The Search for Neutrinoless Double-Beta Decay

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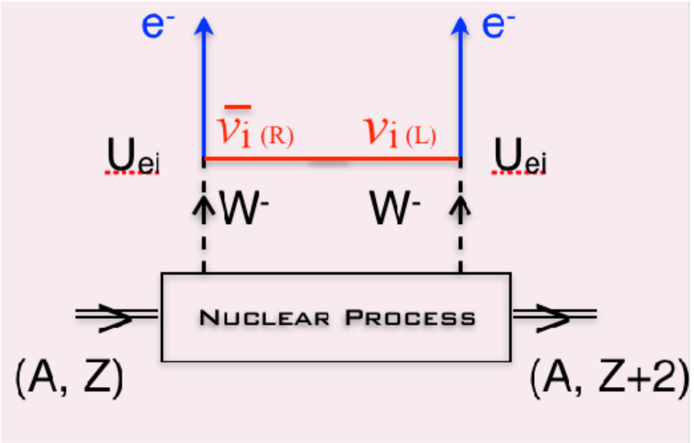
Neutrinoless Double-Beta Decay (0νββ)

Small, non-zero neutrino masses motivate the possibility that neutrinos are Majorana particles, indistinguishable from antineutrinos.

Searches for neutrinoless double-beta decay (0νββ) are the only current practical probes of Majorana nature of neutrinos.



0νββ requires:

Non-zero neutrino masses:

- "wrong-handed" helicity admixture ~ m_i/E_{ν_i}
- *Any process that allows 0νββ to occur requires Majorana neutrinos with non-zero mass.* -Schechter and Valle, 1982

Lepton Number non-conservation

- No experimental evidence that Lepton number must be conserved
- Allowed based on general SM principles, such as electroweak-isospin conservation and renormalizability

Implications of a 0νββ Measurement

Observation of 0νββ:

Immediately implies neutrinos are Majorana particles, regardless of mechanism.

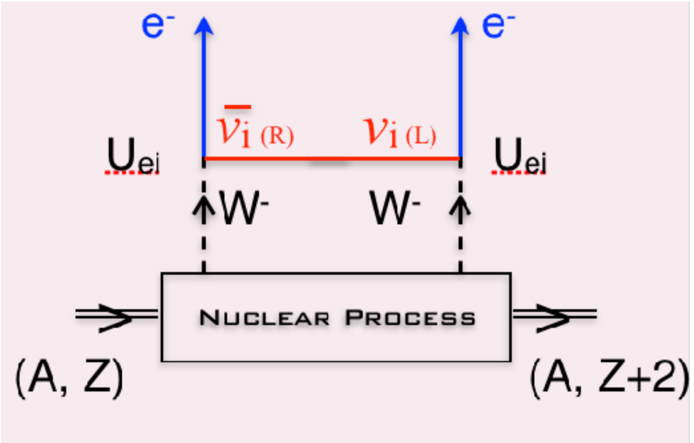
Demonstrates Lepton Number non-conservation.

Provides a model-dependent measurement of absolute neutrino mass.

Allows access to CP-violating Majorana phases in the PMNS neutrino mixing matrix.

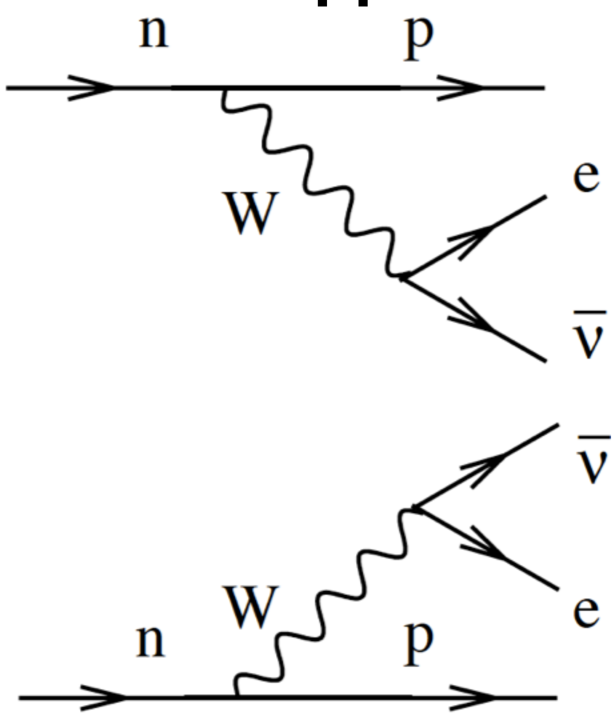
Offers an explanation for the lightness of neutrinos as compared to the other standard model fermions.

Motivates plausible mechanisms for the matter/antimatter asymmetry in the Universe.



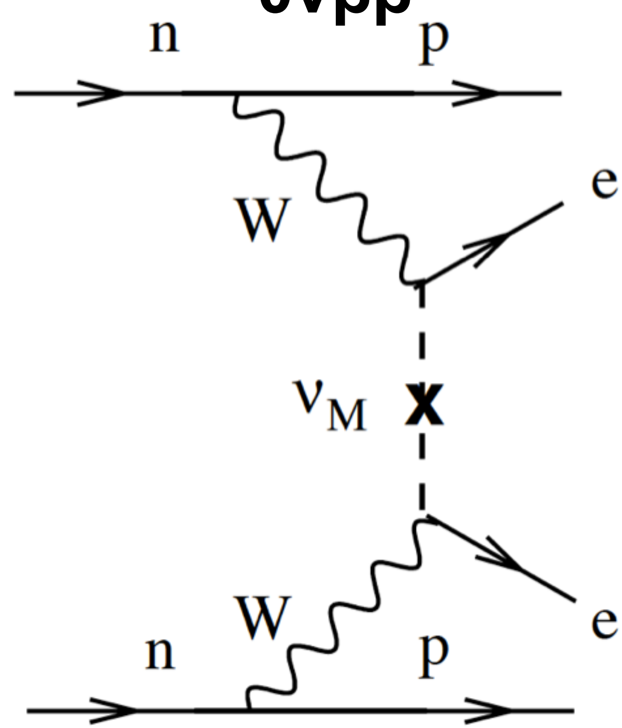
Two Modes of Double-Beta Decay

2νββ



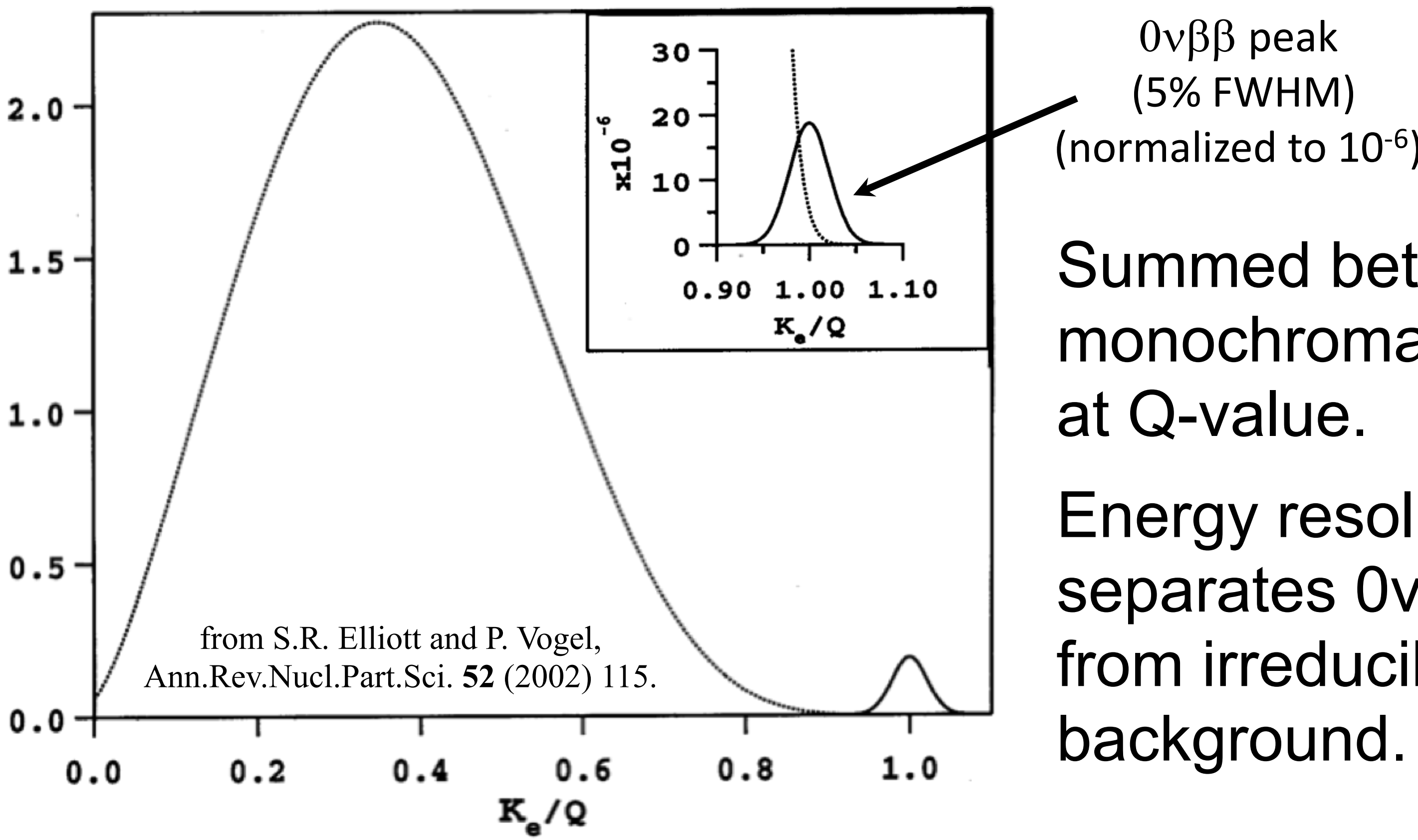
Standard-Model process
Observed in several nuclei
Lifetimes ~10^{21} years

0νββ



Requires Majorana neutrinos
Lepton-Number non-conserving
Lifetimes ≳10^{26} years

Experimental Signature



Summed betas yield monochromatic peak at Q-value.

Energy resolution separates 0νββ signal from irreducible 2νββ background.

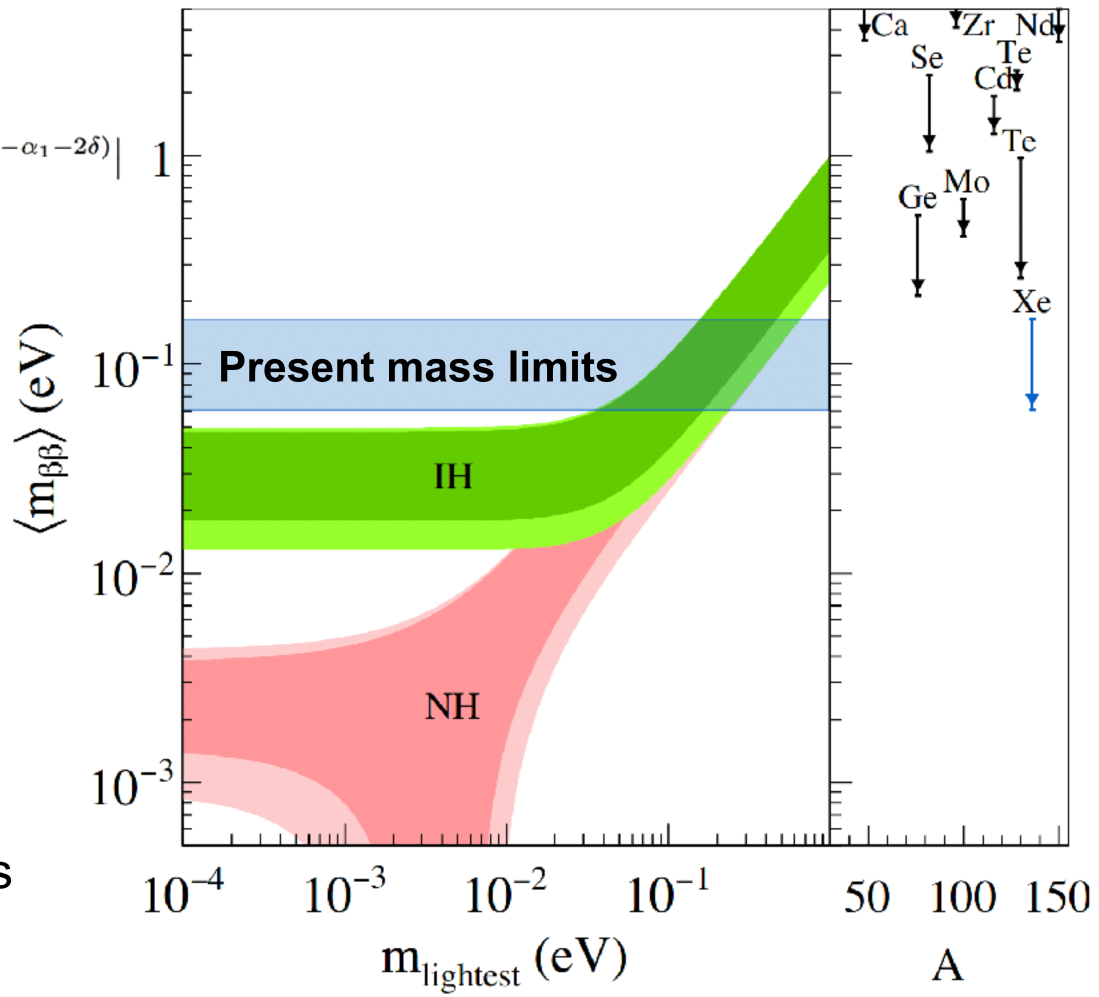
Effective Majorana Masses

$$m_{\beta\beta} \equiv \left|\sum_k m_k U_{ek}^2\right|$$
$$= \left|m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i(\alpha_2-\alpha_1)} + m_3|U_{e3}|^2 e^{i(-\alpha_1-2\delta)}\right|$$

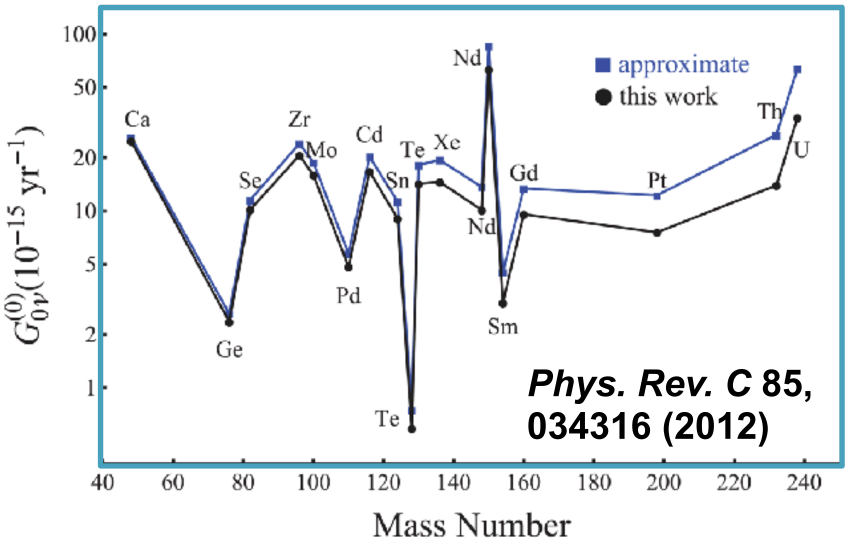
Allowed effective Majorana neutrino masses determined by mass ordering, mixing parameters, $m_{lightest}$.

0νββ mass measurements complimentary to direct mass measurements (^{3}H-decay) and cosmological inferences.

Coverage of Inverted Ordering region motivates sensitivity aims of next-generation experiments.



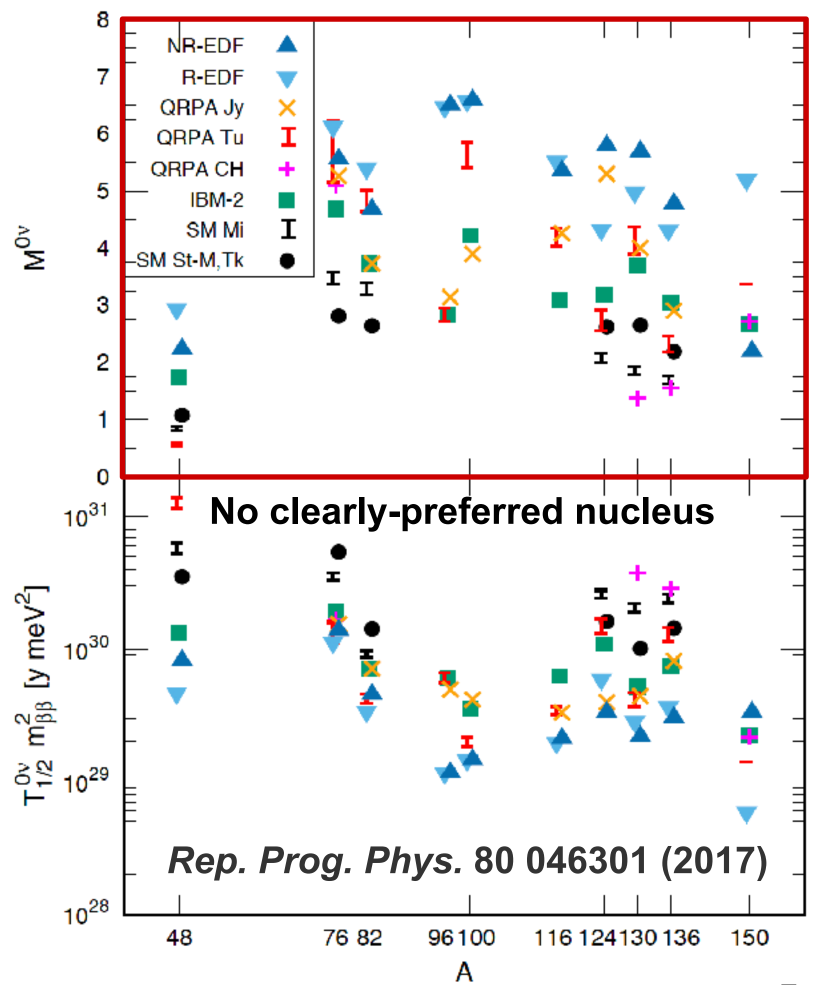
Theoretical Considerations



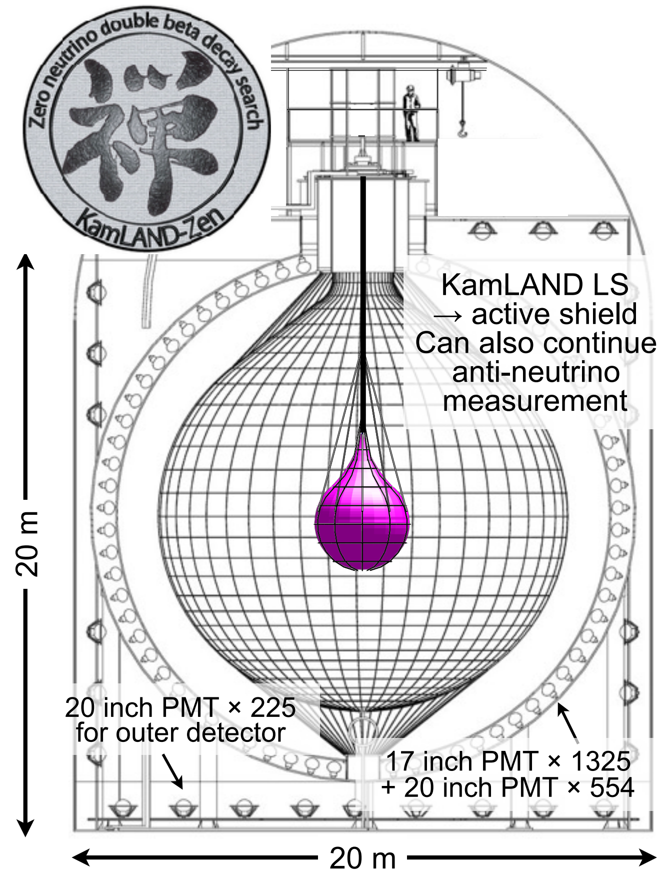
$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2\, m^2_{\beta\beta}$$

$$|M_{0\nu}|^2 \propto g_a^2$$

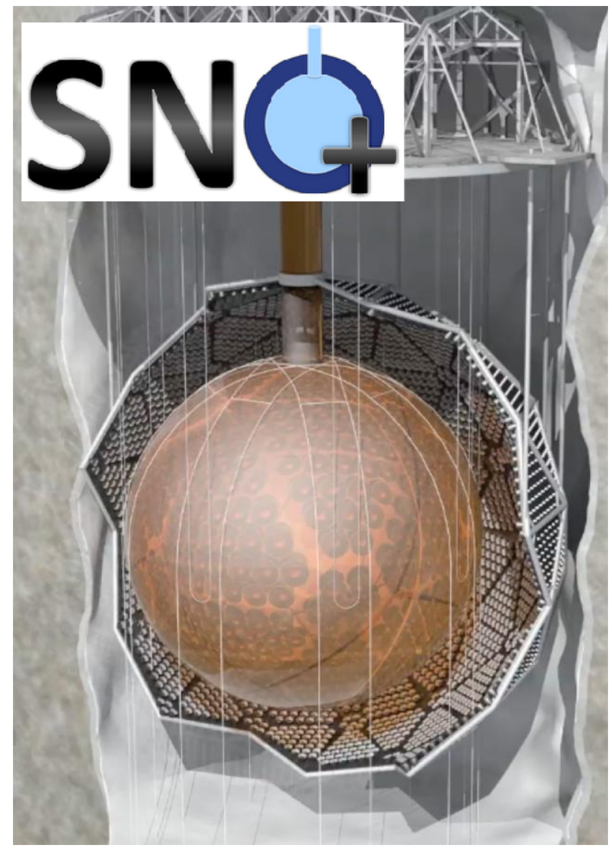
Unknown quenching of g_a, uncertainty of NME and dominant LNV mechanism can impact mass interpretation.



Large Liquid Scintillator Experiments: Making use of existing large detectors



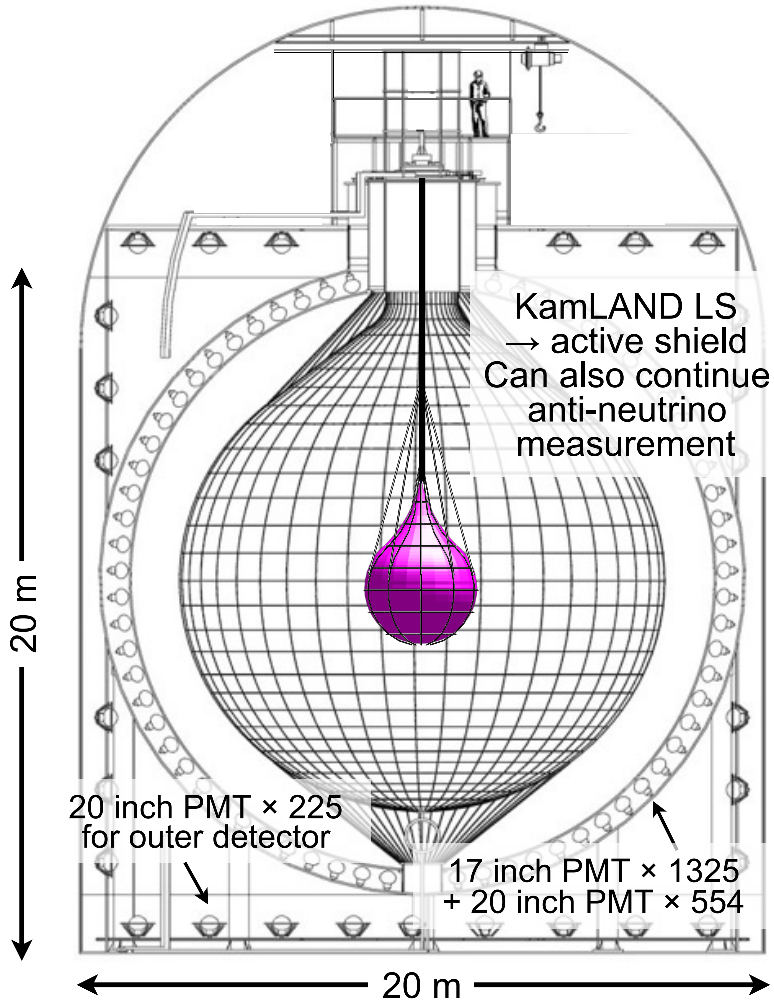
KamLAND-Zen
Xe-doped LS



SNO+
Te-doped LS

KamLAND-Zen

^{136}Xe loaded LS → into KamLAND center with inner balloon.



Double beta decay isotope: ^{136}Xe

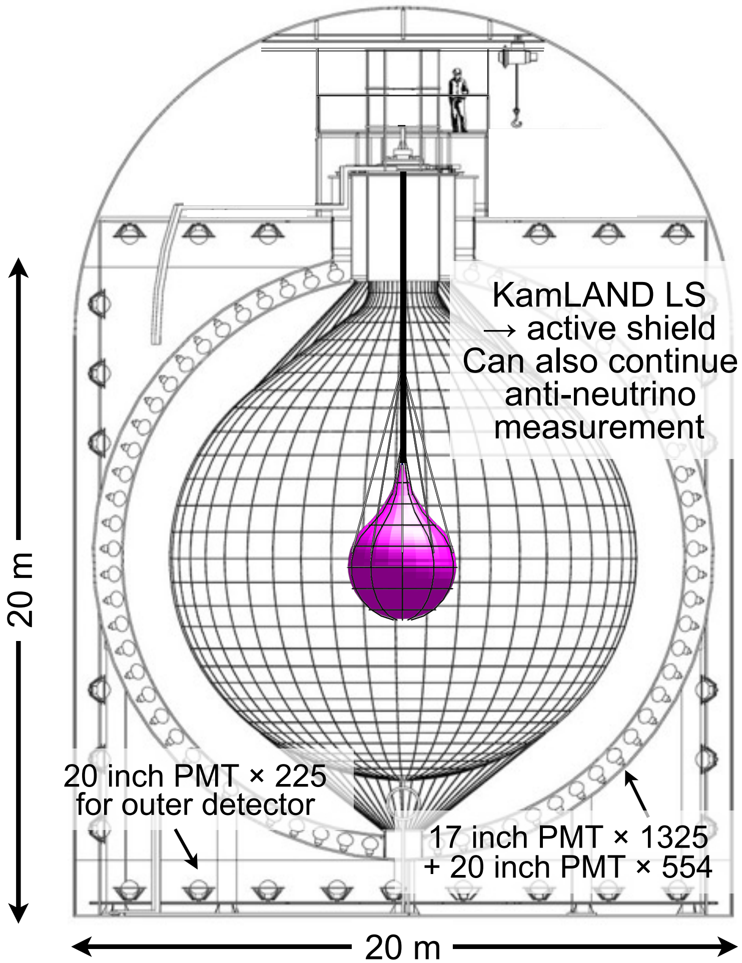
- Q-value 2.458 MeV
- Dissolved into LS ~3% by weight
- Extract from LS (blank measurement)
- Noble gas → chemical stability
- Enrichment ~90%
- Purification method established
- Half life of 2νββ decay is long (~10^{21} yr)

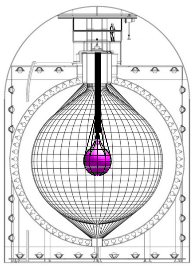
Inner balloon

- 25um thickness clean nylon
  ^{238}U, ^{232}Th ~a few×10^{-12} g/g
- Enough strength & transparency
- Heat welding (no glue)
- Production in class-1 clean room

Gando, Azusa - doi.org/10.5281/zenodo.1286895

Three Phases of KamLAND-Zen

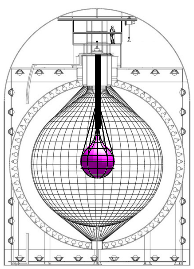




Past

KamLAND-Zen 400

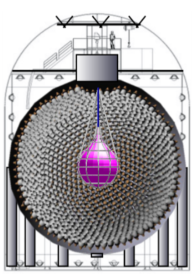
320-380 kg of Xenon
Data taking 2011 ~ 2015



Present

KamLAND-Zen 800

~750 kg of Xenon
DAQ to start in this year



Future

KamLAND2-Zen

~1 ton of ^{136}Xe
Better energy resolution

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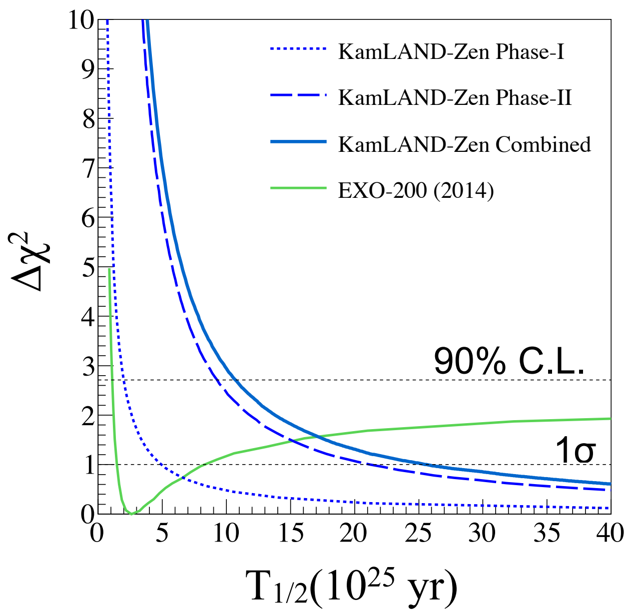
KamLAND-Zen 0νββ Search Results

^{136}Xe Half-life limit



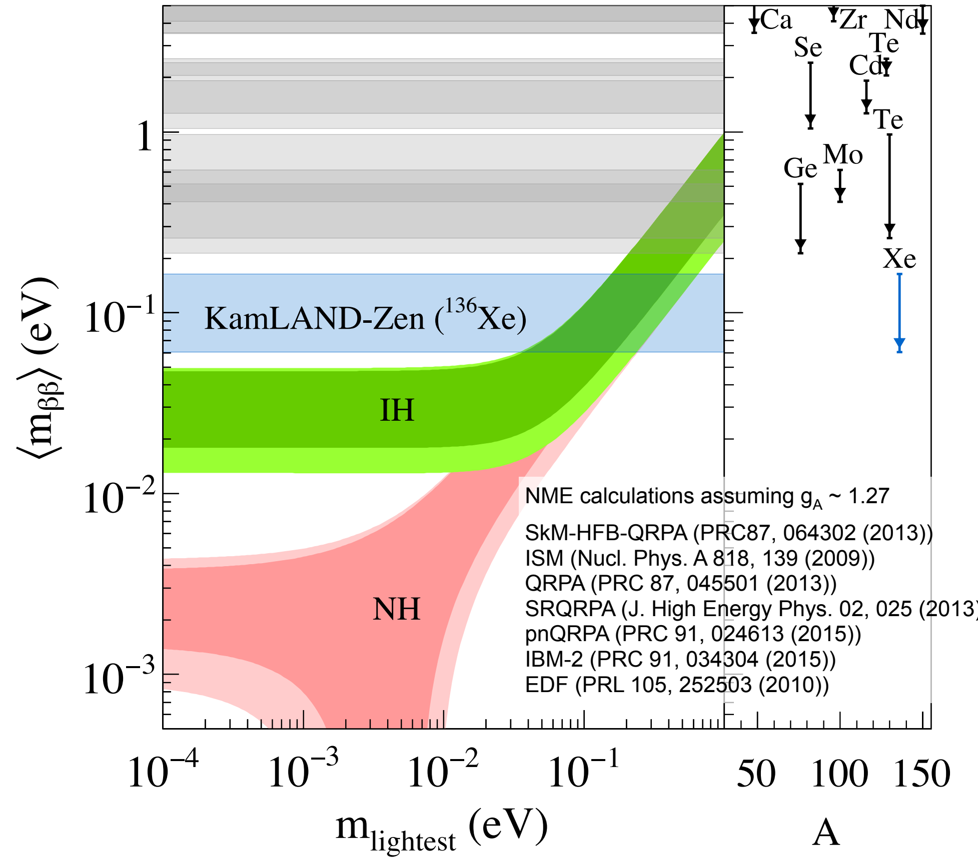
Combined result (90% C.L.)

$T^{1/2}$ > 1.07×10^{26} yr

Phase-I: $T^{1/2}$ > 1.9×10^{25} yr
Phase-II: $T^{1/2}$ > 9.2×10^{25} yr
PRL 117, 082503 (2016)

Gando, Azusa - doi.org/10.5281/zenodo.1286895

Limit for effective neutrino mass

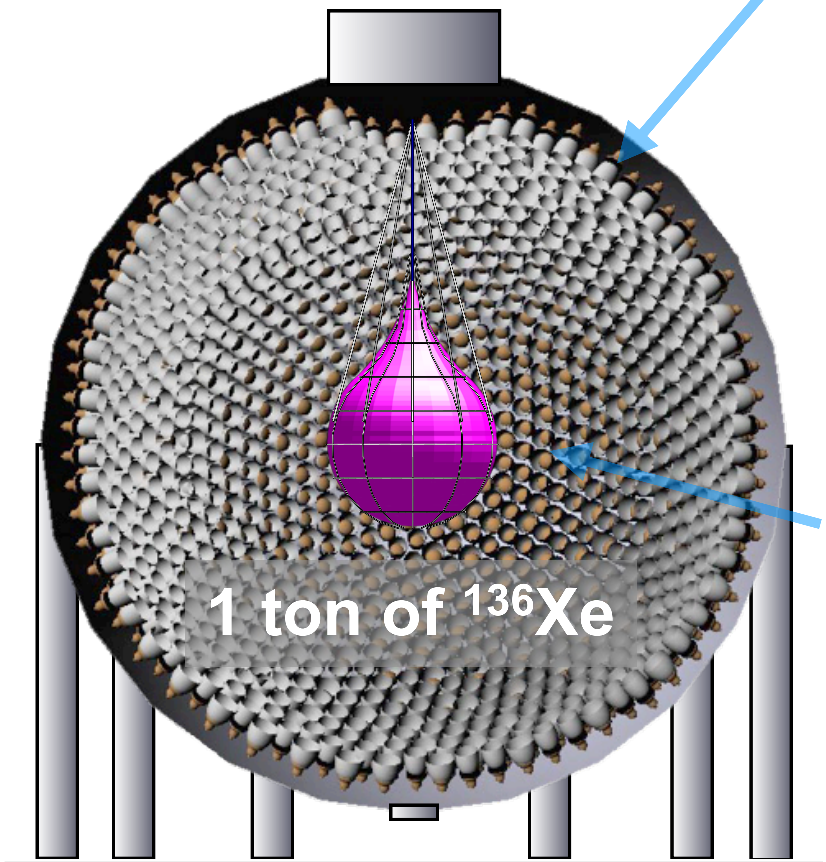


⟨$m_{\beta\beta}$⟩ < 61-165 meV

It reaches below 100 meV!

KamLAND2-Zen

- Enlarge opening
- General use: accommodate various devices such as $CdWO_4$, NaI, CaF_2 detectors



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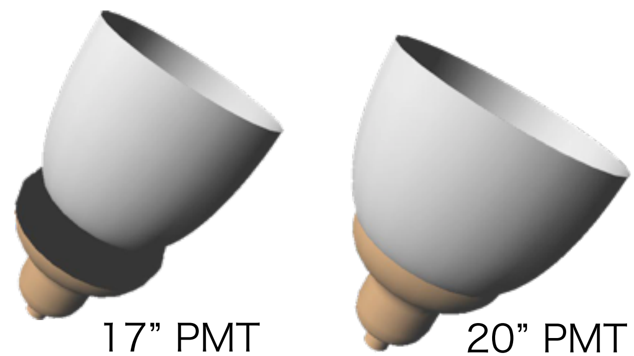
R&D to improve the energy resolution

Winstone cone & High QE PMT

Improve light collection efficiency and photo coverage **×1.9**



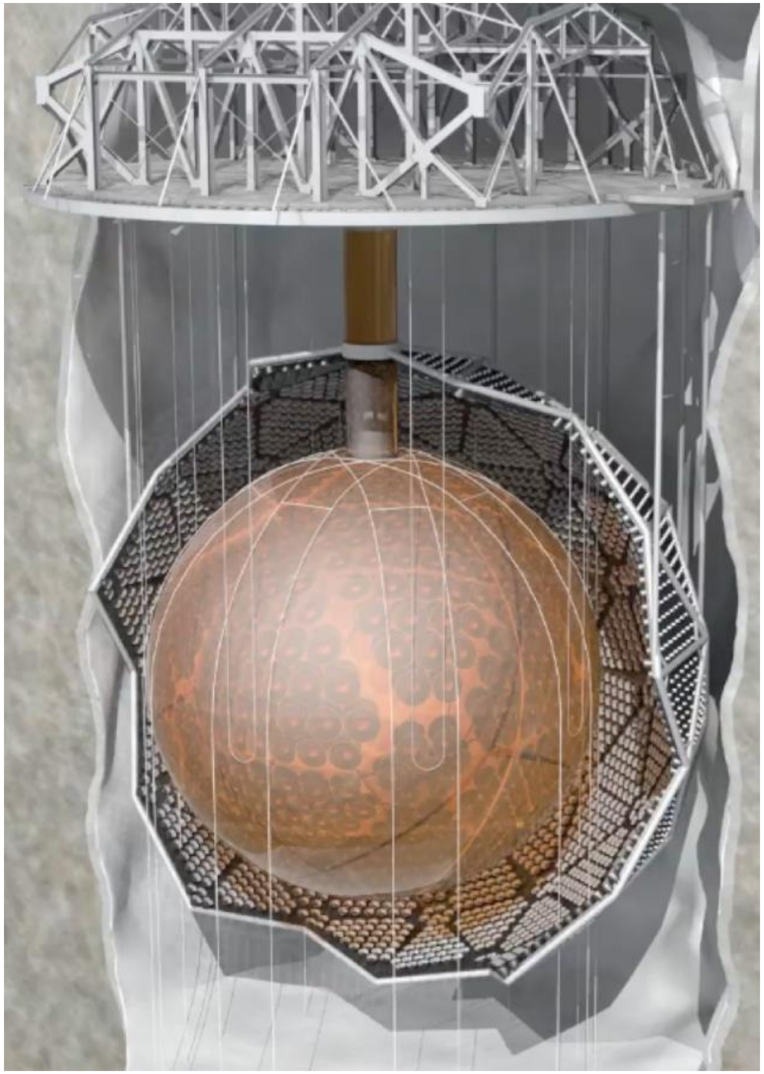
Brighter LS **×1.4**

Current LS ~8,000 photon/MeV
LAB based new LS ~12,000 photon/MeV

σ(2.6MeV)=4% → < 2.5%
Target $\langle m_{\beta\beta} \rangle$ ~20meV in 5 yrs

SNO+

- SNOLAB, Ontario
- 780 ton LAB/PPO (2g/L) in 6m radius acrylic vessel (AV)
- ~9400 PMTs at 8.5m
- Inherited SNO detector
  - Upgraded electronics & DAQ
  - New hold-down rope net
  - New underground LS & Te plants

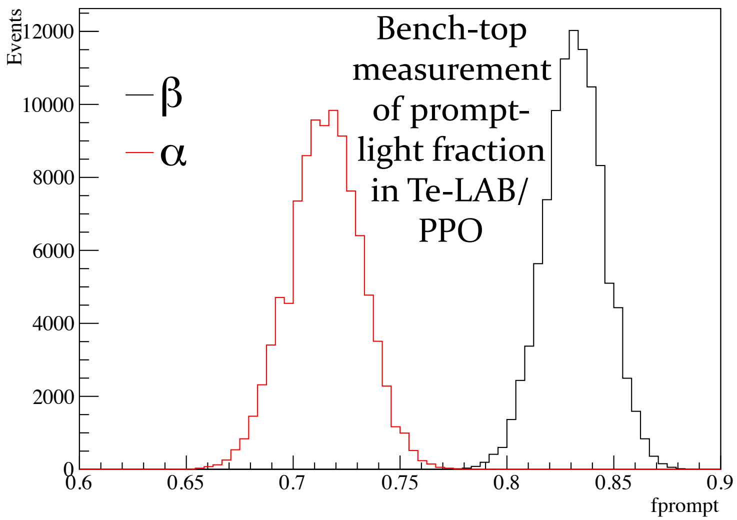


Orebi Gann, Gabriel - doi.org/10.5281/zenodo.1286908

SNO+

Method: Load LAB/PPO with 0.5% $_{nat}$Te

- High nat abundance of ^{130}Te
  → *enrichment unnecessary*
- High intrinsic photon yield, low absn
- Favourable 2νββ:0νββ NME
- Isotope-out background measurement
- High detection efficiency



- Low backgrounds (dominated by ^{8}B ν_e)
  - Fiducialisation ⇒ self-shielding
  - Particle ID and coincident timing
    BiPo rejection > 99.99% in ROI
  - Deep location (6000 m.w.e.)
- Large target mass, easy scaling

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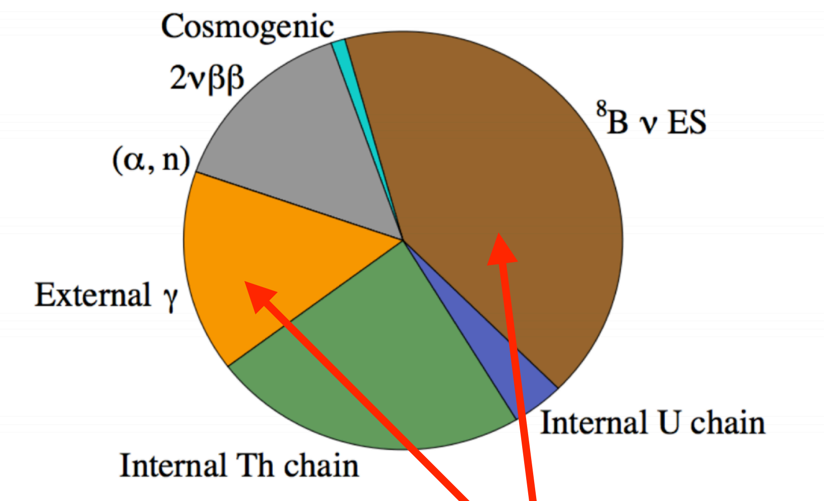
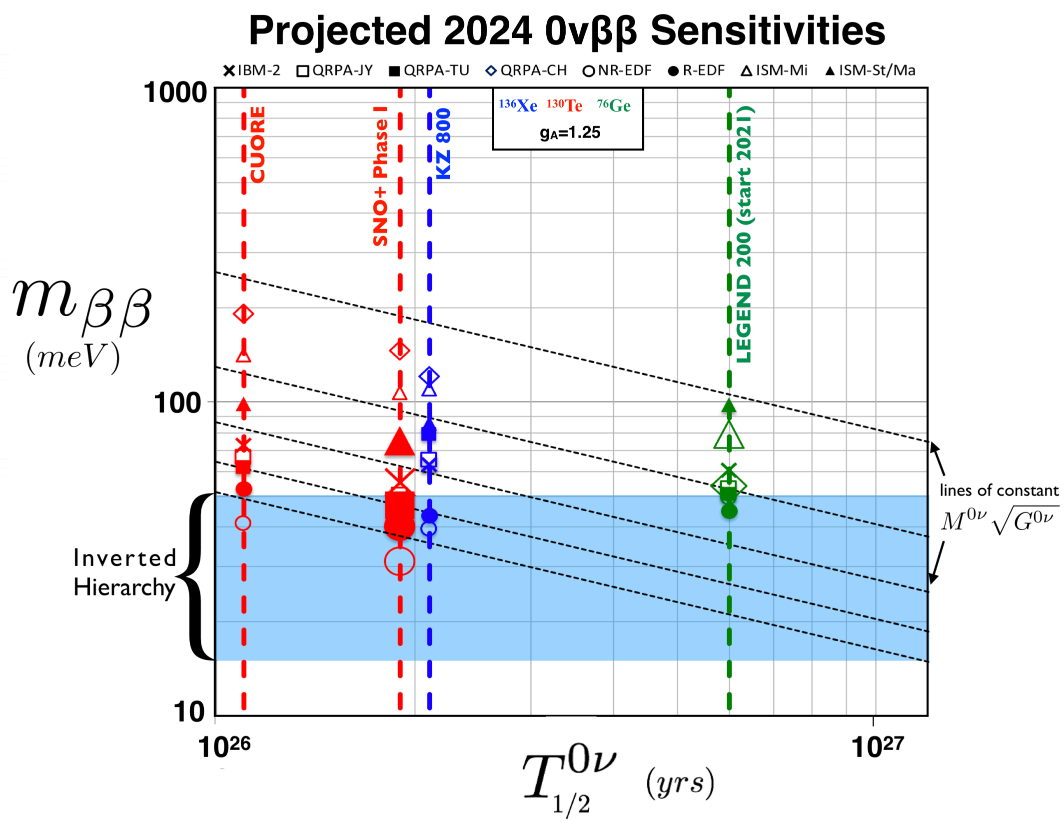
SNO+ Towards 0νββ

Background levels consistent with or below "nominal" value used for sensitivity projections



Source term measured for dominant backgrounds



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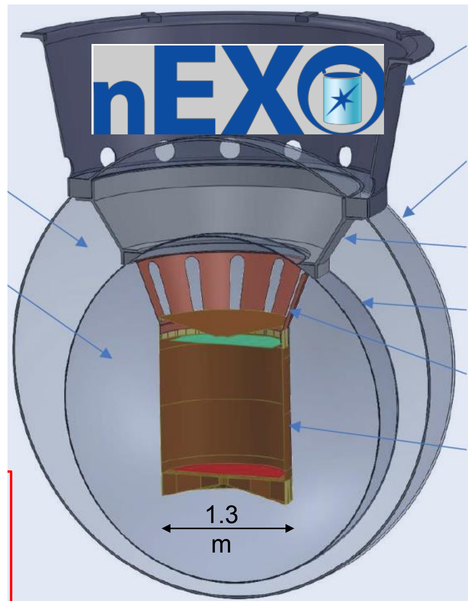
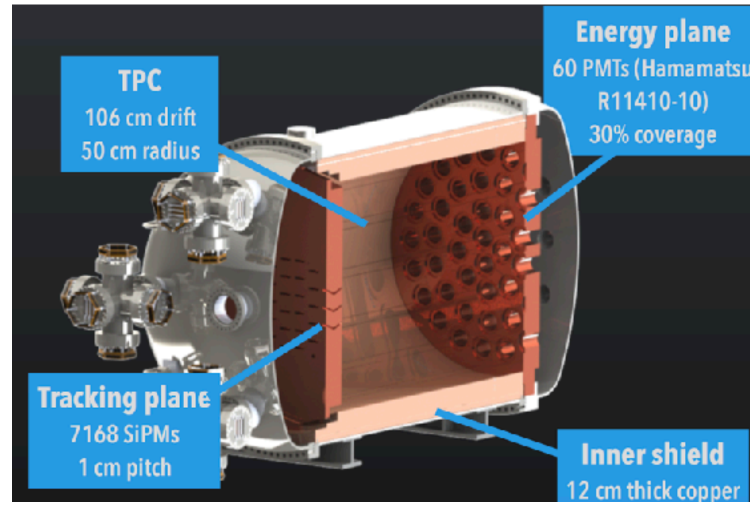
Xenon Time Projection Chambers





next

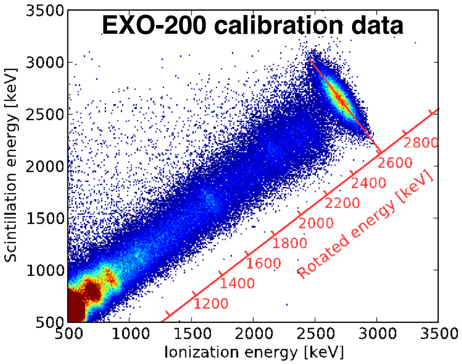
Monolithic TPCs with little/no background-inducing material in central volume, possibility of tagging Ba daughter.

EXO-200, nEXO: Liquid Xe

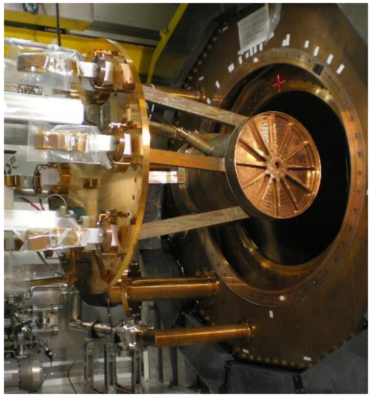
NEXT: High-pressure gaseous Xe

EXO: Enriched Xenon Observatory

The EXO program



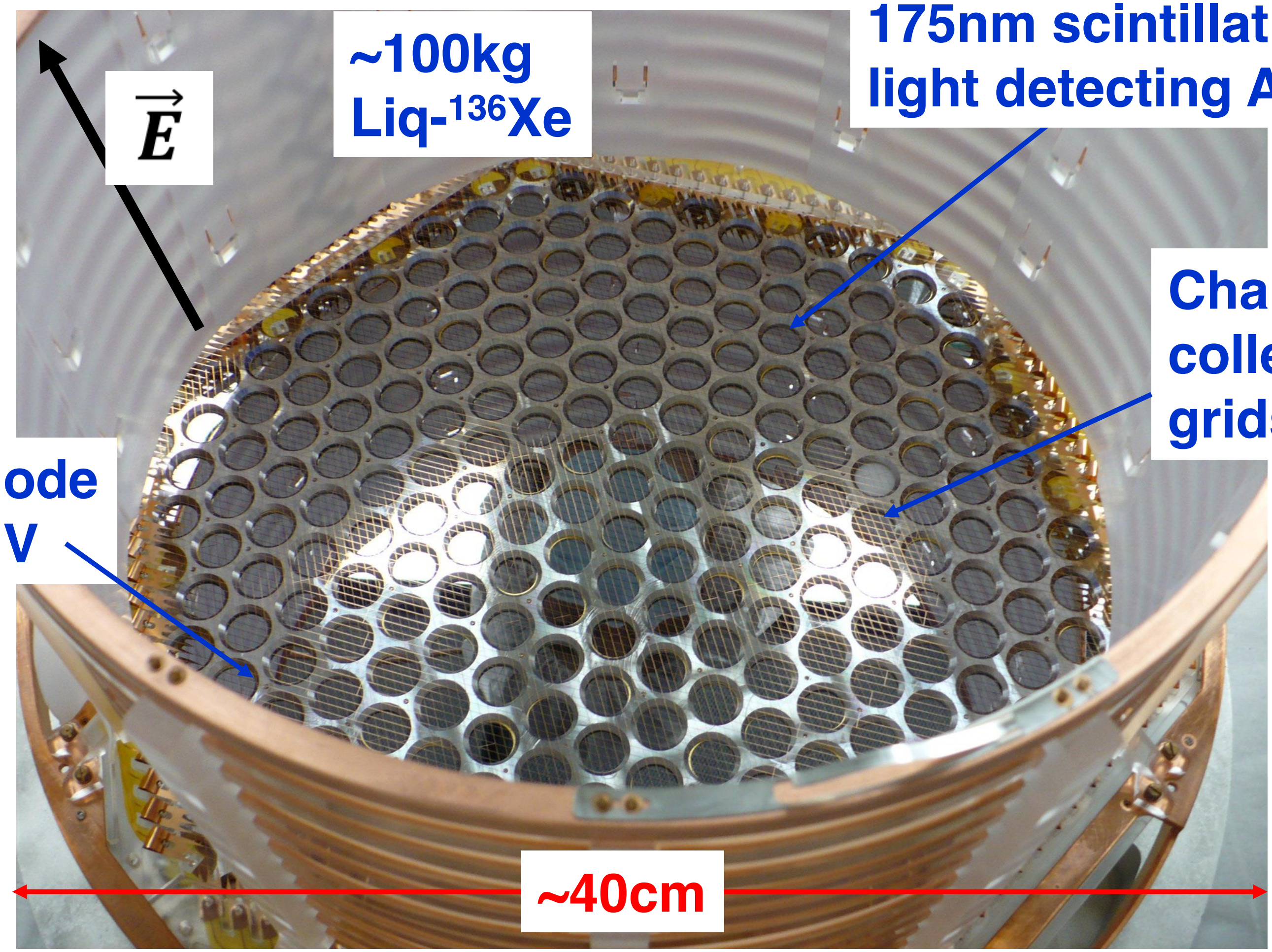
- **Use ^{136}Xe in liquid phase**
- **Initial R&D on energy resolution using scintillation-ionization correlation**



- **Build EXO-200, first 100kg-class experiment to produce results. Phase II in progress, will end in Dec 2018**
- **Build the 5-tonne nEXO, reaching $T_{1/2}$~10^{28} yr and entirely covering the Inverted Hierarchy**
- **Develop a technique for tagging the final state Ba as a possibility to further upgrade nEXO and substantially exceed $T_{1/2}=10^{28}$ yr**

Gratta, Giorgio - doi.org/10.5281/zenodo.1286892

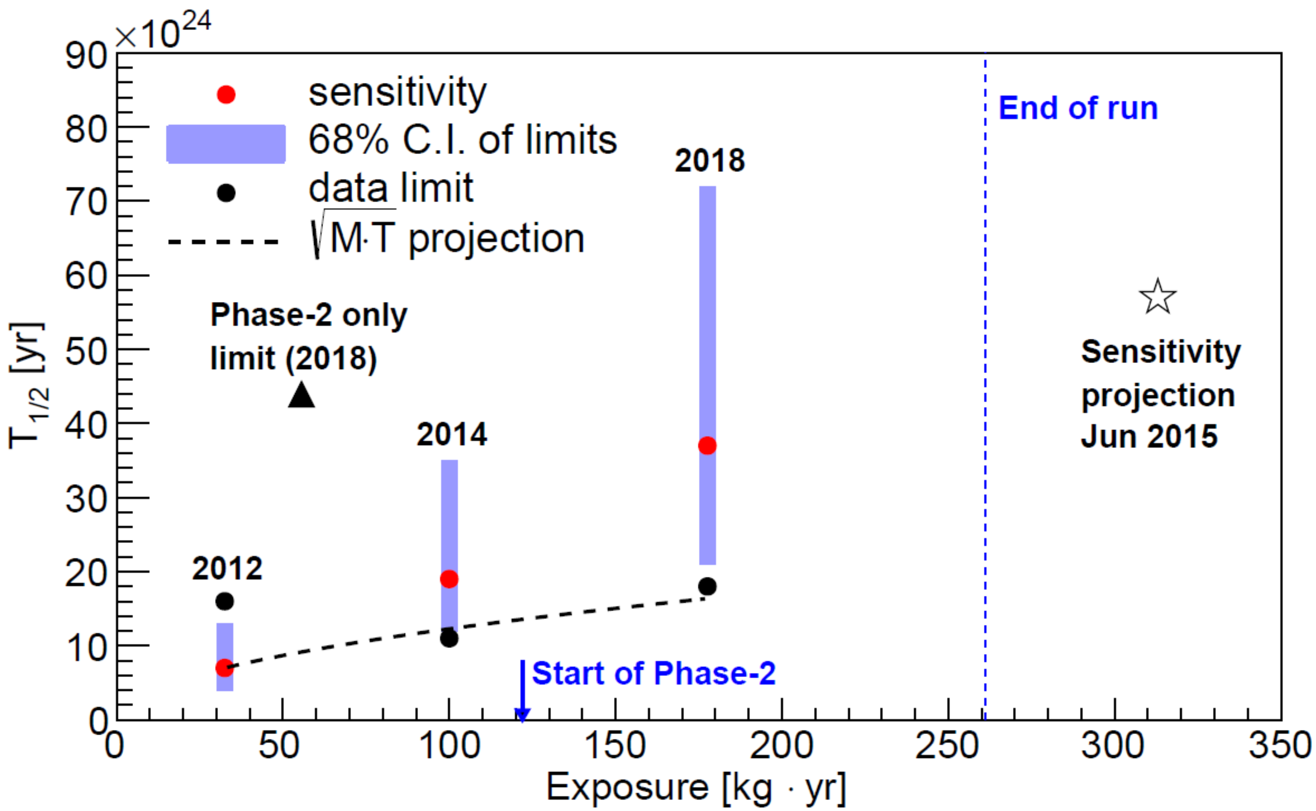
EXO-200 Time Projection Chamber



Gratta, Giorgio - doi.org/10.5281/zenodo.1286892

EXO-200 0νββ Results

	Sensitivity (yr)	90% CL Limit (yr)	<$m_{\beta\beta}$> (meV)
PRL 109, 032505 (2012)	0.7×10^{25}	1.6×10^{25}	
Nature 510, 229 (2014)	1.9×10^{25}	1.1×10^{25}	
PRL 120 072701 (2018)	3.8×10^{25}	1.8×10^{25}	147-398



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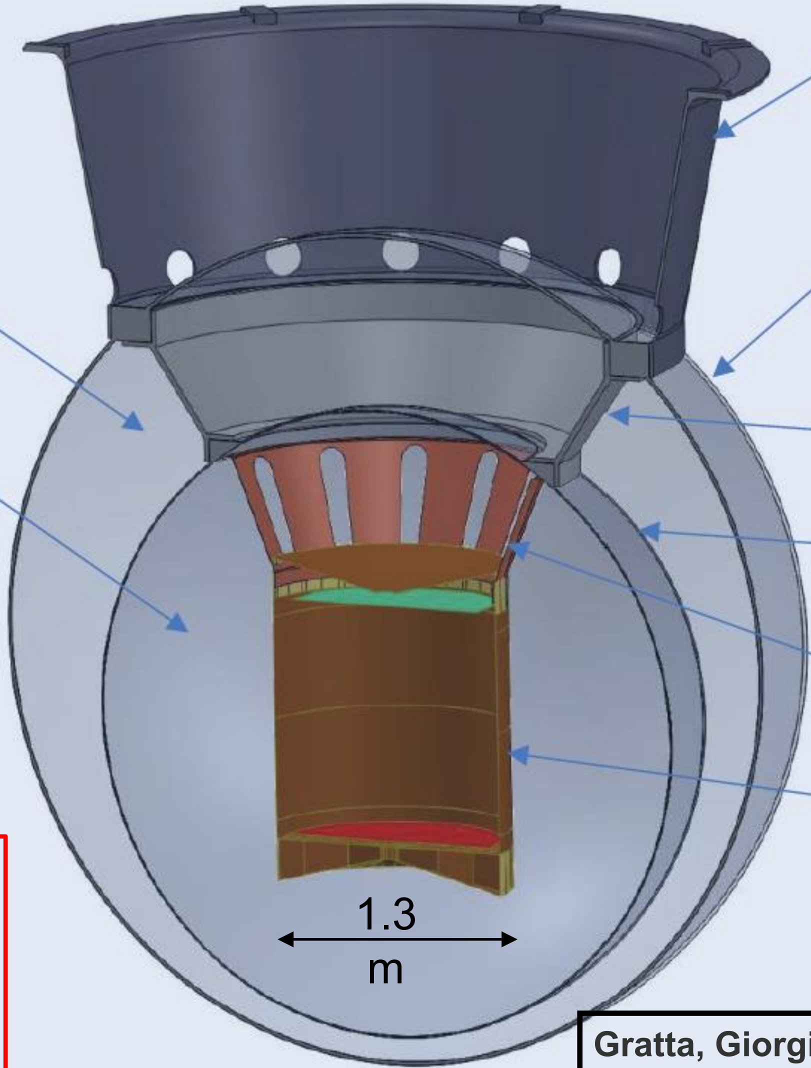
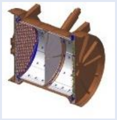
nEXO





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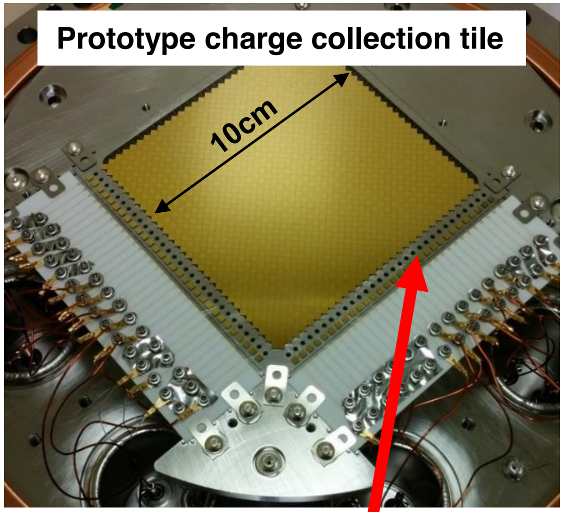
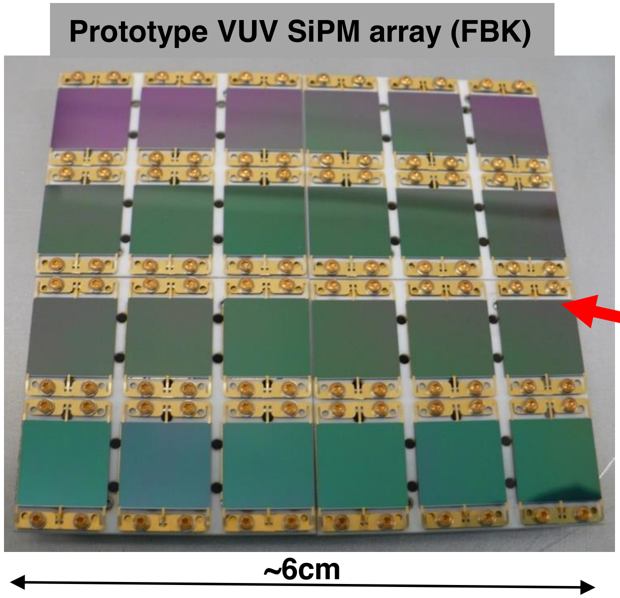
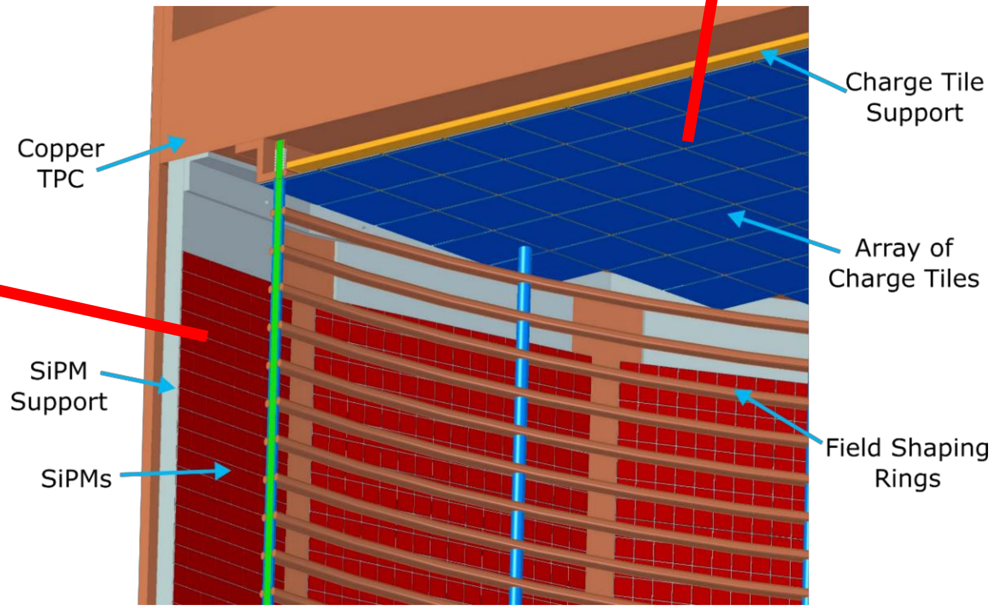
Major changes on the EXO-200 theme

- Only one drift volume
- ASIC electronics in LXe
- Silica substrate charge collection tiles
- VUV SiPMs (~4.5m^2)
- Little plastics in the TPC (Sapphire, Silica)







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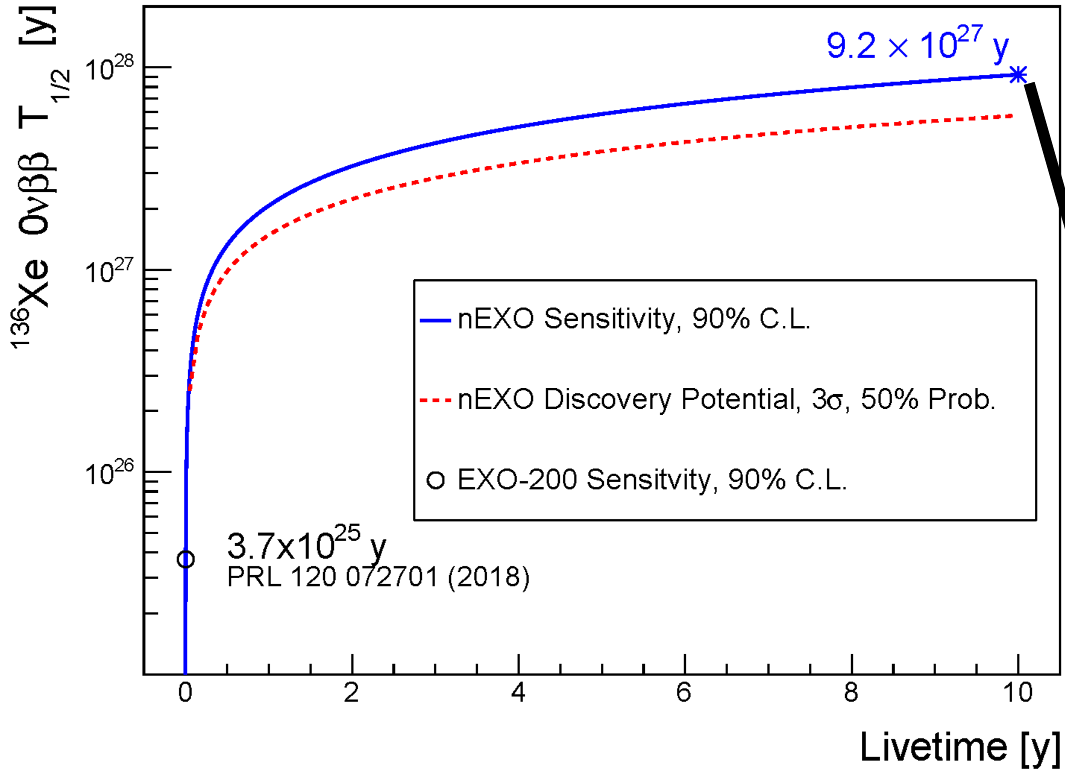
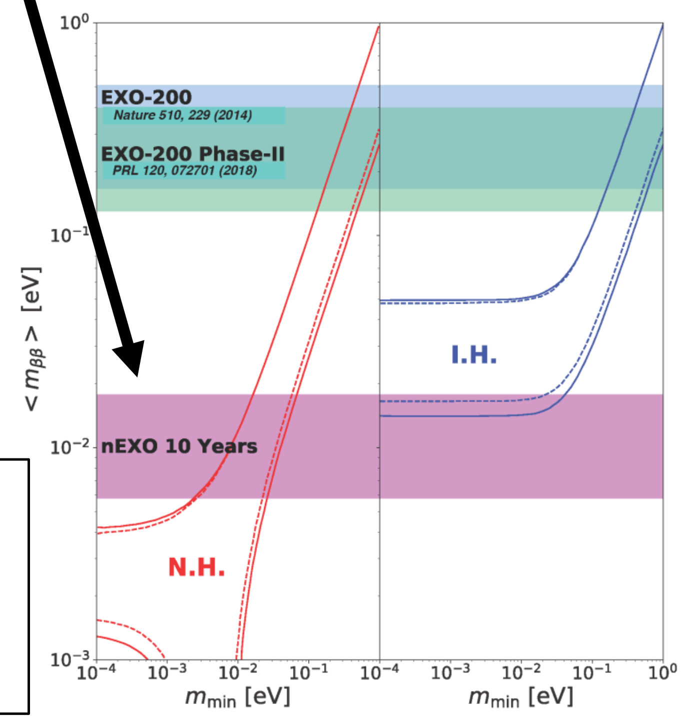
nEXO Sensitivity



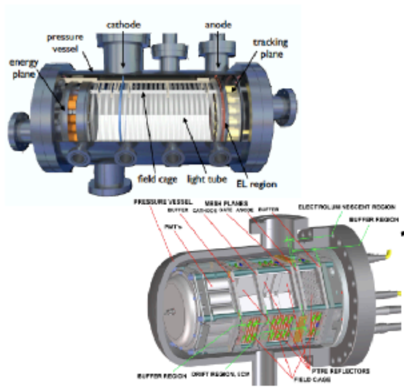


- $g_A = g_A^{free} = -1.2723$
- Band is the envelope of NME:

EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

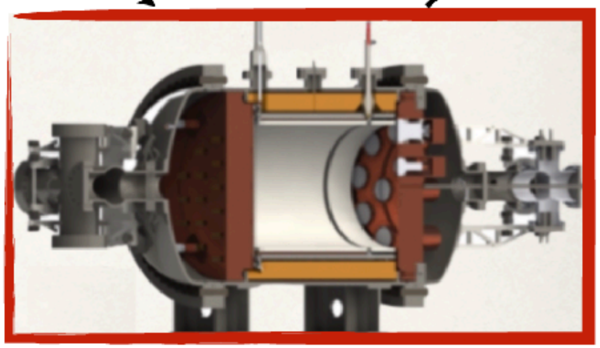
Gratta, Giorgio - doi.org/10.5281/zenodo.1286892

NEXT: Neutrino Experiment with a Xenon TPC



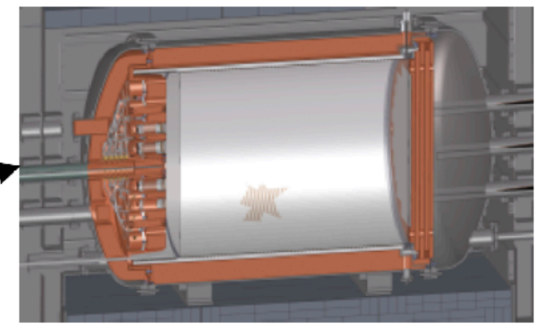
Prototypes (~1 kg)
[2009 - 2014]

Demonstration of detector concept [<1% FWHM, tracking]



NEXT-NEW (~5 kg)
[2015 - 2018]

Underground and radio-pure operations, background, $2\nu\beta\beta$

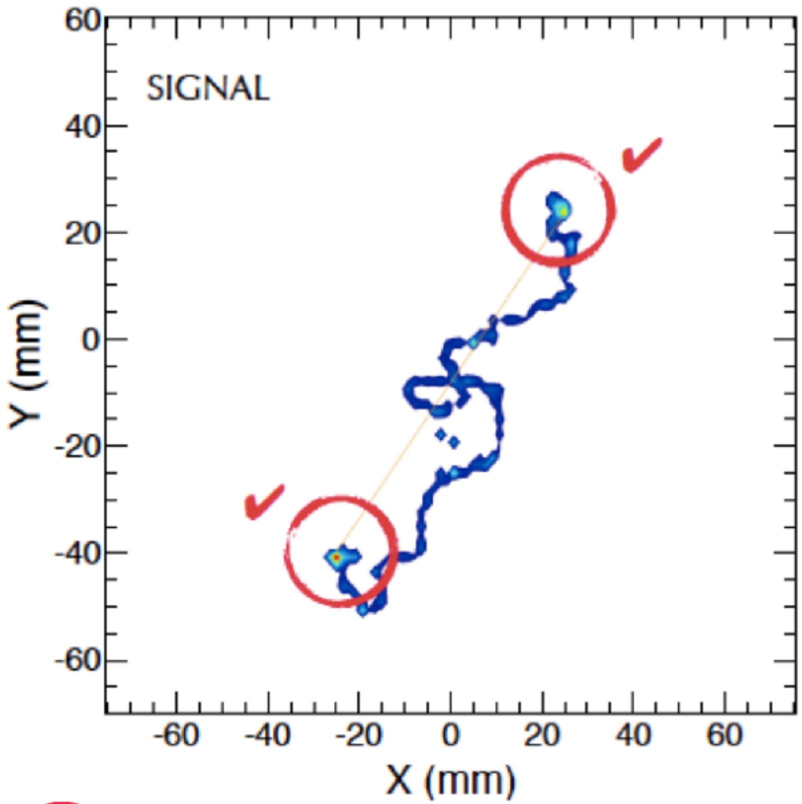


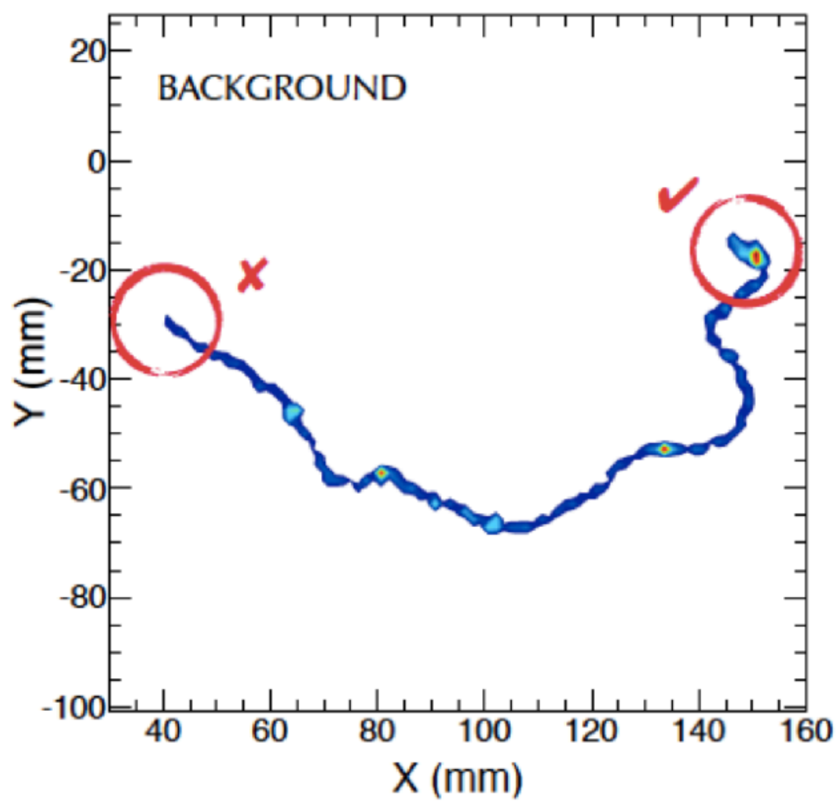
NEXT-100 (~100 kg)
sensitivity: 6×10^{25} yr
[2018 - 2020's]

Neutrinoless double beta decay searches

next

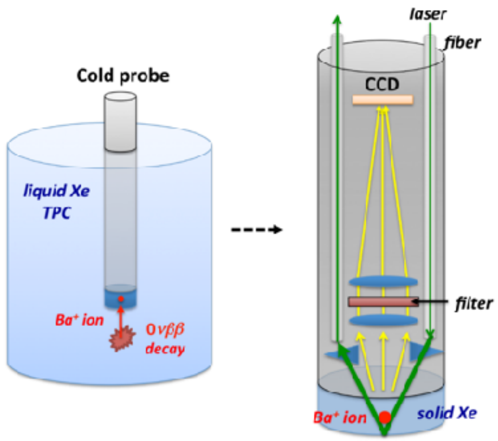
NEXT: Background Suppression through Event Topology

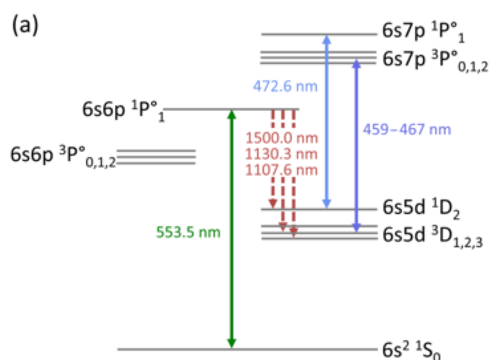


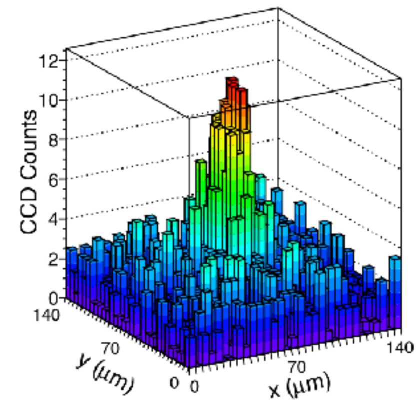


Tagging of the Ba Daughter

EXO: Laser-Induced Fluorescence Spectroscopy

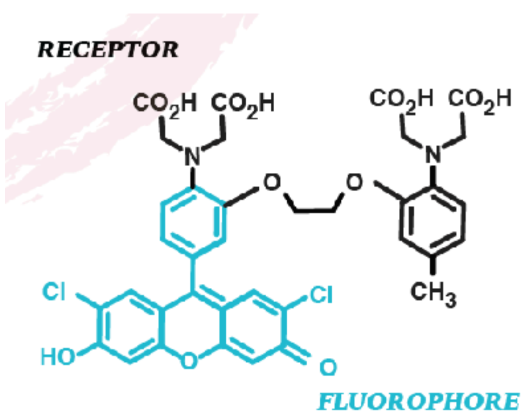


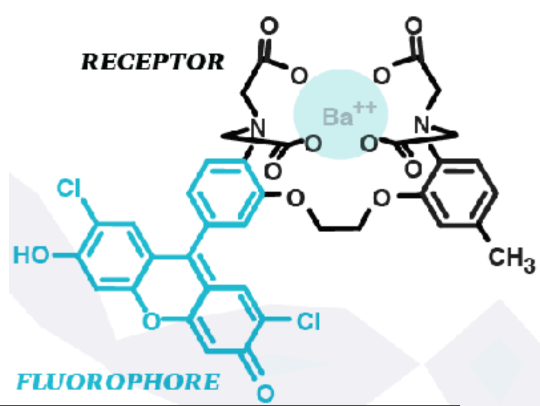


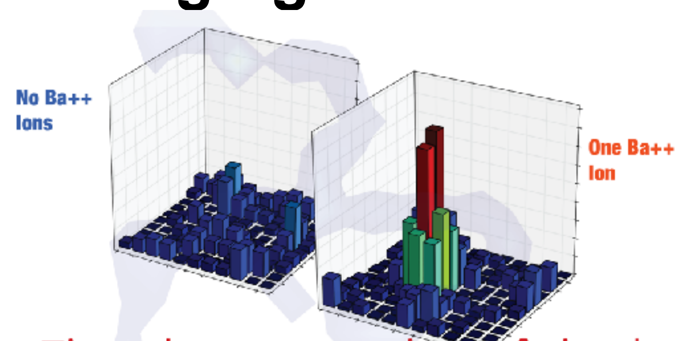


B. Mong, et al. - doi.org/10.1103/PhysRevA.91.022505

NEXT: Single-Molecule Fluorescence Imaging







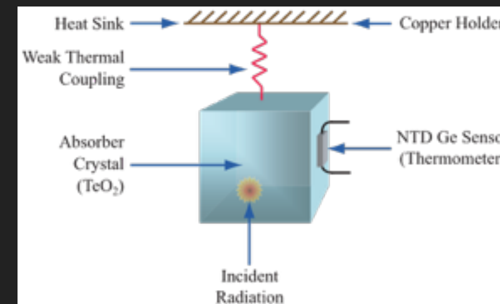
First demonstration of single Ba^{++} ion sensitivity.

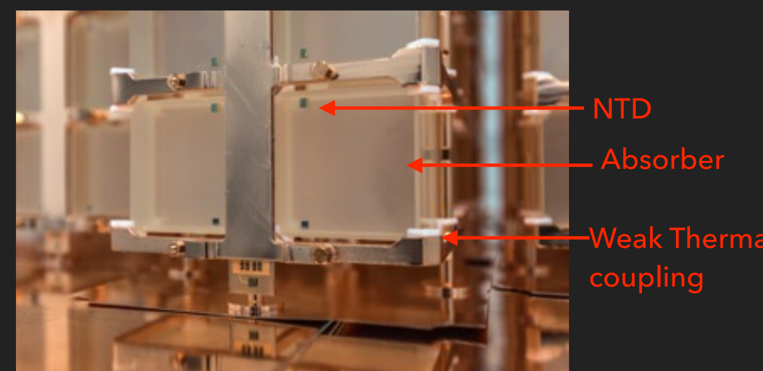
A. McDonald & F. Psihas - doi.org/10.5281/zenodo.1300986

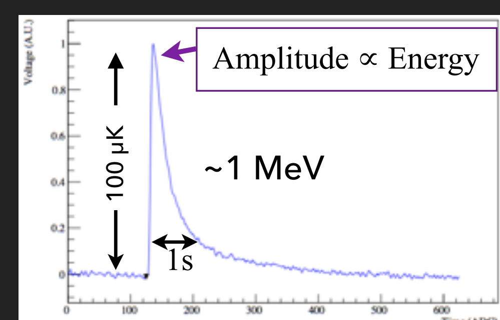
CUORE / CUPID: Te Bolometers

Cryogenic Bolometers

- Solid state detectors operating at low temperatures: ~10mK
- 1 MeV energy deposition causes ~ 100 µK increase in temperature
    - Read out with an Ge Neutron Transmutation Doped thermometer
- Extremely good energy resolution: 5 keV FWHM at 2.5 MeV
- Detector is made out of Te and contains the candidate isotope inside
- Flexible choice of candidate isotope





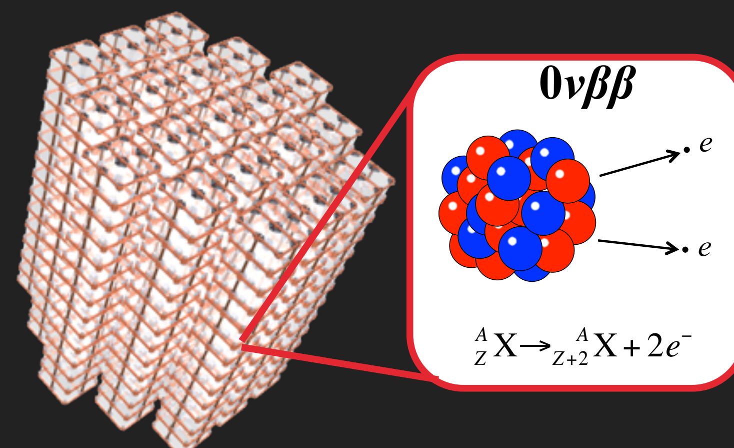


Ouellet, Jonathan - doi.org/10.5281/zenodo.1286904

CUORE / CUPID: Te Bolometers

The CUORE Experiment

- Primary physics goal is the search for 0νββ decay of ^{130}Te
- Array of 988 TeO_2 bolometers
- Located at the Gran Sasso National Lab in Italy (3600 m.w.e. overburden)
  - Large mass of 741 kg (206 kg of candidate isotope ^{130}Te)
  - Energy resolution goal of 5 keV FWHM at $Q_{\beta\beta}$ (2527 keV)
  - Low background goal of 10^{-2} cnts/(keV·kg·yr) at the ROI
  - High uptime and signal efficiency
- Sensitivity to $T_{1/2}=9\times10^{25}$ yr in 5 years of live time



Sensitivity

$$T_{1/2} \sim \varepsilon\sqrt{\frac{Mt}{b\Delta E}}$$

Ouellet, Jonathan - doi.org/10.5281/zenodo.1286904

CUORE

CUORE: Recent Results

Phys. Rev. Lett. 120, 132501 (2018)

Search for 0νββ Decay with CUORE

- Background index is consistent with expectations

  $(1.4 \pm 0.2) \times 10^{-2}$ cnts/(keV·kg·yr)

- Median expected sensitivity

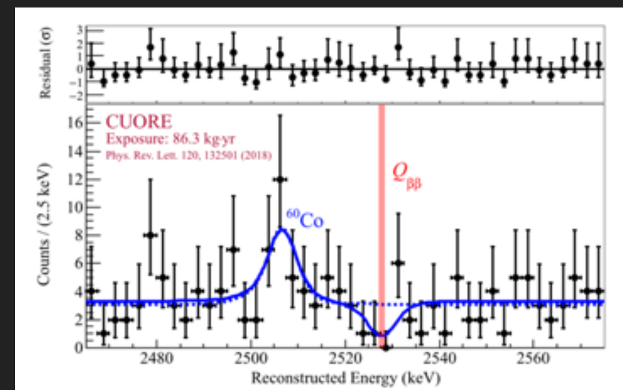
  $T_{1/2}^{0\nu} = 7.0 \times 10^{24}$ yr

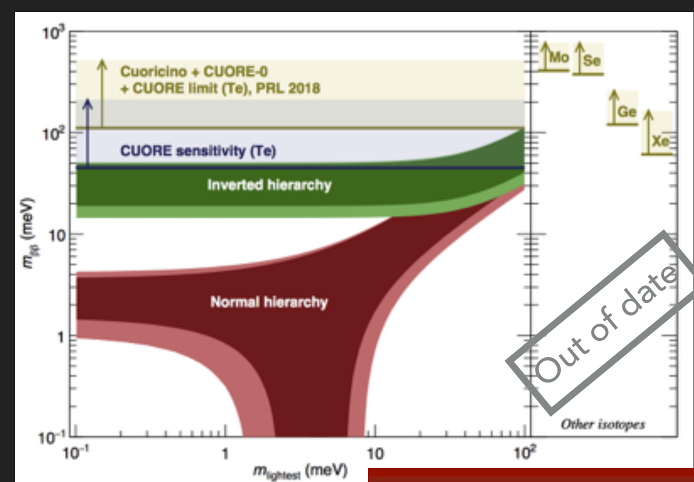
- Combined limit with CUORE-0 and Cuoricino:

$$T_{1/2}^{0\nu} > 1.5 \times 10^{25}\,\mathrm{yr}\ (90\%\mathrm{C.L.})$$

$$m_{\beta\beta} < 110 - 520\,\mathrm{meV}$$

$$m_{\beta\beta} \equiv \left| \sum_i U_{ei}^2 m_i \right|$$



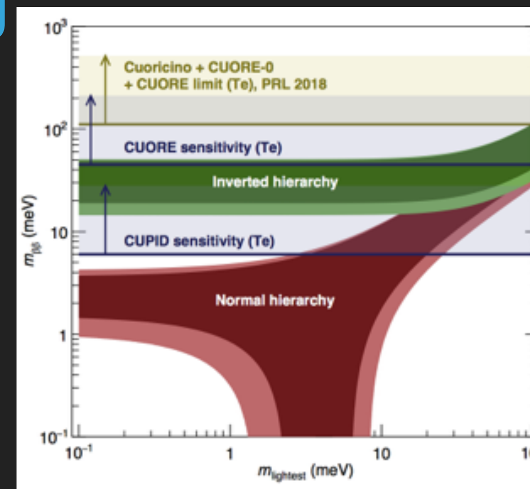


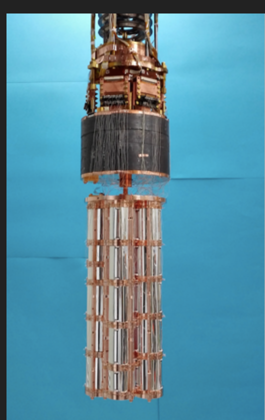
Ouellet, Jonathan - doi.org/10.5281/zenodo.1286904

Next Steps: CUPID

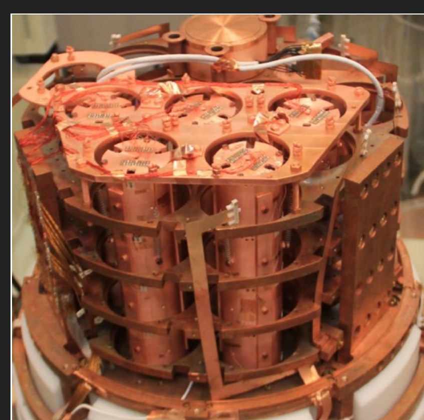
CUORE Upgrade with Particle ID (CUPID) R&D

- Next generation of 0νββ decay experiments seek to be sensitive to the full IH region ($m_{\beta\beta}$ ~ 6 - 20 meV, $T_{1/2}$ ~ 10^{27} yr)
- ~1000 enriched light emitting bolometers mounted in the CUORE cryostat
- Nearly zero background goal of ~ 0.1 cnts/(ROI·yr)
- Worldwide effort focused on demonstrating readiness to construct a tonne-scale bolometric experiment

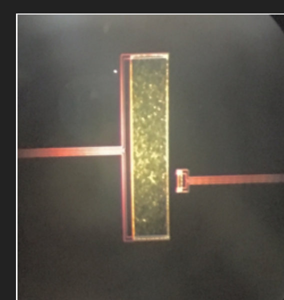




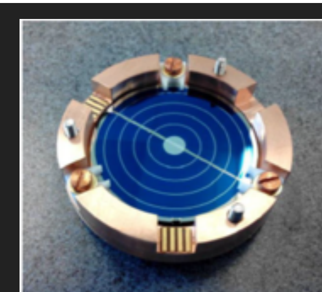
CUPID-0/Se at LNGS
$Zn^{82}Se$



CUPID-Mo at Modane
$Li_2{}^{100}MoO_4$



Neganov-Luke and TES-based light detectors for TeO_2



CUORE

Ouellet, Jonathan - doi.org/10.5281/zenodo.1286904

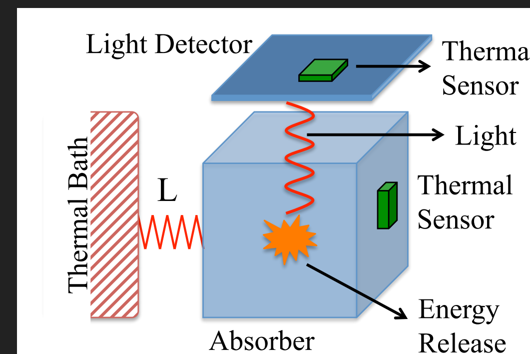
Next Steps: CUPID

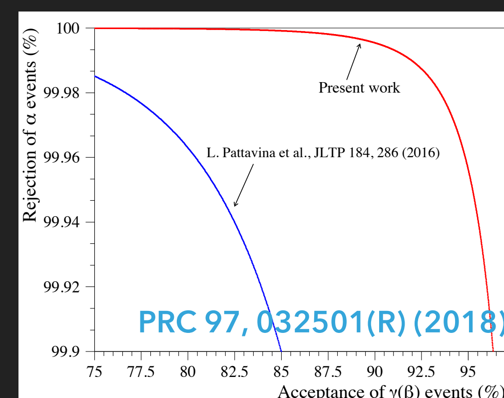
CUORE Upgrade with Particle ID (CUPID) R&D

Goal of reducing the background in the ROI by rejecting all α events with particle ID

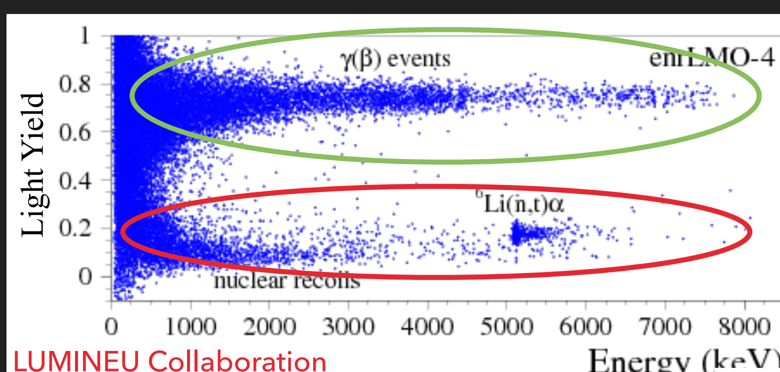
- Add the ability to read out the light emitted in a particle interaction (scintillation/Cherenkov)

➡ Combine the energy resolution of bolometers with the background discrimination of a dual channel detector





PRC 97, 032501(R) (2018)



LUMINEU Collaboration

Ouellet, Jonathan - doi.org/10.5281/zenodo.1286904

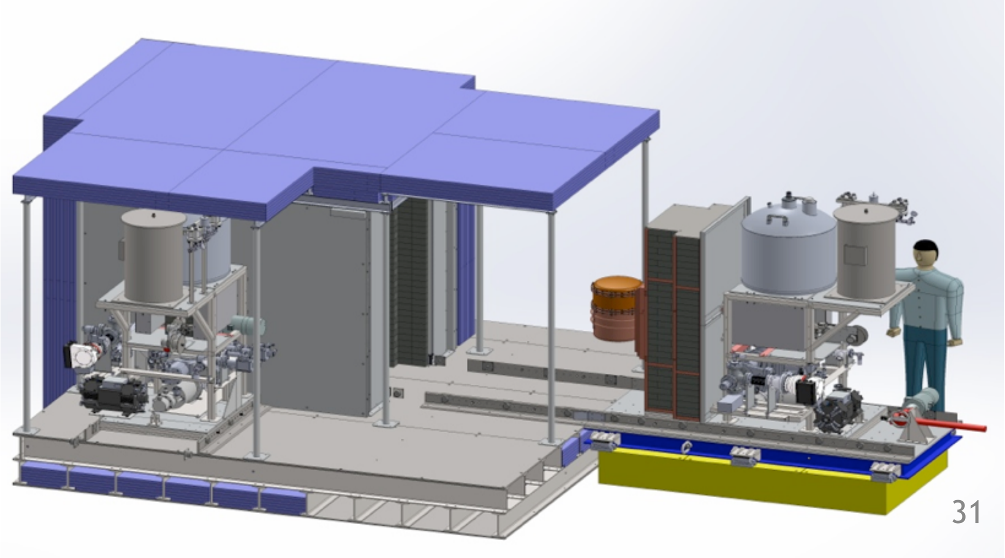
Germanium Semiconductor Detectors

GERDA:

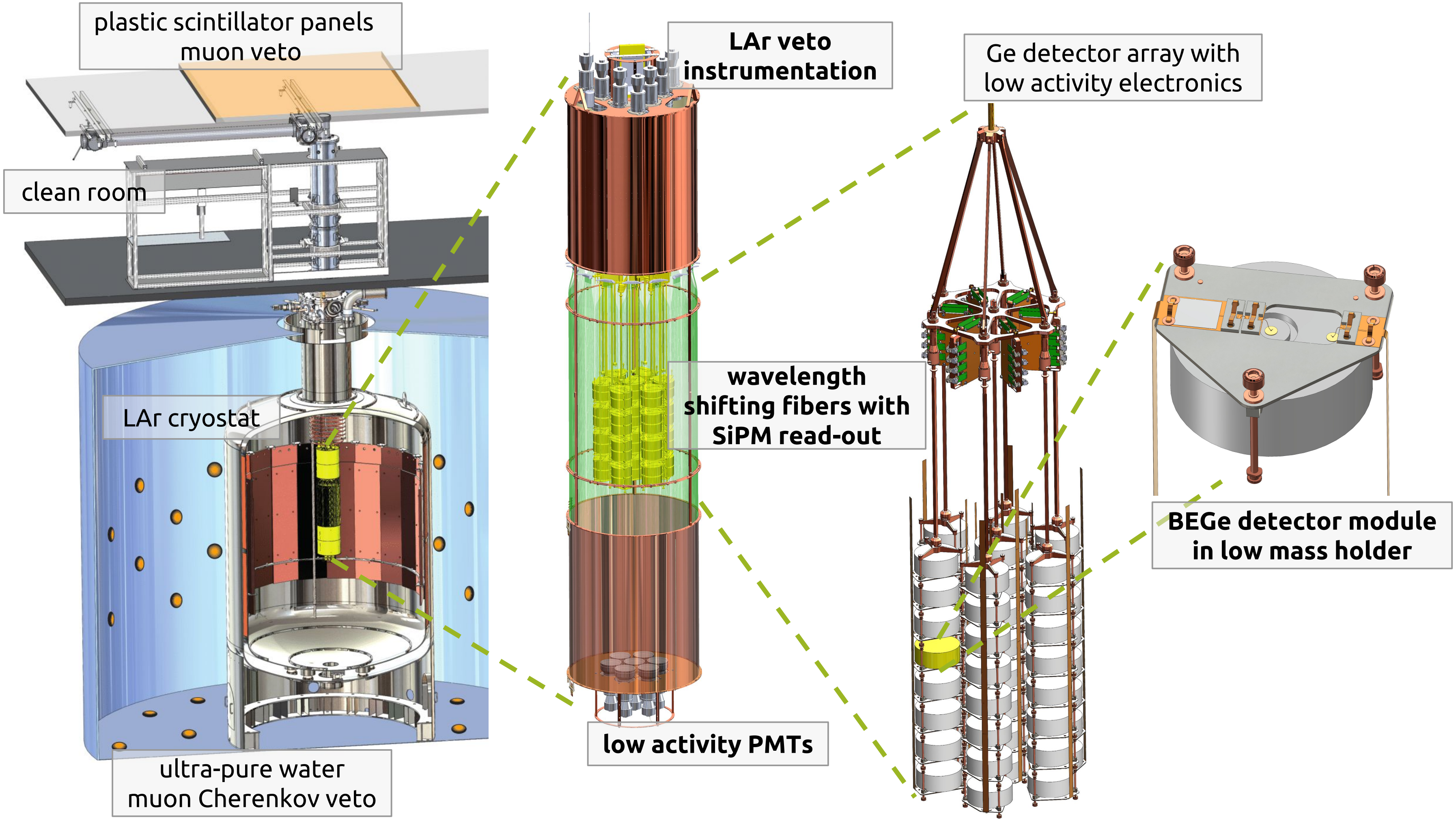
Detector immersion in Argon cryogenic bath and active shielding

MAJORANA DEMONSTRATOR:

Detectors deployed in ultra-low-background vacuum cryostats, compact shield.



GERDA Phase II

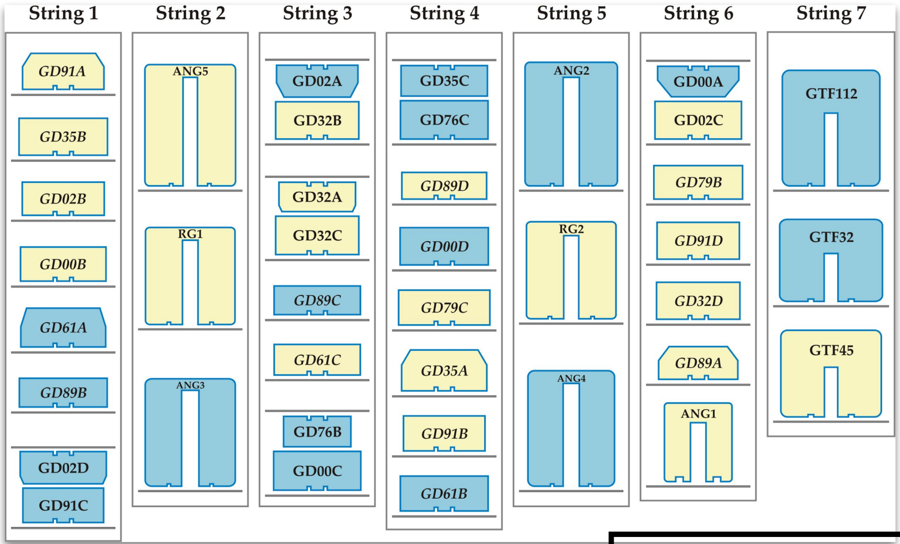


Zsigmond, Anna Julia - doi.org/10.5281/zenodo.1287604

GERDA Ge Detectors

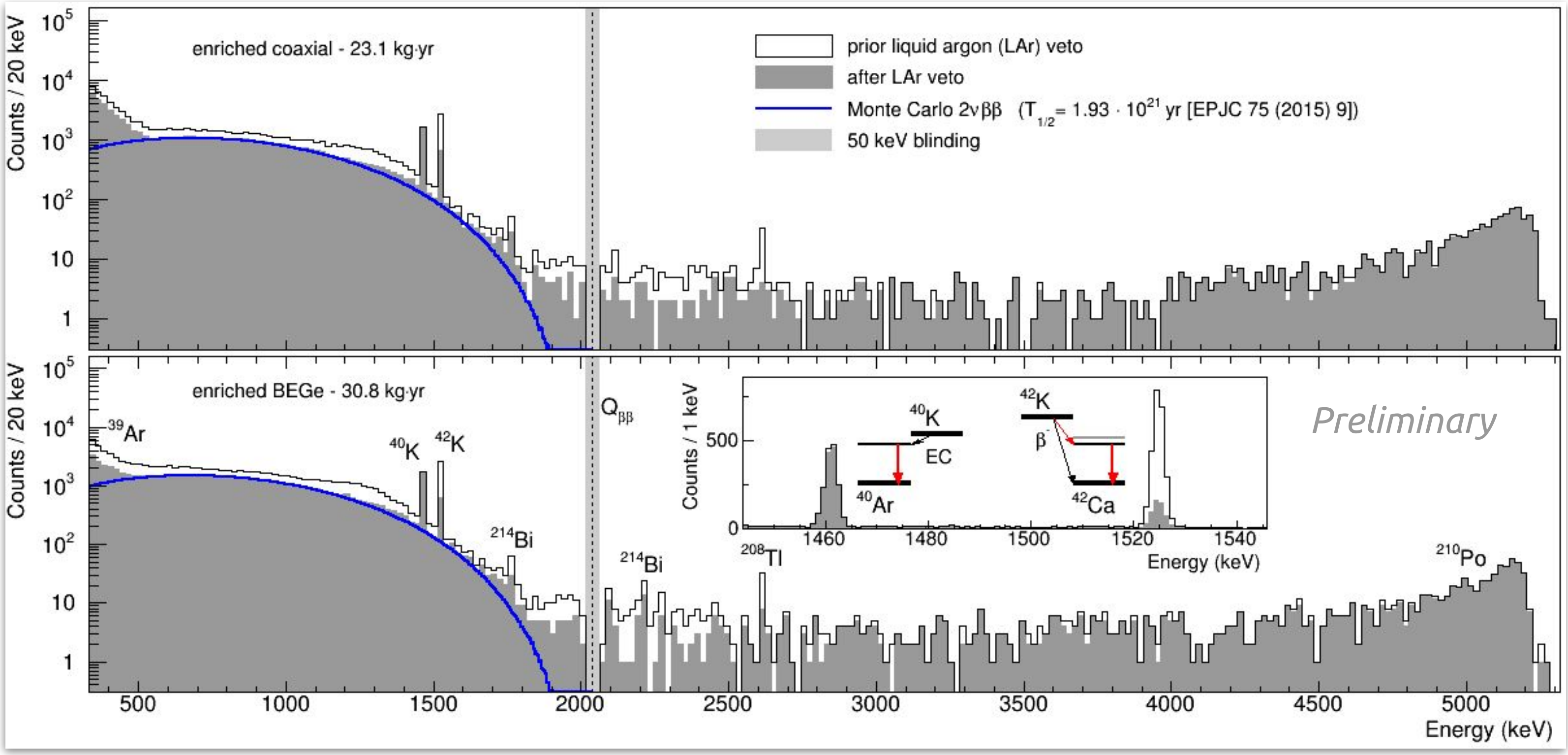
7 strings with 40 detectors in total

- 7 enriched semi-coaxial (15.6 kg)
- 30 enriched thick window BEGe (20.0 kg)
- 3 natural semi-coaxial (7.6 kg)



Zsigmond, Anna Julia - doi.org/10.5281/zenodo.1287604

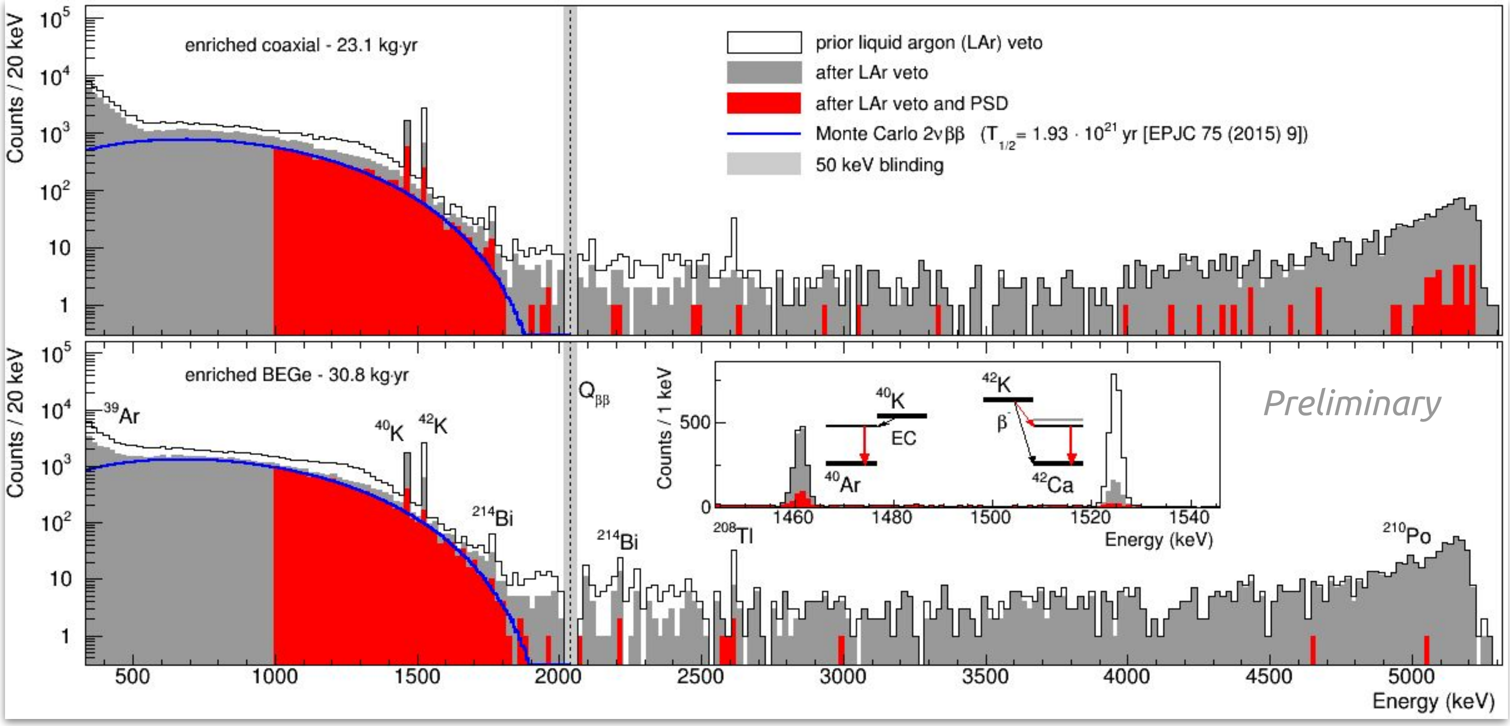
GERDA: Background Suppression with LAr Veto



- Almost pure 2νββ spectrum after LAr veto cut (600-1300 keV)
- LAr veto cut signal acceptance 97.7(1)%

Zsigmond, Anna Julia - doi.org/10.5281/zenodo.1287604

GERDA: Background Suppression with PSD

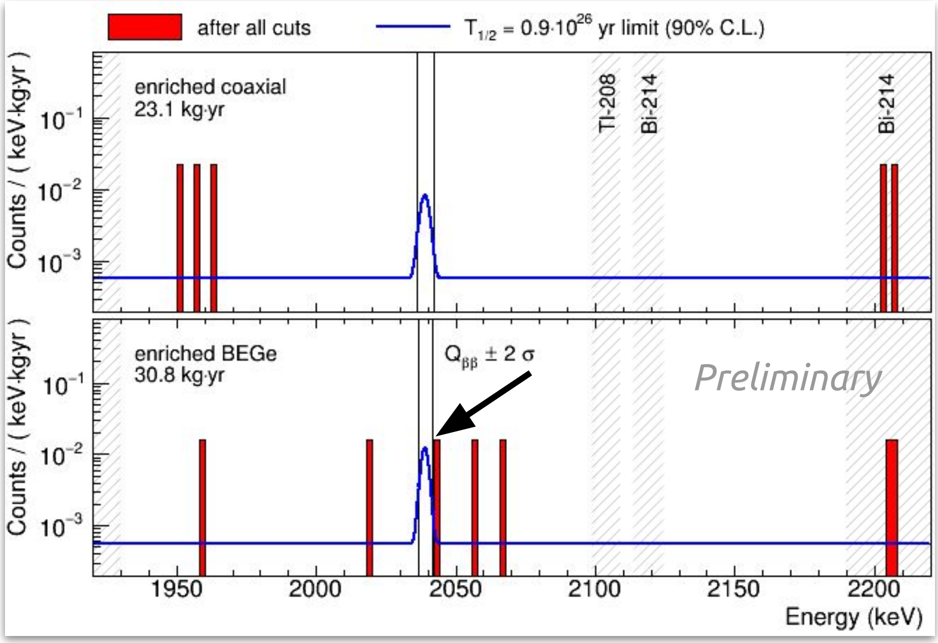


- Both K lines and high energy α events strongly suppressed
- High 0νββ signal efficiency
  (71.2 ± 4.3)% for Coax and (87.6 ± 2.5)% for BEGe detectors

Zsigmond, Anna Julia - doi.org/10.5281/zenodo.1287604

GERDA: Background Index

Background index window: 1930-2190 keV, excl. ±5 keV around two known γ lines and around $Q_{\beta\beta}$



Coax*: $5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/(keV·kg·yr)

BEGe: $5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV·kg·yr)

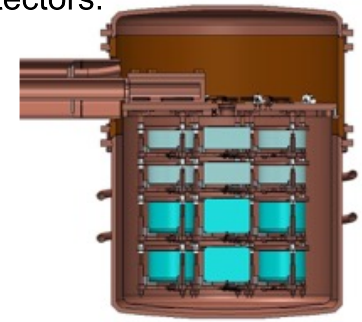
One new event in the BEGe dataset with energy 2042 keV

Zsigmond, Anna Julia - doi.org/10.5281/zenodo.1287604

The MAJORANA DEMONSTRATOR

Operating underground at the 4850' Sanford Underground Research Facility

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



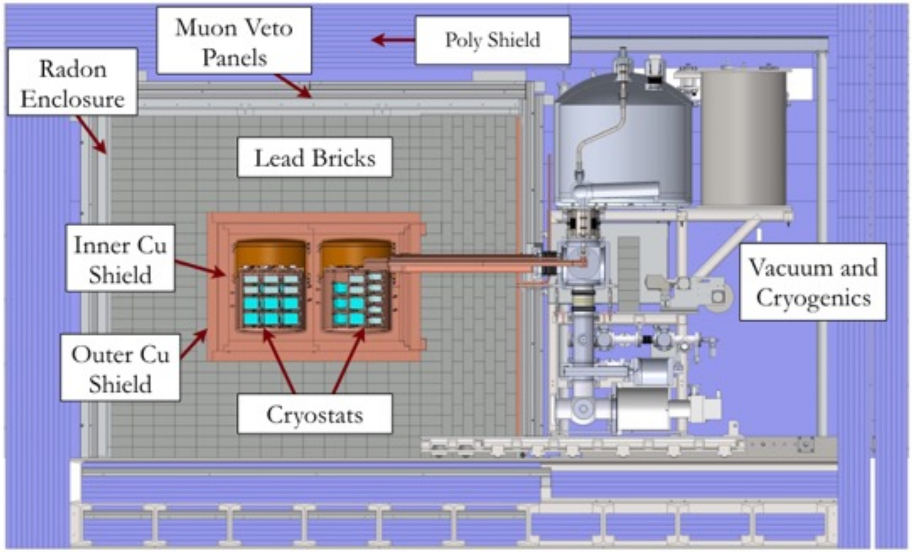
Energy resolution of 2.5 keV FWHM @ 2039 keV is the best of any ββ-decay experiment

Background Goal in the 0νββ peak after analysis cuts:
- With the achieved resolution: 2.5 counts/(FWHM t yr)
- Projected backgrounds based on assay results ≤ 2.2 counts/(FWHM t yr)

44.1-kg of Ge detectors
- 29.7 kg of 88% enriched ^{76}Ge crystals
- 14.4 kg of natGe
- 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



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

[N. Abgrall et al. Adv. High Energy Phys **2014**, 365432 (2014)]

Guiseppe, Vincente - doi.org/10.5281/zenodo.1286900

MAJORANA DEMONSTRATOR Clean Materials

Ultra-pure materials

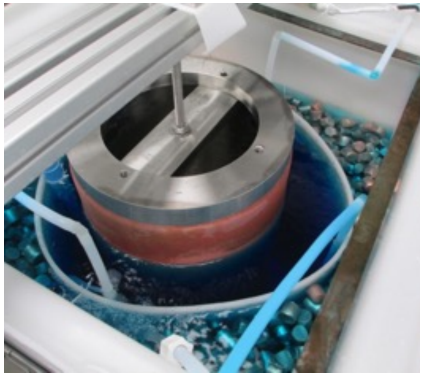
- Low mass design
- Custom cable connectors and front-end boards
- Selected plastics & fine Cu coax cables
- Underground Electro-formed Cu

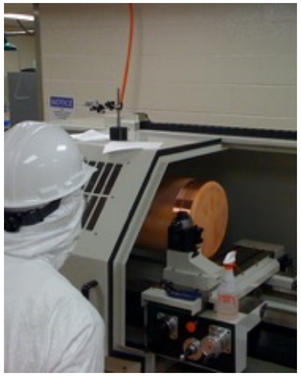
  Th decay chain (ave) ≤ 0.1 µBq/kg

  U decay chain (ave) ≤ 0.1 µBq/kg

Detector assembly

- Dedicated glove boxes with a purged N_2 environment





Machining and Cleaning

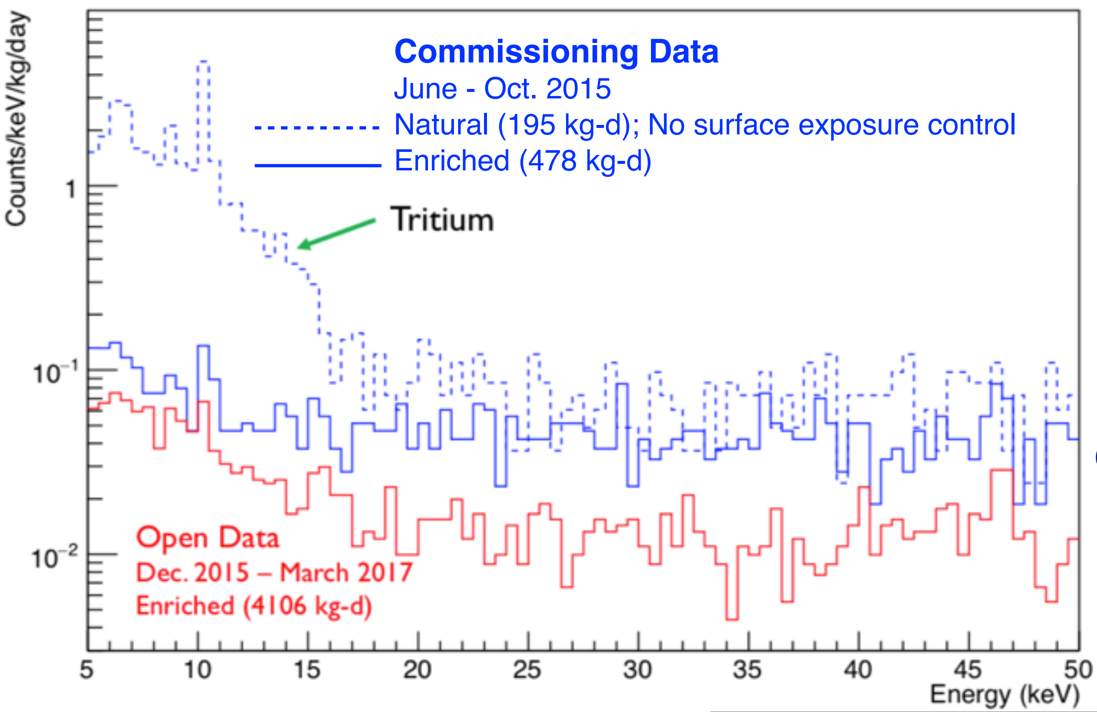
- Cu machining in an underground clean room
- Cleaning of Cu parts by acid etching and passivation
- Nitric leaching of plastic parts

Guiseppe, Vincente - doi.org/10.5281/zenodo.1286900

MAJORANA DEMONSTRATOR Beyond-the-Standard-Model Physics Searches

The low backgrounds at low energy allows additional searches

- Controlled surface exposure of enriched material to minimize cosmogenics
- Sub-keV energy thresholds possible (< 500 eV)
  Efficiency below 5 keV is under study.
- Excellent energy resolution (0.4 keV FWHM at 10.4 keV)



Permits low-energy physics
- pseudoscalar dark matter
- vector dark matter
- 14.4-keV solar axion
- $e^- \Rightarrow 3\nu$

Pauli Exclusion Principle

Phys. Rev. Lett. **118** 161801 (2017)

Other exotic physics
- Lightly ionizing particles

Phys. Rev. Lett. **120** 211804 (2018)

Guiseppe, Vincente - doi.org/10.5281/zenodo.1286900

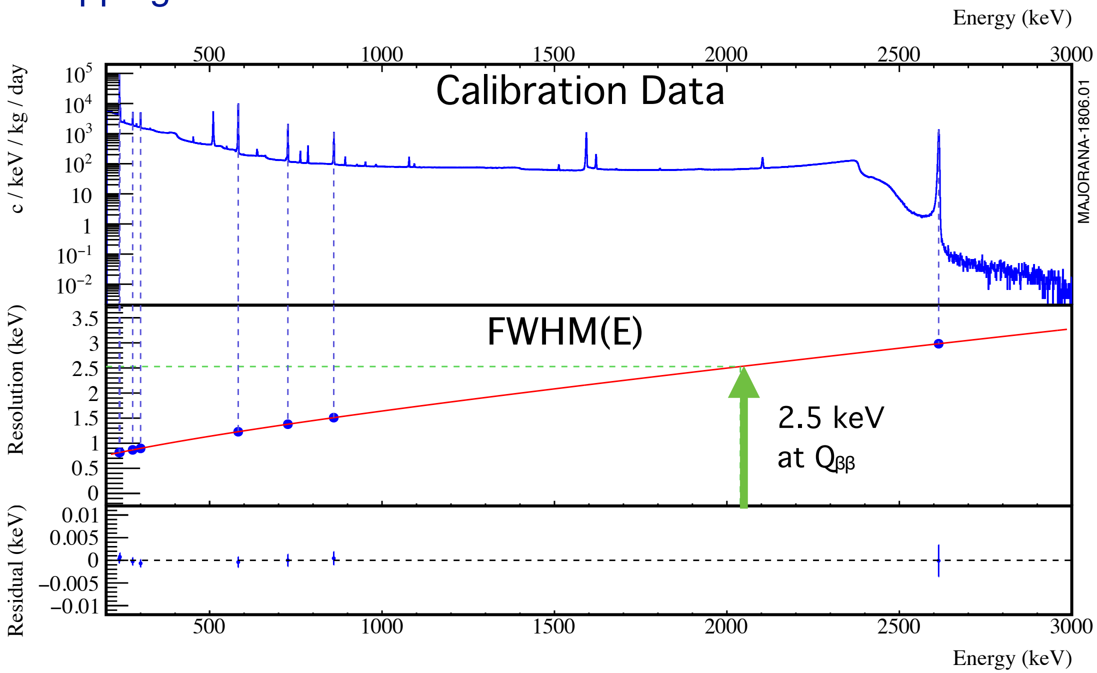
MAJORANA DEMONSTRATOR: Energy Resolution

Calibration of the detector array with a ^{228}Th line source

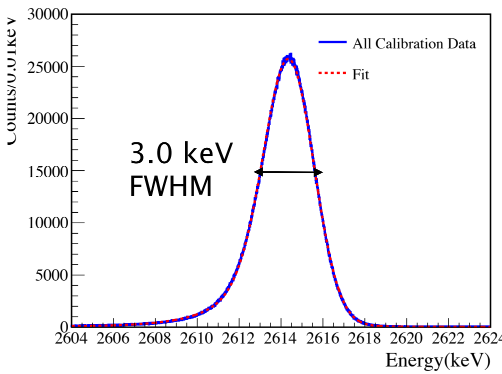
- Source is inserted and retracted for scheduled calibrations
- Provides energy calibration, gain stability checks, and tuning of single-site (DEP) and multi-site (SEP) cuts

Excellent energy resolution attained improved by charge trapping and ADC nonlinearities corrections

[NIMA **872**,16 (2017) arXiv:1702.02466]



^{208}Tl 2615 keV Peak



Best achieved for $0\nu\beta\beta$ searches!

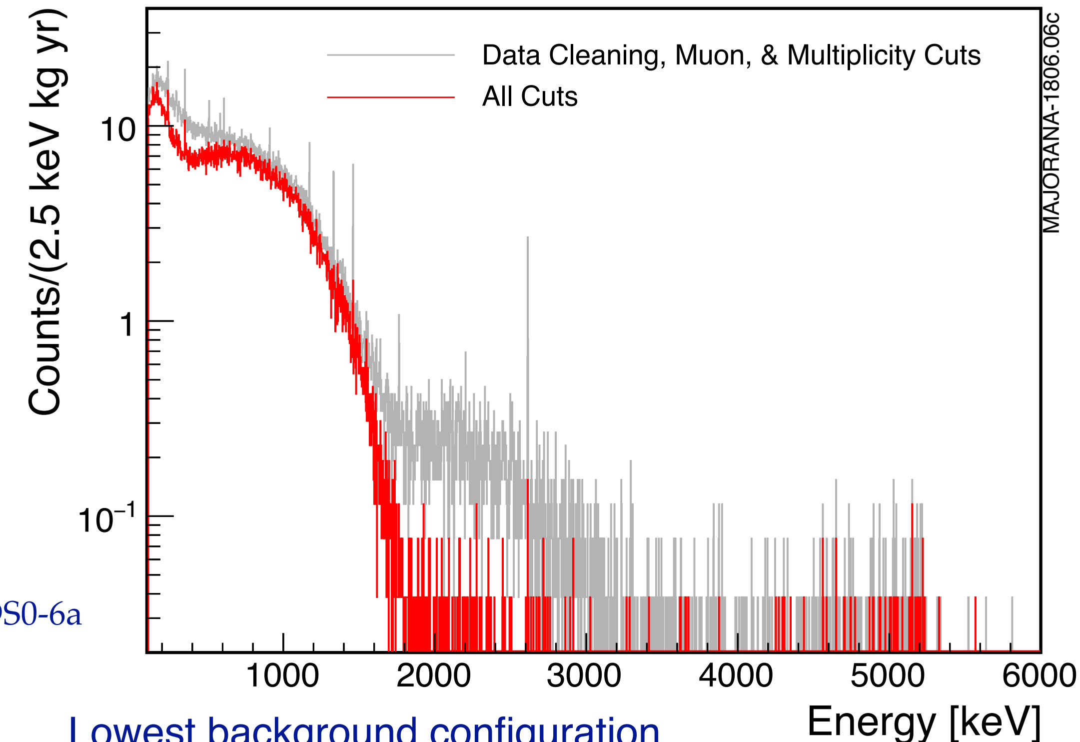
Guiseppe, Vincente - doi.org/10.5281/zenodo.1286900

MAJORANA DEMONSTRATOR: Recent 0νββ Results

All data (all open and previously blinded) up until 15 April 2018

- All data: 26 kg-yr (^{enr}Ge)

PRELIMINARY



DS0-6a

Full Exposure Background

$$15.4 \pm 2.0 \text{ cts/(FWHM t yr)}$$

The expected counts in the optimal ROI (4.13 keV): 0.66

After final unblinding: 1 event at 2040 keV

Lowest background configuration

- Active Exposure: 21.3 kg yr (^{enr}Ge)
- Background rate: $11.9 \pm 2.0 \text{ cts/(FWHM t yr)}; 4.7 \pm 0.8 \times 10^{-3} \text{ cts/(keV kg yr)}$

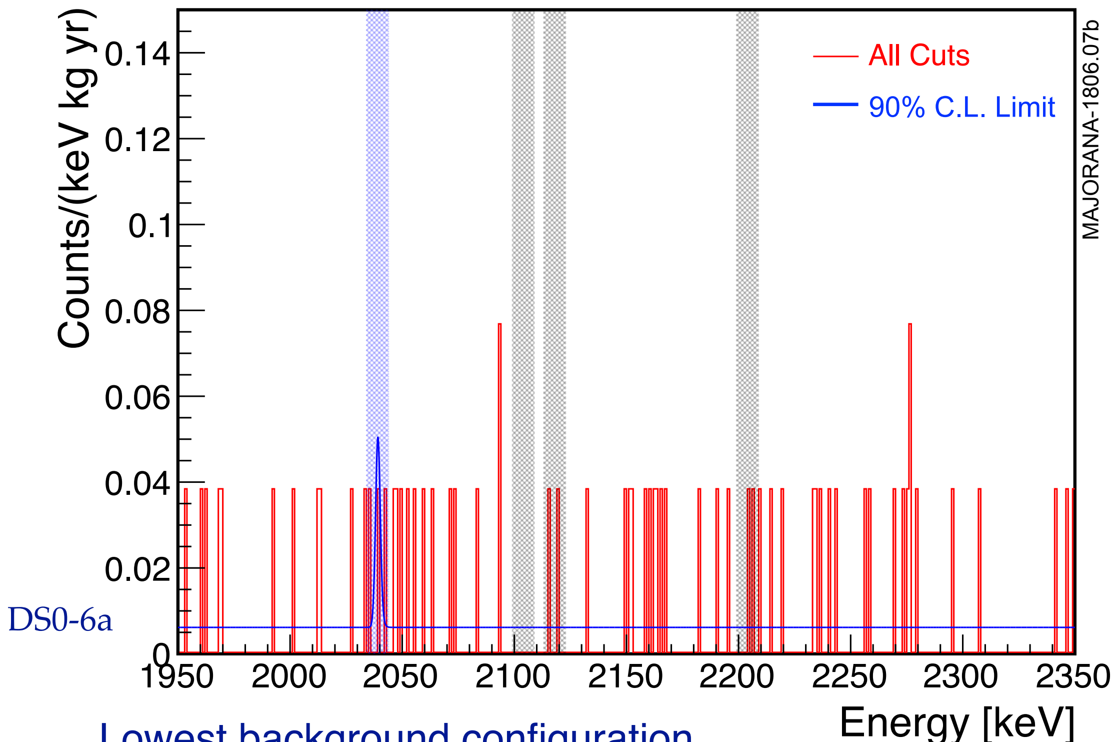
Guiseppe, Vincente - doi.org/10.5281/zenodo.1286900

MAJORANA DEMONSTRATOR: Recent 0νββ Results

All data (all open and previously blinded) up until 15 April 2018

- All data: 26 kg-yr (^{enr}Ge)

PRELIMINARY



Median Sensitivity:

4.8×10^{25} yr (90% CL)

Full Exposure Limit

$T^{0\nu}_{1/2} > 2.7 \times 10^{25}$ yr (90% CL)

Full Exposure Background

15.4 ± 2.0 cts/(FWHM t yr)

The expected counts in the optimal ROI (4.13 keV): 0.66

After final unblinding:
1 event at 2040 keV

Lowest background configuration

- Active Exposure: 21.3 kg yr (^{enr}Ge)
- Background rate: 11.9 ± 2.0 cts/(FWHM t yr); $4.7 \pm 0.8 \times 10^{-3}$ cts/(keV kg yr)

Guiseppe, Vincente - doi.org/10.5281/zenodo.1286900

LEGEND

"The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10 years, using existing resources as appropriate to expedite physics results."

Combining successes of MJD clean materials development, GERDA active shield, and new initiatives.

LEGEND-200:

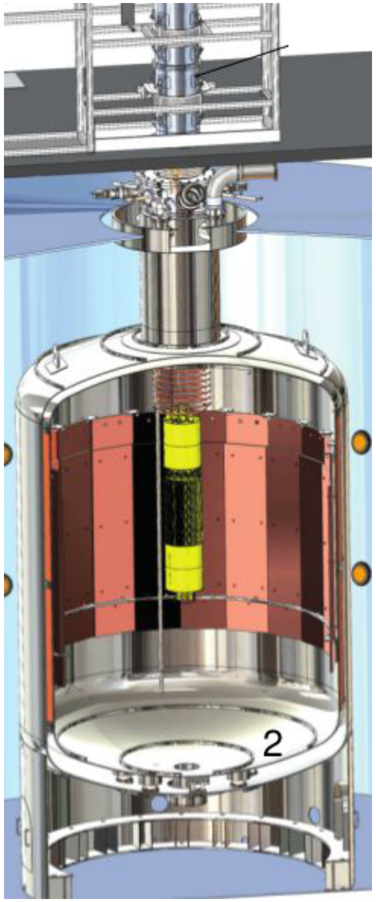
- ~200-kg array deployment in existing GERDA cryostat at LNGS
- BG goal (5x lower) 0.6 c/(FWHM-tn-yr)
- Start by 2021

LEGEND-1k:

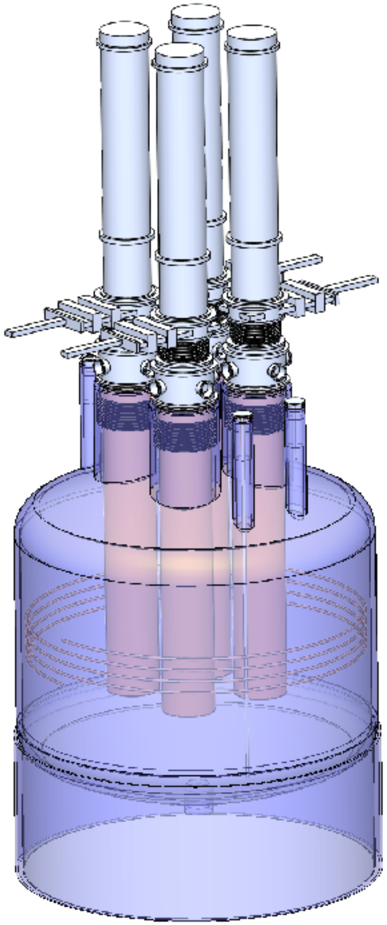
- 1000-kg, ~4-module array with phased deployment.
- BG goal (30x lower) 0.1 c/(FWHM-tn-yr)
- Timeline connected to US DOE down-select
- Location TBD - Required depth under investigation

Active Shield: Investigating reduction of Ar backgrounds:

Depleted Argon
Detector encapsulation
Frozen scintillator
Liquid Neon



LEGEND-200

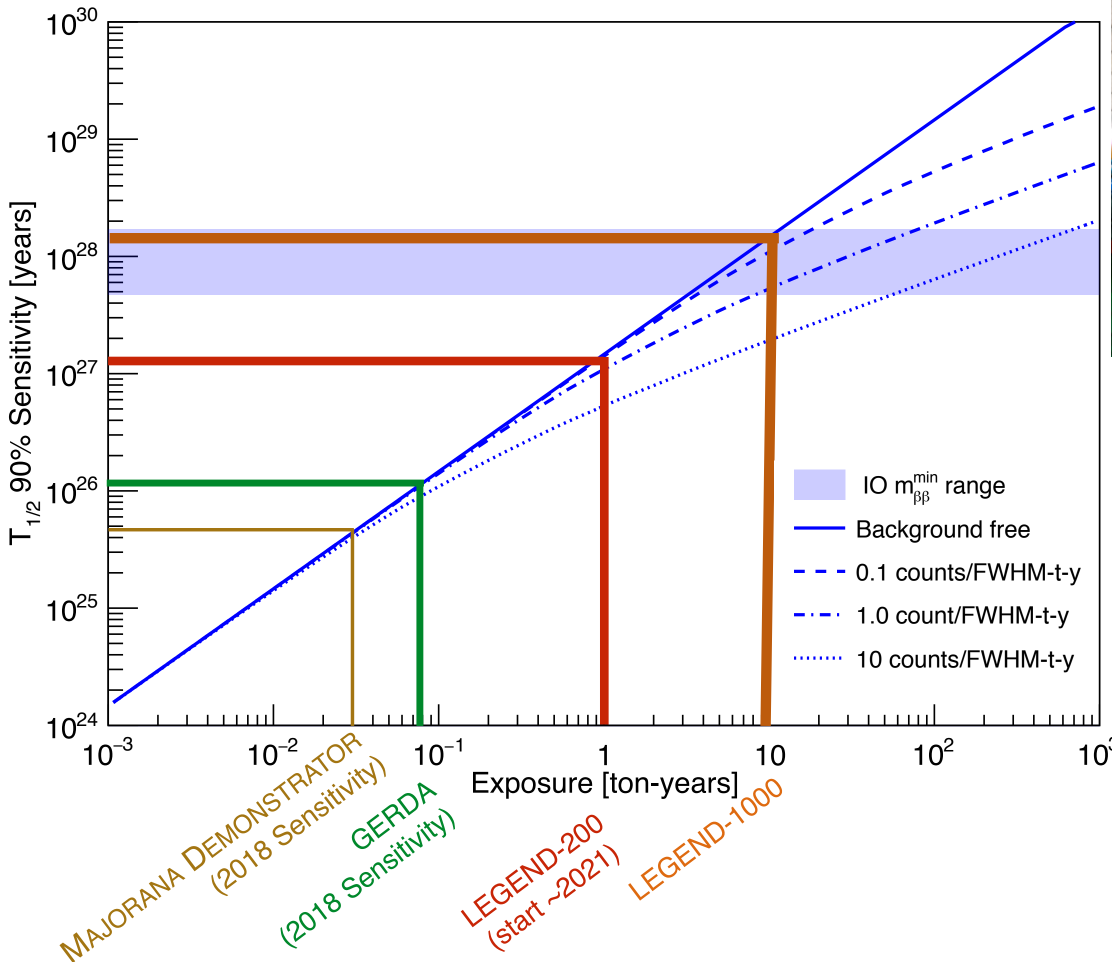


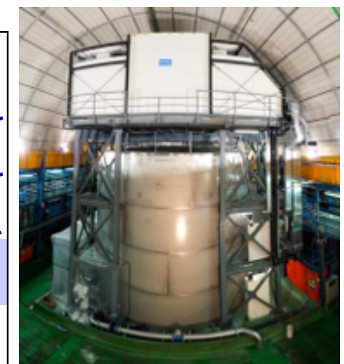
LEGEND-1k

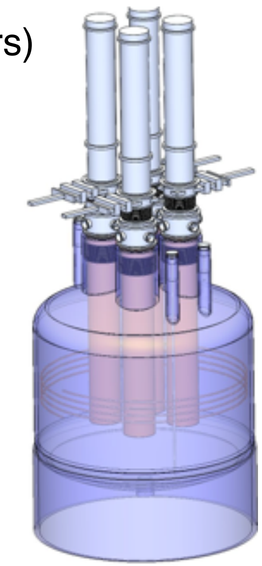
LEGEND: Future Sensitivity

Next Generation ^{76}Ge: LEGEND — Large Enriched Germanium Experiment for Neutrinoless ββ Decay (52 Institutions, ~250 Members)

^{76}Ge (87% enr.)







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 (65 kg), plus new detectors (135 kg)

Subsequent Stages:

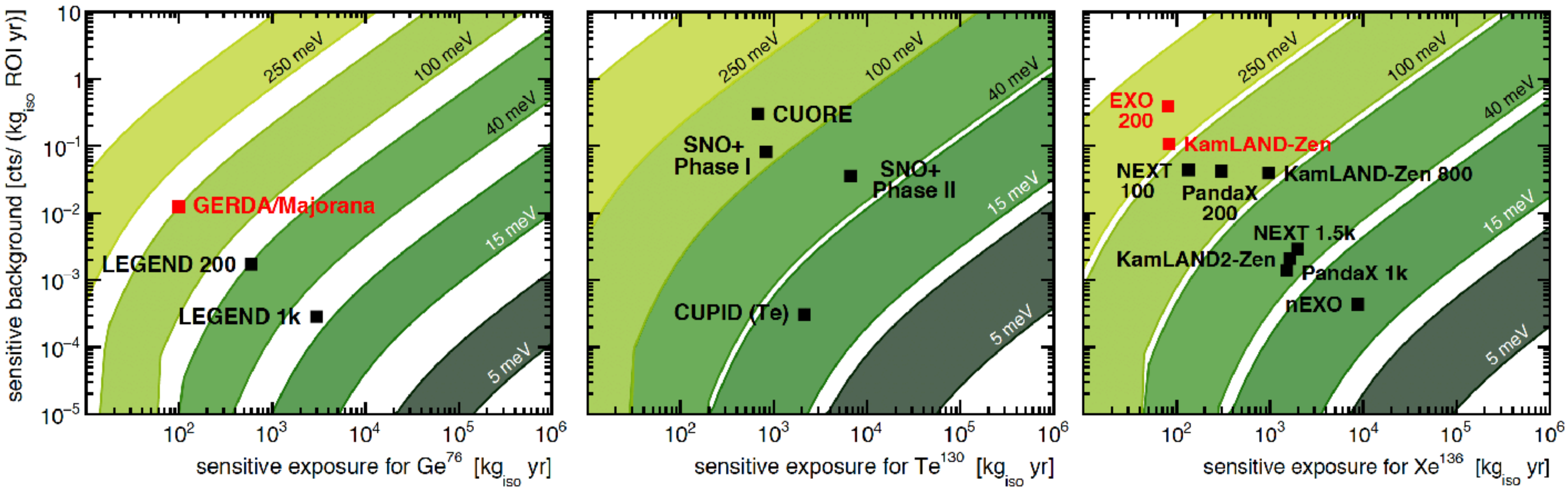
- 1000 kg ^{76}Ge (staged)
- BG goal: 0.1 cts/(FWHM t yr)
- Location: TBD

The Global Picture

Experiment	Iso.	Iso. Mass	σ	ROI	ϵ_{FV}	ϵ_{sig}	$\mathcal{E}$	$\mathcal{B}$	3σ disc. sens. $\hat{T}_{1/2}$	$\hat{m}_{\beta\beta}$	Required Improvement Bkg	σ	Iso. Mass
		[kg_{iso}]	[keV]	[σ]	[%]	[%]	$\left[\frac{kg_{iso}\,yr}{yr}\right]$	$\left[\frac{cts}{kg_{iso}\,ROI\,yr}\right]$	[yr]	[meV]			
LEGEND 200 [62, 63]	^{76}Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	40–73	3	1	5.7
LEGEND 1k [62, 63]	^{76}Ge	873	1.3	[-2, 2]	93	77	593	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{27}$	17–31	18	1	29
SuperNEMO [69, 70]	^{82}Se	100	51	[-4, 2]	100	16	16.5	$4.9 \cdot 10^{-2}$	$6.1 \cdot 10^{25}$	82–138	49	2	14
CUPID [59, 60, 71]	^{82}Se	336	2.1	[-2, 2]	100	69	221	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{27}$	15–25	n/a	6	n/a
CUORE [53, 54]	^{130}Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1 \cdot 10^{-1}$	$5.4 \cdot 10^{25}$	66–164	6	1	19
CUPID [59, 60, 71]	^{130}Te	543	2.1	[-2, 2]	100	81	422	$3.0 \cdot 10^{-4}$	$2.1 \cdot 10^{27}$	11–26	3000	1	50
SNO+ Phase I [67, 72]	^{130}Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2 \cdot 10^{-2}$	$1.1 \cdot 10^{26}$	46–115	n/a	n/a	n/a
SNO+ Phase II [68]	^{130}Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6 \cdot 10^{-2}$	$4.8 \cdot 10^{26}$	22–54	n/a	n/a	n/a
KamLAND-Zen 800 [61]	^{136}Xe	750	114	[0, 1.4]	64	97	194	$3.9 \cdot 10^{-2}$	$1.6 \cdot 10^{26}$	47–108	1.5	1	2.1
KamLAND2-Zen [61]	^{136}Xe	1000	60	[0, 1.4]	80	97	325	$2.1 \cdot 10^{-3}$	$8.0 \cdot 10^{26}$	21–49	15	2	2.9
nEXO [73]	^{136}Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{27}$	9–22	400	1.2	30
NEXT 100 [65, 74]	^{136}Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4 \cdot 10^{-2}$	$5.3 \cdot 10^{25}$	82–189	n/a	1	20
NEXT 1.5k [75]	^{136}Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9 \cdot 10^{-3}$	$7.9 \cdot 10^{26}$	21 49	n/a	1	300
PandaX-III 200 [66]	^{136}Xe	180	31	[-2, 2]	100	35	60.2	$4.2 \cdot 10^{-2}$	$8.3 \cdot 10^{25}$	65–150	n/a	n/a	n/a
PandaX-III 1k [66]	^{136}Xe	901	10	[-2, 2]	100	35	301	$1.4 \cdot 10^{-3}$	$9.0 \cdot 10^{26}$	20–46	n/a	n/a	n/a

Agostini, Benito, Detwiler - doi.org/10.1103/PhysRevD.96.053001

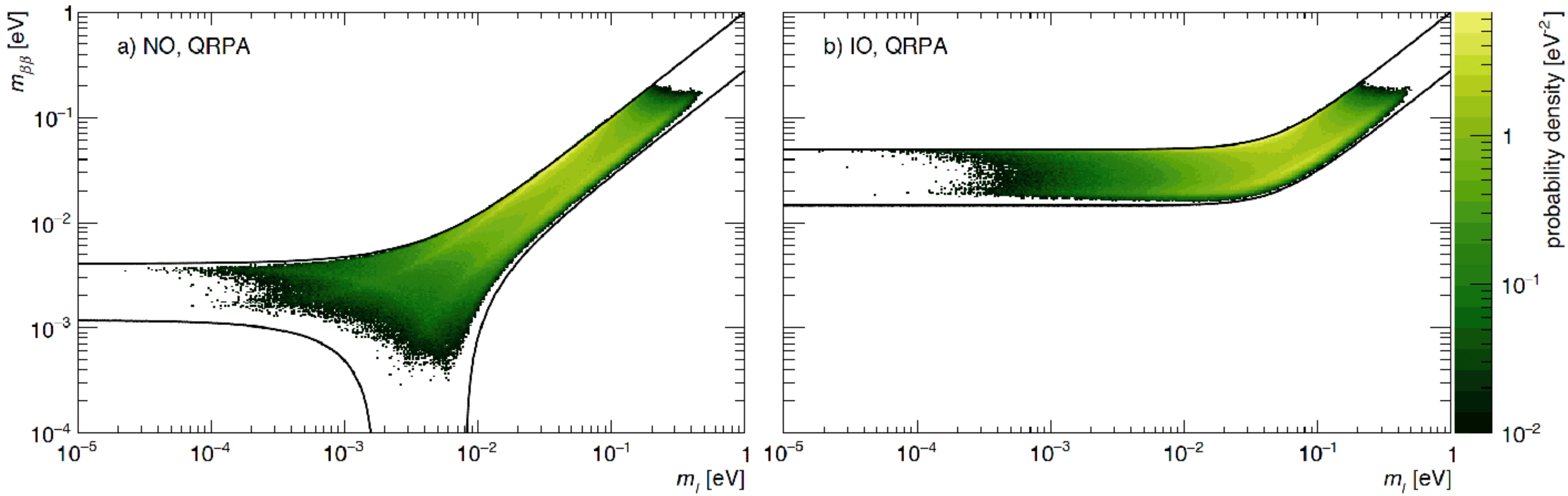
The Global Picture



- Colored bands represent NME uncertainties.
- Assumed g_a = 1.27 (no quenching).

Agostini, Benito, Detwiler - doi.org/10.1103/PhysRevD.96.053001

Discovery Potential



- Increasingly significant evidence is suggesting a preference for Normal Ordering.
- While it is essentially impossible to completely rule out NO Majorana Neutrinos with 0νββ null results, there is significant discovery potential for next-generation experiments even in the case of Normal Ordering.

Agostini, Benito, Detwiler - doi.org/10.1103/PhysRevD.96.053001

Thank you for your attention…

and thank you for your help,
Alfredo Galindo-Uribarri and Andrea Pocar!