Alternatives to See-saw

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What is wrong with seesaw?
Classifying alternatives
Mechanisms never die
Old and New
Extra-D : Extra Possibilities
What is wrong with See-saw?
No clear evidence of the seesaw in the observed pattern of neutrino masses and lepton mixing

- A priori: scenario "HDM + solar (SMA MSW)"
  nearly quadratic mass hierarchy $m_\nu \sim m_u^2$,
  small (similar to quark) mixing
- Instead: bi-large mixing, weak (or none) neutrino mass hierarchy

Seesaw generically does not reproduce the observed pattern of masses and mixings
- tuning of parameters is needed
- particular structure of the RH neutrino mass matrix
  (very strong hierarchy, off-diagonal dominance, etc.)
- Though both large mixing and weak hierarchy can be explained by seesaw
More doubts if

- light sterile neutrinos are found (LSND/MiniBOONE)
- neutrino mass spectrum turns out to be quasi-degenerate

Again, both these features can be accommodated in seesaw:

- Seesaw + additional symmetry -> three active + 1 sterile neutrino
- Seesaw I + symmetry (e.g., SO(3))
- seesaw II + symmetry
- "cascade seesaw":

\[
\begin{pmatrix}
0 & m_D & 0 \\
m_D & 0 & M_D \\
0 & M_D & M
\end{pmatrix}
\]

If \( M_D = A m_D \), and \( M = M_0 I \)

\[
m_D \sim M_0 / A^2 I
\]

R. Mohapatra
S. Petcov, A.S.
E. Ma
J. Valle
2. No way to prove?

- Discovery of the neutrinoless double beta decay
  - Will not prove that seesaw is the main mechanism

- Leptogenesis
  - Difficult to test also

- In SUSY context: lepton violating decays, EDM, ...
  - Indirect, assumptions...

- Easy to disprove seesaw as the dominant mechanism of neutrino mass generation
As it was in the past, neutrinos may not follow our prejudices about simplicity, elegance and naturalness.
- Majorana neutrinos are not particularly favored
- 126 representations - difficult...
- Dirac masses can be very small
- Selection rules...
- Values of Yukawas can be in huge range
- singular structures..
Put seesaw in a general context, consider problems of this general context.

See-saw

$M_R = 10^8 - 10^{15} \text{ GeV}$

Leptogenesis

Gravitino problem in SUSY....

SUSY GUT's

- Proton decay
- FCNC
- EDM
- 126 in SO(10)
No solid objections till now, then

Why alternatives?
Effective operator, S. Weinberg 1979

\[
\frac{\Box_{ij}}{M} (l_i H)^T (l_j H)
\]

\(i, j = e, \mu, \tau\)

\(l_i - \) lepton doublets, \(H - \) Higgs doublet,

\[
m_{ij} = \frac{\Box_{ij} <H>^2}{M}
\]

For \(M = M_{Pl}\) and \(\Box_{ij} \sim 1\):

\(m_{ij} \sim 10^{-5}\) eV

Contributions \(\sim 10^{-5}\) eV are still relevant for phenomenology.

Sub-dominant structures of mass matrix can be generated by Planck scale interactions.

Barbieri Ellis Gailard Akhmedov Berezhiani Senjanovic

Neutrino mass matrix can get relevant contributions from new physics at all possible scales from the EW to Planck scale and from various mechanisms.
In general, 

\[ m = m_{\text{seesaw}} + m_{\text{triplet}} + m_{\text{radiative}} + m_{\text{SUSY}} + m_{\text{Planck}} + \ldots \]

From different scales

1\text{loop}, 2\text{loops},\ldots

- Seesaw can give leading contribution, beyond seesaw \rightarrow sub-leading effects from other mechanisms

- Seesaw may turn out to be sub-leading mechanism...
Where are the right handed neutrinos?

If exist, why the Dirac mass terms are small or absent?

Suppressed by couplings with heavy degrees of freedom

Forbidden by symmetry

See-saw as the mechanism of suppression of the Dirac mass term (but not main contribution to the mass)

Unnatural?
Why the RH neutrinos but not other RH fermions?

J. Valle, R. Mohapatra
Multi-singlet mechanism

Suppressed by seesaw or multi-singlet couplings

Small because of symmetry, seesaw or multi-singlet couplings
Easier to test alternatives new physics at the EW scale can be searched at HE colliders

Exclude alternatives

Not possible to eliminate all alternatives
Still more confidence in that seesaw is realized

Prove validity of the alternative mechanism

Seesaw: sub-leading contribution, bounds
Still more confidence in that seesaw is realized
Classifying
- operators (Babu-Leung/)
- diagrams (E Ma)
- physical context
Classification

Dirac

$$\langle H \rangle \times$$

Small overlap (of wave functions in extra dimensions)

Tree level

Radiative

Majorana

$$\langle H \rangle$$

Small coupling (effective)

Small VEV
Small Yukawa couplings

Unnatural untestable can be excluded if $\bar{\nu}_0$-decay is discovered

Dirac mass term is formed by LH neutrino and new singlet which may have some particular symmetry properties or come from the hidden sector of theory

Usual Dirac term is suppressed by seesaw or multi-singlet couplings

Suppressed by symmetry or seesaw
Effective coupling produced by non-renormalizable operators:

\[ h_{ij} = \frac{a_{ij}}{\cal M} \frac{\langle S \rangle}{\cal M} \]

(renormalizable coupling is suppressed by symmetry)

\[ a_{ij} \Gamma_{iL} \Gamma_{iL} H \frac{S}{\cal M} \]

For \( a_{ij} \sim O(1) \)

\[ \frac{\langle S \rangle}{\cal M} \sim 10^{-13} \]

SUSY / GUT scales?

\[ m_{3/2}/\cal M_{\text{Planck}} \]

Small VEV

L. Hall...

Difficult to test directly

---> test context/models
Higgs Triplet mechanism

No RH neutrinos
Higgs triplet: (D++, D+, D0)

EW precision measurements:
< D0 > / < H > < 0.03
No triplet Majoron → coupling

If g_{ab} \sim 1, < D0 > \sim 1 \text{eV}

If M_\Delta, \bar{\Delta} >> < H >:
< D0 > \sim < H >^2 \bar{\Delta} / M^2
Seesaw type II

If M_\Delta \sim < H >, \bar{\Delta} << < H >
< D0 > \sim \bar{\Delta}

Effective coupling

pseudo Majoron mass \sim \bar{\Delta} \sim 0.03 < H >
excluded by Z^0 -width
Mechanisms never die
\[ m_\nu = A \left[ (f m^2 + m^2 f^T) \right] \]
\[ \sqrt{v} (\cos \theta) \left[ \left( m f_2 + f^T_2 m f^T \right) \right] \]

\[ A = \sin 2\theta Z \ln \left( \frac{M_2}{M_1} \right) / (8\pi^2 v \tan \theta) \]

\[ m = (m_e, m_{\mu}, m_{\tau}) \]

No RH neutrinos
new bosons: singlet \(\nu^+\), doublet \(H_2\)

If only \(H_1\) couples with leptons

Can not reconcile two large mixings 
one small mixing and hierarchy of \(m^2\)

~excluded

- inverse hierarchy of \(f_{\nu R}\)
- \(f_{\nu R} < 10^{-4}\)

X-G He
P. Frampton, M. C. Oh
T. Yoshikawa

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1). Introduction of couplings of both doublets with leptons
   -> diagonal terms are non-zero
   FCNC: e.g. $t \rightarrow m \ell \ell$, $t \rightarrow e e e$, $t \rightarrow m m e$, $m \rightarrow e e e$
   due to Higgs exchange -> 2-3 orders below the present bound
   $\ell \rightarrow e e$

2). Additional contributions to the mass matrix from other mechanism, e.g.
   - Higgs triplet
     - scalar singlet, two loops contribution

3). Introduction of new leptons: sterile neutrinos...

Testable model:

Precision EW measurements
Searches for charged Higgses
rare decays
No RH neutrinos
new scalar singlets $k^-$ and $k^{++}$

\[ m_l \sim 8 \ f m_h m_f I \]

\[ m_l = \text{diag} \ (m_e, m_\mu, m_\tau) \]

$f$ and $h$ are matrices of the couplings in the flavor basis

Features:
- the lightest neutrino mass is zero
- neutrino data require inverted hierarchy of couplings $h$
- $f, h \sim 0.1$

Testable:
- new charged bosons
- decays $k^- \rightarrow e^-$, $k^{++} \rightarrow 3 \ell$
  within reach of the forthcoming experiments
**R-parity violating SUSY**

Superpotential:

\[
W = - \bar{L}_i L_j H_U - 0.5 \bar{L}_m L_j L_e e_m + \bar{L}'_{nm} L_j Q_n d_m - h_{nm} H_U Q_n u_m
\]

\( Z_3 \) - baryon triality (Ibanez, Ross)

Bi-linear (Hall-Suzuki) \( \bar{m} = 0, 1, 2, 3, m = 1, 2, 3 \)

\( L_0 = H_D \)

No RH neutrinos

\[ m_{ij} = X \bar{\nu}_i \bar{\nu}_j, X \sim \cos^2 \frac{\bar{m}}{m} \]

Only one neutrino acquires mass, mixing is determined by \( \bar{\nu}_i / \bar{\nu}_j \)

\[ m_{ij} = A <\bar{\nu}_i> <\bar{\nu}_j> \]

\[ \frac{h_b^2}{16 \bar{m}^2} \]

EW seesaw
$B_m$ - soft symmetry breaking parameter
Neutrinos: natural hierarchy of mass parameters:
  tree level - one mass, large mixing
  loops - other masses, mixing

\[ \Delta m \sim 10^{-4} \text{ GeV} \]

Violation of universality of soft symmetry breaking terms:
both Higgs-lepton and flavor universality
e.g. \( B_m \) are different at GUT

Tests: rich phenomenology
  - colliders,
  - rare decays,
  - new neutrino interactions...
Old and New
Observation: \[ m = \frac{m_{3/2} v_{EW}}{M_{Pl}} \sim 10^{-4} \text{eV} \]

\( m_{3/2} \) - gravitino mass

Mass term which mixes active neutrinos with singlets e.g.
- neutrino-modulino mixing or
- Dirac mass mass terms

Corresponds to Yukawa interaction \( \left[ \right] \) LSH with \( \left[ \right] = m_{3/2} / M_{Pl} \)

It can be generated either by non-renormalizable terms in the superpotential or from the Kahler potential similarly to appearance of the \( \left[ \right] \)-term in Giudice-Masiero mechanism

\[ K = \frac{1}{M_{Pl}} P(S, z, z^*) \text{LH} + \text{h.c.} \]

\( z \) - Wilson lines...

Too small mass?
Increasing $m_D$

$m_D = \frac{m_{3/2} \sqrt{3} m_{Pl} v_{EW}}{M_{Pl}}$

$M_{Pl} \rightarrow M_{GUT}$

$m_{3/2} \rightarrow 10^2 \text{ TeV}$

``Consistent anomaly mediation''
H. Murayama

Large $\square$

S. Abel, A. Dedes
K. Tamvakis

Dominant contribution to the mass:
$\sim v_{EW} F_{\phi}/M^2$

$F_{\phi} = \sqrt{3} M_{Pl} m_{3/2}$

$K = 1/M \ P(S, \square, \square^*) \ L \ H \ N + h.c.$

$M = 10^{17} \text{ GeV} - \text{cut off}$

$\square \square$ fields of the Hidden sector

$m_D = \frac{m_{3/2} v_{EW} \sqrt{3} M_{Pl}}{M} \sim 0.05 \text{ eV}$
Small (Dirac Yukawas) from Superpotential
RH Majorana masses from Kahler potential

\[ W = g \frac{X}{M} L N H \]
\[ K = h \frac{Y^* N N}{M} \]

\( X, Y \) - from hidden sector: \( \langle X_A \rangle = m_I \), \( \langle Y_Y \rangle = m_I^2 \) (int. scale)

\[ m_D = g v_{EW} \left( \frac{m_{3/2}}{M} \right) \]
\[ m_N = h m_{3/2} \]

seesaw

TeV RH neutrinos

If in addition
\[ K = h_B \frac{Y^* Y X^*}{M^3} N N \]

Main contribution \( \sim 0.05 \text{ eV} \)

Arkani-Hamed
Hall, Murayama,
Smith, Weiner
Borzumati, Nomura

J. March-Russel,
S. West

A Yu Smirnov
Model: SU(5) GUT R-symmetry

Matter: $F(5, 1), T(10, 1), N(1, -1)$  \[ \text{R-charge is different} \]

Higgs: $H(5, 0), H(5, 0)$
$H'(5, 2), H'(5, 0)$  \[ \text{New higgs} \]

Superpotential: $\mathbf{W} = f \bar{F} H' N + M_H H' \bar{H}' + \text{usual terms} \ldots$

R-symmetry breaking ->

$W_R = \bar{H} H + \bar{H}' H'$

Mixing of $H$ and $H'$
$H \bar{H} \bar{H}' M_H H'$

\[ f \bar{F} / M_H \bar{F} H N \]
Overlap suppression
Arkani-Hamed, Dvali, Dimopoulos
Large extra D + 3D brane

Wave functions

3D brane

RH neutrinos propagate in the bulk

Width of the brane:
\[ d = 1/M \]

\[ f^R \sim 1/\sqrt{R} \]

\[ M \sim 10 - 100 \text{ TeV} \]
is the fundamental scale
``Overlap of the wave functions:``

\[ d f^R \sim 1/\sqrt{M R} \]

for \[ \square \] extra D:

\[ m_D = \square v_{EW} \left( \frac{1}{M^\square V^{\square}} \right) \]
\[ = \square v_{EW} \frac{M}{M_{Pl}} \]
In Randall–Sundrum (non-factorizable metric)
Setting: 1 extra D S $^{1/2}$

On visible brane:
$$f^{R}_0(\rho) \sim \rho^{0.5}$$

$\rho = m/k$
$m \sim M$

Dirac mass in 5D

$M$ - fundamental Planck scale
$r_c$ radius of extra D
$k \sim M$ - curvature parameter

$$m_D = Y f^{R}_0(\rho) v_{EW}$$
$$\sim M \left( \frac{v_{EW}}{M} \right)^{1/2}$$

RH neutrinos - bulk zero mode localized on the hidden brane
... on the fat brane

Arkani-Hamed, Schnaltz

3D brane

wave functions

overlap

$f^R$

$f^L$
We should consider and further work on the alternatives of the Seesaw: some of them are related to interesting ideas and concepts of physics Beyond the SM and provide tests of these new physics.

Easy to test alternatives (at least some of them):
- exclude alternatives or
- prove one of them thus excluding seesaw

It is not excluded that one of these alternatives gives main contribution to neutrino mass

It is possible that some of them give relevant sub-leading contributions responsible for Physics `beyond seesaw`