Is the Higgs Boson Associated with Coleman-Weinberg Symmetry Breaking?

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Bardeen: Classical Scale Invariance
could be the custodial symmetry
of a fundamental, perturbatively
light Higgs Boson in pure SU(3)xSU(2)xU(1)*

The only manifestations of
Classical Scale Invariance breaking by
quantum loops are d = 4 scale anomalies.

On naturalness in the standard model.
William A. Bardeen
FERMILAB-CONF-95-391-T, Aug 1995. 5pp.

* Modulo Landau pole

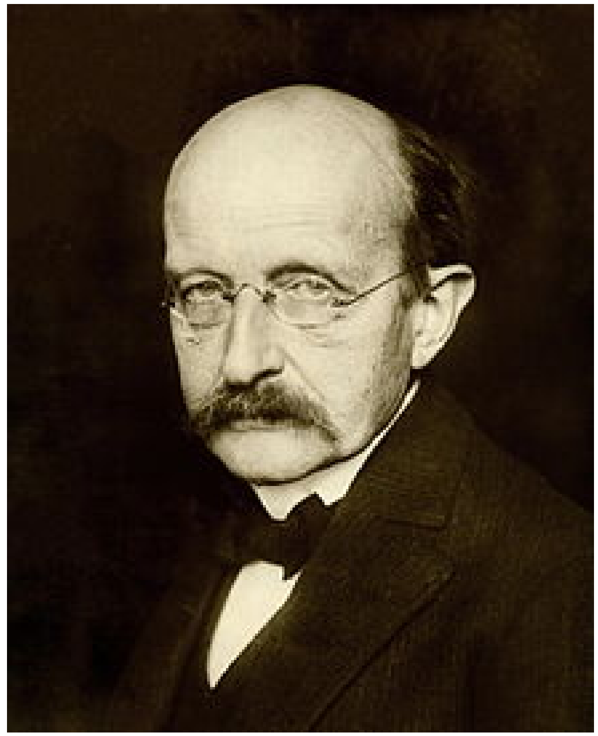
In the real world
there are possible additive effects from higher mass scales, eg: $\delta m_H^2 = \alpha^p M_{GuT}^2 + \alpha^q M_{Planck}^2$.

But the existence of the low mass Higgs may be telling us that such effects are absent (similarly for $\Lambda_{cosmological}$)

To apply this to real world we need some notion of "recovery of scale symmetry in the IR," eg, below M_{Gut} or M_{Planck}. We don't know how nature does this, but we know it happens empirically eg $\Lambda_{cosmological}$ or an isolated Higgs boson.

Assume that below M_{Gut} scale symmetry recovers.

An expanded Conjecture:



Max Planck

All mass is a quantum phenomenon.

$\hbar \Rightarrow 0 \Rightarrow$ Classical scale symmetry

Conjecture on the physical implications of the scale anomaly:
M. Gell-Mann 75th birthday talk: C. T. Hill **hep-th/0510177**

Scale Symmetry in QCD
is broken by quantum loops
and this gives rise to:

The Origin of the Nucleon Mass
(aka, most of the visible mass in
The Universe)

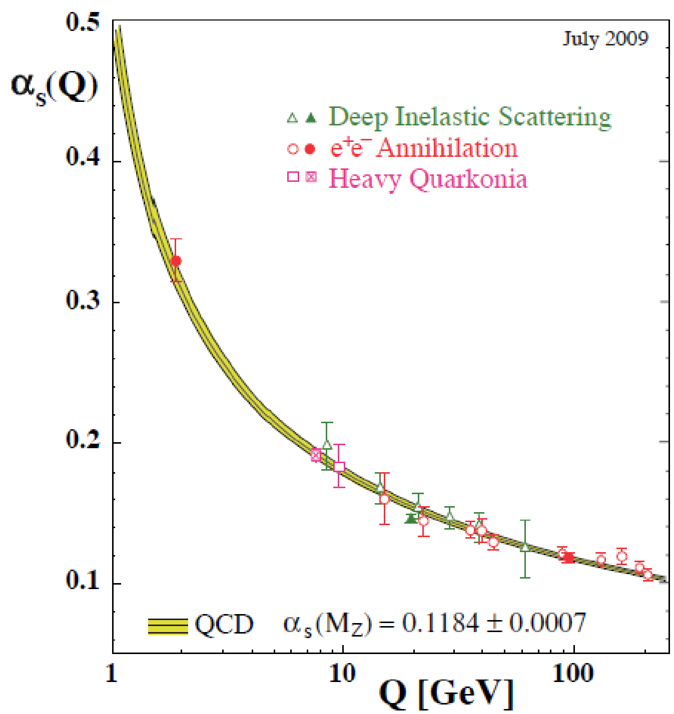
Gell-Mann and Low:

$$\frac{dg}{d\ln\mu} = \beta(g)$$

"running coupling constant"

Gross, Politzer and Wilczek (1973):

$$\beta(g) = \beta_0 g^3 \quad \text{where} \quad \beta_0 = -\frac{\hbar}{16\pi^2}\left(\frac{11}{3}N_c - \frac{2}{3}n_f\right)$$



$$\alpha_s(k^2) \equiv \frac{g_s^2(k^2)}{4\pi} \approx \frac{1}{\beta_0 \ln(k^2/\Lambda^2)}$$

$\Lambda = 200$ MeV

S. Burby and C. Maxwell
arXiv:hep-ph/0011203

A Puzzle: (Murray Gell-Mann's lecture ca 1975)

Noether current of Scale symmetry $$S_\mu = x^\nu T_{\mu\nu}$$

Current divergence $$\partial_\mu S^\mu = T^\mu_\mu$$

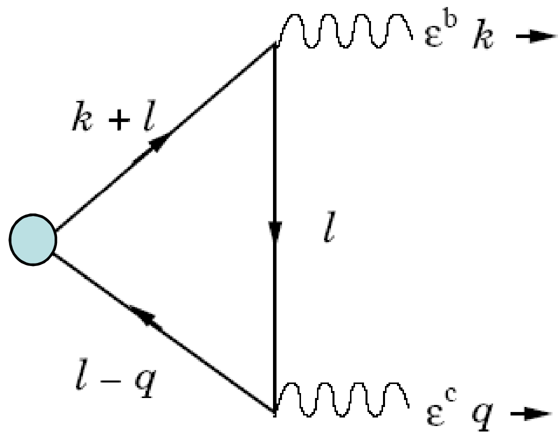
Yang-Mills Stress Tensor $$T_{\mu\nu} = \mathrm{Tr}(G_{\mu\rho}G^\rho_\nu) - \frac{1}{4} g_{\mu\nu}\,\mathrm{Tr}(G_{\rho\sigma}G^{\rho\sigma})$$

Compute: $$\partial_\mu S^\mu = T^\mu_\mu = \mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) - \frac{4}{4}\,\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) = 0$$

QCD is scale invariant!!!???

Resolution: The Scale Anomaly

$$\partial^{\mu} S_{\mu} = T^{\mu}_{\mu}$$



Canonical Trace Anomalies
Michael S. Chanowitz (SLAC), John R. Ellis.
Phys.Rev. D7 (1973) 2490-2506

Resolution: The Scale Anomaly is equivalent to the running coupling constant.

$$\partial_\mu S^\mu \;=\; \frac{\beta(g)}{g}\,\mathrm{Tr}\,G_{\mu\nu}G^{\mu\nu} = \mathcal{O}(\hbar)$$

Origin of Mass in QCD
= Quantum Mechanics !

't Hooft Naturalness:

"Small ratios of physical parameters are controlled by symmetries. In the limit that a ratio goes to zero, there is enhanced symmetry "
(custodial symmetry)

$$\frac{\Lambda}{M} = \exp\left(-\frac{8\pi^2}{|b_0|g^2(M)}\right) \qquad b_0 \propto \hbar.$$

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$\Rightarrow 0 \qquad\qquad \hbar \Rightarrow 0$

Classical Scale Invariance
is the "Custodial Symmetry" of Λ_{QCD}

Coleman-Weinberg Symmetry Breaking also arises from perturbative trace anomaly

Coleman-Weinberg Potential and Trace Anomaly

$$S = \int d^4x \, \mathcal{L} = \int d^4x \left(\frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) \right)$$

Improved Stress tensor:
Callan, Coleman, Jackiw

$$\widetilde{T}_{\mu\nu} = T_{\mu\nu} + Q_{\mu\nu}$$

$$= \frac{2}{3} \partial_\mu \phi \partial_\nu \phi - \frac{1}{6} \eta_{\mu\nu} \partial_\rho \phi \partial^\rho \phi - \frac{1}{3} \phi \partial_\mu \partial_\upsilon \phi + \frac{1}{3} \eta_{\mu\nu} \phi \partial^2 \phi + \eta_{\mu\nu} V(\phi)$$

Trace of improved stress tensor:

$$\widetilde{T}^\mu_\mu = \phi \partial^2 \phi + 4V(\phi) = -\phi \frac{\delta}{\delta \phi} V(\phi) + 4V(\phi)$$

Traceless for a *classically* scale invariant theory:

$$V(\phi) = \frac{\lambda}{4} \phi^4, \quad \Longrightarrow \quad \widetilde{T}^\mu_\mu = 0$$

Conserved scale current

Running coupling constant breaks scale symmetry:

$$\Rightarrow \quad \widehat{T}^{\mu}_{\mu} = -\beta\phi^4 \qquad \text{Trace Anomaly}$$

Coleman-Weinberg Potential can thus be **defined** as the solution to the equation:

$$\Rightarrow \quad \boxed{\phi\frac{\delta}{\delta\phi}V(\phi) - 4V(\phi) = -\beta\phi^4}$$

Running coupling constant breaks scale symmetry:

$$\Rightarrow \quad \widehat{T}^{\mu}_{\mu} = -\beta\phi^4$$ Trace Anomaly

Coleman-Weinberg Potential can thus be **defined** as the solution to the equation:

$$\Rightarrow \quad \phi \frac{\delta}{\delta\phi} V(\phi) - 4V(\phi) = -\beta\phi^4$$

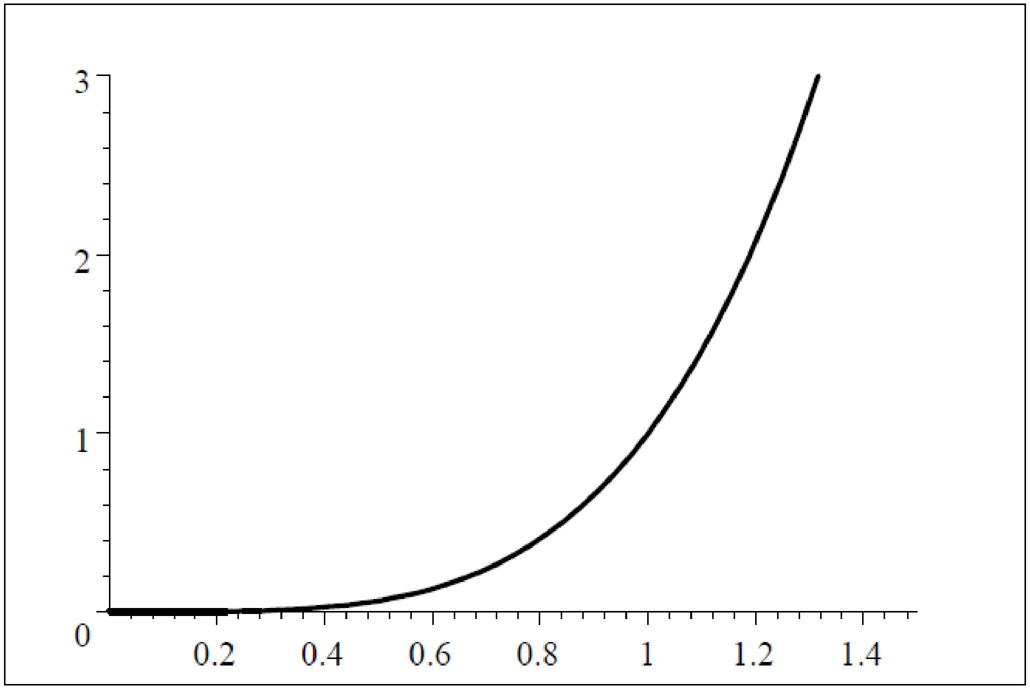
The solution is: $V(\phi) = \lambda(\phi)\phi^4$

$$\frac{d\lambda(\mu)}{d\ln\mu} = \beta(\lambda)$$

True to all orders in perturbation theory!!

In words: Start with the Classically Scale Invariant Higgs Potential

$$\frac{\lambda}{2}|H|^4$$



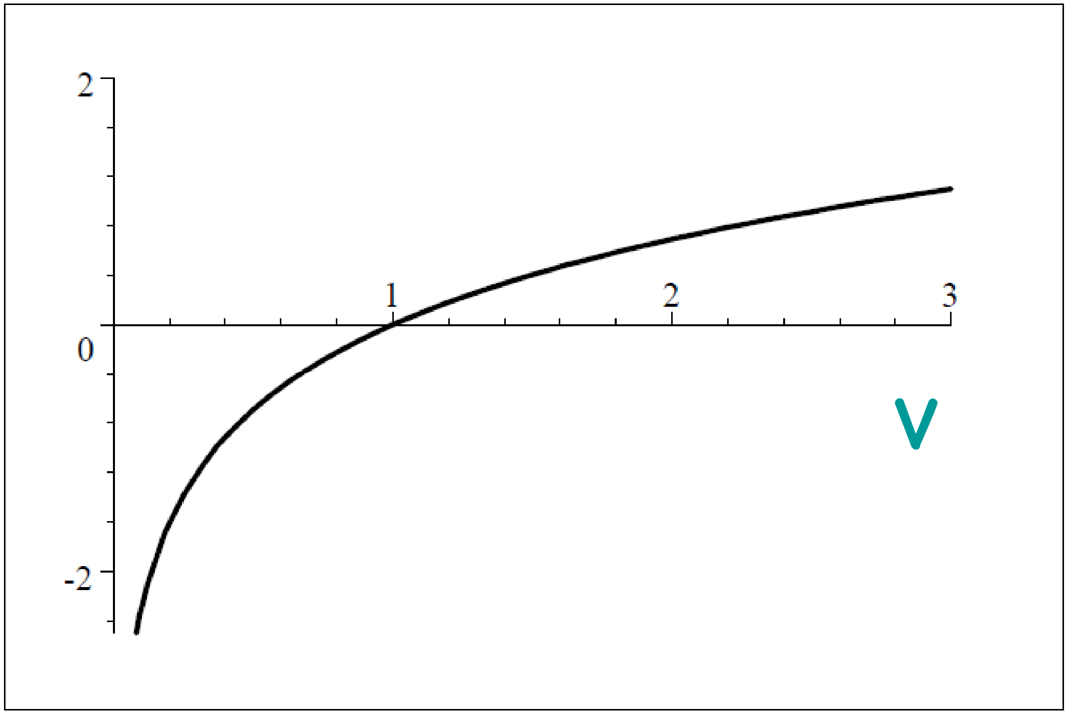
$$\langle H \rangle = v$$

v

Scale Invariance -> Quartic Potential -> No VEV

Quantum loops generate logarithmic "running" of the quartic coupling

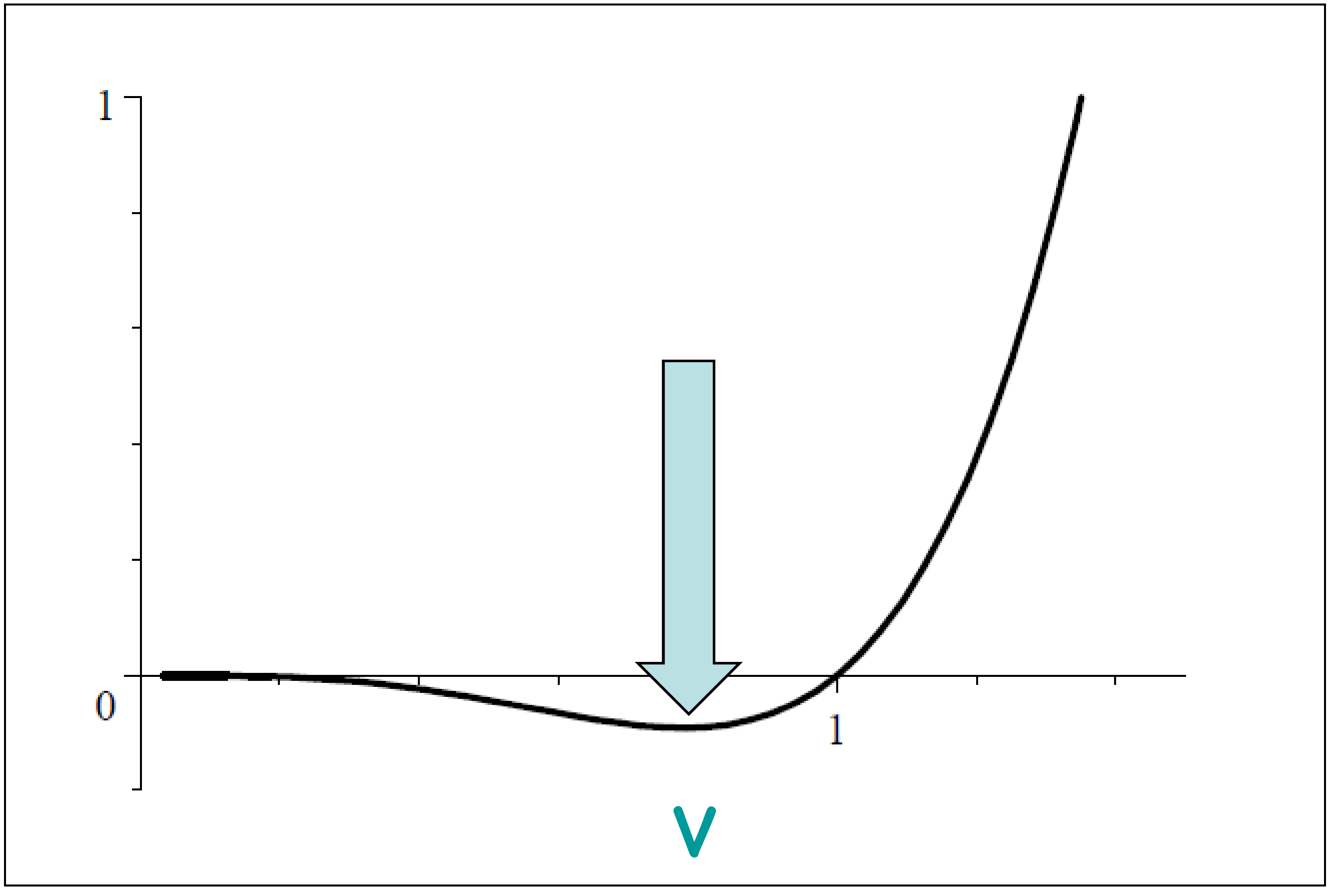
$$\lambda(v) \propto \hbar \beta \log(v/M)$$



Nature chooses a trajectory
determined by dimensionless cc's.

Result: "Coleman-Weinberg Potential:"

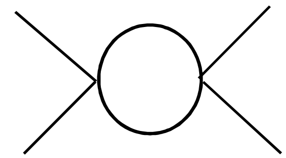
$$\frac{\tilde{\lambda}(v)}{2} \times v^4$$



Potential arises from Quantum Mechanics

Example: ϕ^4 Field theory

$$\frac{d\lambda}{d\ln(\phi)} = \beta(\lambda) = \frac{9\lambda^2}{32\pi^2}$$



$$V_{RG} = \frac{\lambda}{4}\phi^4 + \hbar\frac{9\lambda^2}{32\pi^2}\phi^4\ln(\phi/M) \quad = \hbar\frac{m_h^4}{32\pi^2}(\phi/v)^4\ln(\phi/\tilde{M})$$

agrees with CW original result log (path Integral)

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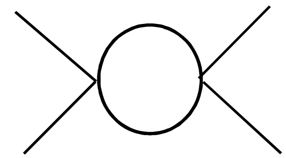


$$V_{RG} = \frac{\lambda}{4}\phi^4 + \hbar\frac{9\lambda^2}{32\pi^2}\phi^4\ln(\phi/M) \qquad = \hbar\frac{m_h^4}{32\pi^2}(\phi/v)^4\ln(\phi/\tilde{M})$$

agrees with CW original result log (path Integral)

Example: Scalar Electrodynamics

$$V(\phi) = \frac{\lambda_0}{2}|\phi|^4 + \frac{1}{16\pi^2}\left(5\lambda^2 - 6\lambda e^2 + 6e^4\right)|\phi|^4\ln\left(\frac{|\phi|}{M}\right)$$

$\phi_c^2 \quad 2|\phi|^2 \quad$ and $\quad \frac{\lambda_{CW}}{4!}\phi_c^4 \quad \frac{\lambda_0}{2}|\phi|^4$

$$V(\phi_c') = \frac{\lambda_{CW}}{4!}\phi_c'^4 + \left(\frac{5\lambda_{CW}^2}{1152\pi^2} + \frac{3e^4}{64\pi^2}\right)\phi_c'^4\ln\left(\frac{\phi_c^2}{M'^2}\right)$$

(C.6)

agrees with CW original result with canonical normalization

The Renormalization Group generates the entire Coleman Weinberg potential:

Theorem: $\phi \frac{\delta}{\delta \phi} V(\phi) - 4V(\phi) = \frac{\beta}{\lambda} V(\phi)$ ⟹ $\beta = -4\lambda.$ at the minimum

The Renormalization Group generates the entire Coleman Weinberg potential:

Theorem: $$\phi\frac{\delta}{\delta\phi}V(\phi) - 4V(\phi) = \frac{\beta}{\lambda}V(\phi) \quad \Longrightarrow \quad \beta = -4\lambda.$$ at the potential minimum

$$
\begin{aligned}
V_{CW}(h) \;=\; & -\frac{1}{8}\beta_1 v^4 + \frac{1}{2}v^2h^2\left(\beta_1 + \frac{1}{4}\beta_j\frac{\partial\beta_1}{\partial\lambda_j}\right) \\
& + \frac{5}{6\sqrt{2}}vh^3\left(\beta_1 + \frac{9}{20}\beta_i\frac{\partial\beta_1}{\partial\lambda_i} + \frac{1}{20}\beta_j\beta_i\frac{\partial^2\beta_1}{\partial\lambda_j\partial\lambda_i}\right. \\
& \left. + \frac{1}{20}\beta_j\frac{\partial\beta_i}{\partial\lambda_j}\frac{\partial\beta_1}{\partial\lambda_i}\right) \\
& + \frac{11}{48}h^4\left(\beta_1 + \frac{35}{44}\beta_i\frac{\partial\beta_1}{\partial\lambda_i} + \frac{5}{22}\beta_j\beta_i\frac{d^2\beta_1}{\partial\lambda_j\partial\lambda_i}\right. \\
& + \frac{5}{22}\beta_j\frac{\partial\beta_i}{\partial\lambda_j}\frac{\partial\beta_1}{\partial\lambda_i} + \frac{1}{44}\beta_k\beta_j\beta_i\frac{d^3\beta_1}{\partial\lambda_k\partial\lambda_j\partial\lambda_i} \\
& + \frac{1}{44}\beta_k\frac{\partial\beta_j}{\partial\lambda_k}\frac{\partial\beta_i}{\partial\lambda_j}\frac{\partial\beta_1}{\partial\lambda_i} + \frac{1}{44}\beta_j\beta_i\frac{d^2\beta_i}{\partial\lambda_j\partial\lambda_i}\frac{\partial\beta_1}{\partial\lambda_i} \\
& \left. + \frac{3}{44}\beta_j\beta_k\frac{\partial\beta_i}{\partial\lambda_k}\frac{d^2\beta_1}{\partial\lambda_j\partial\lambda_i}\right) +
\end{aligned}
$$

$$
\begin{aligned}
& + \frac{h^5}{40\sqrt{2}v}\left(\beta + \frac{25}{12}\beta_i\frac{d\beta}{d\lambda_i} + \frac{35}{24}\beta_j\beta_i\frac{d^2\beta}{d\lambda_j d\lambda_i}\right. \\
& + \frac{35}{24}\beta_j\frac{d\beta_i}{d\lambda_j}\frac{d\beta}{d\lambda_i} + \frac{5}{12}\beta_k\beta_j\beta_i\frac{d^3\beta}{d\lambda_k d\lambda_j d\lambda_i} \\
& + \frac{5}{12}\beta_k\frac{d\beta_j}{d\lambda_k}\frac{d\beta_i}{d\lambda_j}\frac{d\beta}{d\lambda_i} + \frac{5}{12}\beta_j\beta_i\frac{d^2\beta_i}{d\lambda_j d\lambda_i}\frac{d\beta}{d\lambda_i} \\
& + \frac{5}{4}\beta_j\beta_k\frac{d\beta_i}{d\lambda_k}\frac{d^2\beta}{d\lambda_j d\lambda_i} + \frac{1}{24}\beta_i\beta_j\beta_k\beta_\ell\frac{\partial^4\beta}{\partial\lambda_i\partial\lambda_j\partial\lambda_k\partial\lambda_\ell} \\
& + \frac{1}{24}\beta_\ell\frac{\partial\beta_k}{\partial\lambda_\ell}\frac{\partial\beta_j}{\partial\lambda_k}\frac{\partial\beta_i}{\partial\lambda_j}\frac{\partial\beta}{\partial\lambda_i} + \frac{1}{4}\beta_i\beta_j\beta_k\frac{\partial\beta_\ell}{\partial\lambda_k}\frac{\partial^3\beta}{\partial\lambda_i\partial\lambda_j\partial\lambda_\ell} \\
& + \frac{1}{8}\beta_\ell\beta_k\frac{\partial\beta_j}{\partial\lambda_k}\frac{\partial^2\beta_i}{\partial\lambda_j\partial\lambda_\ell}\frac{\partial\beta}{\partial\lambda_i} + \frac{1}{6}\beta_i\beta_\ell\frac{\partial\beta_k}{\partial\lambda_\ell}\frac{\partial\beta_j}{\partial\lambda_k}\frac{\partial^2\beta}{\partial\lambda_j\partial\lambda_i} \\
& + \frac{1}{6}\beta_i\beta_j\beta_\ell\frac{\partial^2\beta_k}{\partial\lambda_\ell\partial\lambda_j}\frac{\partial^2\beta}{\partial\lambda_k\partial\lambda_i} + \frac{1}{24}\beta_\ell\beta_k\beta_j\frac{\partial^3\beta_i}{\partial\lambda_j\partial\lambda_k\partial\lambda_\ell}\frac{\partial\beta}{\partial\lambda_i} \\
& \left. + \frac{1}{8}\beta_\ell\beta_i\frac{\partial\beta_k}{\partial\lambda_\ell}\frac{\partial^2\beta}{\partial\lambda_k\partial\lambda_j}\frac{\partial\beta_j}{\partial\lambda_i} + \frac{1}{24}\beta_\ell\beta_k\frac{\partial^2\beta_j}{\partial\lambda_\ell\lambda_k}\frac{\partial\beta_i}{\partial\lambda_j}\frac{\partial\beta}{\partial\lambda_i}\right) \\
& + O(h^6).
\end{aligned}
$$

CTH arXiv:1401.4185 [hep-ph].
Phys Rev D.89. 073003.

Can the light Higgs Boson mass come from quantum mechanics?

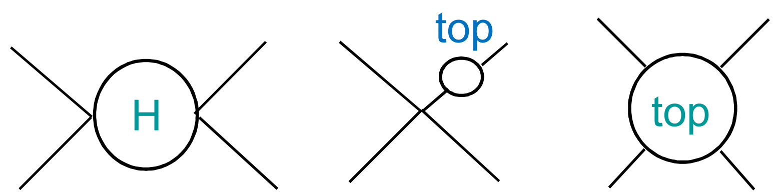
i.e., Is the Higgs potential a Coleman-Weinberg Potential?

Treat this as a phenomenological question !!!

Higgs Quartic coupling $\beta(\lambda)$

$$\frac{d\lambda(v)}{d\ln(v)} = \frac{12}{16\pi^2}(\lambda^2 + \lambda g^2 - g^4) = \beta$$

g : top Yukawa cc



(I am ignoring EW contributions for simplicity of discussion)

approximate physical values from Higgs mass 126 GeV:

$$\left\{ \begin{array}{l} \lambda = 1/4 \\ g = 1 \end{array} \right\} \Rightarrow \beta = -5.2244 \times 10^{-2}$$

$$-\beta/\lambda = 0.21 \quad << \quad 4$$

Far from Coleman-Weinberg

Modify Higgs Quartic coupling $\beta(\lambda)$

Introduce a new field: S

Higgs-Portal Interaction $\lambda' |H|^2 |S|^2$

Two possibilities:

(1) Modifies RG equation to make $\beta > 0$:

$$\frac{d\lambda(v)}{d\ln(v)} = \frac{12}{16\pi^2}(\lambda^2 + \lambda g^2 - g^4 + c\,\lambda'^2)$$

(2) S develops its own CW potential, and VEV
$\langle S \rangle = V'$ and Higgs gets mass, $\lambda' V'$

Simplest hypotheses
S may be:

A new doublet NOT coupled to SU(2) x U(1) (**inert**) w or wo VEV

S. Iso, and Y. Orikasa, PTEP (2013) 023B08;
Hambye and Strumia Phys.Rev. D88 (2013) 055022;
"Ultra-weak sector, Higgs boson mass, and the dilaton,"
K. Allison, C. T. Hill, G. G. Ross. arXiv:1404.6268 [hep-ph];
"Light Dark Matter, Naturalness, and the Radiative Origin of the Electroweak Scale," W. Altmannshofer, W. Bardeen, M Bauer, M. Carena, J. Lykken e-Print: arXiv:1408.3429 [hep-ph] …

Many, many papers on this approach!

} S sector is Dark Matter

A New doublet COUPLED to SU(2)xU(1) with no VEV (**dormant**)

e.g., Is the Higgs Boson Associated with
Coleman-Weinberg Dynamical Symmetry Breaking?
CTH, arXiv:1401.4185 [hep-ph]. Phys Rev D.89.073003….

} S sector is visible at LHC

Massless two doublet potential

$$V(H_1,H_2) = \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 e^{i\theta} + h.c.\right]$$

CTH, Caltech PhD Thesis (1977)

Two doublet RG equations

Portal effect on λ_1

$$16\pi^2\frac{d\lambda_1(\mu)}{d\ln(\mu)} = 12\lambda_1^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2 - 3\lambda_1(3g_2^2+g_1^2) + \frac{3}{2}g_2^4 + \frac{3}{4}(g_1^2+g_2^2)^2 + 12\lambda_1 g_t^2 - 12 g_t^4$$

$$16\pi^2\frac{d\lambda_2(\mu)}{d\ln(\mu)} = 12\lambda_2^2 + 4\lambda_3^2 + 4\lambda_3\lambda_4 + 2\lambda_4^2 + 2\lambda_5^2 - 3\lambda_2(3g_2^2+g_1^2) + \frac{3}{2}g_2^4 + \frac{3}{4}(g_1^2+g_2^2)^2 + 12\lambda_2 g_b^2 - 12 g_b^4$$

$$16\pi^2\frac{d\lambda_3(\mu)}{d\ln(\mu)} = (\lambda_1+\lambda_2)(6\lambda_3+2\lambda_4) + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2 - 3\lambda_3(3g_2^2+g_1^2) + \frac{9}{4}g_2^4 + \frac{3}{4}g_1^4 - \frac{3}{2}g_1^2 g_2^2 + 6\lambda_3(g_t^2+g_b^2) - 12 g_t^2 g_b^2$$

$$16\pi^2\frac{d\lambda_4(\mu)}{d\ln(\mu)} = 2(\lambda_1+\lambda_2)\lambda_4 + 4(2\lambda_3+\lambda_4)\lambda_4 + 8\lambda_5^2 - 3\lambda_4(3g_2^2+g_1^2) + 3g_1^2 g_2^2 - 12 g_t^2 g_b^2$$

$$16\pi^2\frac{d\lambda_5(\mu)}{d\ln(\mu)} = \lambda_5[2(\lambda_1+\lambda_2) + 8\lambda_3 + 12\lambda_4 - 3(3g_2^2+g_1^2) + 2(g_t^2+g_b^2)]$$

CTH, C N Leung, S Rao NPB262 (1985) 517

Can easily solve for portal interaction λ_3:

$$\beta = \frac{1}{16\pi^2}(12\lambda^2 + 12\lambda g^2 - 12g^4 + \boxed{4\lambda_3^2}) \quad + \text{EW, etc.} \qquad g = g_{top} \approx 1$$

$$\left.\begin{array}{l}\lambda = 1/4 \\ g = 1\end{array}\right\} \qquad \boxed{\beta/\lambda = -4}$$

⇨ Solution is: $\lambda_3 = 4.8789$

Mass of New Doublet: $\sqrt{4.8789} \times (175) = 386.54$ GeV

Prediction: Heavy "dormant" Higgs doublet at ~ 400 GeV

No VeV but coupled to SU(2) xU(1):

"Dormant" Higgs Doublet (vs. "Inert")

Production, mass, and decay details are model dependent

Parity $H_2 \to -H_2$ implies stabity: $H_2^+ \to H_2^0 + (e^+\nu)$ if $M^+ > M^0$

Then H_2^0 is stable dark matter WIMP

Best Visible Model:

Break parity by coupling H_2 to b-quarks

The Dormant Doublet is pair produced above threshold near $2M_H \approx 800$ GeV

CalcHEP **estimates**

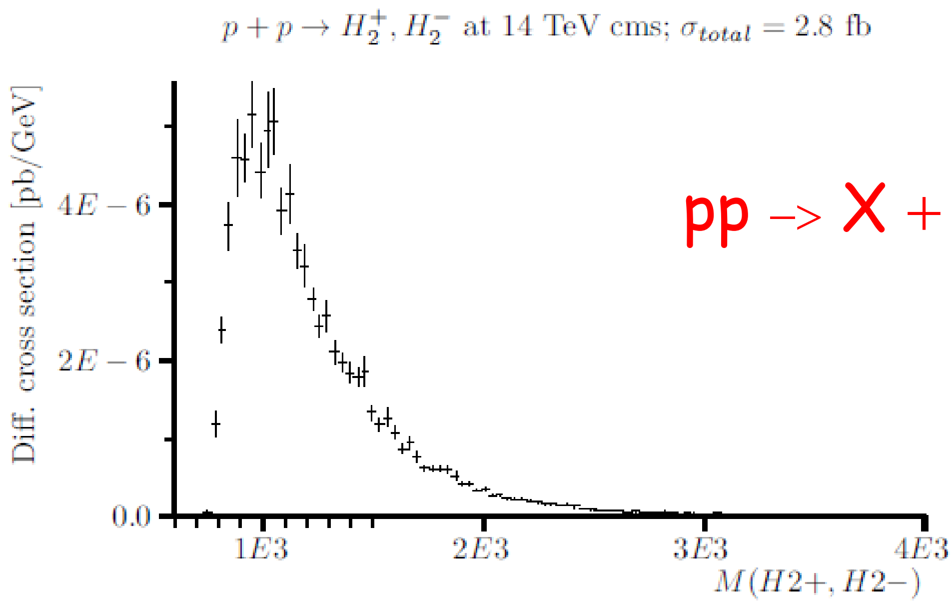


FIG. 1: H^+H^- production at LHC.

pp -> X + $(\gamma^*, Z^*, W^*, h^*)$ -> X + H H^*

pp -> $H^0 H^0$	$\sigma = 1.4$ fb	$\Gamma_{H^0 \to bb} = 45$ GeV
pp -> $H^+ H^-$	$\sigma = 2.8$ fb	$\Gamma_{H+ \to tb} = 14$ GeV
pp -> $H^+ H^0$	$\sigma = 0.9$ fb	

Assume $g_b' = 1$

Maybe in Run II?

TABLE I: Predicted decay widths and production cross-sections for the dormant Higgs bosons. We used CalcHep, and production runs CTEQ61 proton structure functions, 1.64×10^5 calls. All cross-sections are evaluated at 14 TeV cms energy with the mass of H_2 doublet set to 380 GeV/c^2. Model dependent processes have rates or cross-sections that are indicated as $\propto (g_b')^2$.

Process	value	comments
$\Gamma(H^+ \to t + \bar{b}) = \Gamma(H^- \to b + \bar{t})$	$14.5\ (g_b')^2 \pm 5 \times 10^{-5}\%$ GeV	
$\Gamma(H^0 \to b + \bar{b}) = \Gamma(A^0 \to b + \bar{b})$	$5.67\ (g_b')^2 \pm 5 \times 10^{-5}\%$ GeV	
$\Gamma(H^0 \to 2h, 3h) = \Gamma(A^0 \to 2h, 3h)$		absent in model
$pp \to (\gamma, Z^0) \to H^+H^-$	$\sigma_t = 1.4$ fb	
$pp \to (\gamma, Z) \to H^0H^0$		absent in model
$pp \to (\gamma, Z) \to A^0H^0$	$\sigma_t = 1.3$ fb	
$pp \to (\gamma, Z) \to A^0A^0$		absent in model
$pp(gg) \to h \to H^0H^0$ or A^0A^0	$\sigma_t = 1.7 \times 10^{-5}$ fb	
$pp \to W^+ \to H^0H^+$	$\sigma_t = 1.8$ fb	
$pp \to W^+ \to A^0H^+$	$\sigma_t = 1.8$ fb	
$pp \to W^- \to H^0H^-$	$\sigma_t = 0.74$ fb	
$pp \to W^- \to A^0H^-$	$\sigma_t = 0.74$ fb	
$pp \to b + \bar{b} + H^0$ or A^0	$\sigma_t = 1.8\ (g_b')^2$ pb $\pm 2.4\%$	No p_T cuts
	$\sigma_t = 67\ (g_b')^2$ fb $\pm 5\%$	$p_T(b)$ and $p_T(\bar{b}) > 50$ GeV
	$\sigma_t = 9.6\ (g_b')^2$ fb $\pm 3.5\%$	$p_T(b)$ and $p_T(\bar{b}) > 100$ GeV
$pp \to t + \bar{b} + (H^-)$	$\sigma_t = 220\ (g_b')^2$ fb	No cuts
	$\sigma_t = 44\ (g_b')^2$ fb	$p_T(t)$, $p_T(\bar{b}) > 50$ GeV
	$\sigma_t = 14\ (g_b')^2$ fb	$p_T(t)$, $p_T(\bar{b}) > 100$ GeV
$pp \to \bar{t} + b + (H^+)$	$\sigma_t = 270\ (g_b')^2$ fb	No cuts
	$\sigma_t = 46\ (g_b')^2$ fb $p_T(\bar{t})$	$p_T(b) > 50$ GeV
	$\sigma_t = 14\ (g_b')^2$ fb $p_T(\bar{t})$	$p_T(b) > 100$ GeV

CTH, arXiv:1401.4185 [hep-ph].
Phys Rev D.89.073003.

The “smoking gun” of a Coleman-Weinberg mechanism:

Trilinear, quartic and quintic Higgs couplings
will be significantly different than in SM case

$$V_{CW}(H) = \frac{1}{2}m_h^2 h^2 + \frac{5}{6\sqrt{2}v}h^3\left(\beta_1 + \frac{9}{20}\beta_3\frac{\partial\beta_1}{\partial\lambda_3}\right) + \frac{11}{48v^2}h^4\left(\beta_1 + \frac{35}{44}\beta_3\frac{\partial\beta_1}{\partial\lambda_3}\right) + \frac{1}{40\sqrt{2}v}h^5\left(\beta_1 + \frac{25}{12}\beta_3\frac{\partial\beta_1}{\partial\lambda_3}\right) + \ldots$$

$$\text{trilinear} = \frac{5}{3}\left(1 + \frac{v^2}{5m_h^2}\frac{\lambda_3^3}{8\pi^4}\right) \approx 1.75 \; *$$

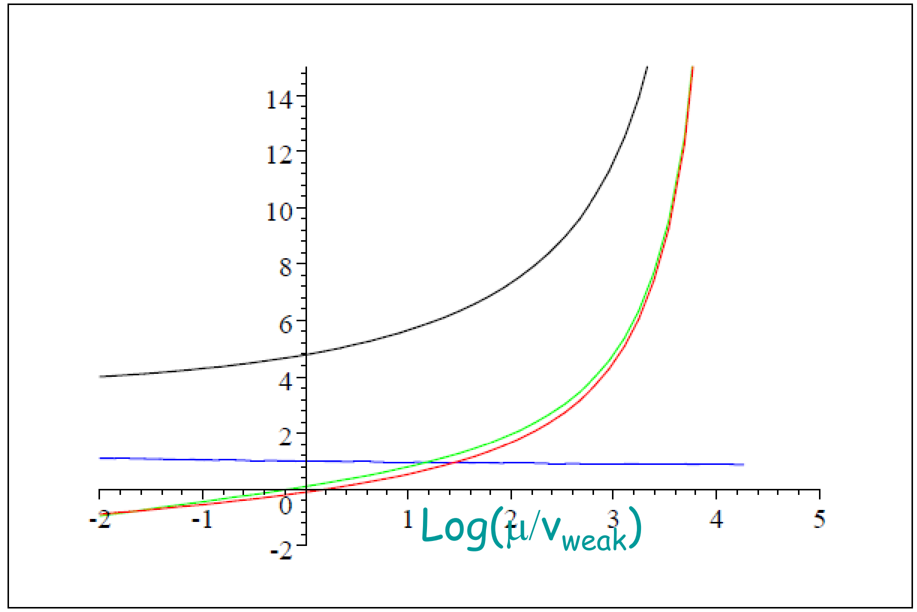
$$\text{quadrilinear} = \frac{11}{3}\left(1 + \frac{35v^2}{44m_h^2}\frac{\lambda_3^3}{8\pi^4}\right) \approx 4.43$$

$$\text{quintic} = \frac{3}{5}\left(\frac{\beta_1}{\hat{\beta}} + \frac{25}{12\hat{\beta}}\frac{\lambda_3^3}{6\pi^4}\right) \approx -8.87$$

* This may be doable at LHC in Run II?

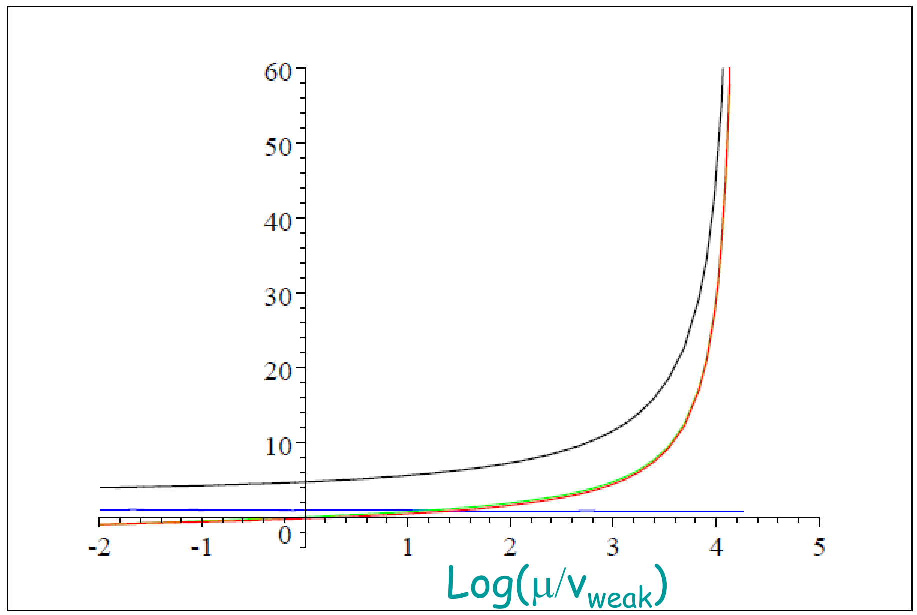
Problem with simplest model: the UV Landau Pole, hard to avoid, implying strong scale

λ_3(175 GeV) = 4.79 (black)
λ_1(175 GeV) = -0.1 (red)
λ_2(175 GeV) = 0.1 (green)
g_{top}= 1 (blue)
$\lambda_4 = \lambda_5 = 0$



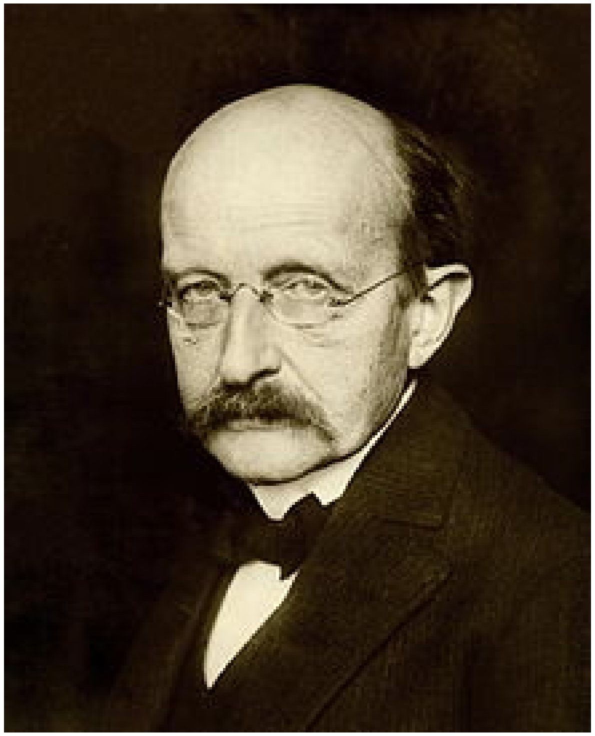
Landau Pole = 10 - 100 TeV

Landau Pole -> Composite H_2 New Strong Dynamics ?



e.g. Higgs mass from compositeness at a multi-TeV scale, Hsin-Chia Cheng Bogdan Dobrescu, Jiayin Gu
e-Print: **arXiv:1311.5928**

The Conjecture:



Max Planck

All mass is a quantum phenomenon.

$\hbar \Rightarrow 0 \Rightarrow$ Classical scale symmetry

Conjecture on the physical implications of the scale anomaly:
M. Gell-Mann 75th birthday talk: C. T. Hill hep-th/0510177

Musings:
What if it's true?

All mass scales in physics are intrinsically quantum mechanical and associated with scale anomalies. The $\hbar \to 0$ limit of nature is exactly scale invariant.

(a heretic)

“Predictions” of the Conjecture:

We live in D=4!

$$T^{\mu}_{\mu} = \mathrm{Tr}\, G_{\mu\nu} G^{\mu\nu} - \frac{D}{4} \mathrm{Tr}\, G_{\mu\nu} G^{\mu\nu}$$

Cosmological constant is zero in classical limit

QCD scale is generated in this way; Hierarchy is naturally generated

Testable in the Weak Interactions !

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Testable in the Weak Interactions!

Does the Planck Mass Come From Quantum Mechanics?

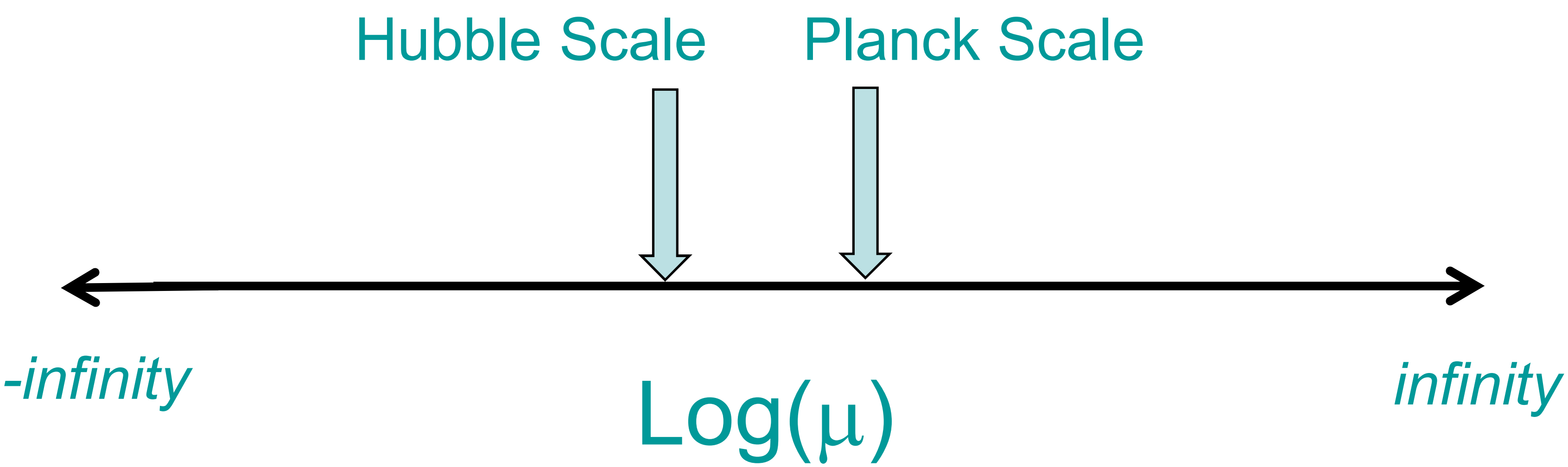
Can String Theory be an effective theory?

... or Weyl Gravity? (A-gravity?)

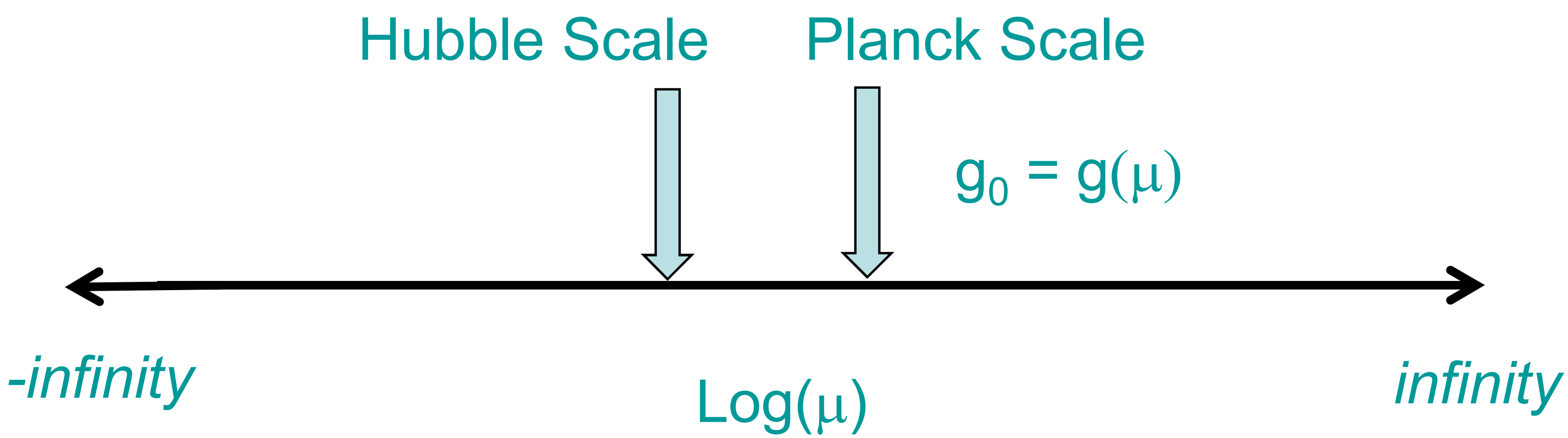
Weyl Gravity is Renormalizable!

Weyl Gravity is QCD-like: $$\frac{1}{h^2}\sqrt{-g}(R_{\mu\nu}R^{\mu\nu} - \frac{1}{3}R^2)$$

The "Scaloplex" (scale continuum)
infinite, uniform, and classically isotropic



Physics is determined by local values of dimensionless coupling constants



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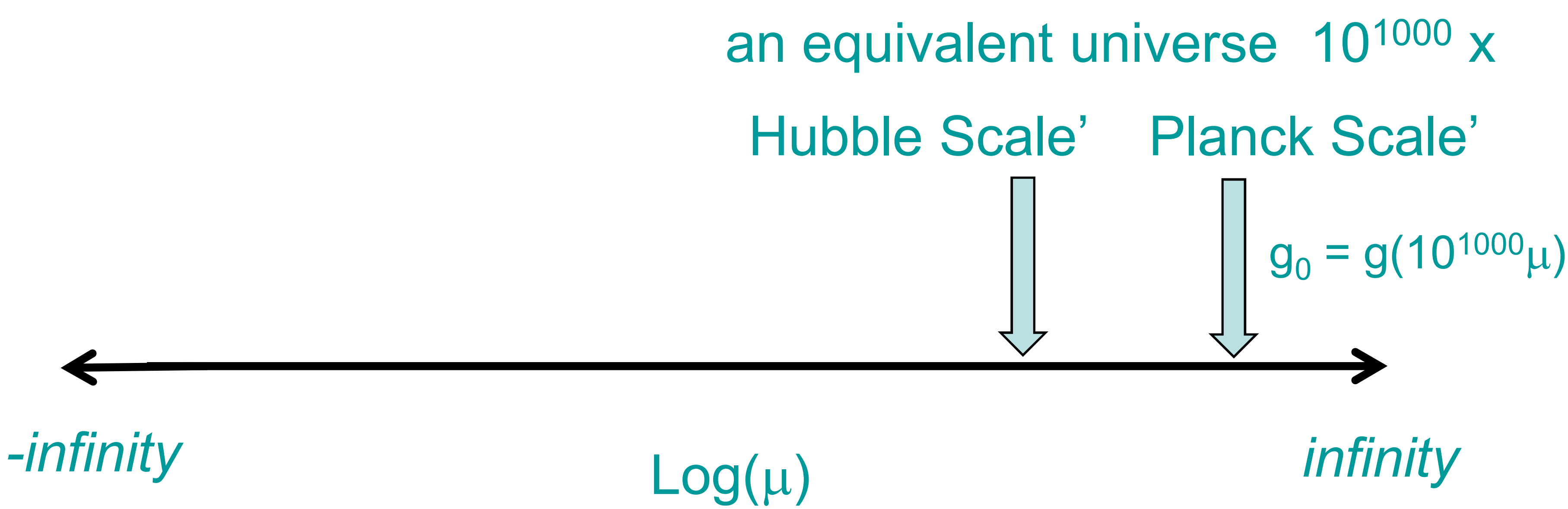

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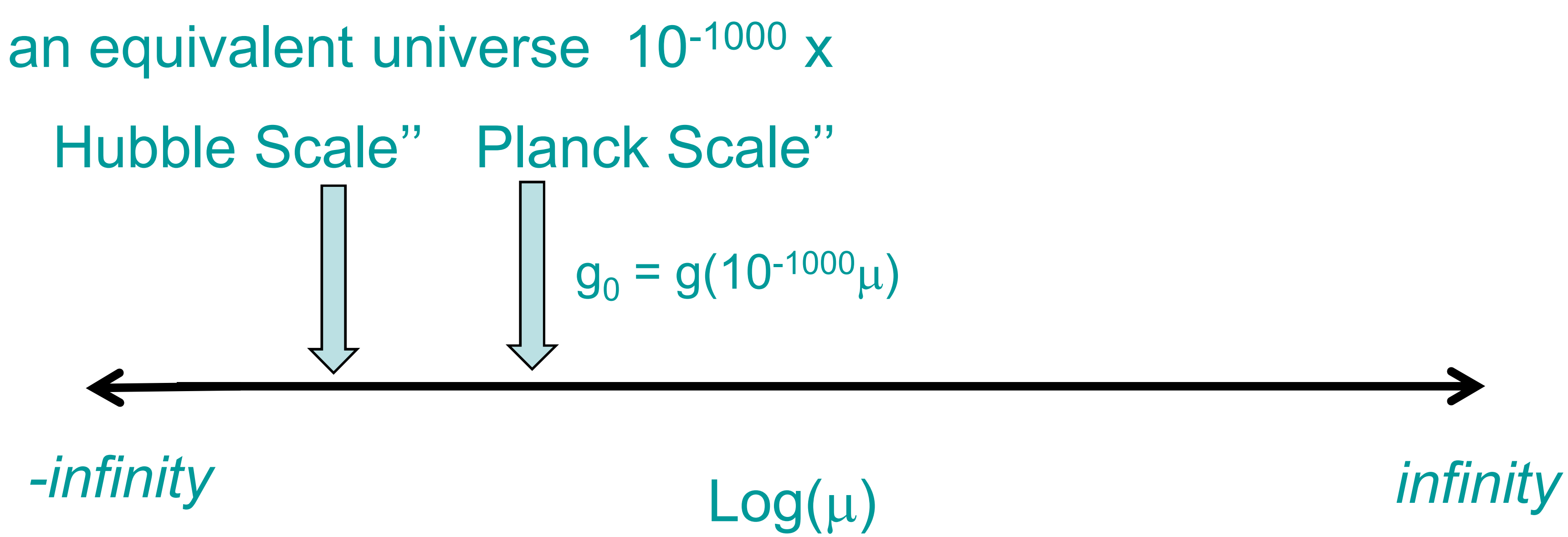

Lack of additive scales: Is the principle of scale recovery actually a "Principle of Locality" in Scaloplex?

Physical Mass Scales, generated by
e.g. Coleman-Weinberg or QCD-like mechanisms,
are Local in scale, and do not add to scales
far away in the scaloplex

E.g, "shining" with Yukawa suppression
in extra dimensional models.

Does Coleman-Weinberg mechanism
provide immunity from additive scales?

Conjecture on a solution to the Unitarity Problem of Weyl Gravity

CTH, P. Agrawal

M_{Planck} arises via QCD-like mechanism.
Theory becomes **Euclidean** for $\mu > M_{Planck}$
(infinite temperature or instanton dominated)
Time is emergent for $\mu << M_{Planck}$

Passage through the Planck Scale

D=4 quantum theory T = 0 ⇒ D=5 quantum theory T = 0 ⇒ D=5 T -> log(μ) theory ⇒ D=5 T -> infinity theory = D=4 Euclidean Theory

Log(μ)

Time emerges
$T < M_{Planck}$

Euclidean D=4

⇑

Hawking-Hartle Boundary Condition?

Conclusions:

An important answerable scientific question:

Is the Higgs potential Coleman-Weinberg?

- We examined a "maximally visible" scheme
- Dormant Higgs Boson from std 2-doublet scheme

$M \approx 386$ GeV

- May be observable, LHC run II, III?
- Higgs trilinear … couplings non-standard

or New bosons may be dark matter

Perhaps we live in a world where all
mass comes from quantum effects
No classical mass input parameters.

Everyone is still missing the
solution to the scale recovery problem!

End