Dirac Neutrinos and Their Many Surprising Connections

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Outline

Mysterious Neutrinos

- Neutrinos are most mysterious and ill understood of all known particles
- Even after 80+ years we know very little about them :
  - Nature of neutrinos: Dirac or Majorana?
  - Number of neutrino species: Sterile Neutrinos?
  - Mass Hierarchy: Normal or Inverted?
  - CP violation: $\delta_{CP} \neq 0$?
  - Octant of θ_{23} mixing angle: $\theta_{23} < 45^\circ$ or $\theta_{23} > 45^\circ$?
  - Why lepton and quark mixing parameters are so different?

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- Perhaps the most important question is about nature of neutrinos i.e. are they Dirac or Majorana particles?

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- The debate about nature of neutrinos is almost as old as the neutrinos themselves
- Small neutrino mass m_ν and the V-A nature of the weak interactions

  $\Rightarrow$ Discerning the nature of neutrinos from experiments is a formidable task
- V-A nature of Standard Model: All observables sensitive to nature of neutrinos suppressed by a power of m_ν
- Still some potentially feasible process:
  - Neutrinoless Double Beta Decay ($0\nu 2\beta$)
  - LHC signatures of lepton number violation
  - KATRIN measures m_ν + no $0\nu 2\beta$
- Current Status: No experimental or observational evidence/hint in favor of either Dirac or Majorana nature of neutrinos

Neutrinos: Dirac or Majorana
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Majorana Neutrinos: The Favorite Child

- No experimental signature/hint $\Rightarrow$ Dirac and Majorana neutrinos equally likely
  - Expectation: Neutrino Models for Dirac and Majorana neutrinos considered almost equally in literature
  - Reality: Theorist predominantly consider/assume/believe neutrinos are Majorana in nature
  - Even books and reviews on neutrinos either never discuss or barely consider Dirac neutrinos, often as a passing afterthought
  - In my knowledge, with possible exception of "String Theory", no under paradigm has such an universal acceptance without any shred of experimental evidence
- This begs the question: Why Majorana neutrinos are the favorite child of theorists?
- Is there any really compelling theoretical reason for such an overwhelming preference for Majorana neutrinos?

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- Majorana neutrinos more natural: In what sense?
- Current understanding: Under Poincaré group
  - Majorana fermions: Two-component fundamental irreducible spinorial representations
  - Dirac fermions: Four component reducible spinorial representations
  - From Poincaré symmetry point of view: Majorana fermions are more fundamental
  - Dirac fermions: Can be thought of as two Majorana fermions degenerate in mass
- Spacetime symmetry: Not the only symmetry conserved in nature
- Otherwise all fermions should be Majorana and all scalars should be real scalars

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- Additional internal symmetries seem to be conserved too
  - In Standard Model both Electromagnetism $U(1)_{EM}$ and Color Symmetries $SU(3)_C$ also seems to be conserved
  - Majorana mass term: Violates both $U(1)_{EM}$ and $SU(3)_C$
  - Conserved Internal Symmetries: Charged leptons and quarks are forced to be Dirac particles
- Dirac/Majorana nature: Only charges under completely conserved symmetries matter
  - Accidental Symmetries: Lepton number $U(1)_L$ and Baryon number $U(1)_B$ are accidentally conserved in SM
  - $U(1)_L$ and $U(1)_B$ conservation has important consequences
    - Baryon number conservation: Proton stability
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  - Accidental Symmetry of SM: New physics beyond SM need not conserve them
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    - Accidental Symmetries: Lepton number $U(1)_L$ and Baryon number $U(1)_B$ are accidentally conserved in SM
    - $U(1)_L$ and $U(1)_B$ conservation has important consequences
        - Baryon number conservation: Proton stability
        - Lepton number conservation: Dirac neutrinos
    - Accidental Symmetry of SM: New physics beyond SM need not conserve them
    - In absence of any other hitherto unknown conserved symmetry, Dirac/Majorana nature depends on the $U(1)_L$ breaking pattern

- Majorana neutrinos: Elegant mass generation mechanisms e.g. seesaws, radiative mechanisms
  - Dirac Neutrinos: Tiny Yukawa coupling of $\mathcal{O}(10^{-12})$ or less is needed
  - Not True: See Salvador's and Eduardo's talks
- Majorana neutrinos more economical in some sense
  - A given model can be more economical than other
  - Certainly not all Majorana neutrino mass models are more economical than any and all Dirac neutrino mass models
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Outline

Dirac Neutrinos: The Neglected Child

- For neutrinos to be Dirac particle:
  - Right handed neutrinos (ν_R) should be added to Standard Model
  - A conserved symmetry is required to protect "Diracness" of neutrinos
  - Preferable: A mass mechanism to naturally explain smallness of m_ν
- If $U(1)_L$ is conserved: Neutrinos are Dirac
  - Accidental Symmetry of SM: New physics beyond SM need not conserve it
- The Lepton number symmetry[1] breaking pattern under new physics will determine the nature of neutrinos
- $U(1)$ symmetry only admits Z_m subgroups i.e. cyclic group of m elements
  - If x is a non-identity group element of Z_m, then $x^{m+1} = x$
  - The Z_m groups only admit one-dimensional irreducible representations
  - Conveniently represented by using the n-th roots of unity, $\omega = e^{\frac{2\pi I}{m}}$, where $\omega^m = 1$

[1] While $U(1)_B$ and $U(1)_L$ both are separately anomalous at the quantum level, there are anomaly free combinations, such as $U(1)_{B-L}$. For simplicity here I discuss only $U(1)_L$, though this argument remains valid for $U(1)_{B-L}$

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- $U(1)_L \to Z_m$ with neutrinos transforming non-trivially under the residual Z_m [2]

$$\begin{aligned} U(1)_L &\to Z_m \equiv Z_{2n+1} \text{ where } n \geq 1 \text{ is a positive integer} \\ &\Rightarrow \text{Neutrinos are Dirac particles} \\ U(1)_L &\to Z_m \equiv Z_{2n} \text{ where } n \geq 1 \text{ is a positive integer} \\ &\Rightarrow \text{Neutrinos can be Dirac or Majorana} \end{aligned}$$

- If the $U(1)_L$ is broken to a Z_{2n} subgroup, then one can make a further broad classification

$$\begin{aligned} \nu &\sim \omega^n \text{ under } Z_{2n} \Rightarrow \text{Majorana neutrinos} \\ \nu &\nsim \omega^n \text{ under } Z_{2n} \Rightarrow \text{Dirac neutrinos} \end{aligned}$$

- Thus, from a symmetry point of view, Majorana neutrinos are the special ones, emerging only for certain transformation properties under the unbroken residual Z_{2n} symmetry

[2] M.Hirsch, RS, J.W.F.Valle, Phys.Lett. B, 781 (2018) 302-305, arXiv:1711.06181

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Dirac Neutrinos: Mass Mechanisms

- Dirac neutrino mass models are gaining attention in last one-two years
- Several Seesaw and loop mechanisms have been developed[3]

[3] E.Ma, RS: 1411.5042; S.C.Chuliá, E.Ma, RS, J.W.F.Valle: 1606.04543; S.C.Chuliá, RS, J.W.F.Valle: 1606.06904,1706.00210; C.Bonilla, E.Ma, E.Peinado, J.W.F.Valle: 1607.03931; E.Ma, O.Popov: 1609.02538; W.Wang, Z.L.Han: 1611.03240,1805.02025; C.Y.Yao, G.J.Ding: 1707.09786,1802.05231; C.Bonilla, J.M.Lamprea, E.Peinado, J.W.F.Valle: 1710.06498; D.Borah, B.Karmakar: 1712.06407; S.C.Chuliá, RS, J.W.F.Valle: 1802.05722,1804.03181; M.Reig, D.Restrepo, J.W.F.Valle: 1803.08528

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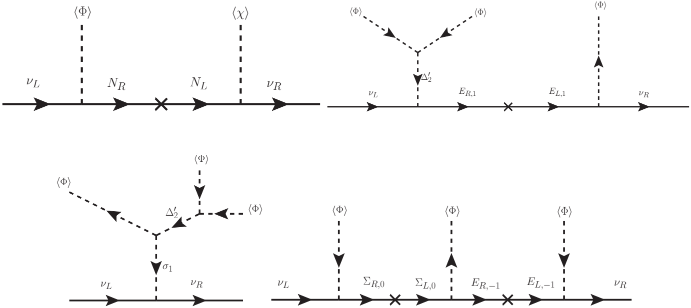

[3] E.Ma, RS: 1411.5042; S.C.Chuliá, E.Ma, RS, J.W.F.Valle: 1606.04543; S.C.Chuliá, RS, J.W.F.Valle: 1606.06904,1706.00210; C.Bonilla, E.Ma, E.Peinado, J.W.F.Valle: 1607.03931; E.Ma, O.Popov: 1609.02538; W.Wang, Z.L.Han: 1611.03240,1805.02025; C.Y.Yao, G.J.Ding: 1707.09786,1802.05231; C.Bonilla, J.M.Lamprea, E.Peinado, J.W.F.Valle: 1710.06498; D.Borah, B.Karmakar: 1712.06407; S.C.Chuliá, RS, J.W.F.Valle: 1802.05722,1804.03181; M.Reig, D.Restrepo, J.W.F.Valle: 1803.08528

Outline

Diracness and Dark Matter Stability

- Symmetry ensuring Dirac nature of neutrinos can also provide stability to the dark matter particle
    - Links Diracness and dark matter stability intimately
    - Works irrespective of the details of the particular mass model, and of the nature of their UV–completion [4]
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    - Such quarticity symmetry in context of Dirac neutrinos may arise as a residual subgroup of $U(1)_L$ or $U(1)_{B-L}$
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- If $U(1)_L$ is completely broken or broken to Z_{2n} with $\nu \sim \omega^n$
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  - Neutrinoless Double Beta Decay[5]
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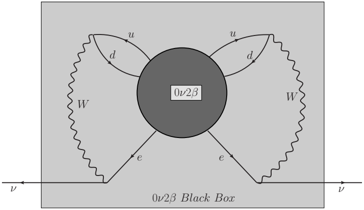

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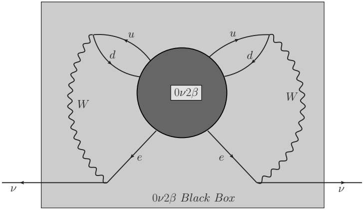

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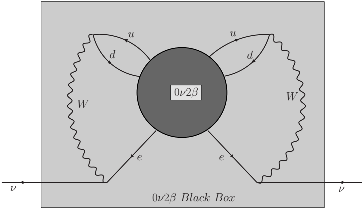

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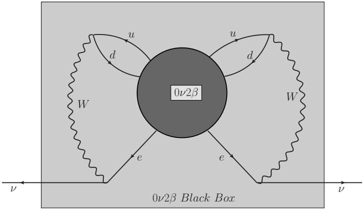

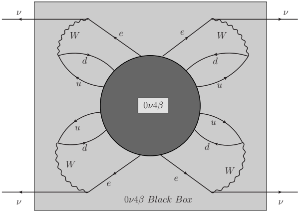

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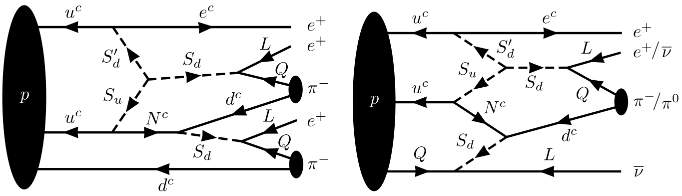

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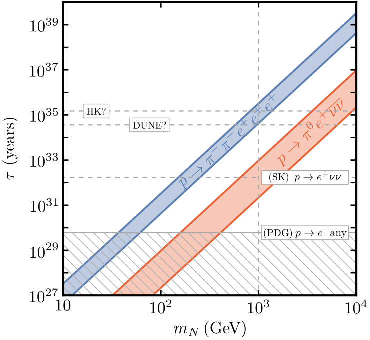

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Conclusions

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Thank You