Conformal Extensions of the Standard Model

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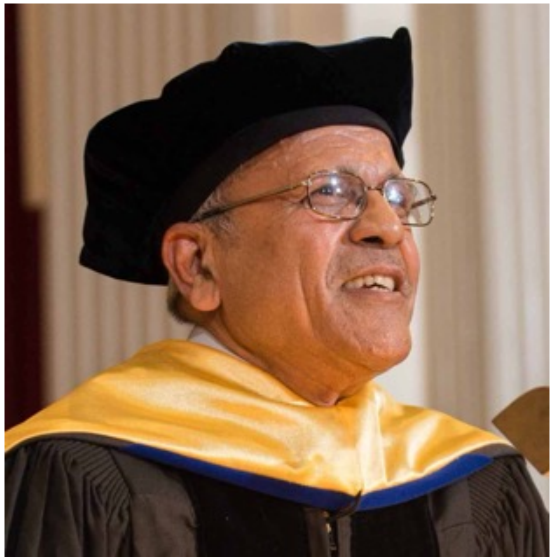


Rabi-Fest, University of Maryland, Oct. 20-22, 2022 (virtual)

Rabi and I:

- admired his work as a late-comer
- we met at different occasions
- joint interests ←→ Rabi's wide interests!

Alexander von Humboldt
Stiftung/Foundation

Humboldt Research Award

- internationally recognized researchers
- all countries (excluding Germany)
- **research stay of up to 12 months in Germany**

➔ 11/2004 proposal ➔ awarded in 2005
➔ first visit at TUM in Munich: 2005
➔ 2006, 2007 TUM ...
➔ problem: ... I had meanwhile moved to MPI in Heidelberg

Later @Heidelberg:
➔ 2009

➔ 2017 at MPIK ➔

ML →

- 1983-present
  SENIOR, Maryland U.
- 1974-1982
  SENIOR, City Coll., N.Y.
- 1971-1974
  POSTDOC, Maryland U.
- 1969-1971
  POSTDOC, SUNY, Stony Brook
- 1966-1969
  PHD, Rochester U.
- 1964-1966
  UNDERGRADUATE, Delhi U.
- 1960-1964
  UNDERGRADUATE, Utkal U.

Rabi’s wishes:

Say “yes” to celebrating,
to big plans,
to everything that matters to you.

There’s no better time
than now!

➔ planned to attend in-person and celebrate with all the Rabi-Fest...

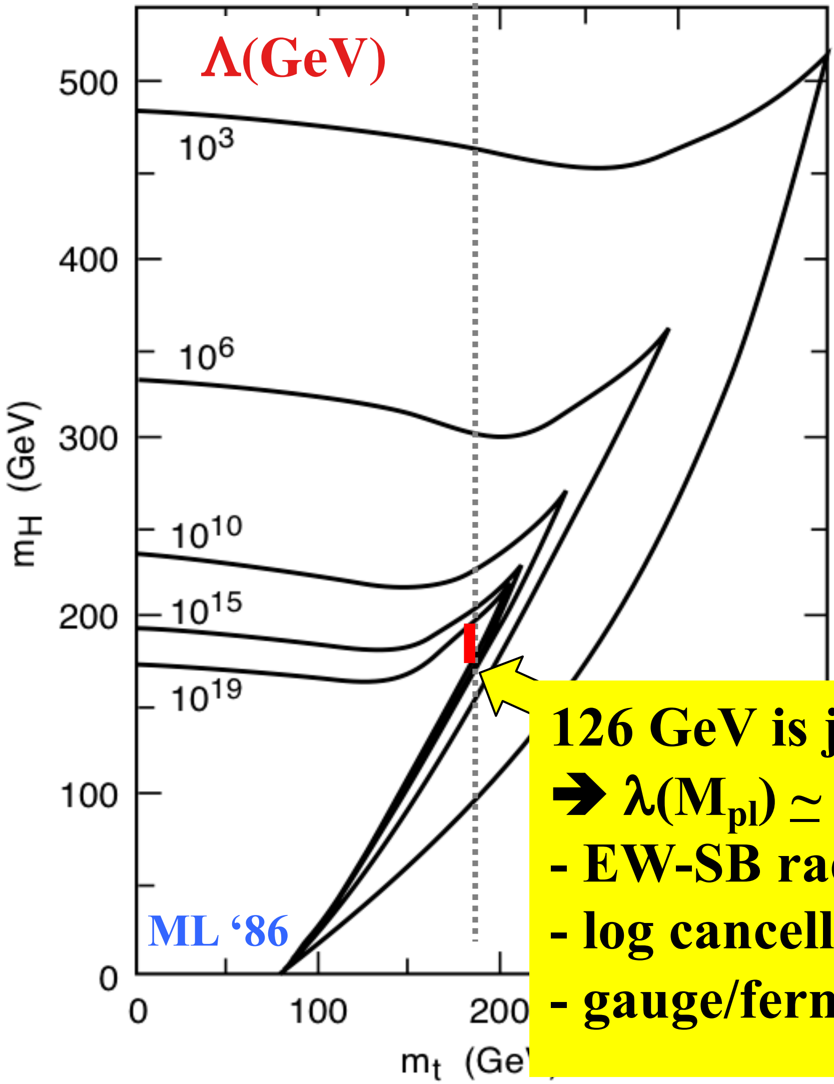
...but unfortunately grounded in the last moment by covid

Problem: What to talk about that is not covered by the all the former collaborators?
Solution: Something Rabi did *NOT* work on!
experimental: ... XENON, CONUS, ... ➔theory: conformal symmetry, but...

Back to the basics: A remarkable coincidence

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

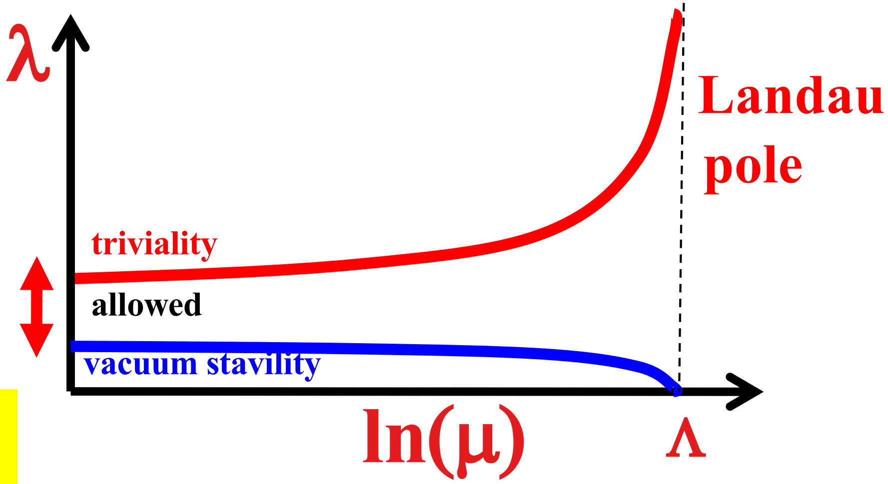
➔ **Cutoff "Λ" has no meaning ➔ triviality, vacuum stability**



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

126 GeV < m_H < 174 GeV

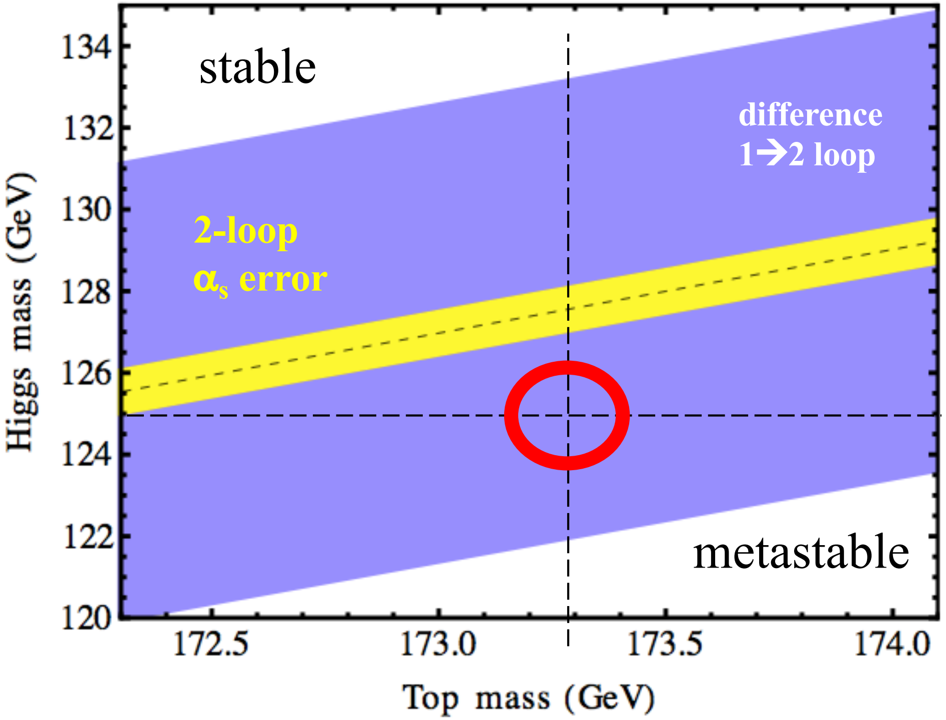
SM does not exist w/o embedding
- U(1) coupling , Higgs self-coupling



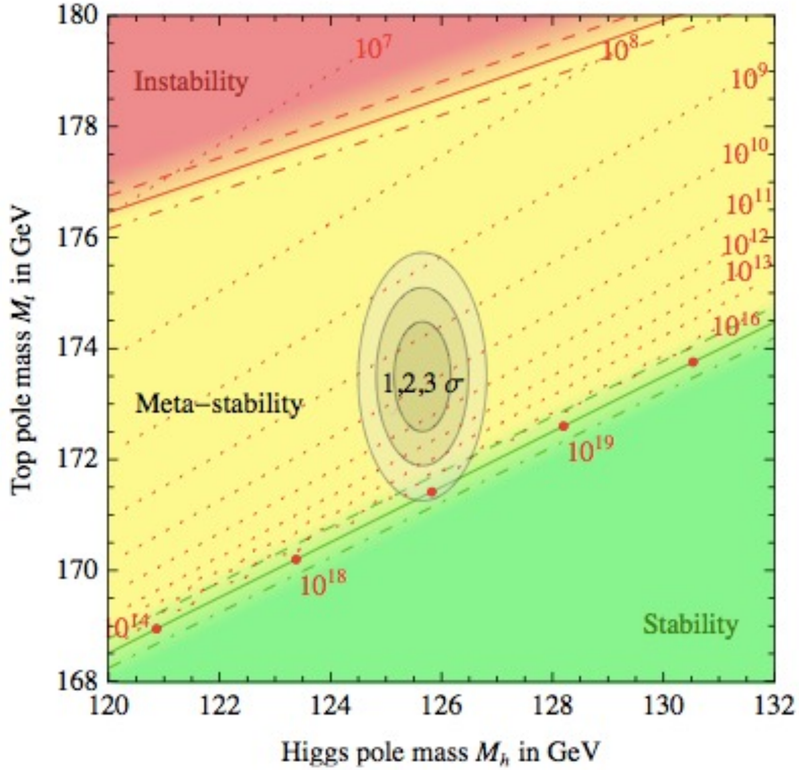
➔ **RGE arguments seem to work**
➔ **but we need some embedding**

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, but,

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

➔ **be cautious about claiming that metastability is established**

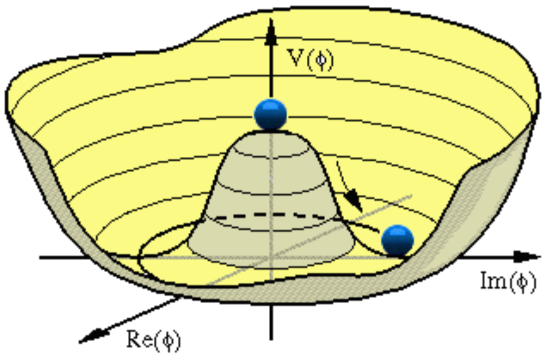
➔ **Important observation:**

- **remarkable relation between weak scale, m_t, couplings and M_{Planck} ←→ precision**
- **interplay between gauge, Higgs and top loops: <u>log divergences – not quadartic div.</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

Hierarchy Problems

1) why are scales vastly different

2) why do scales remain vastly different under quantum corrections

SM + embedding at Λ

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

SM + Dirac neutrino masses: 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**

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

➔ $$M \lesssim 10^7 - 10^8 \text{ GeV}$$

↔ **see-saw, leptogenesis, ...**

➔ there should be some new symmetry (SUSY) at Λ = O(TeV) to solve the hierarchy problem

➔ new particles @ O(TeV)

BUT: So far nothing seen!?

- SUSY at higher scales
- other options? ➔ conformal symmetry

Nevertheless: Very interesting lessons

➔ SM works perfectly

➔ triumph (precision) of concepts (QFT, SM symmetries)

☺ Higgs discovered ←→ SM particle masses

☺ quantum structure of SM

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

➔ requires BSM

The Problem: EXPLICIT Scales

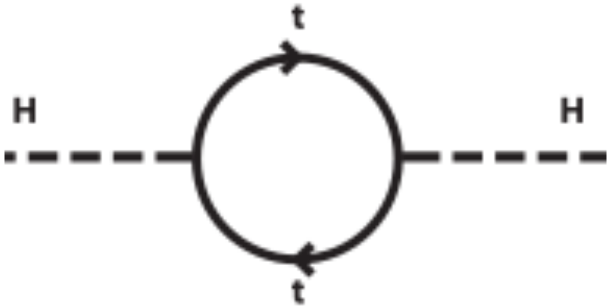
- **Renormalizable QFT with two scalars φ , Φ with masses m, M and a hierarchy m << M**
- **These scalars must interact since $\varphi^+\varphi$ and $\Phi^+\Phi$ are singlets**
  ➔ $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$ (= portal) in addition to φ^4 and Φ^4
- **Quantum corrections ~M^2 drives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

- **Since SM Higgs exists ➔ problem: embedding with a 2nd 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 Higgs ...
- symmetry: SUSY, ... **➔** conformal symmetry = no explicit scales!

Theories without any explicit scale!



<u>Observed scales ←→</u>

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

→ naïve power counting invalid

→ no Λ^2 divergence

Obstacle: Conformal Anomaly = breaking of CS by loops

→ requirement for particle content which cancels CA in UV

→ anomaly ~ trace of energy momentum tensor

←→ β-functions ←→ log(Λ) → UV fixed points

→ a path to avoid hierarchy problems

→ 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...

Bottom-up realizations

Why the minimalistic SM does not work

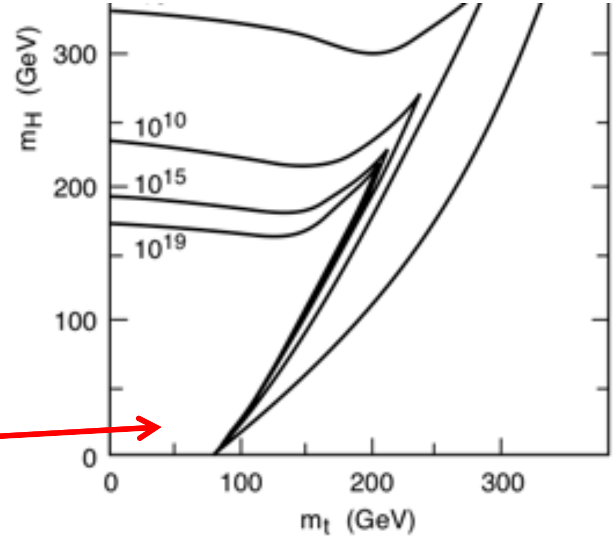
Minimalistic version: → "SM-"

SM + with μ= 0 ←→ CS

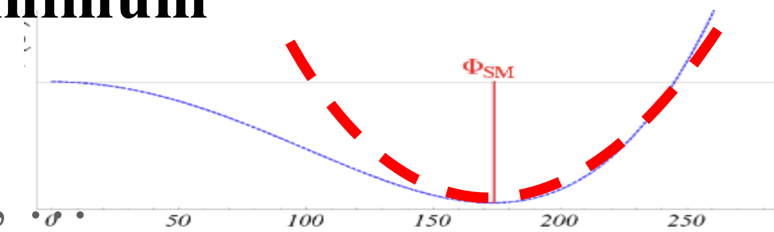
Coleman Weinberg: effective potential

→ CS breaking (dimensional transmutation)

→ induces for $m_t < 79$ GeV
a Higgs mass $m_H = 8.9$ GeV



- **Success: no-scale SM → broken SM but: Higgs and top do not fit**
- **DSB for weak coupling ←→ CS= phase boundary**
  → scale set by log-running couplings ←→ gap eqn: hierarchical!
- **Reason for $m_H << v$: V_{eff} flat around minimum**
  ←→ m_H ~ loop factor ~ $1/16\pi^2$



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

- no CA… → breaking only $\ln(\Lambda)$

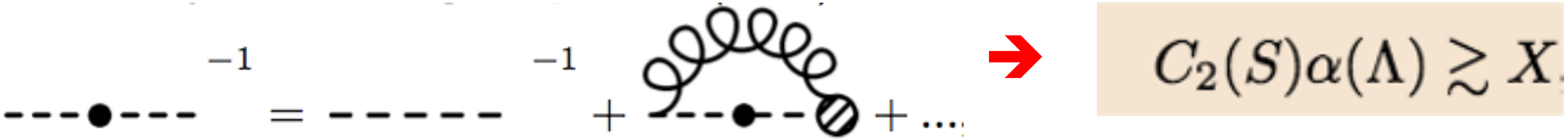
→ implies a TeV-ish condensate for φ to obtain $<\Phi> = 246$ GeV

- <u>Many model building possibilities / phenomenological aspects:</u>
  - 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 →suppressed TeV-ish BSM physics!

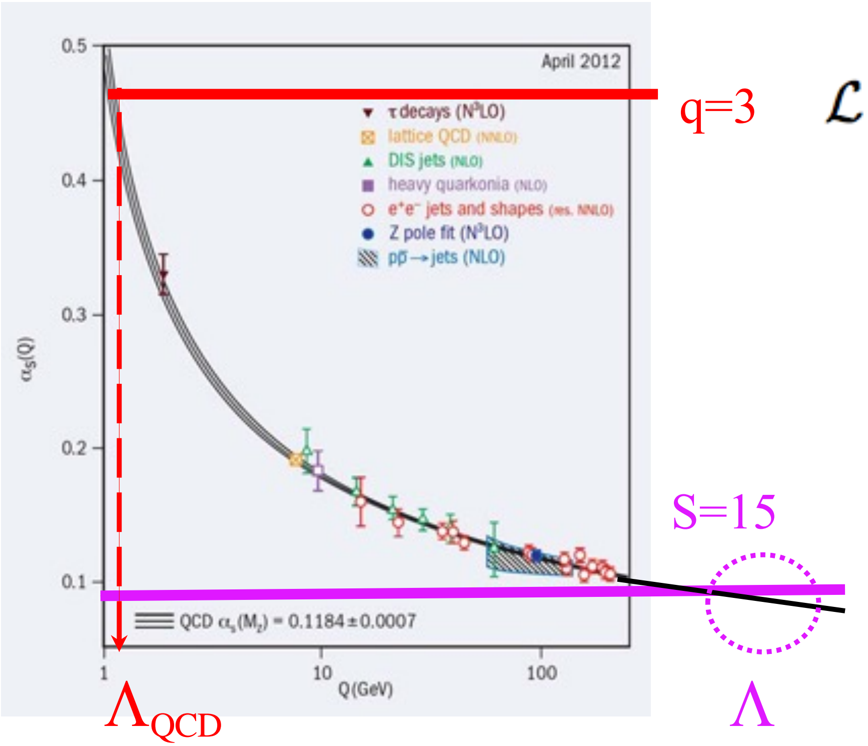
Rather minimalistic: SM + QCD Scalar S

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



$C_2(\Lambda)$ increases with larger representations

←→ condensation for smaller values of running α



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

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

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

SM ⊗ hidden $SU(3)_H$ Gauge Sector

Holthausen, Kubo, Lim, ML

- hidden $SU(3)_H$:

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

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

- SM coupled by S via a Higgs portal:

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

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

➔ transferred into the SM sector through the singlet S

➔ dark pions are PGBs: naturally stable ➔ DM

Realizing the Idea: Many more 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 ⊗ $SU(N)_H$ 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 ⊗ $[SU(2)_X \otimes U(1)_X]$
Altmannshofer, Bardeen, Bauer, Carena, Lykken

… more ...

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 $0\nu\beta\beta$

The punch line:

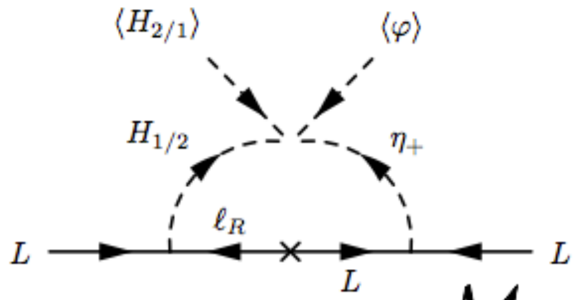
all usual neutrino mass terms can be generated

→ suitable scalars required

→ no explicit masses:
all via Yukawa couplings

→ different numerical expectations ←→ could easily explain keV masses

Radiative masses



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

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

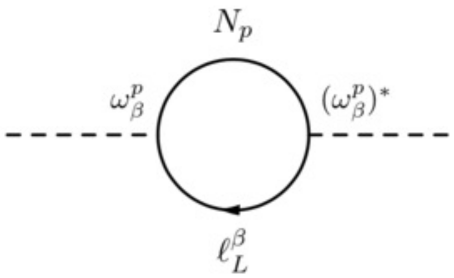
➔ pseudo-Dirac case

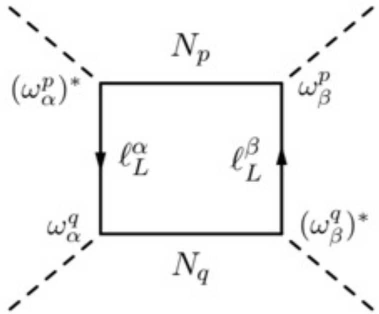
The Neutrino Option

Interesting possibility: Connection between EWSB and neutrinos ←→ ν-hierarchy problem

Neutrino option: Brivio

➔ V_{eff} from neutrino loops





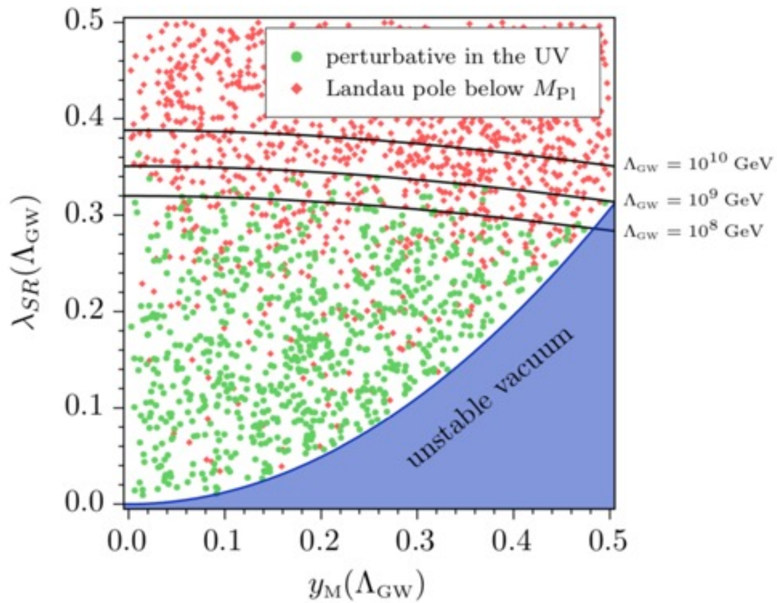
Conformal Realization of the Neutrino Option: Brdar, Emonds, Helmboldt, ML

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

SM particle content
3x NR
2x scalar SM singlets: S, R

$$\mathcal{L} \supseteq \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2}\partial_\mu R \partial^\mu R + \mathrm{i}\bar{N}_R \partial\!\!\!/ N_R - V(H,S,R) - \left(\frac{1}{2}y_{\mathrm{M}} S \bar{N}_R N_R^c + y_\nu \bar{L}\tilde{H} N_R + \mathrm{h.c.}\right)$$

➔ 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} from **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, ...**

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

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 gravity with a dynamically generated M_{Planck}

What about the ghost problem of CG?

...new ideas: J. Kubo and J. Kuntz

Dilaton-Scalaron Inflation

Effective Jordan-frame Lagrangian:

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

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

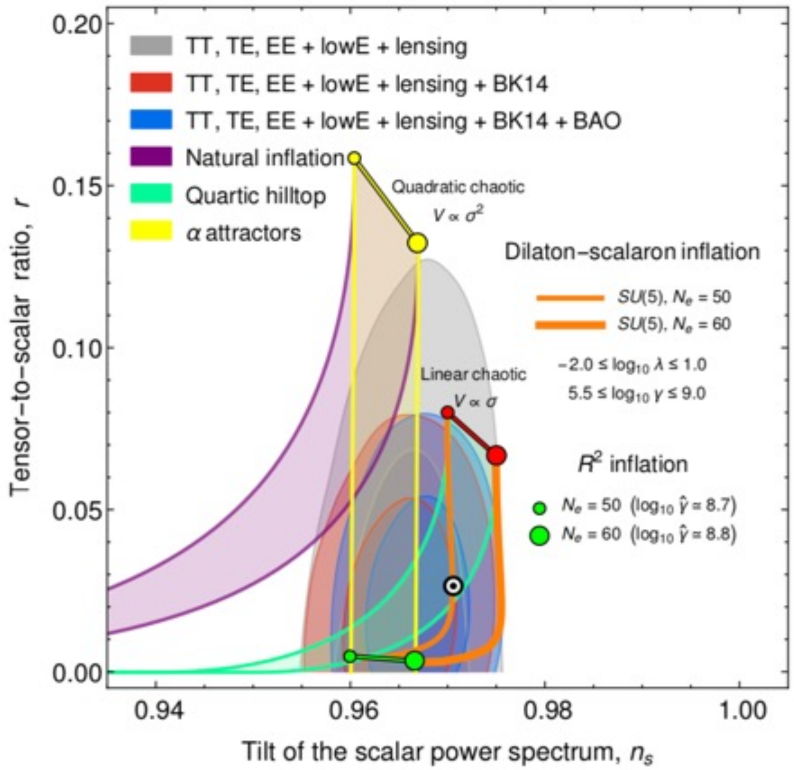
Weyl rescaling: $g_{\mu\nu} = \Omega^2\,g_{\mu\nu}^J \qquad \Omega^2 = e^{\Phi(\phi)}\,, \qquad \Phi(\phi) = \frac{\sqrt{2}\,\phi}{\sqrt{3}\,M_{\rm Pl}}$

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!



Summary

- **SM works (so far) perfectly**
  - the expected TeV physics did so far not show up
  - be a bit more patient: hints ... new physics may be around the corner…
  - or maybe it is time to re-consider some ingredients...?

- **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**

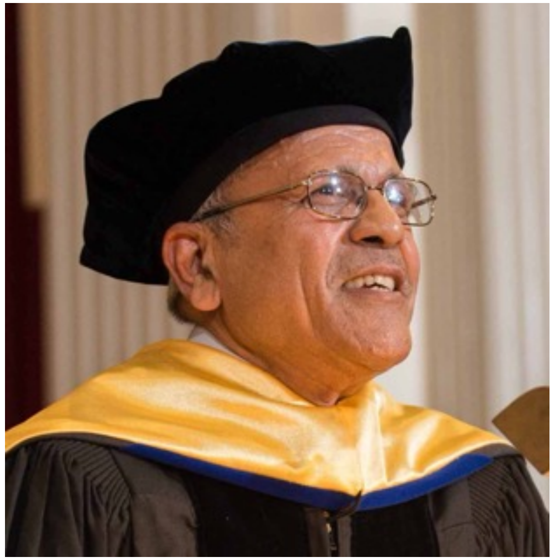
- **Planck scale generation by gauge induced breaking of conformal GR**
  - → very nice phenomenology: inflation…
  - → consistent quantum gravity: renormalizablity?, ghost?
    - ←→ normal GR from a theory with more symmetry
  - → stabilizing large scale hierarchies…
  - → trans-Planck: just be a different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

Congratulations Rabi

- on your impressive achievements
- in a remarkable wide range of topics

and

- in guiding / mentoring many young colleauges



Say "yes" to celebrating,
to big plans,
to everything that matters to you.

There's no better time
than now!