Lecture 1

Neutrinoless Double Beta Decay

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General Remarks

- Student background and preparation varies
  - Some of you will have had nuclear and/or particle physics at an advanced level; but not all of you
  - In the first lecture, I will try to connect to basic graduate subatomic physics
- As postdoctoral researchers, you will learn to cope with imperfect knowledge
  - Qualitative rather than quantitative understanding
  - I am an experimentalist! I will focus on measurements but theory is critical.
- I will try to communicate the “big picture”
  - necessary general knowledge for students focused on other subfields

Resources and Acknowledgements

- The Physics of Massive Neutrinos: Boehm and Vogel, Cambridge University Press, 2nd Edition, 1992
- The Dynamics of the Standard Model: Donoghue, Golowich and Holstein, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology, Second Edition, 2014
- 2016 NNPSS Lectures of Vincenzo Cirigliano at MIT
- Writeup of Lectures by Petr Vogl, Massive Neutrinos, 1997 Mexican Summer School on Astrophysics and Cosmology
- Slides from the opening workshop of the INT Program on Neutrinoless Double-Beta Decay, June 2017: http://www.int.washington.edu/talks/WorkShops/int_17_2a/

The EXO-200 and nEXO collaborations and many other colleagues:
J. Detwiler, J. Engel, K. Heeger, Y. Kolomensky, R. Maruyama, M. Ramsey-Musolf, W. Rodejohann, J. Wilkerson…

Plan for Lectures

- **Lecture 1**

  necessary general knowledge for experimentalists

  - Nomenclature, Theoretical Overview, Physics Motivation, Goal for Experiments, Overview of Experimental Techniques

- **Lecture 2**

  necessary general knowledge for theorists

  - Overview of Experimental Program Worldwide, Details of 3 Initiatives aiming for the Ton-Scale, Detailed Description of EXO-200 and nEXO

Prelude

What are we made of? **What holds us together?**

Fundamental Particles and Forces

How did the complex structures we see emerge from the Big Bang?

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	(0–0.13)×10⁻⁹	0
e electron	0.000511	–1
ν_M middle neutrino*	(0.009–0.13)×10⁻⁹	0
μ muon	0.106	–1
ν_H heaviest neutrino*	(0.04–0.14)×10⁻⁹	0
τ tau	1.777	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

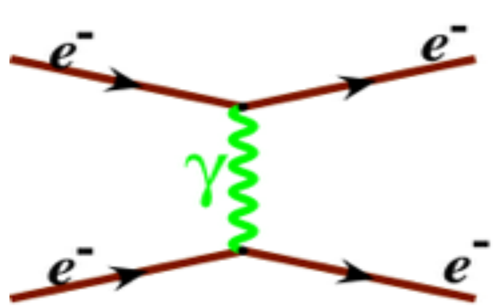
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W⁻	80.39	–1
W⁺ W bosons	80.39	+1
Z⁰ Z boson	91.188	0

Strong (color) spin = 1

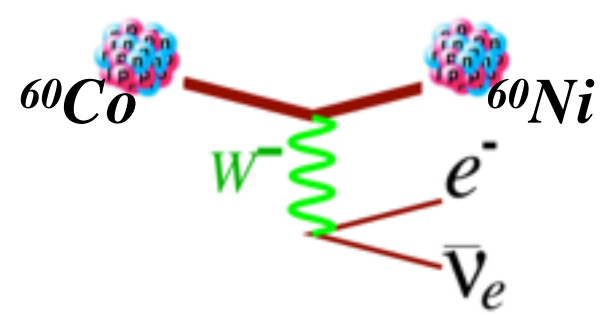
Name	Mass GeV/c²	Electric charge
g gluon	0	0

H^0 spin 0

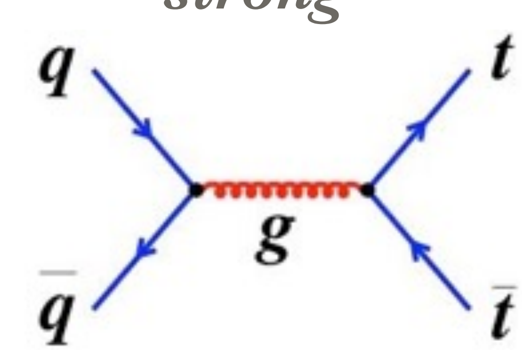
electromagnetic (EM)



Weak



strong



Were there other superweak forces in the early universe?
Was there a single unified superforce in the early universe?
Do quarks and leptons have substructure?
How do protons, neutrons and nuclei emerge from quarks and gluons?
Are there fundamentally new emergent properties of protons and nuclei?

SU(2)$_L$ X U(1)$_Y$ Electroweak Theory: A Model of Leptons

$e^-, \mu^-, \tau^- \Rightarrow Q = -e;$

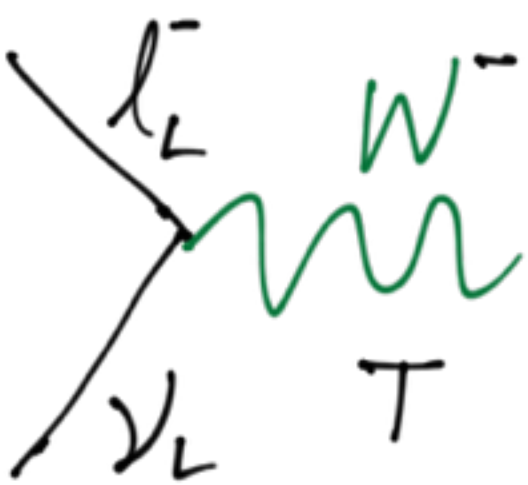
$\nu_e, \nu_\mu, \nu_\tau \Rightarrow Q = 0$

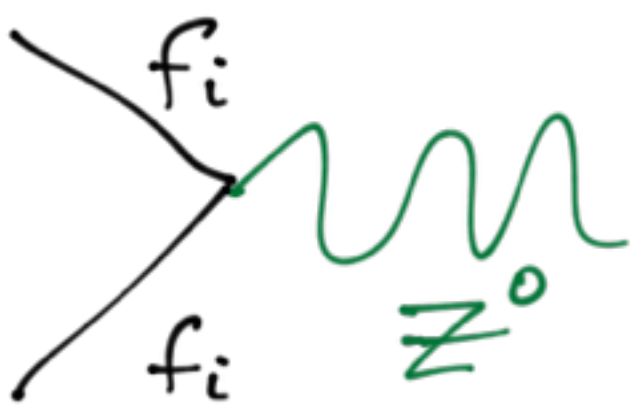
$\begin{pmatrix} \nu \\ \ell^- \end{pmatrix}_L \quad \ell^-_R \quad \nu_R$

$\pm 1/2 \quad 0 \quad 0 \Rightarrow T_3$

$$Q = T_3 + Y/2$$

$Y_{\nu_L} = -1$ $\quad$ $Y_{\nu_R} = 0$





$g_V = T_3 - Q\sin^2\theta_W$

$g_A = T_3$

Right-handed neutrino has no gauge interactions

Neutrino Oscillations!

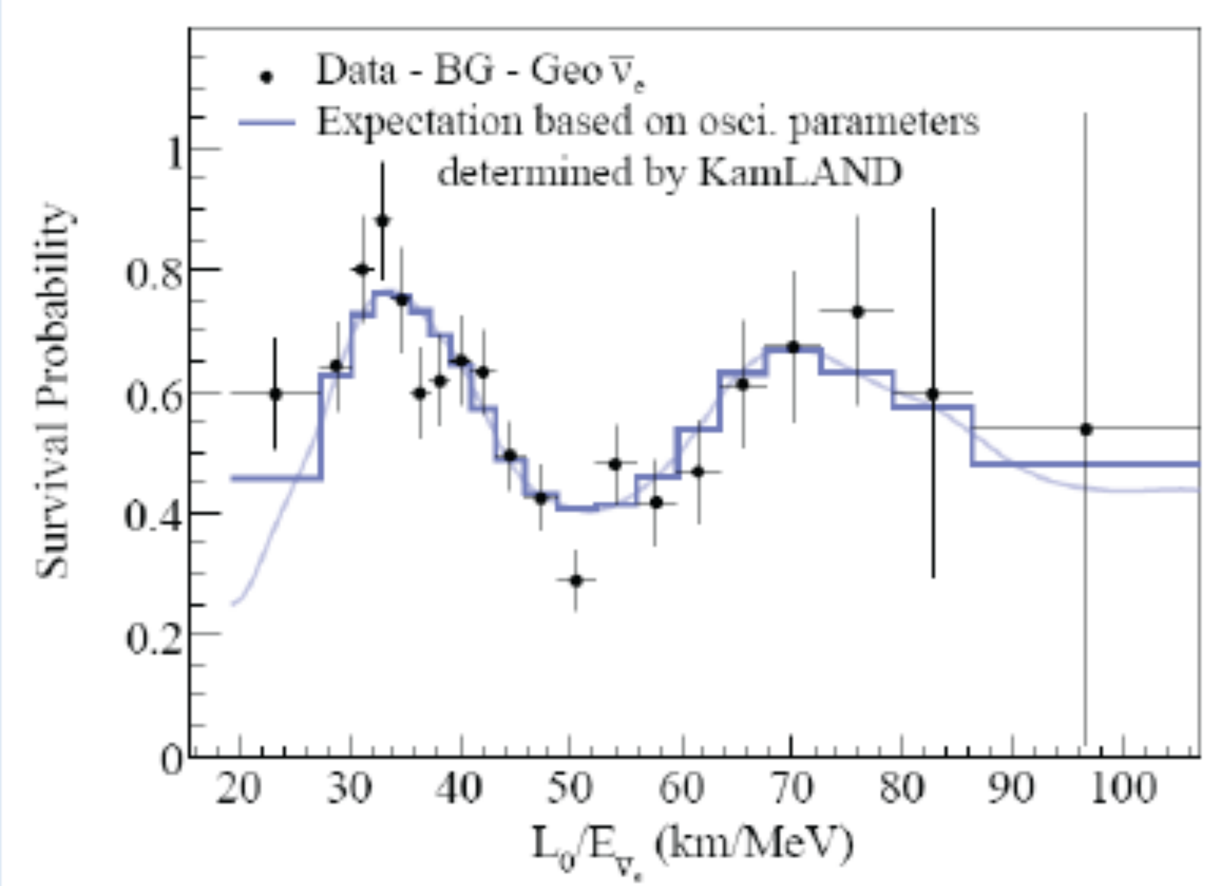
Neutrino Oscillation experiments

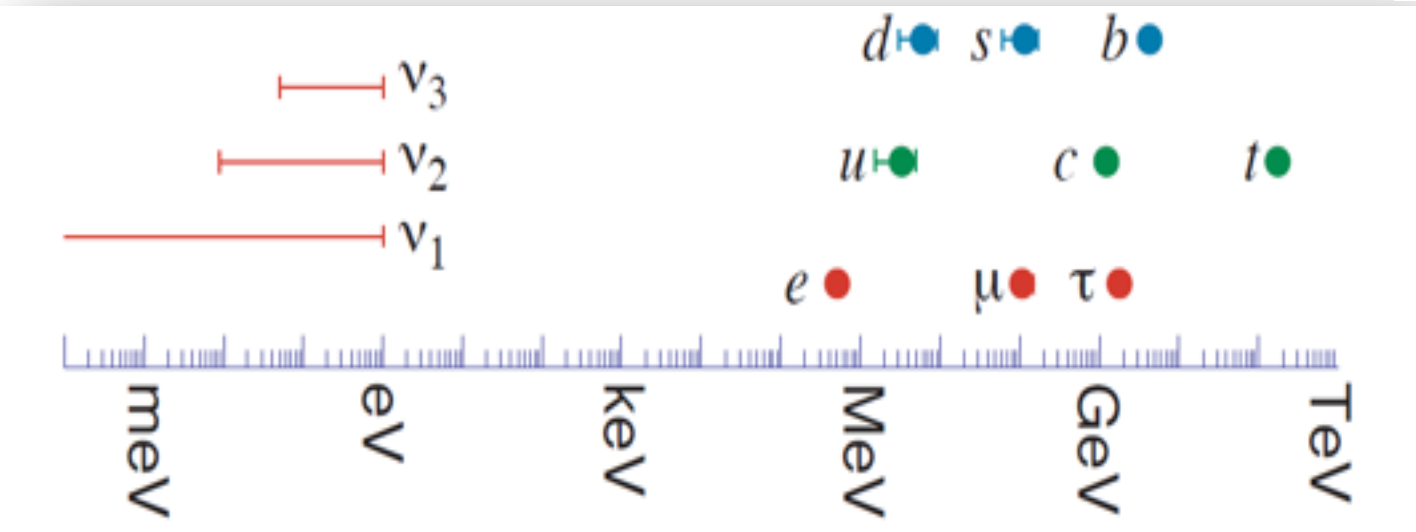
- Neutrinos undergo flavor-changing oscillations
- Neutrinos have mass

$|\Delta m^2_{32}| \simeq 2\times10^{-3} eV^2$ $\quad |\Delta m^2_{21}| \simeq 7.5\times10^{-5} eV^2$

$m_i \equiv$ mass eigenstates

$m_\alpha \equiv$ Flavor eigenstates





- **Why is neutrino mass so small?**
- **How small is it?**
- **What is the mass generating mechanism?**
- **And…**

Used to be trivial when we thought neutrinos were massless

Neutrino Handedness

A massive spin-1/2 fermion has two projections:

→ **left- and right-handed**

Helicity $\equiv \vec{p} \cdot \vec{\Sigma} \equiv h = \pm 1$

$$P_{L,R} u \equiv u_{L,R}$$

$$P_i P_j = \delta_{ij} P_j$$

Chirality $\equiv \frac{1 \pm \gamma^5}{2} \equiv P_{L,R}$

$$\sum_i P_i = I$$

For a massless particle (or ultra-relativistic limit)

→ helicity = chirality

Massive particles: both chiralities must exist

Original formulation of the Standard Model: ν massless and no right-handed state

Postulate the Right-Handed Neutrino

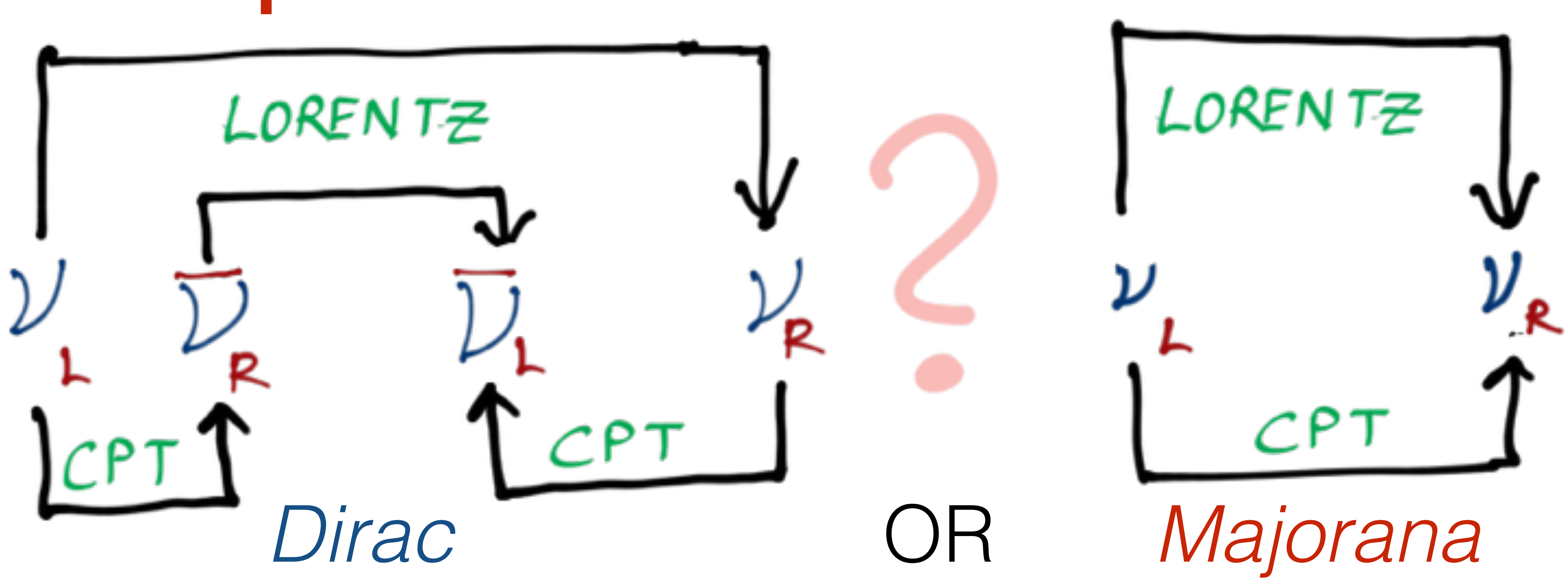
$$\nu_L \xrightarrow[\text{boost}]{\text{Lorentz}} \nu_R \qquad\qquad u_L \xrightarrow[\text{propagation}]{\text{free}} u_R$$

helicity: conserved but not Lorentz invariant

chirality: not conserved but Lorentz invariant

CPT transformation: left-handed particle to right-handed anti-particle

A profound question:



Majorana Particles

Recommended article: F. Wilczek, Nature Physics, Sept. 2009

In 1928, Dirac discovered the framework to describe relativistic spin-1/2 particles

Dirac 4-spinors are complex fields and naturally explain the existence of anti-particles with opposite quantum numbers

In 1937, Majorana discovered that a simple modification to Dirac's equation leads to the possibility to describe electrically neutral, massive spin-1/2 fermions with real fields!

A neutrino can therefore be its own anti-particle

What is the Discovery Measurement?

Neutral Current interactions have subtle differences

But

Dirac-Majorana Confusion Theorem: the difference between ν_D and ν_M interactions vanishes in the ultra-relativistic limit

Exotic possibilities beyond Standard Model V-A

Nevertheless

The most pragmatic approach to discover the Majorana nature of neutrinos is to search for **Lepton Number Violation (LNV)**

Practically: discover **Neutrinoless Double-Beta Decay** **($0\nu\beta\beta$)**

Theoretical Foundations

Symmetries and Conservation Laws

Noether's Theorem: If Euler-Lagrange equation is invariant under any coordinate transformation, $\exists$ an integral of motion

Symmetry		conservation law
translation	⟺	momentum
time	⟺	energy
rotation	⟺	angular momentum

Not just space-time symmetries: Invariance of Lagrangian/Hamiltonian

e.g. Charge Conservation

$$[Q, H] = 0 \rightarrow \frac{d < Q >}{dt} = 0$$

$$Q|\Psi >= q|\Psi >$$

Conserved Quantities/Quantum Numbers

Conserved Quantities

Dirac free particle Lagrangian $\overline{\psi}(i\gamma^{\mu}\partial_{\mu}-m)\psi$

global phase transformation $\psi \rightarrow e^{iq\alpha}\psi$

U(1) Invariance: conserved current $\partial_{\mu}J^{\mu}=0$ $J^{\mu}=q\,\overline{\psi}\gamma^{\mu}\psi$

conserved electromagnetic current → **charge conservation** → **additive conservation law**

$q \rightarrow e^{i\phi_q} q$ $l \rightarrow e^{i\phi_L} l$

*Similarly, SM Lagrangian invariant under global phase transformations associated with total baryon number **B** and total lepton number **L***

$$J_{\mu}^{B}=\frac{1}{3}\left(\overline{u}\gamma_{\mu}u+\bar{d}\gamma_{\mu}d+\ldots\right)$$

$$J_{\mu}^{L}=\bar{e}\gamma_{\mu}e+\overline{\nu}_{eL}\gamma_{\mu}\nu_{eL}+\ldots$$

Example Processes

$p \rightarrow e^+ \pi^0$ Proton Decay

B: +1 → 0 0 Forbidden if B is conserved

$n \rightarrow p e^- \bar{\nu}_e \Rightarrow \bar{\nu}_e p \rightarrow e^+ n$ but never $\bar{\nu}_e n \rightarrow e^- p$

L: 0 → 0 +1 −1; −1 0 → −1 0; −1 0 → +1 0

$\pi^+ \rightarrow \mu^+ \nu_\mu \Rightarrow \nu_\mu N \rightarrow \mu^- X$ but never $\mu^+ X$

L: 0 → −1 +1; +1 0 → +1 0; −1 0

Introduce Lepton Number:

$$L_{e^-} = L_{\nu_e} = -L_{e^+} = -L_{\bar{\nu}_e} = +1$$

This is encoded into the Standard Model Feynman Rules

Conservations Laws consistent with Standard Model

- *Only B-L strictly conserved in the Standard Model*
- *B+L is violated due to anomalies*
- *No fundamental reason to expect B and L to be conserved (assuming only 4 forces in Nature)*

What if CHIRALITY is the key rather Lepton Number?

Neutrinos only interact via the weak interaction, which is parity-violating

$\mu^+ \leftarrow \pi^+ \rightarrow \nu_L \;\Rightarrow\; \nu_L \rightarrow \mu^- \qquad \nu_R \rightarrow \mu^+$

Lepton Number Conservation not required

Dirac and Majorana Masses

If $\nu_R \Longleftrightarrow \overline{\nu}_R$ Majorana Neutrino

L +1 -1

L is violated

No experimental observation precludes this possibility

Most general mass terms for right-handed neutrino:

$$-g_\nu \bar{l}_L \Phi \nu_R - \frac{m_M}{2} (\overline{\nu}_R)^c \nu_R + h.c.$$

After spontaneous symmetry breaking: $m_D \equiv g_\nu \frac{v}{\sqrt{2}}$

$$\mathcal{L}_{D+M} = -\frac{1}{2} \begin{pmatrix} \overline{\nu}_L & \overline{\nu^c_R} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix} + h.c$$

Lepton Number Conservation or Not?

If $\nu \rightarrow e^{i\phi_L}\nu$ m_M term in Lagrangian not invariant

Dirac neutrino: equivalent to demanding L conservation

→ $m_M = 0$, *one limit of general neutrino mass terms*

Another limit: A very heavy m_M and a light state $m = \frac{m_D^2}{m_M}$ (See-Saw mechanism)

No SM symmetry precludes m_M from being arbitrarily large

2 self-conjugate states, each with left- and right-handed components

Natural explanation of light neutrino masses

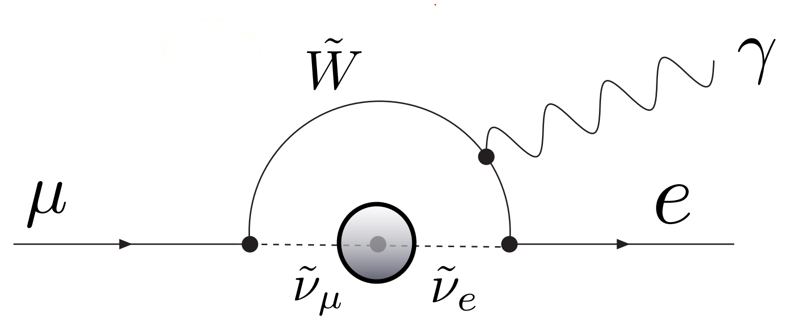
A new heavy scale for physics beyond the SM

Lepton Number vs Lepton Flavor

Neutrino Oscillations: $\nu_e \Leftrightarrow \nu_\mu \Leftrightarrow \nu_\tau$

Neutrino flavor not conserved

Charge lepton flavor not expected to be conserved either



$\mu^- + N \rightarrow e^- + X$

Branching Ratio $< 10^{-50}$

unless there is new physics beyond the Standard Model

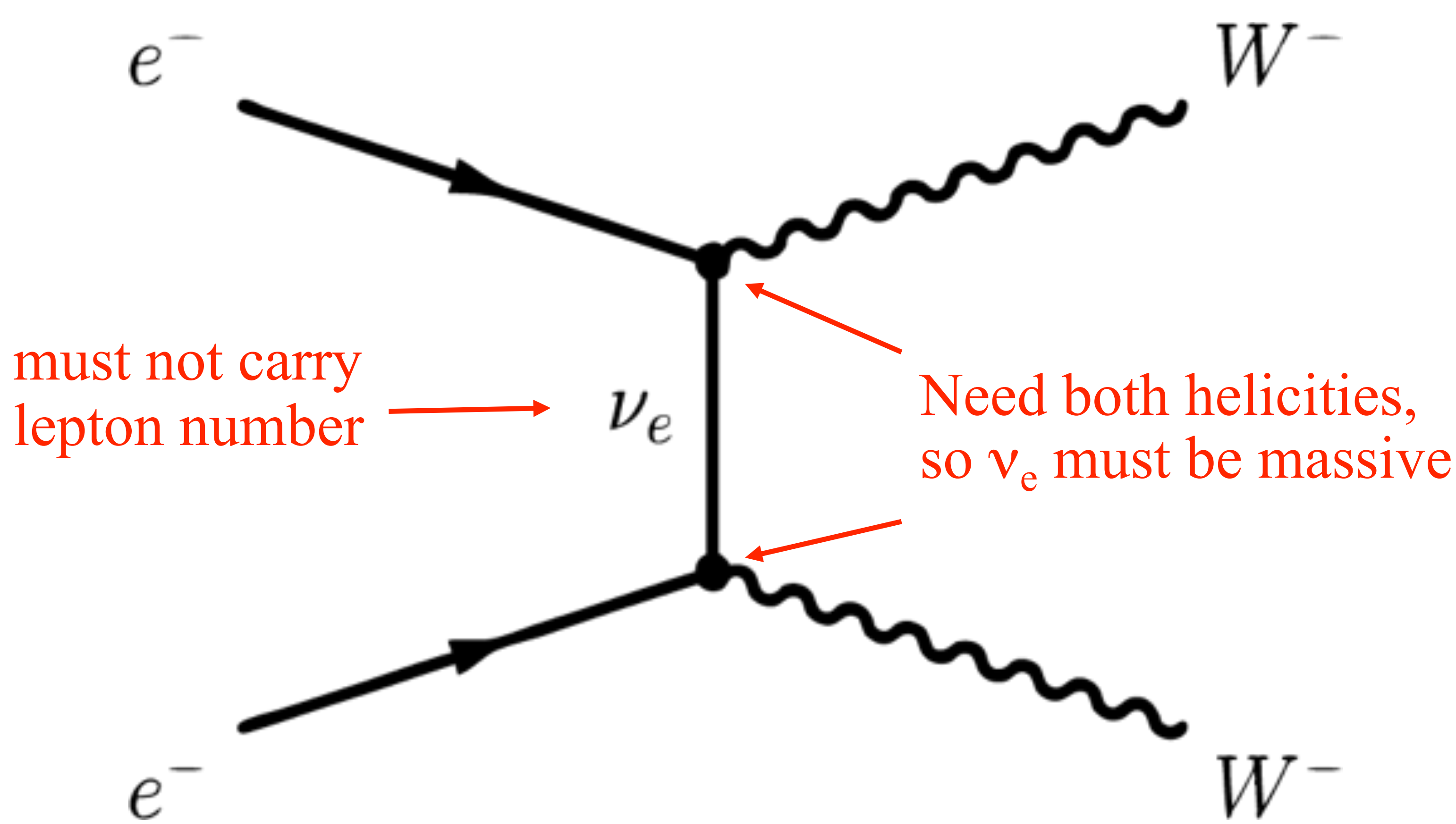
Total lepton number L? total number of $l^- + \nu_l$

Search For Lepton Number Violation

A Gedanken Experiment

L +1 +1 0 0

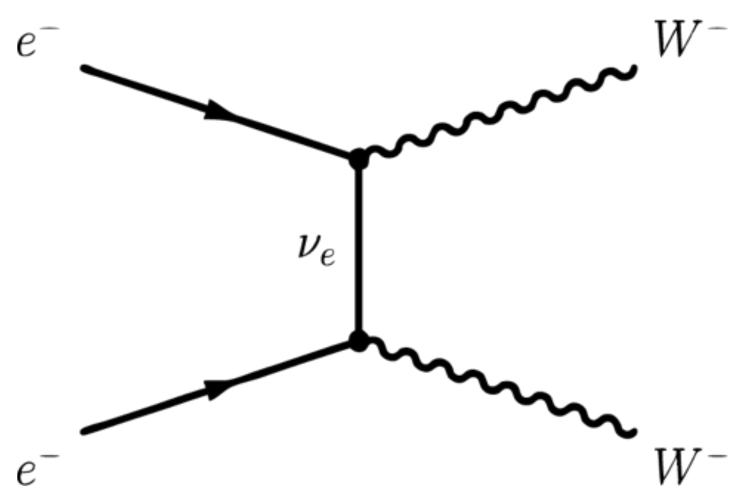
$e^- + e^- \Longrightarrow W^+ + W^-$



Lepton number changes by two units: $\Delta L=2$

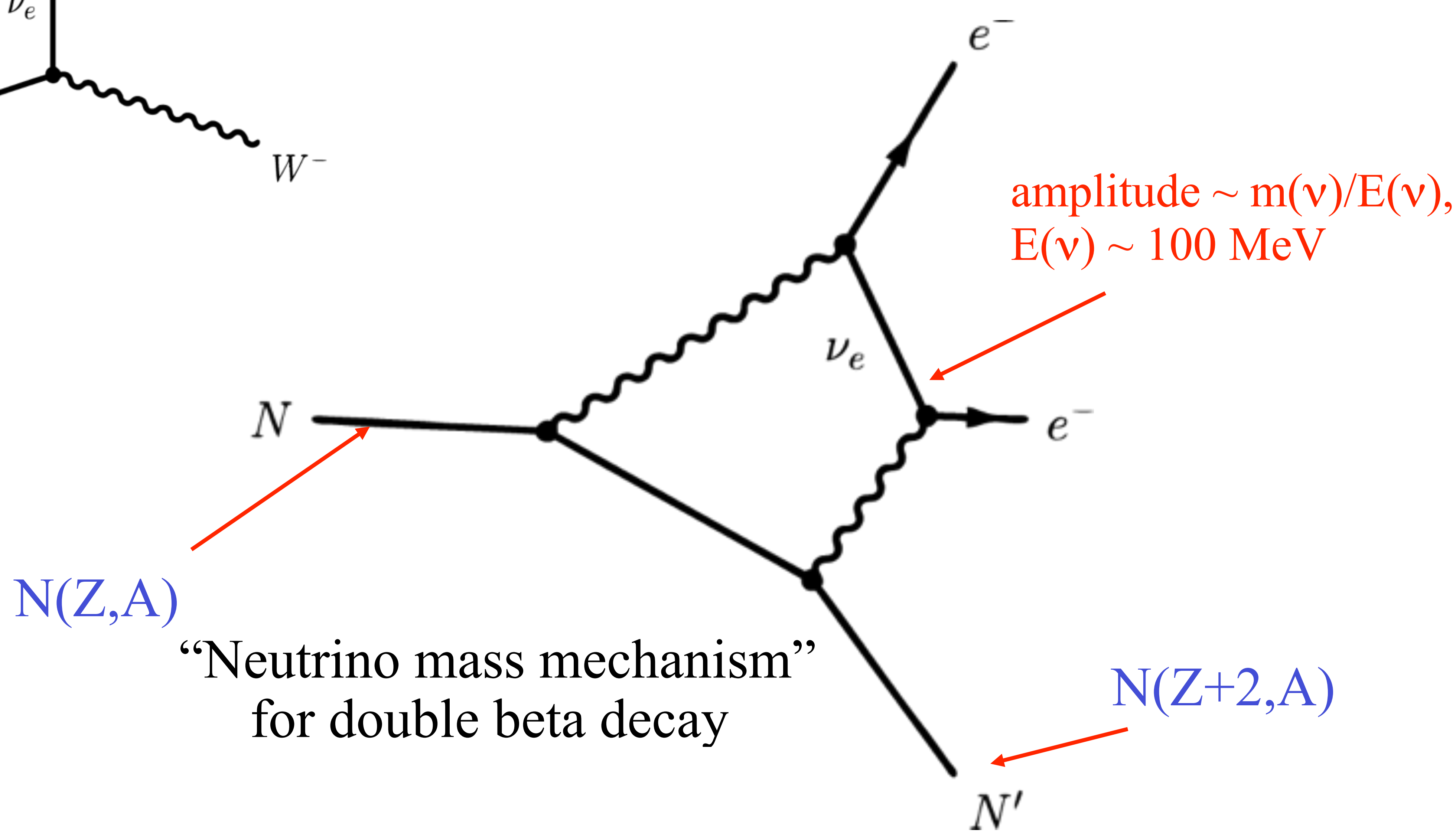
For light neutrinos, this cross-section is unobservably small

Virtual W's Instead



Lepton number changes by two units: ΔL=2

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



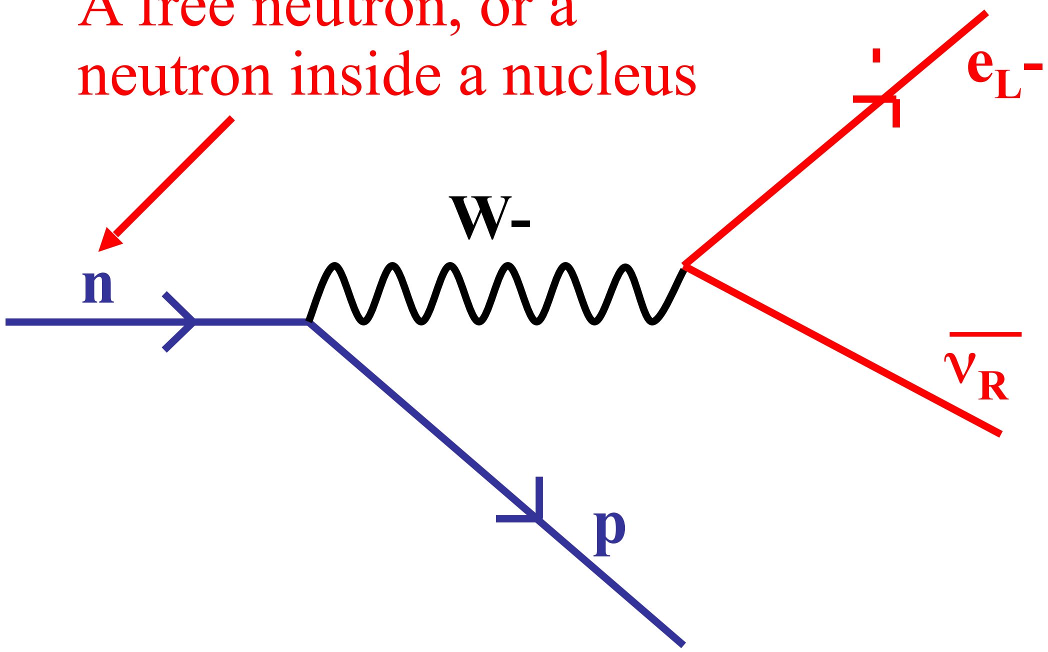
"Neutrino mass mechanism"
for double beta decay

Racah and Furry suggested this was possible for Majorana particles in 1937 soon after Majorana published his theory!

Lepton Number Conserving Standard Model Process

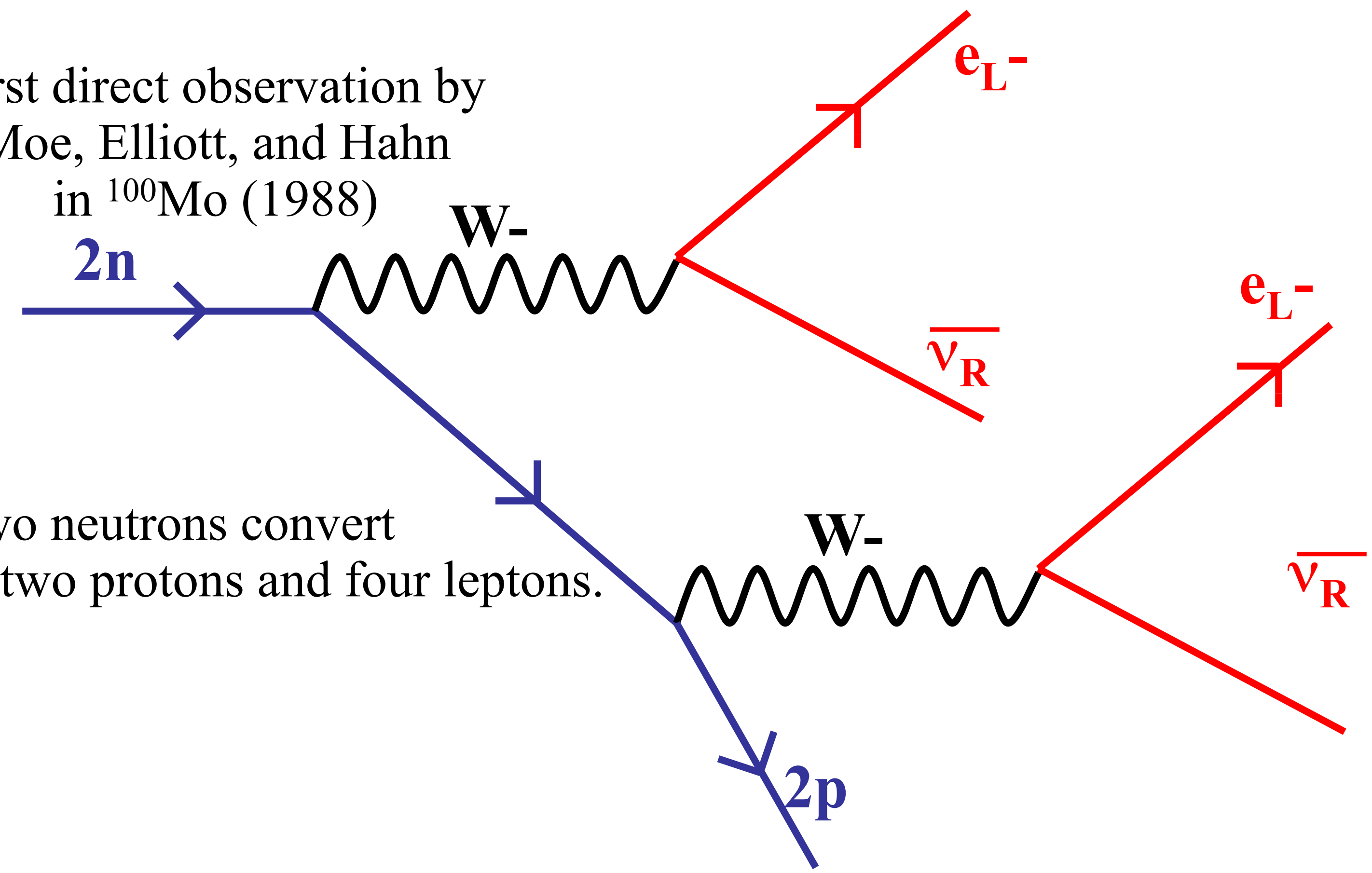
2ν Double Beta Decay

A free neutron, or a neutron inside a nucleus



Nuclear Beta Decay

First direct observation by Moe, Elliott, and Hahn in ^{100}Mo (1988)



Two neutrons convert to two protons and four leptons.

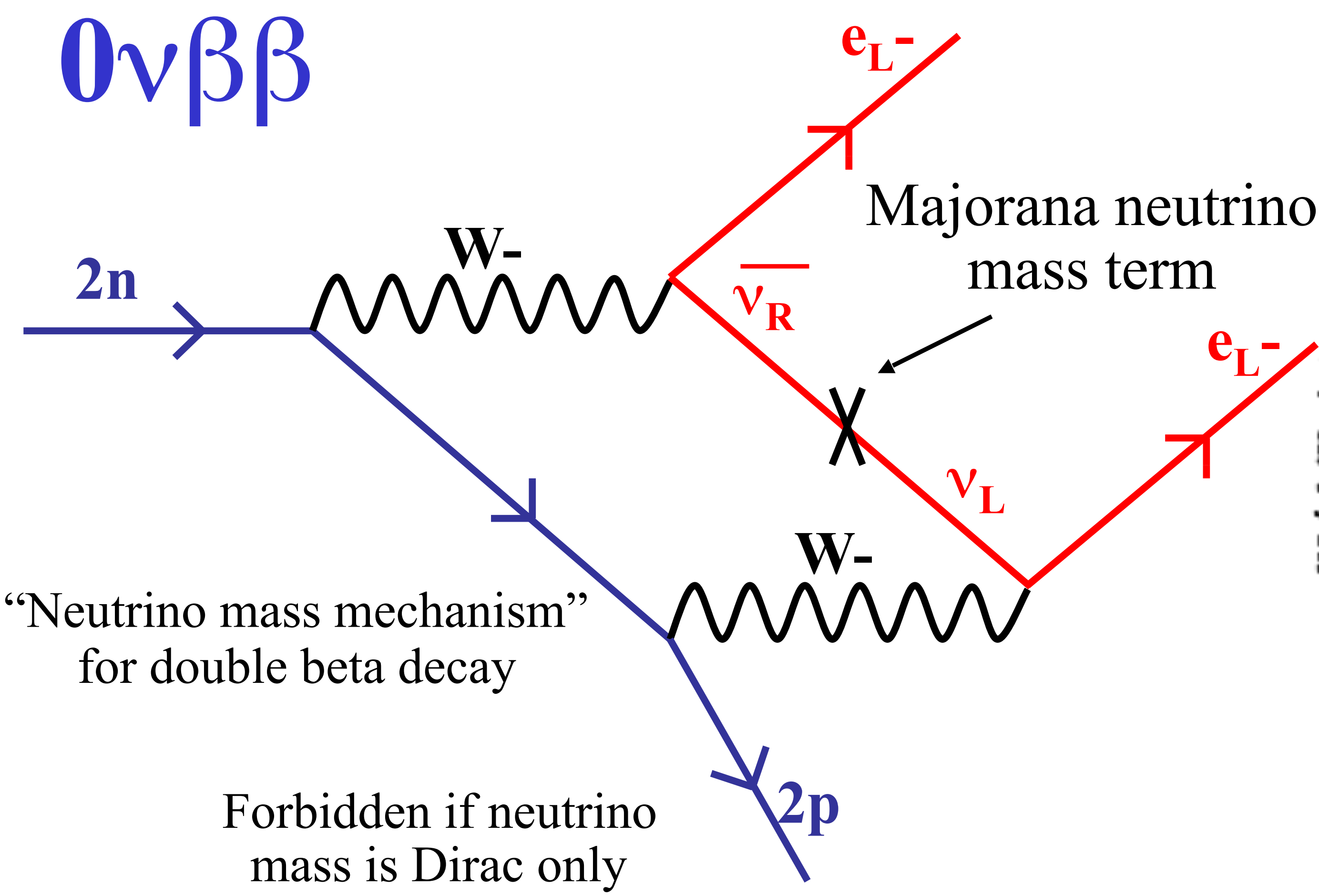
Nuclear Double-Beta Decay with the emission of two neutrinos

Suggested by Maria Goeppert-Mayer in 1935!

0ν Double Beta Decay

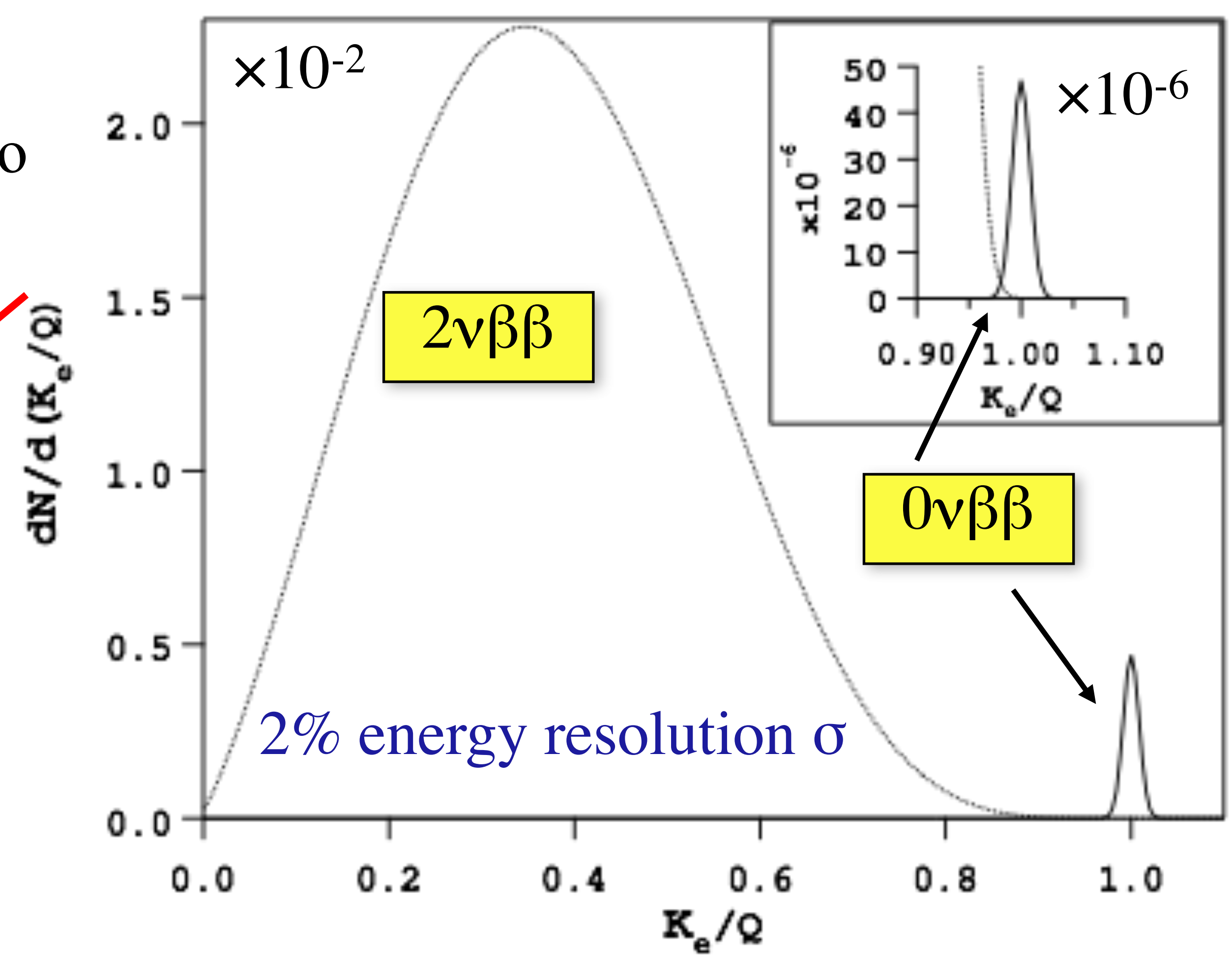
Experimental Signature

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



"Neutrino mass mechanism" for double beta decay

Forbidden if neutrino mass is Dirac only (violates lepton number conservation).

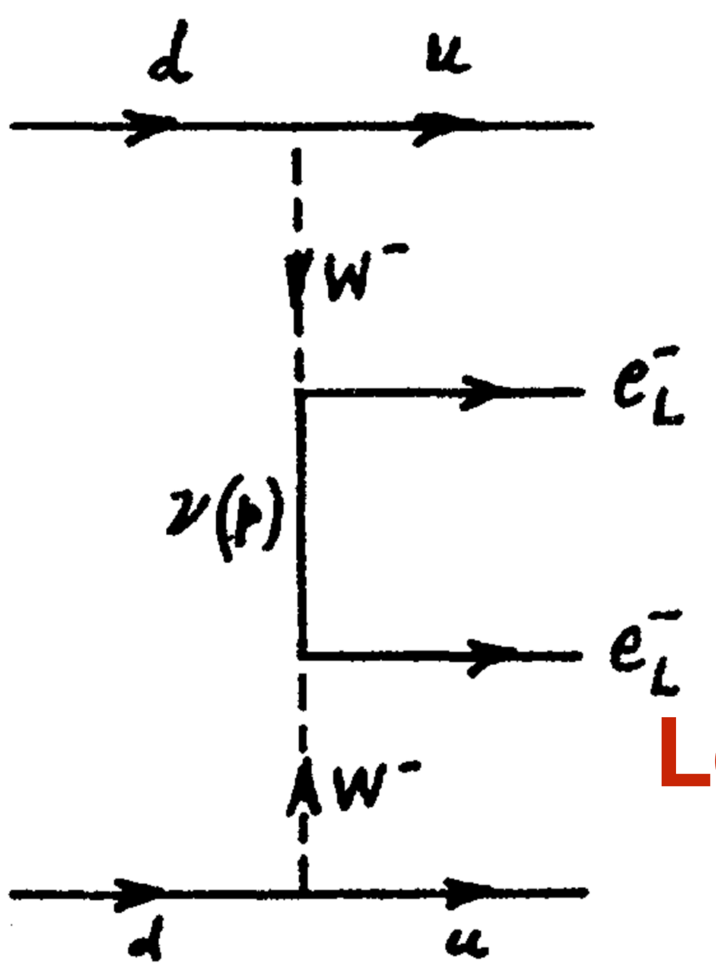


If observed, it would unambiguously signal that Lepton Number is NOT a conserved quantity, and that neutrinos are Majorana particles i.e. their own anti-particles

Schechter and Valle, PRD 25, Vol. 11 (1982)

A Theorem

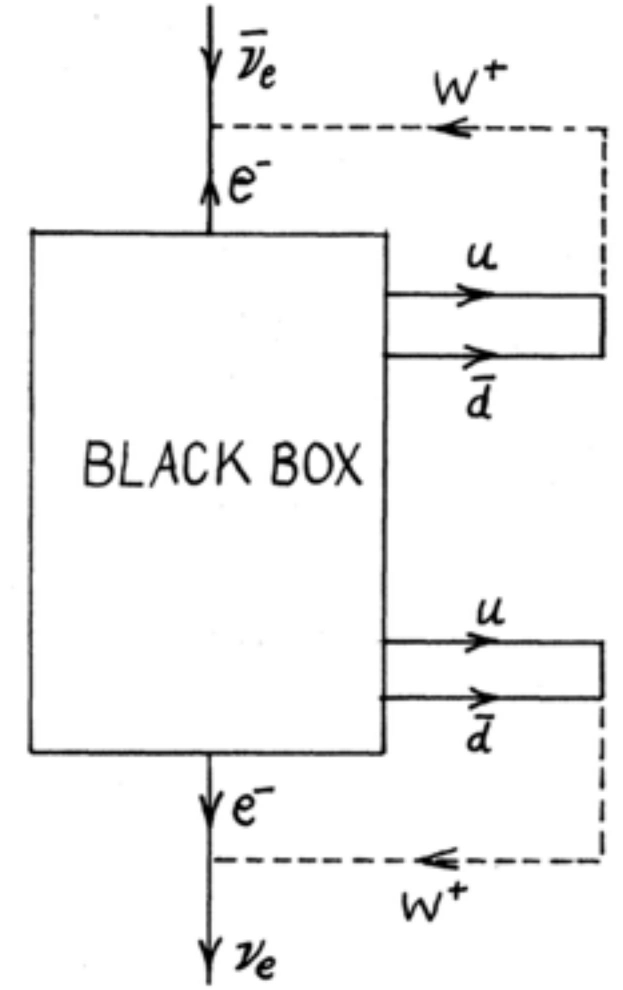
*If neutrinoless double-beta decay occurs, there exists a way to convert an anti-neutrino to a neutrino, a **Majorana mass** amplitude*



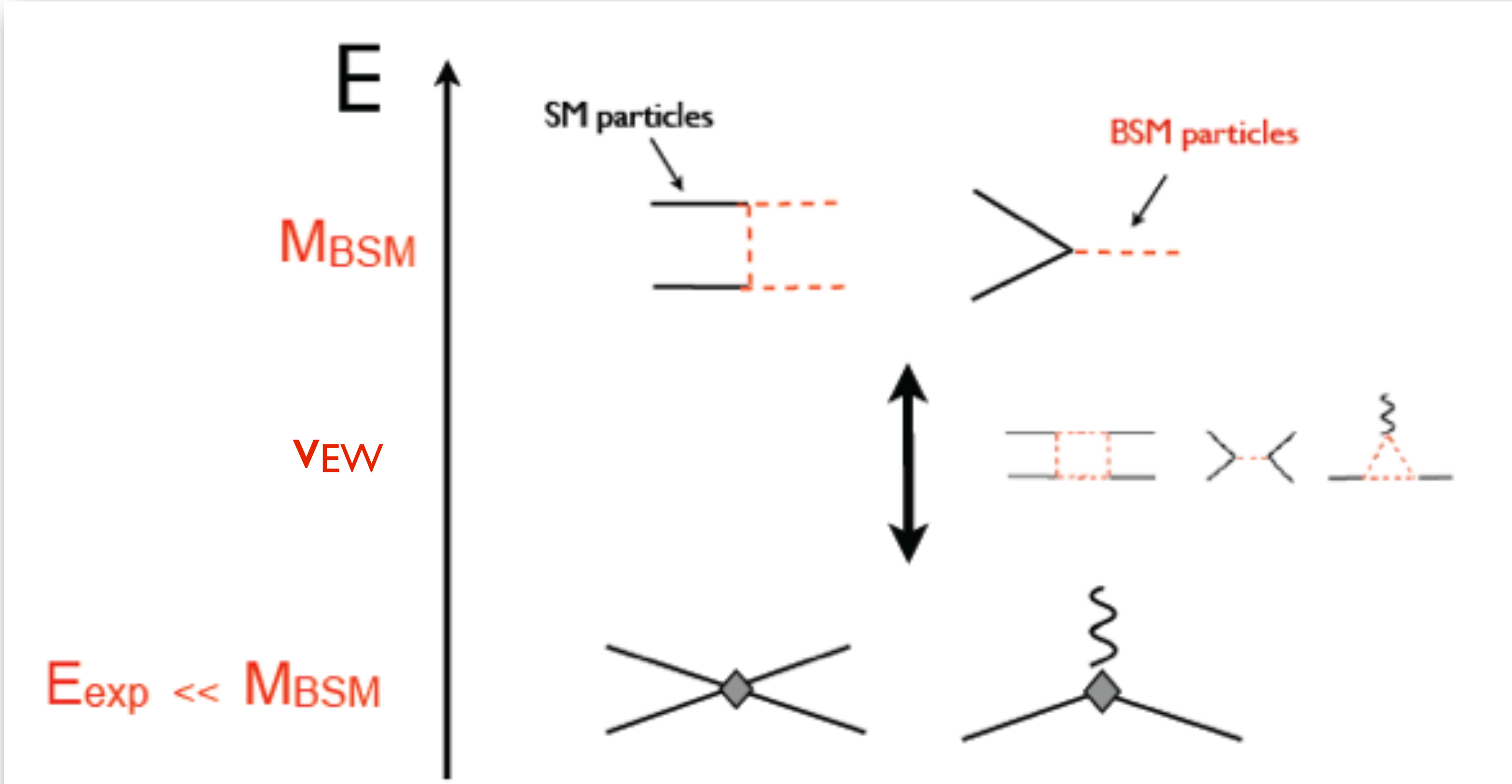
No caveats:

0νββ

Lepton Number Violation
and
Majorana Neutrinos



BSM Effective Theory



- EFT expansion in E/M_{BSM}, M_W/M_{BSM}

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

$$\Lambda \leftrightarrow M_{\rm BSM}$$

$$C_i \; [g_{\rm BSM}, \; M_a/M_b]$$

- Each model generates its own pattern of operators: experiments at $E << M_{BSM}$ can *discover* and *tell apart* new physics scenarios

Dimension-5 Operator

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Weinberg 1979

- Dim 5: only one operator

$$\hat{O}_{\rm dim=5} = \ell^T C \epsilon \varphi \, \varphi^T \epsilon \ell \qquad C = i\gamma_2\gamma_0$$

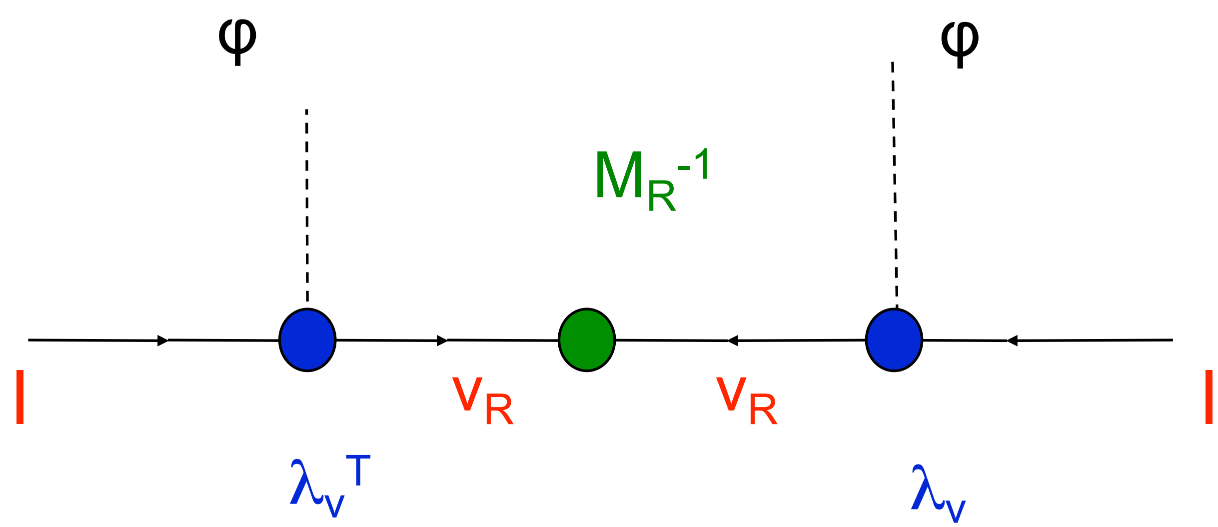
- Violates total lepton number ($l \rightarrow e^{i\alpha} l$, $e \rightarrow e^{i\alpha} e$)
- Generates Majorana mass for L-handed neutrinos (after EWSB)

$$\frac{1}{\Lambda}\hat{O}_{\rm dim=5} \xrightarrow{\langle\varphi\rangle = \binom{0}{v}} \frac{v^2}{\Lambda}\nu_L^T C \nu_L$$

- "See-saw": $m_\nu \sim 1\,{\rm eV} \rightarrow \Lambda \sim 10^{13}\,{\rm GeV}$

Explicit Realizations

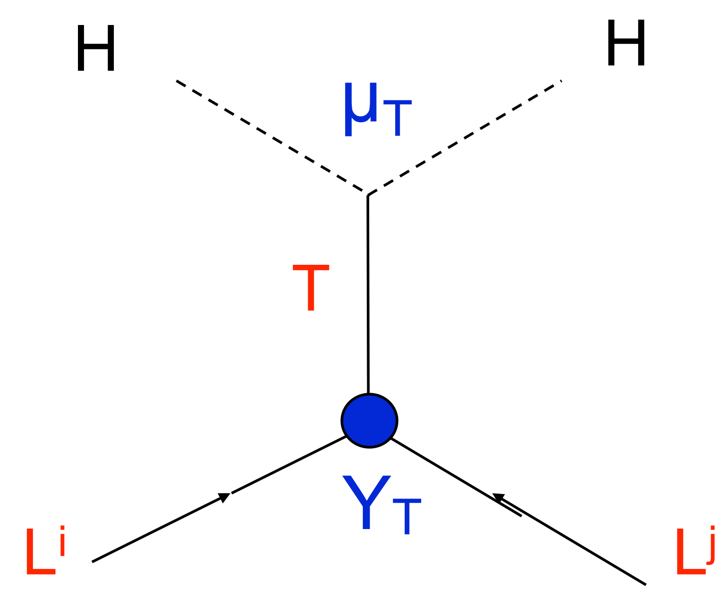
- Models with heavy R-handed Majorana neutrinos



$$g \sim \lambda_\nu^T M_R^{-1} \lambda_\nu$$

$$\mathcal{L}_5 = g_{\alpha\beta}\, \ell_\alpha^T C \epsilon \varphi\, \varphi^T \epsilon \ell_\beta$$

- Or with triplet Higgs field: no heavy neutrinos!



$$g \sim \mu_T M_T^{-2} Y_T$$

$$\mathcal{L}_5 = g_{\alpha\beta}\, \ell_\alpha^T C \epsilon \varphi\, \varphi^T \epsilon \ell_\beta$$

Other Possibilities for the Black Box

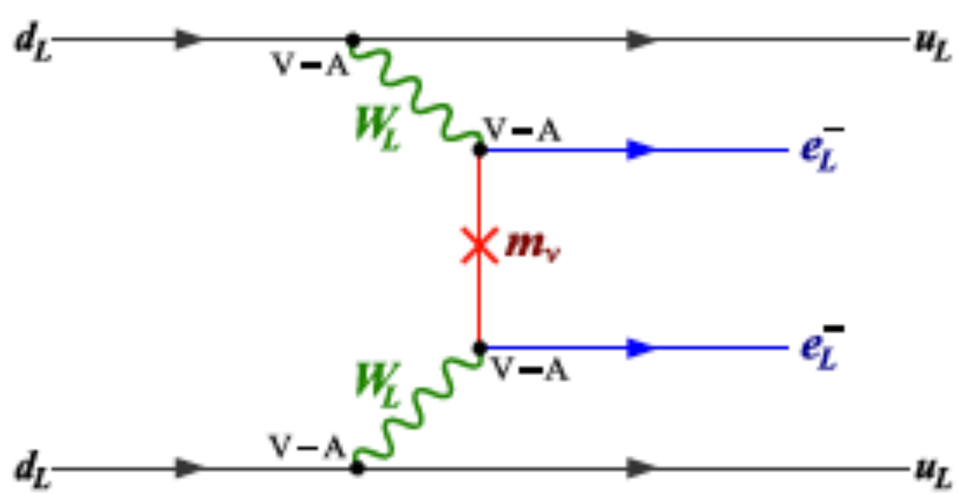
(Classifying sources of LNV: organize discussion by scales)

- LNV dynamics at very high scale (Λ>> TeV)

Low energy footprints encoded in the leading dim-5 operator

$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\, H H$$

This is a Majorana mass term for ν's: NLDBD mediated by light ν exchange



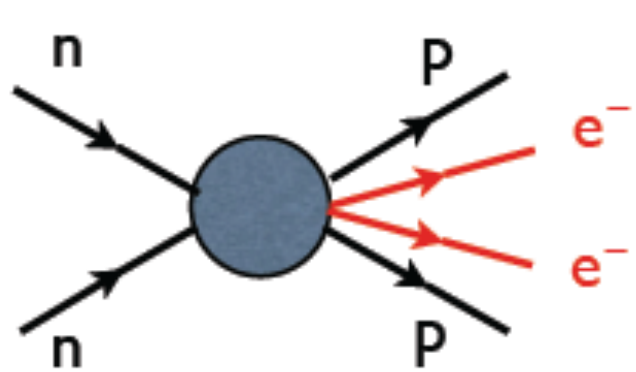
Other Possibilities for the Black Box

(Classifying sources of LNV: organize discussion by scales)

- LNV dynamics at very high scale (Λ>> TeV)

$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\,H\,H$$

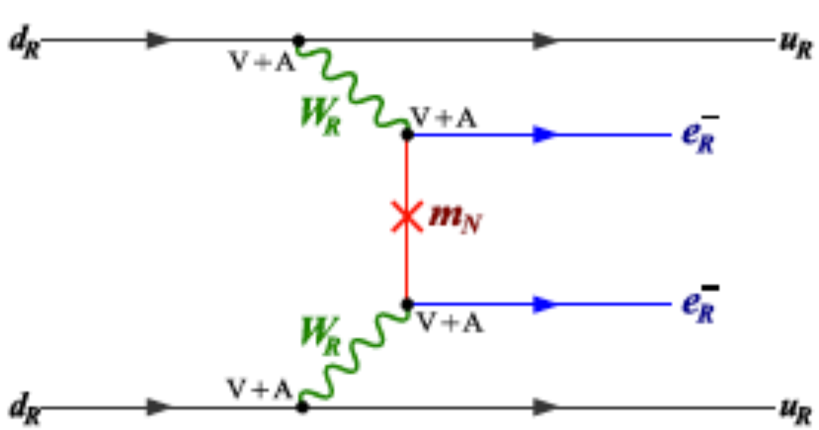
- LNV dynamics at lower scale (Λ~TeV)



Higher dimensional operators become relevant

$$\frac{1}{\Lambda^5}\;\bar{q}q\,\bar{q}q\,\overline{e^c}e$$

Arise in well-motivated models:
Left-Right Symmetric Model,
RPV-SUSY, ...



Other Possibilities for the Black Box

(Classifying sources of LNV: organize discussion by scales)

- LNV dynamics at very high scale (Λ>> TeV)

$$\frac{1}{\Lambda}\,\overline{\ell^c}\ell\,H\,H$$

- LNV dynamics at lower scale (Λ~TeV)

$$\frac{1}{\Lambda^5}\,\bar{q}q\,\bar{q}q\,\overline{e^c}e$$

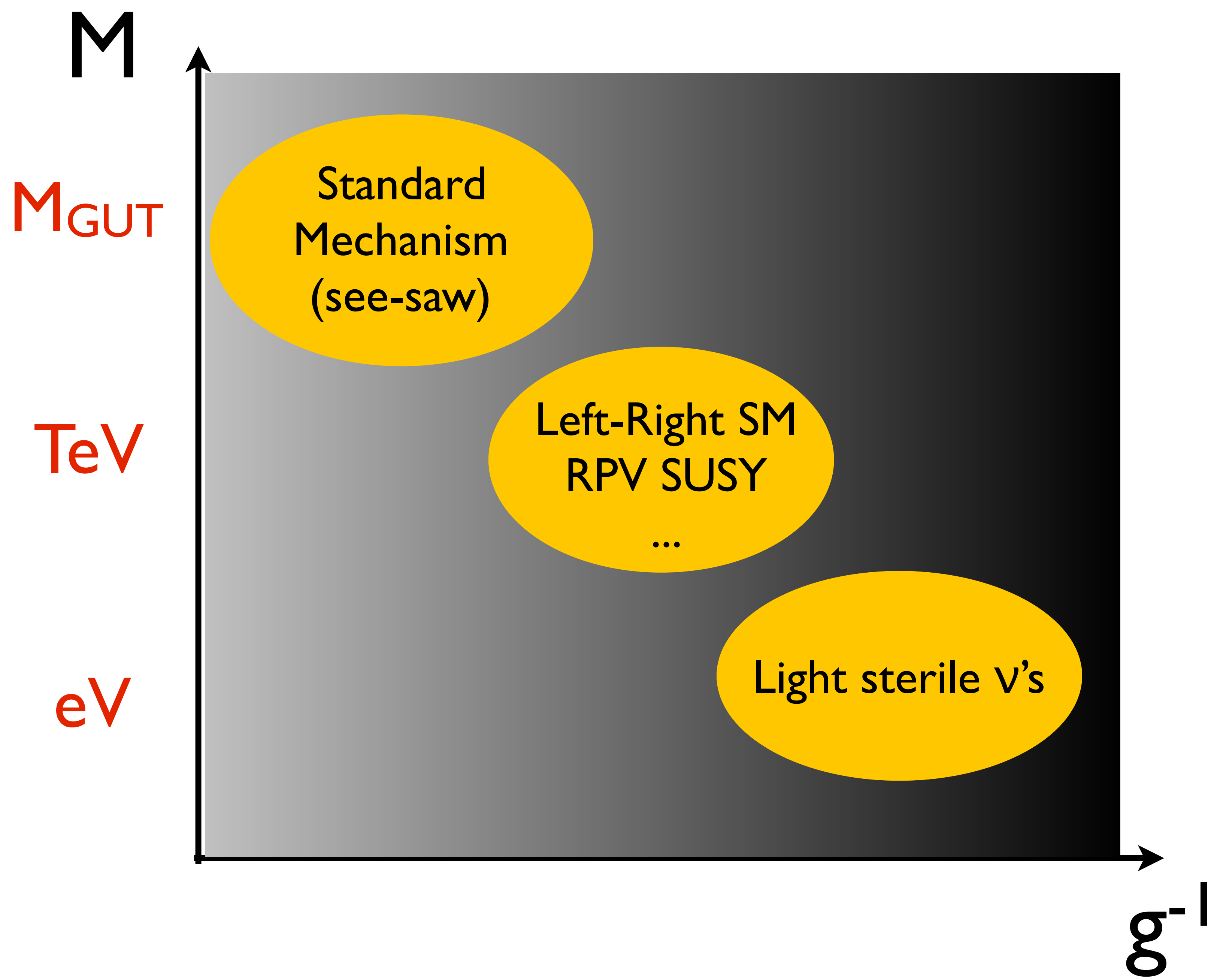
- LNV dynamics at very low energy (e.g. low-scale seesaw)

$$-\frac{1}{2}M_R\,\overline{\nu_R^c}\nu_R\;+\;Y_\nu\,\bar{\ell}\nu_R\,H$$

Affects NLDBD in significant ways, depending on mass scale M_R: eV →100 GeV

Other Possibilities for the Black Box

- In summary: ton-scale $0\nu\beta\beta$ probes LNV from variety mechanisms, involving different scales (M) and coupling strengths (g)



Sensitivity Reach Required

Choosing a Nuclide

Typical 2$\nu\beta\beta$ half-life is very long: second-order weak process

$$\frac{1}{T^{0\nu}_{\frac{1}{2}}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

Atomic mass affected by nuclear pairing term: even A nuclei occupy 2 parabolas, even-even below odd-odd

$$\frac{1}{G^{2\nu}} \simeq 10^{20} \text{ years}$$

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

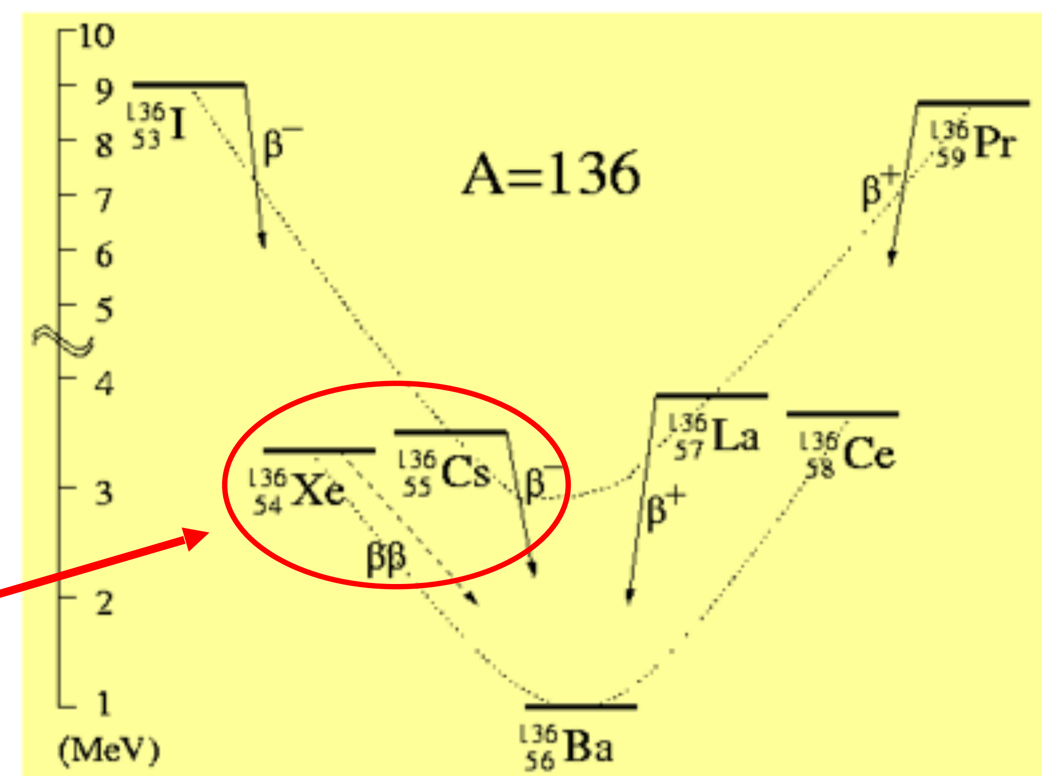
Choose nuclei where single beta decay forbidden

but double-beta decay is possible

Candidate nuclei with Q>2 MeV

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Decay Rate for 0νββ

$$\Gamma^{0\nu} = G(Q,Z)\left|M(A,Z)\eta\right|^2$$

Transition Probability $\alpha \frac{m}{Q^2}$ $(Q \sim m_e)$

Phase Space Factor $G \sim G_F^4 g_A^4 m_e^5$

$M(A,Z)$ Nuclear Matrix Element

η Particle Physics of the Black Box

For light neutrino exchange

PMNS Matrix

All 3 neutrinos will contribute: $\eta \sim m \rightarrow \langle m_{\beta\beta} \rangle = \sum_i U_{ie}^2 m_i$

$m_{\beta\beta} \sim 1$ eV $\Longrightarrow T_{1/2} \sim 10^{24}$ years

$m_{\beta\beta} \sim 0.1$ eV $\Longrightarrow T_{1/2} \sim 10^{26}$ years

$m_{\beta\beta} \sim 0.01$ eV $\Longrightarrow T_{1/2} \sim 10^{28}$ years

The PMNS Matrix

The neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

$(W \to e\nu_e$ or $\mu\nu_\mu$ or $\tau\nu_\tau)$

are superpositions of the mass eigenstates:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \, |\nu_i\rangle \; .$$

Neutrino of flavor $\alpha = e, \mu,$ or τ

Unitary Leptonic Mixing Matrix

Neutrino of definite mass m_i

Atmospheric — Cross-Mixing — Solar

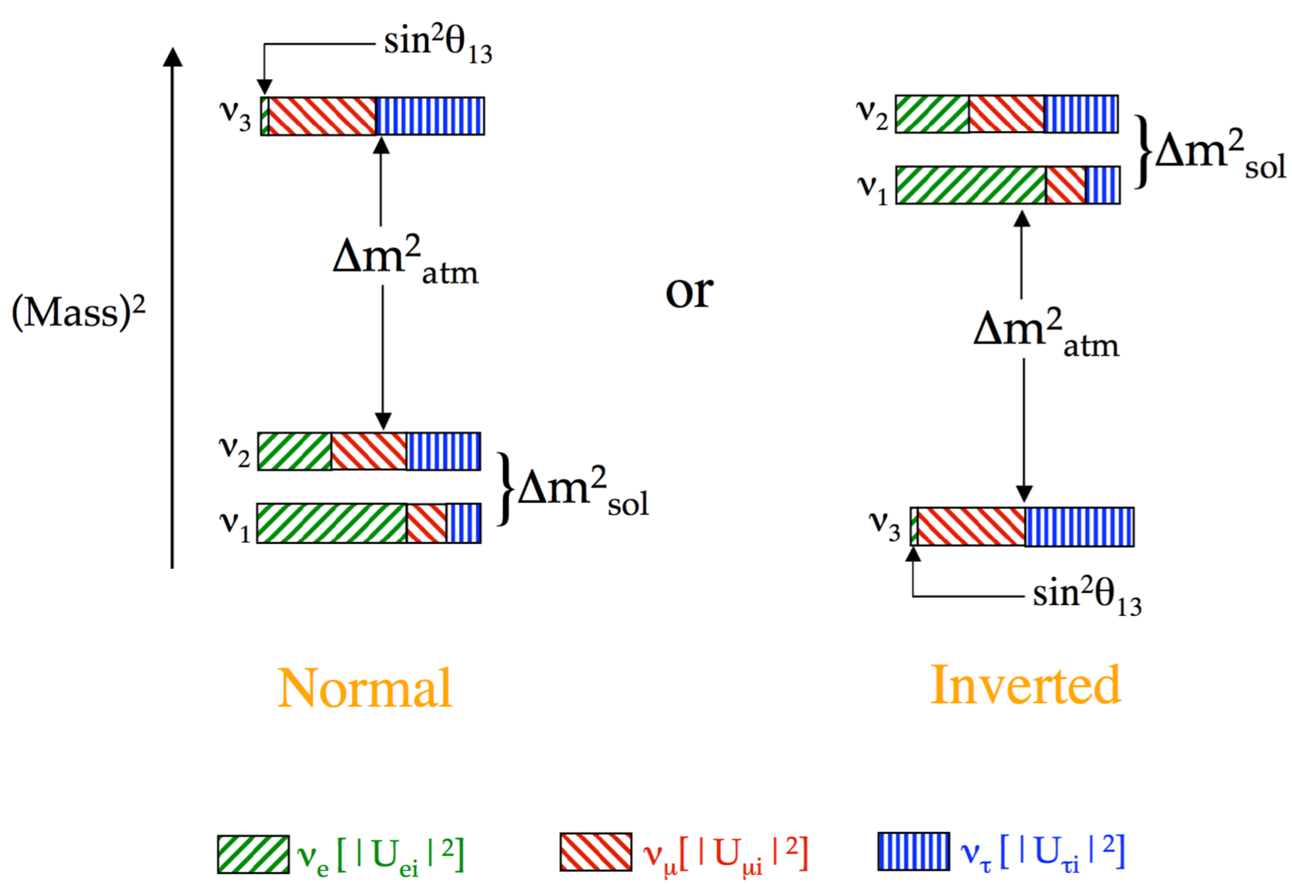
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

Majorana ~~CP~~ phases

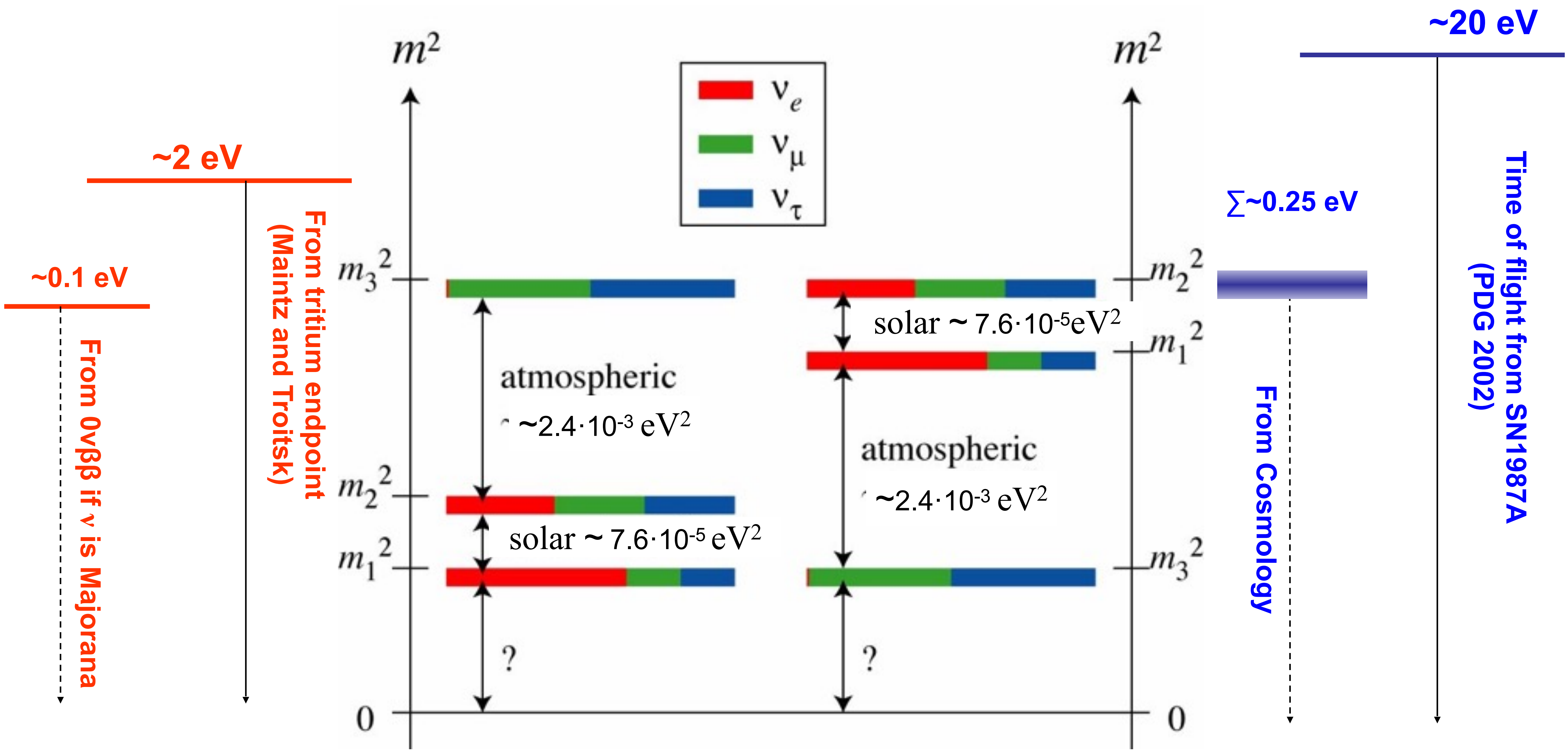
$\theta_{12} \approx \theta_{sol} \approx 34°, \; \theta_{23} \approx \theta_{atm} \approx 37\text{-}53°, \; \theta_{13} \lesssim 10°$



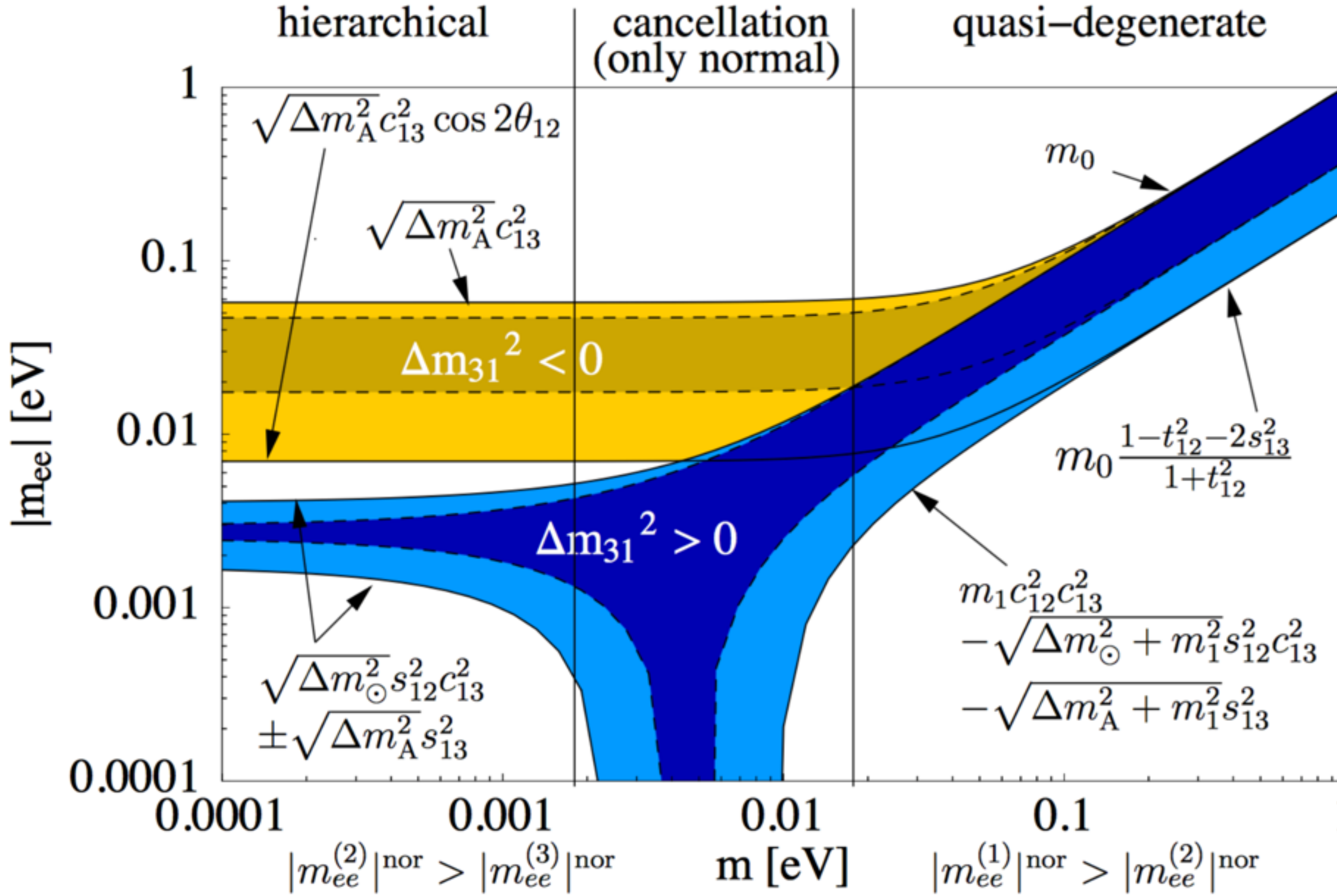
For double-beta decay, the electron content of all 3 mass eigenstates is what is relevant

U_{ie}

Absolute Neutrino Mass Scale



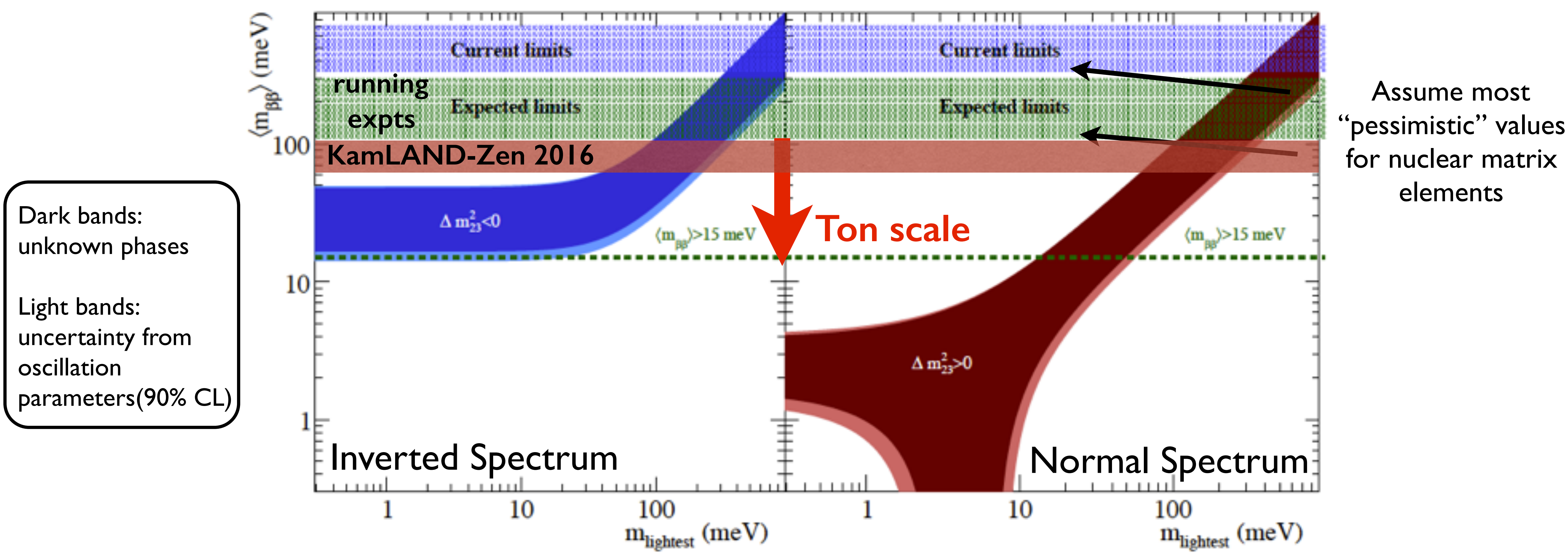
Mass Reach Plot



Discovery Reach

- Strong correlation of $0\nu\beta\beta$ with neutrino phenomenology: $\Gamma \propto (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$



- Discovery *possible* for inverted spectrum OR $m_{lightest}$ > 50 meV

Signal and Background

An experimental challenge of rare events

Most measured half-lives of $2\nu\beta\beta$ are $O(10^{21})$ years
- **Compare to lifetime of Universe: 10^{10} years**
- **Compare to Avogadro's number 6×10^{23}**
- **Mole of isotope will produce ~ 1 decay/day**

If it exists, half-lives of $0\nu\beta\beta$ would be longer (^{136}Xe limits is > 10^{25} years)

Half life (years)	Signal (cts/tonne-year)
10^{25}	500
$5\text{x}10^{26}$	10
$5\text{x}10^{27}$	1
$5\ \text{x}10^{28}$	0.1

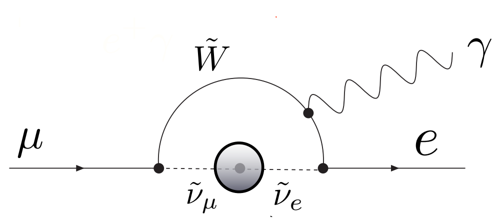
Natural radioactivity: a nanogram produces more than 1 decay/day!
Cosmogenically induced radioactivity exacerbates technical challenge

$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$ **background free**

$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$ **background limited**

backgrounds do not always scale with detector mass

Plausibly Extraordinary Implications



$\mu^- + N \rightarrow e^- + X$

Branching Ratio $<10^{-50}$

A 200M$ experiment is being constructed at Fermilab to reach a branching ratio of 10^{-16}

Current $0\nu\beta\beta$ experiments are accessing m ~ 0.1 eV!

Ton-scale designs under way to access ~ 0.02 eV!

- "See-saw": $m_\nu \sim 1\,\mathrm{eV} \;\rightarrow\; \Lambda \sim 10^{13}\,\mathrm{GeV}$

*Net baryon asymmetry in the universe **(Leptogenesis)**:*

CP-violating heavy neutrino decay could generate more leptons than anti-leptons

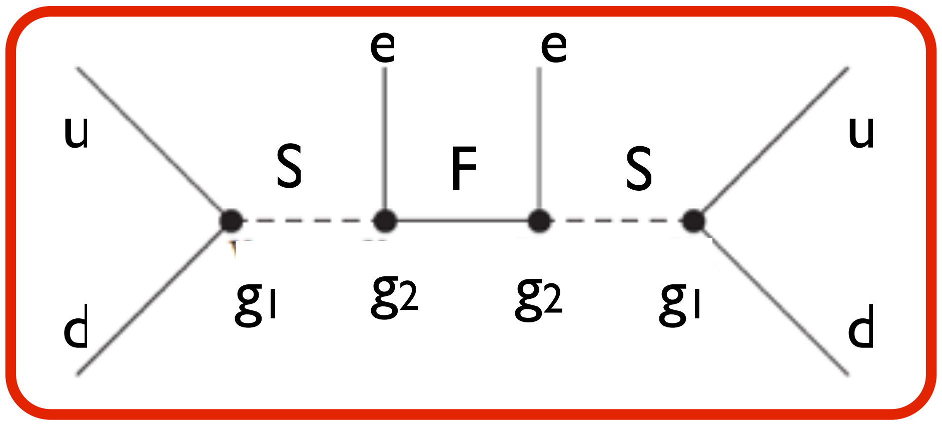
This lepton asymmetry could be reprocessed into a baryon asymmetry via the B+L anomaly in the Standard Model

TeV-Scale Complementarity

- TeV sources of LNV may lead to significant contributions to NLDBD *not directly related to the exchange of light neutrinos*

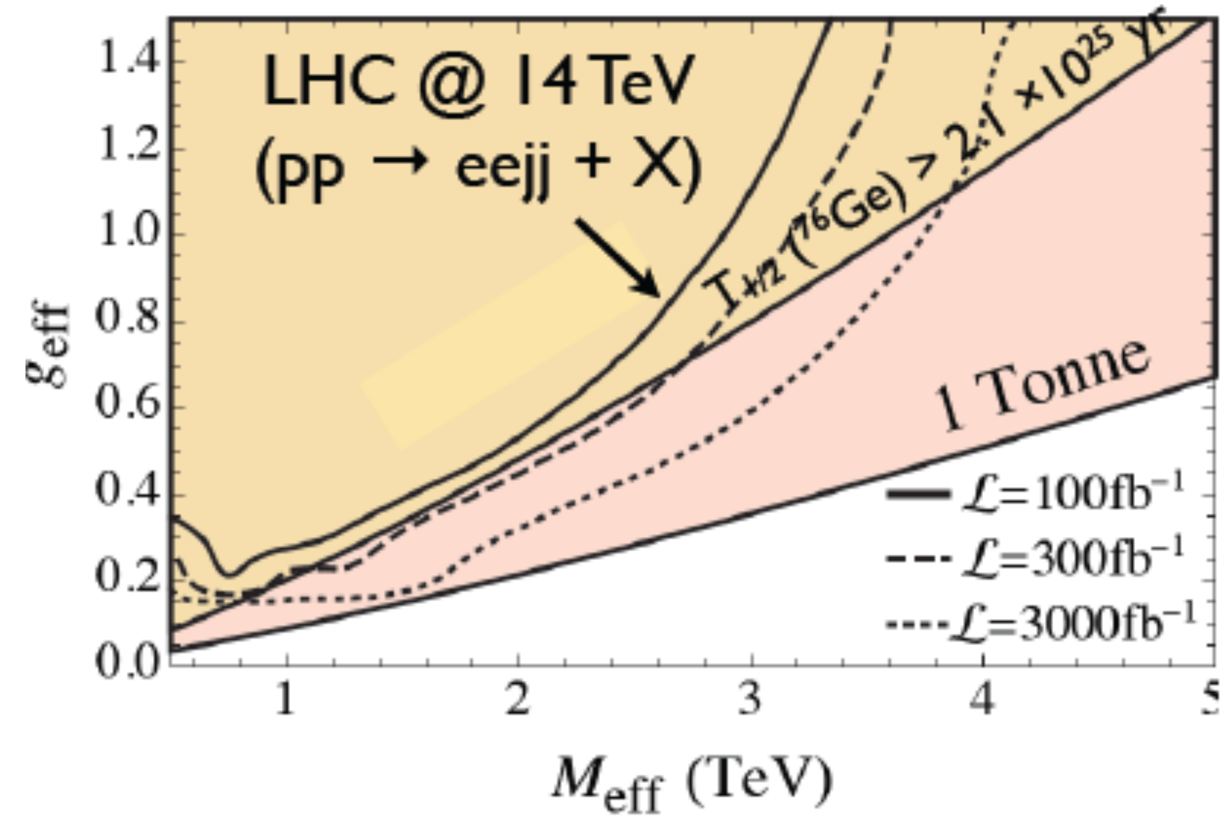
Simplified model ~ RPV-SUSY

$M_S = M_F = M_{eff}$ $(g_{eff})^4 = g_1^2 g_2^2$



$A_{0\nu\beta\beta} \sim (g_{eff})^4 / (M_{eff})^5$

Peng, Ramsey-Musolf, Winslow, 2015

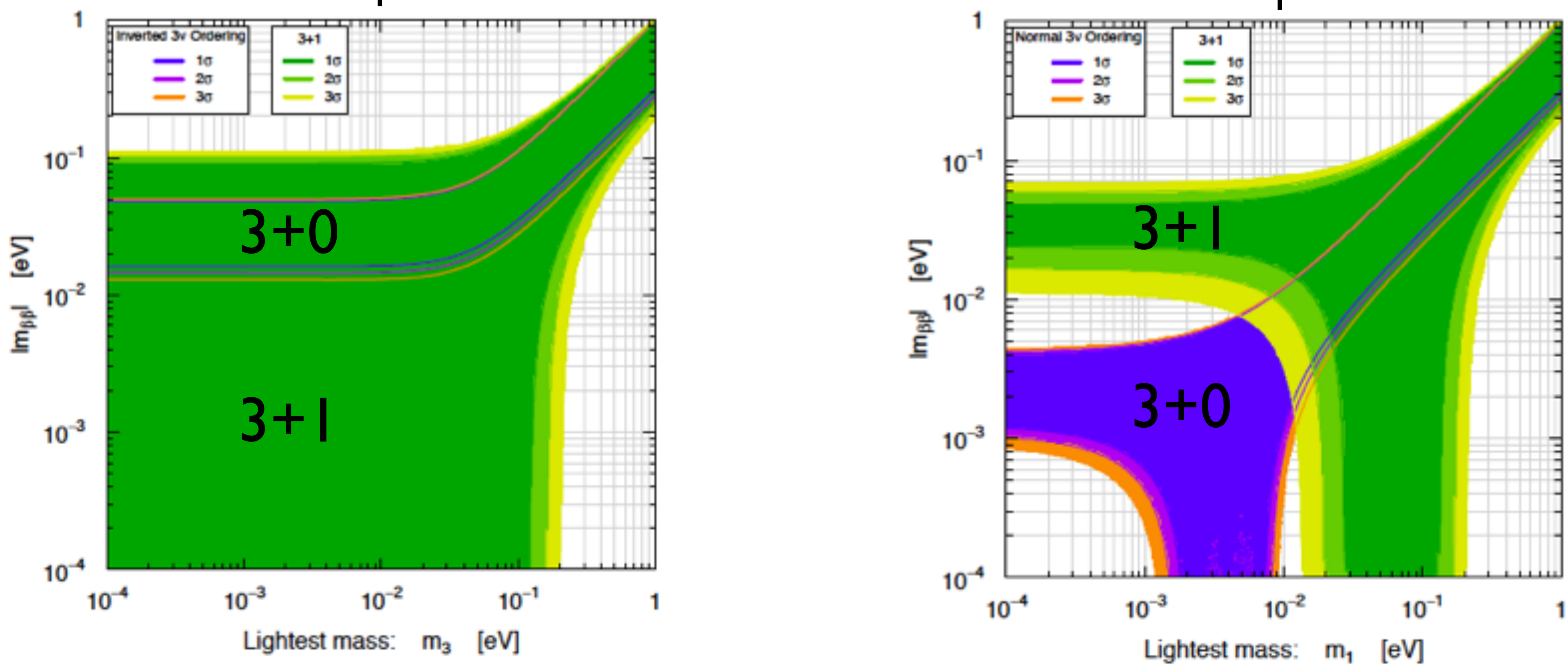


Ton-scale NLDBD significantly extends mass reach (multi TeV) and covers LHC-inaccessible regions

Light Scale BSM

- Low scale seesaw: intriguing example with one light sterile ν_R with mass (~eV) and mixing (~0.1) to fit short baseline anomalies
- Extra contribution to effective mass $m_{\beta\beta} = m_{\beta\beta}|_{\text{active}} + |U_{e4}|^2 \, e^{2i\Phi} \, m_4$

Inverted Spectrum — Normal Spectrum



Giunti-Zavanin 2015

Usual phenomenology turned around!!

Theory Motivation Summary

- The discovery of neutrino oscillations has made the issue of the existence of Majorana neutrinos particularly pressing
- This is intimately connected to the issue of whether Lepton Number is a conserved quantity in Standard Model processes
- Neutrinoless Double-Beta Decay is the only plausible terrestrial experiment that can shed light on the aforementioned critical questions
- The discovery of this process and its subsequent study could shed light on some of the most profound questions in nuclear physics, particle physics, astrophysics and cosmology

Towards Discovery Experiments

Nuclear Matrix Elements

$$M_{0\nu} = M_{0\nu}^{GT} - \frac{g_V^2}{g_A^2} M_{0\nu}^{F} + \dots$$

with

$$M_{0\nu}^{GT} = \langle F | \, | \sum_{i,j} H(r_{ij}) \, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \, \tau_i^+ \tau_j^+ \; | I \rangle + \dots$$

$$M_{0\nu}^{F} = \langle F | \sum_{i,j} H(r_{ij}) \, \tau_i^+ \tau_j^+ \; | I \rangle + \dots$$

$$H(r) \approx \frac{2R}{\pi r} \int_0^\infty dq \frac{\sin qr}{q + \bar{E} - (E_i + E_f)/2} \quad \text{roughly} \propto 1/r$$

Contribution to integral peaks at $q \approx 100$ MeV inside nucleus.

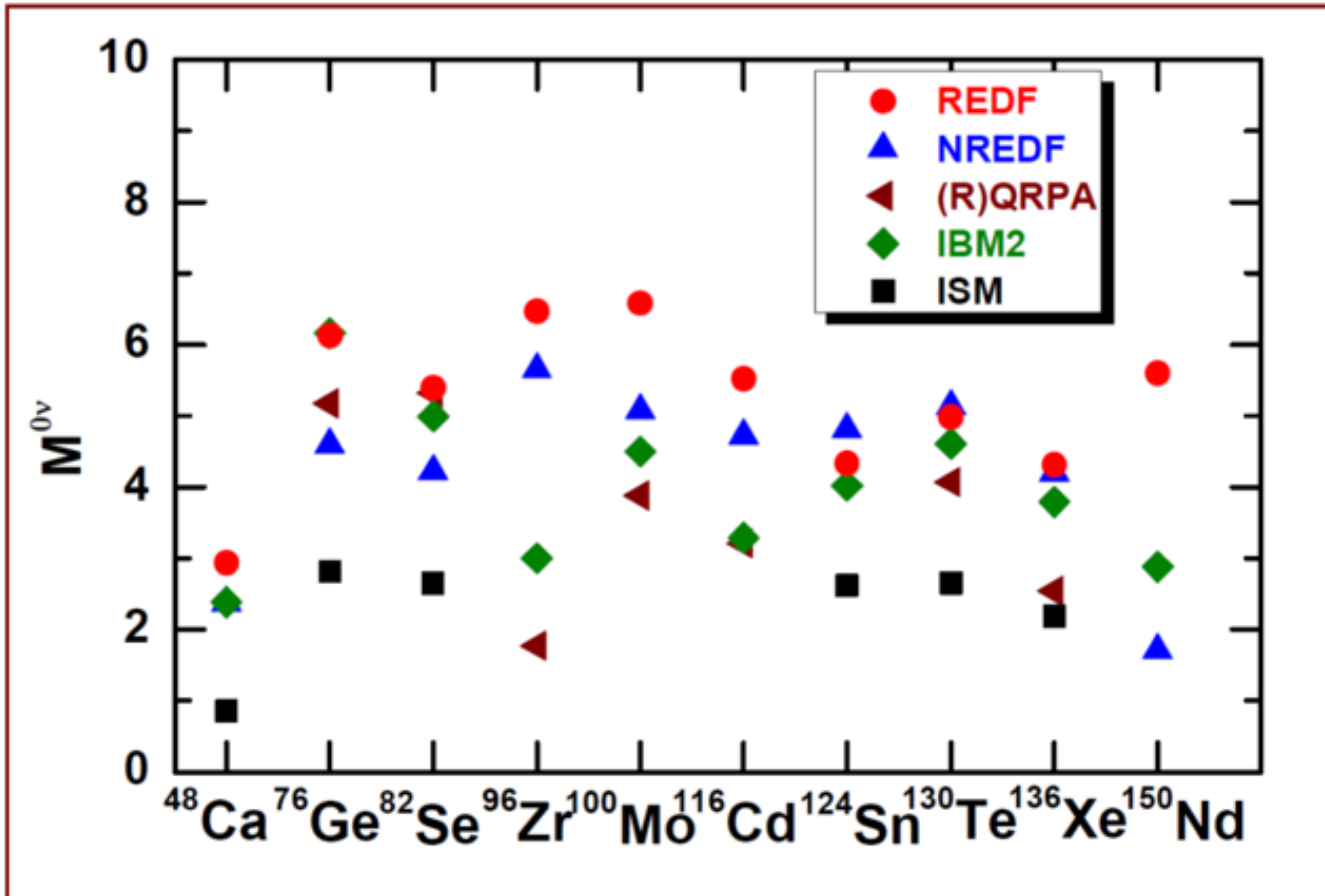
Corrections are from "forbidden" terms, weak nucleon form factors, many-body currents …

NME Current Status

For light neutrino exchange

Significant spread. And all the models could be missing important physics.

Uncertainty hard to quantify.



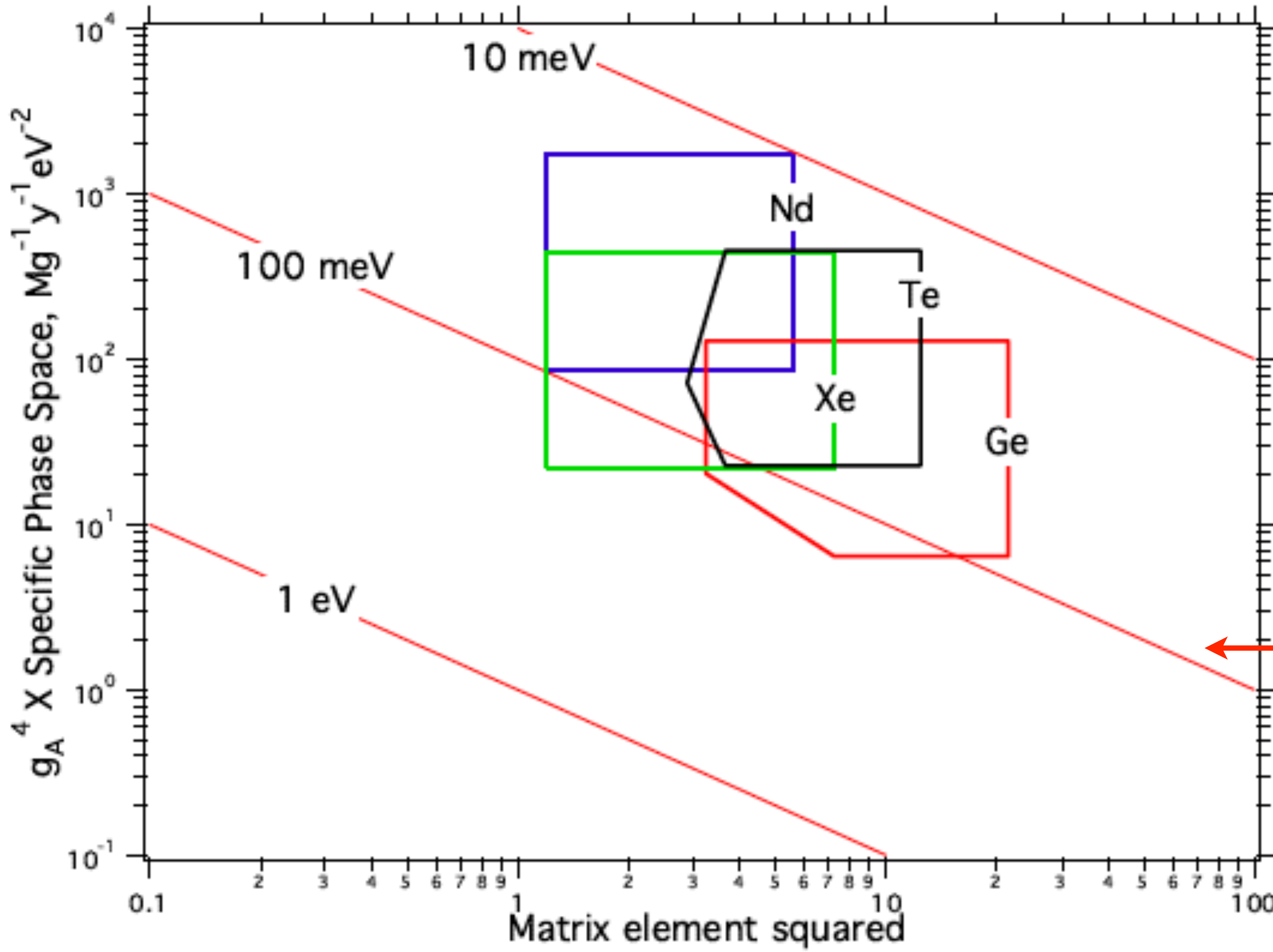
One must do different calculations if other mechanisms are in play

Favorite Isotope?

For Ge, Te, Xe, Nd

← uncertainty on NME^2 →

R.G.H. Robertson, MPL A **28** (2013) 1350021 (arXiv 1301.1323)



uncertainty on value of g_A^4

Signal of 1 cnt/t-y for corresponding values of NME and g_A

The Experimental Challenge

0νββ source with
- high isotopic abundance

Detector with
- high detection efficiency
- good energy resolution
- low-background

Experiment
- long exposure time
- large total mass of isotope

To reach IH region requires sensitivities of

0νββ $T_{1/2} \sim 10^{27}$- 10^{28} years

(2νββ $T_{1/2} \sim 10^{19}$ - 10^{21} years)

$$T^{0\nu}_{1/2} \text{ sensitivity} \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

a = source isotopic abundance

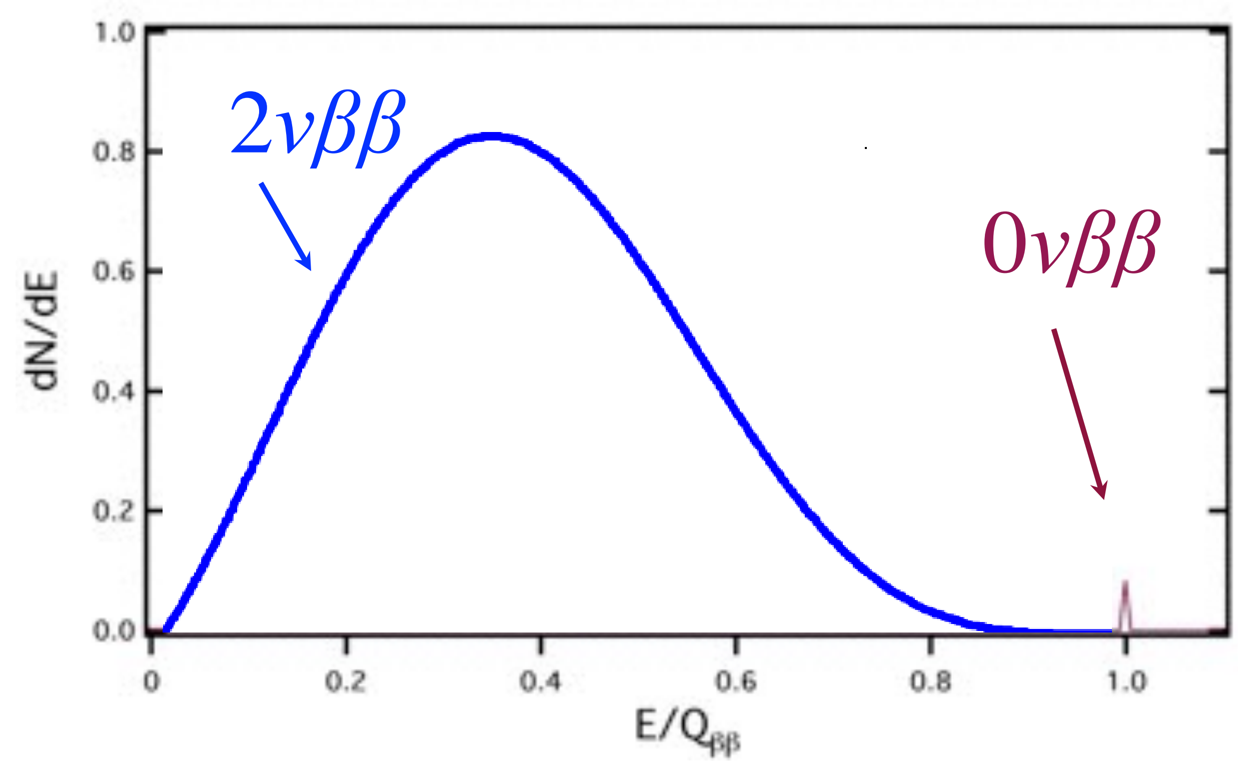
ϵ = detection efficiency

M = total mass

t = exposure time

b = background rate at $0\nu\beta\beta$ energy

δE = energy resolution



Background Strategies

Potential Backgrounds

- Primordial, **natural radioactivity** in detector components: U, Th, K
- Backgrounds from **cosmogenic activation** while material is above ground (ββ-isotope or shield specific, ^{60}Co, ^{3}H...)
- Backgrounds from the **surrounding environment**:
  external γ, (α,n), (n,α), Rn plate-out, etc.
- **μ-induced backgrounds** generated at depth:
  Cu,Pb(n,n' γ), ββ-decay specific(n,n),(n,γ), direct μ
- **2 neutrino double beta decay** (irreducible, E resolution dependent)
- neutrino backgrounds (negligible)

Reduce Backgrounds

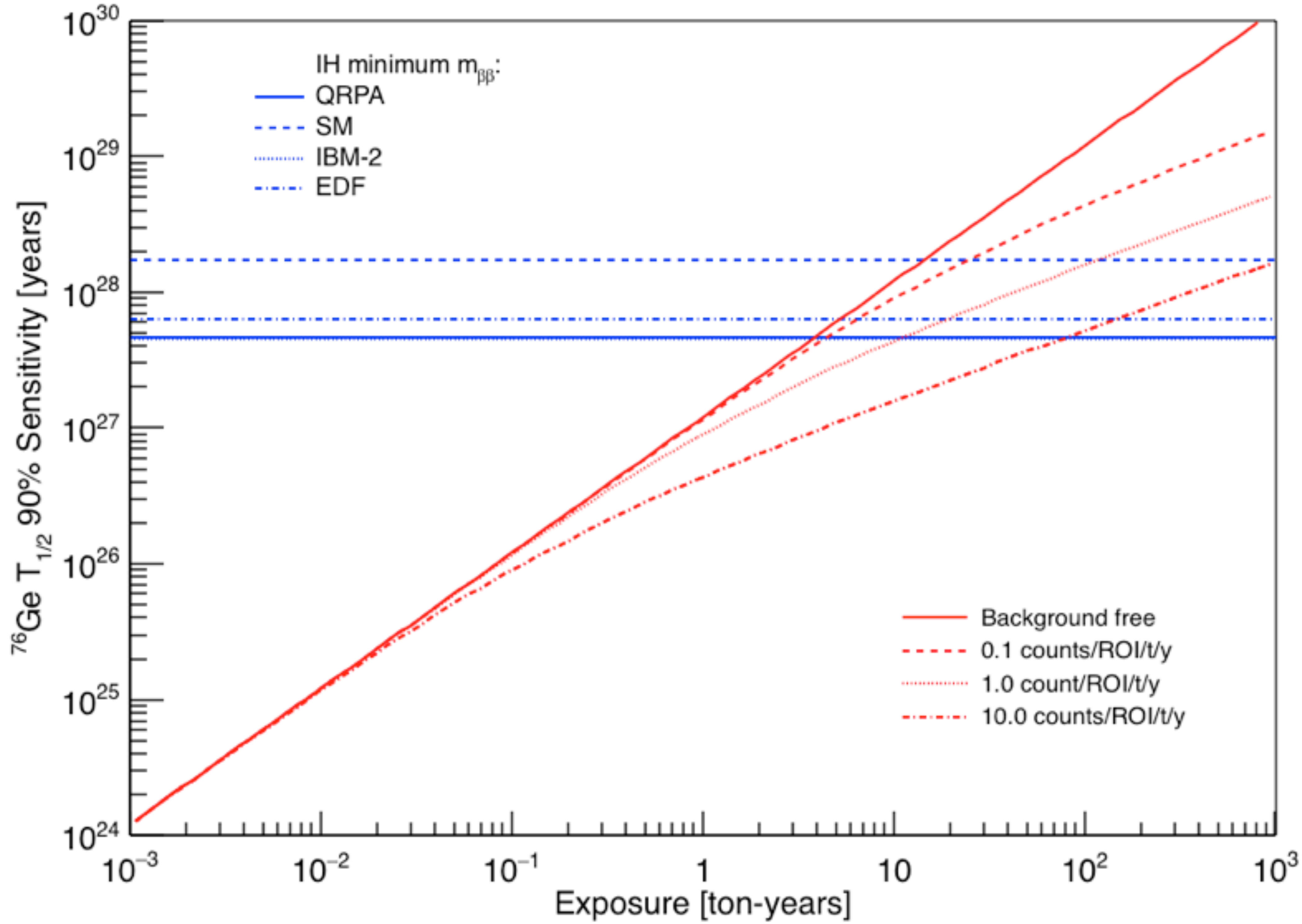
- ultra-pure materials
- shielding
- deep underground
- …

Discriminate Backgrounds

- energy resolution
- tracking (even topology)
- fiducial fits
- pulse shape discrimination (PSD)
- particle ID
-…

Sensitivity vs Exposure

$T_{1/2}^{0\nu}(\text{background free}) \propto \text{MT}$ $T_{1/2}^{0\nu}(\text{backgrounds}) \propto \sqrt{\frac{\text{MT}}{\text{b}\Delta\text{E}}}$

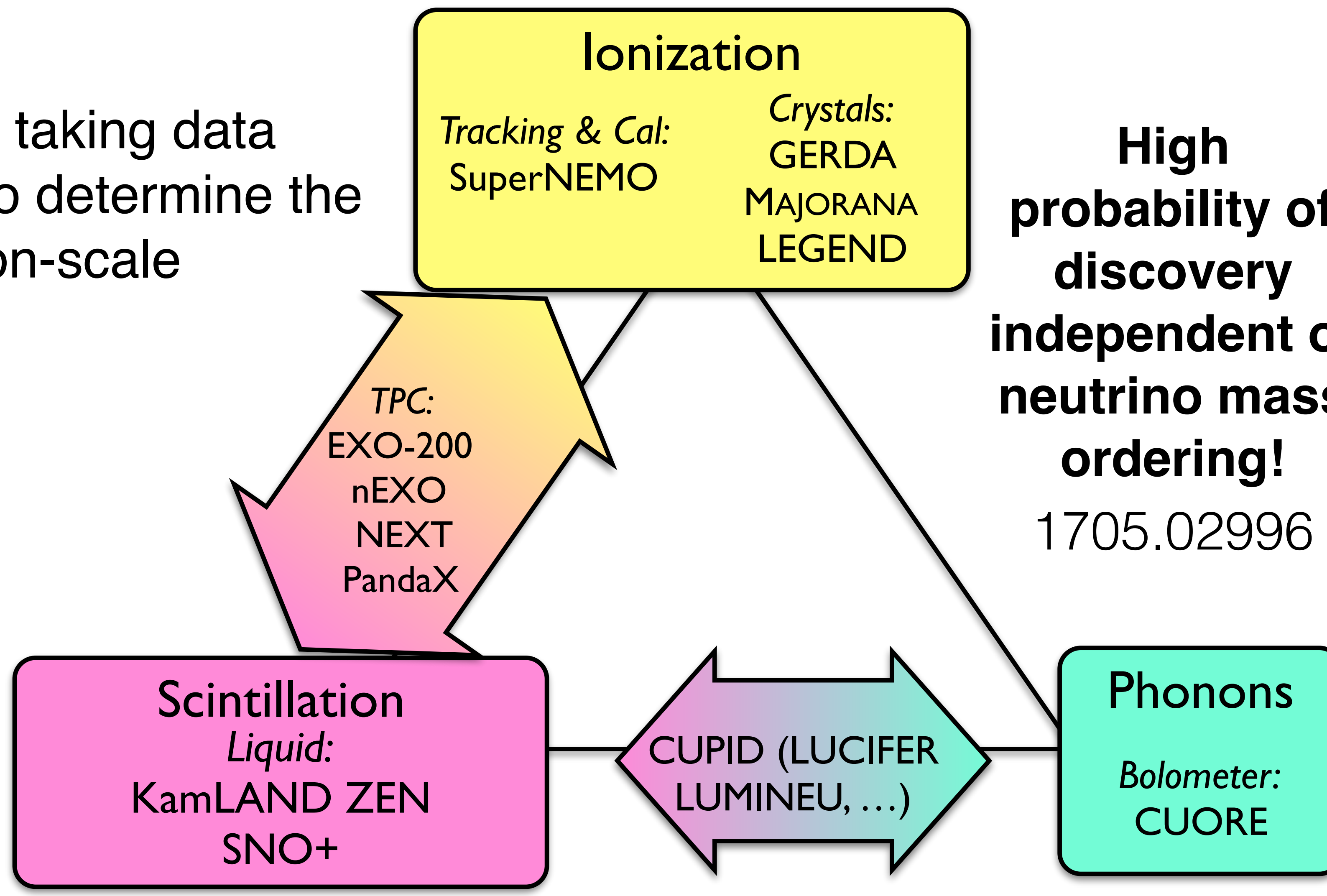


J. Detwiler

A Flavor of Tomorrow's Lecture

- 100 kg class experiments currently taking data
- In parallel, major R&D under way to determine the optimum path to discovery at the ton-scale

^{76}Ge, ^{130}Te, ^{136}Xe



High probability of discovery independent of neutrino mass ordering!

1705.02996

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2}$ >$10^{27\text{-}28}$ yr) probe at unprecedented levels LNV from a variety of mechanisms
- If light Majorana neutrinos are responsible for $0\nu\beta\beta$, then absolute neutrino mass scale determination within reach of ton-scale experiments

Lecture I Summary

- With the discovery of massive neutrinos, we are motivated to ask whether Nature has something really special in store: a massive fermion that is its own anti-particle

- The quest to discover the Majorana nature of neutrinos and Lepton Number Violation likely goes through experiments searching for neutrinoless double-beta decay

- Majorana neutrinos could shed light on some of Nature's most profound puzzles, including the origin of all matter in the Universe

- Tomorrow we will describe how one devises experiments that reach the extraordinary levels of sensitivity required to search for this extremely rare type of radioactivity.