Challenges and progress in Relaxion models

Camila S. Machado

arXiv:1712.07635 (with N. Fonseca, B. von Harling and L. de Lima)
arXiv: 1601.07183 (with N. Fonseca, L. de Lima and R. D. Matheus)

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Outline

Relaxation of EW scale

→ Model building issues

Hierarchical decay constants

→ N-relaxion

CSM, N. Fonseca, L. de Lima
and R. D. Matheus, 1601.07183

UV completion

→ Warped relaxion

CSM, N. Fonseca, B. von Harling
and L. de Lima , 1712.07635

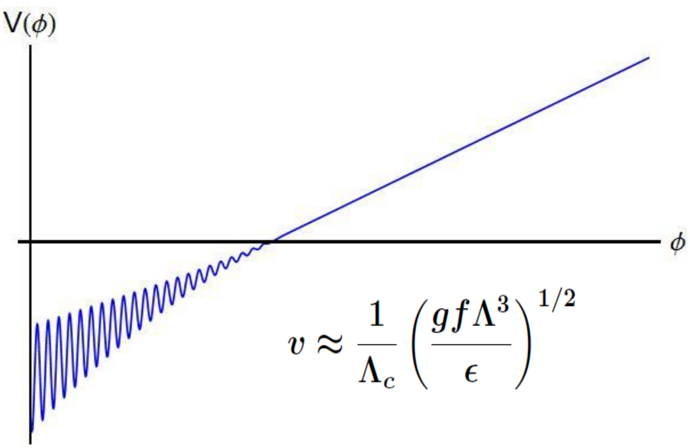
1.

Relaxation of the EW scale

Relaxion idea

Graham, Kaplan, Rajendran (1504.07551)

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right)h^2 + \epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$



$$v \approx \frac{1}{\Lambda_c}\left(\frac{gf\Lambda^3}{\epsilon}\right)^{1/2}$$

Need large field excursions

Linear term breaks the discrete shift symmetry!

Gupta et al (1509.00047)

Origin oscillatory term

Relaxion = qcd axion **vs** $SU(2)_L$ invariant term

Inflation sector

Huge number of e–folds

UV completion

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~~Inflation sector~~

Huge number of e-folds

UV completion

N-relaxion

Warped relaxion

Particle production

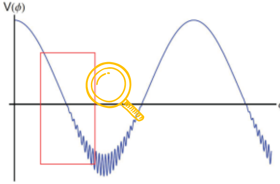
A. Hook and G. M-Tavares, 1607.01786

N. Fonseca, E. Morgante, G. Servant, to appear

2.

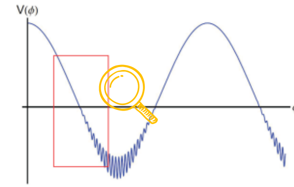
Hierarchical decay constants

Relaxion as a pNGB



$$V(\phi, H) \supset -\left(\Lambda^2 - g'\Lambda\,\phi\right) H^2 + \lambda H^4 + g\Lambda^3\phi + \Lambda_f^4(H)\cos\left(\frac{\phi}{f}\right)$$

Relaxion as a pNGB



$$V(\phi, H) \supset -\left(\Lambda^2 - g'\Lambda\,\phi\right) H^2 + \lambda H^4 + g\Lambda^3\phi + \Lambda_f^4(H)\cos\left(\frac{\phi}{f}\right)$$

$$\downarrow$$

$$V(\phi, H) \supset -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4(H)\cos\left(\frac{\phi}{F}\right) + \Lambda_f^4(H)\cos\left(\frac{\phi}{f}\right)$$

$$F \gg f$$

K. Choi and S.H. Im 1511.00132,
D.E. Kaplan and R. Rattazzi 1511.01827,
CSM, N. Fonseca, L. de Lima, R.Matheus 1601.07183,
CSM, N. Fonseca, B. Von Harling, L. de Lima 1712.07635

$$F \gg f$$

Hierarchical decay constants

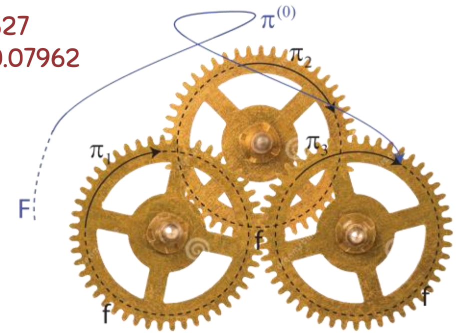
→ ‘Clockwork’ Kaplan and Rattazzi, 1511.01827
Giudice and McCullough, 1610.07962

$U(1)^{N+1}$ → Spont. breaking = N+1 NG’s
Explicity breaking = N pnGB’s

$$U_j(x) = e^{i\pi_j(x)/f} \qquad j = 0, .., N$$

$$\mathcal{L} = -\frac{f^2}{2}\sum_{j=0}^{N} \partial_\mu U_j^\dagger \, \partial^\mu U_j + \frac{m^2 f^2}{2}\sum_{j=0}^{N-1}\left(U_j^\dagger \, U_{j+1}^q + \text{h.c.}\right)$$

$$V(\pi) = \frac{m^2}{2}\sum_{j=0}^{N-1}\left(\pi_j - q\,\pi_{j+1}\right)^2$$



From R.D. Matheus PPC’16

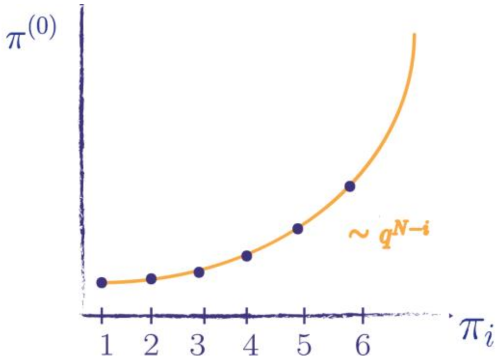
$$q > 1$$

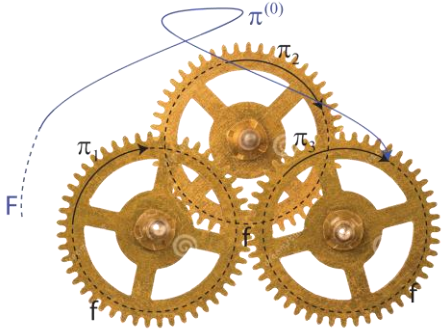
‘Field phase rotations with periods that get successively larger from one field to the next’

$$F \gg f$$

Hierarchical decay constants

→ 'Clockwork'





From R.D. Matheus PPC'16

$$q > 1$$

'Field phase rotations with periods that get successively larger from one field to the next'

$$\pi_i = \sum_{i=0}^{N} O_{i,(n)} \pi^{(n)} \qquad \lambda \pi_0 \mathcal{O}_{\rm SM} \to \lambda q^{-N} \pi^{(0)} \mathcal{O}_{\rm SM}$$

$$F \gg f$$

Hierarchical decay constants

→ 'Clockwork'

$$\mathcal{L} = \frac{\pi_N}{16\pi^2 f} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

$$\mathcal{L} = \frac{1}{16\pi^2} G_{\mu\nu}\widetilde{G}^{\mu\nu} \left(\frac{a_0}{f_0} - \sum_{k=1}^{N} (-)^k \frac{a_k}{f_k} \right)$$

$$\pi_N = \sum_{j=0}^{N} O_{Nj} \; a_j$$

$$O_{j0} \propto q^{-j}$$

$$q > 1$$

$$f_0/f \sim q^N$$

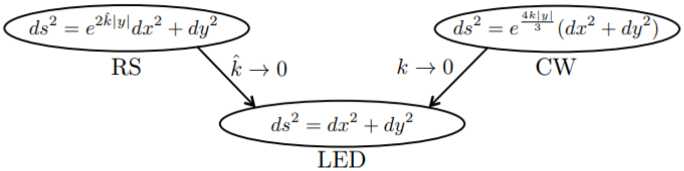
$$F \gg f$$

Hierarchical decay constants

‘Clockwork’

5D continuum limit:

Linear dilaton metric

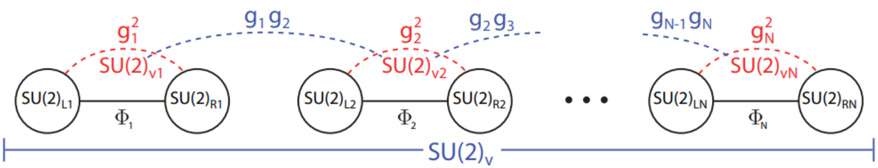


Giudice and McCullough, 1610.07962
Craig et al, 1704.10162
Giudice and McCullough, 1705.10162
Choi et al, 1711.06228

$$F \gg f$$

Hierarchical decay constants

'N-Relaxion' CSM, N. Fonseca, L. de Lima and R. D. Matheus, 1601.07183



$$\mathcal{L}_\Phi = \sum_{j=1}^{N} \mathrm{Tr}\left[\partial_\mu \Phi_j^\dagger \, \partial^\mu \Phi_j + \frac{f^3}{2}(2-\delta_{j,1}-\delta_{j,N}) g_j^2 \left(\Phi_j + \Phi_j^\dagger\right)\right]$$
$$- \frac{f^2}{2} \sum_{j=1}^{N-1} g_j g_{j+1} \mathrm{Tr}\left[(\Phi_j - \Phi_j^\dagger)(\Phi_{j+1} - \Phi_{j+1}^\dagger)\right]$$

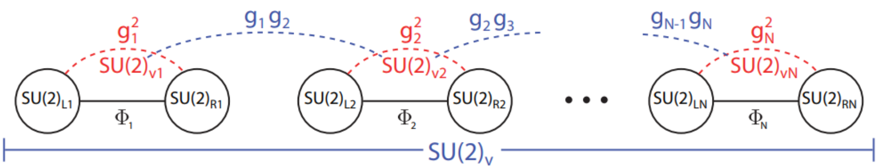
$$\Phi_j \to \frac{f}{2} e^{i\vec{\pi}_j \cdot \vec{\sigma}/f} = \frac{f}{2}\cos\left(\frac{\pi_j}{f}\right) + i\frac{f}{2}\frac{\vec{\pi}_j \cdot \vec{\sigma}}{\pi_j}\sin\left(\frac{\pi_j}{f}\right)$$

break explicitly all symmetries down to a diagonal SU(2)$_V$

$$F \gg f$$

Hierarchical decay constants

'N-Relaxion'



$$\mathcal{L}_\Phi = \sum_{j=1}^{N} \mathrm{Tr}\left[\partial_\mu \Phi_j^\dagger \, \partial^\mu \Phi_j + \frac{f^3}{2}(2-\delta_{j,1}-\delta_{j,N}) g_j^2 \left(\Phi_j + \Phi_j^\dagger\right)\right]$$

$$- \frac{f^2}{2} \sum_{j=1}^{N-1} g_j g_{j+1} \mathrm{Tr}\left[(\Phi_j - \Phi_j^\dagger)(\Phi_{j+1} - \Phi_{j+1}^\dagger)\right]$$

$$\Phi_j \to \frac{f}{2} e^{i\vec{\pi}_j\cdot\vec{\sigma}/f} = \frac{f}{2}\cos\left(\frac{\pi_j}{f}\right) + i\frac{f}{2}\frac{\vec{\pi}_j\cdot\vec{\sigma}}{\pi_j}\sin\left(\frac{\pi_j}{f}\right)$$

e.g. of UV model: 2N multiplets of Dirac fermions transforming as SU(2) doublets...

$$F \gg f$$

Hierarchical decay constants

→ 'N-Relaxion'

$$g_j \to q^j$$
$$0 < q < 1$$

Mass matrix → same as a pNGB in the deconstruction of AdS5

$$F \gg f$$

Hierarchical decay constants

→ 'N-Relaxion'

$g_j \to q^j$
$0 < q < 1$

Mass matrix → same as a pNGB in the deconstruction of AdS5

$$\mathcal{L}_\eta = \sum_{j=1}^{N} \left[\frac{1}{2} \partial_\mu \vec{\eta}_0 \cdot \partial^\mu \vec{\eta}_0 + f^4 (2 - \delta_{j,1} - \delta_{j,N}) q^{2j} \cos \frac{\eta_0}{f_j} \right] + \sum_{j=1}^{N-1} f^4 q^{2j+1} \sin \frac{\eta_0}{f_j} \sin \frac{\eta_0}{f_{j+1}}$$

$$f_j \equiv f \frac{\sqrt{\sum_{k=1}^{N} q^{2(k-1)}}}{q^{N-j}}$$

$$f_1 \approx f/q^{N-1}$$
$$f_N \approx f$$

$$F \gg f$$

Hierarchical decay constants

'N-Relaxion'

5D continuum limit: $N \to \infty,\ q \to 1,\ \text{with } q^{N+1} \text{ kept fixed}$

AdS$_5$ $f_1/f_N \to e^{kL}$

$$F \gg f$$

Hierarchical decay constants

→ 'N-Relaxion'

5D continuum limit: $N \to \infty,\ q \to 1,\ \text{with}\ q^{N+1}\ \text{kept fixed}$

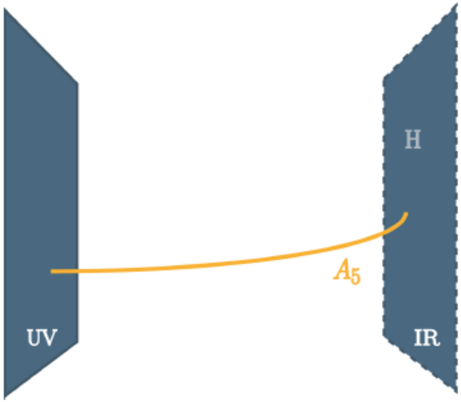
→ AdS_5 $\quad f_1/f_N \to e^{kL}$

but not easy to get the 5D action...

$$F \gg f$$

Hierarchical decay constants

‘Warped relaxion’ CSM, N. Fonseca, B. von Harling and L. de Lima , 1712.07635



T. Flacke et al, hep-ph/0611278
K.-w.Choi, hep-ph/0308024

Bulk fermions

$$S_{5\mathrm{D}} \supset \int d^4x\, dz \left(\frac{c_{\mathrm{B}}}{16\pi^2} \epsilon^{MNPQR} A_M \mathrm{Tr}\left[\boldsymbol{G}_{NP} \boldsymbol{G}_{QR} \right] \right)$$

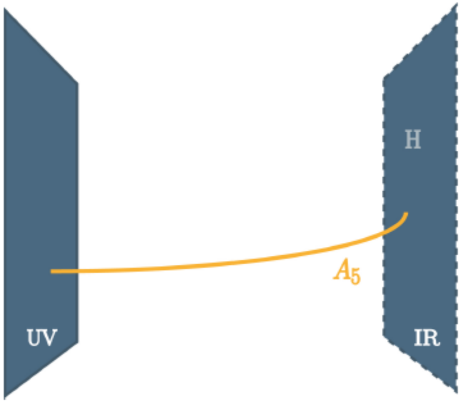
Chern-Simons coupling

$$f = f_{\mathrm{B}} \approx \Lambda_{\mathrm{IR}}$$

$$F \gg f$$

Hierarchical decay constants

‘Warped relaxion’



UV brane

$$S_{5\mathrm{D}} \supset \int d^4x\, dz\, \delta(z - z_{\mathrm{UV}}) \frac{c_{\mathrm{UV}}}{16\pi^2} \frac{A_5}{k}\, \epsilon^{\mu\nu\rho\sigma}\, \mathrm{Tr}\left[G_{\mu\nu} G_{\rho\sigma}\right]$$

Effective anomalous coupling*

$$F = f_{\mathrm{UV}} \approx M_{\mathrm{PL}}^2 / \Lambda_{\mathrm{IR}}$$

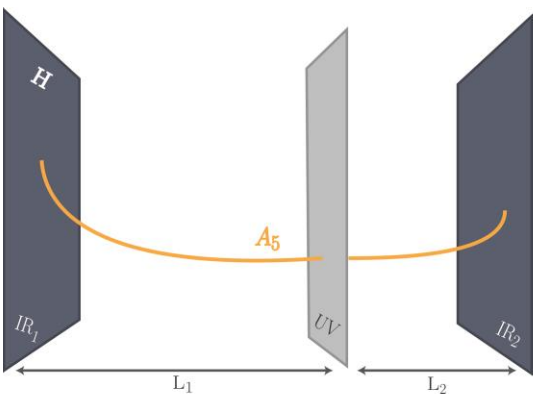
T. Flacke et al, hep-ph/0611278
K.-w.Choi, hep-ph/0308024

$$F \gg f$$

Hierarchical decay constants

Two (or more) bulks

G. Cacciapaglia, C. Csaki, C. Grojean,
M. Reece, and J. Terning, hep-ph/0505001



Effective anomalous coupling*
from a two throats geometry

$$S_{5D} \supset \int d^4x \int_{z_{UV}}^{z_{IR_2}} dz_2 \, \frac{c_{b_2}}{16\pi^2} \epsilon^{MNPQR} A_M \, \mathrm{Tr}\left[\mathbf{G}_{NP}\mathbf{G}_{PQ}\right]$$

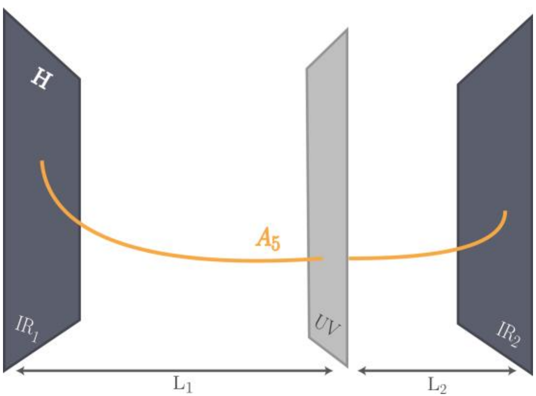
$$f_{B2} \approx \Lambda^2_{IR_2} / \Lambda_{IR_1}$$

$$F \gg f$$

Hierarchical decay constants

Two (or more) bulks

G. Cacciapaglia, C. Csaki, C. Grojean, M. Reece, and J. Terning, hep-ph/0505001



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$$f_{B2} \approx \Lambda_{IR_2}^2 / \Lambda_{IR_1}$$

Working in progress...

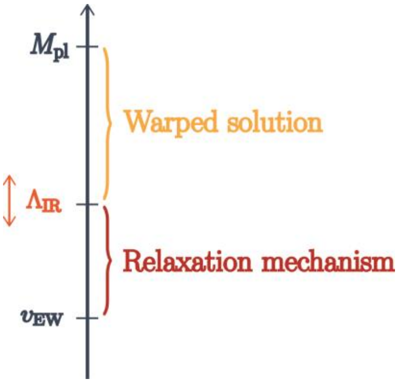
3.

UV completion

A warped UV

$F \gg f$

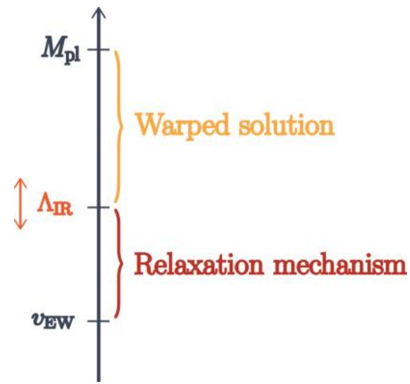
Protection to Higgs mass parameter from EW to Planck



A warped UV

$$F \gg f$$

Protection to Higgs mass parameter from EW to Planck

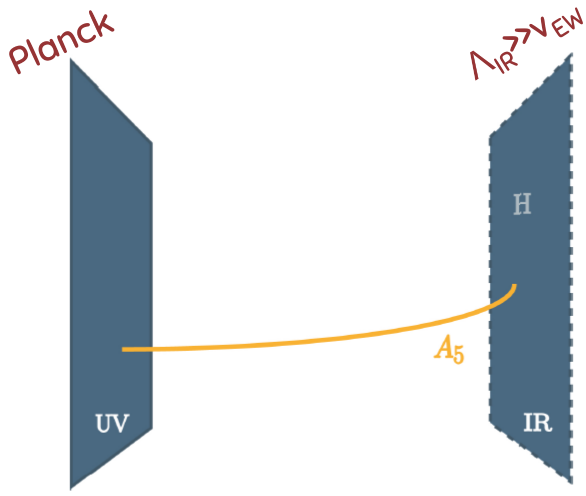


See also SUSY UV completions:

Giudice et al, 1509.00834; Gherghetta et al, 1602.04812

The setup

U(1) gauge boson in the bulk



$z_{\rm UV} = 1/k$ $z_{\rm IR} = e^{kL}/k$

$$ds^2 = a^2(z)\,(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

$$a(z) = (kz)^{-1}$$

$$A_\mu|_{\rm UV,IR} = 0$$

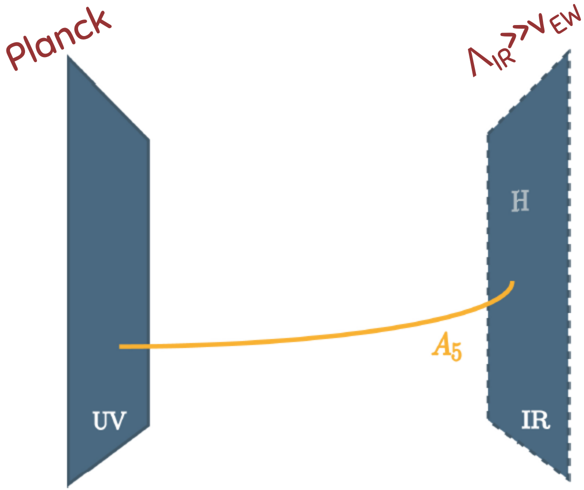
$$\partial_5 \left(a(z) A_5\right)\big|_{\rm UV,IR} = 0$$

$$A_5(x,z) \simeq g_4 \sqrt{2kL}\, e^{-kL} kz\, \phi(x)$$

See e.g.: Flacke et al. hep-ph/0611278
Contino et al. hep-ph/0306259

The setup

U(1) gauge boson in the bulk



$$z_{\rm UV} = 1/k \qquad z_{\rm IR} = e^{kL}/k$$

$$ds^2 = a^2(z)\,(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

$$a(z) = (kz)^{-1}$$

Remnant global U(1)
NGB = no potential...

$$A_5(x,z) \simeq g_4 \sqrt{2kL}\, e^{-kL}\, kz\, \phi(x)$$

See e.g.: Flacke et al. hep-ph/0611278
Contino et al. hep-ph/0306259

Hierarchical decay constants

Non-perturbative potential similar to what happens for the axion in QCD

Effective anomalous coupling on the UV brane

Chern-Simons coupling

$$S_{4D} \supset \int d^4x \, \frac{\phi(x)}{16\pi^2} \, \epsilon^{\mu\nu\rho\sigma} \left(\frac{1}{F} \mathrm{Tr}\left[G^F_{\mu\nu} G^F_{\rho\sigma}\right] + \frac{1}{f} \mathrm{Tr}\left[G^f_{\mu\nu} G^f_{\rho\sigma}\right] \right)$$

$$F = f_{\rm UV} \approx M_{\rm PL}^2 / \Lambda_{\rm IR}$$

$$f = f_{\rm B} \approx \Lambda_{\rm IR}$$

Potential: Dictionary

$$V(\phi, H) \supset -\left(\Lambda^2 - g'\Lambda\,\phi\right) H^2 + \lambda H^4 + g\Lambda^3\phi + \Lambda_f^4(H)\cos\left(\frac{\phi}{f}\right)$$

$$\downarrow$$

$$V(\phi, H) = -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4\left(1 + \frac{H^2}{M_F^2}\right)\cos\left(\frac{\phi}{F}\right) + \Lambda_f^4\left(1 + \frac{H^2}{M_f^2}\right)\cos\left(\frac{\phi}{f}\right)$$

IR scale!

$$g = \frac{\Lambda_F^4}{F\Lambda^3} \qquad g' = \frac{\Lambda_F^4}{F M_F^2 \Lambda}$$

Generating the Potential

$$V(\phi, H) = -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4 \left(1 + \frac{H^2}{M_F^2}\right)\cos\left(\frac{\phi}{F}\right) + \Lambda_f^4 \left(1 + \frac{H^2}{M_f^2}\right)\cos\left(\frac{\phi}{f}\right)$$

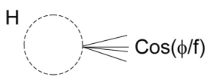
$$S_{5\mathrm{D}} \supset \int d^4x\, dz\, \sqrt{-g_{\mathrm{IR}}}\, \delta(z - z_{\mathrm{IR}})\, m_\chi \left(1 + \frac{H^2}{M_{\mathrm{PL}}^2}\right) \chi\, \chi^c + \mathrm{h.c.}$$

Chiral rotation $\langle \chi \chi^c \rangle = \Lambda_{\mathcal{G}_F}^3$

$$V(\phi, H) \supset m_\chi\, \Lambda_{\mathcal{G}_F}^3 \left(1 + \frac{H^2}{\Lambda_{\mathrm{IR}}^2}\right) \cos\left(\frac{\phi}{F}\right)$$

Generating the Potential

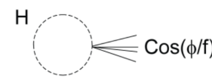
$$V(\phi, H) = -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4 \left(1 + \frac{H^2}{M_F^2}\right) \cos\left(\frac{\phi}{F}\right) + \Lambda_f^4 \left(1 + \frac{H^2}{M_f^2}\right) \cos\left(\frac{\phi}{f}\right)$$



Generating the Potential

$$V(\phi, H) = -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4 \left(1 + \frac{H^2}{M_F^2}\right) \cos\left(\frac{\phi}{F}\right) + \Lambda_f^4 \left(1 + \frac{H^2}{M_f^2}\right) \cos\left(\frac{\phi}{f}\right)$$

$$M_f \approx v_{\rm EW}$$



Graham, Kaplan, Rajendran ,1504.07551

Option 1: Fermions at EW scale ~ coincidence problem

$$S_{5D} \supset \int d^4x\, dz\, \sqrt{-g_{\rm IR}}\, \delta(z - z_{\rm IR}) \left(m_L\, L L^c + m_N\, N N^c + y\, H L N^c + \tilde{y}\, H^\dagger L^c N \right) + {\rm h.c.}\,.$$

Chiral rotation; int-out L and L^c

$$\langle N N^c \rangle = \Lambda_{\mathcal{G}_f}^3$$

$$V(\phi, H) \supset m_N\, \Lambda_{\mathcal{G}_f}^3 \left(1 - \frac{y \tilde{y}\, H^2}{m_N m_L}\right) \cos\left(\frac{\phi}{f}\right)$$

Generating the Potential

$$V(\phi, H) = -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4 \left(1 + \frac{H^2}{M_F^2}\right)\cos\left(\frac{\phi}{F}\right) + \Lambda_f^4 \left(1 + \frac{H^2}{M_f^2}\right)\cos\left(\frac{\phi}{f}\right)$$

$$M_f \gg v_{\rm EW}$$

Option 2: Double scanner mechanism

J.R. Espinosa, C. Grojean, G. Panico, A. Pomarol, O. Pujolàs, G. Servant. 1506.09217

$$S_{4D} \supset \int d^4x \, \frac{1}{16\pi^2} \frac{\phi}{f} \, \epsilon^{\mu\nu\rho\sigma} \left(\mathrm{Tr}\left[G^{f_1}_{\mu\nu} G^{f_1}_{\rho\sigma}\right] - \mathrm{Tr}\left[G^{f_2}_{\mu\nu} G^{f_2}_{\rho\sigma}\right] + \mathrm{Tr}\left[G^{f_3}_{\mu\nu} G^{f_3}_{\rho\sigma}\right] - \mathrm{Tr}\left[G^{f_4}_{\mu\nu} G^{f_4}_{\rho\sigma}\right] \right)$$

$$S_{4D} \supset \int d^4x \, \frac{1}{16\pi^2} \frac{\sigma}{\tilde{F}_\sigma} \, \epsilon^{\mu\nu\rho\sigma} \left(\mathrm{Tr}\left[G^{f_3}_{\mu\nu} G^{f_3}_{\rho\sigma}\right] + \mathrm{Tr}\left[G^{f_4}_{\mu\nu} G^{f_4}_{\rho\sigma}\right] \right)$$

$$\begin{array}{ccc} \mathcal{G}_{f_1} & \overset{\mathbb{Z}_2}{\longleftrightarrow} & \mathcal{G}_{f_2} \\ \mathbb{Z}_2' \updownarrow & & \updownarrow \mathbb{Z}_2' \\ \mathcal{G}_{f_3} & \underset{\mathbb{Z}_2}{\longleftrightarrow} & \mathcal{G}_{f_4} \end{array} .$$

Parameter space

Λ	F	Λ_F	M_F	f	Λ_f	M_f	
$\Lambda_{\rm IR}$	$\frac{M_{\rm PL}^2}{\Lambda_{\rm IR}}$	$\Lambda_{\rm IR}$	$\Lambda_{\rm IR}$	$\Lambda_{\rm IR}$	$\frac{\Lambda_{\rm IR}^{3/2}}{M_{\rm PL}^{1/2}}$	$v_{\rm EW}$	$10\,{\rm TeV} \lesssim \Lambda_{\rm IR} \lesssim 4 \cdot 10^3\,{\rm TeV}$

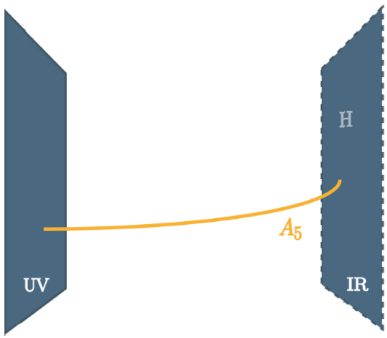
Flavor bounds on the KK modes

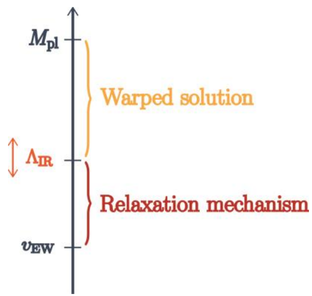
Higgs-relaxion mixing

$$g = \frac{\Lambda_{\rm IR}^2}{M_{\rm Pl}^2}$$

Not a free parameters here!

Summary





UV completion ✓

Many model building possiblities...

Hierarchical decay constants ✓

Applications other than relaxion models?

From N. Fonseca talk (Trento ‘17)

Incomplete list!

Cosmological Relaxation of the Electroweak Scale, GKR ’15

inspired by Abbott’s attempt to solve the CC problem, ’85

Cosmological Constant

- Graham, Kaplan, Rajendran; 1709.01999
- Alberte, Creminelli, Khmelnitsky, Pirtskhalava, Trincherini ‘16

Dynamics during Inflation

- Non-constant Hubble;

  Patil, Schwaller '15

Observational Constraints

- Higgs-relaxion coupling;

  Flacke, Frugiuele, Fuchs, Gupta, Perez; '16

- New strongly coupled sector;

  Beauchesne, Bertuzzo, di Cortona; 1705.06325

Double scanner mechanism

Espinosa, Grojean, Panico, Pomarol, Pujolàs, Servant ‘16

Model building front

- 4D site models; Choi, Im '16; Kaplan, Rattazzi '16; NF, Lima, Machado, Matheus '16
- 5D continuum limit; Giudice, McCullough '16
- String theory (Monodromy);

  McAllister, Schwaller, Servant, Stout, Westphal ‘16

- Relaxion from Warped Space

  NF, von Harling, Lima, Machado ‘in preparation

Alternatives to Inflation

- Friction from particle production;

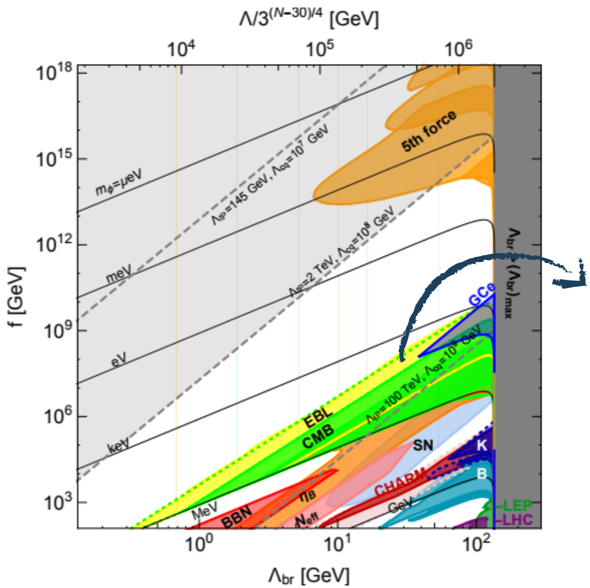
  Hook, Marques-Tavares; ‘16

16

Relaxing with gravitational waves,
CSM, P. Schwaller, Ben A. Stefanek, W. Ratzinger

Backup

Parameter space



$$\Lambda_{\rm br}^2 = \Lambda_f^2 v_{\rm EW}/M_f$$

Distortion of diffuse extragalactic background light spectrum due to relaxion late decays

Flacke, Frugiuele, Fuchs, Gupta and Perez, 1610.02025

Generating the Potential

$$V(\phi, H) = -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4 \left(1 + \frac{H^2}{M_F^2}\right) \cos\left(\frac{\phi}{F}\right) + \Lambda_f^4 \left(1 + \frac{H^2}{M_f^2}\right) \cos\left(\frac{\phi}{f}\right)$$

$\Lambda \sim \Lambda_{\rm IR}$

	χ	χ^c	N	N^c	L	L^c
$\mathcal{G}_F$	$\square$	$\bar{\square}$	–	–	–	–
$\mathcal{G}_f$	–	–	$\square$	$\bar{\square}$	$\square$	$\bar{\square}$
$SU(2)_L$	–	–	–	–	$\square$	$\square$
$U(1)_Y$	–	–	–	–	$-\frac{1}{2}$	$+\frac{1}{2}$

$$M_f^2 = \frac{m_N m_L}{y\tilde{y}} \quad M_F^2 = \Lambda_{\rm IR}^2$$

$$\Lambda_F^4 = m_\chi \Lambda_{\mathcal{G}_F}^3 \quad \Lambda_f^4 = m_N \Lambda_{\mathcal{G}_f}^3$$

$$m_\chi, \Lambda_{\mathcal{G}_F} \sim \Lambda_{\rm IR}$$

* M_F and F are of order $\Lambda_{\rm IR}$, whereas M_f is of order v_{EW}.
* F and f are given in terms of $\Lambda_{\rm IR}$ and M_{PL}
* Λ_f is fixed as a function of the other parameters

$$\epsilon \Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

Origin of the oscillatory term

* **n=1:** relaxion = QCD axion

$$\Lambda_c = \Lambda_{QCD}$$

$$\epsilon = Y_u$$

$$V(\phi, H) \sim m_u(H) \langle q\bar{q} \rangle \cos(\phi/f)$$

$$\theta_{QCD} \sim 1$$

however, see: 1708.00010 and 1711.00858

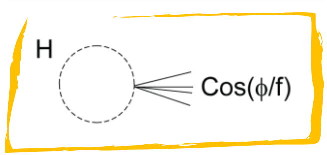
$$\epsilon\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

Origin of the oscillatory term

* n=2: $SU(2)_L$ invariant term

Λ_c ~ TeV but requires new fermions at TeV scale.

$\Lambda_c \sim \Lambda$ but high barriers everywhere.



however, see: double scanner mechanism, Espinosa et al. 1506.09217

Generating the Potential

$$V(\phi, H) = -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4 \left(1 + \frac{H^2}{M_F^2}\right) \cos\left(\frac{\phi}{F}\right) + \Lambda_f^4 \left(1 + \frac{H^2}{M_f^2}\right) \cos\left(\frac{\phi}{f}\right)$$

Option 2: double scanner mechanism

	χ	χ^c	η_1	η_1^c	η_2	η_2^c	η_3	η_3^c	η_4	η_4^c
$\mathcal{G}_F$	$\square$	$\bar{\square}$	$-$	$-$	$-$	$-$	$-$	$-$	$-$	$-$
$\mathcal{G}_{f_1}$	$-$	$-$	$\square$	$\bar{\square}$	$-$	$-$	$-$	$-$	$-$	$-$
$\mathcal{G}_{f_2}$	$-$	$-$	$-$	$-$	$\square$	$\bar{\square}$	$-$	$-$	$-$	$-$
$\mathcal{G}_{f_3}$	$-$	$-$	$-$	$-$	$-$	$-$	$\square$	$\bar{\square}$	$-$	$-$
$\mathcal{G}_{f_4}$	$-$	$-$	$-$	$-$	$-$	$-$	$-$	$-$	$\square$	$\bar{\square}$

Generating the Potential

$$V(\phi, H) = -\Lambda^2 H^2 + \lambda H^4 + \Lambda_F^4 \left(1 + \frac{H^2}{M_F^2}\right) \cos\left(\frac{\phi}{F}\right) + \Lambda_f^4 \left(1 + \frac{H^2}{M_f^2}\right) \cos\left(\frac{\phi}{f}\right)$$

Option 2: Double scanner mechanism

$$V(\phi, \sigma, H) \supset \Lambda_f^4 \left(1 - \tilde{g}_\sigma \frac{\sigma}{\Lambda} \tan\left(\frac{\phi}{f}\right) + \tilde{g}\frac{\phi}{\Lambda} + \frac{H^2}{M_f^2}\right) \cos\left(\frac{\phi}{f}\right)$$

$$\tilde{g} = |c_{\chi\eta_1}| \frac{|m_\chi| \Lambda^3_{\mathcal{G}_F}}{\Lambda^3_{\rm IR} F} \qquad g_\sigma = \frac{|m_\rho|\, \Lambda^3_{\mathcal{G}_{F_\sigma}}}{F_\sigma\, \Lambda^3_{\rm IR}}$$