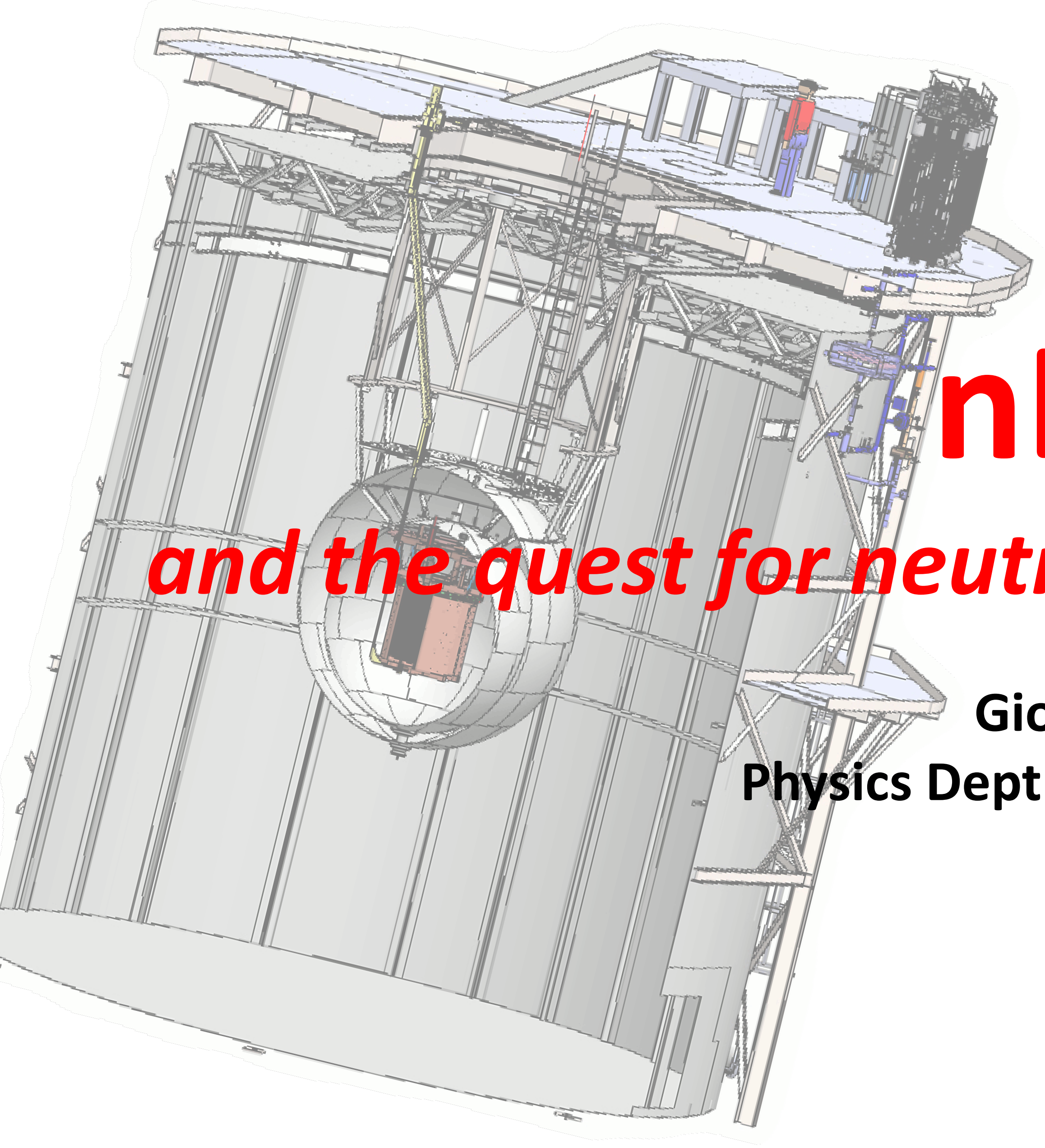
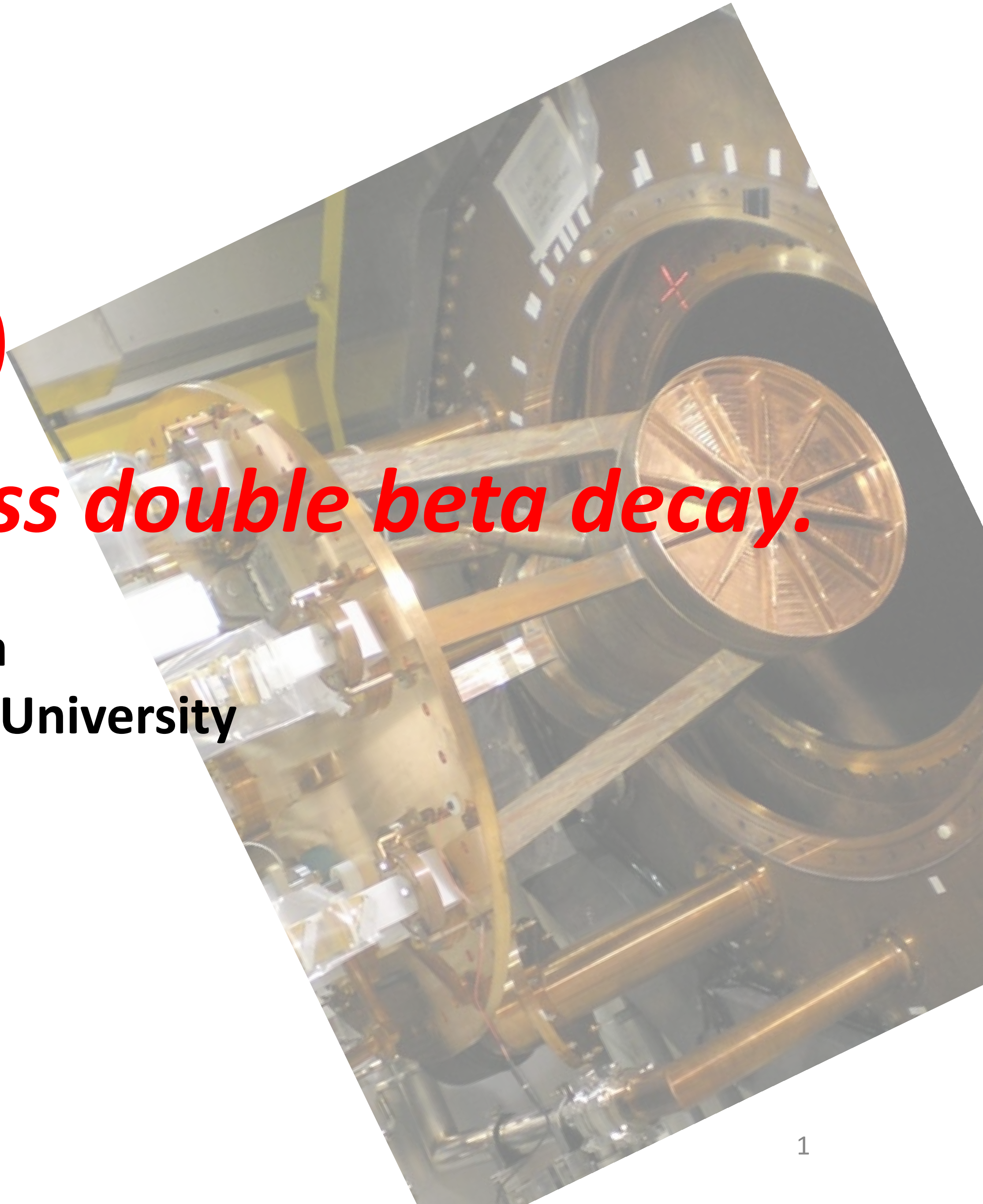




nEXO

and the quest for neutrino-less double beta decay.

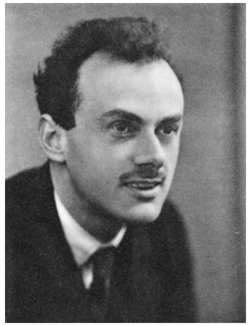
Giorgio Gratta
Physics Dept., Stanford University

There are two possible ways to describe *neutral* 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…)

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

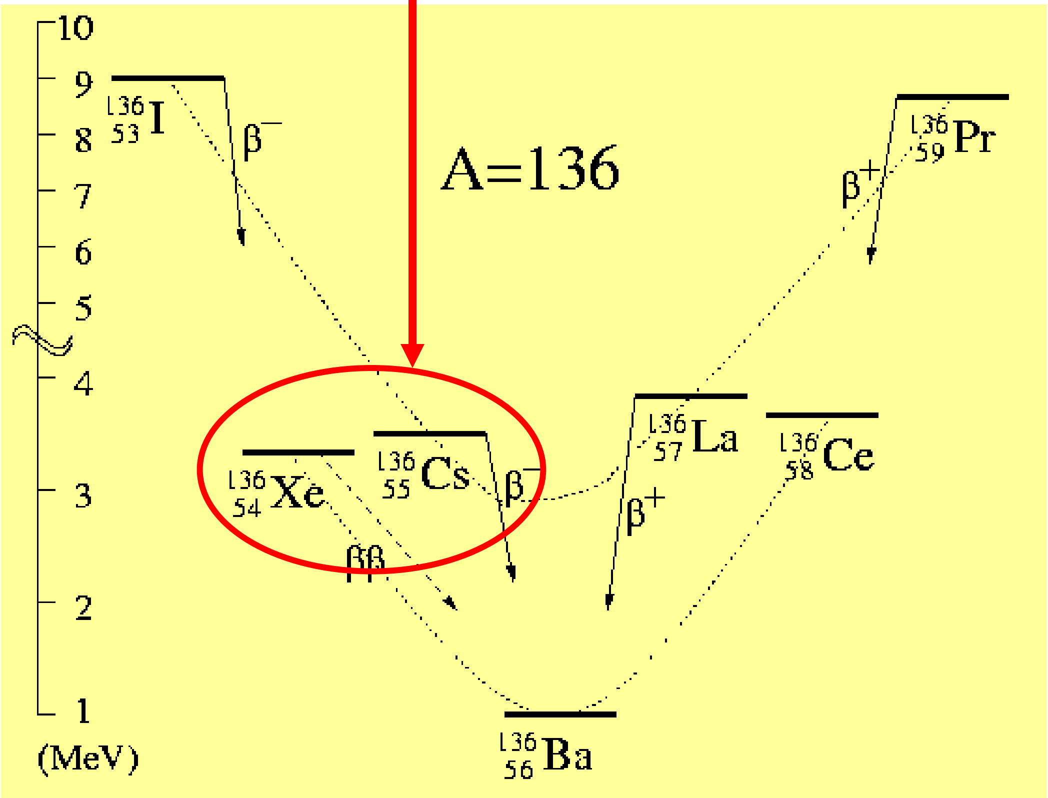
Which way Nature has chosen to proceed is an experimental question

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

(and the observable difference → 0 for m_ν → 0)

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



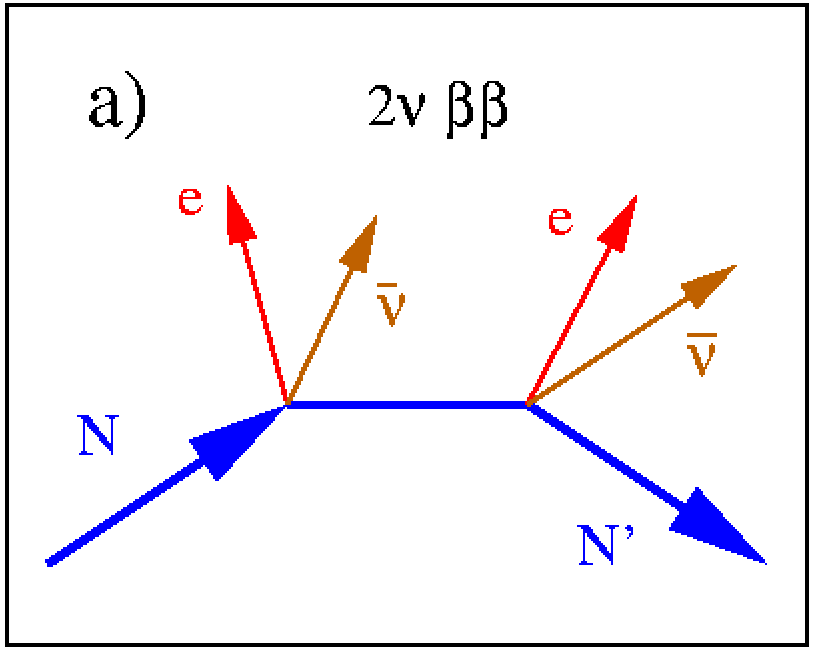
Candidate nuclei with Q>2 MeV

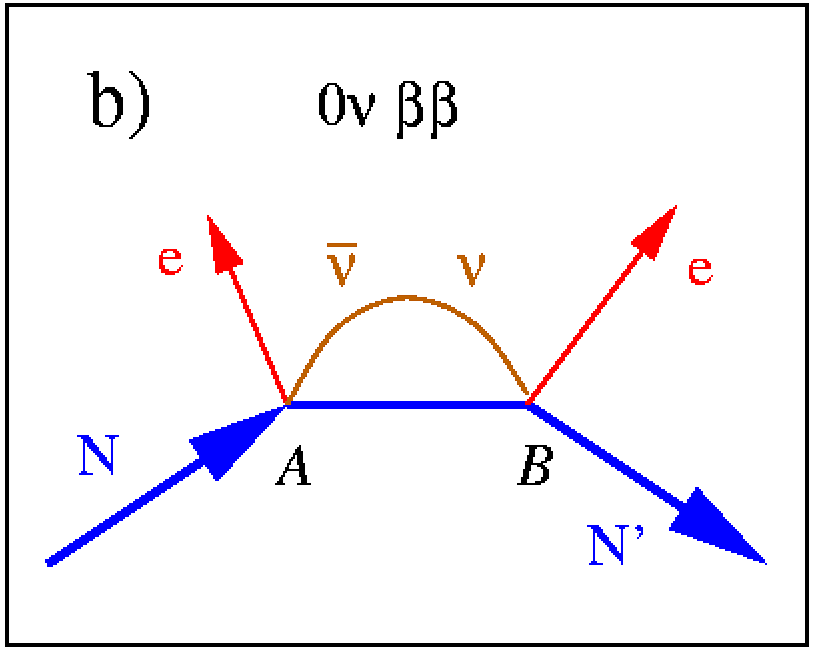
Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

There are two varieties of ββ decay

2ν mode:
a conventional
2^{nd} order process
in nuclear physics

0ν mode: a hypothetical
process can happen
only if: $M_\nu \neq 0$
$\nu = \bar{\nu}$
$|\Delta L|=2$
$|\Delta(B-L)|=2$





There are two varieties of ββ decay

0ν mode: a hypothetical process can happen only if:

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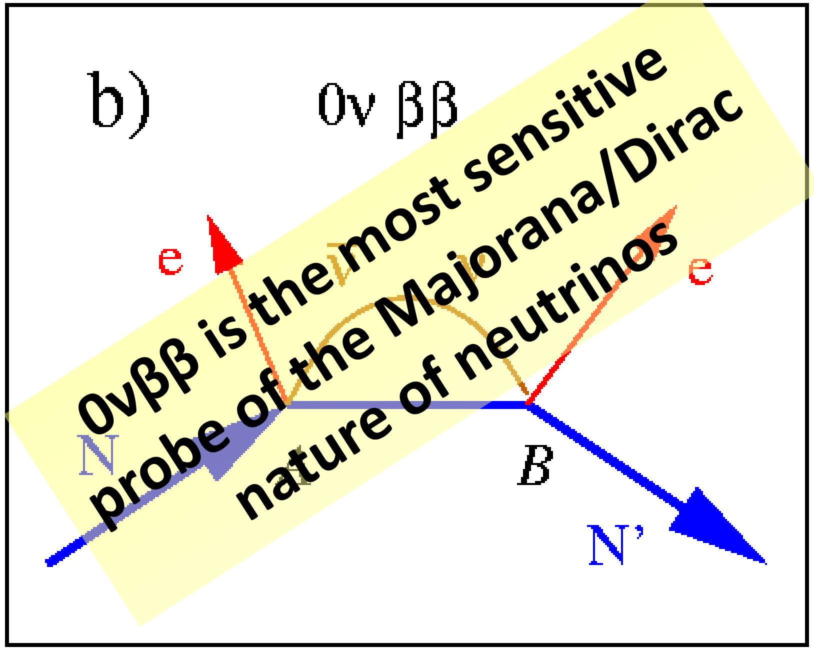
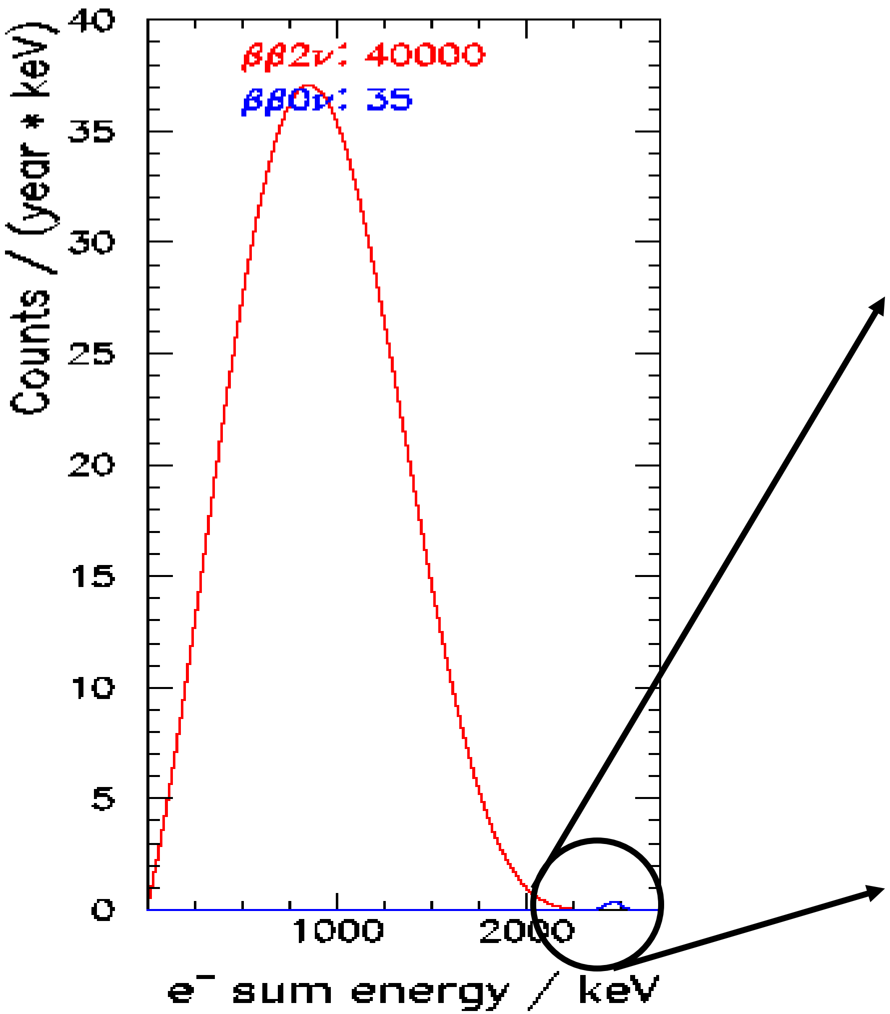
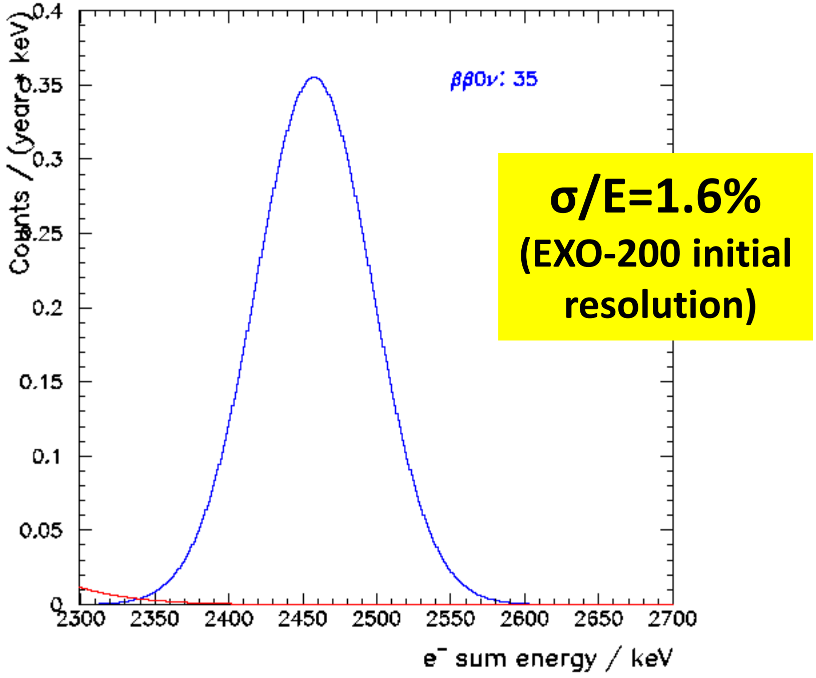


0νββ is the most sensitive probe of the Majorana/Dirac nature of neutrinos

Background due to the Standard Model $2\nu\beta\beta$ decay





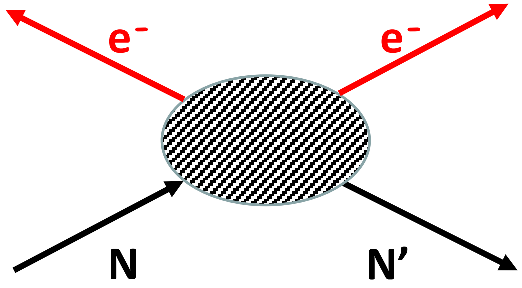
The two can be separated in a detector with sufficiently good energy resolution

Topology and particle ID are also important to recognize other backgrounds

“Black box” theorem*: **“0νββ decay always implies new physics”**

There is no scenario in which observing 0νββ decay would not be a great discovery

- ➔ Majorana neutrinos
- ➔ Lepton number violation
- ➔ Probe new mass mechanism up to the GUT scale
- ➔ Probe key ingredient in generating cosmic baryon asymmetry



Neutrino masses have to be non-zero for 0νββ to be possible.

➔ **Because the distinction between Dirac and Majorana particles is only observable for particles of non-zero mass.**

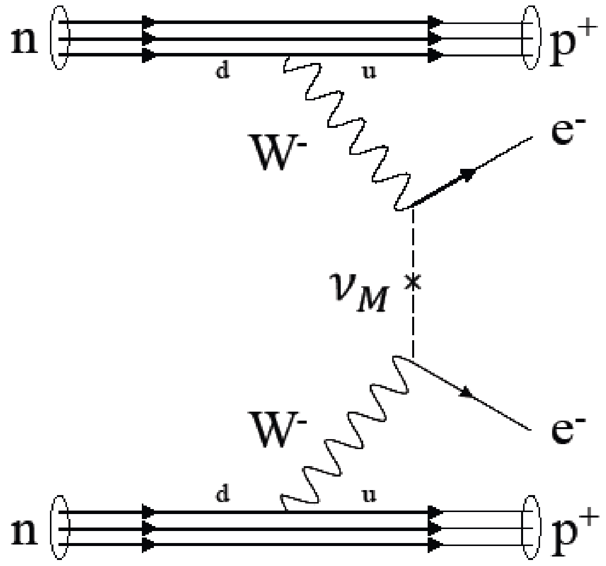
Strictly speaking, this is the ONLY connection with neutrino masses relevant to discover new physics.

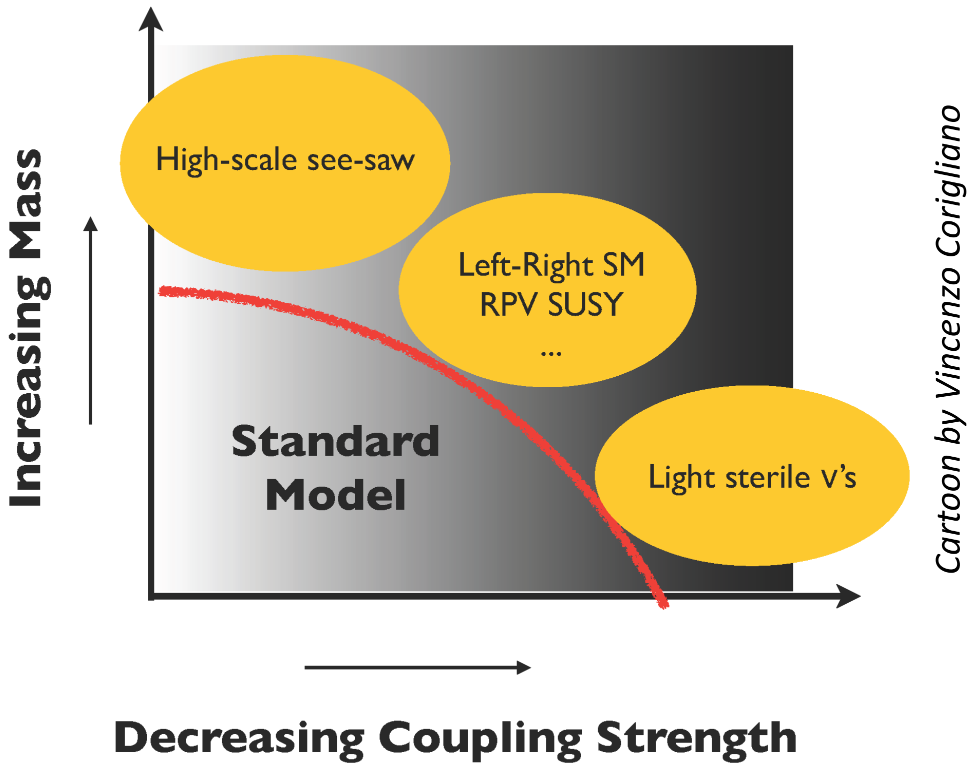
Hence it is appropriate to think of the sensitivity to new physics as scaling with $T_{1/2}$, irrespective of the neutrino mass scenarios. A $T_{1/2}$ sensitivity increase from ~10^{26} to ~10^{28} yr (~100x), should be compared, e.g., to the √s increase from Tevatron to LHC (~20), although, admittedly, with a smaller array of channels for new physics.

* J. Schechter, and J. W. F. Valle, Phys. Rev. D25, 2951 (1982).

One can also think about the lepton-number non-conservation in neutrinoless double-beta decay as the mechanisms producing matter (the two electrons) without antimatter (the missing neutrinos).

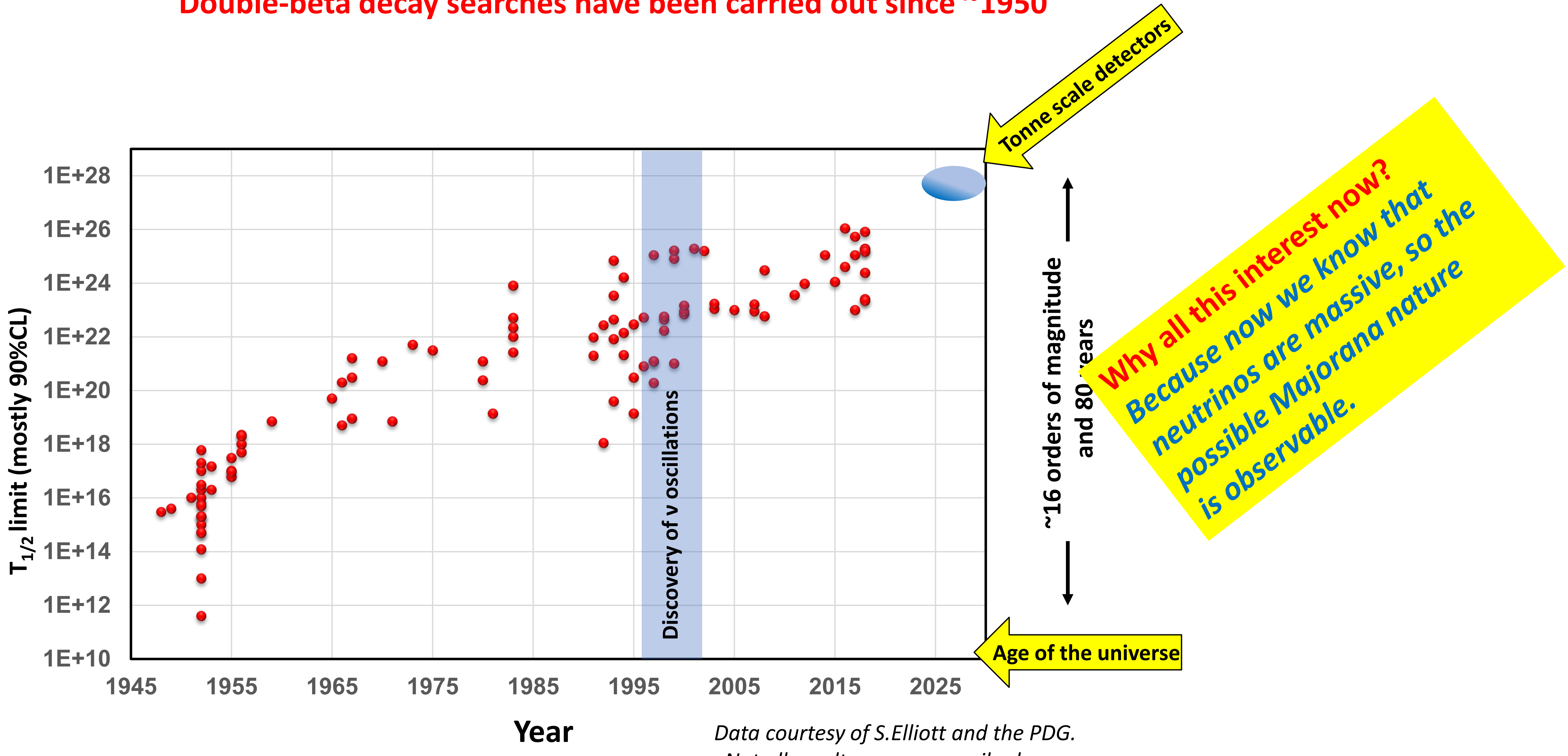
This may be the key to explain why the current universe is matter dominated.





At the same time, it is unclear what kind of physics may produce the decay.

Double-beta decay searches have been carried out since ~1950

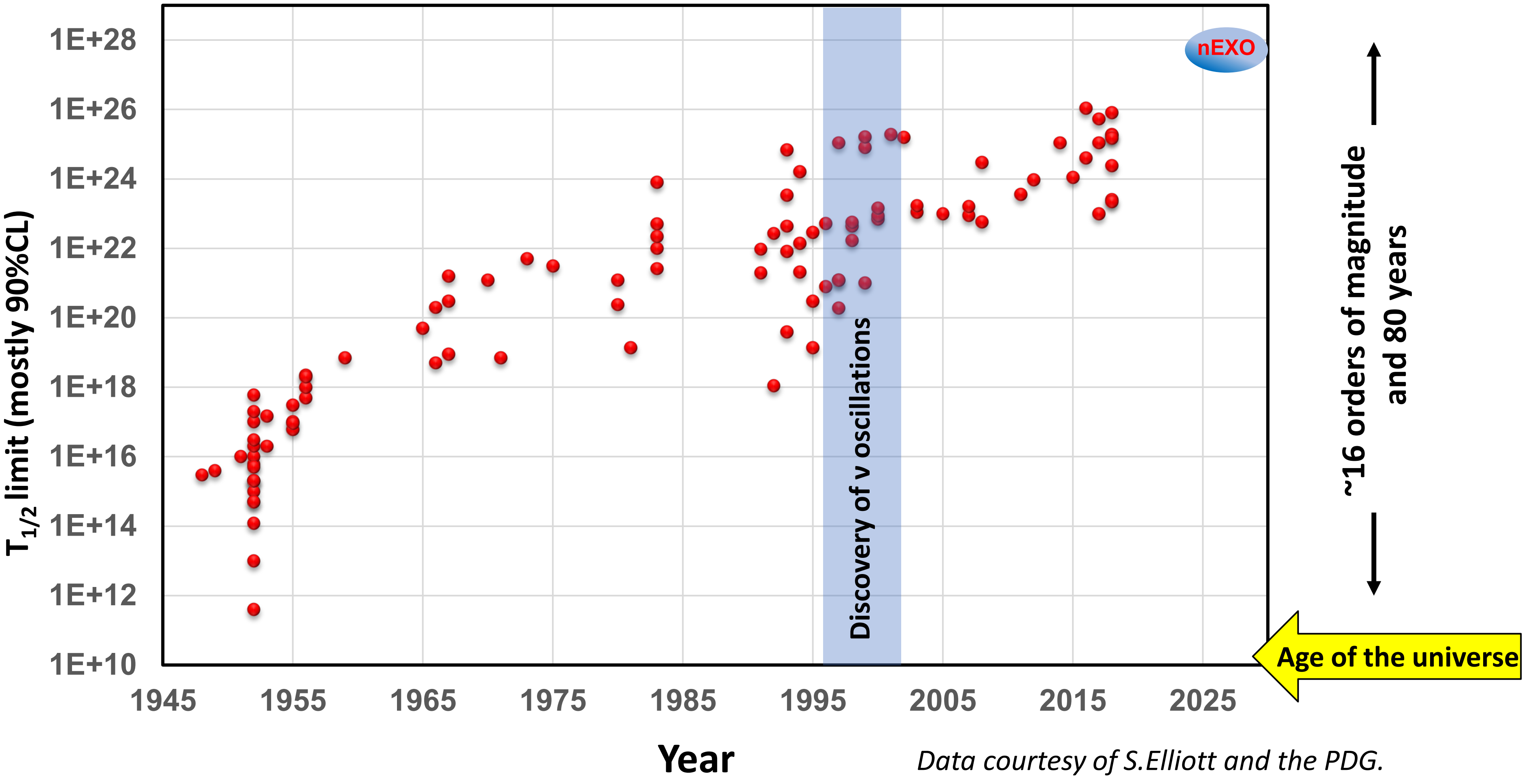


Data courtesy of S.Elliott and the PDG.
Not all results are necessarily shown.

Seeing the 0νββ = new physics, so the sensitivity to new physics is represented by the $T_{1/2}$ sensitivity.

Note that: - there is no theoretical uncertainty on this.

- the only connection to m_ν is that $m_\nu \equiv 0$ would make 0νββ unobservable



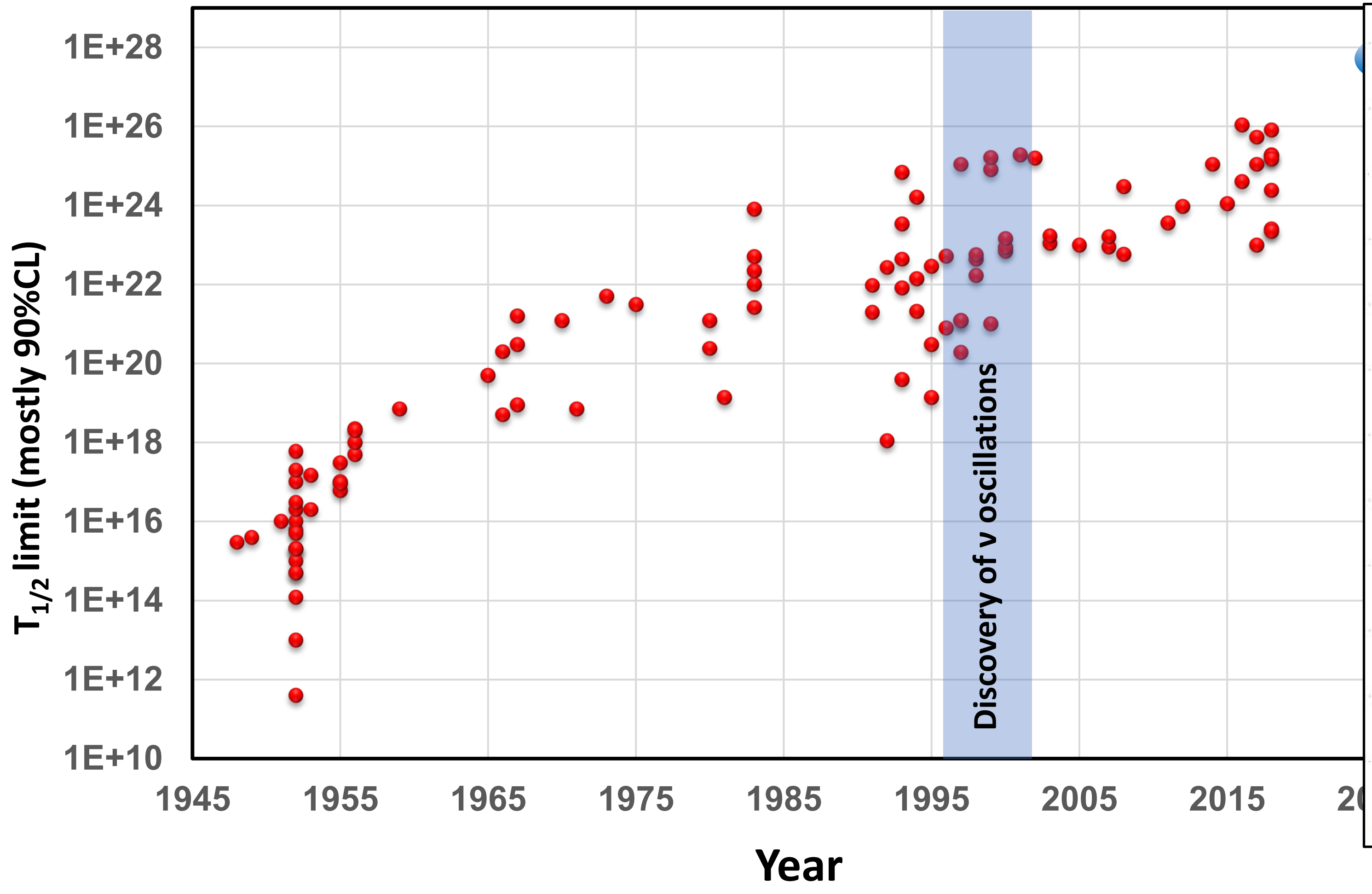
Data courtesy of S.Elliott and the PDG.
Not all results are necessarily shown.

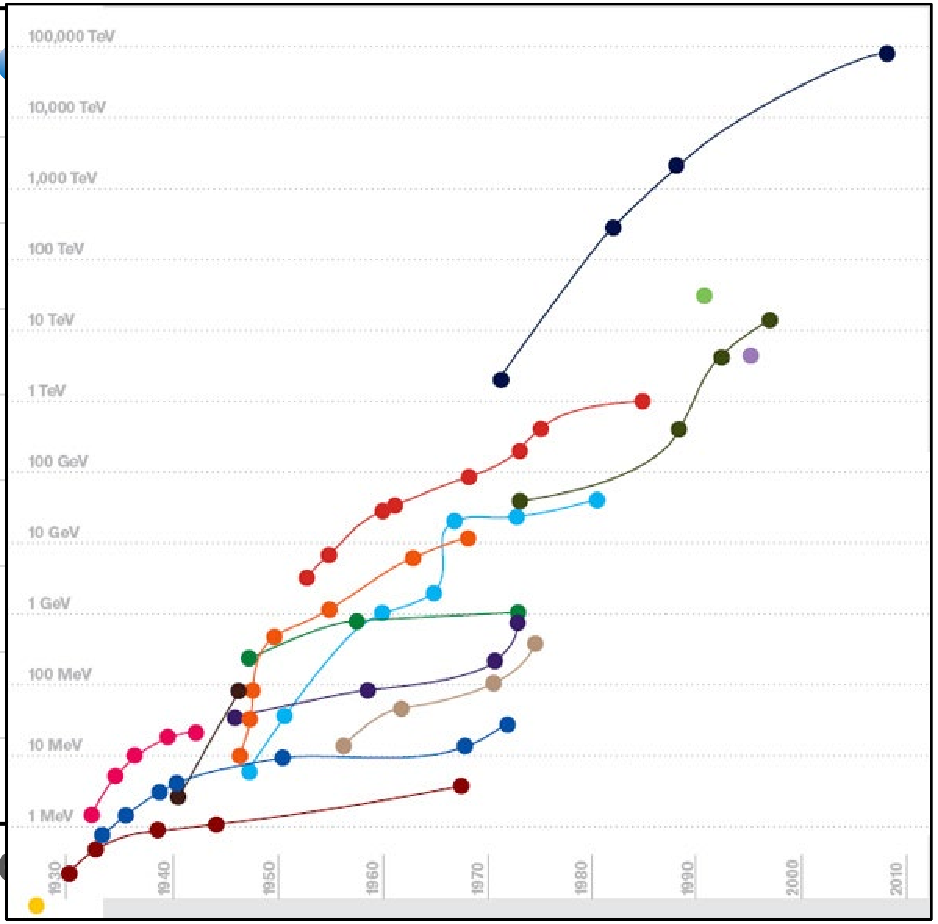
For accelerators this plot has a name: "Livingston plot"

Here the vertical scale for colliders is the lab energy of a particle hitting a proton in the lab frame that produces the same center-of-mass energy of the collider.

Different colors correspond to different technologies.

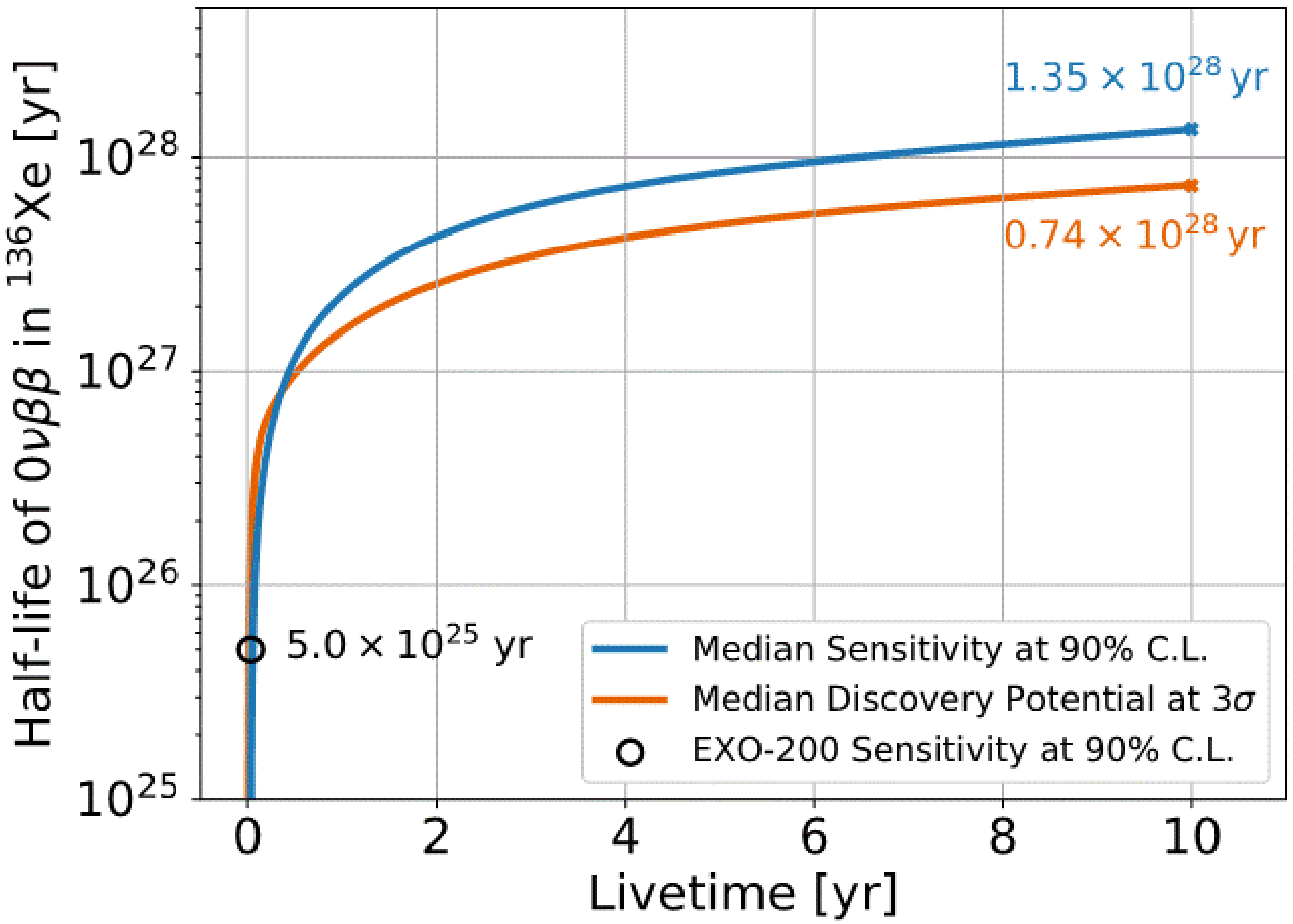
Some of you may have seen similar plots before….





(from Symmetry Magazine)

Regrettably, life is harder in this case:
Example of projected sensitivity for nEXO



We owe the spectacular 10^{28} half life sensitivity to Mr. Avogadro, so there is no silver bullet to improve it.

Amedeo Avogadro

This has two manifestations, contrasting the case of accelerators:

- **There is no such thing as "a new technology" that suddenly permits a drastically better sensitivity reach (essentially, this is because of the density of matter)**
- **Once data taking starts, most of the sensitivity is reached rapidly. This is a property of statistics.**

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 eventually 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.

Nuclear structure

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \; G^{0\nu\beta\beta}(E_0, Z) \; \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$ a known phasespace factor

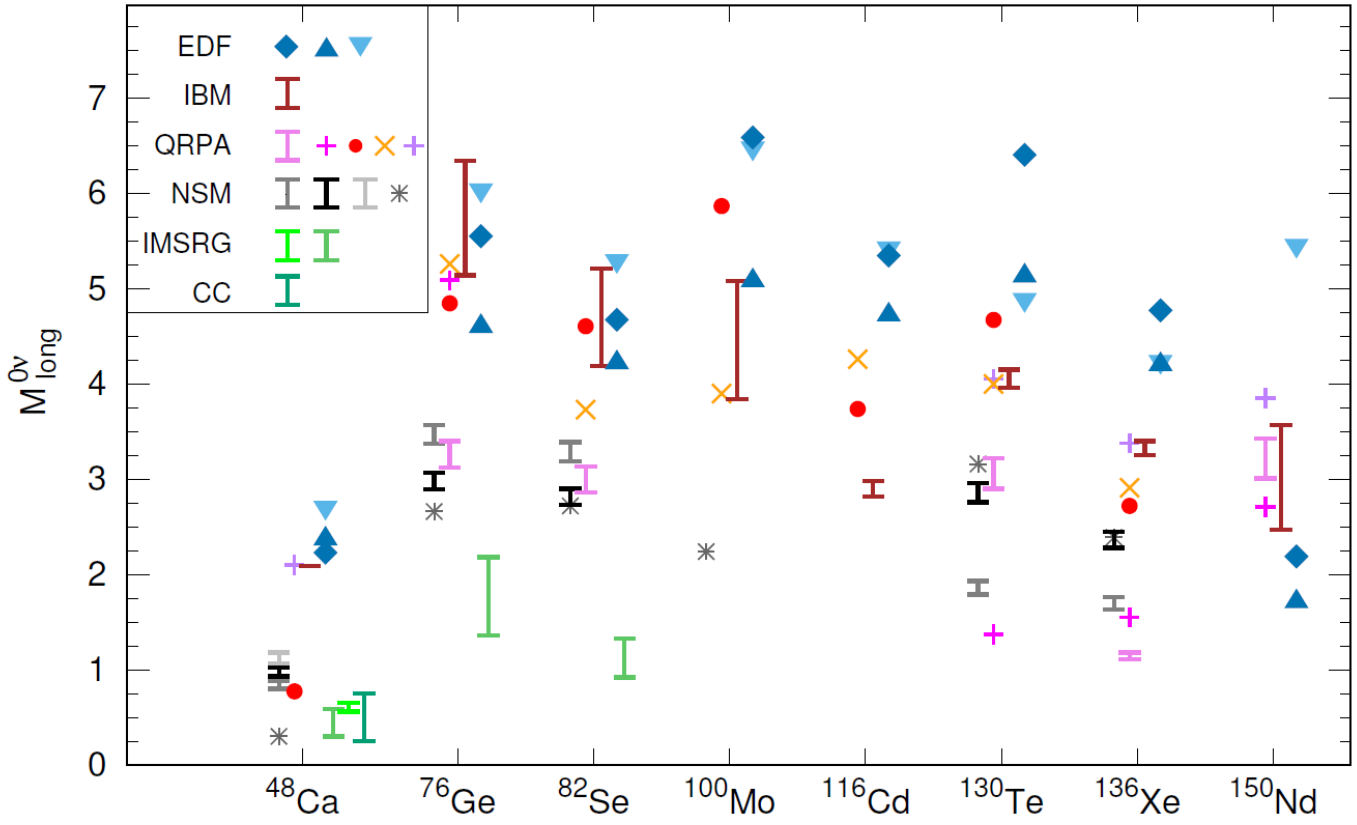
$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i \; \varepsilon_i$$

is the effective Majorana ν mass
(ε_i = ±1 if CP is conserved)

Nuclear Matrix elements are still rather different, for different calculations.

Below is the case, more commonly calculated, of light neutrino exchange.



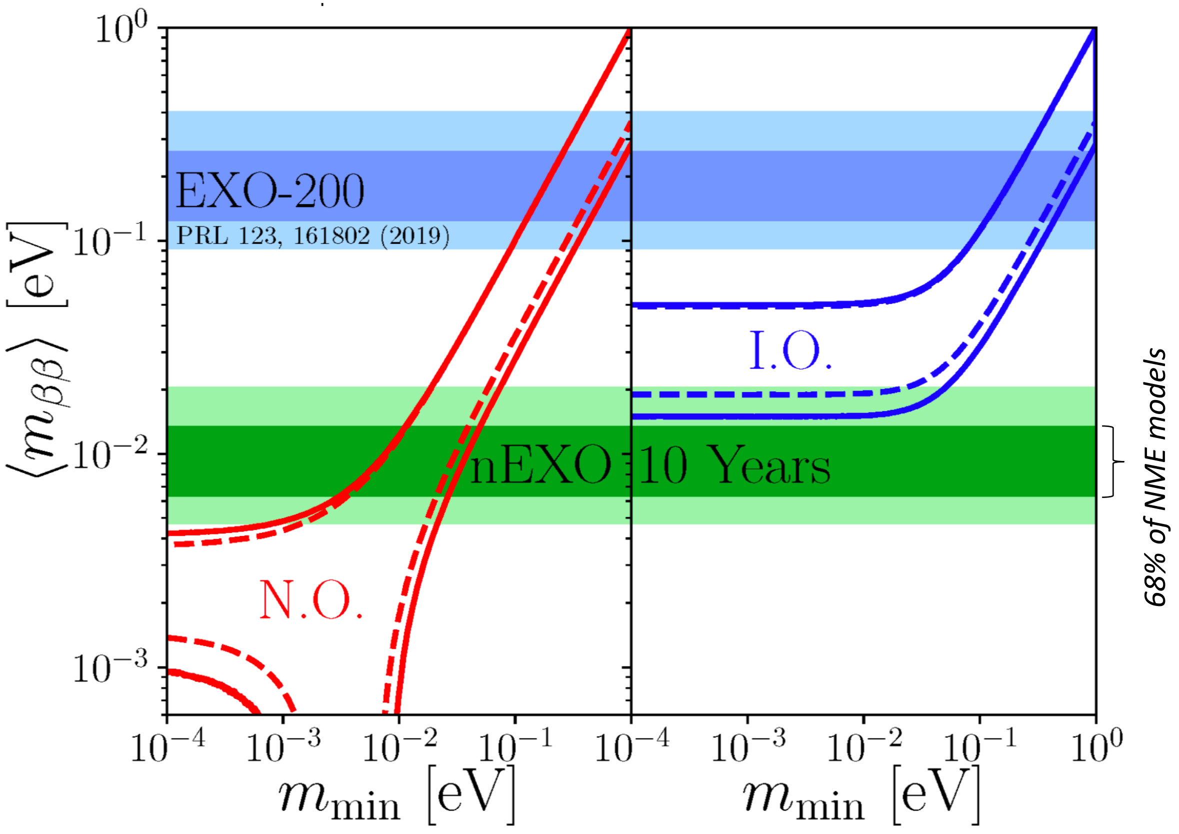
In fact, this is not even the entire story, as there are questions on what value of g_A, the axial coupling constant, should be used. This is probably kind-of-common for all NMEs and usually not shown.

But there is great recent progress in understanding these issues.

M.Agostini et al., arXiv:2202.01787, 2022 (to be also consulted for the references to the individual calculations)
See also J.Engel & J.Menendez, Rep. Prog. Phys. 80, 046301.

With all the above caveats the we can express the sensitivity to Majorana Mass for light neutrino exchange

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

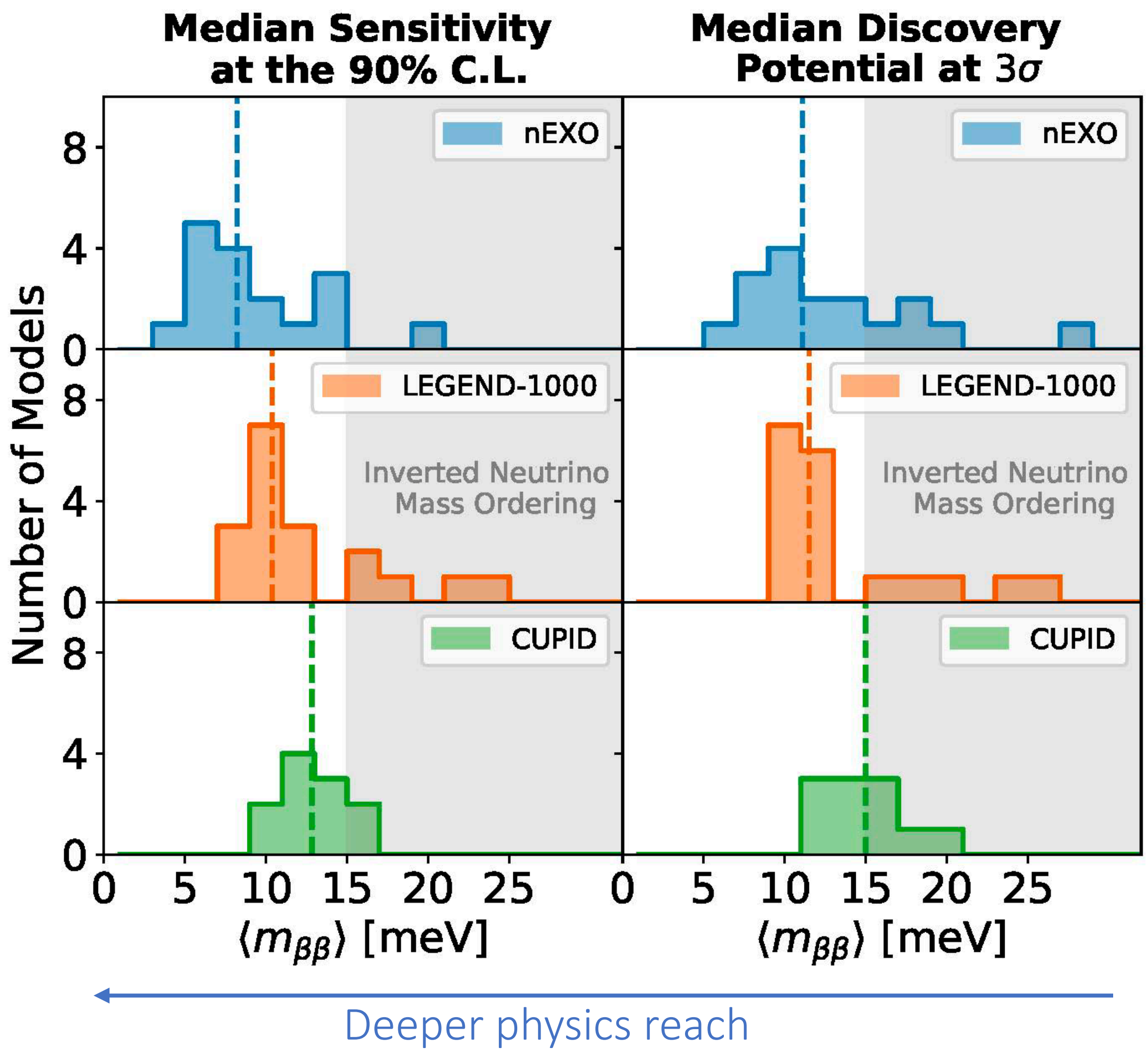


Here the extent of the darker bands contains 68% of the NMEs (but not the uncertainty from g_A).

The lighter bands also contains uncertainties from the oscillation measurements.

We are ready to compare experiments based on different isotopes

(shown here are the experiments moving towards construction)



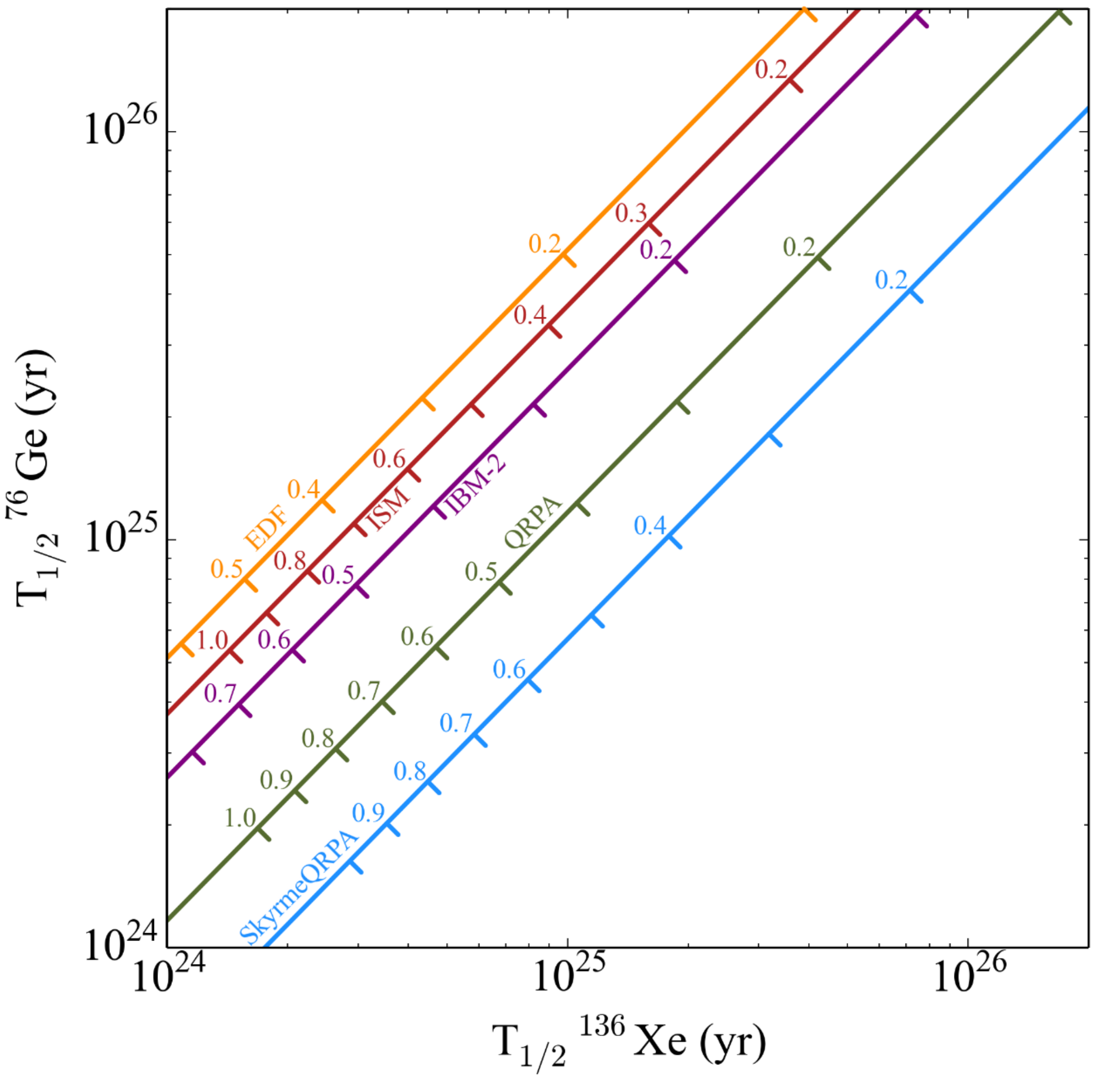
	$m_{\beta\beta}$ [meV], (*median NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

$T_{1/2}$ 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.)

A useful way to relate different isotopes and compare results

(assumes the standard mechanism, this is an example, not all NMEs are shown)



EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

A useful way to relate different isotopes and compare results

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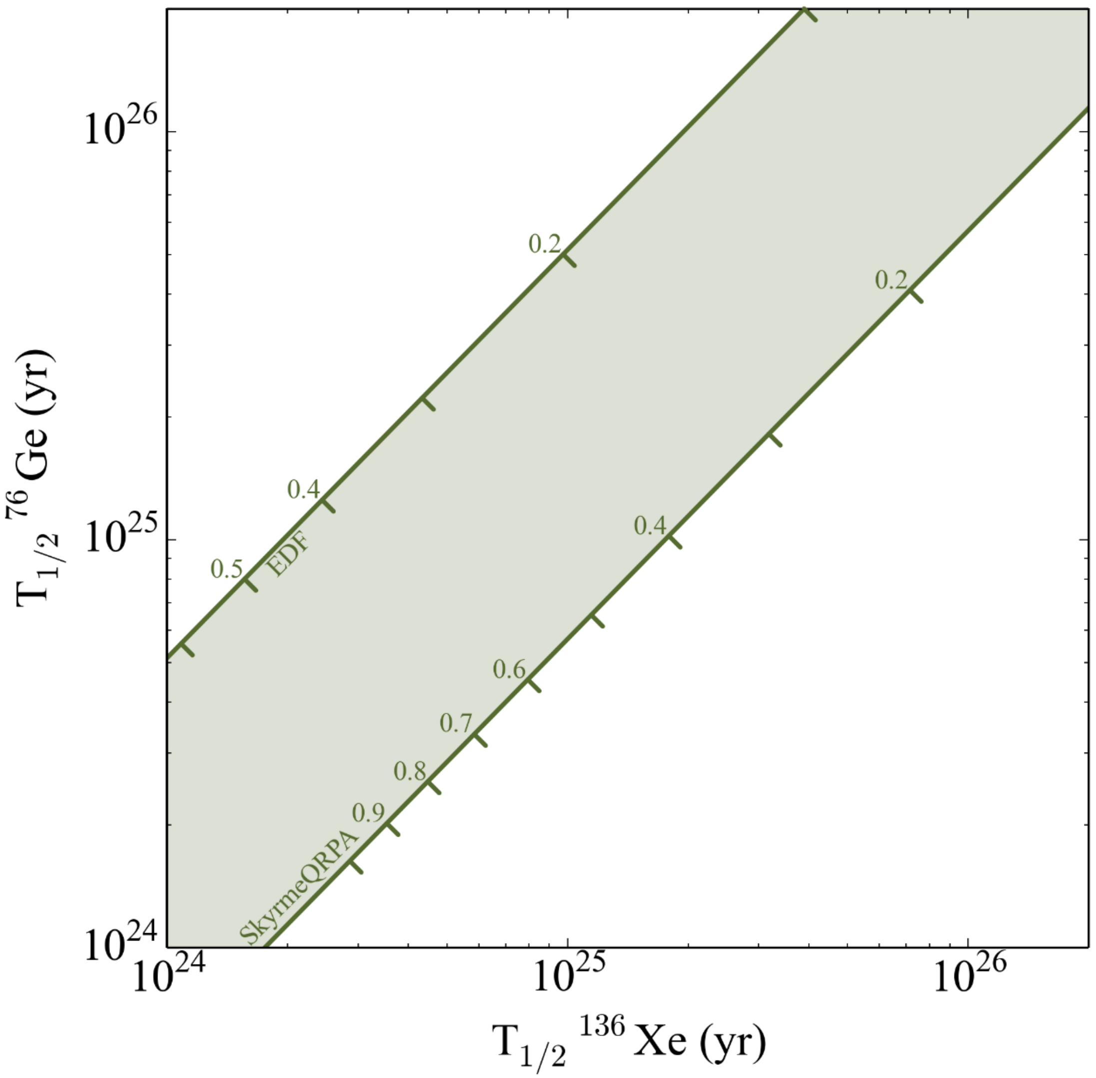
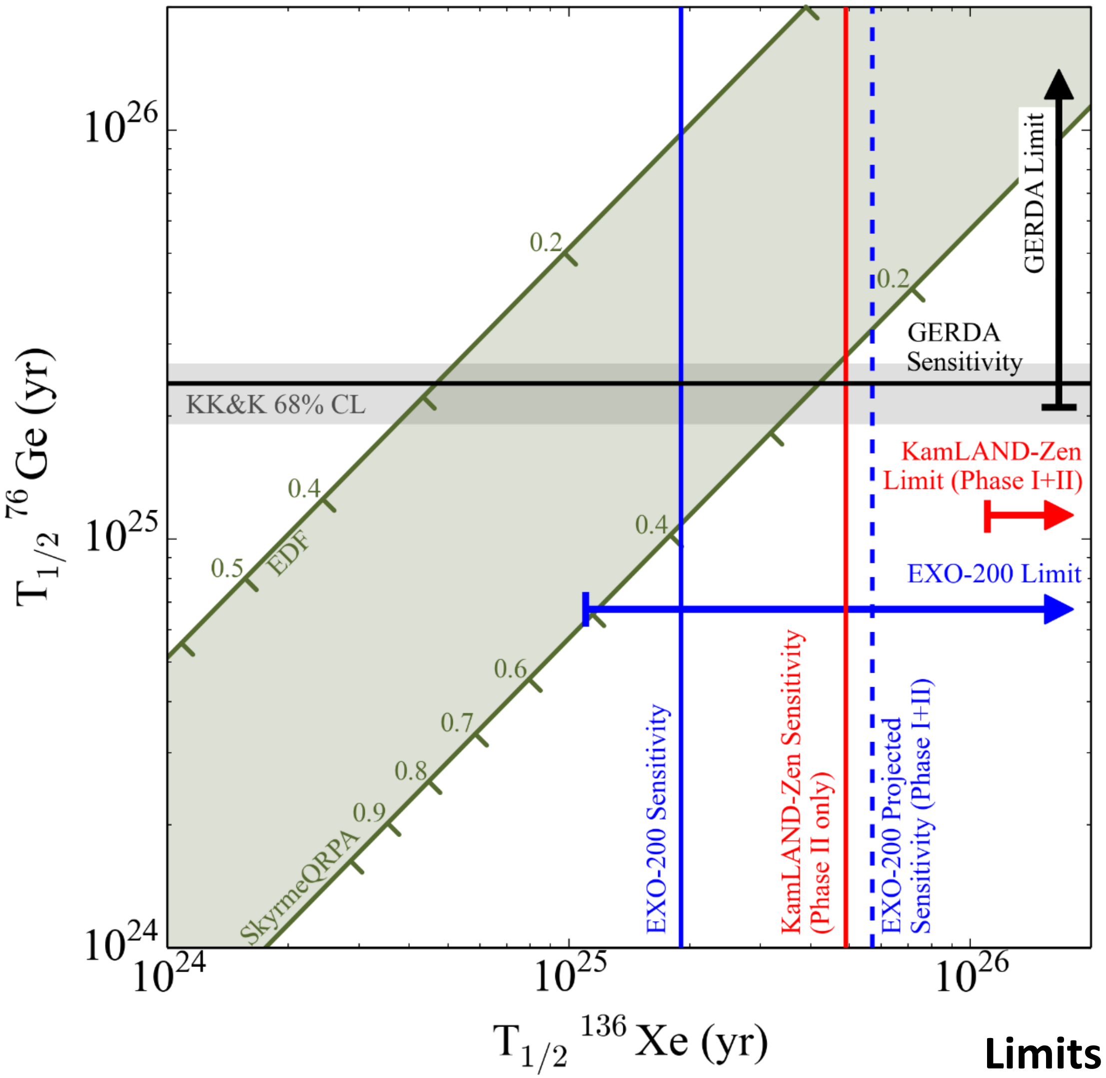


There are more/better results by now (both from theory and experiments);
this old plot is just to illustrate the idea.



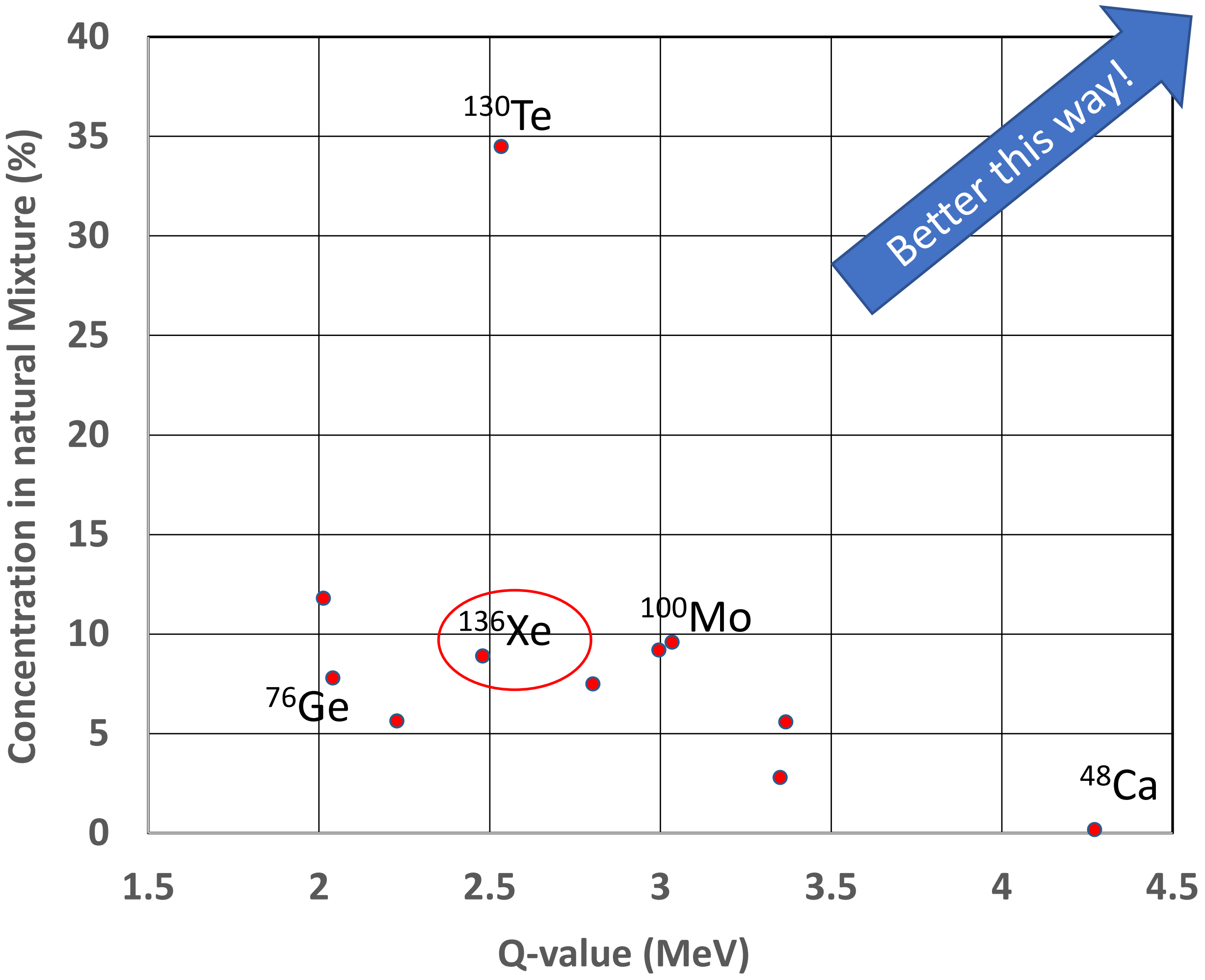
GERDA: M.Agostini et al., Phys. Rev. Lett. 111 (2013) 122503

KLZ: A.Gando et al., arXiv:1605.02889 (May 2016)

EXO-200: J.B.Albert et al., Nature 510 (2014) 299

Limits are 90% CL

Except for one case, all interesting double-beta decay isotopes have <10% concentration in the natural mix.
➔ Isotope enrichment is used in modern experiments.

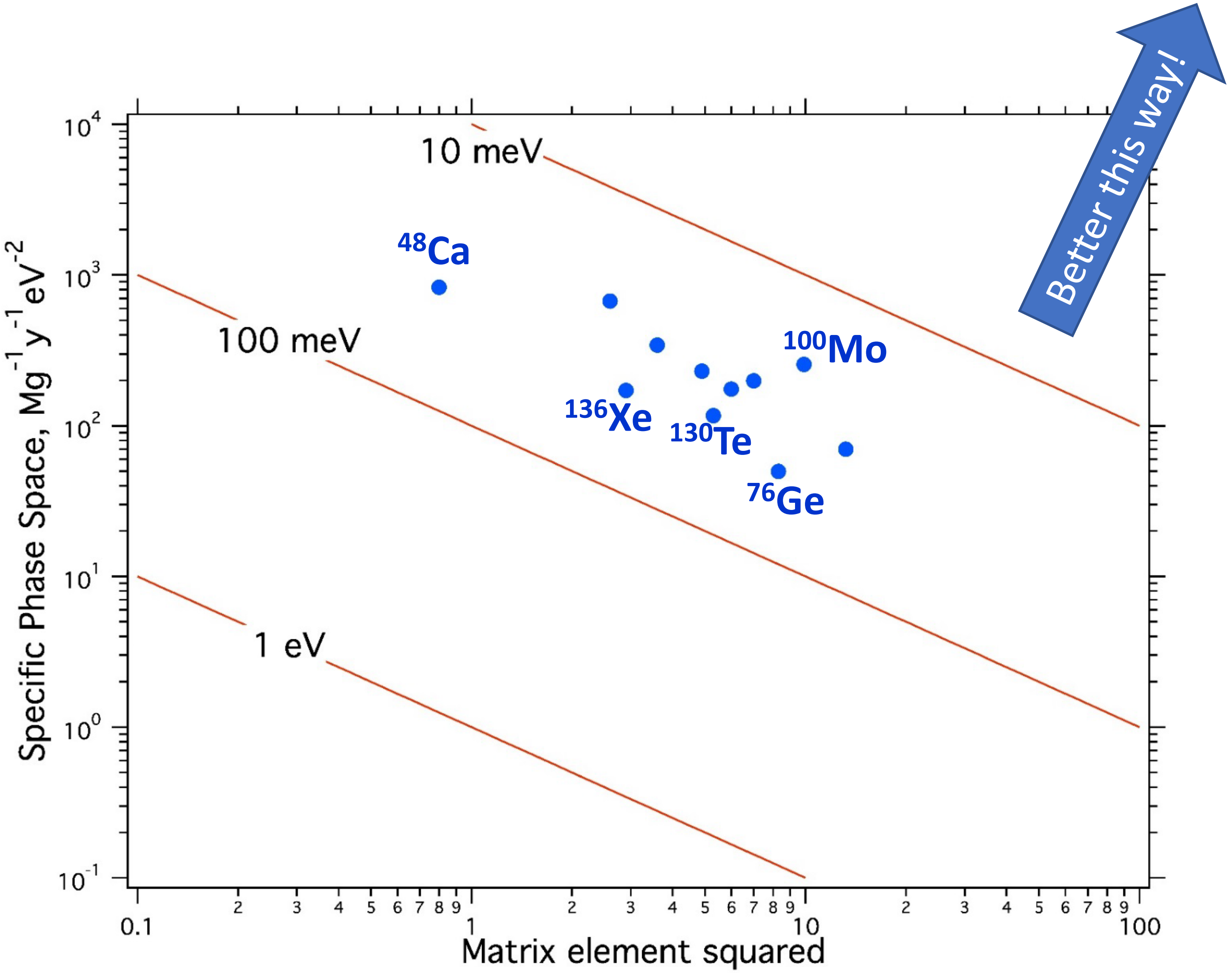


- Isotopic enrichment is required in nEXO
- However, unlike other applications, where high rejection of certain isotopes is is important, in our case we only care that most of the Xe is the isotope 136.
- Initial optimization shows that enrichment grade between 85% and 90% is optimal. [higher grade: more cost in enrichment but cheaper (smaller) detector]. (EXO-200 used 80%, but most other experiments settled on 90%)
- Isotope enrichment and natural Xe procurement are coupled problems.

How to choose the "right" isotope

Note that there is an "empirical" anticorrelation between phasespace and NME.

Unfortunately, there is no a-priori magic isotope and one can really only answer the question bringing in detector technology, which is intimately connected to the choice of isotope.



R.G.H. Robertson, MPL A 28 (2013) 1350021

Conclusion #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***

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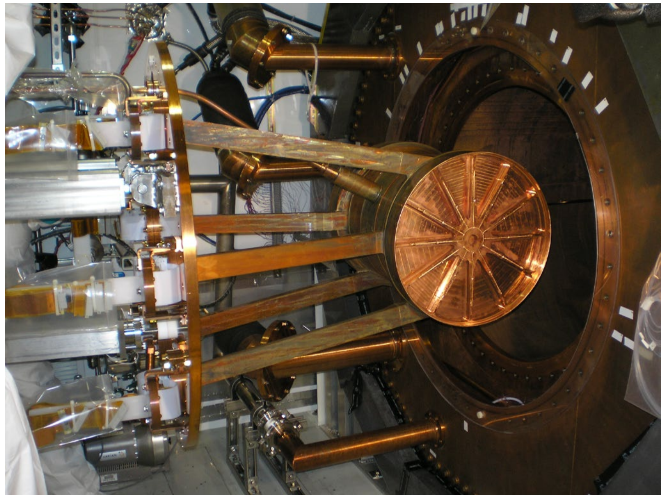
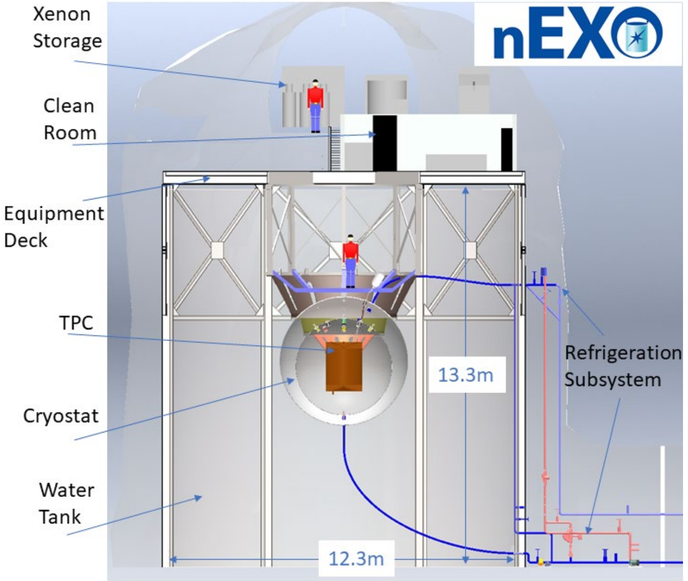
Today, these principles are well recognized by funding agencies.

Milestones in the EXO program
Since 2001

- 2001: "EXO" started as an R&D 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 run
- 2019-now: nEXO project developed; substantial nEXO engineering at SNOLAB
- Feb 2021: nEXO budget review
- Jul 2024: Dry run for CD-1 ("Director's review")





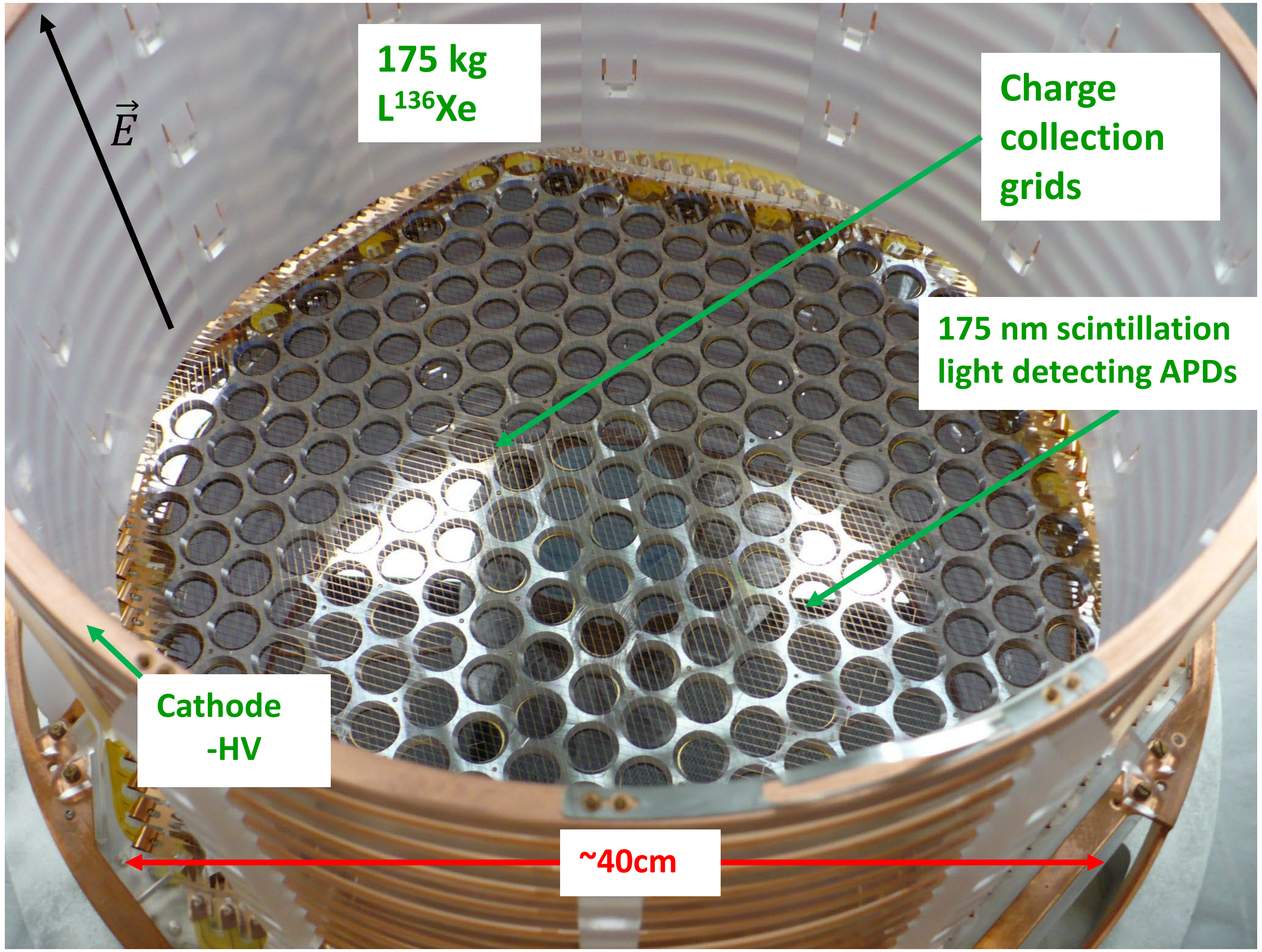
EXO-200

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.

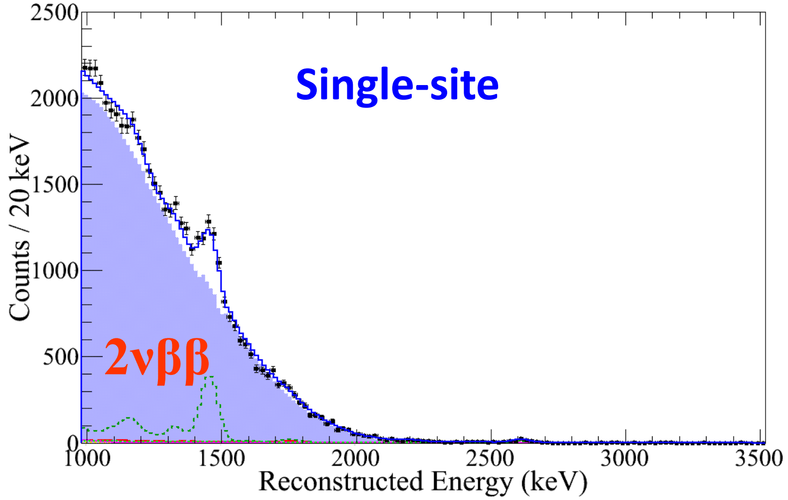
The same principle is used in nEXO

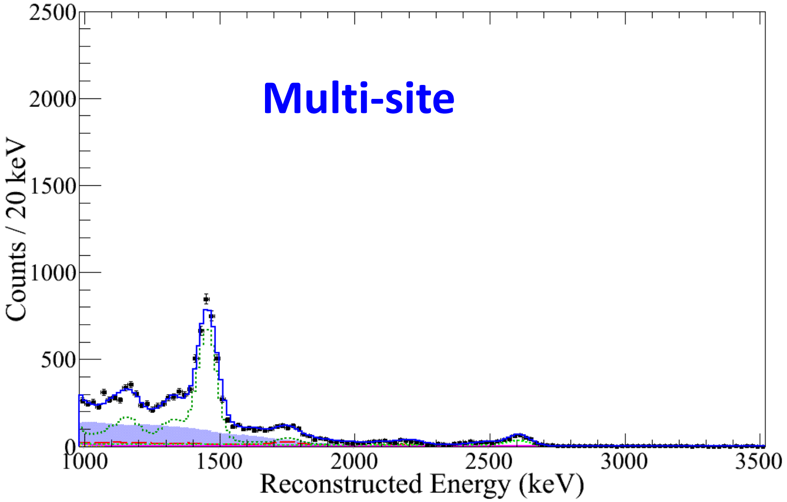


Using event multiplicity to recognize backgrounds

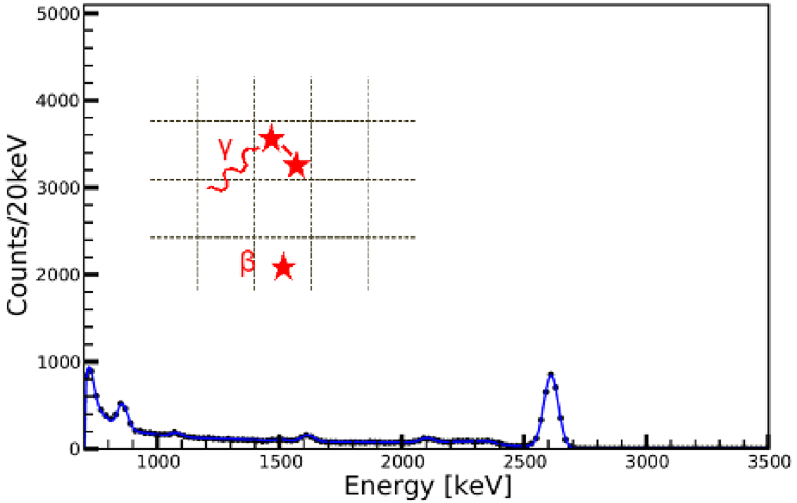
EXO-200 data

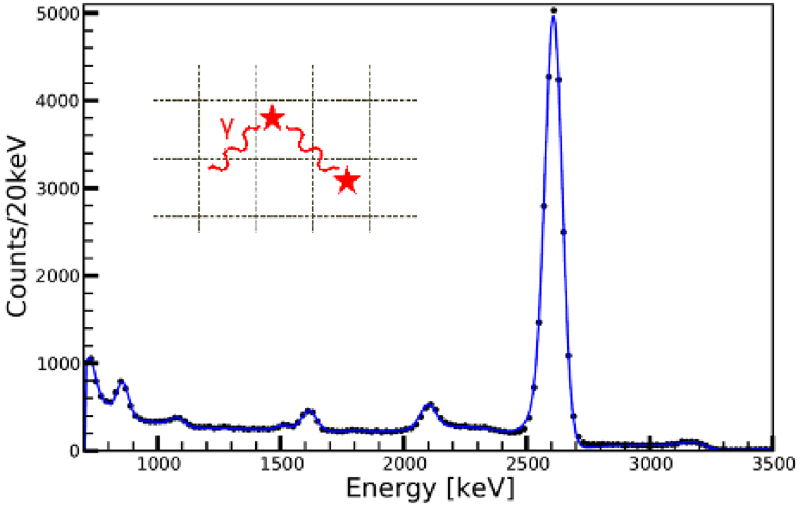
Low background data



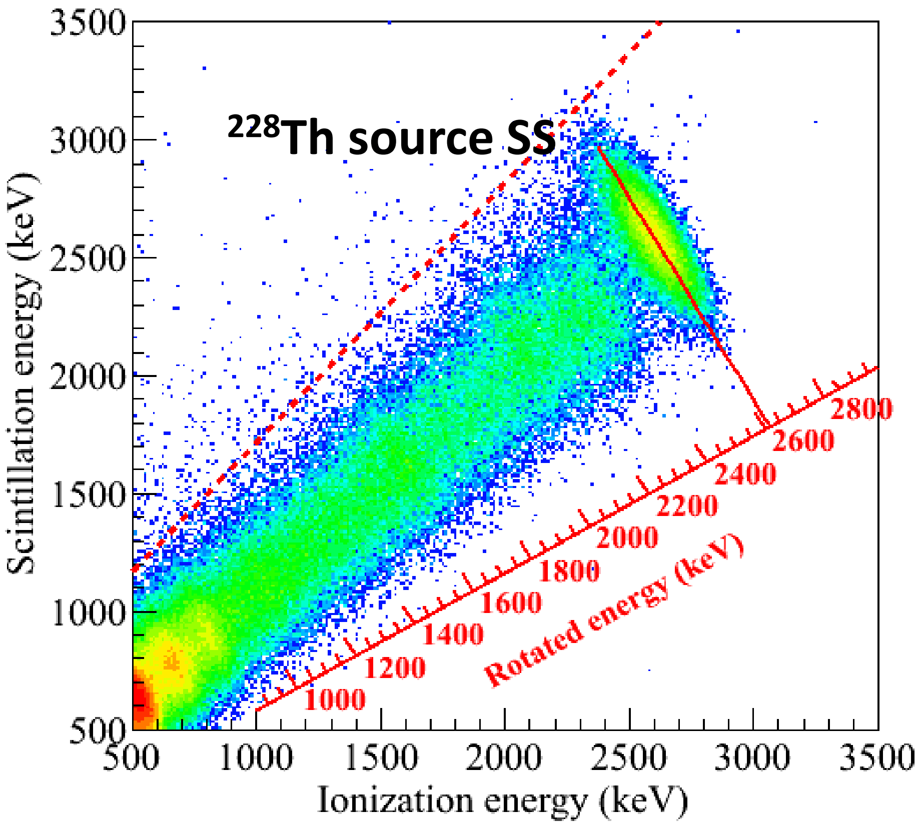


^{228}Th calibration source





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

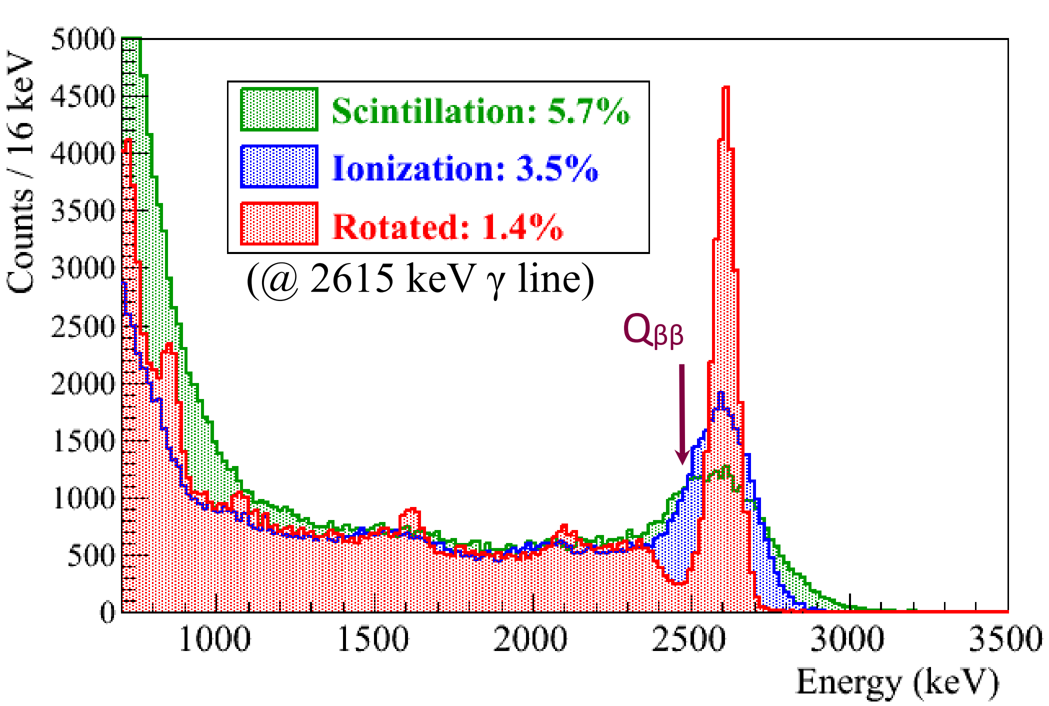


Rotation angle chosen to optimize energy resolution near $Q_{\beta\beta}$=2457.83 keV

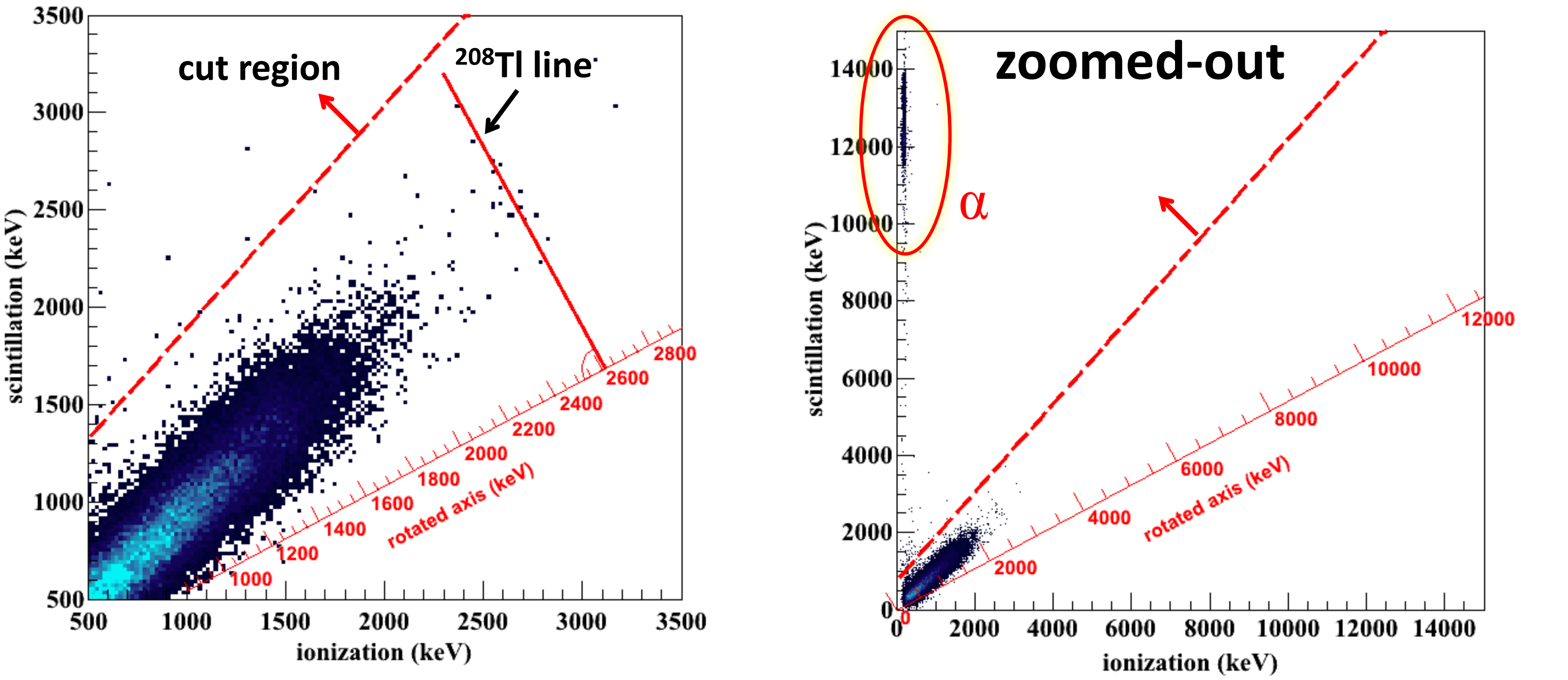
Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

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.

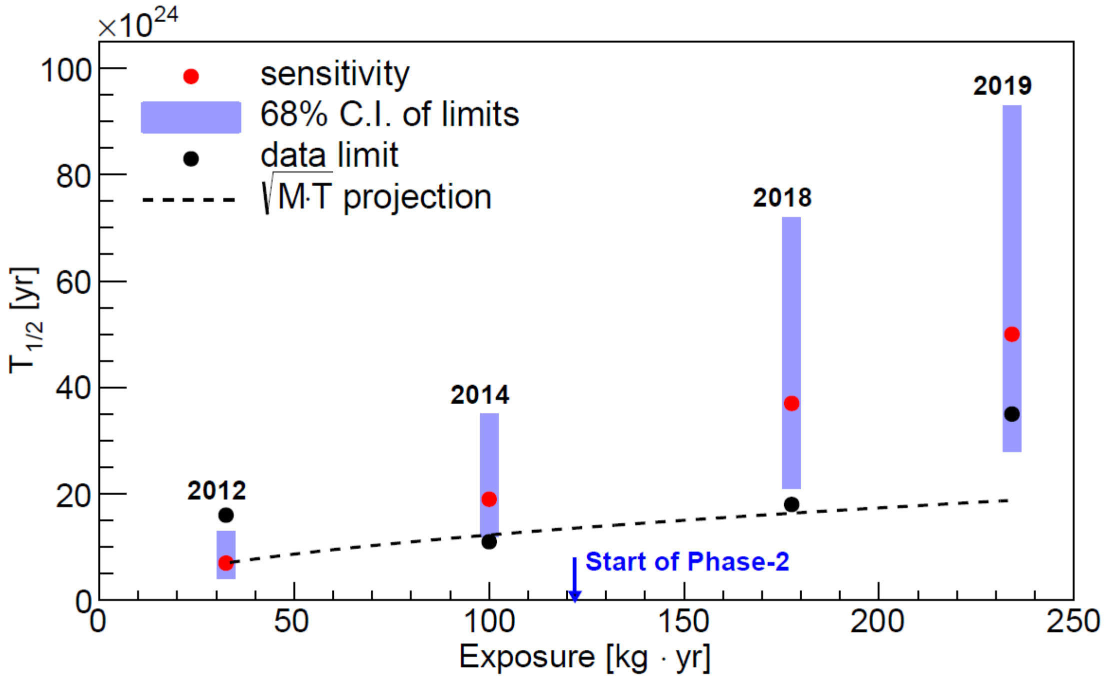
Cosmogenic backgrounds:

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		

Some notable successes of EXO-200

- EXO-200 was the first 100 kg-class experiment to take data.
- With its excellent background and pioneering multi-parameter event tagging
  - Published some of the most sensitive searches for the neutrinoless double-beta decay
  - Its sensitivity increased linearly with exposure (because of various software and hardware upgrades)



Main neutrinoless double-beta decay papers

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

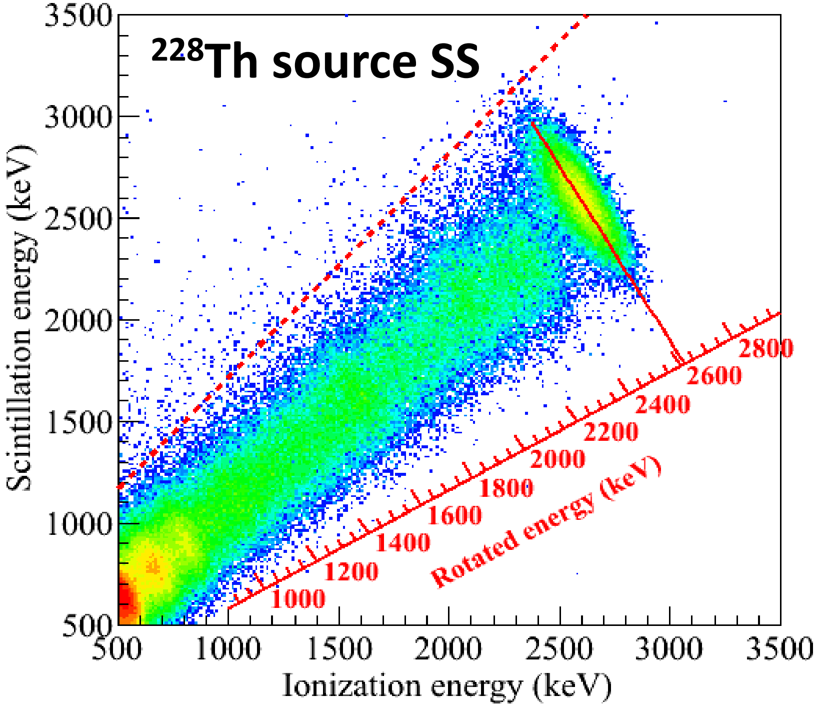
Limit: $T_{1/2}^{0\nu\beta\beta} > 3.5\times10^{25}$ yr (90% CL)

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

Sensitivity: 5.0×10^{25} yr

Some notable successes of EXO-200

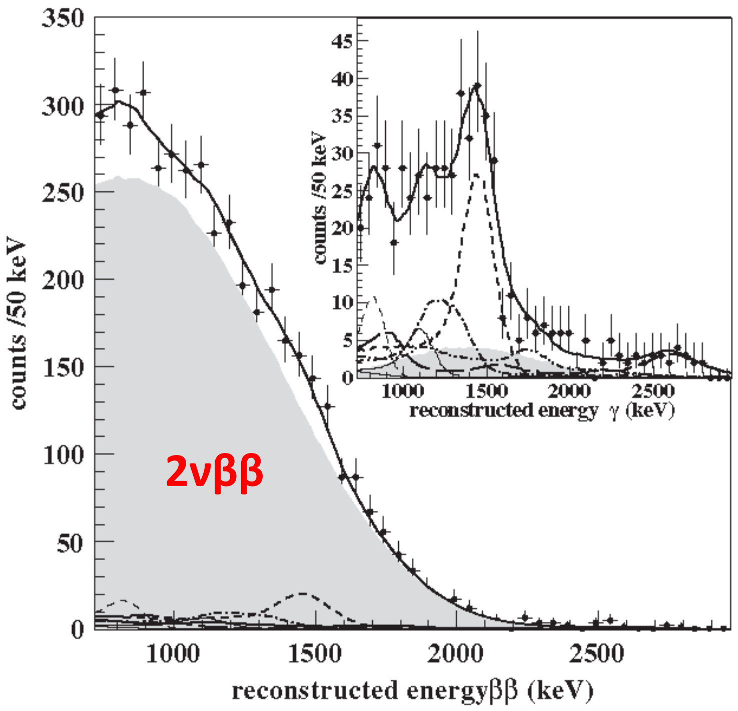
- Procurement of 200kg of enriched Xe:
  at the time considered
  an impossible proposition



- Energy resolution:
  designed for 1.6%, obtained <1.2%

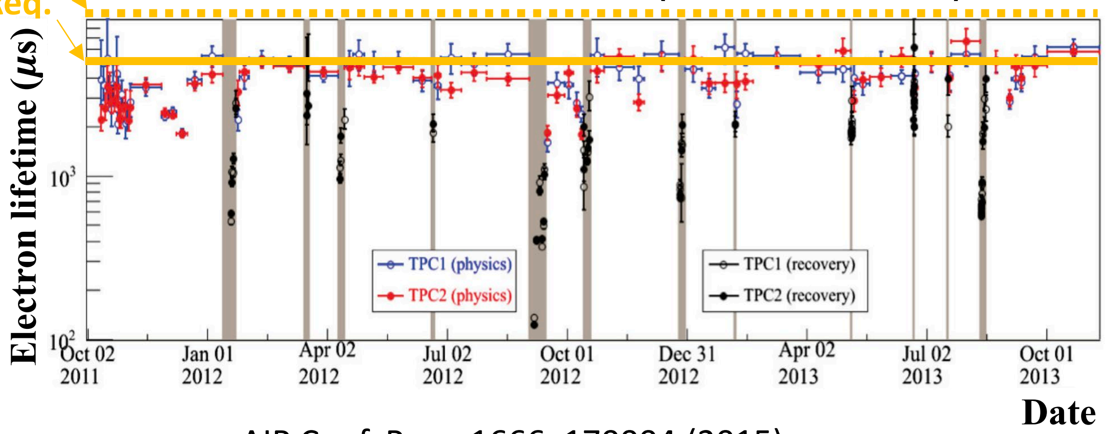
Some notable successes of EXO-200

- Discovered 2-neutrino decay in ^{136}Xe in the first week of data and in direct contradiction with existing limits.
  ➔ Unmistakable signal!



From PRL 107 (2011) 212501 (precision measurement followed)

nEXO Goal
nEXO Req.



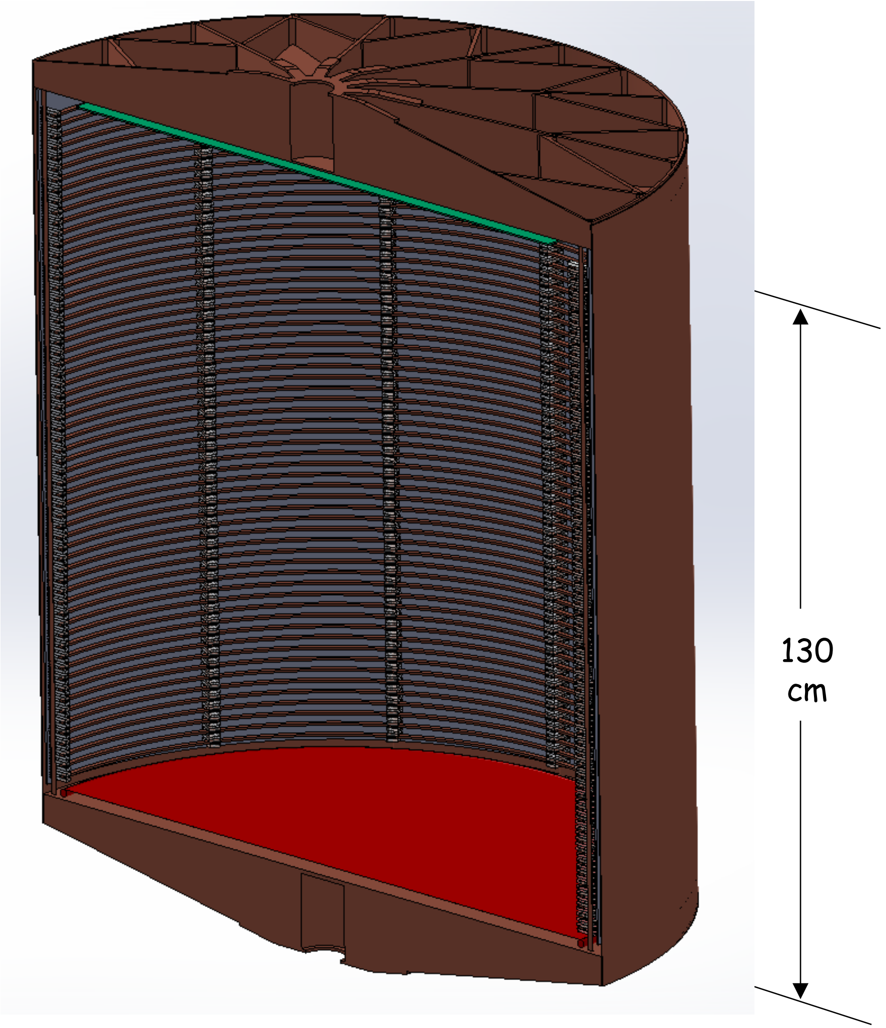
AIP Conf. Proc. 1666, 170004 (2015)

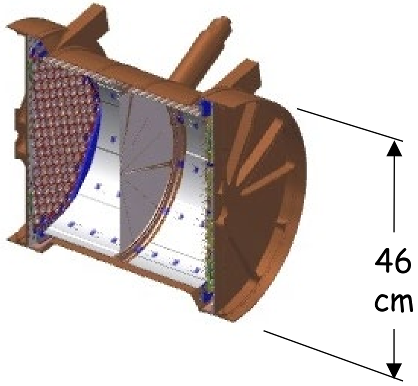
- Electron lifetimes as long as 5 ms have been reached, beyond what was then thought possible and already at the nEXO req. level.

Some notable successes of EXO-200

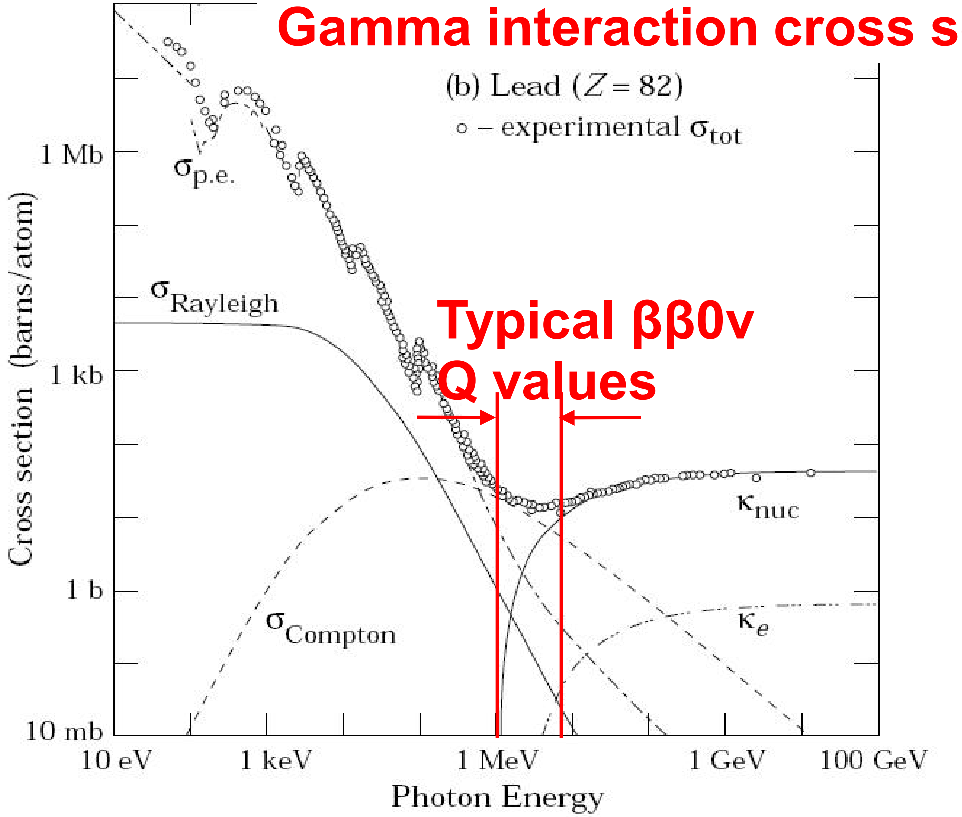
- (non-EXO-200) fire and closure of the WIPP underground:
  → No Xe loss
  → No detector damage

From EXO-200 to nEXO





Shielding a detector from ~MeV γs is difficult!



Example:

γ interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

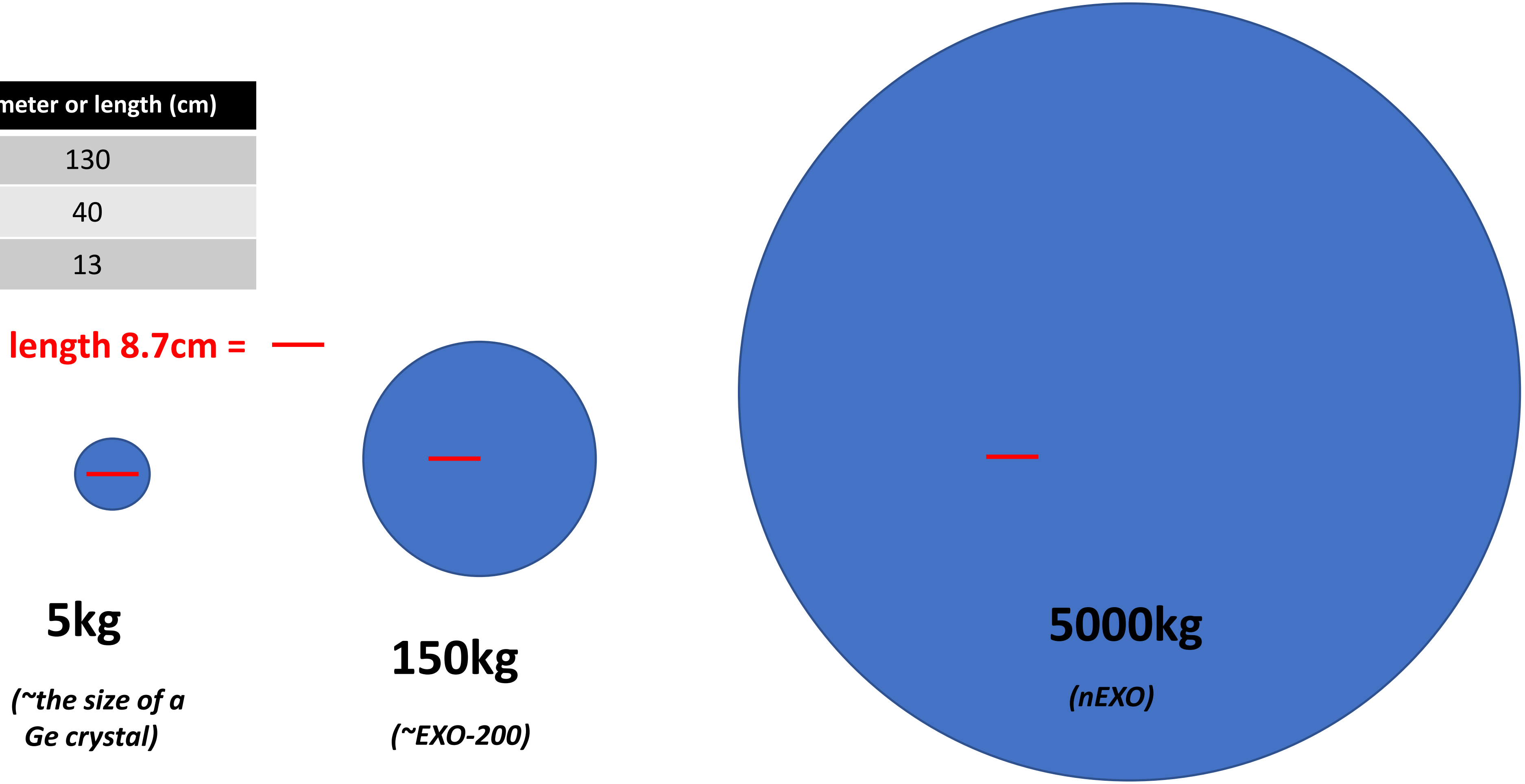
Shielding ββ decay detectors is much harder than shielding Dark Matter ones

We are entering the "golden era" of ββ decay experiments as detector sizes exceed interaction lengths

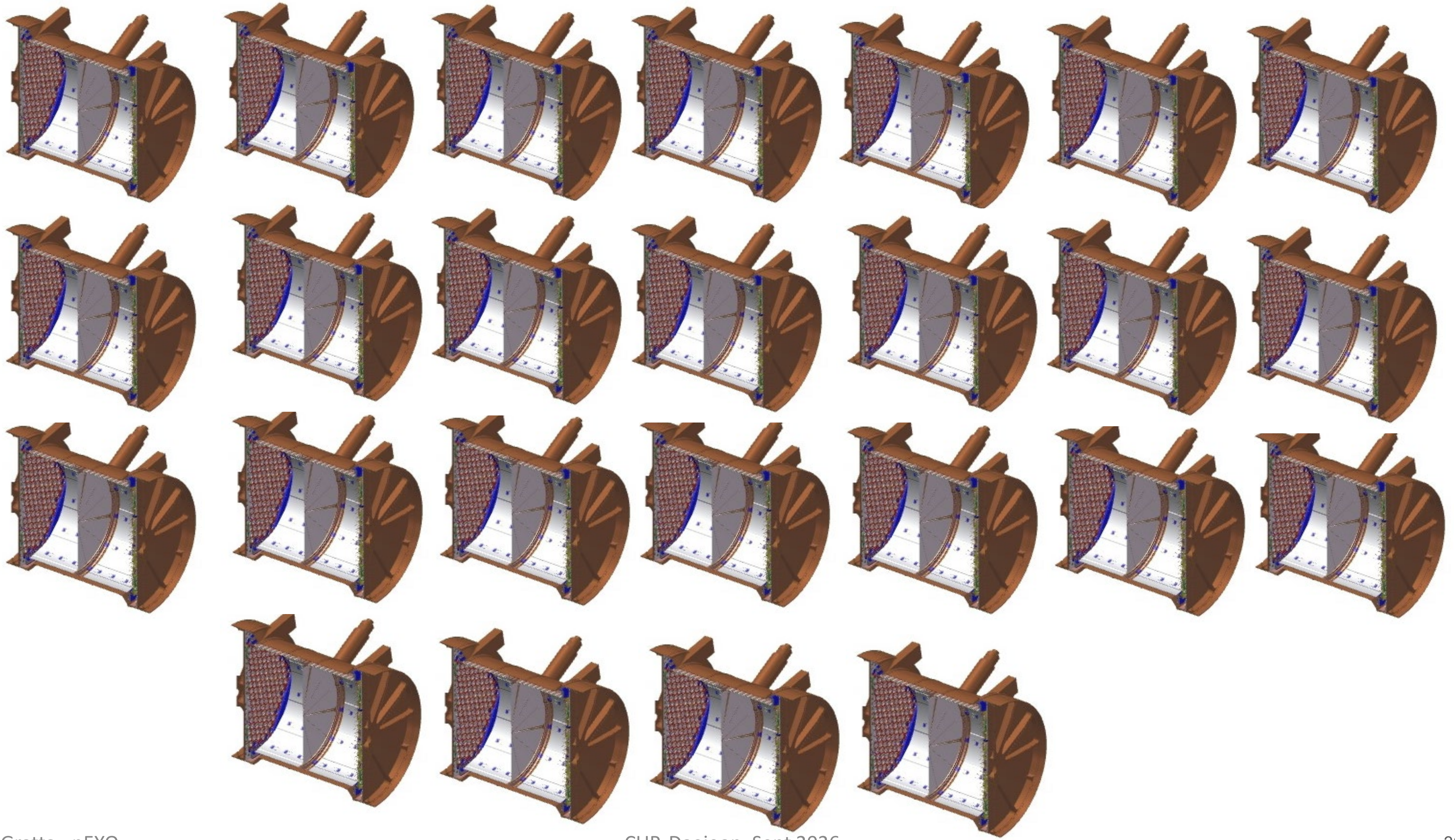
Monolithic/Homogeneous is key because extraneous material is all external → this is the lesson from KamLAND, SNO, Borexino, SuperK, …

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

2.5 MeV γ attenuation length 8.7cm = —

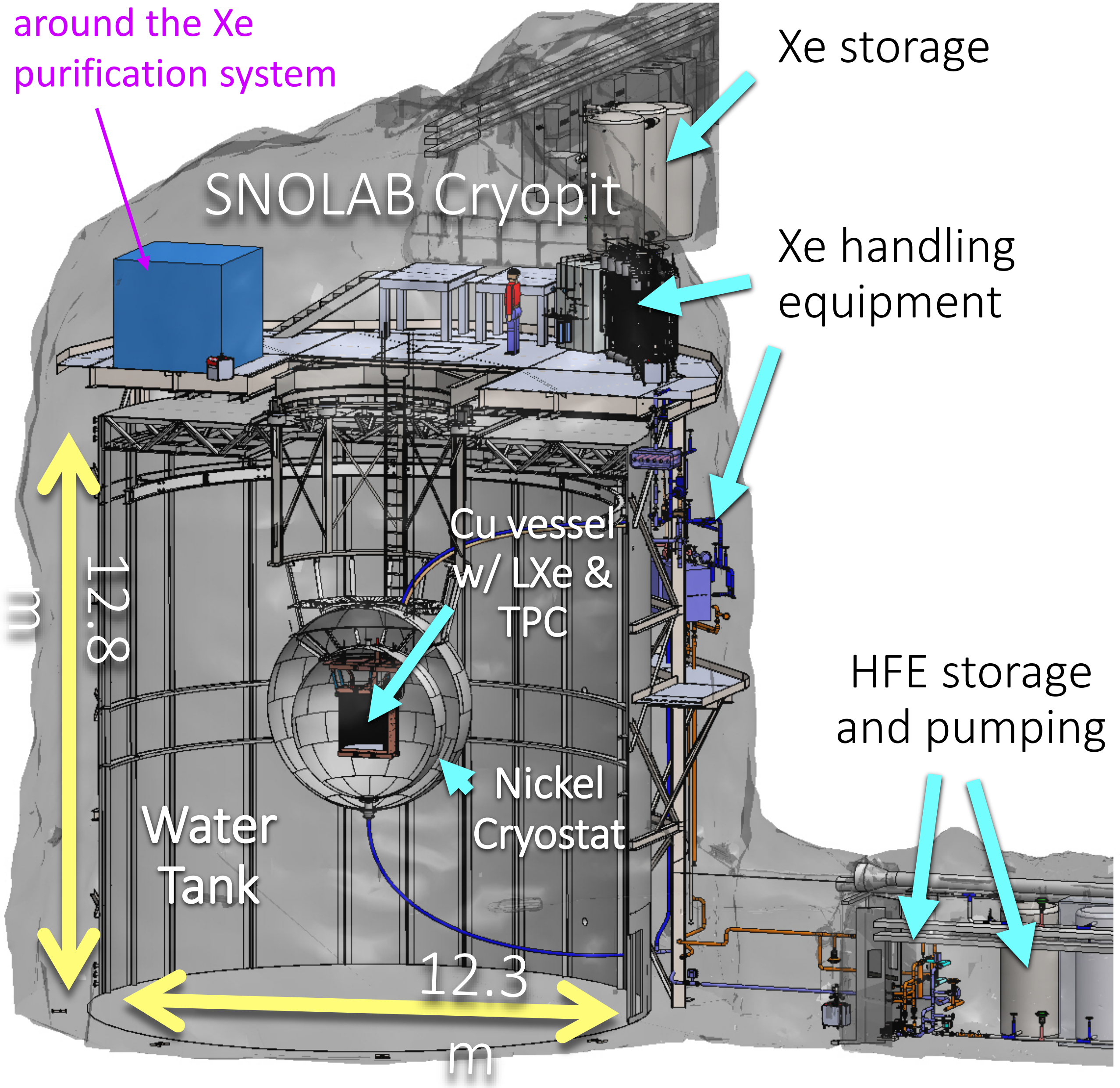


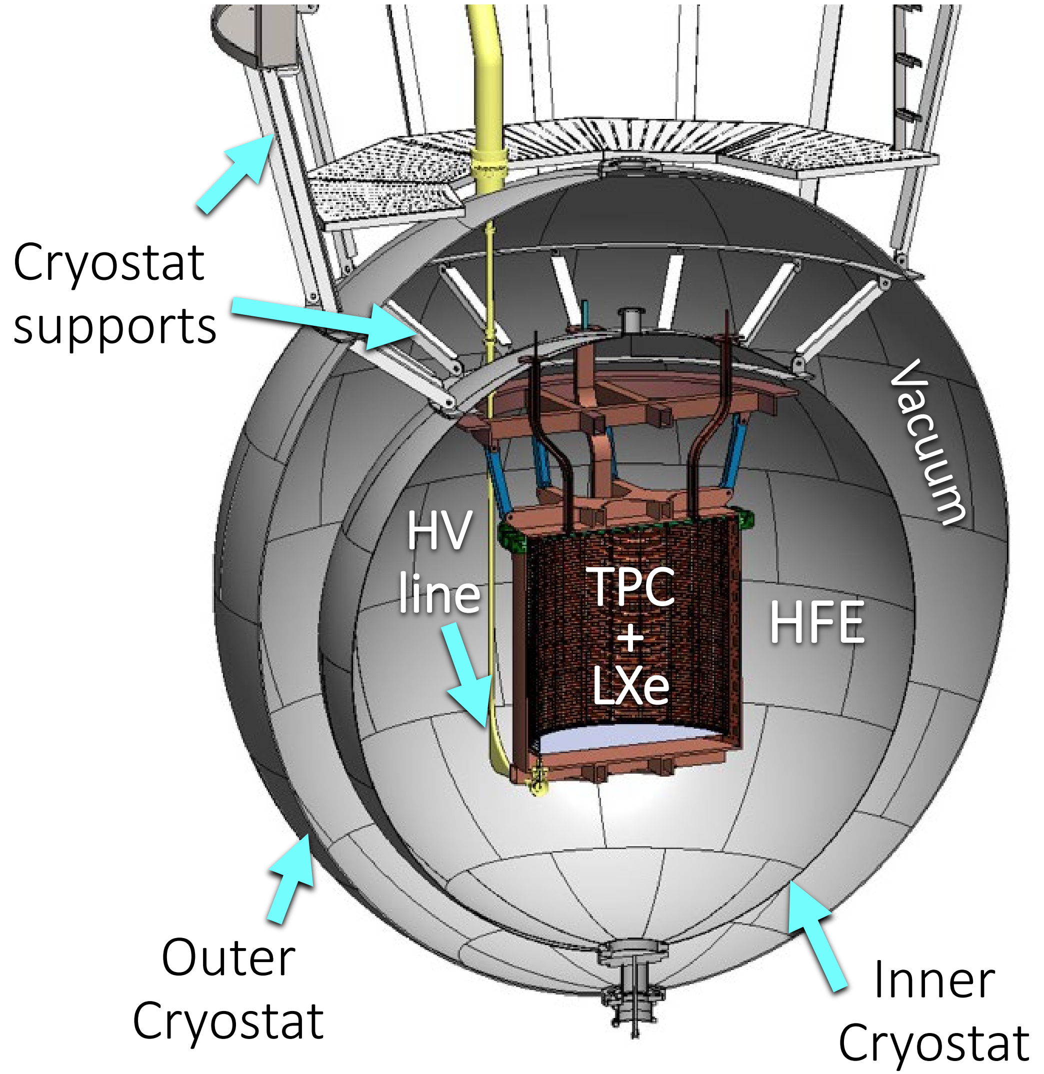
The wrong design for nEXO (requiring nothing new!)



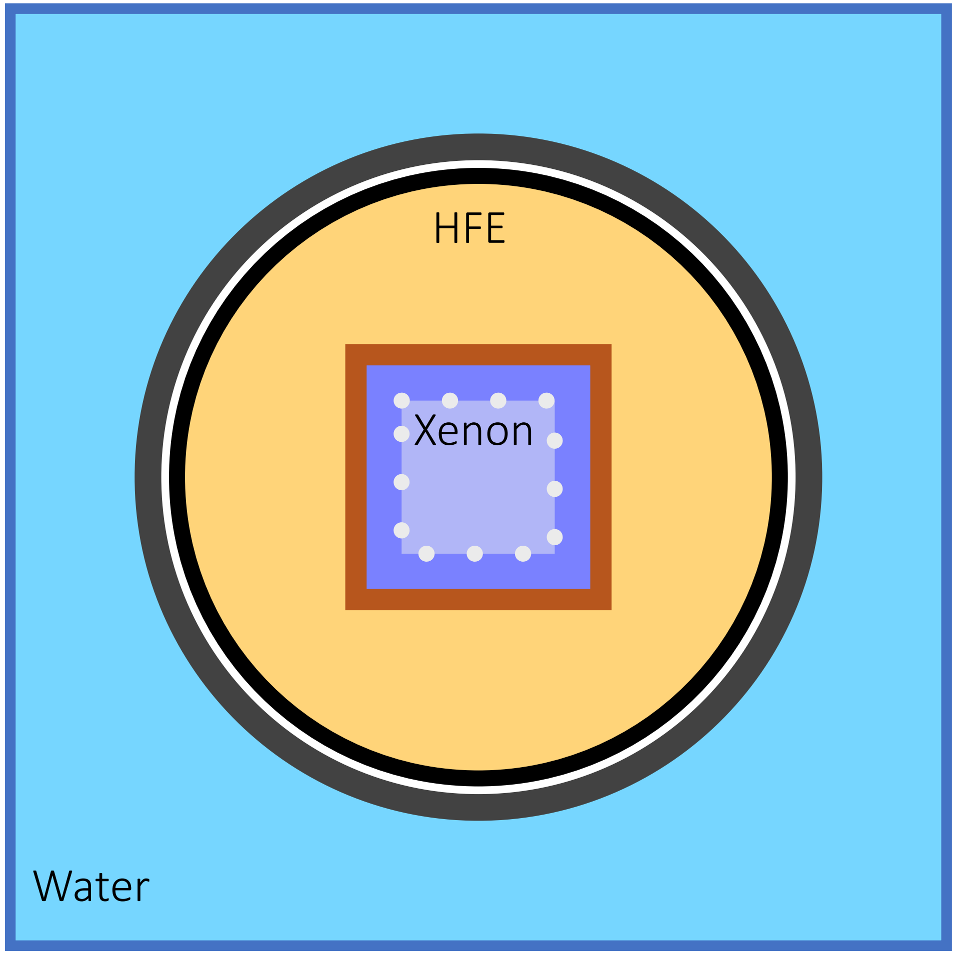
The nEXO detector at SNOLAB

Note the neutron box around the Xe purification system





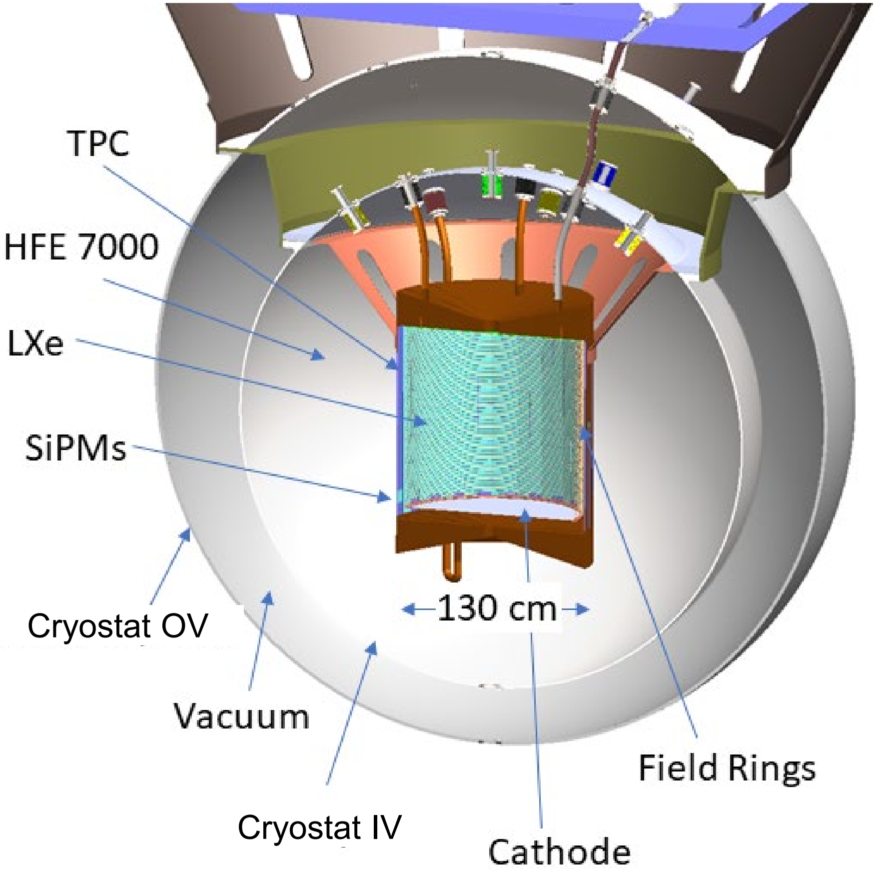
nEXO cryogenics driven by low background design (pioneered in EXO-200)



i) **Goal: largest Xe volume with the lowest background**
   - Minimize the radioactivity of the TPC vessel
   - Single, light, low-background copper TPC vessel
   - Move the double vessel cryostat away from the TPC
   - Fill the gap with low-background, high density fluid
   - Use the same fluid to also transfer the pressure to the cryostat (inner) vessel

ii) **The HFE fluid is cleaner than any known structural solid material ➔ need to balance:**
   - Desire to push cryostat as far out as possible
   - Cryostat mass/background/cost/feasibility vs. size
   - Cost and handling/storage of HFE
   - Background contributions from cryostat ≈ HFE

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

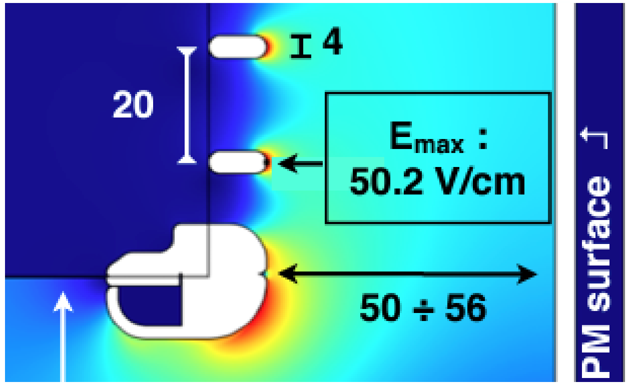


	EXO-200:	*nEXO:*	Improvements:
Vessel and cryostat	Thin-walled commercial Cu w/HFE	*Thin-walled electroformed Cu w/HFE*	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	*Operating voltage: 50 kV*	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad polyimide (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%	*1.1% (req.), 0.8% (design)*	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

nEXO Geometry

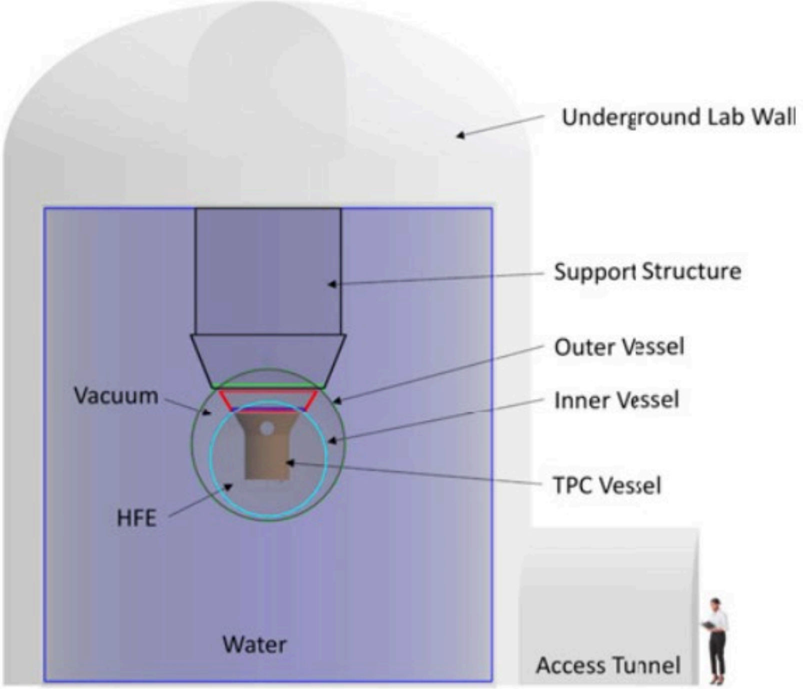
- High-fidelity renderings of nEXO are implemented in the simulations to capture detailed features of conceptual design
  - Accurately simulate location of background sources and shielding (Geant4)
  - Directly import CAD geometry with all details for ray-tracing simulations of light collection (Chroma)
  - Simulation of full field cage for electrostatic simulations (COMSOL)

Electrostatic FEA (COMSOL):

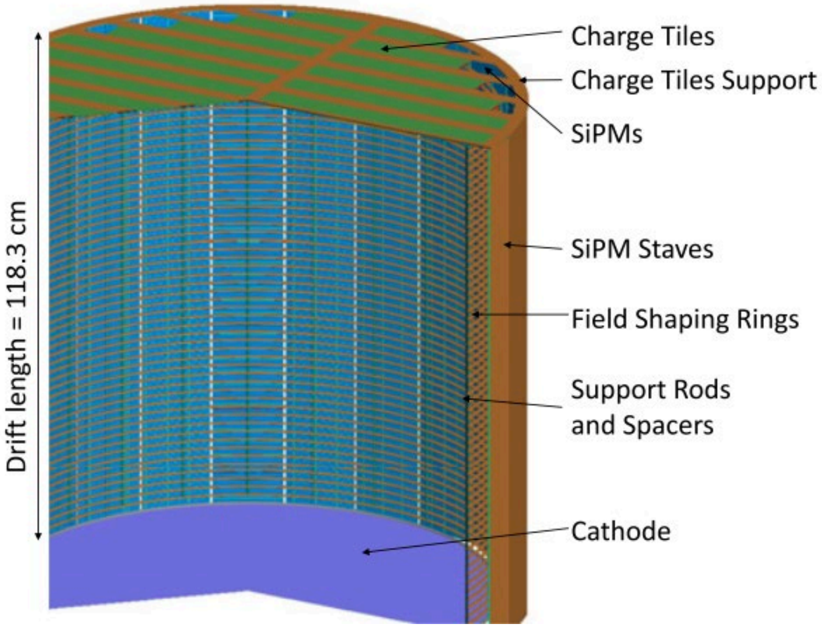


Geant4 geometry:

Outer detector and cavern:

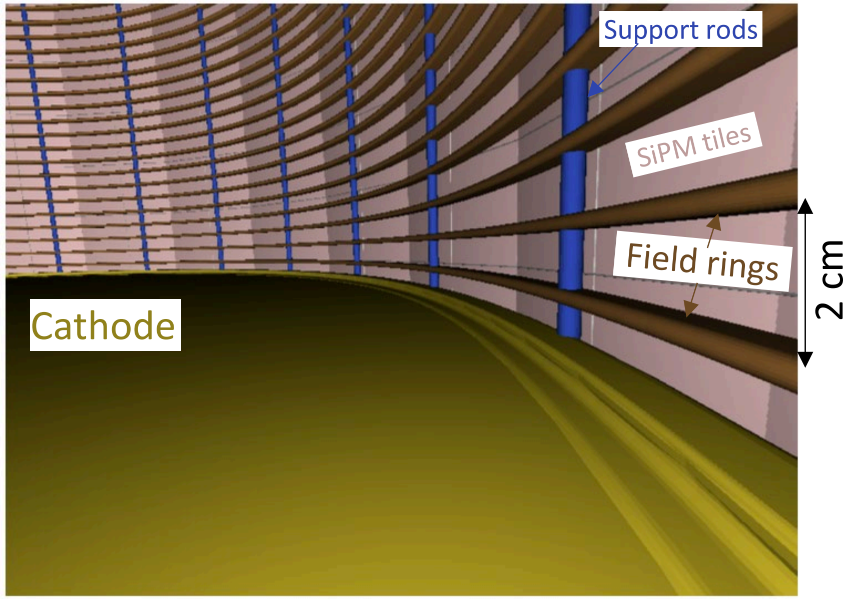


TPC:



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

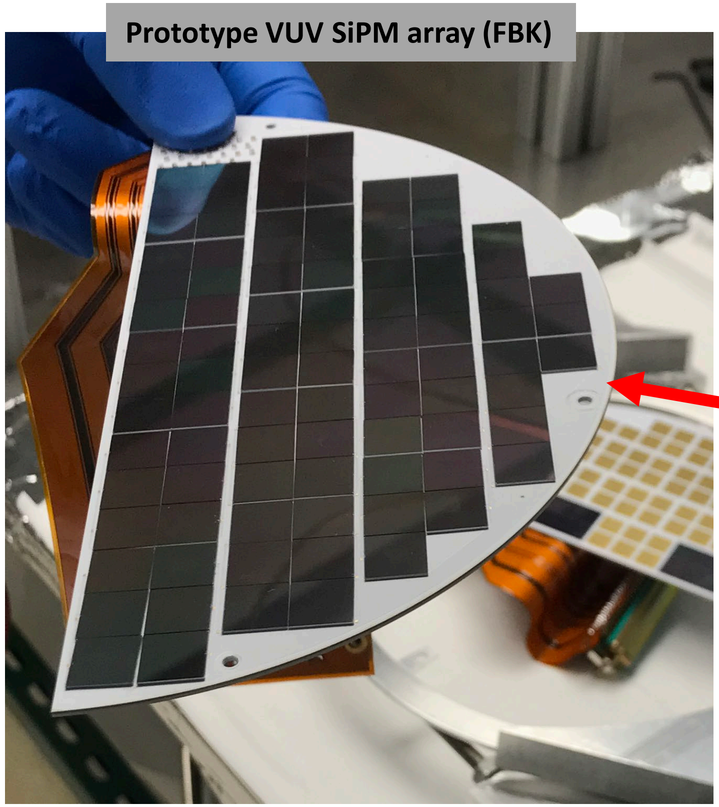
Rendering of cathode in Chroma:

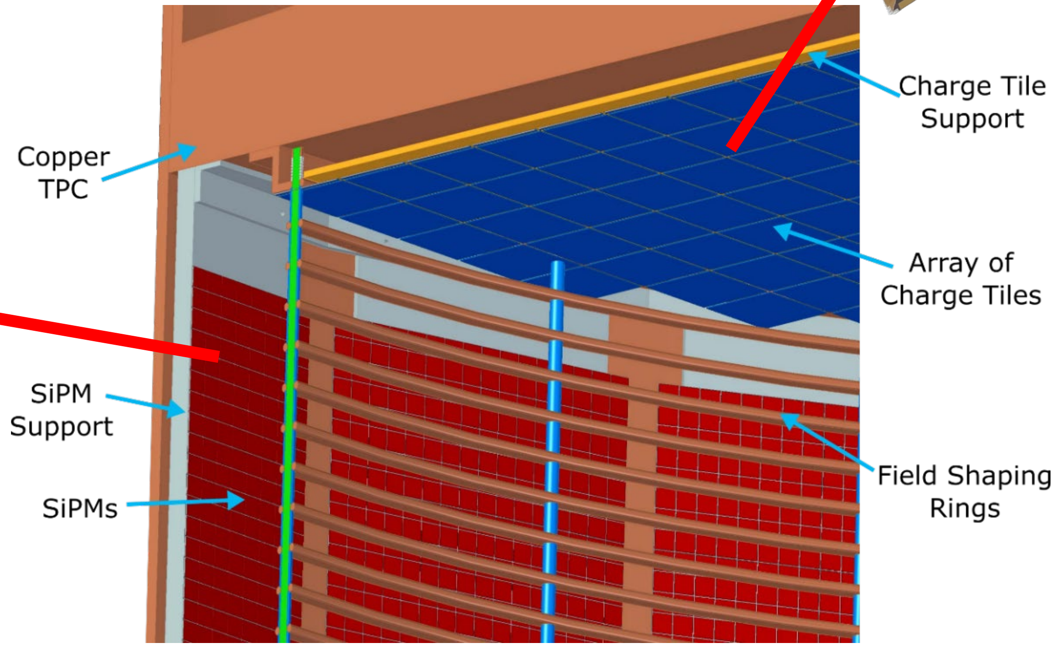


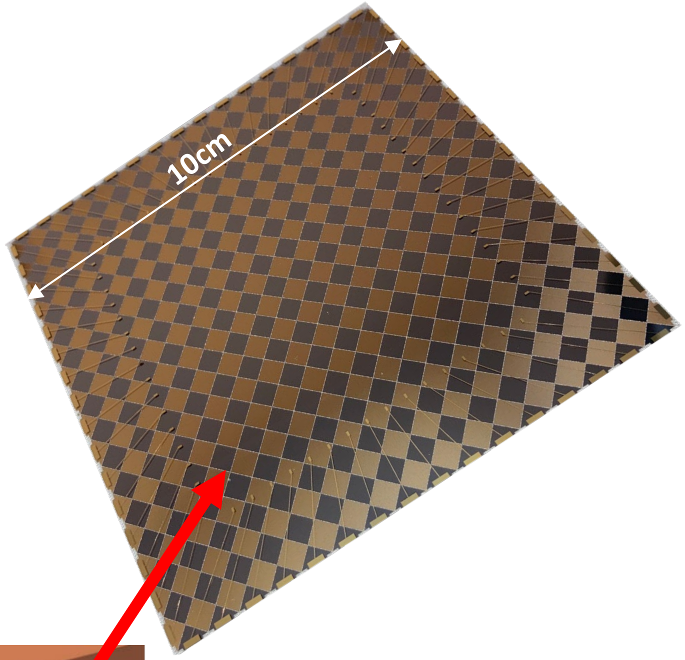
A. Jamil PhD Thesis (Yale), 2022

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)

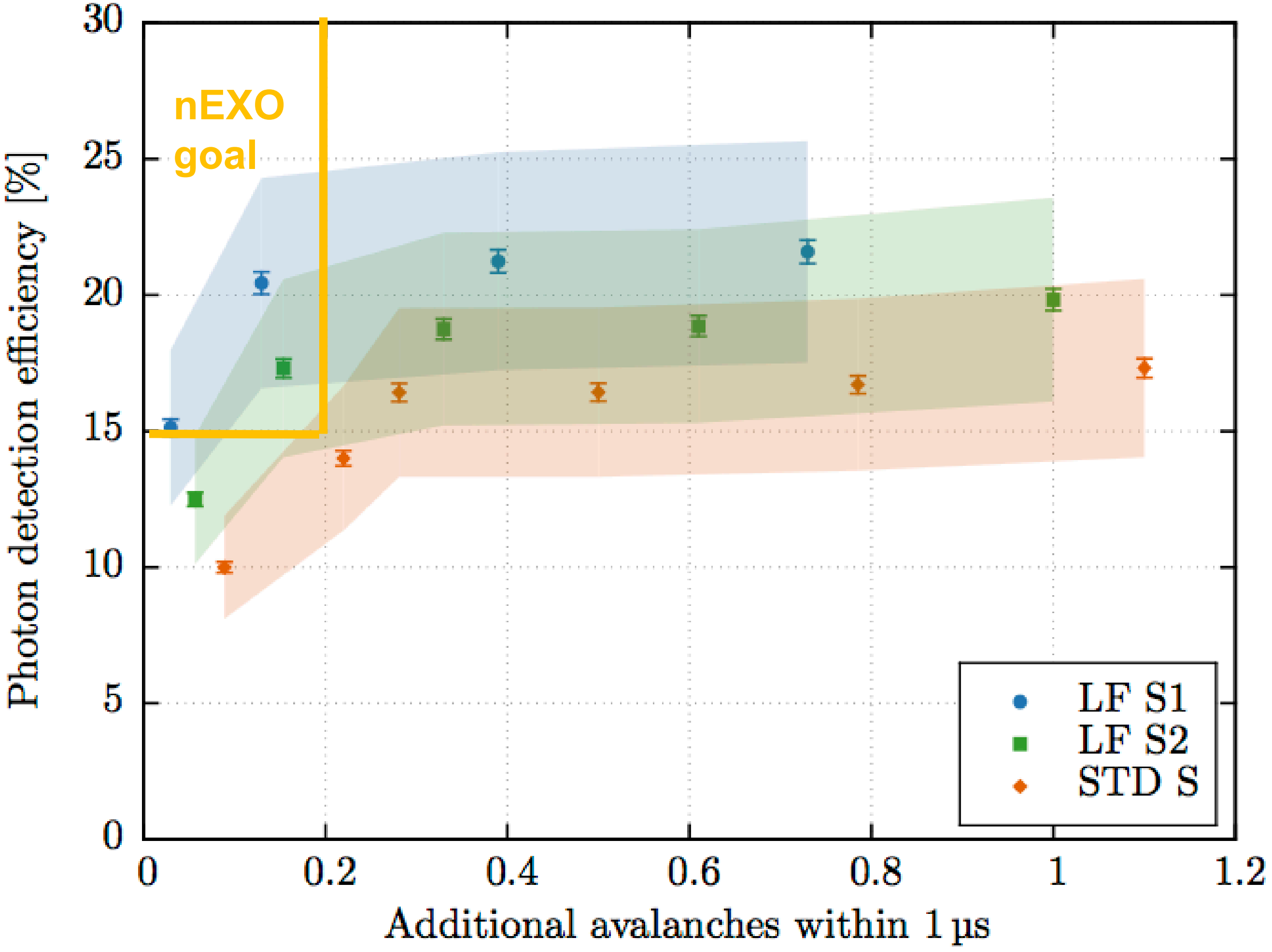




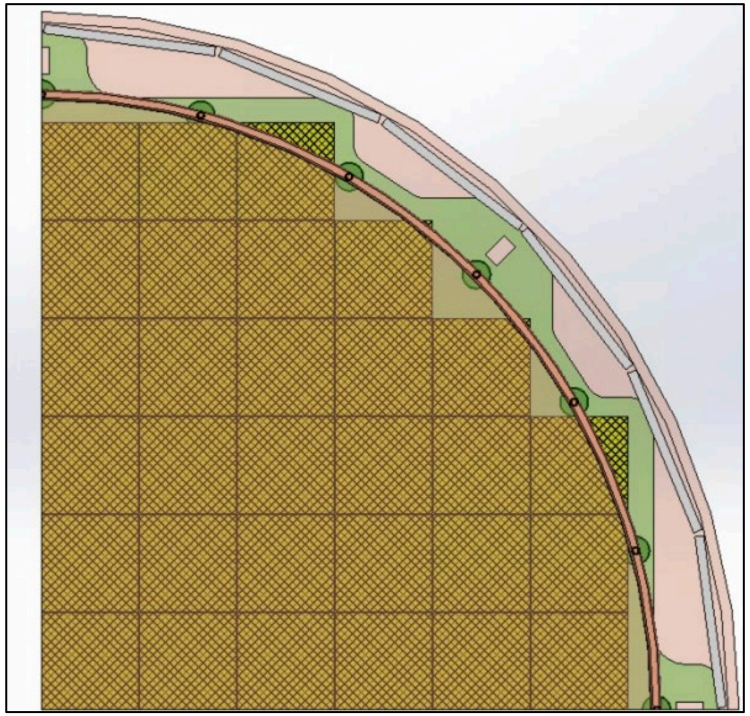


SiPM-based scintillation readout: high gain and ~30V bias

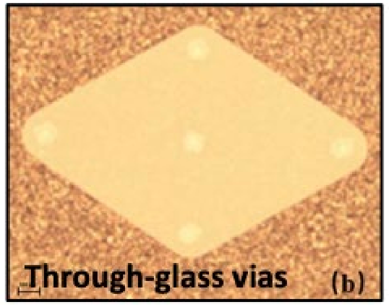
(as opposed to the 1500V of EXO-200 APDs)

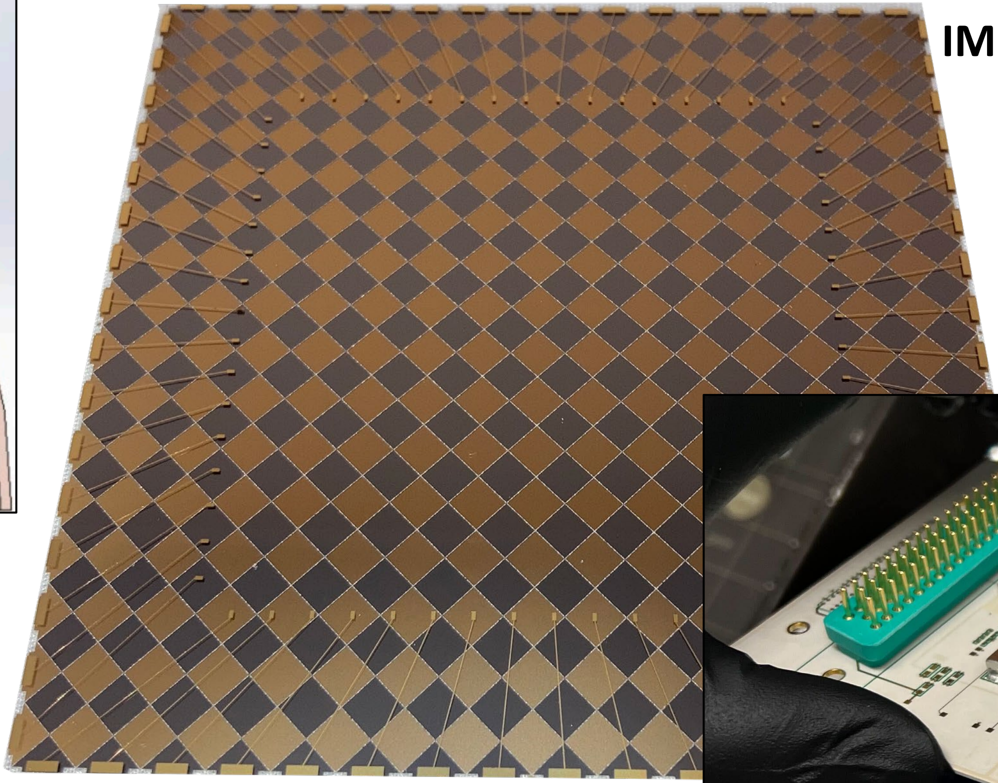


Charge collection tiles with crossed strips on silica substrate and built-in ASICs electronics

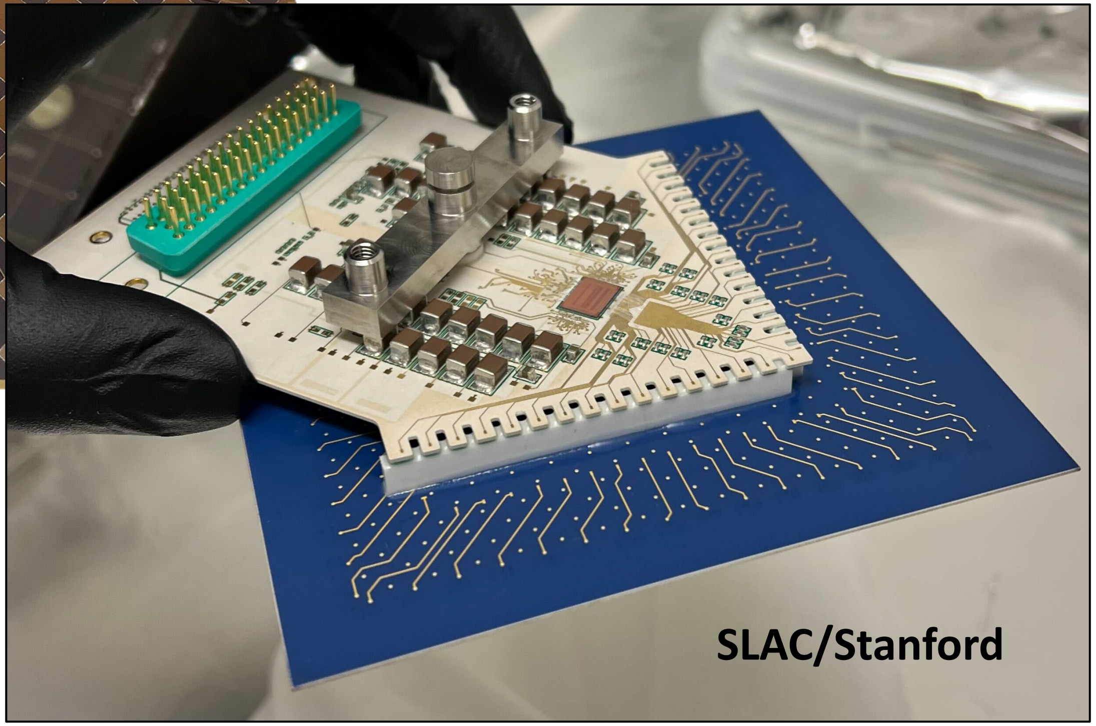


Wu, X et al., *Electronics* (2023)

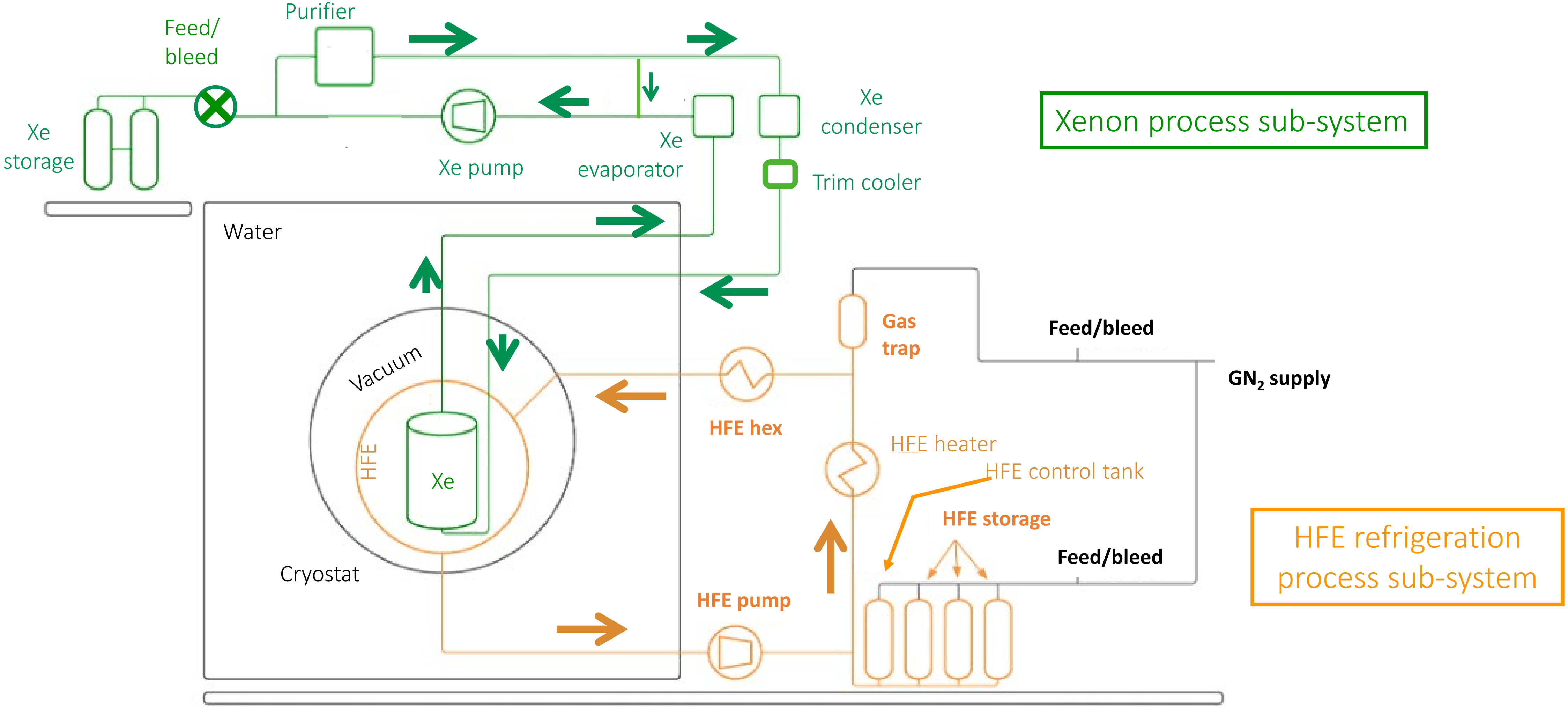




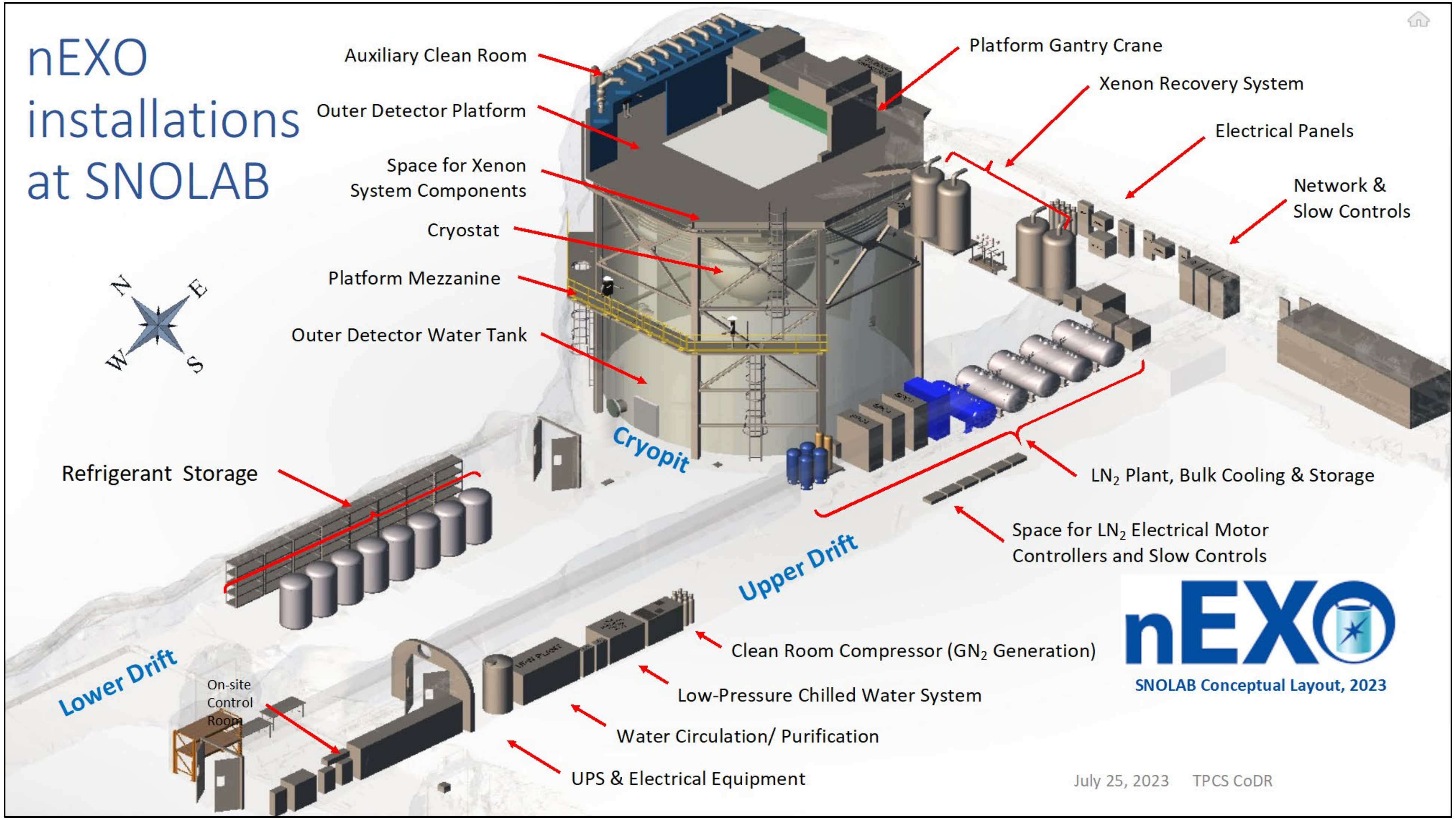
IME-CAS



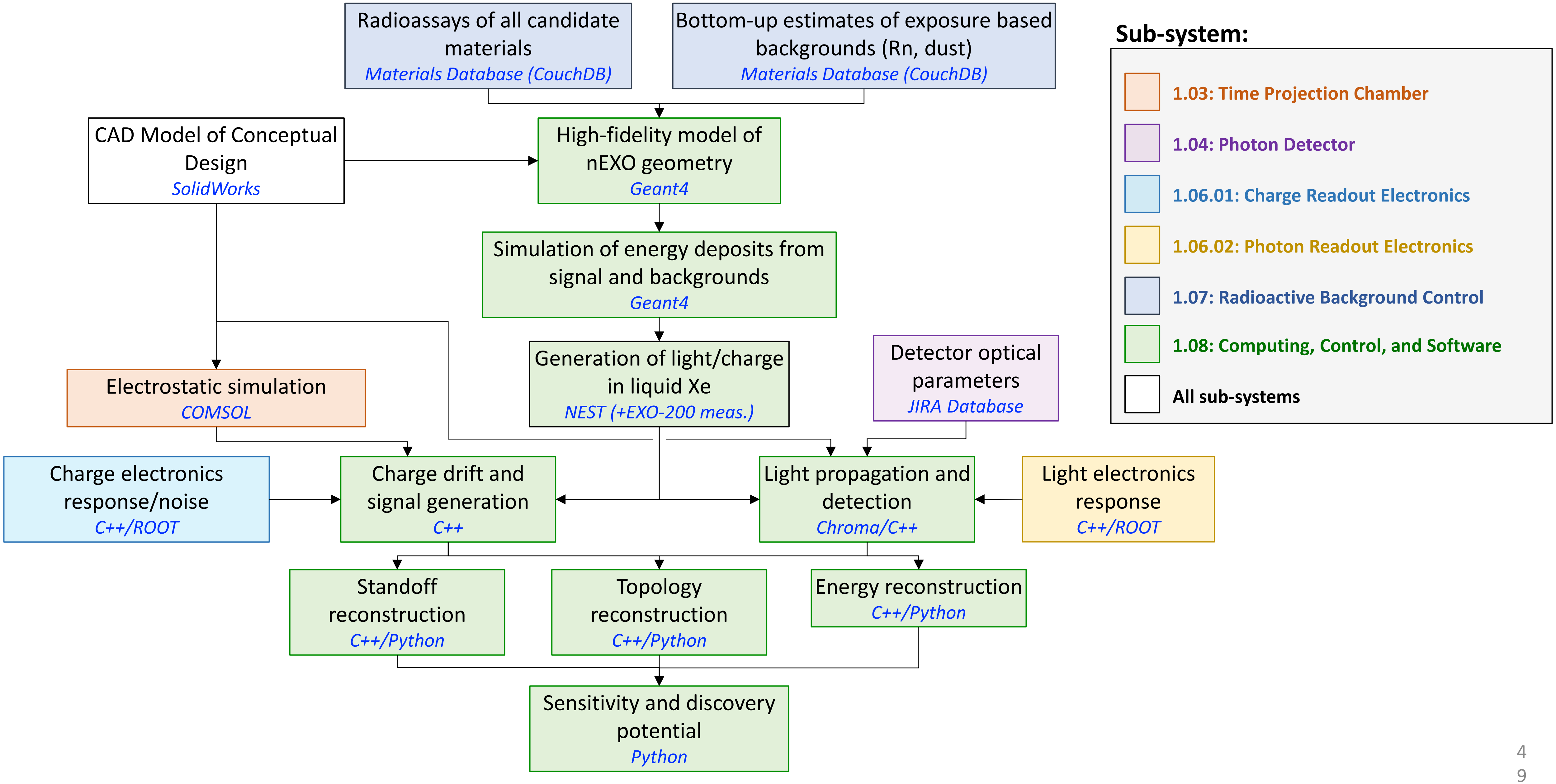
The nEXO fluid handling and cryogenic layout (2 fluids, ~165K, principled tested in EXO-200)



The nEXO experiment – Full facility



Modeling flow and software



Radioactivity Database

- Radioassays of ***all*** candidate materials are a key input ensuring the accuracy of the sensitivity estimate and optimization of conceptual design
  - Assays are managed by custom “Materials Database” which is directly integrated with the Geant4 based simulation as input (*NIM A 1055, 168477 [2023]*)
  - Each sub-system has identified candidate materials tracked in the materials database required to implement the conceptual design

Example screenshot of materials tracked in database:

Materials Database

| Radioassay | Monte Carlo | Background Spreadsheet | EXO-200 Radioassay Data | EXO-200 Radon Data | Assay Request | Allowed Radioactivity Calculator | Background Investigator | Sampling Calculator |

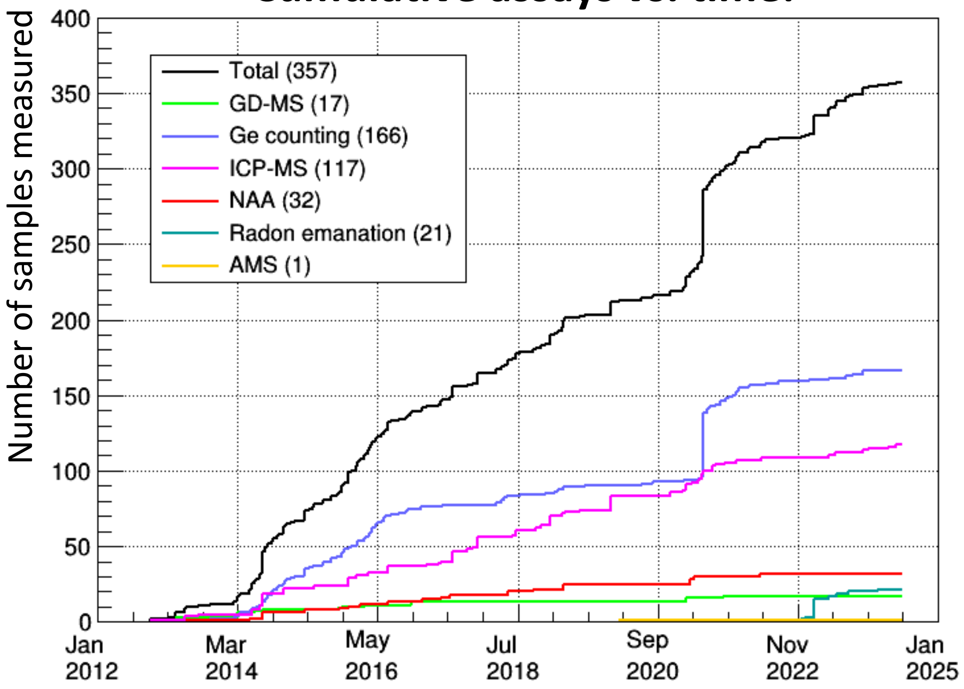
Unit: mBq/kg | ppt | ppb

Radon units: Atoms emanated | Atoms supported | Activity

Show: Raw values | Feldman-Cousins limits | Flip-flopping limits | Truncated Gaussian

ID	Date of measurement	Measured by	Material	Sample ID	Institution	Technique	U-238	U-238 (Ra-226)
			Kapton HN		PNNL			
R-093.1.1	2017-06-30	Isaac Arnquist	Kapton HN from CS Hyde	Kapton HN 5 mil CS Hyde	Pacific Northwest National Laboratory (PNNL)	ICP-MS	11.4 ± 0.136	
R-092.1.1	2017-06-30	Isaac Arnquist	Kapton HN from Dupont	Kapton 300HN Dupont	Pacific Northwest National Laboratory (PNNL)	ICP-MS	13.4 ± 0.531	
R-092.2.1	2017-06-30	Isaac Arnquist	Kapton HN from Dupont	Kapton 500HN Dupont	Pacific Northwest National Laboratory (PNNL)	ICP-MS	10.2 ± 0.901	
R-092.3.1	2017-06-30	Isaac Arnquist	Kapton HN from Dupont	Kapton 100HN Dupont	Pacific Northwest National	ICP-MS	11.9 ± 0.173	

Cumulative assays vs. time:

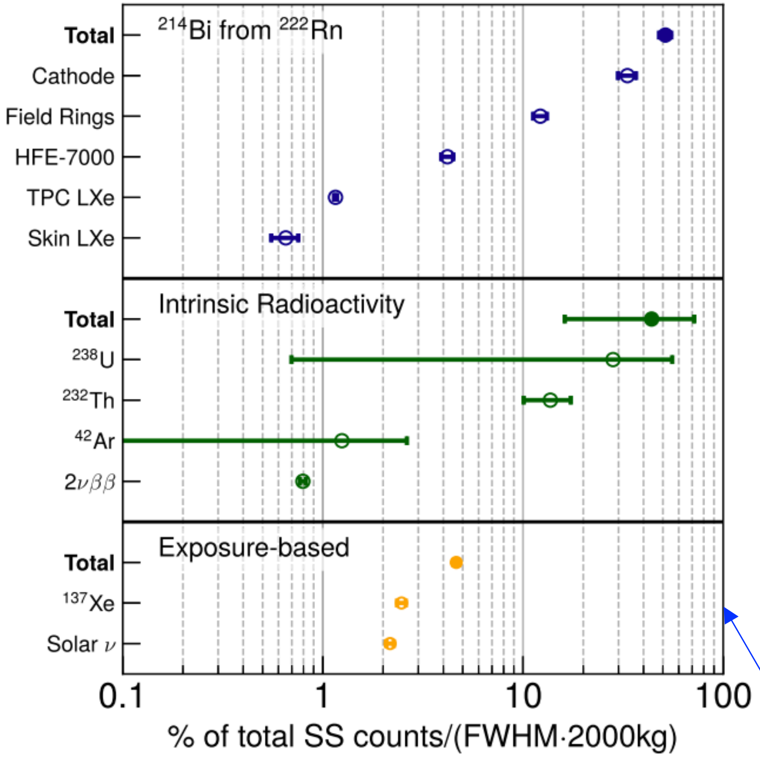


Background Modeling (SNOLAB)

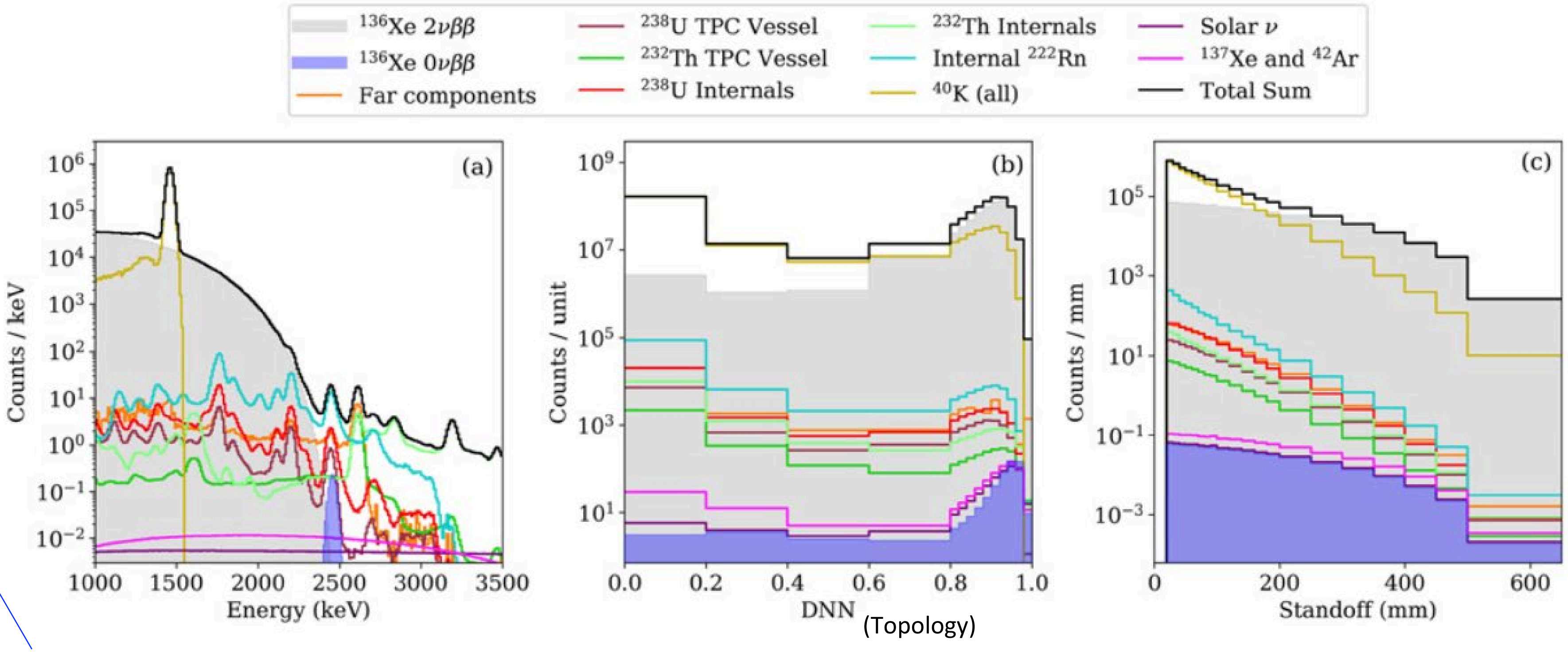
- Simulations indicate that backgrounds are dominated by ^{214}Bi γ originating from ^{222}Rn daughter plate out and intrinsic ^{238}U contamination in materials
- Uncertainty in intrinsic radioactivity is dominated by underlying radioassay uncertainties
- Exposure based backgrounds/cosmogenics are a sub-dominant contributor

(at SNOLAB, see next talks for YEMILAB)

Backgrounds by source:



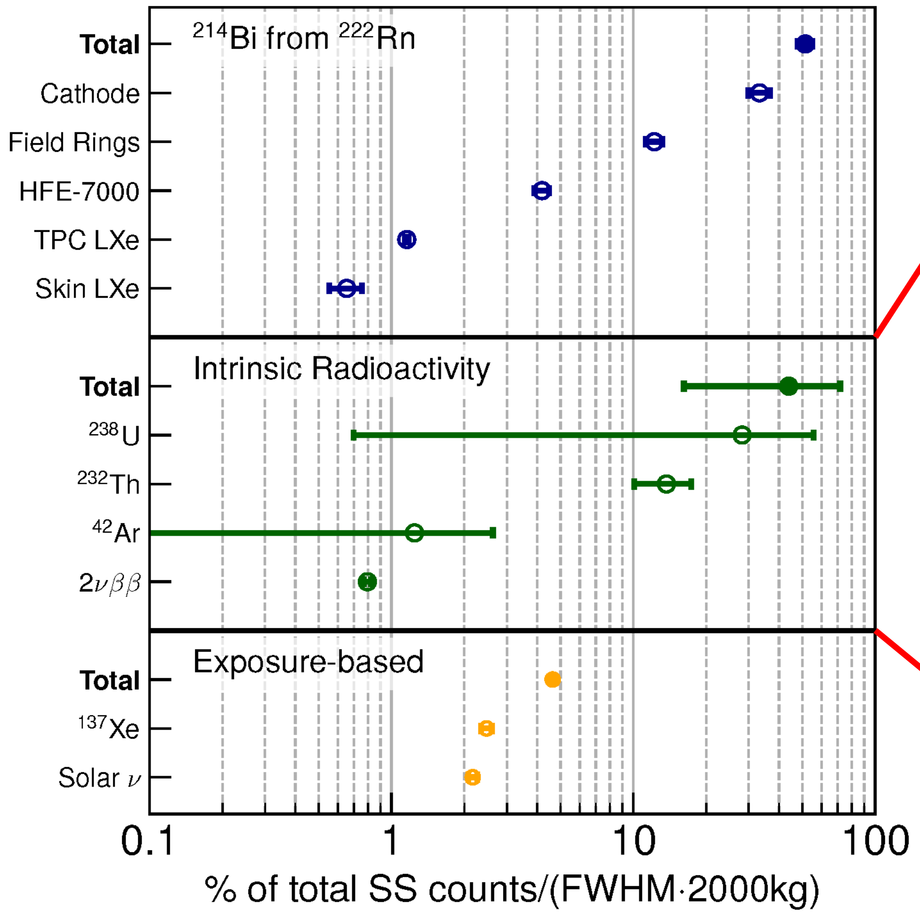
Simulated signal/background distributions (energy, topology, location):

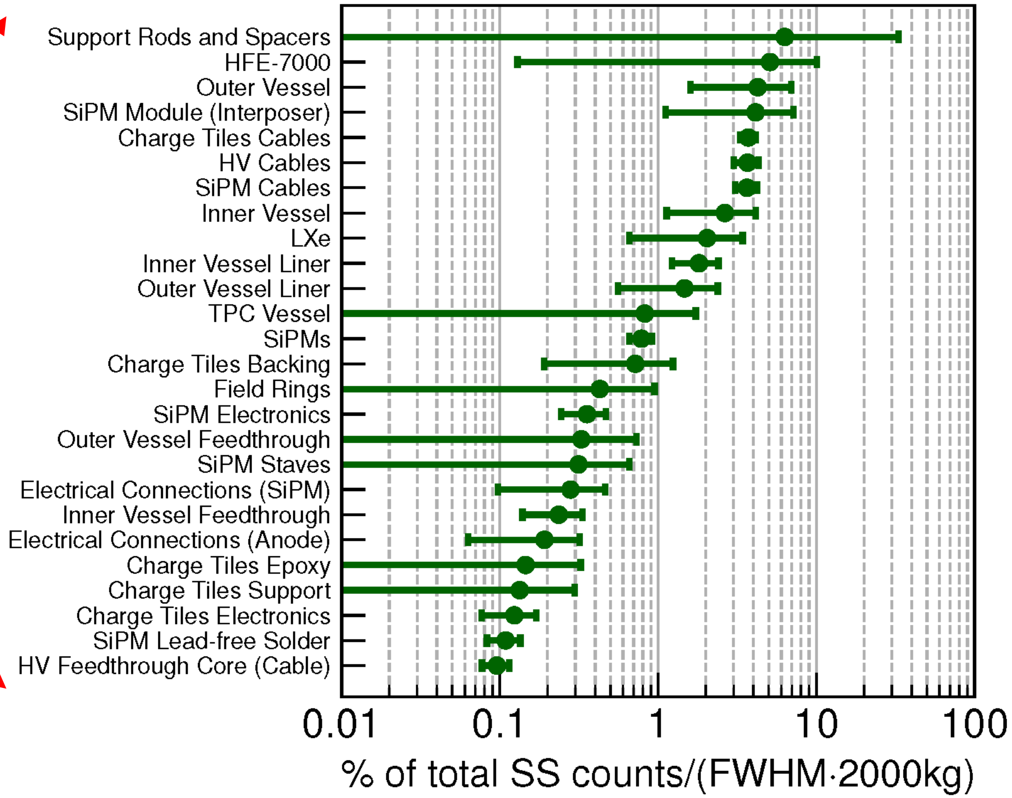


Current background estimate:
0.26±0.07 cts/(FWHM·t·y)

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

Contribution by component
(but see later for cryostat contribution)





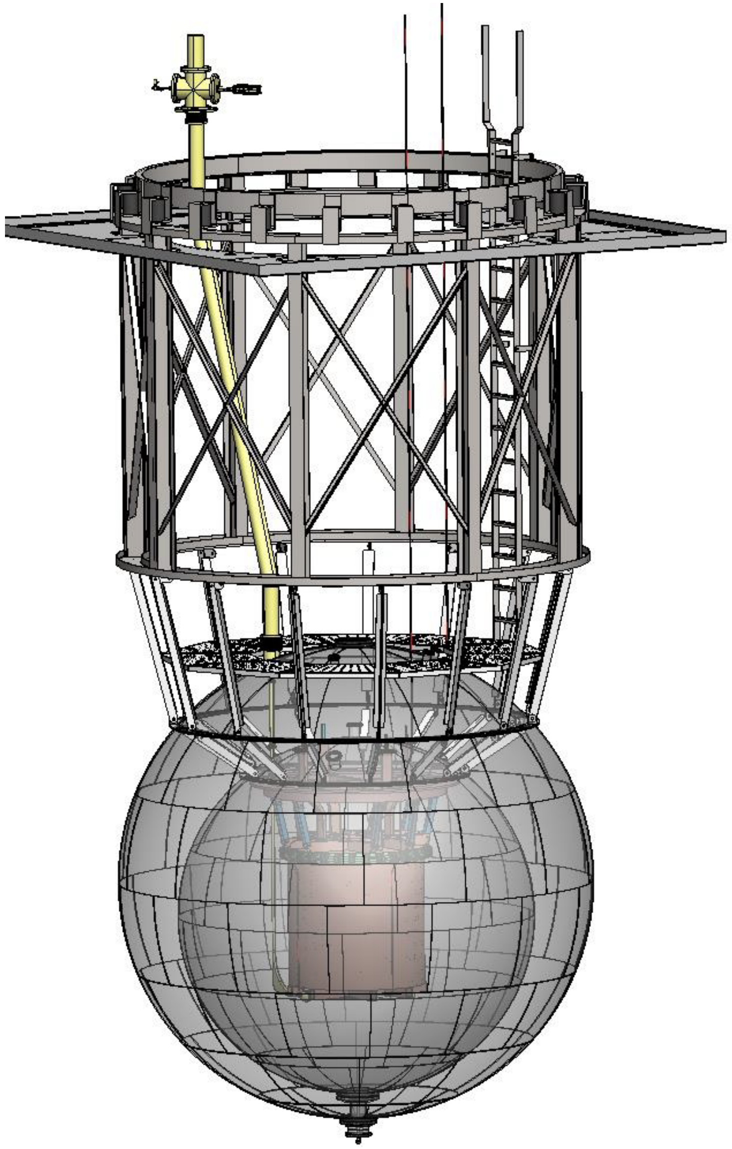
Activities are all measured from materials in hand (but not necessarily in the correct amount)

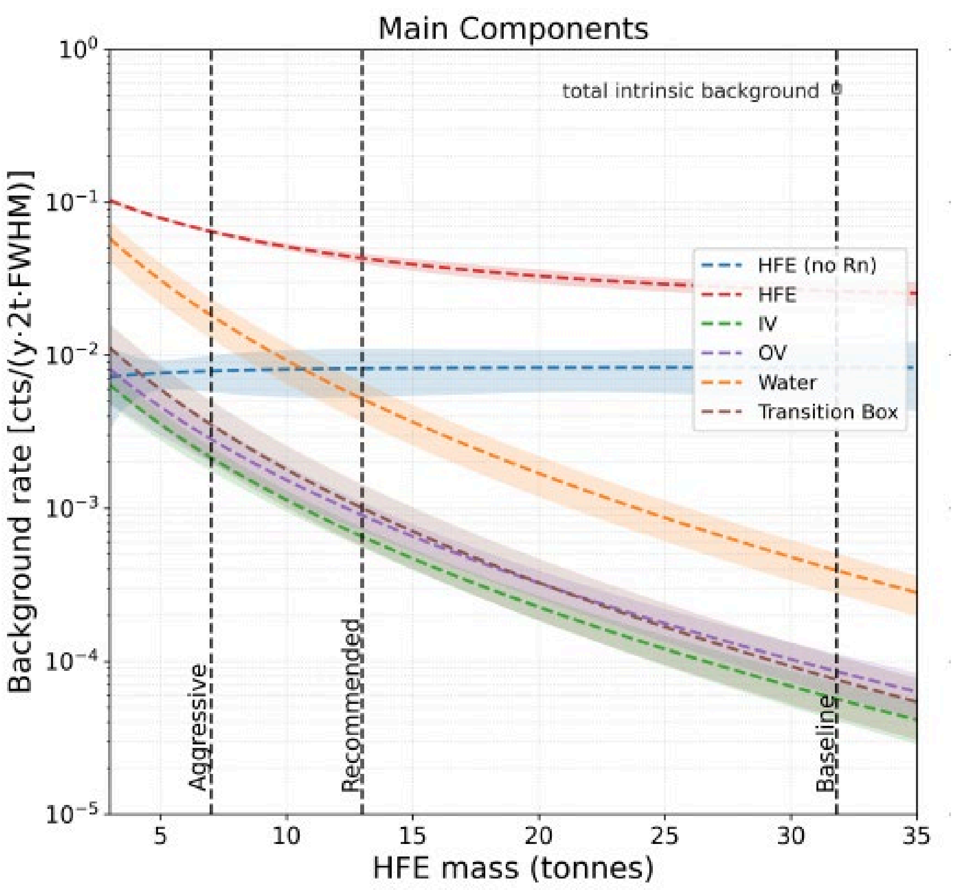
(

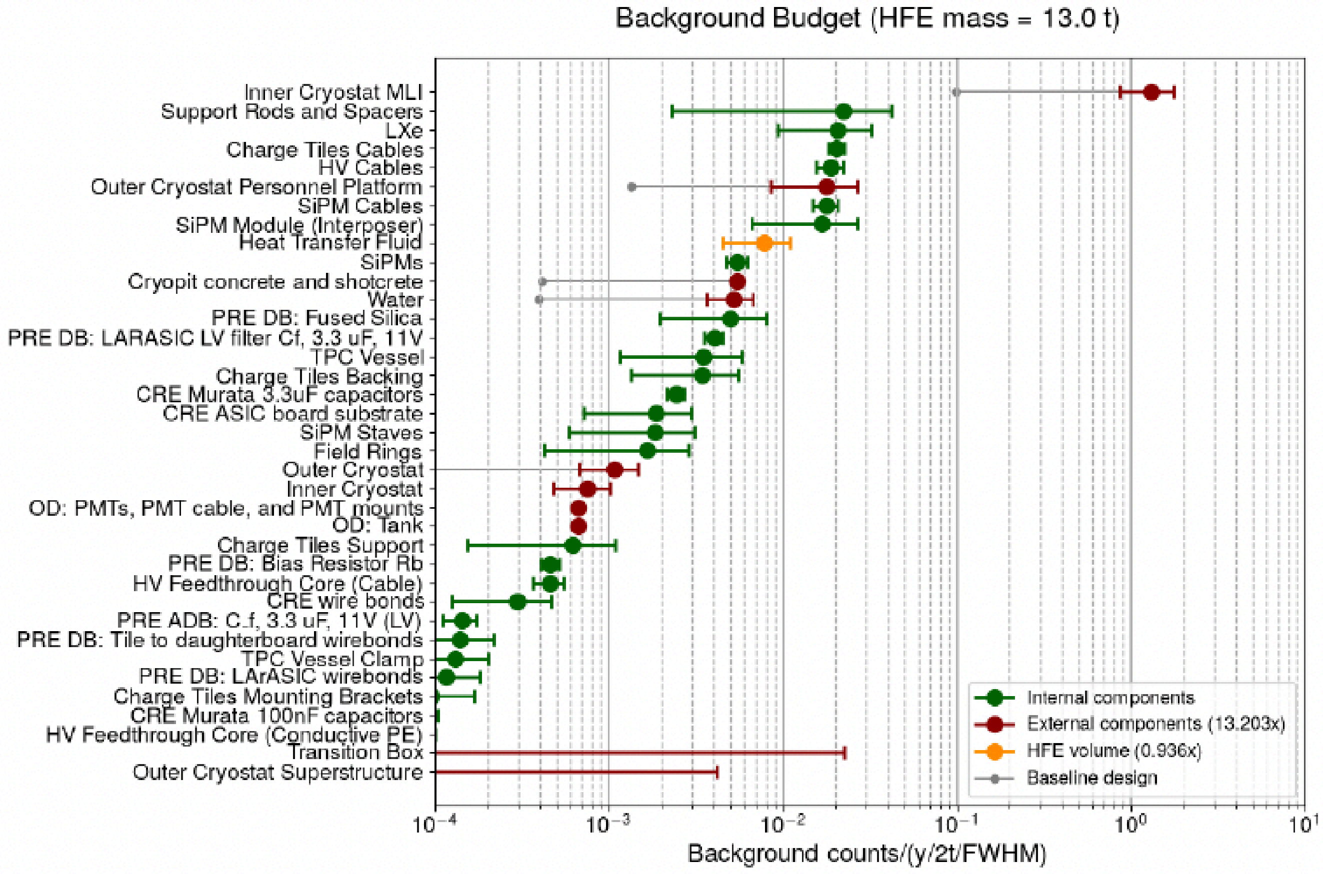
arXiv:2508.08230

A CVD Nickel cryostat and less water?

- The fully studied option for the cryostat material is carbon composite (IV: 3.4m diameter, OV: 4.5m diameter + few layers of superinsulation)
- However, CVD nickel welded in situ has been recently explored as a way to reduce radioactivity and hence the HFE mass.
- CVD nickel displays excellent radiopurity and better mechanical properties than copper.
- 13 tonnes of HFE (instead of 32) appear possible.
- This would also reduce the cryostat diameter maybe by 1m, in addition the current 12.3m diameter water tank is overkill. It is likely that the tank can be shrunk to 10.5 m.




Main Components
total intrinsic background
HFE (no Rn)
HFE
IV
OV
Water
Transition Box
Aggressive
Recommended
Baseline
Background rate [cts/(y·2t·FWHM)]
HFE mass (tonnes)

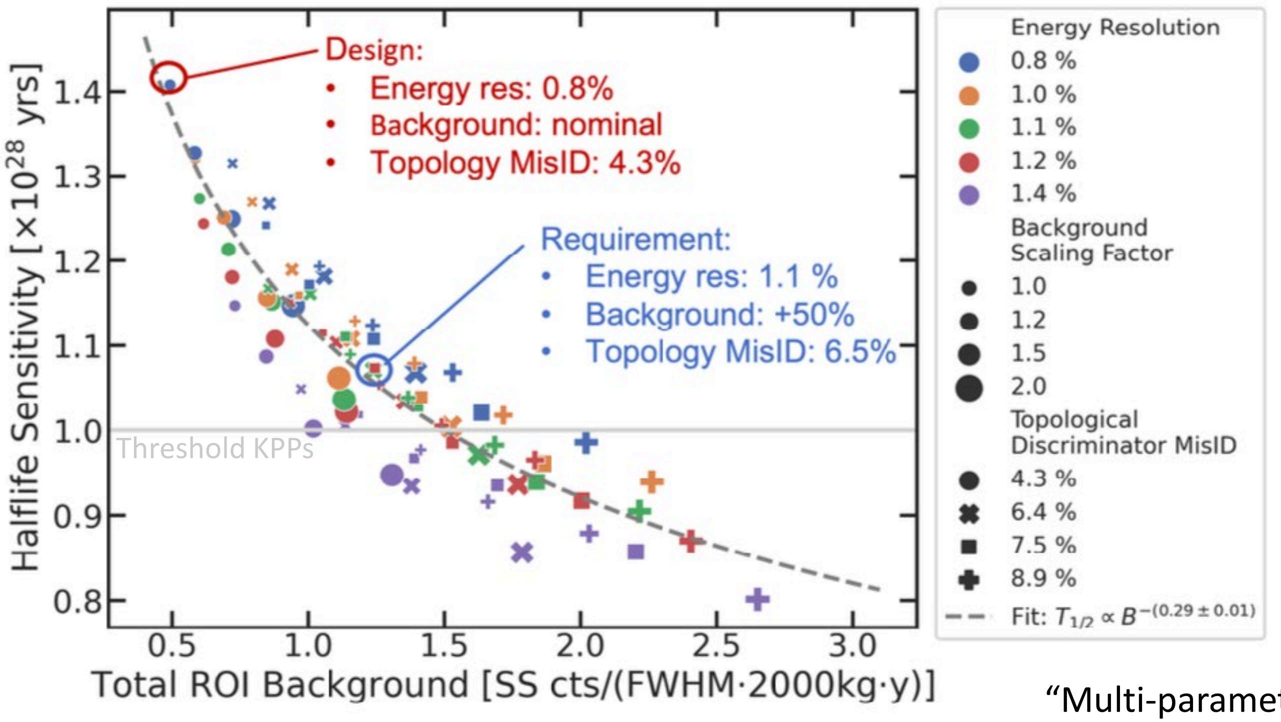

Background Budget (HFE mass = 13.0 t)
Inner Cryostat MLI
Support Rods and Spacers
LXe
Charge Tiles Cables
HV Cables
Outer Cryostat Personnel Platform
SiPM Cables
SiPM Module (Interposer)
Heat Transfer Fluid
SiPMs
Cryopit concrete and shotcrete
Water
PRE DB: Fused Silica
PRE DB: LARASIC LV filter Cf, 3.3 uF, 11V
TPC Vessel
Charge Tiles Backing
CRE Murata 3.3uF capacitors
CRE ASIC board substrate
SiPM Staves
Field Rings
Outer Cryostat
Inner Cryostat
OD: PMTs, PMT cable, and PMT mounts
OD: Tank
Charge Tiles Support
PRE DB: Bias Resistor Rb
HV Feedthrough Core (Cable)
CRE wire bonds
PRE ADB: C.f, 3.3 uF, 11V (LV)
PRE DB: Tile to daughterboard wirebonds
TPC Vessel Clamp
PRE DB: LArASIC wirebonds
Charge Tiles Mounting Brackets
CRE Murata 100nF capacitors
HV Feedthrough Core (Conductive PE)
Transition Box
Outer Cryostat Superstructure
Internal components
External components (13.203x)
HFE volume (0.936x)
Baseline design
Background counts/(y/2t/FWHM)

)

Variation in detector parameters

- Sensitivity variation with major detector parameters (energy resolution, background, topological discrimination) studied
- Detailed allocations have been further developed to flow major detector parameters to technical requirements for all sub-systems

Simulated sensitivity vs detector parameters:



Design and requirement values for major parameters:

		Design	Requirement
^{136}Xe $T^{0\nu}_{1/2}$ 90% CL Sens	[10^{28}y]	1.41	1.06
Energy Resolution	$\sigma E/E$ [%]	0.8	1.1
Background Mis ID	[%]	4.3	6.4
Background Scaling Factor		1.0	1.5
Total ROI Background	SS cts/(FWHM·2000kg·y)	0.493	1.240
ROI bkg from materials	(^{238}U, ^{232}Th, ^{222}Rn, ^{42}Ar)	0.469 [95.3%]	1.176 [94.8%]
Irreducible ROI bkg	(solar ν, $2\nu\beta\beta$)	0.016 [3.2%]	0.044 [3.6%]
Underground cosmogenic ROI bkg	(^{137}Xe)	0.008 [1.6%]	0.020 [1.6%]
Cryopit rock/concrete ROI bkg		negligible	

"Multi-parametric Sensitivity Study and Sensitivity-derived Requirements" (NEXO-12211 Rev A)

Validation from EXO-200

- The sensitivity estimation procedure followed for nEXO builds on the success of EXO-200
- Radioassays of all EXO-200 materials coupled with detailed simulation accurately predicted backgrounds ultimately observed
- nEXO sensitivity estimates build on this track record with significant improvements:
  - More comprehensive radioassay program and allocations
  - Improved radioassay sensitivity
  - Improved simulation tools (Geant 4, Chroma, etc)
  - Collaboration expertise gained from operation of EXO-200

Predicted and observed EXO-200 backgrounds:

Part/material	Expected counts/yr in $0\nu\beta\beta$ ROI	
	^{232}Th	^{238}U
APDs	<0.6	<0.05
Bronze cathode	$(6-10)\times10^{-5}$	$(6-8)\times10^{-3}$
Bronze wires	0.04–0.07	0.07–0.08
Other Bronze	0.08–0.13	0.25–0.3
Flat cables (in TPC)	<0.44	1.5–2.3
Flat cables (in TPC legs)	<0.04	0.1–0.14
Teflon reflectors, HV insulators	0.06–0.1	<0.07
Teflon behind APDs	0.2–0.3	<0.08
Acrylic spacers, insulators	<0.3	<0.6
Field cage resistors	<0.01	<0.01
Cu TPC vessel	<3	<3.8
Cu TPC legs	<0.07	<0.05
HV cable	<0.13	<0.6
Cu calibration tube + support	0.1–0.2	0.15–0.35
Cu cryostat	<1.3	<0.5
HFE-7000	<0.1	<0.1
Pb shielding	<0.9	<0.5
Total predicted rates (sum):	0.5–7.7	2–9.5
Total predicted rates from Ref. [5]:	0.9–10.3	6.3–26.8
Observed rates from Ref. [3]:	10.3–13.9	5.3–7.1

Phys. Rev. C 92, 015503 (2015)

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 $0\nu\beta\beta$ 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.

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

nEXO Pre-Conceptual Design Report

nEXO

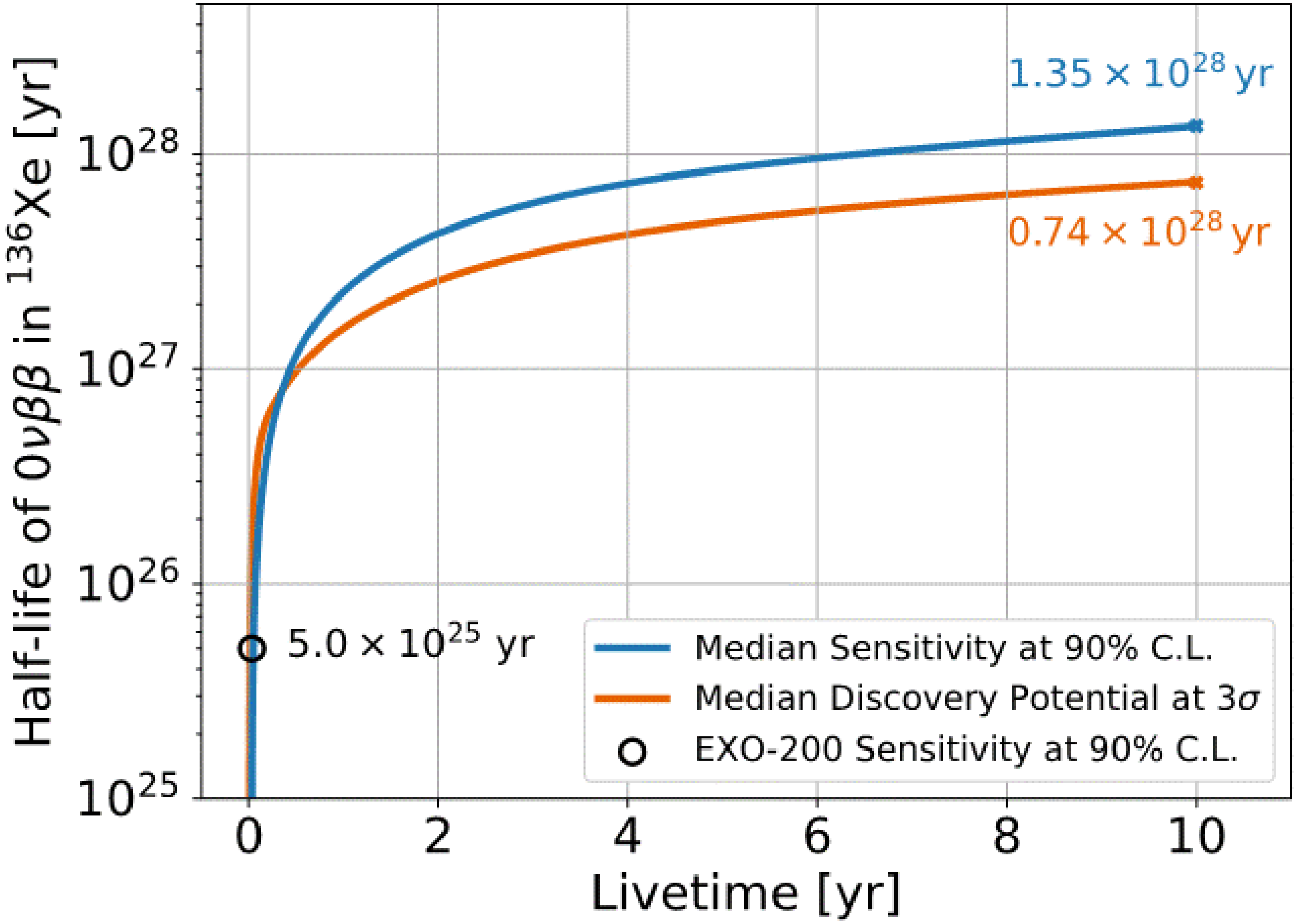
Abstract

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 $\sim$ 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 designed to reach a half-life sensitivity beyond 10^{28} years
~2 orders of magnitude the current state of the art



The new physics reach can be parameterized in the effective Majorana mass.

This is also useful to compare different experiments.

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

Phase space factor

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

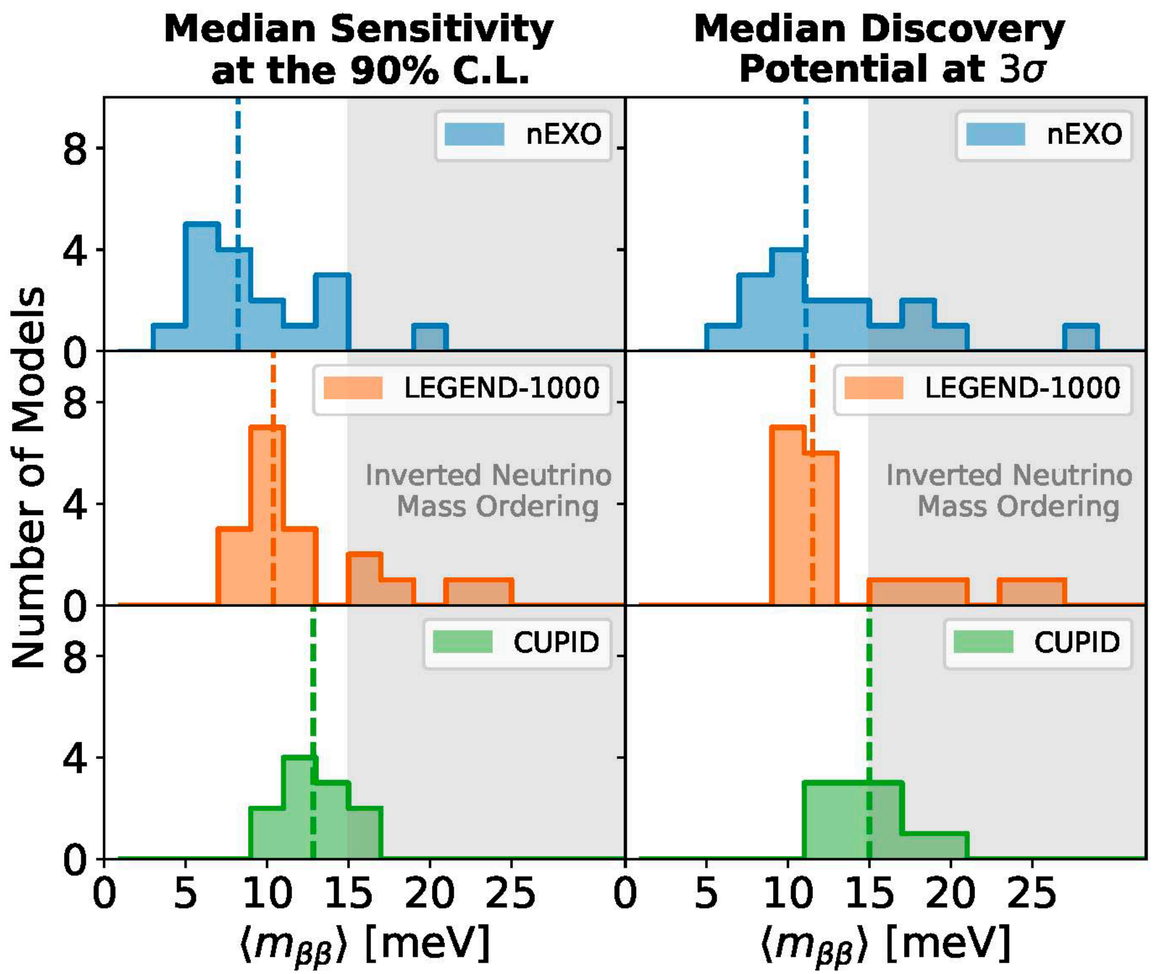
Axial coupling, $g_A = 1.27$

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**

nEXO is very competitive in its physics reach



Deeper physics reach

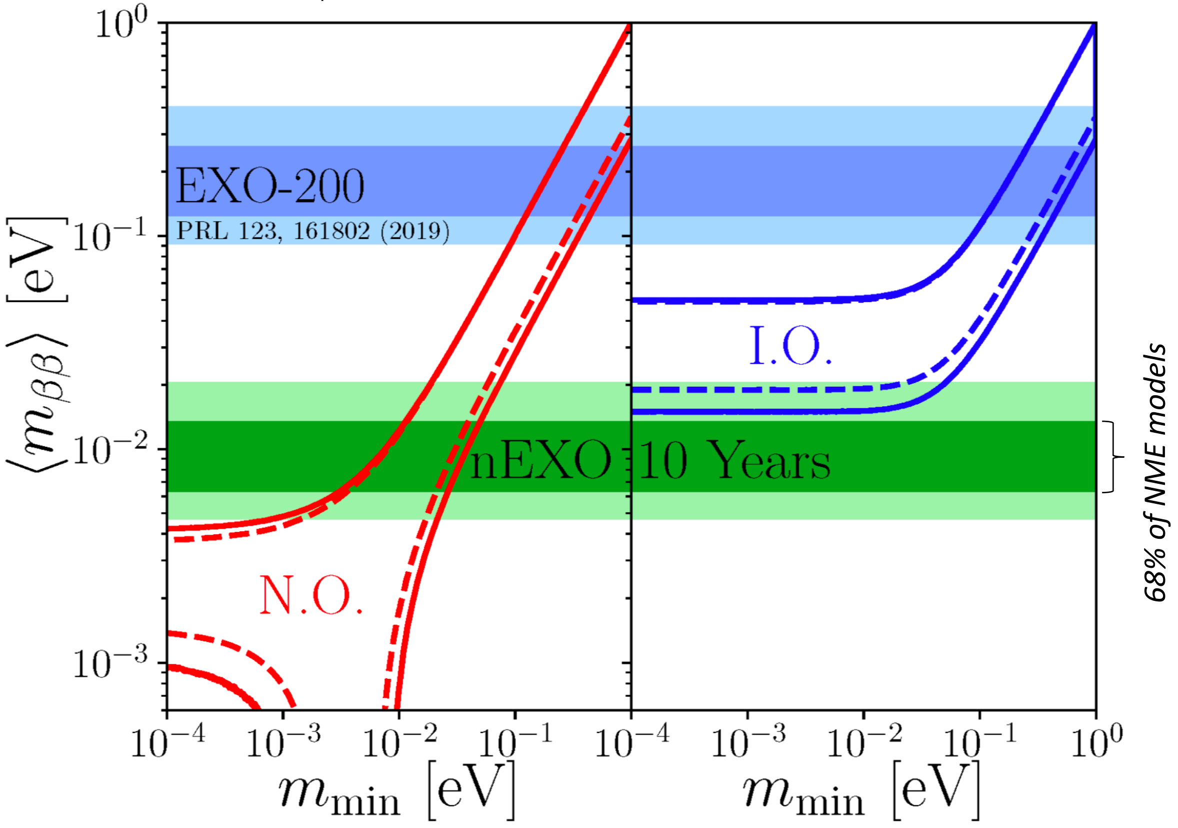
	$m_{\beta\beta}$ [meV], (*median NME*)	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

$T_{1/2}$ 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):

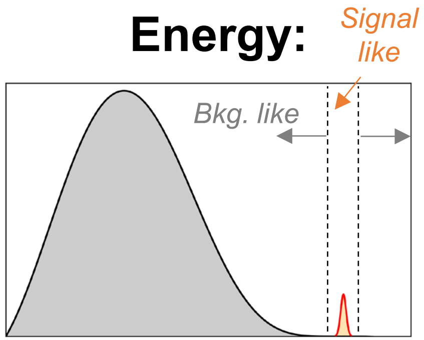


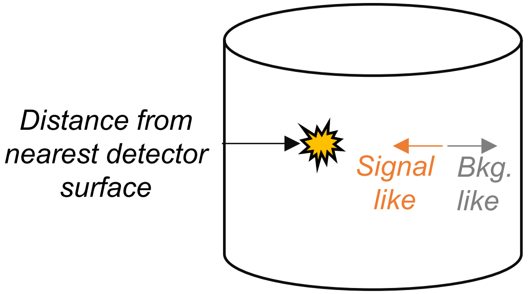
nEXO 3σ discovery sensitivity for the median NME model considered is 11.1 meV, reaching beyond IO further into NO

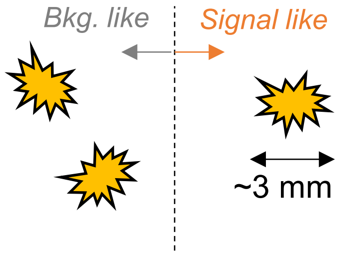
Conclusions:

- **nEXO extends the reach into new physics by ~2 orders of magnitude, with substantial chance to make a discovery.**
- **Nominally, 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, as I now show…**

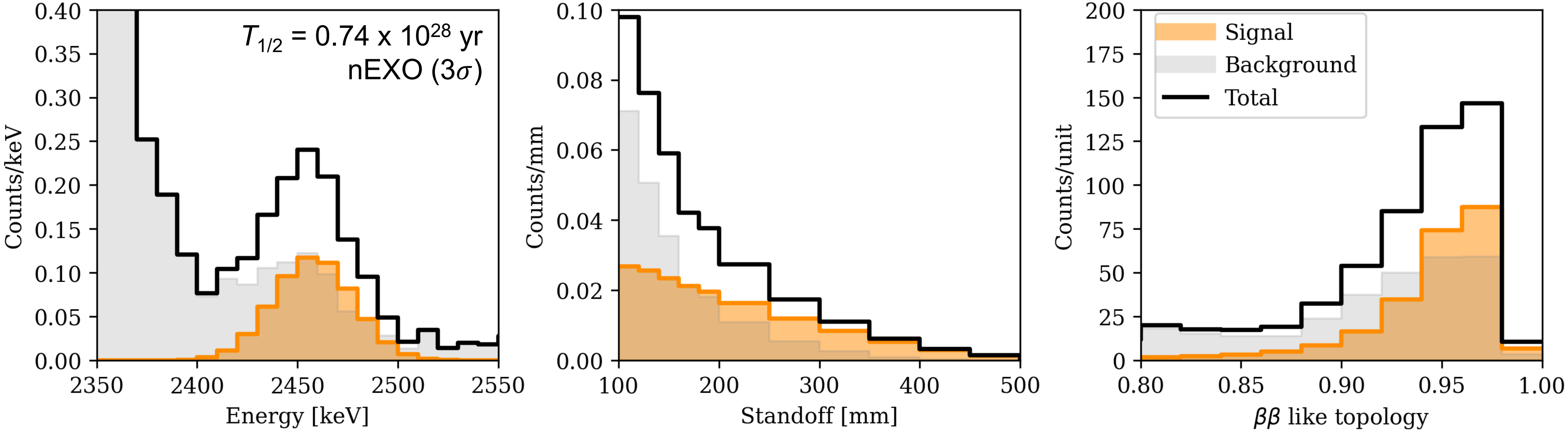
Signal-background separation in nEXO



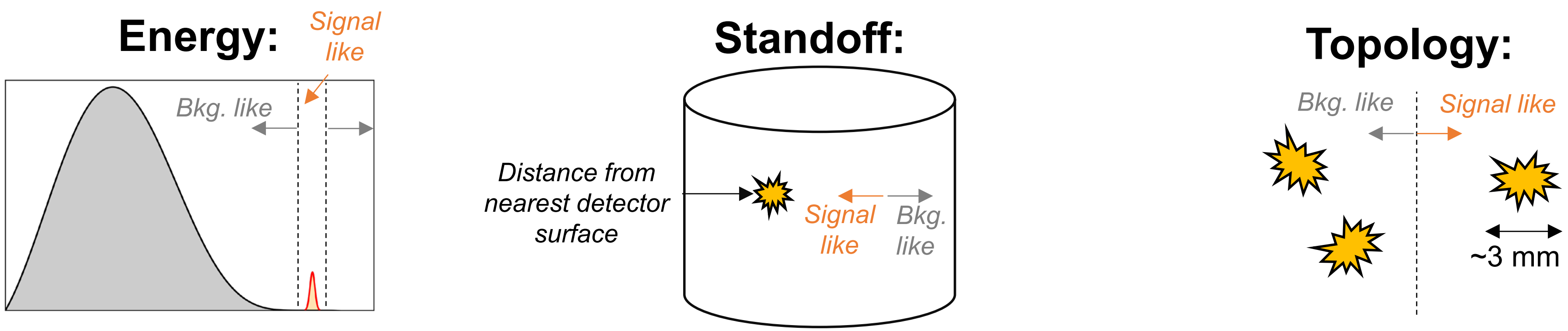




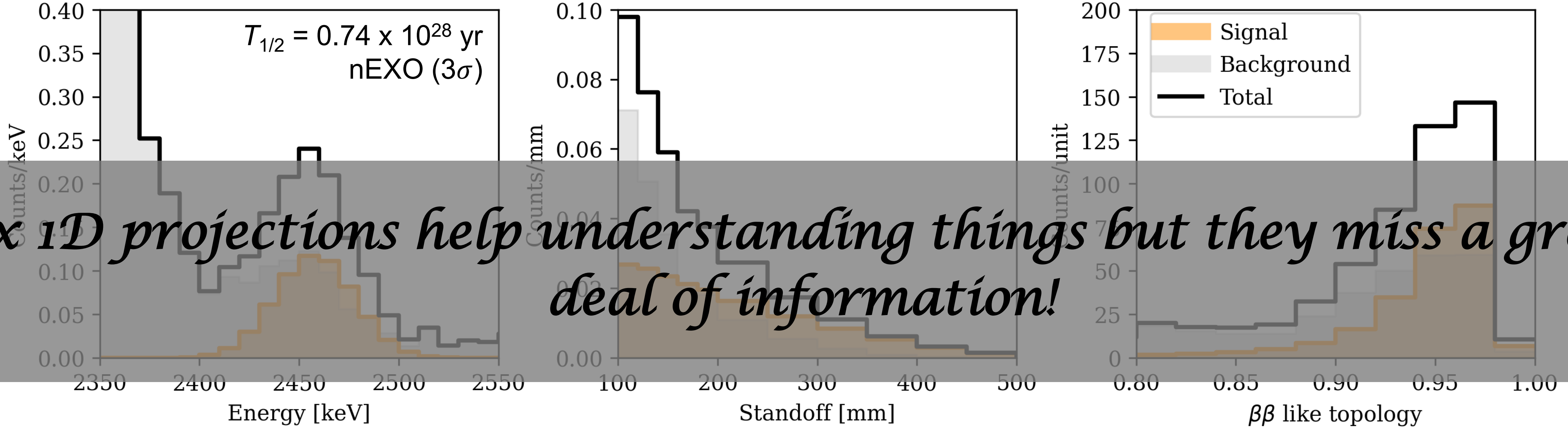
1D projections of simulated signal and backgrounds



Signal-background separation in nEXO



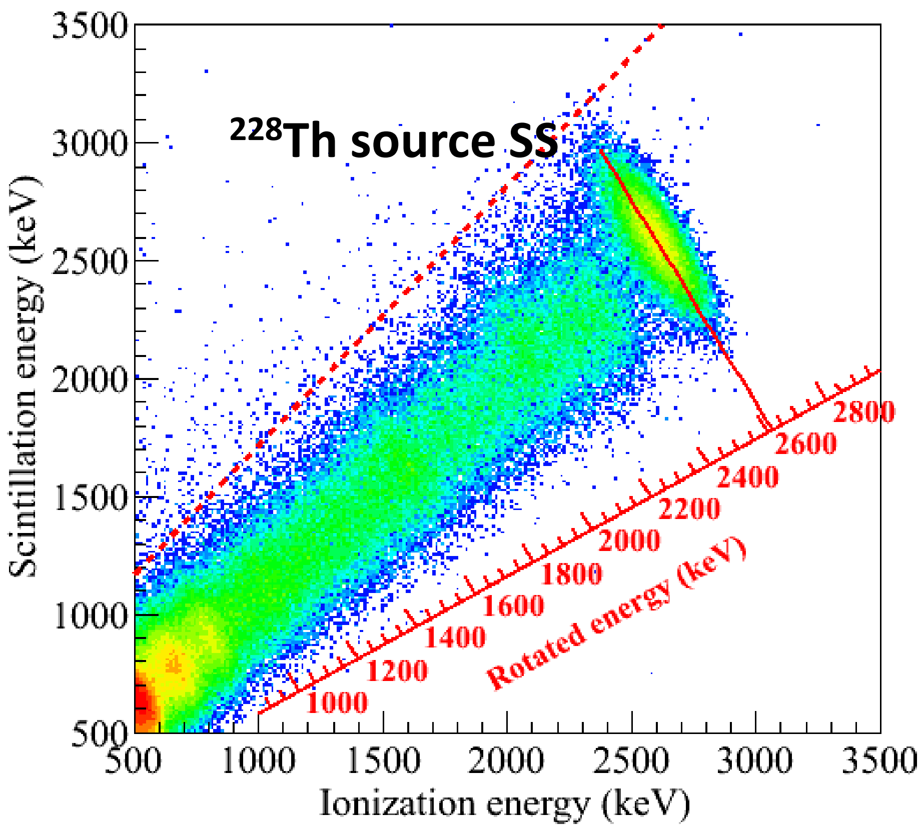
1D projections of simulated signal and backgrounds



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

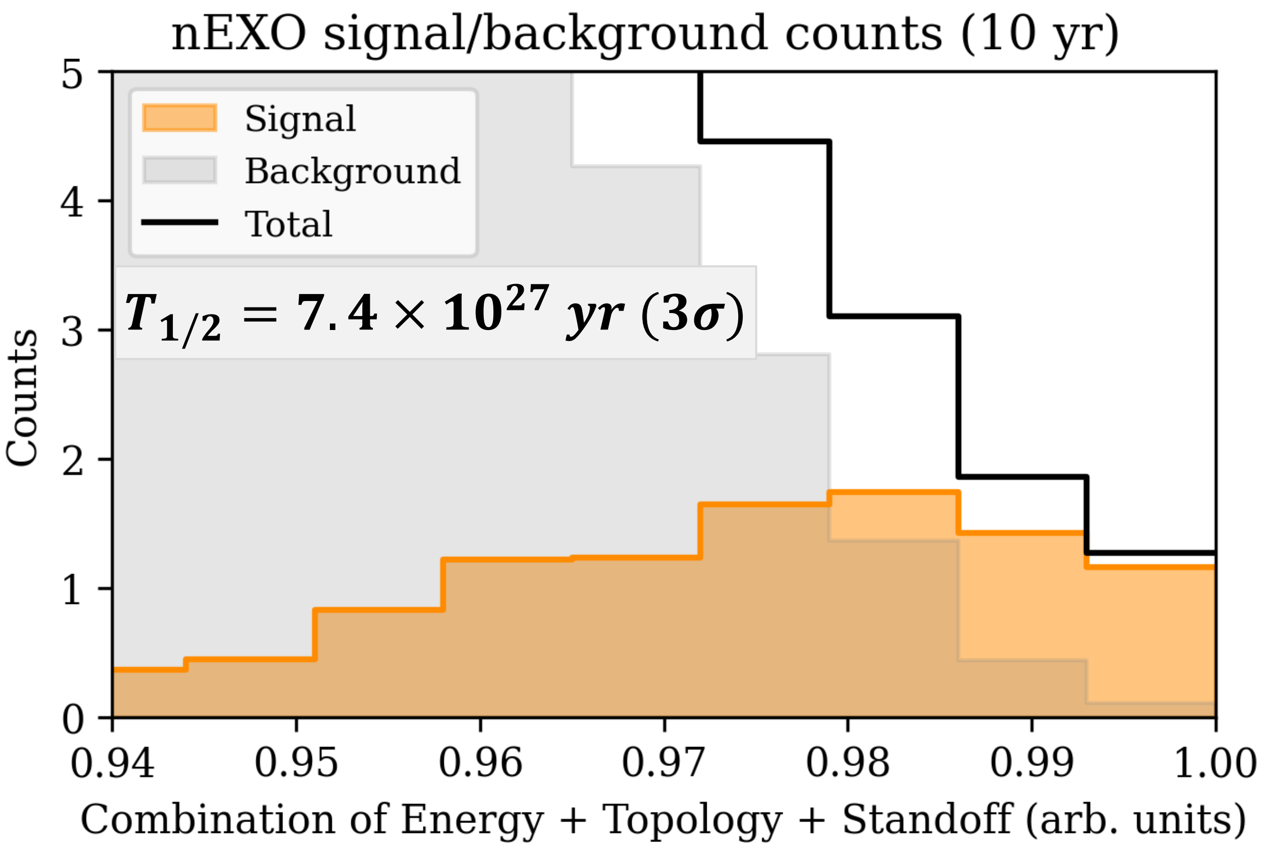
This is obvious in the simpler case of 2D:

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



- **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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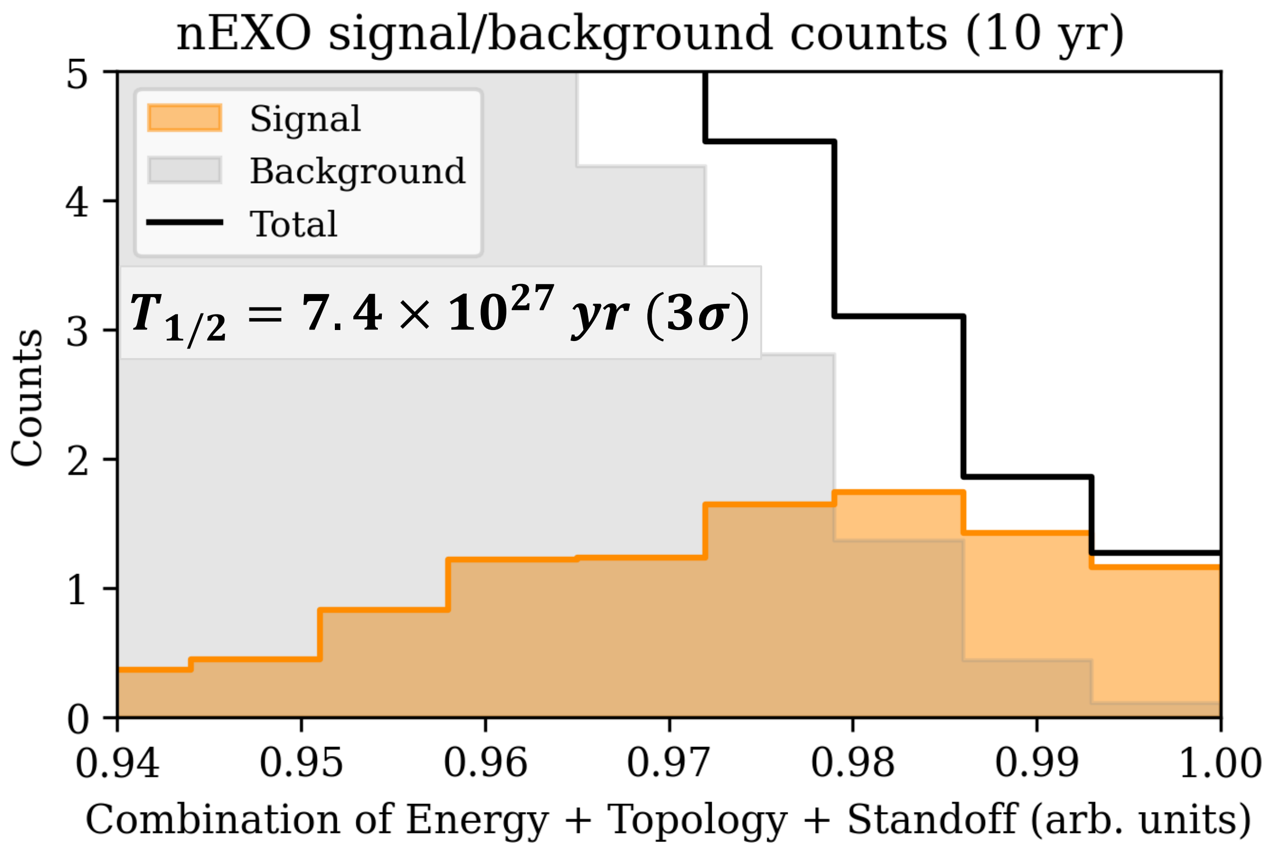


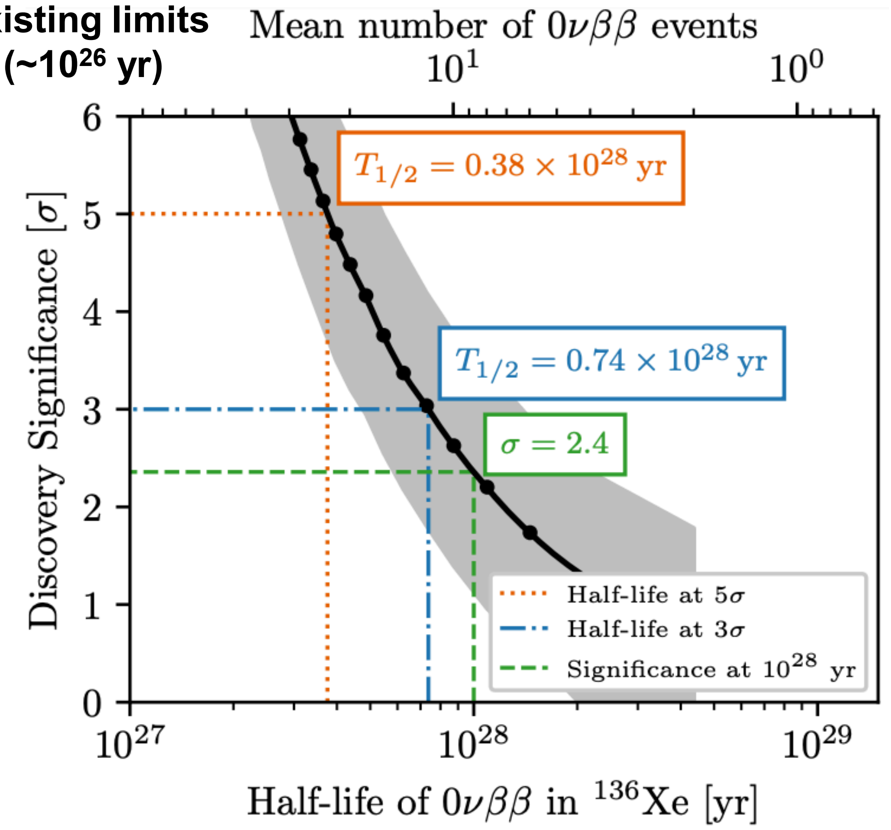
0 ← Background-like ***Signal-like → 1***

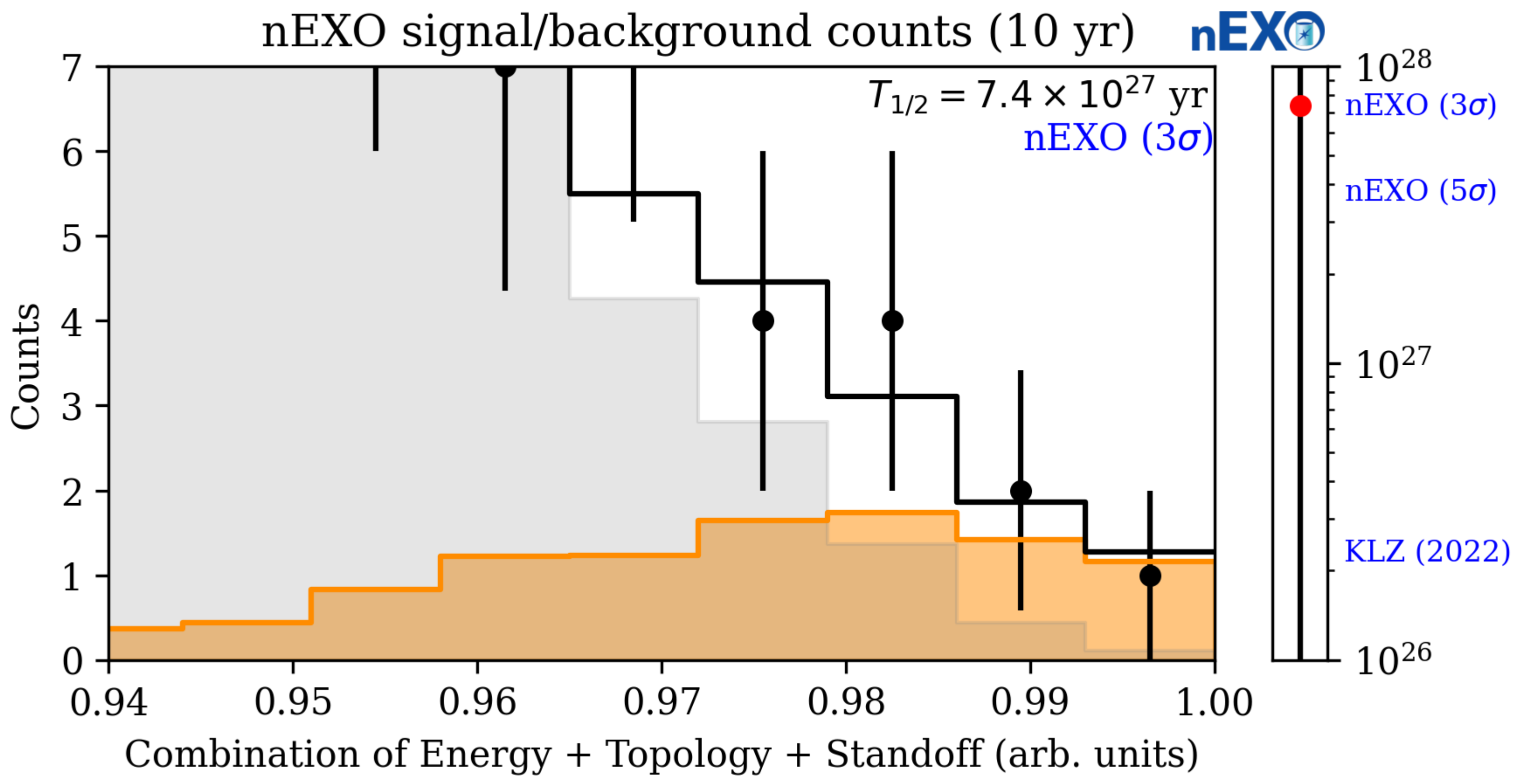
➔ nEXO is a “background-free” experiment

But Nature does not need to be so unkind
Slightly faster half-lives provide stunning signals!

nEXO Discovery Potential vs. Half-Life:

Existing limits (~10^{26} yr)





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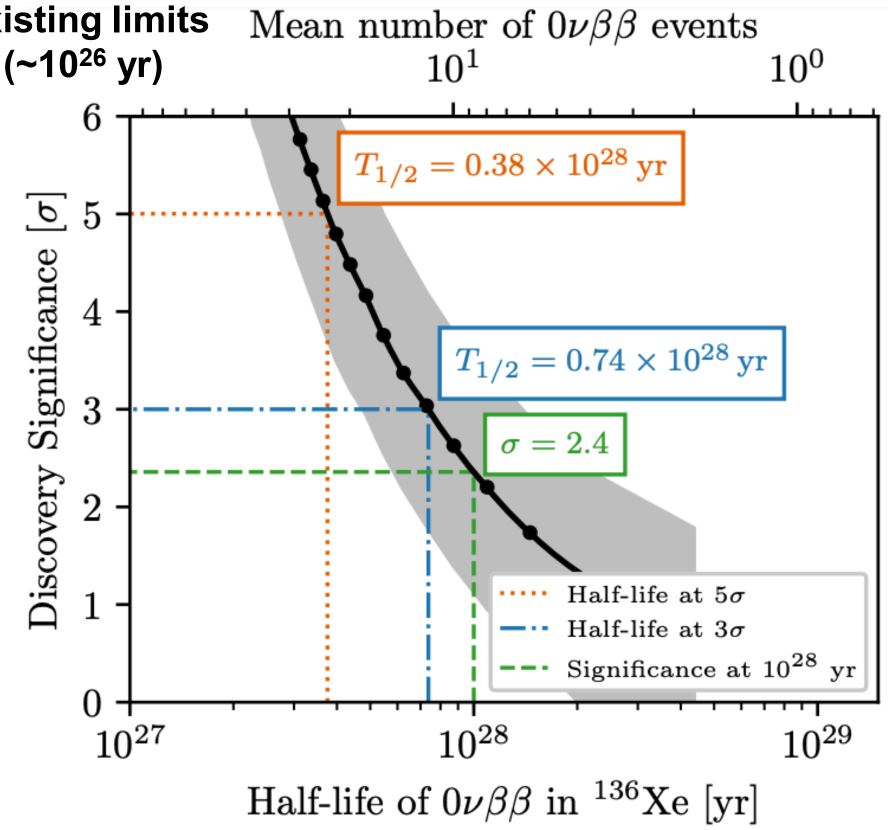
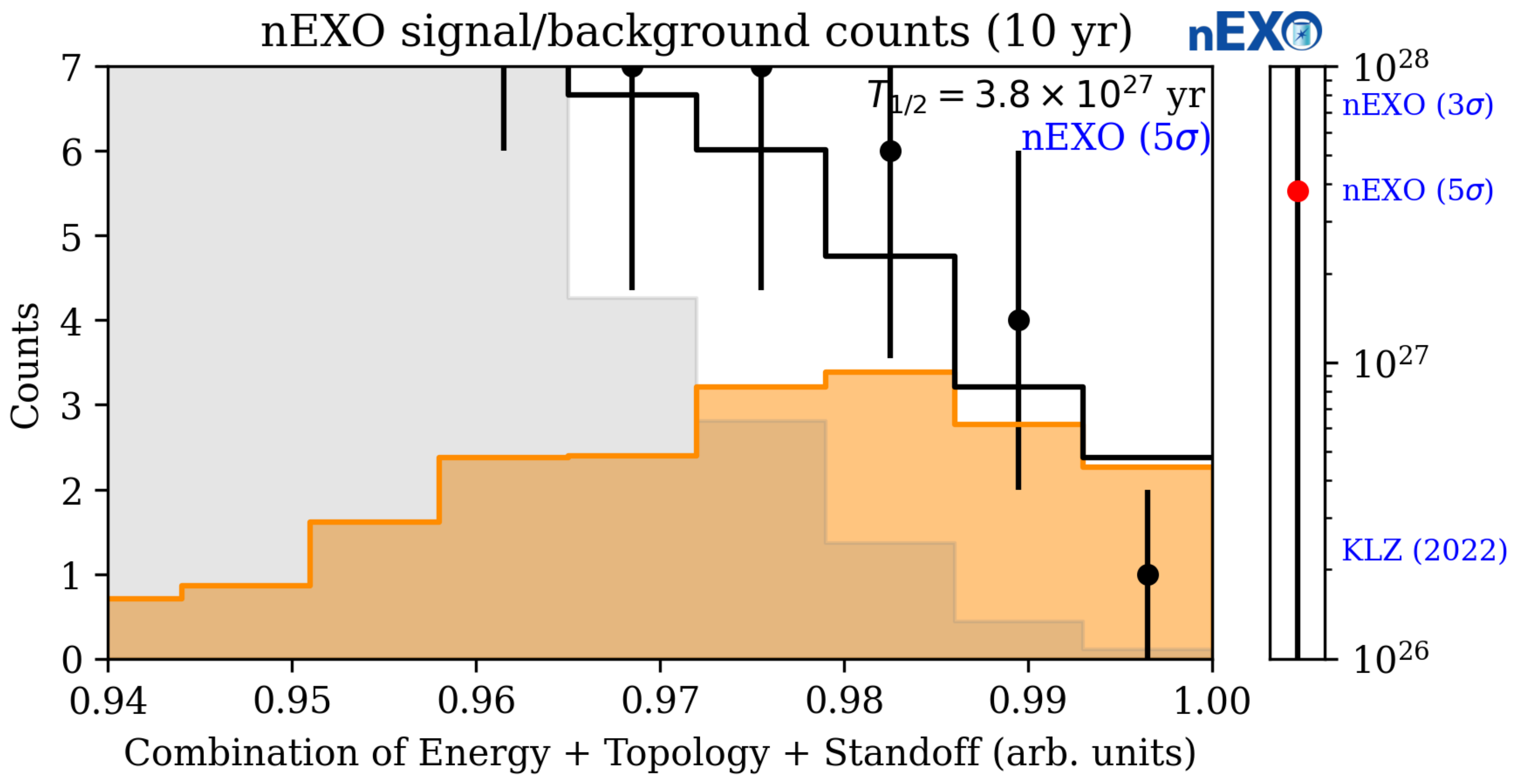




0 ← Background-like *Signal-like → 1*

Some comments on Xenon

Stable isotopes of xenon

isotope	Concentration in natural material (%)
124	0.10
126	0.09
128	1.91
129	26.4
130	4.1
131	21.2
132	26.9
134	10.4
136	8.9

A large effort, but not unprecedented and there is specific experience in the collaboration and in the field.

- **The standard enrichment method is ultracentrifugation**
- **Pioneering enrichment for ββ decay carried out at ORNL in the '80s:**
  Roberts, NIM A282 (1989) 271 and Szady, NIM A282 (1989) 277
  ~7 kg (~64% in 136) used by Bellotti et al. Phys Lett 266 (1991) 193
  ~5 kg (~64% in 136) used by Wong et al., J. Phys. G 17 (1991) S165

  ➔ Same centrifuge technology to be used by one of the western suppliers identified by nEXO
- **Similar effort in Soviet Union, supplying ~10 kg of 94% enriched Xe for the ITEP experiment Belov et al. Inst. Exp. Tech. 55 (2012) 532 (also nEXO colleagues)**
- **EXO-200 procured 200 kg of enriched Xe (to 80% in 136) some 15 years ago (in Russia)**
- **More recently, KamLAND-ZEN procured ~900 kg of 90% enriched Xe (also in Russia)**
- **Ton scale quantities of Xe have been processed also by at least by one of the western primarily to extract isotopes of medical interest.**

A few notes from EXO-200 experience, informing the nEXO plans

- Purification during filling and while recirculating is very effective, since Xe is a noble element.
- All chemically active species are efficiently removed by purification, but some care is required to remove potential fluorinated molecules introduced by the gas centrifuges (nEXO will have a pre-purification stage for those).
- Once 90% enrichment in isotope 136 is selected, the rest (10%) is isotope 134. All other isotopes are greatly suppressed to trace amounts (unless we want to deliberately add some back!).
- Kr and Ar are overwhelmingly suppressed to a level that make their radioactive isotopes not a concern (essentially, this comes for free).
- Re-stocking of “tails” was possible for EXO-200.

Enrichment: final comments

- Enrichment process latency is a month or less, so the amount of Xe in the process is ~1 tonne at any given time, producing ~100 kg/month of enriched material

- Most enrichment companies need time and capital up front to build up or configure cascades

- Of course, details depend on contracts, how many producers and the schedule for the feed stock.

The amount of Xe feed stock is large, but not unprecedented for science experiments

- Plenty of Xe in the atmosphere! (~2×10^{12} kg, volume concentration of 8.7 ppb)
- DM experiments have sourced 10s of Tonnes of natural Xenon in the last several years.
- The enrichment of 100 kg of the 200 kg of EXO-200 Xenon was fed natural Xe "on loan" from a gas company. The depleted fraction was returned for a credit (~80% of the original value).
- A similar arrangement was obtained by KamLAND-ZEN (900 kg enriched).
- With the return of the depleted Xe, the transaction is quite a bit smaller that the ones already completed by the Dark Matter experiments, as, in total, only ~5 Tonnes will be removed from the market (<1.5% of the world production).
- With the enrichment schedule discussed, only 1 tonne of natural Xe would be out of the market at any given time.

Natural Xenon Suppliers

- **A few major (independent) feed stock suppliers source from a larger number of locations world wide:**
  - **The xenon production is distributed because the source is air liquefaction plants located all over the world, and the large feed stock suppliers consolidate from a number of plants.**
  - **The exact locations are proprietary, but we know the total production of xenon is 50-100 tonnes/yr.**
  - **Competition keeps the costs down and we may source from both, as well as from smaller suppliers.**
  - **In the last few years, China has become a major player.**

Synthetic Xenon

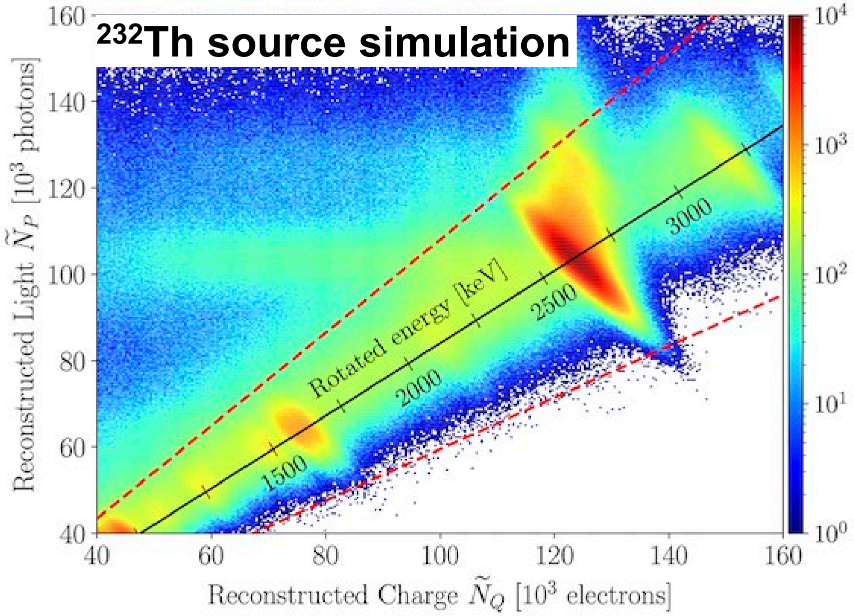
- **Nuclear fission results in Xenon, with 40% concentration in the isotope 136.**
- **The xenon is sealed in fuel elements.**
- **In the US, spent fuel is stored as is, indefinitely.**
- **France reprocesses spent fuel and is estimated to produce ~5 tonnes/yr of ^{136}Xe.**
- **The possibility of obtaining such xenon was carefully investigated with the French nuclear industry.**
- **Unfortunately, regulatory and economic considerations make this option unavailable at the present time.**

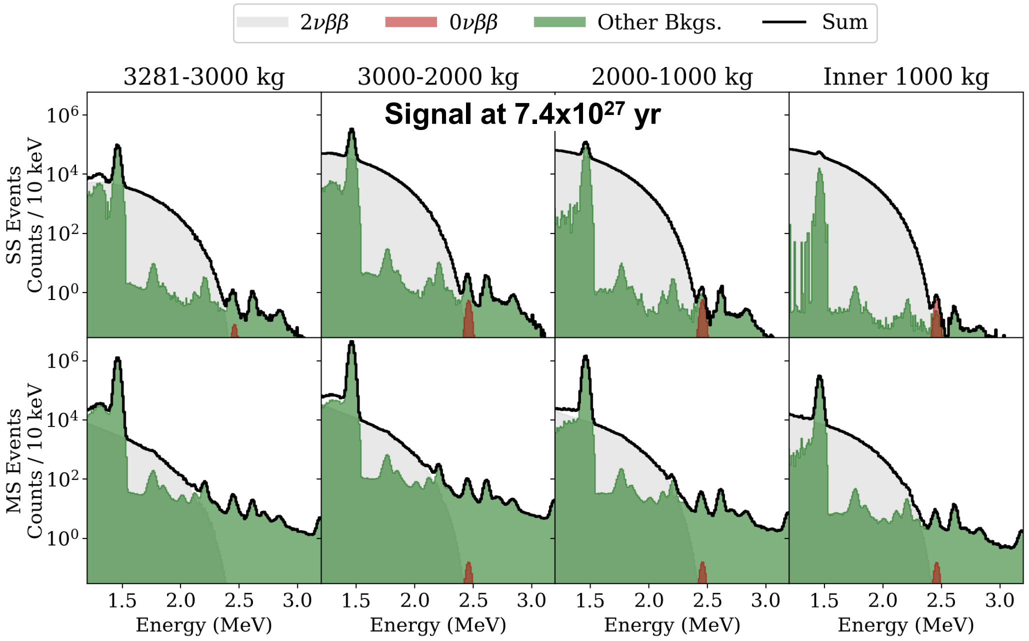
nEXO is the best option for a very large detector

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 identification and rejection.

   Multi-parameter analysis also makes the measurement robust also with currently unknown backgrounds.





2. The energy resolution, still important, is quite good, 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 entirely removes α backgrounds.

nEXO is the best option for a very large detector:
Using xenon results in reliability and cost effectiveness

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

5. 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.

6. 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 already available.

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

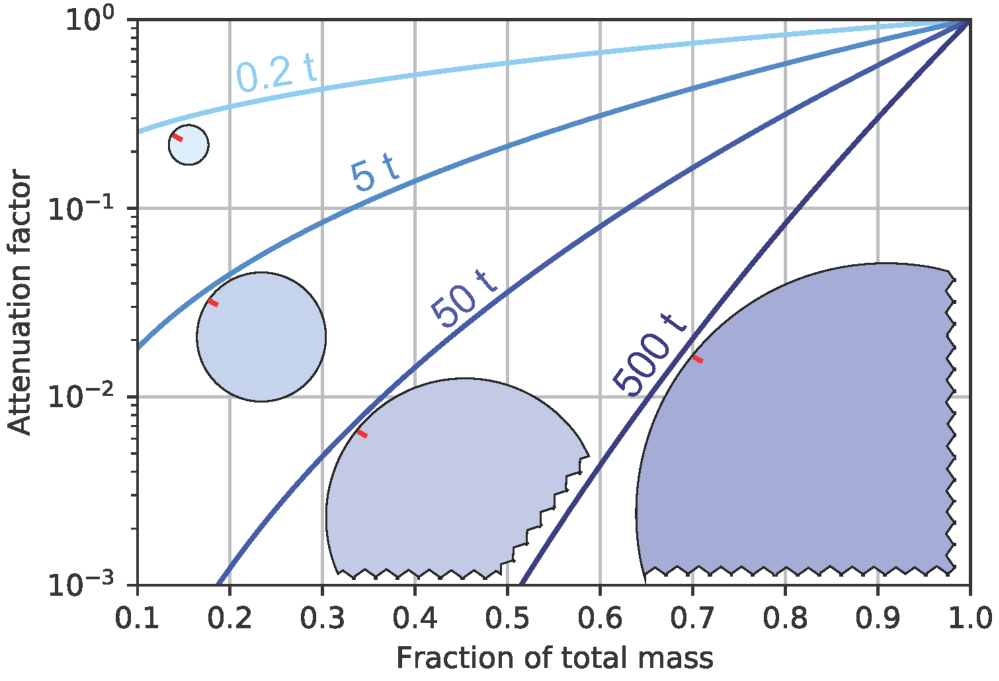
nEXO is the best option for a very large detector
beyond nEXO

7. If nEXO discovers 0νββ decay:

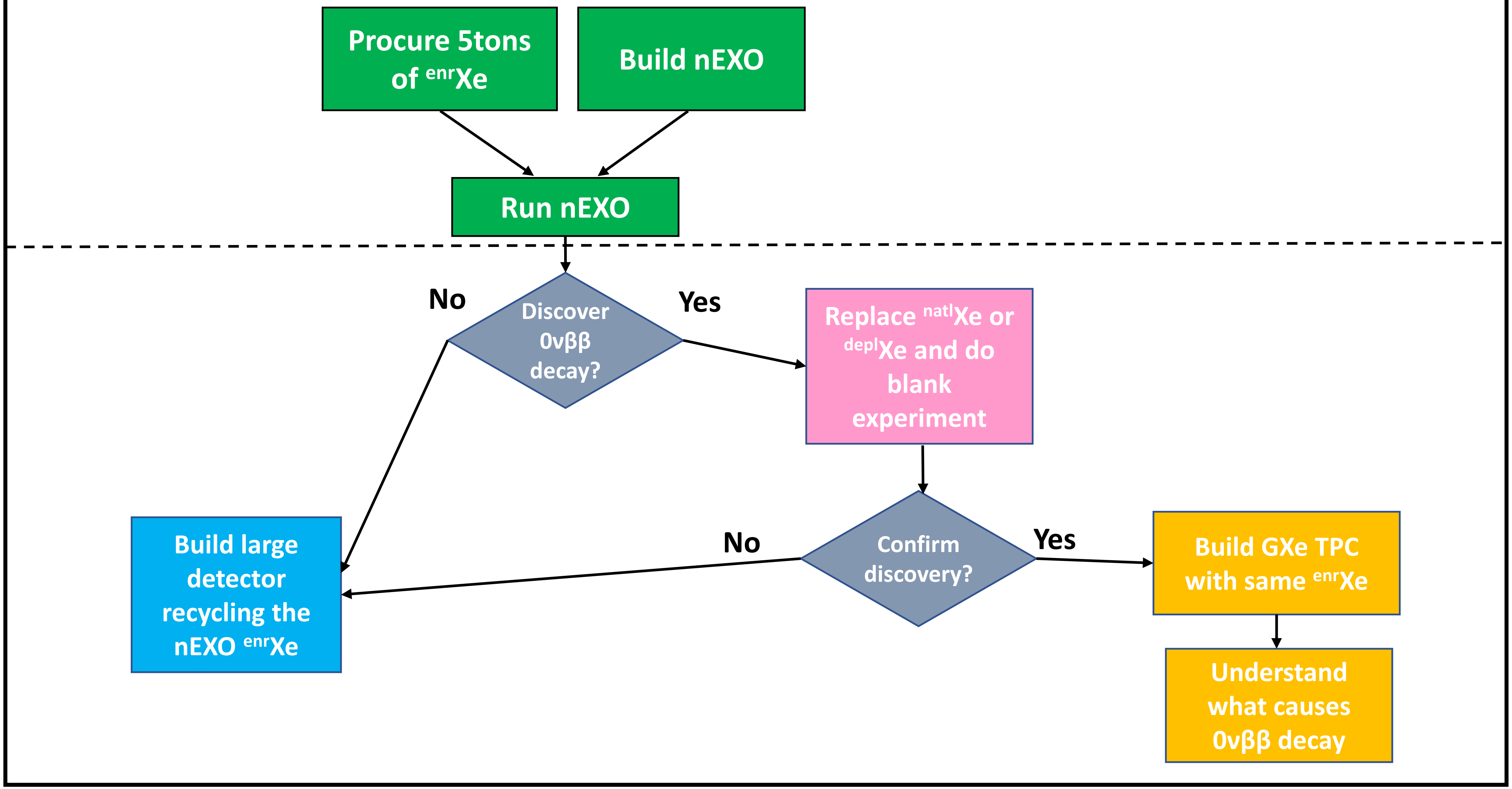
The enriched xenon is NOT "frozen" in a particular detector. Should 0νββ decay be discovered by nEXO, the xenon could be re-used in a different experimental configuration to investigate the underlying physics. ***This is particularly important at the tonne scale, given the cost of the material.***

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. ***A clear avenue for the future is essential.***



nEXO and beyond nEXO: a wealth of possibilities



Summary

- Neutrinoless double beta decay is discovery science and tonne-scale experiments are consistently rated as the highest priority for nuclear and particle physics.
- A full, well optimized detector design already exists.
- nEXO can also be the steppingstone for a larger detector with the same technology…
- …or a different detector to further explore the physics, in case of a discovery.
- Unfortunately, DOE ran out of money, so in the US we are stuck.
- This could be a great opportunity for Korea, CUP, and YEMILAB