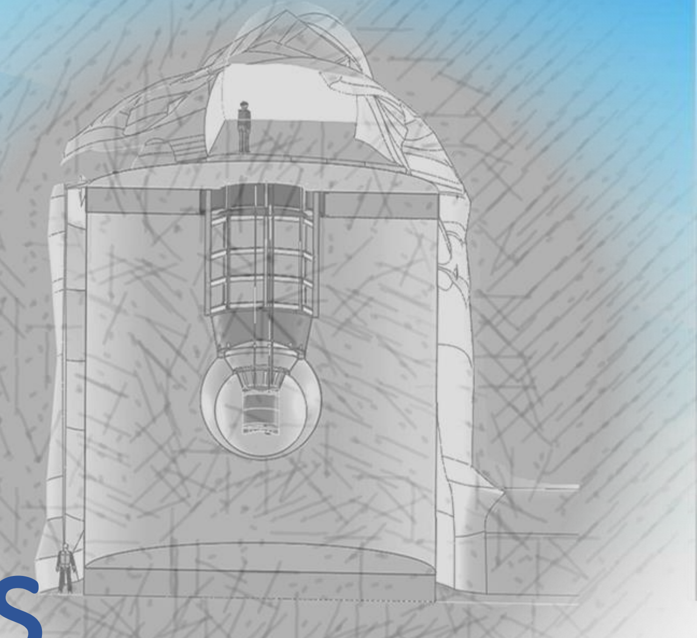
nEXO



The search for neutrinoless double beta decay with nEXO

Caio Licciardi (U Windsor)

Bromont, 16 February 2024

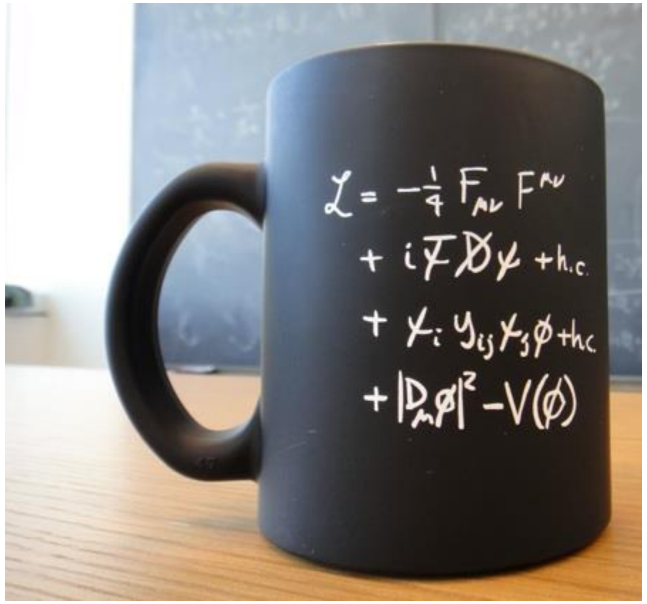
WNPPC 2024

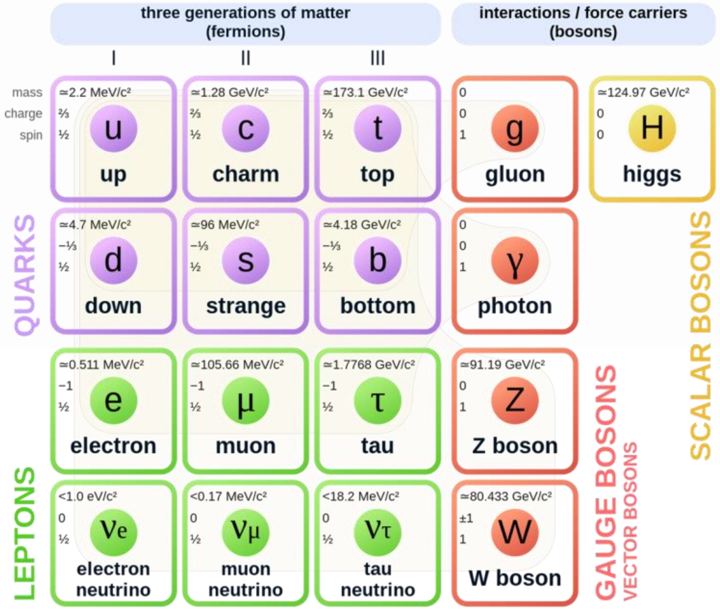
Talk Outline

- Standard Model (SM) of Particle Physics
  - New physics beyond SM (BSM)
- Search for violation of the lepton number conservation
  - Neutrinoless double beta decay ($0\nu\beta\beta$)
- The nEXO Experiment

Standard Model of Particle Physics

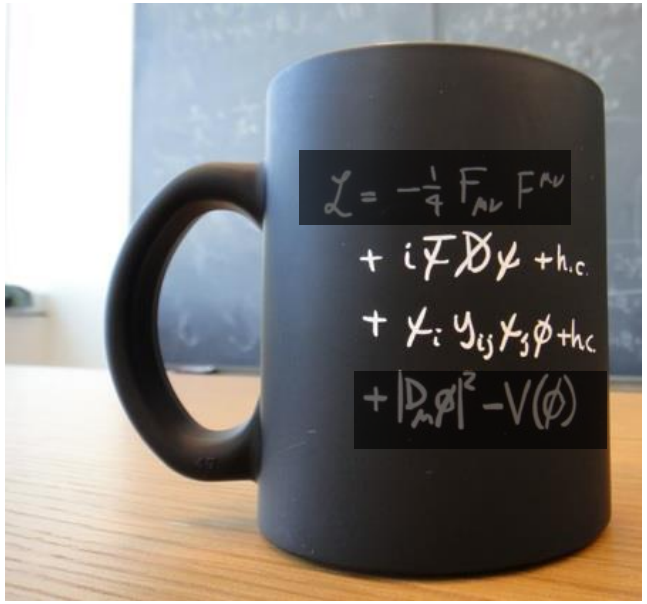
- Successful quantum field theory
- Unifies matter or fermions into two types of particles:
  - Leptons (ψ, $\bar{\psi}$) and quarks (ψ, $\bar{\psi}$)
- Describes particle interactions in terms of gauge bosons
- Lepton number conservation
  - Accidental global symmetry
- Historically driven by neutrinos

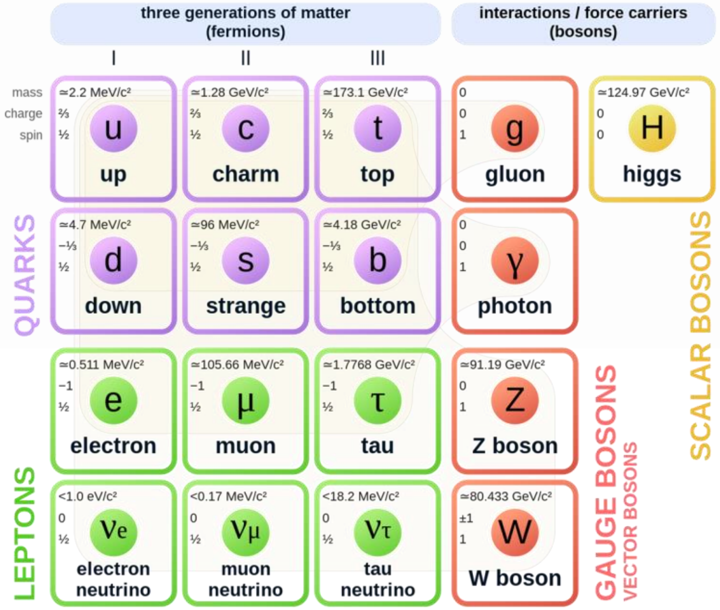




Standard Model of Particle Physics

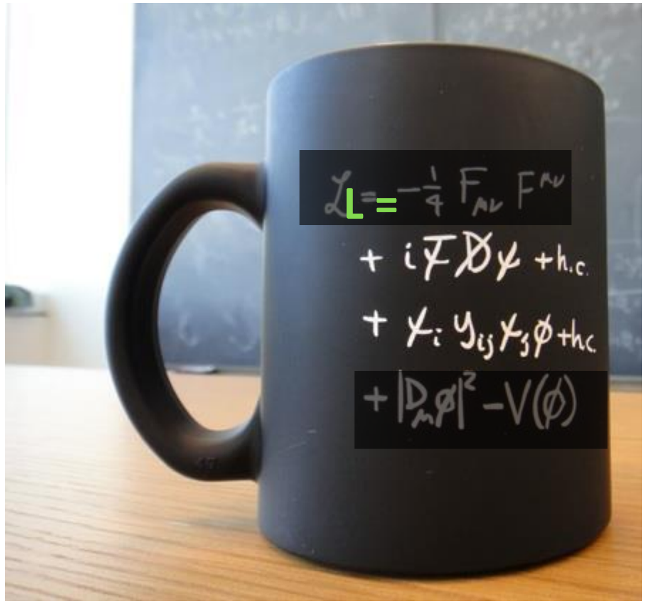
- Successful quantum field theory
- Unifies matter or fermions into two types of particles:
  - Leptons ($\psi, \bar{\psi}$) and quarks ($\psi, \bar{\psi}$)
- Describes particle interactions in terms of gauge bosons
- Lepton number conservation
  - Accidental global symmetry
- Historically driven by neutrinos

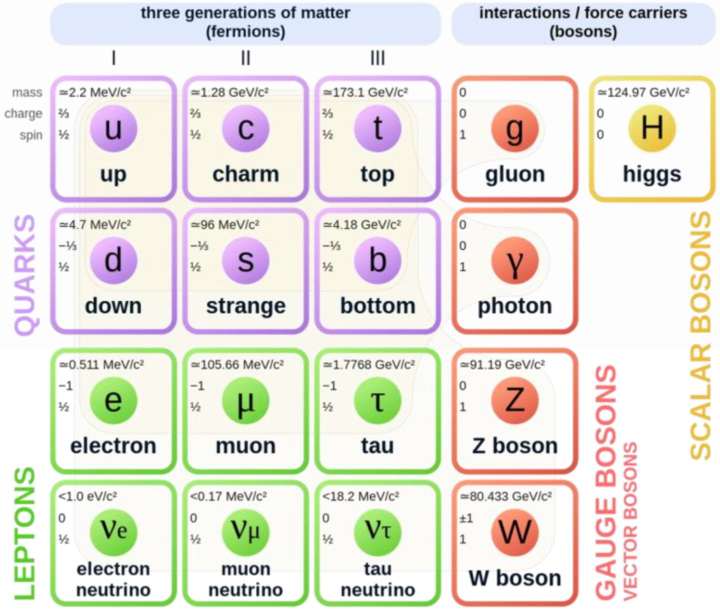




Standard Model of Particle Physics

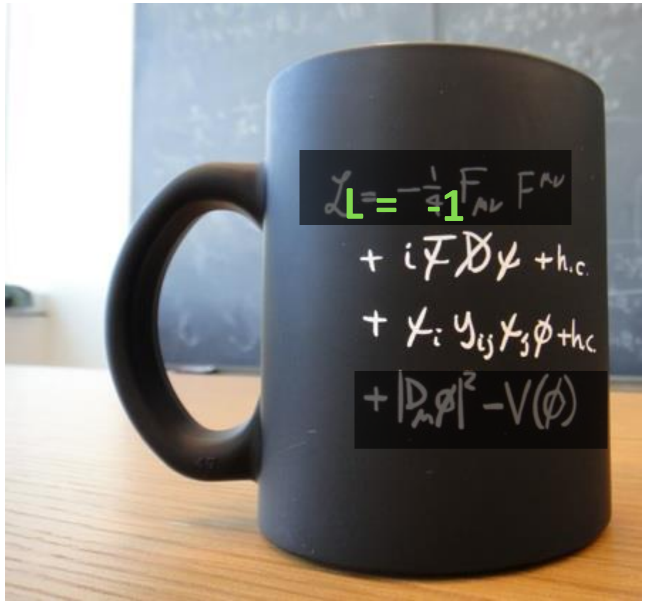
- Successful quantum field theory
- Unifies matter or fermions into two types of particles:
  - Leptons (ψ, $\bar{\psi}$) and quarks (ψ, $\bar{\psi}$)
- Describes particle interactions in terms of gauge bosons
- Lepton number conservation
  - Accidental global symmetry
- Historically driven by neutrinos

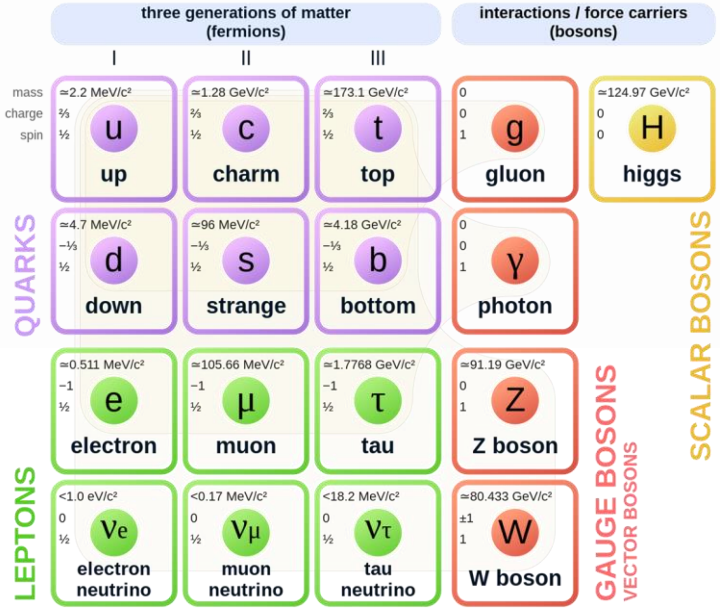




Standard Model of Particle Physics

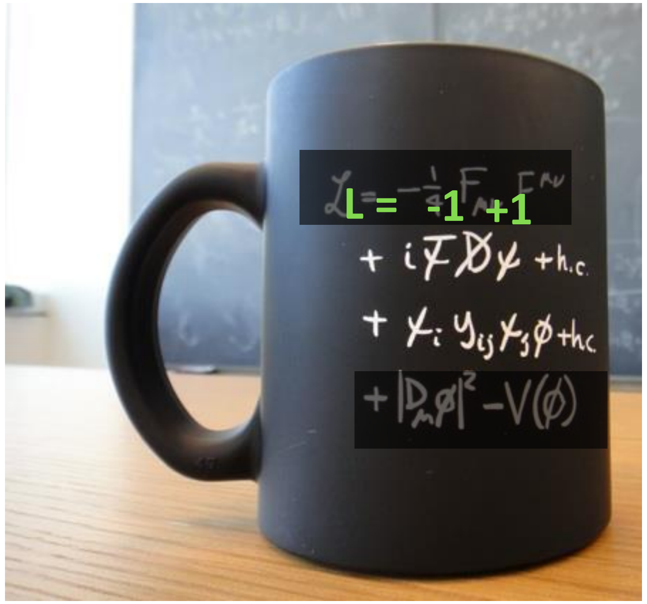
- Successful quantum field theory
- Unifies matter or fermions into two types of particles:
  - Leptons ($\psi, \bar{\psi}$) and quarks ($\psi, \bar{\psi}$)
- Describes particle interactions in terms of gauge bosons
- Lepton number conservation
  - Accidental global symmetry
- Historically driven by neutrinos

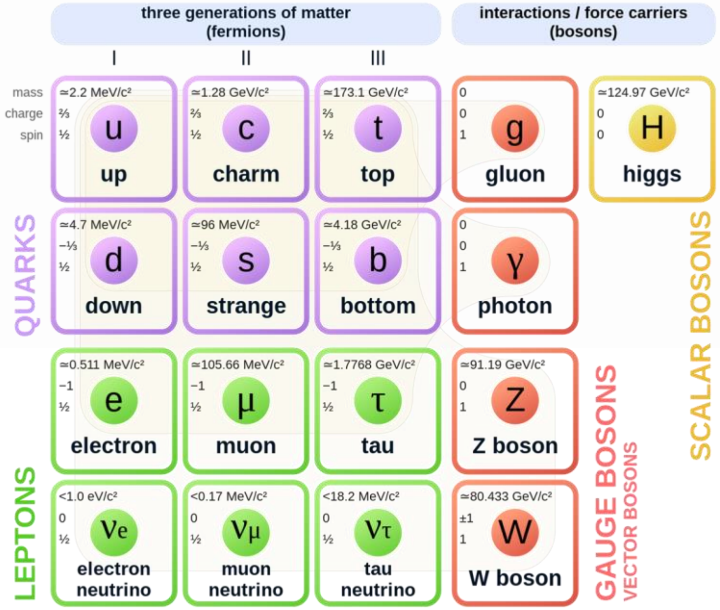




Standard Model of Particle Physics

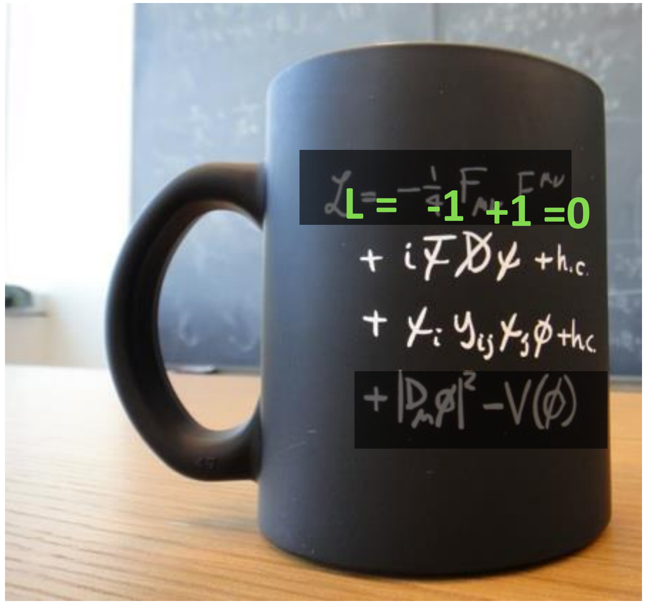
- Successful quantum field theory
- Unifies matter or fermions into two types of particles:
  - Leptons ($\psi, \bar{\psi}$) and quarks ($\psi, \bar{\psi}$)
- Describes particle interactions in terms of gauge bosons
- Lepton number conservation
  - Accidental global symmetry
- Historically driven by neutrinos

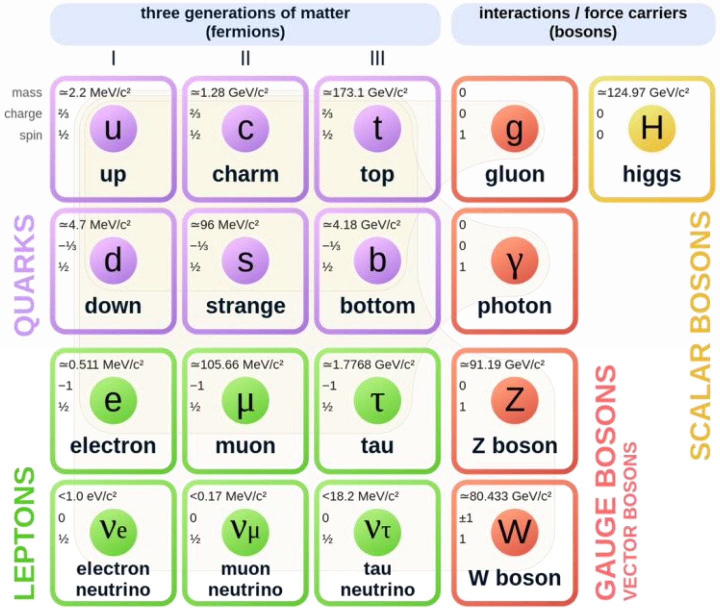




Standard Model of Particle Physics

- Successful quantum field theory
- Unifies matter or fermions into two types of particles:
  - Leptons (ψ, $\bar{\psi}$) and quarks (ψ, $\bar{\psi}$)
- Describes particle interactions in terms of gauge bosons
- Lepton number conservation
  - Accidental global symmetry
- Historically driven by neutrinos





Neutrino Oscillations

- Our most direct evidence for BSM physics comes from neutrinos
- Observation of neutrino oscillations → neutrinos have non-zero masses

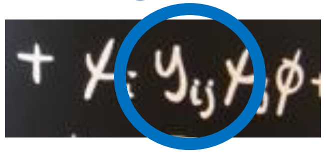
→ Nobel Prize in Physics 2015:
A.B. McDonald (SNO), T. Kajita (Super-K)

Neutrino Oscillations

- Our most direct evidence for BSM physics comes from neutrinos
- Observation of neutrino oscillations → neutrinos have non-zero masses

  → Nobel Prize in Physics 2015:
  A.B. McDonald (SNO), T. Kajita (Super-K)

Neutrino mixing matrix:



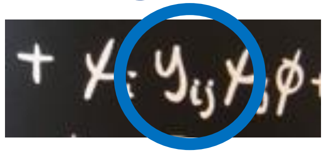
$$\underbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}_{\text{Flavor eigenstates}} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}}_{\text{PMNS mixing matrix (angles + CP phases)}} \underbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}_{\text{Mass eigenstates}}$$

Flavor eigenstates — PMNS mixing matrix (angles + **CP phases**) — Mass eigenstates

Neutrino Oscillations

- Our most direct evidence for BSM physics comes from neutrinos
- Observation of neutrino oscillations → neutrinos have non-zero masses
  → Nobel Prize in Physics 2015: A.B. McDonald (SNO), T. Kajita (Super-K)

Neutrino mixing matrix:



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigenstates | PMNS mixing matrix (angles + **CP phases**) | Mass eigenstates

Flavor eigenstates evolve in time as:

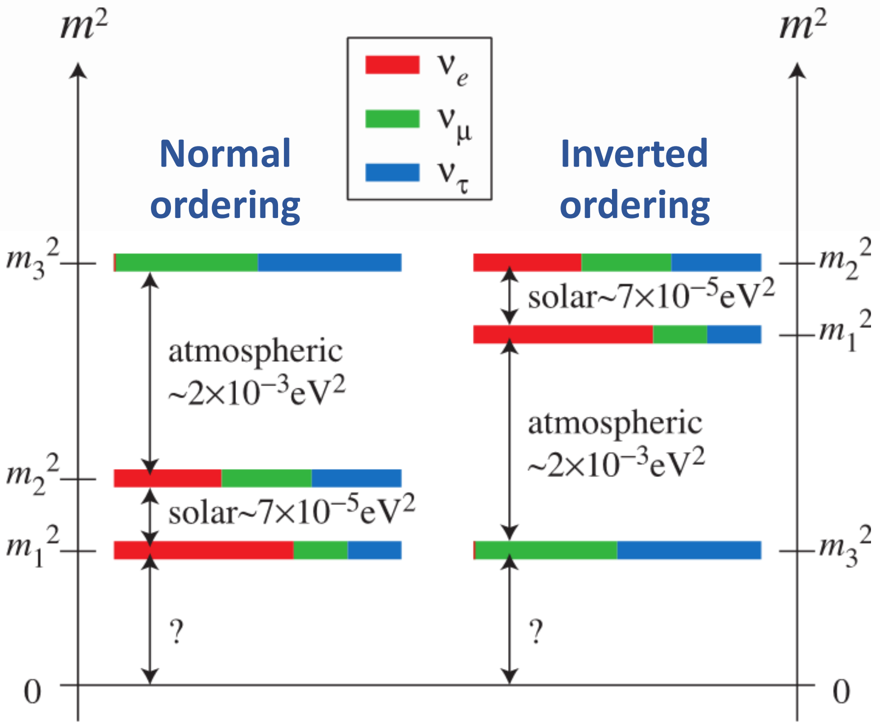
$$|\nu_\alpha(t)\rangle = \sum_i U^*_{\alpha i} e^{-iE_i t} |\nu_i\rangle$$

$\alpha = e, \mu, \tau$ $\quad E_i^2 = p^2 + m_i^2$ $\quad i = 1, 2, 3$

Oscillation Experiments

- Oscillation experiments are sensitive only to the mass differences: $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- Matter effects are sensitive to the mass ordering
- Global fits to all oscillation data give:
  - $m_2^2 - m_1^2 \approx 7.5 \times 10^{-5}\ \mathrm{eV}^2$
  - $|m_3^2 - m_{1,2}^2| \approx 2.3 \times 10^{-3}\ \mathrm{eV}^2$

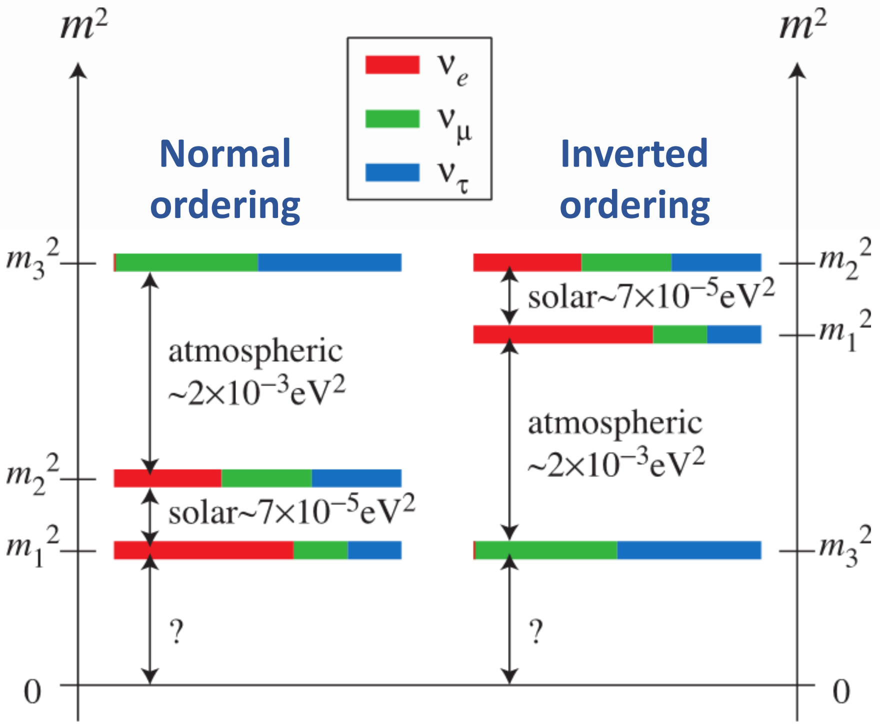
Mass ordering from oscillation experiments



Oscillation Experiments

- Oscillation experiments are sensitive only to the mass differences: $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- Matter effects are sensitive to the mass ordering
- Global fits to all oscillation data give:
  - $m_2^2 - m_1^2 \approx 7.5 \times 10^{-5}\ \text{eV}^2$
    → $\sim 10\ \text{meV}$
  - $|m_3^2 - m_{1,2}^2| \approx 2.3 \times 10^{-3}\ \text{eV}^2$
    → $\sim 50\ \text{meV}$

Mass ordering from oscillation experiments



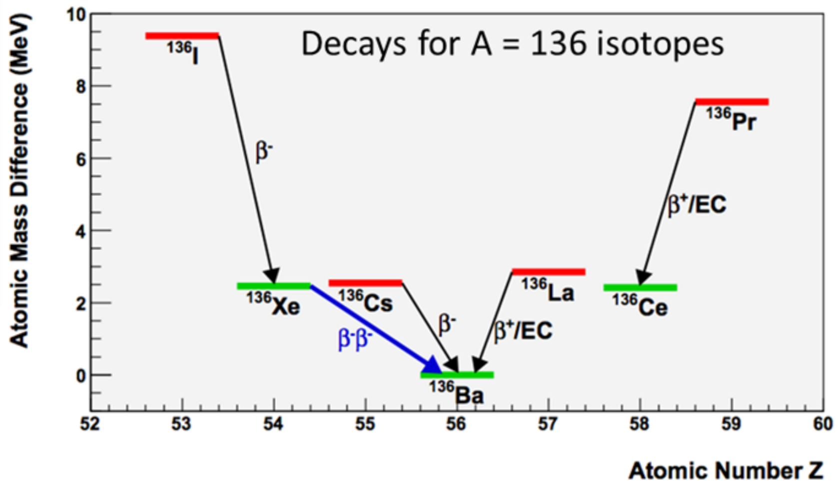
BSM Physics

- Low energy physics
  - Must be “very” rare events, not yet have been observed

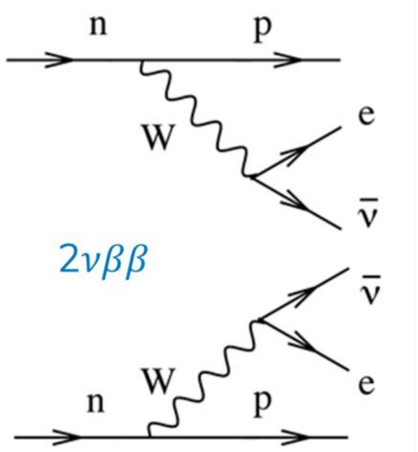
- Main candidates
  - Dark matter: another ψ
  - Majorana particles: $\psi \equiv \bar{\psi}$
  - Majorana neutrinos: $\nu \equiv \bar{\nu}$

Neutrinoless Double Beta Decay

- β decays occur because it brings the atom nuclei into a more stable protons/neutrons ratio
- The SM allows nuclei, for which β decay is energetically forbidden, decay through a second-order transition, the double beta ($\beta\beta$) decay

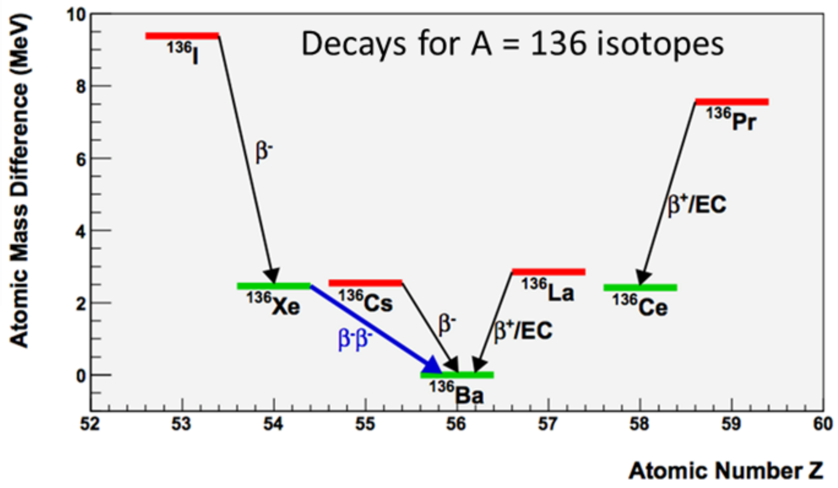


- Observation of $\beta\beta$ without $\bar{\nu}$ in the final state neutrinoless mode ($0\nu\beta\beta$) would:
  - **Violate lepton number conservation → beyond SM**
  - Prove the Majorana nature of neutrinos
  - Constrain the neutrino absolute mass scale
  - Help explain matter existence in the Universe

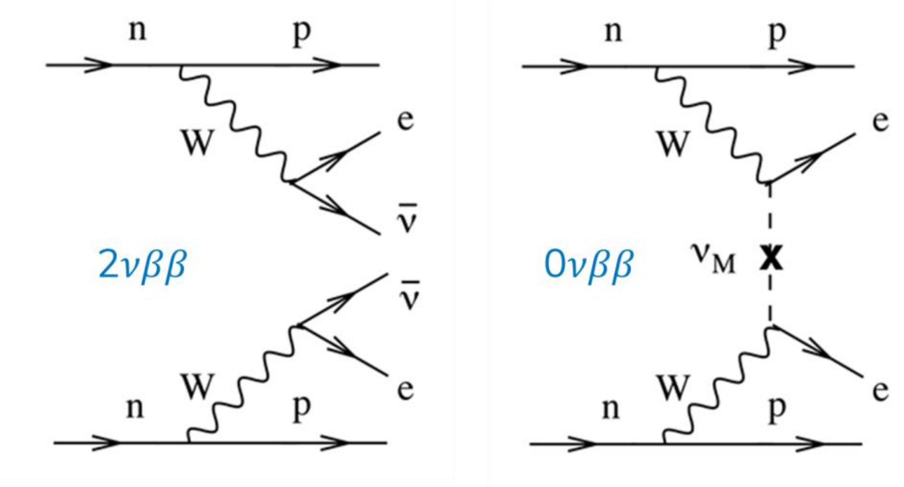


Neutrinoless Double Beta Decay

- β decays occur because it brings the atom nuclei into a more stable protons/neutrons ratio
- The SM allows nuclei, for which β decay is energetically forbidden, decay through a second-order transition, the double beta ($\beta\beta$) decay

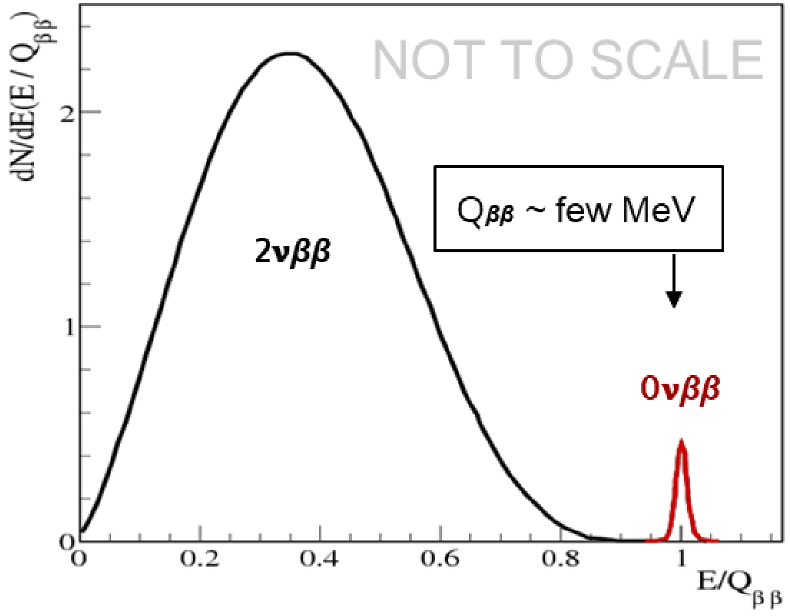


- Observation of $\beta\beta$ without $\bar{\nu}$ in the final state neutrinoless mode ($0\nu\beta\beta$) would:
  - **Violate lepton number conservation → beyond SM**
  - Prove the Majorana nature of neutrinos
  - Constrain the neutrino absolute mass scale
  - Help explain matter existence in the Universe



Search with Liquid Xenon

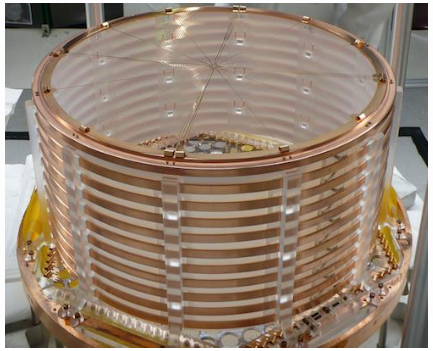
- ^{136}Xe is one among 35 nuclides that $\beta\beta$
  - Q-value: relatively large 2.45 MeV
  - Energy resolution: good
  - Occurrence: 9% of natural xenon
- Distinguishable features
  - Noble gas: easy to purify
  - Liquid phase: high density, self-shielding
  - Single phase: Monolithic
  - **Excels: scalability!**
- Possibility of run control

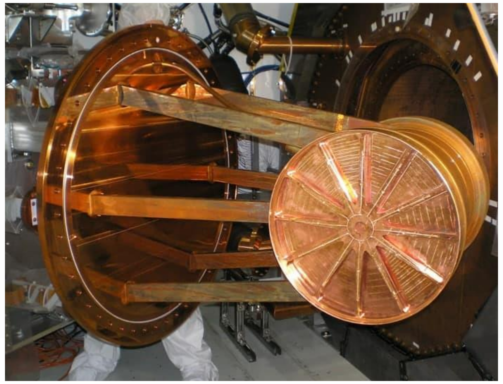


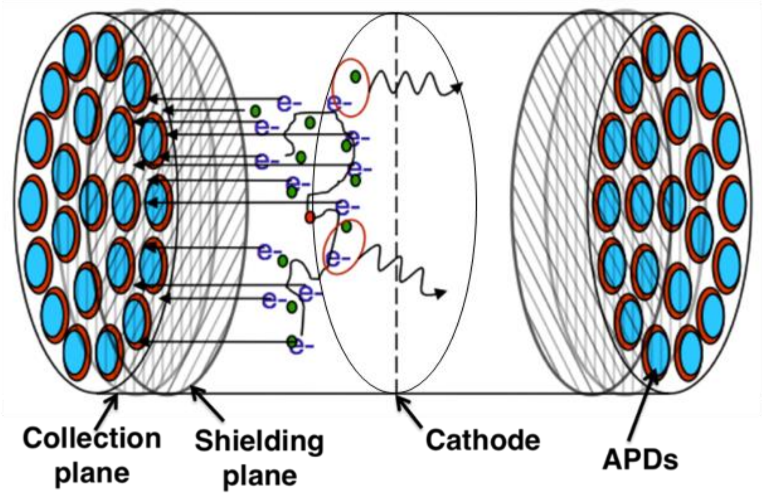
- Current experiments set 90% CL limits at $T_{1/2} > 10^{25-26}$ yr
  - ~150 kg, ~1 count / 15 days
- Next generation of experiments aiming at $T_{1/2} > 10^{28}$ yr
  - ~5000 kg, < 1 count / year

The EXO-200 Detector

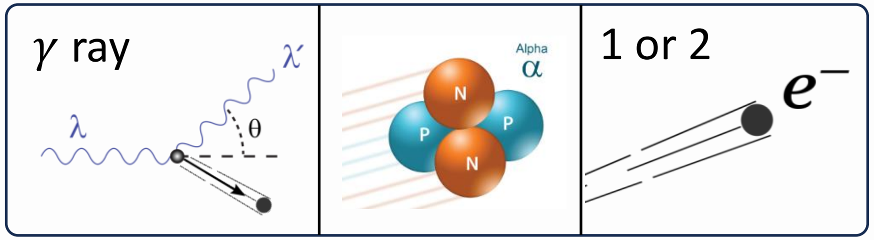
- Located at WIPP mine, Carlsbad, NM
  - Operational 2011 - 2018
- 100kg-class radiopure time projection chamber (TPC)
  - Filled with enriched LXe to 80.6% in ^{136}Xe
- HV applied between cathode and anodes
  - Uniform electric field ~350-600 V/cm
- Two measurements of energy deposited in event
  - UV scintillation light: large avalanche photo-diodes
  - Ionization: 2 wire grids, induction and collection
- Particle identification
  - Charge/light ratio
  - Event topology of the energy deposits
- ~60,000 observed ^{136}Xe $2\nu\beta\beta$ decays



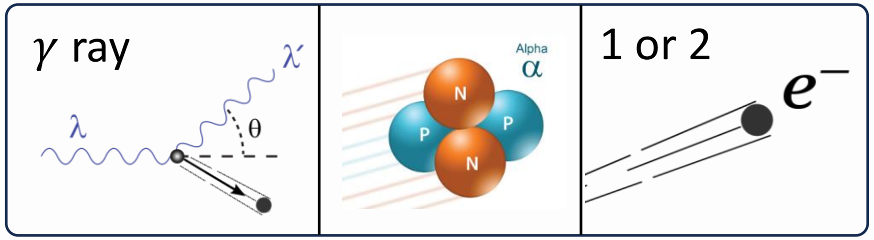


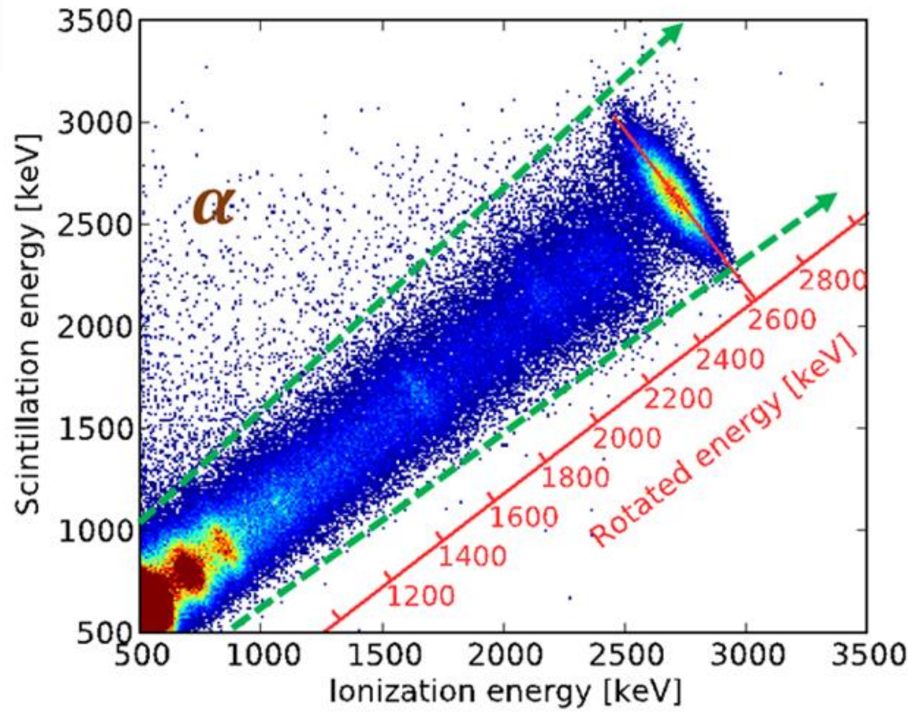


Particle Identification

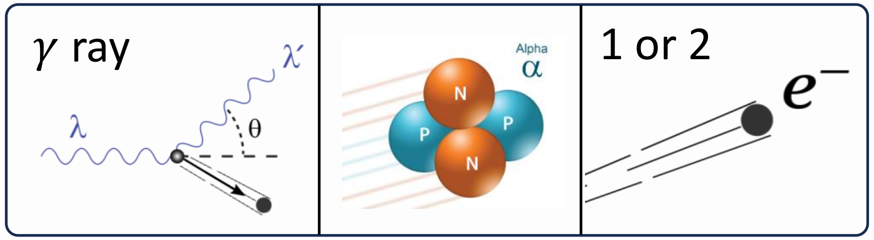


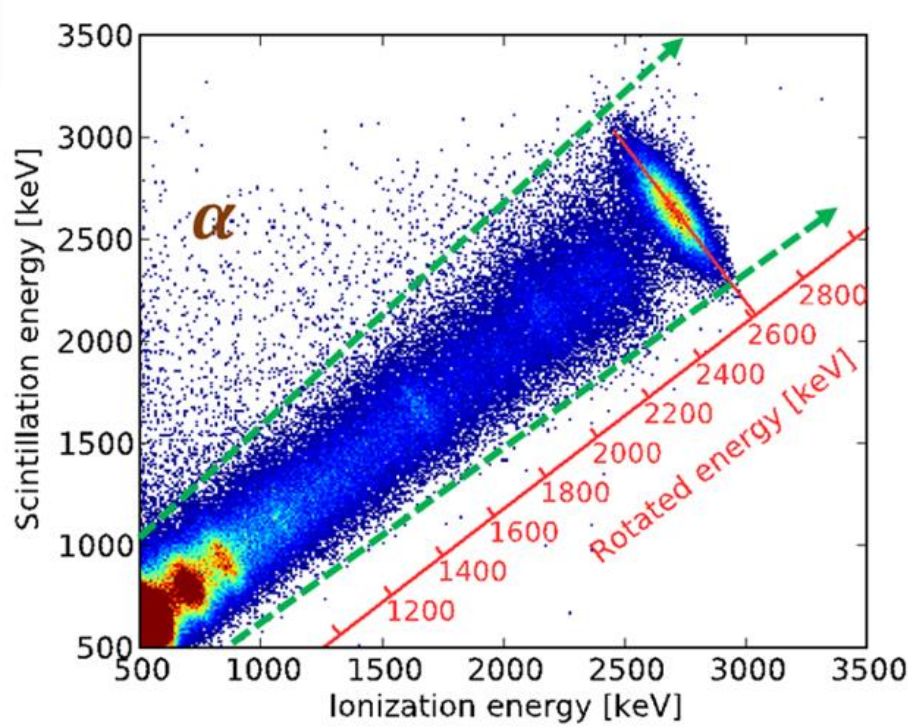
Particle Identification

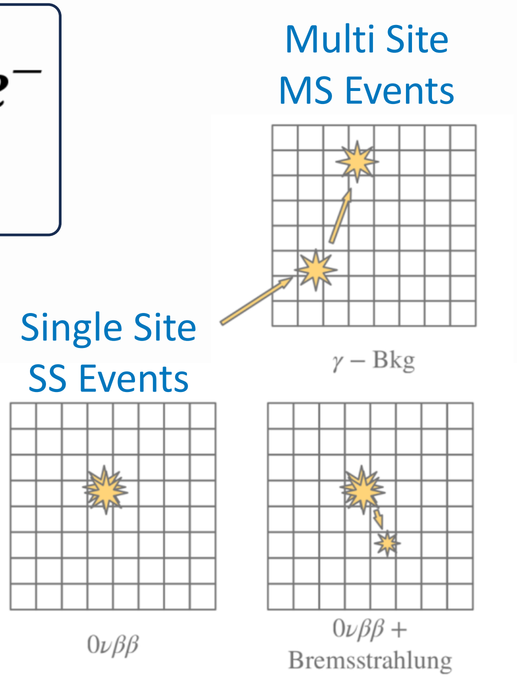




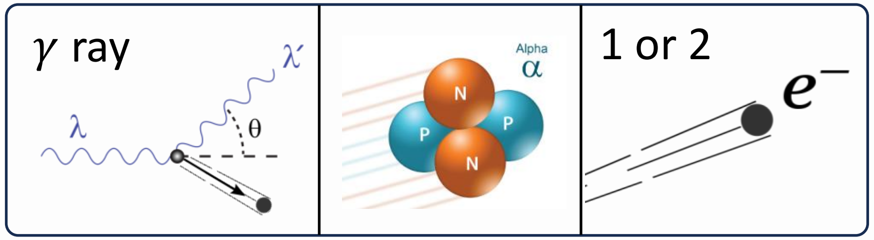
Particle Identification

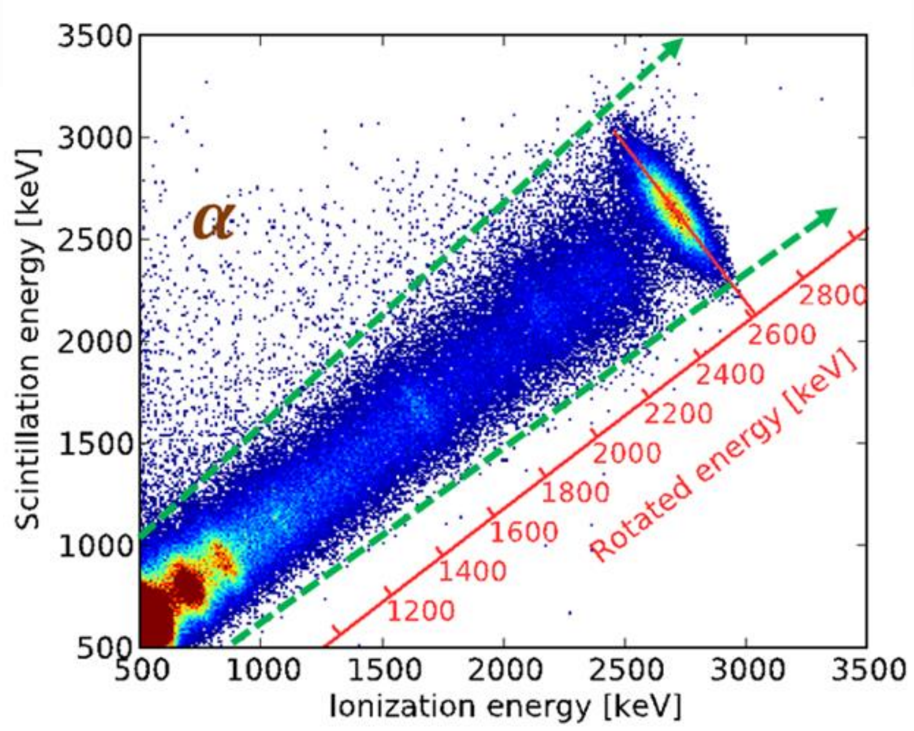


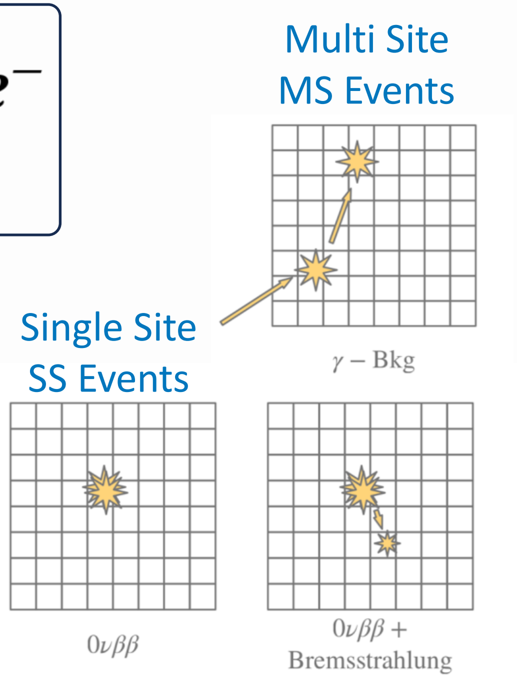


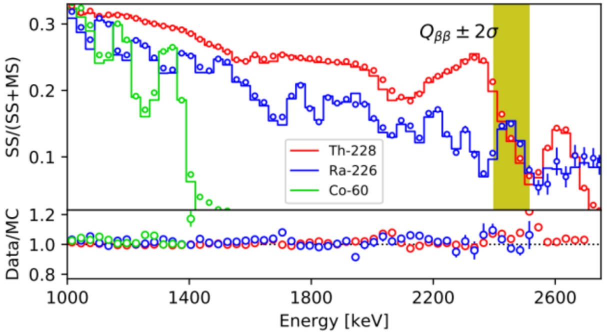


Particle Identification

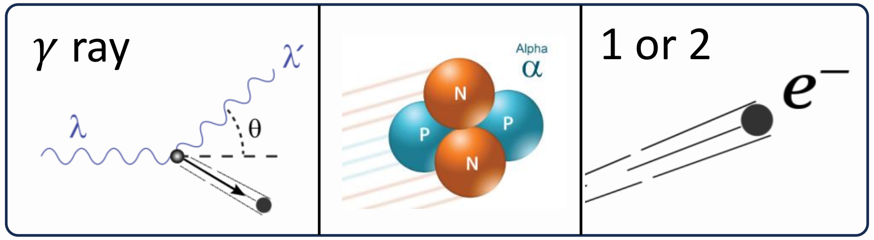


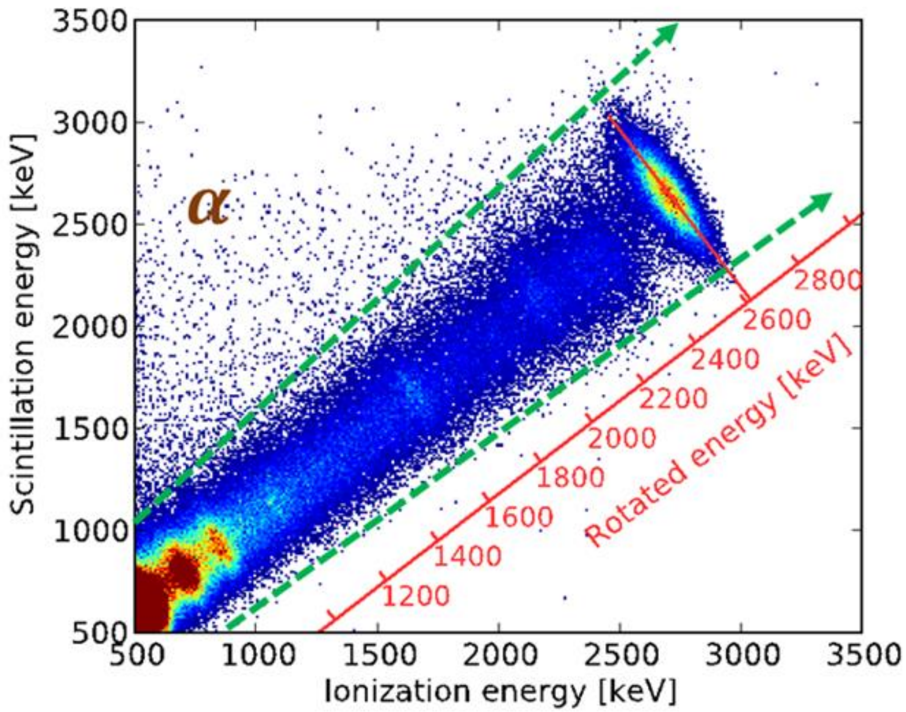


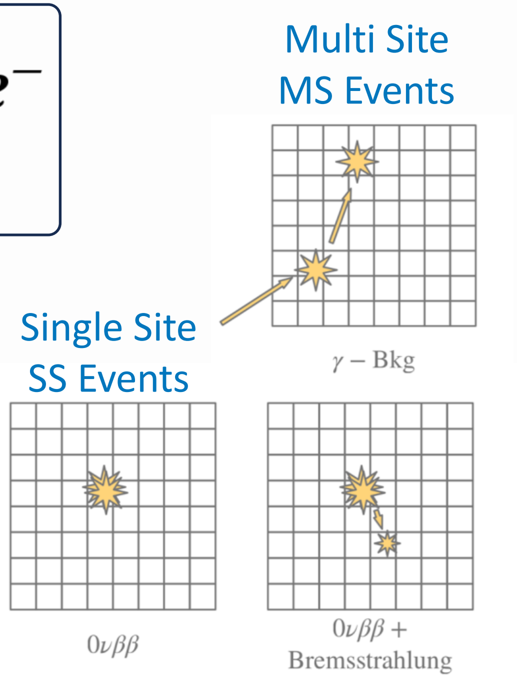


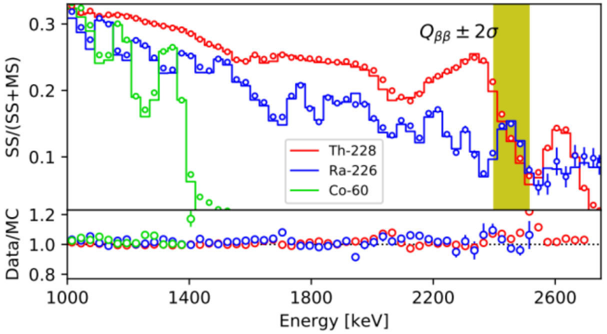


Particle Identification

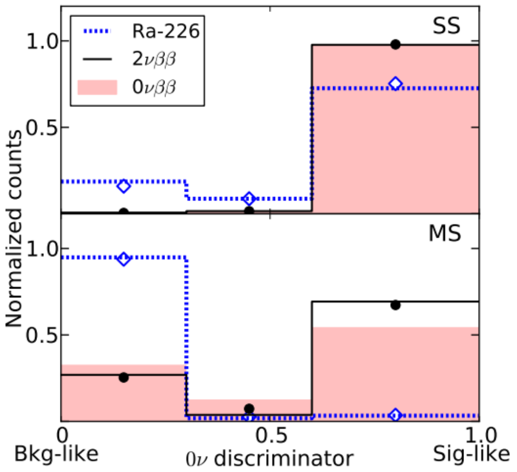




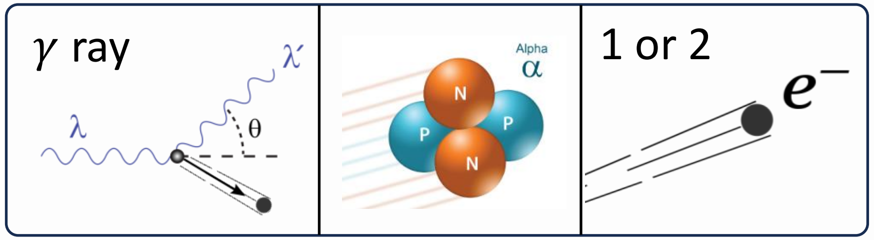


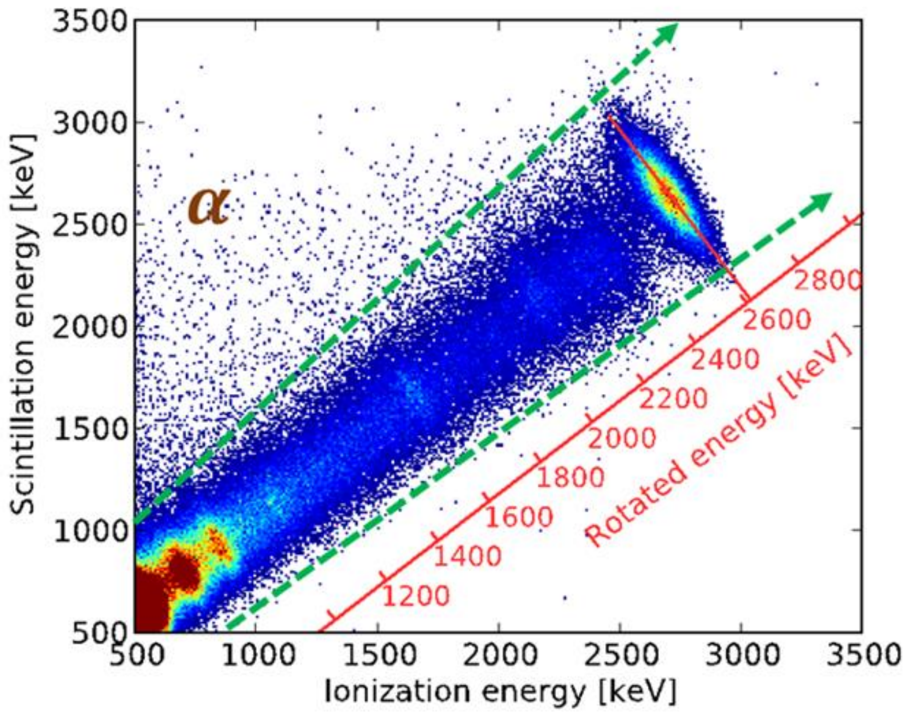


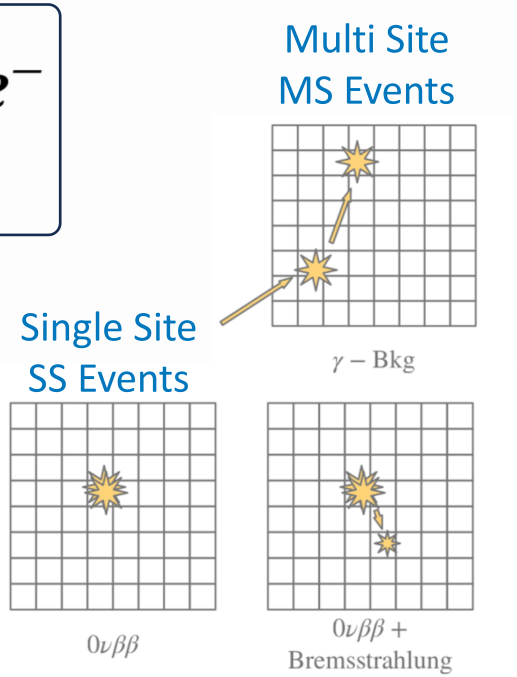
Deep Neural Network

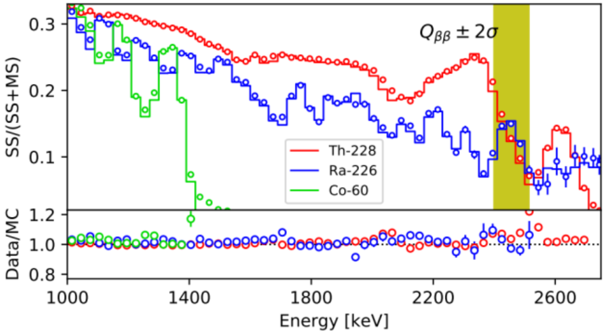


Particle Identification

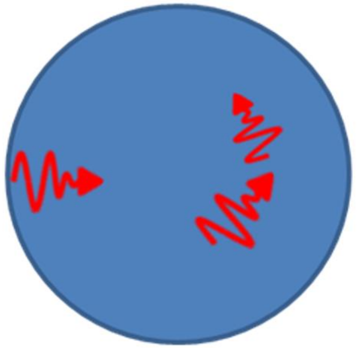






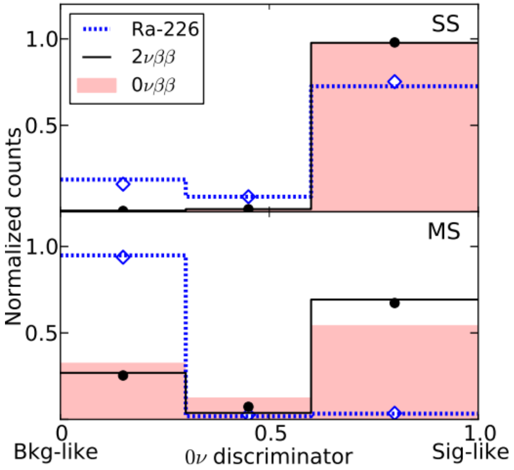


LXe self-shielding:

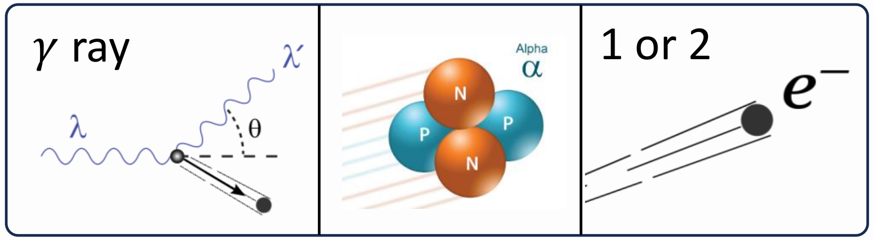


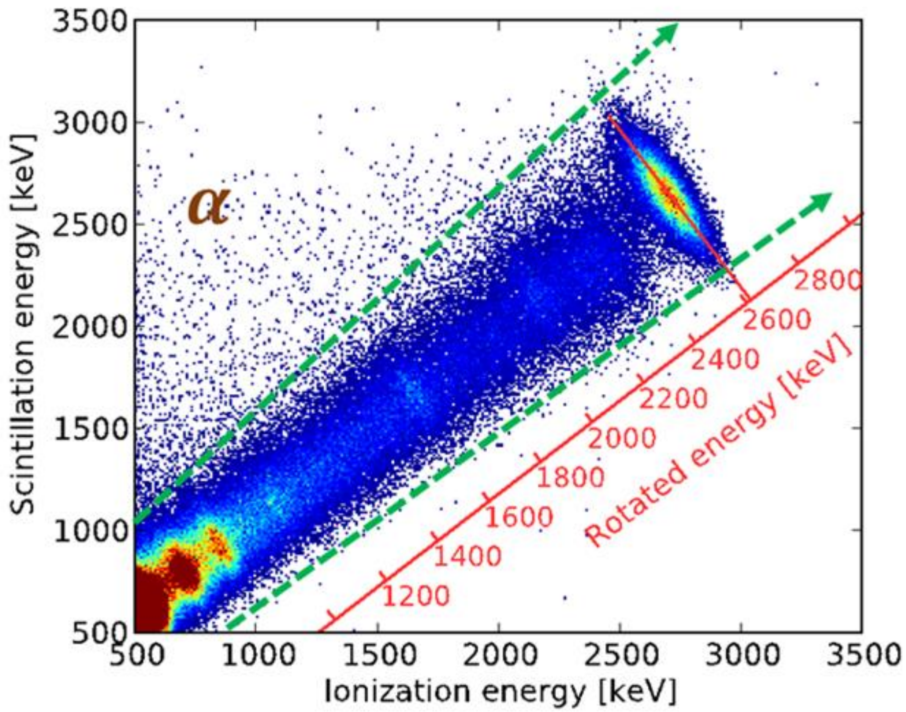
2.5MeV γ attenuation length: 8.5cm =

Deep Neural Network



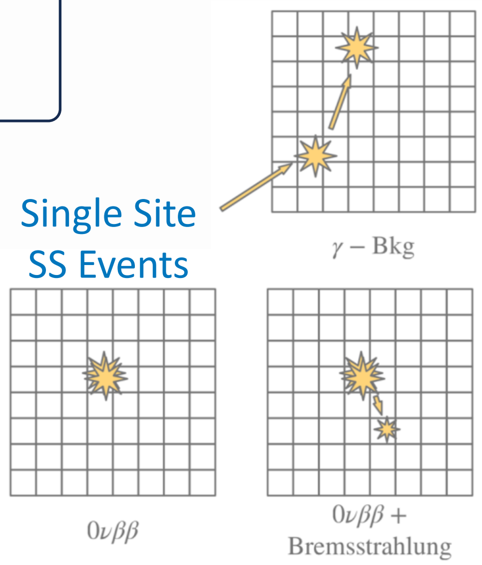
Particle Identification

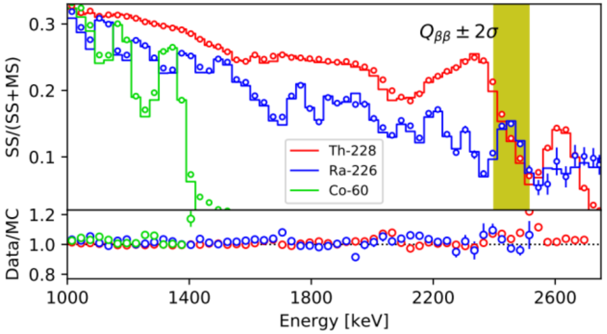




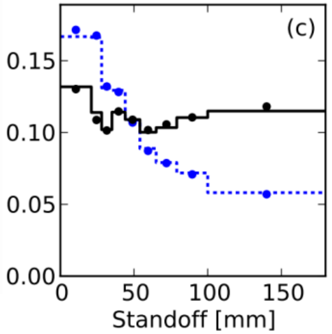
Multi Site
MS Events

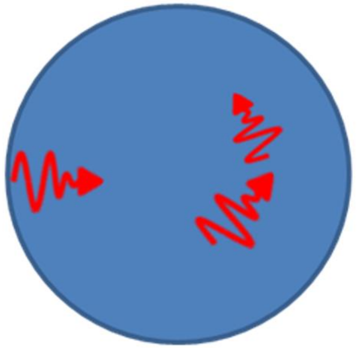
Single Site
SS Events





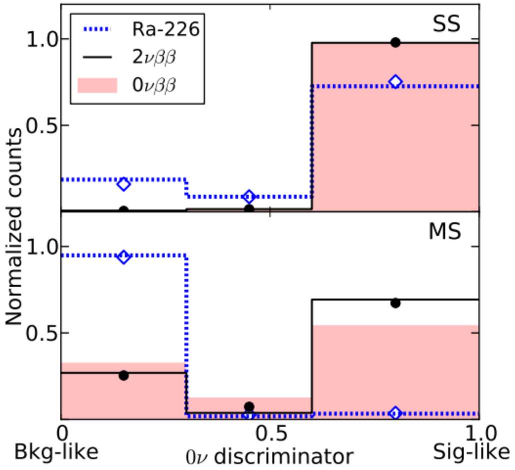
LXe self-shielding:





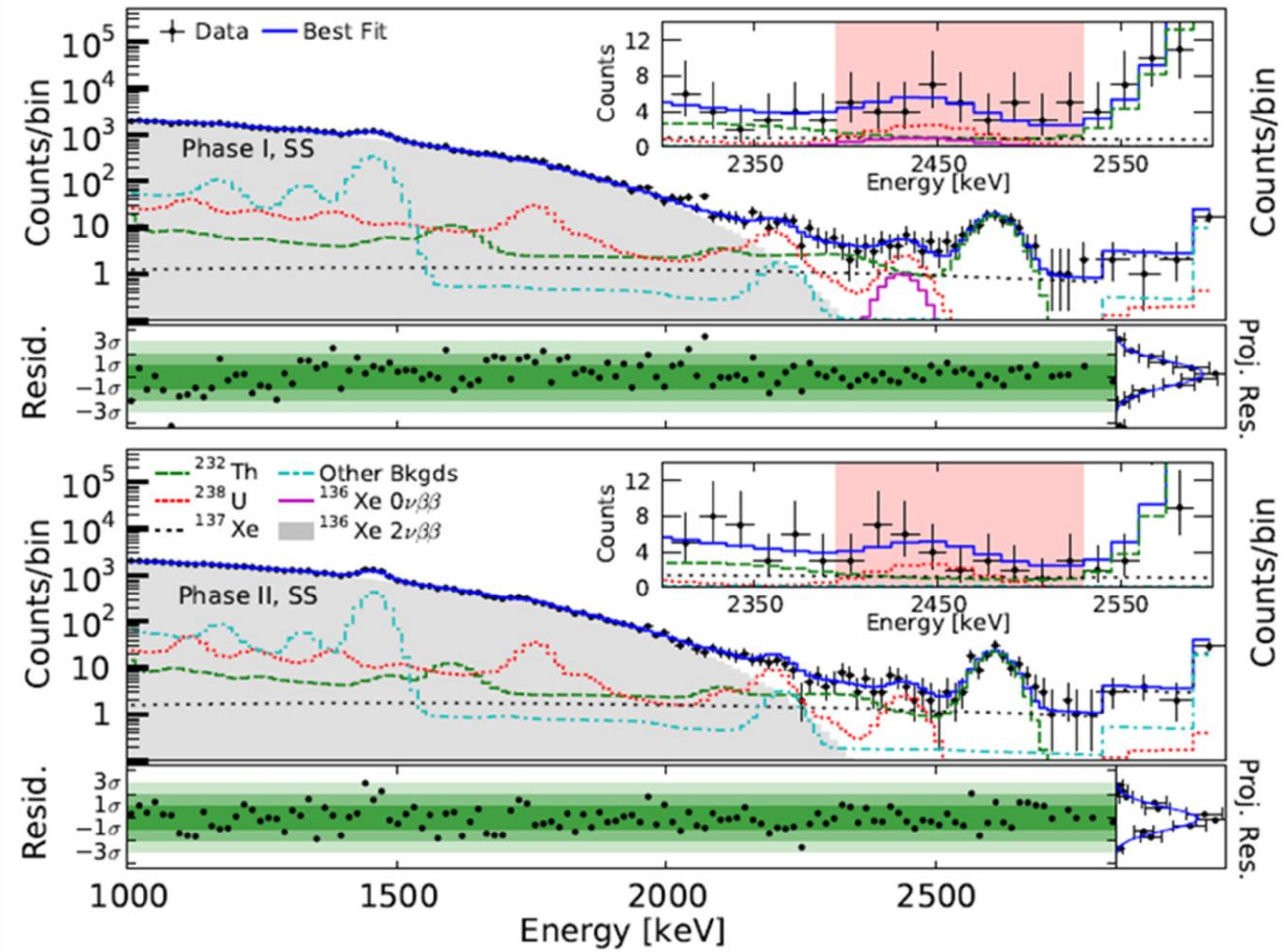
2.5MeV γ attenuation length: 8.5cm =

Deep
Neural
Network



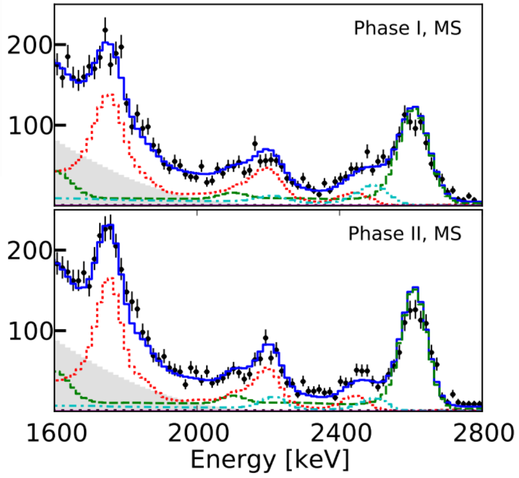
Final EXO-200 Results

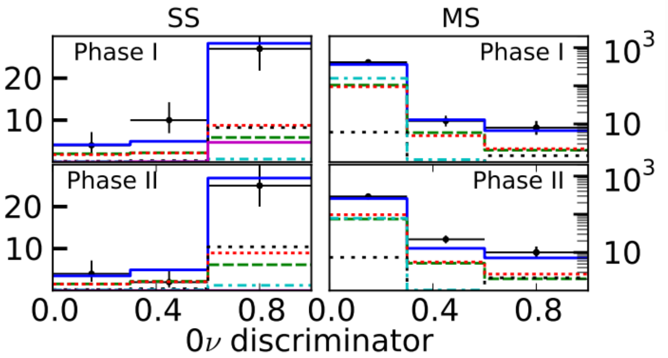
EXO-200 Collaboration, Phys. Rev. Lett. 123, 161802 (2019)



Running EXO-200 taught us a lot!

Very successful project





Detection efficiency: $96.4 \pm 3.0\%$ (Phase II)

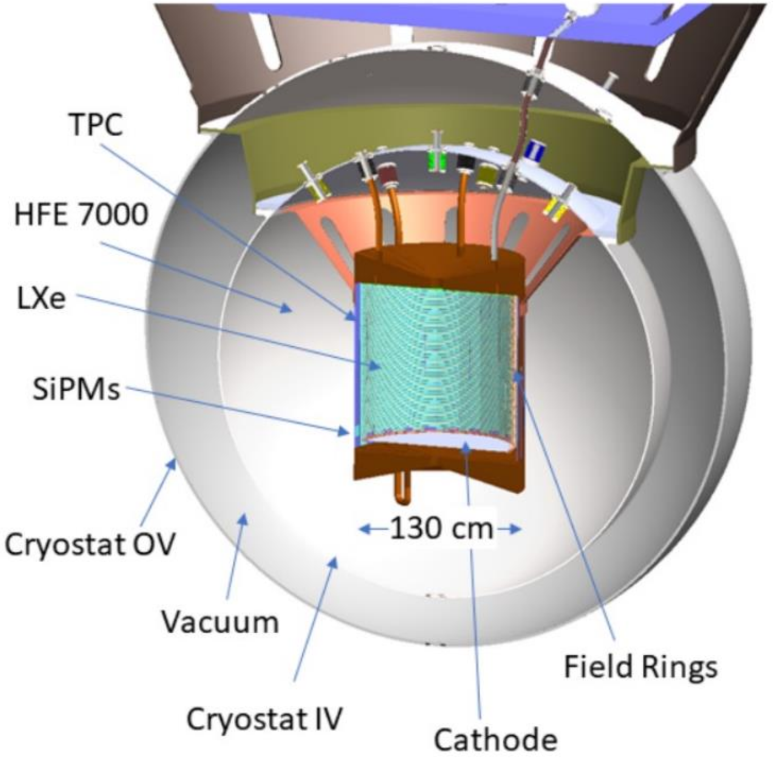
Limit: $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}\ yr\ (90\%\ C.L.)$

Sensitivity: $5.0 \times 10^{25}\ yr\ (90\%\ C.L.)$

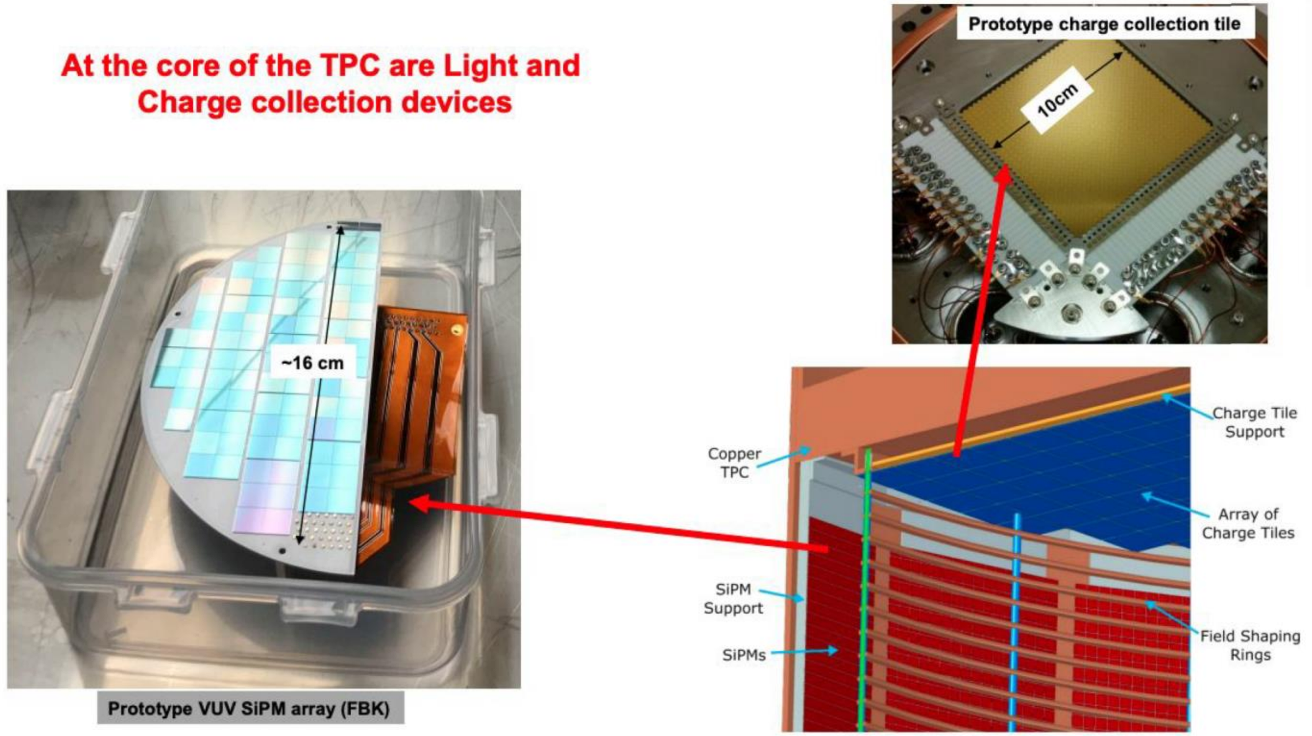
No statistically significant signal observed.

The nEXO Experiment

- TPC with 5000 kg enriched to 90% liquid ^{136}Xe
- Rooted in success of EXO-200
- Intended to be at the Cryopit of SNOLAB



At the core of the TPC are Light and Charge collection devices

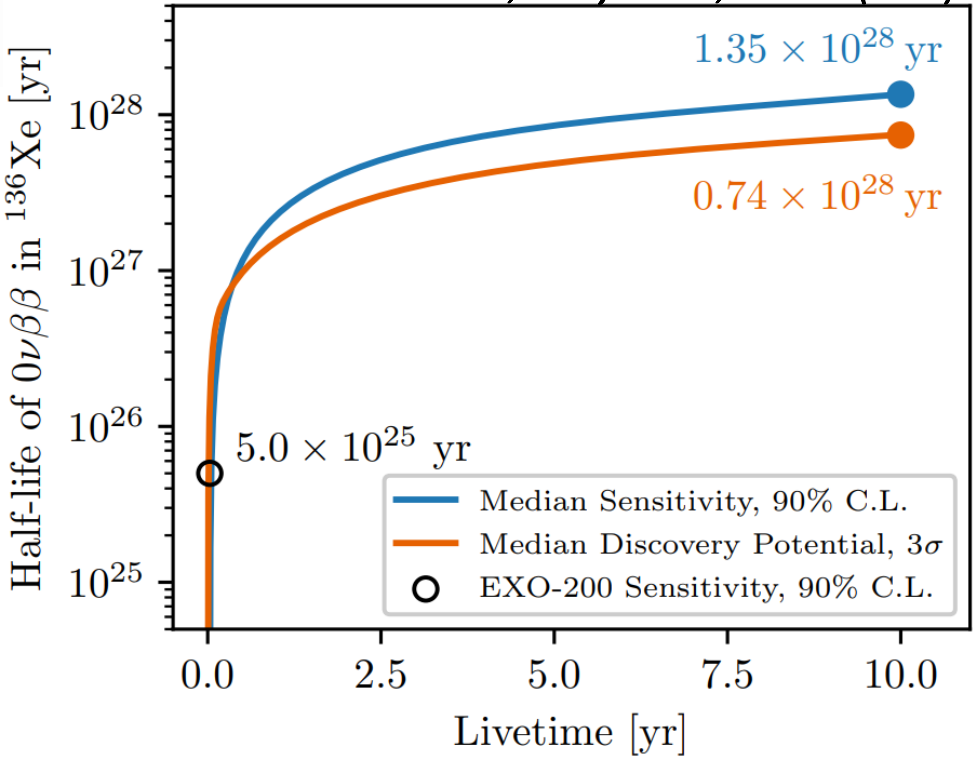


Prototype VUV SiPM array (FBK)

Sensitivity to New Physics

- $0\nu\beta\beta$ half-life sensitivity in 6.5 years:
  - Exclusion >10^{28} yr at 90 %CL
  - 3σ discovery ~10^{28} yr, 50% cases

nEXO Collaboration, J. Phys. G 49, 015104 (2022)

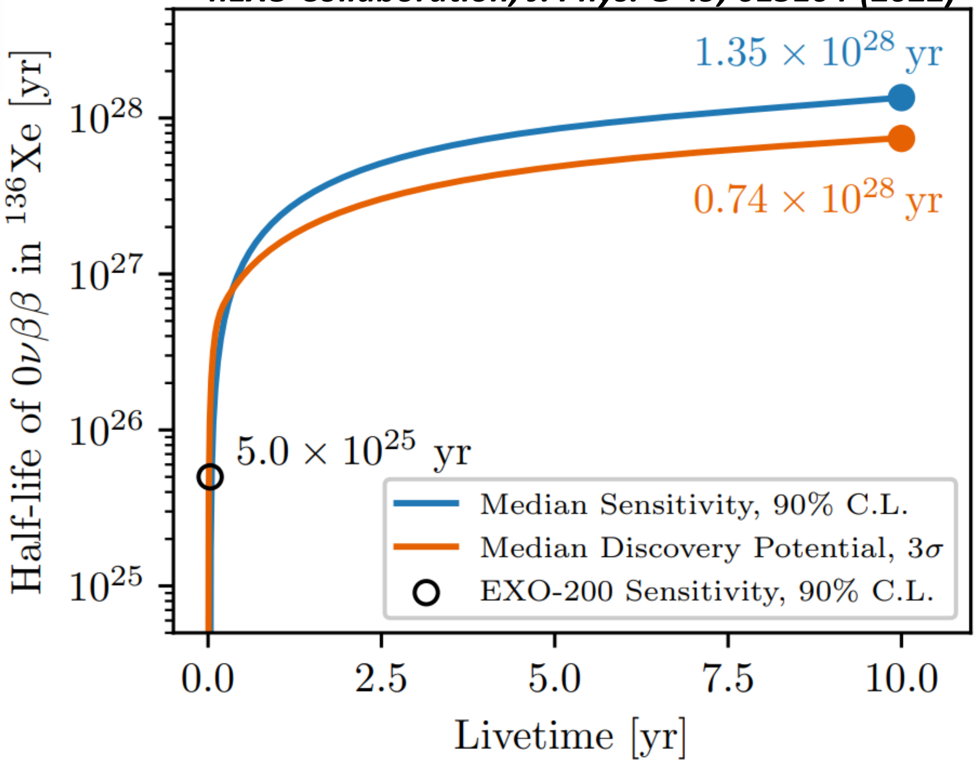


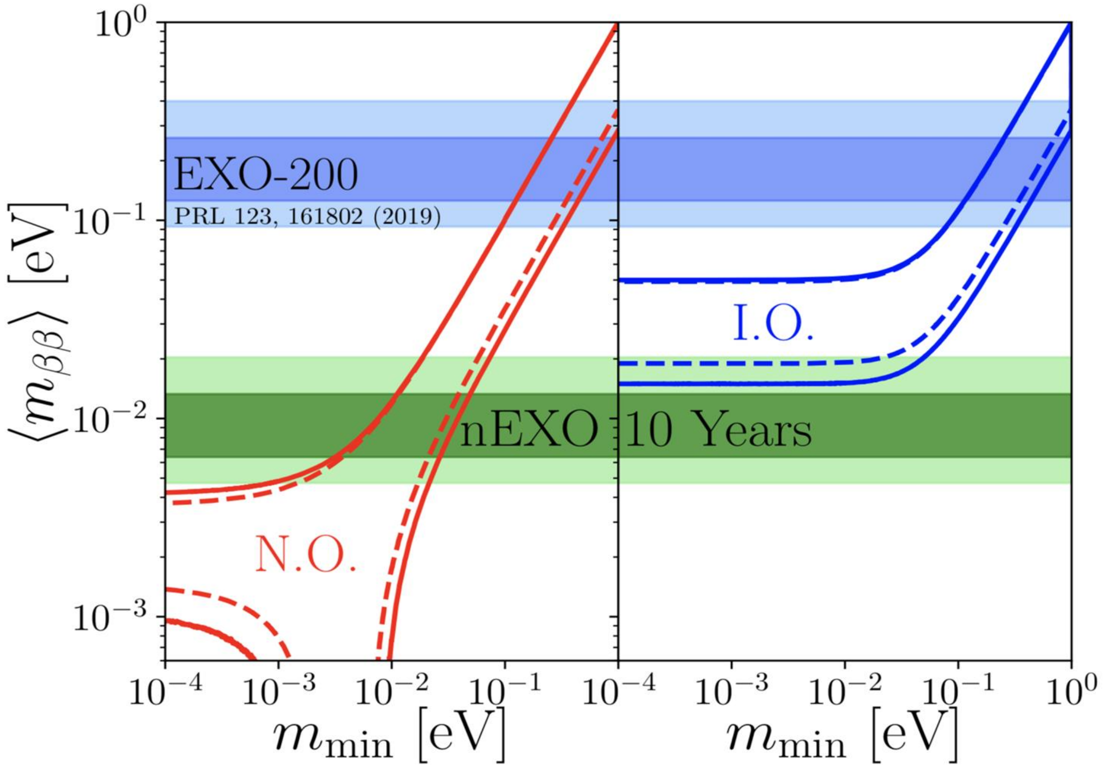
Sensitivity to New Physics

- $0\nu\beta\beta$ half-life sensitivity in 6.5 years:
  - Exclusion >10^{28} yr at 90 %CL
  - 3σ discovery ~10^{28} yr, 50% cases

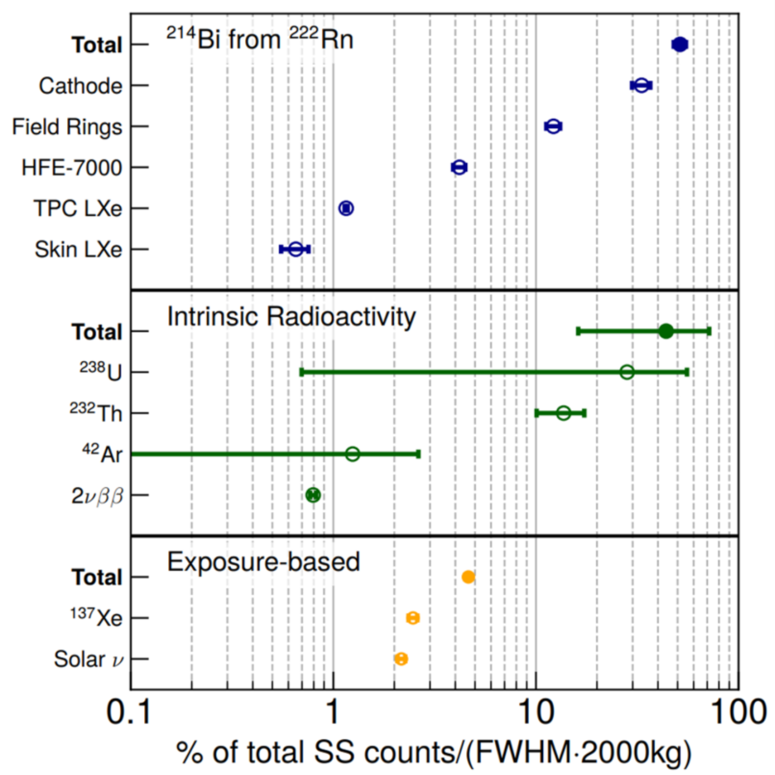
$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right| \qquad [T_{1/2}]^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} M^{0\nu}$$

nEXO Collaboration, J. Phys. G 49, 015104 (2022)



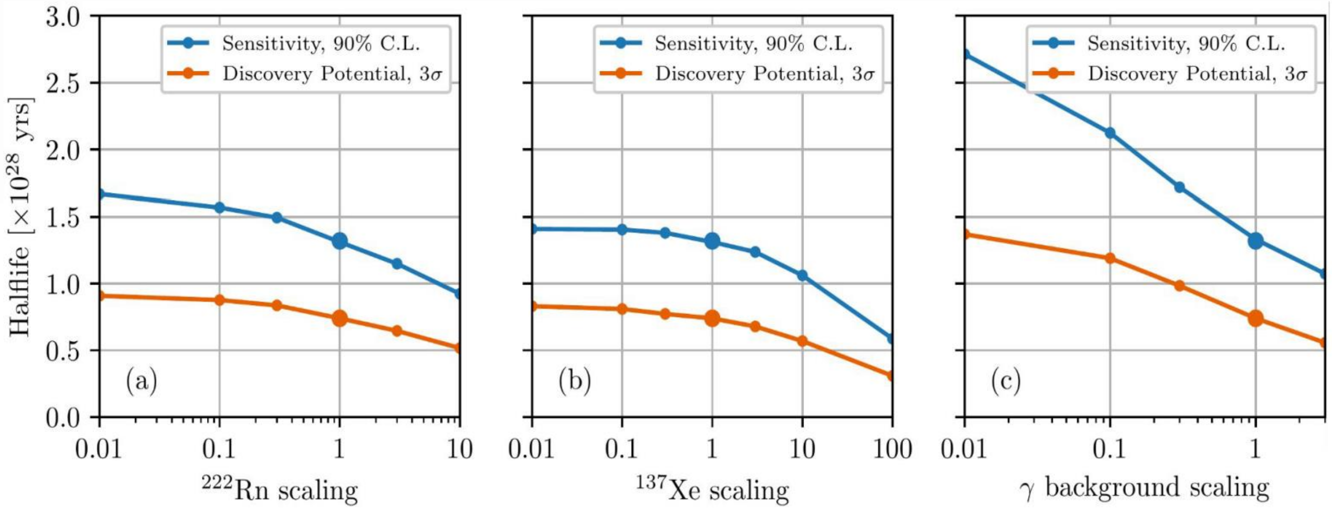


nEXO Backgrounds

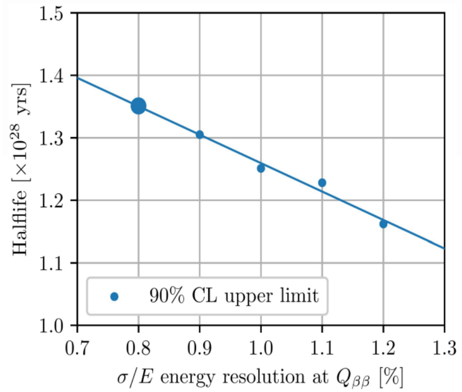


Background dominated by radon in LXe & all intrinsic radiation from components

- nEXO is fairly robust versus fluctuations in background models

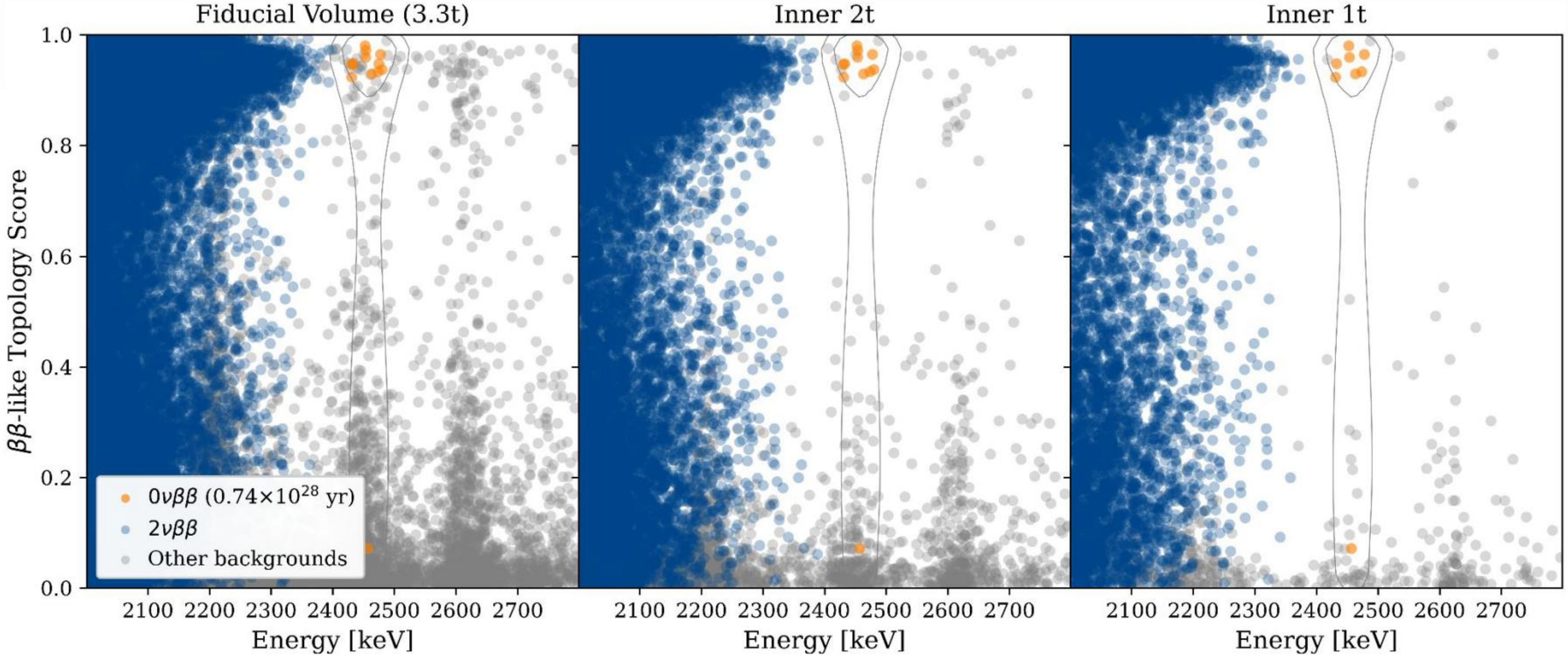


as well as energy resolution



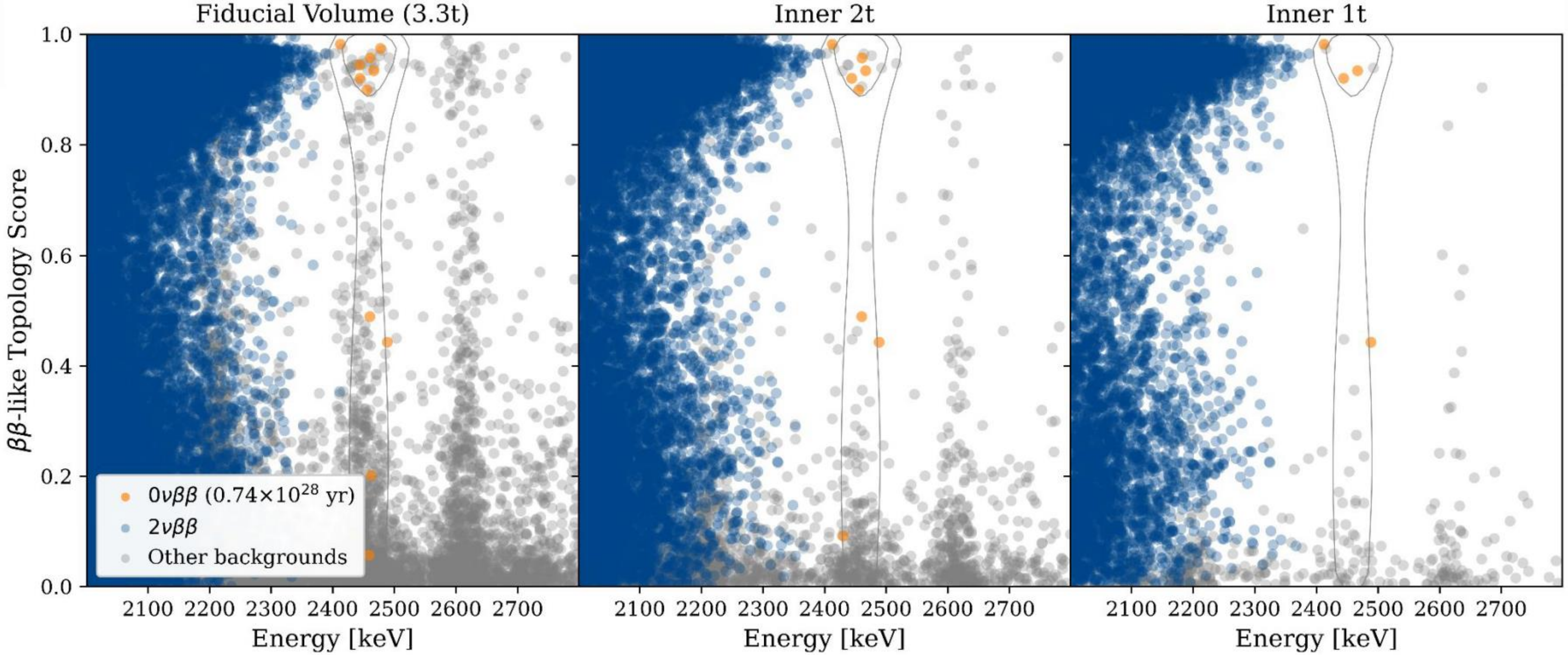
Multiparameter Analysis

- 1σ and 2σ contours on signal
- Realizations of nEXO 10 yr dataset at assumption of discovery potential half-life



Multiparameter Analysis

- 1σ and 2σ contours on signal
- Realizations of nEXO 10 yr dataset at assumption of discovery potential half-life



Summary

- Potential new physics with neutrinoless double beta decay
  - Lepton number violation beyond SM
- Liquid ^{136}Xe TPC is a proved technology
- nEXO will be a tonne-scale detector
  - Fully probe the inverted ordering of neutrino masses
- Majorana neutrinos is an exciting search
  - With a certain answer

Thank you