Conformal Extensions of the Standard Model

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Hierarchy Problems

1) why are scales vastly different

2) why do scales remain vastly different under quantum corrections

SM + embedding at Λ

$$\delta M_H^2 = \frac{\Lambda^2}{32\pi^2 V^2}\left(6M_W^2 + 3M_Z^2 + 3M_H^2 - 12M_t^2\right) \quad \sim\Lambda^2 \gg M_H^2$$

SM + Dirac neutrinos: no problem – just like SM

SM + Majorana neutrinos:

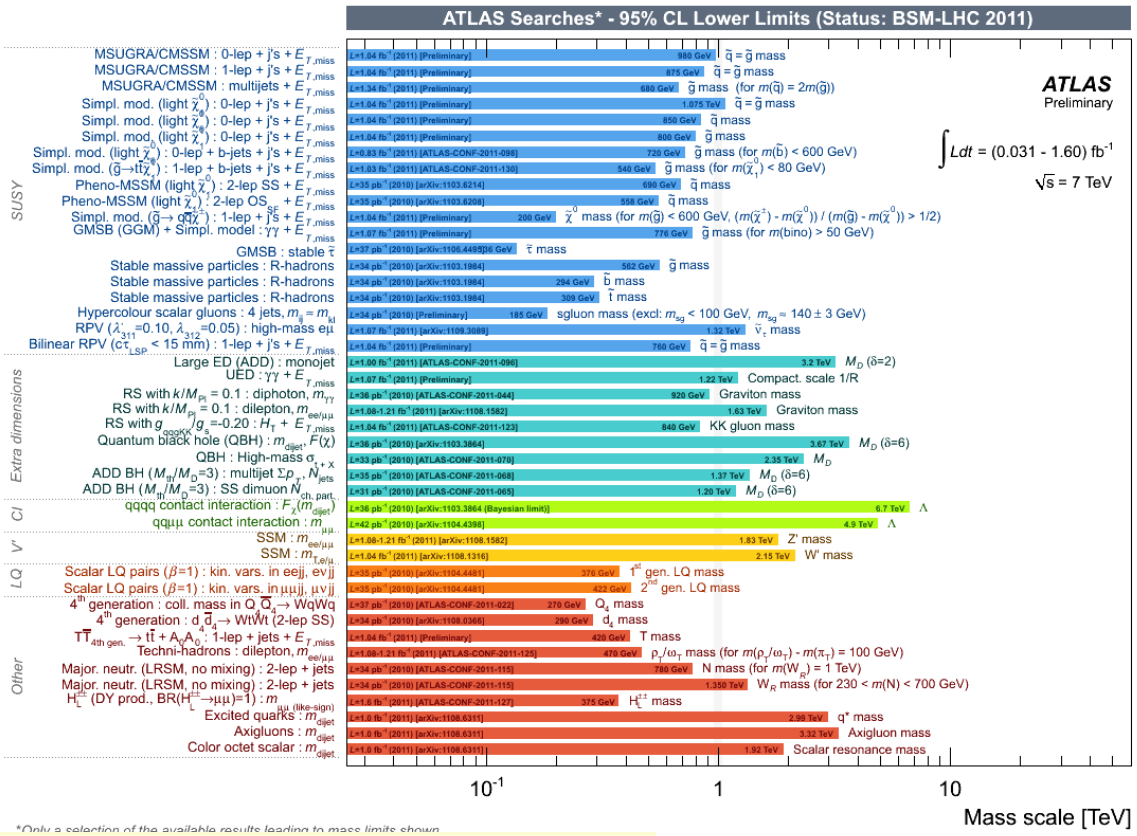
- more than one scale: VEV and the Majorana mass(es) M

➔ **generates a HP problem for large M even if y_ν is tiny**

$$\delta m_H^2 \simeq \frac{y_\nu^2}{16\pi^2} M^2 \qquad y_\nu^2 = M m_\nu / v^2$$

➔ $M \lesssim 10^7 - 10^8\ \mathrm{GeV}$ ⟷ **see-saw, leptogenesis, ...**

The Problem



There should be some new physics at Λ = O(TeV)

BUT: So far nothing!

Nevertheless: Very interesting lessons

→ SM works perfectly

→ triumph (precision) of concepts (QFT, symmetries)

☺ Higgs discovered ←→ SM particle masses

☺ quantum structure of SM

☺ neutrino masses, - DM, - DE … ➔ very exciting, but…

☹ nothing BSM connected to EWSB (so far…)

→ exp. facts require new ideas ➔ bottom-up guided

Look again carefully at the SM as a QFT

- **The SM itself (without embedding) is a 4d QFT like QED**
  - infinities, renormalization ←→ δ∗δ → only differences are calculable
  - SM itself is perfectly OK → many things unexplained…
- **Has (like QED) a triviality problem (Landau poles ←→ infinite λ)**
  - triviality = inconsistency → **requires some scale Λ where the SM is embedded**
  - running $U(1)_Y$ coupling: pole well beyond Planck scale… - like in QED
  - running Higgs / top coupling → **upper bounds on m_H and m_t**
- **Another potential problem is vacuum instability (←→negative λ)**
  - does occur in SM for large top mass > 79 GeV → **lower bounds on m_H**
- **→ important detail: SM has only one single scale v=246 GeV**

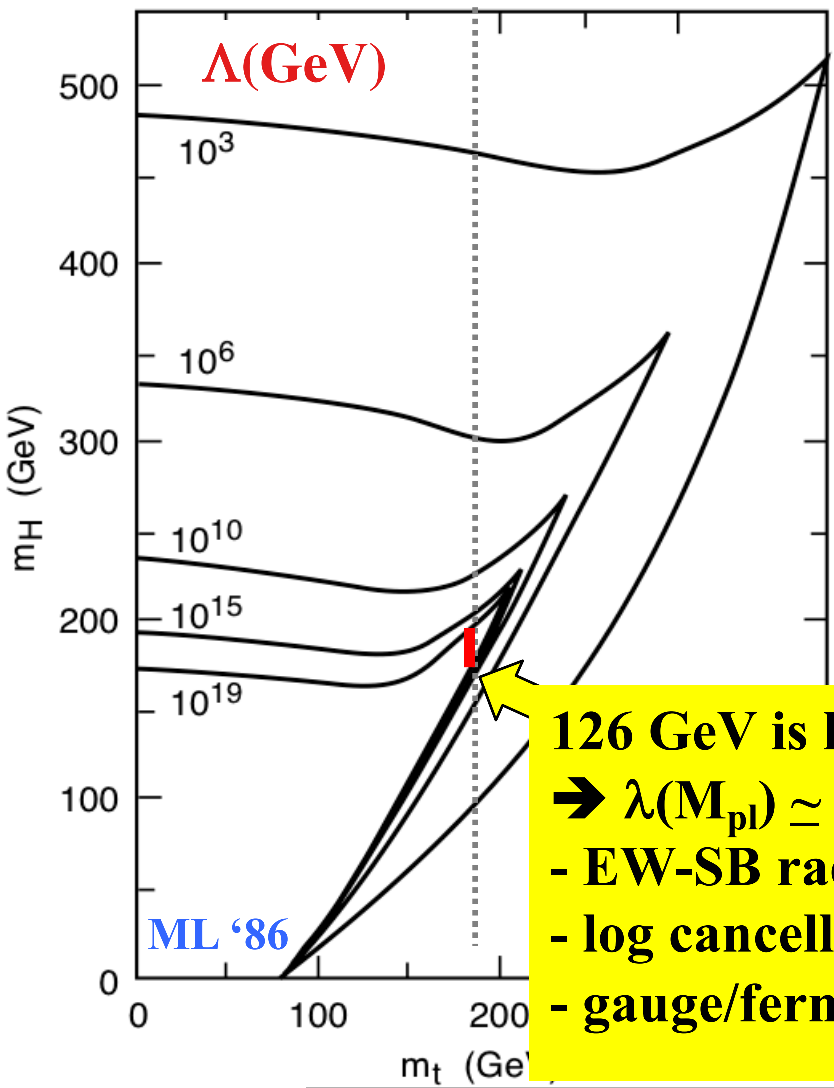
The SM as QFT (without an embedding) works perfectly:

- **a hard cutoff Λ and the sensitivity towards Λ has no meaning**
- **renormalizable, calculable … - just like QED**
- **BUT: an embedding is required ←→ triviality…**

A remarkable Coincidence

➔ SM is a renormalizable QFT like QED w/o hierarchy problem

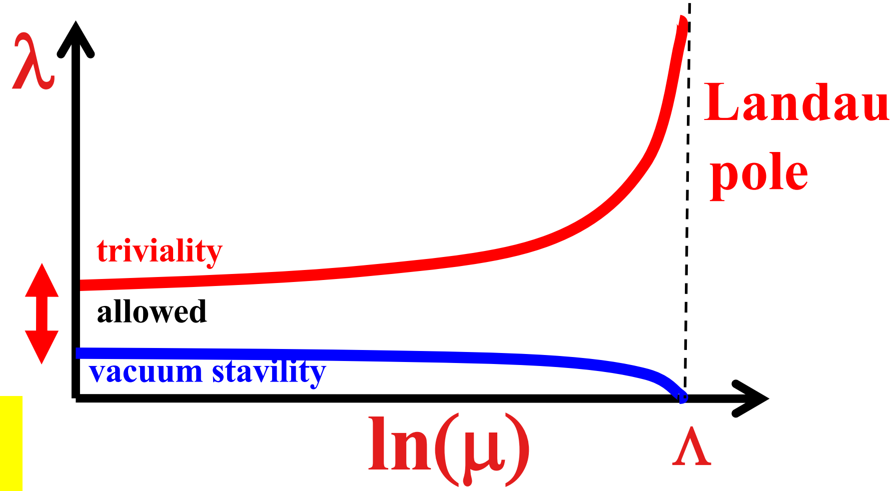
➔ Cutoff "Λ" has no meaning ➔ triviality, vacuum stability



126 GeV is here!
➔ $\lambda(M_{pl}) \simeq 0$
- EW-SB radiative
- log cancellations
- gauge/fermion/scalar

126 GeV < m_H < 174 GeV

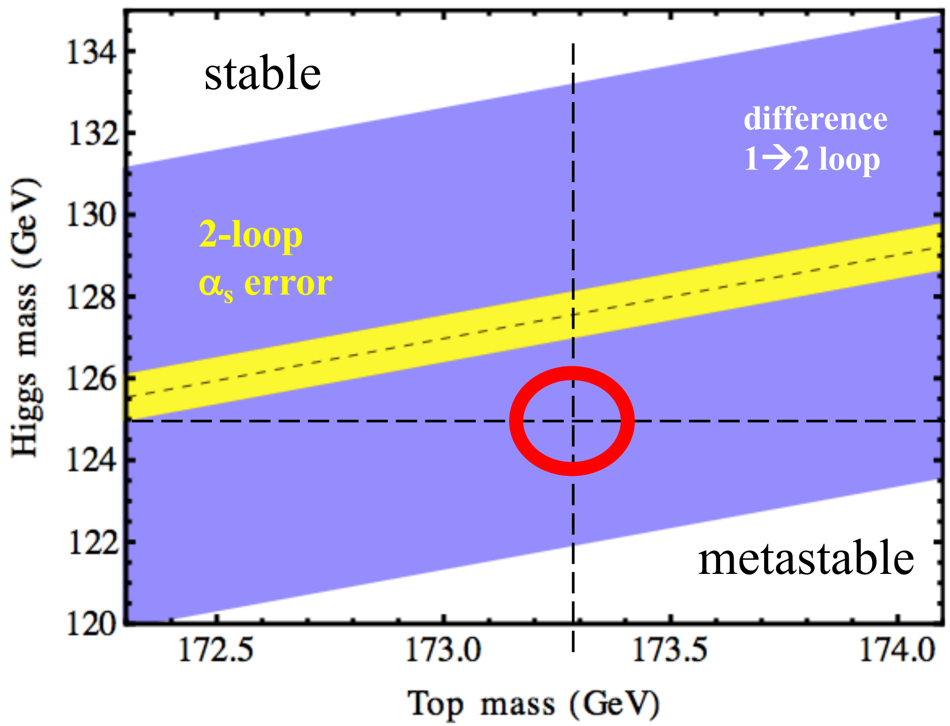
SM does not exist w/o embedding
- U(1) coupling , Higgs self-coupling



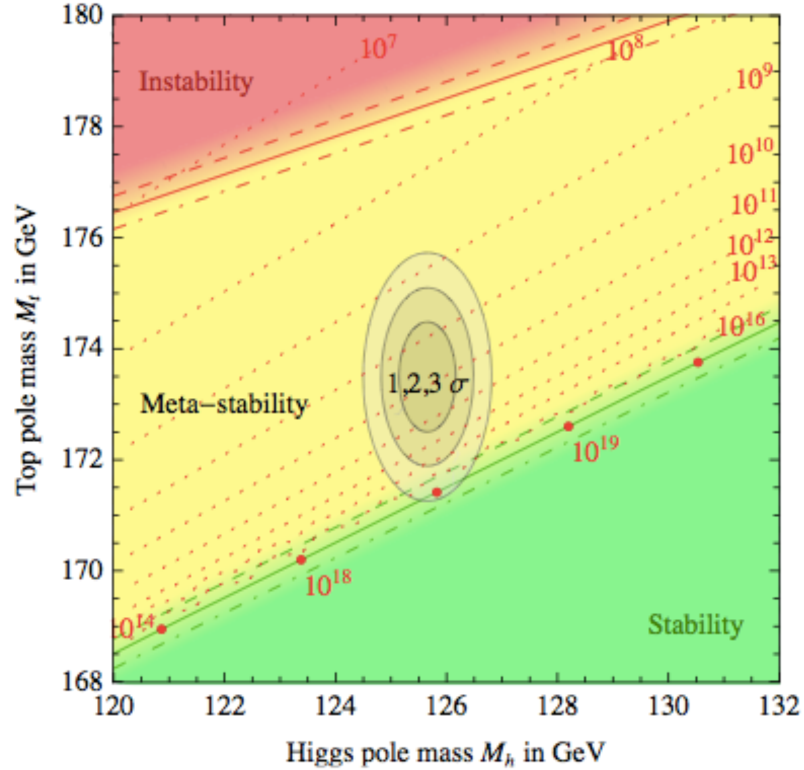
➔ RGE arguments seem to work
➔ but we need some embedding

Is the Higgs Potential at M_{Planck} flat?

Holthausen, ML, Lim
12 Dec 2011



Elias-Miro, Espinosa, Giudice, Isidori, Riotto, Strumia
13 Dec 2011



Experimental values indicate metastability. Is it fully established?

➔ we need to include DM, neutrino masses, …? are all errors (EX+TH) fully included?

➔ be cautious about claiming that metastability is established

➔ An important observation:

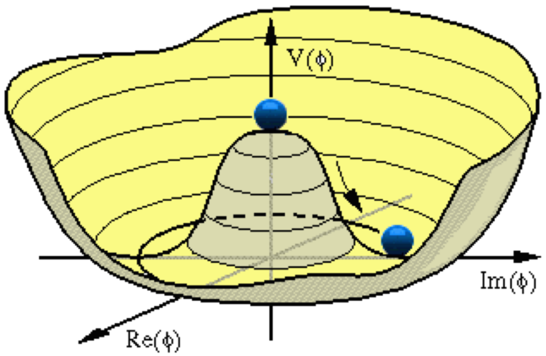
- remarkable relation between weak scale, m_t, couplings and M_{Planck} ←→ precision

- remarkable interplay between gauge, Higgs and top loops (<u>log divergences – not Λ^2</u>)

Is there a Message?

- **$\lambda(M_{Planck}) \simeq 0$? ➔remarkable log cancellations ⇔ CA~ β-fcts.**
  M_{planck}, M_{weak}, gauge, Higgs & Yukawa couplings are unrelated

- **remember: μ is the only single scale of the SM ➔ special role**
  ➔ if in addition $\mu^2 = 0$ ➔ $V(M_{Planck}) \simeq 0$
  ➔ flat Mexican hat (<1%) at the Planck scale!



➔

➔ conformal (or shift) symmetry as solution to the HP

➔ combined conformal & EW symmetry breaking

- conceptual issues
- minimal realizations ⇔ SM seems to know about high scales → bottom-up
⇔ many new d.o.f. (fields, big reps.) ~ UV-instabilities

The Problem: EXPLICIT Scales

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

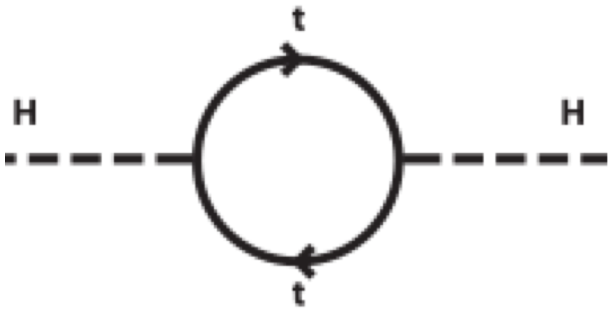
- **Since SM Higgs exists ➔ problem: embedding with a 2^{nd} scalar**
  - gauge extensions: LR, PS, GUTs → must be broken…
  - even for SUSY GUTS → doublet-triplet splitting...
  - also for fashinable Higgs-portal scenarios...

Ways out:

- **no 2^{nd} Higgs** → just the SM → triviality → requires a new scale...
- **symmetry: SUSY, ...** **➔ conformal symmetry = no explicit scales!**

  ➔ all scales emerge from no-scale theories

Conformal Symmetry and the Hierarchy Problem



Theories without any scale in $\mathcal{L}$ ➔ CS

<u>Non-linear realizations of CS:</u>

➔ symmetry is classically preserved

➔ naïve power counting invalid

➔ classically: no Λ^2 , $\log(\Lambda)$ divergences

Conformal Anomaly (CA = breaking by loops)

anomaly ~ trace of energy momentum tensor

←→ β-functions ←→ $\log(\Lambda)$

➔ CA does not fully restore naive power counting: $\log(\Lambda)$, but no Λ^2

➔ avoids hierarchy problem

➔ dimensional transmutation of conformal theories by log running of couplings like in chiral QCD

Conformal Symmetry and SM Extensions

Main idea:

- **Do not introduce any fundamental (explicit) scales**
  ➔ theories with conformal or shift symmetry

- **Dynamical breaking of CS ➔ Coleman Weinberg V_{eff}**
  ➔ all scale(s) by dimensional transmutation
  ➔ non-linear realization of CS:
  - naïve power counting ($\sim\Lambda^2$) misleading
  - similar to gauge symmetry and vector boson masses

- **An UV complete theory should have UV fixedpoints...**

The SM parameters may point in that direction!

Generic Questions

- **Isn't the Planck-scale spoiling things (explicit scale, cut-off, …)?**
  ➔ non-linear realization of conformal symmetry…
    ➔ conformal gravity…
  ➔ protected by conformal symmetry up to conformal anomaly
  ➔ generate M_{Planck} by dimensional transmutation
  ➔ for now assumption: M_{Planck} somehow generated in a conformal setting

- **Are M_{planck} and M_{weak} connected?**
  ➔ 1st part: assumed to be independently generated scales
  ➔ later more…

- **UV: ultimate solution should be asymptotically safe ➔ UV-FPs…**

- **Significant conceptual change for scale setting:**
  Until now a rollover of scale generation: SM➔ BSM➔ GUT➔ gravit @M_{Planck}
  Requires a new concept @M_{planck} ➔ strings, …
  CS: Absolute scales meaningless, relative scales are calculable quantum effects
  Fully consistent realization ➔ now new concept for scale setting required

Realizing the Idea

Why the minimalistic SM does not work

Minimalistic version: → "SM-"

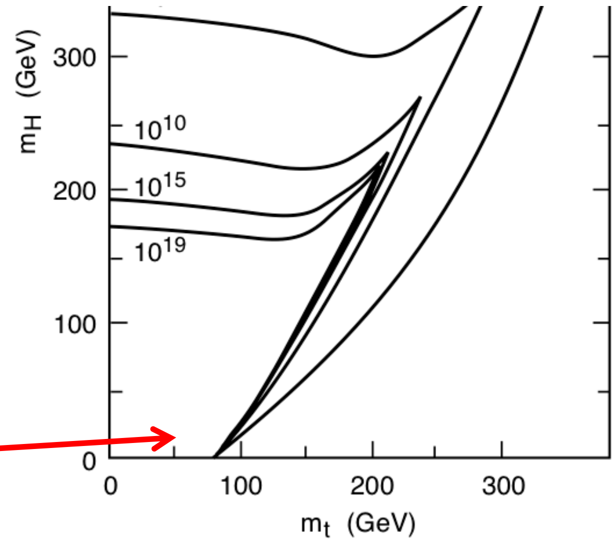
SM + with $\mu = 0$ ←→ CS

Coleman Weinberg: effective potential

→ CS breaking (dimensional transmutation)

→ induces for $m_t < 79$ GeV

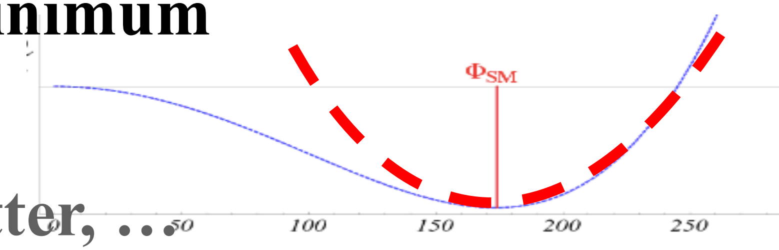
a Higgs mass $m_H = 8.9$ GeV



- Success: no-scale SM → SM but: Higgs and top too do not fit

- DSB for weak coupling ←→ CS= phase boundary
  → scale set by running couplings → gap eqn: hierarchical!

- 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 scalar portal $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$ 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 $\ln(\Lambda)$

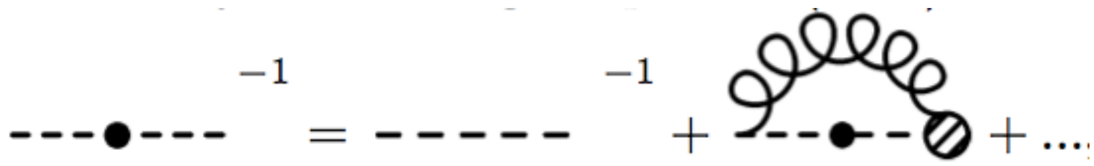
→ implies a TeV-ish condensate for φ to obtain $<\Phi> = 246$ GeV

- 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!

Rather minimalistic: SM + QCD Scalar S

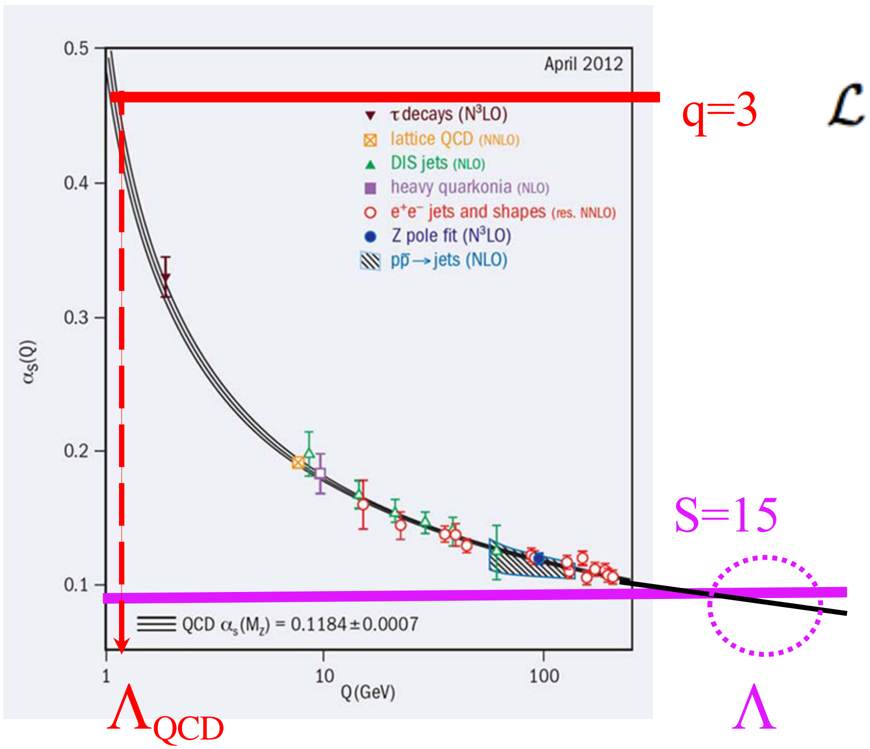
J. Kubo, K.S. Lim, ML New scalar representation S → QCD gap equation:



→ $C_2(S)\alpha(\Lambda) \gtrsim X$

$C_2(\Lambda)$ increases with larger representations

↔ condensation for smaller values of running α



$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + (D_{\mu,ij}S_j)^\dagger (D^\mu_{ik} S_k) + \lambda_{HS} H^\dagger H S^\dagger S - \lambda_{1_i} \left[\bar{\boldsymbol{S}} \times \boldsymbol{S} \times \bar{\boldsymbol{S}} \times \boldsymbol{S}\right]_{1_i}$$

$$\lambda_{HS}\langle S^\dagger S\rangle H^\dagger H \to \lambda_{HS}\Lambda^2 H^\dagger H$$

$$m_h^2 = 2\lambda_{HS}\Lambda^2 \qquad \frac{\lambda_h}{\lambda_{HS}} = \frac{\Lambda^2}{v^2}$$

SM ⊗ hidden $SU(3)_H$ Gauge Sector

Holthausen, Kubo, Lim, ML

- hidden $SU(3)_H$:

$$\mathcal{L}_H = -\frac{1}{2}\mathrm{Tr}\ F^2 + \mathrm{Tr}\ \bar{\psi}(i\gamma^\mu D_\mu - yS)\psi$$

gauge fields ; $\psi = 3_H$ with $SU(3)_F$; S = real singlet scalar

- SM coupled by S via a Higgs portal:

$$V_{SM+S} = \lambda_H (H^\dagger H)^2 + \frac{1}{4}\lambda_S S^4 - \frac{1}{2}\lambda_{HS} S^2 (H^\dagger H)$$

- no scalar mass terms
- use similarity to QCD, use NJL approximation, …
- χ–ral symmetry breaking in hidden sector: $SU(3)_L x SU(3)_R \rightarrow SU(3)_V$ ➔ **generation of TeV scale**

➔ **transferred into the SM sector through the singlet S**

➔ **dark pions are PGBs: naturally stable ➔ DM**

Realizing the Idea: Specific Models

SM + extra singlet or doublet: Φ, φ
Nicolai, Meissner Farzinnia, He, Ren, Foot, Kobakhidze, Volkas, Hill, …

Minimal B-L extension if SM: $SU(3)c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
Iso, Okada, Orikasa

Minimal LR-model: $SU(3)c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ Holthausen, ML, Schmidt

SM $\otimes$ $SU(N)_H$ **with new N-plet in a hidden sector**
Ko, Carone, Ramos, Holthausen, Kubo, Lim, ML, Hambye, Strumia , …

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

SM $\otimes$ $[SU(2)_X \otimes U(1)_X]$
Altmannshofer, Bardeen, Bauer, Carena, Lykken

…

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

Conformal Symmetry & Neutrino Masses

ML, S. Schmidt and J.Smirnov

- 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) + induced EW scale

Important consequence for fermion mass terms:
➔ spectrum of Yukawa couplings ⊗ TeV or EW scale
➔ interesting consequences ←→ Majorana mass terms are no longer expected at the generic L-breaking scale → anywhere

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

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

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

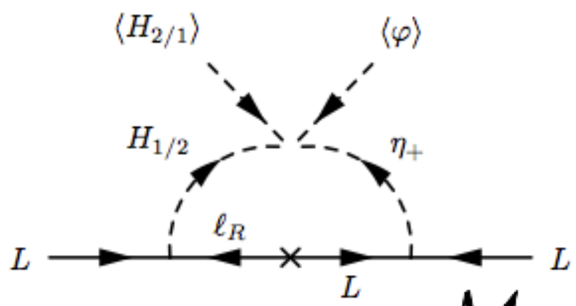
➔ generically expect a TeV seesaw

BUT: y_M can be tiny

➔ wide range of sterile masses ➔ including pseudo-Dirac case

➔ suppressed $0\nu\beta\beta$

Radiative masses



$$\mathcal{M} = m_L \quad \text{or}$$

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

➔pseudo-Dirac case

The punch line:

all usual neutrino mass terms can be generated

→ suitable scalars required

→ no explicit masses:
all via Yukawa couplings

→ different numerical expectations ←→ could easily explain keV masses

Phenomenological Impact

Conventional see-saw:

$$\begin{pmatrix} 0 & \mathbf{m_D} \\ \mathbf{m_D} & \mathbf{M_R} \end{pmatrix}$$

➔ **ultra heavy** $\simeq M_R$ ➔ **ultra light** $\simeq \frac{m_D^2}{M_R} << m_D$

- **Explains nicely known active neutrino masses**
- **But what if intermediate sterile neutrino states were found?**
  - keV sterile ν's as warm dark matter
  - evidences for eV sterile
  - TeV-ish sterile neutrinos and improved EW precision fits (e.g. 1302.1872)

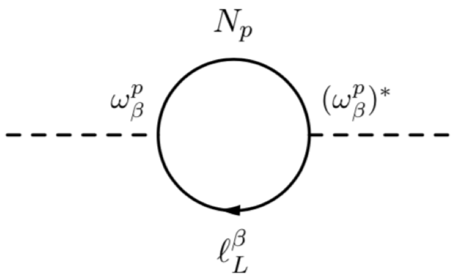
➔ **hard to explain in conventional see-saw and variants**
➔ **easy in conformal neutrino scenarios ⟷ $M_R = g_Y$ * <VEV>**

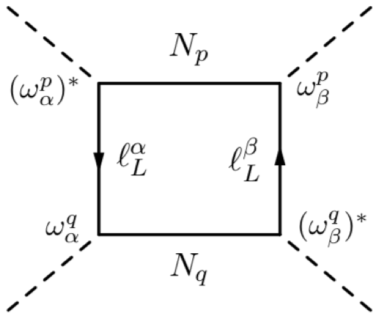
The Neutrino Option

An interesting possibility: Connection between EWSB and neutrinos

Neutrino option: Brivio

➔ Veff from neutrino loops





Conformal Realization of the Neutrino Option: Brdar, Emonds, Helmboldt, ML

➔ conformal symmetry + V_{eff} from neutrino loops (not from Higgs portal)

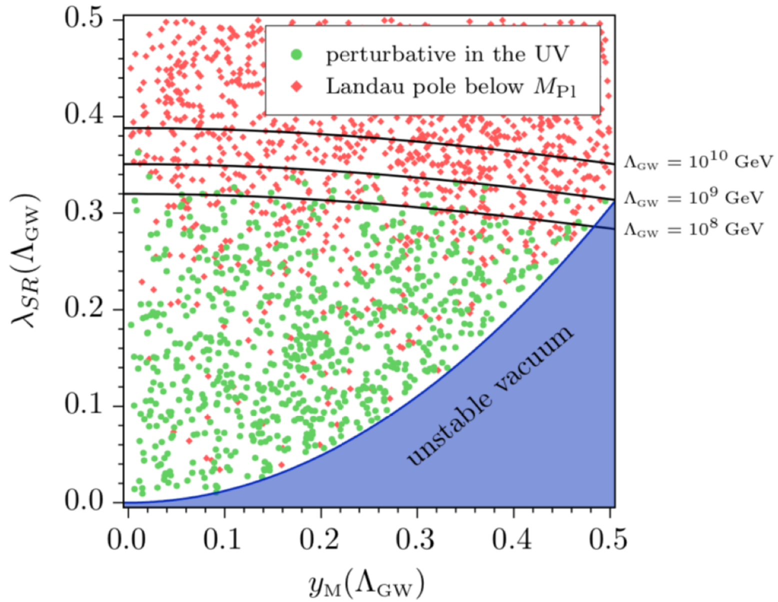
SM particle content

3x NR

2x scalar SM singlets: S, R

$$\mathcal{L} \supseteq \tfrac{1}{2}\partial_\mu S \partial^\mu S + \tfrac{1}{2}\partial_\mu R \partial^\mu R + \mathrm{i}\bar{N}_R \not{\partial} N_R - V(H,S,R) - \left(\tfrac{1}{2} y_{\mathrm{M}} S \bar{N}_R N_R^c + y_\nu \bar{L}\tilde{H} N_R + \mathrm{h.c.}\right)$$

➔ consistent UV-complete realization of the idea



Conformal Symmetry & Dark Matter

Different natural and viable options:

1) eV, **keV = DM**, TeV, … sterile neutrino mass easily possible ←→ not so easy in standard see-saw's

2) New particles which are fundamental or composite DM candidates:
   - hidden sector pseudo-Goldstone-bosons
   - stable color neutral bound states from new QCD representations

→ some look like WIMPs
→ others are extremely weakly coupled (via Higgs portal)
→ or even coupled to QCD (threshold suppressed…)

Including the Planck Scale

The Planck Scale from CS Breaking

Conformal Gravity (CG):

- more symmetry ➔ CG claimed to be power counting renormalizable
- CG may have a ghost... ➔ see later

Idea: Generate M_{Planck} in **conformal gravity ⊗ SU(N)**

➔ gauge assisted condensate via SU(N) field

➔ M_{Planck} becomes an effective scale

Kubo, ML, Schmitz, Yamada similar ideas: **Donoghue, Menezes, ...**

$$\boxed{\begin{aligned} S_C = \int d^4x \sqrt{-g} \Big[-\hat{\beta}\, S^\dagger S\, R + \hat{\gamma}\, R^2 - \frac{1}{2} \mathrm{Tr}\, F^2 + \\ + g^{\mu\nu} (D_\mu S)^\dagger D_\nu S - \hat{\lambda} (S^\dagger S)^2 + a\, R_{\mu\nu} R^{\mu\nu} + b\, R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta} \end{aligned}}$$

R = Ricci curvature scalar, $R_{\mu\nu}$ = Ricci tensor, $R_{\mu\nu\alpha\beta}$ = Riemann tensor

F = field-strength tensor of the SU(N_c) gauge theory ; S = complex scalar in fund. rep. ➔ N_c

➔ most general diffeomorphism invariance, gauge invariance, and global scale invariance

Condensation in SU(N_c) gauge sector
➔ **dimensional transmutation:** $\langle S^+S \rangle$ ➔ effective Planck mass

$$M_{planck} = 2\,\beta\, f_0 = \frac{N_c \beta}{16\pi^2}(2\,\lambda\, f_0)\left(1 + 2\,\ln\frac{2\,\lambda\, f_0}{\Lambda^2}\right) \quad \text{with} \quad f_0 = \langle S^+S \rangle$$

➔ Effectively normal GR

What about the ghost problem of CG?
➔ go into broken phase after condensation:
- normal gravity
+ hidden CS – nonlinearly realized + CA = β-functions
- renormalizability should be preserved
- ghost: should be absent like in normal GR ←→ M_{Planck} is effective

➔ May lead to viable QFT with dynamical CS breaking

Dilaton-Scalaron Inflation

Effective Jordan-frame Lagrangian:

$$\frac{\mathcal{L}^J_{\rm eff}}{\sqrt{-g_J}} = -\frac{1}{2}\,B\,(\chi)\,M_{\rm Pl}^2\,R_J + G\,(\chi)\,R_J^2 + \frac{1}{2}\,g_J^{\mu\nu}\,\partial_\mu\chi\,\partial_\nu\chi - U\,(\chi)$$ ➔ auxiliary field Ψ ➔

$$\frac{\mathcal{L}^J_{\rm eff}}{\sqrt{-g_J}} = -\left[\frac{1}{2}\,B\,(\chi)\,M_{\rm Pl}^2 - 2\,G\,(\chi)\,\psi\right]R_J + \frac{1}{2}\,g_J^{\mu\nu}\,\partial_\mu\chi\,\partial_\nu\chi - U\,(\chi) - G\,(\chi)\,\psi^2$$

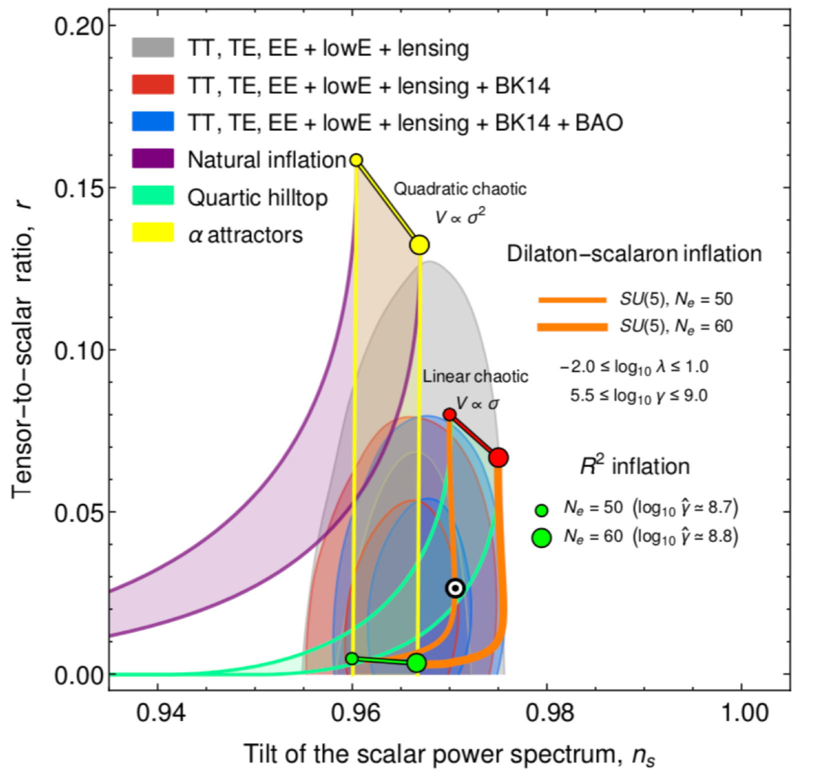
Weyl rescaling: $g_{\mu\nu} = \Omega^2\,g^J_{\mu\nu}$ $\quad \Omega^2 = e^{\Phi(\phi)}\,,\quad \Phi\,(\phi) = \dfrac{\sqrt{2}\,\phi}{\sqrt{3}\,M_{\rm Pl}}$

Einstein-frame scalar potential:

$$V\,(\chi,\phi) = e^{-2\,\Phi(\phi)}\left[U\,(\chi) + \frac{M_{\rm Pl}^4}{16\,G\,(\chi)}\left(B\,(\chi) - e^{\Phi(\phi)}\right)^2\right]$$

➔ Slow role inflation

➔ fits data very well!



Scale Dependence: EW vs. Planck Scale

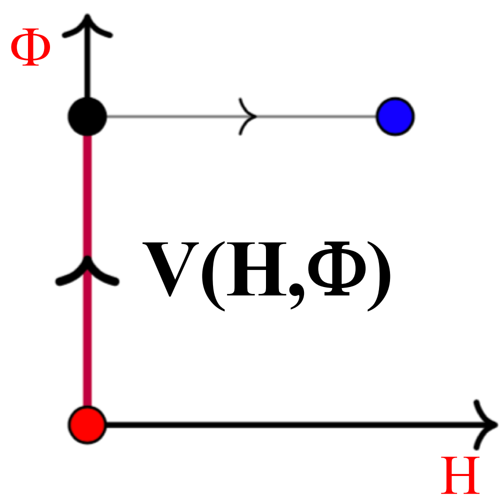
- **Assume:**
  - SM scale generated by some TeV-ish conformal extension
  - Planck scale generation by conformal gravity ⊗ gauge sector

➔ Do we understand the hierarchy between EW and Planck scale?

$$\mathbf{V} = \lambda_1(\mathbf{H}^\dagger\mathbf{H})^2 + \underbrace{\lambda_2(\mathbf{H}^\dagger\mathbf{H})(\mathbf{\Phi}^\dagger\mathbf{\Phi})}_{\text{portal coupling}} + \lambda_3(\mathbf{\Phi}^\dagger\mathbf{\Phi})^2$$

➔ Does λ_2 portal lead to the usual hierarchy problem? ➔ ideas

- sequential breaking by RG running ➔ \`CW tumbling‘
  $m^2 = 0$ is boundary broken/unbroken
  ➔ SSB for tiny attractive force
  ➔ if $<\Phi^+\Phi>$ condenses first (stronger coupling)
  ➔ portal can induce $m^2 > 0$ for H ➔shifts SSB boundary
  ➔ 2nd SSB by log running of couplings



Summary

- **SM works (so far) perfectly**
  - be a bit more patient: new physics may be around the corner…
  - or maybe it is time to re-consider some things…

- **The old hierarchy problem(s)…? No new physics observed**
  $\lambda(M_{Planck}) = 0$? ⇔ **precise value for m_t ➔ is there a message?**

  ➔ SM embedings into QFTs with conformal symmetry
  → combined conformal & electro-weak symmetry breaking
  → implications for BSM phenomenology
  → implications for Higgs couplings, neutrino physics, dark matter, …

  ➔ testable consequences: @LHC, dark matter, neutrinos

- **Planck scale generation by gauge induced breaking of conformal GR**
  → very nice phenomenology: inflation…
  → consistent quantum gravity: renormalizablity?, ghost?
  ←→ normal GR from a theory with more symmetry
  → stabilizing large scale hierarchies…
  → trans-Planck: just be a different phase - no new concept required