nEXO: a status report

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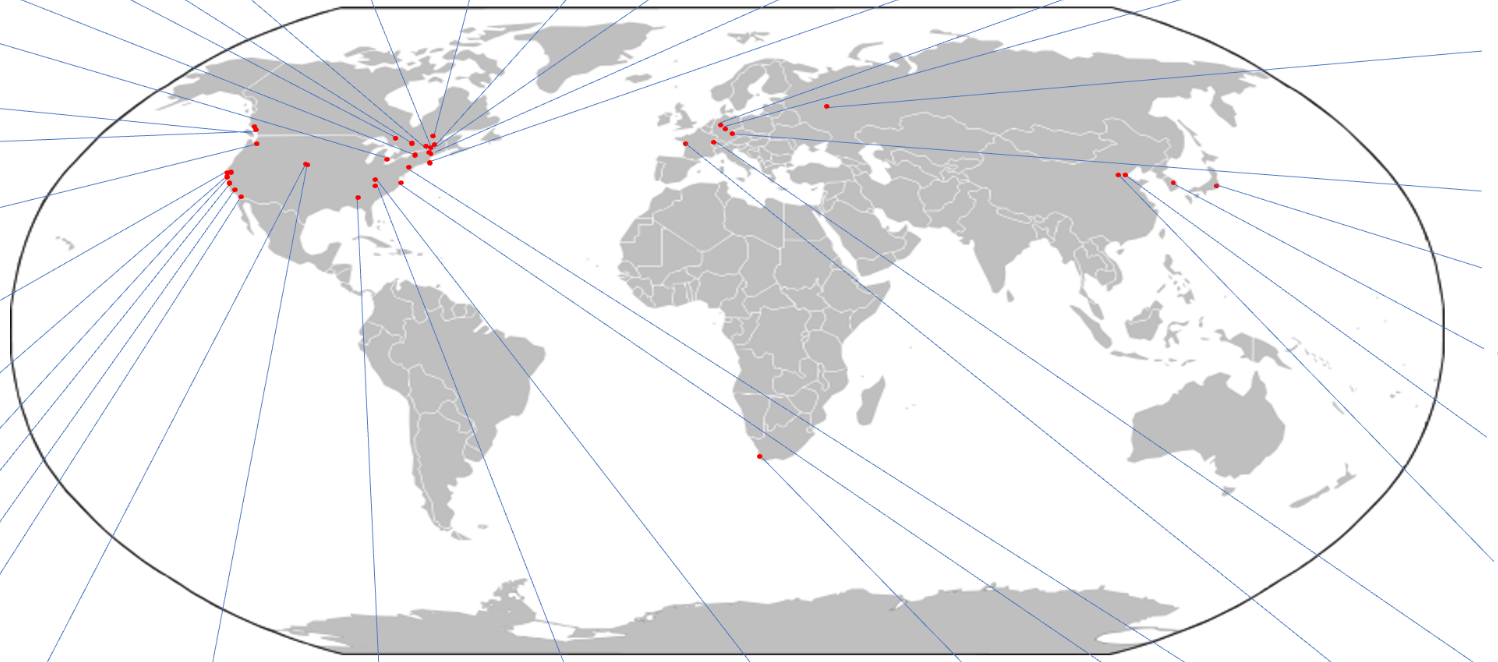
nEXO collaboration



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Queen's University
Université de Sherbrooke
McGill
University of Massachusetts Amherst
Yale University
Brookhaven National Laboratory
WWU Münster
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Université Laurentienne
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University of Windsor
The University of British Columbia
TRIUMF
Pacific Northwest National Laboratory
Skyline College
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Lawrence Livermore National Laboratory
SLAC National Accelerator Laboratory
Stanford University
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UC San Diego
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ibs Institute for Basic Science
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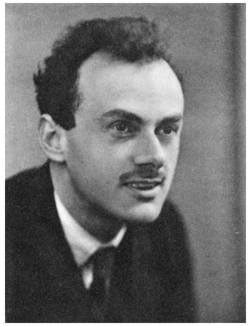
We have two possible ways to describe neutrinos:

“Dirac” neutrinos

(some “redundant” information but the “good feeling” of things we know…)

$$\nu^D = \begin{pmatrix} \nu_L \\ \bar{\nu}_L \\ \nu_R \\ \bar{\nu}_R \end{pmatrix}$$



“Majorana” neutrinos

(more efficient description, no lepton number conservation, new paradigm…)

$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Which way Nature has chosen to proceed
is an experimental question

However, the two descriptions are distinguishable only if $m_\nu \neq 0$

(and the observable difference → 0 for $m_\nu \to 0$)

Neutrinoless double beta decay is the most sensitive probe for this.

Fact #1:

The finite neutrino mass from oscillations means that, if neutrinos are Majorana particles, 0νββ decay is observable.

Fact #2:

The observation of the 0νββ decay, i.e. the measurement of a finite half life, would be a great discovery with no other qualification.

This is why we are doing those experiments!

Fact #3:
A healthy neutrinoless double-beta decay program requires several isotopes.

This is because:

- *Different isotopes correspond to vastly different experimental techniques*
- *Because of the uncertainties in Nuclear Matrix Elements any given isotope could come with unknown liabilities*
- *The elucidation of the mechanism producing the decay requires the analysis of more than one isotope*
- *2 neutrino background is different for various isotopes*
- *There could be unknown γ transitions and a line observed at the "end point" in one isotope does not necessarily imply the $0\nu\beta\beta$ decay discovery (although, in modern detectors, this is somewhat less of an issue)*

Today, these principles are well recognized by funding agencies.


1 | EXECUTIVE SUMMARY

- How do we use atomic nuclei to uncover physics beyond the Standard Model?

These questions are addressed by thousands of nuclear scientists working in experimental, theoretical, and computational investigations. Anchoring this world-leading program are the four national user facilities, each with unique capabilities for addressing our science questions: the Argonne Tandem Linac Accelerator System (ATLAS), CEBAF, FRIB, and the Relativistic Heavy Ion Collider (RHIC). A consortium of 13 university-based accelerator laboratories, known collectively as the Association for Research at University Nuclear Accelerators (ARUNA) laboratories, provide additional capability for cutting-edge experiments while training the next-generation scientists in the tools and techniques of nuclear science. Our work is done in small and large collaborations across the country, connecting theoretical and ex-

- Explaining how data gathered in these endeavors are connected and consistent through theory and computation. Nuclear theory motivates, interprets, and contextualizes experiments, opening up fresh research vistas.

Here are the recommendations of the 2023 Long Range Plan.

RECOMMENDATION 1

The highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments of the United States. We must draw on the talents of all in the nation to achieve this goal.

This recommendation requires

research budget that advances
gram through support of
experimental research across the
y expanding discovery potential,
nnovation, and workforce
the benefit of society.

ective operation of the national
TLAS, CEBAF, and FRIB, and
RHIC science program, pushing
human knowledge.

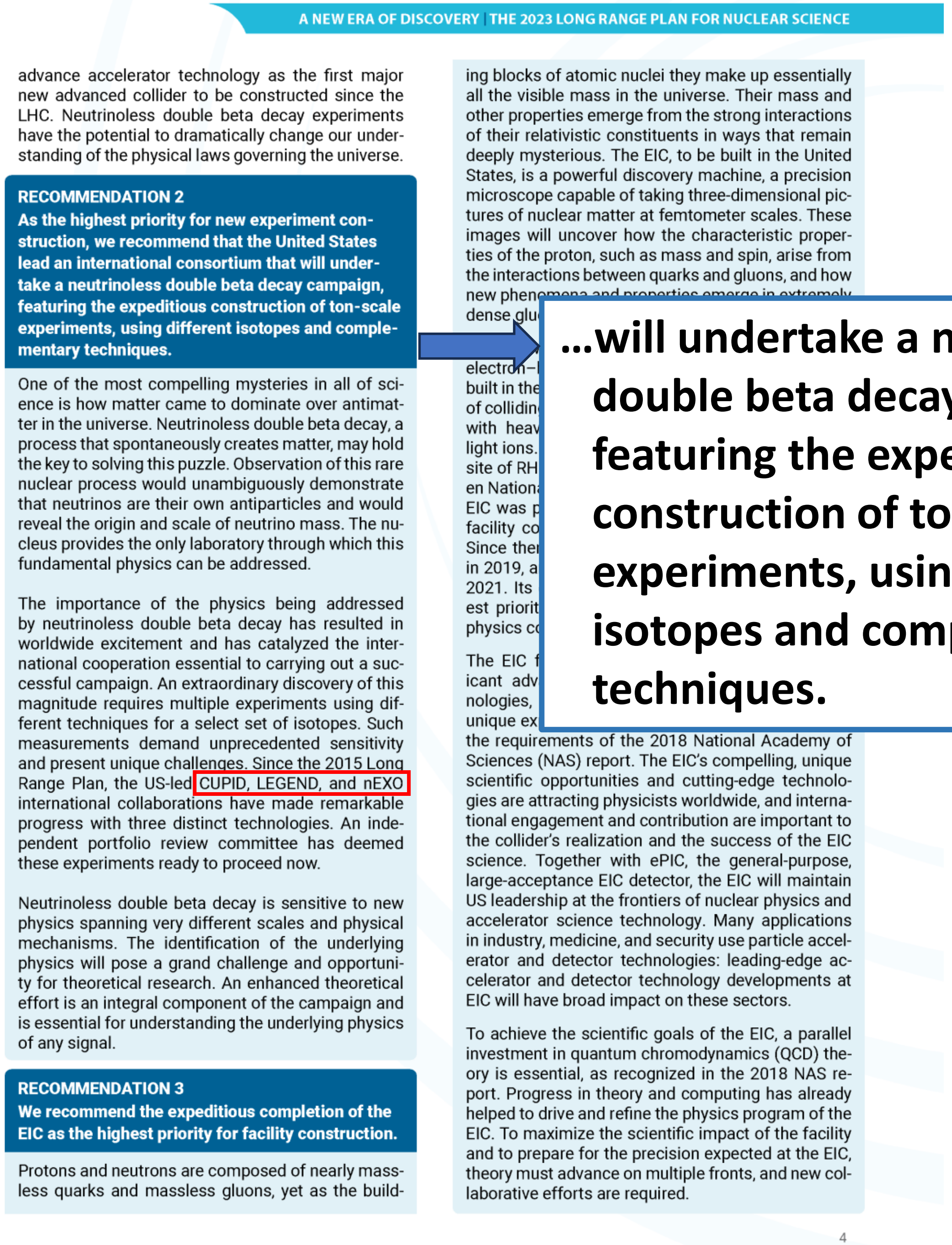
mpensation of graduate
levels commensurate with
ing—without contraction of the
vering barriers and expanding
n STEM for all, and so boosting
etitiveness.

cy and resources to ensure a
ctful environment for everyone,
ll potential of the US nuclear

is an ecosystem in which facility
search at laboratories and universi-
stigators, technical staff, postdocs,
k together to drive progress on the
questions discussed above and
ong Range Plan. A healthy work-
t only to these scientific goals but
n's security, technological innova-
ty.

the exceptionally high priority of
investments in new capabilities
s. The Electron–Ion Collider (EIC),
United States, will elucidate the ori-
er in the universe and significantly

A NEW ERA OF DISCOVERY
THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE
2023 | VERSION 1.3


A NEW ERA OF DISCOVERY | THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

advance accelerator technology as the first major new advanced collider to be constructed since the LHC. Neutrinoless double beta decay experiments have the potential to dramatically change our understanding of the physical laws governing the universe.

RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

One of the most compelling mysteries in all of science is how matter came to dominate over antimatter in the universe. Neutrinoless double beta decay, a process that spontaneously creates matter, may hold the key to solving this puzzle. Observation of this rare nuclear process would unambiguously demonstrate that neutrinos are their own antiparticles and would reveal the origin and scale of neutrino mass. The nucleus provides the only laboratory through which this fundamental physics can be addressed.

The importance of the physics being addressed by neutrinoless double beta decay has resulted in worldwide excitement and has catalyzed the international cooperation essential to carrying out a successful campaign. An extraordinary discovery of this magnitude requires multiple experiments using different techniques for a select set of isotopes. Such measurements demand unprecedented sensitivity and present unique challenges. Since the 2015 Long Range Plan, the US-led CUPID, LEGEND, and nEXO international collaborations have made remarkable progress with three distinct technologies. An independent portfolio review committee has deemed these experiments ready to proceed now.

Neutrinoless double beta decay is sensitive to new physics spanning very different scales and physical mechanisms. The identification of the underlying physics will pose a grand challenge and opportunity for theoretical research. An enhanced theoretical effort is an integral component of the campaign and is essential for understanding the underlying physics of any signal.

RECOMMENDATION 3

We recommend the expeditious completion of the EIC as the highest priority for facility construction.

Protons and neutrons are composed of nearly massless quarks and massless gluons, yet as the build-

ing blocks of atomic nuclei they make up essentially all the visible mass in the universe. Their mass and other properties emerge from the strong interactions of their relativistic constituents in ways that remain deeply mysterious. The EIC, to be built in the United States, is a powerful discovery machine, a precision microscope capable of taking three-dimensional pictures of nuclear matter at femtometer scales. These images will uncover how the characteristic properties of the proton, such as mass and spin, arise from the interactions between quarks and gluons, and how
dense glu

electron–I
built in the
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facility co
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2021. Its
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The EIC f
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unique ex
the requirements of the 2018 National Academy of Sciences (NAS) report. The EIC's compelling, unique scientific opportunities and cutting-edge technologies are attracting physicists worldwide, and international engagement and contribution are important to the collider's realization and the success of the EIC science. Together with ePIC, the general-purpose, large-acceptance EIC detector, the EIC will maintain US leadership at the frontiers of nuclear physics and accelerator science technology. Many applications in industry, medicine, and security use particle accelerator and detector technologies: leading-edge accelerator and detector technology developments at EIC will have broad impact on these sectors.

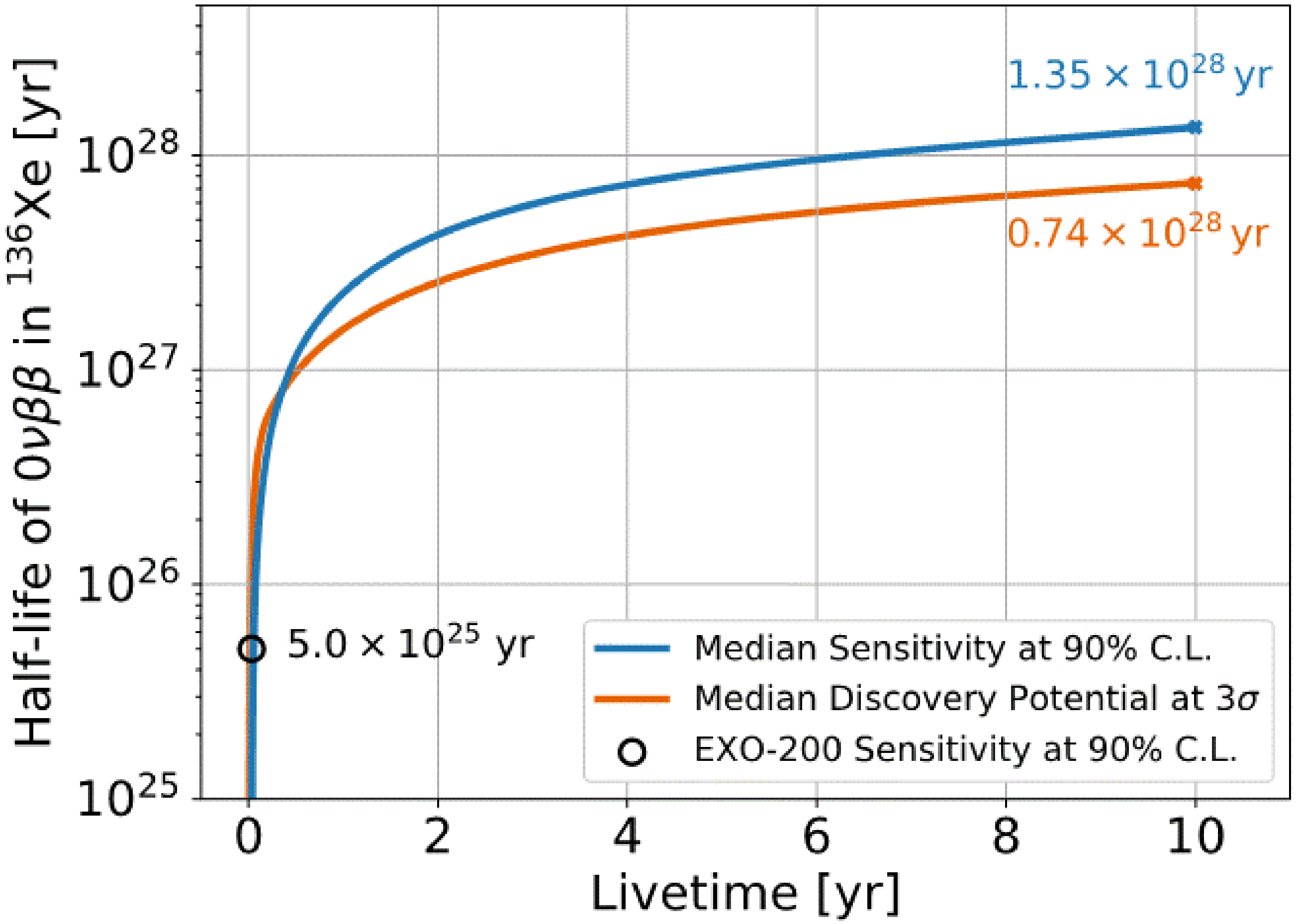
To achieve the scientific goals of the EIC, a parallel investment in quantum chromodynamics (QCD) theory is essential, as recognized in the 2018 NAS report. Progress in theory and computing has already helped to drive and refine the physics program of the EIC. To maximize the scientific impact of the facility and to prepare for the precision expected at the EIC, theory must advance on multiple fronts, and new collaborative efforts are required.

4

…will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

The crucial parameter in assessing the sensitivity to new physics is $T_{1/2}$

nEXO sensitivity as a function of livetime



Yet, the sensitivity in terms of half-life has an empirical flavor that is not satisfying:

One would like to express the sensitivity in terms of some deeper parameter of the theory.
This is not only matter of intellectual satisfaction, because it is also the only practical way of comparing physics reach from experiments using different isotopes.

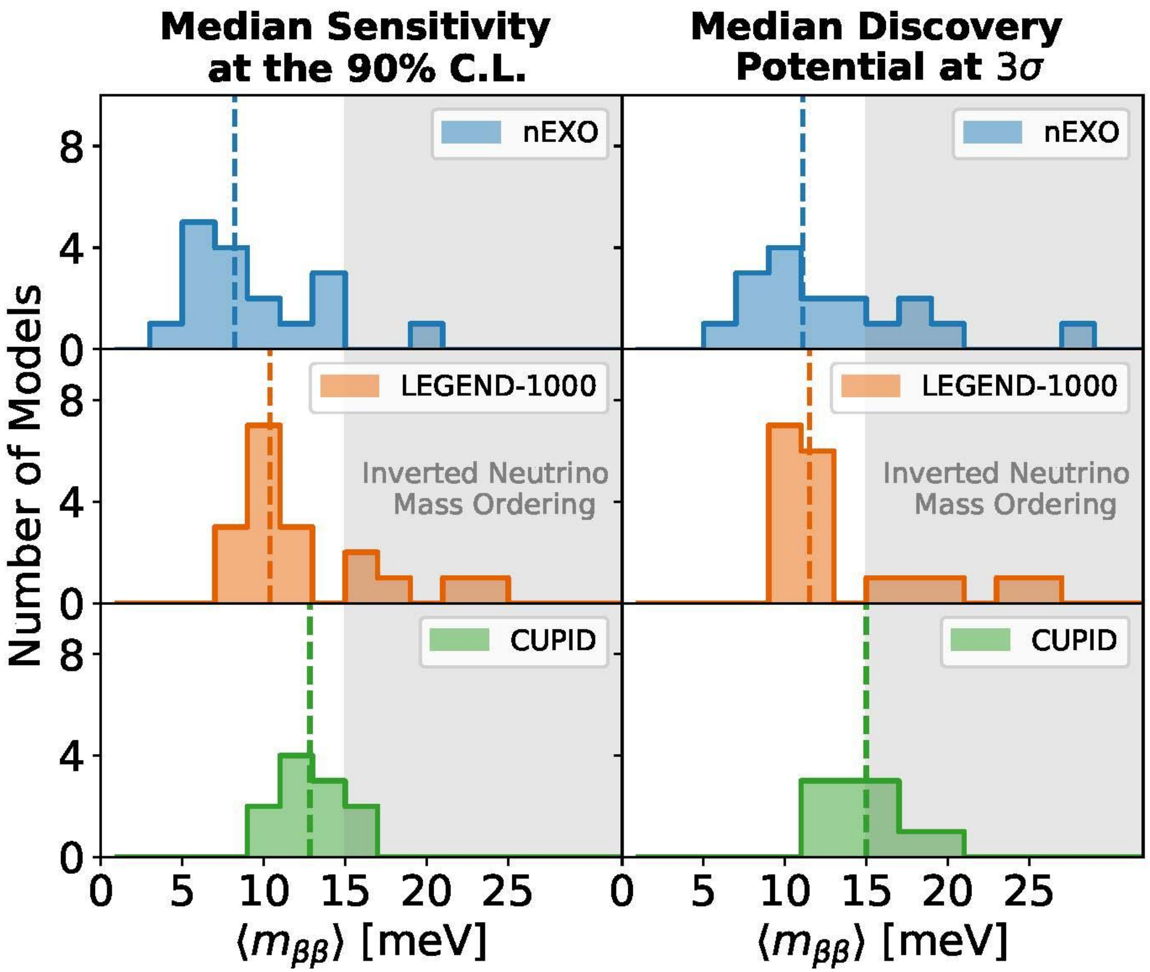
There are two problems with this:

1) We do not know which kind of new physics may be responsible for a certain half-life we may observe.
2) In any case, there is complicated nuclear physics between $T_{1/2}$ and the particle physics. If you are not a theorist, you can very naively think of this as describing the overlap of nucleon wavefunctions due to nuclear structure.

So, what to do? For 1) there is not much one can do, but chose one model and use it (or maybe show the reach for different models). Usually the "light neutrino exchange" model is used, with the sensitivity expressed in terms of "Majorana neutrino mass", but this is really only one possibility out of many!
For 2) the idea is to do the best possible nuclear structure calculation(s) and try estimating their uncertainties. A number of auxiliary experiments may help estimating such uncertainties.

We are ready to compare experiments based on different isotopes

(shown here are the experiments moving towards construction)



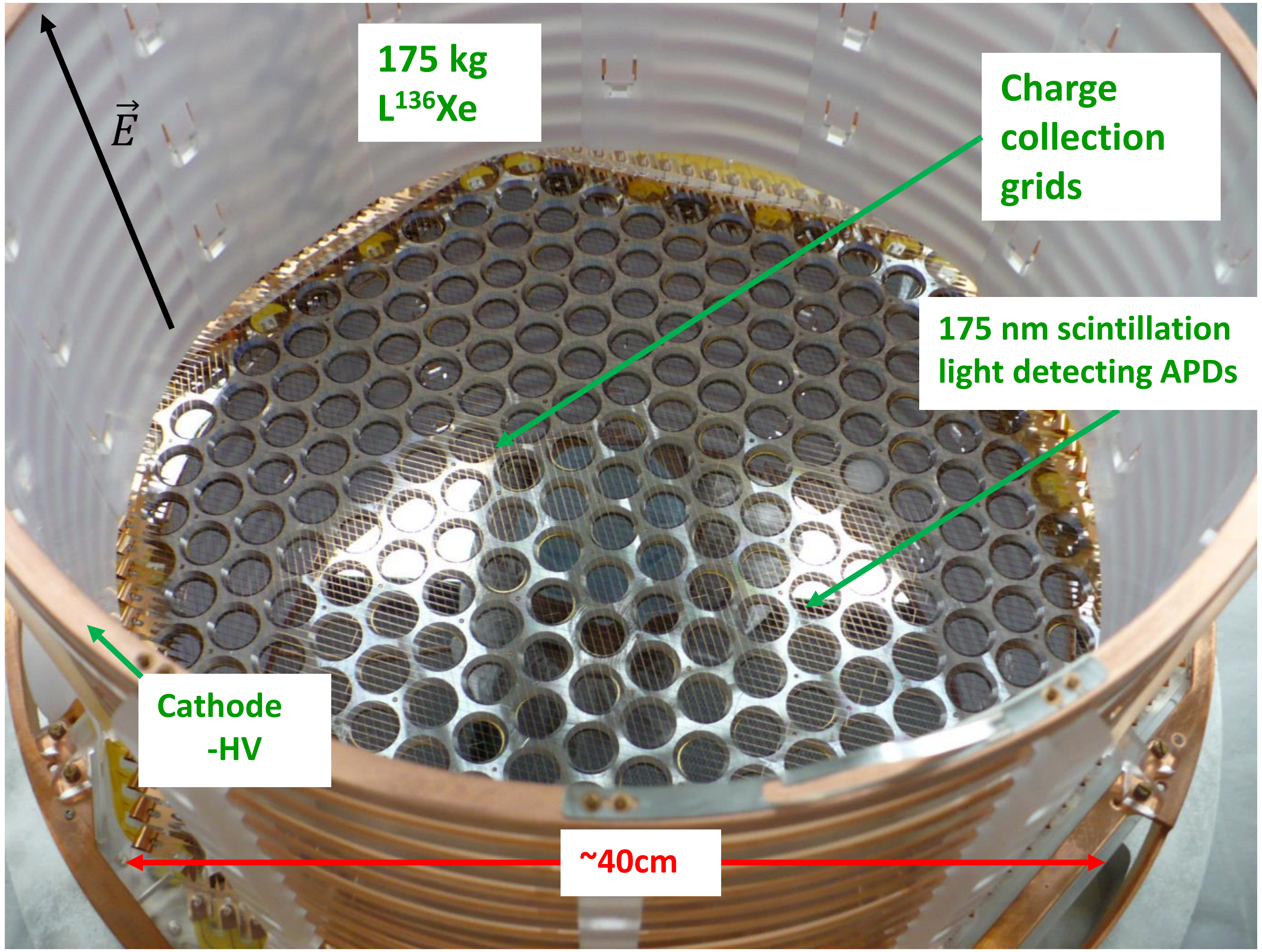
	$m_{\beta\beta}$ [meV], (*median NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

$T_{1/2}$ 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.)

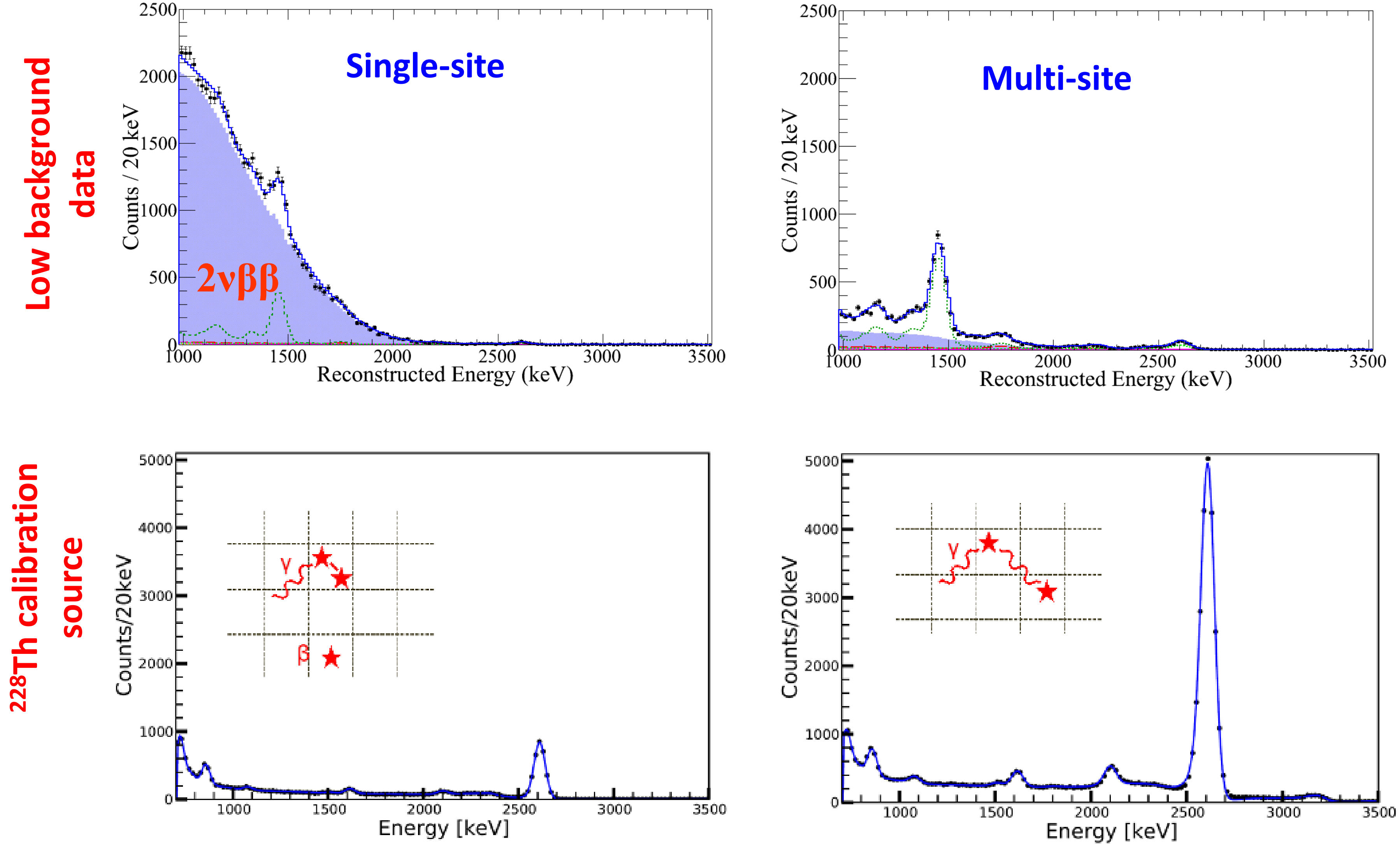
nEXO directly derives from EXO-200

(1/2 of its TPC shown here without the liquid Xe)

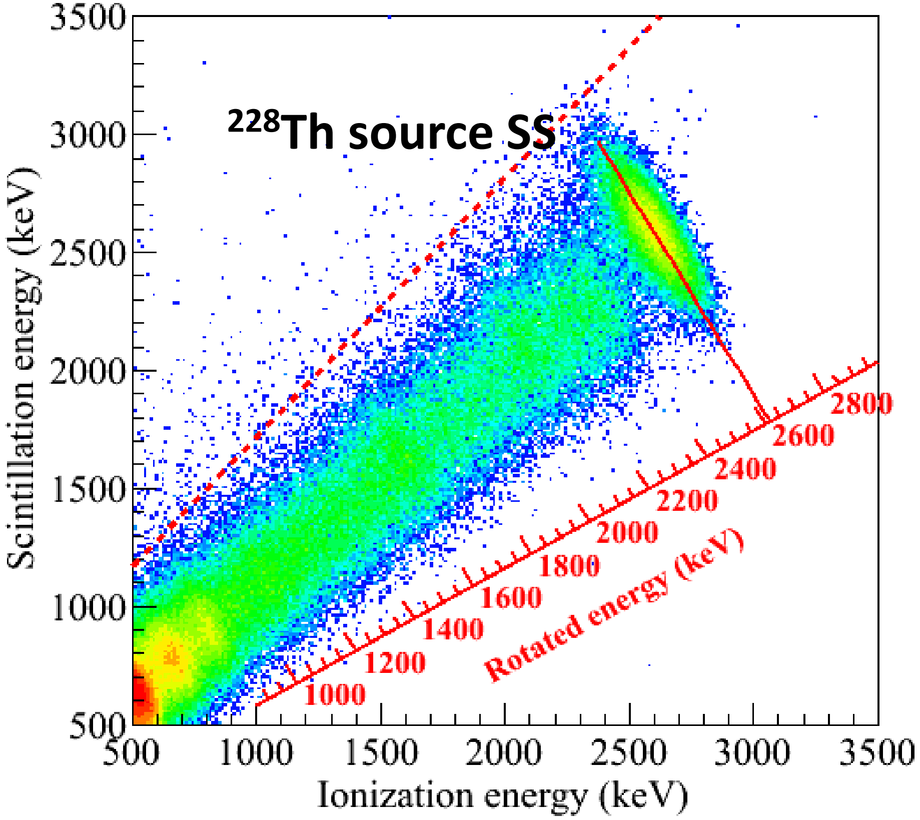


Using event multiplicity to recognize backgrounds

EXO-200 data



In addition, the scintillation light was found to be anticorrelated with the free ionization, so that combining the two yields the best energy resolution.

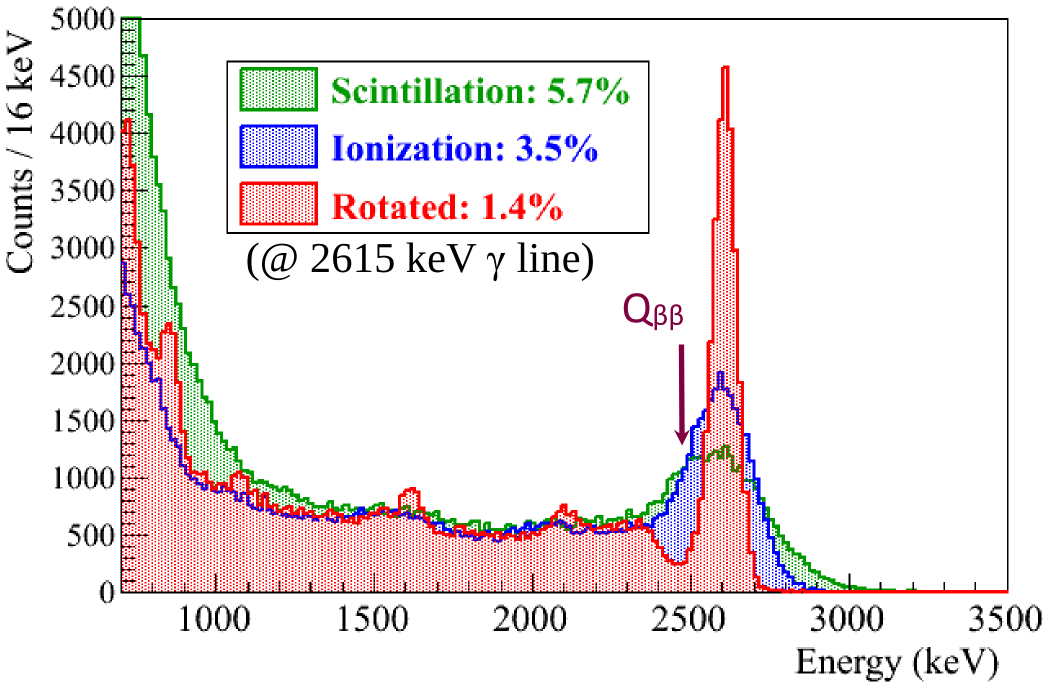


Rotation angle chosen to optimize energy resolution near $Q_{\beta\beta}$=2457.83 keV

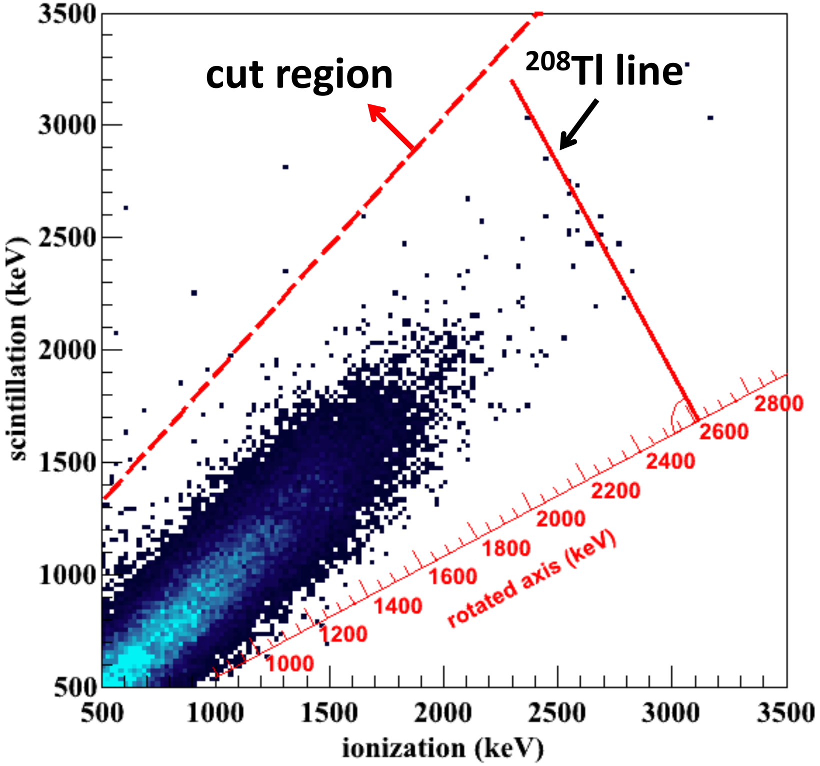
Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

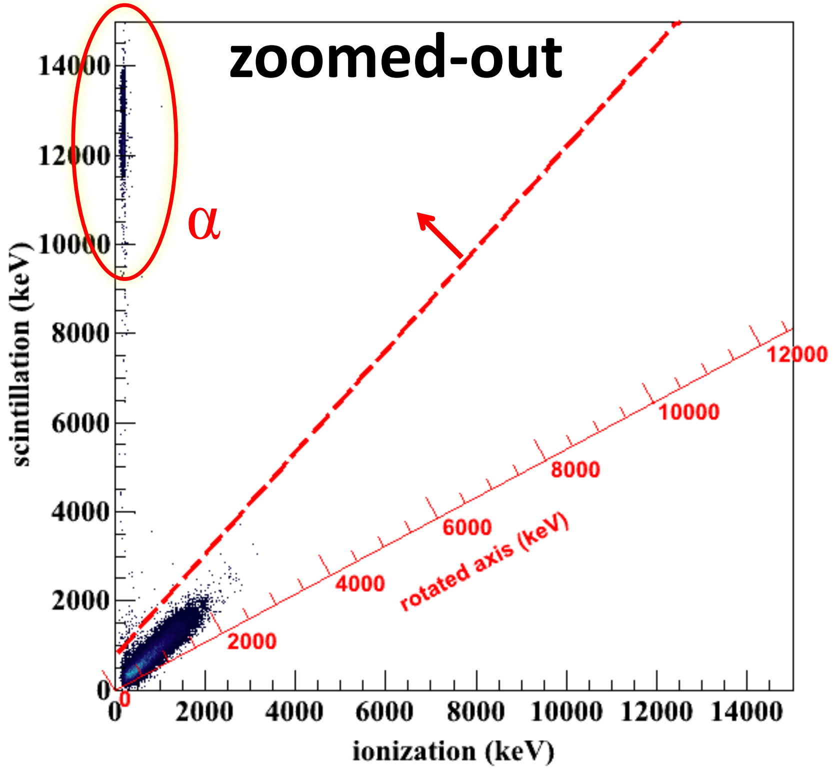
E.Conti et al. Phys Rev B 68 (2003) 054201

By now this is a common technique in LXe



The relative strength of free ionization vs scintillation is also very powerful in discriminating against α or events at the edge of the TPC.





Events removed by diagonal cut:

- α (larger ionization density → more recombination → more scintillation light)
- events near detector edge → not all charge is collected

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.

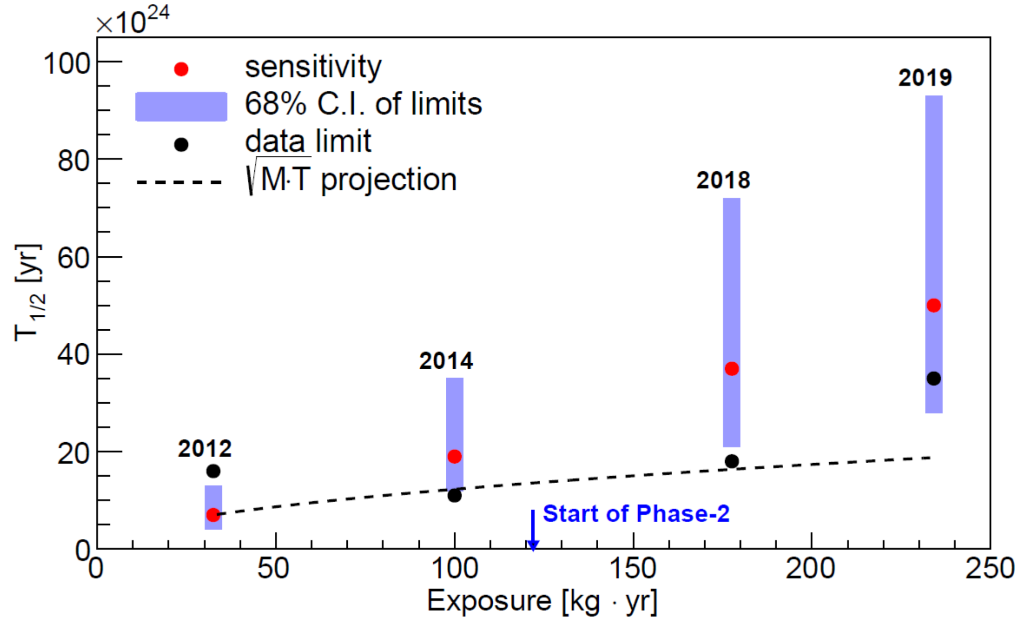
Cosmogenic backgrounds:

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		

EXO-200 sensitivity grew linearly with exposure

- 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

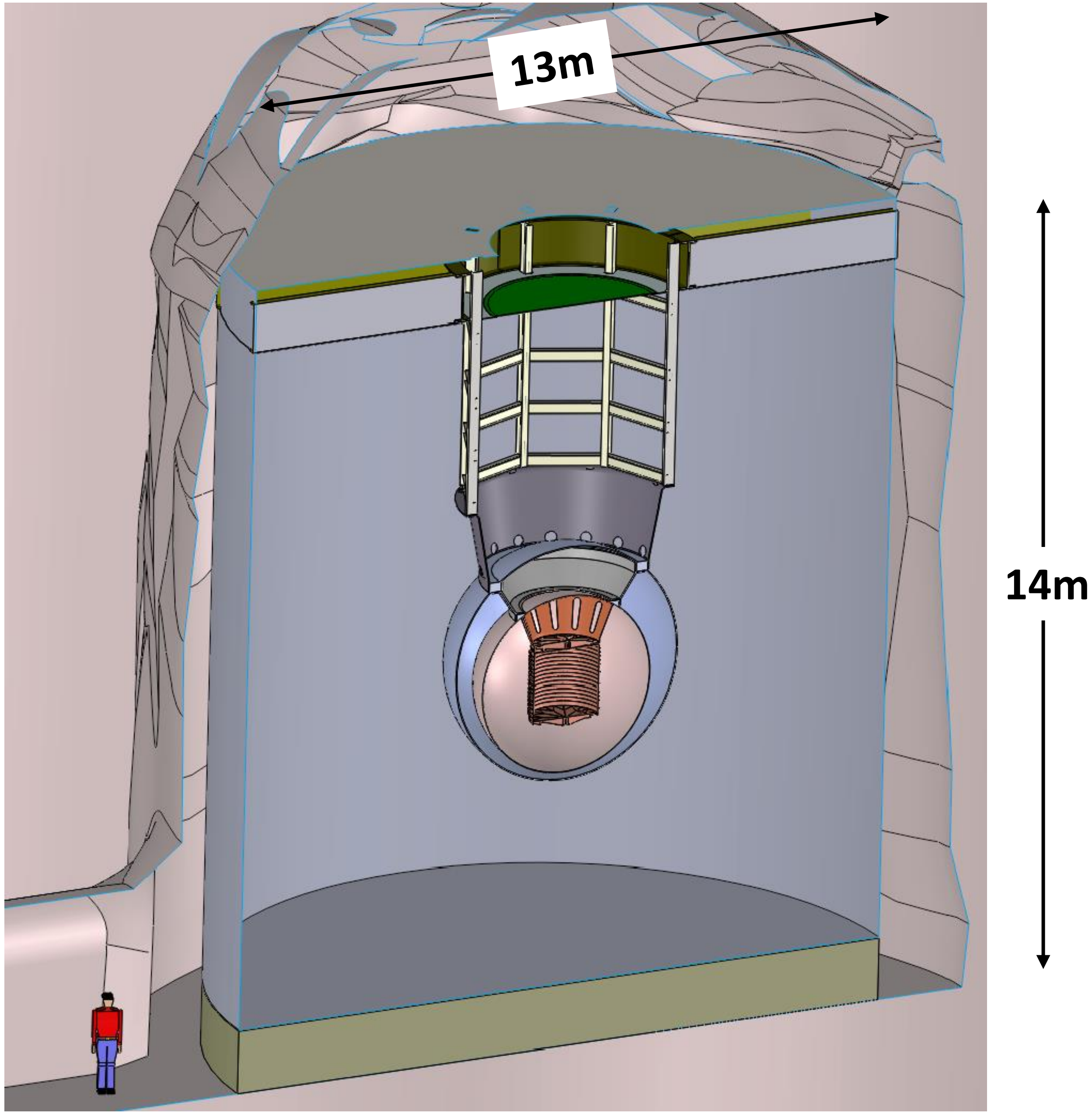
Limit: $T_{1/2}^{0\nu\beta\beta} > 3.5\text{x}10^{25}$ yr (90% CL)

$\langle m_{\beta\beta} \rangle$ < (93 -286) meV

Sensitivity: $5.0\text{x}10^{25}$ yr

nEXO

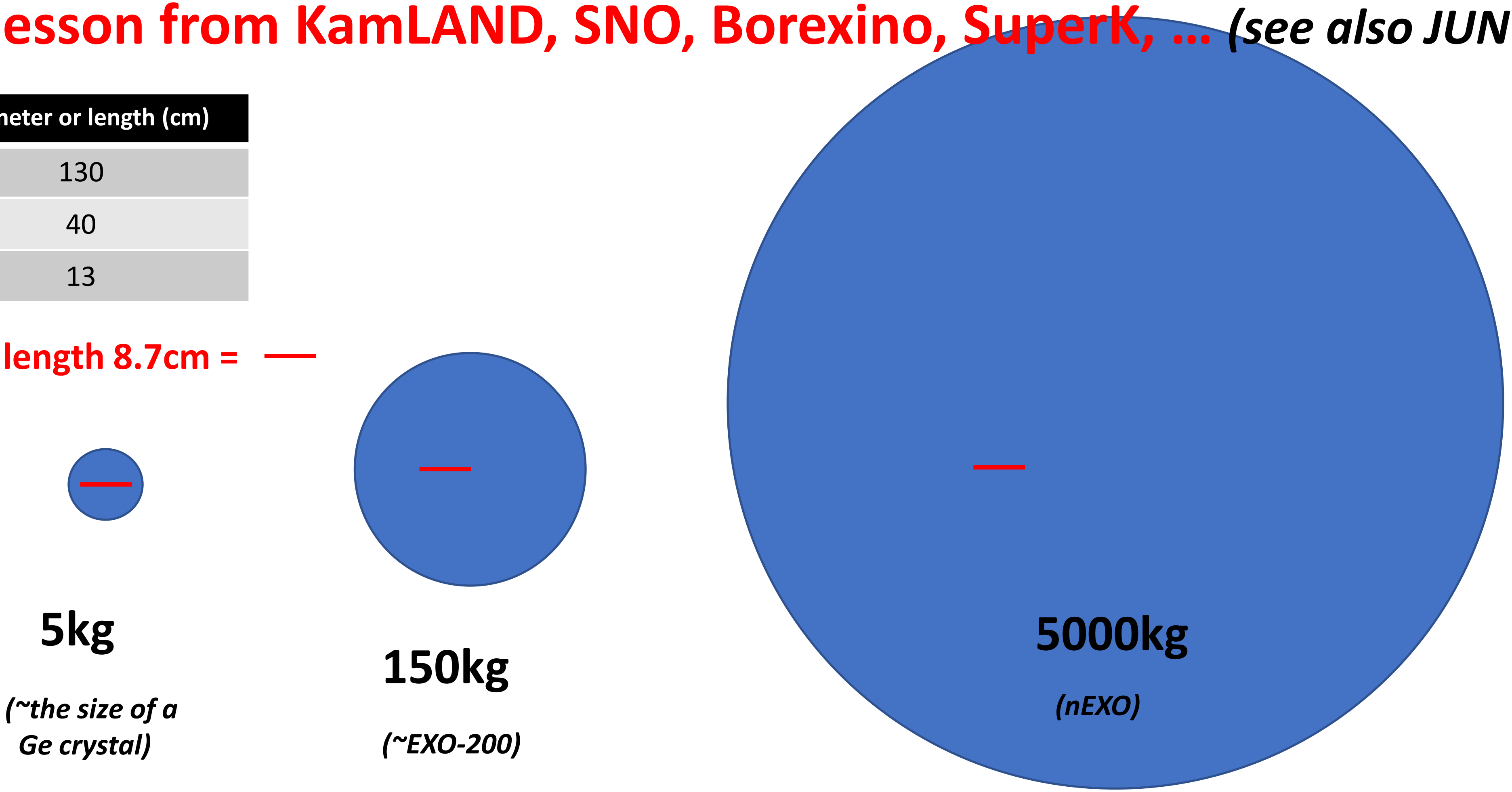
A 5000 kg enriched LXe TPC,
directly extrapolated from **EXO-200**



Monolithic/Homogeneous is key because extraneous material is all external → this is the lesson from KamLAND, SNO, Borexino, SuperK, … *(see also JUNO)*

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

2.5 MeV γ attenuation length 8.7cm = —



5kg

(~the size of a Ge crystal)

150kg

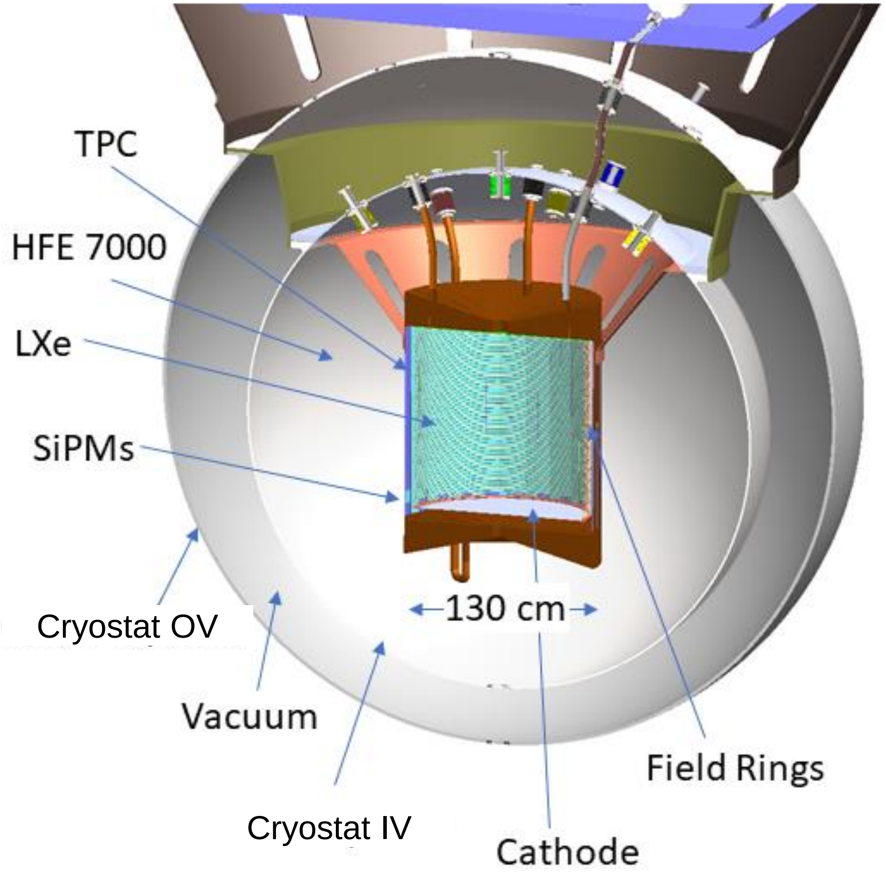
(~EXO-200)

5000kg

(nEXO)

Among the projects selected and funded by DoE for tonne-scale, nEXO is the only Monolithic/Homogeneous detector

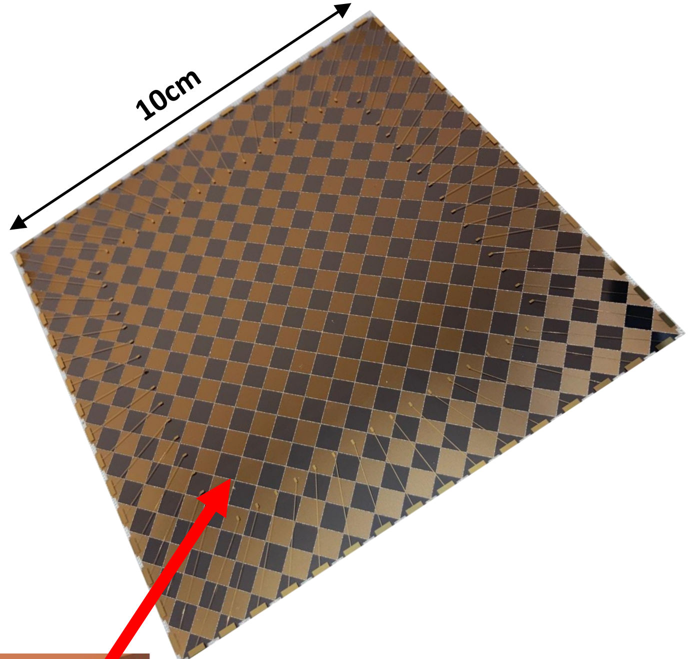
The nEXO detector is an evolution from EXO-200, with specific R&D done over the last 10 years



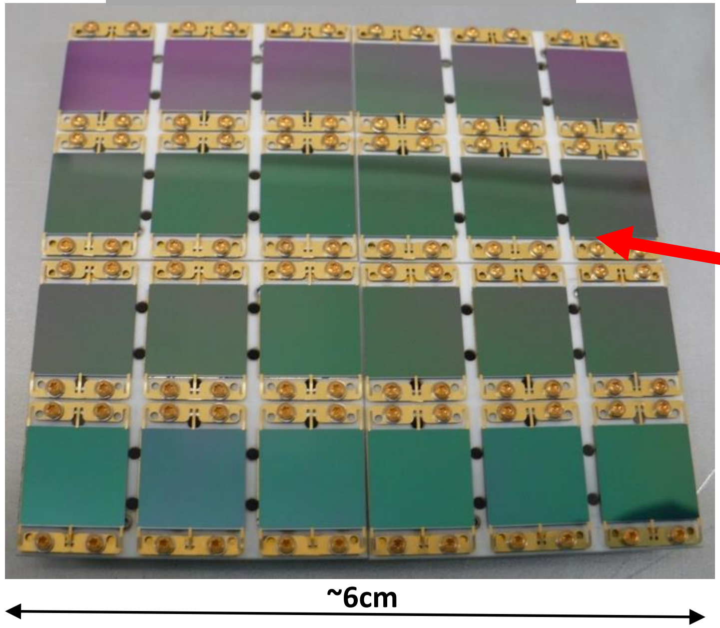
	EXO-200:	*nEXO:*	Improvements:
Vessel and cryostat	Thin-walled commercial Cu w/HFE	*Thin-walled electroformed Cu w/HFE*	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	*Operating voltage: 50 kV*	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad polyimide (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

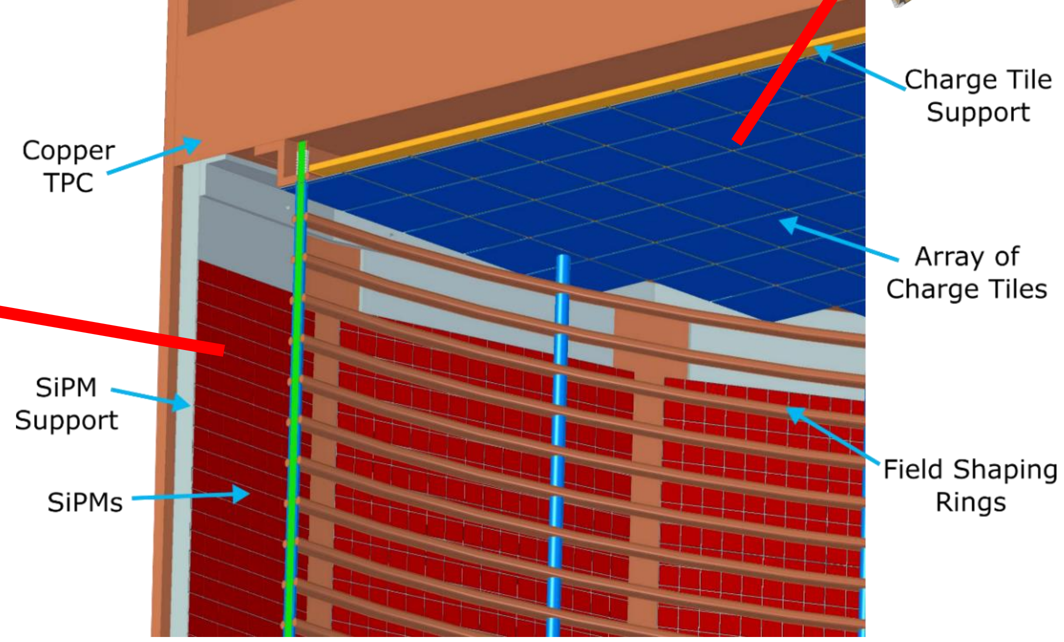
Main technical changes on the EXO-200 theme

- Only one drift volume
- ASIC electronics in LXe
- Silica substrate charge collection tiles
- VUV SiPMs (~4.5m^2)
- Little plastics in the TPC (Sapphire, Silica)

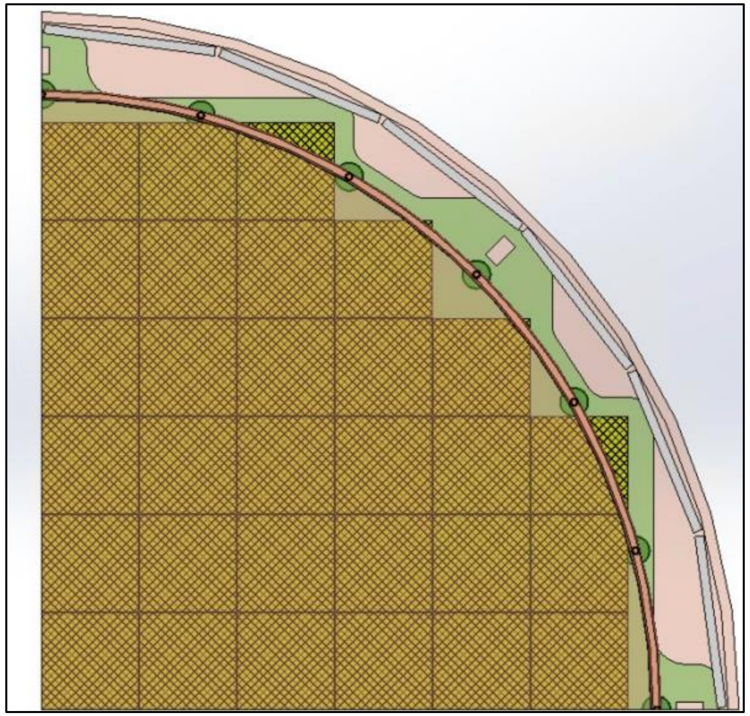


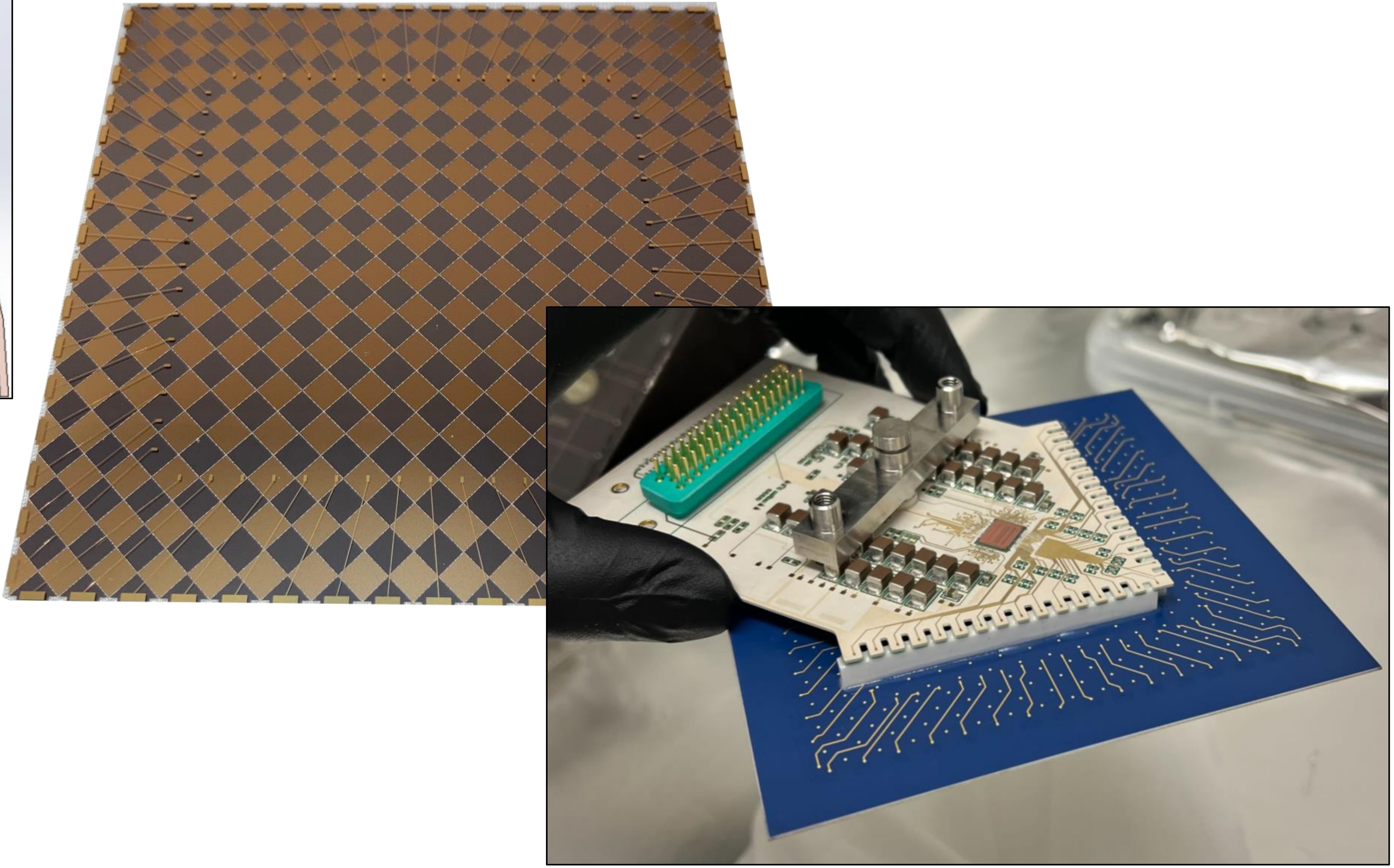
Prototype VUV SiPM array (FBK)



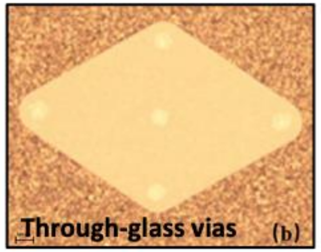


Charge collection tiles with crossed strips on silica substrate and built-in ASICs electronics



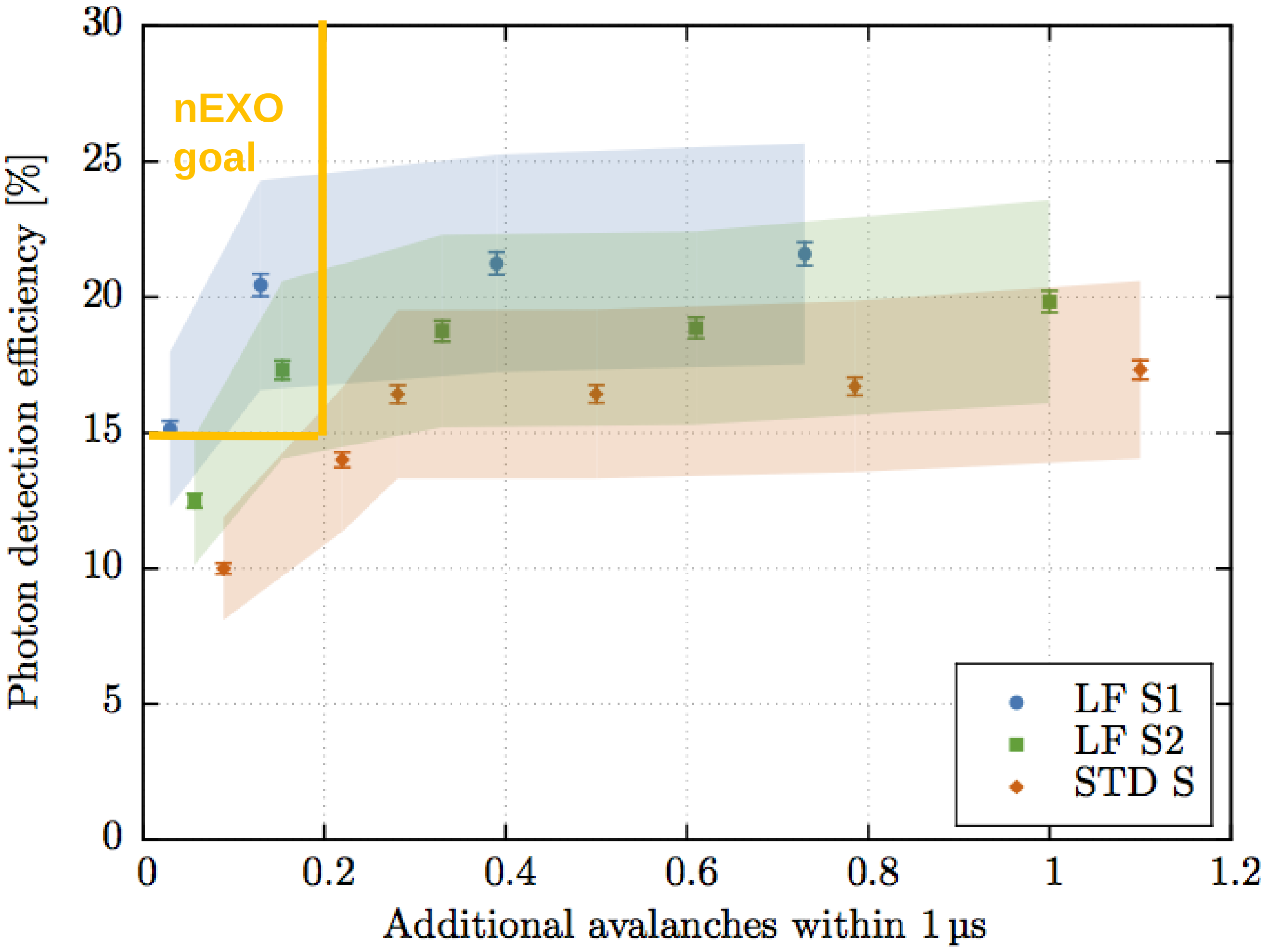


Wu, X et al., *Electronics* (2023)



SiPM-based scinetillation readout: high gain and ~30V bias

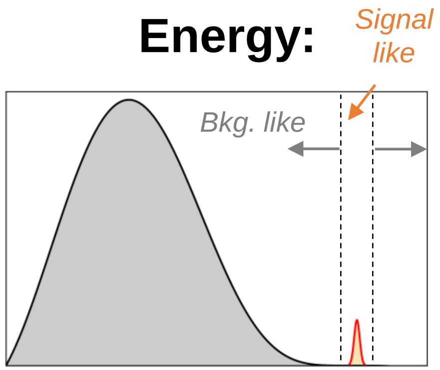
(as opposed to the 1500V of EXO-200 APDs)



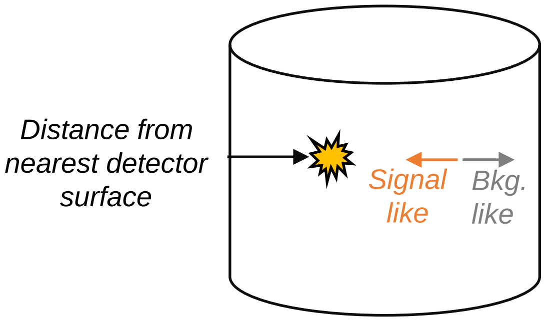
nEXO Signal and Background

- nEXO measures multiple parameters for each event to be able to robustly identify a $0\nu\beta\beta$ signal
- As a fully homogeneous detector, it precisely measures backgrounds in situ
    - No internal materials (other than Xe), making nEXO uniquely robust against unknown backgrounds

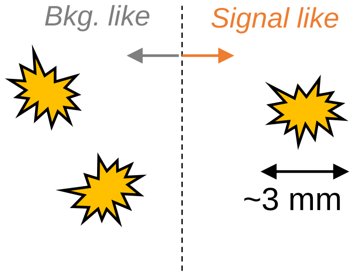
Energy:



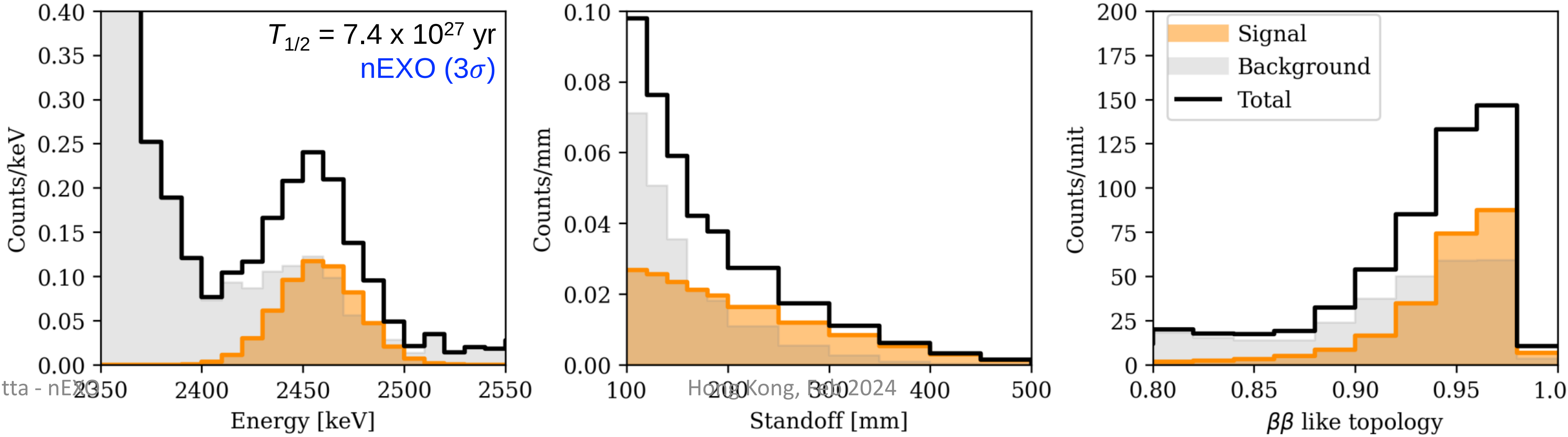
Standoff:



Topology:



1D projections of simulated nEXO signal and backgrounds:



nEXO Signal and Background

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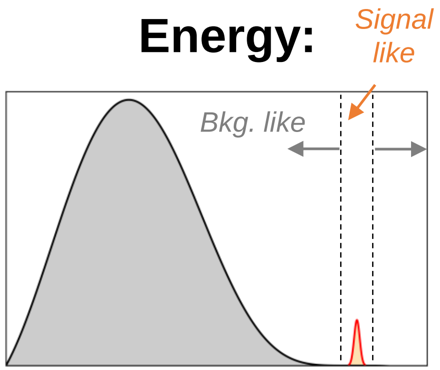
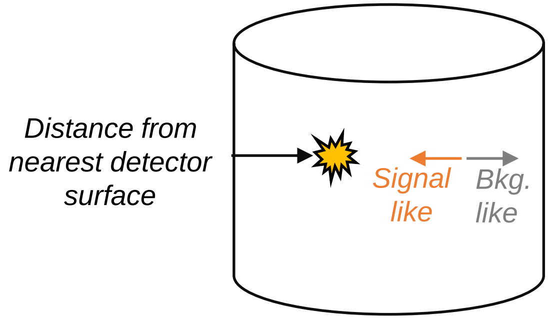
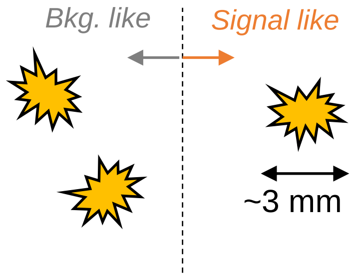
Energy:



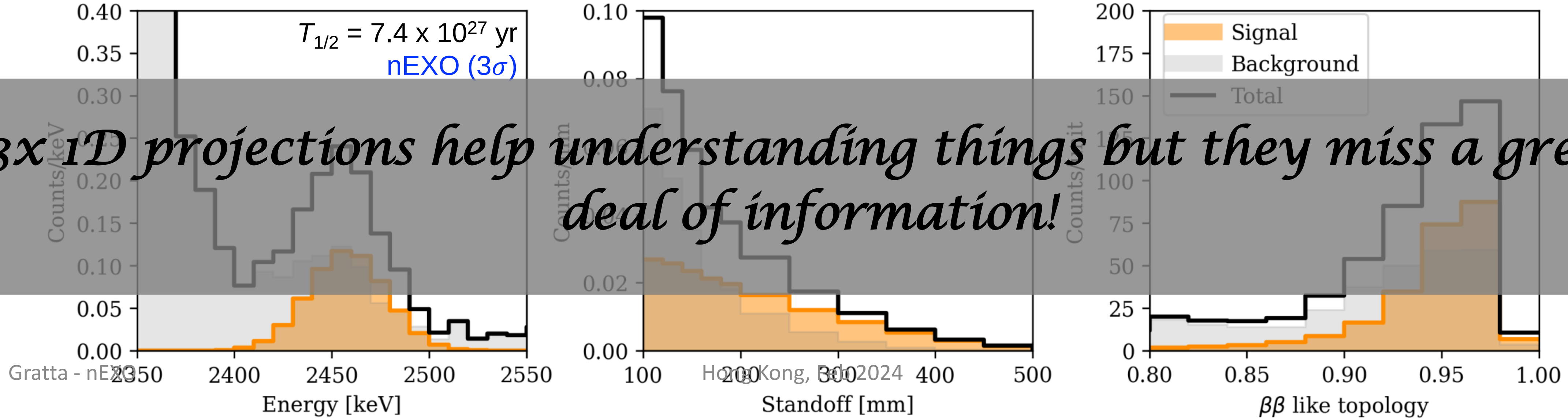
Standoff:



Topology:



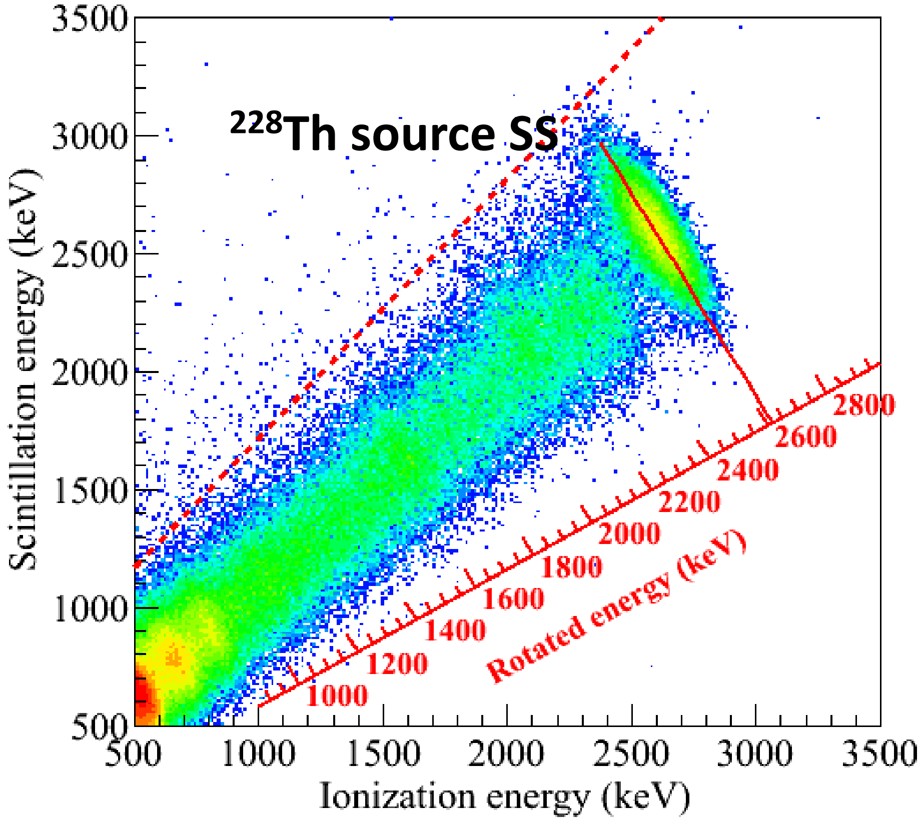
1D projections of simulated nEXO signal and backgrounds:



3x1D projections help understanding things but they miss a great deal of information!

This is obvious in the simpler case of 2D:

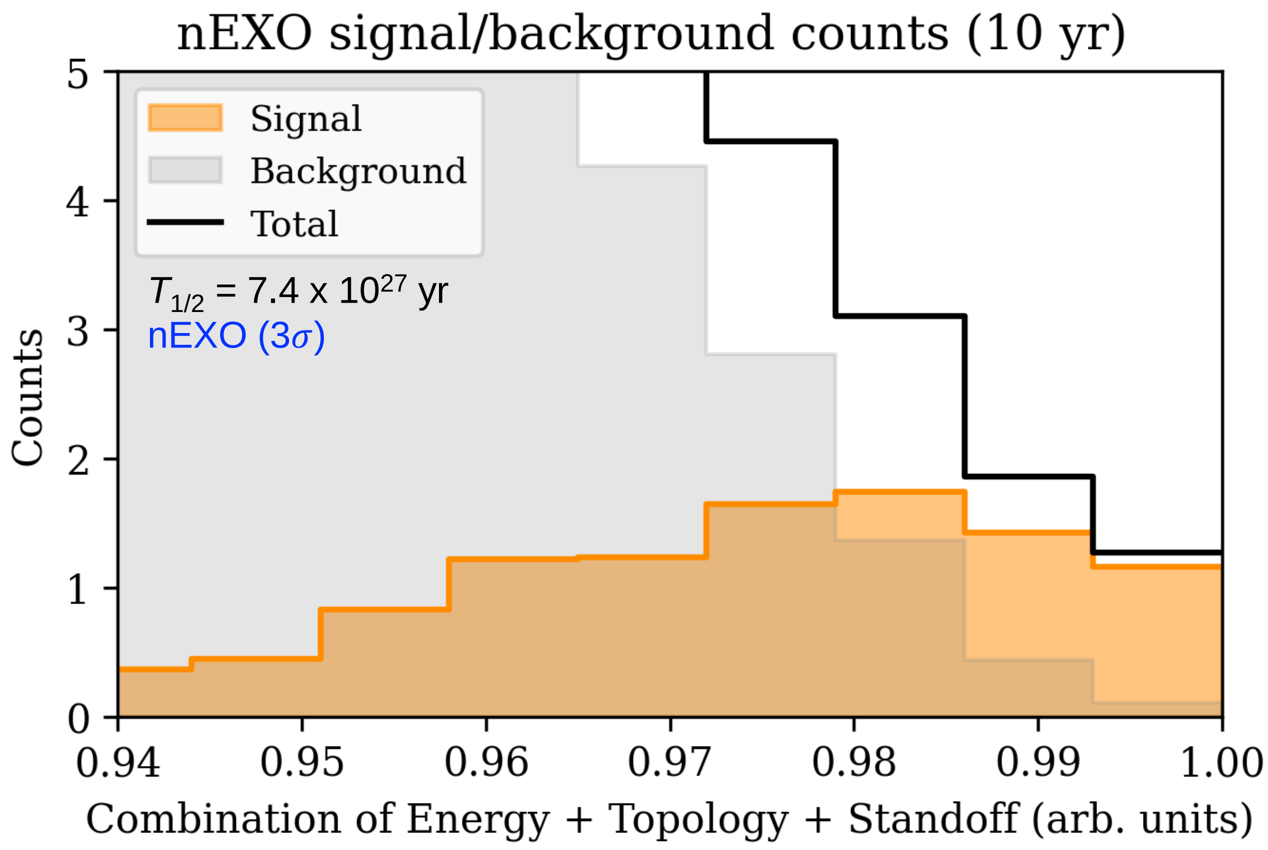
There is more information in the scatter plot than in the two separate projections of it



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

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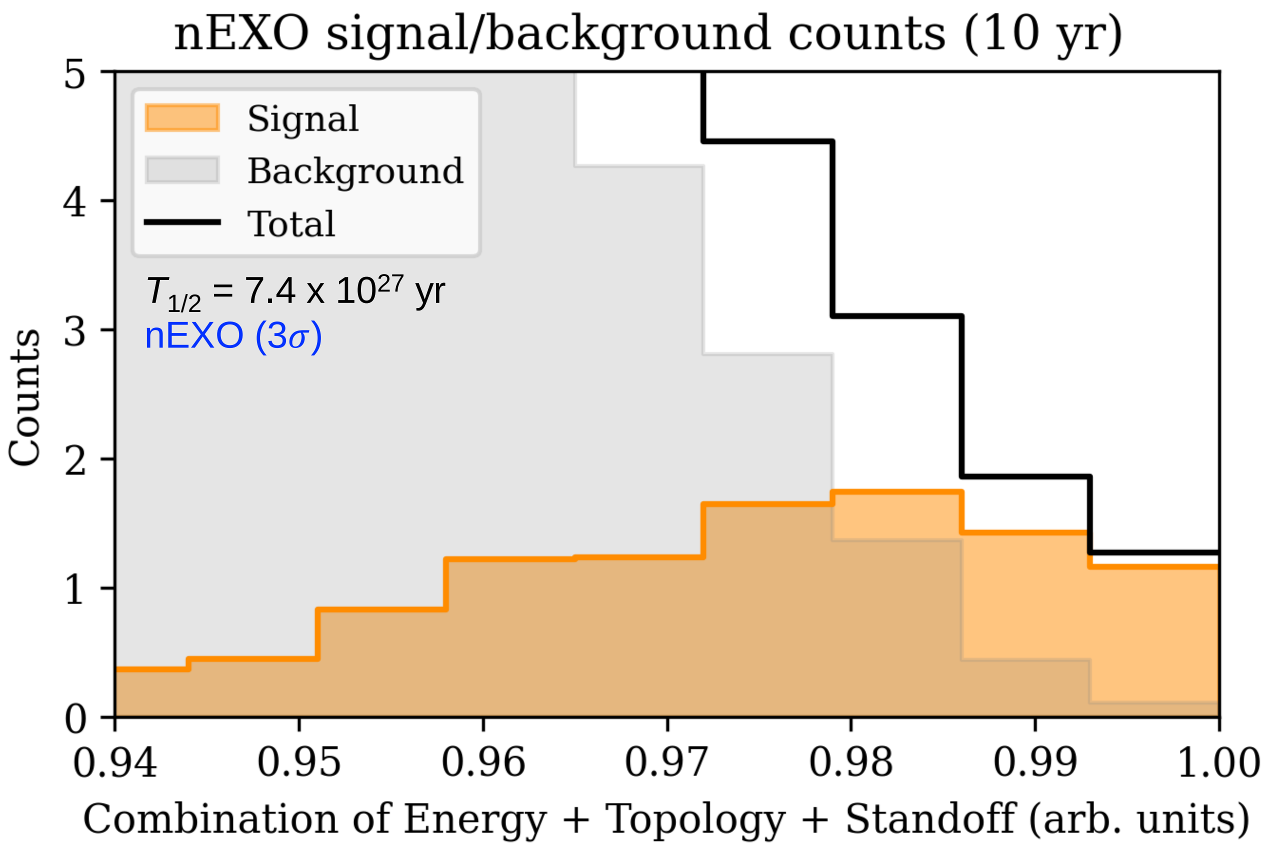
- For clarity, we arrange the 3D bins into 1D, ordered by signal-to-background ratio.

Combine energy, topology, and standoff (preserving correlations)



0 ← Background-like

Signal-like → 1

➔ nEXO is a "background-free" experiment

Other Unique Features of nEXO:

- **LXe reduces risk, as the purification system can be upgraded if unexpected backgrounds are discovered and/or if new technology becomes available.**

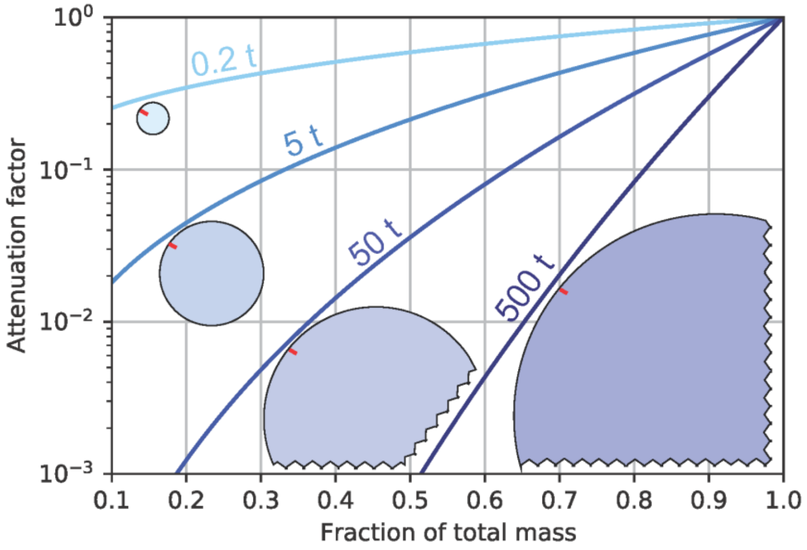
- **nEXO can make a discovery by itself, by repeating the experiment with non-enriched Xenon to confirm that a signal goes away**

- **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.**

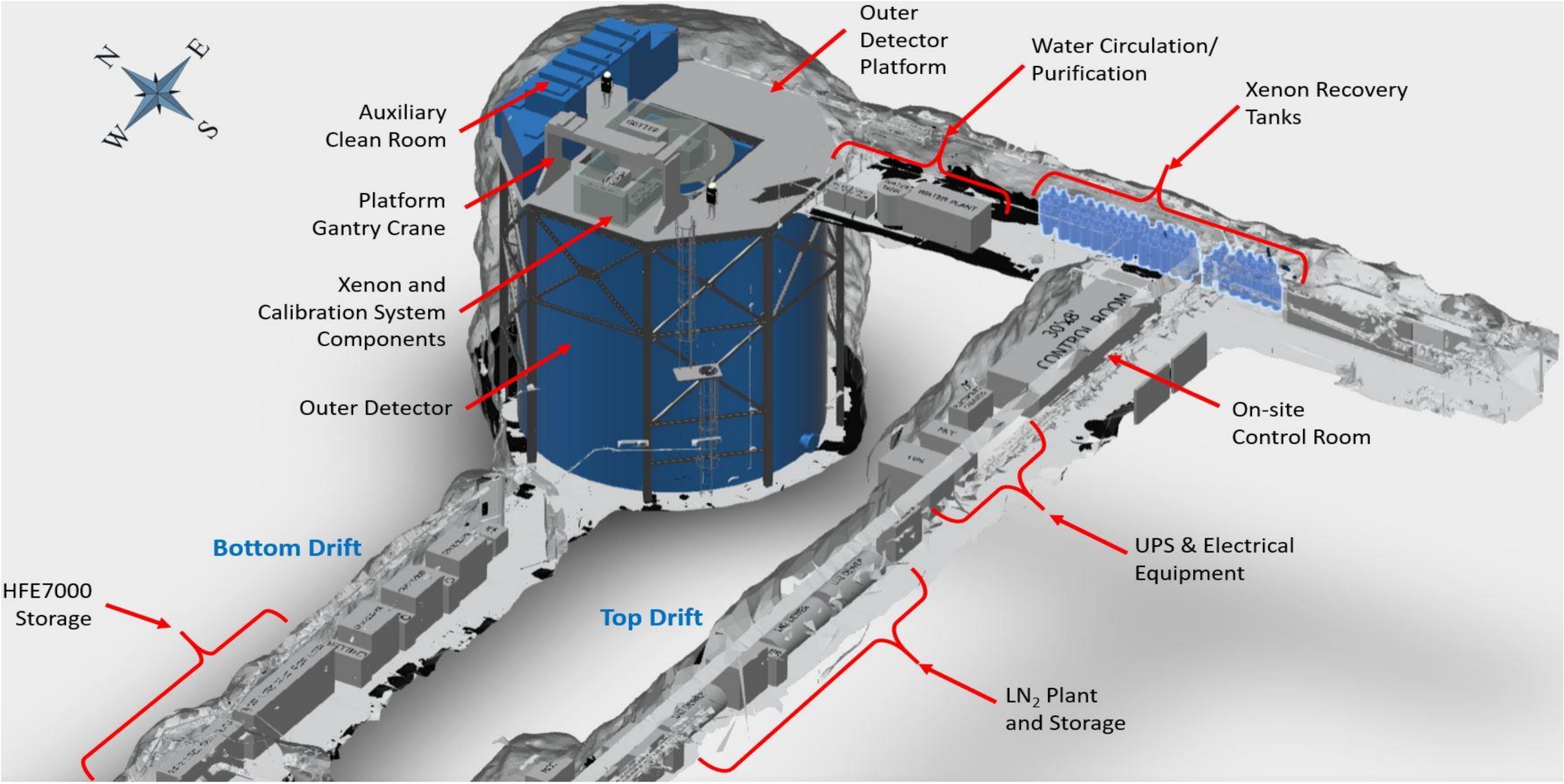
This is particularly important at the tonne scale, given the cost of the material.

- **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 possible** (A.Avasthi et al, Phys. Rev. D 104, 112007 (2021))

The technology is developed with an eye to the future.



Very substantial engineering done by SNOLAB.



Summary

- nEXO is the only tonne-scale homogeneous detector being planned
- nEXO is the only experiment that can run a blank measurement
- nEXO is the only experiment that can recycle the active isotope after a discovery
- nEXO is the only experiment that is scalable to 100+ tonne
- nEXO is the only experiment that can repurify the active material while running
- nEXO has a sensitivity that is at least as good as any other planned experiment