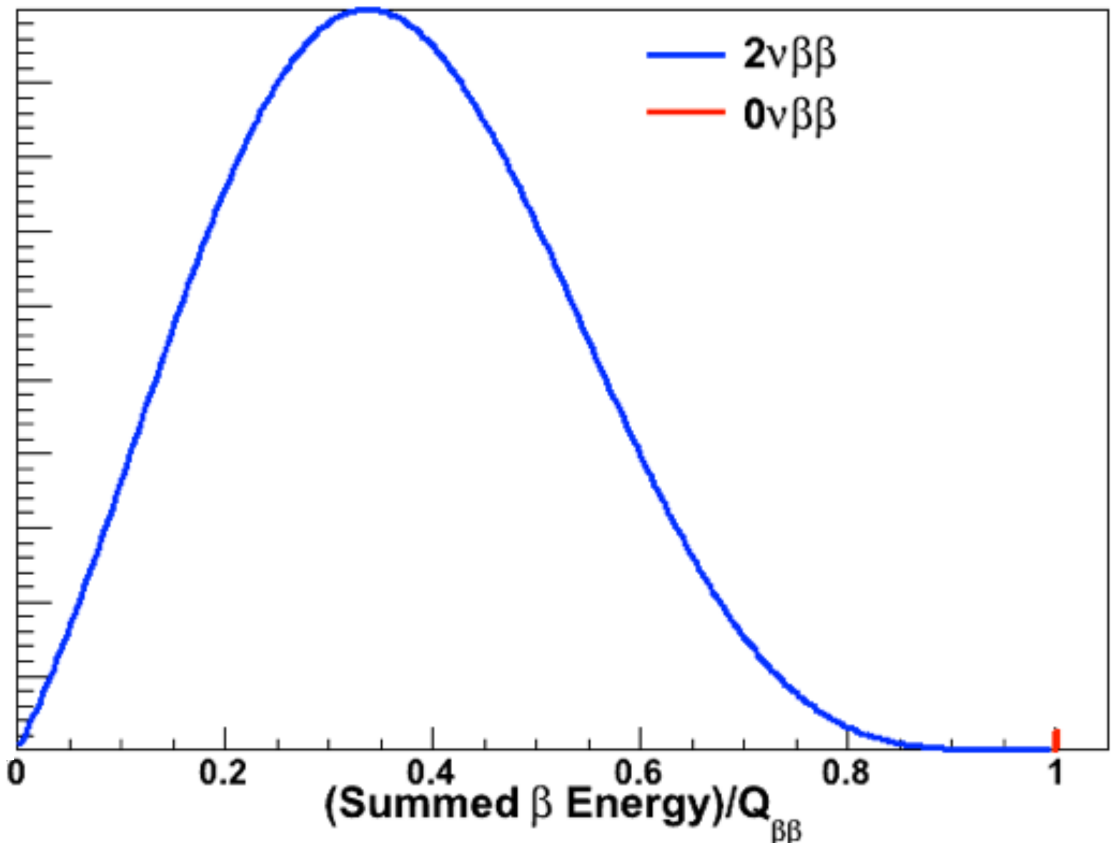
Status of Neutrinoless Double-Beta Decay Experiments



Jason Detwiler

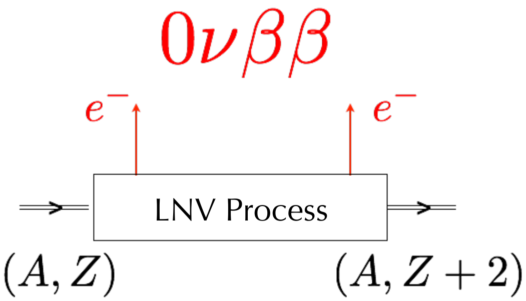
Assistant Professor, University of Washington / CENPA

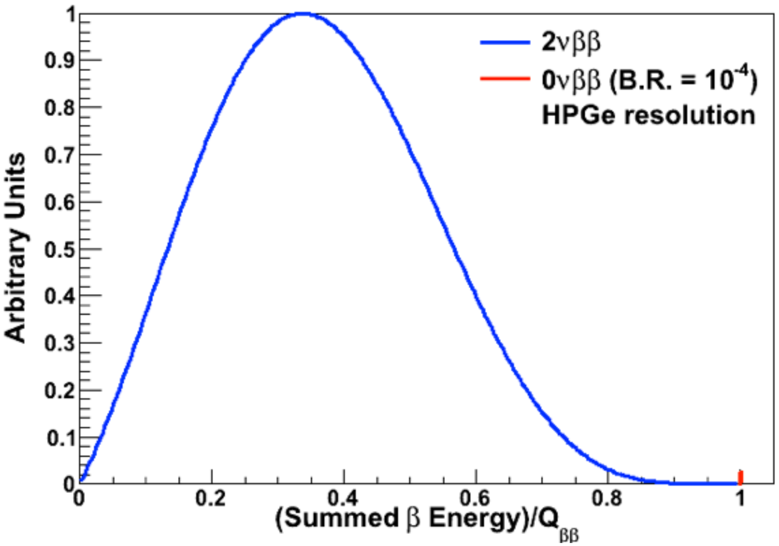
INT Seminar, March 8, 2018

Outline

- Introduction to 0νββ experiments
- Status of current leaders
- Prospects for next-generation experiments

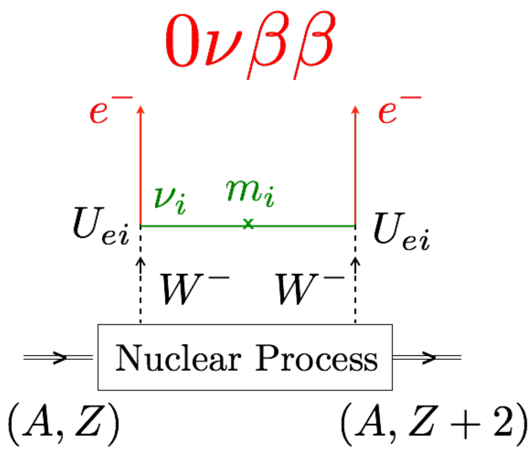
Neutrinoless Double-Beta Decay





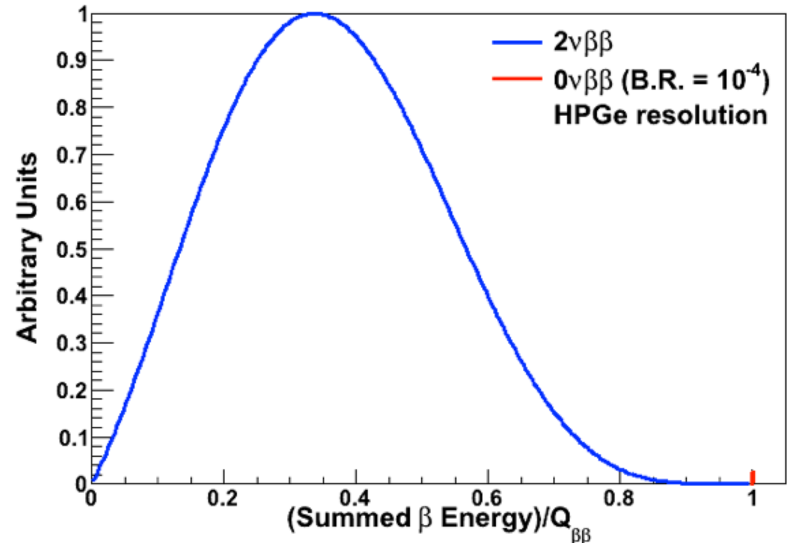
- Matter-creating process
- Must measure summed electron kinetic energy to distinguish from Standard-Model 2ν process: scintillation, ionization, and/or heat
- Some experiments can also measure electron momenta (tracking), provides a handle on the LNV process
- The peak in the plot exceeds current limits

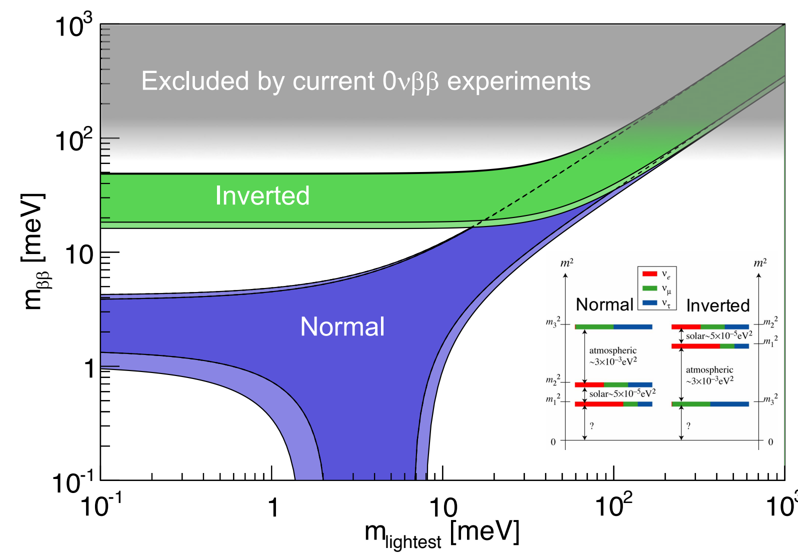
Pure-Majorana SM Neutrino Exchange



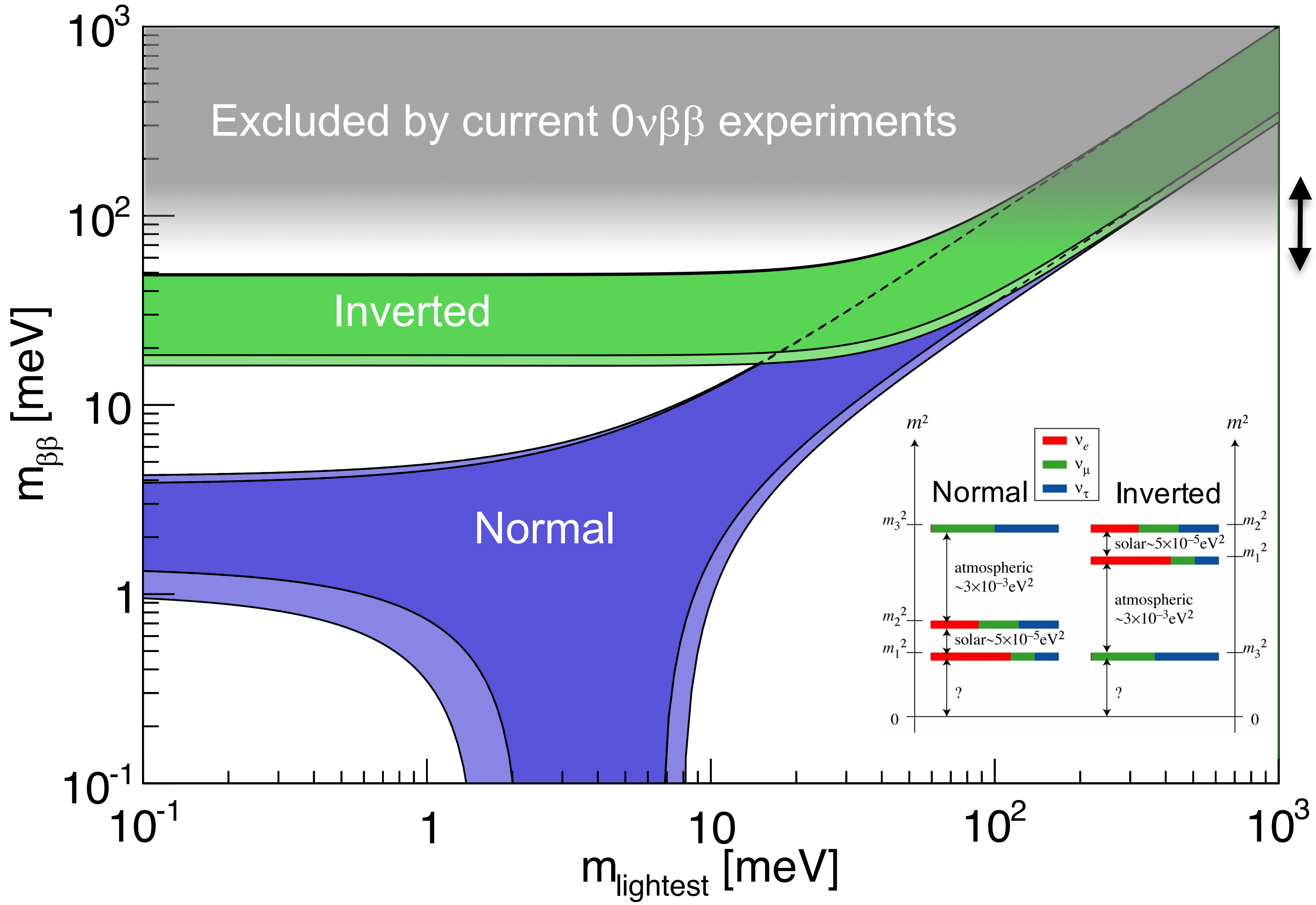
$$\Gamma_{1/2}^{0\nu} = G^{0\nu} |M^{0\nu}|^2 \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2$$

- Expensive experiments require a goal post
- “Minimal” model: add just one parameter to the SM Lagrangian



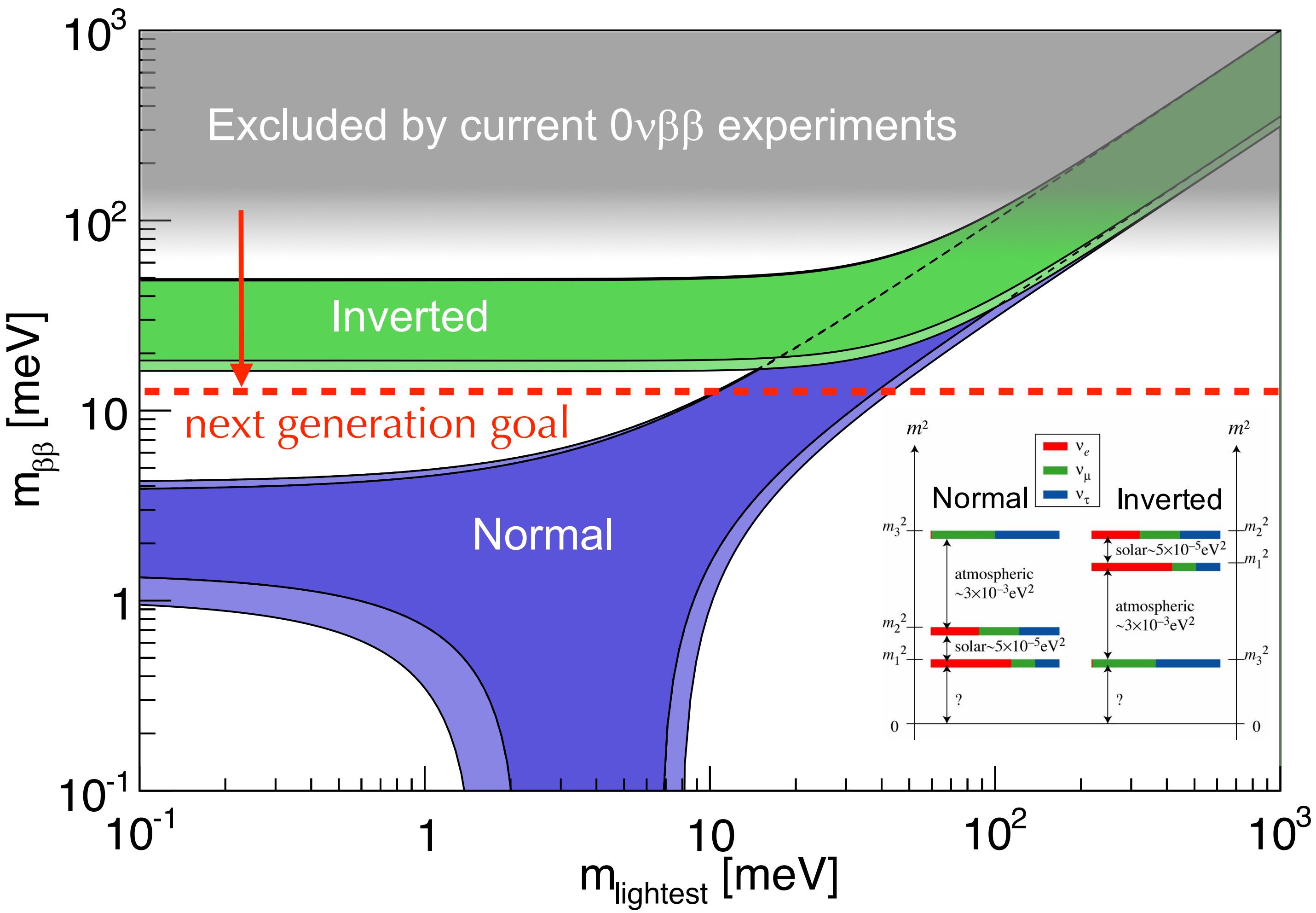


Light Neutrino Exchange



NME ambiguity

Light Neutrino Exchange



Qualitative Experimental Description

- Energy is the only observable that is a necessary and sufficient condition for discovery of 0νββ decay
- Sensitivity is dominated by 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

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

detection efficiency (ϵ), fiducial mass of isotope (m_{iso}^{FV}), counting time (t)

Sensitive Background

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

background counts (N_{bg})

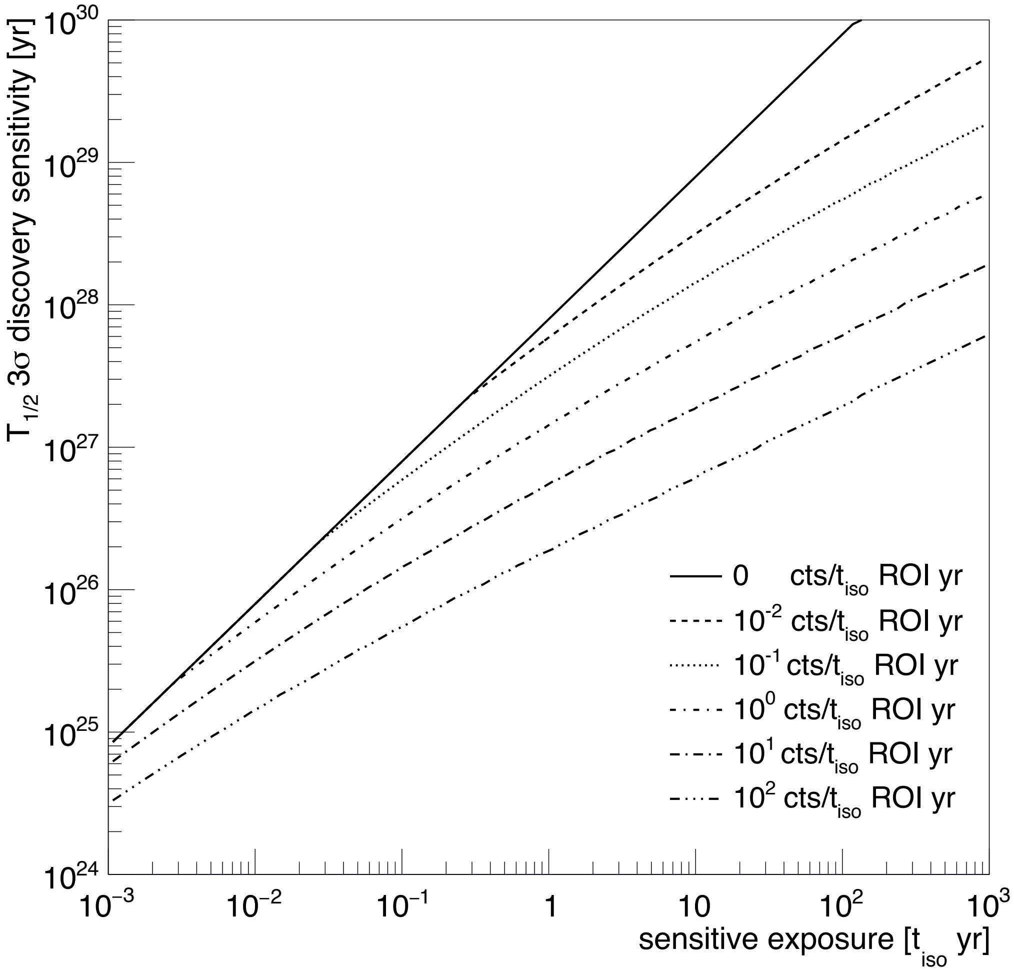
- In most (all) experiments, background is well-constrained, either from energy or volumetric side-bands

Experimental Goal: Discovery

- 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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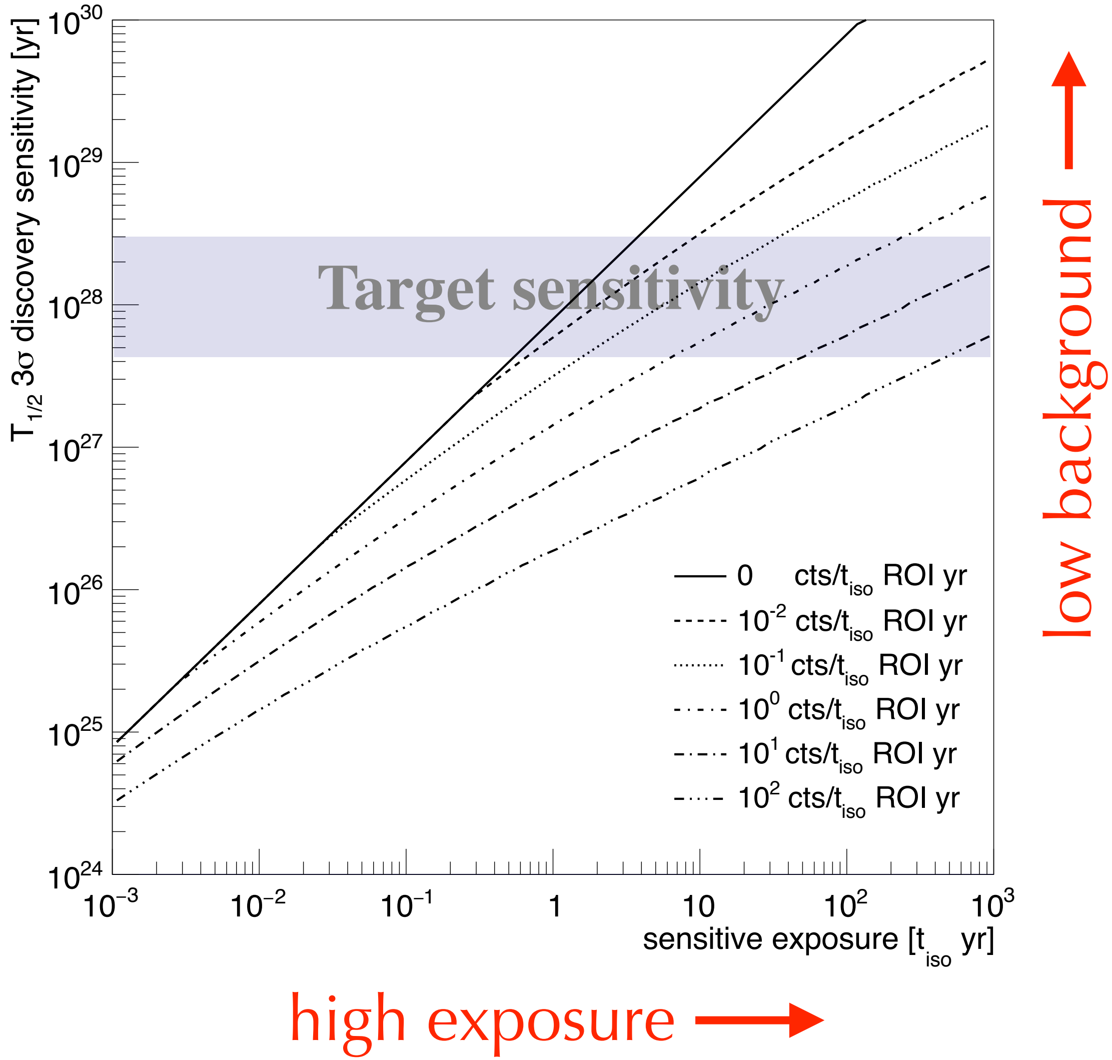
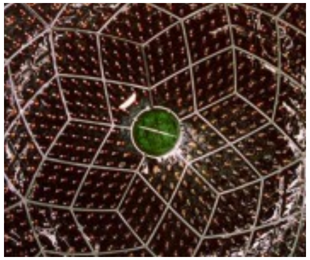
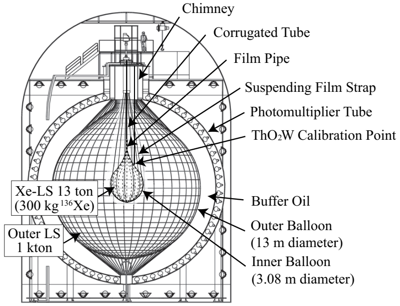
Requirements:



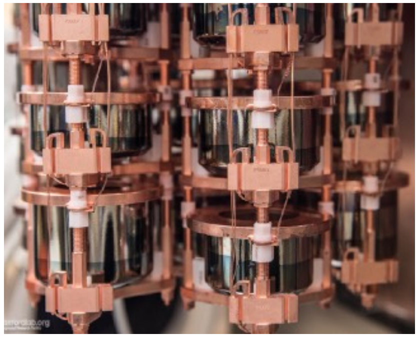
Experimental Categories

- Large liquid scintillators:
  - KamLAND-Zen
  - SNO+

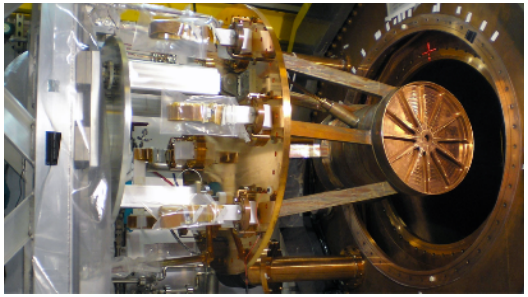




- Granular arrays: ionization / heat
  - MAJORANA
  - GERDA
  - LEGEND
  - CUORE
  - CUPID



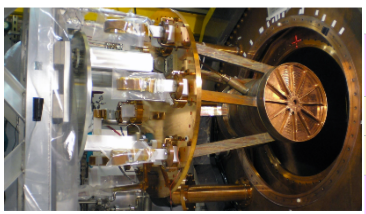
- TPCs: ionization + scintillation
  - EXO-200
  - nEXO
  - NEXT
  - PandaX



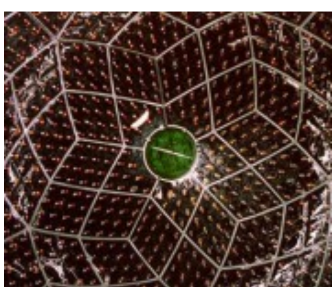
0νββ Experiments

CUORE

EXO-200



KamLAND-Zen

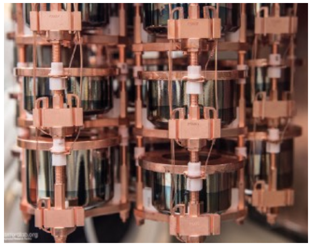


Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
AMoRE	Mo-100	CaMoO4 bolometers (+ scint.)	5	Construction
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Operating
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in active LAr	20 kg	Operating
Majorana Demonstrator	Ge-76	Point contact Ge in Lead	30 kg	Operating
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
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
CUPID	Several	Scintillating Bolometers	~tonne	R&D
SNO+	Te-130	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
KamLAND-Zen	Xe-136	2.7% in liquid scint.	370 kg	Complete
KamLAND-Zen 800	Xe-136	2.7% in liquid scint.	750 kg	Construction
KamLAND2-ZEN	Xe-136	2.7% in liquid scint.	~tonne	R&D
NEXT-100	Xe-136	High pressure Xe TPC	10 kg	Construction
PandaX	Xe-136	2 phase Xe liquid TPC	~tonne	R&D
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



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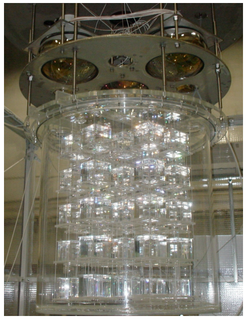


J. Detwiler

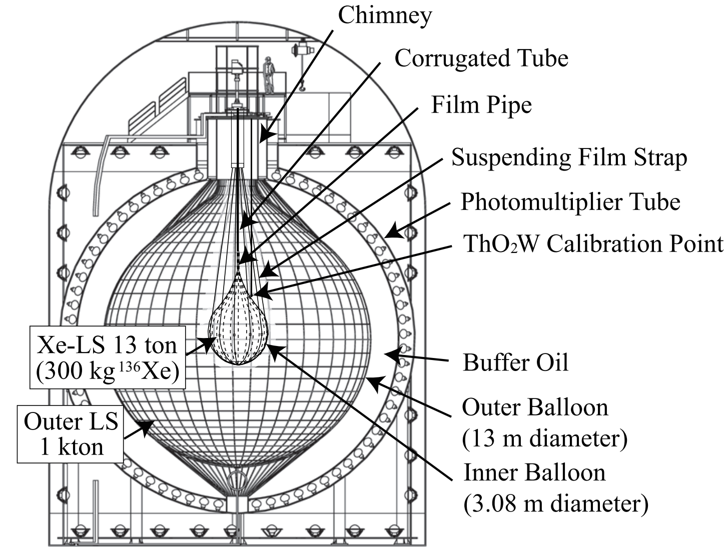
From J. F. Wilkerson

Outline

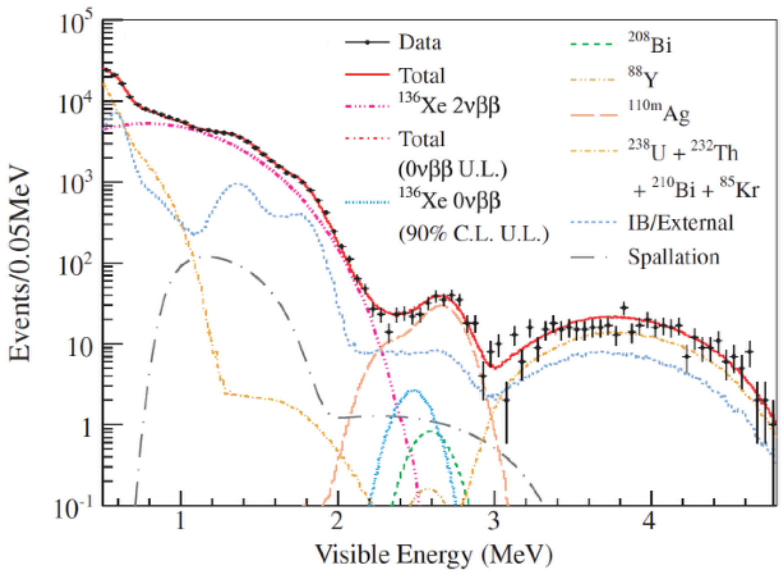
- Introduction to 0νββ experiments
- Status of current leaders
- Prospects for next-generation experiments

Best Exposure: KamLAND-Zen

- KamLAND-Zen
  - Phase I (2011-2012):
    320 kg 90% ^{enr}Xe, 89.5 kg-yr exposure
  - Phase II (2013-2015):
    383 kg 90% ^{enr}Xe, 504 kg-yr exposure
  - High initial background from ^{110m}Ag (Fukushima fallout)
  - $T_{1/2}(^{136}\text{Xe}) > 1.6 \times 10^{26}$ yr



- KamLAND-Zen 800
  - New, bigger balloon: remove ^{110m}Ag, double the mass
  - 2016 deployment: 5 holes :(
  - 2nd balloon fabrication nearly finished
  - Deploy April 2018, running by Summer 2018



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

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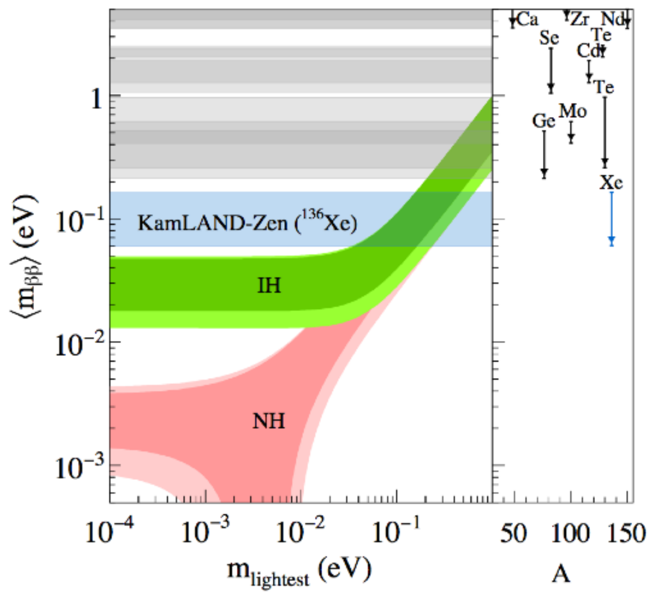
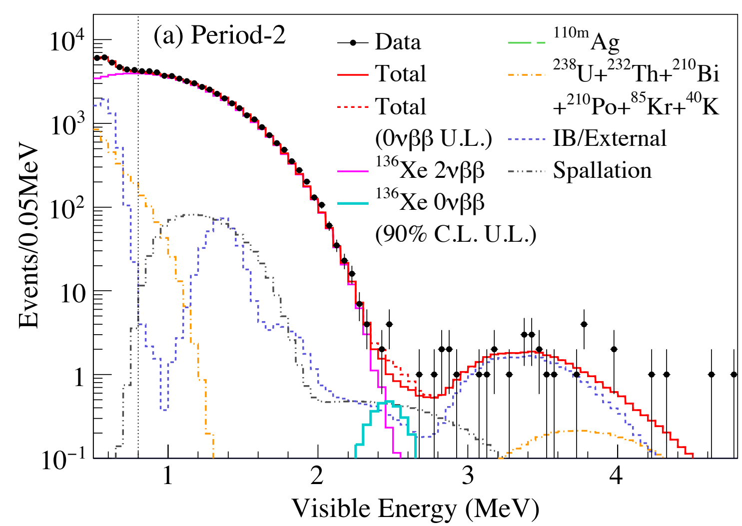




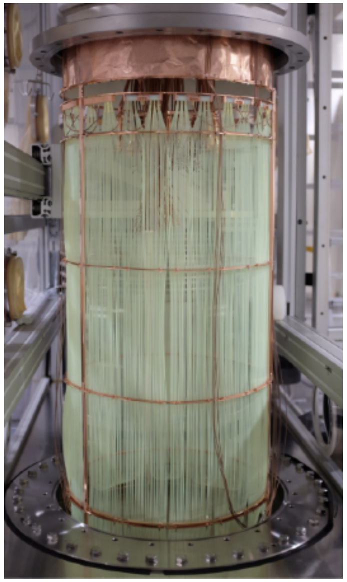
PRL **117**, 082503 (2016).

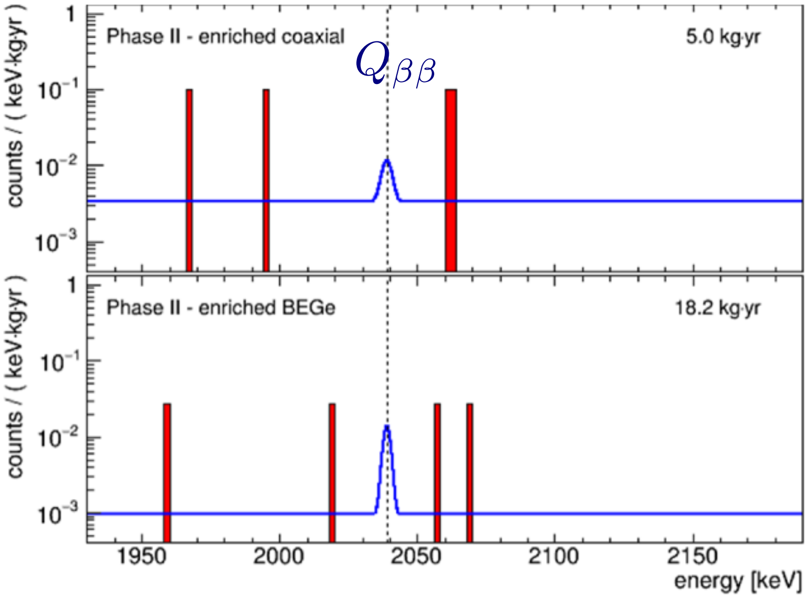
Best Background: HPGe

- GERDA
  - Direct immersion in active LAr shield
  - Phase I (Nov 2011- May 2013):
    - Refurbished HdM and IGEX
    - 18 kg + new BEGe Phase II detectors
    - BG ≈ 10 cts / (keV t yr)
    - No LAr readout (passive shield)
  - Phase II (Dec 2015- ongoing):
    - Add new 87% ^{enr}BEGe detectors (20 kg)
    - LAr active shield
  - Latest Combined Result:
    - Exposure: 46.7 kg yr

$$\mathrm{BG} = 1.0^{+0.6}_{-0.4}\,\mathrm{cts/(keV\,t\,yr)}$$

$$T^{0\nu}_{1/2} > 8.0 \times 10^{25}\,\mathrm{yr}\,(90\%\,\mathrm{CL})$$

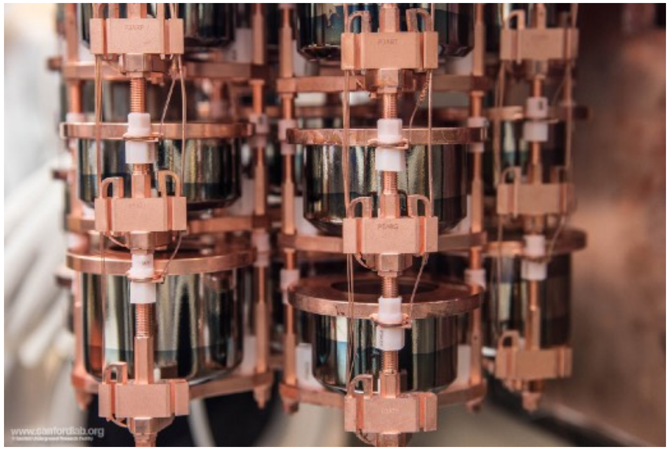


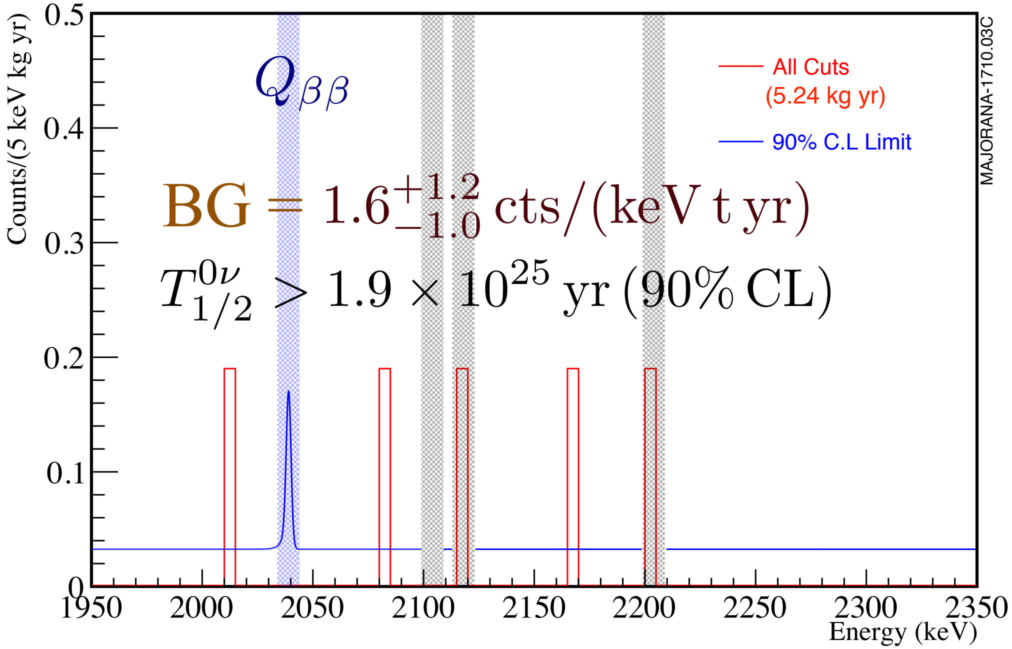


Accepted in PRL (arXiv:1710.07776)

Best Background: HPGe

- MAJORANA DEMONSTRATOR
  - Vacuum cryostats in a passive graded shield with ultra-clean materials
  - 88% ^{enr}Ge PPC detectors
  - 44.1-kg of Ge detectors, 29.7 kg of 88% enriched ^{76}Ge
  - First result (2015-2017): 9.95 kg yr

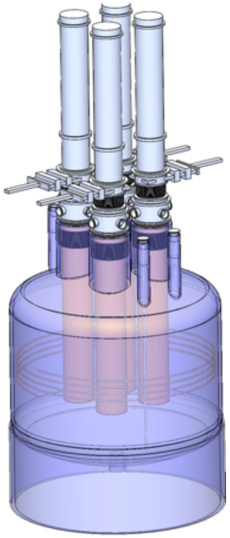




Accepted in PRL (arXiv:1710.11608)

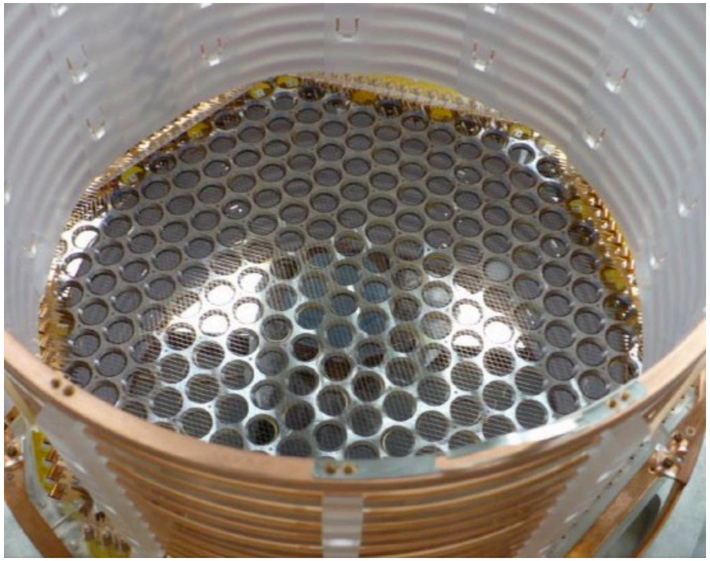
Best Background: HPGe

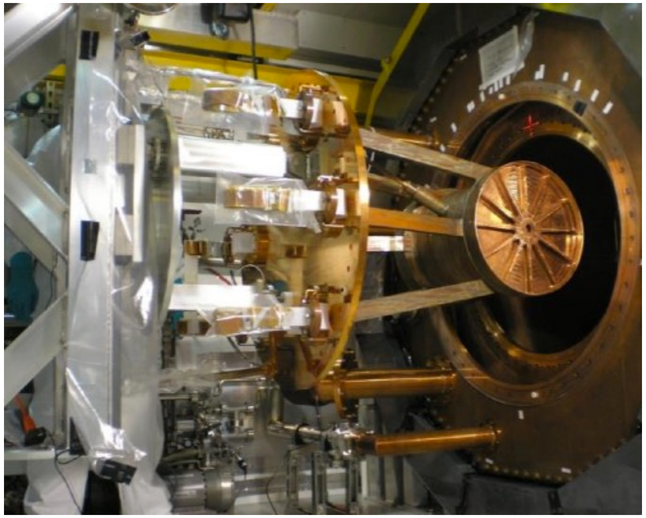
- LEGEND
  - Combines the best techniques of MAJORANA and GERDA: clean materials and active liquid argon veto
  - 88% ^{enr}Ge PPC detectors
  - First stage: LEGEND 200
    - (Up to) 200 kg in upgrade of existing GERDA infrastructure at LNGS
    - BG goal 0.6 cts/(FWHM t yr)
    - Sensitivity: $T_{1/2} > 10^{27}$ yr
    - Data start ~2021
  - Subsequent stages:
    - 1000 kg (staged)
    - Timeline coordinated with LEGEND 200
    - BG goal 0.1 cts/(FWHM t yr)
    - Sensitivity: $T_{1/2} > 10^{28}$ yr
    - Location TBD



Best of Both Worlds: EXO

- EXO-200
  - 200 kg 80% ^{enr}Xe
  - LXe TPC: Full 3D reconstruction
  - Measure scintillation and ionization
  - Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
  - Phase I
    - 2011-2014: 596.7 days
    - First and most precise $2\nu\beta\beta$ measurement
    - $T_{1/2} > 1.1 \times 10^{25}$ yr
  - Phase II
    - Clean up / upgrade after WIPP accidents
    - 2016 - present. 271.8 day result presented last summer
    - $T_{1/2} > 1.8 \times 10^{25}$ yr





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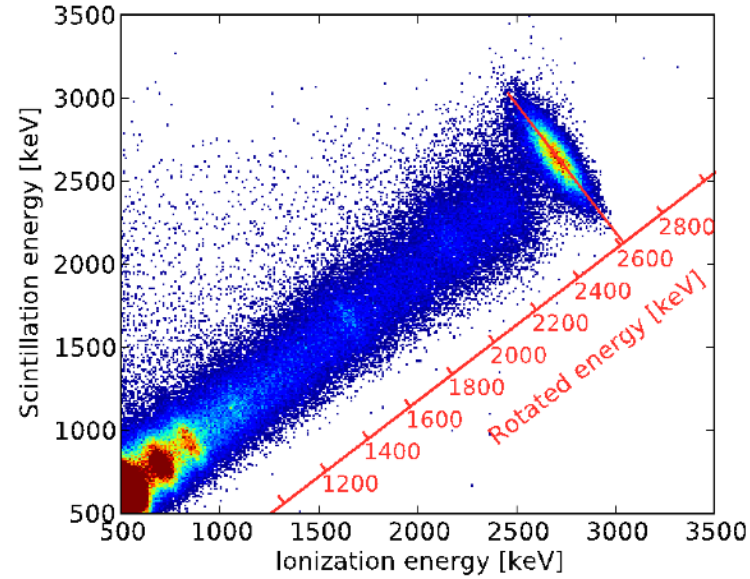
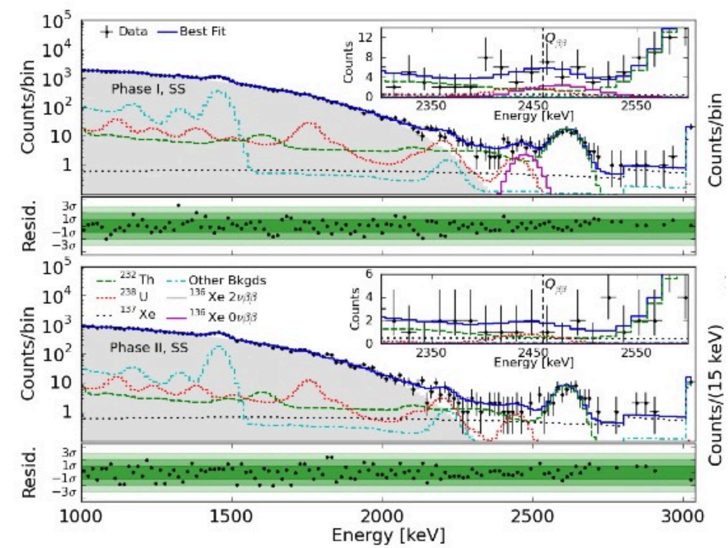
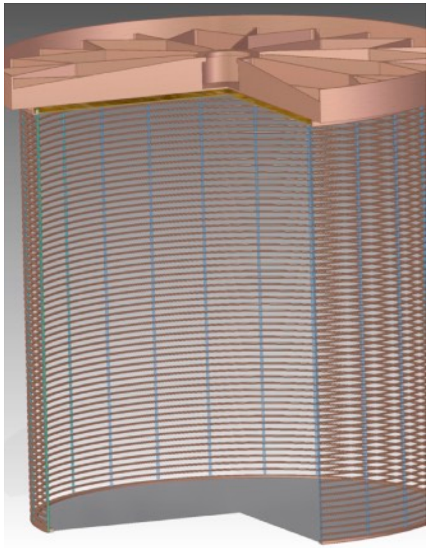


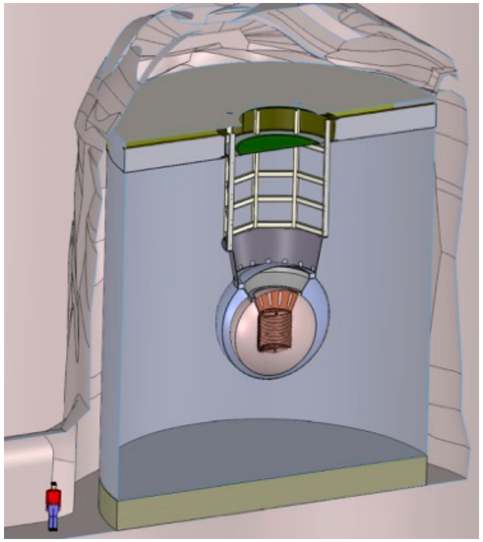


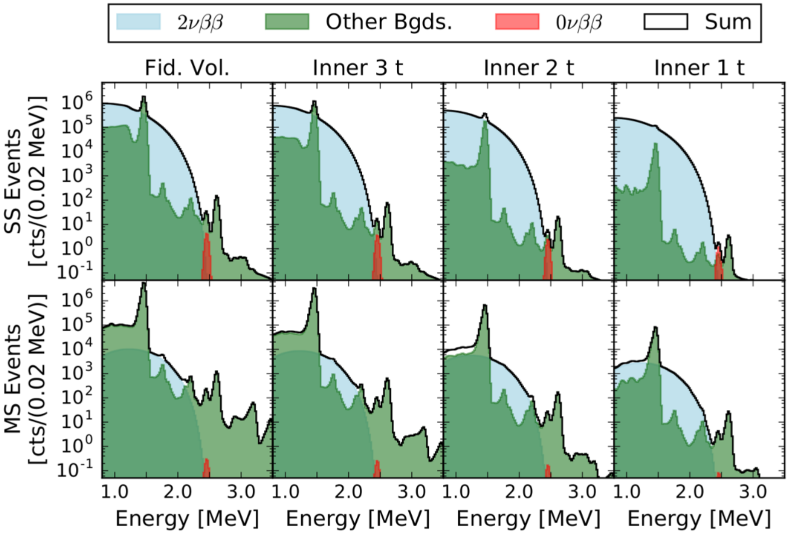
C. Licciardi , TAUP 2017

Best of Both Worlds: EXO

- nEXO
  - 5 tons of 90% ^{enr}Xe
  - Homogenous LXe TPC
  - Improved light and charge collection
  - Self-shielding
  - Planning to deploy in SNOLab
  - Discovery sensitivity for 10 years livetime: $T_{1/2}$ = 5 x 10^{27} yr (see plot to right)



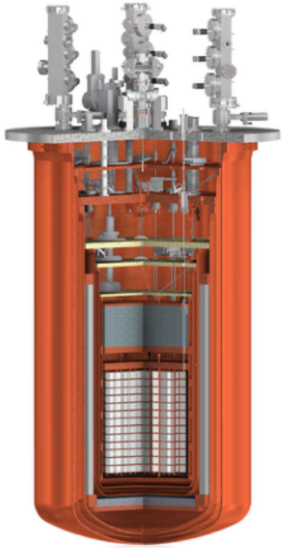


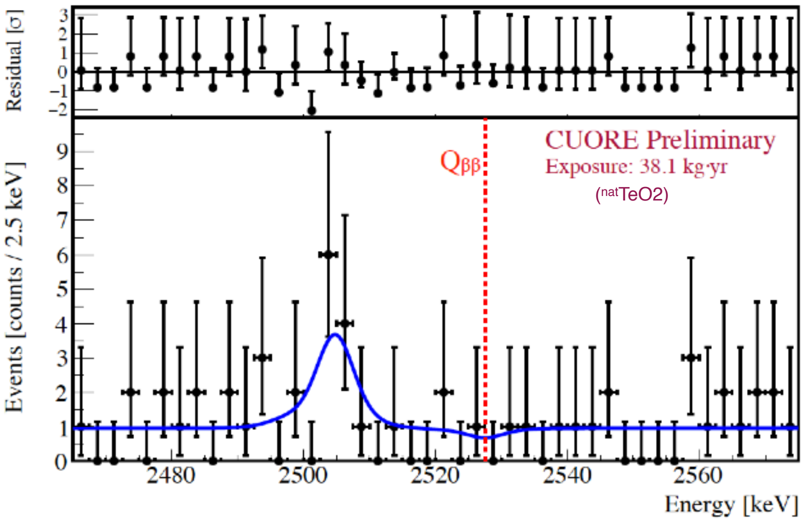


T. Brunner, TAUP 2017

Big Experiments with Big Results Soon

- CUORE / CUPID
  - CUORE
    - 750 kg array of $^{nat}TeO_2$ bolometers
    - Running at LNGS in "coldest cubic meter in the known universe"
    - TAUP data set: April-June 2017
    - BG = $9.8_{-1.5}^{+1.7} \times 10^{-3}$ c/(keV kg yr)
    - $T_{1/2} > 4.5 \times 10^{24}$ yr ($> 6.6 \times 10^{24}$ yr when combined with CUORE-0)
    - Fall: failed valves caused calibration source to freeze, had to warm up. Restart is imminent
  - CUPID
    - Reject CUORE alpha background by detecting coincident scintillation (Se, ZnSe) or Cherenkov (Te)
    - R&D underway
    - Would re-use CUORE cryostat

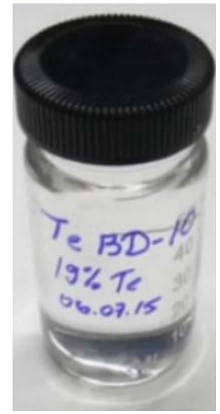


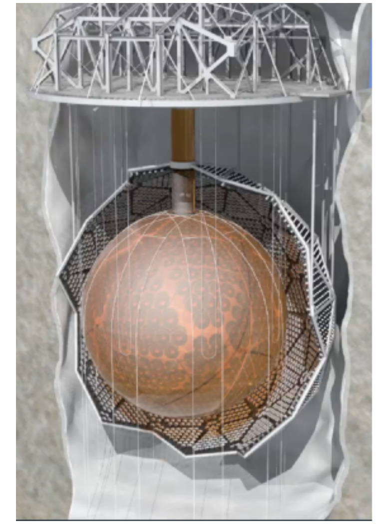


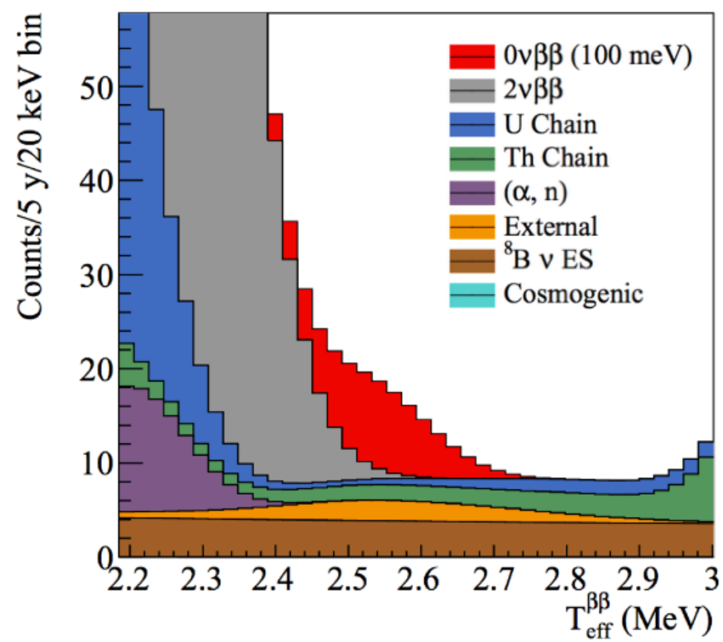
O. Cremonesi, TAUP 2017

Big Experiments with Big Results Soon

- SNO+
  - Refurbished SNO detector: convert inner D2O volume to 780 t liquid scintillator loaded with 3.9 t ^{nat}Te
  - Have to tie down the acrylic vessel rather than hold it up!
  - Novel chemistry for loading metals in organic liquid
  - Had to patch many cavern holes during filling, now running with water
  - Scintillator to be loaded imminently, expect first data this summer?



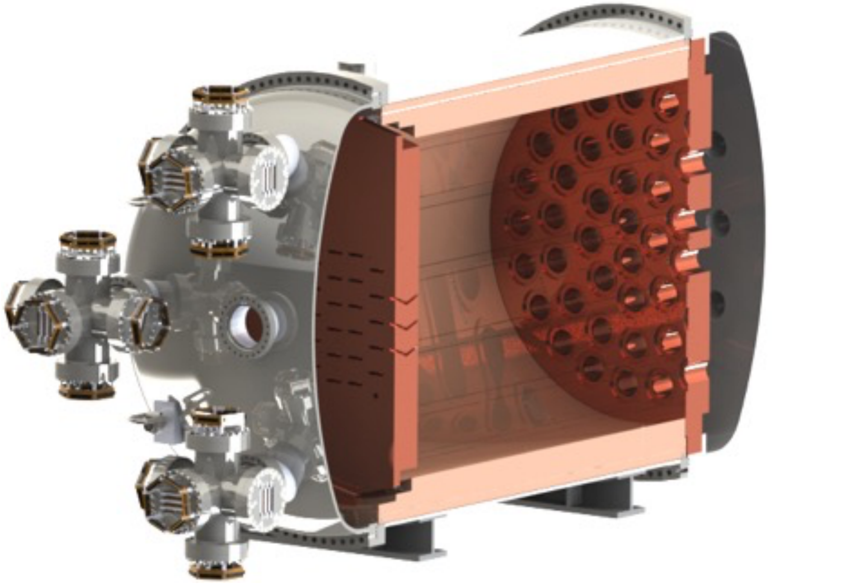


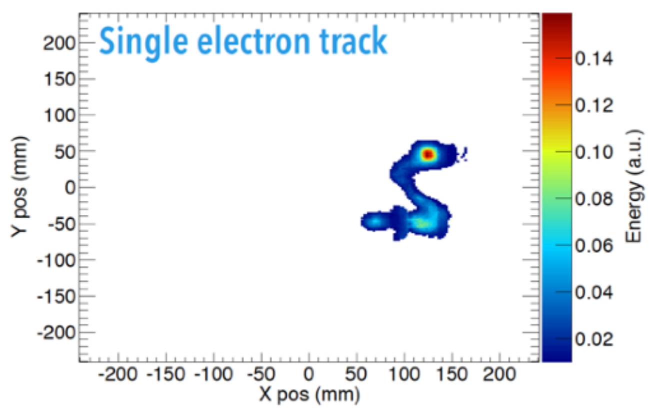


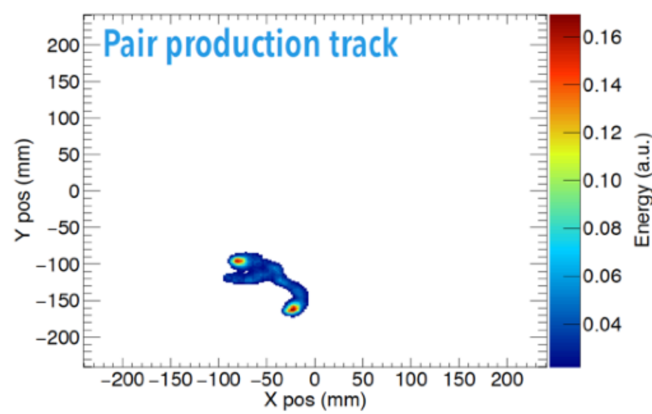
E. Caden, TAUP 2017

Tracking Detectors to Watch

- NEXT 100
  - High-pressure gas TPC: full track reconstruction
  - 100 kg 90% ^{enr}Xe
  - Electroluminescence amplification achieves theoretical best σ_E
  - NEXT-WHITE 5 kg prototype running underground at Canfranc
  - NEXT-100 construction scheduled to finish late 2018







A. ESTÉVEZ, TAUP 2017

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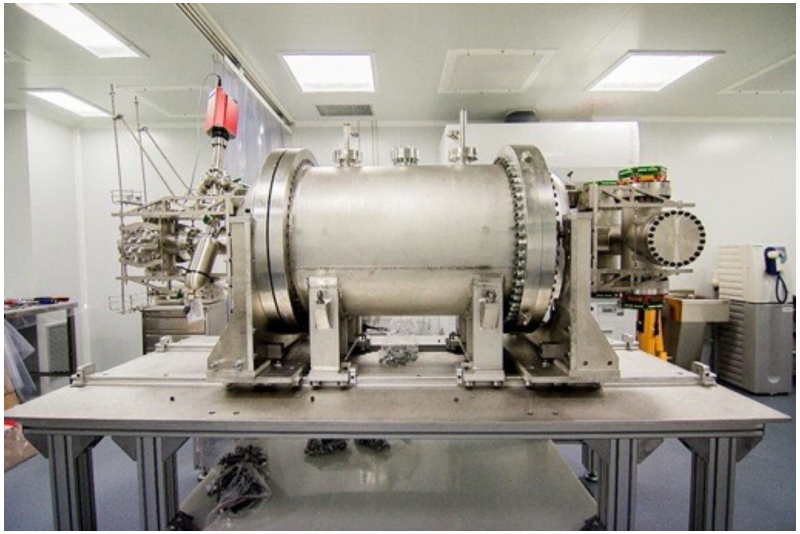
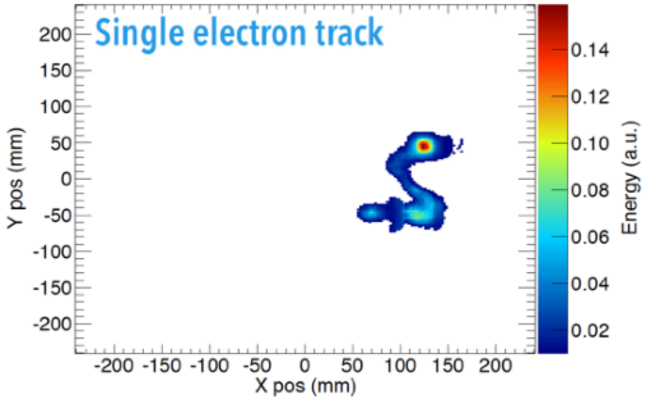
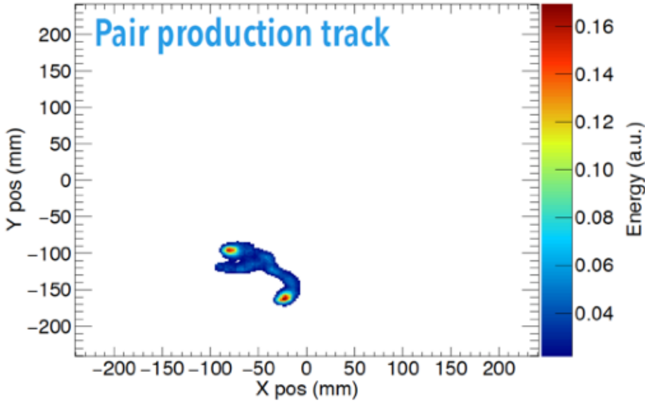


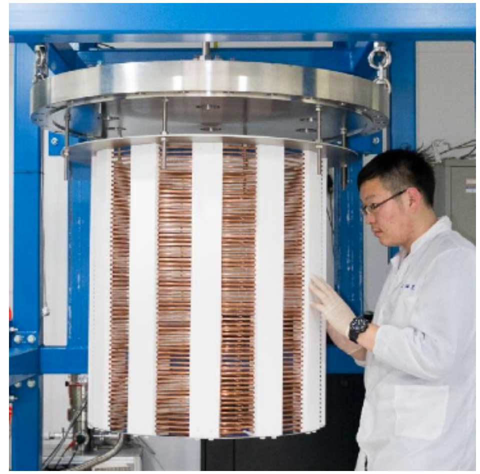


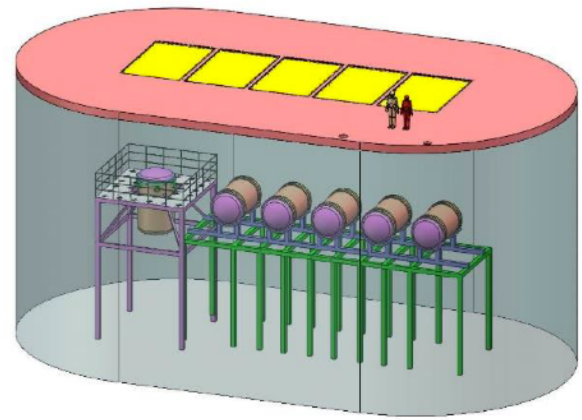


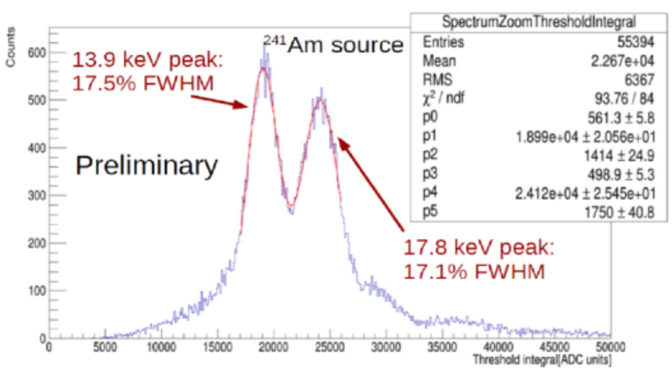
A. ESTÉVEZ, TAUP 2017

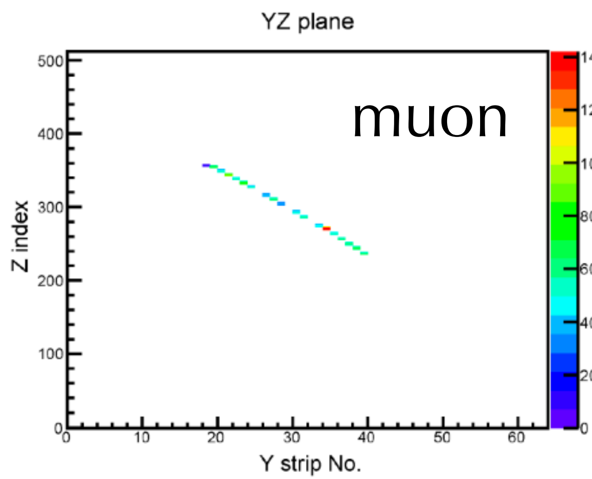
Tracking Detectors to Watch

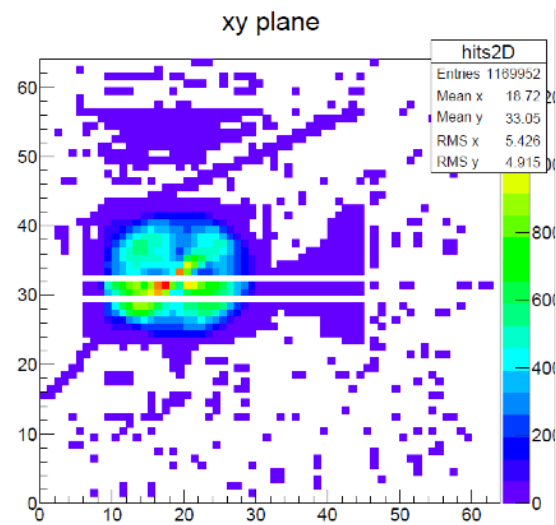
- PandaX-III
  - High-pressure gas TPC
  - 5 x 200 kg 90% ^{enr}Xe
  - Alternative readout technology to NEXT
  - Will be located at CJPL-II









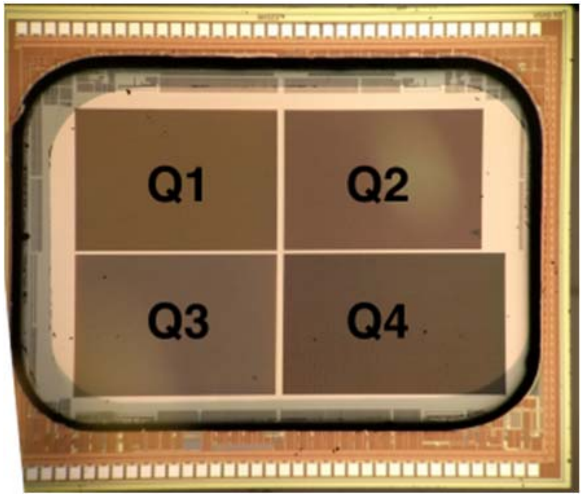


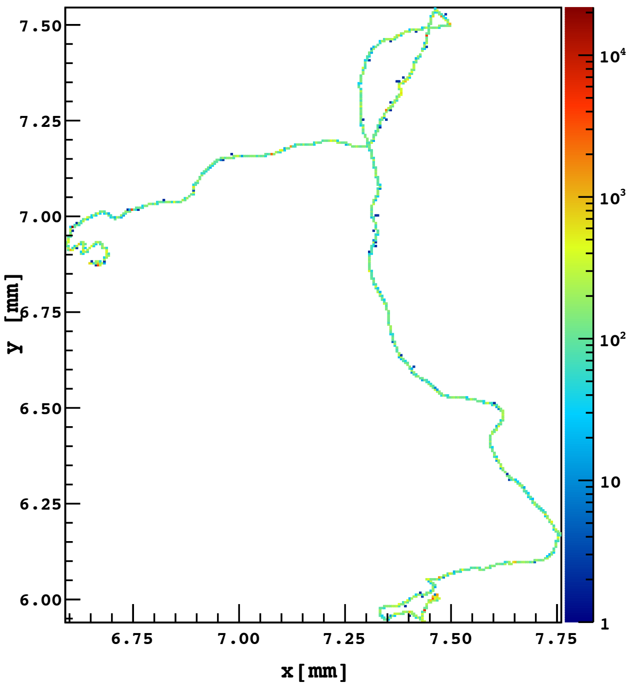
α source

K. Han, TAUP 2017

Tracking Detectors to Watch

- SELENA
  - ^{82}Se high-$Q_{\beta\beta}$ (3.0 MeV): above natural radioactivity
  - Build on existing technology of amorphous Se (aSe) large-area medical flat panel imagers: Develop a CMOS pixel array interfaced with aSe
  - High pixel pitch and low pixel noise will allow to image ββ decay tracks from ^{82}Se decay in the aSe layer with high resolution
  - Stack towers of detectors to get to high mass
  - R&D getting started at UW (Chavarria)

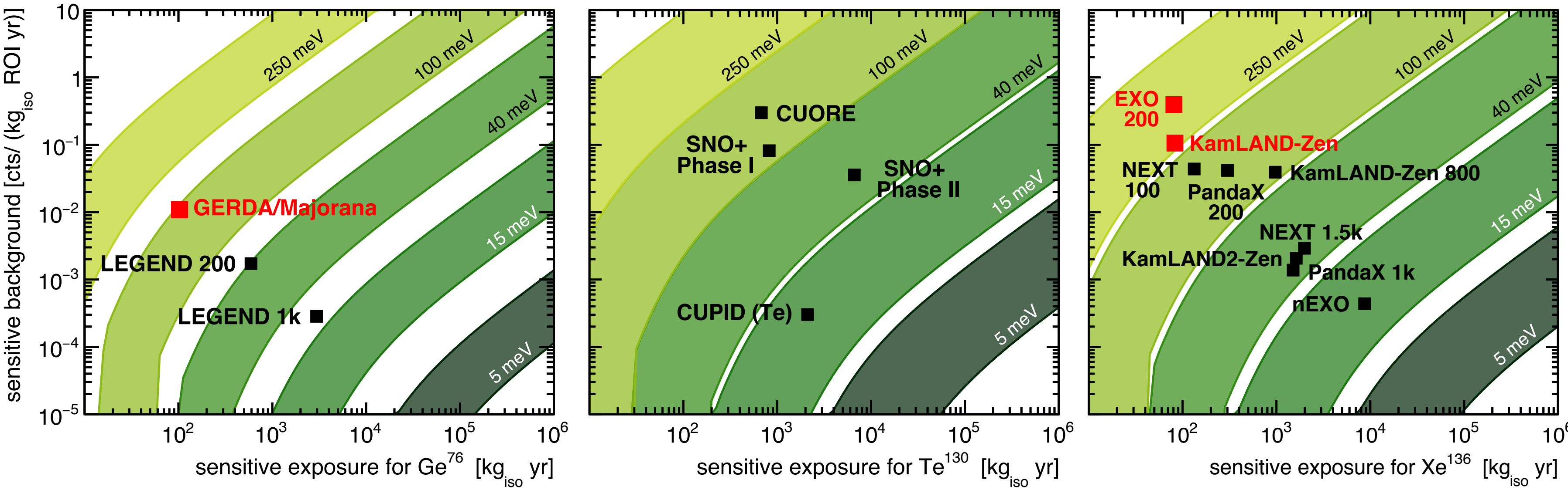




Outline

- Introduction to $0\nu\beta\beta$ experiments
- Status of current leaders
- Prospects for next-generation experiments

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

PRD **96** 053001 (2017).

Discovery Probability

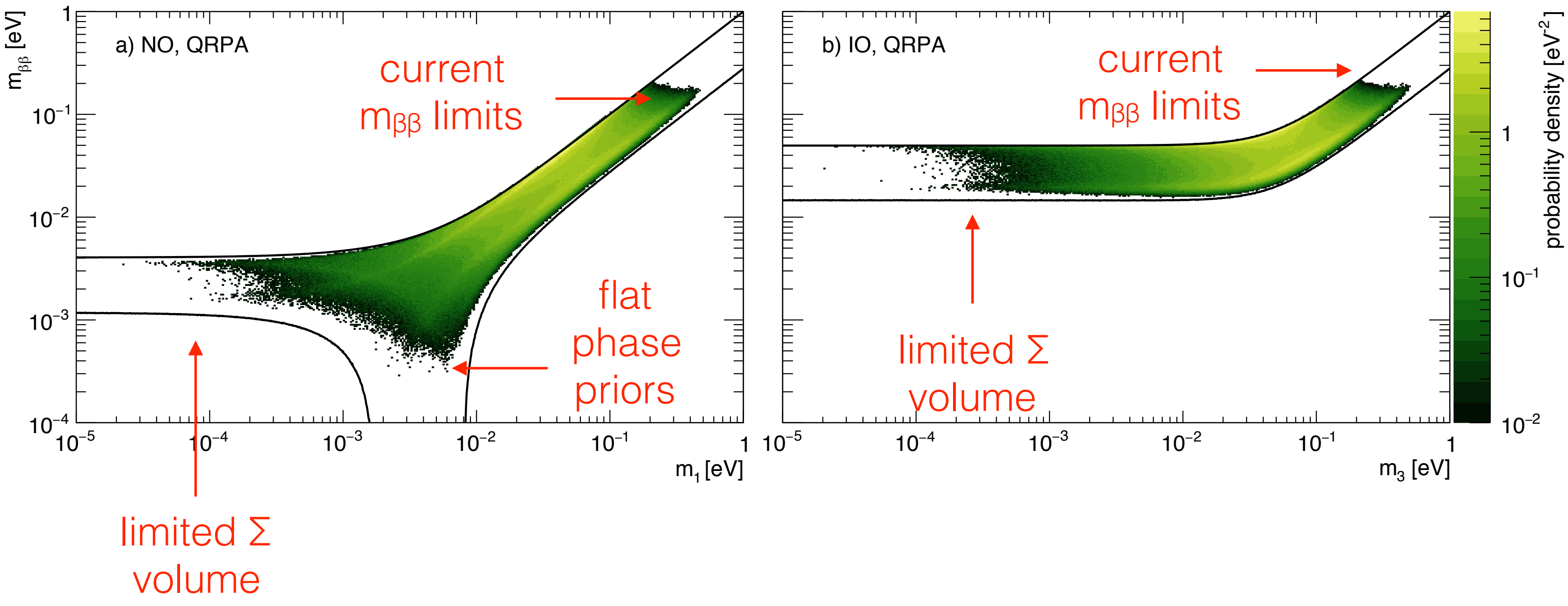
What are the chances that these next-generation experiments will make a discovery? How much should humanity invest in 0νββ?

- 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



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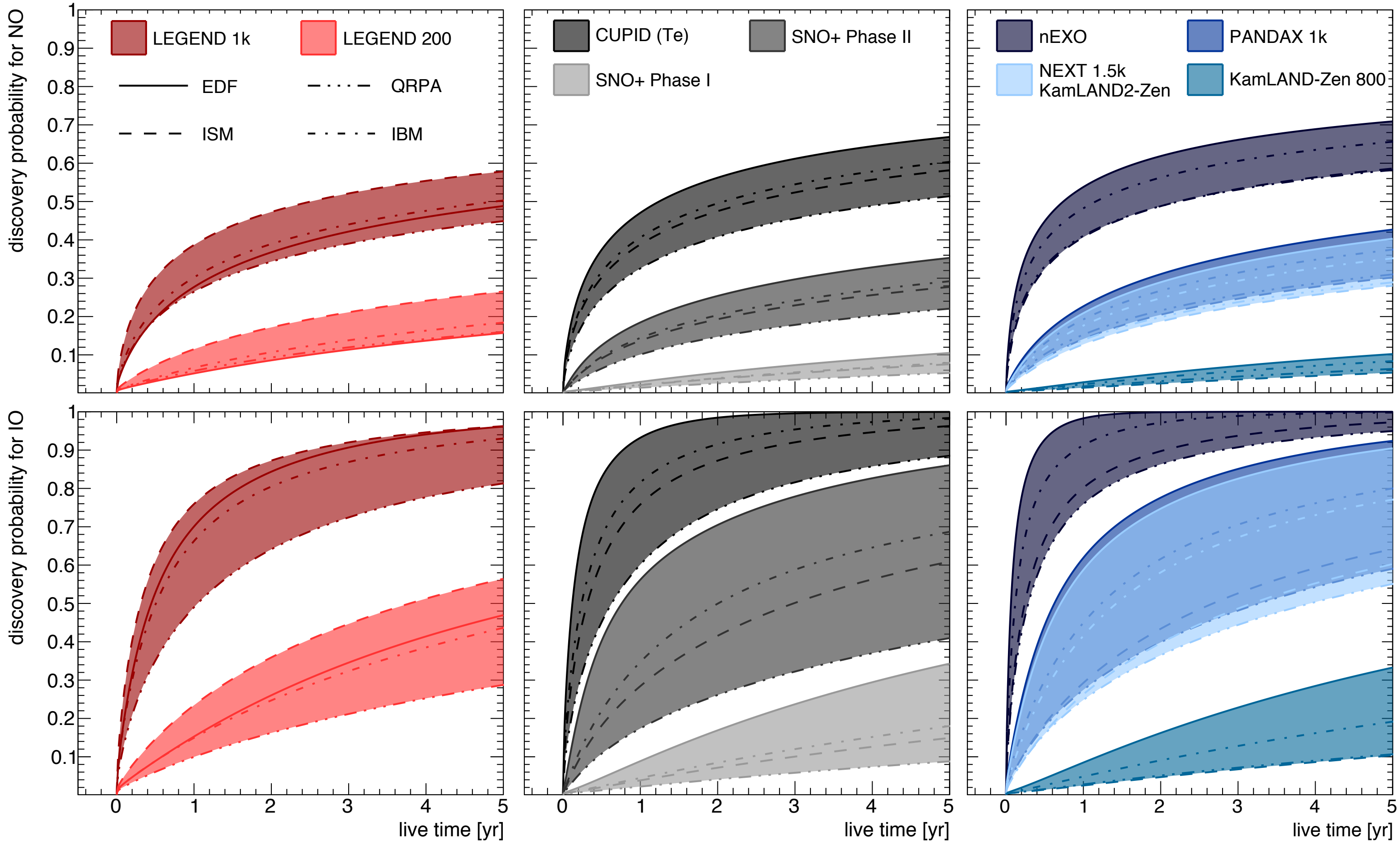
Discovery Probabilities

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



PRD **96** 053001 (2017).

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 mββ 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.

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

Summary

- Promising future 0nbb experiments must have high sensitive exposure with low sensitive background.
- Proposed experiments balance exposure, background using different techniques in different nuclei with different systematics
- These experiments have good discovery probability: discovery may be just around the corner!