The Dilaton, the Radion and Duality

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Work done in collaboration with
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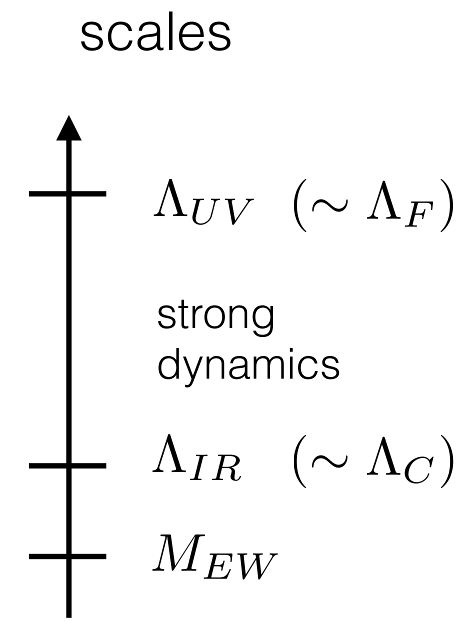
Based on:
Effective Theory of a Light Dilaton (Phys. Rev. D87 (2013) 11, 115006)
Dynamics of a Stabilized Radion and Duality (JHEP 1309 (2013) 121)
Interactions of a Stabilized Radion and Duality (Phys. Rev. D92 (2015) 056004)

Motivation

Strong hint of a SM like Higgs at 125 GeV

There are two possibilities

- Elementary Higgs
- Composite Higgs (focus of the talk)



Addresses Hierarchy Problem: Loop contribution to Higgs mass are under control.

If Higgs is a pNGB of an approximate global symmetry, it can be lighter than the compositeness scale

$$m_h \sim \epsilon \, \Lambda_C$$

In composite Higgs scenarios, Flavor changing operators are generated from the dynamics above compositeness scale

$$\frac{qqqq}{\Lambda_F^2}$$

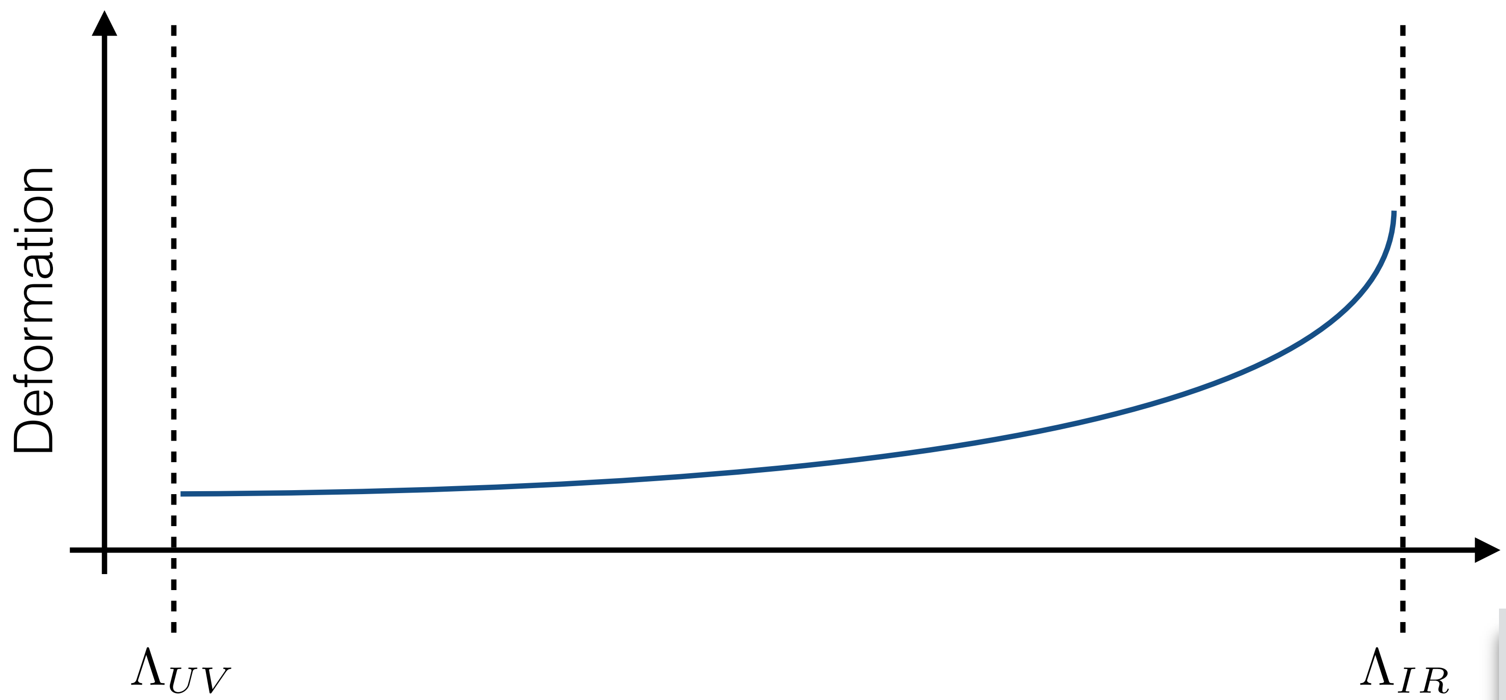
$\Lambda_F \gtrsim 10^5 \text{ TeV}$

e.g. $K\bar{K}$ mixing.

Composite scenario offers a natural solution to hierarchy problem, but the flavor constraints must be satisfied.

How do we ensure $\Lambda_{IR} << \Lambda_{UV}$ naturally?

Separation between scales can be achieved if the dynamics between the UV and IR scales is approximately conformal



IR scale is generated by the deformation growing strong.

$$\mathcal{L}_{CFT} + c\,\Lambda_{UV}^{4-\Delta}\,\mathcal{O}_\Delta$$

$$\Lambda_{IR} \sim c^{\frac{1}{4-\Delta}}\Lambda_{UV}$$

For a hierarchy:

$c \lesssim 1$	$c << 1$
$4-\Delta << 1$	$\Delta < 4$

$$c = 0.1, \Delta = 3.9 \Rightarrow \Lambda_{IR}/\Lambda_{UV} = 10^{-10}$$

$$c = 10^{-10}, \Delta = 3 \Rightarrow \Lambda_{IR}/\Lambda_{UV} = 10^{-10}$$

What are the low energy observables of this scenario?

- **Focus on the mass and coupling of the pNGB of CFT breaking, the dilaton.**
- **Show a realization of this in the RS framework, via AdS/CFT.**

Outline

- CFT breaking and effective potential of the Dilaton
- Mass and couplings of Dilaton in approximate CFT
- Holographic Realization in RS models
- Mass and couplings of the Radion
- Conclusion

Conformal Field Theory

Conformal symmetry = Poincare symmetry + Scaling + SCT

$$x^\mu \to x^\mu + a^\mu$$

$$x^\mu \to \Lambda_\mu^\nu \, x^\nu$$

$$x^\mu \to e^{-\omega} \, x^\mu$$

$$\frac{x^\mu}{x^2} \to \frac{x^\mu}{x^2} - b^\mu$$

Irreducible representations of CFT algebra contain a primary operator and its descendants. Primary operators can be scalar, vector, tensor etc. Descendants are related to primary operators by derivatives.

Local operators in CFT labelled by spin (s, s') and scaling dimension Δ

$$x^\mu \to e^{-\omega} \, x^\mu \qquad \mathcal{O}(0) \to e^{\omega\Delta} \, \mathcal{O}(0)$$

$$x^\mu \to \Lambda_\mu^\nu \, x^\nu \qquad \mathcal{O}(0) \to \Sigma_{\mu\nu} \cdot \mathcal{O}(0)$$

At the quantum level, the theory is at a fixed point. $g(\mu) = g^*$

Spontaneously broken CFT

CFT $\rightarrow$ Poincare $\quad\quad \langle \mathcal{O}(x) \rangle \neq 0 \quad\quad \mathcal{O}(x)$:scalar primary operator of dimension Δ

Total of 5 generators broken, but only 1 NGB in spectrum

Dilaton is the NGB of spontaneously broken CFT.

$$\sigma(x) \; : \; x^\mu \rightarrow e^{-\omega} \, x^\mu \; , \; \sigma \rightarrow \sigma + \omega \, f$$

Easier to work with $\chi = f \, e^{\sigma/f}$

$$\chi(x) \; : \; x^\mu \rightarrow e^{-\omega} \, x^\mu \; , \; \chi \rightarrow e^{\omega} \, \chi$$

Low energy Lagrangian contains all terms allowed by symmetry.

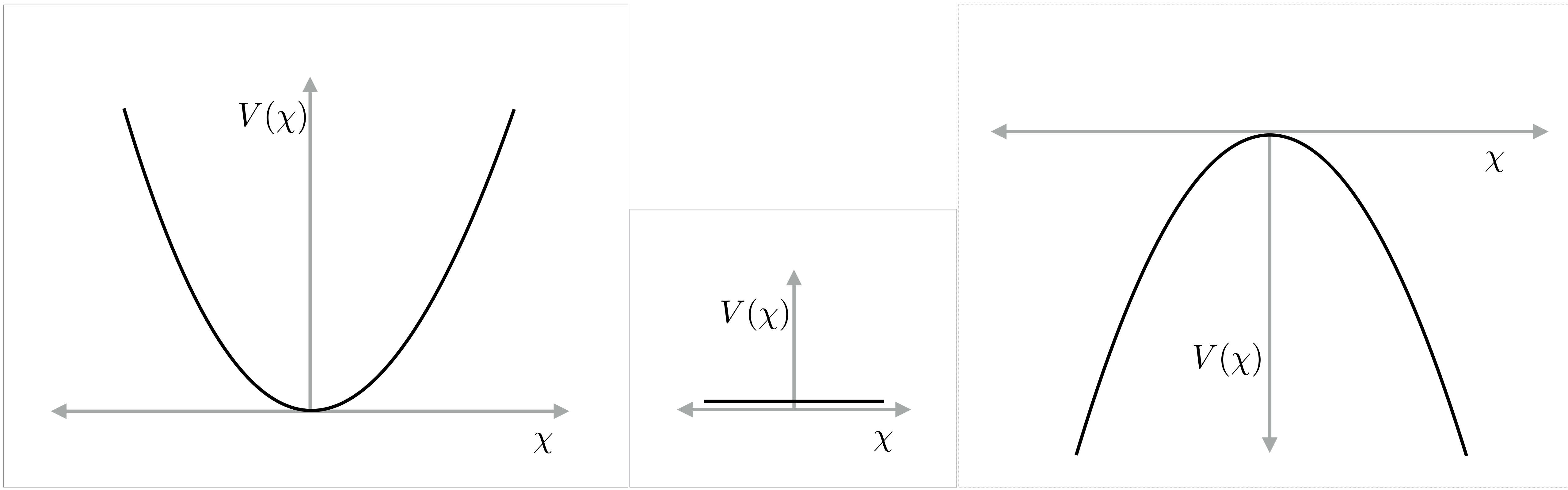
- $\partial_\mu \chi \partial^\mu \chi$
- $(\partial_\mu \chi \partial^\mu \chi)^2 \, \chi^{-4} \; , \; (\partial_\mu \chi \partial^\mu \chi)^3 \, \chi^{-8} \; , \; \cdots$
- χ^4

Unlike NGBs of spontaneously broken Global symmetry, a potential is allowed for the Dilaton

$$V(\chi) = \kappa_0 \, \chi^4$$

Spontaneously broken CFT

$$V(\chi) = \kappa_0\, \chi^4$$



$\kappa_0 > 0$	$\kappa_0 = 0$	$\kappa_0 < 0$
$\langle\chi\rangle = f = 0$	Tuned	$\langle\chi\rangle = f \to \infty$
CFT never broken		CFT never realized

Spontaneously broken approximate CFT

$$\mathcal{L}_{CFT} + \lambda_{\mathcal{O}}\ \mathcal{O}(x)$$

$$\hat{\lambda}_{\mathcal{O}} = \mu^{\Delta-4}\lambda_{\mathcal{O}}$$

$$\hat{\lambda}_{\mathcal{O}} \sim 1\ \ :\ \text{Strong Coupling}$$

$$\frac{d\ \log \hat{\lambda}_{\mathcal{O}}}{d\ \log \mu} = -(4-\Delta)$$

To track the effect of the deformation, make $\lambda_{\mathcal{O}}$ a spurion.

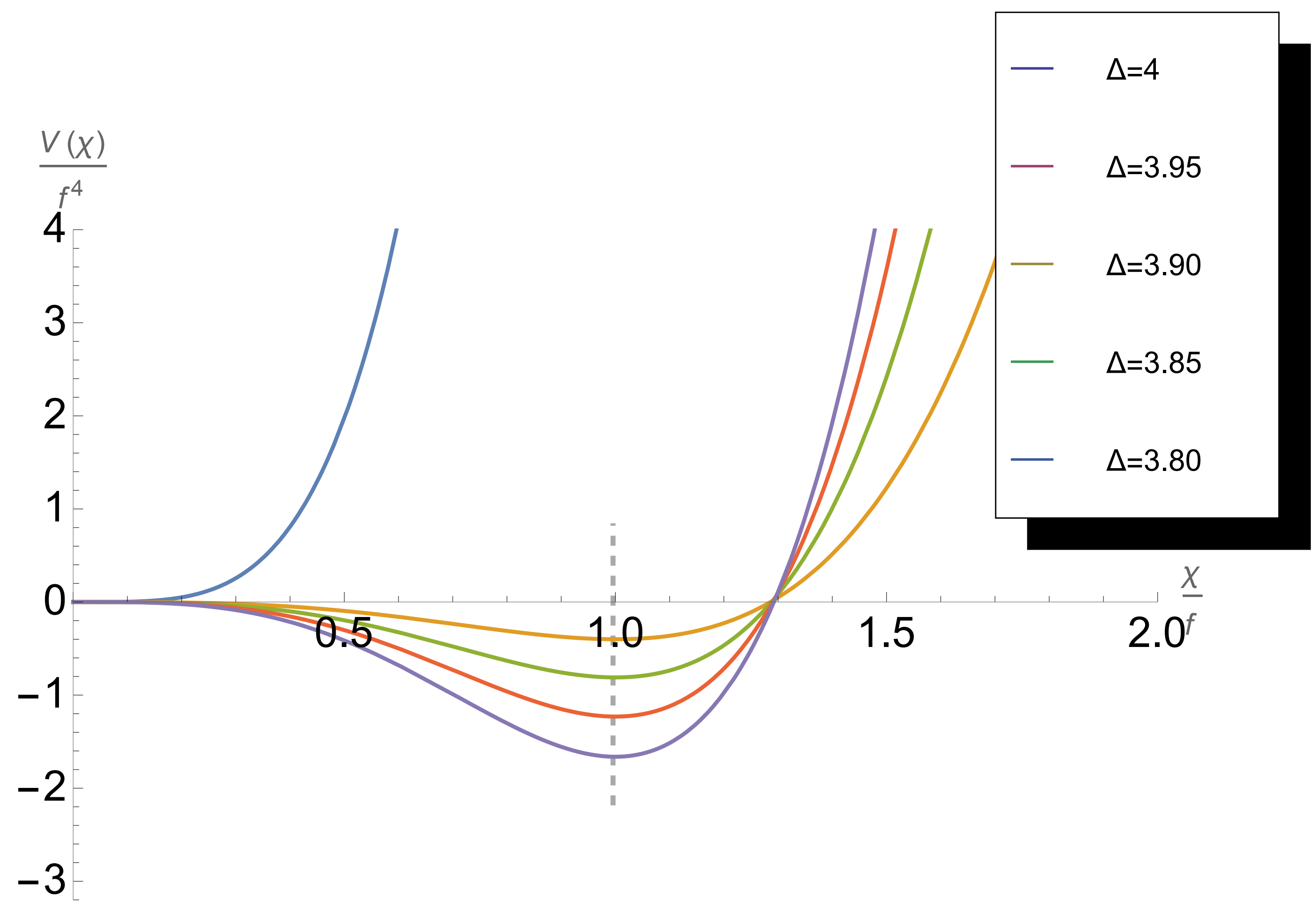
$$x^{\mu} \to e^{-\omega} x^{\mu}\ ,\ \mathcal{O} \to e^{\omega\Delta}\mathcal{O}\ ,\ \lambda_{\mathcal{O}} \to e^{\omega(4-\Delta)}\lambda_{\mathcal{O}}$$

Include polynomial powers of the invariant combination $\lambda_{\mathcal{O}}\chi^{\Delta-4}$

To lowest order: $V(\chi) = \kappa_0\chi^4 - \kappa_1\lambda_{\mathcal{O}}\chi^{\Delta}$

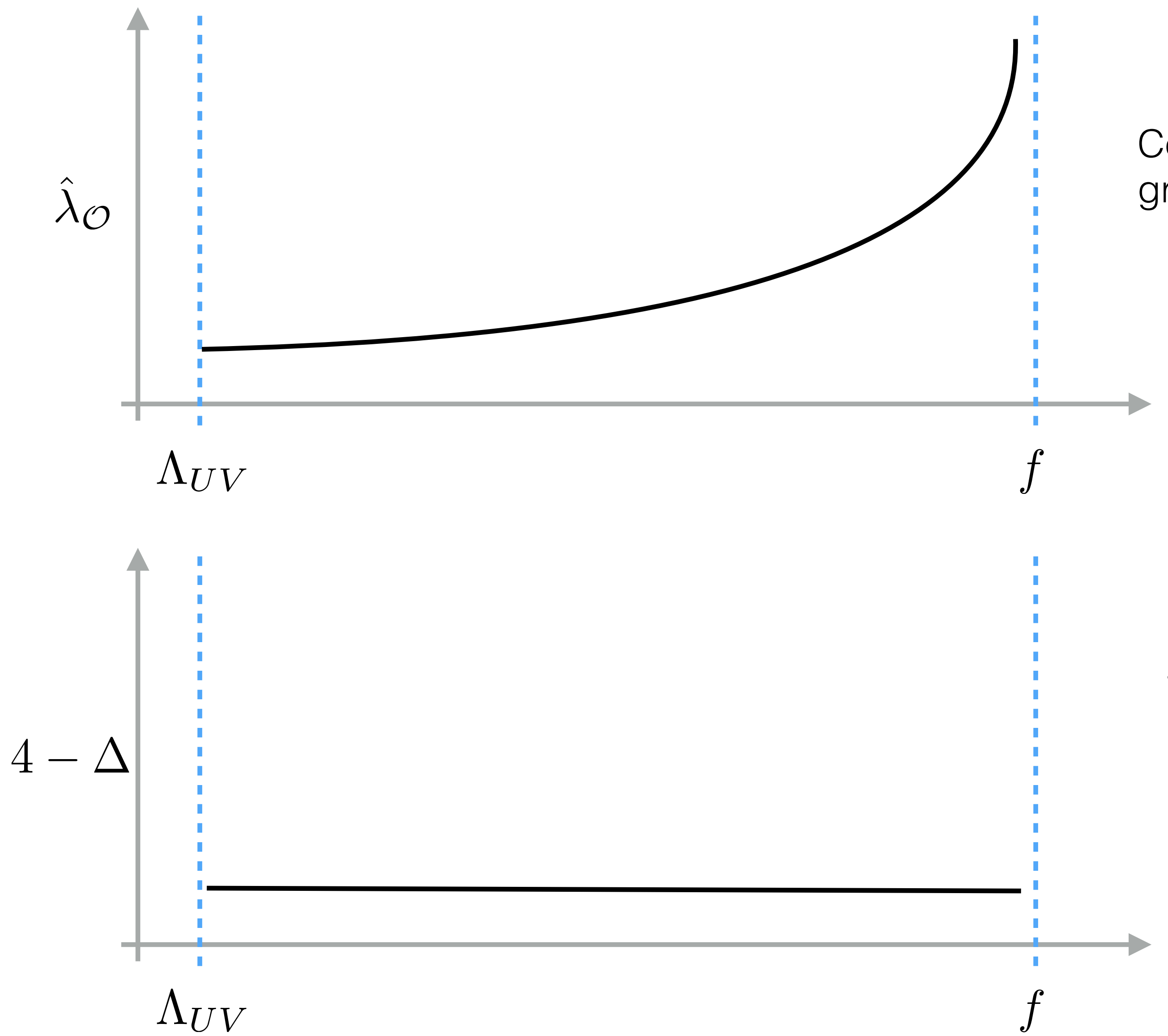
$$m_{\sigma}^2 = 4\kappa_0(4-\Delta)f^2$$

$\Delta \lesssim 4$: light dilaton?



Requirements for a light Dilaton.

$\hat{\lambda}_{\mathcal{O}} \to 1, \; 4 - \Delta << 1$



Coefficient of deformation grows to trigger breaking

Scaling dimension of deformation does not become large.

Are these two compatible? We will work to all orders of perturbation theory, and check if the result survives as the coupling is pushed to its strong coupling value.

Four effects that need to be accounted for

- Scaling symmetry violated by regulator

$$\kappa_0(\mu)\ \chi^4$$

- Dilaton potential has higher order contributions from deformation

$$V(\chi) = \chi^4 \left[\kappa_0 - \sum_n \kappa_n \lambda_{\mathcal{O}}^n\ \chi^{n(\Delta-4)}\right]$$

- Minimize effective potential in the analysis

$$V_{eff}(\chi)$$

- Higher order terms present in the RG equation for the deformation

$$\frac{d\log\hat{\lambda}_{\mathcal{O}}}{d\log\mu} = -g(\hat{\lambda}_{\mathcal{O}}) = -\left[(4-\Delta) + c_1\hat{\lambda}_{\mathcal{O}} + c_2\hat{\lambda}_{\mathcal{O}}^2 + \cdots\right]$$

$g(\hat{\lambda}_{\mathcal{O}}) > 0$ for growth

  - First term is required to be small to generate a hierarchy. No such condition on subsequent terms.
  - Even before strong coupling, second term can dominate the first term.

First three effects do not change any conclusions, but the last one does.

Changes from earlier analysis

Spurion Transformation: $x^\mu \to e^{-\omega} x^\mu$, $\hat{\lambda}_{\mathcal{O}}(\mu) \to \hat{\lambda}'_{\mathcal{O}}(\mu) = \hat{\lambda}_{\mathcal{O}}(\mu e^{-\omega})$

Invariant (scaling + RG) combination: $\bar{\Omega} = \hat{\lambda}_{\mathcal{O}} \left(\frac{\chi}{\mu}\right)^{-g(\hat{\lambda}_{\mathcal{O}})}$ for perturbative $\hat{\lambda}$

Potential: $V(\chi) = \chi^4 \left(\kappa_0 - \kappa_1 \bar{\Omega}\right)$

Mass: $m_\sigma^2 = 4\,\kappa_0\, g(\hat{\lambda}_{\mathcal{O}}) f^2$

Earlier: $m_\sigma^2 = 4\,\kappa_0\,(4-\Delta)\, f^2$

Recall: $g(\hat{\lambda}_{\mathcal{O}}) = (4-\Delta) + c_1 \hat{\lambda}_{\mathcal{O}} + c_2 \hat{\lambda}_{\mathcal{O}}^2 + \cdots$

For a light dilaton, $g(\hat{\lambda}_{\mathcal{O}})$ must be small.

Two possibilities:

- Near a conformal fixed line (has a simple interpretation in RS models.)
- Tuning (scales linearly with mass)

Tuning for a light Dilaton

Suppose the CFT in such that the quartic is slightly below its strong coupling value.

$$\kappa_0 = \frac{16\pi^2}{Q}$$

Potential: $\chi^4 \left(\kappa_0 - \kappa_1 \hat{\lambda}_{\mathcal{O}} \left(\frac{\chi}{\mu} \right)^{-g(\hat{\lambda}_{\mathcal{O}})} \right)$ minimized at: $\hat{\lambda}_{\mathcal{Q}} \sim \frac{1}{Q}$

$$g(\hat{\lambda}_{\mathcal{O}}) = (4 - \Delta) + c_1 \hat{\lambda}_{\mathcal{O}} + c_2 \hat{\lambda}_{\mathcal{O}}^2 \sim \frac{1}{Q}$$

$$m_\sigma^2 = 4\kappa_0 g(\hat{\lambda}_{\mathcal{O}}) f^2 \sim 1/Q^2$$

Tuning is mild, scaling linearly with mass. To get a dilaton 1/5 below the strong coupling scale, a mild tuning of 20% needed.

Dilaton Couplings in the absence of deformation

In the limit of no deformation, coupling is fixed by non-linear realization of symmetry.

Consider gauge Bosons with a mass, arising from weak gauging of a global symmetry of CFT. Mass is generated by the usual Higgs mechanism. The dominant contribution to dilaton coupling comes from the mass term.

$$\frac{m_W^2}{g^2} W_\mu^+ W^{\mu +} \to \left(\frac{\chi}{f}\right)^2 \frac{m_W^2}{g^2} W_\mu^+ W^{\mu +}$$

$$\left(\frac{\chi}{f}\right)^2 = 1 + \frac{2\sigma}{f} + \cdots$$

Coupling: $\frac{2m_W^2}{g^2}\frac{\sigma}{f} W_\mu^+ W^{\mu +}$ Same as SM Higgs.

Generic result: In the classical limit, with Higgs potential switched off, the Higgs can be identified with the Dilaton.

Dilaton Couplings in the presence of deformation

In the limit of no deformation, coupling was fixed by non-linear realization of symmetry. In the presence of deformation, we will use compensator to track the effect of CFT breaking.

Consider again gauge Bosons with a mass, arising from weak gauging of a global symmetry of CFT. Mass is generated by the usual Higgs mechanism. The dominant contribution to dilaton coupling comes from the mass term.

$$\frac{m_W^2}{g^2} W_\mu^+ W^{\mu -} \to \left(\frac{\chi}{f}\right)^2 \left[1 + \alpha_W \hat{\lambda}_{\mathcal{O}} \chi^{\Delta - 4}\right] \frac{\hat{m}_W^2}{\hat{g}^2} W_\mu^+ W^{\mu -}$$

$$\frac{m_W^2}{g^2} = \left[1 + \alpha_W \hat{\lambda}_{\mathcal{O}}(f) f^{\Delta - 4}\right] \frac{\hat{m}_W^2}{\hat{g}^2}$$

Mass receives correction from CFT.

$$\frac{\sigma}{f}\left[2 + a\frac{m_\sigma^2}{(4\pi f)^2}\right] \frac{m_W^2}{g^2} W_\mu^+ W^{\mu -} \quad , a \sim \mathcal{O}(1)$$

Corrections scale as : $\dfrac{m_\sigma^2}{(4\pi f)^2}$

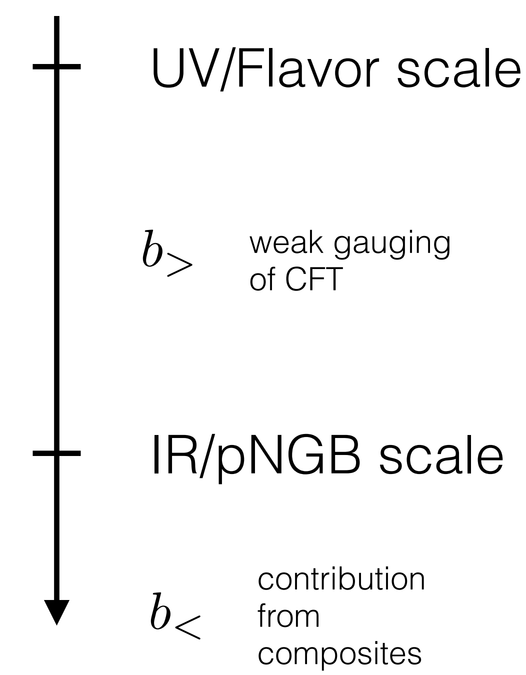
We will see this is a generic result: Corrections scale as this ratio.

Corrections are small for a light dilaton, tuned or otherwise.

Dilaton Couplings from loop effects.

Consider next, massless gauge Bosons. The dominant contribution now comes from the kinetic term. The term is scale invariant classically, but not in a quantum theory.

$$-\frac{1}{4g^2(\mu)}F_{\mu\nu}F^{\mu\nu}$$



gauge coupling runs both above and below CFT breaking scale

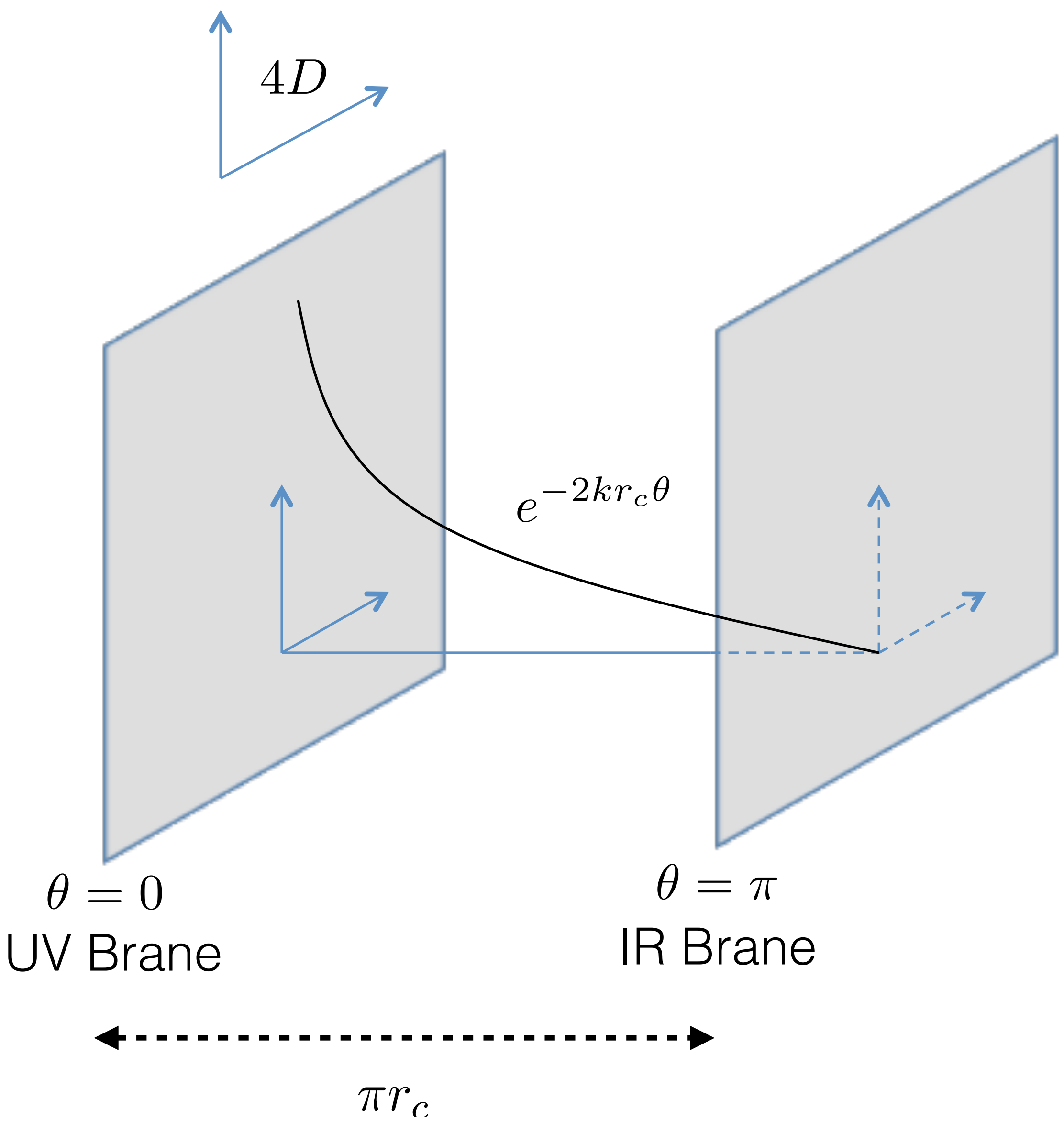
$$\frac{d}{d\log\mu}\frac{1}{g^2} = \frac{b_>(b_<)}{8\pi^2}, \qquad \mu > (<) f$$

Leading Coupling: $\frac{b_< - b_>}{32\pi^2}\frac{\sigma}{f}F_{\mu\nu}F^{\mu\nu}$

Correction from CFT breaking effect result in: $\frac{b_< - b_>}{32\pi^2}\left(1 + a\frac{m_\sigma^2}{(4\pi f)^2}\right)\frac{\sigma}{f}F_{\mu\nu}F^{\mu\nu},\ a \sim \mathcal{O}(1)$

Holographic realization

The CFT scenario we considered is dual to RS model with UV and IR brane, in the presence of a GW scalar to stabilize the geometry.



Metric

$$ds^2 = e^{-2kr_c|\theta|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\theta^2 \qquad -\pi \leq \theta < \pi$$

$$\frac{e^{kr_c\theta}}{k} \sim 1/\mu$$

Extra-dimension: RG scale in CFT

UV Brane: Explicit breaking of CFT in UV

IR Brane : Spontaneous breaking of CFT in IR

Radion: $r_c \to r(x)$: Dilaton in spontaneously broken CFT

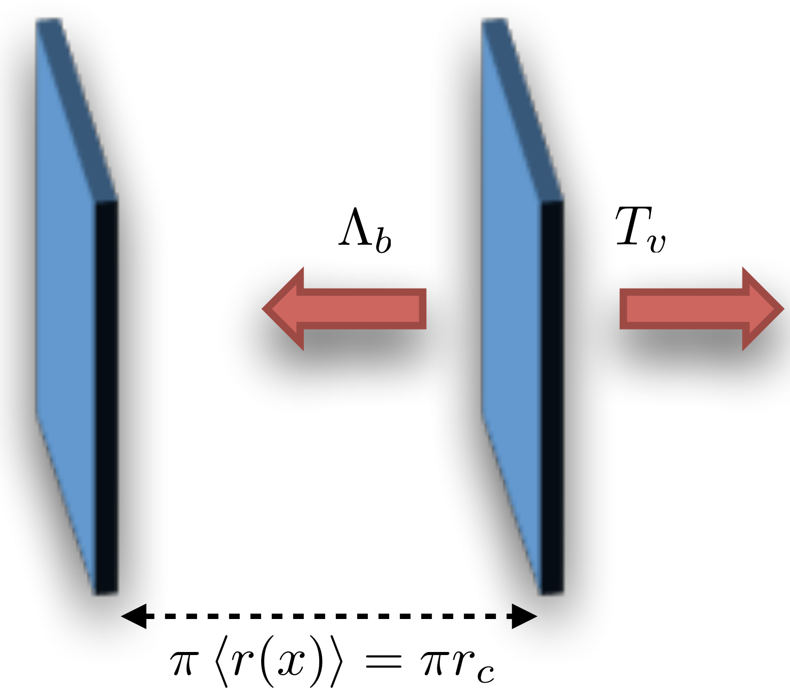
GW Scalar: Φ_{GW} : scalar deformation in CFT

Without a stabilization mechanism

To parametrize the radion dynamics: $r_c \to r(x)$ and integrate over extra dimension.

$$\mathcal{S} = \int d^4x \int_{-\pi}^{\pi} d\theta \, \left[\sqrt{G}\left(-2M_5^3\mathcal{R}[G] - \Lambda_b\right) - \sqrt{-G_h}\delta(\theta)T_h - \sqrt{-G_v}\delta(\theta-\pi)T_v\right]$$

$$= \int d^4x \left(\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi)\right)$$



$$\varphi = Fe^{-k\pi r(x)} \, , \qquad F = \sqrt{24M_5^3/k}$$

$$V(\varphi) = \left(\frac{T_v - \Lambda_b/k}{F^4}\right)\varphi^4$$

Recall in the CFT:

$$V(\chi) = \kappa_0 \, \chi^4$$

$$\kappa_0 = 0$$

RS tuning: $k \, T_v = \Lambda_b$

Stabilization with a GW scalar

$$\mathcal{S}_{GW} = \int d^4x \int_{-\pi}^{\pi} d\theta \left[\sqrt{G} \left(\frac{1}{2} G^{AB} \partial_A \Phi \partial_B \Phi - V_b(\Phi) \right) - \sqrt{-G_h}\delta(\theta) V_h(\Phi) - \sqrt{-G_v}\delta(\theta - \pi) V_v(\Phi) \right]$$

Changes from earlier analysis: Detuning + Self-interactions

- Both GR and GW sectors contribute to radion potential.
- GW sector has self-interactions.

$$V_b(\Phi) = \frac{1}{2} m^2 \Phi^2 + \frac{1}{3!} \eta \Phi^3 + \frac{1}{4!} \xi \Phi^4 + \cdots$$

All these terms allowed in the absence of a symmetry reason.

Brane potentials fix boundary conditions. We choose Dirichlet BC on UV boundary to source GW scalar

IR brane: $V_v(\Phi) = 2k^{5/2} \alpha \Phi$ Consistent in the absence of symmetries.

In general a non-linear equation:

$$\partial_\theta^2 \Phi - 4kr_c \partial_\theta \Phi - r_c^2 V_b'(\Phi) = 0$$

$$\theta = 0 \quad : \quad \Phi = k^{3/2} v$$

$$\theta = \pi \quad : \quad \partial_\theta \Phi = -\alpha k^{3/2} k r_c$$

Singular Perturbation theory

$$\partial_\theta^2 \Phi - 4kr_c \partial_\theta \Phi - r_c^2 V_b'(\Phi) = 0$$

$kr_c \gg 1$

$$-4kr_c \partial_\theta \Phi - r_c^2 V_b'(\Phi) = 0$$

Outer Region (OR)

$$0 \leq \theta < \pi - 1/4kr_c$$

$$\partial_\theta^2 \Phi - 4kr_c \partial_\theta \Phi = 0$$

Boundary Region (BR)

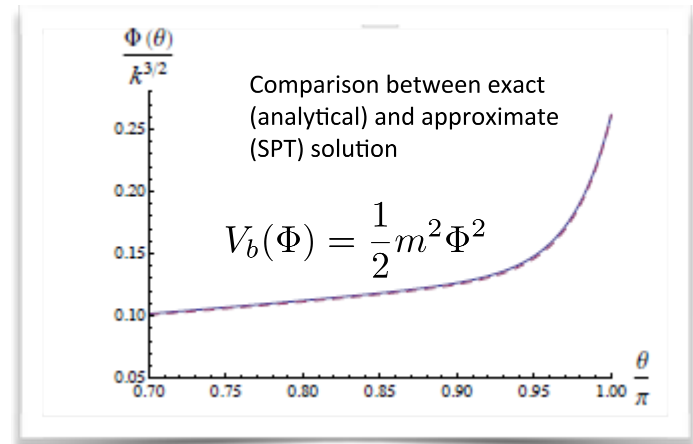
$$\pi - 1/4kr_c < \theta \leq \pi$$

$$\int \frac{d\Phi}{V_b'(\Phi)} = -\frac{r_c}{k}\theta$$

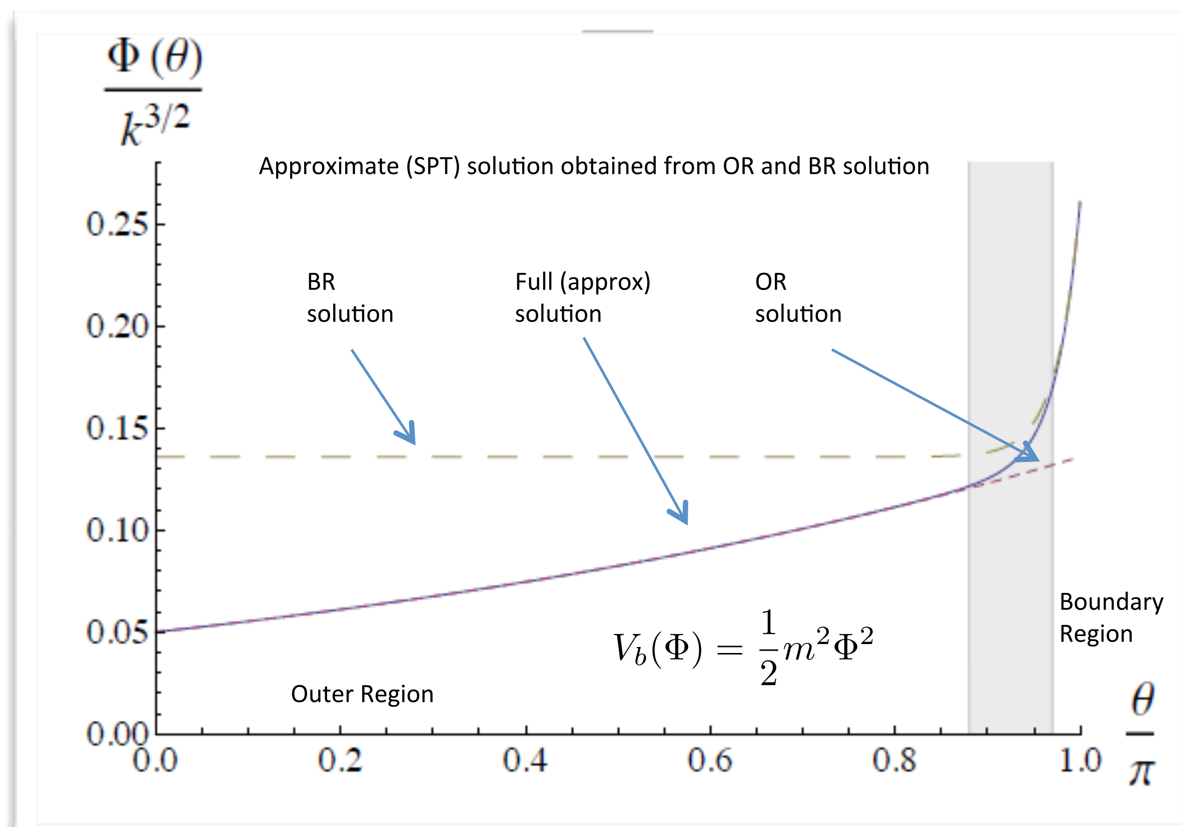
$$\Phi(\theta) = -\frac{k^{3/2}\alpha}{4} e^{4kr_c(\theta - \pi)} + C$$

Adjust C

$\Phi(\theta)$



$$m^2/4k^2 = -0.1,\ k\pi r_c = 10,\ v = 0.05,\ \alpha = -0.5$$



RS Holography for GW scalar

CFT	AdS
$\mathcal{L}_{CFT} + \lambda_{\mathcal{O}}\mathcal{O}$	$\mathrm{AdS} + \Phi_{GW}$
$[\mathcal{O}] = \Delta$	$m^2/k^2 = \Delta(\Delta - 4)$
$\hat{\lambda}_{\mathcal{O}} = \mu^{\Delta-4}\lambda_{\mathcal{O}}$	$\Phi(\theta = 0)/k^{3/2} = \hat{\lambda}_{\mathcal{O}}(\Lambda_{UV})$

For large hierarchy: Δ close to, but less than 4 $\quad \Delta \approx 4 + \dfrac{m^2}{4k^2}$

$m^2/k^2 < 0$ for a relevant deformation

Stable as long as Breitenlohner-Freedman bound, $m^2/k^2 > -4$ is satisfied.

Φ satisfies: $\partial_\theta^2\Phi - 4kr_c\partial_\theta\Phi - r_c^2 V_b'(\Phi) = 0$

To remove the effect of spontaneous breaking, send the IR brane to infinity. In this limit, the first term in the GW scalar equation can be dropped.

$$\frac{d\log\Phi}{d(kr_c\theta)} = -\frac{m^2}{4k^2} - \frac{\eta}{8\sqrt{k}}\frac{\Phi}{k^{3/2}} - \frac{\xi\ k}{24}\frac{\Phi^2}{k^3} + \cdots$$

$$\frac{d\log\hat{\lambda}_{\mathcal{O}}}{d\log\mu} = (\Delta - 4) - c_1\hat{\lambda}_{\mathcal{O}} - c_2\hat{\lambda}_{\mathcal{O}}^2 + \cdots$$

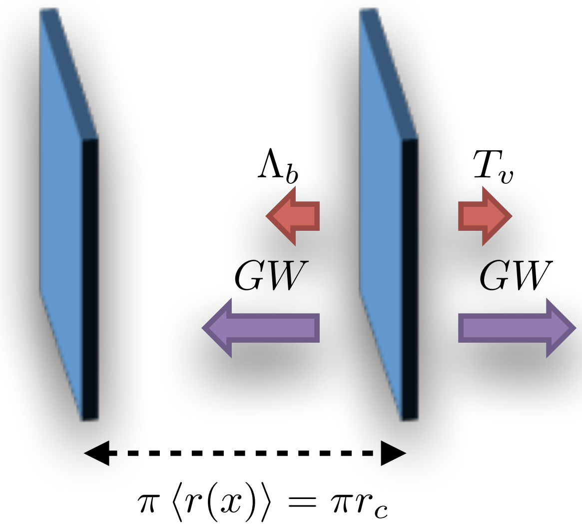
The one to one correspondence is very explicit now.

Self Interactions in GW potential are necessary to model a generic strongly coupled CFT.

It follows that: $\hat{\lambda}_{\mathcal{O}}\, g(\hat{\lambda}_{\mathcal{O}}) \sim \dfrac{\Phi}{k^{3/2}}\dfrac{d\log\Phi}{d(kr_c\theta)} \sim \dfrac{d\Phi}{d(kr_c\theta)}$

Mass of radion depends on the first derivative of GW scalar.

Effect on the mass of Radion



We solve for $\Phi(\theta)$, promote $r_c \to r(x)$ and integrate over extra dimension.

We will consider two cases, with CFT side in mind.

$V_b(\Phi)$	$\frac{1}{2}\, m^2\, \Phi^2$	$\frac{1}{3!}\, \eta\, \Phi^3$
$k^{-3/2}\, \Phi(\theta)$	$-\frac{\alpha}{4} e^{4kr_c(\theta-\pi)} + v e^{-(m^2/4k^2)kr_c\theta}$	$-\frac{\alpha}{4} e^{4kr_c(\theta-\pi)} + \frac{v}{1+(\eta v/8\sqrt{k})kr_c\theta}$
$V(\varphi)$	$\varphi^4 \frac{k^4}{F^4}\left[\tau + 2\alpha v \left(\frac{\varphi}{F}\right)^{m^2/4k^2}\right]$ $\tau = \frac{T_v - \Lambda_b/k - k^4\alpha^2/4}{k^4}$	$\varphi^4 \frac{k^4}{F^4}\left[\tau + \frac{w}{1-(\eta v/8\sqrt{k})\log(\varphi/F)}\right]$ $w = 2\alpha v + \frac{\alpha^2 \eta v}{64\sqrt{k}}$
$\frac{m_\varphi^2}{m_{KK}^2}$	$\sim -\frac{m^2}{4k^2}\, \tau$	$\sim \tau^2$
$\frac{m_\sigma^2}{(4\pi f)^2}$	$\sim (4-\Delta)\kappa_0$	$\sim \kappa_0^2$

Combined effect of detuning and self-interactions is now explicit.

In summary

- Radion mass is generally of the order of KK scale. It can be naturally light if GW scalar is a pNGB (corresponds to fixed line in CFT). Other theories with a light radion need mild tuning.
- Terms in radion potential have contribution from both gravity and GW sector and are balanced together.
- Cubic and higher order interactions in GW potential are expected to be present, and their presence changes the parametric dependence of Radion mass.
- In all cases with light mass, GW profile slowly changes in the extra dimension. $\frac{d\Phi}{d(kr_c\theta)} \ll 1$

Coupling to massive gauge bosons

In the absence of GW stabilization

Dominant contribution comes from the mass term.

$$\mathcal{S} \supset \int d^4x \int d\theta \delta(\theta - \pi) \sqrt{-G_{IR}} G^{\mu\nu}_{IR} (\mathcal{D}H)(\mathcal{D}H)^\dagger$$

$$= \int d^4x \, e^{-2k\pi r(x)} W_\mu W^\mu \langle H \rangle^2 = \int d^4x \left(\frac{\varphi}{F}\right)^2 W_\mu W^\mu \langle H \rangle^2$$

Expanding about its VEV, $r(x) \to r_c + \delta r$, or equivalently, $\varphi \to \langle \varphi \rangle + \widetilde{\varphi}$

$$= \int d^4x \left(\frac{\langle \varphi \rangle}{F}\right)^2 \langle H \rangle^2 W_\mu W^\mu \left(1 + 2\frac{\widetilde{\varphi}}{f}\right)$$

$$\langle \varphi \rangle = f = F e^{-k\pi r_c}$$

Coupling: $\dfrac{2m_W^2}{g_4^2} \dfrac{\widetilde{\varphi}}{f} W_\mu W^\mu$

Same as a SM Higgs, and the dilaton earlier.

Working in a non-canonical kinetic basis.

Coupling to massive gauge bosons

In the presence of GW stabilization

We consider new interactions between GW scalar and gauge Bosons.

$$\int d^4x \, e^{-2k\pi r(x)} \langle H \rangle^2 \, W_\mu W^\mu \left(1 + \beta_W \frac{\Phi(\pi)}{k^{3/2}}\right)$$

Once again expanding as, $r(x) \to r_c + \delta r$, or equivalently, $\varphi \to \langle \varphi \rangle + \widetilde{\varphi}$

we see that GB mass has new contributions.

$$\int d^4x \frac{m_W^2}{g_4^2} W_\mu W^\mu \left[1 + \frac{\widetilde{\varphi}}{f}\left(2 - \frac{\beta_W \Phi'(\pi)/k^{3/2}}{1 + \beta_W \Phi(\pi)/k^{3/2}}\right)\right]$$

From the analysis of the radion mass, we have: $\Phi'(\pi) \sim \dfrac{m_\varphi^2}{m_{KK}^2}$

Corrections scale as: m_φ^2 / m_{KK}^2

Recall: $\dfrac{\sigma}{f}\left[2 + a\dfrac{m_\sigma^2}{(4\pi f)^2}\right]\dfrac{m_W^2}{g^2} W_\mu^+ W^{\mu -} \quad , a \sim \mathcal{O}(1)$

Coupling to massless gauge bosons

In the absence of a stabilization mechanism

Relevant part of action looks like:

$$-\int d^4x \int d\theta \, \frac{F_{\mu\nu}^2}{4} \left[\delta(\theta) \frac{\sqrt{-G_{UV}}}{g_{UV}^2} + \frac{\sqrt{G}}{g_5^2} + \delta(\theta - \pi) \frac{\sqrt{-G_{IR}}}{g_{IR}^2} \right]$$

Zero mode has a flat profile. We can integrate over extra dimension to get:

$$\frac{1}{g_4^2} = \frac{1}{g_{UV}^2} + \frac{2\pi r_c}{g_5^2} + \frac{1}{g_{IR}^2}$$

g_4 is the coupling at the symmetry breaking scale. It is related to the coupling below the symmetry breaking scale by RG equation.

$$\frac{1}{g^2(\mu)} = \frac{1}{g_4^2} - \frac{b_<}{8\pi^2} \log\left(\frac{\Lambda_{UV} e^{-k\pi r_c}}{\mu} \right)$$

To get the coupling in the low energy, we let $r(x) \to r_c + \delta r$. The coupling has two terms.

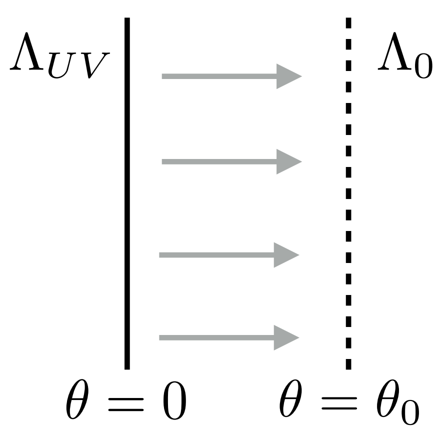
$$\left(\frac{1}{2kg_5^2} + \frac{b_<}{32\pi^2} \right) \frac{\widetilde{\varphi}}{f} F^2$$

How do we relate to the CFT form?

Coupling to massless gauge bosons

We need to relate to the CFT parameter $b_>$

To do this, we move the UV brane from $\theta = 0$ to $\theta = \theta_0$ and track the dependence of the gauge coupling



Integrating out the action from $\theta = 0$ to $\theta = \theta_0$ and matching, we get

$$\frac{1}{g^2(\theta_0)} = \frac{1}{g_{UV}^2} + \frac{2\theta_0 r_c}{g_5^2}$$

$$\Rightarrow \frac{b_>}{8\pi^2} = \frac{d}{d\log\Lambda_0}\frac{1}{g^2(\Lambda_0)} = -\frac{1}{kr_c}\frac{d}{d\theta_0}\frac{1}{g^2(\theta_0)} = -\frac{2}{kg_5^2}$$

$$\left(\frac{1}{2kg_5^2} + \frac{b_<}{32\pi^2}\right)\frac{\widetilde{\varphi}}{f}F^2 \to \left(\frac{b_< - b_>}{32\pi^2}\right)\frac{\widetilde{\varphi}}{f}F^2$$

Coupling to massless gauge bosons

In the presence of GW stabilization

Interaction terms between GW scalar and the gauge Bosons:

$$-\int d^4x \int d\theta \, \frac{F_{\mu\nu}^2}{4} \left[\delta(\theta)\frac{\sqrt{-G_{UV}}}{g_{UV}^2}\beta_{UV} + \frac{\sqrt{G}}{g_5^2}\beta_5 + \delta(\theta-\pi)\frac{\sqrt{-G_{IR}}}{g_{IR}^2}\beta_{IR}\right]\frac{\Phi}{k^{3/2}}$$

Once again, we need to identify the right $b_>$

$$\frac{b_>}{8\pi^2} = -\frac{2}{kg_5^2}\left(1 + \frac{\beta_5}{k^{3/2}}\Phi(\pi)\right)$$

Large Correction

Contribution from below the CFT breaking scale does not change.

Expanding about the VEVS, we get:

$$\left[\frac{b_< - b_>}{32\pi^2} + \frac{\beta_{IR}}{4g_{IR}^2}\frac{\Phi'(\pi)}{k^{3/2}}\right]\frac{\widetilde{\varphi}}{f}F_{\mu\nu}^2$$

Corrections scale as: m_φ^2/m_{KK}^2

In summary

- Identification of CFT parameters with RS parameters gets modified in the presence of GW scalar.
- Correction to the form of the couplings scale as the square of the ratio of radion to KK scale, in agreement with the result from the dilaton analysis.
- Similar conclusions hold for the case of fermions in bulk. Identification of CFT parameters to RS parameters changes once again. The analysis is complicated because the zero mode profiles are not flat any more.

Conclusion

- Composite Higgs theories with a CFT UV completion may have a light dilaton in the spectrum, as a result of near-conformality near the breaking scale, or mild tuning.
- Corrections to dilaton couplings can be calculated and match the radion analysis
- Corrections scale as square of (mass/composite-scale). Small for a lighter dilaton.
- A realistic modeling of the CFT scenario organizes the choice of parameters/interactions in the RS picture. (e.g. negative GW mass and GW self-interactions)