Higgs Criticality and Radion Dynamics

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Ongoing work with: Cem Eröncel, Gabriele Rigo

A Meso-Tuned Higgs?

- The Higgs boson is light, and no obvious states nearby
- It may be that the Higgs is thus *tuned* to be close to a critical point of some form
  - SM: tuning of SM parameters to lie absurdly close to critical surface in “space” of SM’s (mega-tuning from GUT/M_{Pl})
- Tuning takes different form in different UV completions that ameliorate tuning
  - e.g. SUSY “meso”-tuning - SUSY breaking at M, $m_h << M \sim 10\text{-}100$ TeV

Moduli and Tuning

- Singlet scalars couple to Higgs doublet - effective Higgs mass is function of value of singlet field value

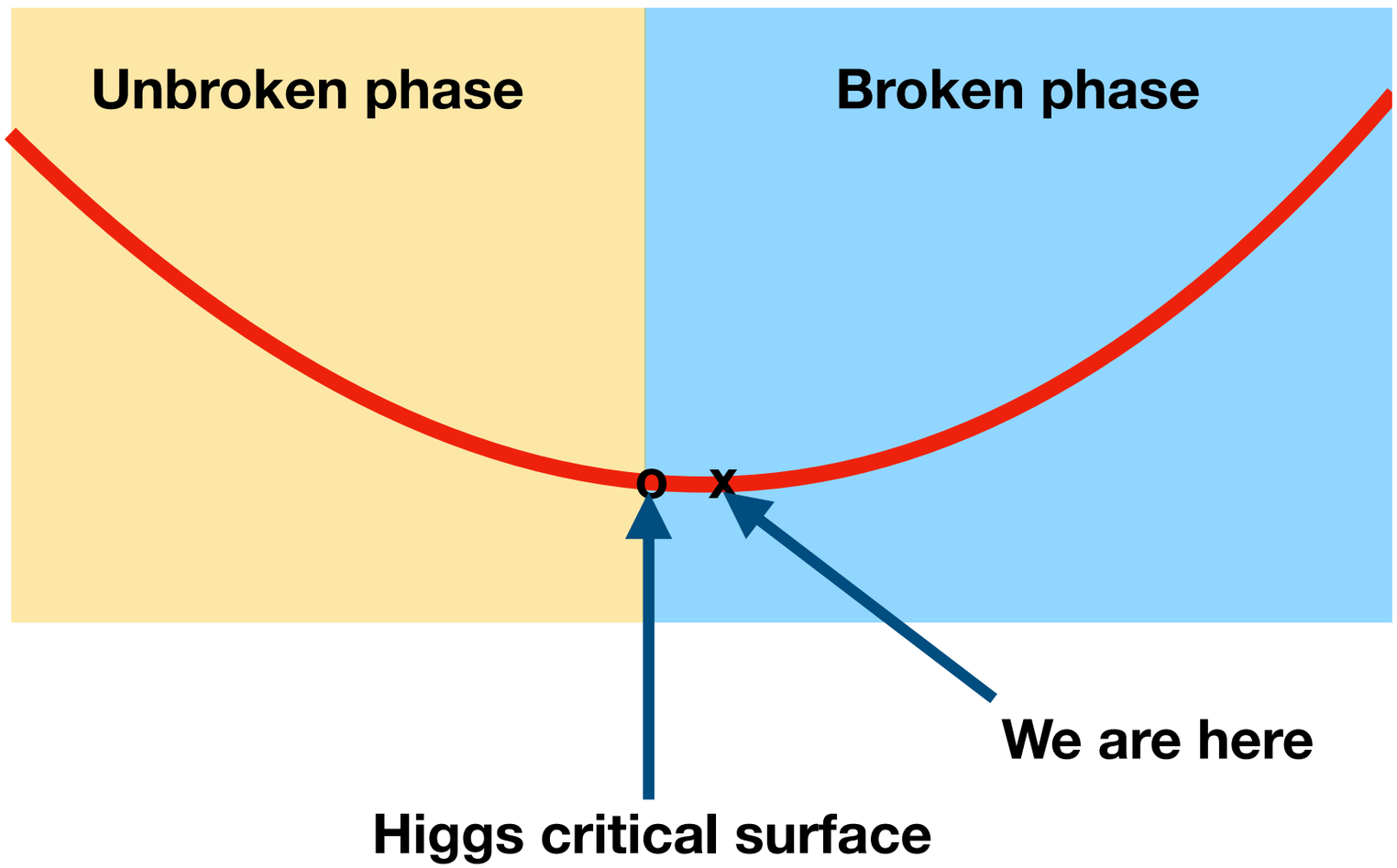
$$\mathscr{L} \ni \left(m_H^2 - \lambda\phi\right)|H|^2 + V(\phi)$$

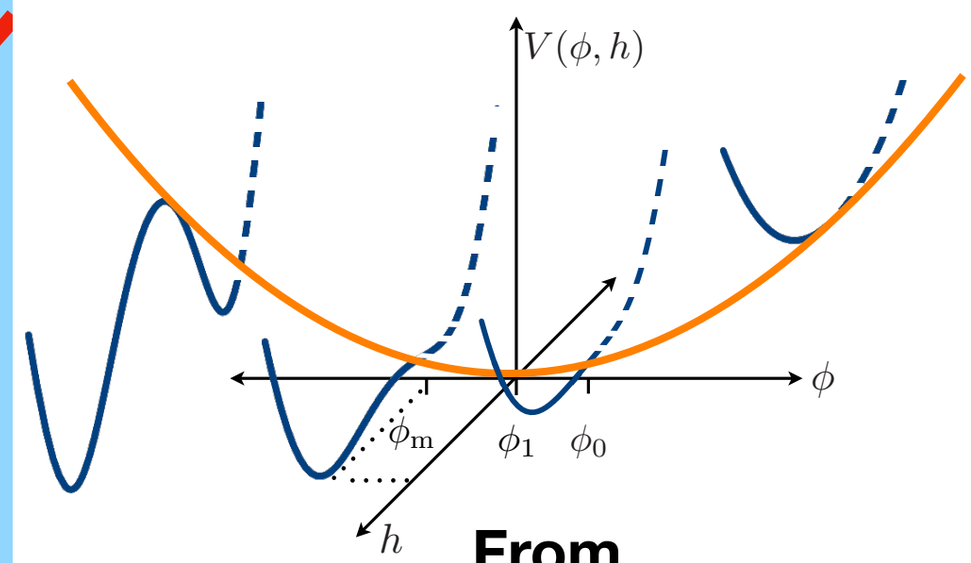
- singlet scans Higgs mass if initial conditions displace it
- being close to Higgs critical surface means minimum of multi-scalar potential tuned to be close to Higgs critical surface
  - see also relaxion type models - wiggles in shallow linear potential start at critical surface, stop rolling at small vev

See e.g.
Amin, Fan, Lozanov, Reece 1802.0044

Moduli and Tuning

Small vev due to tuning of modulus potential minimum near Higgs critical point





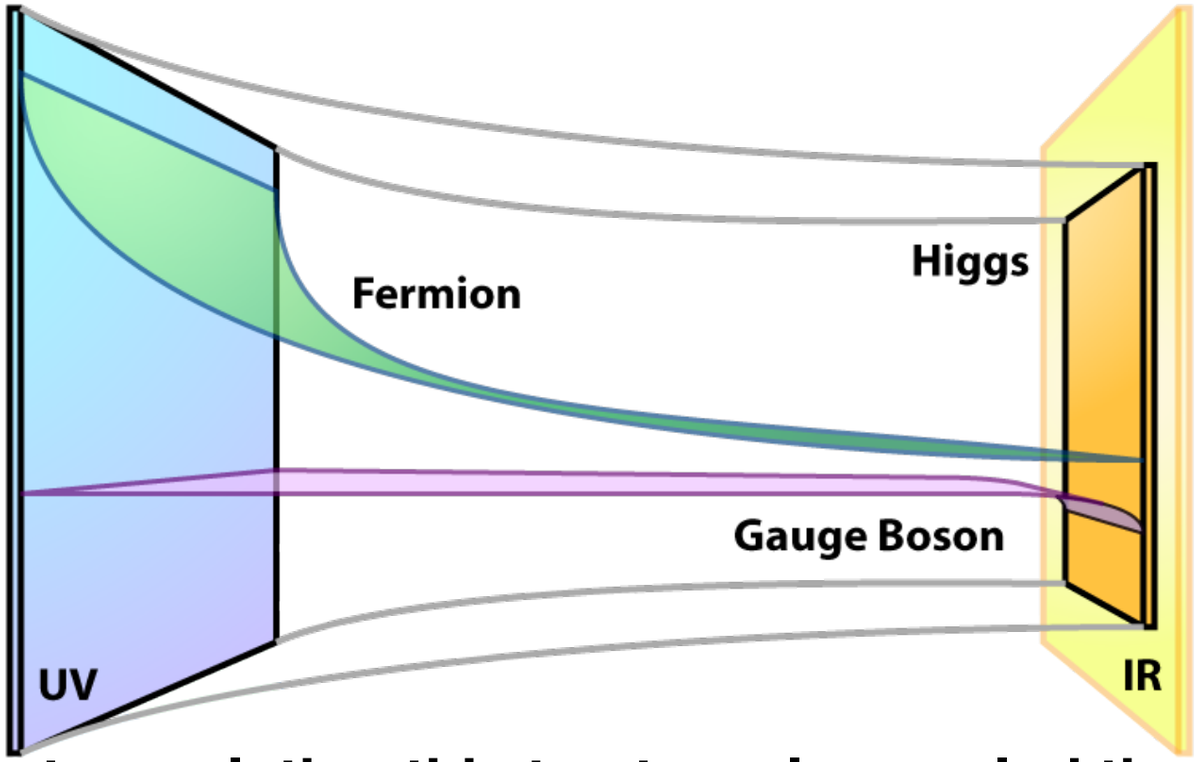
From Amin, Fan, Lozanov, Reece

Mass Scales and Moduli Example (RS):

In extra compactified dimensions, constants describing 4D EFT depend on compactification radius

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{eff}}(R)$$

Famously employed to obtain hierarchies of mass scale: $m \sim f = ke^{-ky_1} \ll m_{\text{UV}}$



AdS/CFT gives a nice story relating this to strongly coupled theories with ~conformal behavior over large range of mass scales: radion=dilaton

Unstable RS

$$ds^2 = e^{-2ky} dx_4^2 - dy^2$$

The original RS radion/dilaton potential is a quartic

Presume tuning of 4D bare cosmological constant: $T_0 = \frac{6}{\kappa^2} k$

Integrate out the bulk, get 4D effective potential (PURE BOUNDARY):

$$V(f = ke^{-ky_1}) = \left[T_0 - \frac{6}{\kappa^2} k \right] + f^4 \left[\frac{T_1}{k^4} + \frac{6}{\kappa^2 k^3} \right]$$

Remaining tuning required - imposes flat direction for the radion/dilaton:

$$f = ke^{-ky_1}$$

Stabilizing RS: Goldberger-Wise

5D Scalar fields get VEV's - break isometries of AdS,

$$dx^2 = e^{-2A(y)}dx_4^2 - dy^2 \qquad A'' \neq 0$$

Potential is still pure boundary, depends on f both in UV and IR portion:

$$V(f) = k^4\left[\frac{V_0(\phi_0(f))}{k^4} - \frac{6}{\kappa^2 k^4}A_0(\phi_0(f))\right] + f^4\left[\frac{V_1(\phi_1(f))}{k^4} + \frac{6}{\kappa^2 k^4}A_1(\phi_1(f))\right]$$

For smallish O(1/10) 5D mass for ϕ, can stabilize geometry - f is the Kaluza Klein scale

$$\phi = \phi_0 e^{\epsilon k y} + \phi_c e^{(4-\epsilon)k y_1}$$

generate large hierarchy without severe tuning

$$V(f) \sim \lambda_\epsilon k^\epsilon f^{4-\epsilon} + \lambda_4 f^4$$

mild explicit breaking of conformal invariance/AdS isometries = massive dilaton/radion

Higgs-radion potential

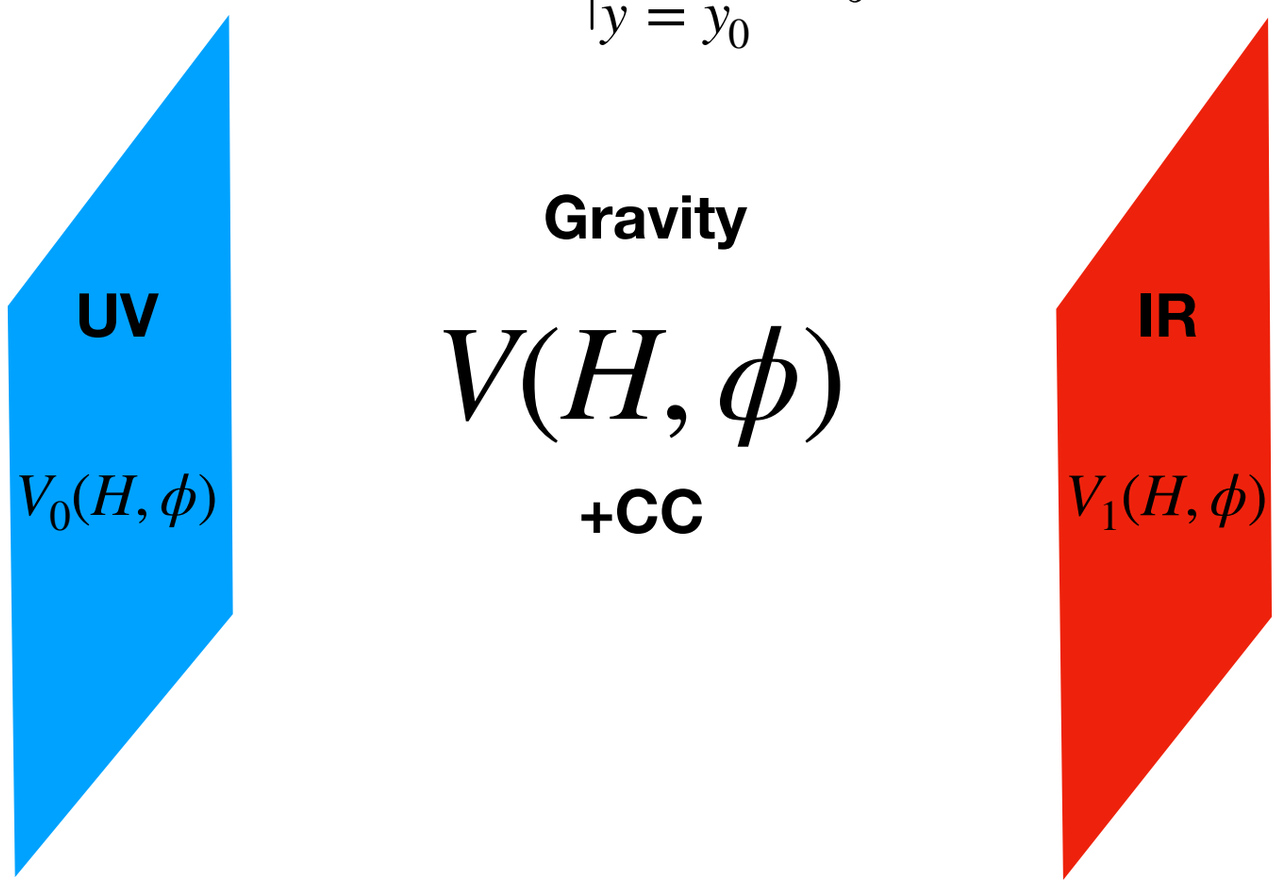
- This is all great, and you can suppress mass scales, up to a point
  - typical masses are at the KK scale
- Usually just fine (or meso-fine) tune the Higgs mass
  - most studies neglect (allowed by symmetry) couplings between Higgs sector and stabilization
- But the Higgs is generically influenced by (and influences) stabilization

The couplings

Generic problem is one of one or more scalar fields (e.g. Higgs + GW field) backreacting on geometry

$$S = \int d^4x dy \sqrt{-g}\left[\frac{1}{2}\sum_i (\partial_M \phi_i)^2 - V(\{\phi_i\}) - \frac{1}{2\kappa^2}R\right]$$

$$- \int d^4x \sqrt{-g_0} V_0(\{\phi_i\})\Big|_{y=y_0} - \int d^4x \sqrt{-g_1} V_1(\{\phi_i\})\Big|_{y=y_1}$$



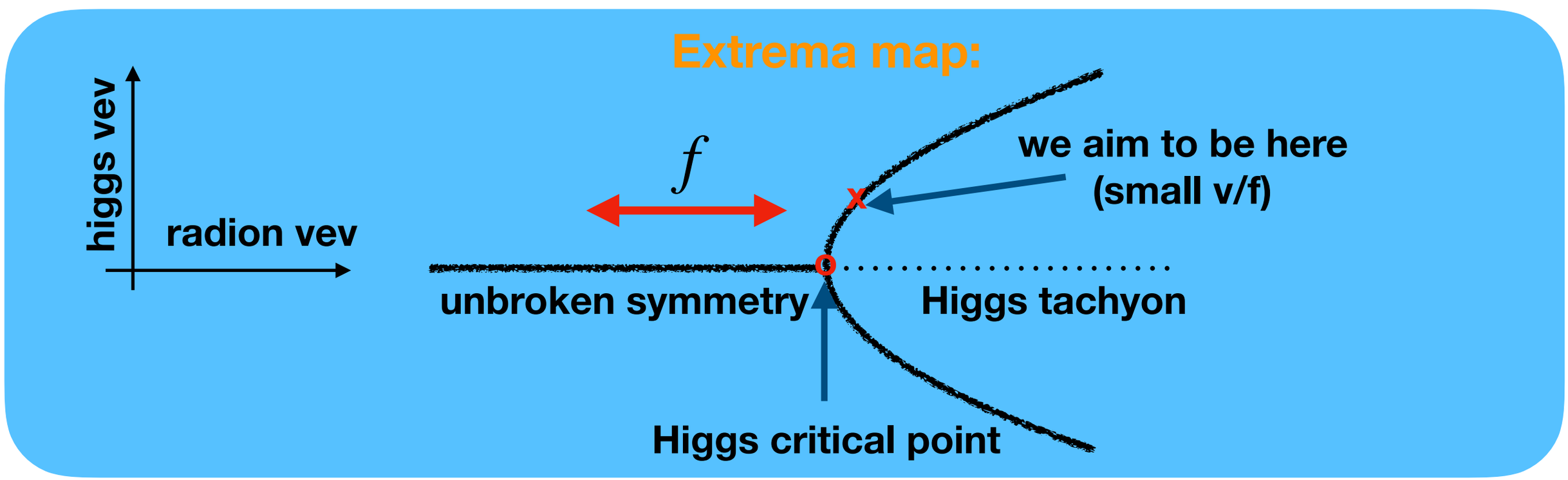
The radion-Higgs Potential

The procedure to add more scalars is straightforward

$$V(f) = \mu_0^4 \left[\frac{V_0(\phi_0(f), H_0(f))}{\mu_0^4} - \frac{\kappa^2}{6\mu_0^4} A_0(\phi_0(f), H_0(f)) \right] + f^4 \left[\frac{V_1(\phi_1(f), H_1(f)))}{k^4} + \frac{\kappa^2}{6k^4} A_1(\phi_1(f), H_1(f)) \right]$$

Now the effective potential is multi-dimensional

Couplings between radius and Higgs can make electroweak criticality a function of brane separation



The Holographic Potential

With single stabilizing field, impose all scalar BC, potential is function only of y_1

Generalizing to many scalar fields?

$V_{\text{eff}}(\phi_0, H_0)$

INTEGRATE OUT BULK AND IR BRANE PHYSICS

- Impose bulk equations of motion and IR brane boundary conditions for arbitrary y_1

- Find y_1 that satisfies metric junction conditions ($V_{IR}=0$)

  (may be subtleties here - may be multiple solutions)

- Will obtain potential as function of UV brane values of the scalar fields

3 Simple Examples

A Toy Model: Higgs on the IR brane

A standard Goldberger wise scalar, coupled to Higgs on IR brane

IR brane potential:

$$V_1(\phi, H) = T_1 + \lambda_h |H|^2 \left(|H|^2 - v_H^2 - \lambda\phi \right) + \frac{\gamma_1}{2}(\phi - v_1)^2$$

Bare Higgs mass

Scanning coupling

non-stiff mass term

In the bulk, GW scalar has small-ish mass to generate large hierarchy

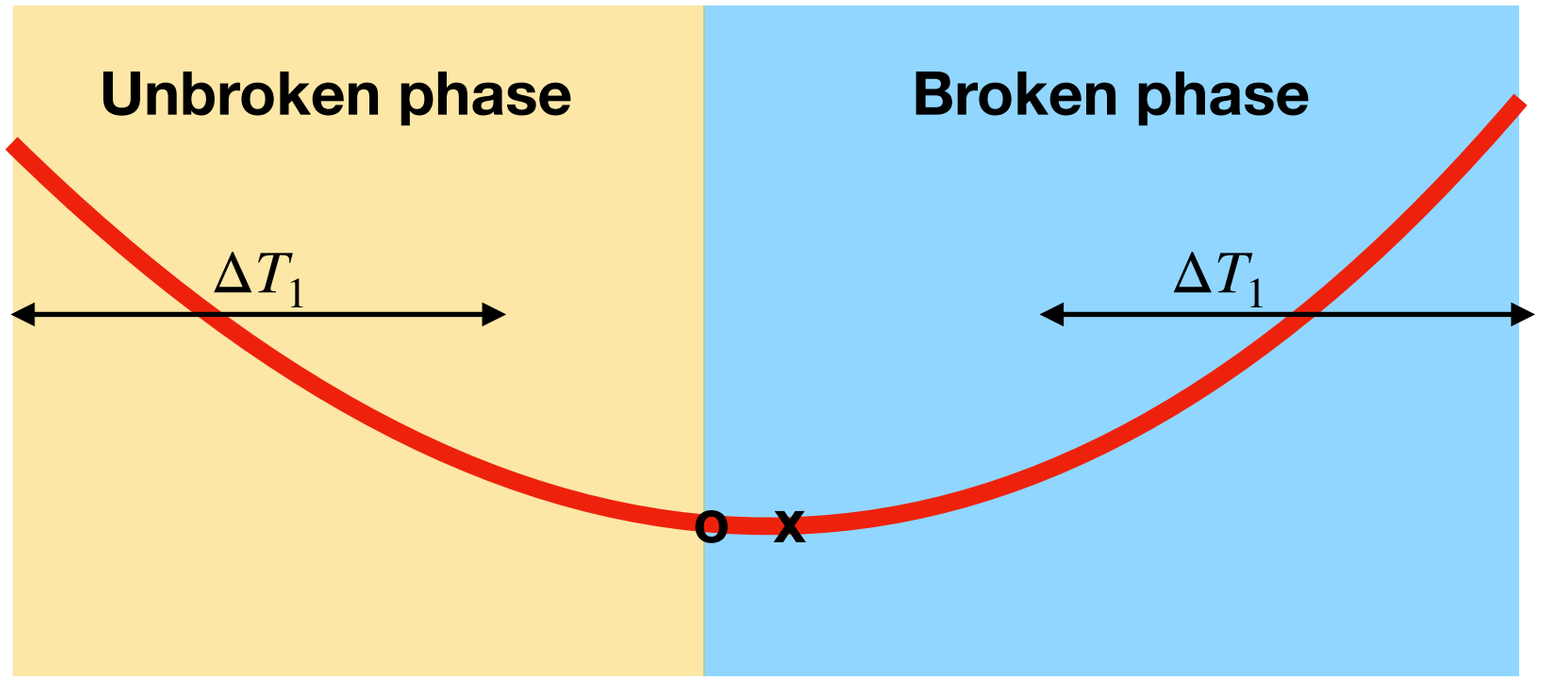
GW field value on IR brane varies with y_1

$$\phi_1 = \phi_1(y_1)$$

In the absence of Higgs, T_1 selects the position of the GW minimum

(Higgs on the IR brane)

Tuning the quartic to get a light Higgs



Changing T_1 moves the modulus potential left and right

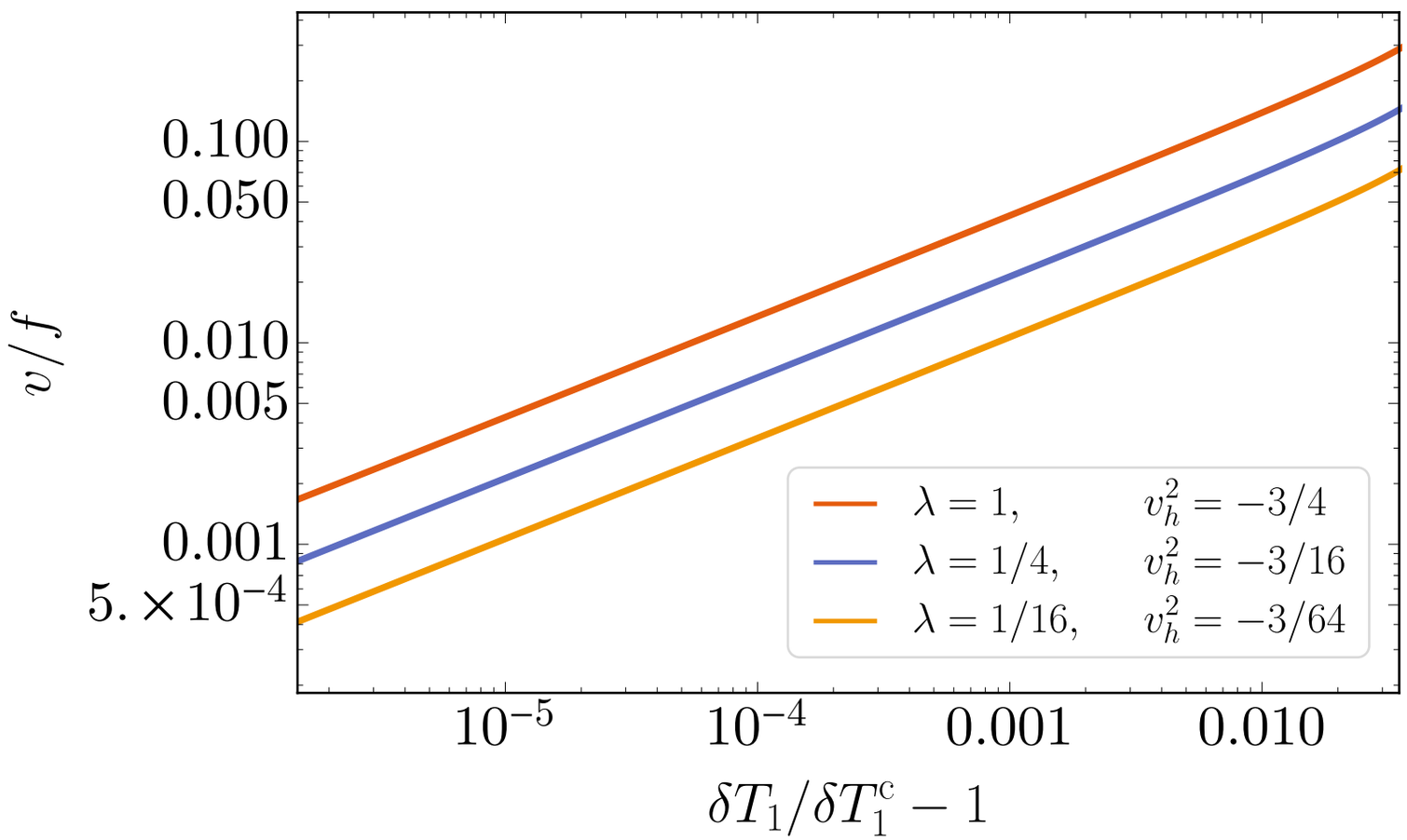
minimum moves to the right and left relative to the critical point

Closer/further from Higgs criticality

There is a critical value of the IR brane tension that aligns minimum with massless Higgs: T_1^c

(Higgs on the IR brane)

IR brane mistune selects the Higgs VEV



Shows ratio of Higgs vev to KK scale as mistune is varied

Different values of scanning coupling - small = slow scanning
Slow scanning = lighter Higgs/smaller vev

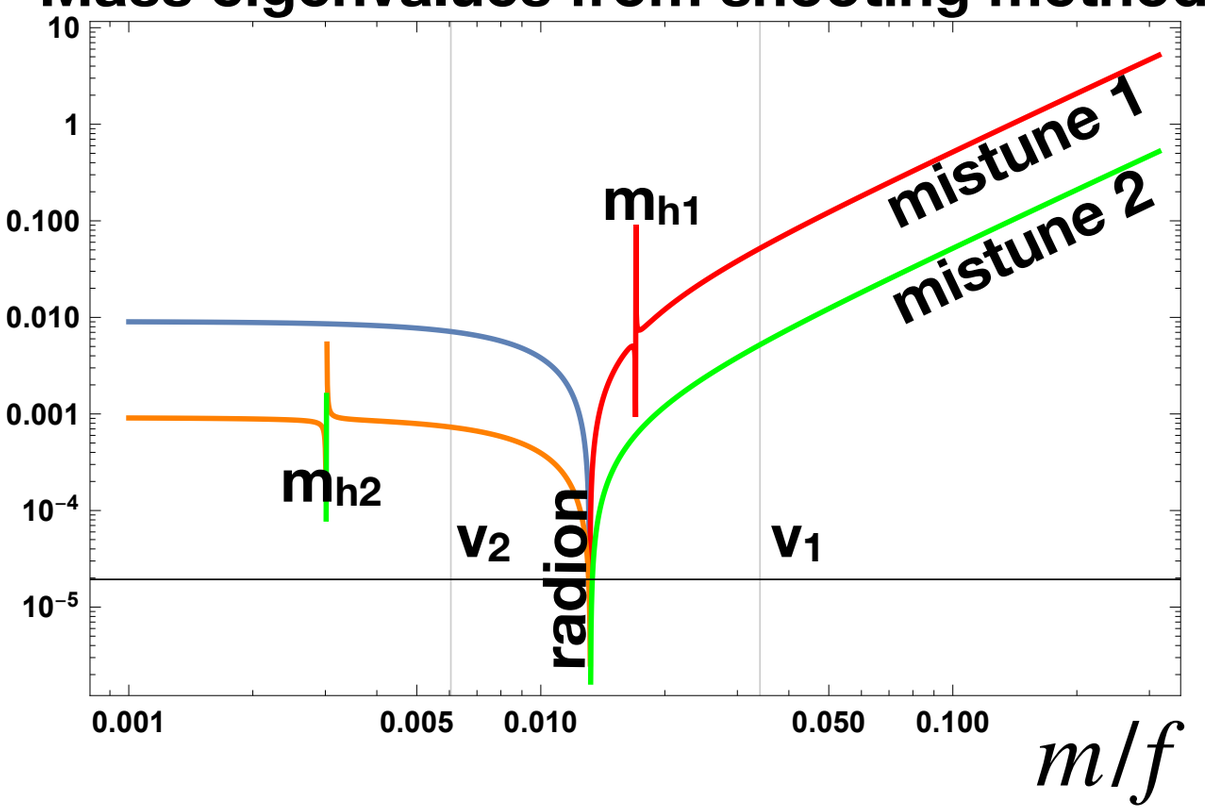
(Higgs on the IR brane)

The Radion Mass?

The radion mass is set primarily by the dynamics of the GW bulk scalar field

Consistent with naive power counting argument for pseudogoldstone of spontaneous ~conformal symmetry breaking: $m_r = \kappa \epsilon f$

Mass eigenvalues from shooting method



There is some mild mixing with the Higgs, but radion mass is essentially constant as one tunes the dilaton quartic parameter, T_1

Radion not required to be lightest

Bulk Higgs - Bulk GW

(PRELIMINARY)

Can also do the complete picture of Higgs in the bulk
First results are simplified picture - no *direct* coupling

$$M_H^2 = -4 + \nu^2$$

$$H(y) = h_+ e^{(2+\nu)ky} + h_- e^{(2-\nu)ky}$$

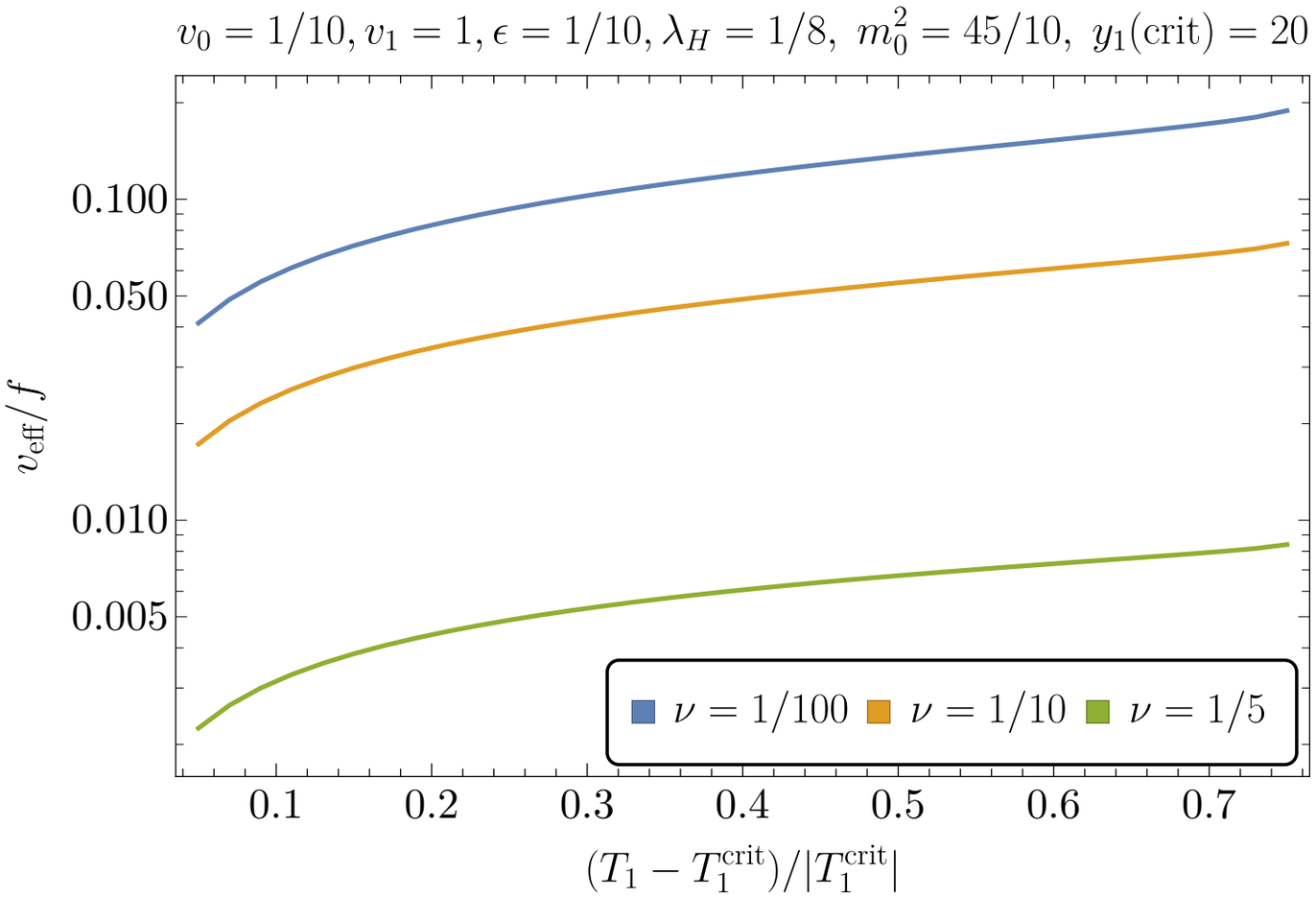
$$V_1(\phi, H) = T_1 + \lambda_h |H|^2 \left(|H|^2 - v_H^2 \right) + \frac{\gamma_1}{2}(\phi - v_1)^2$$

for now take the stiff wall limit of infinite mass

Coefficients provide y_1 dependence
may toggle electroweak symmetry breaking for some value of y_1

Bulk Higgs (PRELIMINARY)

Can again get a picture of how to get small v/f by putting the minimum of the effective potential in the vicinity of the Higgs critical surface



Naively, tuning in this picture looks small, however the tuning here was hidden
getting a critical y_1 in the first place is not easy
tuning hidden in brane localized Higgs mass term

$$\frac{v_H^2(y_1(\text{crit}) = 20) - v_H^2(y_1(\text{crit}) = 30)}{v_H^2(y_1(\text{crit}) = 20)} = 3 \cdot 10^{-4}$$

<u>Shallow</u> dependence of Higgs mass² term on radion

An Interesting Variant: Higgs near the BF bound

Nothing but the Higgs in the bulk

Bulk Higgs mass is near the Breitenlohner-Freedman bound:
$M_H^2 \sim -4$ in units of AdS Curvature

$$H(y,x) \sim e^{2ky}(1 + r\log y)h(x) \qquad \mathrm{Dim}[\mathrm{O_H}] \approx 2$$

At large N, double trace operator is nearly marginal: $\mathrm{Dim}[O_H^\dagger O_H] \approx 4$

Compare with GW interpretation: $\phi \sim e^{\epsilon k y}$ $\qquad \mathrm{Dim}[O_\phi] \approx 4 - \epsilon$

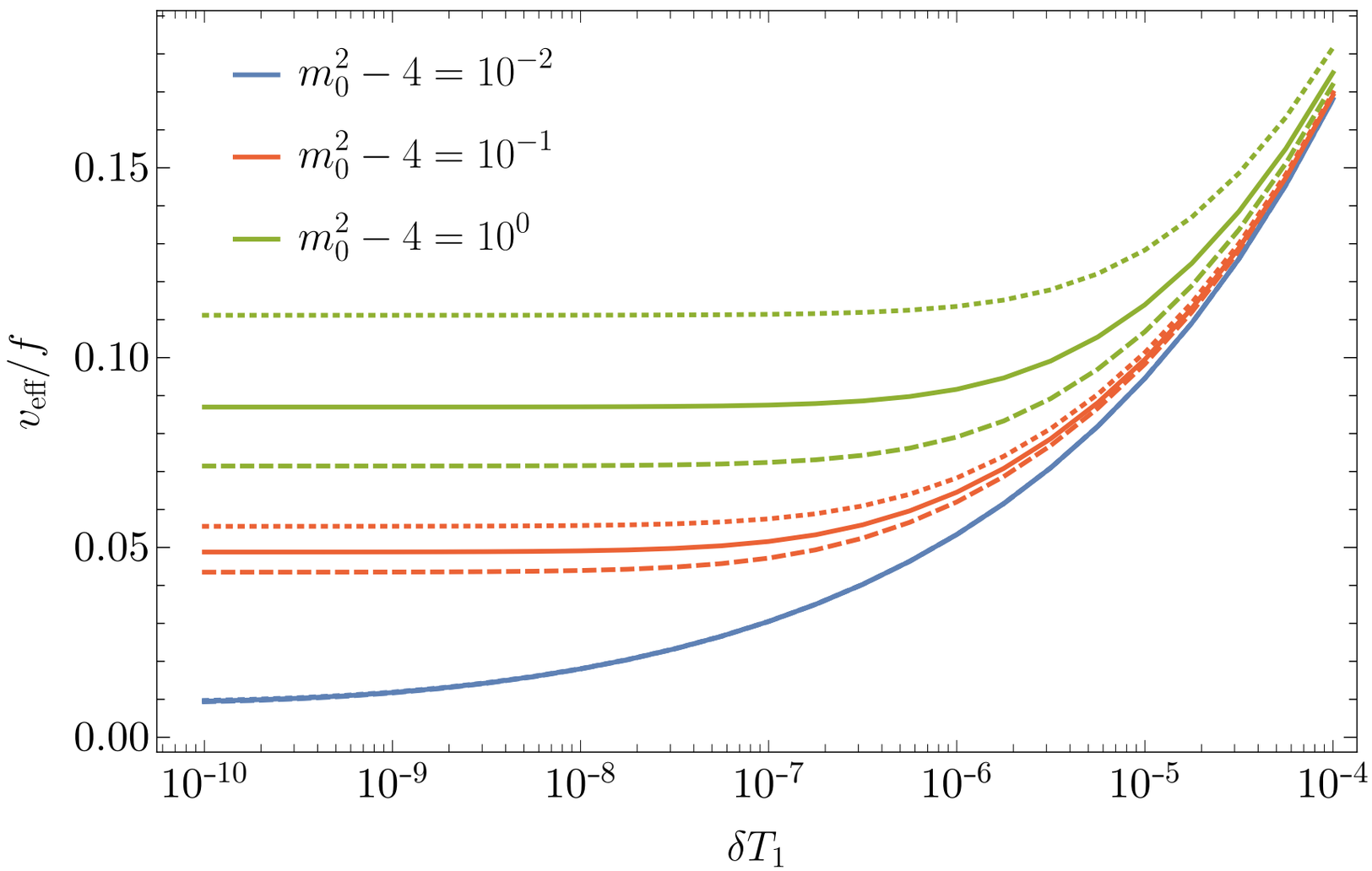
Another type of near-marginal deformation of CFT that can stabilize the dilaton

Important term - UV mass: $V_0(H) = m_0^2 |H|^2$

Vecchi 1012.3742
Geller, Bar-Shalom, Soni 1312.3331

BF Bound Higgs Tuning

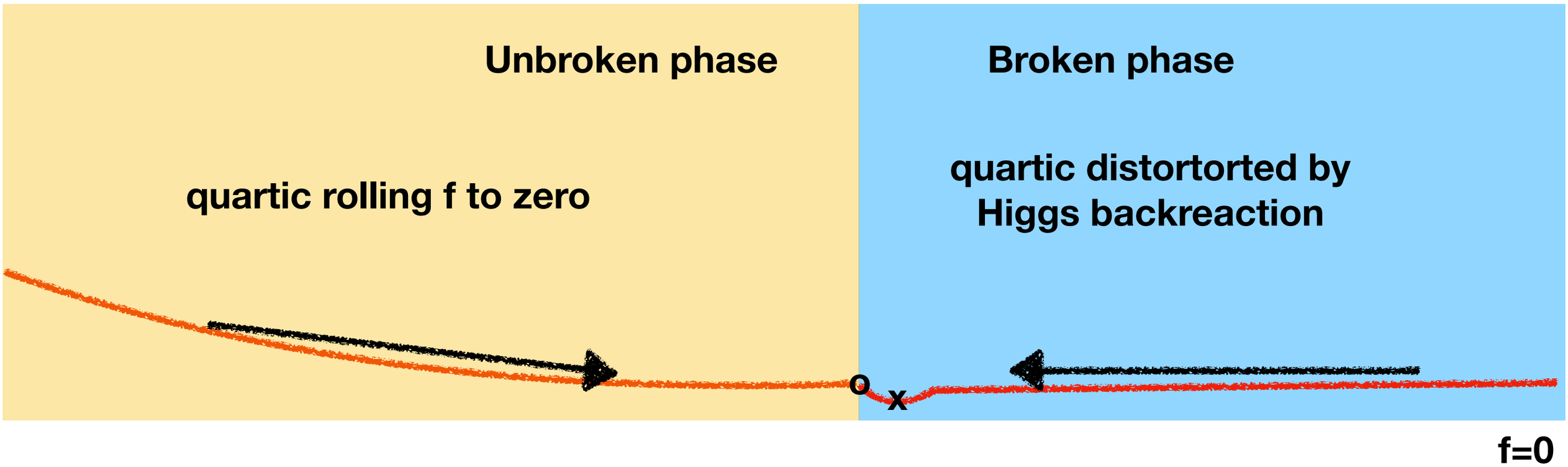
You can get small vev and light Higgs at price of *tiny* mistune (force a flat direction)



Here we require positive mistune (positive quartic) otherwise Higgs vacuum is metastable to collapse of branes

Slow roll radion

With the exception of vicinity of critical point, potential is very flat if you require very small Higgs vev



Caveat:

Picture with very small v/f (tiny mistune) might get distorted from casimirs communicating other breaking of scale invariance to effective potential

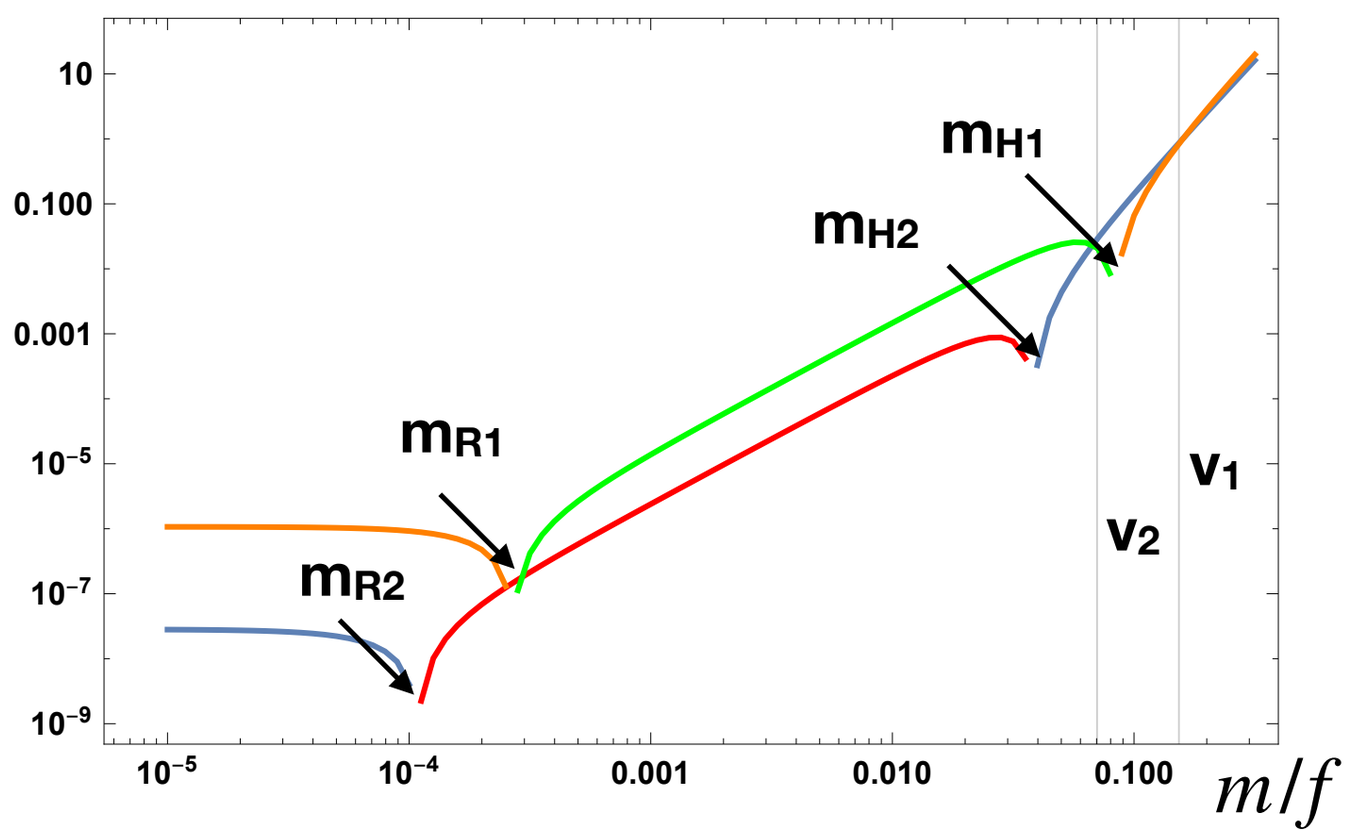
Higgs and Radion Masses

Higgs mass and radion mass track together with tuning

radion gains mass by mixing with Higgs proportional to Higgs vev

Radion generically *lighter* than Higgs due to large N (perturbativity of 5D description)

Mass eigenvalues from shooting method



May be challenging to match phenomenology

A few words about cosmology

- Meso-tuning of the Higgs mass (small v/f) in context of RS type models leads to novel (and distinct) classes of radion potentials
  - radion scans the Higgs mass, plays role in (possibly non-thermal) phase transition
- Story of conformal phase transition (and especially what follows) may be very non-standard, model dependent

Radion-Higgscitement?

Amin, Fan, Lozanov, Reece 1802.0044

If radion scans the Higgs mass, can oscillate across the phase transition possibly violent ~TeV scale dynamics - Production of Higgs particles

Parameters of interest:

additional depth higgs gives to potential

$$b = \frac{f^4}{2\lambda_H(\Delta\phi)^2 m_r^2}$$

breaking scale f

radion mass $\kappa\epsilon f$

field range $4\pi f$

modulus lifetime $\Gamma^{-1} \sim \left(\frac{4\pi f}{m_r}\right)^2 m_r^{-1} \gg m_r^{-1}$

When b ~ O(1), and perturbative modulus decay allots few hundreds of oscillations:

violent period of interplay between higgs and modulus
equation of state w~1/4-1/3
production of ~kHz gravitational waves (in addition to conformal transition)

Conclusions

- Meso-tuning in Higgs sector in extra dimension/strongly coupled conformal models seems to point to novel dynamics of the phase transitions
- Tunneling from hot conformal phase to displaced radion
  - What happens next?
    - Brane Higgs - strong dependence of Higgs mass on radion (big b)
    - Bulk Higgs (ours) - weak dependence of Higgs mass on radion (b smaller)
    - BF Bound Higgs - shallow potential, mini-inflation?
- Meso-tuning can have phenomenological consequences, and they're not unique
- Realistic models?… e.g. composite (A_5 gauge-Higgs) residual tuning? Non-light dilaton/radion?