CPAD INSTRUMENTATION FRONTIER WORKSHOP 2019

University of Wisconsin-Madison

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Neutrinoless double beta decay with nEXO

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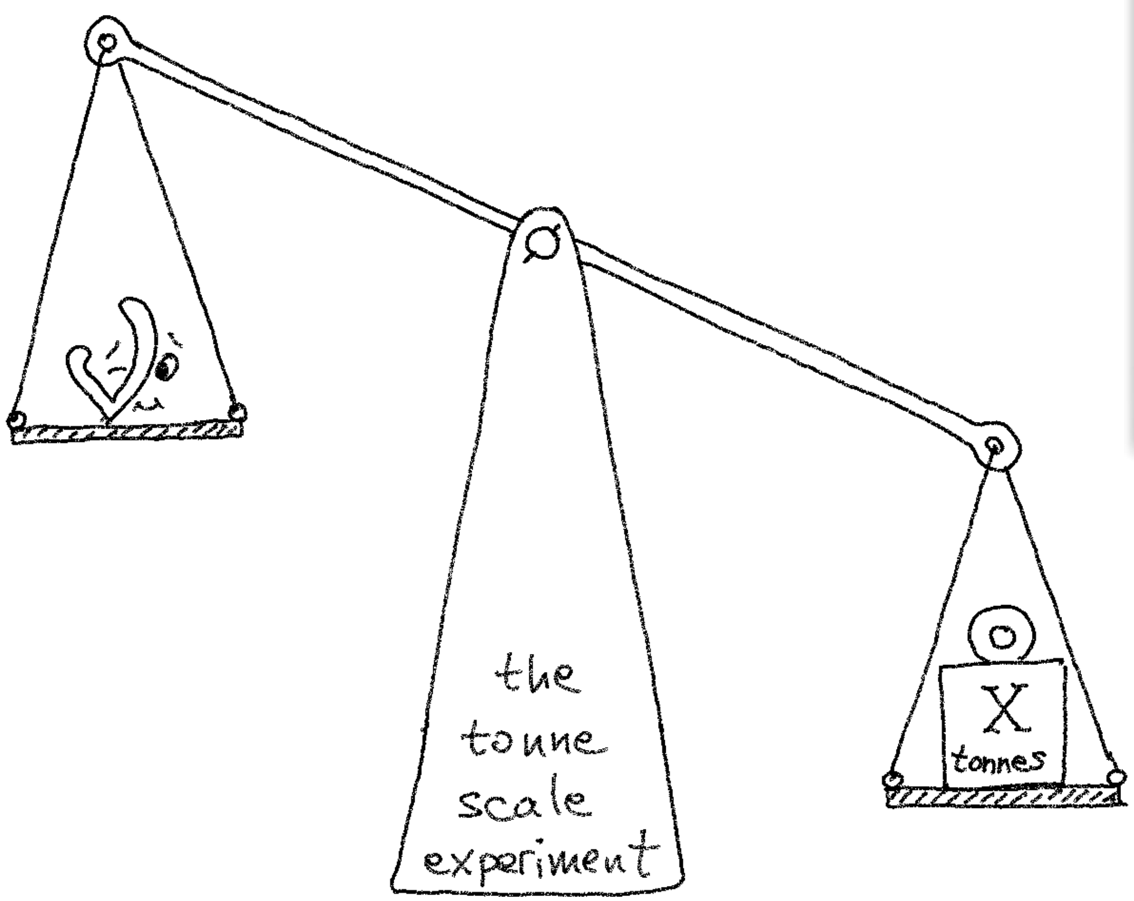
(on behalf of the nEXO Collaboration)

UMass Amherst

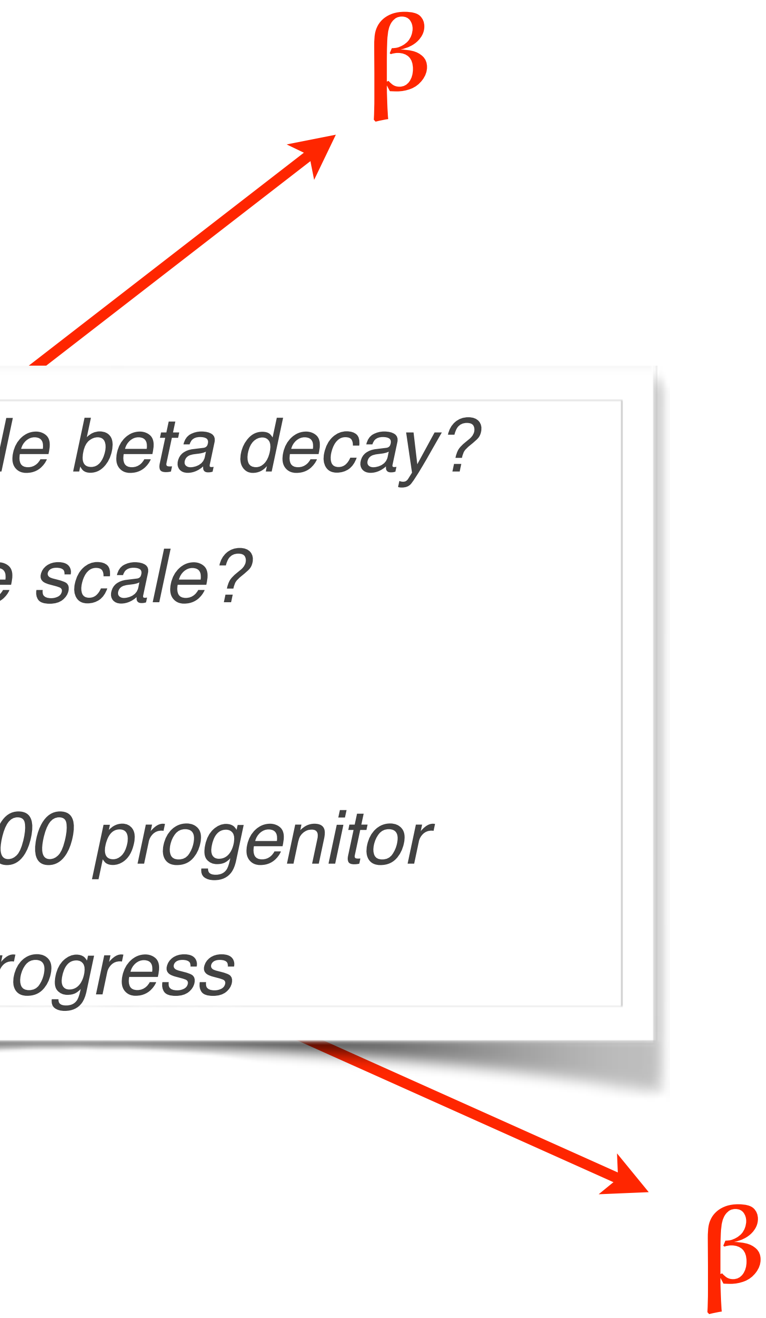
NSF

Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

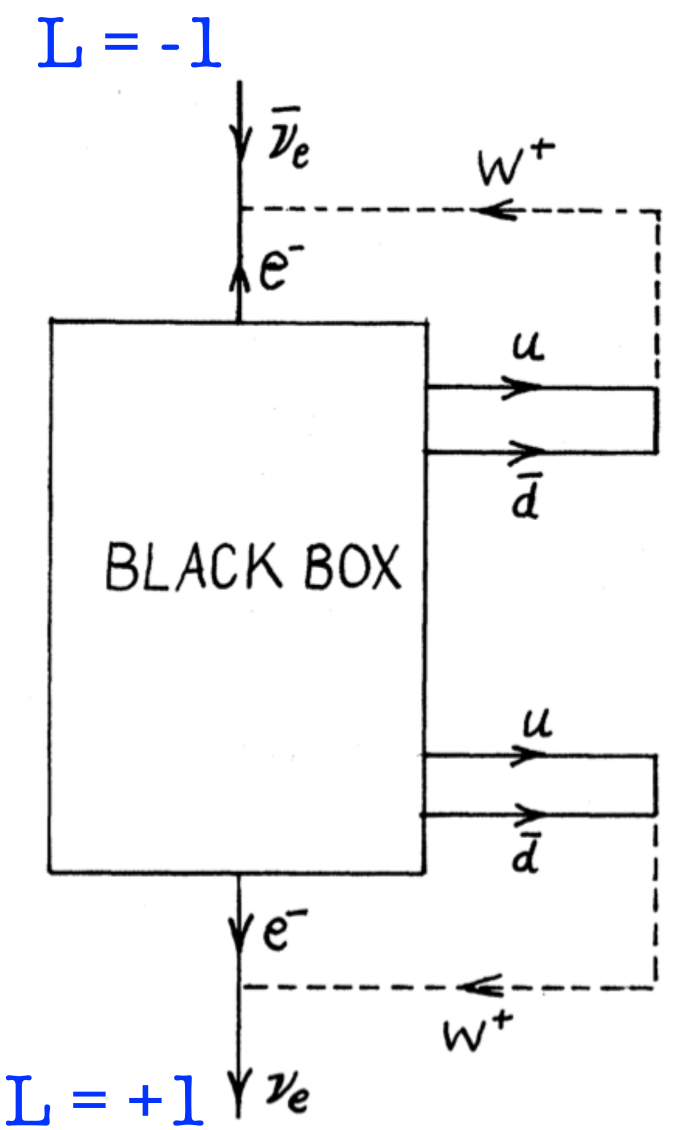
Playbill



- *Why double beta decay?*
- *Why tonne scale?*
- *nEXO*
    - *EXO-200 progenitor*
    - *R&D progress*



0νββ decay = new physics



[Schechter and Valle, 1982]

observation of 0νββ decay

- massive, Majorana neutrinos
- **lepton number violation (ΔL = 2)**
- new mass creation mechanism
- new mass scale

0νββ rate

- absolute neutrino mass (model dependent)

possible probe for understanding the matter dominance in the universe through leptogenesis (via Δ(B-L))

0νββ decay rate

$$\Gamma^{0\nu} = G(Q,Z)\left|M(A,Z)\eta\right|^2$$

transition probability

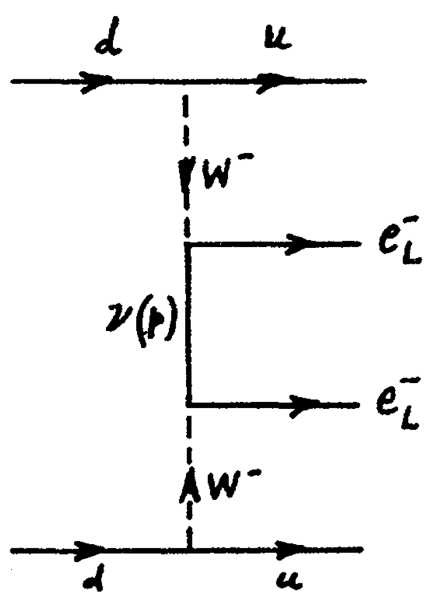
$$\alpha \frac{m}{Q^2} \quad (Q \sim m_e)$$

phase space factor:

$$G \sim G_F^4 g_A^4 m_e^5$$

nuclear matrix element

particle physics of the 'black box'



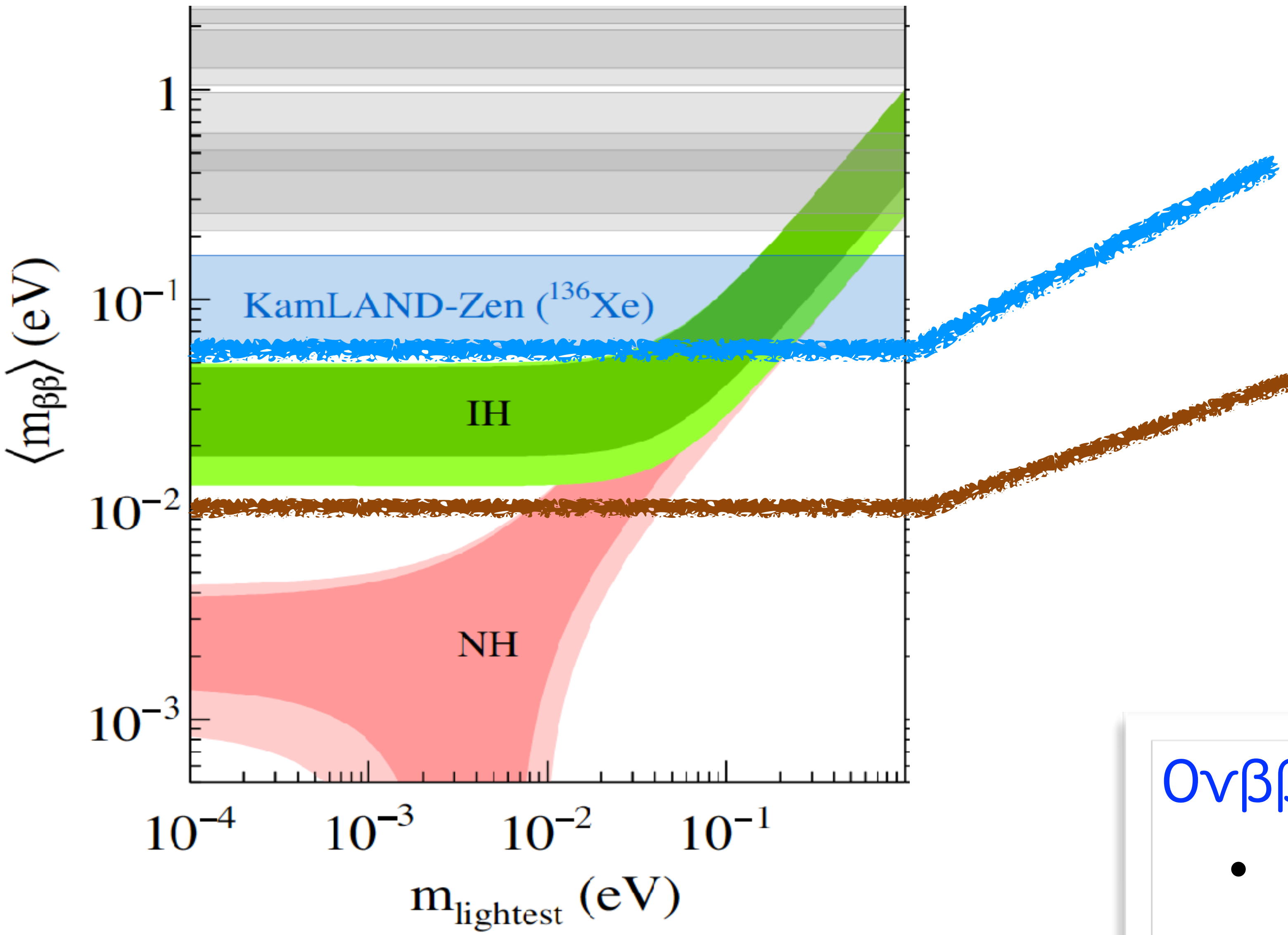
For virtual exchange of light Majorana neutrinos, the decay rate depends on an effective neutrino mass

$$\eta \sim < m_{\beta\beta} >$$

Current state of the art

$T^{0\nu}_{1/2}\ (10^{25}\ yr)$ (sensitivity)	$T^{0\nu}_{1/2}\ (10^{25}\ yr)$ (lower limit)	isotope	experiment	year	status
5.6 (8.0)	>10.7 (>4)	Xe-136	KamLAND-Zen (phase I+II) (KL-Z 800)	2016 (2019)	completed (running)
11	>9	Ge-76	Gerda (phase I+II)	2018	running
4.8	>2.7	Ge-76	Majorana Demonstrator	2018	running
5.0	>3.5	Xe-136	EXO-200 (phase I+II)	2019	completed
1.5	>2.3	Te-130	Cuore (w/ Cuoricino)	2019	running
0.5	>0.35	Se-82	Cupid-0	2019	completed
		Te-130	SNO+		commissioning

0νββ decay and neutrino mass (See-Saw I mechanism)



current experiments
(~100 kg, $T_{1/2}$~10^{26} y)

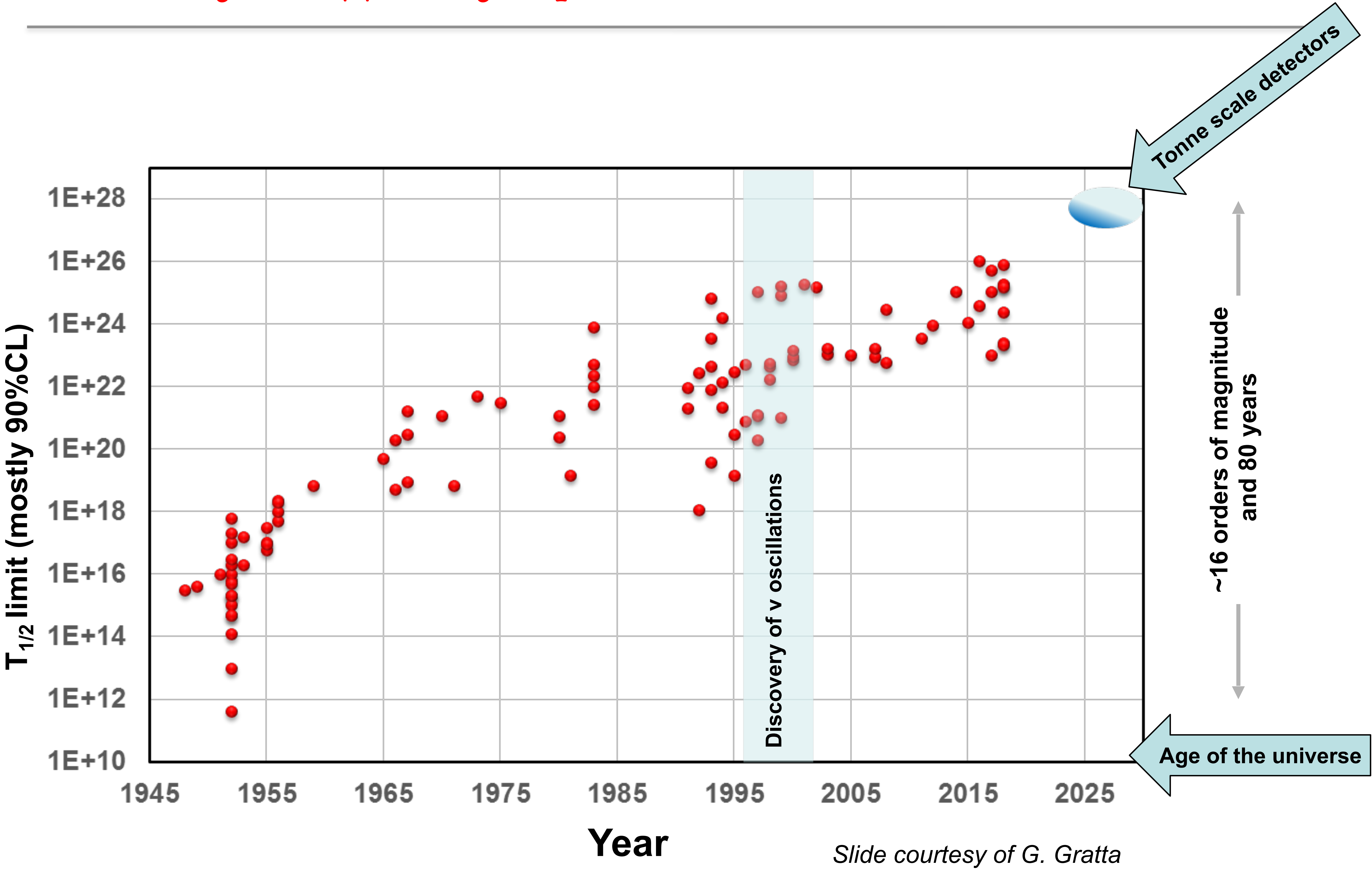
"tonne-scale"
($T_{1/2}$~10^{28} y)

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q,Z)|M_{0\nu}|^2 < m_{\beta\beta} >^2$$

0νββ rate

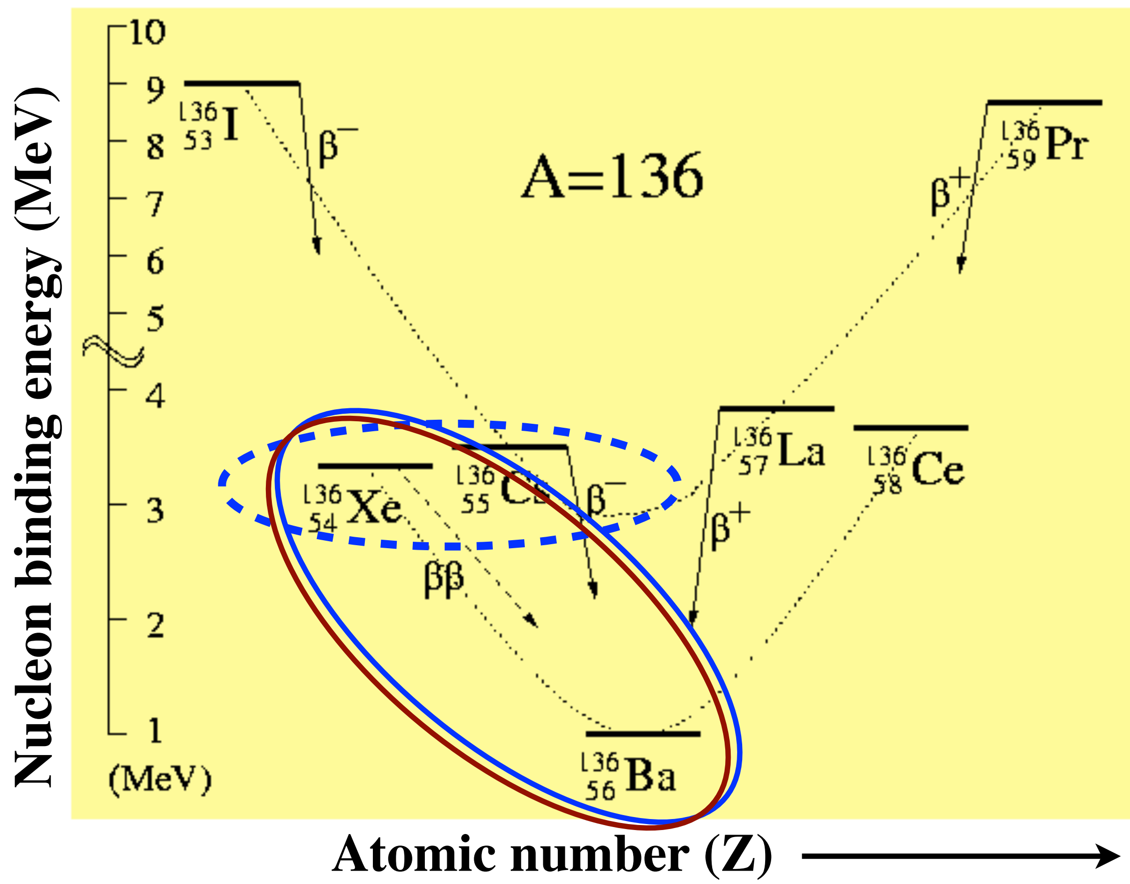
- absolute neutrino mass (model dependent)

The history of 0νββ decay experiments in one slide

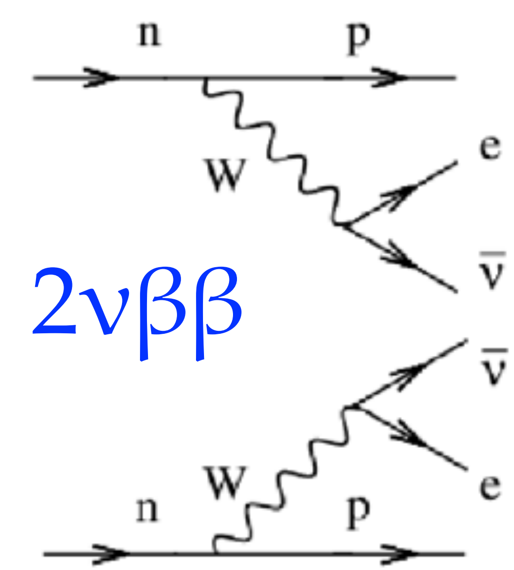


Slide courtesy of G. Gratta
Data courtesy of S.Elliott and the PDG.
Not all results are necessarily shown.

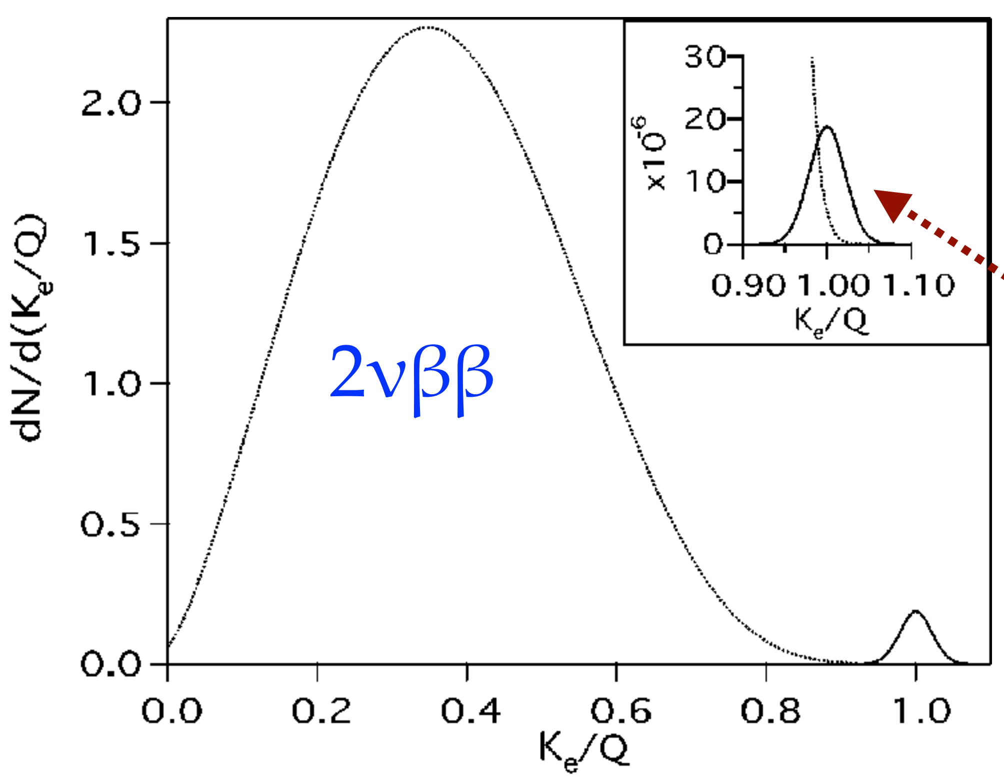
Neutrino-less double beta decay



observable when single β-decay is forbidden or disfavored



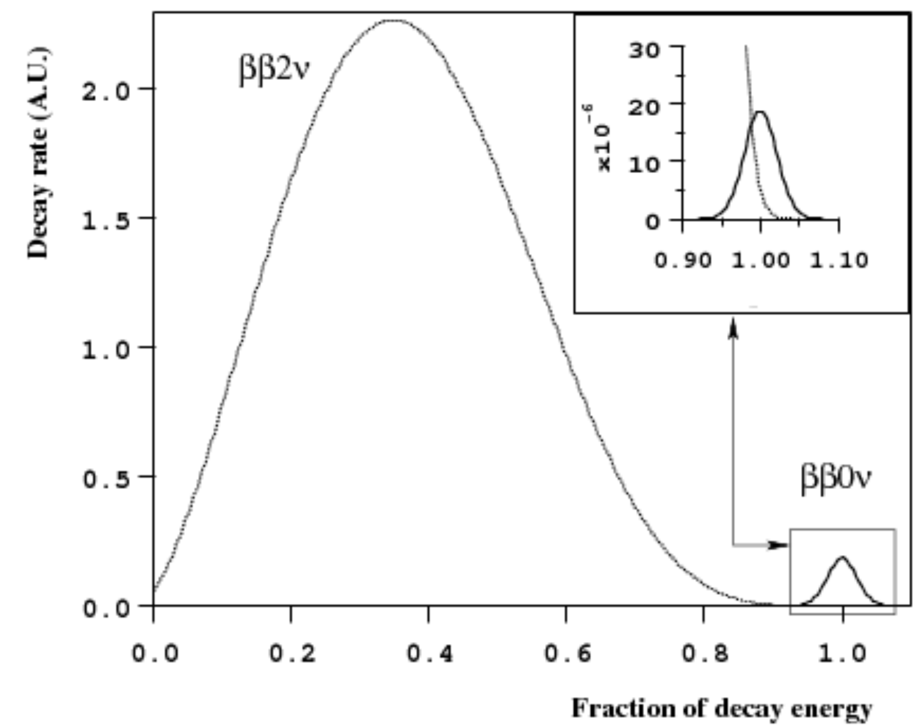
predicted and calculated in 1935 by Maria Göppert-Meyer



new physics 0νββ

proposed in 1937 by Racah + Furry

How does one look for a faint (at best) peak?



Source mass

- observe as many nuclei as possible
- isotopic enrichment

Energy resolution

- spurious events from other processes
- separate 2νββ decay events

Radioactive background control

- eliminate other events (go underground, shielding, materials selection)

Background discrimination

- measure residual background as precisely as possible and extrapolate it to the energy+volume region of interest

A note for the pessimist:
How well one can achieve the above goals determines the physics that can be done in the absence of a signal

Dura lex, sed lex

$$N_A = 6.022 \times 10^{23}$$

Amedeo Avogadro

- DBD candidate isotopes: 48→150 grams/mole
- 10^{28} nuclei = 16,600 moles → 800—2,500 kg
- Add-in real-life non-idealities:
  detection efficiency, isotopic fraction, backgrounds, detector live time, ….

the Enriched Xenon Observatory (EXO) program

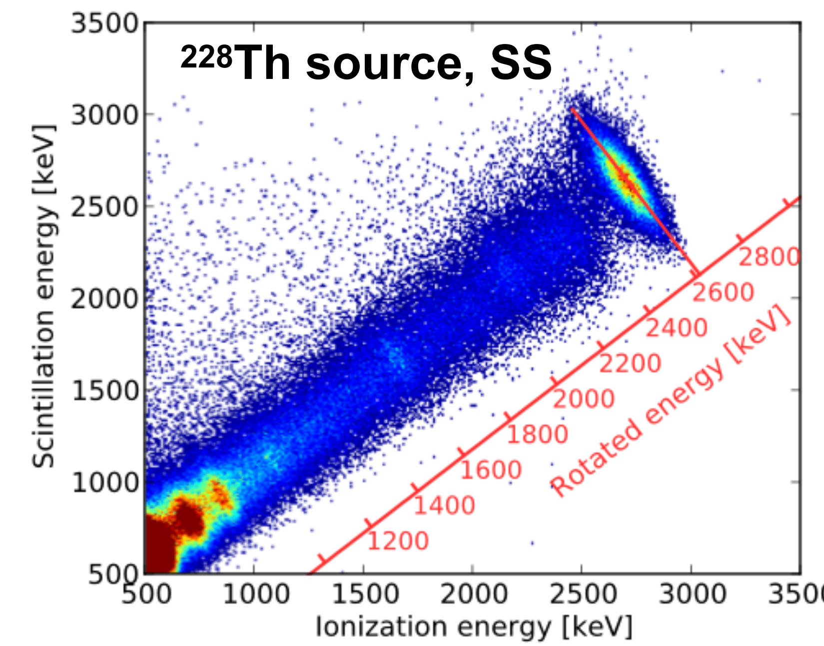
Enriched Liquid Xenon Time Projection Chambers (TPCs) of increasing sensitivity

1. Liquid enriched xenon (>80% ^{136}Xe)
2. EXO-200 (Phases 1/2)
   (200 kg; opened kmole era; ν mass sensitivity ~100 meV)
3. nEXO, R&D underway, towards a project
   (5 tonnes; ν mass sensitivity ~10 meV, cover inverted mass ordering)
4. nEXO "Phase 2" with Ba-daughter ID (~ meV)

Enriched LXe TPCs

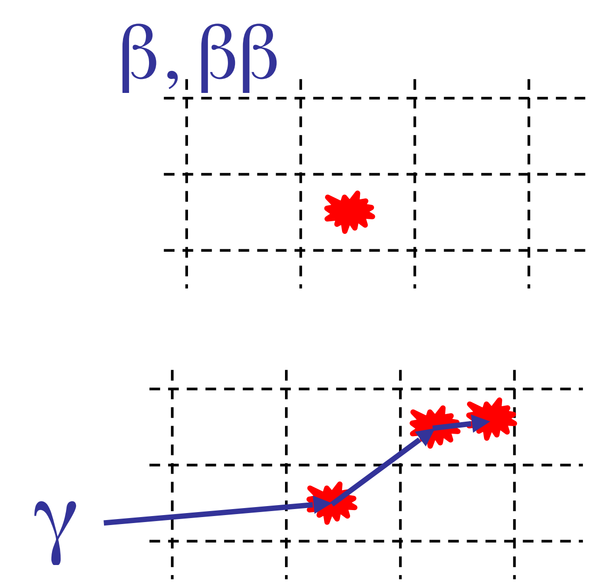
Why xenon?

- Monolythic (efficient background mapping)
- In-line purification of xenon
- Simple-minded enrichment



Liquid xenon TPC's

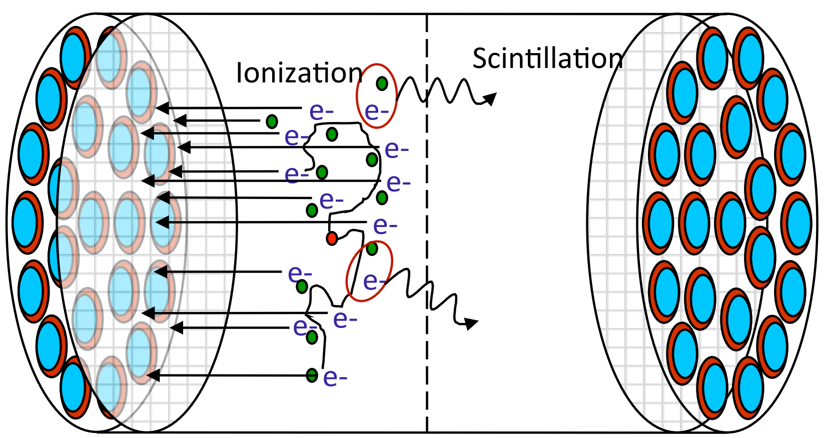
- Active self-shielding (improves with size)
- Good energy resolution
  (ionization+scintillation, 0ν/2ν separation)
- Particle ID (scintillation vs. ionization)
- Event topology (single-/multi-site events)

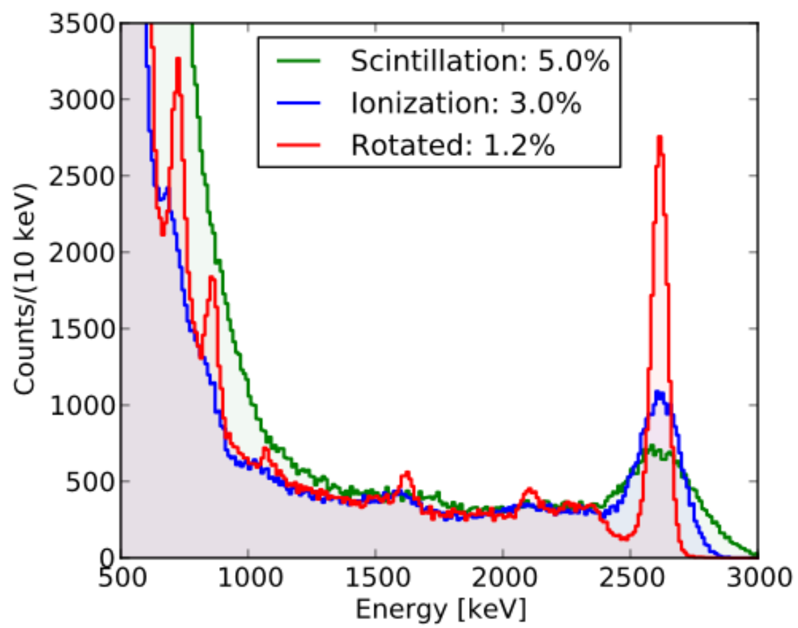


Scale-up:

EXO-200 (200 kg) ➔ nEXO (5,000 kg)

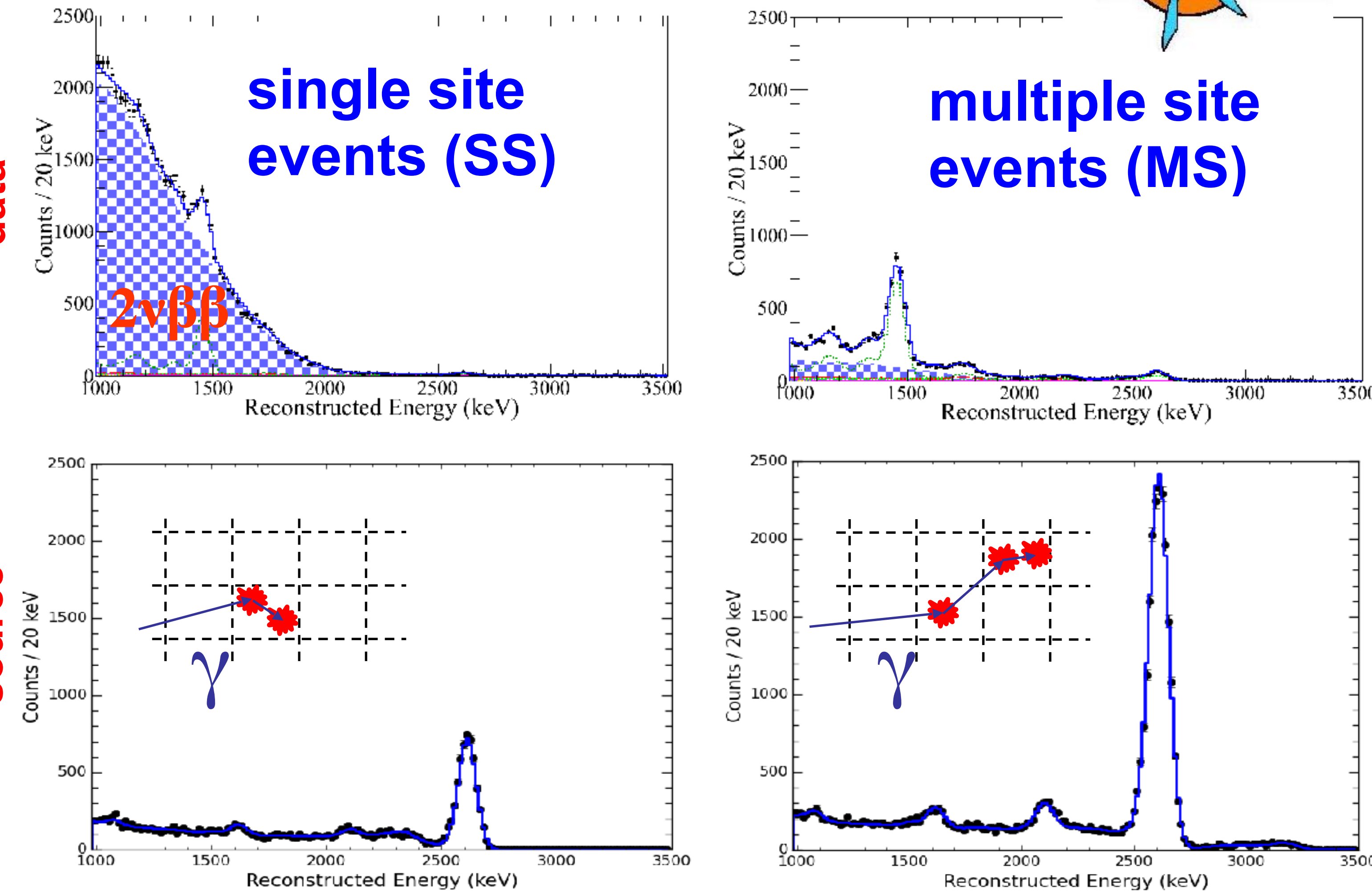
The EXO-200 precursor to nEXO

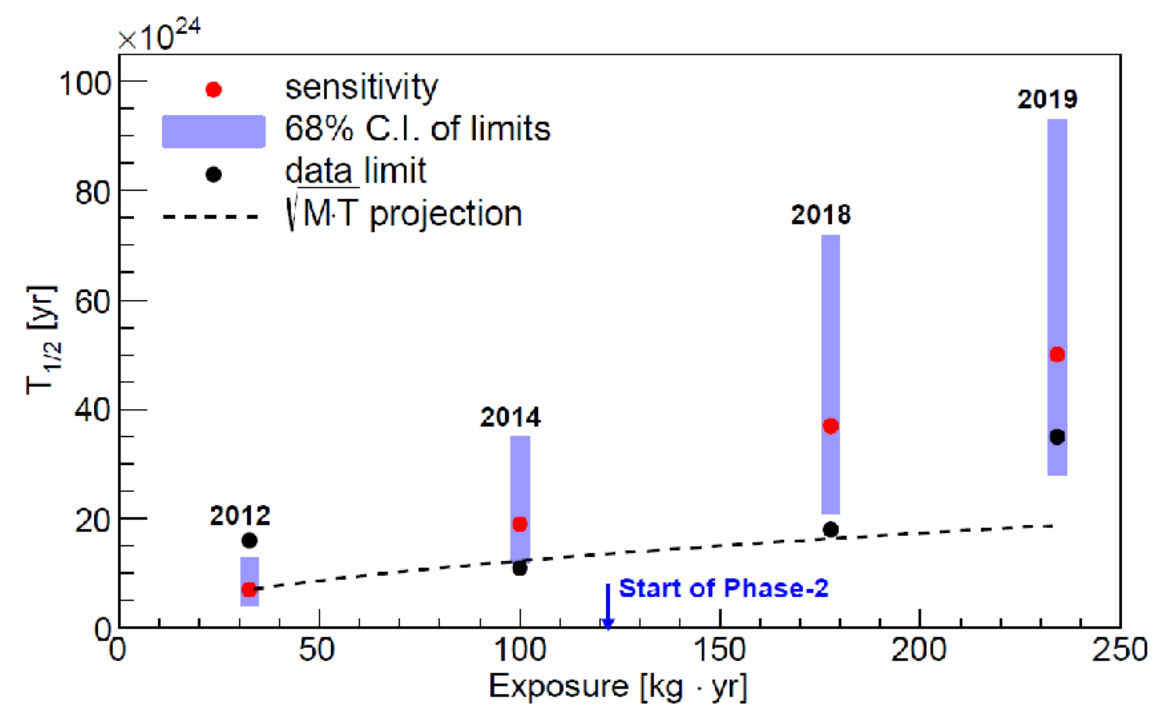




Low background data

^{228}Th calibration source





Phase I+II: 234.1 kg·yr ^{136}Xe exposure

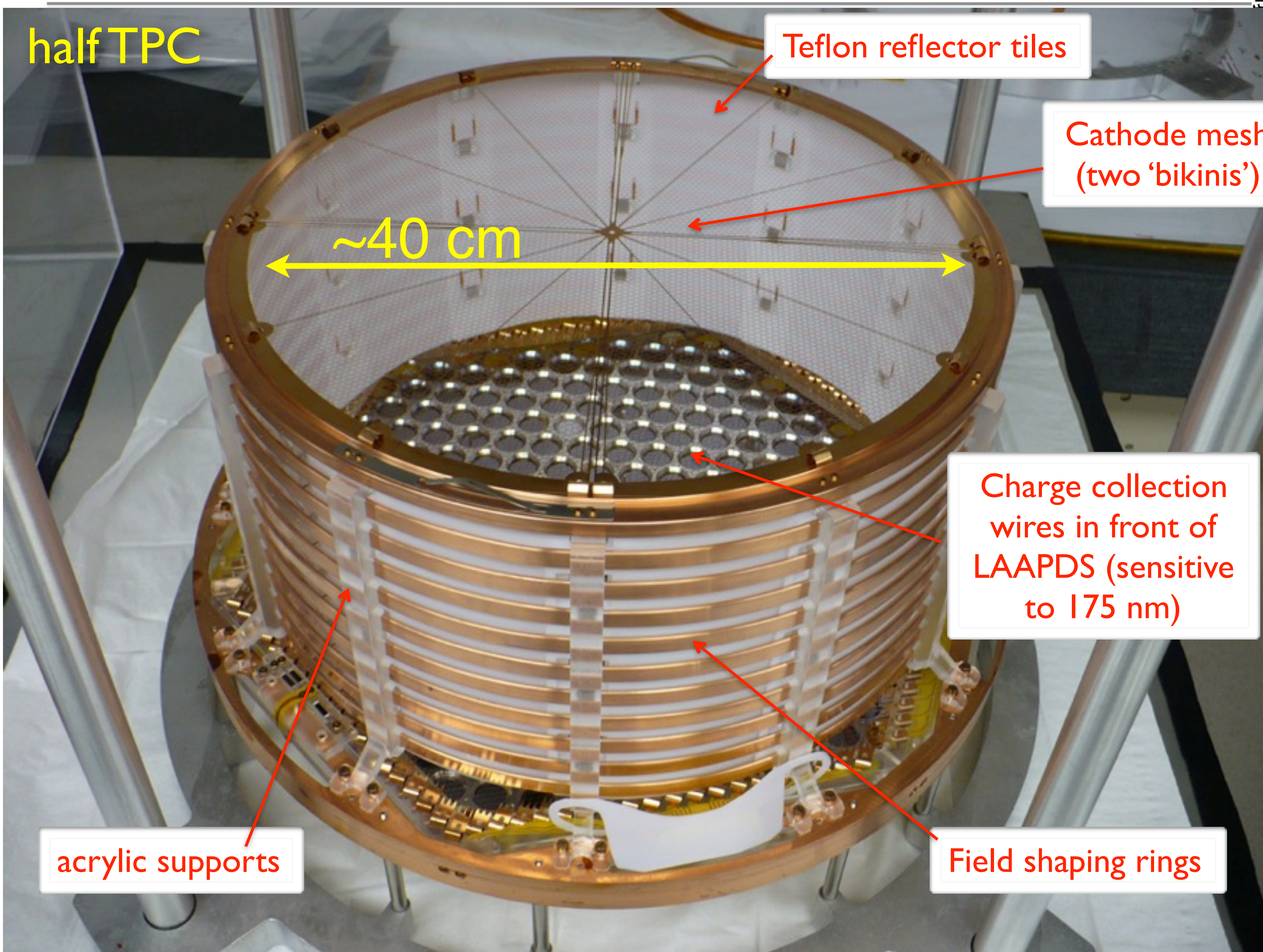
Limit $T_{1/2}^{0\nu\beta\beta}$ > 3.5 x 10^{25} yr (90% C.L.)

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

Sensitivity 5.0x10^{25} yr

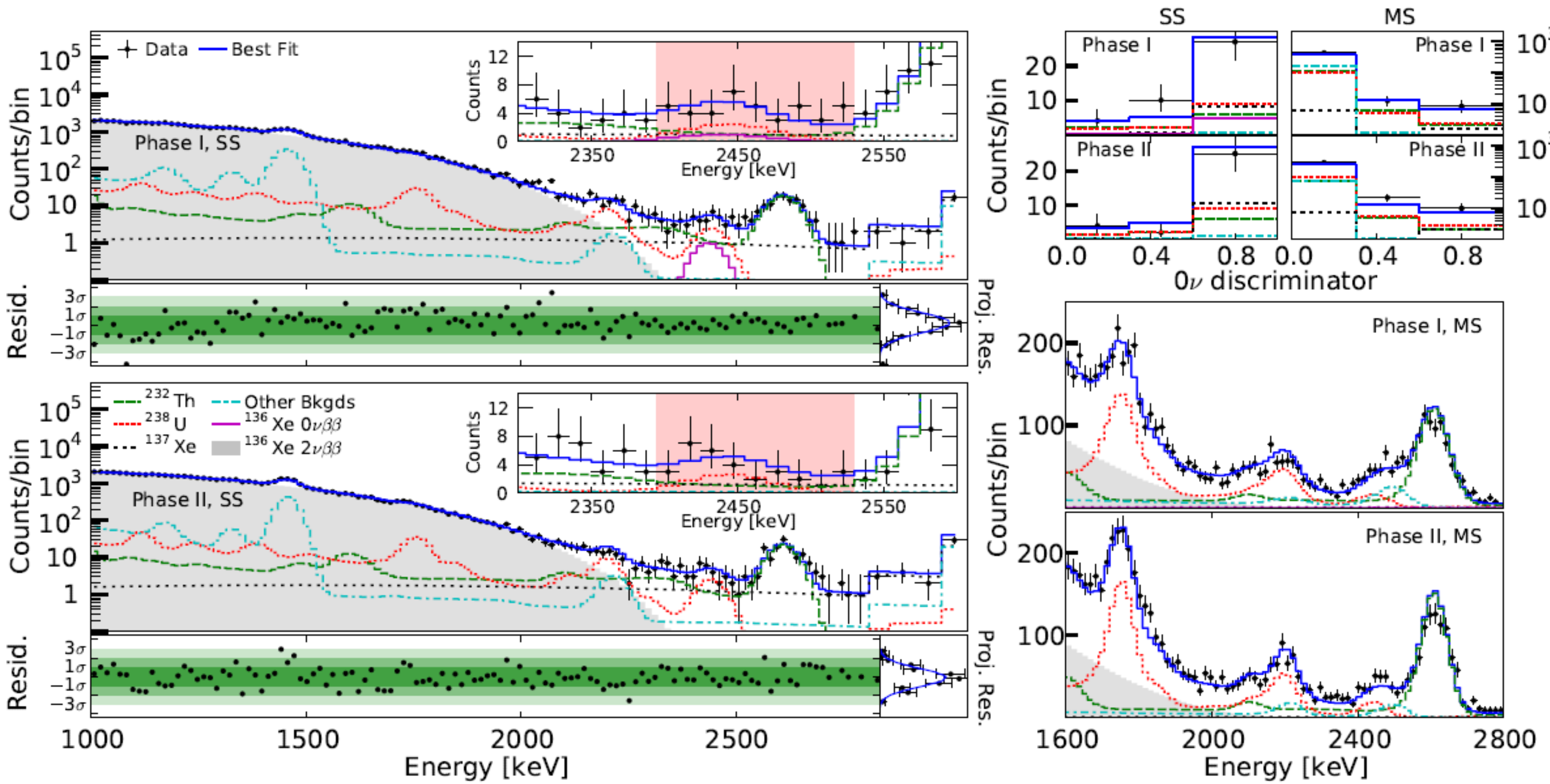
PRL 123(2019)161802

the EXO-200 TPC



the EXO-200 full Phase II results

PRL 123(2019)161802



2019 release uses machine learning (DNN) for improved signal-to-background discrimination

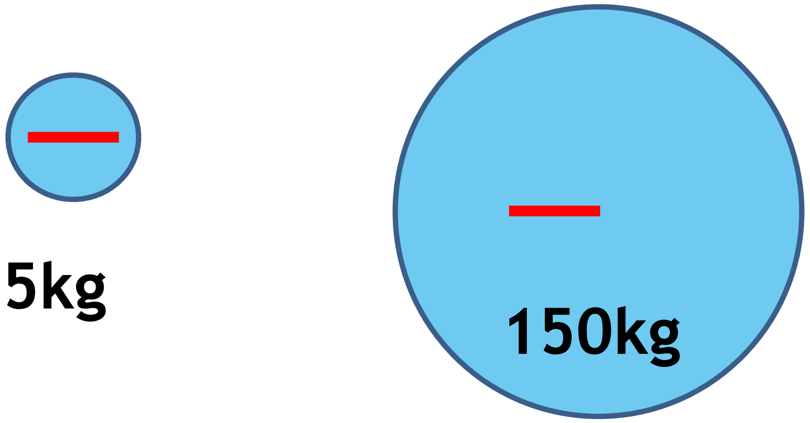
Phase I+II: 234.1 kg·yr ^{136}Xe exposure

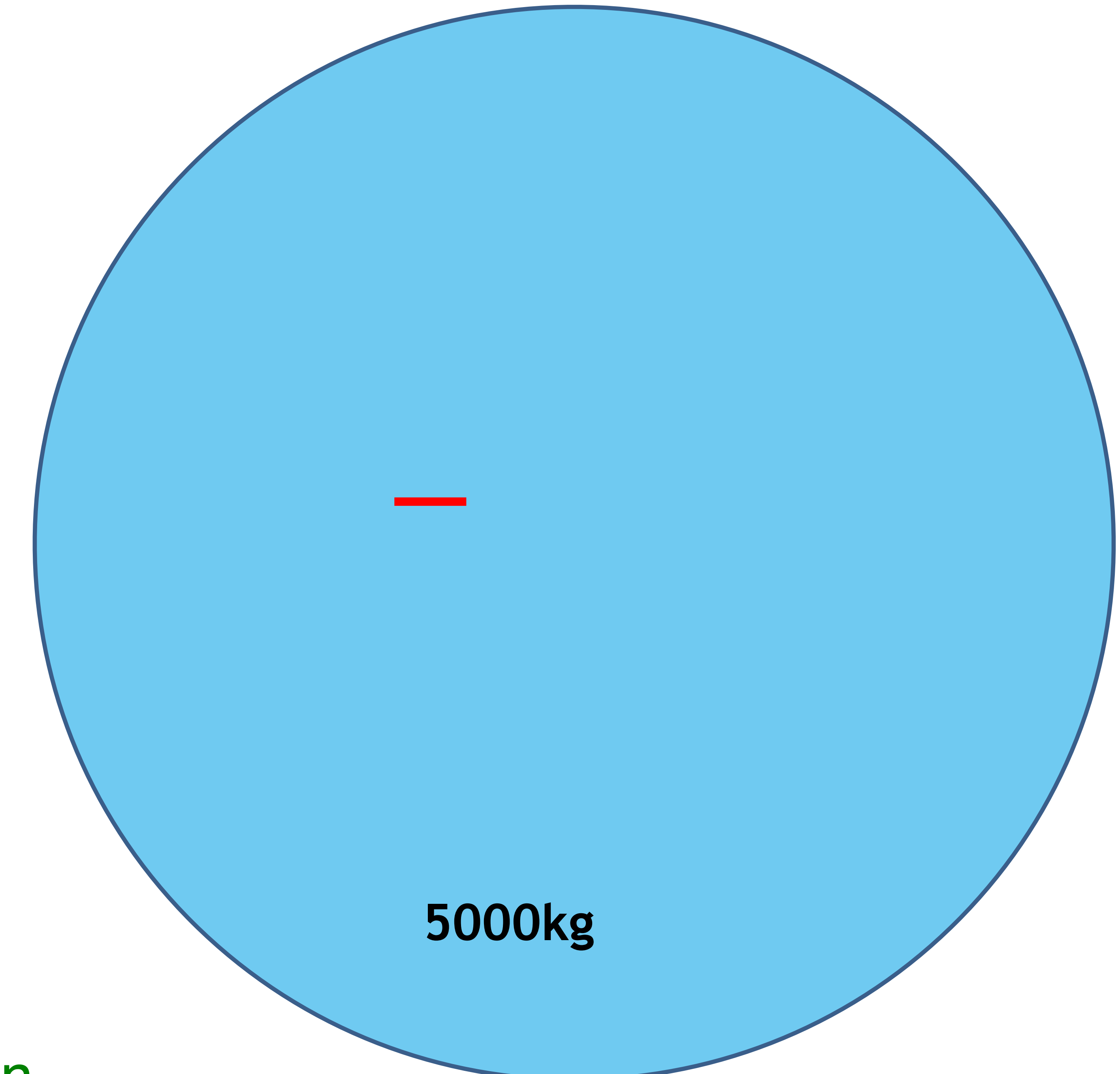
Limit $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr (90% C.L.)

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

Sensitivity 5.0×10^{25} yr

nEXO: a homogeneous detector





— Attenuation Length of a 2.4 MeV γ-ray in LXe (~ 8.5 cm)

take full advantage of:

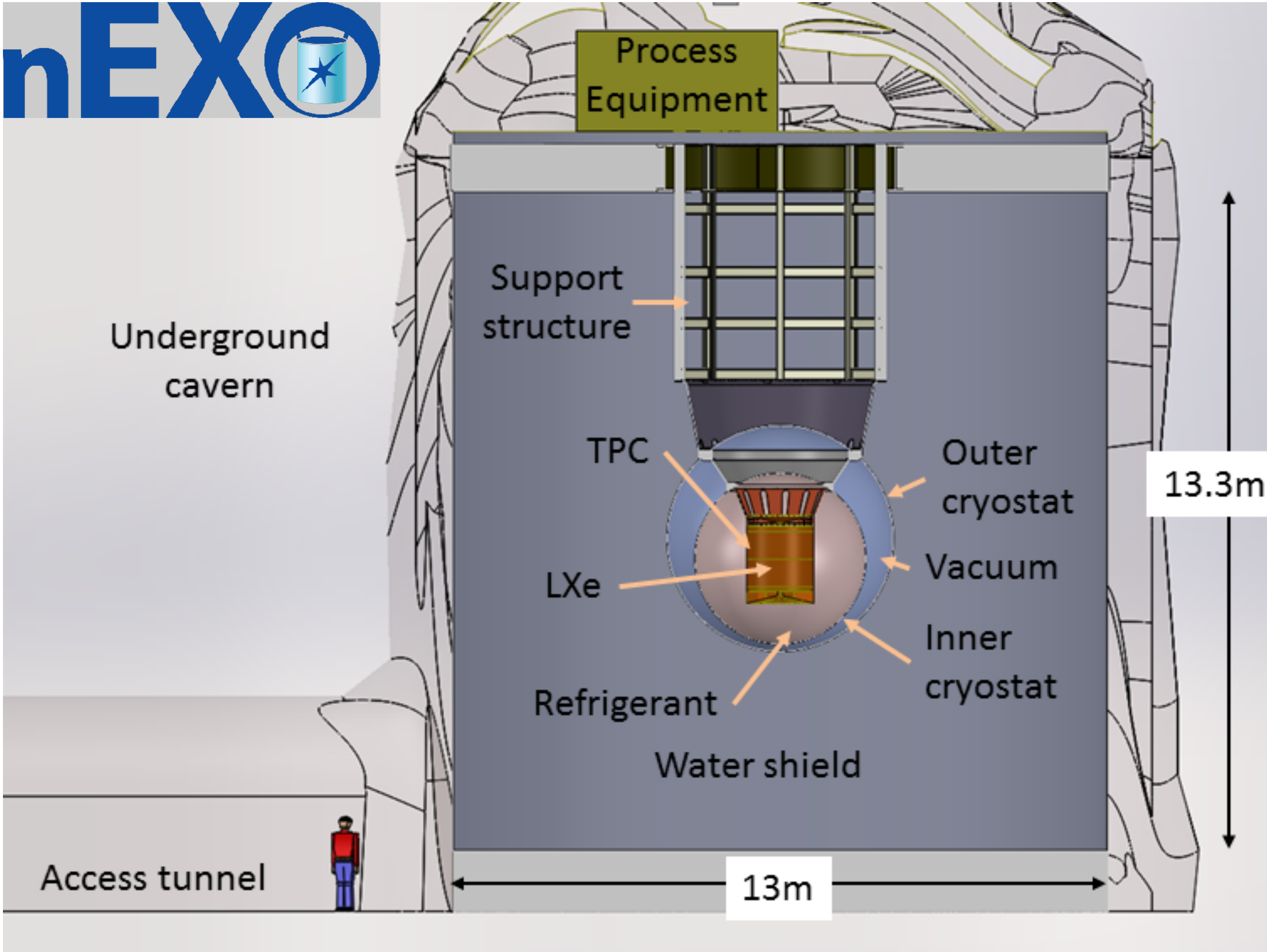
1) Compton tag and rejection

2) External background identification and rejection

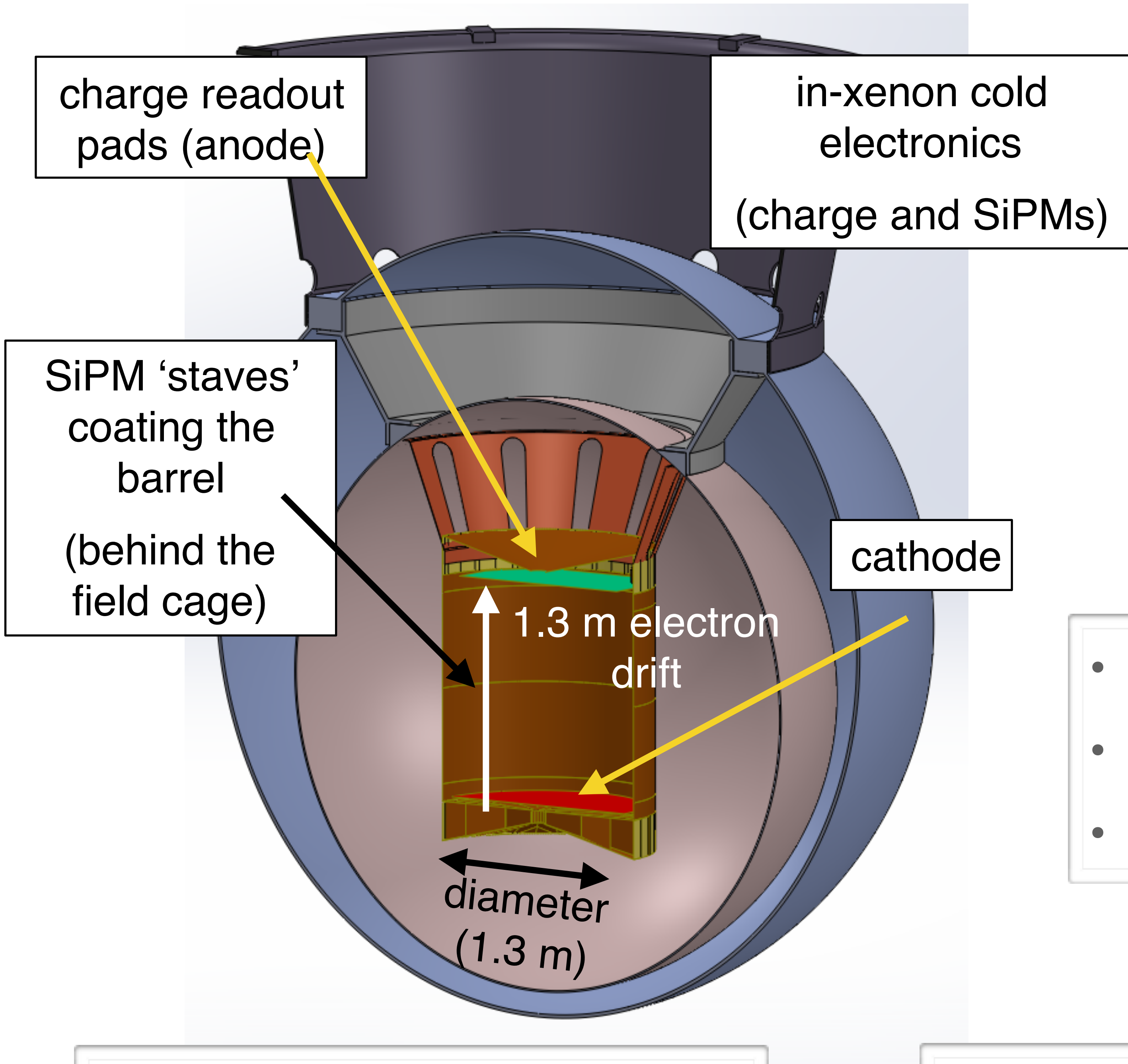
The larger and monolithic the detector, the more useful this is.

→ Ton scale is where these features become dominant.

Preliminary artist view of nEXO in the SNOLAB Cryopit



nEXO: a 5 tonnes LXe TPC



- < 1% energy resolution
- no central cathode
- ≳ 10 ms electron lifetime
- ~500 Rn atoms

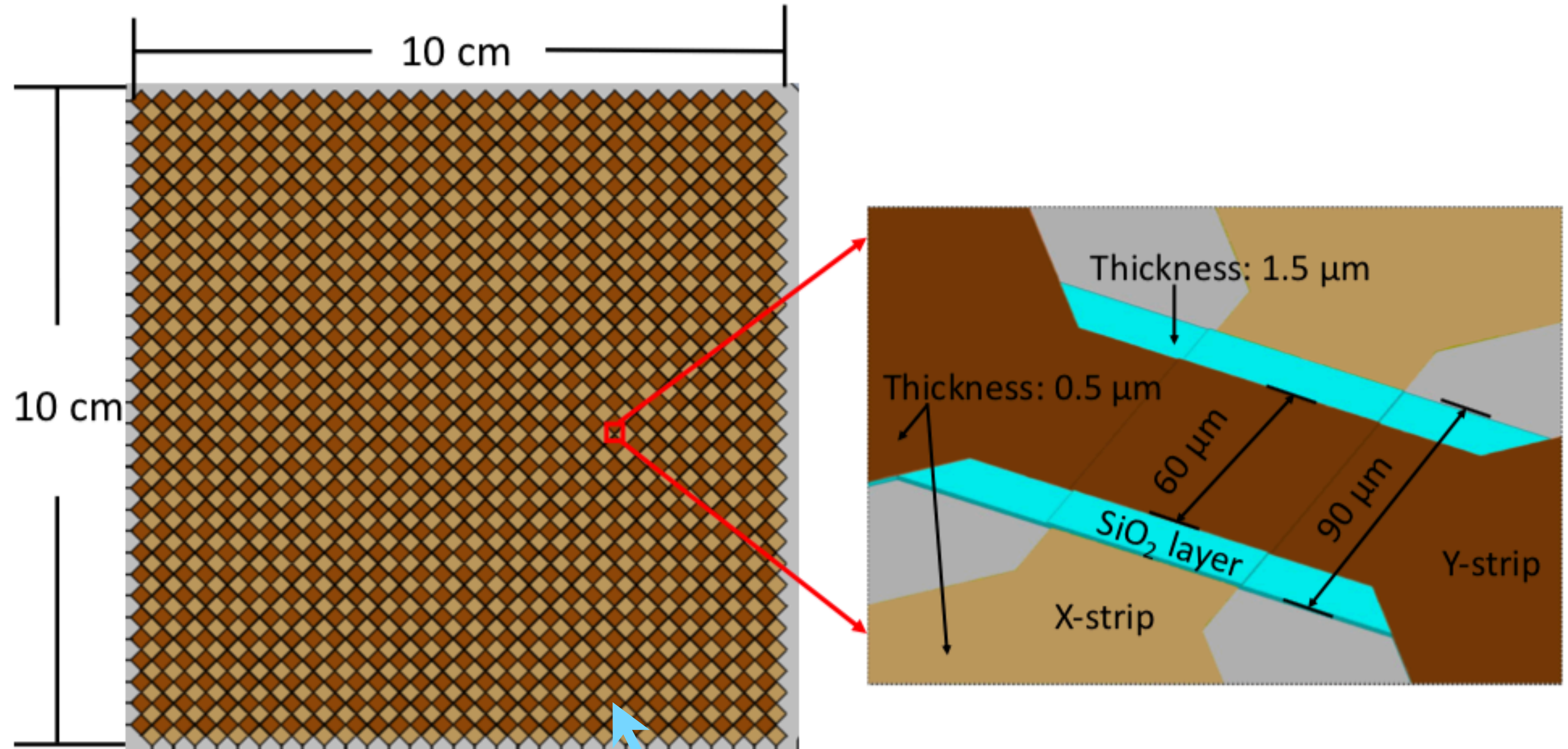
- no plastics, in-Xe cold electronics
- VUV-sensitive SiPMs behind field cage
- charge readout strips

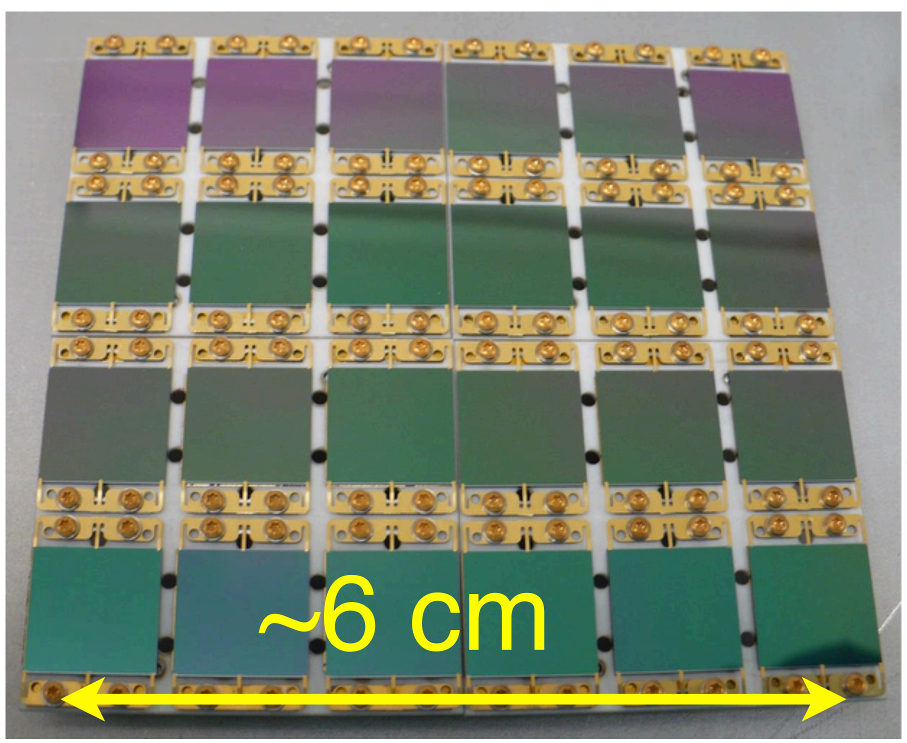
- 25x EXO-200
- enhanced self-shielding
- x100 better $T_{1/2}$ sensitivity

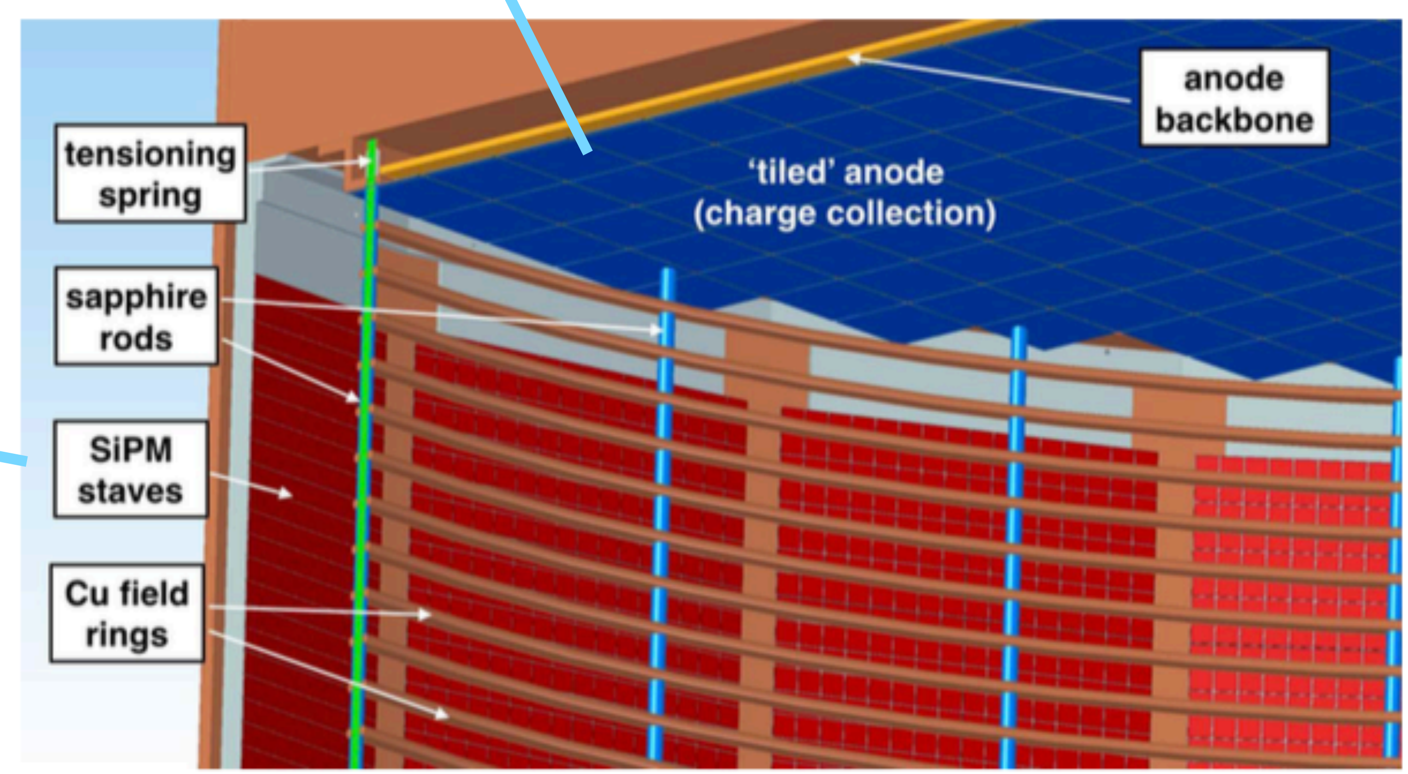
- sensitivity (10 years): 9×10^{27} yr
- energy, topology, standoff & particle ID

nEXO TPC highlights

- A pad-like charge collection detector to replace a more traditional wire readout.
- VUV-sensitive SiPMs
- in-LXe readout electronics under development

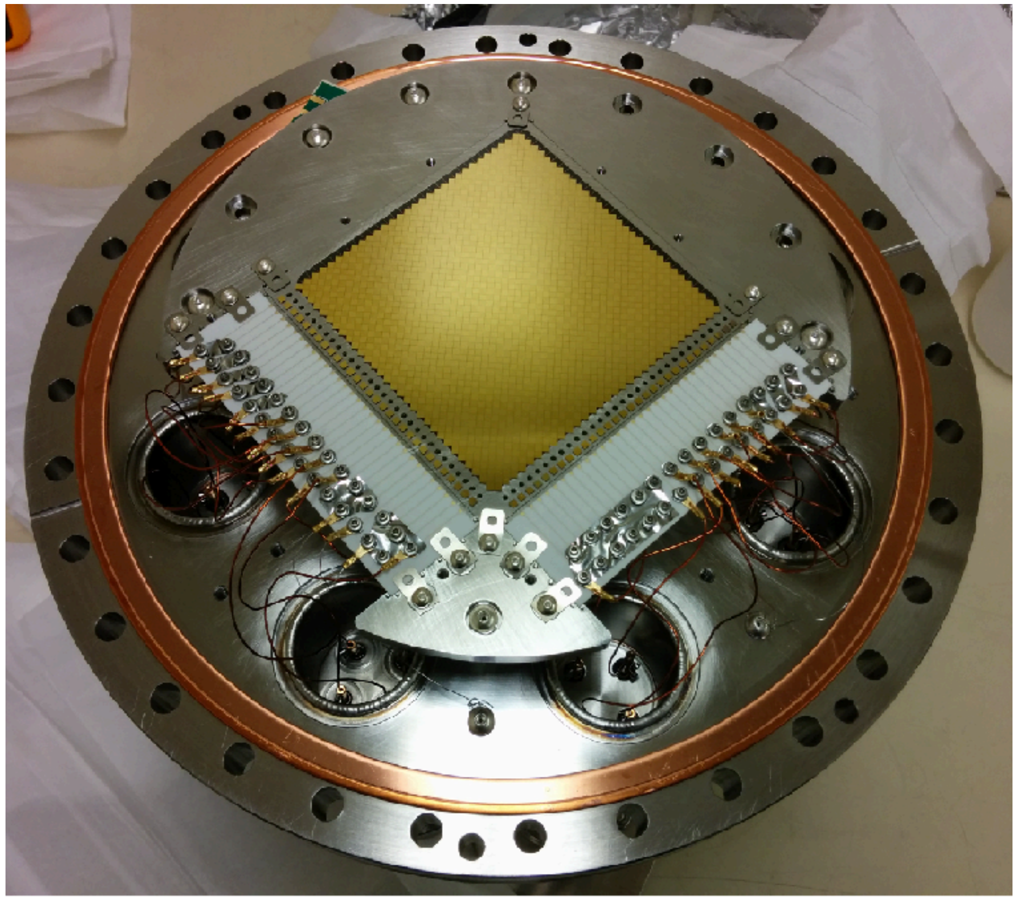




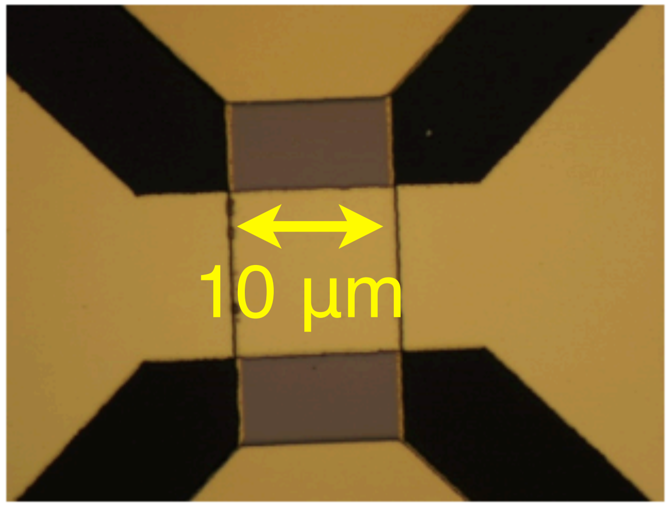


Charge collection 'tiles' (ionization detector)

JINST 13, P01006 (2018)



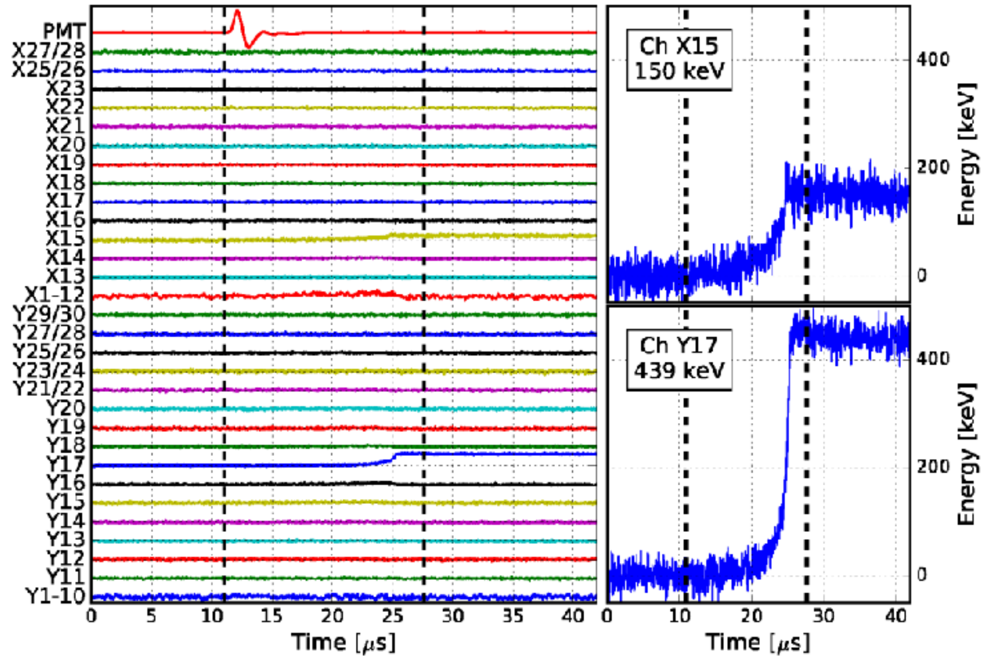
- Prototype 3mm pitch, crossed strips deposited on a 10 cm x 10 cm quartz tile produced and tested in liquid xenon.

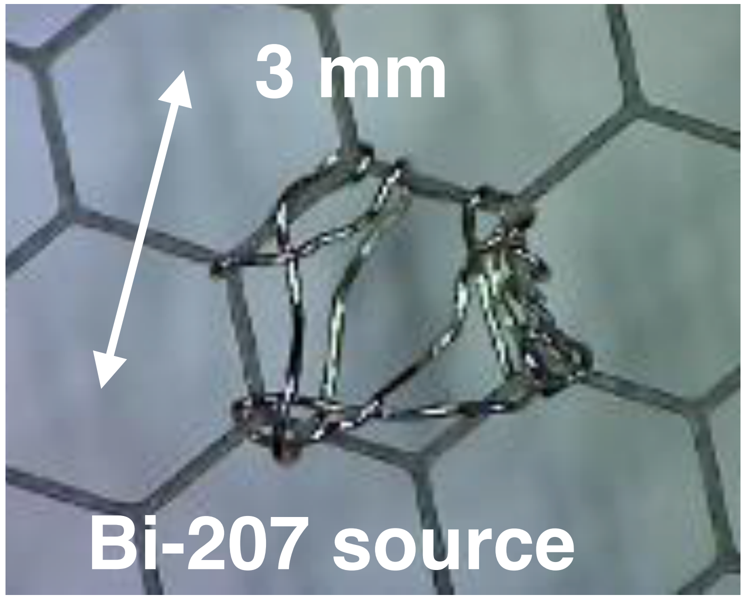


80 fF at crossings

0.86 pF between adjacent strips

no shielding Frisch grid



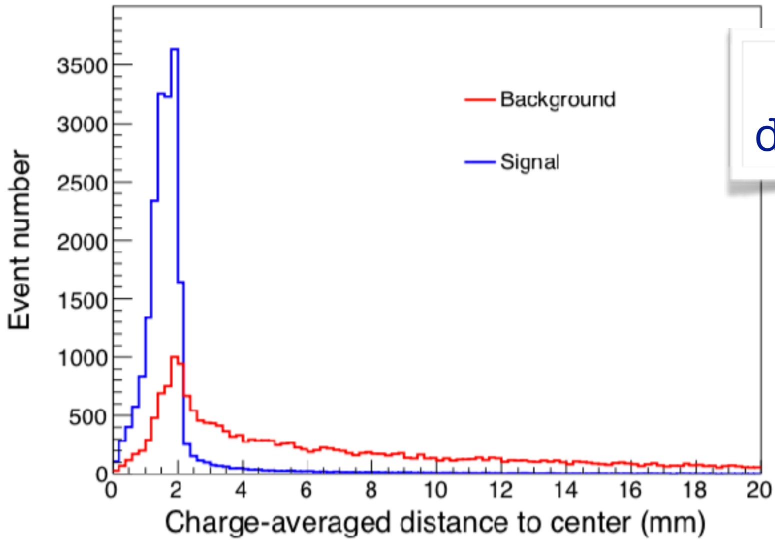


M.Jewell et al., "Characterization of an Ionization Readout Tile for nEXO", *J.Inst. 13 P01006 (2018)*

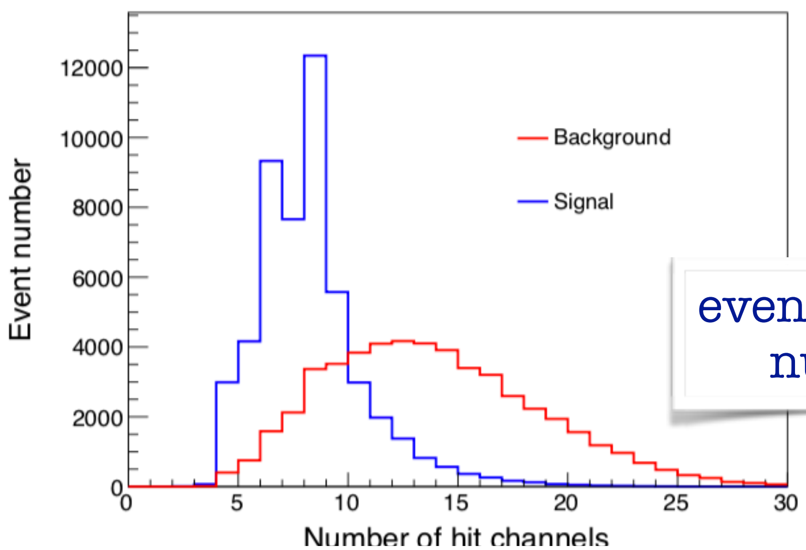
Detailed charge reconstruction

nEXO

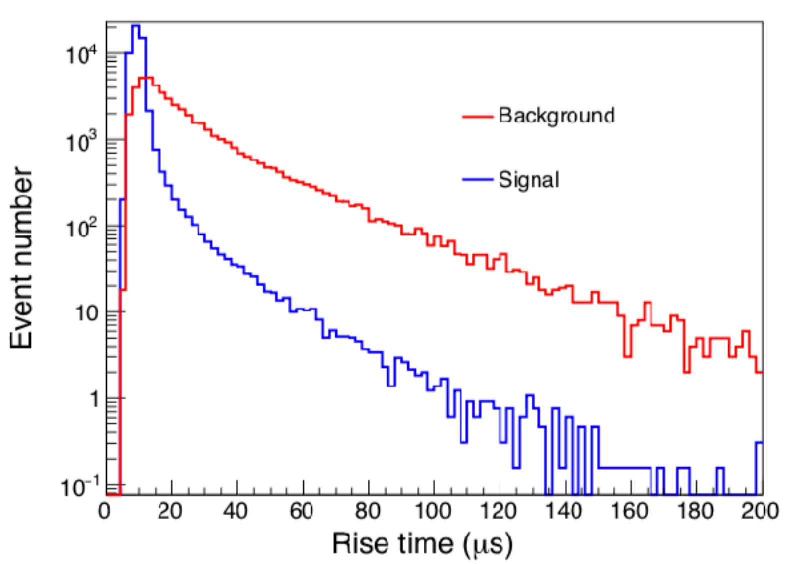
2019 JINST 14 P09020



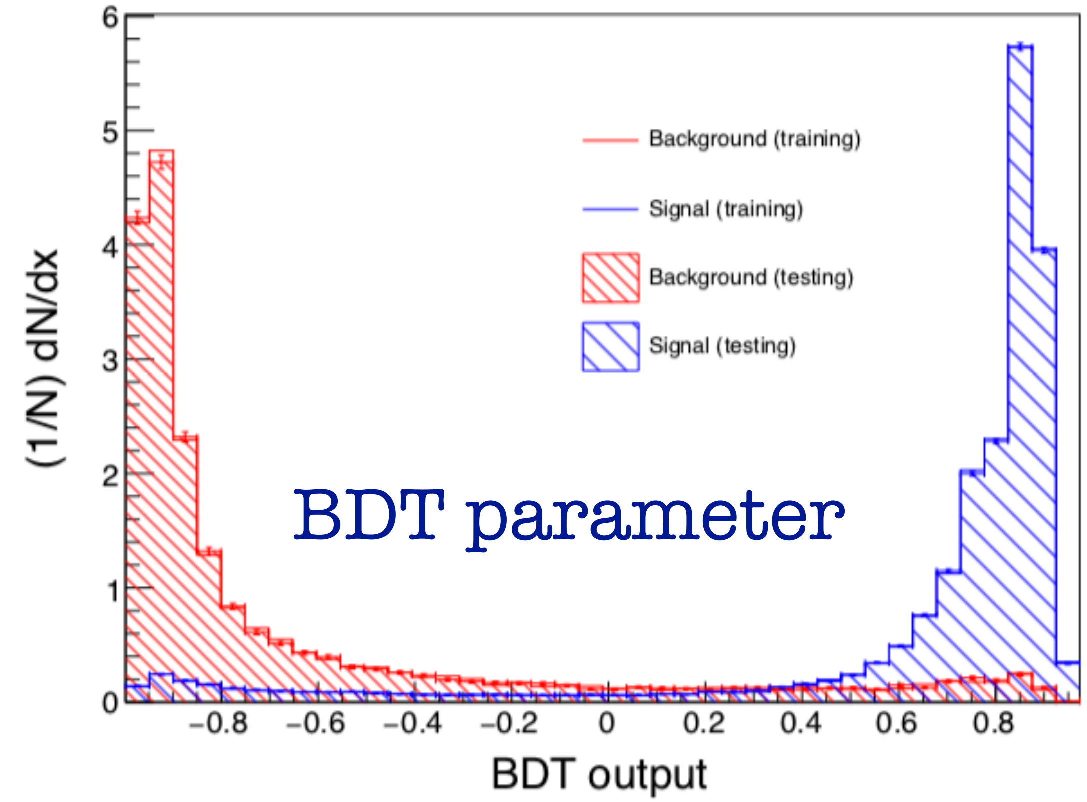
charge-average distance to center



event channel number



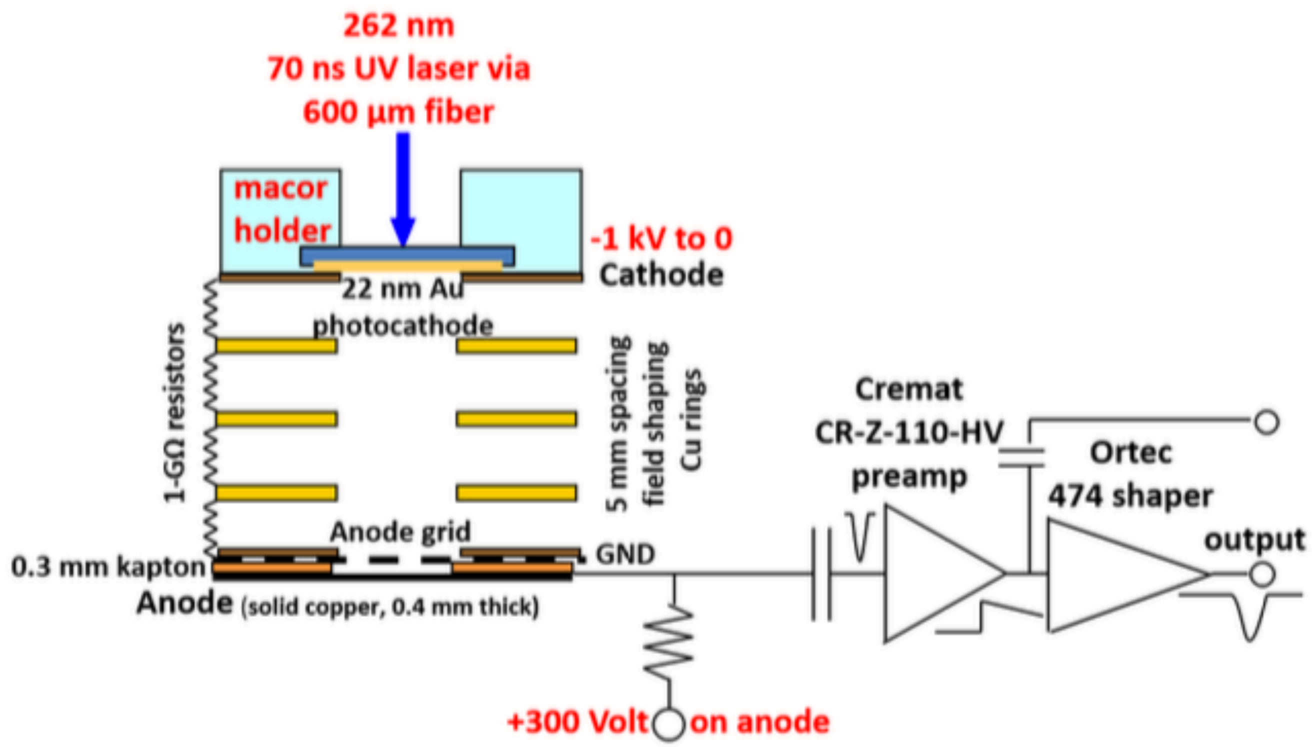
rise time distribution

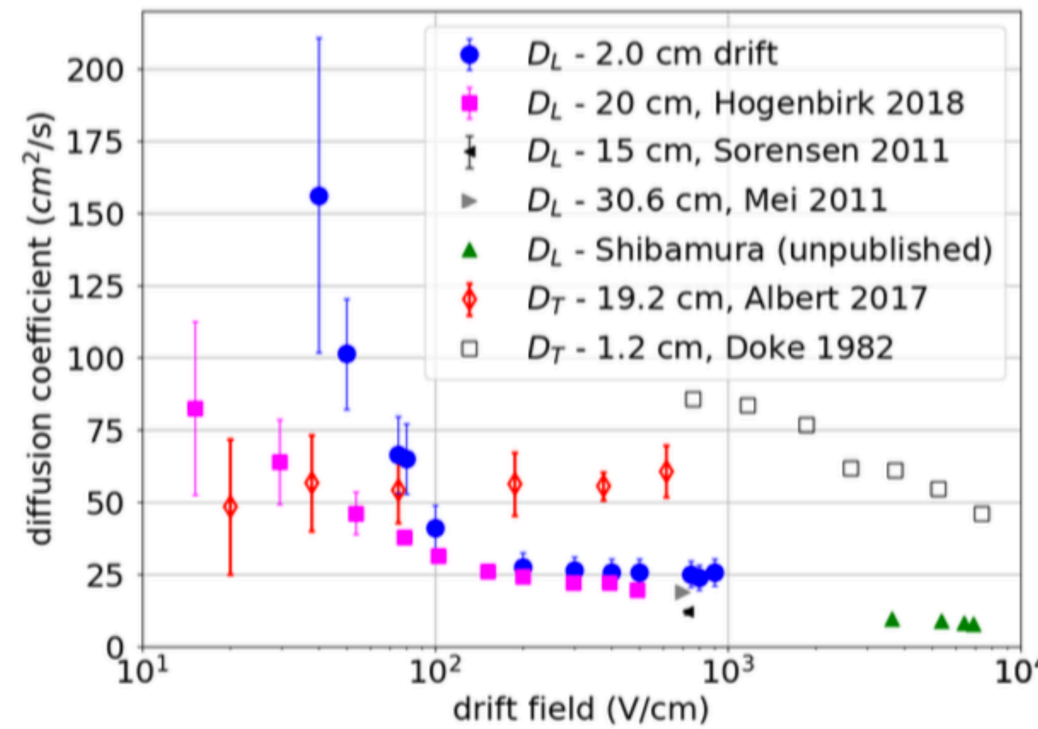


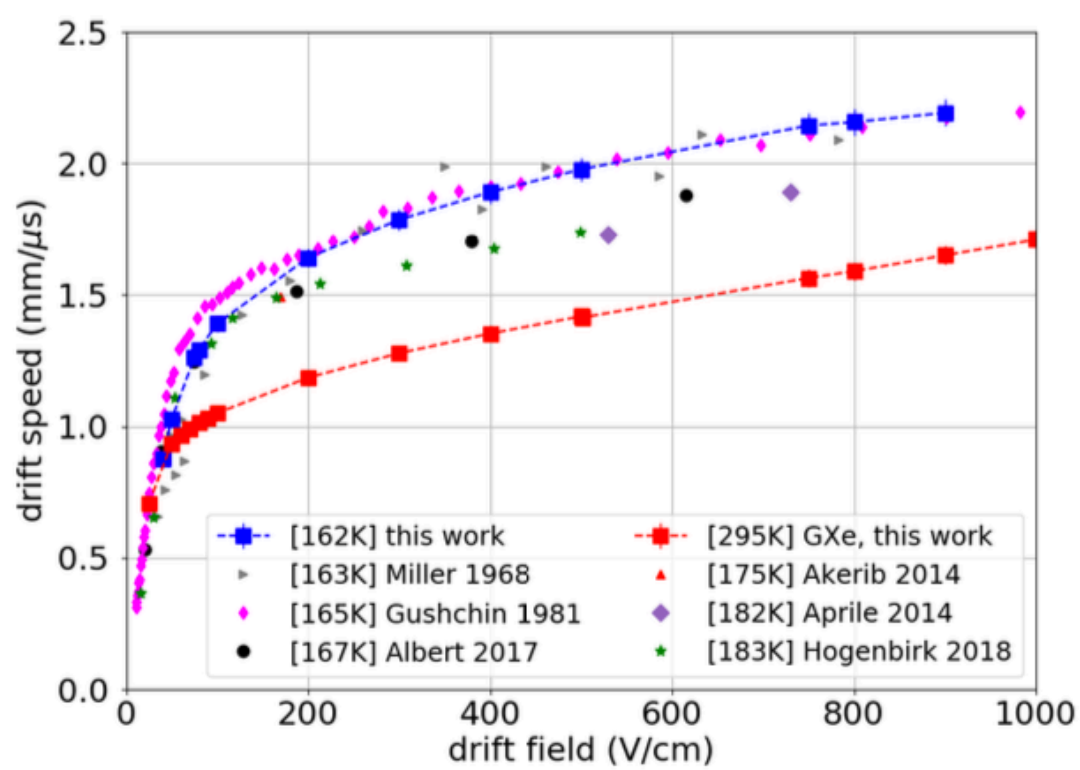
~20% sensitivity improved with EXO-200-derived multi-variate analysis

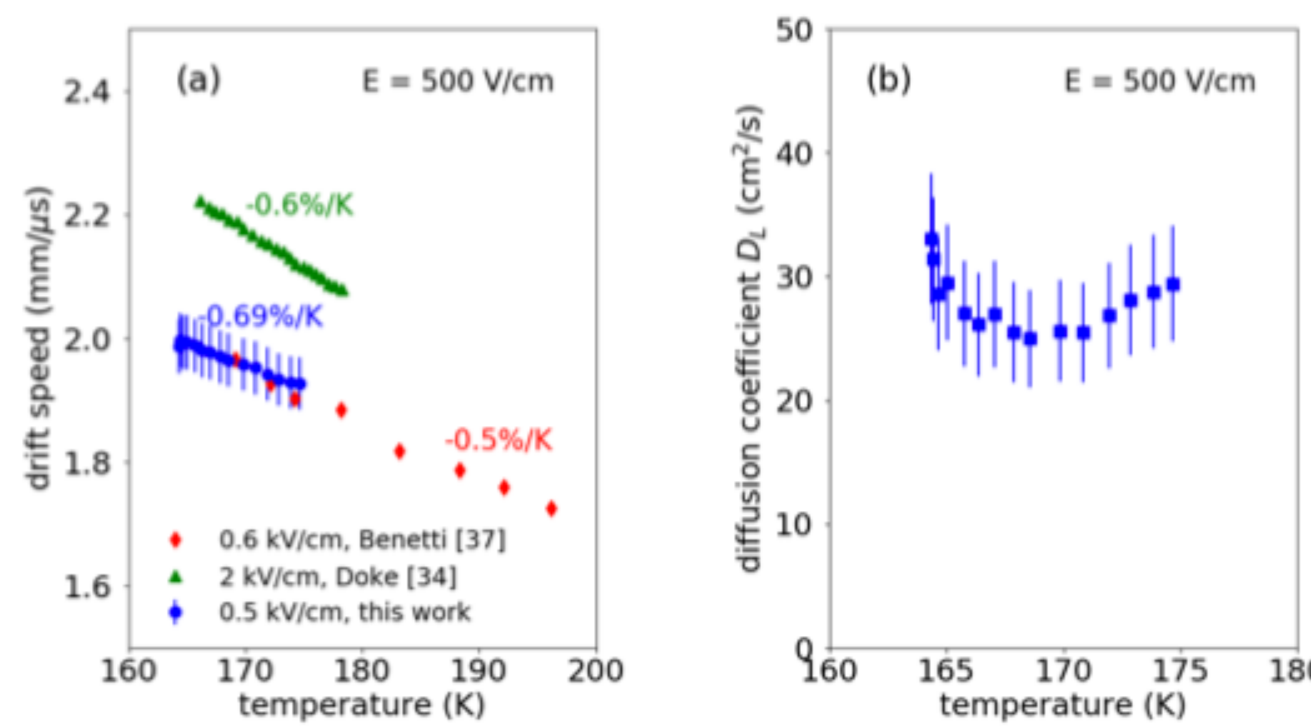
~30% improvement possible with DNN treatment of charge waveforms

arXiv:1911.11580



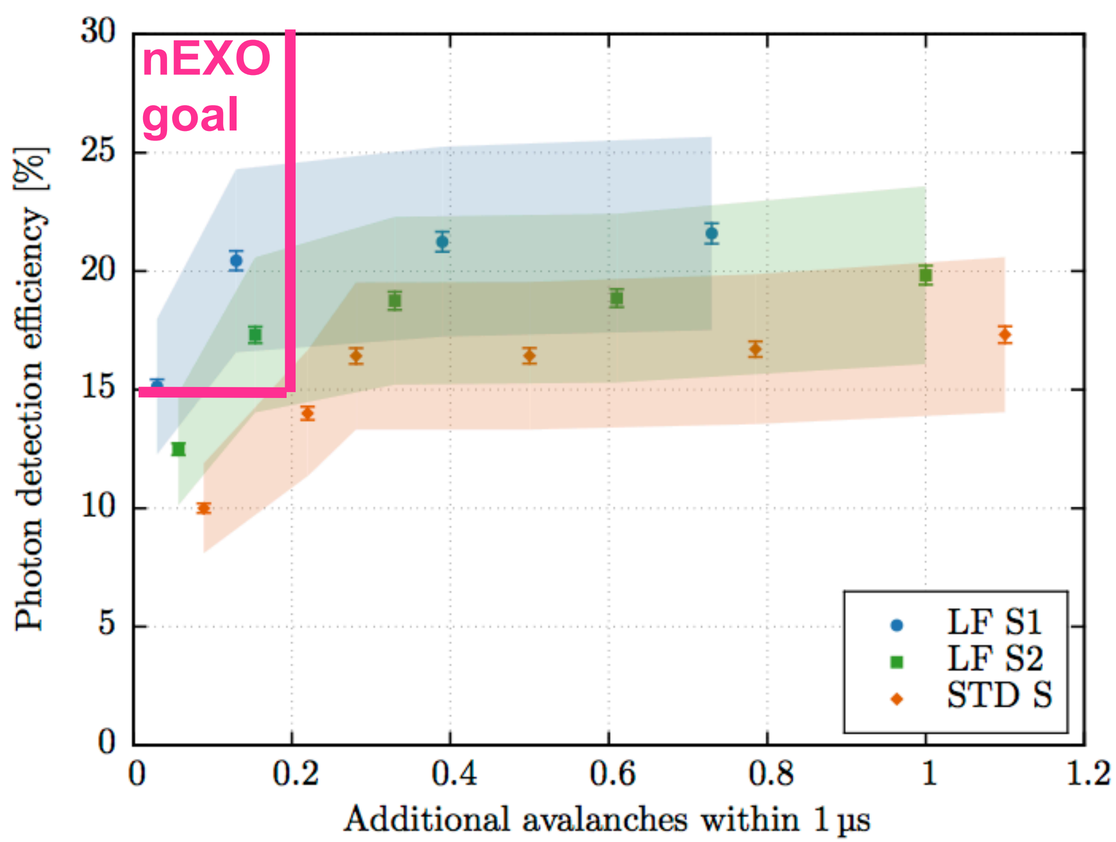


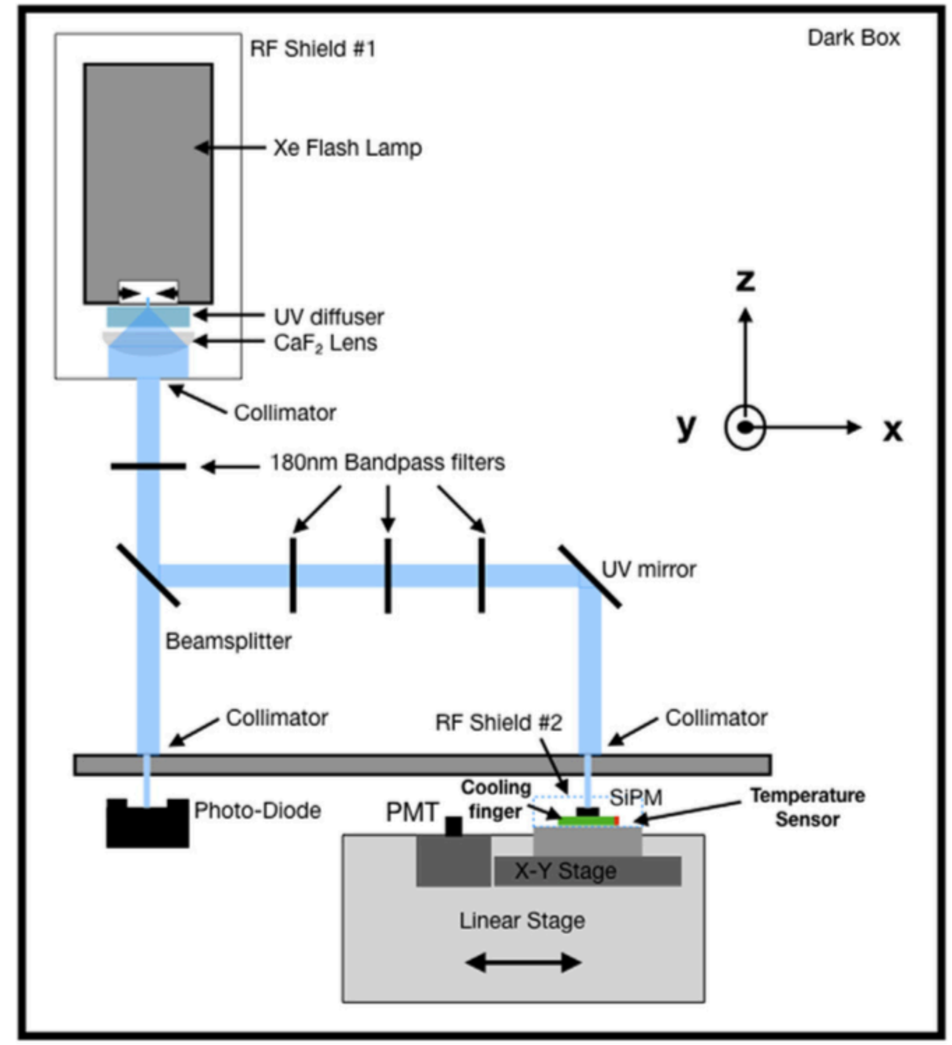




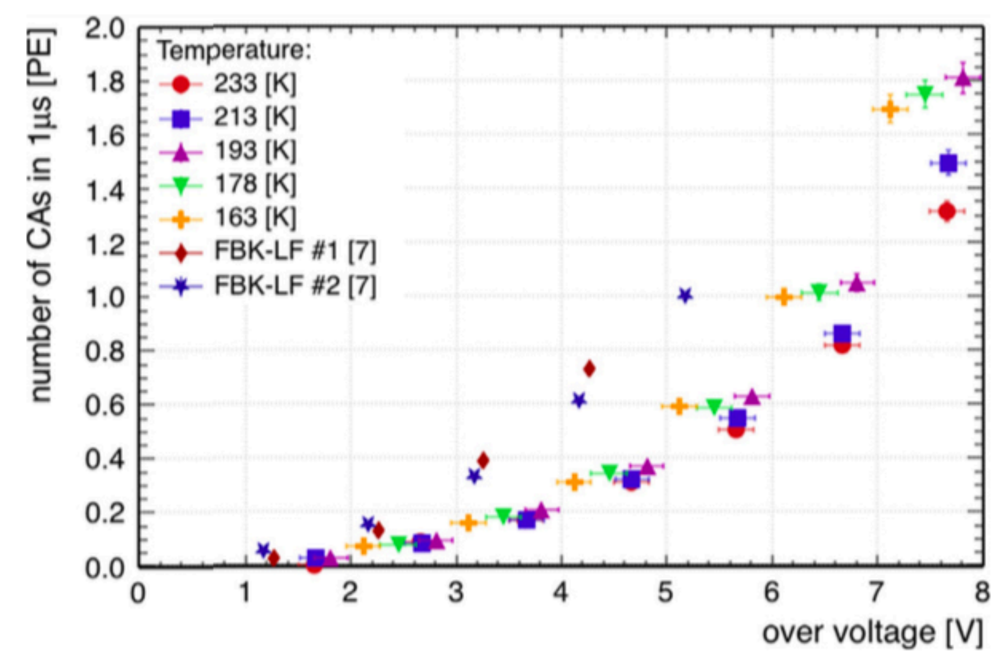
Progress on VUV-sensitive SiPM's

IEEE Trans NS 65 (2018) 2823





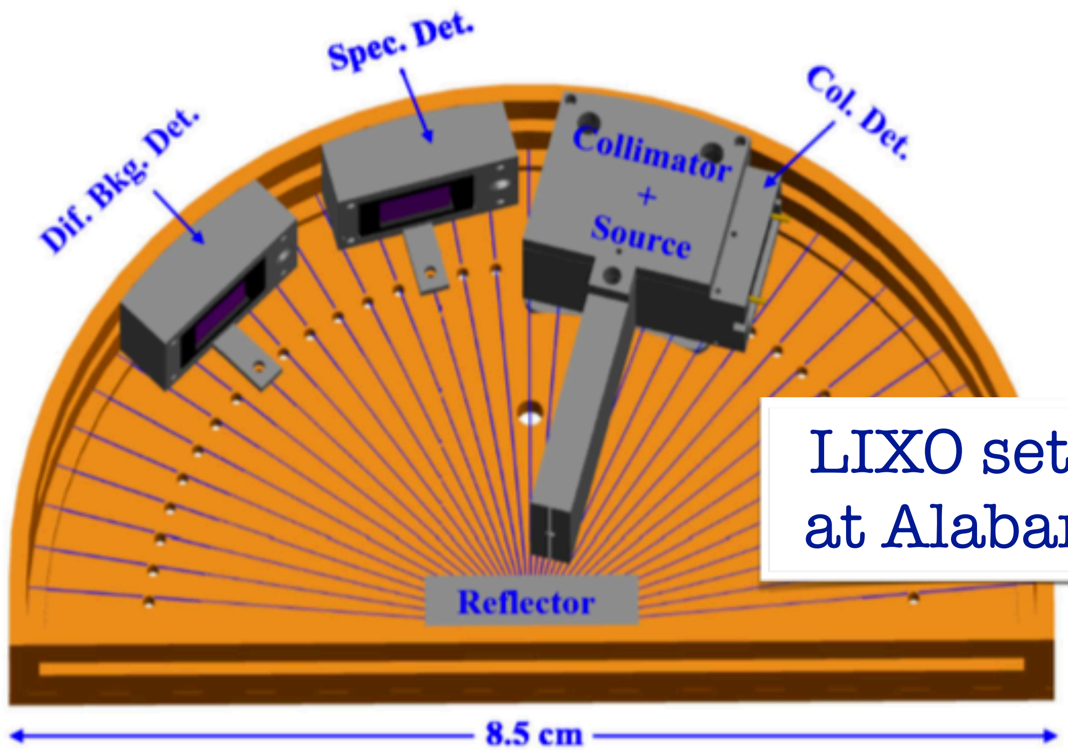
NIM A 940, 371 (2019)



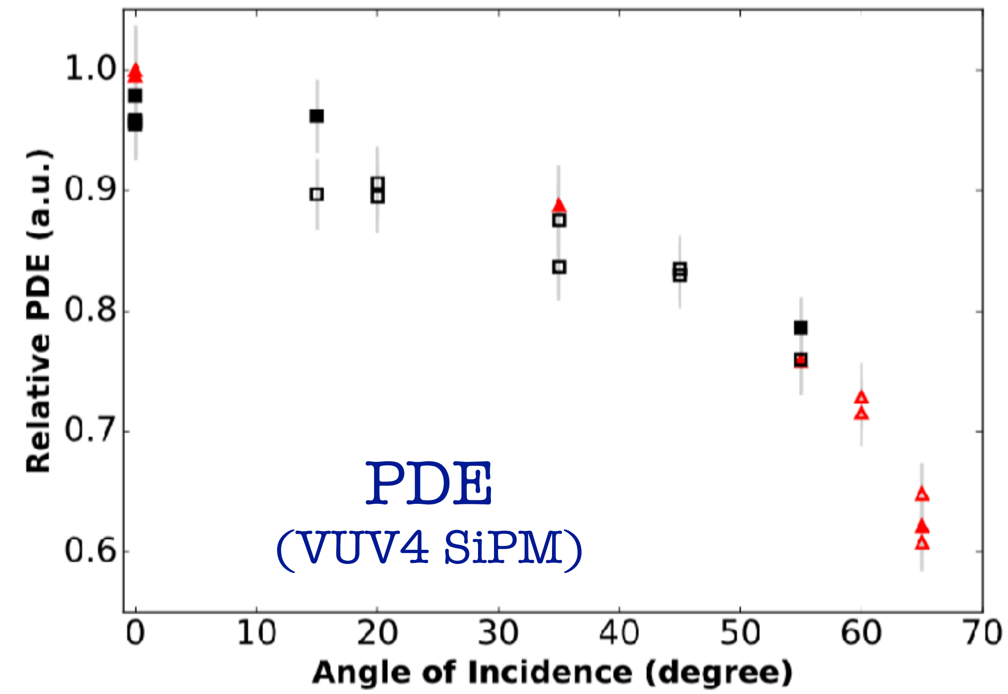
Some 1cm² VUV devices now match our desired properties, with a bias of ~30V

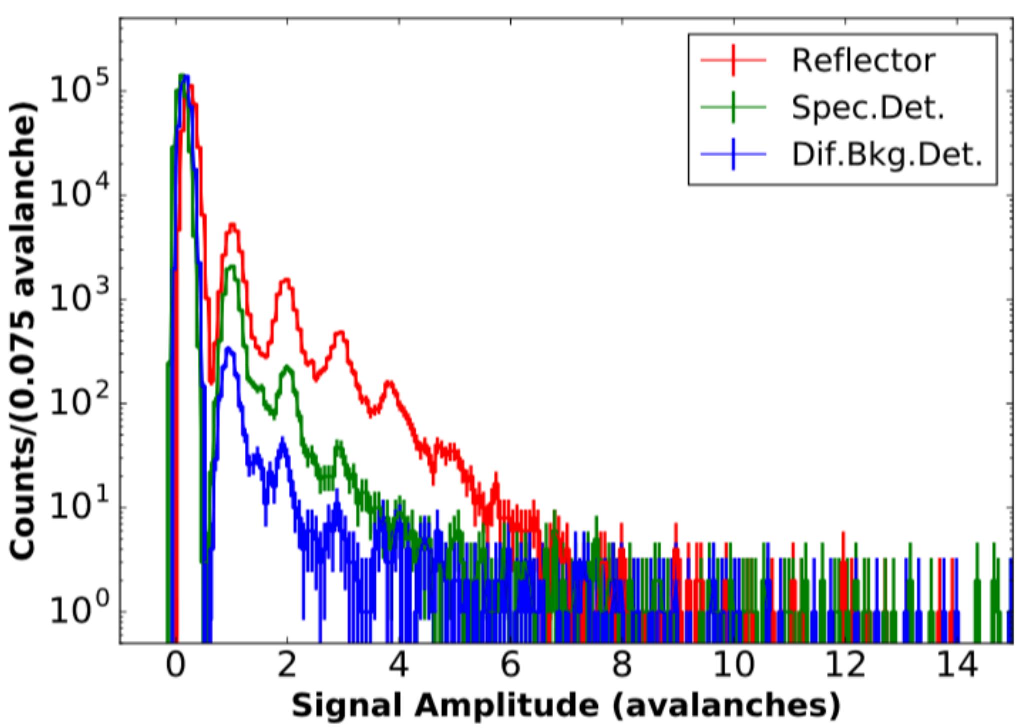
SiPM reflectivity (LXe)

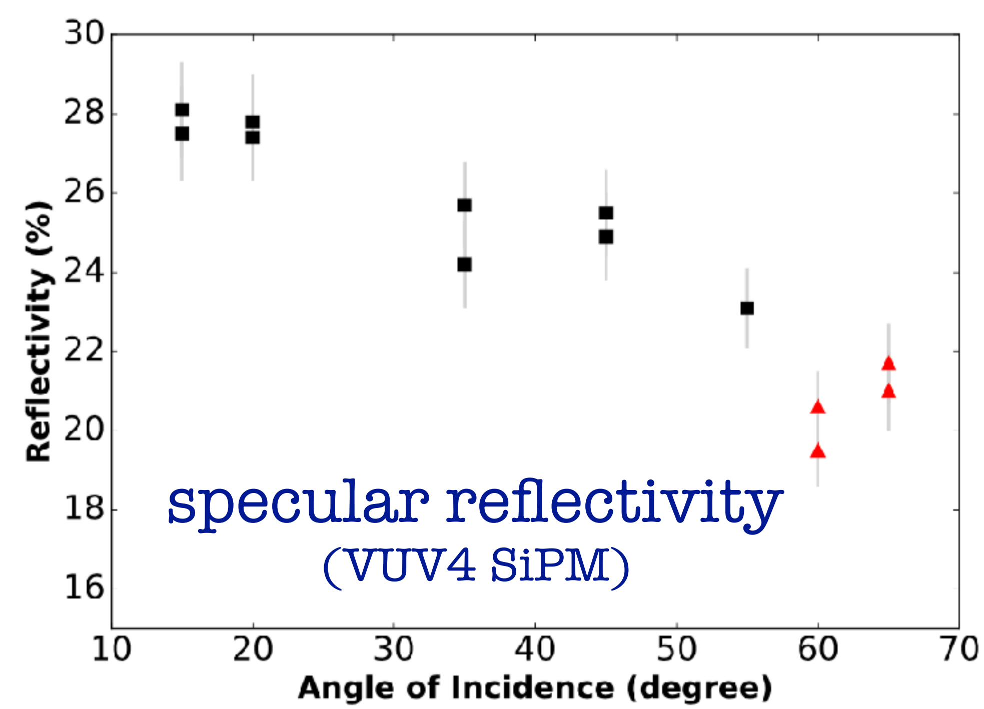
arXiv:1910.06438



LIXO setup at Alabama

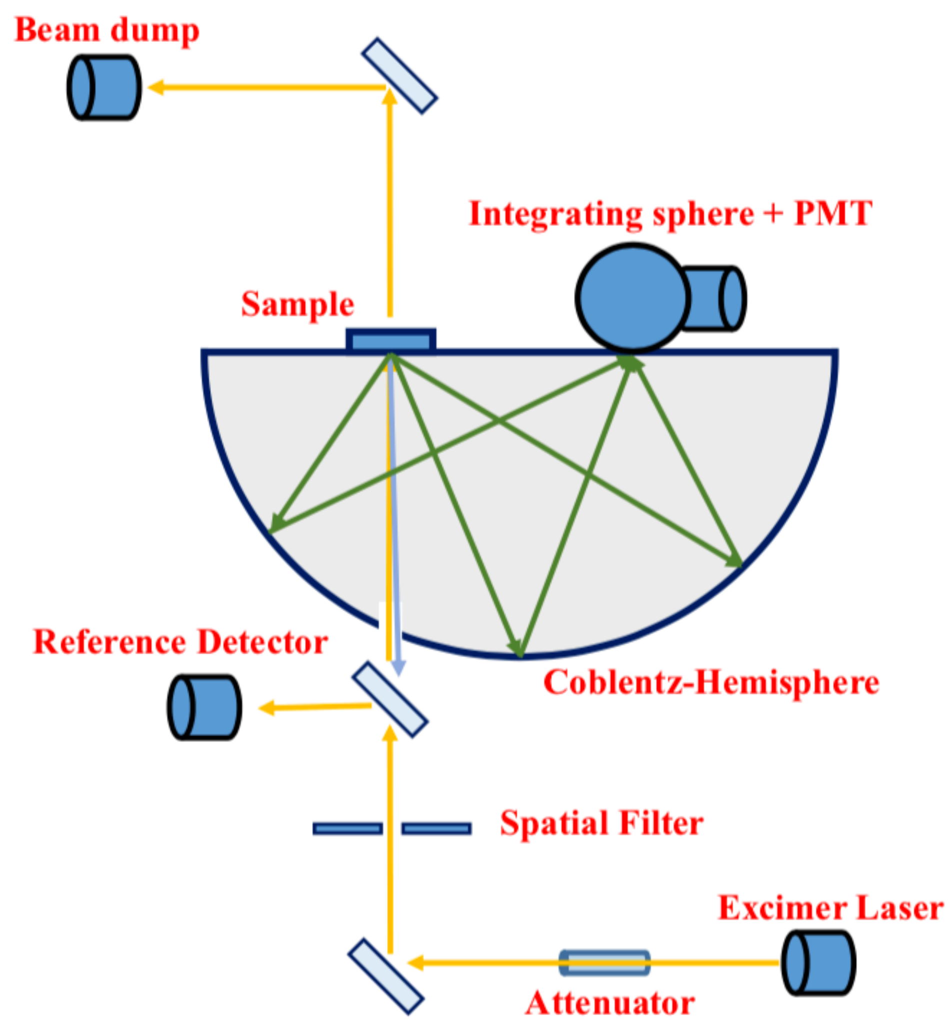






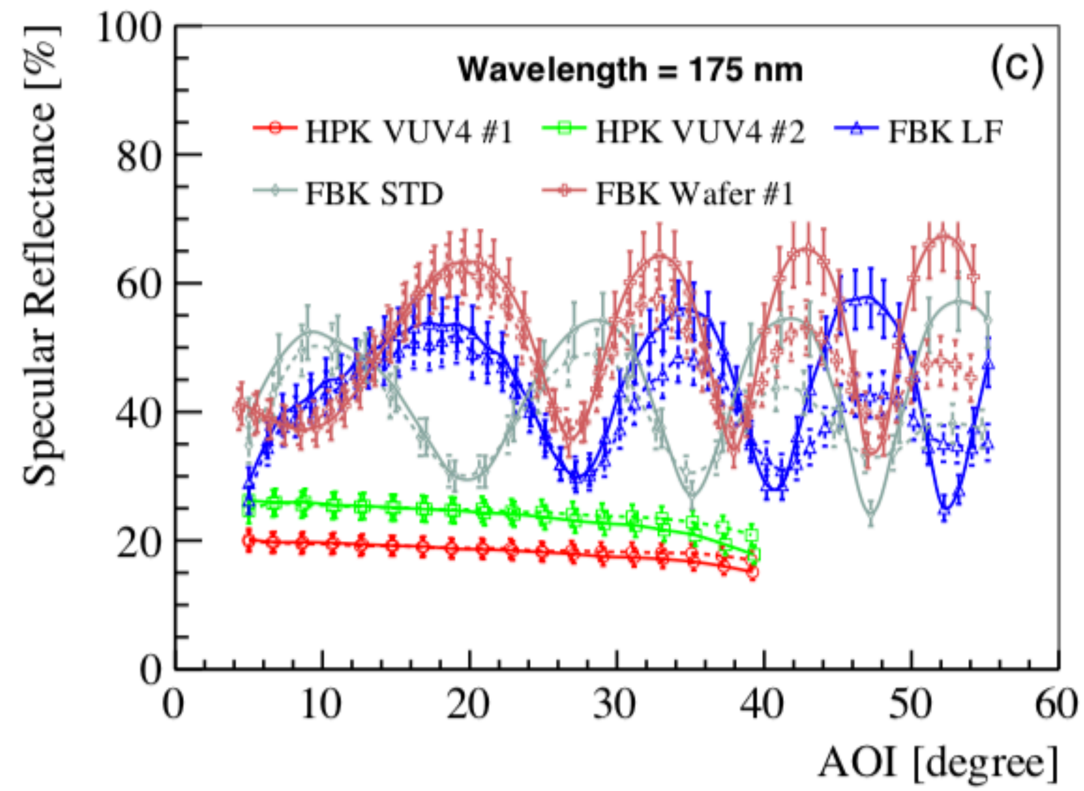
Optics / SiPM reflectivity

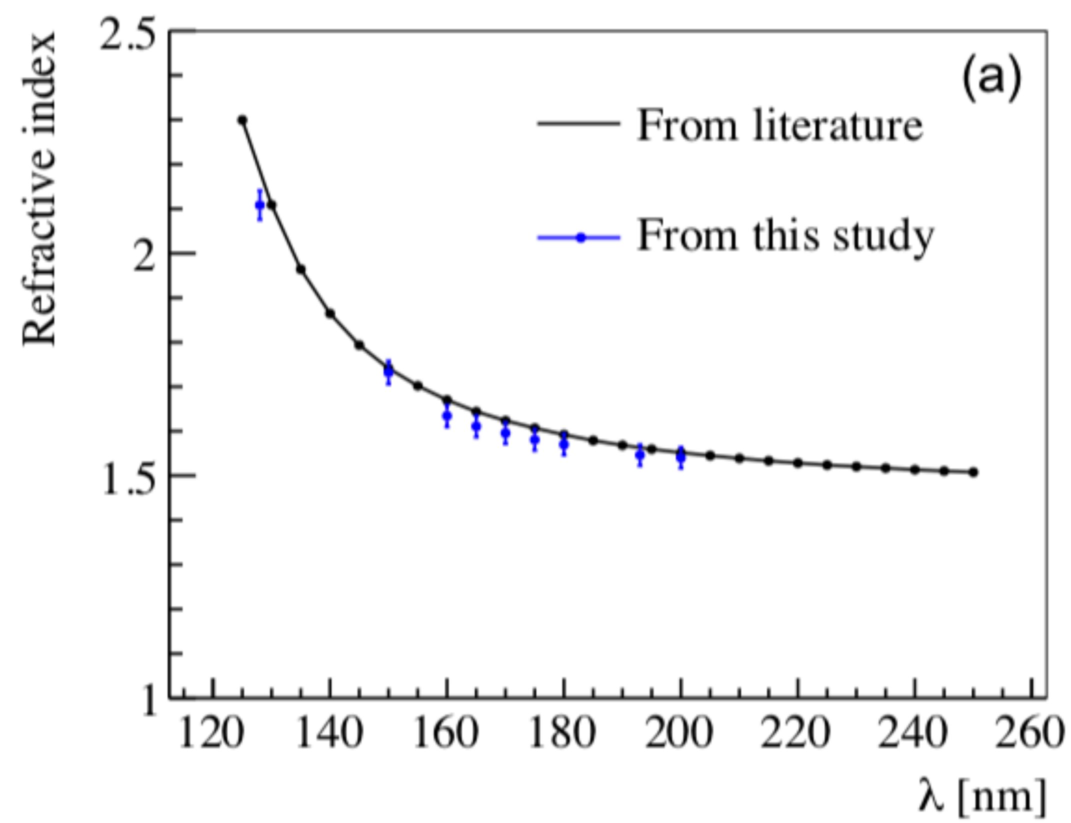
arXiv:1912.01841



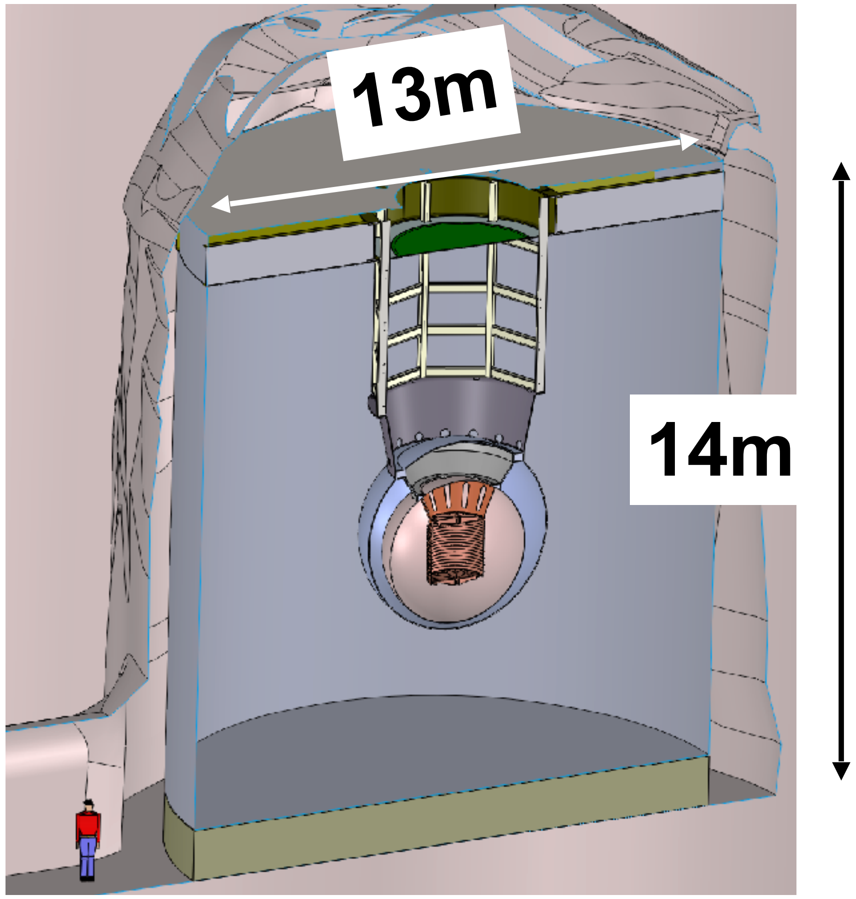
setup at IHEP Beijing

(in gas/vacuum)

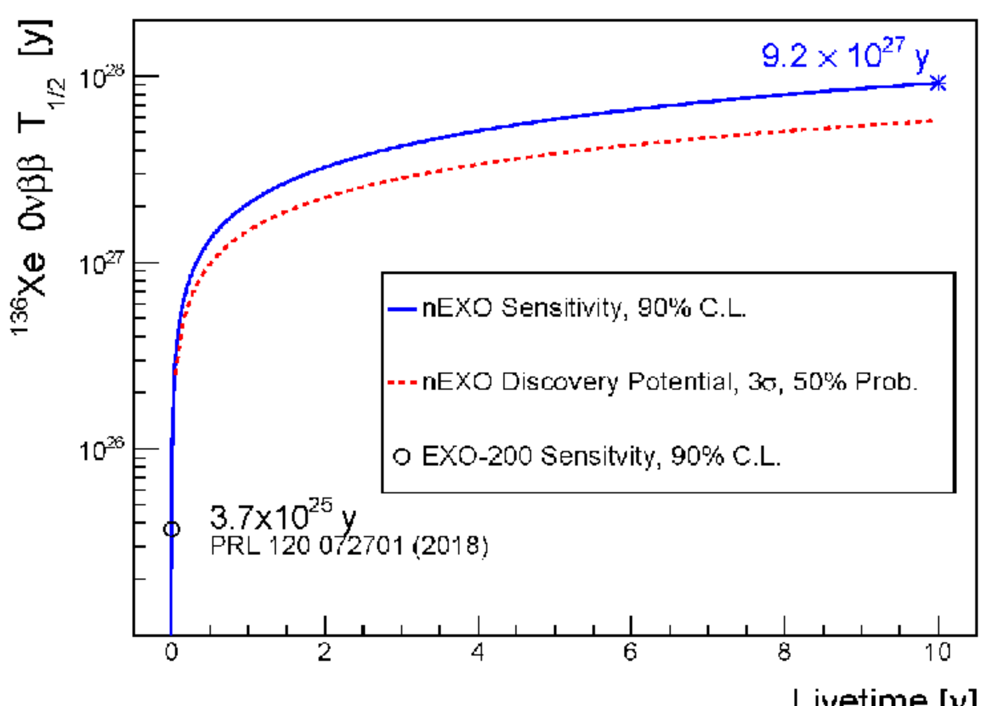


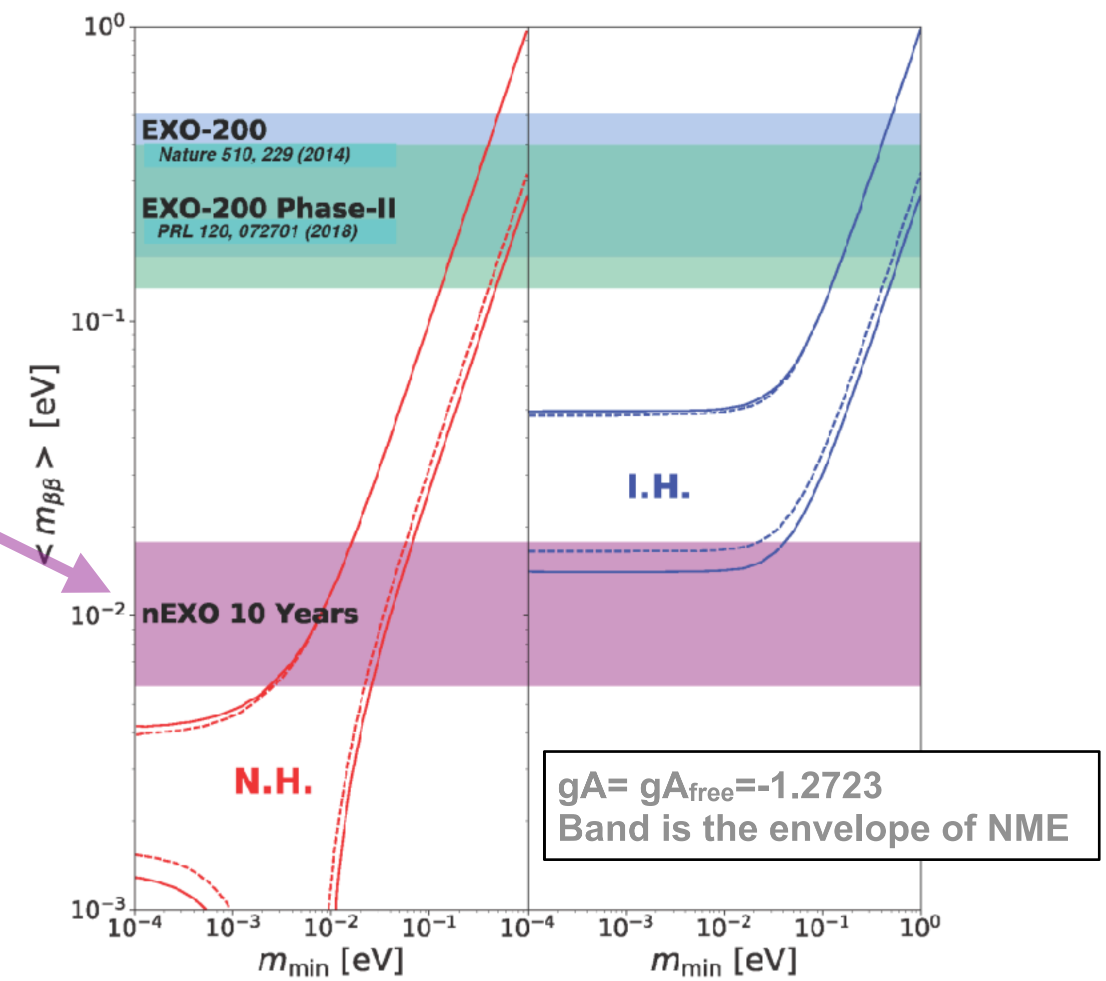


nEXO sensitivity timeline



- Ultra-low background 'core'
- Precisely measure background at the periphery
- Incorporate knowledge of background in sensitivity calculation
- 'Background index' is fiducial volume-dependent

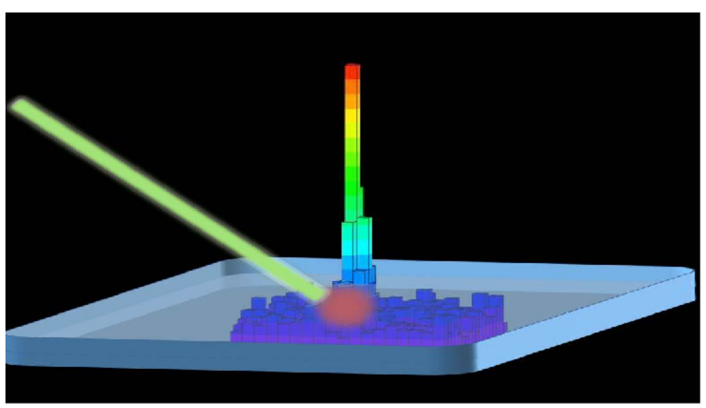




Imaging individual Ba atoms for barium tagging in ^{136}Xe neutrinoless double beta decay

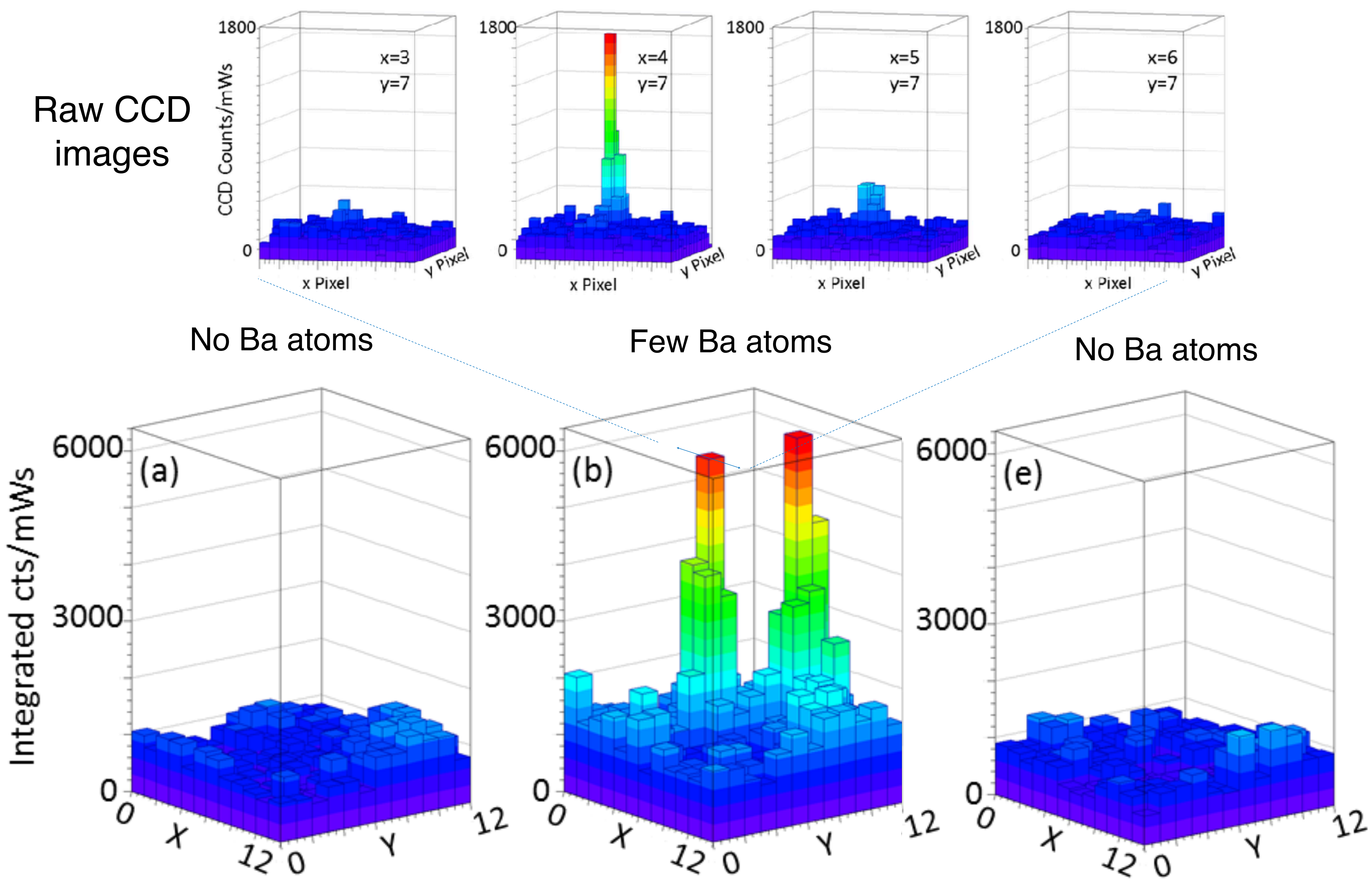
A first demonstration of counting the number of Ba atoms captured in solid xenon to be applied eventually to counting 0 or 1 Ba daughter in a candidate $0\nu\beta\beta$ decay event.

Laser scans across solid Xe deposit and generates large fluorescence when it hits one captured Ba atom.



First imaging of individual atoms in a solid noble element matrix.

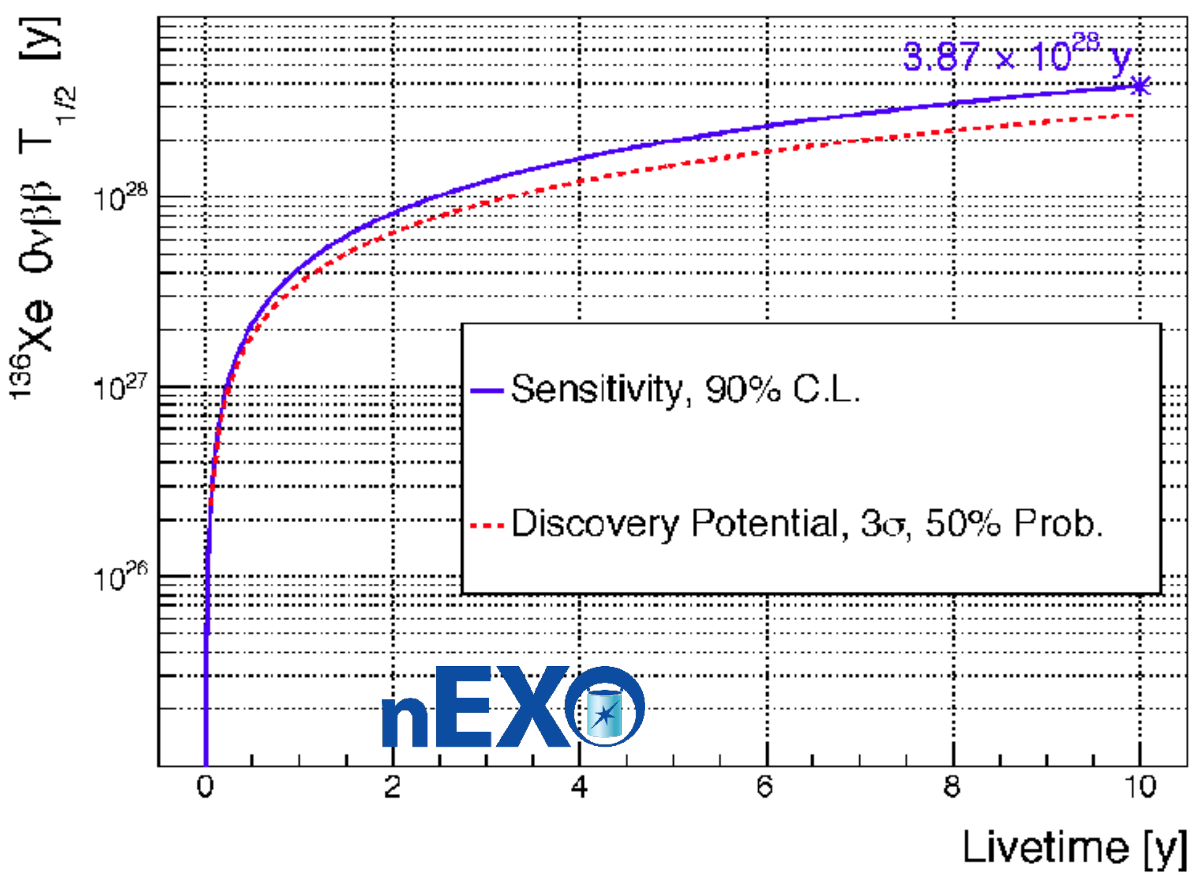
C. Chambers et al., Nature 569, 203 (2019).



Composite scan image of two Ba atoms

Potential application is other nuclear physics experiments

Beyond the inverted hierarchy (>10^{28} yr)



Xenon offers the possibility of:

- re-use the enriched isotope in follow-up detectors (particularly compelling in case of a hint of discovery)
- tag the product nucleus of double beta decay (Ba-136)

Ba-tagging is not part of the nEXO baseline

Publications: detector, sensitivity, R&D

— "Reflectance of Silicon Photomultipliers at Vacuum Ultraviolet Wavelengths" arXiv:1912.01841

— "Measurements of electron transport in liquid and gas Xenon using a laser-driven photocathode" arXiv:1911.11580

— "Reflectivity and PDE of VUV4 Hamamatsu SiPMs in Liquid Xenon" arXiv:1910.06438

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— "nEXO pCDR" arXiv:1805.11142 (2018)

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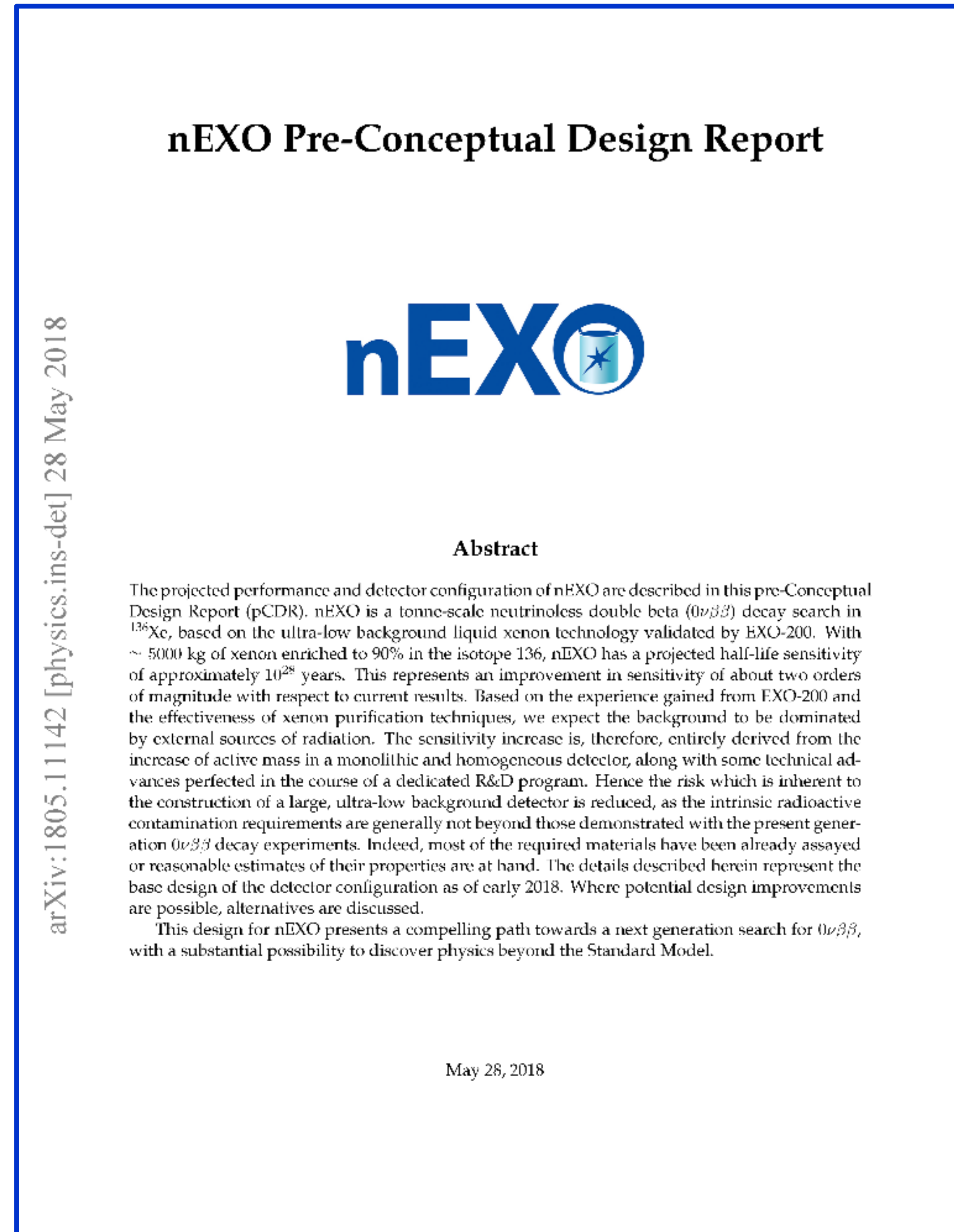
— "Characterization of an Ionization Readout Tile for nEXO" J.Inst. 13 P01006 (2018)

— "Characterization of Silicon Photomultipliers for nEXO" IEEE Trans. NS 62 1825 (2015)



nEXO Pre-Conceptual Design Report

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

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.

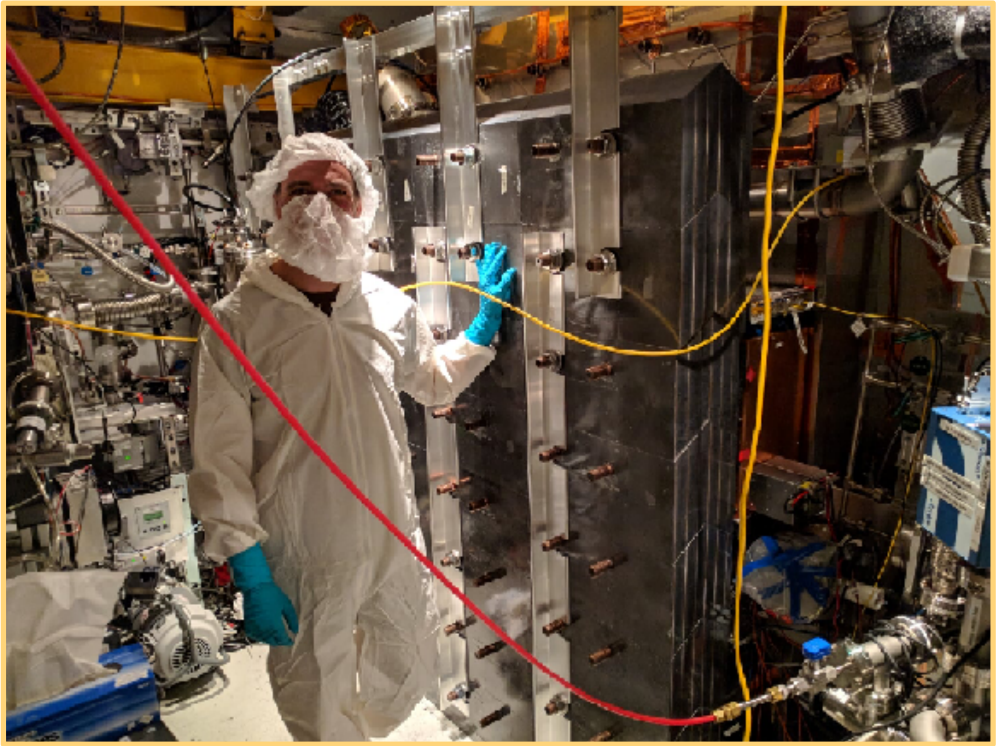
This design for nEXO presents a compelling path towards a next generation search for $0\nu\beta\beta$, with a substantial possibility to discover physics beyond the Standard Model.

May 28, 2018

** Not nEXO baseline*

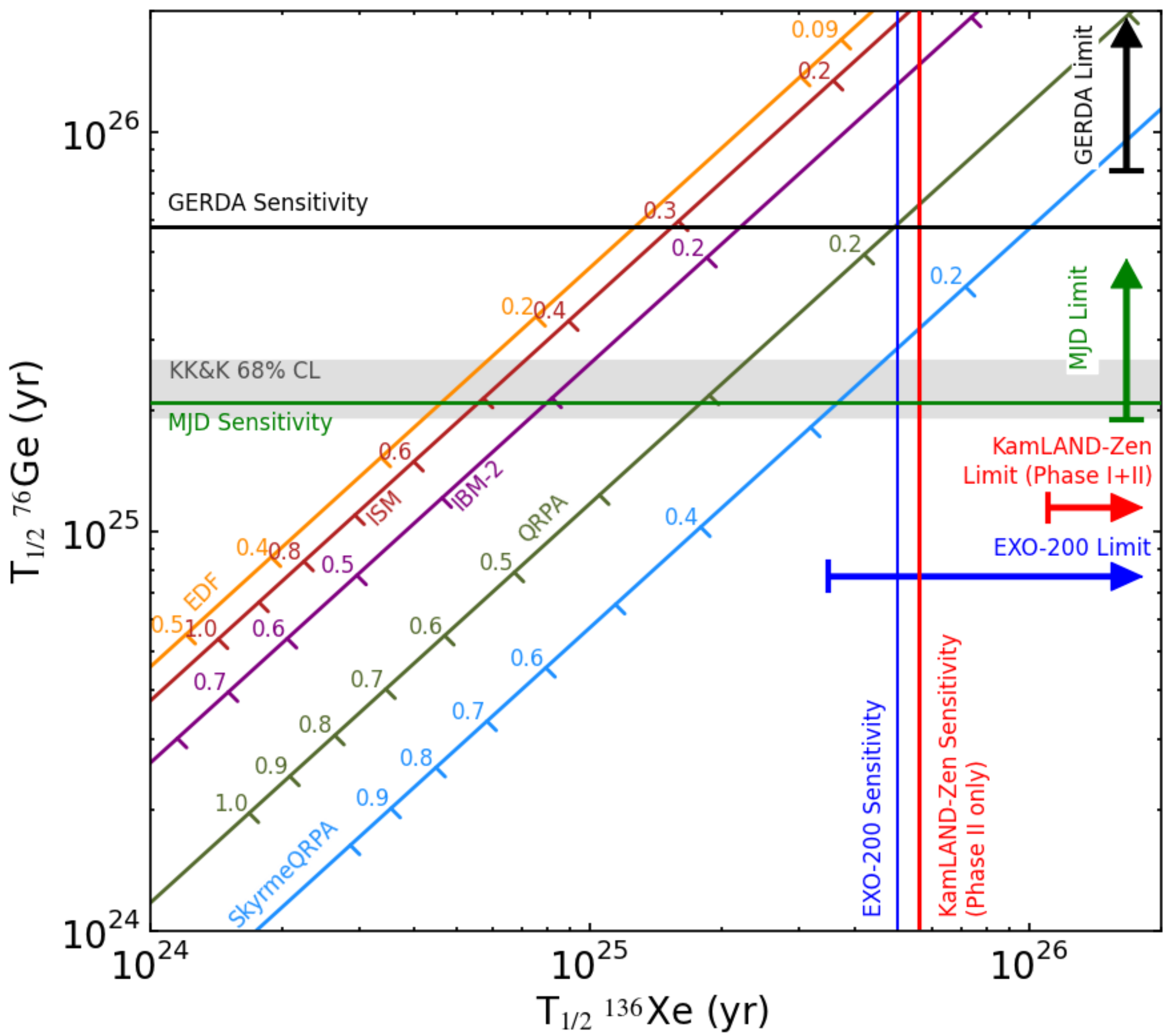
Closing remarks

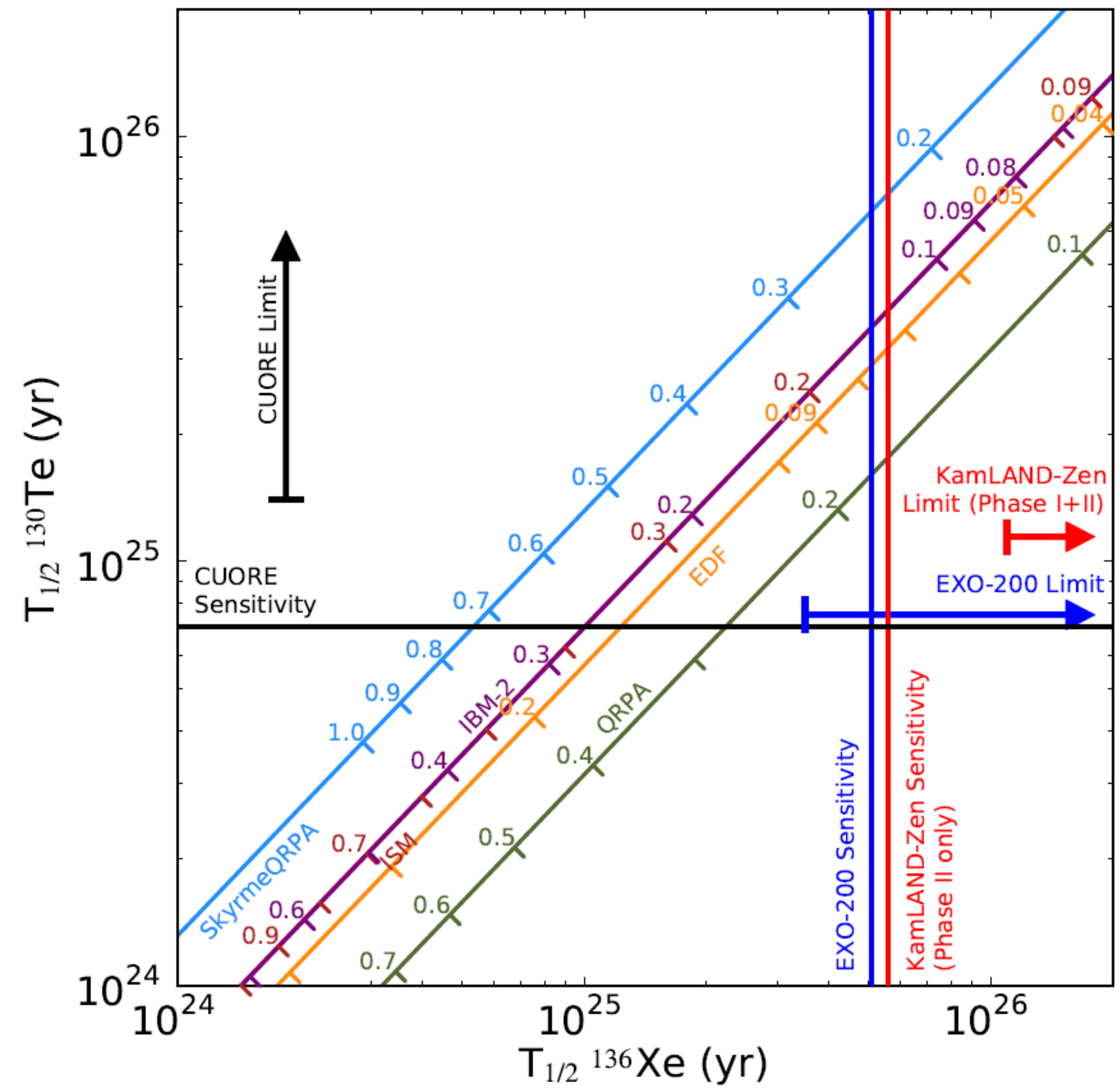
stay hungry, my friend



- In addition to Ba-tagging, ideas are emerging for larger xenon detectors that could reach $0\nu\beta\beta$ half lives of 10^{29} year (and perhaps 10^{30} yr)
- The next 5-10 years could identify paths for very large, ultra-low background detectors (with procurement/cost aside)
- The tonne-scale experiments might not have the final say, especially if a discovery is hinted at

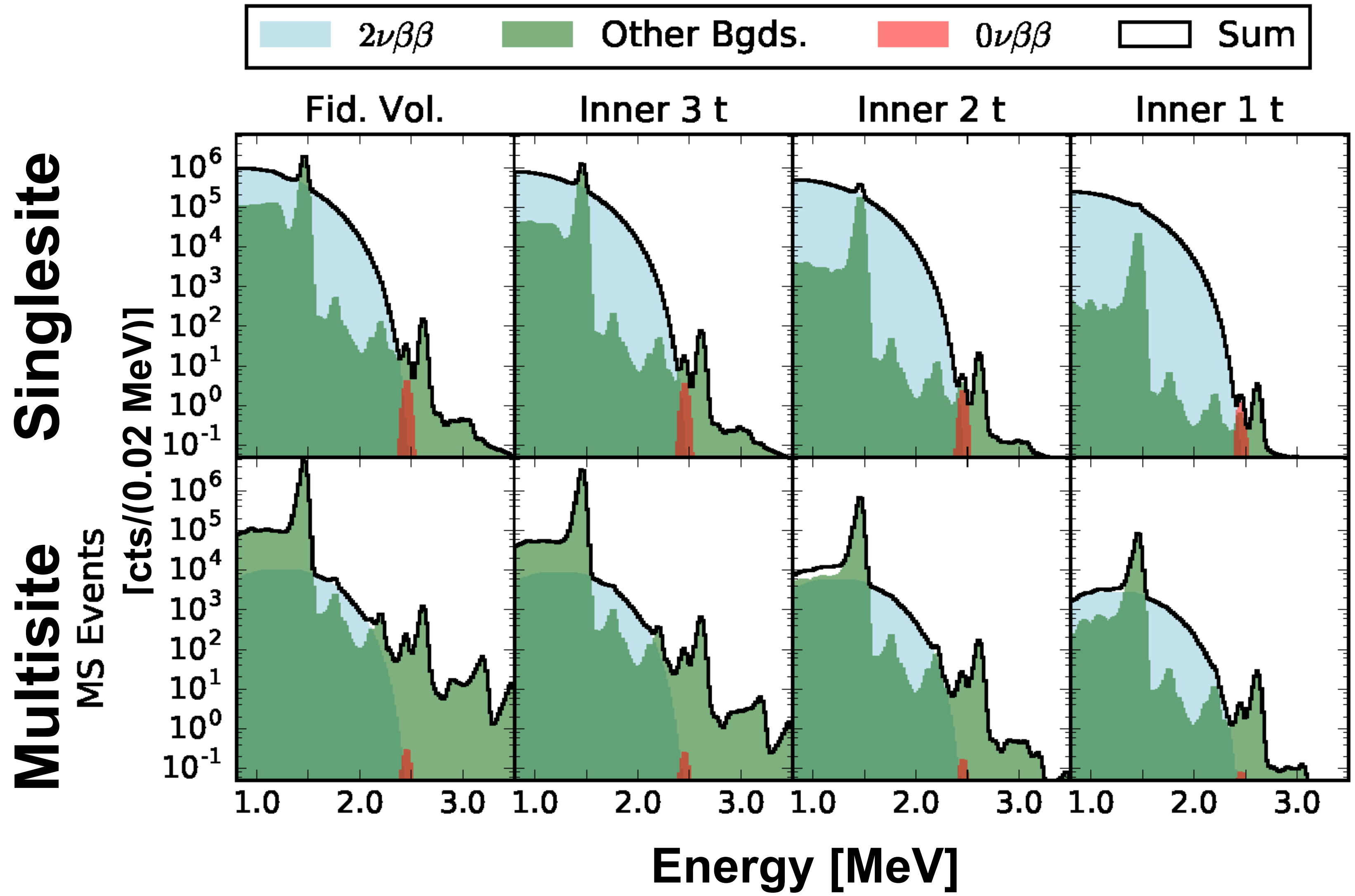
Comparing isotopes





A comparison to experiments using other isotopes requires assumptions on the mass mechanism and the matrix elements

Signal and background volume profiles



Corresponding to 10 yr data, with $0\nu\beta\beta$ $T^{1/2}=5.7\times10^{27}$ yr

Particularly in the larger nEXO, background identification and rejection fully use a fit considering simultaneously energy, e-γ and α-β discrimination and event position.

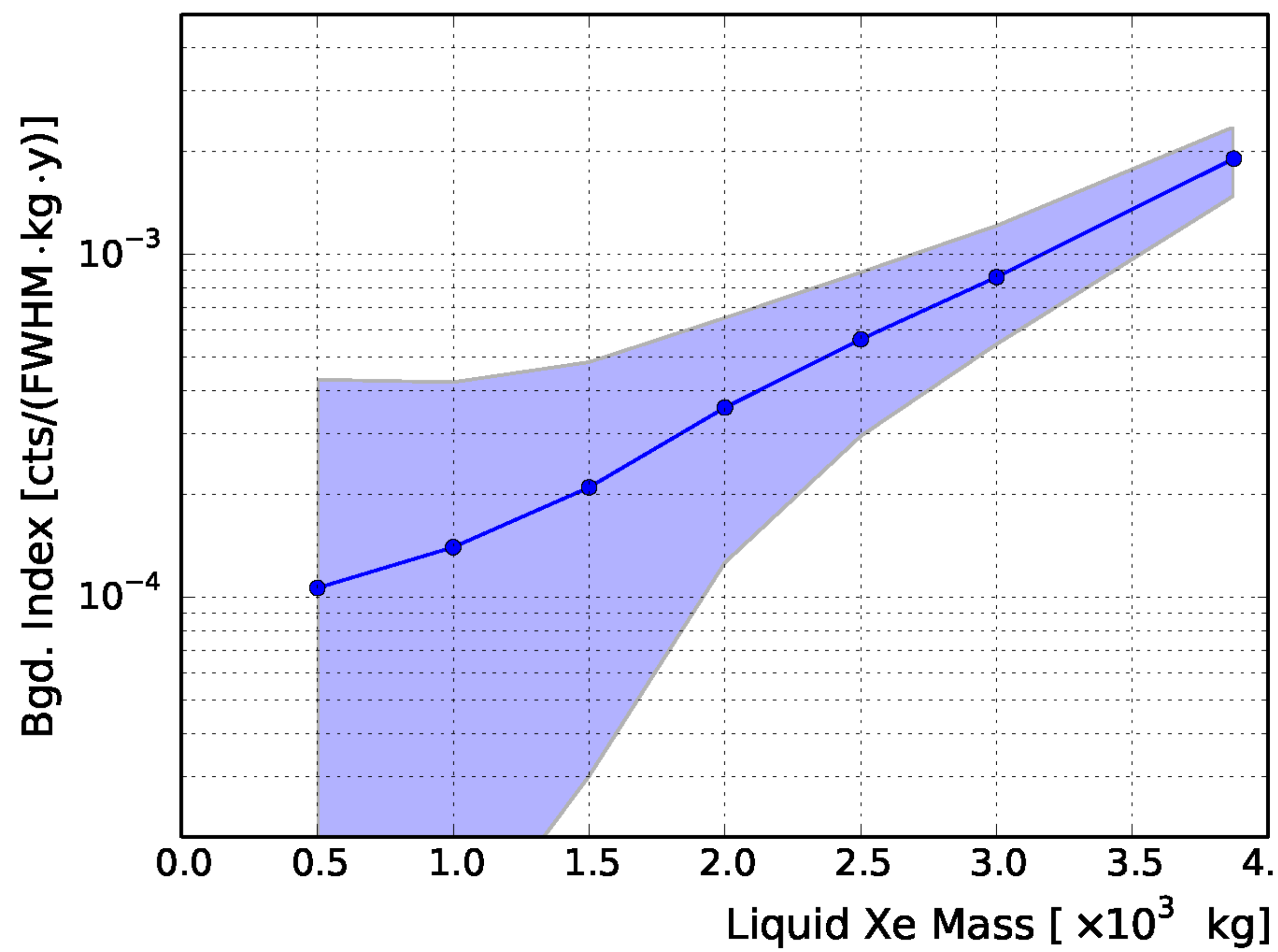
→ ***The power of the homogeneous detector, this is not just a calorimetric measurement!***

No unique ‘background index’

A single “background index” is not the entire story.

-The innermost LXe mostly measures signal
-The outermost LXe mostly measures background
-The overall fit knows all this (and more) and uses all the information available to obtain the best sensitivity

Nevertheless, here is the ‘background index' as a function of depth in the TPC. For the inner 3000 kg this is better than 10^{-3} (kg yr FWHM)$^{-1}$

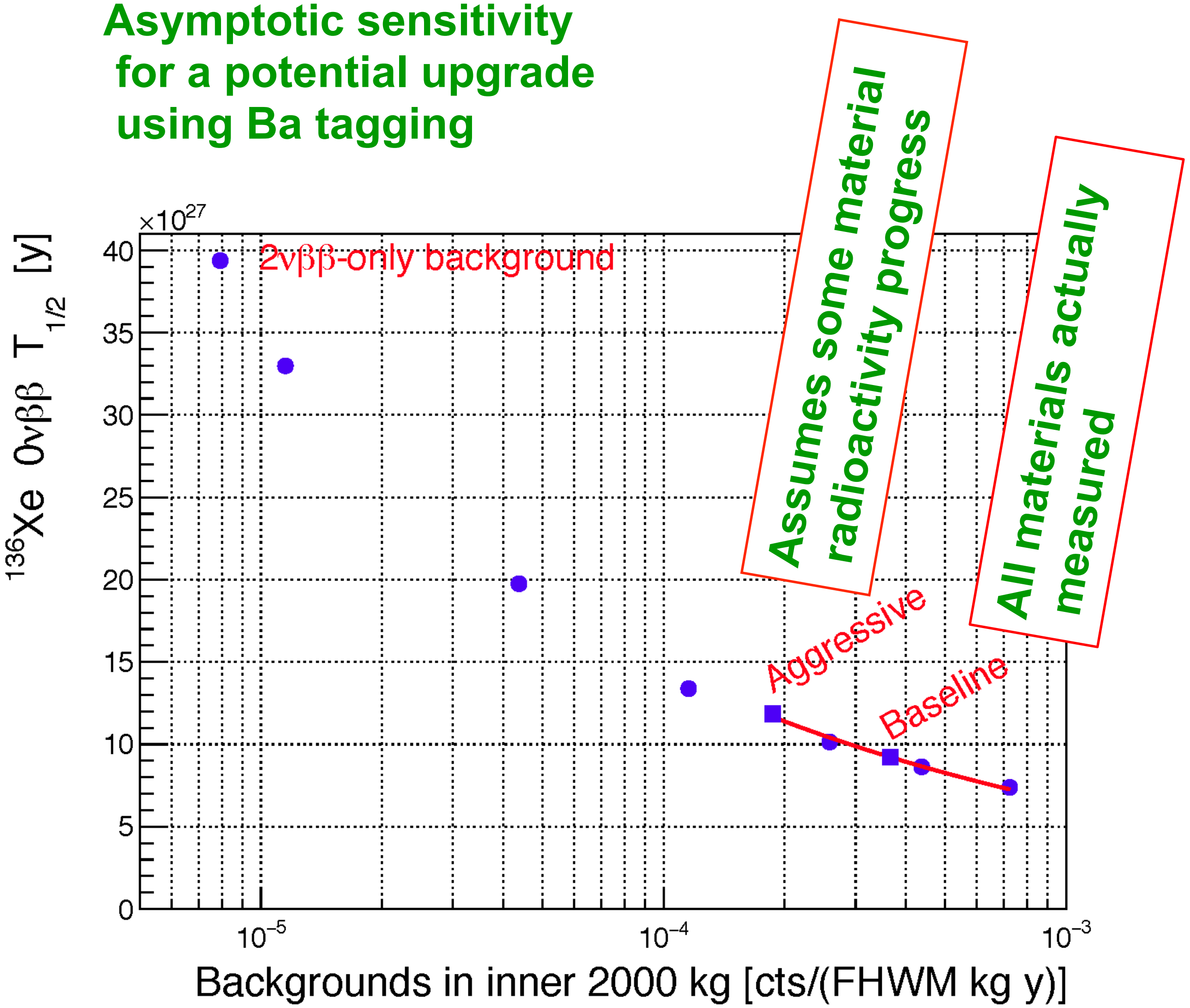


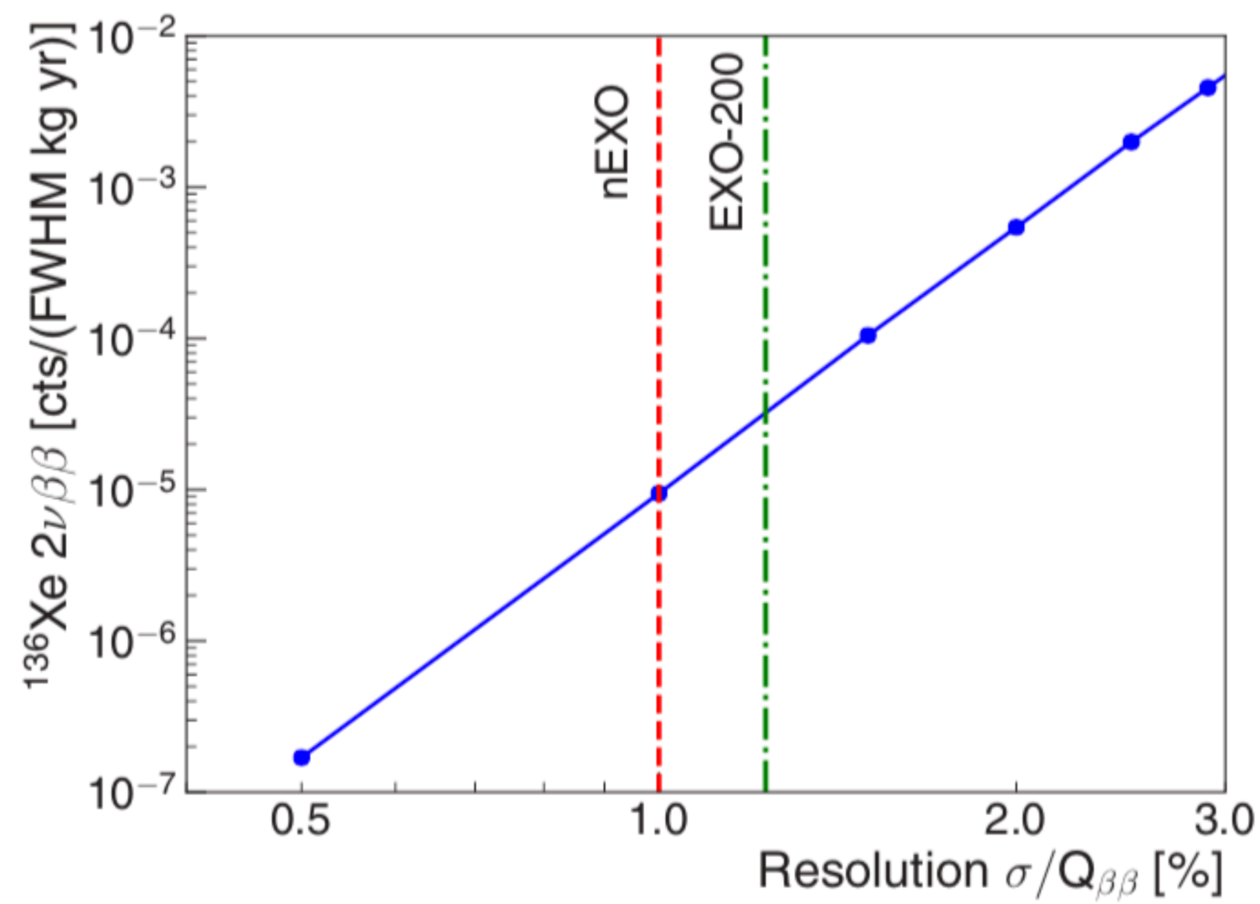
nEXO sensitivity vs. background

PRC **97**,065503(2018)

How does the sensitivity scale with background assumptions?

Asymptotic sensitivity for a potential upgrade using Ba tagging





nEXO sensitivity vs. energy resolution

How does the sensitivity scale with energy resolution?