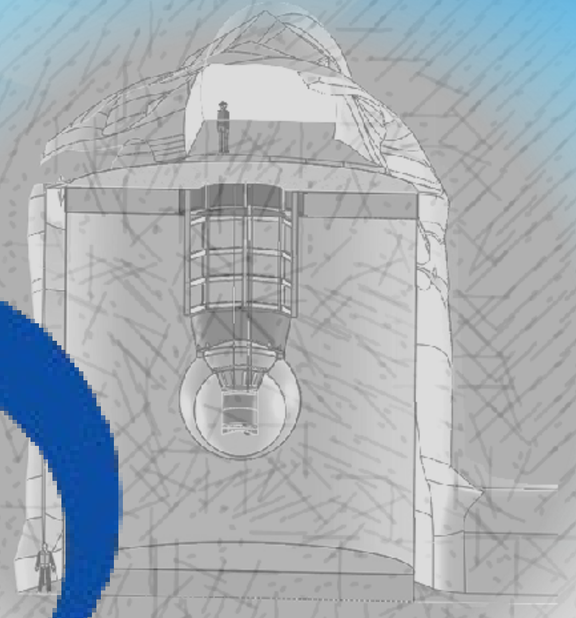
nEXO

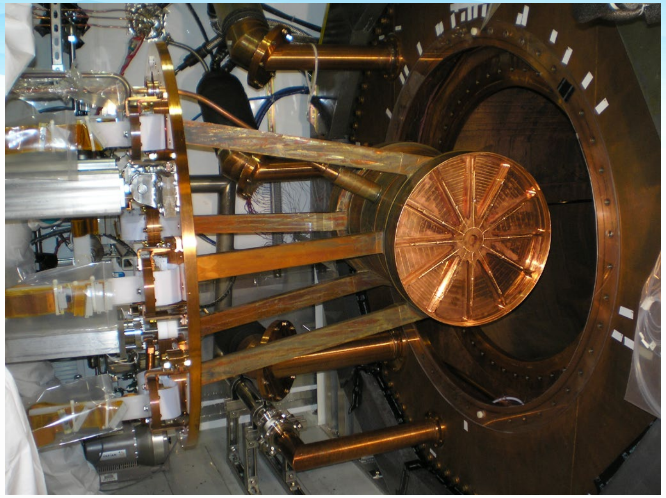


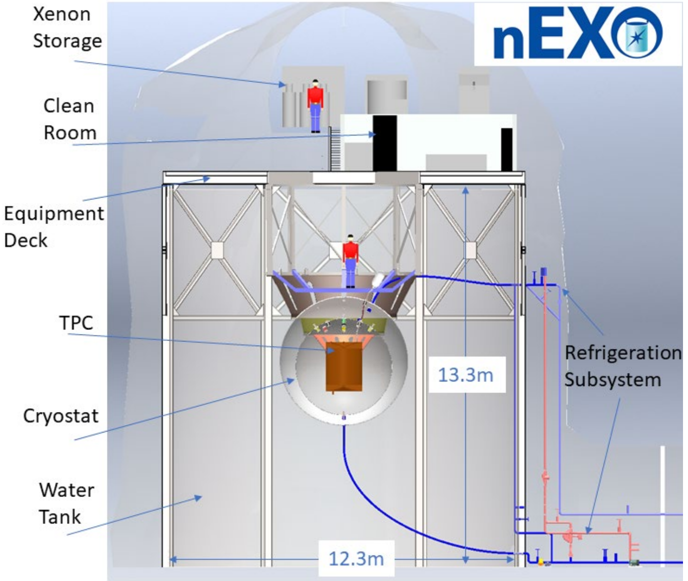
Giorgio Gratta

Physics Dept, Stanford University

Milestones in the EXO program
Since 2001

- 2001: "EXO" started as an R&D effort towards a ^{136}Xe ββ decay experiment.
- 2002: The improved energy resolution in LXe using the correlation between scintillation and ionization is discovered.
- Circa 2005: Settled on a LXe TPC design for a "prototype" 200 kg detector.
- 2007-2010: The EXO-200 detector is designed and built (circa 20M$), with major contributions from Canada, Russia and Switzerland.
- 2012-2016: After EXO-200 started taking data, showing excellent performance, the idea of a 5000 kg was further developed.
- 2014: The "nEXO collaboration" was formed.
- 2014-2016: Five US Nat'l Labs join the collaboration.
- May 2018: nEXO pre-CDR posted on the arXiv
- Nov 2018: CD-0 for tonne-scale ββ decay
- Dec 2018: End of EXO-200 running
- 2019-now: nEXO project developed; substantial nEXO engineering at SNOLAB
- Feb 2020: nEXO MAC review
- Feb 2021: nEXO budget review
- Jul 2021: LLNL Director's review and DoE Portfolio review





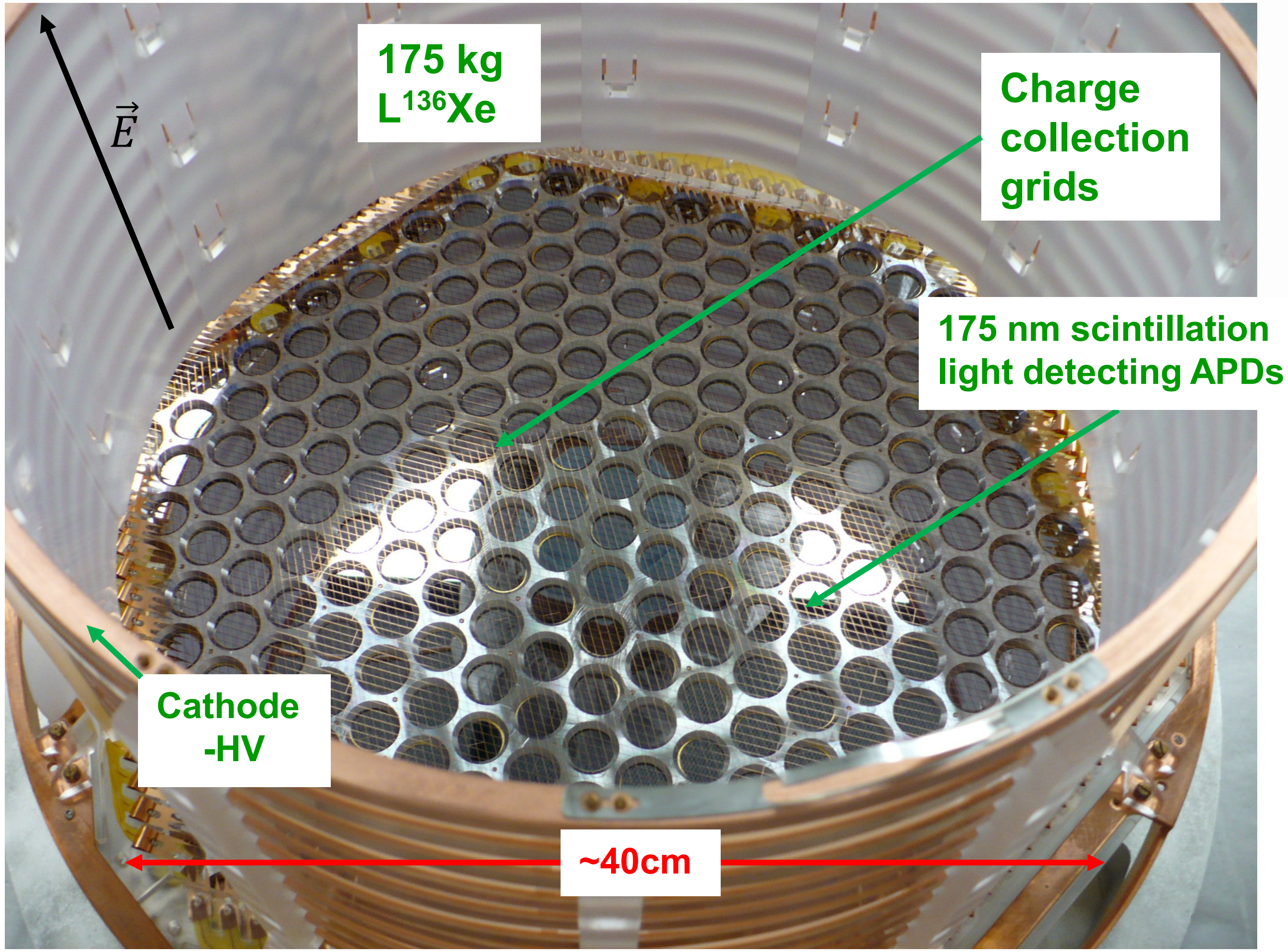
EXO-200

nEXO follows a safe and scalable technique, pioneered by EXO-200

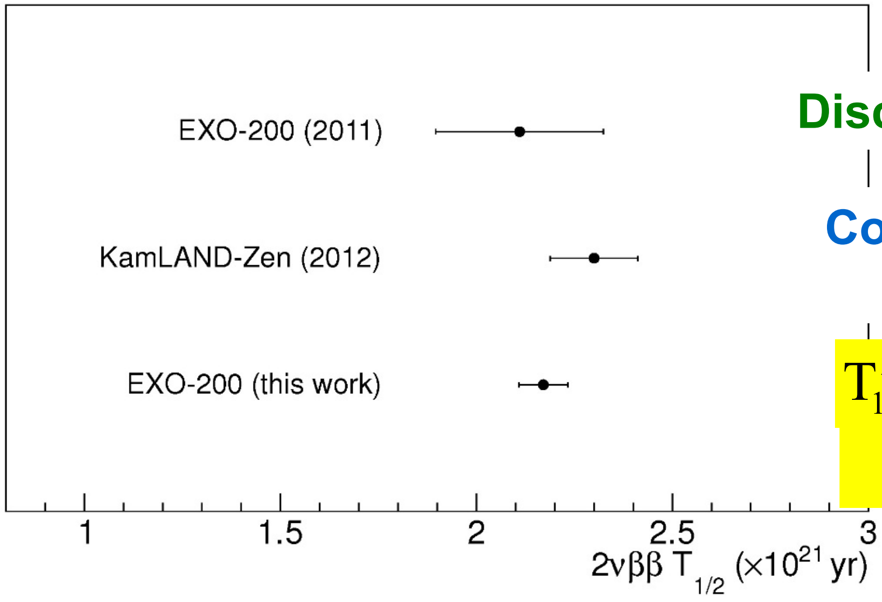
The EXO-200 LXe TPC pioneered the use of topology, position, energy, and scintillation/ionization to independently ***measure*** signal and background(s) for the expected MeV-scale energy deposits.

➔ **Substantially more powerful than a simple energy measurement.**

The same principle is used in nEXO



The 2νββ decay in ^{136}Xe was discovered in the first week of EXO-200 data



Discovery of 2ν mode ***[PRL 107, 212501 (2011)]***

Confirmation by KamLAND-Zen ***[PRC 85, 045504 (2012)]***

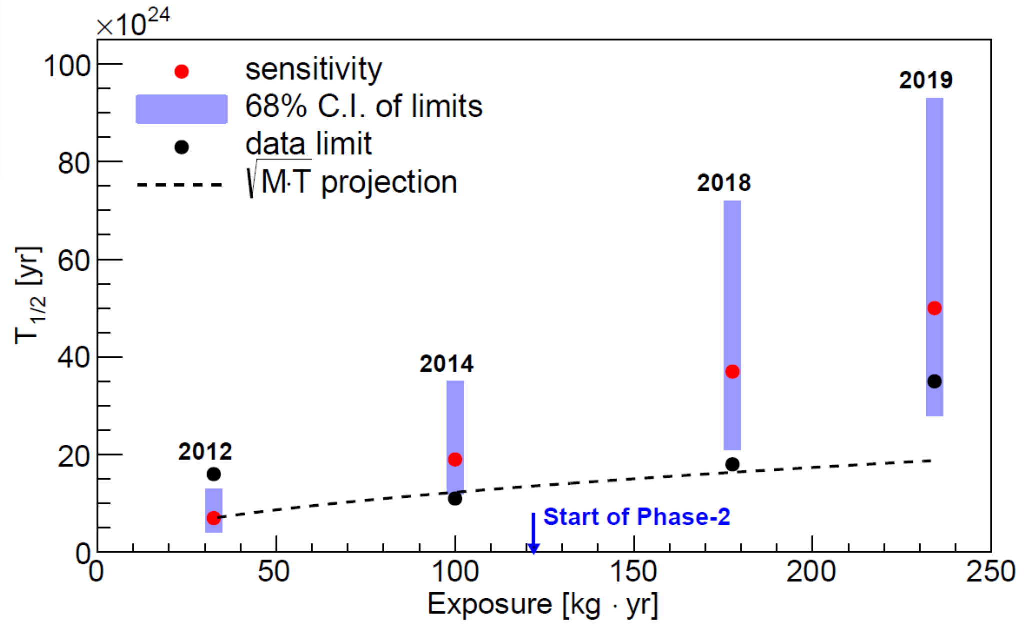
$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\mathrm{stat}} \pm 0.059^{\mathrm{syst}}\right) \cdot 10^{21}\ \mathrm{yr}$$

[Phys. Rev. C 89 (2014) 015502]

For a while, this was the most accurately measured 2ν decay.

EXO-200 results for 0νββ

- First 100 kg-class experiment to take data.
- Excellent background, very well predicted by the massive material characterization program (and the simulation). ***This is essential for nEXO design.***
- Sensitivity increased linearly with exposure.
- More papers on non-ββ decay physics.



2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: Phys. Rev. Lett. 123 (2019) 161802

Final result

Phase I+II: 234.1 kg yr of ^{136}Xe exposure
Limit: $T_{1/2}^{0\nu\beta\beta}$ > 3.5x10^{25} yr (90% CL)
$\langle m_{\beta\beta} \rangle$ < (93 -286) meV
Sensitivity: 5.0x10^{25} yr

Radioactivity in EXO-200 was successfully predicted *before* turning on the detector

➔ **Massive effort on material radioactive qualification, using:**

- **NAA**
- **Low background γ-spectroscopy**
- **α-counting**
- **Radon counting**
- **High performance GD-MS and ICP-MS**

The materials database includes >300 entries

D.S. Leonard et al., Nucl. Ins. Meth. A 591 (2008) 490
D.S. Leonard et al., Nucl. Inst. Meth. A 871 (2017) 169
M. Auger et al., J. Inst. 7 (2012) P05010.

The background can then be directly measured in the data:

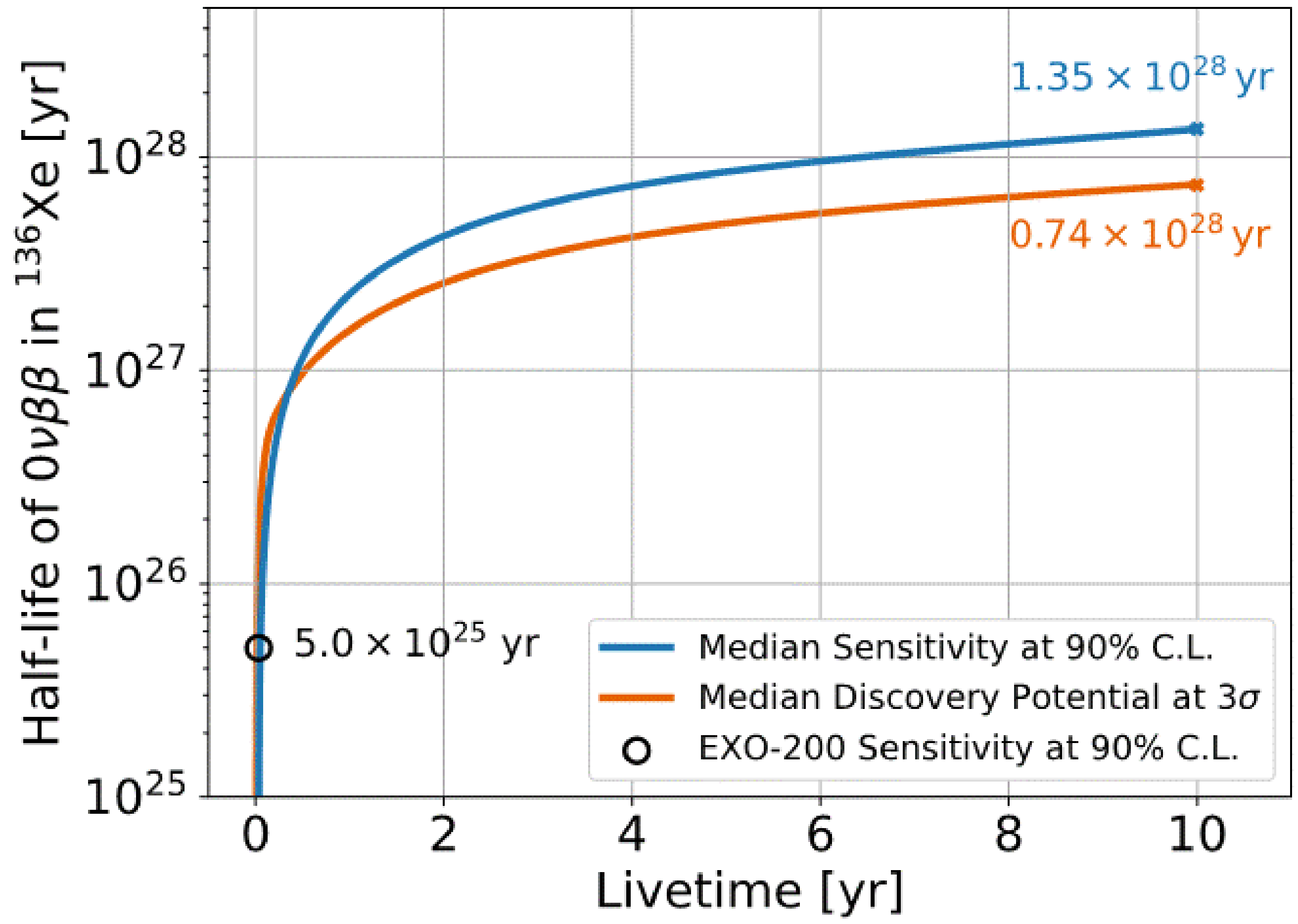
J.B. Albert et al. Phys. Rev. C 92 (2015) 015503.

Cosmogenic backgrounds:

J.B. Albert et al., JCAP 04 (2016) 029.

Events in ±2σ around Q	Radioactive bkgd prediction using certification data and G4 Monte Carlo	^{137}Xe bkgd	Background from 0ν analysis fit
90%CL Upper	56	18	63.2 ± 4.7 (65 events observed)
90%CL Lower	8.2		

nEXO: In the land of large, scalable double-beta decay experiments

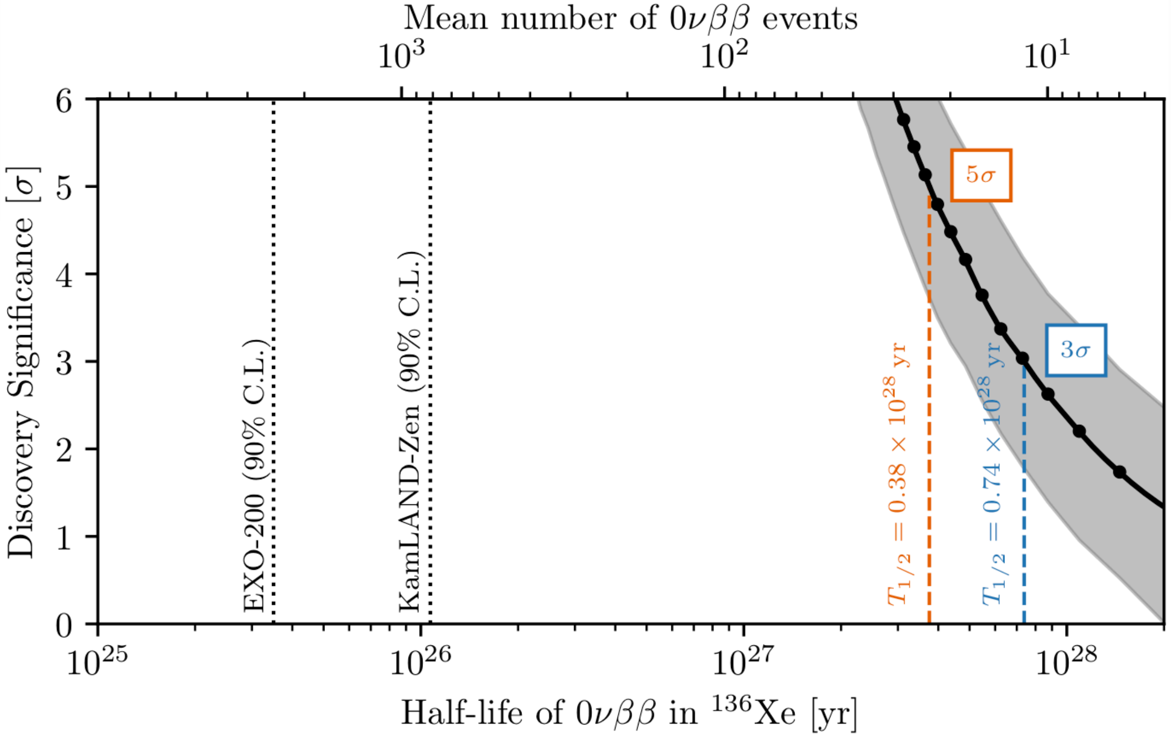


nEXO sensitivity reaches 10^{28} yr in 6.5 yr data taking

Sensitivity and Discovery Potential

nEXO is a discovery experiment that will search for lepton number violation over a large, unexplored parameter space

- **10^{27} - 10^{28} yr $T_{1/2}$ sensitivity**
- **Can provide compelling evidence of discovery without other experiments**
- **Probes effective Majorana neutrino masses, $\langle m_{\beta\beta} \rangle$, down to 15 meV**



	Limit / Discovery Sensitivity	Reference:
EXO-200	0.35×10^{26} yr (90% CL)	PRL 123 (2019) 161802
KamLAND-Zen	1.07×10^{26} yr (90% CL)	PRL 117 (2016) 082503
nEXO	0.38×10^{28} (5σ) 0.74×10^{28} (3σ)	arXiv:2106.16243

The new physics reach can be parameterized in the effective Majorana mass.
This is also useful to compare different experiments.

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

Phase space factor
J. Kotila and F. Iachello, Phys Rev C 85, 034316 (2012)

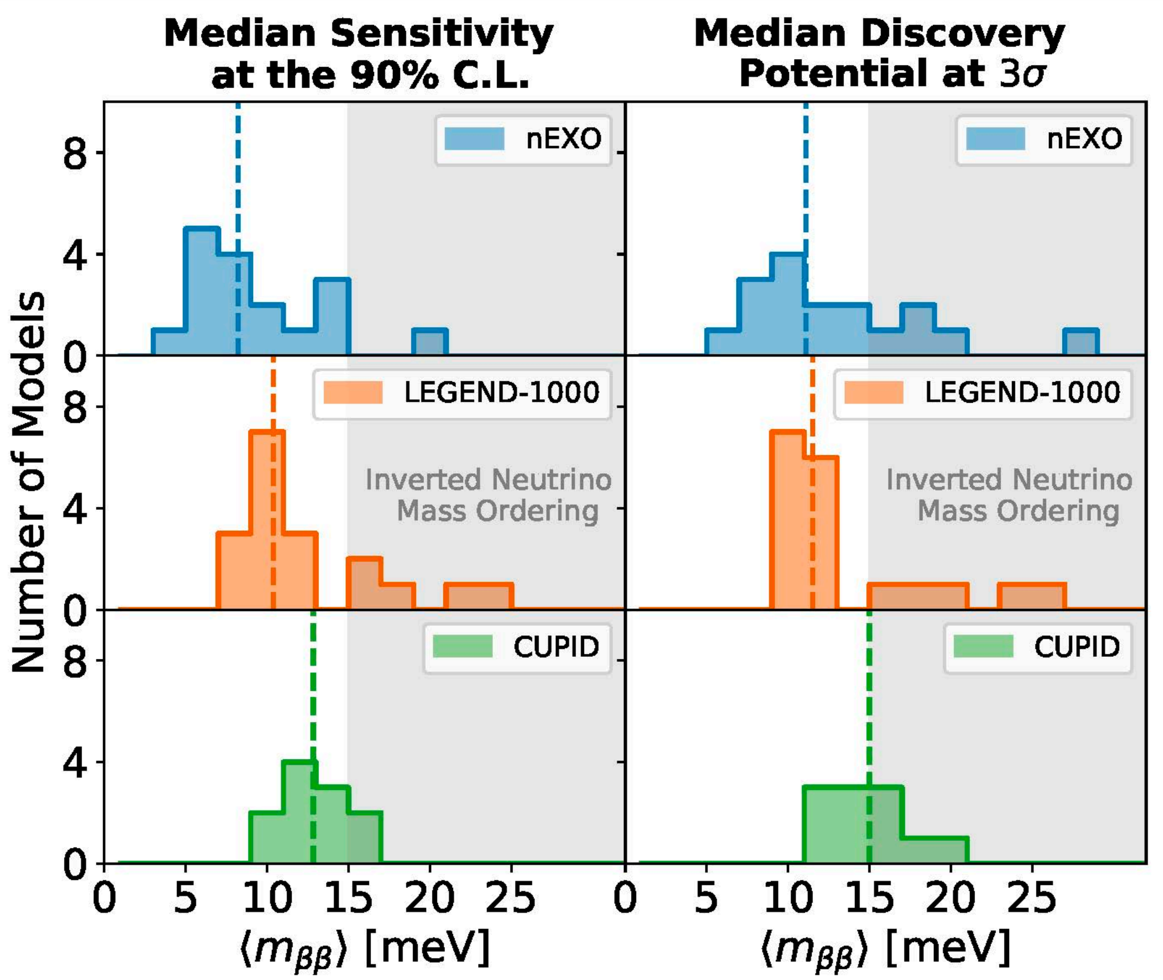
Axial coupling, $g_A = 1.27$

References for the NMEs used

Method	Year	Citation
IBM	2015	PRC 91 034304 (2015)
NSM	2008	PRL 100, 052503 (2008)
IBM	2020	PRD 102, 095016 (2020)
QRPA	2014	PRC 89, 064308 (2014)
NSM	2016	PRC 93, 024308 (2016)
QRPA	2015	PRC 91, 024613 (2015)
QRPA	2018	PRC 98, 024608 (2018)
NSM	2018	JPS Conf. Proc. 23, 012036 (2018)
QRPA	2013	J. High Energ. Phys. 2013, 25 (2013)
QRPA	2013	PRC 87, 064302 (2013)
QRPA	2013	PRC 87, 045501 (2013)
QRPA	2018	PRC 97, 034315 (2018)
QRPA	2010	Nucl.Phys.A 847 (2010) 207
EDF	2013	PRL 111, 142501 (2013)
EDF	2015	PRC 91, 024316 (2015)
QRPA	2018	PRC 97, 045503 (2018)
EDF	2017	PRC 96, 054310 (2017)
QRPA	2015	PRC 91, 024613 (2015)
EDF	2010	Prog.Part.Nucl.Phys. 66 (2011) 436

- **^{136}Xe benefits from larger $G^{0\nu}$ than lighter isotopes ($G^{0\nu}$ is known precisely)**
- **Significant theoretical uncertainty in NMEs**
  - **Adopt agnostic approach considering all published NMEs not directly superseded by later publications**
  - **Conclusions not qualitatively changed if *all* published NMEs are considered**

Comparison with other experiments



Deeper physics reach

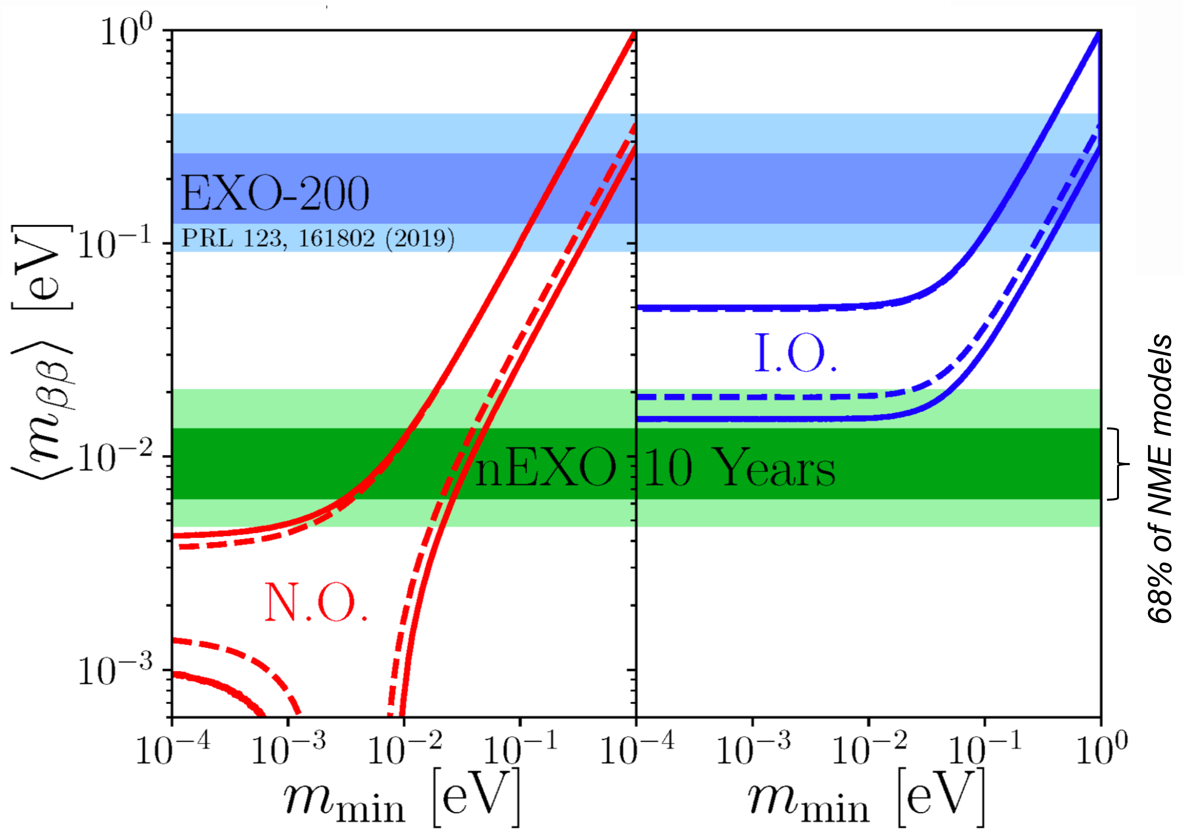
	$m_{\beta\beta}$ [meV], (*median NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

$T_{1/2}$ values used [x10^{28} yr]:

nEXO: 1.35 (90% sens.), 0.74 (3σ discov.)
LEGEND: 1.6 (90% sens.), 1.3 (3σ discov.)
CUPID: 0.15 (90% sens.), 0.11 (3σ discov.)

Majorana Mass Reach

Allowed parameter space and nEXO exclusion sensitivity (90% CL):



nEXO 3σ discovery sensitivity for the median NME model considered is 11.1 meV, reaching beyond IO further into NO

Conclusions:

- **nEXO extends the $T_{1/2}$ reach into new physics by ~2 orders of magnitude, with substantial chance of making a discovery.**
- **nEXO has a slightly better physics reach with respect to other experiments (but the NME uncertainty is large).**
- **The most important conclusion is that nEXO's sensitivity estimates are robust and built from a bottom-up approach based on measured data (coming up in a minute).**

A healthy neutrinoless double-beta decay program requires several isotopes.

This is because:

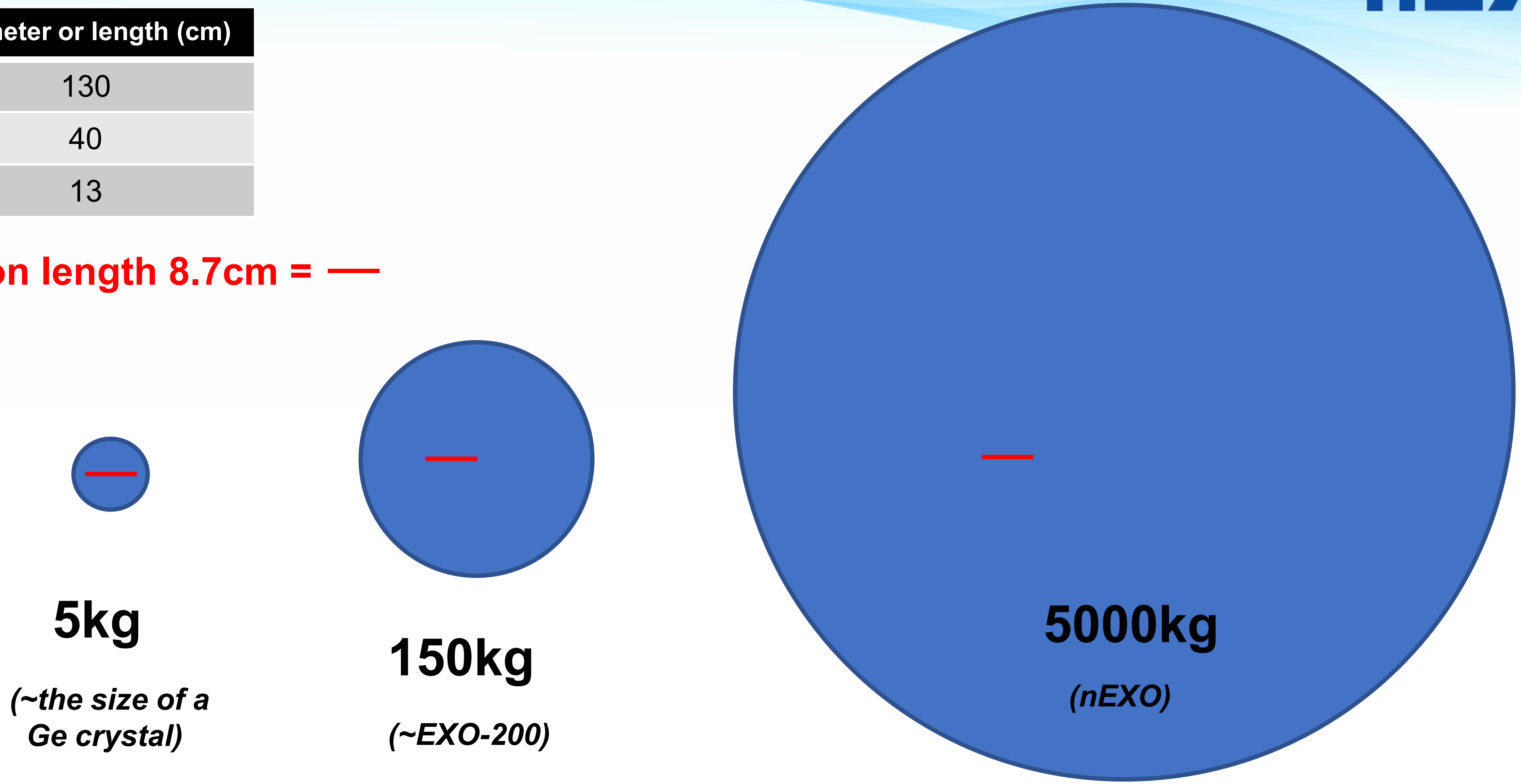
- ***Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities***
- ***Different isotopes correspond to vastly different experimental techniques***
- ***2 neutrino background is different for various isotopes***
- ***Disentangling nucl. Matrix element effects from the mechanism producing the decay requires the analysis of more than one isotope***

  ➔ *see Francesco Vissani*

Monolithic/Homogeneous is key

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5 MeV γ attenuation length 8.7cm = —

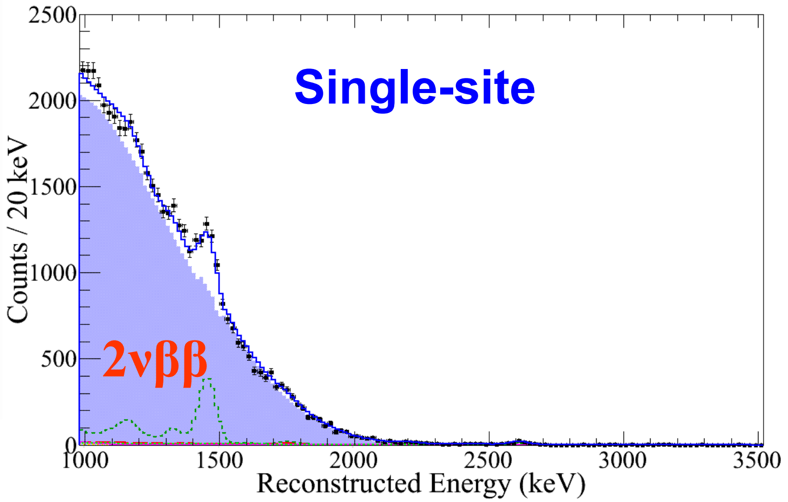


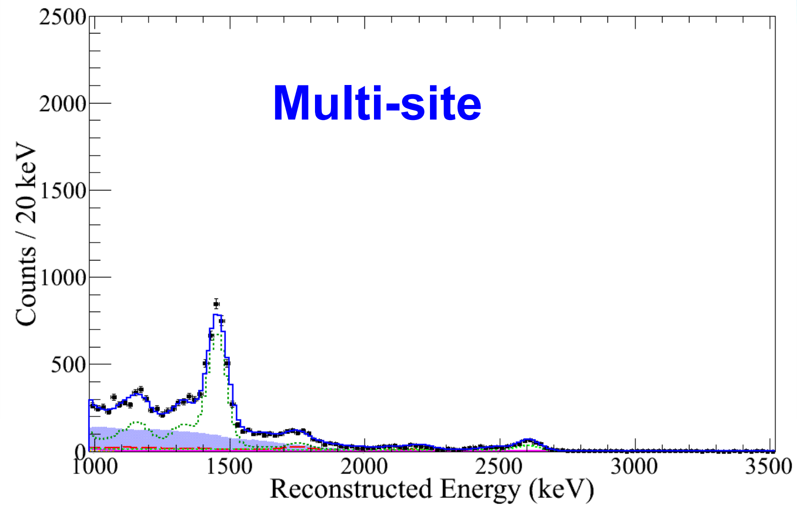
Important: The estimate of the nEXO sensitivity relies only on materials already tested for radioactivity (except for the intrinsic contamination of the LXe which can be/is repurified during running)

Using event multiplicity to recognize backgrounds

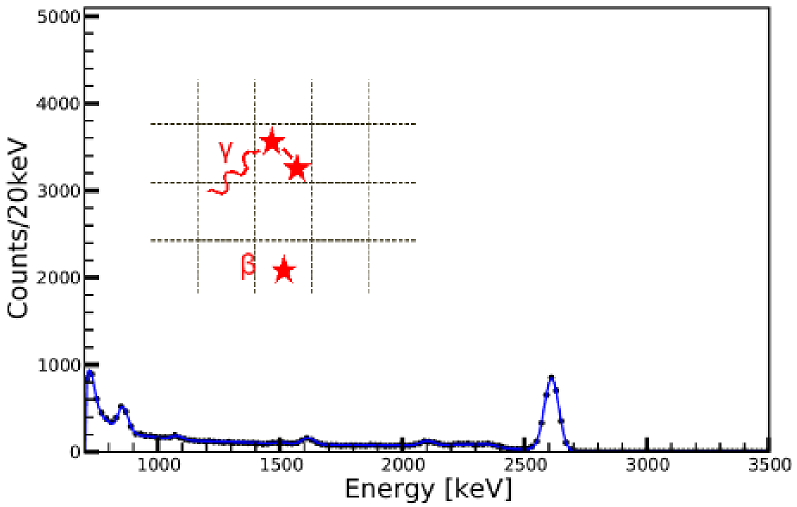
EXO-200 data

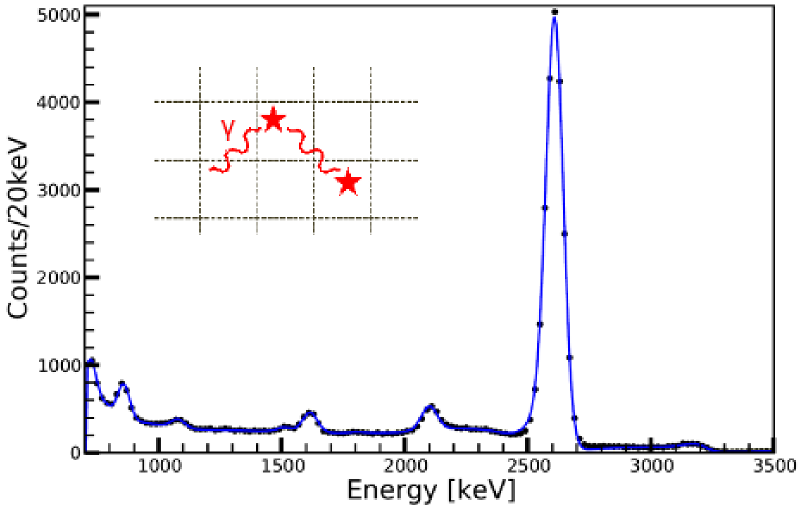
Low background data





^{228}Th calibration source



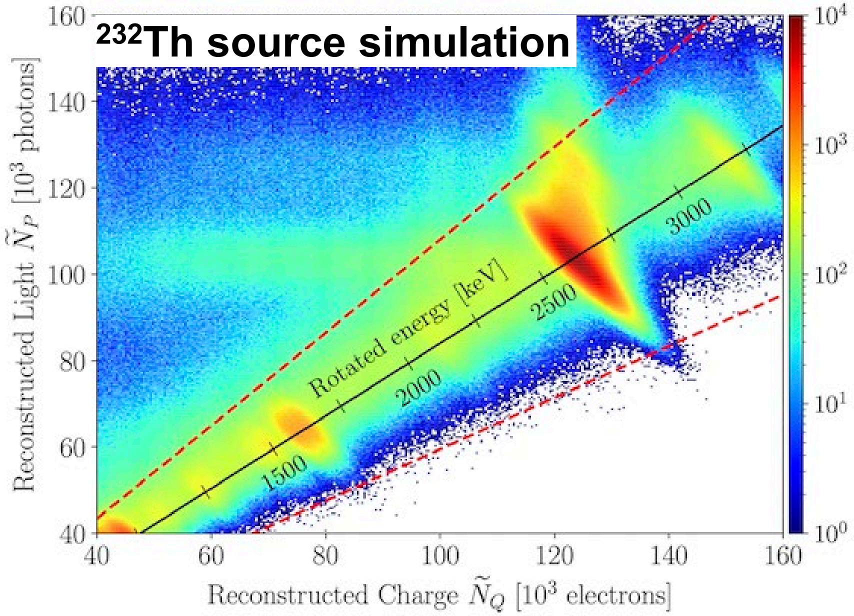


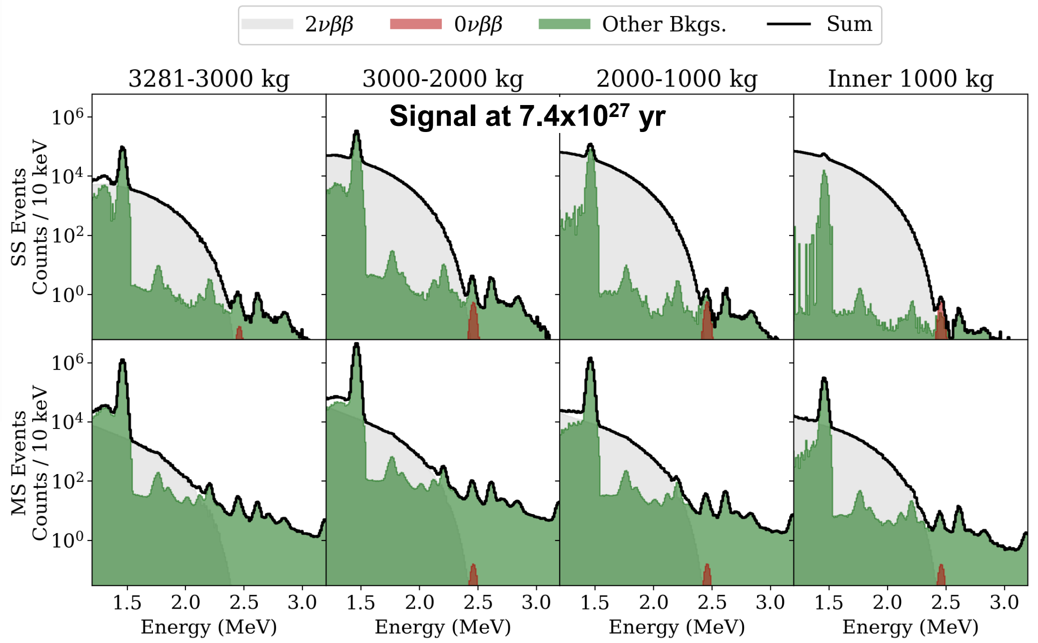
nEXO is the best option for a very large detector

Multi-parameter analysis: much more information than just energy

1. **The homogeneous detector with advanced topological reconstruction has a proven track record for γ background <u>identification</u> and <u>rejection.</u>**

Multi-parameter analysis also makes the measurement robust with currently unknown backgrounds. ***Since there is no internal passive materials, any unknown gamma lines give a very clear reading in the multi-site channel.***





2. **The energy resolution, still important, is good enough, once the scintillation and ionization are used in tandem. nEXO will have a resolution <1% at the Q-value.**

3. **The ratio of scintillation to ionization allows to quantify background due to radon contained in the LXe by tagging alphas.**

nEXO is the best option for a very large detector:

Using xenon results in reliability and cost effectiveness

4. Recirculating Xenon reduces risk, as the purification system can be upgraded if unexpected backgrounds are discovered and/or if new technology becomes available.
   Note that xenon has no long-lived, unstable isotopes.

5. Xenon enrichment is well understood and cost effective.

   - EXO-200 used 200 kg of Xe enriched to 80% in 136, at the time a pioneering production.
   - KamLAND-ZEN more recently purchased ~800 kg of xenon enriched to 90% in 136.
   - The nEXO need is only 5x of what is already available.
   - nEXO has identified at least two western suppliers each with enough enrichment capacity for the entire production at competitive price. We also have two backup (western) options. All options have been extensively investigated and we have carried out site visits for three of them.

"And then I thought, What better hedge than a ~~uranium~~ centrifuge?"
xenon

nEXO is __unique__ among proposed experiments
because…

nEXO

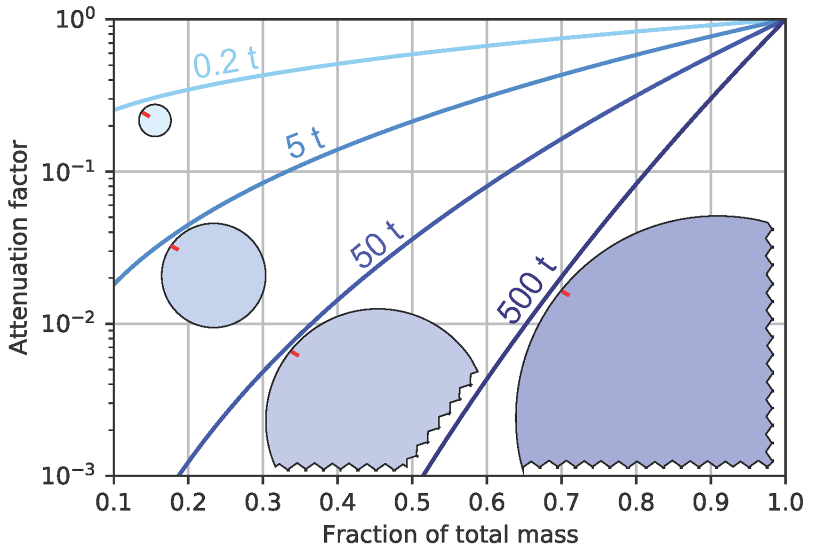
6. nEXO can make a discovery by itself, by repeating the experiment with non-enriched Xenon to confirm that a signal goes away (see "Standard of proof" in the 2014 NSAC ββ NSAC subcommittee report)

7. If nEXO discovers 0νββ decay:

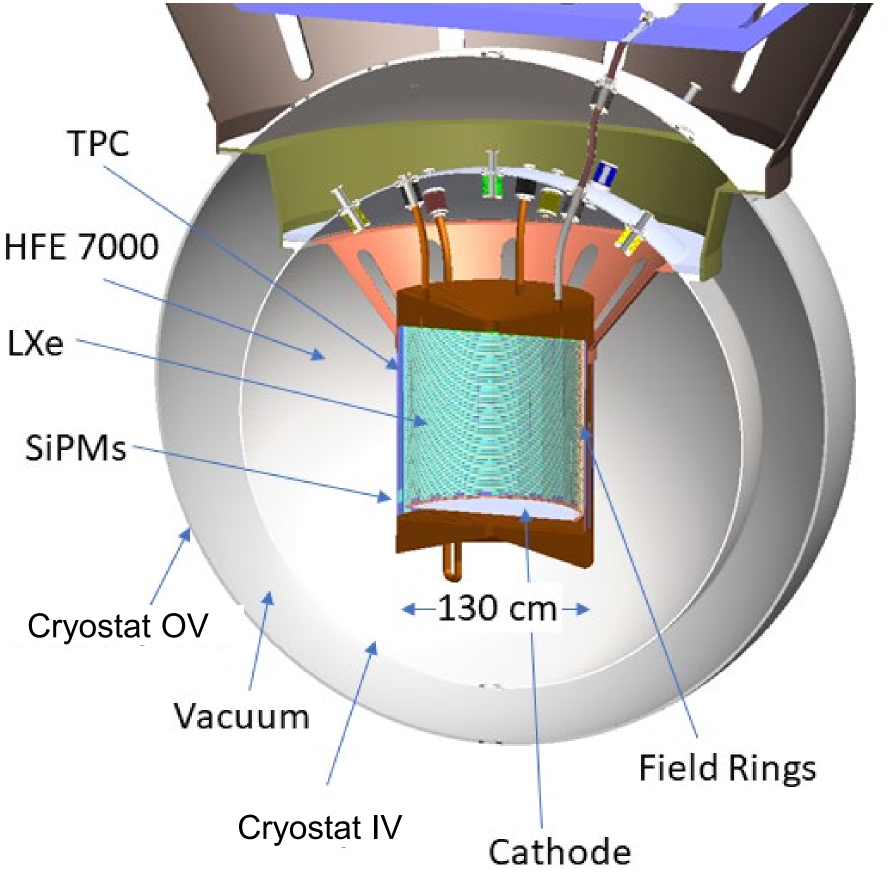
The enriched xenon is NOT "frozen" in a particular detector. Should 0νββ decay be discovered by nEXO, the xenon could be re-used in a different experimental configuration to investigate the underlying physics.
This is particularly important at the tonne scale, given the cost of the material.

8. If nEXO does not discover 0νββ decay:

The advantages of the homogeneous detector keep improving with size. Should 0νββ decay not be discovered by nEXO, larger detectors using the same technology are plausible. There is enrichment capacity for this, although the feed stock will need to be directly extracted from air; again, this is plausible.
The technology needs to be developed with an eye to the future.
➔ see Andrea Giuliani



The nEXO detector is an evolution from EXO-200, with specific R&D done over the last 10 years



	EXO-200:	*nEXO:*	Improvements:
Vessel and cryostat	Thin-walled commercial Cu w/HFE	*Thin-walled electroformed Cu w/HFE*	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	*Operating voltage: 50 kV*	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad polyimide (analog)	*Cu clad polyimide (digital)*	Same cable/feedthrough technology, R&D identified 10x lower bkg substrate and demonstrated digital signal transmission
e^- lifetime	3-5 ms	*5 ms (req.), 10 ms (goal)*	Minimal plastics (no PTFE reflector), lower surface to volume ratio, detailed materials screening program
Charge collection	Crossed wires	*Gridless modular tiles*	R&D performed to demonstrate charge collection with tiles in LXe, detailed simulation developed
Light collection	APDs + PTFE reflector	*SiPMs around TPC barrel*	SiPMs avoid readout noise, R&D demonstrated prototypes from two vendors
Energy resolution	1.2%	*1.2% (req.), 0.8% (goal)*	Improved resolution due to SiPMs (negligible readout noise in light channels)
Electronics	Conventional room temp.	*In LXe ASIC-based design*	Minimize readout noise for light and charge channels, nEXO prototypes demonstrated in R&D and follow from LAr TPC lineage
Background control	Measurement of all materials	*Measurement of all materials*	RBC program follows successful strategy demonstrated in EXO-200
Larger size	>2 atten. length at center	*>7 atten. length at center*	Exponential attenuation of external gammas and more fully contained Comptons

The design of nEXO is mature:

Basic elements contained in the pre-CDR:

“nEXO pCDR” arXiv:1805.11142 (May 2018)

Initial sensitivity estimate:

"Sensitivity and Discovery Potential of nEXO to 0νββ decay"
Phys. Rev. C 97 (2018) 065503.

Updated sensitivity estimate:

“nEXO: Neutrinoless double beta decay search beyond 10^{28} year half-life sensitivity”, arXiv:2106.16243 (Jul 2021)

Several instrumentation papers published in the last few years.

nEXO Pre-Conceptual Design Report

nEXO

arXiv:1805.11142 [physics.ins-det] 28 May 2018

Abstract

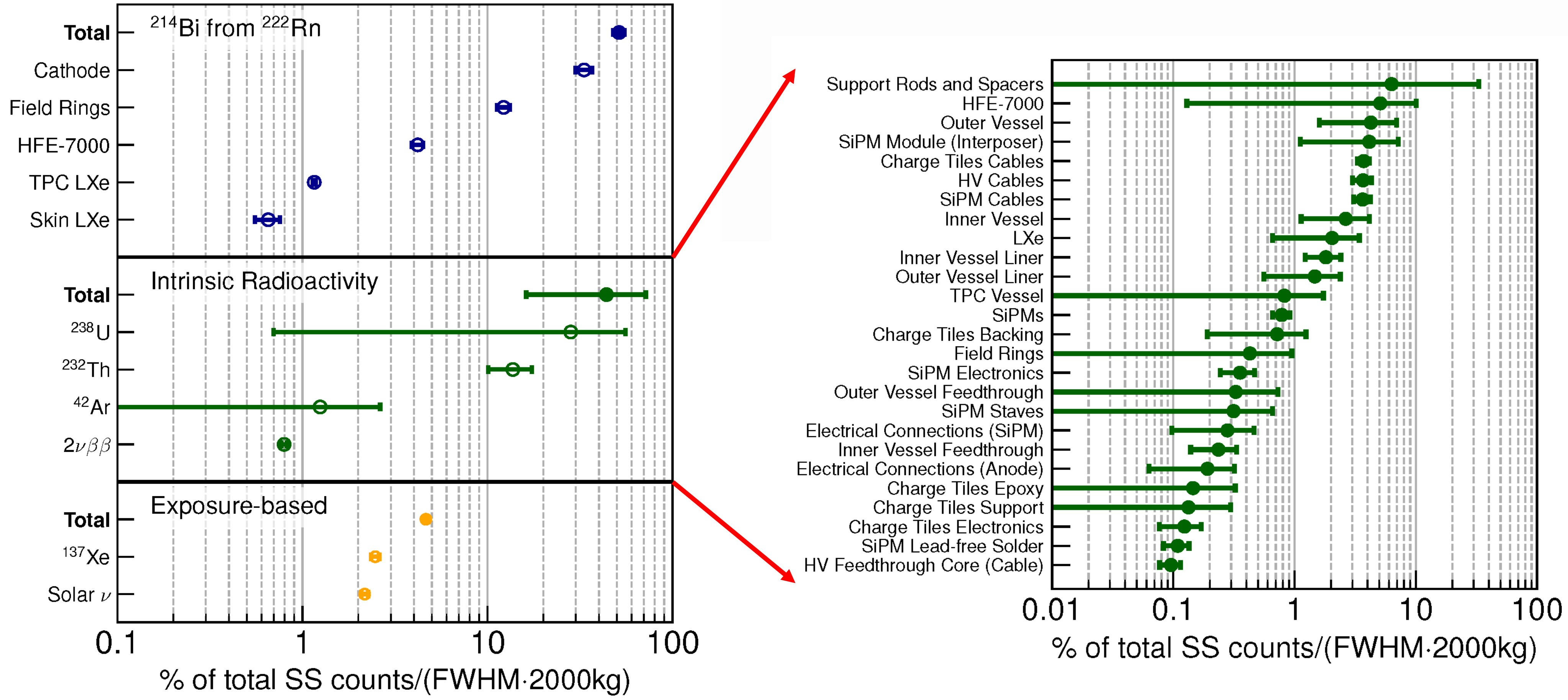
The projected performance and detector configuration of nEXO are described in this pre-Conceptual Design Report (pCDR). nEXO is a tonne-scale neutrinoless double beta ($0\nu\beta\beta$) decay search in ^{136}Xe, based on the ultra-low background liquid xenon technology validated by EXO-200. With ~ 5000 kg of xenon enriched to 90% in the isotope 136, nEXO has a projected half-life sensitivity of approximately 10^{28} years. This represents an improvement in sensitivity of about two orders of magnitude with respect to current results. Based on the experience gained from EXO-200 and the effectiveness of xenon purification techniques, we expect the background to be dominated by external sources of radiation. The sensitivity increase is, therefore, entirely derived from the increase of active mass in a monolithic and homogeneous detector, along with some technical advances perfected in the course of a dedicated R&D program. Hence the risk which is inherent to the construction of a large, ultra-low background detector is reduced, as the intrinsic radioactive contamination requirements are generally not beyond those demonstrated with the present generation $0\nu\beta\beta$ decay experiments. Indeed, most of the required materials have been already assayed or reasonable estimates of their properties are at hand. The details described herein represent the base design of the detector configuration as of early 2018. Where potential design improvements are possible, alternatives are discussed.

This design for nEXO presents a compelling path towards a next generation search for $0\nu\beta\beta$, with a substantial possibility to discover physics beyond the Standard Model.

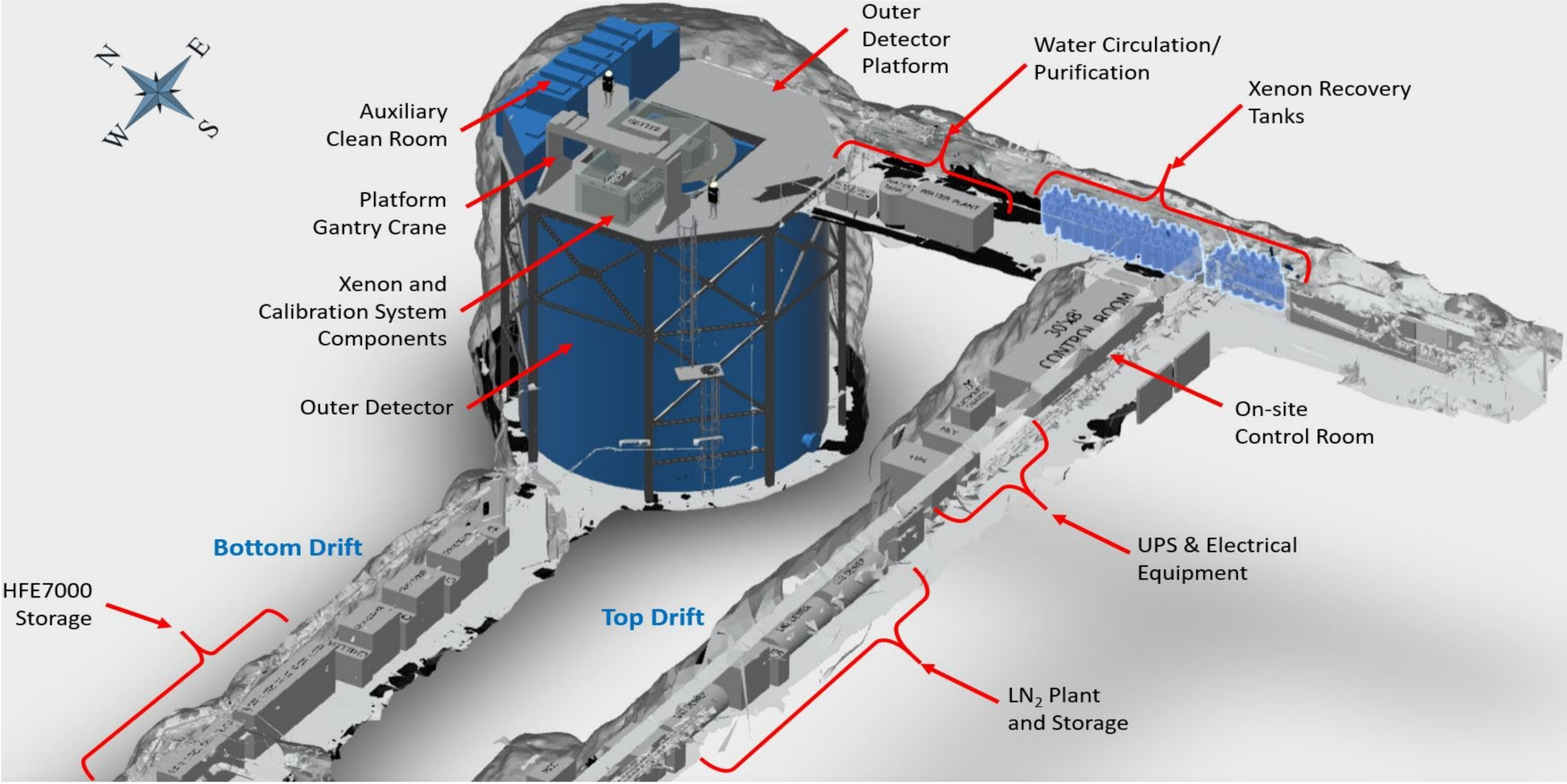
May 28, 2018

nEXO is well optimized

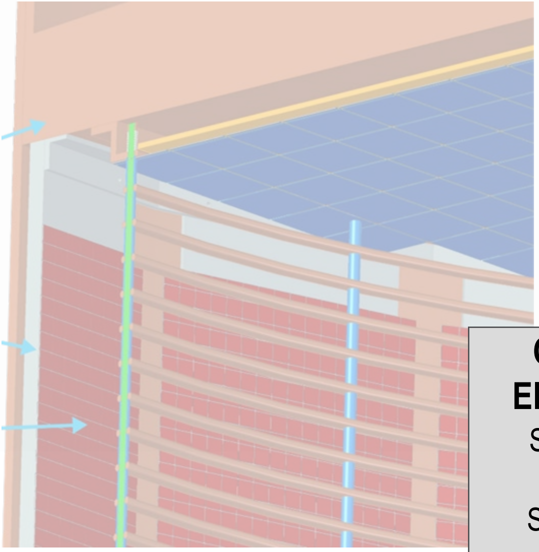
No detector component dominates the background.



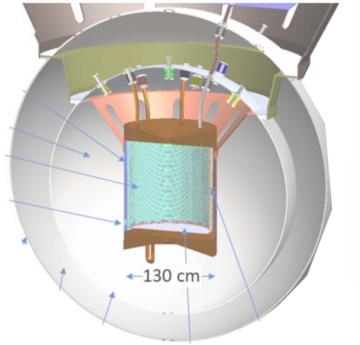
The SNOLAB Cryopit is the favourite location for nEXO and plenty of site engineering for us has been already carried out by SNOLAB



Fully developed, DoE-style, project structure



One to one mapping of subsystem to WBS
(+Management, systems engineering, integration)



Charge Readout Electronics (SLAC)
Subsystem Scientist:
L. Yang (UCSD)
Subsystem Manager:
A. Dragone (SLAC)

Photon Readout Electronics (BNL)
Subsystem Scientist:
M. Chiu (BNL)
Subsystem Manager:
L. DeMino (BNL)

TPC (PNNL)
Subsystem Scientist:
J. Orrell (PNNL)
Subsystem Manager:
A. Gorham (PNNL)

Photon Detector (BNL)
Subsystem Scientist:
D. Moore (Yale)
Subsystem Manager:
M. Worcester (BNL)

Computing, Control and Software (LLNL)
Subsystem Scientist:
S. Sangiorgio (LLNL)
Subsystem Manager:
TBD

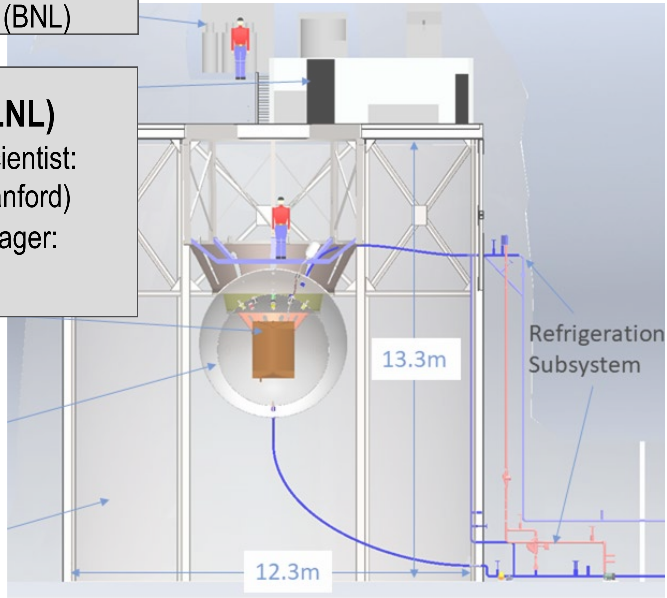
Radioactive Background Control (SLAC)
Subsystem Scientist:
A. Piepke (UA)
Subsystem Manager:
TBD

TPC Support Systems (LLNL)
Subsystem Scientist:
A. Pocar (Umass)
Subsystem Manager:
A. House (LLNL)

Xenon (LLNL)
Subsystem Scientist:
G. Gratta (Stanford)
System Manager:
TBD

Facility (SNOLAB)
Subsystem Scientist:
E. Caden
Subsystem Manager:
D. Hawkins

Outer Detector (SNOLAB)
Subsystem Scientist:
T. Brunner
Subsystem Manager:
D. Hawkins



The WBS is Detailed, Full Dictionary

nEXO

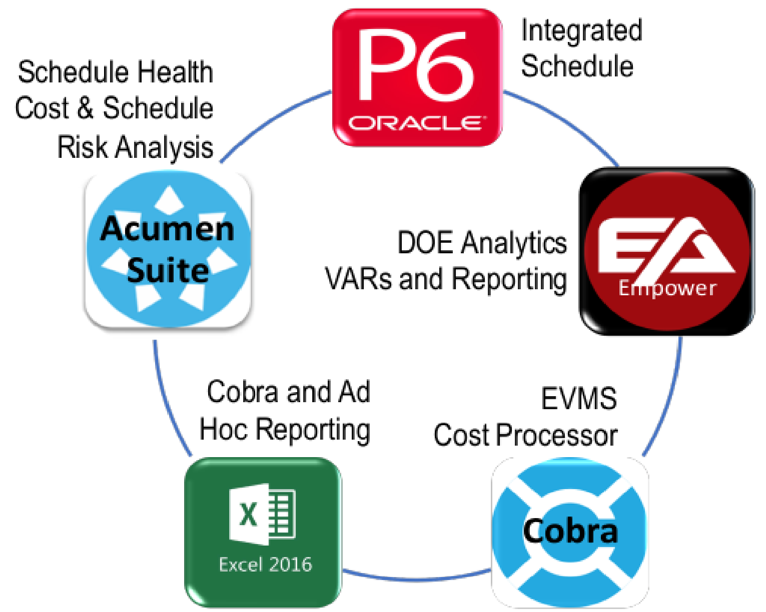
L2		L3	L4	Scope	CAM
1.01	Management	1.01.01		Management	Riot
		1.01.02		Project control	Riot
		1.01.03		QA and Safety	Riot
1.02	System engineering, Integration and commissioning	1.02.01		Systems Engineering	Hunt
		1.02.02	1.02.02.01	Integration and Commissioning Management	Nordby
			1.02.02.02	TPC Integration	Nordby
			1.02.02.03	Cryostat Integration	Nordby
			1.02.02.04	Facilities Operations and Management	Nordby
			1.02.02.05	nEXO Commissioning	Nordby
1.03	Time Projection Chamber	1.03.01		TPC Management	Gorham
		1.03.02		TPC Vessel	Gorham
		1.03.03		High Voltage and Field Cage	Gorham
		1.03.04		Charge Detector and Anode	Gorham
		1.03.05		TPC Cables and Interconnects	Gorham
		1.03.06		Calibration Systems	Gorham
1.04	Photon Detector	1.04.01		Photon Detector Management	Worcester
		1.04.02		SiPM Procurement	Worcester
		1.04.03		SiPM Test Facility	Worcester
		1.04.04		SiPM Tile Modules	Worcester
		1.04.05		Stave Assemblies	Worcester
1.05	TPC Support Systems	1.05.01		TPC Support Systems Management	House
		1.05.02		TPC Support Systems Cryostat	House
		1.05.03		Xenon Handling and Purification	House
		1.05.04		HFE Process and Refrigeration	House
1.06	Electronics	1.06.01	1.06.01.01	Charge Readout Electronics Management	Dragone
			1.06.01.02	Charge Readout ASIC	Dragone
			1.06.01.03	Charge Readout Daughter Board	Dragone
			1.06.01.04	Charge System Support Boards	Dragone
		1.06.02	1.06.02.01	Photon Readout Electronics Management	DeMino
			1.06.02.02	Photon Readout ASIC	DeMino
			1.06.02.03	Photon System Transition Board	DeMino
			1.06.02.04	Photon System Controller/Receiver Board	DeMino

L2		L3	L4	Scope	CAM
1.07	Radioactive Background Control	1.07.01		Radioactive Background Control Management	Acting - Piepke
		1.07.02		Radioactivity in Materials	Acting - Piepke
		1.07.03		Radon Outgassing	Acting - Piepke
		1.07.04		Exposure Based backgrounds	Acting - Piepke
		1.07.05		Surface Cleaning and Testing	Acting - Piepke
		1.07.06		Materials Synthesis and Industry Survey	Acting - Piepke
1.08	Computing, Controls and Software	1.08.01		CCS Management	Acting - Sangiorgio
		1.08.02		Slow Control	Acting - Sangiorgio
		1.08.03		DAQ	Acting - Sangiorgio
		1.08.04		Analysis Software	Acting - Sangiorgio
		1.08.05		Simulations Software	Acting - Sangiorgio
		1.08.06		Infrastructure Software	Acting - Sangiorgio
		1.08.07		Data and Computing Facilities	Acting - Sangiorgio
		1.08.08		Sensitivity and Science Readiness	Acting - Sangiorgio
1.09	Xenon	1.09.01		Management for Xenon sub-system	Acting - Riot
		1.09.02		Enriched Xenon procurement	Acting - Riot
		1.09.03		Xenon Assaying Systems	Acting - Riot
		1.09.04		Xenon Transfer Vessels	Acting - Riot
1.10	Outer Detector	1.10.01		Outer Detector Management	Hawkins
		1.10.02		Water Tank	Hawkins
		1.10.03		Muon Veto	Hawkins
		1.10.04		Water Circulation System	Hawkins
		1.10.05		Outer Detector Test Facility	Hawkins
1.11	Facilities	1.11.01		SNOLAB Facility Management	Hawkins
		1.11.02		SNOLAB Cryopit Infrastructure	Hawkins
		1.11.03		SNOLAB Clean Rooms	Hawkins
		1.11.04		SNOLAB LN2 Plant	Hawkins

Cost Estimate

- **Follows US accounting practices**
  - In particular, all project manpower is accounted for explicitly, typically at Nat'l lab rates
  - Contingency also properly accounted for
- **Bottom up: each subsystem generated a list of activities**
  - Description
  - Basis of estimate
  - Cost/labor
  - Risk Factors
- **~13,000 activities in the current plan**
- **Internal and external review**
  - Each item independently reviewed
  - Top level comparison with similar projects

EVMS Tool Set



Cost estimate example: Charge Readout ASIC prototyping excerpt

Activity ID	[illegible]tivity Name	Resource Id	Activity Type	Duration(d)	Labor (hrs)	Dollars	Global Milestone Level	nEXO Milestone Description	nEXO Risk Mitigation Item
CRE04130	Prototype 2 Charge Readout CRE ASIC test board multichannel readout firmware development	SL[illegible]	[illegible]ete	30	80	[illegible]			CRE-R2-1
CRE04140	Prototype 2 Charge Readout CRE ASIC test board multichannel readout software development from exisiting test suite	SL[illegible]	[illegible]ete	30	60	[illegible]			CRE-R2-1
CRE04230	Prototype 2 Charge Readout CRE ASIC digital backend functionality test	SLAC-EE3	Percent Complete	10	40	0			CRE-R2-1
CRE04240	Prototype 2 Charge Readout CRE ASIC preamp functionality test	SLAC-EE3	Percent Complete	[illegible]	[illegible]	[illegible]			CRE-R2-1
CRE04250	Prototype 2 Charge Readout CRE ASIC ADC functionality test	SLAC-EE3	Percent Complete	[illegible]	[illegible]	[illegible]			CRE-R2-2
CRE04260	Prototype 2 Charge Readout CRE ASIC LDO functionality test	SLAC-EE3	Percent Complete	10	40	0			CRE-R2-3
CRE04270	Prototype 2 Charge Readout CRE ASIC digital performance test	SLAC-EE3	Percent Complete	20	60	0			CRE-R2-1
CRE04280	Prototype 2 Charge Readout CRE ASIC preamp performance test	SLAC-EE4	Percent Complete	20	160	[illegible]			CRE-R2-2
CRE04290	Prototype 2 Charge Readout CRE ASIC ADC performance test	SLAC-EE5	Percent Complete	20	160	[illegible]			CRE-R2-3
CRE04300	Prototype 2 Charge Readout CRE ASIC LDO performance test	SLAC-EE3	Percent Complete	20	60	0			CRE-R2-1
CRE04310	COMP: Prototype 2 Charge Readout CRE ASIC Complete		0-100%	0	0	0	L4	Prototype 2 CRE ASIC tests complete	CRE-R2-2
CRE04320	Prepare Handled Prototype 2 ASIC for Assaying	SLAC-EE3	Percent Complete	20	10	0			
CRE04330	AVAIL: Handled Prototype 2 ASIC for Assaying		0-100%	0	[illegible]	[illegible]		Handled ASIC samples [illegible]leaned, bagged and ready for shipping	
CRE04340	Generate Prototype 2 test report	SLAC-EE4	Percent Complete	30	40	0			

Detailed activities

Resource code (in this case electrical engineer level 3)

If activities are a risk mitigation, risk reference is captured

Calendar duration in days

Cost here for M&S

Labor hours

Cost estimate example: Charge Readout ASIC prototyping excerpt

Activity ID	Activity Name	EDIA Code	Project Phase	nEXO Estimator Name	nEXO Estimate Date	nEXO Estimate Summary
CRE04130	Prototype 2 Charge Readout CRE ASIC test board multichannel readout firmware development	Eng[illegible]h specs.; conceptual, prelimi[illegible]s-built drawings, etc	Preliminary Design	Angelo Dragone	3/9/2021	SLAC-EE3 - 50 hrs for firmware dev, 20 hrs for debugging and [illegible]mentation
CRE04140	Prototype 2 Charge Readout CRE ASIC test board multichannel readout software development from existing test suite	Engin[illegible] - Design: A/E, tech specs.; conceptual, preliminary, and final design; as-built drawings, etc	Preliminary Design	Angelo Dragone	3/9/2021	SLAC-EE3 - [illegible], 10 hrs for debugging and [illegible]umentation
CRE04230	Prototype 2 Charge Readout CRE ASIC digital backend functionality test	Engineer - Design: A/E, tech specs.; conceptual, preliminary, and final design; as-built drawings, etc	Pre[illegible]	[illegible]	[illegible]021	SLAC-EE3 - 35 hr t[illegible]sing communication to the chip, 5 hrs documentation
CRE04240	Prototype 2 Charge Readout CRE ASIC preamp functionality test	Engineer - Design: A/E, tech specs.; conceptual, preliminary, and final design; as-built drawings, etc	Preliminary Design	Angelo Dragone	3/9/2021	SLAC-EE3 - 10 hrs setup, 70 hrs to check functionalities of all 64 preamp on the chip, 10 hrs documentation
CRE04250	Prototype 2 Charge Readout CRE ASIC ADC functionality test	Engineer - Design: A/E, tech specs.; conceptual, preliminary, and final design; as-built drawings, etc	Preliminary Design	[illegible]	[illegible]	[illegible]AC-EE3 - 10 hrs setup, 70 hrs to check all 64 ADC on the chip, 10 hrs documentation
CRE04260	Prototype 2 Charge Readout CRE ASIC LDO functionality test	Engineer - Design: A/E, tech specs.; conceptual, preliminary, and final design; as-built drawings, etc	Preliminary Design	[illegible]	[illegible]	[illegible]E3 - 35 hr testing on chip regulators, 5 hrs documentation
CRE04270	Prototype 2 Charge Readout CRE ASIC digital performance test	Engineer - Design: A/E, tech specs.; conceptual, preliminary, and final design; as-built drawings, etc	Preliminary Design	Angelo Dragone	3/9/2021	SLAC-EE3 - 50 hr measuring reliability of the backend communication, 10 hrs documentation
CRE04280	Prototype 2 Charge Readout CRE ASIC preamp performance test	Engineer - Design: A/E, tech specs.; conceptual, preliminary, and final design; as-built drawings, etc	Preliminary Design	Angelo Dragone	3/9/2021	SLAC-EE4 - 10 hrs setup, 2 hrs ea to measure noise of the preamp with difference loads, 64 channels, 12 hrs of debugging, 10 hrs documentation
CRE04290	Prototype 2 Charge Readout CRE ASIC ADC performance test	Engineer - Design: A/E, tech specs.; conceptual, preliminary, and final design; as-built drawings, etc	Preliminary Design	Angelo Dragone	3/9/2021	SLAC-EE5 - 10 hrs setup, 2 hrs ea to measure INL, DNL, and other performance parameter of ADCs, 64 channels, 12 hrs of debugging, 10 hrs documentation

EDIA Code for future reporting

Basis of estimate

Project Phase

Estimator name and date

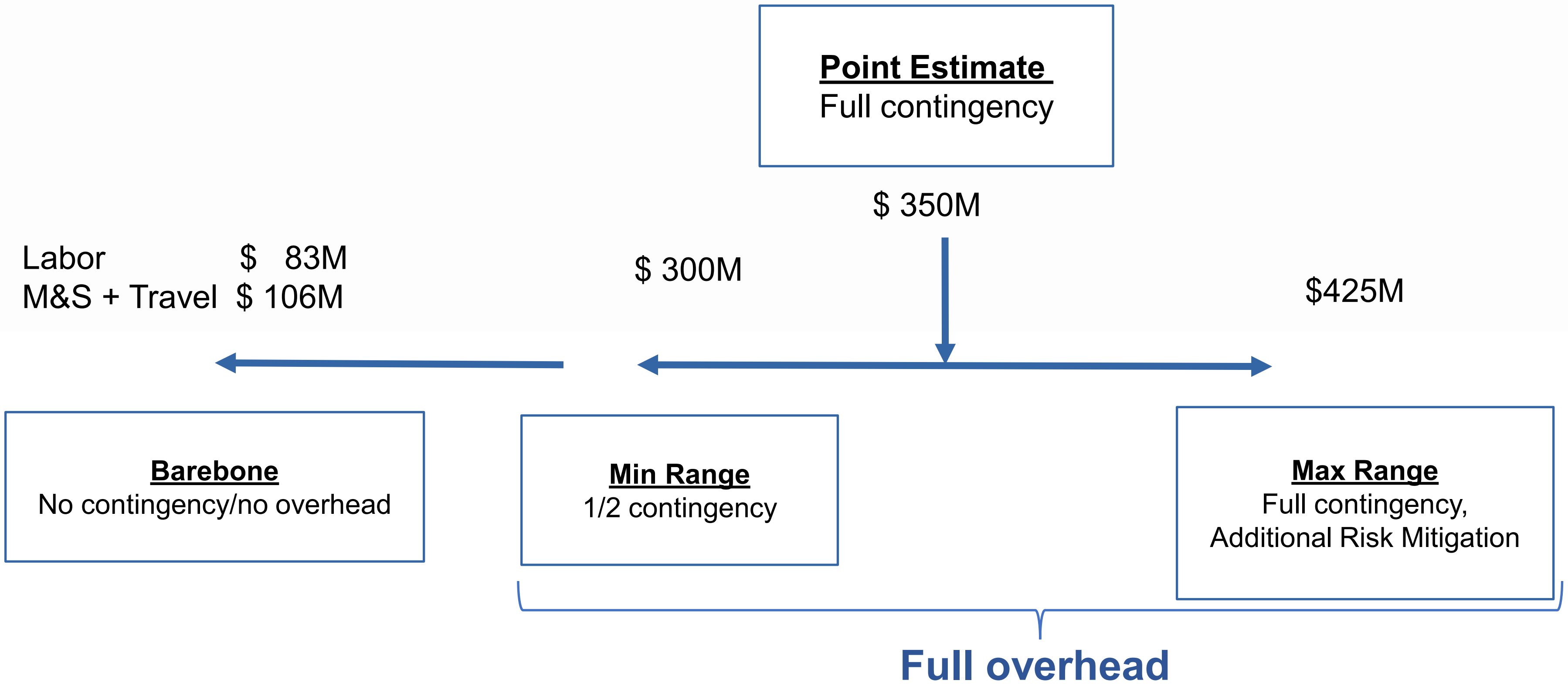
Cost estimate example: Charge Readout ASIC prototyping excerpt

Activity ID	Activity Name	Technical Risk Factor Description	Cost Risk Factor Description	Schedule Risk Factor Description	Location Risk Factor Description	Source Risk Factor Description	Min %	Most Likely %	Max %
CRE04130	Prototype 2 Charge Readout CRE ASIC test board multichannel readout firmware development	New design/procedure, nothing exotic	In-house estimate ba… previous similar exp…	…completion of non- …subsystem items	Domestic location	Multiple possible sources	77%	100%	153%
CRE04140	Prototype 2 Charge Readout CRE ASIC test board multichannel readout software development from existing test suite	New design/procedure, nothing exotic	In-house estimate ba… previous similar expe…ence	…completion of non- critical path subsystem items	Domestic location	Multiple possible sources	77%	100%	153%
CRE04230	Prototype 2 Charge Readout CRE ASIC digital backend functionality test	Extensive modifications to an existing design/procedure	In-house estimate based on previous similar experience	Delays completion of critical path subsystem items	Domestic location	Multiple possible sources	78%	100%	155%
CRE04240	Prototype 2 Charge Readout CRE ASIC preamp functionality test	Extensive modifications to an existing design/procedure	In-house estimate based on previous similar experience	Delays completion of critical path subsystem items	Domestic location	Multiple possible sources			
CRE04250	Prototype 2 Charge Readout CRE ASIC ADC functionality test	Extensive modifications to an existing design/procedure	In-house estimate based on previous similar experience	Delays completion of critical path subsystem items	Domestic location	Multiple possible sources			
CRE04260	Prototype 2 Charge Readout CRE ASIC LDO functionality test	Extensive modifications to an existing design/procedure	In-house estimate based on previous similar experience	Delays completion of critical path subsystem items	Domestic location	Multiple possible sources	78%	100%	155%
CRE04270	Prototype 2 Charge Readout CRE ASIC digital performance test	Extensive modifications to an existing design/procedure	In-house estimate based on previous similar experience	Delays completion of critical path subsystem items	Domestic location	Multiple possible sources	78%	100%	155%
CRE04280	Prototype 2 Charge Readout CRE ASIC preamp performance test	Extensive modifications to an existing design/procedure	In-house estimate based on previous similar experience	Delays completion of critical path subsystem items	Domestic location	Multiple possible sources	78%	100%	155%
CRE04290	Prototype 2 Charge Readout CRE ASIC ADC performance test	Extensive modifications to an existing design/procedure	In-house estimate based on previous similar experience	Delays completion of critical path subsystem items	Domestic location	Multiple possible sources	78%	100%	155%
CRE04300	Prototype 2 Charge Readout CRE ASIC LDO performance test	Extensive modifications to an existing design/procedure	In-house estimate based on previous similar experience	Delays completion of critical path subsystem items	Domestic location	Multiple possible sources	78%	100%	155%

Risk Factors

Uncertainty range computed from risk factors

nEXO cost estimate summary



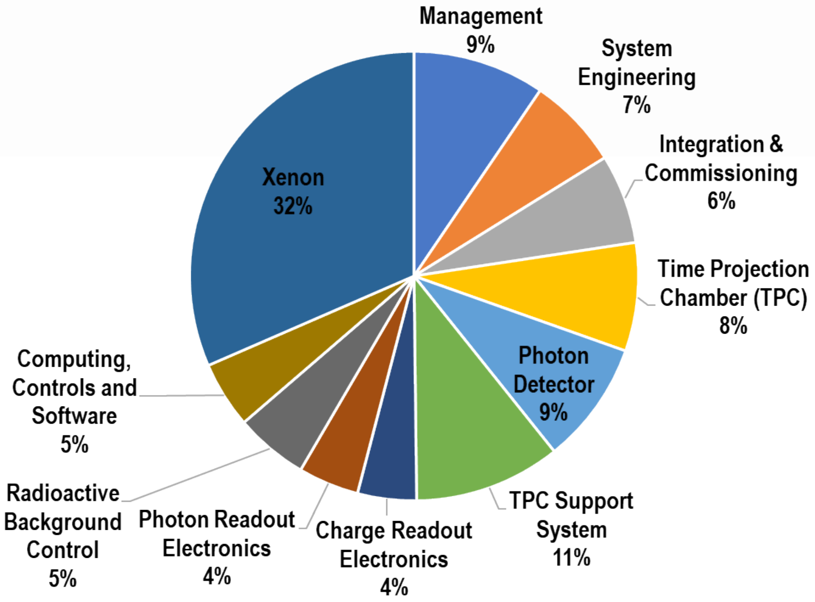
- Assumes SNOLAB/CFI contributions
- FY22 start, escalation and contingency included

Cost development and assumptions

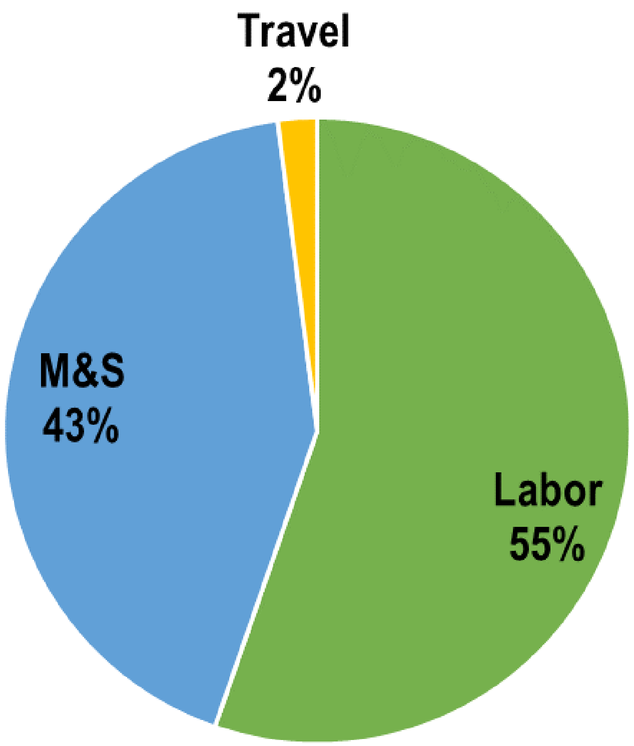
- The cost estimate was developed bottom-up from the 13 separate major sub-systems teams.
- The cost is a roll-up of 13,288 work packages (activities), each defined with the basis for the estimate (justification), number of hours/cost of procurement, resource type, estimate confidence factors covering 24 institutions and over 350 resource types. All activities are in P6.
- The base cost is in FY22 rates as collected from each institution. Escalation was applied based on the preliminary schedule and uses the LLNL standard yearly escalation rate of 4.2% for labor and 2% for Procurement. The project start date was set to 10/01/2021 (FY22) and escalation was applied starting in FY23. The project duration was determined to be 6.5 years.
- The cost assumes that TEC funding has preferential rates when available at the institution for MIE project. This special rate is applied to LLNL and SLAC. BNL and PNNL may provide preferential rates before CD-1.
- All work was included whether it is contributed or not to ensure the full scope is understood. Canadian contribution cost are in CAD $. However, only project cost were selected to establish the "DOE Project" costs.
- Procurement cycles have been detailed and incorporated in the estimate, based on standard procurement cycles at US national laboratories.

nEXO – DOE project cost

WBS		FY22 Direct ($K)	Burden ($K)	Escalation ($K)	Total ($K)
1.01	Management	$12,258	$8,894	$2,595	**$23,747**
1.02.01	Systems Engineering	$8,513	$6,321	$1,801	**$16,634**
1.02.02	Integration & Commissioning	$11,948	$2,432	$1,680	**$16,061**
1.03	Time Projection Chamber (TPC)	$12,062	$6,320	$1,095	**$19,477**
1.04	Photon Detector	$14,419	$6,267	$1,396	**$22,082**
1.05	TPC Support System	$19,282	$5,853	$1,234	**$26,369**
1.06.01	Charge Readout Electronics	$8,356	$1,585	$661	**$10,602**
1.06.02	Photon Readout Electronics	$5,644	$4,730	$549	**$10,922**
1.07	Radioactive Background Control	$8,834	$3,396	$912	**$13,142**
1.08	Computing, Controls and Software	$6,944	$4,118	$888	**$11,950**
1.09	Xenon	$71,605	$6,451	$624	**$78,679**
1.10	Outer Detector	*Contributed*	*Contributed*	*Contributed*	*Contributed*
1.11	Facilities	*Contributed*	*Contributed*	*Contributed*	*Contributed*
Sub-Total		**$179,863**	**$56,367**	**$13,435**	**$249,665**
Contingency (40%)					**$99,866**
Total Project Cost					**$349,532**

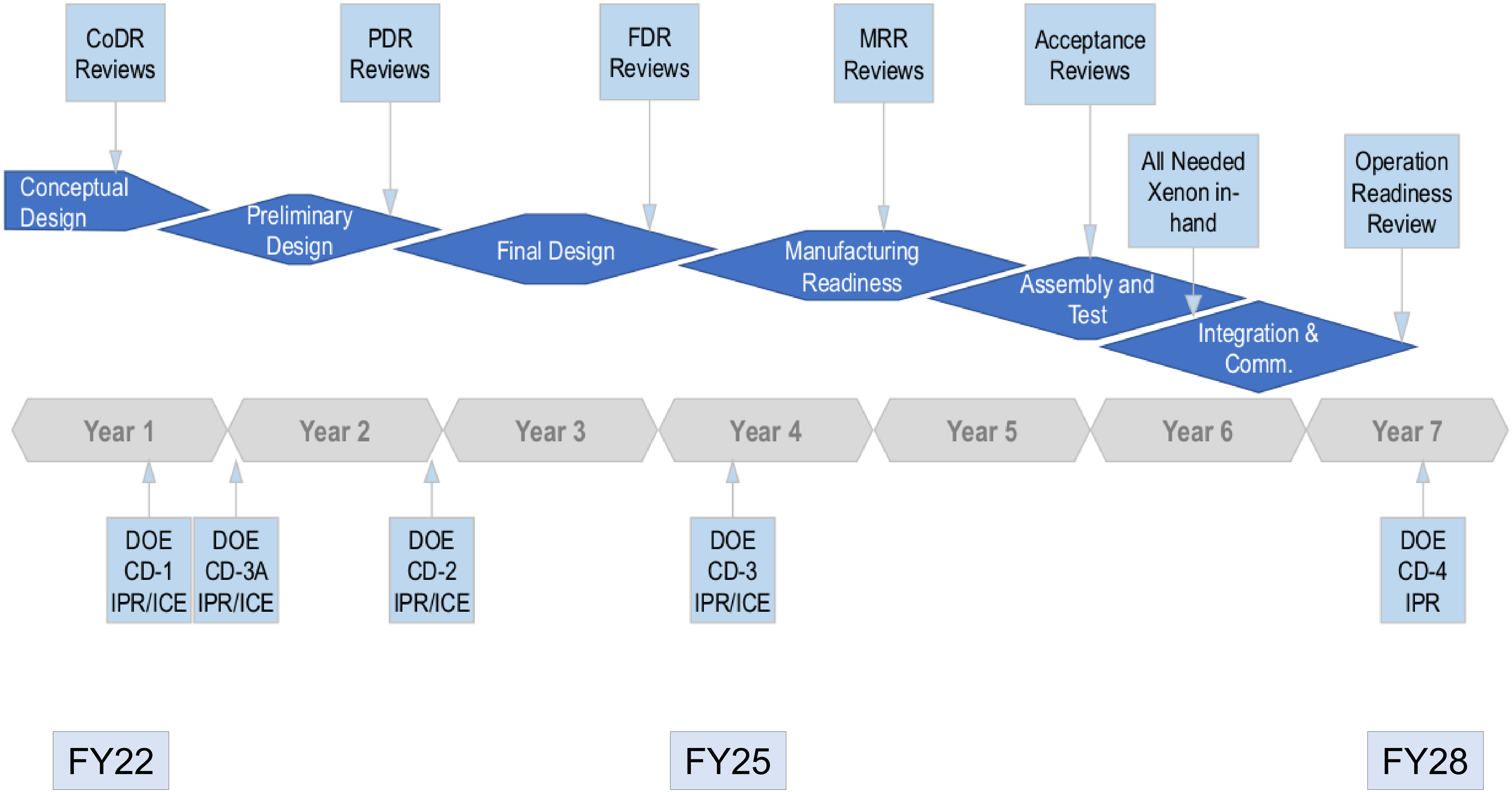


nEXO – DOE project cost by labor/M&S/travel



WBS		Labor ($K)	M&S ($K)	Travel ($K)	Total ($K)
1.01	Management	$21,884	$396	$1,468	**$23,747**
1.02.01	Systems Engineering	$15,716	$192	$727	**$16,634**
1.02.02	Integration & Commissioning	$14,511	$1,007	$544	**$16,061**
1.03	Time Projection Chamber (TPC)	$16,294	$2,892	$291	**$19,477**
1.04	Photon Detector	$10,286	$11,474	$321	**$22,082**
1.05	TPC Support System	$12,405	$13,680	$284	**$26,369**
1.06.01	Charge Readout Electronics	$8,979	$1,541	$82	**$10,602**
1.06.02	Photon Readout Electronics	$8,791	$1,902	$230	**$10,922**
1.07	Radioactive Background Control	$8,486	$4,095	$560	**$13,142**
1.08	Computing, Controls and Software	$10,866	$889	$195	**$11,950**
1.09	Xenon	$9,823	$68,537	$319	**$78,679**
1.10	Outer Detector	*Contributed*	*Contributed*	*Contributed*	*Contributed*
1.11	Facilities	*Contributed*	*Contributed*	*Contributed*	*Contributed*
	Sub-Total	**$138,041**	**$106,606**	**$5,019**	**$249,665**
	Contingency (40%)				**$99,866**
	Total Project Cost				**$349,532**

Schedule



First publication with data from nEXO

nEXO

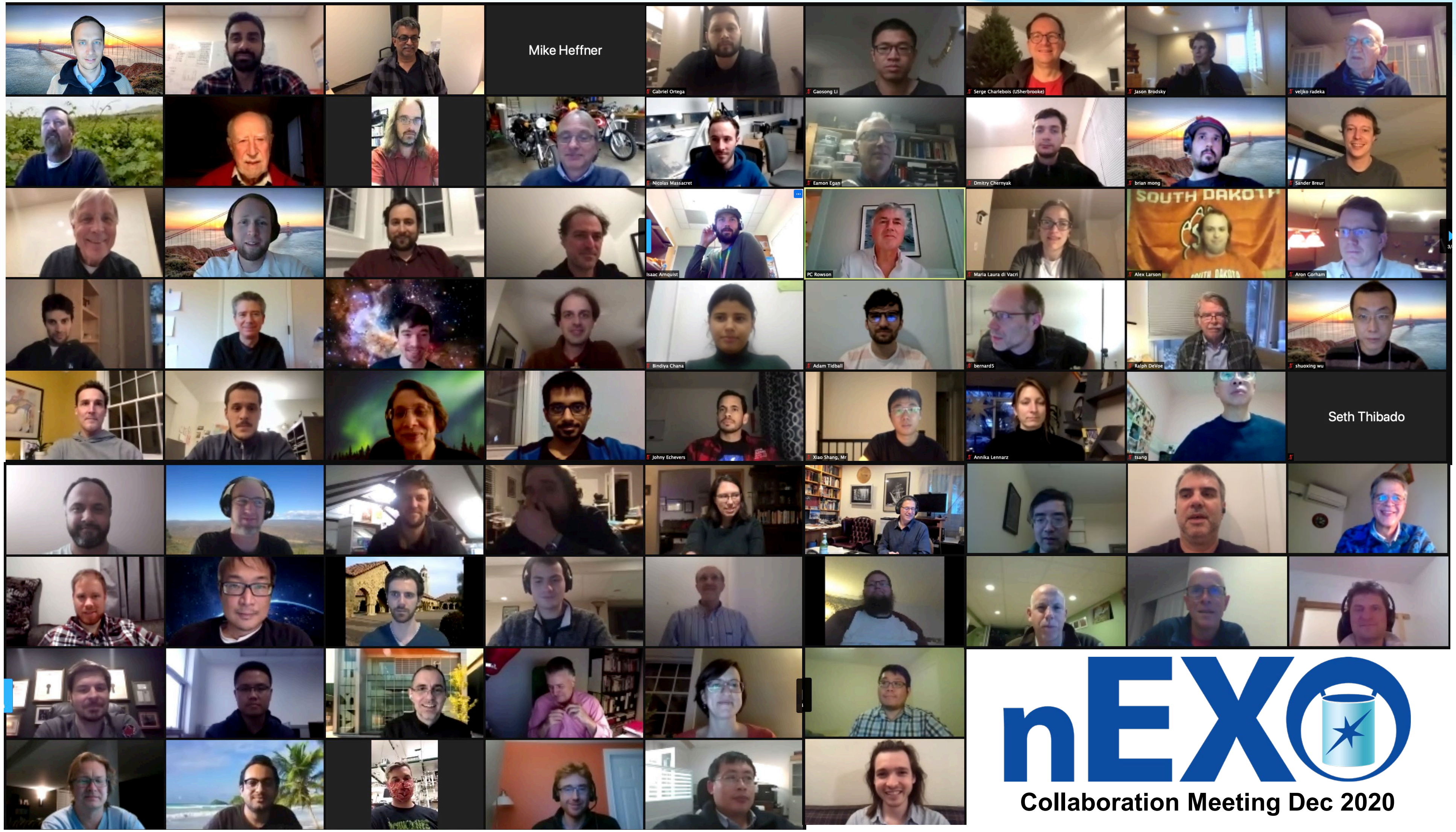
University of Munster (Germany)
Skyline (USA)
Subatech (France)
U of Western Cape (South Africa)

all joined the collaboration in the last year

nEXO is a world-wide effort, including, for the time being, 9 Countries, 33 institutions, 186 collaborators

More colleagues with interests in the science, the detector technology (or both) are encouraged to discuss possible collaboration.

(Part of) The nEXO Collaboration



nEXO

Collaboration Meeting Dec 2020