Neutrino Masses and Conformal
Electro-Weak Symmetry Breaking

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Neutrino Mass Terms: New Physics...

Simplest possibility: add 3 right handed neutrino fields

\[ \nu_L \quad g_N \quad \nu_R \]
\[ <\phi> = v \]

Majorana

\[ \nu_R \quad \nu_R \]

\[ (\nu_L \quad \nu_R^c) \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} (\nu_L^c \quad \nu_R) \]

like quarks and charged leptons \( \rightarrow \) Dirac mass terms (including NMS mixing)

New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

6x6 block mass matrix
block diagonalization
\( M_R \) heavy \( \rightarrow \) 3 light \( \nu \)'s

NEW ingredients, 9 parameters \( \rightarrow \) SM+
Are right-handed neutrinos established?

New scalar tripelts \((3_L)\) or fermionic \(1_L\) \(\rightarrow\) \(3_L\)

\(\Rightarrow\) left-handed Majorana mass term:

\[ M_L \overline{L} L^c \]

Both \(\nu_R\) and new singlets / triplets:

\(\Rightarrow\) see-saw type II, III

\[ m_\nu = M_L - m_D M_R^{-1} m_D^T \]

Higher dimensional operators: \(d=5, \ldots\)
Radiative neutrino mass generation

SUSY, extra dimensions, ...

- inspiring options, many questions, connections to LFV, LHC, ...
- SM+ can/may solve two of the SM problems:
  - Leptogenesis as explanation of BAU
  - keV sterile neutrinos as excellent warm dark matter candidate

progress:
- new experimental results ...waiting...
- theoretical guidance ...guessing...
Guidance by the larger Picture: GUTs

Gauge unification suggests GUTs

Ingredients:
- unified gauge group
- unified particle multiplets ↔ ν_R
  → Q,L Yukawa couplings connected
  ....
→ proton decay, ...
- generations are just copies

\[ \begin{align*}
\text{Quarks} & : & u & c & t \\
& & \sim 5 & \sim 1350 & 175000 \\
& & -1/3 & -1/3 & -1/3 \\
\text{Leptons} & : & \nu_1 & \nu_2 & \nu_3 \\
& & 0^+ & 0^+ & 0^+ \\
& e & \mu & \tau \\
& \text{1.} & \text{2.} & \text{3. generation}
\end{align*} \]
Flavour Unification

- so far no understanding of flavour, 3 generations
- apparent regularities in quark and lepton parameters
  ➔ flavour symmetries (finite number for limited rank)
  ➔ symmetry not texture zeros

Examples:

\[ O(3)_L \times O(3)_R \]

\[ \text{SU}(3) \]
\[ \text{SO}(3) \]
\[ \text{SU}(2) \]
\[ \text{A}_4; Z_3 \triangleleft Z_2 \]
\[ \text{U}(1) \]
\[ \text{S}(3)_L \times S(3)_R \]
\[ \text{S}(3) \]

Leptons            Quarks
1. 2. 3. generation

\begin{array}{cccc}
u & c & t \\
\hline
2/3 & 2/3 & 2/3 \\
-1/3 & -1/3 & -1/3 \\
0 & 0 & 0 \\
\end{array}

\begin{array}{cccc}
d & s & b \\
\hline
-1/3 & -1/3 & -1/3 \\
-2/3 & -2/3 & -2/3 \\
0 & 0 & 0 \\
\end{array}

\begin{array}{cccc}
\nu_1 & \nu_2 & \nu_3 \\
\hline
0.511 & 0.511 & 0.511 \\
105.66 & 105.66 & 105.66 \\
1777.2 & 1777.2 & 1777.2 \\
\end{array}
GUT & Flavour Unification

GUT group x flavour group

example: $SO(10) \times SU(3)_F$

- SSB of $SU(3)_F$ between $\Lambda_{GUT}$ and $\Lambda_{Planck}$
- all flavour Goldstone Bosons eaten
- discrete sub-groups survive $\leftrightarrow$ SSB
e.g. $Z_2$, $S_3$, $D_5$, $A_4$, ...

$\Rightarrow$ structures in flavour space
$\Rightarrow$ compare with data

$\Rightarrow$ aim: distinguish models by future precision and learn about the origin of flavour

$\Rightarrow$ reality so far: many models get killed by data (see e.g. $\theta_{13}$...)
Generic & Suggestive See-Saw Features

QFT: natural value of mass operators $\leftrightarrow$ scale of symmetry

$m_D = g_D v$; $v \sim$ electro-weak scale; $0 \leq g_D \leq 2 \Rightarrow 0 \leq m_D \leq 2v$

$M_R \sim L$ violation scale $\leftrightarrow?\Rightarrow$ embedding (GUTs, …)

See-saw (type I)

$m_\nu = m_D M_R^{-1} m_D^T$

$m_h = M_R$

Numbers: For $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim$ leptons $\Rightarrow$ $M_R \sim 10^{11} - 10^{16}$GeV

$M_R$ suggests that sterile neutrinos must be very heavy – really?

$\Rightarrow$ are there indications / arguments for light sterile states?

$\Rightarrow$ theoretical arguments in favour of light steriles
2nd Look Questions

Quarks & charged leptons → hierarchical masses → neutrinos?

Quarks and charged leptons:
$m_D \sim H^n; \ n = 0, 1, 2 \Rightarrow H \geq 20...200$

Neutrinos: $m_\nu \sim H^n \Rightarrow H \leq 10$

See-saw:

$m_\nu = -m_D^T M_R^{-1} m_D$

→ inversely correlated hierarchy in $M_R$? → not related!
→ other version of see-saw? → type II, III, …? Dirac masses?
→ b.t.w: see-saw may explain tiny masses, but what about mixings…?
Neutrino masses require some new BSM physics:
- Simplest option: add $\nu_R$
- Many other options with new fields, symmetries, concepts
- Dirac or Majorana?
- If Majorana $\rightarrow$ heavy steriles quite natural, but not testable…

What about `Light’ Sterile Neutrinos?

Light is any value $\ll 10^{13}$ GeV

3x3 leptonic mixing matrix of active $\nu$’s is almost unitary
$\Rightarrow$ at most small admixtures of sterile $\nu$’s Antusch et al., others…
Hints / Arguments / … for Sterile Neutrinos

Particle Physics: LSND, Gallium, MiniBooNE, reactor anomaly, …

CMB: $N_\nu = 3.3 \pm 0.27 \rightarrow$ extra eV-ish $\nu$’s possible  PLANCK 2013

BBN: $N_\nu = 3$-4 $\rightarrow$ possible  e.g. Coc

Astrophysics: keV-ish sterile neutrinos could explain pulsar kicks
Kusenko, Segre, Mocioiu, Pascoli, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, …

Dark matter: keV sterile neutrinos are excellent WDM
Asaka, Blanchet, Shaposhnikov, … ML, Bezrukov, Hettmanperger

Sterile $\nu$’s and improved EW fits: TeV-ish $\nu$’s improve $\chi^2$
Akhmedov, Kartavtsev, ML, Michaels and J. Smirnov

Most likely not all true, but one is enough:
VERY IMPORTANT IMPLICATIONS $\rightarrow$ new direct experiments
Options for Neutrino Mass Spectra

\[
\begin{pmatrix}
\bar{\nu}_L & \bar{\nu}_R^c
\end{pmatrix}
\begin{pmatrix}
M_L & m_D & \nu_L^c \\
m_D & M_R & \nu_R
\end{pmatrix}
\begin{pmatrix}
\nu_L \\
\nu_R
\end{pmatrix}
\]

\(M_L, m_D, M_R\) may have almost any form / values:
- zeros (symmetries)
- 0 + tiny corrections
- scales: \(M_W, M_{GUT}\), ...

\(\Rightarrow\) diagonalization: 3+N EV
\(\Rightarrow\) 3x3 active almost unitary

- \(M_L = 0, m_D = M_W, M_R = \text{high: see-saw}\)
- \(M_R\) singular singular-SS
- \(M_L = M_R = 0\) Dirac
- \(M_L = M_R = \epsilon\) pseudo Dirac

M. Lindner, MPIK
Interesting Directions: E.g. Pseudo Dirac Neutrinos

• Might be useful / indications (?) from SK-upturn (see e.g. A. Smirnov)
• May also be useful in HE neutrinos and GRBs (see e.g. Esmaili and Farzan)
• Theory ideas
  - mirror worlds (e.g. Joshipura, Mohanty, Pakvasa)
  - implications for $0\nu\beta\beta$ (e.g. P.Gu)
  - role in leptogenesis (e.g. Abel, Page)
  - left right symmetry and gauged B,L (e.g. Duerr, Perez, ML)
  - … sugra (e.g. Dedes)
  - … many others
Explaining light Sterile Neutrinos

Possible scenario: See-saw + a reason why 1 sterile $\nu$ is light

- heavy sterile neutrinos typ. $\geq 10^{13}$ GeV

- extra dimensional physics → ‘split see-saw’
  - Kusenko, Takahashi, Yanagida,

- flavour symmetries explaining active neutrino masses + charged leptons + quarks
  - consequences for heavy mass matrix
  - $L_e - L_\mu - L_\tau$ DM ↔ flavour problem
  - ML, Merle, Niro ; Merle, Niro,
  - Barry, Rodejohann, Zhang
    - one light sterile neutrino $\sim$ keV = DM

- light active neutrinos $< eV$
Light Sterile Neutrinos from $L_e - L_\mu - L_\tau$

- Flavour symmetries have been studied to explain apparent regularities of masses and mixing: $A4$, $S3$, $D5$, …
  - implications for sterile sector?
  - could the same symmetries explain a keV-ish sterile $\nu$?

Model with $L_e - L_\mu - L_\tau$ symmetry:
  - by Lavoura & Grimus $\Rightarrow$ extended: ML, Merle, Niro
  $\text{SM} + \nu_{iR} +$ softly broken $U(1) \leftrightarrow \mathcal{F} \equiv L_e - L_\mu - L_\tau$
  - type II see-saw $\Rightarrow$ +Higgs triplet

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

<table>
<thead>
<tr>
<th></th>
<th>$L_e L$</th>
<th>$L_\mu L$</th>
<th>$L_\tau L$</th>
<th>$e_R$</th>
<th>$\mu_R$</th>
<th>$\tau_R$</th>
<th>$N_{1R}$</th>
<th>$N_{2R}$</th>
<th>$N_{3R}$</th>
<th>$\phi$</th>
<th>$\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{F}$</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

M. Lindner, MPIK
• Mass matrix for right-handed neutrinos:

\[ \mathcal{L}_{\text{mass}} = -M_R^{12} \, (N_{1R})^C \, N_{2R} - M_R^{13} \, (N_{1R})^C \, N_{3R} + h.c. \]

• Dirac masses

\[ \mathcal{L}_{\text{mass}} = -Y_D^{e1} \, \overline{L_e} \, \tilde{\phi} \, N_{1R} - Y_D^{\mu2} \, \overline{L_{\mu}} \, \tilde{\phi} \, N_{2R} - Y_D^{\mu3} \, \overline{L_{\mu}} \, \tilde{\phi} \, N_{3R} - Y_D^{\tau2} \, \overline{L_{\tau}} \, \tilde{\phi} \, N_{2R} - Y_D^{\tau3} \, \overline{L_{\tau}} \, \tilde{\phi} \, N_{3R} + h.c., \]

• In addition: Triplet masses

\[ \mathcal{L}_{\text{mass}} = -Y_L^{e\mu} \, (\overline{L_e})^C (i\sigma_2 \Delta) \, L_{\mu} - Y_L^{e\tau} \, (\overline{L_e})^C (i\sigma_2 \Delta) \, L_{\tau} + h.c. \]
Example: Singular heavy neutrino mass matrix:

\[
\Psi \equiv ( (\nu_{eL})^C, (\nu_{\mu L})^C, (\nu_{\tau L})^C, N_{1R}, N_{2R}, N_{3R} )^T
\]

\[
M_\nu = \begin{pmatrix}
0 & m_{e\mu}^e & m_{e\tau}^e & m_{e1}^D & 0 & 0 \\
0 & 0 & 0 & m_{D}^{\mu2} & 0 & m_{D}^{\mu3} \\
0 & 0 & 0 & m_{D}^{\tau2} & m_{D}^{\tau3} & m_{D}^{\tau3}
\end{pmatrix}
\]

\[\det(M_{ij}) = 0 \implies M_1 = 0\]

- massless sterile state + soft breaking
- naturally light sterile \(\nu\)
- mechanism possible in many models
Leptogenesis

...there still exist heavy sterile states ...

$m_\nu$

heavy sterile neutrinos typ. $> 10^{13}$ GeV

$\Rightarrow$ Leptogenesis from the decay of the remaining heavy sterile neutrinos works perfectly!
Bezrukov, Kartavtsev, ML

leptogenesis

one light sterile neutrino $\sim$ keV = DM

light active neutrinos $< eV$
Sterile Neutrinos & Conformal
Electro-Weak Symmetry Breaking
SM: Triviality and Vacuum Stability Bounds

126 GeV < m_H < 174 GeV

- RGE arguments seem to work
- just SM?
- no BSM physics observed!
- just a SM Higgs

ML '86

126 GeV is here!
λ(M_{pl}) ∼ 0
- EW-SB radiative
- just SM?

Holthausen, ML, Lim (2011)

SM does not exist w/o embedding
- U(1) coupling, Higgs self-coupling

Landau pole

Λ(GeV)

ln(μ)

Λ

10^3
10^6
10^10
10^15
10^19

m_t (GeV)

m_H (GeV)

0
100
200
300
400
500

ML, MPIK
Is the Higgs Potential at $M_{\text{Planck}}$ flat?

**Notes:**

- remarkable relation between weak scale, $m_t$, couplings and $M_{\text{Planck}}$ ↔ precision
- strong cancellations between Higgs and top loops
  → very sensitive to exact value and error of $m_H$, $m_t$, $\alpha_s = 0.1184(7)$ → currently 1.8σ in $m_t$
- higher orders, other physics, ... Planck scale thresholds... Lalak, Lewicki, Olszewski,
  → important: watch central values & errors → important: new physics ↔ DM, $m_\nu$
The Hierarchy Problem: Specify $\Lambda$

- Renormalizable QFTs with two scalars $\varphi$, $\Phi$ with masses $m$, $M$ and a mass hierarchy $m << M$
- These scalars must interact since $\varphi^+\varphi$ and $\Phi^+\Phi$ are singlets
  $\Rightarrow \lambda_{\text{mix}}(\varphi^+\varphi)(\Phi^+\Phi)$ must exist in addition to $\varphi^4$ and $\Phi^4$
- Quantum corrections $\sim M^2$ drive both masses to the (heavy) scale
  $\Rightarrow$ two vastly different scalar scales are generically unstable

Therefore: If (=since) the SM Higgs field exists
$\Rightarrow$ problem: embedding with a 2$^{\text{nd}}$ scalar with much larger mass
$\Rightarrow$ usual solutions:

\begin{align*}
a) & \text{new scale @TeV} \\
b) & \text{protective symmetry @TeV}
\end{align*}

$\Rightarrow$ LHC!

b) is usually SUSY, but SUSY & gauge unification = SUSY GUT
  $\Rightarrow$ doublet-triplet splitting problem $\Rightarrow$ hierarchy problem back
Conformal Symmetry as Protective Symmetry

- Exact (unbroken) CS
  - absence of $\Lambda^2$ and $\ln(\Lambda)$ divergences
  - no preferred scale and therefore no scale problems

- Conformal Anomaly (CA): Quantum effects explicitly break CS
  - existence of CA $\rightarrow$ CS preserving regularization does not exist
  - dimensional regularization is close to CS and gives only $\ln(\Lambda)$
  - cutoff reg. $\rightarrow$ $\Lambda^2$ terms; violates CS badly $\rightarrow$ Ward Identity

Bardeen: maybe CS still forbids $\Lambda^2$ divergences
  - CS breaking $\leftrightarrow$ $\beta$-functions $\leftrightarrow$ $\ln(\Lambda)$ divergences
  - anomaly induced spontaneous EWSB

IMPORTANT: The conformal limit of the SM (or extensions) may have no hierarchy problem!
Implications

Gauge invariance $\Rightarrow$ only log sensitivity

Relics of conformal symmetry $\Rightarrow$ only log sensitivity

- With CS there no hierarchy problem, even though it has anomaly
- Dimensional transmutation due to log running like in QCD
  $\Rightarrow$ scalars can condense and set scales like fermions
  $\Rightarrow$ use this in Coleman Weinberg effective potential calculations
  $\leftrightarrow$ most attractive channels (MAC) $\leftrightarrow$ $\beta$-functions
Why the minimalistic SM does not work

**Minimalistic:**

SM + choose $\mu = 0 \iff$ CS

Coleman Weinberg: effective potential

$\Rightarrow$ CS breaking (dimensional transmutation)

$\Rightarrow$ induces for $m_t < 79$ GeV

a Higgs mass $m_H = 8.9$ GeV

This would conceptually realize the idea, but:

Higgs too light and the idea does not work for $m_t > 79$ GeV

Reason for $m_H << v$: $V_{\text{eff}}$ flat around minimum

$\iff m_H \sim$ loop factor $\sim 1/16\pi^2$

AND: We need neutrino masses, dark matter, …
Realizing the Idea via Higgs Portals

- SM scalar $\Phi$ plus some new scalar $\varphi$ (or more scalars)
- CS $\rightarrow$ no scalar mass terms
- the scalars interact $\Rightarrow \lambda_{\text{mix}}(\varphi^+\varphi)(\Phi^+\Phi)$ must exist

$\Rightarrow$ a condensate of $<\varphi^+\varphi>$ produces $\lambda_{\text{mix}}<\varphi^+\varphi>(\Phi^+\Phi) = \mu^2(\Phi^+\Phi)$
$\Rightarrow$ effective mass term for $\Phi$

- CS anomalous … $\rightarrow$ breaking $\rightarrow$ only $\ln(\Lambda)$
$\Rightarrow$ implies a TeV-ish condensate for $\varphi$ to obtain $<\Phi> = 246$ GeV

- Model building possibilities / phenomenological aspects:
  - $\varphi$ could be an effective field of some hidden sector DSB
  - further particles could exist in hidden sector; e.g. confining…
  - extra hidden U(1) potentially problematic $\leftrightarrow$ U(1) mixing
  - avoid Yukawas which couple visible and hidden sector
$\Rightarrow$ phenomenology safe due to Higgs portal, but there is TeV-ish new physics!
Realizing the Idea: Other Directions

**SM + extra singlet: \( \Phi, \varphi \)**
Nicolai, Meissner, Farzinnia, He, Ren, Foot, Kobakhidze, Volkas

**SM + extra SU(N) with new N-plet in a hidden sector**
Ko, Carone, Ramos, Holthausen, Kubo, Lim, ML

**SM embedded into larger symmetry (CW-type LR)**
Holthausen, ML, M. Schmidt

**SM + colored scalar which condenses at TeV scale**
Kubo, Lim, ML

Since the SM-only version does not work \( \Rightarrow \) observable effects:
- Higgs coupling to other scalars (singlet, hidden sector, …)
- dark matter candidates \( \Leftarrow \Rightarrow \) hidden sectors & Higgs portals
- consequences for neutrino masses
Implications for Neutrino Masses


• No explicit scale ➔ no explicit (Dirac or Majorana) mass term
  ➔ only Yukawa couplings ⊗ generic scales

• Enlarge the Standard Model field spectrum
  like in 0706.1829 - R. Foot, A. Kobakhidze, K.L. McDonald, R. Volkas

• Consider direct product groups: SM ⊗ HS

• Two scales: CS breaking scale at O(TeV) + EW scale

  ➔ spectrum of Yukawa couplings ⊗ TeV or EW scale
  ➔ many possibilities
Examples

\[ \mathcal{M} = \begin{pmatrix} 0 & y_D \langle H \rangle \\ y_D^T \langle H \rangle & y_M \langle \phi \rangle \end{pmatrix} \]

\( \Rightarrow \) generically expect a TeV seesaw

BUT: \( y_M \) might be tiny

\( \Rightarrow \) wide range of sterile masses \( \Rightarrow \) includes pseudo-Dirac case

Yukawa seesaw:

SM + \( \nu_R \) + singlet

\( \langle \phi \rangle \approx \text{TeV} \)

\( \langle H \rangle \approx 1/4 \text{ TeV} \)

Radiative masses

\[ \mathcal{M} = m_L \]

\[ \mathcal{M} = \begin{pmatrix} \mu_1 & y_D \langle H \rangle \\ y_D^T \langle H \rangle & \mu_2 \end{pmatrix} \]

\( \Rightarrow \) pseudo-Dirac case
More Examples: Inverse Seesaw

Seesaw & LNV

\[ \nu_R : (1_{SU(2)}, 0_Y, 0_{HS}) \]

\[ \nu_x : (1_{SU(2)}, 0_Y, n_{HS}) \]

\[ \mathcal{M} = \begin{pmatrix} 0 & y_D \langle H \rangle & 0 \\ y_D^T \langle H \rangle & 0 & y_{Rx} \langle \phi \rangle \\ 0 & y_{Rx}^T \langle \phi \rangle & \mu \end{pmatrix} \]

\[ \epsilon = \frac{1}{2} y_D^\dagger (y_{Rx}^{-1})^* \left(y_{Rx}^{-1}\right)^T y_D \cdot \frac{\langle H \rangle^2}{\langle \phi \rangle^2} \]

\[ \langle \phi \rangle > \langle H \rangle \text{ and } m_\nu \approx \mu \epsilon \]

\( \mu \) is suppressed (LNV) natural scale keV

The punch line:

- all usual neutrino mass terms can be generated
- No explicit masses\( \Rightarrow \) all via Yukawa couplings\( \Rightarrow \) different numerical expectations
SM works perfectly – no signs of new physics

The standard hierarchy problem suggests TeV scale physics … which did (so far…) not show up

Revisit how the hierarchy problem may be solved

- $\lambda(M_{\text{Planck}}) = 0$ ? ↔ precise value for $m_t$
- Embeddings into QFTs with classical conformal symmetry
  - SM: Coleman Weinberg effective potential – excluded
  - extended versions → work!
  → implications for Higgs couplings, dark matter, …
  → implications for neutrino masses
  → testable consequences @ LHC, DM search, neutrinos