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?

1. No evidence of seesaw

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 $m_{\square} \sim m_u^2$,
  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

R.Mohapatra

- - Seesaw I + symmetry (e.g., SO(3))
  - seesaw II + symmetry
  - ``cascade seesaw'':

S.Petcov, A.S.
E.Ma
J. Valle

$$m_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M_D \\ 0 & M_D & M \end{pmatrix}$$

If $M_D = A\, m_D$,
and $M = M_0 I$

$\Rightarrow$ $m_\nu \sim M_0 / A^2 \; I$

2. No way to prove?

Discovery of the neutrinoless double beta decay

Will not prove that seesaw is the main mechamism

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

3. Unpredictable neutrinos...

As it was in the past,
neutrinos may not follow
our prejudices
about simplicity
elegance and
naturalness

4. String theory tells us:

- 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..

5. General context

Put seesaw in a general context, consider problems of this general context

See-saw

$M_R = 10^8 - 10^{15}$ 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?

Remarks

Effective operator, S. Weinberg 1979

$$\frac{\Box_{ij}}{M}(l_i H)^T (l_j H) \quad i, j = e, \Box, \Box \quad \Rightarrow \quad m_{ij} = \frac{\Box_{ij}\langle H\rangle^2}{M}$$

l_i - lepton doublets, H - Higgs doublet,

- For $M = M_{Pl}$ and $\Box_{ij} \sim 1$: $m_{ij} \sim 10^{-5}$ eV

Barbieri Ellis Gailard
Akhmedov Berezhiani
Senjanovic

- Contributions ~ 10^{-5} eV are still relevant for phenomenology. Sub-dominant structures of mass matrix can be generated by Planck scale interactions

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

Superformula

In general,

$$m_{\square} = \square\, m_{seesaw} + m_{triplet} + \square\, m_{radiative} + m_{SUSY} + m_{Planck} + \ldots$$

From different scales

1loop, 2loops,...

- Seesaw can give leading contribution, beyond seesaw -> sub-leading effects from other mechanisms
- Seesaw may turn out to be sub-leading mechanism...

Questions to alternatives

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)

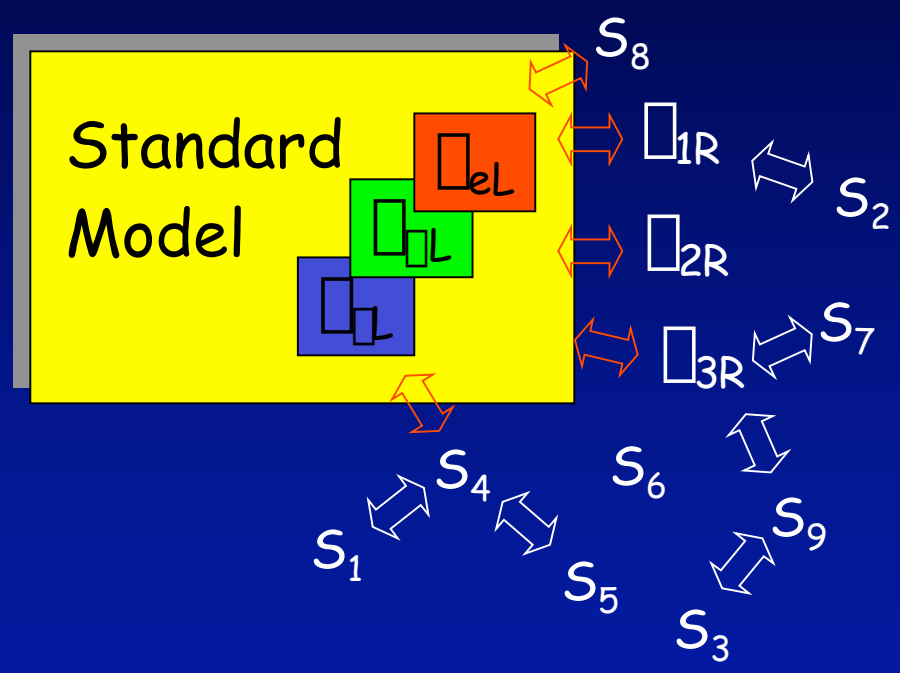
$$\begin{matrix} \nu \\ \nu_R \\ N \end{matrix} \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

$m(\nu) = 0$

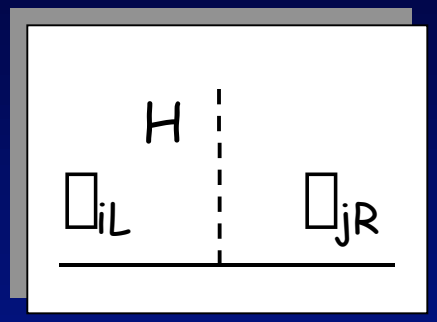
Unnatural?
Why the RH neutrinos but not other RH fermions?

J. Valle,
R. Mohapatra

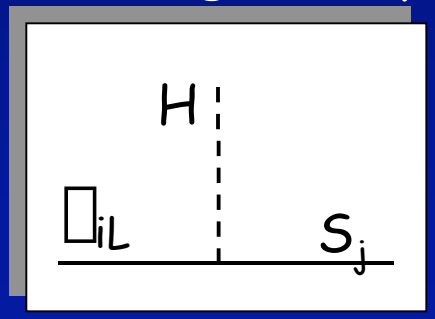
General Context



Multi-singlet mechanism



Suppressed by seesaw or multi-singlet couplings



Small because of symmetry, seesaw or multi-singlet couplings

Prove or disprove

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

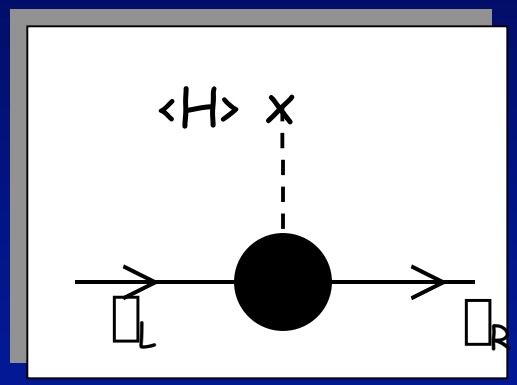
Classifying Alternatives

Classifying

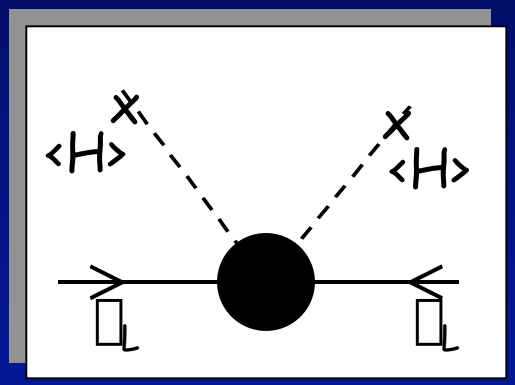
- operators (Babu-Leung/
- diagrams (E Ma)
- physical context

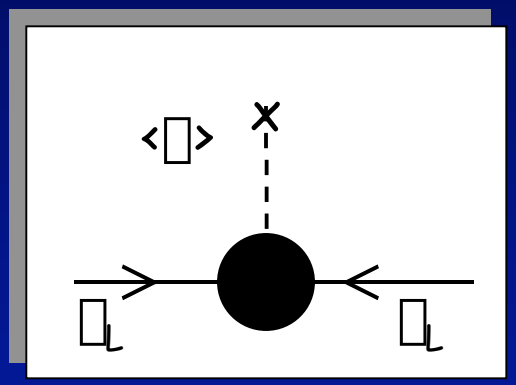
Classification

Dirac



Majorana





Small overlap
(of wave functions
inextra dimensions)

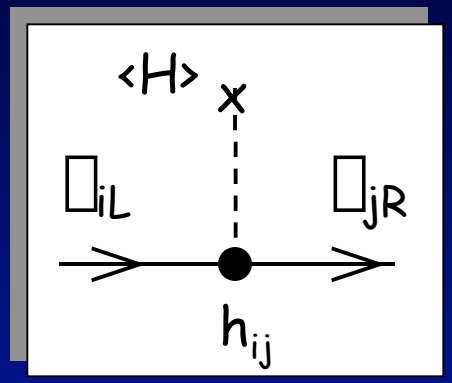
Small coupling
(effective)

Tree level

Radiative

Small VEV

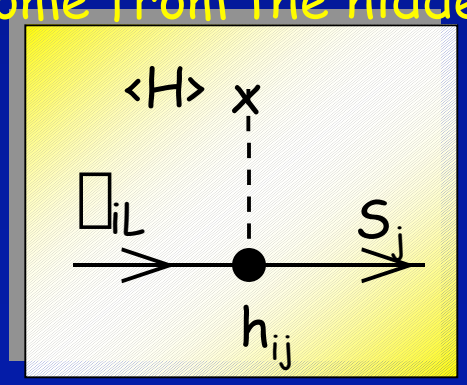
Small Yukawa couplings



$h_{ij} \sim 10^{-13}$

Unnatural
untestable
can be excluded
if $\beta\beta_{0\nu}$-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

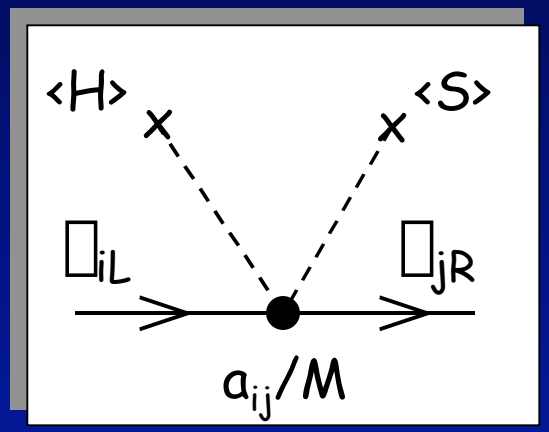
Suppressed by
symmetry or seesaw

Small effective couplings

effective coupling produced by non-renormalizable operators:

$$a_{ij}\, l_{iL} \square_{iL}\, H\, \frac{S}{M}$$

(renormalizable coupling is suppressed by symmetry)



$$h_{ij} = a_{ij} \frac{\langle S \rangle}{M}$$

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

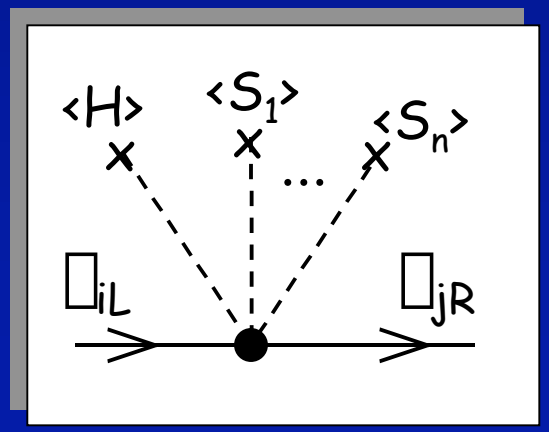
$$\frac{\langle S \rangle}{M} \sim 10^{-13}$$

SUSY / GUT scales?

$m_{3/2}/M_{Planck}$

Small VEV

L. Hall...



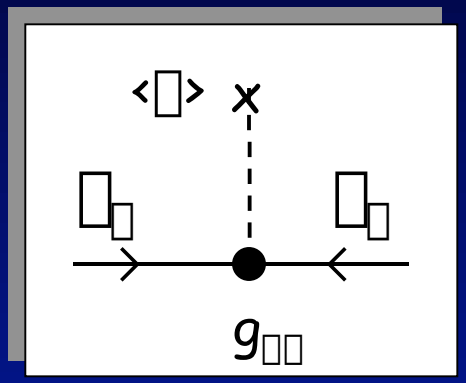
In general

Difficult to test directly

--> test context/models

Higgs Triplet mechanism

E. Ma



No RH neutrinos

Higgs triplet: (Δ^{++}, Δ^{+}, Δ^{0})

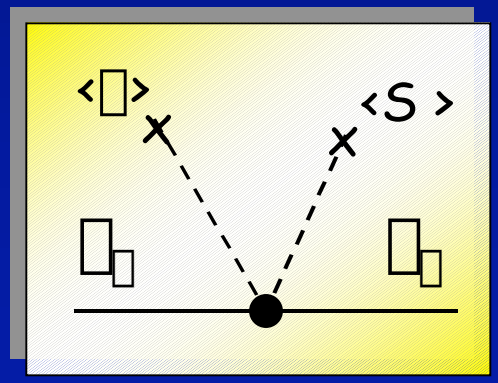
EW precision measurements:

$\langle \Delta^0 \rangle / \langle H \rangle < 0.03$

No triplet Majoron -> coupling $\Delta\Delta H H$

If $g_{\Delta\Delta} \sim 1$, $\langle \Delta^0 \rangle \sim 1$ eV

Effective coupling



If M_Δ, $\Delta \gg \langle H \rangle$:

$\langle \Delta^0 \rangle \sim \langle H \rangle^2 \Delta / M^2$

Seesaw type II

If $M_\Delta \sim \langle H \rangle$, $\Delta \ll \langle H \rangle$

$\langle \Delta^0 \rangle \sim \Delta$

pseudo Majoron

mass ~ $\Delta \sim 0.03\langle H \rangle$

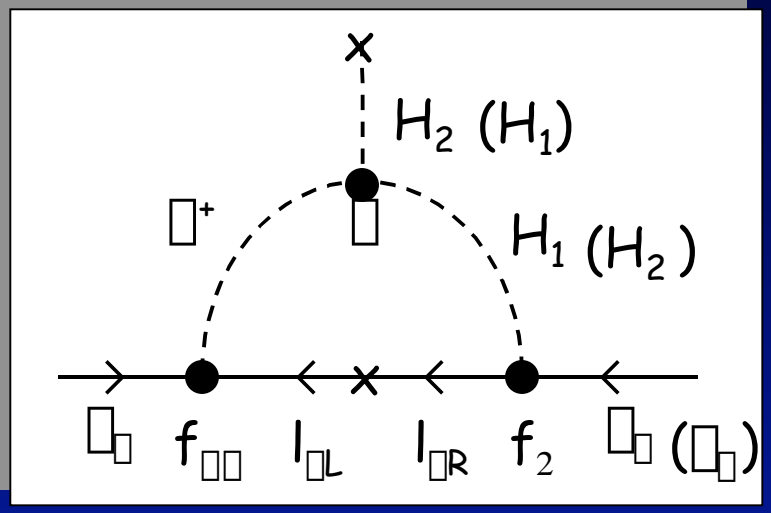
excluded by

Z^0 -width

„Mechanisms never die"

A Yu Smirnov

Zee-mechanism



No RH neutrinos

new bosons: singlet $\square^+$, doublet H_2

$$m_{\square} = A\,[(f\,m^2 + m^2 f^T)\,\square \;\; v\,(\cos\square)^{\square 1}\,(\,f\,m\,f_2 + f_2{}^T m\;\; f^T\,)\,]$$

$$A = \sin 2\square_Z \;\ln(M_2/M_1)/\,(8\square^2 v \tan\square)$$

$$m = (m_e\,,\, m_{\square},\, m_{\square})$$

If only H_1 couples with leptons

~excluded

$$\begin{pmatrix} 0 & m_{e\square} & m_{e\square} \\ & 0 & m_{\square\square} \\ & & 0 \end{pmatrix}$$

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

X-G He

P. Frampton, M. C. Oh

T. Yoshikawa

- inverse hierarchy of $f_{\square\square}$
- $f_{\square\square} < 10^{-4}$

Reviving Zee model

1). Introduction of couplings of both doublets with leptons

-> diagonal terms are non-zero

FCNC: e.g. □ -> □ □□, □ -> □ee, □ -> □ □ e, □ -> eee

due to Higgs exchange -> 2-3 orders below the present bound

□ -> 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...

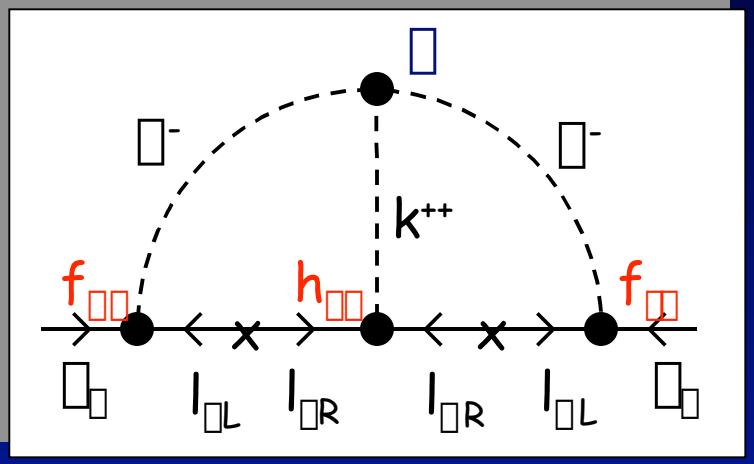
Testable model:

Precision EW measurements

Searches for charged Higgses

rare decays

Zee-Babu mechanism



K.S. Babu,
C. Macesanu

No RH neutrinos

new scalar singlets $\Box^-$ and k^{++}

$m_\Box \sim 8\ \Box\ f\ m_l\ h\ m_l\ f\ I$

$m_l = \mathrm{diag}\ (m_e, m_\Box, m_\Box)$

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 ~ 0.1

Testable:

- new charged bosons
- decays $\Box\Box > \Box\ e$, $\Box\Box > 3\ \Box$ within reach of the forthcoming experiments

R-parity violating SUSY

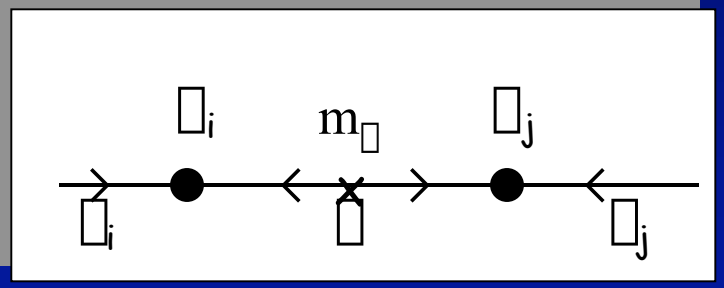
Superpotential:

Z_3 - baryon triality (Ibanez, Ross)

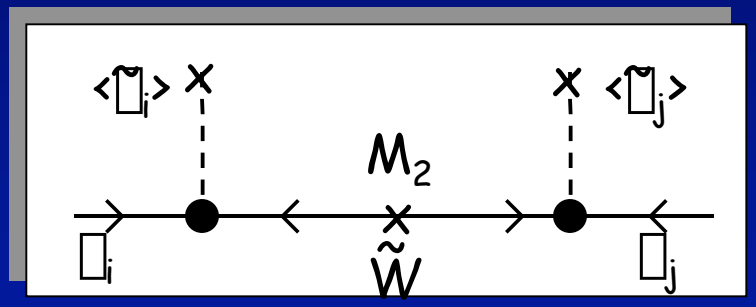
$$W = -\mu_\alpha L_\alpha H_U - 0.5\,\lambda_{\alpha\beta m} L_\alpha L_\beta e_m + \lambda'_{\alpha nm} L_\alpha Q_n d_m - h_{nm} H_U Q_n u_m$$

Bi-linear (Hall-Suzuki) $\alpha = 0, 1, 2, 3$, $m = 1,2,3$ $L_0 = H_D$

No RH neutrinos



in the basis $\langle\tilde{\mu}_m\rangle = 0$



in the basis $\mu_m = 0$

Neutrino mass

$m_{ij} = X\,\mu_i\,\mu_j$, $X \sim \cos^2\beta/m$

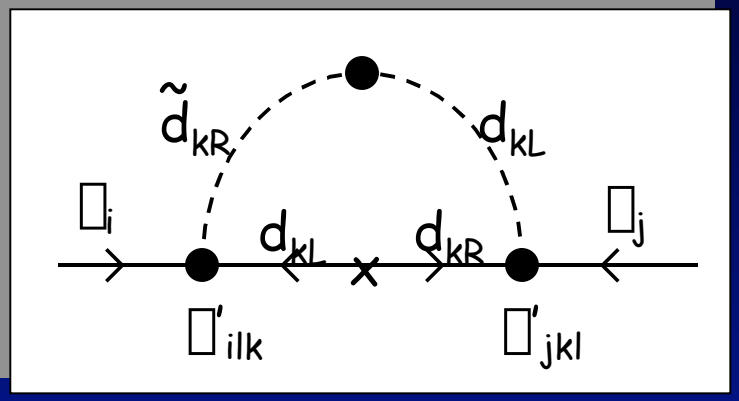
$m_{ij} = A\,\langle\mu_i\rangle\,\langle\mu_j\rangle$

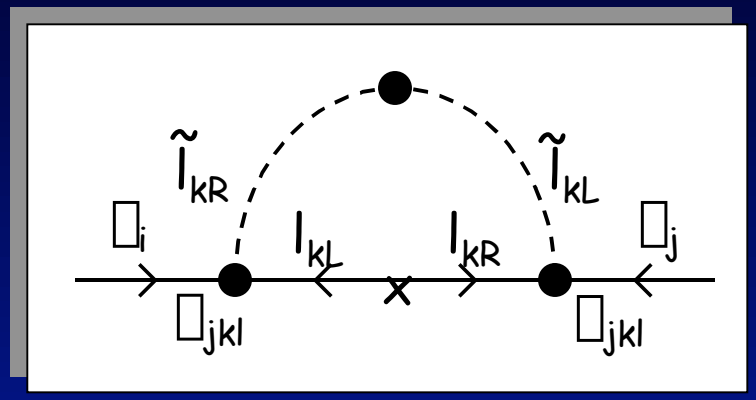
$$\frac{h_b^2}{16\pi^2}$$

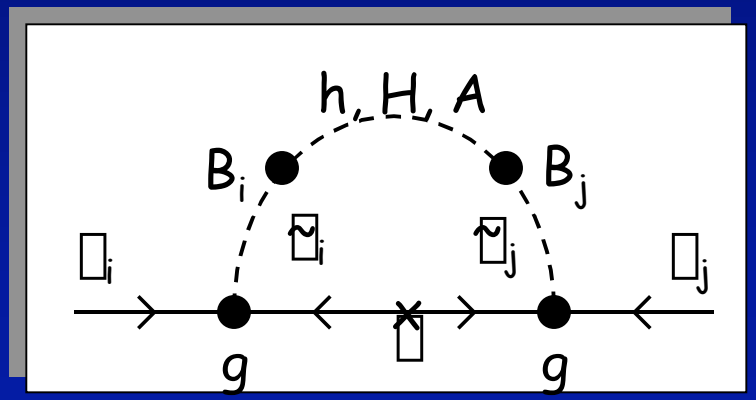
EW seesaw

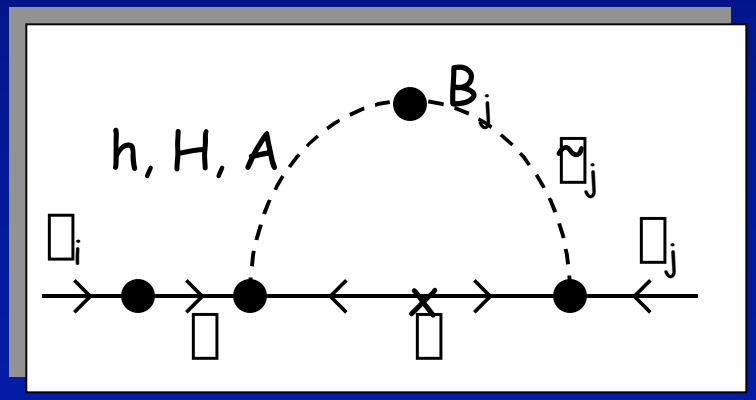
Only one neutrino acquires mass, mixing is determined by μ_i/μ_j

RpV: loops









B_m- soft symmetry breaking parameter

...

RpV: phenomenology

Neutrinos: natural hierarchy of mass parameters:

tree level - one mass, large mixing

loops - other masses, mixing

$\square_m \sim 10^{-4}$ GeV

Violation of universality of soft symmetry breaking terms:

both Higgs-lepton and flavor universality

e.g. B_m are different at GUT

J. Valle ….

Y. Grossman

Tests: rich phenomenology

- colliders,
- rare decays,
- new neutrino interactions…

Old and New

SUSY violation & neutrino mass

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

K. Benakli, A.S.

Corresponds to Yukawa interaction ΦLSH with $\Phi = m_{3/2} / M_{Pl}$

It can be generated either by non-renormalizable terms in the superpotential or from the Kahler potential similarly to appearance of the μ-term in Giudice-Masiero mechanism

$$K = 1/M_{Pl}\ P(S, z, z^*)\ LH + h.c.$$

z - Wilson lines...

Too small mass?

Increasing m_D

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

$\square$ -renormalization effect

M_{Pl} -> M_{GUT}

$m_{3/2}$ --> 10^2 TeV

``Consistent anomaly mediation''
H. Murayama

Large $\square$

S. Abel, A. Dedes
K.Tamvakis

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

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

$\square\ \square$ fields of the Hidden sector

Dominant contribution to the mass:

$\sim v_{EW}\ F_{\square}/M^2$

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

$$m_D = \frac{\square\ m_{3/2}\ v_{EW}}{M}\ \frac{\sqrt{3} M_{Pl}}{M} \sim 0.05\ \text{eV}$$

Variation on theme

Small (Dirac Yukawas) from Superpotential
RH Majorana masses from Kahler potential

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

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

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

$$m_D = g\, v_{EW} \sqrt{\frac{m_{3/2}}{M}} \qquad m_N = h\, m_{3/2}$$

seesaw

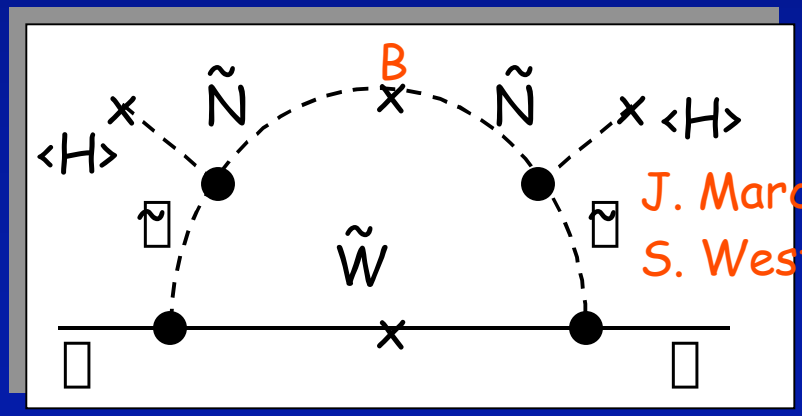
$$m_\nu \sim \frac{v_{EW}^2 g^2}{M\ h} \sim 10^{-3} \text{eV}$$

TeV RH neutrinos

If in addition

$$K = h_B \frac{Y^*\, Y\, X^*}{M^3} N N$$

Main contribution ~ 0.05 eV



J. March-Russel,
S. West

□ - term mixing

Model: SU(5) GUT R-symmetry

R.Kitano

Matter: $\bar{F}(\bar{5}, 1)$, $T(\underline{10},1)$, $N(1, -1)$ ⇐ R-charge is different

Higgs : $H(5, 0)$, $\bar{H}(5, 0)$
$H'(5, 2)$, $H'(5, 0)$ ⇐ New higgs

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

couples with new higgs

SUSY breaking ->
R-symmetry breaking: $W_R = \square\, H\,\bar{H} + \square'\, H\,\bar{H}'$

Mixing of
H and H' $\quad H \;\square\; \bar{H}' \;\; M_H \;\; H'$ ⇒ $f\,\square/M_H\,\bar{F}\,H\,N$

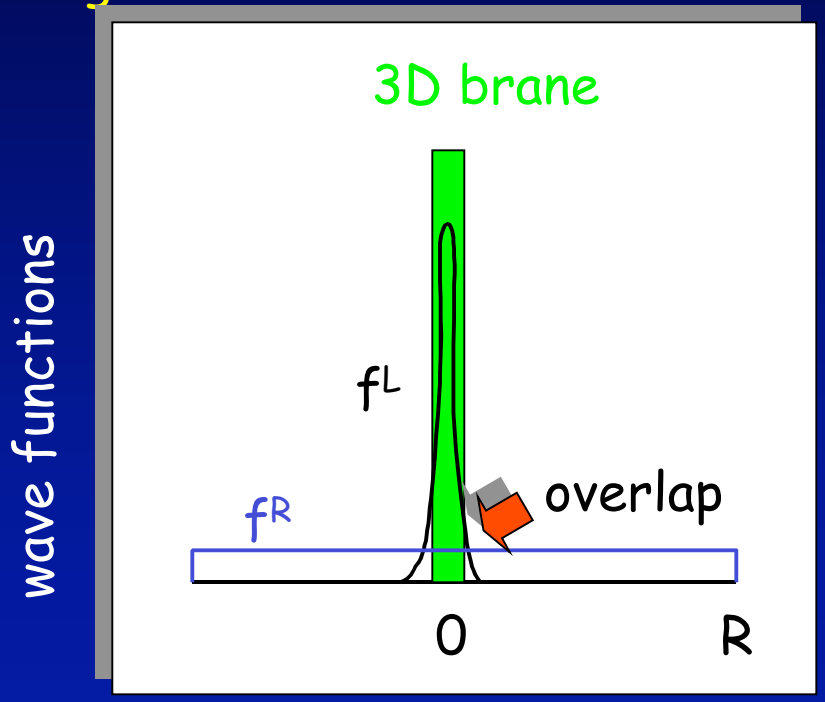
Extra Dimensions & Extra Possibilities

Overlap suppression

A Yu Smirnov

...in large flat extra D

Arkani-Hamed, Dvali, Dimopoulos
Large extra D + 3D brane



RH neutrinos propagete in the bulk

$$f^R \sim 1/\sqrt{R}$$

Width of the brane:

$$d = 1/M$$

$M \sim 10$ -100 TeV is the fundametal scale

``Overlap of the wave functions:"

$$d\, f^R \sim 1/\sqrt{MR}$$

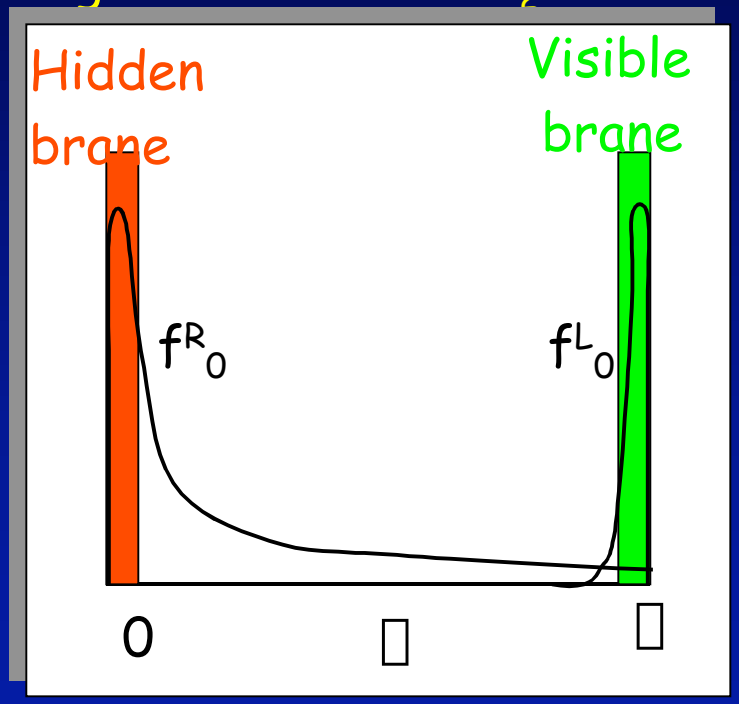
for $\square$ extra D: $1/\sqrt{M^{\square} V_{\square}}$

$$m_D = \square\, v_{EW} \left(\frac{1}{M^{\square} V_{\square}} \right) = \square\, v_{EW}\, M/M_{Pl}$$

...in warped extra D

Grossman
Neubert
Huber, Shafi...

In Randall -Sundrum (non-factorizable metric)
Setting: 1 extra D S^1/Z_2



RH neutrinos - bulk zero mode localized on the hidden brane

On visible brane:

$$f^R_0(\square) \sim \square^{\square\square 0.5}$$

$\square = m/k$
$m \sim M$
Dirac mass in 5D

$$\square = e^{-kr_c\square} = \frac{v_{EW}}{M} = 10^{-16}$$

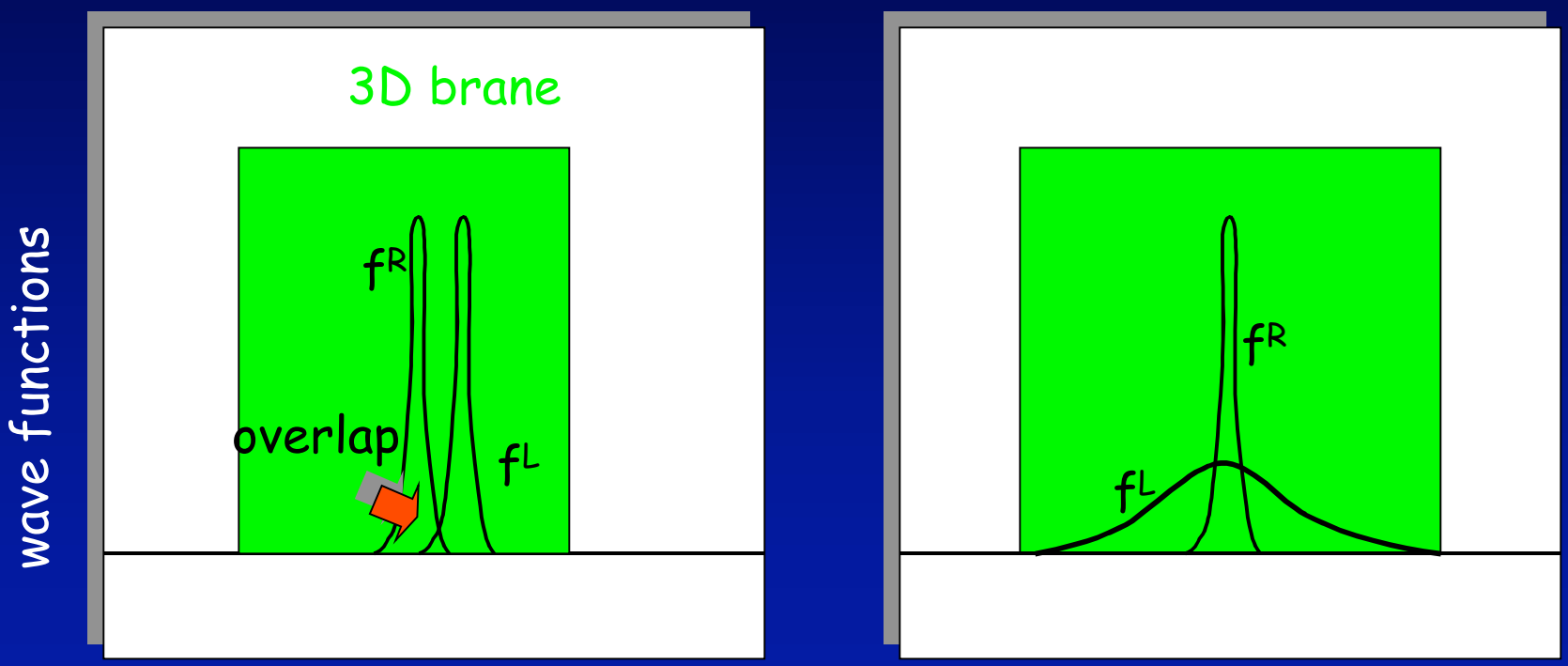
M - fundamental Planck scale
r_c radius of extra D
$k \sim M$ - curvature parameter

$$m_D = Y f^R_0(\square)\, v_{EW} \sim M \left(\frac{v_{EW}}{M}\right)^{\square + 1/2}$$

$\square\square 1.1 \square 1.6$

... on the fat brane

Arkani-Hamed, Schnaltz



Conclusions

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"