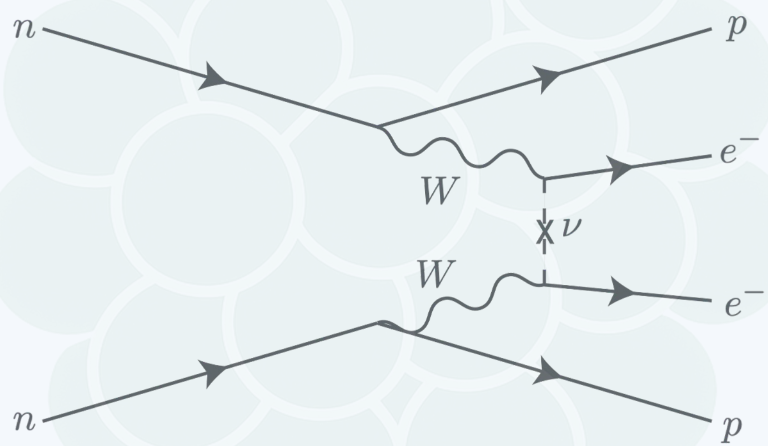
Neutrinoless Double Beta Decay and Neutrino Mass

Krishan Mistry

Neutrino University



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νRES NEUTRINOS AND RARE EVENT SEARCHES

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krishan.mistry@uta.edu

Outline

1. Motivations for Majorana Neutrinos
    - Including neutrino mass mechanism example
    - How they can help solve matter-antimatter asymmetry

2. Neutrinoless Double Beta Decay

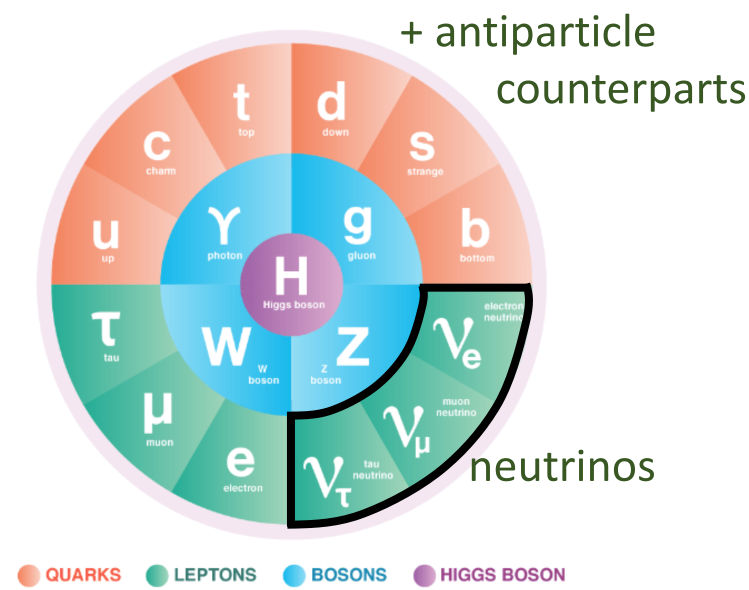
3. Neutrino Mass Measurements

4. Outlook and Conclusions

Standard Model of Particle Physics

$$
\begin{gathered}
\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^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \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^2_w} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - 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^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w (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) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^- \right) - \\
\tfrac{1}{8}g^2 \alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2 \right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c^2_w} Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig \left(W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0) \right) + \\
\tfrac{1}{2}g \left(W^+_\mu (H\partial_\mu \phi^- - \phi^- \partial_\mu H) + W^-_\mu (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H) \right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
M \left(\tfrac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+ \right) - ig\tfrac{s^2_w}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - \\
W^-_\mu \phi^+) - ig\tfrac{1-2c^2_w}{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 \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^- \right) - \tfrac{1}{8}g^2 \tfrac{1}{c^2_w} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2 \phi^+\phi^- \right) - \\
\tfrac{1}{2}g^2 \tfrac{s^2_w}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \tfrac{1}{2}ig^2 \tfrac{s^2_w}{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^2_w - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^2 s^2_w A_\mu A_\mu \phi^+ \phi^- + \tfrac{1}{2}ig_s \lambda^a_{ij} (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda (\gamma\partial + m^\lambda_\nu) \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + \\
m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu \left(-(\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) \right) + \\
\tfrac{ig}{4c_w} Z^0_\mu \{ (\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s^2_w - 1 - \gamma^5) e^\lambda) + (\bar{d}^\lambda_j \gamma^\mu (\tfrac{4}{3}s^2_w - 1 - \gamma^5) d^\lambda_j) + \\
(\bar{u}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3}s^2_w + \gamma^5) u^\lambda_j) \} + \tfrac{ig}{2\sqrt{2}} W^+_\mu \left((\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j) \right) + \\
\tfrac{ig}{2\sqrt{2}} W^-_\mu \left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda} \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1+\gamma^5) u^\lambda_j) \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_e (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1-\gamma^5) e^\kappa) + m^\lambda_\nu (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1+\gamma^5) e^\kappa) \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_e (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1+\gamma^5) \nu^\kappa) - m^\kappa_\nu (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1-\gamma^5) \nu^\kappa) \right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M} H (\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \tfrac{1}{4} \bar{\nu}_\lambda M^R_{\lambda\kappa} (1-\gamma_5) \hat{\nu}_\kappa - \\
\tfrac{1}{4} \bar{\nu}_\lambda M^R_{\lambda\kappa} (1-\gamma_5) \hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j) \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1-\gamma^5) u^\kappa_j) \right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu + \\
\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c^2_w}) 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 \left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c^2_w} \bar{X}^0 X^0 H \right) + \tfrac{1-2c^2_w}{2c_w} igM \left(\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^- \right) + \\
\tfrac{1}{2c_w} igM \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + igMs_w \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + \\
\tfrac{1}{2} igM \left(\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0 \right) .
\end{gathered}
$$

The Standard Model Lagrangian L_{SM}



Our tool for explaining the fundamental constituents of the universe and their interactions

Neutrinos (ν) come in three “flavours” and are neutral spin-half leptons that only interact weakly

How did the Universe come to be?

- The Standard Model is our best theory, but it has some shortfalls
- Neutrinos are one of the least understood particles and may give some clues

Neutrino mass mechanism

Antimatter-matter asymmetry

Dark Matter/Energy

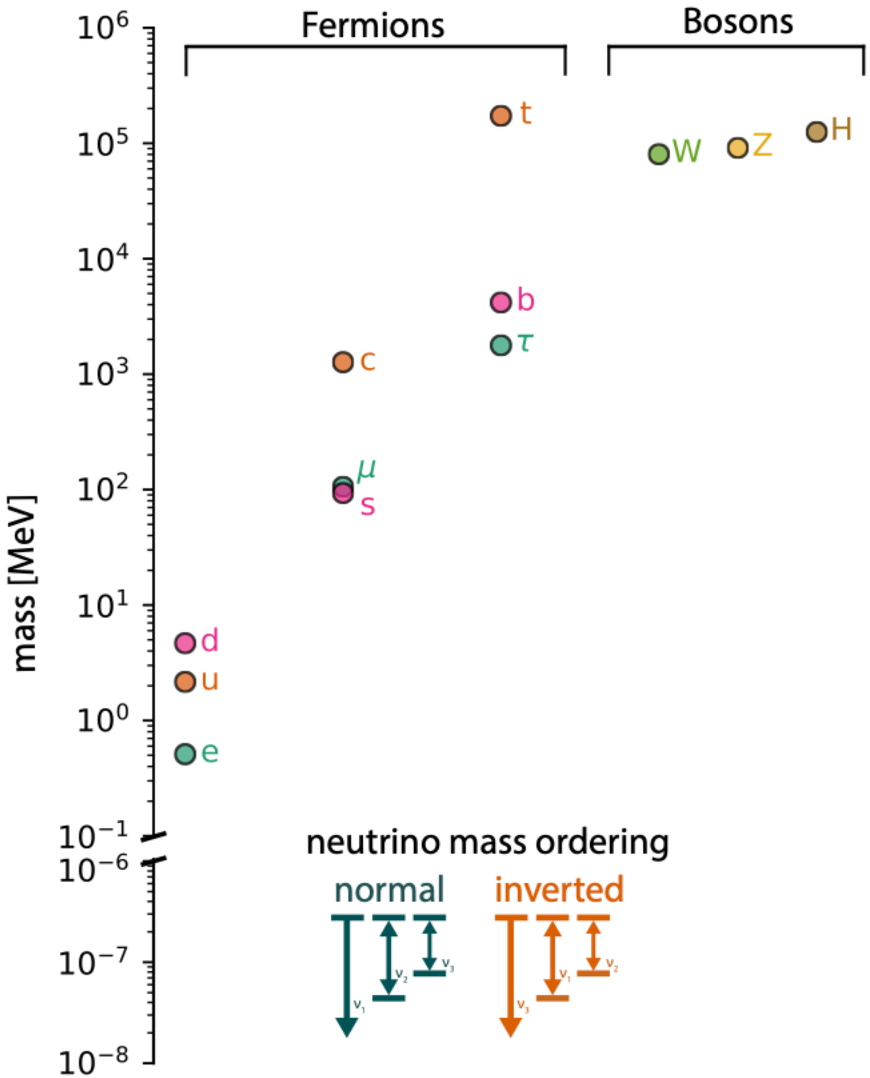
Grand Unified Theory

Quantum Gravity

ν's have mass and it's really small!

- Standard Model includes massless neutrinos
- Discovery of neutrino oscillations means they have mass
  - Five orders of magnitude smaller than electron

What is the explanation for this light mass?



Adding a mass term (Higgs Mechanism)

- If we include mass mechanism like the other fermions, we add a right-handed (**but sterile**) neutrino:

$$-L_D = m_D(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L), \qquad m_D = y\, v/\sqrt{2}$$

Yukawa coupling

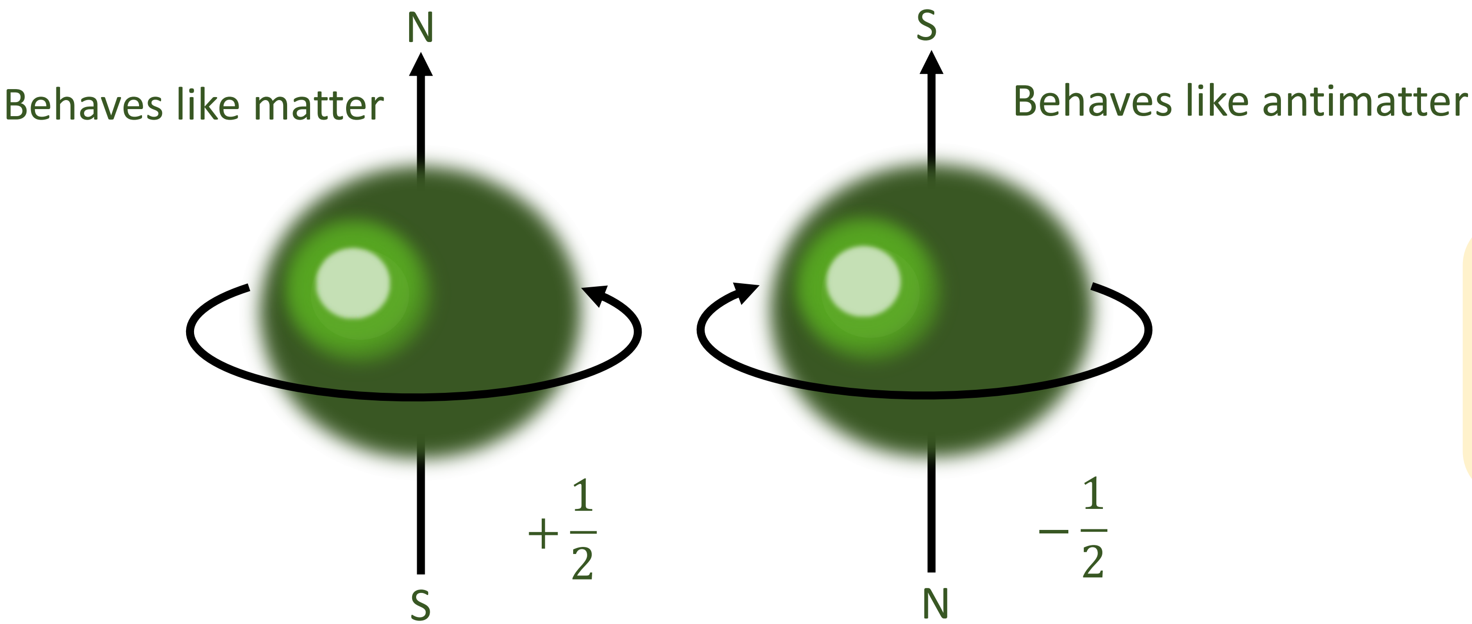
Dirac (D)

Expectation value of Higgs after EW symmetry breaking

- Yukawa coupling constant must be extremely small ($\sim 10^{-12}$)
  - Gets the job done, but the fine-tuning seems unnatural

The Majorana Neutrino

- 1937: Ettore Majorana realized for neutral fermions you could impose the condition that they can be their own antiparticle "Majorana"
  - Neutrino is the only fermion that you can impose this condition



We do not know if the neutrino is Majorana!!

- Lepton number is conserved in the Standard Model
  - A Majorana neutrino introduces processes that violates lepton number by two units (LNV)

An analogy

Take the Mass-Energy Equation from Special Relativity

$$E = \gamma m c^2 \qquad \gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$

In limit $v \ll c$

$$\gamma \approx 1 + \frac{v^2}{2c^2} + \alpha \left(\frac{v^2}{c^2}\right)^2 + \cdots$$

$(1+x)^n \approx 1 + nx + \frac{1}{2}n(n-1)x^2 + \cdots$

Use expansion for v^2/c^2

$$E \approx mc^2 + \frac{mv^2}{2} + \cdots$$

Our Energy looks more like Newtonian Mechanics at low velocities!

*Newtonian Mechanics is just a low energy approximation of Special Relativity

SM: Low-energy effective field theory (EFT)

$$L = L_{\text{SM}} + \frac{1}{E_{\text{new}}} L_1 + \frac{1}{E_{\text{new}}^2} L_2 + \cdots$$

(dim 4) (dim 5) (dim 6)

- By same analogy, we can take the Standard Model as just the low-energy approximation of a larger theory
- Taylor series form, expanded in terms of powers of new physics scale E_{new} (can be large e.g. 10^{15} GeV)
- These terms consist of "operators" in the effective field theory consisting of different energy dimensions (4, 5, 6,…)

SM: Low-energy effective field theory (EFT)

$$L = L_{\mathrm{SM}} + \frac{1}{E_{\mathrm{new}}} L_1 + \frac{1}{E_{\mathrm{new}}^2} L_2 + \cdots$$

This is the only energy dimension-5 operator we can add obeying SM gauge symmetry

$$\frac{L_1}{E_{\mathrm{new}}} = y_{ij} \frac{\nu^i H \nu^j H}{E_{\mathrm{new}}}$$

Weinberg 1979

Weinberg Operator

SM: Low-energy effective field theory (EFT)

$$L = L_{\mathrm{SM}} + \frac{1}{E_{\mathrm{new}}} L_1 + \frac{1}{E_{\mathrm{new}}^2} L_2 + \cdots$$

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$$\frac{L_1}{E_{\mathrm{new}}} = y_{ij} \frac{\nu^i H \nu^j H}{E_{\mathrm{new}}}$$

Weinberg 1979

Weinberg Operator

Term has one function: makes Majorana neutrinos with mass suppressed by new physics scale E_{new}!

$\rightarrow$ $m_L \sim \frac{1}{E_{\mathrm{new}}}$

Not renormalizable → implies SM EFT

Mass mechanism: Seesaw

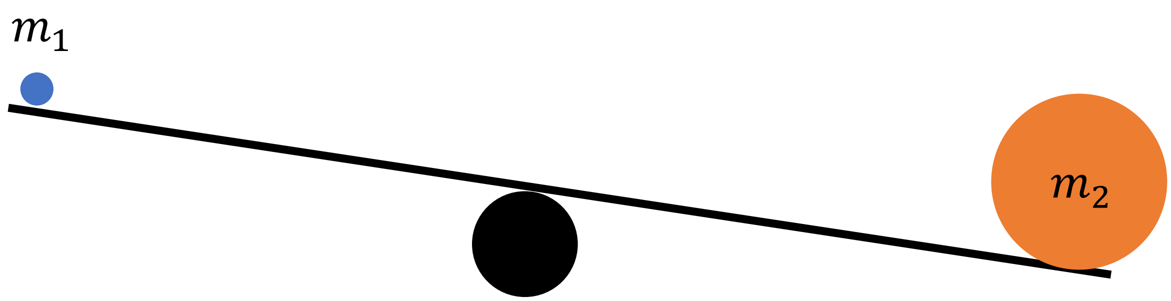
Seesaw Mechanism (Type-I)

$\frac{1}{2} m_R(\overline{\nu_R}(\nu_R)^C + \overline{(\nu_R)^C}\nu_R)$

Right-handed Majorana Mass term

- Include a right-handed Majorana mass term m_R located at a much higher energy scale: $m_D \ll m_R$
- This term mixes with the Dirac mass term introduced earlier that results in the the following masses
  - For brevity I skip the mathematical details which can be found in arXiv 0310238v2

$m_1 \simeq m_D^2/m_R$ $m_2 \simeq m_R$

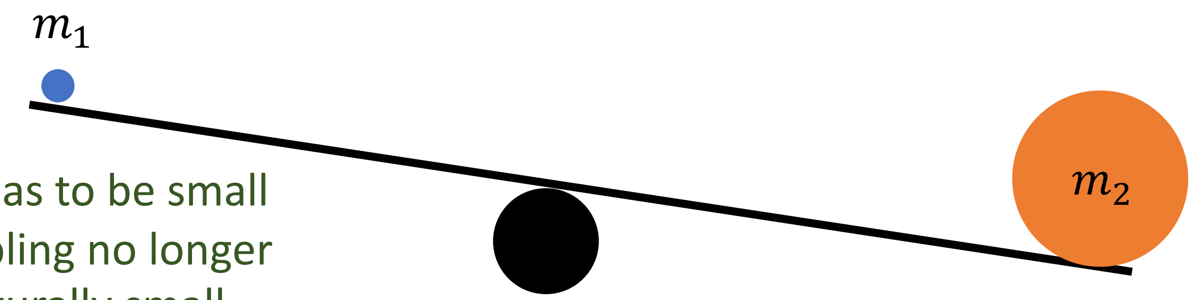


Corresponds to the neutrino that participates in weak interactions

This state is practically decoupled from interactions with matter (sterile state)

Seesaw Mechanism (Type-I)

$m_1 \simeq m_D^2/m_R$ $\qquad$ $m_2 \simeq m_R$



m_D no longer has to be small → Yukawa coupling no longer has to be unnaturally small

m_R >> m_D as not fixed to EW scale

- Generate mass with the introduction of heavy right-handed neutrinos
  - More natural way to explain the neutrino mass

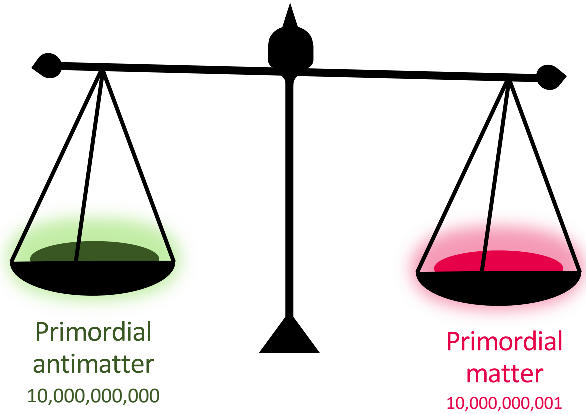
- Also see Seesaw Type-II and Type-III for alternative mechanisms

Matter-Antimatter Asymmetry

- Something tipped the scales to make more matter over antimatter
- Our current knowledge of the SM does not explain this
- Need processes to satisfy the Sakharov Conditions

1. C and CP Violation
2. Interactions out of thermal equilibrium
3. Baryon number violation

1 part in 10 billion was all that was needed!



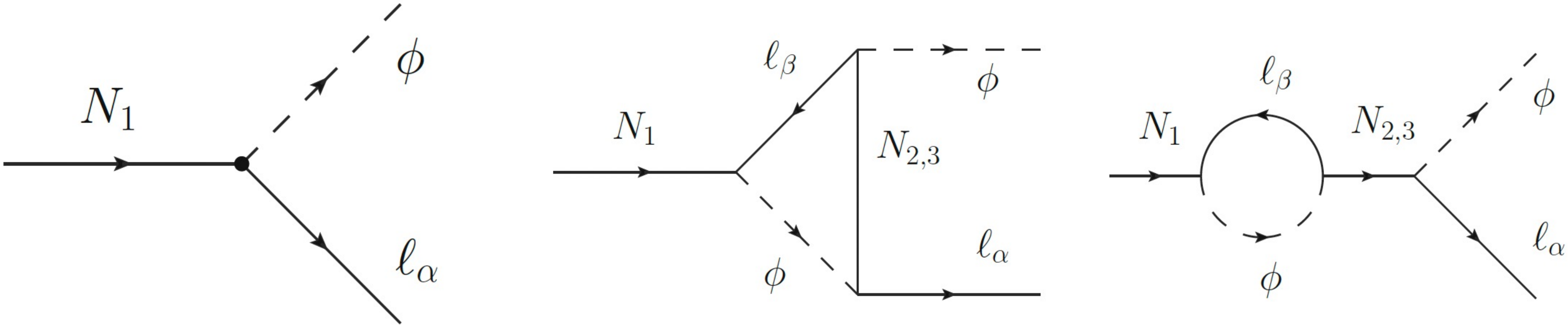
- Introduce Thermal Leptogenesis
  - Include heavy RH Majorana neutrino (typically around GUT scale)
  - Associated with right-handed Majorana neutrinos from the Seesaw type-I model

Thermal Leptogenesis

Fukugita and Yanagida, Phys, Lett., B174:45,1986

1. Heavy Majorana Neutrino Decays to leptons + Higgs: $l_\alpha \phi$ and $\overline{l_\alpha \phi}$
   - Decays violate C and CP symmetry
   - If rate of interaction is slower than universe expansion at time of decoupling, we depart from thermal equilibrium
   - We can drive one decay process more than the other creating LNV

2. Sphaleron process then generates the baryon asymmetry from LNV satisfying Sakharov Conditions (B-L conserved)



See Physics Reports, 466(4–5), 105–177 (2008) for more leptogenesis models

Takeaways for Majorana ν's

1. Lepton Number Violation

2. Neither matter or antimatter

"Majorana Fermion"

3. SM with a Majorana term in is non renormalizable → SM EFT

Physics at a higher scale

4. New mass mechanism

e.g. Seesaw Mechanism

5. Leptogenesis to explain matter-antimatter asymmetry

Requires Majorana ν's

Dirac

or

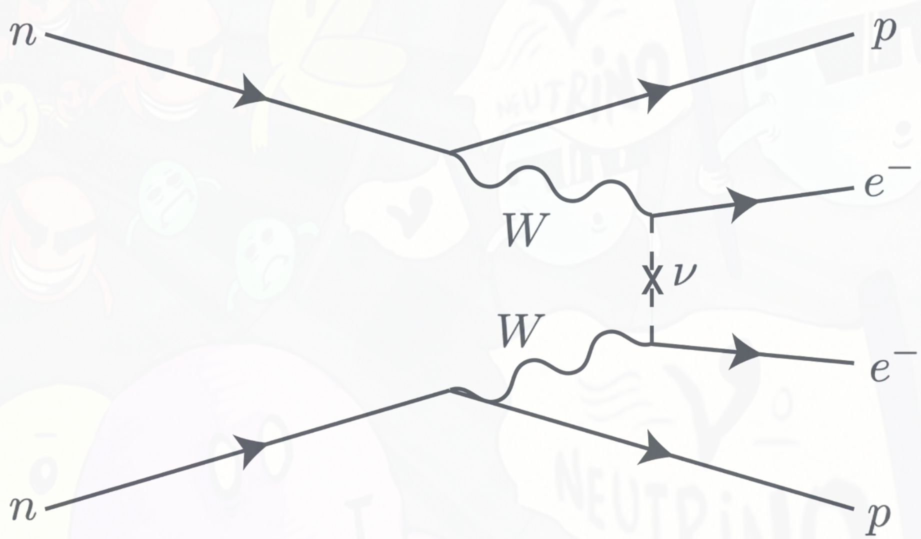
Majorana?

Look for neutrinoless double beta decay!

Dirac

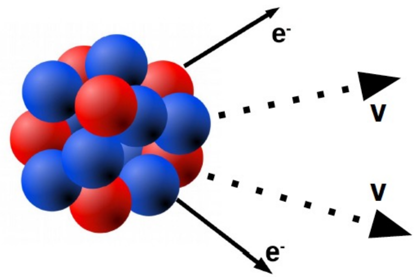
or

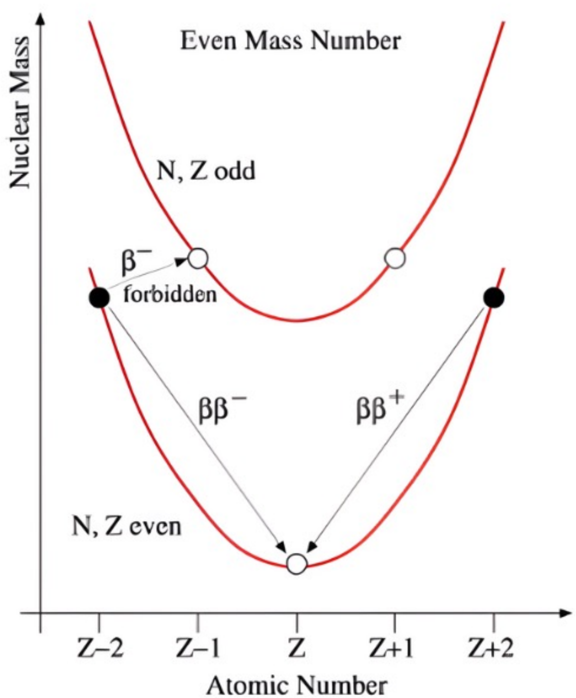
Majorana?



Double Beta decay (2νββ)

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\overline{\nu}_e$$



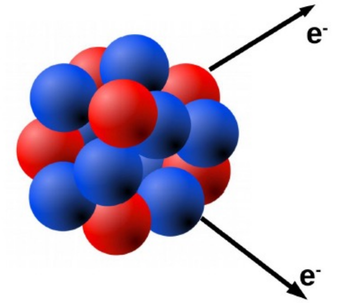


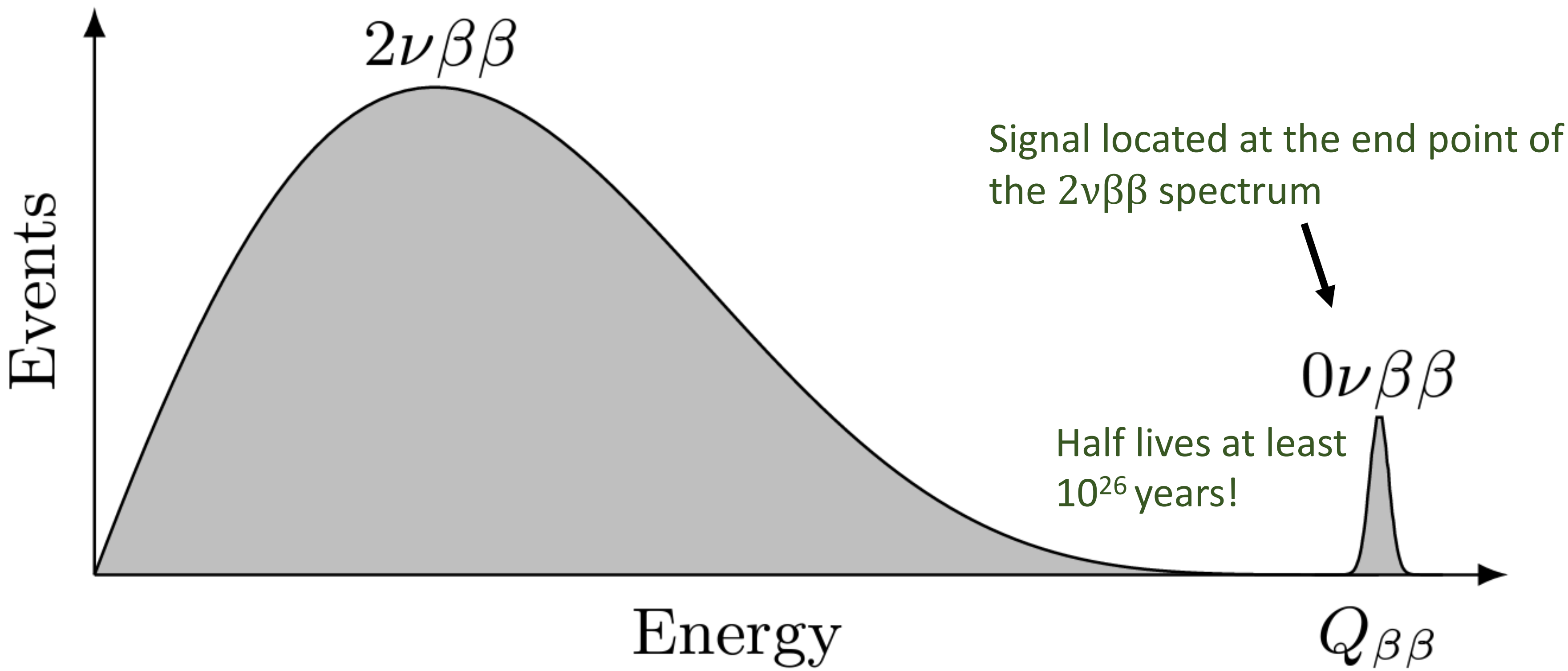
- Even-even nuclei are more stable due to the pairing-force
- Transition is mostly to ground state
  - Excited states are suppressed by phase-space
- Second order weak process
  - Half-lives ~10^{19}-10^{21} yr
- A known (and measured) SM process

Neutrinoless Double Beta decay (0νββ)

- Majorana neutrinos annihilate giving almost all the energy to the electrons
  - Cannot happen for Dirac neutrino

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$



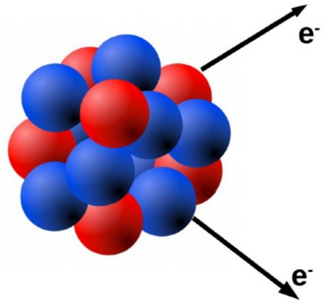


Q-value: Energy released in decay

Neutrinoless Double Beta decay (0νββ)

- Majorana neutrinos annihilate giving almost all the energy to the electrons
  - Cannot happen for Dirac neutrino

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-}$$



Half-life

$$T_{1/2} = \left[\mathrm{G} \times |M(g_{\mathrm{A}})|^2 \times m_{\beta\beta}^2 / \mathrm{m_e^2} \right]^{-1}$$

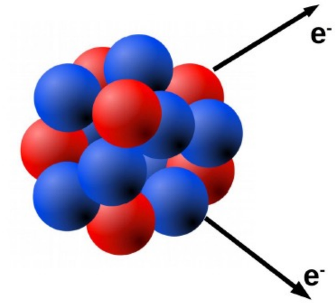
Phase-space factor
Atomic Physics

Matrix element
Nuclear Physics

Effective mass of neutrino
Particle Physics

Neutrinoless Double Beta decay ($0\nu\beta\beta$)

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$



- Majorana neutrinos annihilate giving almost all the energy to the electrons
  - Cannot happen for Dirac neutrino

Half-life

$$T_{1/2} = \left[\, G \times |M(g_A)|^2 \times m_{\beta\beta}^2 / \mathrm{m}_e^2 \right]^{-1}$$

Phase-space factor
Atomic Physics

Matrix element
Nuclear Physics

Effective mass of neutrino
Particle Physics

Bit of control based on your choice of double-beta decay isotope

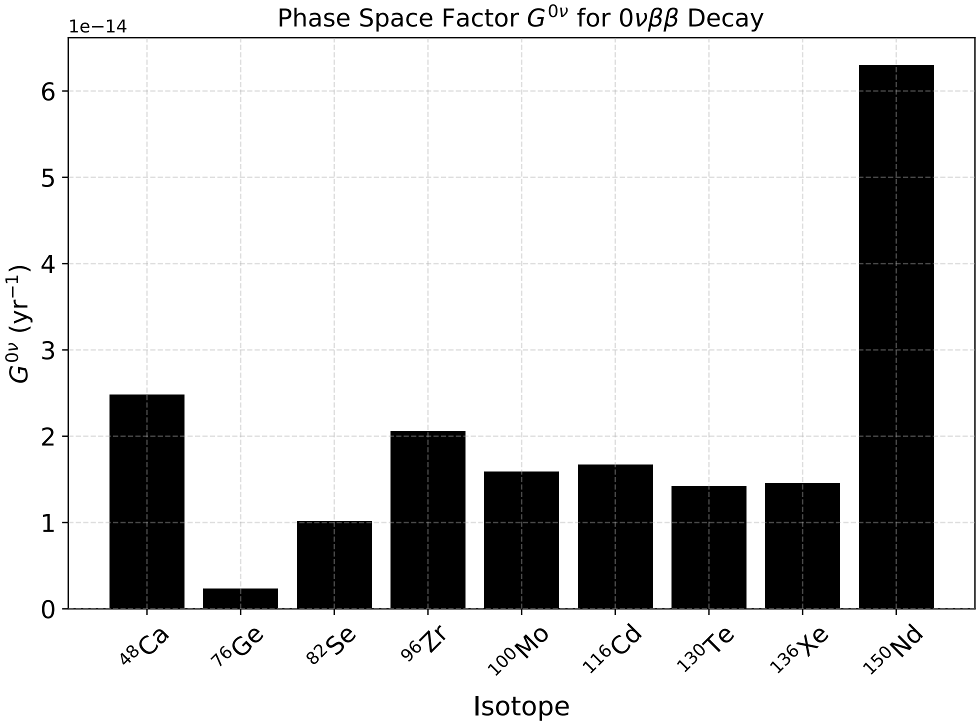
No control, whatever nature decided!

Phase Space Factor: G

- Factor accounts for the atomic physics relating to the emitted electrons

- Dependence on the Q^5 and Z of the isotope

- Can be calculated with reasonable accuracy
    - Need good accurate description of the Coulomb field on the decay electron wave-functions



Phys. Rev. C **85**, 034316

Nuclear Matrix Elements (NME): $|M^2|$

- Accounts for the structure of the initial and final states of the nucleus
  - Challenging and is one of the largest sources of theoretical uncertainty

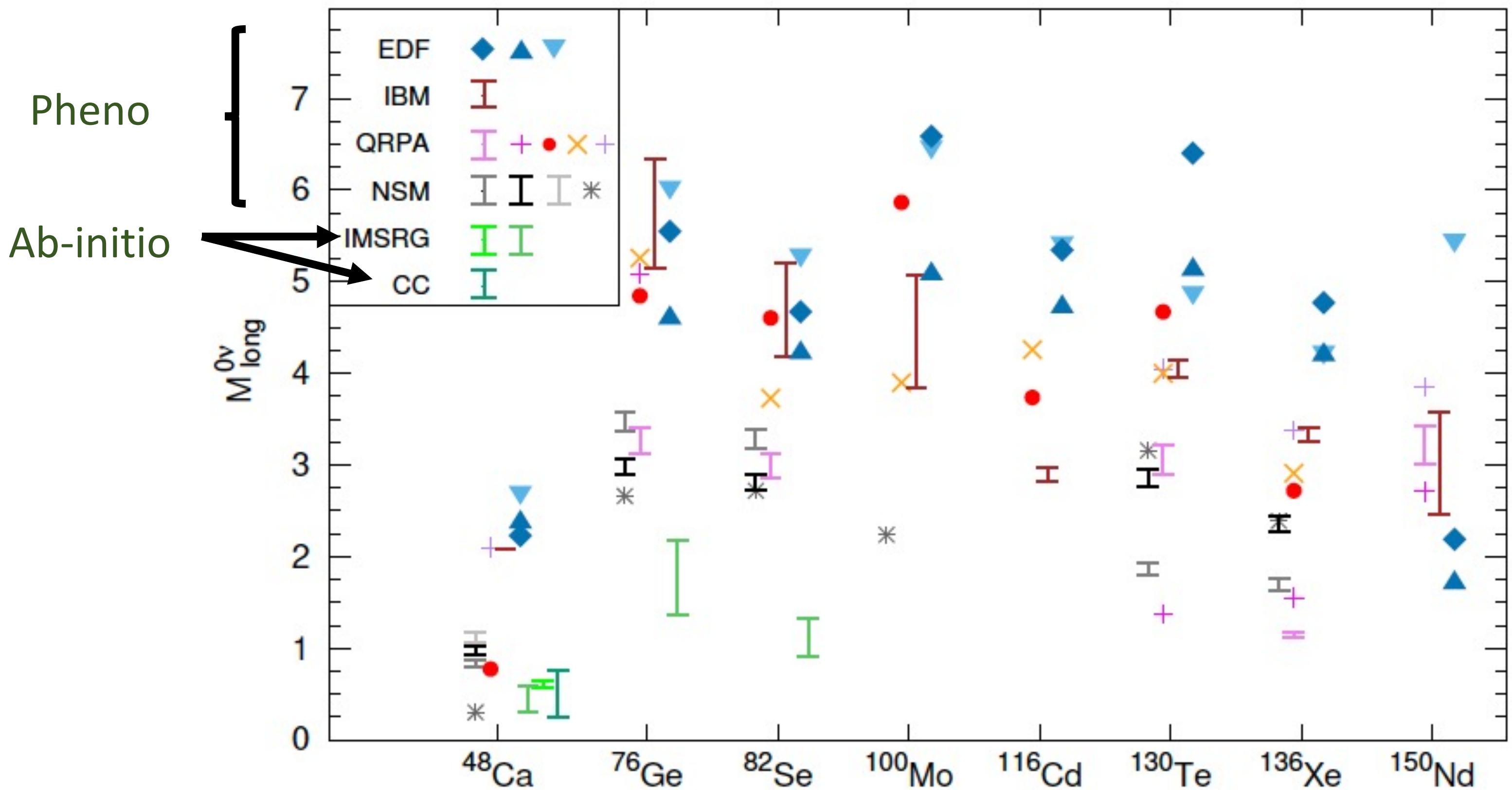
- Many methods used to calculate:
  - E.g. Shell Model, EDF, IBM2, QRPA, Ab-Initio

- Consists of two parts: $M = M_{\mathbf{long}} + M_{\mathbf{short}}$
  - $M_{\mathbf{long}}$ accounts for long range physics such as pion exchange
  - $M_{\mathbf{short}}$ newer addition (2018) to account for shorter-range physics (see Phys. Rev. Lett. 120, 202001)
  - Generally harder to calculate for larger nuclei

Nuclear Matrix Elements (NME): $|M^2|$

- Nuclear models have variability, each with different physics approaches
  - Lack of constraining data
  - Spread is dependent on isotope

Contributes to the large uncertainty which covers full range of predictions



$m_{\beta\beta}$ in the minimal mechanism

Minimal mechanism: exchange of light Majorana neutrinos

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

U_{ei}^2 = ei element of PMNS matrix

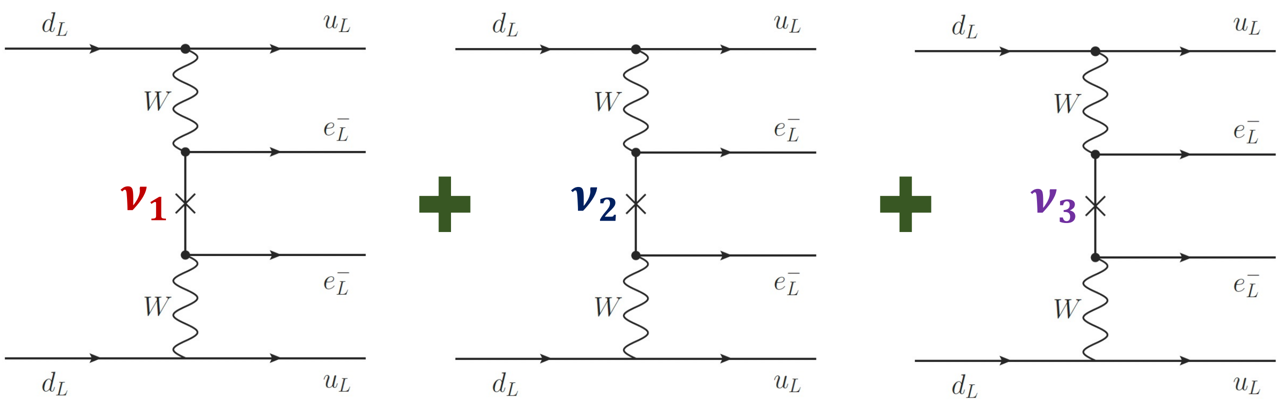
$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

- Due to the Majorana condition, we need to include two more complex phases α_1 and α_2
- These phases do not affect neutrino oscillations (appear on the diagonal), only measurable with double beta decay

$m_{\beta\beta}$ in the minimal mechanism

Minimal mechanism: exchange of light Majorana neutrinos $m_{\beta\beta} = \left|\sum_{i=1}^{3} m_i U_{ei}^2\right|$

$m_{\beta\beta}^2 =$ | diagram(ν_1) + diagram(ν_2) + diagram(ν_3) $|^2$



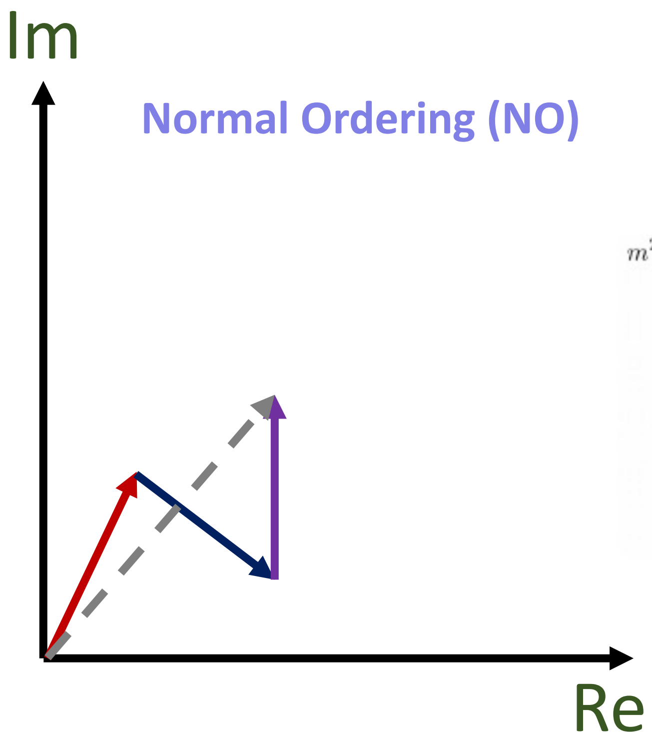
$$= \left| (U_{e1})^2 m_1 + (U_{e2})^2 m_2 + (U_{e3})^2 m_3 \right|^2$$

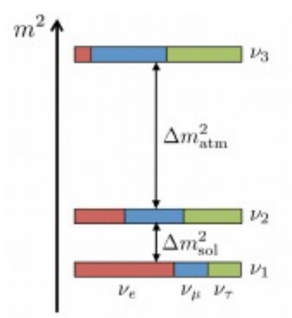
$$= \left| c_{12}^2 c_{13}^2 m_1 + c_{12}^2 s_{12}^2 e^{i2\alpha_1} m_2 + s_{13}^2 e^{-2i\delta_{CP}} e^{2i\alpha_2} m_3 \right|^2$$

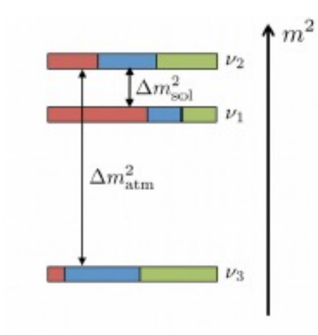
$m_{\beta\beta}$ in the minimal mechanism

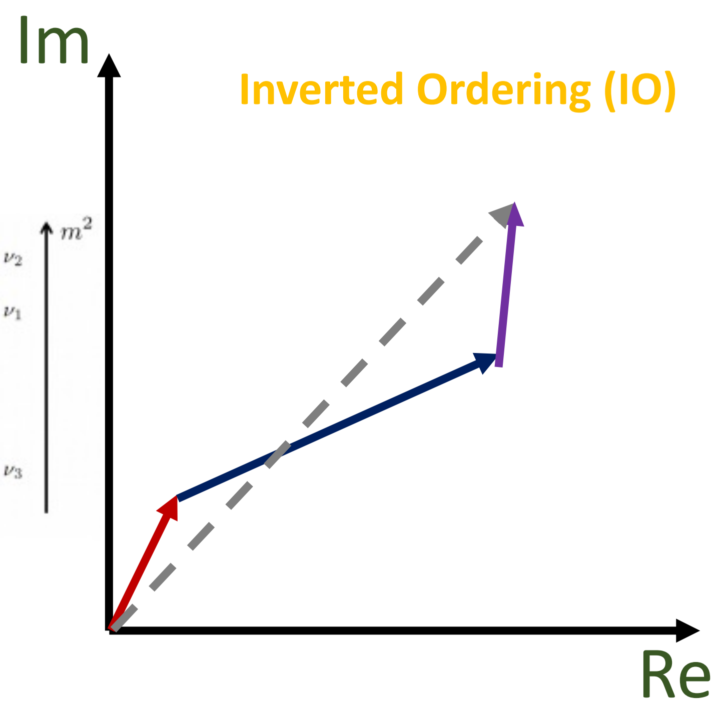
Minimal mechanism: exchange of light Majorana neutrinos

$$m_{\beta\beta}^2 = \left| c_{12}^2 c_{13}^2 m_1 + c_{12}^2 s_{12}^2 e^{2i\alpha_1} m_2 + s_{13}^2 e^{-2i\delta_{CP}} e^{2i\alpha_2} m_3 \right|^2$$









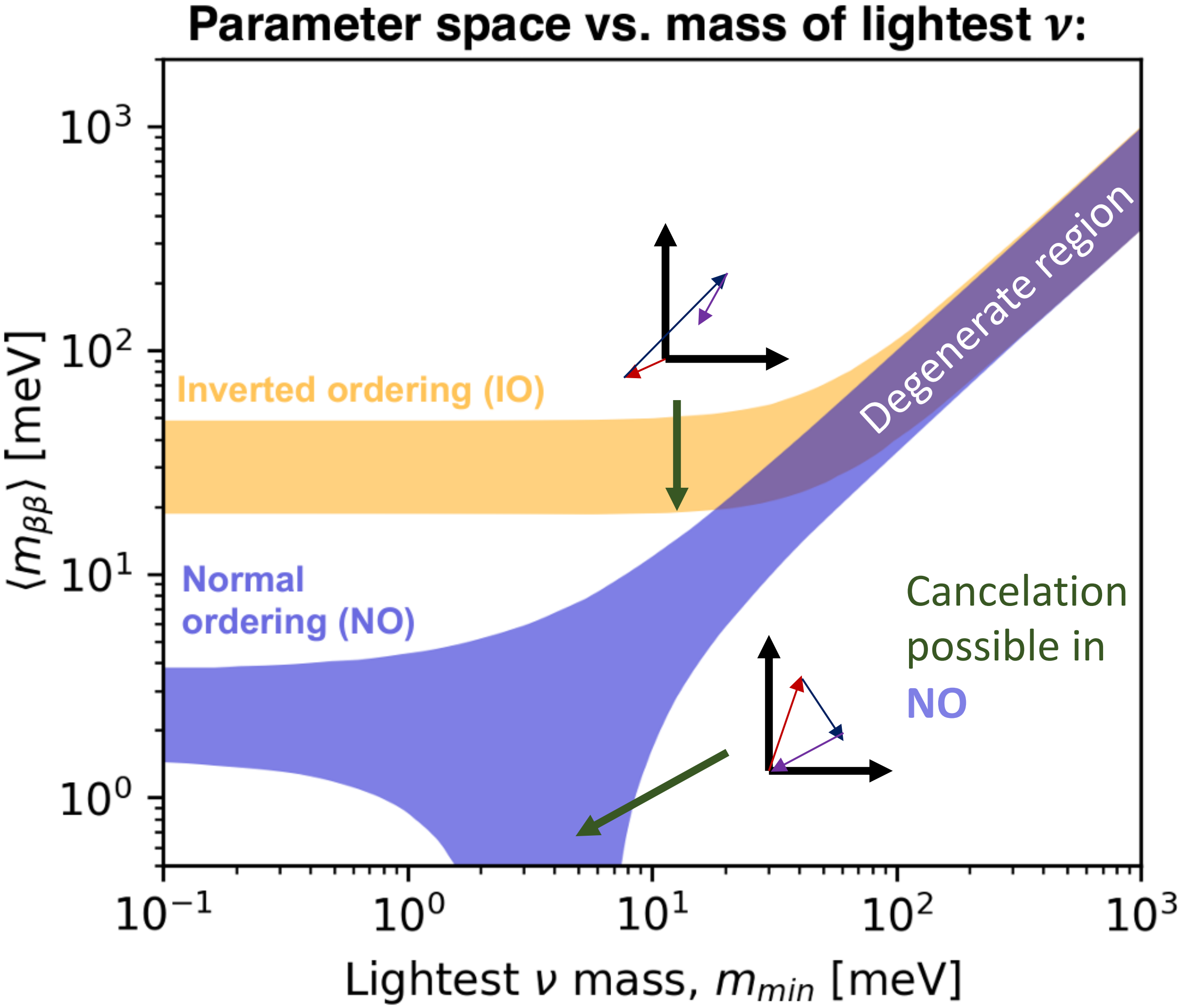
$m_{\beta\beta}$ in the minimal mechanism

The so-called "lobster plot"

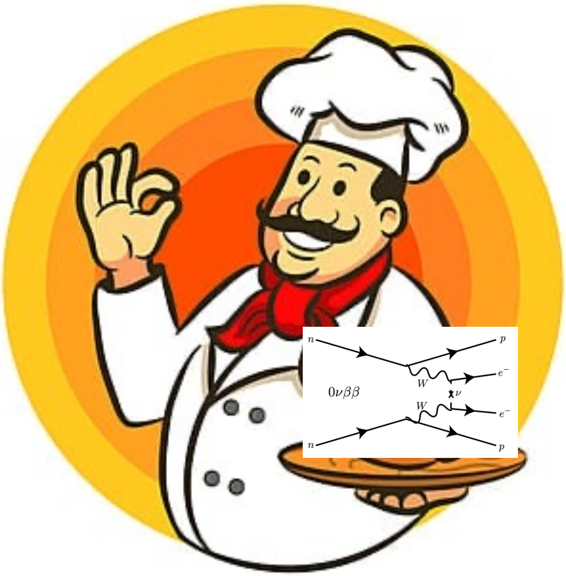
- NO and IO have different lightest neutrino mass

- Thickness to bands due to uncertainty on phases
  - Additional contribution from neutrino oscillation uncertainties

- Smallest value of $m_{\beta\beta}$ in IO is ~20meV



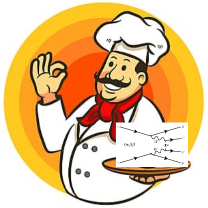
Cooking up your 0νββ experiment



0νββ Recipe

1. 2νββ Isotope Selection
2. Energy Resolution
3. Low Background
4. Detector

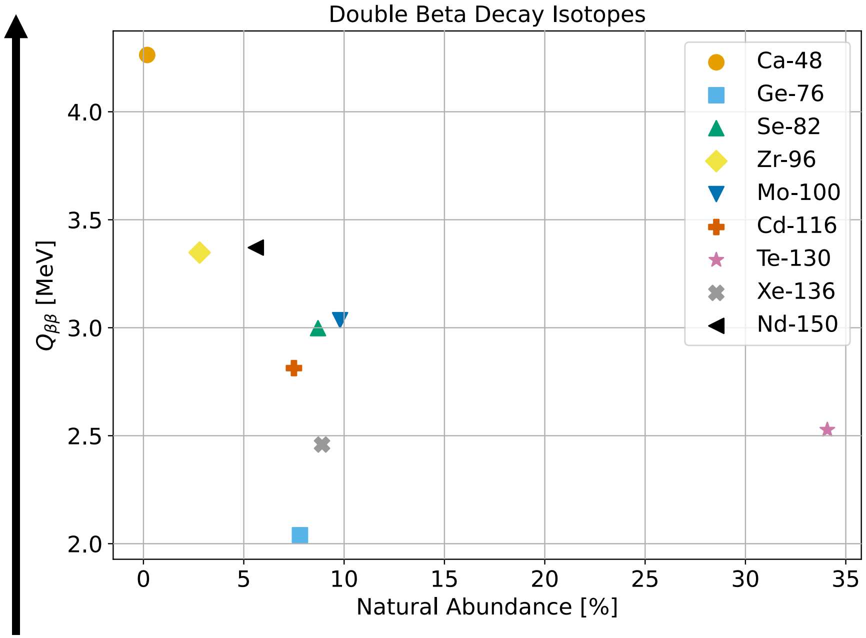
1. $2\nu\beta\beta$ Isotope Selection



There are 35 naturally occurring $2\nu\beta\beta$ emitters, not all are practical to use though

1. High Q-value
2. Isotopic Abundance
3. Larger Matrix Elements
4. Feasibility of procurement
5. Enrichment
6. Cost
7. Manufacture of compound

^{40}Ca has the best Q-value



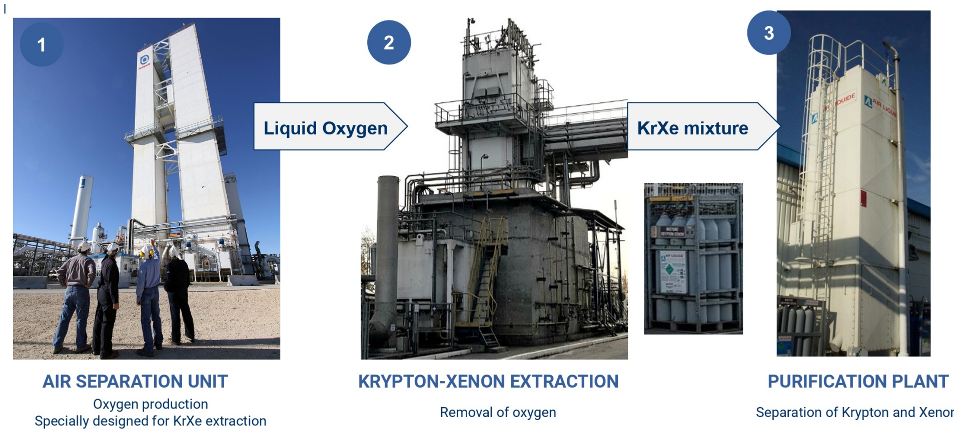
^{130}Te has the best natural abundance

1. 2νββ Isotope Selection

1. High Q-value
2. Isotopic Abundance
3. Larger Matrix Elements
4. Feasibility of procurement
5. Enrichment
6. Cost
7. Manufacture of compound

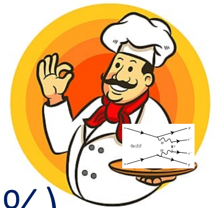
Example: Xenon

- Obtained from the air (0.087 ppm)
- By-product of extraction of oxygen from air with air separation units (ASUs)
- Steel industry has the largest ASU
  - Xe production is tied heavily to this industry (**market volatility!**)
  - China is currently largest industry (60%), loss of industry from Russia/Ukraine



See talk from Air Liquide

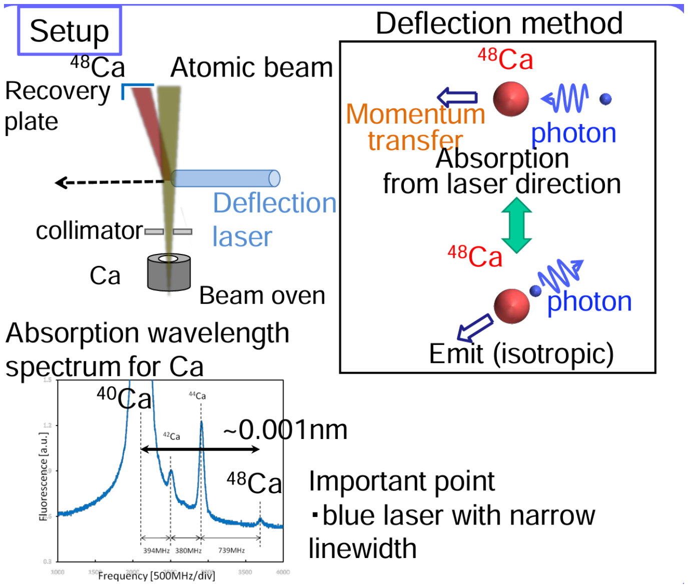
1. 2νββ Isotope Selection



1. High Q-value
2. Isotopic Abundance
3. Larger Matrix Elements
4. Feasibility of procurement
5. Enrichment
6. Cost
7. Manufacture of compound

Example: ^{48}Ca

- Small natural abundance (0.19%), need to separate from the other Ca isotopes
- CANDLES experiment is using laser isotope separation to enrich!
  - Laser tuned to ^{48}Ca and use momentum transfer of laser to deflect it in an atomic beam



J. Phys.: Conf. Ser. 2147 012012

1. 2νββ Isotope Selection

1. High Q-value
2. Isotopic Abundance
3. Larger Matrix Elements
4. Feasibility of procurement
5. Enrichment
6. Cost
7. Manufacture of compound

Example: ^{130}Te (SNO+)

- 34% natural abundance so no need to enrich
- Need to put into a form that can be loaded into liquid scintillator
- Manufacture of oil-soluble compounds derived from Telluric acid + stabilizing agents
- Mixing plant located underground at SNOLAB

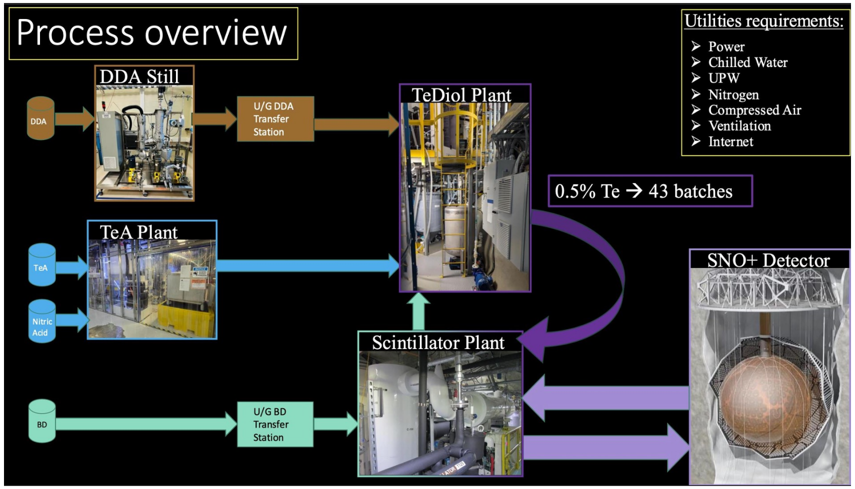


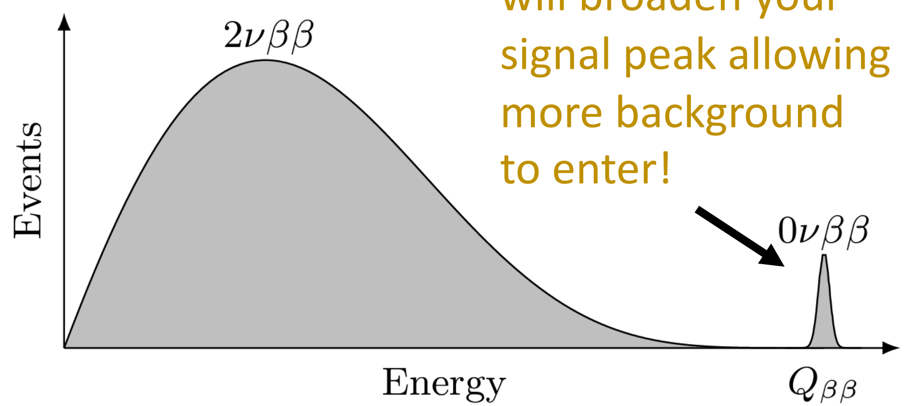
Image from talk by Mark Chen

NIM A,Volume 1051, 2023, 168204

2. Energy Resolution

- Mitigates the $2\nu\beta\beta$ background
- Avoid other backgrounds depositing energy in/close to the region of interest
- Detector resolutions vary depending on detector technology

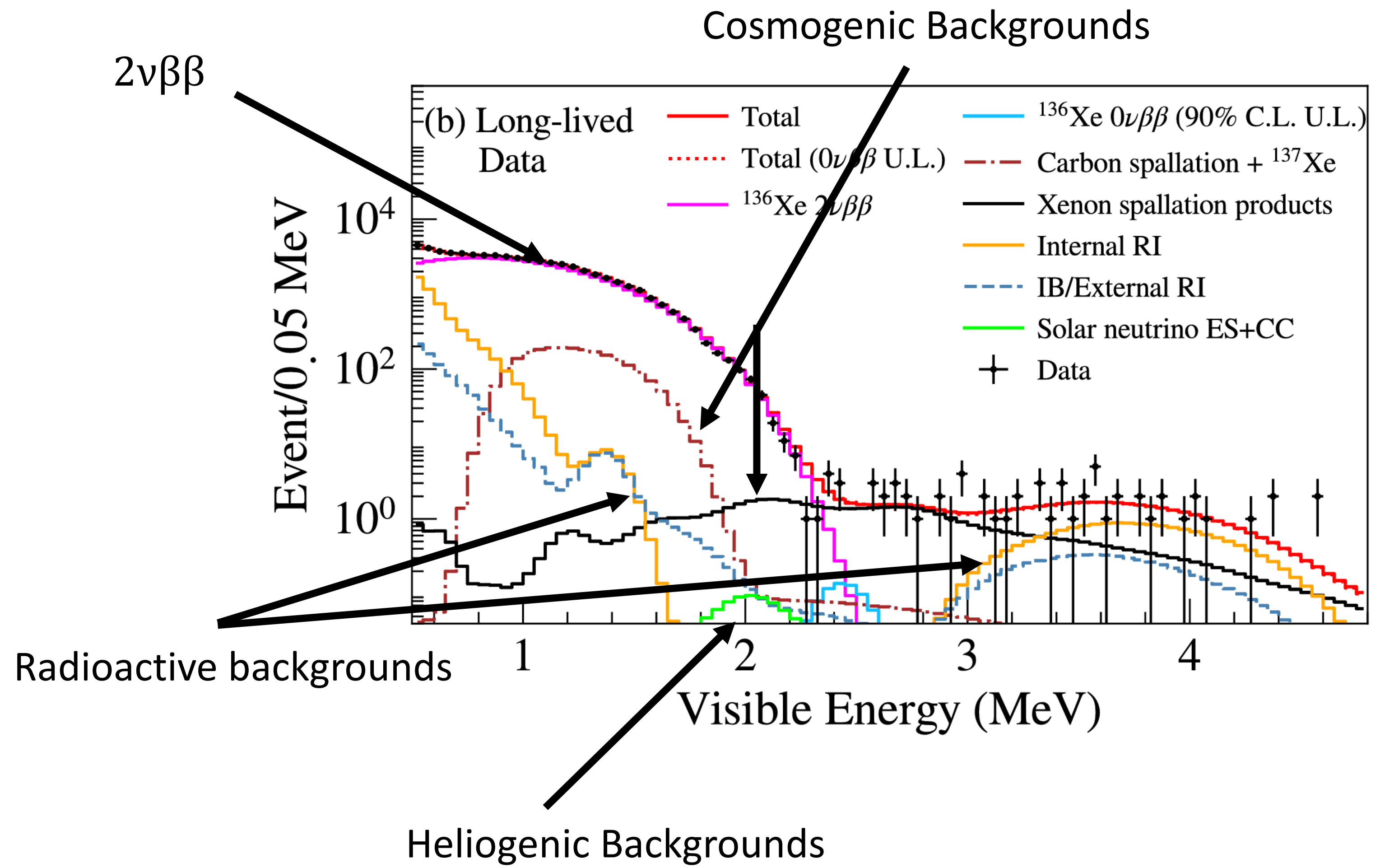
Type	Energy Resolution (FWHM)
Liquid TPC	2-3%
Gaseous TPC	0.5-1%
Germanium	0.1-0.2%
Bolometer	0.25%
Scintillator	10%



Poorer resolution will broaden your signal peak allowing more background to enter!

3. Low Background

Target background counts are a fraction of a count per tonne per year in ROI



Example spectra from KamLAND-Zen

3. Low Background: Radiogenics

α, β, γ, n can all be produced in natural radioactive decay chains, spontaneous fissions, and other rare radioactive processes

- → Can deposit energy in the region of interest

Mitigation Strategies

1. Radioactive screening of materials
2. Topological rejection (e.g. γ are more likely multi-site/single e^- signatures)
3. Possibility of tagging the daughter isotope with electron signal (e.g. tag ^{136}Ba from $^{136}Xe \rightarrow {}^{136}Ba^{2+} + 2e^-$)
4. Self-shielding (e.g. use large active volumes and use fiducial cuts)
5. Particle ID e.g Pulse-shape discrimination
6. Surface/Bulk Discrimination
7. Timing
8. Measurements with enriched/depleted sources

3. Low Background: Radiogenics

Radioactive screening of materials

Example: CUORE

Sourced lead bricks from 2000 yr old ancient Roman shipwreck!

Underwater lead has been shielded from cosmic activation proving to be low-background

Lead is factor 100,000 times lower activity in ^{210}Pb (22 yr half-life)

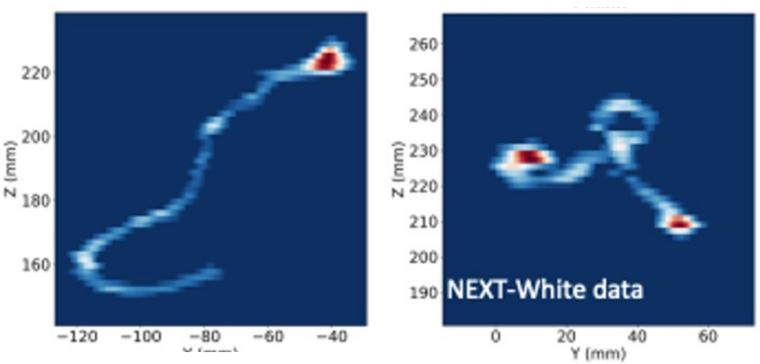
https://cerncourier.com/a/roman-lead-will-shield-cuore-experiment/

Topological Rejection

Example: NEXT

Gaseous TPC technology → the electron tracks are extended

You can resolve the electron tracks for signal ($2e^-$) and background separation ($1e^-$)

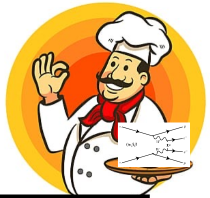


$1e^-$ bkg

$2e^-$ signal

3. Low Background: Radiogenics

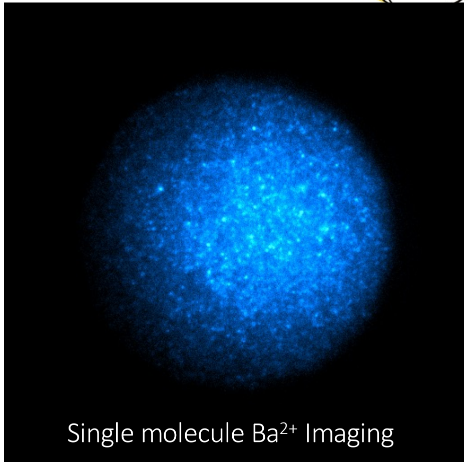
Tagging the daughter isotope



Example: NEXT

Use chemical method to ID barium

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



Single molecule Ba^{2+} Imaging

A non-fluorescent molecule becomes fluorescent (or vice versa) upon the introduction of an ion species such as barium

Not-Fluorescent

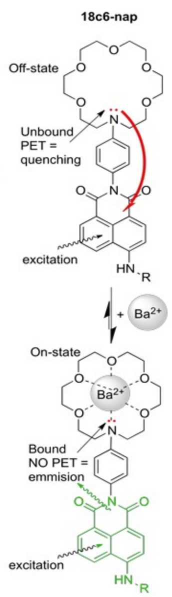
↓

Add Ba^{2+}

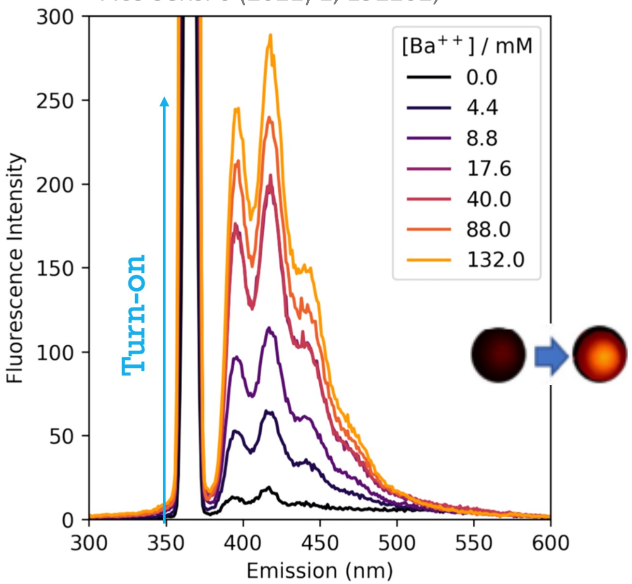
↓

Fluorescent!

Single-ion sensitivity!

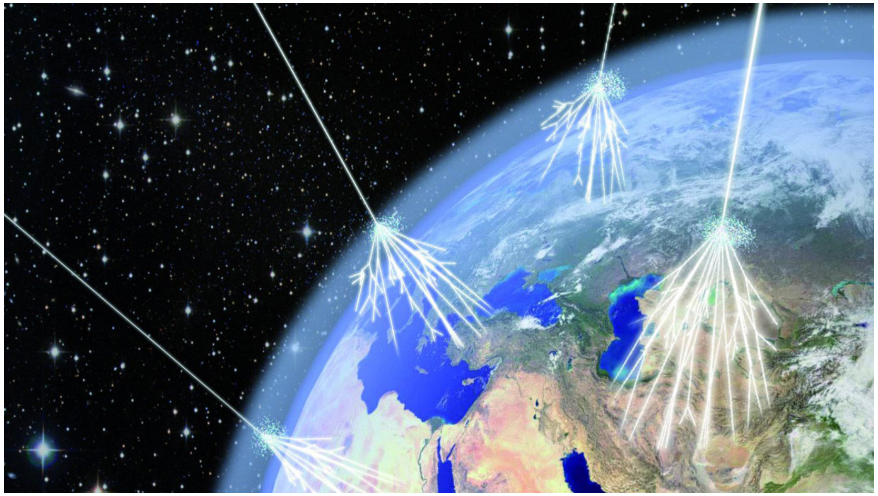


Phys. Rev. Lett. 120 (2018) 13, 132504; ACS Sens. 6 (2021) 1, 192202;

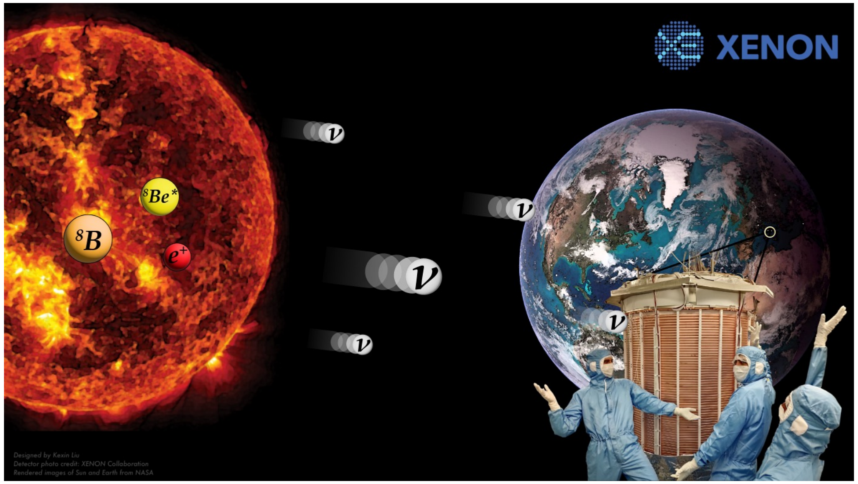


3. Low Background: Others

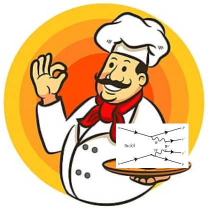
- Cosmogenics
  - Muon spallation can produce neutrons that activate stable isotopes e.g copper



- Heliogenic (from Sun)
  - Problem when the detector gets large
  - Elastic and charged-current scattering can lead to prompt betas, nuclear deexcitations and daughter beta decays



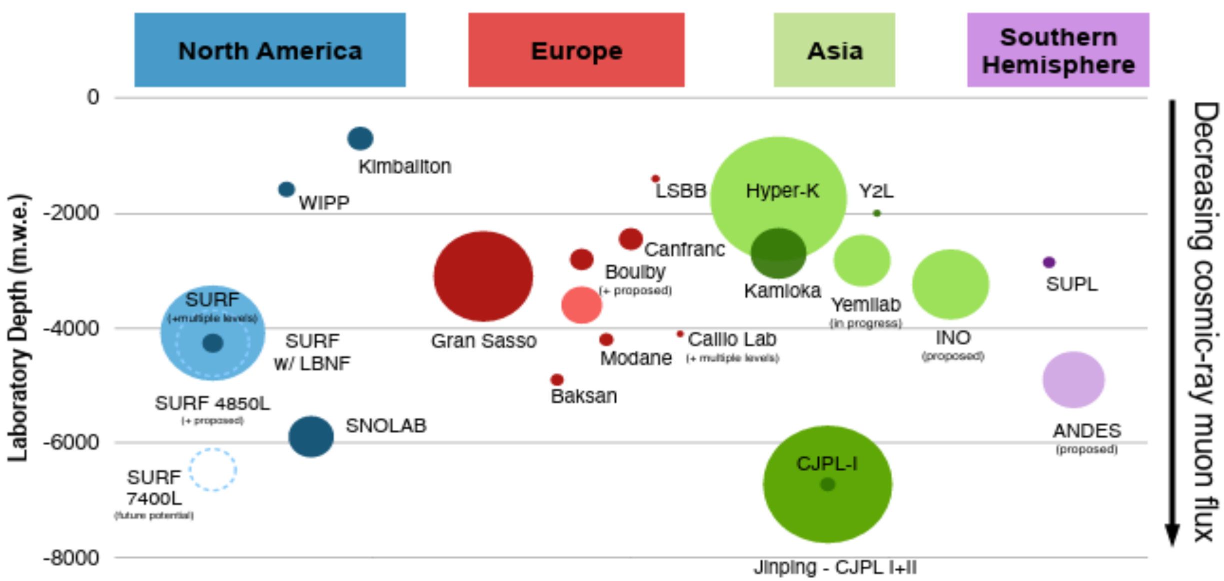
3. Low Background: Others



Mitigation Strategies for Cosmogenic + Heliogenic

- Go deep underground
- Manufacture materials underground
- Prompt background removed with muon veto
- Outer-shielding such as water to absorb neutrons
- Topology/directionality

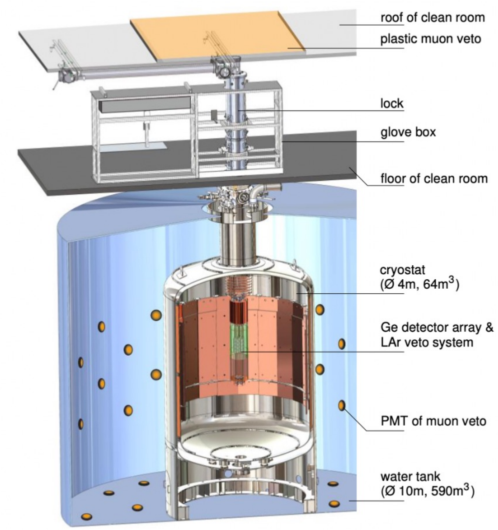
Current deepest facilities include SNOLAB and Jingping



Note: Circles represent volume of science space

arXiv 2212.07037

e.g LEGEND-200 has a 10m veto + water tank surrounding detector



3. Low Background: Others

Mitigation Strategies for Cosmogenic + Heliogenic

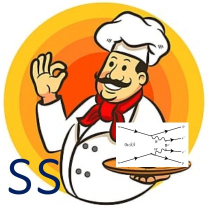
- Go deep underground
- Manufacture materials underground
- Prompt background removed with muon veto
- Outer-shielding such as water to absorb neutrons
- Topology/directionality

Example: MAJORANA Demonstrator

- Copper manufactured underground with electroforming!
- Worlds purest copper (measured to part per quadrillion, 10^{15})
- Extremely slow process
  - Copper dissolved in acid then use electrical currents to pull copper ions onto surface
  - 1 mm per month, 3.4 times slower than a fingernail growing!
- Parts are then machined from copper

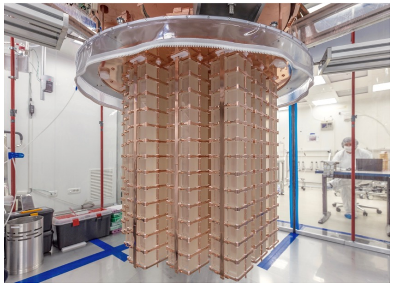
https://sanfordlab.org/news/legacy-majorana-demonstrator

4. Detector



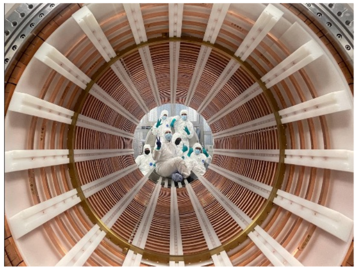
- Ensure it is **scalable** to accommodate large isotopic mass
- There are quite a lot of past, preliminary, and current experiments ranging across many detector technologies

Cryogenic Bolometers



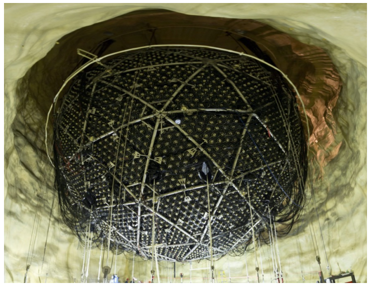
e.g. CUORE, CURICINO, CUPID, AMoRE, LUMINEU, MiDBD

TPCs



e.g. NEXT, nEXO, EXO-200, AXEL, νDEX, XMASS, Panda-X-III, XENON, LZ, Gotthard, XLZD

Scintillators



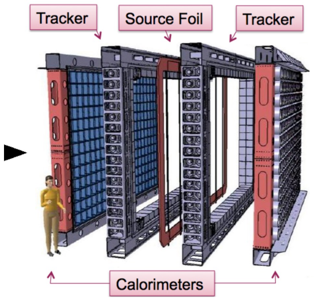
e.g. SNO+, KamLAND-Zen, Aurora, MOON, Solotvina, ELEGANT-VI, THEIA, ZICOS

Semiconductor

e.g. LEGEND, MAJORANA, GERDA, CANDLES, Heidelberg-Moscow (HM), COBRA, IGEX, TIN.TIN, CDEX

HM claimed discovery (2002) ← Modern Physics Letters A, 16(37), 24092420

Tracko-Calo

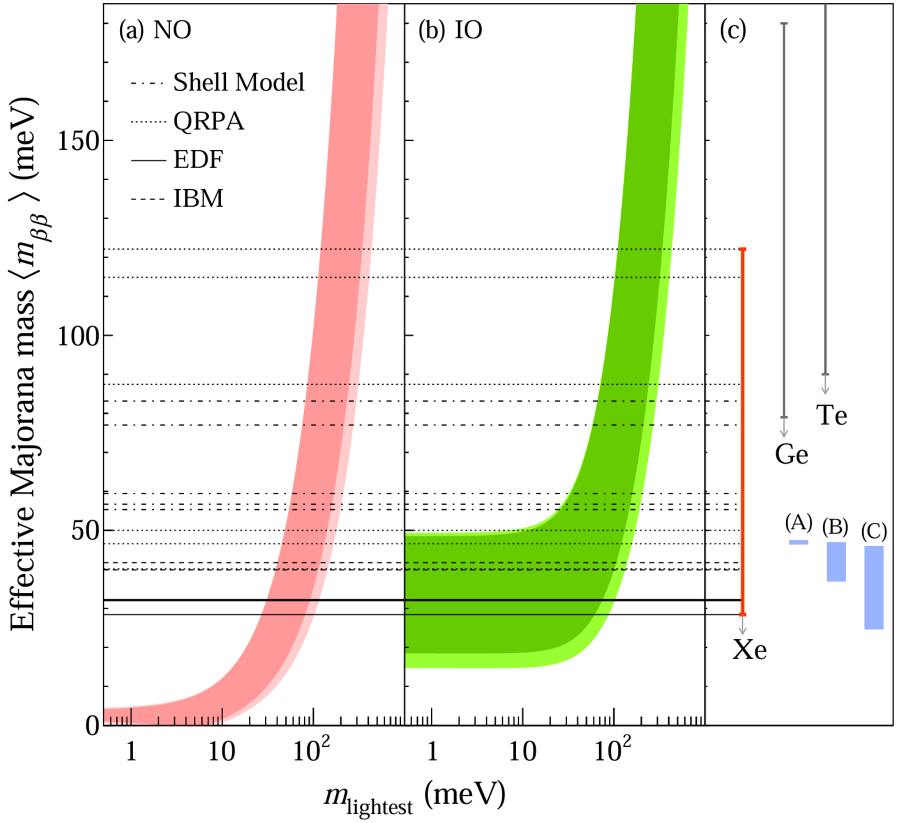


e.g. SuperNEMO, NEMO-3

Experimental Limits

Phys. Rev. Lett. **130**, 051801
Phys. Rev. Lett. **125**, 252502

- Limits often reported using range of matrix element calculations
  - Not all included e.g. ab-initio
  - Not all include short-range contributions
- Best limit is from KamLAND-Zen (^{136}Xe): 28-122 meV
- Followed by GERDA (^{76}Ge): 79-180 meV
- Not yet covered inverted neutrino ordering



Experiment	$T_{1/2}$ Limit
KamLAND-Zen	3.8×10^{26} yr (^{136}Xe)
GERDA	1.8×10^{26} yr (^{76}Ge)

Neutrino Mass Measurements

- Many ways to probe, the quantity you measure varies a bit also depending on the method
  - Difference in double beta decay vs single beta decay is due to exchange of virtual neutrinos in the double beta decay

Method	Quantity	Current Limit
Cosmology	$\sum m_i$	$\sum m_i$ < 0.064 eV arXiv 2503.14744
Double Beta Decay	$\sum \lvert U_{ei} \rvert^2 m_i$	$m_{\beta\beta}$ < 0.028-0.122 eV Phys. Rev. Lett. **130**, 051801
Beta Decay end-point kinematics	$\sum \lvert U_{ei} \rvert^2 m_i^2$	$m_\nu < 0.45$ eV Science **388** (6743), 180–185 (2025)
Supernova time of flight	$\sum \lvert U_{ei} \rvert^2 m_i^2$	$m_\nu < 5.7$ eV M. Roos 1987 EPL 4 953

Cosmology

- Relic neutrino background leaves detectable imprints on cosmological observations
  - Neutrinos behave as “hot” dark matter which supress clustering of matter
  - They affect the baryon acoustic oscillations (BAO) in the primordial plasma and structure formation

- Sensitive to number of neutrino species and total mass

- Latest results from Dark Energy Spectroscopic Instrument (DESI) assuming ΛCDM and using BAO data
  - $\sum m_i$<0.064 eV
  - Some tensions with other experimental data e.g. reporting 3 sigma tensions with neutrino oscillations
  - Stay tuned for next week's lecture on neutrino Cosmology!

arXiv: 2503.14744

Beta Decay Kinematics

Introducing KATRIN

- Took a 9000-kilometre journey around Europe from its construction to installation
  - Huge vacuum chamber requiring specialist welding

- Device was too large and heavy to be transported on the roads between towns

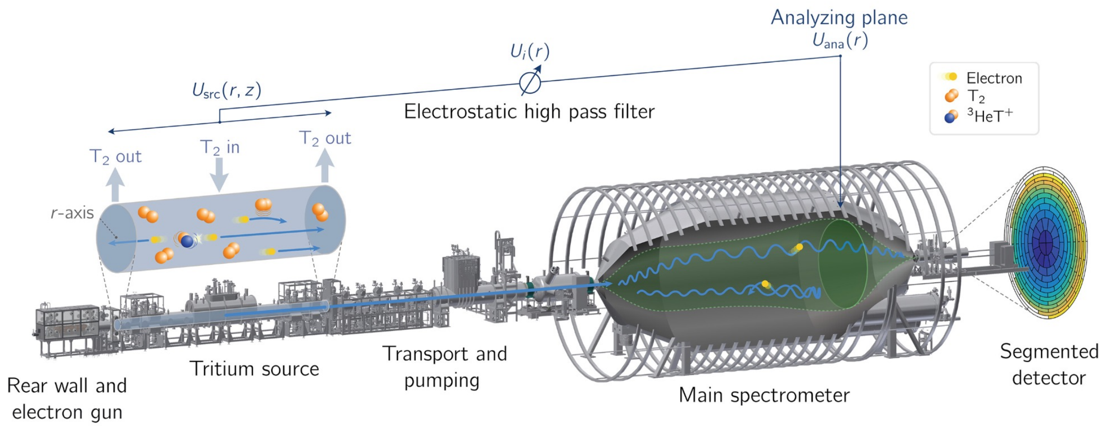
10 meters wide, 200 tonnes!

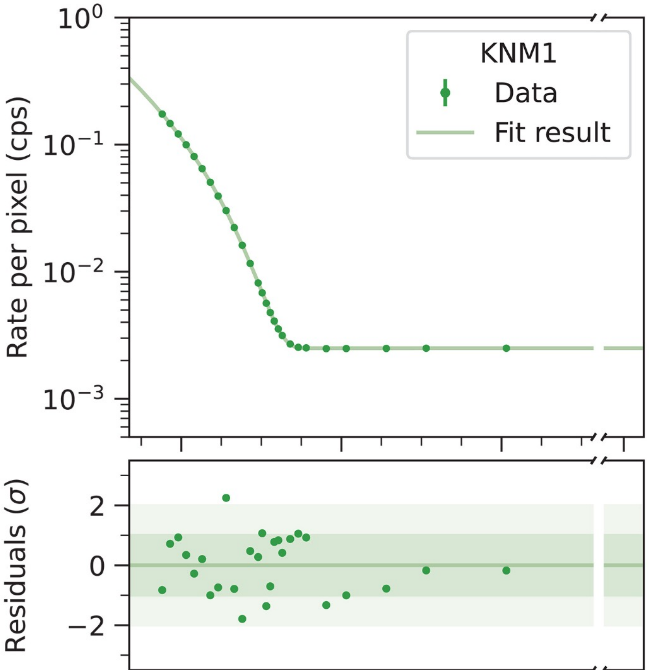
[Read about its journey here]

Beta Decay Kinematics

- Look at the beta decay end point
  - Neutrino mass takes away a bit of energy
  - Fit the end point spectra to extract the mass

- KATRIN has produced the leading limit based on the Magnetic Adiabatic Collimation with electrostatic filtering (MAC-E) principle
  - $m_\nu < 0.45$ eV





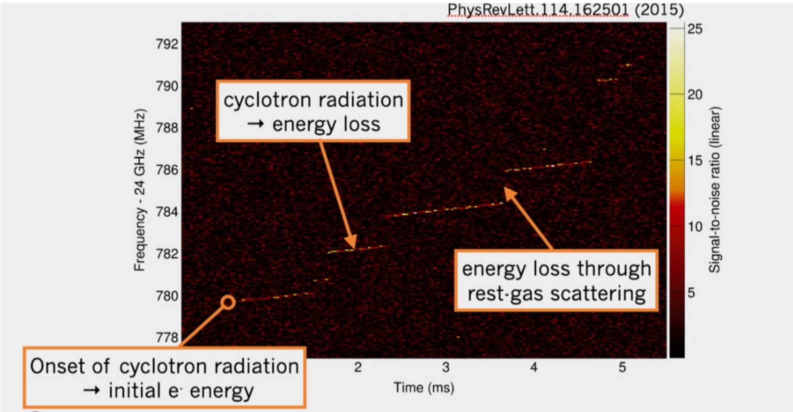
Science **388** (6743), 180–185 (2025)

Beta Decay Kinematics

More ways to probe the end-point spectrum

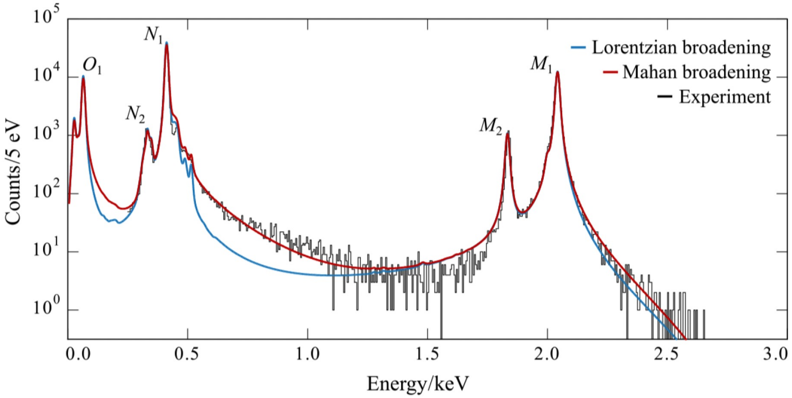
- Project-8:
  - Uses cyclotron radiation emission spectroscopy (CRES) of tritium
  - Precisely measure the start frequency of radiating electron

Spectrogram from Project 8



Phys. Rev. Lett. 131, 102502

- ECHo and HOLMES:
  - Use ^{163}Ho which decays by electron capture
  - Measure precisely all the atomic deexcitation energy



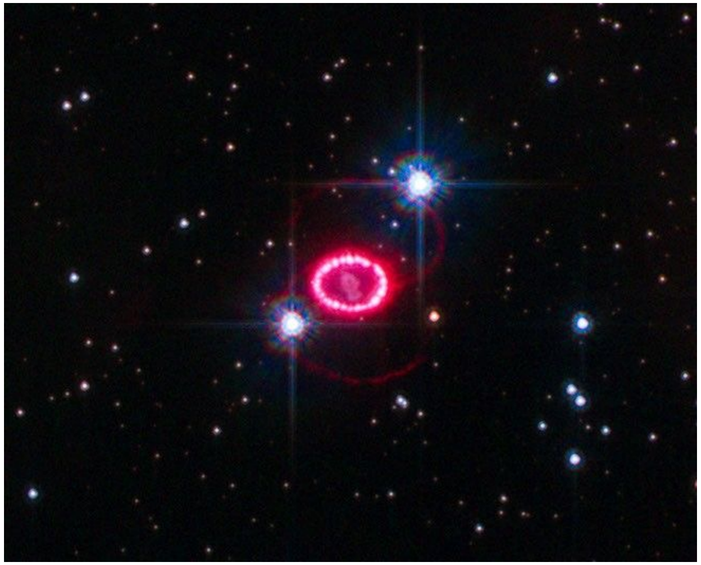
J Low Temp Phys 193, 1137–1145 (2018).

Astrophysics

M. Roos 1987 EPL 4 953

- Timing distribution of neutrinos arriving from a supernova
  - Example is Supernova 1987A
  - Measurements from Kamiokande-II, Mont Blanc, Irvine-Michigan-Brookhaven (IMB), and Baskan
  - 24 neutrinos total
  - $m_\nu < 5.7$ eV
- Current and future neutrino experiments are designed to collect much larger statistics

SN 1987A (~50 kpc)
Large Magellanic Cloud



$$\Delta t = t_2 - t_1 = \frac{Lm^2}{2c}\left(\frac{1}{E_2^2} - \frac{1}{E_1^2}\right)$$

Neutrinos arrive in order of descending energy assuming emitted at the same time

Outlook

Double Beta Decay

- Leading experiments are targeting 10^{28} yr half-life sensitivity
  - ⇥ Will cover inverted mass ordering region
- Active theory effort on matrix element calculations
- To target majority of phase-space we need 10^{30} yr half-life
  - ⇥ New methods needed for large isotope acquisition

Neutrino Mass

- KATRIN finished (new experiment planned), strong experimental efforts from experiments such as Project-8 and Holmium-based experiments so keep an eye out for these
- Maybe we get lucky with another supernova!

Summary

- Neutrinos may be Majorana particles which could provide a source of lepton number violation, a more natural way to explain the neutrino mass and is key for leptogenesis

- Observation of $0\nu\beta\beta$ will tell you neutrinos are Majorana
  - Would be the rarest decays ever discovered

- There is a strong push for discovery with many next-generation experiments targeting 10^{28} year half-life sensitivity

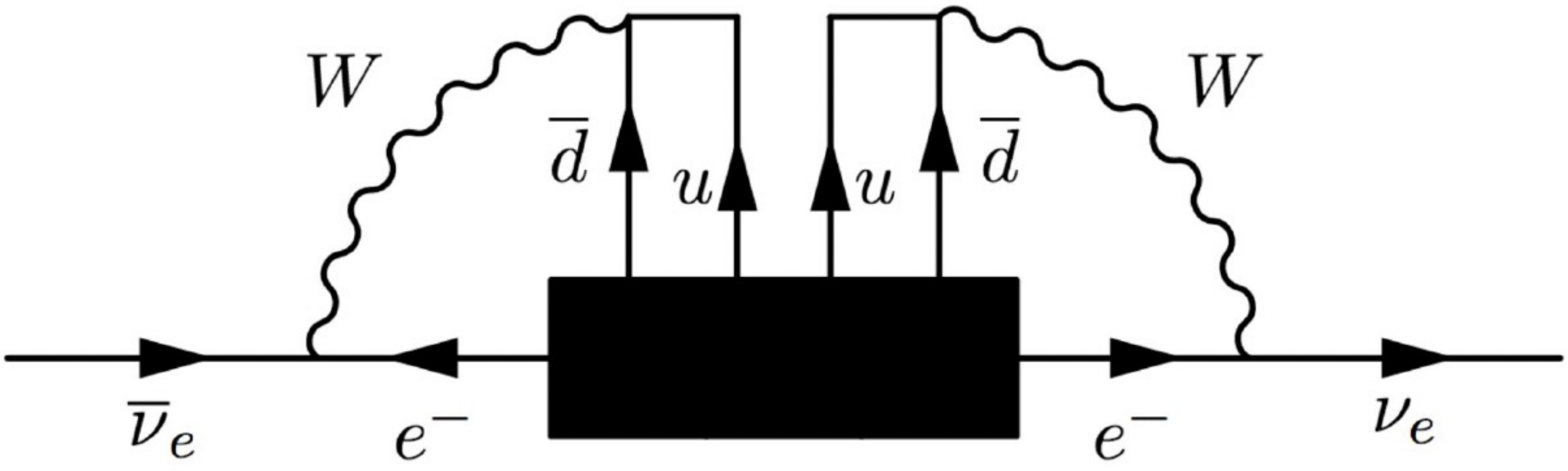
- We don’t know what the neutrino mass is except that its light
  - Being probed using astrophysical methods, cosmology, and beta decay

Extras

Black Box Theorem (Schechter-Valle)

J. Schechter and J. W. F. Valle
Phys. Rev. D 25, 2951

- Light Majorana exchange may induce $0\nu\beta\beta$ and a give source of LNV
  - It may not be the only mechanism driving the process
- Black-box theorem states that for any possible source of LNV that causes $0\nu\beta\beta$, we can draw a Feynman diagram enclosing this new physics
  - We still learn neutrinos are Majorana from observing $0\nu\beta\beta$

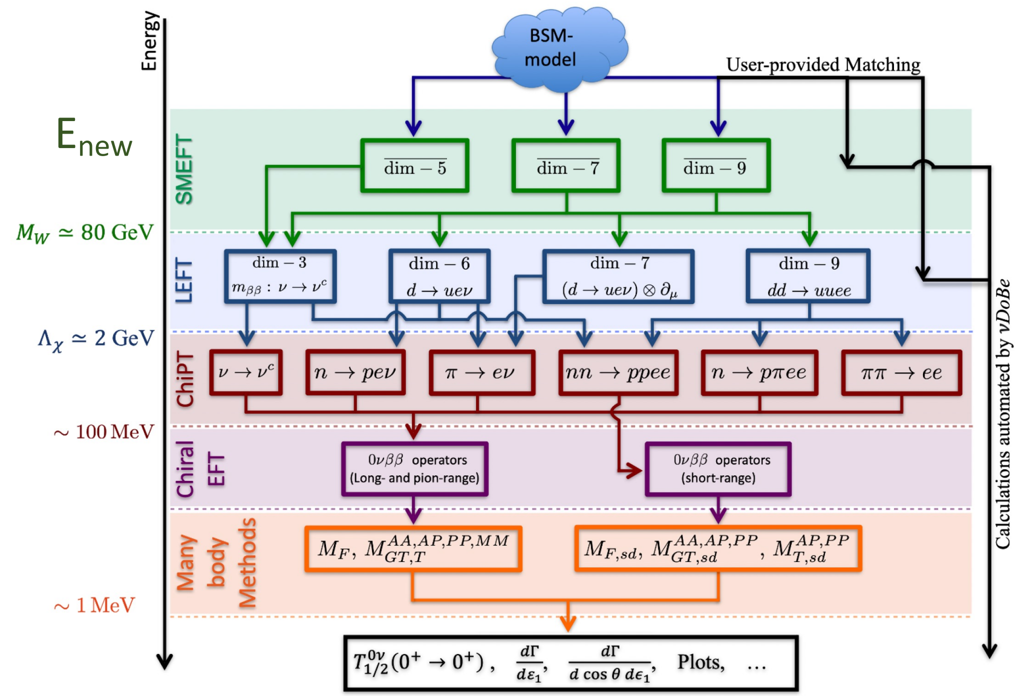


Decay Rate with higher dim operators

- More general form of the decay rate accounting for LNV physics in an EFT framework

$$L = L_{\text{SM}} + \frac{1}{E_{\text{new}}} L_1 + \frac{1}{E_{\text{new}}^2} L_2 + \cdots$$

- Odd operators provide sources of LNV
- Higher order operators can also drive the rate of 0νββ!
- They also change the half-life and beta kinematics like the individual beta energies and their angle
  - If your detector can resolve this information, you can probe the underlying mechanism



Scholer et al JHEP. 2023, 43 (2023)