Neutrinoless Double Beta Decay: Status

Los Alamos NATIONAL LABORATORY

Steve Elliott

PHYSICS SINCE 1943

TRI-INSTITUTE SUMMER SCHOOL ON ELEMENTARY PARTICLES

PI • SNOLAB • TRIUMF

TRISEP

History
R&D Landscape
Upcoming Experimental Status

3ν Scenario and LNV are Prime Motivation

- For a 3 ν, inverted ordering scenario, there is an obvious sensitivity target (~15 meV or ~$10^{27/28}$ y). This target has motivated the design specifications for the next generation ββ experiments.
  - The 15-meV target scale is also motivated by anticipated technical capability (background levels and detector size).

- Over the coming decade anticipated physics results could alter this 'standard IO scenario'.
  - Still, the need to test LNV motivates going to ever longer half-lives.

Potential Future Experimental Results
$\beta\beta$ will still be a critical program, no matter the answers

Technique	Result	$\beta\beta$ Influence
Oscillations	Θ_{12} Measured	Would better define boundaries of IO/NO bands. That would be good for $\beta\beta$.
Oscillations	Mass ordering determined	Inverted order with 3 ν's might become irrelevant. Even so, the NO branch still extends to high $m_{\beta\beta}$ values. LNV processes other than light ν aren't constrained by oscillations. Significance of IO exclusion still rather low.
LHC	Heavy ν or LR symmetry found	The result would be complementary to $\beta\beta$. It would be an interesting test of the underlying physics if both techniques saw an effect.
Cosmology	Σm_ν constrained <100 meV	Cosmology does not discern Majorana/Dirac character. A 3ν NO scenario with Σ near its minimum would not constrain other potential LNV processes that might contribute to $\beta\beta$. Importantly, laboratory measurements will help resolve tensions/degeneracies in cosmology.
Short Baseline Oscillation	Sterile ν discovered	If a 4th ν is seen, it fits the Majorana ν paradigm, increasing $\beta\beta$ interest. The new ν might contribute to $\beta\beta$ and significantly alter predicted $m_{\beta\beta}$ curves. The accessible sensitivity regions remain.
β decay	m_β measured	Would make the observation/non-observation of $\beta\beta$ even more exciting. Null $\beta\beta$ result might indicate Dirac ν.

Complementarity of $0\nu\beta\beta$ and Cosmology

- The ΛCDM model has become a ‘standard model’ for cosmology. Within the next decade, observations will have sensitivity to neutrino mass below the IO boundary.
- The most restrictive m_ν limits arise from fitting the largest variety of input cosmology data with the ΛCDM parameters.
- However, ΛCDM has components that are not yet fully understood.
  - –What mechanism leads to inflation?
  - –What components comprise the dark matter?
  - –What is dark energy?
  - –There is tension in the values for H_0 derived from different data sets.
- As a standard model with significant unknowns, all tests of ΛCDM must be considered.
- Neutrino mass is one parameter of ΛCDM that can be measured in the laboratory and hence provides a crucial test of ΛCDM.
- $0\nu\beta\beta$ and direct m_ν experiments should be considered a component of cosmology.
- Additionally, cosmology measurements do not test lepton number violation or the Majorana/Dirac character of neutrinos.

$\beta\beta$ History

- $2\nu\beta\beta$ rate first calculated by Maria Goeppert-Mayer in 1935.
- First observed directly in 1987.
- Why did this take so long? Background

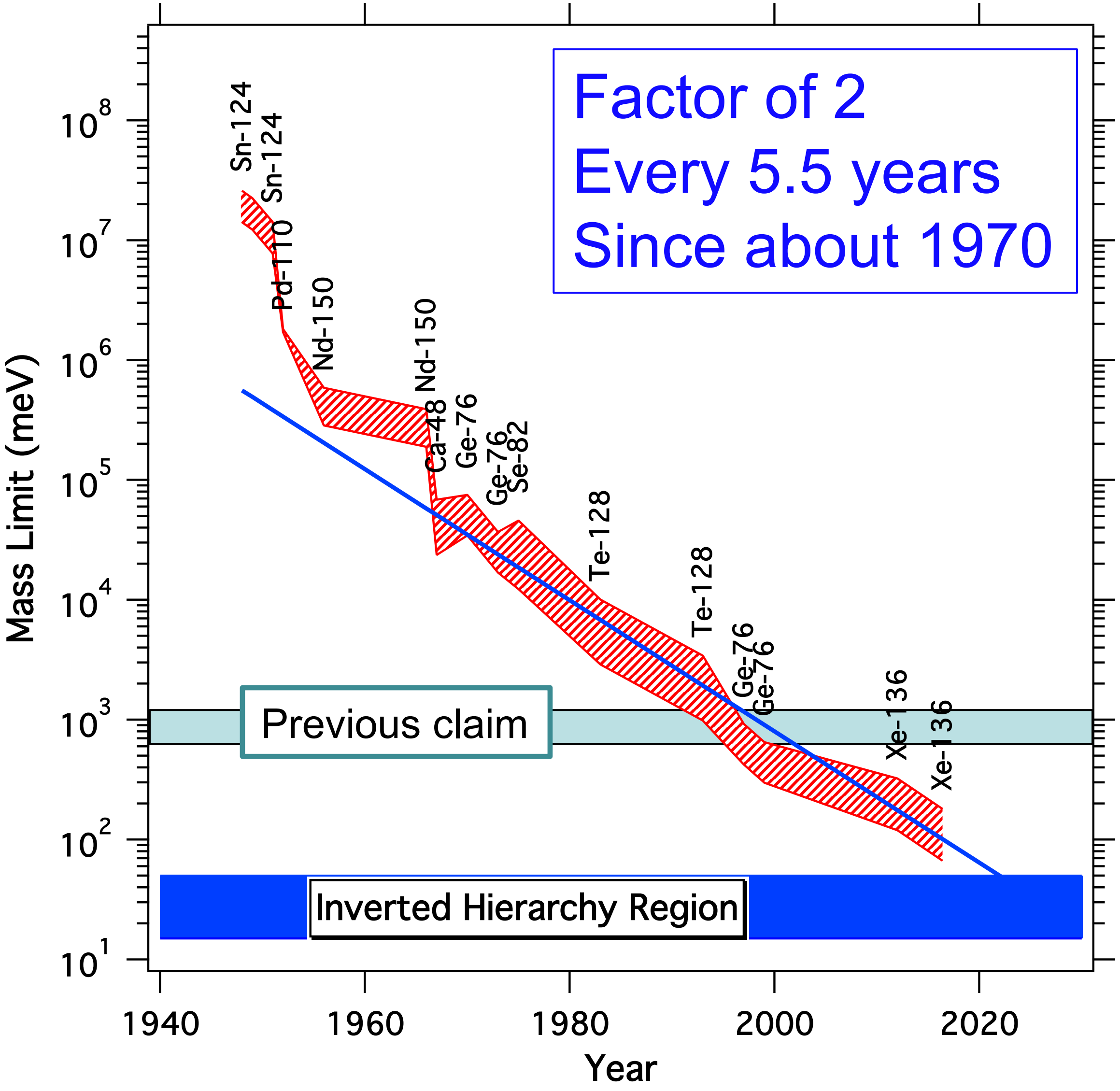
$$\tau_{1/2}(\mathrm{U, Th}) \sim T_{\mathrm{universe}}$$

$$\tau_{1/2}(2\nu\beta\beta) \sim 10^{10}\ T_{\mathrm{universe}}$$

- But next we want to look for a process with:

$$\tau_{1/2}(0\nu\beta\beta) \sim 10^{18}\ T_{\mathrm{universe}}$$

ββ History: Moore's law of 0νββ



Historically, there are > 100 experimental limits on the $T_{1/2}$ of 0νββ. Here are the best constraints expressed as limits on $\langle m_{\beta\beta} \rangle$ using a range of nuclear matrix elements. Note the approximate linear slope vs. time on a semi-log plot.

By 2021, Xe and Ge provided about equal exclusion levels, although Ge is more direct at excluding claim, which is now discredited.

2νββ Results

There are a lot of measurements now. Most are ground state to ground state transitions. Some excited state results, and ECEC.

Second order weak interaction. Hence long half lives.

Fantastic progress. All help with matrix element work.

Table 3. Half-life and effective nuclear matrix element values for $2\nu\beta\beta$ decay (see Section 4).

Isotope	$T_{1/2}(2\nu)$, yr	$\mid M_{2\nu}^{eff} \mid$ ($G_{2\nu}$ from [25])	$\mid M_{2\nu}^{eff} \mid$ ($G_{2\nu}$ from [26])	Recommended Value
$2\nu\beta\beta$:				
^{48}Ca	$5.3^{+1.2}_{-0.8} \cdot 10^{19}$	$0.0348^{+0.0030}_{-0.0034}$	$0.0348^{+0.0030}_{-0.0034}$	0.035 ± 0.003
^{76}Ge	$(1.88 \pm 0.08) \cdot 10^{21}$	$0.1051^{+0.0023}_{-0.0024}$	$0.1074^{+0.0024}_{-0.0022}$	0.106 ± 0.004
^{82}Se	$0.87^{+0.02}_{-0.01} \cdot 10^{20}$	$0.0849^{+0.0005}_{-0.0010}$	$0.0855^{+0.0005}_{-0.0010}$	0.085 ± 0.001
^{96}Zr	$(2.3 \pm 0.2) \cdot 10^{19}$	$0.0798^{+0.0037}_{-0.0032}$	$0.0804^{+0.0038}_{-0.0033}$	0.080 ± 0.004
^{100}Mo	$7.06^{+0.15}_{-0.13} \cdot 10^{18}$	$0.2071^{+0.0019}_{-0.0022}$	$0.2096^{+0.0020}_{-0.0022}$	
		$0.1852^{+0.0017}_{-0.0019}$ (a)		0.185 ± 0.002
^{100}Mo-^{100}Ru(0^+_1)	$6.7^{+0.5}_{-0.4} \cdot 10^{20}$	$0.1571^{+0.0048}_{-0.0056}$	$0.1619^{+0.0050}_{-0.0058}$	
		$0.1513^{+0.0047}_{-0.0053}$ (a)		0.151 ± 0.005
^{116}Cd	$(2.69 \pm 0.09) \cdot 10^{19}$	$0.1160^{+0.0020}_{-0.0019}$	$0.1176^{+0.0020}_{-0.0019}$	
		$0.1084^{+0.0024}_{-0.0019}$ (a)		0.108 ± 0.003
^{128}Te	$(2.25 \pm 0.09) \cdot 10^{24}$	$0.0406^{+0.0008}_{-0.0008}$	$0.0454^{+0.0009}_{-0.0009}$	0.043 ± 0.003
^{130}Te	$(7.91 \pm 0.21) \cdot 10^{20}$	$0.0288^{+0.0004}_{-0.0004}$	$0.0297^{+0.0004}_{-0.0004}$	0.0293 ± 0.0009
^{136}Xe	$(2.18 \pm 0.05) \cdot 10^{21}$	$0.0177^{+0.0002}_{-0.0002}$	$0.0184^{+0.0002}_{-0.0002}$	0.0181 ± 0.0006
^{150}Nd	$(9.34 \pm 0.65) \cdot 10^{18}$	$0.0543^{+0.0020}_{-0.0018}$	$0.0550^{+0.0020}_{-0.0018}$	0.055 ± 0.003
^{150}Nd-^{150}Sm(0^+_1)	$1.2^{+0.3}_{-0.2} \cdot 10^{20}$	$0.0438^{+0.0042}_{-0.0046}$	$0.0450^{+0.0043}_{-0.0048}$	0.044 ± 0.005
^{238}U	$(2.0 \pm 0.6) \cdot 10^{21}$	$0.1853^{+0.0361}_{-0.0227}$	$0.0713^{+0.0139}_{-0.0088}$	$0.13^{+0.09}_{-0.07}$
ECEC(2ν):				
^{78}Kr (b)	$1.9^{+1.3}_{-0.8} \cdot 10^{22}$	$0.2882^{+0.0829}_{-0.0706}$ [106]	$0.3583^{+0.1126}_{-0.0822}$	$0.32^{+0.15}_{-0.11}$
^{124}Xe (b)	$(1.8 \pm 0.5) \cdot 10^{22}$	$0.0568^{+0.0101}_{-0.0650}$ [106]	$0.0607^{+0.0107}_{-0.0070}$	$0.059^{+0.013}_{-0.009}$
^{130}Ba	$(2.2 \pm 0.5) \cdot 10^{21}$	$0.1741^{+0.0239}_{-0.0170}$ [106]	$0.1754^{+0.0241}_{-0.0171}$	$0.175^{+0.024}_{-0.017}$

(a) Obtained using the SSD model. (b) Value for 2K capture. For the ECEC process, the half-life value will be approximately 15–20% less, and the NME value approximately 7–10% higher.

Universe 6 (2020) 159, arXiv:2009.14451

$0\nu\beta\beta$ Results

Isotope	Technique	$T^{0\nu}_{1/2}$	$\langle m_{\beta\beta}\rangle$ (eV)	
^{48}Ca	CaF_2 scint. crystals	$> 5.8 \times 10^{22}$ y	<3.5-22	PRC 78 (2008) 058501
^{76}Ge	^{enr}Ge det.	$> 1.8 \times 10^{26}$ y	<0.079-0.180	PRL 125 (2020) 252502
^{82}Se	Thin metal foils and tracking	$> 3.2 \times 10^{23}$ y	<0.94-1.71	AIP proc1417 (2011) 125
^{100}Mo	Thin metal foils and tracking	$> 1.0 \times 10^{24}$ y	<0.47-0.96	AIP proc1417 (2011) 125
^{116}Cd	$^{116}CdWO_4$ scint. crystals	$> 1.7 \times 10^{23}$ y	<1.7	PRC 68 (2003) 035501
^{128}Te	geochemical	$> 7.7 \times 10^{24}$ y	<1.1-1.5	PRC 47 (1993) 806
^{130}Te	TeO_2 bolometers	$> 2.2 \times 10^{25}$ y	<0.090-0.305	arXiv:2104.06906
^{136}Xe	Liq. Xe scint.	$> 1.07 \times 10^{26}$ y	<0.061-0.165	PRL 117 (2016) 082503
^{150}Ne	Thin metal foil within TPC	$> 1.8 \times 10^{22}$ y	N.A.	PAN 74 (2011) 312

Again fantastic progress. Technologies advancing quickly and soon will cover IO.

Lots of R&D Efforts Based on Many Isotopes

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III	^{48}Ca	300 kg	CaF_2 scint. crystals	Operating	Kamioka
GERDA	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Complete	LNGS
MAJORANA	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Operating	SURF
CDEX-1T	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Prototype	CJPL
LEGEND-200	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Construction	LNGS
LEGEND-1000	^{76}Ge	ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0	^{82}Se	5 kg	Zn^{enr}Se scintillating bolometers	Prototype	LNGS
SuperNEMO-Dem	^{82}Se	7 kg	^{enr}Se foils/tracking	Construction - 2019	Modane
SuperNEMO	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
CMOS Imaging	^{82}Se		^{enr}Se, CMOS	Development	
AMoRE-Pilot	^{100}Mo	1 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Operation	YangYang
AMoRE-I	^{100}Mo	6 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Construction - 2019	YangYang
AMoRE-II	^{100}Mo	200 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Construction - 2020	Yemi
CROSS	^{100}Mo	5 kg	Li$_2$^{100}MoO$_4$ surface coated Bolometers	Construction - 2020	Canfranc
LUMINEU	^{100}Mo		Li^{enr}MoO$_4$, Zn^{enr}MoO$_4$ scint. bolometers	Development	LNGS, LSM
China-Europe	^{116}Cd		^{enr}CdWO$_4$ scintillating crystals	Development	CJPL
Aurora	^{116}Cd	1 kg	^{enr}CdWO$_4$ scintillating crystals	Development	LNGS
COBRA-dem	^{116}Cd	0.38 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Tin.Tin	^{124}Sn	1 kg	Tin bolometers	Development	INO
CALDER	^{130}Te		TeO_2 bolometers with Cerenkov Light	Development	LNGS
CUORE	^{130}Te	1 ton	TeO_2 bolometers	Operating	LNGS
SNO+	^{130}Te	1.3 t	0.5% ^{enr}Te loaded liq. scint.	Commissioning	SNOLab
nEXO	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100	^{136}Xe	100 kg	gas TPC	Prototype	Canfranc
AXEL	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen	^{136}Xe	800 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
LZ	^{136}Xe		Dual phase Xe TPC	Construction - 2020	SURF
PANDAX-III	^{136}Xe	1 ton	Dual phase Xe TPC	Construction - 2019	CJPL
XENON1T	^{136}Xe	1 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
NuDot	Various		Cherenkov and scint. detection in liq. scint.	Development	
FLARES	Various		Scint. crystals with Si photodetectors	Development	

- **Signal near the inverted ordering scale is about 1/(t yr) or less.**
- **To reach IO scale need background lower than that.**

PHYSICS SINCE 1943 Los Alamos NATIONAL LABORATORY

Isotope Choice is Critical

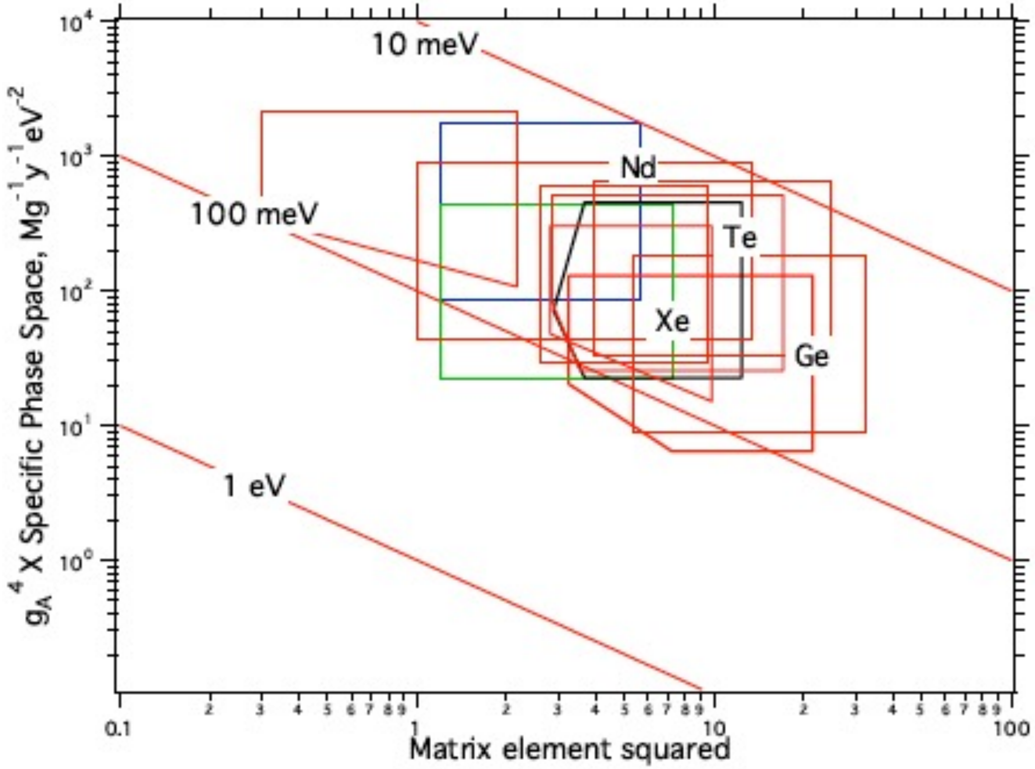
$$MT = (2.50 \times 10^{-5} meV)^2 \frac{NW}{fx\epsilon G_{0\nu}} \left(\frac{1}{\langle m_{\beta\beta} \rangle M_{0\nu} {g_A}^2} \right)^2$$

$$N = \sqrt{B} = \sqrt{b\Delta EMT} \text{ background limited}$$

Many authors ignore:
f, x, ε, W
when comparing isotopes

All isotopes are roughly comparable.

Robertson Mod. Phys. Lett. A, **28** (2013) 1350021



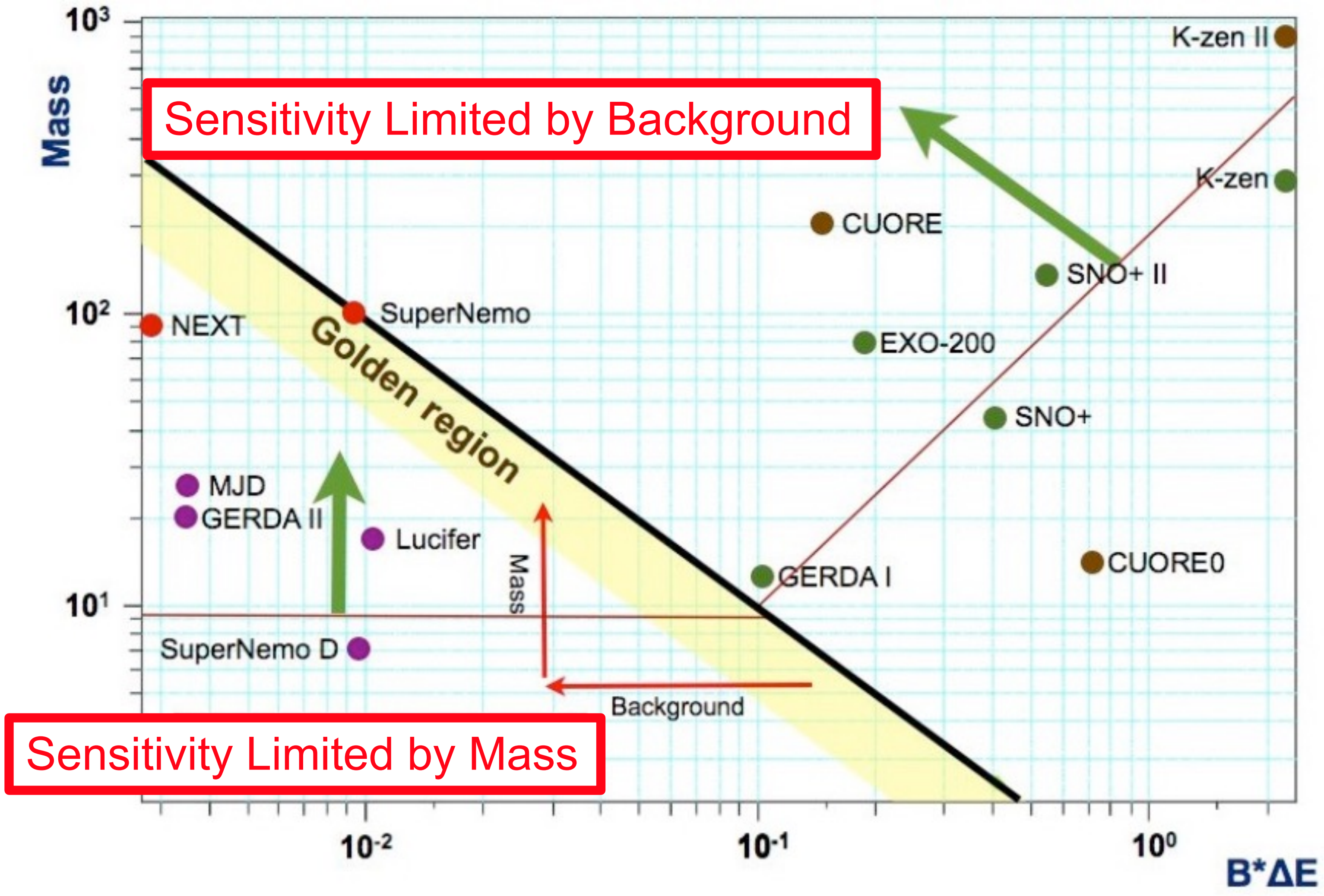
Signal / Background - reminder
Background is a key issue in ββ

Half life (years)	~Signal (cnts/ton-year)	~Neutrino mass scale (meV)	
10^{25}	530	400	Degenerate
$5\text{x}10^{26}$	10	100	
$5\text{x}10^{27}$		40	Atmospheric, IO
$>10^{29}$	<0.05	<10	Solar, NO

To reach atmospheric scale need BG better than 1/t-y.

The "Mass vs. Background" Plot

NP B (proc suppl) 237 (2013) 7



$$\langle m_{\beta\beta} \rangle \sim \left[\frac{MT}{B\Delta E} \right]^{\frac{1}{4}}$$

<u>Optimization</u>

Increase M

Decrease B

Improve ΔE

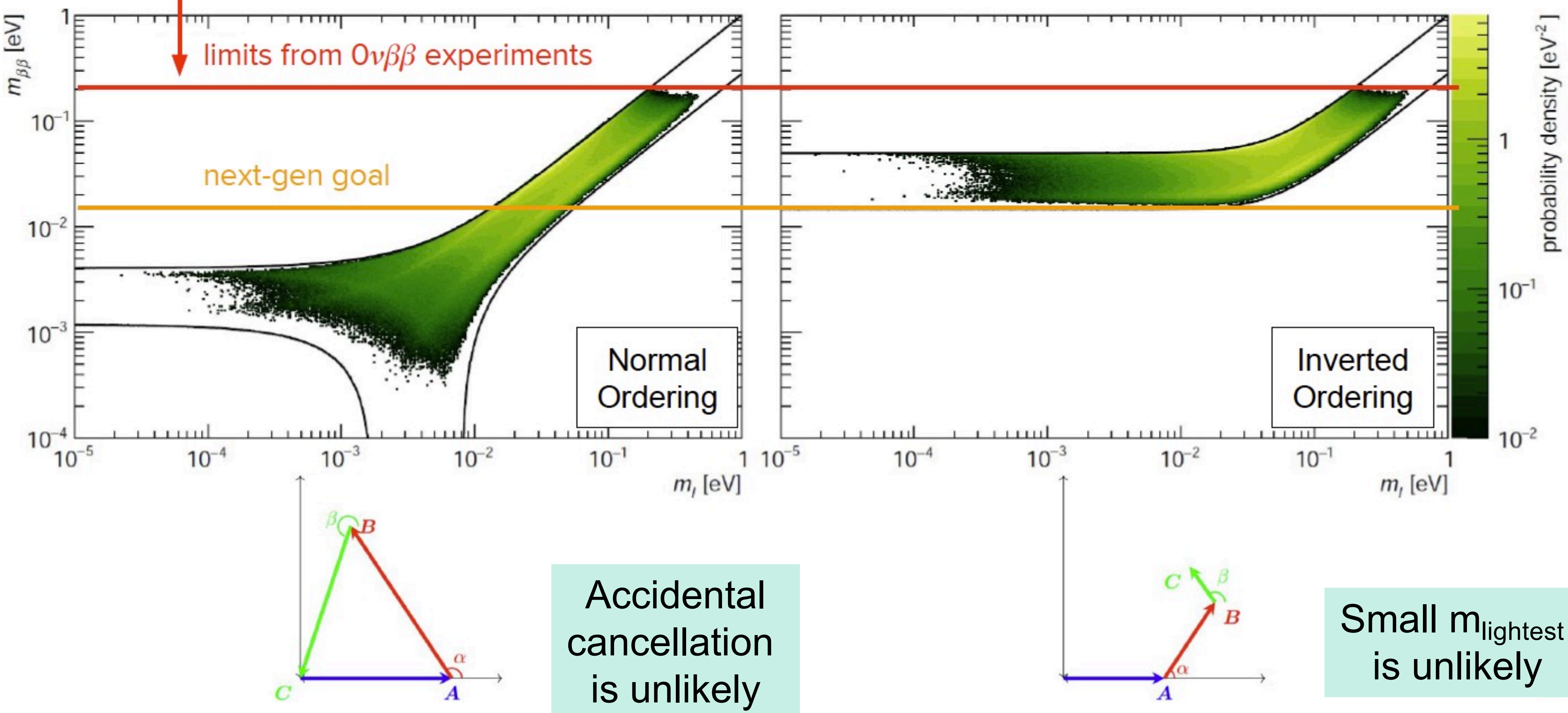
Frequently these are in tension.

Note 'golden' region where it becomes 'nearly' background free

Phase Space for Discovery

Very encouraging for ton scale projects

[M. Agostini, G. Benato, J Detwiler, et a., PRD 96, 053001 (2017)]



Accidental cancellation is unlikely

Small $m_{lightest}$ is unlikely

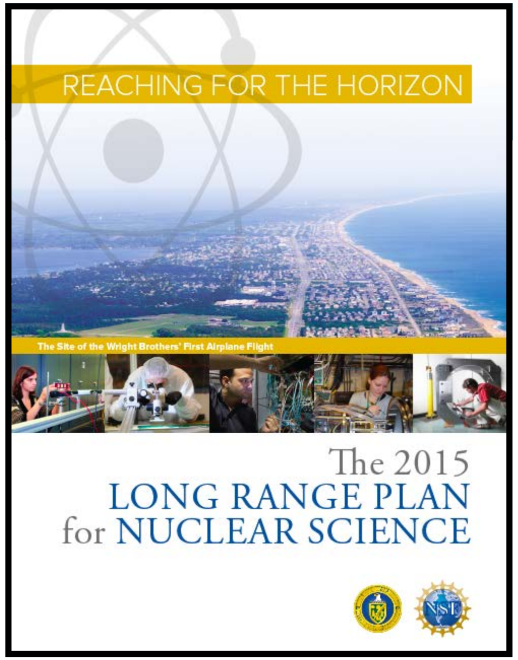
The need for several $\beta\beta$ experiments

- With limited statistics, the signature of a small peak on a continuum background is not so distinct. Multiple results will help prove observation.
- Different isotopes studied with different techniques have different systematic uncertainties.
- Different $\beta\beta$ endpoints lead to different background conditions, especially in the case of unidentified γ lines.
- Different nuclear matrix elements have different uncertainties.
- Results from different isotopes can help unravel the underlying physics of the process.

The observation of lepton number violation would be convincing if detected in more than one isotope.

The 2015 NSAC Long-Range Plan

The US-DOE is looking to make a significant investment in $0\nu\beta\beta$



RECOMMENDATION II

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

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

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

NSAC Sub-Committee Recommendations April 2014

1. **Discovery potential**: Favor approaches that have a credible path toward reaching 3σ sensitivity to the effective Majorana neutrino mass parameter $m_{\beta\beta}$=15 meV within 10 years of counting, assuming the lower matrix element values among viable nuclear structure model calculations.
2. **Staging**: Given the risks and level of resources required, support for one or more intermediate stages along the maximum discovery potential path may be the optimal approach.
3. **Standard of proof**: Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal.
4. **Continuing R&D**: The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing NLDBD searches.
5. **International Collaboration**: Given the desirability of establishing a signal in multiple isotopes and the likely cost of these experiments, it is important to coordinate with other countries and funding agencies to develop an international approach.
6. **Timeliness**: It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.

US NSAC Subcommittee Science Assessment

Part of review and planning for ton-scale project

"…it is important to remember that NLDBD has a unique role in potentially addressing the issue of Dirac vs. Majorana nature of neutrinos. The Subcommittee remains convinced that the scientific case for pursuing NLDBD experiments at the ton-scale is very compelling."

Robert McKeown, NSAC meeting Oct. 2015

Review Schedule Presented in NSAC Presentation

Tim Hallman, March 18, 2021

- Ongoing interactions with potential international collaborators to introduce U.S. perspectives, hear European perspectives, and suggest a global approach to investment in DBD science

- DBD Portfolio Review will be held July 13-16, 2021 to inform U.S. investment strategy. Instructions published by April 15, 2021.

- North American – European Summit will be held September 27-29, 2021 to see if common ground exists for an international approach to DBD investment

- Funding for ton-scale $0\nu\beta\beta$ is going to be challenging

U.S. DEPARTMENT OF ENERGY | Office of Science   NSAC Meeting   March 18, 2021   10

Near-Term Upcoming Results

	Mass	Status
AMoRE-I	~3 kg	Running
CUORE	~200 kg	Running
EXO-200	~100 kg	Complete
GERDA I/II	~36 kg	Complete
KamLAND-Zen800	~750 kg	Running
MAJORANA	~30 kg	Complete
LEGEND-200	~200 kg	Construction-2021
NEXT	~100 kg	Construction-2022
SNO+	~120 kg	Commissioning-2022
SuperNEMO Dem.	~7 kg	Commissioning-2021

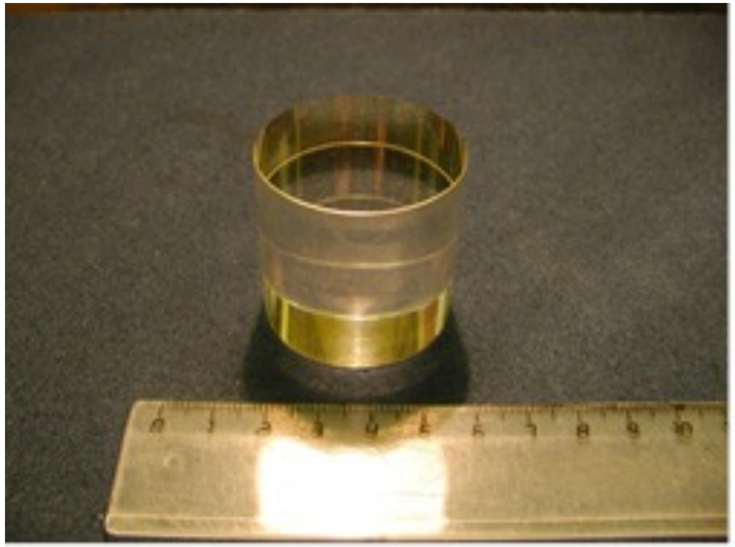
Experiments are beginning to reach below 100 meV.

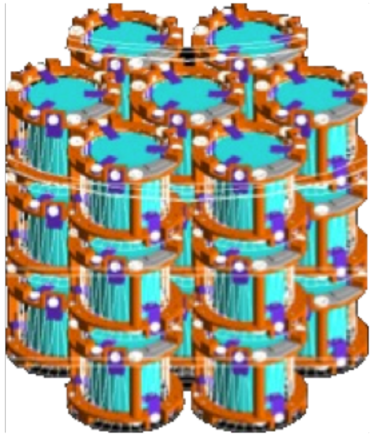
ββ technology is ready for detectors at the ton scale. At the ton scale, the IO is a convenient goalpost.

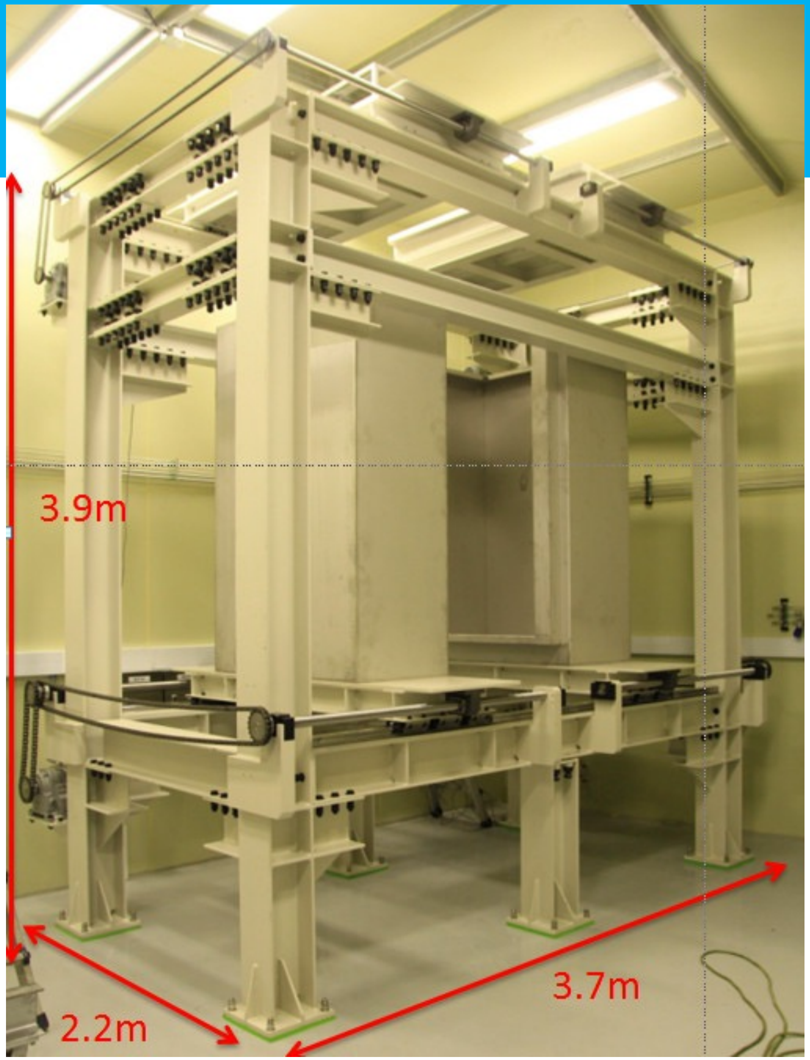
AMoRE (arXiv: 1512.05957)

Mo-100

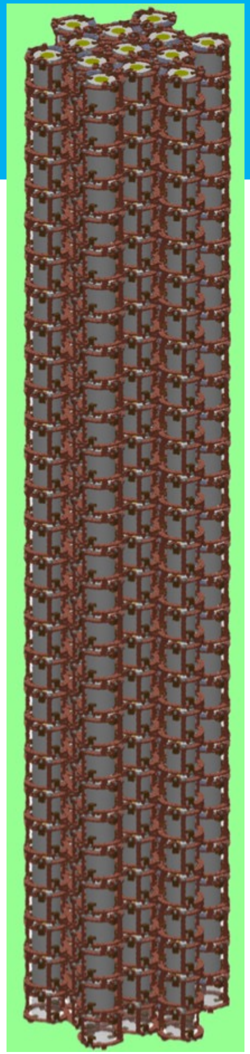
AMoRE-II
$^{48depl}Ca^{100}MoO_4$ crystals
Scintillating Bolometers
200 kg
Background 10^{-4}/(keV kg yr)
$\tau > 1.1 \times 10^{27}$ yr







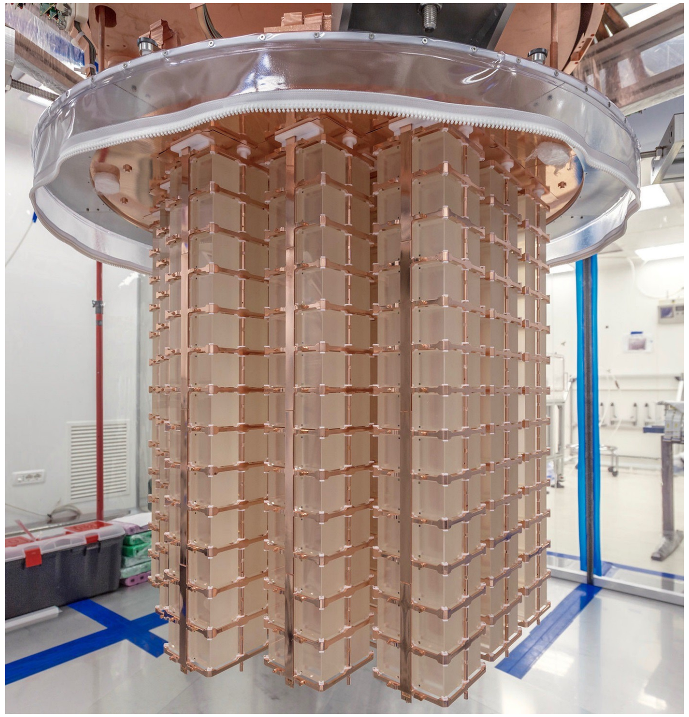
AMoRE-I
5 kg
Yangyang UG Lab



AMoRE-II
200 kg
Yemi UG Lab

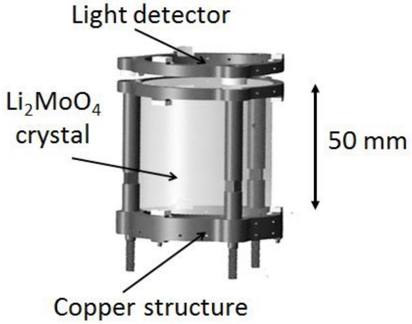
CUORE/CUPID (PRL 120 (2018) 132501,1907.0937)

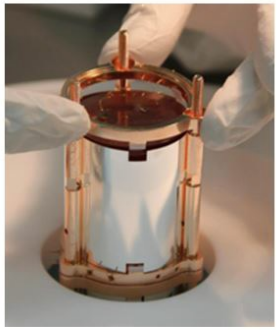
Te-130/Mo-100

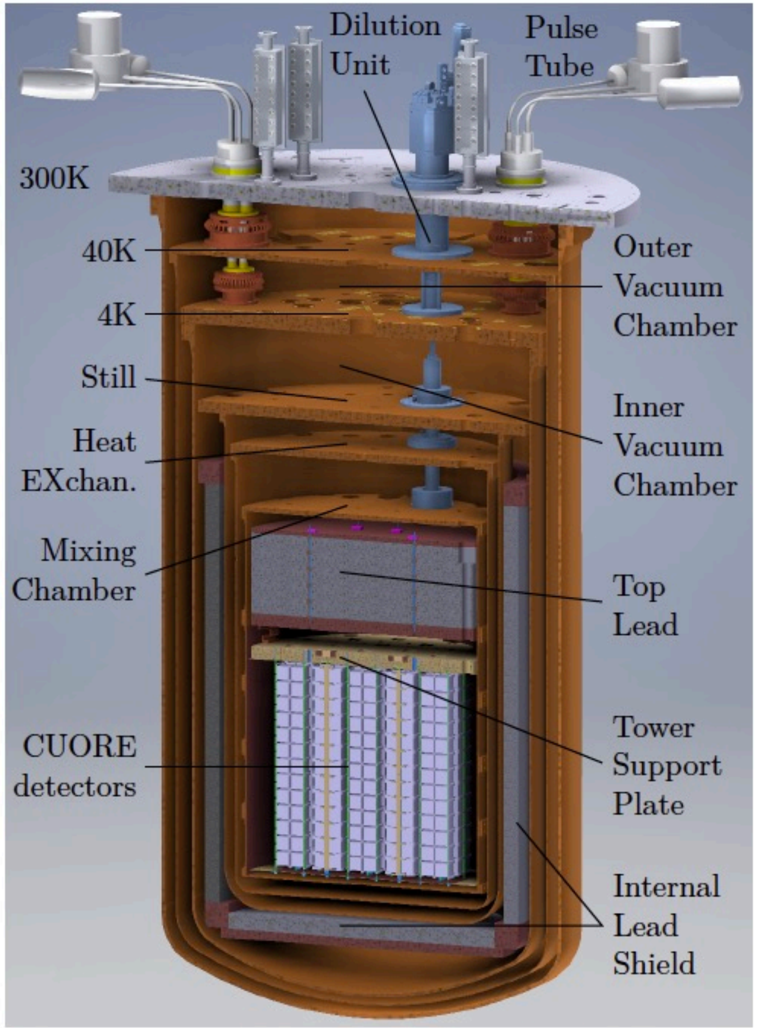


988 TeO_2 bolometers
742 kg of TeO_2
206 kg of ^{130}Te
Resolution, 5 keV at Q
Background estimate 0.01 c/(keV kg y)

1534 Li_2MoO_4 bolometers
472 kg of crystal
253 kg of Mo-100
Background 10^{-4}/(keV kg yr)
Discovery sensitivity 1.1×10^{27} yr

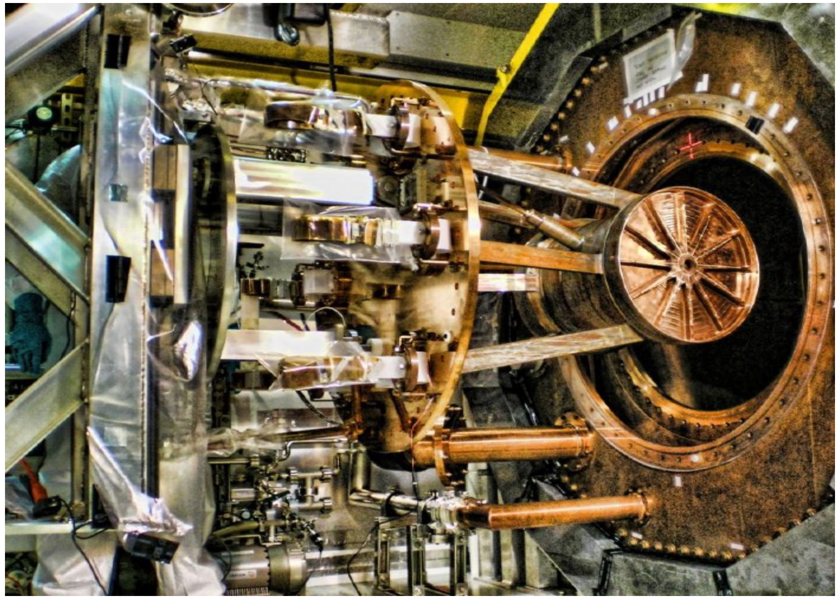






EXO-200 & nEXO (PRL 123, (2019) 161802, arXiv:1805.11142)

Xe-136



nEXO

~5 tonne LXe TPC

SNOLAB

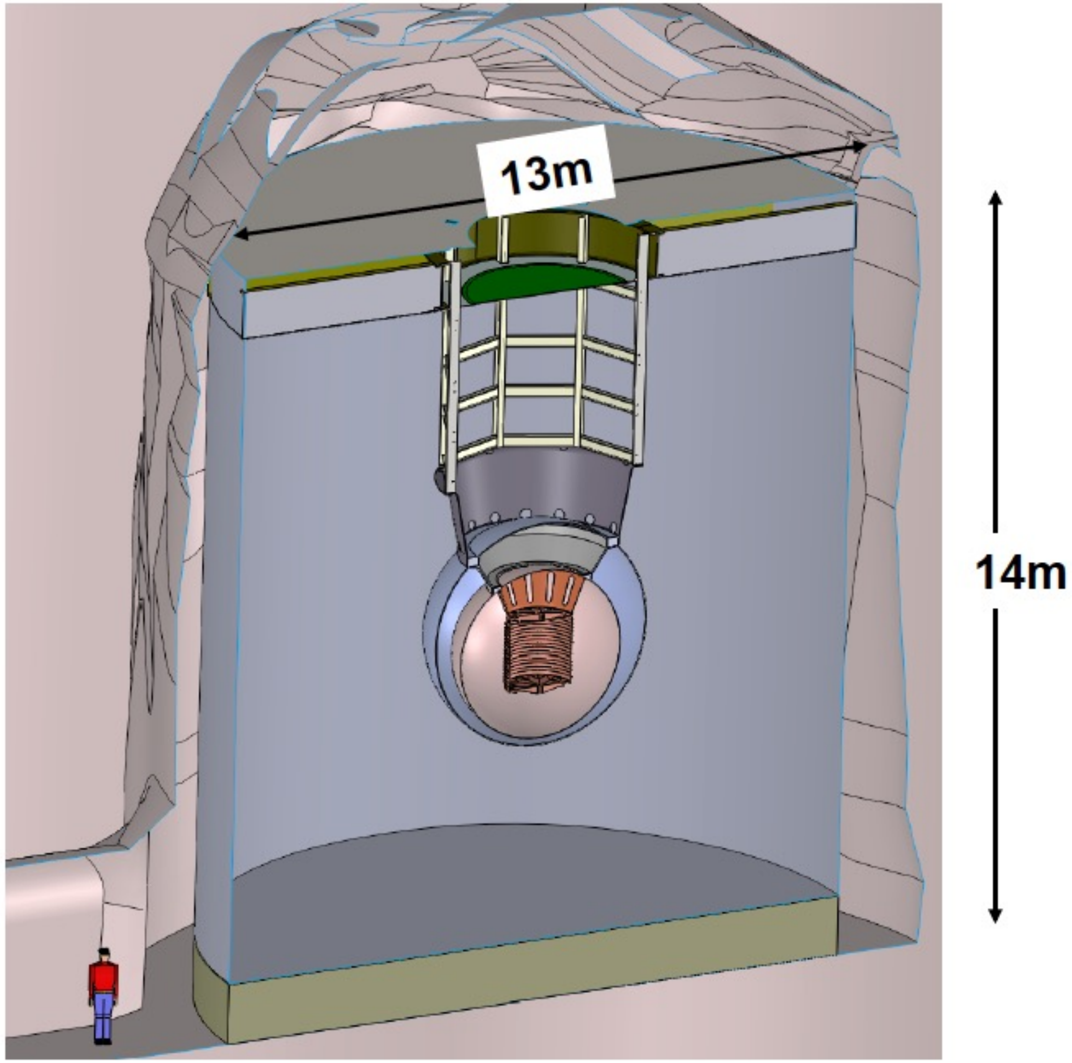
4.038 t active Xe

90% enrichment

<1% resolution

τ>9.210[27] yr

Potential daughter ID



EXO-200 @ WIPP

1.25% resolution

110 kg active Xe

234.1 kg yr

$T_{0\nu}$>3.5x10^{25} yr (90% CL)

LEGEND (arXiv:1709.01980, pCDR to be posted soon)
Ge-76

Mission: "The collaboration aims to develop a phased, **Ge-76 based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} 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.

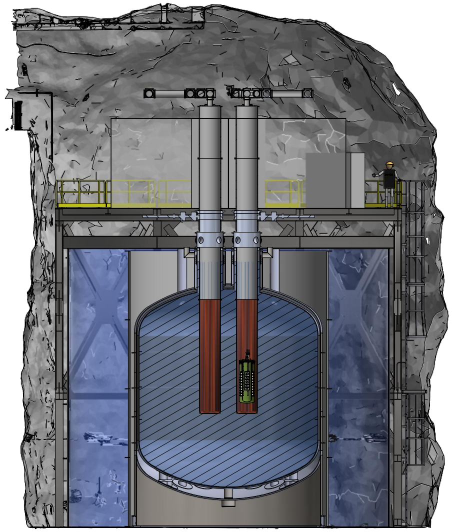
MAJORANA
- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics improves PSD
- Low energy threshold (helps reject cosmogenic background)

GERDA
- LAr veto
- Low-A shield
- no Pb

Both
- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- Lowest background and best resolution $0\nu\beta\beta$ experiments

LEGEND

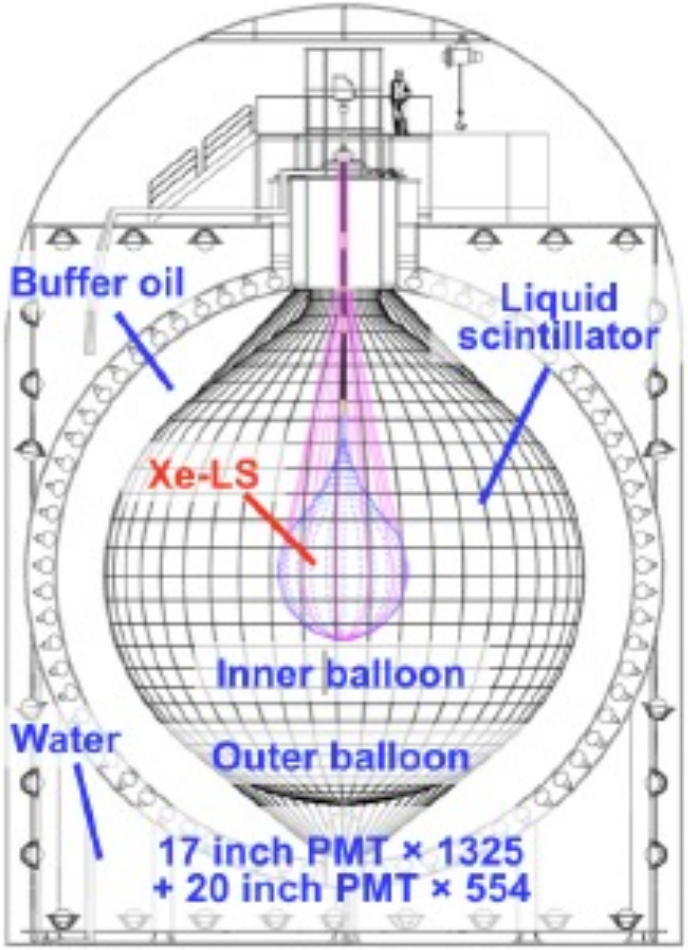
First phase:
- (up to) 200 kg in upgrade of existing infrastructure at LNGS
- BG goal: <0.6 c /(FWMH t y)
- Discovery sensitivity at a half-life of 10^{27} years
- Data start late 2021

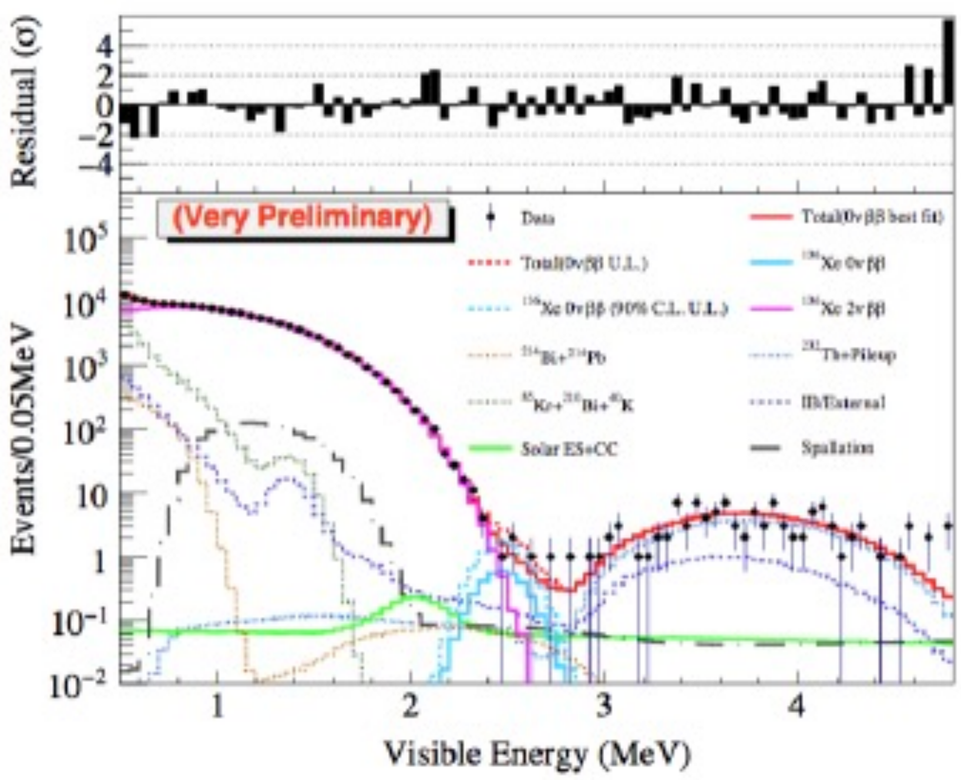


Subsequent stages:
- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal <0.03 cts/(FWHM t yr)
- Cover IO region
- Location to be selected

KamLAND-Zen (J. Phys.: Conf. Ser. 1468 012142)

Xe-136





Kamioka mine

KZ-400 $\tau > 1.07 \times 10^{26}$ yr

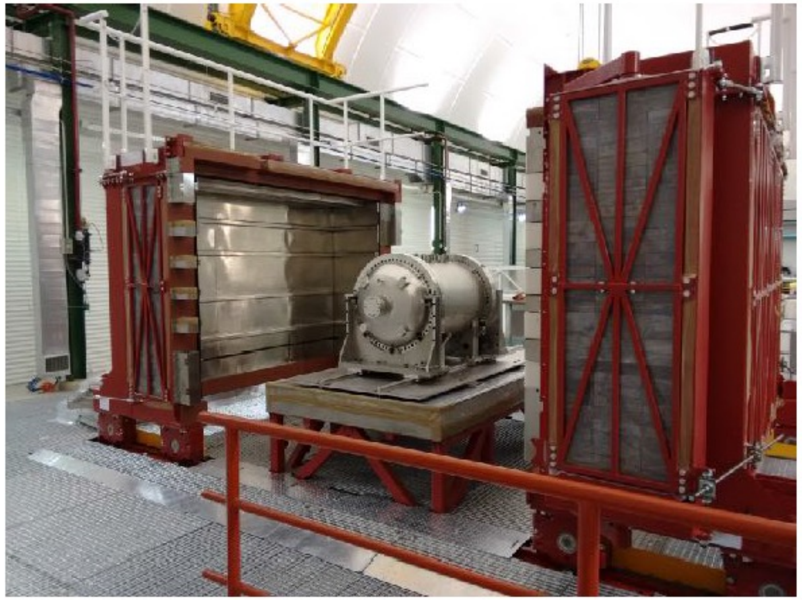
Xe loaded liquid scintillator

- 3.0% by weight
- 745 kg of Xe, 91% enriched

KZ-800 underway, with early results presented

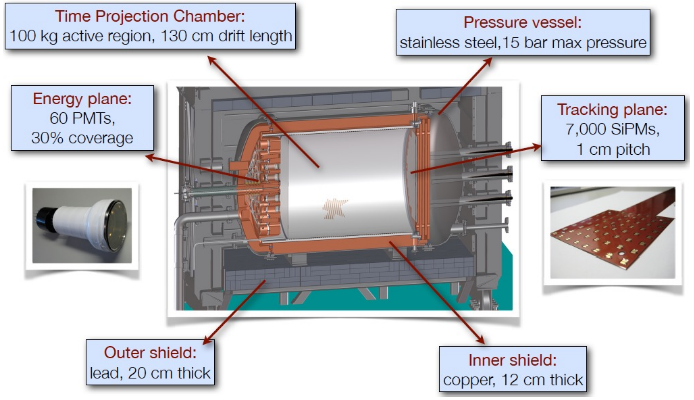
NEW & NEXT (arXiv:2005.06467)

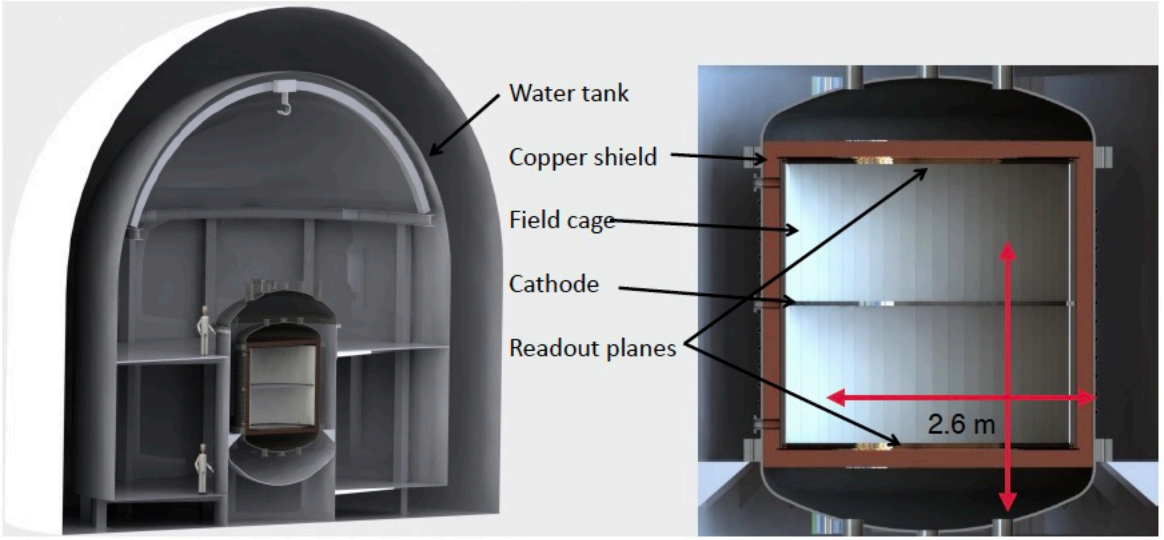
Xe-136



NEW, 1st stage of NEXT at LSC
Operating with initial resolution studies
10 kg Xe at 15 bar
54 cm of drift

NEXT-100 under preparation



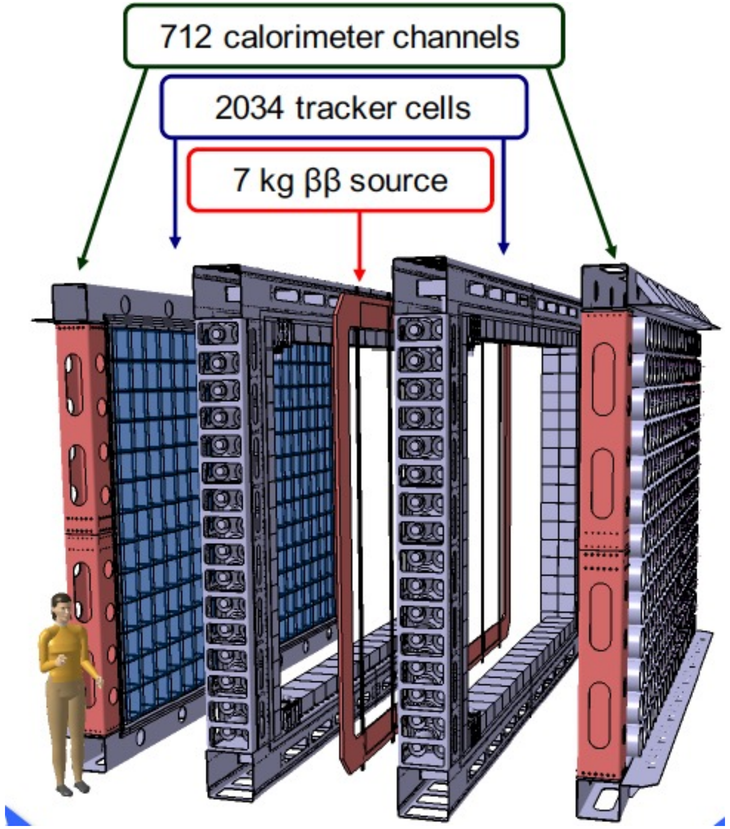


High pressure Xe gas, 15 bar
TPC for electron events
Bragg peak provides way to show two electron events
Expect resolution below 1% FWHM
Potential for daughter ID
Potential for kinematic data

1 ton Xe at 15 bar, t>10^{27} yr

SuperNEMO (arXiv:1504.08304)

Se-82



NEMO3
Operated 2003-11 at Modane
Various isotopes
Great $2\nu\beta\beta$ data
Track electrons, Kinematical data

SuperNEMO
Improve Rn levels, material purity and efficiency
1^{st} demonstrator module assembled
Physics runs later this year
SuperNEMO sensitivity 6.25-kg Se-82 $T_{0\nu}$>20^{26} y

SNO+ (arXiv:2104.11687)

Te-130

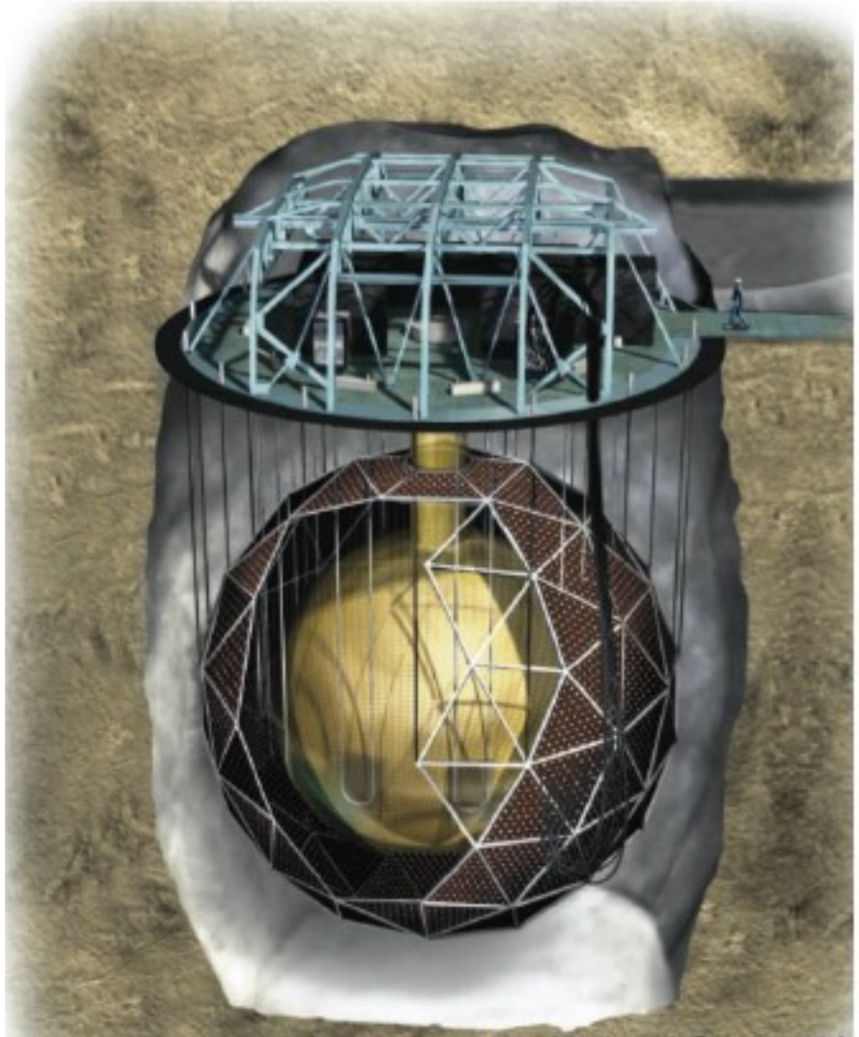
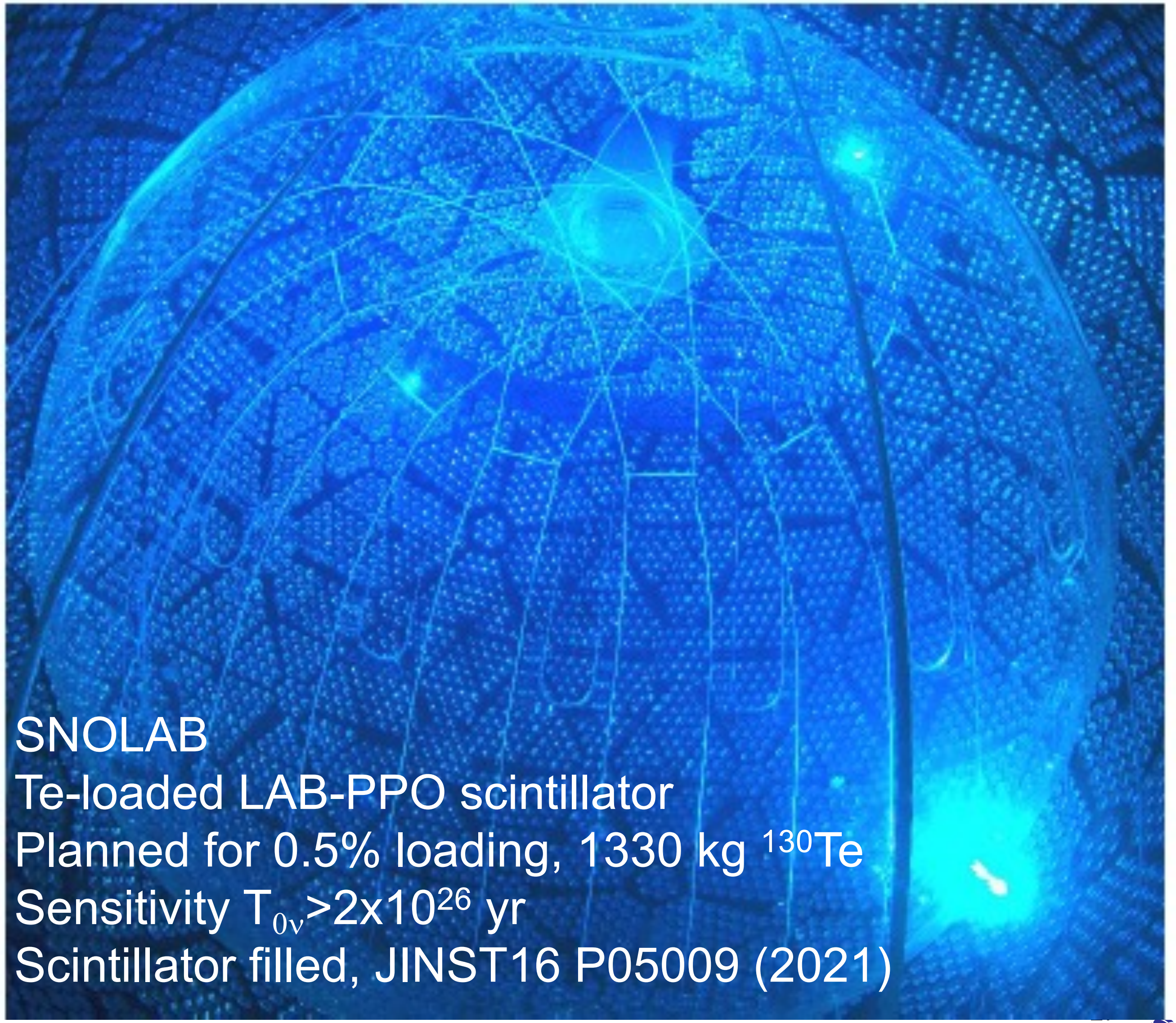


Image courtesy National Geographic



SNOLAB

Te-loaded LAB-PPO scintillator

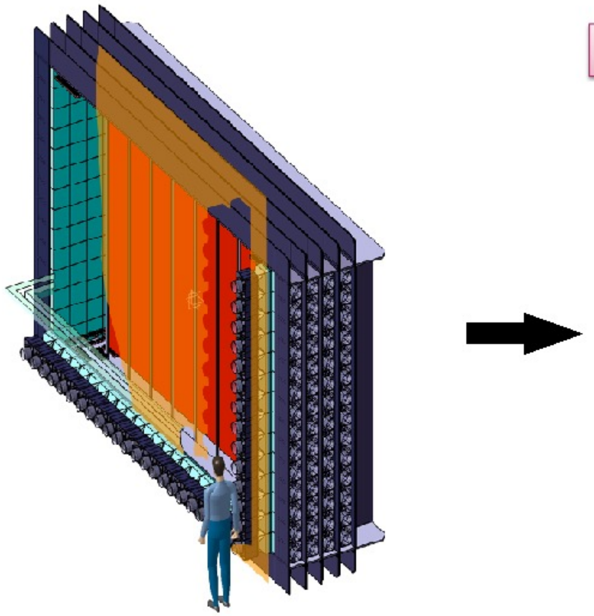
Planned for 0.5% loading, 1330 kg ^{130}Te

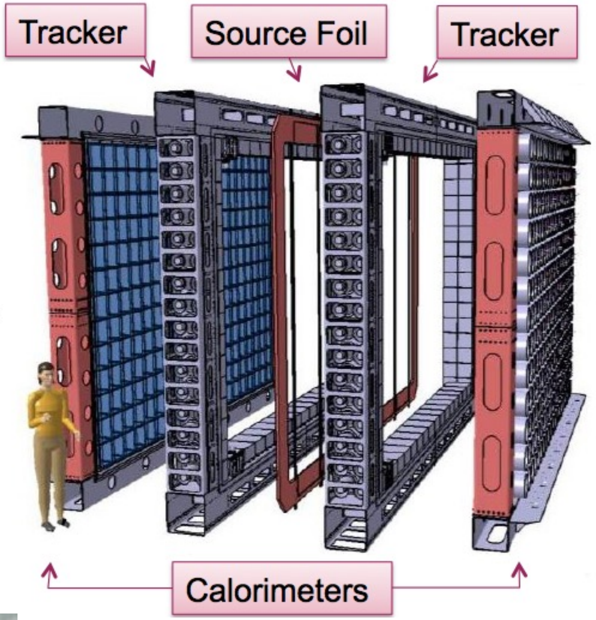
Sensitivity $T_{0\nu}$>2x10^{26} yr

Scintillator filled, JINST16 P05009 (2021)

SuperNEMO

- Tracking – will be important if ββ is observed.
  - NEMO has provided best 2νββ opening angle and lone electron spectra to date. PRD 92 (2015) 072011
  - NEMO3 is still providing ββ information
    - Eur Phys. J. C78 (2018) 821, Eur. Phys. J C79 (2019) 440
  - Can establish that event is two electrons.
  - SuperNEMO, arXiv:1704.06670
  - Energy resolution improving with R&D (~8%/√E),
    - NIM A868 (2017) 98
  - But the requirement for a thin source to minimize scattering still limits mass.
  - SuperNEMO Demonstrator is in final stages of commissioning and should be running this year.





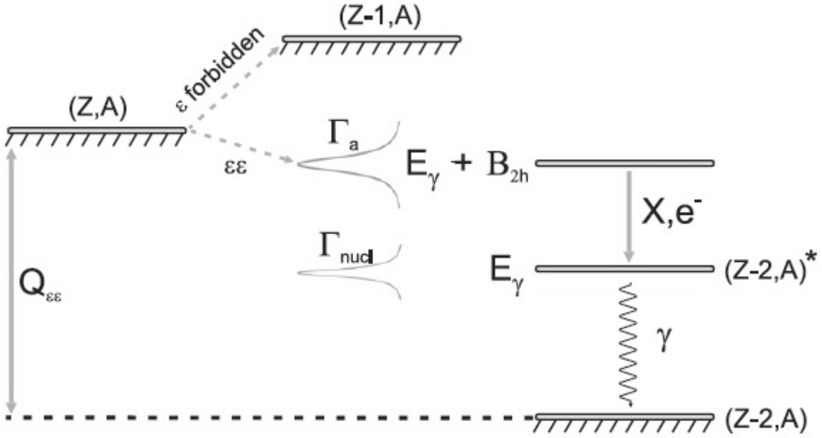
Is 0νECEC an Alternative to 0νββ?

Review: Rev. Mod. Phys. 92, 045007 (2020)

PRC89, 064319 (2014)

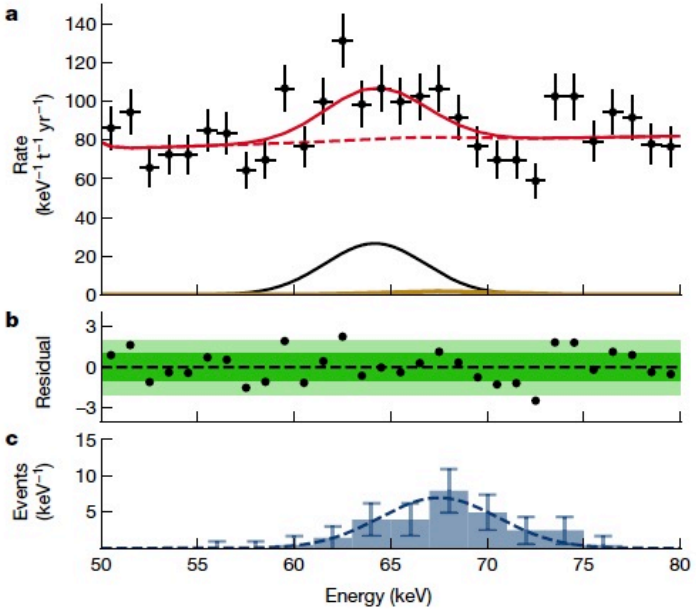
$$[\tau_{1/2}^{ECEC}]^{-1} = G_{0\nu}^{EC} M_{0\nu,EC}^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2 mc^2 R \qquad [\tau_{1/2}^{0\nu}]^{-1} = G_{0\nu}\, M_{0\nu}^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$$R = \frac{\Gamma}{\Delta^2 + 0.25\Gamma^2} \qquad \Delta = Q - B_{2h} - E^*$$



J.Phys.G:NPP 39(2012) 124003

Compare ^{124}Xe to ^{136}Xe. Recent 2νECEC measurement.
Not a good resonance(Δ~1.9 keV). R_{exp} ~5.7x10^{-6}/eV, $R_{\Delta=0}$ ~ 0.2/eV.
But 2γ emission from 2790 keV is similar to 2450 keV ββ peak.
Similar technologies, so it's a good hypothetical comparison.
Define r as the ratio of the expected half lives.
ECEC half-life x32 longer than 0νββ, even if Δ=0.



Nature 568 (2019) 532

$$\tau_{1/2}^{ECEC} = \frac{8.7\times10^{24}\ yr\ eV}{R}\left(\frac{1\ eV}{m_{\beta\beta}}\right)^2 \qquad \tau_{1/2}^{0\nu} = 1.3\times10^{24} yr \left(\frac{1\ eV}{m_{\beta\beta}}\right)^2$$

$$r = \frac{\tau_{1/2}^{ECEC}}{\tau_{1/2}^{0\nu}} = \frac{6.7/eV}{R}$$

$r_{\Delta=0}$ ~ 32, r_{exp} ~ 10^6

PHYSICS Los Alamos NATIONAL LABORATORY

0νECEC – ^{156}Dy

Some more theory and Penning-trap work would be useful

$$R = \frac{\Gamma}{\Delta^2 + 0.25\Gamma^2}$$

- ^{156}Dy $\Longrightarrow$ ^{156}Gd*(1988 keV) may have optimum overlap.
  - Δ = 0.54$\pm$0.24 keV.
  - It has a small $M_{0\nu,EC}$~0.3. With R_{Best} = 0.53/eV, r_{Best} is 120 meaning for the same $m_{\beta\beta}$, the half life is x120 longer compared to ^{136}Xe. Not all that encouraging.
- Penning trap measurements have done a great job looking for overlaps with a precision of a few hundred eV. Not many possibilities remain.
  - Γ values are 10-100 eV, so some improvement in precision for the still-interesting cases would be helpful.
- There are few careful $M_{0\nu,EC}$ calculations. This is a significant caveat. If $M_{0\nu,EC}$ is x10 larger, 0νECEC could be competitive. Additional effort on any key isotope would be good.

The Ongoing Program

each decision point depends on background demonstration

Expt. Size: up to 10 kg
Sensitivity: ~1 eV
$\tau > 10^{24/25}$ years
~10 $\beta\beta(2\nu)$ measurements

Expt. Size: 30-200 kg
Sensitivity: ~100 meV
$\tau > 10^{26/27}$ years
Quasi-degenerate
~8-10 expts. worldwide

Expt. Size: ~1T
~3 experiments
Sensitivity: 15 meV
$\tau > 10^{28}$ years
Atmos. scale

If $\beta\beta$ obs.

Expt. Size: few T
>3 experiments
Program to measure rate in several isotopes.
Kinematic meas.

Expt. Size: > 10T
Sensitivity: 5 meV
$\tau > 5\text{x}10^{28}$ years
Solar scale

1985- 2005 | 2005-2025 | 2020-2030 | Future

List of 0νββ Review Articles (not exhaustive, but long anyway)

[1] Frank T. Avignone III and Steven R. Elliott. The search for double beta decay with germanium detectors: Past, present, and future. *Frontiers in Physics*, 7, Feb 2019.

[2] F. T. Avignone III, S. R. Elliott, and J. Engel. Double beta decay, majorana neutrinos, and neutrino mass. *Rev. Mod. Phys.*, 80:481, 2008.

[3] A. S. Barabash. Double beta decay experiments. *Phys. Part. Nucl.*, 42:613, 2011.

[4] A. S. Barabash. Main features of detectors and isotopes to investigate double beta decay with increased sensitivity. *International Journal of Modern Physics A*, 33(09):1843001, Mar 2018.

[5] A. S. Barabash. Possibilities of future double beta decay experiments to investigate inverted and normal ordering region of neutrino mass, 2019.

[6] L. Cardani. Neutrinoless double beta decay overview, 2018.

[7] O. Cremonesi. Experimental searches of neutrinoless double beta decay. *Nucl. Phys. B Proc. Supp.*, 237:7, 2013.

[8] Stefano Dell'Oro, Simone Marcocci, Matteo Viel, and Francesco Vissani. Neutrinoless double beta decay: 2015 review. *Advances in High Energy Physics*, 2016:1?37, 2016.

[9] Michelle J. Dolinski, Alan W.P. Poon, and Werner Rodejohann. Neutrinoless double-beta decay: Status and prospects. *Annual Review of Nuclear and Particle Science*, 69(1):219, Oct 2019.

[10] S. R. Elliott and J. Engel. Double beta decay. *J. Phys. G: Nucl. Part. Phys.*, 30:R 183, 2004.

[11] S. R. Elliott and P. Vogel. Double beta decay. *Ann. Rev. Nucl. Part. Sci.*, 52:115, 2002.

[12] Steven R. Elliott. Recent progress in double beta decay. *Mod. Phys. Lett. A*, 27:1230009, 2012.

[13] Steven R. Elliott and Marcel Franz. Colloquium: Majorana fermions in nuclear, particle, and solid-state physics. *Rev. Mod. Phys.*, 87:137, 2015.

[14] Jonathan Engel and Javier Menéndez. Status and future of nuclear matrix elements for neutrinoless double-beta decay: A review. *Rep. Prog. Phys.*, 80:046301, 2017.

[15] Jonathan Engel and Javier Menndez. Status and future of nuclear matrix elements for neutrinoless double-beta decay: a review. *Reports on Progress in Physics*, 80(4):046301, Mar 2017.

[16] A. Giuliani, J. J. Gómez-Cadenas, S. Pascoli, E. Previtali, R. Saakyan, K. Schaeffner, and S. Schoenert. Double beta decay appec committee report, 2020.

[17] J. J. Gómez-Cadenas, J. Martín-Albo, M. Mezzetto, F. Monrabal, and M. Sorel. The search for neutrinoless double beta decay. *Riv. Nuovo Cim.*, 35:29–98, 2012.

[18] Yong-Hamb Kim. Neutrinoless double beta decay experiment, 2020.

[19] Igor Ostrovskiy and Kevin O'Sullivan. Search for neutrinoless double beta decay. *Modern Physics Letters A*, 31(18):1630017, Jun 2016.

[20] Heinrich Päs and Werner Rodejohann. Neutrinoless double beta decay. *New Journal of Physics*, 17(11):115010, Nov 2015.

[21] Werner Rodejohann. Neutrino-less double beta decay and particle physics. *Int. J. Mod. Phys. E*, 20:1833, 2011.

[22] Bernhard Schwingenheuer. Status and prospects of searches for neutrinoless double beta decay. *Ann. der Physik*, 525:269–280, 2013.

[23] V. I. Tretyak, Osvaldo Civitarese, Ivan Stekl, and Jouni Suhonen. False starts in history of searches for 2β decay, or discoverless double beta decay. *AIP Conf. Proc.*, 2011.

[24] J. D. Vergados, H. Ejiri, and F. Šimkovic. Neutrinoless double beta decay and neutrino mass. *International Journal of Modern Physics E*, 25(11):1630007, Nov 2016.