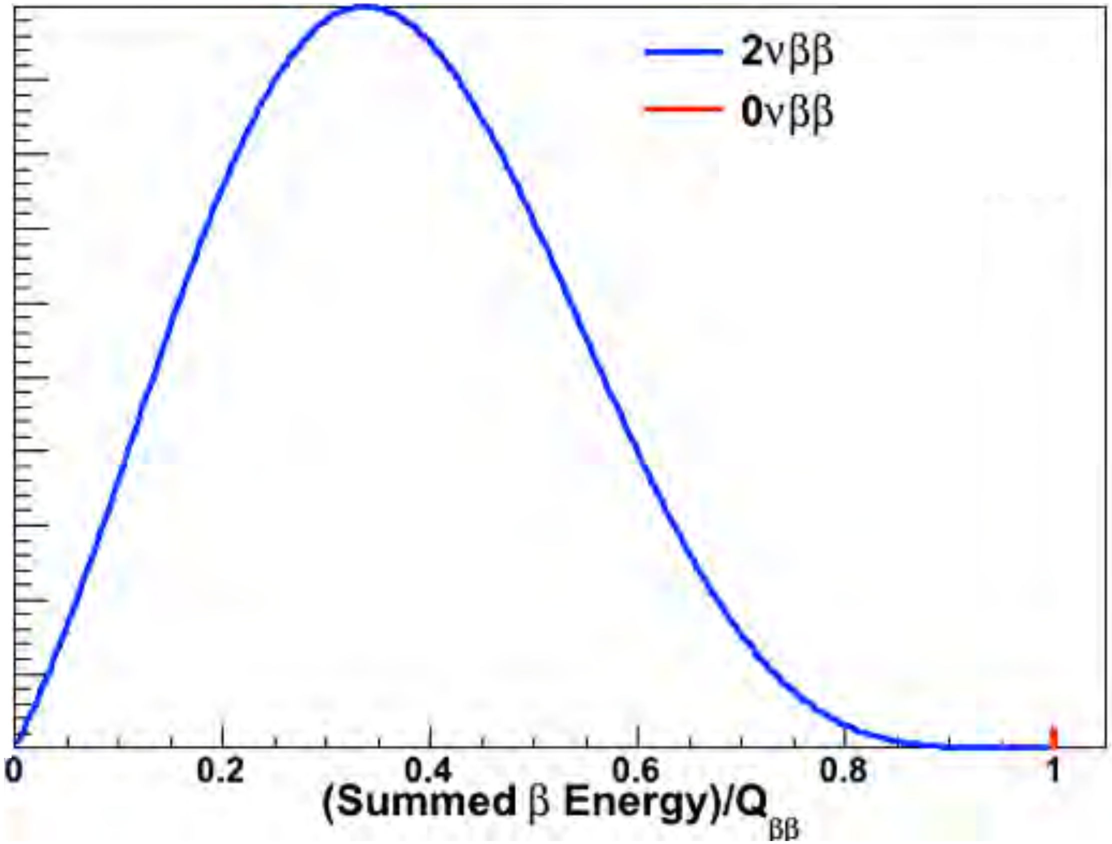
The Quest for Neutrinoless Double-Beta Decay



Zero neutrino double beta decay search

KamLAND-Zen

GERDA

LEGEND

Jason Detwiler

Assistant Professor, University of Washington / CENPA

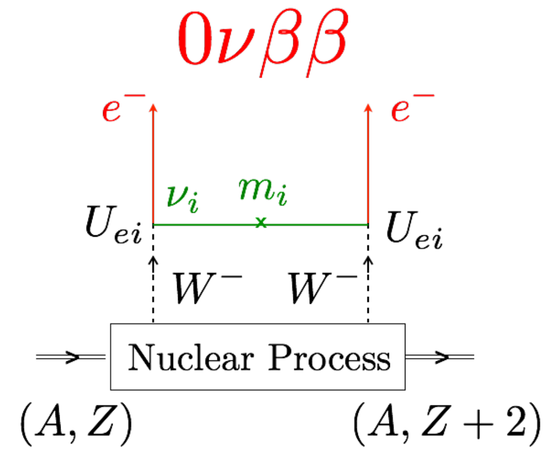
Kavli IPMU Seminar, August 18, 2017

Outline

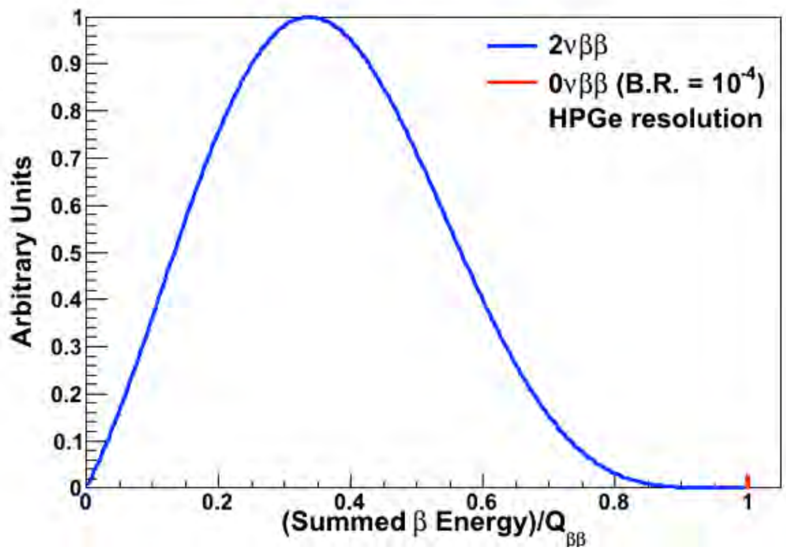
- Introduction: exposure and background
- High exposure: KamLAND-Zen
- Low background: MAJORANA / GERDA / LEGEND
- Discovery potential of future experiments

Neutrinoless Double-Beta Decay

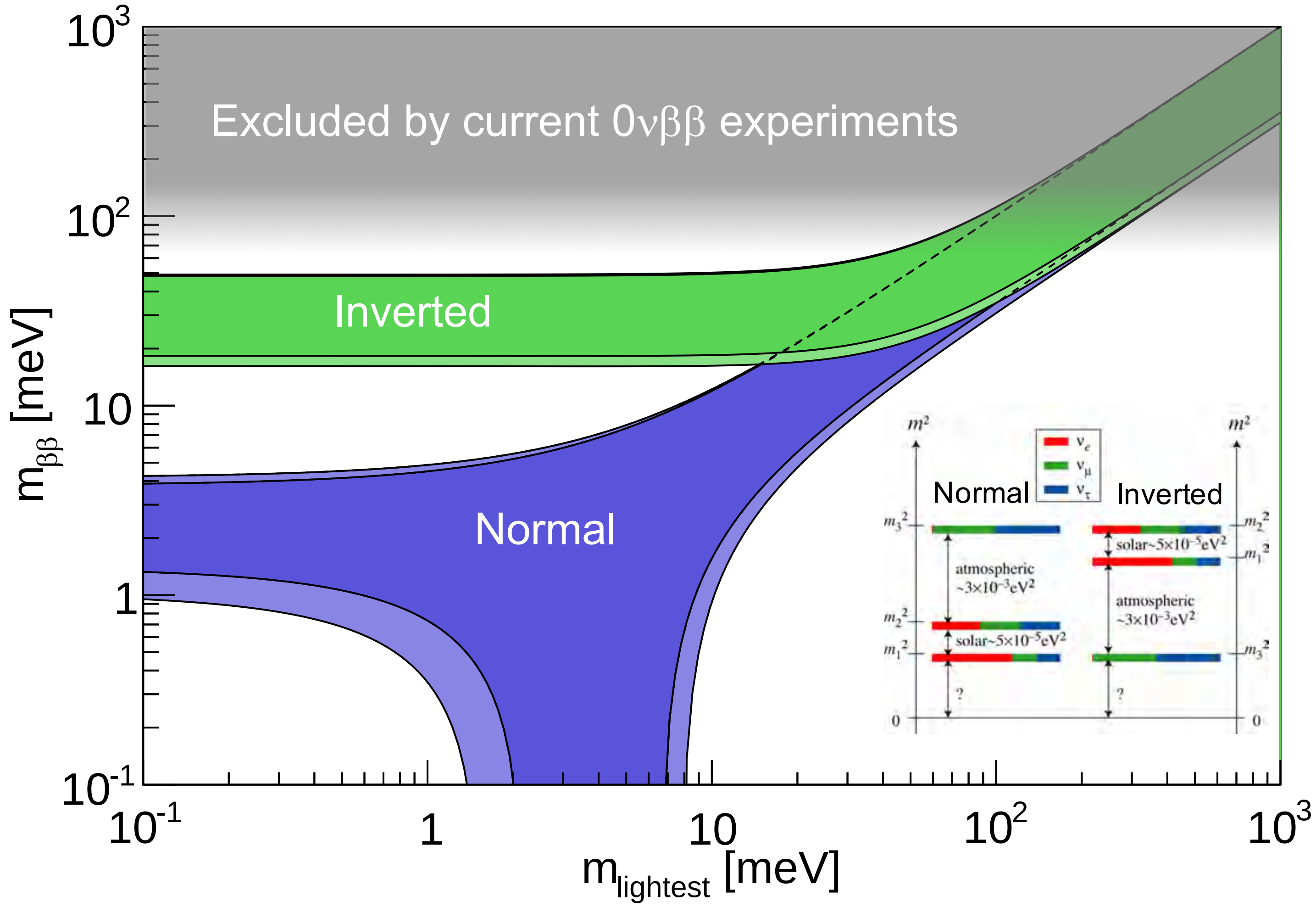
- Neutrino mass requires BSM physics
  - Dirac mass: new particle ν_R and extra-small Higgs coupling
  - Majorana mass: new unrenormalizable mass mechanism
- Motivation for Majorana neutrinos
  - L violation
  - “Minimally” non-renormalizable
  - Emerge “naturally” from GUTs (seesaw mechanism)
  - “Predicted” by leptogenesis
- Only feasible detection method: 0νββ decay



$$\Gamma^{0\nu}_{1/2} = G^{0\nu}|M^{0\nu}|^2 \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2$$



Light Neutrino Exchange



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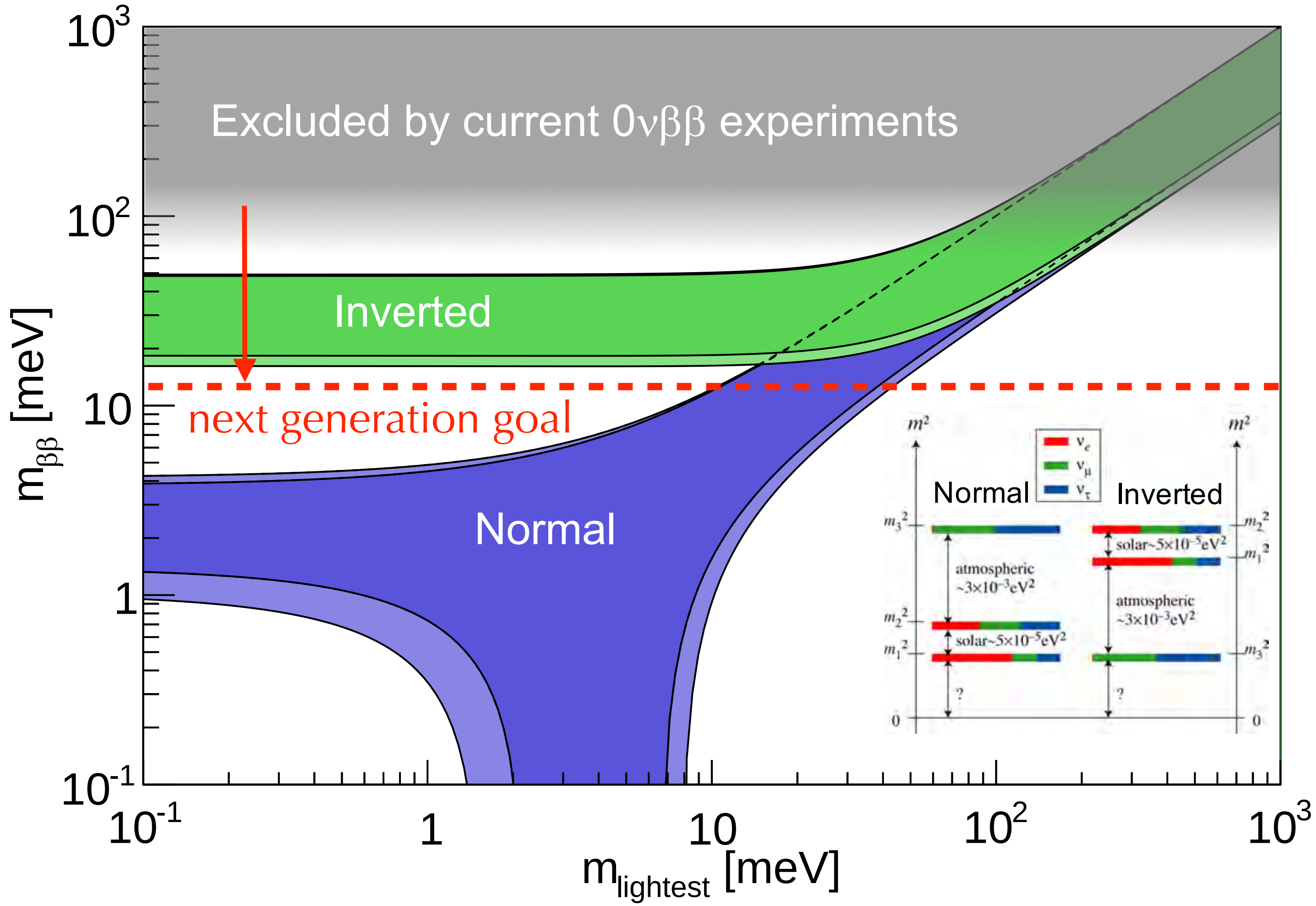


Experimental Requirements

- Energy is the only observable that is a necessary and sufficient condition for discovery of 0νββ decay
- Sensitivity is dominated by straight Poisson counting in the region-of-interest (ROI): observing some number of counts during an exposure in the presence of background.
- Relevant parameters:

Sensitive Exposure

$$\mathcal{E} = \epsilon \, m_{iso}^{FV} \, t$$

ϵ: detection efficiency; m_{iso}^{FV}: fiducial mass of isotope; t: counting time

Sensitive Background

$$\mathcal{B} = N_{bg}/\mathcal{E}$$

N_{bg}: background counts

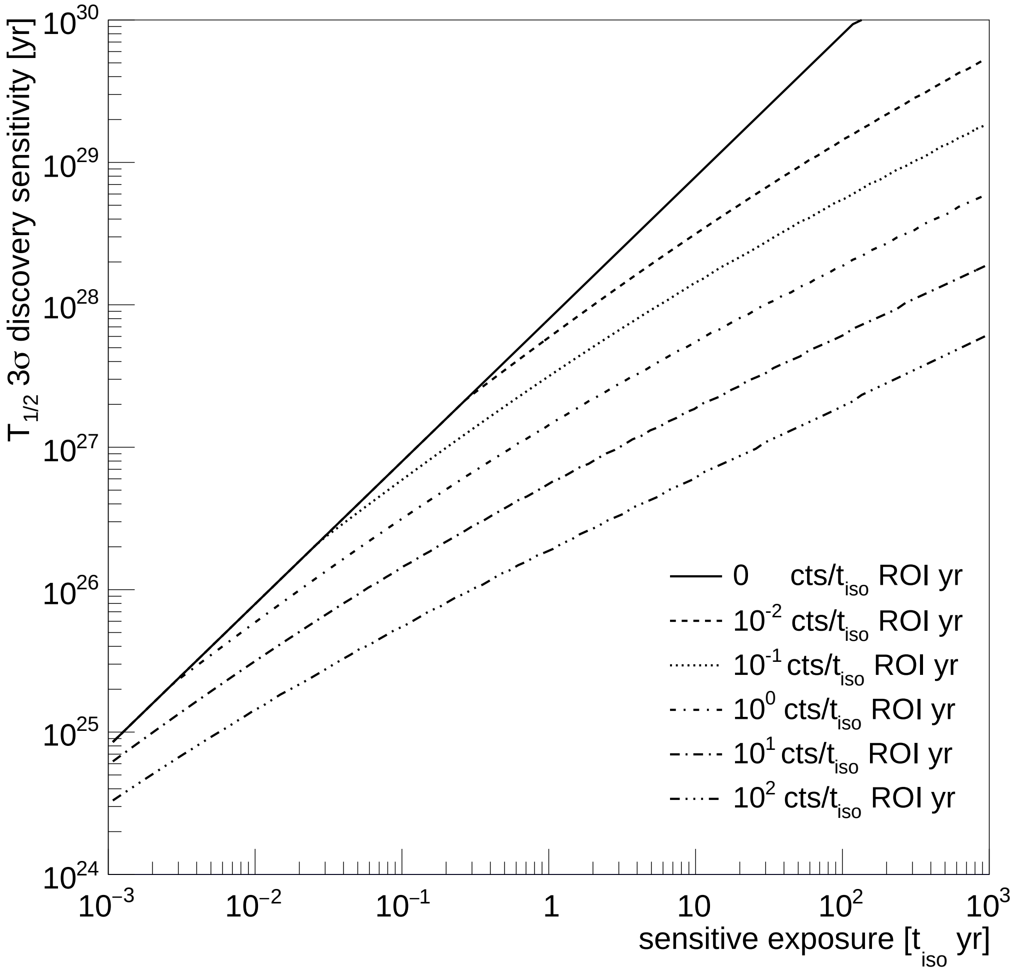
- In most (all) experiments, background is well-constrained, either from energy or volumetric side-bands

Discovery Sensitivity

- Discovery sensitivity: the value of $T_{1/2}$ for which an experiment has a 50% chance to observe a signal above background with 3σ significance:

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

- $S_{3\sigma}(B)$ = Poisson signal expectation at which 50% of experiments report 3σ fluctuation above $N_{bg} = \mathcal{B}\mathcal{E}$



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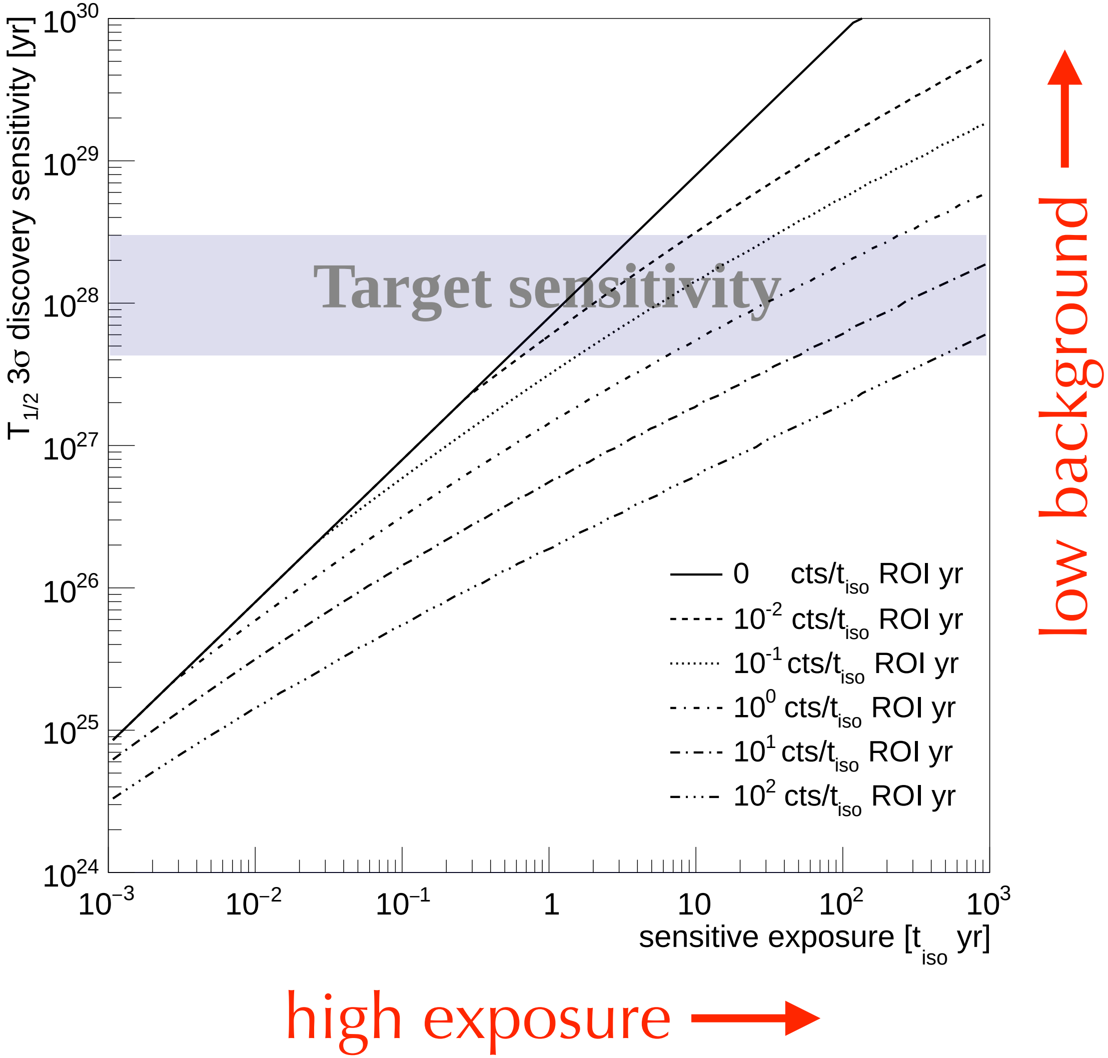
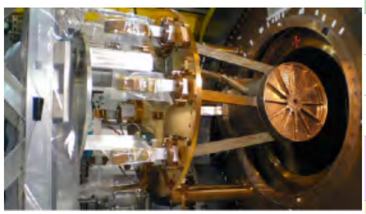
Requirements:



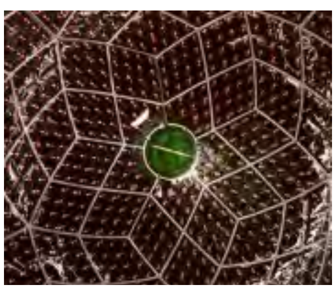
$0\nu\beta\beta$ Experiments

CUORE

EXO-200



KamLAND-Zen

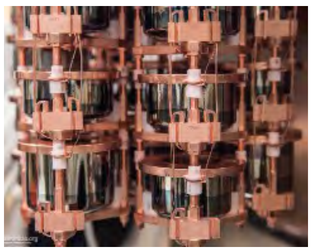


Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
AMoRE	Mo-100	CaMoO4 bolometers (+ scint.)	5	Construction
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Operating
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Operating
GERDA II	Ge-76	Point contact Ge in LAr	20 kg	Construction
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge in Lead	26 kg	Construction
1TGe (GERDA & MAJORANA)	Ge-76	Best of GERDA + MJD	~tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
CAMEO	Cd-116	$CdWO_4$ crystals	21 kg	R&D
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	Operating / Construction
CUORICINO	Te-130	TeO_2 Bolometer	11 kg	Complete
CUORE-0	Te-130	TeO_2 Bolometer	11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	206 kg	Operating
SNO+	Te-130	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	370 kg	Operating
KamLAND2-ZEN	Xe-136	2.7% in liquid scint.	~tonne	R&D
NEXT-100	Xe-136	High pressure Xe TPC	10 kg	Construction
EXO-200	Xe-136	Xe liquid TPC	160 kg	Operating
nEXO	Xe-136	Xe liquid TPC	5 tonnes	R&D
DCBA	Nd-150	Nd foils & tracking chambers	30 kg	R&D

Complete | Construction | Operating

GERDA

MAJORANA



CANDLES

J. Detwiler

From J. F. Wilkerson

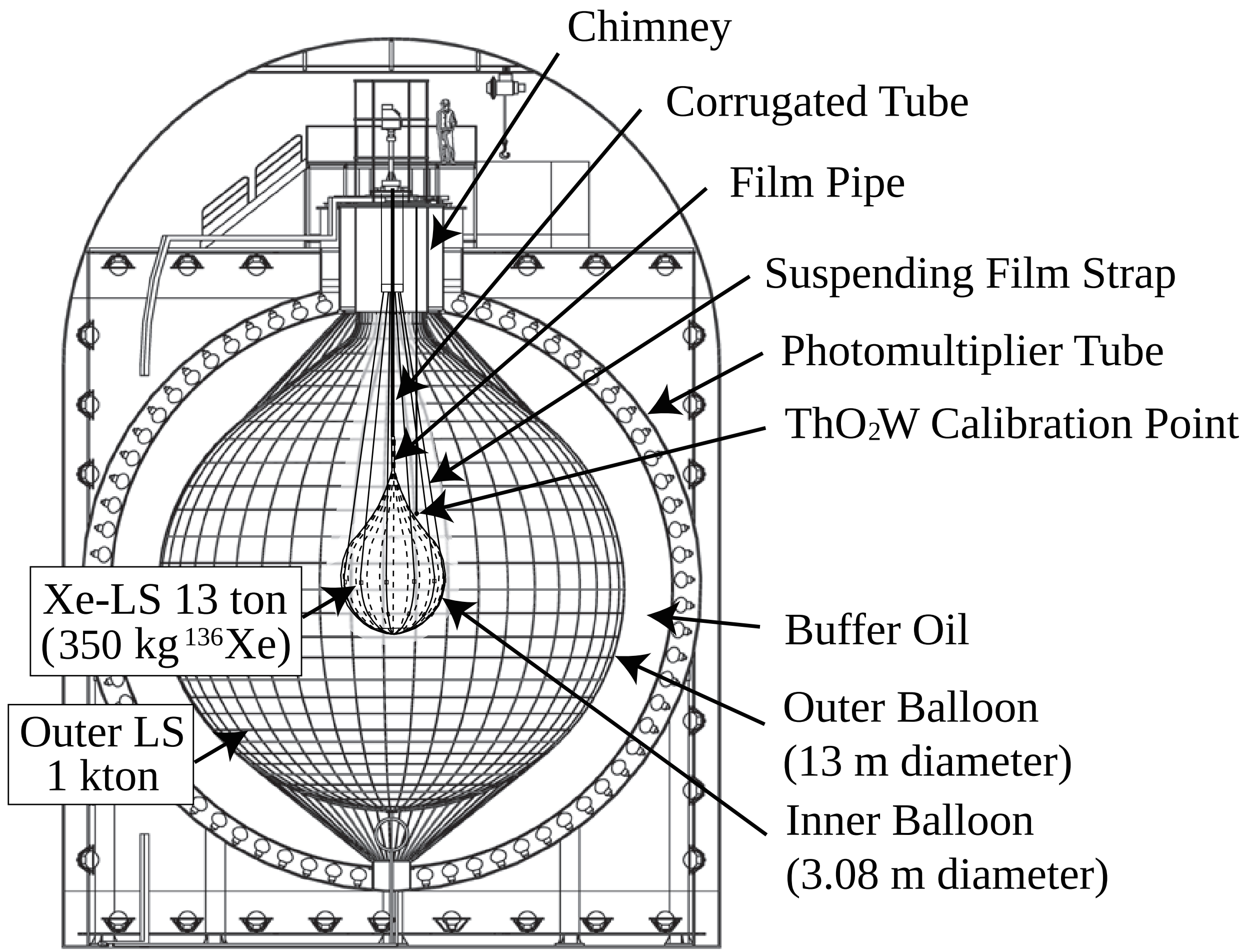
Outline

- Introduction: exposure and background
- High exposure: KamLAND-Zen
- Low background: MAJORANA / GERDA / LEGEND
- Discovery potential of future experiments

Xe-Loaded LS

- Xe gas has high solubility in KamLAND's low-background liquid scintillator (LS)
- Xe gas is easy to enrich in ^{136}Xe via centrifuging
- Noble gas: easy to purify, chemically stable
- However: large LS detectors have relatively poor resolution, calorimetry only

KamLAND-Zen



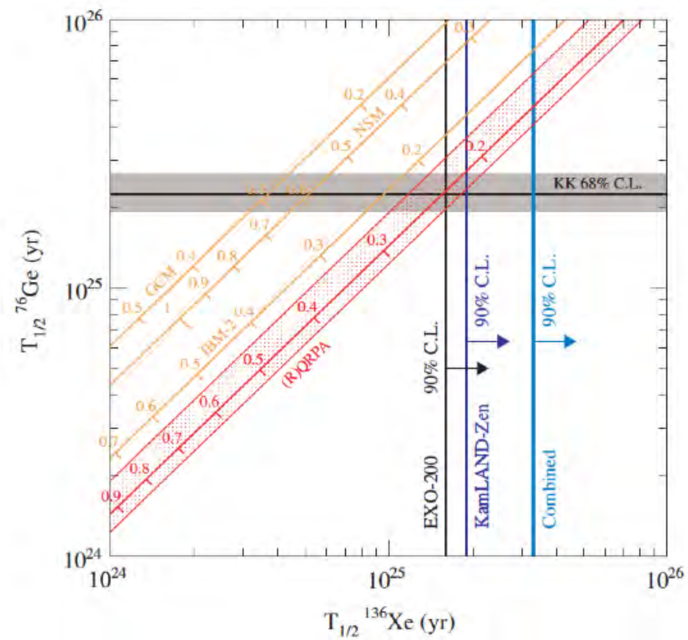
Chimney
Corrugated Tube
Film Pipe
Suspending Film Strap
Photomultiplier Tube
ThO_2W Calibration Point
Buffer Oil
Outer Balloon
(13 m diameter)
Inner Balloon
(3.08 m diameter)
Xe-LS 13 ton
(350 kg ^{136}Xe)
Outer LS
1 kton

KamLAND-Zen Collaboration

Tohoku U: A.Gando, Y.Gando, T.Hachiya, A.Hayashi, S.Hayashida, Y.Honda, K.Hosokawa, H.Ikeda, K.Inoue, K.Ishidoshiro, K.Kamisawa, Y.Karino, M.Koga, S.Matsuda, T.Mitsui, K.Nakamura, S.Obara, H.Ozaki, Y.Shibukawa, I.Shimizu, Y.Shirahata, J.Shirai, K.Soma A.Suzuki, T.Takai, K.Tamae, Y.Teraoka, K.Ueshima, H.Watanabe
IPMU: A.Kozlov, Y.Takemoto, B.E.Berger, D.Chernyak **Oska U**: S.Yoshida **Tokushima U**: K.Fushimi
LBNL: T.I.Banks, B.K.Fujikawa, T.O'Donnell **MIT**: L.A.Winslow, J.Ouellet, E.Krupczak **UT Knoxville**: Y.Efremenko
UNC Chapel Hill: H.J.Karwowski, D.M.Markoff **Duke**: W.Tornow **UW**: J. Detwiler, S.Enomoto
U Amsterdam / Nikhev: M.P.Decowski

KamLAND-Zen History

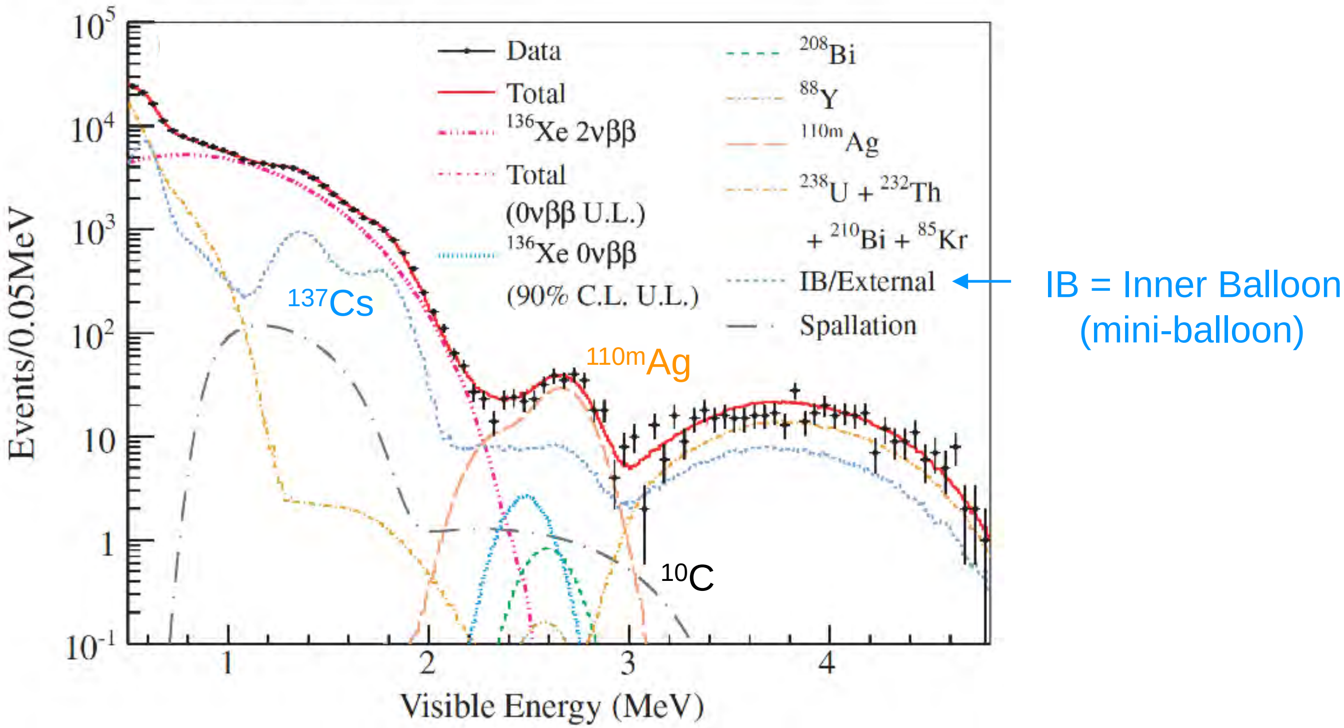
- May-Aug. 2011: Mini-balloon construction and installation
- Oct. 2011 - June 2012: Phase I
  - 320 kg ^{enr}Xe, 89.5 kg-yr exposure
  - $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ years (90% C.L.)
- July 2012 - Oct. 2013: Xe-LS Purification
- Nov. 2013 - Oct. 2015: Phase II
  - 383 kg ^{enr}Xe, 504 kg-yr exposure
- Oct. 2015 - present: preparation for next phase



PRL **110**, 062502 (2013).

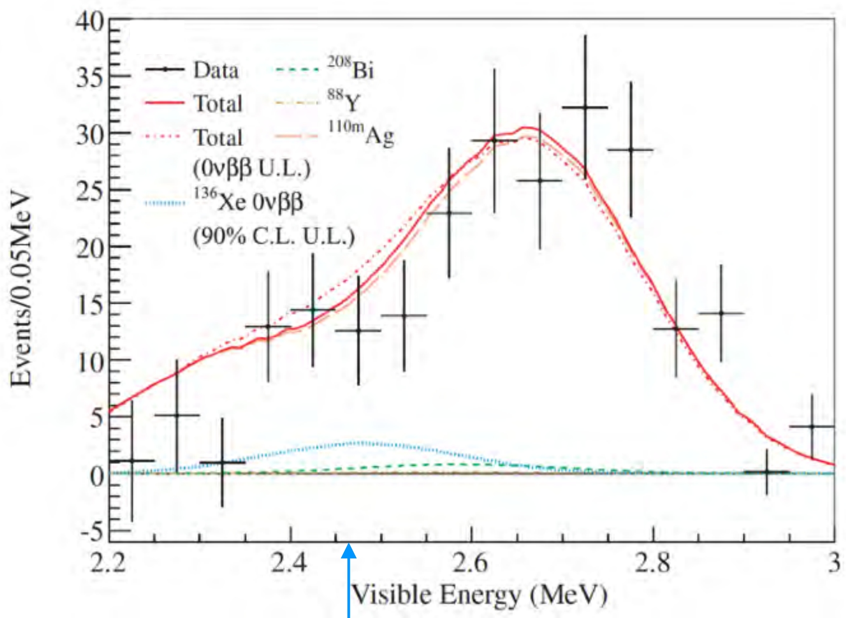
Phase I Results

- Observed background on mini-balloon consistent with fallout from 3/2011 Fukushima nuclear disaster



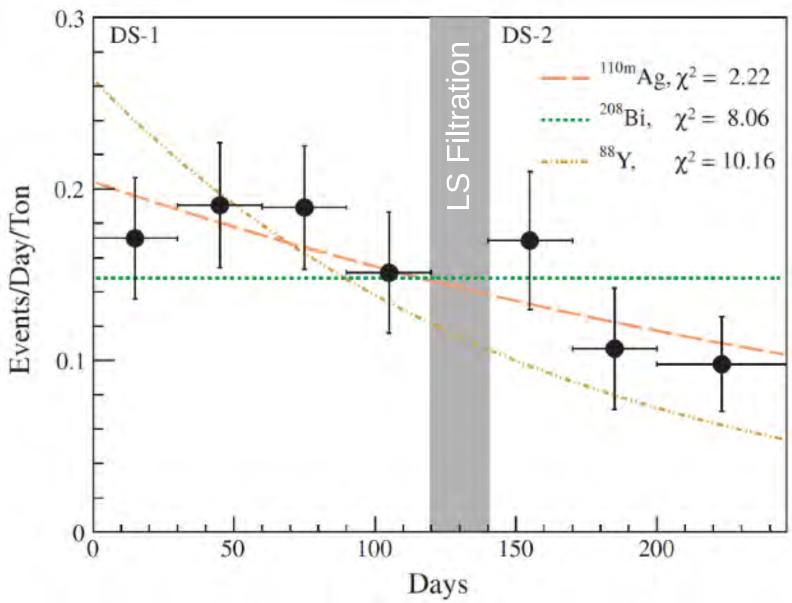
PRL **110**, 062502 (2013).

0νββ ROI Dominated by ^{110m}Ag



$Q_{\beta\beta}$ = 2.458 MeV

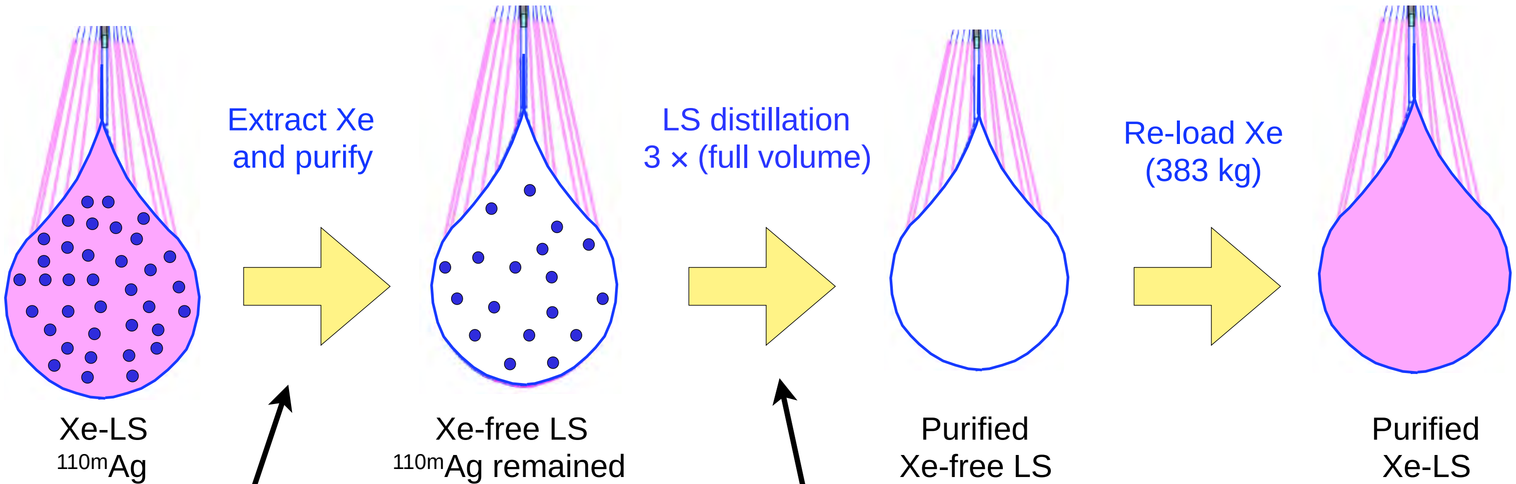
Event rate in 2.2 < E < 3.0 MeV

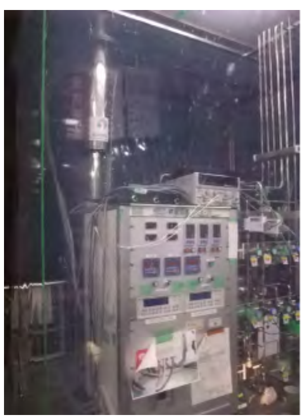


τ_{110mAg} = 250 days

PRL **110**, 062502 (2013).

Xe-LS Purification



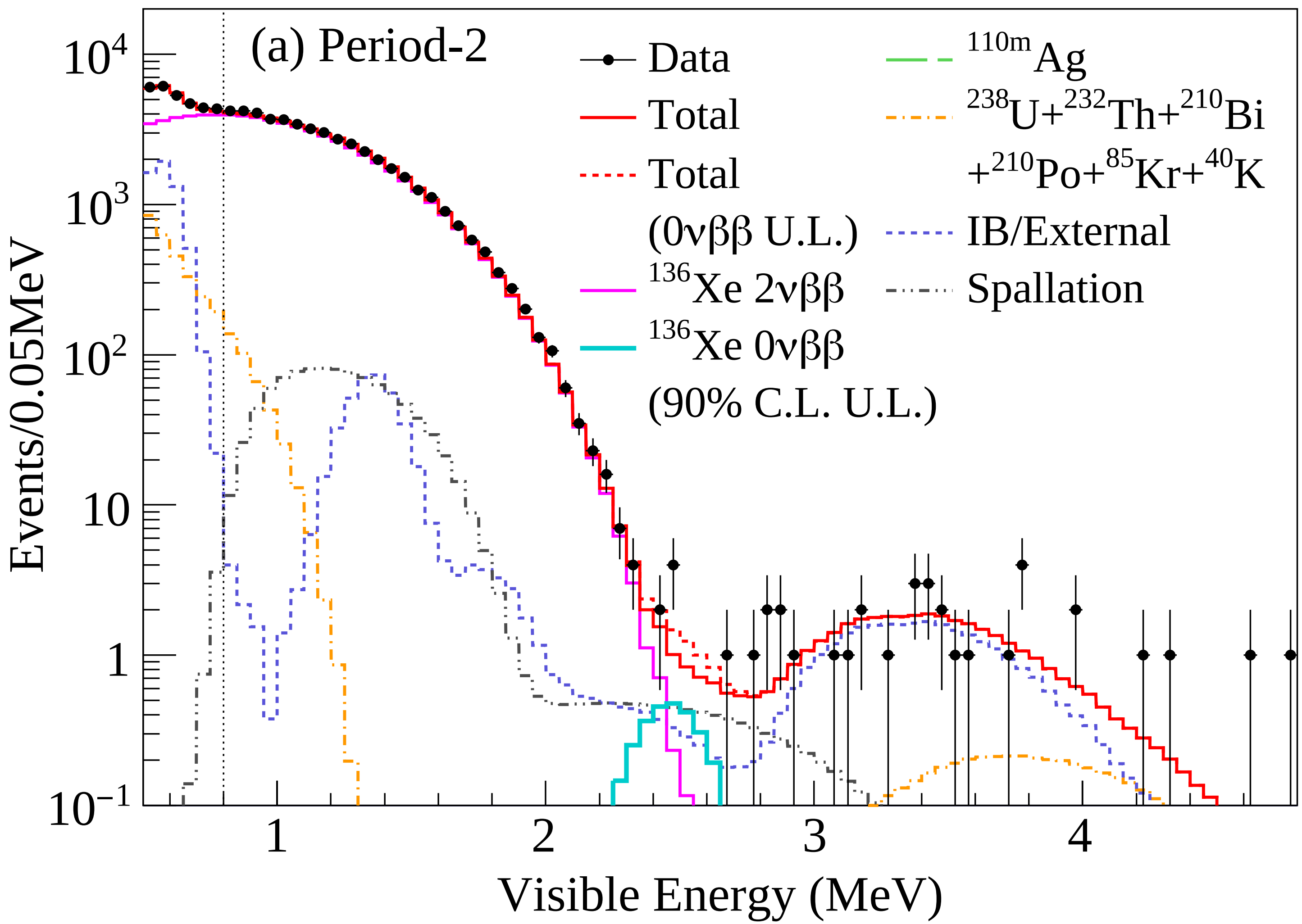


Xe distillation + filtration (charcoal, sintered metal, 3nm PTFE)+ getter

LS vacuum distillation (+water extraction, N_2 purge)

Phase II Results

(*r* < 1m)



PRL **117**, 082503 (2016).

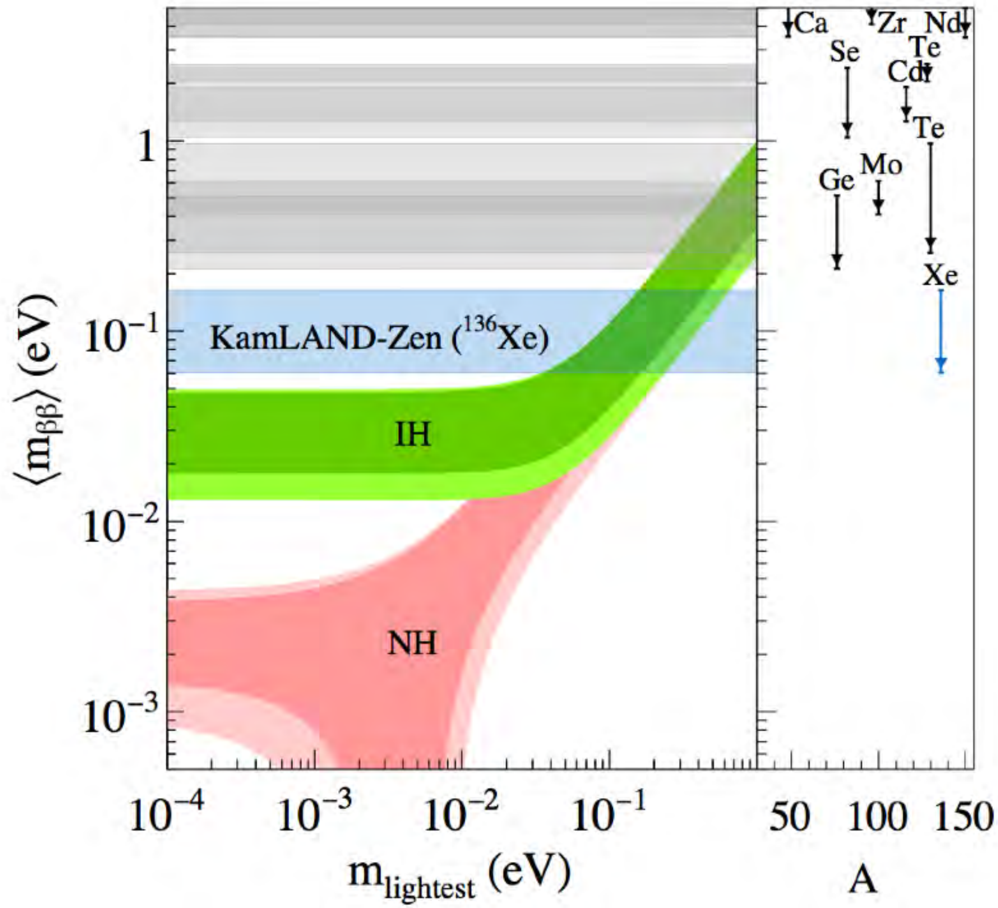
$m_{\beta\beta}$ Limits

$\langle m_{\beta\beta} \rangle$ < (61- 165) meV

Using common NME with g_A~1.27,
Improved phase space calculations.

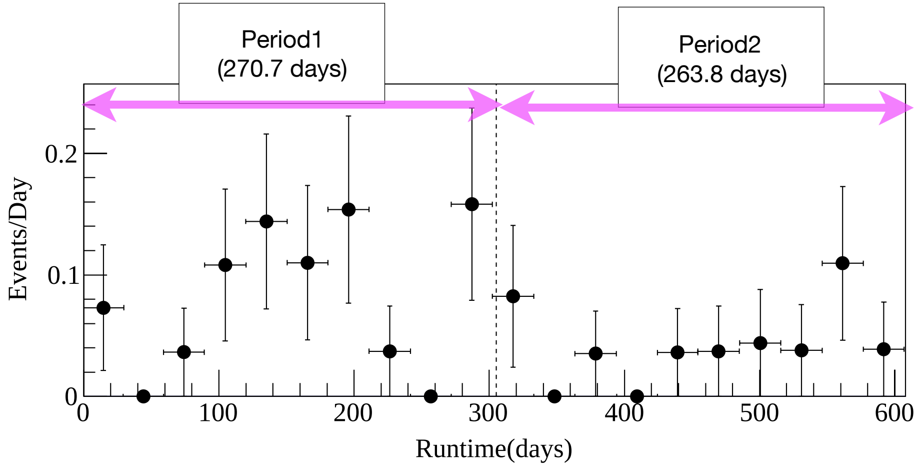
***$m_{lightest}$* < (180~480) meV**

Our $m_{\beta\beta}$ limit reaches below 100 meV and approaches the IH region for the largest NME

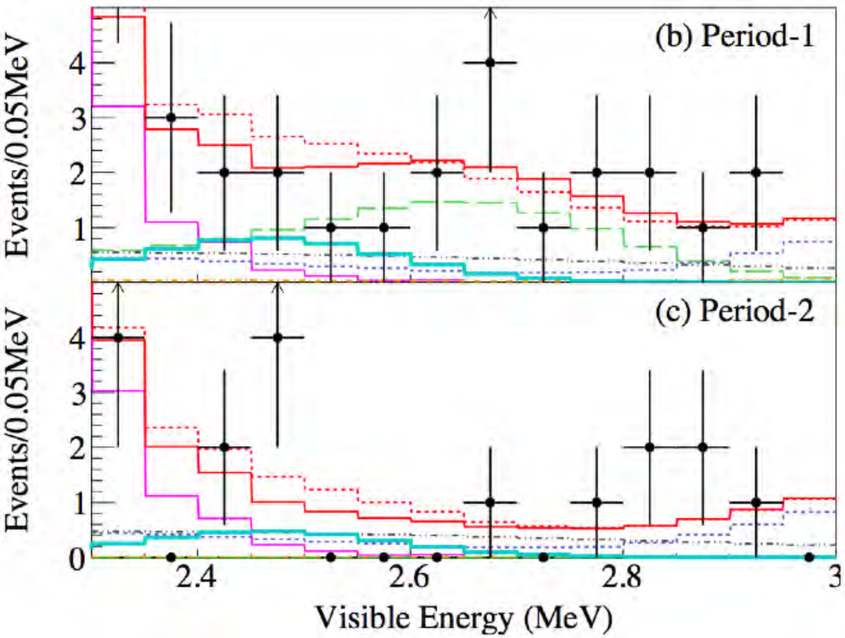


PRL **117**, 082503 (2016).

Phase II Results



(^{110m}Ag $T_{½}$ = 250 days)



PRL **117**, 082503 (2016).

Background Summary

2.3 < E < 2.7 MeV, R < 1m

	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.5	-	0.0
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.56	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.003	-	0.002
Spallation products				
^{10}C	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4

PRL **117**, 082503 (2016).

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→ improve σ_E

→ replace mini-balloon

→ improve post-μ n detection

PRL **117**, 082503 (2016).

Recent Activity

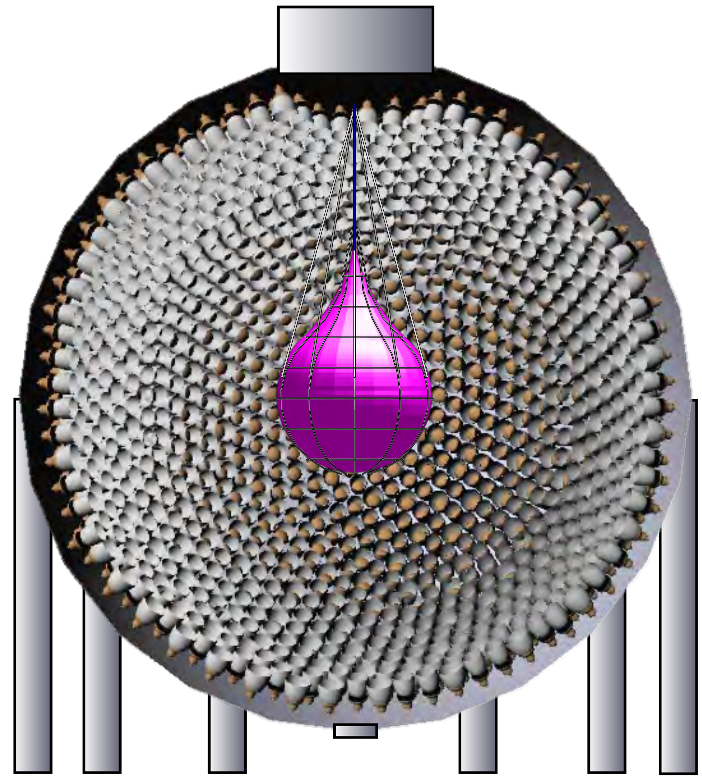
- Summer 2015: New mini-balloon fabrication
- Fall 2015 - Winter 2016: Extract old mini-balloon, refurbish OD, Xe/LS distillation
- Summer - Fall 2016: New mini-balloon deployment
  - Leak detected. Balloon extracted
  - 5 holes found along weld seams
- Winter 2016-present: New new mini-balloon fabrication
- Fall/Winter 2016: Start new phase: KamLAND-Zen 800 kg

Washing nylon films (Ultra-pure water + ultrasonic machine)

Gore welding

Toward Higher Sensitivity: KamLAND2-Zen

- More photons!
  - New LAB-based LS (L.Y.×1.4)
  - New High Q.E. PMTs (×1.9)
  - Light collectors (×1.8)
- Background rejection
  - Scintillating balloon (^{214}Bi rejection)
  - LS purification via molecular sieve, metal scavenger
  - Event imaging cameras
- Larger exposure
  - 1000 kg Xe-LS
  - Pressurized for increased loading



Upgraded inner detector

Outline

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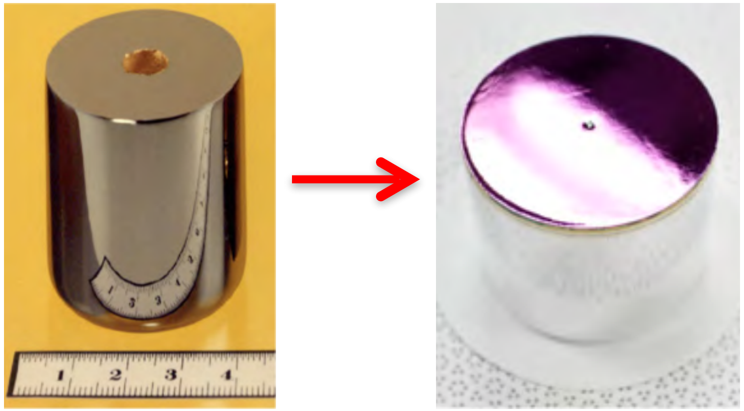
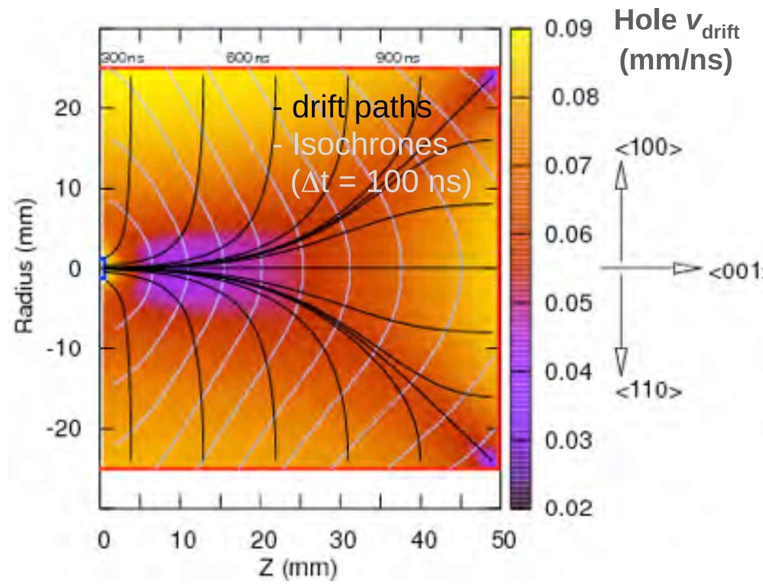
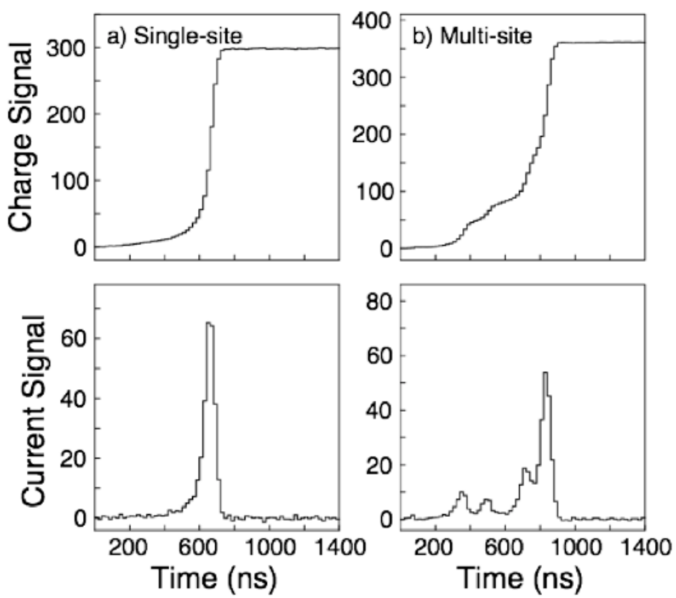
Advantages of ^{76}Ge

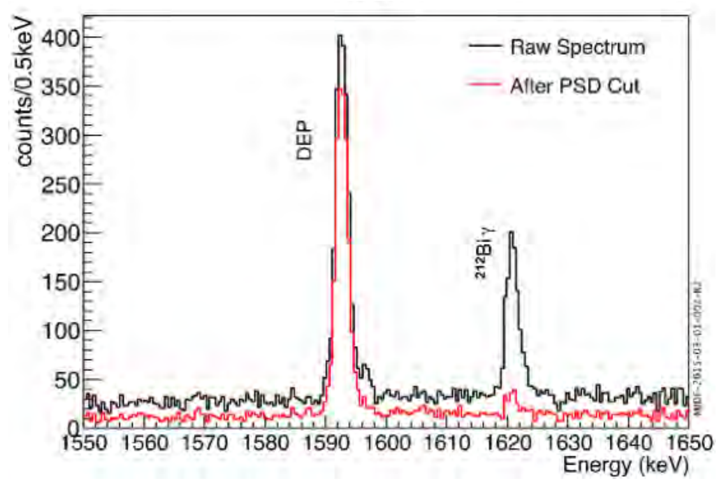
- Intrinsic high-purity Ge detectors = source
- Excellent energy resolution: approaching 0.1% at 2039 keV (~2.4 keV ROI)
- Demonstrated ability to enrich from 7.44% to ≥87%
- Powerful background rejection: multiplicity, timing, pulse-shape discrimination

0νββ with Point Contact HPGe Detectors







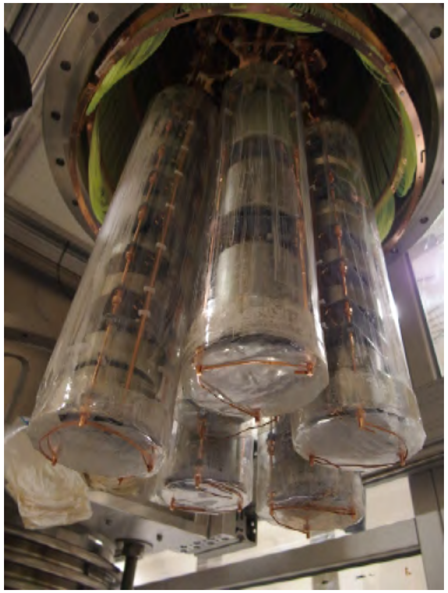


Luke et al., IEEE trans. Nucl. Sci. 36 , 926 (1989)
Barbeau, Collar, and Tench, J. Cosm. Astro. Phys. 0709 (2007).

MAJORANA and GERDA

MAJORANA:
"Traditional" configuration:
Vacuum cryostats in a
passive graded shield
with ultraclean materials

GERDA:
"Novel" configuration:
Direct immersion
in active LAr shield



The MAJORANA Collaboration

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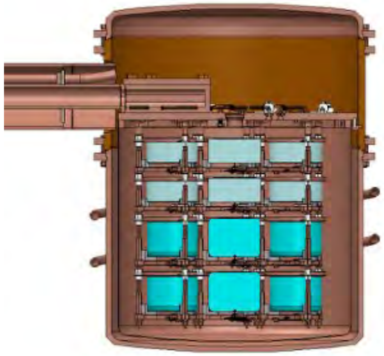
Sebastian Alvis, Tom Burritt, Micah Buuck, Clara Cuesta, Jason Detwiler, Julieta Gruszko, Ian Guinn, David Peterson, R. G. Hamish Robertson, Tim Van Wechel

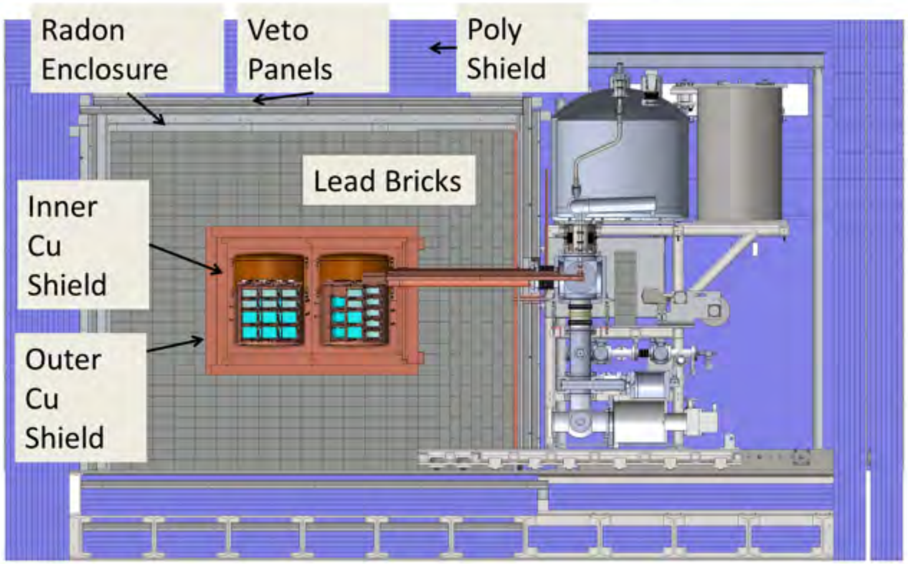
The MAJORANA DEMONSTRATOR

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

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



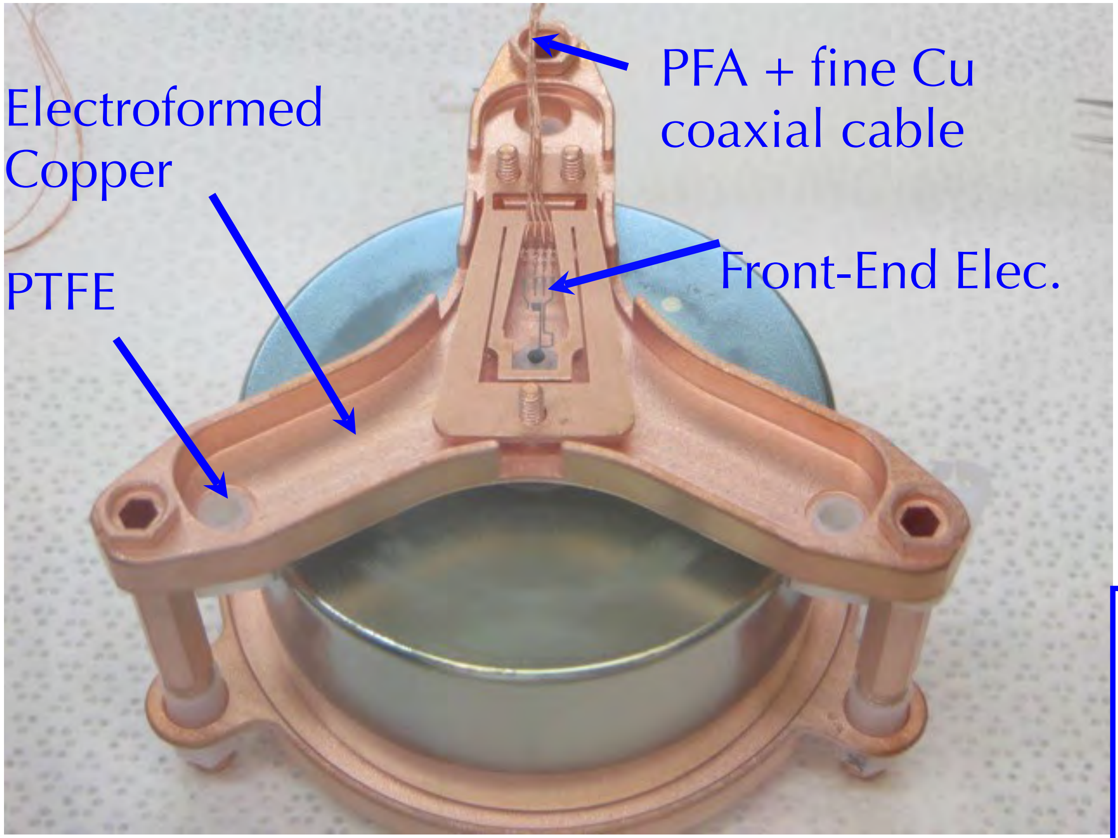
- Located underground at 4850' Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/(ROI t y) (after analysis cuts) Assay U.L. currently ≤ 3.5
  scales to 1 count/(ROI t y) for a tonne experiment
- 44.1-kg of Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto

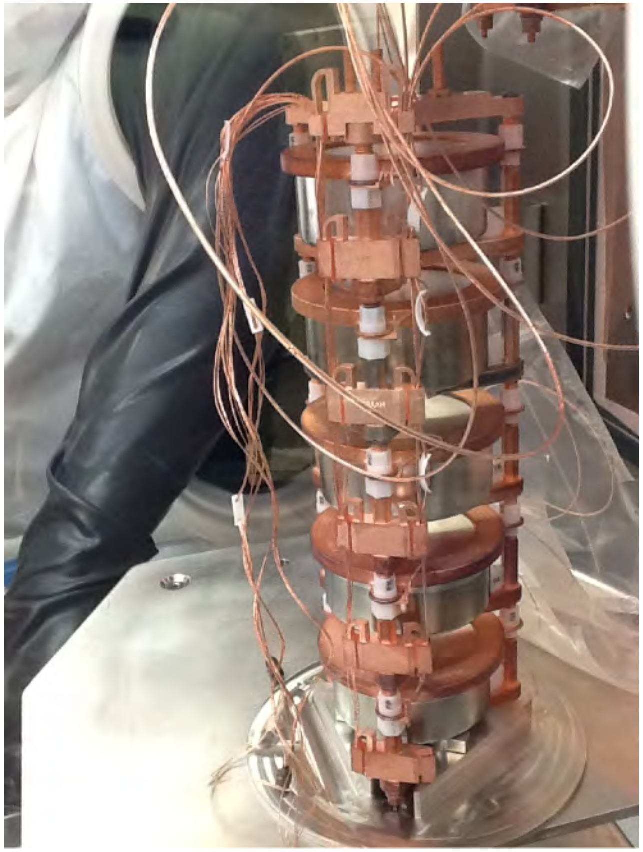


N. Abgrall *et al.*, Adv. High Ener. Phys. **2014**, 365432 (2013)
arXiv:1308.1633

Assembled Detector Unit and String

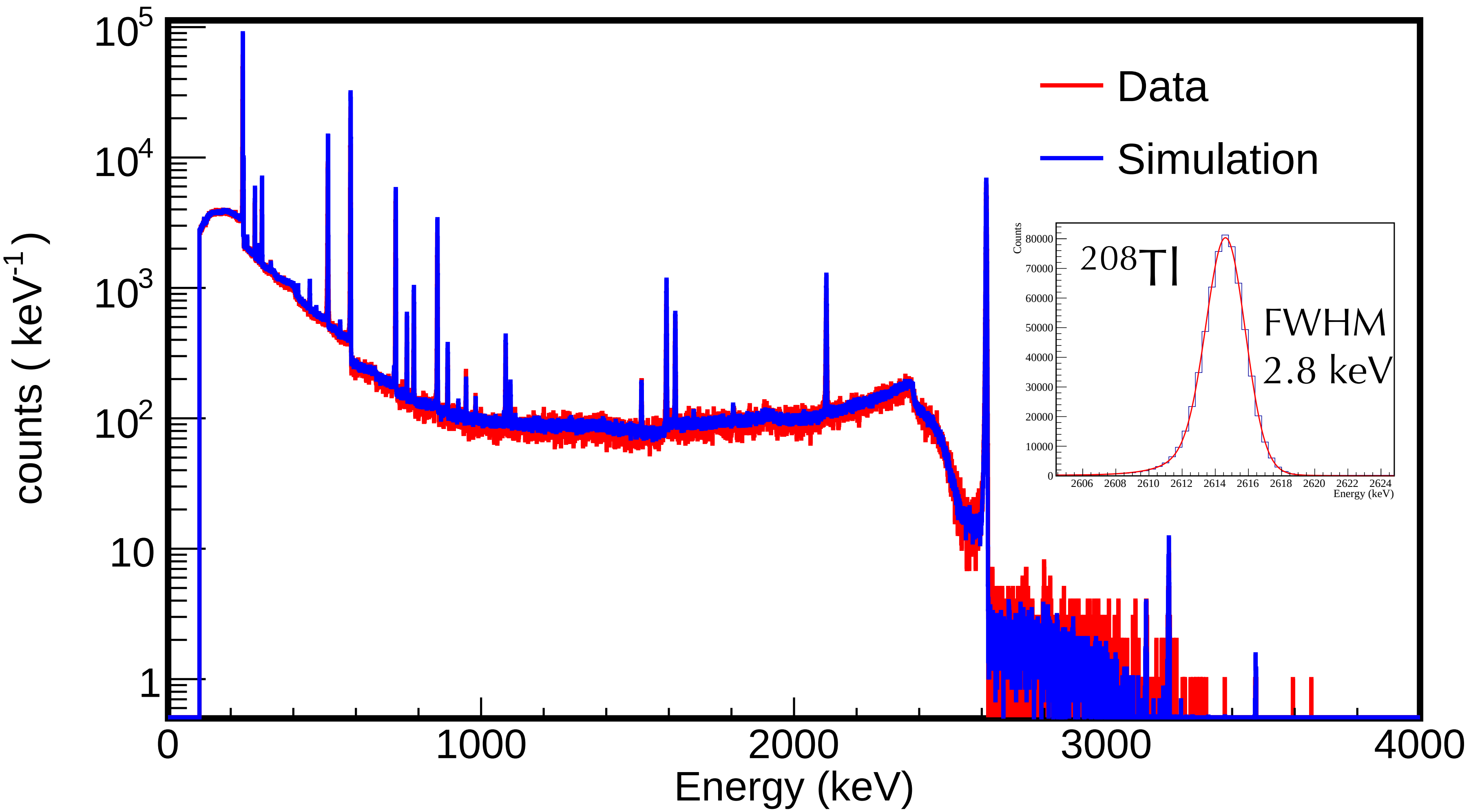
AMETEK (ORTEC) fabricated enriched detectors.
35 Enriched detectors at SURF 29.7 kg, 88% ^{76}Ge.
20 kg of modified natural-Ge BEGe (Canberra) detectors in hand (33 detectors UG).





All detector assembly performed in N_2 purged gloveboxes.
All detectors' dimensions recorded by optical reader.

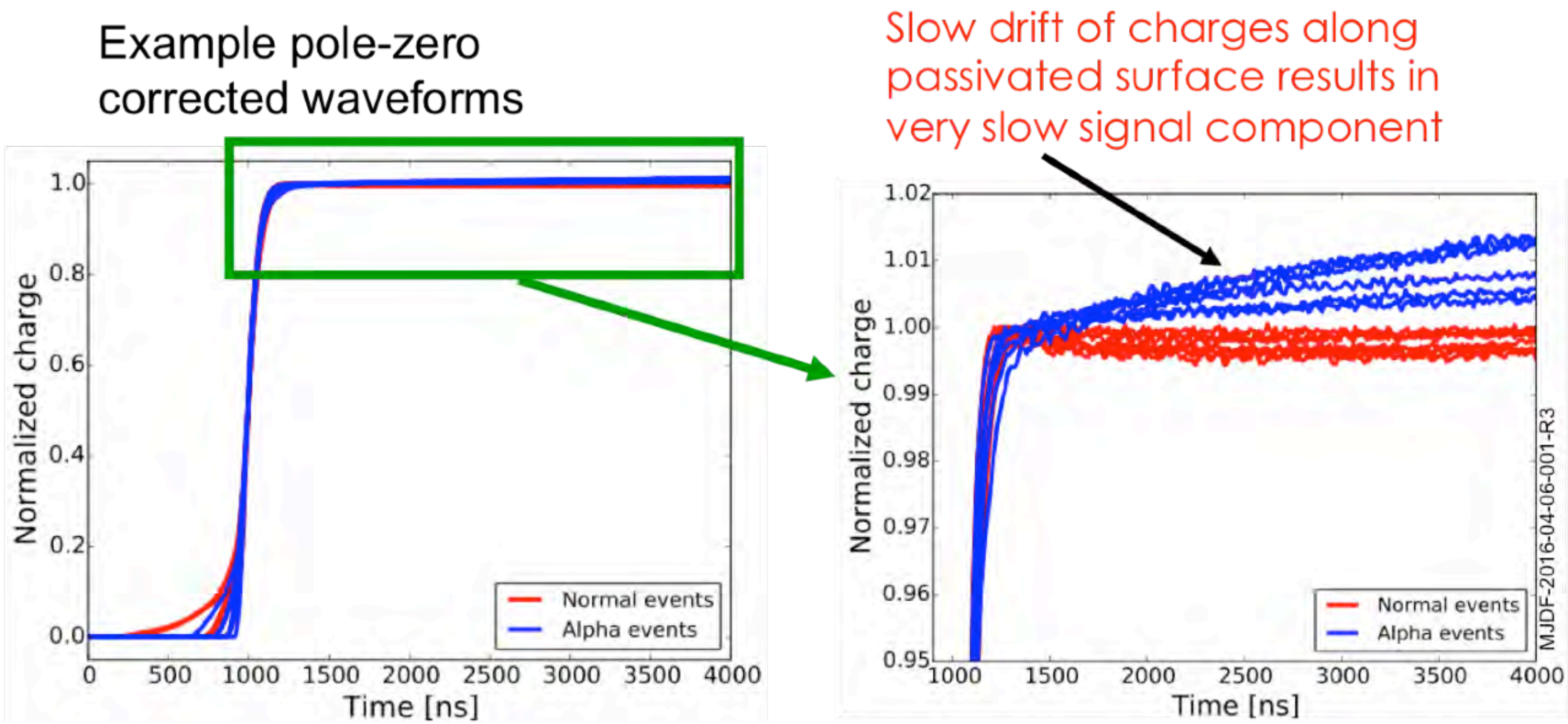
Summed ^{228}Th Calibration (DS1) & Simulation



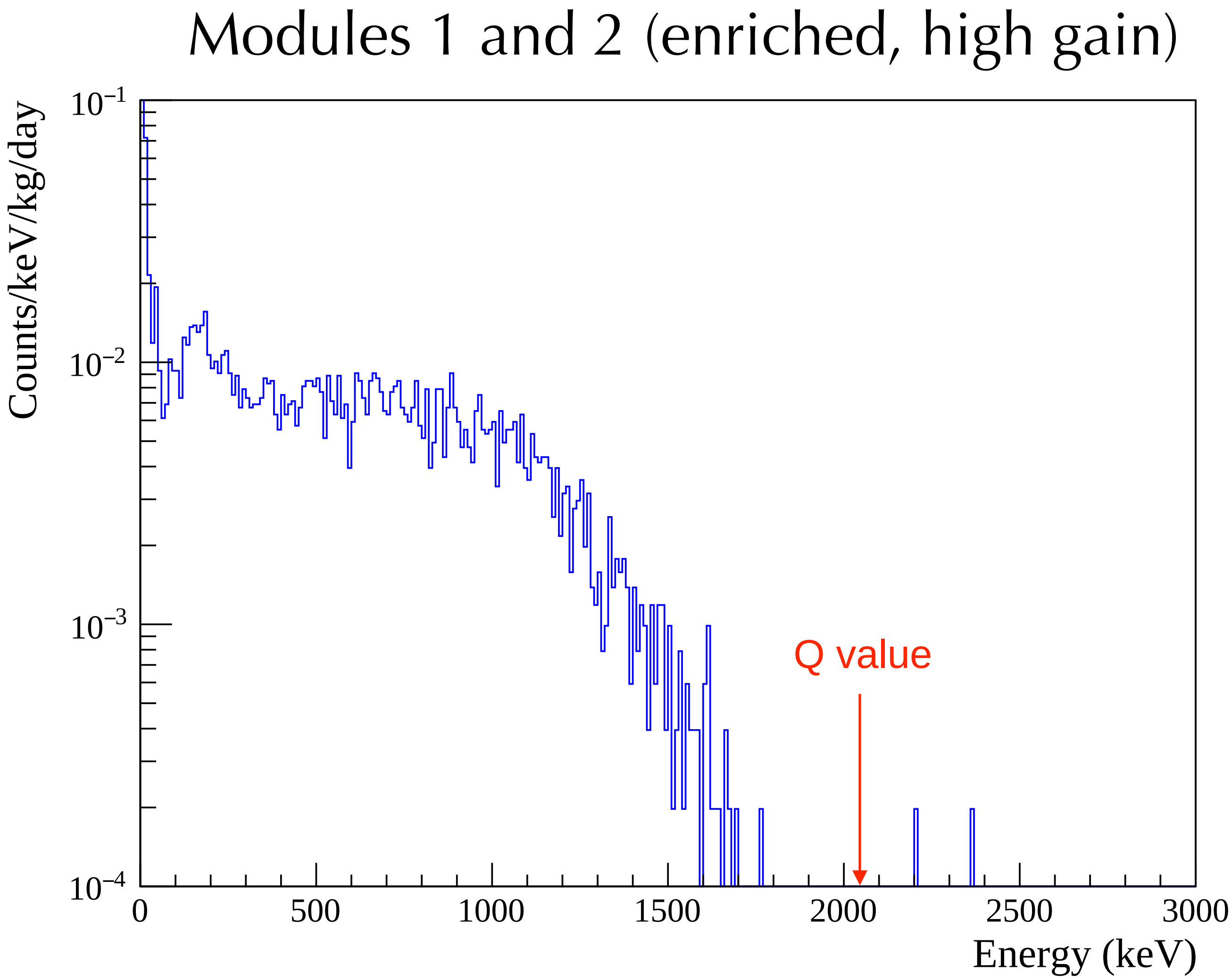
Calibration paper
arXiv:1702.02466

Cut for α's: Delayed Charge Recovery

- Alpha background with degraded energies observed in DS0
- Charge of these events drifts along the detector surface, not bulk
- Produces a distinctive waveform allowing a high efficiency cut



Initial results from the DEMONSTRATOR



- Exposure: 1.39 kg y (DS3+4)
- After cuts, 1 count in 400 keV window centered at 2039 keV ($0\nu\beta\beta$ peak)
- Projected BG rate is $5.1\,^{+8.9}_{-3.2}$ c /(ROI t y) for a 2.9 keV (M1) & 2.6 keV (M2) ROI (68% CL).
- Background index of 1.8×10^{-3} c/(keV kg y)
- Analysis cuts are still being optimized.

Low-energy spectrum

Controlled surface exposure of enriched material.

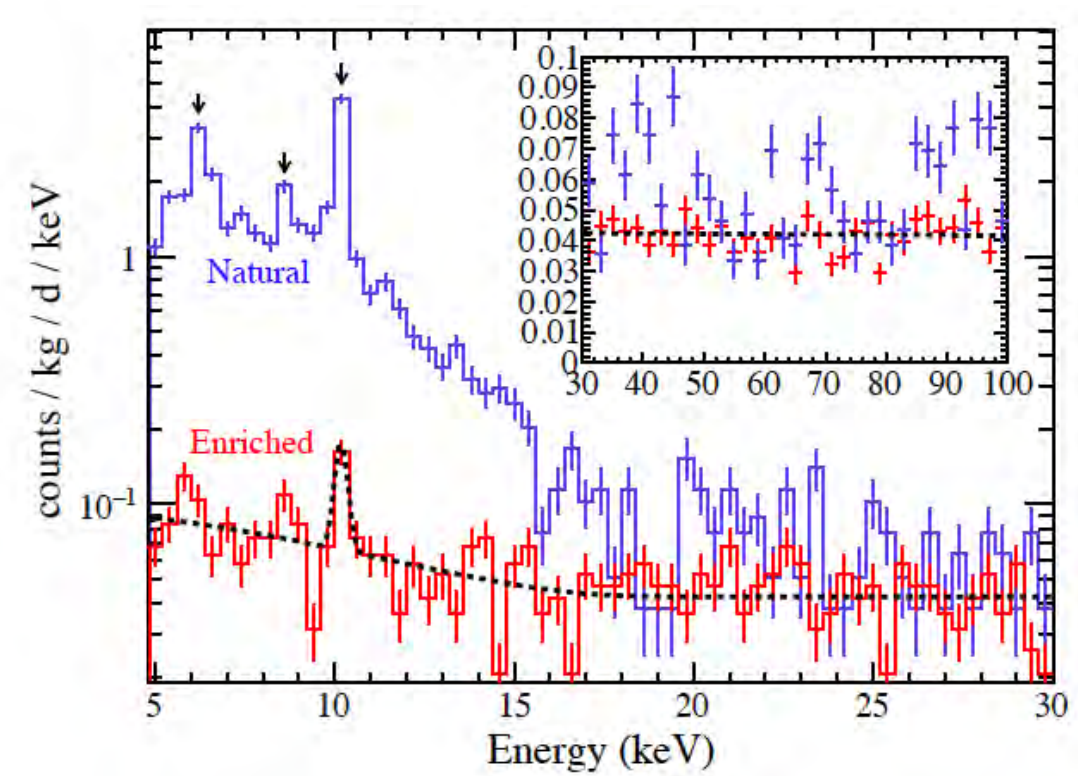
For the DEMONSTRATOR, the enriched detector ^{68}Ge rate is low enough that an X-ray delayed coincidence cut will not be necessary.

Significant reduction of cosmogenics in the low-energy region. Factor of a few better in DS1.

Tritium is obvious and dominates in natural detectors below 20 keV.

Efficiency below 5 keV is under study.

Natural 4.1 kg Enriched 10.06 kg: 478 kg d



Low-Energy Searches for Physics Beyond SM

- Pseudoscalar dark matter
- Vector dark matter
- 14.4-keV solar axion
- $e^- \rightarrow 3\nu$
- Pauli Exclusion Principle violation

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

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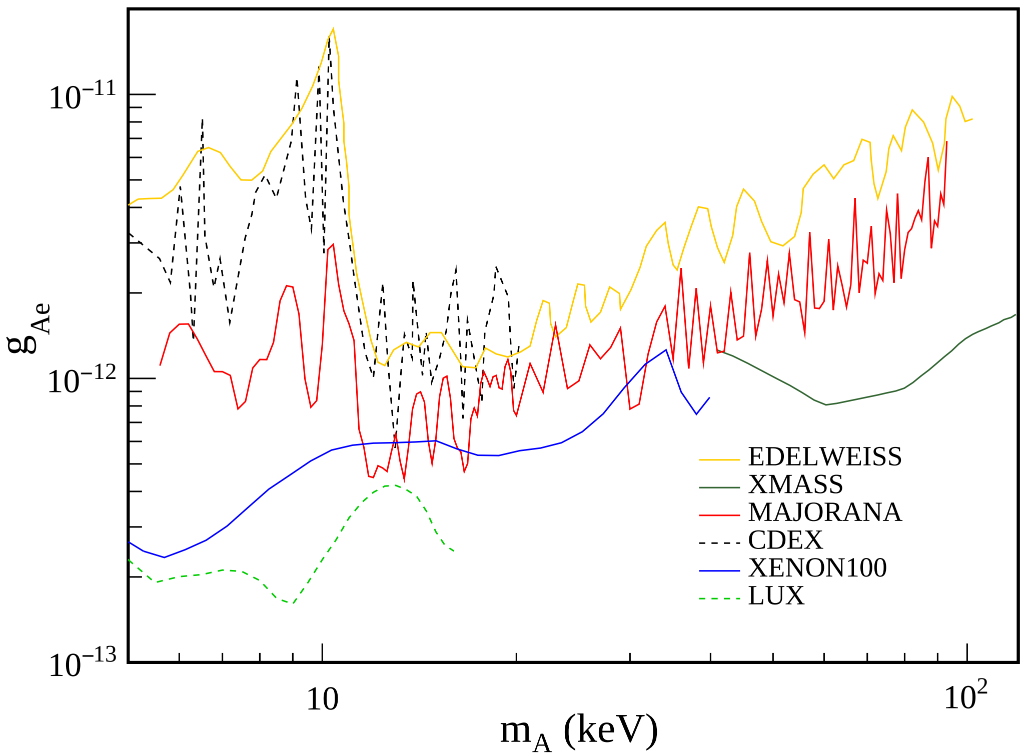

Low-Energy Searches for Physics Beyond SM

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- $e^- \rightarrow 3\nu$
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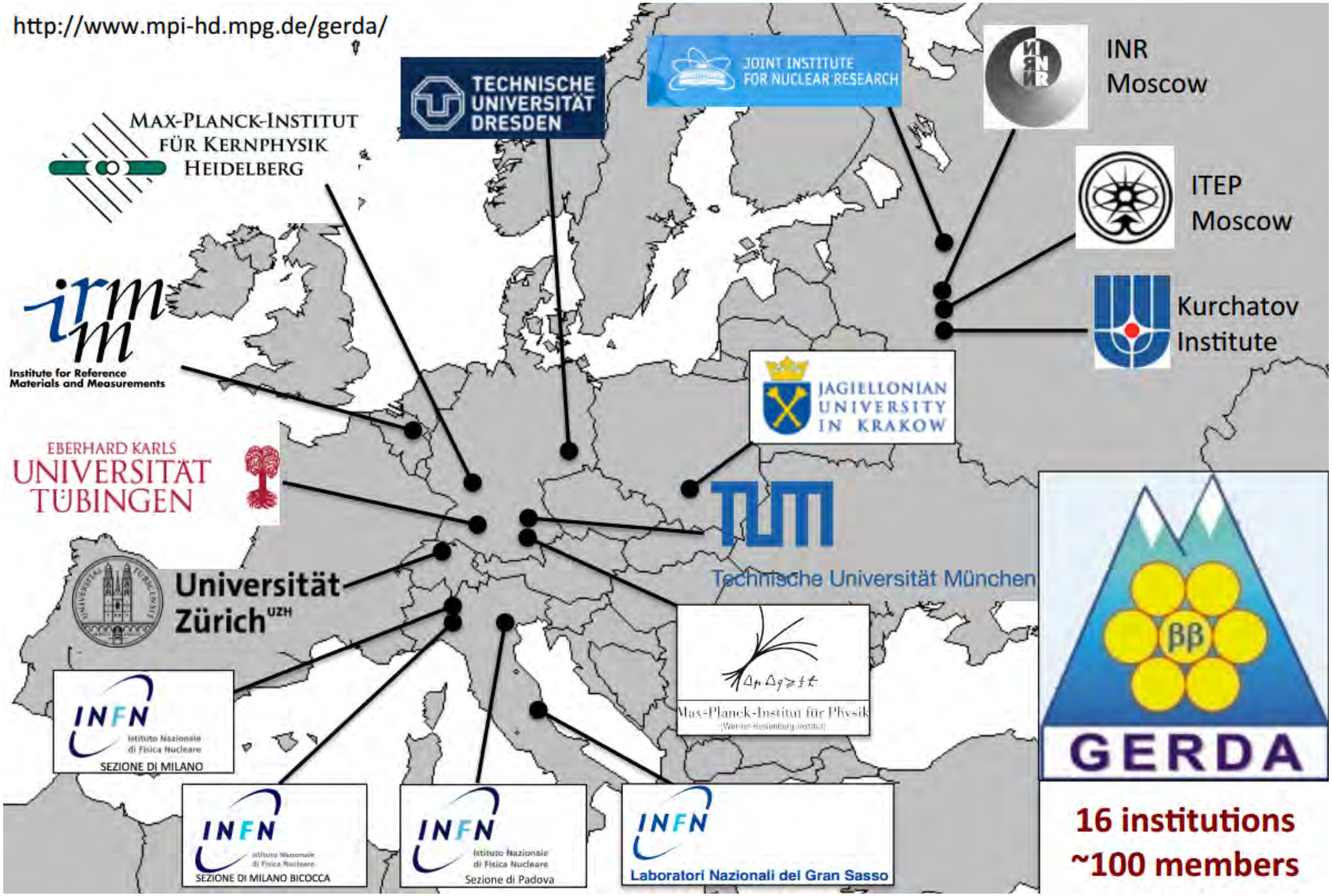
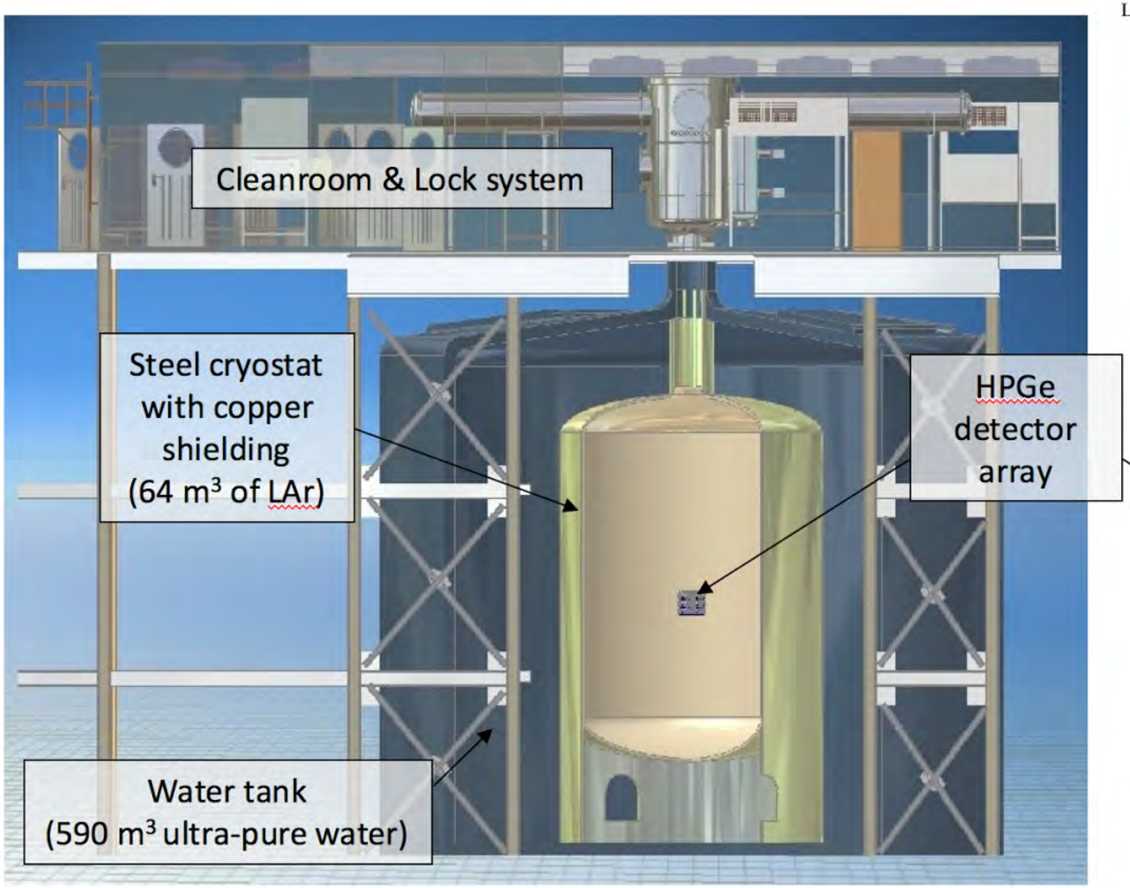
Phys. Rev. Lett. **118**, 161801 (2017).

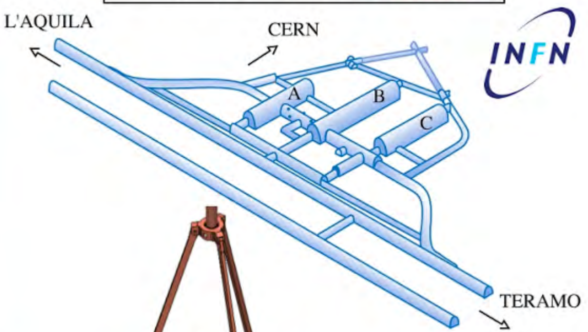
The GERDA Collaboration

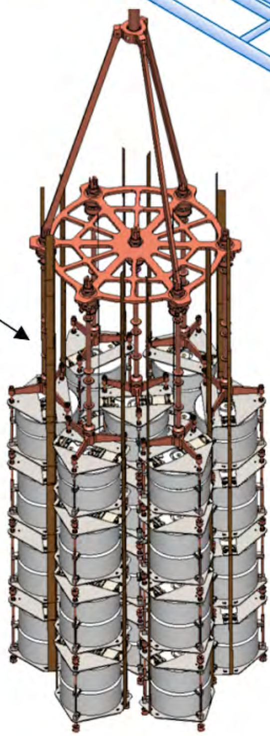


GERDA Configuration



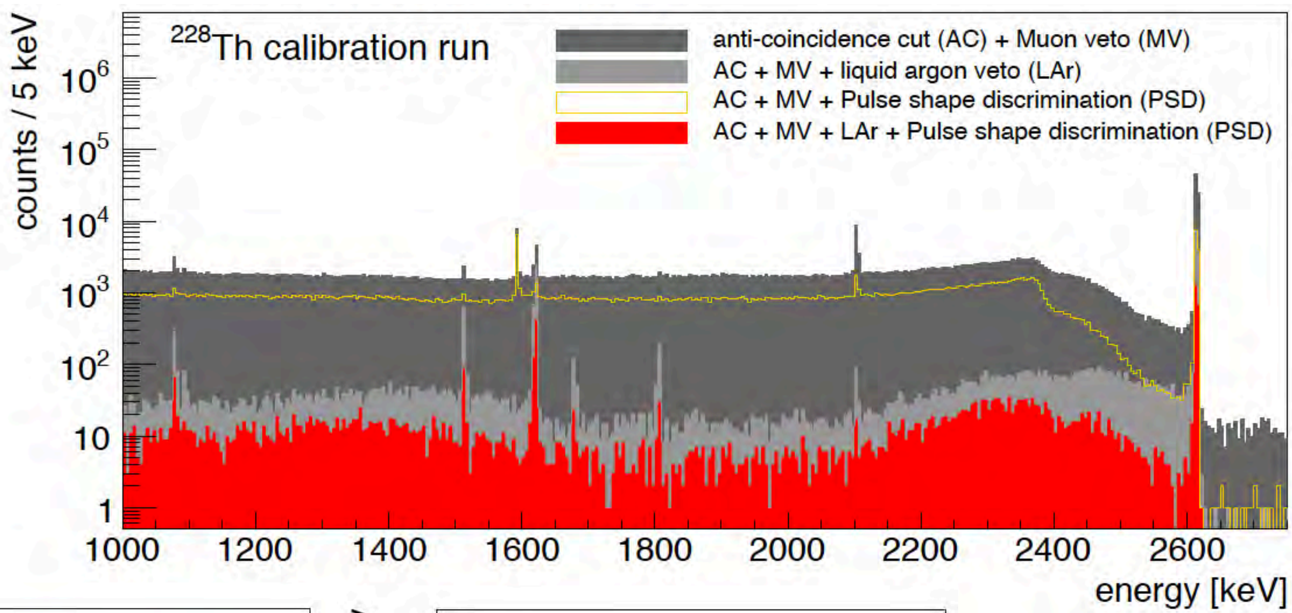
LNGS (INFN) 3500 m.w.e.

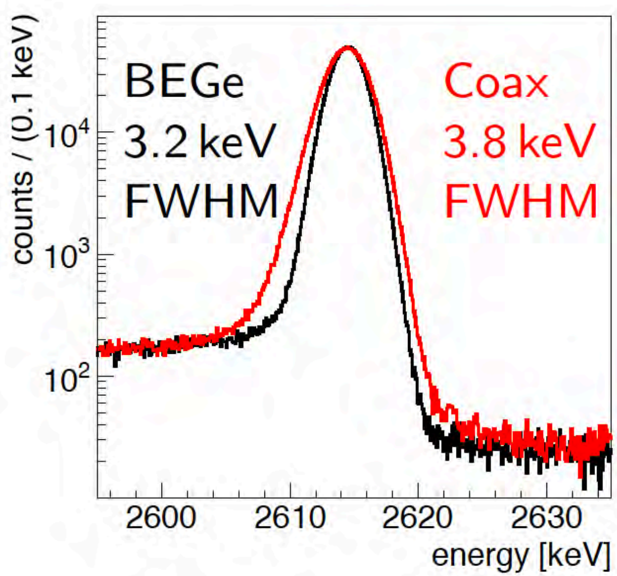


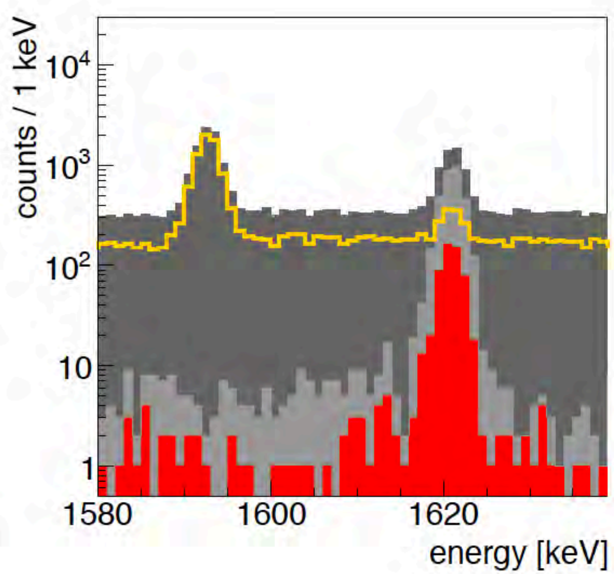


30 BEGe (20 kg) and
7 Coax (15.6 kg)
(Phase II)

Detector Performance



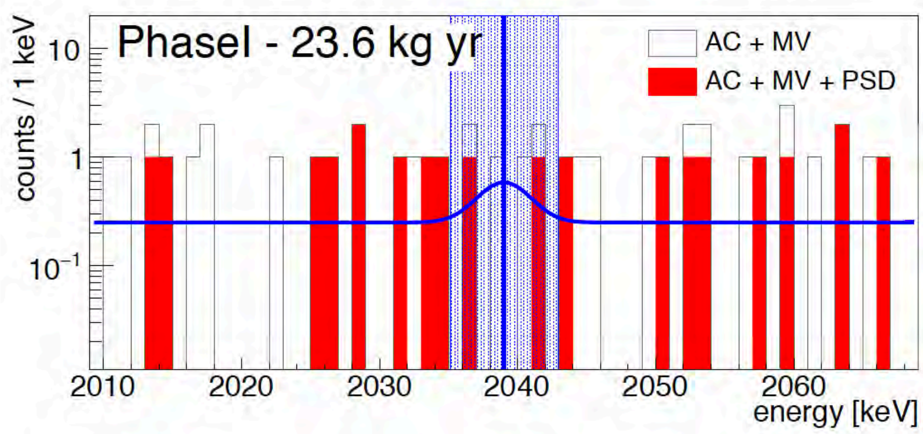


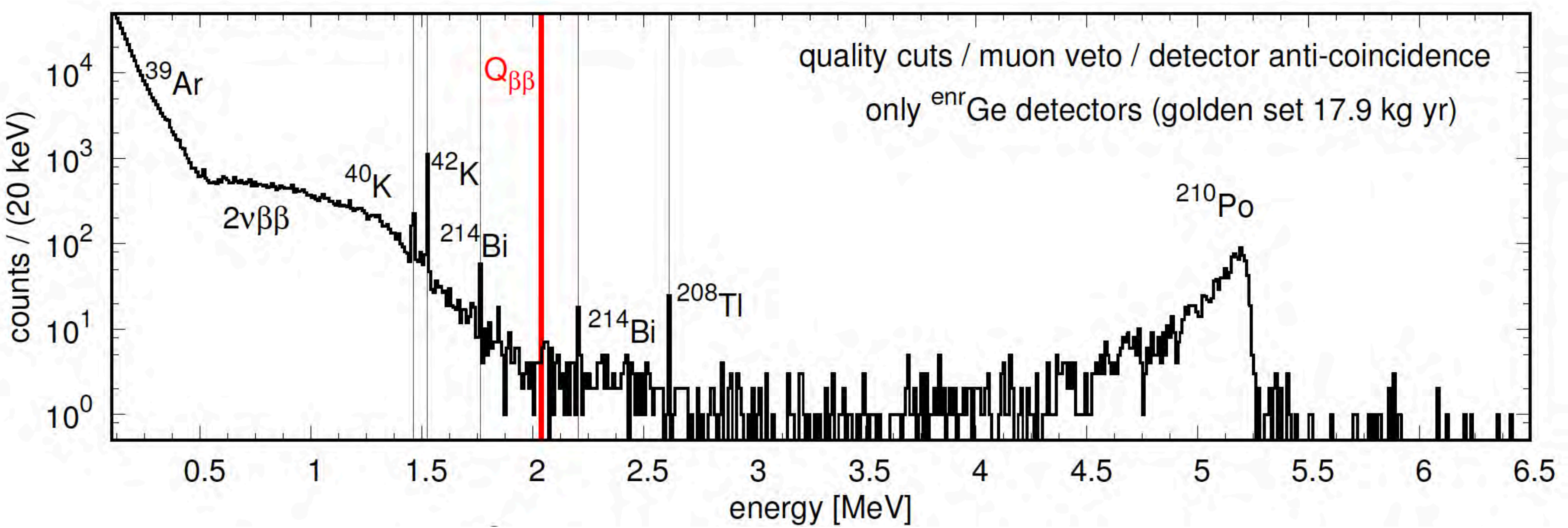


Direct immersion and active rejection work beautifully!

GERDA Phase I

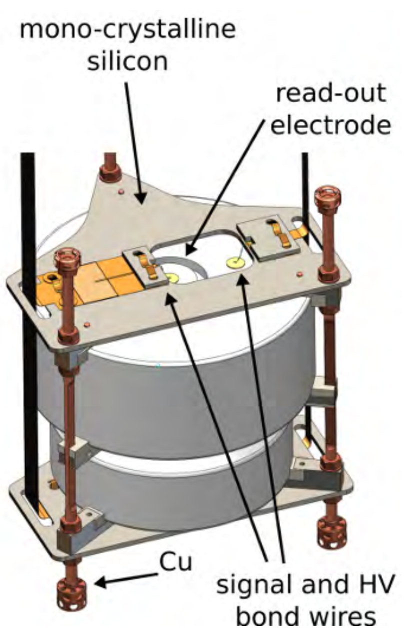
- Mostly refurbished coaxial detectors from previous-generation experiments, no LAr active veto
- Analysis cuts:
  - Anti-coincidence (AC)
  - Muon veto (MV)
  - Pulse-shape discrimination (PSD)



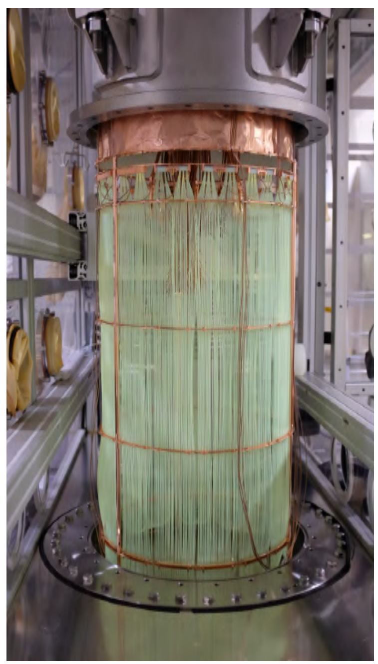


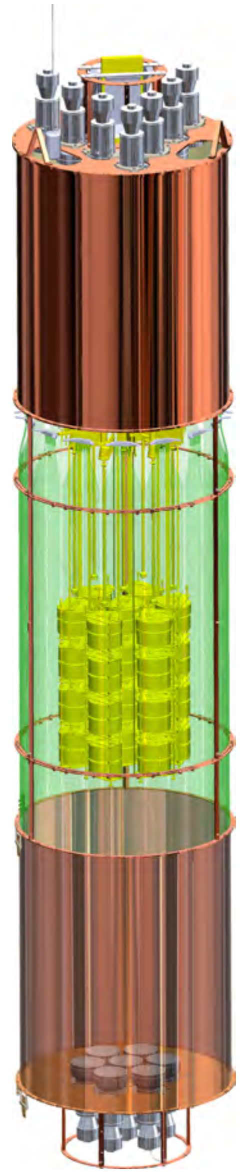
Phase II Upgrades

Double the mass with BEGe's (PPCs), lower-BG mounts

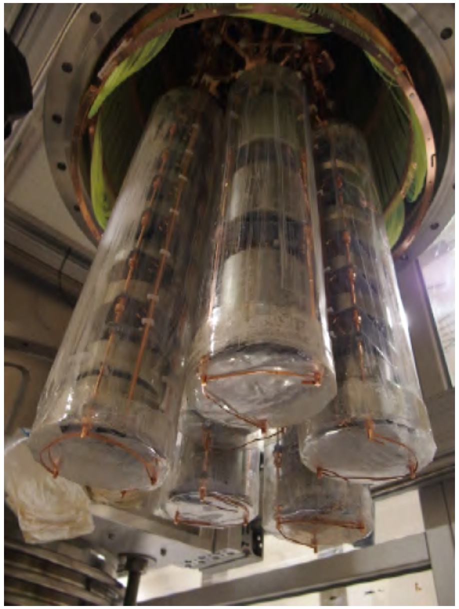


Instrument the LAr veto with SiPM's plus WLS fibers

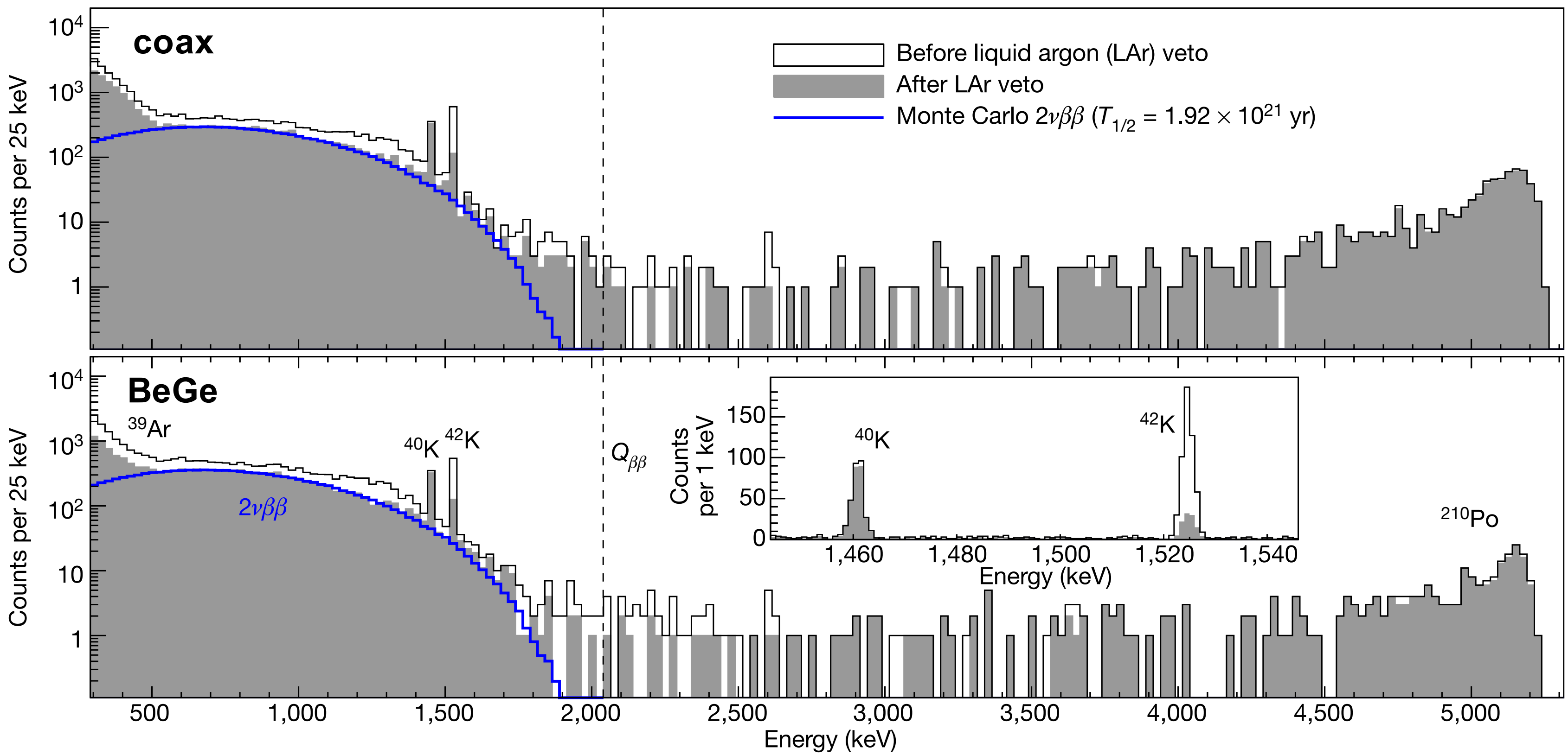




Enshroud strings in WLS nylon



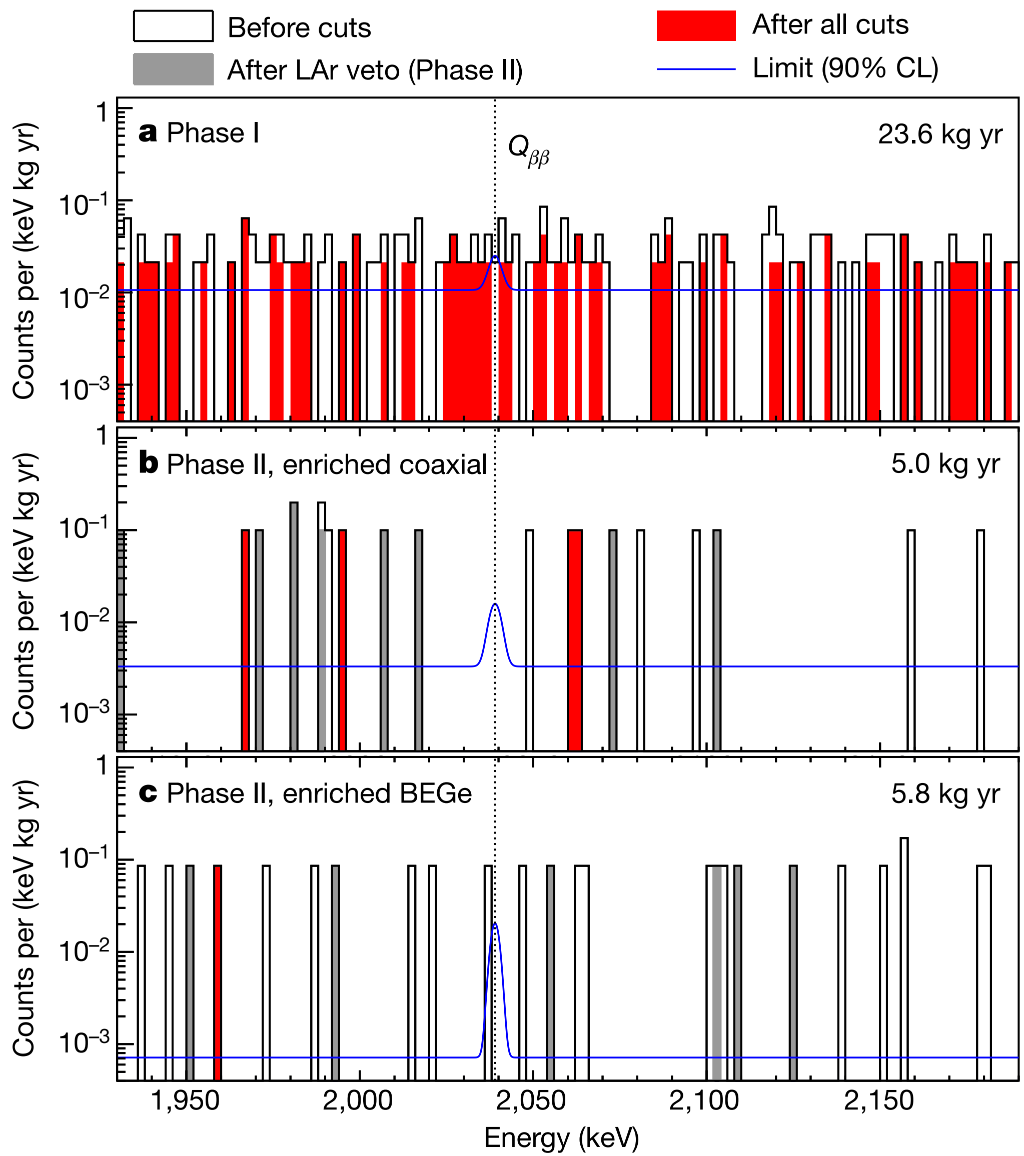
Phase II Background Performance



Nature **544**, 47–52 (2017).

Phase I + II results

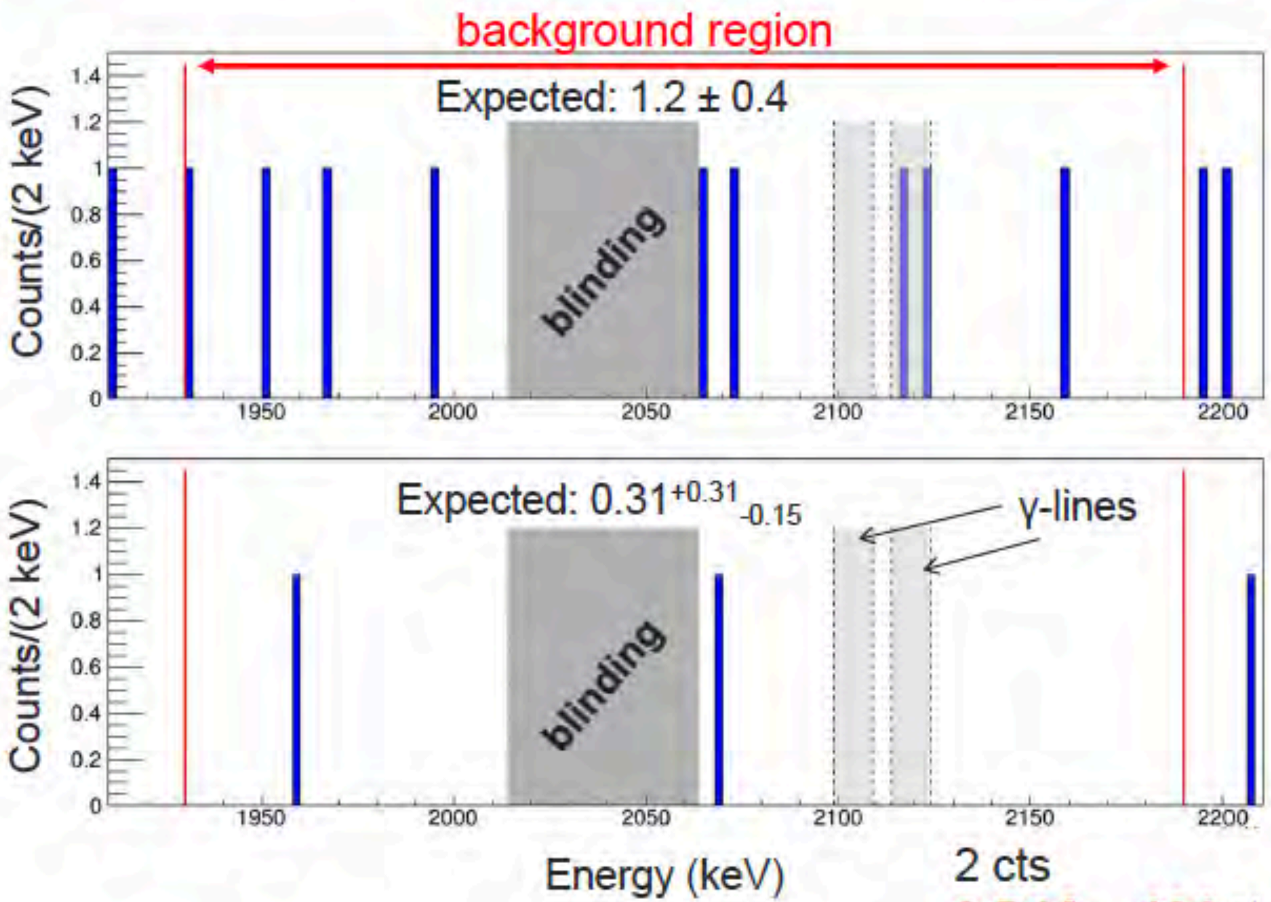
- Phase I and II Exposure: 34.4 kg y
- Projected background from 1930 to 2190 keV window excludes 2104 ± 5 keV and 2119 ± 5 keV. Window of ±20 keV around $Q_{\beta\beta}$ blinded.
- For Phase II BEGes, have achieved "background free" measurement with background index of 1.8 c/(FWHM-t-y) or (0.6 +0.6-0.4)) x 10^{-3} c/kky)
- $T_{1/2}$ ($0\nu\beta\beta$) ≥ 5.3 x 10^{25} years (90%CL)



Nature **544**, 47–52 (2017).

Spectra in the ROI

7 cts (+2 known in blinded box)
$2.7^{+1.0}_{-0.8}\ 10^{-3}$ cts/(keV kg yr)



enrCoax
16.2 kg·yr
(all cuts)

enrBEGe
18.2 kg·yr
(all cuts)

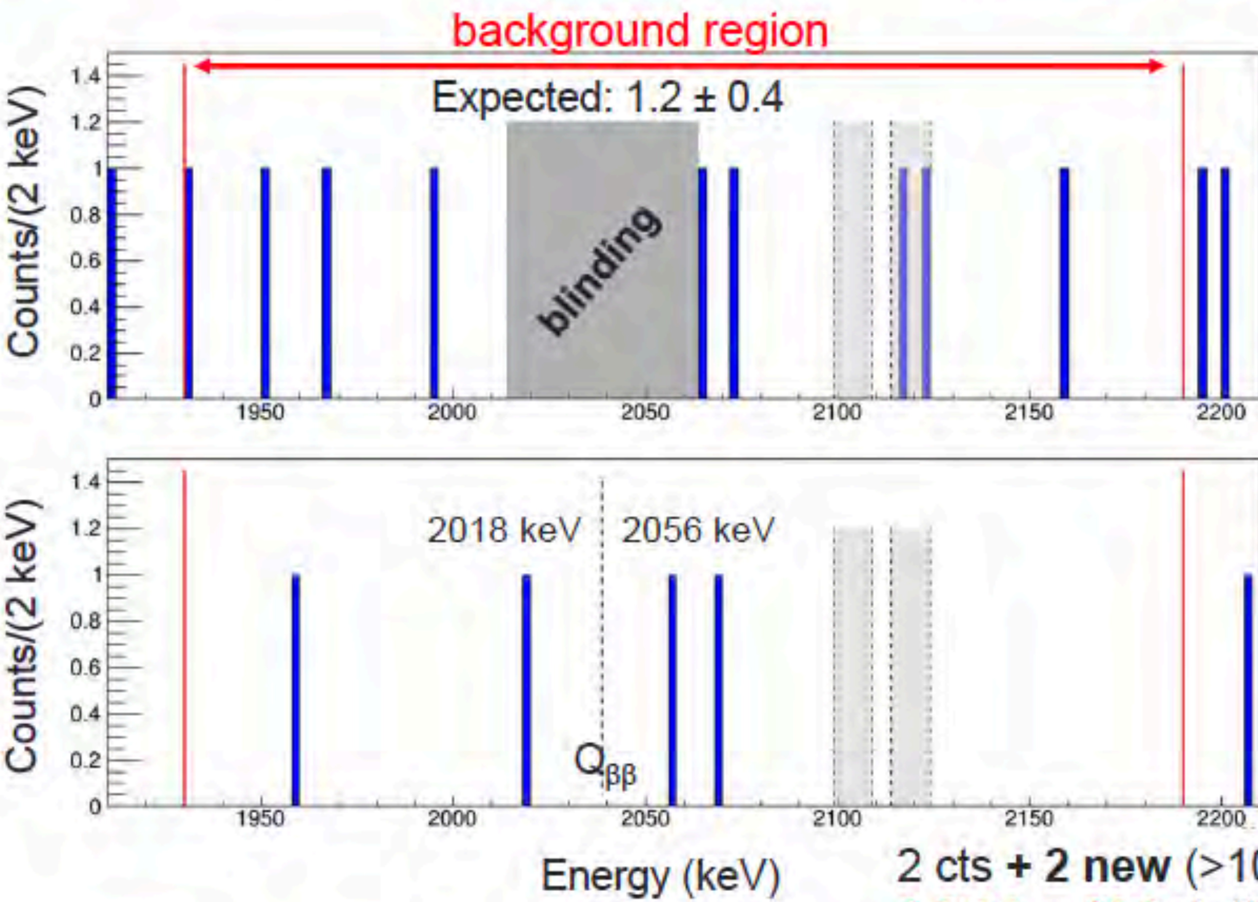
2 cts
$0.5^{+0.5}_{-0.3}\ 10^{-3}$ cts/(keV kg yr)

Pandola, TAUP 2017

Update from TAUP

Spectra in the ROI

7 cts (+2 known in blinded box)
$2.7^{+1.0}_{-0.8}$ 10^{-3} cts/(keV kg yr)



^{enr}Coax
16.2 kg·yr
(all cuts)

Previously unblinded: 5.0 kg yr

^{enr}BEGe
18.2 kg·yr
(all cuts)

2 cts **+ 2 new** (>10σ from $Q_{\beta\beta}$)
$1.0^{+0.6}_{-0.4}$ 10^{-3} cts/(keV kg yr)

Pandola, TAUP 2017

LEGEND

Mission: The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results.

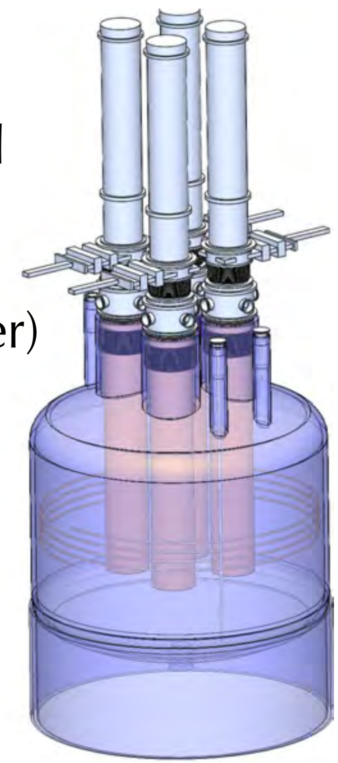
Select best technologies, based on what has been learned from GERDA and the MAJORANA Demonstrator, as well as contributions from other groups and experiments.

First Phase: L200

- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal (x3 lower) 0.6 c /(FWMH t y)
- start by 2021

Subsequent stages:

- 1000 kg (staged)
- timeline connected to U.S. DOE down select process
- BG: goal (x30 lower) 0.1 c /(FWHM t y)
- Location: TBD
- Required depth (^{77m}Ge) under investigation



LEGEND Collaboration

Univ. New Mexico
L'Aquila Univ. and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
Univ. Texas
Tsinghua Univ.
Lawrence Berkeley Natl. Lab.
Leibniz Inst. Crystal Growth
Comenius Univ.
Lab. Naz. Sud
Univ. of North Carolina
Sichuan Univ.
Univ. of South Carolina
Jagiellonian Univ.
Banaras Hindu Univ.
Univ. of Dortmund
Tech. Univ. – Dresden
Joint Inst. Nucl. Res. Inst.
Nucl. Res. Russian Acad. Sci.
Joint Res. Centre, Geel
Chalmers Univ. Tech.

Collaboration formed:

- 1st: Munich April 2016
- 2nd: Atlanta October 2016
- 3rd: LNGS May 2017

47 Institutions
219 Scientists

Max Planck Inst., Heidelberg
Dokuz Eylul Univ.
Queens Univ.
Univ. Tennessee

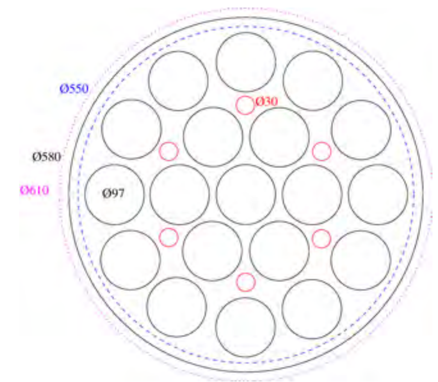
Argonne Natl. lab.
Univ. Liverpool
Univ. College London
Los Alamos Natl. Lab.

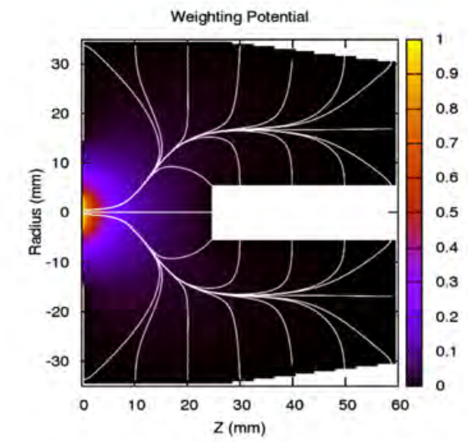
Lund Univ.
INFN Milano Bicocca
Milano Univ. and Milano INFN
Natl. Res. Center Kurchatov Inst.

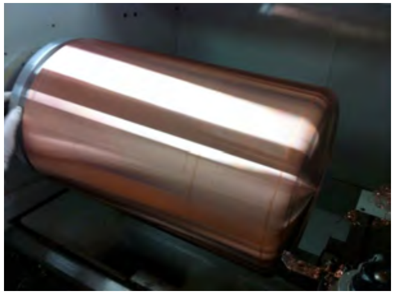
Lab. for Exper. Nucl. Phy. MEPhI
Max Planck Inst., Munich
Tech. Univ. Munich
Oak Ridge Natl. Lab.
Padova Univ. and Padova INFN
Czech Tech. Univ. Prague
Princeton Univ.
North Carolina State Univ.
South Dakota School Mines Tech.
Univ. Washington
Academia Sinica
Univ. Tuebingen
Univ. South Dakota
Univ. Zurich

LEGEND 200

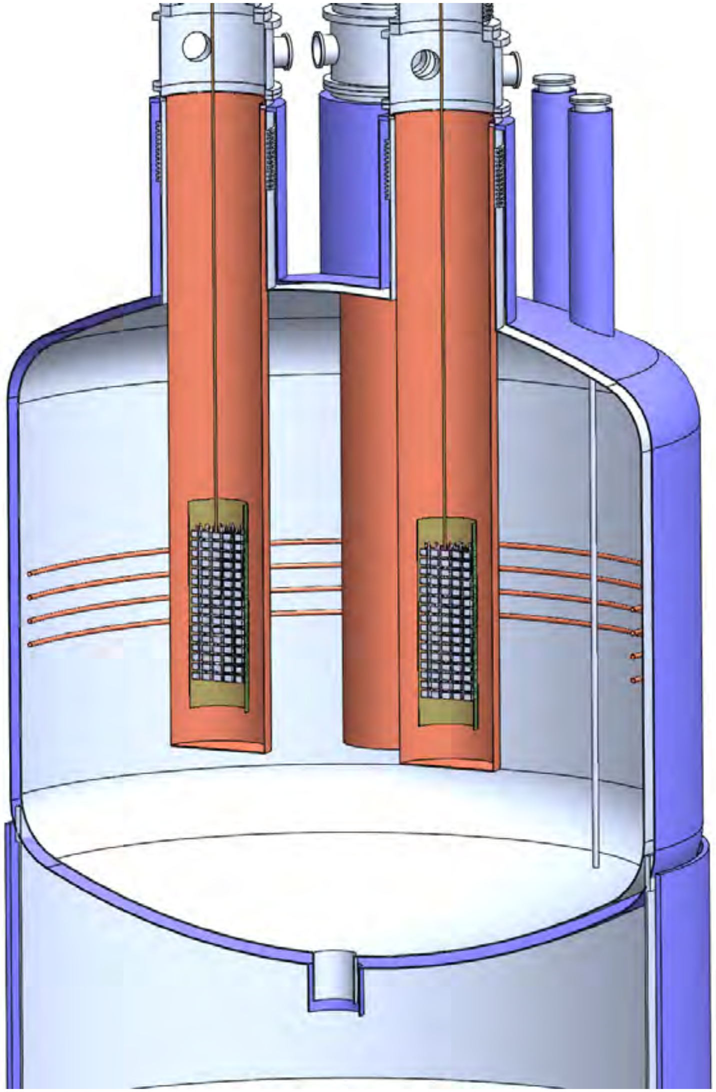
- Modifications of internal GERDA cryostat piping so can accommodate up to 200 kg of detectors.
- Improvements
  - use some larger Ge detectors (1.5 - 2.0 kg)
  - improve LAr scintillator light collection (2x in test stand)
  - lower mass, cleaner cables
  - lower noise electronics
- Estimate background improvement by ~x3 over GERDA/ MAJORANA. Goal: 0.6 cnt/(FWMH t y)
  - intrinsic: including $^{68}Ge/^{60}Co$ all OK
  - external Th/U: cleaner materials based on those used in DEMONSTRATOR
  - surface events: alpha & beta rejection via PSD
  - ^{42}Ar: better suppression & mitigation
  - muon induced: OK
- Contingent upon funding, data taking by 2021







LEGEND 1000: “Baseline Design”

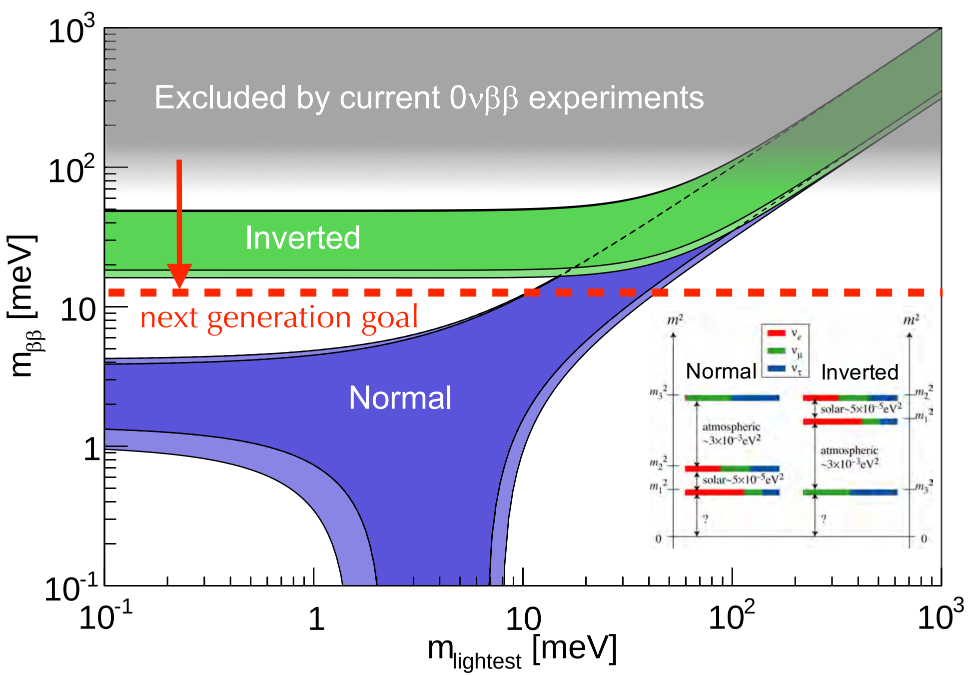


- 1000 kg
- BG goal (x30 lower): 0.1 c/(FWHM t y)
- 4-5 payloads in LAr cryostat in separate 3 m^3 volumes, payload 200-250 kg, with ~100+ detectors.
- Every payload “independent” with individual lock
- LAr detector volume separated by thin (electro-formed) Cu from main cryostat volume.
- Use depleted LAr in inner detector volumes
- Modest sized LAr cryostat in “water tank” (6 m Ø LAr, 2-2.5 m layer of water)
  or
  large LAr cryostat w/o water (9 m Ø) with separate neutron moderator

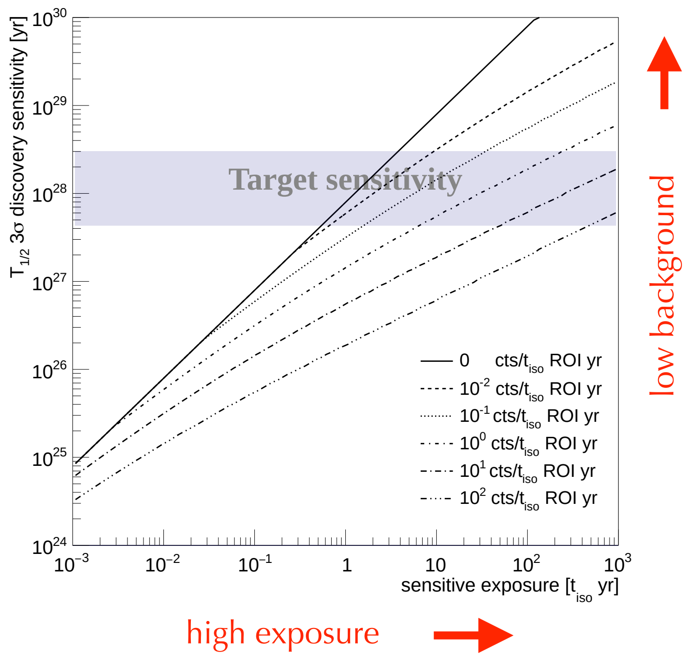
Outline

- Introduction: exposure and background
- High exposure: KamLAND-Zen
- Low background: MAJORANA / GERDA / LEGEND
- Discovery potential of future experiments

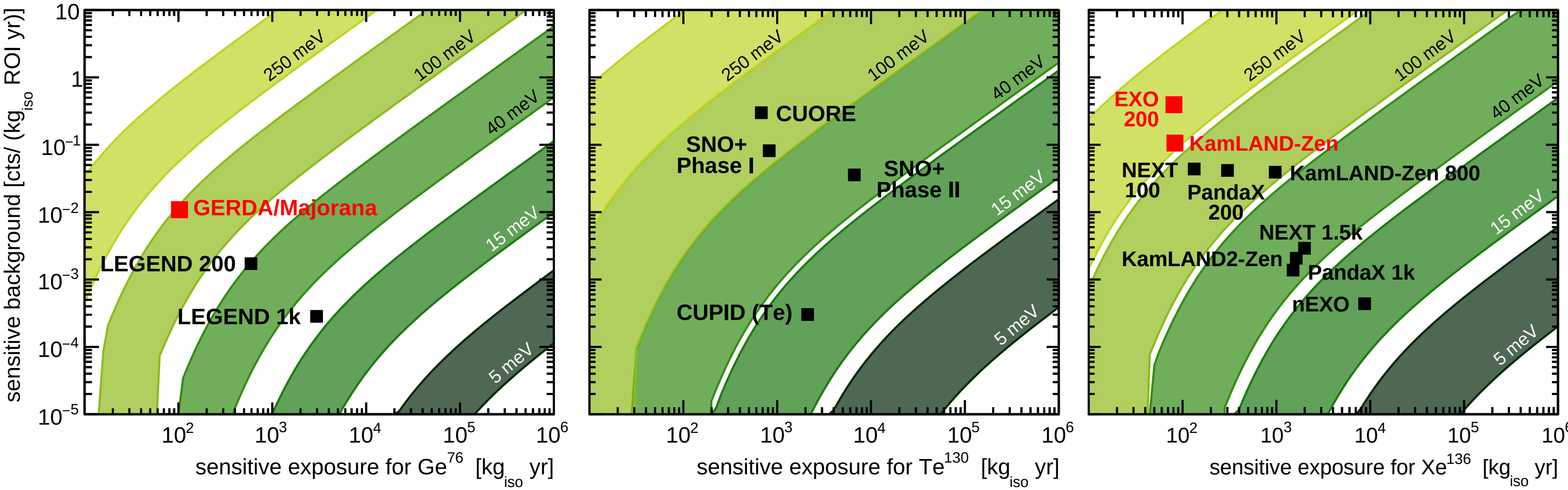
Light Neutrino Exchange



Requirements:



Discovery Sensitivity



- Red dots: published limits. Black dots: 3σ discovery sensitivities with 5 yrs live time
- Discovery sensitivity after 10 yr is ~√2 higher for all experiments
- Bands represent NME spread

arXiv:1705.02996 [hep-ex]

Discovery Probability

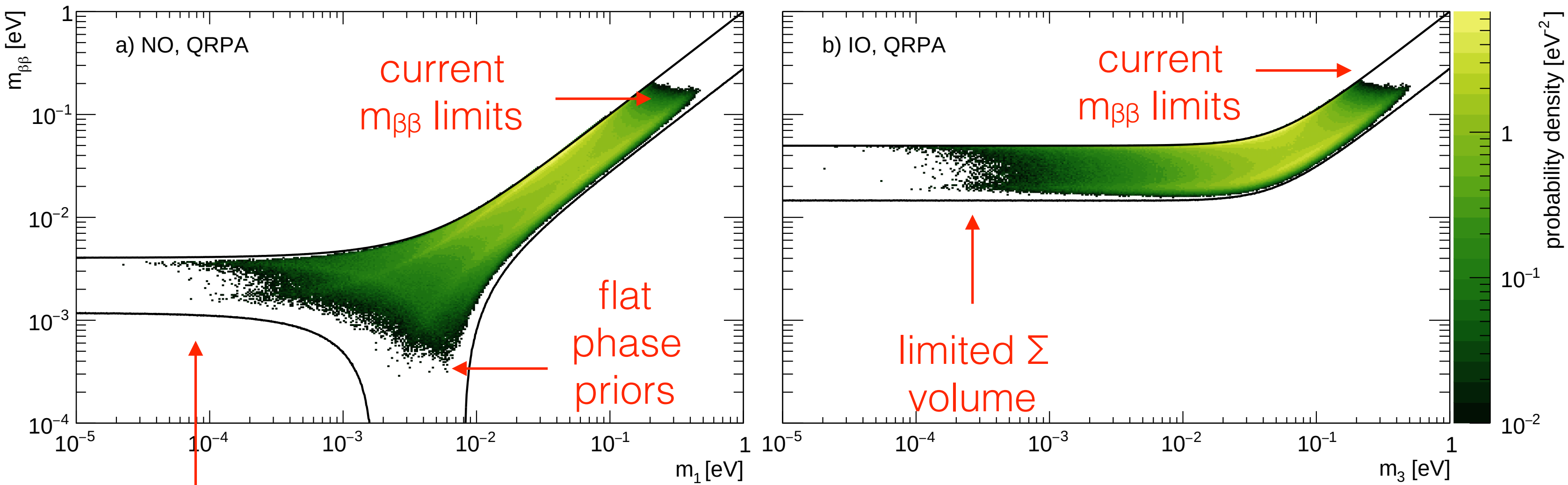
What are the chances that these next-generation experiments will make a discovery? How much should humanity invest in 0νββ?

- Bayesian methods are the only tools available by which such a "value" question can be approached:
  - Quantify the "volume" in the available parameter space (assign priors). Equal volumes = equal relative probability of discovery
  - Compute the amount of volume left to be explored (apply constraints from available measurements)
  - Compute the fraction of the remaining volume that will be explored by next-generation experiments. This is the "discovery probability" (DP).
- Equivalent / technical description:
  - Compute the posterior PDF for $m_{\beta\beta}$ given all experiments to date, and use it as a prior for next-generation experiments
  - For each value of $m_{\beta\beta}$, compute the probability that a next-generation experiment will make a 3σ discovery. Then sum up those probabilities weighted by the $m_{\beta\beta}$ PDF.

Priors and Basis

- Neutrino mass scale is unknown: use log-flat prior for all mass parameters
- Angles and phases: use flat prior in [0, 2π)
- Constrain with all available data: NuFit (osc.), β-decay, ββ-decay
- Evaluate for multiple NME, with/without g_A quenching, with/without cosmological limits
- Basis choice: Σ vs. m_l
    - m_l: log-flat prior gives huge preference for extreme-hierarchical scenarios ($m_l \ll m_2$). Results are trivial: DP ~ 100% for IO, and ~0 for NO
    - Σ: represents theoretical prejudice that neutrino masses are generated by a different mechanism than the other SM fermions
    - We choose Σ as our "reference" basis. One can re-weight our results according to his or her own prejudice for this vs. extreme hierarchical scenarios

$m_{\beta\beta}$ PDF

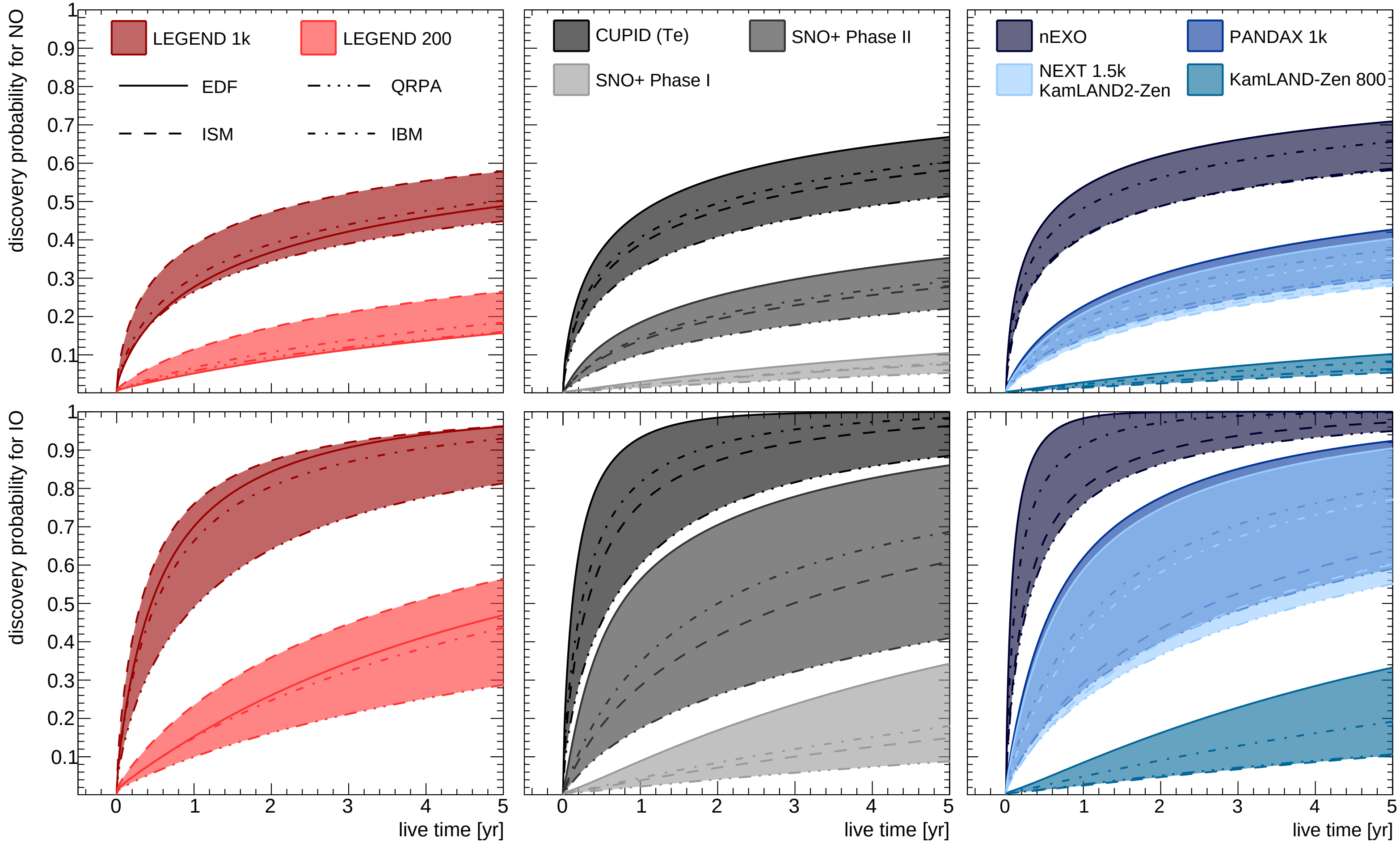


limited Σ volume

arXiv:1705.02996 [hep-ex]

Discovery Probabilities

Fold $m_{\beta\beta}$ PDF with discovery sensitivity



arXiv:1705.02996 [hep-ex]

Alternative Analyses

- Adding 30% g_A quenching: volume opens up at high $m_{\beta\beta}$, mitigating g_A^4 dependence. DP drops by only ~15% (25%) for IO (NO)
- Adding cosmological constraints: NO DP reduced by ~30%. No effect for IO.
- Both cosmological limits + g_A quenching: Planck rules out the region opened up at high $m_{\beta\beta}$ from relaxed GERDA / KLZ limits. IO DP drops to ~50%, NO DP drops to 10-20%.
- If KATRIN sees a positive signal: DP = 100% regardless of ordering, mass model, NME, quenching, cosmology.

Almost all scenarios have significant discovery probability, regardless of the mass ordering!

Summary

- Promising future 0nbb experiments must have high sensitive exposure with low sensitive background.
- KamLAND-Zen has the current best limit, with excellent limit sensitivity on the way with high-exposure KamLAND-Zen 800
- MAJORANA and GERDA have the best resolution and lowest demonstrated backgrounds by an order of magnitude. Combining forces to build LEGEND, with 200 kg apparatus on a short time scale, and a ton-scale apparatus to follow.
- These experiments have surprisingly high discovery probability: discovery may be just around the corner!