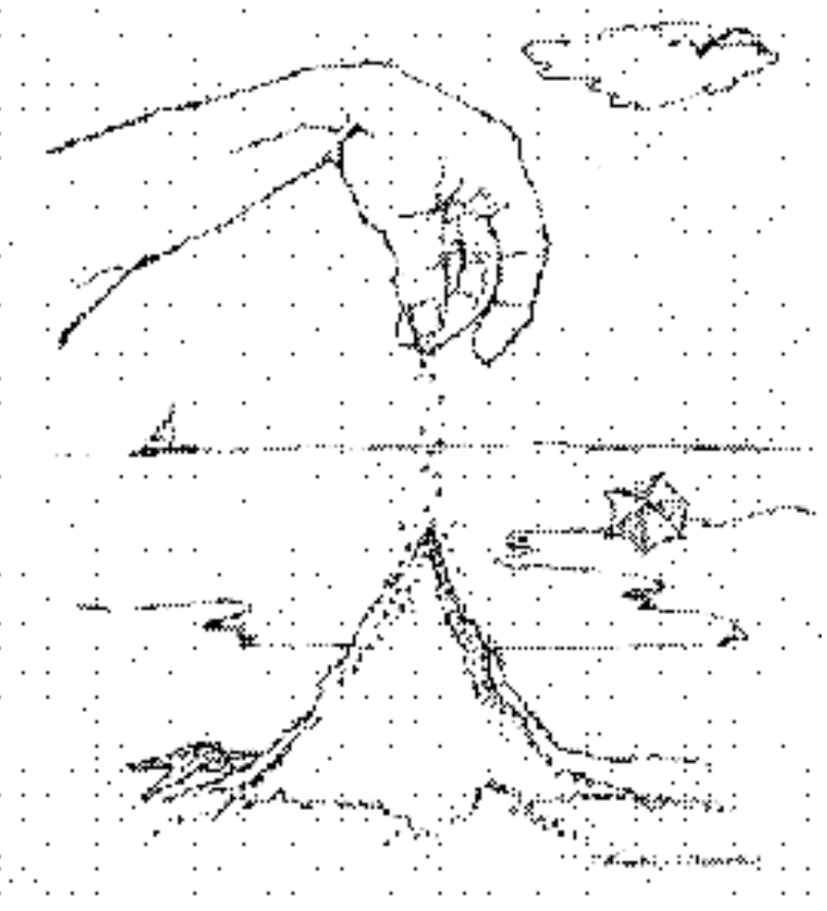
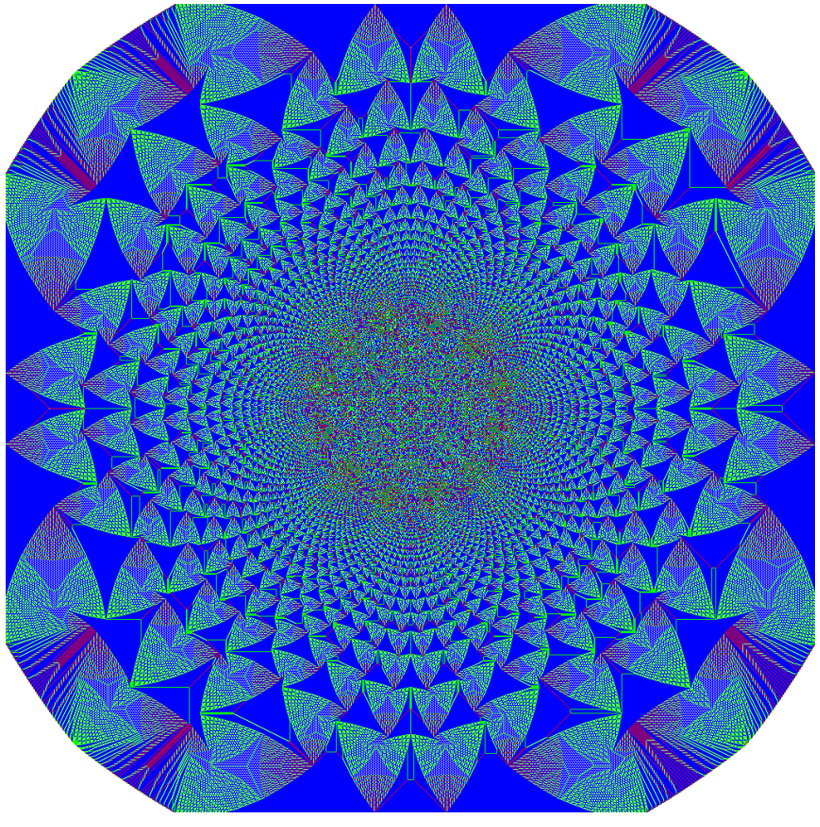
(Seeking)

Self-Organizing Higgs



Jay Hubisz

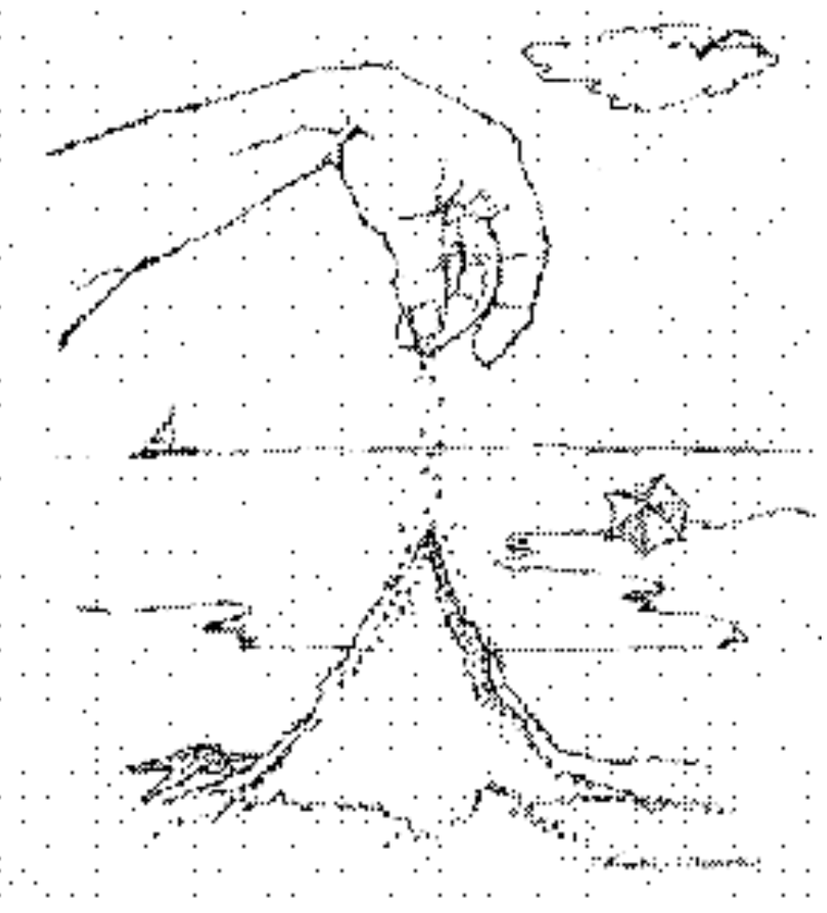
JHU Workshop - Oct 2018
GGI



(Seeking)

Self-Organizing Higgs

(?)?



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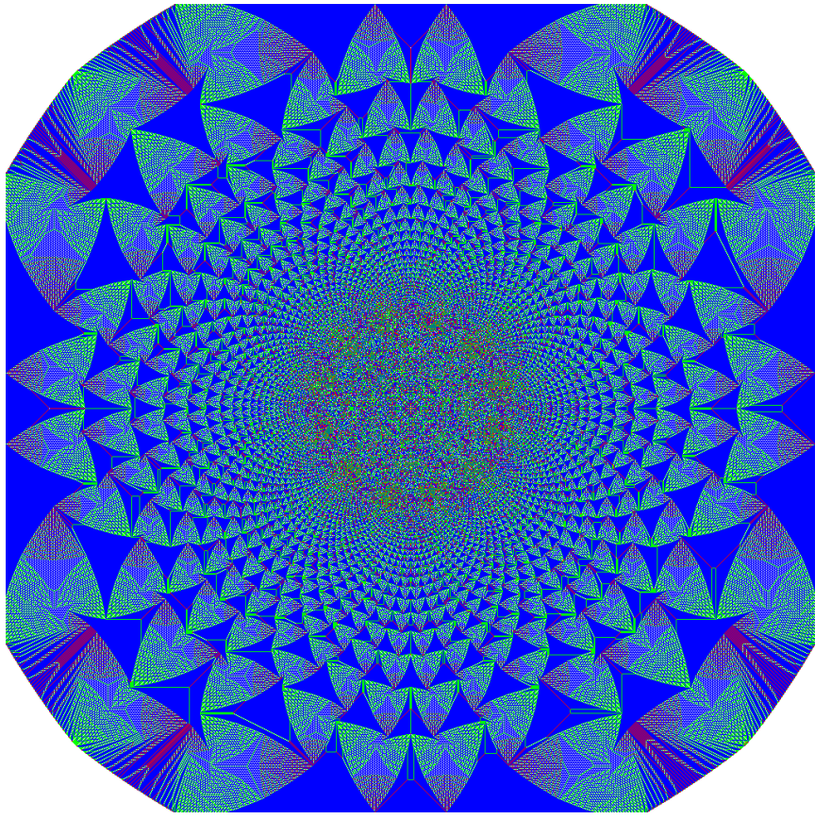


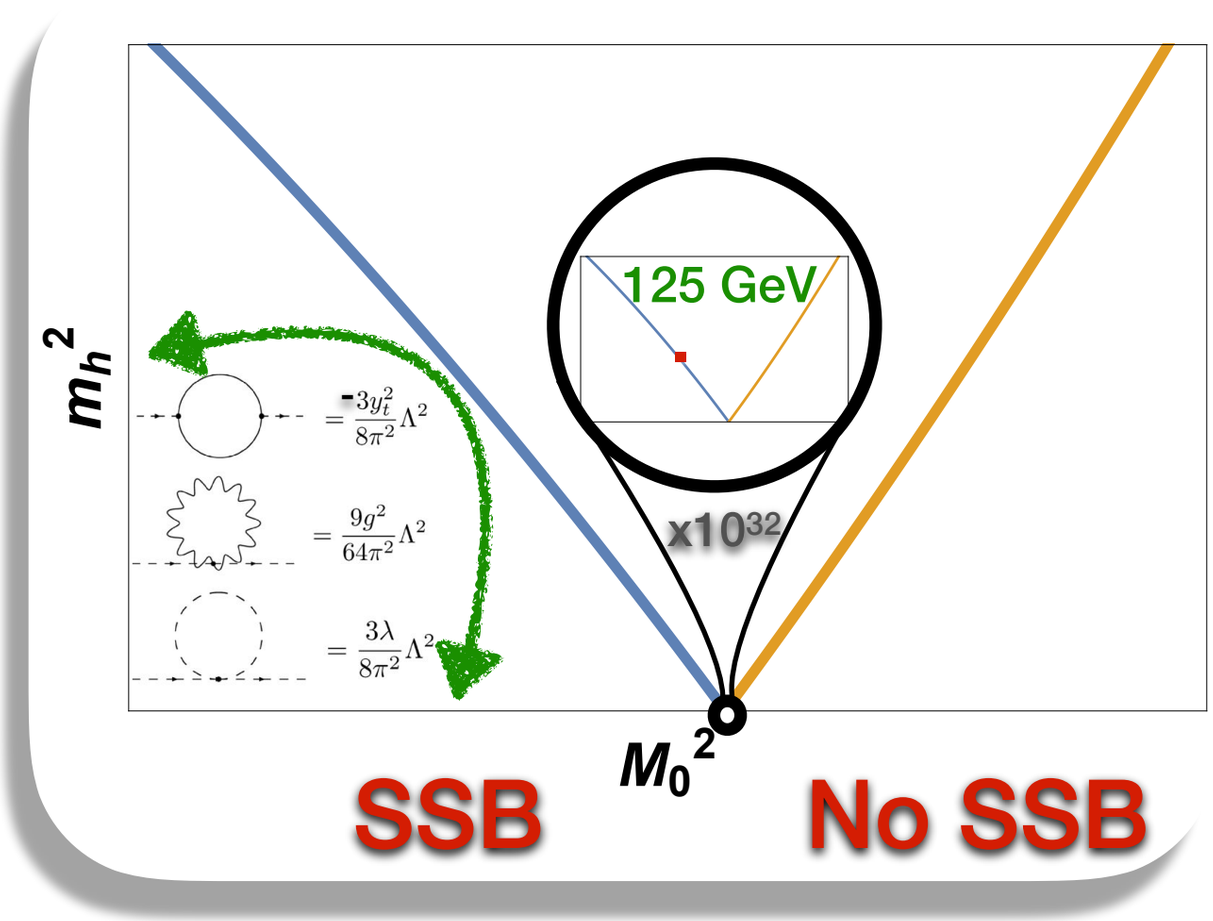
The SM Higgs is Light

(and we don't know why)

Nature gives us this:

$$V(|H|) = M_0^2 |H|^2 + \lambda_0 |H|^4$$

At some high physical mass scale



Our SM is outrageously close to a critical point that appears thus far to be unprotected by symmetry

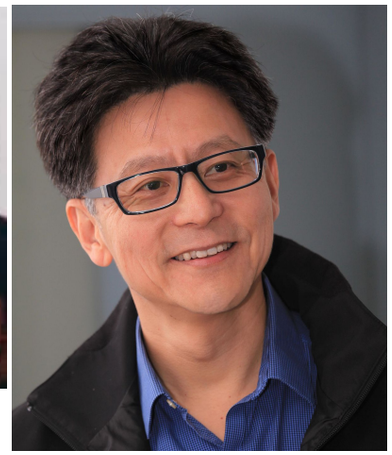
Many great ideas, no exp. evidence for them (yet)
many ruled out,
most of rest under tension

Self-Organization?

- Many (time-dynamical) systems are naturally and easily driven into a state exhibiting characteristics of a critical point
(no tuning needed)
  - Idealized sandpiles (under slow addition of sand)
  - Earthquakes (under continued techtonic strain)
  - Stellar plasma phenomena (injection of star burning energy via convective processes)
  - Financial Markets (inexhaustible supply of human greed)
- Perturbations exhibit scaling laws
  - <u>non-equilibrium critical points</u>

Per Bak

Chao Tang



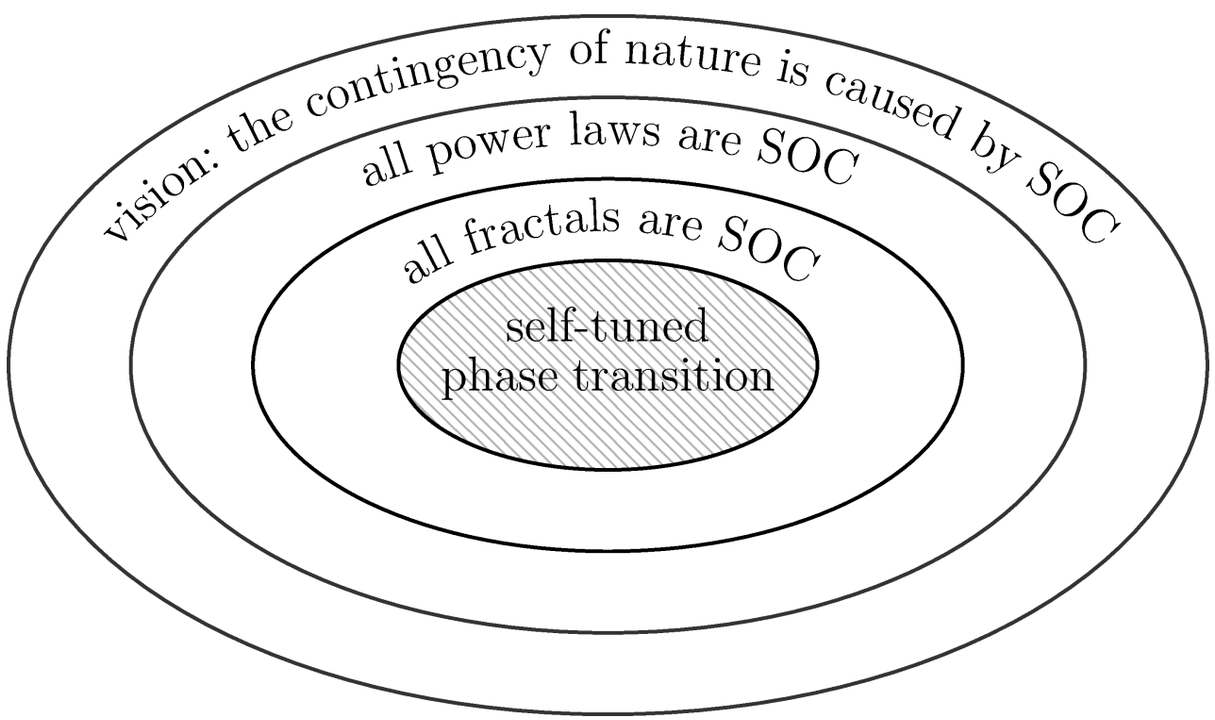
Kurt Weisenfeld

Electroweak physics? Giudice in “Naturally Speaking”

Definition?

- “you know it when you see it…”
- A theory with no relevant scalar deformations

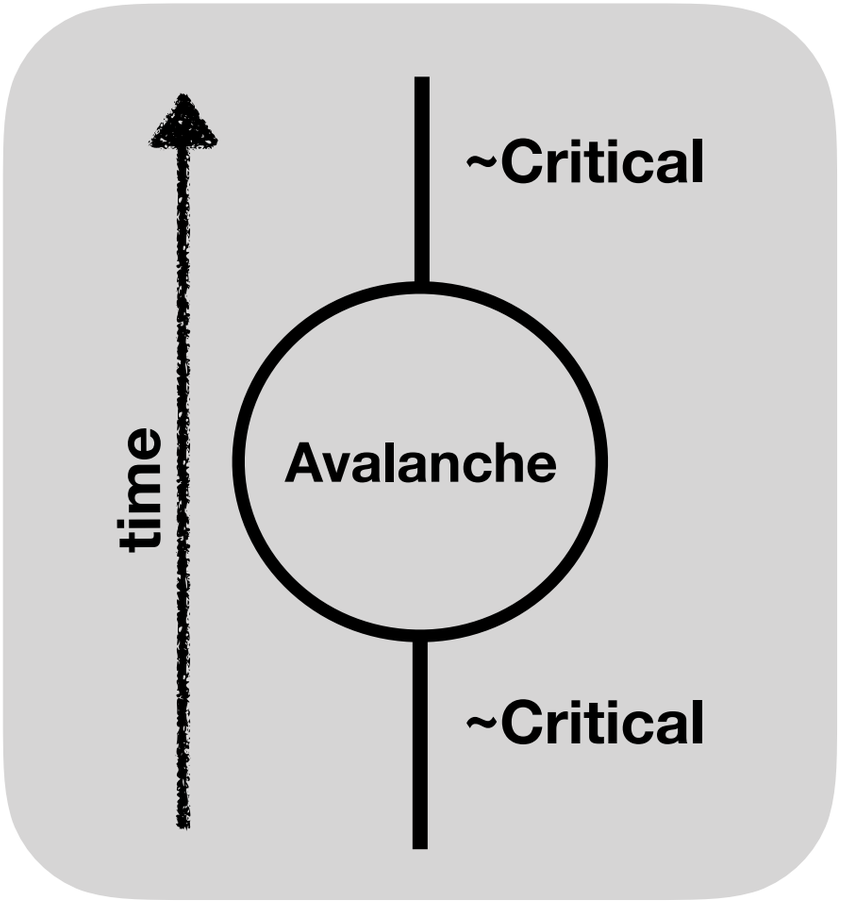
Self-tuning phase transition



Watkins et. al.: 1504.04991

Toy model: Sandpiles (in Nerja)

Slow addition of sand (driving) + release mechanism (avalanches)



Classical events Connect the ~critical state to a new (but self-similar) ~critical state

These events are <u>responsible</u> for maintaining the state of criticality

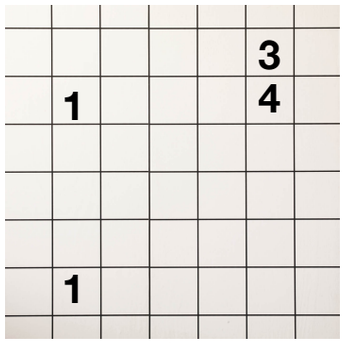
Far-From-Equilibrium system

Microphysics (sand grain) doesn't take into account large scale correlations (pile)

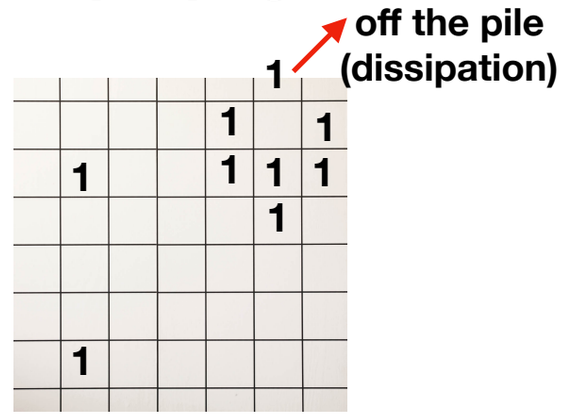
Evolution in time domain

Abelian Sandpile:

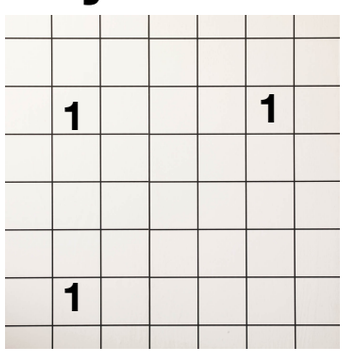
If you hit 4 spread out



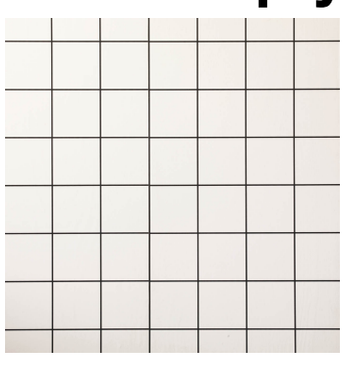
Have to propagate rule



Populate with grains randomly one at a time



Start with empty grid



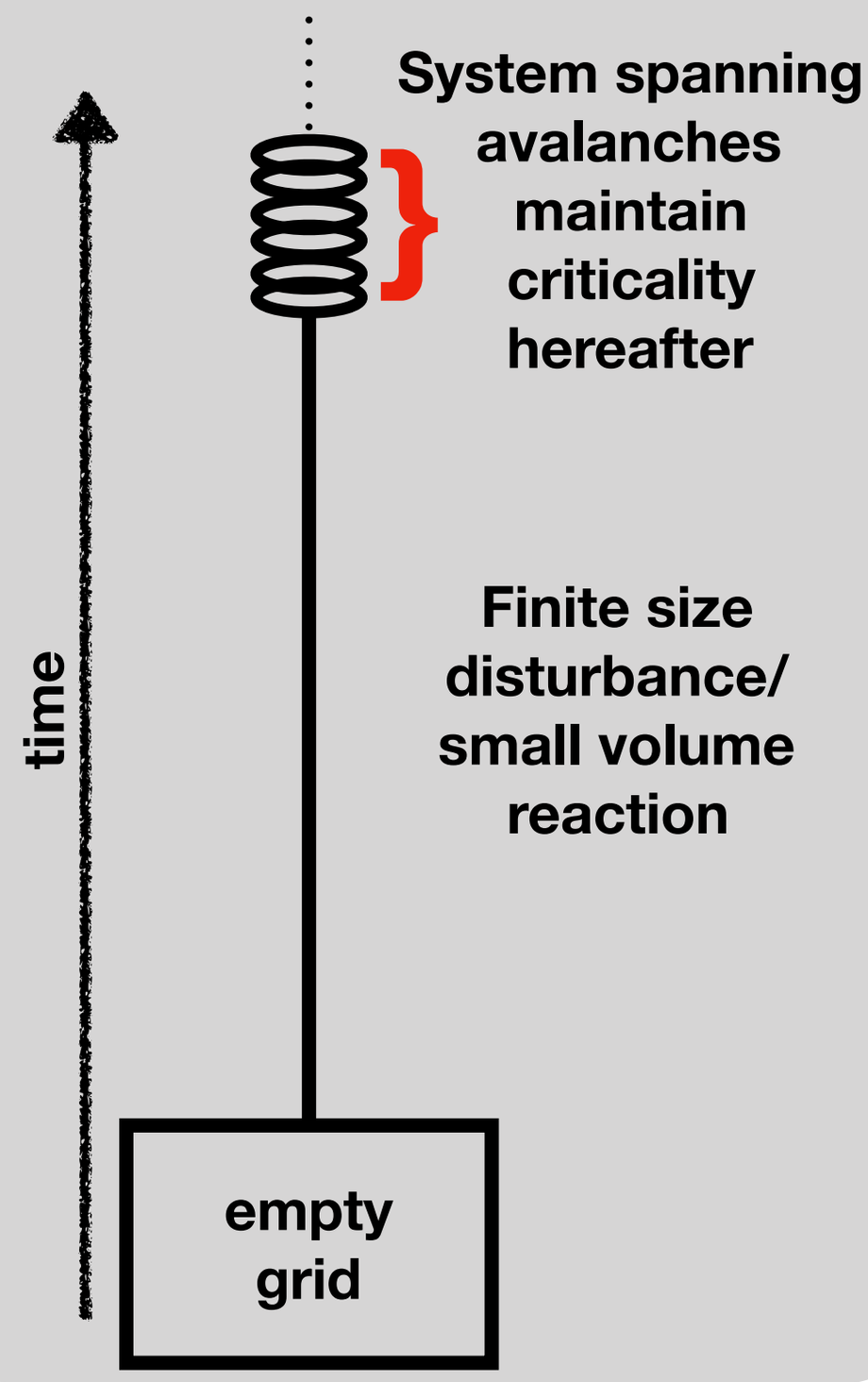
Wait for relaxation*

Continuing, reach critical state

(average occupation 2.125)

*** (hidden tuning)**
overlapping avalanches
overshoot criticality
explicit breaking of conformal invariance

Dynamical "flow"



Complex Scaling Laws?

- It has been guessed at that (at least some) systems with SOC exhibit log-periodic scaling = discrete scale invariance at threshold of adjustment (e.g. work of Didier Sornette et. al. on earthquakes, financial markets)

- The log-periodic power law - discrete scale invariance

$$\Delta = \delta \pm i\gamma \qquad \langle O(0)O(x)\rangle \propto \frac{1}{|x|^{2\Delta}} \sim \frac{1}{|x|^{2\delta}}\cos(\gamma \log|x|)$$

- Issue? Discrete scale invariance/limit cycles not an "allowed" endpoint for 4D RG flow (a-theorem)
  (Komargodski/Schwimmer, Luty/Polchinski/Rattazzi)

  - In 4D, if such a behavior is approached in IR, likely a gap/phase transition

- In AdS/CFT, complex scalar scaling law = violation of Breitenlohner Freedman bound ($m^2 = -4$ in 5D AdS) - tachyons in spectrum of fluctuations

5D AdS: $\mathscr{L} = \frac{1}{2}((\partial_M\phi)^2 - m^2\phi^2)$ $\qquad \phi \propto z^{2\pm\sqrt{4+m^2}} \sim z^2\cos(\gamma \log z)$

Plays leading role in novel phases of quantum matter in holographic superconductors
Hartnoll, Sachdev 1612.07324

Critical Phenomena

Static

Dynamical

AdS/CFT

$$Z_{\textbf{string}}\left[\phi(x,z)\,|_{z=0}=\phi_0(x)\right]=\left\langle\int d^4x\phi_0(x)\mathcal{O}(x)\right\rangle_{\textbf{CFT}}$$

Jarzynski equality

$$e^{-\Delta F/kT}=\overline{e^{-W/kt}}$$

non-unitary ℂFT's
de Sitter space

Bulk masses = scaling dimensions

$$\phi\propto z^{\Delta_\pm}=z^{2\pm\nu}$$

Conformality Lost

AdS Tachyon

complex scaling laws
discrete scale invariance
log-periodicity

$$z^\sigma\cos(\lambda\log z)$$

O(N) **Log CFT's** **O(-N)**

percolation
turbulence
earthquakes

Randall-Sundrum
dimensional transmutation
conformal symmetry breaking
Goldberger-Wise stabilization

Abelian
Sandpile
c=-2 logCFT
Ruelle - 1303.4310

Out of equilbrium but
steady state conformal
self-organized criticality
violations of locality = memory

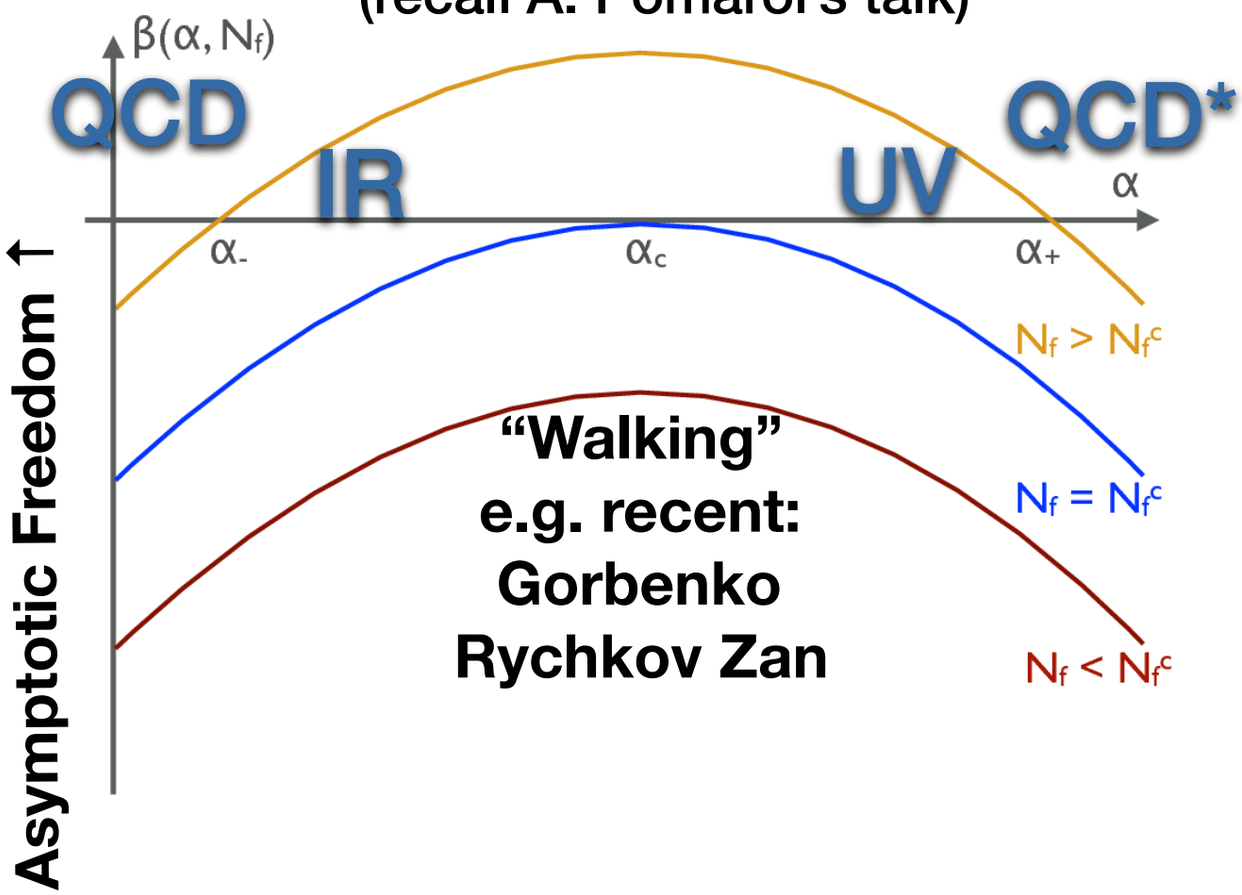
Hogervorst, Paulos, Vichi - 1605.03959
Cardy - 1302.4279

Conformality Lost

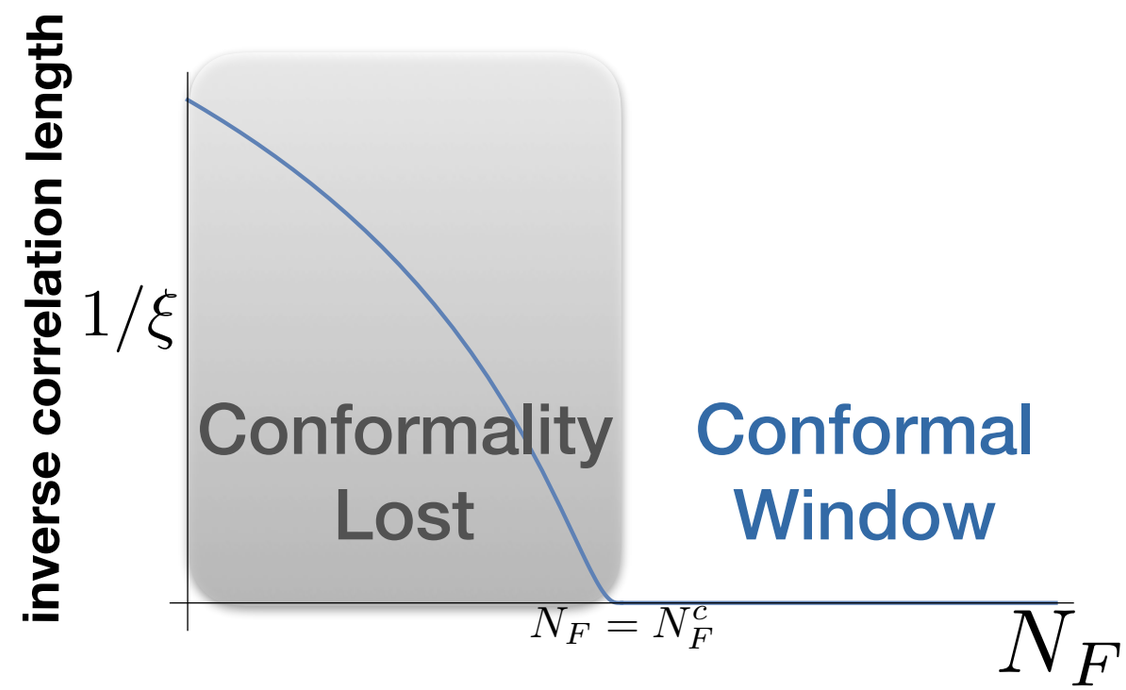
Kaplan, Lee, Son, Stephanov 0905.4752

QCD in/out of conformal window?

(recall A. Pomarol's talk)



Extended critical region Infinite order PT



BKT type scaling below critical N_f

However, QCD* not found by lattice, also global symmetry changing

but could be any external descriptor - not QCD

Holographic Conformality Lost
Two Theories in one bulk:

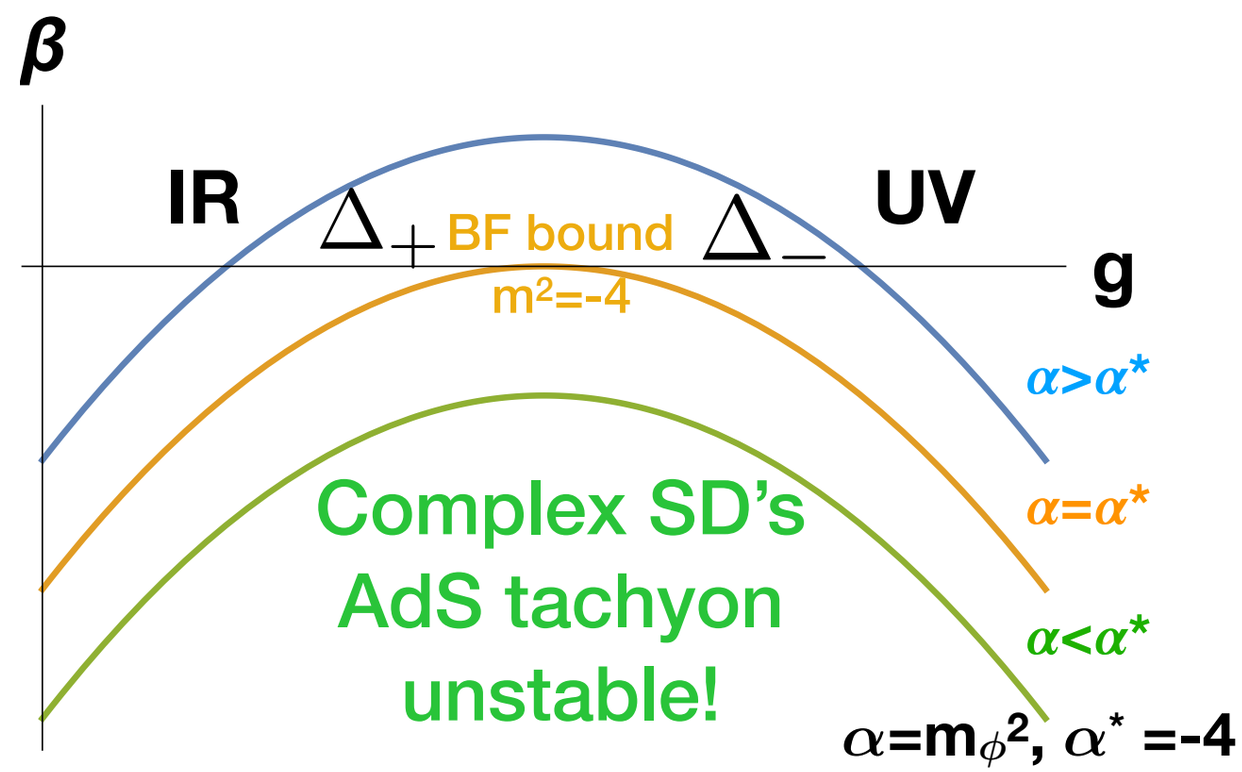
imaginary for $m^2 < -4 \iff$ Log periodic + scaling
(Breitenlohner-Freedman Bound)

Scalar solutions in AdS_5: $\phi \propto z^{2\pm\sqrt{4+m_\phi^2}}$

scaling dimensions
at fixed points
(same operator O)

Conjecture of KLSS:
two solutions are same
microscopic at
different FP

fine tune AdS boundary
theory to hug UV FP



$m^2 < -4$ - An instability arises (AdS tachyon)… Theory must gap to "fix" the instability

Cross the divide dynamically?

attempt a "controlled" experiment - holographic RG flow through the ensemble of theories
Arrange for a walking tour of this landscape

AdS/CFT

$$Z_{\textbf{string}}\left[\phi(x,z)\,|_{z=0}=\phi_0(x)\right]=\left\langle\int d^4x\phi_0(x)\mathcal{O}(x)\right\rangle_{\textbf{CFT}}$$

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Bulk masses = scaling dimensions

$$\phi\propto z^{\Delta_\pm}=z^{2\pm\nu}$$

AdS Tachyon

Slow RG flow

Conformality Lost

complex scaling laws
discrete scale invariance
log-periodicity

$$z^\sigma\cos(\lambda\log z)$$

percolation
turbulence
earthquakes

? ? IR ? ? ?

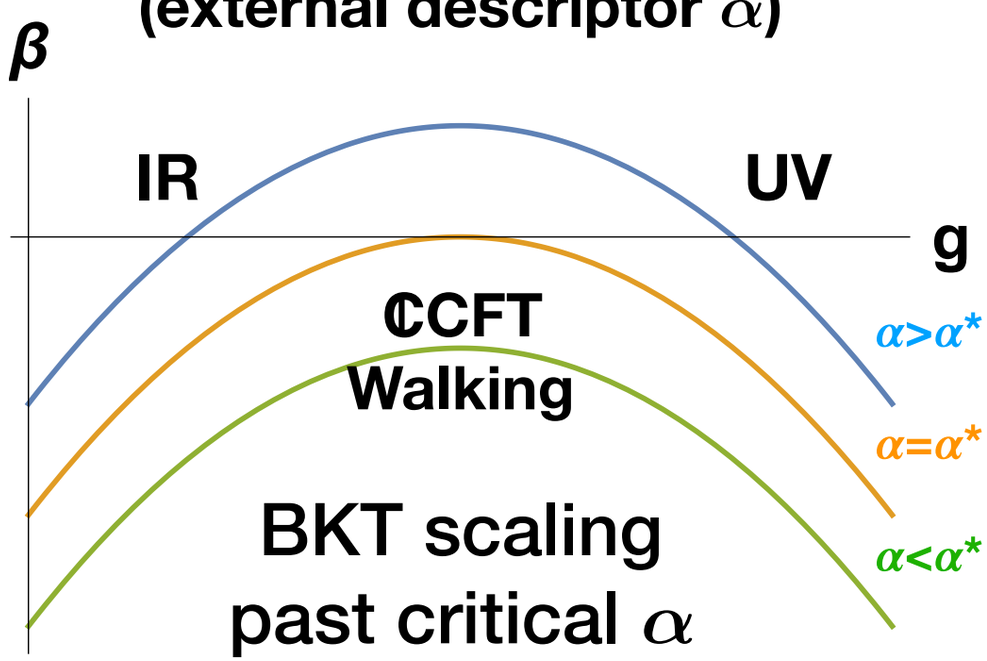
Randall-Sundrum
dimensional transmutation
conformal symmetry breaking
Goldberger-Wise stabilization

Out of equilbrium but
steady state conformal
self-organized criticality
violations of locality = memory

Slowly Driving off the Edge

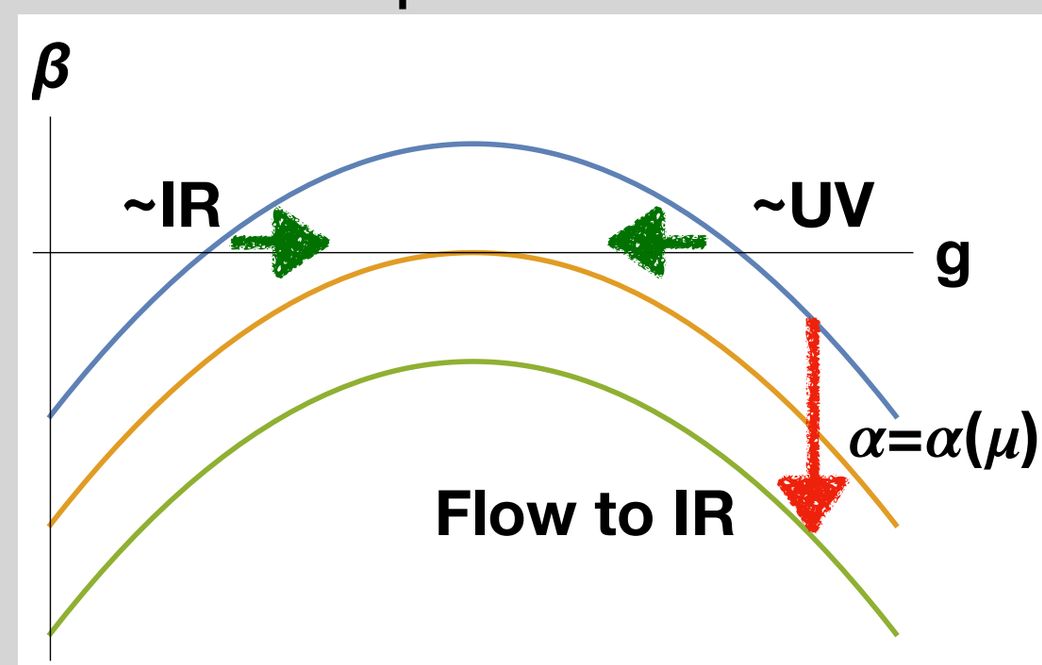
RG flow "builds" the sandpile?

Conformality Lost
in/out of the conformal window
(external descriptor α)



Our Proposal: Eröncel, Rigo, JH - 1804.00004

enlarge theory, break CFT explicitly
(but slightly)
Walk out the quasi-conformal window



~Fixed point <u>flows</u> into
ℂ-plane, ℂ scaling law

Instability arrived at via dimensional transmutation (like dyn. EWSB)

Spontaneously broken ~CFT? TC/QCD type confinement?
Not "standard" instability…Something more novel?
Striped/crystalline phases in Holographic Superconductors… Hartnoll Lucas Sachdev 2016

4D picture:
Two operators and a 3-point

- CFT with two operators O_ϕ and O_H, with O_H transforming under some global symmetry

- Dimensions are $[O_\phi] = 4-\varepsilon$ and $[\, O_H \,] \approx 2$, and (large N): $[\, O_H^\dagger\, O_H \,] \approx 4$

- Non-trivial 3 point: $\langle\, O_\phi\, O_H^\dagger\, O_H \,\rangle \neq 0$

- Turn on O_ϕ - marginally relevant deformation, would (on its own) condense/cause confinement of some variety $\mathscr{L} = \mathscr{L}_{\textbf{CFT}} + g O_\phi$

  - but dimension of O_H <u>runs</u> due to 3-pt (into complex plane/discrete scaling law regime)

Holographic dual:

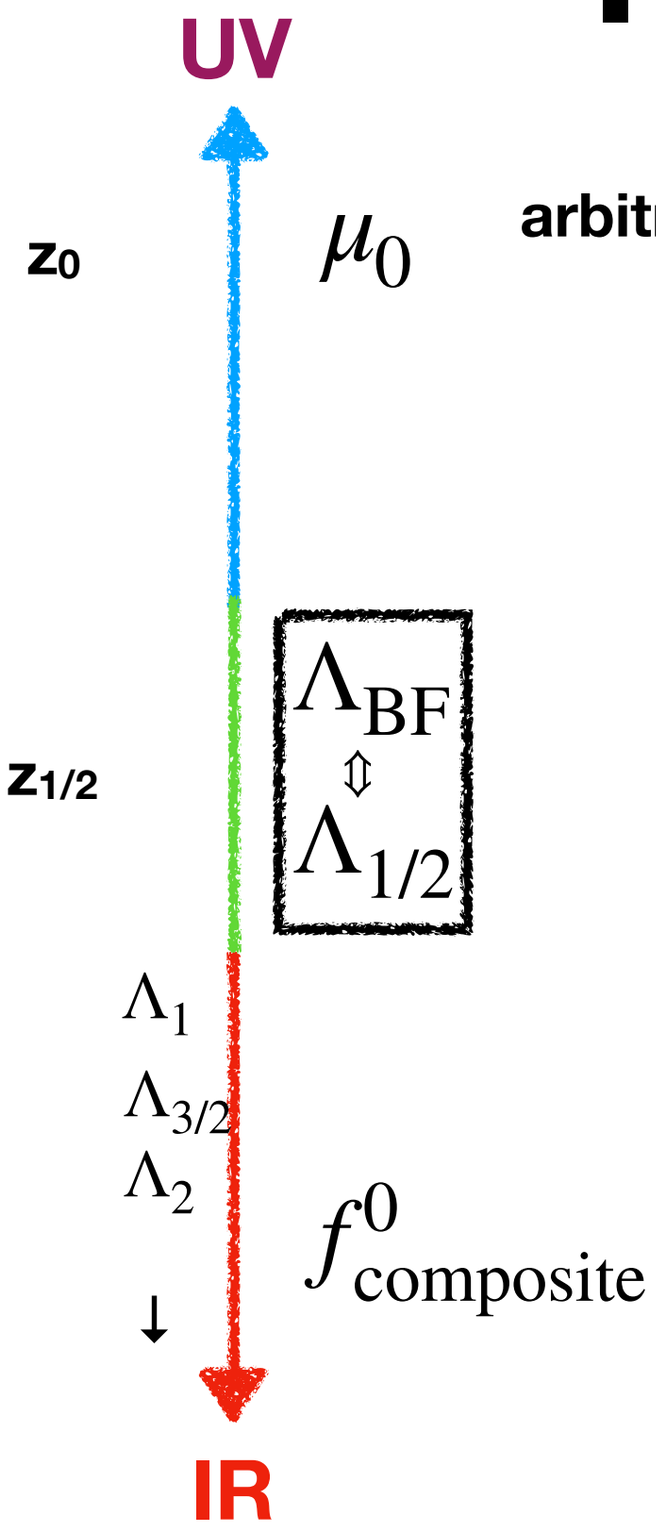
- We “send in” to the 5D bulk the dual to a marginally relevant deformation of CFT - vev of 5D scalar with small negative 5D mass^2
  (same as Goldberger-Wise stabilization story)

- BUT: 5D physics is arranged such that this growing deformation inevitably sends dual to scaling dimension of another operator into complex plane
  (effective 5D mass^2 term of 2nd scalar crosses BF bound)
  Happens somewhere deep into the bulk, away from UV brane

- bulk physics can be solved for classically, 5D physics giving us clues to possible vacuum characteristics of dual strongly coupled theories that “walk out of the (quasi) conformal window”
  (and towards forbidden discrete scaling laws = instability)

- result of “experiment” specifies resulting emergent IR physics, telling us manner in which the theory gaps to avoid the instability

IR Scales



arbitrary place to set UV boundary condition
BF bound not violated

$\alpha(\mu_0)$

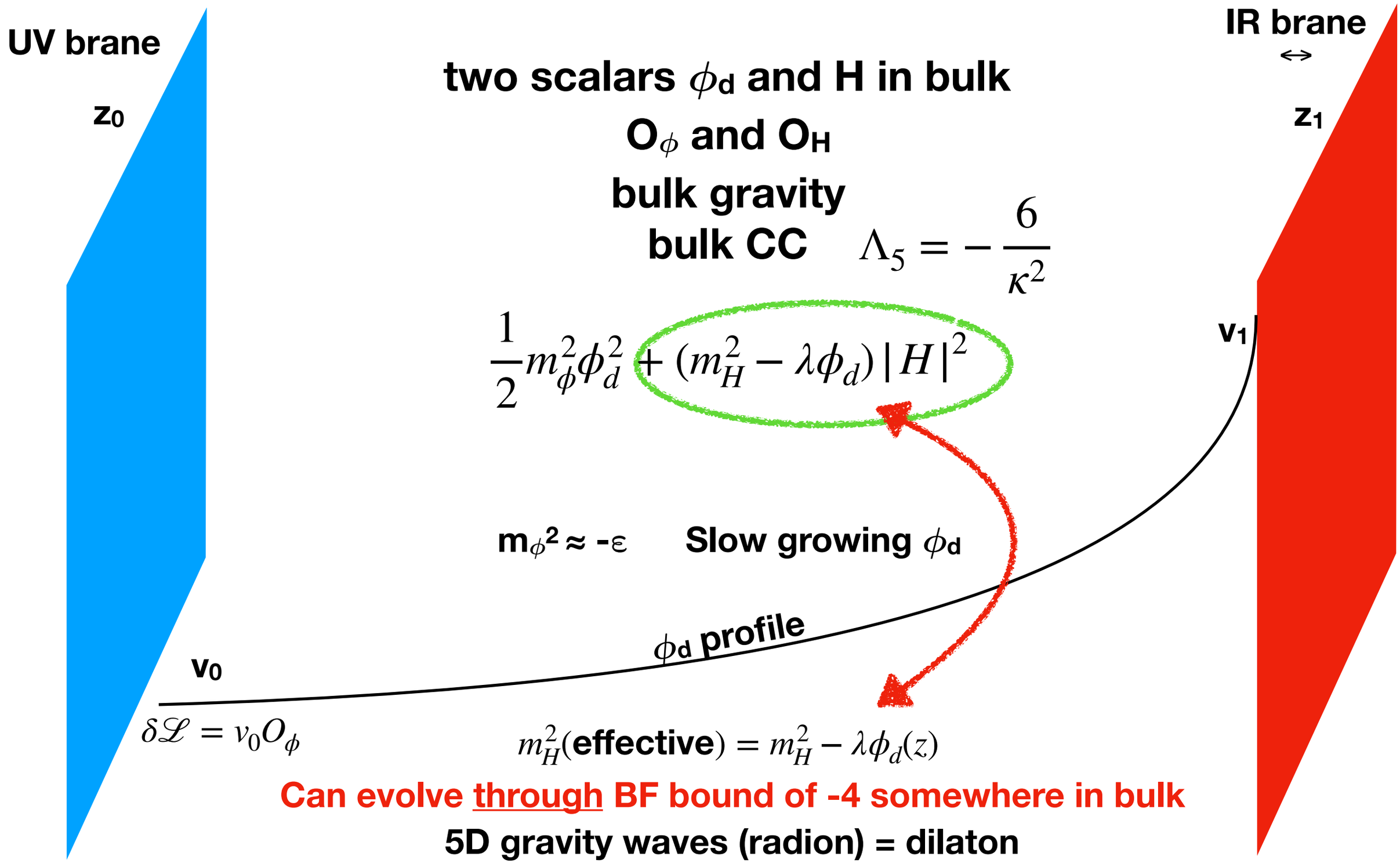
violation of BF bound in 5D
AdS tachyon at or before $\Lambda_{1/2}$
1/2 cycle of discrete SI

Scales of physical gap around here?

Compositeness (KK) scale
in absence of BF bound violation

only $\alpha(\mu)$ deformation

Corresponding 5D Model:



two scalars ϕ_d and H in bulk

O_ϕ and O_H

bulk gravity

bulk CC $\Lambda_5 = -\dfrac{6}{\kappa^2}$

$$\frac{1}{2}m_\phi^2\phi_d^2 + (m_H^2 - \lambda\phi_d)|H|^2$$

$m_\phi^2 \approx -\varepsilon$ **Slow growing ϕ_d**

$\delta\mathscr{L} = v_0 O_\phi$

m_H^2(**effective**) $= m_H^2 - \lambda\phi_d(z)$

Can evolve <u>through</u> BF bound of -4 somewhere in bulk

5D gravity waves (radion) = dilaton

$V_0(|H|) = m_0^2|H|^2$

$V_1(|H|) = \lambda_H|H|^2(|H|^2 - v_H^2)$

Procedure:

- Find solutions to scalar equations of motion
- back-react on geometry - solve for metric from Einstein equations
- Compute effective 4D potential:
  - classical brane Casimir = radion potential (dual to dilaton potential)
  - read off dynamics of IR brane

5D Gravity

$$ds^2 = \frac{1}{z^2}\left[dx_4^2 - \frac{dz^2}{G(z)}\right]$$

AdS space: $G(z) \to 1$

- Imposing 55-component of EE's on bulk action (taking into account GHY boundary terms) total action reduces to pure boundary term, giving effective "potential":

$$V_{\text{rad}} = \frac{1}{z_0^4}\left[V_0 - \frac{6}{\kappa^2}\sqrt{G_0}\right] + \frac{1}{z_1^4}\left[V_1 + \frac{6}{\kappa^2}\sqrt{G_1}\right]$$

00-component (or ii) give brane junction conditions - Gauss Law constraints requires vanishing of both UV and IR terms - satisfy trivially with $\delta g_{\mu\nu}$=0

consistency condition for metric ansatz often same as finding minimum of above

$$G = -\frac{\frac{\kappa^2}{6}V(\phi_d, |H|)}{1 - \frac{\kappa^2}{12}\sum (z\phi'_i)^2}$$

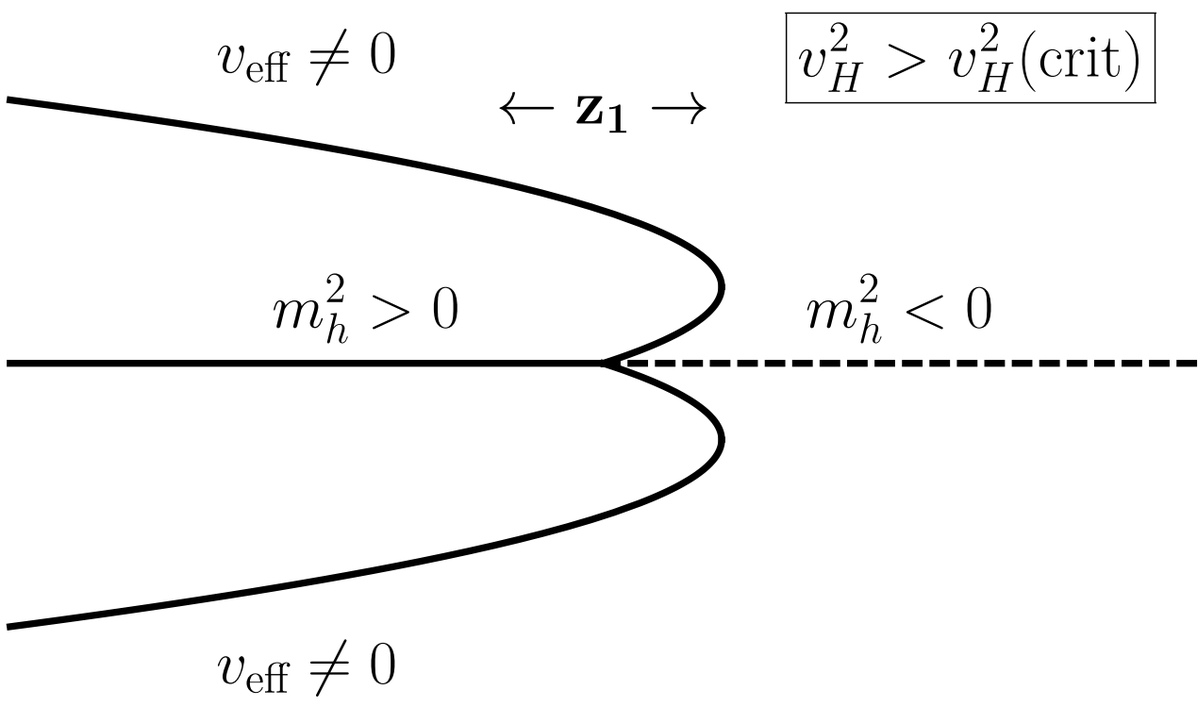
Just plug in solutions for scalar fields on boundaries to get potential

Solving for the Higgs

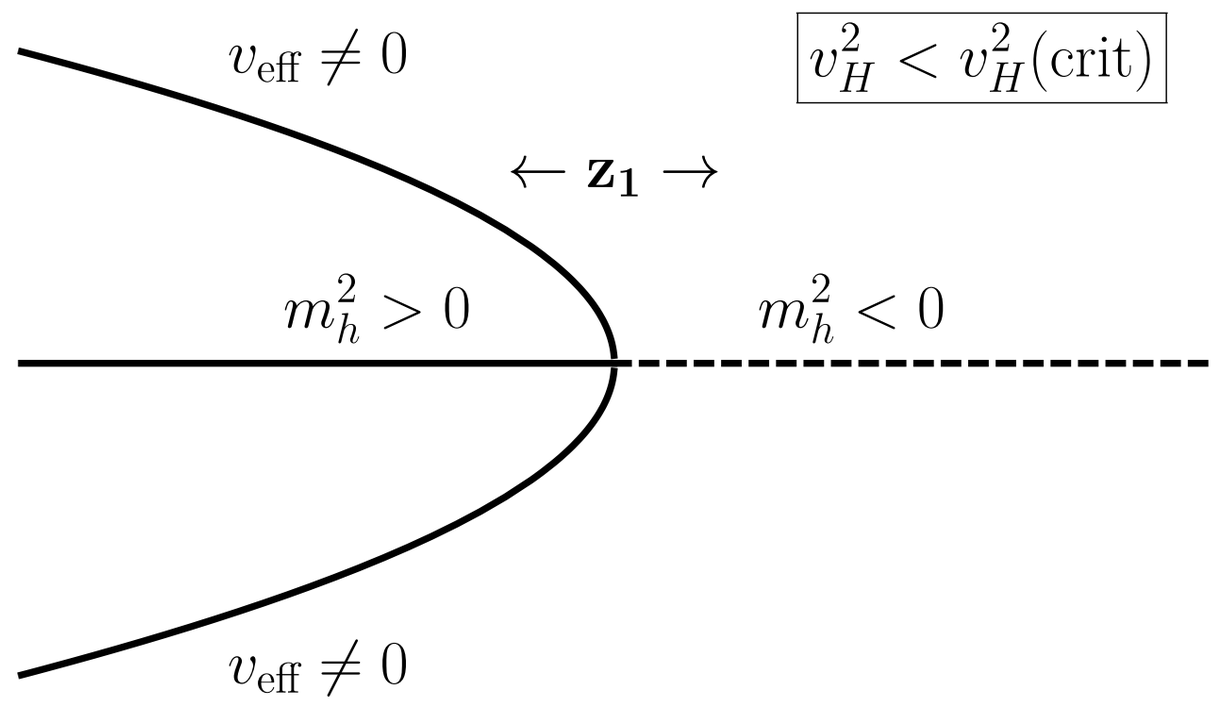
Behavior depends crucially on value of IR brane localized Higgs mass squared term

$$V_1(|H|) = \lambda_H |H|^2 (|H|^2 - v_H^2)$$

More tachyonic



Less tachyonic
(even positive brane Higgs mass²)



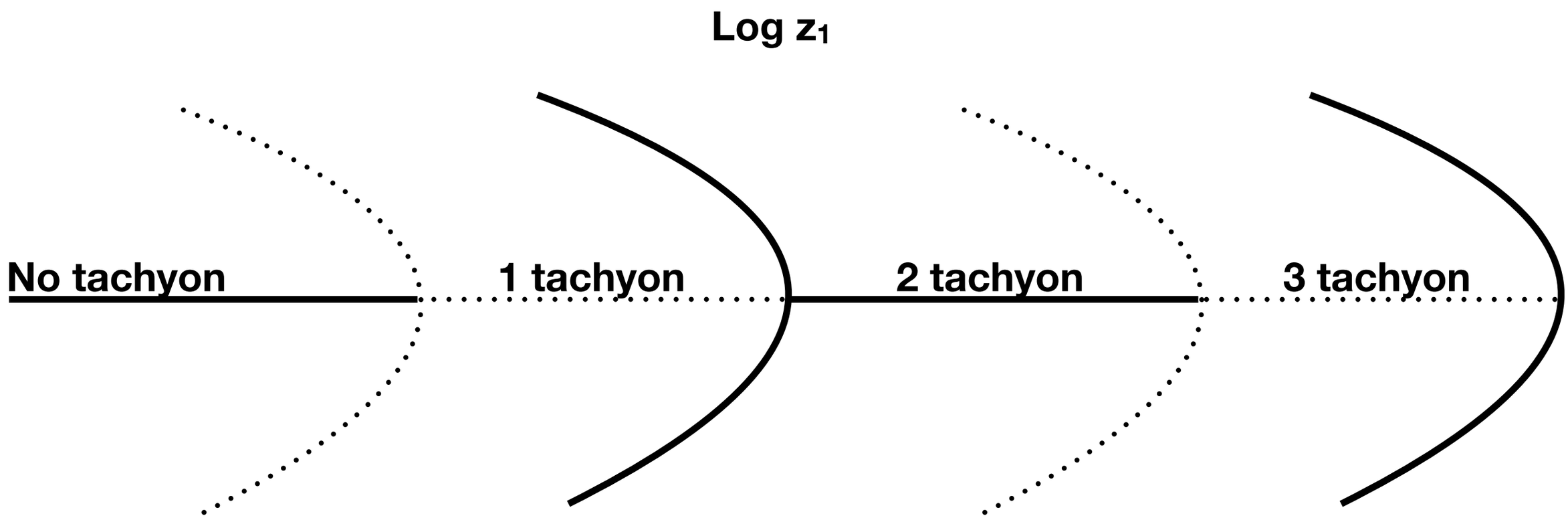
For given z_1, may be two solutions, one with no Higgs vev, the other with "symmetry breaking"
for larger z_1, no solution at all without instability

$$f_{\mathbf{tot}} \sim 1/z_1$$

For given f_{tot}, two configs of operator vevs - minimum value of f_{tot} (avoiding tachyon)

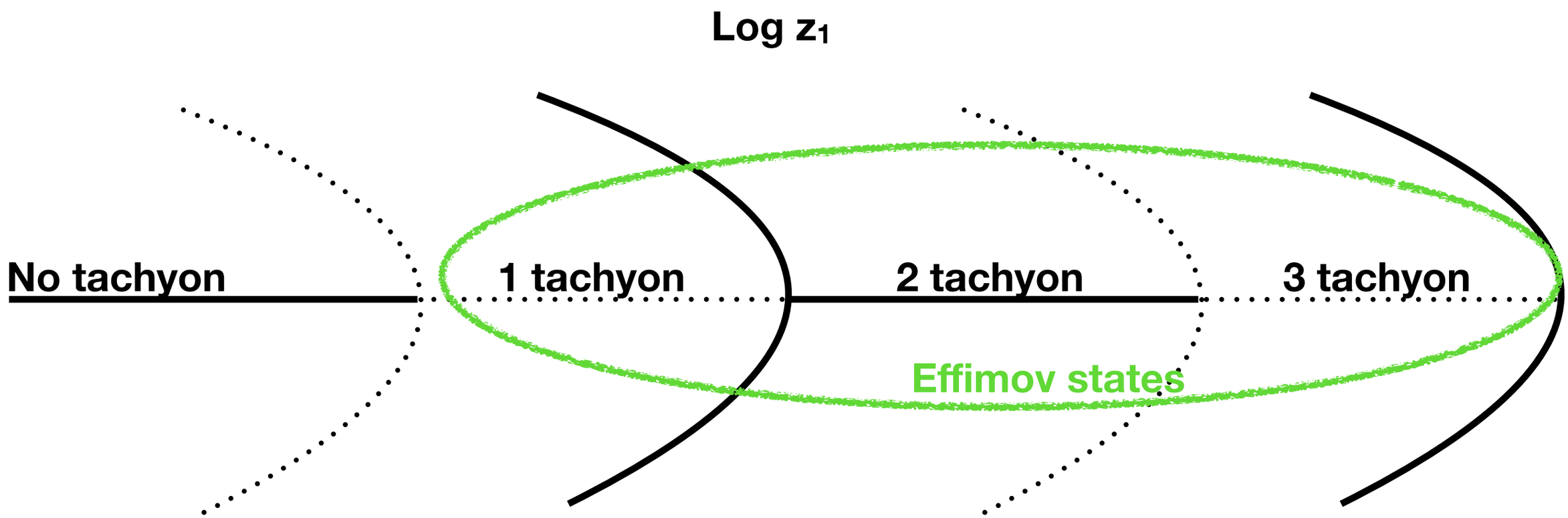
Mapping out the potential Preliminary:

0-momentum solutions to Higgs EOM



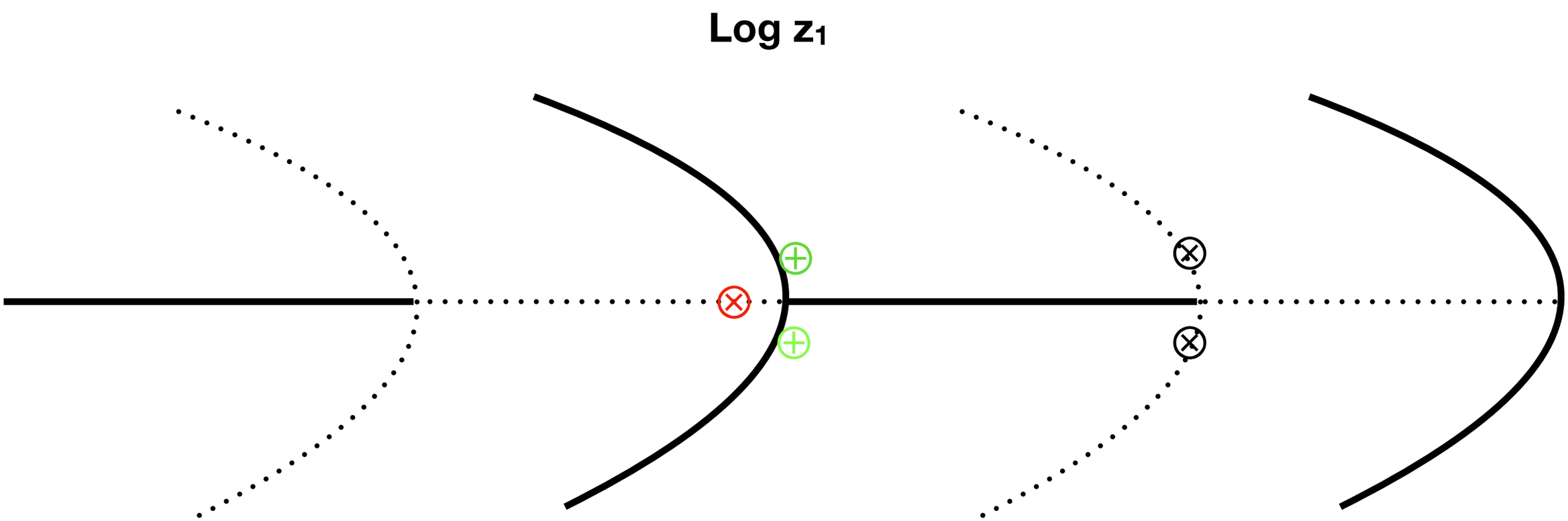
Mapping out the potential Preliminary:

0-momentum solutions to Higgs EOM



Mapping out the potential Preliminary:

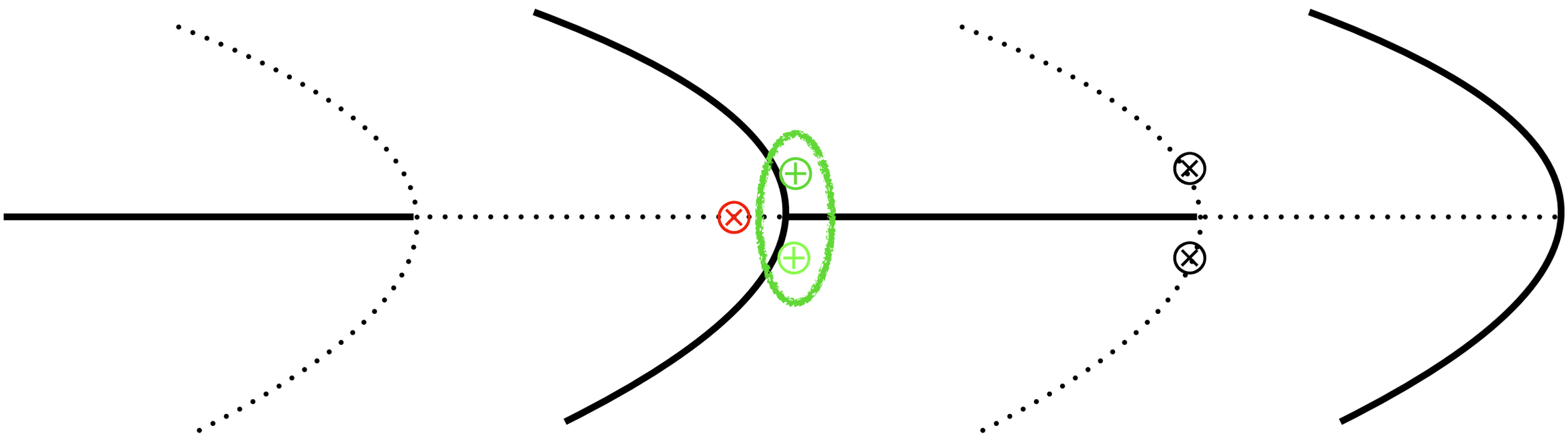
Where is brane junction condition satisfied?



Mapping out the potential Preliminary:

Where is brane junction condition satisfied?

Log z_1



Metric junction conditions satisfied here
Numerically extremely close to axis (tiny v/f)

What's not clear - it's the 2nd KK mode that is picking a vev here

Prospects

- Still a (long) journey before this can be thought of as applicable to Higgs sector of SM

- really need to know what the cosmology is…what are details of brane stabilization?

  - are all the tachyons resolved?

Conclusions

- We have tried to tackle an emergent AdS tachyon and relate to Higgs pheno
  (motivated by pre-existing conjectures about the self-organized critical state)

  - reached by dual to RG flow starting from seemingly healthy UV FP

  - requires bulk interaction term

- Preliminary evidence for semi-classical vacuum solutions with very small v/f