BSM theories of neutrino masses

Seesaw (Type-I/II/III), νMSM, radiative mass models, GUTs ...

The SM fermions

$$\begin{bmatrix} u_L \\ d_L \end{bmatrix} \quad \begin{matrix} u_R \\ d_R \end{matrix}$$

$$\begin{bmatrix} \nu_L \\ e_L \end{bmatrix} \quad \begin{matrix} \square \\ e_R \end{matrix}$$

- In the SM, every fermion has $L \leftrightarrow R$, except for ν
- Why not add ν_R here?
  - Historically, absent due to massless neutrinos

Now, ν-osc $\Rightarrow$ masses $\Rightarrow$ natural extension: adding ν_R.

$$\mathcal{L}_{\text{Yukawa}} = y_e H^\dagger L e_R + y_e \tilde{H}^\dagger L \nu_R$$
$$\to m_e e_L e_R + m \nu_L \nu_R$$

So, in principle, neutrinos could obtain masses like other fermions ... However, there is something non-trivial compared to other fermions

ν_R is not charged in $SU(3)_c \times SU(2)_L \times U(1)_Y$

So ...

$$\mathcal{L} \to \mathcal{L} + M \nu_R \nu_R$$

The seesaw mechanism

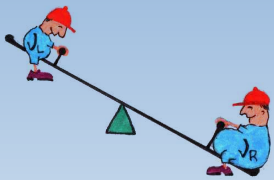
So ...

$\mathcal{L} \to \mathcal{L} + M\nu_R\nu_R + m\nu_L\nu_R \quad \longrightarrow \quad \mathcal{L}_{\text{mass}} = [\nu_L,\ \nu_R] \begin{bmatrix} 0 & m \\ m & M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$

↓ diagonalize the matrix

get the light mass eigenvalue

(the other mass eig.$\approx M$)



The seesaw relation

$$m_\nu = \frac{m^2}{M}$$

- Compared to other SM fermion masses, we have the extra M term.
- It's OK to have M here, if it's heavy.
  - Heavy $M \to$ light m_ν
  - Heavy M favored by GUTs and other theories.

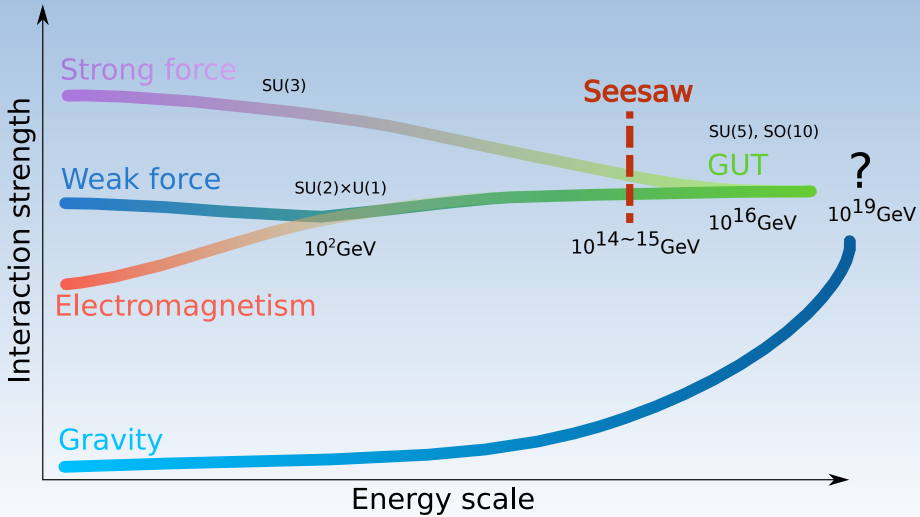
The underlying philosophy: If you cannot forbid it, let it grow!

The seesaw relation

$$m_\nu = \frac{m^2}{M}$$

For $m_\nu \sim 0.1$ eV and $m \sim 100$ GeV → $M \sim 10^{14}$GeV

known as the seesaw scale



Weyl/Dirac/Majorona spinors and Majorana masses

$m_e e_L e_R + m \nu_L \nu_R$ or $m_e e_L^\dagger e_R + m \nu_L^\dagger \nu_R$?

I'm using the Weyl spinor notation:

Two-component spinor techniques and Feynman rules for quantum field theory and supersymmetry #1

Herbi K. Dreiner (Bonn U.), Howard E. Haber (UC, Santa Cruz), Stephen P. Martin (Northern Illinois U. and Fermilab)

(Dec, 2008)

Published in: *Phys.Rept.* 494 (2010) 1-196 • e-Print: 0812.1594 [hep-ph]

pdf links DOI cite claim reference search 548 citations

a must-read in our neutrino group

$SO(3,1) \sim SU(2) \times SU(2)$, simplest non-trivial rep: $\left(\frac{1}{2},\ 0\right)$ and $\left(0,\ \frac{1}{2}\right)$.

$\left(\frac{1}{2},\ 0\right) \to \chi, \xi, \ldots$

$\left(0,\ \frac{1}{2}\right) \to \chi^\dagger, \xi^\dagger, \ldots$

Lorentz invariants

$\chi\chi = \chi^a \chi_a$, $\chi_{\dot a}^\dagger \chi^{\dot a}$

$\chi\xi = \xi\chi$, ...

Dirac spinor

$$\Psi = \begin{bmatrix} \chi \\ \xi^\dagger \end{bmatrix}$$

$$\overline{\Psi} = \Psi^\dagger \gamma^0 = (\xi^\dagger,\ \chi)$$

Charge conj. $\Psi^c = \begin{bmatrix} \xi \\ \chi^\dagger \end{bmatrix}$

mass: $m\overline{\Psi}\Psi = m\chi\xi + \mathrm{h.c.}$

Majorana spinor

$\Psi = \begin{bmatrix} \chi \\ \chi^\dagger \end{bmatrix}$ i.e., half d.o.f

Charge conj. $\Psi^c = \begin{bmatrix} \chi \\ \chi^\dagger \end{bmatrix} = \Psi$

mass: $m\overline{\Psi}\Psi = m\chi\chi + \mathrm{h.c.}$

which is why you often hear "Majorana fermions are their own antiparticles"

Weyl/Dirac/Majorona spinors and Majorana masses

- Weyl spinors (χ, $\chi^\dagger$, ξ, ...):
  - the most fundamental building block
  - conceptually and formally simple: $m\chi\xi$, $m\chi\chi$, ...,
  - but not popular in Feynman diagram calculations

    though I do know some people use it to compute everything
- Dirac spinors $\Psi = (\chi, \xi^\dagger)$:
  - familiar to everybody;
  - convenient in calculations;
    - in particular, in calculation tools (FeynCalc/Package X, ...)
- Majorana spinors $\Psi = (\chi, \chi^\dagger)$:
  - inherit the above convenience;
    - practically useful to deal with $m\chi\chi$
  - but, quite often, conceptually misleading to those who lack the knowledge of χ.

    E.g., "Majorana neutrinos $\rightarrow$ particle=antiparticle" in conflict with "solar neutrino/reactor antineutrino"?

Note

Majorana spinors are only computational techniques!

The Majorana paradox

We often say "If neutrinos are Majorana, they are their own antiparticles".
But why in actual experiments, neutrinos $\neq$ antineutrinos?

E.g.,
IBD-based detectors only detect electron antineutrinos, unable to detect solar neutrinos.

Reactors produce antineutrinos

T2K switches between neutrino and antineutrino modes

Answer:
Saying "Majornana neutrinos" itself is misleading.
What would you call them if $(\nu_L,\ \nu_R)$ have the following mass matrices?

$$\begin{bmatrix} 0 & \times \\ \times & 0 \end{bmatrix}, \begin{bmatrix} \times & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} \times & 0 \\ 0 & \times \end{bmatrix}, \begin{bmatrix} \epsilon & \times \\ \times & \epsilon \end{bmatrix}, \begin{bmatrix} 0 & \times \\ \times & \times \end{bmatrix}$$

Dirac? Majorana? Hybrid? Pseudo-Dirac?

The way to avoid confusion

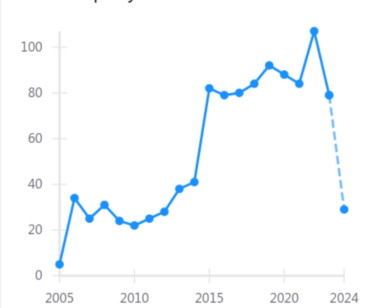
Majorana neutrinos ✗
Majorana masses ✓

The νMSM, dark matter and baryon asymmetry of the universe

Takehiko Asaka (IPT, Lausanne), Mikhail Shaposhnikov (IPT, Lausanne)

May, 2005

16 pages
Published in: *Phys.Lett.B* 620 (2005) 17-26
e-Print: hep-ph/0505013 [hep-ph]
DOI: 10.1016/j.physletb.2005.06.020
View in: ADS Abstract Service



Abstract:
We show that the extension of the standard model by three right-handed neutrinos with masses smaller than the electroweak scale (the νMSM) can explain simultaneously dark matter and baryon asymmetry of the universe and be consistent with the experiments on neutrino oscillations. Several constraints on the parameters of the νMSM are derived.

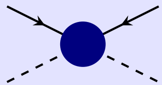
Due to its success, many people believe this is the necessary step (final step?) to go beyond the SM.

- Essentially the seesaw model
  - or, we could say: νMSM $\subset$ the seesaw model
- Main difference: ν_R below the EW scale
  - one of them is particularly light (keV) $\rightarrow$ dark matter
    - in general, unstable; but keV $\rightarrow \tau_{\nu_R} \gg \tau_{\text{universe}}$.

In fact, without introducing new particles to the SM, it is also possible to generate neutrino masses, if you give up renormalizability.

Weinberg operator

$$\mathcal{L} \supset \frac{1}{\Lambda}\left(L^\dagger \tilde{H}\right)^2$$

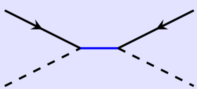


Higgs VEV $\langle H \rangle \sim v$, so $m_\nu \sim \frac{v^2}{\Lambda}$

$m_\nu \sim 0.1$ eV $\to \Lambda \sim 10^{14}$ GeV

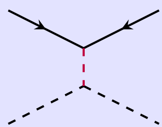
UV completions at tree level: three ways to open up the effective vertices:

Type I



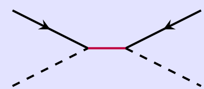
introducing ν_R
$SU(2)_L$ singlet fermion

Type II



$\Delta = (\Delta^{\pm\pm}, \Delta^{\pm}, \Delta^0)$
$SU(2)_L$ triplet scalar

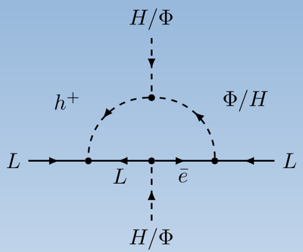
Type III



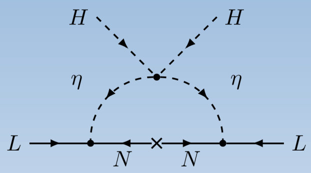
$N = (N^{\pm\pm}, N^{\pm}, N^0)$
$SU(2)_L$ triplet fermion

Basic idea: neutrino masses don't have to be a tree-level effect. They could be a loop effect.

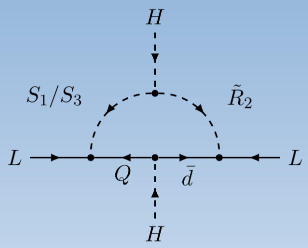
see 1706.08524 for a review



the Zee model



the scotogenic model



leptoquark

More comments on the scotogenic model:

- by E. Ma [hep-ph/0601225], ~ 1.5 k citations, the simplest model $\supset \nu$ mass + stable DM
- All new particles $\sim Z_2$ or $U(1)_{\rm dark}$, $\Rightarrow$ the stability of DM.
- scoto (Greek word) $\approx$ darkness. "scotogenic" $\approx$ "created from darkness"

Majorana masses and $0\nu\beta\beta$

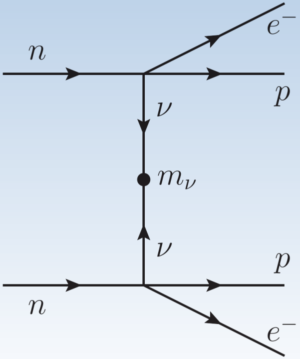
Very common: most models $\Rightarrow$ the Weinberg operator

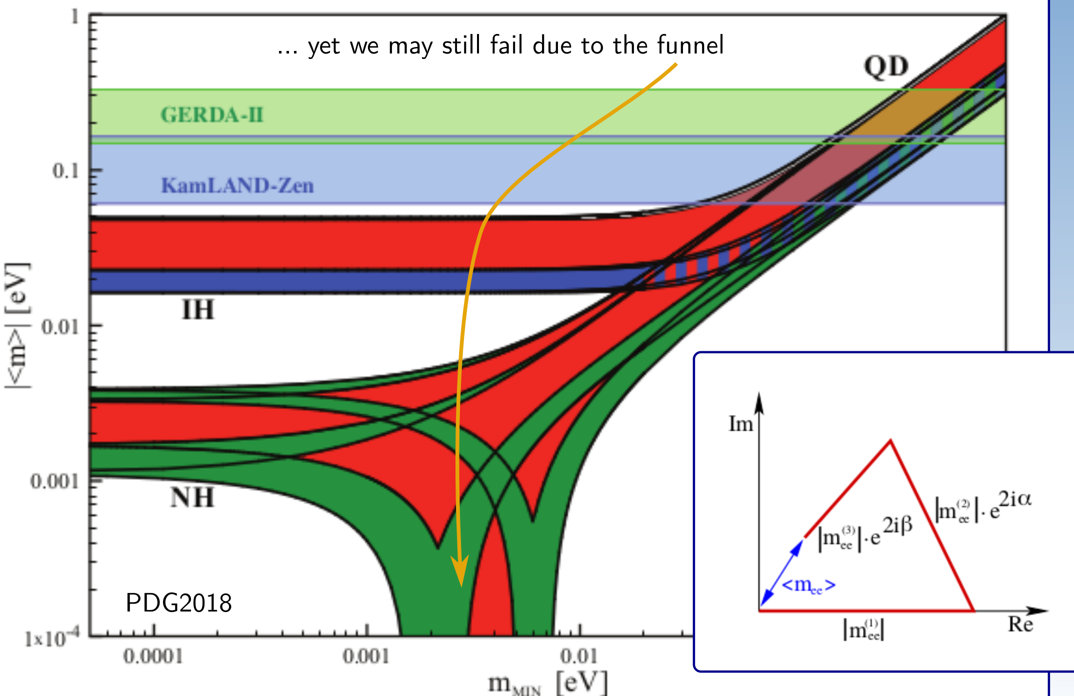
... which always gives neutrinos Majorana masses

How do we test this? Searching for lepton-number-violating (LNV) processes.

The most promising approach: neutrinoless double beta decay ($0\nu\beta\beta$).

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




... yet we may still fail due to the funnel
QD
GERDA-II
KamLAND-Zen
IH
NH
PDG2018
|<m>| [eV]
1
0.1
0.01
0.001
1x10^-4
0.0001
0.001
0.01
m_MIN [eV]
Im
Re
|m_ee^(1)|
|m_ee^(2)|· e^2iα
|m_ee^(3)|·e^2iβ
<m_ee>