Relaxions & the Little Hierarchy Problem

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Gupta, Komargodski, GP & Ubaldi (15)

Gearing up for LHC13 -- Conference

ERC TOPCHARM

The scope of this talk & its perspective

- SM: Higgs being a scalar leads to the fine tuning problem.

- Fine tuning problem, sensitivity to high scales <=> UV problem.

- Most concrete (exciting) solutions are in form of IR naturalness <=> field theory solution, understood from IR perspective. Giudice (13)

- Relaxion: switch attention from one scalar (H) to another scalar, the relaxion (ϕ).

- Talk's scope: applying similar consideration: IR natural $V(\phi)$; String theory/non-QFT => beyond the scope …

Outline

- ♦ The challenge, a toy model U(1) example (induction, going reverse order from a working model).

- ♦ Possible ways out.

- ♦ Some pheno': familon-relaxion model & its miracle.

- ♦ Conclusions.

Ex.: pNGB-relaxion model

Constructing a toy U(1) relaxion model

Consider a theory with a spontaneously broken global G=U(1) symmetry.

For simplicity: realise it linearly via a scalar Φ that carries a unit charge.

L is invariant under a global transformation: $\Phi \to \Phi \exp(i\theta)$.

Φ develop VEV $\langle \Phi \rangle = f$.

Below the scale f: a single light (massless) DOF ϕ .

Obtained via the identification $\Phi \equiv \rho \exp\left(i \frac{\phi}{f}\right)$.

A toy U(1) relaxion model

Several points are in order:

(i) $\phi = \frac{1}{f}\arctan\left(\frac{\Im\Phi}{\Re\Phi}\right) = -\frac{\pi}{2}..\frac{\pi}{2}$ is compact;

(ii) $\phi \to \phi + 2\pi n f$ maps Φ onto itself.

(iii) Breaking G $\Rightarrow V(\phi) \neq 0$:

$(\mathrm{iii})_a$ Planck suppressed $\frac{\Phi^5}{M_{\rm Pl}} + h.c \Rightarrow V(\phi) \propto \frac{f^5}{M_{\rm Pl}}\cos\left(\frac{5\phi}{f}\right)$;

$(\mathrm{iii})_b$ $\mathcal{L}^{\rm soft}_{\rm FN} = \left(\frac{\Phi}{\Lambda}\right)^n LHN + y_c L^c \tilde{H} N + m_L L^c L + m_N NN$

$\Rightarrow V_{\rm FN}(\phi) \propto m_L m_N y y_c H^\dagger H \cos\left(\frac{n\phi}{f}\right)$.

(note: a sector \w charge n)

A toy U(1) relaxion model

Structure seems compatible with the relaxion framework:

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$V_{\mathrm{FN}}(\phi, \langle H \rangle) \propto m_L m_N y y_c v^2 \cos\left(\frac{n\phi}{f}\right) \;\Leftrightarrow$ generates backreaction.

Additional breaking is required to provide Higgs-mass scan:

$\mu_H^2(\phi) H^\dagger H \sim \left[\Lambda^2 + M_x^2 \cos\left(\frac{\phi}{f}\right)\right] H^\dagger H \;\Leftrightarrow$
generated via a (unit charge) sector with $M_x \gg m_{L,N}$.

Sufficient to write a complete & consistent model.

A consistent U(1) relaxion model

$$\mu_H^2(\phi)H^\dagger H \sim \left[\Lambda^2 + M_x^2 \cos\left(\frac{\phi}{f}\right)\right] H^\dagger H \text{ with } M_x \gtrsim \Lambda \gg v \equiv 174\,\text{GeV};$$

$$V(\phi, v) \sim r^2 \Lambda^2 M_x^2 \cos\left(\frac{\phi}{f}\right) + y y_c v^2 m_L m_N \cos\left(\frac{n\phi}{f}\right)\ .\ (r \gtrsim \tfrac{1}{4\pi})$$

$$\phi_{\text{rel}} \text{ is found via } V'(\phi, v) = 0 \Rightarrow r^2\Lambda^4 \sim n y y_c m_L m_N v^2$$

$$(\text{for } \phi \sim f\ \&\ M_x \sim \Lambda).$$

$$\text{Dominant backreaction} \Rightarrow m_{L,N} \lesssim 4\pi v\,.$$

Espinosa, Grojean, Panico, Pomarol, Pujolàs & Servant (15)

⇓

$$\Lambda \lesssim 10\,\text{TeV} \times \frac{(y y_c v^2 m_L m_N)^{\frac{1}{4}}}{4\pi v} \times \left(\frac{1}{4\pi r}\right)^{\frac{1}{2}} \times \left(\frac{n}{10}\right)^{\frac{1}{4}}$$

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Intermediate summary

- Can raise cutoff but only up to O(10 TeV). (pheno' discussed below)

- Relation is independent of sym' breaking scale, *f*.

- *n* raises cutoff, but only weakly, every decade => 10^4 charges.

- Large *n* => irrelevant operators => tiny back reaction or fine tuning: $\mathcal{L}_{\rm FN}^{\rm soft} = \left(\frac{\Phi}{\Lambda}\right)^n LHN + y_c L^c \tilde{H} N + m_L L^c L + m_N NN \,.$ ($n \to 10^{12}$?)

- Is this artefact of above simple model? can it be circumvented?

Back to Original Relaxion Proposal

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$$\left(\Lambda^2 - g^2\phi^2\right) H^\dagger H \;\Rightarrow\; \phi_{\rm relaxed} \sim \frac{\Lambda}{g}\,; \quad (\text{assume} : \Lambda \gg v)$$

$$V(\phi) = r^2 g^2 \Lambda^2 \phi^2 - v^n M_X^{4-n} \cos(\phi/f) \;\; (\text{expect} : M_X < 4\pi v;\, 4 \geq n > 0)$$

$$V'(\phi) = 0 \;\Rightarrow\; \frac{\phi_{\rm relaxed}}{f} \gtrsim \left(\frac{\Lambda}{4\pi v}\right)^4 \times r^2 \qquad \left[g \lesssim \left(\frac{4\pi v}{\Lambda}\right)^4 \times \frac{\Lambda}{f r^2}\right]$$

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$$\Lambda \gg \text{ TeV} \;\Rightarrow\; \langle\phi\rangle \gg f \text{ required to be physical.}$$

The (compact) Relaxion Proposal

Gupta, Komargodski, GP & Ubaldi (15)

$\Lambda \gg \text{ TeV } \Rightarrow \langle \phi \rangle \gg f$ required to be physical.

However, local-global-finite EFT: pNGB => compact manifold.

Again: $\phi \to \phi + 2n\pi f \ \ (n \in \mathcal{Z})$ lead to same physics.

This is a redundant description of the theory <=> discrete gauge sym' (no example \w local operator that breaks it)

As long as relaxion potential is controlled by global internal sym' EFT locality seems to implies compactness of pNGB manifold:

$$\langle \phi \rangle \lesssim f \,.$$

Brief: Comments on the Relaxion Proposal

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Hence upon the identification:

axion $\leftrightarrow \phi$, U(1) $\leftrightarrow$ PQ , and

$$y_u H f_\pi^3 \;\text{ or }\; y_u^2 H^\dagger H f_\pi^2 \leftrightarrow m_L m_N y y_c H^\dagger H \, ,$$

we expect a similar bound to hold:

$$\Lambda \lesssim 10\,\text{TeV} \times \frac{[(yv)^{1,2} f_\pi^{3,2}]^{\frac{1}{4}}}{4\pi v} \times \left(\frac{1}{4\pi r}\right)^{\frac{1}{2}} \times \left(\frac{n}{10}\right)^{\frac{1}{4}}$$

Note: axion realisations also suffer from inflated *n* => irrelevant operators => tiny backreaction/fine tuning/monstrous beta function.

Potential interesting ways out

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- Combination \w incommensurate coefficients, still $\langle\phi\rangle \lesssim O(f)$.

- Non-compact internal sym' \w consistent finite QFT ?

- Non-compact relaxions from space time sym':

  i. SUSY - pseudo moduli, however, tend to pick up mass at SUSY breaking scale;

  ii. CFT => dilaton, large N & very special structure.

… Coradeschi, Lodone, Pappadopulo, Rattazzi & Vitale; Bellazzini, Csaki, Hubisz, Serra & Terning (13) …

Or: raise cutoff but only up to O(few TeV).

Brief pheno' of the little familon-relaxion model

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A little-“miraculous”-familon-relaxion model

Gupta, Komargodski, GP & Ubaldi (15)

$$\mathcal{L} = -y_1 e^{i\frac{2n\phi}{f_{\rm UV}}} \epsilon^{\alpha\beta} h_\alpha L_\beta N - y_2 h^{\dagger\alpha} L^c_\alpha N - m_L \epsilon^{\alpha\beta} L_\alpha L^c_\beta - \frac{m_N}{2} NN + \text{h.c.}\,.$$

$$V_{\rm CW}(\phi) \simeq -\frac{1}{4\pi^2} m_L m_N y_1 y_2 |h^0|^2 \cos\left(\frac{\phi}{f}\right) \log\left(\frac{\Lambda^2}{\tilde{m}^2}\right)\,,$$

$$V(h) = \left[\Lambda^2 - M^2 \cos\left(\frac{\phi}{f_{\rm UV}}\right)\right] h^\dagger h + \lambda (h^\dagger h)^2\,,$$

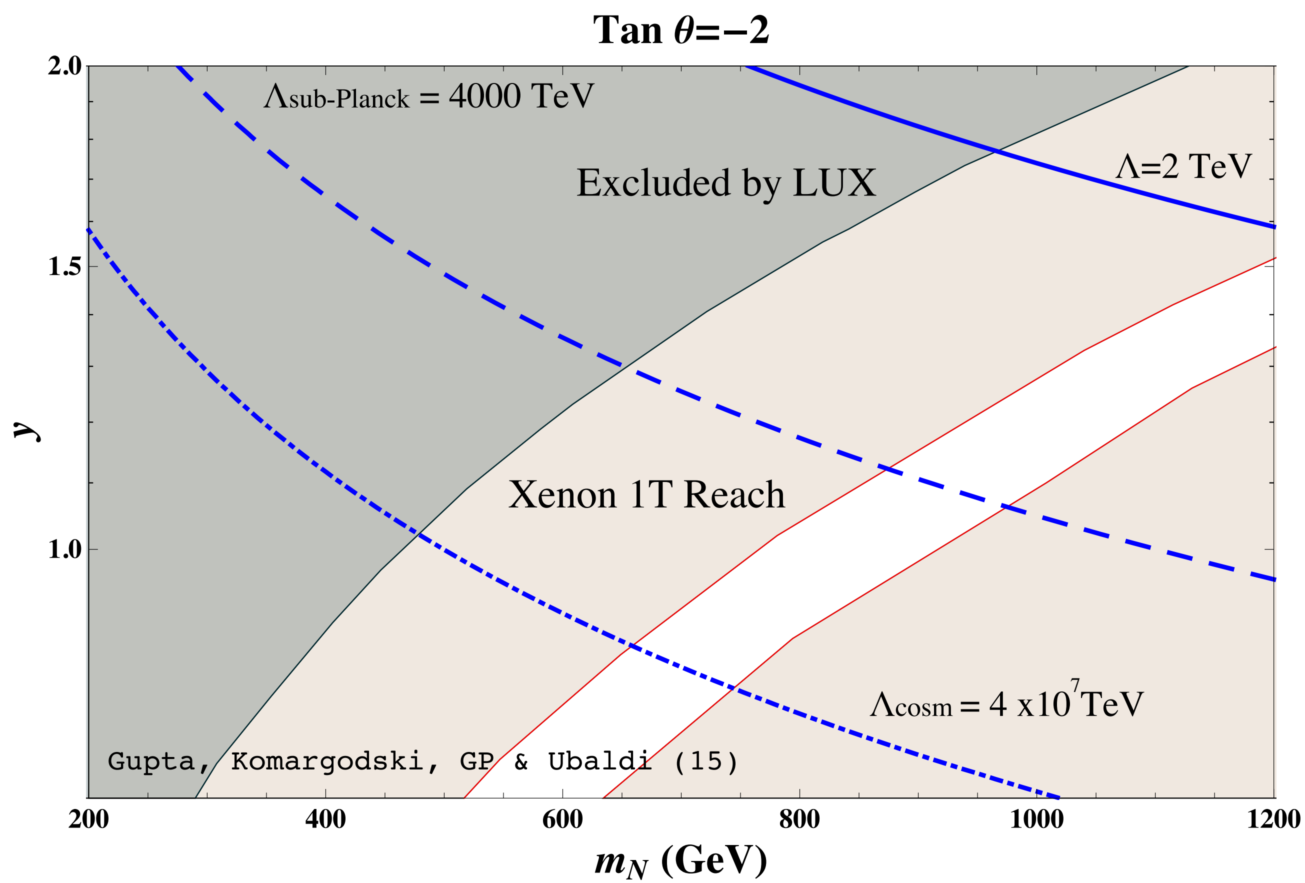
$$V(\phi) = \frac{\Lambda^2 M^2}{16\pi^2} \cos\left(\frac{\phi}{f_{\rm UV}}\right)\,,$$

	$U(1)_{NL}$
N	-n
L	-n
L^c	n
h	0
$e^{i\phi/f_{\rm UV}}$	1
SM	0

$$\Lambda \lesssim 3,5\ \text{TeV} \left(\frac{m_L}{900\ \text{GeV}}\right)^{\frac{1}{4}} \left(\frac{m_N}{900\ \text{GeV}}\right)^{\frac{1}{4}} \left(\frac{y_1}{4\pi}\right)^{\frac{1}{4}} \left(\frac{y_2}{4\pi}\right)^{\frac{1}{4}} \left(\frac{n}{1,10}\right)^{\frac{1}{4}}\,.$$

Doublet-singlet dark matter

Cohen, Kearney, Pierce & Tucker-Smith (11); Cheung & Sanford (13); Abe, Kitano & Sato (14); Calibbi, Mariotti & Tziveloglou (15)



Constraints from dark matter phenomenology on our parameter space: $y_1 = y\cos\theta$, $y_2 = y\sin\theta$, and m_L is adjusted according to the observed relic density. The blue contours correspond to the following upper bounds on the cut-off: the cosmological constraints (dot-dashed), the requirement that $f_{\rm UV} < M_{\rm Pl}$ (dashed), and by requiring a consistent theory that does not break the discrete gauge symmetry using (3.15) with $n = 10$ (solid). The region shaded in grey is excluded by LUX, while the brown region will be probed in the near future by the XENON 1 Ton experiment.

Conclusions

- Relaxion models: new paradigm to generate hierarchies.

- Existing proposals: large hierarchies use (compact) pNGBs => going beyond local-internal-EFTs.

- Relaxion models can address the little hierarchy problem:

(i) constructed a simple (perturb.) familon model \w extra vector-like "leptons"; no new coloured state (t'/W' ...), $\Lambda \gtrsim$ few TeV ;

(ii) accidentally, simplest model contains a viable dark matter candidate, discoverable at XENON1T.

Backups