XeSAT 2022 — Coimbra, 23-26 May 2022

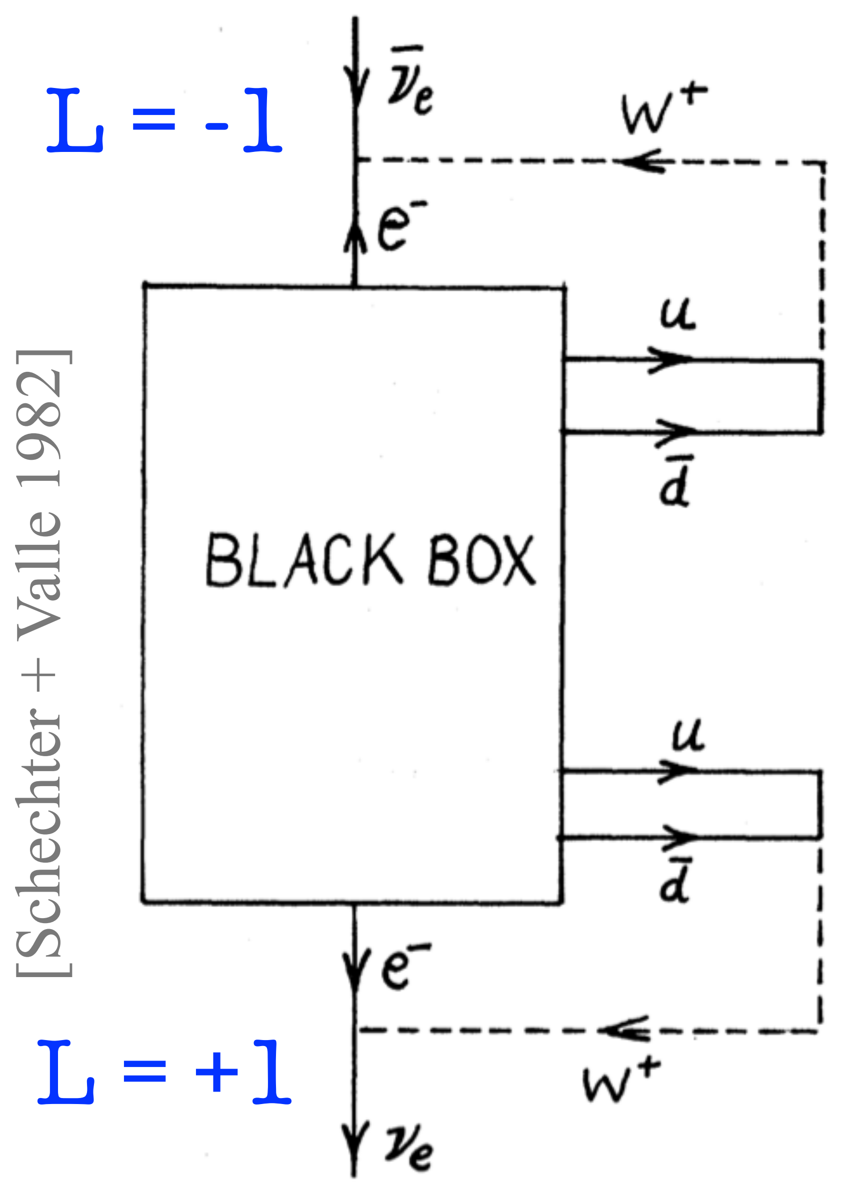
International Workshop on Applications of Noble Gas Xenon to Science and Technology

Searching for Majorana neutrinos with nEXO

Andrea Pocar @ University of Massachusetts, Amherst

on behalf of the nEXO collaboration

0νββ decay — motivation

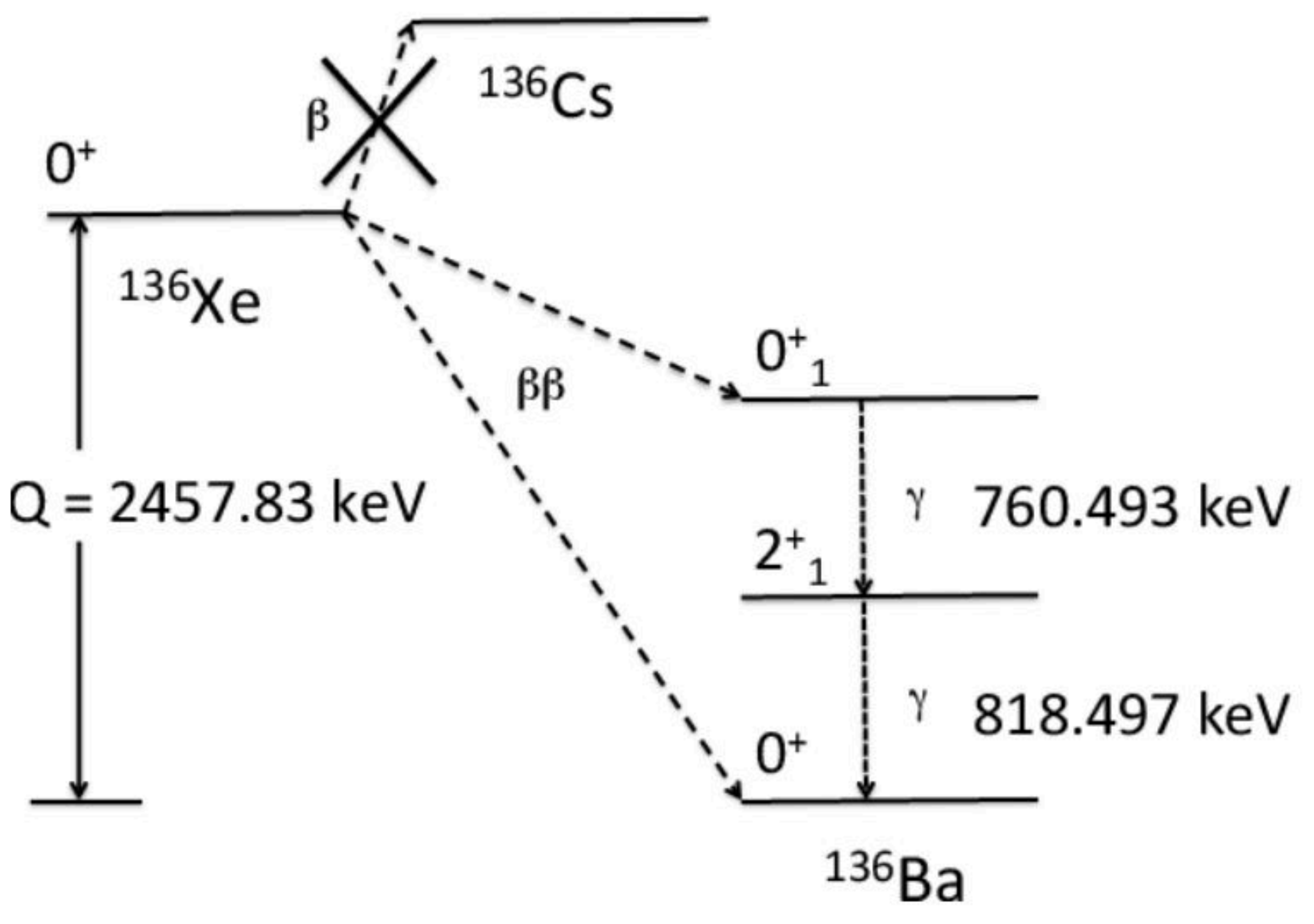


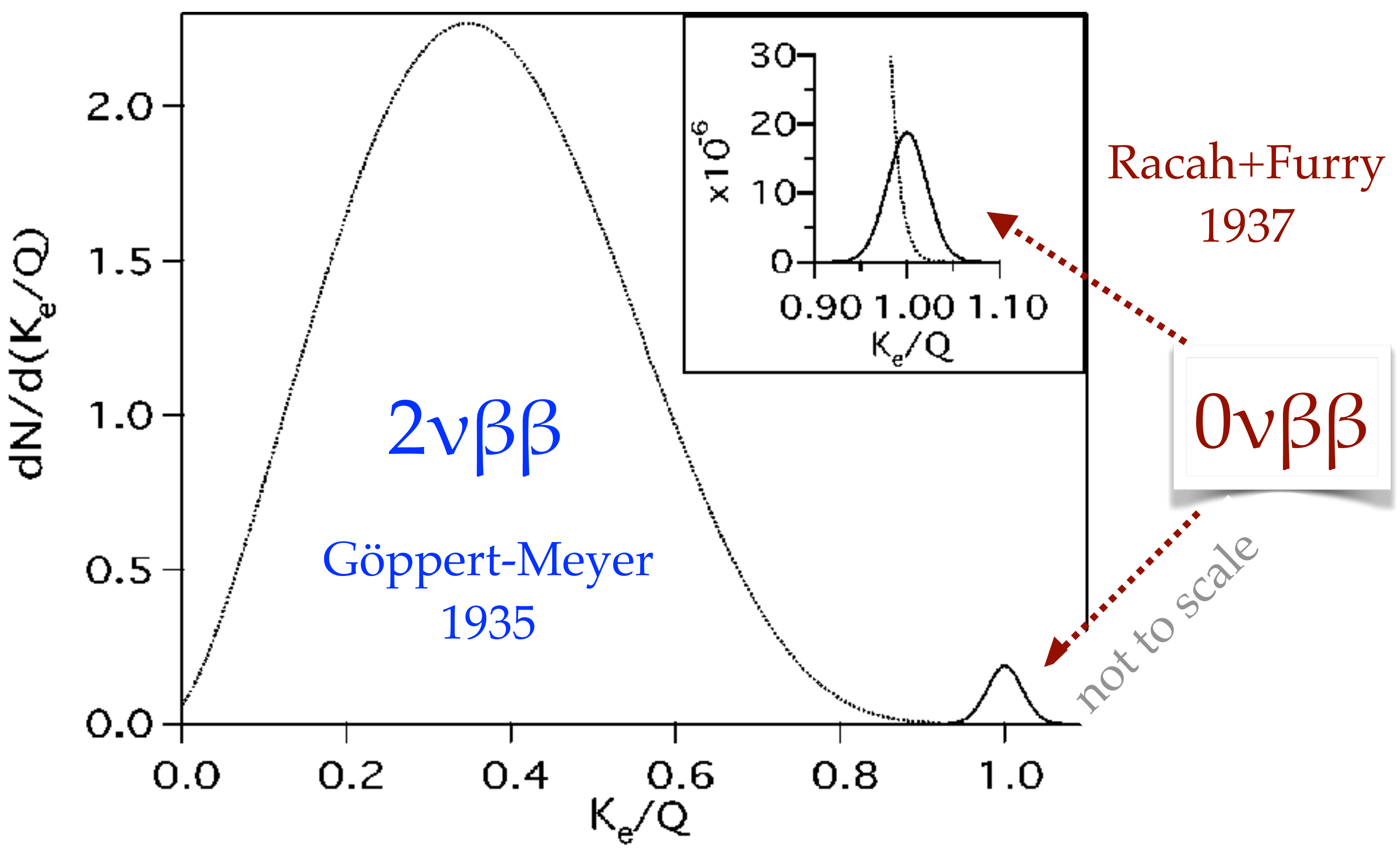
observation of 0νββ decay:

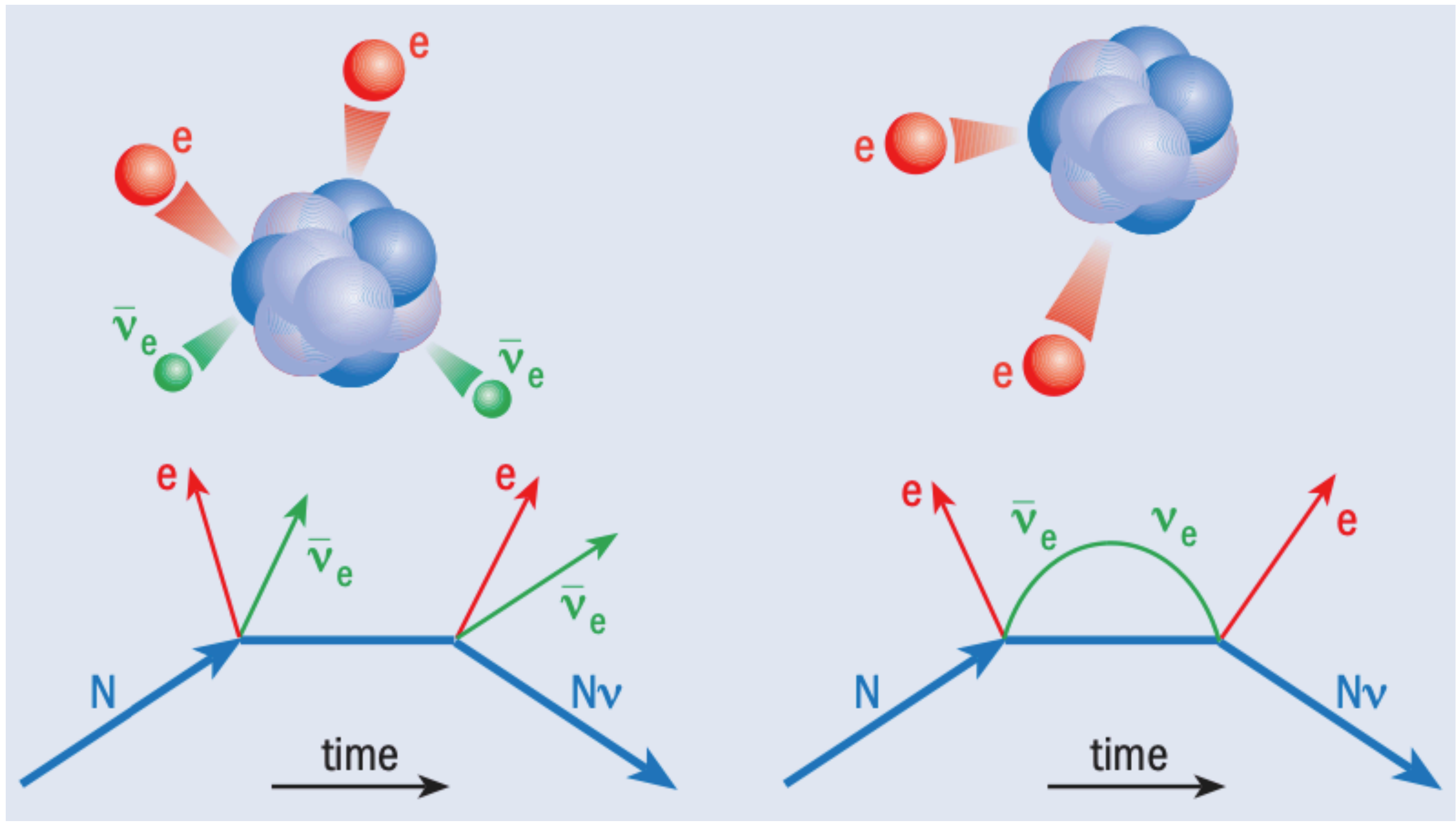
- massive, Majorana neutrinos
- lepton number violation (ΔL=2)
- new mass creation mechanism (non Higgs)
- matter dominance in the universe, Δ(B-L) leptogenesis
- smallness of neutrino mass -> new BSM physics mass scale

0νββ rate

- absolute neutrino mass (model dependent)





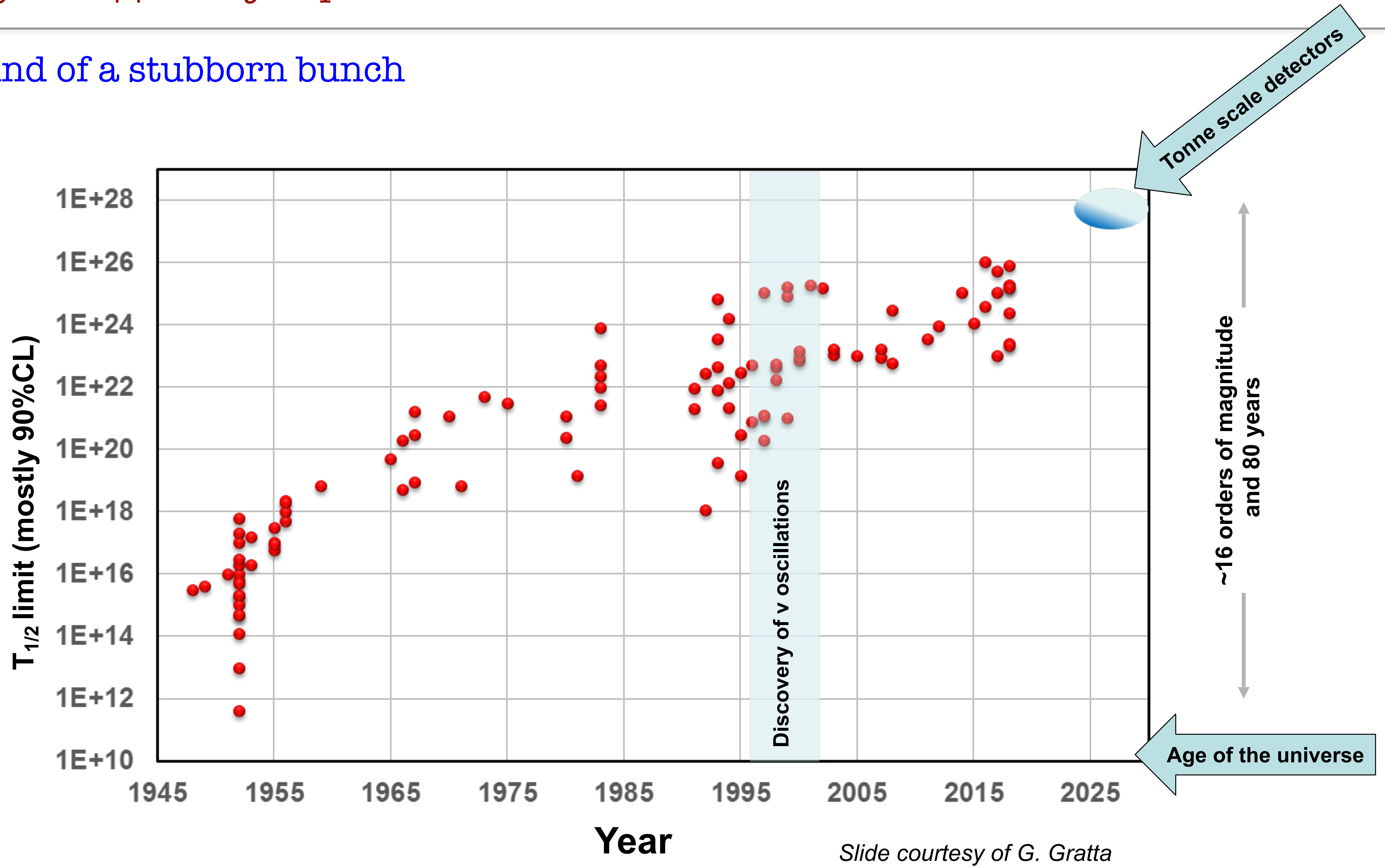


nEXO : A world wide effort involving 9 countries, 33 institutions, ~200 collaborators

Laurentian University Université Laurentienne
Carleton University
McGill
Université de Sherbrooke
UMass Amherst
Yale University
Brookhaven National Laboratory
WWU Münster
Rensselaer
The University of British Columbia
TRIUMF
Pacific Northwest National Laboratory
Skyline College Achieve
Lawrence Livermore National Laboratory
SLAC National Accelerator Laboratory
Stanford University
Caltech
UC San Diego
Colorado School of Mines
Colorado State University
The University of Alabama 1831
Oak Ridge National Laboratory
University of Kentucky
University of the Western Cape
UNCW University of North Carolina Wilmington
Drexel University
FAU Friedrich-Alexander Universität Erlangen-Nürnberg
ИТЭФ
Technical University of Munich
ibs Institute for Basic Science
IHEP
IMECAS
u^b Universität Bern
Subatech

The history of 0νββ decay experiments in one slide

…we are kind of a stubborn bunch



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

nEXO in the 0νββ decay landscape

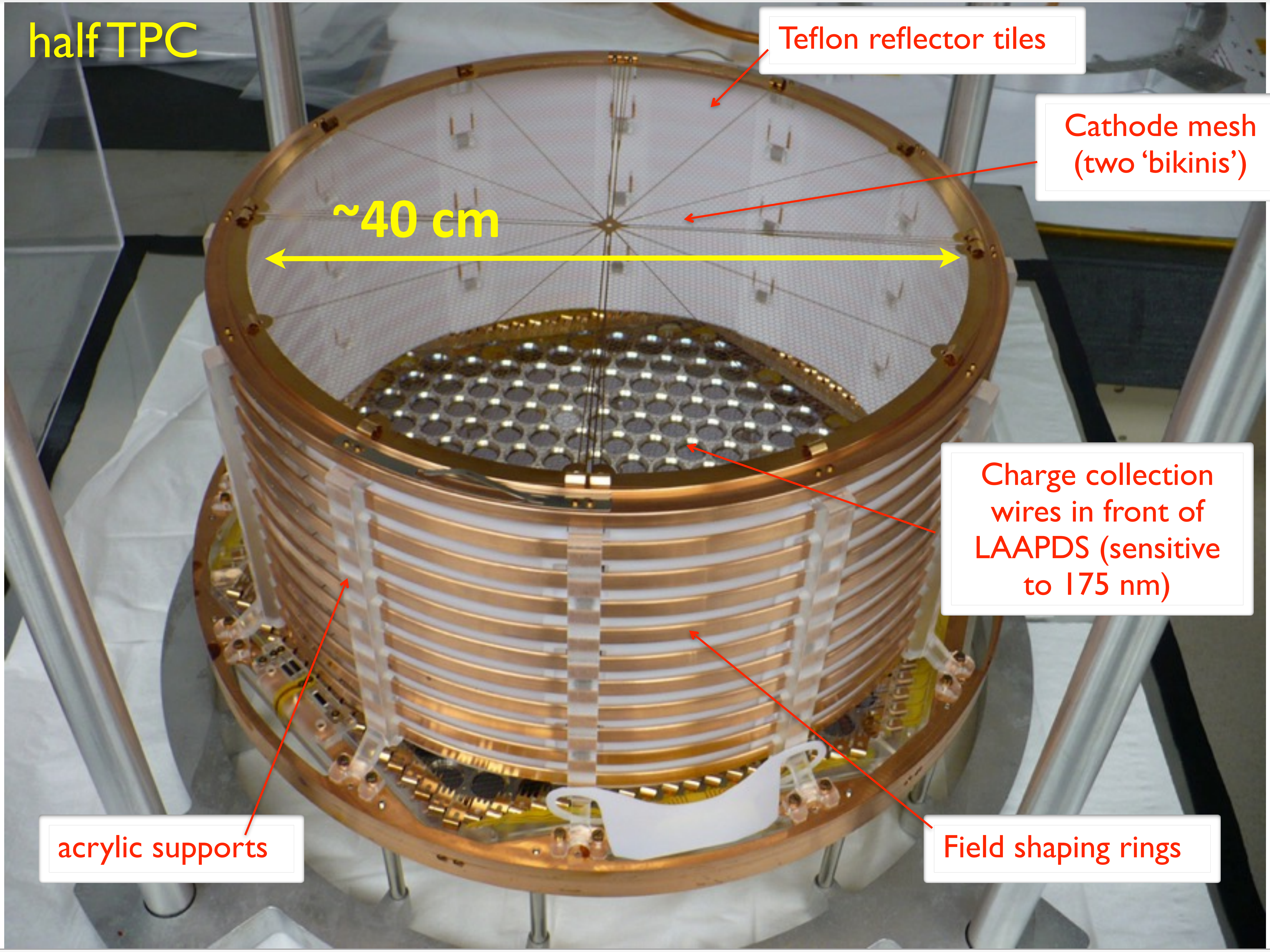
- The global 0νββ decay program is gearing up for the so-called "tonne-scale" phase (as communicated by the European and North American funding agencies at the 10/2021 International Forum at LNGS)
- Three major experiments with different isotopes:
  - nEXO (^{136}Xe), Legend-1000 (^{76}Ge), CUPID (^{100}Mo)
  - very different experimental techniques, healthy program
- nEXO plans a 5-tonne, single phase, LXe TPC (90% enriched in 136 isotope) 100-fold increase in sensitivity wrt current experiments
- nEXO builds on the successful EXO-200 program which has demonstrated the key technical features of this technology at scale, such as:
  - Effectiveness of self-shielding and low intrinsic background
  - Energy resolution via collection of ionization and scintillation
  - Event topology (β vs. γ) and particle ID (β/γ vs. α)
  - Continuous purification of the source

EXO milestones (2001-): R&D -> EXO-200 -> nEXO

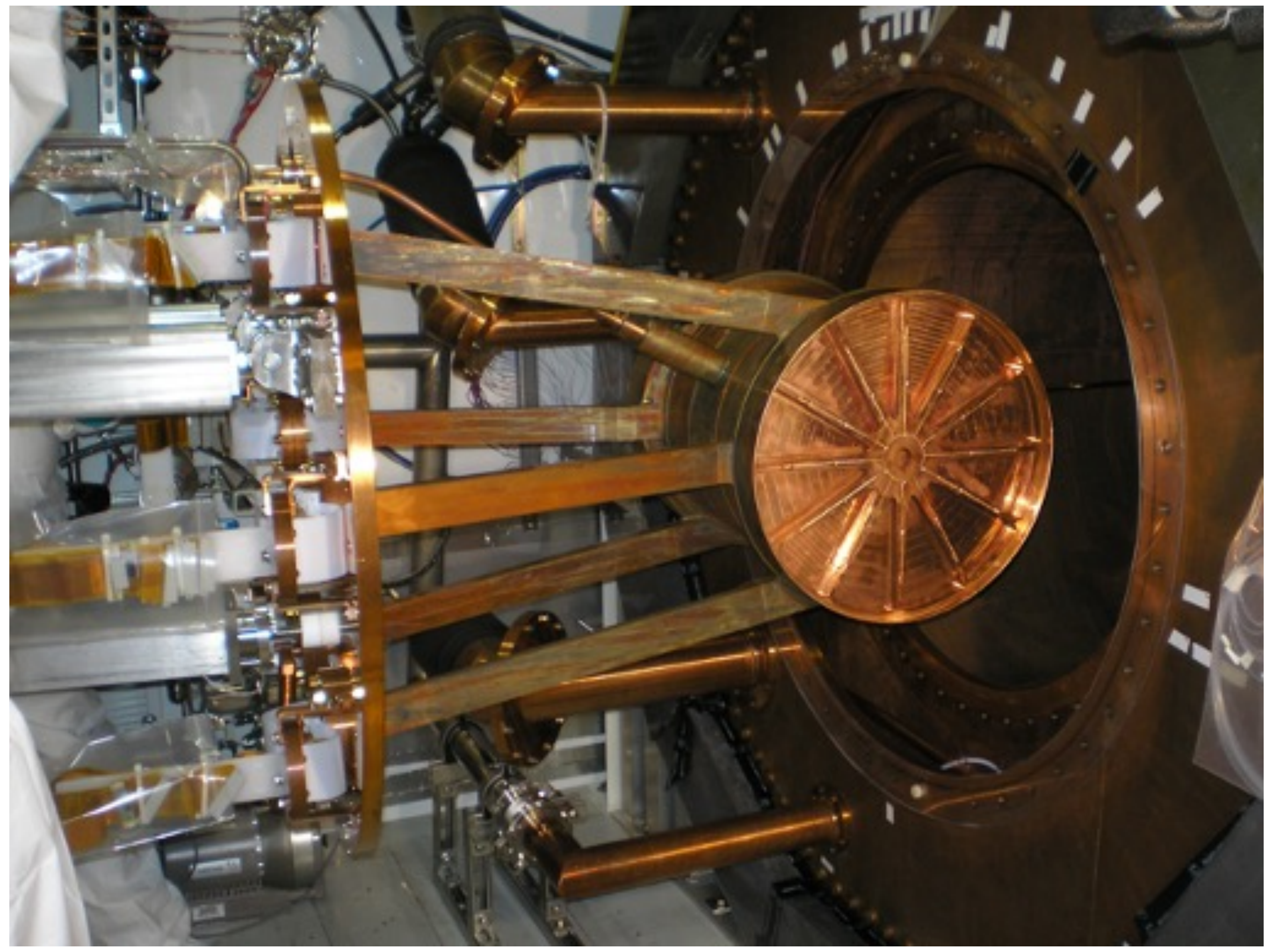
nEXO

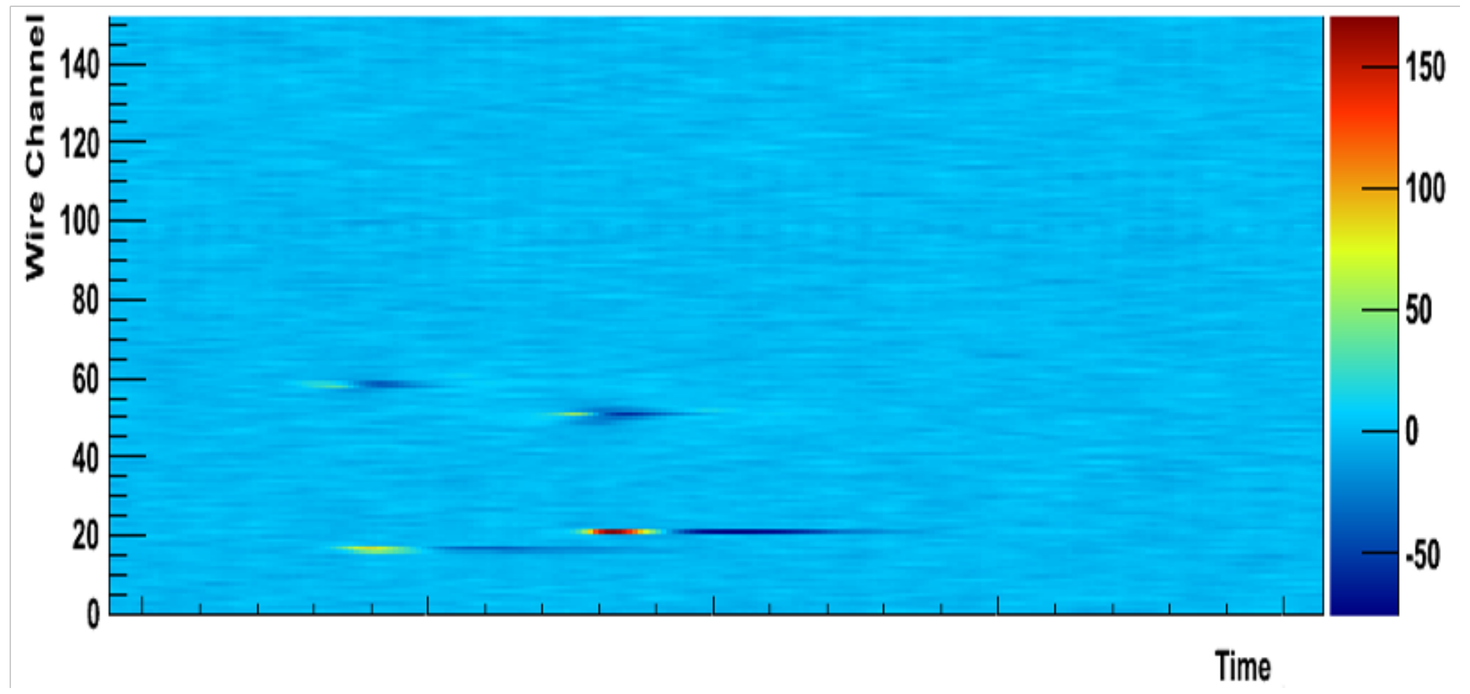
2001	“EXO” started as an R&D towards a ^{136}Xe ββ decay experiment.
2002	Improved energy resolution in LXe using the correlation between scintillation and ionization is discovered.
Ca. 2005	Settled on a LXe TPC design for a “prototype” 200 kg detector.
2007-2010	The EXO-200 detector is designed and built, 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 2020	nEXO MAC review
Feb 2021.	nEXO budget review
Jul 2021	DoE portfolio review
Sept 2021	Europe – North America Summit at LNGS

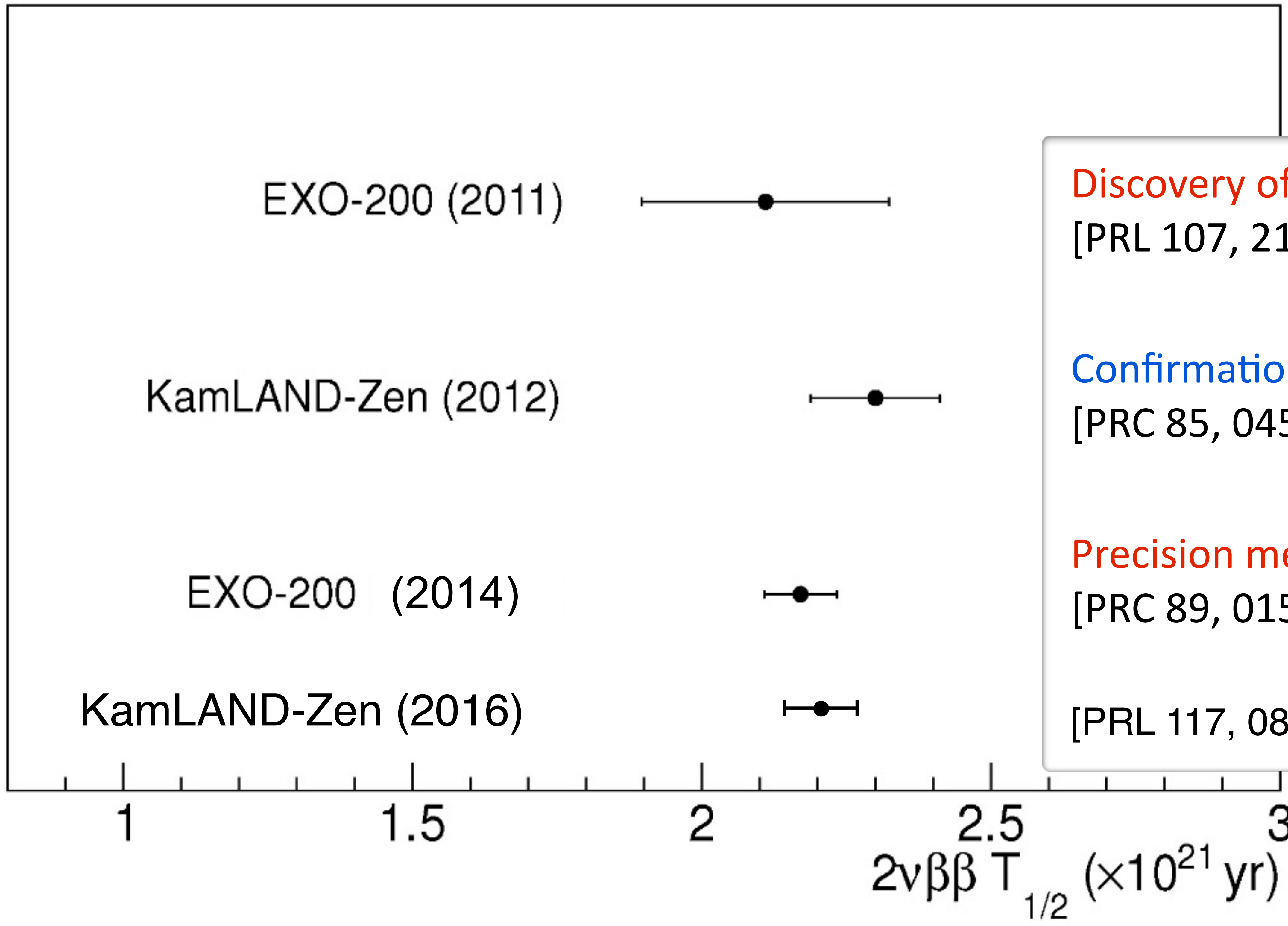
the EXO-200 TPC



Precision measurement of 2νββ







Discovery of 2νββ decay of ^{136}Xe
[PRL 107, 212501 (2011)]

Confirmation by KamLAND-Zen
[PRC 85, 045504 (2012)]

Precision measurement (~3%)
[PRC 89, 015502 (2014)]

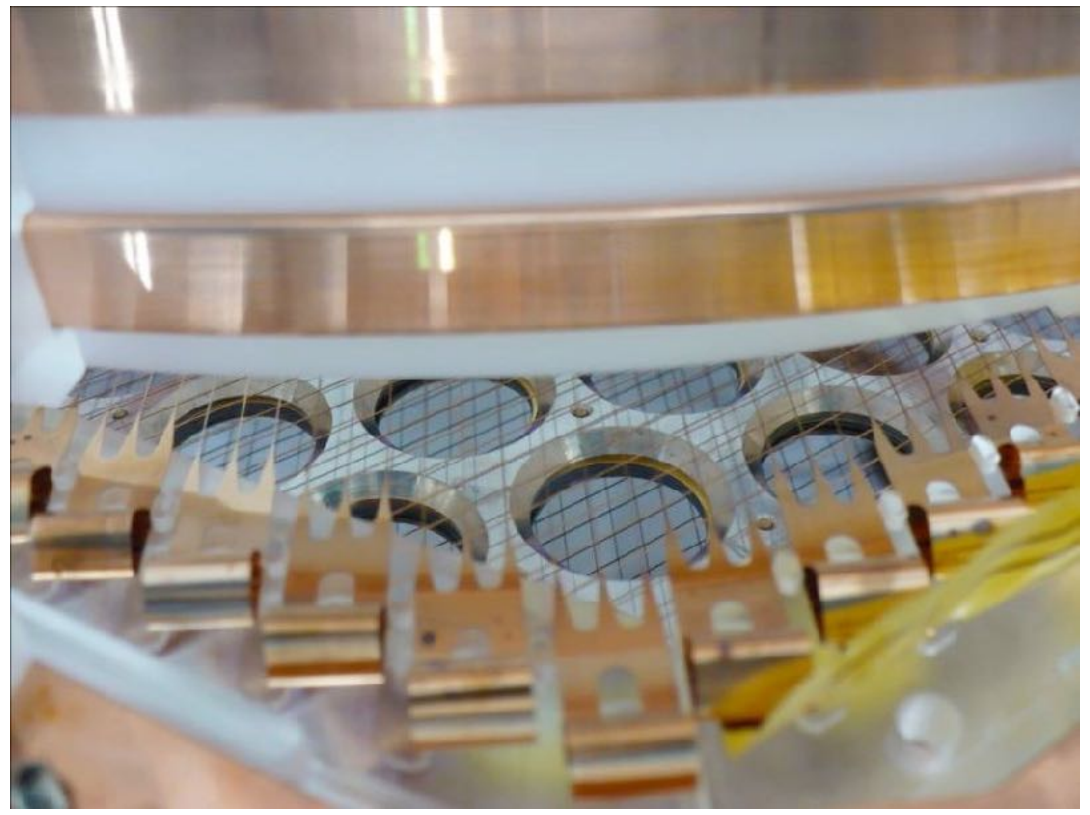
[PRL 117, 082503 (2016)]

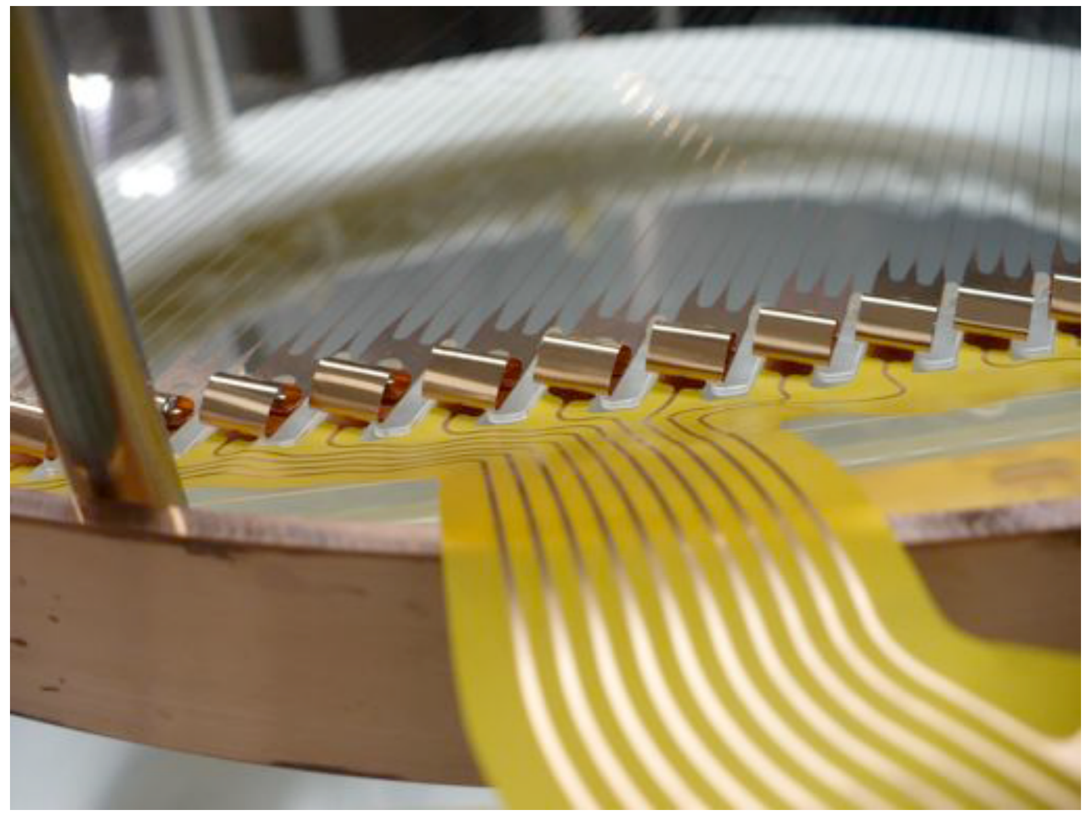
$$T^{2\nu\beta\beta}_{1/2} = (2.165 \pm 0.016(\text{stat}) \pm 0.059(\text{syst})) \times 10^{21}\text{yr}$$

(longest, first to be precisely* (directly) measured 2νββ decay of all ‘practical’ isotopes)

(* Ge-76 and Te-130 have similarly precise measurements)

EXO-200 0νββ decay results





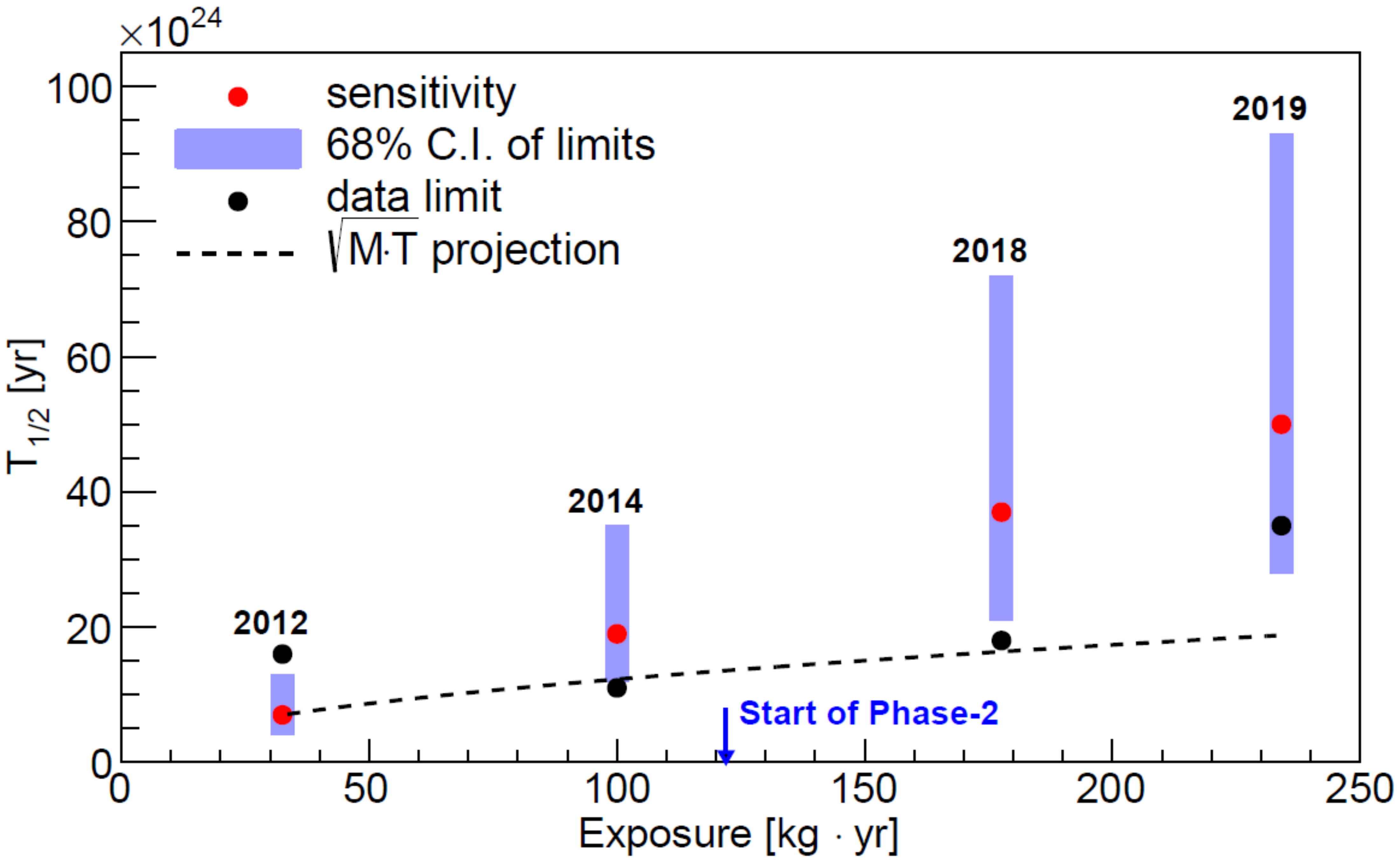
Phase I+II: 234.1 kg·yr ^{136}Xe exposure

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

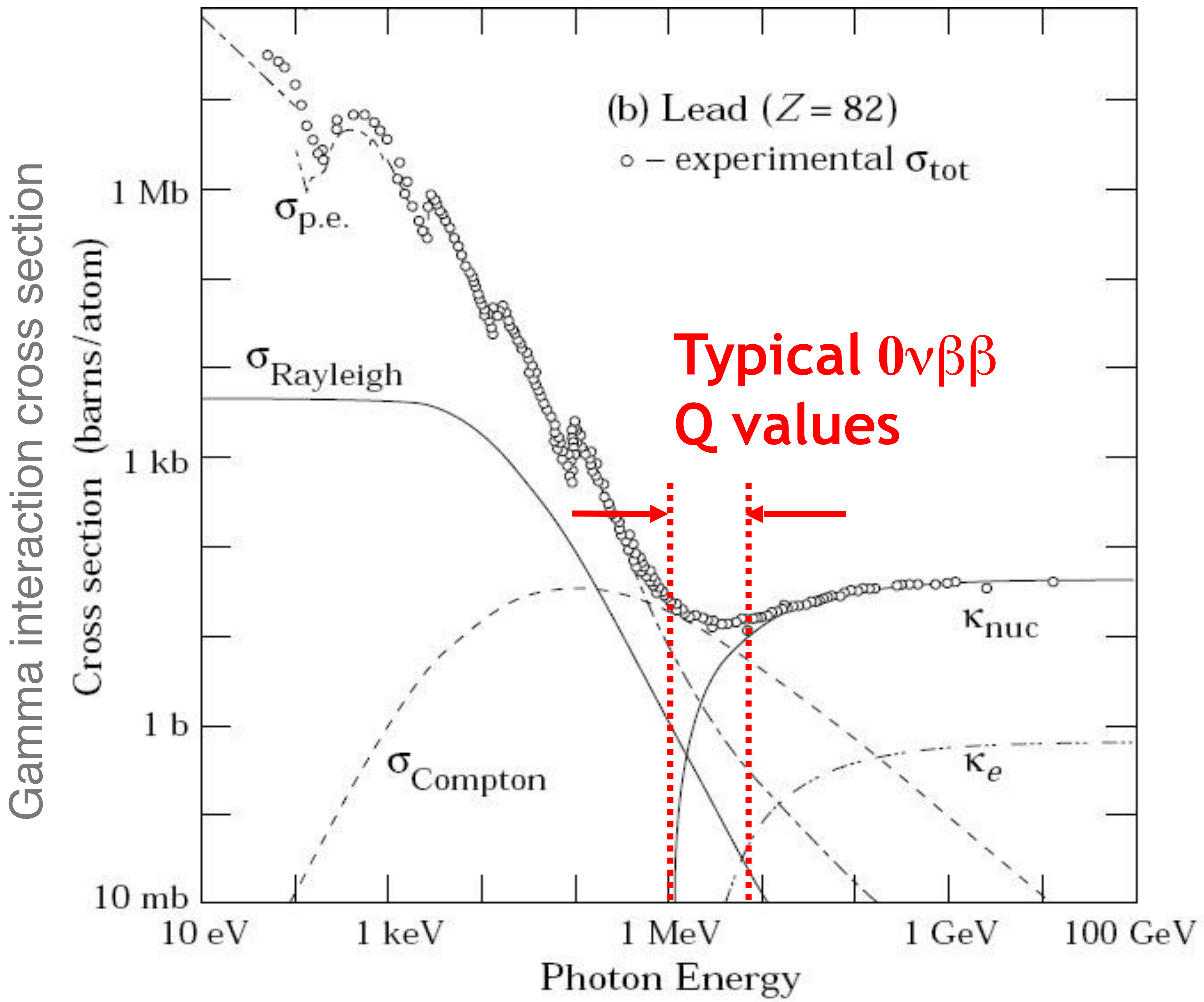
Sensitivity 5.0×10^{25} yr

No statistically significant signal observed



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, 161802 (2019)

Key requirement: shielding from MeV γ-rays



Shielding ββ decay detectors from external electromagnetic background is harder/different than shielding Dark Matter detectors

We are entering the “golden era” of ββ decay experiments as detector sizes exceed gamma-ray interaction lengths

E.g: the γ-ray interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector

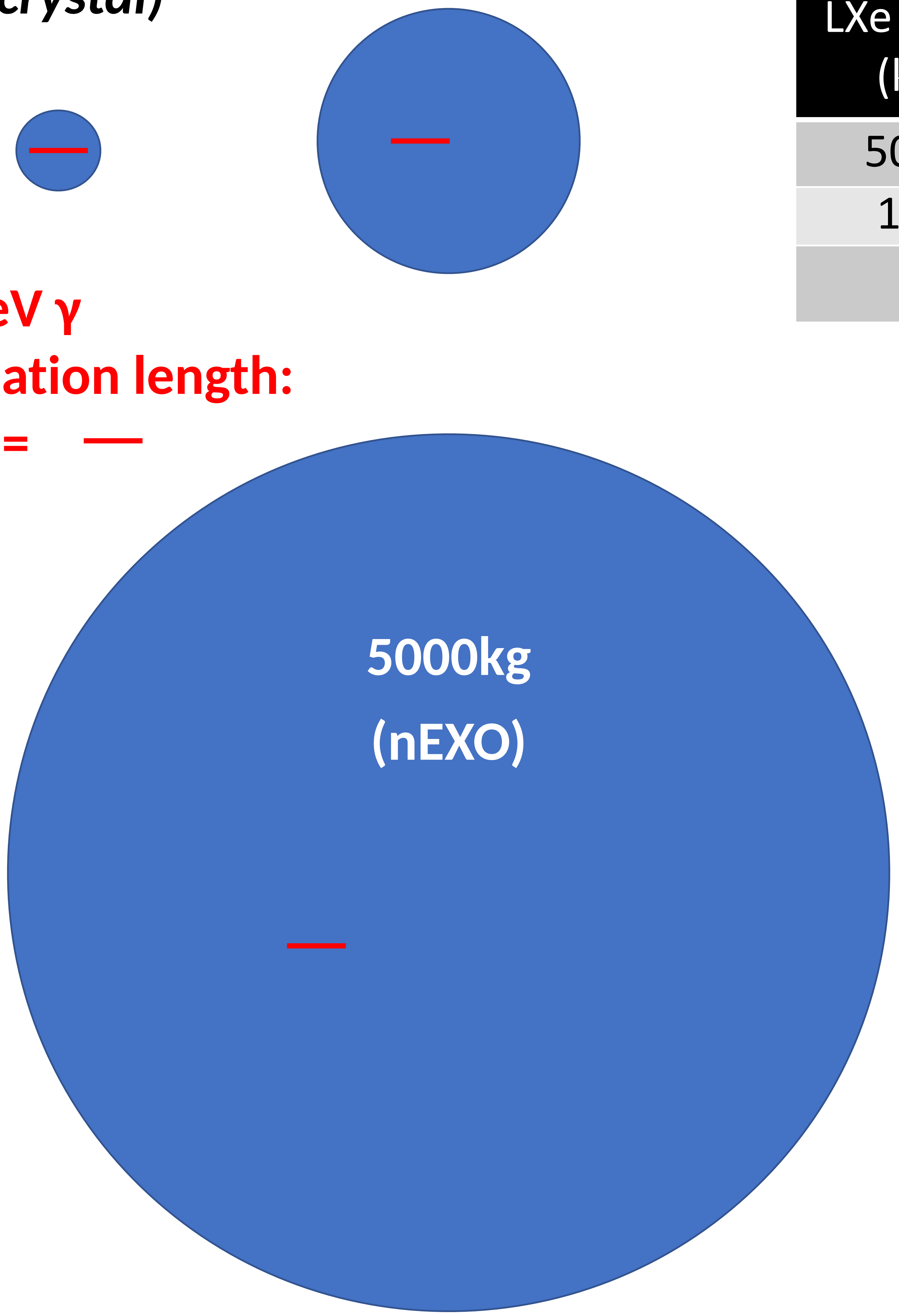
Power of self-shielding, monolithic, homogeneous detector

5kg

(~size of a Ge crystal)

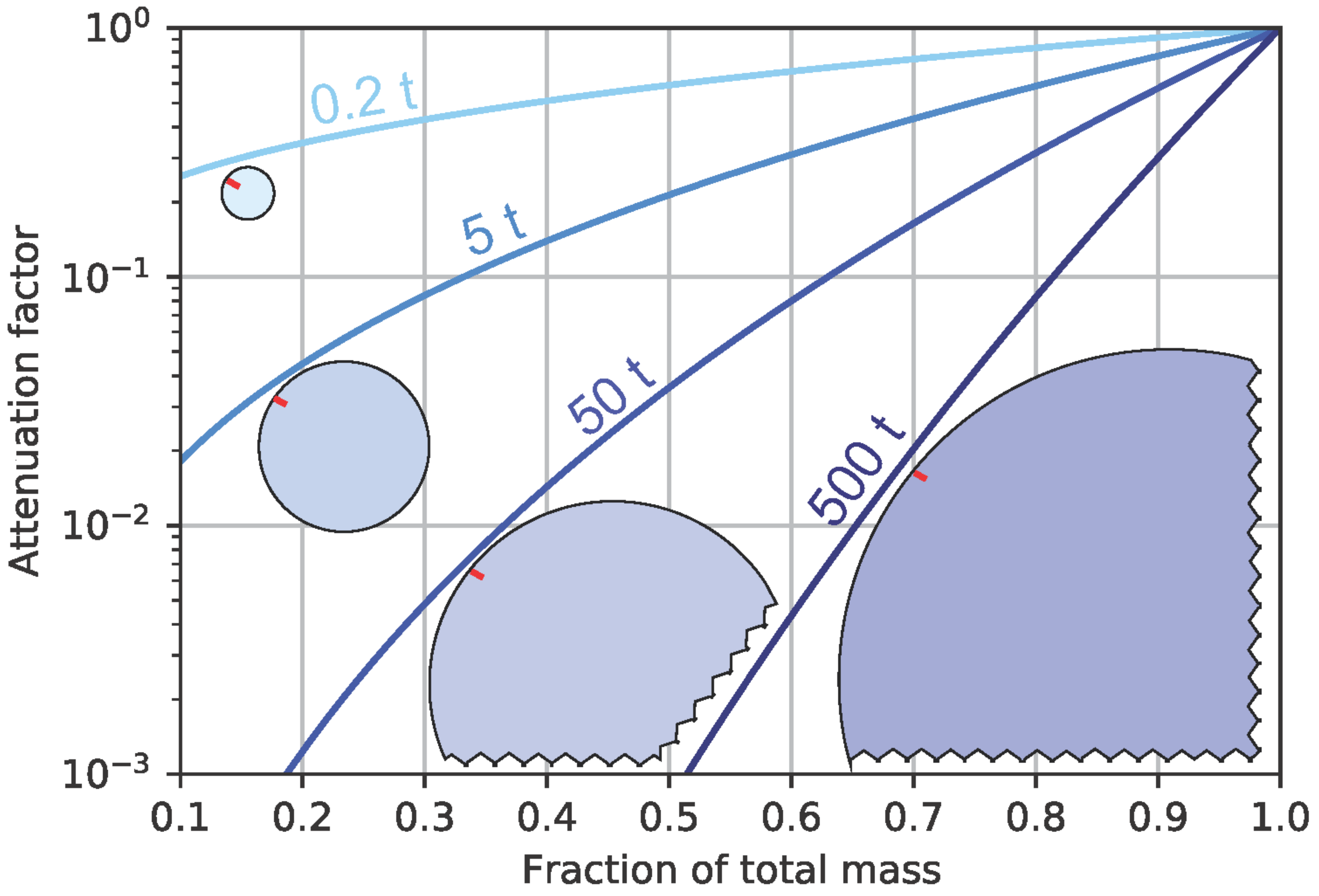
150kg

(~EXO-200)



2.5 MeV γ attenuation length: 8.7cm = —

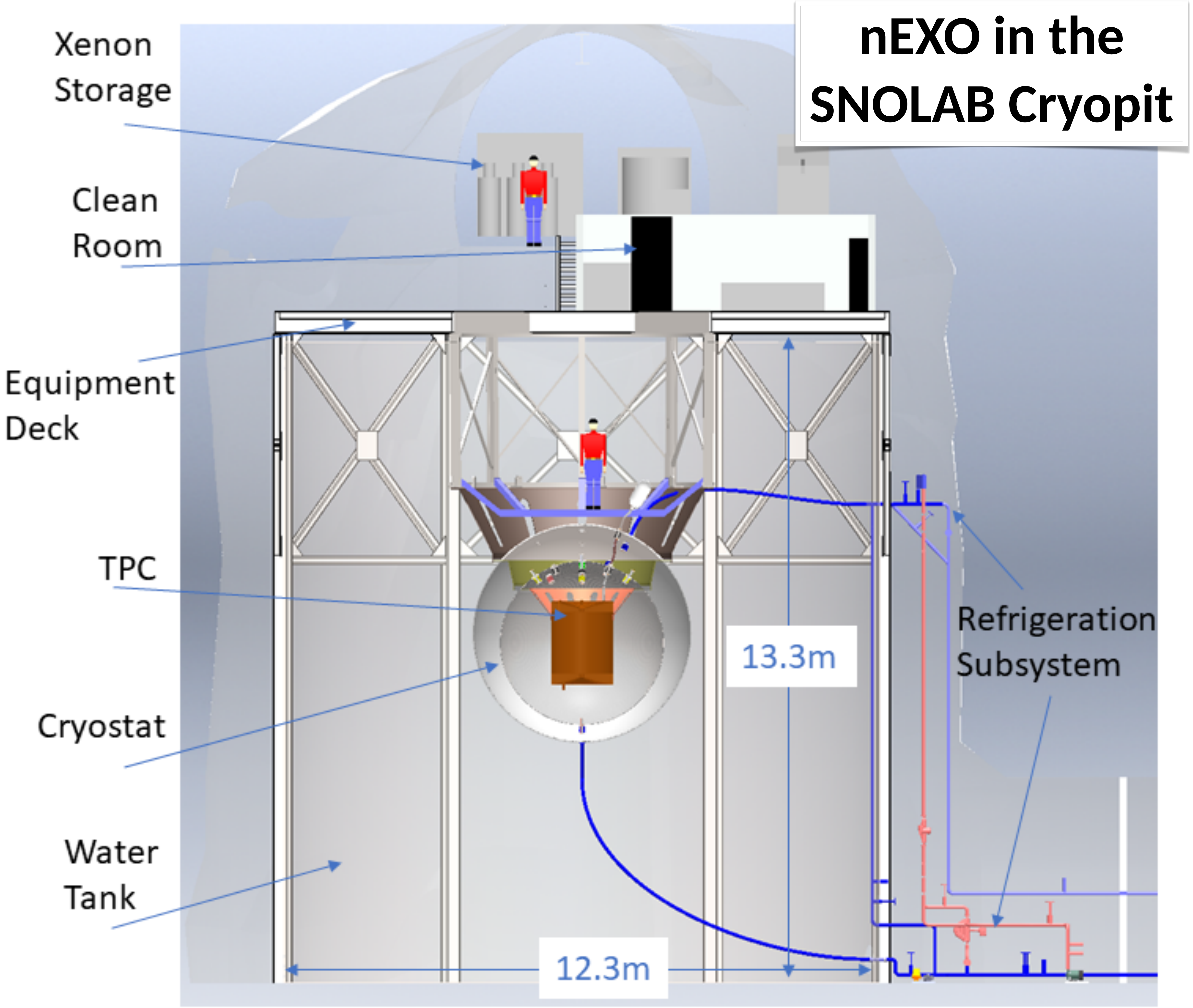
LXe mass (kg)	Linear size (cm)
5000	130
150	40
5	13



Advantages of LXe technology for 0νββ decay:

- *Scalable, re-purifiable, transferable between detectors*
- *Low intrinsic background (fully exploited at the tonne scale)*
- *Particle ID (β/α), event topology (β/γ)*
- *Possibility of no-source control experiment*

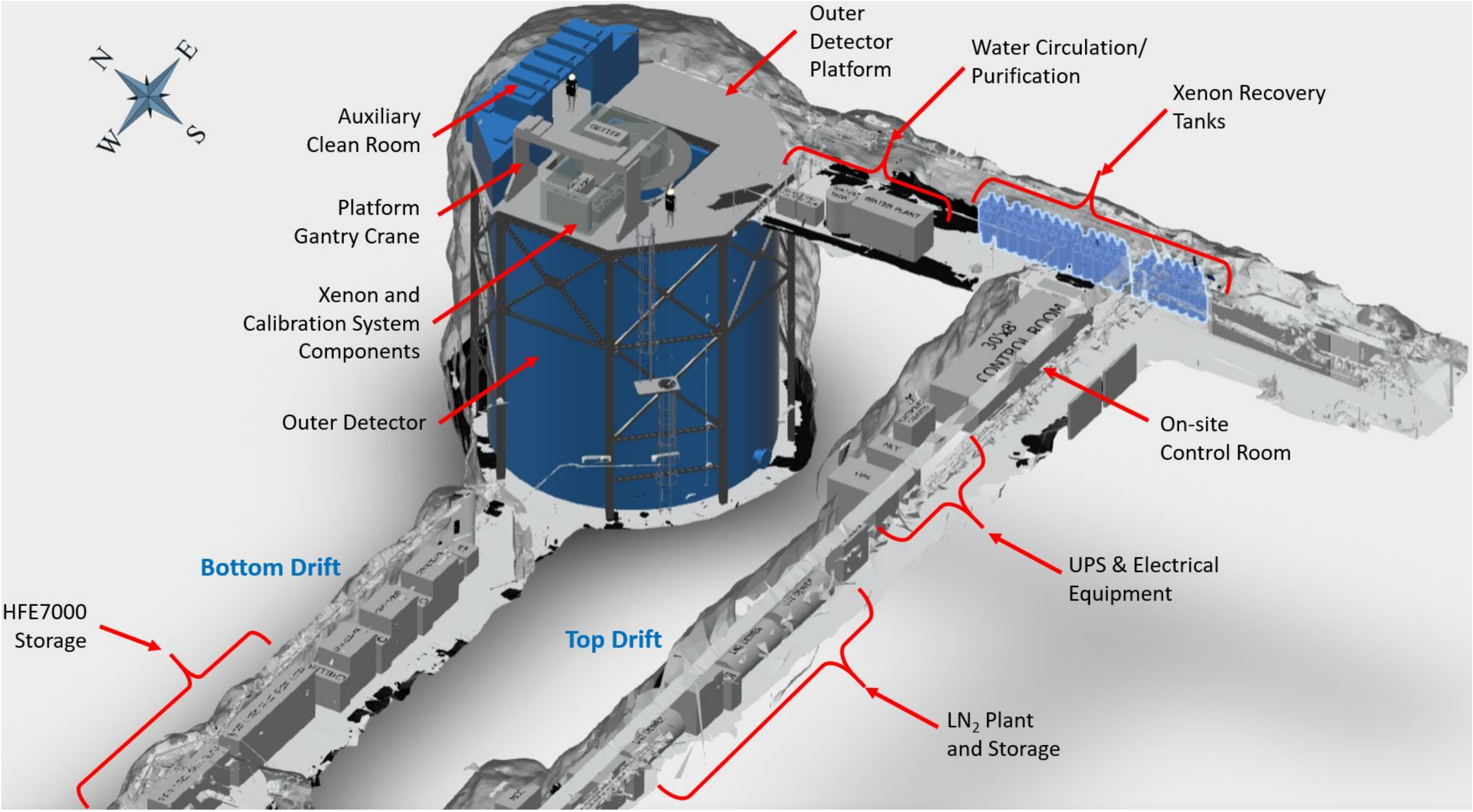
Graded shielding: low background and detector stability



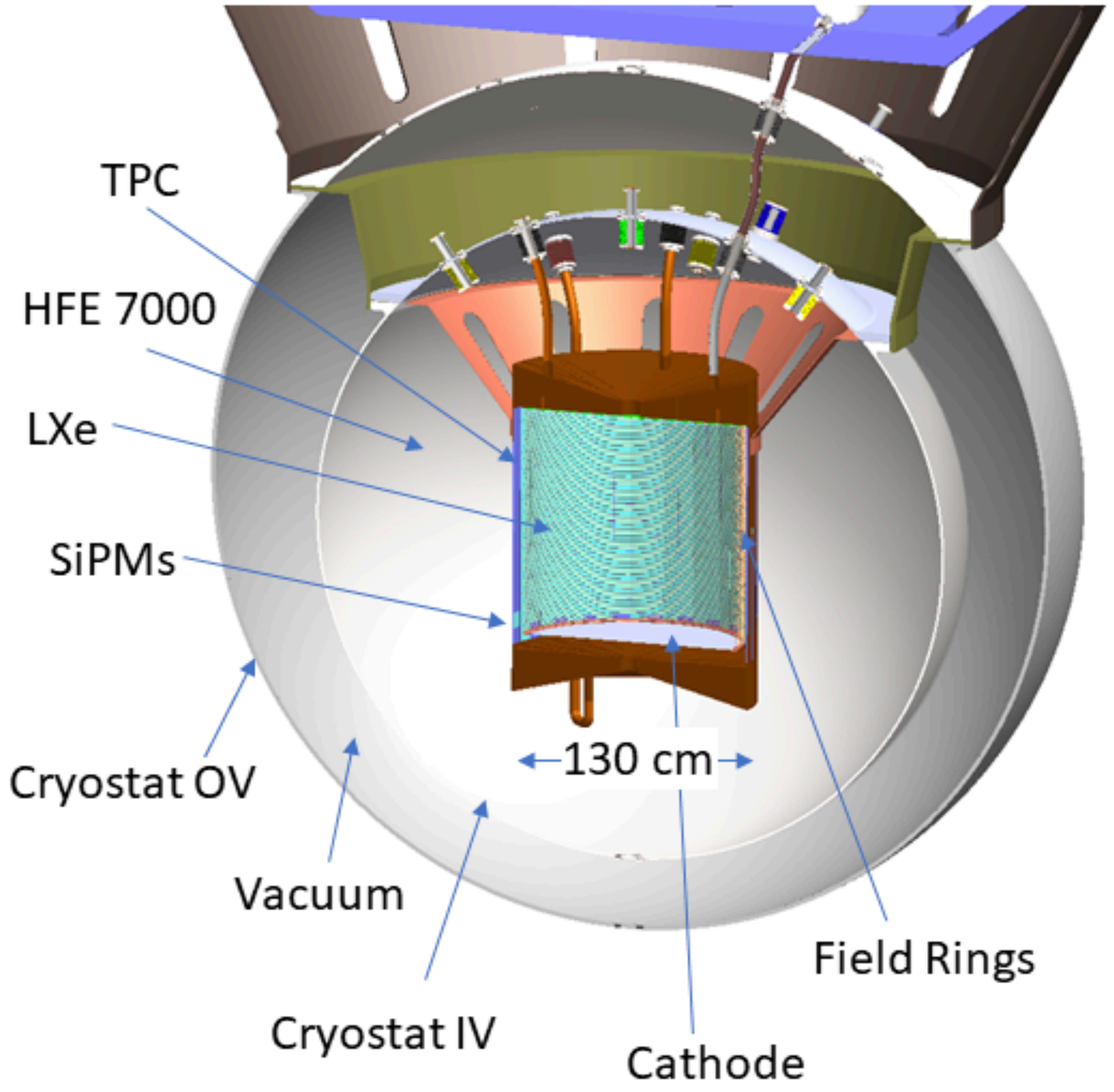
- Double-walled, vacuum-insulated carbon composite cryostat
- Refrigeration via 32 tonnes of Hydro-fluoro ether (HFE) 3M Novec-7000
- Design proven with EXO-200
- HFE-7000 intrinsically ultra radio-pure
- Excellent temperature stability (~165K)
- Thermal storage in case of power loss
- Lightweight, ultra-low background Xe vessel (pressure set at the Inner Cryostat)
- Active water-Cherenkov muon veto

nEXO pre-conceptual Design Report: **arXiv:1805.11142**

nEXO conceptual layout at SNOLAB (preferred site)



The nEXO detector is an evolution from EXO-200

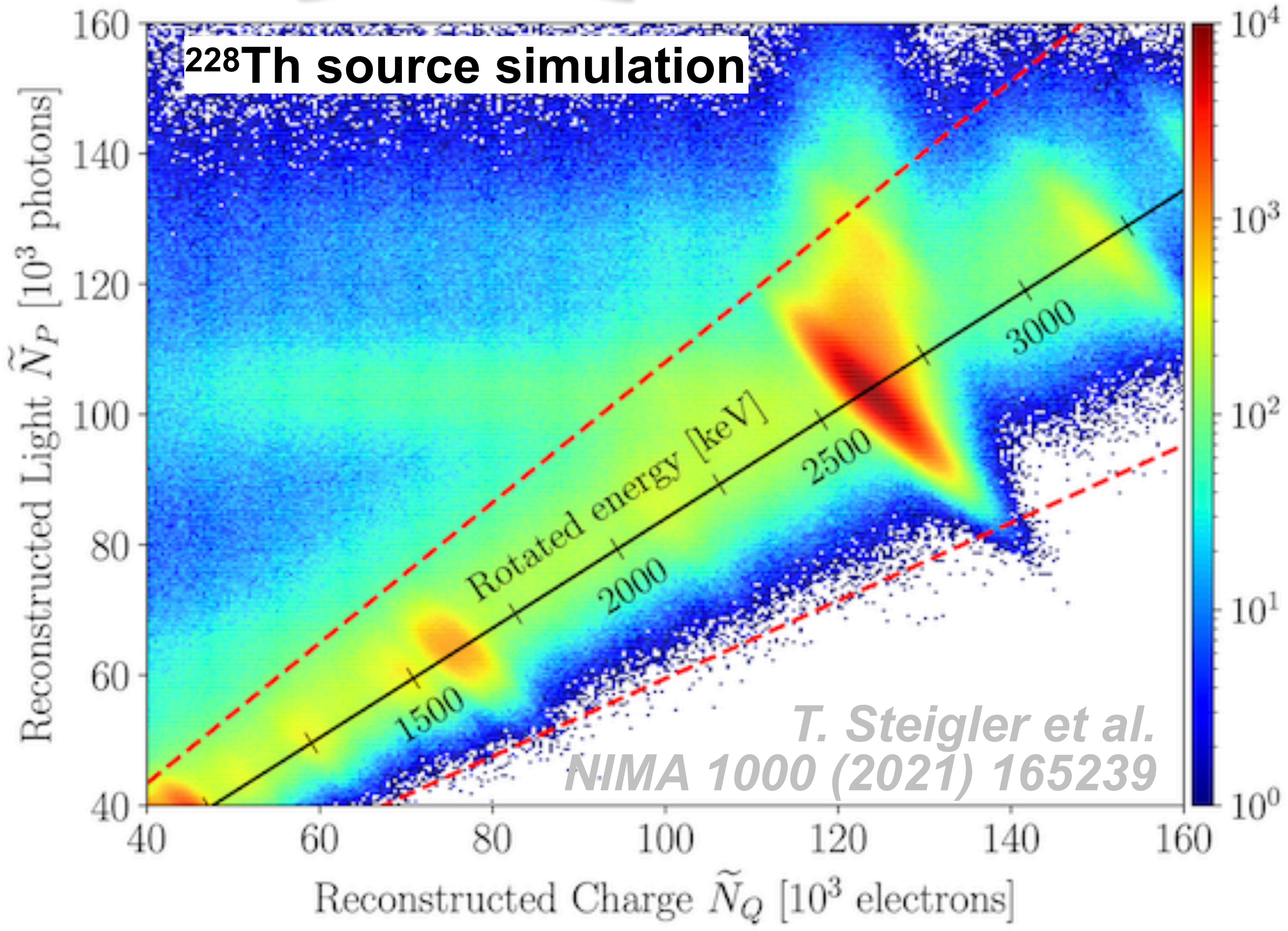


- *5000 kg of 90%-enriched LXe*
- *Single 120 cm drift volume; 130 cm diameter*
- *Drift E-field ~400 V/cm*
- *Ionization electrons collected on charge tile detectors at the anode (no gain), ~6,000 channels*
- *VUV (178 nm) scintillation light is detected by a large array of SiPMs (~45,000 devices, ~4.5 m^2)*

	EXO-200:	***nEXO:***	***Improvements:***
Vessel and cryostat	Thin-walled commercia 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

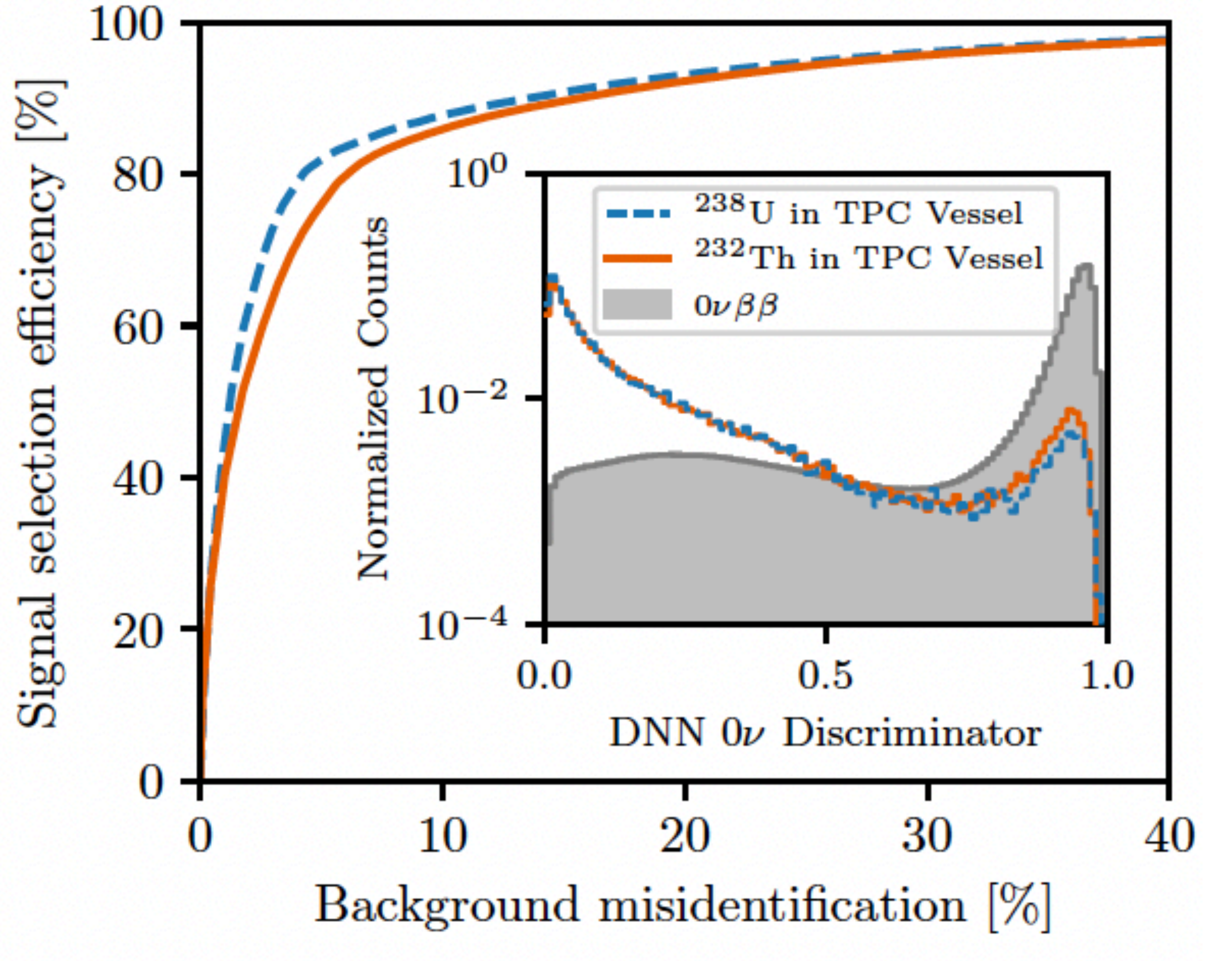
nEXO TPC performance: robust, multidimensional information

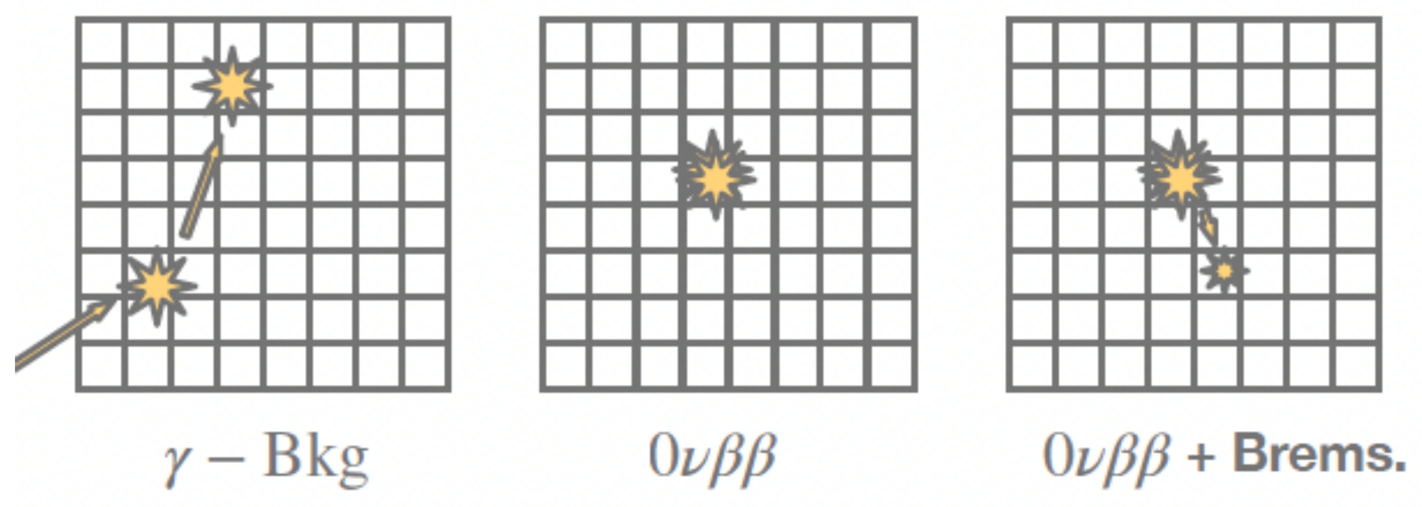
Energy



- Event-by-event anti-correlation between ionization and scintillation (known since the early EXO R&D)
- Improved energy resolution
  - expect $\sigma/Q_{\beta\beta}$ = 0.8% (1.2% with EXO-200)
- Optically open TPC field cage

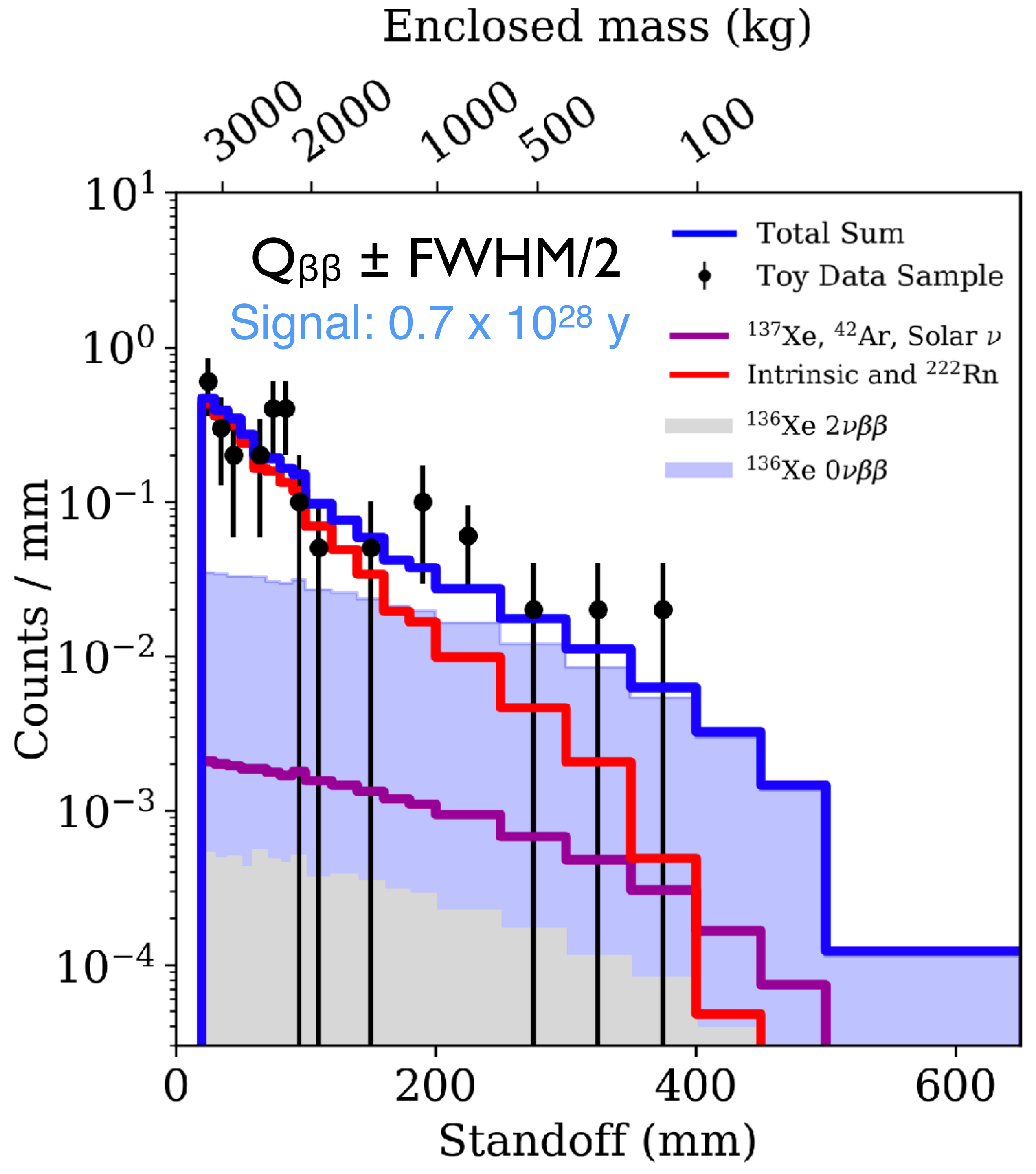
Event topology





- Single- vs. multi- site energy depositions

Standoff distance

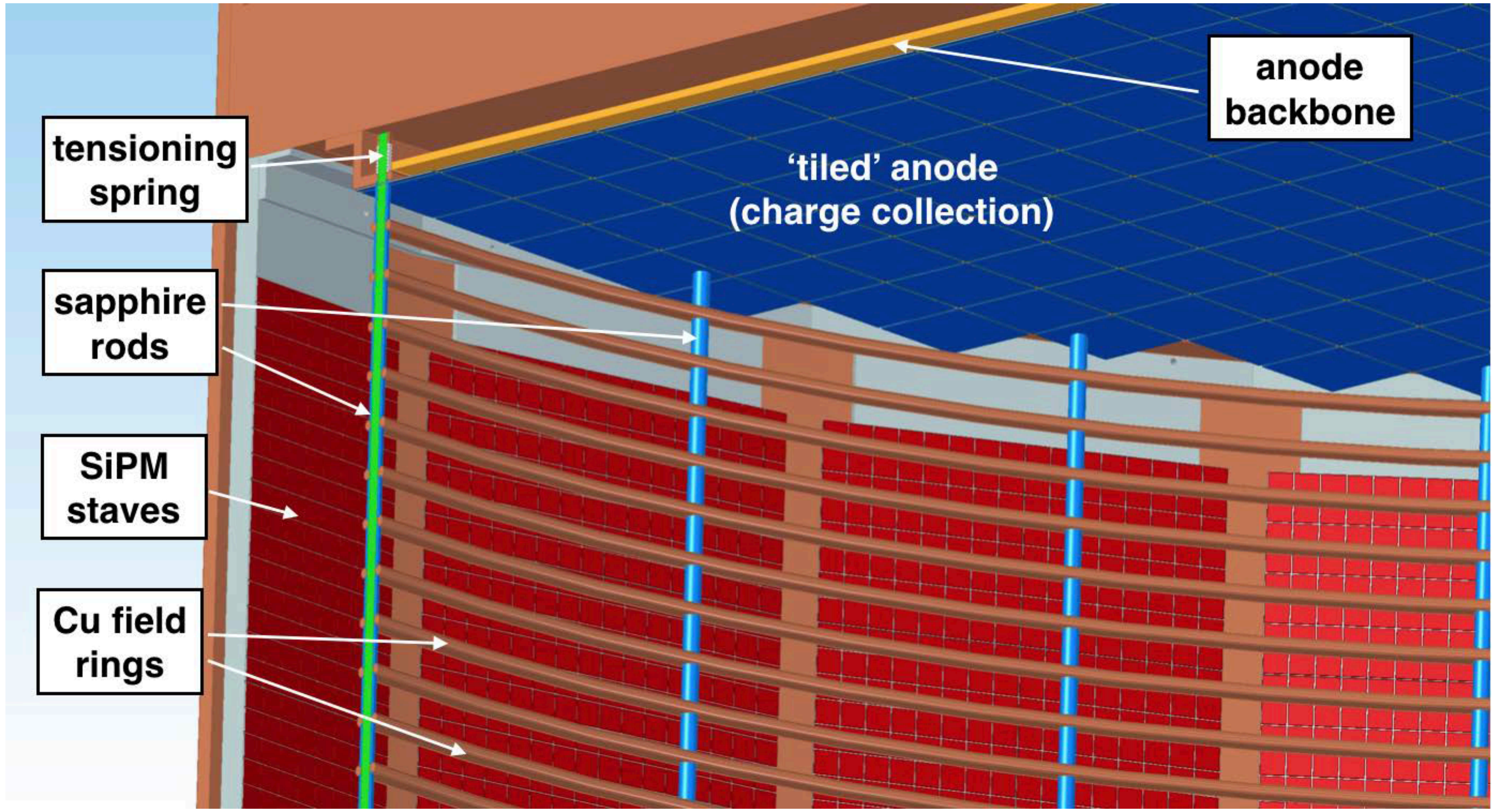


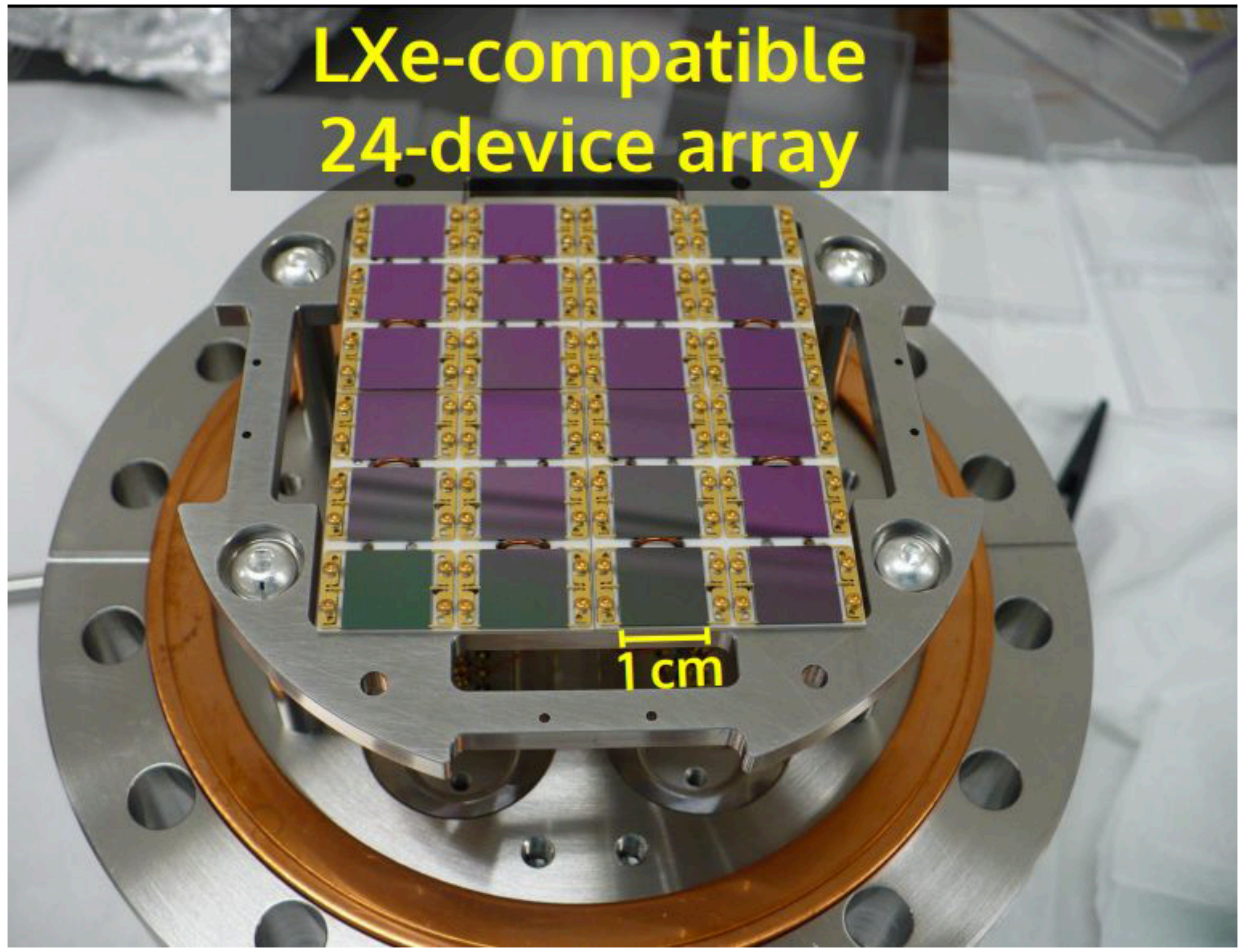
- ββ events are uniformly distributed in the LXe volume
- Most backgrounds originate from outside of the TPC

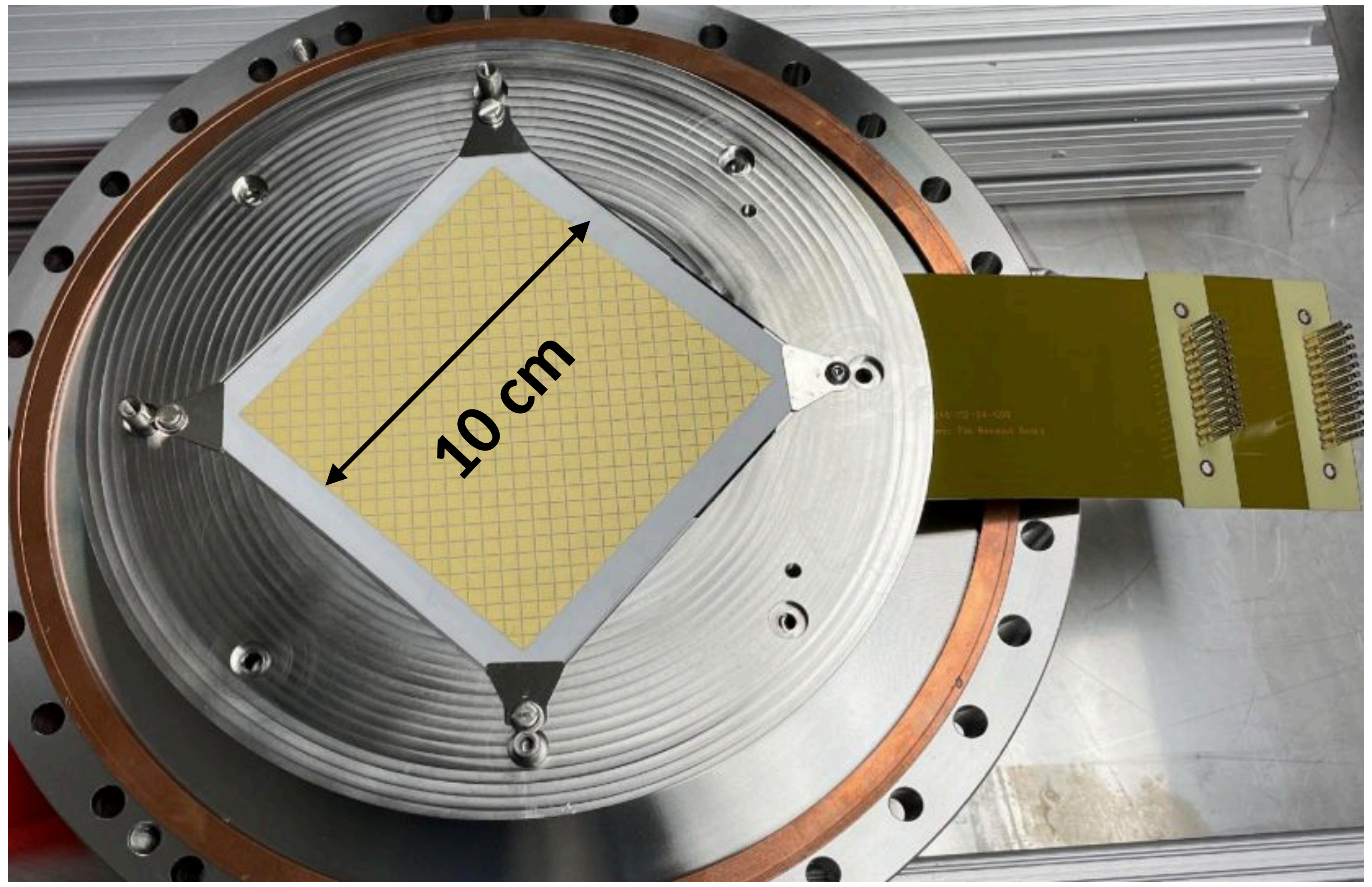
E.Conti et al. Phys Rev B 68 (2003) 054201

nEXO Sensitivity and Discovery Potential: **J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)**

Charge and light readout





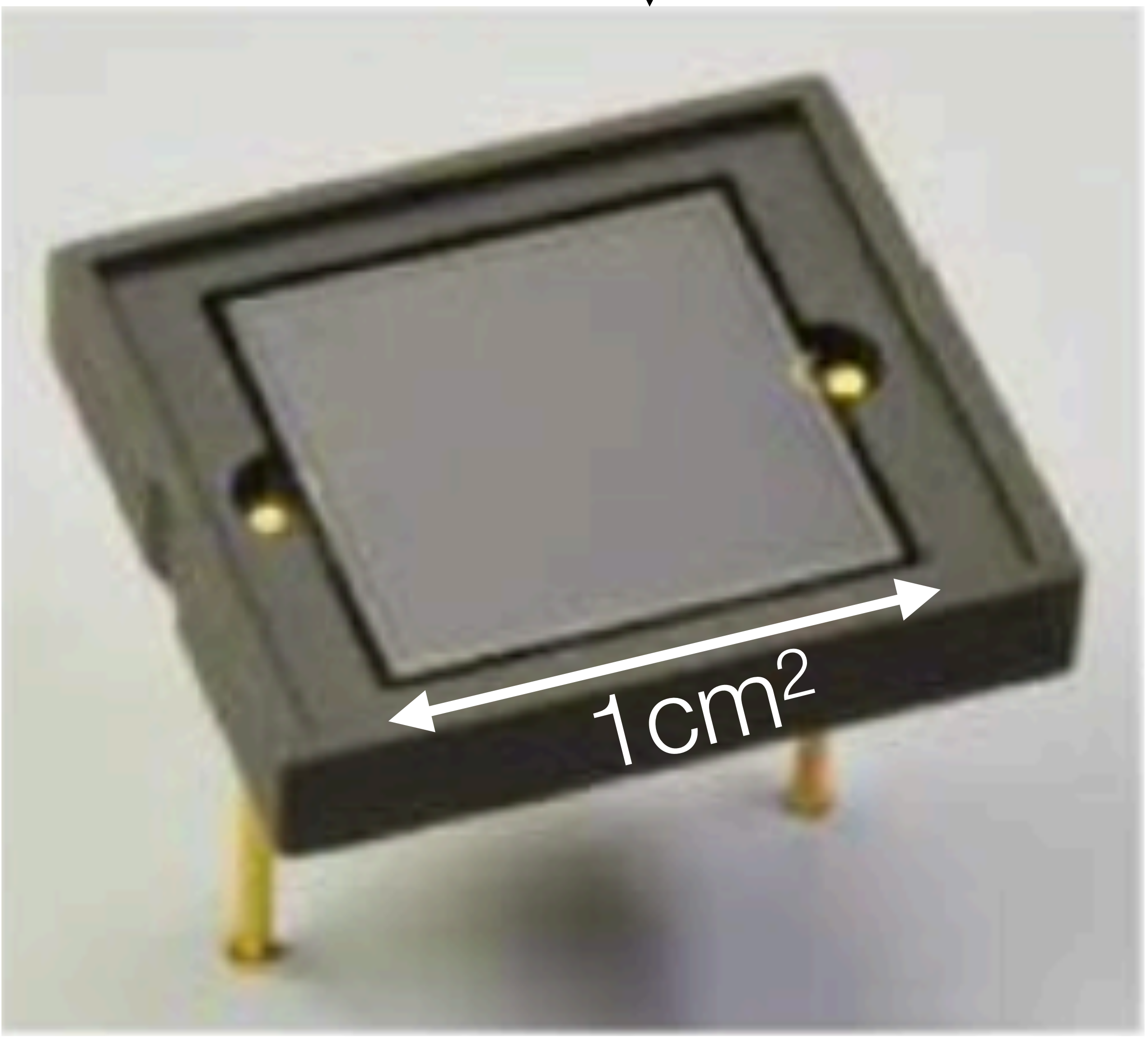


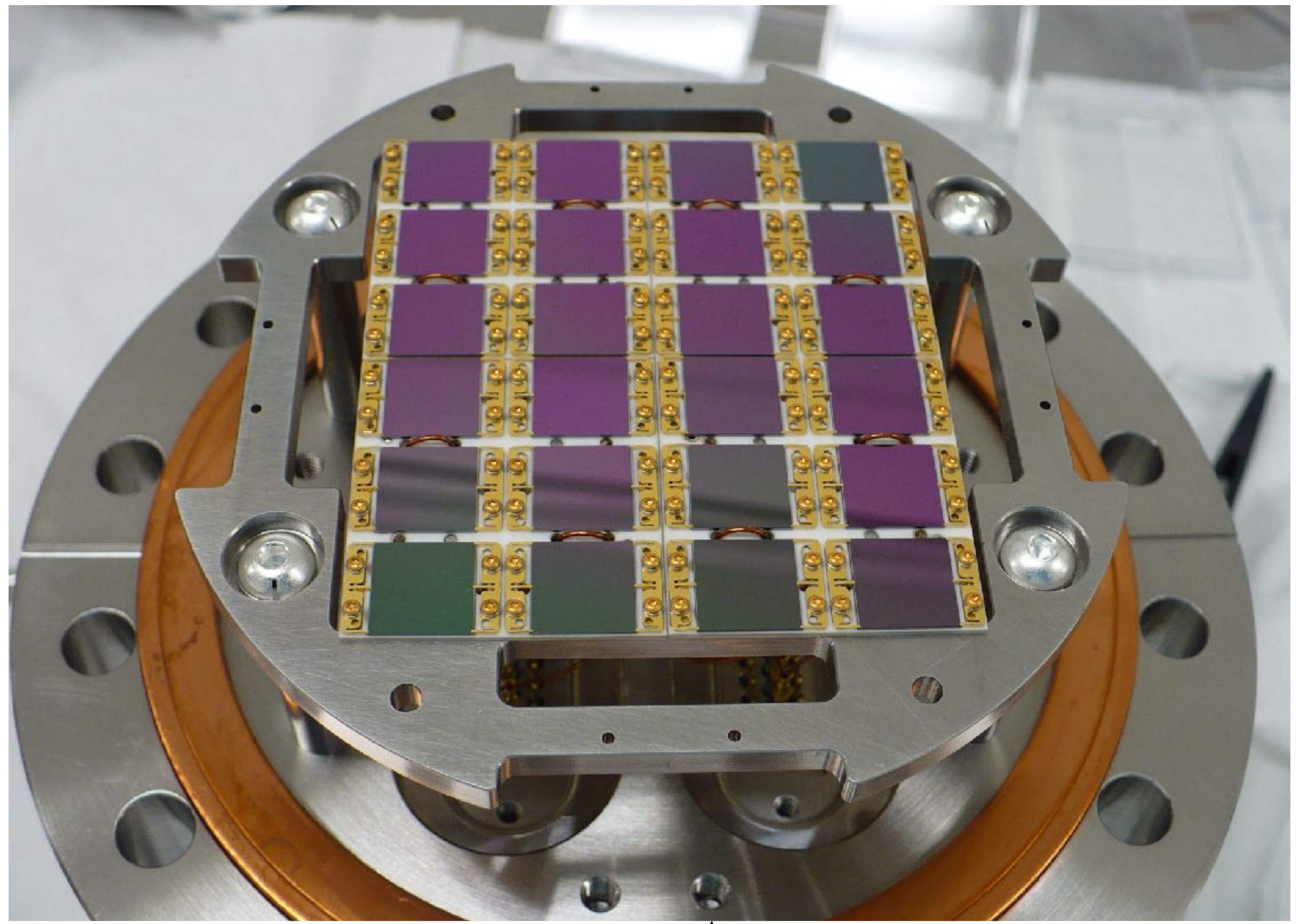
- SiPMs instead of PMTs
- no reflector panels
- Field rings and cathode coated with reflective aluminum deposition (capped by fluoride)

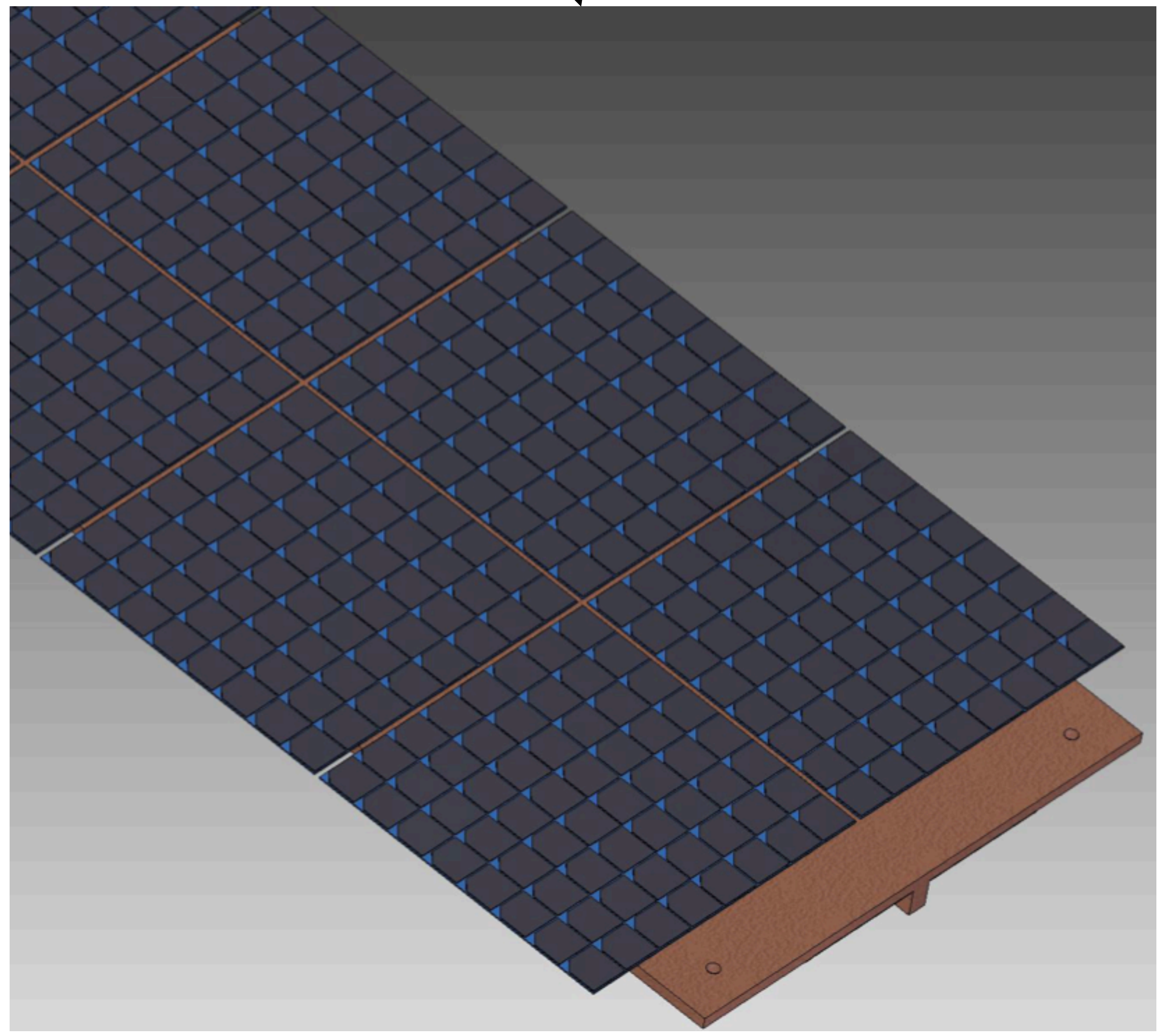
Light Detection in nEXO

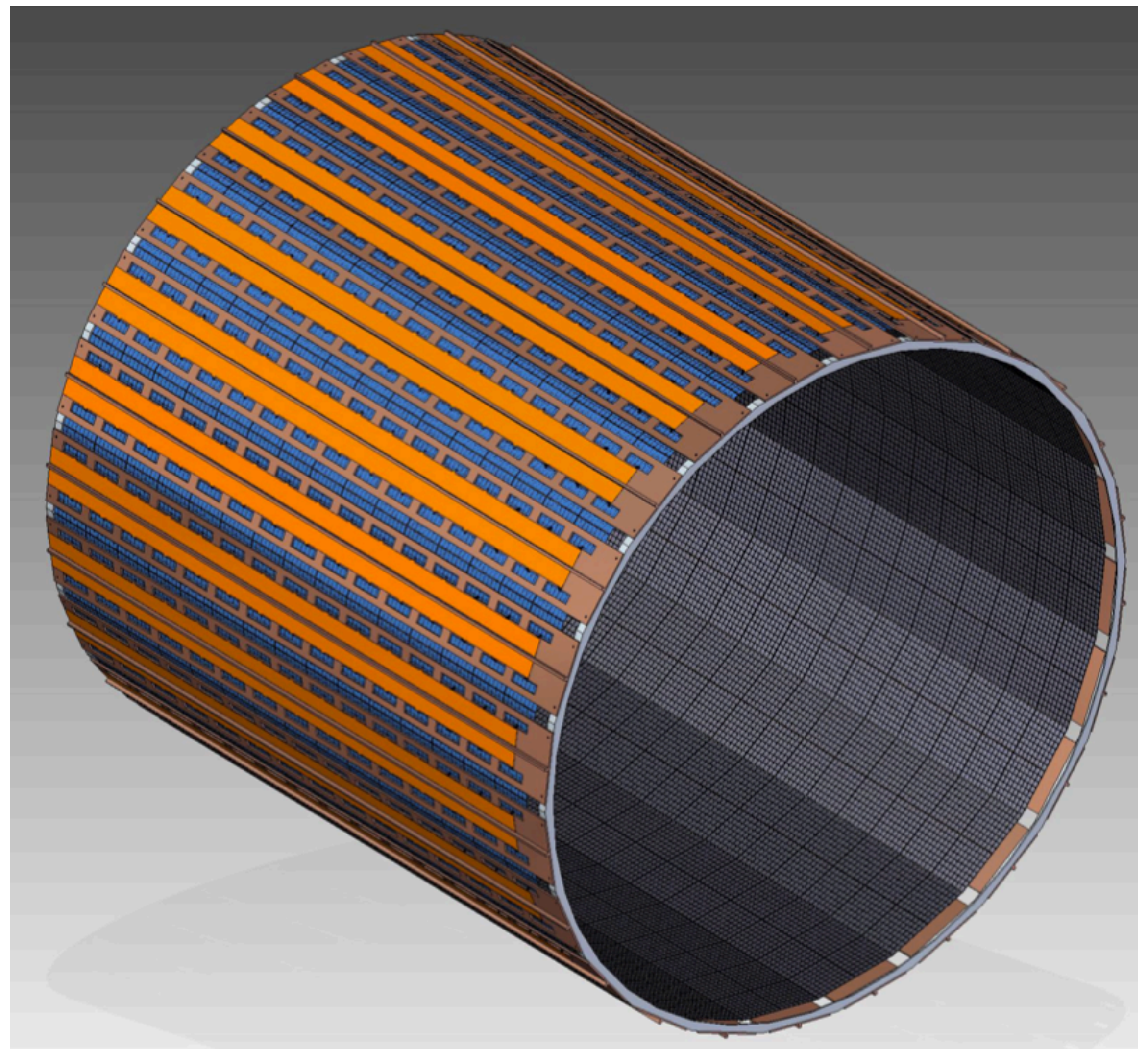
Single Sipm

SiPM Stave









SiPM Array

Full light detection system

Light transport simulations

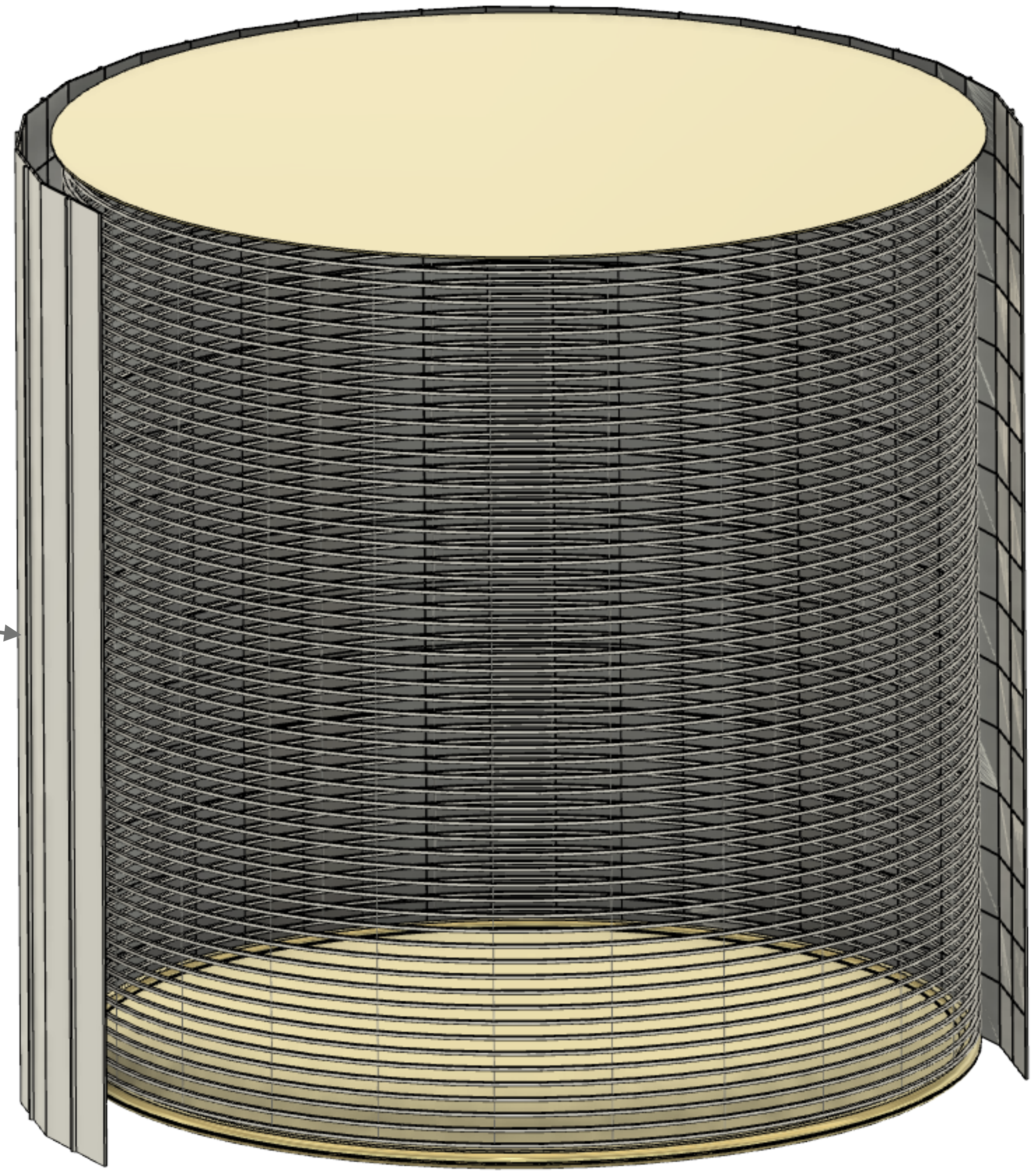
- Crucial to optimize Photon Transport Efficiency for increased light collection

$$\epsilon = \mathrm{PDE} \cdot \mathrm{PTE}$$

- Highly dependent on reflectivity of TPC components

- Developed new light simulation of nEXO with GPU-based Chroma software
  https://github.com/nEXO-collaboration/chroma
  - > 300x faster
  - More detailed geometry

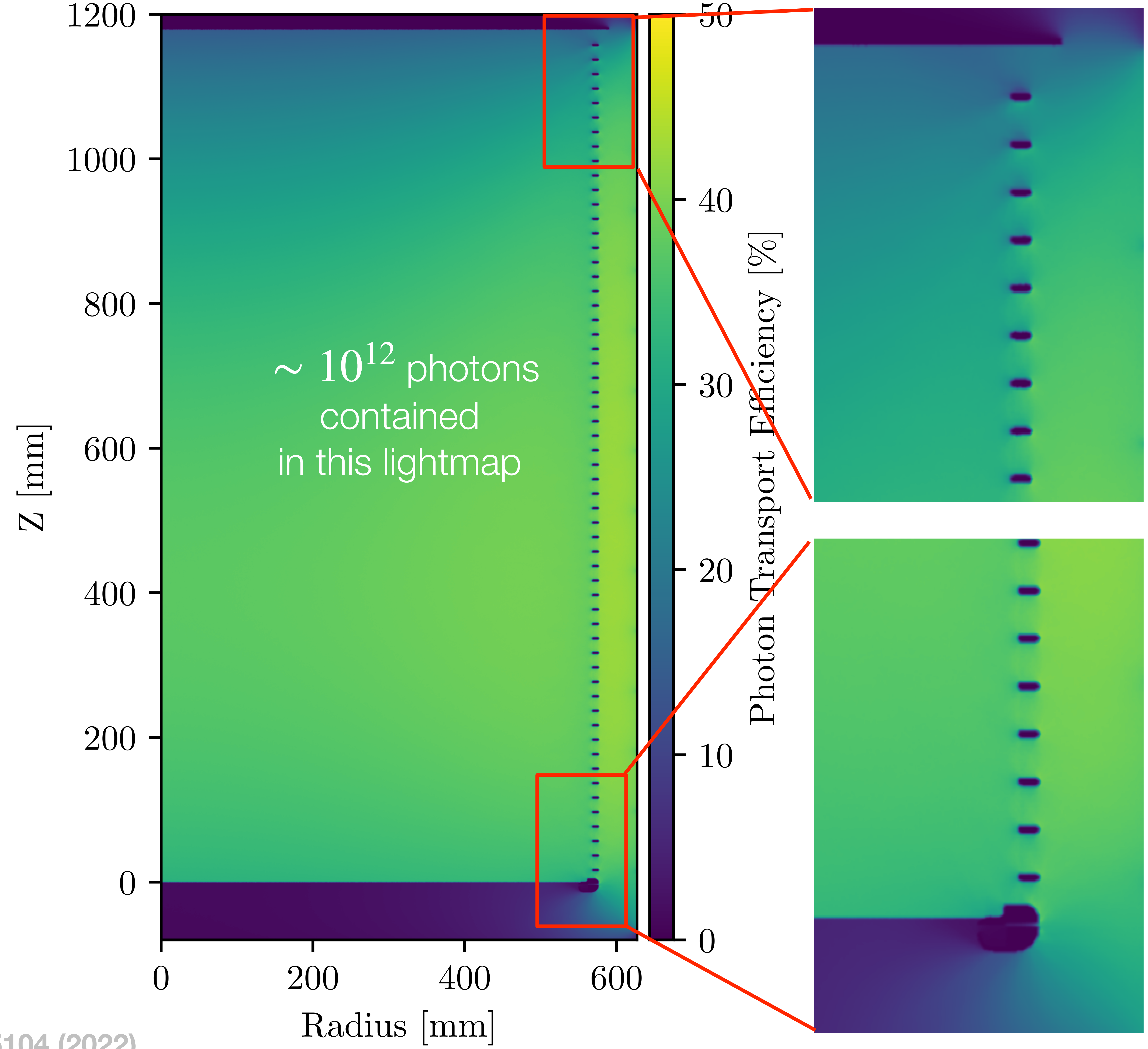
CAD Model of nEXO



Lightmap optical simulation

- Varied optical parameters and evaluated systematic error
- Estimated PTE combined with measured PDE results in

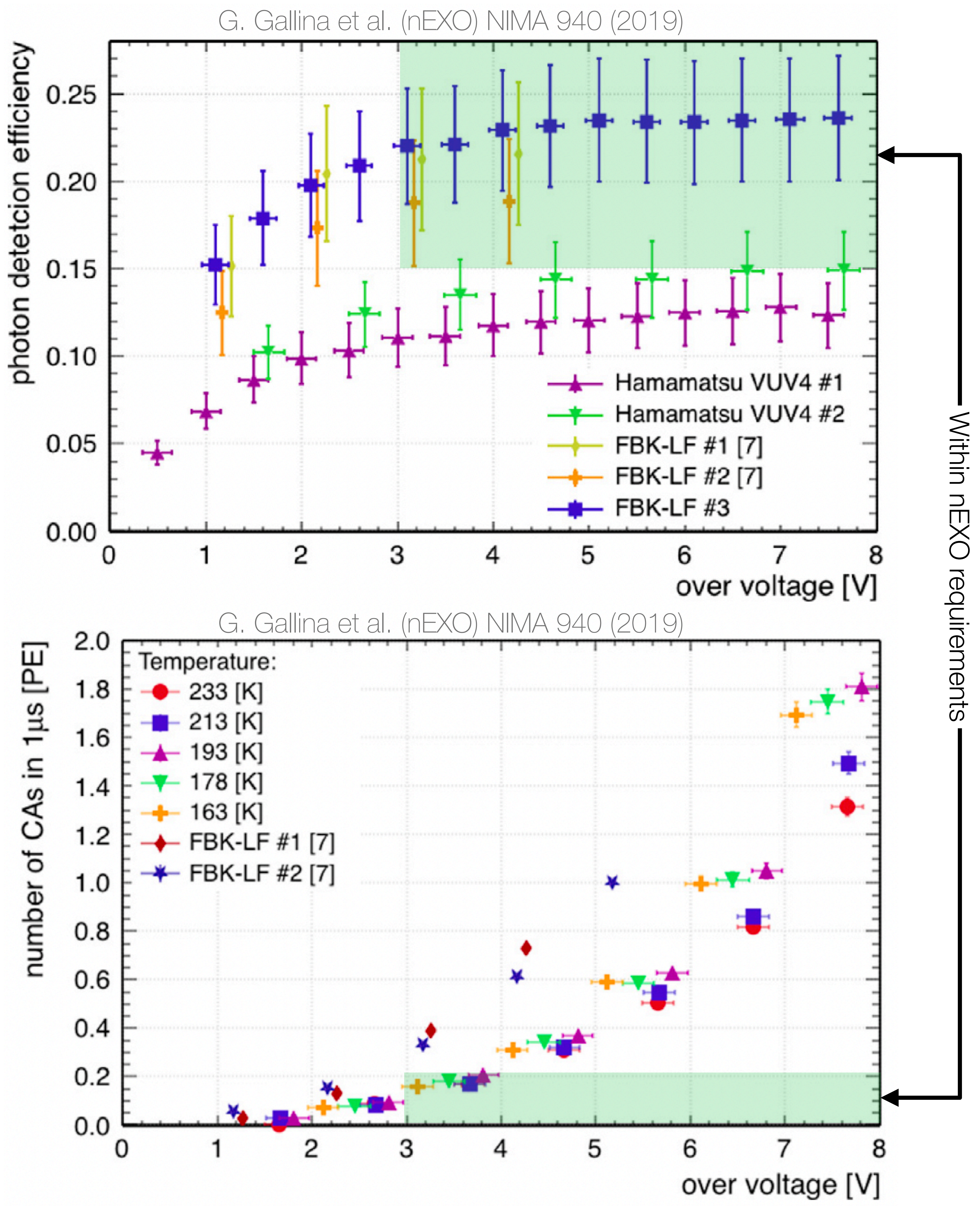
$$\epsilon = \text{PDE} \cdot \text{PTE} \approx 6.7\,\%$$



nEXO Sensitivity and Discovery Potential: **J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)**

Characterization of SiPM Performance

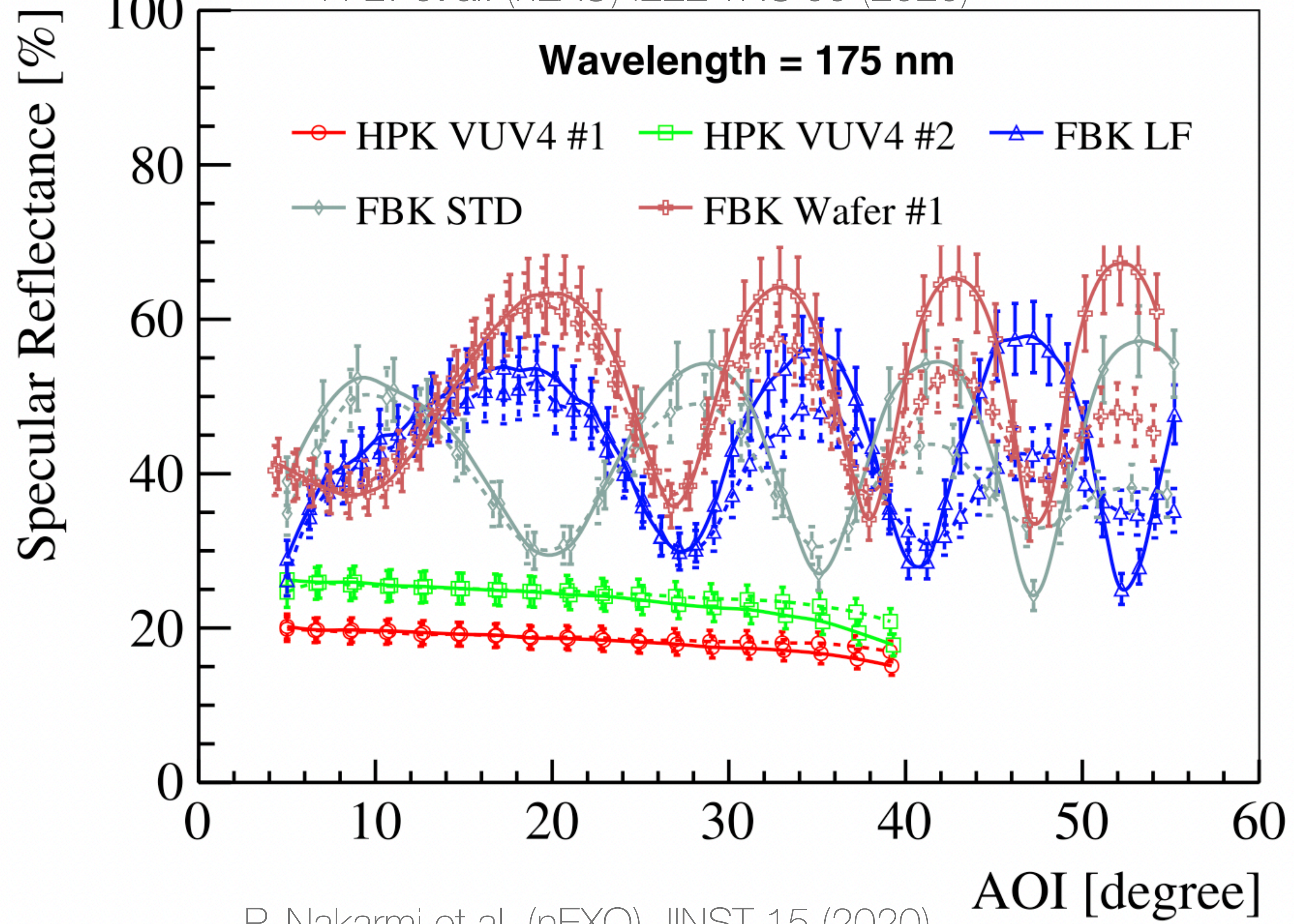
- nEXO is running an extensive characterization campaign with several setups measuring
  - Absolute PDE in vacuum
    - Ostrovskiy et al. (nEXO) IEEE TNS 62 (2015)
    - A. Jamil et al. (nEXO) IEEE TNS 65 (2018)
    - G. Gallina et al. (nEXO) NIMA 940 (2019)
  - Have identified devices from two manufacturers (FBK and HPK) that meet our requirements
  - Working together with vendors to increase operational range
  - More results soon



Characterization of SiPM Performance

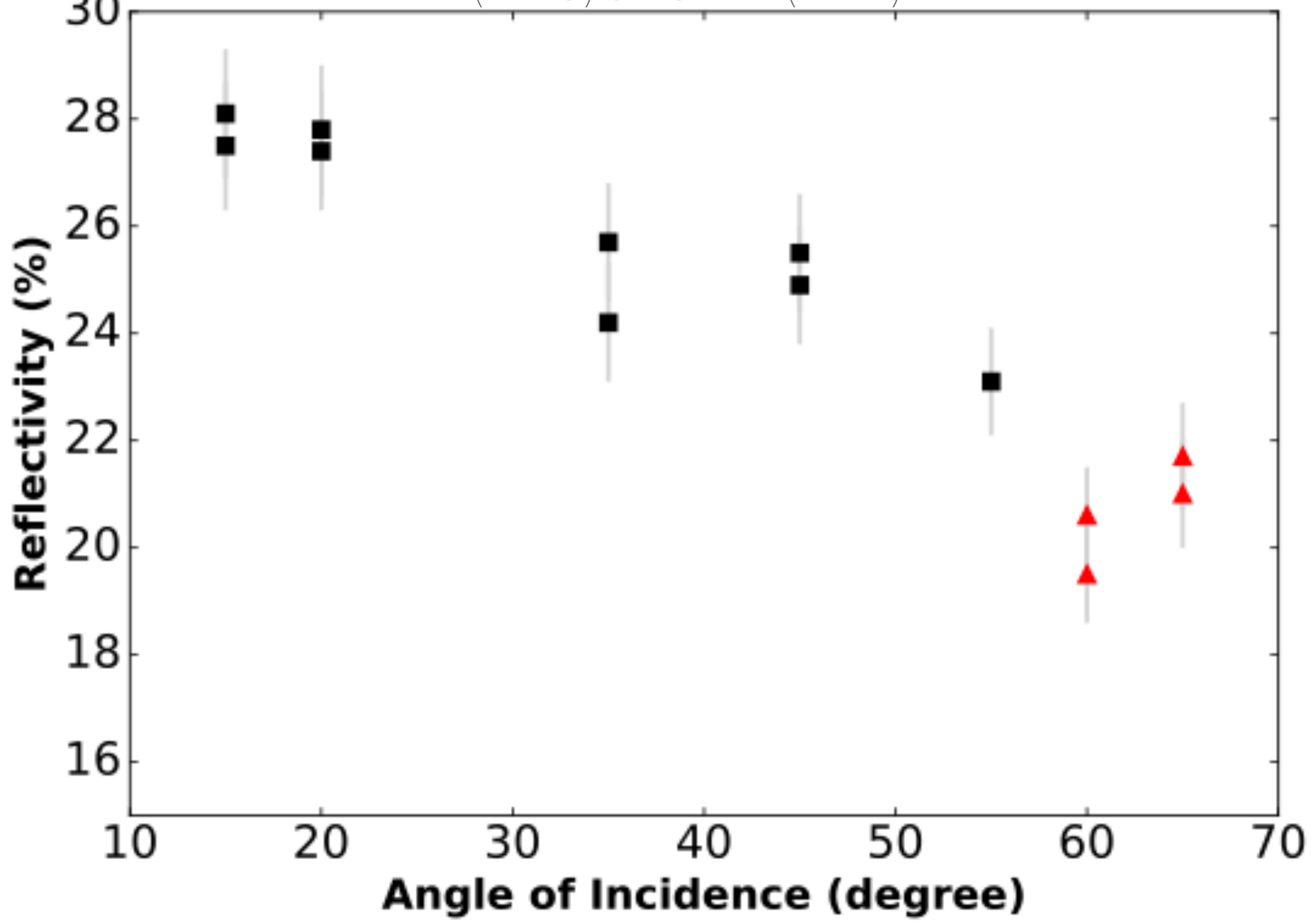
- nEXO is running an extensive characterization campaign with several setups at various institutions
  - Reflectivity in vacuum and LXe
    - P. Nakarmi et al. (nEXO) JINST 15 (2020)
    - P. Lv et al. (nEXO) IEEE TNS 99 (2020)
    - M. Wagenpfeil et al. (nEXO) In prep. (2021
  - Photons reflected from SiPM surface can be detected by other SiPMs
  - Reflectivity of passive TPC components (e.g. field shaping rings, cathode, …) crucial for good light collection efficiency

P. Lv et al. (nEXO) IEEE TNS 99 (2020)



Vacuum

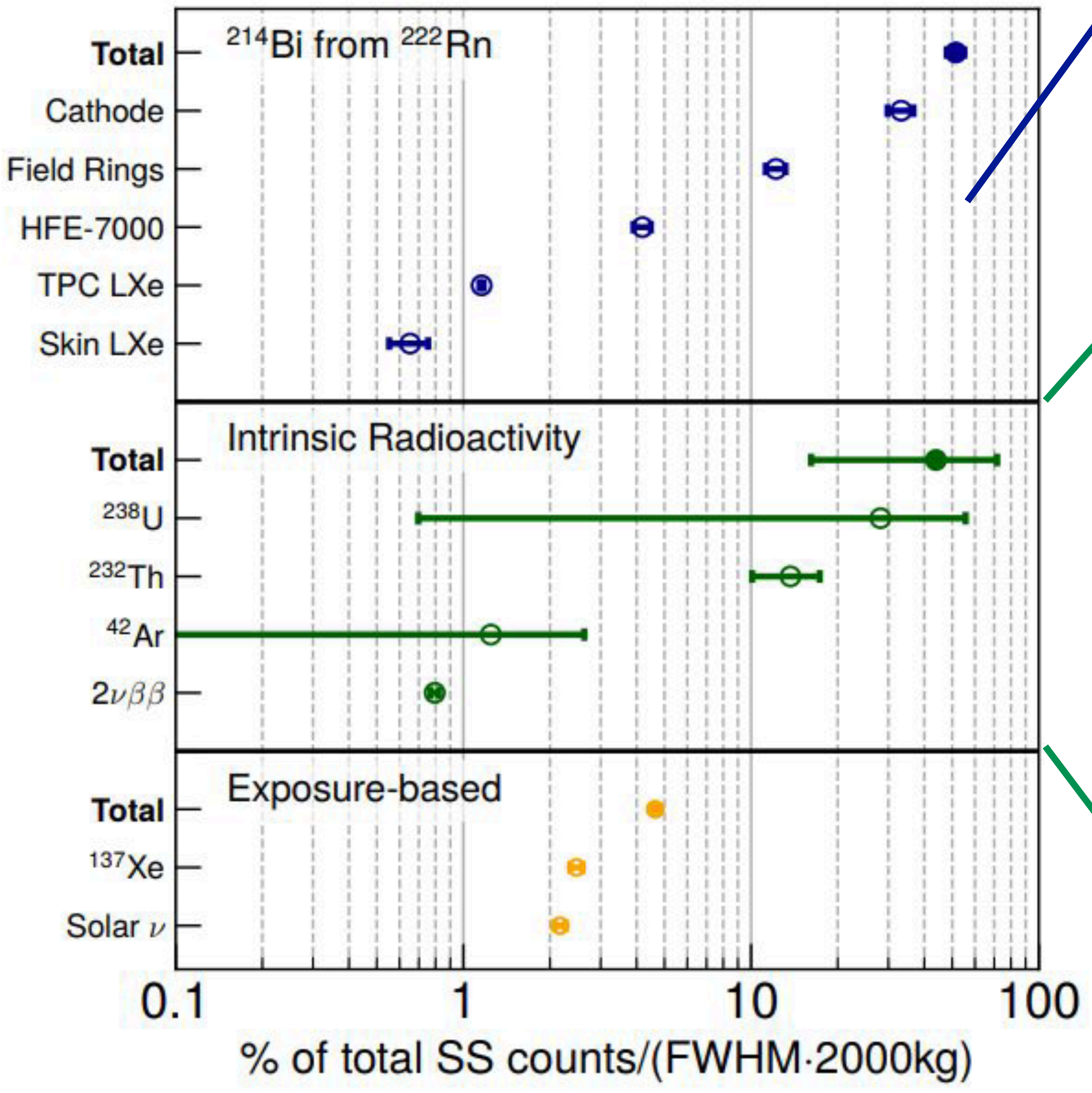
P. Nakarmi et al. (nEXO) JINST 15 (2020)



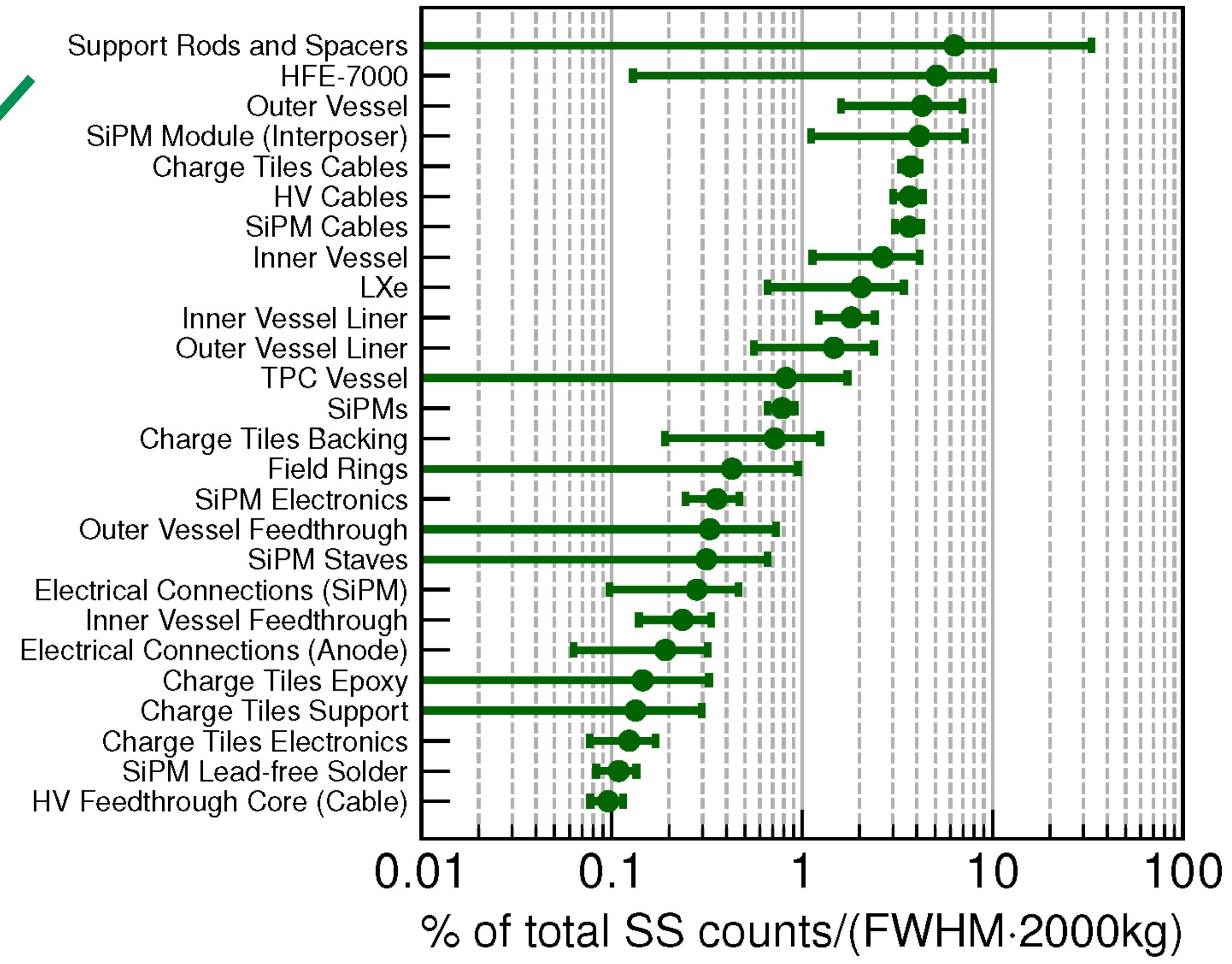
Liquid xenon

Robust and validated background model

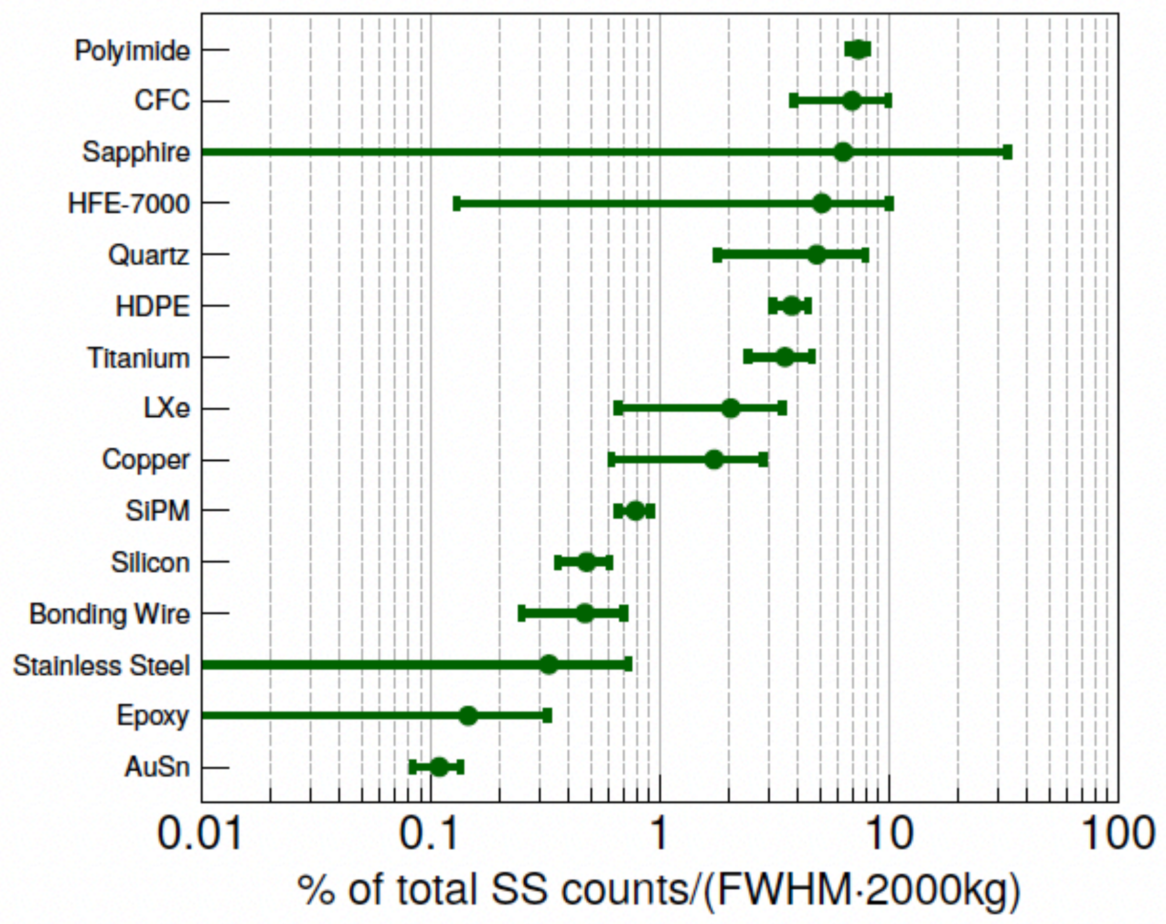
- Materials screening
- Bottom-up background model
- Optimized: no detector component dominates the bg
- Electro-formed copper for TPC components
- R&D to further reduce radon
- ^{137}Xe con be vetoed with ε>70% at ~no exposure loss



Extrapolated from EXO-200



from
radio assay

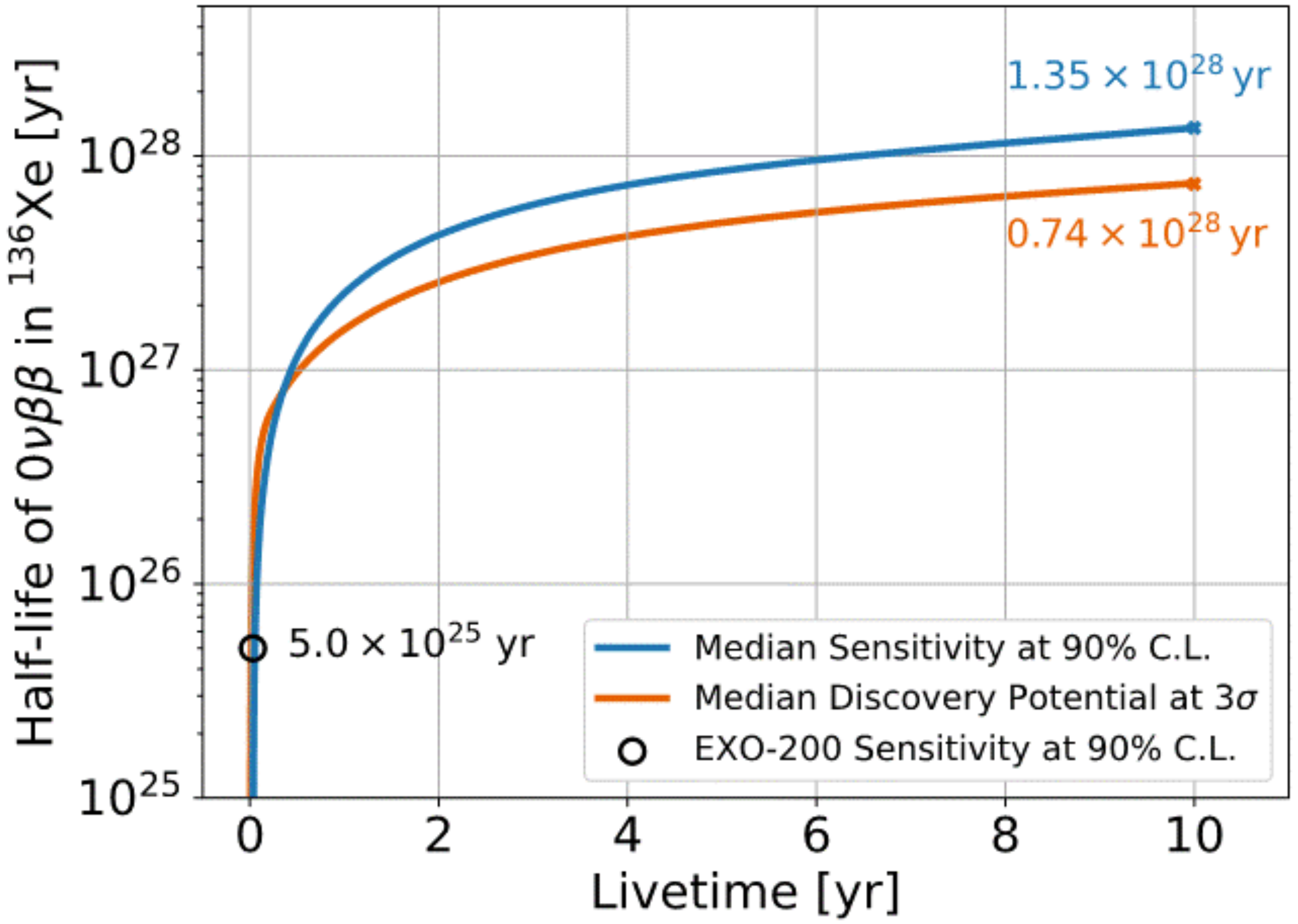


Xe procurement and enrichment

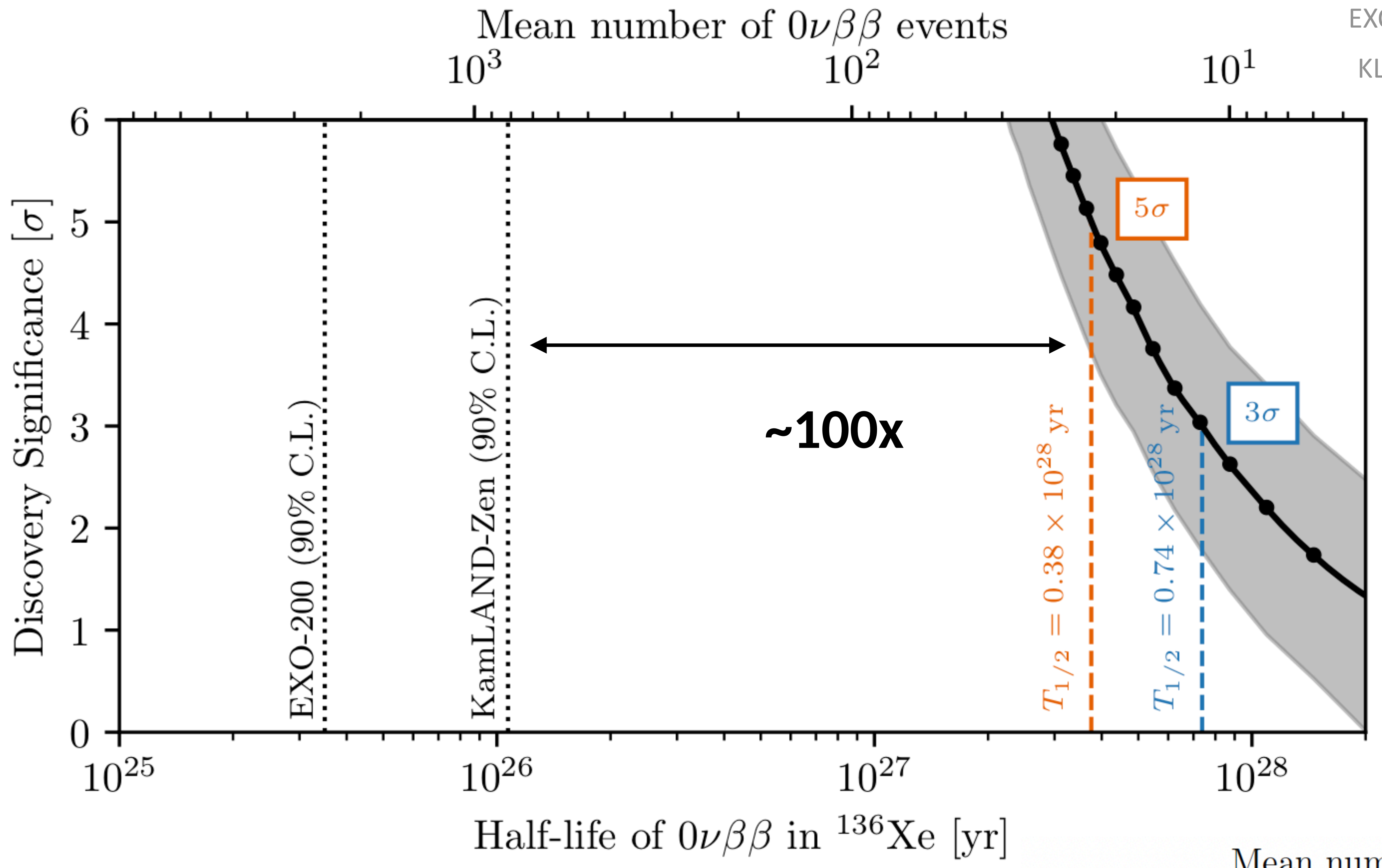
Xenon enrichment is well understood and cost effective:

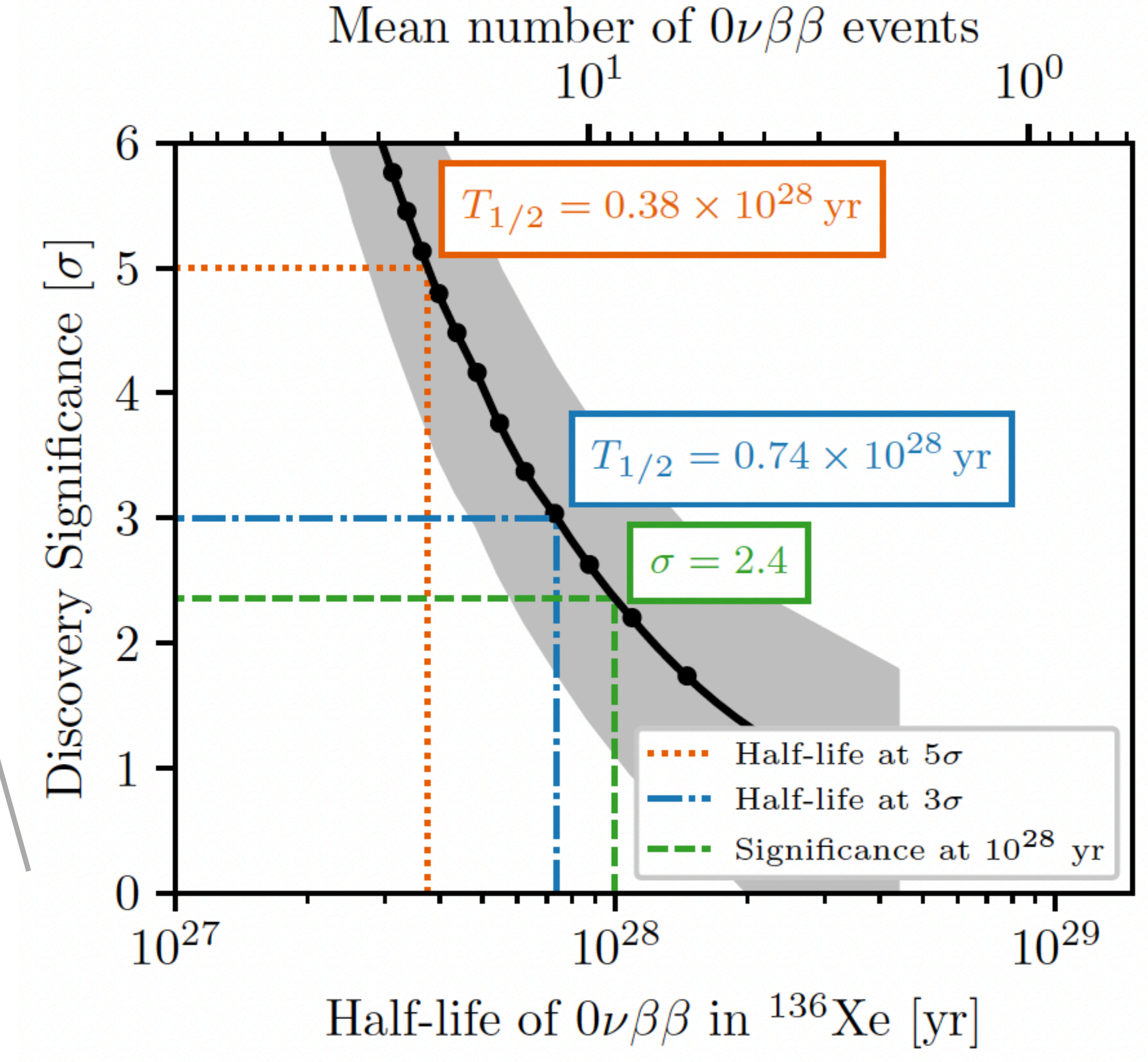
- **EXO-200 used 200 kg of Xe enriched to 80% in 136, at the time a pioneering production.**
- **KamLAND-ZEN more recently purchased ~800 kg of xenon enriched to 90% in mass 136 isotope.**
- **The nEXO need is only 5x of what already available.**
- **nEXO has identified at least two western suppliers each with enough enrichment capacity for the entire production at competitive price.**
- **We also have two backup options (neither in eastern Europe)**

nEXO sensitivity and discovery potential



EXO-200: PRL 123, 161802 (2019)
KL-Z: arXiv:2203.02139 (2022)

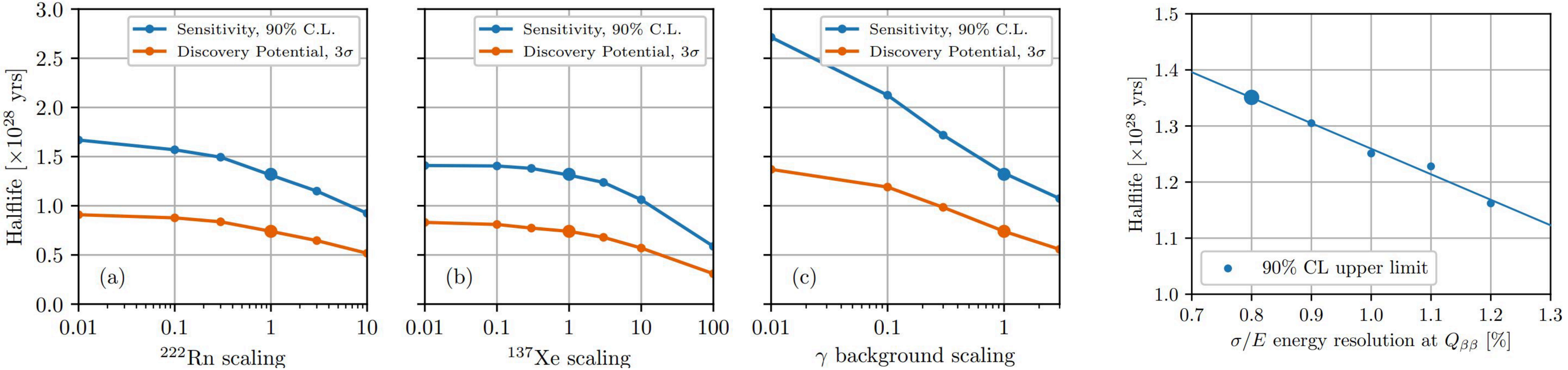




- $>10^{28}$ year sensitivity reach in 10 years
- Can provide compelling evidence of 0νββ decay discovery
- Probes $m_{\beta\beta}$ ~ 15 meV (model and NME dependent)

nEXO Sensitivity and Discovery Potential: **J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)**

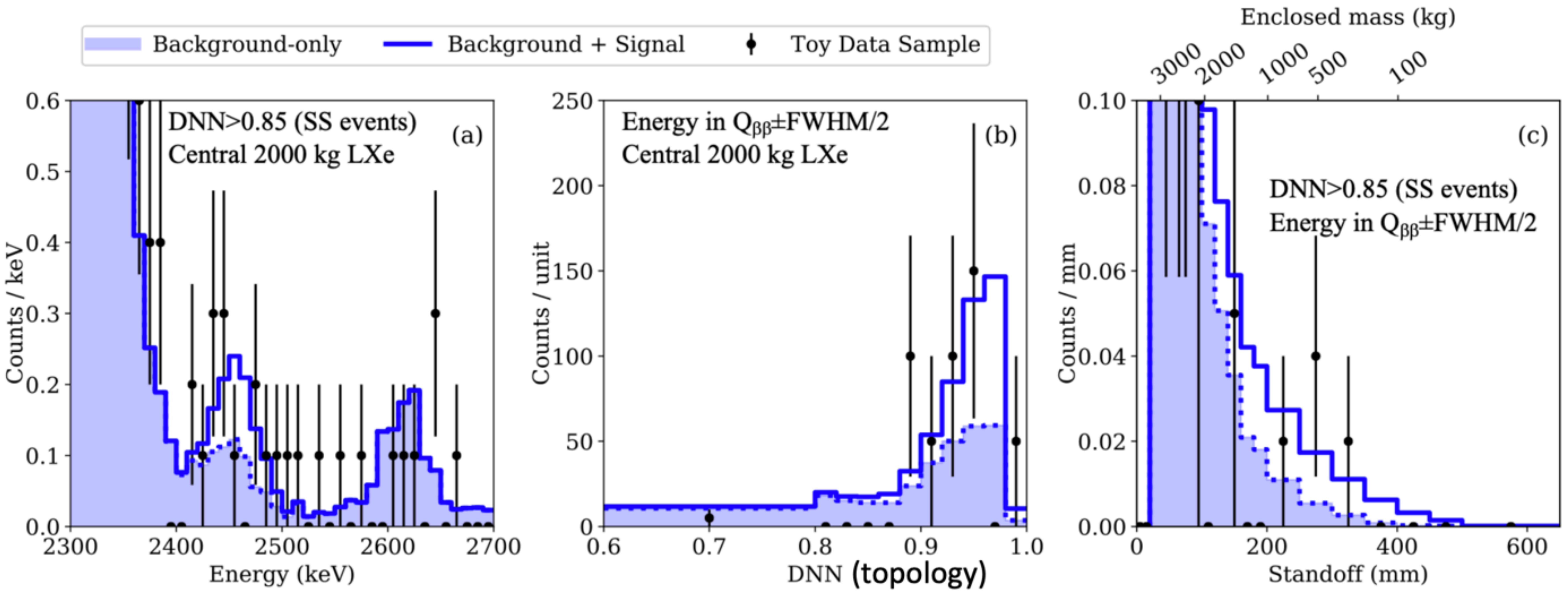
Robust against background and energy resolution scaling



- nEXO sensitivity is robust against background mis-estimations
- Good data/MC agreement was demonstrated with EXO-200
- Point design (=1):
  - 600 steady state radon atoms (EXO-200 had ~200)
  - ^{137}Xe: 0.85x10^{-3} atoms/kg/year

nEXO Sensitivity and Discovery Potential: **J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)**

A robust discovery signal



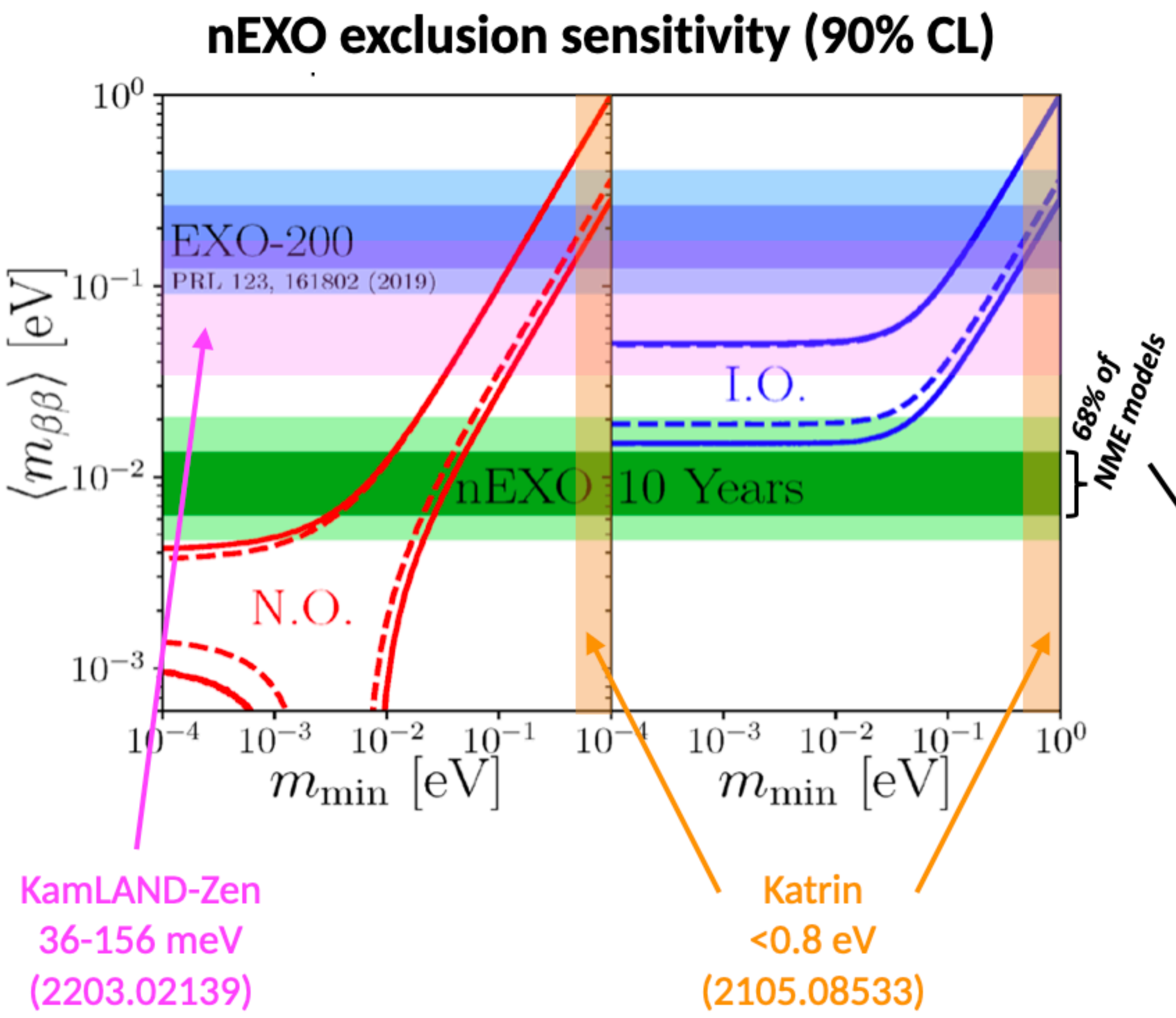
Region of Interest:

- $Q_{\beta\beta}$ ± FWHM/2 (FWHM = 46 keV)
- DNN > 0.85 (signal-like events)
- Innermost 2 tonnes of LXe (standoff > 20mm)

$$T_{1/2} = 0.74 \times 10^{28} \text{ years}$$

- A positive signal unlikely to be mistaken for an unforeseen background
- A control run with depleted xenon could be run to confirm a discovery signal

Neutrino mass sensitivity



Phase-space factor

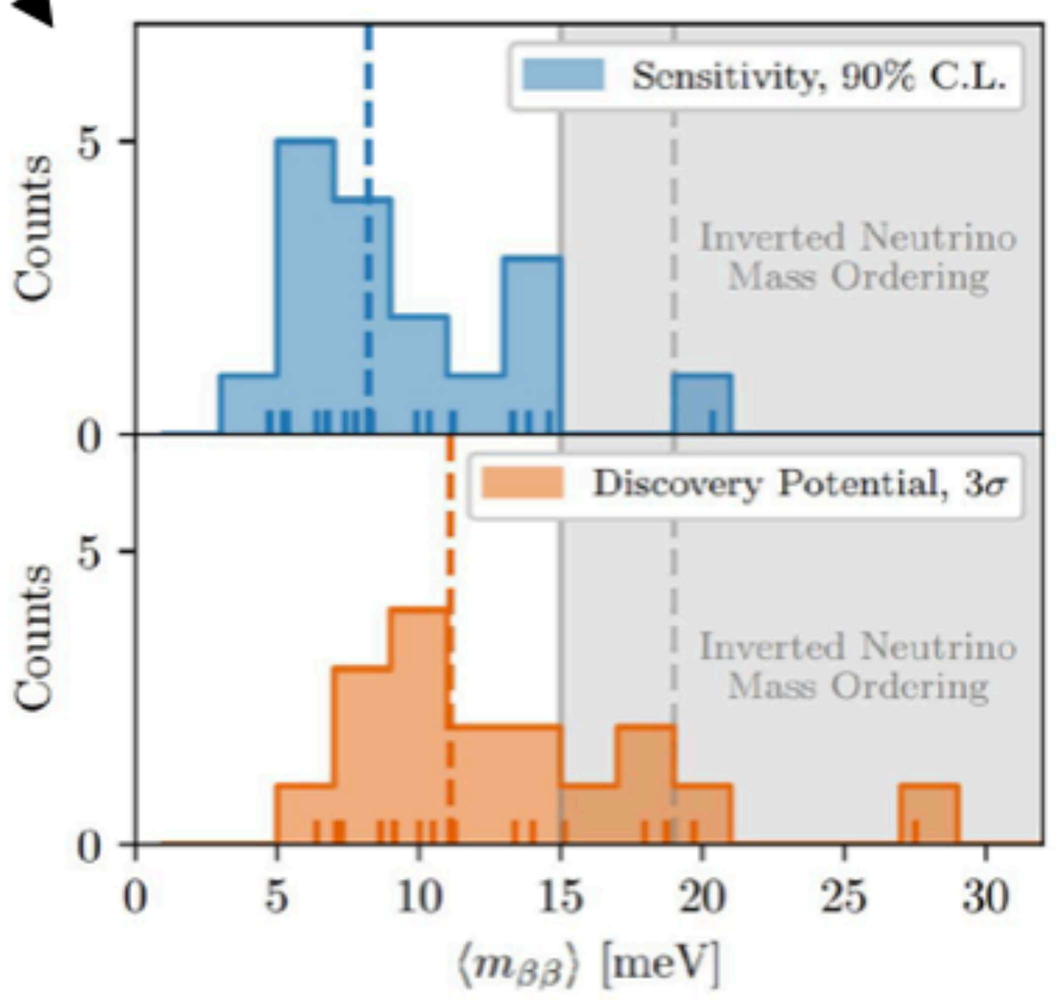
J. Kotila and F. Iachello, Phys Rev C 85, 034316 (2012)

Axial coupling

$g_A = 1.27$

$$\frac{1}{T^0_{1/2}} = \frac{<m_{\beta\beta}>^2}{m_e^2} G^{0\nu} g_A^4 \left|\mathcal{M}^{0\nu}\right|^2$$

Nuclear Matrix Element



- Agnostic approach: show all published NMEs
- nEXO 3σ discovery sensitivity for the median NME is 11.1 meV, below/ beyond I.O.

nEXO is the best option for a very large detector

beyond nEXO

If nEXO discovers 0νββ decay:

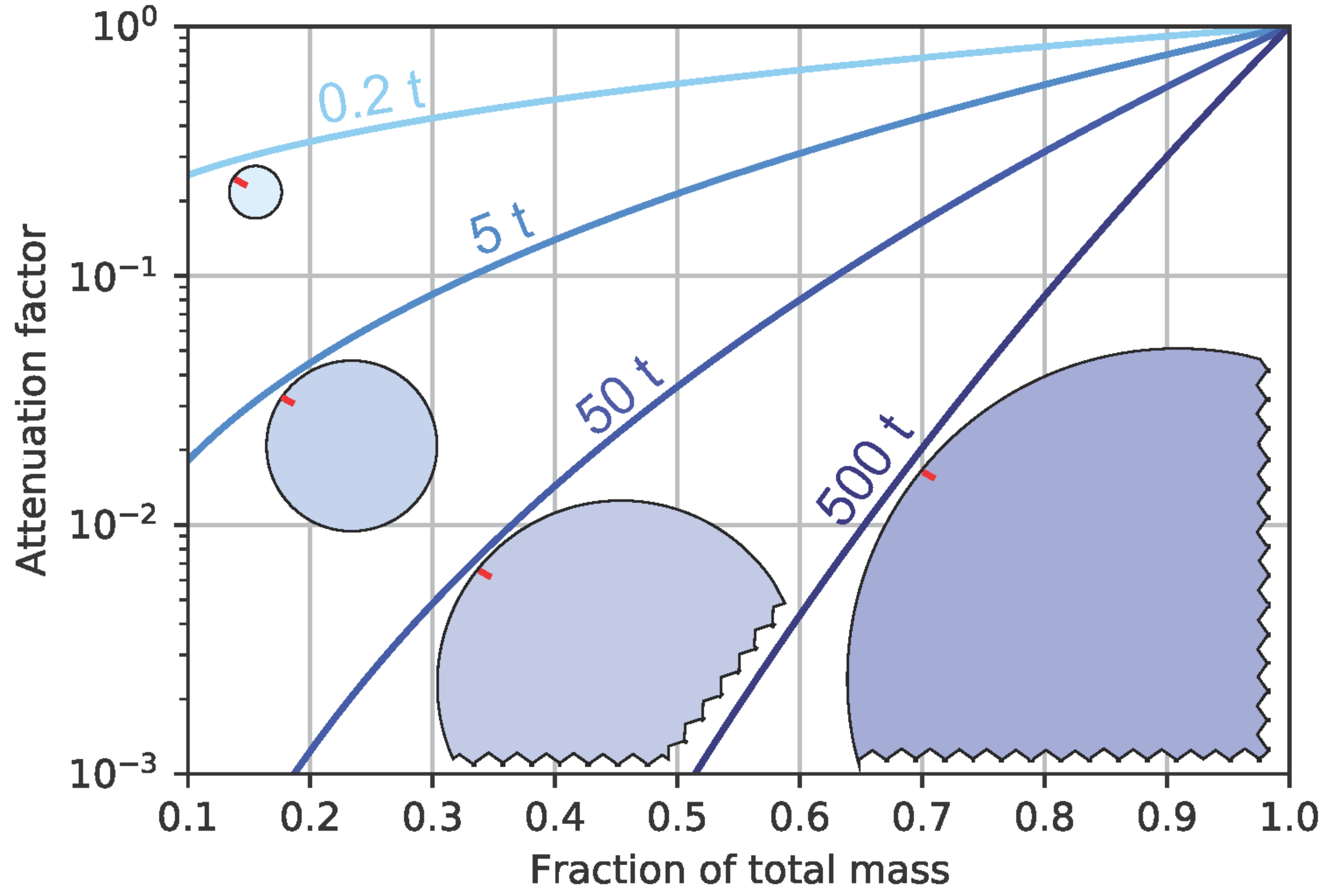
The enriched xenon is NOT "frozen" in a particular detector. Should 0νββ decay be discovered by nEXO, the xenon could be re-used in a different experimental configuration to investigate the underlying physics.

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 plausible. There is enrichment capacity for this, although the feed stock will need to be directly extracted from air. Again, this is plausible, with proper planning.

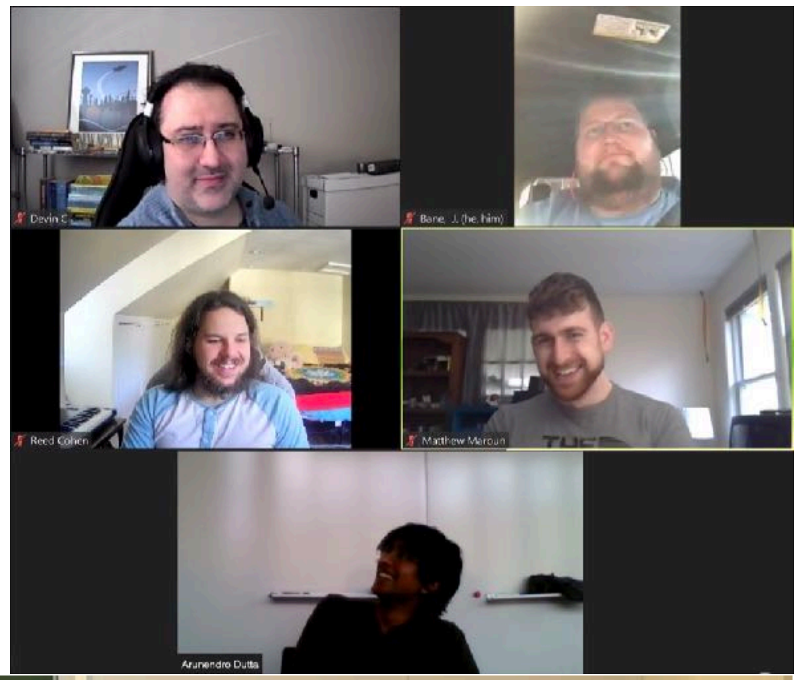
A clear avenue for the future.



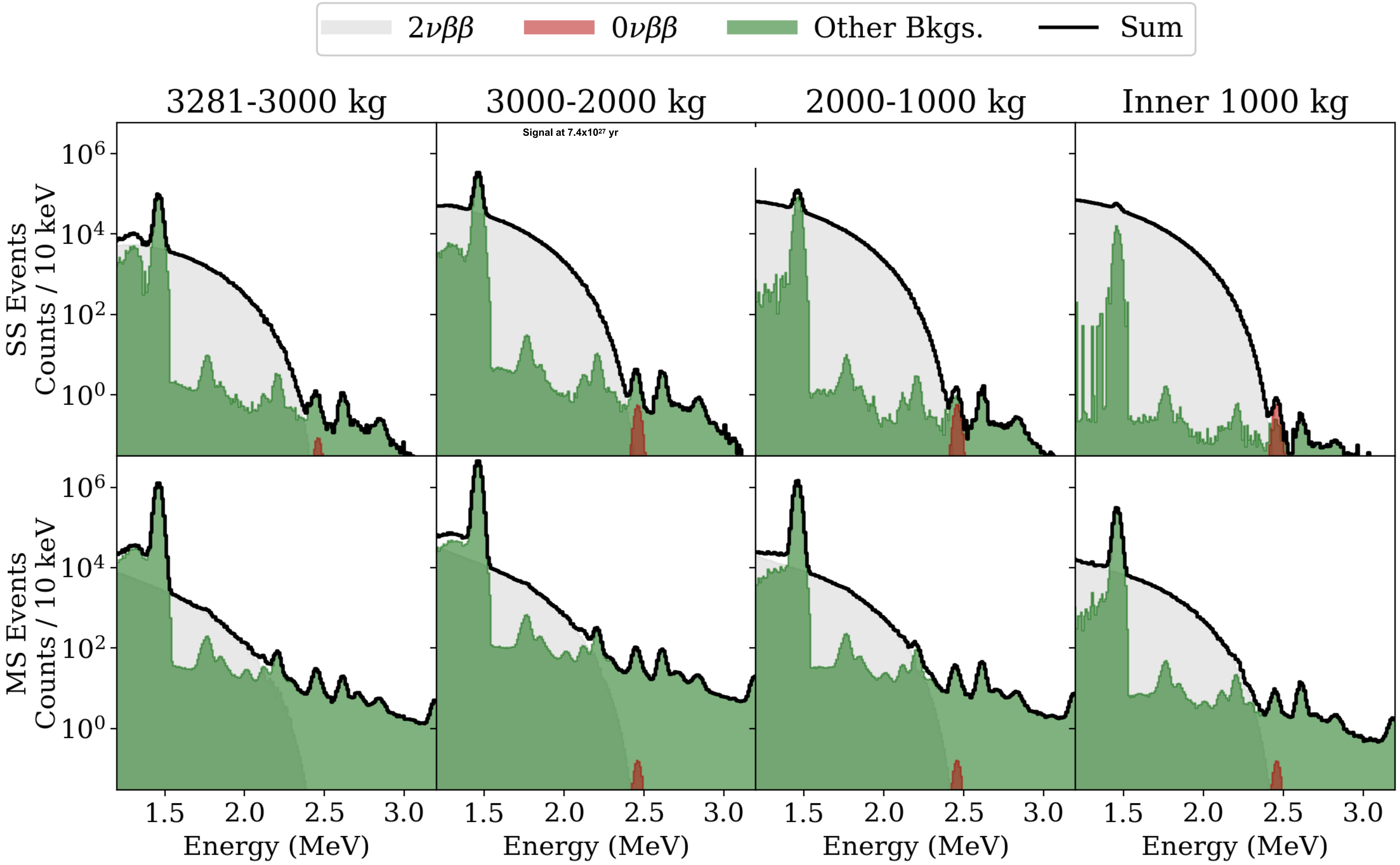
Summary and Outlook

- nEXO will explore beyond the current $0\nu\beta\beta$ decay sensitivity 100-fold
  - Are neutrinos their own antiparticles?
  - Origin of neutrino mass
  - Matter/antimatter asymmetry
- 5 tonnes, enriched LXe TPC
  - Low background design rooted in EXO-200 experience
  - Robust bg model, powerful bg discrimination
  - Benefits from and contributes to rapid evolution of LXe technology

- URL: nexo.llnl.gov
- Twitter: @nEXOexperiment
- Code of Conduct: https://nexo.llnl.gov/diversity-equity-and-inclusion

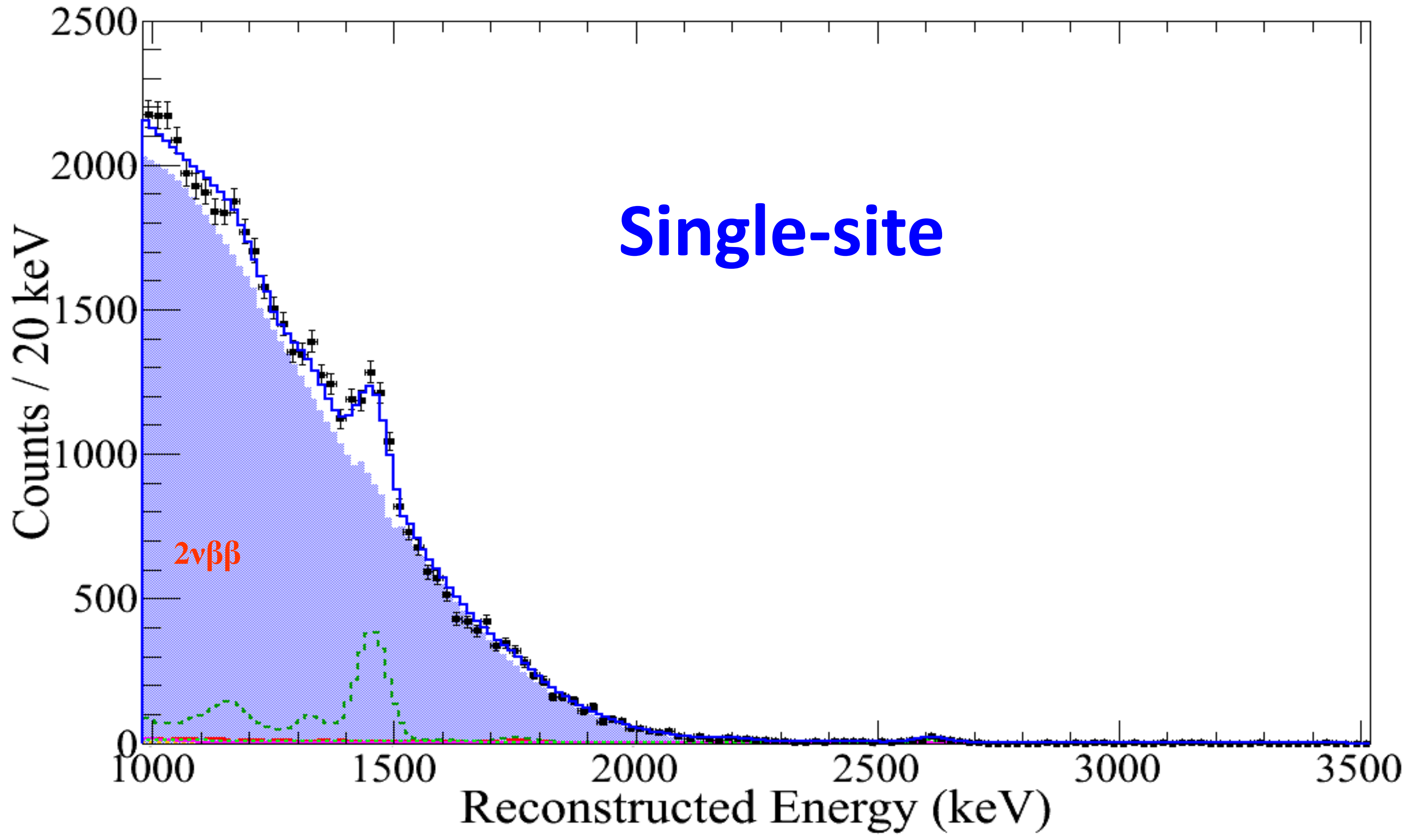


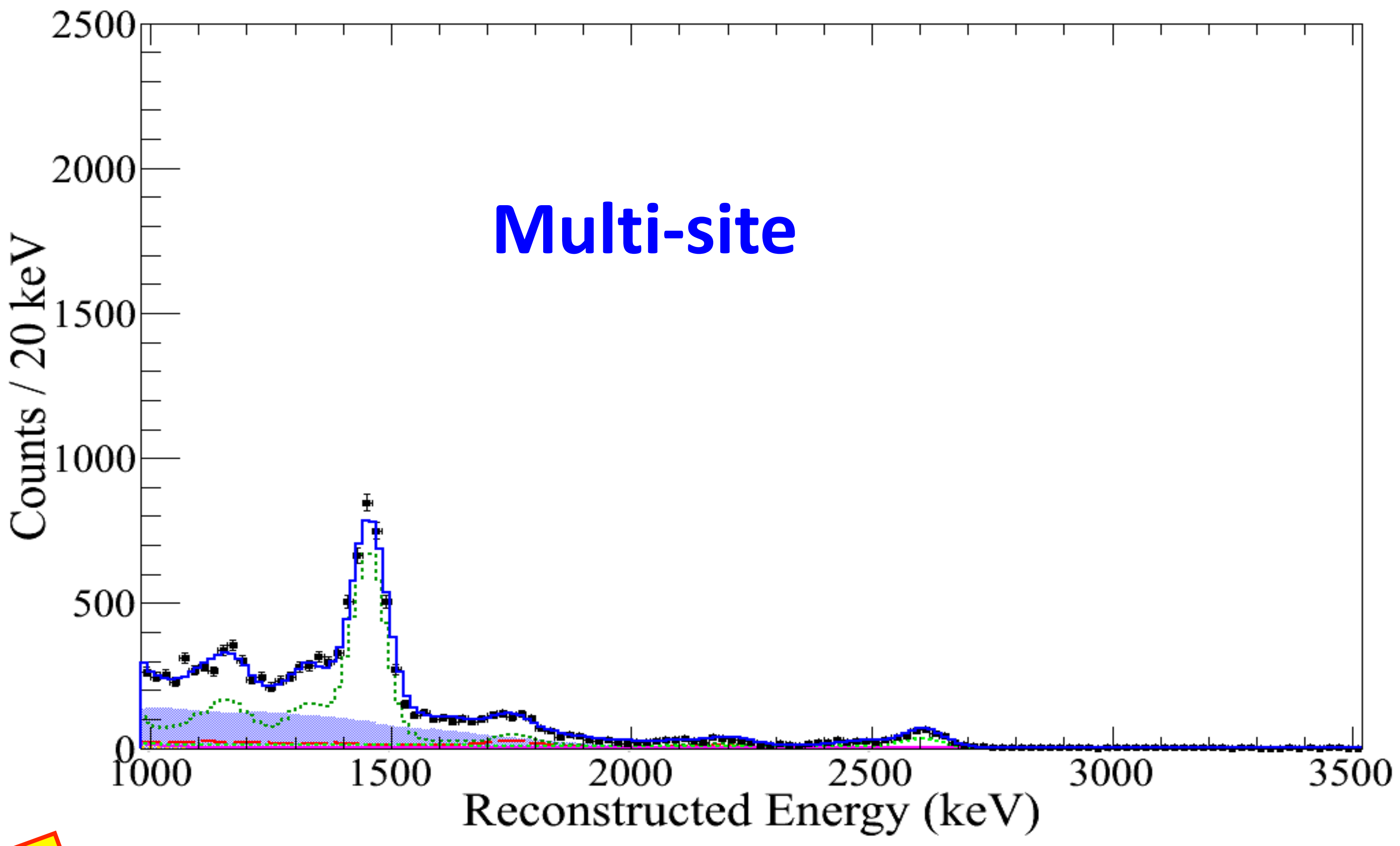
Energy resolution



Event topology and background discrimination in EXO-200

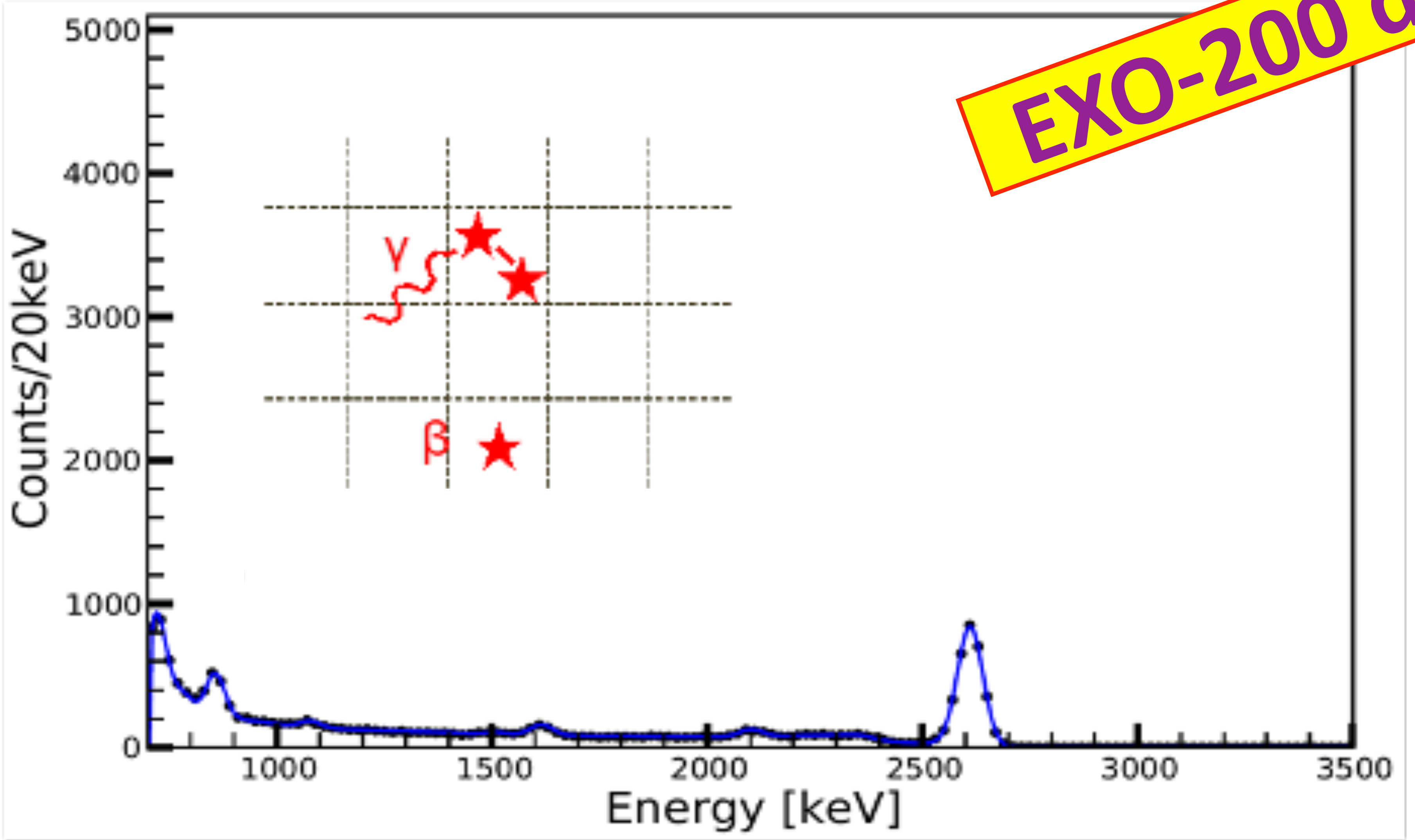
Low background data

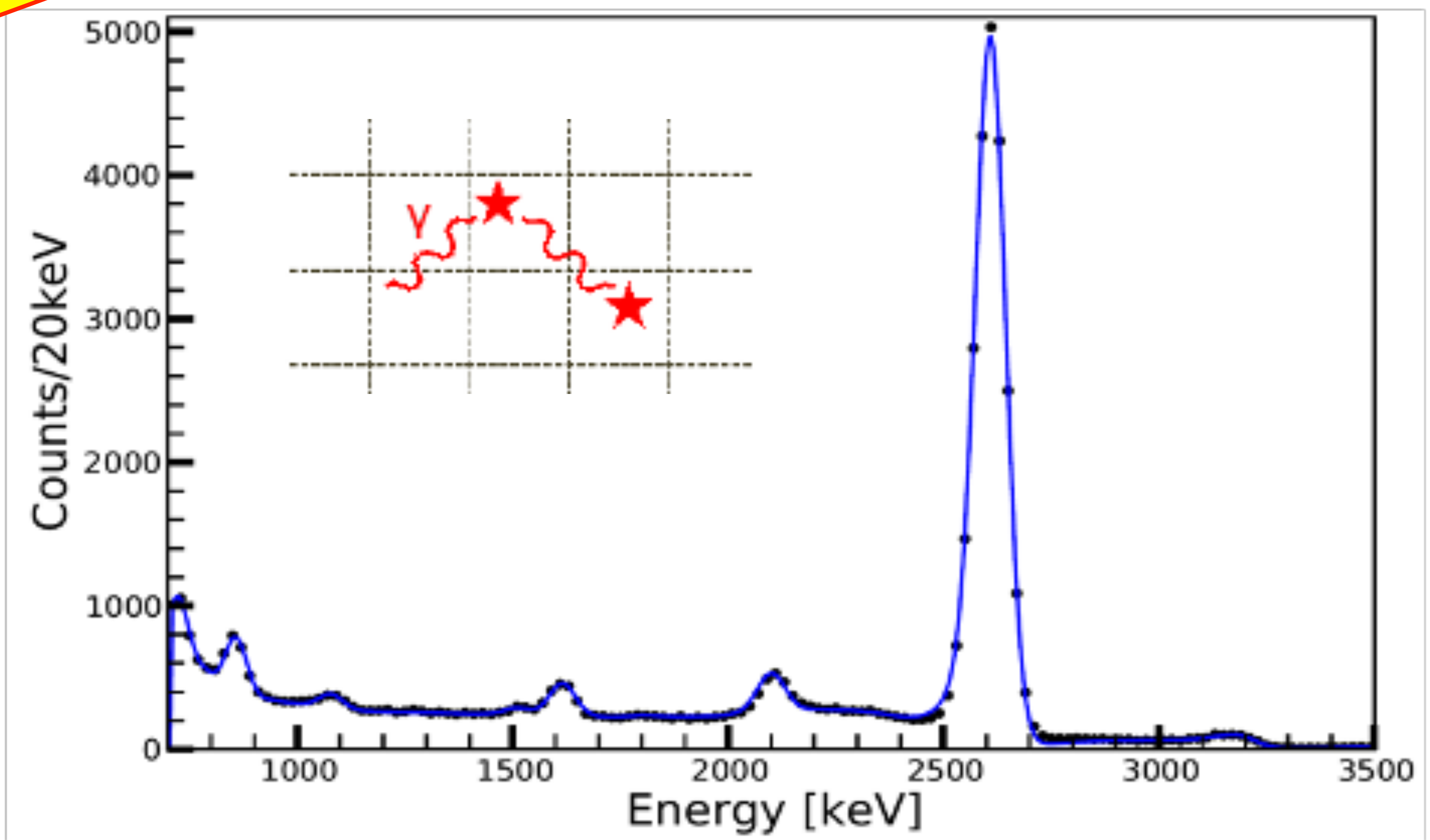




EXO-200 data

^{228}Th calibration source





nEXO: multidimensional information for ~$Q_{\beta\beta}$ events

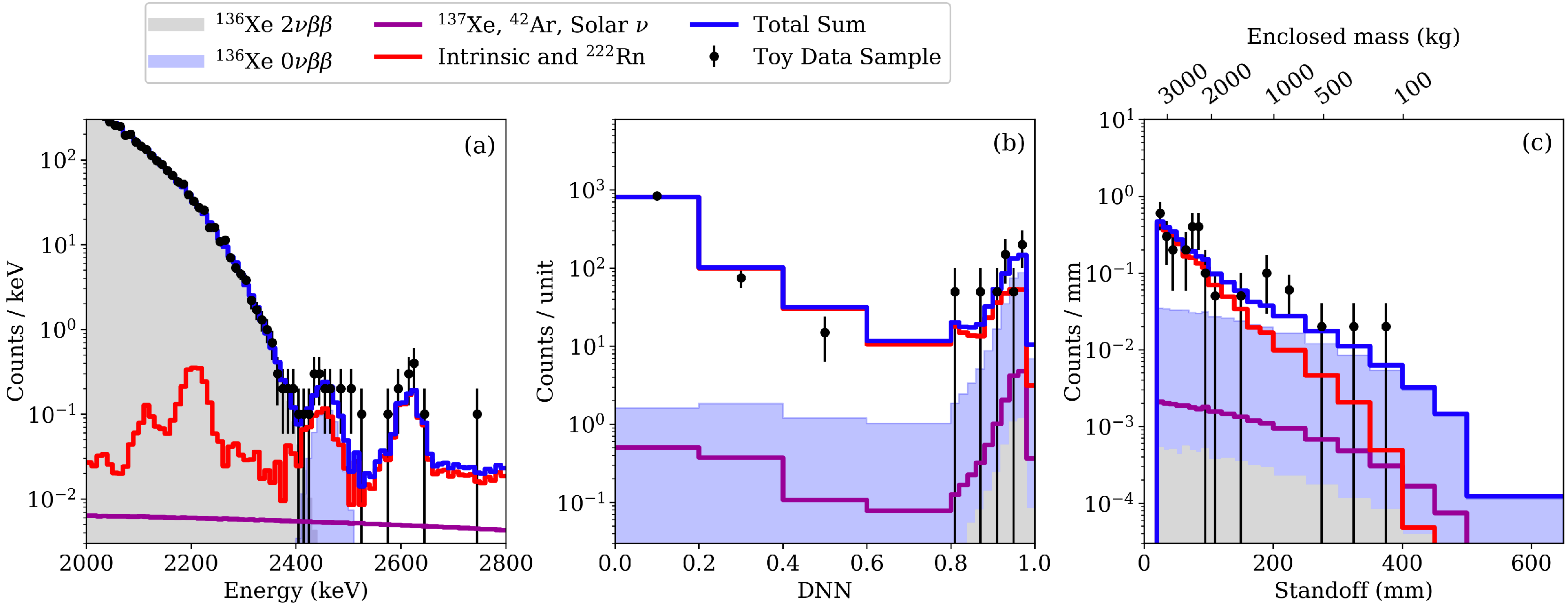


Figure 11. Event distributions for an example of toy dataset (black points) and combined groups of the fitted PDFs projected onto the three axes used in the sensitivity analysis. In (a) the event energy distribution is shown for SS-like events (DNN >0.85) in the central 2000 kg LXe and in the 2000–2800 keV region; (b) the DNN $0\nu\beta\beta$ discriminator distribution is shown for events with energy within $Q_{\beta\beta}\pm$ FWHM/2 and in the same central volume; and (c) the standoff distance distribution is shown for SS-like events within $Q_{\beta\beta}\pm$ FWHM/2. The $0\nu\beta\beta$ decay signal corresponds to a half-life of 0.74×10^{28} yr.

Signal: 0.7×10^{28} y

nEXO Sensitivity and Discovery Potential: **J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)**

nEXO: multidimensional information

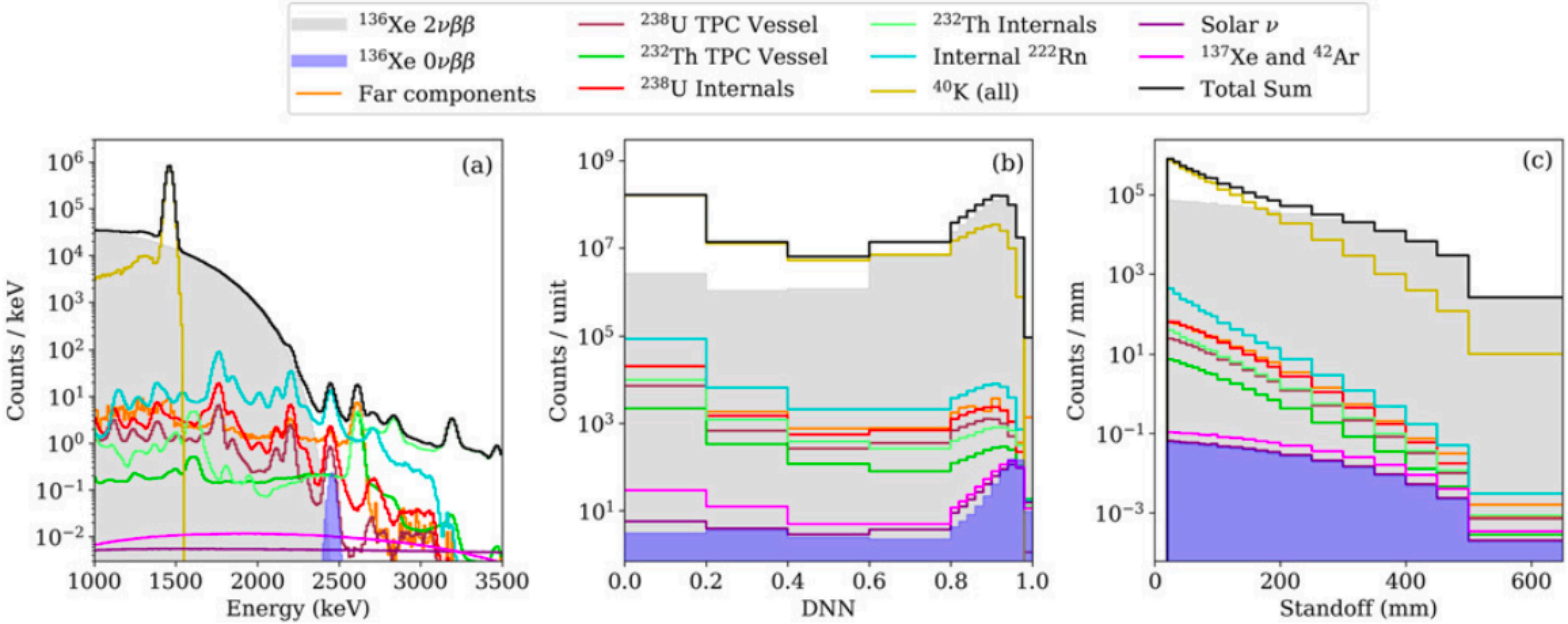
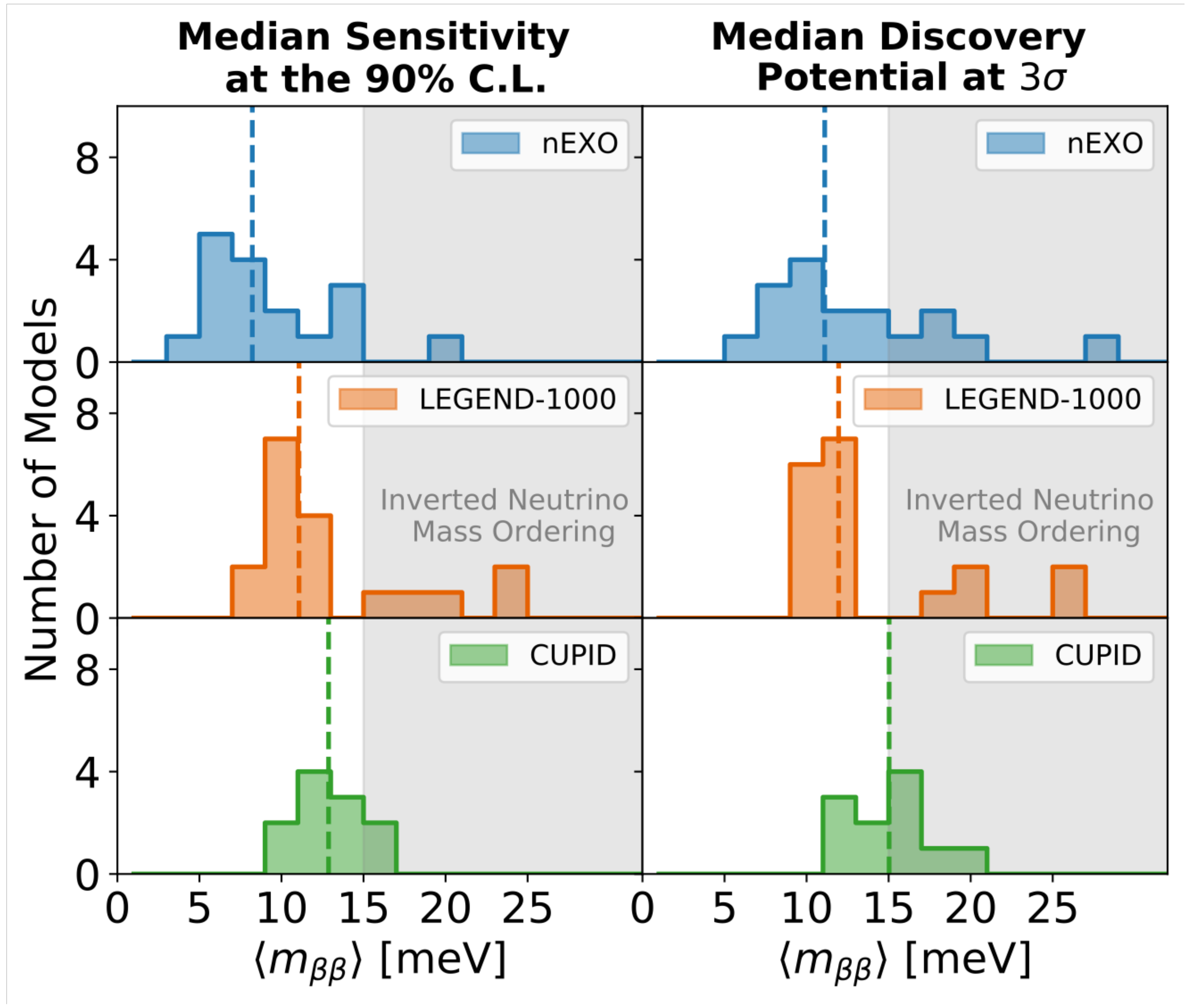


Figure 10. Nominal model of event distributions in nEXO, projected onto each of the three axes used in the sensitivity analysis: (a) event energy, (b) DNN $0\nu\beta\beta$ discriminator, and (c) standoff distance. The $0\nu\beta\beta$ decay signal corresponds to a half-life of 0.74×10^{28} yr.

Signal: 0.7×10^{28} y

nEXO Sensitivity and Discovery Potential: **J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)**

NMEs and other experiments



	[meV] (*median NME*)	
	90% excl. sens.	discov. potential
nEXO	**8.2**	**11.1**
LEGEND	**11.1**	**12.0**
CUPID	**12.9**	**15.0**

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

***$T_{1/2}$ values used [x10^{28} yr]:**

nEXO: 1.35 (90% sens.), 0.74 (3σ discov.) [1]

LEGEND: 1.4 (90% sens.), 1.2 (3σ discov.) [2]

CUPID: 0.15 (90% sens.), 0.11 (3σ discov.) [3]