The naturalness problem in the light of space-time symmetry breaking

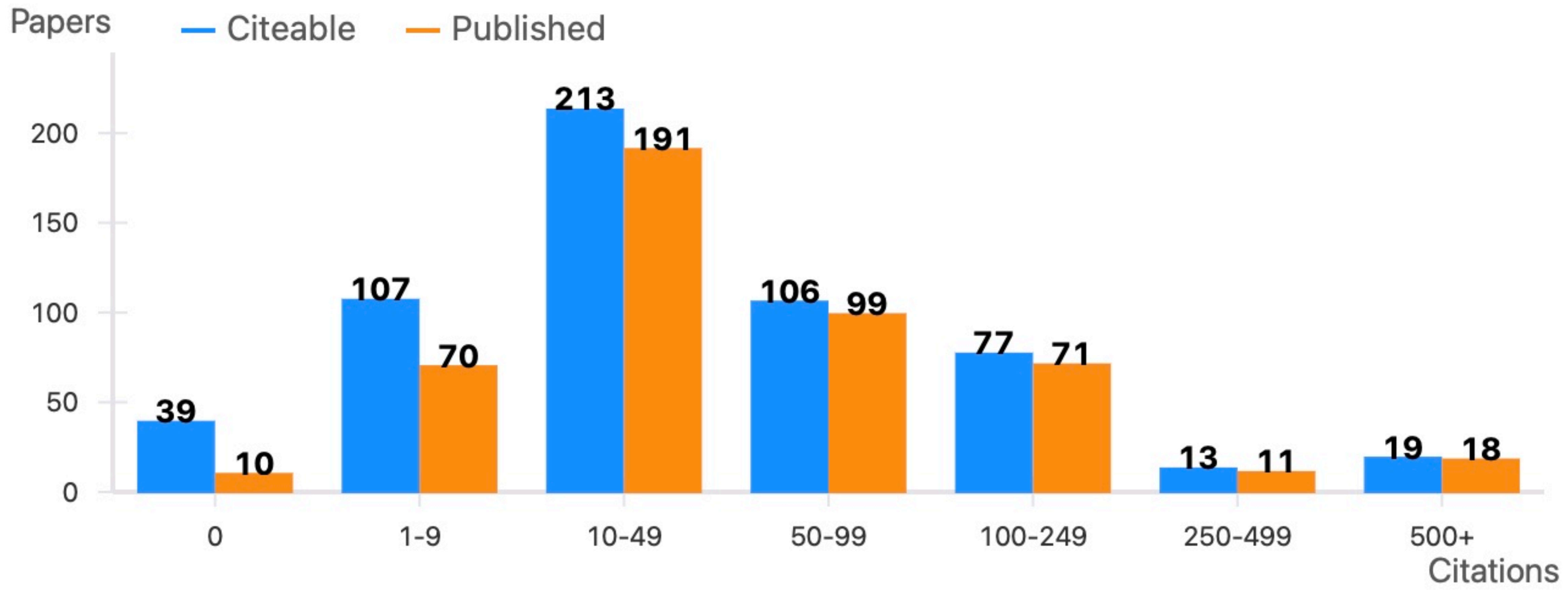
Ira Rothstein (CMU)

(Work done in Collaboration with Alberto Nicolis)

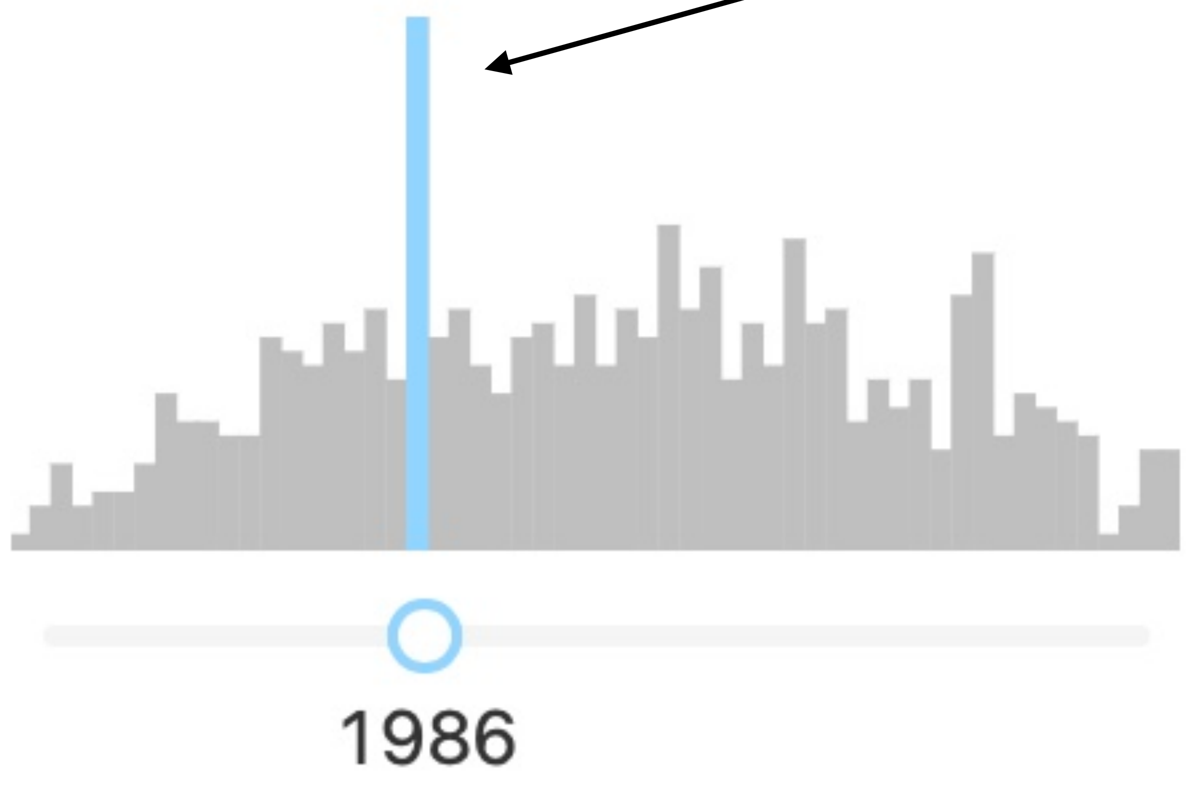
Rabi-fest

- Hadronic Sum Rules and Regge Trajectories
- Canonical Quantization of Yang Mills Theory
- CP Violation
- Left Right Symmetric Models
- Finite Temperature Field Theories
- Baryon number violation/Proton Decay
- Neutrino mass models
- Neutron-Anti-Neutron Oscillations
- GUTS/SO(10)
- String Phenomenology
- Constraints from Astrophysics (neutron stars)
- Radiative Mass Generation
- Nucleosynthesis constraints
- Dark Matter (SIMPS/Mirror)
- Family Symmetries and Mass Hierarchies
- Super-Symmetric Phenomenology
- Lepto genesis

	Citeable	Published
Papers	574	470
Citations	55,227	51,391
h-index	103	100
Citations/paper (avg)	96.2	109.3



38 papers in 1986!



Naturalness Terminology

A dimensionless numbers (or dimensionful number in units of the cut-off) in the action which is much less than one we will call this a
Dirac Fine Tuning

A Dirac fine tuning which is not radiatively stable we will call a t'Hooft fine tuning.

Dirac fine tunings of relevant operators which are not protected by symmetry are t'Hooft fine tuned

Some Examples:

Dirac	t'Hooft
Fermion masses in the SM, the Theta parameter	Higgs mass, CC

Resolutions to Naturalness Problems

- Enhanced Symmetry (SUSY).
- Strong coupling dynamics shifts relevant to marginal.   (RS)

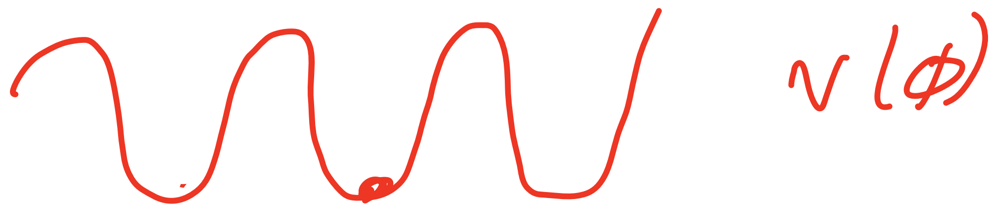
``UV Solutions''

- Relaxation Mechanisms. (PQ mechanism (strong CP), Abbot (CC), Relaxion (EW Hierarchy)

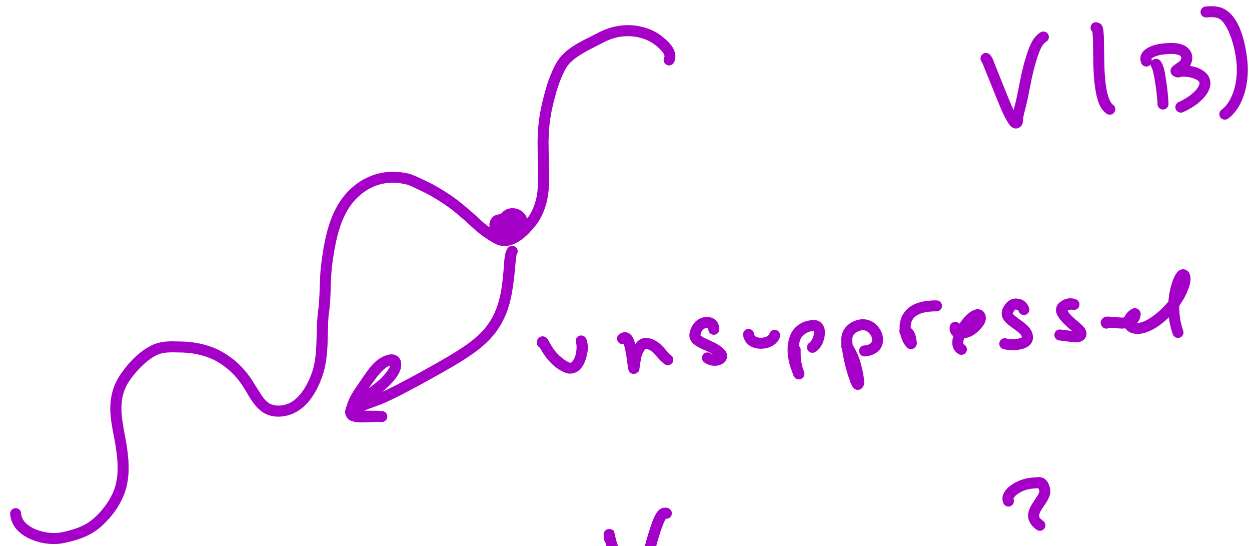
``IR Solutions''

Relaxation Mechanisms

$U(1)_A \to \emptyset$ $\qquad L = \phi F \wedge F$ $\qquad \langle \phi \rangle \equiv \theta$



Abbotts : Relaxation of c.c



$$\frac{V}{M_{pl}^2} > \Lambda^{?}$$

$\Lambda \equiv$ phantom sector strong scale

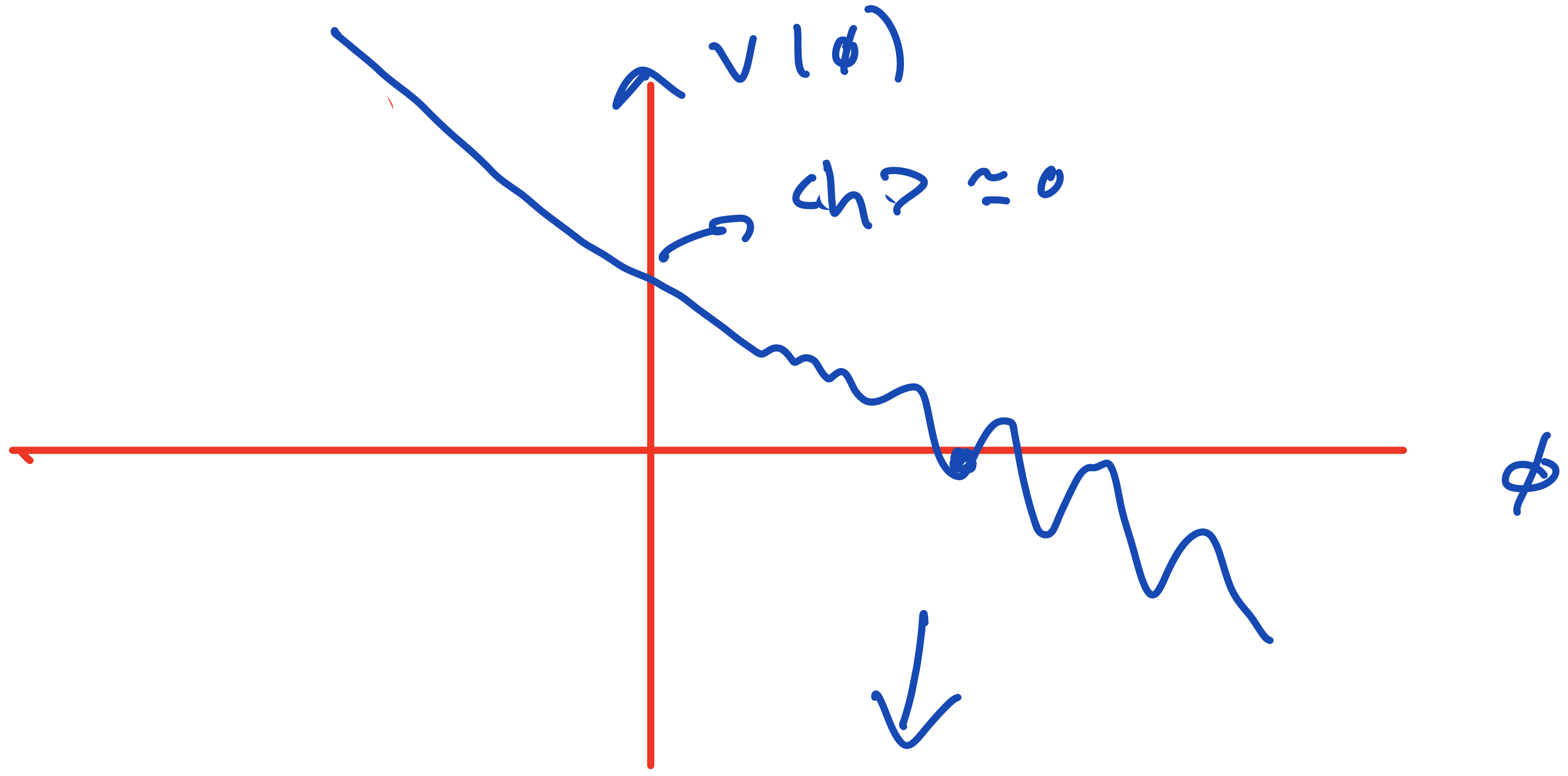
$$V = V_0 + \frac{\epsilon B}{f_B} - \Lambda^4 \cos(B/f_B)$$

Relaxion

Graham
Kaplan
Rajendran

$$V \sim g\Lambda^3\phi - (M^2 - g\Lambda\phi)|h|^2 + v(h)\cos(\phi/f)$$

$g \sim 10^{-36}$



Slide stops @ EW scale

These paradigm are compelling (though they still suffer from Dirac fine-tunings) especially since one need not have any new physics beyond the weak scale (testability?) But they dont seem very generic

However, perhaps the problem is that we are thinking in to narrow a space of themes

Consider any macroscopic object

Λ Interactomic spacing

$$R \sim N\Lambda \qquad N \sim 10^{23}$$

To determine if this system his fine tuned we need to place it in a theoretical context. Perhaps we can learn about field theories which look finely tuned but are not.

Effective Field Theory of Solids

Label the atoms by D fields $\phi^I(t,\vec{x})$ $\quad I = 1 - D$

Lagrangian ``Co-moving coordinates''

$X^I(\phi, t)$ Eulerian

$\langle \phi^I \rangle = \alpha x^I$ Ground state solution

Assumption: of homgeneity and isotropy on large scales

Broken spacte-time symmetries but leaves unbroken diagonal sub-groups

$$x^I \to x^I + a^I$$

$$\phi^I \to \phi^I - a^I$$

$$T_{ST} \otimes T_I \otimes SO(3)_I \otimes SO(3)_{ST} \to T_{I+ST} \otimes SO(3)_{T+ST}$$

$$L = F(\partial_\mu \phi^I \partial^\mu \phi^J)$$

Only three Goldstones

Inverse Higgs Constraints

Power Counting: $\partial\phi \sim 1$ $\quad$ $\partial^2\phi \sim \ll 1$

$$S = \int d^d x \frac{1}{2}(\dot{\phi}_L^2 + \dot{\phi}_T^2) - \frac{1}{2}v_T^2(\nabla\phi_T)^2 - \frac{1}{2}v_L^2(\nabla\phi_L)^2 + \ldots..$$

Nothing terribly interesting from a Wilsonian point of view, but there is something hidden here!

Consider a “Beam” (string) Embedded Solid

$d/L \ll 1$

Consider the action for the transverse mode: $$S = \int d^2x \frac{1}{2}\dot{\phi}^2 + C_1(\nabla^2\phi)^2 + ...$$

Conspicuously absent is : $(\nabla\phi)^2$

There is no symmetry to protect this term:
Apparent fine tuning

How can we understand this from the point of view of quantum field theory?

$$\phi(\sigma, \tau)$$

Labels atoms along the string

$$g_{\alpha\beta} = \partial_\alpha X^\mu \partial_\beta X_\mu$$

Action for embedded one D string:

$$S = \int d^2\sigma_i \sqrt{g} F(g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi)$$

Fix gauge expand around:

$$\phi \to \sigma + \phi(x, t)$$

$X^0 = \tau \quad X^3 = \sigma$

$$S = \int d\tau d\sigma \frac{1}{2}(\partial\phi)^2 + \ldots$$

No fine tuning apparent

Need to impose boundedness of target space

$$| \phi | < L$$

$$S_{\rm bar} = \int d\tau d\sigma \, \theta(\phi - \phi^\star) \sqrt{g} \, G(B) \; , \qquad B \equiv g^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi$$

$$T_{\mu\nu} = \theta\big(F(\phi)\big) \tilde{T}_{\mu\nu} \qquad \tilde{T}_{\mu\nu} \; = \; 2 \frac{\partial(\sqrt{g} \, G)}{\partial g^{\mu\nu}}$$

(On shell)

$$\partial_i T^{i\nu} = \delta\big(F(\phi)\big) \frac{\partial F}{\partial \phi^K} (\partial_i \phi^K) \tilde{T}^{i\nu} + \theta\big(F(\phi)\big) \cancel{\partial_i \tilde{T}^{i\nu}} = 0$$

$$n_i(\phi^\star) \, \tilde{T}^{i\nu}(\phi^\star) = 0 \longrightarrow \boxed{\tilde{T}^{ij} = 0}$$

What does this imply for the Wilson Coefficients?

$$S_{\text{bar}} \supset \frac{1}{2}\int d^4x\, \tilde{T}^{\alpha\beta}\, \partial_\alpha \vec{\varphi} \cdot \partial_\beta \vec{\varphi}$$

We see that the vanishing of the Wilson coefficient Is a conequence of the boundedness of the target space. This is a dynamical relaxation mechanism though we have not had to do ``engineering".

How can we generalize this mechanism?

-Space-time symmetry breaking

-Boundedness of Target Space

How can we choose our vanishing Wilson coefficients?

Consider a Superfluid

$$S = \int d^d x P(X)$$

$$X = \partial_\mu \phi \partial^\mu \phi$$

$$\phi = \mu t + \pi(x)$$

Analogy: ``time solid"

Bound target space

$$\theta(F(\phi)) = \theta(\phi - \phi_\star)$$

Following the same line of reasoning as for the solid we find

$$\boxed{\langle \tilde{T}^{0\nu}(\mu t = \phi_\star) \rangle = 0.}$$

But we can do even better: We want to see if we can make the CC vanish

Consider a Super-Solid

$$F(\phi^I, \phi) = \theta(\phi^I - \phi_0^I)\theta(\phi - \phi_0)$$

$$\langle T_{\mu\nu} \rangle = 0$$

This seems to work in setting Wilson coefficients to zero, but what about finite but small Wilson coefficients?

The theta function breaks the shift symmetry: No new terms must be included on the boundary

$$\theta_\ell(x) = \theta(x) + C_1\, \ell\, \delta(x) + \frac{1}{2!} C_2\, \ell^2 \delta'(x)$$

Thickness of surface

$$\theta_\ell\big(F(\phi^I)\big) = \theta\big(F(\phi^I)\big) + C_1\, \ell\, \delta\big(F(\phi^I)\big)\ |\ \partial_I F\ | + \ldots\ , \qquad C_1 = \mathcal{O}(1)\ ,$$

$$S_{\mathrm{bdy}} = \ell \int d^4x\, \delta(F(\phi^I))\ |\ \partial_I F\ |\ \mathcal{L}_{\mathrm{bdy}}(B^{IJ}, \phi^I)$$

Surface effects are suppressed by the ratio: l/R

$R =$ Extrinsic curvature:

So including the effects of surface terms leads to a new relaxation condition

$$T \sim \frac{l}{R}\Lambda^4$$

Perhaps no new physics at TeV is even ``More Interesting”?