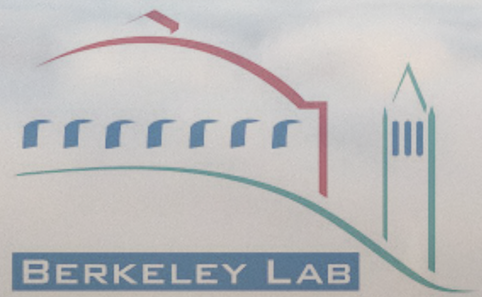
Neutrinoless Double Beta Decay ($0\nu\beta\beta$) & Lattice QCD

Lattice field theory at the frontier of nuclear and particle physics

3-5 November, 2026

André Walker-Loud



Plan & Acknowledgements

1. Neutrinoless Double Beta Decay
2. What can LQCD do for $0\nu\beta\beta$?
3. Research talk: NN @ light pion mass

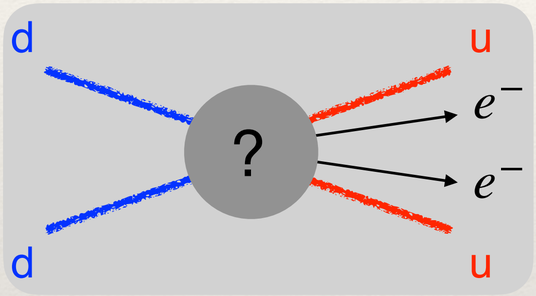
- These lectures are heavily inspired from
  - lectures of Vincenzo Cirigliano
  - seminars by Amy Nicholson and Evan Berkowitz

Neutrinoless Double Beta Decay

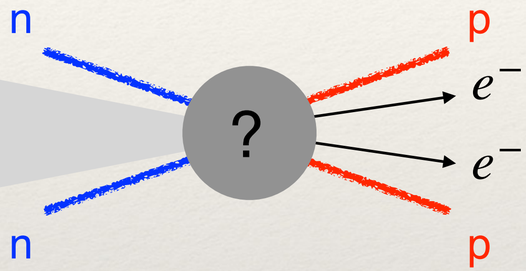
If neutrinos are their own antiparticle (Majorana neutrinos)…

Through a double-weak process, a neutrinoless double β-decay process can occur

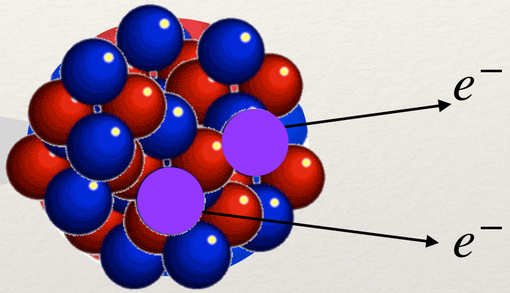
$$(N, Z) \longrightarrow (N-2, Z+2) + e^- + e^-$$



$\Delta L = 2$



$\Delta L = 2$



$\Delta L = 2$

$\Delta L = 2$ process in which 2 down quarks convert to 2 up quarks and two electrons

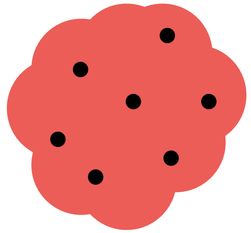
At the hadronic level, this would manifest as 2 neutrons undergoing β-decay to 2 protons and 2 electrons

If it happens, this process is so rare, the only way to observe it is through observing large quantities of nuclear double β-decay

Desperate Remedy



- Spin of ^{14}N and ^{6}Li conflicted with the Rutherford model of the nucleus (protons+electrons)



- β decay seemed to violate sacrosanct conservation laws.

- Both puzzles could be resolved with a single light charge-neutral spin-½ particle!

ikalisches Institut
Eidg. Technischen Hochschule
ich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst zuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

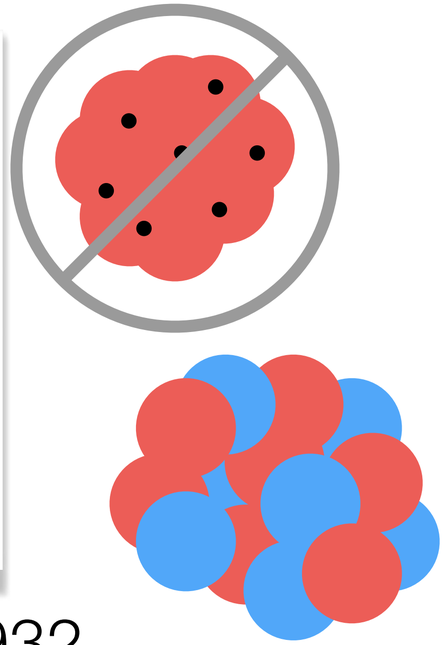
Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

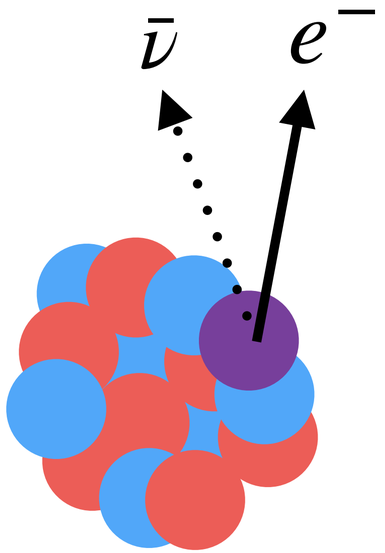
gez. W. Pauli

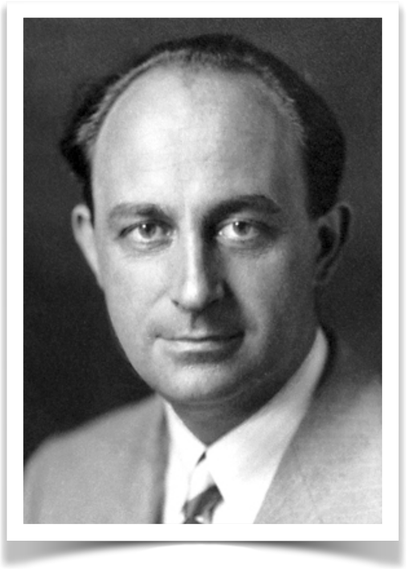
neutrons and β decay





Chadwick 1932

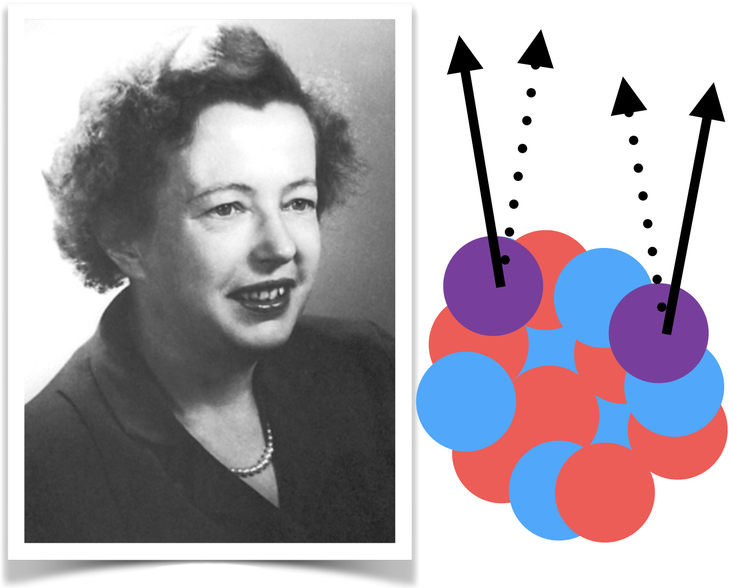




Fermi 1934

Double β decay

$10^{21\text{-}22}$ yr



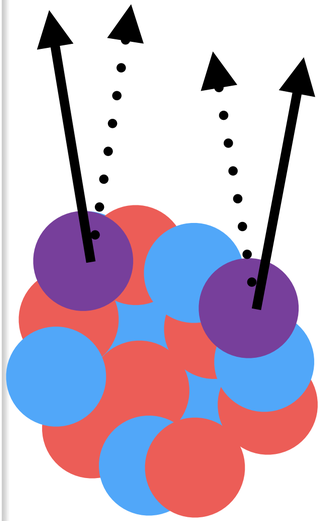
Goeppert-Mayer 1934

- Goeppert-Mayer proposed double β-decay to explain the observation of nuclei stable against β-decay still decaying to more stable isobar nuclei
- She calculated the half-lives to be $> 10^{17}$ years
- First observed experimentally in 1987 by S. Elliot, A. Hahn, M. Moe enriched ^{82}Se $(8.7\,\% \longrightarrow 97\,\%)$

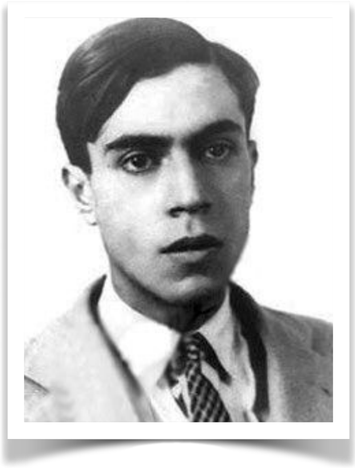
Double β decay

$10^{21\text{-}22}$ yr





Goeppert-Mayer 1934



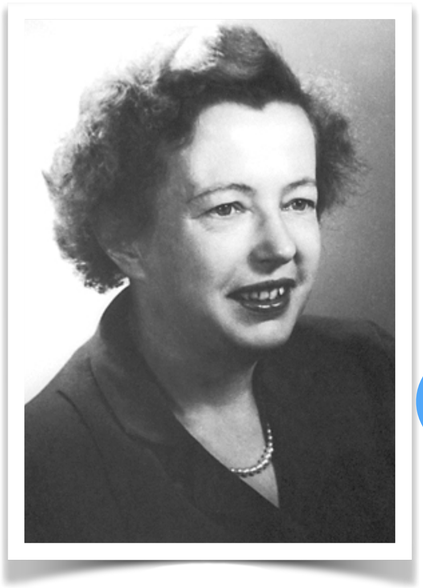
Majorana 1937

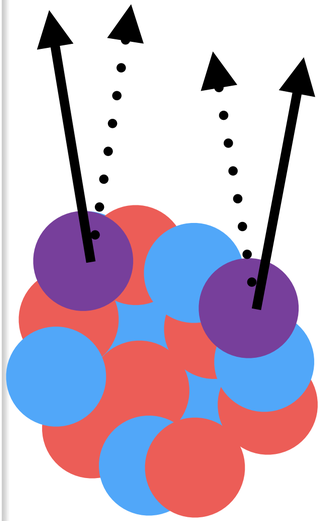
$$\nu \stackrel{?}{=} \bar{\nu}$$

- Majorana recognized that the charge neutral nature of neutrinos meant they could be described by a real-valued wave-equation
- A consequence being that neutrinos would be their own anti-particle as the charge-conjugation operator would leave the state unchanged

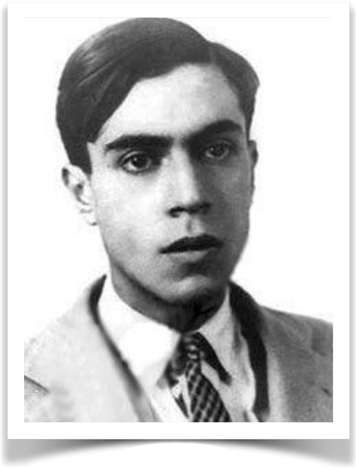
Double β decay

$10^{21\text{-}22}$ yr





Goeppert-Mayer 1934



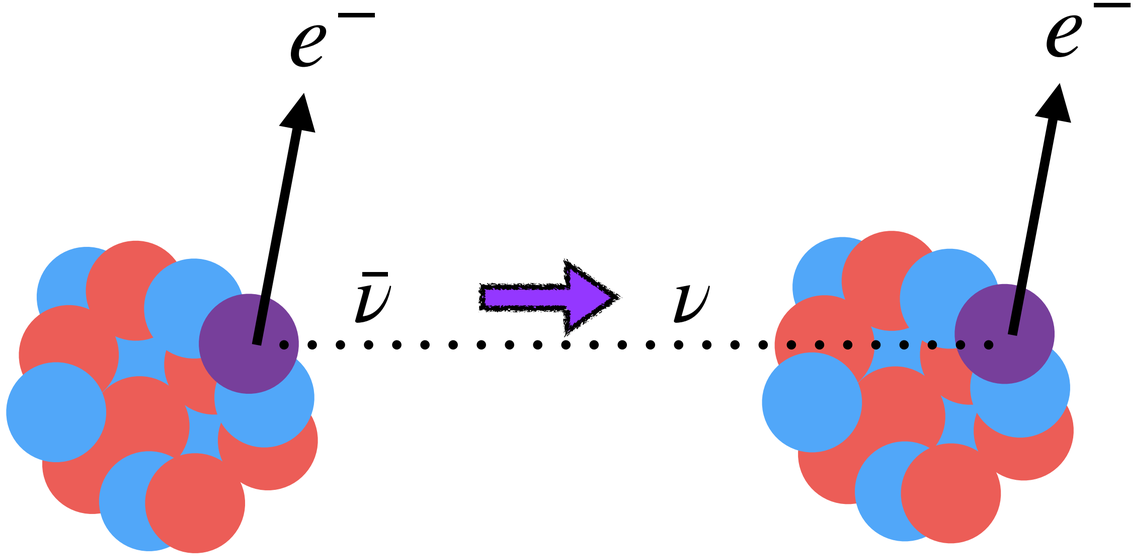
Majorana 1937

$\nu \stackrel{?}{=} \bar{\nu}$



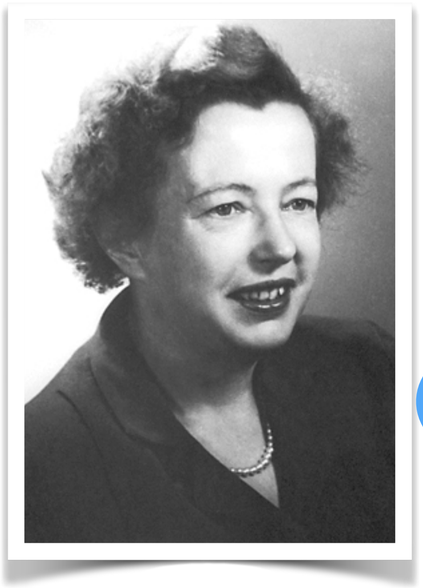
Racah 1937

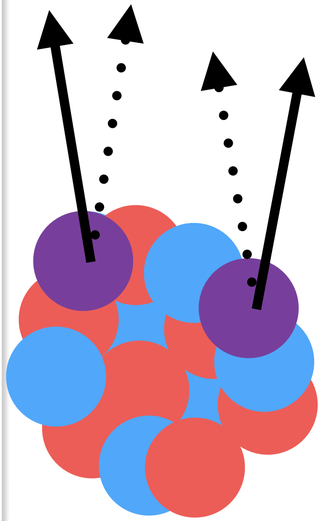
- Racah suggested if $\nu = \bar{\nu}$, one nucleus undergoing β -decay could trigger another β-decay in a 2nd nucleus



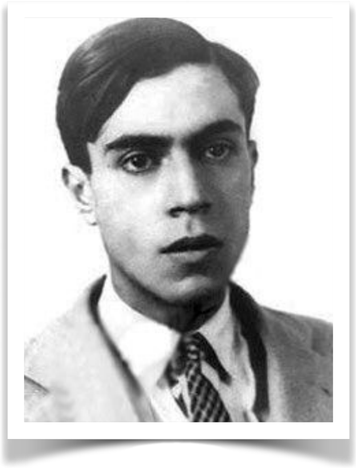
Double β decay

$10^{21\text{-}22}$ yr





Goeppert-Mayer 1934



Majorana 1937

$\nu \stackrel{?}{=} \bar{\nu}$



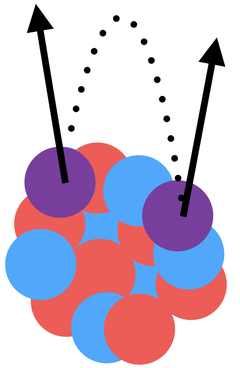
Racah 1937



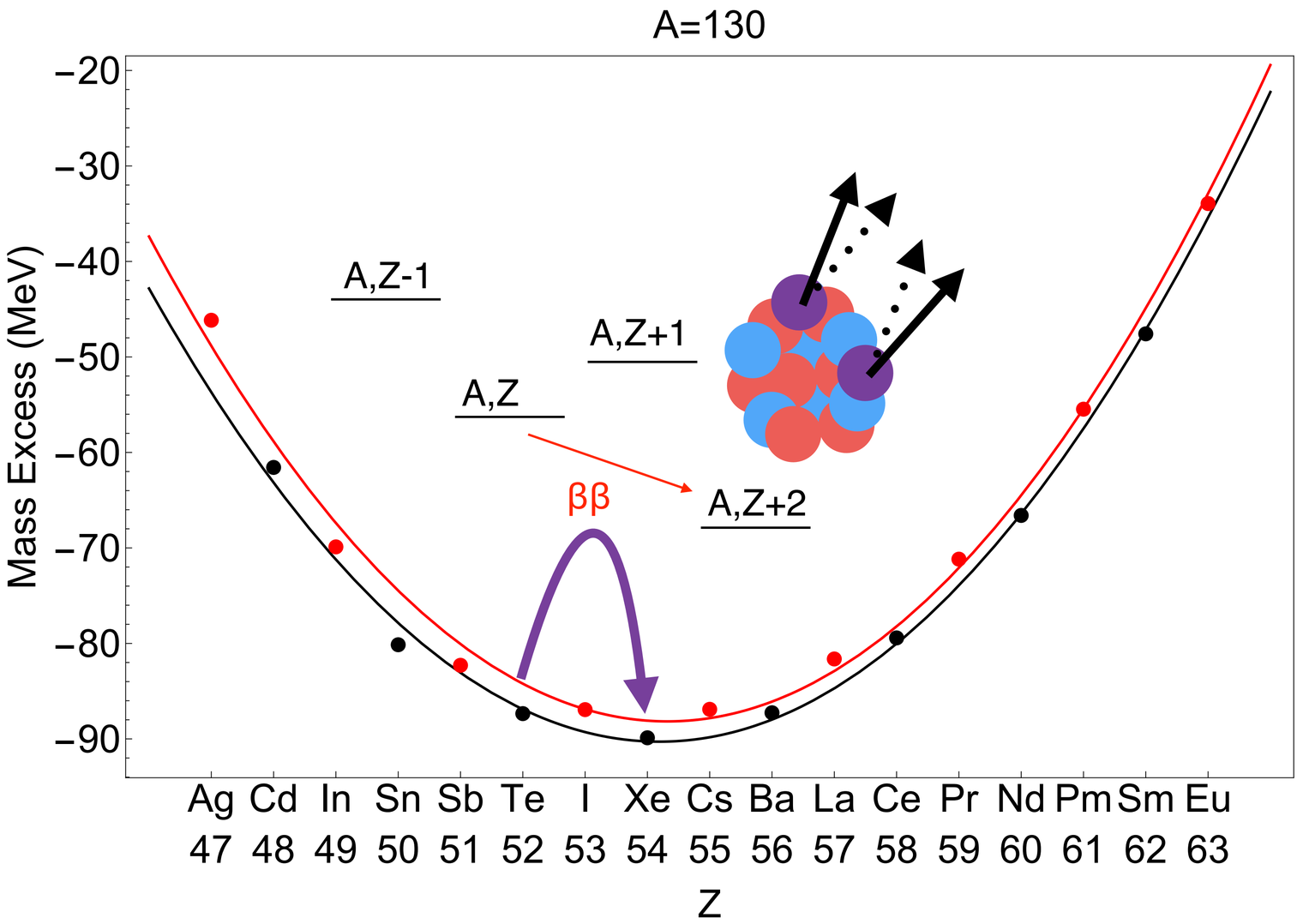
Furry 1939

- Furry developed the idea further and suggested the initial neutrino could be absorbed within the same nucleus — what we now call $0\nu\beta\beta$

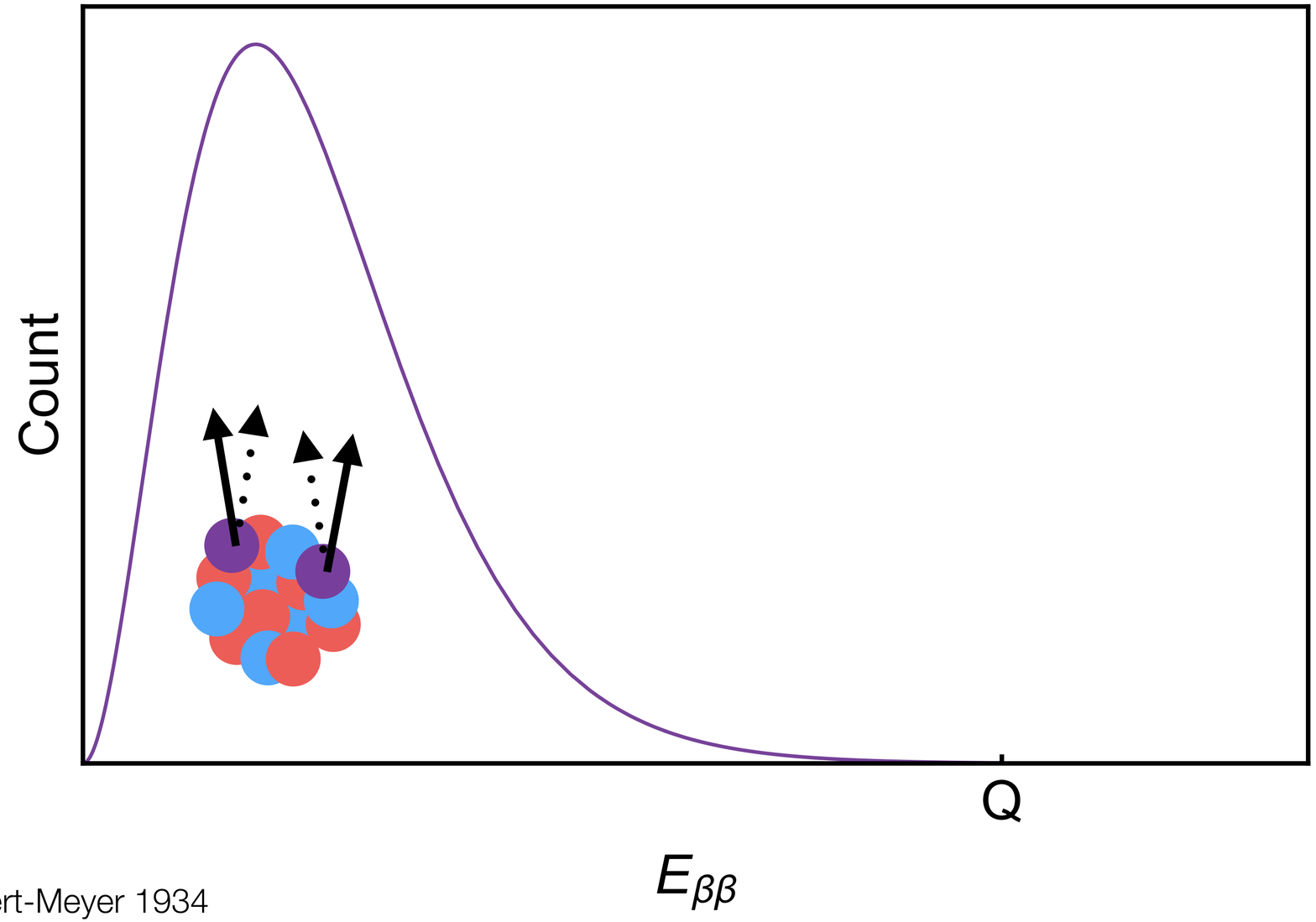
- As $\nu/\bar{\nu}$ remains virtual, e^- cary away all energy, leaving sharp, distinct end-point peak



Nuclear Laboratory

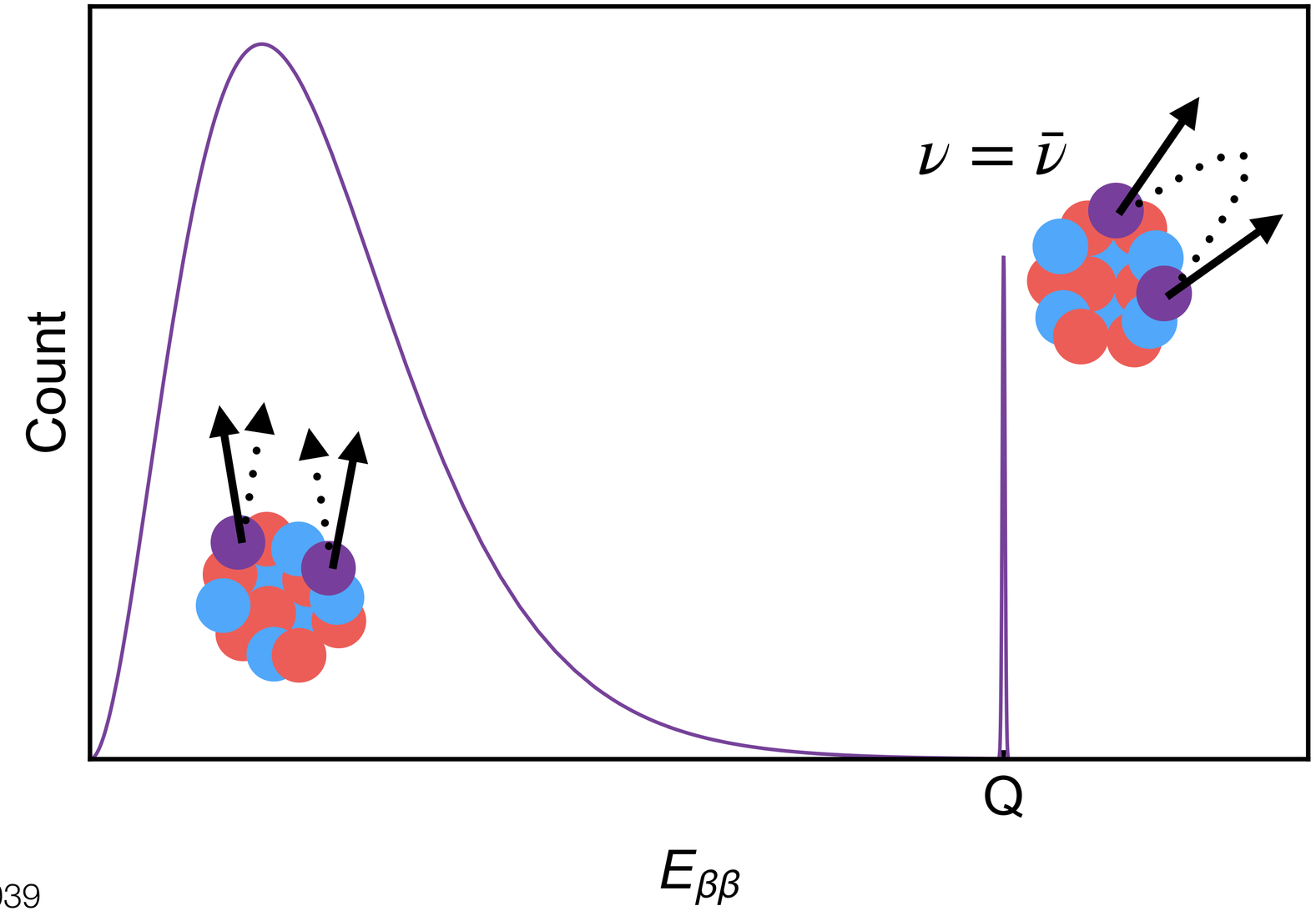


2νββ



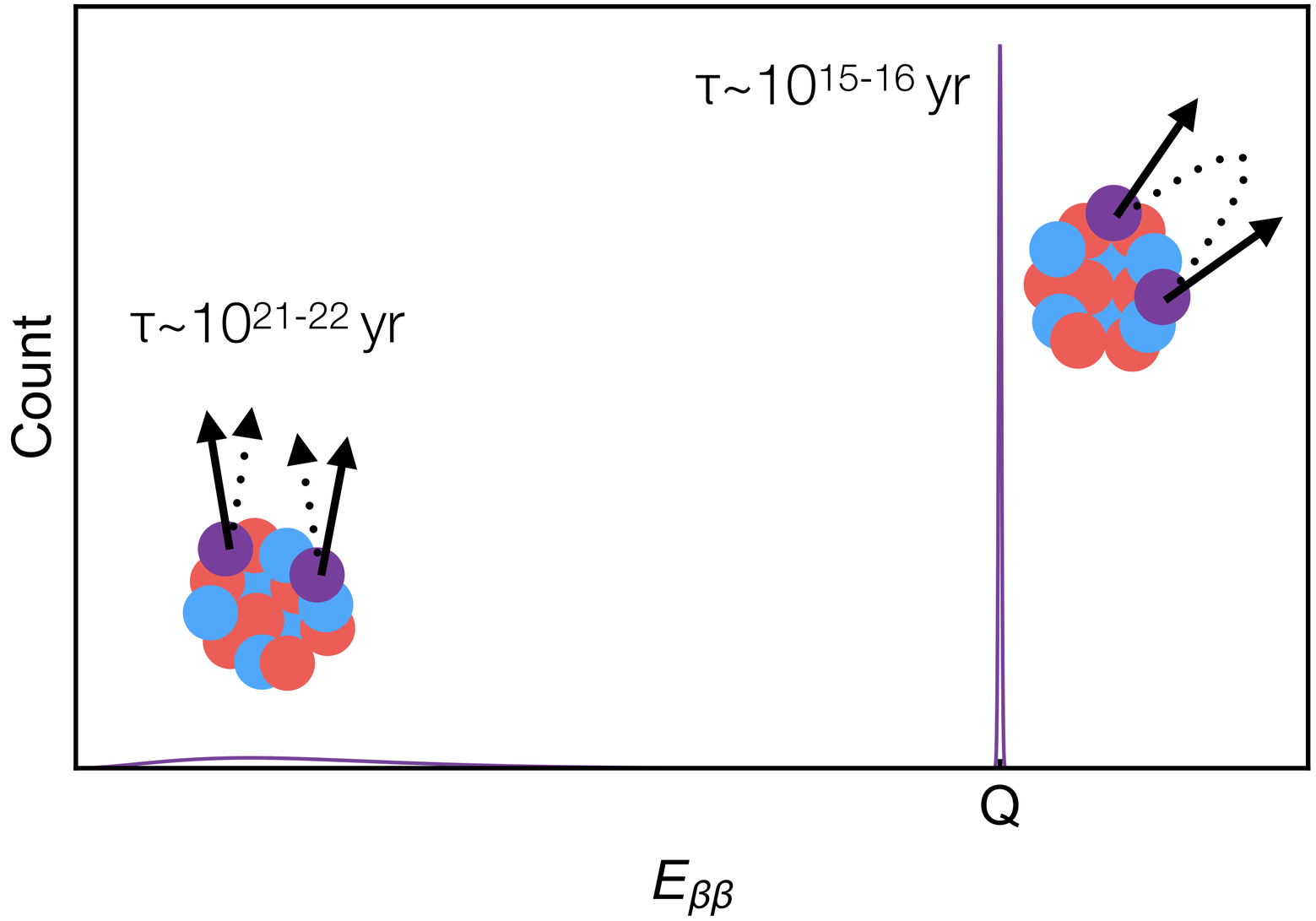
Goeppert-Meyer 1934

2νββ + 0νββ

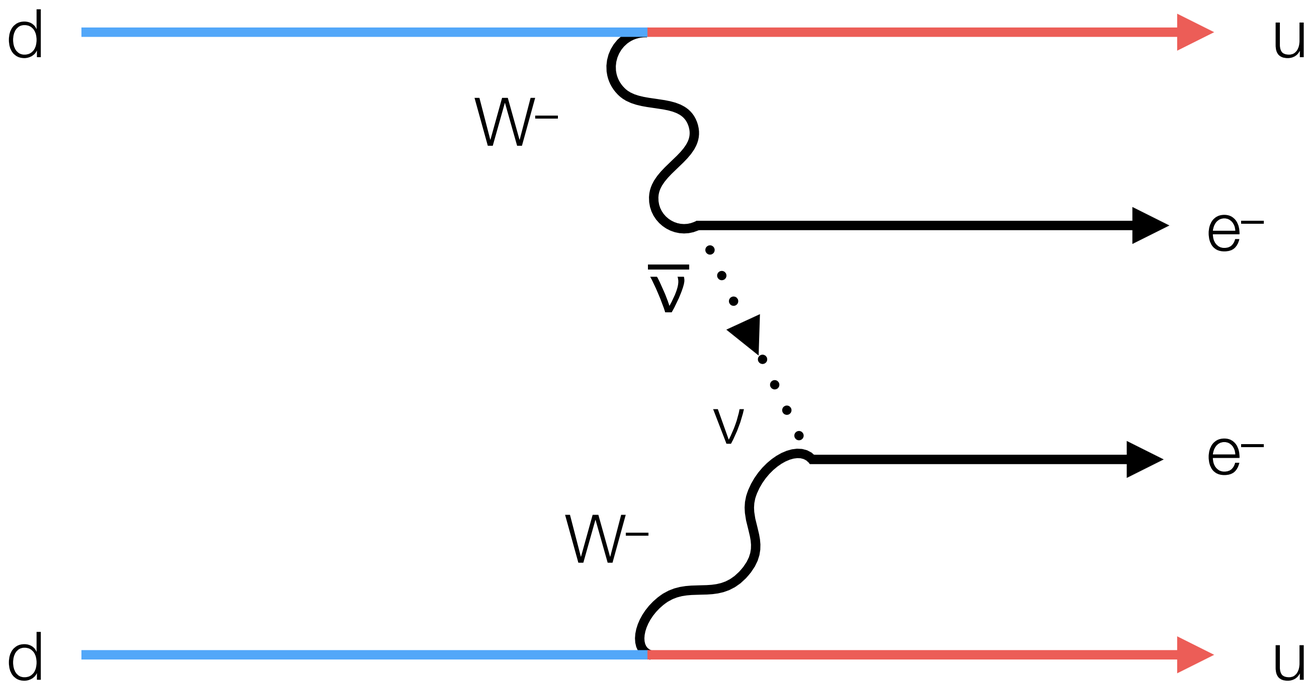


Furry 1939

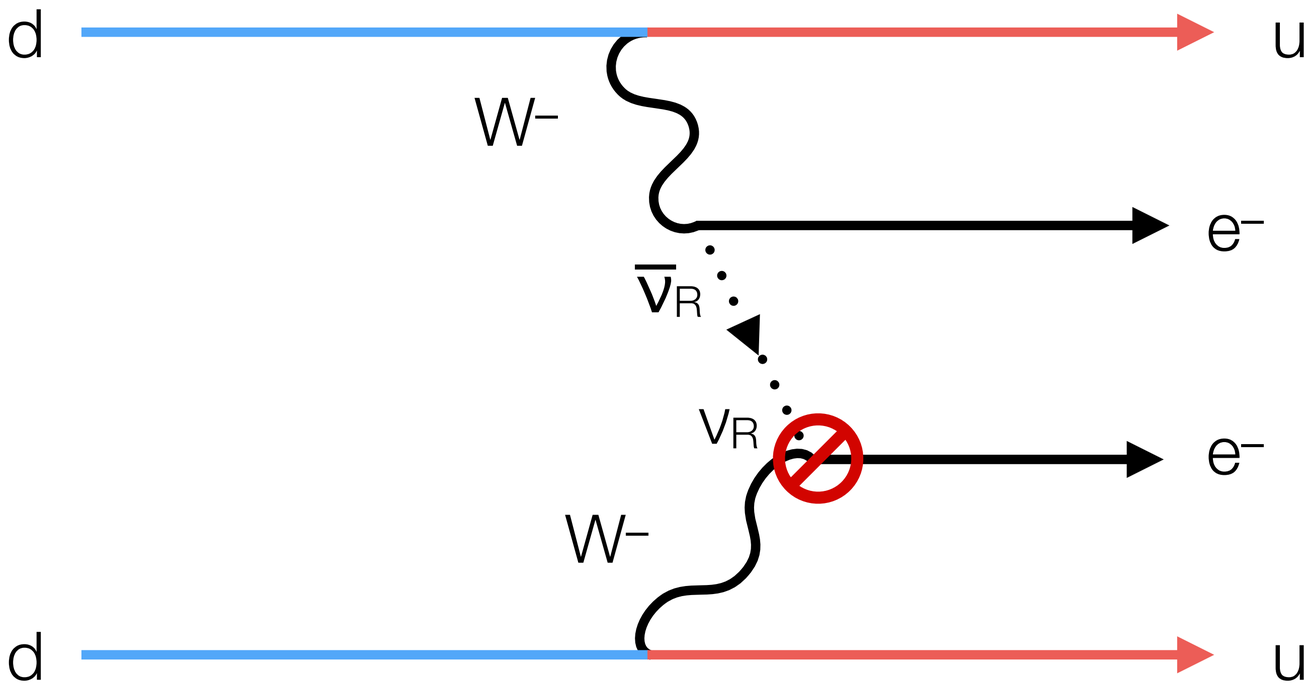
1940s Expectation / Hope



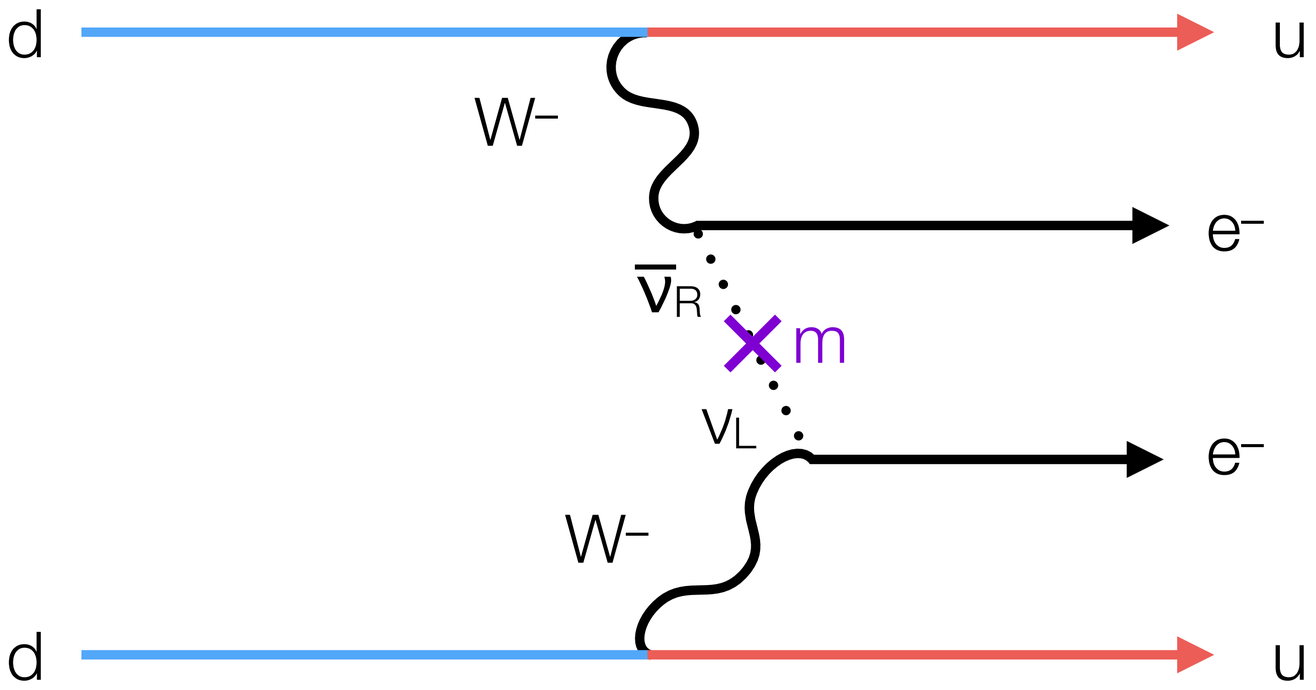
So? Nu?



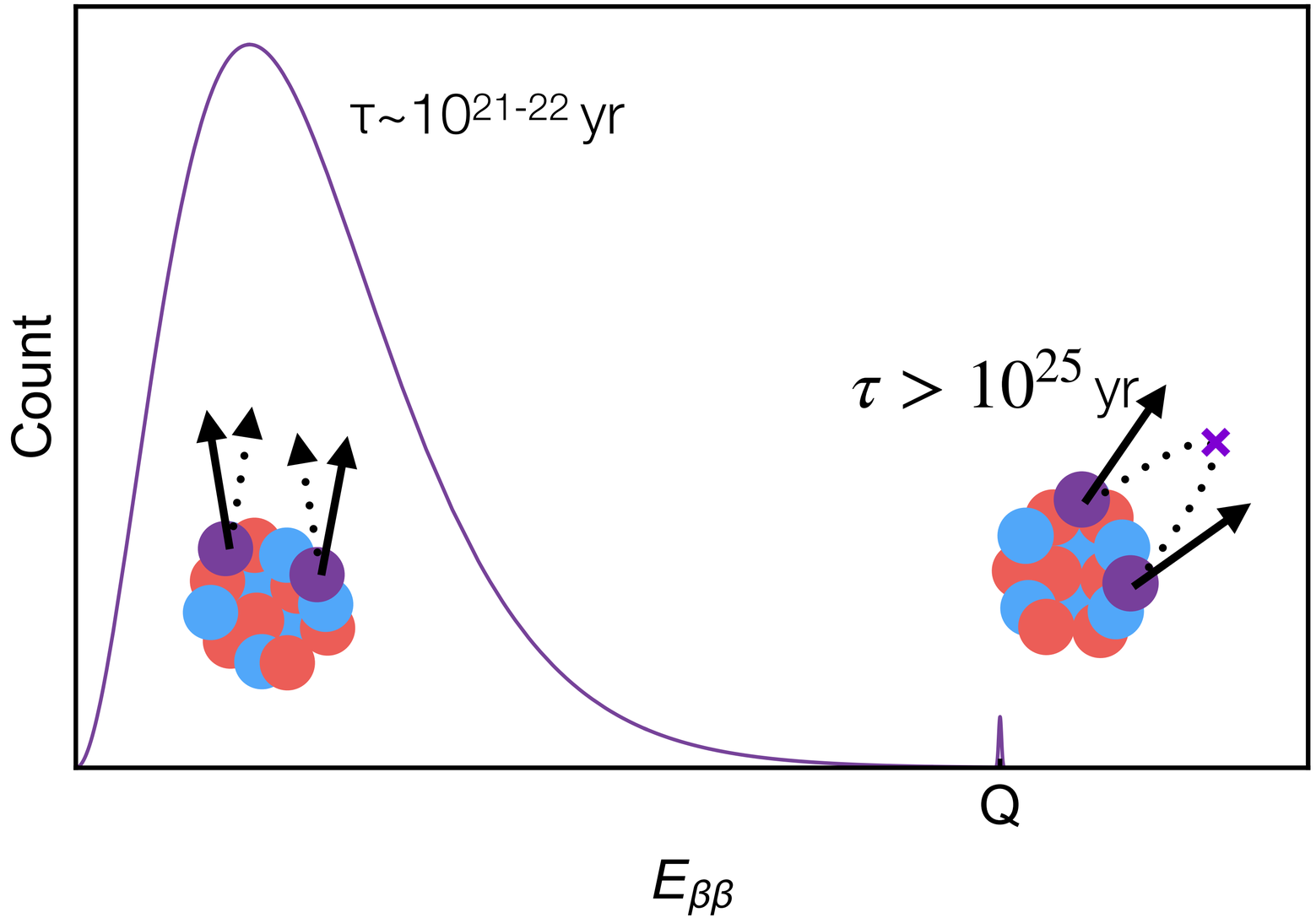
V – A



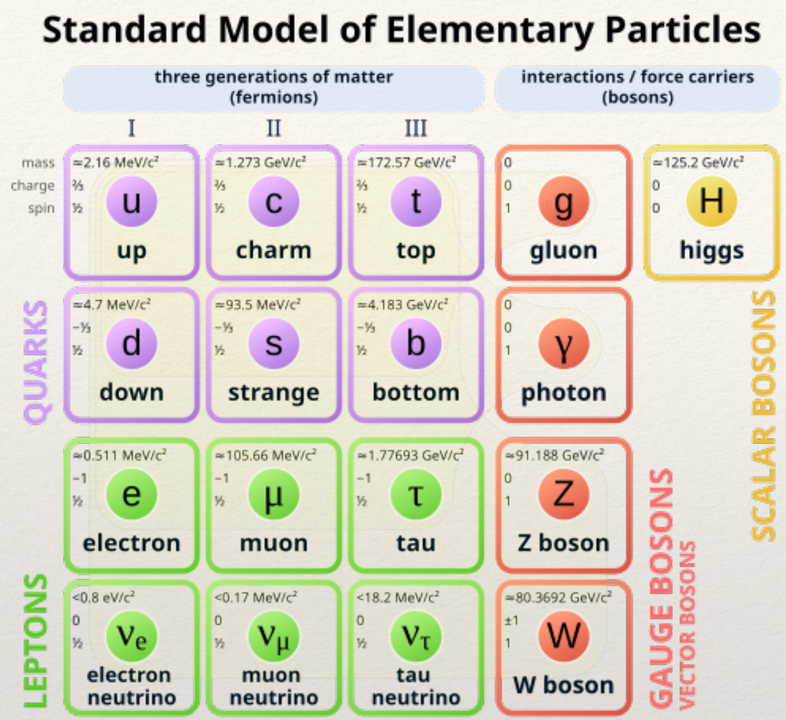
Massive Relief

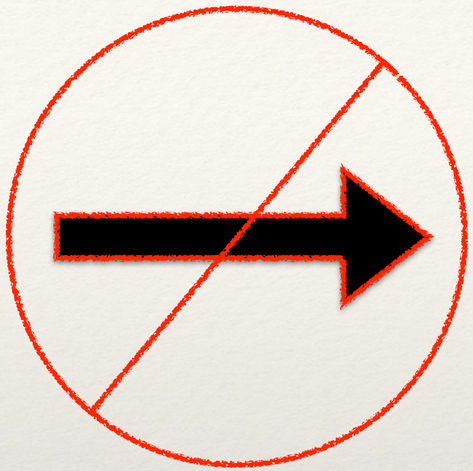


Modern Expectation

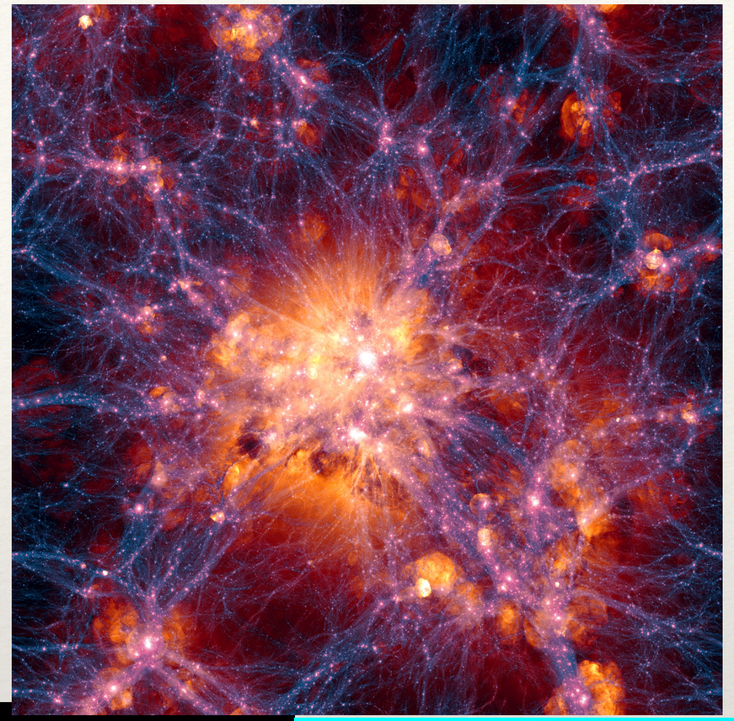


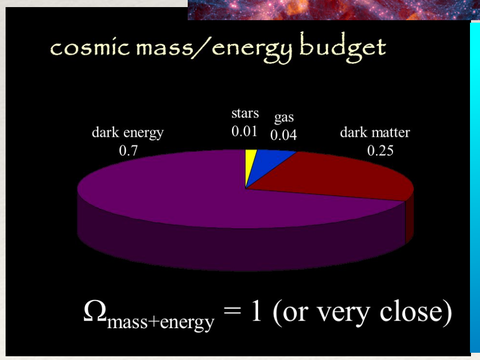
Why is $0\nu\beta\beta$ interesting?

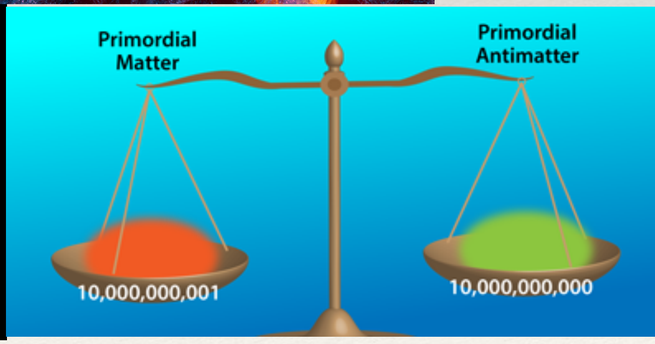




img: Ilustris Collaboration







img: APS/Alan Stonebraker

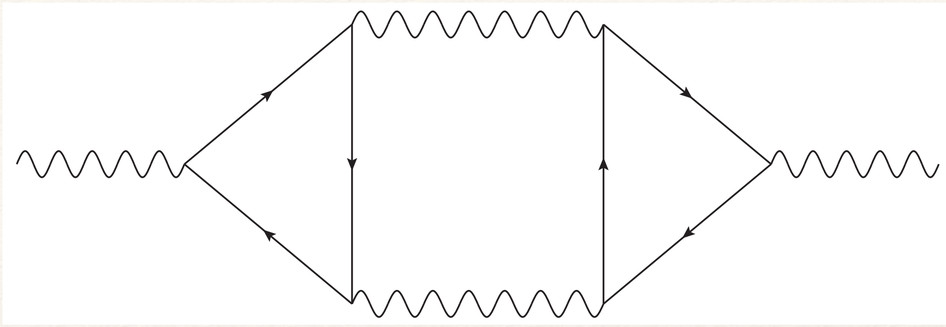
- Despite its remarkable success, the Standard Model is not sufficient to explain
  - Nature of Dark Energy
  - Nature of Dark Matter
  - Excess of matter over anti-matter
  - Nature of the neutrino

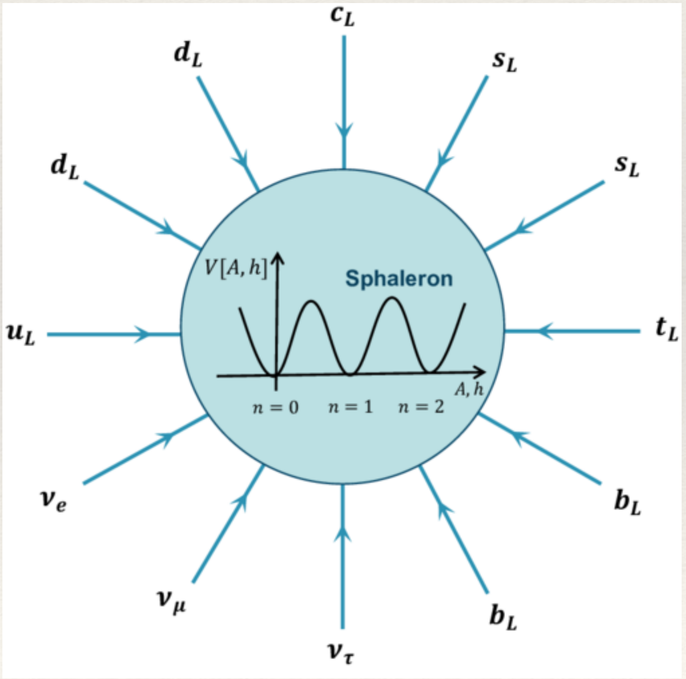
Why is $0\nu\beta\beta$ interesting?

- If neutrinos are Majorana in nature, then Lepton number is not a symmetry of nature
- The SM preserves B-L
- Through sphaeleron processes (triangle diagrams) SM interactions can turn excess Lepton number into excess Baryon number

  $n_B = N \times n_L$

- Leptogenesis





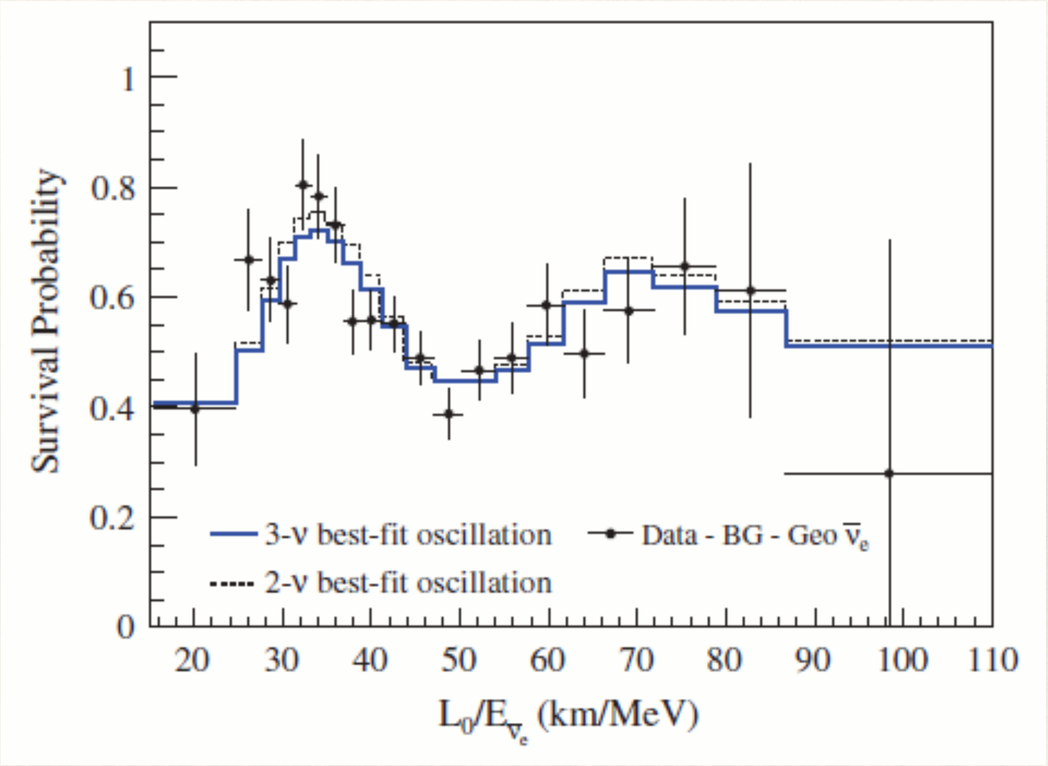
img: F.P. Huang - 2501.15543

Why is $0\nu\beta\beta$ interesting?

- The Standard Model was "arbitrarily" defined with massless neutrinos

- The observation of neutrino flavor-oscillation taught us that at least two of the three neutrino species must have a non-zero mass

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



img: KamLAND Collaboration
Gando et al. PRD 83 (2011) 052002

- From a modern Effective Field Theory (EFT) perspective, very natural to include both Dirac and Majorana mass operators

Anything not forbidden is compulsory

Neutrino mass operators

Dirac Mass

$$m_D \overline{\psi_L} \psi_R + \text{h.c.}$$

4 spinor degrees of freedom

$$\nu = \nu_L + \nu_R$$

Majorana Mass

$$m_M \psi_L^T C \psi_L + \text{h.c.} \qquad \frac{1}{2} M_R \overline{\nu_R^c} \nu_R$$

2 spinor degrees of freedom

$$\nu = \nu_L + \nu_L^c = \nu^c$$

$$\psi_{L,R} = \frac{1 \mp \gamma_5}{2} \psi$$

$$C = i\gamma_2\gamma_0$$

$$\psi^c = C\overline{\psi}^T = i\gamma_2\psi^*$$

Neutrino mass operators

Dirac Mass

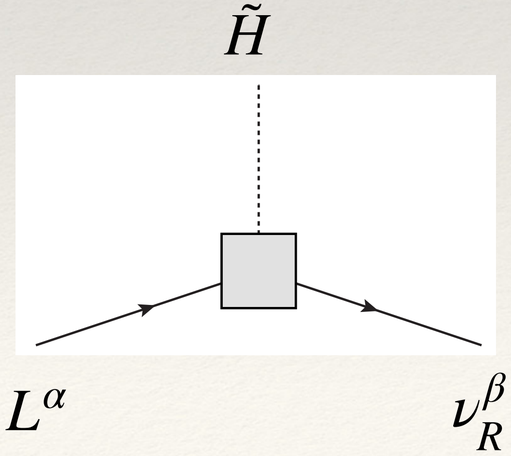
$$m_D \overline{\psi_L} \psi_R + \text{h.c.}$$

- For a Dirac mass, we can not simply write this operator down without breaking SU(2) gauge symmetry of weak interactions

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \tilde{H} = i\sigma_2 H^* = \begin{pmatrix} h^{0*} \\ -h^- \end{pmatrix}$$

$$y_\nu^{\alpha\beta} \overline{L}^\alpha \tilde{H} \nu_R^\beta \xrightarrow[h^0 \to v/\sqrt{2}]{} m_D^{\alpha\beta} \bar{\nu}_L^\alpha \nu_R^\beta$$

$$m_D^{\alpha\beta} = \frac{y_\nu^{\alpha\beta} v}{\sqrt{2}}$$



Majorana Mass

$$m_M \psi_L^T C \psi_L + \text{h.c.} \qquad \frac{1}{2} M_R \overline{\nu_R^c} \nu_R$$

- The Yukawa coupling of the neutrino to the Higgs is arbitrary, like with other fermions
- We've written a general form that can mix different Lepton flavors $\alpha = (e, \mu, \tau)$
- This operator is mass-dimension 4 and consistent with the Standard Model symmetries

Neutrino mass operators

Dirac Mass

$$m_D \overline{\psi_L} \psi_R + \text{h . c .}$$

Majorana Mass

$$m_M \psi_L^T C \psi_L + \text{h . c .} \qquad \frac{1}{2} M_R \overline{\nu_R^c} \nu_R$$

- We are also free to add a right-handed Majorana mass term
- Since ν_R is a singlet under all SM gauge symmetries, nothing forbids this term
- We can not write down a left-handed mass term at mass-dimension 4 without breaking SU(2) gauge symmetry

Neutrino mass operators

Mass-dimension 4 + SM gauge symmetries

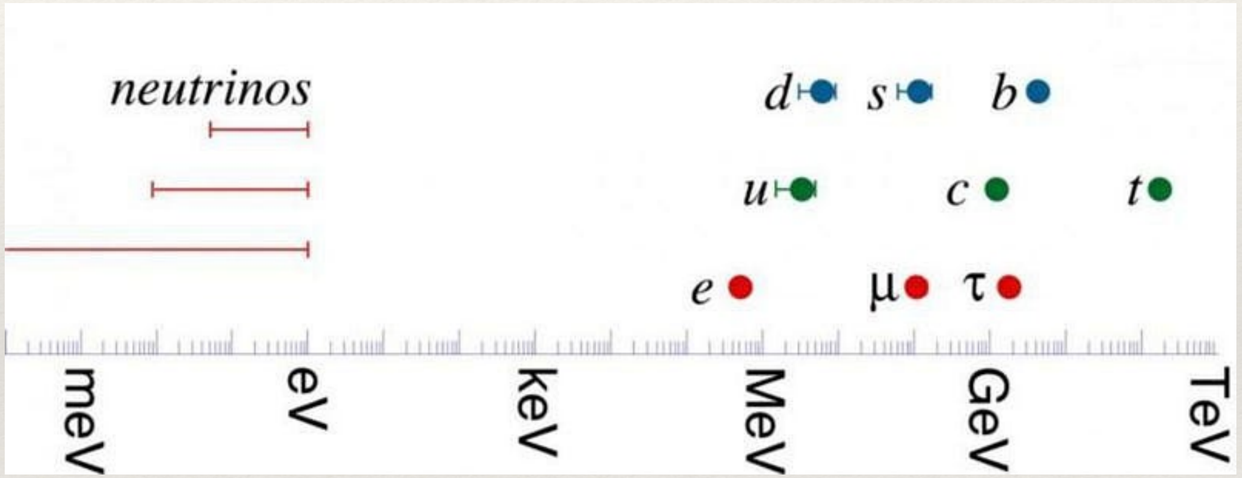
Dirac Mass

$$m_D \overline{\psi_L} \psi_R + \text{h.c.}$$

Majorana Mass

$$\frac{1}{2} M_R \overline{\nu_R^c} \nu_R$$

- From modern EFT viewpoint, since these are not forbidden, they are compulsory
- What does this get us?
- We have no handle on size of $m_D = y_\nu v/\sqrt{2}$ or M_R
  But we observe that $m_\nu \ll m_e$
- We don't like small numbers without explanation, such as symmetry constraints
- The "sea-saw" mechanism is popular way to have these two mass terms and a "naturally" small m_ν
- For heavy M_R and typical m_D, $m_\nu \lesssim 1$ ev "naturally"



$$\psi_L = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \quad \mathscr{L}_{m_\nu} = -\frac{1}{2} \overline{\psi_L^c} \mathscr{M} \psi_L + \text{h.c.} \quad \mathscr{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

$$m_\pm = \frac{M_R \pm \sqrt{M_R^2 + 4m_D^2}}{2} \xrightarrow[M_R \to \infty]{} m_- = -\frac{m_D^2}{M_R}$$

Neutrino mass operators

Can we build a Majorana mass with left-handed neutrinos?

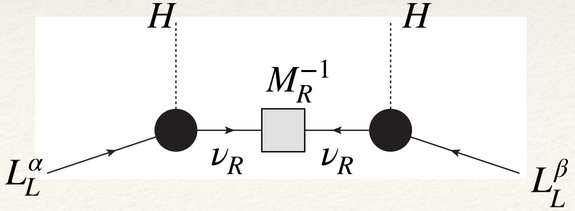
Dirac Mass

$$m_D \overline{\psi_L} \psi_R + \text{h.c.}$$

- There is one dimension-5 operator allowed that is consistent with gauge symmetries of the SM
- Below Electro-weak symmetry breaking scale, this looks like a neutrino mass term with

$$m_\nu = c_5 \frac{v^2}{\Lambda_{UV}}$$

- This also provides a "natural" mechanism to produce a small neutrino mass
- It is also the "low-energy" manifestation of the sea-saw mechanism

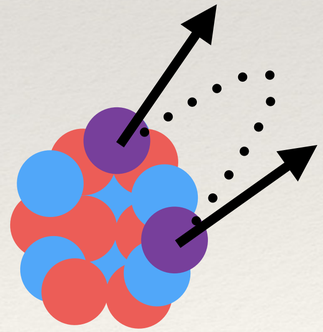


Majorana Mass

$$m_M \psi_L^T C \psi_L + \text{h.c.}$$

$$\mathcal{O}_5 = \frac{c_5}{\Lambda_{UV}} (\bar{L}\tilde{H})(\tilde{H}L)^\dagger \longrightarrow c_5 \frac{v^2}{\Lambda_{UV}} \overline{\nu_L^c} \nu_L$$

If we observe $0\nu\beta\beta$, this is conclusive evidence the neutrinos at least have a Majorana component and that Lepton number is not conserved



Lets introduce some complications

There are three+ complications to this simple picture that "naturally" arise

- Assuming the standard "light Majorana exchange mechanism"
  already at the $nn \to ppee$ amplitude level, the nature of the nuclear strong interaction leads to a short-distance contact operator (mediated by a "hard" neutrino exchange) — new operator = new unknown coefficient

- Once we allow for dimension-5 BSM operators to give rise to a Majorana neutrino mass
  why not also even higher dimension operators?

- To compare theory to experiment (and extract $m_{\beta\beta}$), we need to be able to compute the many-body nuclear wave functions and corresponding matrix elements

Nuclear Matrix Elements

- If observed - no further theory needed to understand it is new physics
- Theory is presently needed to interpret constraints on the $0\nu\beta\beta$ decay rate in terms implications for heavy new physics

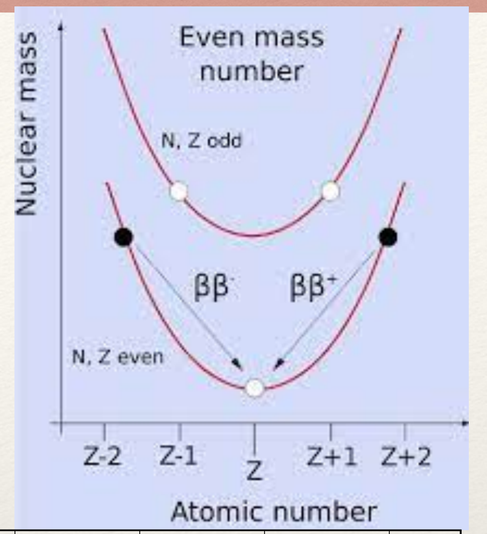
$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2\,m^2_{\beta\beta}$$

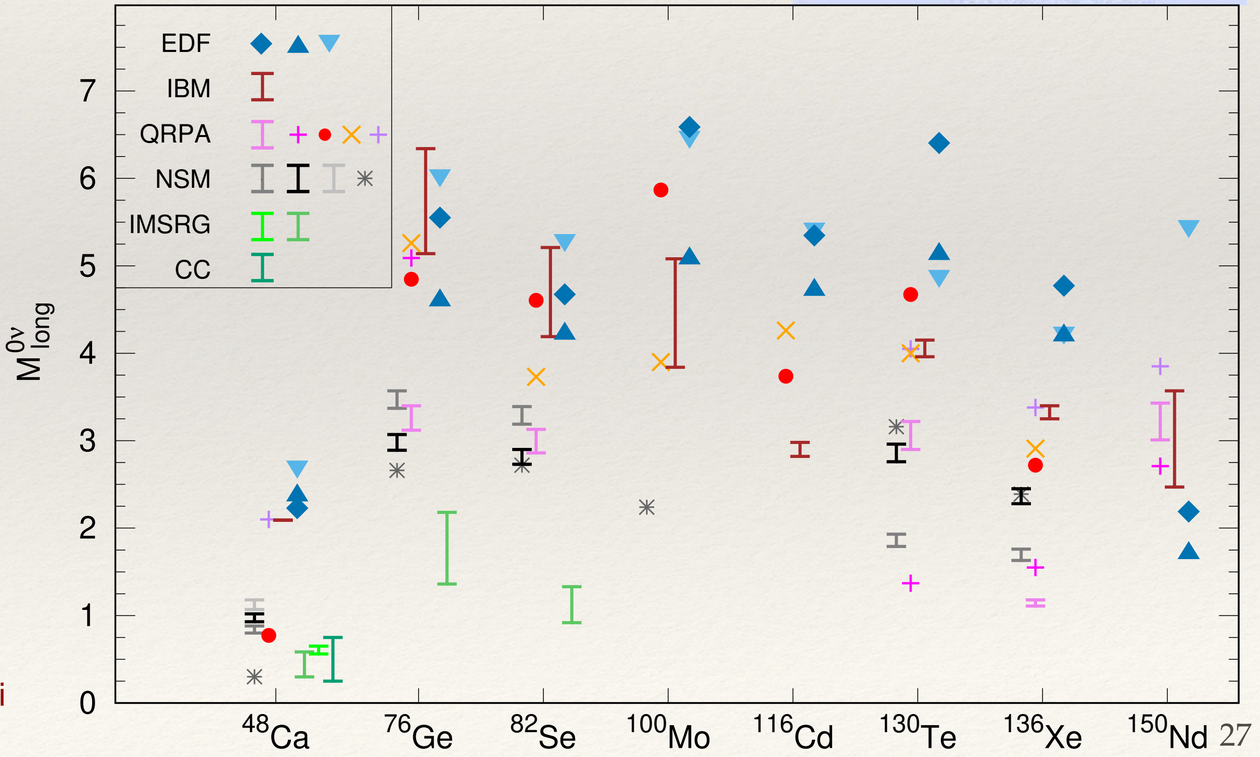
- $G_{0\nu}(Q,Z)$ = kinematic phase space factor
- $|M_{0\nu}|^2$ = complicated many-body nuclear matrix element
- $m_{\beta\beta}$ = effective Majorana neutrino mass
  BSM models predict this quantity

  take your favorite BSM theory - match to
  Standard Model EFT (SMEFT)
  stick it in νDoBe

  [Scholer, de Vries, Gráf JHEP08 (2023), 2304.05414]
  to predict $[T^{0\nu}_{1/2}]^{-1}$

- **First challenge** - nuclear matrix elements require modeling large discrepancies between models



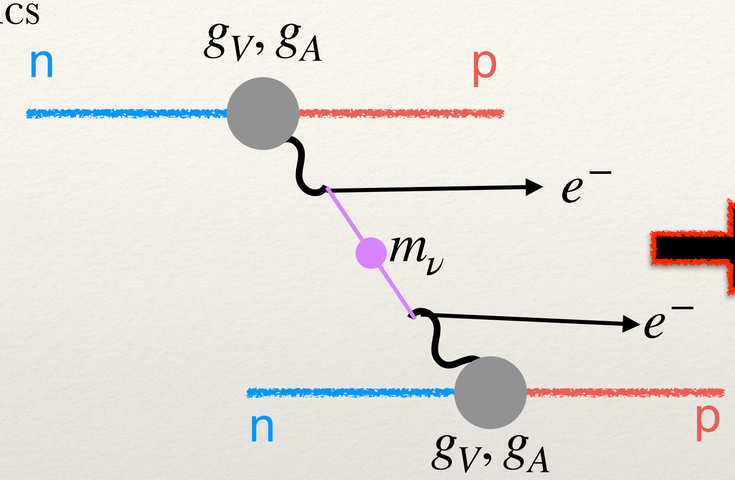


Agostini, Benato, Detwiler, Menéndez, Vissani
RevModPhys.95.025002 (2023)

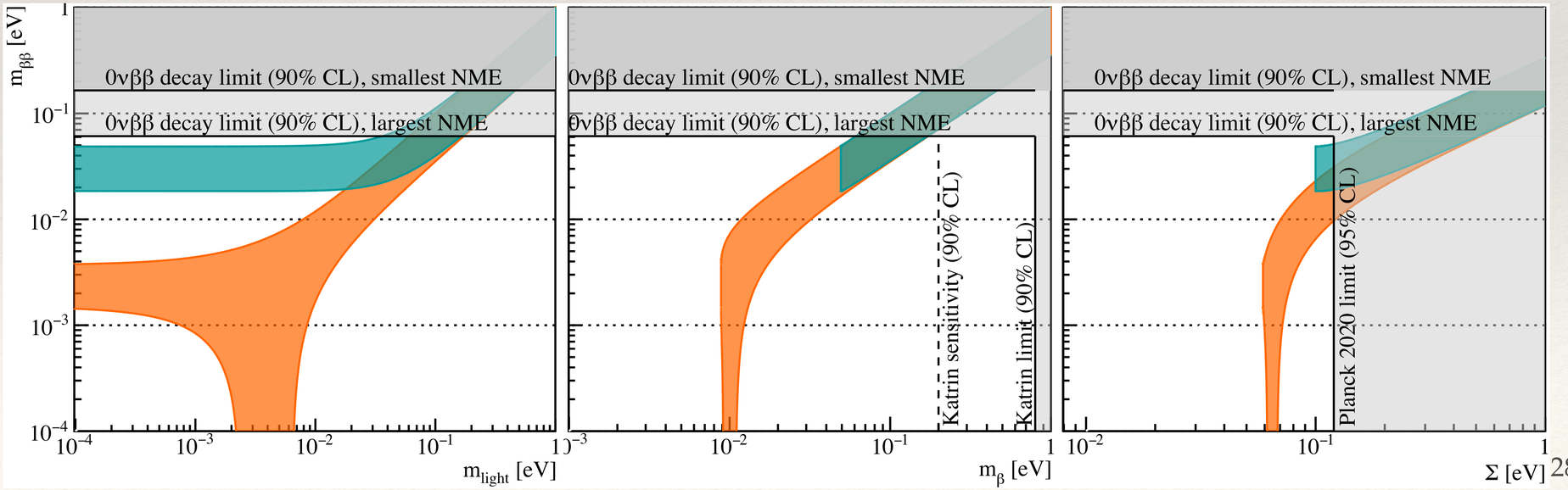
Nuclear Matrix Elements: simplest scenario

- If observed - no further theory needed to understand it is new physics
- Theory is presently needed to interpret constraints on the $0\nu\beta\beta$ decay rate in terms implications for heavy new physics

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2 m^2_{\beta\beta}$$



$$V_{nn\to pp} \Rightarrow \langle A, Z+2 \,|\, V_{nn\to pp} \,|\, A, Z\rangle$$

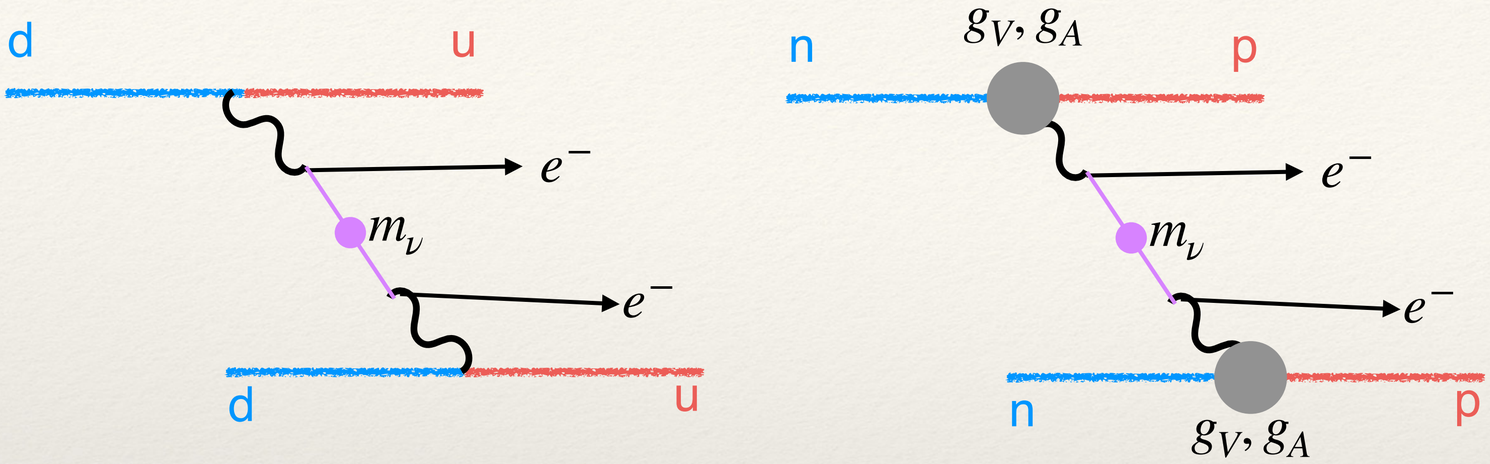


Agostini, Benato, Detwiler, Menéndez, Vissani
RevModPhys.95.025002 (2023)

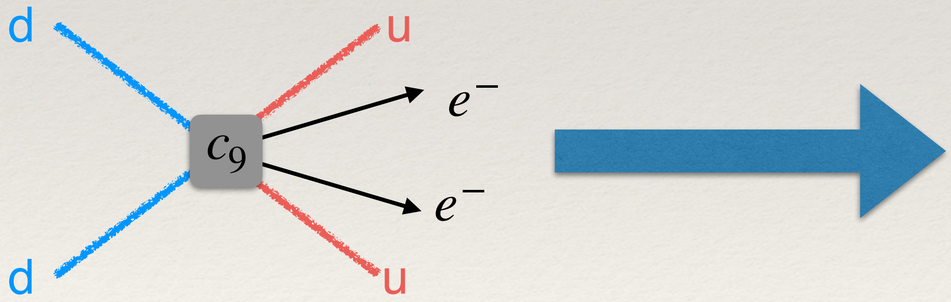
Higher Dimension Operators

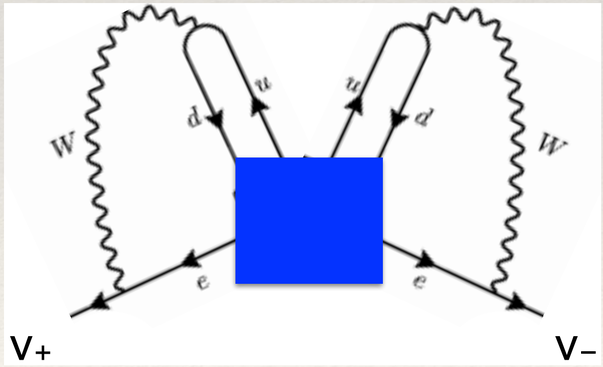
Furry, 1939





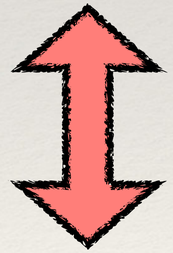
"The Majorana form of the theory is not the only one that permits this new form of disintegration… The Majorana theory provides, so to speak, a canonical form."





Schechter-Valle 1982

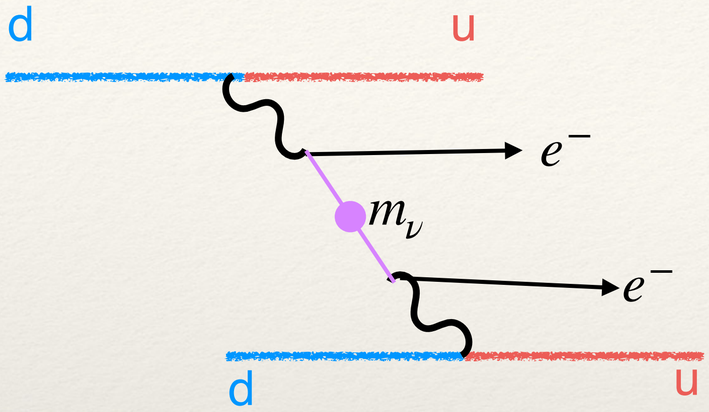
Neutrino is a Majorana fermion

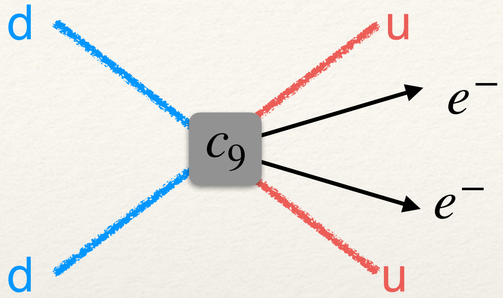


$0\nu\beta\beta$ decay happens at some rate

$$\mathcal{L} = \frac{c_5}{\Lambda_{UV}}\mathcal{O}_5 + \frac{c_7}{\Lambda_{UV}^3}\mathcal{O}_7 + \frac{c_9}{\Lambda_{UV}^5}\mathcal{O}_9 + \cdots$$

Higher Dimension Operators





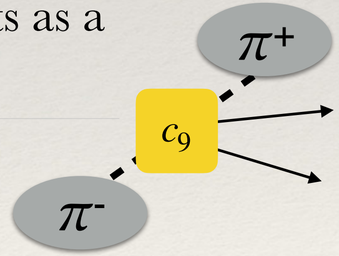
$$\mathcal{L} = \frac{c_5}{\Lambda_{UV}}\mathcal{O}_5 + \frac{c_7}{\Lambda_{UV}^3}\mathcal{O}_7 + \frac{c_9}{\Lambda_{UV}^5}\mathcal{O}_9 + \cdots$$

$\mathcal{O}_7$: modifications of SM currents

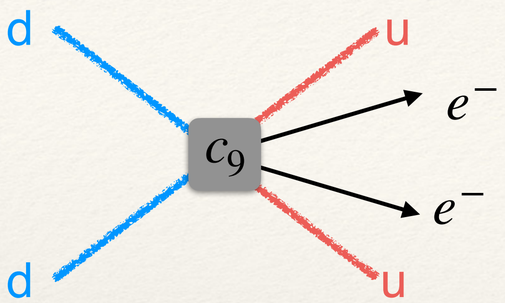
- Why can't we just ignore these higher dimensional operators?
- Depends upon the BSM physics
  - If new physics happens at GUT scale, only $\mathcal{O}_5$ matters
  - If new physics happens at 10^{1-4} TeV scale, these effects may be important
- Consider SM Yukawa couplings

$$\frac{y_{\text{top}}}{y_{e^-}} \simeq 3 \times 10^5$$

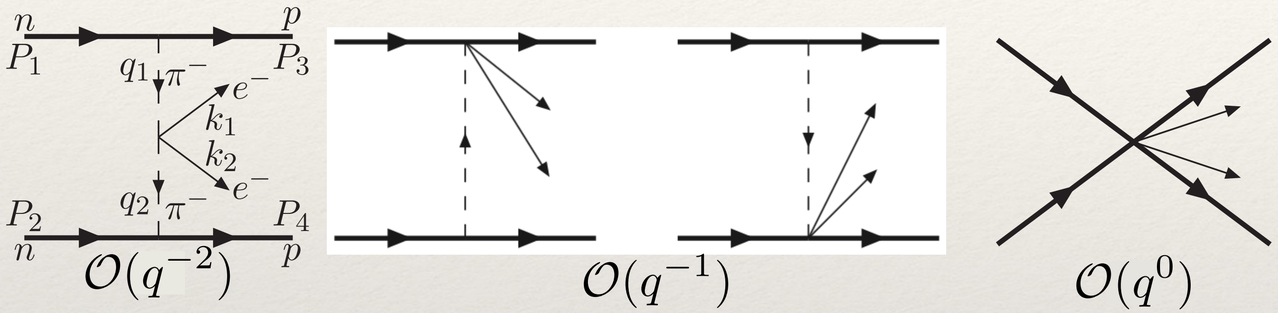
- Even though these are new short-distance operators, they can manifest as "long-distance" effects in nuclei
- The leading contribution manifests as a $\pi^- \longrightarrow \pi^+ e^- e^-$ transition



Higher Dimension Operators

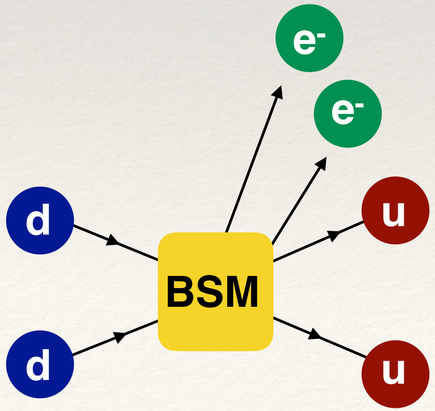


- Manifestation of short distance operator at hadronic level
  Prezeau, Ramsey-Musolf, Vogel (2003)

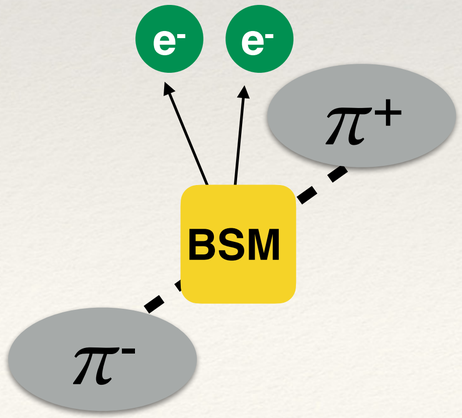


Before considering complications related to power-counting in NN EFT, we see that

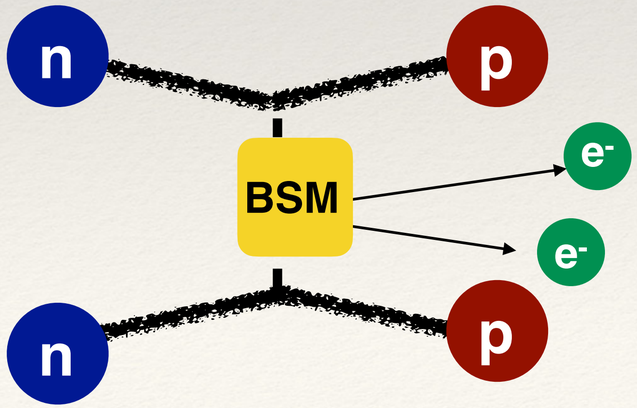
- the leading order (LO) contribution from this short-distance physics comes from a pion-exchange potential
- NLO comes from modified *NNπ* vertex
- NNLO comes from short-distance NN operator



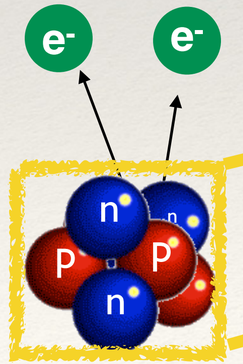
LQCD



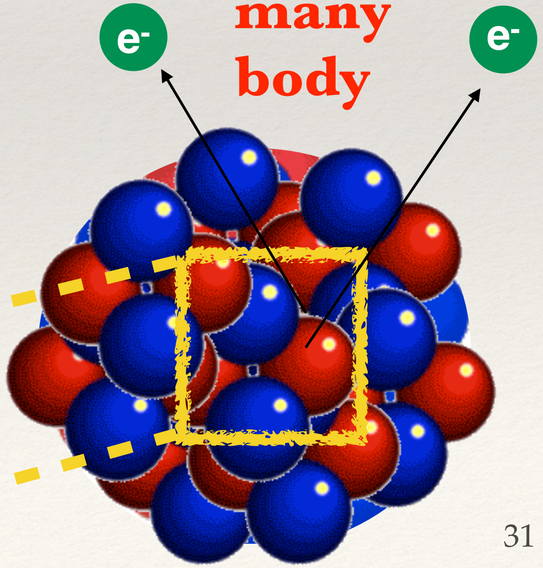
EFT



ab-initio



many body



NN EFT and light Majorana Exchange

- NN interactions are strong & finally tuned

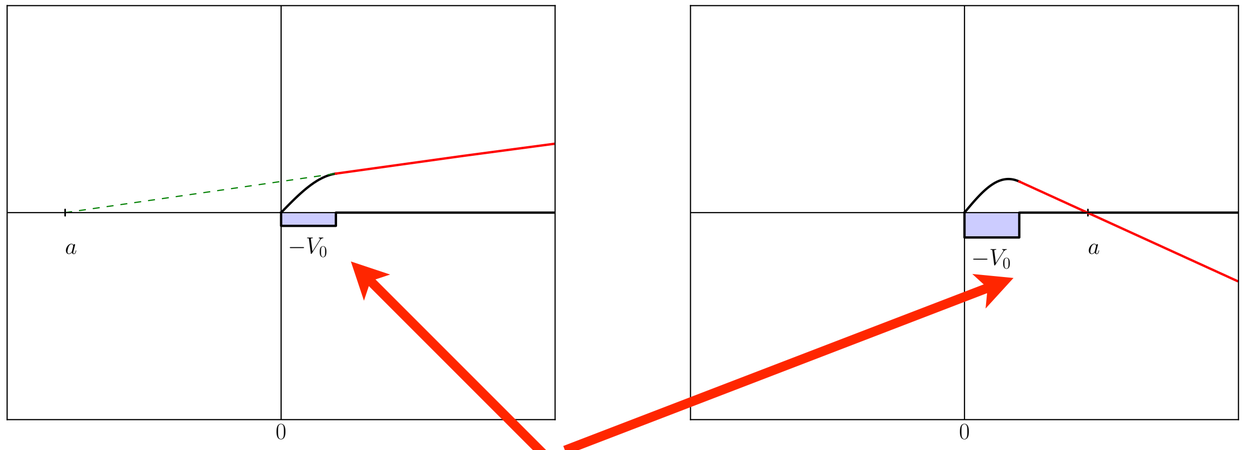
$$A = \frac{4\pi}{M}\frac{1}{p\cot\delta - ip}$$

$$p\cot\delta = -\frac{1}{a} + \frac{1}{2}rp^2 + \cdots$$

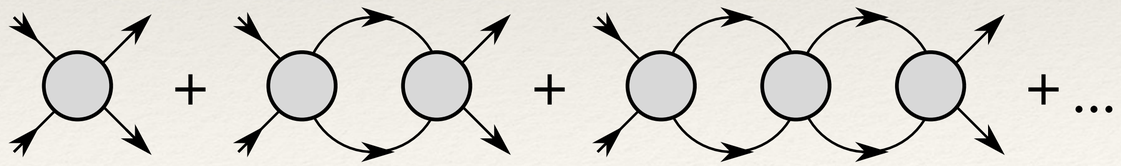
  - fine tuned
    - scattering lengths are much larger than other scales of the system
    - small change in potential large change in a

- strong interactions
  - presence of bound state (deuteron) indicates need for non-perturbative sum of interactions
  - Long history of determining power counting Weinberg, KSW, …

$^1S_0 : a \simeq -24$ fm $^3S_1 : a \simeq 5.5$ fm



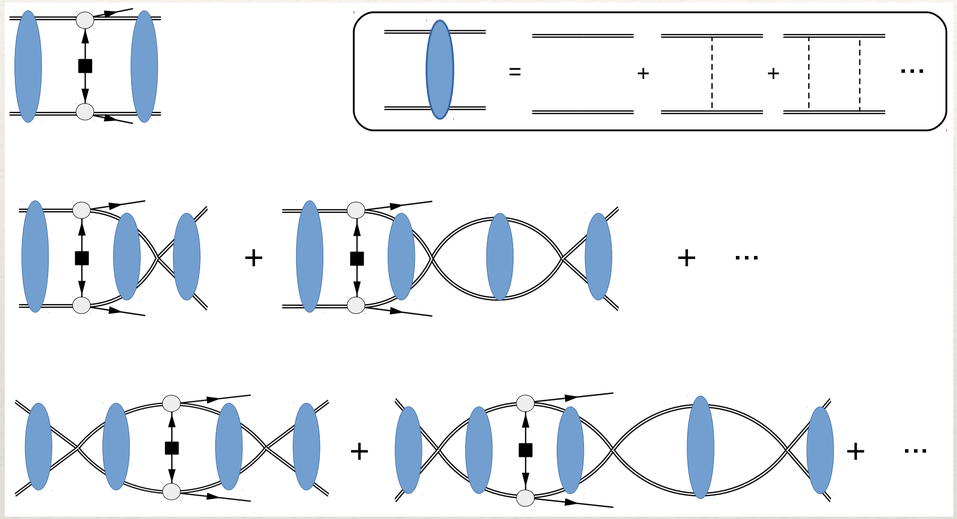
$$R_{NN} \simeq \frac{1}{m_\pi} \simeq 1.4 \text{ fm}$$

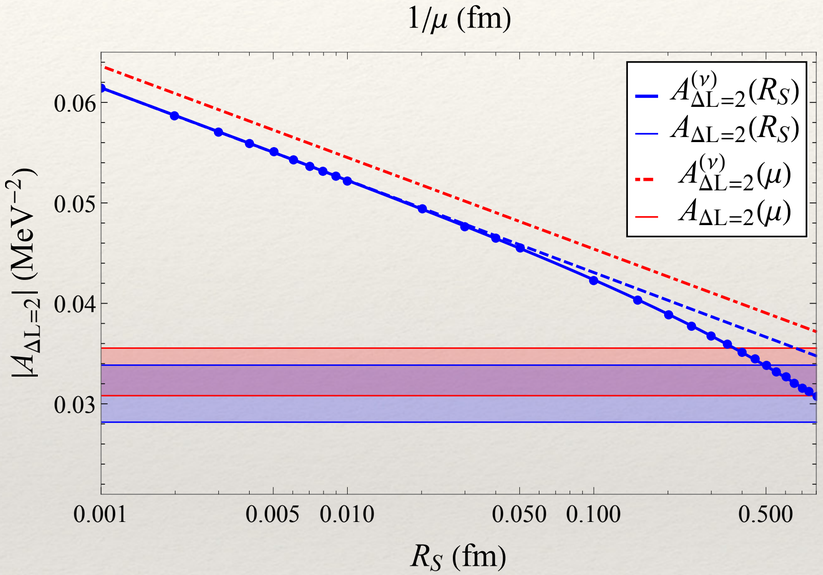


NN EFT and light Majorana Exchange

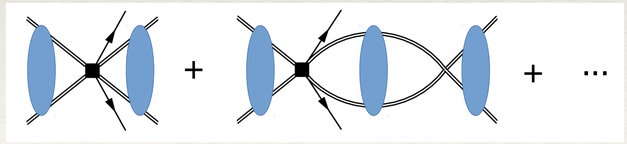
- Inclusion of light-Majorana exchange in NN EFT
  Cirigliano et al 1710.01729, 1802.10097

- With initial power-counting, log-divergence





- Need to promote NLO operator to LO to absorb divergence

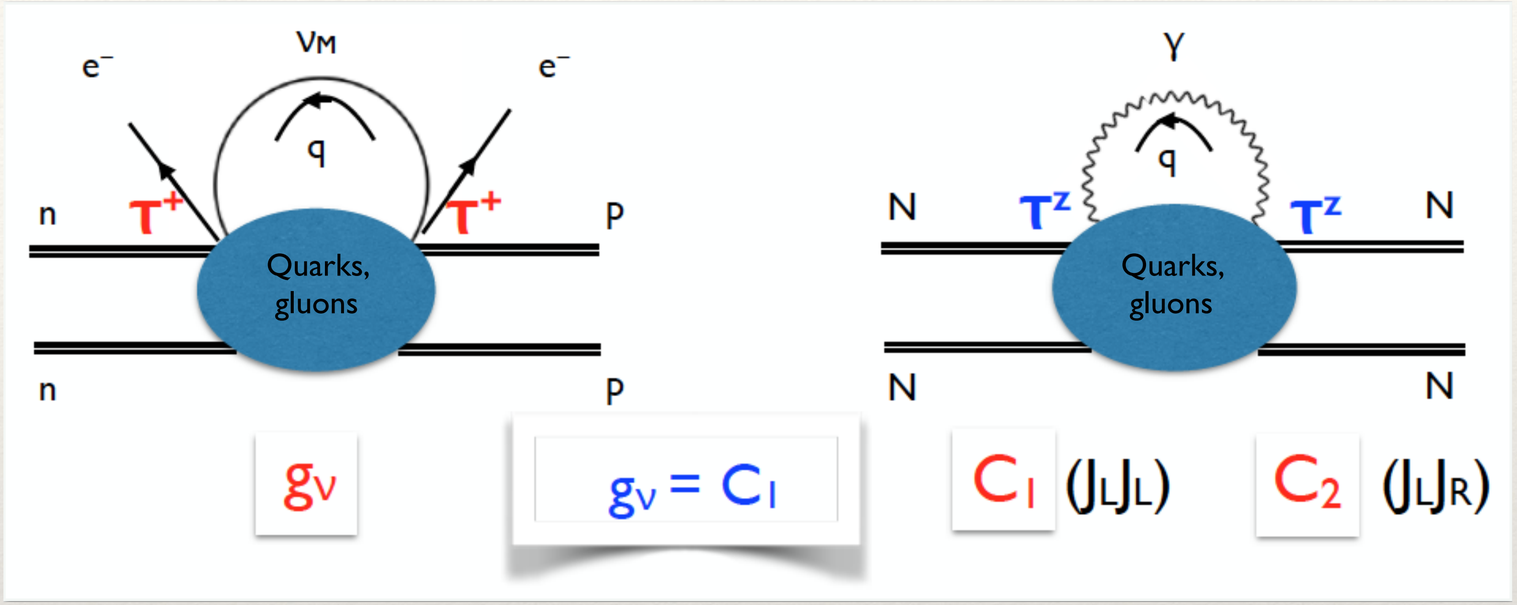


- Introduces new operator with unknown coupling… loss of predictive power even for light-Majorana exchange mechanism 😰

NN EFT and light Majorana Exchange

- Isospin symmetry relates NN contact operator from neutrinos to that from photons

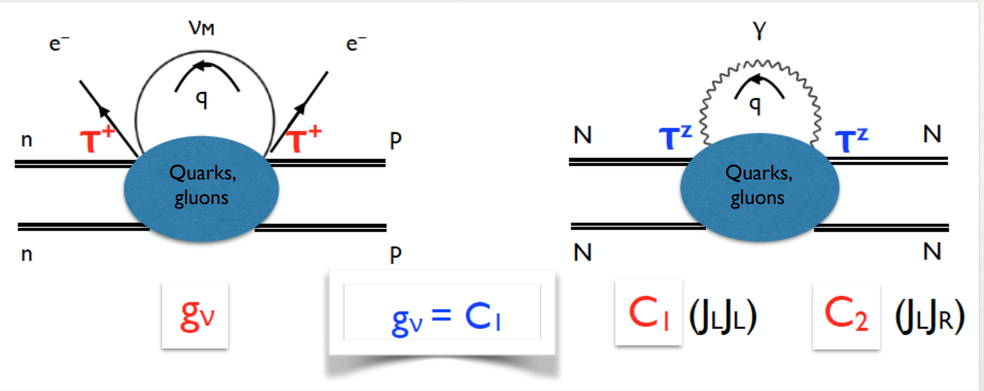
  - Unfortunately, experimental data sensitive to C_1 and C_2 while we need just C_1



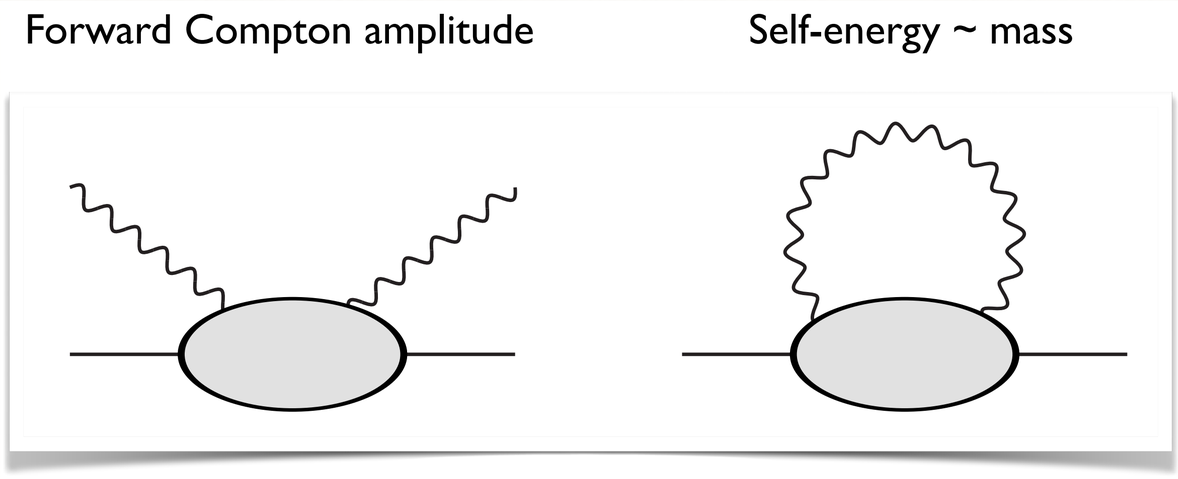
NN EFT and light Majorana Exchange

- Isospin symmetry relates NN contact operator from neutrinos to that from photons

  - Cirigliano, Dekens, deVries, Hoferichter, Mereghetti 2102.11602, 2102.03371



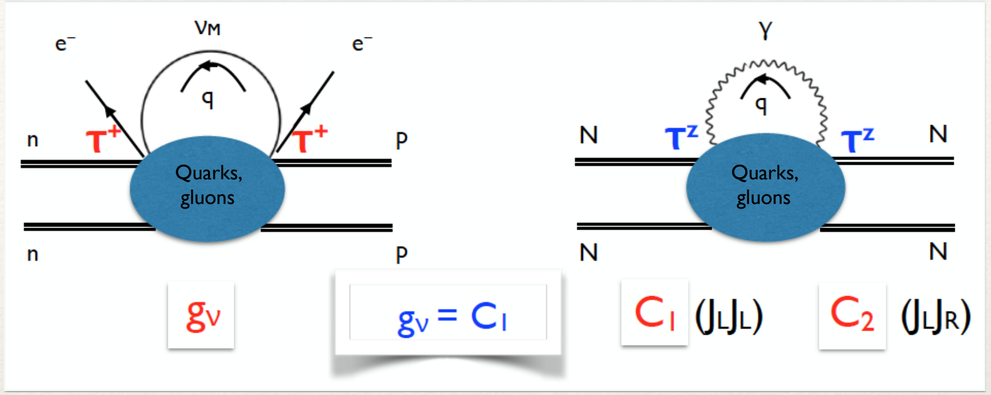
Estimate contact operator with "Cottingham" method



- Cottingham (1963): Forward Compton amplitude (plus subtracted dispersion relation) predict QED correction to nucleon mass

NN EFT and light Majorana Exchange

- Isospin symmetry relates NN contact operator from neutrinos to that from photons



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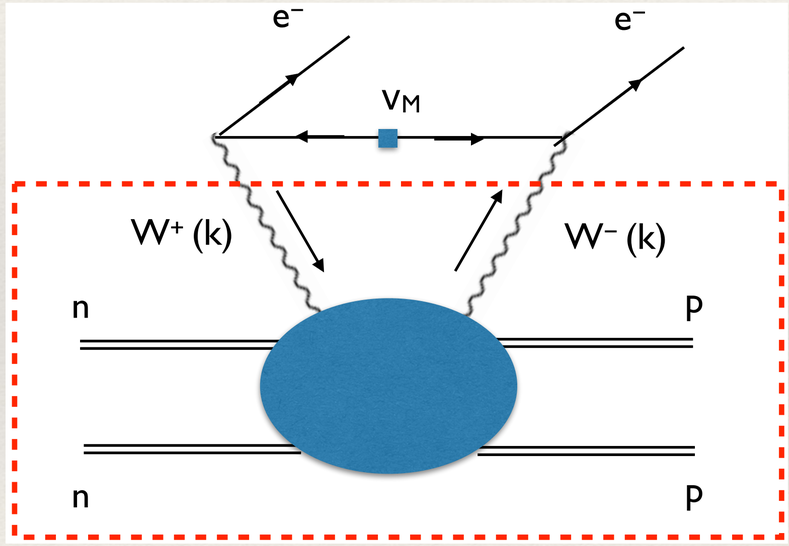


- Determined g_ν^{NN} with ~30% uncertainty

- Contact term (g_ν^{NN}) used in ab-initio calculations

^{48}Ca [1], ^{130}Te [2], ^{136}Xe [2], ^{76}Ge [3]

[1] Wirth, Yao, Hergert, 2105.05415; [2] Belley et al, 2307.15156; [3] Belley et al, 2308.15634

- ~40% enhancement for [Ca, Ge] and > 50% for [Te,Xe]

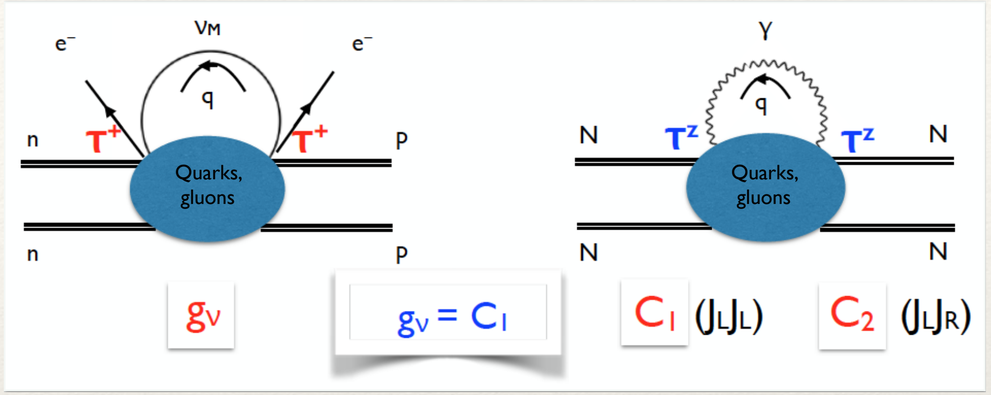
NN EFT and light Majorana Exchange

- Isospin symmetry relates NN contact operator from neutrinos to that from photons

  - Richardon, Schindler, Pastore, Springer 2102.02184

    Large N_c used to estimate short distance contact operator

$$g_\nu^{NN} = \frac{1}{2}(C_1 + C_2) + \mathcal{O}\left(\frac{1}{N_c}\right)$$



- Consistent with estimate in Cirigliano et al 1802.10097, 1907.11254, 2102.11602, 2102.03371

- With these works, we have a determination of g_ν^{NN} reliable at the ~30% uncertainty

- Is this good enough? Do we need to do better?

Improving input for $0\nu\beta\beta$ ME calculations

- If observed - no further theory needed to understand it is new physics
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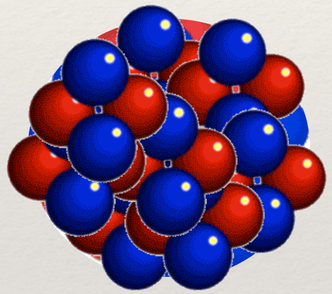
$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2 m^2_{\beta\beta}$$

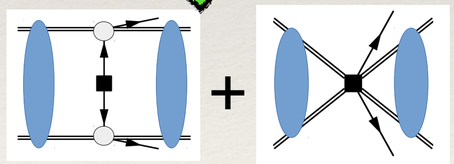
- **In principle** - this process can be coupled from quarks and gluons, to hadrons, to light AND large nuclei



Valence Space In Medium Similarity Renormalization Group (VS-IMSRG)

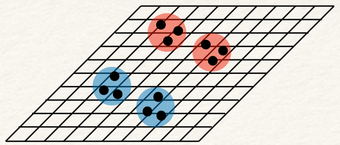
Tsukiyama, Bogner, Schwenk, PRL 106 (2011)

…

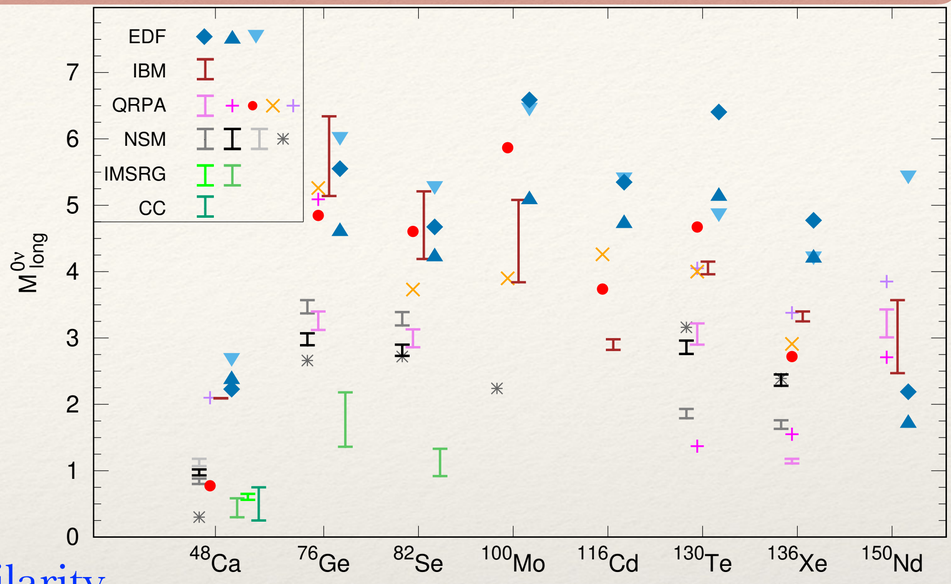


Match to NN EFT to determine LECs

In essence - use EFT to add corrections to the nuclear shell model that incorporate core-excitation corrections



Lattice QCD calculations of $nn \to ppee$ from both long and short distance



Nuclear ME calculations > 30% uncertainty…

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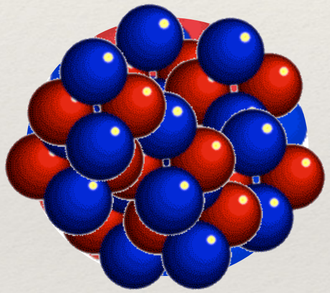
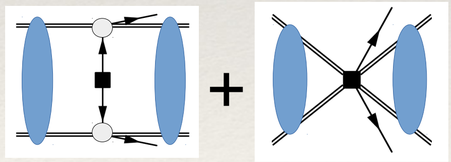
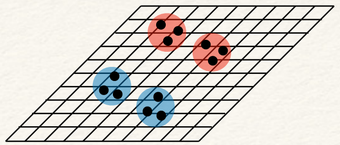


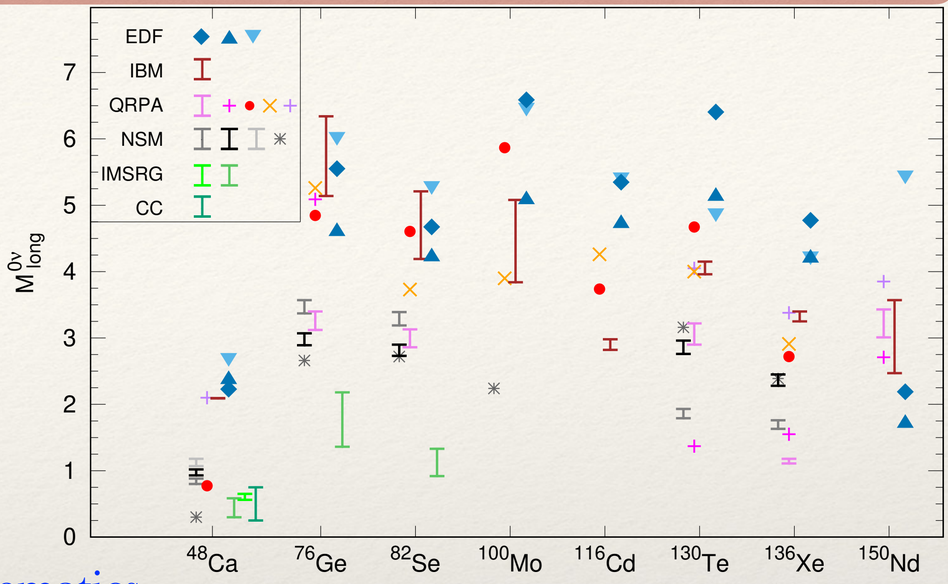
These many body methods work in principle - many systematics to bring under control
relies upon input from NN EFT which is often not rigorous EFT



NN EFT has convergence issues, and debates about correct power counting persists, and most results based on perturbative treatment of potential, which is not an observable



Lattice calculations often plagued by systematic uncertainties sometimes not known or acknowledged



Nuclear ME calculations
> 30% uncertainty…

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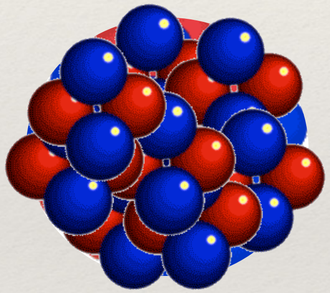
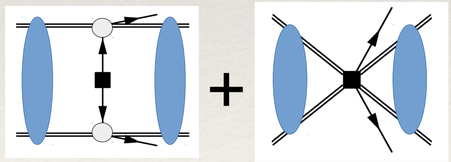
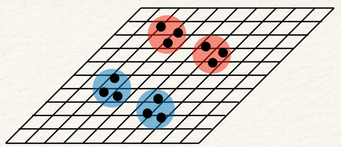
- **Should we carry out the calculations?**



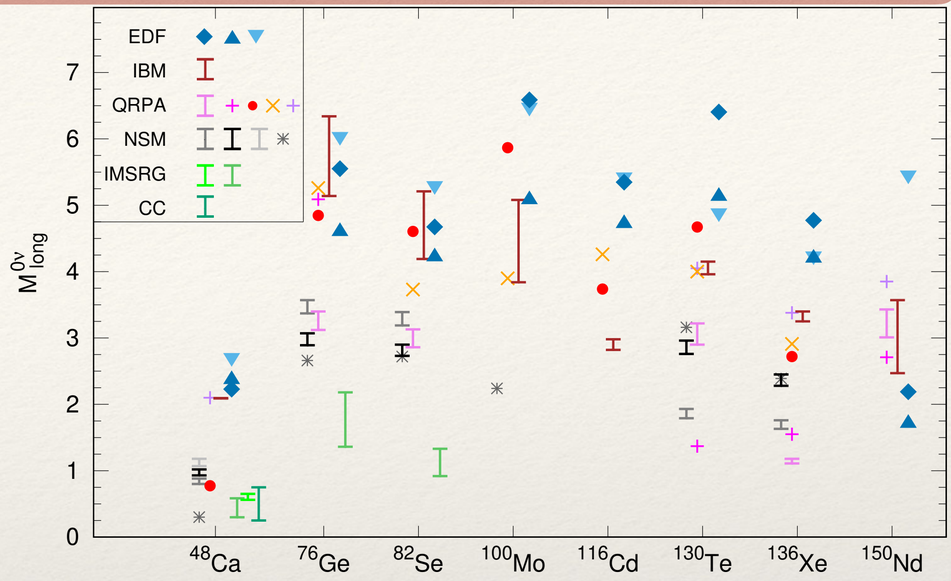
- Critical to get nuclear matrix elements under control
- Calculations require modest computing resources
- yes



- Light Majorana exchange:
  - pheno estimate of LEC with 30% uncertainty
  - calculation requires many years of exaScale resources
  - no, not until there is an experimental measurement



- Short-distance Majorana mechanism (4-quark/2-electron)
  - no easy pheno way to estimate
  - calculations require relatively modest resources
  - yes, will help understand potential nuclear matrix element contributions



Nuclear ME calculations
> 30% uncertainty…