# Searching for neutrinoless double beta decay with nEXO

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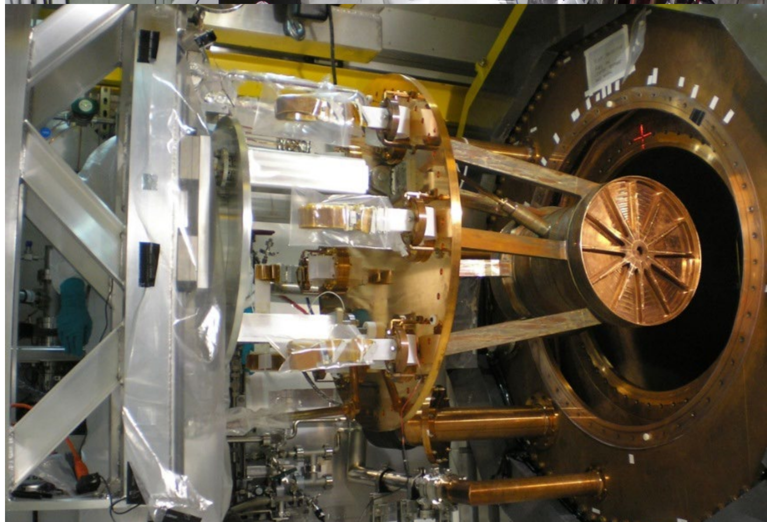
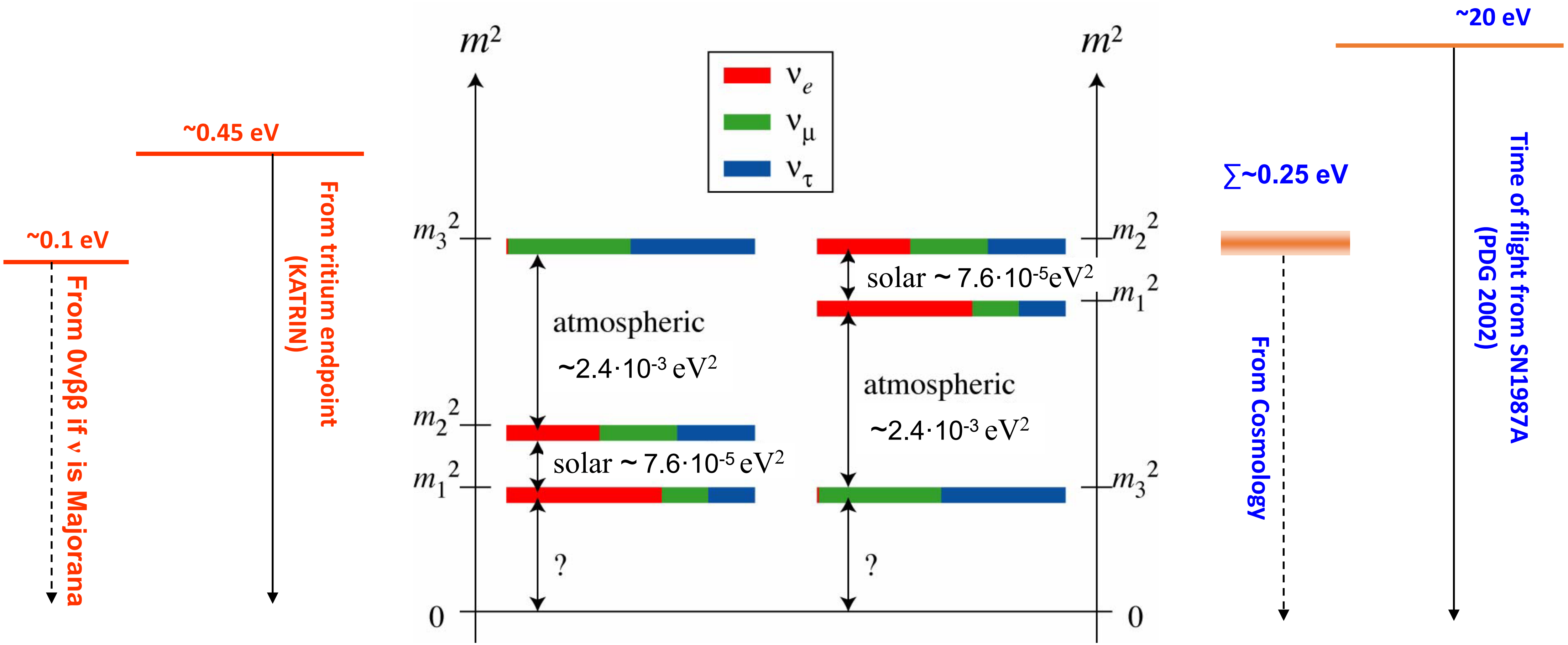
TRIUMF Science Week

July 23, 2024

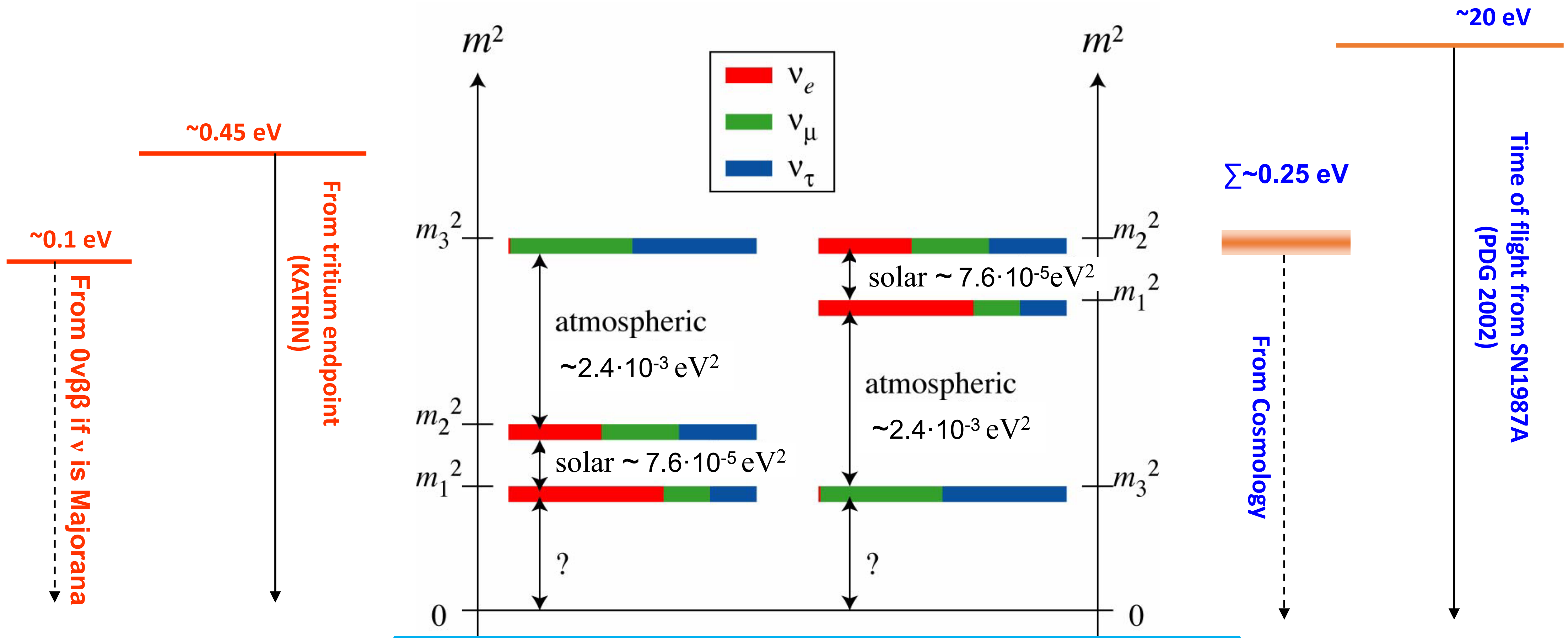
https://neutrino.physics.mcgill.ca/



# What we know about neutrinos



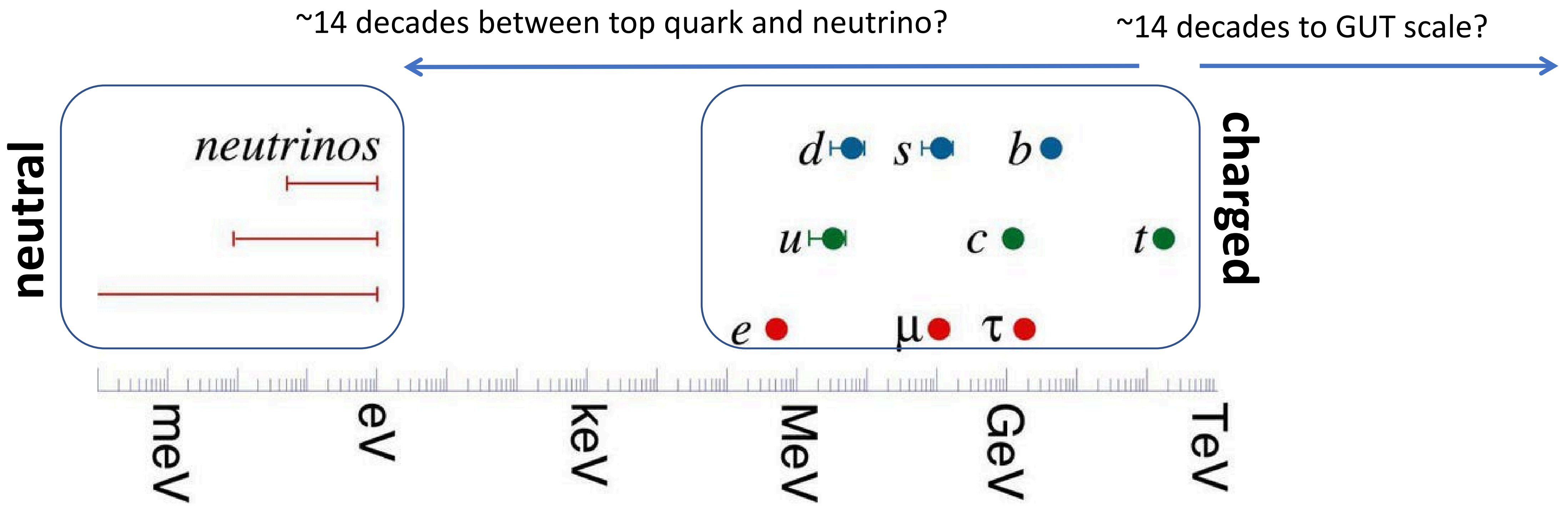
# What we know about neutrinos




**Big questions in neutrino physics (in my view):**

- What is the neutrino mass?
- Why is the mass of the neutrino so small?
- What is the nature of the neutrino? Dirac or Majorana?

# Spin ½ Fermion Mass spectrum




Adopted from: Hitoshi

- Neutrinos are 6 orders of magnitude lighter than the next heavy particle.
- What determines the mass scale hierarchy of elementary particles?
- Is the Higgs mechanism responsible for neutrino mass?
- Perhaps neutrinos are very different from other fermions and are Majorana particle?

# Electrical neutral neutrinos

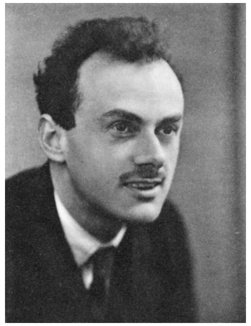
**Generation**

| Charge | 1st | 2nd | 3rd |
|---|---|---|---|
| 1 | $e^+$ | $\mu^+$ | $\tau^+$ |
| 2/3 | u | c | t |
| 1/3 | $\bar{d}$ | $\bar{s}$ | $\bar{b}$ |
| 0 | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
| -1/3 | d | s | b |
| -2/3 | $\bar{u}$ | $\bar{c}$ | $\bar{t}$ |
| -1 | $e^-$ | $\mu^-$ | $\tau^-$ |

- Neutrinos do not carry charge. What about lepton number?
- Lepton number conservation is just an empirical notion and not as “serious” as, e.g., energy conservation.
- Basically, lepton number is conserved “because”, experimentally, $\bar{\nu} \neq \nu$ . But the distinction could derive from the different helicity states.

# Quantum Nature of the Neutrino

"Dirac" neutrinos $\nu \neq \bar{\nu}$



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

"Majorana" neutrinos $\nu = \bar{\nu}$

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

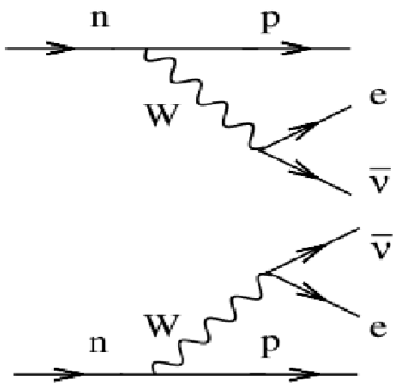
Which way Nature chose to proceed is an open experimental question, although Majorana neutrinos are favored by theory.

# How can we determine if $\nu = \bar{\nu}$?

The answer may be neutrinoless $\beta\beta$ decay

# Double Beta Decay

Maria Goeppert Mayer




Two neutrino double beta decay

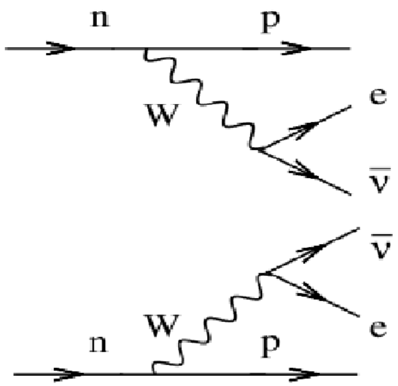
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$

1935 Maria Goeppert Mayer first proposed the idea of two neutrino double beta decay

1987 first direct observation in $^{82}$Se by M. Moe

# Double Beta Decay

Maria Goeppert Mayer

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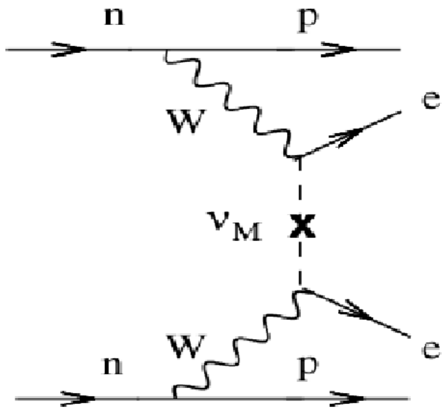
Ettore Majorana




## Neutrinoless double beta decay

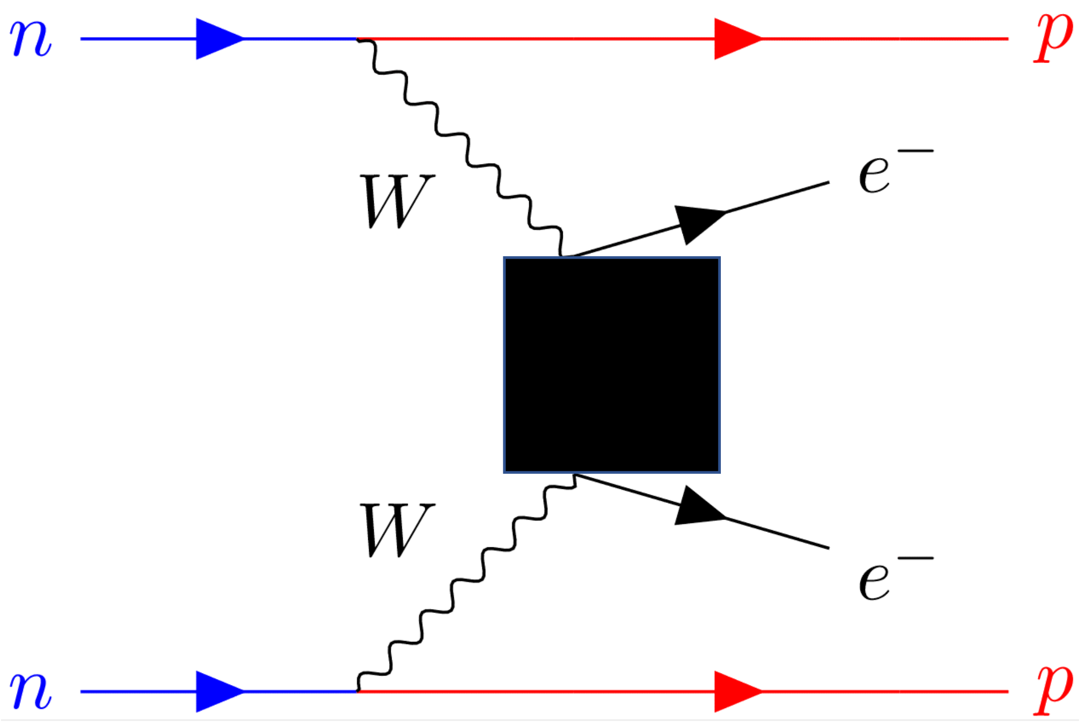
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-}$$

1937 Ettore Majorana proposed the theory of Majorana fermions

1939 Wendell Furry proposed neutrinoless double beta decay

# Black Box Theorem

- “Black box” theorem*: **Observation of 0νββ always implies <u>new physics</u>:**
  - Majorana neutrinos
  - Lepton number violation
  - Help explain observed cosmic baryon asymmetry → leptogenesis




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

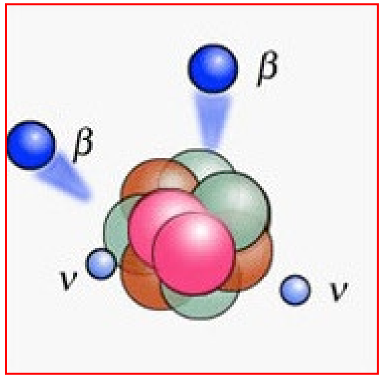
# Matter-Antimatter Asymmetry

**Neutrinos could be the key to explaining the matter-antimatter asymmetry in the universe.**

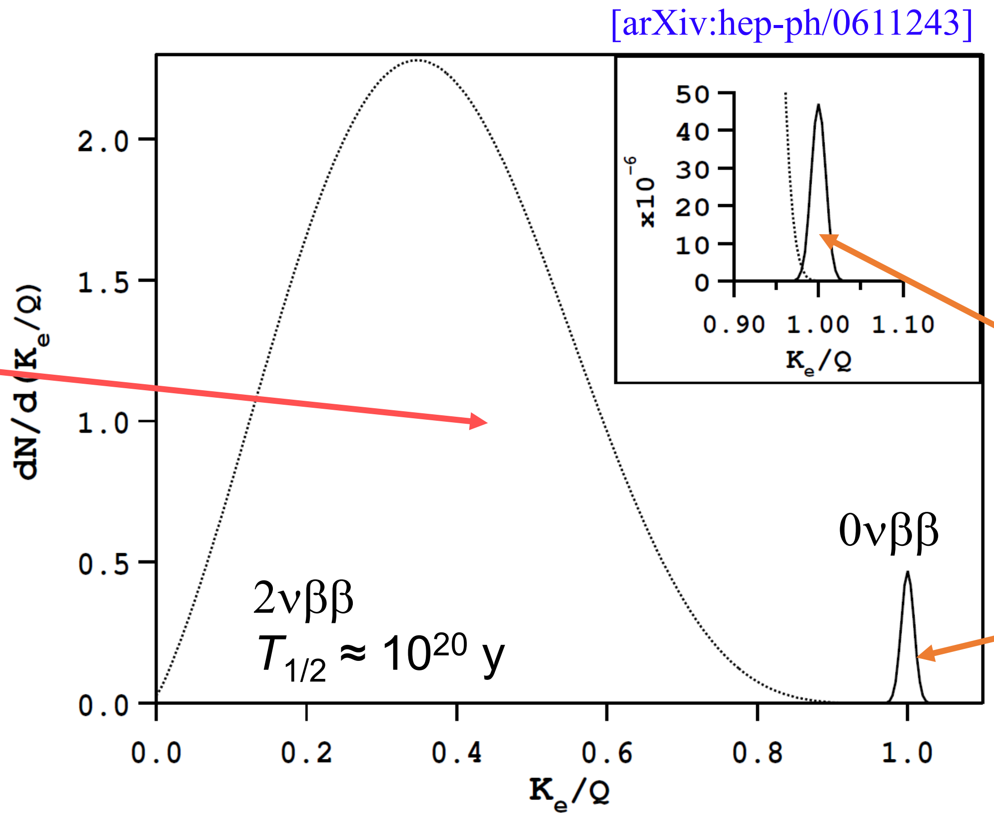


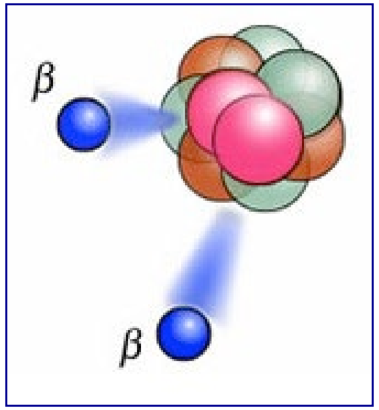
Source: https://www.spacetelescope.org/

# Double Beta Decay




2νββ spectrum
(normalized to 1)



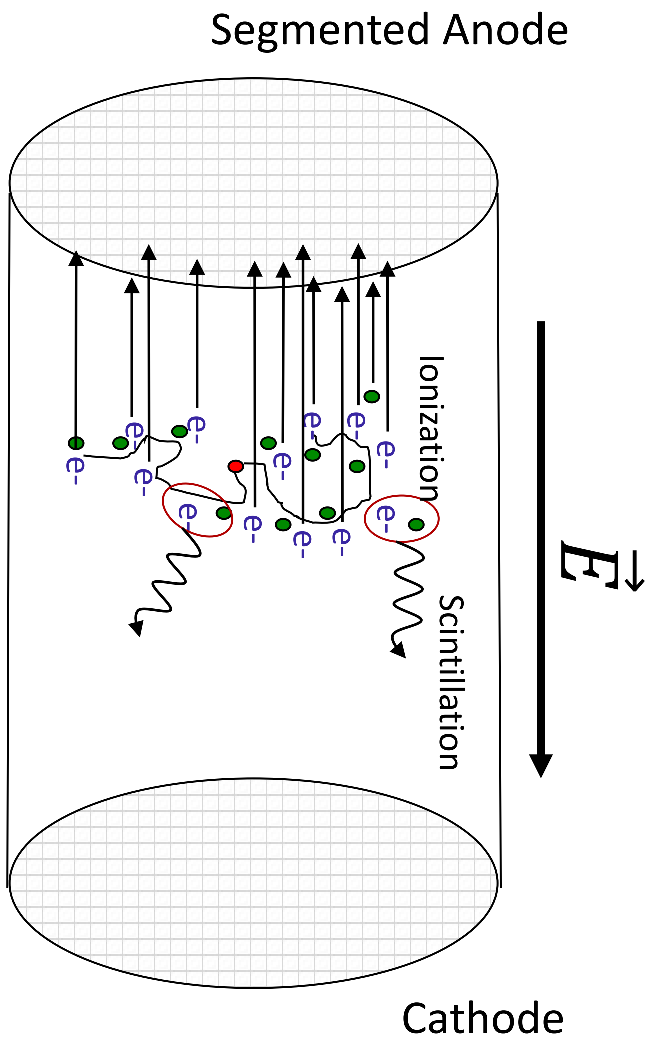




**0νββ peak**
**(normalized to $10^{-6}$)**

**0νββ peak**
**(normalized to $10^{-2}$)**

- 0νββ – Can only happen for Majorana neutrinos!
- Current experiments: $T_{1/2} > 10^{25\text{-}26}$ y
- Sensitivity goal for next generation experiments: $T_{1/2} > 10^{28}$ y

# EXO's search for $0\nu\beta\beta$ in $^{136}Xe$ with liquid Xe TPC




## Liquid-Xe Time Projection Chamber (TPC)

- Xe is used both as the source and detection medium.
- LXe is continuously recirculated and purified.
- No long-lived cosmogenically activated Xe isotopes
- Monolithic detector structure enables excellent background rejection capabilities.

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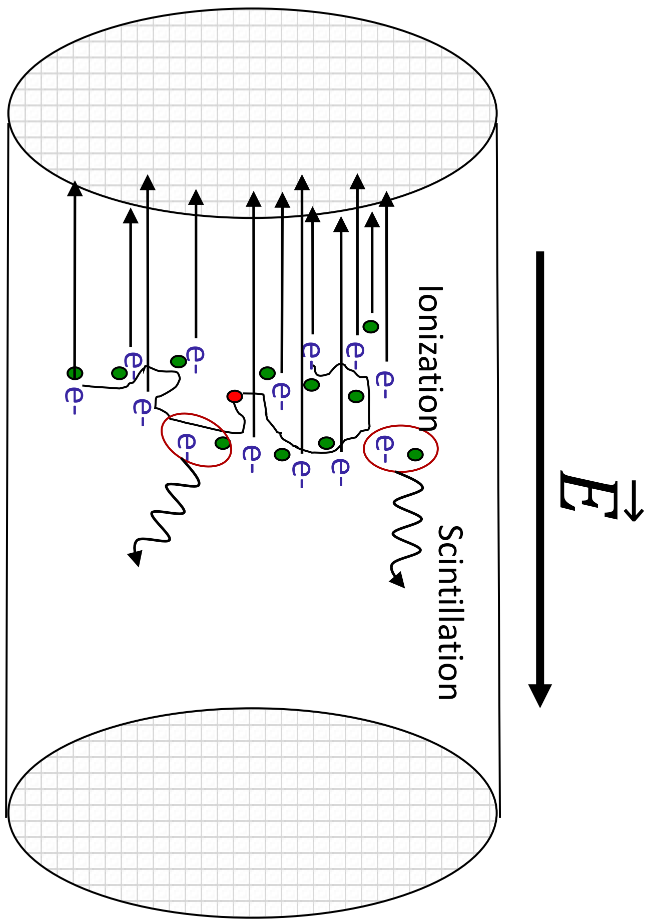


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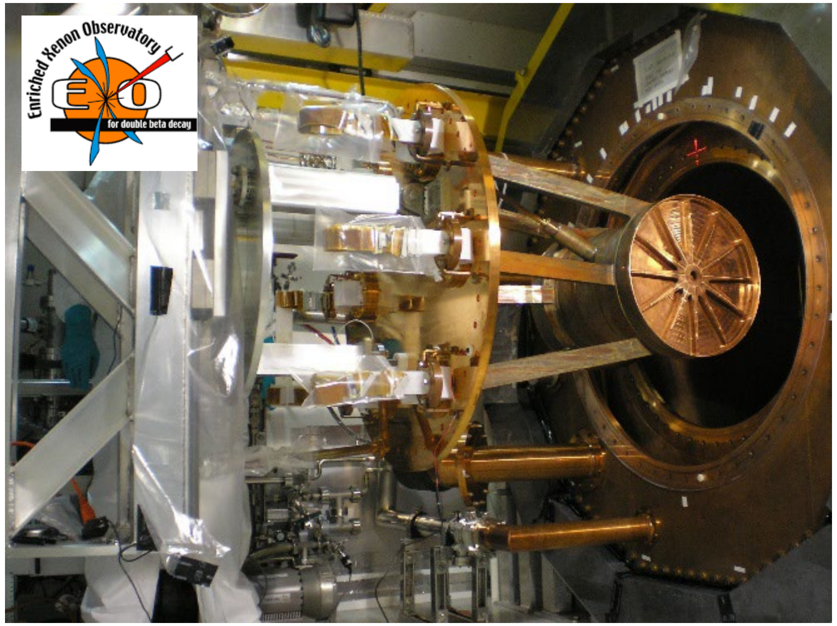
- Monolithic detector structure enables excellent background rejection capabilities.
- Multiparameter measurement from detection of scintillation light and ionization signal:
    1. Energy from combined scintillation/ionization
    2. Topology, e.g., single-site or multi-site
    3. Position distribution from 3D event reconstruction
    4. Particle identification from scintillation/ionization ratio

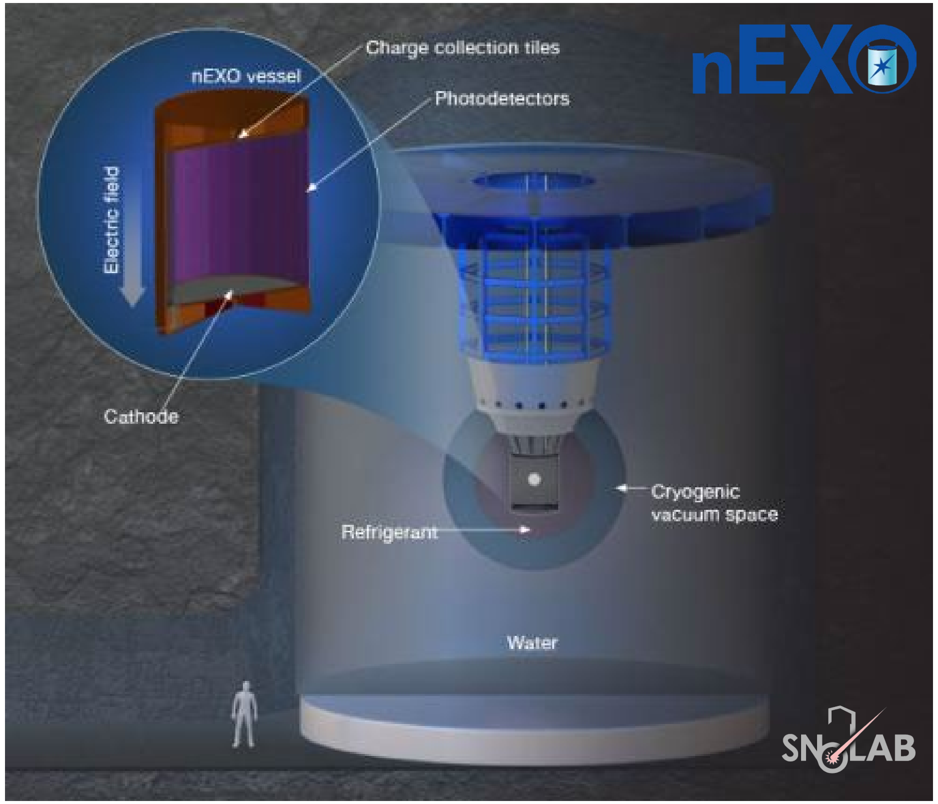
# Searching for 0νββ in $^{136}$Xe – a phased approach

**EXO-200:**
- EXO-200 first 100-kg class ββ experiment
- 175kg liquid-Xe TPC with ~80% Xe-136
- Located at the WIPP mine in NM, USA
- Decommissioned in Dec. 2018
- Analyze data from end-of-run calibration campaign
  → data informs the detailed design of nEXO




https://www-project.slac.stanford.edu/exo/

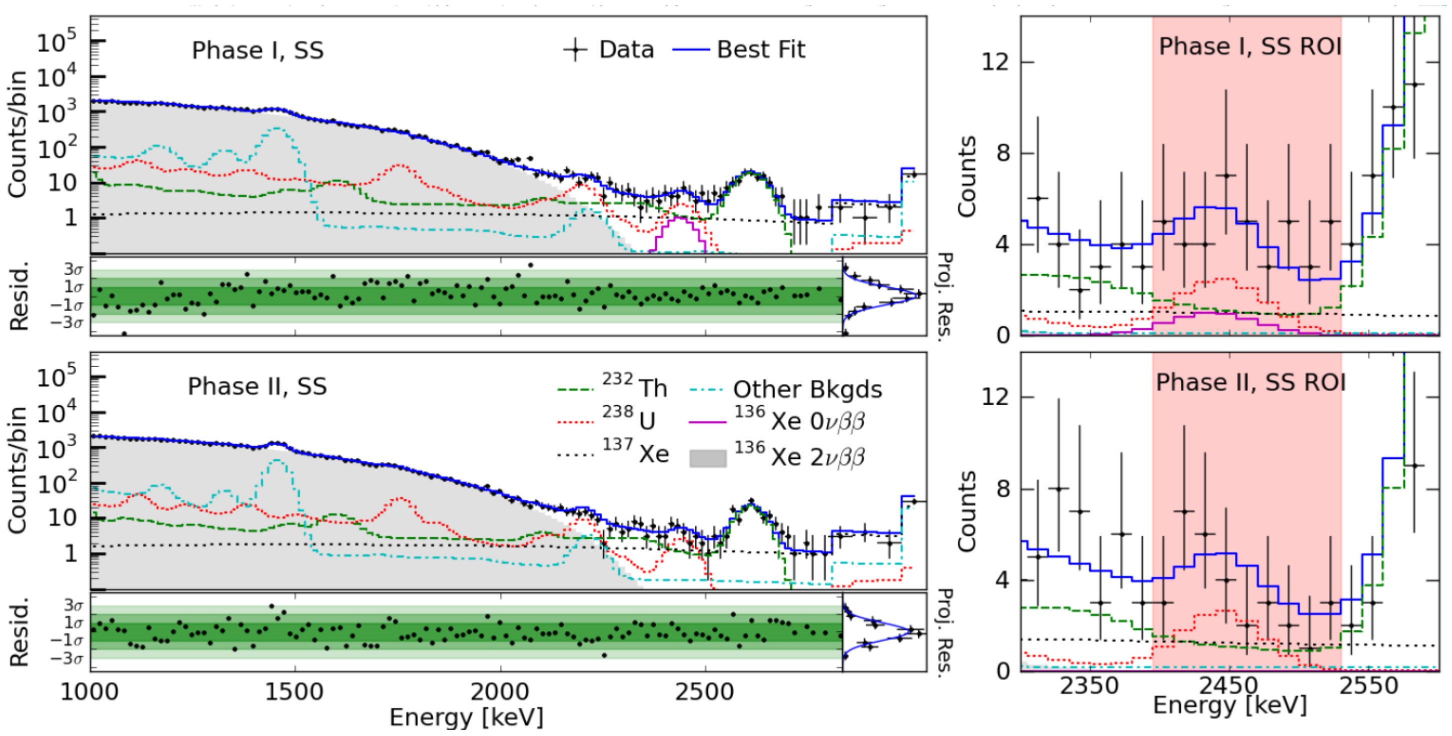
**nEXO:**
- 5-tonne liquid Xe TPC
- Enriched in Xe-136 at ~90%
- SNOLAB cryopit preferred location by collaboration




https://nexo.llnl.gov/

# Final EXO-200 Result

- EXO-200 demonstrated excellent background, very well predicted by the massive material characterization program and simulations → ***This is essential for nEXO design***




**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.)**

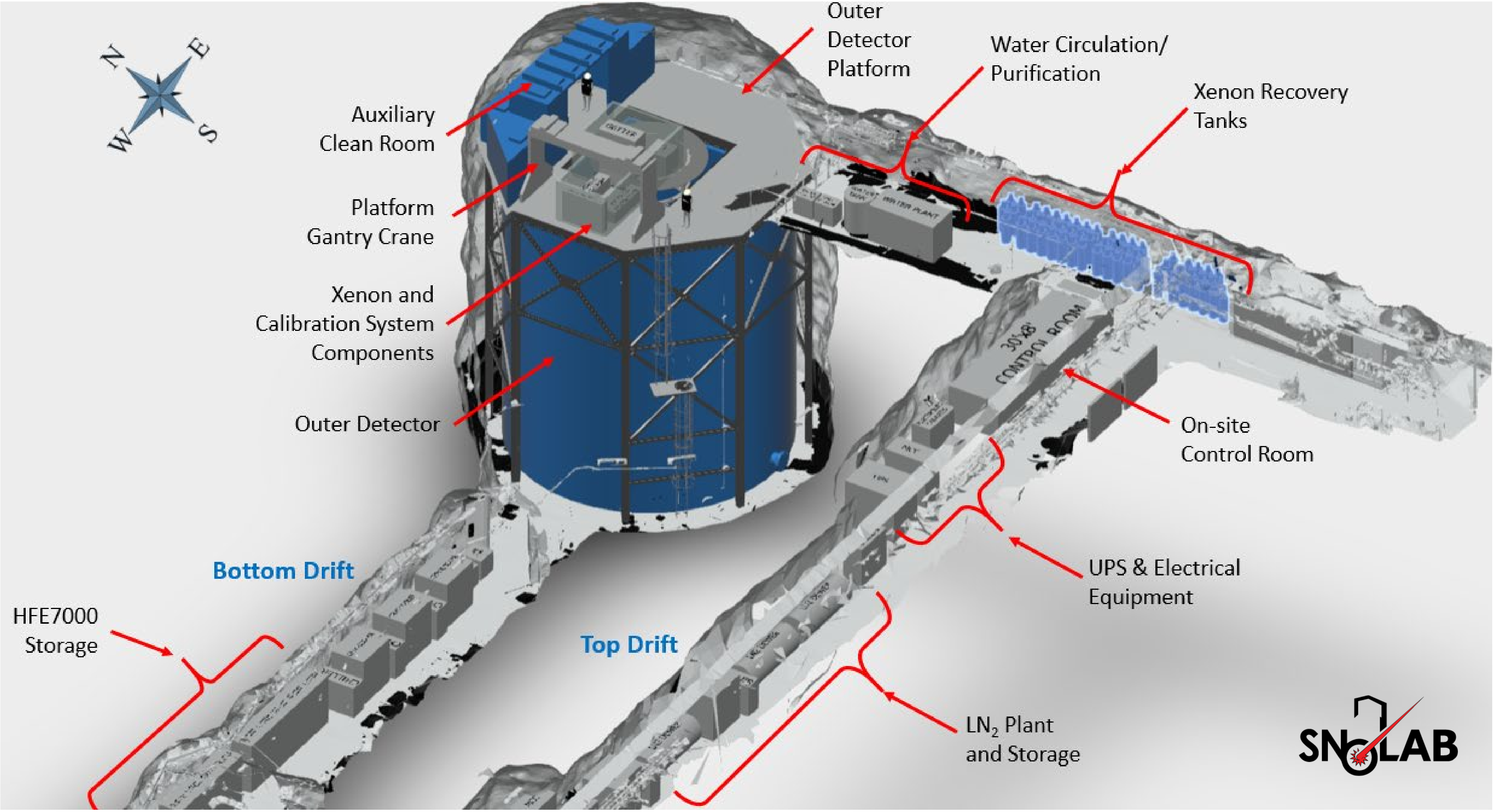
**$\langle m_{\beta\beta} \rangle$ < (93 – 286) meV**

**Sensitivity 5.0x$10^{25}$ yr**

*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)*

EXO-200 has achieved 1.15 ± 0.02% energy resolution at the Q-value.

# nEXO at SNOLAB, 2 km below surface



# The nEXO collaboration

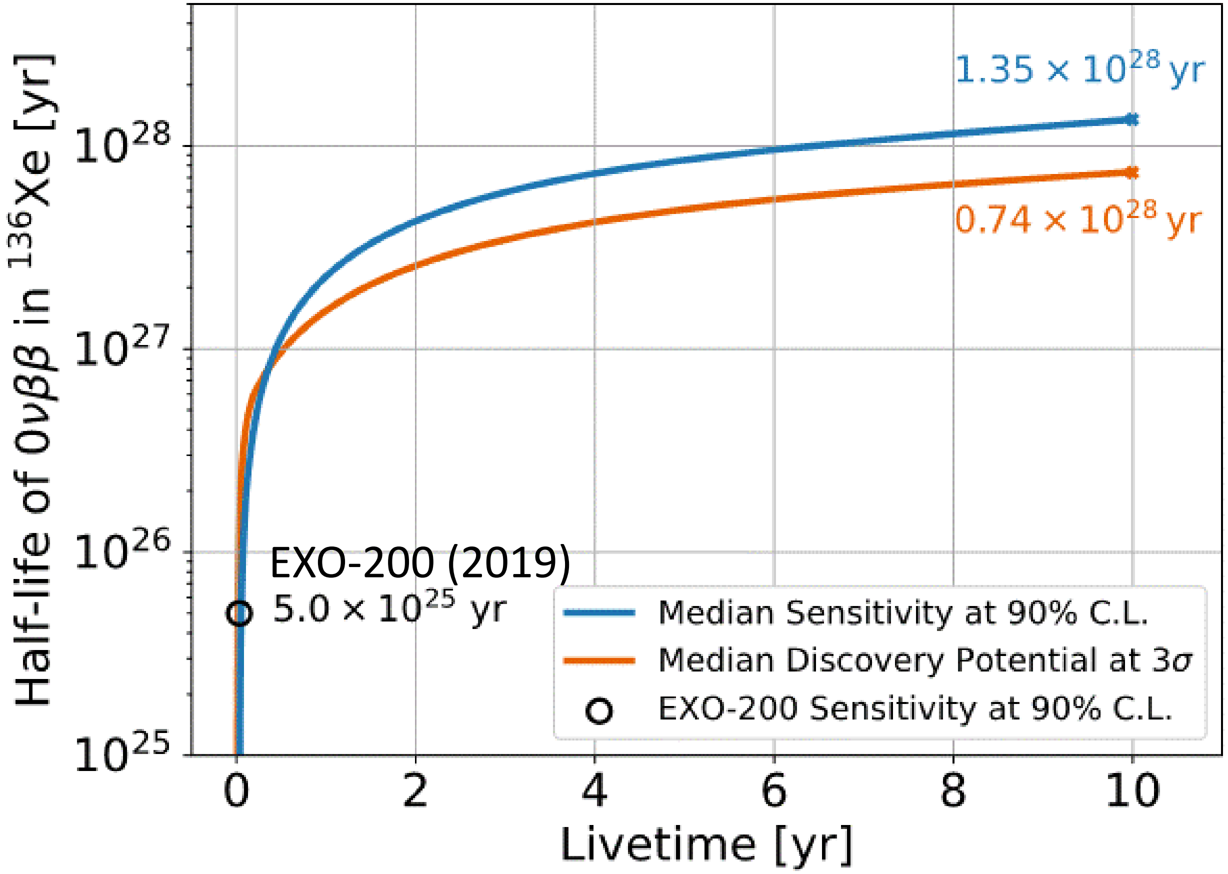

>200 scientists, 38 institutions in 10 countries on 4 continents

nEXO

Collaboration Meeting in Montreal 2023

# nEXO Projected Sensitivity

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

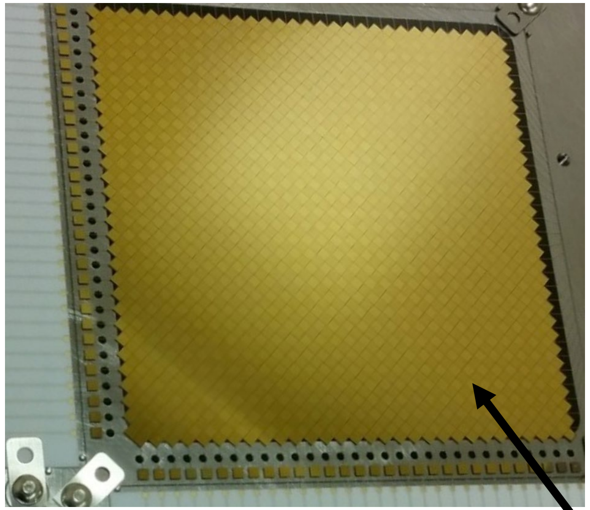



**nEXO sensitivity reaches $10^{28}$ yr in 6.5 yr data taking**

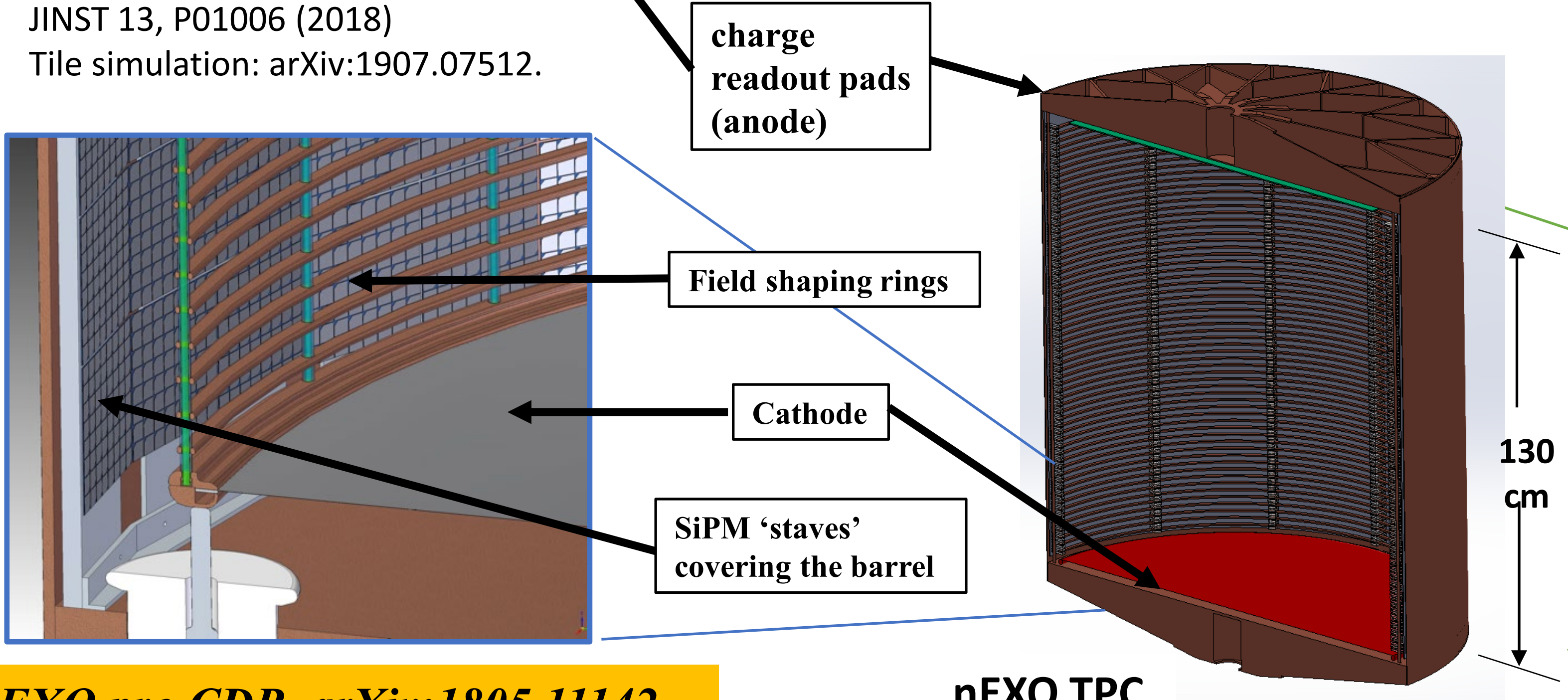
Projected sensitivity based on actual background level measurements!

# The nEXO detector

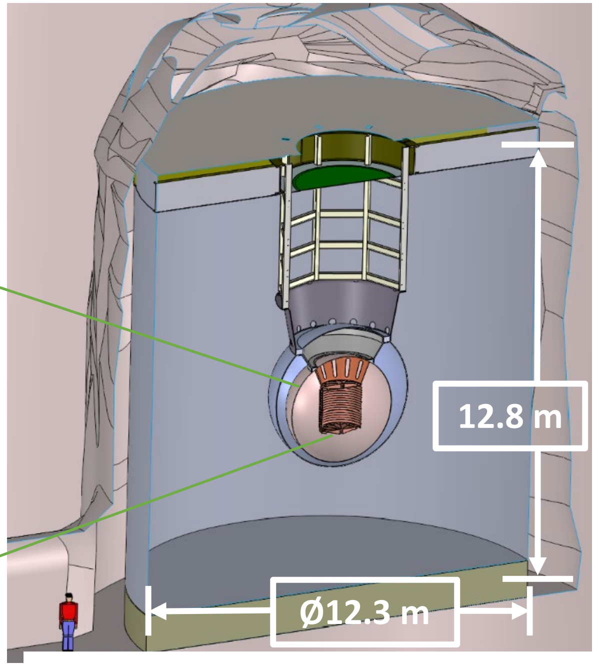
- Next-generation neutrinoless double beta decay detector.
- 5 t liquid xenon TPC (90% enriched in Xe-136).
- SiPM for 175nm scintillation light detection, ~4.5m$^2$ SiPM array in LXe.
- Tiles for charge read out in LXe.
- In-cold electronics inside TPC in liquid Xe.
- 3D event reconstruction.
- Combine charge and light readout. Goal → $\sigma/E < 1\%$ at Q-value.
- 1.5 ktonnes water-Cherenkov detector for muon tagging and shielding.



Picture: 10 x 10 cm$^2$ tile prototype
JINST 13, P01006 (2018)
Tile simulation: arXiv:1907.07512.




nEXO TPC




nEXO at the SNOLAB Cryopit

***nEXO pre-CDR, arXiv:1805.11142***

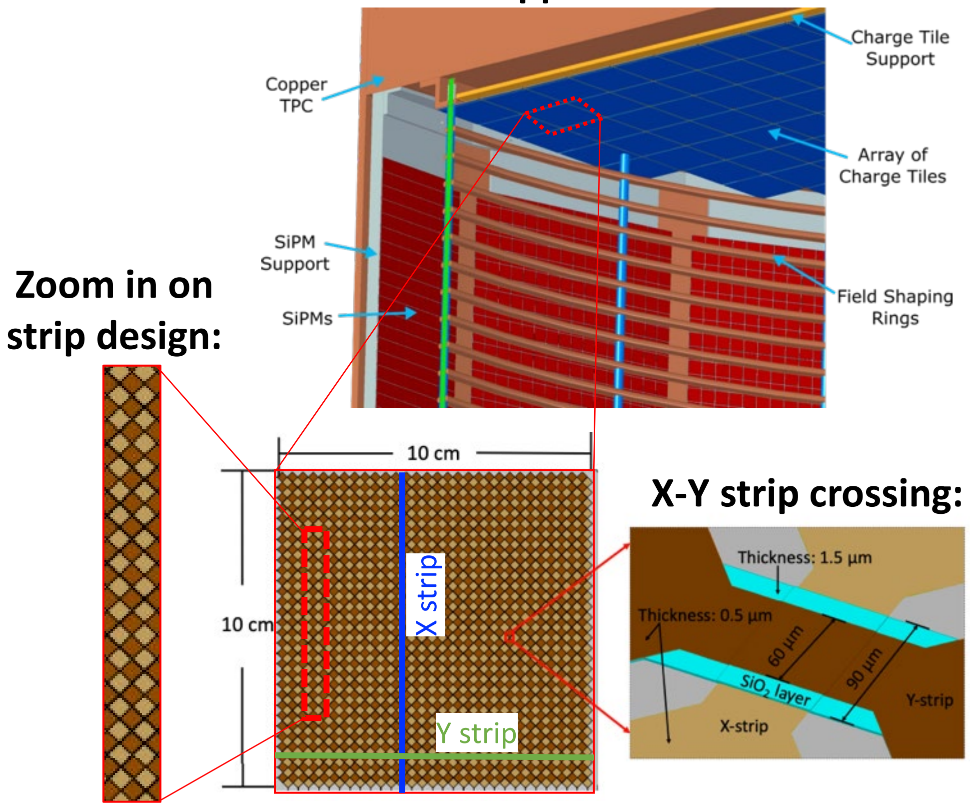
# Anode Charge Readout

- Charge collection on tiled anode plane
- Full simulation of charge collection in nEXO used to optimize design
  - Crossed strips with no shielding grid
  - Channel pitch: 6mm
  - Tile size: 10 cm x 10 cm

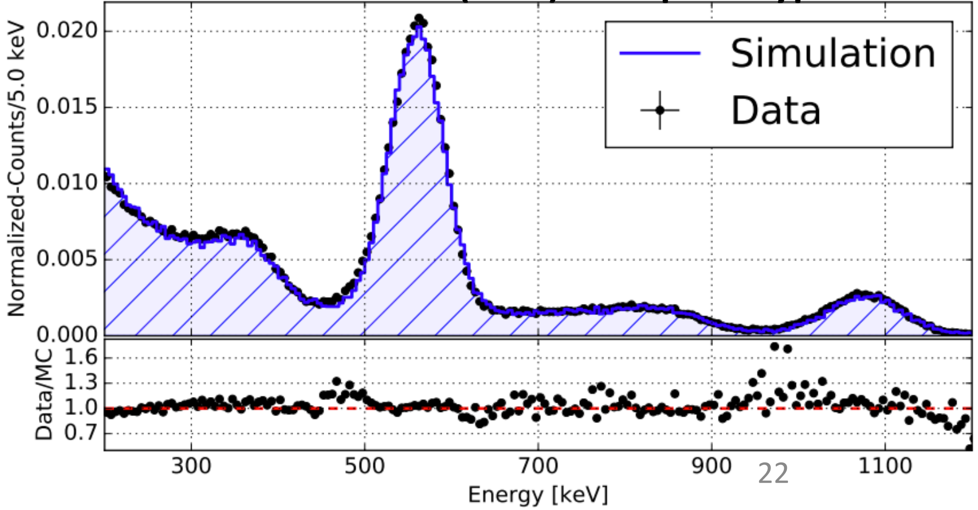
*Z. Li et al. (nEXO Collab) "Simulation of charge readout with segmented tiles in nEXO," JINST 14 P09020 [2019]*

- Prototype tiles have been measured in LXe to validate simulation

*M. Jewell et al. (nEXO Collab) "Characterization of an ionization readout tile for nEXO," JINST 13 P01006 [2018]*

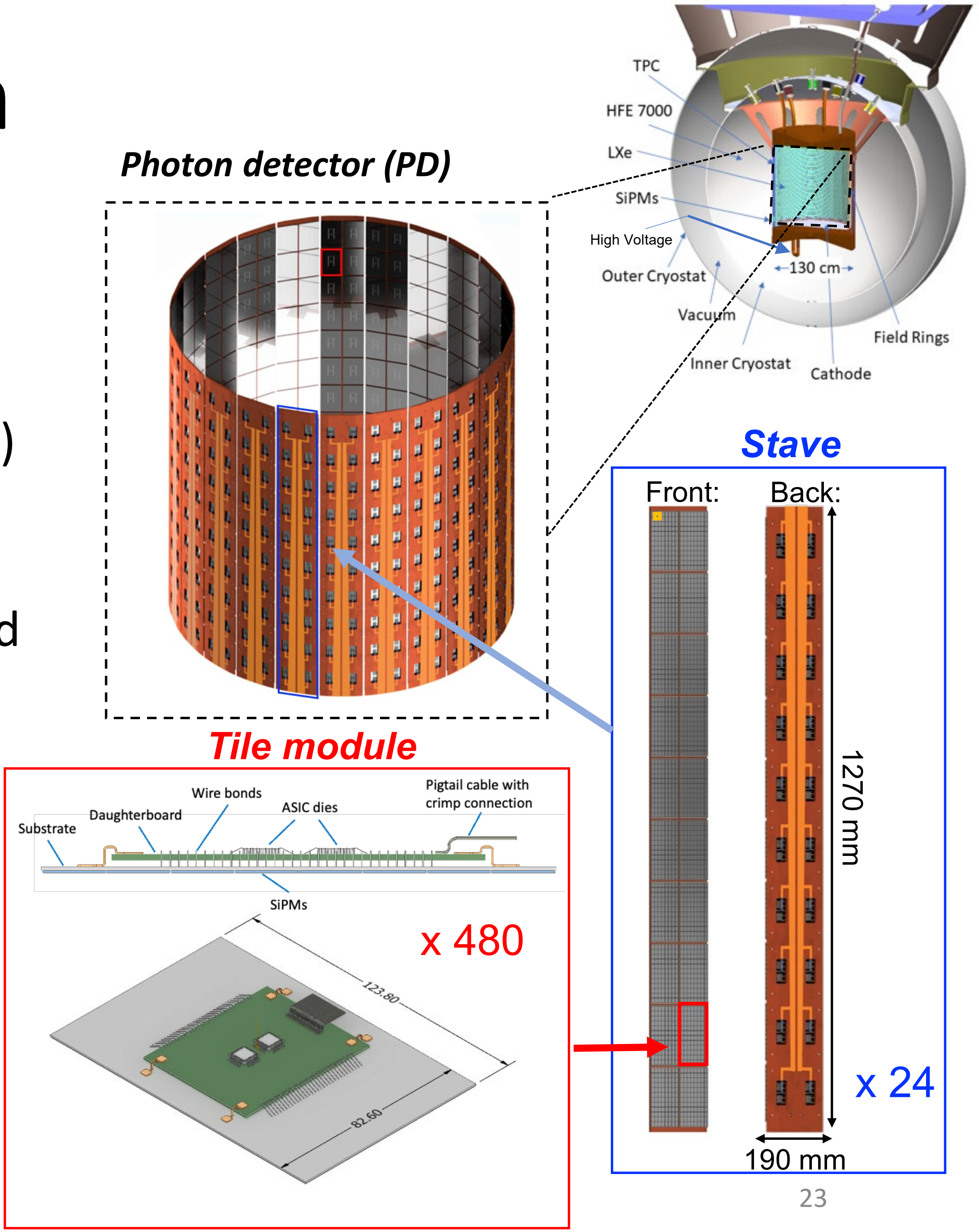



Source calibration ($^{207}Bi$) with prototype tile:



# SiPMs for photon detection

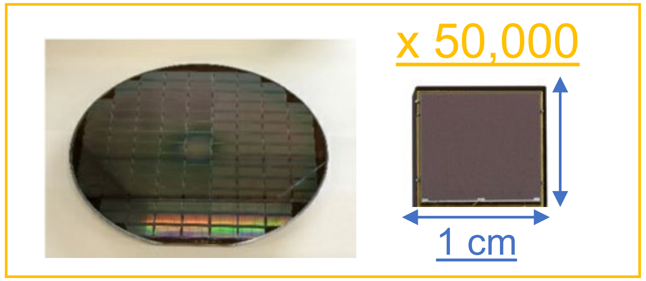
- Advantages of SiPMs for photon detection
  - Low intrinsic radioactive backgrounds
  - Improved energy resolution (SiPMs high gain)
  - Lower bias required for SiPMs (~50 V versus ~1.5 kV)
  - Devices meeting requirements demonstrated through nEXO R&D
  - Prototype SiPMs from two vendors have been tested by nEXO and meet requirements (FBK and HPK)




*A. Jamil et al. (nEXO collab.) "VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO," IEEE Trans. Nucl. Sci. 65, 11 (2018)*

*G. Gallina et al. (nEXO collab.) "Characterization of the Hamamatsu VUV4 MPPCs for nEXO," NIM A 940, 371 (2019)*

*G. Gallina et al. (nEXO), "Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO," Eur. Phys. J. C 82, 1125 (2022)*

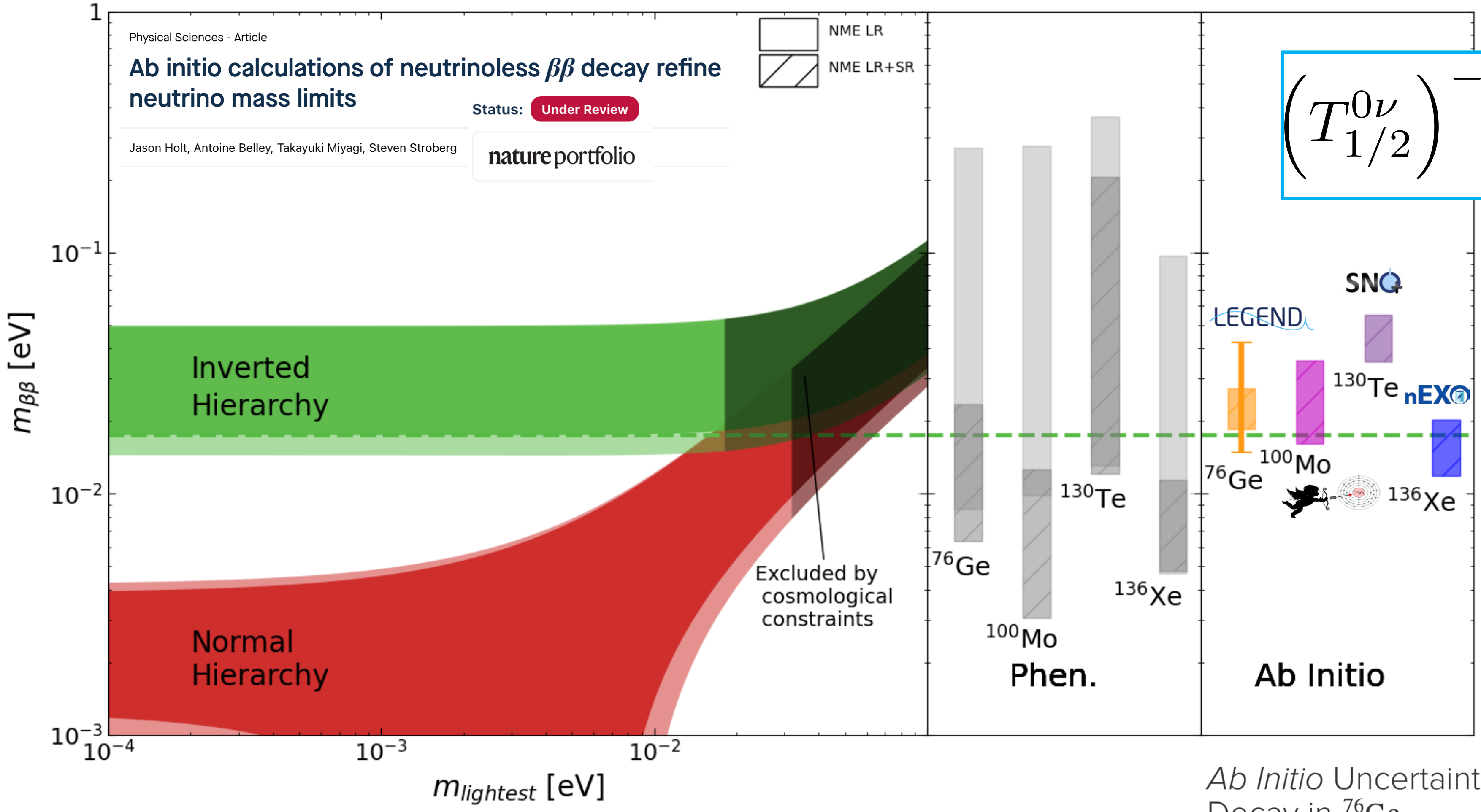



**SiPM Devices**

# Ab Initio Impact on Ton-Scale Searches

**Converged ab initio NMEs** for major players in global searches: $^{76}$Ge, $^{100}$Mo $^{130}$Te, $^{136}$Xe

Impact for next-generation searches: sensitivities from LEGEND, SNO+, nEXO, CUPID




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

Phase space factor

Axial coupling, $g_A$

NME

*Ab Initio* Uncertainty Quantification of Neutrinoless Double-Beta Decay in $^{76}$Ge

A. Belley, J. M. Yao (尧江明), B. Bally, J. Pitcher, J. Engel, H. Hergert, J. D. Holt, T. Miyagi, T. R. Rodríguez, A. M. Romero, S. R. Stroberg, and X. Zhang (张馨)
Phys. Rev. Lett. **132**, 182502 – Published 30 April 2024

Uncertainty reduced ***over one order of magnitude!***

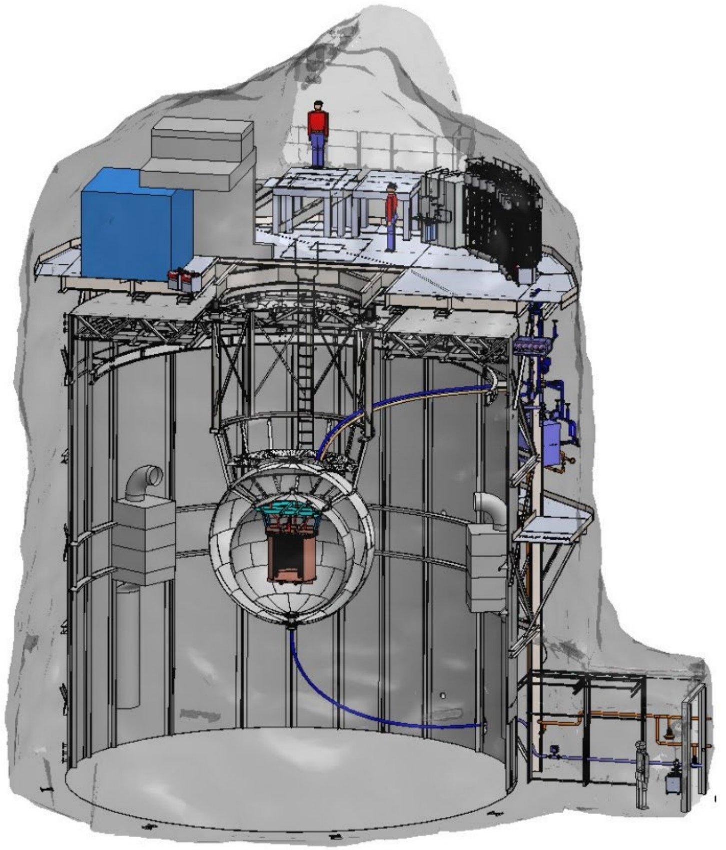
# nEXO publications

- The nEXO collaboration is pursuing a targeted, successful research program.
- **Most of the studies were led by graduate students and postdocs.**

- **Supernova Electron-Neutrino Interactions with Xenon in the nEXO Detector,** S. Hedges, et al., to be submitted to the arXiv shortly (2024)
- **An integrated online radioassay data storage and analytics tool for nEXO,** R.H.M. Tsang, et al., NIMA 1055, 168477 (2023)
- **Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO,** G. Gallina, et al., Eur. Phys. J. C 82, 1125 (2022)
- **Development of a $^{127}Xe$ calibration source for nEXO,** B. G. Lenardo, et al., JINST, 17, 07, P07028 (2022)
- **nEXO: neutrinoless double beta decay search beyond $10^{28}$ year half-life sensitivity,** G. Adhikari et al., J. Phys. G: Nucl. Part. Phys. 49 015104 (2022)
- **Reflectivity of VUV-sensitive silicon photomultipliers in liquid Xenon,** M. Wagenpfeil, et al., JINST 16 P08002 (2021),
- **SNEWS 2.0: A Next-Generation SuperNova Early Warning System for Multi-messenger Astronomy,** SNEWS 2 collaboration, New J. Phys. 23 031201 (2021)
- **Event Reconstruction in a Liquid Xenon Time Projection Chamber with an Optically-Open Field Cage,** T. Stiegler, et al, NIMA 1000, 165239 (2021)
- **Reflectance of Silicon Photomultipliers at Vacuum Ultraviolet Wavelengths,** P. Lv, et al, IEEE Trans. Nucl. Sci. 67, 2501 (2020)
- **Reflectivity and PDE of VUV4 Hamamatsu SiPMs in liquid xenon,** P. Nakarim, et al., JINST 15, P01019 (2020)
- **Measurements of electron transport in liquid and gas Xenon using a laser-driven photocathode,** O. Njoya, et al., NIM A 972, 163965 (2020)
- **Characterization of the Hamamatsu VUV4 MPPCs for nEXO**, G. Gallina, et al., NIMA 940, 371 (2019)
- **Simulation of charge readout with segmented tiles in nEXO,** Z. Li, et al., JINST 14, P09020 (2019)
- **Imaging individual Ba atoms in solid xenon for barium tagging in nEXO,** C. Chambers, et al., Nature 569, 203 (2019)
- **Study of Silicon Photomultiplier Performance in External Electric Fields,** X.L. Sun, et al., JINST 13, T09006 (2018)
- **VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO,** IEEE Transactions on Nuclear Science 1 (2018)
- **nEXO Pre-Conceptual Design Report,** arXiv:1805.11142v2
- **Characterization of an Ionization Readout Tile for nEXO,** M. Jewell, et al., JINST 13, P01006 (2018)
- **Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay,** J.B. Albert, et al., Physical Review C 97, 065503 (2018)

# Summary

- The search for 0νββ is the most promising approach to determine the quantum nature of neutrinos: Dirac versus Majorana.
- Next-generation 0νββ are being designed to reach sensitivities beyond $10^{28}$ years (this is $10^{18}$ times the age of the Universe!).
- nEXO is one of the most sensitive next-generation experiments.
- An observation of 0νββ always implies physics beyond the Standard Model, independent of the underlying process!



Join our search for 0νββ with nEXO!

Thank You!