Neutrinoless Double Beta Decay: Physics

Los Alamos NATIONAL LABORATORY

Steve Elliott

PHYSICS SINCE 1943

TRI-INSTITUTE SUMMER SCHOOL ON ELEMENTARY PARTICLES

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The Neutrino and $0\nu\beta\beta$

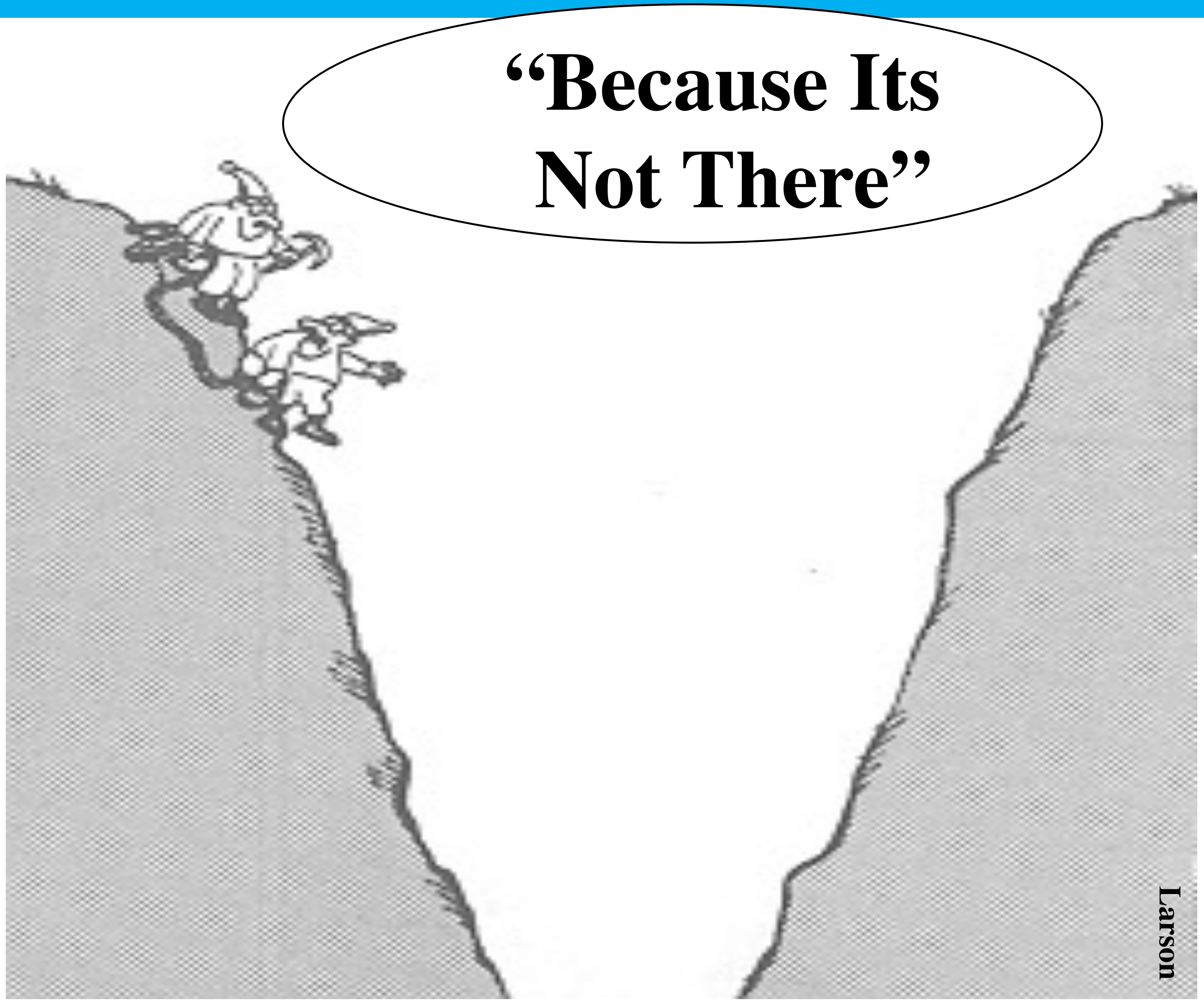
Some Nuances in $m_{\beta\beta}$

Nuclear Matrix Elements

Three Lectures

- Basic physics issues of double beta decay
  - The Neutrino and $0\nu\beta\beta$
  - Some Nuances in $m_{\beta\beta}$
  - Nuclear Matrix Elements
- Technology for double beta decay studies
  - Background Issues
  - Related Physics Measurements
  - Some Recent Technical Progress
- Experimental Status
  - History
  - R&D Landscape
  - Upcoming Experimental Status

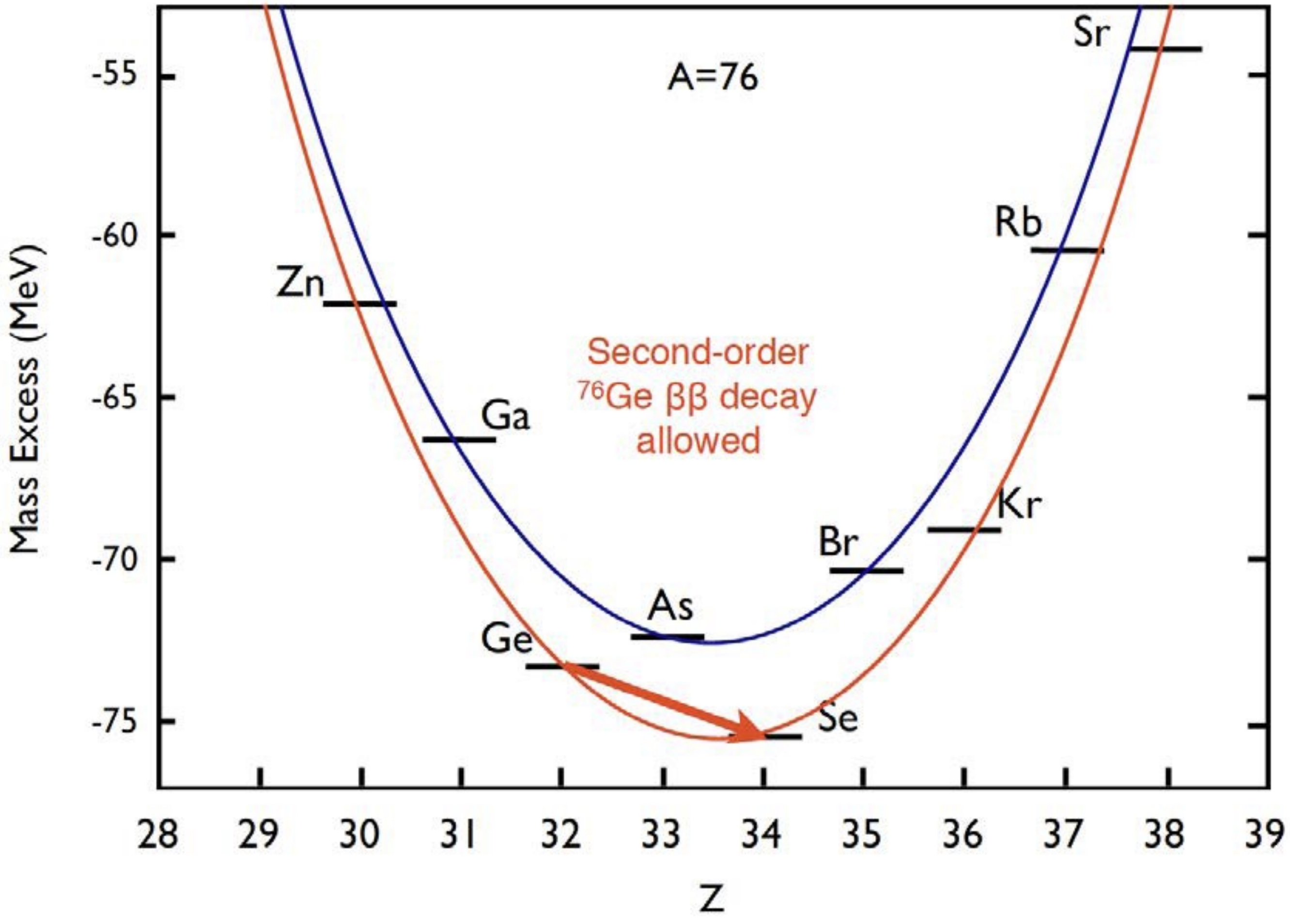
Why look for $\beta\beta$?



Historically this was the view. $0\nu\beta\beta$ constrained lepton number violation. A never-ending reduction of limits.

This is still true, however, we now know neutrinos have mass and experiments will be sensitive to an interesting range.

Example of Ge-76



Nuclei are held together by the strong nuclear force and by spin-pairing forces.

The spin pairing between nucleons, neutron-neutron, proton-proton and neutron-proton, is effectively a force of attraction.

Leads to tighter binding for even-even nuclei. Many such nuclei are energetically (or spin-inhibited, ^{48}Ca) from β decay.

What is ββ?

$2\nu\beta\beta$ is a second-order weak process, expected within the standard model.

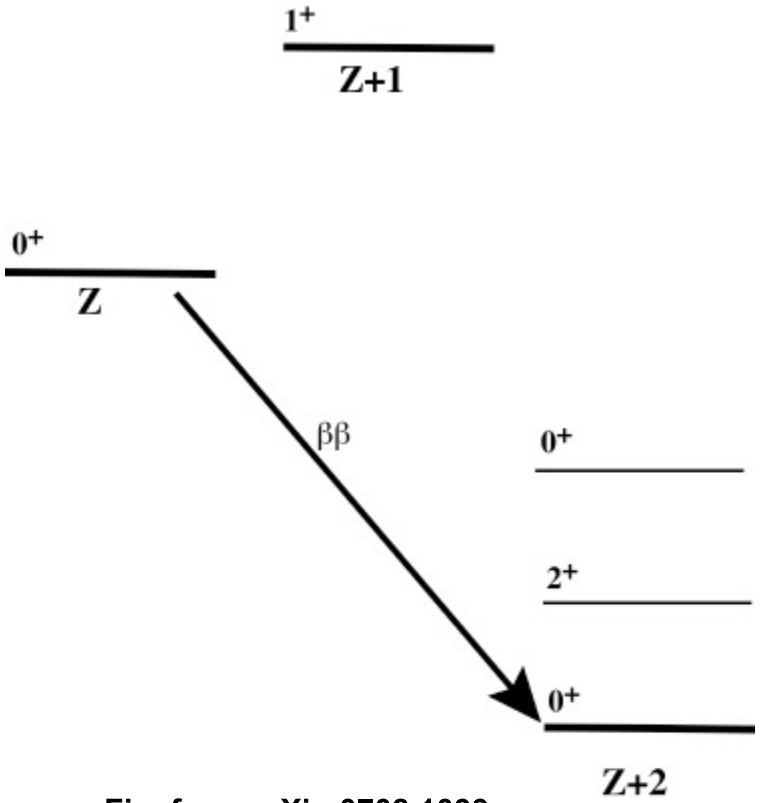


Fig. from arXiv:0708.1033

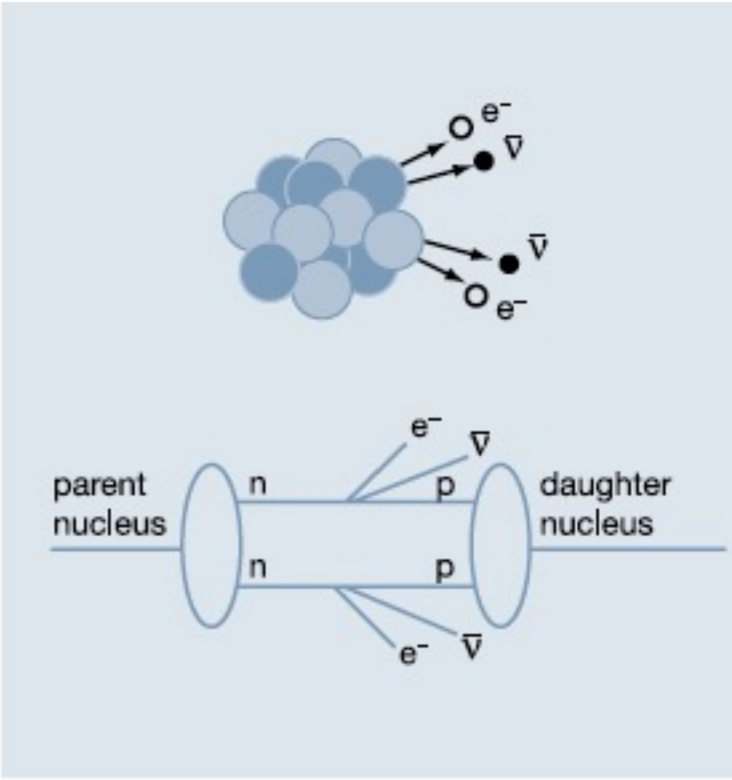
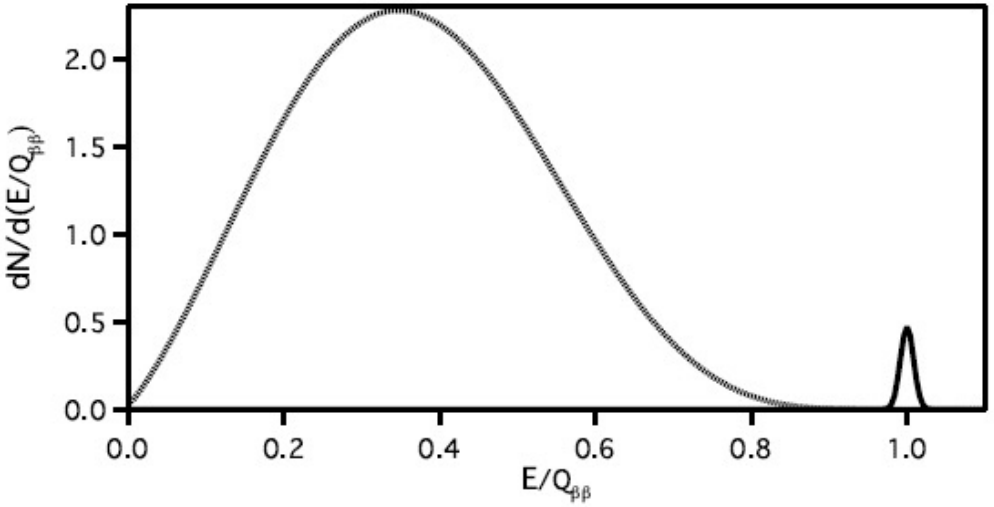


Fig. from Deep Science

What is ββ?

$$n \Rightarrow p + e^- + \bar{\nu}_e \qquad \nu_e + n \Rightarrow p + e^-$$



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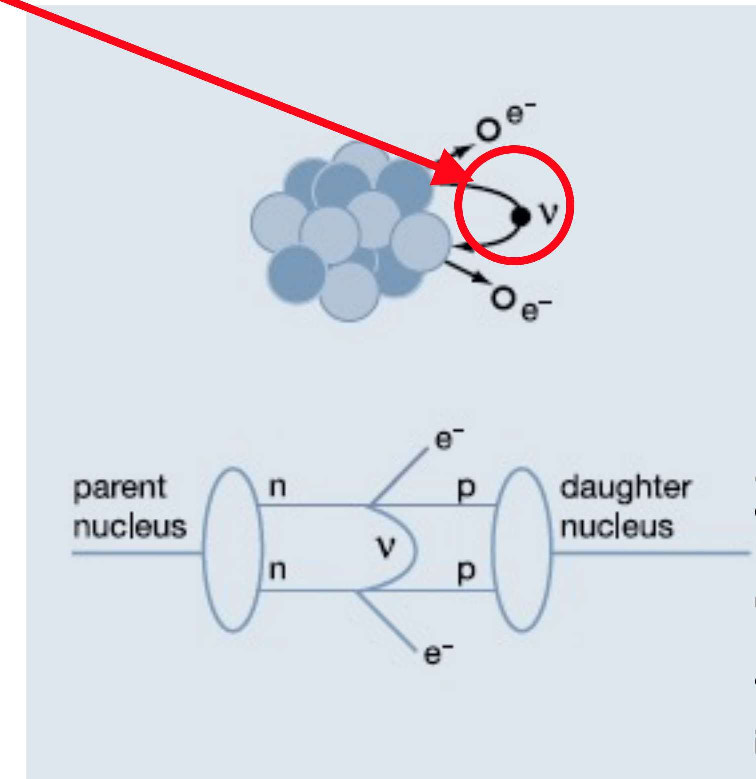
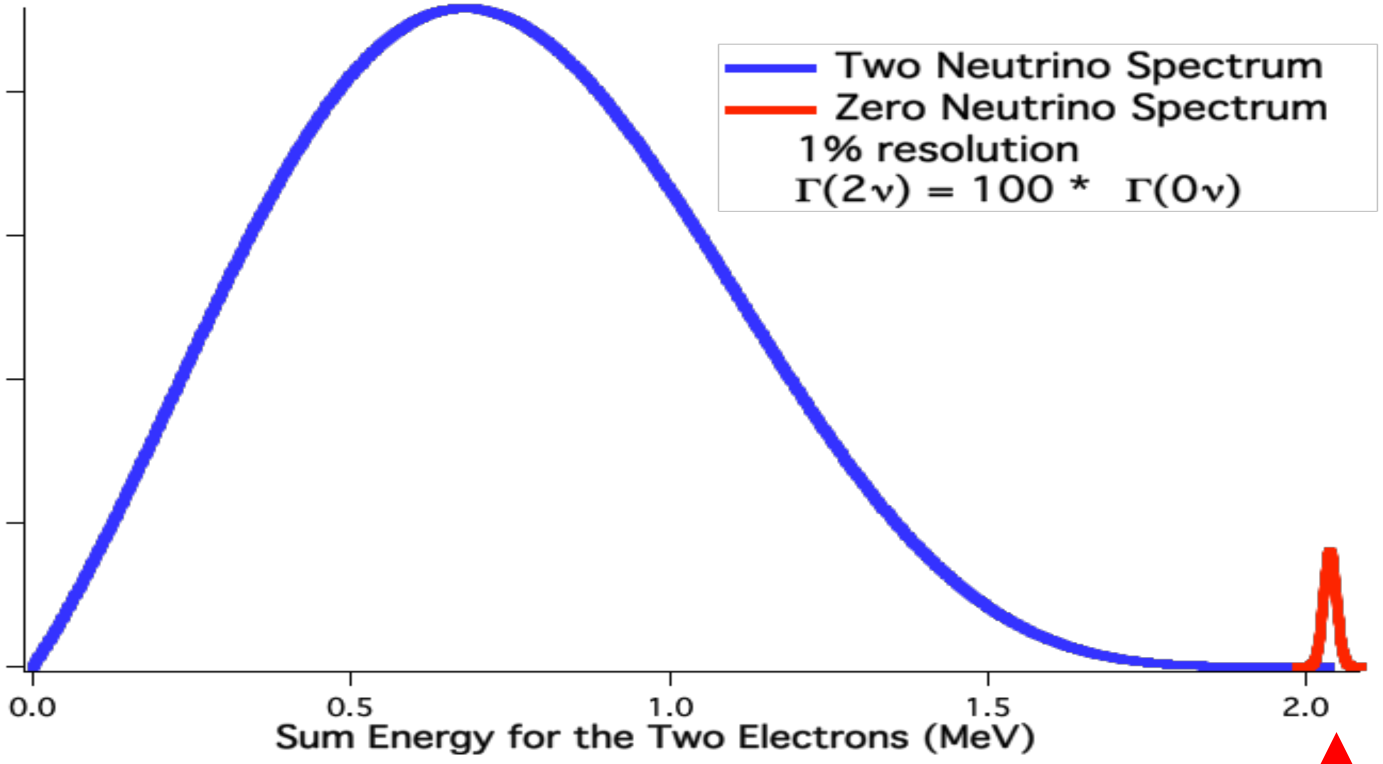


Fig. from Deep Science

Energy Spectrum for the 2 e⁻



Endpoint Energy, $Q_{\beta\beta}$

ββ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2$$

$$\boxed{\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_\nu^2}$$

G are calculable phase space factors.

$G_{0\nu} \sim Q^5$

|M| are nuclear physics matrix elements.

Hard to calculate.

m_ν is where the interesting physics lies.

The Importance of Majorana Neutrinos and Lepton Number Conservation Violation

Dirac Picture

A Dirac mass mixes these Helicity-related states

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

Majorana Picture

$$\begin{pmatrix} \nu_L \\ \bar{\nu}_R \end{pmatrix} \quad \begin{pmatrix} \bar{\nu}_L \\ \nu_R \end{pmatrix}$$

A Majorana mass mixes these Helicity-related states

Majorana neutrinos lead to Lepton number violation

All ββ transitions

Require Majorana mass to mix helicity states for non-zero rate

Standard Model
LHC vertices
(Similar for 2 RHC vertices)

Majorana-style helicity flip

$$n \Rightarrow p + e_L^- + \bar{\nu}_R \qquad \nu_L + n \Rightarrow p + e_L^-$$

LHC at 1st vertex
RHC at 2nd vertex

Again requires
Majorana mass

$$\bar{\nu}_L$$

Dirac-style flip

Majorana-style flip

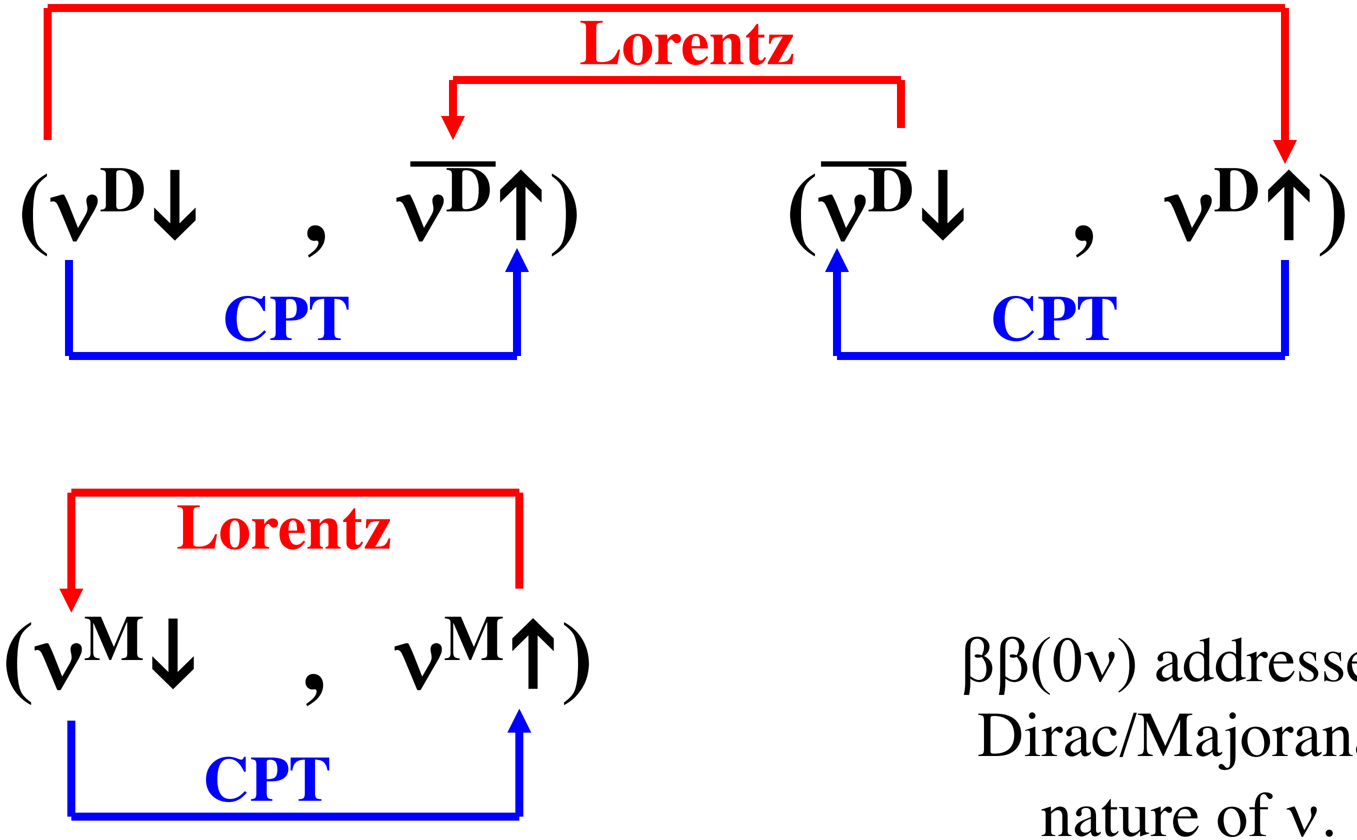
$$n \Rightarrow p + e_L^- + \bar{\nu}_R \qquad \nu_R + n \Rightarrow p + e_R^-$$

Majorana-style flip

Dirac-style flip

$$\nu_L$$

Dirac vs. Majorana



$\beta\beta(0\nu)$ addresses Dirac/Majorana nature of ν.

So, what do we know about neutrino masses?

- The results of oscillation experiments indicate ν do have mass!, set the relative mass scale, and a minimum for the absolute scale.

- β decay experiments (KATRIN) set a maximum for the absolute mass scale.

$$50 \text{ meV} < m_\nu < 800 \text{ meV}$$

We know ν mix

The weak interaction produces ν_e, ν_μ, ν_τ. (flavors)

These are not pure mass states but a linear combination of mass states.

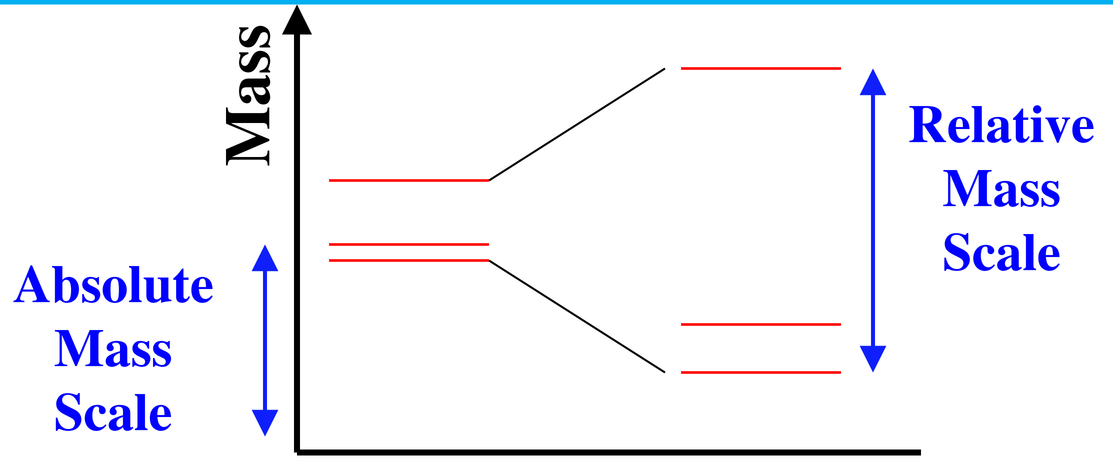
As a ν propagates, it can oscillate between flavors. This requires non-degenerate mass eigenstates.

For example, ν_μ's might be produced in an accelerator beam dump, but ν_e's might be detected some distance away.

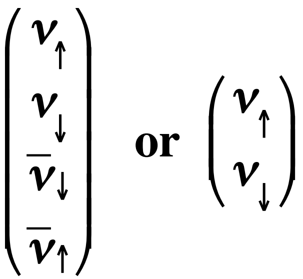
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

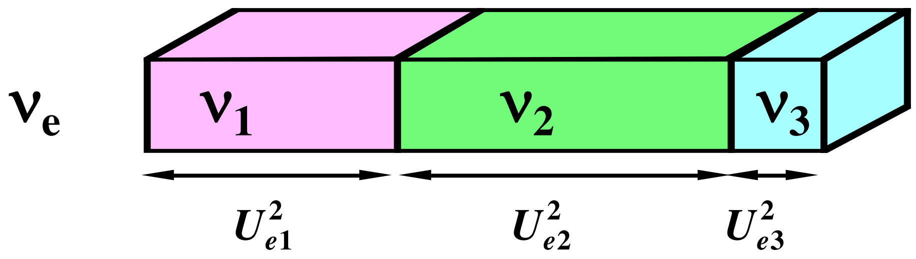
Oscillation experiments indicate that ν mix and measure $U_{\alpha i}$.

What do we want to know about neutrinos?



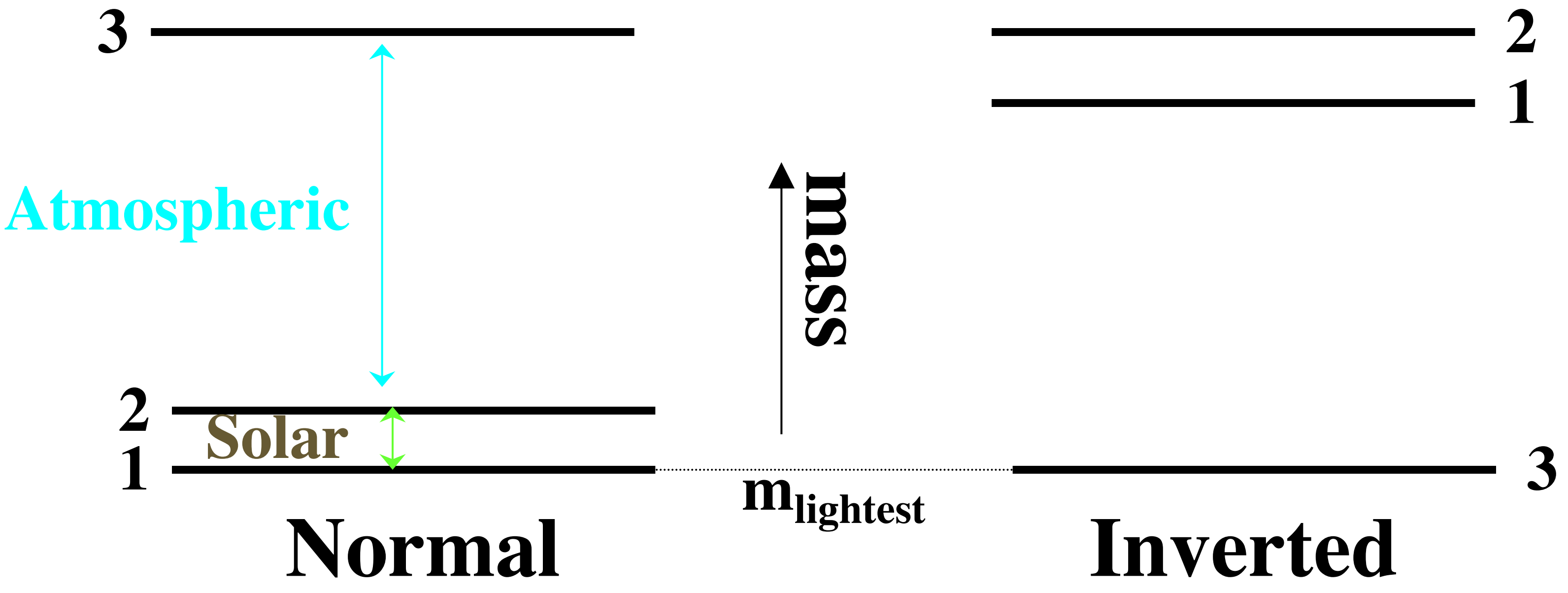
Dirac or Majorana





Mixing

We understand some, but not all, of the ν mass spectrum



Convention: ν_e is composed of a large fraction of mass eigenstate ν_1.
What we don't know is whether ν_1 is the lightest ν.

What about mixing, m_ν & $0\nu\beta\beta$?

No mixing: $\boxed{\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1}$

virtual ν exchange $\boxed{\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} U_{ei}^2 m_i}$

Compare to β decay:

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

real ν emission

Compare to cosmology:

$$\Sigma = \sum m_i$$

What can be learned from Oscillations & ββ?

- From oscillations, we have:

  Information on U_{ei}

  Information on δm^2

- With $<m_{\beta\beta}>$ constraints, we can constrain m_1: (2 flavor example)

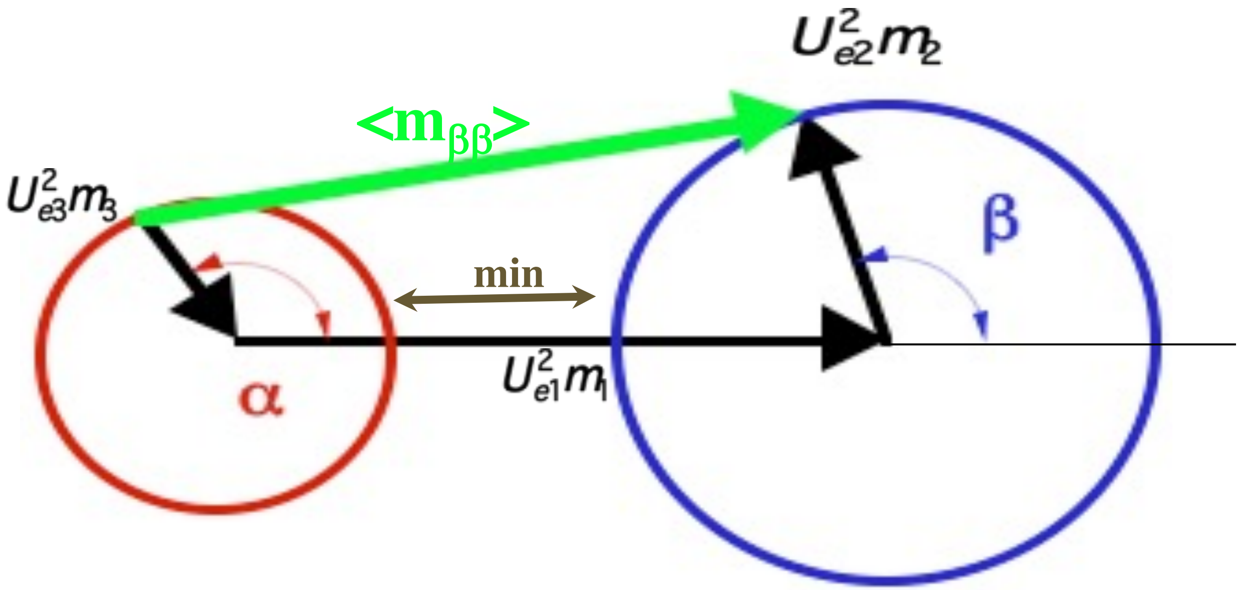
$$\langle m_{\beta\beta} \rangle = \left| U_{e1}^2 m_1 + \varepsilon_{21} U_{e2}^2 \sqrt{m_1^2 + \delta m_{21}^2} \right|$$

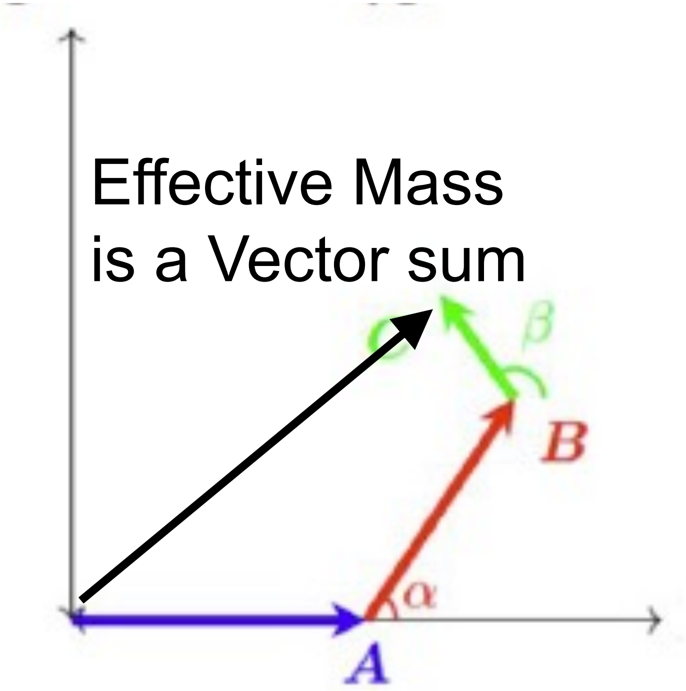
Min. <$m_{\beta\beta}$> as a vector sum. General Case

$$\boxed{\langle m_{\beta\beta}\rangle = \left| \left|U_{e1}\right|^2 m_1 + e^{i\beta}\left|U_{e2}\right|^2 m_2 + e^{i\alpha}\left|U_{e3}\right|^2 m_3 \right|}$$

<$m_{\beta\beta}$> is the modulus of the resultant.

In this 'bicycle-diagram' example, <$m_{\beta\beta}$> has a min. It cannot be 0.





The Lobster Diagram

- The 3 neutrino version results in the ‘Lobster Diagram’.
- One can calculate the maximum and minimum values from the below formula.
- Then any value between the two extremes is possible, depending on the values of the phases.
- Most often this is expressed as a function of the lightest neutrino mass.

$$\langle m_\nu \rangle_{max} = \sum_i |U_{ei}|^2 m_i \ , \ \langle m_\nu \rangle_{min} = \max[(2|U_{ei}|^2 m_i - \langle m_\nu \rangle_{max}), 0] \ .$$

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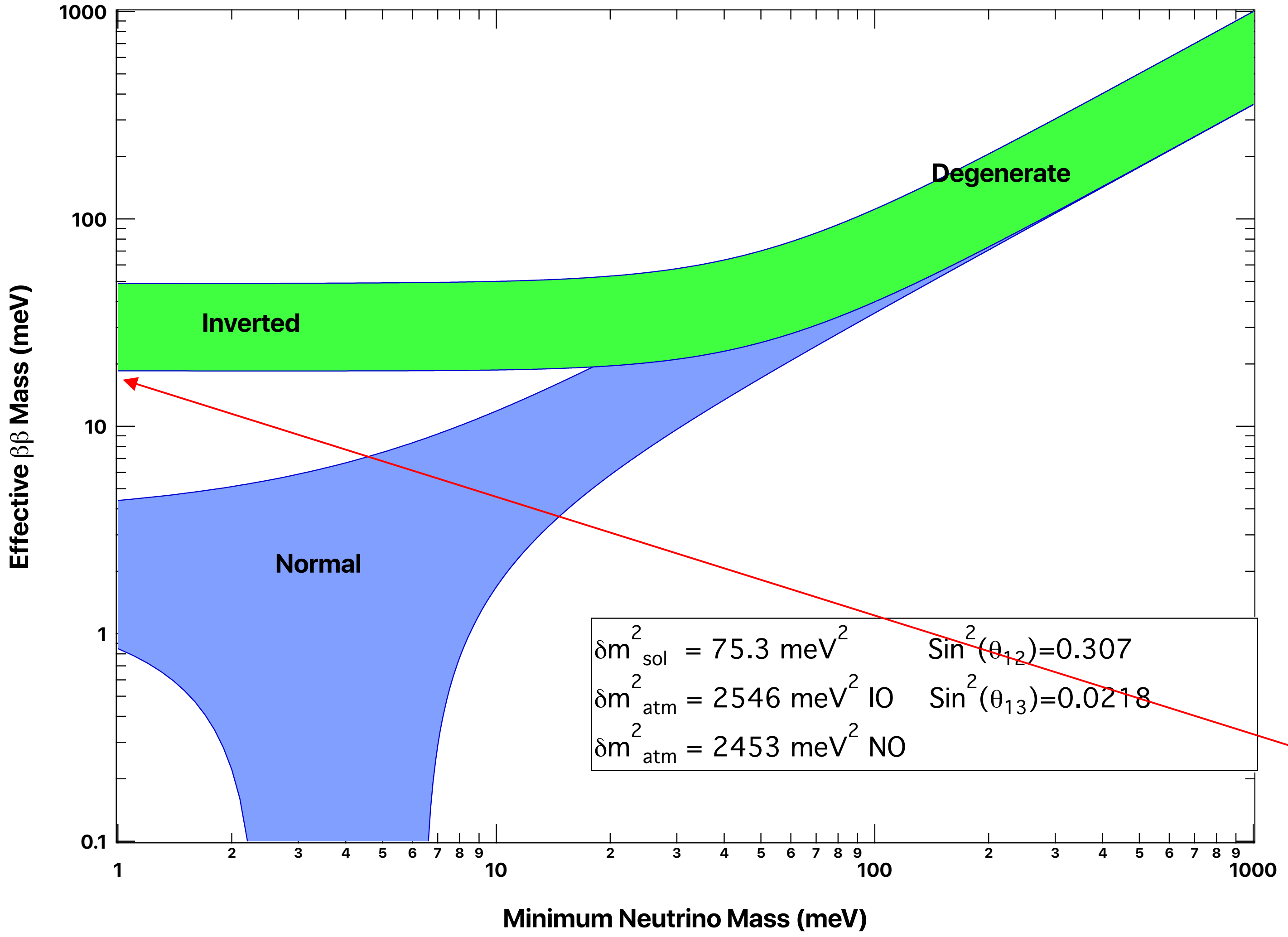
0νββ Sensitivity

(mixing parameters from PDB-2020, without uncertainties)

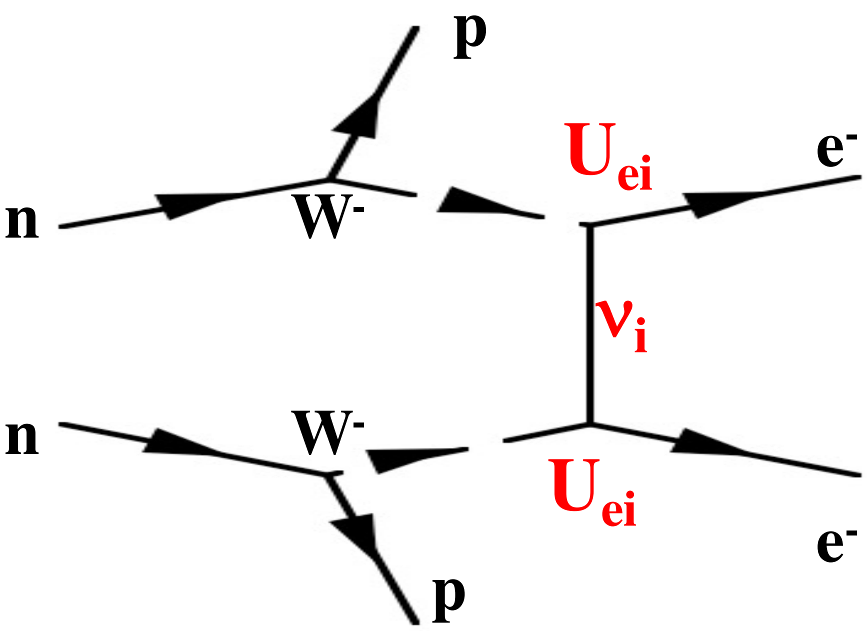


Even a null result will constrain the possible mass spectrum possibilities!

A $m_{\beta\beta}$ limit of ~18-19 meV would exclude Majorana neutrinos in an inverted ordering (IO).

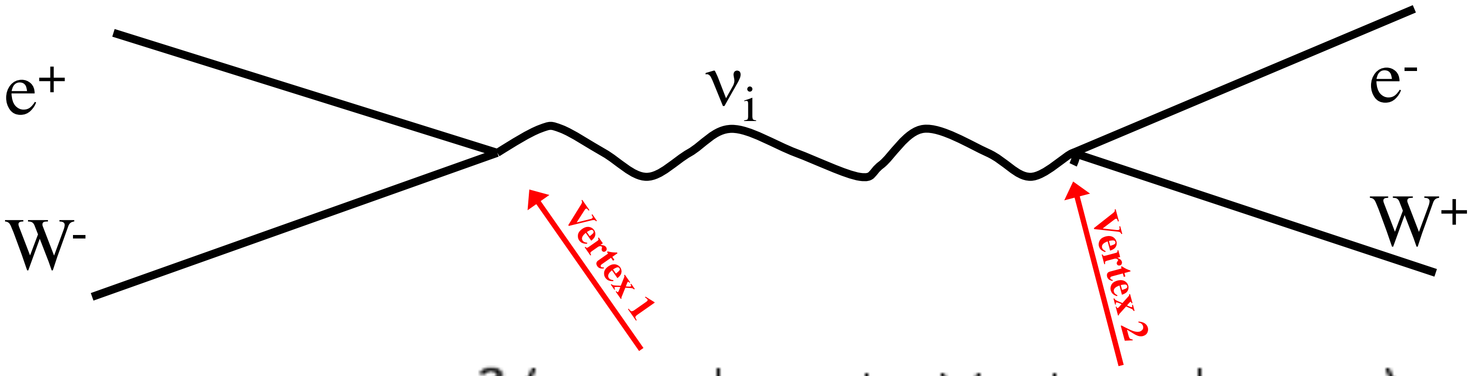
Why does the CP parity appear in $<m_{\beta\beta}>$?

$A_{0\nu} \sim \Sigma_i$



Look at the critical part of this diagram.

The crossed channel.



$$A \propto \sum_i U_{ei}^2 \langle e^+ W^- | H_{SM} | \nu_i \rangle \langle \nu_i | H_{SM} | e^- W^+ \rangle$$

The 1st vertex creates the CP partner of the particle needed by the 2nd vertex.

$$\text{but } CP|\nu_i\rangle = \epsilon_i |\nu_i\rangle$$

Upon substitution, the factor ε_i appears.

The Origin of the Majorana Phases

Sov. J. Nucl. Phys. 32 (1980) 823

- In a 3x3 mass matrix of Dirac νs, all but one phase can be absorbed into a redefinition of the ν and anti-ν fields.
- For Majorana νs, the ν and anti-ν are correlated and two fewer phases can be absorbed. This leaves 3 phases. For N neutrinos, there are N-1 Majorana phases.
- For an NxN matrix, there are N(N-1)/2 angles and N(N-1)/2 phases of which N-1 arise from the Majorana nature.
  - If light sterile neutrinos exist with CP violation, the mixing matrix will be very complicated.

An exciting time for ββ!

For at least one neutrino: $$m_i > \sqrt{\delta^2_{atom}} \approx 50\ meV$$

For the next experiments: $$\langle m_{\beta\beta} \rangle \leq 20\ meV$$

< $m_{\beta\beta}$ > in the range of 20 - 50 meV is very interesting.

The See-Saw mechanism

- Provides an understanding of why neutrinos are so light compared to their charged lepton partners.
- Provides an understanding as to why no right-handed currents are observed.
- Results in 3 light majorana neutrinos and 3 heavy sterile neutrinos.
- A Dirac mass term *m* (something like the electron mass), and a Majorana mass term μ (something like the GUT scale).

Mass matrix: $A = \begin{pmatrix} 0 & m \\ m & \mu \end{pmatrix}$

Eigenvalues: $M_{\pm} = \dfrac{\mu \pm \sqrt{\mu^2 + 4m^2}}{2}$

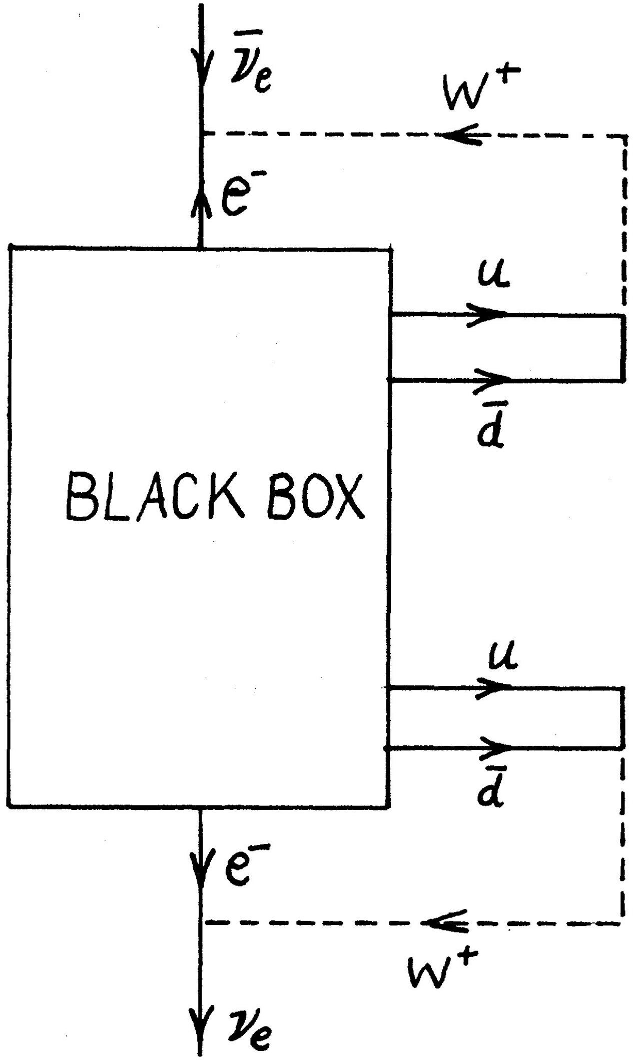
If μ >> *m*, the eigenvalues are approximately:

$$M_+ = \mu \qquad M_- = \frac{m^2}{\mu}$$

Schechter-Valle Black Box Theorem

The theorem states that: if $0\nu\beta\beta$ is observed, there must be a majorana mass term in the neutrino lagrangian.

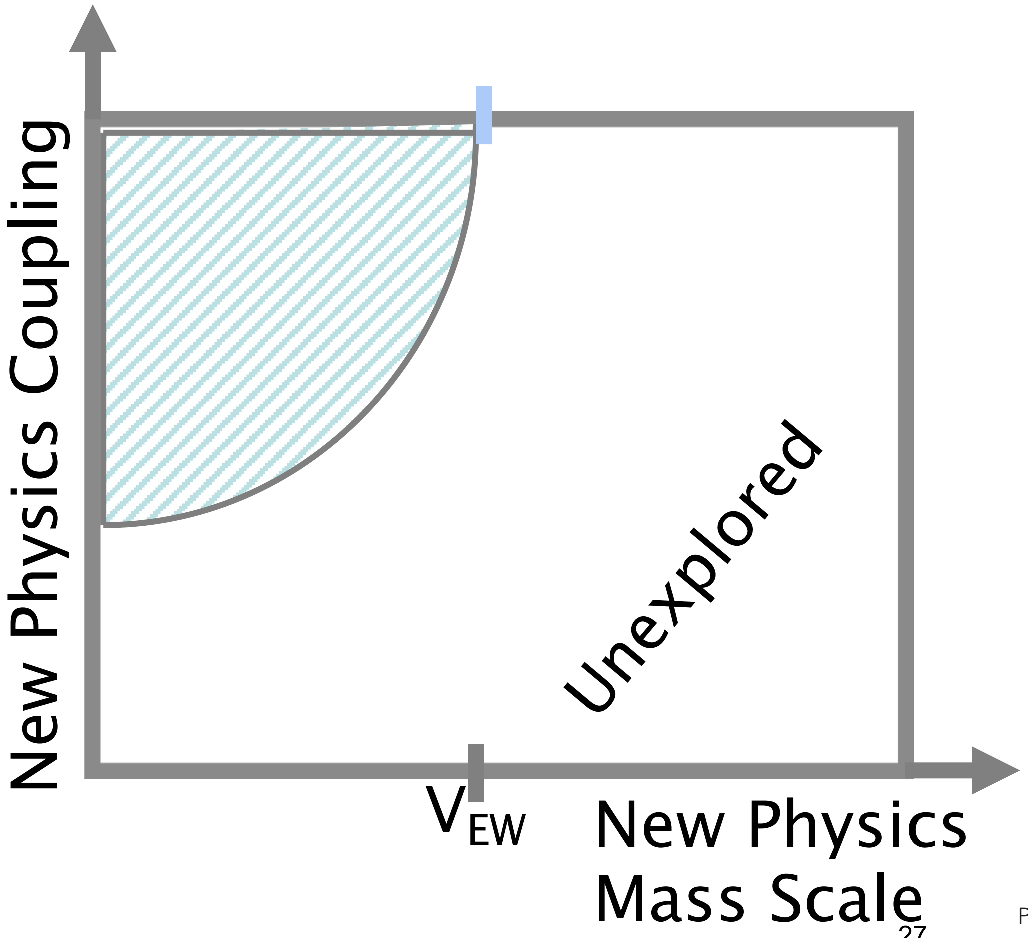
Note this diagram shows the transition from anti-neutrino to neutrino. Such a conversion indicates a majorana neutrino.



Schechter, Valle PRD 25 (1982) 2951

New BSM Physics is required, with several possibilities

- Baryon asymmetry, dark matter, dark energy, neutrino mass are all unexplained phenomena.
- But where does this new physics lie?
  - Is it heavy?
  - Is it light and weakly coupled?
- $0\nu\beta\beta$ will provide key data for this new physics over a range of scale.
- $0\nu\beta\beta$ compliments the global search along with accelerators and cosmology.



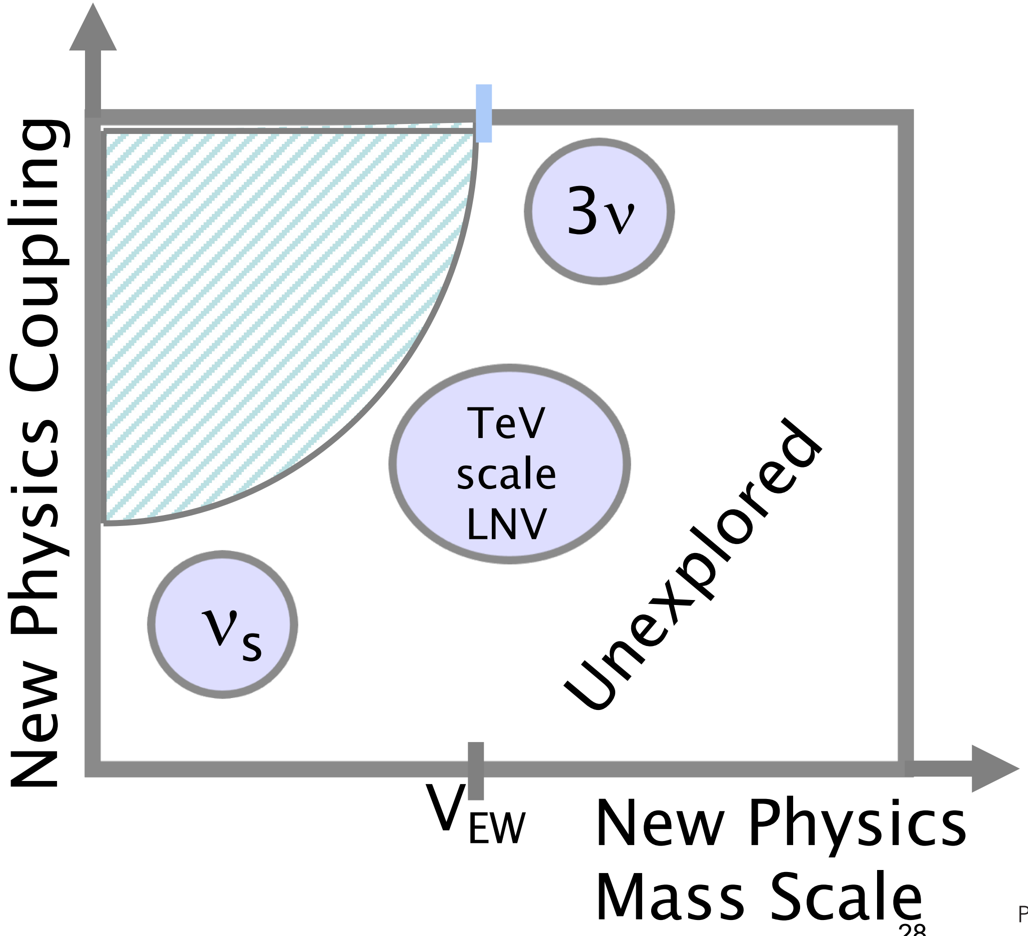
New BSM Physics Required: How LNV fits in

Map the $0\nu\beta\beta$ black box onto new physics parameter space.
$0\nu\beta\beta$ addresses a rich variety of physics at a variety of scales.

${}^{Z}A \rightarrow$

- 3ν with heavy Maj. Partners
- TeV Scale LNV
  - Heavy ν's
  - LR symmetry
  - RPV SUSY
  - other Majorana Particles
- Sterile ν's, >3 light ν's

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



Slide adapted from presentations by
V. Cirigliano and M.J. Ramsey-Musolf

Fully understanding the underlying physics requires results in several isotopes

If $\Gamma^{0\nu}$ is non-zero, ν's are massive Majorana particles, but…

$$\Gamma_{0\nu} = G_{0\nu} \left| M_{0\nu} \eta \right|^2 \quad \text{or} \quad G_{0\nu} \left| M_{0\nu} \right|^2 m_{\beta\beta}^2$$

- There are many physics models that lead to Lepton Number Violation (η), |M| can change with the model
  - –Light neutrino exchange
  - –Heavy neutrino exchange
  - –R-parity violating supersymmetry
  - –RHC
  - –etc.

The double-edged sword

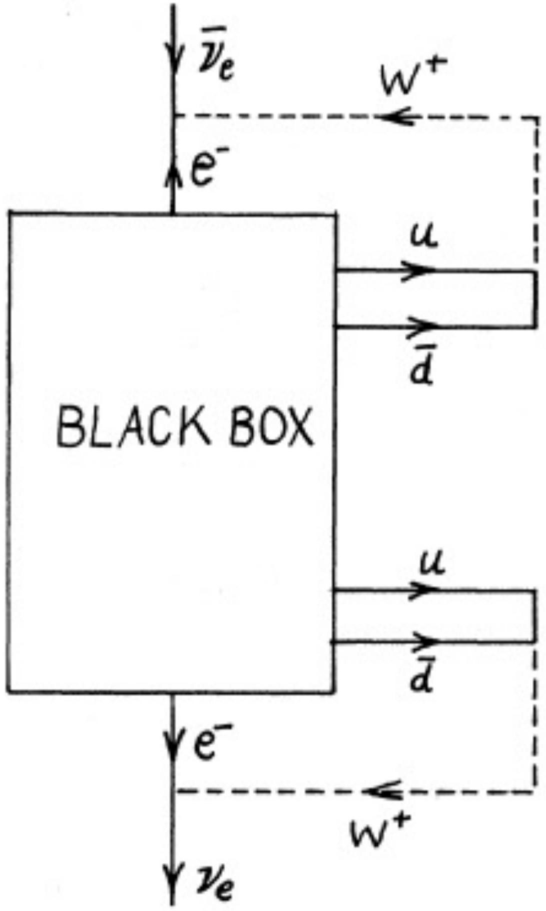
Double beta decay can have contributions from a large variety of underlying physics. This is both good and bad news.

- It enriches the science and makes $\beta\beta$ results complementary to many other BSM studies. $\beta\beta$ has provided constraints on many BSM extensions.

- It makes interpretation open to many caveats.

ββ implies LNV and Majorana ν, but…

- The Schechter-Valle theorem states there must be a Majorana component to the neutrino mass term if ββ exists.
- However, the S-V "black-box" operator contribution to m_ν is very small. Other leading contributions from BSM physics are required to explain an observable decay rate.
- Its possible to have a significant ββ rate with negligible ν mass. (See JHEP 1106:091,2011)
- Still we know there are light, massive νs.
- They may get their mass from a Majorana term in the $\mathcal{L}_\nu$.
- The simplest hypothesis to test is three light neutrinos, either Majorana or Dirac. This hypothesis has the least new physics.
- ββ is the best way to explore this hypothesis. This ansatz is also the usual basis to compare techniques.



PRD 25 (1982) 2951

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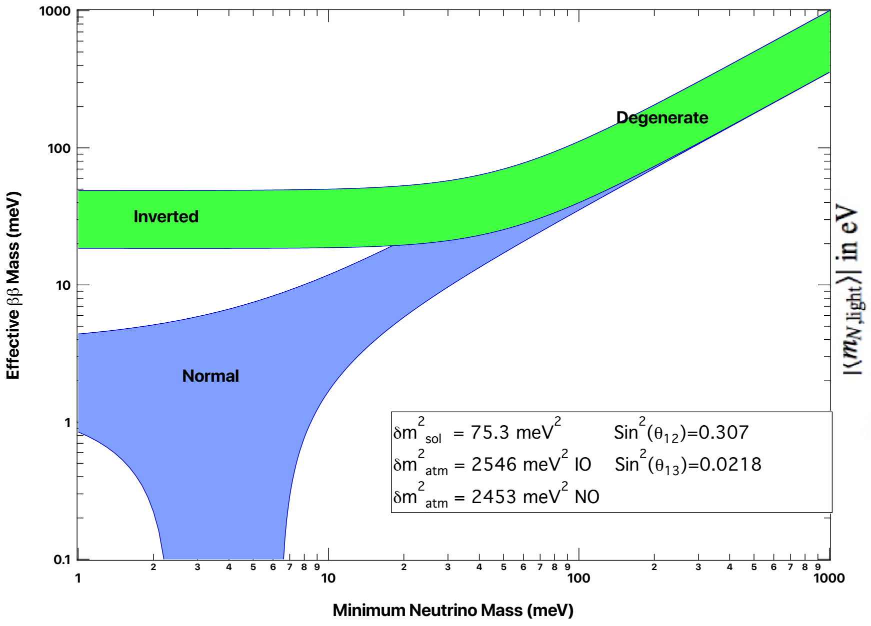
ββ is sensitive to a lot of physics

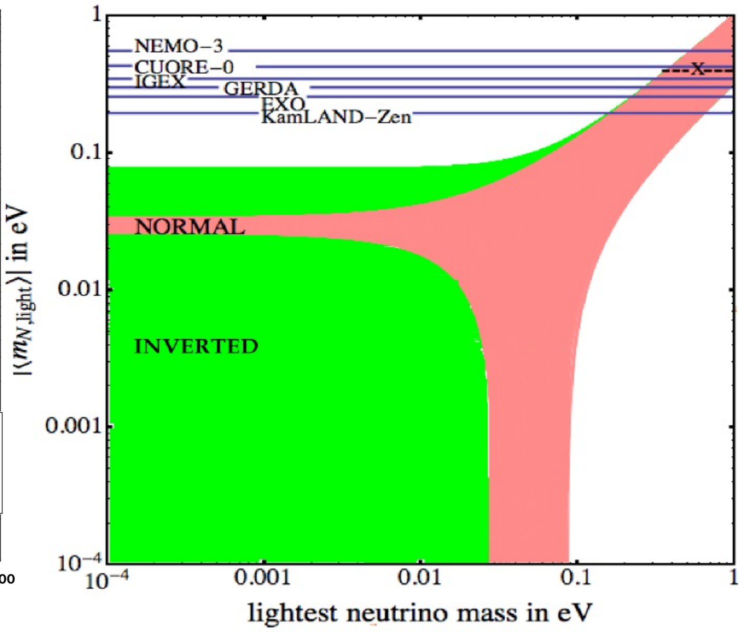
$$\Gamma_{0\nu} = G_{0\nu} \left| M_{0\nu} \eta \right|^2 \quad \text{or} \quad G_{0\nu} \left| M_{0\nu} \right|^2 m_{\beta\beta}^2$$

- A measurement or limit on ββ is a powerful way to constrain many beyond-the-standard models.
- η is a lepton number violating parameter that might depend on $M_{0\nu}$. Its form depends on the LNV model.

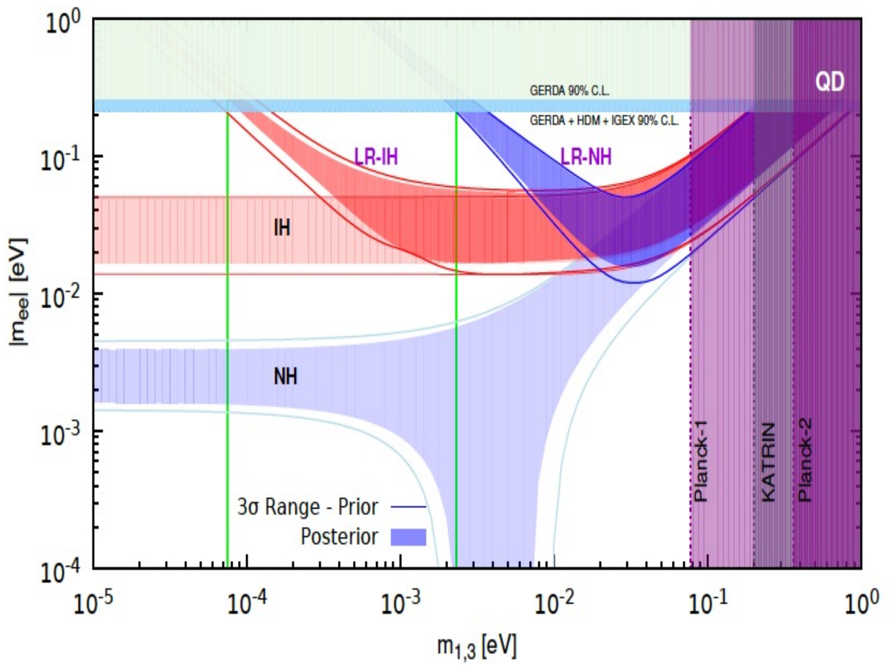
ββ Addresses Key Physics Regardless of Mass Ordering



3 neutrino paradigm



Light sterile neutrino contribution
An example: PRD92, 093001 (2015)
Many papers on this topic.



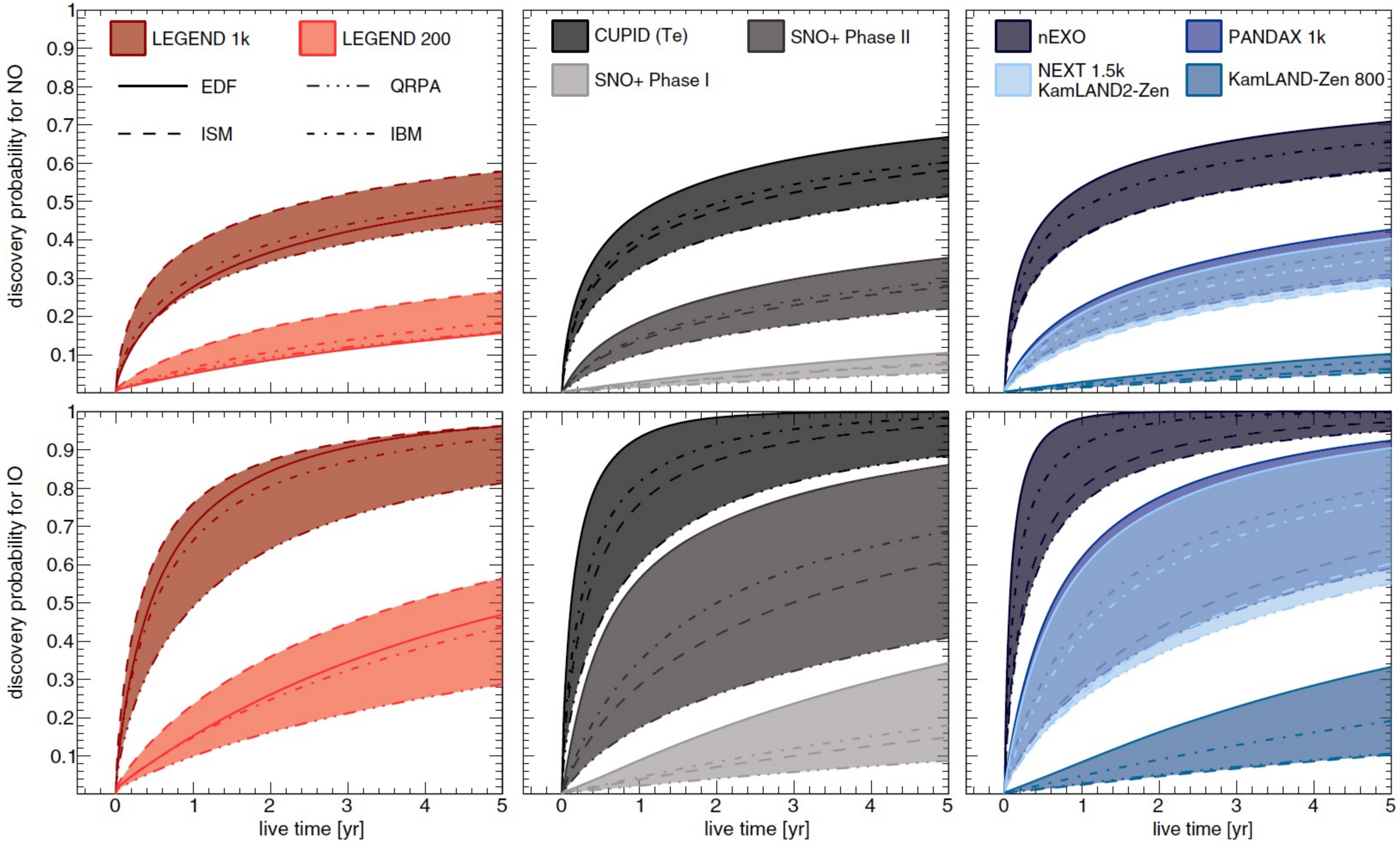
Left-Right symm., Type II contributions
From J. HEP 10, 077 (2015)
Also many papers on this topic.

If ββ is seen, the qualitative conclusions are profound, but observations in several nuclei will be required to fully understand the underlying physics.

ββ discovery potential high, even for NO

Even for the case of normal ordering of neutrino masses in a 3-ν paradigm, the discovery potential is high because the phases and lightest neutrino mass value have no a priori preferred values.

This qualitative conclusion is not changed due to cosmological constraints or if g_A quenching is included.



Example analysis from PRD 96, 053001 (2017)

Other Manifestation of $\beta\beta$

- $2\nu\beta\beta/0\nu\beta\beta$
  - Standard modes most frequently discussed.
- $2\nu\beta^+\beta^+/0\nu\beta^+\beta^+$
  - Phase space greatly decreased leading to very long half lives.
  - 2ν mode interesting for matrix element tests.
- $2\nu EC\beta^+/0\nu Ec\beta^+/2\nu EcEC/0\nu ECEC$
  - 0ν ECEC mode requires a radiative emission to conserve energy.
  - Opportunity for significant background reduction, but requires resonance for appreciable half life.

ββ and the ν

- **0νββ decay rate proportional to neutrino mass squared**
  - **Most sensitive laboratory technique (if Majorana particle).**
- **Decay can only occur if lepton number conservation is violated.**
  - **May result in leptogenesis model for the matter/antimatter asymmetry.**
- **Decay can only occur if νs are massive Majorana particles.**
  - **Critical for understanding incorporation of mass into standard model.**
  - **ββ is only practical experimental technique to answer this question.**
- **Fundamental nuclear/particle physics process.**

Matrix Elements

Nice Overview J. Engel, J. Phys. G 42 (2015) 034017

- QRPA/RQRPA: uses a large valence space, but only a class of configurations is included. Hence the technique describes collective states, but not details of dominantly few particle states.

- NSM: uses a limited valence space but all configurations of valence nucleons are included. The technique describes well properties of low-lying nuclear states.

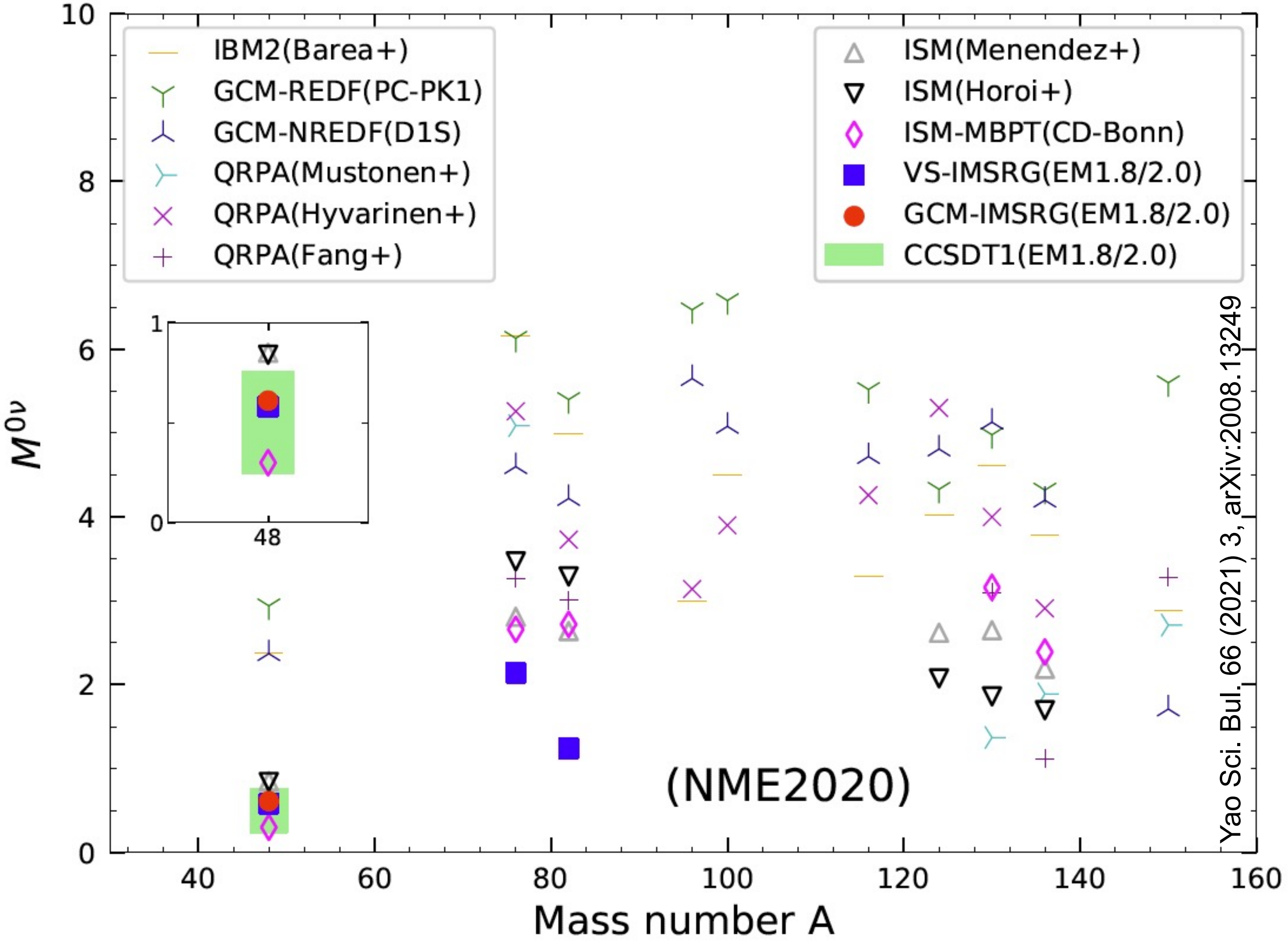
- PHFB: uses wavefunctions of good angular momentum

- EDF (generator coordinator): is an enhancement to the PHFB calculations. It uses state-of-the-art density functional methods and a much larger single particle basis.

- IBM-2: models the low lying states of the nucleus in terms of bosons. These bosons have either L=0 (s boson) or L=2 (d boson) descriptions. The bosons can interact through one and two body forces giving rise to bosonic wave functions.

- ab initio: Calculate the NMEs from first principles, taking advantage of the recent progress in nuclear-structure theory. The starting point for any ab initio calculation is a Hamiltonian with coupling constants fit to reproduce data in few-nucleon systems. The 'quenching' effect would be included in this calculations. (PRL 124 (2020) 232501)

Matrix Element Results



The calculations vary by a factor of 2-3. Usually taken as an estimate of the uncertainty.

It is not a true uncertainty because the different models neglect different physics.

Example of Calculations for Ge-76

Framework	Nuclear Matrix Element Values ($M_{0\nu}$)
Nuclear Shell Model	3.37 - 3.57 [22], 2.89 - 3.07 [23], 2.66 [24]
Quasiparticle Random Phase Approximation	5.09 [25], 5.26 [26], 4.85 [27], 3.12 - 3.40 [28]
Interacting Boson Model	4.68 [29]
Energy Density Functional	4.60 [30, 31], 5.55 [32], 6.04 [33]
Range	2.66 – 6.04

Spread typically is factor of 2-3.

Axial Vector coupling constant appears as 4th power – big effect

$$M_{0\nu} = M_{\rm GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_{\rm F}^{(0\nu)} + M_{\rm T}^{(0\nu)}.$$

- In β-decay, the theoretical matrix elements are larger than the experimental ones. The ratio is nearly constant, so to account for this, the value of g_A is "quenched" by a factor of about 0.8.
- The level of quenching will depend on the number single particle states included in the shell.
- In $2\nu\beta\beta$, quenching is also observed and its size depends on the configurations used in the calculation. Calculations tend to find a g_A near 1.0, instead of 1.27 works best. Some comparisons (e.g. IBM-2) between $M_{2\nu}$ and measured rates, the result gives g_A ~0.6. This is a factor of 2^4=16 in the required exposure.
- $2\nu\beta\beta$ only connects 1+ states in intermediate nucleus, whereas $0\nu\beta\beta$ connects a large number of states. The $2\nu\beta\beta$ momentum transfer is a few MeV, whereas for $0\nu\beta\beta$ it is about 100 MeV. Big difference in operator expansions.
- Is quenching required in $0\nu\beta\beta$? Unlike $2\nu\beta\beta$, $0\nu\beta\beta$ has a Fermi matrix element in addition to Gamov-Teller. The Fermi part does not include quenching, hence although still a big effect, its not as big for $2\nu\beta\beta$.
- Simply scaling M_0 as g_A^2, quenching would introduce a 40%. Since the Fermi contribution is sizable, it's closer to 20-30%. Since the decay rate depends on M_0^2, a 25% quenching would reduce the decay rate by 44%.
- Other processes, such as mu-capture, that involve all such states and has a similar momentum transfer don't require quenching. If quenching is present, it is unlikely to be as large as in the $2\nu\beta\beta$ case. Question certainly needs further study.

Contact Term

$$T_{1/2}^{-1} = G_{01} \left(g_A^2 M^{0\nu} + g_\nu^{\mathrm{NN}} m_\pi^2 M_{\mathrm{cont}}^{0\nu} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

- Citation: PRL 120 (2018) 202001, PRC 100 (2019) 055504

- Recently it has been recognized that a leading order, short-range contribution has previously been ignored in calculations of decay transition operators. This “contact term" represents the effects of heavy mesons and quark/gluon physics that can be excited by the exchanged neutrino when its energy is above about a GeV.

- Effective field theory and ab-initio nuclear structure provide a scheme for estimating how large the coefficient of such a term in the double-beta operator should be, and recent work in this direction (arXiv:2105.05415) indicates that this term is potentially tens of percent of M_0 in magnitude with the same sign, leading to enhancement of the decay rate.

- The early work indicates an increase in M_0.

ββ is best way to determine Majorana-Dirac (light ν's)

$\nu \Rightarrow \bar{\nu}$ $$R_{\nu\nu} = F\sigma_0 h_{\nu\nu}^2$$

$\beta\beta$ $$R_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 h_{\beta\beta}^2$$

$(\beta\beta)^{-1}$ @NLC $$R_{ee} = L_0\sigma_0 h_{ee}^2$$

$e^- e^- \rightarrow W^- W^-$

Rates per target.
ββ is the most sensitive experimental technique regardless of Avogadro's number.

F: flux, L_0: reduced luminosity, h: 'helicity suppression' factor

The 'h's are comparable for all 3.
The number of targets are similar for ββ and oscillation
But GM^2 is huge compared to Fσ, gives $\times 10^{11}$ advantage.
It's GM^2, not N_A that gives ββ its strength.

$\beta\beta$ & LHC are complementary (Heavy ν's)

$\beta\beta$

$$R_{0\nu} = G_{0\nu} \left| M_{0\nu} \right|^2 \left(\frac{m_p}{M_{ee}} \right)^2$$

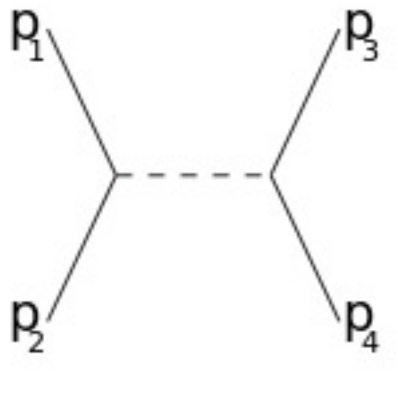
$(\beta\beta)^{-1}$ @NLC

$$R_{ee} = L_0 \sigma_0 h_{ee}^2$$

$$\sigma_0 = \frac{G_F^2}{16\pi} s^2 \left(\frac{m_p}{m_\nu} \right)^2$$

The s^2 factor is significant. And σ_0 might be especially large in the case of resonance.

For heavy ν's, LHC/NLC are competitive, depending on model, with $\beta\beta$.



s-channel

$$S = (\overrightarrow{P_1} + \overrightarrow{P_2})^2$$

There are lots of papers on the comparison between NLC/LHC and $\beta\beta$. See for example:

- London arXiv:hep-ph/9907419
- Peng et al. PRD 93 (2016) 093002
- Helo et al. PRD 88 (2013) 011901, 073011
- Helo et al. PRD 92 (2015) 073017
- Rodejohann PRD 81 (2011) 114001
- Lindner PLB 762 (2016) 190
- Gonzales et al. arXiv:1606.09555