Double Beta Decay III: The State of the Field

Julieta Gruszko

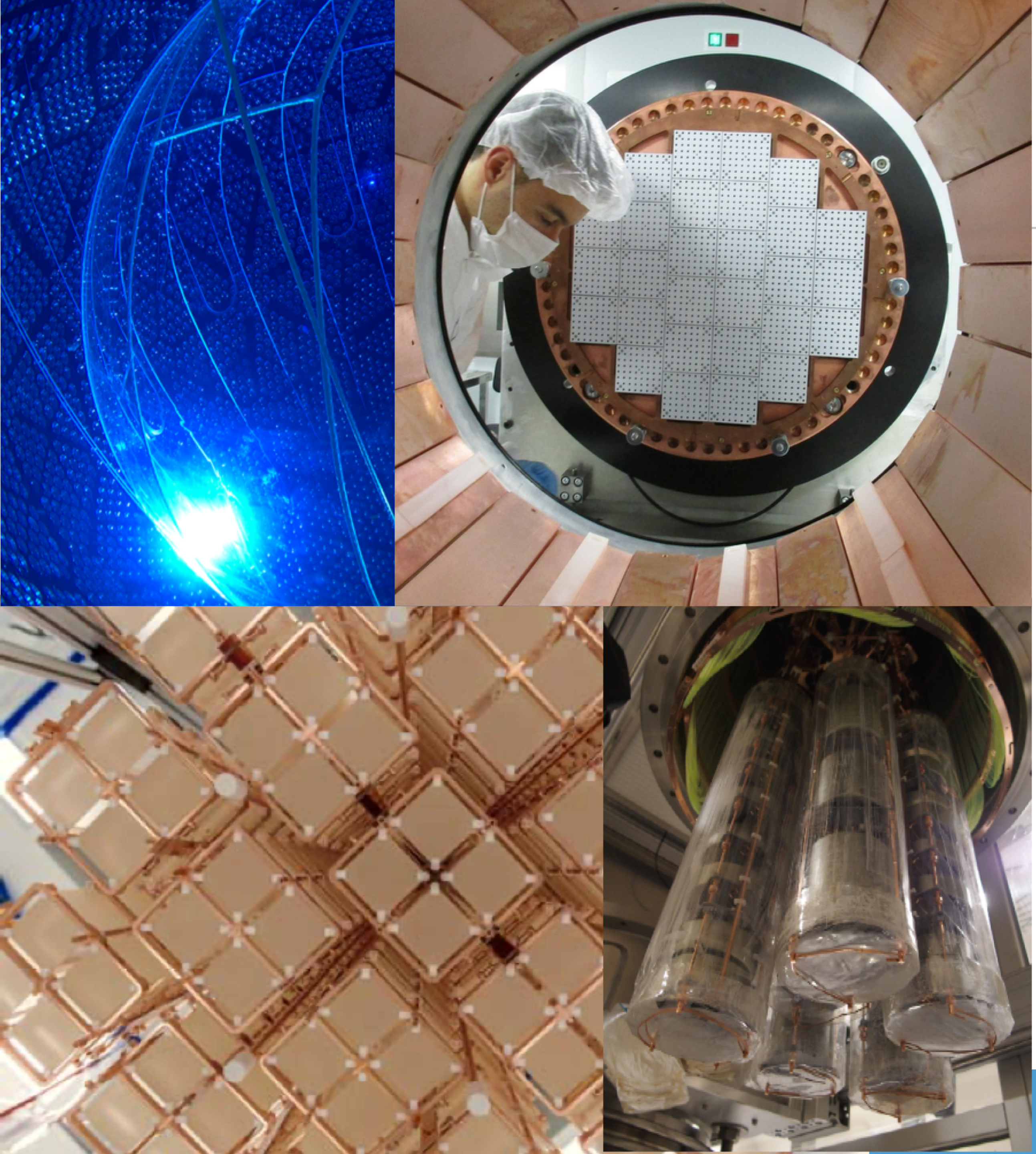
National Nuclear Physics Summer School

July 15, 2022

THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

Reminder from Yesterday

- Calculating NMEs for 0νββ is challenging:
  - Mean-field methods let you calculate matrix elements for large nuclei, but uncertainties are impossible to quantify
  - Ab-initio methods are advancing quickly, but can’t address all ββ decay elements yet
- To discover 0νββ, we need very large experiments with very low backgrounds
  - Most experiments use a source=detector strategy to maximize efficiency
  - Background rejection based on event topology, location, type of interaction, and other information is helpful



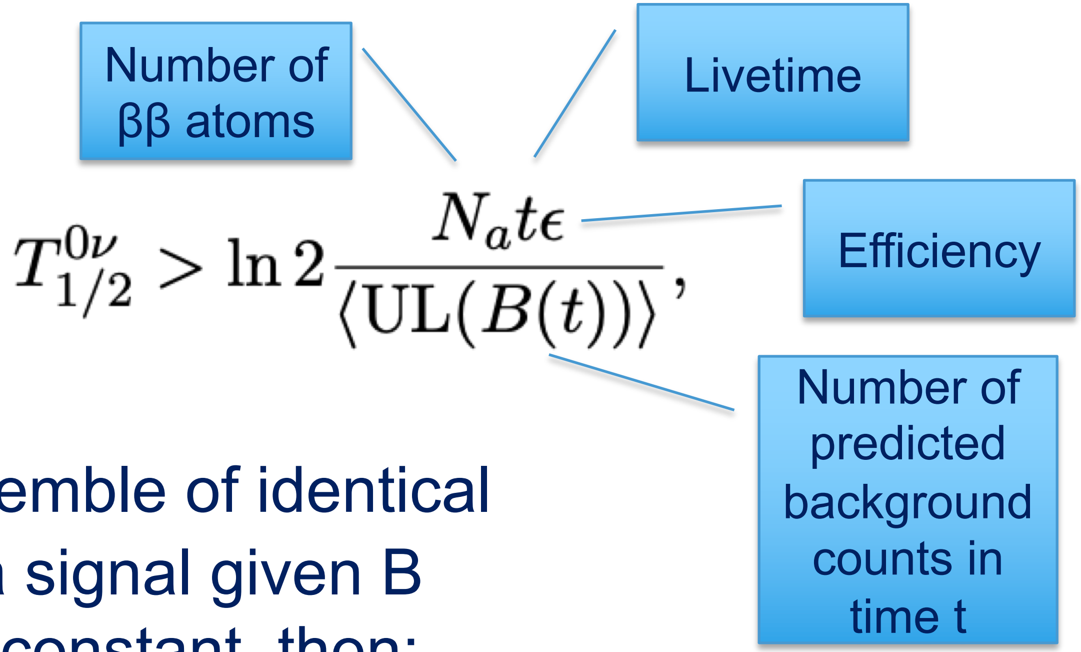
Outline

- Wednesday: Why look for 0νββ?
- Thursday: How to look for 0νββ
- Friday: The State of the Field
  - How Measurements Work
  - The 0νββ Search Landscape
  - The Experiments:
    - Liquid Scintillator Experiments
    - TPCs: Liquid and Gas
    - Bolometer Experiments
    - Germanium Experiments
    - Tracking Experiments
  - Doing other physics with 0νββ experiments
  - What comes after discovery?

How Measurements Work

Measuring and Setting Limits on $T_{1/2}$

- 0νββ experiments measure a half-life
- Before you run an experiment, you can calculate its expected half-life sensitivity:



$$T^{0\nu}_{1/2} > \ln 2 \frac{N_a t \epsilon}{\langle \mathrm{UL}(B(t)) \rangle},$$

Number of ββ atoms

Livetime

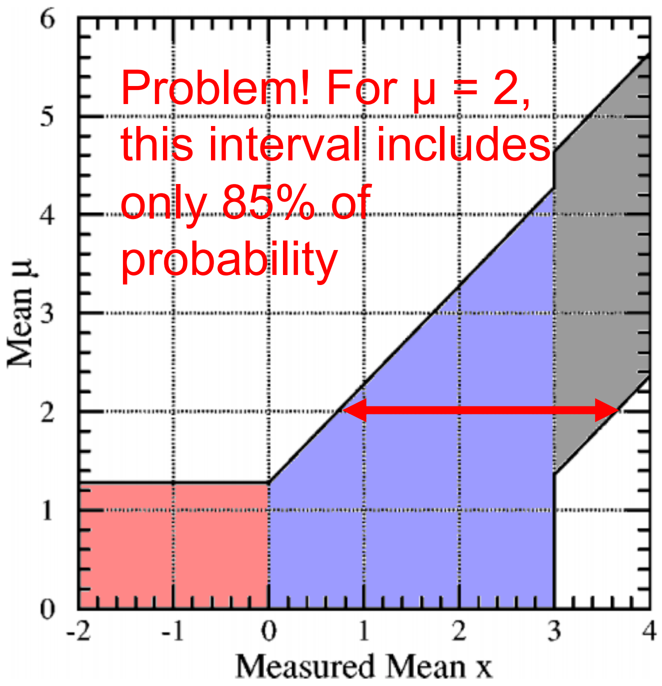
Efficiency

Number of predicted background counts in time t

- $\langle UL(B(t)) \rangle$ is the average upper limit an ensemble of identical experiments would place in the absence of a signal given B background counts. If B(t) = bt, where b is a constant, then:
  - If bt >> 1, $\langle UL(B(t)) \rangle = \sqrt{bt}$ (background limited)
  - If bt << 1, $\langle UL(B(t)) \rangle = constant$ (background free)
  - In between, you have to use Feldman-Cousins statistics

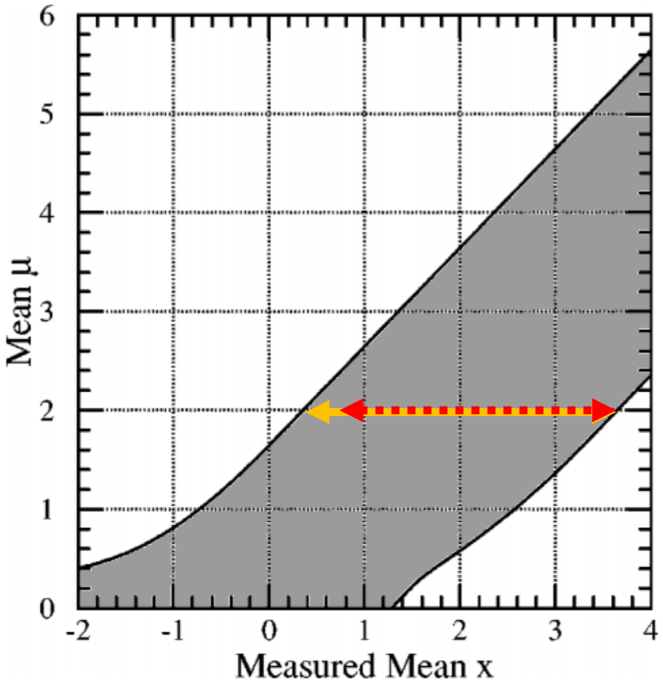
Feldman-Cousins Statistics

- In classical frequentist statistics, you have to decide **ahead of making a measurement** whether you'll be setting confidence intervals or an upper limit.
- If you "flip-flop," you will end up with under-coverage.



Problem! For μ = 2, this interval includes only 85% of probability

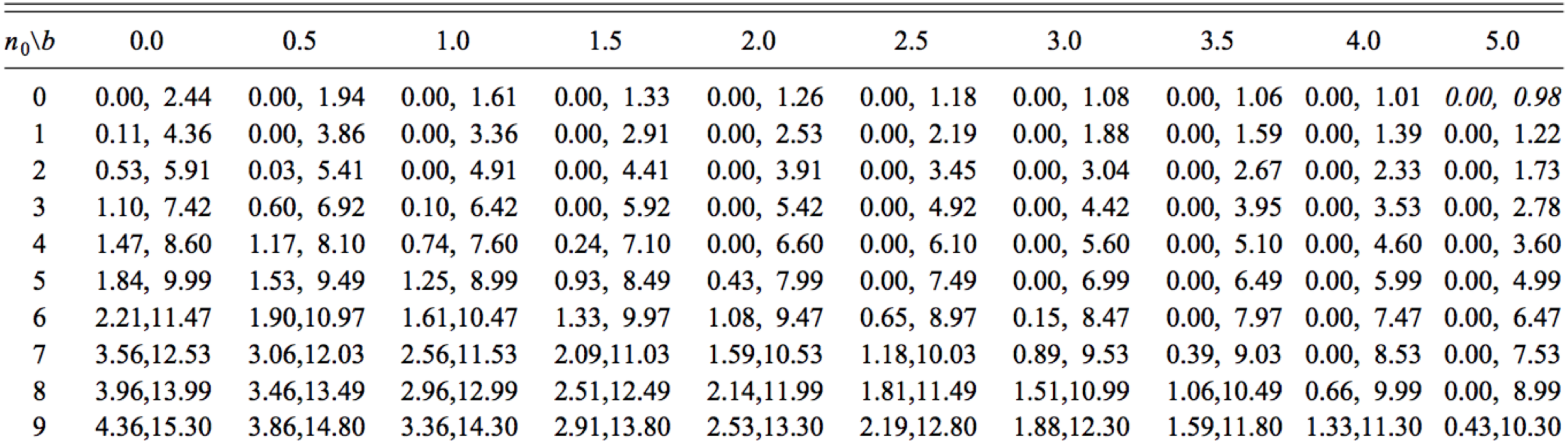
Flip-flopping:
If the experiment measures…
- x < 0, use a 3σ UL
- x < 3σ, use a 3σ UL
- x > 3σ, use a CL



- Feldman-Cousins gives a recipe for building confidence intervals that don't lead to under-coverage, and transition smoothly between UL and CL

How to Use Feldman-Cousins

- Look-up table for 90% CL from the Feldman-Cousins paper
- ROOT and python packages for calculating F.C. intervals are also available



$n_0 \backslash b$	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
0	0.00, 2.44	0.00, 1.94	0.00, 1.61	0.00, 1.33	0.00, 1.26	0.00, 1.18	0.00, 1.08	0.00, 1.06	0.00, 1.01	*0.00, 0.98*
1	0.11, 4.36	0.00, 3.86	0.00, 3.36	0.00, 2.91	0.00, 2.53	0.00, 2.19	0.00, 1.88	0.00, 1.59	0.00, 1.39	0.00, 1.22
2	0.53, 5.91	0.03, 5.41	0.00, 4.91	0.00, 4.41	0.00, 3.91	0.00, 3.45	0.00, 3.04	0.00, 2.67	0.00, 2.33	0.00, 1.73
3	1.10, 7.42	0.60, 6.92	0.10, 6.42	0.00, 5.92	0.00, 5.42	0.00, 4.92	0.00, 4.42	0.00, 3.95	0.00, 3.53	0.00, 2.78
4	1.47, 8.60	1.17, 8.10	0.74, 7.60	0.24, 7.10	0.00, 6.60	0.00, 6.10	0.00, 5.60	0.00, 5.10	0.00, 4.60	0.00, 3.60
5	1.84, 9.99	1.53, 9.49	1.25, 8.99	0.93, 8.49	0.43, 7.99	0.00, 7.49	0.00, 6.99	0.00, 6.49	0.00, 5.99	0.00, 4.99
6	2.21,11.47	1.90,10.97	1.61,10.47	1.33, 9.97	1.08, 9.47	0.65, 8.97	0.15, 8.47	0.00, 7.97	0.00, 7.47	0.00, 6.47
7	3.56,12.53	3.06,12.03	2.56,11.53	2.09,11.03	1.59,10.53	1.18,10.03	0.89, 9.53	0.39, 9.03	0.00, 8.53	0.00, 7.53
8	3.96,13.99	3.46,13.49	2.96,12.99	2.51,12.49	2.14,11.99	1.81,11.49	1.51,10.99	1.06,10.49	0.66, 9.99	0.00, 8.99
9	4.36,15.30	3.86,14.80	3.36,14.30	2.91,13.80	2.53,13.30	2.19,12.80	1.88,12.30	1.59,11.80	1.33,11.30	0.43,10.30

The original paper is a classic: 10.1103/PhysRevD.57.3873, and some nice slides on the subject can be found at https://www.pas.rochester.edu/~sybenzvi/courses/phy403/2015s/p403_19_intervals.pdf

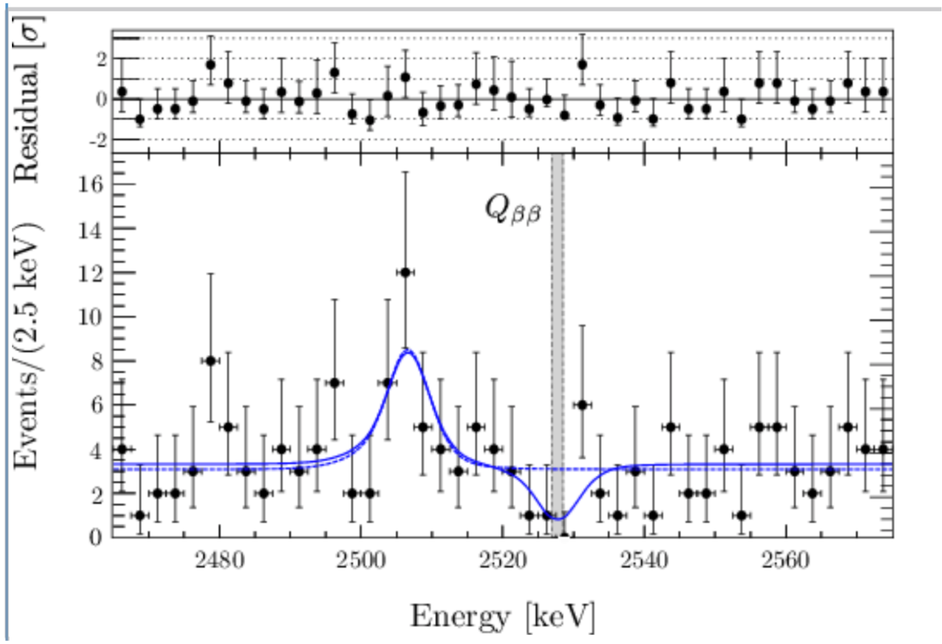
Measuring and Setting Limits on $T_{1/2}$

- After you run a 0νββ search…
  - You either see an excess at the Q value, and fit a peak with some rate to it
  - Or you don't see an excess. In that case, you set a lower limit on half-life:

$$T_{1/2}^{0\nu} > \ln(2)\,\frac{N_a T \epsilon}{S}$$

  - S is the upper limit on the signal counts based on the observed data. Again, use F.C. to calculate if it's appropriate.
- Experiments that don't see anything report sensitivity and a limit. If they get lucky and have a downward fluctuation, limit will exceed sensitivity.

CUORE 2018 Result

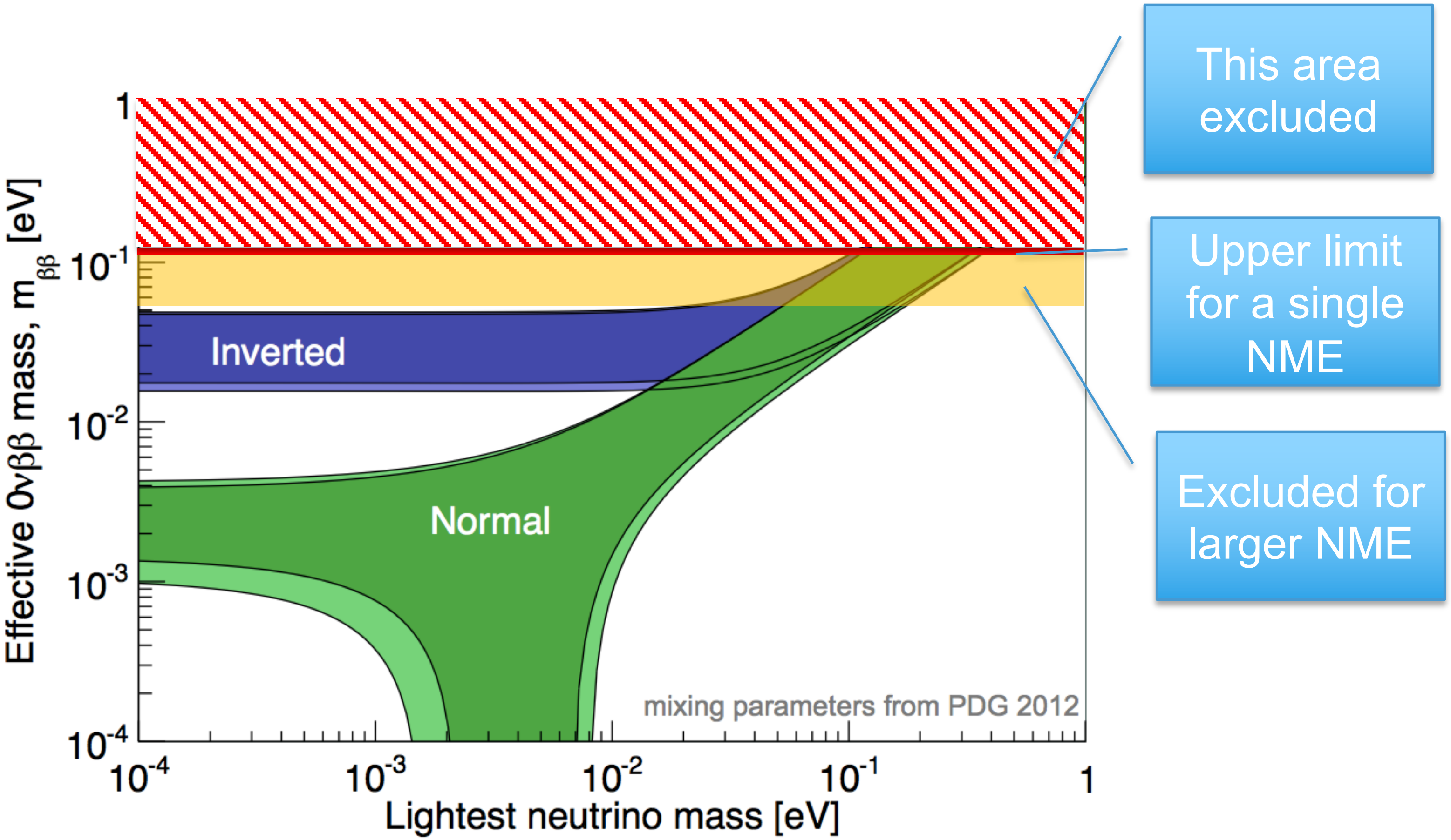


Sensitivity: 7×10^{24} yrs
Limit: $T_{1/2} > 1.3\times10^{25}$ yrs

10.1103/PhysRevLett.120.132501

Translating Half-Life to $m_{\beta\beta}$

- Need to use a particular model, the phase space factor and a nuclear matrix element to turn half-life into $m_{\beta\beta}$
- Results are generally reported for the full set of NMEs, so the upper limit in $m_{\beta\beta}$ has a range



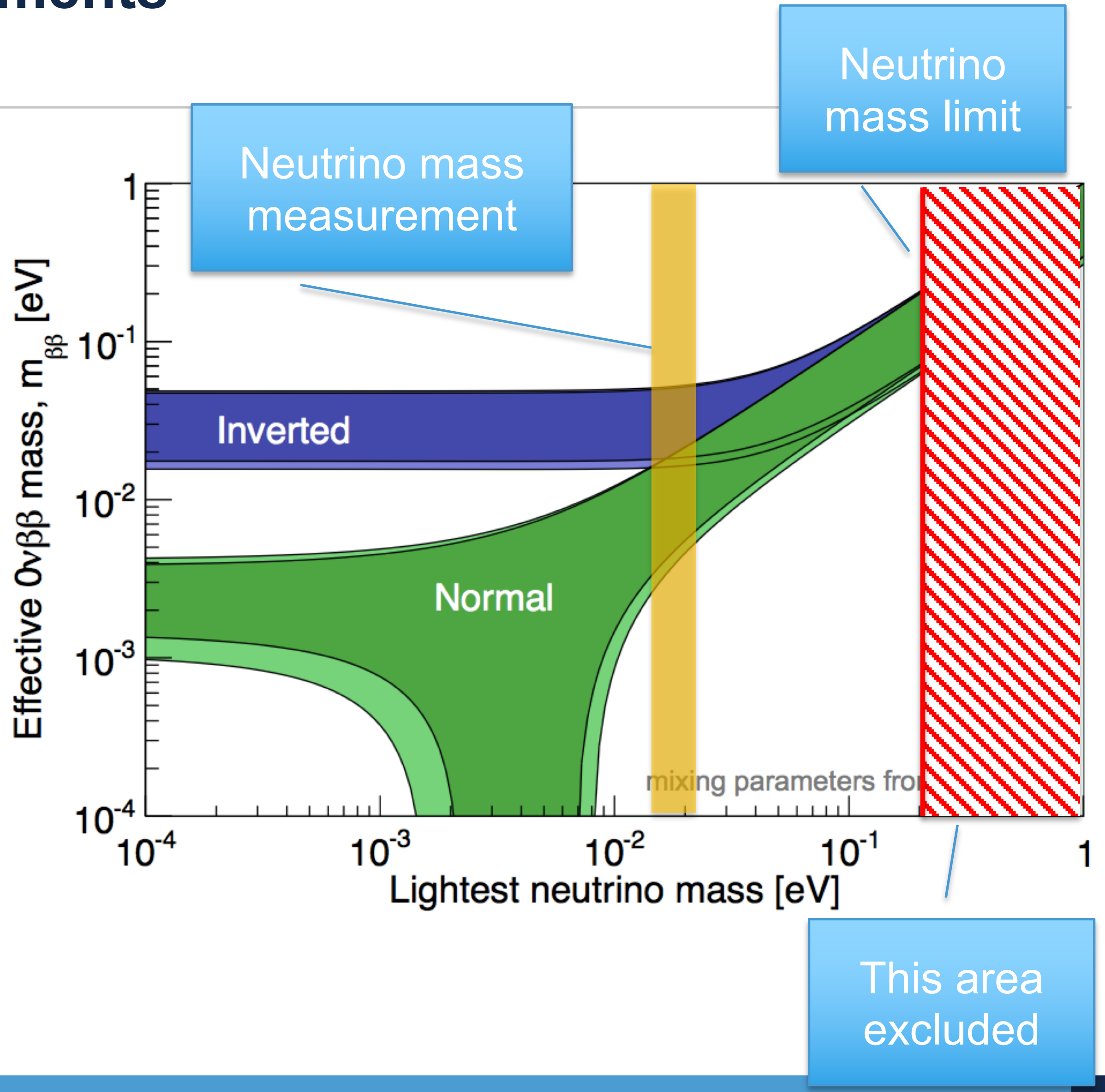
This area excluded

Upper limit for a single NME

Excluded for larger NME

Information from Other Neutrino Experiments

- Light-colored edges are 3σ uncertainty on neutrino mixing and mass splittings
- Measuring hierarchy would tell us which branch we need to look in
- Mass measurement would tell us which vertical band to look in



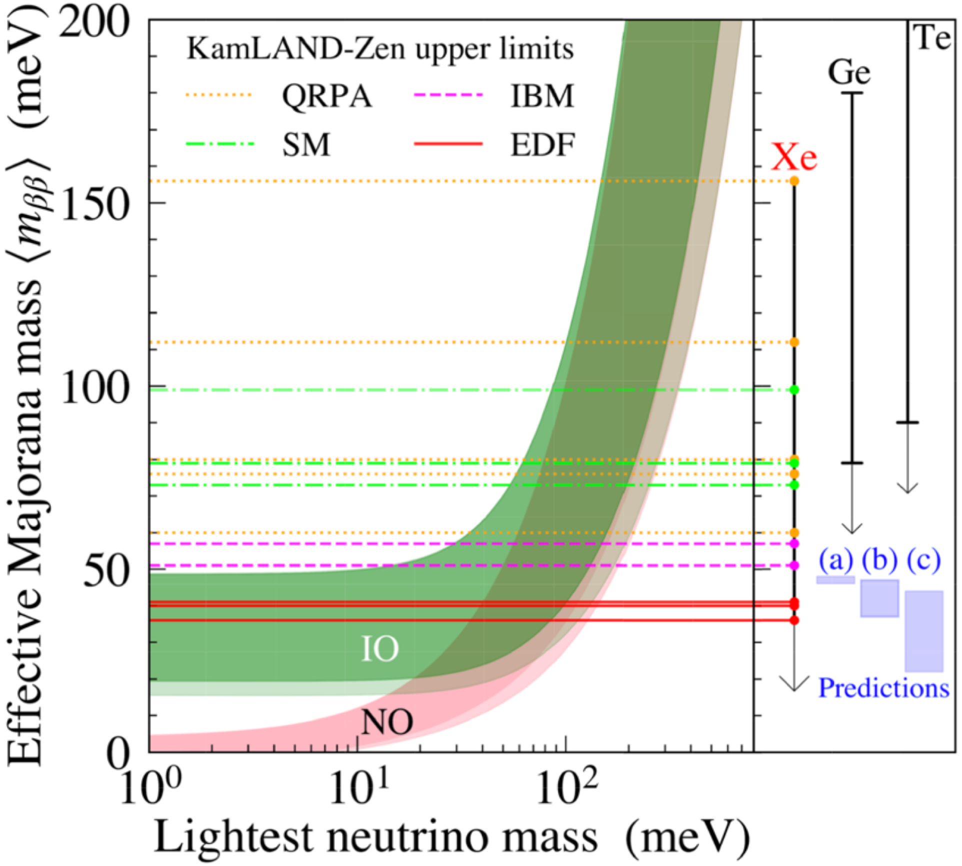
Neutrino mass measurement

Neutrino mass limit

This area excluded

The 0νββ Search Landscape

Current Best Limits on 0νββ



arXiv: 2203.02139

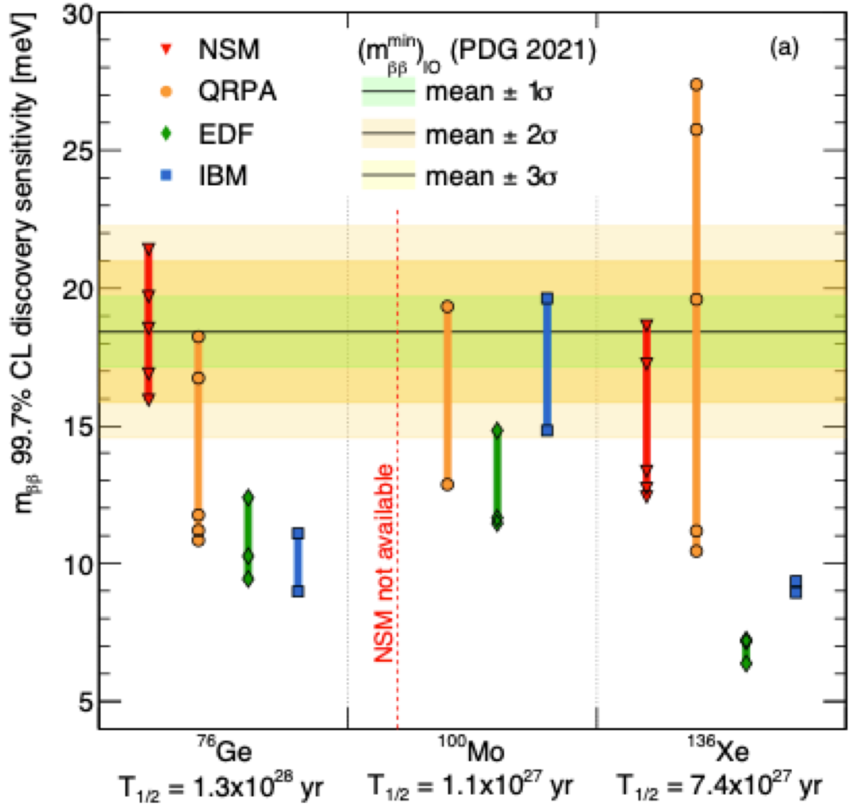
Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}$ [10^{25} yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	8.3	113-269
KamLAND-Zen	^{136}Xe	970	23	36-156
EXO-200	^{136}Xe	234.1	3.5	93-286
CUORE	^{130}Te	1038.4	2.2	90-305

NSAC recommendation: quote a range of $m_{\beta\beta}$ using the largest and smallest available NME from the 4 main calculation methods; g_A=1.27; no contribution from the contact term

The Ton-Scale Generation

- The next-generation of experiments seeks to cover the IO region in discovery mode
- That will take O(1 ton) of isotope
- 3 candidate experiments with US participation, in addition to other efforts: LEGEND, nEXO, and CUPID
- All 3 were evaluated by the DOE in Summer 2021. DOE-NP is seeking international support to pursue all 3 experiments.

Discovery Sensitivity for the “Big 3”



10.1103/PhysRevC.104.L042501

Discovery and Sensitivity

- All 3 experiments cover the IO for some matrix elements, and miss for others
- Larger background = more difference between discovery and exclusion

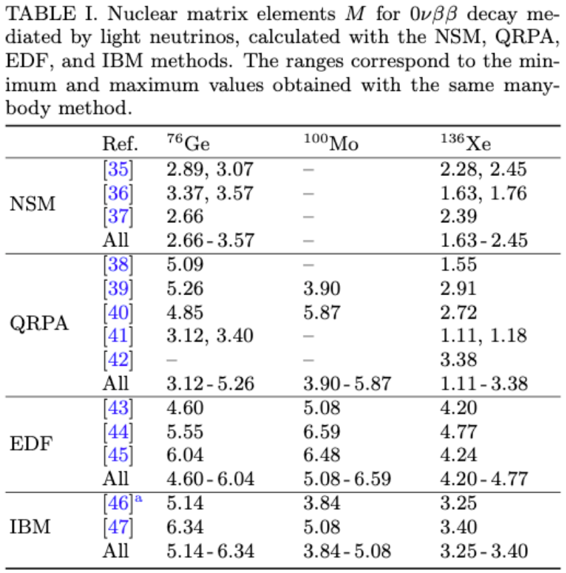
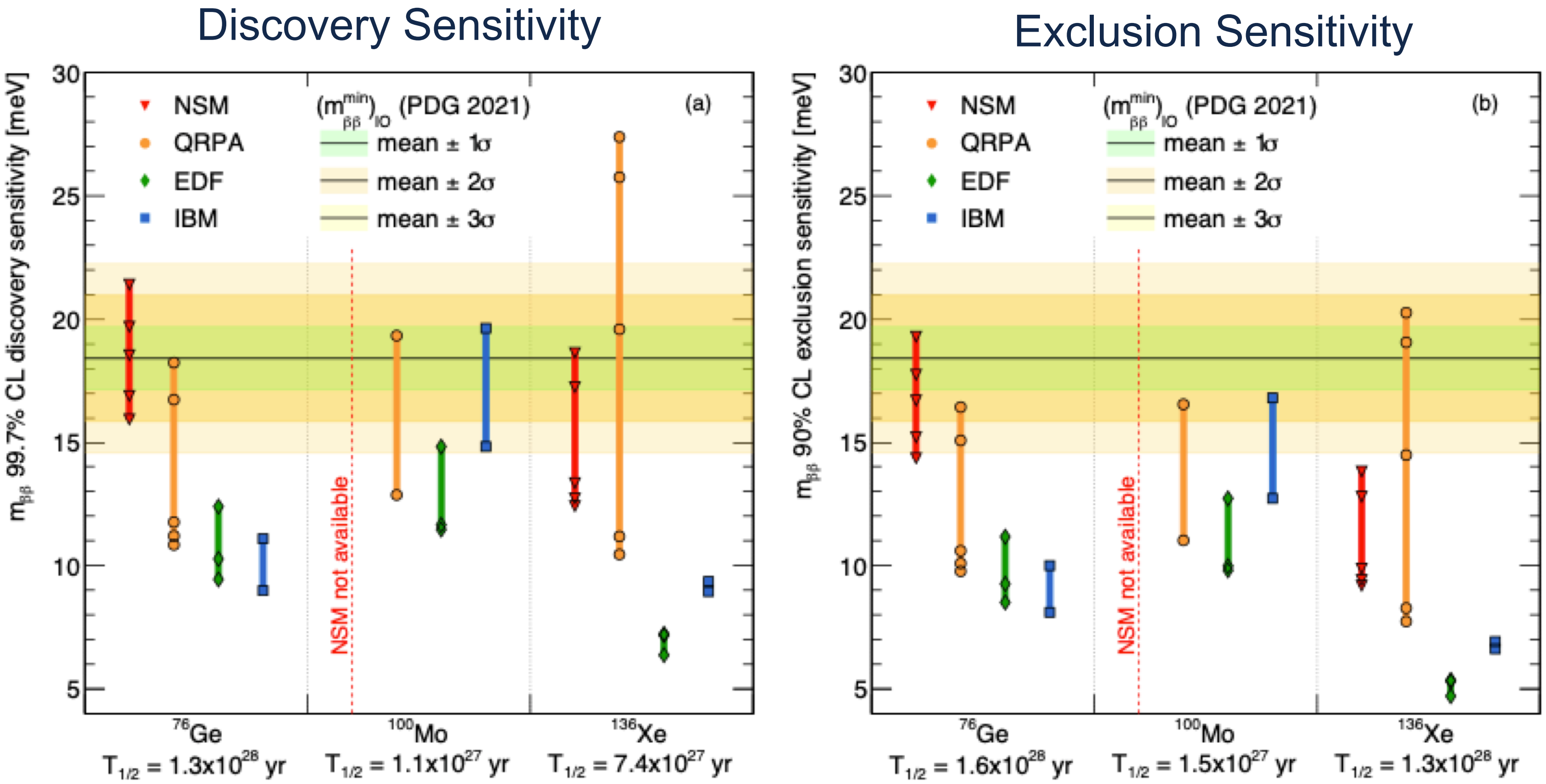


TABLE I. Nuclear matrix elements M for $0\nu\beta\beta$ decay mediated by light neutrinos, calculated with the NSM, QRPA, EDF, and IBM methods. The ranges correspond to the minimum and maximum values obtained with the same many-body method.

	Ref.	^{76}Ge	^{100}Mo	^{136}Xe
NSM	[35]	2.89, 3.07	–	2.28, 2.45
	[36]	3.37, 3.57	–	1.63, 1.76
	[37]	2.66	–	2.39
	All	2.66 - 3.57	–	1.63 - 2.45
QRPA	[38]	5.09	–	1.55
	[39]	5.26	3.90	2.91
	[40]	4.85	5.87	2.72
	[41]	3.12, 3.40	–	1.11, 1.18
	[42]	–	–	3.38
	All	3.12 - 5.26	3.90 - 5.87	1.11 - 3.38
EDF	[43]	4.60	5.08	4.20
	[44]	5.55	6.59	4.77
	[45]	6.04	6.48	4.24
	All	4.60 - 6.04	5.08 - 6.59	4.20 - 4.77
IBM	[46][a]	5.14	3.84	3.25
	[47]	6.34	5.08	3.40
	All	5.14 - 6.34	3.84 - 5.08	3.25 - 3.40

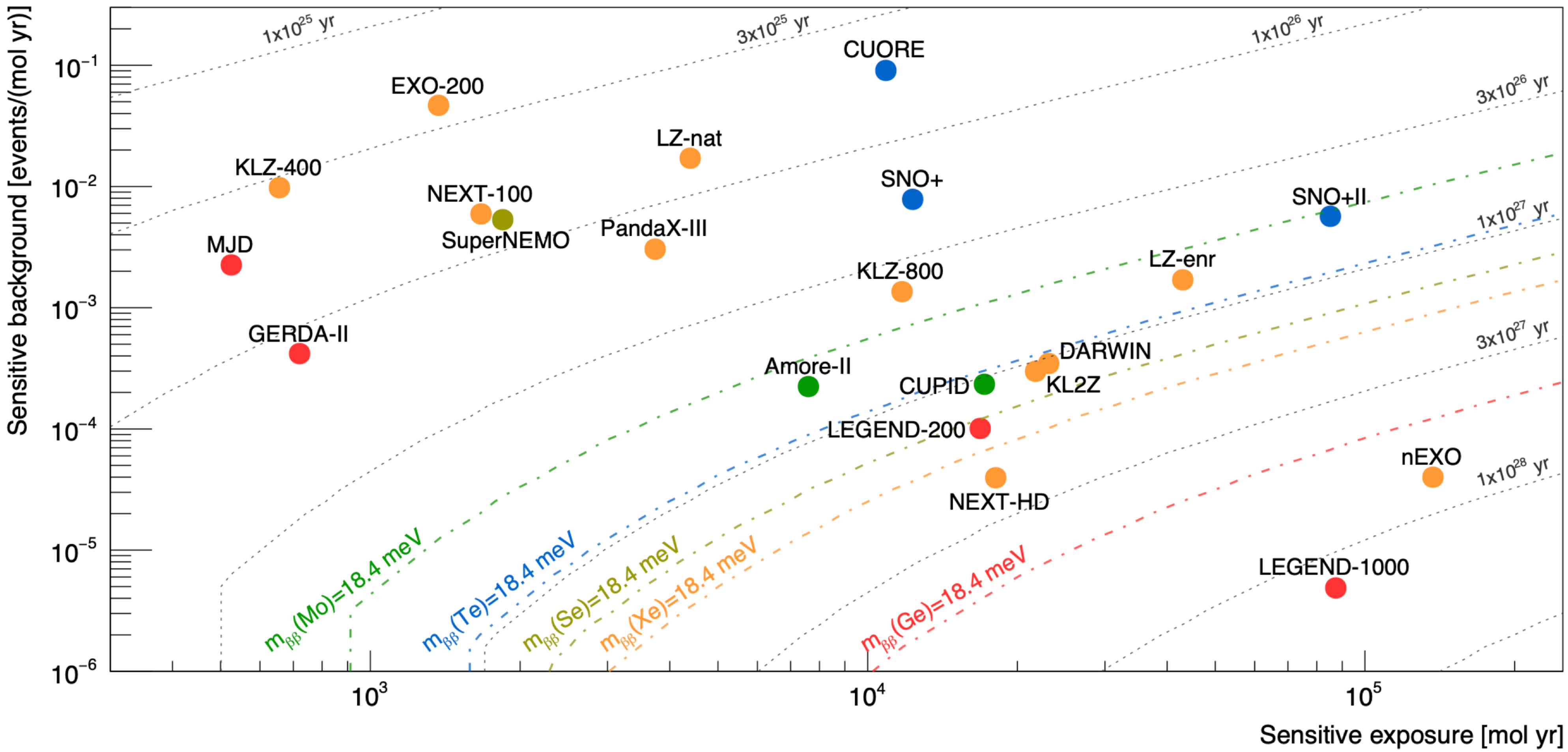


Discovery Sensitivity

Exclusion Sensitivity

From Agostini et al., PRC **104**, L042501 (2021)

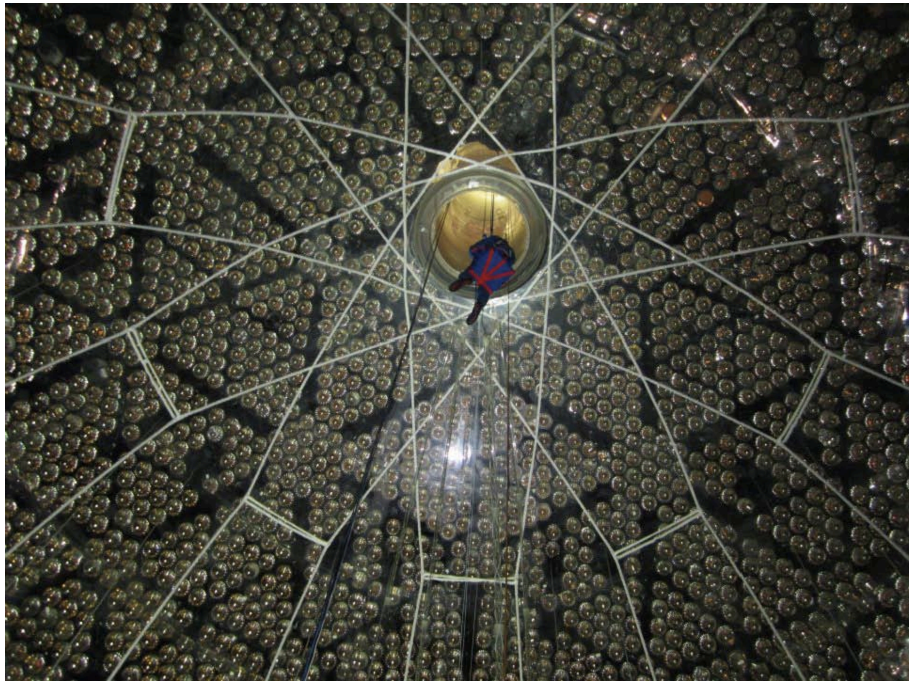
Recent and Proposed Experiments



The Experiments

Liquid Scintillators

Liquid Scintillator Detector Concept

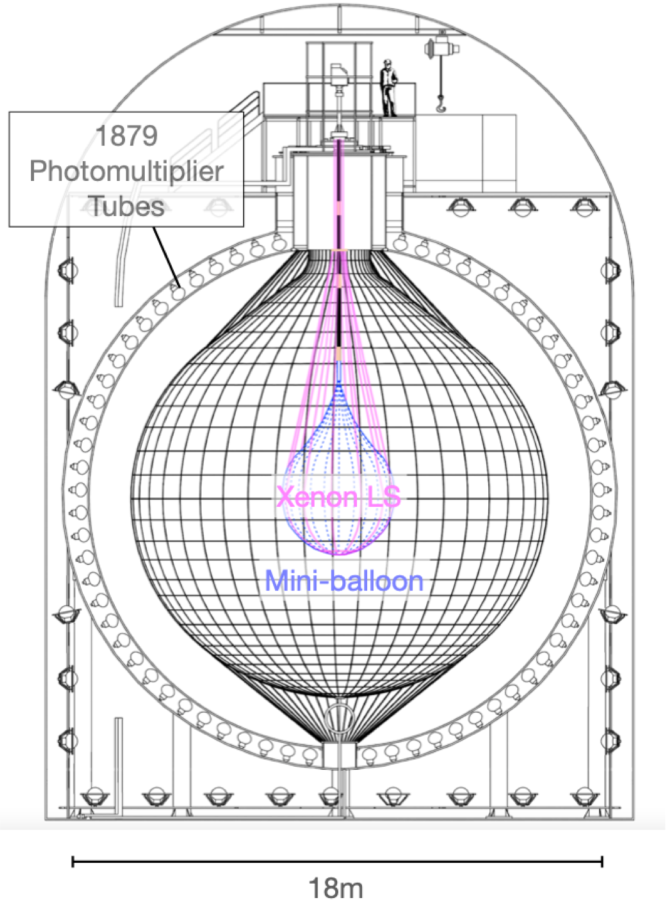


Measure isotropic scintillation light to extract energy

- Self-shielding, fiducialization
- Interior materials can be made extremely pure
- Some event topology and particle ID, with additional future improvements expected
- Measurement with and without isotope is possible
- Other strengths: flexible and scalable design
- Weakness: energy resolution and spatial resolution; large “target” for cosmogenics

KamLAND-Zen

- Adaptation of existing reactor neutrino experiment
- ^{136}Xe concentrated in inner balloon, holds LS doped with 3.13% enriched Xenon by weight
- Relatively shallow site, spallation backgrounds dominate
- KamLAND-Zen 400: 2011-2014
  - Phase I: 320 kg 90% enriched ^{136}Xe
  - Phase II: 380 kg
  - $T_{1/2} > 1.07 \times 10^{26}$ yr, $m_{\beta\beta} < 61-165$ meV
- KamLAND-Zen 800:
  - Data-taking began in January 2019
  - Scintillator purification campaign
  - Larger, cleaner inner balloon
  - 750 kg enriched ^{136}Xe
- Currently has the largest single-experiment half-life limit: $T_{1/2} > 2.3 \times 10^{26}$ yrs



Backgrounds in KamLAND-Zen

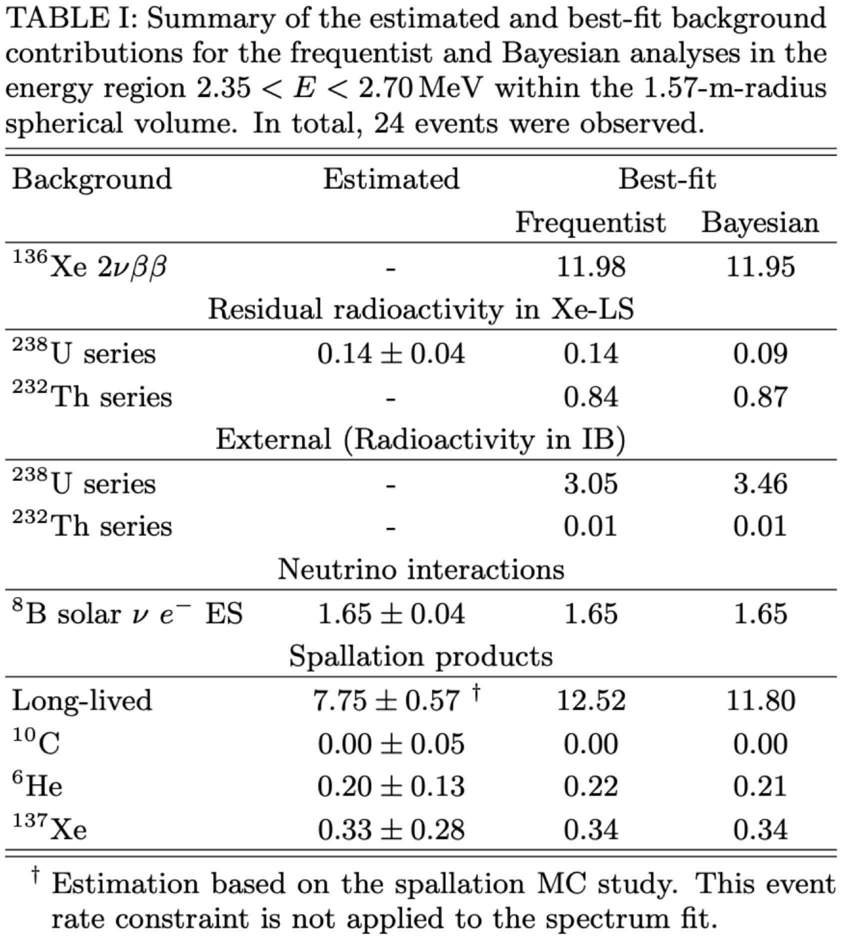


TABLE I: Summary of the estimated and best-fit background contributions for the frequentist and Bayesian analyses in the energy region $2.35 < E < 2.70$ MeV within the 1.57-m-radius spherical volume. In total, 24 events were observed.

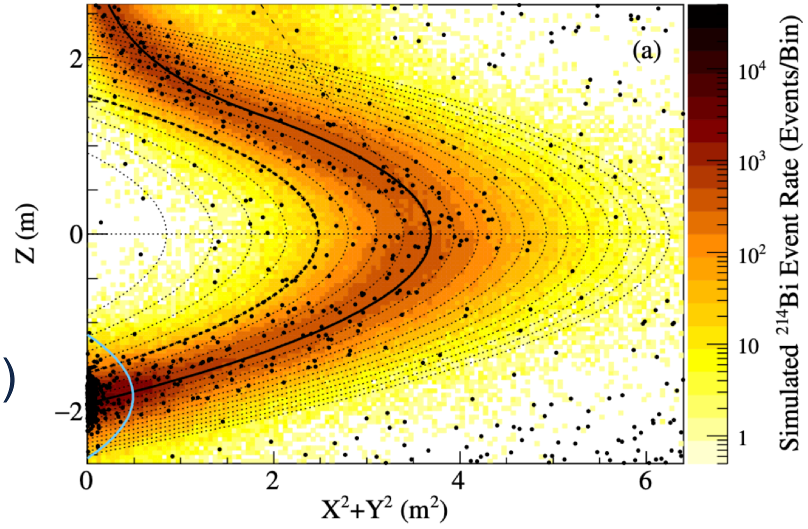
Background	Estimated	Best-fit	
		Frequentist	Bayesian
^{136}Xe $2\nu\beta\beta$	-	11.98	11.95
Residual radioactivity in Xe-LS			
^{238}U series	0.14 ± 0.04	0.14	0.09
^{232}Th series	-	0.84	0.87
External (Radioactivity in IB)			
^{238}U series	-	3.05	3.46
^{232}Th series	-	0.01	0.01
Neutrino interactions			
^{8}B solar ν e^- ES	1.65 ± 0.04	1.65	1.65
Spallation products			
Long-lived	7.75 ± 0.57 †	12.52	11.80
^{10}C	0.00 ± 0.05	0.00	0.00
^{6}He	0.20 ± 0.13	0.22	0.21
^{137}Xe	0.33 ± 0.28	0.34	0.34

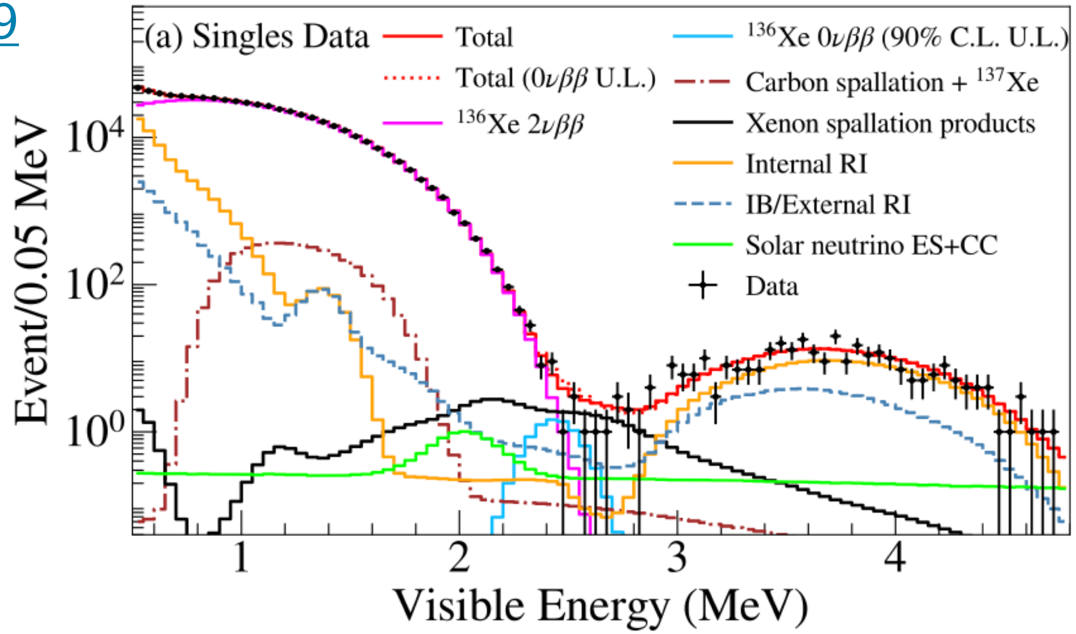
† Estimation based on the spallation MC study. This event rate constraint is not applied to the spectrum fit.

Energy resolution: 6.7%/$\sqrt{E}$(MeV)
Vertex resolution 13.7 cm/ $\sqrt{E}$(MeV)

Poor energy resolution means that 2vββ is the largest background

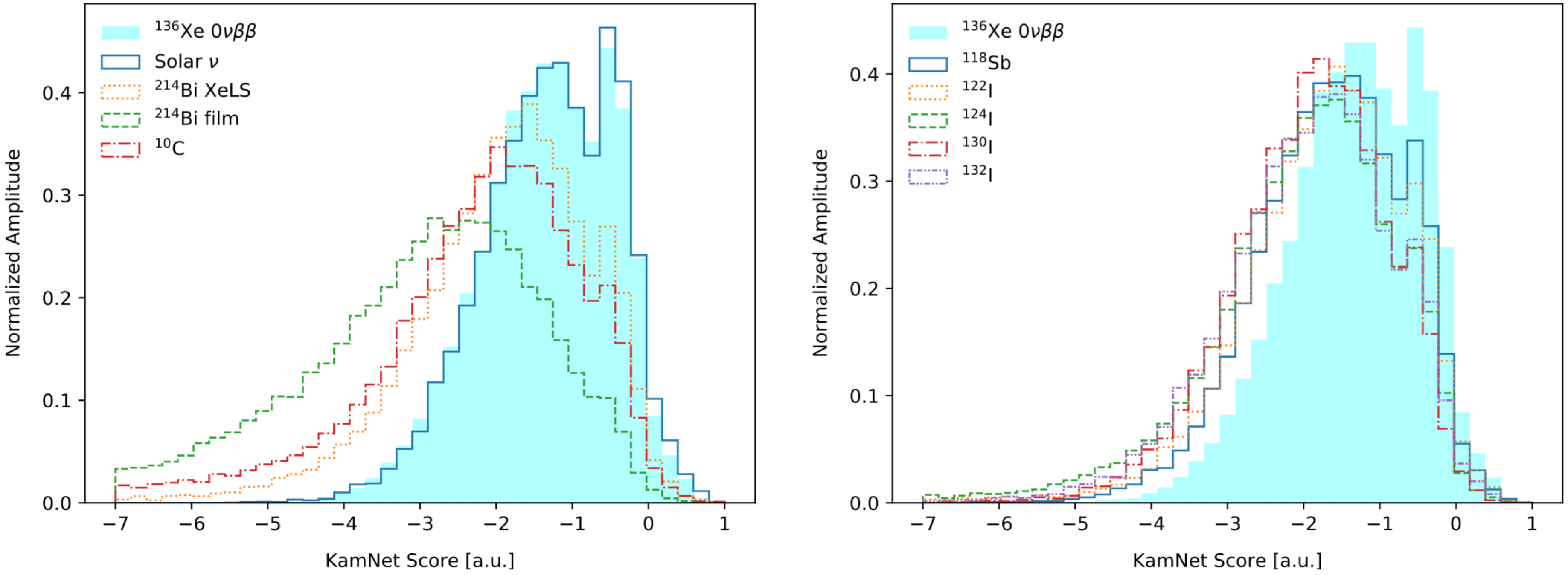
arXiv:2203.02139





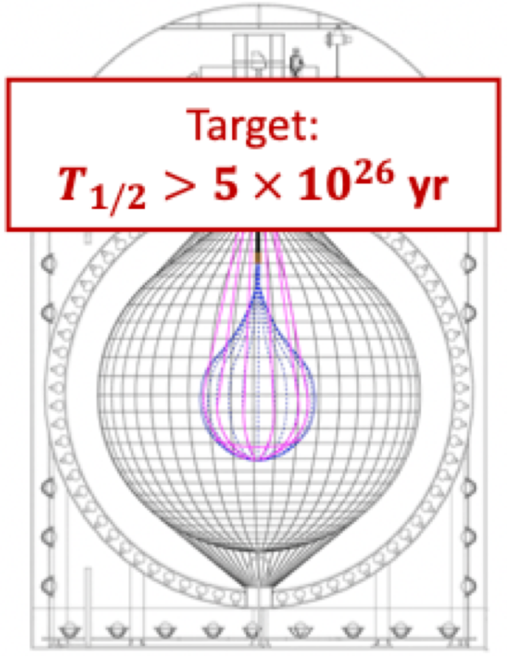
Machine Learning-Based Analysis: KamNET

- Machine learning model using LSTM + spherical CNN can be used to reject balloon and spallation backgrounds
- Complementary to other spallation-tagging methods
- arXiv:2203.01870



KamLAND2-Zen

KamLAND-Zen 800



Target:
$T_{1/2} > 5 \times 10^{26}$ yr

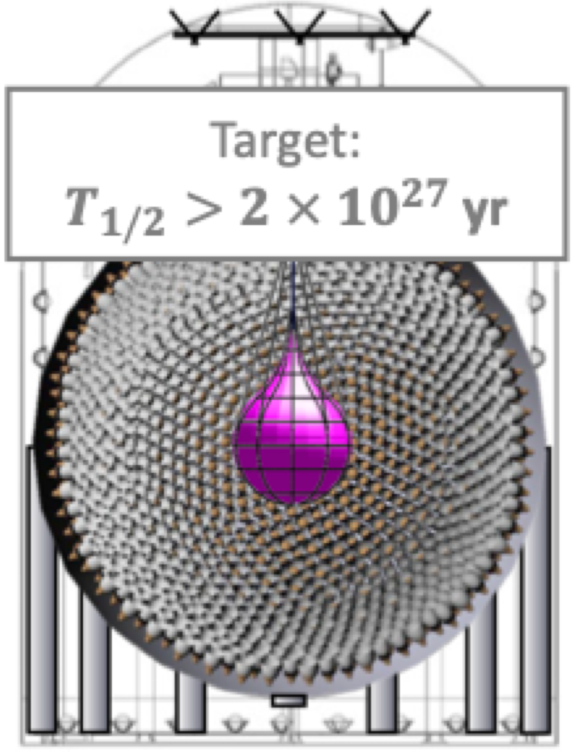
KamLAND-Zen 800

Mini-balloon Radius = 1.90 m

Xenon mass = 745 kg

90% exclusion sensitivity

KamLAND2-Zen



Target:
$T_{1/2} > 2 \times 10^{27}$ yr

Primary goal: improve energy resolution

Secondary goal: record longer-buffer data to improve cosmogenic rejection

- 1 ton of ^{enr}Xe
- New, brighter LAB-based scintillator
- Winston cones and HQE PMTs
- Scintillating balloon film
- Improved front-end electronics

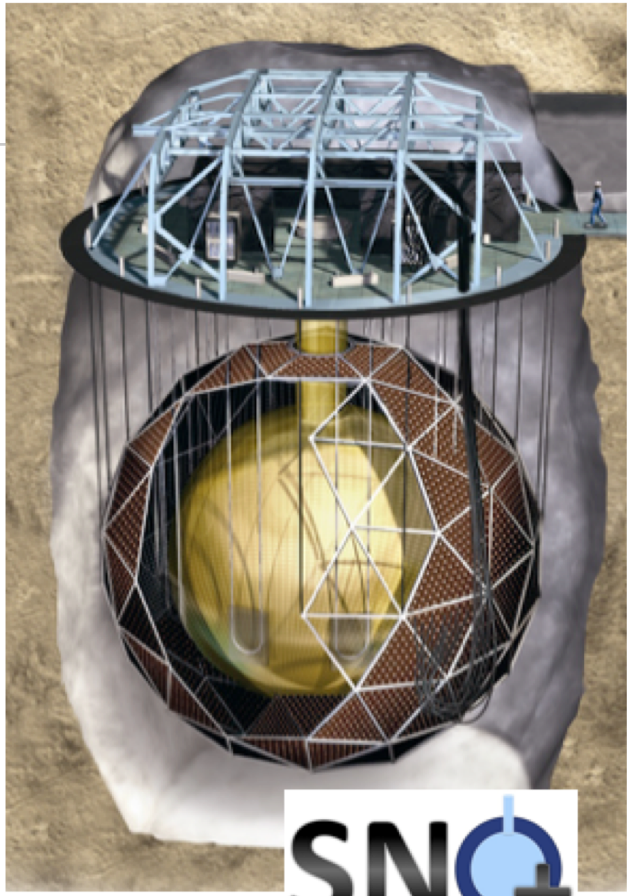
SNO+

- Adaptation of existing solar neutrino experiment
- Switch from heavy water to liquid scintillator
- ^{nat}Te loaded throughout
- Deeper site, solar ν backgrounds expected to dominate

Status

- Ultra-pure water Cherenkov phase completed
  - Solar neutrino and BSM physics results released
- Unloaded liquid scintillator phase completed, scintillator characterized
- Tellurium loading underway @ 0.3%
  - Expected loading: 800 kg of ^{130}Te
- Expected 5 year sensitivity:

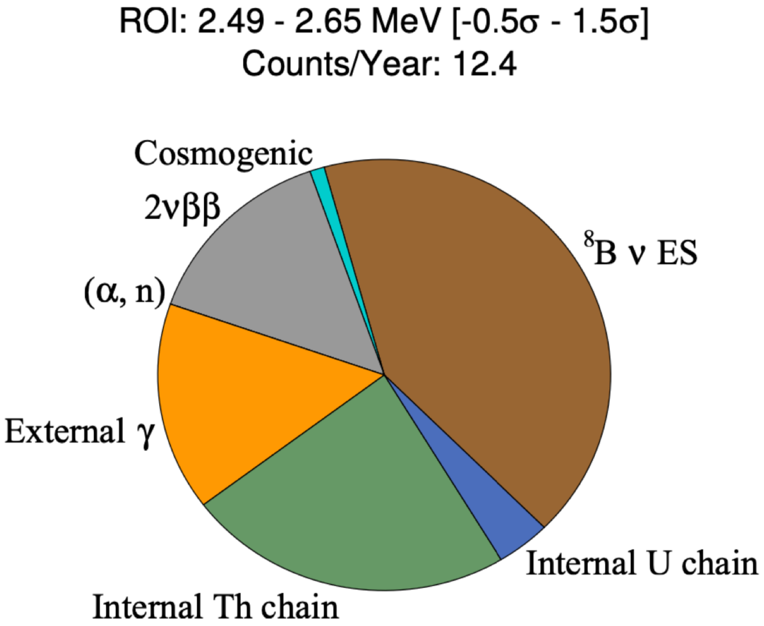
$T_{1/2} > 9\times10^{25}$ yrs , $m_{\beta\beta} < 55 - 133$ meV

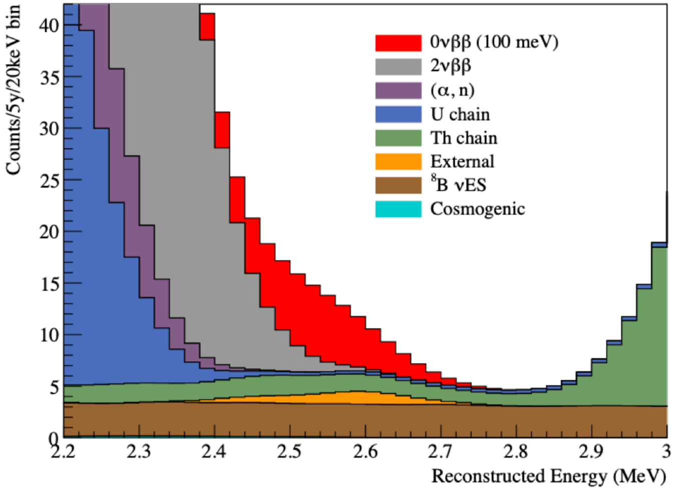


Initial loading: 0.5% natural Te by weight

Backgrounds in SNO+

- Expected backgrounds before running
- Since then, U and Th backgrounds have been measured to be smaller than expected!
- Solar neutrino scattering will dominate





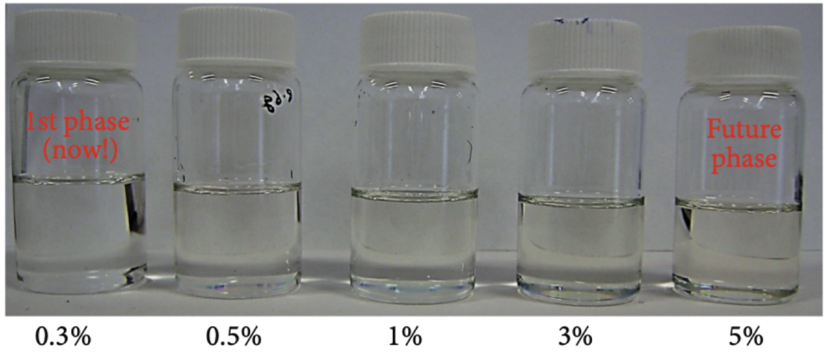
arXiv:1809.05986

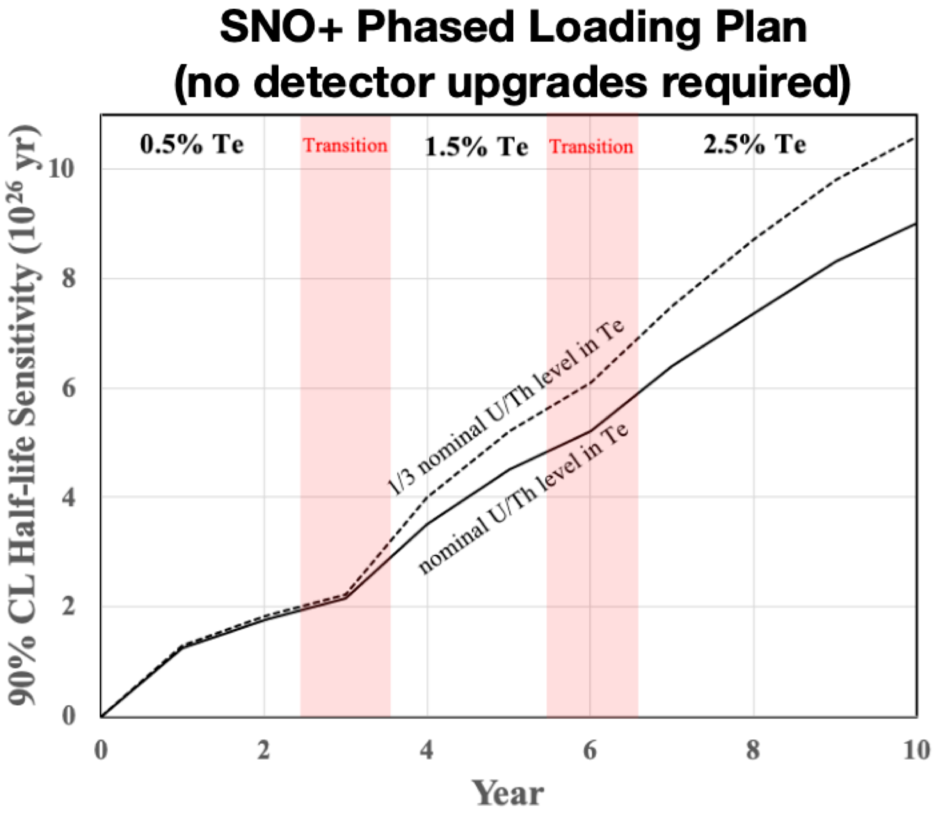
SNO+ Future Improvements

Planning to move to 3% ^{nat}Te loading for future data-taking

No hardware changes needed: just add more Te

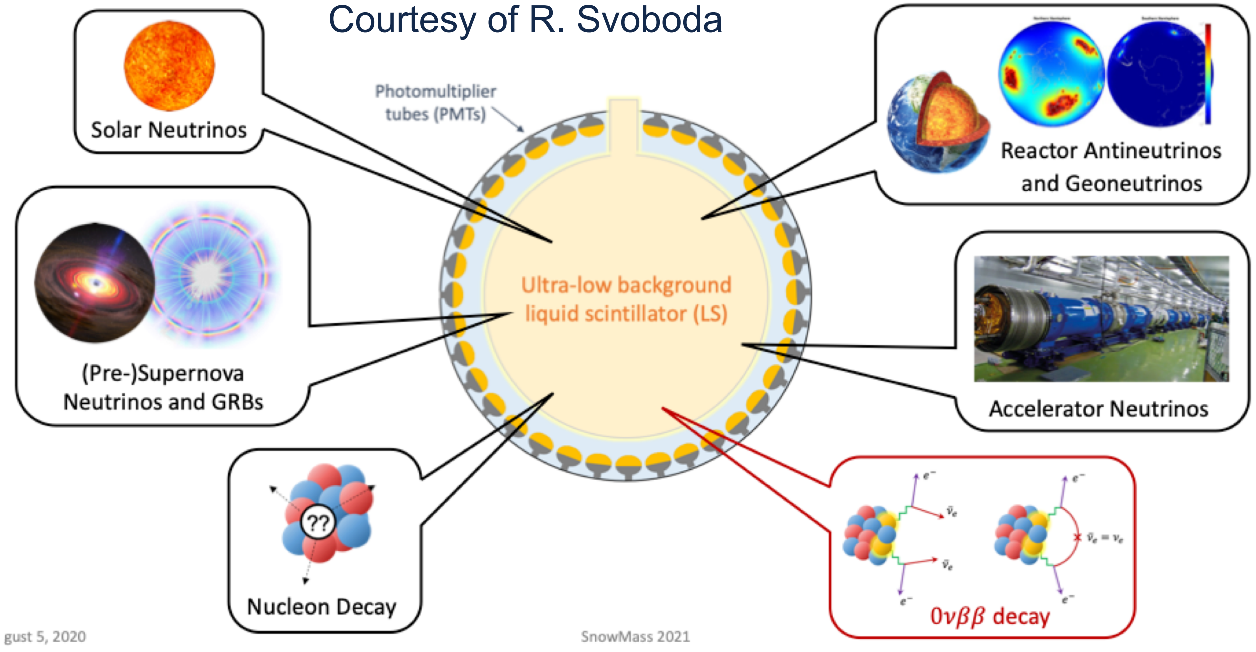
Extends exclusion sensitivity to > ~10^{27} yrs



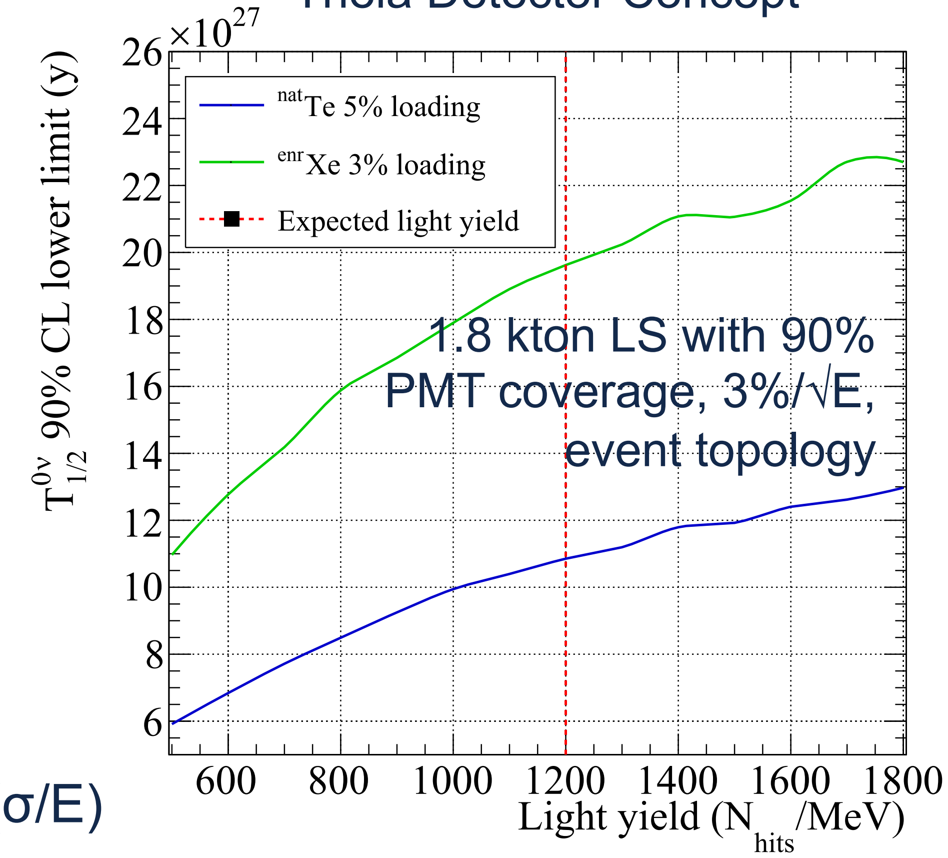


Multi-purpose Liquid Scintillator Experiments

Courtesy of R. Svoboda



Theia Detector Concept



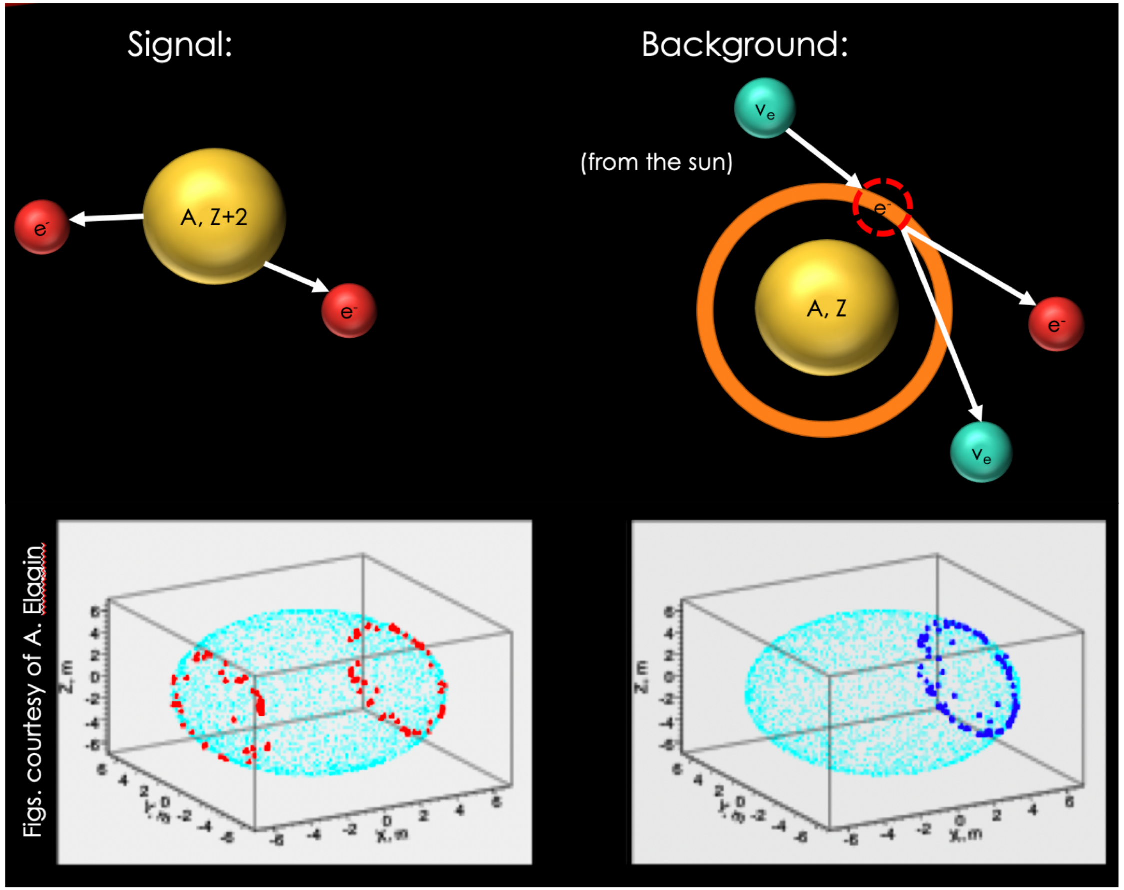
1.8 kton LS with 90% PMT coverage, 3%/√E, event topology

Eur. Phys. J. C (2020) 80:416

JUNO 0νββ Search Proposal:

- 50 tons of ^{136}Xe, expected energy resolution better than 2% (σ/E)
- Exclusion sensitivity: 1.8×10^{28} yr, 5-12 meV
- 0νββ upgrade starting in 2030s

Solar Neutrino Scattering in Liquid Scintillator Detectors



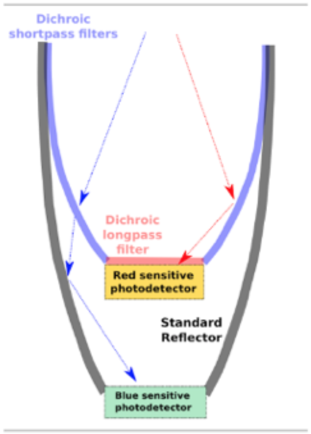
Figs. courtesy of A. Elagin

- How to reduce this “irreducible background”?
- If you can measure Cherenkov **and** scintillation light (separately) you can tell them apart
- Timing- and wavelength-based separation have been demonstrated in benchtop test-stands

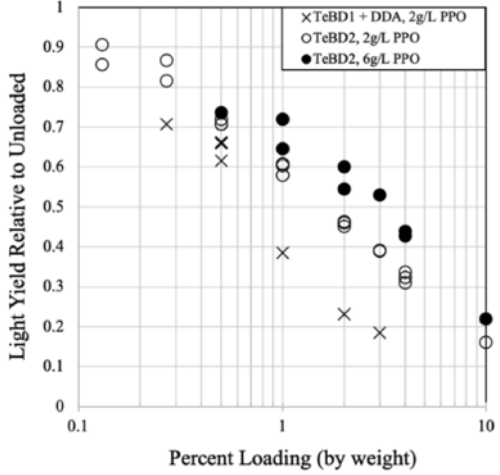
R&D Efforts for Liquid Scintillators

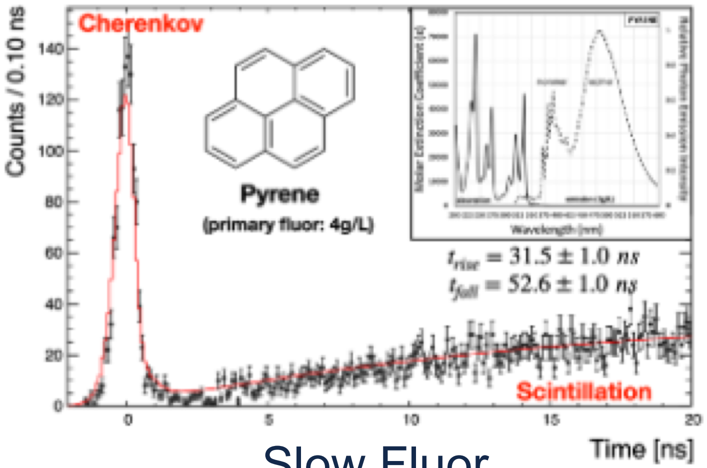
- Hybrid Cherenkov/scintillation detectors:
  - Reduce backgrounds by measuring 2 e- signature
  - Timing-based separation: slower fluors, faster photodetectors
  - Wavelength-based separation: dichroic filers
- New scintillator cocktails and isotopic loading techniques:
  - Water-based Liquid Scintillator: purification and stability, gadolinium loading, pulse shape discrimination
  - Tellurium loading: several % loading demonstrated, increased loading and purification R&D underway
  - Quantum dot-based isotope loading: production scaling, stability, and optical performance studies underway
- Advanced photon sensors and collectors:
  - LAPPDs: ongoing R&D on high-channel-count readout techniques, self-triggering and synchronization, streamlined fabrication
- Advanced simulation and analysis techniques

Dichroicon



Te Loading

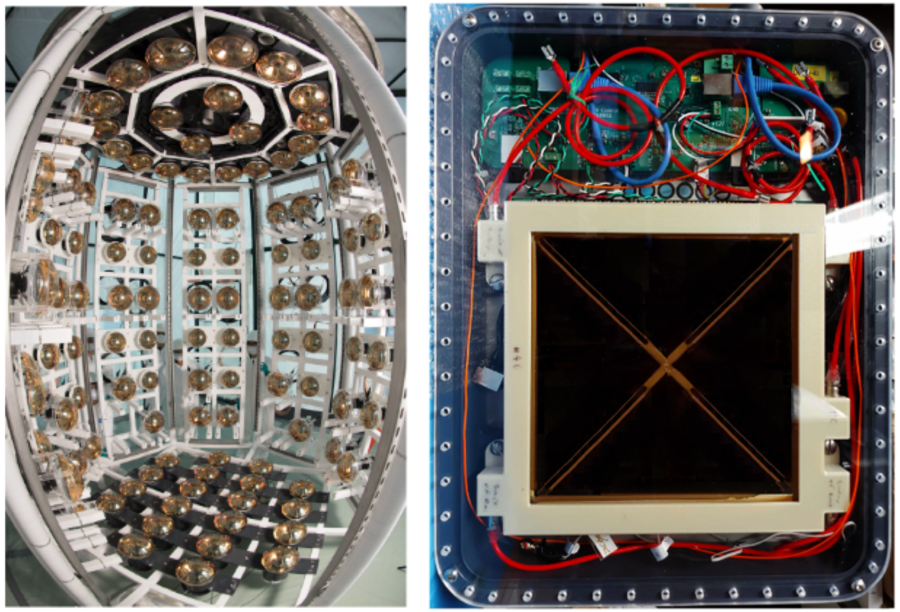




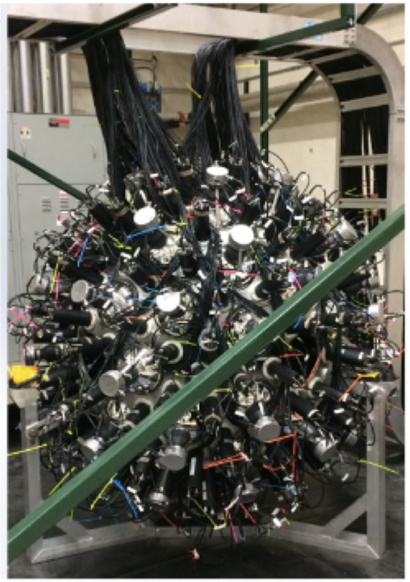
Slow Fluor

Mid-Scale Test Stands for Future Liquid Scintillator Detectors

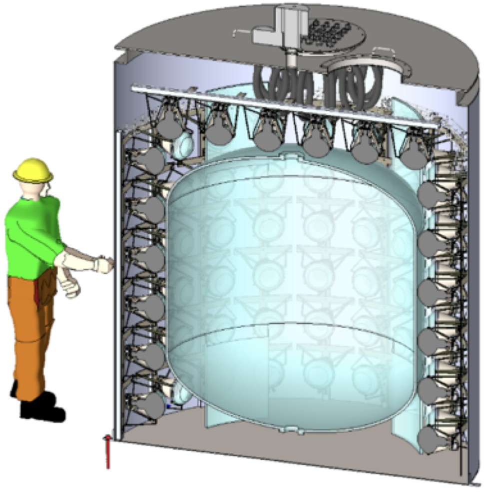
- ANNIE: first large-scale test of LAPPDs, planning for Gd-loaded WbLS



ANNIE detector and LAPPD module



NuDot: ½ ton test stand



Eos: few-ton WbLS

- NuDot: timing-based Cherenkov/scintillation separation and quantum dot loading
- Eos: Cherenkov/scintillation separation and WbLS, validation of microphysics simulations at low energy

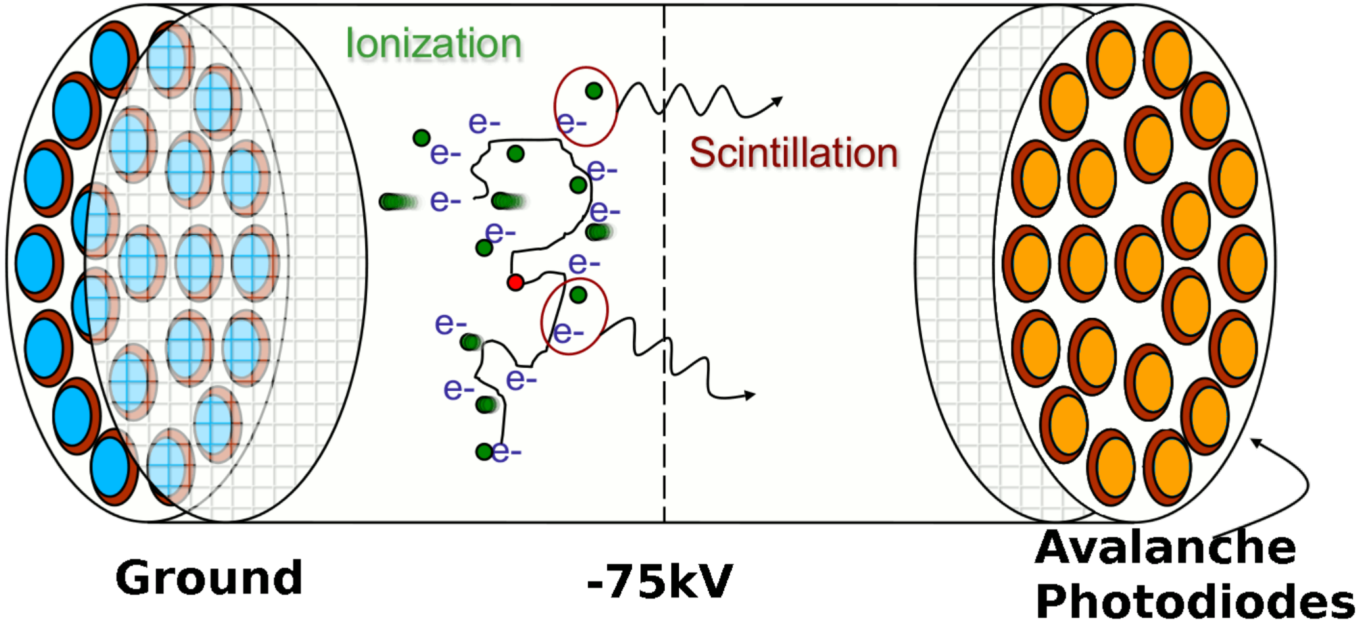
The Experiments

TPCs: Liquid and Gas

Liquid Xenon TPC Concept

- Single-phase time projection chamber, made out of enriched Xenon
- Read out ionization and scintillation
- Dark matter experiments use dual-phase to amplify the ionization signal – not needed for higher-energy ββ
- Take advantage of self-shielding, (non-binary) fiducialization, and event topology information to reduce backgrounds
- Better energy resolution and spatial resolution than LS, while still being monolithic
- Weaknesses: background peak overlapping $Q_{\beta\beta}$, cost/Xe availability

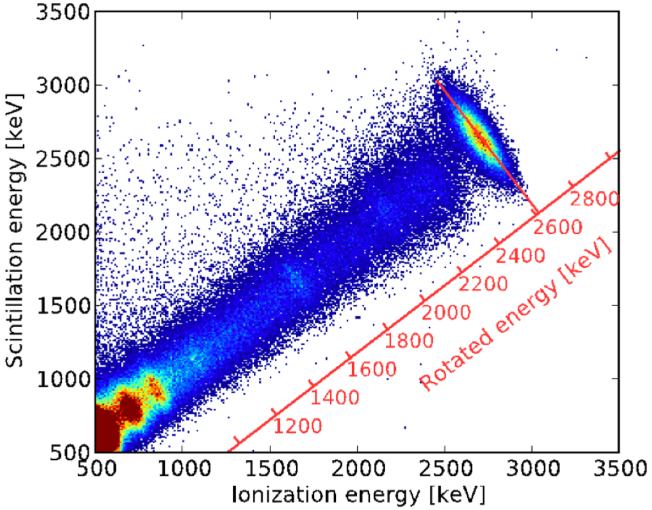
EXO-200

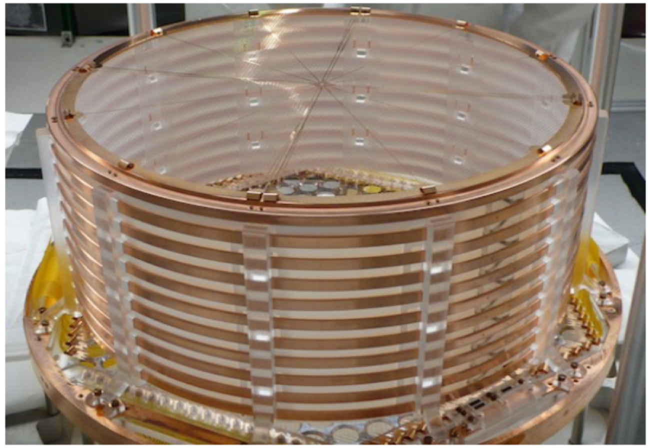


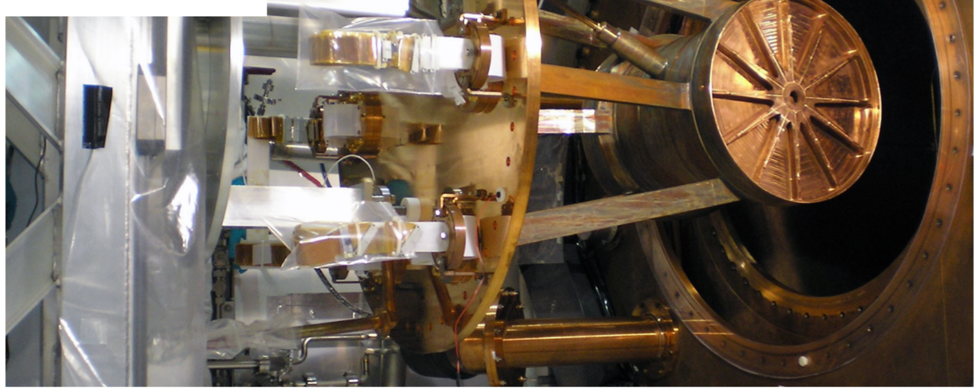
EXO-200

- 200 kg TPC with a center wire grid cathode
- Ran starting in 2011, then stopped in 2014 due to WIPP fire
- Upgrade in 2016: improved electronics led to better energy resolution
- Use anticorrelation between charge and scintillation to improve resolution: σ/E = 1.15%

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





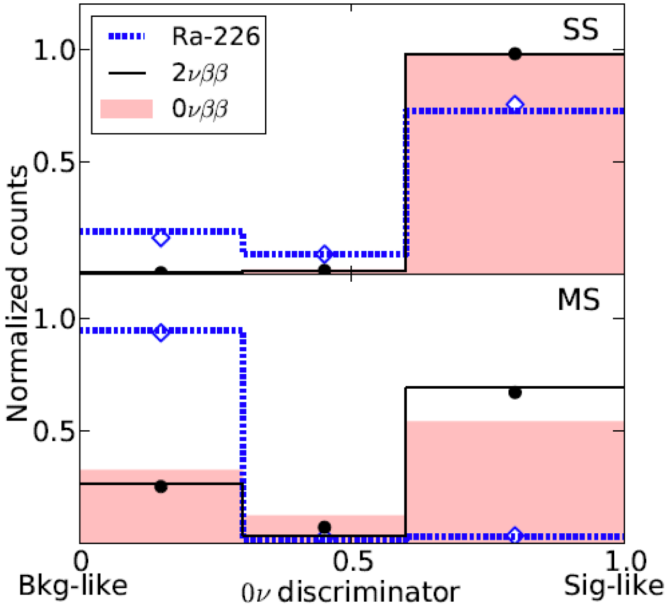


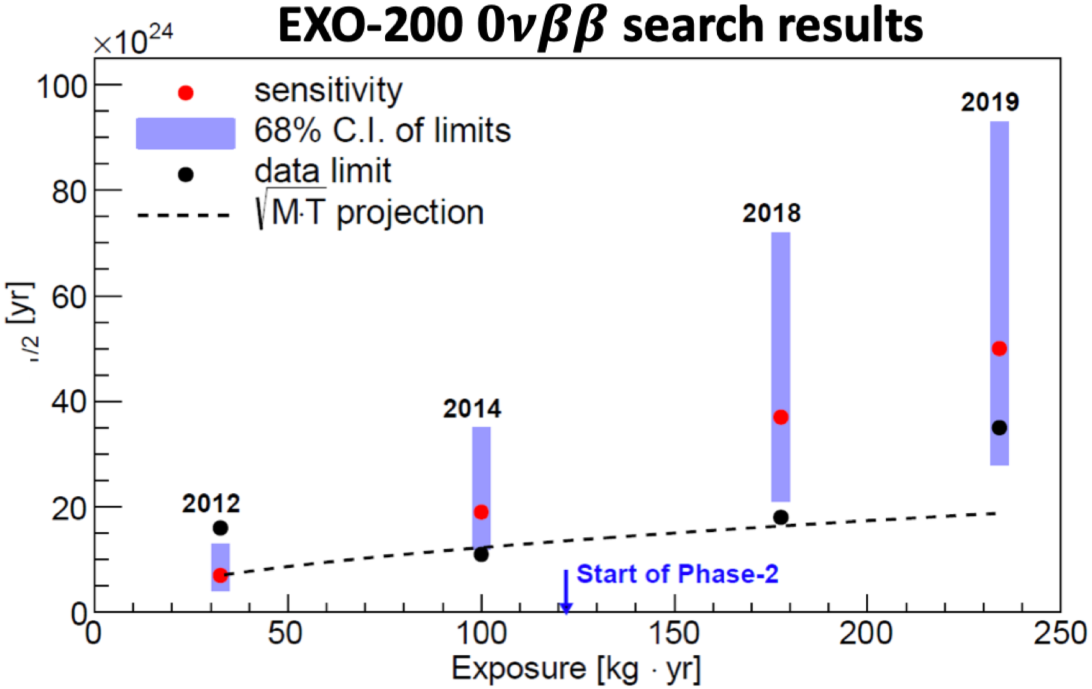
EXO-200 Results

- Detector upgrade and improved analysis techniques have led to linear sensitivity growth over time

$T_{1/2} > 3.5 \times 10^{25}$ yrs

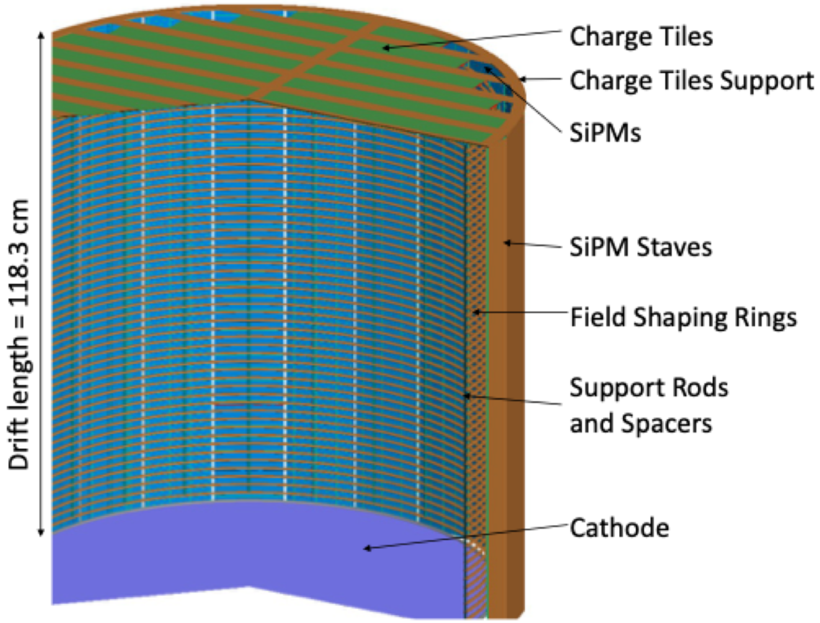
- Deep Neural Network, stand-off distance, and cluster size used to reduce backgrounds





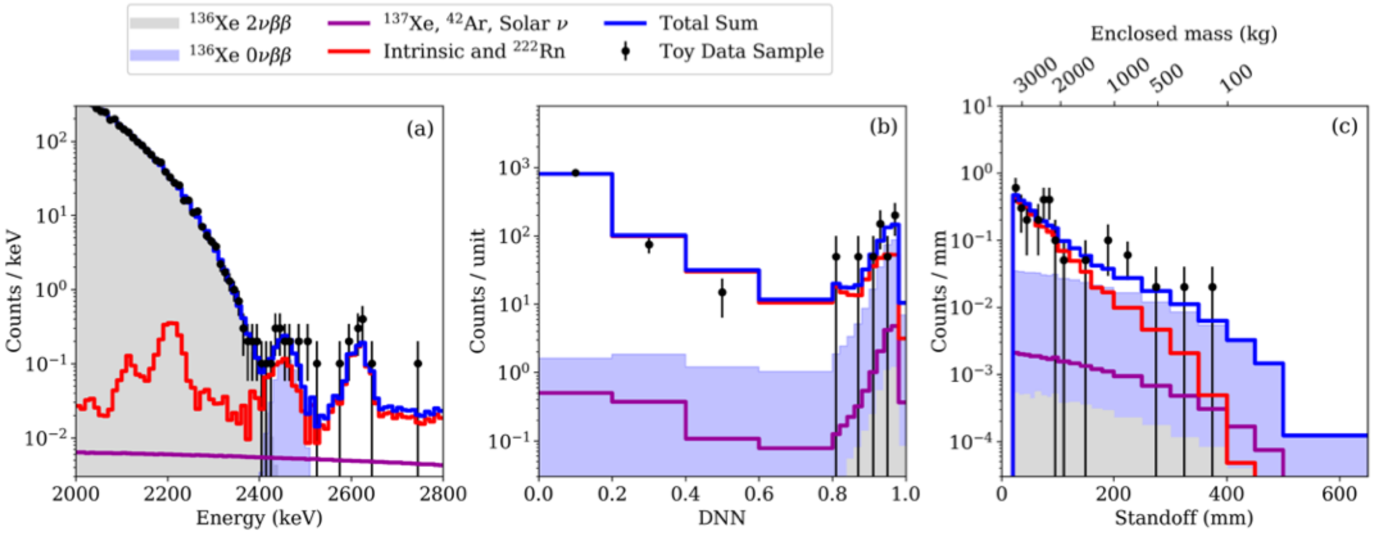
2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: arXiv 1906.02723

Proposed Next-Generation: nEXO



- Large single-phase LXe TPC, building on EXO-200 experience
- Switches to charge tiles for ionization readout, SiPMs for light readout

- 5000 kg of ^{enr}Xe
- Enriched to 90% ^{136}Xe
- Energy res. (σ_E/E): 0.8%
- Discovery sensitivity: $T_{1/2} \sim 7.4\times10^{27}$yrs
- $m_{\beta\beta}$ discovery sensitivity: 5-27 meV



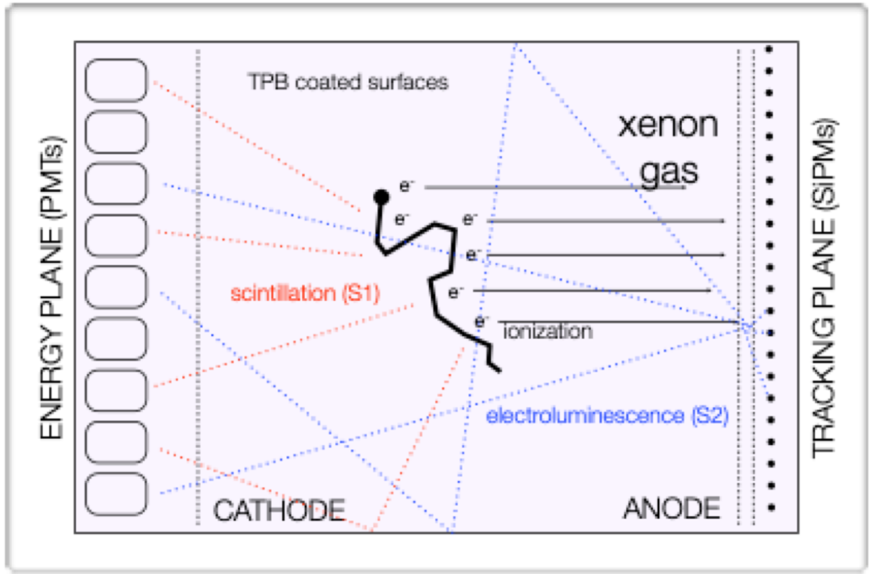
J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)

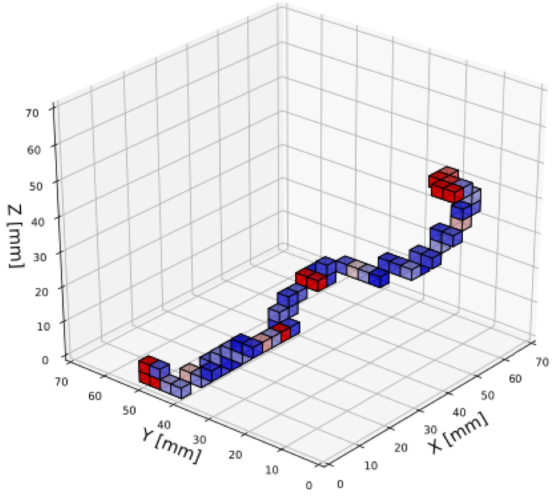
High-Pressure Gas TPC Concept

High-pressure gas Xenon time projection chamber:

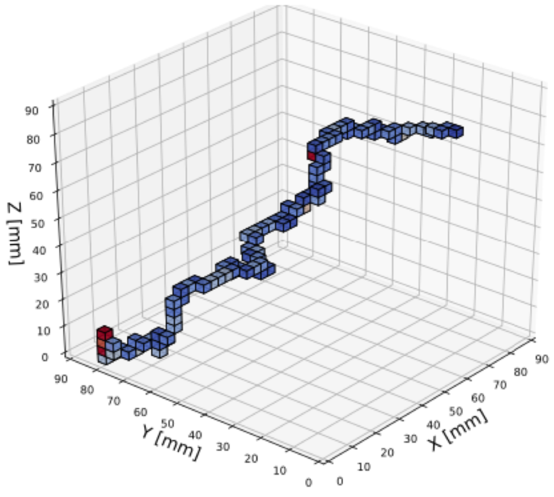
- Energy resolution is intrinsically better in gas
- Event topology tracking information, fiducialization, and particle ID
- Can actually see β tracks!

Other TPC gases could use this technique: SeF_6 in R&D





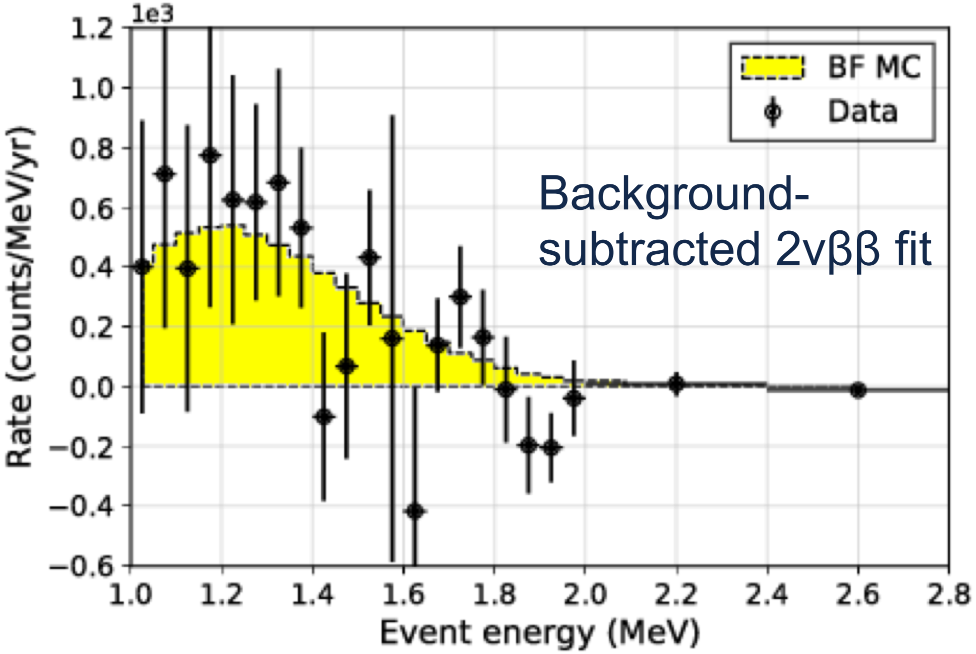
ββ Signal



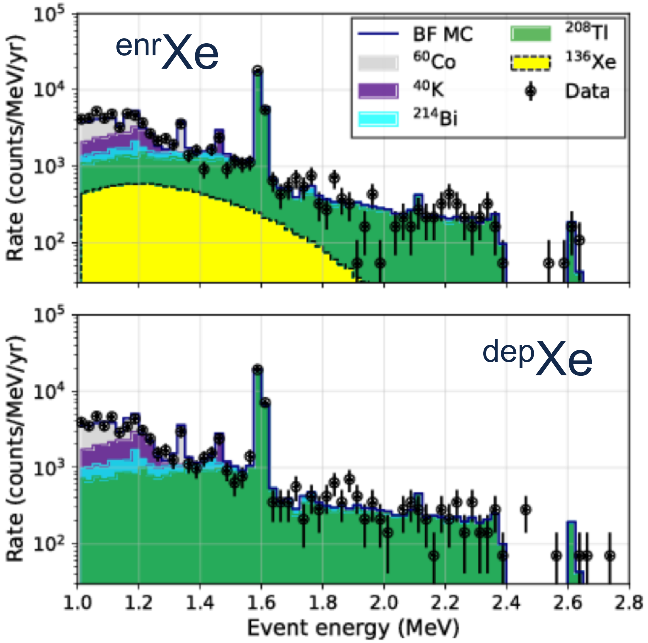
e- Track Background

NEXT-White

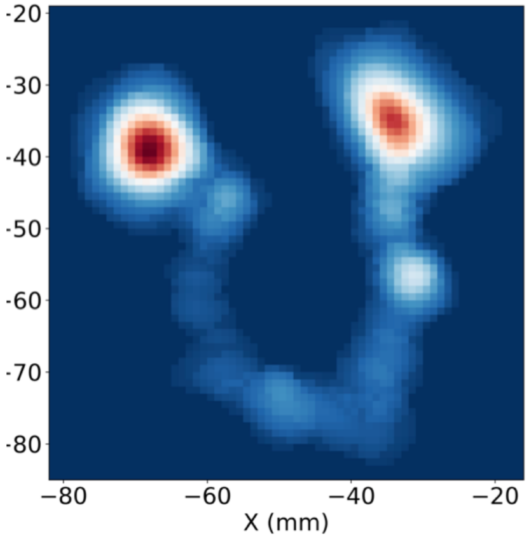
- 5kg demonstrator TPC, ran 2016-2021
- 10 bar pressure, energy resolution: 0.91% σ/E
- Right now, one issue is relatively low efficiency, larger detector will improve that



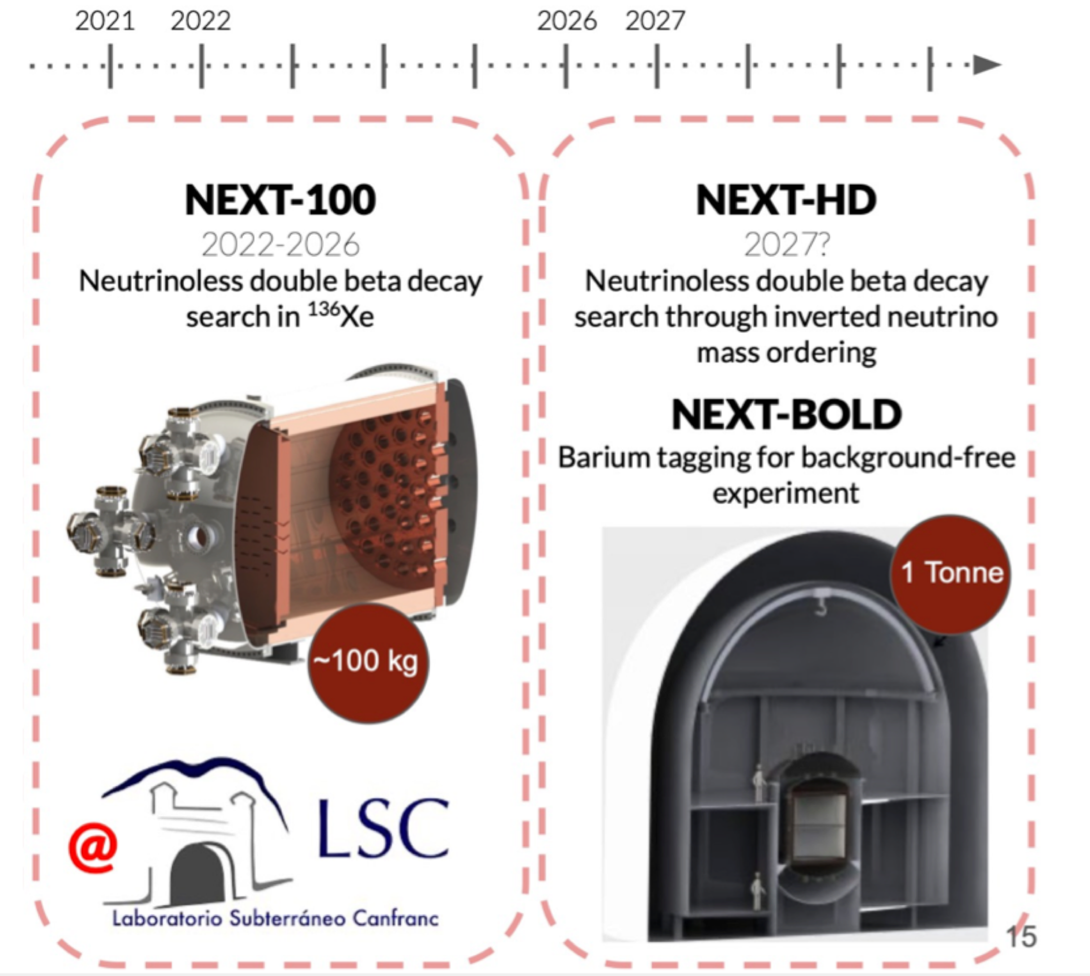
Background-subtracted 2νββ fit



arXiv:2201.10907



Future Directions for NEXT



NEXT-100

2022-2026

Neutrinoless double beta decay search in ^{136}Xe

NEXT-HD

2027?

Neutrinoless double beta decay search through inverted neutrino mass ordering

NEXT-BOLD

Barium tagging for background-free experiment

NEXT-100

- 100 kg at 15 bar
- Construction started in 2021
- Expected sensitivity: $6{\times}10^{25}$ yrs

NEXT-HD

- 1230 kg of ^{enr}Xe
- 1109 kg of ^{136}Xe
- Energy res. (FWHM/E): 0.5%
- BI < $4\text{x}10^{-6}$ cnts/(keV kg yr)
- Discovery sensitivity: $T_{1/2} \sim 2.7{\times}10^{27}$yrs
- $m_{\beta\beta}$ discovery sensitivity: 8-45 meV

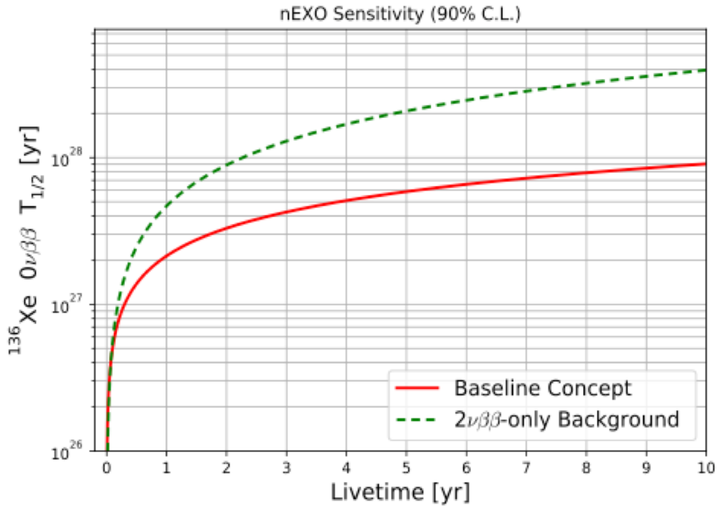
Barium Tagging

$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$

“Tagging” Ba daughter has potential to eliminate all but 2νββ backgrounds

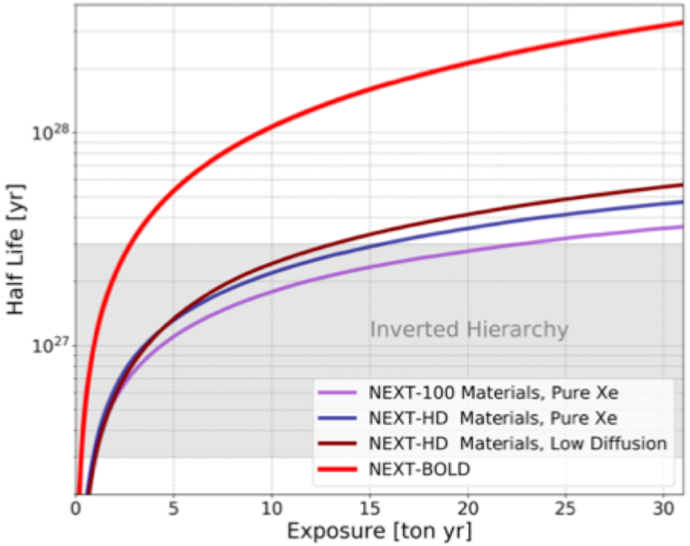
M. Moe, Phys. Rev. C 44, R931 (1991)

In nEXO, eliminating other backgrounds could give up to 4x higher sensitivity



nEXO Collaboration, *Phys. Rev. C* **97**, 065503 (2018)

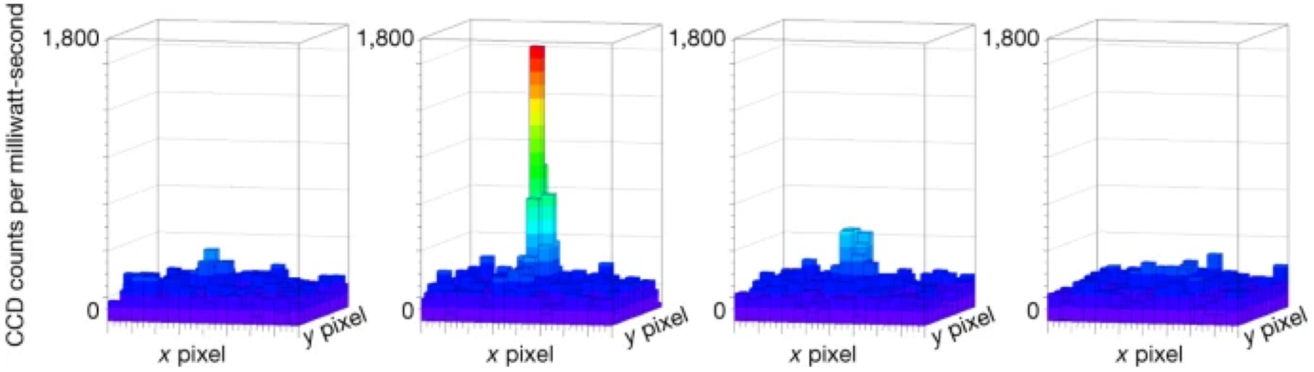
In NEXT, higher efficiency with Ba tagging and eliminating other backgrounds could provide up to a factor of 6 higher sensitivity



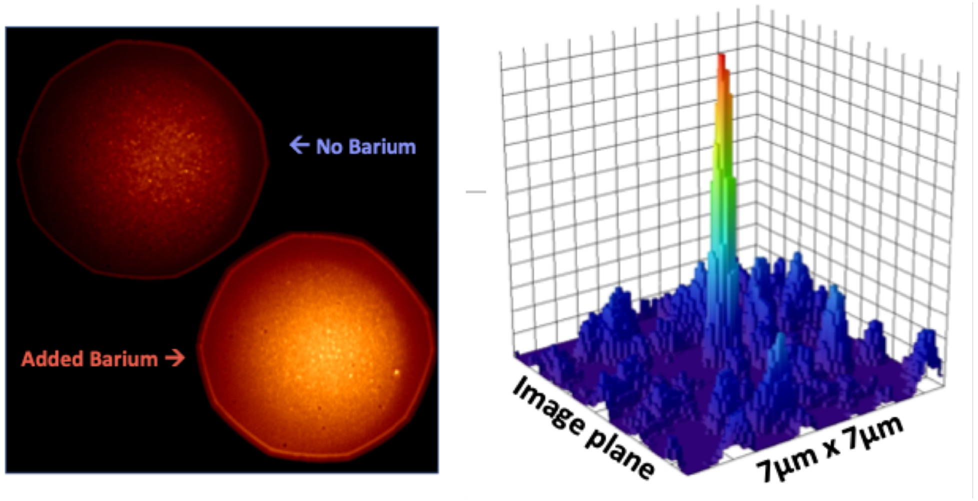
Materials courtesy of the NEXT and nEXO Collaborations, from B. Fairbank

- Considered a possible upgrade path for the tonne-scale TPC experiments
- Could extend sensitivity (further) into the normal ordering region!

R&D for Barium Tagging

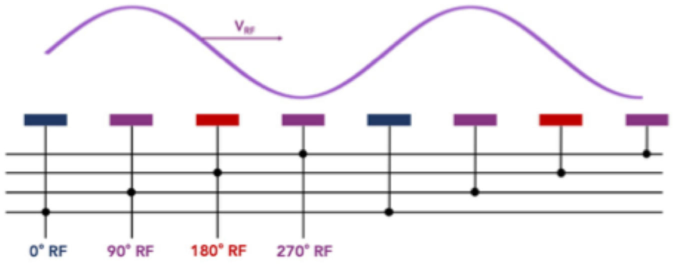


Laser-based ID in solid Xe for nEXO, *Nature 569, 203-207 (2019)*



Fluorescent molecule-based ID for NEXT, *ACS Sens. 2021, 6, 1, 192–202 (2021)*

Cryoprobe-based extraction for nEXO



RF carpet-based transport for NEXT, *arXiv:2111.11091 (2021)*

- Feasible single-ion sensing techniques have been demonstrated in GXe and LXe
- Next steps: Barium capture, transport, and sensing in more-realistic detector environments

Other TPC R&D

For Xe, isotope acquisition is a challenge:

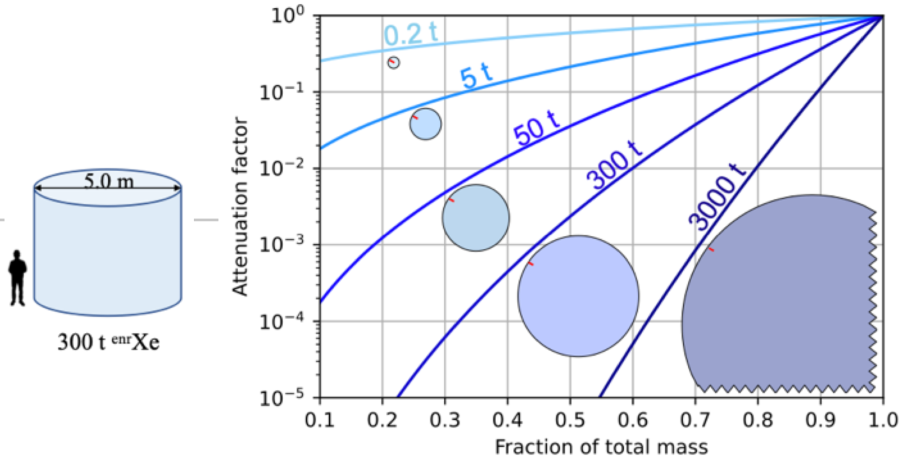
- Currently depends on liquid oxygen production for steel industry, limiting supply
- R&D on alternative extraction methods: Xe-adsorbing materials, could be implemented at CO2 capture plants

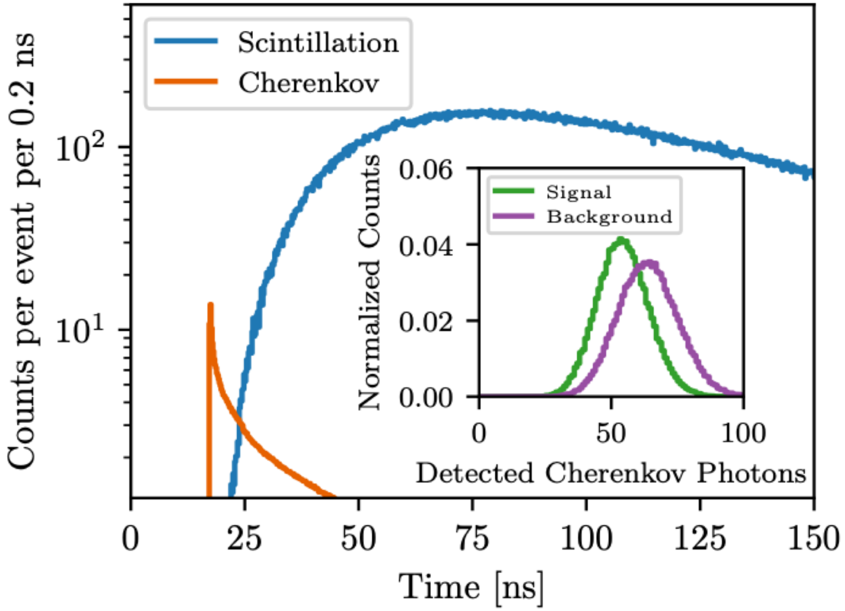
If acquisition can be resolved, kiloton-scale GXe and LXe TPCs should be feasible:

- R&D: increasing light detection efficiency, Cherenkov light-based background reduction
- Projected sensitivity ~10^{30} yrs

Other ideas:

- DUNE and DarkNoon: Xe-doped LAr; R&D on energy resolution, gas mixture handling, and Cherenkov/scintillation response
- SeF_6 TPCs: R&D on ion readout techniques





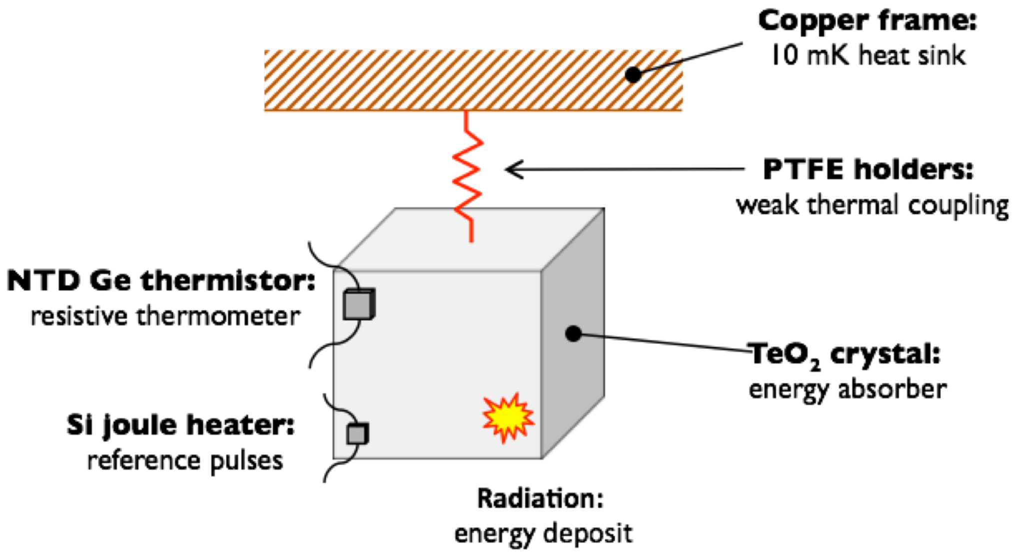
Physical Review D 104 (11): 112007 (2021)

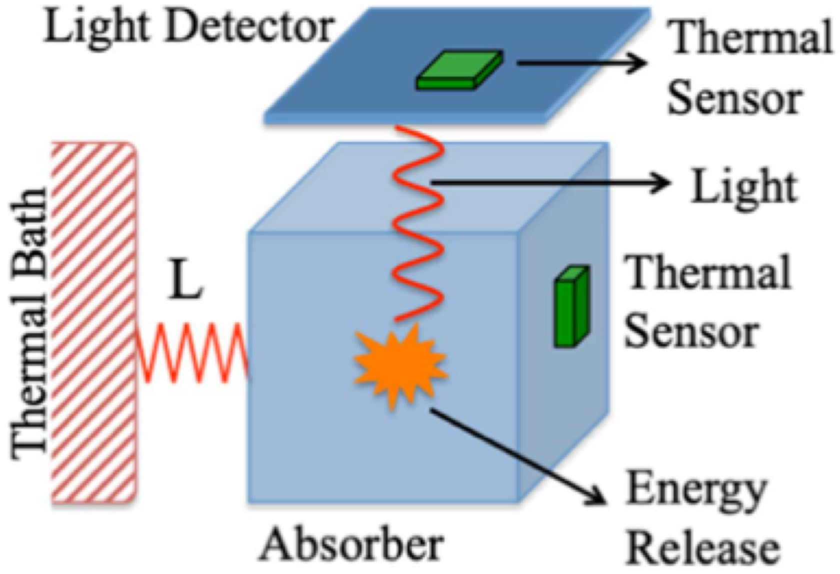
The Experiments

Bolometer Experiments

Bolometer Detector Concept

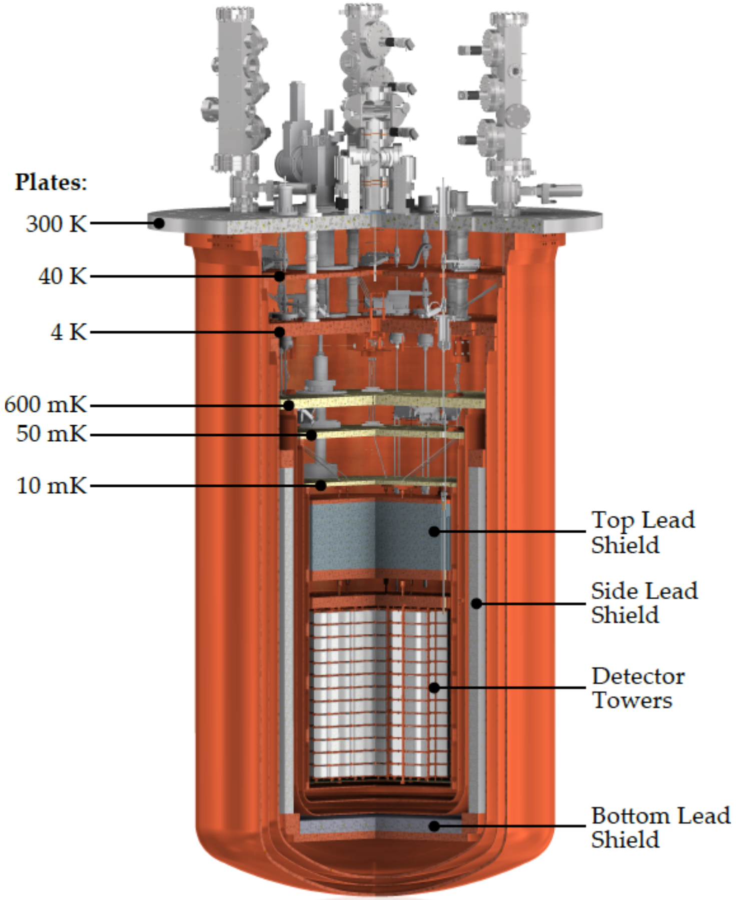
- Keep crystals at ~15 mK temperature in dilution fridge
- Interactions create phonons, read out with temperature sensor
- Some experiments use scintillating crystals and add a light detector: lets you distinguish α from β/γ



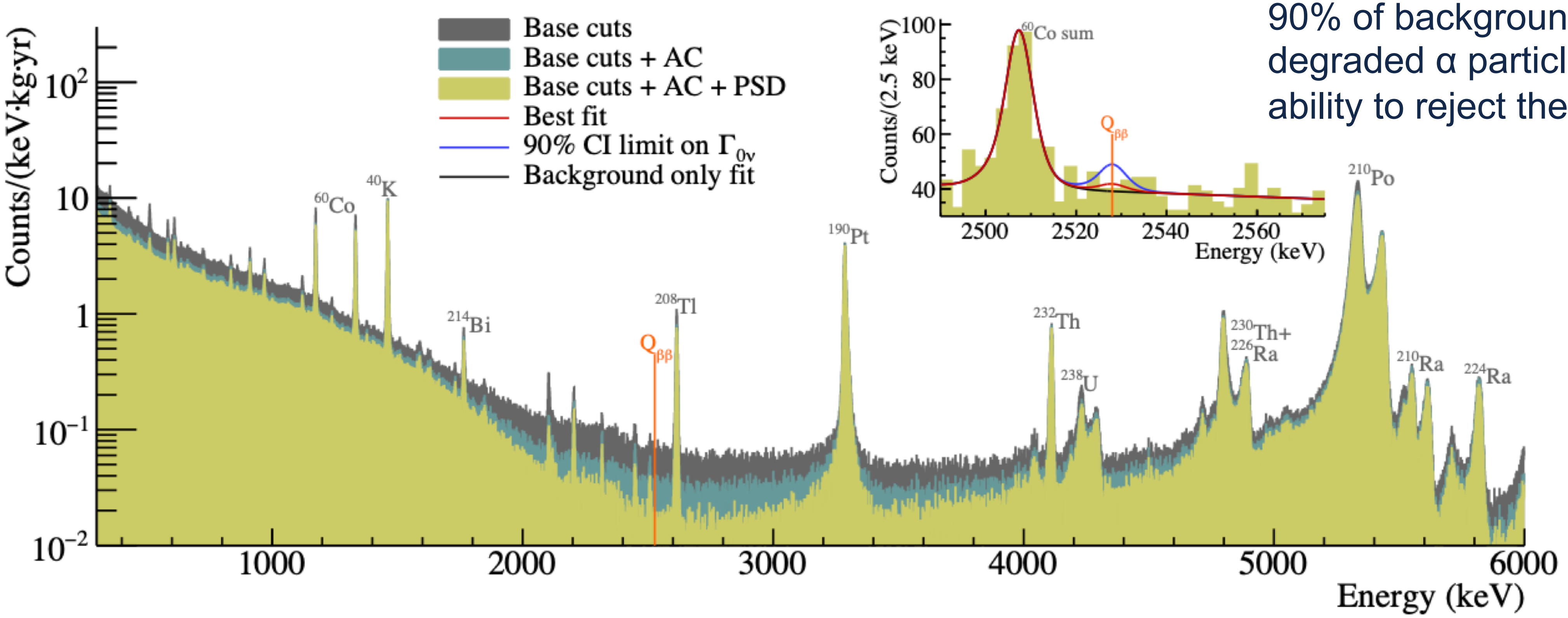


CUORE

- 988 natural-abundance TeO_2 crystals operated as bolometers
- 742 kg of detectors, 206 kg of ^{130}Te
- Energy resolution is 7.4 - 8.3 keV FWHM at $Q_{\beta\beta}$
- Taking data since 2017
- Will continue to take data until CUPID begins



CUORE Results



90% of backgrounds from degraded α particles: no ability to reject these

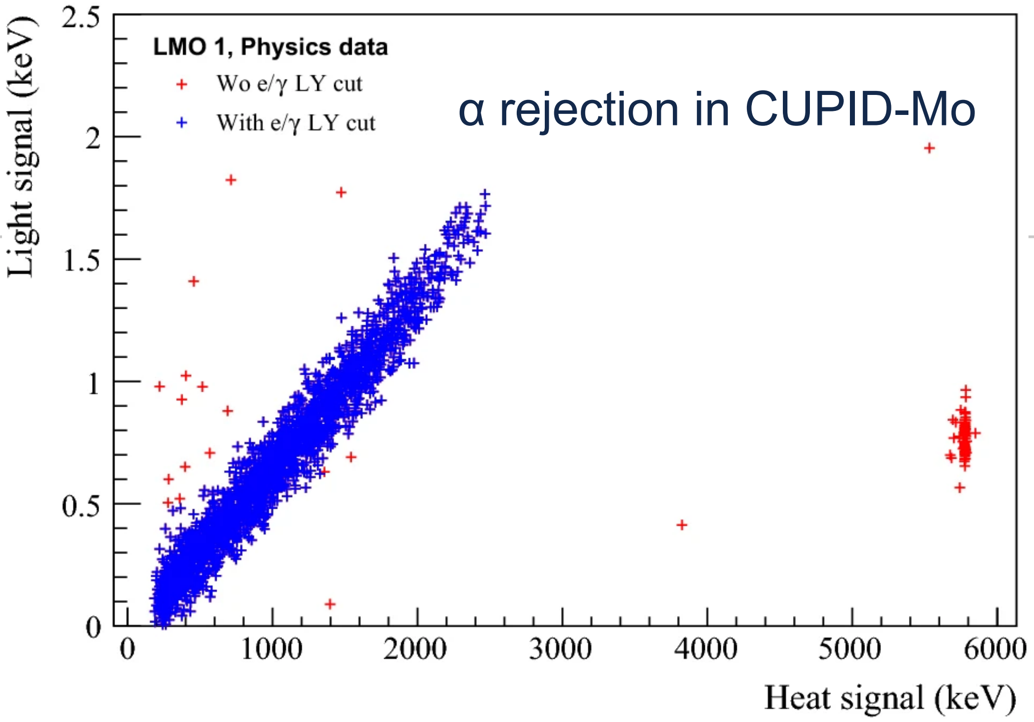
2021 Results: $T_{1/2} > 2.2 \times 10^{25}$ yr, $m_{\beta\beta} > 90 – 305$ meV

DOI: 10.1038/s41586-022-04497-4

CUPID

- Tonne-scale bolometer approach demonstrated in CUORE
- ^{100}Mo Q-value: 3.03 MeV
- Scintillating bolometer technique demonstrated in CUPID-Mo and other experiments, allows for α rejection
- Switch from CUORE crystals to scintillating bolometers with light readout in existing infrastructure
- Other options for crystal/isotope: ZnSe (candidate ^{82}Se), $CdWO_4$ (candidate ^{116}Cd), and TeO_2 (candidate ^{130}Te)

Material provided by CUORE, CUPID, CUPID-Mo, and CUPID-0 Collaborations



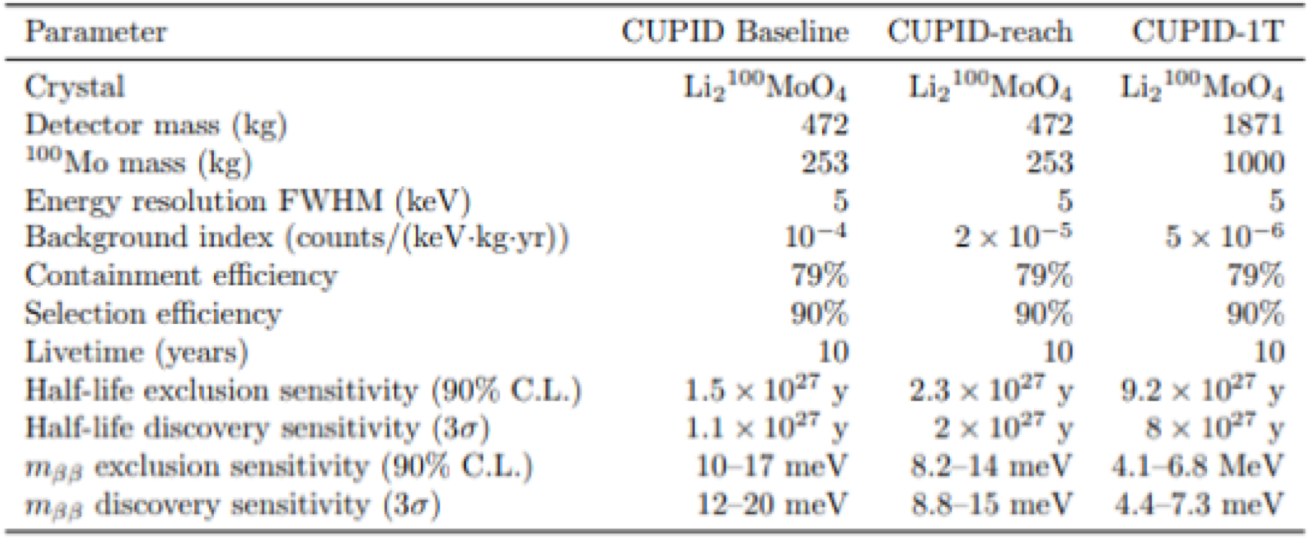
α rejection in CUPID-Mo

DOI: 10.1140/epjc/s10052-019-7578-6

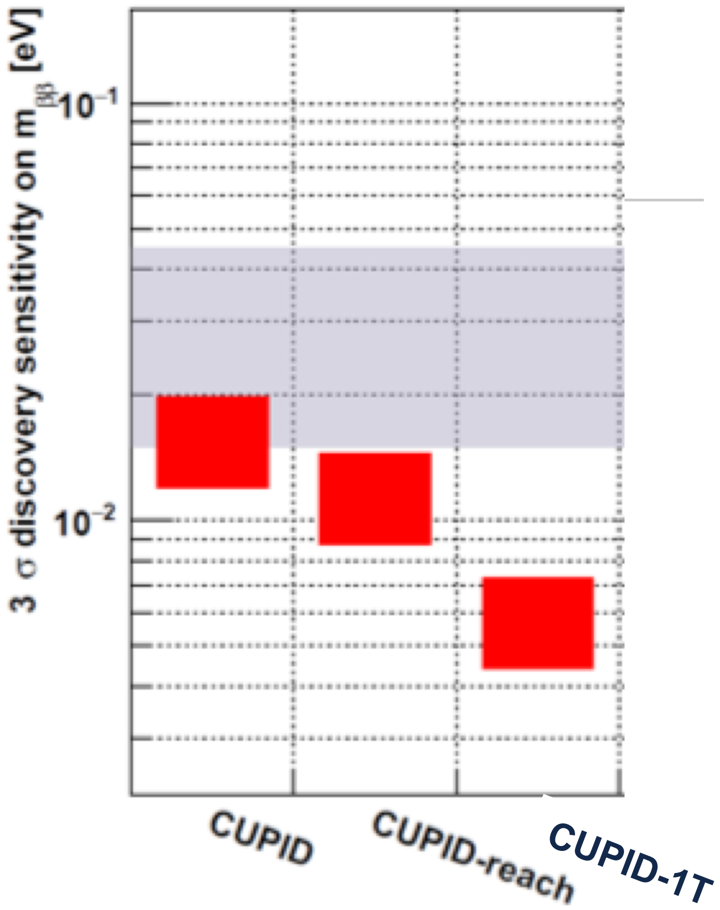
- Crystal: $Li_2{}^{100}MoO_4$
- Enrichment > 95% → 253 kg of ^{100}Mo
- Energy res. (FWHM): 5 keV
- BI < 10^{-4} cnts/(keV kg yr)
- Discovery sensitivity: $T_{1/2} \sim 1.1{\times}10^{27}$yrs
- $m_{\beta\beta}$ discovery sensitivity: 12-20 meV

Beyond Ton-Scale in Bolometers

- R&D Areas: high-speed superconducting sensors, multiplexed readout technologies, active γ veto, CMOS and ASIC instrumentation for quantum sensors, superconducting crystal coatings for improved PSD
- Could adopt a diffuse staging technique, with sites around the world



Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV



"Toward Sensitivity to the Neutrino Normal Hierarchy with Quantum Calorimetry," D. Speller, Y. Kolomensky, L. Winslow, Snowmass LOI

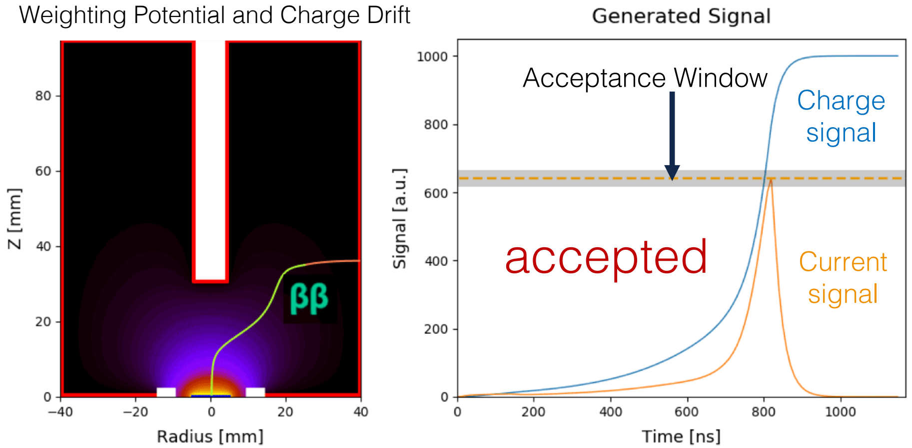
The Experiments

Germanium Experiments

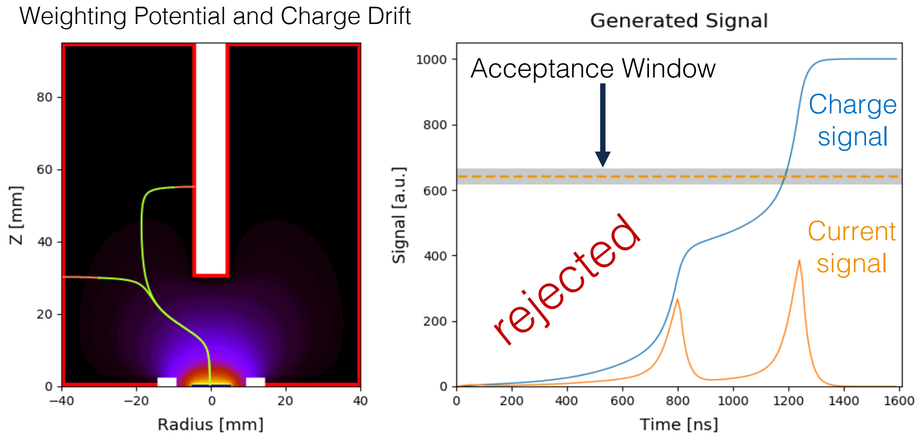
Germanium Detector Concept

- Single-crystal semiconductor diode made from enriched Ge
- Read out ionization signal– pulse shape can be used to distinguish multi-site and surface events from ββ events
- Excellent energy resolution: ~0.05% σ/E

0νββ signal candidate (single-site)



γ-background (multi-site)

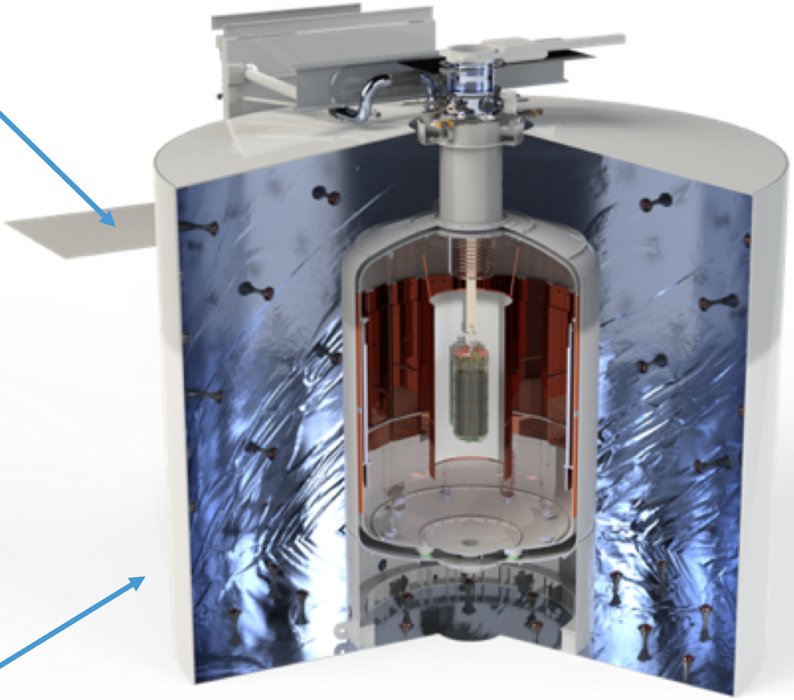


Ge-Based 0νββ Program

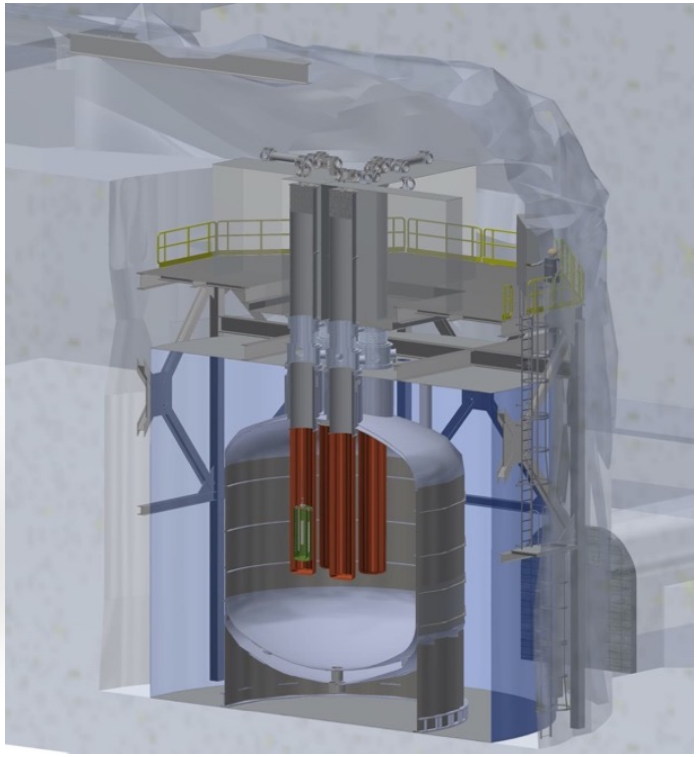
MJD: Final results recently announced

GERDA: Final 0νββ results published

PRL 125, 252502 (2020)



LEGEND-200: Now in commissioning

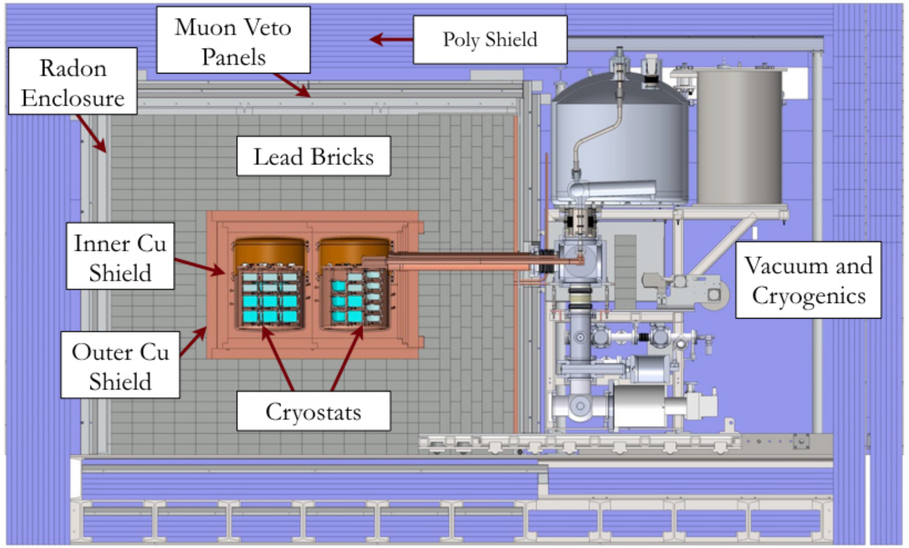


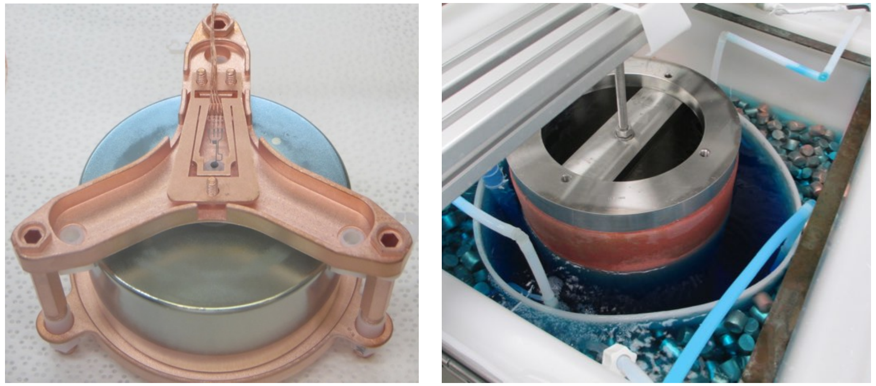
LEGEND-1000: Conceptual design development ongoing

arXiv: 2107.11462

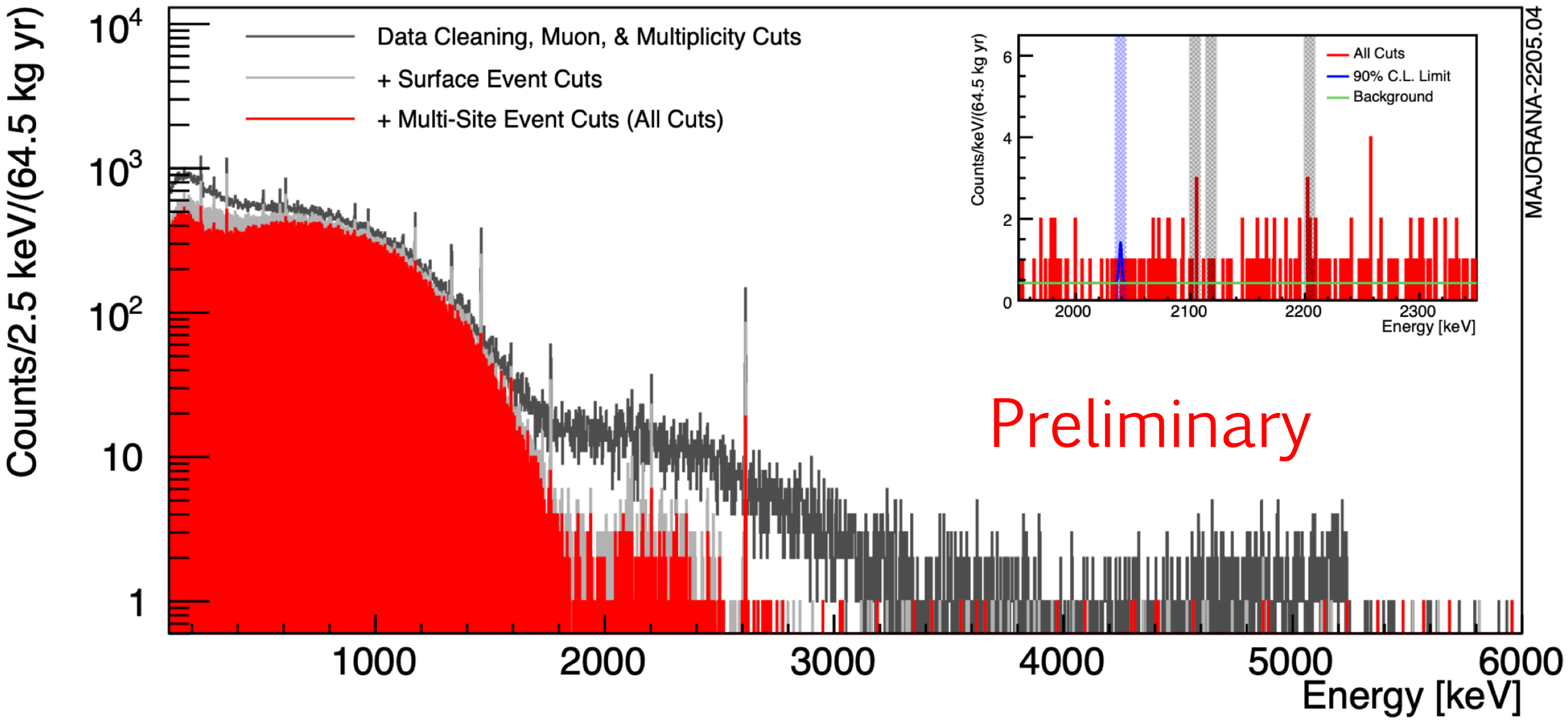
The MAJORANA DEMONSTRATOR

- ~30kg of enriched Ge detectors in a compact graded shield
- Innovations:
  - make underground electroformed copper (“the cleanest copper in the world”)
  - Low-mass low-noise low-background electronics enable the best energy resolution of any 0νββ experiment and a low energy threshold





The MAJORANA DEMONSTRATOR Results



Final enriched detector active exposure:

64.5 ± 0.9 kg yrs

Background Index at 2039 keV in lowest background config:

15.7 ± 1.4 cts/(FWHM t yr)

Background Index:

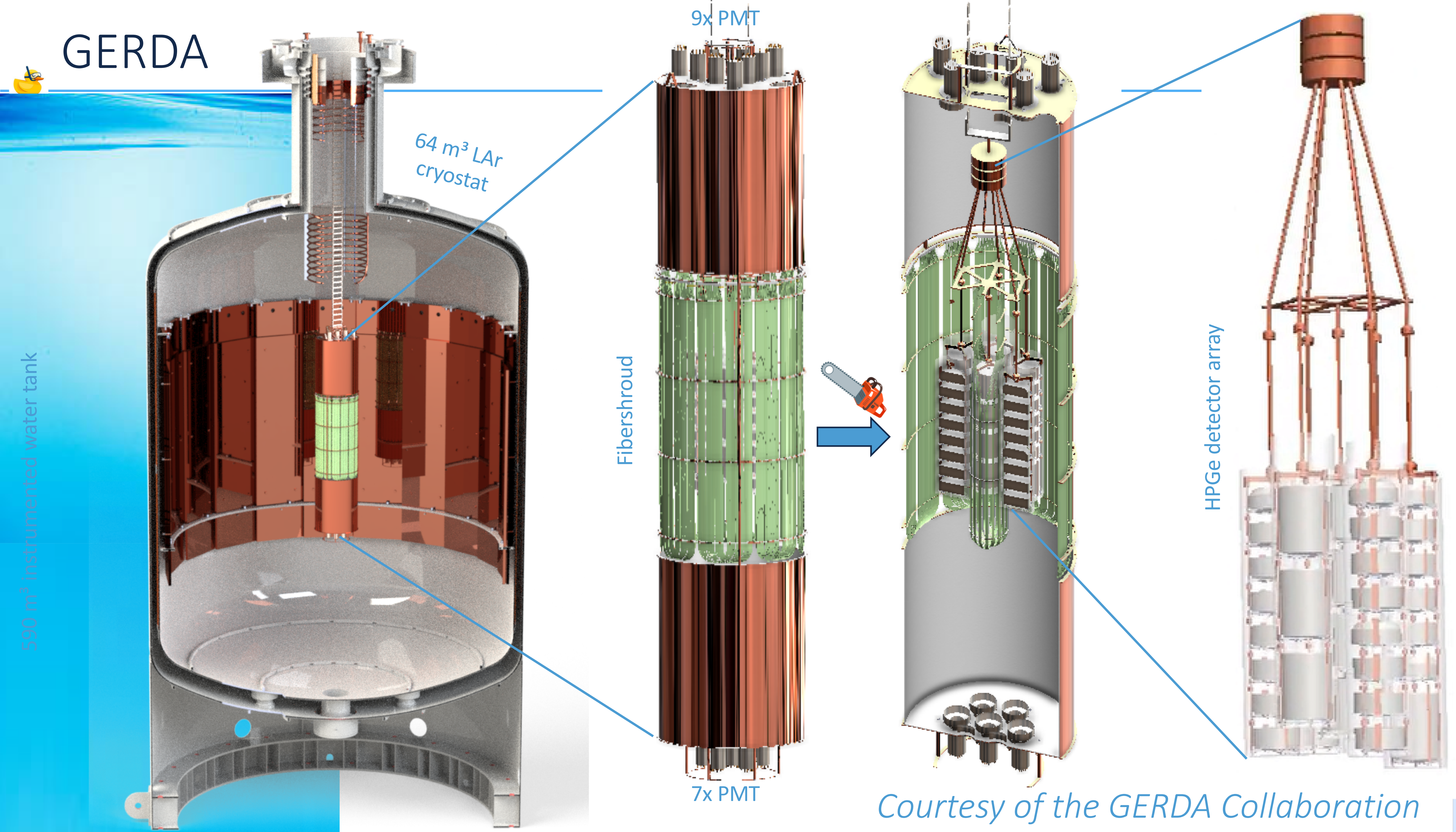
(6.2 ± 0.6) × 10^{-3} cts/(keV kg yr)

Energy resolution (FWHM) : 2.5 keV

Median $T_{1/2}$ Sensitivity: 8.1 × 10^{25} yr (90% C.I.)

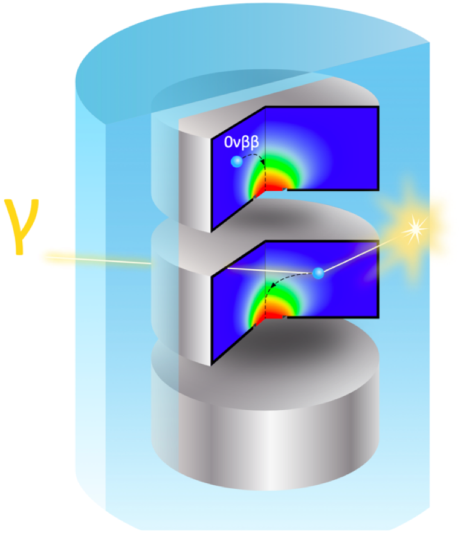
65 kg-yr Exposure Limit: **$T_{1/2}$ > 8.3 × 10^{25} yr** (90% C.I.)

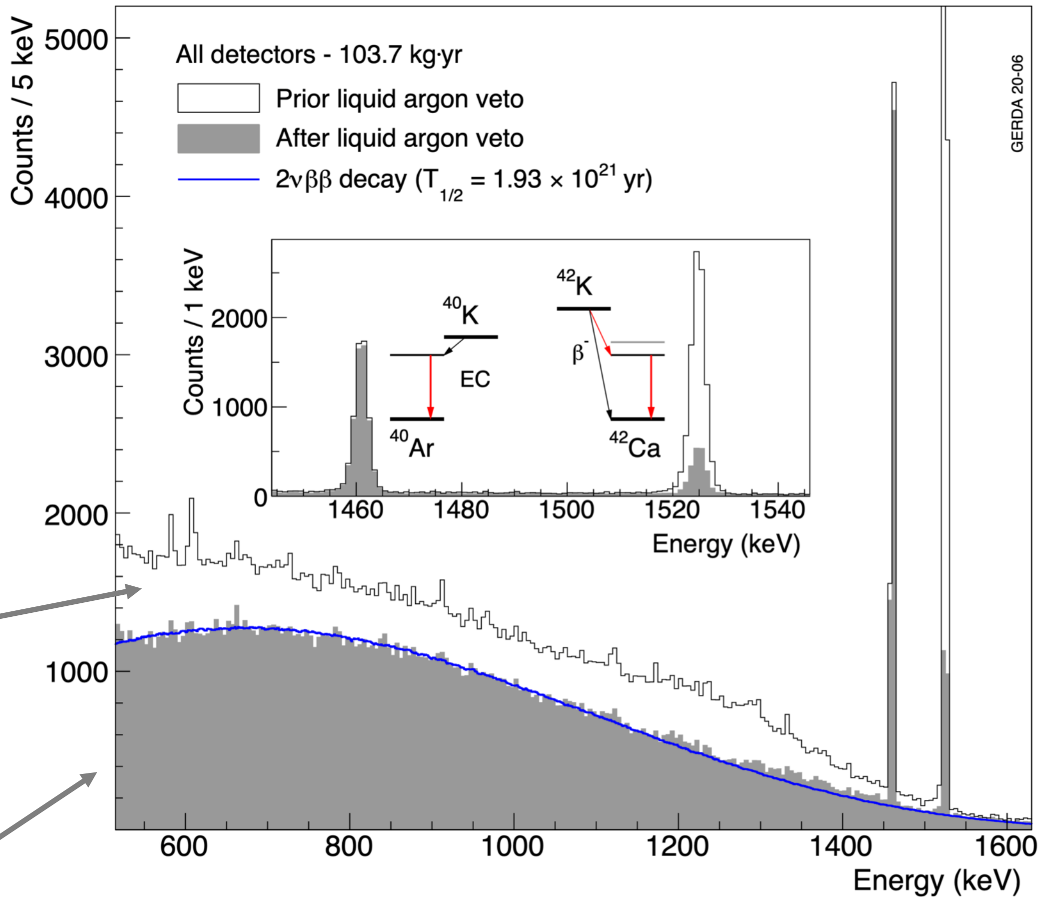
GERDA



Courtesy of the GERDA Collaboration

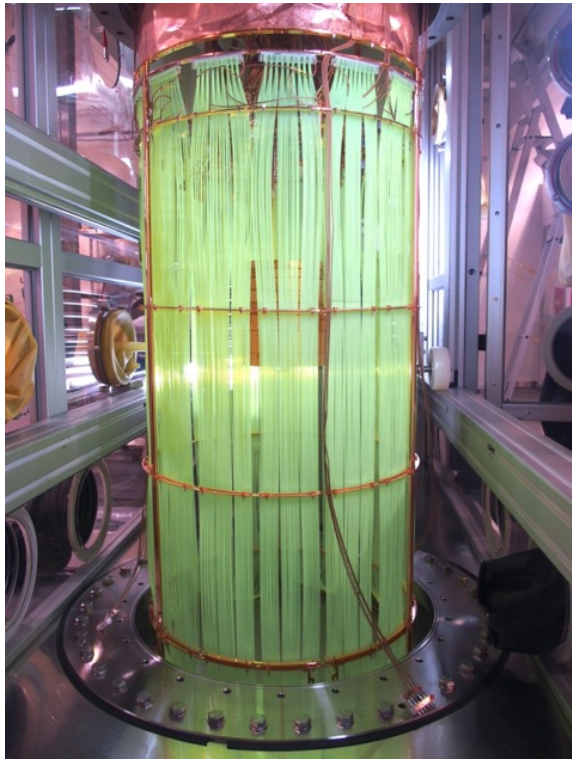
LAr Active Veto





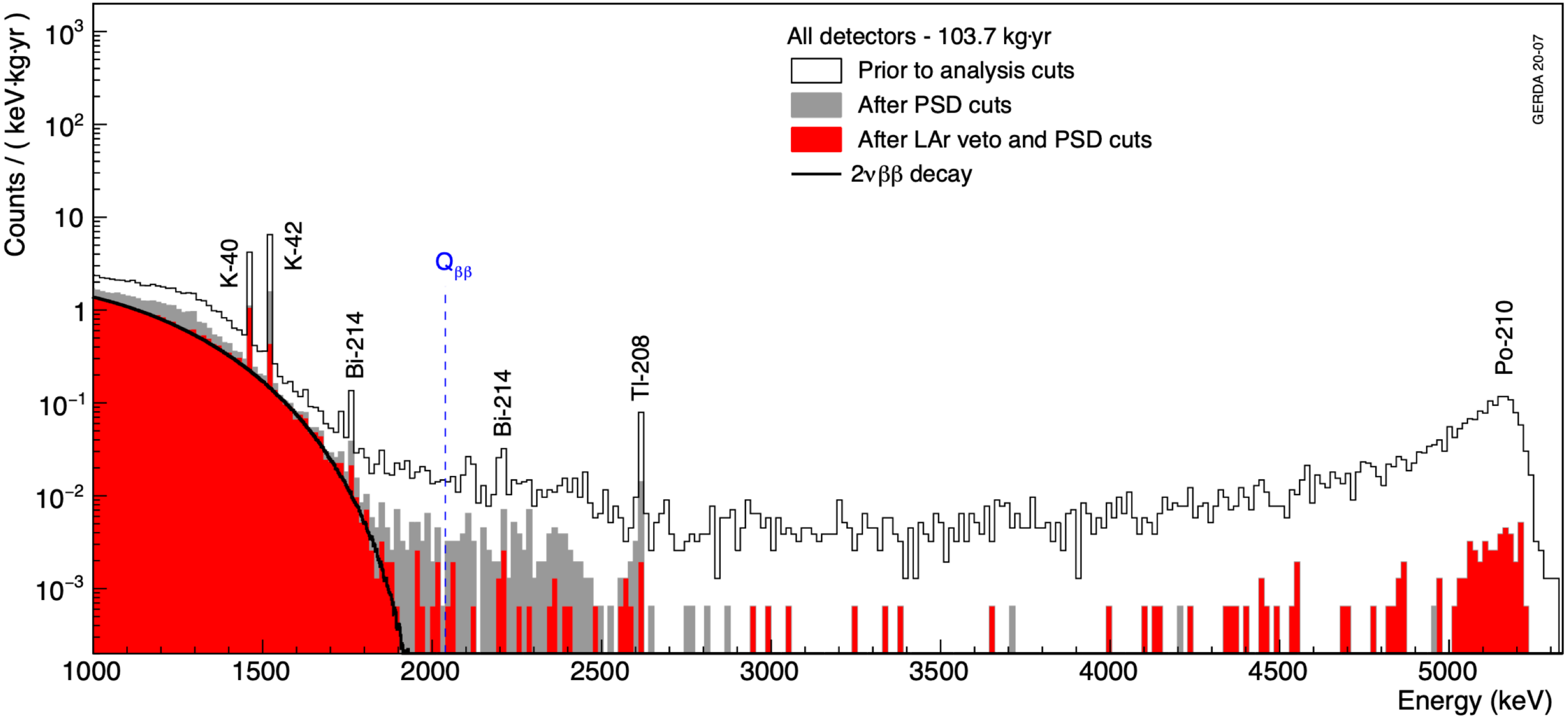
Compton events with energy deposition in the LAr

Pure 2νββ spectrum after LAr signal suppression



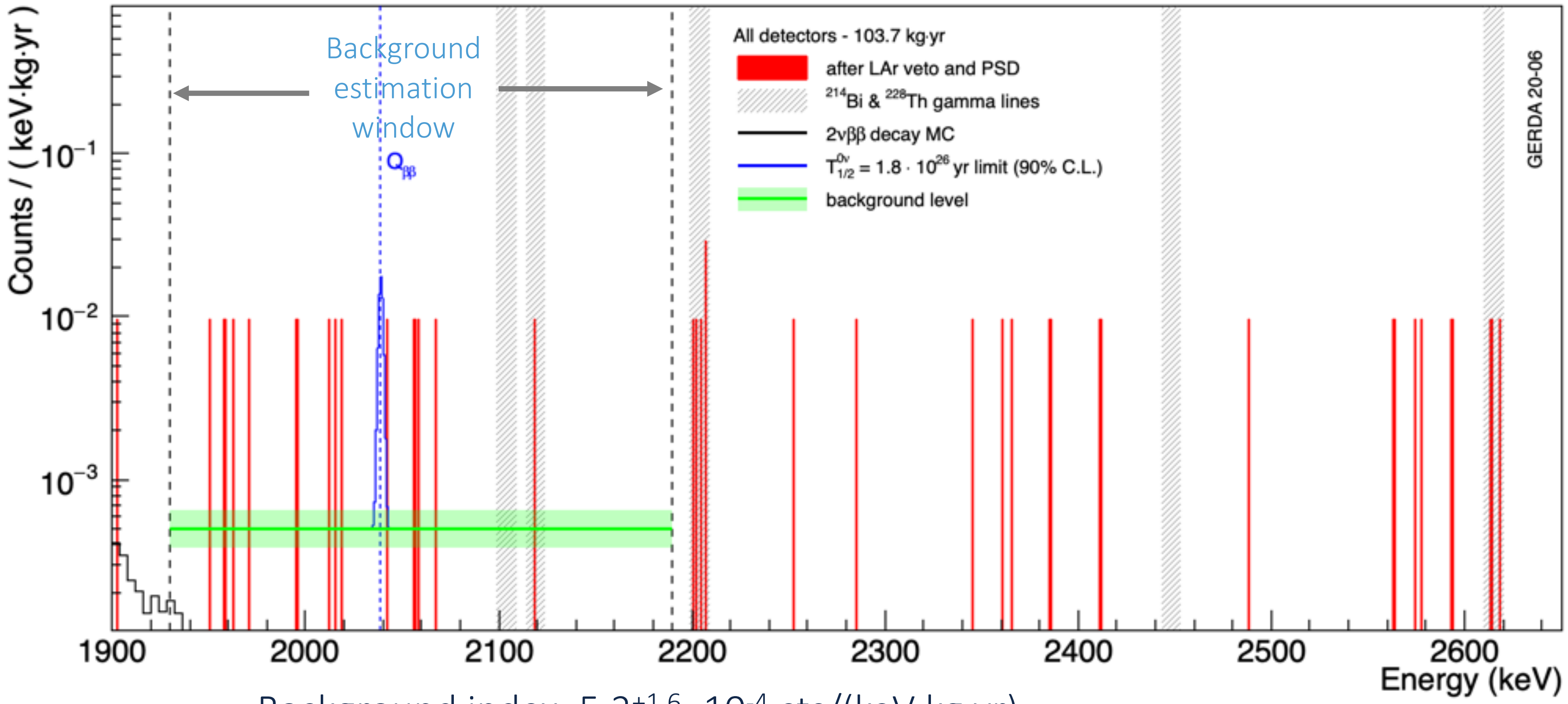
Courtesy of the GERDA Collaboration

GERDA Final-Exposure Spectrum



Courtesy of the GERDA Collaboration

GERDA Results



PRL 125, 252502 (2020)

Background index: $5.2^{+1.6} \cdot 10^{-4}$ cts/(keV kg yr),

Energy resolution ~3 keV (FWHM)

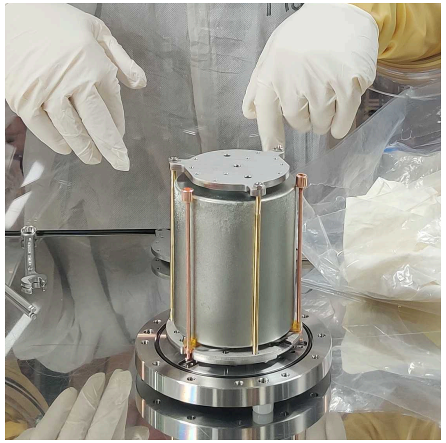
Frequentist: $N^{0\nu} = 0$ best fit, $T_{1/2} > 1.8 \cdot 10^{26}$ yr at 90% C.L.

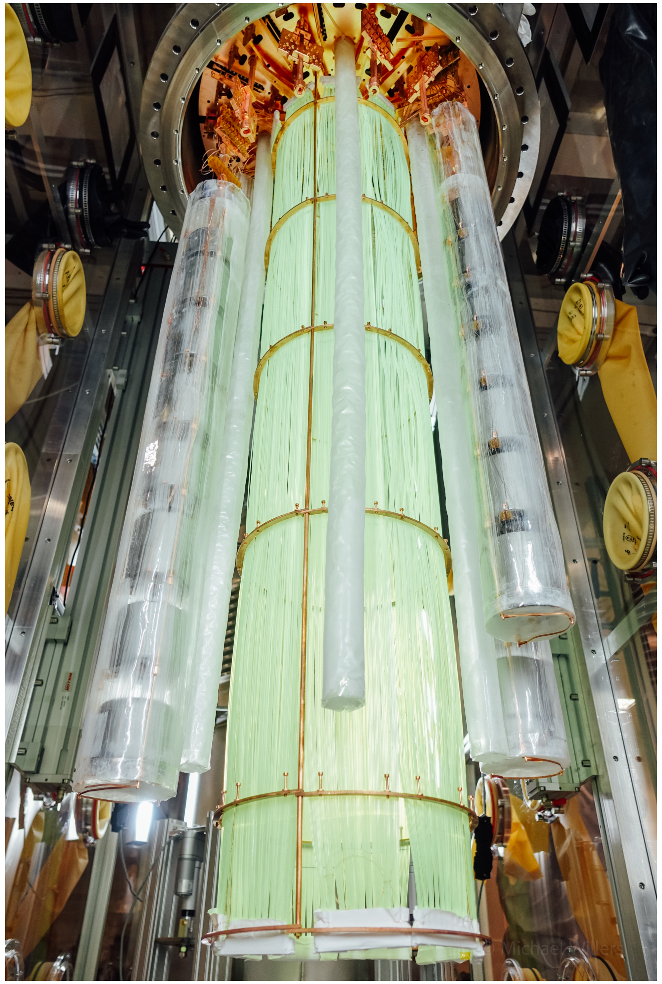
Courtesy of the GERDA Collaboration

LEGEND-200

- 200 kg of HPGe ICPC detectors enriched to 91% ^{76}Ge, operated in active LAr shield
- Upgrade of GERDA infrastructure
- Uses new, larger inverted-coxial point-contact detectors
- >2.5x background reduction relative to GERDA expected
- Commissioning underway, full detector deployment expected this year
- Final expected sensitivity:

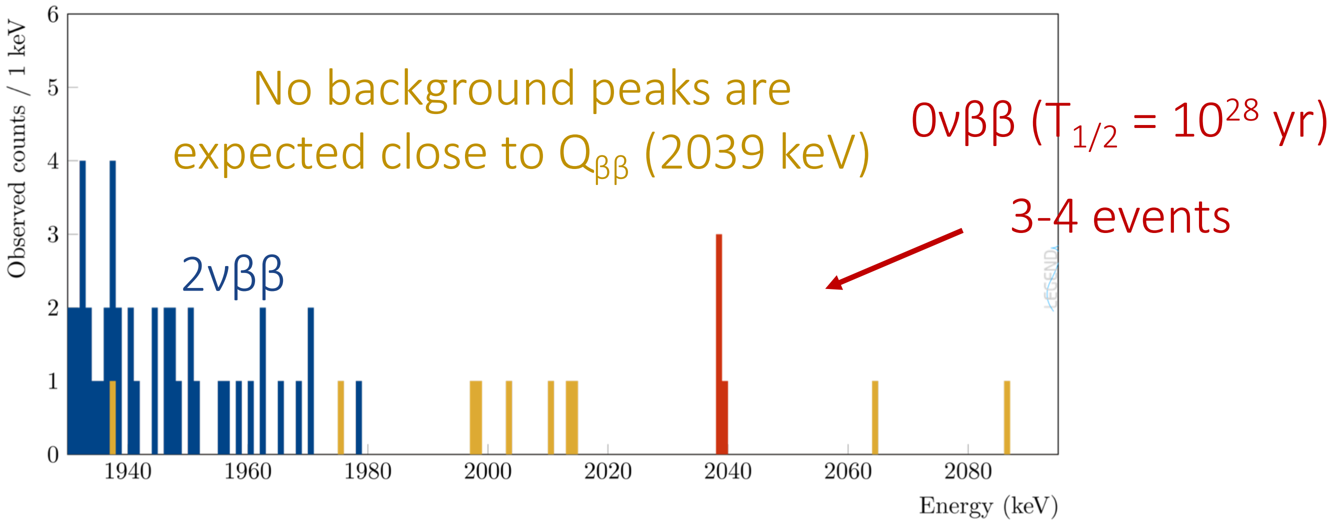
  $T_{1/2} > 1 \times 10^{27}$ yrs





LEGEND-1000

- New cryostat either at LNGS or SNOLAB; 4 independent payloads with depleted UAr in inner volumes
- 1000 kg of enriched Ge detectors: fabricate 870 kg of new detectors; use 130 kg from LEGEND-200; recycle 50 kg of small detectors
- Multi-dimensional analysis nearly eliminates γ, surface α and β backgrounds
- LEGEND goal: BI < 1x10^{-5} cnts/keV kg yr, Discovery up to 1.3×10^{28} yrs



Projected spectrum: even a signal at the bottom of the inverted ordering will be visible to the eye

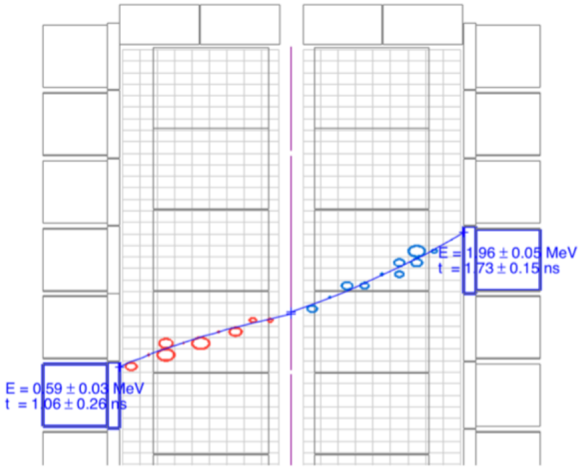
Multi-dimensional analysis can also be conducted

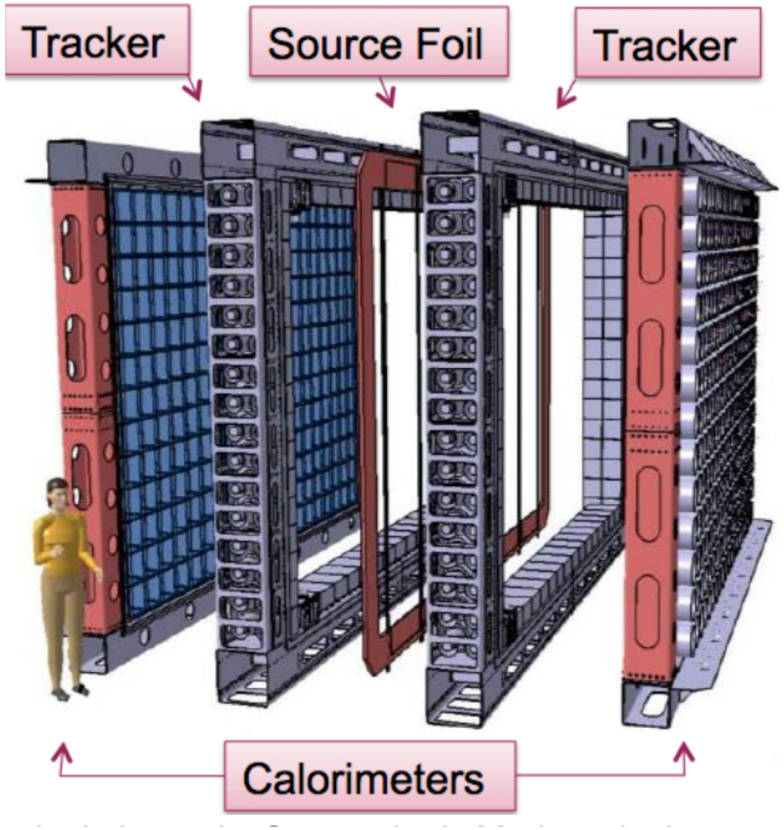
The Experiments

Tracking Experiments

Tracking Detector Concept

- Source ≠ Detector!
- Thin foils of ββ decay materials sandwiched between tracking planes and surrounded by calorimeters
- Magnetic field for charge ID
- Allows full track reconstruction of ββ decays and energy measurement
- Can use any isotope
- Foils have to be just 0.3mm thick so βs can escape



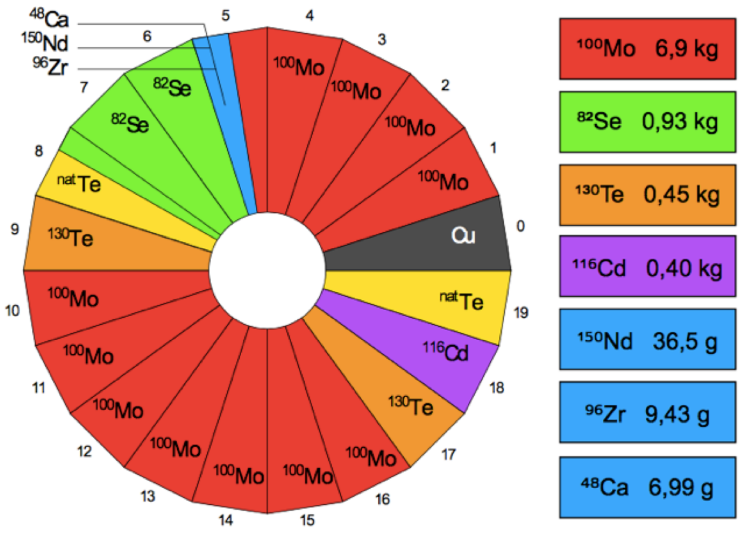


Images courtesy of the NEMO Collaboration

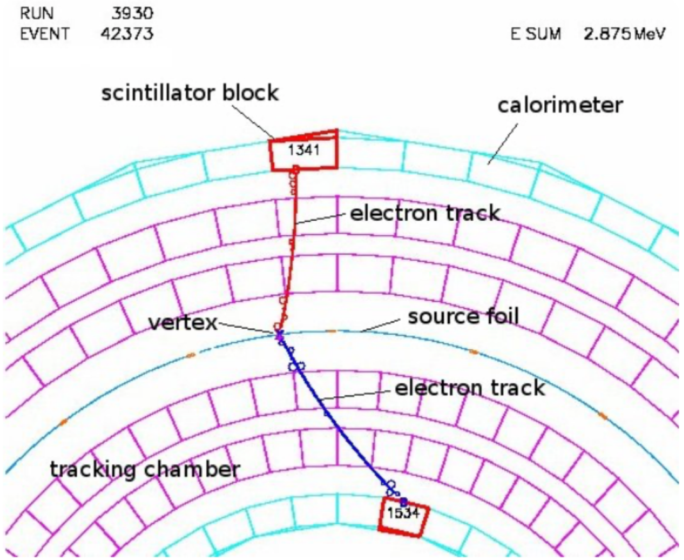
NEMO-3

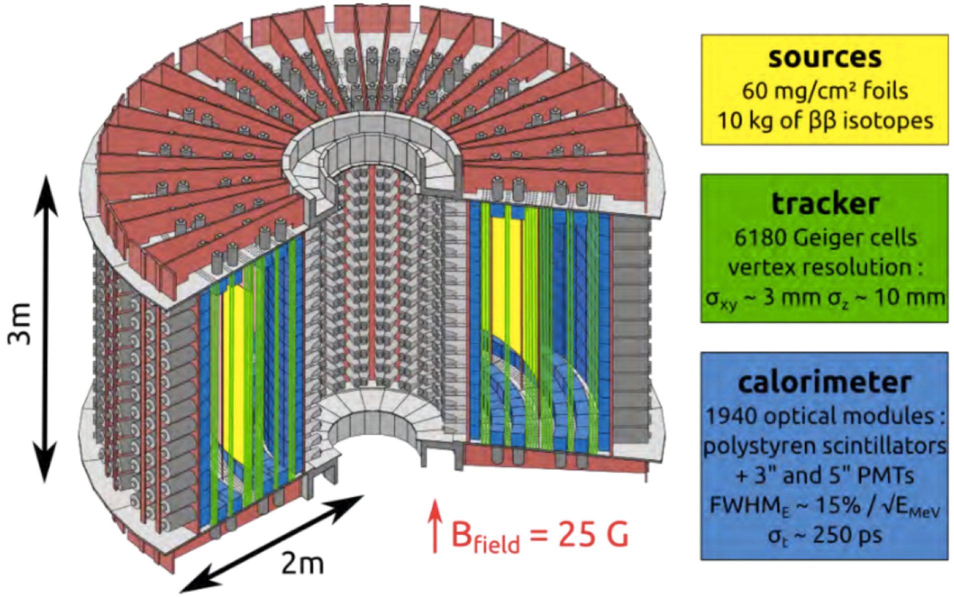
- Ran from 2003-2011 with 10 kg total mass
- Measured many isotopes simultaneously (including some first measurements)

NEMO-3 "camembert" (source top view)



^{100}Mo	6,9 kg
^{82}Se	0,93 kg
^{130}Te	0,45 kg
^{116}Cd	0,40 kg
^{150}Nd	36,5 g
^{96}Zr	9,43 g
^{48}Ca	6,99 g





sources
60 mg/cm² foils
10 kg of ββ isotopes

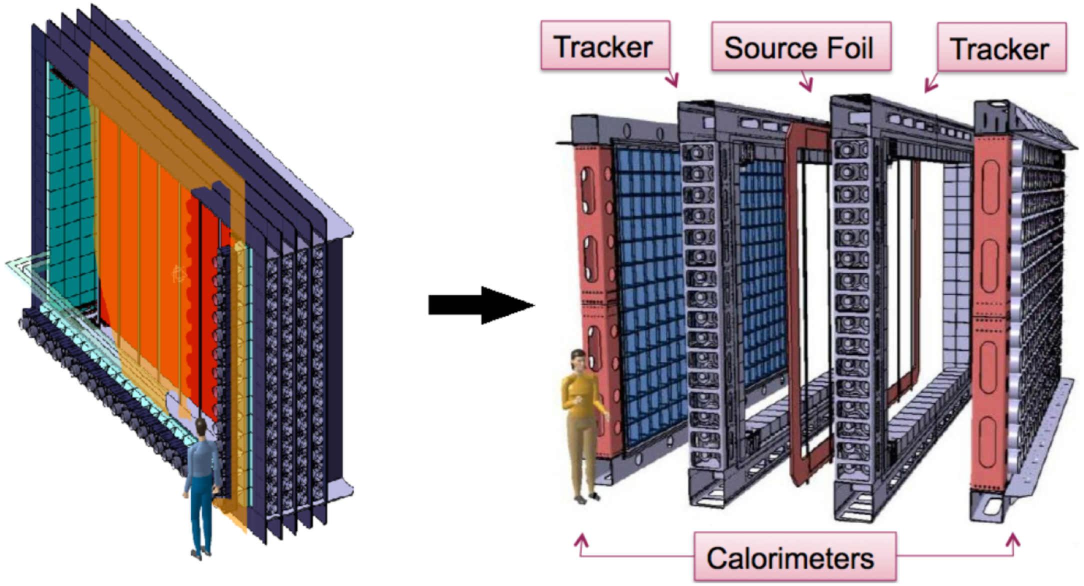
tracker
6180 Geiger cells
vertex resolution :
$\sigma_{xy} \sim 3$ mm $\sigma_z \sim 10$ mm

calorimeter
1940 optical modules :
polystyren scintillators
+ 3" and 5" PMTs
$FWHM_E \sim 15\% / \sqrt{E_{MeV}}$
$\sigma_t \sim 250$ ps

Images courtesy of the NEMO Collaboration

Super-NEMO and Science Goals

- Using ^{82}Se foils for initial run
- 1 module to start, up to 20 after that
- Low mass, so not much sensitivity (~10^{24} yrs)
- Tracking allows you to look for new physics in 2νββ decays
- R&D for future Majorana mass mechanism investigations?



Doing Other Physics with 0νββ Experiments

Not Just 0νββ…

- Once you've built a large low-background detector, there's a lot of other physics you can do with it!
- ββ-related searches
- Standard Model rare-event searches
- Dark matter searches
- Other BSM physics

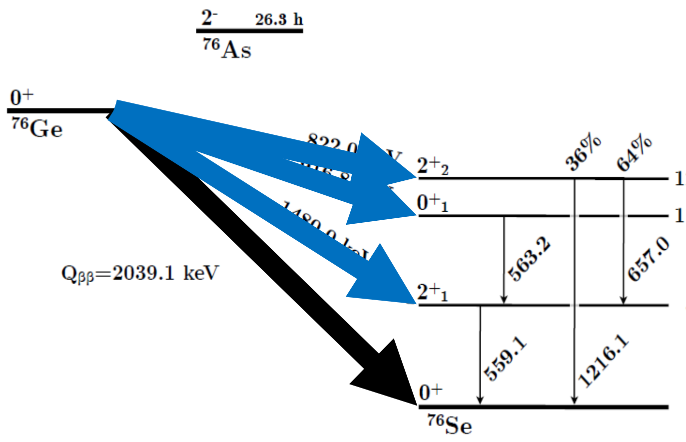
Other ββ-related Physics

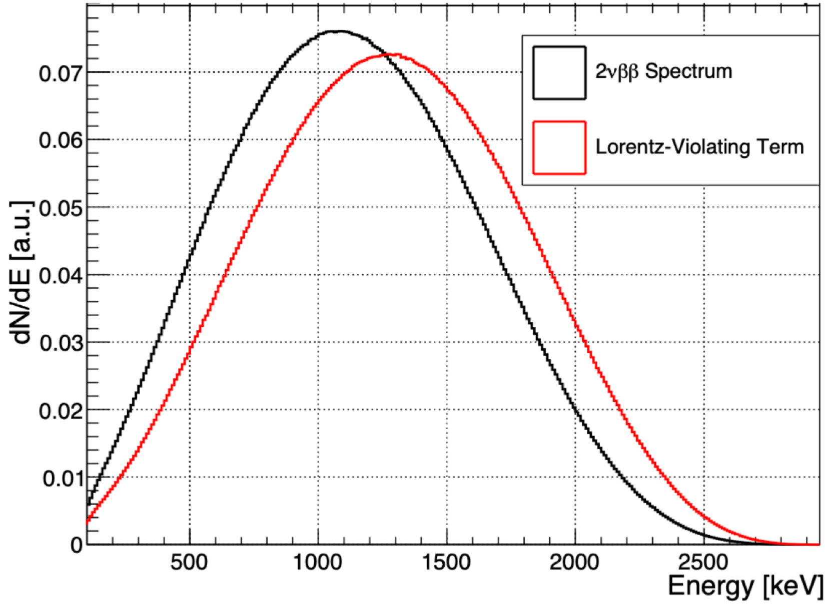
Excited-state decays:

- 2νββ and 0νββ decays to excited states can also occur
- ββ decay, followed by γ emission from de-excitation
- The 2νββ decay to the 0_1^+ state has been measured in ^{150}Nd and ^{100}Mo. Other first measurements may be around the corner!
- 0νββ excited state decay measurements could help constrain the Majorana mass mechanism some day

Lorentz violation:

- Violation in 2νββ decay would change the spectral shape





DOI: 10.1103/PhysRevD.100.092002

Standard Model Rare-Event Searches

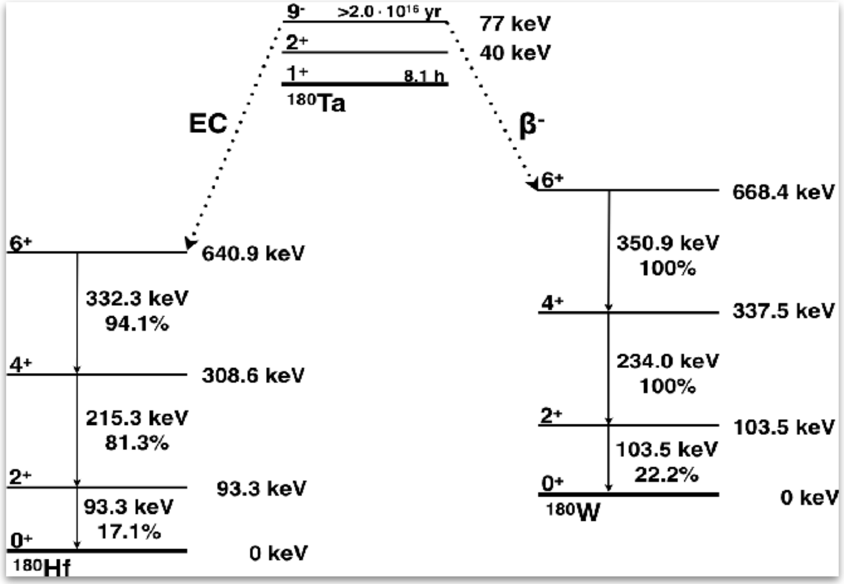
Addressing uncertainties in expected rates of SM processes:

- Studies of in-situ cosmogenics for future low-background experiments
- (α, n) reactions from calibration sources

Rare-event searches with added sources:

- The Majorana Demonstrator is now searching for the decay of $^{180\mathrm{m}}$Ta: “nature’s longest-lived excited state”
- Expected sensitivity: 10^{19} yrs

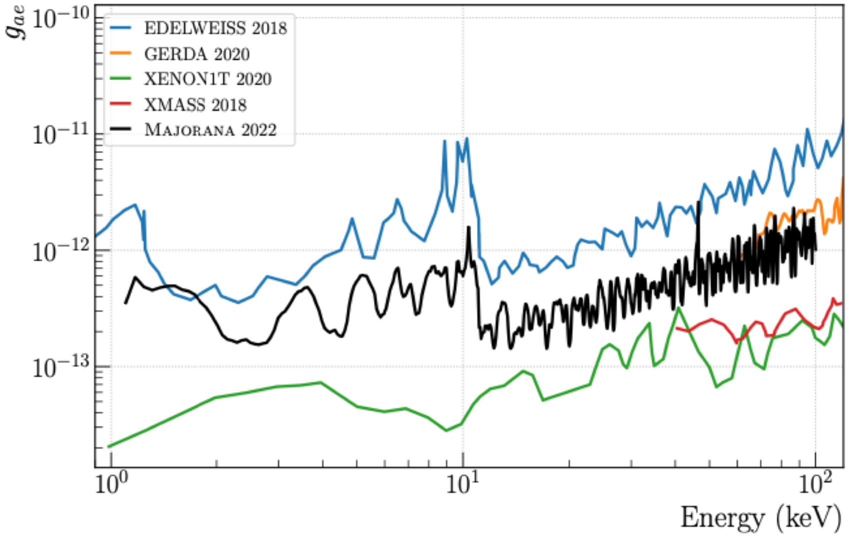
Added Ta foils



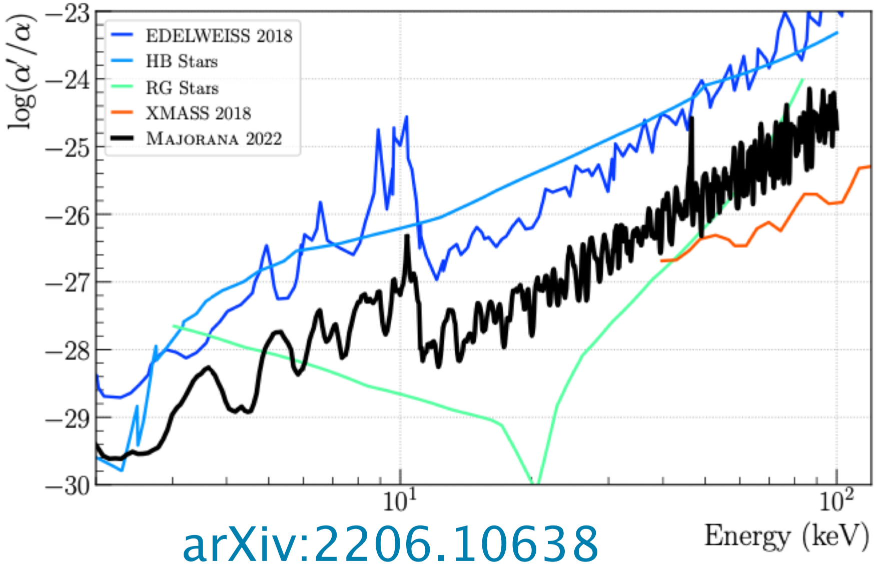
Dark Matter Searches

- Many searches enabled by low energy threshold and low backgrounds:
  - Pseudoscalar dark matter: axion-like particles
  - Vector dark matter: dark photons
  - Fermionic dark matter
  - Sterile neutrino
  - Primakoff solar axion
  - 14.4-keV solar axion
- Dark matter searches at higher energy:
  - keV-scale dark matter
  - Bosonic super-WIMPs
- 0νββ experiments can be competitive with dedicated dark matter experiments!

Pseudoscalar Dark Matter



Vector Boson Dark Matter

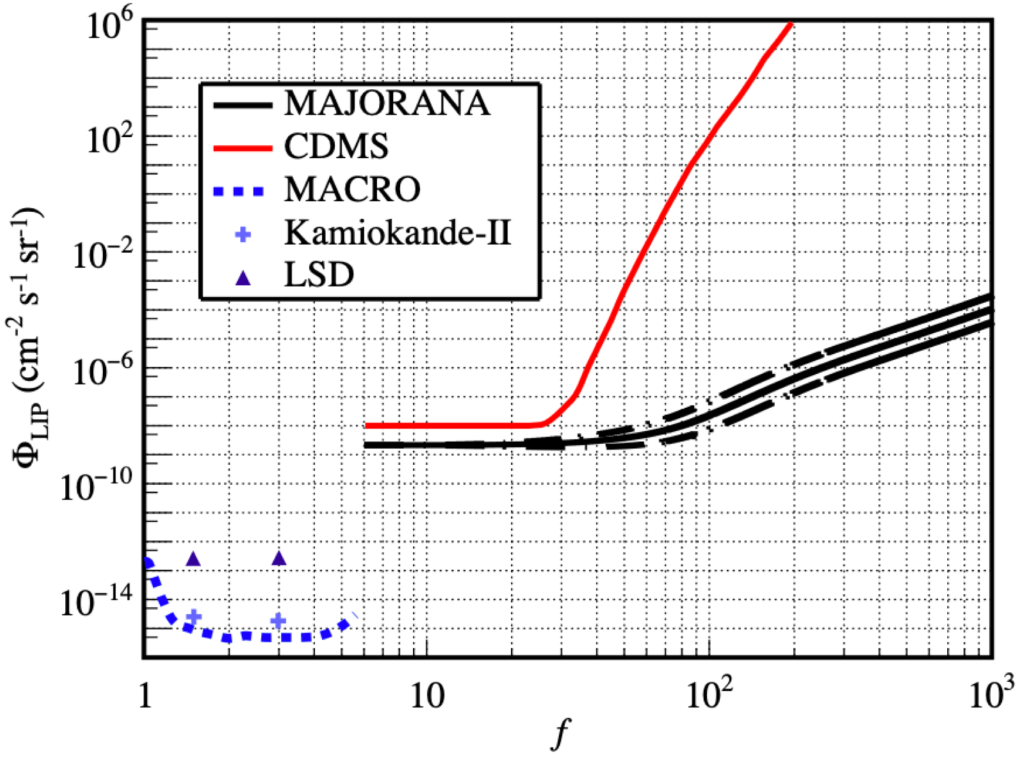


arXiv:2206.10638

Other BSM Searches

- Tests of fundamental symmetries and conservations:
  - Baryon number violation
  - Pauli exclusion principle violation
- Other exotic physics:
  - Quantum wavefunction collapse
  - Lightly-ionizing (fractionally charged) particles

Limits on fractionally charged particles



DOI: 10.1103/PhysRevLett.120.211804

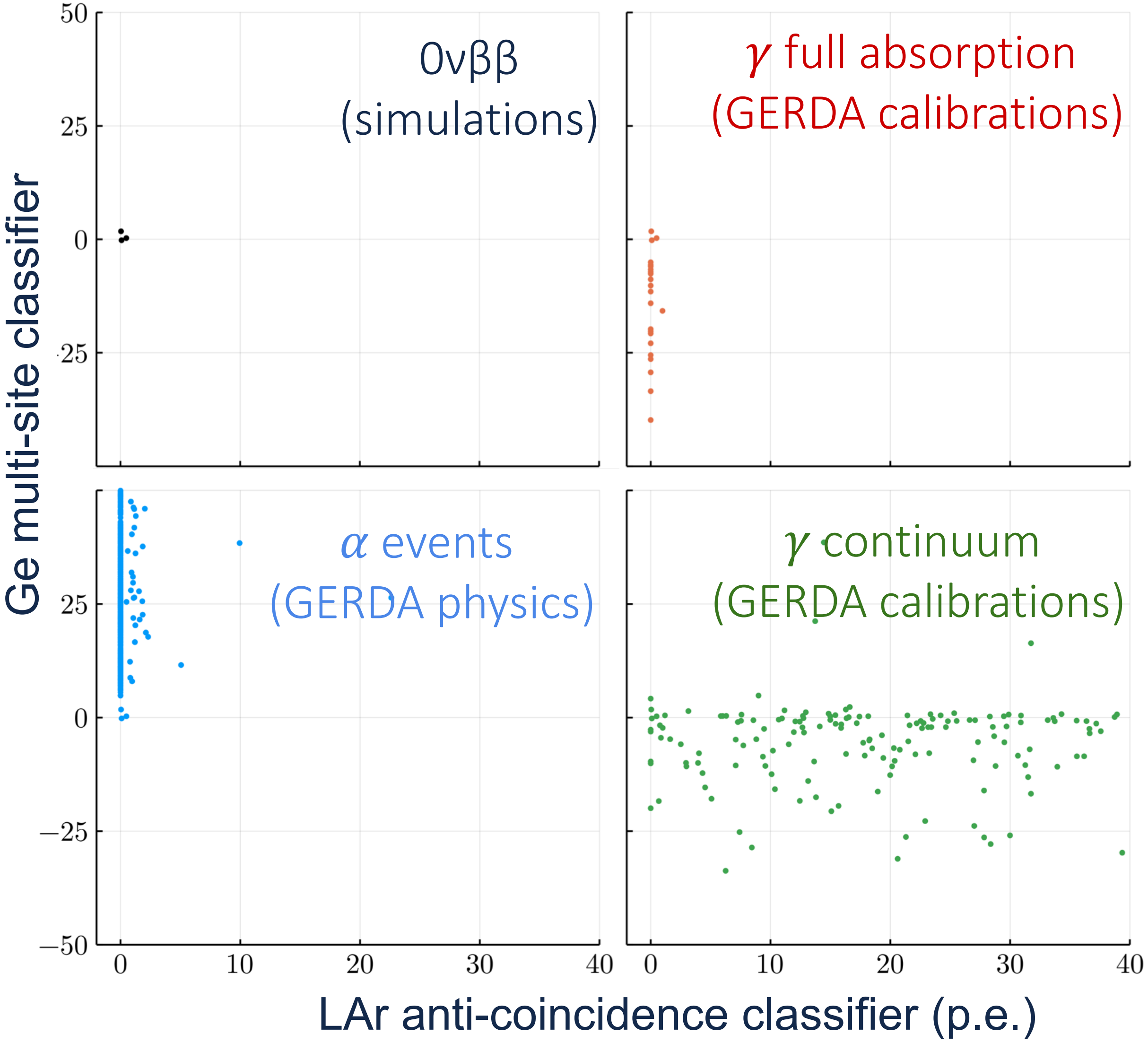
What comes after discovery?

Confirming a Signal

- Make sure your signal behaves correctly as a function of your analysis parameters
- Depending on the experiment, you may be able to do an “on/off” measurement.
- Or, if your backgrounds are low enough, run for longer and increase your signal!
- Add more mass, if you can!
- If the signal is confirmed…

Example from LEGEND:

Three counts in 0νββ region: What is their origin?



Hand out the Nobel Prizes!

Where do we go from there?

- If we discover 0νββ, we'll want to measure it in more isotopes: ratios between isotopes could provide insight into mechanism
- Precision measurements, along with measurements of other neutrino properties, would let us figure out the Majorana phases: many theories of flavor predict specific phases
- Try to measure excited-state decays to get more insight into mechanism
- Measure outgoing electron energies and momenta: some Majorana mass mechanism models make specific predictions
  - Build HyperNEMO for this?

Conclusion

- I hope you've enjoyed learning something about 0νββ!
- This is a rich field with a lot of ongoing activity, and big things coming soon!
- We're entering a regime where discovery could come at any time, giving us vital insight into the nature of neutrino mass and potentially, the origin of the matter/anti-matter asymmetry.