Neutrinoless double beta decay with nEXO

Marie Vidal on behalf of the nEXO collaboration

XeSat2023 – Nantes Subatech

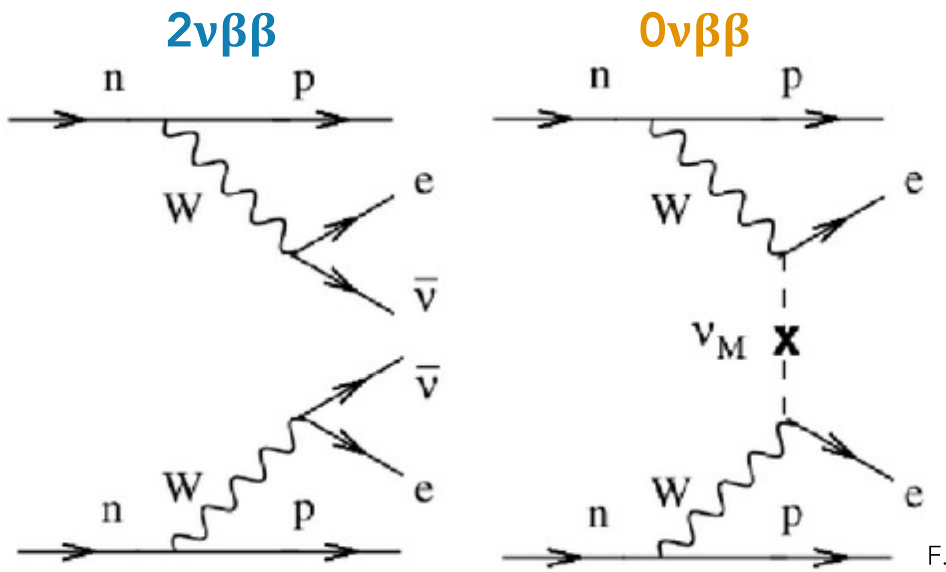
5-8 June 2023

Outline

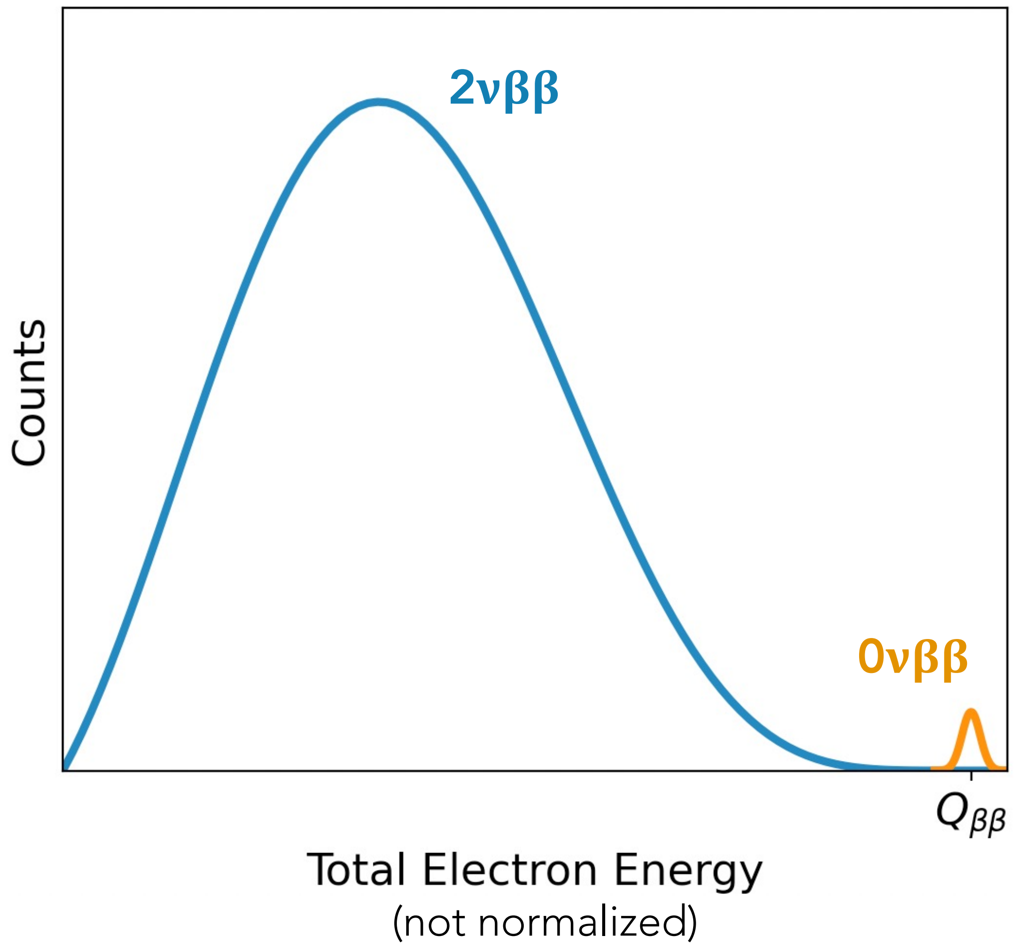
1. **Physics motivation & current landscape of 0νββ decay**
2. **nEXO: scaling up from EXO-200**
3. **Instrumentation R&D:**
   1. Charge
   2. Light
4. **Background estimations**
   1. Modeling and projected distributions
5. **nEXO: detector performances**
6. **nEXO sensitivity**

Physics motivation

- **0νββ decay**
  - 1937 hypothesis: $\bar{\nu} = \nu$
  - Probing neutrino's nature: Majorana/Dirac particle? $\bar{\nu} = \nu$
  - Lepton number violation
  - Understanding matter/antimatter asymmetry
  - New mechanism to generate mass

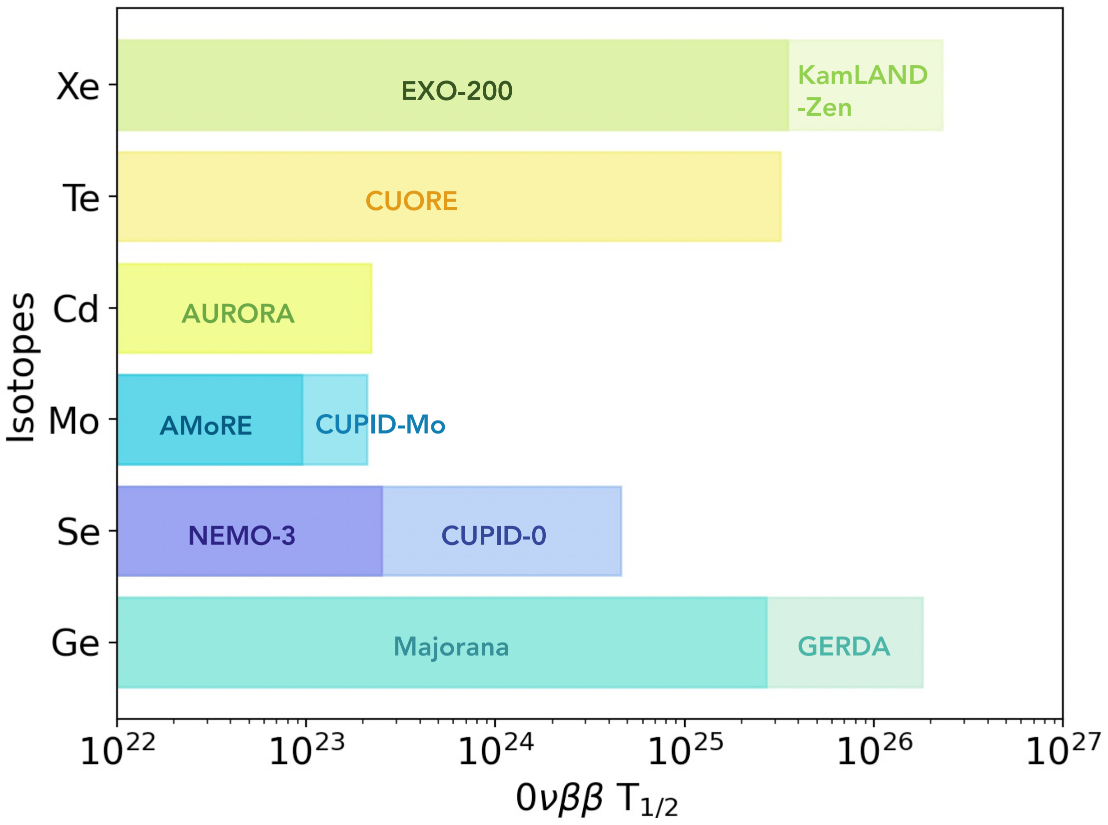


F.T. Avignone III et al.,
Rev. Mod. Phys. 80 (2008)



0νββ landscape

- State of the art:
  - CUORE ^{130}Te: $T_{1/2} > 3.6 \times 10^{24}$ y
  - Gerda ^{76}Ge: $T_{1/2} > 0.9 \times 10^{26}$ y
  - EXO-200 ^{136}Xe: $T_{1/2} > 3.5 \times 10^{25}$ y
  - KamLAND-Zen ^{136}Xe: $T_{1/2} > 2.3 \times 10^{26}$ y
- The 0νββ program is reaching the tonne-scale phase
- 3 leading experiments launched using different isotopes and technologies
  - nEXO: TPC using ^{136}Xe
  - LEGEND-1000: PC using ^{76}Ge crystals
  - CUPID: calorimeters using ^{100}Mo doped crystals



(Particle Data Group), Prog. Theor. Exp. Phys. 2020, 2021 update
D. Q. Adams et al. (CUORE Collaboration), Phys. Rev. Lett. 129, 2022
Gerda Collaboration, Phys. Rev. Lett. 125, 2020
G. Anton et al., Phys. Rev. Lett. 123, 2019
KamLAND-Zen Collaboration, Phys. Rev. Lett. 130, 2023
arXiv:2207.09577 [nucl-ex]

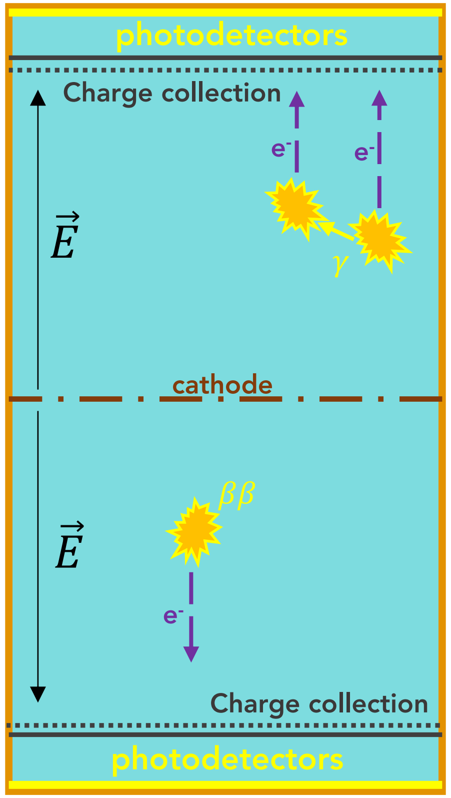
EXO-200

- EXO-200 at WIPP – ran between 2011 and 2018
  - First 100 kg class $\beta\beta$ experiment
  - 175 kg of LXe TPC enriched @ 80% with ^{136}Xe
  - 1st observation of $2\nu\beta\beta$ in ^{136}Xe

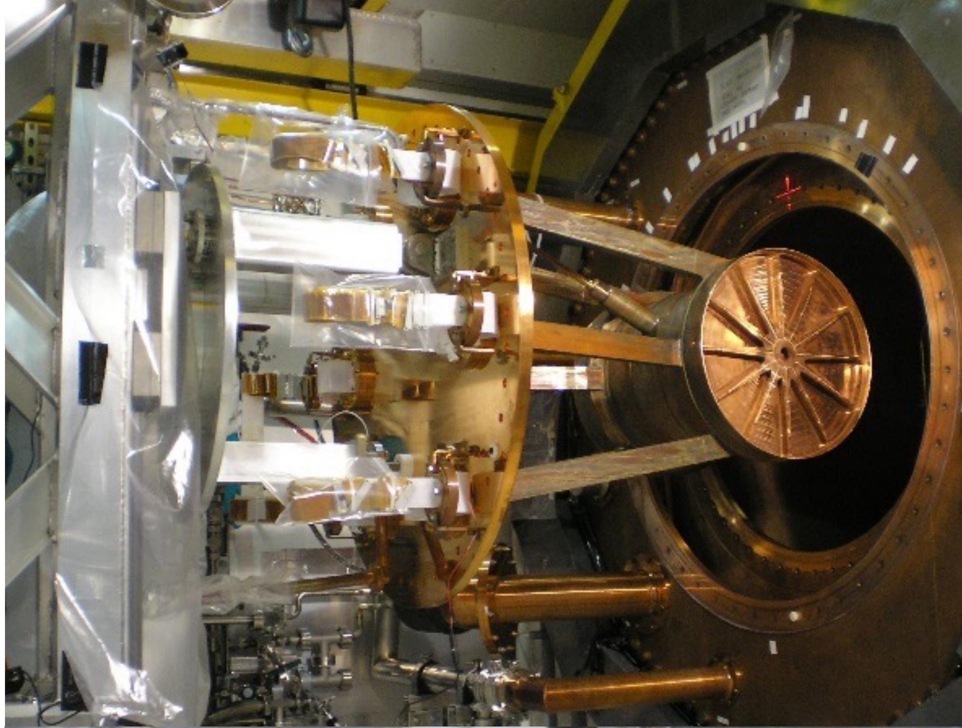
- EXO-200
  - 2 drift volumes
  - 1 meshed cathode in the middle
  - Charge readout: induction (Frisch grid) + collection wire planes @ top & bottom
  - Light readout: LAAPDs @ the top & bottom

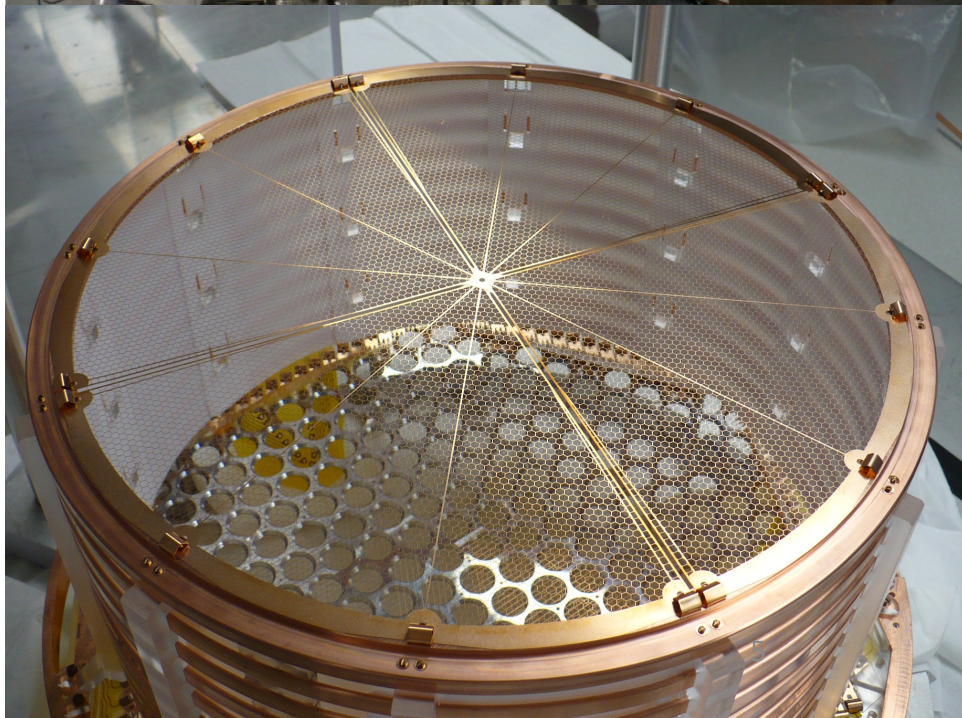
→ Demonstrated feasibility of rejecting background by identification using multiplicity and location of events

→ Limit: $T_{1/2} > 3.5 \times 10^{25}$ yr (90% C.L.)



EXO-200 diagram





The nEXO experiment

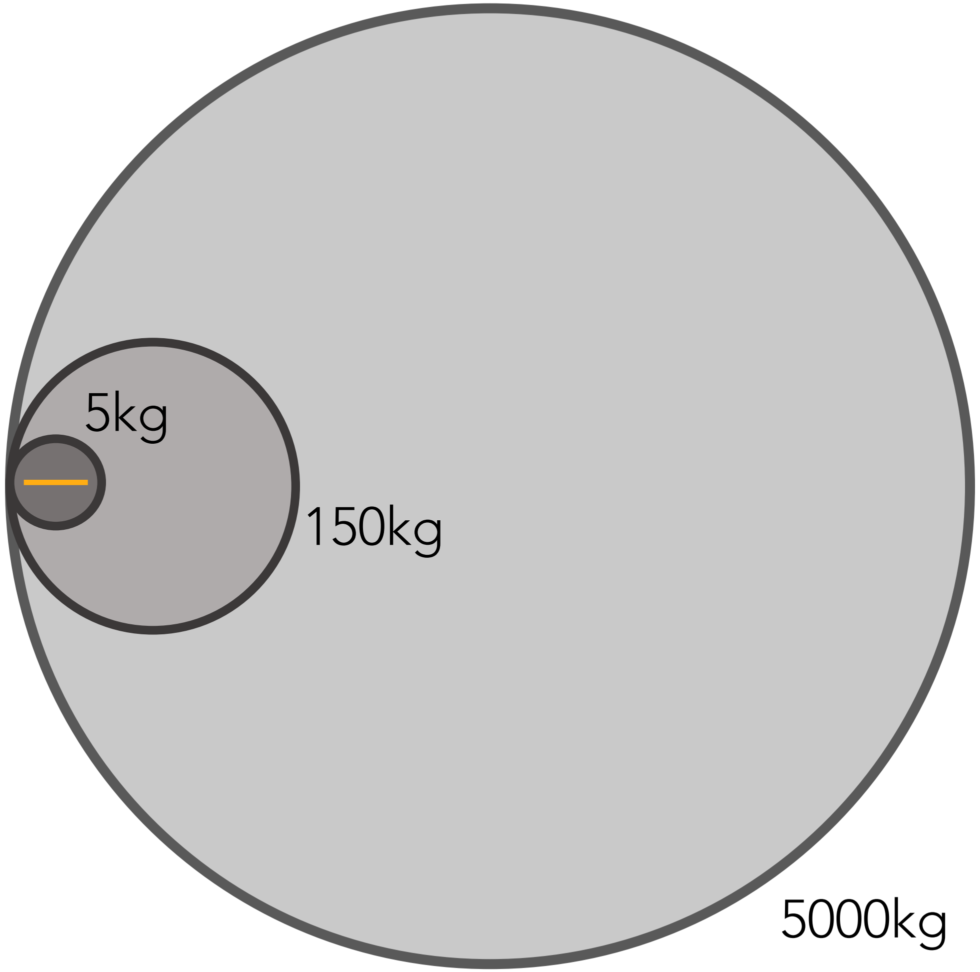
- Worldwide collaboration
  - 9 countries, 34 institutions, ~ 200 scientists
  - 18% faculty
  - 32% staff
  - 8% postdocs
  - 40% grad students
- Aims at detecting $0\nu\beta\beta$ decay
- Building upon EXO-200 success

Scalability

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

2.5 MeV γ-ray attenuation length in LXe:
8.5 cm =

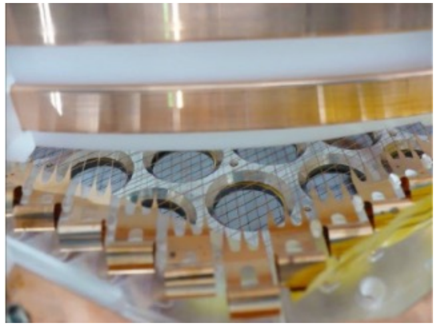
The **homogeneous** feature of nEXO is key because the γ background typically comes from the surfaces (wall) of the detector.
→ The larger the detector the more background free the center of the detector becomes

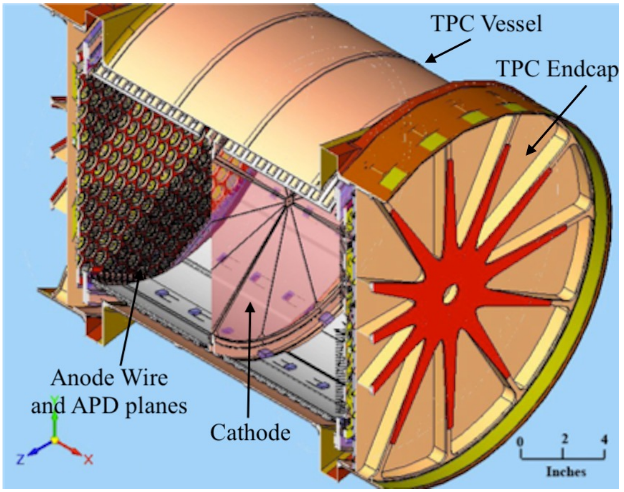


Cartoon illustrating the power of self shielding for large homogeneous detectors

Evolution from EXO-200 to nEXO

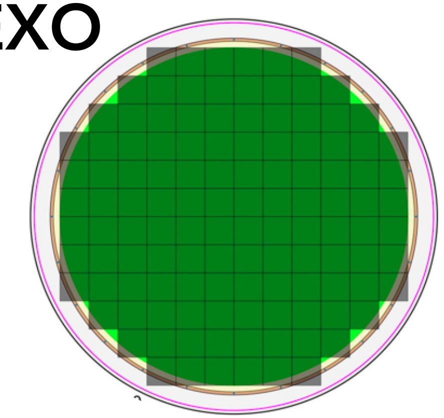
EXO-200

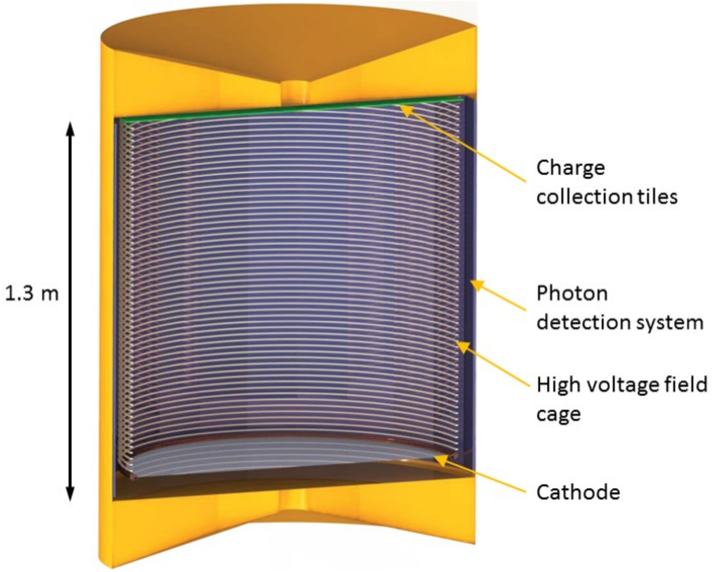




- 40 cm Ø TPC
- Charge readout: planes of crossed wires
- Light readout: LAAPDs + PTFE reflector
- Energy resolution: 1.2%
- >2 attenuation length @ center
- 80% enriched ^{136}Xe
- WIPP: 1624 mwe

nEXO



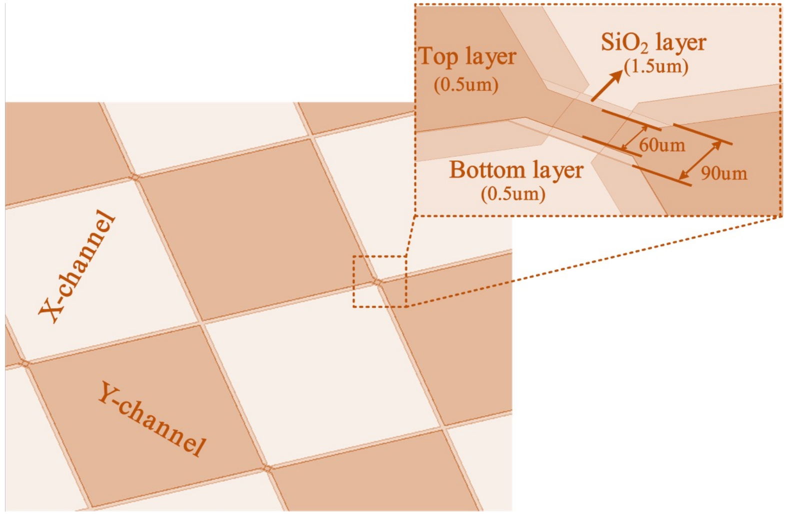


- 130. cm Ø TPC
- Charge readout: gridless modular tiles (CRYO ASIC in LXe lower noise)
- Light readout: SiPMs (avoid readout noise)
- Energy resolution: < 1% (projected)
- > 7 attenuation length @ center
- 90% enriched ^{136}Xe
- SNOLAB: 6010 mwe

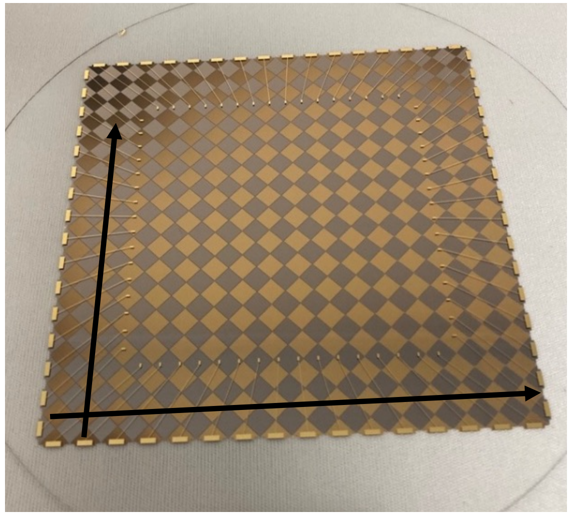
Instrumentation R&D: charge

Motivation:

- Less mechanical stress applied on the charge readout, simpler support
- Can mount electronics directly to the back of the tiles: reduce noise



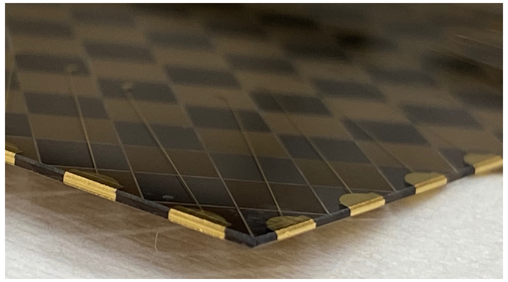
Multilayered tiles, with quartz substrate and deposition of layers of Ti and Au for the collecting material.



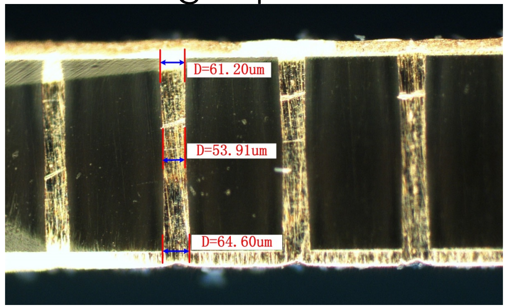
1 tile: 10 cm length square, with strips along x and y for 2D position reconstruction.

2 laboratories in charge of charge tile development: SLAC & IME

Wrap-around traces



Through quartz vias



The **traces are sent to the back** of the tile via 2 different methods:

- SLAC: around the edge deposition
- IME: via hole through quartz

Both methods were tested and demonstrated

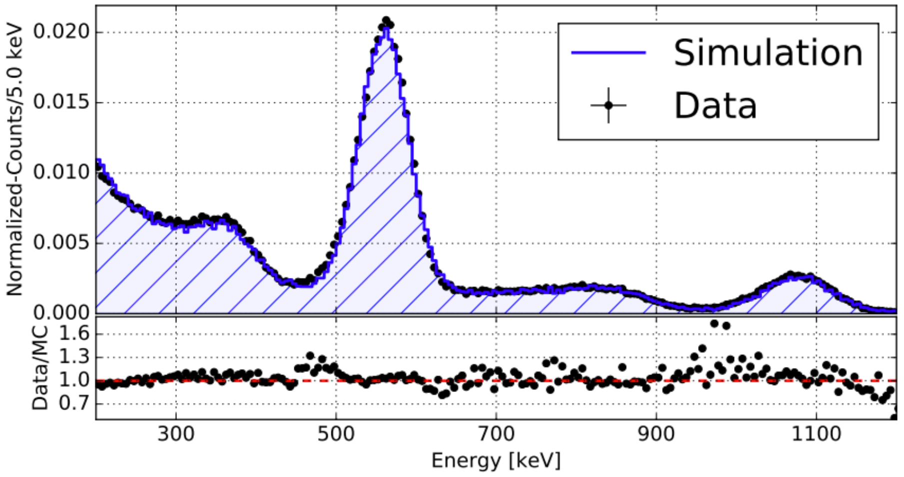
Instrumentation R&D: charge

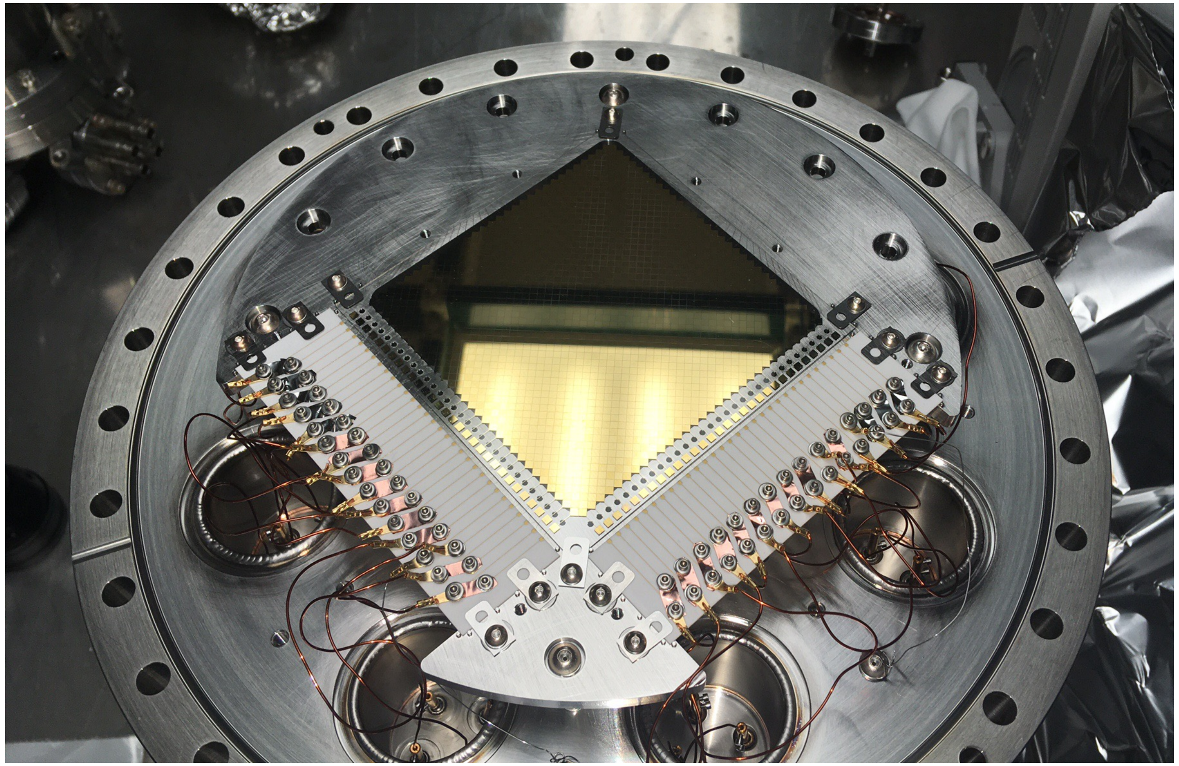
- **Testing of prototype tile** @ Stanford (IME), *M. Jewell et. al JINST 13 P01006*

→Proof of concept

- Tile used as default charge readout of all TPC detectors @ Stanford (using external electronics)
- **nEXO: 120 charge tiles**

→ Study multiple charge tile configuration





←

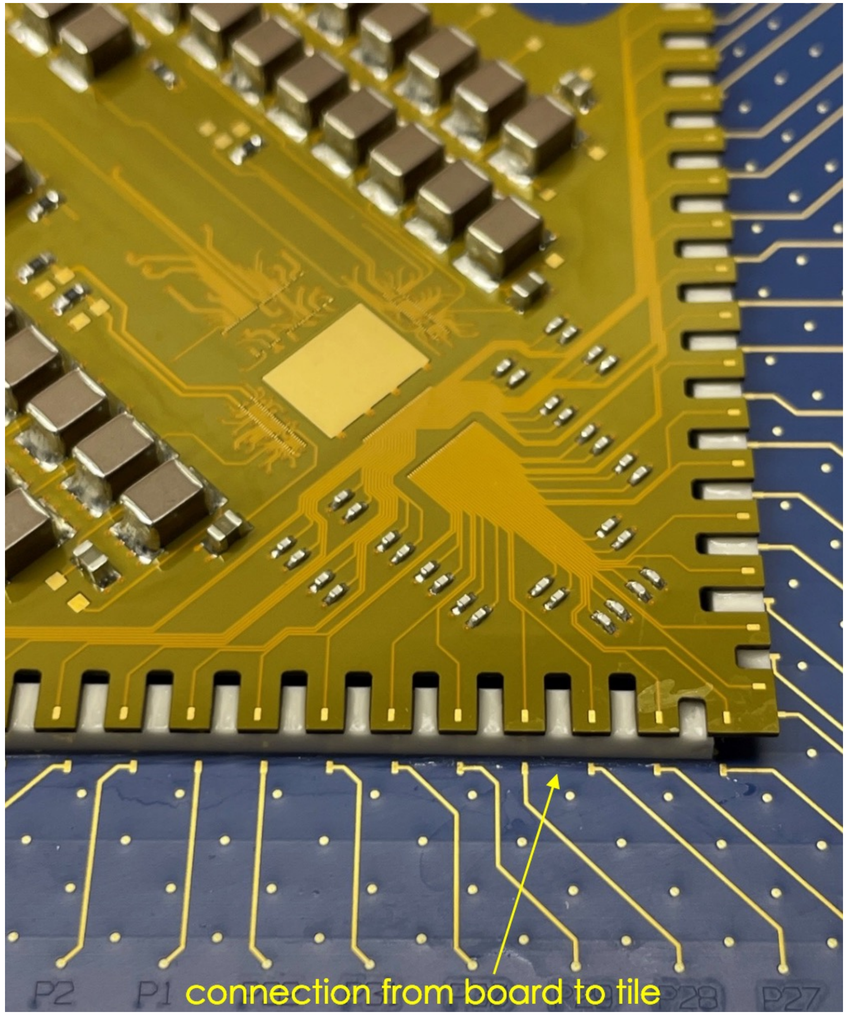
Characterization of the charge tile in LXe in TPC with drift length of 3.3 cm, using a ^{207}Bi source.

Charge readout electronics

- Want to have the amplification and digitization electronics on the back of the charge tiles
  - Lower intrinsic noise due to cable length
  - Lower noise because of cryogenic temperature
  - Reduce any impact on analog signal from electromagnetic pick-up

- Development of CRYO ASIC @ SLAC
  - To be used in noble liquid element
  - Low power dissipation: no boiling of Lxe
  - Testing of CRYO ASIC prototypes @ SLAC demonstrated functionality and performed as expected relative to simulation

- Integration of ASIC in detector: in progress
  - Charge tile + ASIC board + ASIC



Integration testing: E. Angelico

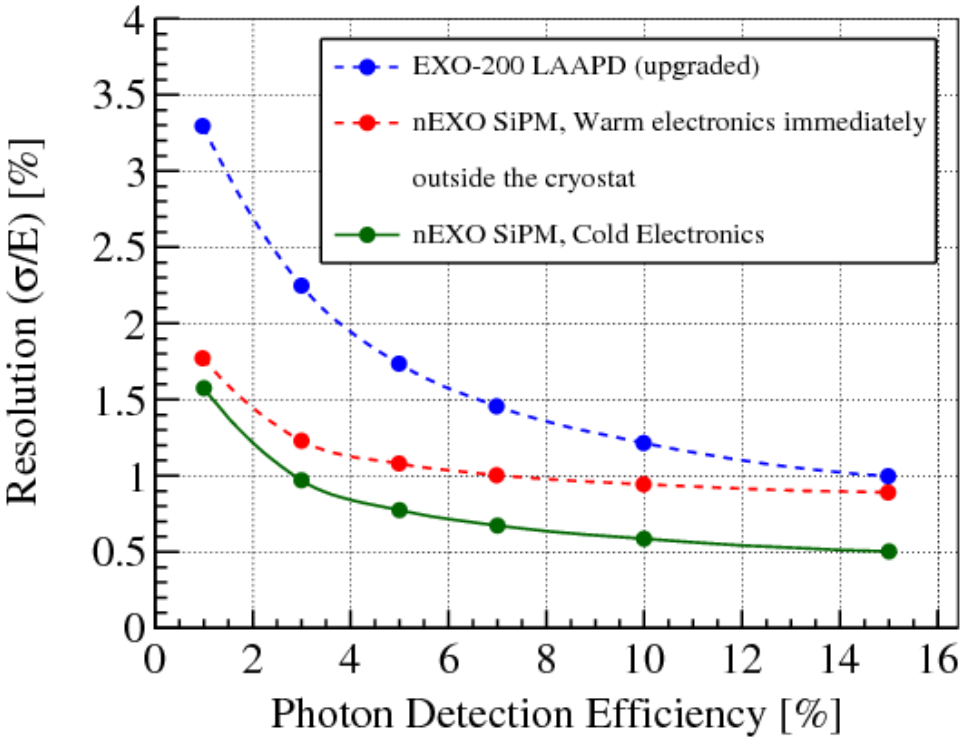
Instrumentation R&D: light

Photodetectors location

- Xenon TPC barrel surface, behind the field shaping rings

→Improve light collection efficiency with larger area covered

→New charge readout design (cathode) – no longer optically transparent



SiPMs for photodetection – Motivation

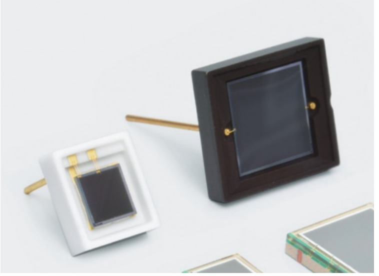
- Cryogenic SiPMs developed
- Low intrinsic radioactive background
- Due to high gain → improved energy resolution
- Lower bias required for SiPMs (~ 50 V) vs LAAPDs (~ 1.5 kV)

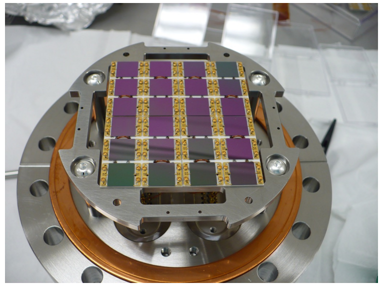
Devices from 2 different vendors meet nEXO requirements through R&D

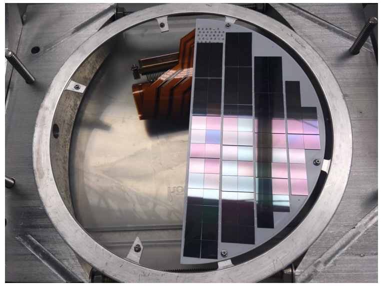
- Absolute photodetection efficiency in vacuum
- Reflectivity in vacuum and LXe

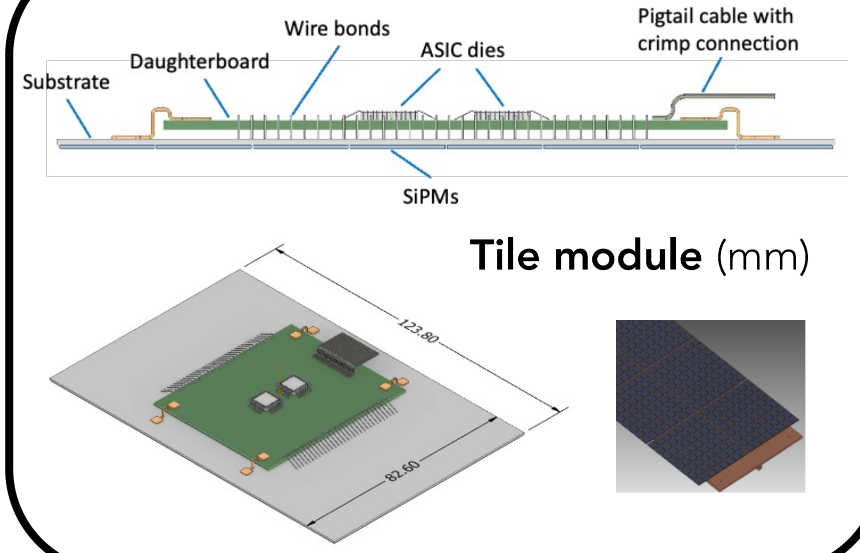
Ostrovskiy et al. (nEXO) IEEE TNS 62 (2015)
A. Jamil et al. (nEXO) IEEE TNS 65 (2018)
G. Gallina et al. (nEXO) NIMA 940 (2019)
P. Nakarmi et al. (nEXO) JINST 15 (2020)
P. Lv et al. (nEXO) IEEE TNS 99 (2020)
M. Wagenpfeil et al. (nEXO) JINST 16 (2021)
**G. Gallina et al. (nEXO) Eur. Phys. J. C 82 (2022)*

Instrumentation R&D: light

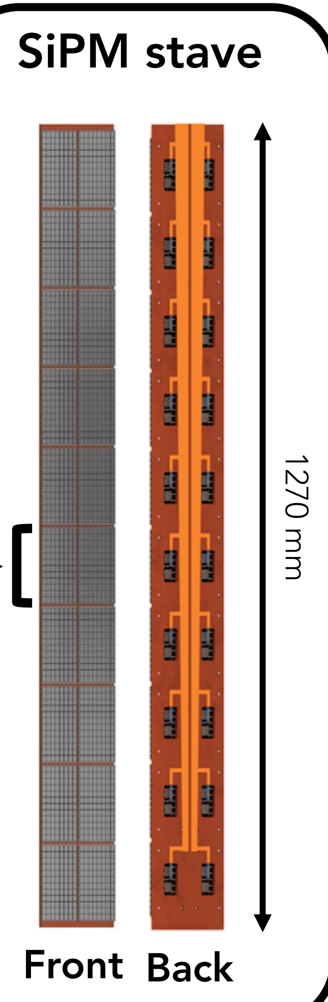

SiPM 1 x 1 cm^2


SiPM array R&D

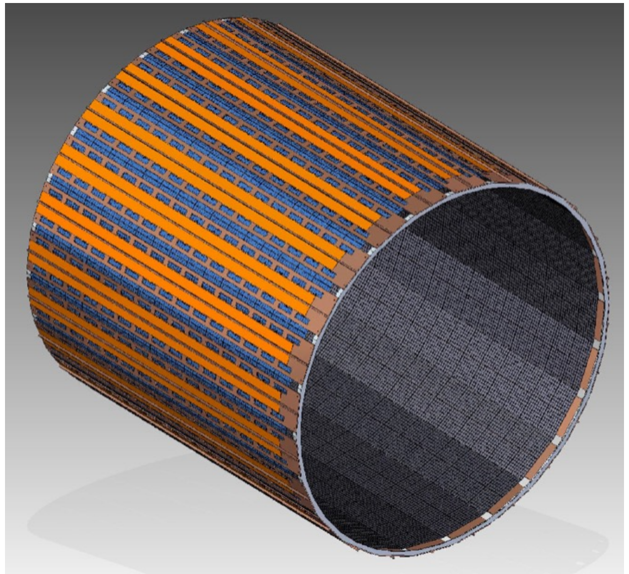

Scaling up SiPM arrays



Tile module with integrated ASIC
20 light tile modules per stave



Full assembly of the light readout



Total light area for nEXO: **4.5 m^2**

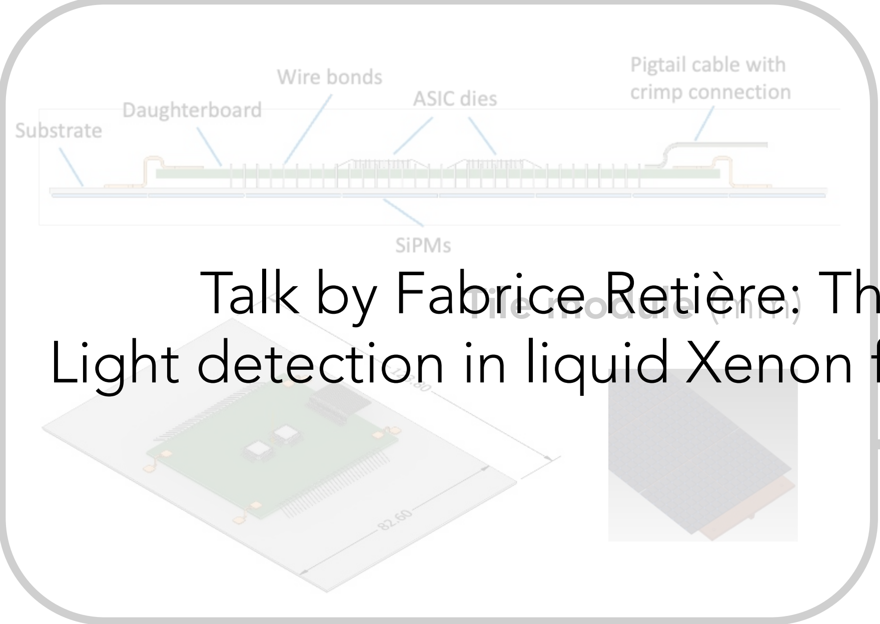
24 staves around the TPC barrel

Instrumentation R&D: light

SiPM 1 x 1 cm^2

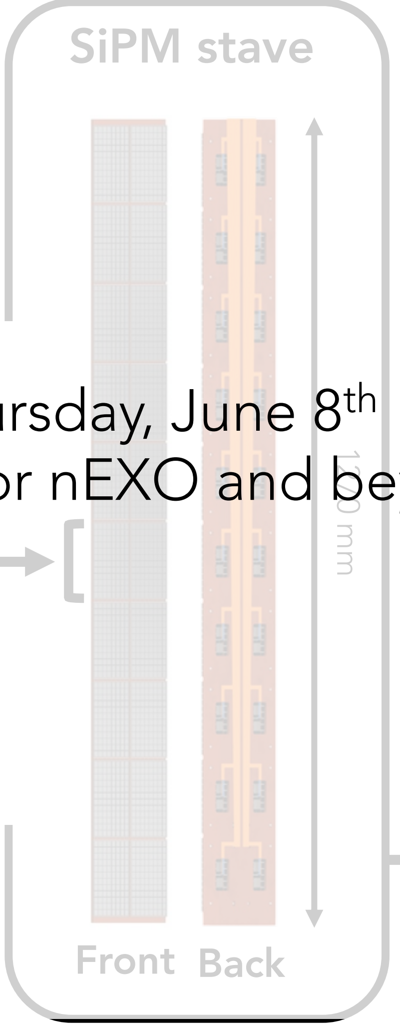
SiPM array R&D

Scaling up SiPM arrays

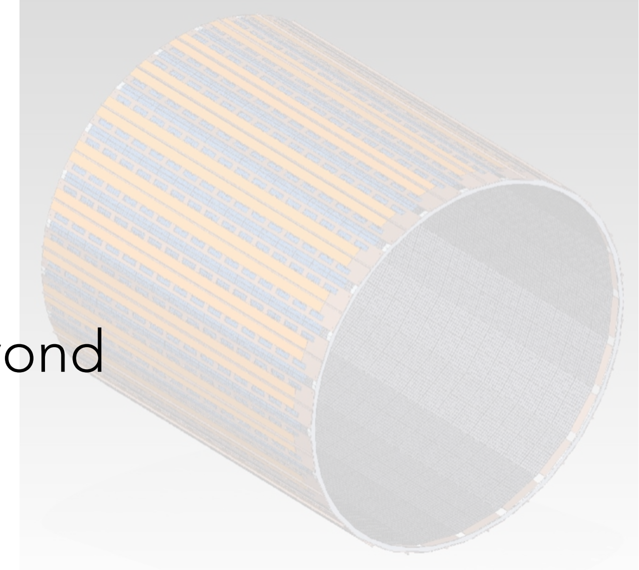


Tile module with integrated ASIC

20 light tile modules per stave



Full assembly of the light readout



Total light area for nEXO: **4.5 m^2**

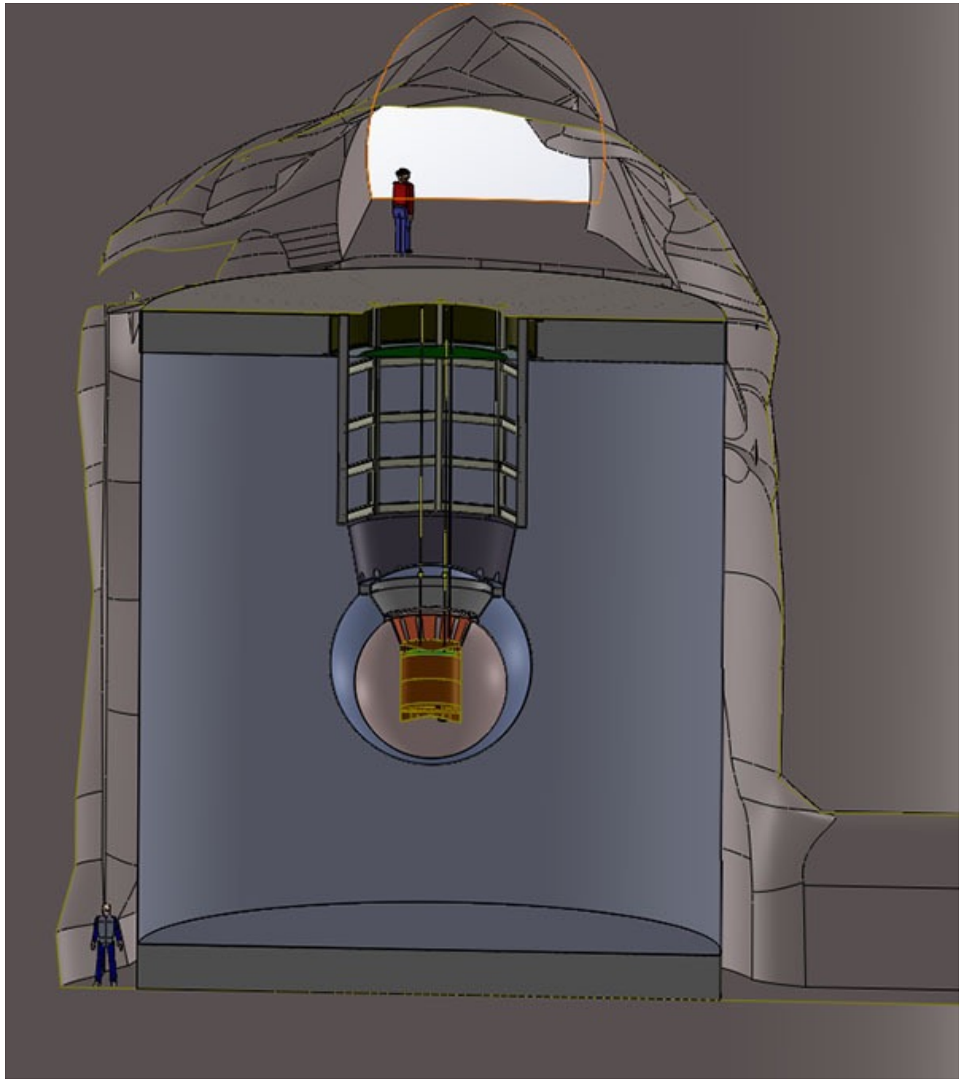
24 staves around the TPC barrel

Talk by Fabrice Retière: Thursday, June 8th

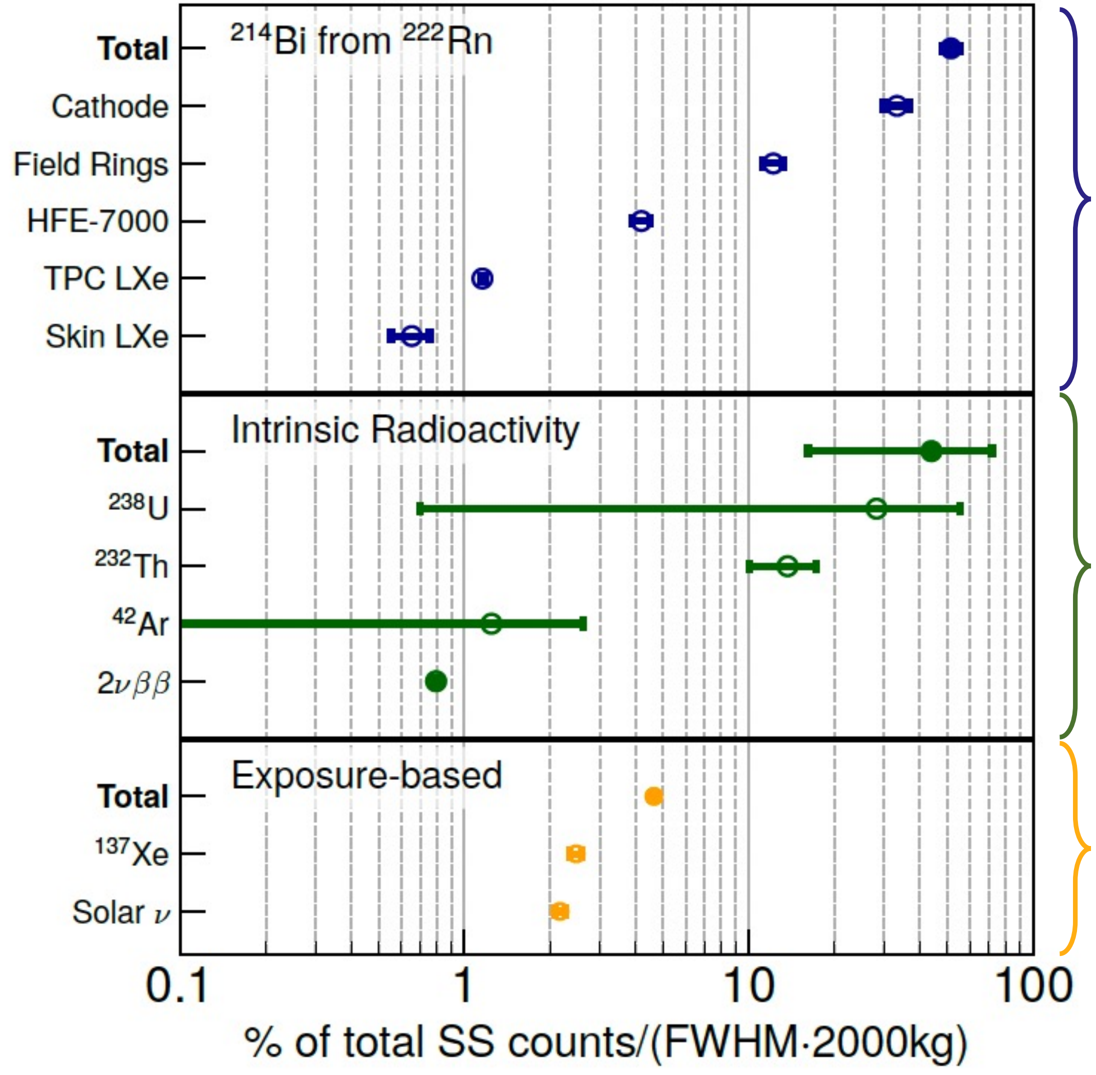
Light detection in liquid Xenon for nEXO and beyond

Background

- Planning to have nEXO in the SNOLAB cryopit
- Water tank:
  - Shield against γ-rays coming from the wall of the cavern
  - Moderate and stop neutrons coming also from the wall of the cavern
  - Detect cosmic radiation (PMTs): active water-Cherenkov muon veto
- Cryogenic vessel:
  - Cu electroformed
  - double walled, vacuum insulated
  - Filled with 32 tonnes of HFE-7000 (ultra radio-pure)
- Ultra-low background TPC vessel and components (electroformed copper cathode)



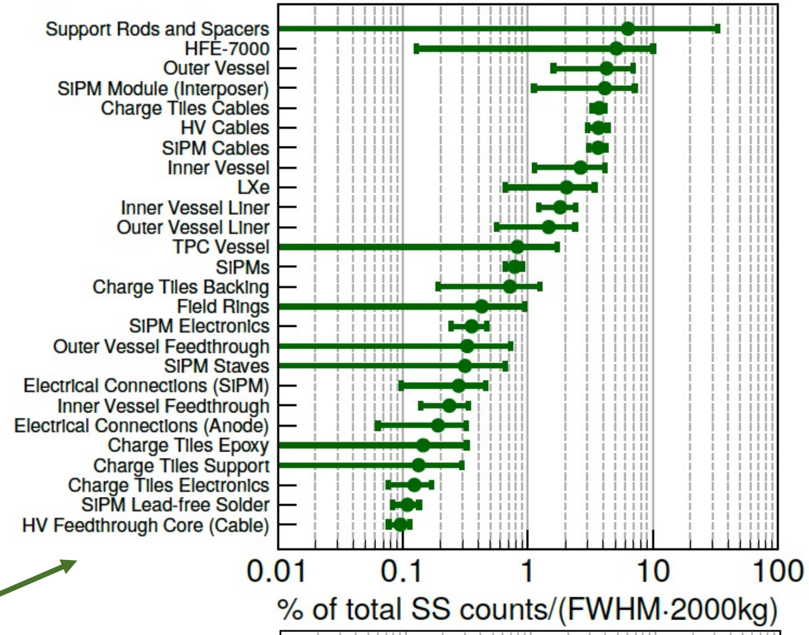
Data-driven background modeling

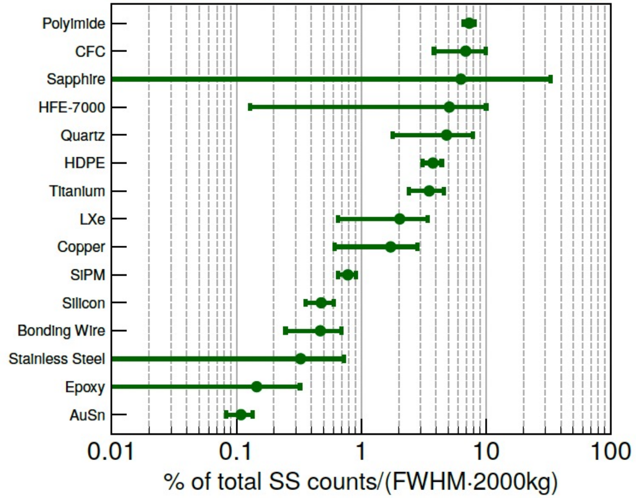


Extrapolated from EXO-200

Radioassay measurements of materials

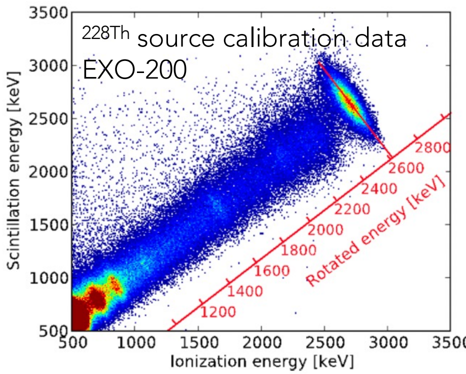
Predicted from external measurements





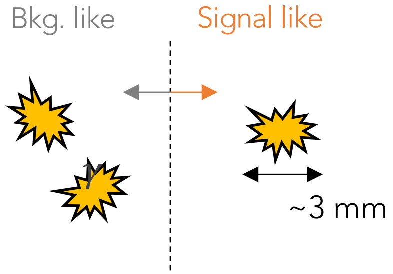
The nEXO detector performance

Energy:



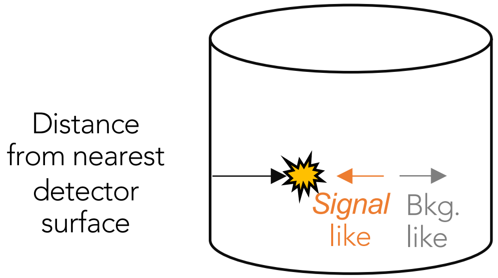
Combination of scintillation light and ionization channels: Improve energy resolution < 1%

Topology:

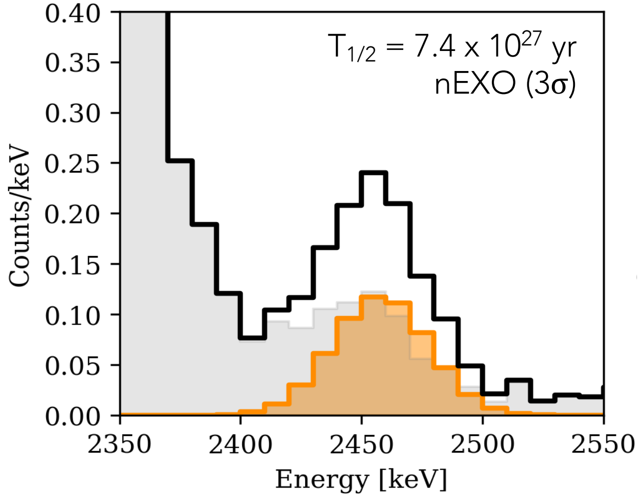


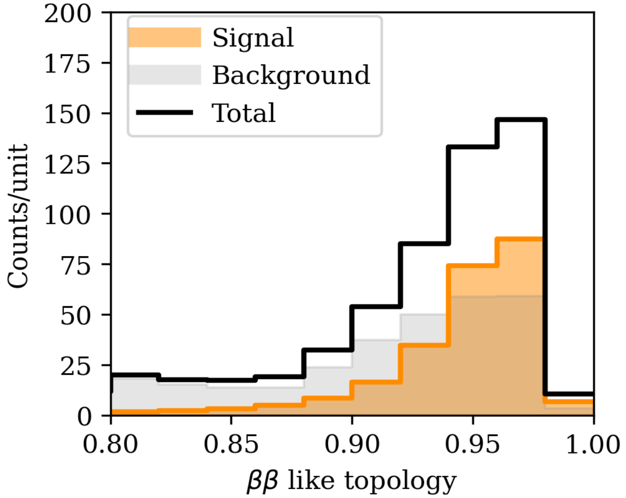
Homogeneous volume:
γ bkg. rejection based on multiplicity of events

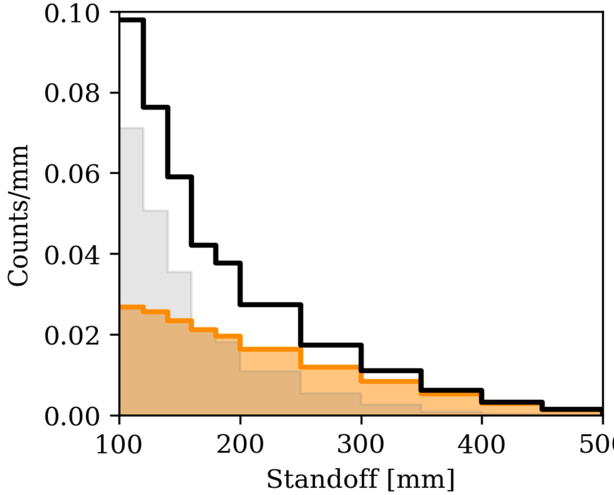
Standoff:



Homogeneous volume:
Self-shielding of γ radiation

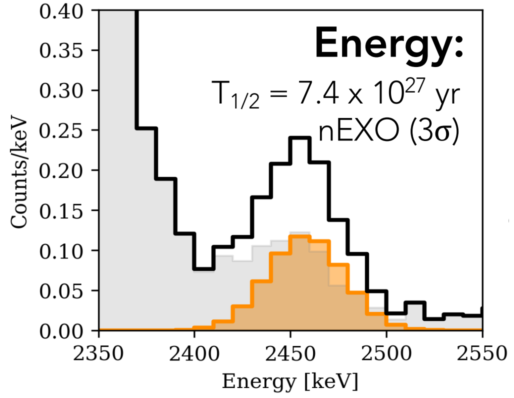


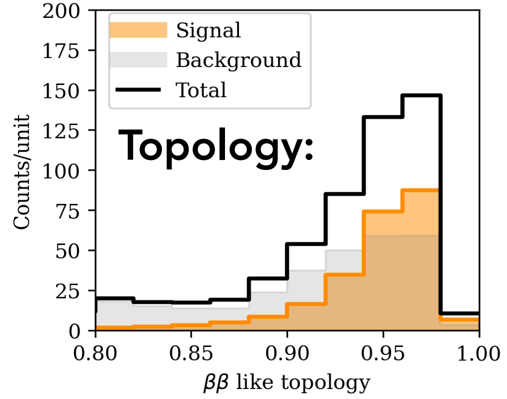


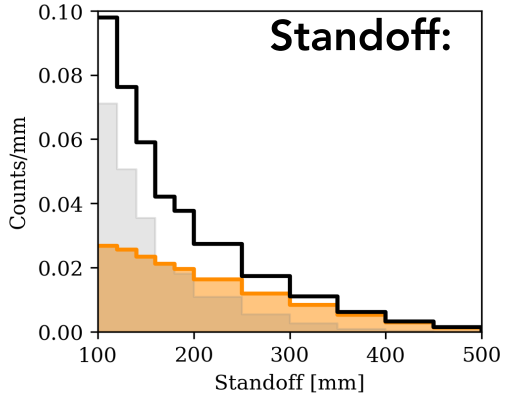


1D projections of simulated nEXO signal and backgrounds:

The nEXO detector performance

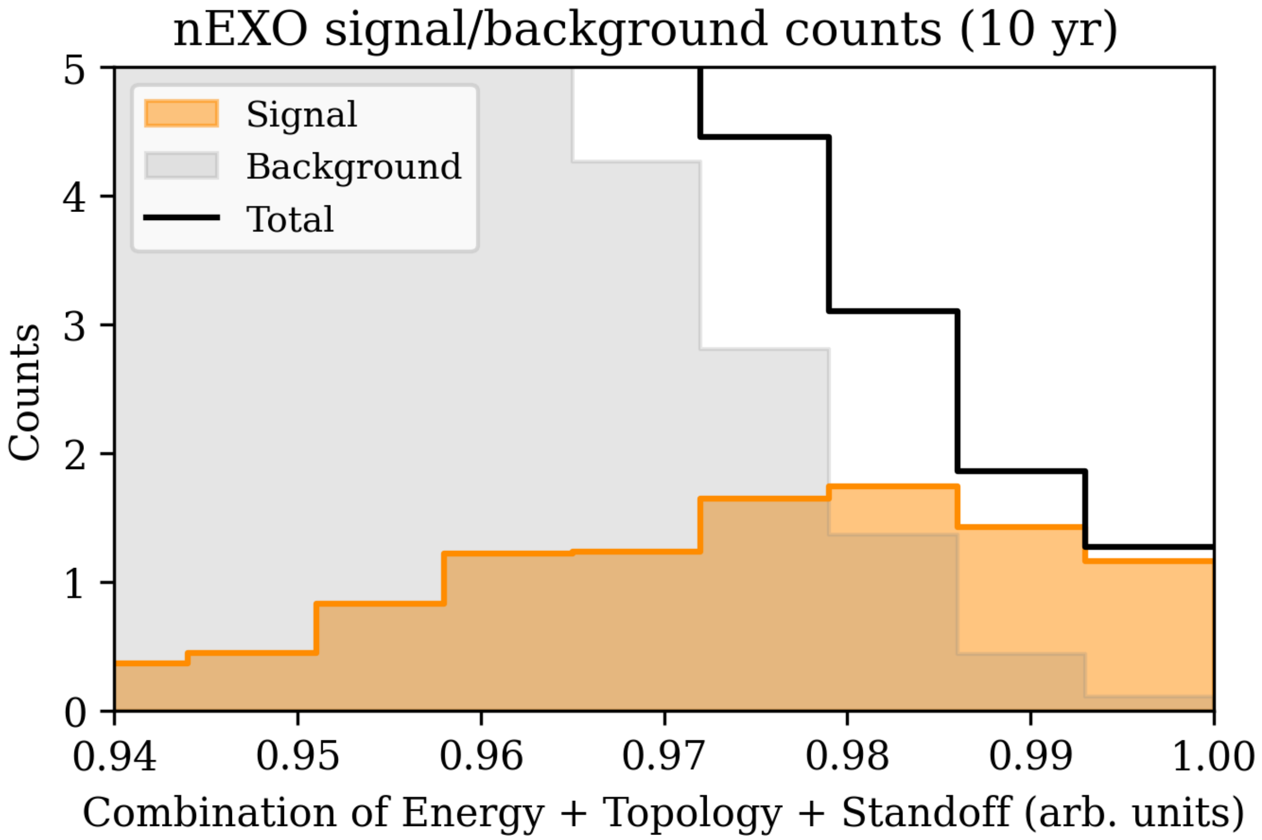






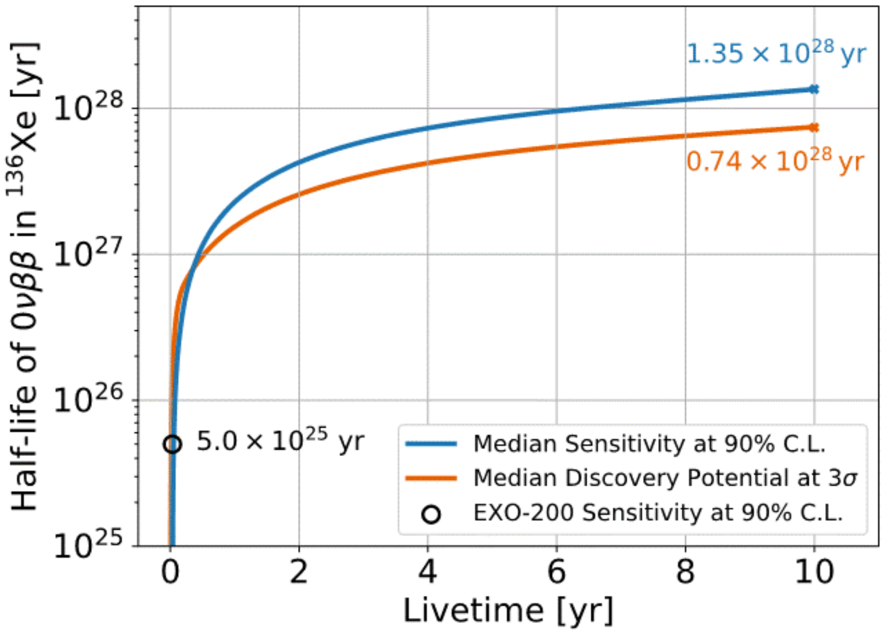
We perform a 3D likelihood fit in the energy-topology-standoff space

Arranging the 3D bins into 1D, ordered by S/B, helps visualize the signal and background separation in nEXO: *Conservation of correlations*



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

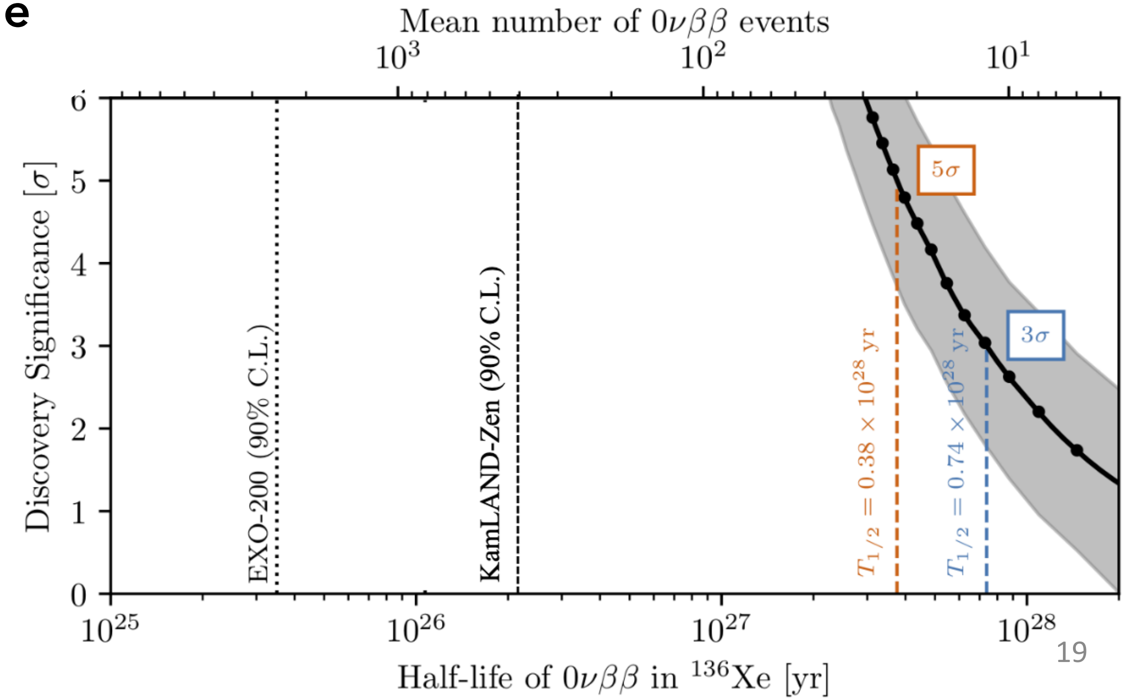
nEXO sensitivity



Projected sensitivity based on:

- background levels measured in samples of all detector materials
- model of event distributions in nEXO

If no signal is observed during nEXO life time, then the median exclusion is close to **2 orders of magnitude higher** than the current best lower limit.
→ 1.35 x 10^{28} yr



Discovery potential of nEXO probes unexplored parameter space.

Adhikari et al., J. Phys. G 49 (2022)

Conclusion

- **$0\nu\beta\beta$ decay is a powerful way to search for physics beyond the SM:**
  - Most sensitive probe of lepton number violation
  - Potentially connected to neutrino mass and matter/antimatter asymmetry
- **nEXO is a discovery experiment that aims at observing $0\nu\beta\beta$ decay**
- **nEXO is a next-generation experiment using a LXe TPC, with unique features that makes competitive:**
  - Multi-parameter analysis for signal extraction: energy + multiplicity + standoff = "bkg. free" $0\nu\beta\beta$ search
  - Can replace enriched xenon with natural xenon if $0\nu\beta\beta$ is observed
- **nEXO R&D:**
  - Cryogenic ASIC for light and charge readout
  - New modular charge and light tiles
- **Significant improvements** (bkg. reduction, energy resolution) in comparison to previous gen. exp.
- **nEXO and the other next generation of experiments will push two orders of magnitude in sensitivity to the $0\nu\beta\beta$ half-life.**

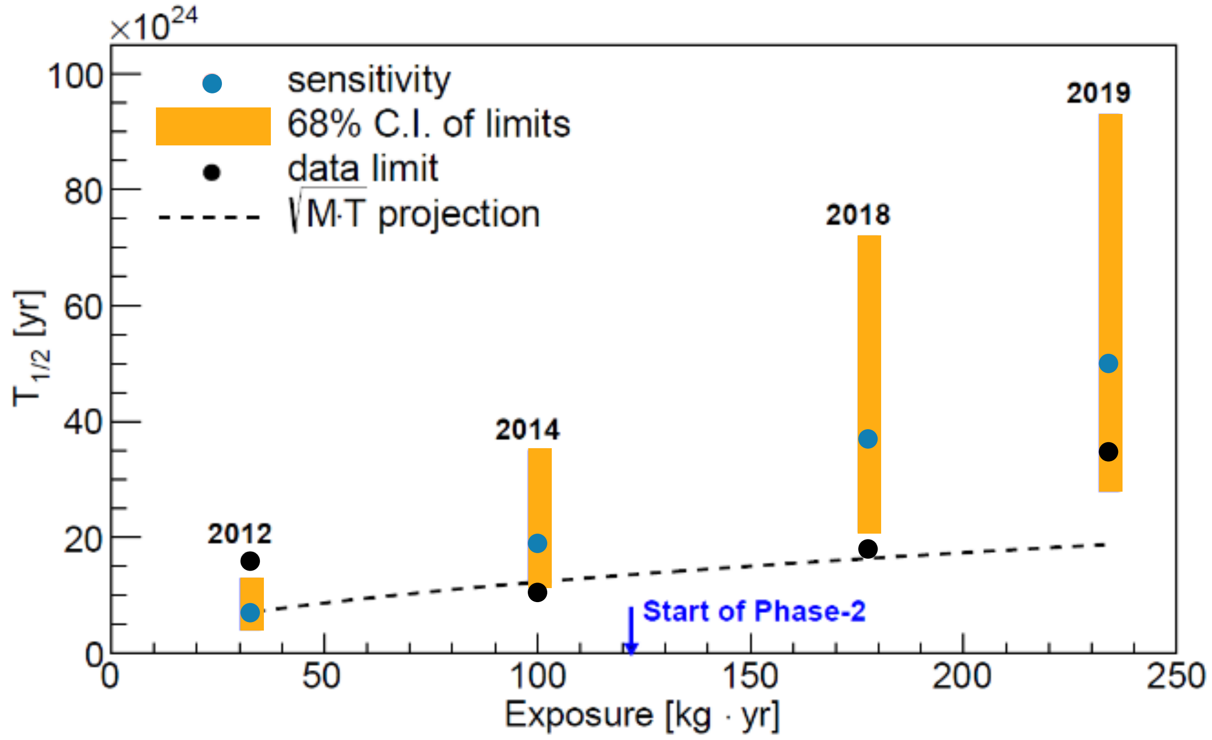
Thank you

Backup slides

EXO-200: results

Final results of the EXO-200 experiment *Phys. Rev. Lett. 123 (2019) 161802*

- Phase I+II: 234.1 kg.yr of ^{136}Xe exposure
- No statistically significant $0\nu\beta\beta$ observed
- Limit: $T_{1/2} > 3.5 \times 10^{25}$ yr (90% C.L.)
- Background: low levels and excellent understanding due to extensive material characterization program + simulation



Xenon procurement

- Xenon enrichment is well known and cost effective
- EXO-200 had 200 kg of xenon enriched up to 80% with ^{136}Xe
- Since, KAMLAND-Zen used 745 kg of xenon enriched up to 90% with ^{136}Xe
- nEXO will need about 5 times what is already available
- nEXO has identified at least two western suppliers each with enough enrichment capacity for the entire production at competitive price

Physics reach: mass ordering

Parametrization with the effective neutrino Majorana mass:

$$\left[T^{0\nu}_{1/2}\right]^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} \left|\mathcal{M}^{0\nu}\right|^2$$

Phase space factor

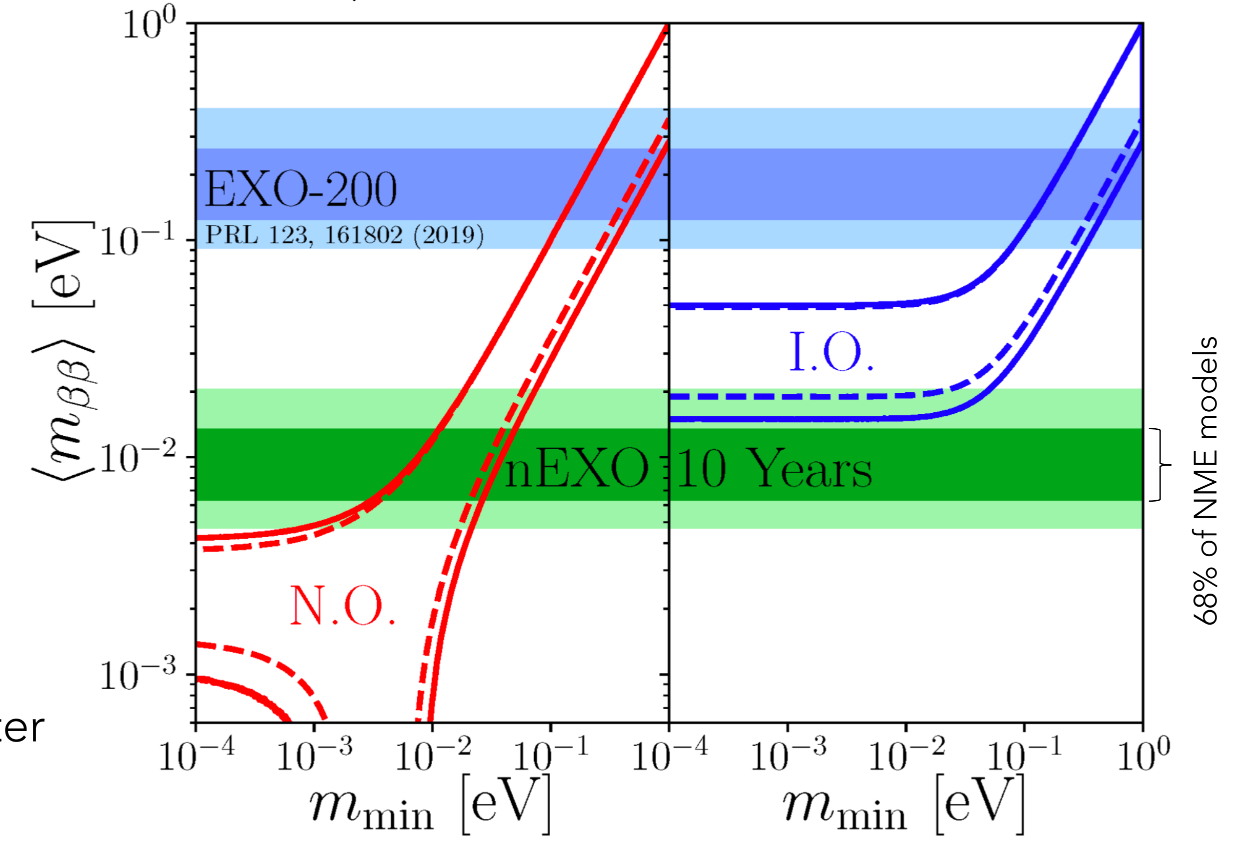
^{136}Xe benefits from a larger $G^{0\nu}$ compared to lighter isotopes

Nuclear matrix element

- Calculations challenging: significant theoretical uncertainty
- Consider all published NMEs not supplanted by later publications

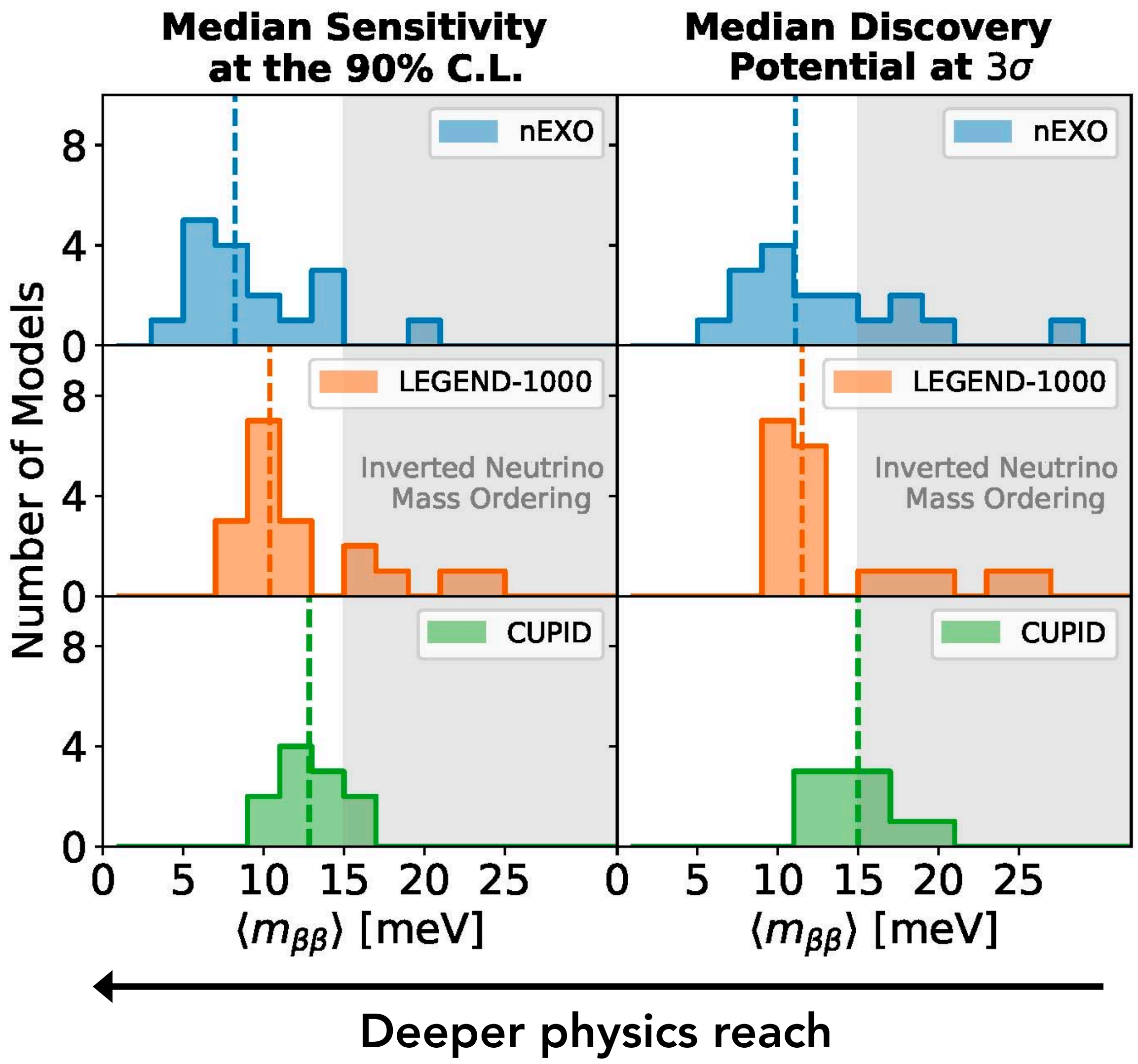
$\mathbf{m_{\beta\beta}}$ (median NME) :

- 8.2 meV 90% exclusion sensitivity
- 11.1 meV 3σ discovery potential



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

Comparison with other experiments



	$m_{\beta\beta}$ [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.)

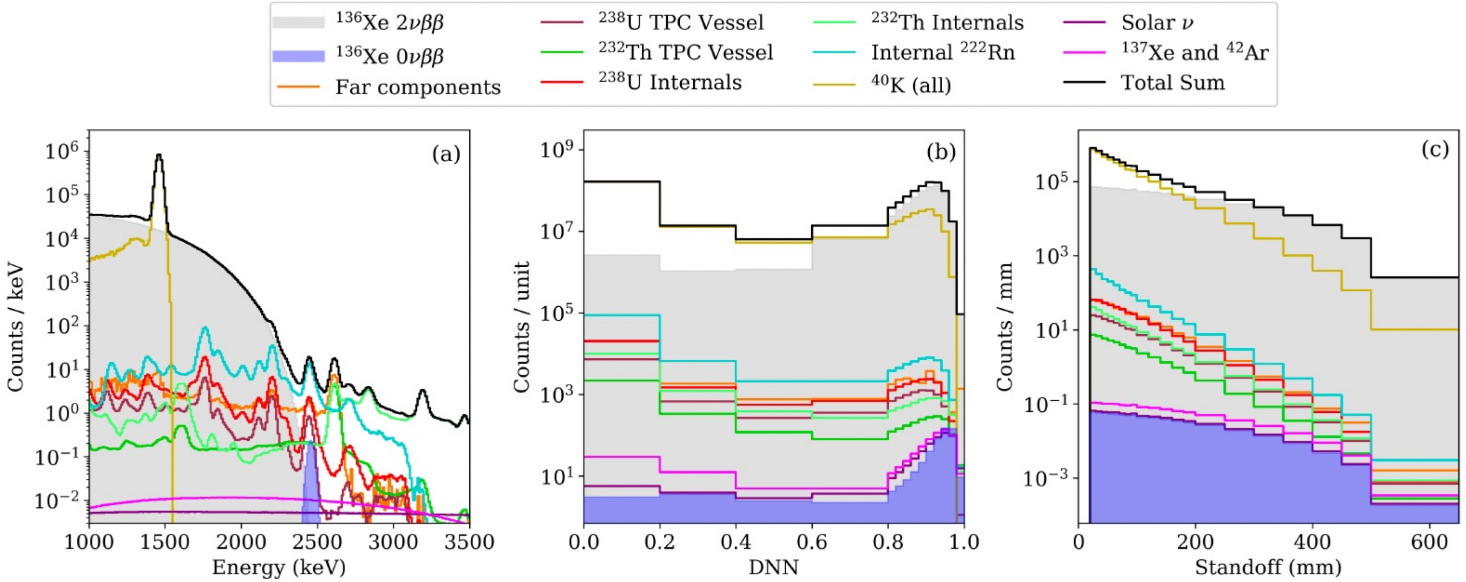
nEXO collaboration, J. Phys. G: Nucl. Part. Phys. 49 015104 (2022), arXiv:2106.16243
LEGEND pCDR, arXiv: 2107.11462
CUPID pCDR, arXiv:1907.09376

Projected event distribution in nEXO

Model of event distributions in nEXO, projected onto each of the three axes used in the sensitivity analysis:

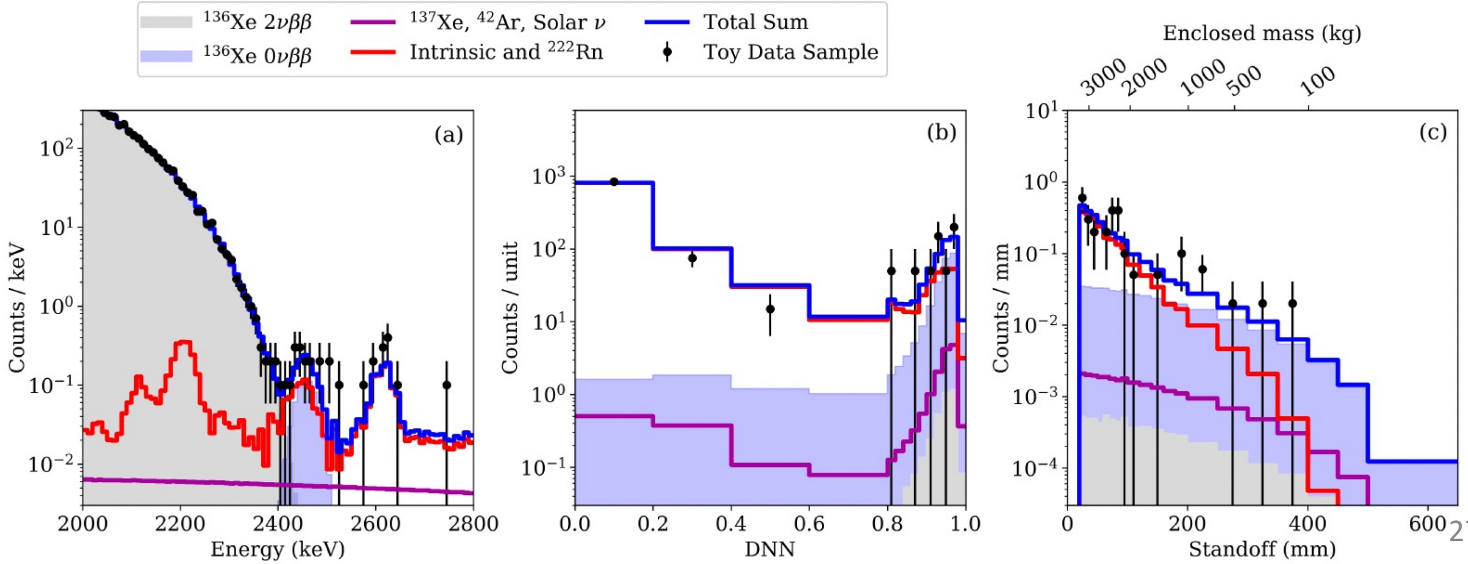
- Event energy
- Multi/single site event discriminator
- Standoff distance from wall

The $0\nu\beta\beta$ signal assumes a $T_{1/2}$ of 0.74×10^{28} y

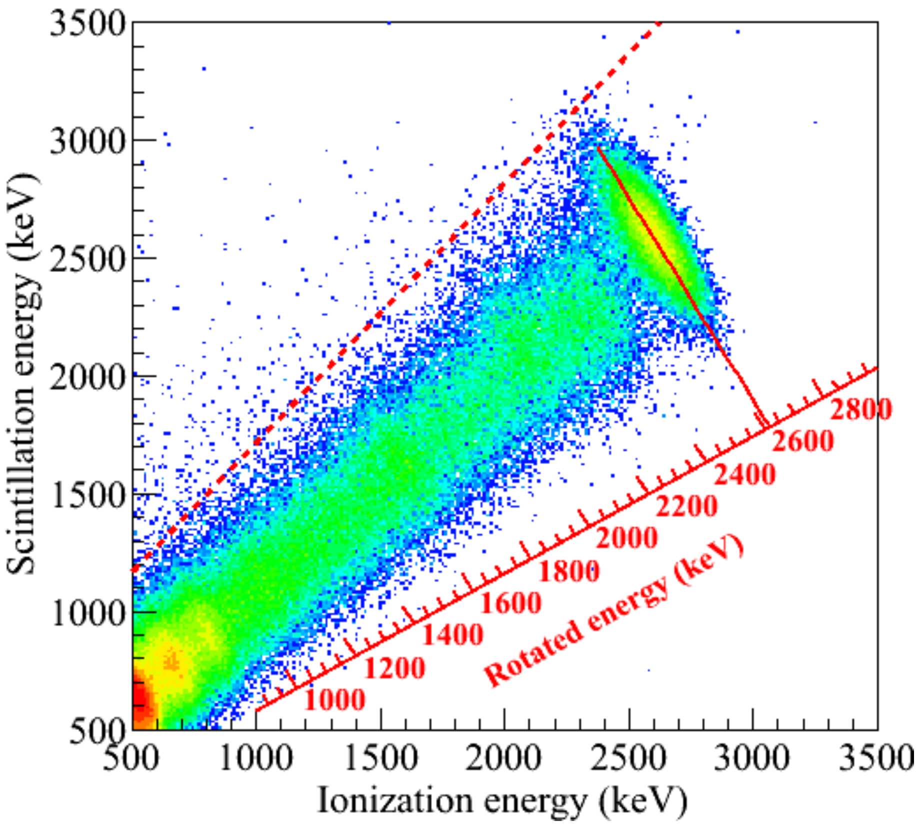


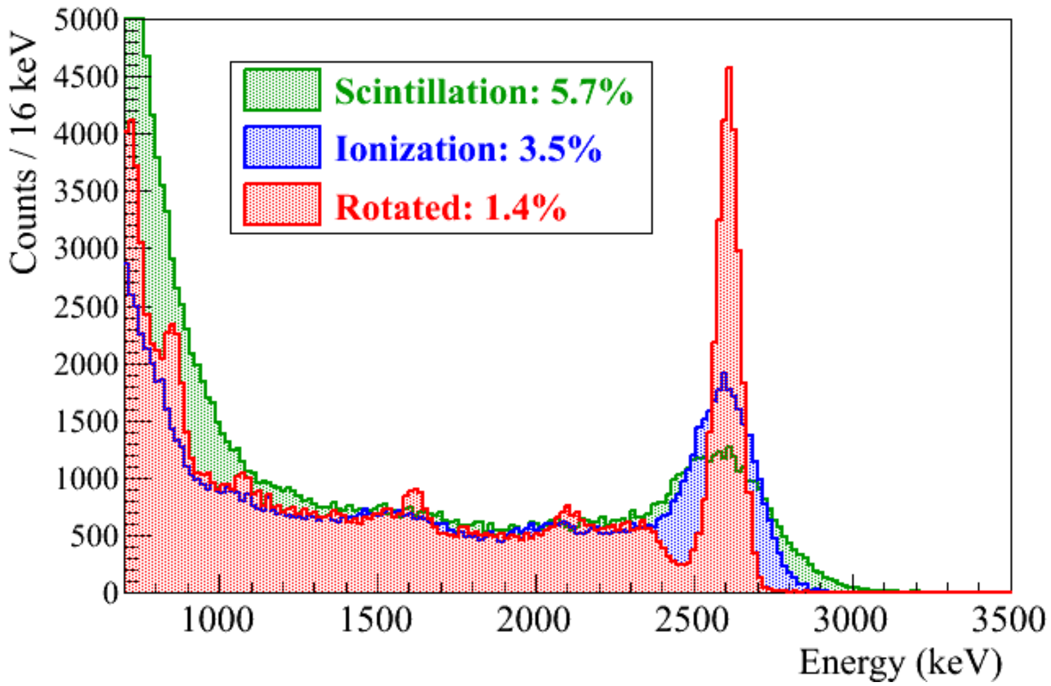
Distributions of events in the "ROI":

- Event energy within the signal FWHM
- Event multiplicity DNN > 0.85
- Innermost 2 tonnes of LXe



There is a simple example from EXO-200 (not nEXO) early R&D
(AKA how to measure energy in LXe)





Anticorrelation between scintillation and ionization requires 2D analysis.

Projections are not sufficient, but the correct linear combination is very powerful.

E. Conti et al. Phys Rev B 68 (2003) 054201