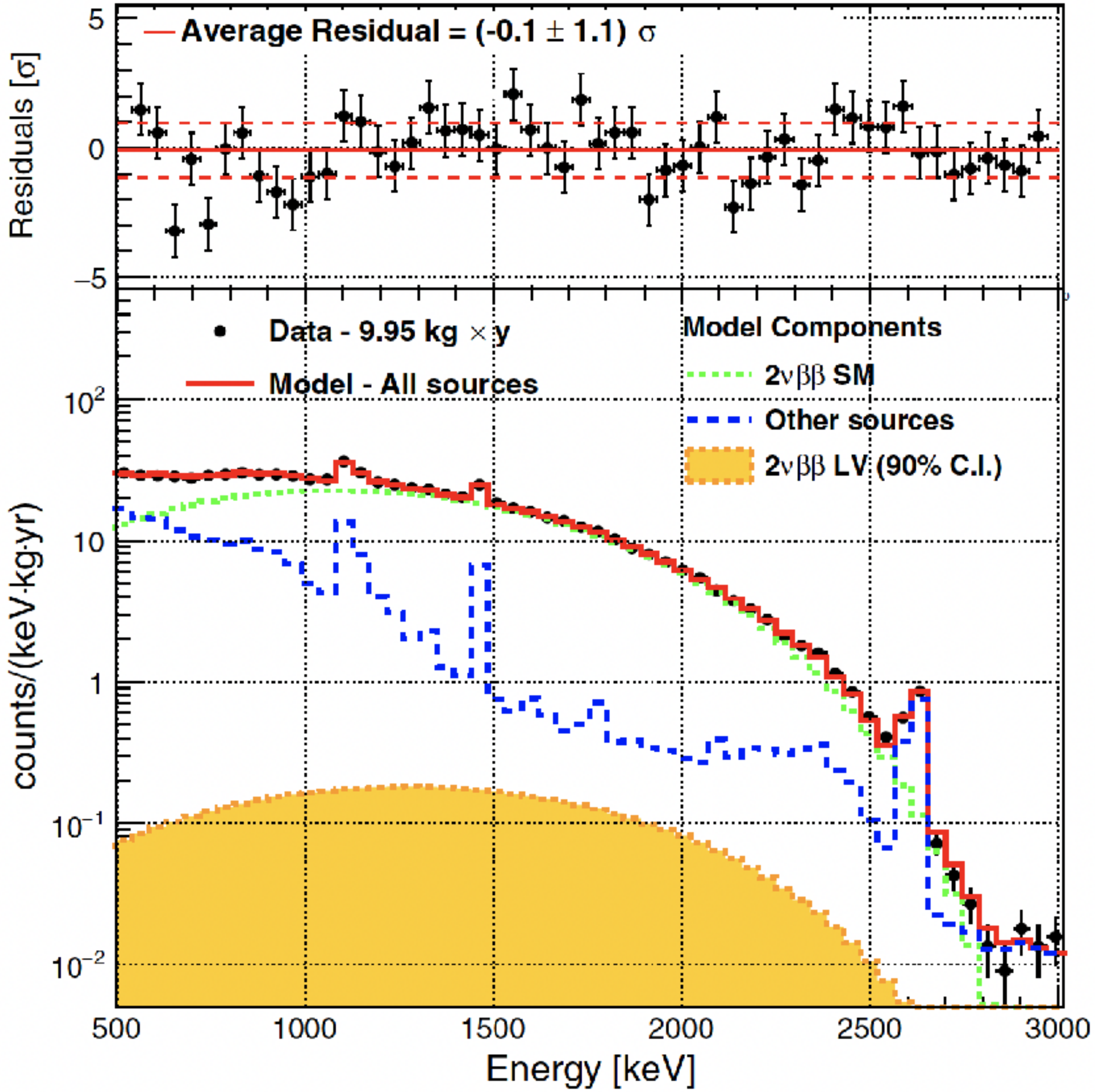
Lorentz violation

Added a new component to the background model

Systematic effects from energy scale, binning, source choice, threshold accounted for

No evidence for Lorentz violation, can set Bayesian 90% C.I. limit

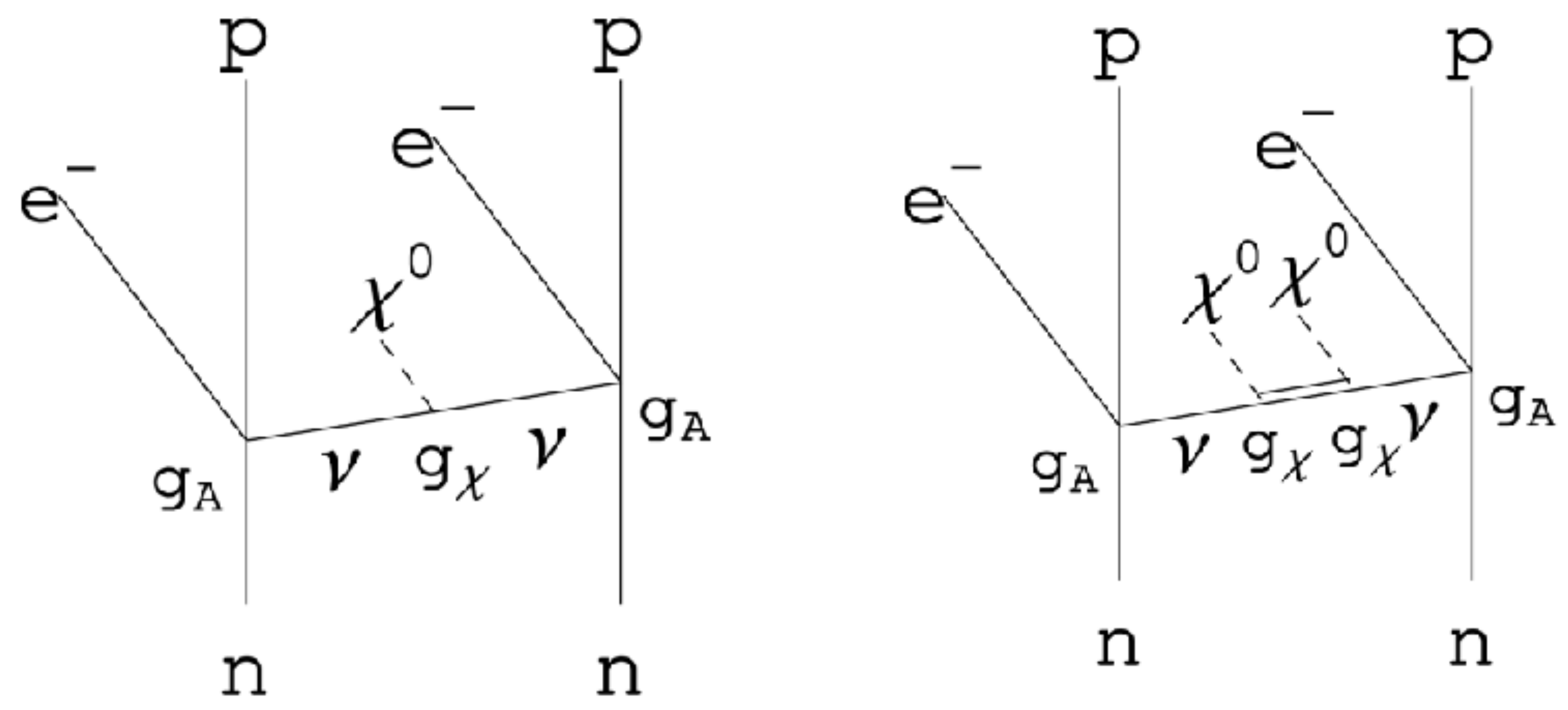
$$\mathring{a}_{of}^{(3)} < 4.1 \times 10^{-6}\ \mathrm{GeV}$$



0νββ with Majoron emission

Phys. Rev. C 103, 044302
10.1103/PhysRevC.103.044302

Several new physics models predict the existence of a Majoron-like particle coupled to the neutrino in 0νββ decay



Model	Decay mode	NG boson	L	n	NME
IB	$0\nu\beta\beta\chi_0$	No	0	1	M_1
IC	$0\nu\beta\beta\chi_0$	Yes	0	1	M_1
ID	$0\nu\beta\beta\chi_0\chi_0$	No	0	3	M_3
IE	$0\nu\beta\beta\chi_0\chi_0$	Yes	0	3	M_3
IIB	$0\nu\beta\beta\chi_0$	No	-2	1	M_1
IIC	$0\nu\beta\beta\chi_0$	Yes	-2	3	M_2
IID	$0\nu\beta\beta\chi_0\chi_0$	No	-1	3	M_3
IIE	$0\nu\beta\beta\chi_0\chi_0$	Yes	-1	7	M_3
IIF	$0\nu\beta\beta\chi_0$	Gauge boson	-2	3	M_2
"Bulk"	$0\nu\beta\beta\chi_0$	Bulk field	0	2	-

1 or 2 Majorons emitted

Majoron Nature (to be or not to be a Nambu Goldstone boson)

Leptonic charge ($0\nu\beta\beta\chi_0$ violates or not Lepton symmetry)

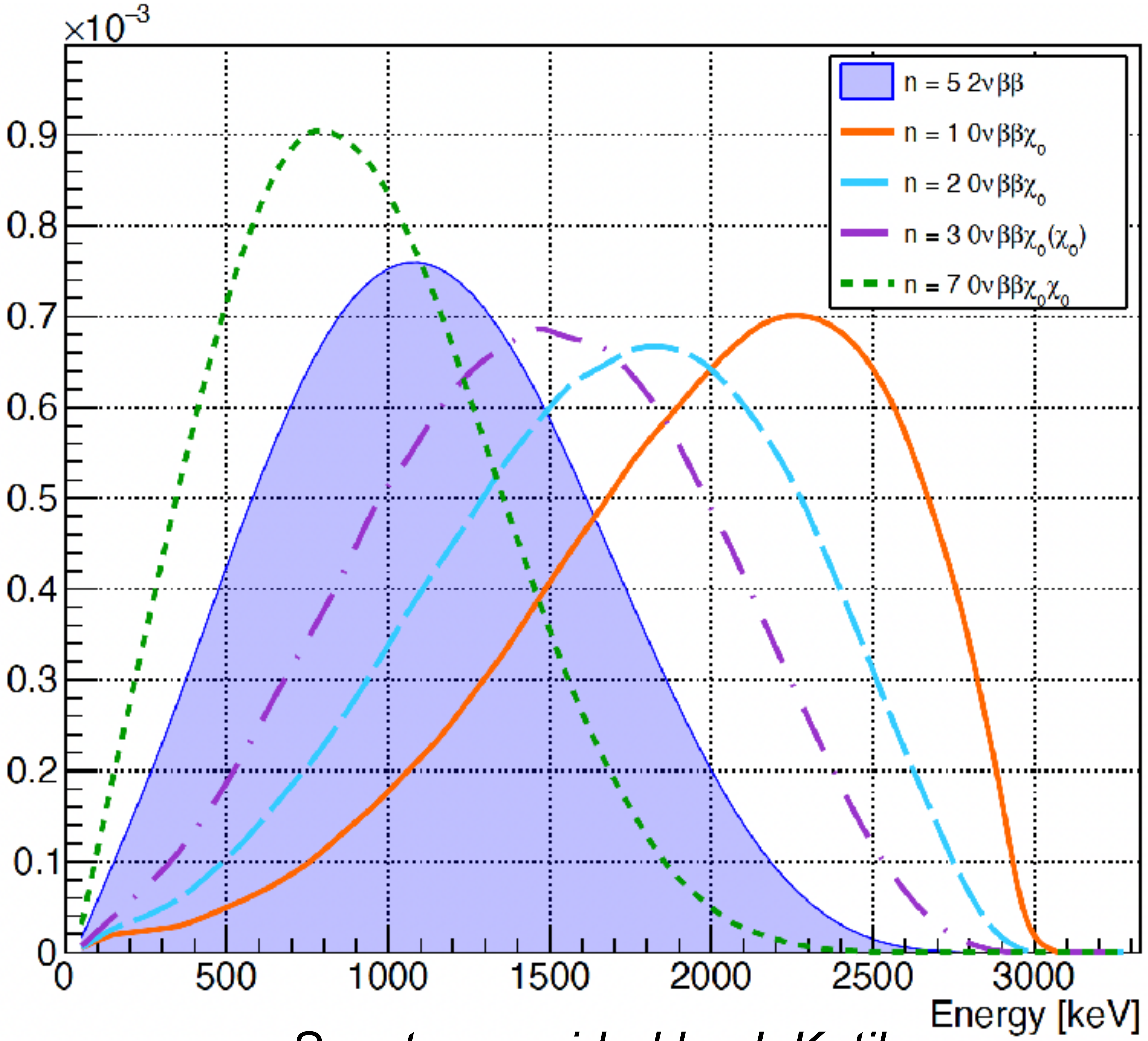
Spectral Index

0νββ with Majoron emission

The experimental signature of different Majoron emitting channels is a modified phase space as

$$\frac{d\Gamma_{0\nu\beta\beta\chi_0}}{dE} \sim (Q_{\beta\beta} - E)^n$$

We investigated single Majoron emission modes 0νββχ n=1,2,3 and double Majoron emission modes 0νββχχ n=3,7



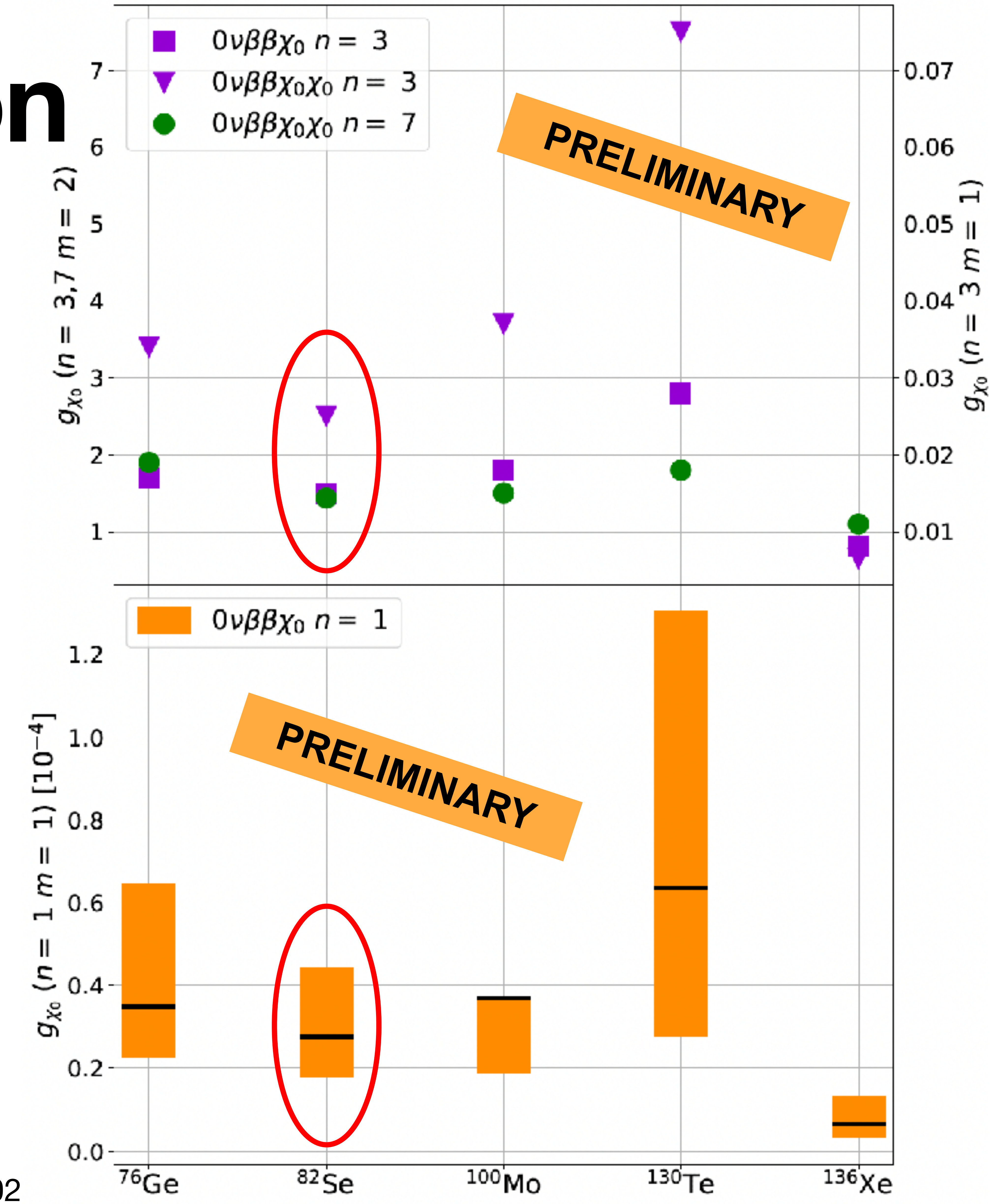
Spectra provided by J. Kotila

0νββ with Majoron emission

- No evidence for Majoron emitting modes
- Upper limits at 90% Bayesian C.I.
- Interpretation as upper limits on Majoron-neutrino coupling constant

$$[t_{1/2}]^{-1} = |\langle g_{\chi_0} \rangle|^{2m} G^{(0)}_{(m,n)} |M_{(m,n)}|^2$$

where m = 1,2 number of final-state Majorons



^{82}Se		this work
^{76}Ge		Eur. Phys. J. Plus (2015) 130: 139 10.1140/epjp/i2015-15139-8
^{100}Mo		Eur. Phys. J. C (2019) 79:440 10.1140/epjc/s10052-019-6948-4
^{130}Te		C.J. Davis, PhD Thesis, Yale University 2020
^{136}Xe		Phys. Rev. D 104, 112002 10.1103/PhysRevD.104.112002

CUPID baseline design

45 x 45 x 45 mm^3 $Li_2{}^{100}MoO_4$ crystals

- Crystal mass: 280 g

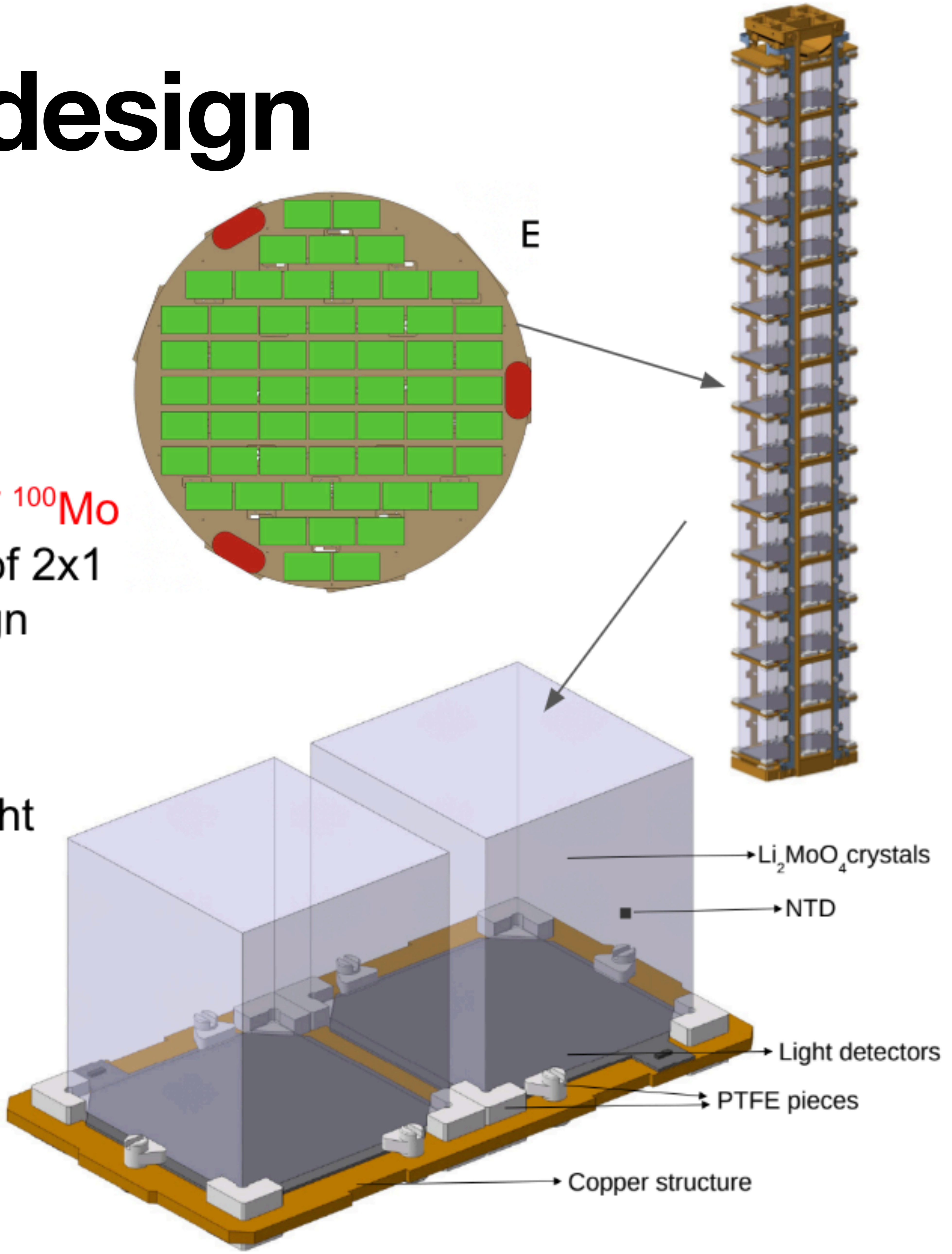
1596 total crystals

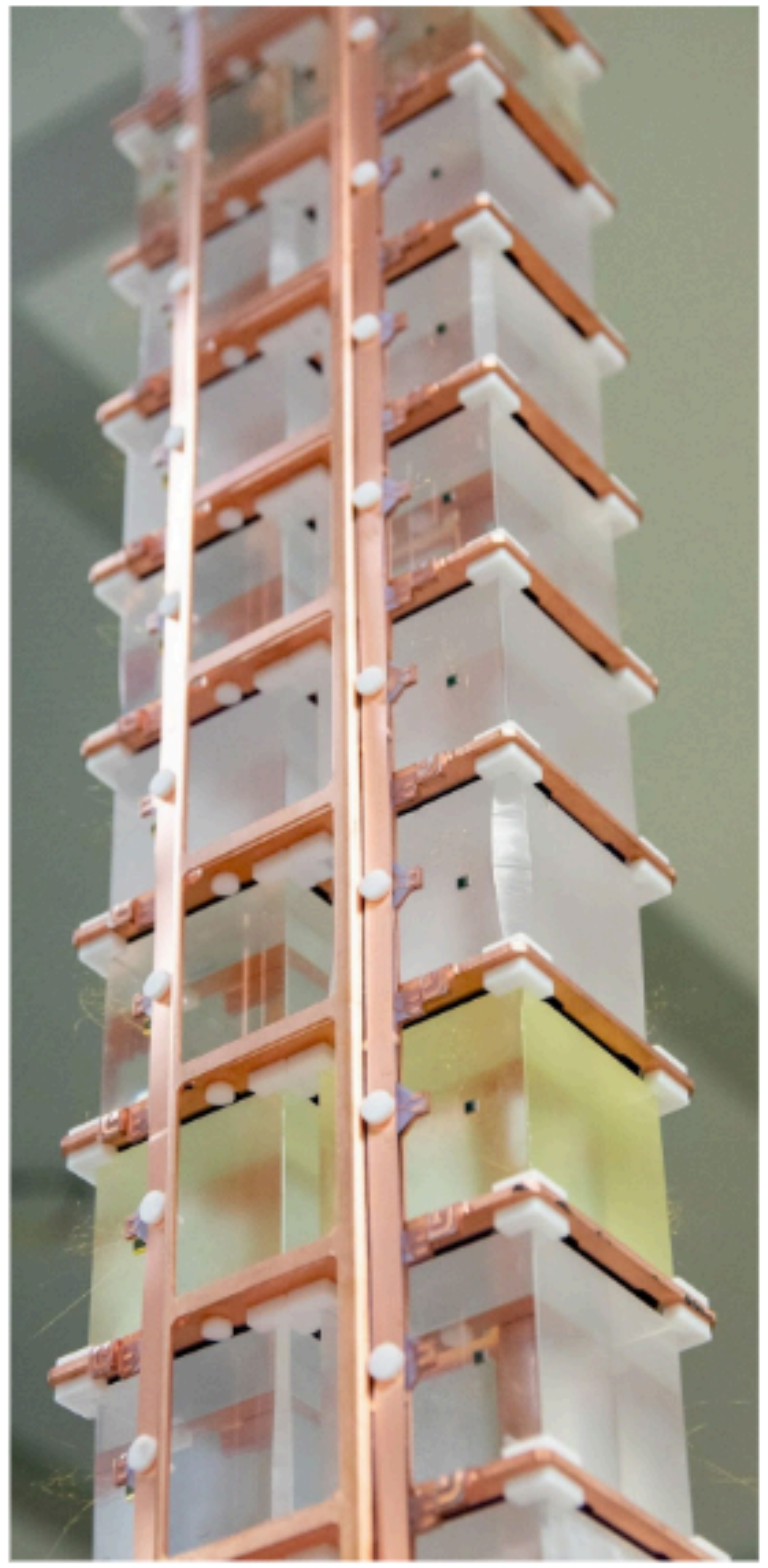
- 450 kg of $Li_2{}^{100}MoO_4$
- 95% enrichment in ^{100}Mo: 240 kg of ^{100}Mo
- 57 towers of 28 crystals. 14-floors of 2x1 crystal pairs. Gravity-assisted design

Ge light detectors with SiO anti-reflective coating

- Each crystal has top and bottom light detectors
- No reflective foils

Muon veto for muon-induced background suppression





Summary

- CUPID-0 successfully concluded operation in 2020
- The full CUPID-0 statistics can constrain 0vββ to

$$T^{0\nu}_{1/2} > 4.6 \times 10^{23} \text{ yr}$$

- Just phase-I data can produce multiple results on the ββ continuous energy spectrum:

$$T^{2\nu}_{1/2} = [8.60 \pm 0.03(\text{stat.}) \, ^{+0.19}_{-0.13}(\text{syst.})] \times 10^{19} \text{ yr}$$

$$\mathring{a}^{(3)}_{of} < 4.1 \times 10^{-6} \text{ GeV}$$

Decay	n	$t_{1/2}$ 90%C.I. (yr)
$0\nu\beta\beta\chi_0$	1	$>1.2 \times 10^{23}$
$0\nu\beta\beta\chi_0$	2	$>3.8 \times 10^{22}$
$0\nu\beta\beta\chi_0$	3	$>1.4 \times 10^{22}$
$0\nu\beta\beta\chi_0\chi_0$	3	$>1.4 \times 10^{22}$
$0\nu\beta\beta\chi_0\chi_0$	7	$>2.2 \times 10^{21}$

PRELIMINARY

- CUPID will use dual readout technology and $Li_2{}^{100}MoO_4$ to fully explore the inverted hierarchy of neutrino masses

Backup

Backup — References for Majoron emission

- n = 1 (black line), 3 and 7: https://doi.org/10.1103/physrevc.103.044302
- Orange Bands for n = 1:
  - https://doi.org/10.1016/j.nuclphysa.2008.12.005
  - https://doi.org/10.1088/1361-6471/aa9bd4
  - https://doi.org/10.1103/PhysRevC.93.024308
  - https://doi.org/10.1103/physrevc.101.044315
  - https://doi.org/10.1103/PhysRevC.91.034304
  - https://doi.org/10.1103/PhysRevD.102.095016
  - https://doi.org/10.1103/physrevc.103.044302
  - https://doi.org/10.1103/PhysRevC.87.064302
  - https://doi.org/10.1103/PhysRevC.87.045501
  - https://doi.org/10.1103/PhysRevC.98.064325
  - https://doi.org/10.1103/PhysRevC.91.024613
  - https://doi.org/10.1103/PhysRevC.97.045503
  - https://doi.org/10.1103/physrevc.102.044303
  - https://doi.org/10.1103/PhysRevLett.105.252503
  - https://doi.org/10.1103/PhysRevLett.111.142501
  - https://doi.org/10.1103/PhysRevC.95.024305
  - https://doi.org/10.1103/PhysRevC.88.064322
  - https://doi.org/10.1103/PhysRevC.91.024316

- Phase Spaces: https://doi.org/10.1103/physrevc.91.064310