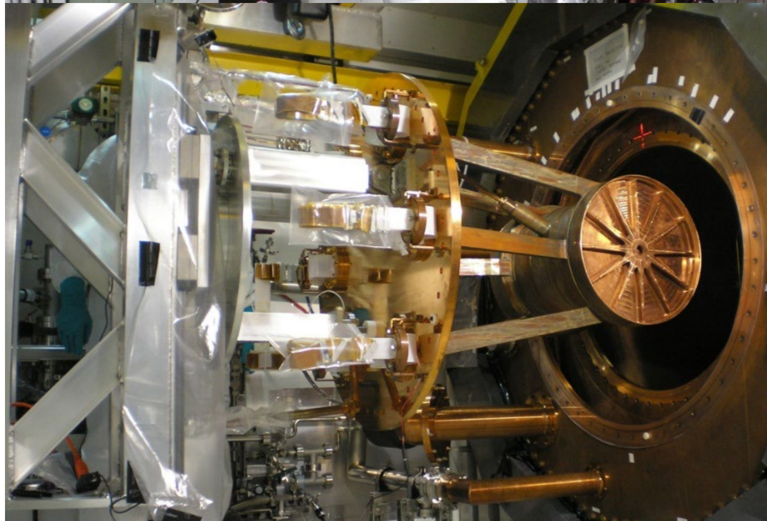
Hunting for Majorana neutrinos with nEXO

Thomas Brunner
McGill University and TRIUMF

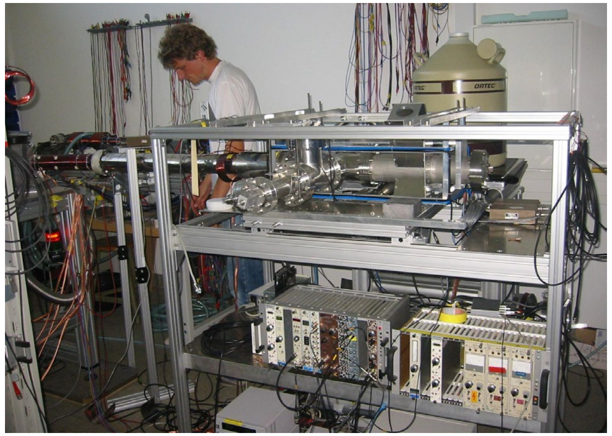
The summer particle (astro)physics workshop

May 10, 2024

https://www.hep.physics.mcgill.ca/neutrino



My Career Path



Studied Physics at the Technical University Munich (2001 – 2011)

- Undergraduate research project
  - Programming of positron beam line in LabView
- Diploma thesis (MSc equivalent)
  - Investigation of positronium formation on cold surfaces
- PhD project, stationed at TRIUMF, Vancouver
  - In-trap decay spectroscopy with the TITAN EBIT

Post doctoral research fellow at Stanford (2011 – 2015)

- EXO-200, nEXO, and Ba-tagging

Assistant professor at McGill (2015 – 2020)

- EXO-200, nEXO, Ba-tagging, and in-trap decay spectroscopy

Associate professor at McGill (2020 – now)

- nEXO, Ba-tagging, and in-trap decay spectroscopy
- Parental leave for five months in 2021

(Condensed matter physics)

↓

Atomic physics

↓

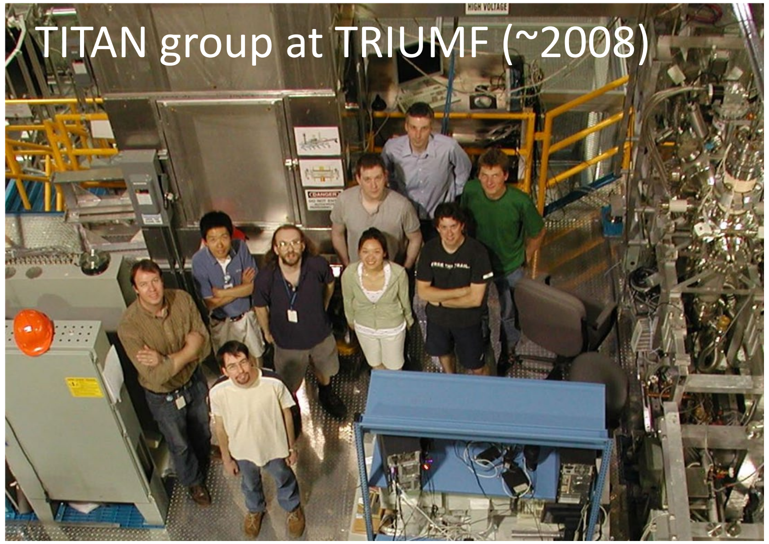
Nuclear physics
(decay spectroscopy and
mass measurements)

↓

Particle/neutrino/nuclear physics

Don't be afraid to change fields!

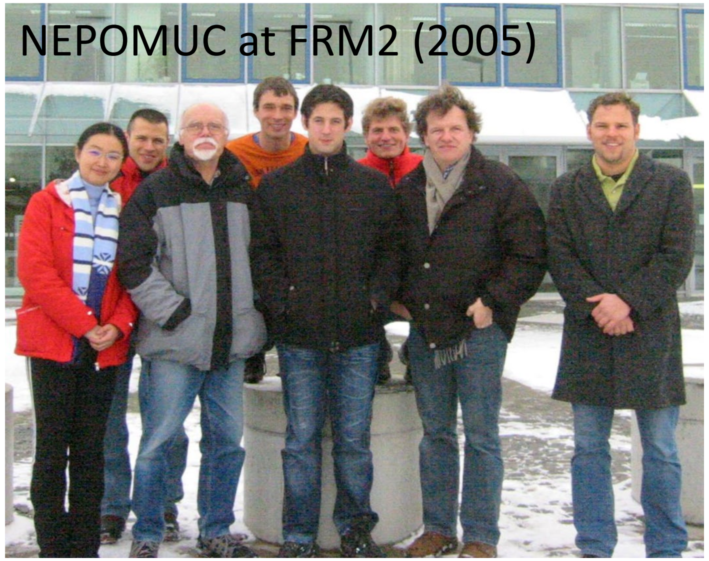
I enjoy research because of the people

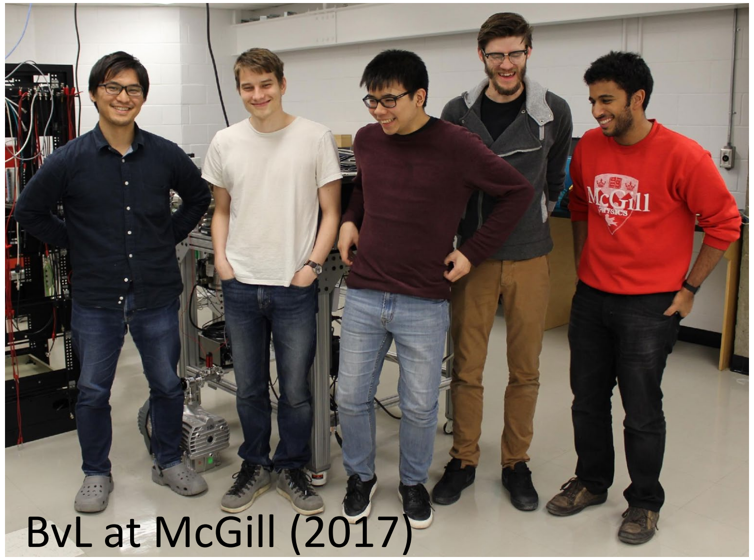

TITAN group at TRIUMF (~2008)


BvL at McGill (2022)


TRISTAN group (sabbatical 2021)

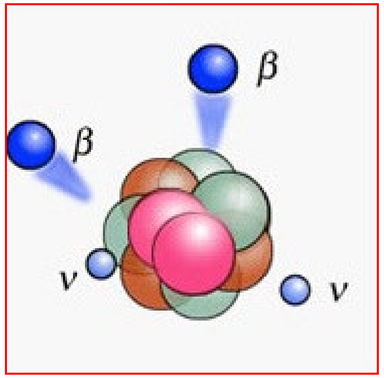

Gratta group at Stanford (2015)


NEPOMUC at FRM2 (2005)


BvL at McGill (2017)

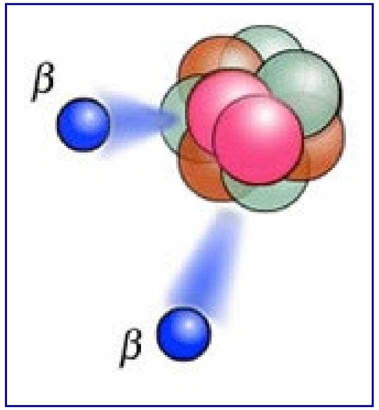
How to search for Majorana neutrinos?

Double Beta Decay



2νββ

$T_{1/2} \approx 10^{20}$ y

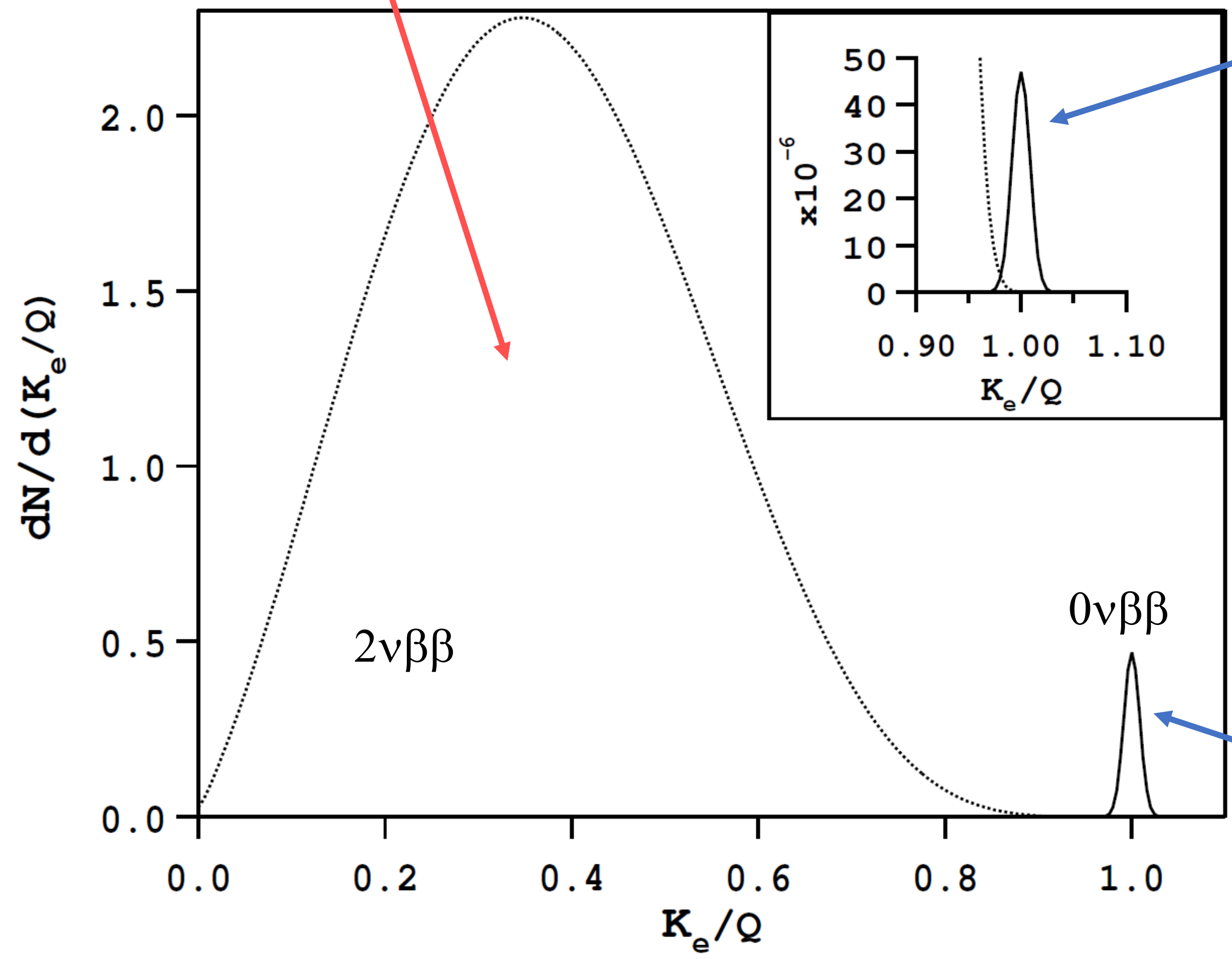


0νββ

$T_{1/2} > 10^{25\text{-}26}$ y

2νββ spectrum (normalized to 1)

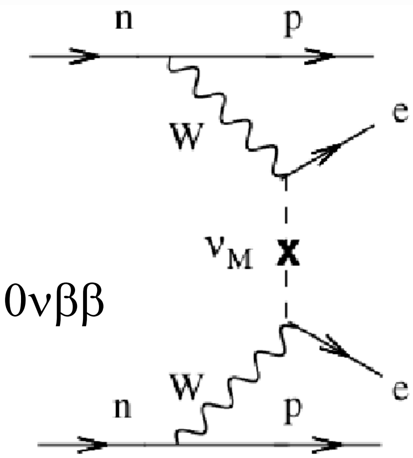
[arXiv:hep-ph/0611243]



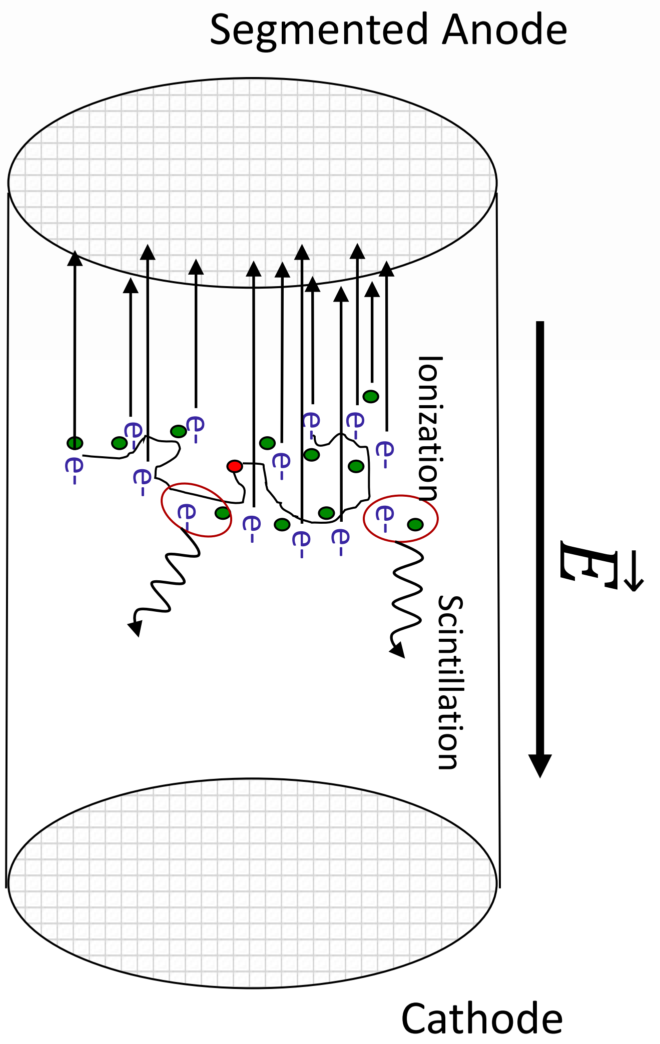
0νββ peak (normalized to 10^{-6})

0νββ peak (normalized to 10^{-2})

0νββ



Searching for $0\nu\beta\beta$ in ^{136}Xe with liquid Xe TPC nEXO



^{136}Xe is great to study because:

- Good $0\nu\beta\beta$ peak location above most bgnds.
- Easy to enrich.
- We know how to build a detector out of it!

<u>Natural radiation decay rates</u>

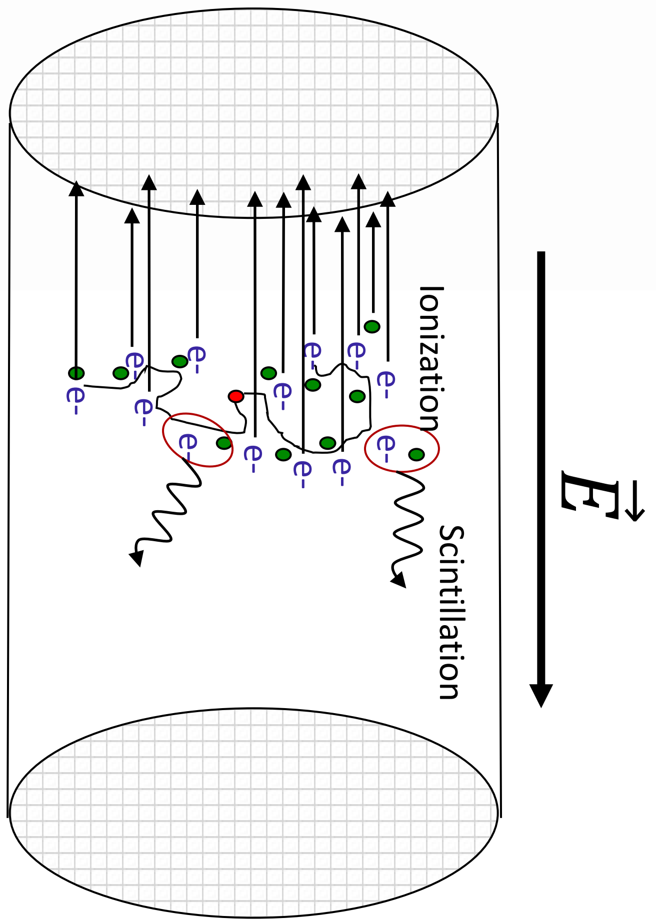
A banana	~10 decays/s
A bicycle tire	~0.3 decays/s
1 l outdoor air	~1 decay/min
100 kg of ^{136}Xe (2ν)	~1 decay/10 min

$T_{1/2}^{0\nu} > 10^{25}$ years !!

→Need:

- o high target mass
- o high exposure
- o low background rate
- o good energy resolution

nEXO's 0νββ search with a liquid Xe TPC



Liquid-Xe Time Projection Chamber (TPC)

- Xe is used both as the source and detection medium.
- LXe is continuously recirculated and purified.
- LXe TPCs are well understood. As a fully homogeneous detector, it precisely measures backgrounds in situ.

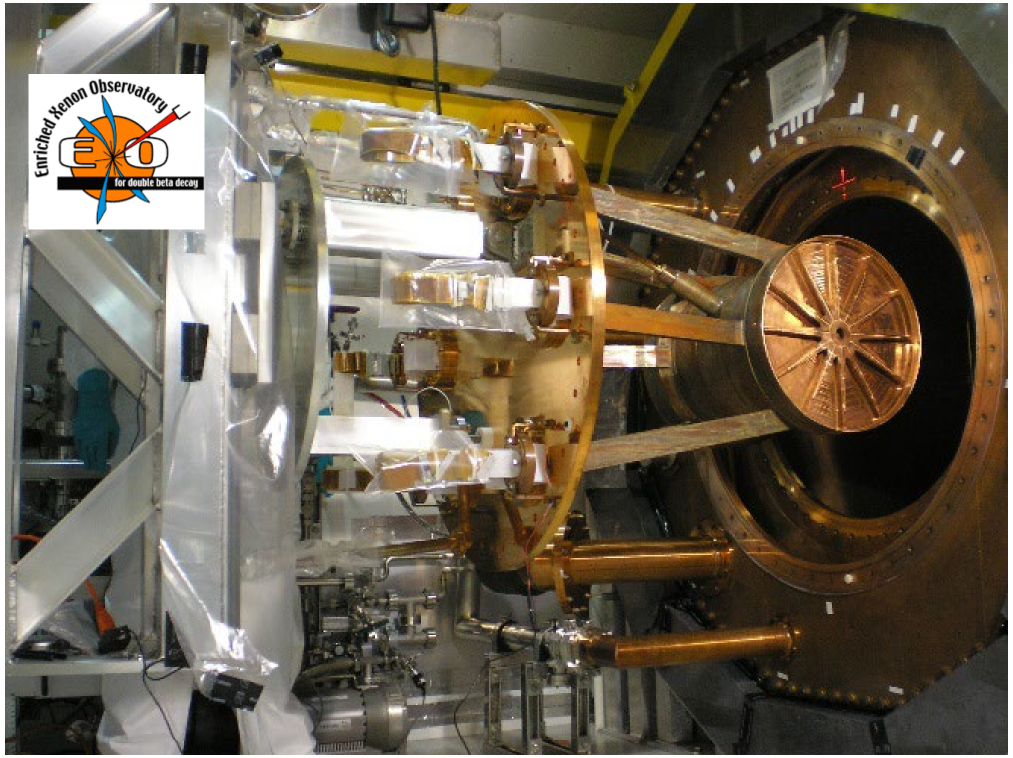
  → **No internal materials (other than Xe), making nEXO uniquely robust against unknown backgrounds**

- Multiparameter measurement from scintillation light and ionization signal:
  1. **Energy** from combined scintillation/ionization
  2. **Topology**, e.g., single-site or multi-site event
  3. **Position distribution** from 3D event reconstruction
  4. **Particle identification** from scintillation/ionization ratio

Searching for 0νββ in ^{136}Xe – a phased approach

EXO-200 at WIPP (Decommissioned in Dec. 2018)**:**

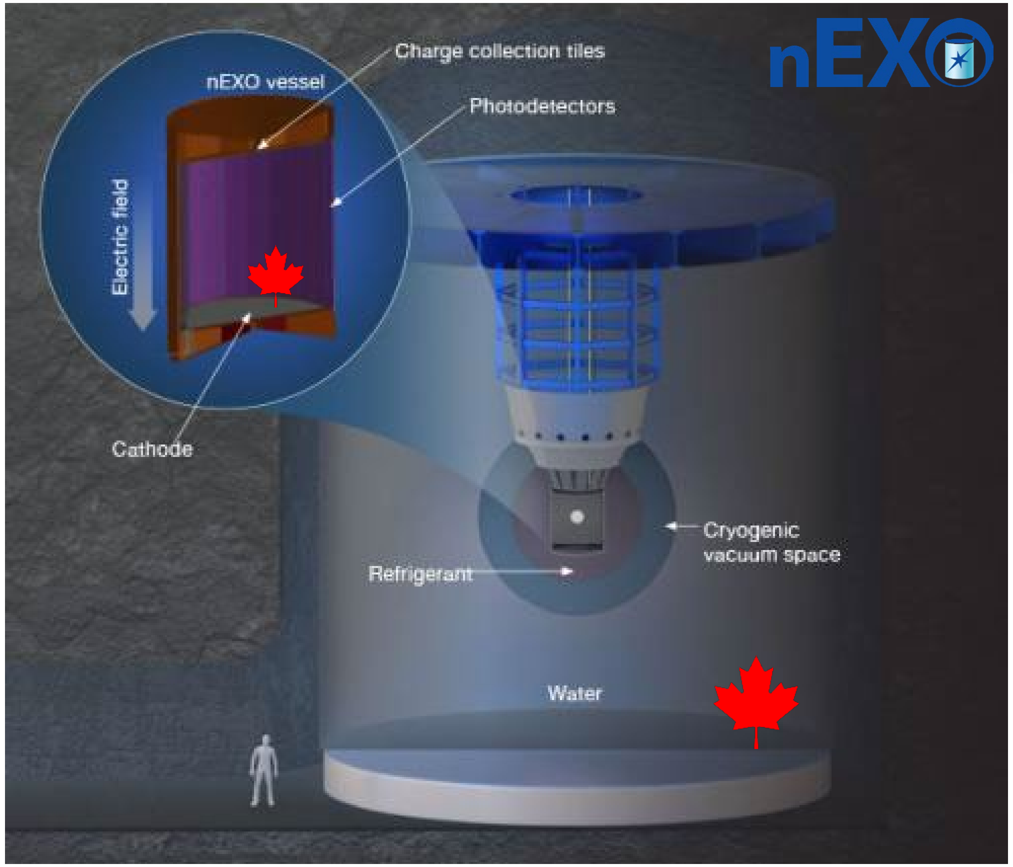
- EXO-200 first 100-kg class ββ experiment
- 175 kg liquid-Xe TPC with ~80% Xe-136
- Discovered 2νββ in Xe-136
- **Demonstrated excellent background identification through multiplicity and location of events in TPC**



https://www-project.slac.stanford.edu/exo/

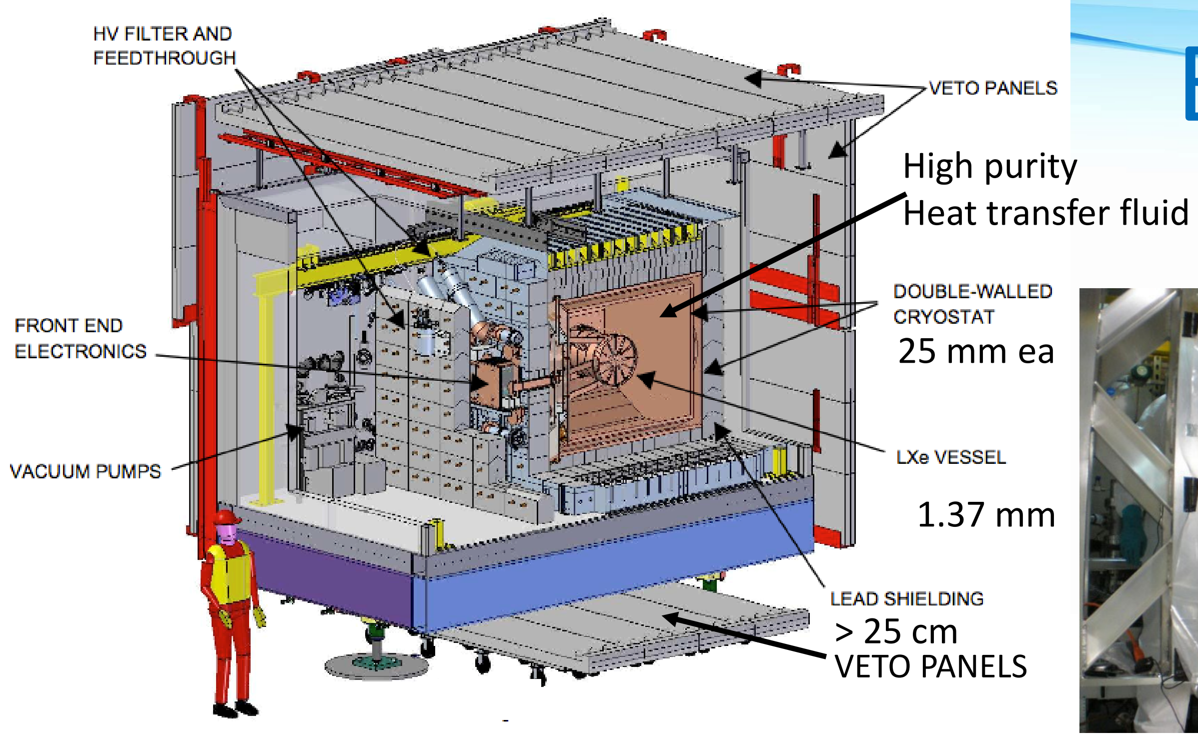
nEXO:

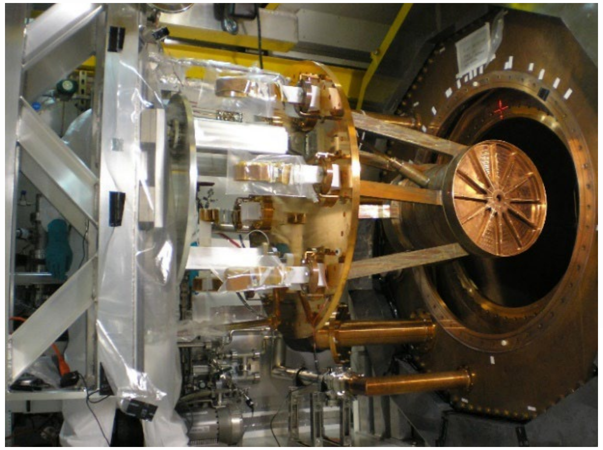
- 5-tonne liquid Xe TPC
- Enriched in Xe-136 at ~90%
- SNOLAB cryopit preferred location by collaboration

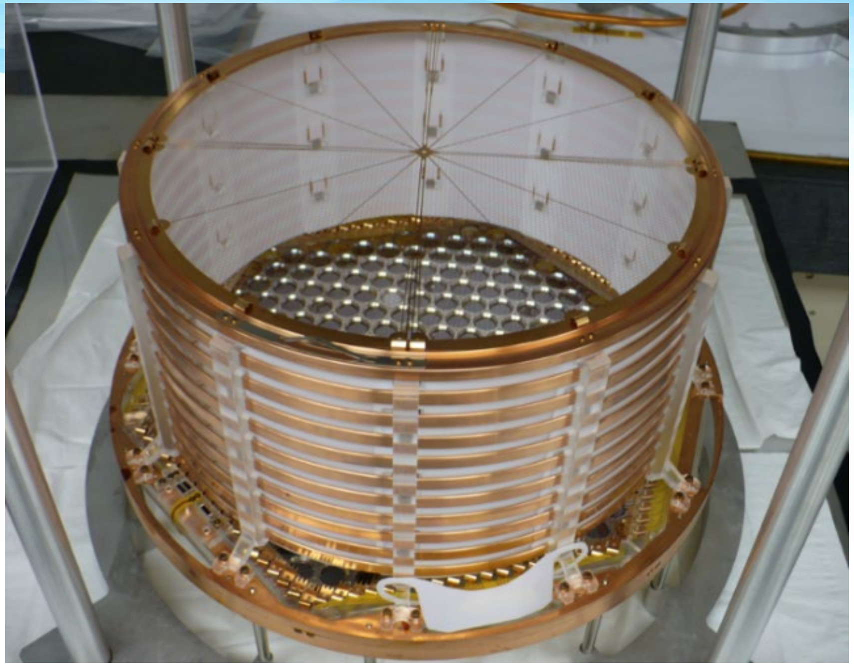


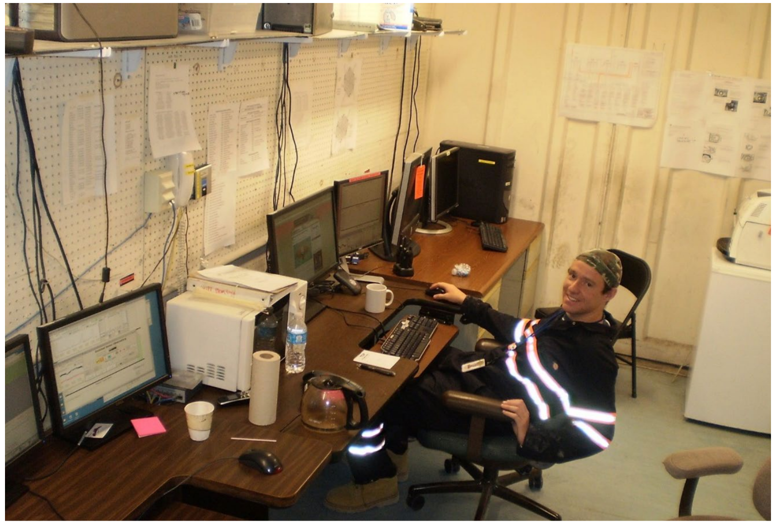
https://nexo.llnl.gov/

EXO-200


HV FILTER AND
FEEDTHROUGH
VETO PANELS
High purity
Heat transfer fluid
FRONT END
ELECTRONICS
DOUBLE-WALLED
CRYOSTAT
25 mm ea
VACUUM PUMPS
LXe VESSEL
1.37 mm
LEAD SHIELDING
> 25 cm
VETO PANELS

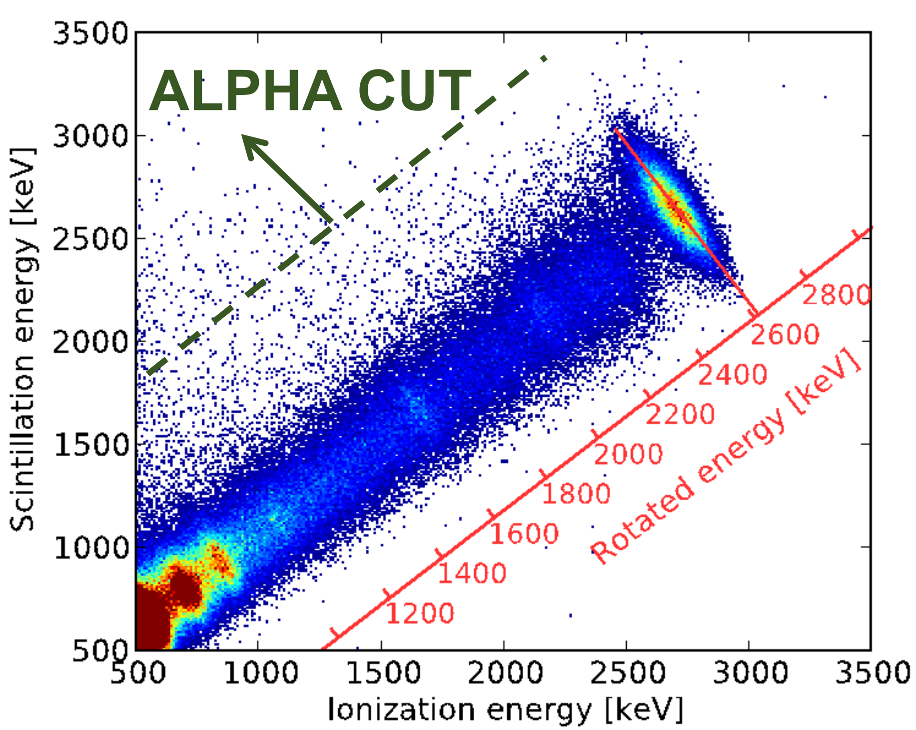




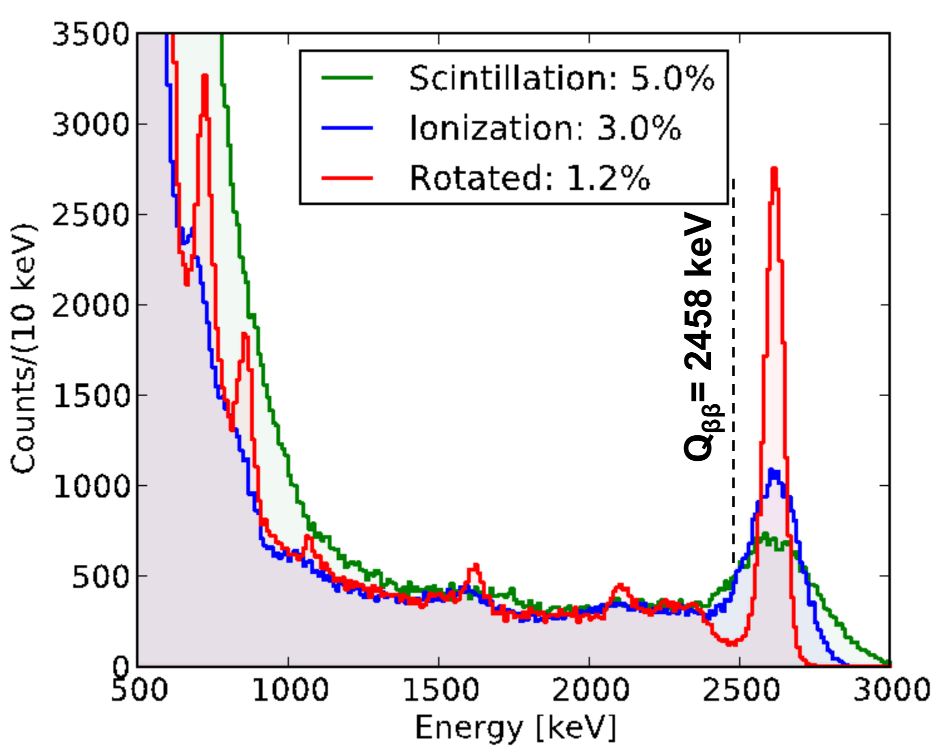


Energy measurement (EXO-200 data)

Scintillation vs. ionization, ^{228}Th calibration:



Reconstructed energy, ^{228}Th calibration:

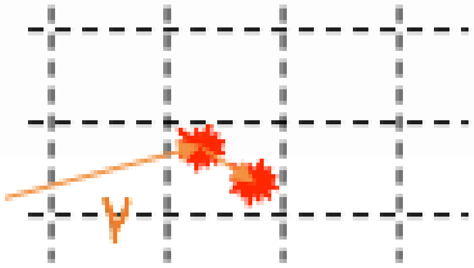


- Anticorrelation between scintillation and ionization in LXe known since early EXO R&D and now standard in LXe detectors [E.Conti et al. Phys Rev B 68 (2003) 054201]
- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- EXO-200 has achieved ~ 1.15% (PRL123,161802(2019)) energy resolution at the ββ decay Q value in Phase II

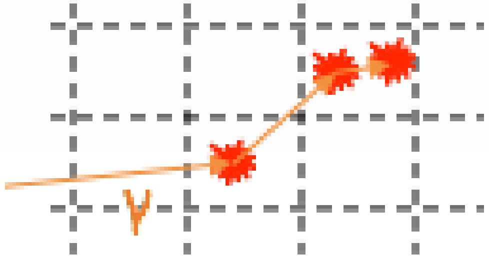
Position and multiplicity (EXO-200 data)

Allows for background measurement and reduction

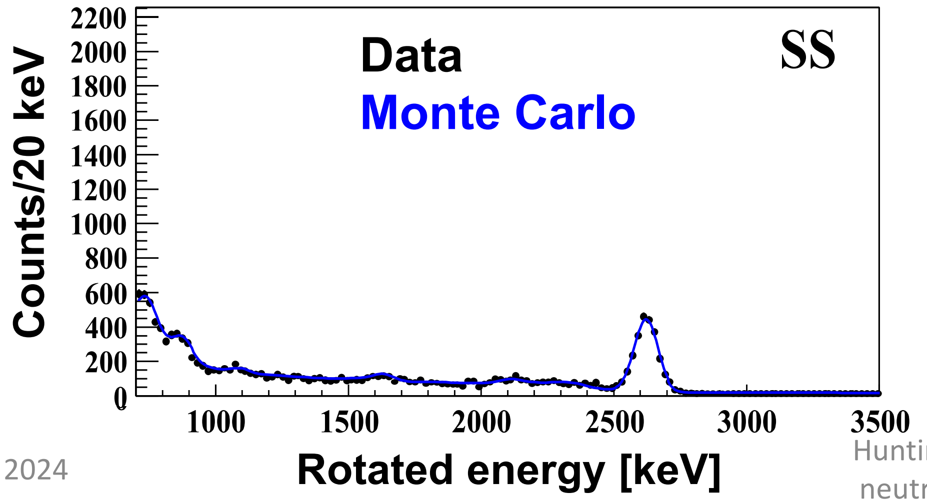
Events with **> 1** charge cluster: multi-site events (MS)
Events with **1** charge cluster: single-site events (SS)



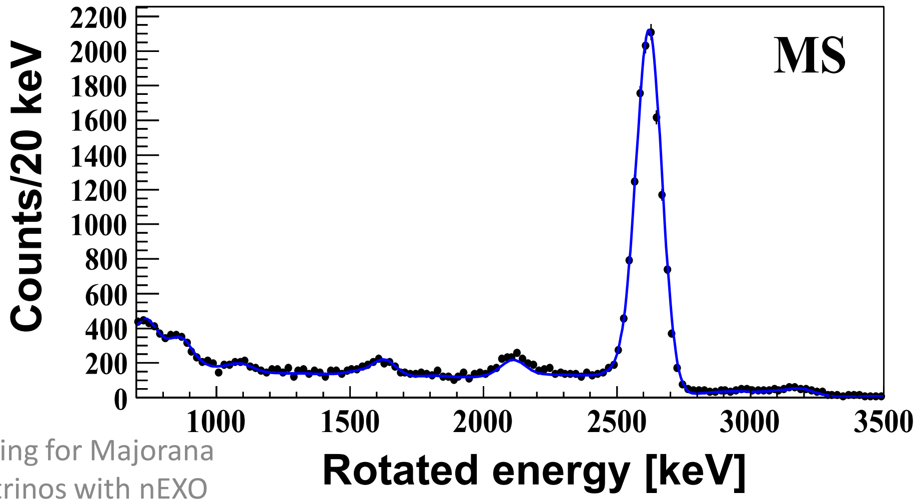
$0\nu\beta\beta$: ~90% SS
γ-rays: ~15% SS at $0\nu\beta\beta$ Q-value



^{228}Th calibration data, SS:



^{228}Th calibration data, MS:

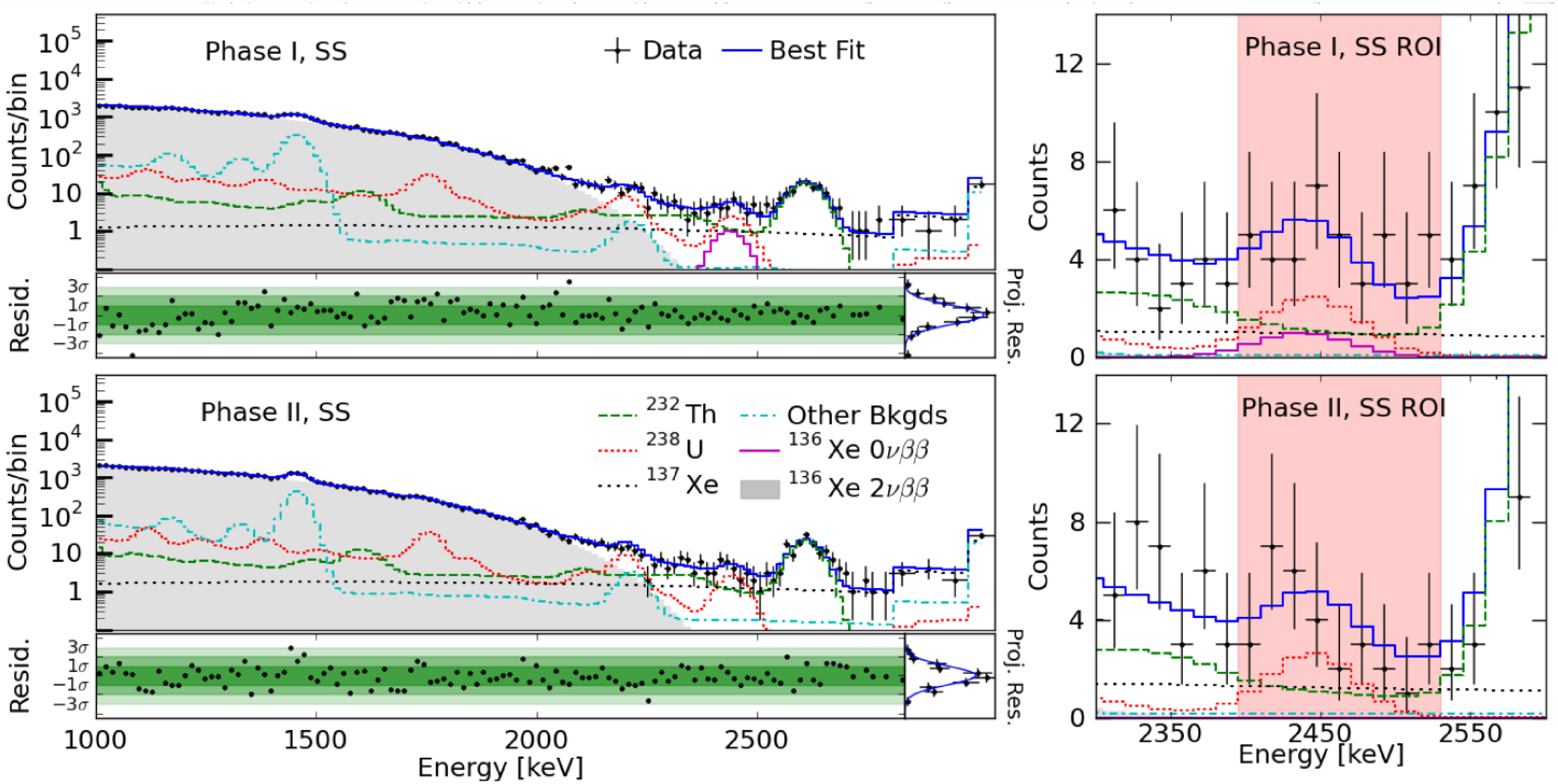


Final EXO-200 Results

Slide from: M. Jewell
September, 2019
TAUP2019, Toyama, Japan

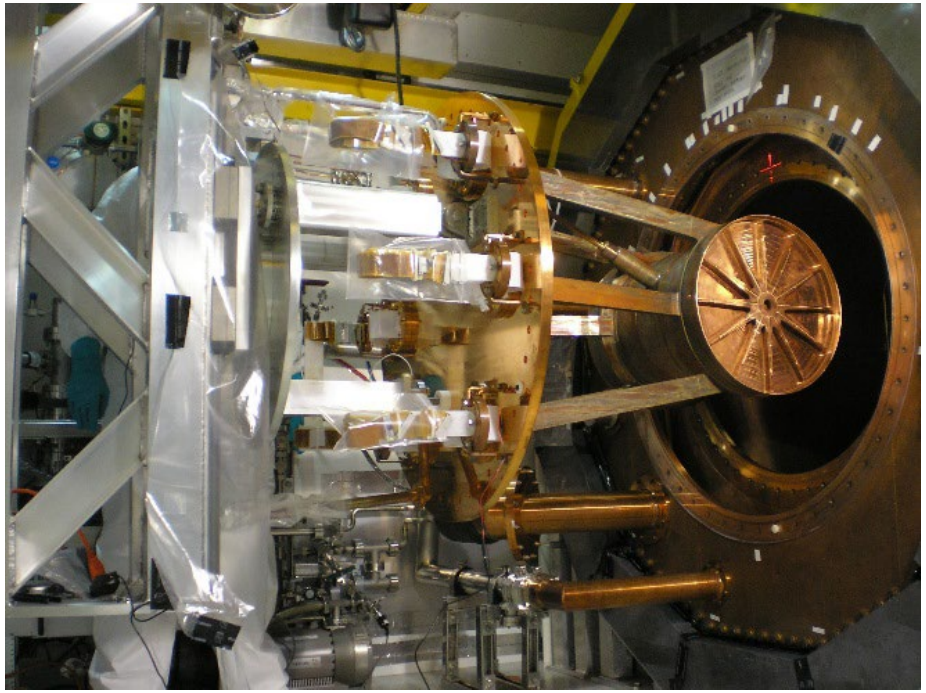
No statistically significant 0νββ signal observed

PRL 123 (2019) 161802



EXO-200 0νββ results

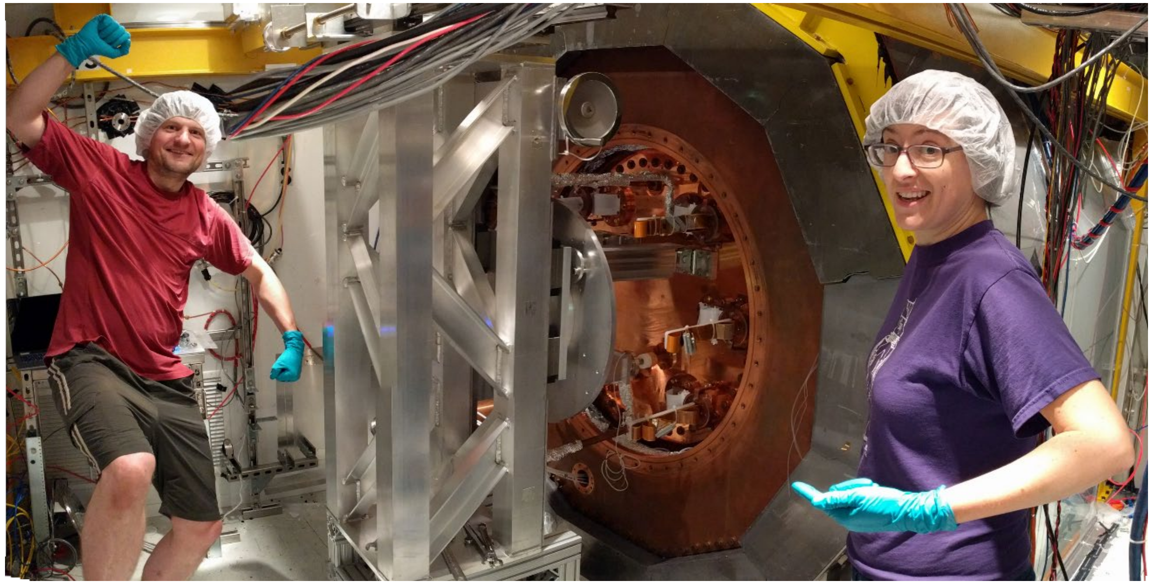
- First 100 kg-class experiment to take data.
- Excellent background, very well predicted by the massive material characterization program (and the simulation) → ***This is essential for nEXO design.***
- More papers on non-ββ decay physics.



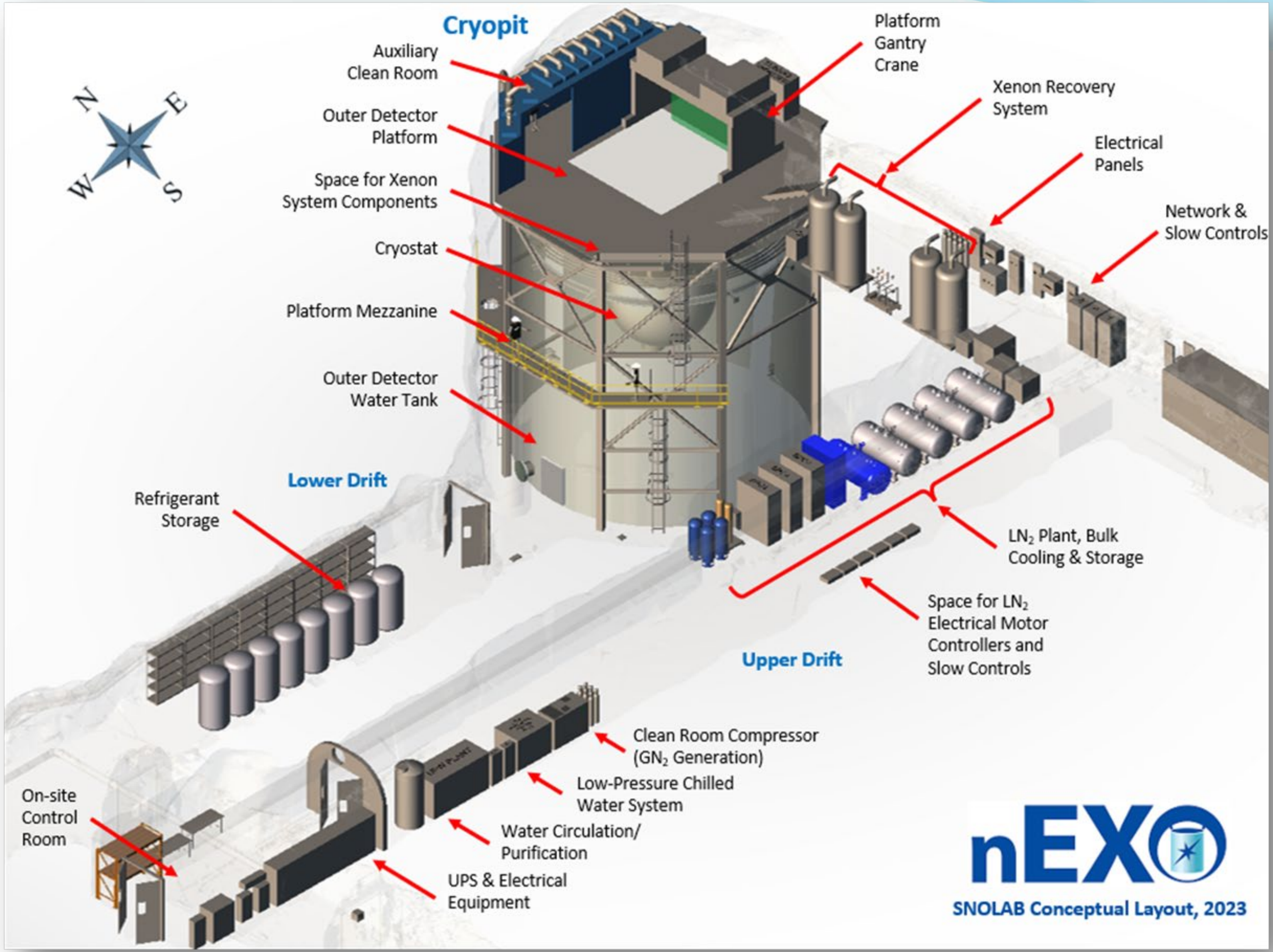
2012: Phys.Rev.Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: Phys. Rev. Lett. 123 (2019) 161802

Final result
Phase I+II: 234.1 kg yr of ^{136}Xe exposure
Limit: $T_{1/2}^{0\nu\beta\beta}$ > 3.5×10^{25} yr (90% CL)
$\langle m_{\beta\beta}\rangle$ < (93 -286) meV
Sensitivity: 5.0×10^{25} yr

EXO-200 decommissioning



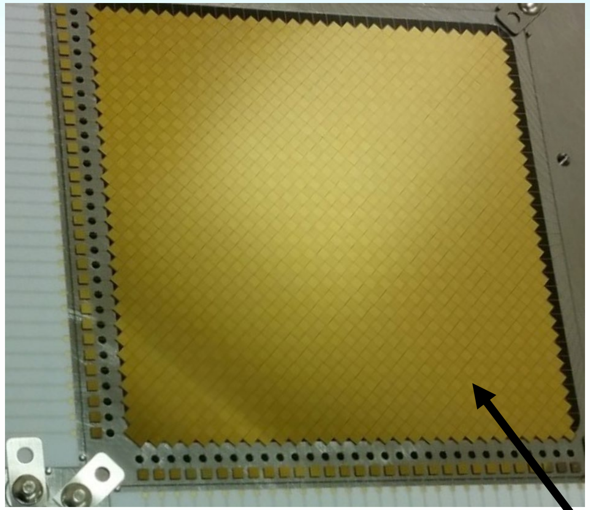
nEXO at SNOLAB



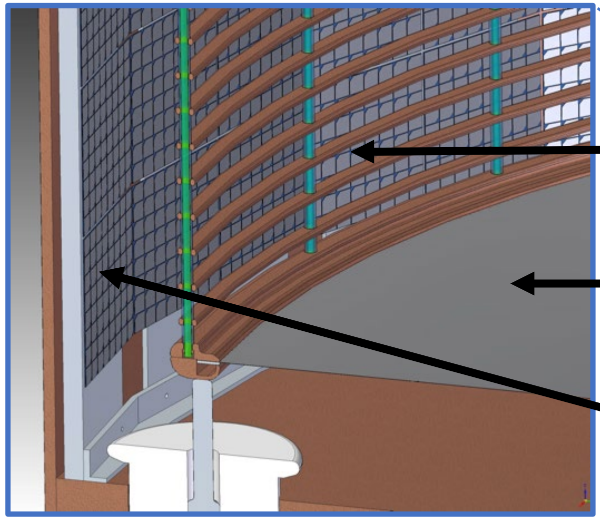
The Cryopit

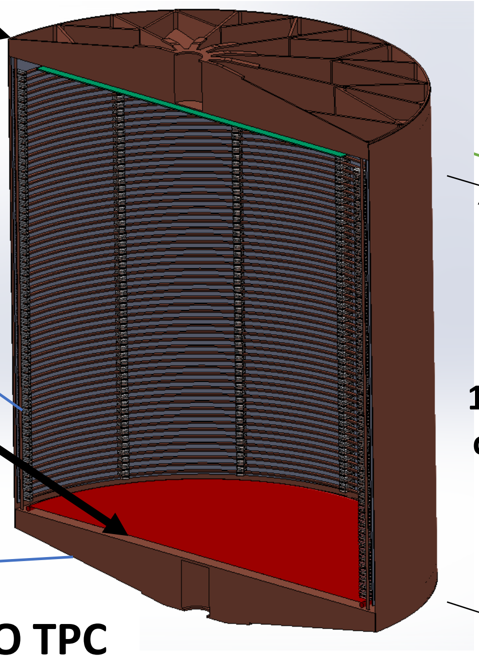
The nEXO detector

- 5 t liquid xenon TPC similar to EXO-200 (~30x the volume).
- SiPM for 175nm scintillation light detection, ~4.5m^2 SiPM array in LXe.
- Tiles for charge read out in LXe.
- Cold electronics inside TPC in liquid Xe.
- 3D event reconstruction.
- Combine charge and light readout. Goal → σ/E of <1% at Q-value.
- 1.5 ktonnes water-Cherenkov detector for muon tagging and shielding.

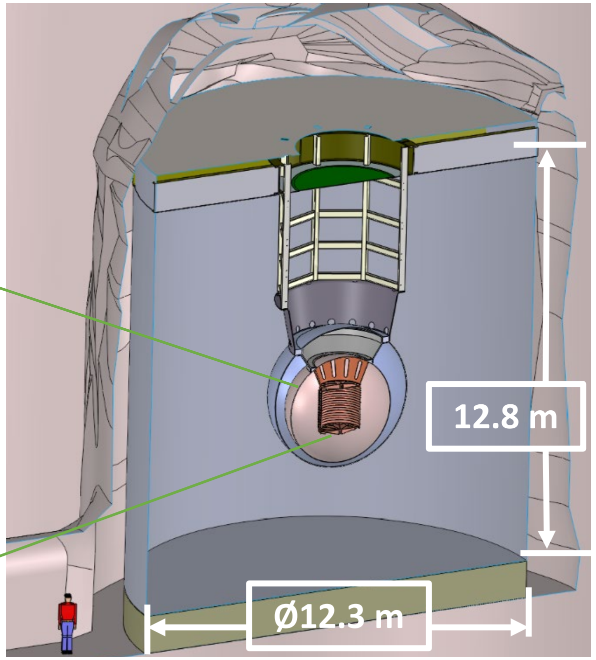


Picture: 10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)
Tile simulation: JINST 14 P09020 (2019)





nEXO TPC



nEXO at the SNOLAB Cryopit

nEXO pre-CDR, arXiv:1805.11142

Anode Charge Readout

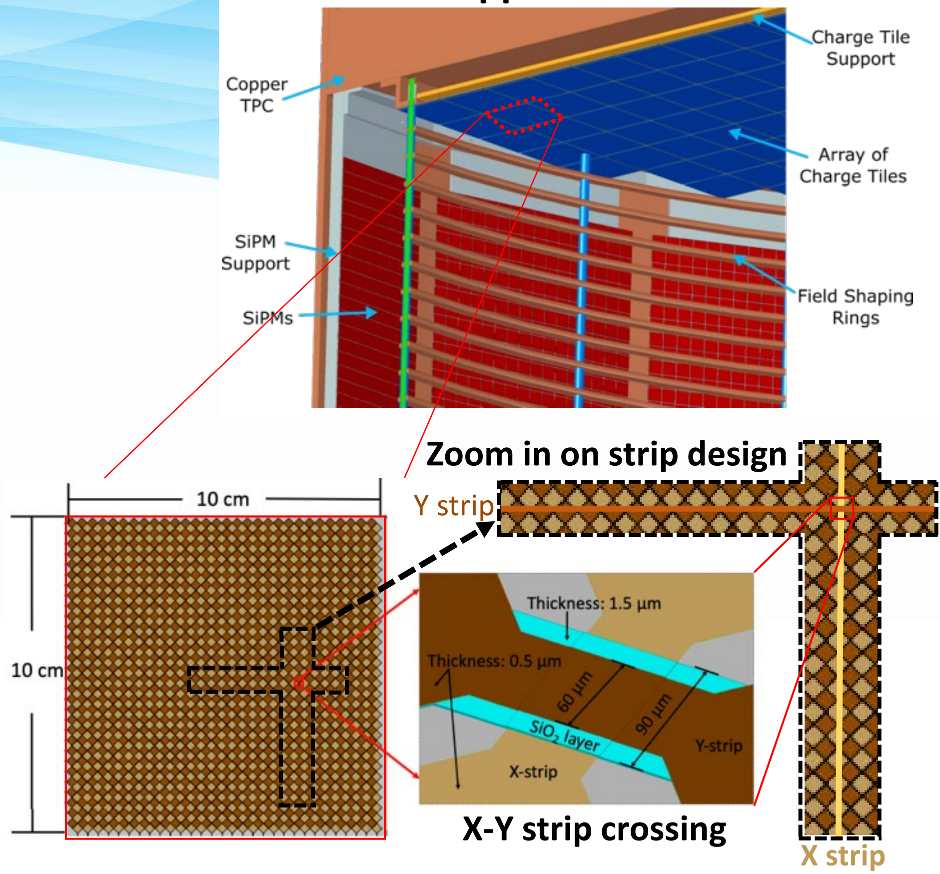
- Charge collection on tiled anode plane
- Full simulation of charge collection in nEXO used to optimize design
  - Crossed strips with no shielding grid
  - Channel pitch: 6mm
  - Tile size: 10 cm x 10 cm

Z. Li et al. (nEXO Collab) "Simulation of charge readout with segmented tiles in nEXO," JINST 14 P09020 (2019)

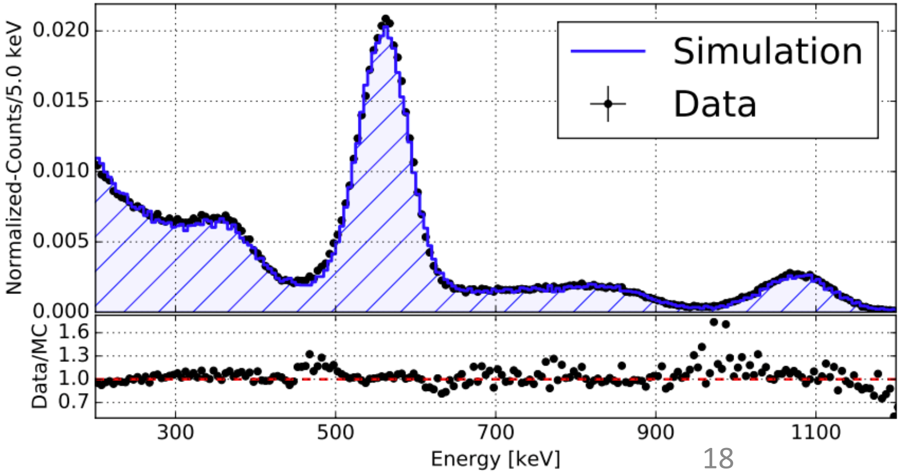
- Prototype tiles have been measured in LXe to validate simulation

M. Jewell et al. (nEXO Collab) "Characterization of an ionization readout tile for nEXO," JINST 13 P01006 (2018)

Zoom in on upper corner of TPC:

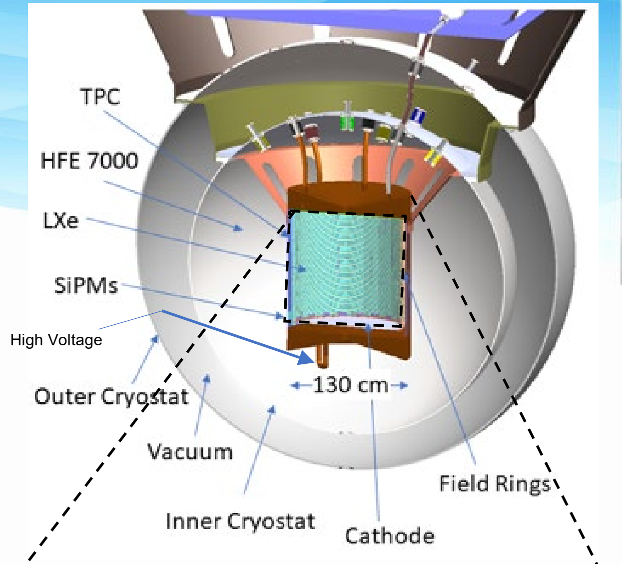


Source calibration (^{207}Bi) with prototype tile:

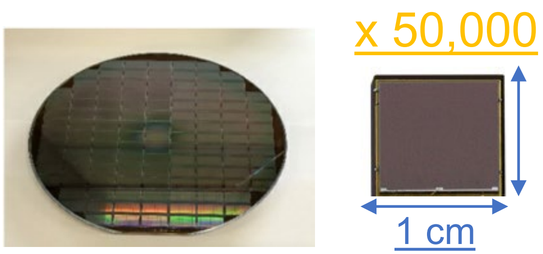


SiPMs for photon detection

- Advantages of SiPMs for photon detection
  - Low intrinsic radioactive backgrounds.
  - Improved energy resolution (SiPMs high gain).
  - Lower bias required for SiPMs (~50 V versus ~1.5 kV).
  - Devices from 2 vendors meeting requirements, demonstrated through R&D.



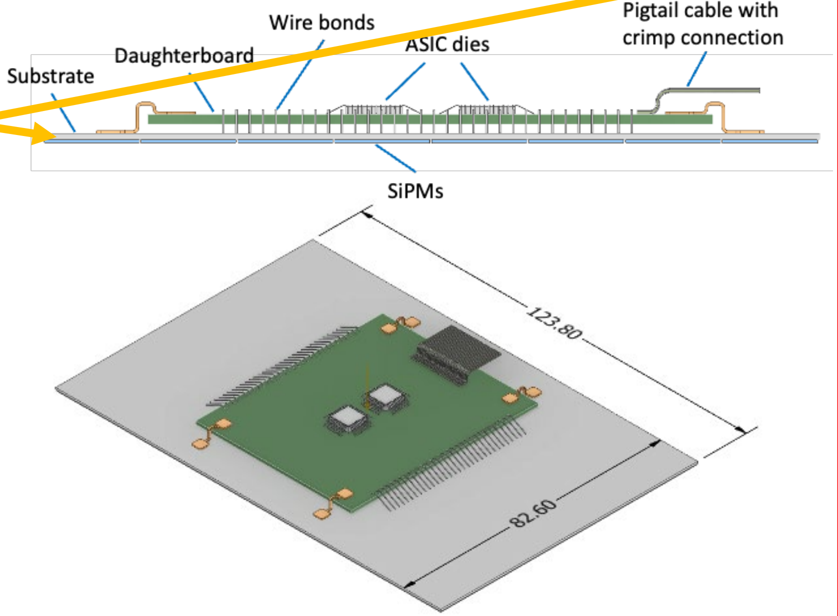
SiPM Devices



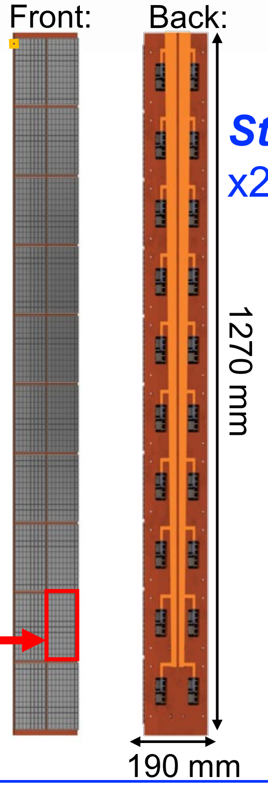
A. Jamil et al. (nEXO collab.) "VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO," IEEE Trans. Nucl. Sci. 65, 11 (2018)

G. Gallina et al. (nEXO collab.) "Characterization of the Hamamatsu VUV4 MPPCs for nEXO," NIM A 940, 371 (2019)

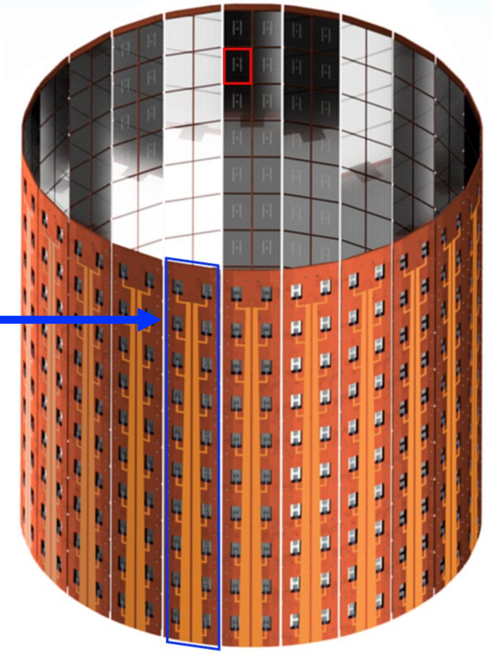
G. Gallina et al. (nEXO), "Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO," Eur. Phys. J. C 82, 1125 (2022)



Tile module x 480

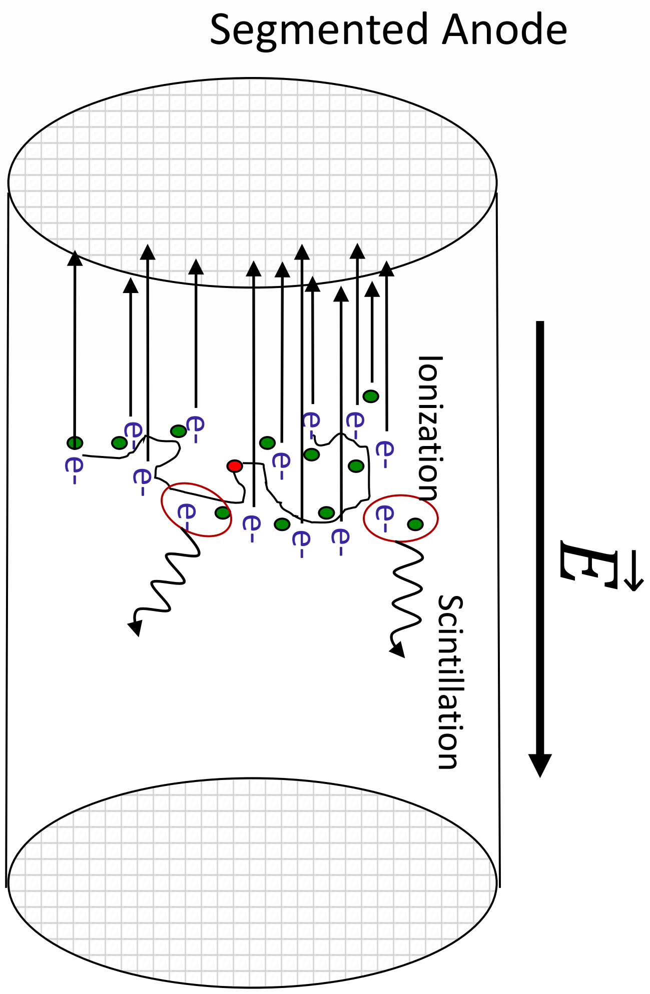


Stave x24



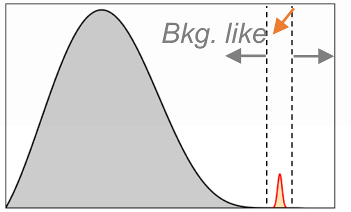
Photon detector (PD)

nEXO Signal and Background

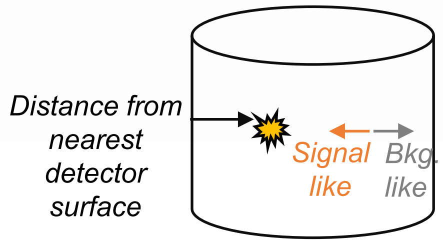


nEXO measures multiple parameters for each event to be able to robustly identify a 0νββ signal

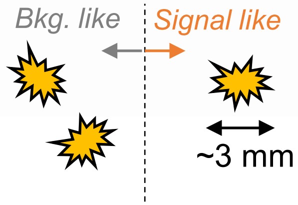
Energy:



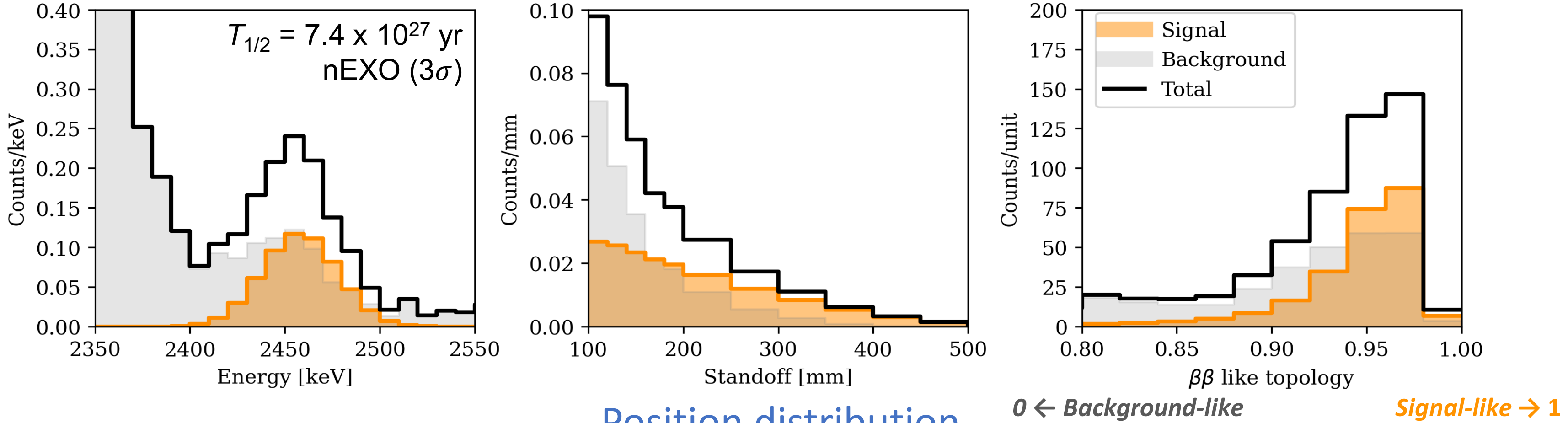
Standoff:



Topology:



1D projections of simulated nEXO signal and backgrounds:



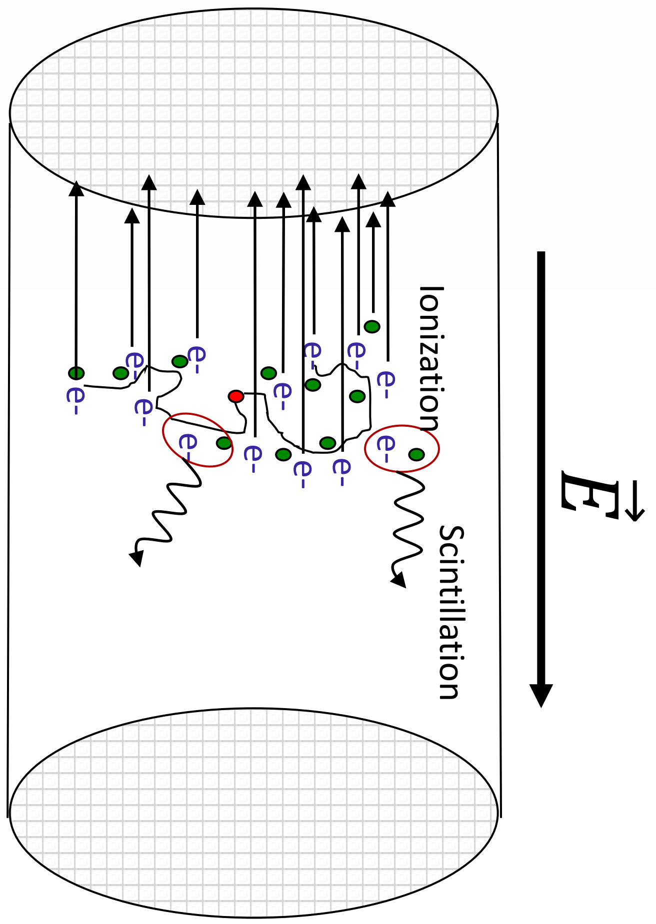
Energy from combined scintillation/ionization

Position distribution from 3D event reconstruction

Topology, e.g., single-site or multi-site

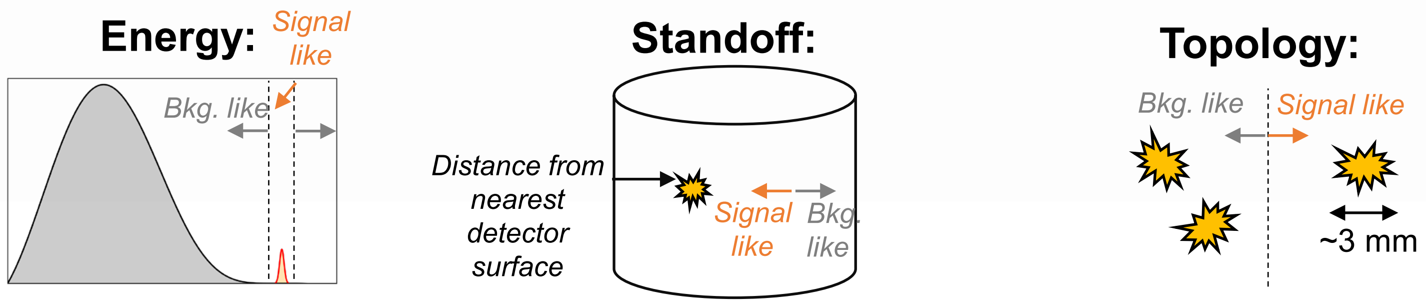
nEXO Signal and Background

Segmented Anode

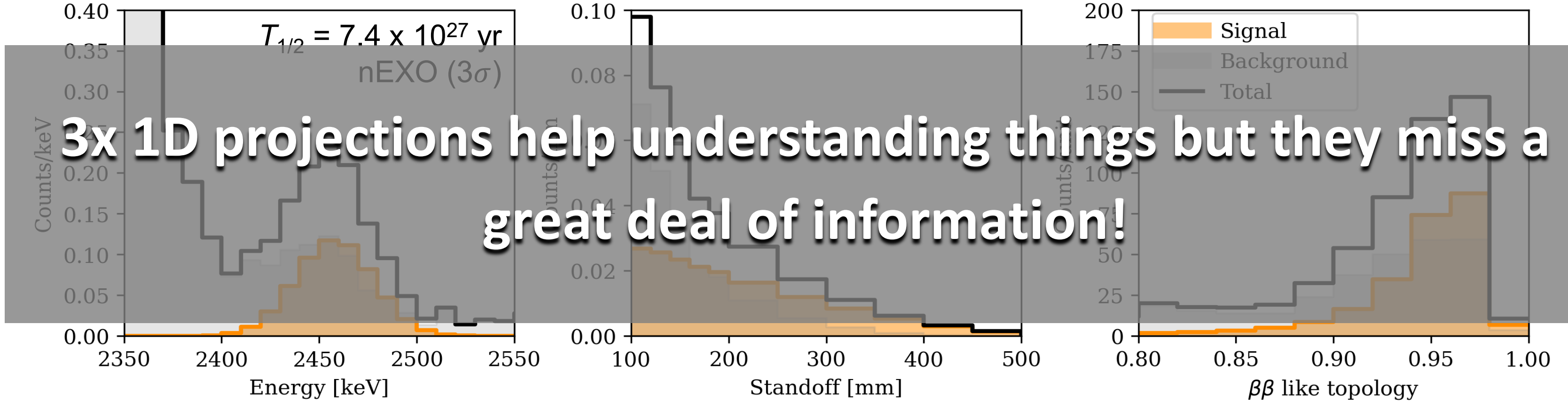


Cathode

nEXO measures multiple parameters for each event to be able to robustly identify a 0νββ signal



1D projections of simulated nEXO signal and backgrounds:



3x 1D projections help understanding things but they miss a great deal of information!

Energy from combined scintillation/ionization

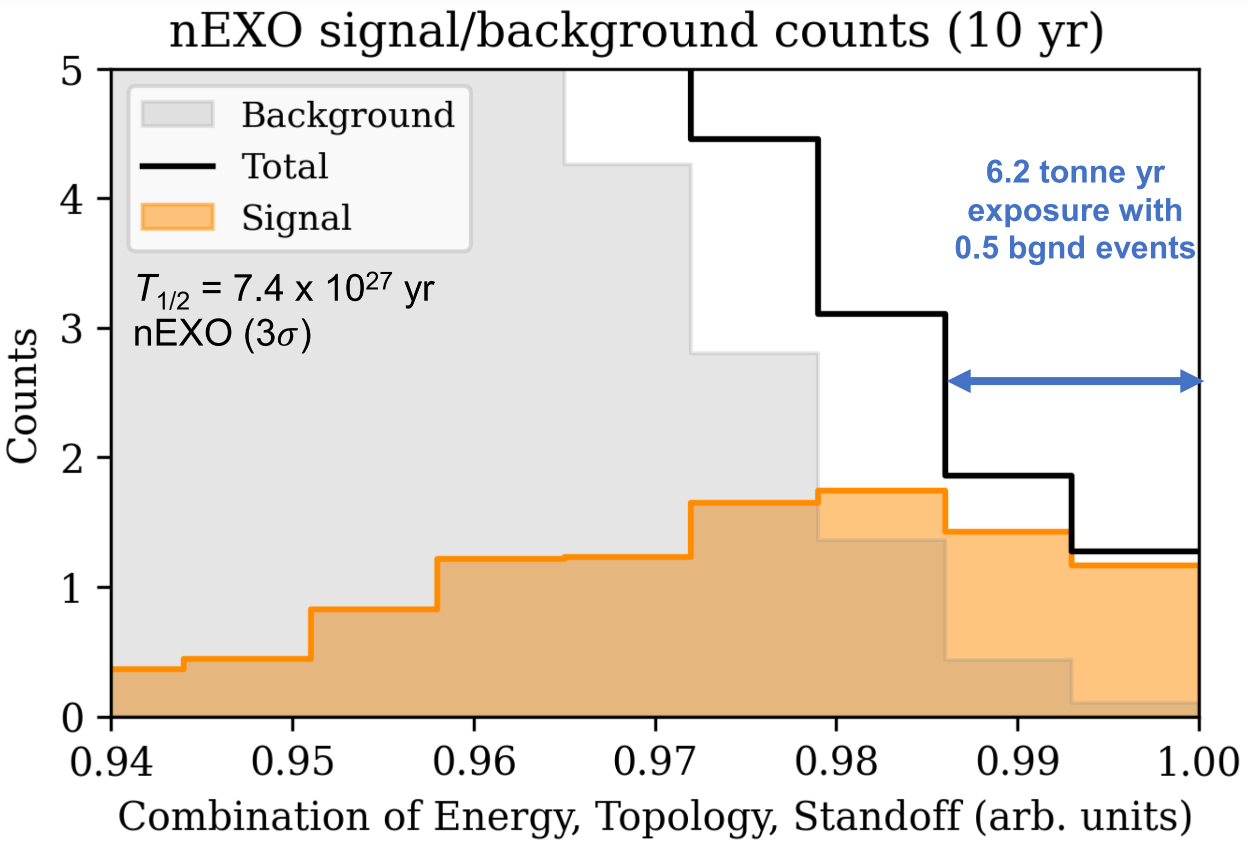
Position distribution from 3D event reconstruction

Topology, e.g., single-site or multi-site

nEXO Signal and Background

- Likelihood fit allows optimal weighting between signal and background combining energy, topology, and standoff over full 3D parameter space
- For clarity, we arrange the 3D bins into 1D, ordered by signal-to-background ratio.

Combine energy, topology, and standoff (preserving correlations)



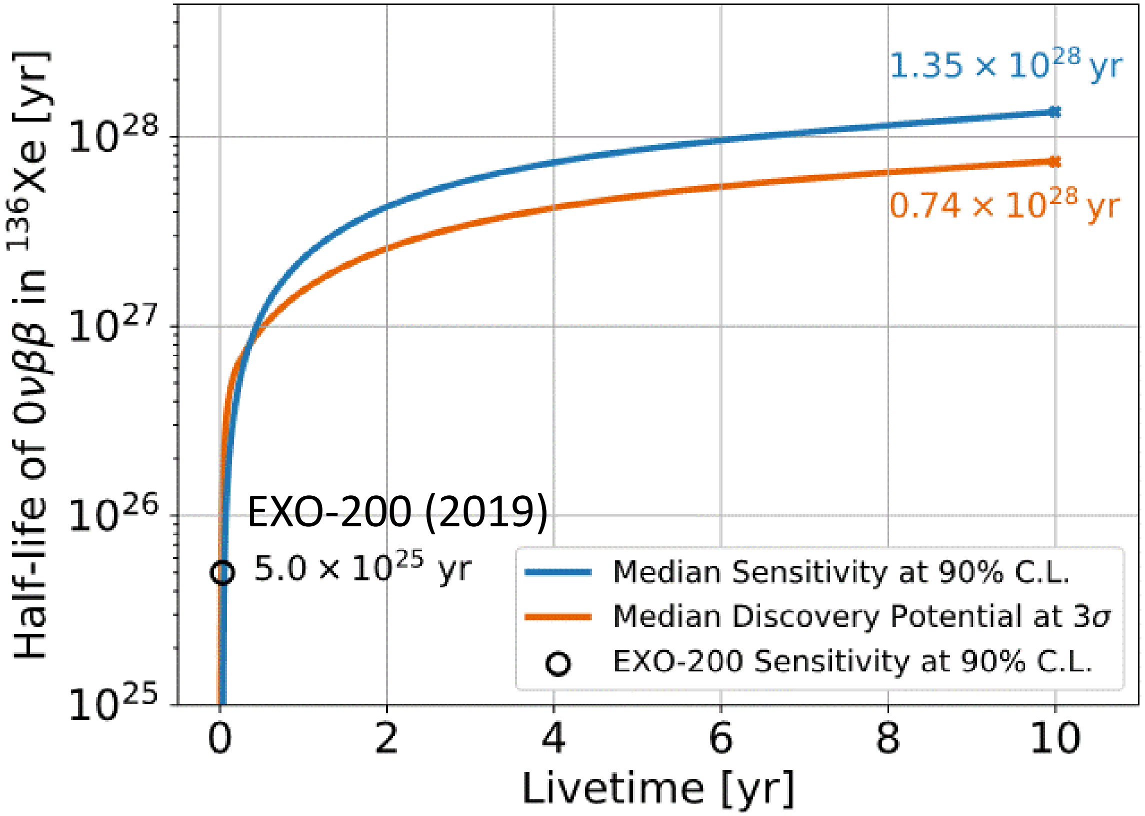
0 ← Background-like ***Signal-like → 1***

→ **nEXO is a "background-free" experiment**

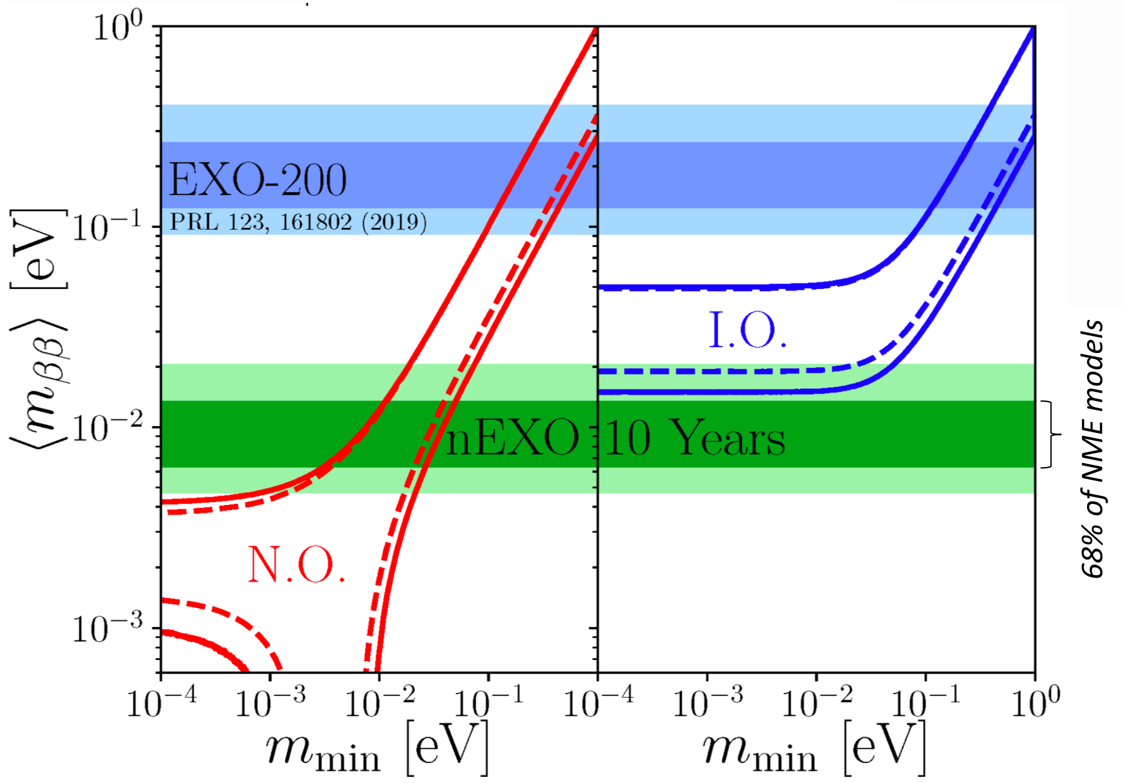
nEXO Projected Sensitivity

nEXO

J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022), arXiv:2106.16243



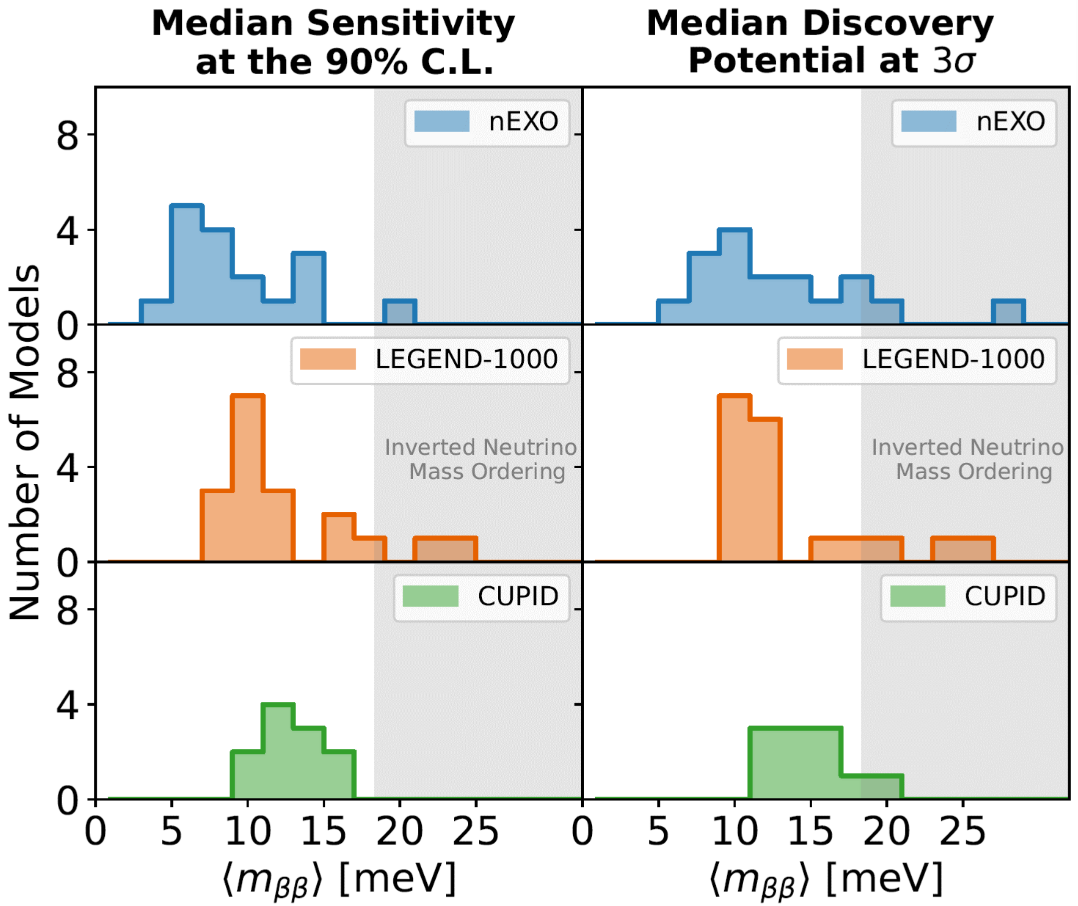
Allowed parameter space and nEXO exclusion sensitivity (90% CL):



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

Projected sensitivity based on background levels measured in samples of all detector materials!

Comparison with other experiments



Deeper Physics Reach

Effective Majorana mass $\langle m_{\beta\beta} \rangle$ is an effective, albeit imperfect, metric to compare physics reach between isotopes and 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; Axial coupling, $g_A = 1.27$; NME

	$m_{\beta\beta}$ [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.) [1]
- LEGEND: 1.6 (90% sens.), 1.3 (3σ discov.) [2]
- CUPID: 0.15 (90% sens.), 0.11 (3σ discov.) [3]

[1] nEXO collaboration, J. Phys. G: Nucl. Part. Phys. 49 015104 (2022), arXiv:2106.16243
[2] LEGEND pCDR, arXiv: 2107.11462
[3] CUPID pCDR, arXiv:1907.09376

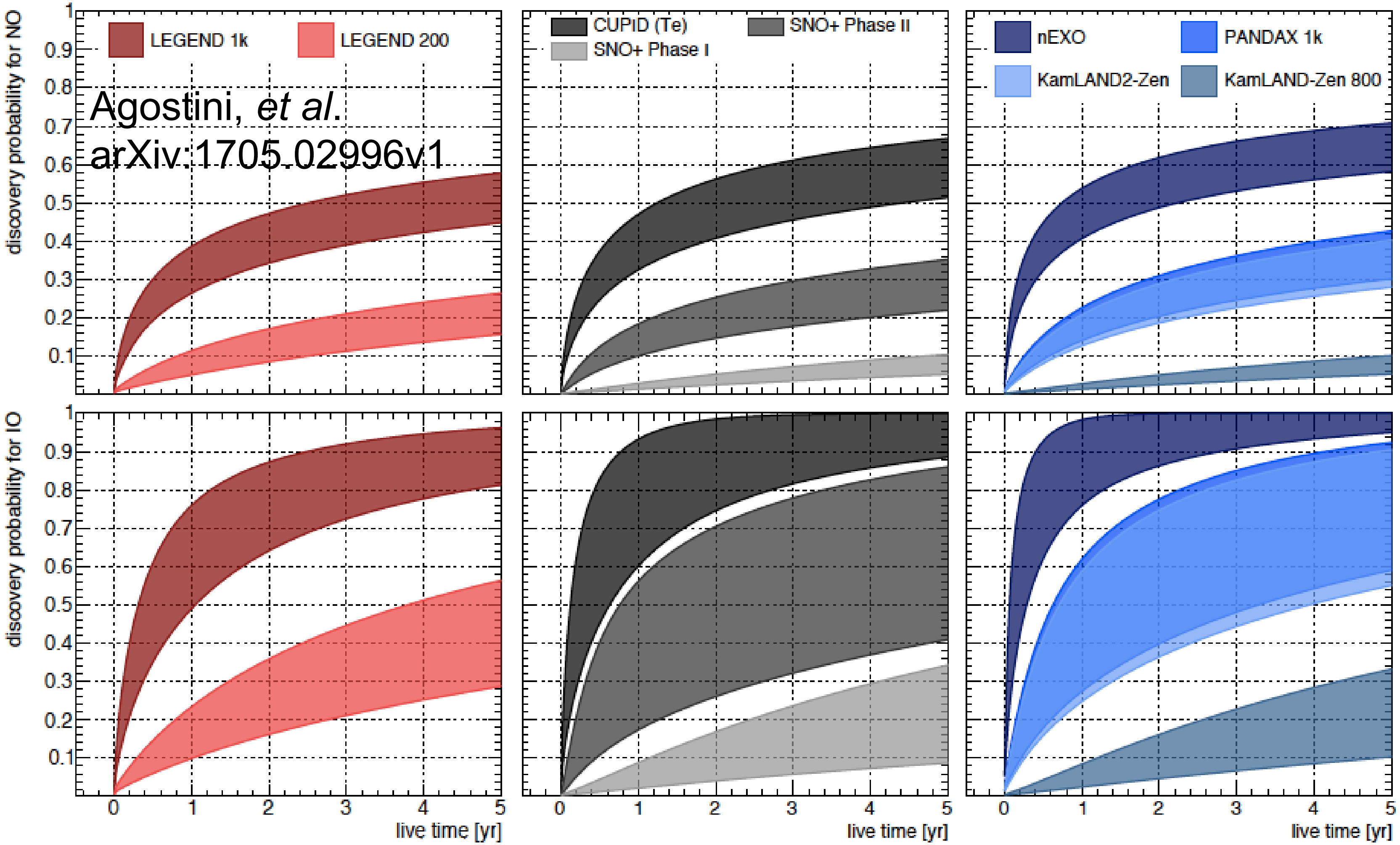
The international nEXO collaboration

nEXO

~200 scientists, 34 institutions in 9 countries on 4 continents


nEXO
Collaboration Meeting in Montreal 2023

$0\nu\beta\beta$ Discovery Potential



$0\nu\beta\beta$ is the most practical way to test the Majorana nature of neutrinos.
An observation of $0\nu\beta\beta$ always implies 'new' physics!

Summary

- **nEXO is a discovery focussed 0νββ experiment.**
- nEXO's multi-parameter signal extraction enables a "background-free" 0νββ search that is particularly robust against unknown backgrounds.
- nEXO is being designed to reach a sensitivity beyond ~10^{28} years and will probe the entire inverted ordering parameter space.
- **We are looking for students and postdocs to join our exciting search for 0νββ with nEXO!**