The nEXO $0\nu\beta\beta$ Experiment

Searching for Lepton Number Violation and Majorana Neutrinos with ^{136}Xe

Soud Al Kharusi, McGill University

Canadian Association of Physicists
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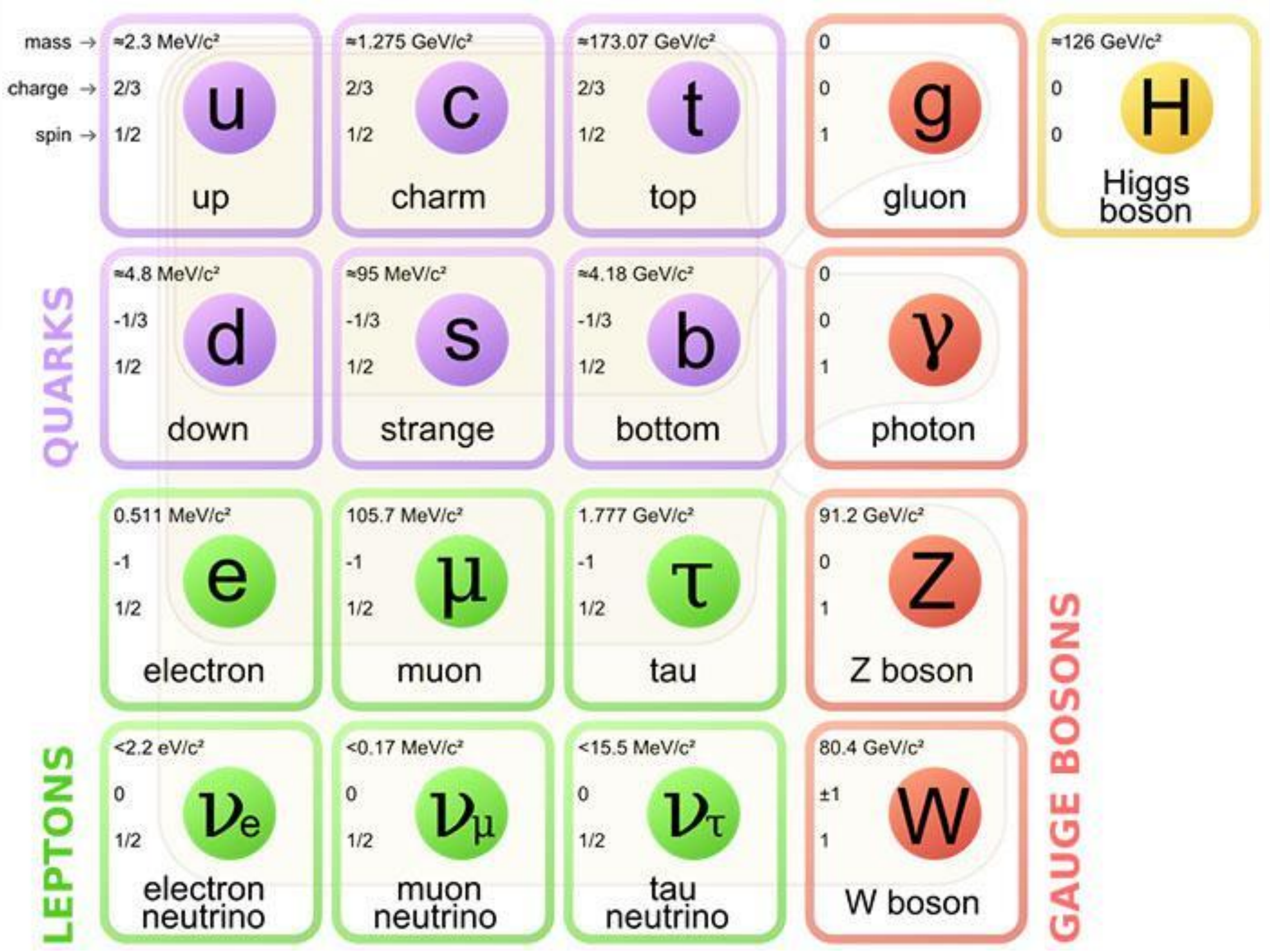
soud.alkharusi@mail.mcgill.ca

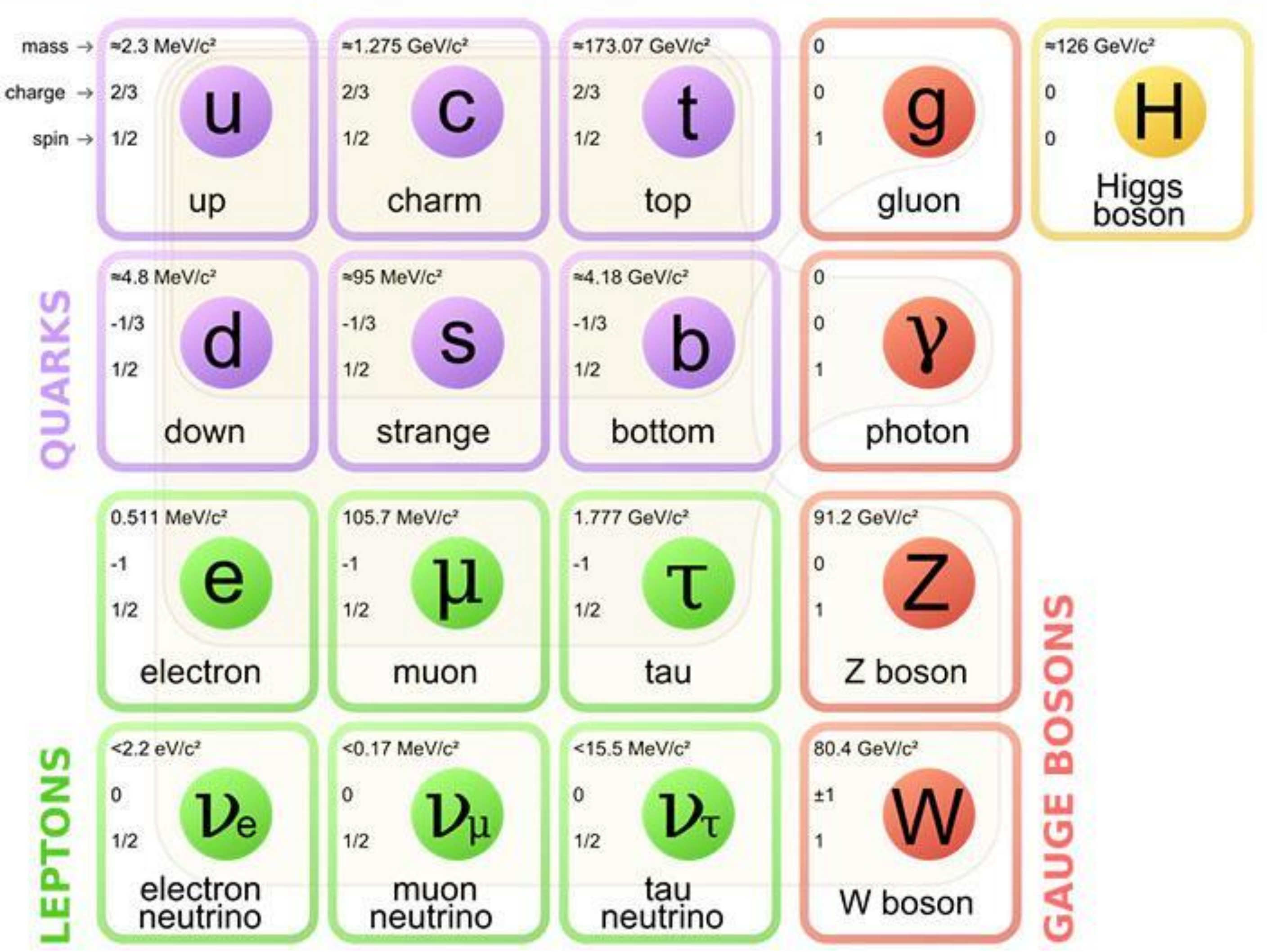
https://www.physics.mcgill.ca/~soudal/

(on behalf of the nEXO Collaboration)

The Standard Model (SM) of Particle Physics

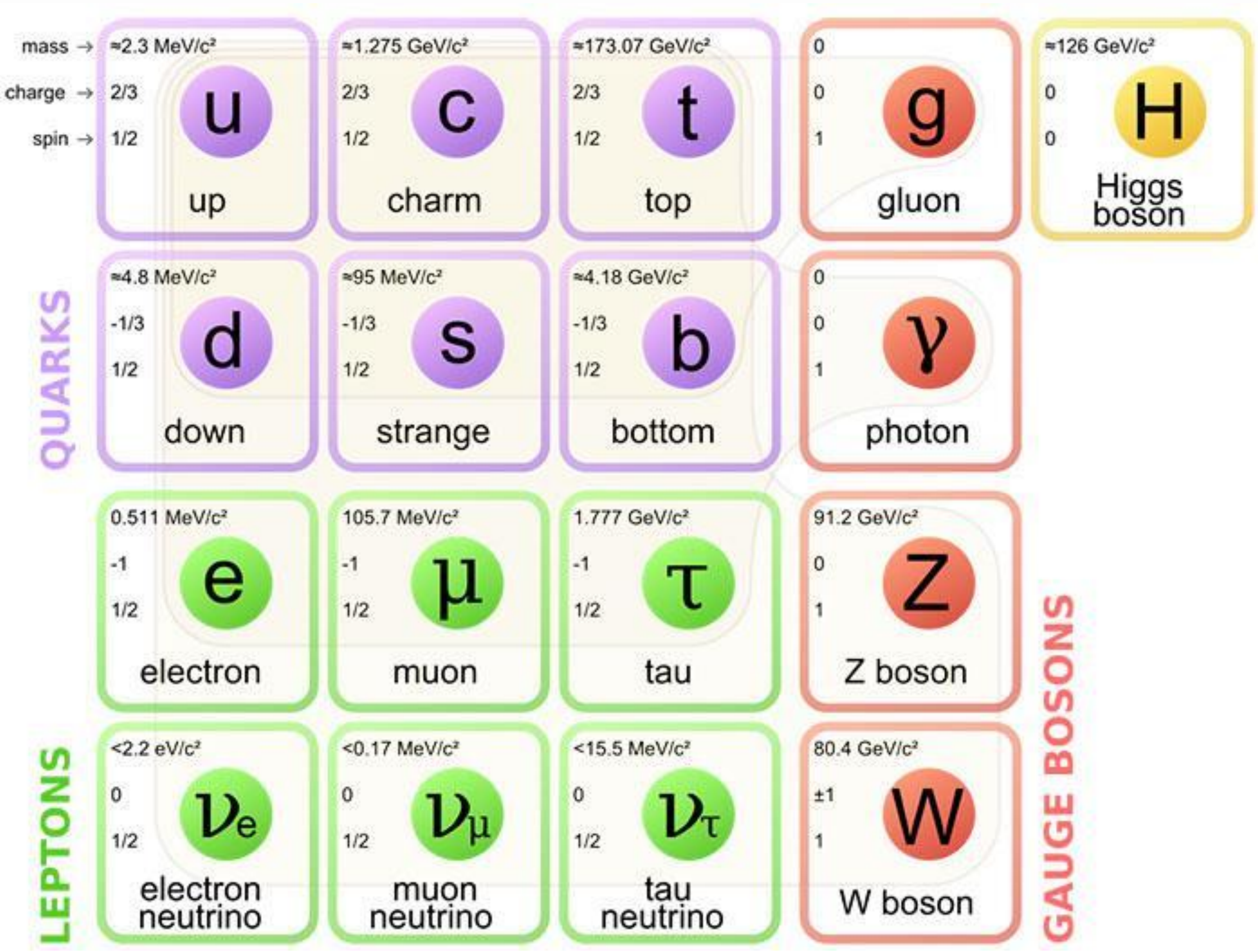


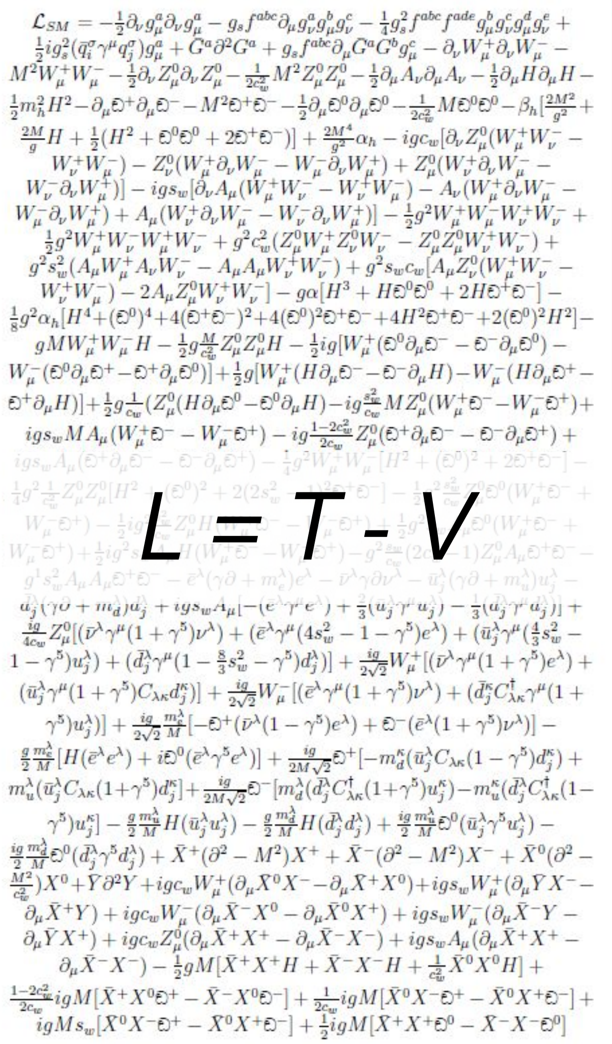
The Standard Model: Lagrangians



$$
\begin{aligned}
\mathcal{L}_{SM} = & -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
& M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h\left[\tfrac{2M^2}{g^2} + \right. \\
& \left.\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
& W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
& \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
& W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
& gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
& \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
& igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
& W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
& g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
& \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
& (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
& \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1- \\
& \gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
& \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
& \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
& \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{aligned}
$$

The Standard Model: Lagrangians



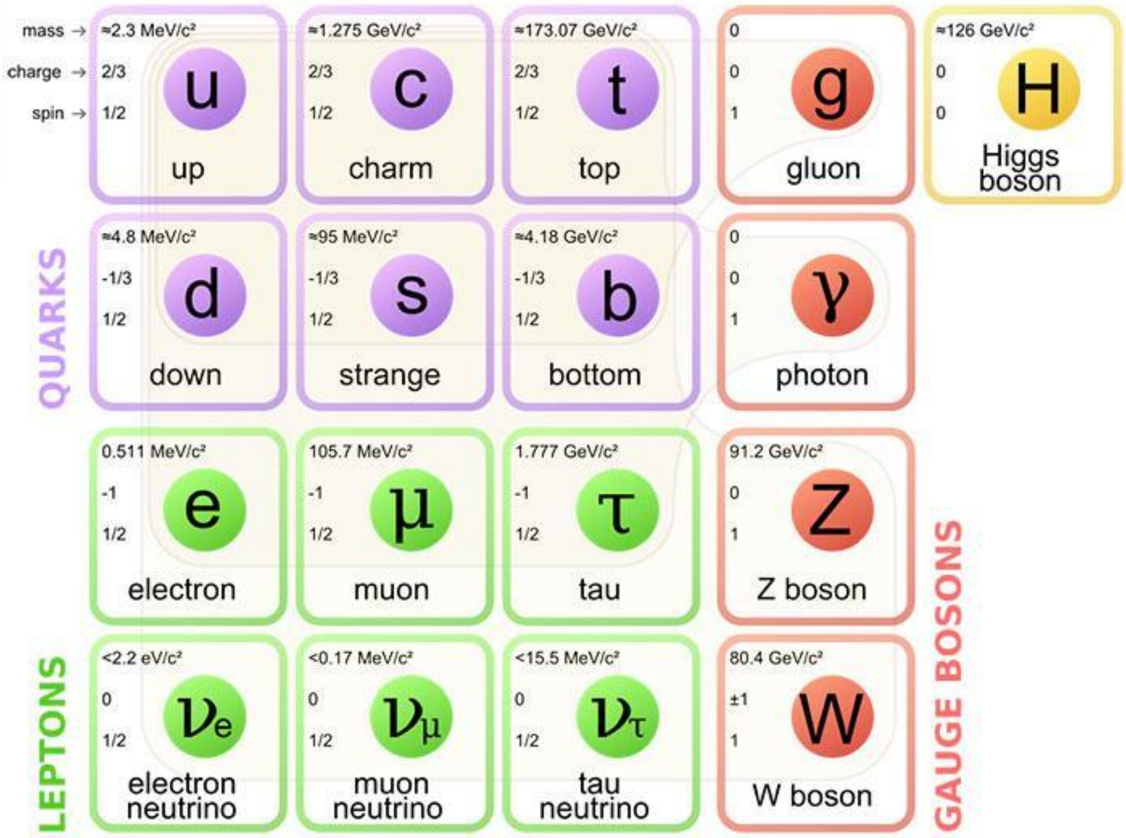


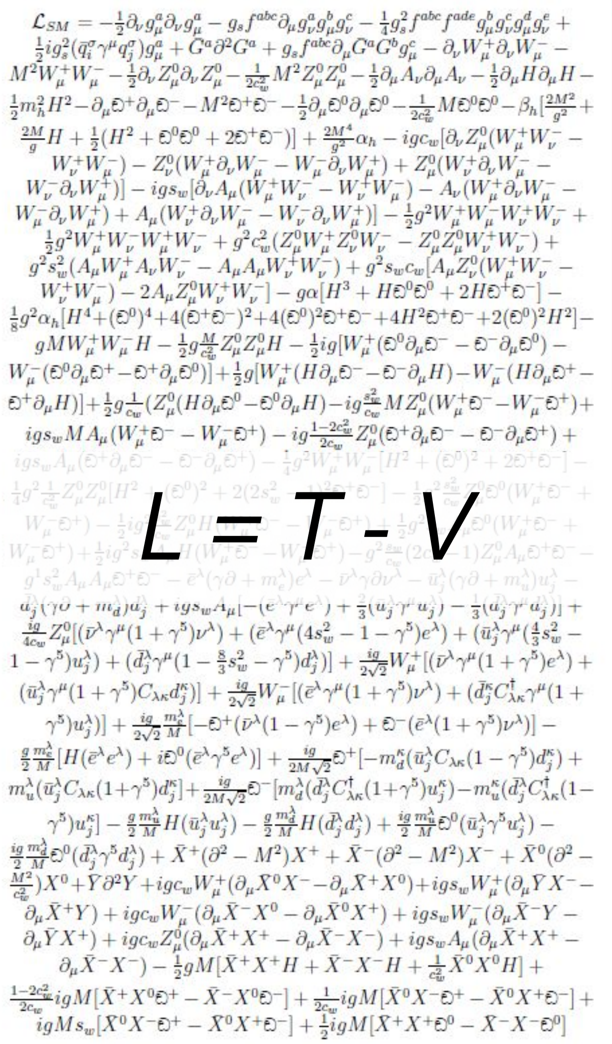
$L = T - V$

The Standard Model: Symmetries, Gauges & Groups

nEXO

$$SU(3) \times SU(2)_L \times U(1)_Y$$

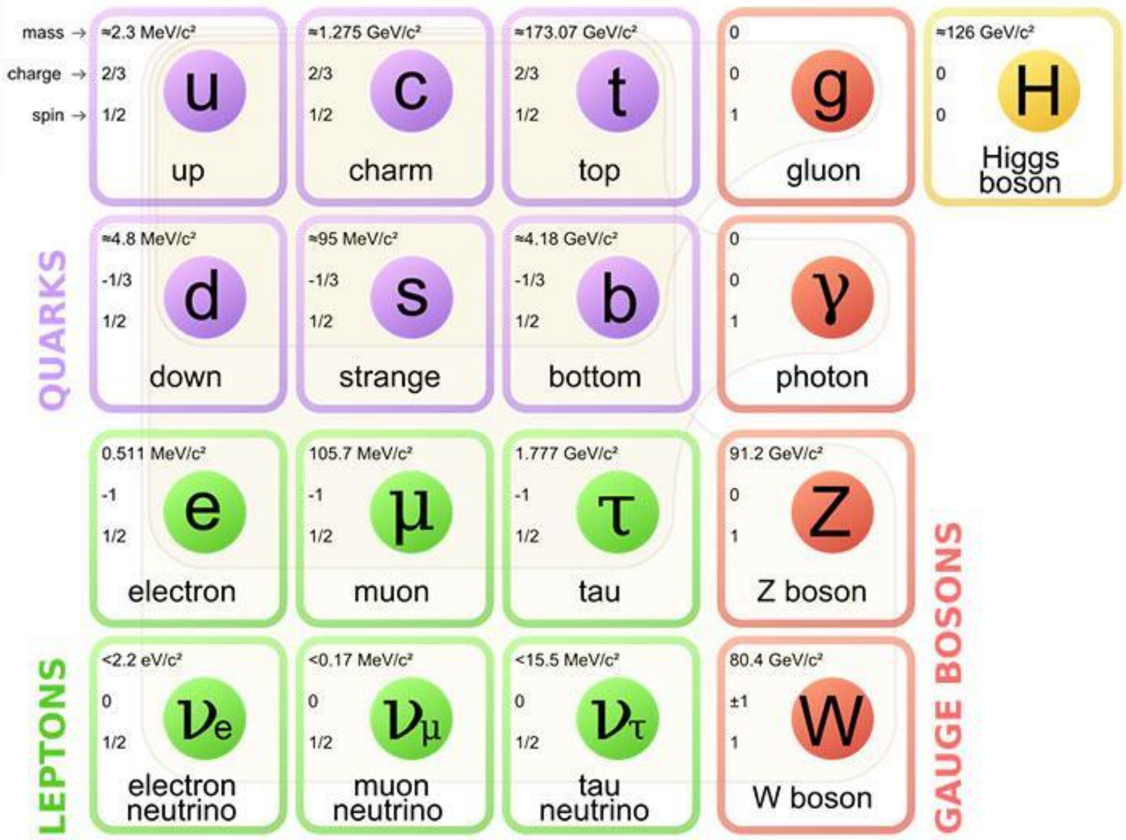


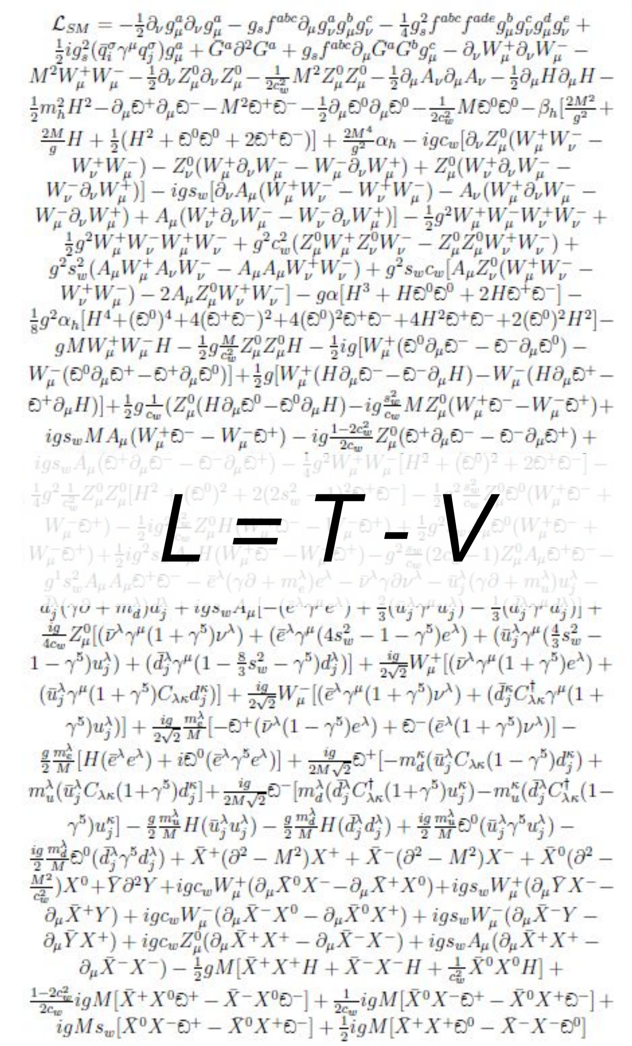


$$L = T - V$$

The Standard Model: Electroweak Symmetry

$SU(3) \times \mathbf{SU(2)_L \times U(1)_Y}$





$L = T - V$

The Standard Model: Electroweak Symmetry

$$SU(3) \times \mathbf{SU(2)_L \times U(1)_Y}$$

Only left handed fields feel the weak force;
It is parity violating

The Standard Model: Electroweak Symmetry nEXO

$$SU(3) \times \mathbf{SU(2)_L \times U(1)_Y}$$

Forces you to write down your theory in left- and right- chiral components

$$\Psi \longrightarrow \Psi_L + \Psi_R$$

e.g. for electrons…

$$e \longrightarrow e_L + e_R$$

The Standard Model: Electroweak Symmetry

$$SU(3) \times \mathbf{SU(2)_L \times U(1)_Y}$$

Y is "weak hypercharge", a quantum number

If electroweak gauge invariance holds, **Y** is conserved
⟶ has to be zero for all terms of the SM Lagrangian

The Standard Model: Electroweak Symmetry

$$SU(3) \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$$

$$L_{SM} = \ldots + \sim e_L \bar{e}_R$$

Not allowed!

e_L has hypercharge -1

e_R has hypercharge +2

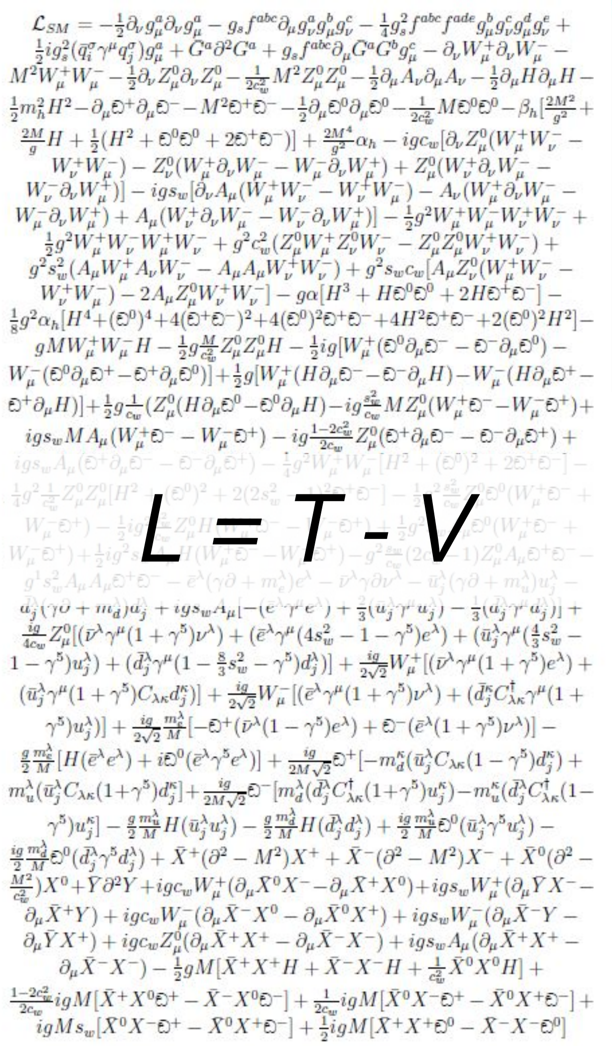
Y is "weak hypercharge", a quantum number

If electroweak gauge invariance holds, **Y** is conserved
⟶ has to be zero for all terms of the SM Lagrangian

Mass in the Context of the SM

What does it mean for something to have “mass”?

- **Rest energy**! ⟶ Ignore *kinetic* terms in Lagrangian



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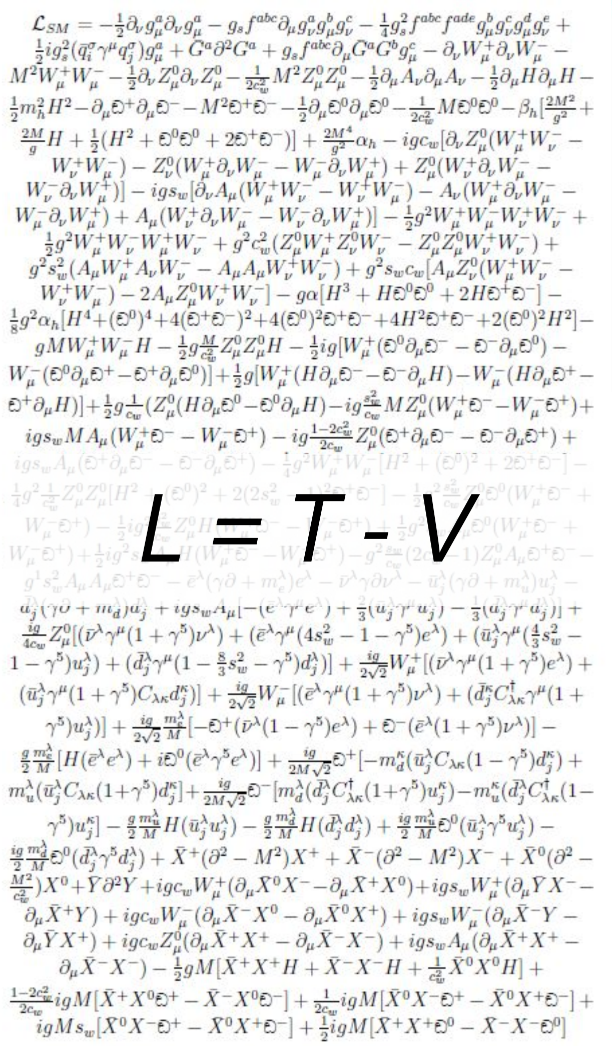
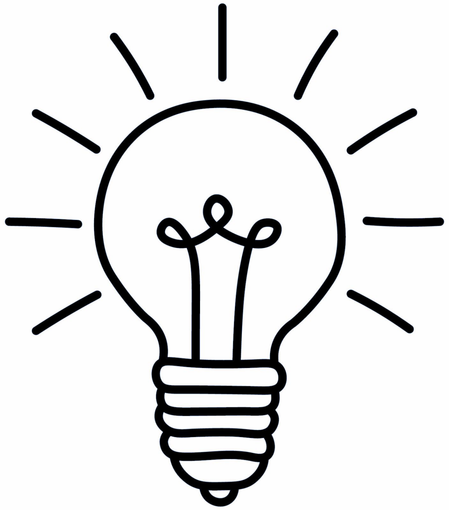


$$L_{SM} = \ldots + mc^2 \left(\bar{e}_L e_R + \bar{e}_R e_L\right)$$

Electroweak Symmetry & The Higgs

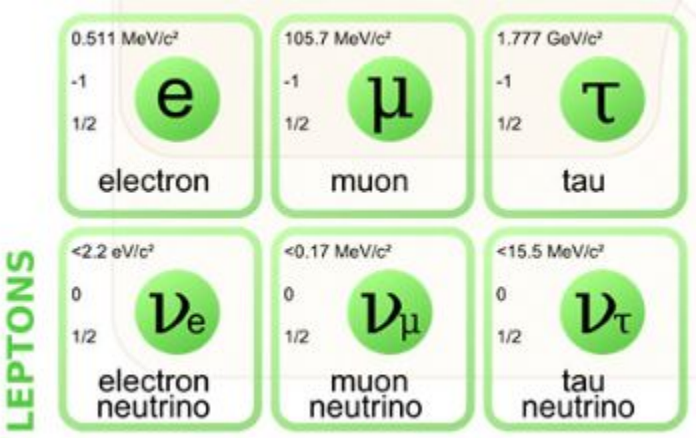
$$SU(3) \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$$

1. Postulate the existence of an SU(2) scalar doublet field "The Higgs field"



H^+

H^0



Electroweak Symmetry & The Higgs

$$SU(3) \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$$

1. Postulate the existence of an SU(2) scalar doublet field "The Higgs field"

$$L_{SM} = \ldots + Y_c H (\bar{e}_L e_R + \bar{e}_R e_L)$$

Electro/\weak Sym/metry Brea\king (EWSB)

$$SU(3) \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$$

electroweak force → EM + weak force

(lower energies)

E < 246 GeV

$T < 10^{15}$ K

$$SU(3) \times U(1)_{EM}$$

EWSB, The Higgs, and Dirac Mass Generation

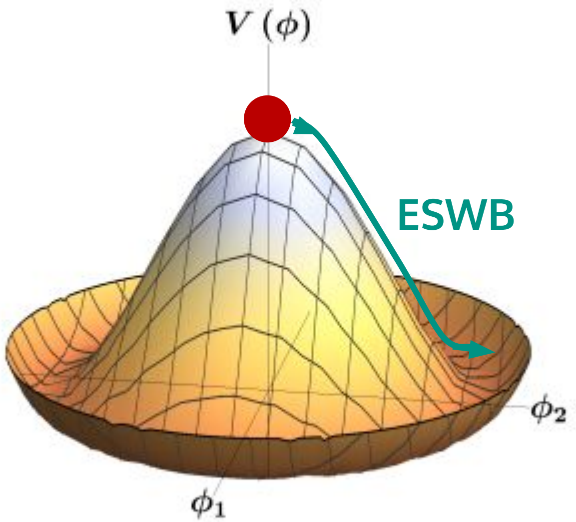
$$SU(3) \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$$

2. **Spontaneous Symmetry Breaking** takes the Higgs doublet to a 0 and a constant vacuum expectation value, **v** (VEV)

(lower energies)
electroweak force → EM + weak force

$$SU(3) \times U(1)_{EM}$$

Image Credit: J.A. Gonzalez



$$H \sim (\varphi_1, \varphi_2) \rightarrow (0, \mathbf{v} + \delta\varphi)$$

EWSB, The Higgs, and Dirac Mass Generation

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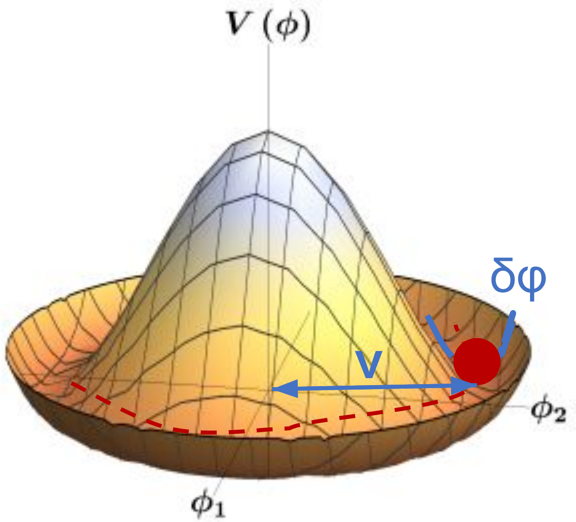

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EWSB, The Higgs, and Dirac Mass Generation

$$SU(3) \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$$

(lower energies)
electroweak force ⟶ EM + weak force

$$SU(3) \times U(1)_{EM}$$

$$L_{SM} = \ldots + Y_c H\,(\bar{e}_L e_R + \bar{e}_R e_L)$$

EWSB, The Higgs, and Dirac Mass Generation

nEXO

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EWSB

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$$L_{SM} = \ldots + Y_c \mathbf{v} (e_L \bar{e}_R + e_R \bar{e}_L) + Y_c \delta\varphi (e_L \bar{e}_R + e_R \bar{e}_L)$$

EWSB, The Higgs, and Dirac Mass Generation

$$SU(3) \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$$

(lower energies)

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$$SU(3) \times U(1)_{EM}$$

$$L_{SM} = \ldots + Y_c\, v\, (e_L \bar{e}_R + e_R \bar{e}_L) + Y_c\, \delta\varphi\, (e_L \bar{e}_R + e_R \bar{e}_L)$$

Coupling Constant * VEV

Coupling constant * fluctuation

EWSB, The Higgs, and Dirac Mass Generation

$$SU(3) \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$$

(lower energies)

electroweak force ⟶ EM + weak force

$$SU(3) \times U(1)_{EM}$$

$$L_{SM} = \ldots + Y_c\, v\, (e_L \bar{e}_R + e_R \bar{e}_L) + Y_c\, h\, (e_L \bar{e}_R + e_R \bar{e}_L)$$

this is a mass term!

this is an interaction term with the Higgs boson (h)!

EWSB, The Higgs, and Dirac Mass Generation

nEXO

$$SU(3) \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$$

(lower energies)
electroweak force ⟶ EM + weak force

$$SU(3) \times U(1)_{EM}$$

Nobel Prize in Physics 1979

Photo from the Nobel Foundation archive.
Sheldon Lee Glashow
Prize share: 1/3

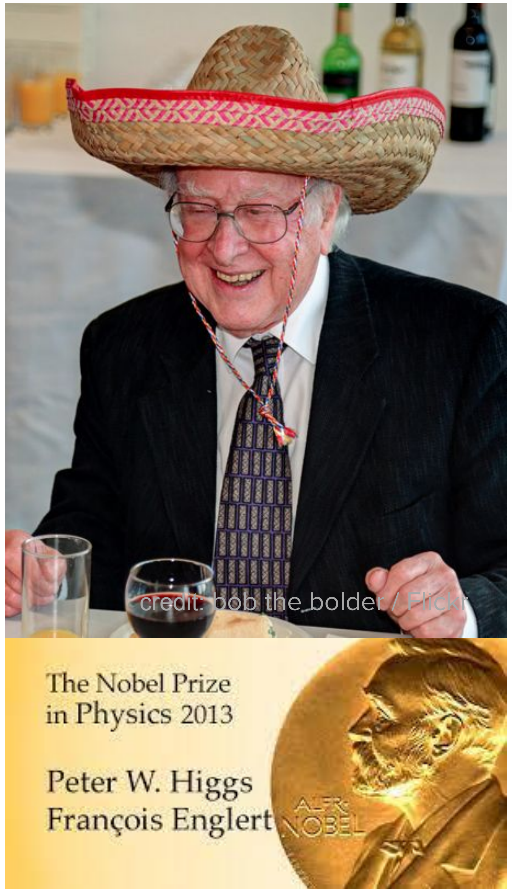
Photo from the Nobel Foundation archive.
Abdus Salam
Prize share: 1/3

Photo from the Nobel Foundation archive.
Steven Weinberg
Prize share: 1/3

Nobel Prize in Physics 1999

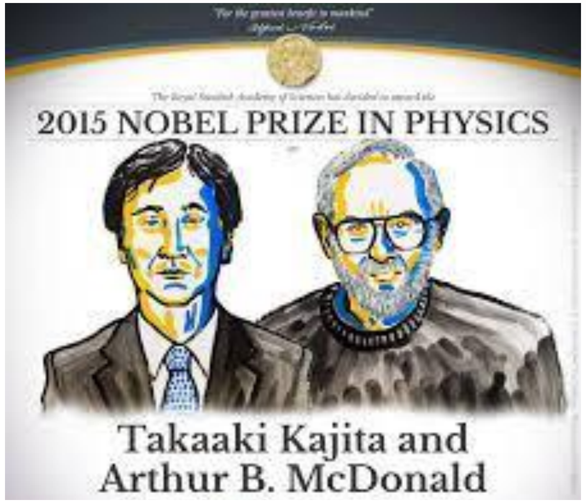
Martinus Veltman
Professor Emeritus at the University of Michigan, Ann Arbor, USA, formerly at the University of Utrecht, Utrecht, the Netherlands.

Gerardus 't Hooft
Professor at the University of Utrecht, Utrecht, the Netherlands.

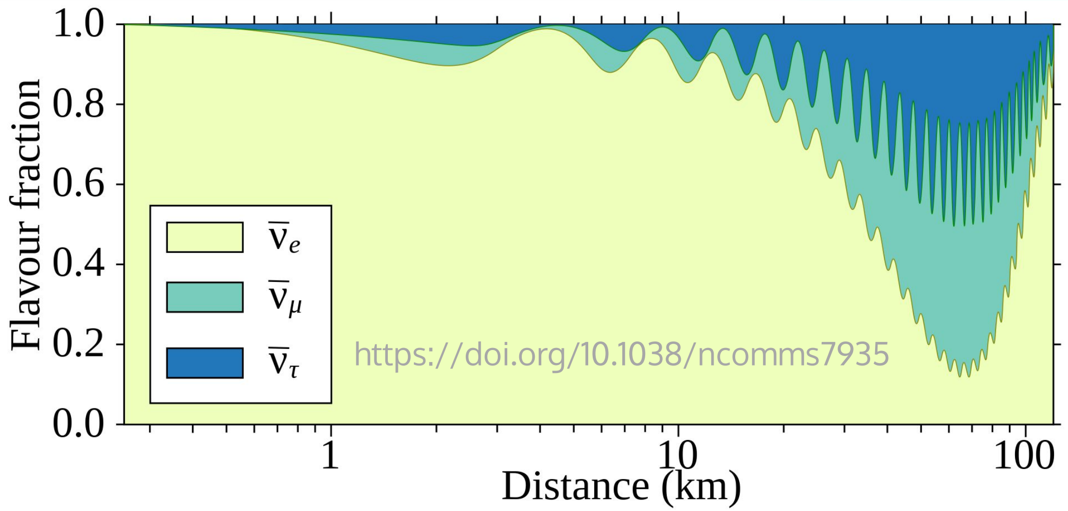


Neutrinos *must* have mass because they ~OSCILLATE~ !

- Neutrino mass & flavour eigenstates are not the same, but related by a matrix



Solar neutrino problem: SOLVED

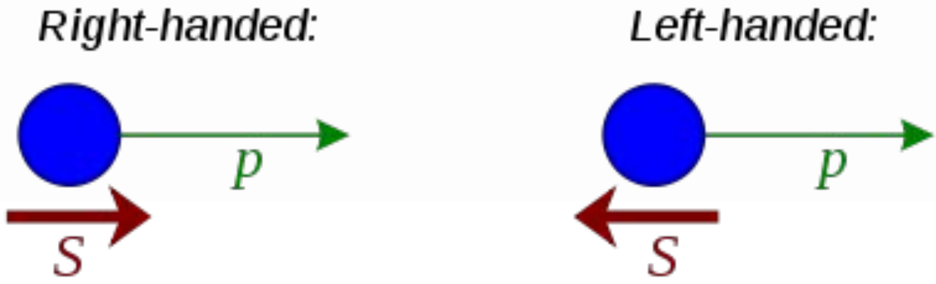


$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix relates flavour and mass eigenstates of neutrinos

Where do neutrino masses come from?

- **Experimentally**: all neutrinos we've ever seen have left-handed helicity, and all anti-neutrinos are right-handed



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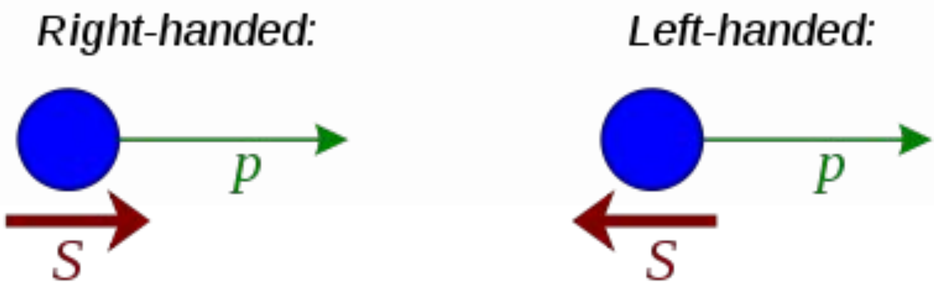

Given the fact that **neutrinos are massive**, they **do not travel at *c***

You can Lorentz boost into a frame where you will have the opposite helicity

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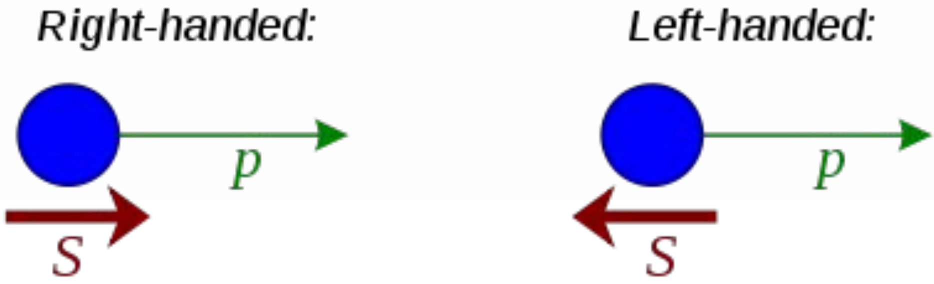

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Neutrinos are neutral particles, so **are neutrinos their own antiparticle (Majorana fermions)**?

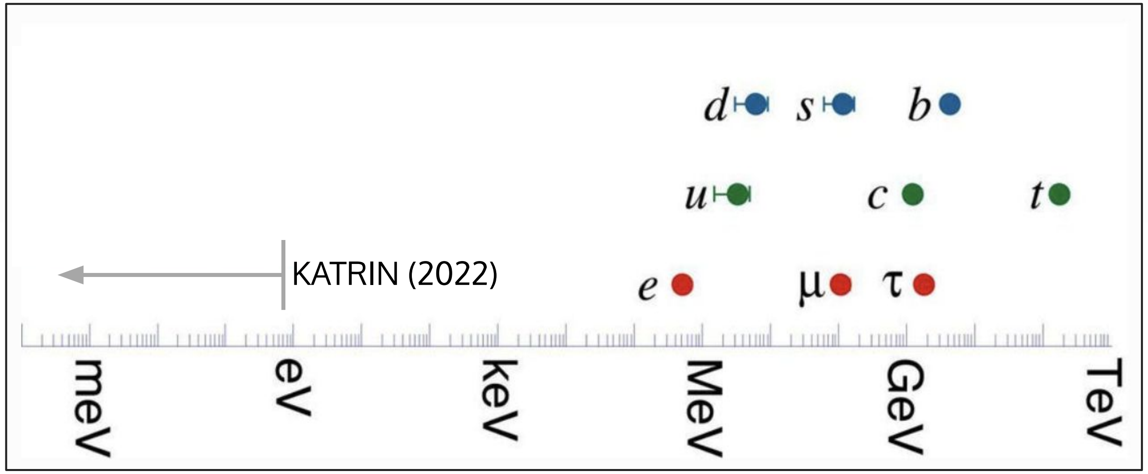
(neutrinos are almost always ultra relativistic, E >> m … the limit where helicity ⟵⟶ chirality)

The Neutrino Mass Problem

Are neutrinos Dirac or Majorana fermions?

If Dirac: why is the coupling of neutrinos to the Higgs $>10^6$ times smaller than that of the next lightest fermion?

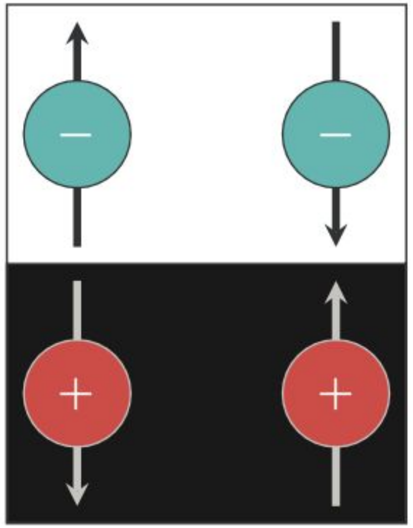
If Majorana: could this explain the smallness of neutrino masses?

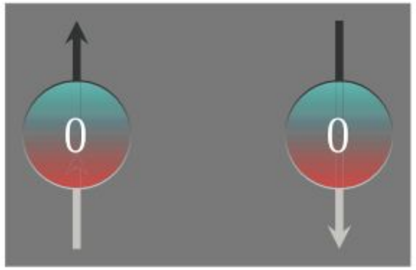


Standard Model Fermion masses / HITOSHI MURAYAMA (adapted)

Do Majorana neutrinos help us?

- **Lose two degrees of freedom** in the SM for Majorana neutrinos
- Weinberg operator:
- Seesaw mechanisms:
- Matter vs Antimatter?





Credit: The State of the Art of Neutrino Physics

Do Majorana neutrinos help us?

- Lose two degrees of freedom in the SM for Majorana neutrinos
- **Weinberg operator:** there is **one unique way** you can construct a **next-leading-order operator** in the SM **using only SM particles**.
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    - **Naturally produces Majorana neutrinos & violates Lepton number conservation**
- Seesaw mechanisms:
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$$L_{real} \sim L_{SM} + L_{Weinberg}$$

$$L_{Weinberg} = Y_c/\Lambda \ \bar{L}_L \tilde{\Phi} \Phi^{\dagger} L_L$$

Λ: energy scale of new physics
Y_c: coupling constant
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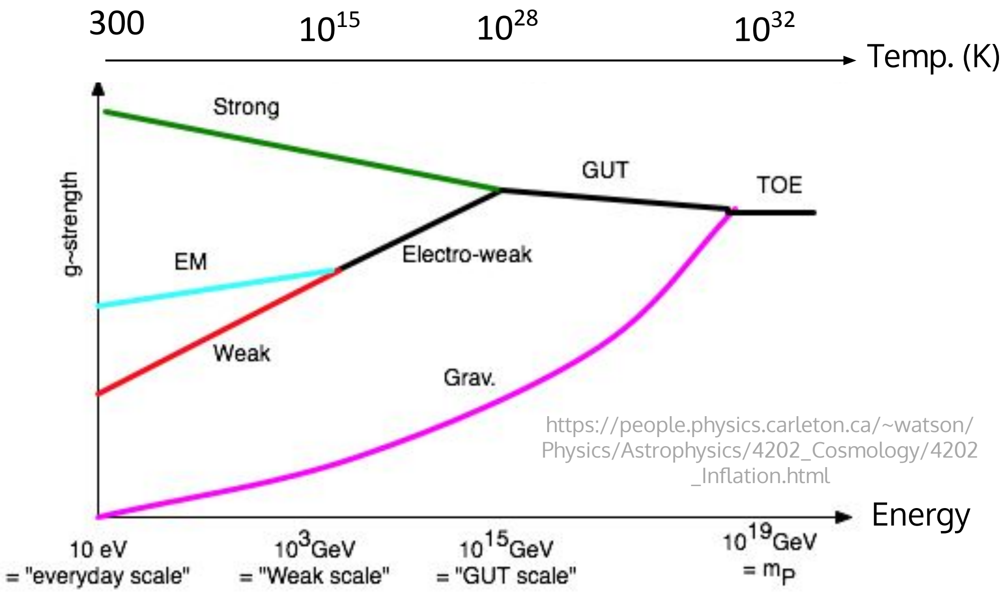

https://people.physics.carleton.ca/~watson/Physics/Astrophysics/4202_Cosmology/4202_Inflation.html

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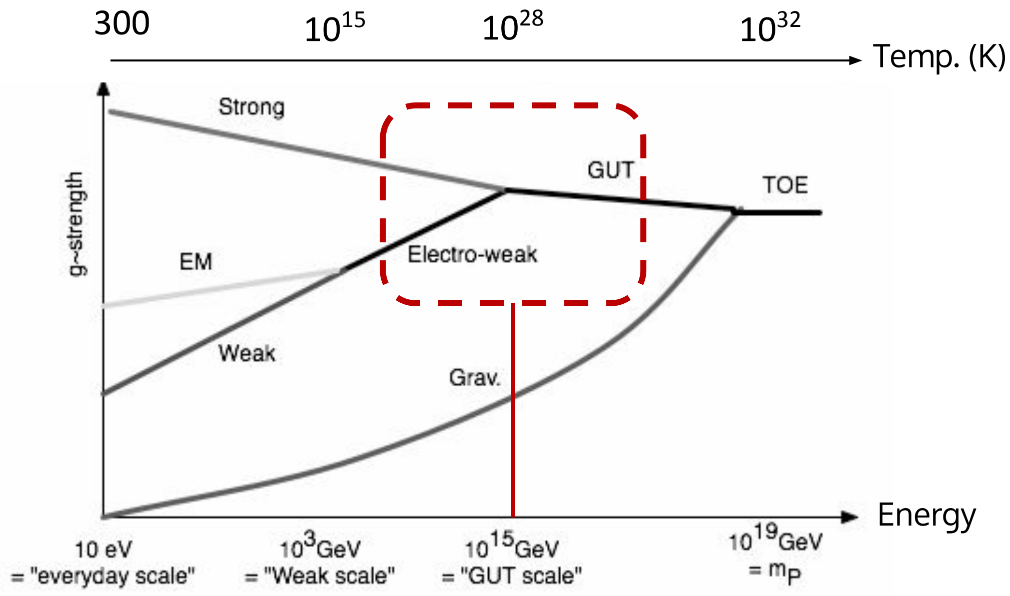

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m_D is the Dirac mass ~ VEV

diagonalize the mass matrix to find mass eigenvalues

$$\mathscr{L}_m = \frac{1}{2}((\bar{\nu}_L)^c \bar{\nu}_R) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix} + h.c..$$

$$m_1 = \frac{m_D^2}{m_R - m_L}$$

$$m_2 = m_R - m_L.$$

m_R and m_L are Majorana masses (not connected to Higgs)

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$m_L = 0$ due to $SU(2)_L x U(1)_Y$ gauge invariance

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m_1 can be made *really* small if $m_D << m_R$

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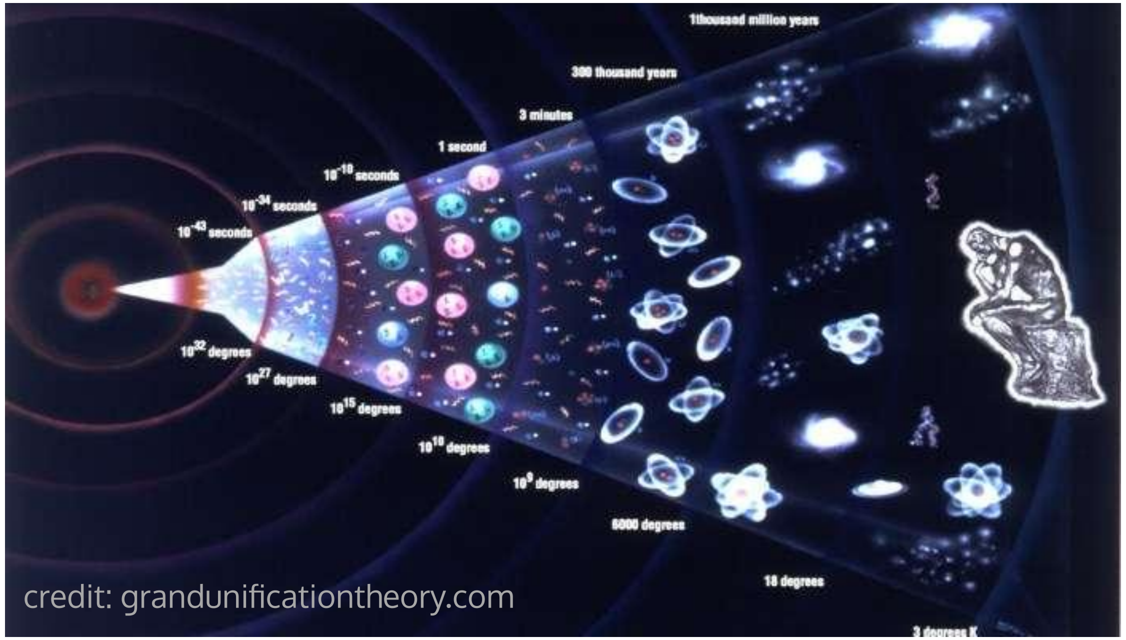
Do Majorana neutrinos help us?

- **Lose two degrees of freedom** in the SM for Majorana neutrinos
- **Weinberg operator**
- **Seesaw mechanisms**
- **Matter vs Antimatter?** Maybe $\mathbf{m_R}$ associated with Λ and are *really* heavy?
  - Possible explanation for the matter / antimatter asymmetry!! (leptogenesis)



credit: grandunificationtheory.com

But how can we test these ideas?

- **Lose two degrees of freedom** in the SM for Majorana neutrinos
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NB: if neutrinos have masses ~meV, then Λ will be ~10^{12} TeV

LHC √s energy is ~13 TeV: **we should not expect to see *this* new physics at colliders in our lifetime!**

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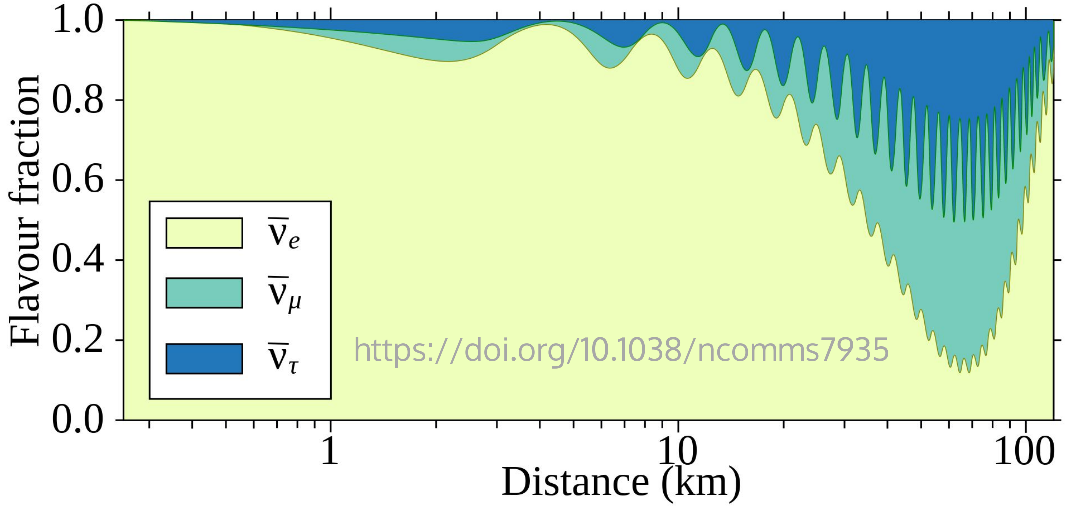
… so what do we do?

What can neutrino ~OSCILLATIONS~ tell us?



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

The PMNS matrix relates flavour and mass eigenstates of neutrinos

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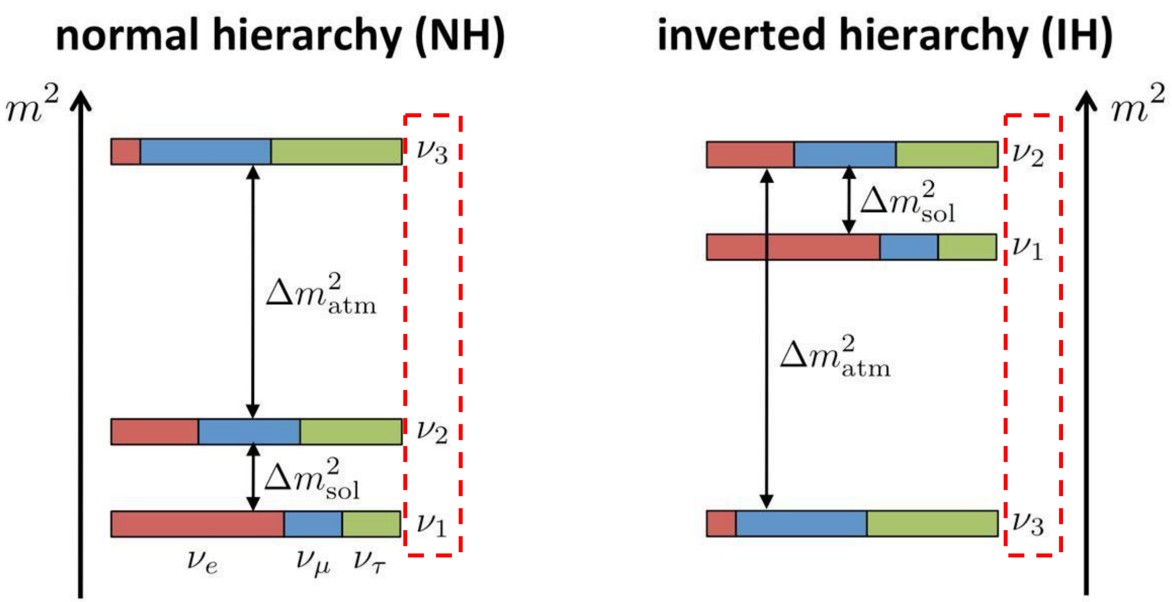

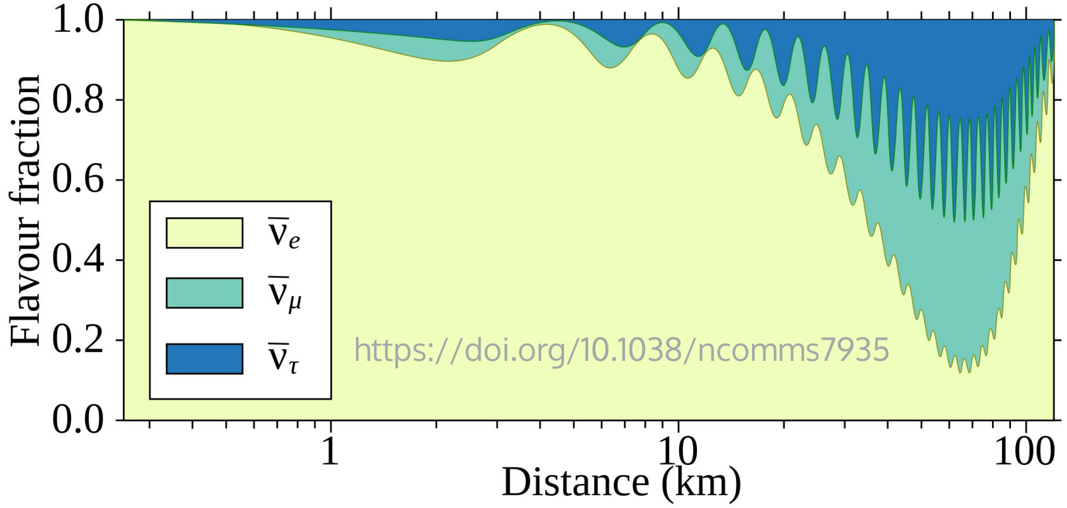

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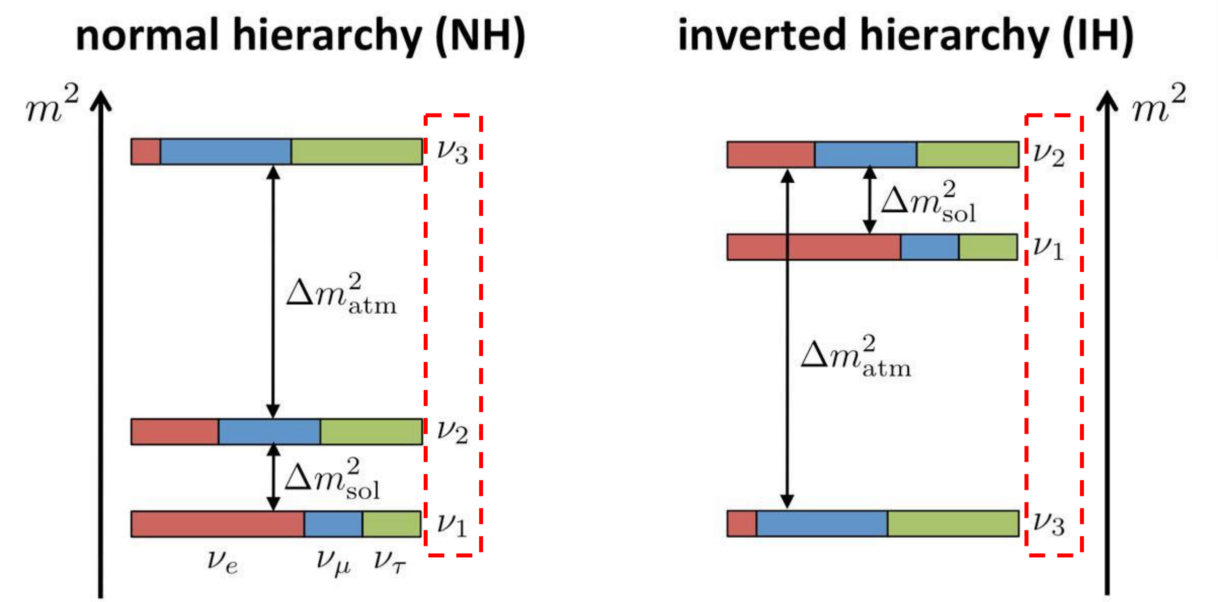

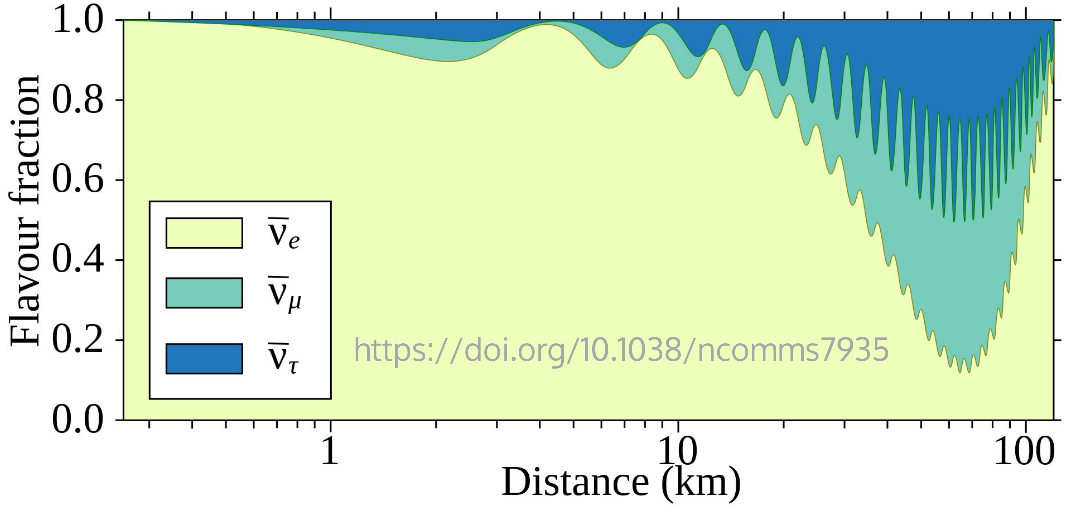

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The PMNS matrix relates flavour and mass eigenstates of neutrinos

… but no information on Majorana vs Dirac :(

The Ultimate Test: Neutrinoless Double Beta Decay

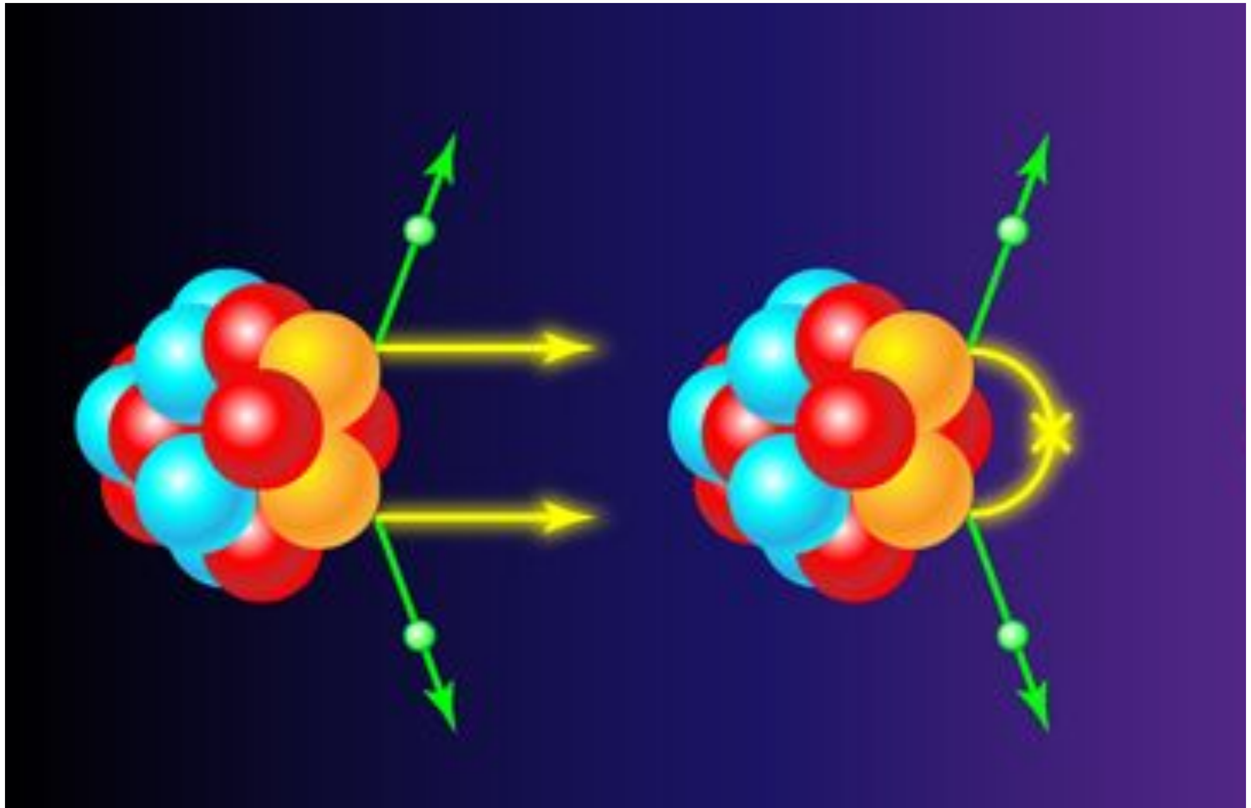
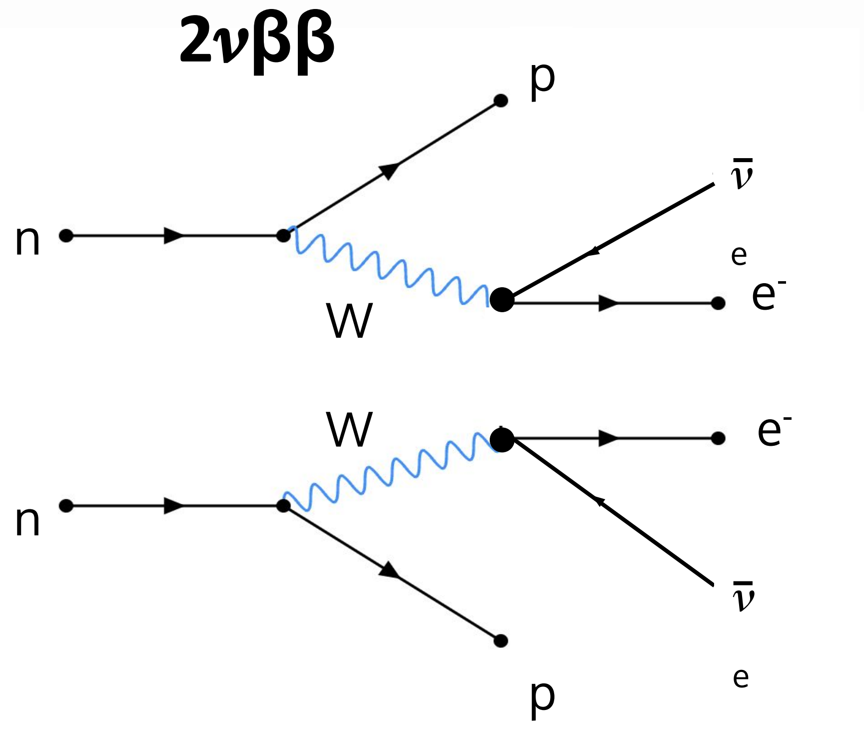


Image credit: APS/Alan Stonebraker

What is 2νββ?

- Simultaneous conversion of two nucleons into two charged leptons and two antineutrinos



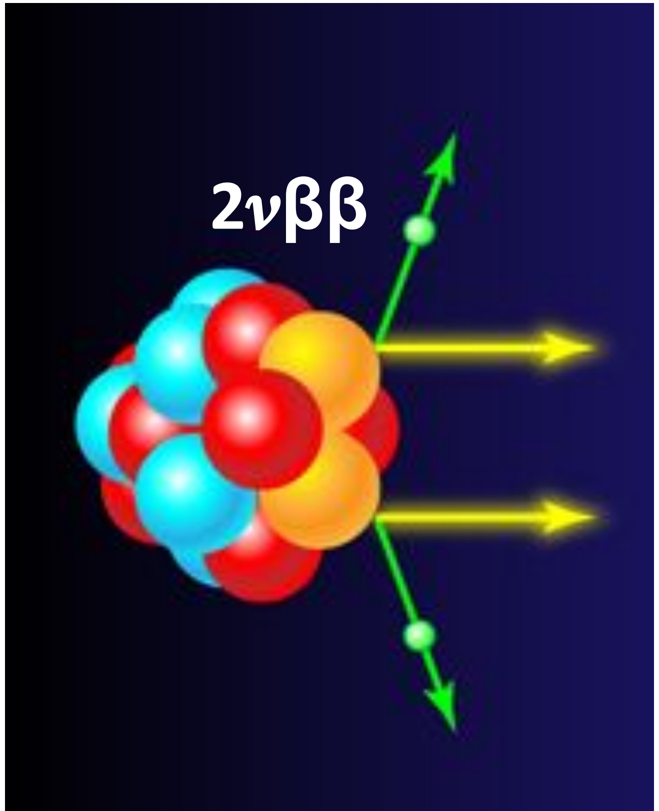
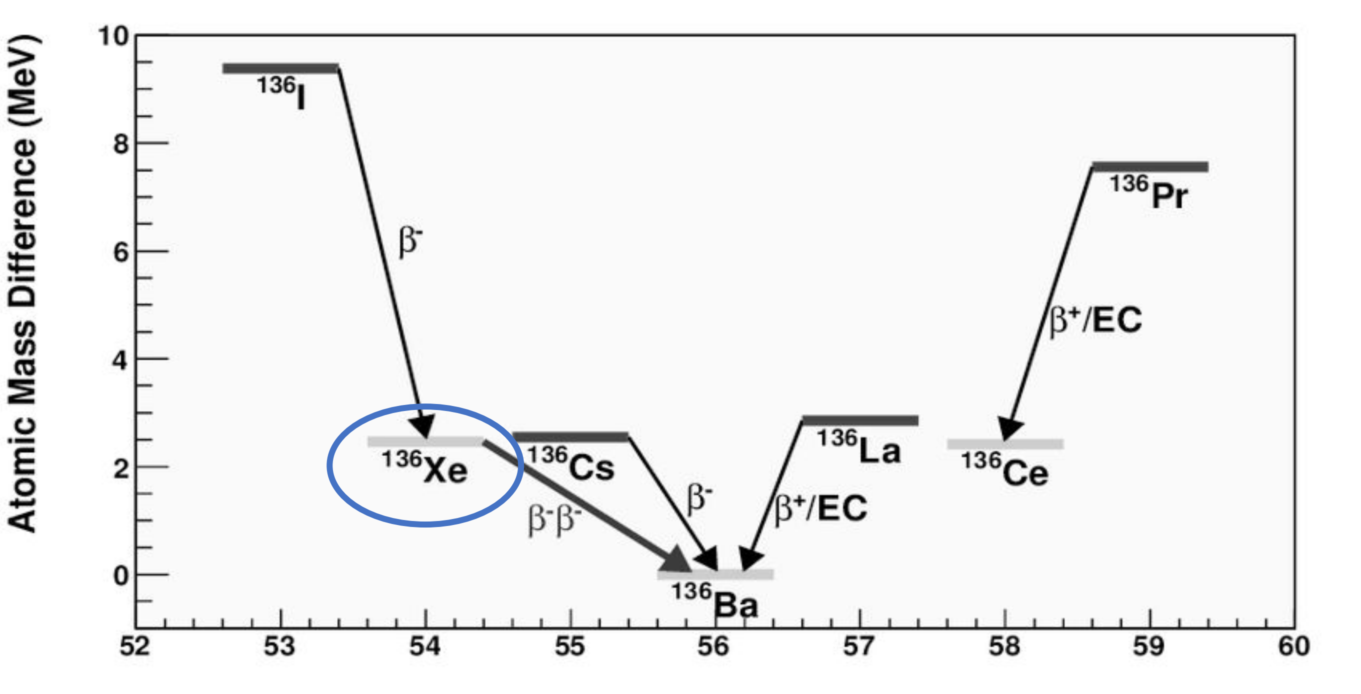


Image credit: APS/Alan Stonebraker

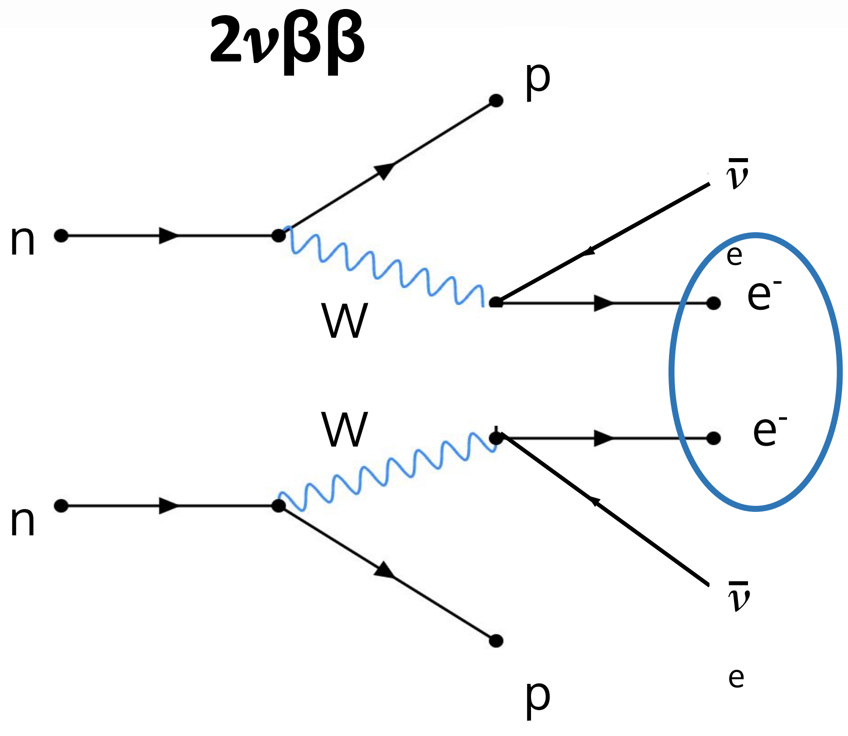
ββ-decays are rare

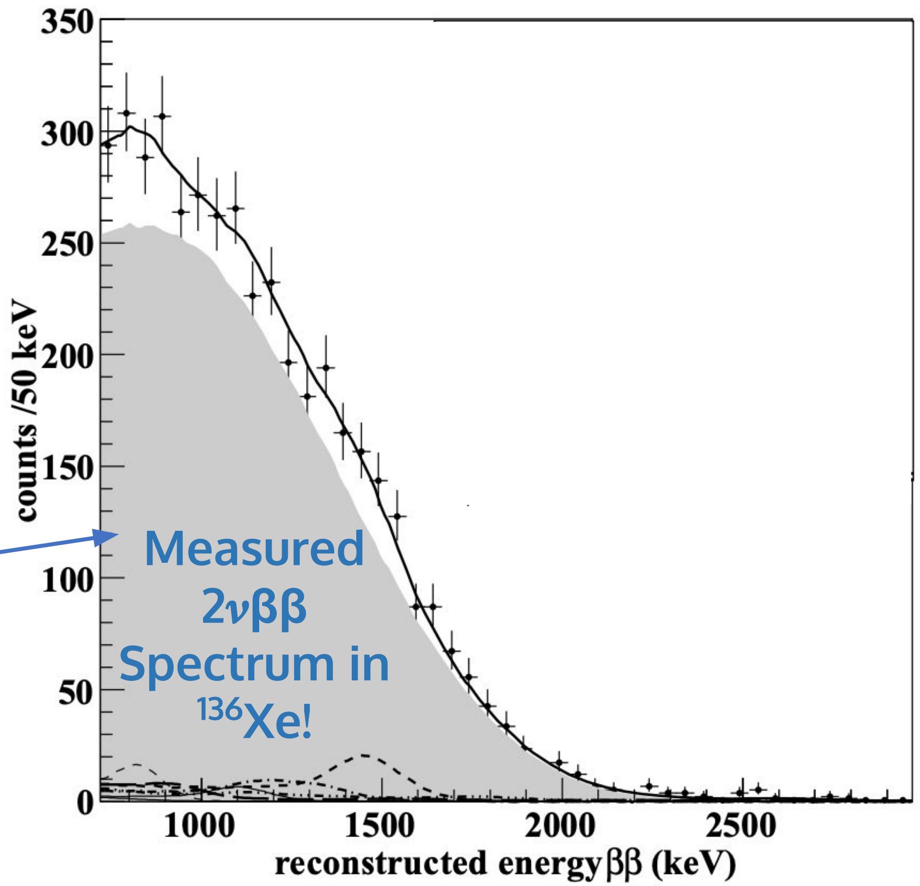
- Second-order weak interaction process



Source: 10.1393/ncr/i2012-10074-9 / arXiv:1109.5515

0νββ vs 2νββ





Adapted from: Ackerman, N., et al. "Observation of two-neutrino double-beta decay in Xe-136 with the EXO-200 Detector." *Phys Rev Lett* 107.21 (2011): 212501.

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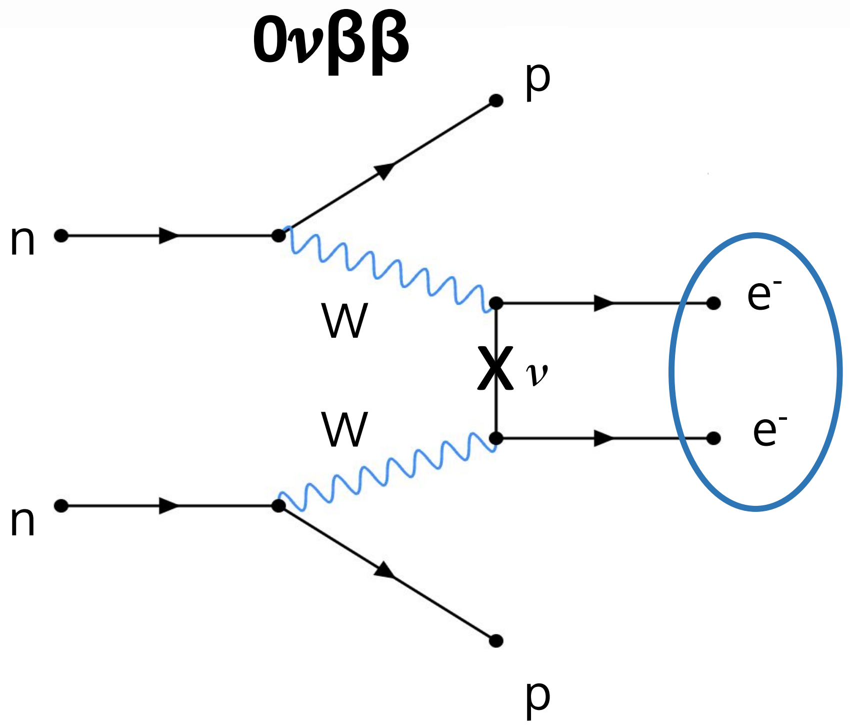
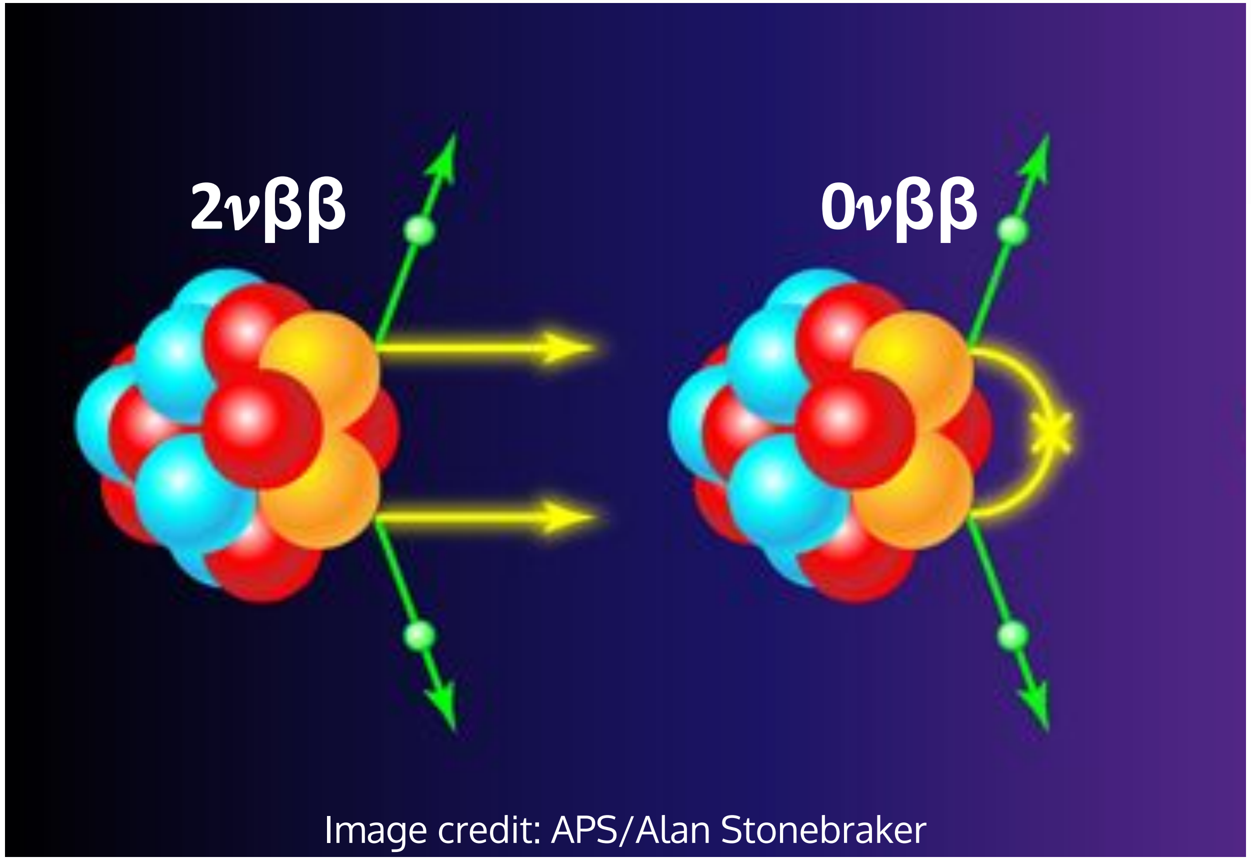
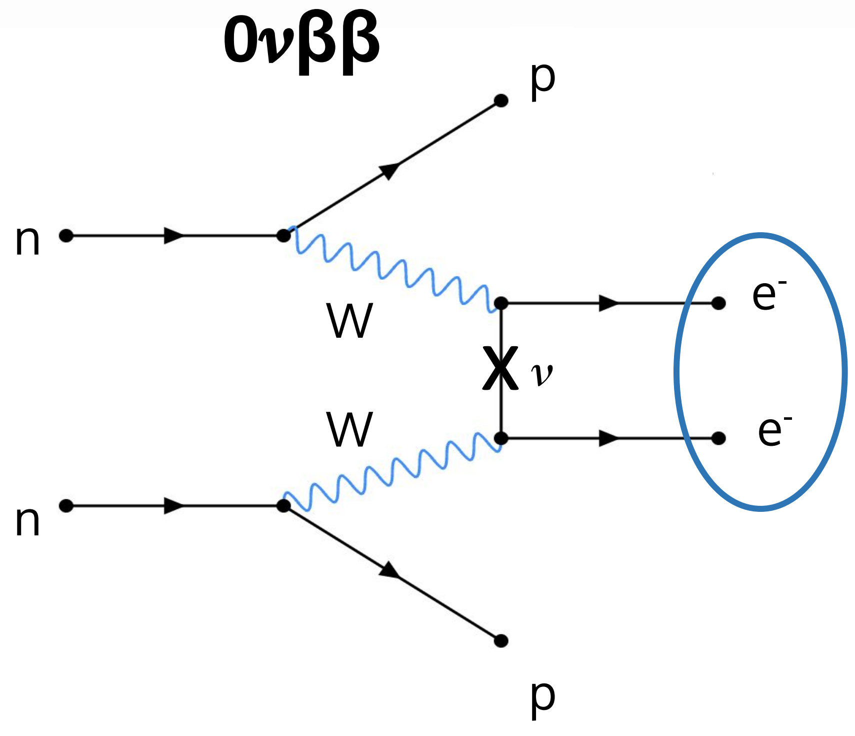
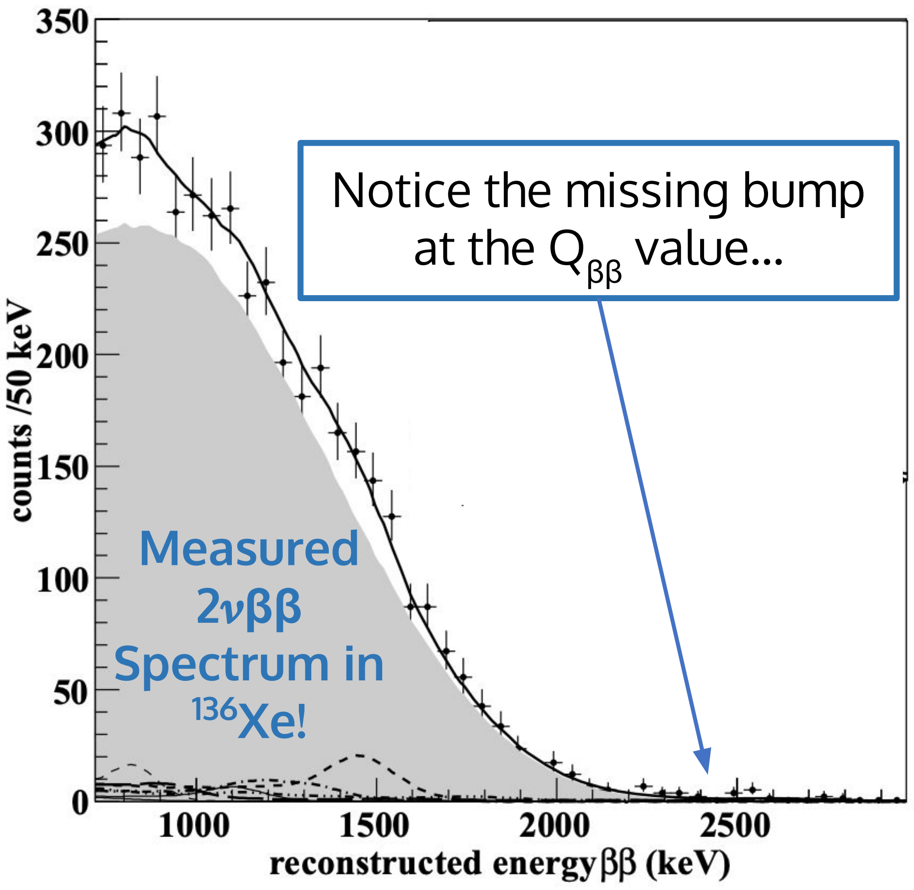




$0\nu\beta\beta$ vs $2\nu\beta\beta$





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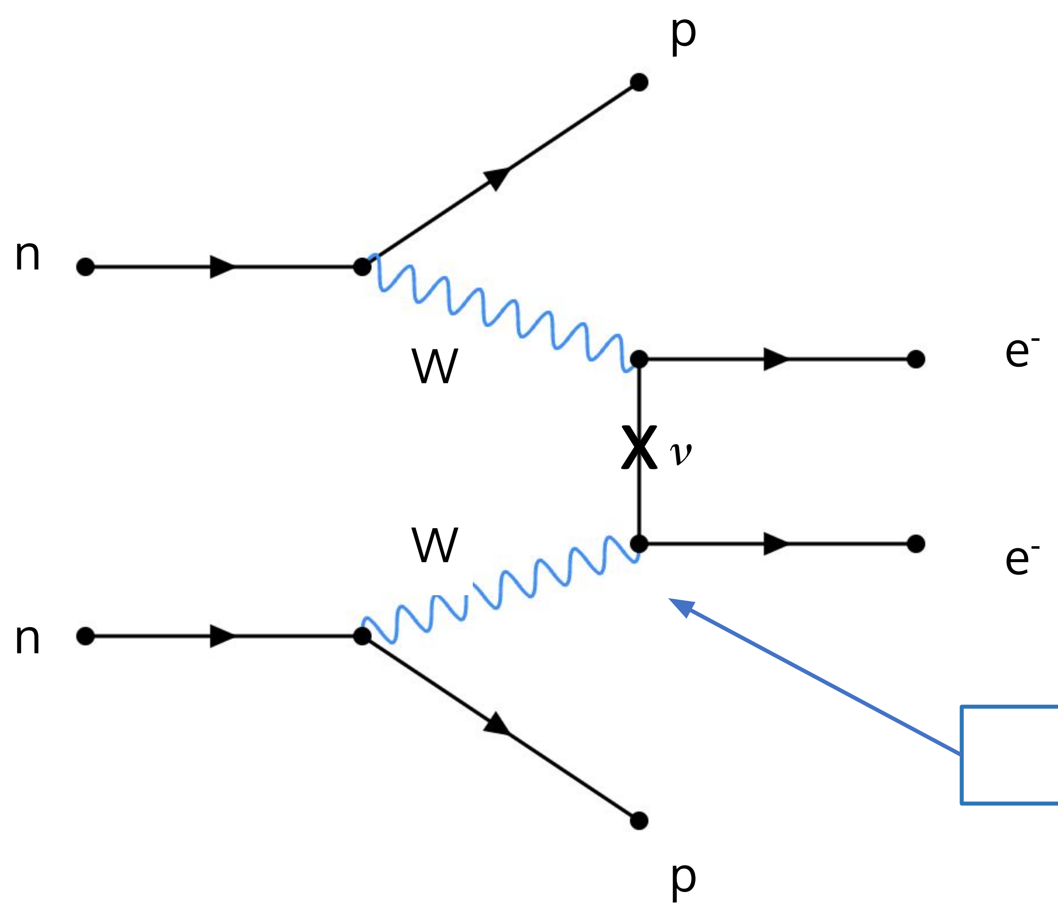
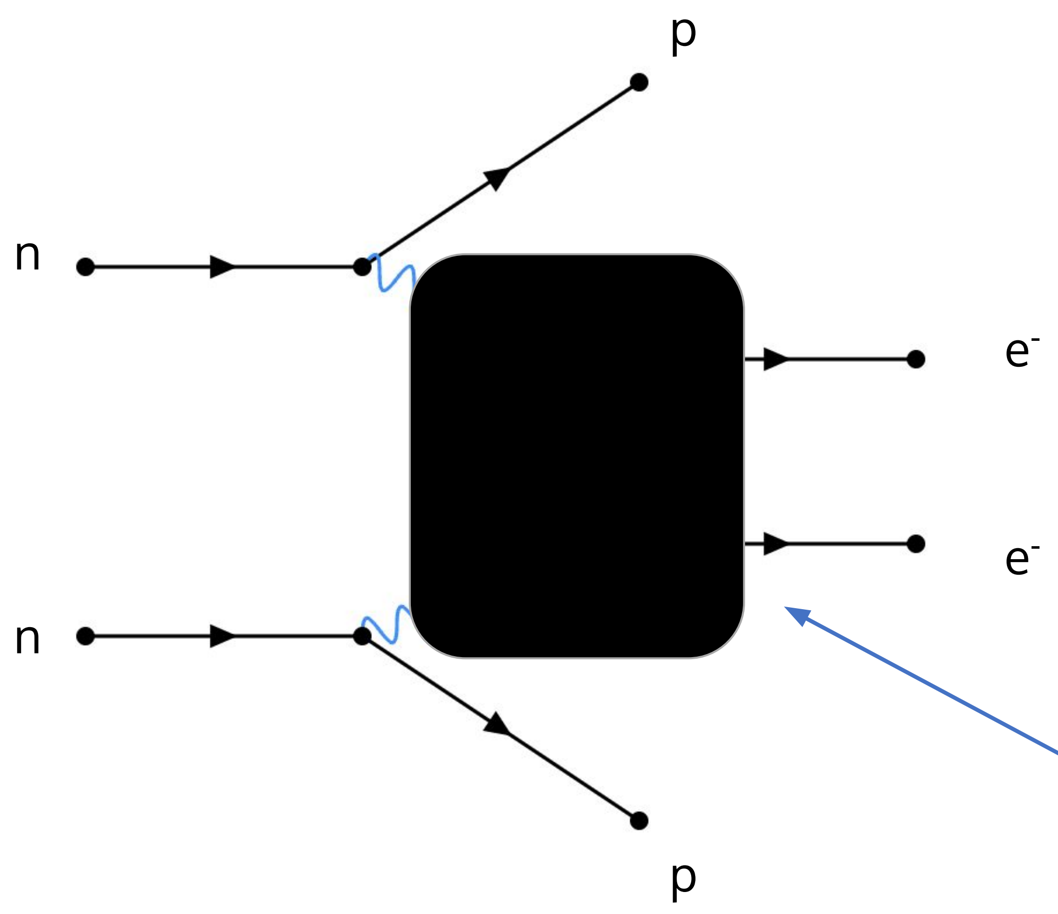
How would $0\nu\beta\beta$ even work?



Light Majorana neutrino exchange?

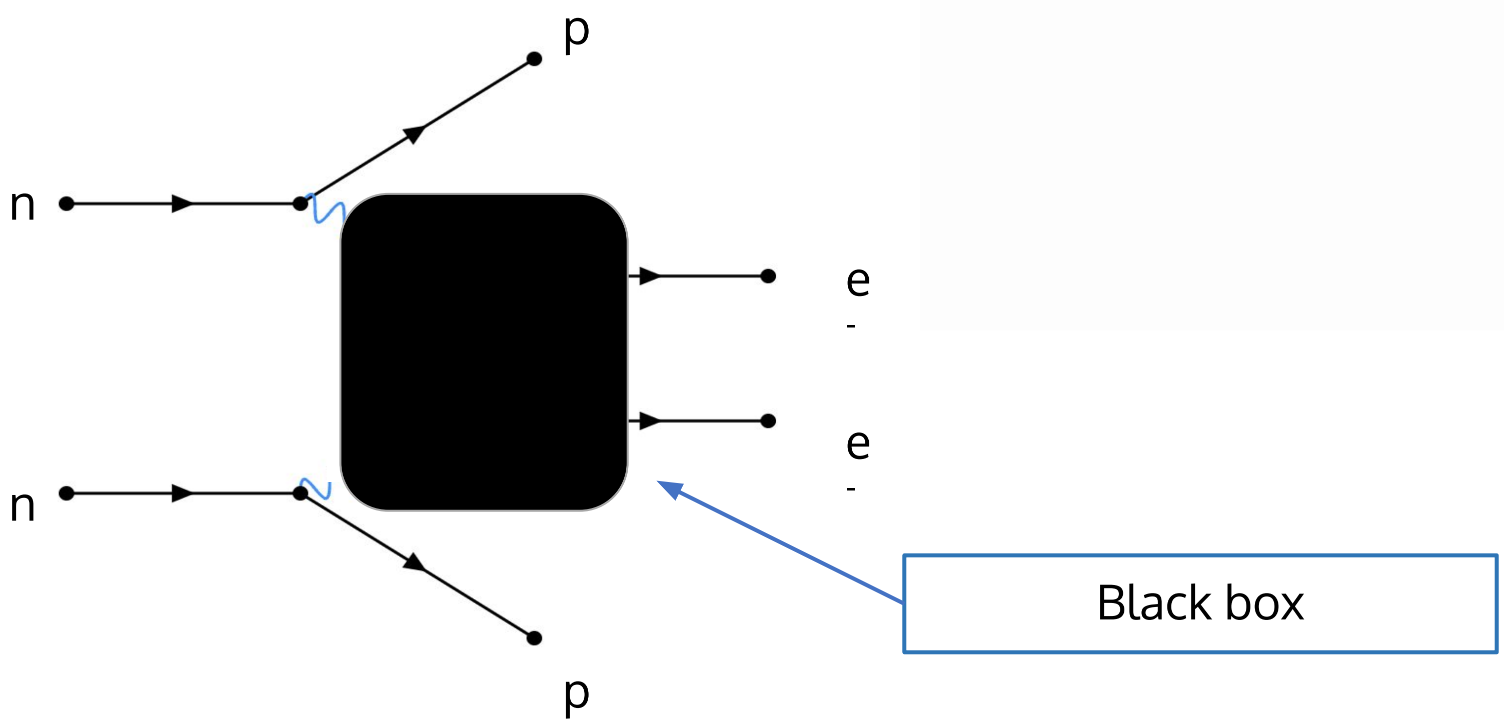
How would 0νββ even work?



Some other mechanism?

The Black Box Theorem

Searching for 0νββ: The Black Box



Regardless of what mechanism $0\nu\beta\beta$ proceeds by, it always implies new physics

(Schechter, and Valle. Phys. Rev. D 25.11 (1982): 2951. "black box theorem")

Searching for $0\nu\beta\beta$: The Real Motivation

Particle physics community searching for physics beyond the standard model

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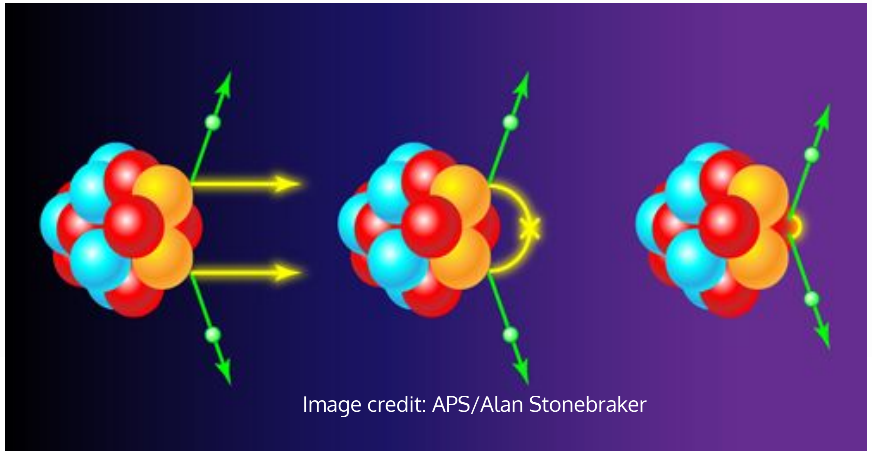
Why Search for $0\nu\beta\beta$?

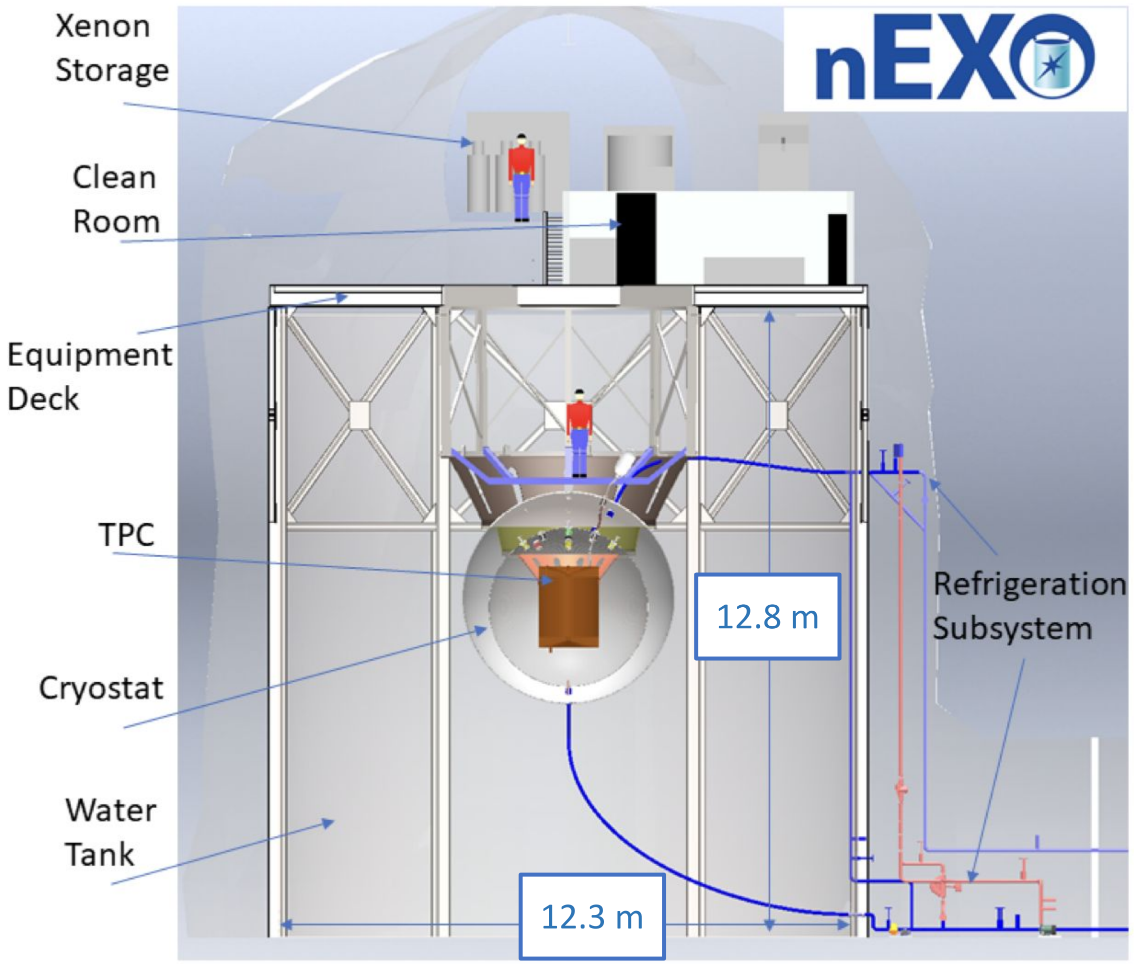
- The discovery of neutrino mass from oscillation experiments provides **new pathways to mass generation** in the SM
  - Dirac vs Majorana masses
  - feeble couplings to Higgs field vs seesaw mechanisms
- Implications for **matter-antimatter asymmetry problem**
- Neutrinoless double beta decay ($0\nu\beta\beta$) **exploits the nucleus as a virtual environment to probe high energy physics** processes



Searches for neutrinoless double beta decay ($0\nu\beta\beta$) are searches for Lepton Number Violation & Physics Beyond the Standard Model

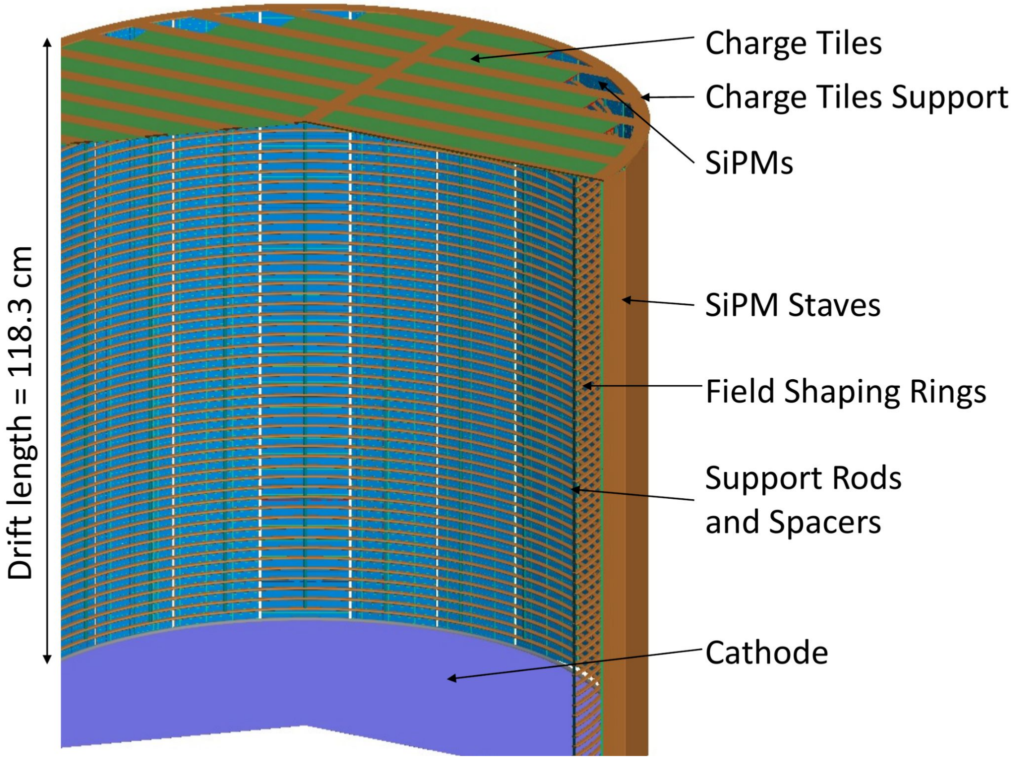
What is nEXO?

- 5-tonne single-phase liquid xenon Time Projection Chamber (**LXe TPC**)
- LXe is **enriched to 90% in the target isotope, ^{136}Xe**
- Extensive radio-assay program
    - ultra low backgrounds **validated by EXO-200 data**



nEXO: Distinguishing Features

- Homogeneous, dense, liquid detector medium with high-Z nucleus
  - online purification
  - self-shielding of γ radiation
  - scalability
- Multiparameter Analysis
- Possibility to tag daughter nucleus
- Possibility for control run in case of discovery



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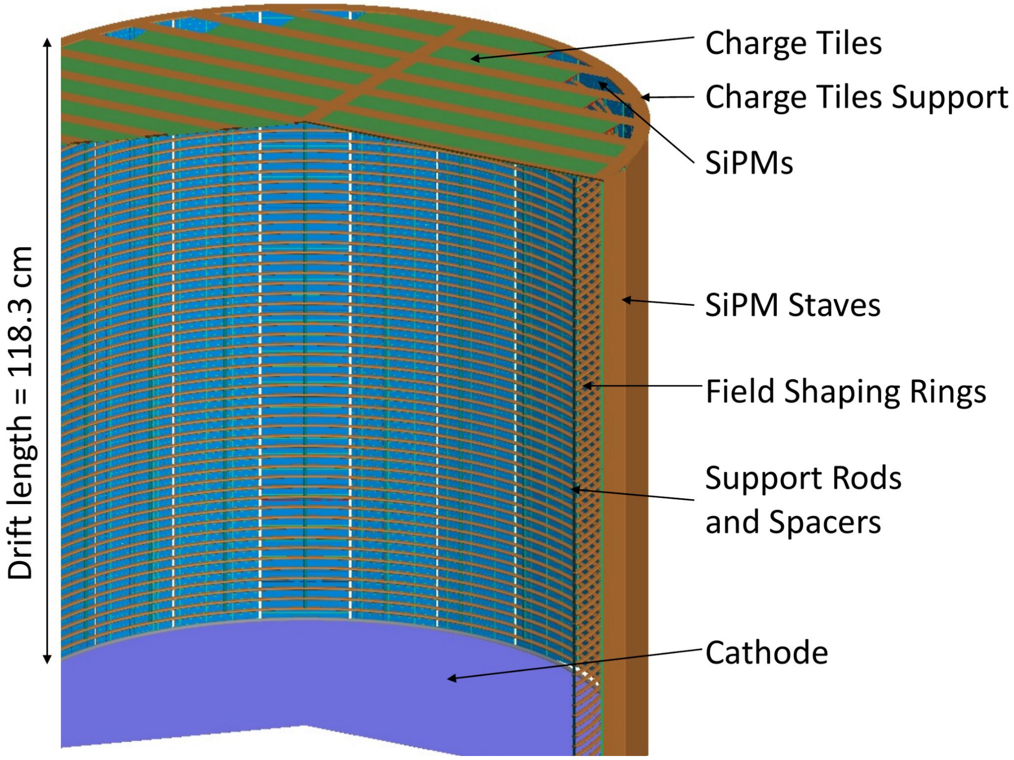

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  - Nature 569, no. 7755 (2019): 203-207
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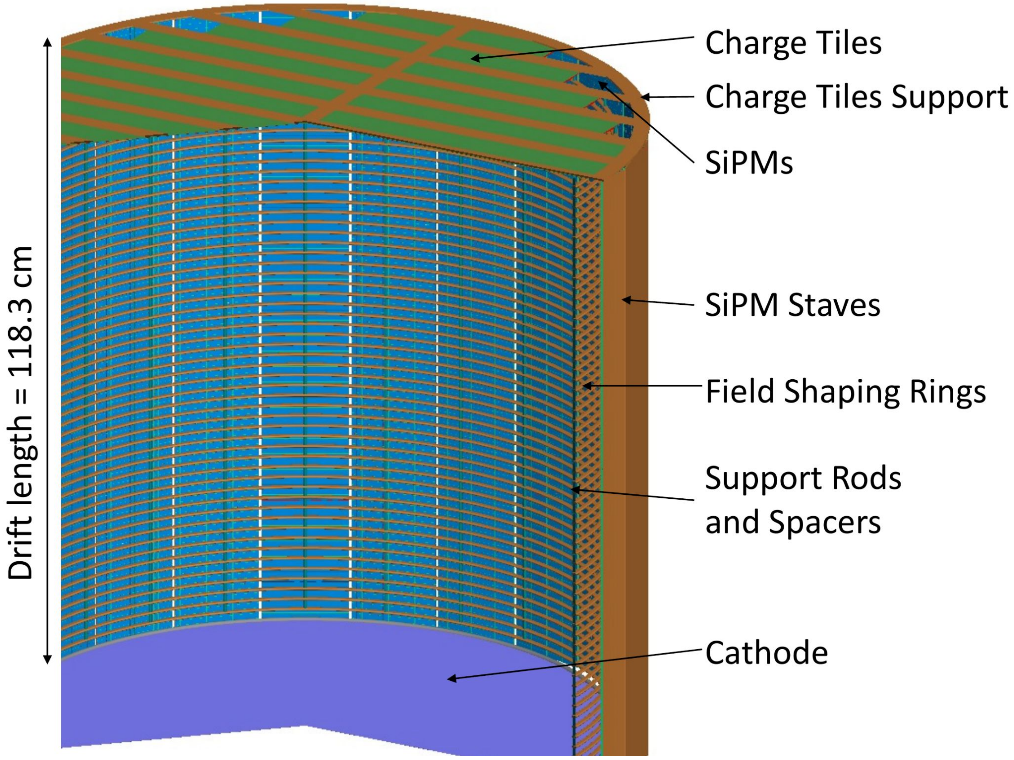

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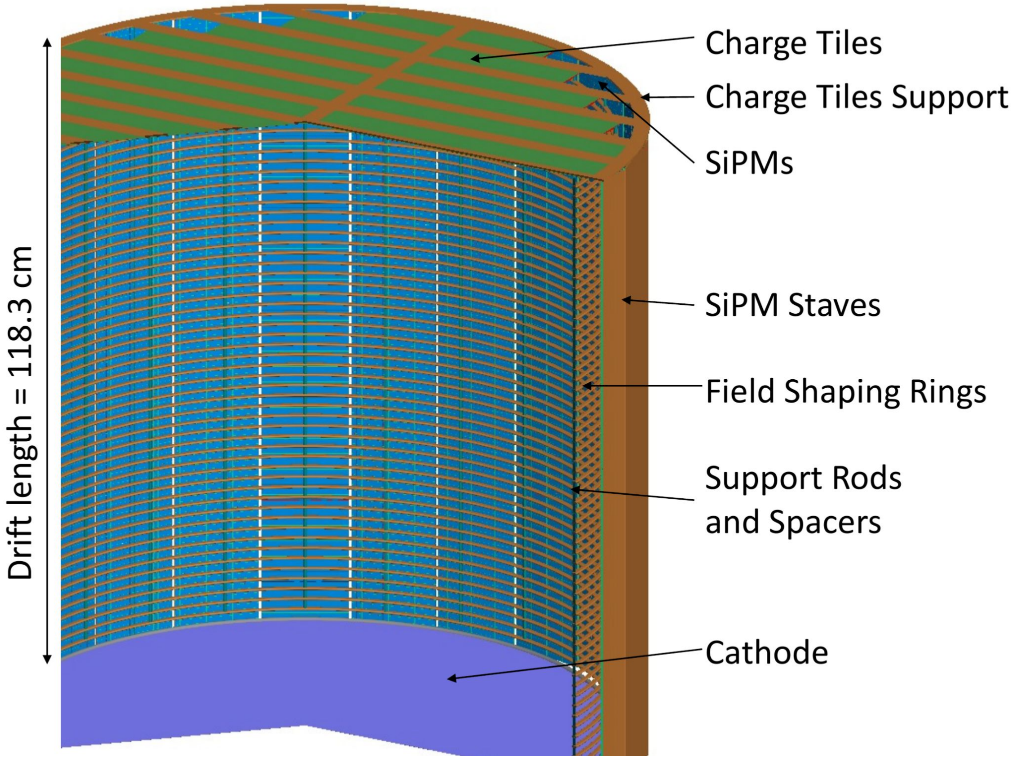
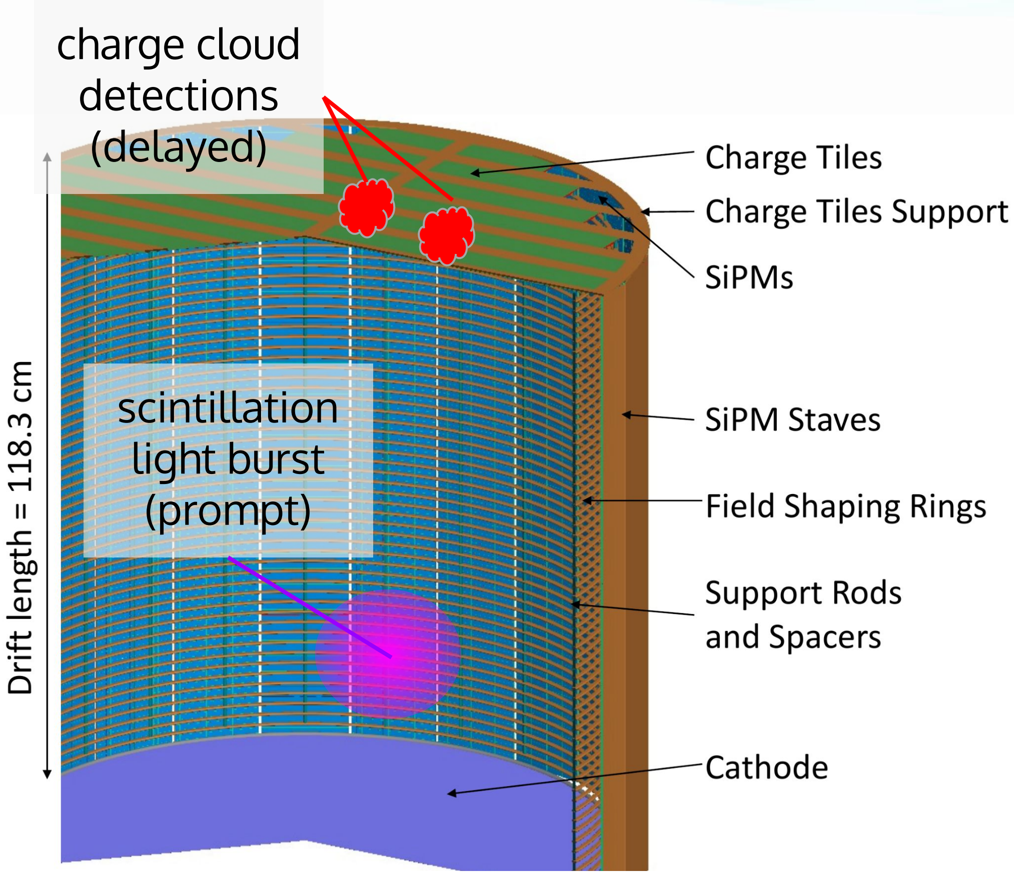
  - Nature 569, no. 7755 (2019): 203-207
- Possibility for control run in case of discovery
  - use unenriched xenon & repeat the experiment!

… and the ability to go to a GXe TPC and study $0\nu\beta\beta$ mechanism if discovered.



How does nEXO's TPC work?

- Energy deposits in the LXe liberate electrons, ionize the surrounding liquid
  - excited dimers Xe_2 release ~175 nm scintillation light
  - ionization clouds drift to segmented anode in applied E-field
- Combination of light + charge readout gives us...



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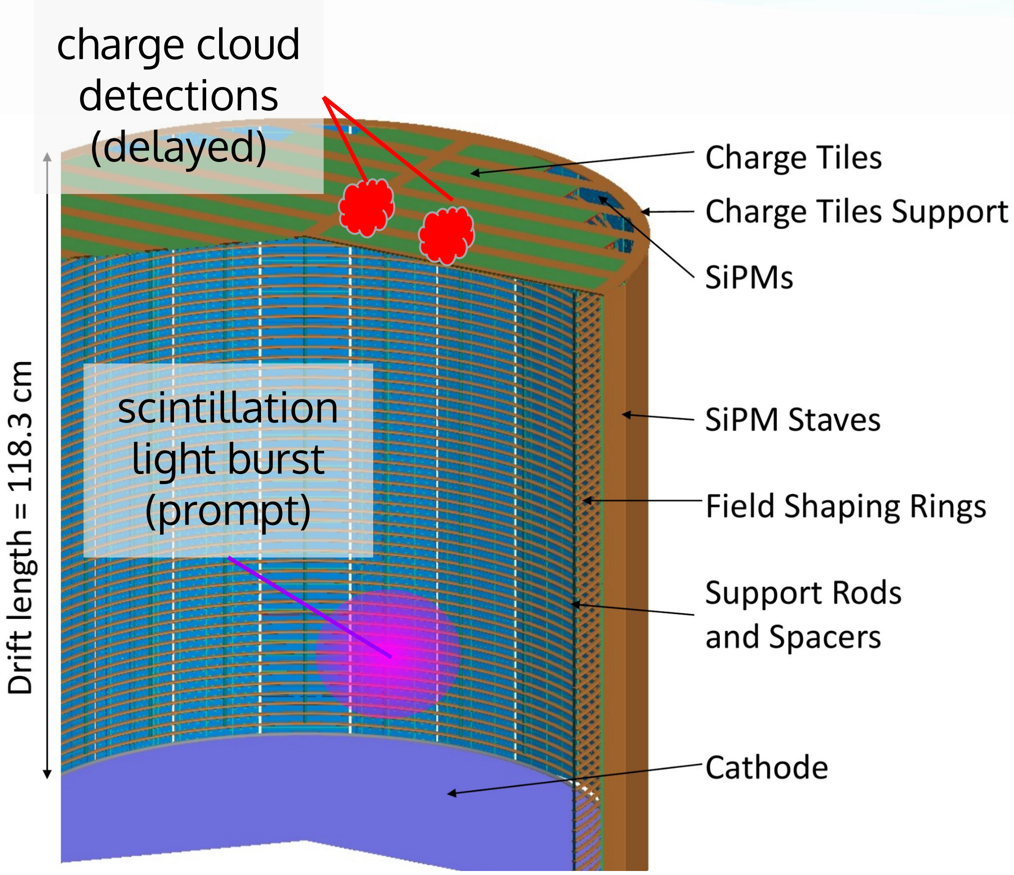
  - Improved energy resolution
  - Improved spatial positioning (event localization)
  - Discriminator between α, β and γ events



An Active R&D Program
Hardware?

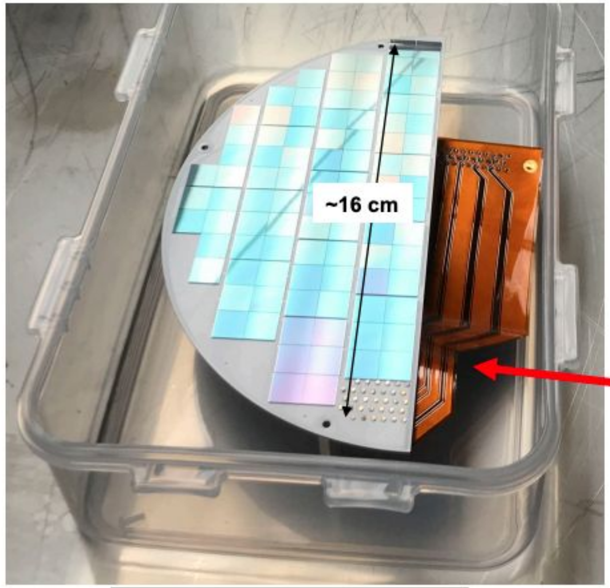
Basic principles and backgrounds

validated and measured by EXO-200

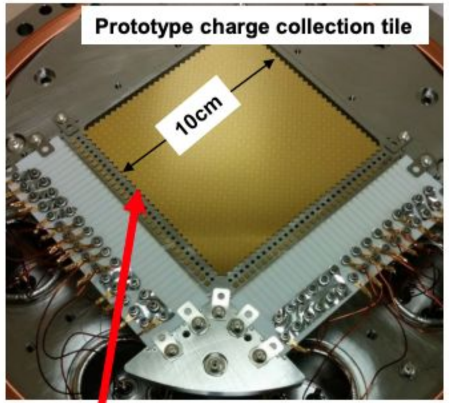
nEXO upgrades from EXO-200 include

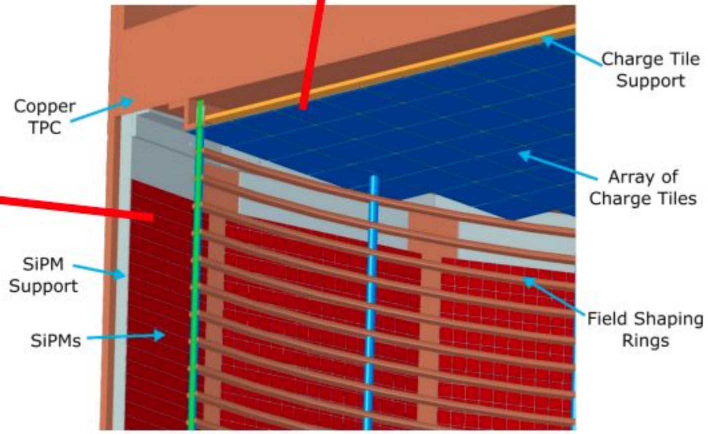
- use of SiPMs
- custom made charge tiles
- electroformed copper for TPC
- water-Cherenkov muon veto

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



Prototype VUV SiPM array (FBK)





Many Canadian Contributions

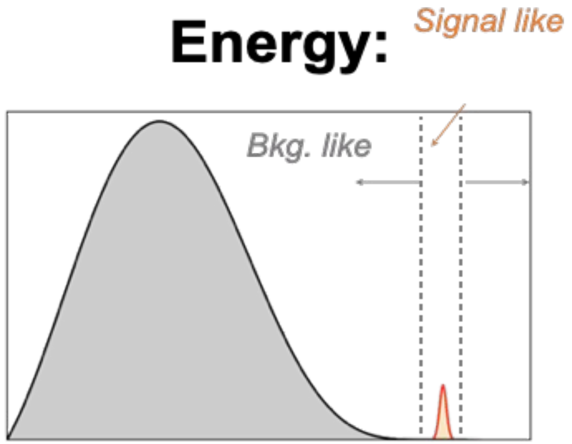
- **SiPM use in liquid xenon** environments (LOLX experiment)
  - see talk by S. Bron & poster by L. Rudolph
- **Characterization & stability of SiPMs**
  - see talk by L. Darroch
- **water-Cherenkov Outer Detector** & radiation shield
  - see talk by S. Majidi
- R&D toward **potential Ba-tagging upgrade**
  - see talks by H. Rasiwala, D. Ray, R. Collister
- Many **Equity Diversity & Inclusion** activities
  - see talk from E. Caden

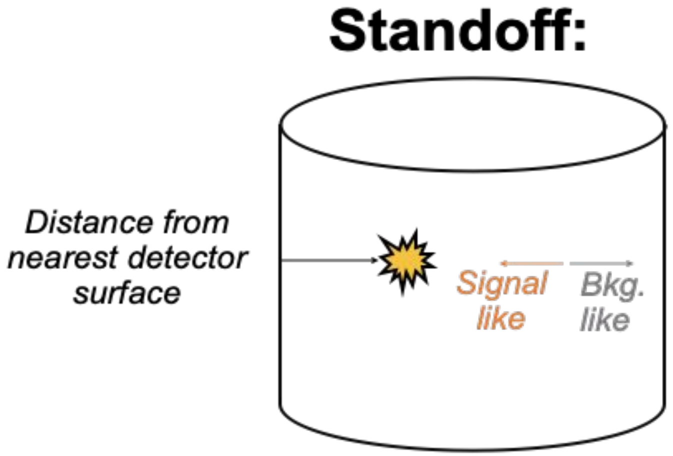
Multiparameter Analysis

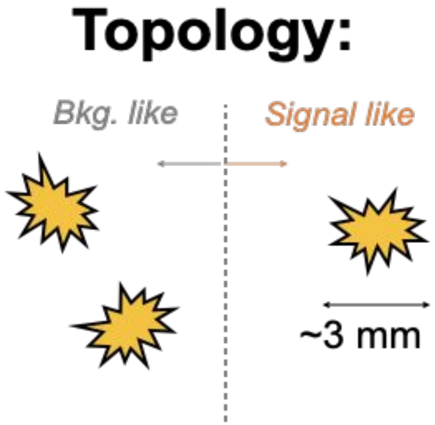
nEXO is not a counting experiment

Three high-level variables:

- ~1% **Energy** resolution at $Q_{\beta\beta}$
- **Standoff** distance to detector components (precise event localization, **depth in xenon**)
- **Topology** score (DNN): single- and multi-site discrimination (β-like vs γ-like event separation)

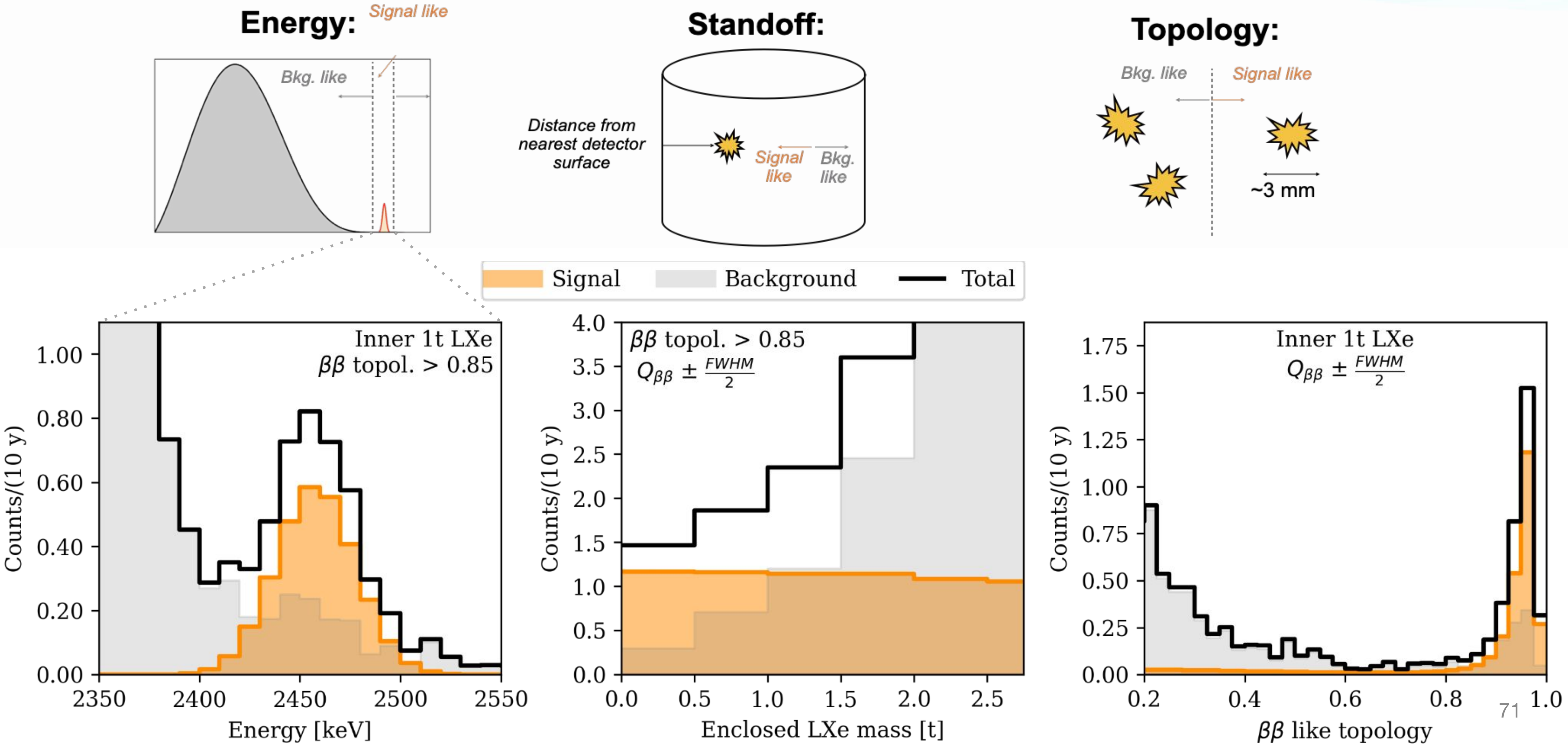






Multiparameter Analysis

A 3D Parameter Space



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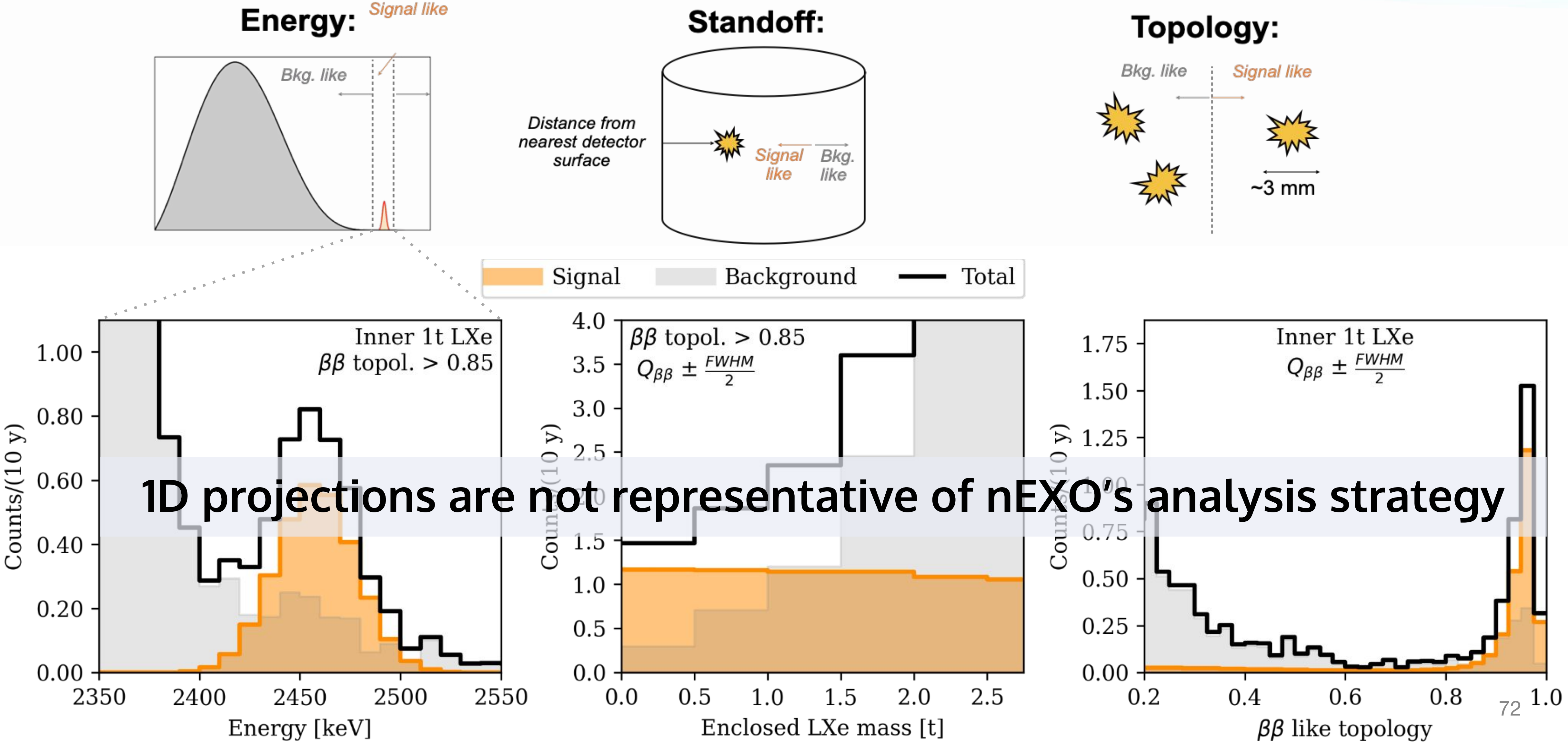
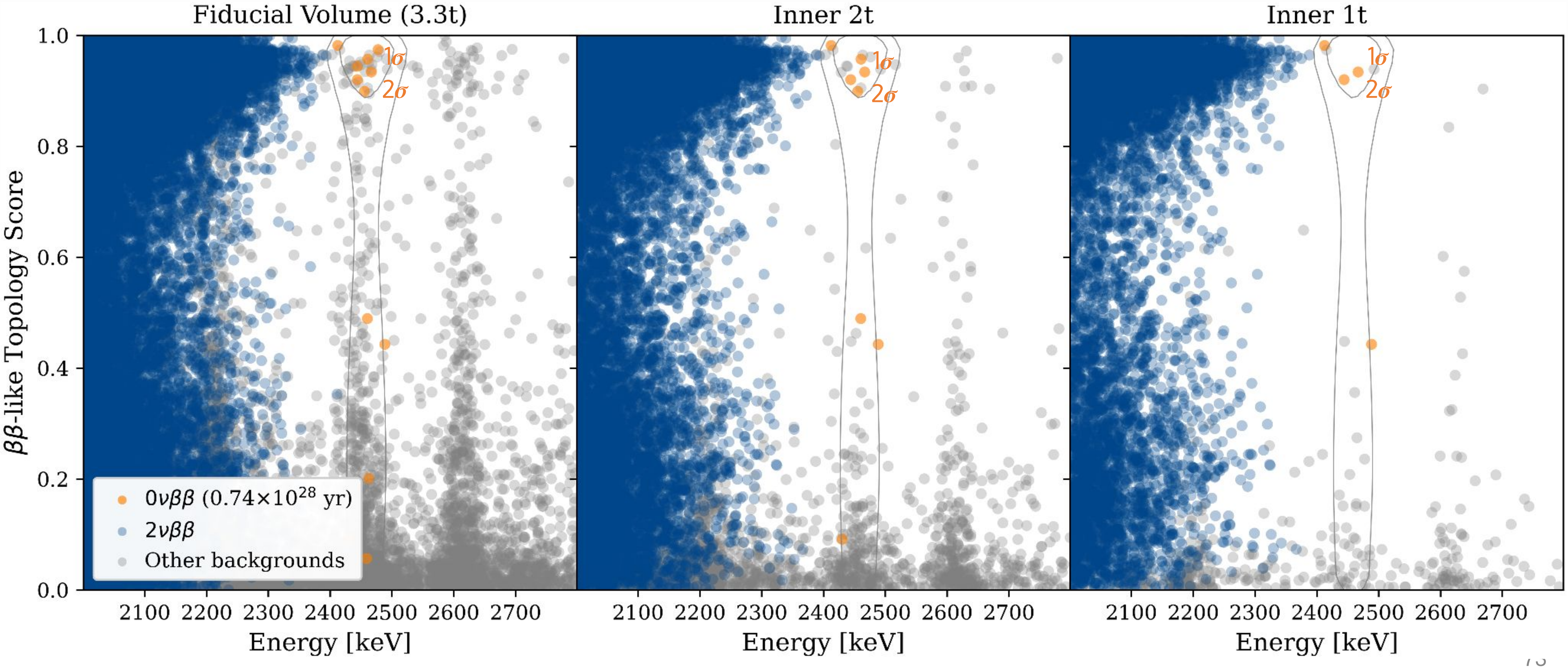


1D projections are not representative of nEXO's analysis strategy

Multiparameter Analysis
What will nEXO data look like?

- Below: realizations of nEXO 10 yr dataset at 7.4x10^{27} yr half life(3σ discovery potential)



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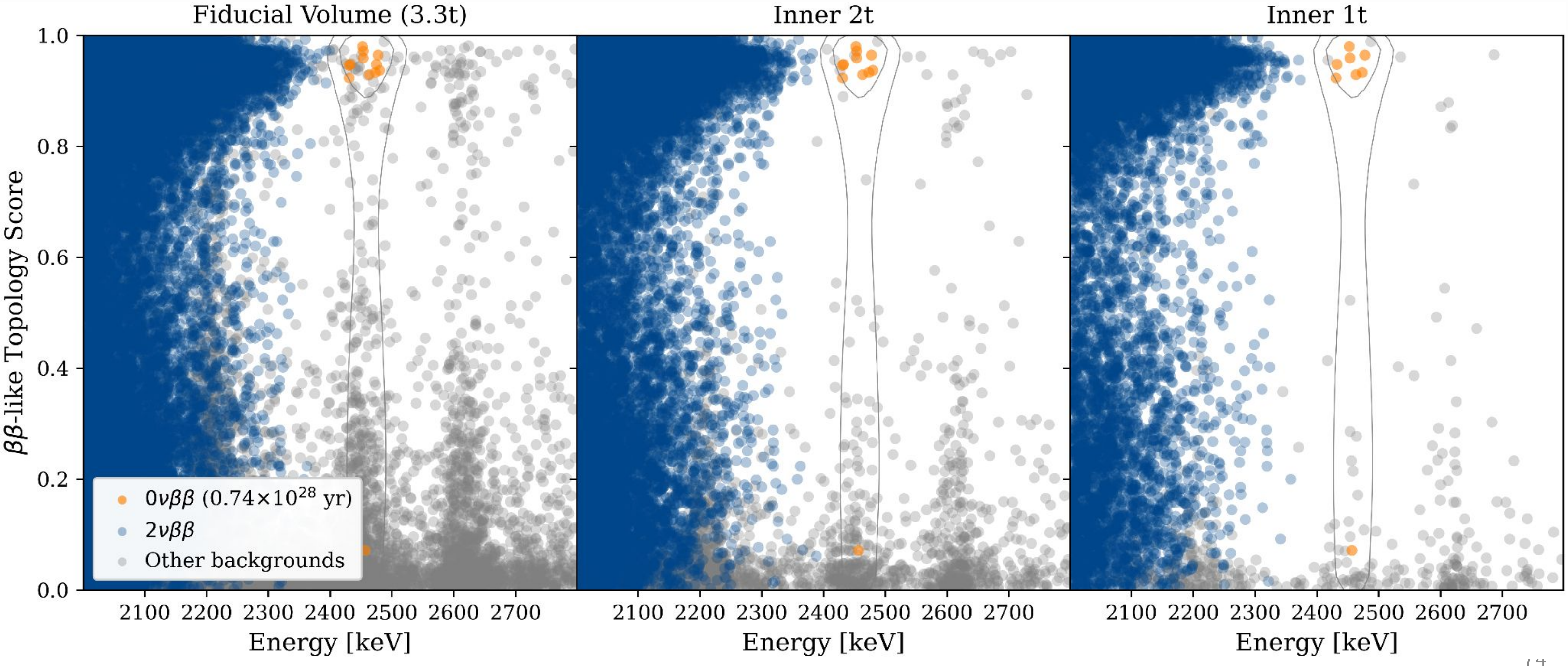
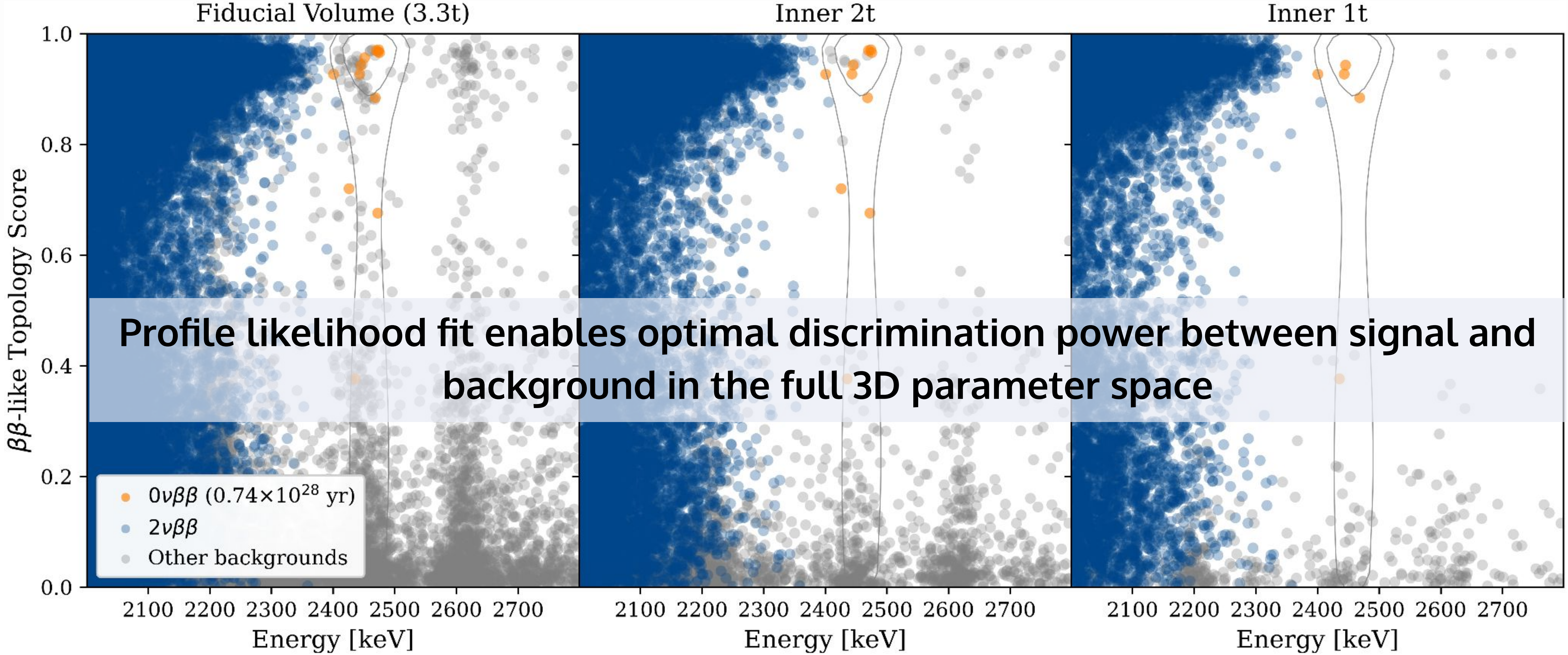


Multiparameter Analysis

3D profile likelihood fit: ultimate test of $0\nu\beta\beta$ hypothesis

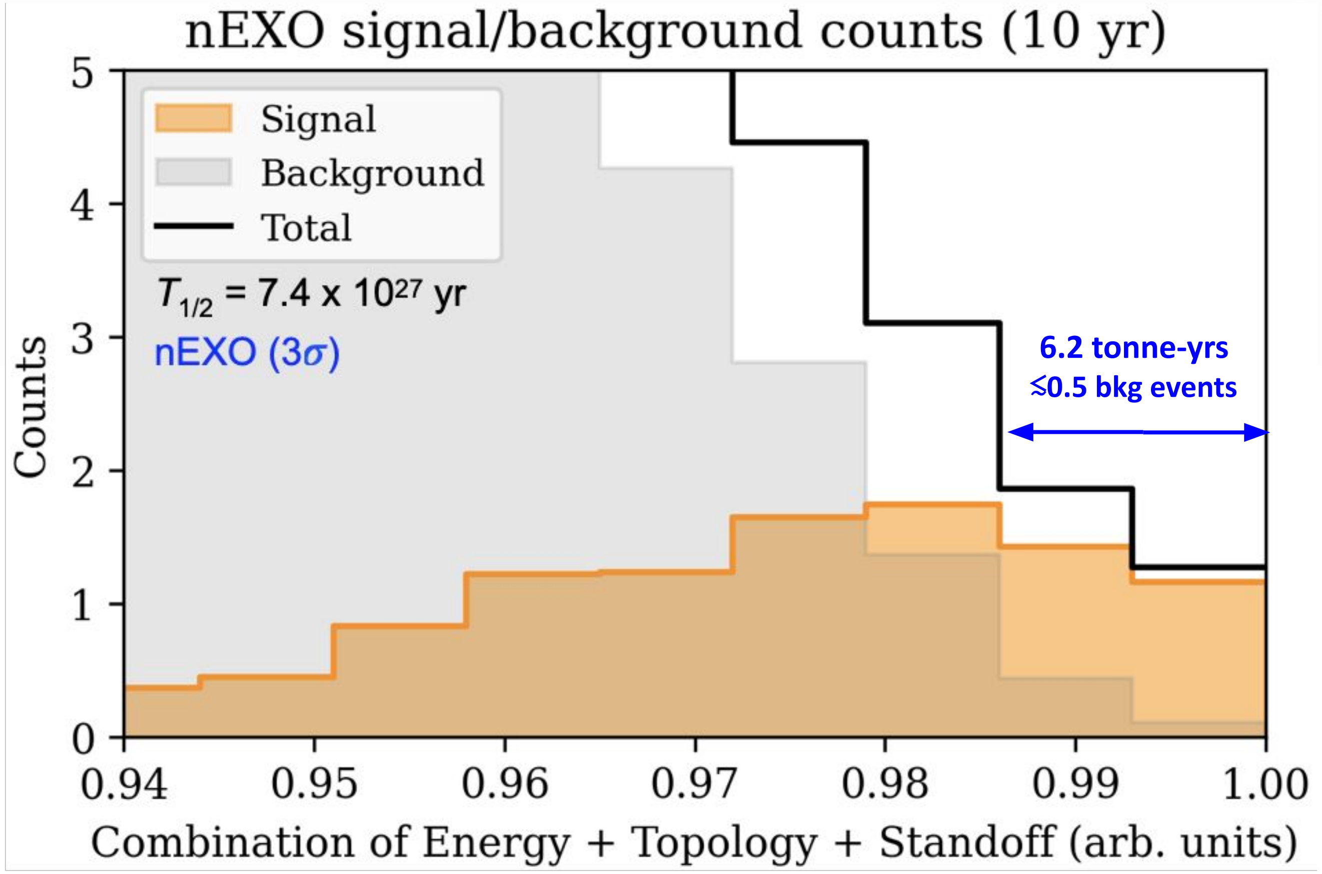


Profile likelihood fit enables optimal discrimination power between signal and background in the full 3D parameter space

Multiparameter Analysis

3D⟶ 1D visualization

Arranging the 3D bins into 1D, ordered by signal-to-background ratio, helps **visualize the signal and background separation** in nEXO

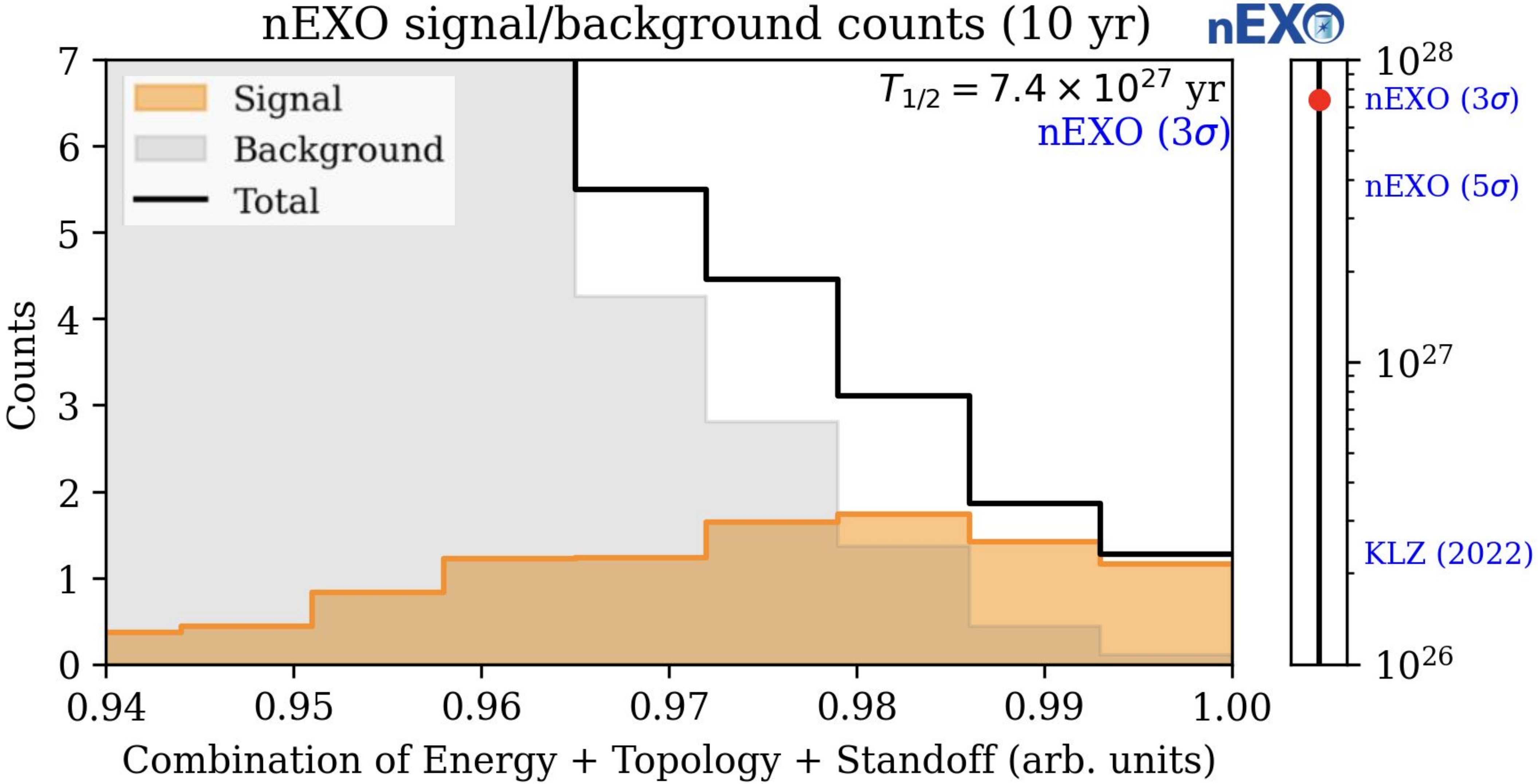


0 ← Background-like

Signal-like → 1

Multiparameter Analysis

3D⟶ 1D visualization



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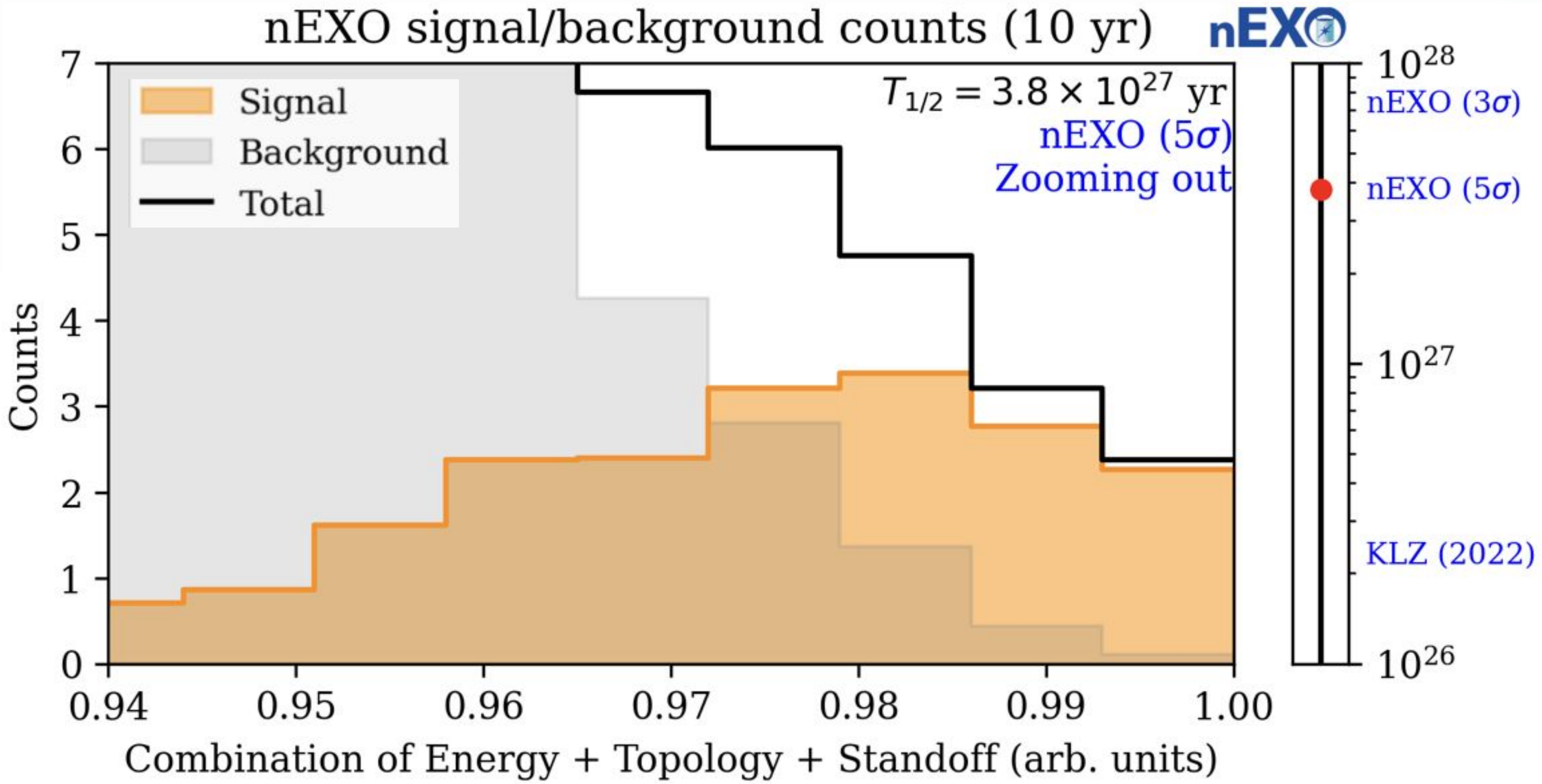

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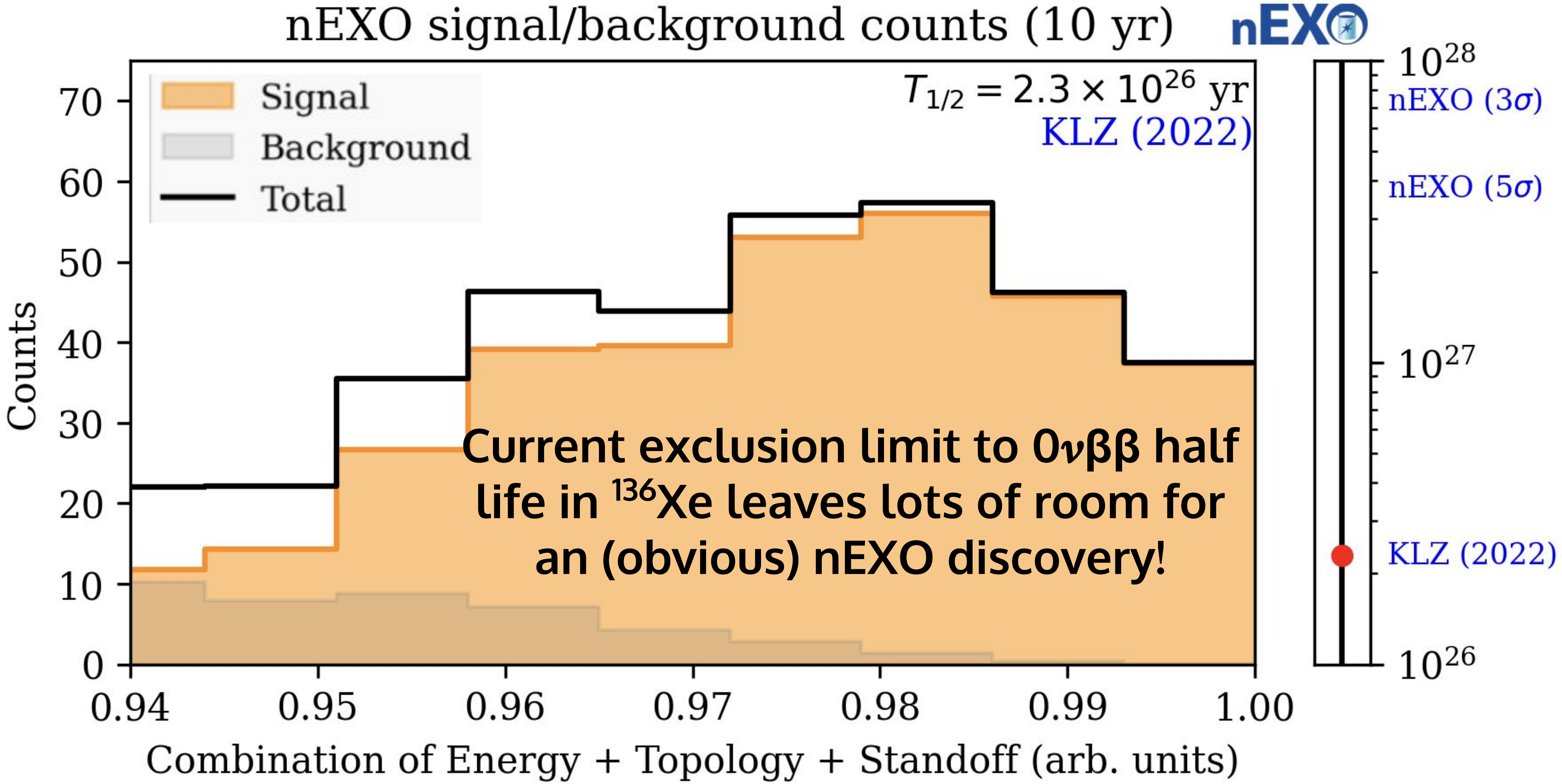
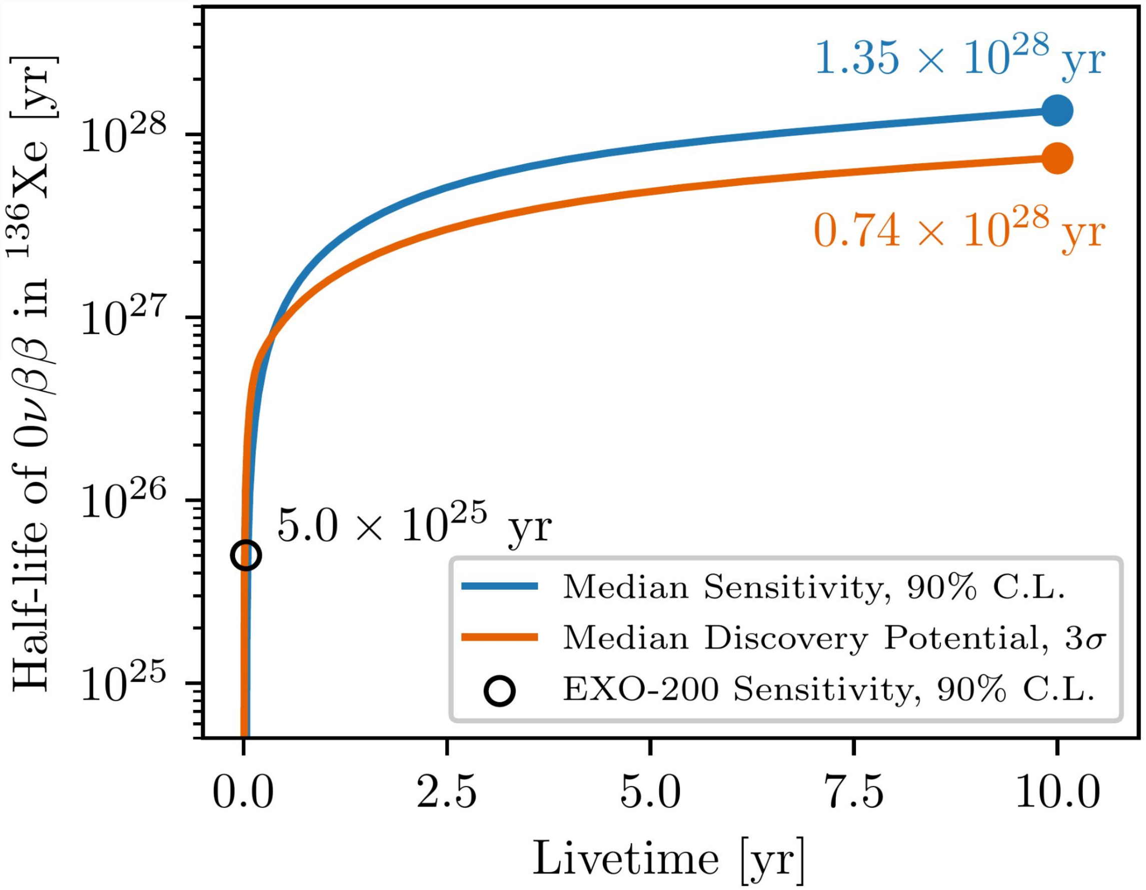


KLZ exclusion limit: https://doi.org/10.1103/PhysRevLett.130.051801

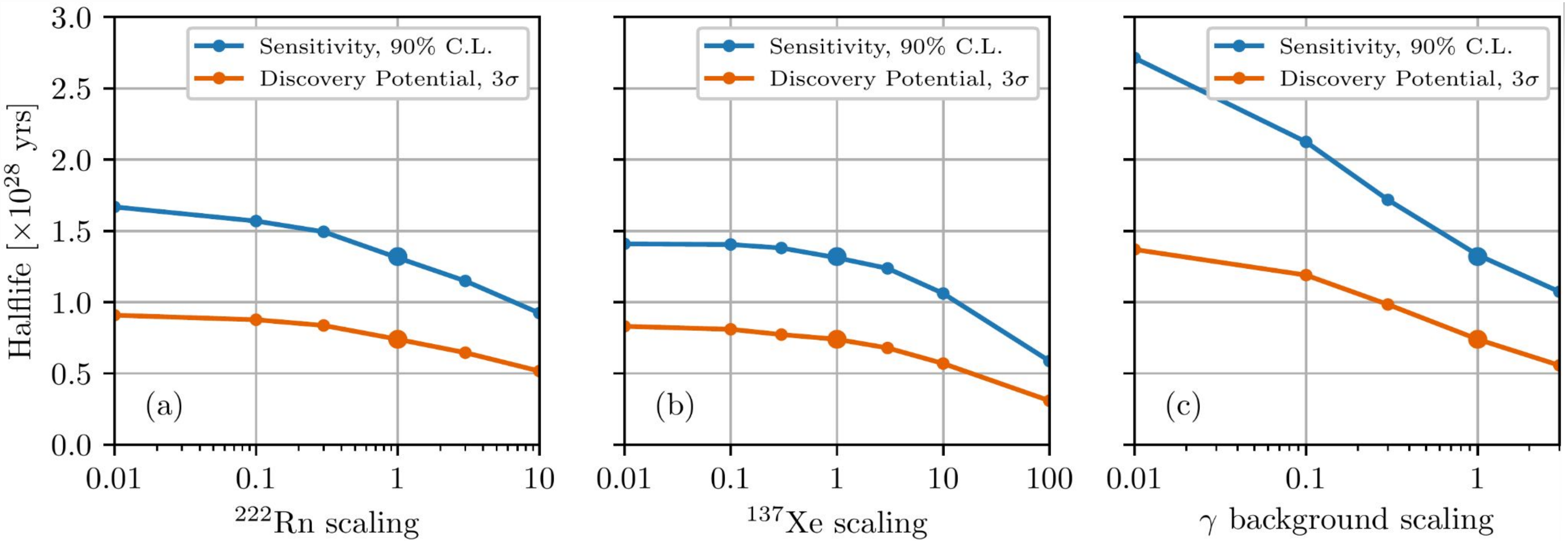
nEXO Sensitivity

Ultimate Goal of 1.35×10^{28} yr half life

- In 6.5 years of data, nEXO will reach a exclusion **sensitivity to $0\nu\beta\beta$ half life in xenon >10^{28} years** (90% C.L.)
  - Age of the universe $\times 10^{18}$!



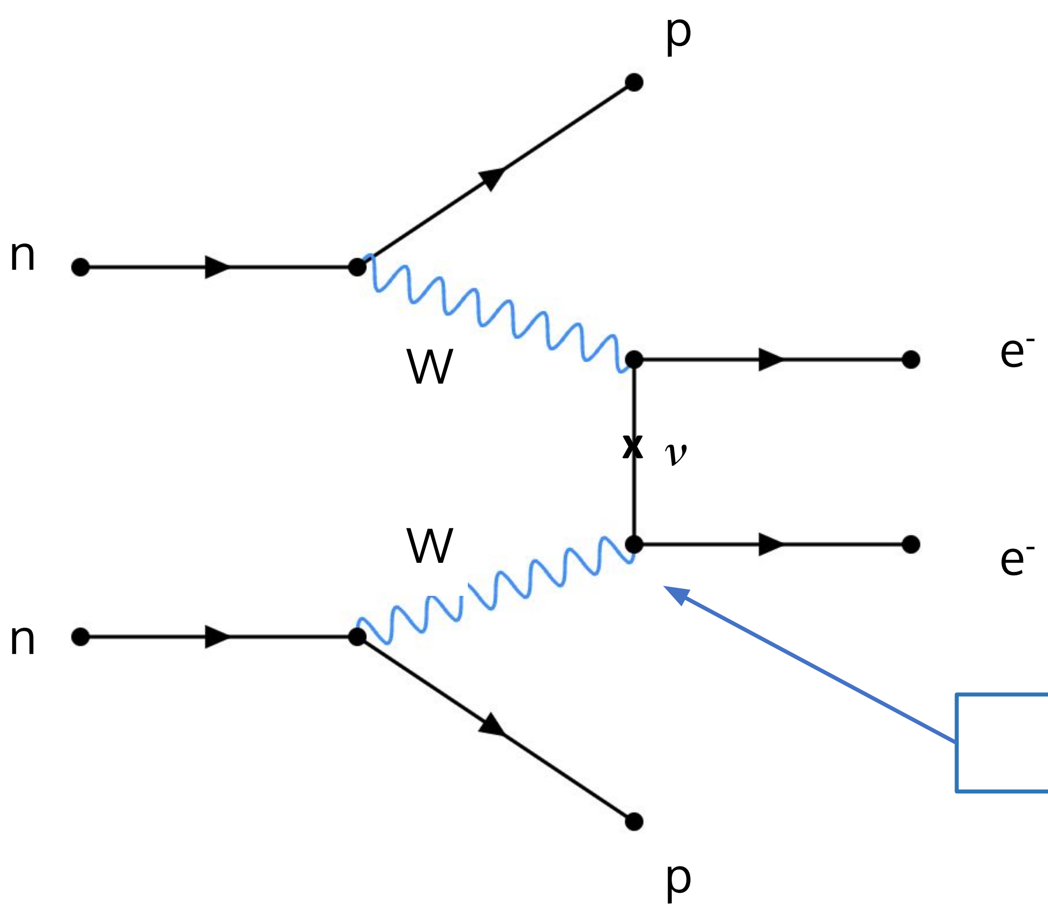
nEXO Sensitivity Robustness



Confidence in the sensitivity estimate arises from a detailed conservative model with measured input parameters

G Adhikari et al. (nEXO Collaboration), 2022 J. Phys. G: Nucl. Part. Phys. 49 015104

A Neutrino Mass Measurement?



Light Majorana neutrino exchange

nEXO Sensitivity

Neutrino Mass Measurement

- **Half lives of 0νββ correspond to an effective Majorana mass** of the electron neutrino **<m$_{\beta\beta}$>**
  - combination of 3 neutrino mass states
  - **Assumes dominant process for 0νββ is light-Majorana neutrino exchange**
- <m$_{\beta\beta}$> is isotope-independent

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

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

The PMNS matrix relates flavour and mass eigenstates of neutrinos

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The PMNS matrix relates flavour and mass eigenstates of neutrinos

nEXO Sensitivity
Neutrino Mass Measurement

- Half lives of $0\nu\beta\beta$ correspond to an effective Majorana mass of the electron neutrino $\langle m_{\beta\beta} \rangle$
- $\langle m_{\beta\beta} \rangle$ is isotope-independent
  - BUT: depends on your choice nuclear matrix element (NME) when converting from a half life measurement to neutrino mass, **NME is least constrained theoretical parameter below**

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

Phase space factor ($G^{0\nu}$)
J. Kotila and F. Iachello, Phys Rev C 85, 034316 (2012)

Axial coupling, $g_A = 1.27$

Nuclear Matrix Element (NME)

nEXO Sensitivity

Neutrino Mass Measurement

- Half lives of $0\nu\beta\beta$ correspond to an effective Majorana mass of the electron neutrino $<m_{\beta\beta}>$
- $<m_{\beta\beta}>$ is isotope-independent
  - Depends on your choice nuclear matrix element (NME) when converting from a half life measurement to neutrino mass, **NME is least constrained theoretical parameter below**
  - Complex nuclear physics could change $<m_{\beta\beta}>$ estimates ⟶ **we need to search for $0\nu\beta\beta$ in multiple isotopes**

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

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Axial coupling, $g_A = 1.27$

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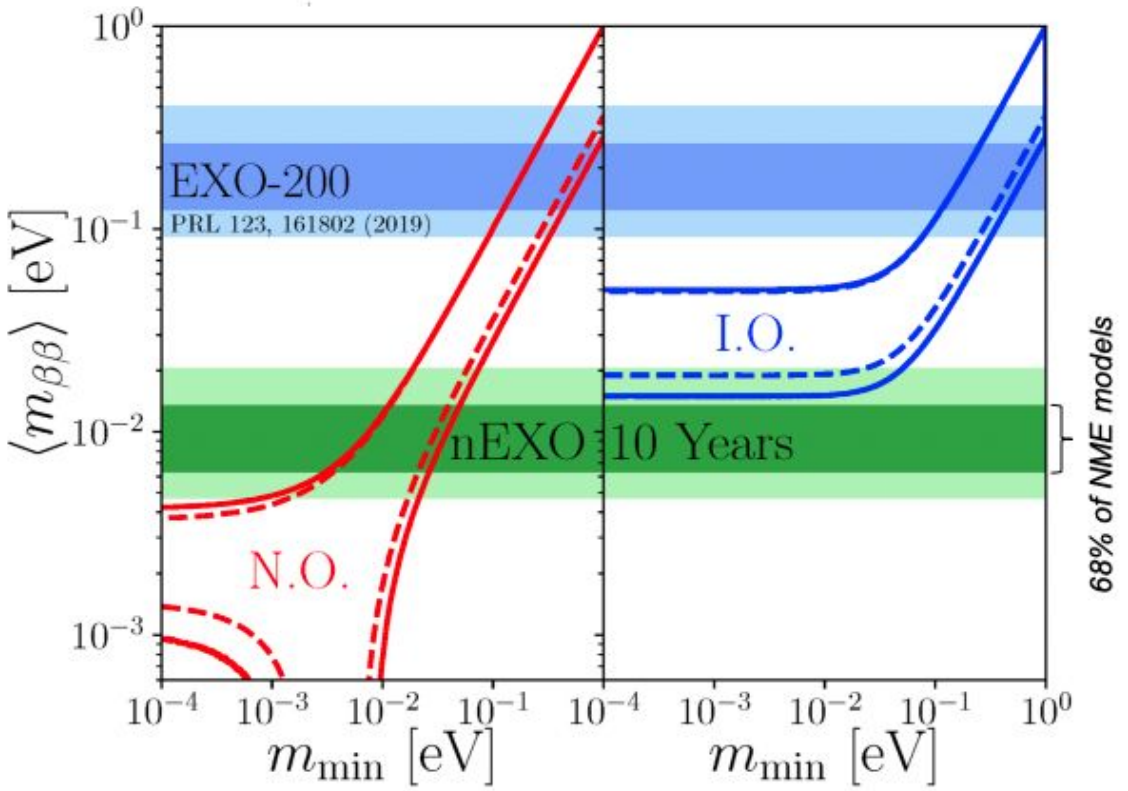
nEXO Sensitivity

Neutrino Mass Measurement

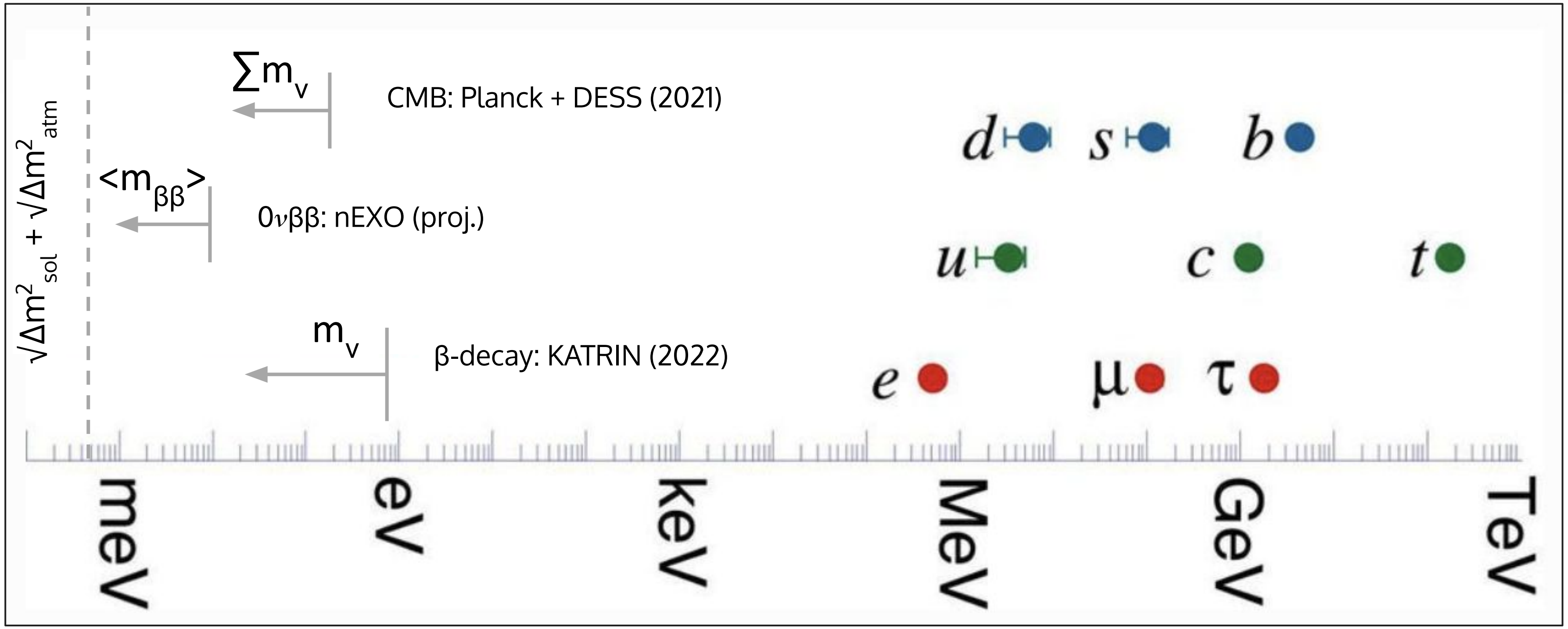
- In 6.5 years, **nEXO will reach a sensitivity to $0\nu\beta\beta$ half life in xenon $>10^{28}$ years**
  - Age of the universe x 10^{18} !
- **Effective Majorana mass of the neutrino ≲8 meV**; excludes inverted mass ordering parameter space



nEXO sensitivity to neutrino mass $<m_{\beta\beta}>$

a neutrino mass measurement in an exciting time!

- In 6.5 years, **nEXO will reach a sensitivity to 0νββ half life in xenon >10^{28} years**
- **Effective Majorana mass of the neutrino ≲8 meV**



Standard Model Fermion masses / HITOSHI MURAYAMA (adapted)

Summary

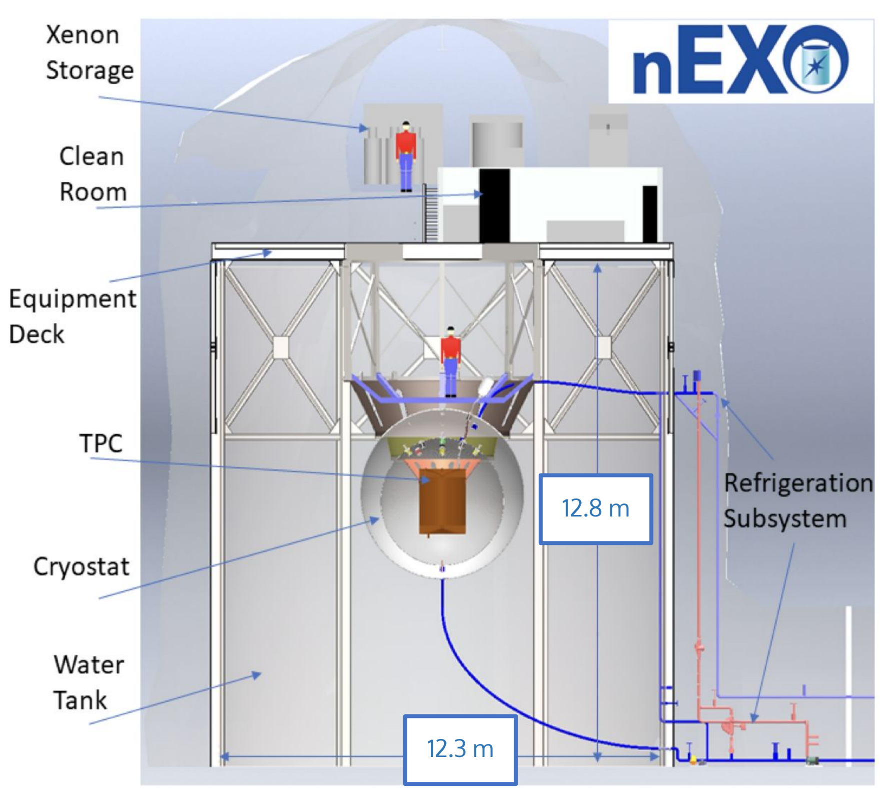
nEXO is **searching for Lepton Number Violation via 0νββ in ^{136}Xe**

A **multiparameter likelihood fit maximizes the physics reach of nEXO** and **significantly reduces the probability of false-positives**

Several **upgrades to nEXO are possible in case of a 0νββ discovery** (depleted xenon control run, ^{136}Ba tagging)

Obvious pathway to exploring 0νββ mechanisms post-discovery (GXe TPCs)

We live in a very exciting time for fundamental/neutrino physics!



Thank you!

Ask me about nEXO Diversity Equity & Inclusion Activities:

- Mentorship program
- Climate surveys
- Outreach

Follow us!
@nEXOexperiment

soud.alkharusi@mail.mcgill.ca

https://www.physics.mcgill.ca/~soudal/

Thank you!

nEXO

nEXO Publications:

2022:

- Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO
- Development of a 127Xe calibration source for nEXO

2021:

- nEXO: neutrinoless double beta decay search beyond 1028 year half-life sensitivity
- Reflectivity of VUV-sensitive silicon photomultipliers in liquid Xenon
- Event reconstruction in a liquid xenon Time Projection Chamber with an optically-open field cage

2020:

- Reflectance of Silicon Photomultipliers at Vacuum Ultraviolet Wavelengths
- Measurements of electron transport in liquid and gas Xenon using a laser-driven photocathode

2019:

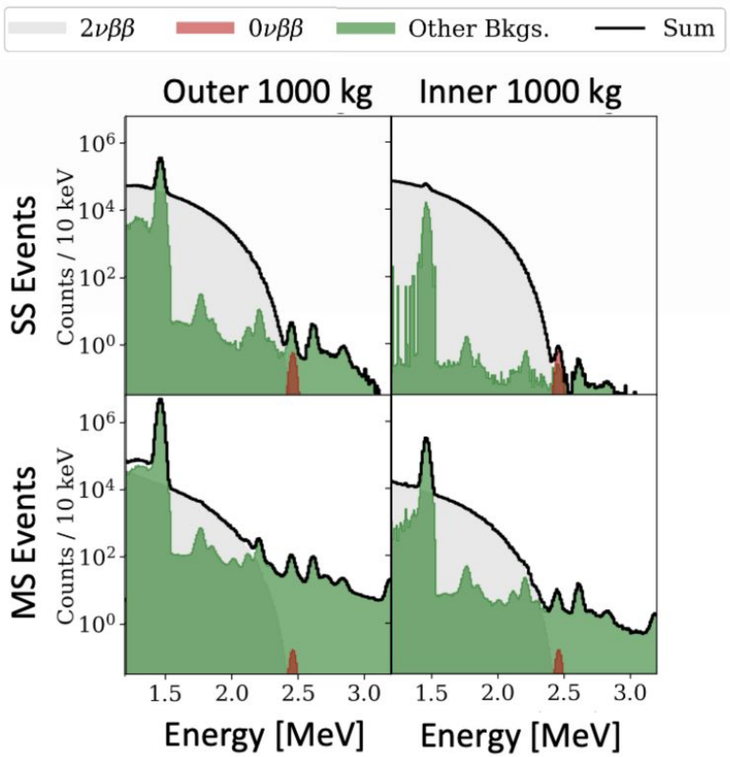
- Characterization of the Hamamatsu VUV4 MPPCs for nEXO
- Simulation of charge readout with segmented tiles in nEXO

2018

- nEXO pre-conceptual design report

Unknown external background?

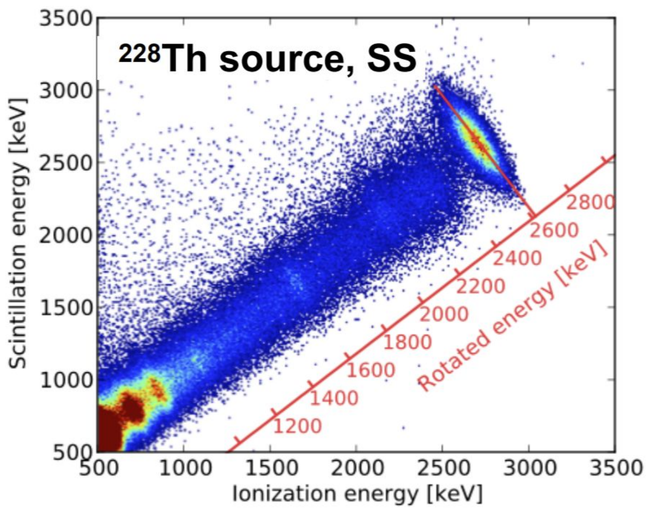
If an unknown decay were strong enough to produce as many SS events in the inner 3000 kg as a 3σ discovery at a half-life of 5.7×10^{27} yr, this decay would produce 271 counts in the MS outer volume, enough to rule out the expected background model at $p < 0.00001$.

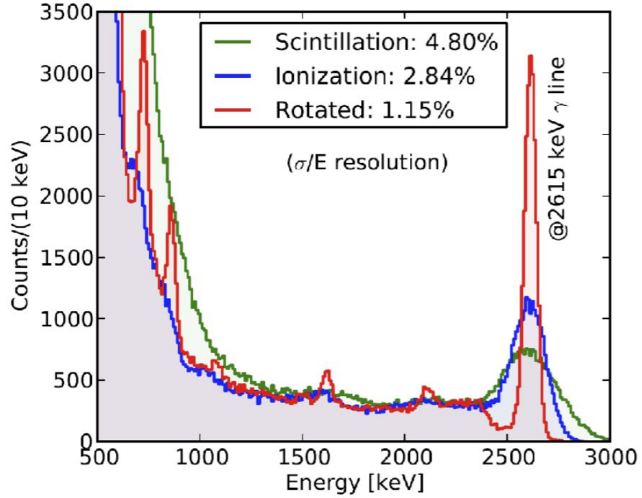


Phys. Rev.C 97, 065503 (2018)

Rotated energy scale

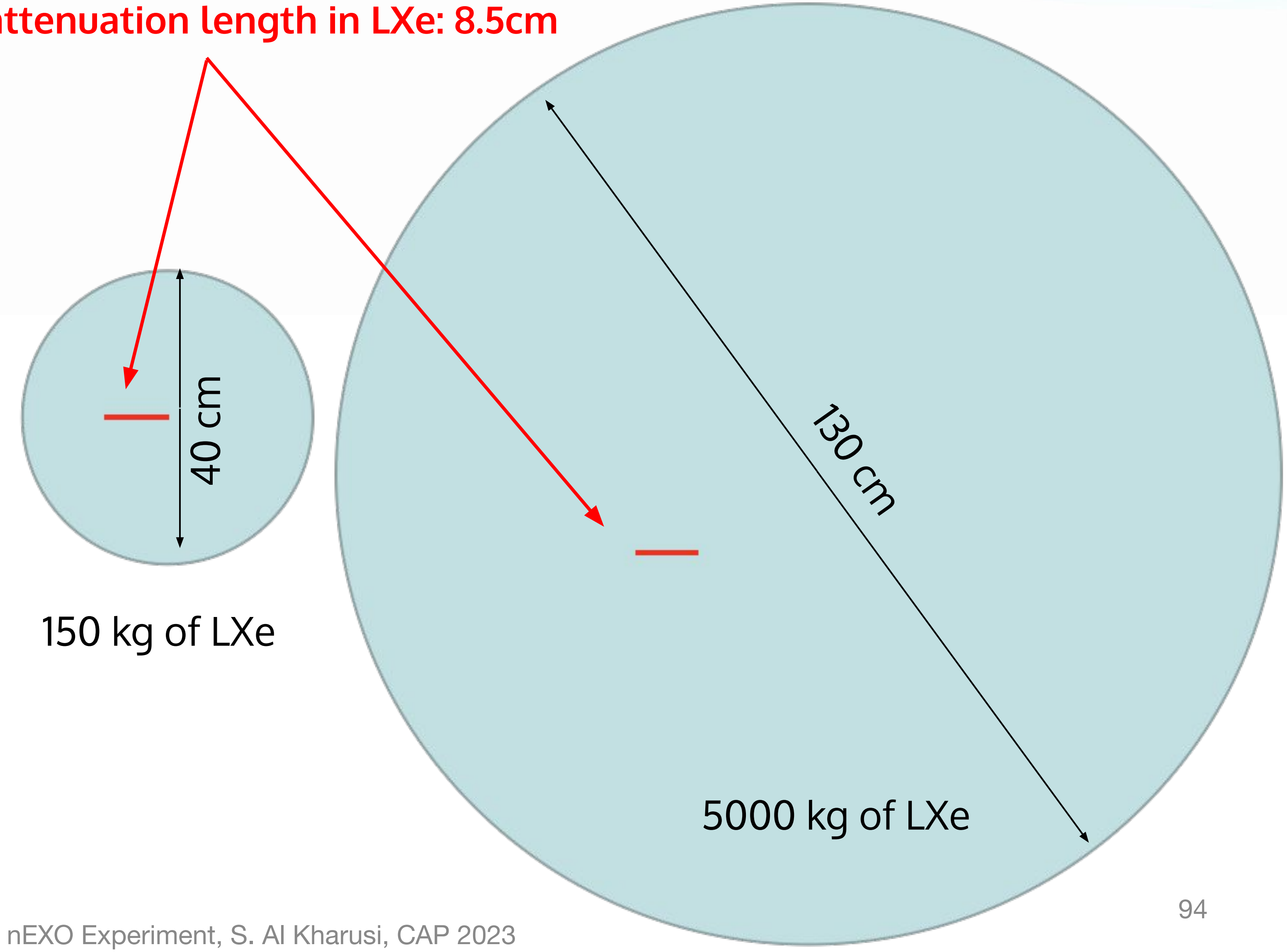
- LXe rotated energy (exploiting anticorrelation in charge and light) allows for optimization of energy resolution
  - Conti, E., et al. "Correlated fluctuations between luminescence and ionization in liquid xenon." Phys. Rev. B 68.5 (2003): 054201.
- 2022: LZ achieved <0.7% energy resolution in LXe!





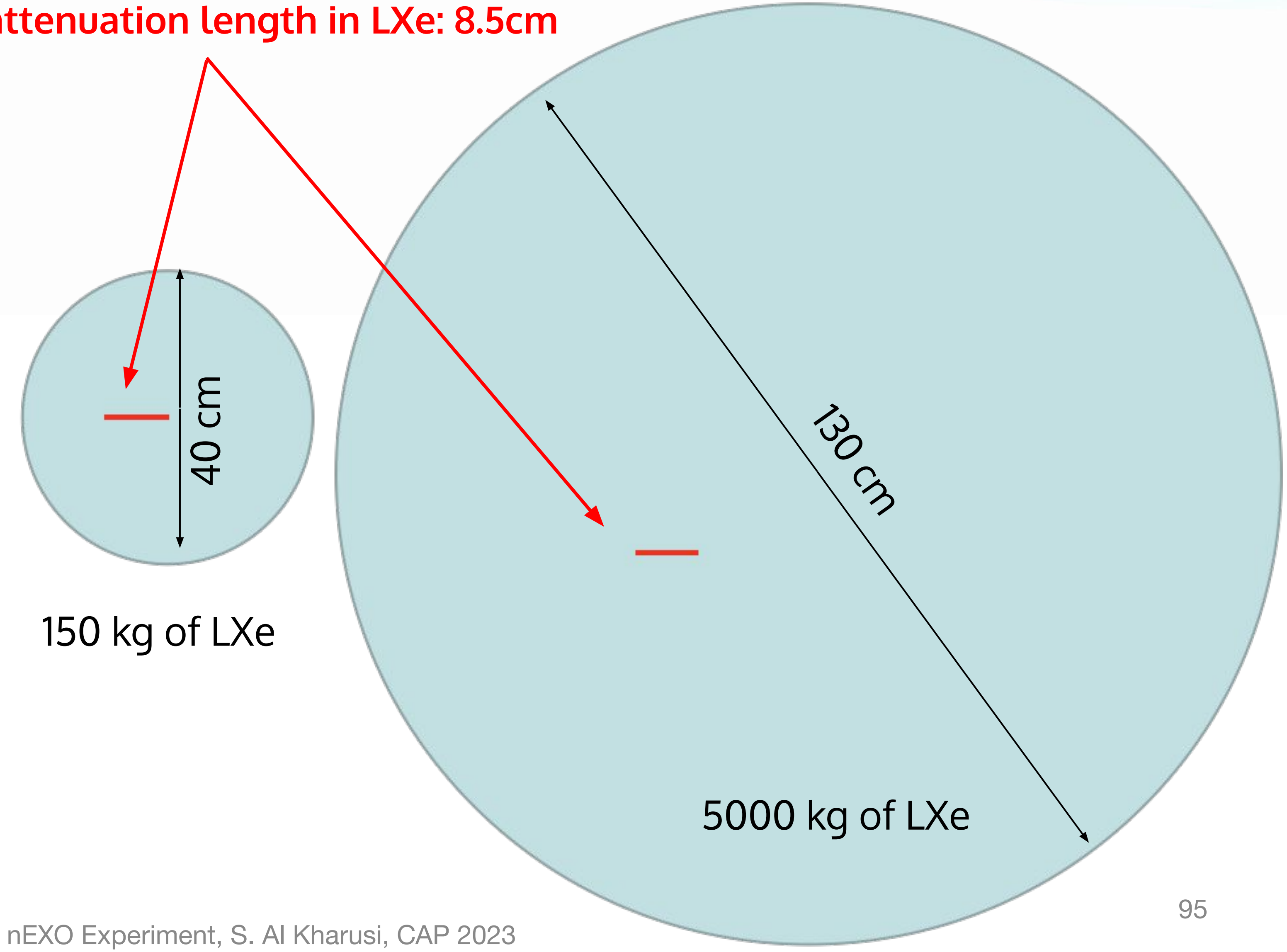
LXe TPC Scalability (1/2)

- LXe is self shielding: larger TPC means **better attenuation of gammas**, and even **better constraints on fluctuations to backgrounds.**
- **Any potential 0νββ signal** would have to **not be anomalous in all 3 high level distributions**: Energy, Standoff, and Topology.
  - Due to gamma attenuation lengths << detector scale, this improves with larger masses



LXe TPC Scalability (2/2)

- Going from 5 tonne to 100 tonne would require LXe TPCs of size scale = 1.3*(100/5)^(1/3) ~ 3.5 m
- We know how to make liquid noble TPCs even larger (see DUNE)



Beyond $0\nu\beta\beta$ discovery?

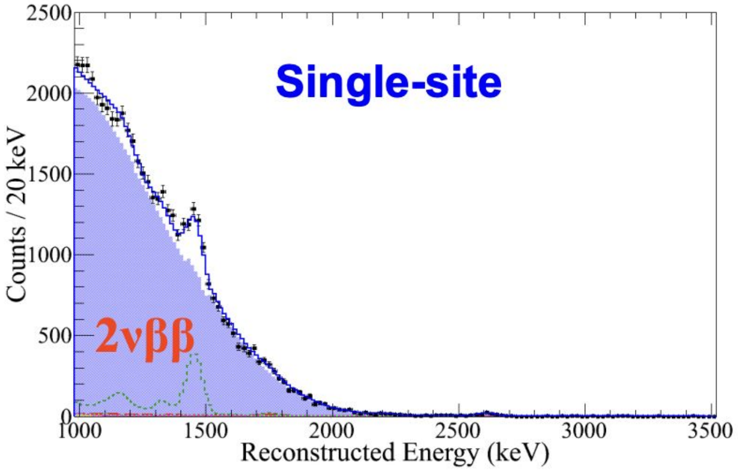
- **If $0\nu\beta\beta$ is discovered in any isotope**, we would want to explore **what mechanism is producing the decay**
  - We would do this by measuring the **energy and angular distributions** of the two emitted electrons in $0\nu\beta\beta$ events
    - Straightforward in an enriched gaseous xenon TPC
    - Design constraints set by half life measurements in an LXe TPC (e.g. nEXO)
- $0\nu\beta\beta$ decay mechanisms change the value of $\langle m_{\beta\beta} \rangle$, and probe couplings to BSM physics
- Discovering $0\nu\beta\beta$ and exploring it in multiple isotopes is key
  - Nuclear physics is hard, and extracting BSM physics couplings without multiple isotopes confirming $0\nu\beta\beta$, half lives, mechanisms etc... will be difficult

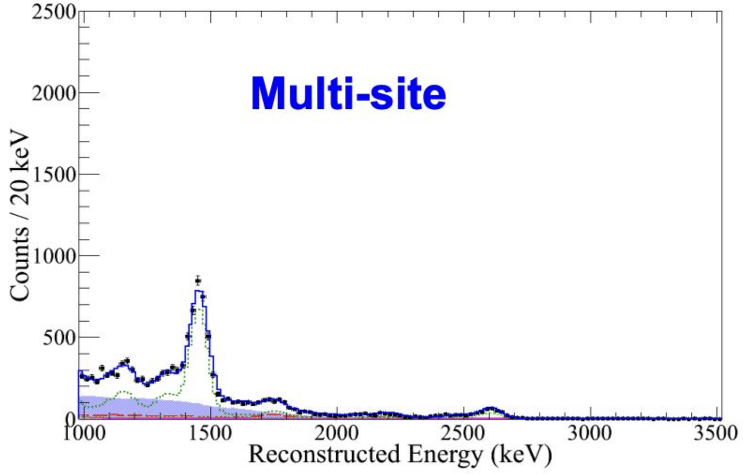
Multiparameter Analysis

EXO-200 Validation

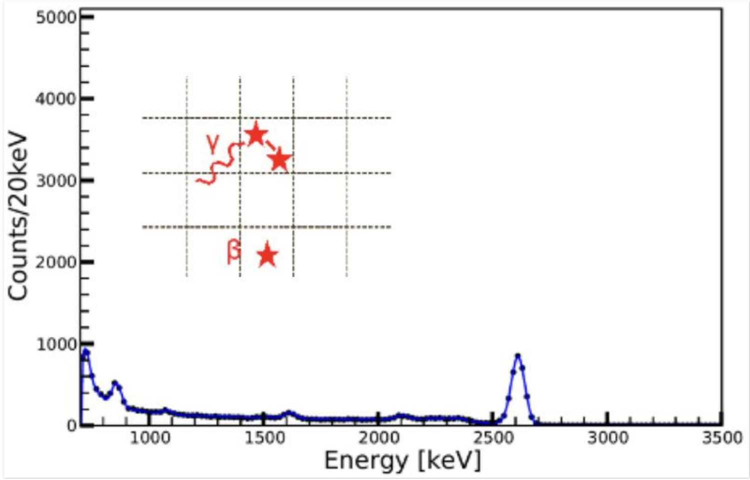
EXO-200 data

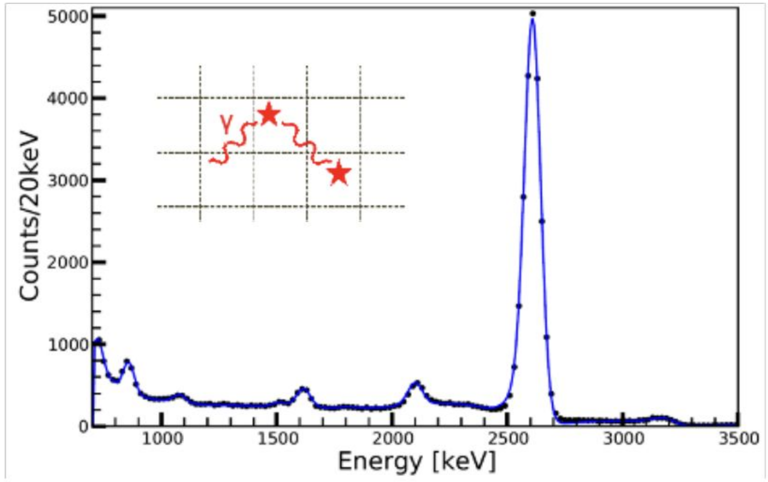
Low background data





^{228}Th calibration source





Do Majorana neutrinos help us?

- **Lose two degrees of freedom** in the SM for Majorana neutrinos
- **Weinberg operator**
- **Seesaw mechanisms**
- **Matter vs Antimatter?** Maybe $\mathbf{m_R}$ associated with Λ and are *really* heavy?
  - Possible explanation for the matter / antimatter asymmetry!! (leptogenesis)

Sakharov conditions

1. CP Violation
2. Non-equilibrium state
3. Baryon number violation

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Sakharov conditions (in the context of leptogenesis)

1. CP Violation ⟶ m_R is Majorana; no lepton number.
2. Non-equilibrium state ⟶ Universe is expandING
3. Baryon number violation ⟶ sphaleron processes