Neutrino Masses and Conformal Electro-Weak Symmetry Breaking

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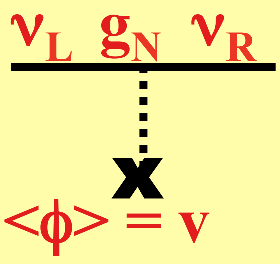
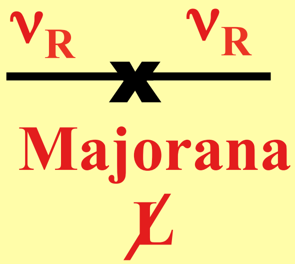
Neutrino Mass Terms: New Physics...

Simplest possibility: add 3 right handed neutrino fields





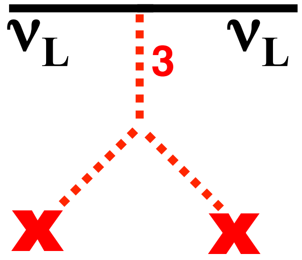
$$\rightarrow \quad \begin{pmatrix} \bar{\nu}_L & \bar{\nu}^c_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}$$

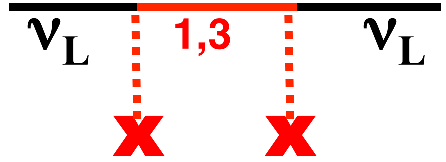
like quarks and charged leptons → Dirac mass terms (including NMS mixing)	New ingredients: 1) Majorana mass (explicit) 2) lepton number violation	6x6 block mass matrix block diagonalization M_R heavy → 3 light ν's

NEW ingredients, 9 parameters → SM+

Are right-handed neutrinos established?

New scalar tripelts (3_L)
or fermionic 1_L ro 3_L





➔ left-handed Majorana mass term:

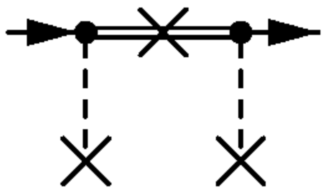
➔ $M_L \bar{L} L^c$

Both ν_R and new singlets / triplets:

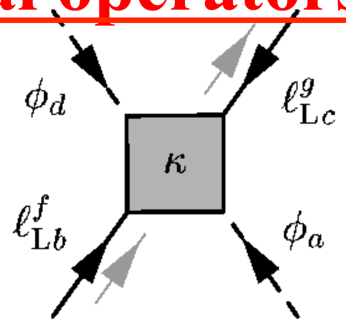
➔ see-saw type II, III

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

Higher dimensional operators: d=5, …



$\Rightarrow$

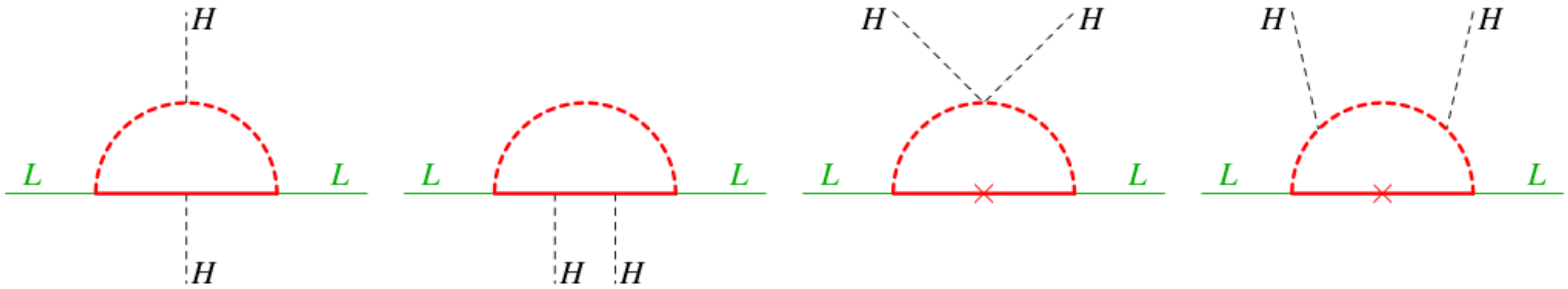


$\Leftrightarrow$

$$\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}^C_L \nu_L \Phi^T \Phi$$

➔ $M_L \bar{L} L^c$

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:**

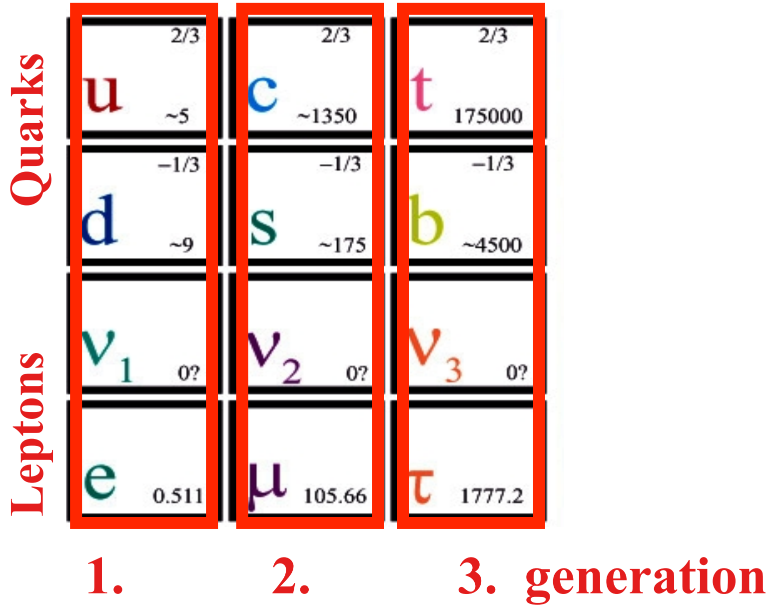
- **new experimental results ...waiting...**
- **theoretical guidance ...guessing...**

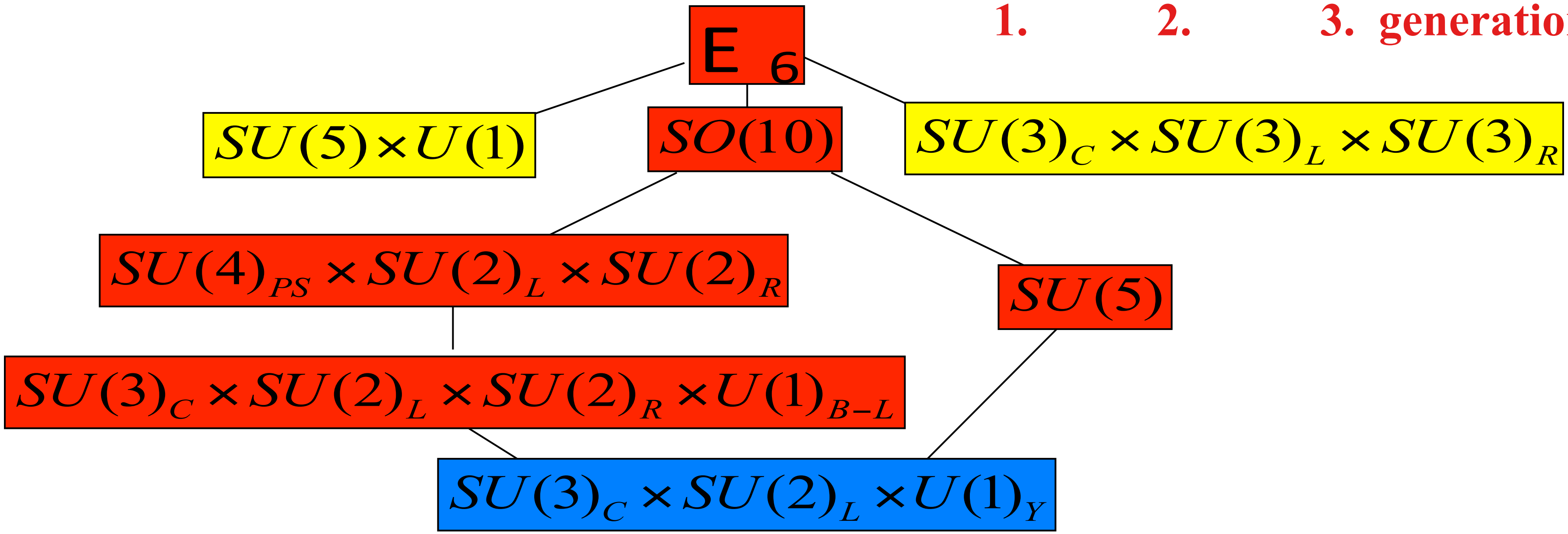
Guidance by the larger Picture: GUTs

Gauge unification suggests GUTs

Ingredients:

- unified gauge group
- unified particle multiplets ⇔ ν_R
  ➔ Q,L Yukawa couplings connected
  ….
  ➔ proton decay , …
- generations are just copies



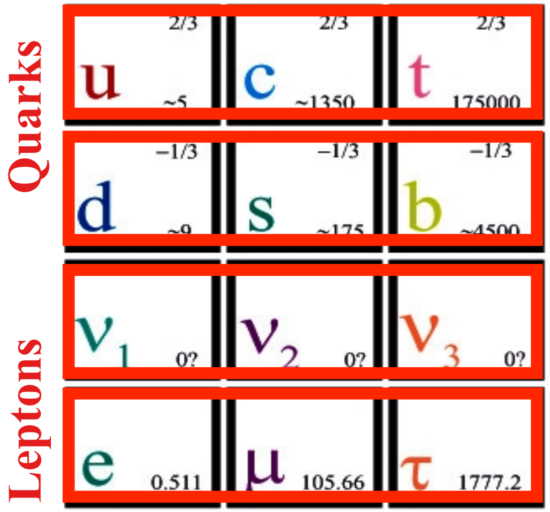


Flavour Unification

- so far **no understanding of flavour, 3 generations**
- apparant regularities in quark and lepton parameters

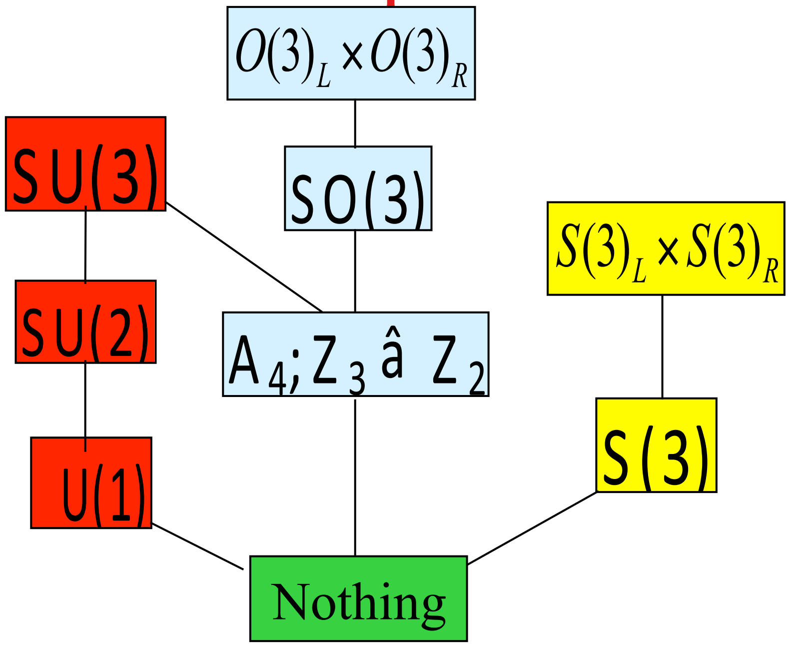
➔ flavour symmetries (finite number for limited rank)

➔ **symmetry** not texture zeros

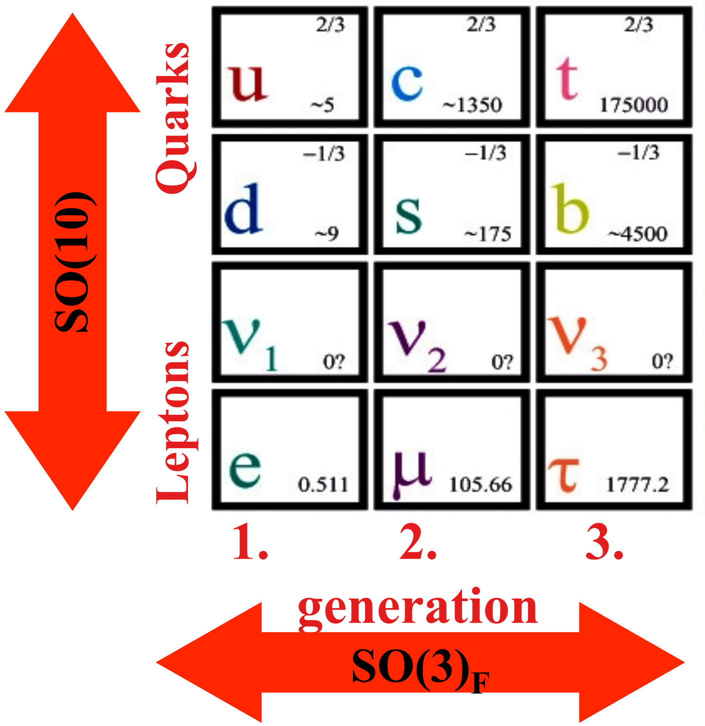


1. 2. 3.
generation

Examples:



GUT & Flavour Unification



➔ GUT group x flavour group

example: SO(10) x $SU(3)_F$

- SSB of $SU(3)_F$ between Λ_{GUT} and Λ_{Planck}
- all flavour Goldstone Bosons eaten
- discrete sub-groups survive ⇐⇒SSB
  e.g. Z2, S3, D5, A4, ...
  ➔ structures in flavour space
  ➔ compare with data

➔ aim: distinguish models by future precision and learn about the origin of flavour

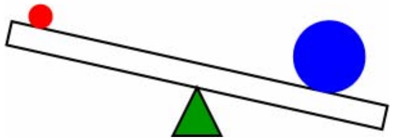
➔ reality so far: many models get killed by data (see e.g. θ_{13}…)

Generic & Suggestive See-Saw Features

QFT: natural value of mass operators ⇔ scale of symmetry

$m_D = g_D * v$; $v \simeq$ electro-weak scale ; $0 \leq g_D \leq 2$ ➔ $0 \leq m_D \leq 2*v$
$M_R \sim$ L violation scale ←?➔ embedding (GUTs, …)

See-saw (type I)



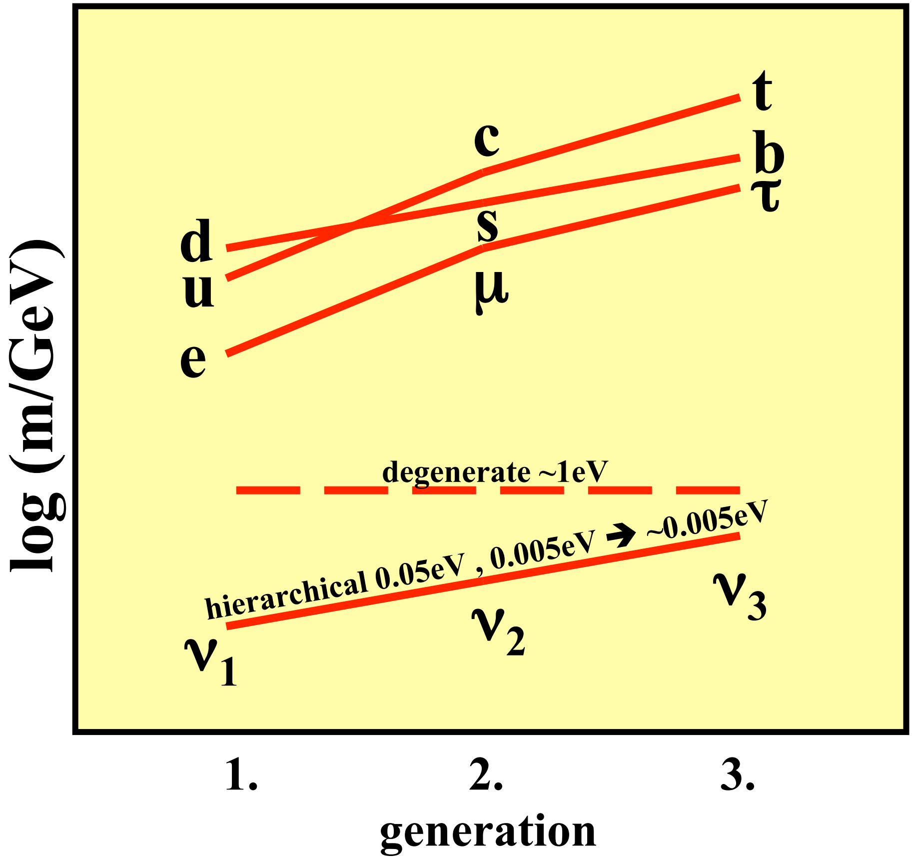
$m_\nu = m_D M_R^{-1} m_D^T$ $m_h = M_R$

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

M_R suggests **that sterile neutrinos must be very heavy** – really?
➔ are there indications / arguments for light sterile states?
➔ theoretical arguments infavour of light steriles

2nd Look Questions

Quarks & charged leptons ➔ hierarchical masses ➔ neutrinos?



Quarks and charged leptons:

$m_D \sim H^n$; $n = 0,1,2$ ➔ $H \geq 20...200$

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

See-saw:

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

H	m_ν	m_D^T	M_R^{-1}	m_D
H	~10	≥20	?	≥20

➔ 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 ν_R
- Many other options with new fields, symmetries, concepts
- Dirac or Majorana?
- If Majorana → heavy steriles quite natural, but not testable…

What about `Light' Sterile Neutrinos?

Light is any value << 10^{13} GeV

3x3 leptonic mixing matrix of active ν's is almost unitary
→ at most small admixtures of sterile ν's Antusch et al., others…

Hints / Arguments / … for Sterile Neutrinos

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

CMB: N_ν = 3.3 $\pm$ 0.27 → **extra eV-ish ν's possible** **PLANCK 2013**

BBN: N_ν = 3-4 → **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**

claims

Asaka, Blanchet, Shaposhnikov, … ML, Bezrukov, Hettmanperger

Sterile ν's and improved EW fits: **TeV-ish ν's improve χ^2**

Akhmedov, Kartavtsev, ML, Michaels and J. Smirnov

Most likely not all true, but one is enough:

VERY IMPORTANT IMPLICATIONS → new direct experiments

Options for Neutrino Mass Spectra

3   0 … N   3x3 matrix   3xN   NxN

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}^c_R \end{pmatrix} \begin{pmatrix} M_L & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}$$

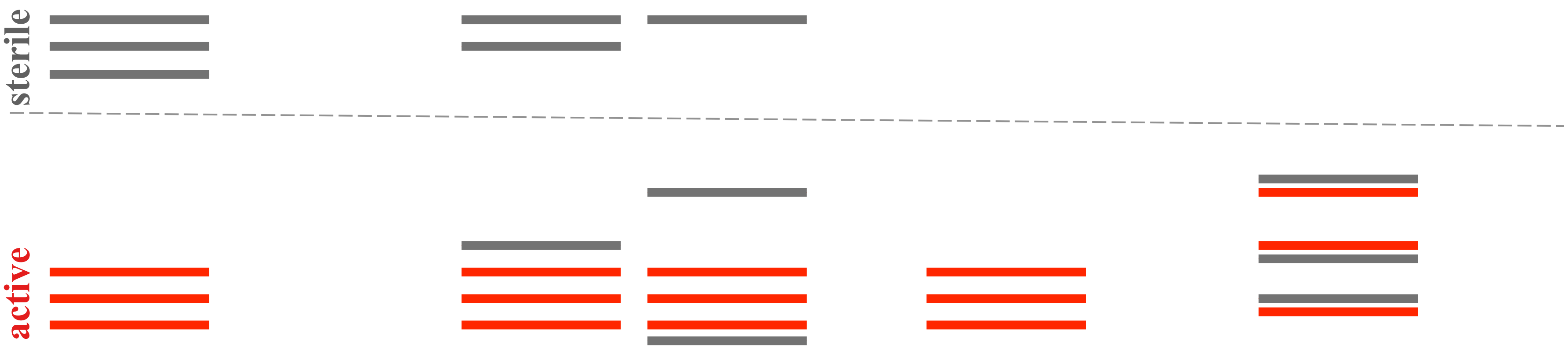
M_L, m_D, M_R may have almost any form / values:

- zeros (symmetries)
- 0 + tiny corrections
- scales: M_W, M_{GUT}, …

➔ diagonalization: 3+N EV

➔ 3x3 active almost unitary

M_L=0, $m_D = M_W$, M_R=high: see-saw	M_R singular singular-SS	$M_L = M_R = 0$ Dirac	$M_L = M_R = \varepsilon$ pseudo Dirac

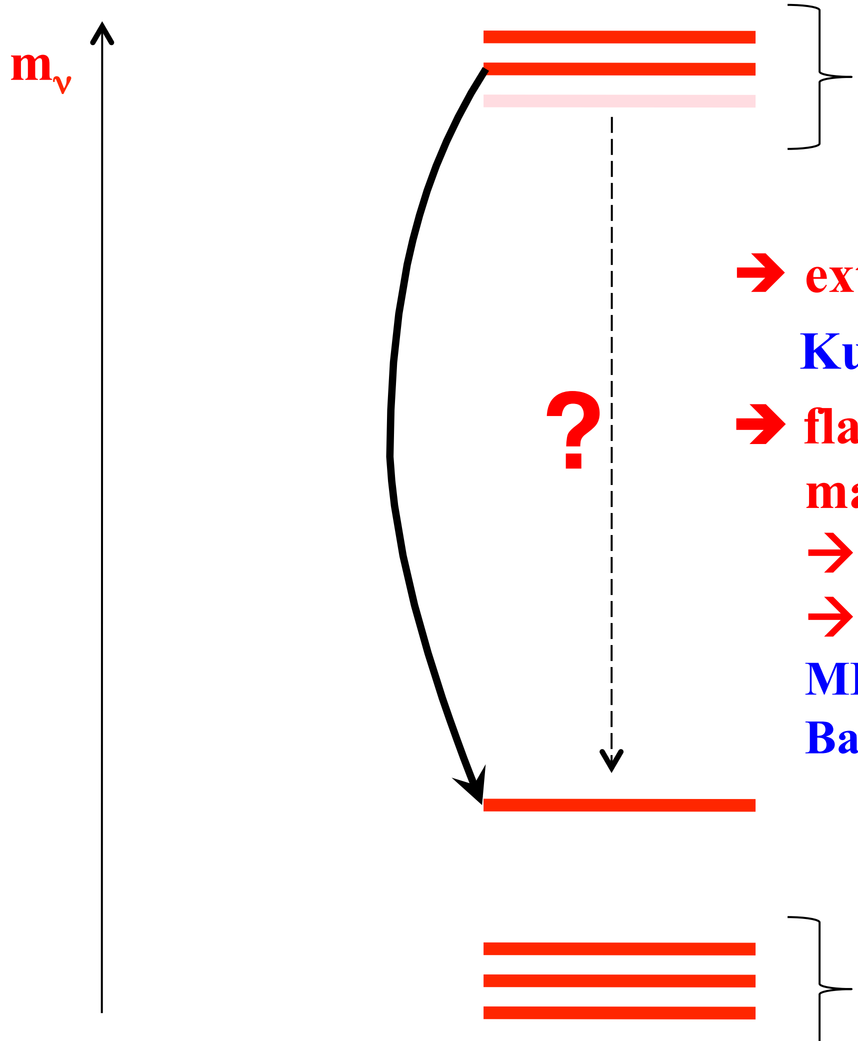


Interesting Directions: E.g. Pseudo Dirac Neutrinos

- **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 ν 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_μ-L_τ DM←→ flavour problem

ML, Merle, Niro ; Merle, Niro,

Barry, Rodejohann, Zhang

one light sterile neutrino $\simeq$ keV = DM

light active neutrinos < eV

Light Sterile Neutrinos from L_e-L_μ-L_τ

- 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 ν?

Model with L_e-L_μ-L_τ symmetry:
by Lavoura & Grimus ➔ extended: ML, Merle, Niro

SM + ν_{iR} + softly broken U(1) ←→ $\mathcal{F} \equiv L_e - L_\mu - L_\tau$

type II see-saw ➔ +Higgs triplet $\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$

	L_{eL}	$L_{\mu L}$	$L_{\tau L}$	e_R	μ_R	τ_R	N_{1R}	N_{2R}	N_{3R}	ϕ	Δ
$\mathcal{F}$	1	-1	-1	1	-1	-1	1	-1	-1	0	0

- **Mass matrix for right-handed neutrinos:**

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

- **Dirac masses**

$$\begin{aligned}\mathcal{L}_{\text{mass}} \;=\; & -Y_D^{e1}\,\overline{L_{eL}}\,\tilde{\phi}\,N_{1R} - Y_D^{\mu 2}\,\overline{L_{\mu L}}\,\tilde{\phi}\,N_{2R} - Y_D^{\mu 3}\,\overline{L_{\mu L}}\,\tilde{\phi}\,N_{3R} - \\ & -Y_D^{\tau 2}\,\overline{L_{\tau L}}\,\tilde{\phi}\,N_{2R} - Y_D^{\tau 3}\,\overline{L_{\tau L}}\,\tilde{\phi}\,N_{3R} + h.c.,\end{aligned}$$

- **In addition: Triplet masses**

$$\mathcal{L}_{\text{mass}} = -Y_L^{e\mu}\,\overline{(L_{eL})^C}\,(i\sigma_2\Delta)\,L_{\mu L} - Y_L^{e\tau}\,\overline{(L_{eL})^C}\,(i\sigma_2\Delta)\,L_{\tau L} + h.c.$$

Example: Singular heavy neutrino mass matrix:

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

$$\mathcal{M}_\nu = \left(\begin{array}{ccc|ccc} 0 & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\ m_L^{e\mu} & 0 & 0 & 0 & m_D^{\mu 2} & m_D^{\mu 3} \\ m_L^{e\tau} & 0 & 0 & 0 & m_D^{\tau 2} & m_D^{\tau 3} \\ \hline m_D^{e1} & 0 & 0 & 0 & M_R^{12} & M_R^{13} \\ 0 & m_D^{\mu 2} & m_D^{\tau 2} & M_R^{12} & 0 & 0 \\ 0 & m_D^{\mu 3} & m_D^{\tau 3} & M_R^{13} & 0 & 0 \end{array}\right)$$

$\det(M_{ij}) = 0$ ➔ $M_1 = 0$

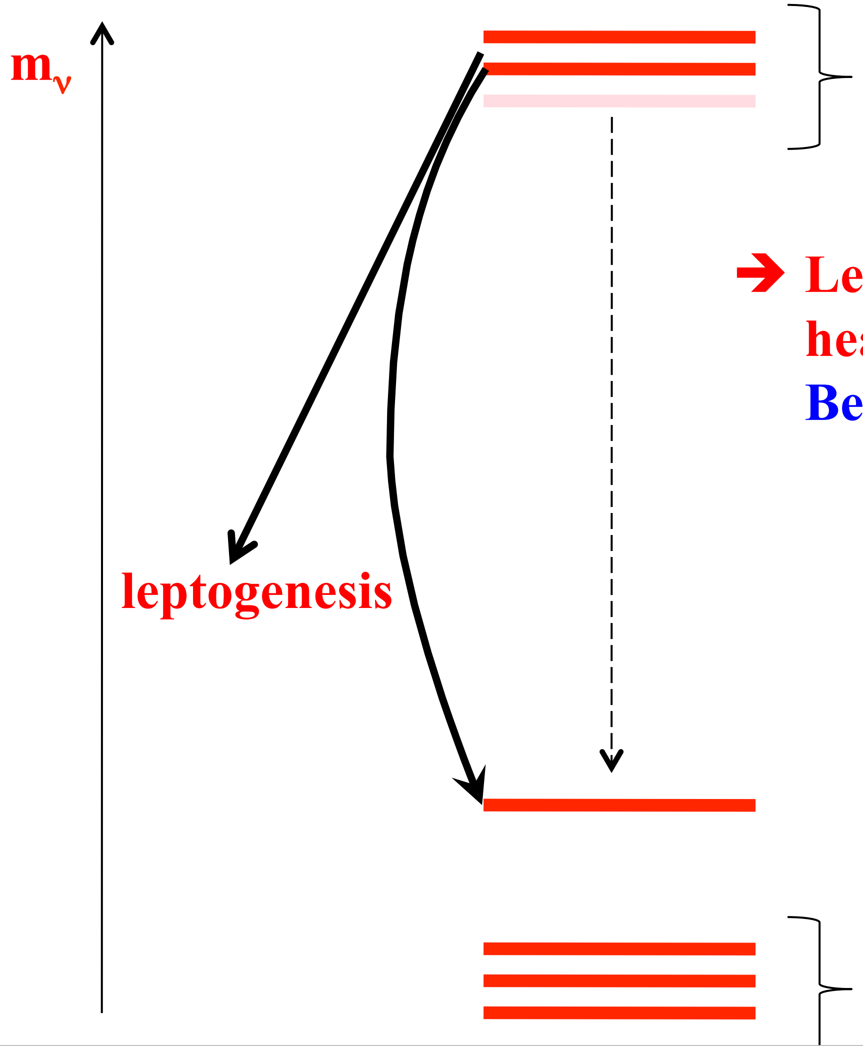
➔ massless sterile state + soft breaking

➔ naturally light sterile ν

➔ mechanism possible in many models

Leptogenesis

…there still exist heavy sterile states …



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

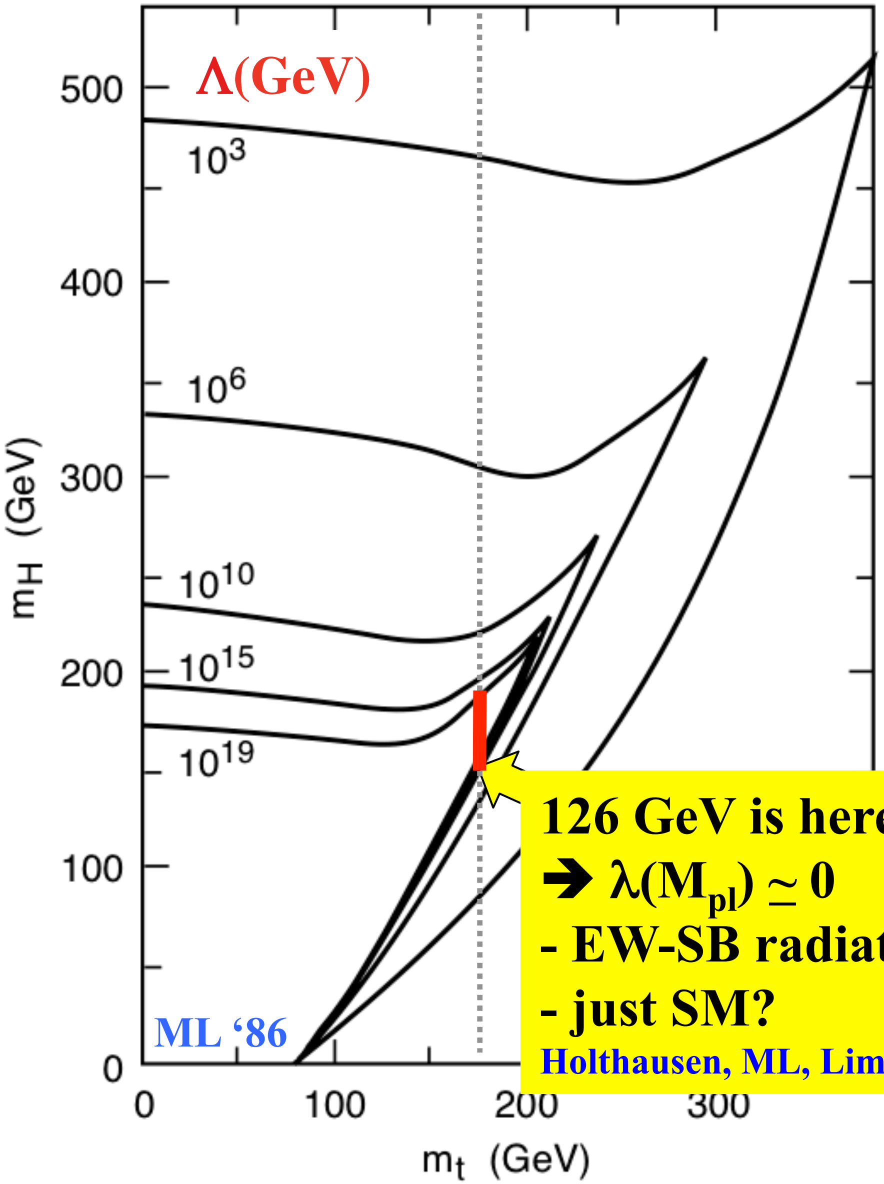
➔ Leptogenesis from the decay of the remaining heavy sterile neutrinos works perfectly!
Bezrukov, Kartavtsev, ML

one light sterile neutrino $\simeq$ keV = DM

light active neutrinos < eV

Sterile Neutrinos & Conformal Electro-Weak Symmetry Breaking

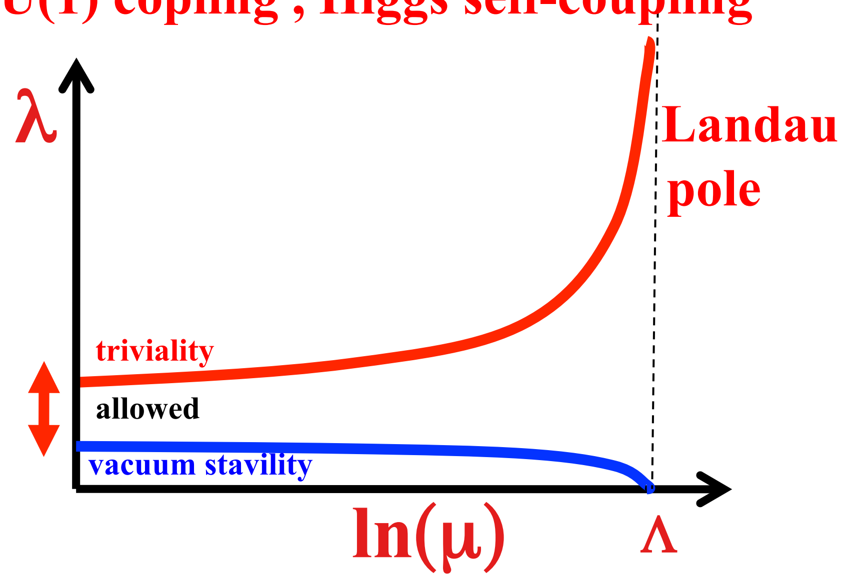
SM:Triviality and Vacuum Stability Bounds



126 GeV is here!
➔ $\lambda(M_{pl}) \simeq 0$
- EW-SB radiative
- just SM?
Holthausen, ML, Lim (2011)

126 GeV < m_H < 174 GeV

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

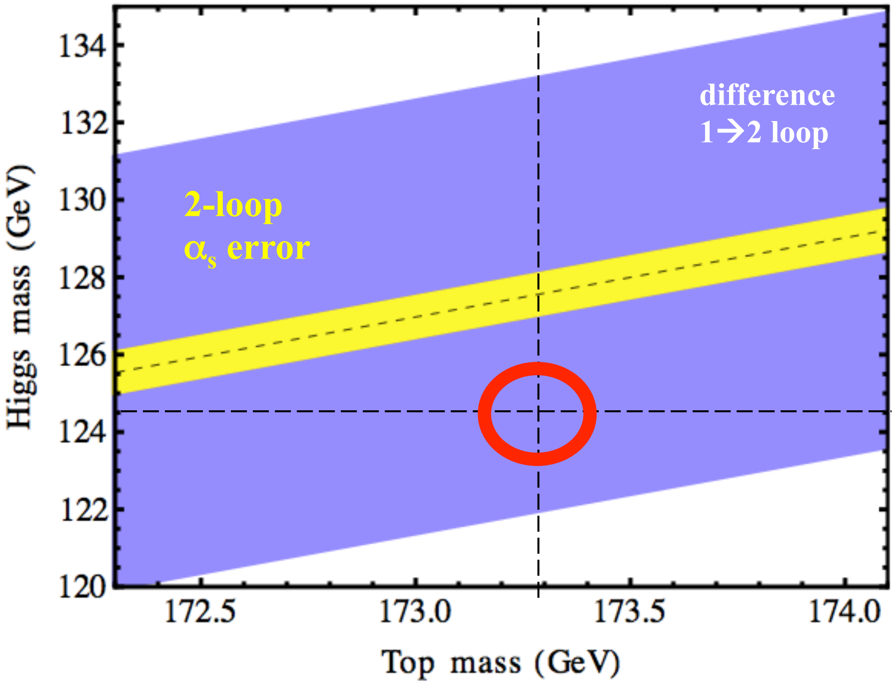


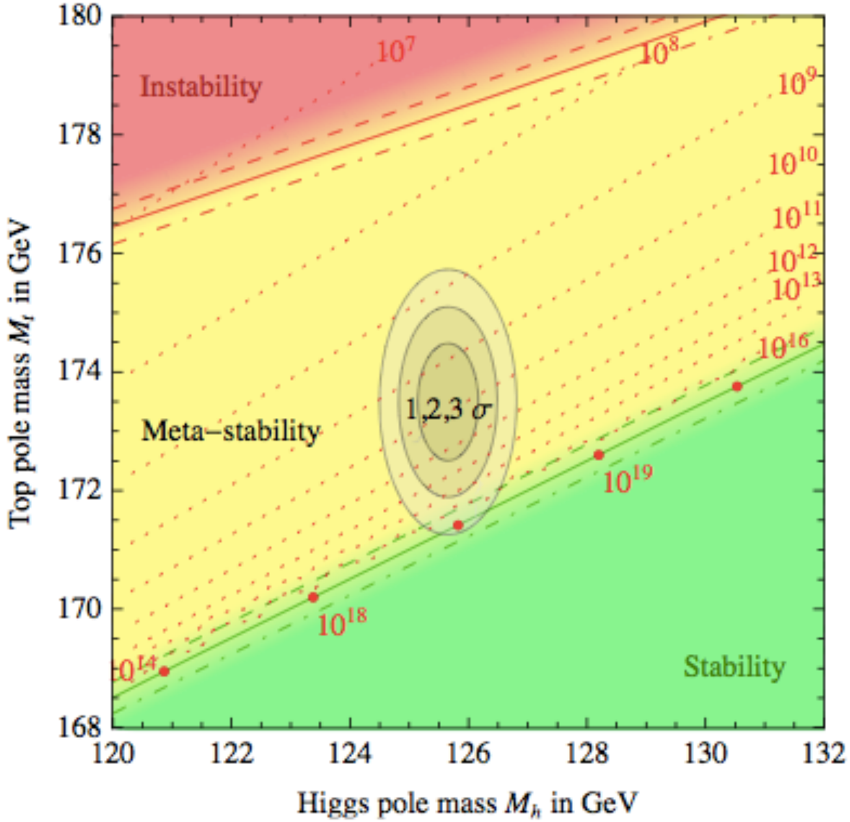
- **➔ RGE arguments seem to work**
- **➔ we need some embeding**
- **⟷ no BSM physics observed!**
- **➔ just a SM Higgs**

Is the Higgs Potential at M_{Planck} flat?

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia

Holthausen, ML, Lim





Notes:

- remarkable relation between weak scale, m_t, couplings and M_{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_ν

The Hierarchy Problem: Specify Λ

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

Therefore: If (=since) the SM Higgs field exists

→ problem: embeding with a 2nd scalar with much larger mass

→ usual solutions:

a) new scale @TeV
b) protective symmetry @TeV

→ LHC !

b) is usually SUSY, but SUSY & gauge unification = SUSY GUT →
→ doublet-triplet splitting problem → hierarchy problem back

Conformal Symmetry as Protective Symmetry

- Exact (unbroken) CS

→ absence of Λ^2 and $\ln(\Lambda)$ divergences

→ no preferred scale and therefore no scale problems

- Conformal Anomaly (CA): Quantum effects explicitly break CS

existence of CA → CS preserving regularization does not exist

- dimensional regularization is close to CS and gives only $\ln(\Lambda)$
- cutoff reg. → Λ^2 terms; violates CS badly → Ward Identity

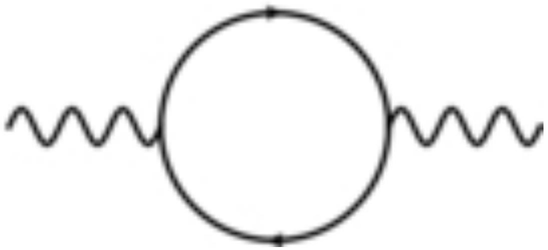
Bardeen: maybe CS still forbids Λ^2 divergences

→ CS breaking ←→ β-functions ←→ $\ln(\Lambda)$ divergences

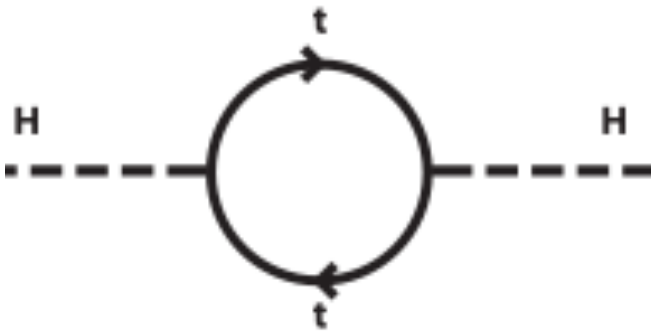
→ anomaly induced spontaneous EWSB

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

Implications



Gauge invariance ➔ only log sensitivity



Relics of conformal symmetry ➔ only log sensitivity

- **With CS there no hierarchy problem, even though it has anomaly**
- **Dimensional transmutation due to log running like in QCD**

  ➔ scalars can condense and set scales like fermions

  ➔ use this in Coleman Weinberg effective potential calculations

  ←→ most attractive channels (MAC) ←→ β-functions

Why the minimalistic SM does not work

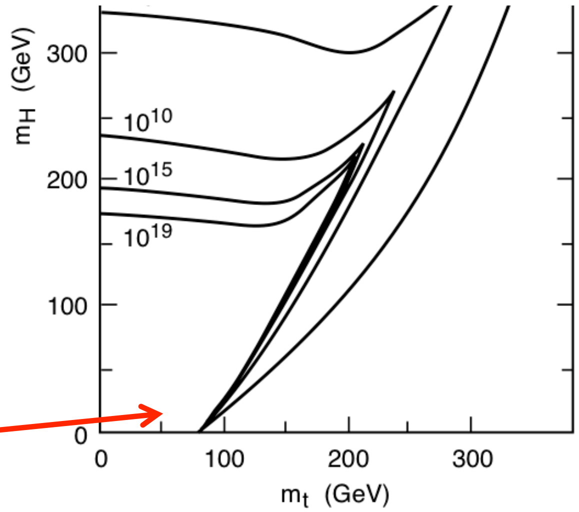
Minimalistic:

SM + choose $\mu = 0$ ←→ CS

Coleman Weinberg: effective potential

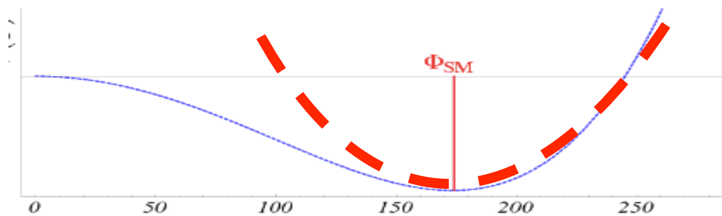
→ CS breaking (dimensional transmutation)

→ 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_{eff} flat around minimum
←→ $m_H \sim$ loop factor $\sim 1/16\pi^2$



AND: We need neutrino masses, dark matter, …

Realizing the Idea via Higgs Portals

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

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

- CS anomalous … → breaking → only $\ln(\Lambda)$

→ implies a TeV-ish condensate for φ to obtain $<\Phi> = 246$ GeV

- Model building possibilities / phenomenological aspects:
  - φ 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 ←→ U(1) mixing
  - avoid Yukawas which couple visible and hidden sector

  → phenomenology safe due to Higgs portal, but there is TeV-ish new physics!

Realizing the Idea: Other Directions

SM + extra singlet: Φ, φ

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 ➔ observable effects:
- Higgs coupling to other scalars (singlet, hidden sector, …)
- dark matter candidates ←→ hidden sectors & Higgs portals
- consequences for neutrino masses

Implications for Neutrino Masses

ML, S. Schmidt and J.Smirnov, arXiv:1405.6204

- 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

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

Yukawa seesaw:

SM + ν_R + singlet

$$\langle\phi\rangle \approx \text{TeV}$$

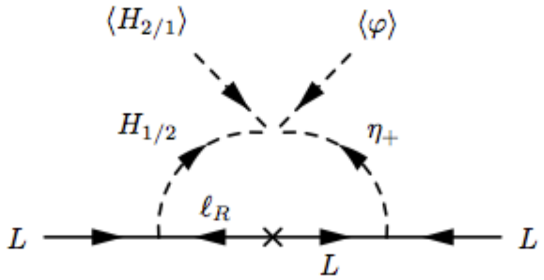
$$\langle H\rangle \approx 1/4\,\text{TeV}$$

➔ **generically expect a TeV seesaw**

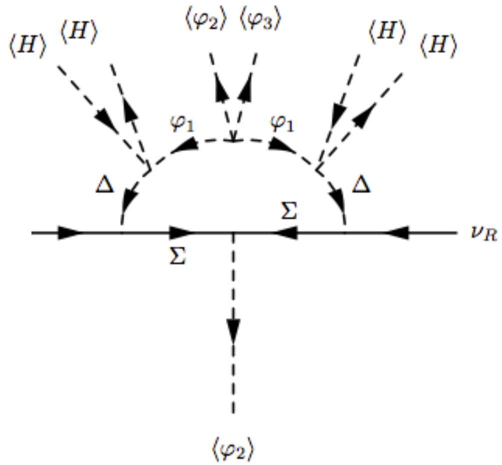
BUT: y_M might be tiny

➔ **wide range of sterile masses** ➔ **includes pseudo-Dirac case**

Radiative masses



Potential: $V = \lambda_L \eta H_1^\dagger H_2 \varphi + h.c. + \ldots$



Potential: $V = \lambda\varphi_1 H^T i\sigma_2 \mathbf{\Delta}^\dagger \tilde{H} + \lambda'\varphi_1^2\varphi_2\varphi_3 + h.c. + \ldots$

$$\mathcal{M} = m_L$$

or

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

➔**pseudo-Dirac case**

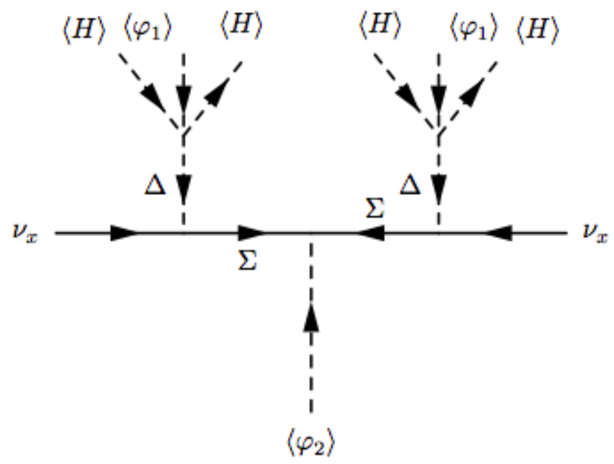
More Examples: Inverse Seesaw

Seesaw & LNV

$$\nu_R \;:\; (1_{SU(2)}, 0_Y, 0_{HS})$$
$$\nu_x \;:\; (1_{SU(2)}, 0_Y, n_{HS})$$

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

$$\epsilon = \frac{1}{2} y_D^\dagger (y_{Rx}^{-1})^* (y_{Rx}^{-1})^T y_D \cdot \frac{\langle H\rangle^2}{\langle\phi\rangle^2}$$
$$\langle\phi\rangle > \langle H\rangle \text{ and } m_\nu \approx \mu\,\epsilon$$



μ is suppressed (LNV) natural scale keV

The punch line:
- **all usual neutrino mass terms can be generated**
- **No explicit masses➔ all via Yukawa couplings➔ different numerical expectations**

Summary

- **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**

- $\lambda(M_{Planck}) = 0$? ←→ **precise value for m_t**
- Embedings 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**