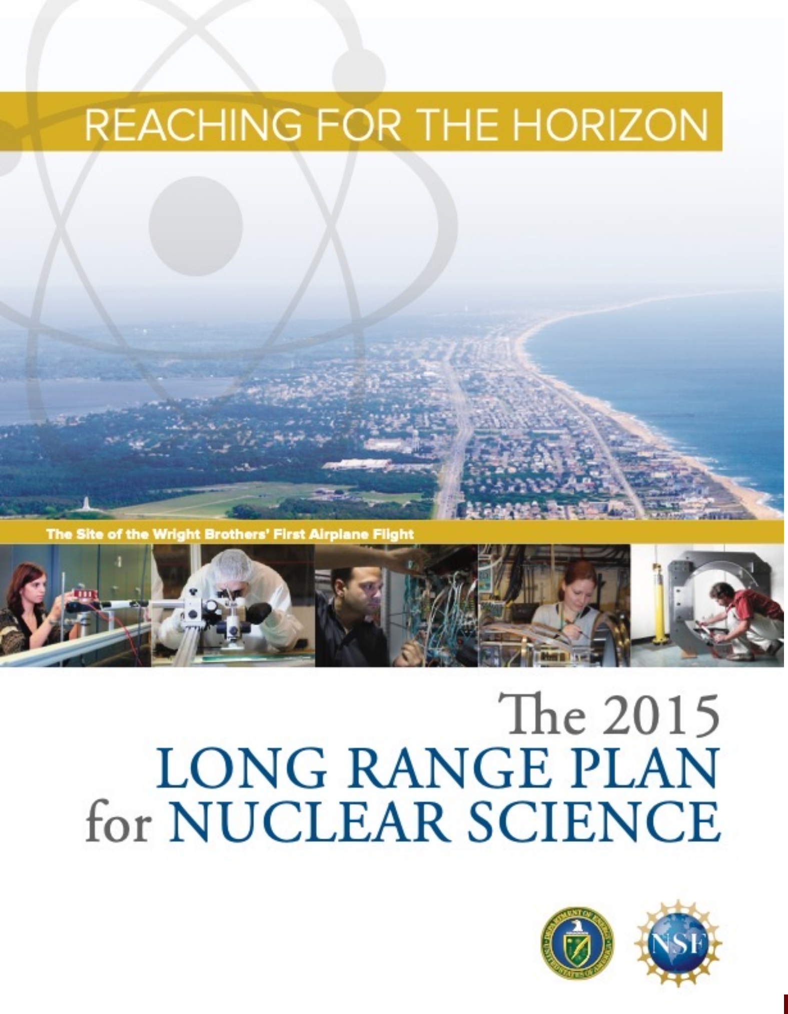
Walter C. Pettus

Neutrinoless Double Beta Decay Experiments

International Neutrino Summer School

8 August 2023

INDIANA UNIVERSITY



Nuclear Physics Roadmap

RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

Particle Physics Science Drivers

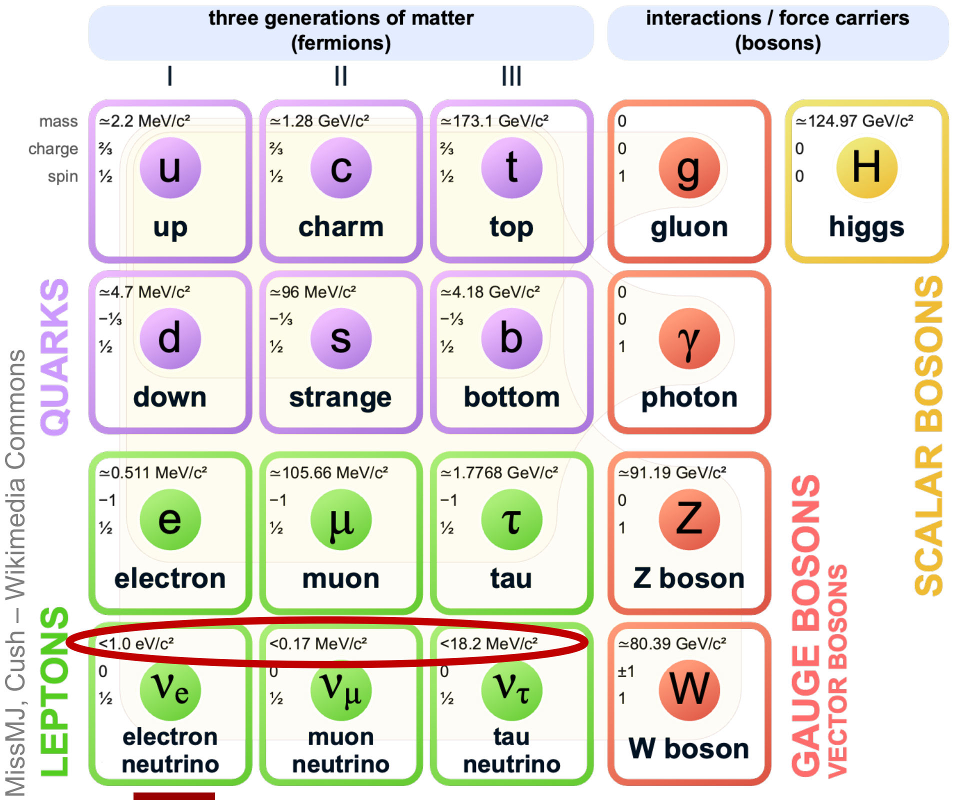
2014 (the last) P5 report identified five science drivers:

1. Use the Higgs Boson as a Tool for Discovery,
2. Pursue the Physics Associated with Neutrino Mass,
3. Identify the New Physics of Dark Matter,
4. Understand Cosmic Acceleration: Dark Energy and Inflation,
5. Explore the Unknown: New Particles, Interactions, and Physical Principles.

Reaffirmed by 2021 Snowmass Community Study

Snowmass 2021

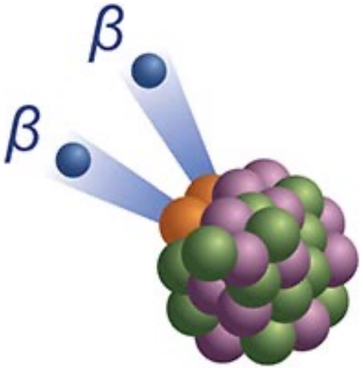
Opportunity of Neutrino Mass

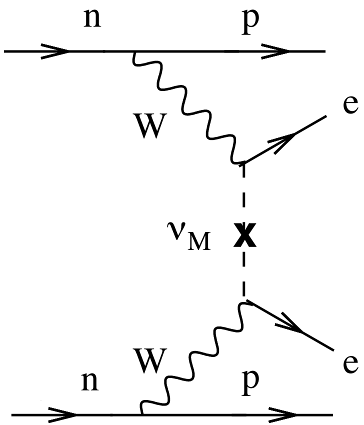


Neutrino mass is BSM physics!

- What is the neutrino mass?
- Why is the neutrino mass so much smaller than other fermion masses?
- How much CP violation in lepton sector?
- Other new physics hiding with neutrinos?

Neutrinoless Double Beta Decay (0νββ)





Searching for theoretical process:

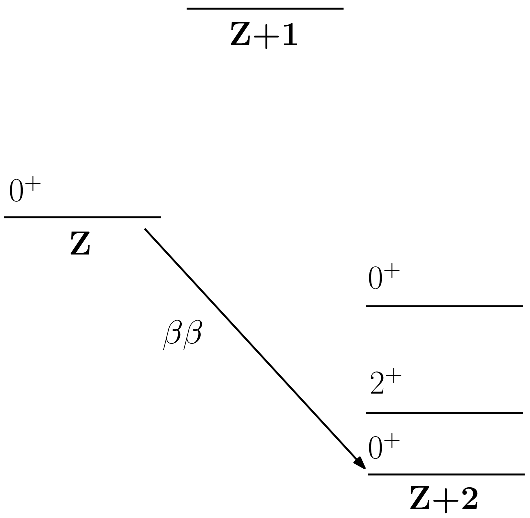
- $(\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}+2) + 2\mathrm{e}^-$
  - Contrast with $(\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}+2) + 2\mathrm{e}^- + 2\bar{\nu}_e$, observed

0νββ always implies new physics

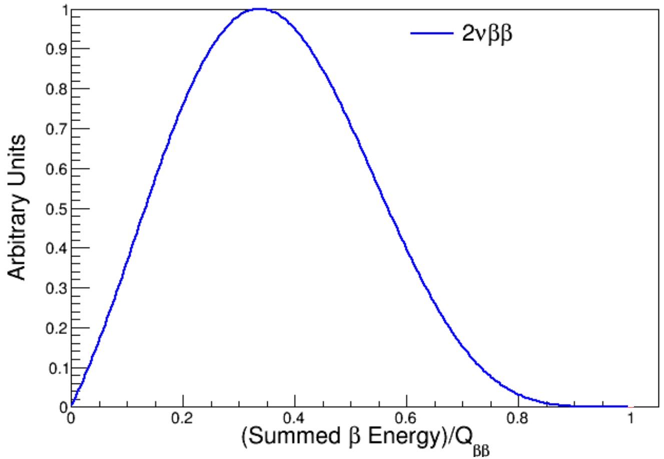
- Lepton number violating process (ΔL=2)
- Majorana neutrinos generate 0νββ
- Majorana neutrinos help explain small observed neutrino masses via see-saw mechanism
- Leptogenesis as ingredient for explaining matter-antimatter asymmetry

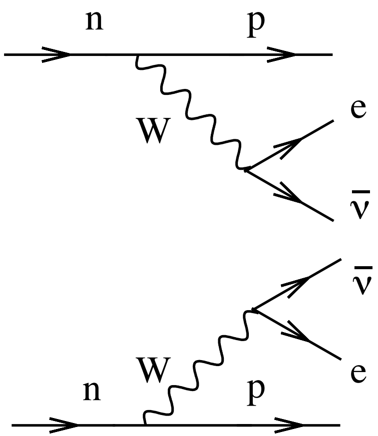
Double-Beta Decay

- Double-beta decay with two neutrinos is the rarest observed weak nuclear process



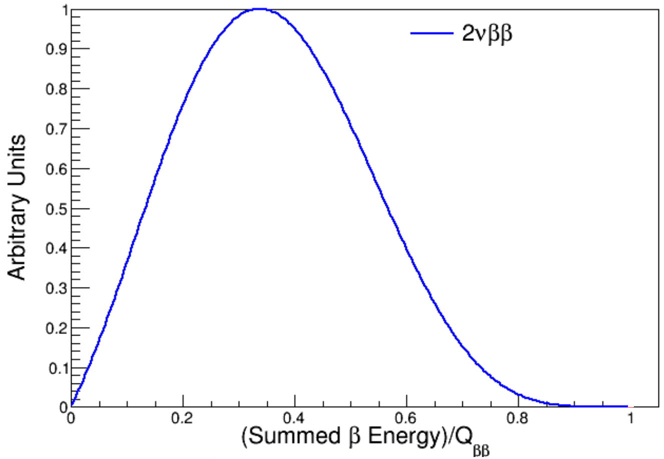
F. Avignone *et al.* Rev. Mod. Phys. 2008

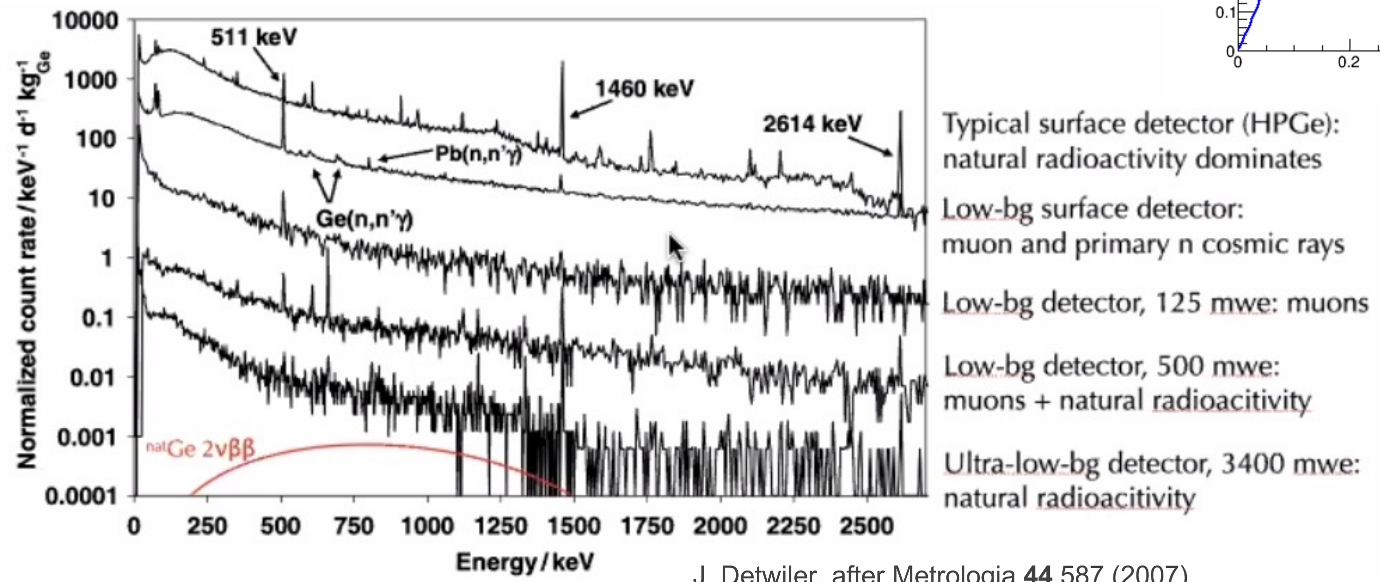




Experimental Backgrounds

- Signal is buried under myriad other backgrounds

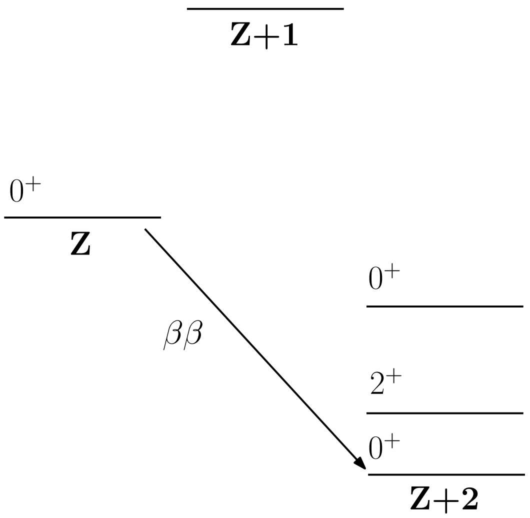




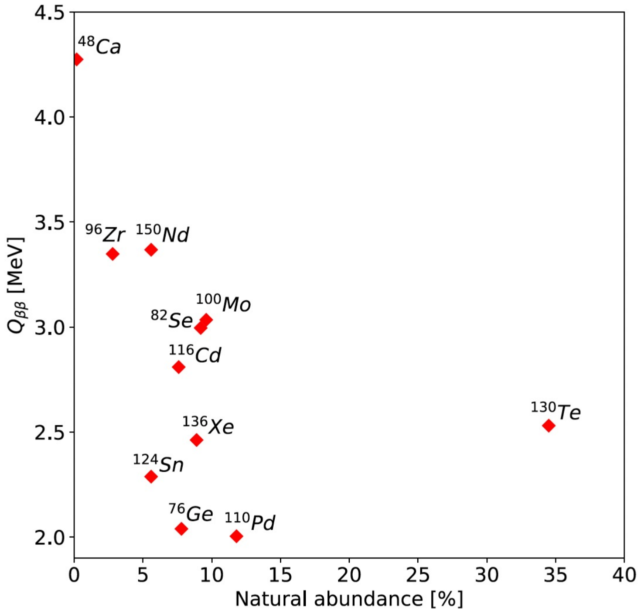
J. Detwiler, after Metrologia **44** 587 (2007)

Menu of Isotopes

- O(50) isotopes are capable of ββ
  - Only directly measured in 9 isotopes



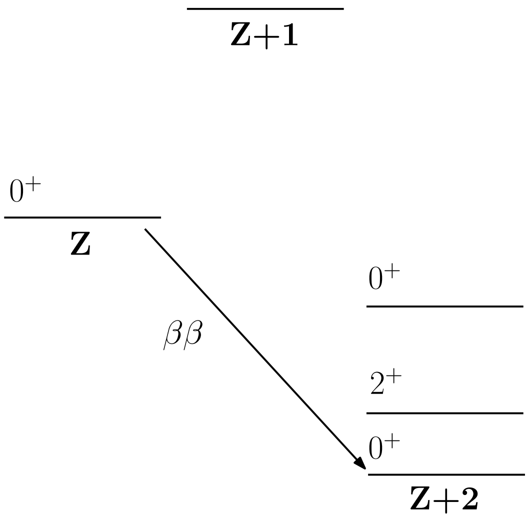
F. Avignone *et al.* Rev. Mod. Phys. 2008



- Availability/cost of element
- Suitability of enrichment
- Compatibility with detector technology
- …

Double-Beta Decay

- Double-beta decay with two neutrinos is the rarest observed weak nuclear process



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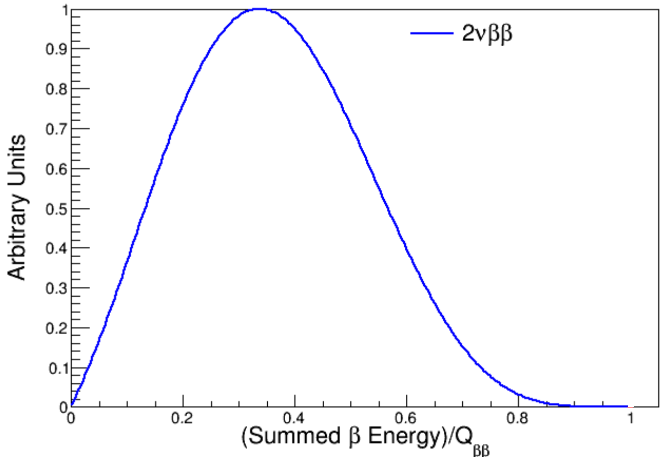
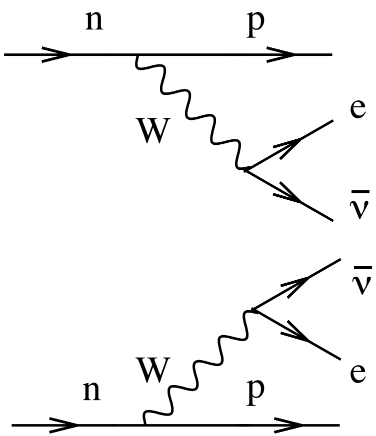
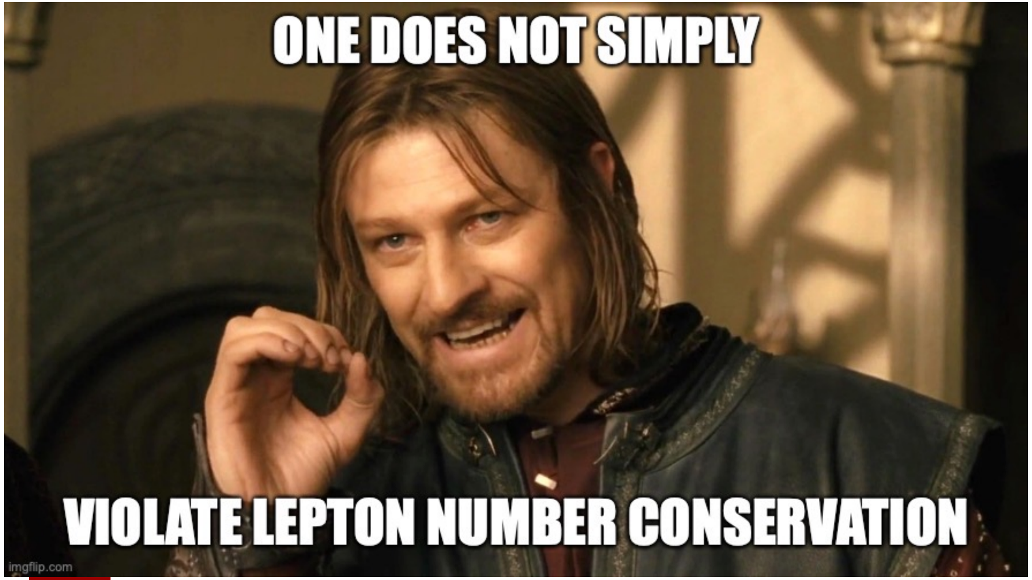
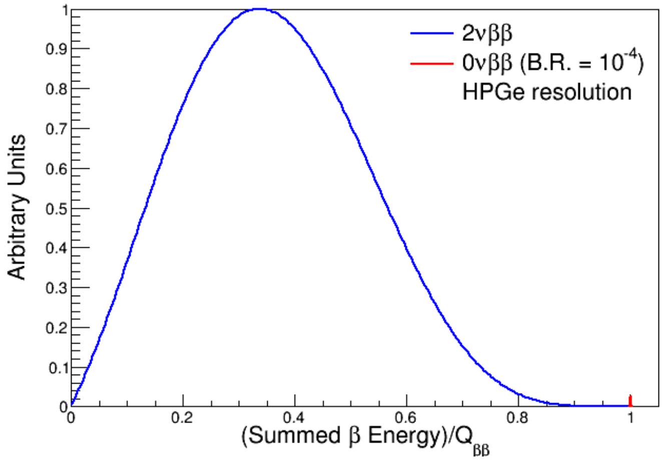


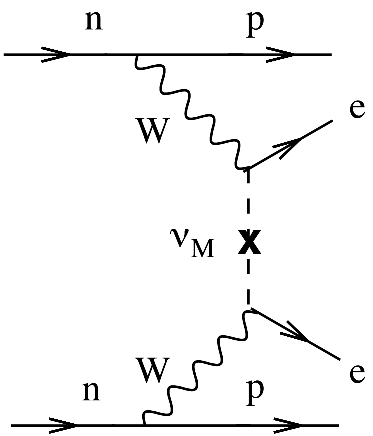


Neutrinoless Double-Beta Decay

- Neutrinoless double-beta decay is an analogous nuclear process wherein lepton number is violated

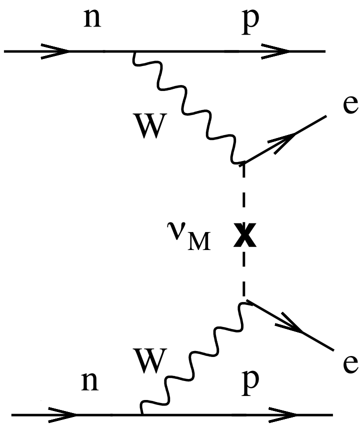






From Half-Life to Neutrino Mass

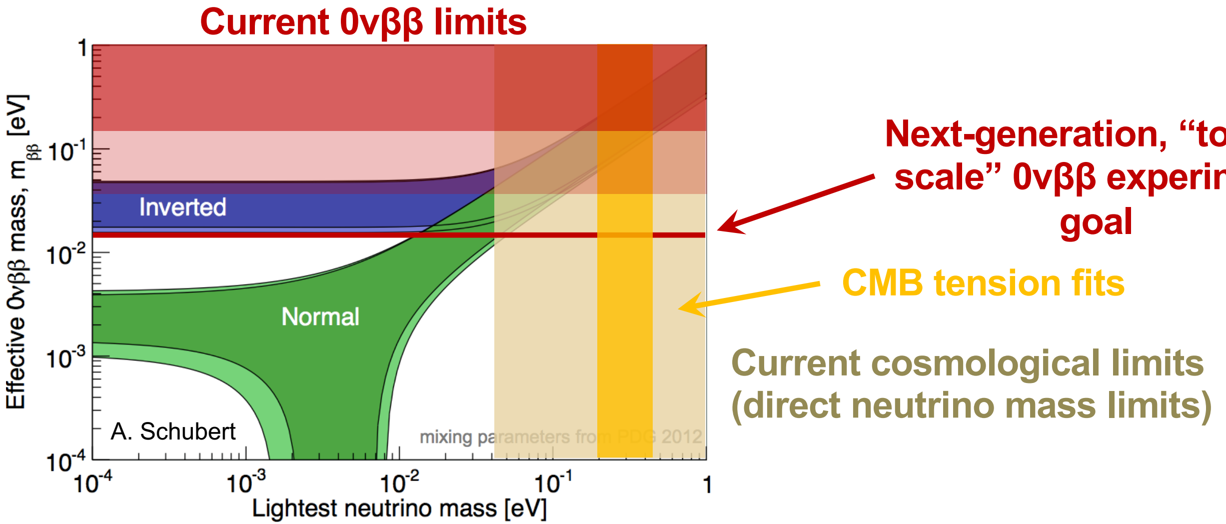
- Half-life of 0νββ related to neutrino mass scale
  - $\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$
  - $\langle m_{\beta\beta}\rangle = \left|\sum U_{ei}^2 m_i\right|$



$$U'_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\phi_1} & 0 \\ 0 & 0 & e^{-i\phi_2} \end{pmatrix}$$

Sensitivity to Neutrino Mass

- Half-life of 0vββ related to neutrino mass scale
  - $\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$
  - $\langle m_{\beta\beta}\rangle = \left|\sum U_{ei}^2 m_i\right|$



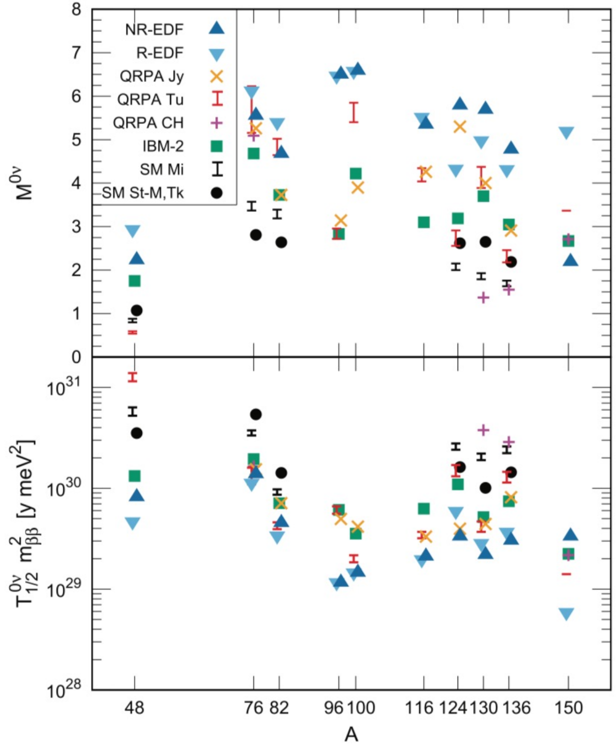
Plus a Dose of Theory

- Half-life of 0νββ related to neutrino mass scale
  - $\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$

Double-beta candidate	Q-value (MeV)	Phase space G_{01} (y^{-1})	Isotopic abundance (%)	Enrichable by centrifugation
^{48}Ca	4.27226 (404)	6.05×10^{-14}	0.187	No
^{76}Ge	2.03904 (16)	5.77×10^{-15}	7.8	Yes
^{82}Se	2.99512 (201)	2.48×10^{-14}	9.2	Yes
^{96}Zr	3.35037 (289)	5.02×10^{-14}	2.8	No
^{100}Mo	3.03440 (17)	3.89×10^{-14}	9.6	Yes
^{116}Cd	2.81350 (13)	4.08×10^{-14}	7.5	Yes
^{130}Te	2.52697 (23)	3.47×10^{-14}	33.8	Yes
^{136}Xe	2.45783 (37)	3.56×10^{-14}	8.9	Yes
^{150}Nd	3.37138 (20)	1.54×10^{-13}	5.6	No

  - also g_A quenching…

Engel and Menendez,
Rep. Prog. Phys. (2017)



Experimental Peak Search

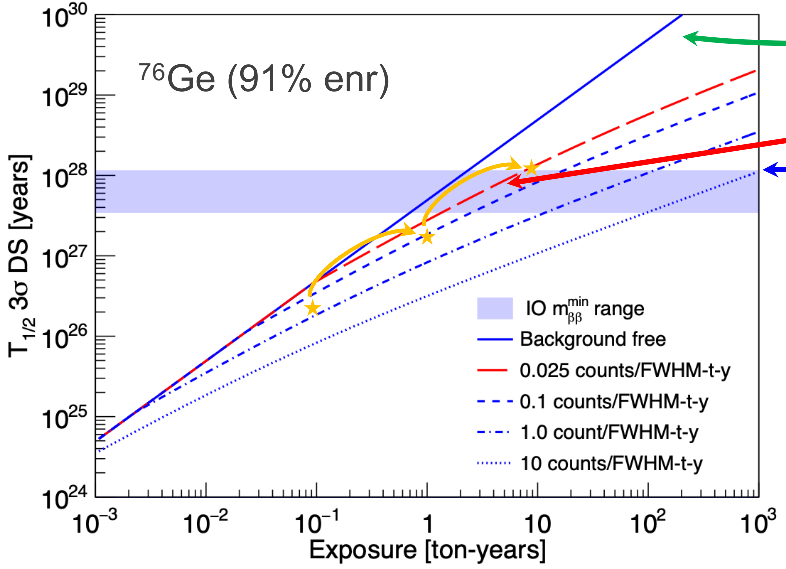
- Experiment sensitivity can largely be reduced to only two parameters, following prescription of Agostini-Benato-Detwiler:
    - Phys. Rev. D **96** (2017) 053001, arXiv:1705.02996
  - Sensitive exposure: $\mathcal{E}$
    - Product of active isotope mass and livetime, corrected by efficiency and ROI containment
  - Sensitive background: $\mathcal{B}$
    - Number of background events in ROI divided by sensitive exposure

- Parameters allow relevant statistical quantities to be calculated directly
  - Signal counts: $N_{0\nu\beta\beta} = \frac{\ln 2 \cdot N_A \cdot \mathcal{E}}{m_a \cdot T_{1/2}}$
  - Background counts: $N_{bkg} = \mathcal{B} \cdot \mathcal{E}$

Experimental Sensitivity

- Current world-leading sensitivity:
  - $T_{1/2} \approx 10^{26}$ yr
- Next-generation target sensitivity:
  - $T_{1/2} \approx 10^{28}$ yr

x100 in $T_{1/2}$, x10 in $m_{\beta\beta}$



background-free: linear scaling

quasi-background-free

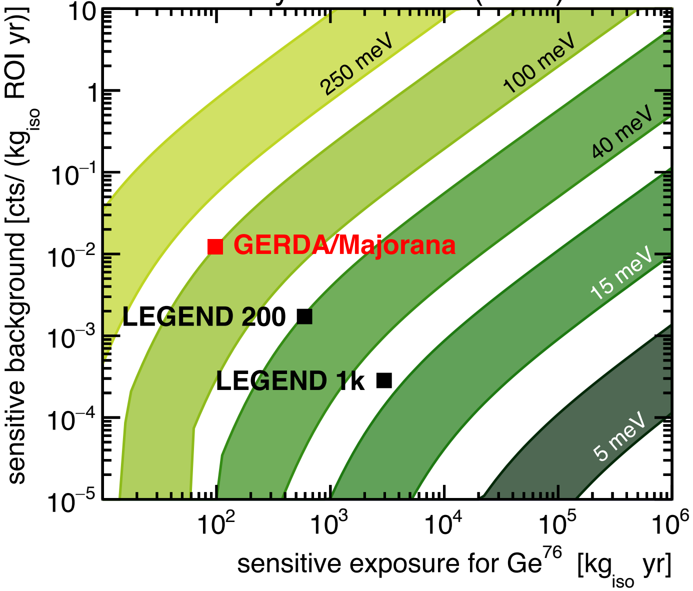
high background: square-root scaling

Example experiment progression
GERDA/MJD > LEGEND-200 > LEGEND-1000

Translating to Mass Sensitivity

- Experimental $T_{1/2}$ sensitivity is tradeoff of exposure and background
  - Typically design next-generation improvements in both simultaneously
- Width of mass bands relates to matrix element theory uncertainty

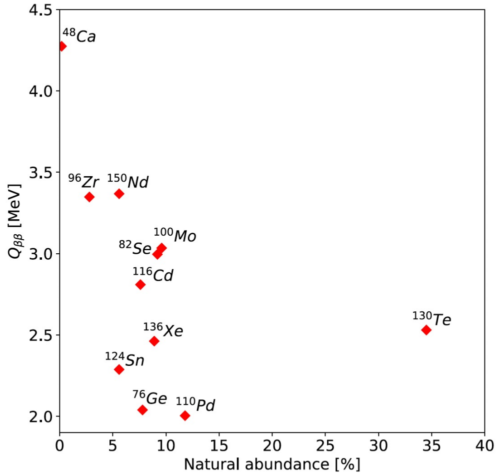
Phys. Rev. D **96** (2017) 053001



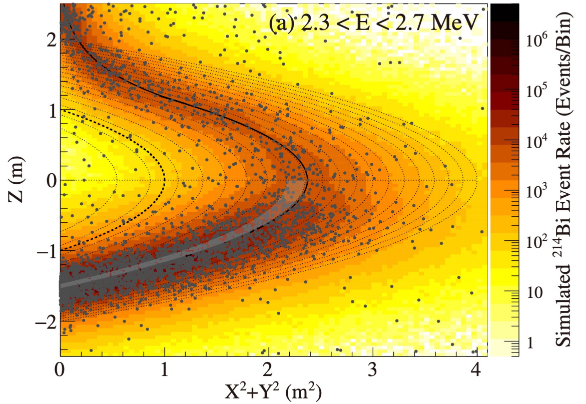
$$T_{1/2} = \frac{\ln 2 \cdot N_A \cdot \mathcal{E}}{m_a \cdot S_{3\sigma}(\mathcal{B} \cdot \mathcal{E})}$$

Experimental Considerations

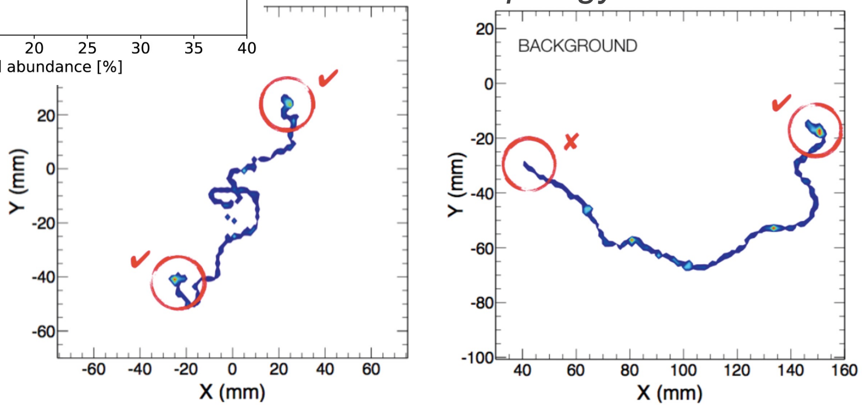
- Maximize exposure
  - Larger source
  - Higher enrichment*
  - Higher efficiency
- Minimize background
  - Deep underground
  - Material purity
  - Energy resolution
  - Decay Q-value*
  - Background rejection via cuts**



KamLAND: Fiducialization



NEXT: Topology Simulation



Classifying Experiments

- At gross simplification, there are two kinds of detectors:
  - Monolithic
    - Simpler size scaling
    - Self-shielding for lower background
  - Granular
    - Better energy resolution
    - Modularity

- Detectors leverage all basic signal readouts (charge, light, heat)

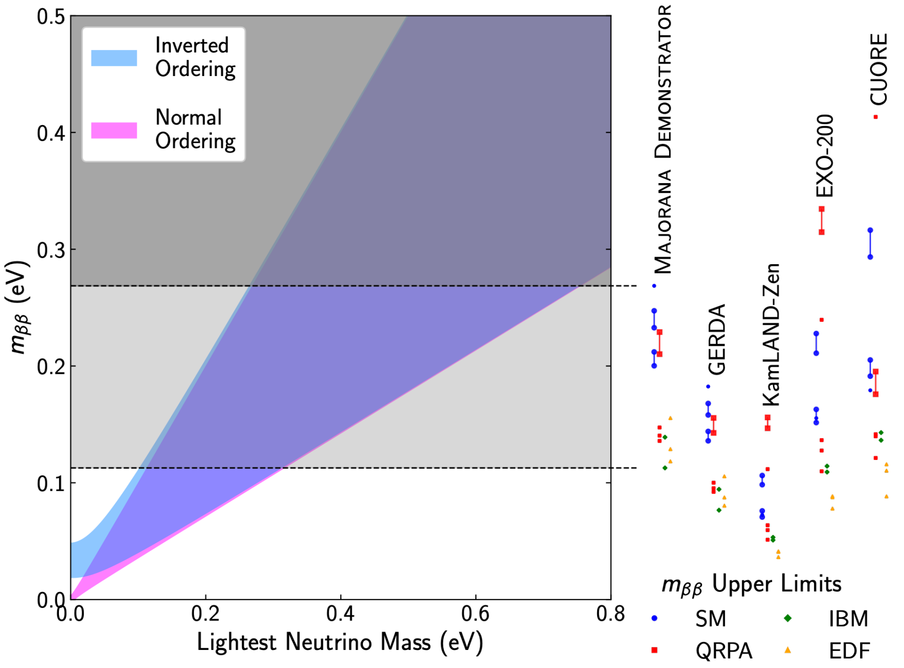
Contextualizing Experiments

- “Current leaders” have 10^{25}-10^{26} yr sensitivity
    - CUORE, EXO-200, GERDA, KamLAND-Zen, MAJORANA DEMONSTRATOR

- “Tonne-scale” experiments target 10^{28} yr sensitivity
    - CUPID, nEXO, LEGEND-1000

- With various other experimental programs targeting intermediate reach, or R&D towards beyond tonne-scale

Current 0νββ Field Context



Experiment	Half-Life Limit (yr)	Exposure (kg*yr)
MAJORANA DEMONSTRATOR	8.3e25	65
GERDA [1]	1.8e26	127
KamLAND-Zen800 [2]	2.3e26	970
EXO-200 [3]	3.5e25	234
CUORE [4]	3.2e25	373

[1] M. Agostini et al. (GERDA Collaboration), PRL **125**, 252502 (2020)
[2] S. Abe et al (KamLAND-Zen Collaboration), PRL **130**, 051801 (2023)
[3] G. Anton et al. (EXO-200 Collaboration), PRL **123**, 161802 (2019)
[4] D. Q. Adams et al. (CUORE Collaboration) PRL **124**, 122501 (2019)

Best-fit values of neutrino oscillation parameters from 2022 PDG [PTEP **2022** 083C01 (2022)]

Too Many Experiments to Discuss

A non-exhaustive, and slightly outdated list

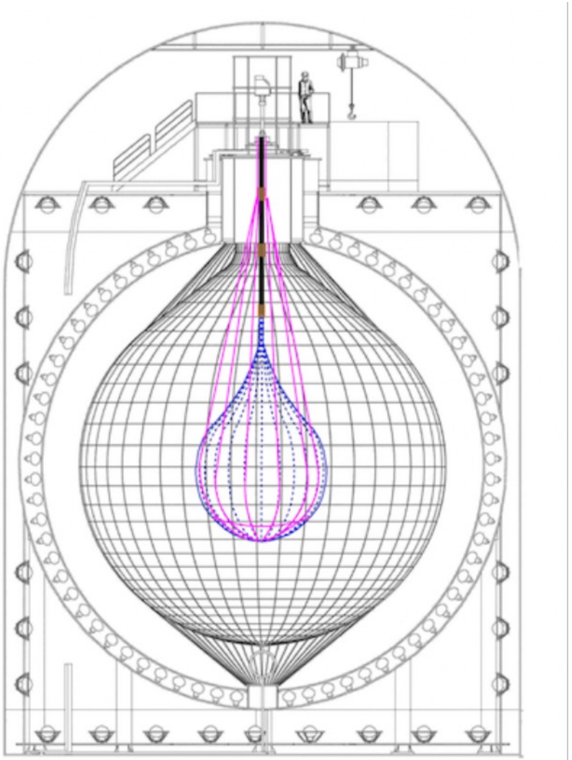
- (*there's a lot to keep track of*)

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	^{48}Ca	305 kg CaF_2 crystals - liq. scint	0.3 kg	Operating
CARVEL	^{48}Ca	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	^{76}Ge	Ge diodes in LAr	15 kg	Complete
GERDA II	^{76}Ge	Point contact Ge in active LAr	44 kg	Operating
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
NEMO3	$^{100}Mo/^{82}Se$	Foils with tracking	6.9 kg/0.9 kg	Complete
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF6 high pressure gas TPC	50 kg	R&D
AMoRE	^{100}Mo	CaMoO4 bolometers (+ scint.)	5 kg	Construction
CUPID	^{100}Mo	Scintillating Bolometers	250 kg	R&D
COBRA	$^{116}Cd/^{130}Te$	CdZnTe detectors	10 kg	Operating
CUORE-0	^{130}Te	TeO_2 Bolometer	11 kg	Complete
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
SNO+ Phase II	^{130}Te	3% ^{nat}Te in liquid scint.	8 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scint.	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scint.	750 kg	Operating
KamLAND2-ZEN	^{136}Xe	2.7% in liquid scint.	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	Xe liquid TPC	3.5 tonnes	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DCBA	^{150}Nd	Nd foils & tracking chambers	30 kg	R&D

R&D Construction Operating Complete

from John Wilkerson

KamLAND-Zen

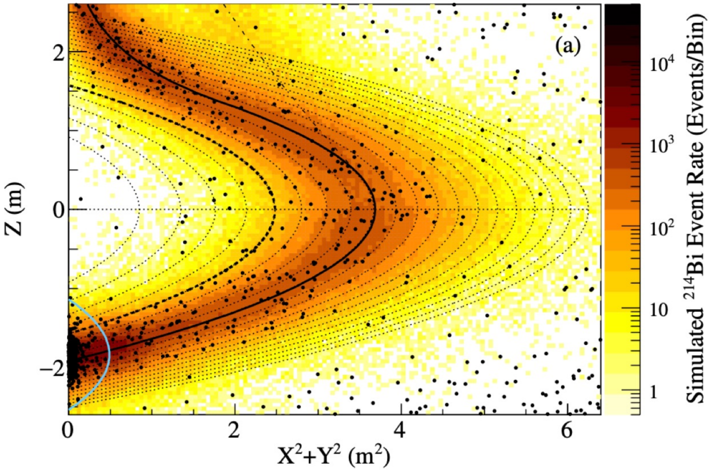


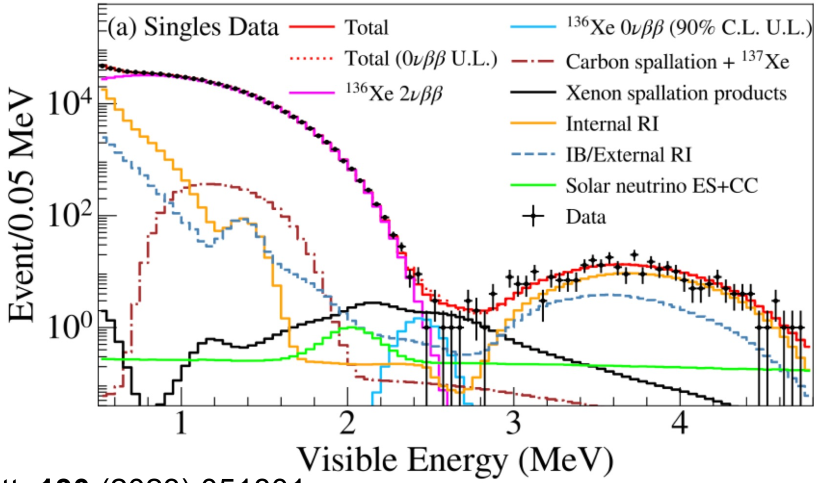
From Azusa Gando, Nu2022

- Builds on successful KamLAND detector and physics program
  - Ultra-clean large-volume liquid scintillator detector
- Inner volume segregated by clean balloon with ^{136}Xe dissolved
- Phased program scaling isotope mass and background
  - KamLAND-Zen 400 : first experiment to reach $T_{1/2} > 10^{26}$ yr exclusion
  - KamLAND-Zen 800 : current leading single-experiment sensitivity, $T_{1/2} > 2.3\times10^{26}$ yr exclusion
  - KamLAND2-Zen : planned future iteration

KamLAND-Zen 800 Result

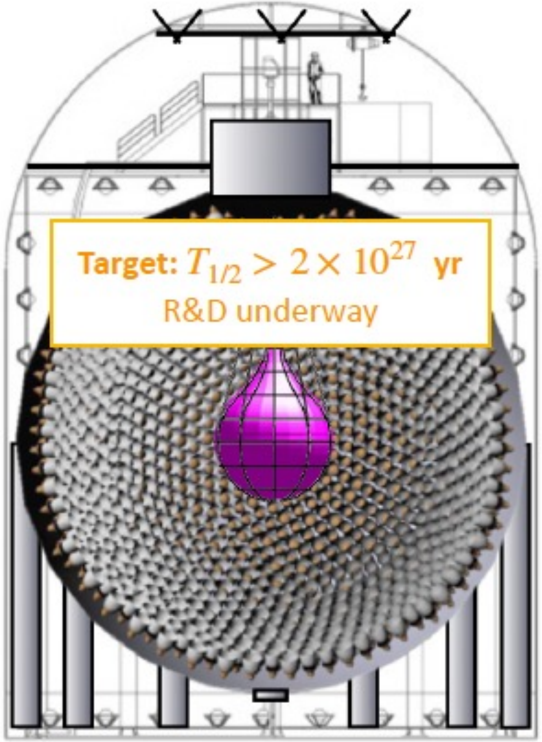
- Current experimental campaign began January 2019
  - 750 kg of ^{136}Xe (double 400 phase), cleaner material
- Current result, $T_{1/2} > 2.3{\times}10^{26}$ yr exclusion
  - Sensitivity target of $T_{1/2} > 5{\times}10^{26}$ yr





(KamLAND-Zen) Phys. Rev. Lett. **130** (2023) 051801

KamLAND-Zen Future



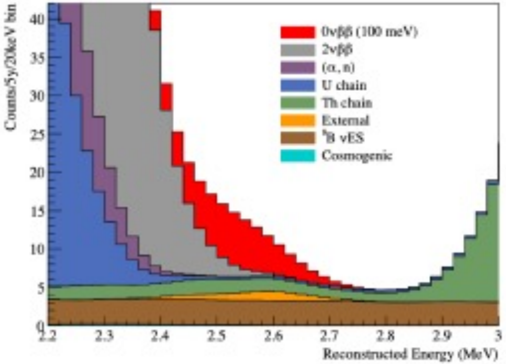
From Azusa Gando, Nu2022

- Increase loading to 1 tonne ^{136}Xe
- Increased energy resolution from new high-QE PMTs with Winston cones and brighter scintillator
- New electronics with longer acquision to suppress (dominant) cosmogenic background
- Scintillating balloon for surface background suppression

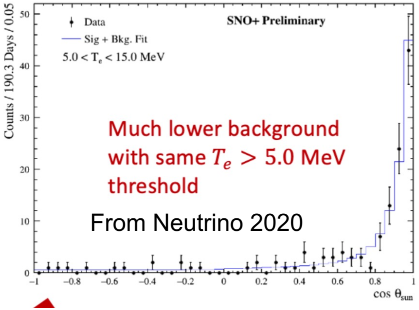
- Sensitivity target of $T_{1/2} > 2{\times}10^{27}$ yr

SNO+

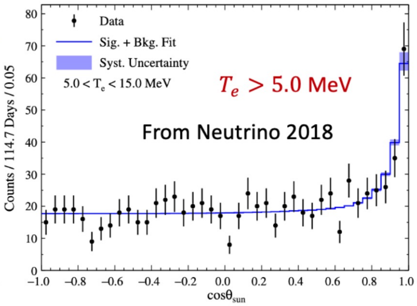
- Builds on successful SNO detector and physics program
  - Liquid scintillator active volume replaces heavy water
  - Tellurium compound dissolved in LS
    - >1.3 tonne ^{130}Te beginning at 0.5% ^{nat}Te loading
- Water phase 2017-2019, LS fill complete April 2021



(SNO+) AHEP 2016 (2016) 6194250

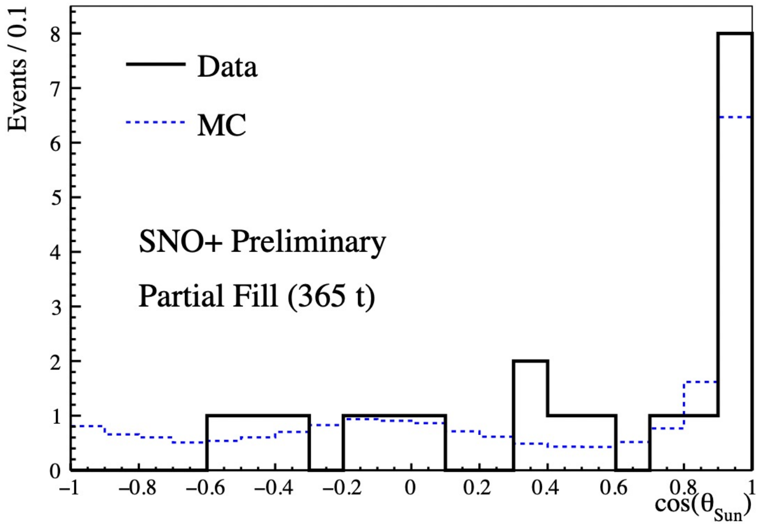


Phys. Rev. D **99**, 012012



SNO+ Results

- Partial fill data (COVID-imposed) provided first demonstration of event-by-event direction reconstruction in large scale LS detector

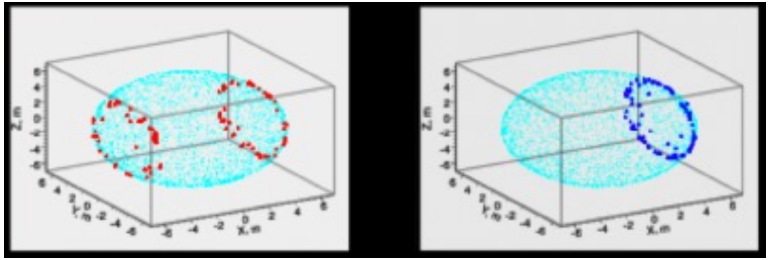


From Will Parker, NDM22

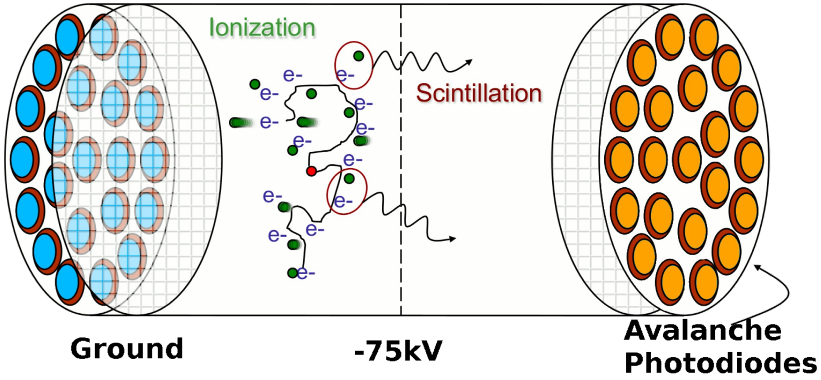
Future LS-Based Experiments

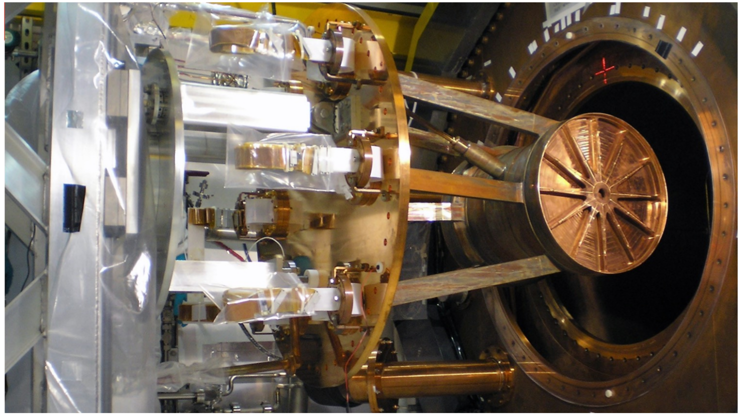
- JUNO boasts very large volume, low-background, high light-yield base
  - Could dissolve 50T of ^{136}Xe
  - Switch to $0\nu\beta\beta$ operations in 2030s

- R&D on timing/wavelength separation of Cerenkov and scintillation signals
  - Need push on light emission (slow fluors, dichroic filler) and detection (LAPPDs)
  - Plus work on loading (quantum dots), WbLS, etc.

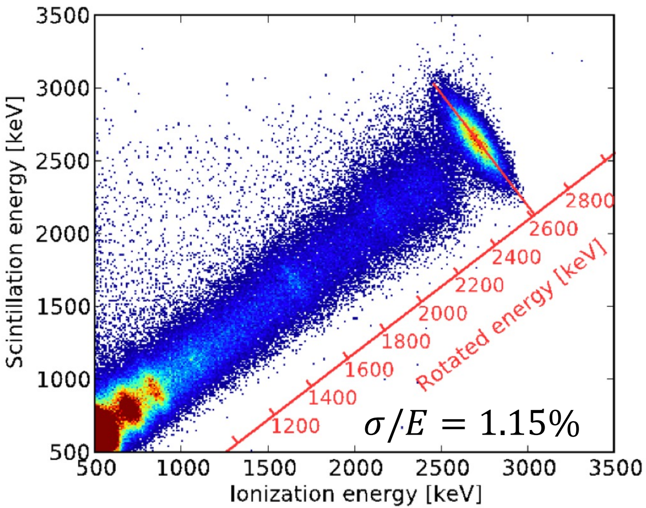


EXO-200





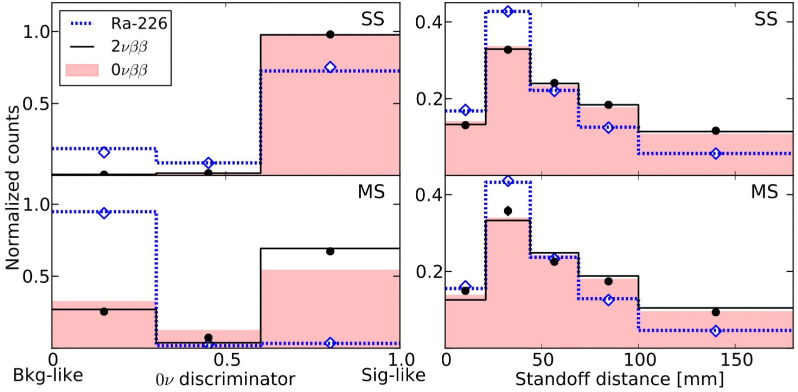
- Experimental program ran 2011-2018
- Single-phase liquid xenon time projection chamber (TPC)
  - Light and charge signals collected



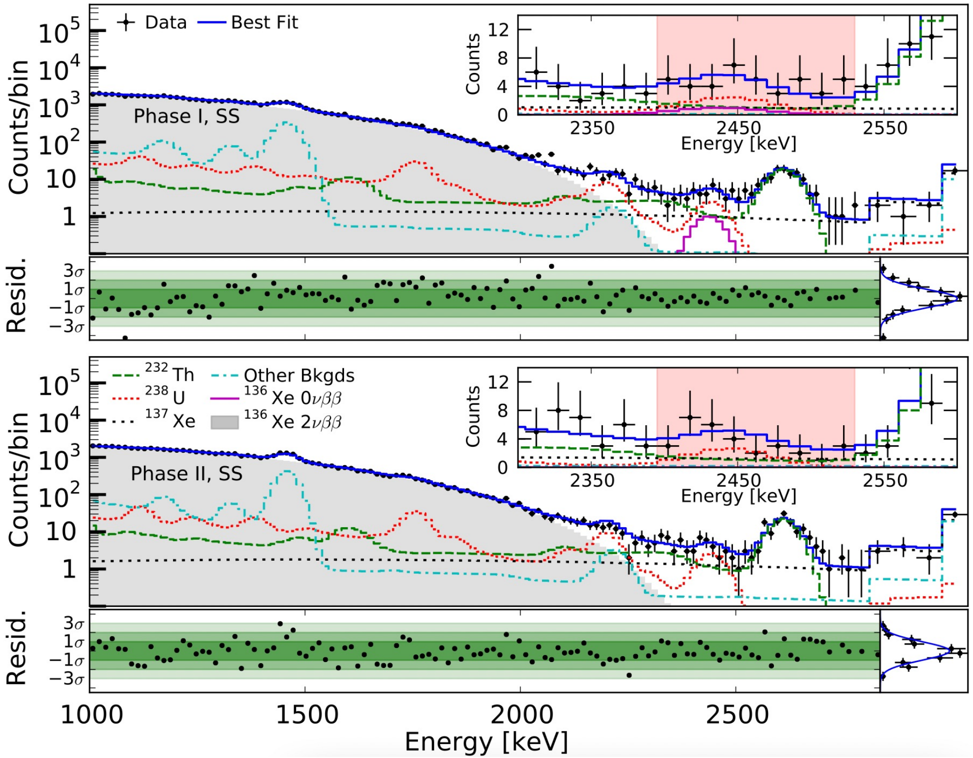
EXO-200 Final Result

- Limit of $T_{1/2} > 3.5 \times 10^{25}$ yr
- Roughly balanced ROI background from U/Th/^{137}Xe

- DNN signal classifier

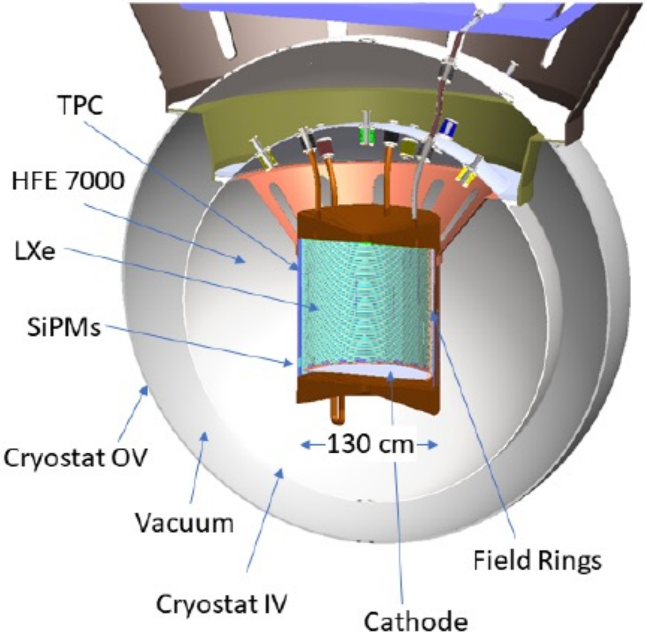


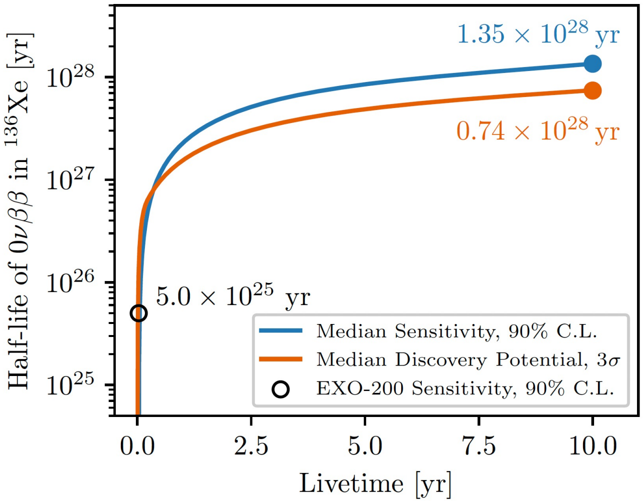
(EXO-200) Phys. Rev. Lett. **123** (2019) 161802



nEXO

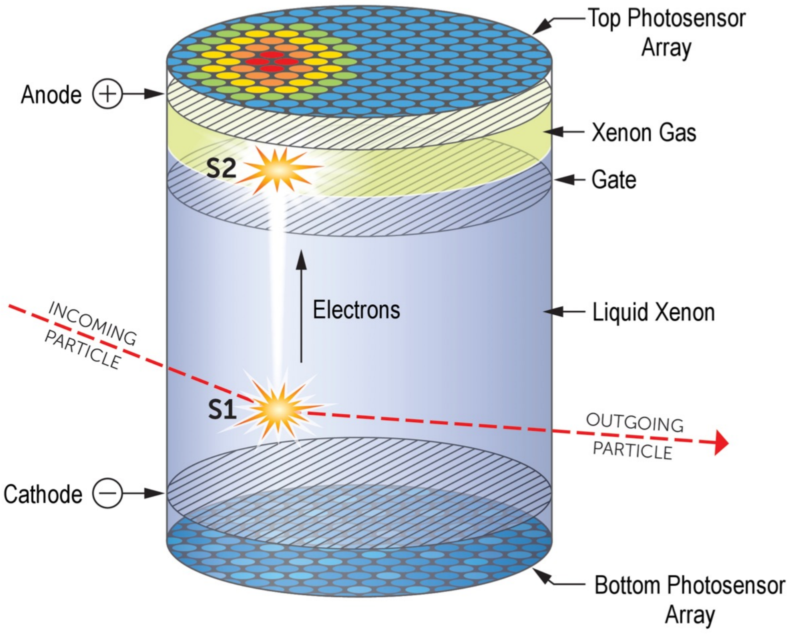
- Single-phase LXe time projection chamber
    - Monolithic single drift volume of 1.2 m length
- Proposed 5 tonne target enriched to 90% in ^{136}Xe
- Solid xenon barium tagging under investigation for zero-background upgrade





pCDR: arXiv1805.11142
Sensitivity: arXiv 2106.16243

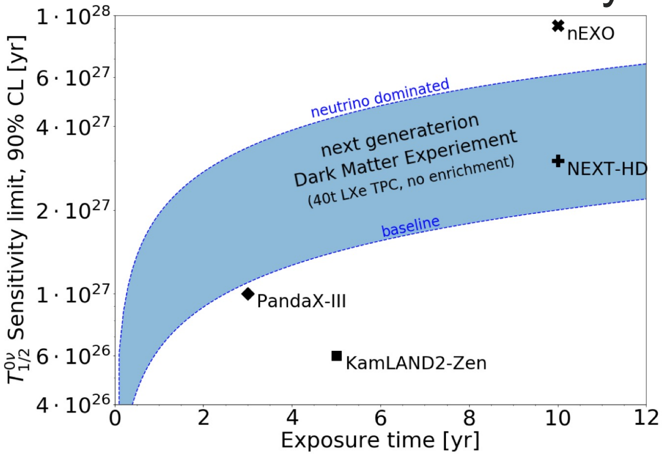
Xenon Dark Matter Detectors



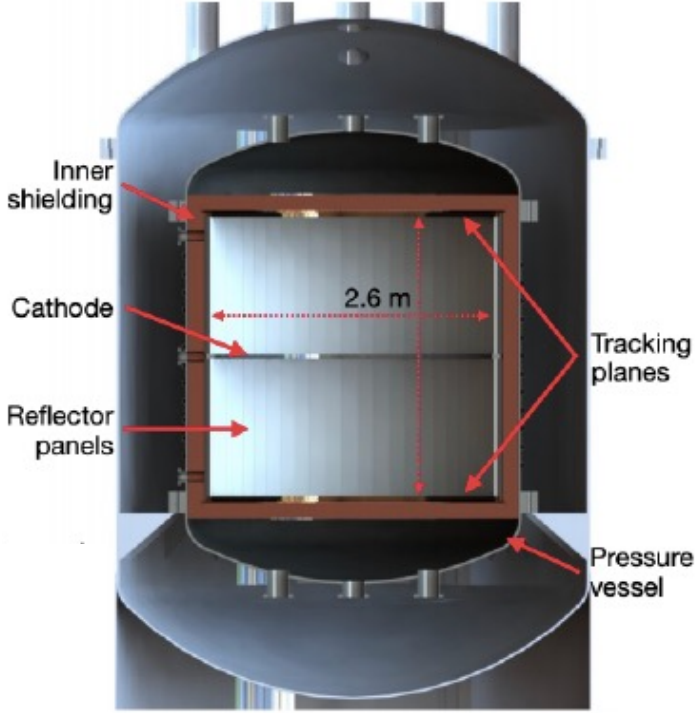
J. Aalbers *et al*. J. Phys. G **50** (2023) 013001

- Dual-phase xenon TPCs dominant in dark matter field
  - Carry $0\nu\beta\beta$ sensitivity for free
  - But not optimized for this search

40T Detector Sensitivity

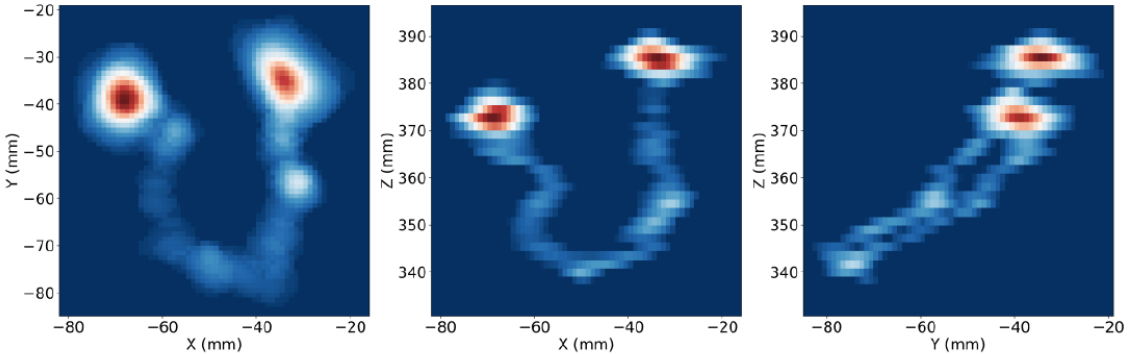


NEXT & PandaX-III



From Alberto Usón Andrés, TAUP21

- Distinct R&D programs focused on high-pressure gaseous xenon TPC technologies
  - Centered at Canfranc (Spain) and CJPL (China)
  - Evolving to O(100) kg in ~last year
- Topological information provides powerful background rejection
- Barium-tagging technologies being pursued



(NEXT) JHEP **7** (2021) 146

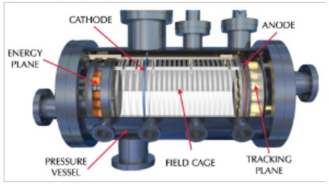
NEXT Progression

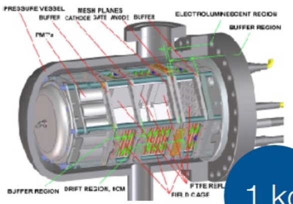
From Michel Sorel, Nu2022

Prototypes

2008-2015

- Demonstration of detector concept



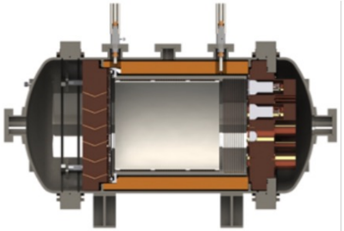


1 kg

NEXT-White

2016-2021

- Det. performance near $Q_{\beta\beta}$
- Background measurement
- $2\nu\beta\beta$ measurement

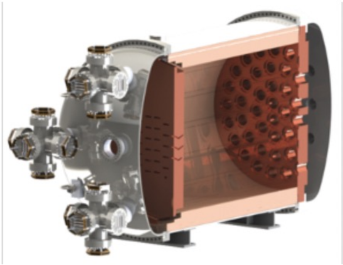


4 kg

NEXT-100

2022-2025

- Background measurement
- $0\nu\beta\beta$ search



100 kg

NEXT-HD

2026?

- $0\nu\beta\beta$ search through inverted ν mass ordering

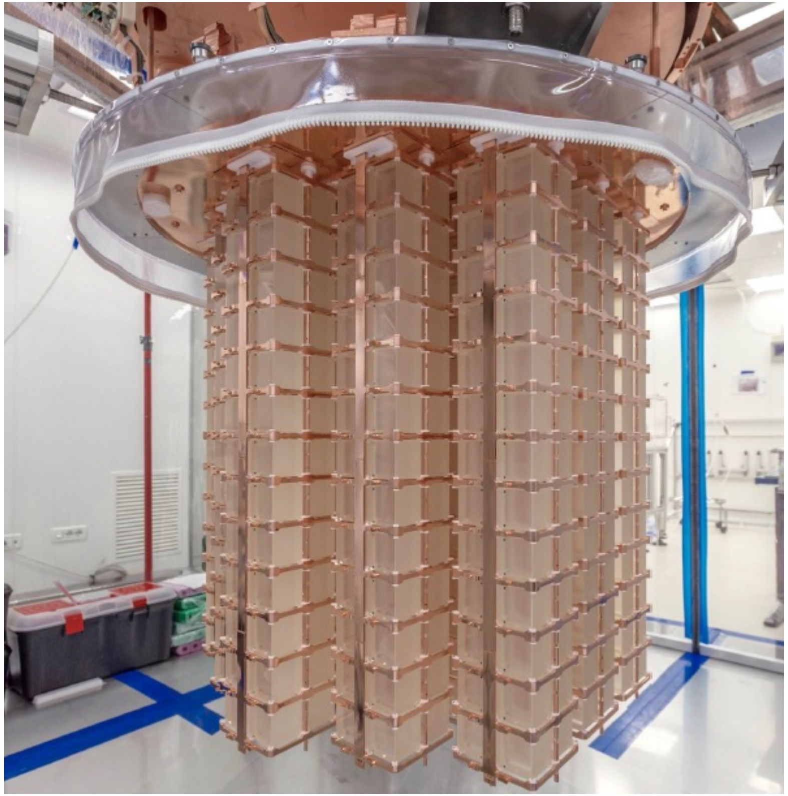
1 ton

NEXT-BOLD

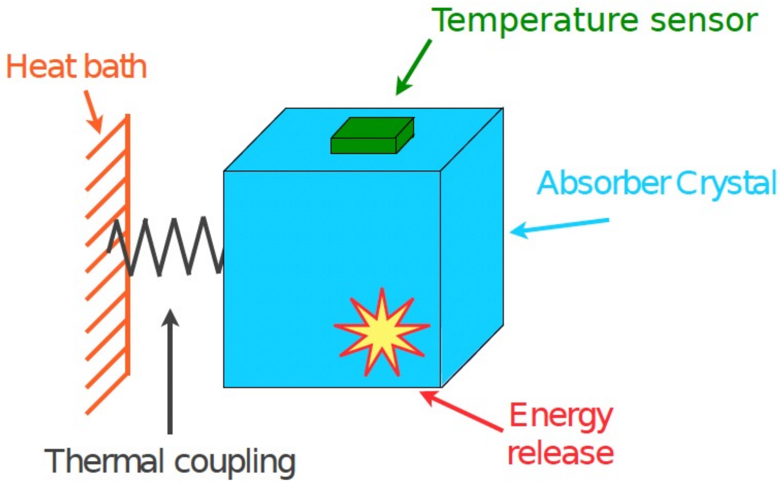
- Barium tagging for bgr-free experiment

2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030

CUORE Cryogenic Underground Observatory for Rare Events

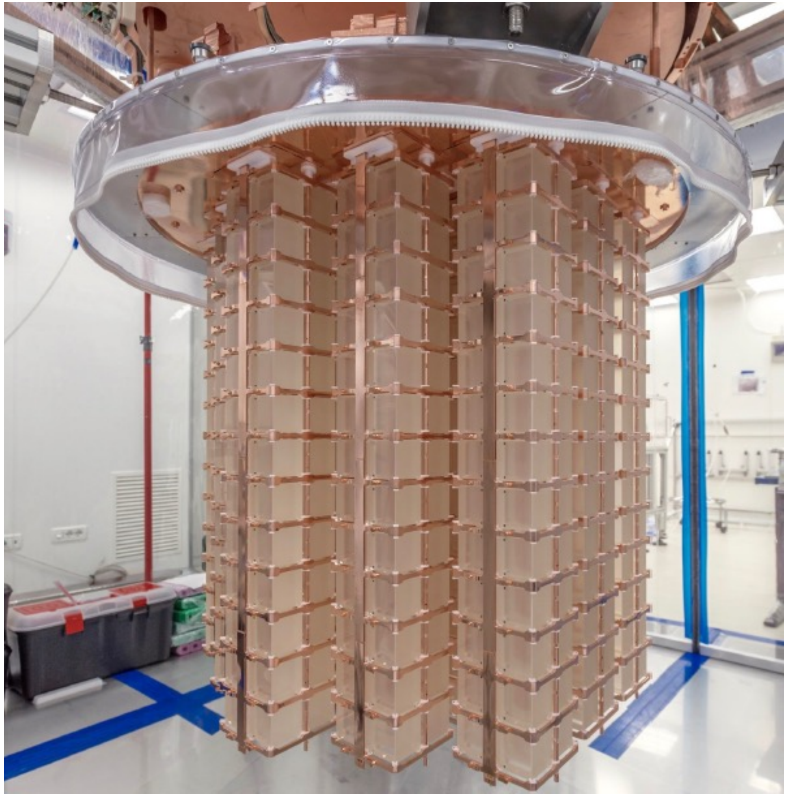


- Array of cryogenic TeO_2 bolometers operated at 10 mK
  - 988 channels with 206 kg ^{130}Te
- Operating since Spring 2017



From Irene Nutini, Nu2022

CUORE Cryogenic Underground Observatory for Rare Events



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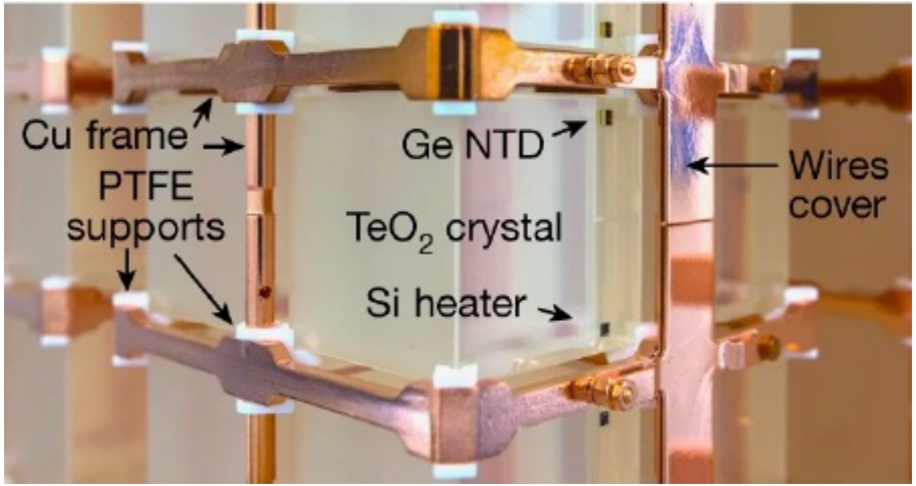
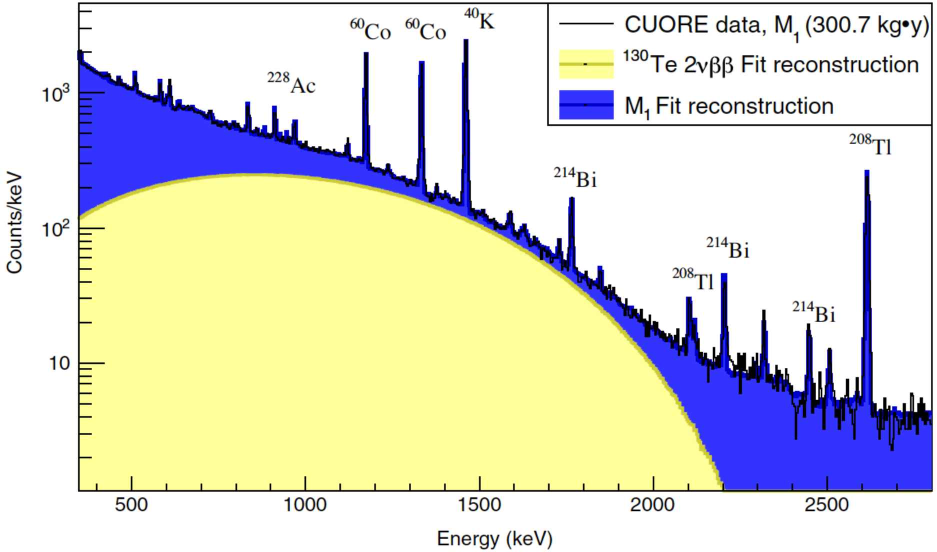


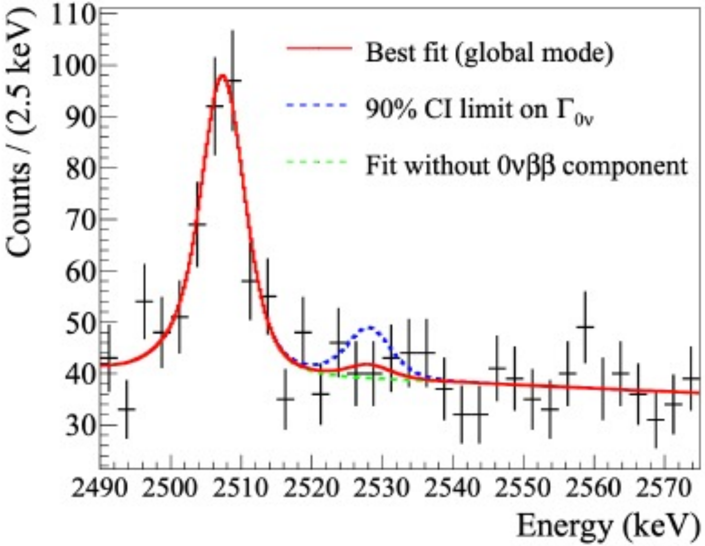
From Irene Nutini, Nu2022

CUORE Cryogenic Underground Observatory for Rare Events



- Latest result $T_{1/2} > 2.2{\times}10^{25}$ yr
- Based on 1 tonne*yr (TeO_2)
  - 1/3 of planned dataset

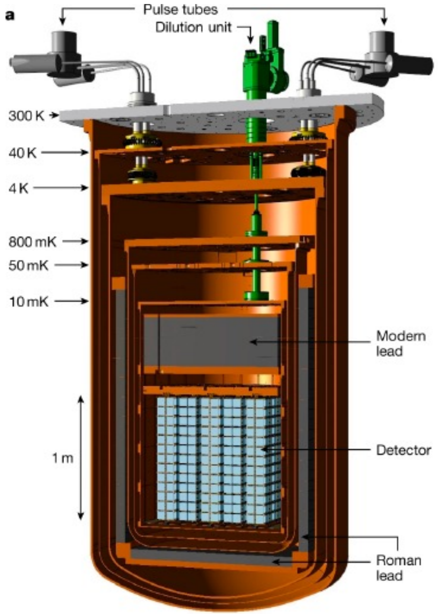
- Spectrum surprisingly not dominated by 2νββ events



From Irene Nutini, Nu2022

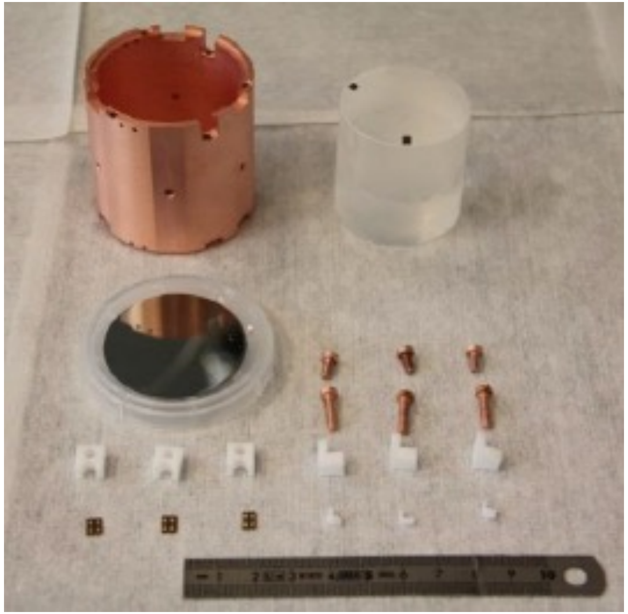
Fun Aside on CUORE

If you haven't read about CUORE's Roman lead, look it up

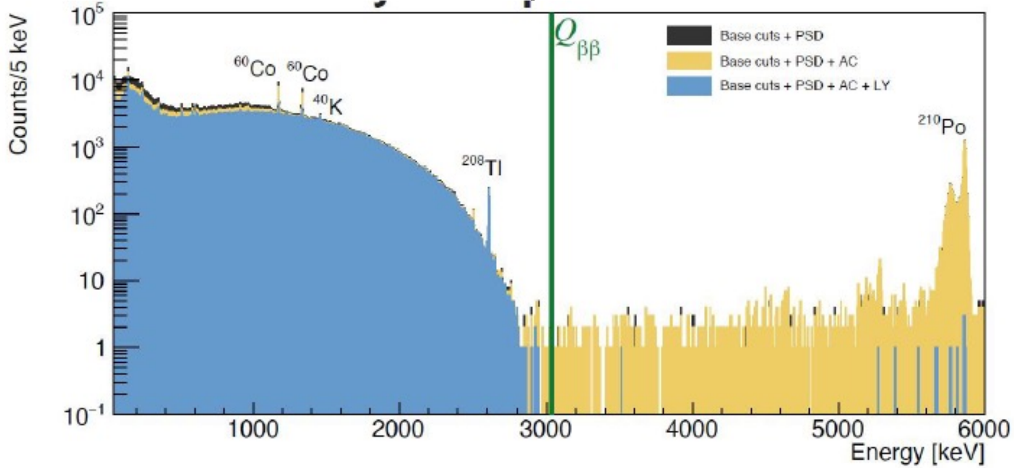


(CUORE) Nature **604** (2022) 53

CUPID: CUORE Upgrade with Particle ID



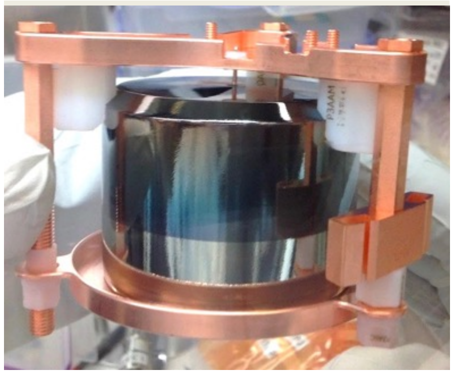
- Array of cryogenic $Li_2{}^{100}MoO_4$ bolometers
- ^{100}Mo affords higher $Q_{\beta\beta}$ = 3.034 MeV
- Charge+light readout for background suppression
- Also conducted R&D tests of $Zn^{82}Se$ crystals
  - Minimal modification required to switch source

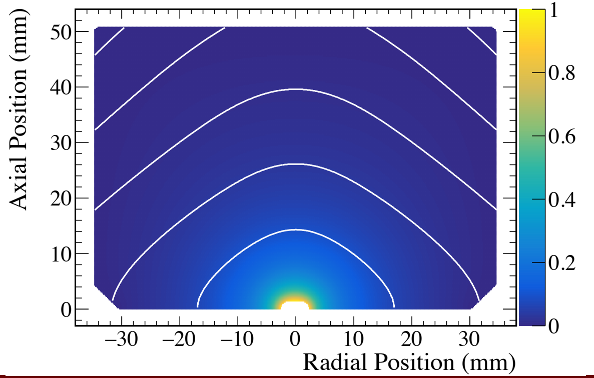


From Anastasiia Zolotarova, Nu2022

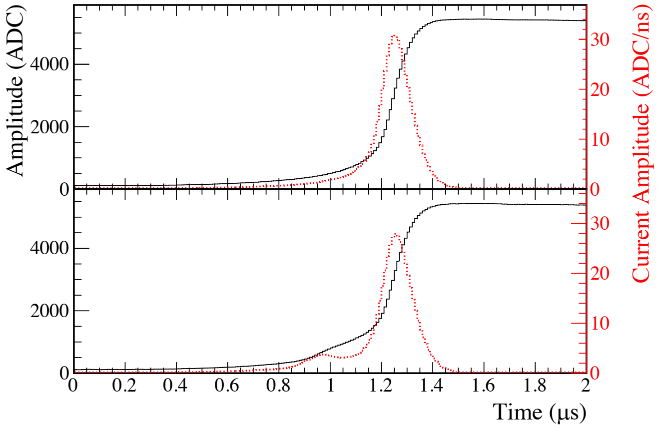
^{76}Ge Searches

- Modern germanium-based 0vββ boast the lowest backgrounds with best energy resolution for quasi-background free operation
  - Combined have best half-life sensitivity
- Share common "point-contact" germanium detector design
  - Excellent energy resolution
  - Excellent pulse shape discrimination performance
  - Low noise, low threshold for BSM searches

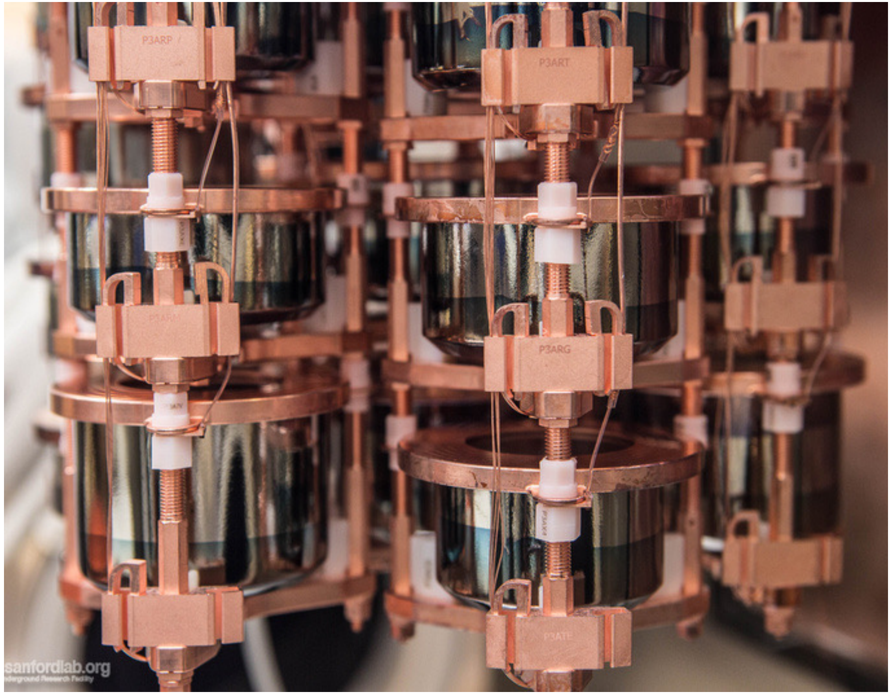




(MAJORANA) Phys. Rev. C **99** 065501 (2019)



MAJORANA DEMONSTRATOR



- Ge arrays in vacuum cryostat in large layered passive shield (Cu and Pb)
- 30 kg enriched to 88% in ^{76}Ge
- 0vββ operations 2015-2021

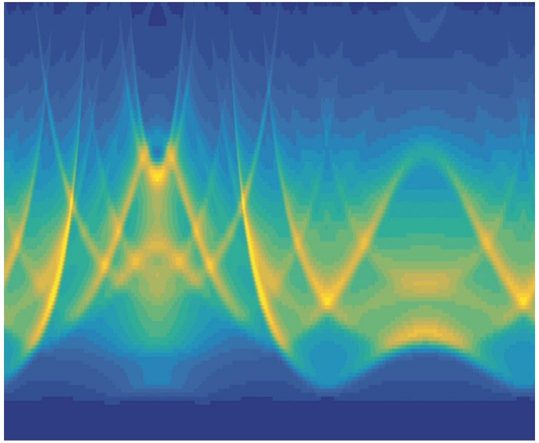
- Focus on low-background materials and low-noise electronics developed
  - Underground electroformed copper
  - Low-mass front-ends enable best energy resolution of 0.12% (FWHM)

- Still operating, conducting world-leading search for decay of ^{180m}Ta

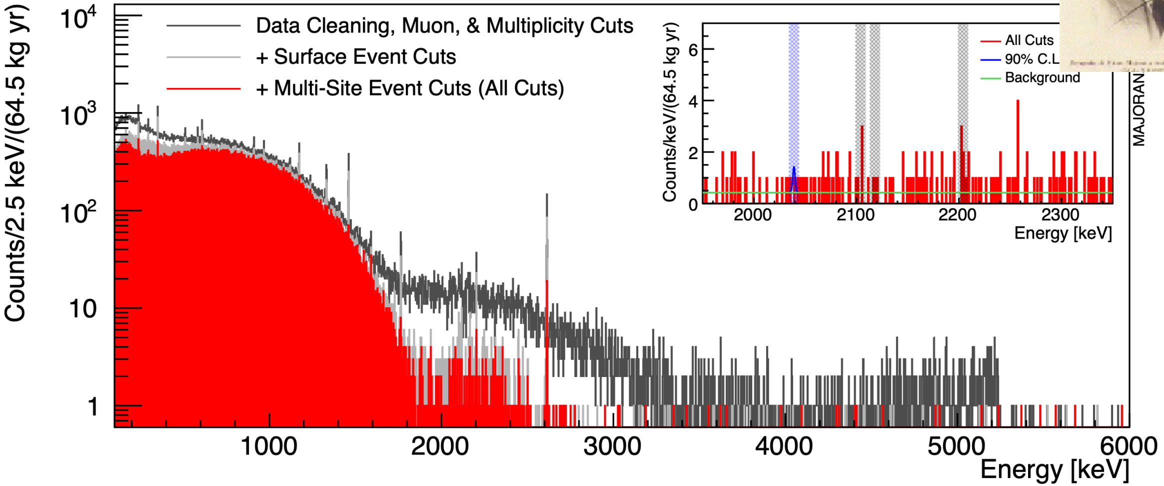
MAJORANA Results

- 65 kg*yr exposure
- $T_{1/2} > 8.3{\times}10^{25}$ yr

(MAJORANA) Phys. Rev. Lett. **129** (2022) 081803

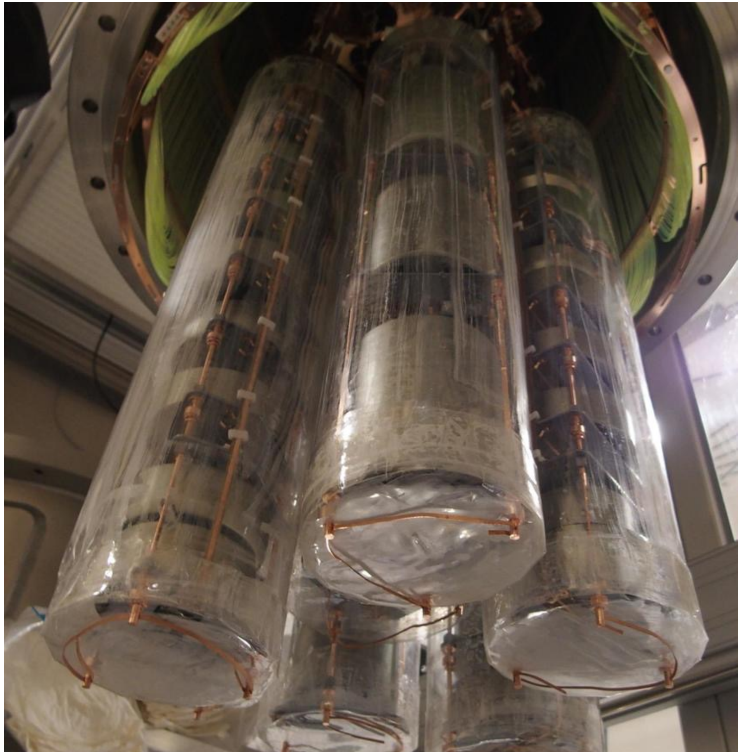


(MAJORANA) Phys. Rev. Lett. **130** (2023) 062501



- Notable other searches leverage energy resolution and low energy threshold
  - Tantalum, excited states decay, solar axions, quantum wavefunction collapse, lightly ionizing particles, bosonic dark matter, tribaryon decay, cosmogenics

GERDA

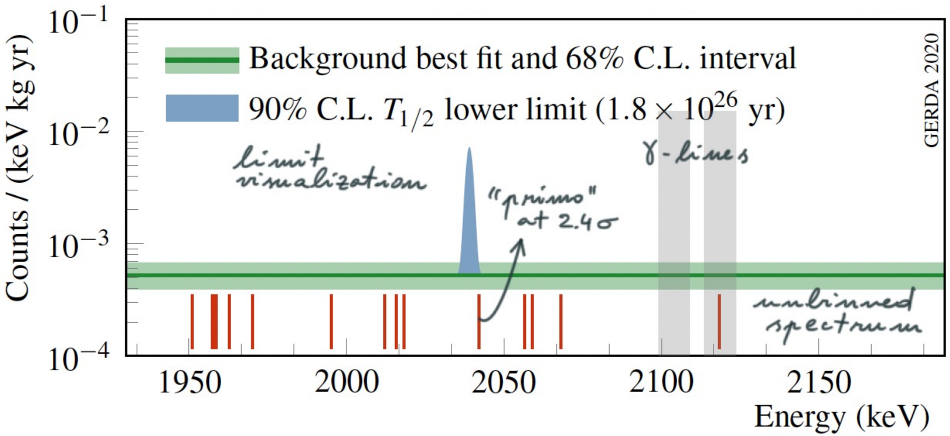


From Luigi Pertoldi, PANIC21

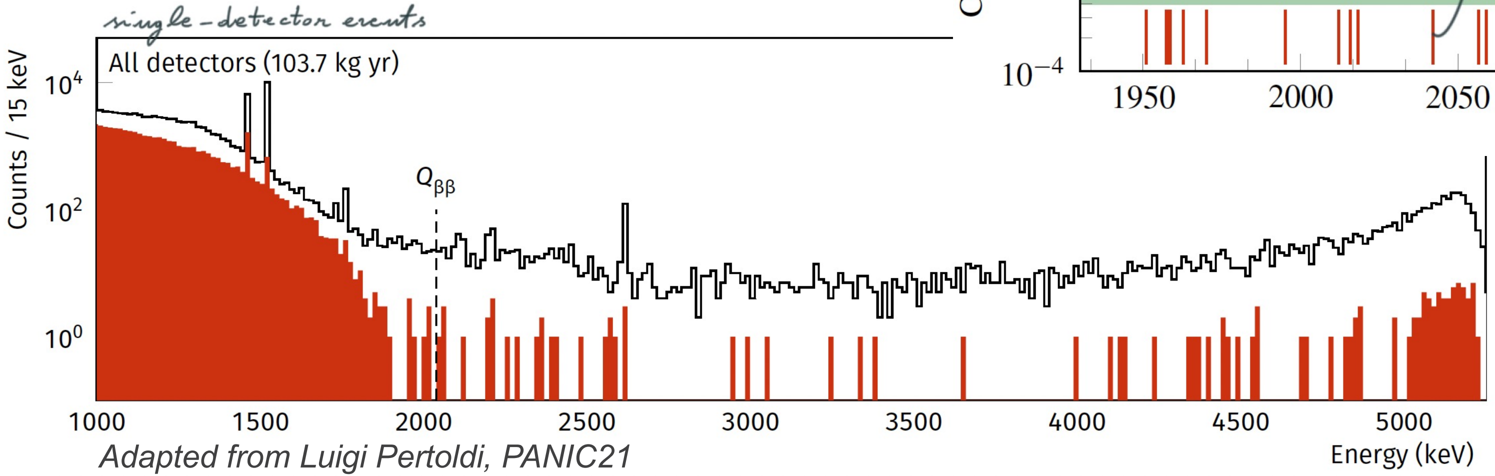
- Ge detector array immersed in novel active liquid argon veto
- ~40 kg enriched in ^{76}Ge
- Operated 2015-2019
- Achieved $\mathrm{T}_{1/2} > 1.8 \cdot 10^{26}\ \mathrm{yr}$ sensitivity
- Background index $5 \cdot 10^{-4}$ cts / (keV kg yr)
  - World-leading
  - Achieved quasi-background free operation with no background observed in ROI in exposure

GERDA Result

- Liquid argon veto decimates background with minimal cut efficiency variation

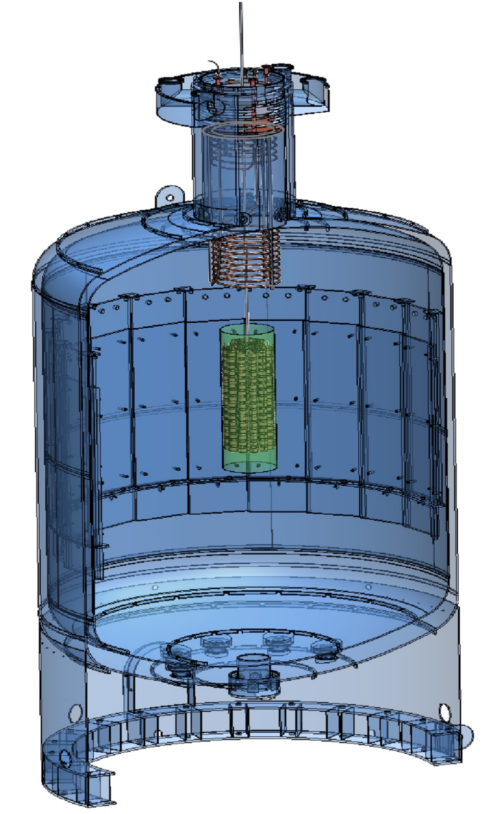


From Luigi Pertoldi, PANIC21



Adapted from Luigi Pertoldi, PANIC21

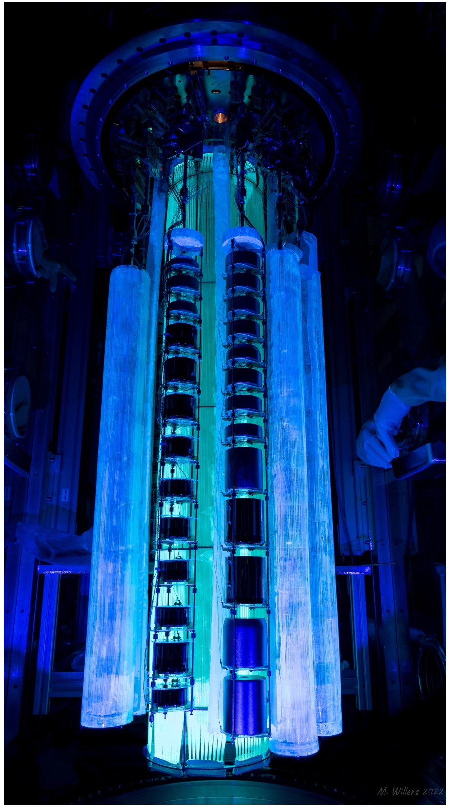
LEGEND-200



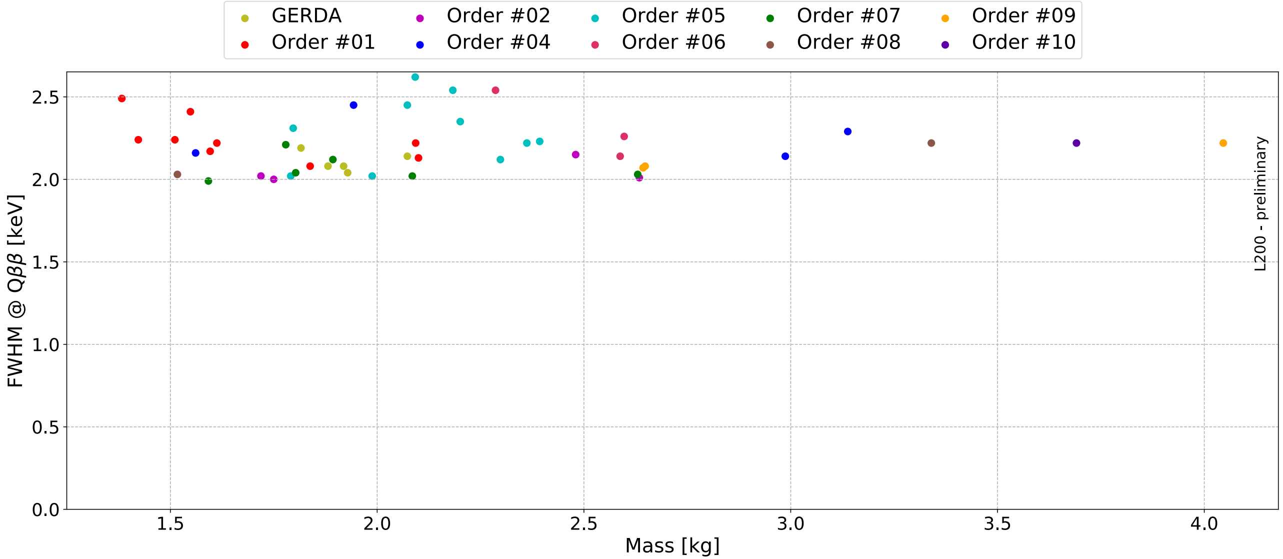
- Collaboration formed by merger of GERDA and MAJORANA (and some others)
- Leveraging best advances from each experiment
  - Liquid argon active veto from GERDA
  - Ultra-low-background materials from MAJORANA
- Primarily composed of new larger-mass inverted coaxial point contact detectors
  - Average detector mass >3x those of last-generation
  - Enriched detectors from predecessors also running in L200

- First results coming at TAUP later this month
- Sensitivity goal of 10^{27} yr in 5 yr run

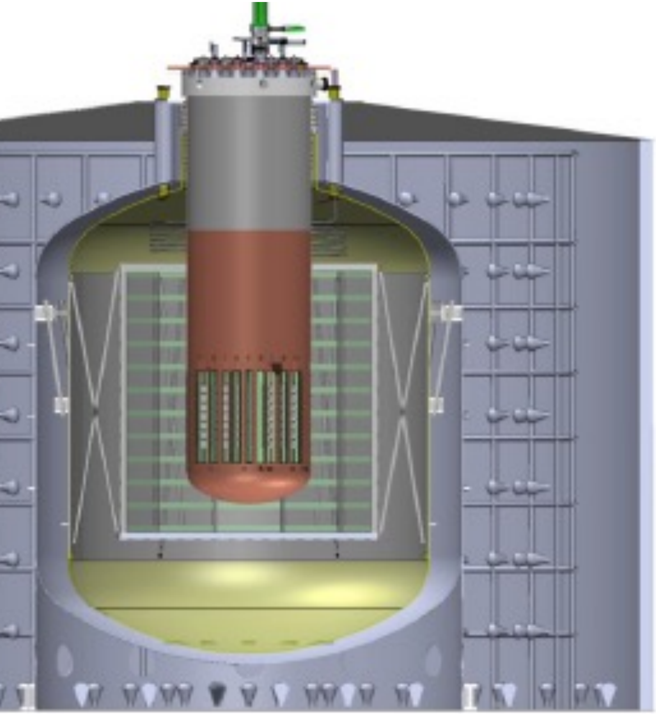
LEGEND-200



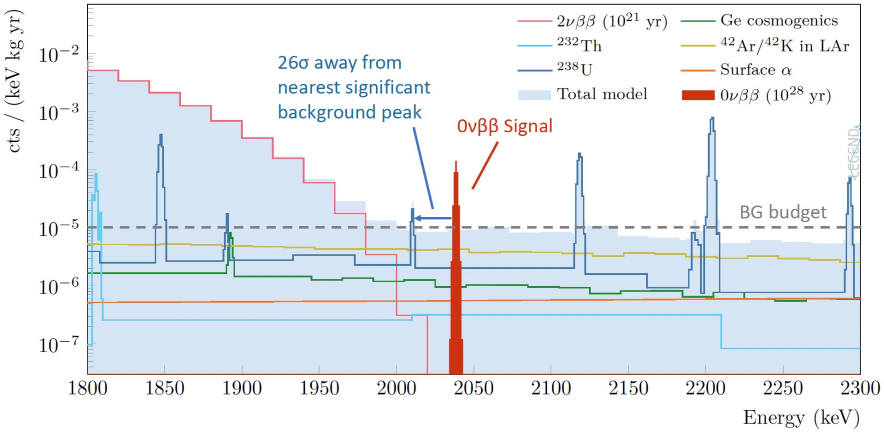
- New large-mass detectors achieving excellent performance for resolution (and PSA)



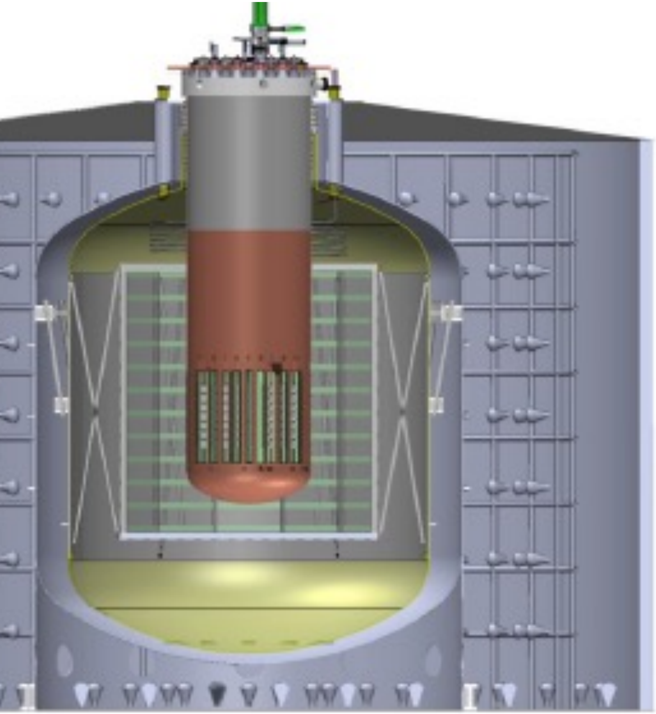
LEGEND-1000



- Tonne-scale continuation of ^{76}Ge program
- Underground argon volumes reduce surface bg
  - Reopen low-energy physics program
- Proposes lowest background, best resolution, greatest discovery potential



LEGEND-1000



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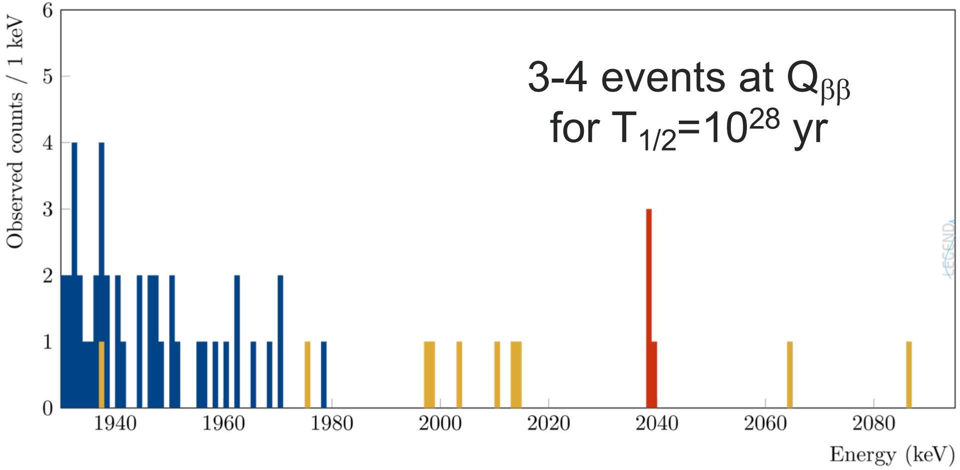
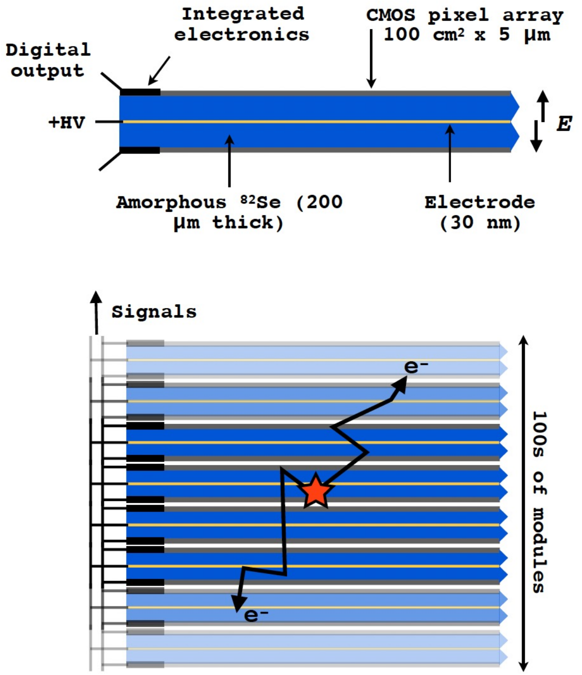


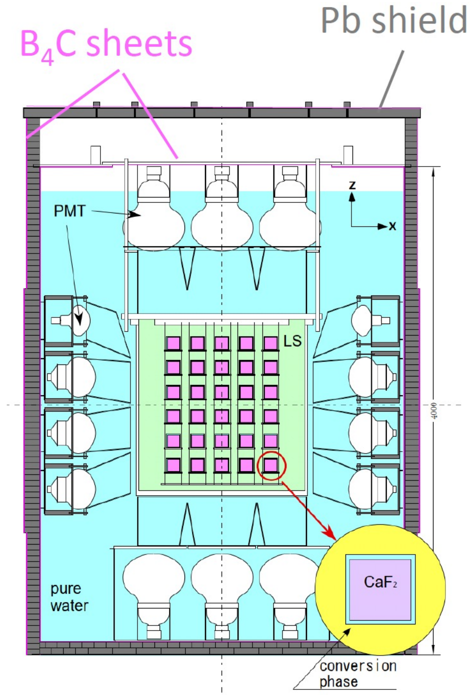
Plus Many Other Technologies

SELENA: pixel array to capture topology



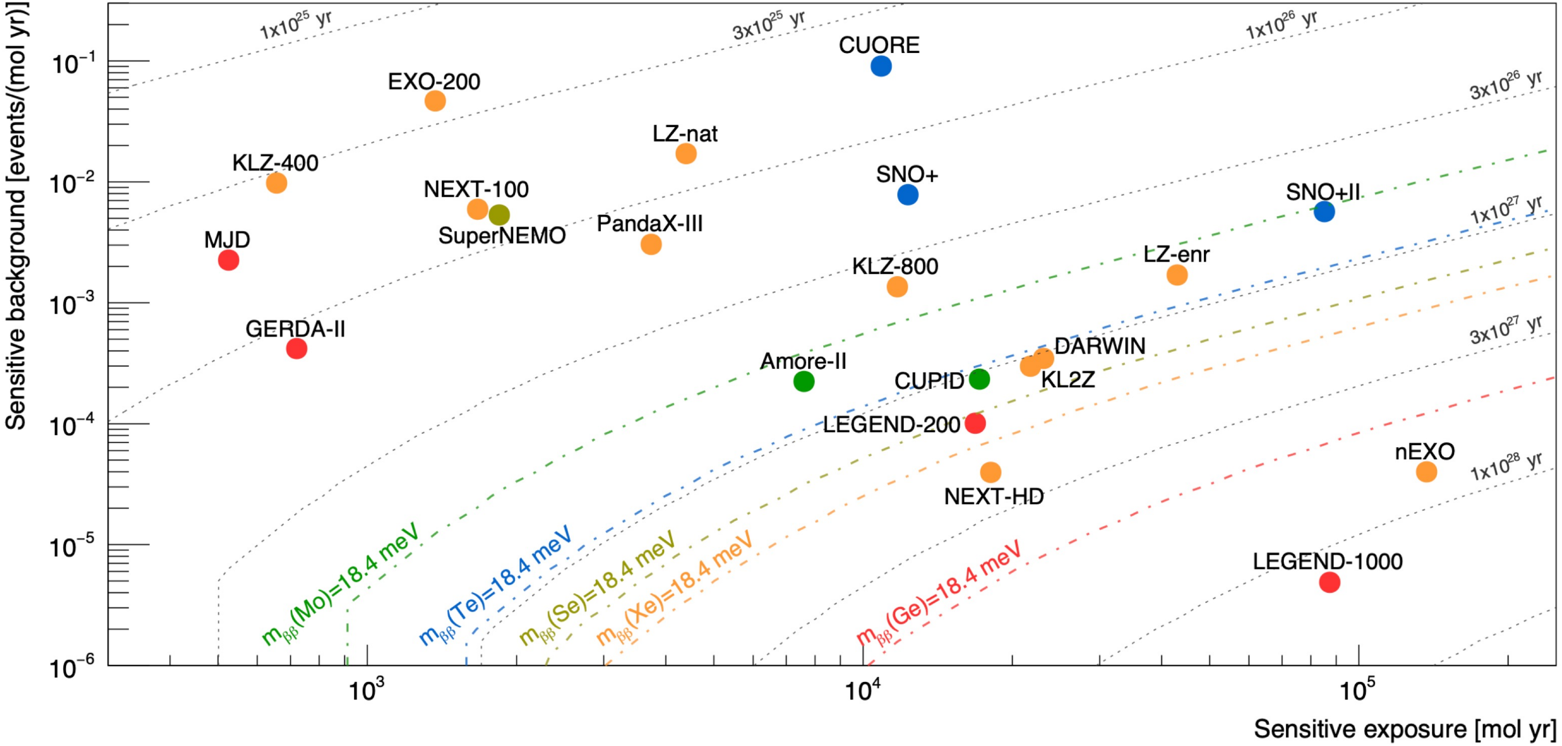
From Alvaro Chavarria, TAUP21

CANDLES: exploit high ^{48}Ca Q-value



From Yuto Minami, TAUP21

The Path Ahead



M. Agostini *et al*. Rev. Mod. Phys. **95** (2023) 025002

Summary

- Discovery of neutrinoless double beta decay would fundamentally reshape what we know about particle physics
- Experimental challenges in searching for neutrinoless double beta decay are real and varied
- Broad experimental program searching for this compelling new physics
- Compelling experimental programs taking data now
- Exciting prospects to cover inverted ordering range
- R&D looking for solution to beyond-next-generation sensitivity