THE UNIVERSITY
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TUNL

Neutrino-less double beta decay experiments

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Outline

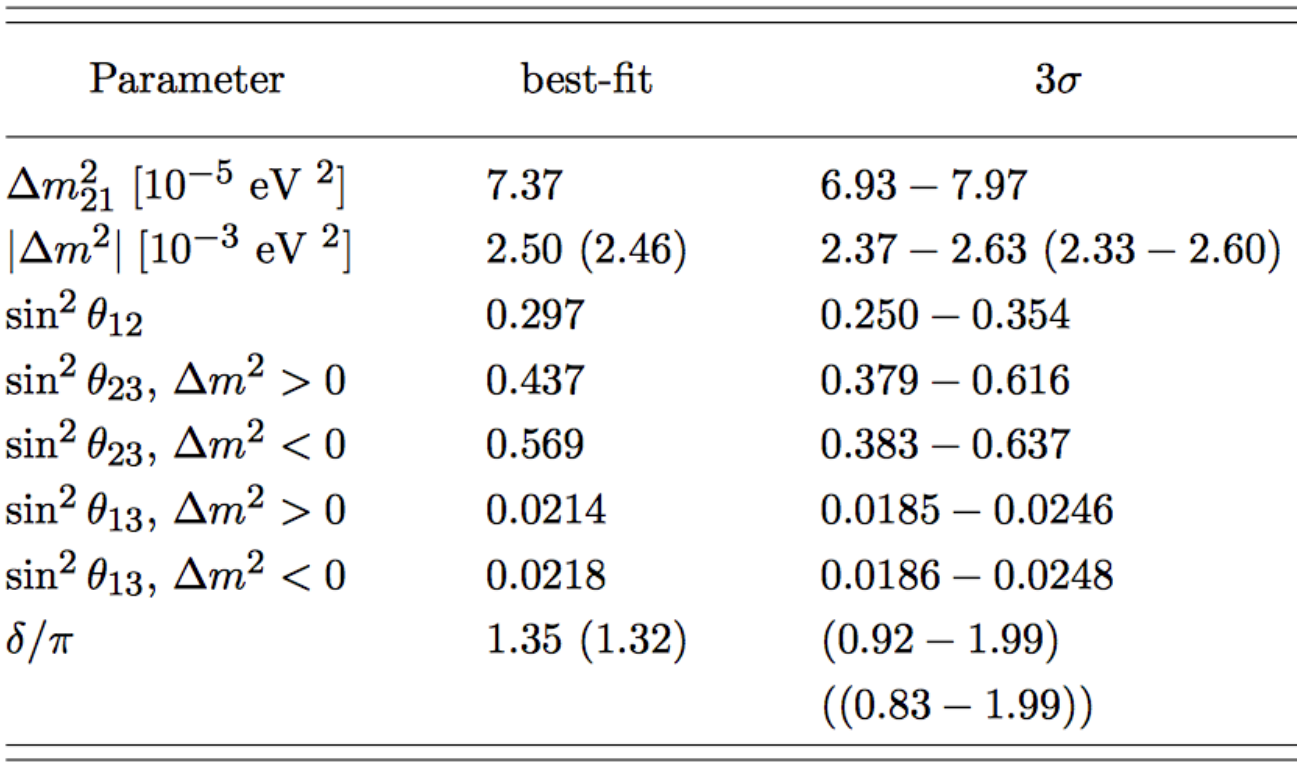
- Overview and Motivation
- History
- Recent Experiments
- Future Experiments

Neutrino Flavor Mixing

Mass eigenstates different than flavor eigenstates.

$\Rightarrow$ Propagating neutrinos undergo flavor oscillations.

Mass to flavor relationship described by neutrino mixing matrix



Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99) ((0.83 – 1.99))

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

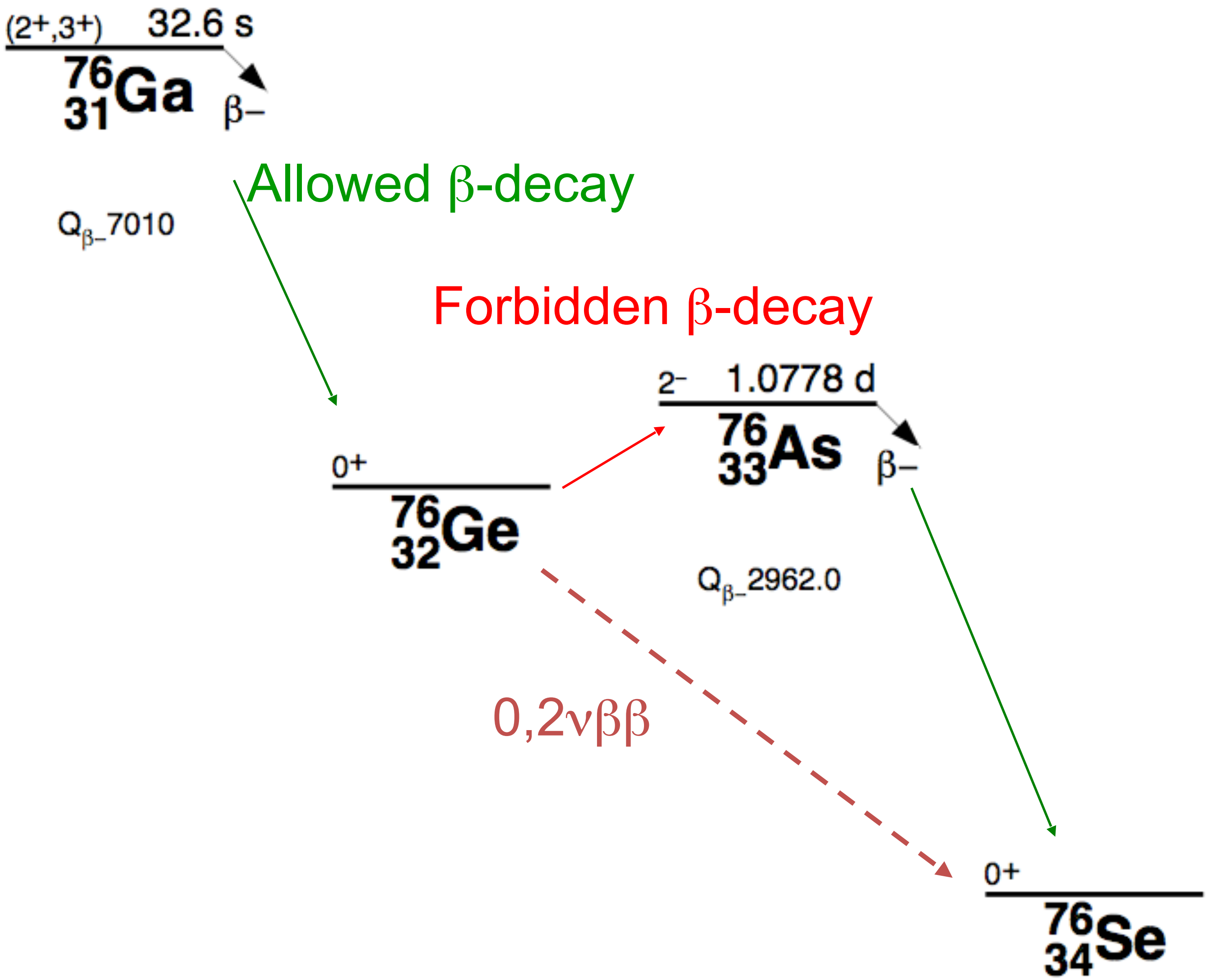
CP Phase

Neutrinoless double-beta decay

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-}$$

Energetically allowed in many nuclei.

Prefer nuclei stable against β-decay (about 30)



2υββ: Observed 2nd order weak process.

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-} + 2\overline{\nu}_{\epsilon}$$

History

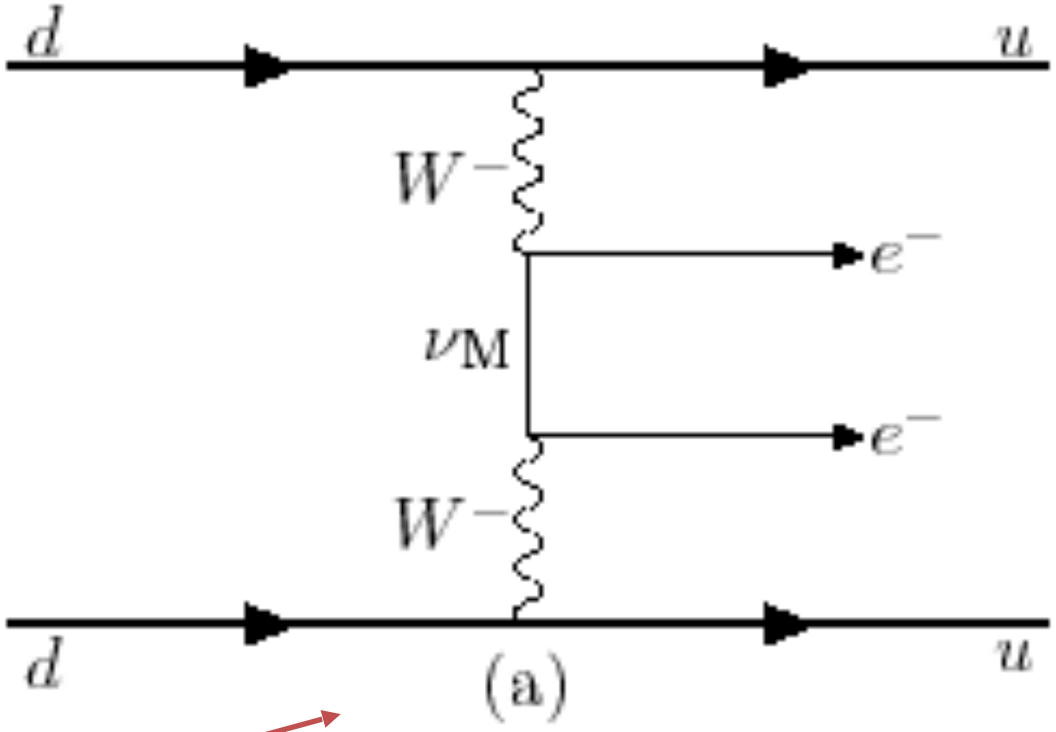
1935: Double beta decay postulated by
Maria Goeppert-Mayer *Phys. Rev. 48 (1935) 512*

1937: Ettore Majorana formulates theory with no distinction between ν and anti-ν.
Nuovo Cimento 14 (1937) 171

1937: Giulio Racah suggests zero-neutrino double-beta decay as test for Majorana's theory. *Nuovo Cimento 14 (1937) 322*

Motivation for 0υββ Search

- Implications of discovery:
  - Neutrino is Majorana* (own antiparticle)
  - Total lepton number is not conserved
  - Neutrinos have mass* (known)
  - Absolute neutrino mass.
- 0υββ nuclear decay may occur via several processes (SUSY, RH currents, etc)
- Canonical example: Exchange of virtual Majorana neutrino + helicity flip



* Schechter et al, Phys. Rev. D**25**, 2951 (1982)

0νββ Rate and Neutrino Mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(E_0,Z)\left|\langle m_{\beta\beta}\rangle\right|^2\left|M^{0\nu}\right|^2$$

$T_{1/2}^{0\nu}$: Half-life

Assumes ν_m exchange

$G^{0\nu}$: Phase Space (Known)

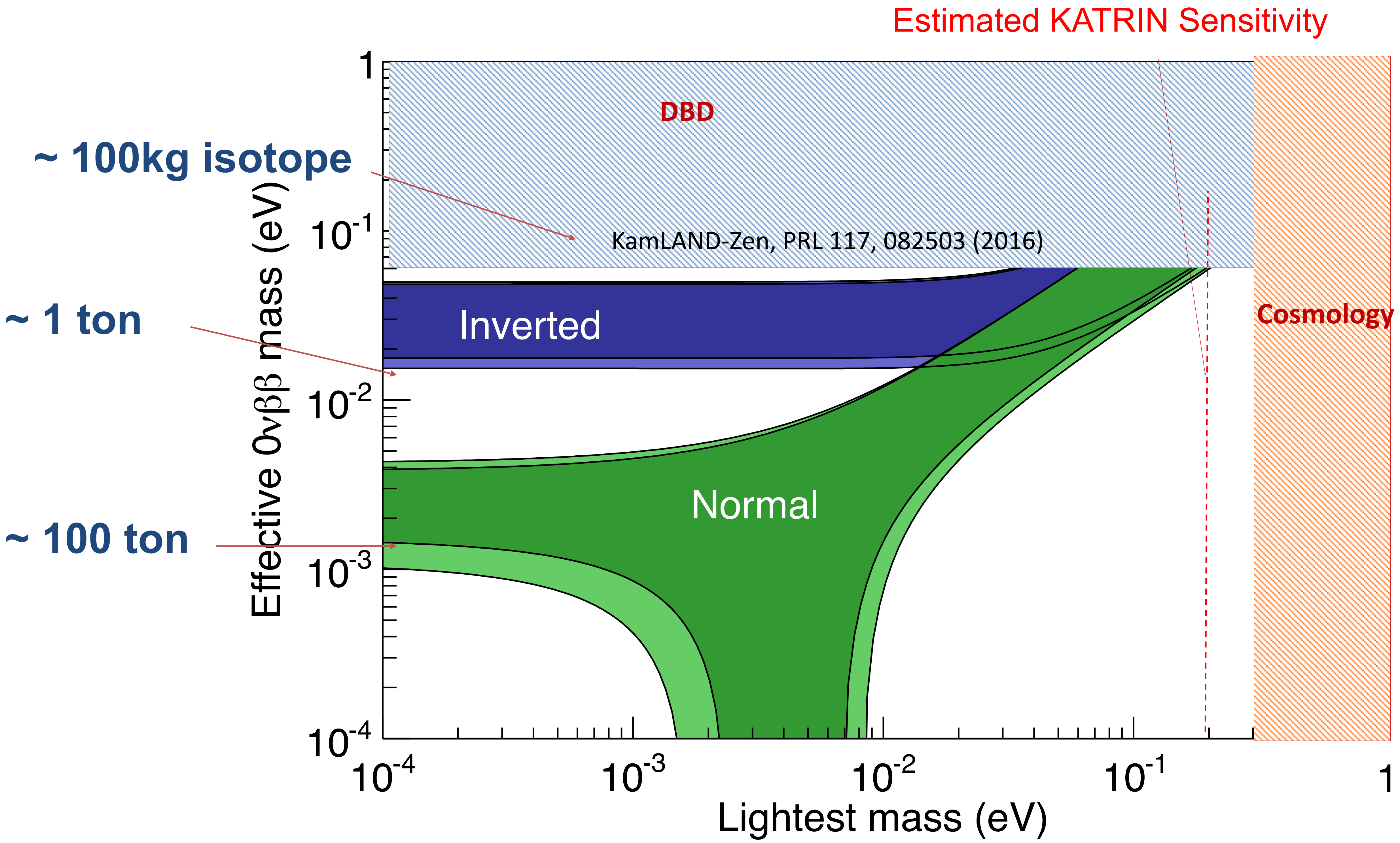
$M^{0\nu}$: Nuclear Matrix Element (large uncertainty)

$$\left|< m_{\beta\beta} >\right| = \left|\sum_i \left|U_{ei}\right|^2 m_{\nu_i} e^{i\alpha_i}\right|$$

Effective Majorana electron neutrino mass*

- ☞ 0υββ decay can probe **absolute** neutrino mass scale and mixing.
- ☞ Current neutrino experiments measure mass squared differences: Δm^2.

Combined Mass Limits

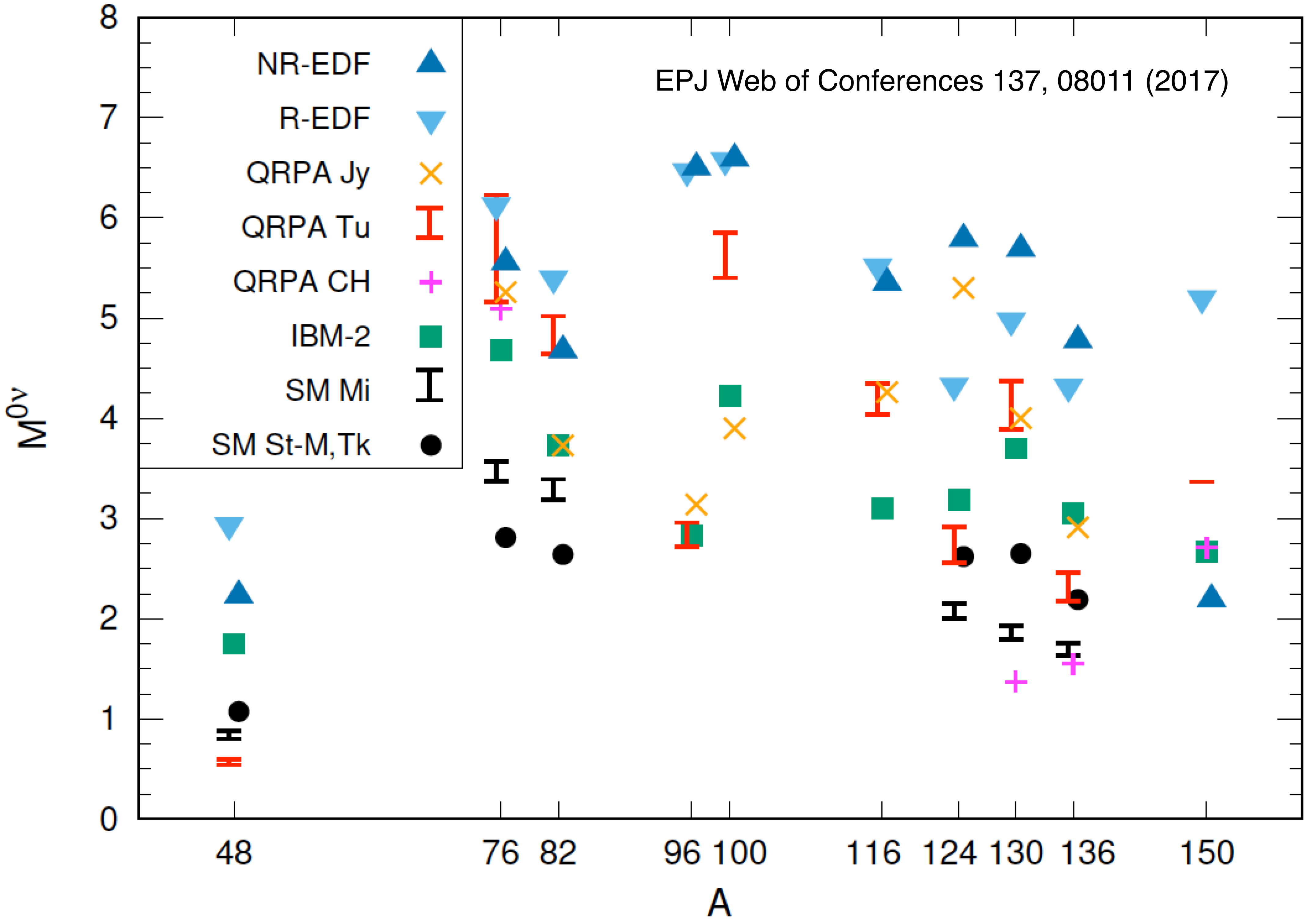


~ 100kg isotope

~ 1 ton

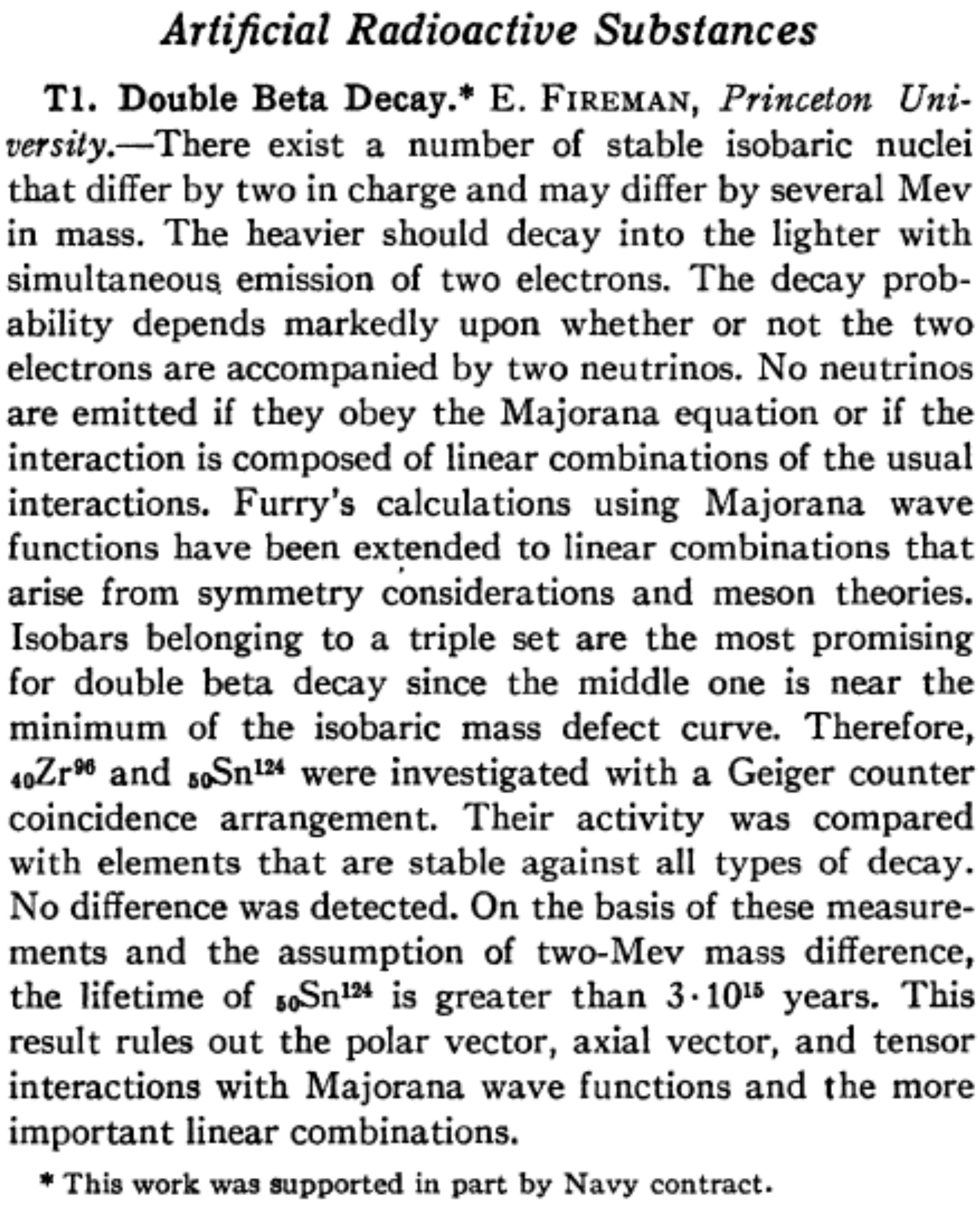
~ 100 ton

Matrix Elements



First Experimental Search for DBD Decay

Phys. Rev. 74 (1948) 1248 (conference proceedings)



Artificial Radioactive Substances

T1. Double Beta Decay.* E. Fireman, *Princeton University.*—There exist a number of stable isobaric nuclei that differ by two in charge and may differ by several Mev in mass. The heavier should decay into the lighter with simultaneous emission of two electrons. The decay probability depends markedly upon whether or not the two electrons are accompanied by two neutrinos. No neutrinos are emitted if they obey the Majorana equation or if the interaction is composed of linear combinations of the usual interactions. Furry's calculations using Majorana wave functions have been extended to linear combinations that arise from symmetry considerations and meson theories. Isobars belonging to a triple set are the most promising for double beta decay since the middle one is near the minimum of the isobaric mass defect curve. Therefore, ${}_{40}\text{Zr}^{96}$ and ${}_{50}\text{Sn}^{124}$ were investigated with a Geiger counter coincidence arrangement. Their activity was compared with elements that are stable against all types of decay. No difference was detected. On the basis of these measurements and the assumption of two-Mev mass difference, the lifetime of ${}_{50}\text{Sn}^{124}$ is greater than $3 \cdot 10^{15}$ years. This result rules out the polar vector, axial vector, and tensor interactions with Majorana wave functions and the more important linear combinations.

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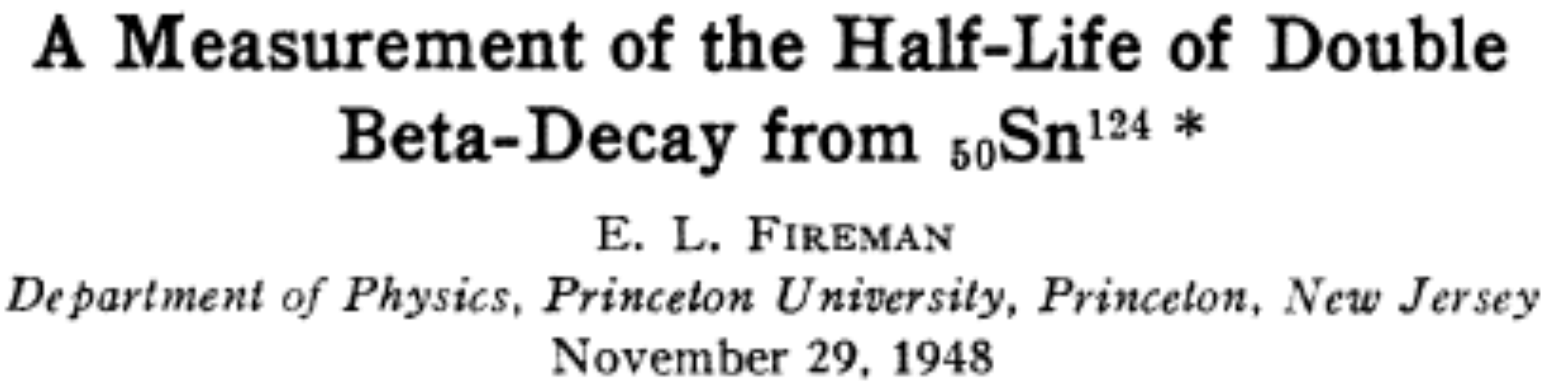
* This work was supported in part by Navy contract.

Searched for coincident betas from target materials using Geiger tubes

Followed by Discovery!



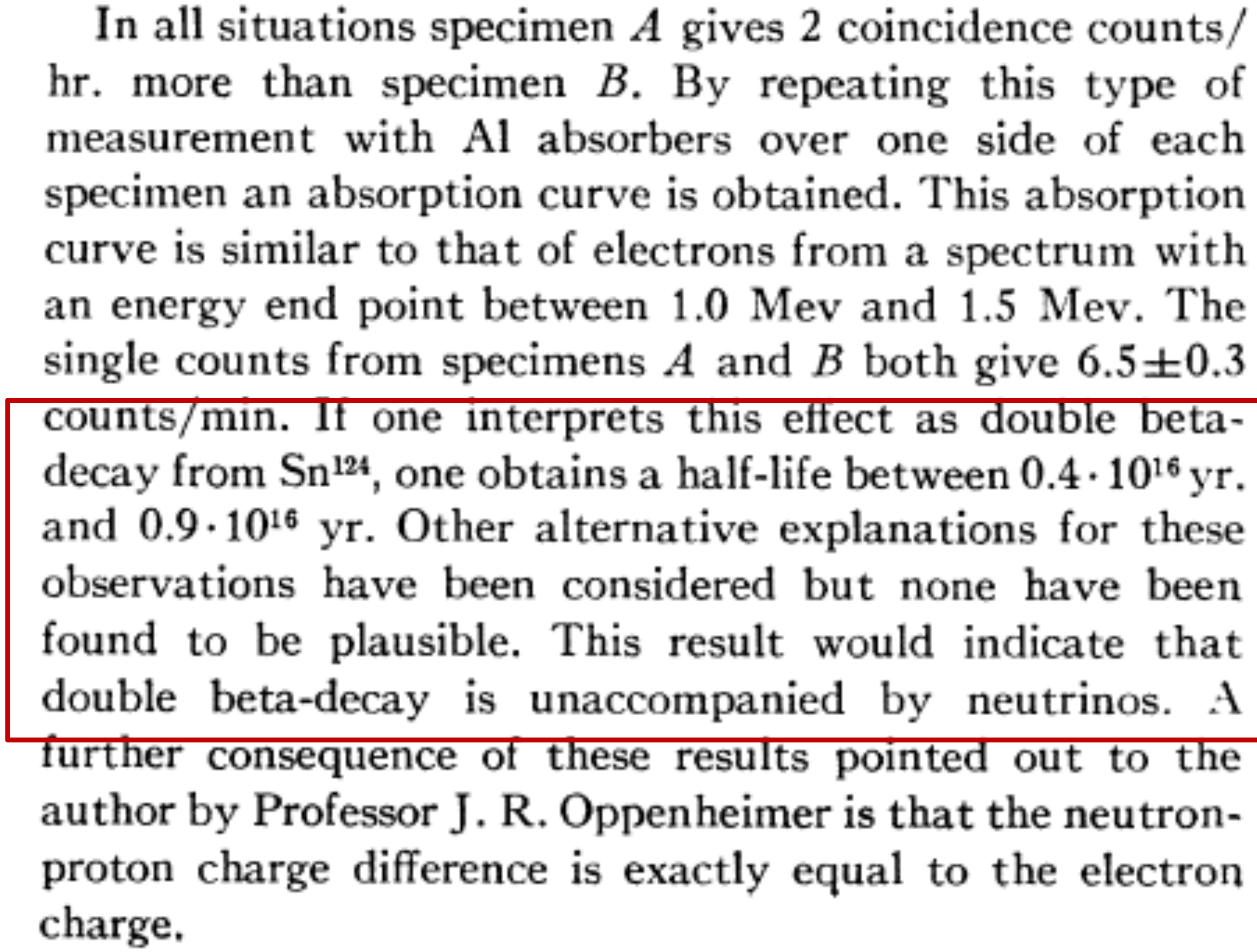
A Measurement of the Half-Life of Double Beta-Decay from $_{50}Sn^{124}$ *

E. L. FIREMAN

Department of Physics, Princeton University, Princeton, New Jersey

November 29, 1948

Phys. Rev. 75 (1949) 323



In all situations specimen *A* gives 2 coincidence counts/hr. more than specimen *B*. By repeating this type of measurement with Al absorbers over one side of each specimen an absorption curve is obtained. This absorption curve is similar to that of electrons from a spectrum with an energy end point between 1.0 Mev and 1.5 Mev. The single counts from specimens *A* and *B* both give 6.5±0.3 counts/min. If one interprets this effect as double beta-decay from Sn^{124}, one obtains a half-life between $0.4\cdot10^{16}$ yr. and $0.9\cdot10^{16}$ yr. Other alternative explanations for these observations have been considered but none have been found to be plausible. This result would indicate that double beta-decay is unaccompanied by neutrinos. A further consequence of these results pointed out to the author by Professor J. R. Oppenheimer is that the neutron-proton charge difference is exactly equal to the electron charge.

2.6 sigma effect

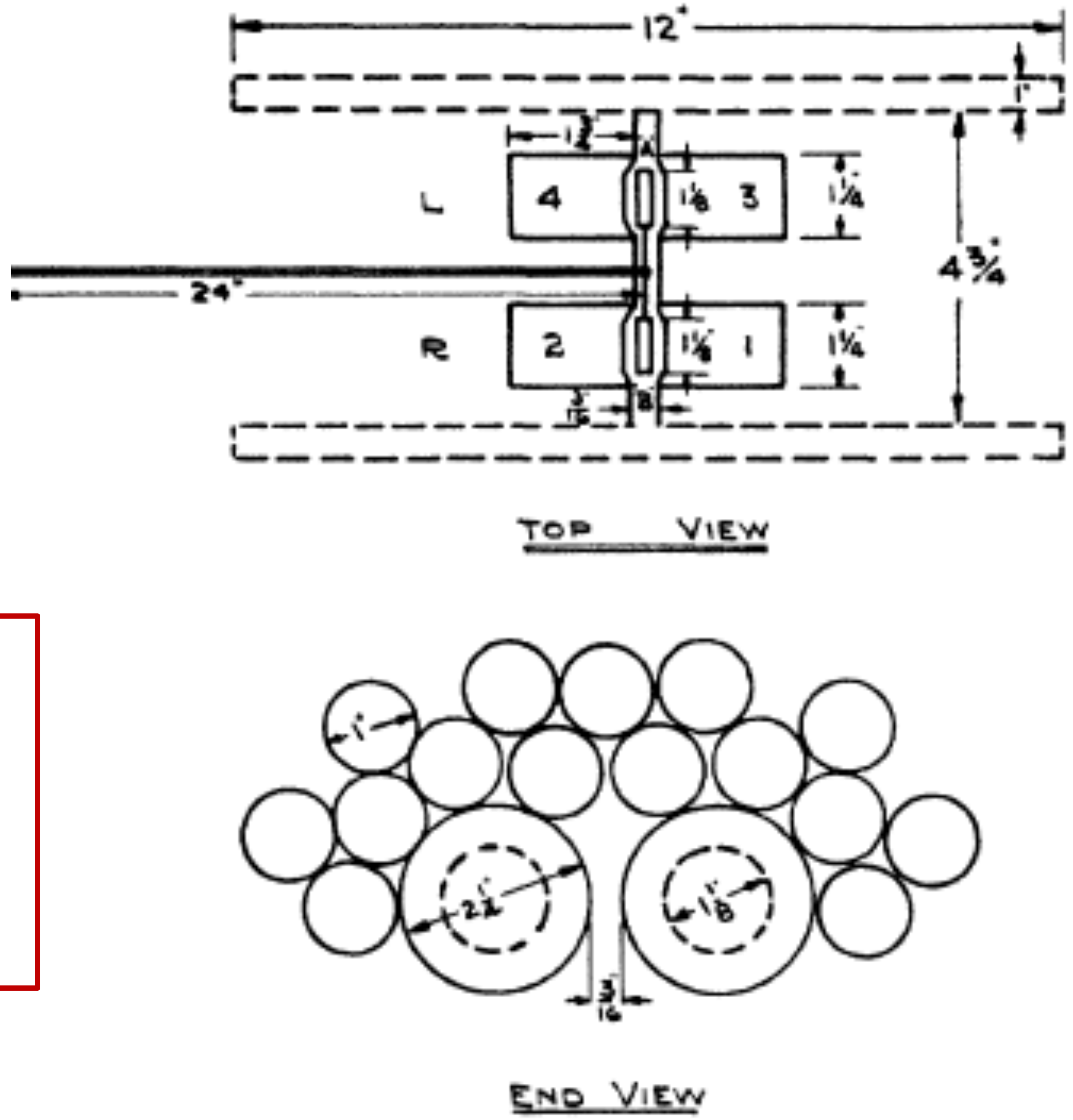


FIG. 1. Experimental arrangement.

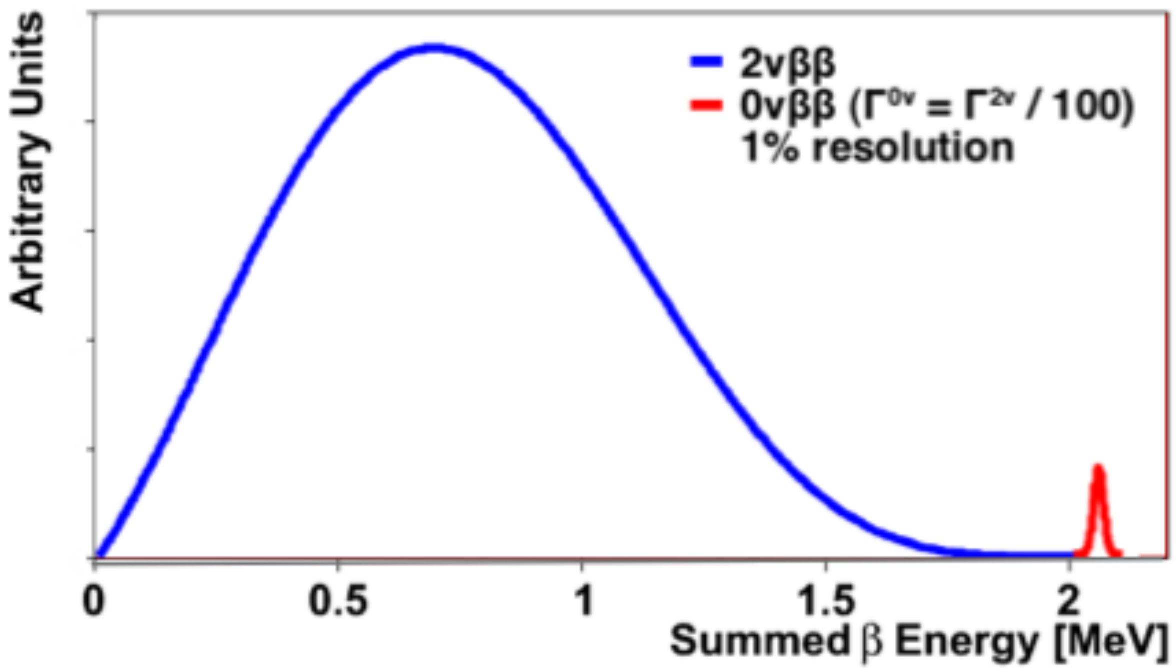
Discussion

- Ruled out by subsequent measurements, though (Astropart. Phys. 31 (2009) 412) $T_{1/2}(^{124}Sn, 0n)>2.0\times10^{19}yr$)
- Likely due to radioactive contamination, uncontrolled systematics (no discussion of calibrations), sample thickness
- Limited handles on data
- About 10 "claims" in literature, all debunked
- Three explanations:
  - Unknown backgrounds
  - Statistical fluctuations
  - Systematics / unknown detector response

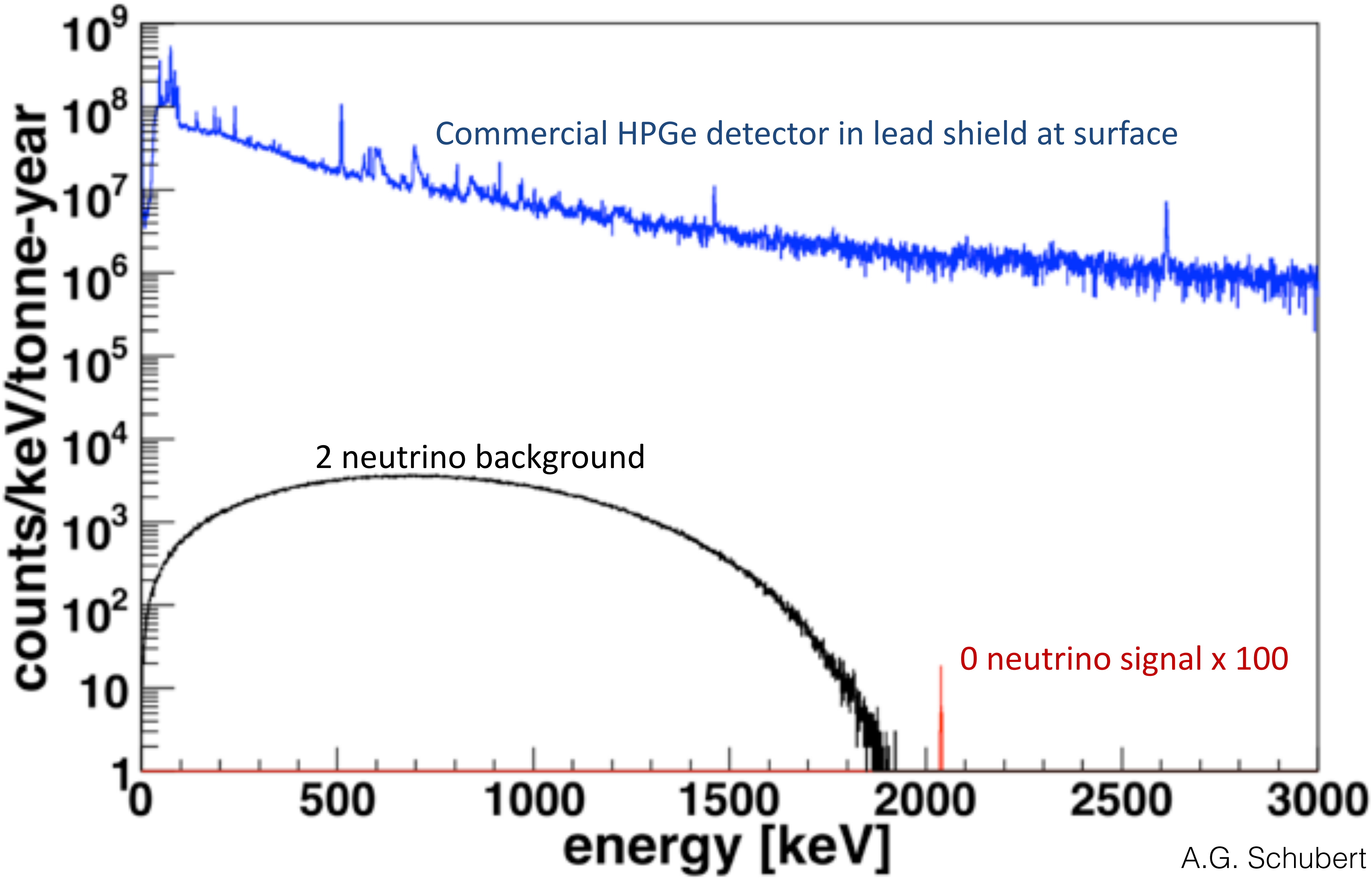
Experimental Considerations

- Measure ***extremely*** rare decay rates :
    - $T_{1/2} \sim 10^{26}$ -10^{27} years ~ few decays per tonne per year.
- Large, highly efficient source mass.
- Extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region-of-interest (ROI)

1. High *Q* value
2. Best possible energy resolution
    - Minimize $0\nu\beta\beta$ peak ROI to maximize S/B
    - Separate $2\nu\beta\beta/0\nu\beta\beta$



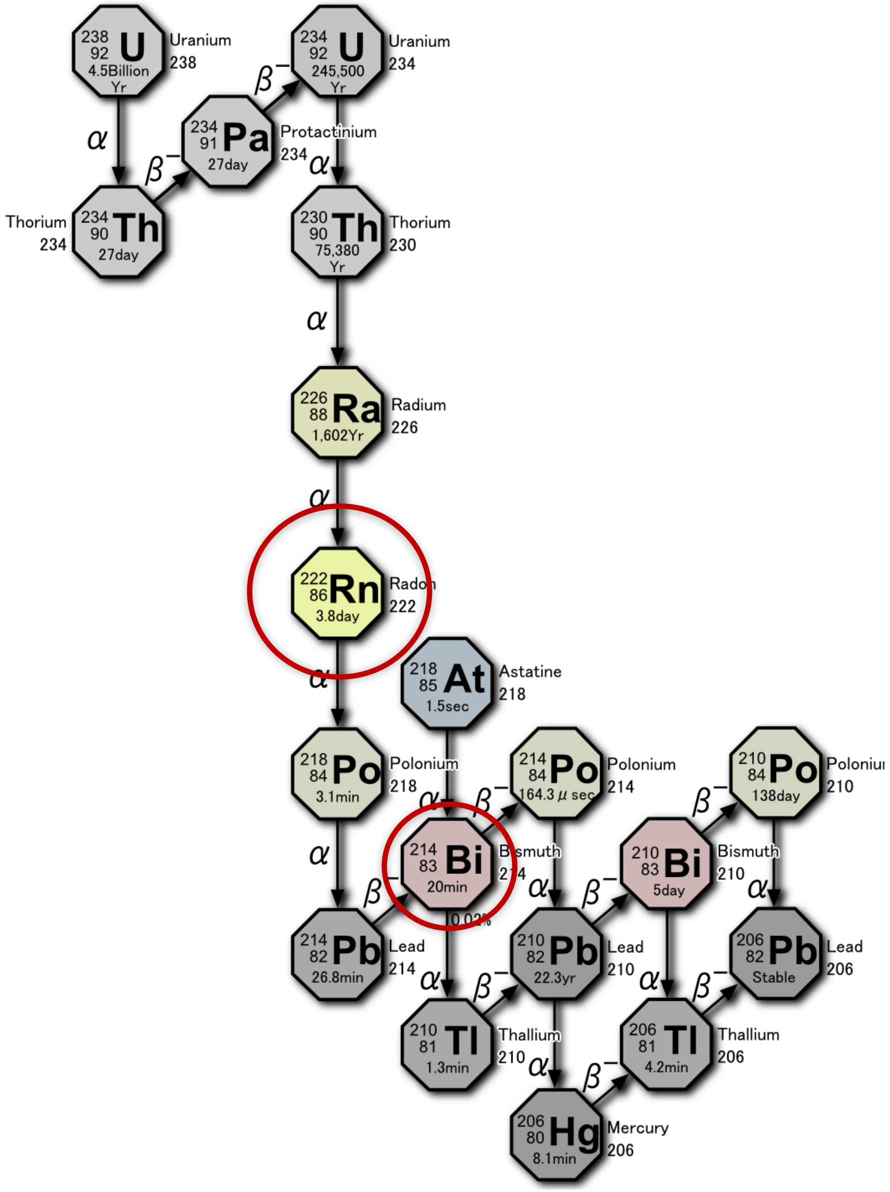
Background Reduction Challenges

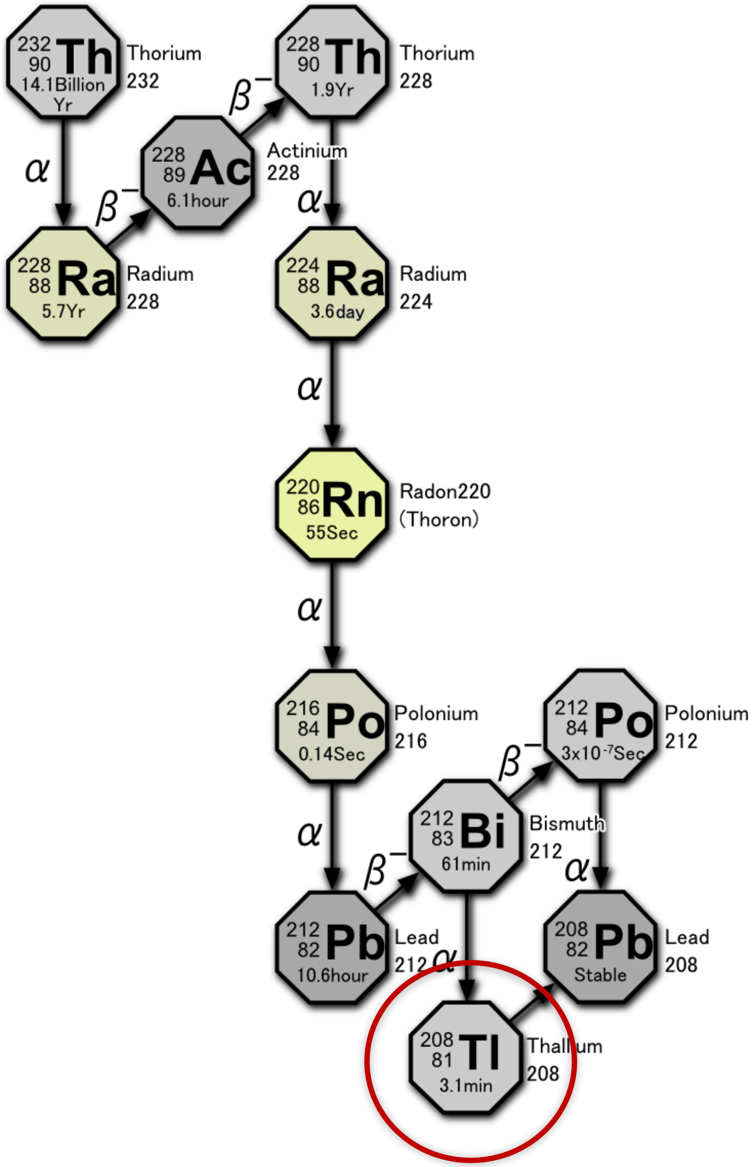


A.G. Schubert

Background Identification

- Natural isotope chains:
  - ^{232}Th, ^{235}U, ^{238}U, Rn
- $2\nu\beta\beta$-decays
- Cosmic Rays:
  - Activation at surface
  - Hard neutrons from cosmic rays in rock and shield.
  - Prompt
- Pushing limits in ICP-MS, materials science, radio-assay. Ie. Ultra-low radioactive background, fast, low-noise electronics





Industrial Assay Programs

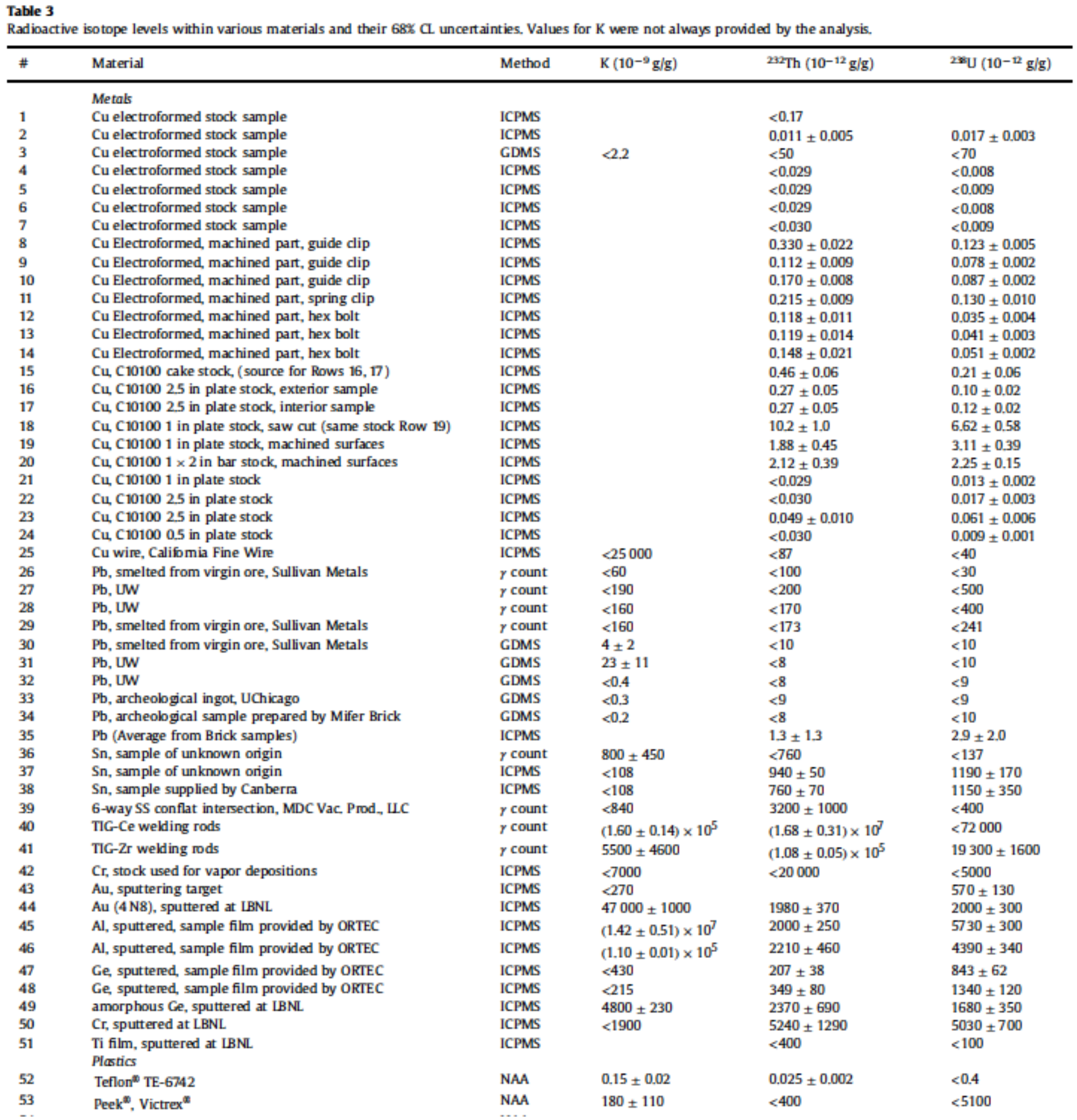


Table 3
Radioactive isotope levels within various materials and their 68% CL uncertainties. Values for K were not always provided by the analysis.

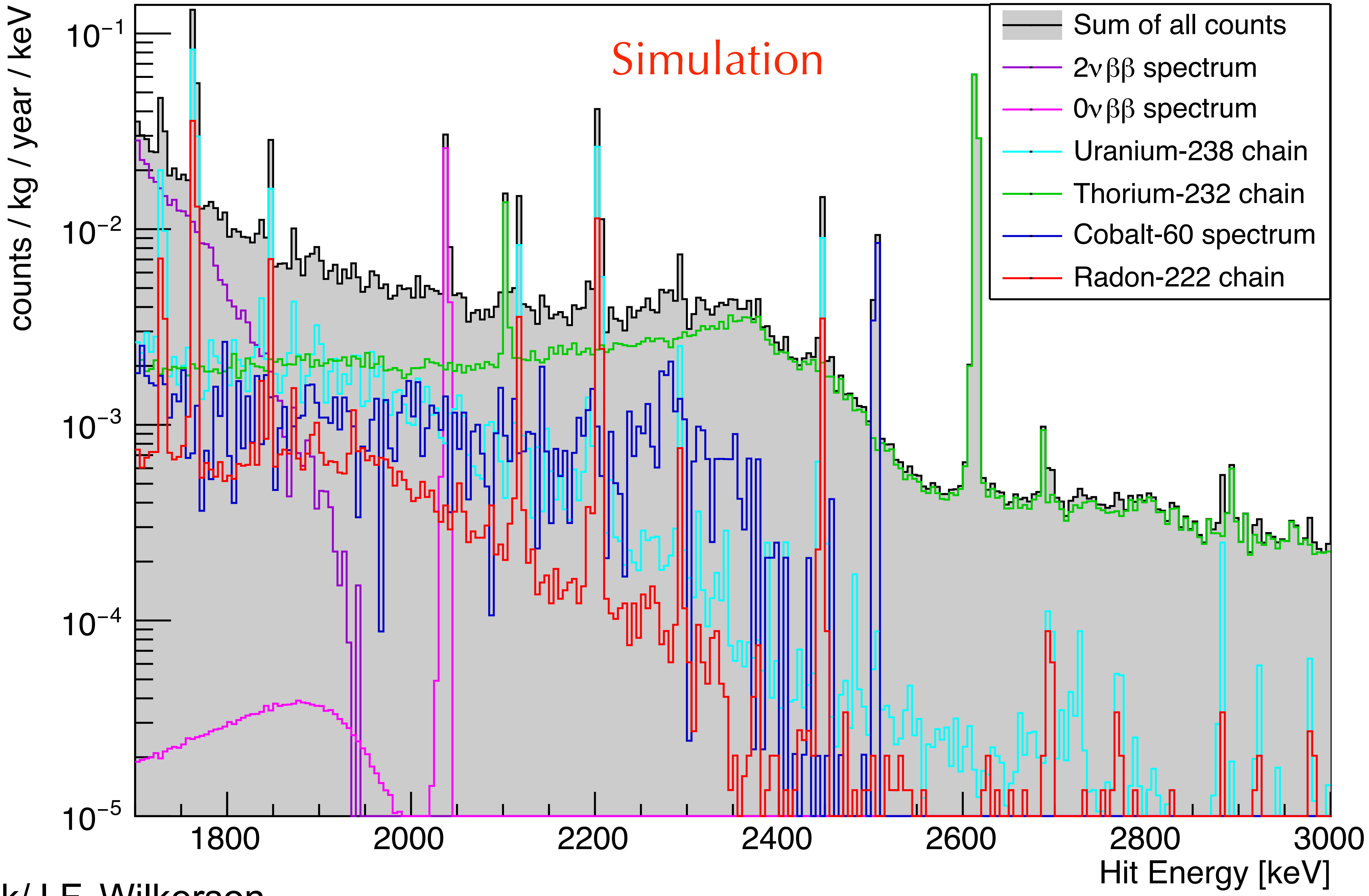
#	Material	Method	K (10^{-9} g/g)	^{232}Th (10^{-12} g/g)	^{238}U (10^{-12} g/g)
	Metals				
1	Cu electroformed stock sample	ICPMS		<0.17	
2	Cu electroformed stock sample	ICPMS		0.011 ± 0.005	0.017 ± 0.003
3	Cu electroformed stock sample	GDMS	<2.2	<50	<70
4	Cu electroformed stock sample	ICPMS		<0.029	<0.008
5	Cu electroformed stock sample	ICPMS		<0.029	<0.009
6	Cu electroformed stock sample	ICPMS		<0.029	<0.008
7	Cu electroformed stock sample	ICPMS		<0.030	<0.009
8	Cu Electroformed, machined part, guide clip	ICPMS		0.330 ± 0.022	0.123 ± 0.005
9	Cu Electroformed, machined part, guide clip	ICPMS		0.112 ± 0.009	0.078 ± 0.002
10	Cu Electroformed, machined part, guide clip	ICPMS		0.170 ± 0.008	0.087 ± 0.002
11	Cu Electroformed, machined part, spring clip	ICPMS		0.215 ± 0.009	0.130 ± 0.010
12	Cu Electroformed, machined part, hex bolt	ICPMS		0.118 ± 0.011	0.035 ± 0.004
13	Cu Electroformed, machined part, hex bolt	ICPMS		0.119 ± 0.014	0.041 ± 0.003
14	Cu Electroformed, machined part, hex bolt	ICPMS		0.148 ± 0.021	0.051 ± 0.002
15	Cu, C10100 cake stock, (source for Rows 16, 17)	ICPMS		0.46 ± 0.06	0.21 ± 0.06
16	Cu, C10100 2.5 in plate stock, exterior sample	ICPMS		0.27 ± 0.05	0.10 ± 0.02
17	Cu, C10100 2.5 in plate stock, interior sample	ICPMS		0.27 ± 0.05	0.12 ± 0.02
18	Cu, C10100 1 in plate stock, saw cut (same stock Row 19)	ICPMS		10.2 ± 1.0	6.62 ± 0.58
19	Cu, C10100 1 in plate stock, machined surfaces	ICPMS		1.88 ± 0.45	3.11 ± 0.39
20	Cu, C10100 1 × 2 in bar stock, machined surfaces	ICPMS		2.12 ± 0.39	2.25 ± 0.15
21	Cu, C10100 1 in plate stock	ICPMS		<0.029	0.013 ± 0.002
22	Cu, C10100 2.5 in plate stock	ICPMS		<0.030	0.017 ± 0.003
23	Cu, C10100 2.5 in plate stock	ICPMS		0.049 ± 0.010	0.061 ± 0.006
24	Cu, C10100 0.5 in plate stock	ICPMS		<0.030	0.009 ± 0.001
25	Cu wire, California Fine Wire	ICPMS	<25 000	<87	<40
26	Pb, smelted from virgin ore, Sullivan Metals	γ count	<60	<100	<30
27	Pb, UW	γ count	<190	<200	<500
28	Pb, UW	γ count	<160	<170	<400
29	Pb, smelted from virgin ore, Sullivan Metals	γ count	<160	<173	<241
30	Pb, smelted from virgin ore, Sullivan Metals	GDMS	4 ± 2	<10	<10
31	Pb, UW	GDMS	23 ± 11	<8	<10
32	Pb, UW	GDMS	<0.4	<8	<9
33	Pb, archeological ingot, UChicago	GDMS	<0.3	<9	<9
34	Pb, archeological sample prepared by Mifer Brick	GDMS	<0.2	<8	<10
35	Pb (Average from Brick samples)	ICPMS		1.3 ± 1.3	2.9 ± 2.0
36	Sn, sample of unknown origin	γ count	800 ± 450	<760	<137
37	Sn, sample of unknown origin	ICPMS	<108	940 ± 50	1190 ± 170
38	Sn, sample supplied by Canberra	ICPMS	<108	760 ± 70	1150 ± 350
39	6-way SS conflat intersection, MDC Vac. Prod., LLC	γ count	<840	3200 ± 1000	<400
40	TIG-Ce welding rods	γ count	$(1.60 \pm 0.14) \times 10^5$	$(1.68 \pm 0.31) \times 10^7$	<72 000
41	TIG-Zr welding rods	γ count	5500 ± 4600	$(1.08 \pm 0.05) \times 10^5$	19 300 ± 1600
42	Cr, stock used for vapor depositions	ICPMS	<7000	<20 000	<5000
43	Au, sputtering target	ICPMS	<270		570 ± 130
44	Au (4 N8), sputtered at LBNL	ICPMS	47 000 ± 1000	1980 ± 370	2000 ± 300
45	Al, sputtered, sample film provided by ORTEC	ICPMS	$(1.42 \pm 0.51) \times 10^7$	2000 ± 250	5730 ± 300
46	Al, sputtered, sample film provided by ORTEC	ICPMS	$(1.10 \pm 0.01) \times 10^5$	2210 ± 460	4390 ± 340
47	Ge, sputtered, sample film provided by ORTEC	ICPMS	<430	207 ± 38	843 ± 62
48	Ge, sputtered, sample film provided by ORTEC	ICPMS	<215	349 ± 80	1340 ± 120
49	amorphous Ge, sputtered at LBNL	ICPMS	4800 ± 230	2370 ± 690	1680 ± 350
50	Cr, sputtered at LBNL	ICPMS	<1900	5240 ± 1290	5030 ± 700
51	Ti film, sputtered at LBNL	ICPMS		<400	<100
	Plastics				
52	Teflon® TE-6742	NAA	0.15 ± 0.02	0.025 ± 0.002	<0.4
53	Peek®, Victrex®	NAA	180 ± 110	<400	<5100

Abgrall et al. NIM A 828 (2016) 22

… 170 entries …

Backgrounds, resolution, discovery

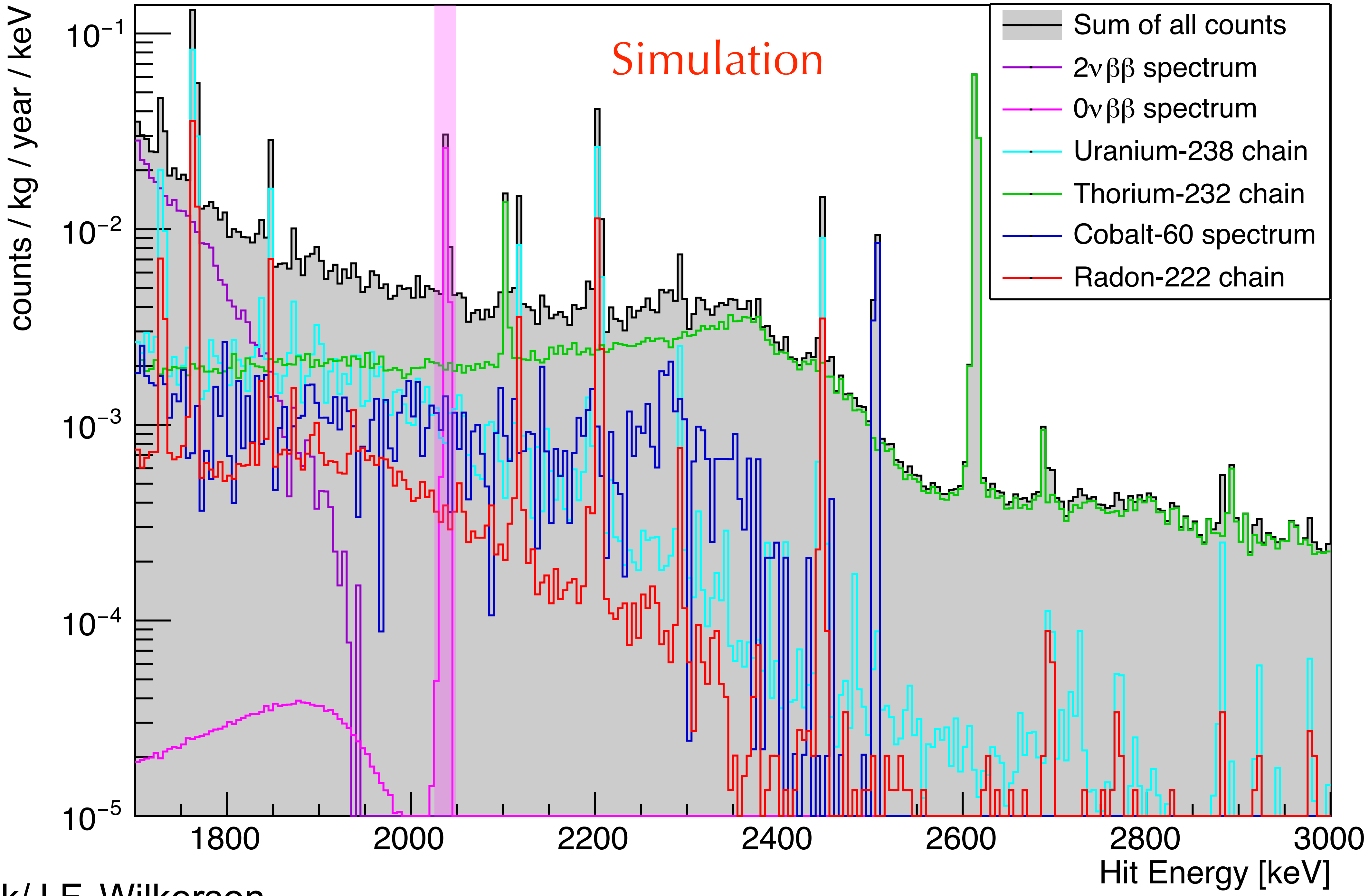
Resolution@2039keV: 2.5 keV, 0νββ HL: ~2e25 y



M. Buuck/J.F. Wilkerson

Backgrounds, resolution, discovery

Resolution@2039keV: 2.5 keV, 0νββ HL: ~2e25 y



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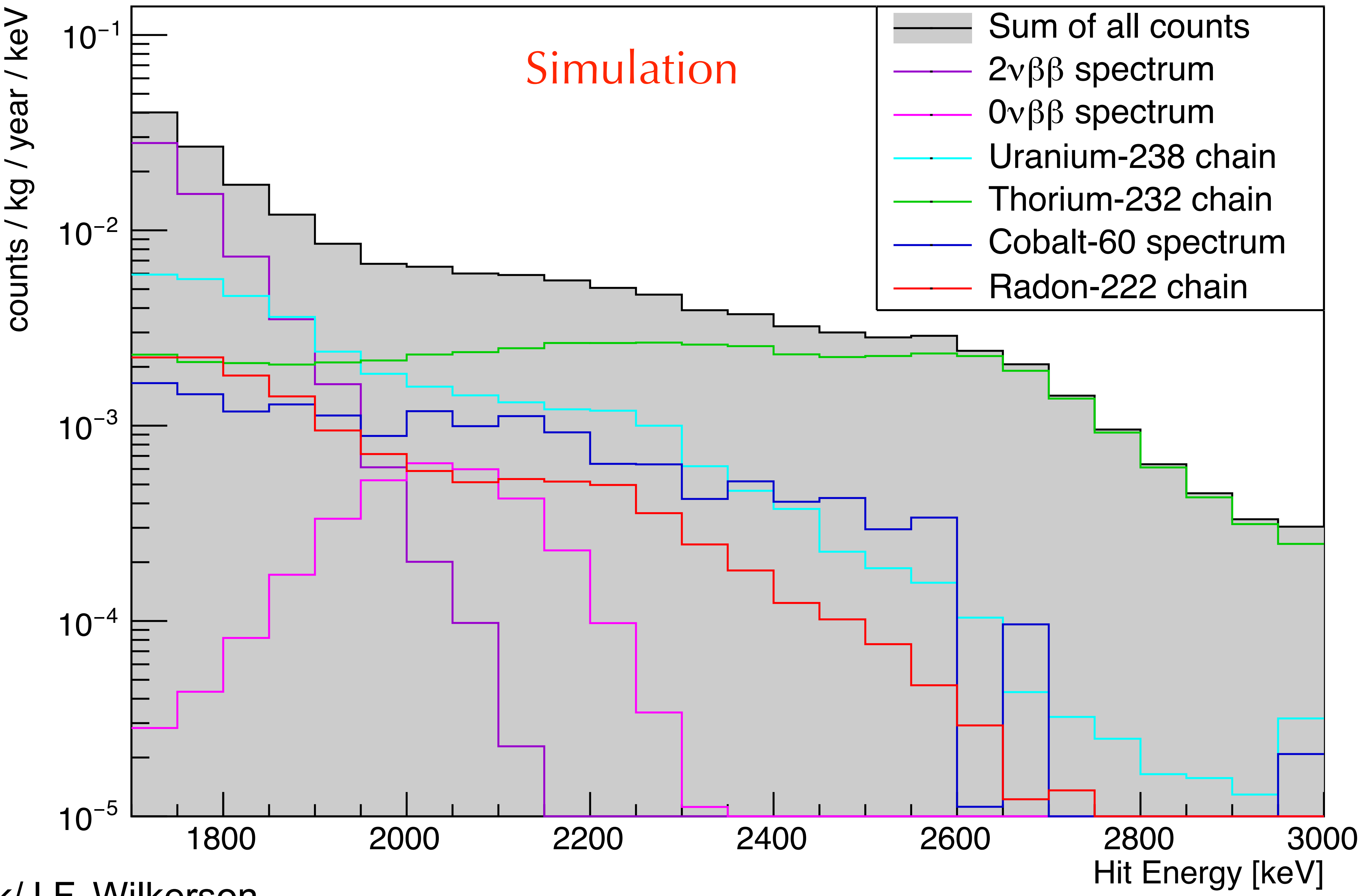
Backgrounds, resolution, discovery

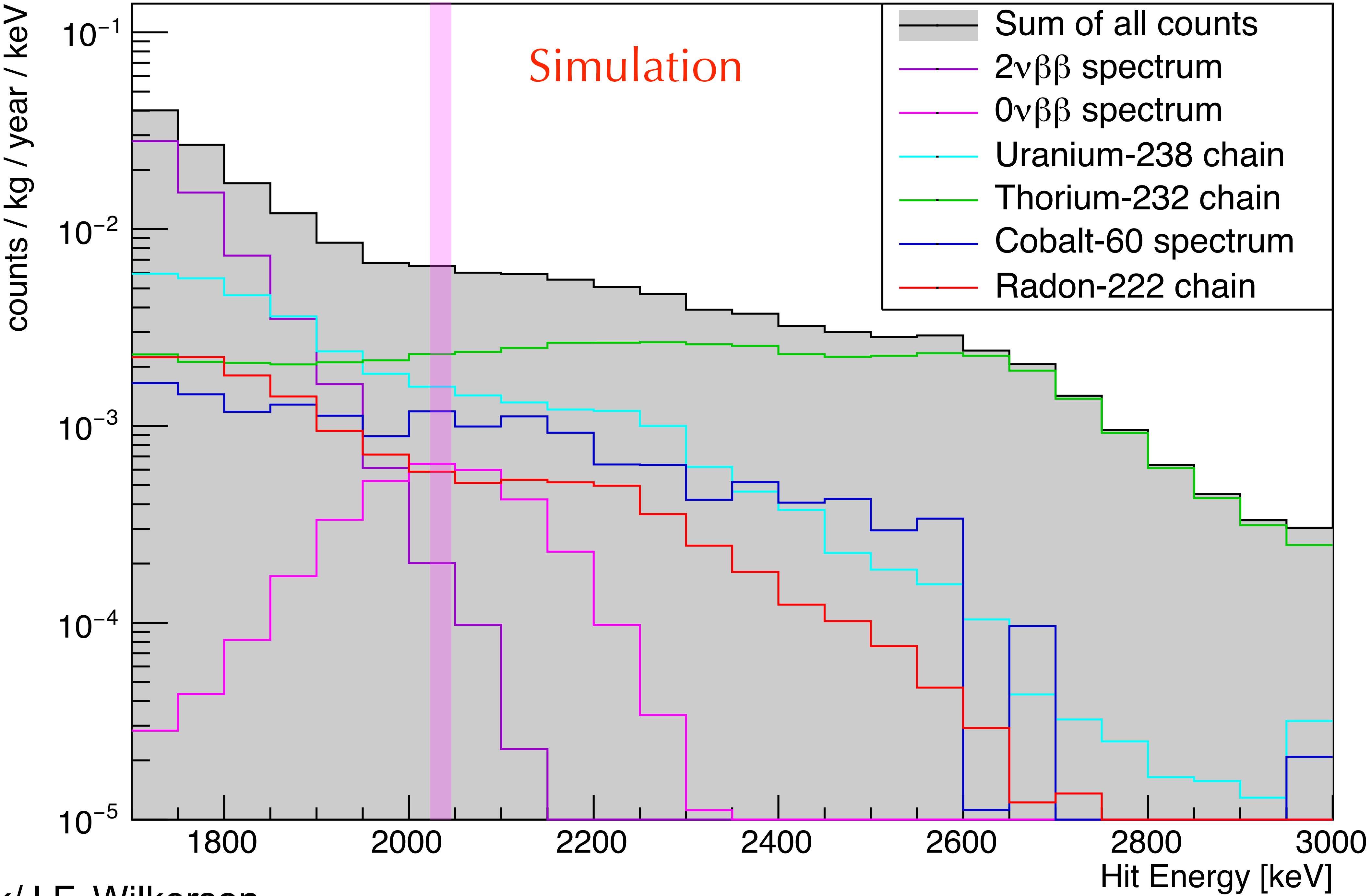
Resolution@2039keV: 250 keV, 0νββ HL: ~2e25 y



M. Buuck/J.F. Wilkerson

Backgrounds, resolution, discovery

Resolution@2039keV: 250 keV, 0νββ HL: ~2e25 y



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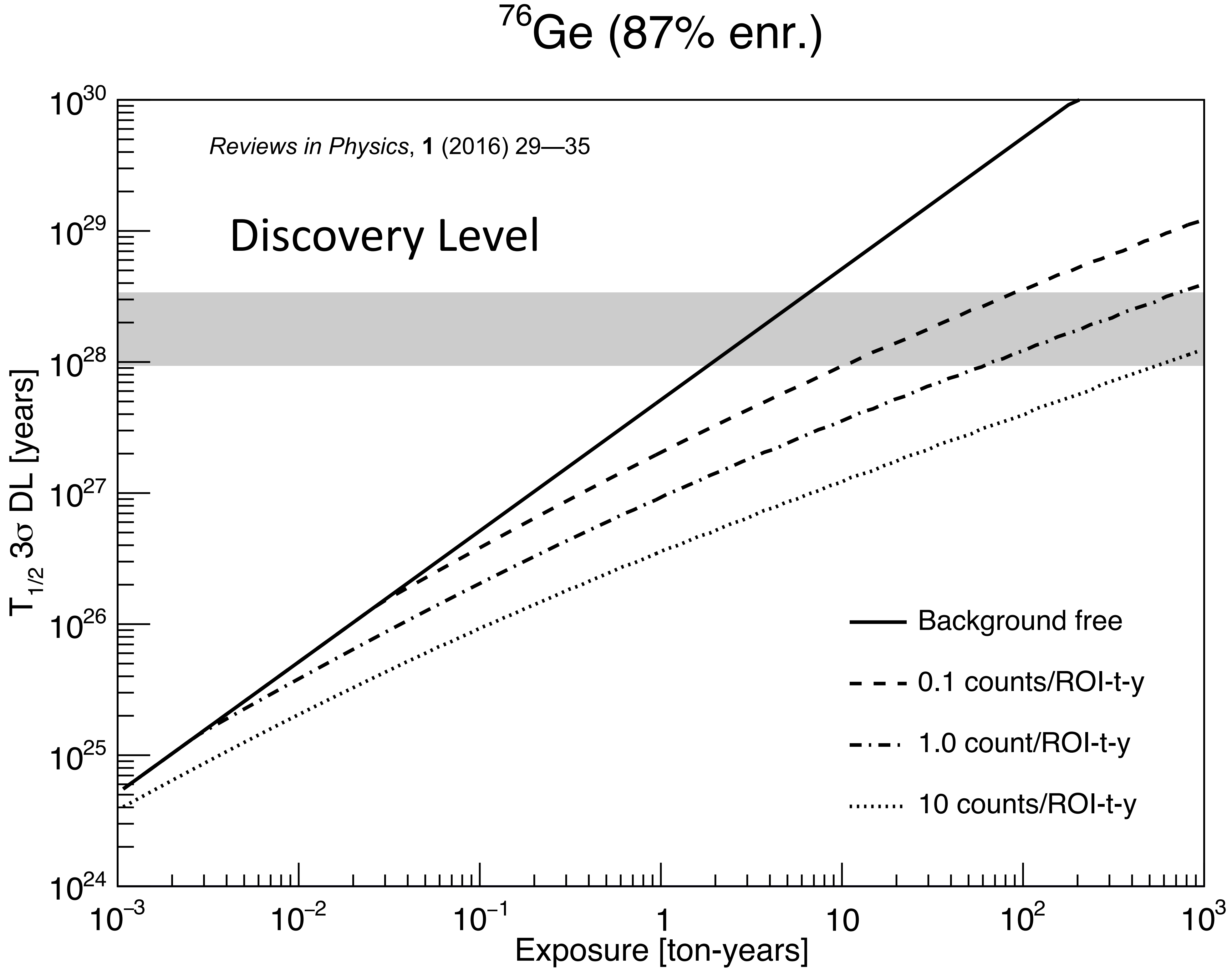
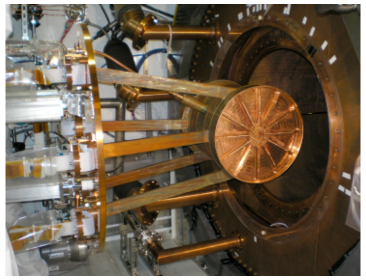
Sensitivity, Background and Exposure



0νββ decay Experiments - Efforts Underway

CUORE

EXO200

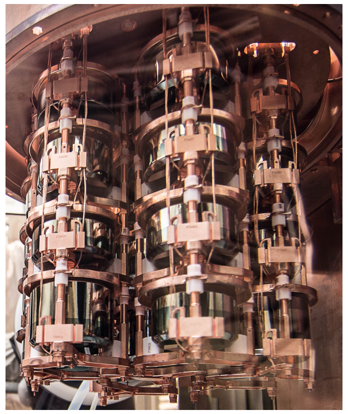


KamLAND Zen

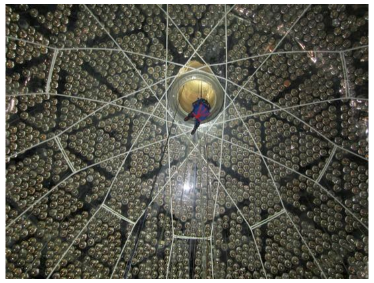
Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
Majorana Demonstrator	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact with active veto	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - III	Xe-136	High pressure Xe TPC	~ **ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

MAJORANA



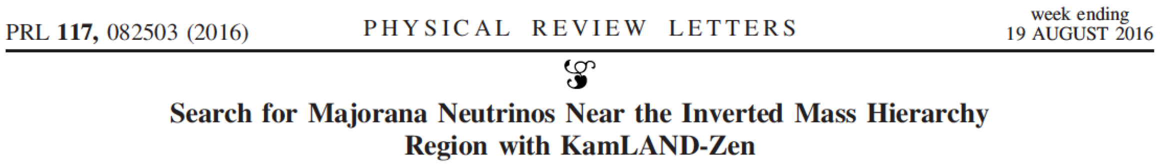
SNO+



J.F. Wilkerson

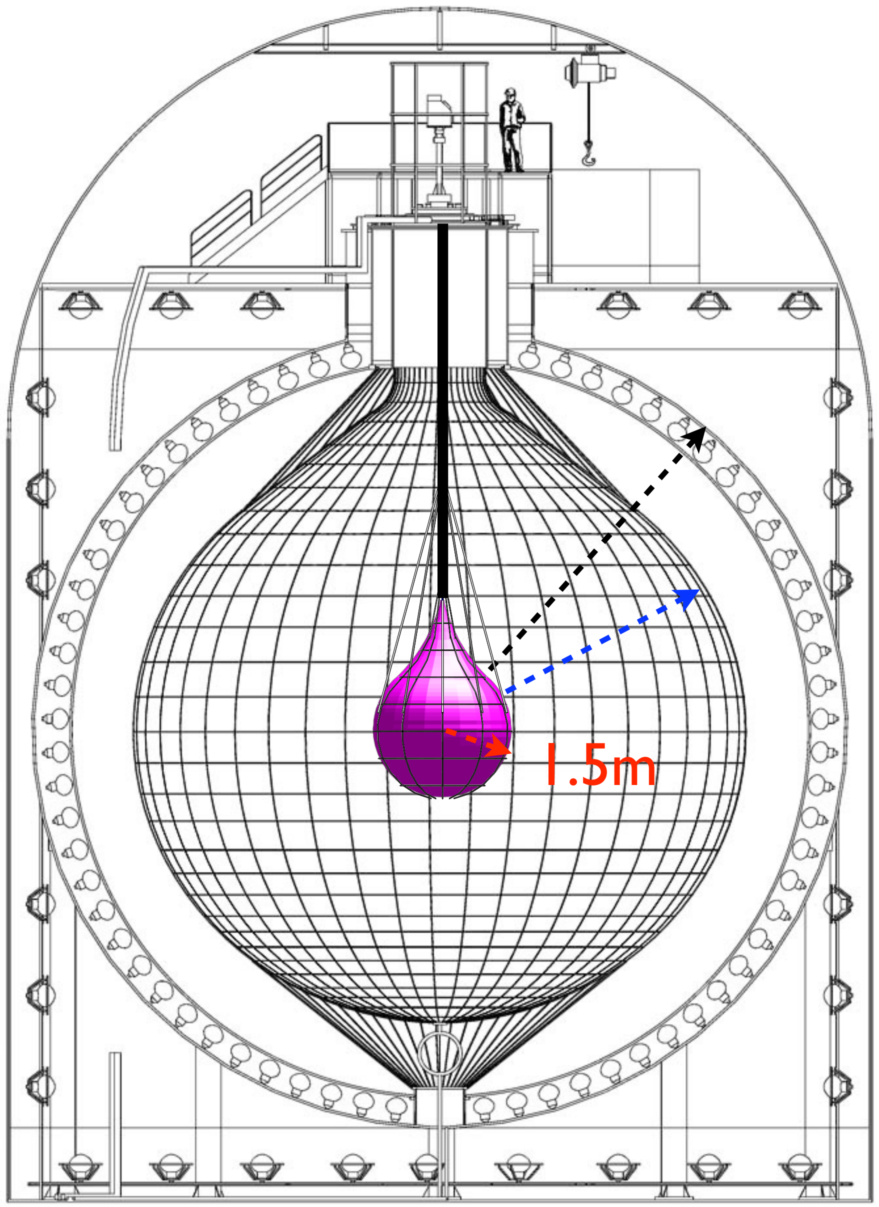
Recent Results

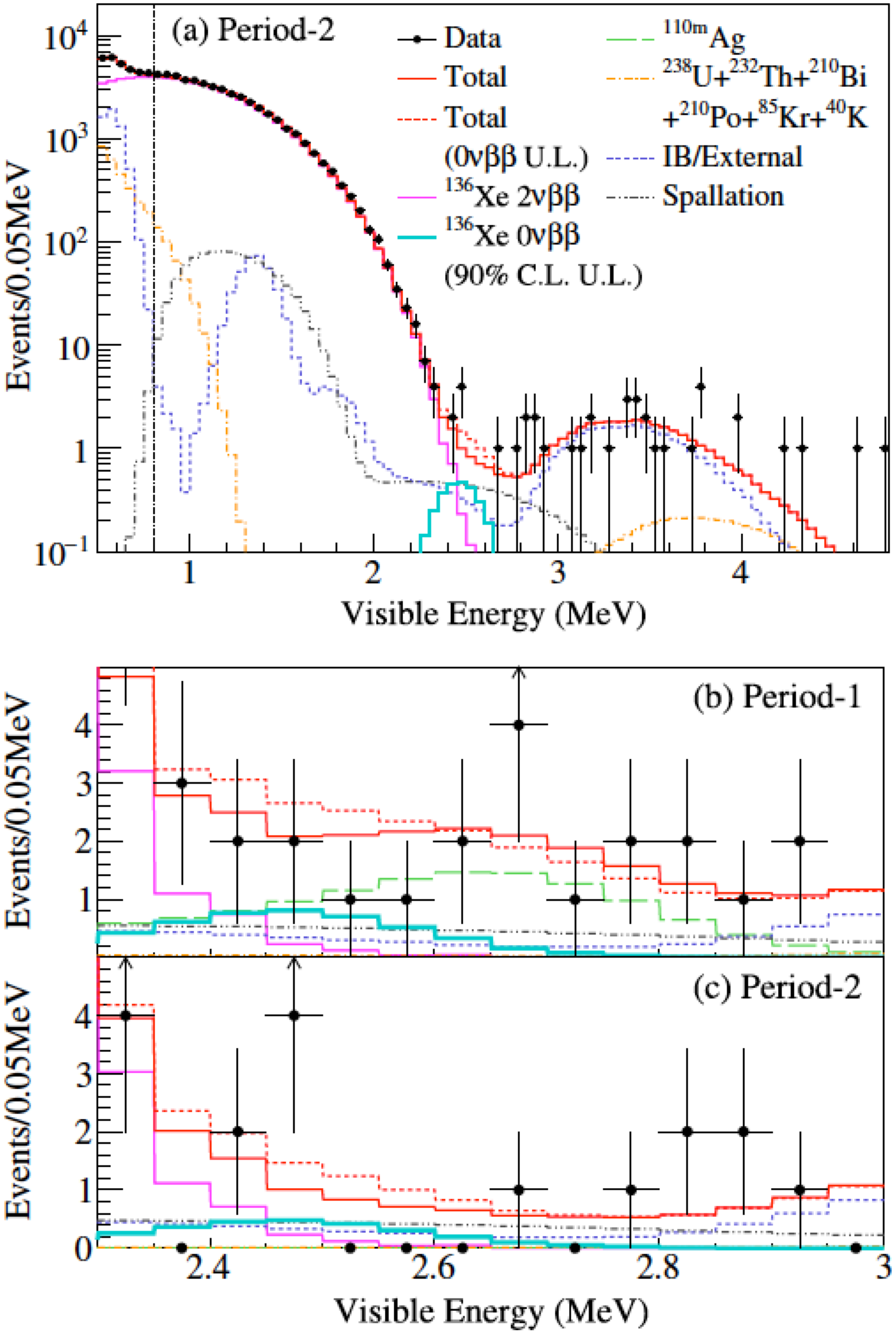
KamLand-ZEN



PRL **117,** 082503 (2016) PHYSICAL REVIEW LETTERS week ending 19 AUGUST 2016

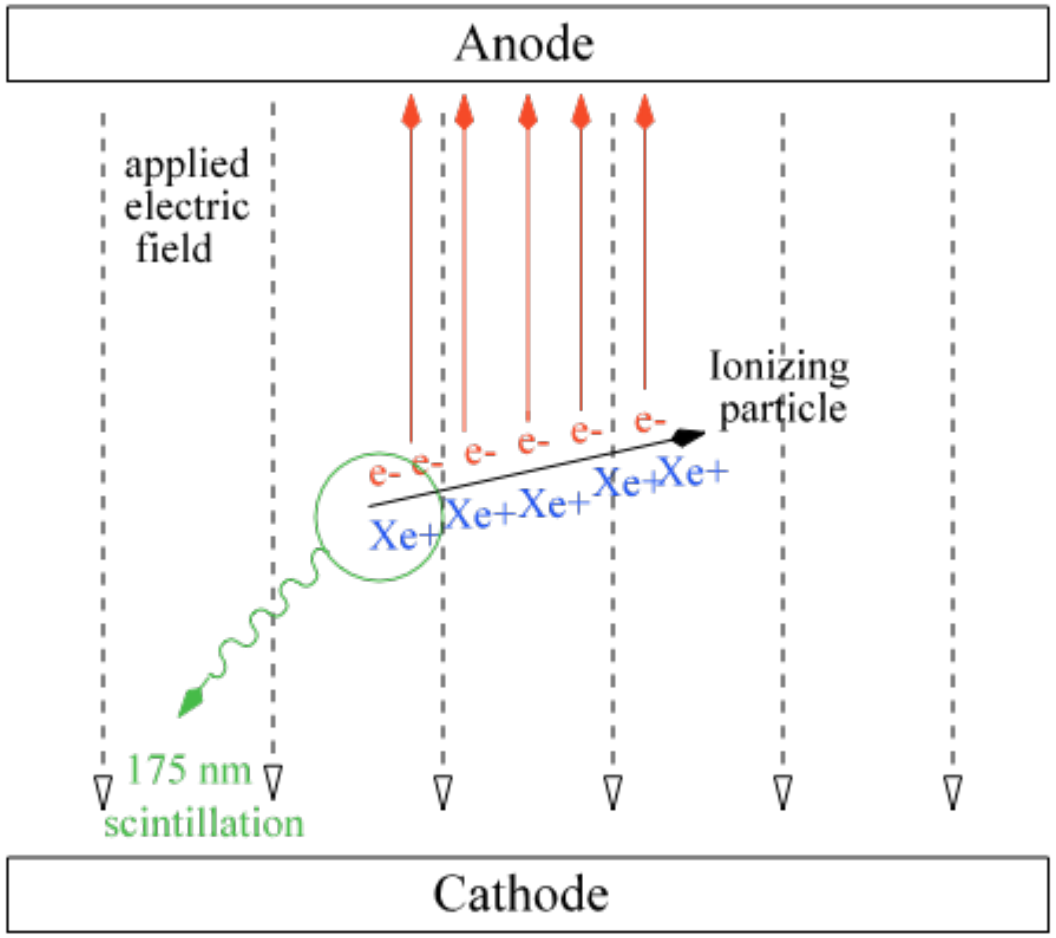
Search for Majorana Neutrinos Near the Inverted Mass Hierarchy Region with KamLAND-Zen

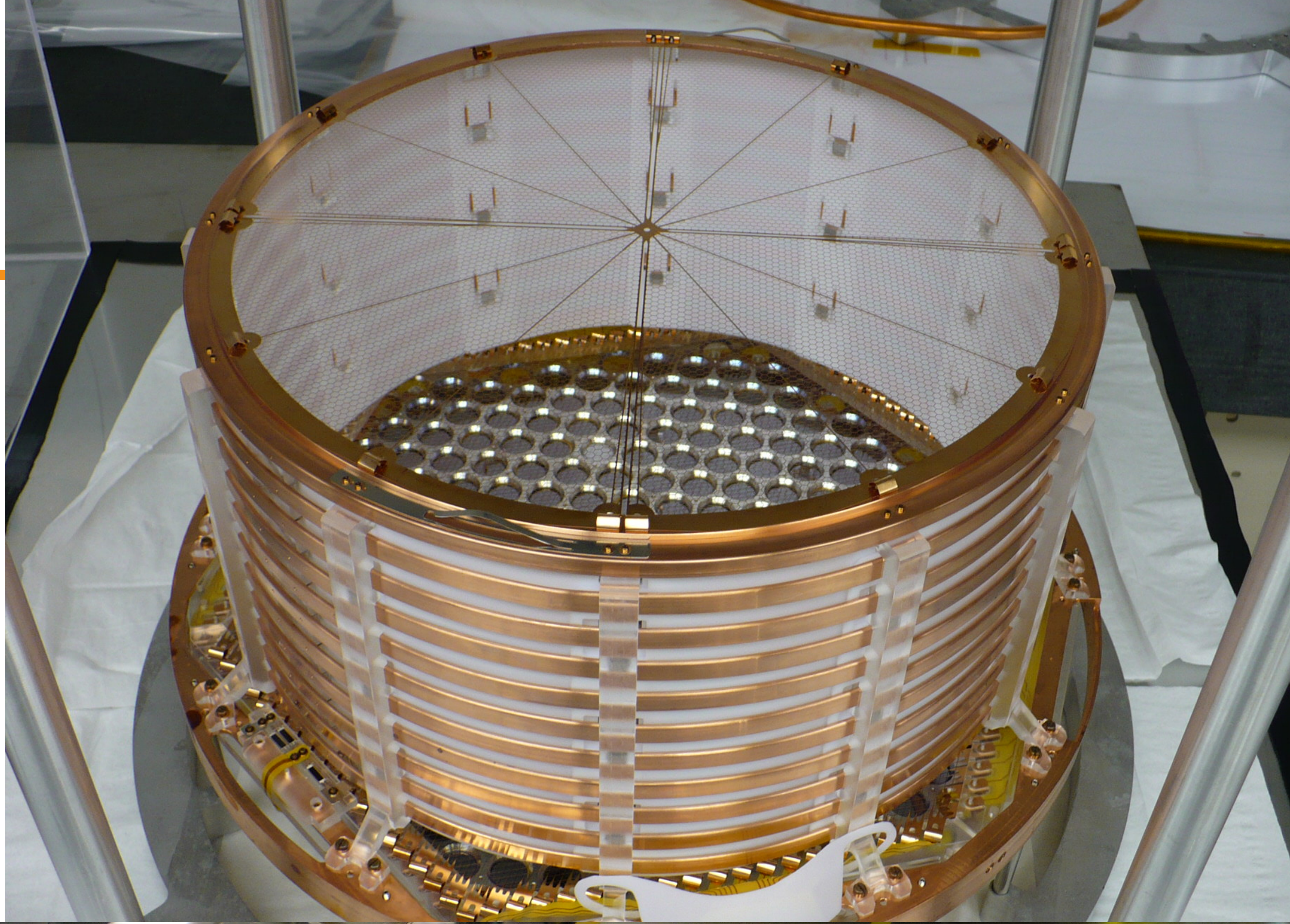


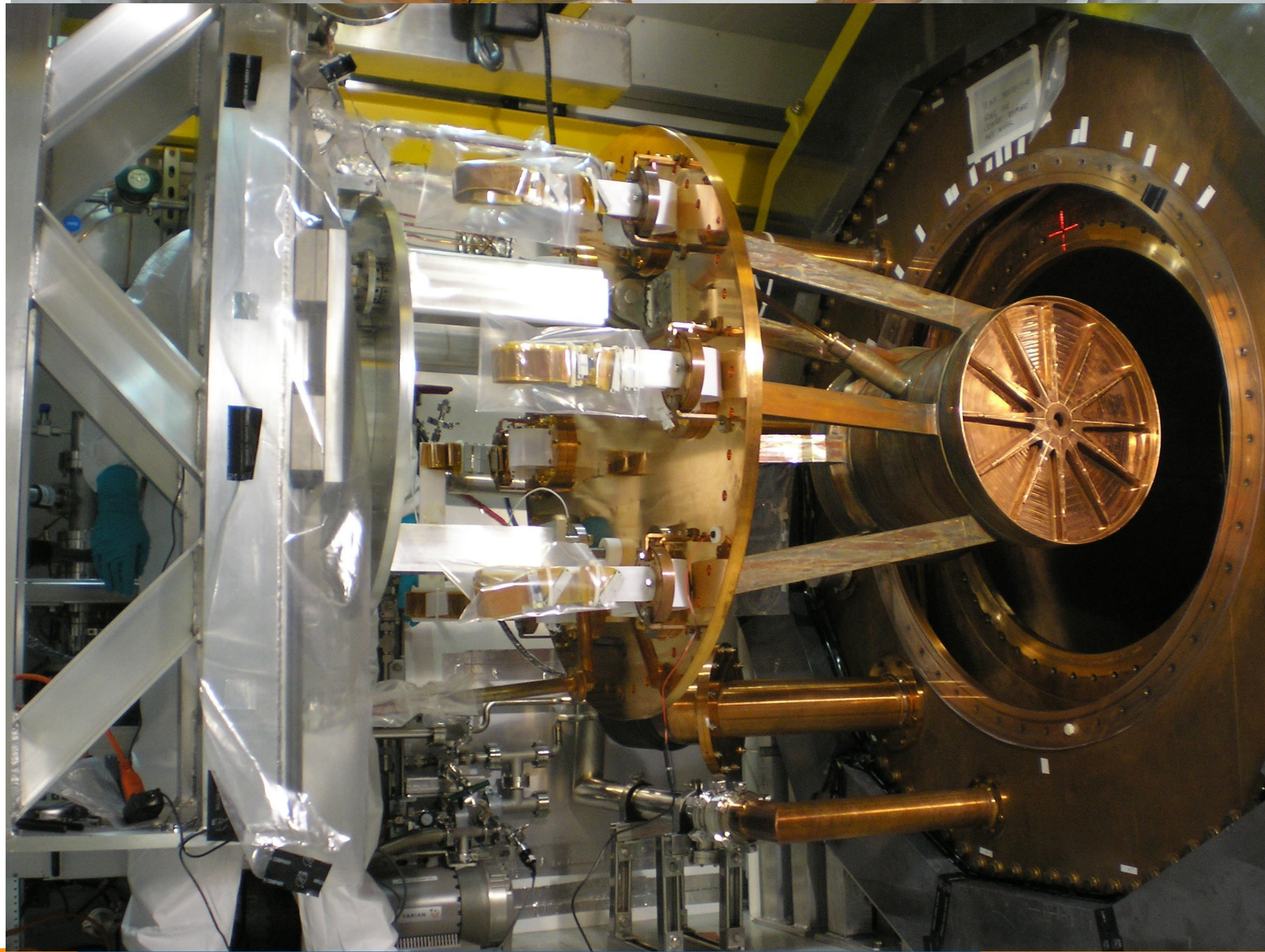


380kg: $T_{1/2} > 1.07 \times 10^{26}$ y (90% CL)

EXO-200







~100 kg fiducial mass Xe enriched to 80% in ^{136}Xe,

Readout plane is made up of LAAPDs + crossed wire grid.

Operated at WIPP (~1600 m.w.e.) with enriched Xe from May 2011 to Feb. 2014 (Phase I)

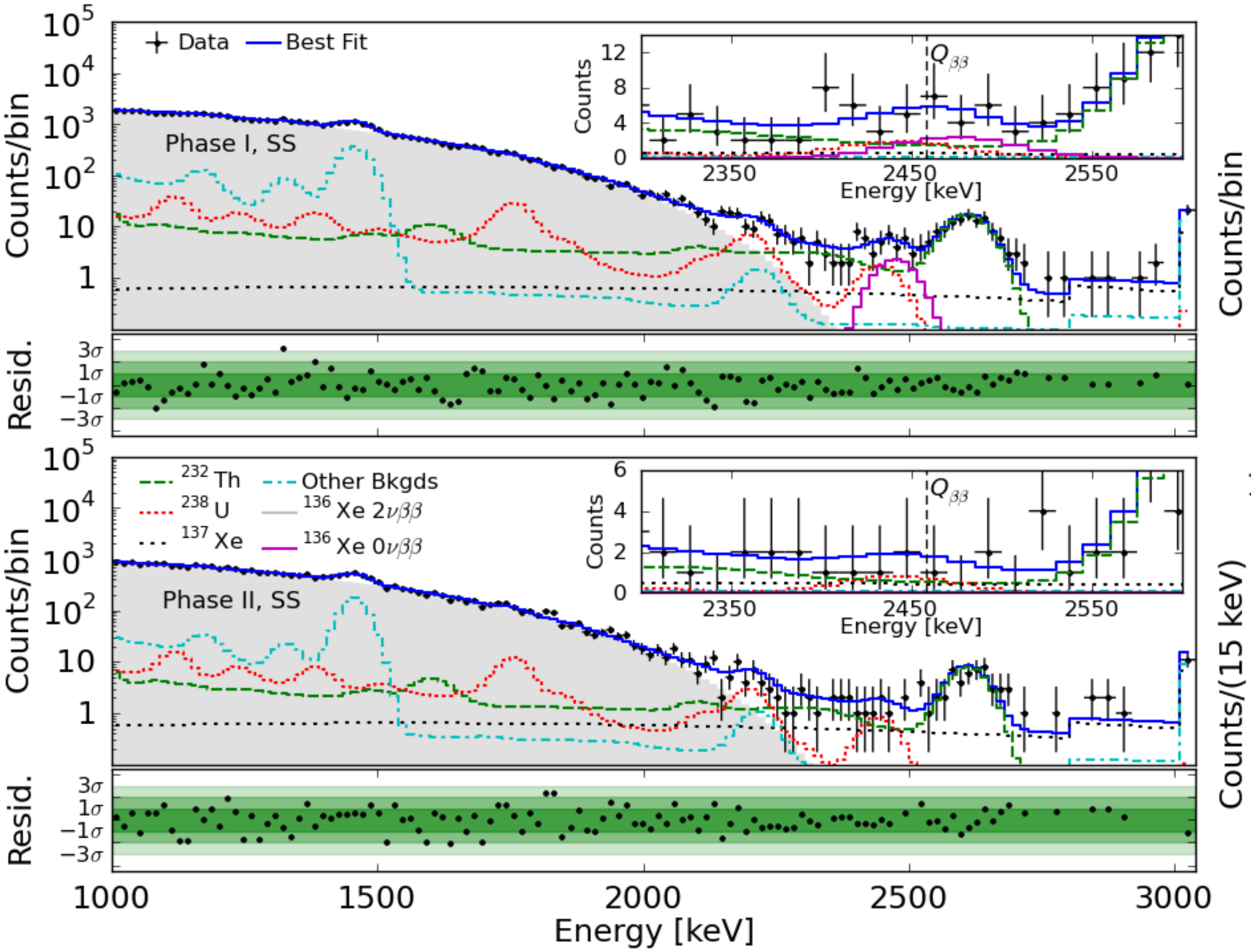
Upgraded detector operating running since June 2016 (Phase II)

EXO-200 *0*νββ Search Results

PHYSICAL REVIEW LETTERS **120,** 072701 (2018)

Search for Neutrinoless Double-Beta Decay with the Upgraded EXO-200 Detector

Combine Phase I + Phase II profiles: Total exposure = 177.6 kg.yr

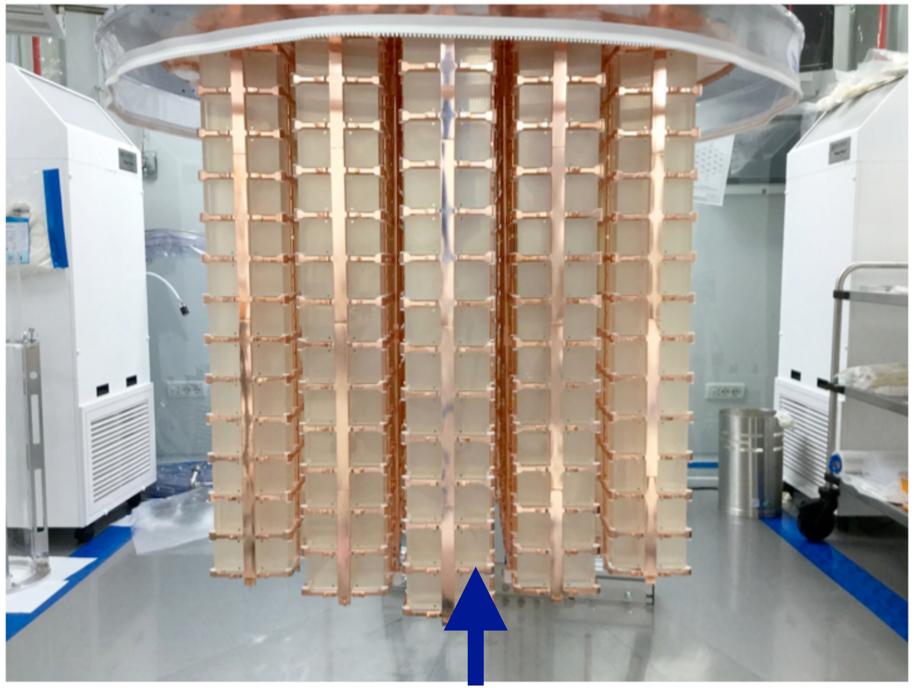


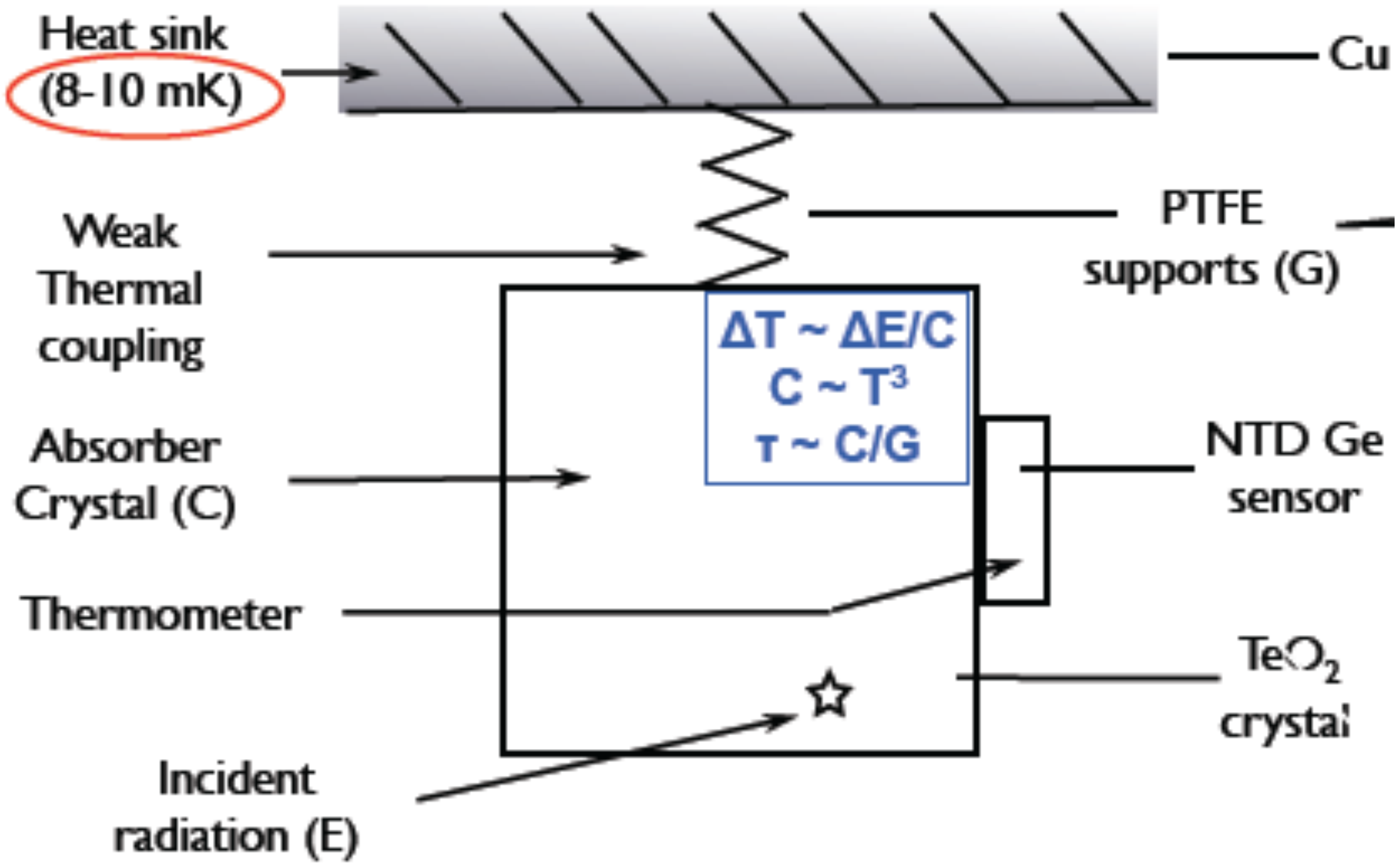
Sensitivity of $3.7\text{x}10^{25}$ yr (90% CL)

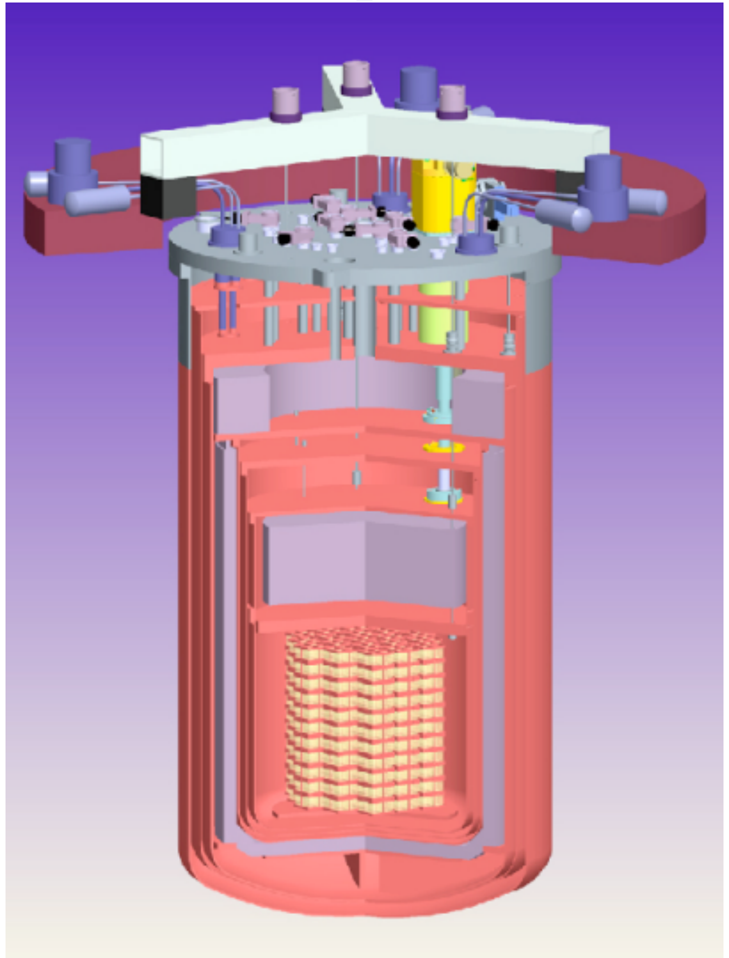
$T_{1/2}^{0\nu\beta\beta} > 1.8 \text{ x } 10^{25}$ yr

CUORE
Cryogenic Underground Observatory for Rare Events

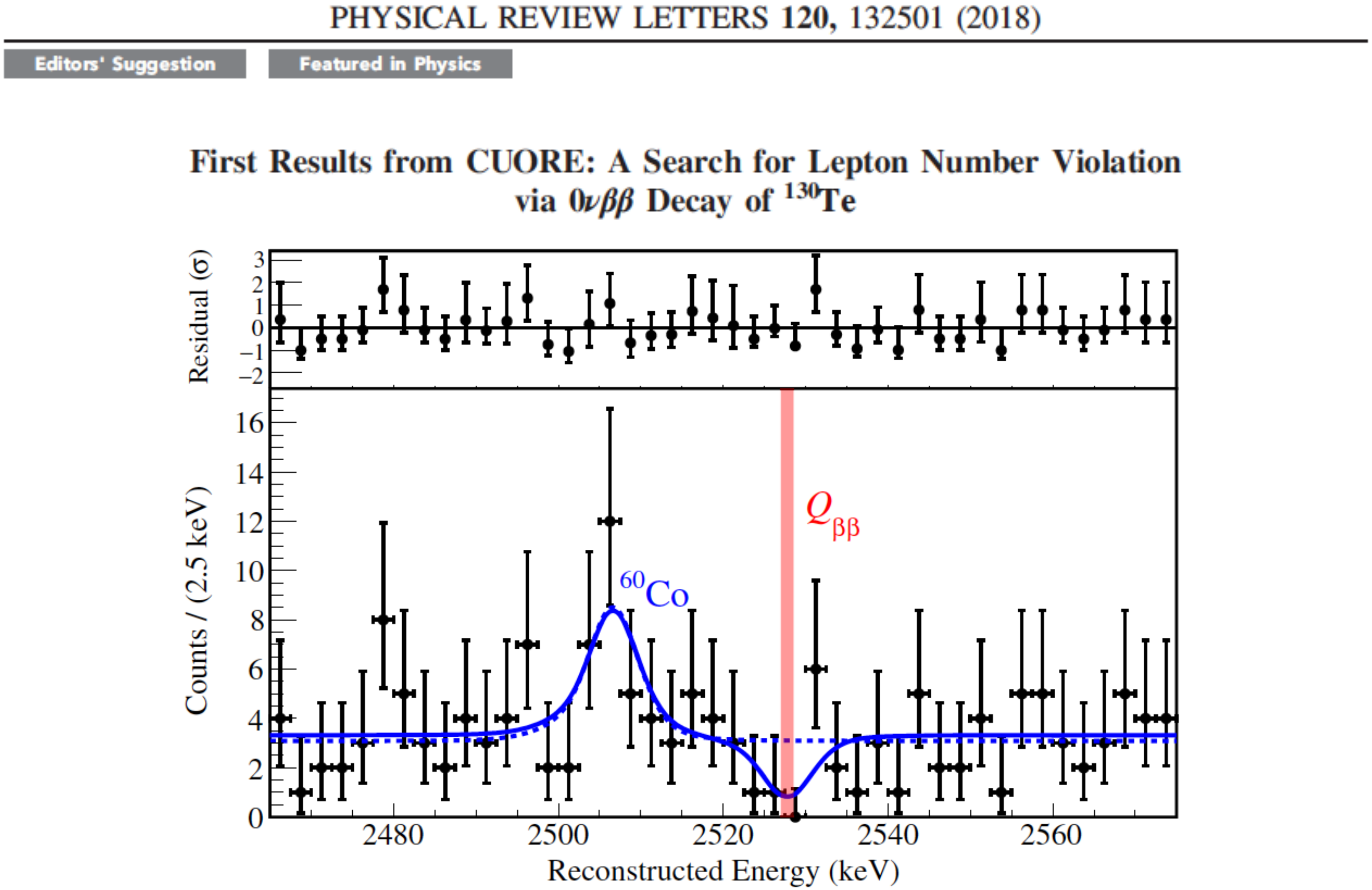
- 19 Towers, 988 TeO2 crystals operated as bolometers.
- At 10 mK, claimed “Coldest cubic meter in the known universe”.
- Marvel of cryogenics







CUORE Result



PHYSICAL REVIEW LETTERS **120**, 132501 (2018)

Editors' Suggestion **Featured in Physics**

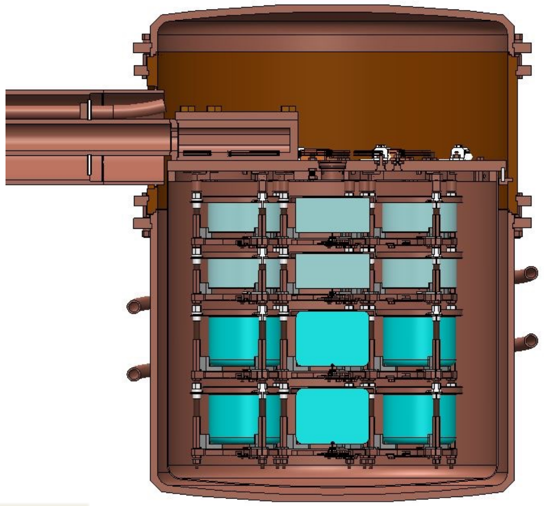
First Results from CUORE: A Search for Lepton Number Violation via $0\nu\beta\beta$ Decay of ^{130}Te

$T_{1/2} > 1.5\times10^{25}$ years (with CUORE-0/Cuoricino)

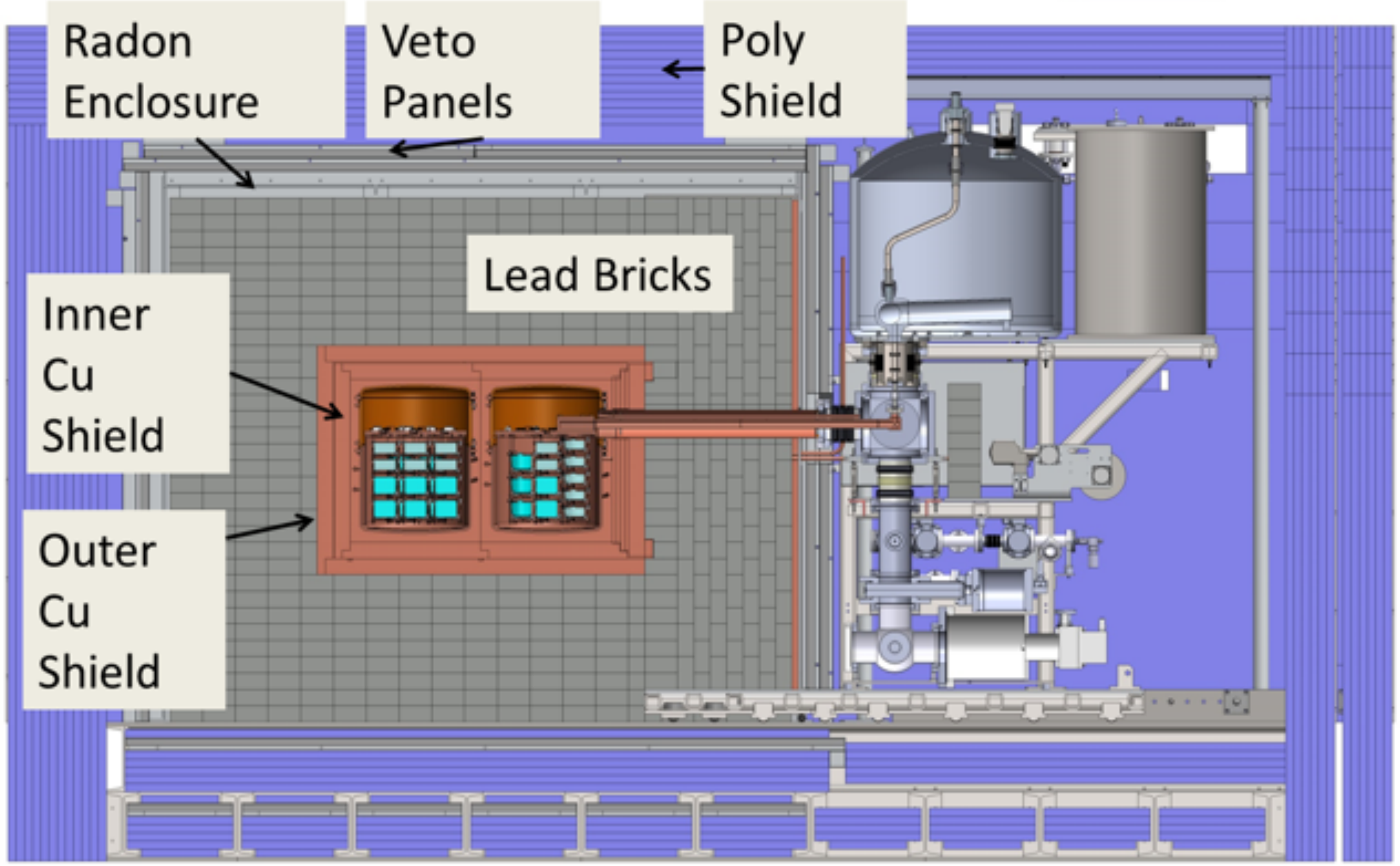
The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, & NSF Nuclear Physics with additional contributions from international collaborators.

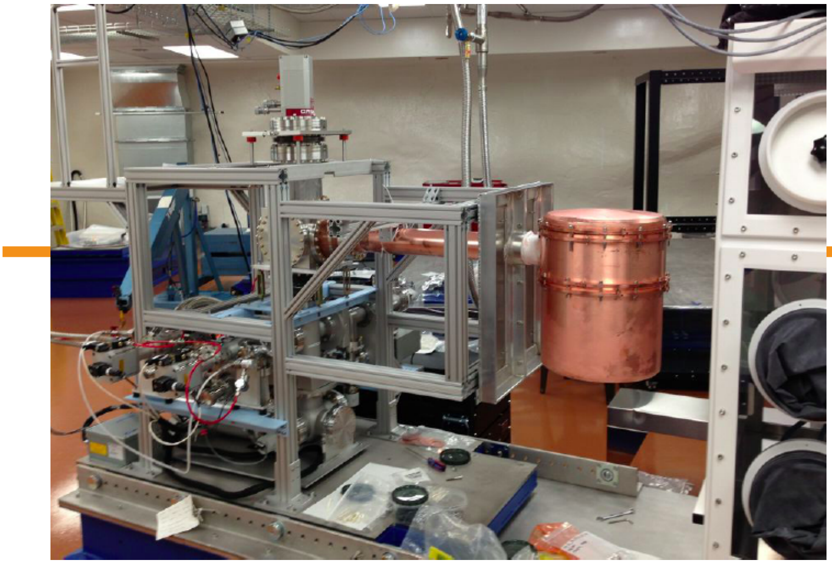
Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

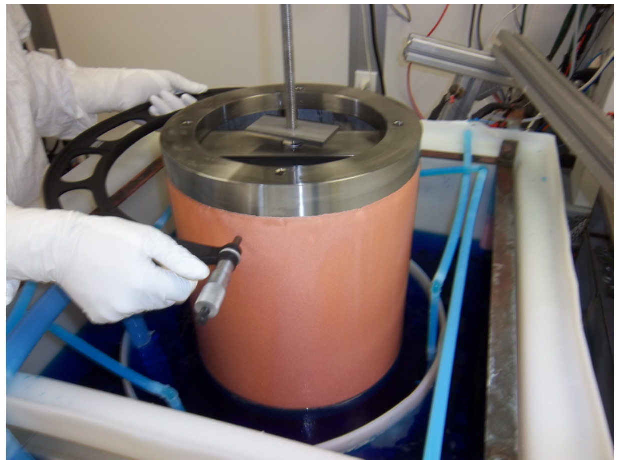


- Located underground at 4850’ Sanford Underground Research Facility
- Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)
- 44.1-kg of Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



MJD Construction





Electroformed Cu and enriched Ge

Fig: Courtesy M. Kapust

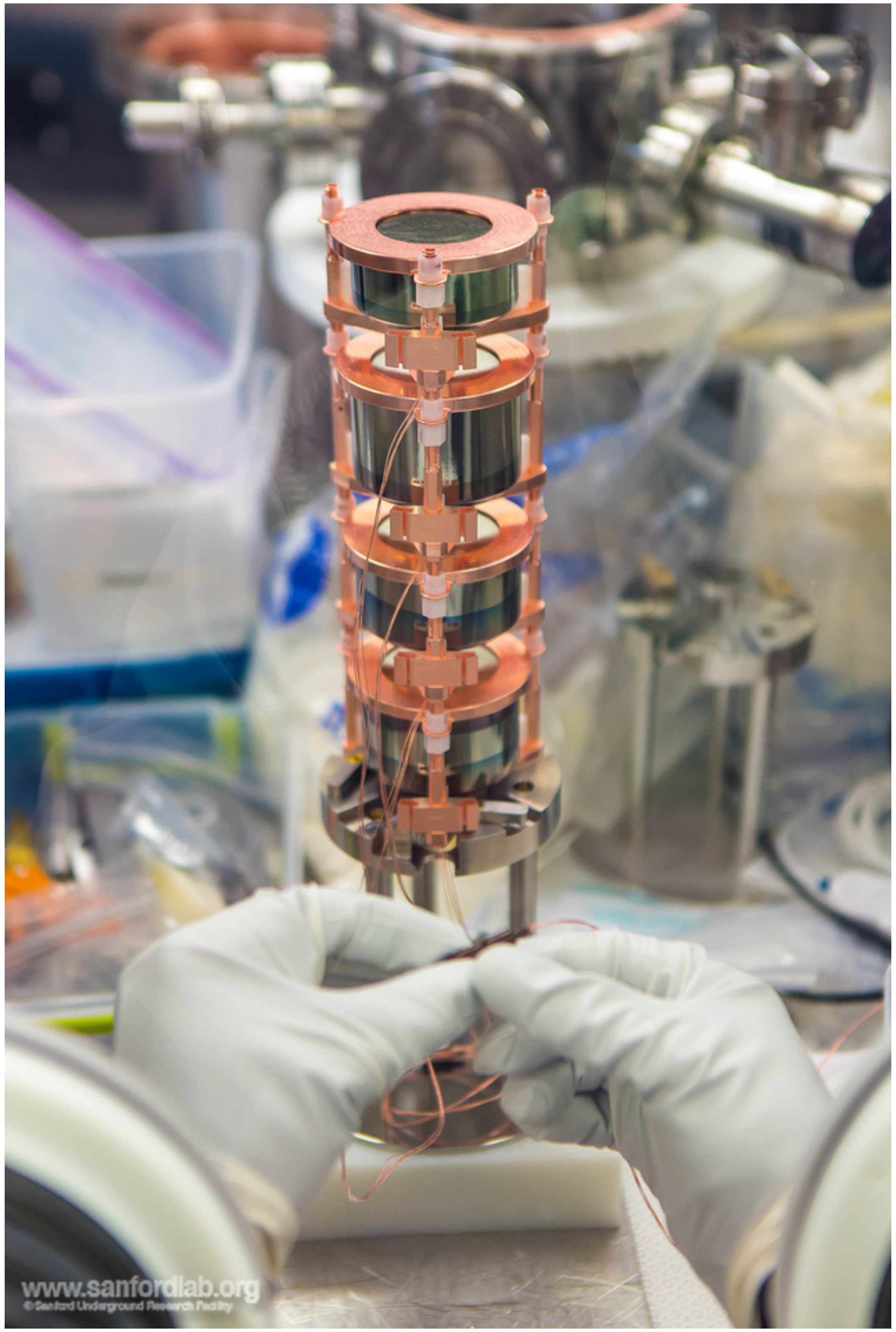
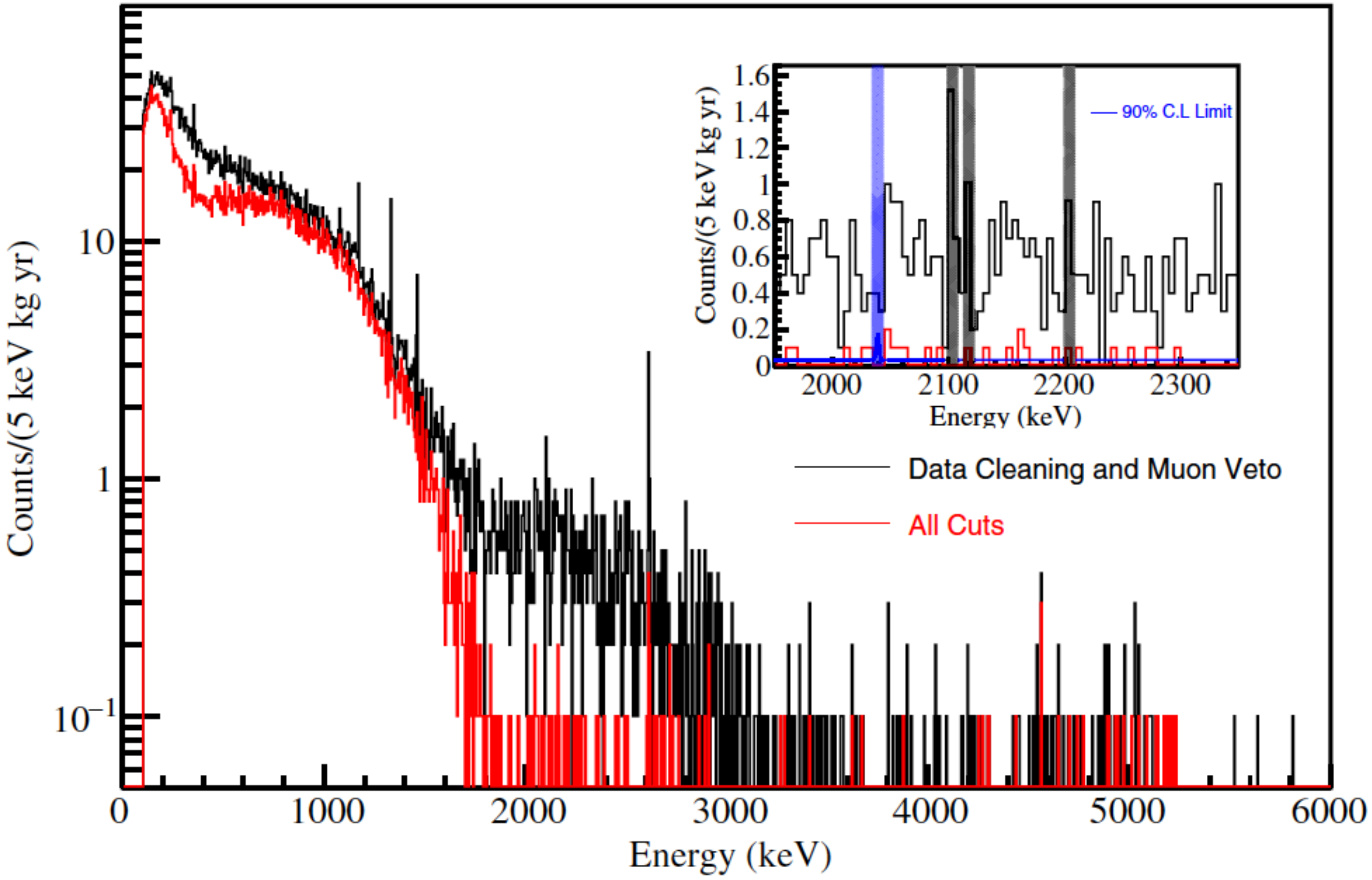


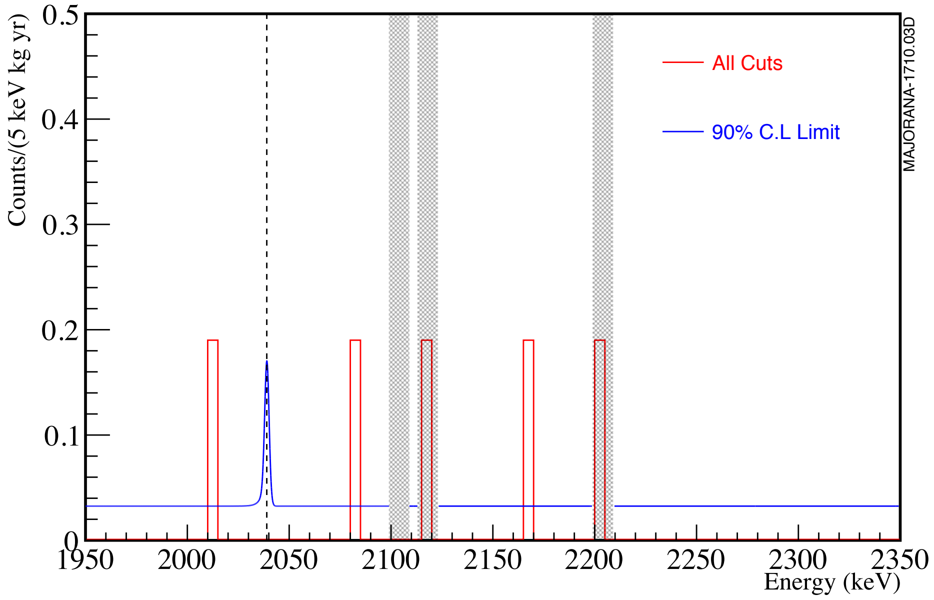
Fig: Courtesy M. Kapust

MAJORANA Results

PHYSICAL REVIEW LETTERS **120,** 132502 (2018)

Editors' Suggestion **Featured in Physics**



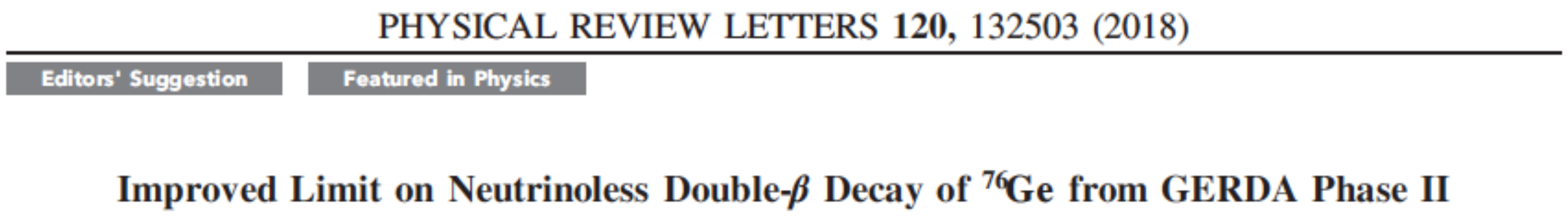


$T_{1/2} > 1.9\times10^{25}$ years

GERDA

- Direct immersion of enriched Ge detectors in LAr
- Phase I (Nov 2011- May 2013)
- Phase II (Dec 2015- ongoing)

GERDA Results

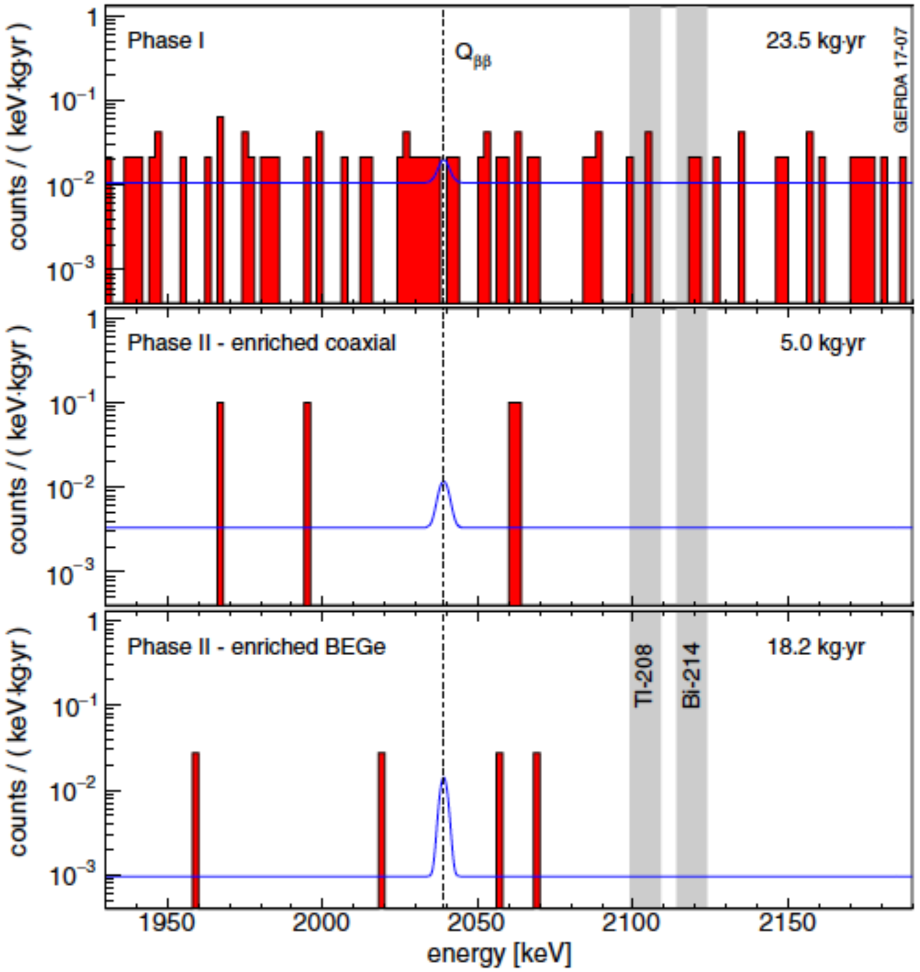


PHYSICAL REVIEW LETTERS 120, 132503 (2018)

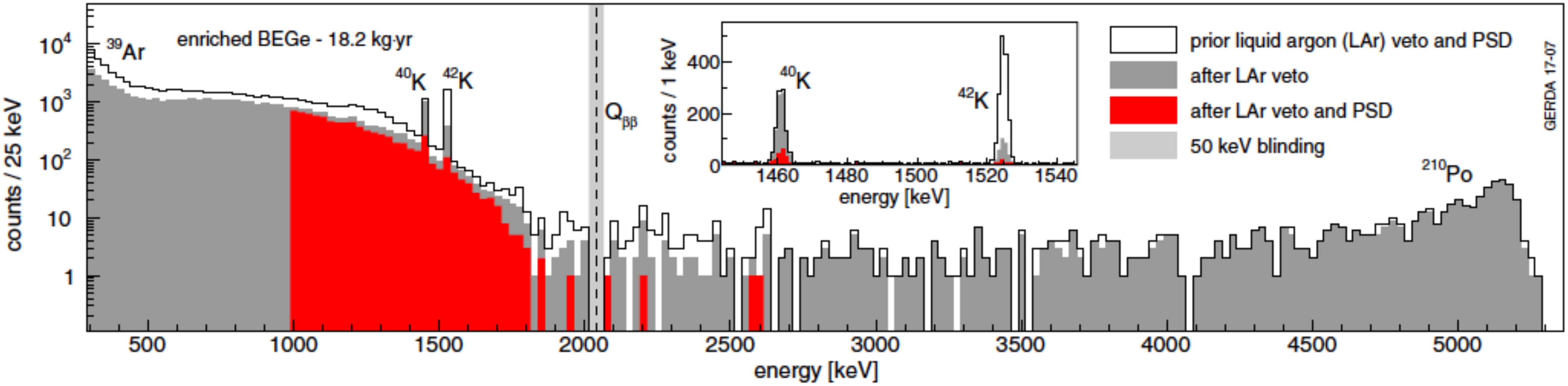
Editors' Suggestion

Featured in Physics

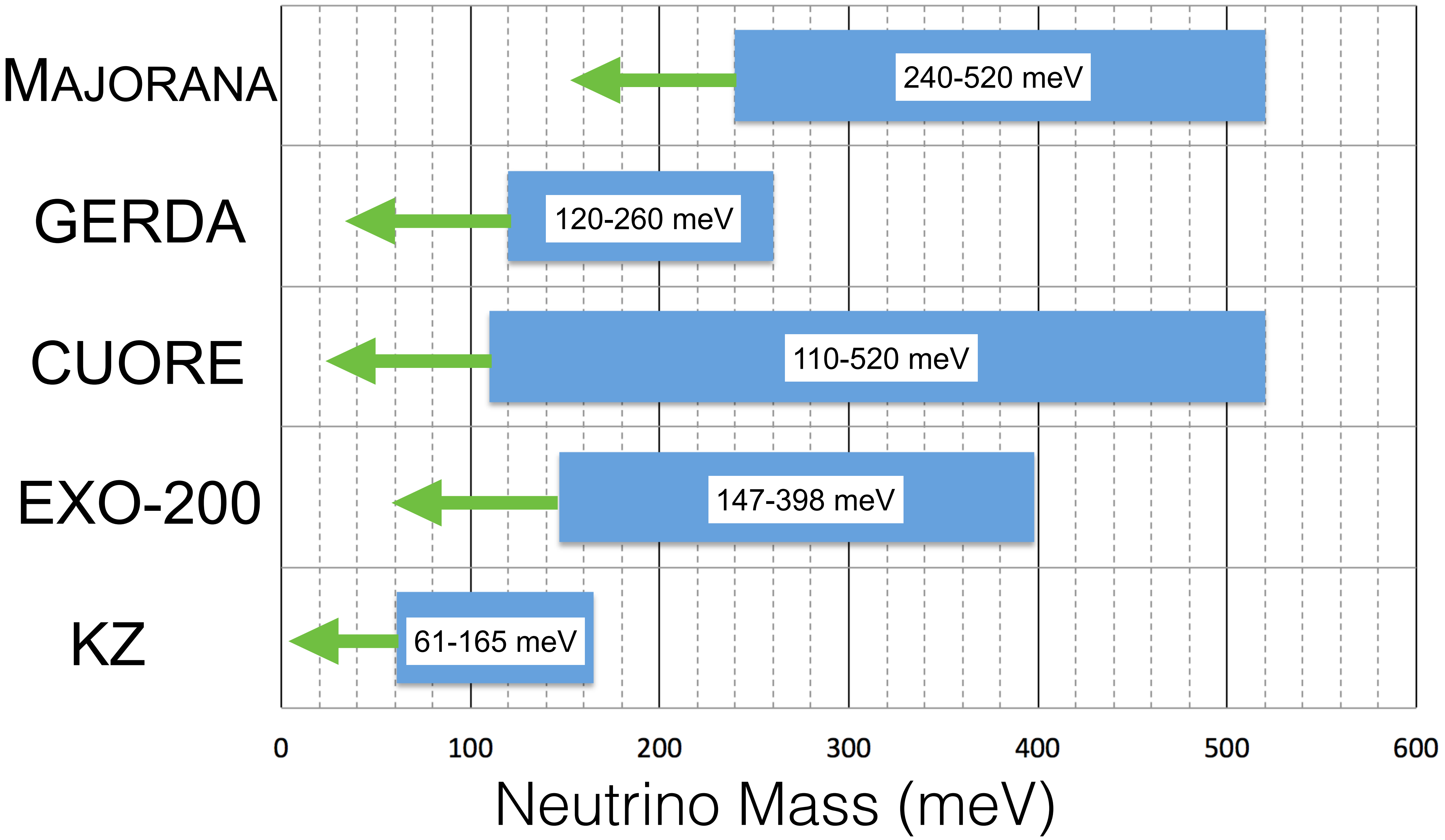
Improved Limit on Neutrinoless Double-β Decay of ^{76}Ge from GERDA Phase II



$T_{1/2} > 8.0\times10^{25}$ years



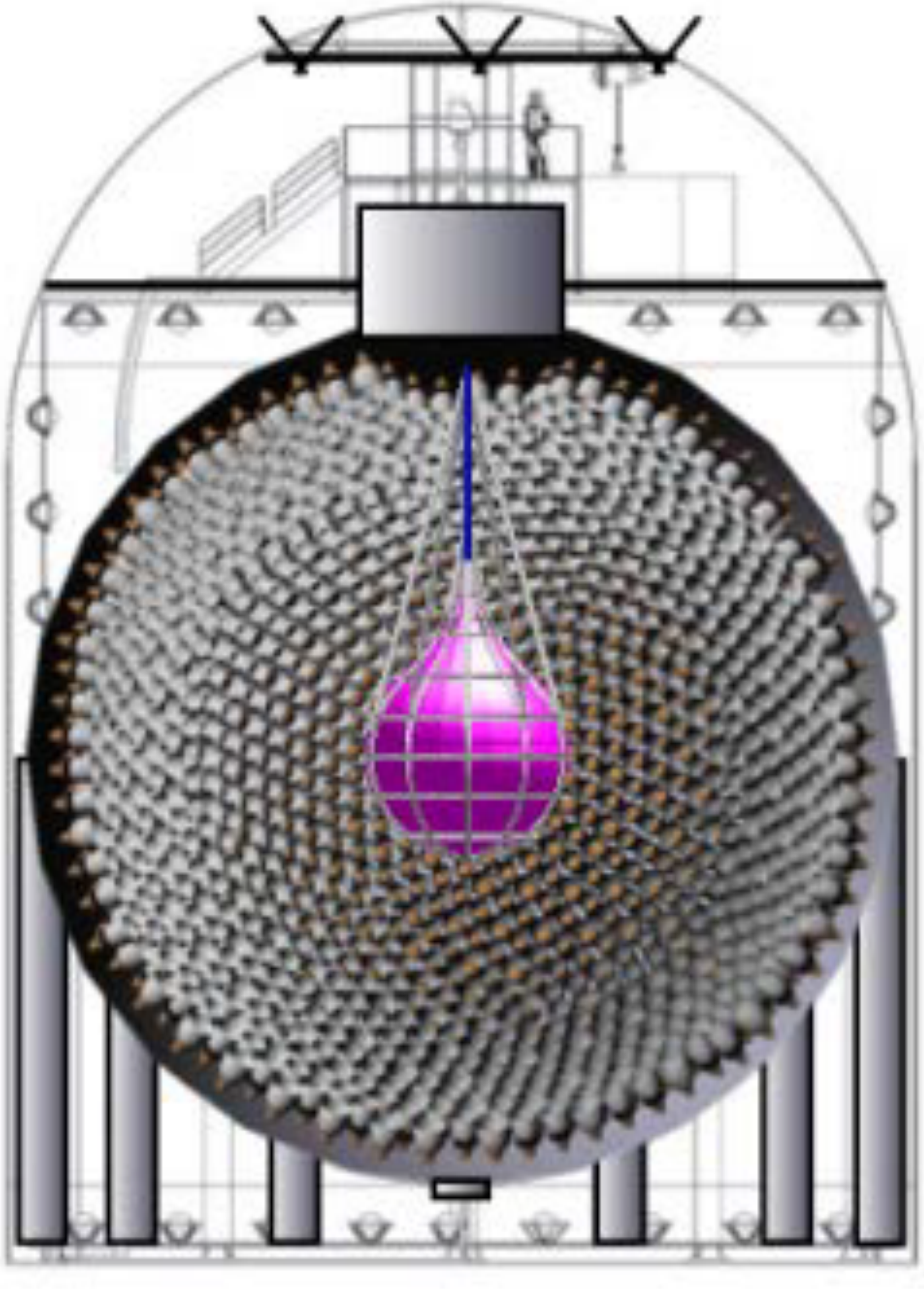
Mass Limit Summary



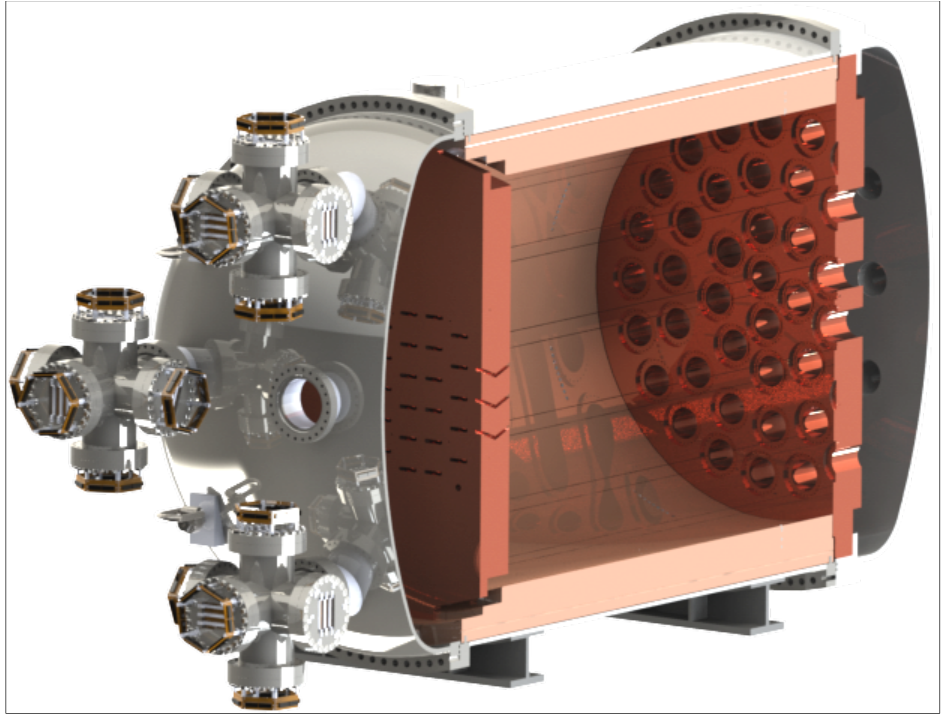
The FUTURE…

KamLAND2-Zen

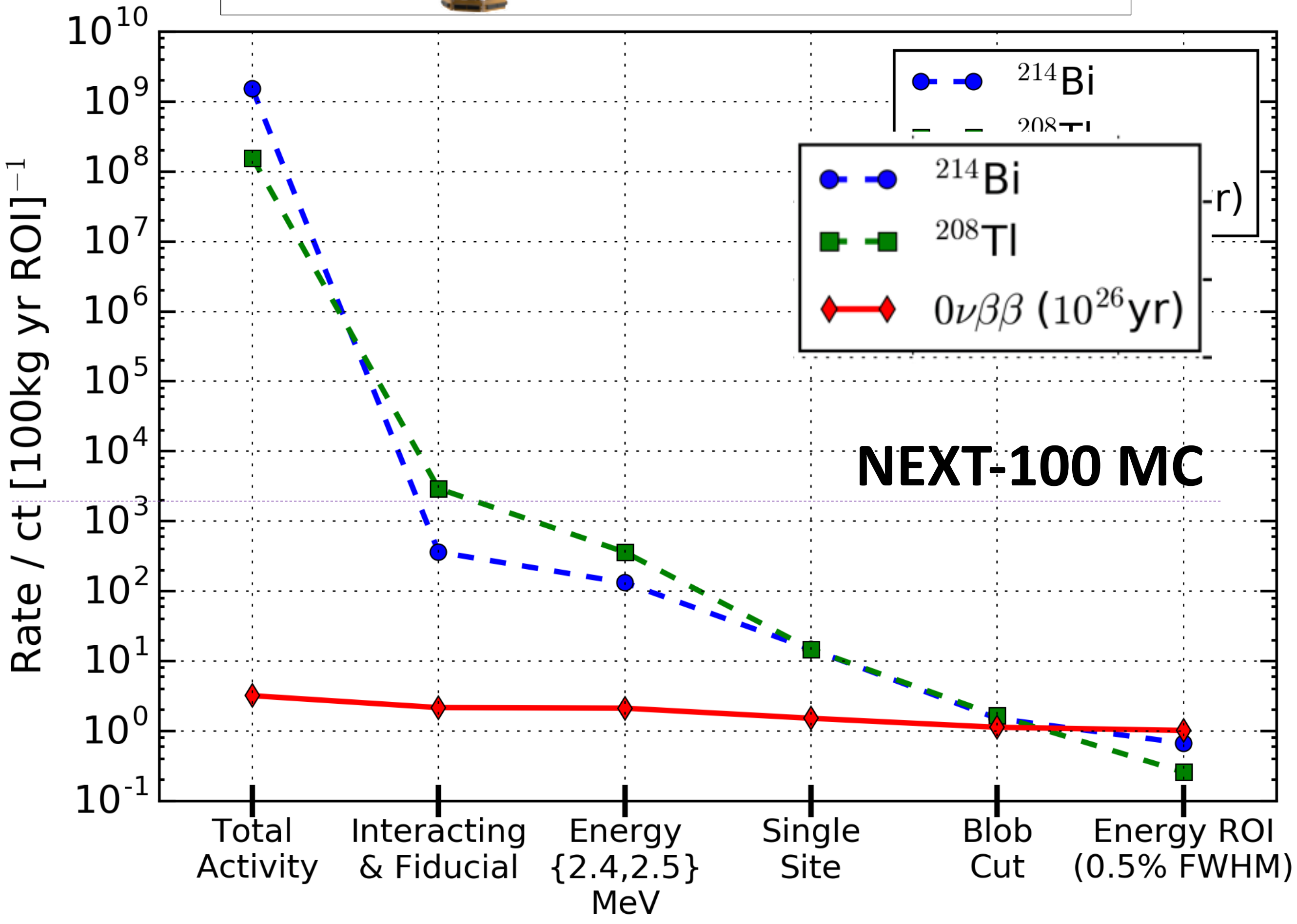
- Problems with leaky balloon
- Data taking 750 kg enriched Xe starting summer 2018
- KamLAND2-Zen with 1000kg+ proposed with improved light collection efficiency



NEXT-100



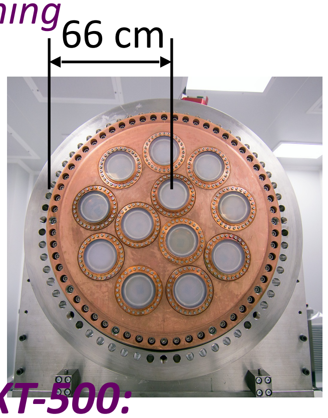
- Xe-based high pressure TPC
- NEXT-100 in construction now thru 2019.
- Demonstrate “background free@100kg-scale” technology by 2021.
- Performance informs DOE down-select for ton-scale experiment in 2021.



NEXT-Ton

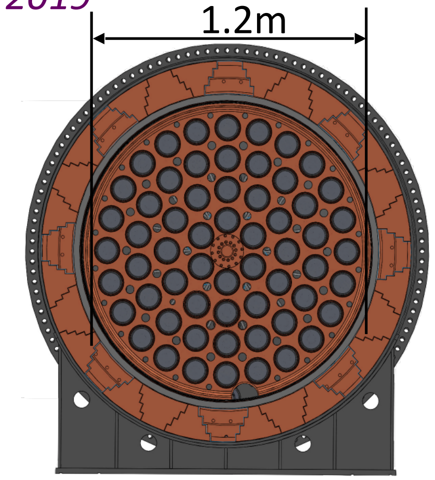
- Strong active background rejection relaxes self-shielding requirements, enabling a staged program.
- Expect deployment of several few-hundred-kg modules 2021-202N.
- Barium Tagging

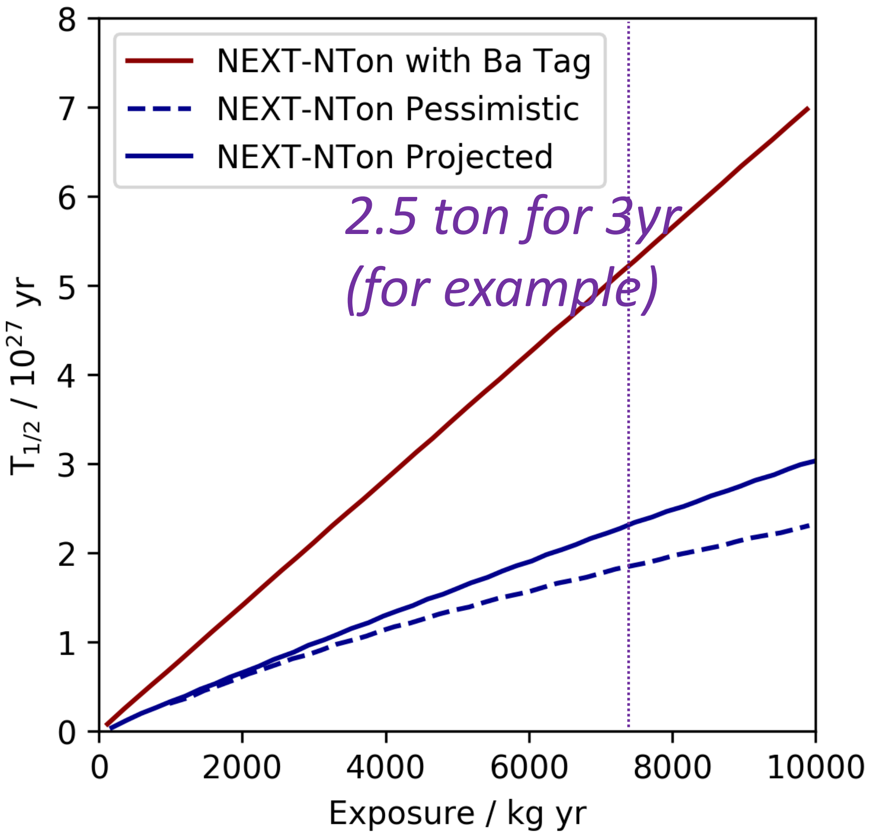
NEXT-White
Running

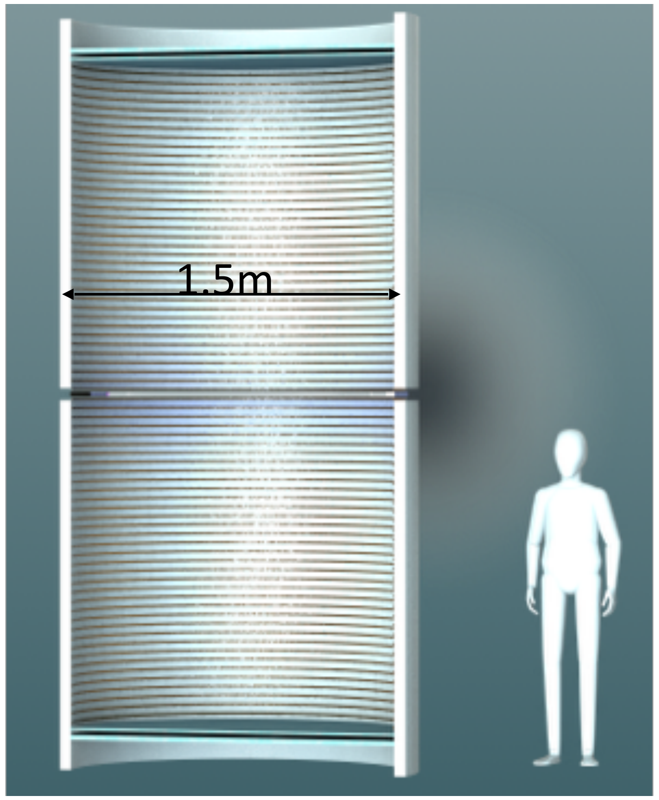


NEXT-300:
2022?

NEXT-100
2019





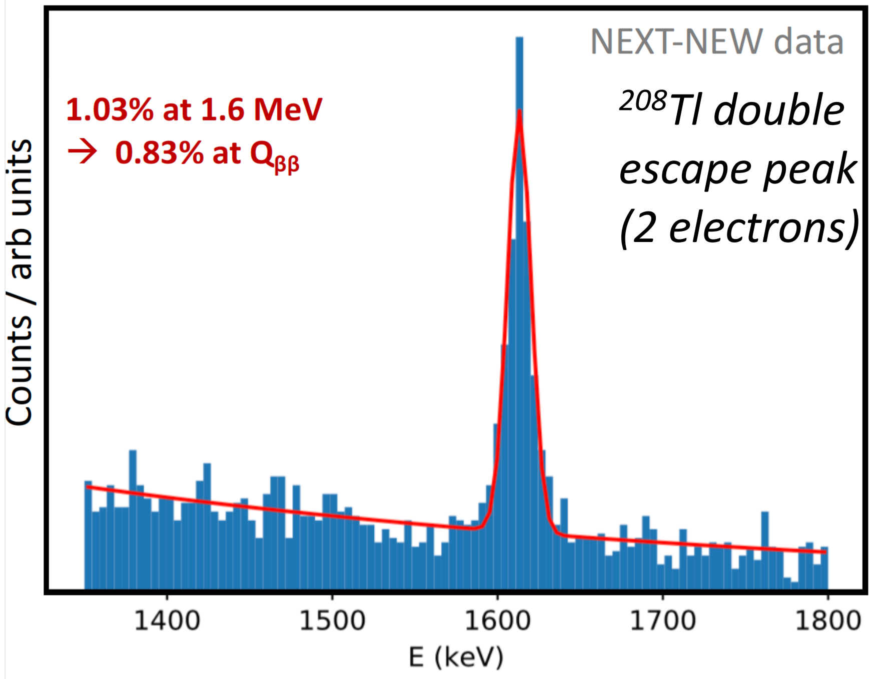


NEXT Program – recent achievements

***TARGET*:**

Energy resolution <1% FWHM at $Q_{\beta\beta}$

to efficiently reject 2nubb background



NEXT-NEW data

1.03% at 1.6 MeV
→ 0.83% at $Q_{\beta\beta}$

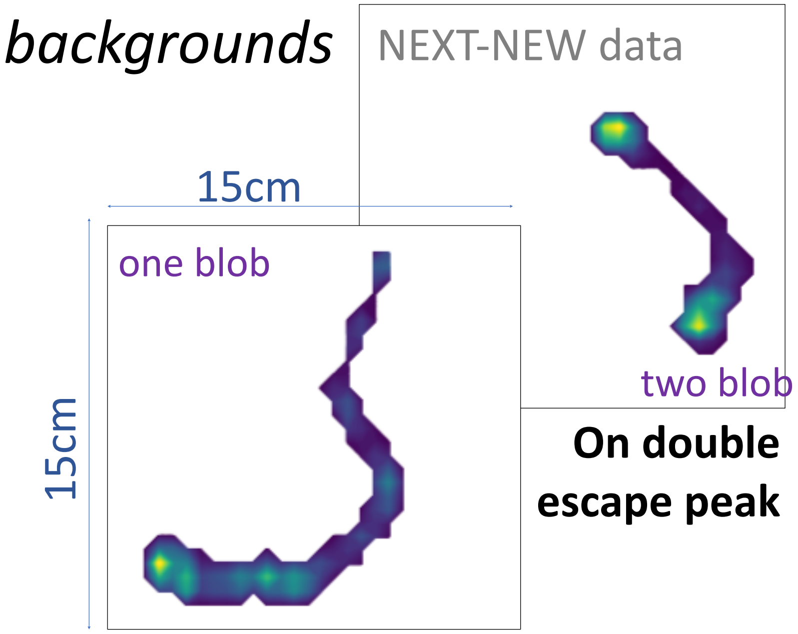
^{208}Tl double escape peak (2 electrons)

Energy resolutions extrapolating to substantially better than 1% at $Q_{\beta\beta}$ demonstrated in NEXT-White

***TARGET*:**

Topological discrimination of 1e / 2e

to reject extraneous γ-ray backgrounds



NEXT-NEW data

On double escape peak

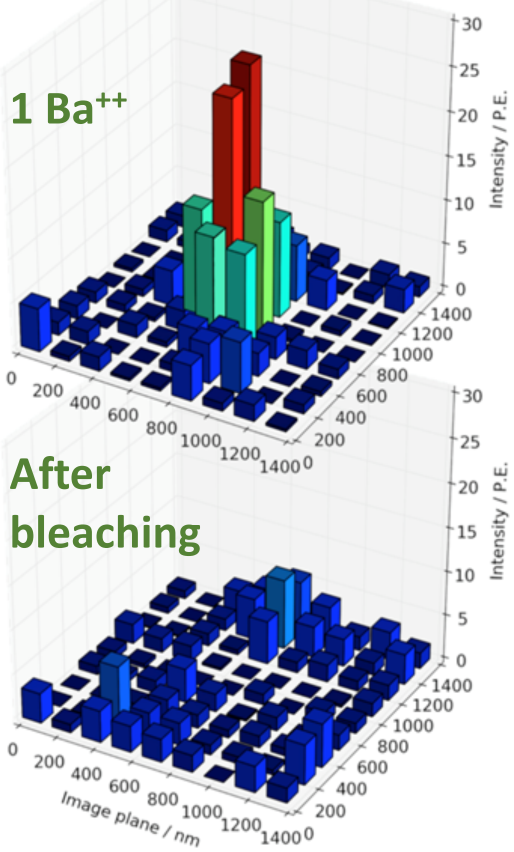
Off double escape peak

Clear two-electron events observed in NEXT-White at double escape peaks

***TARGET*:**

Single barium ion sensitivity

completely reject non ββ backgrounds

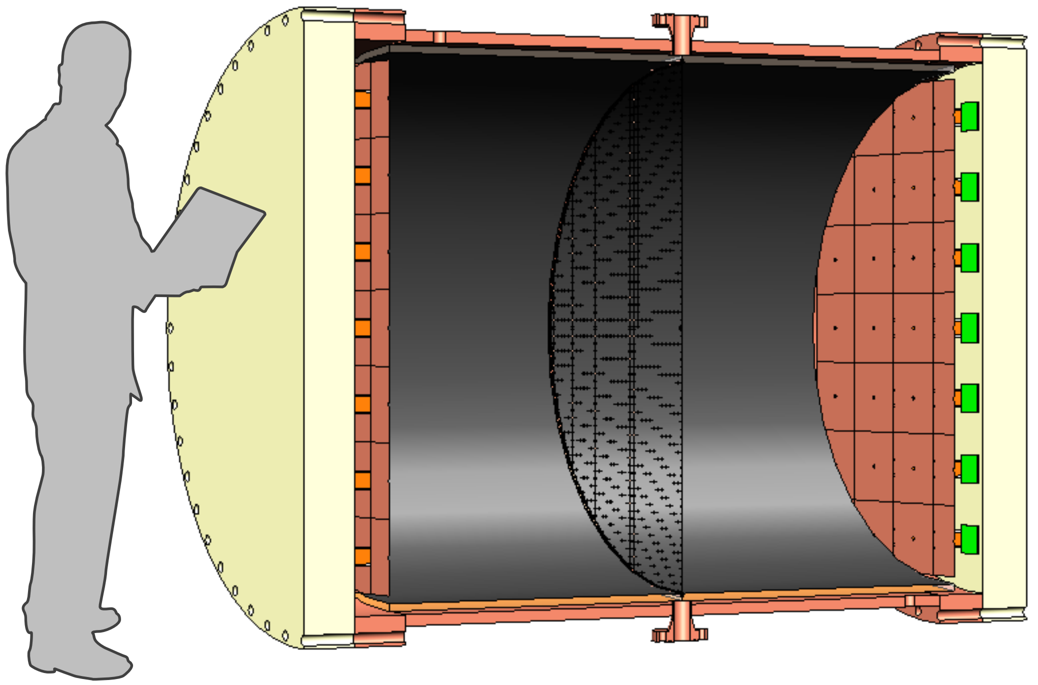


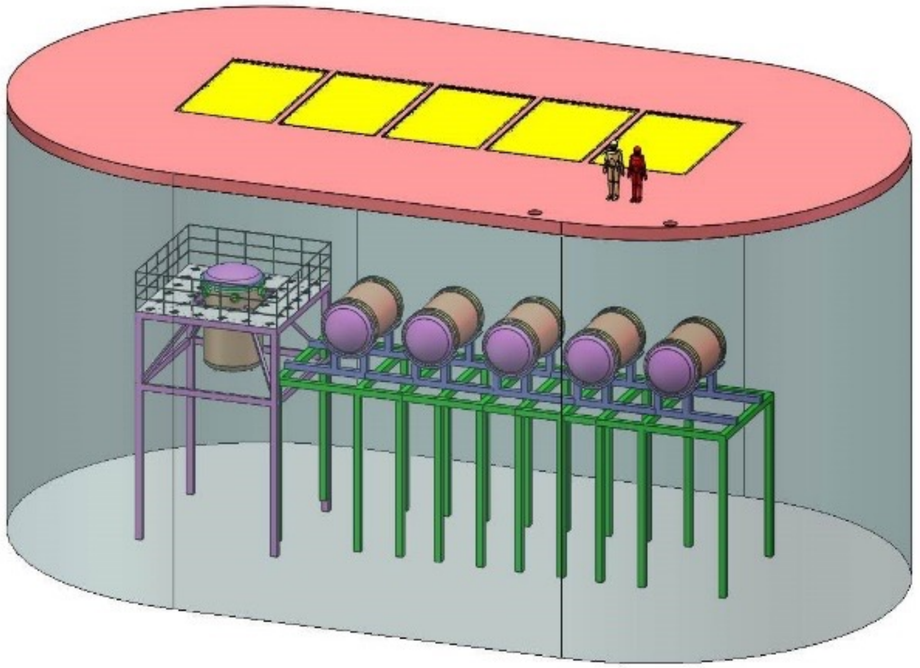
1 Ba^{++}

After bleaching

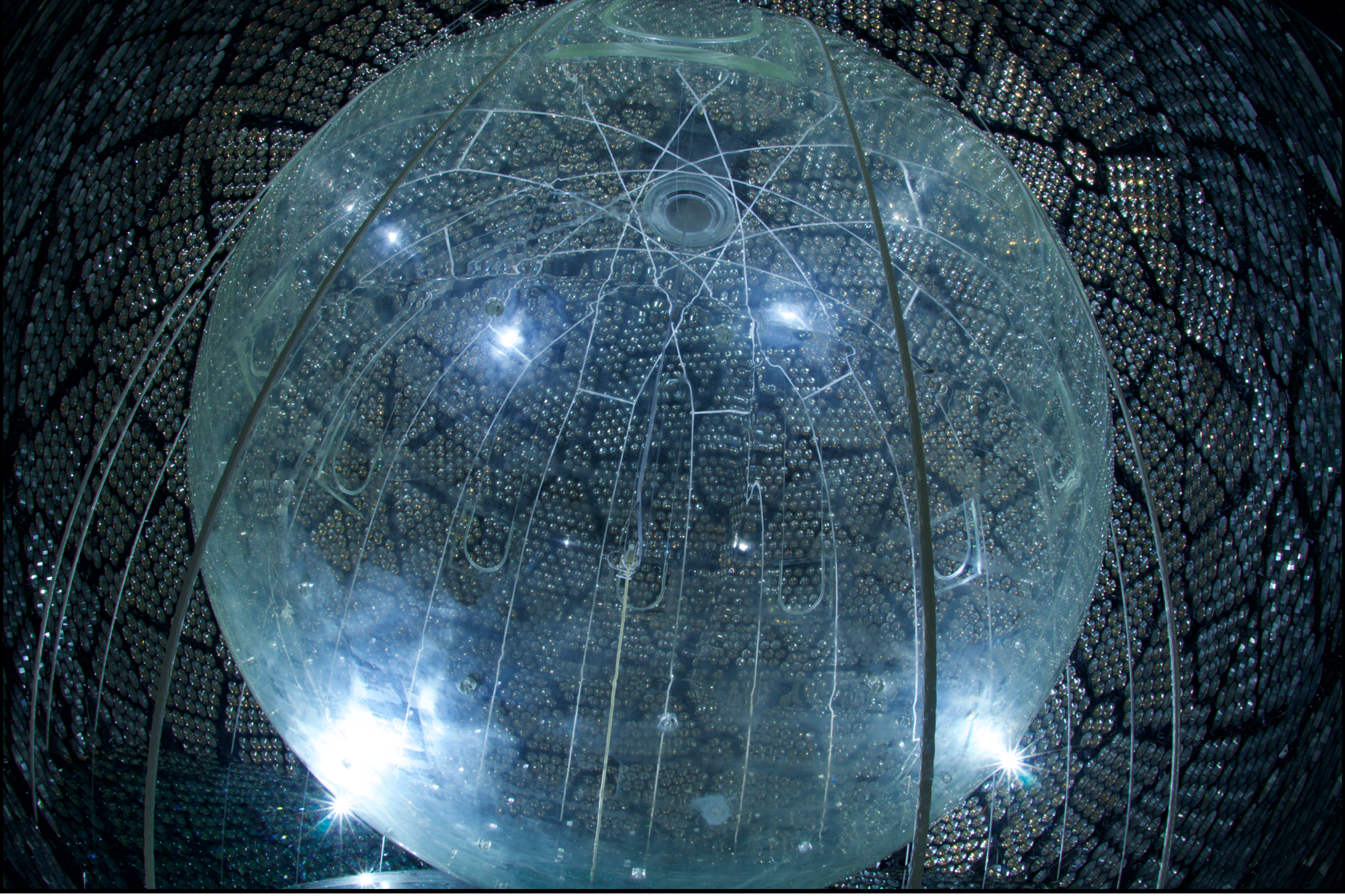
Single barium ion sensitivity demonstrated with SMFI at UTA

PandaX-III ^{136}Xe

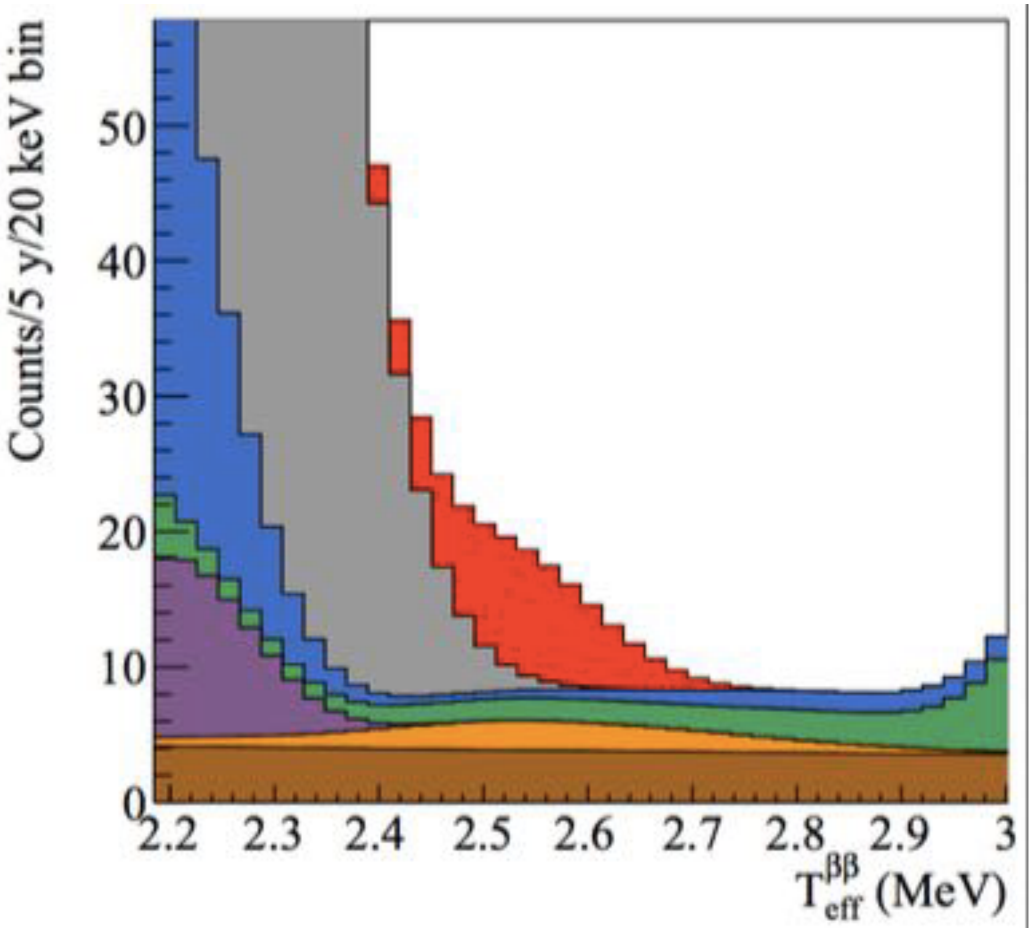


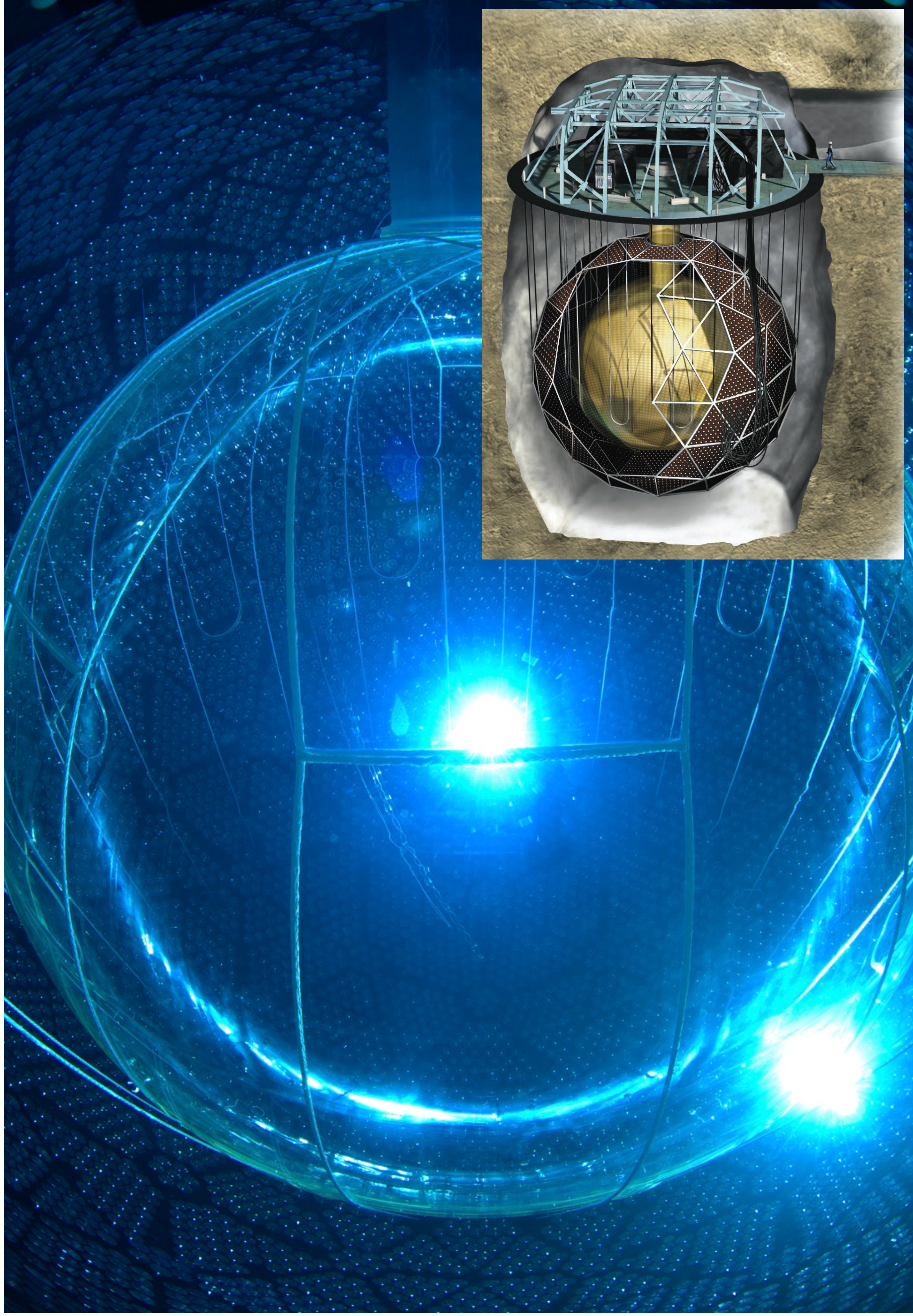


- High pressure gas TPC, phased approach with multiple 200-kg enriched xenon gas TPC for a ton-scale 0νββ experiment [arXiv:1610.08883]
- Prototype being commissioned.
- First 200 kg detector: construction starts summer 2018. Located at CJPL.
- TPC with two charge readout planes on two ends
- 4 m^3 inner volume and 10 bar working pressure
- Main design features: Micromegas modules for charge readout. good energy resolution and background suppression with tracking [arXiv:1802.03489]

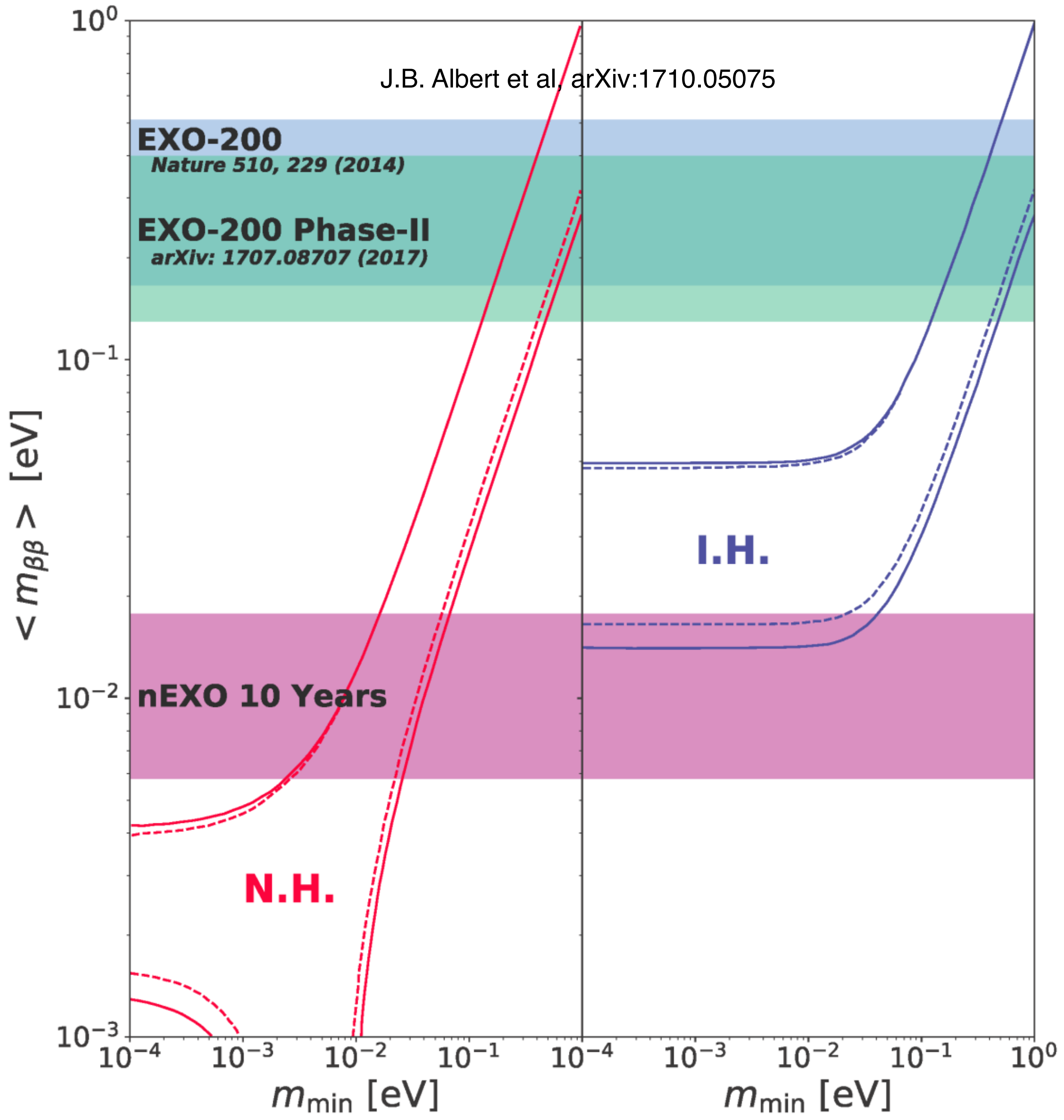


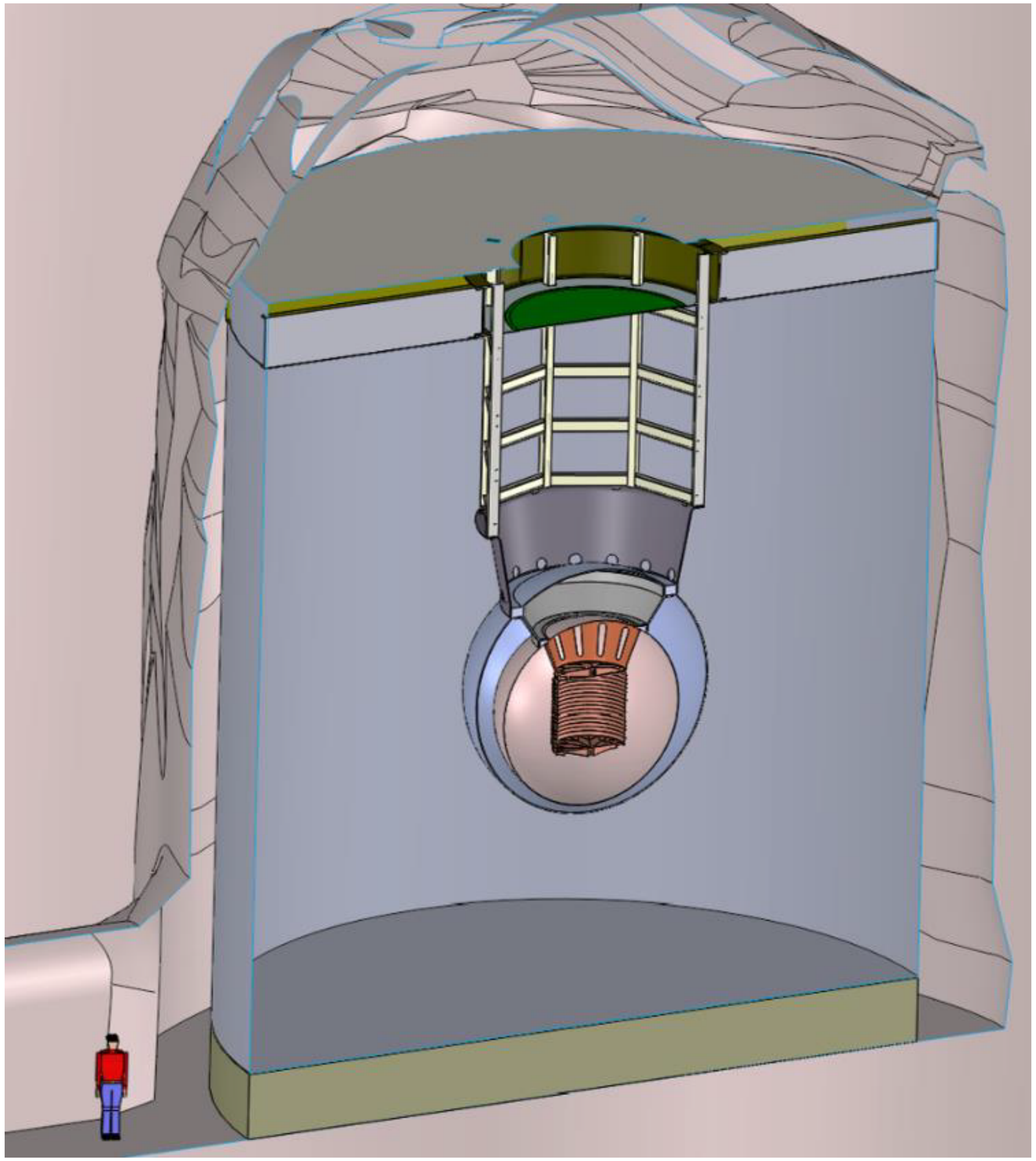
- Phase-I: 3.9 t Te → 1300 kg ^{130}Te
- Water data taking started May 2017
- 780 tonnes linear alkyl benzene (+PPO +Te-ButaneDiol)
- 3.8 tonnes TeA underground cooling; 4 tonnes en route from China
- Phase-I Goal: $T_{1/2} > 1.96 \times 10^{26}$ yr (90% CL); $m_{\beta\beta} < 36$-90 meV





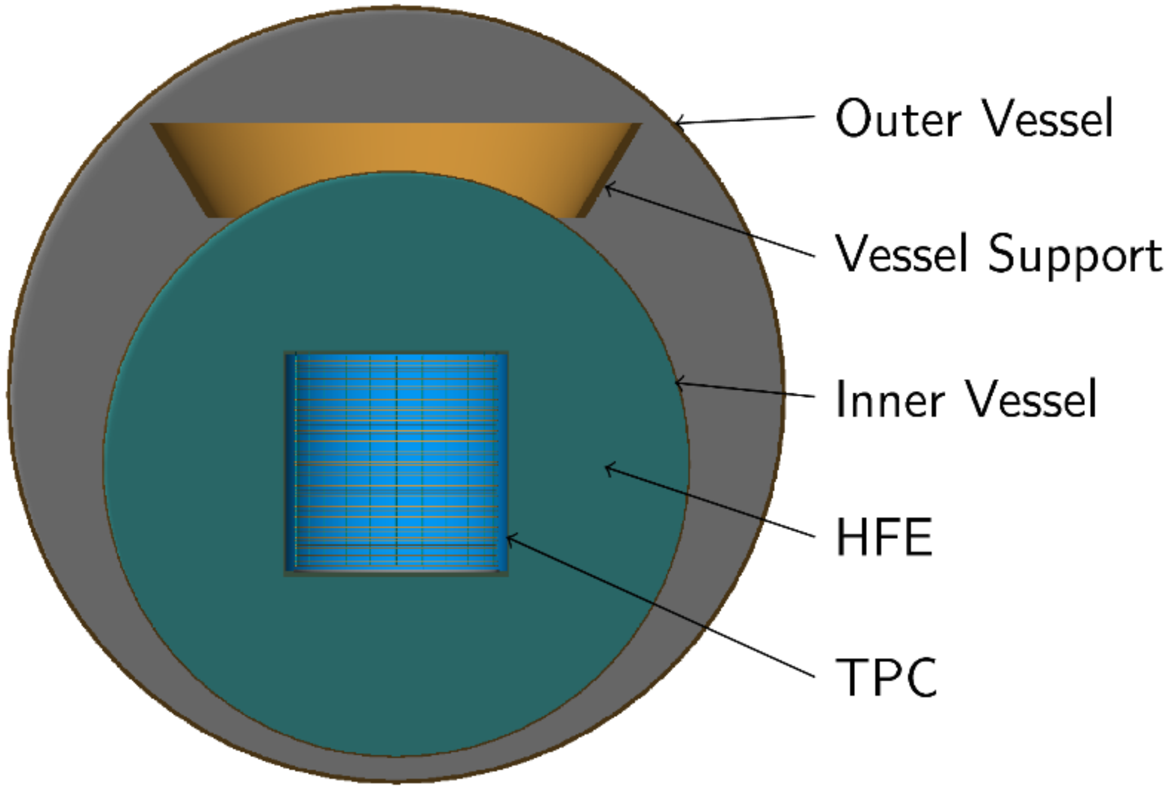
nEXO

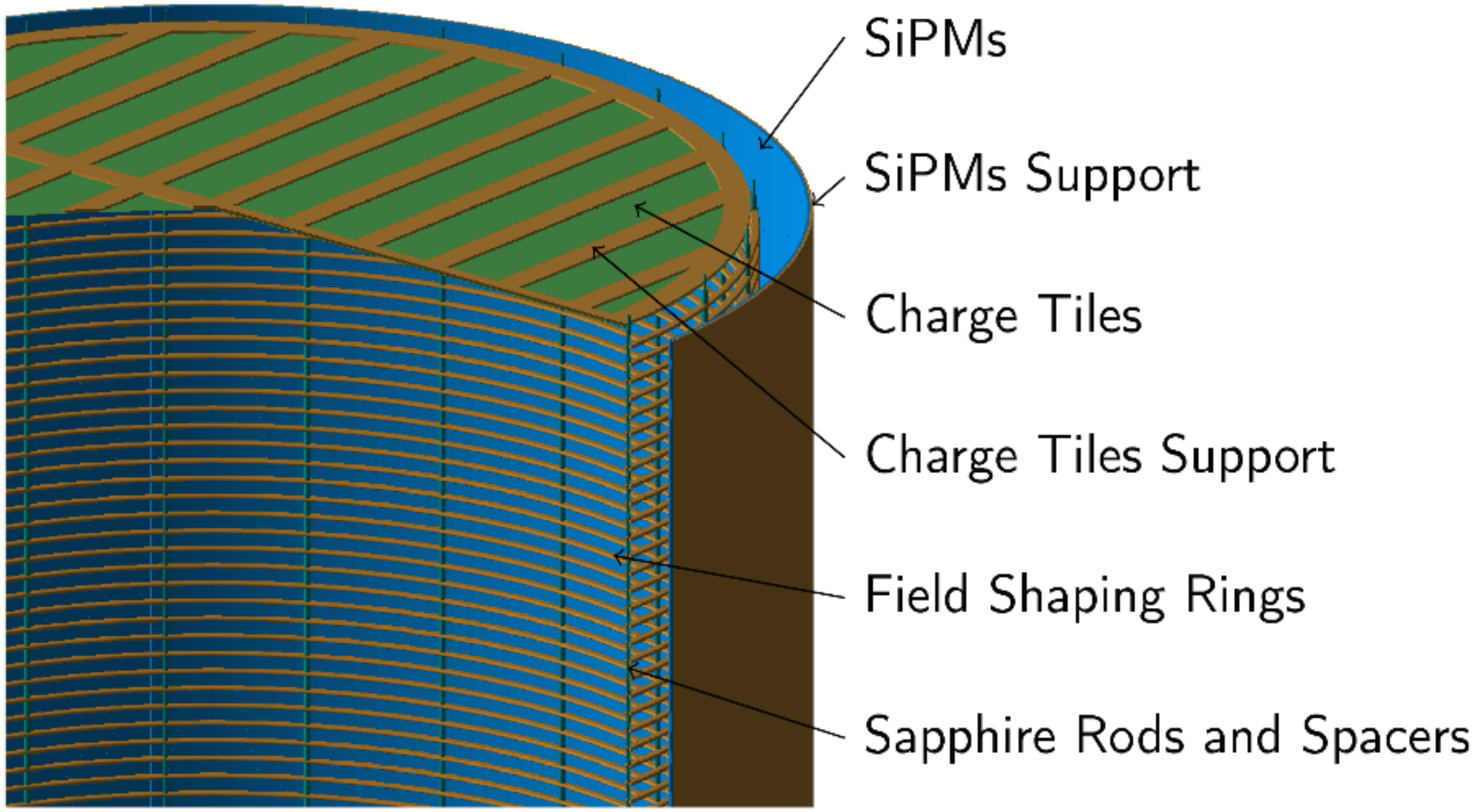

J.B. Albert et al. arXiv:1710.05075
EXO-200
Nature 510, 229 (2014)
EXO-200 Phase-II
arXiv: 1707.08707 (2017)
nEXO 10 Years
N.H.
I.H.
$< m_{\beta\beta} >$ [eV]
$m_{\min}$ [eV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}



nEXO

- 5 tonne isotopically enriched liquid xenon TPC
- Conservative design. R&D is focused scaling the technology to 5 tonne.
- Light and charge readout is fundamental to nEXO and central to the R&D plan
- Radioassay
- Installation and operation (location, water shield, carbon fiber vessels, calibration, fluid systems, etc…)





LEGEND ^{76}Ge

Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay

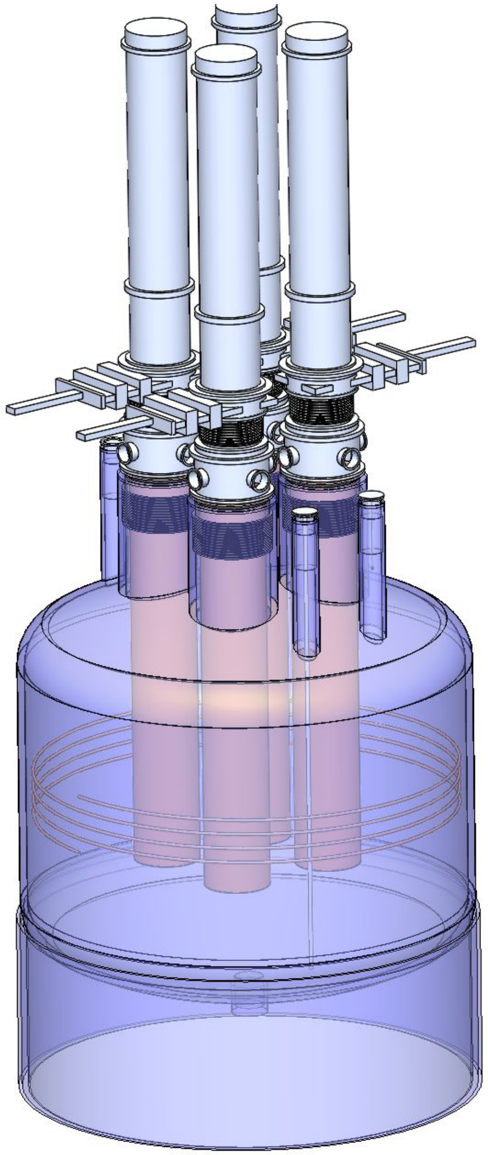
LEGEND mission: “The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results.”

First Stage:

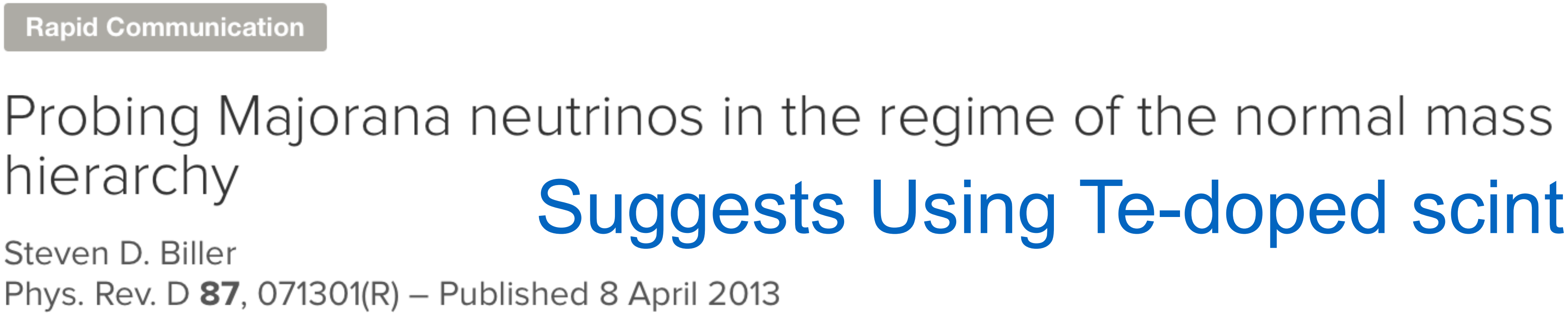
- (up to) 200 kg ^{76}Ge in upgrade of existing infrastructure at LNGS
- BG goal
  0.6 cts/(FWHM t yr)
- Data start ~2021
- Will use existing MAJORANA & GERDA detectors
- Proposal submitted to LNGS in March 2018
- Have funding for 130 of the 200 kg in place.

Subsequent Stages:

- 1000 kg ^{76}Ge (staged)
- Timeline coordinated with First Stage
- BG goal
  0.1 cts/(FWHM t yr)
- Location tbd
- Required depth (Ge-77m) under investigation



Toward the Normal Mass Hierarchy

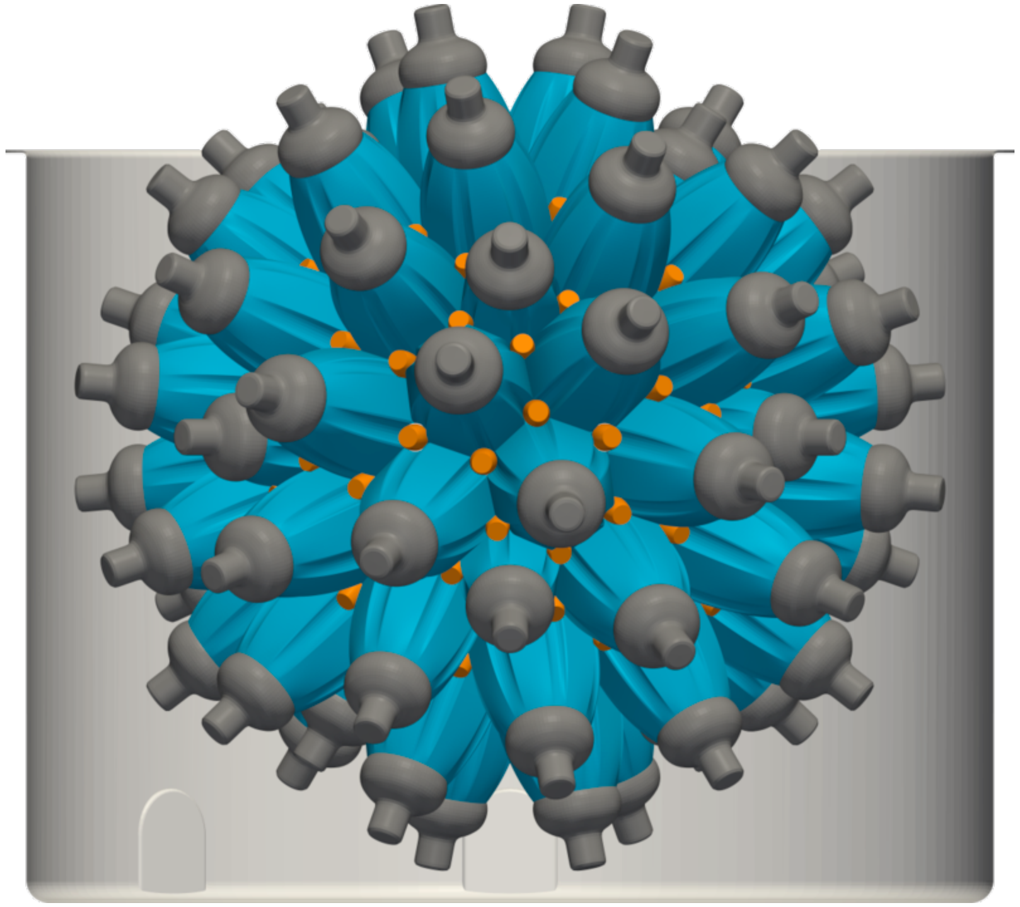


Rapid Communication

Probing Majorana neutrinos in the regime of the normal mass hierarchy

Steven D. Biller
Phys. Rev. D **87**, 071301(R) – Published 8 April 2013

Suggests Using Te-doped scintillator



- NuDot (prototype shown)
- Directional information from Cerenkov light in scintillator
- Doped w/ QM dots that can be loaded w/ DBD isotopes + modify scintillation properties.

Recent Review: Nucl. Phys. News 27 (2017) no.3, 14-19

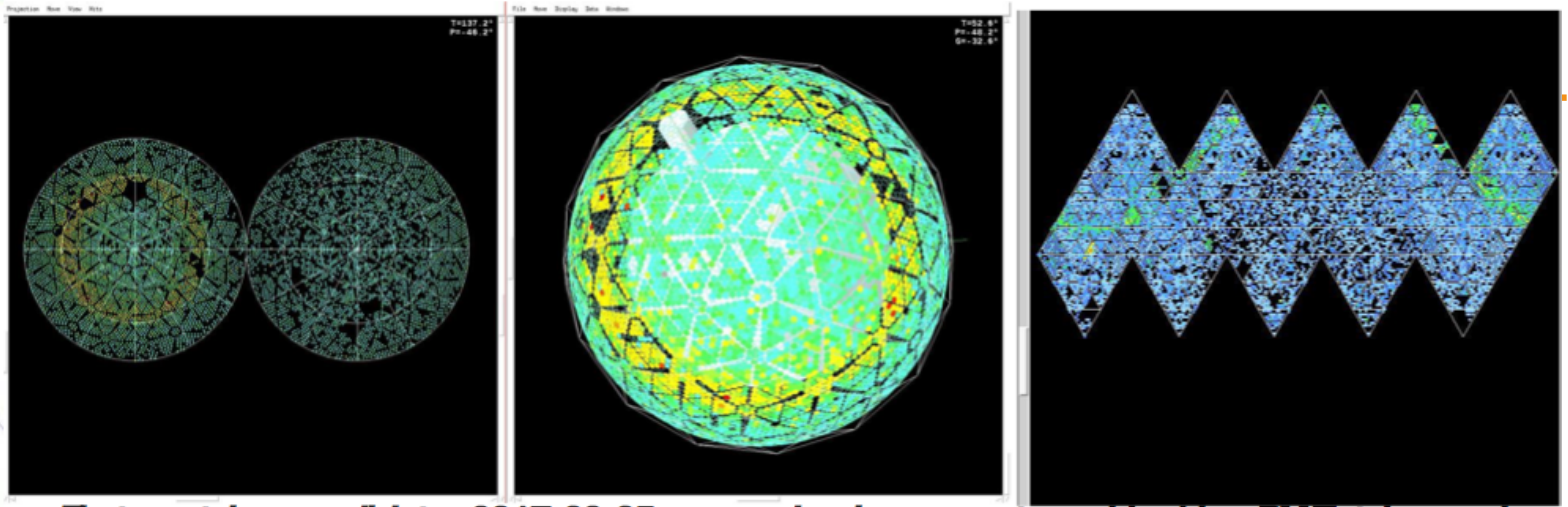
Conclusions

- NDBD has had immense success during last year
- Tonne-scale experiments becoming realistic
- Poised to make significant progress in coming years to complete probe IH and make progress into NH

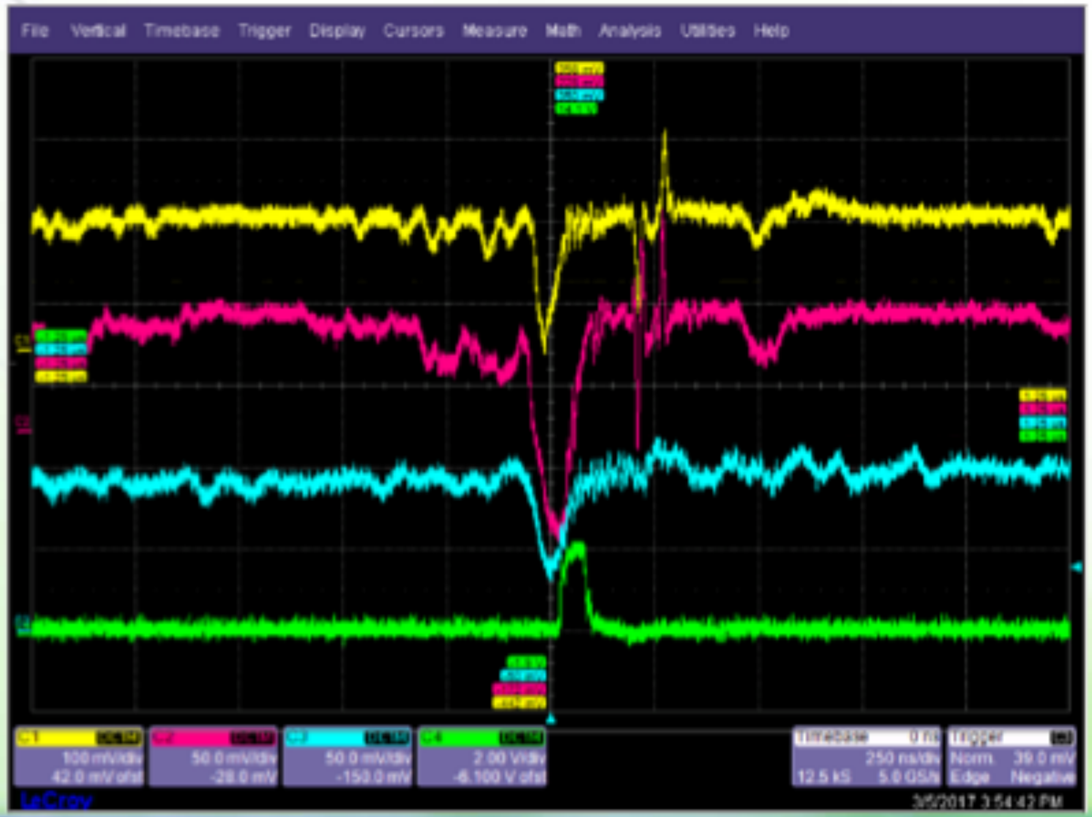
Acknowledgements

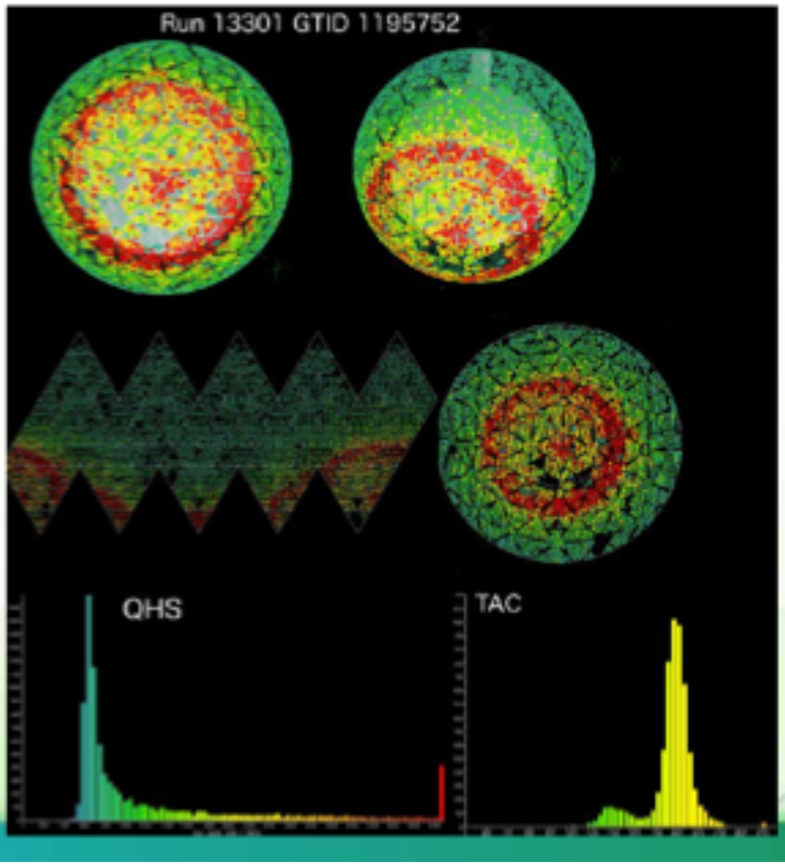
- John Wilkerson
- Giorgio Gratta
- Michelle Dolinski
- Lindley Winslow
- Mark Chen
- David Nygren
- Micah Buuck
- Others…

Bonus slides



First neutrino candidate: 2017-02-05, upward-going, no outward-looking PMTs triggered

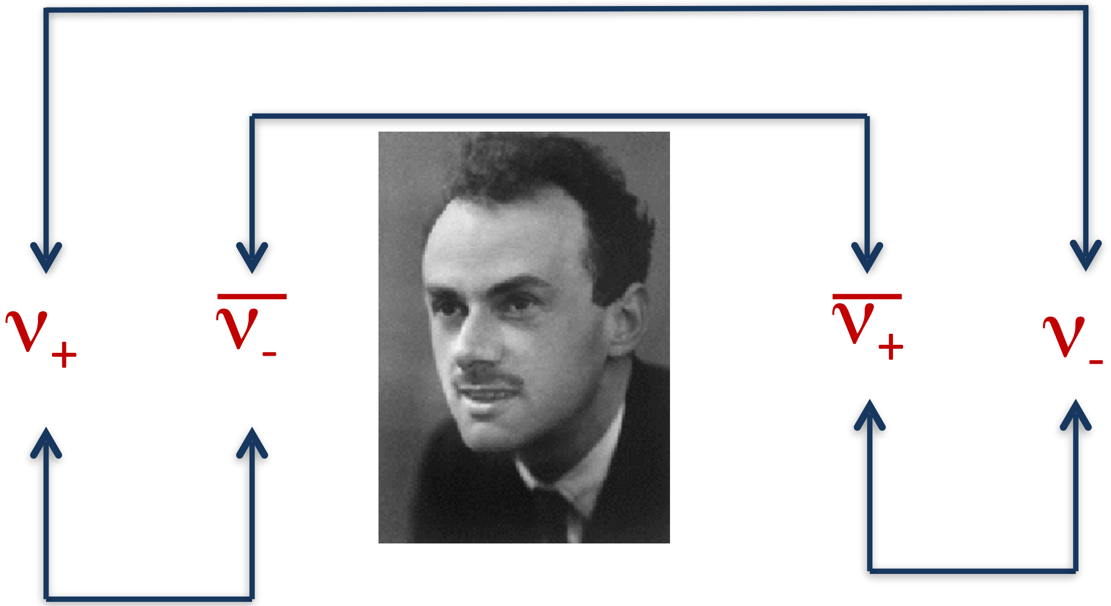




Electronics working well

More about Majorana vs. Dirac

Note: Only valid if neutrinos are massive.



Lorentz Boost

ν_+ $\bar{\nu}_-$ $\bar{\nu}_+$ ν_-

CPT

$\nu \neq \bar{\nu}$

CPT

Lorentz Boost

ν^M_- ν^M_+

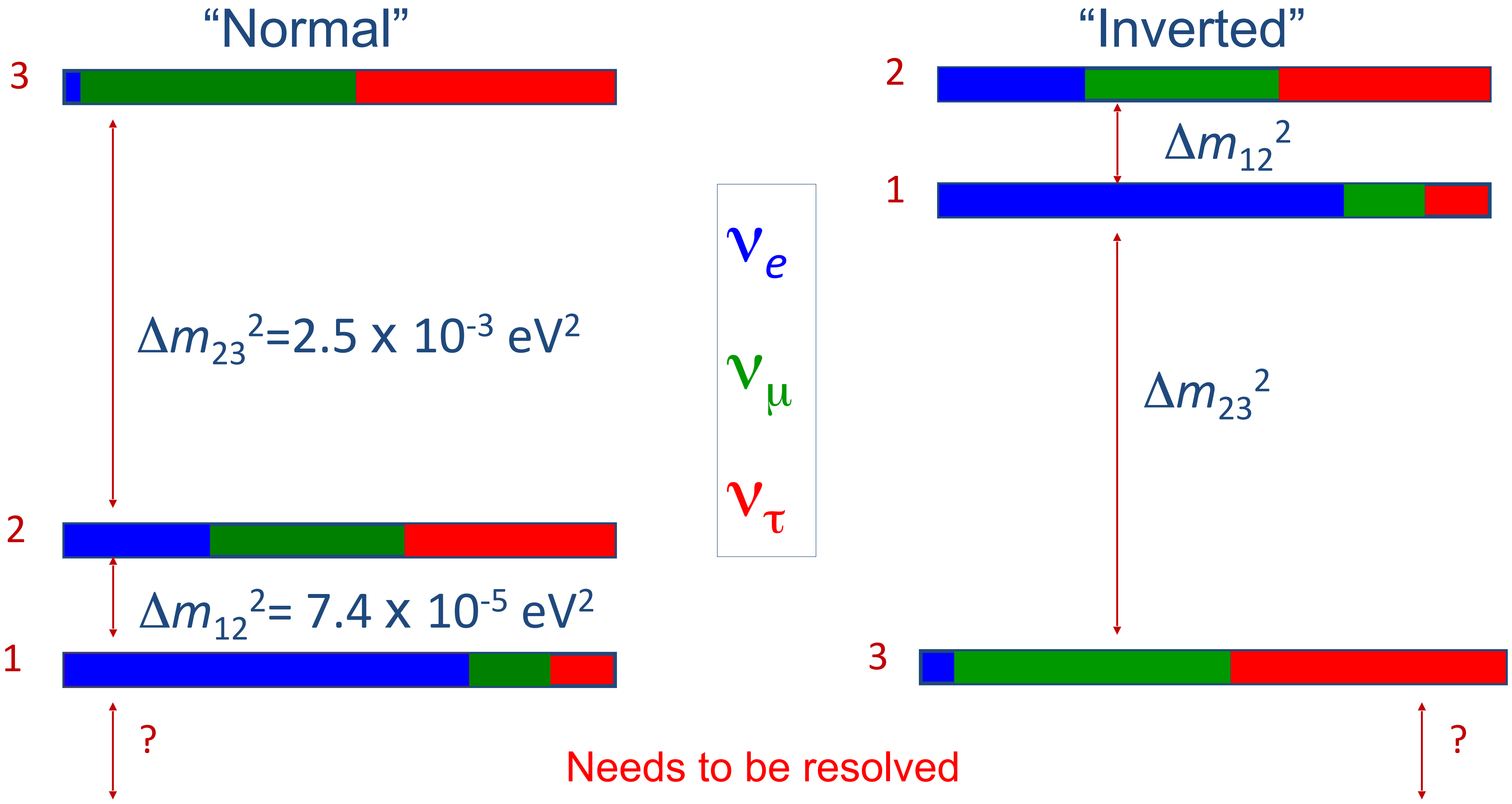
CPT

$\nu = \bar{\nu} = \nu^M$

Original argument by Kayser, 1985

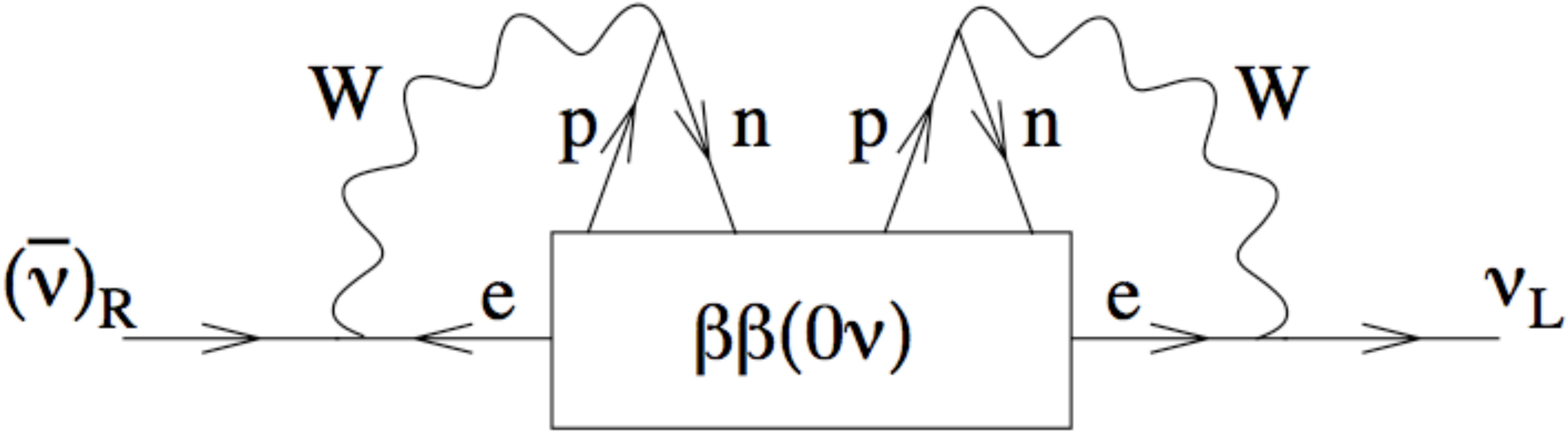
Neutrino Masses

- Absolute masses weakly constrained, < 1eV.
- Relative mass-squared differences known.
- Three possible scenarios: Quasi-degenerate, also:



Needs to be resolved

$0\nu\beta\beta$–decay and Majorana Neutrinos



Schechter et al, Phys. Rev. D**25**, 2951 (1982)

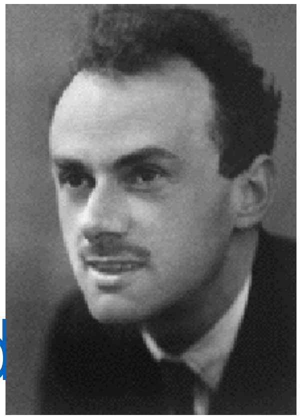
Majorana nature verification ***independent*** of process that mediates $0\nu\beta\beta$ decay!

Majorana vs. Dirac

Ettore Majorana

- Majorana fermions are their own anti-particles.
- Dirac fermions are not.
- No fermions are known to be Majorana.
  - Electrically charged fermions have good QM # to distinguish particle/anti-particles, hence are Dirac
- **Experimental evidence consistent with both Majorana o neutrinos.**
- Verification difficult due to small neutrino masses and handedness of weak interaction.

Paul Dirac



Neutrinoless double-beta decay is the only practical process that can resolve this mystery.

Origin of Matter

Majorana neutrinos

Required by

See-Saw mass-generating mechanism

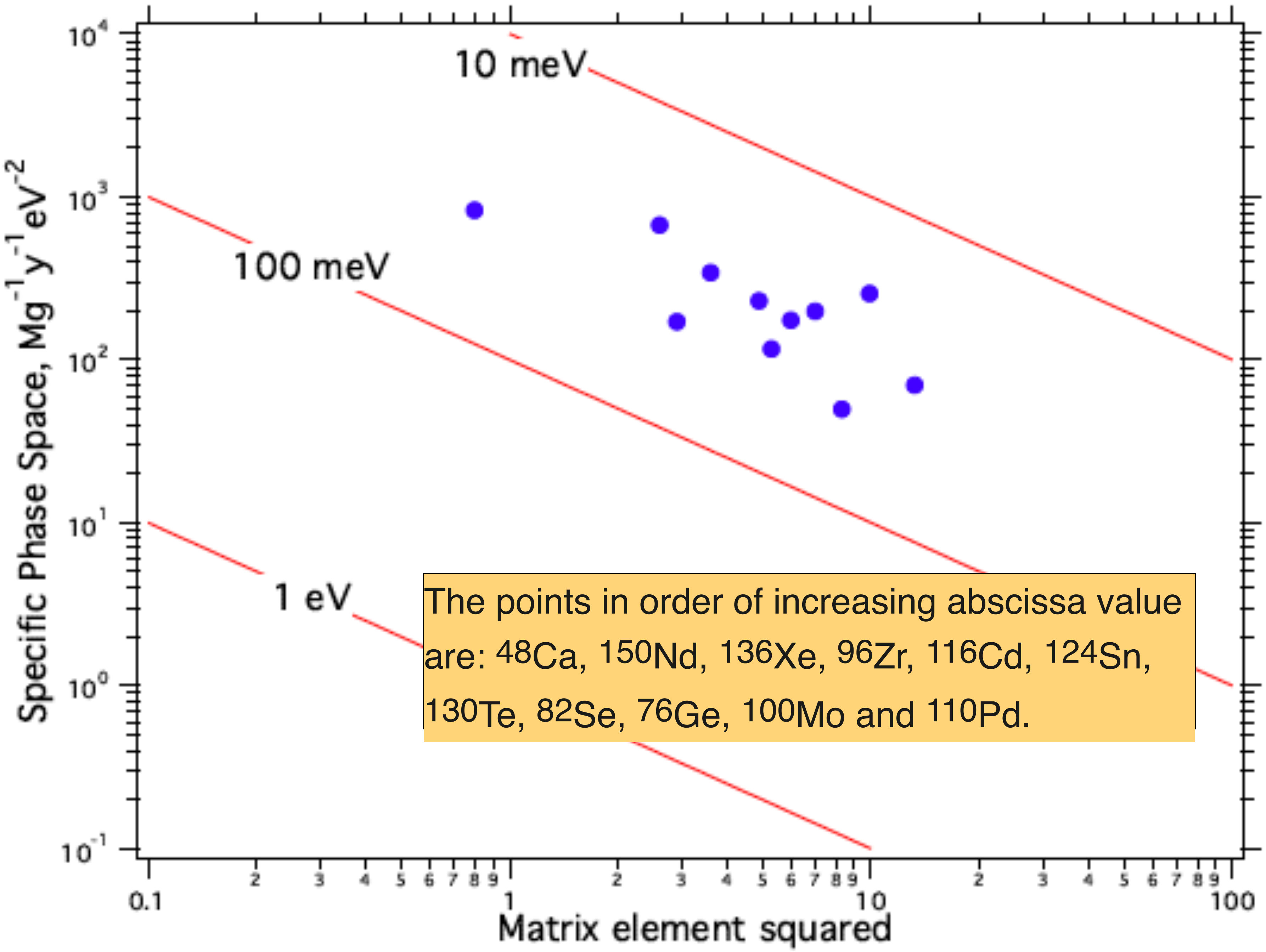
Required (in general) by

Leptogenesis

Matter dominated universe?

Sensitivity per unit mass of isotope

➡ Isotopes have comparable sensitivities in terms of rate per unit mass



The points in order of increasing abscissa value are: ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo and ^{110}Pd.

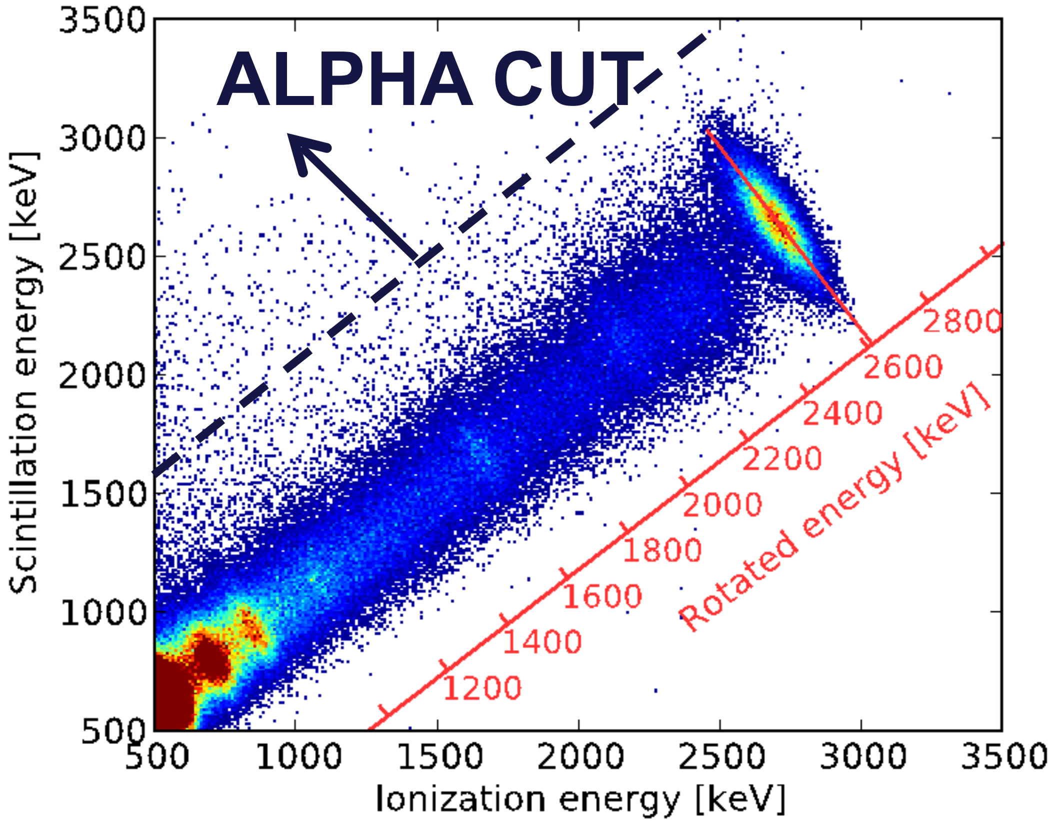
R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)

Inverse correlation observed between phase space and the square of the nuclear matrix element .

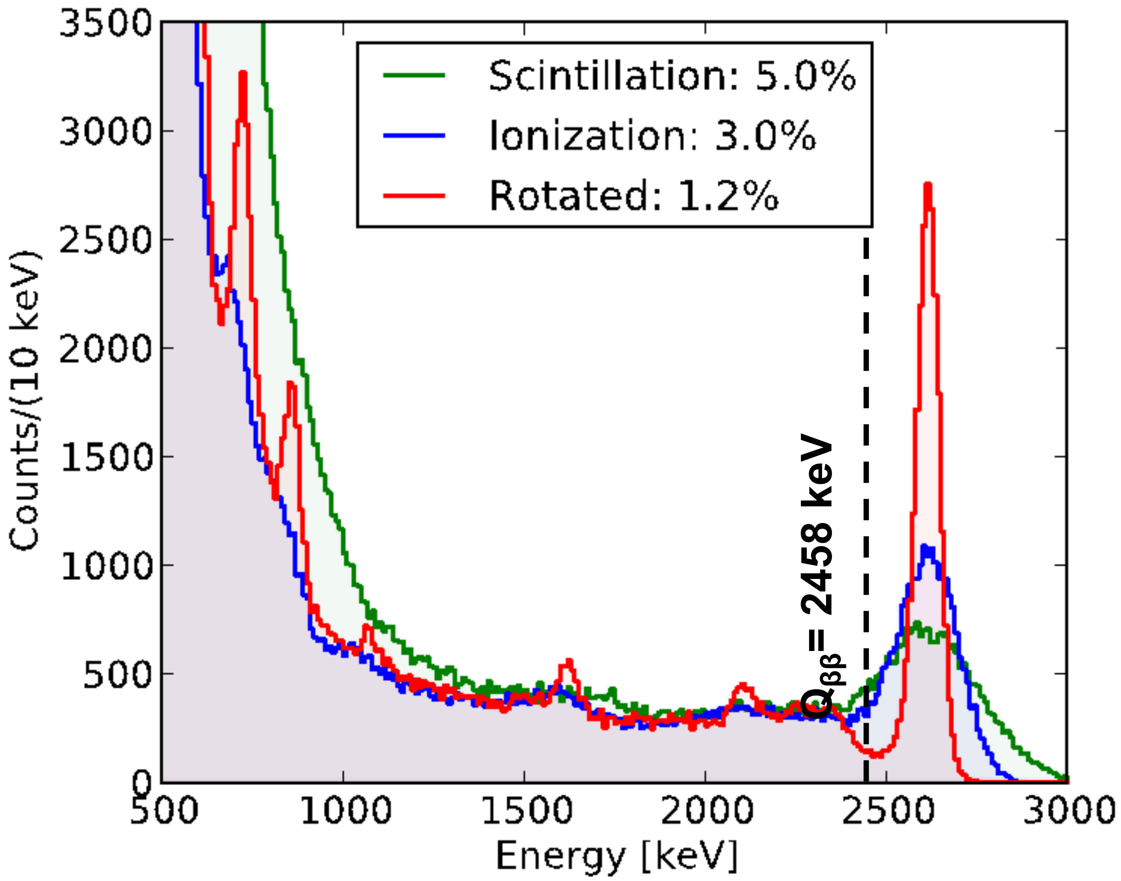
geometric mean of the squared matrix element range limits & the phase-space factor evaluated at g_A=1

Energy measurement

Scintillation vs. ionization, ^{228}Th calibration:



Reconstructed energy, ^{228}Th calibration:



- Anticorrelation between scintillation and ionization in LXe known since early EXO R&D [E.Conti et al. Phys Rev B 68 (2003) 054201]
- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- EXO-200 has achieved ~ 1.23% energy resolution at the double-beta decay Q value in Phase II.