Self-Organized Higgs Criticality

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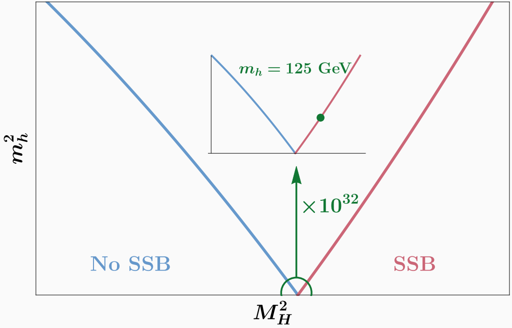
Fine Tuning Problem of the Higgs Mass

The Higgs mass is obtained from a potential defined at some high mass scale like M_{pl} or M_{GUT}, with a bare mass term.

$$V(|H|) = M_H^2 |H|^2 + \lambda_H |H|^4 \quad , \quad m_h^2 \sim -M_H^2 + \Lambda^2$$



Standard Model seems to be very very close to the critical point unprotected by a symmetry

Possible Solutions to Fine Tuning

A partial set of proposed solutions include

- Supersymmetry
- Composite Higgs — Kaplan, Georgi '84
- Large Extra Dimensions — Arkani-Hamed, Dimopoulos, Dvali '98
- Warped Extra Dimensions — Randall, Sundrum '99
- Anthropics — Weinberg '89
- Relaxion — Graham, Kaplan, Rajendran '15
- NNaturalness — Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16
- Neutral Naturalness — Craig, Knapen, Longhi '14

Most of the solutions require new symmetries and new particles around the mass scale $\sim$ TeV which have not been seen so far.

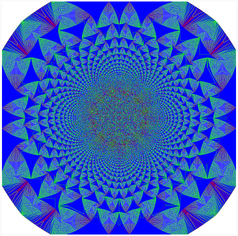
Self-Organized Criticality

Bak, Tang, Wiesenfeld '87

Systems driven naturally to their critical points, no fine tuning needed!

All length/time scales become important at the point of criticality.

The system remains critical under slow temporal loading of the system.



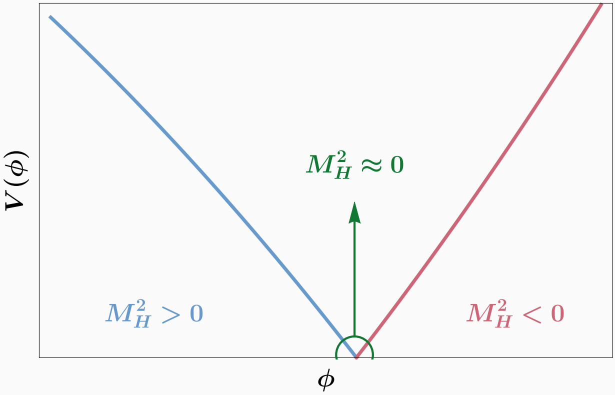
Sandpile with 28M grains[1]

Can the critical point for the Higgs sector arise naturally not due to symmetry but because of some analog self-organization? Guidice '08

[1]Abelian Sandpile Model by Claudio Rocchini. Used under CC BY 3.0

Self-Critical Higgs

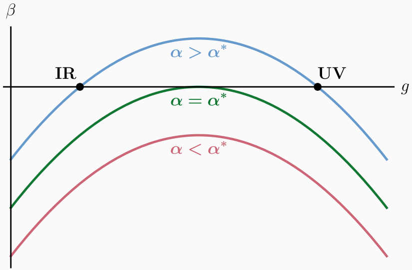
Looking for a model for SSB, where Higgs is driven to the critical point naturally, i.e. Higgs self-tunes.



Somewhat similar to the Relaxion solution to the Hierarchy problem or axion solution to the Strong CP problem.

Lost of Conformality

Kaplan, Lee, Son, Stephanov '09



An operator $\mathcal{O}$ with different scaling dimensions $\Delta_{\mathrm{UV}}/\Delta_{\mathrm{IR}}$ at the UV/IR fixed points determined by some external parameter α.

Under variation of α, fixed points and scaling dimensions move to each other, merge at some critical α^*, become complex after that.

For $\alpha < \alpha^*$ the theory has no longer a conformal phase. Fixed point merger gives rise to a BKT type phase transition.

Holographic Perspective $\mathcal{O} \leftrightarrow \phi$ Klebanov, Witten '99

A higher dimensional classical gravity theory on AdS_5 containing a scalar field ϕ of mass $-4 < m^2 < -3$

$$S = \frac{1}{2}\int \mathrm{d}^4x\,\mathrm{d}z\,\sqrt{g}\left[(\partial_n\phi)^2 - m^2\phi^2 - \frac{1}{\kappa^2}\mathcal{R}\right], \quad z > 0$$

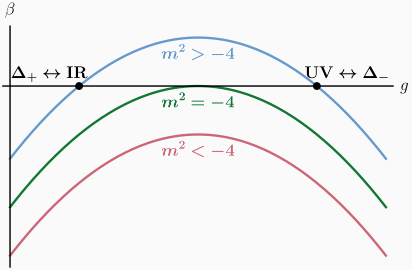
The field ϕ has two scaling solutions near the boundary $z \sim 0$ corresponding two different boundary theories with $[\mathcal{O}] = \Delta_\pm$.

$$\phi(z \sim 0) = c_\pm(x) z^{\Delta_\pm}, \quad \Delta_\pm = 2 \pm \sqrt{4 + m^2}$$

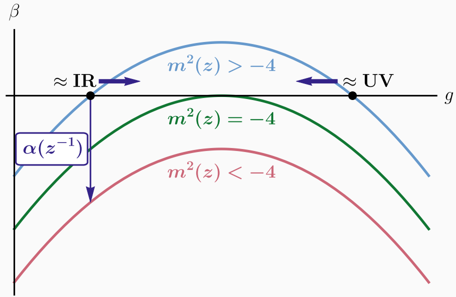
Two solutions merge at the BF bound $m^2 = -4$, below which the theory becomes unstable.

Breihenlohner, Freedman '82

One expects generation of an IR scale through condensation of ϕ.



Decreasing Bulk Mass



Consider a model where the bulk mass m^2 is slowly decreasing function of the bulk coordinate z. The dual theories are approximate CFT's with different quasi fixed points.

Two fixed points walk with RG flow (moving in bulk) and merge at the BF bound resulting loss of conformality and condensation of ϕ.

$$m^2(z) \leftrightarrow \alpha(\mu \sim z^{-1}) \leftrightarrow \text{temporal loading in SOC}$$

Ansatz for the Bulk Mass

Study the theory on AdS_5 where the scalar field ϕ is replaced by the Higgs H with the following bulk dependence for its mass.

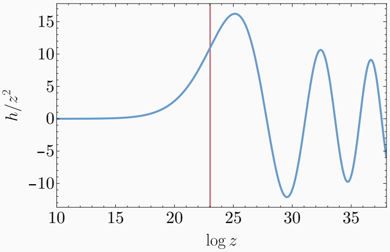
$$m^2(z) = -4 + \delta m^2 - \lambda z^\epsilon, \quad \epsilon \sim \mathcal{O}(.1), \quad \delta m^2 \sim \mathcal{O}(1) > 0$$

The bulk mass starts above the BF bound $m^2 = -4$ at $z = 0$ and crosses it at some value of z.

The behavior of the Higgs VEV $h = \langle H \rangle / \sqrt{2}$ changes after $m^2(z)$ crosses the BF Bound

UV : $h \sim z^{2+\sqrt{\delta m^2}}$

IR : $h \sim z^{2-\epsilon/4} \cos\left(\sqrt{\lambda} \log z\right)$



5D Model for Self-Critical Higgs

CE, Hubisz, Rigo '18

A 5D Higgs with changing bulk mass and UV brane sent to the AdS boundary (with $k = 1$)

$$S = \int \mathrm{d}^5x \, \sqrt{g} \left[|\partial_m H|^2 + \frac{6}{\kappa^2} - m^2(z)|H|^2 - \frac{1}{2\kappa^2}\mathcal{R} \right] - \int \mathrm{d}^4x \, \sqrt{g_0} M_0^2 |H|^2 \bigg|_{z \to 0} - \int \mathrm{d}^4x \, \sqrt{g_1} V_1(|H|) \bigg|_{z=z_1}$$

The metric is asymptotically AdS, up to a backreaction term

$$\mathrm{d}s^2 = \frac{1}{(kz)^2} \left(\eta_{\mu\nu} \, \mathrm{d}x^\mu \, \mathrm{d}x^\nu - \frac{\mathrm{d}z^2}{G(z)} \right),$$

Bunk, Jain, Hubisz '17

The effective potential for the radion is a pure IR boundary term

$$V_{\text{rad}} = \frac{1}{z_1^4} \left[V_1(|H|) + \frac{6}{\kappa^2}\sqrt{G} \right]$$

Belazzini, Csáki, Hubisz, Serra, Terning '14

Spontaneous Symmetry Breaking

Whether the Higgs gets a non-zero VEV will be determined by the IR brane potential through the IR boundary condition

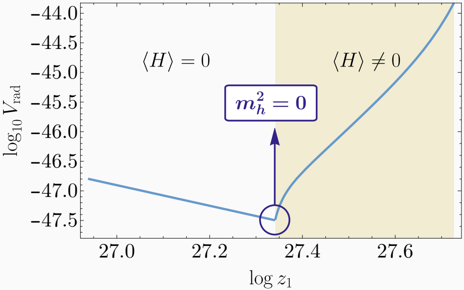
$$z_1 H'(z_1) = -\frac{1}{2}\frac{\partial V_1}{\partial H^\dagger}\bigg|_{z=z_1} \quad , \quad V_1(|H|) = T_1 + \lambda_H |H|^2 \left(|H|^2 - v_H^2\right)$$

A non-trivial Higgs VEV ($\langle H \rangle \neq 0$) exists when

$$\frac{1}{\epsilon}\left(\lambda_H v_H^2 - 4\right) \geq \frac{x J'_\nu(x)}{J_\nu(x)}, \quad \nu \equiv \frac{2\sqrt{\delta m^2}}{\epsilon}\, , \; x \equiv \frac{2\sqrt{\lambda} {z_1}^{\epsilon/2}}{\epsilon}$$

Existence of SSB will be determined by the brane separation and $m^2(z_1)$ should be below BF bound (log-periodic regime needed).

Radion Potential



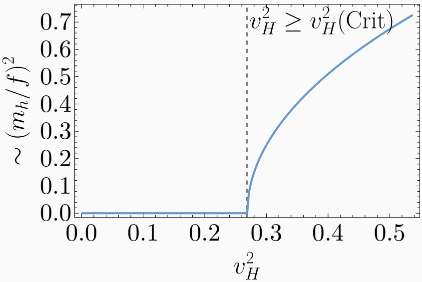
There exist a kink singularity in the radion potential when

$$0 < \delta T < \frac{1}{128\lambda_H}\left[4m^2(z_c) - \lambda_H v_H^2\left(\lambda_H v_H^2 - 8\right)\right]^2$$

which can be achieved without tuning.

Higgs drives itself to its critical region and remains critical under small perturbations like in Self-Organized Criticality.

Broad Critical Region



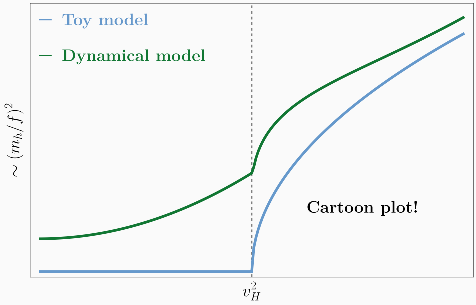
Crucial to the success of the model as self-critical is the existence of a broad critical region over which Higgs remains massless.

In this model this condition is satisfied as there exists a zero mode Higgs for all $v_H^2 < v_H^2(\mathrm{Crit})$. For this region correlation length ξ diverges and all length scales become important.

The running bulk mass $m^2(z)$ can arise from a dynamical model where another scalar bulk field ϕ is coupled to the Higgs.

$$m^2(z) = (m_H^2 - \lambda\phi(z)), \quad \phi \sim \phi_0 z^\epsilon \text{ for small } H$$

In this model $\langle H \rangle \neq 0$ at the minimum of the radion potential but decreases when the brane mass for the Higgs, $m_H^2(\text{brane}) \sim -v_H^2$, becomes more positive, i.e. v_H^2 becomes more negative.



Conclusion

In this work we have discusses a solution to the Higgs hierarchy problem that does not require the presence of light field and tiny couplings.

The model shares common features with Self-Organized systems, namely

- Higgs is driven to its critical point naturally and remains critical under small perturbations.
- There is a broad critical region over which Higgs remains massless.

Next tasks are studying the dynamical model better, include other Standard Model fields into the picture, and investigate the cosmological dynamics.

Thank you!