Seminário do GRHAFITE

Generating the electroweak scale from cosmological evolution

Ricardo D'Elia Matheus

IFT - Instituto de Física Teórica - UNESP

The Hierarchy Problem

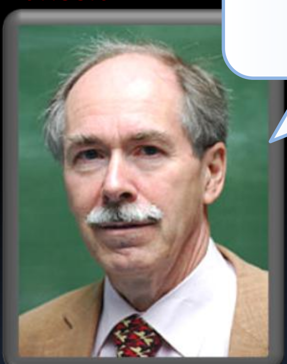
Think about the Standard Model (SM) as an EFT with a cut-off at M_p:

$$V(H) = m_H^2(\alpha,\beta)H^2 + \lambda h^4 + \mathcal{O}(1/M_p^2)$$

$$\langle H \rangle = v$$

The only mass scale is M_p!

't Hooft



Technical Naturalness

$$m_H^2 \equiv \rho\, M_P^2$$

⇨ All dimensionless Wilson coefficients should be of order one.

$$Dim[\rho] = Dim[\lambda] = 0$$

$$\rho \approx \lambda \approx 1$$

Important exception: taking a coefficient to zero increases symmetry. In that case it can be arbitrarily small.

The Hierarchy Problem

Think about the Standard Mo … a cut-off at M_p:

$$V(H) = m_H^2 \; \ldots \; H\rangle = v$$

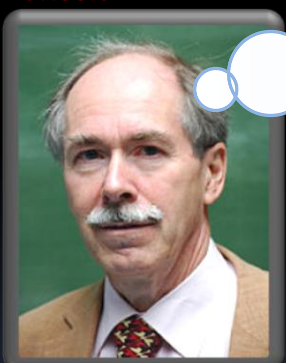
The only ma …

… fficients

Think about quark masses in QCD!

Each one can be as small as you want because you are always getting a new chiral symmetry

'‘t Hooft



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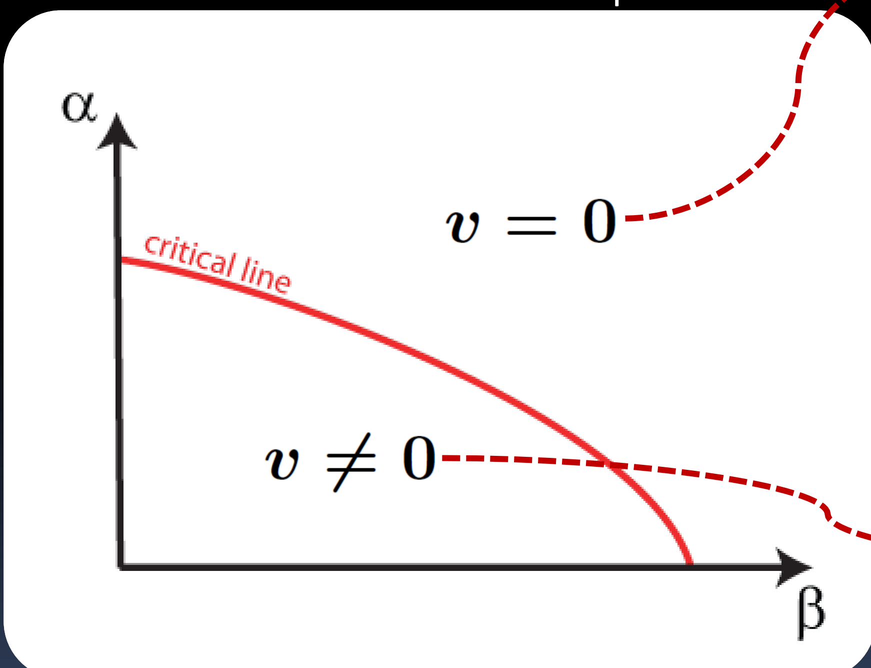

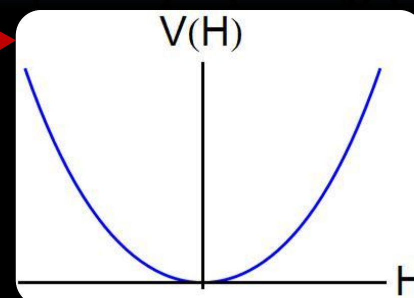

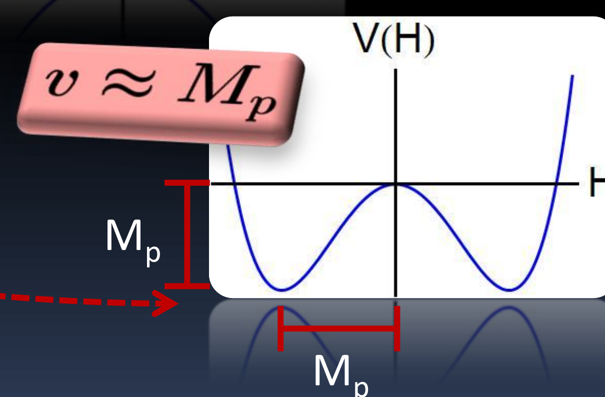

(inspired by Alex Pomarol)

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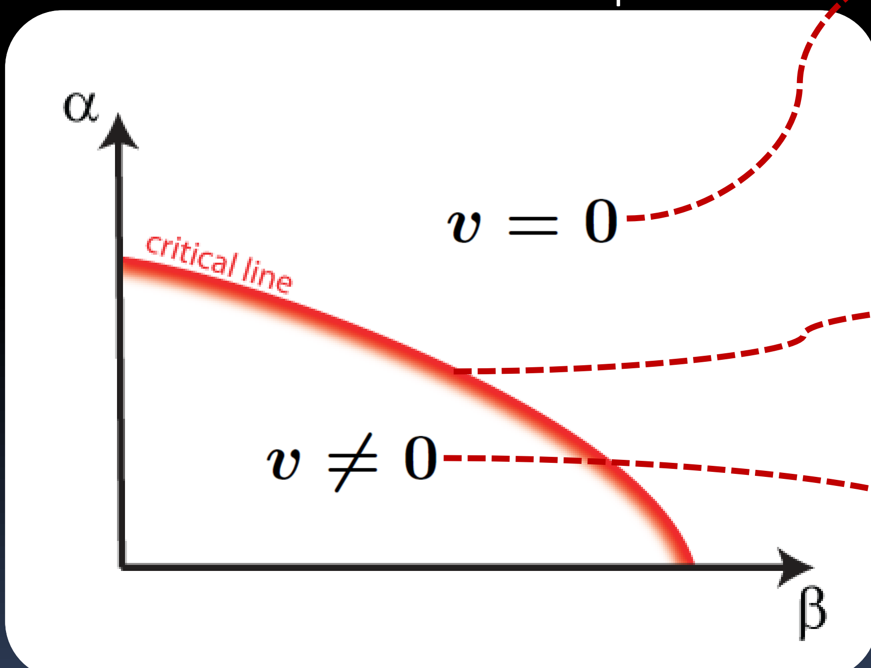
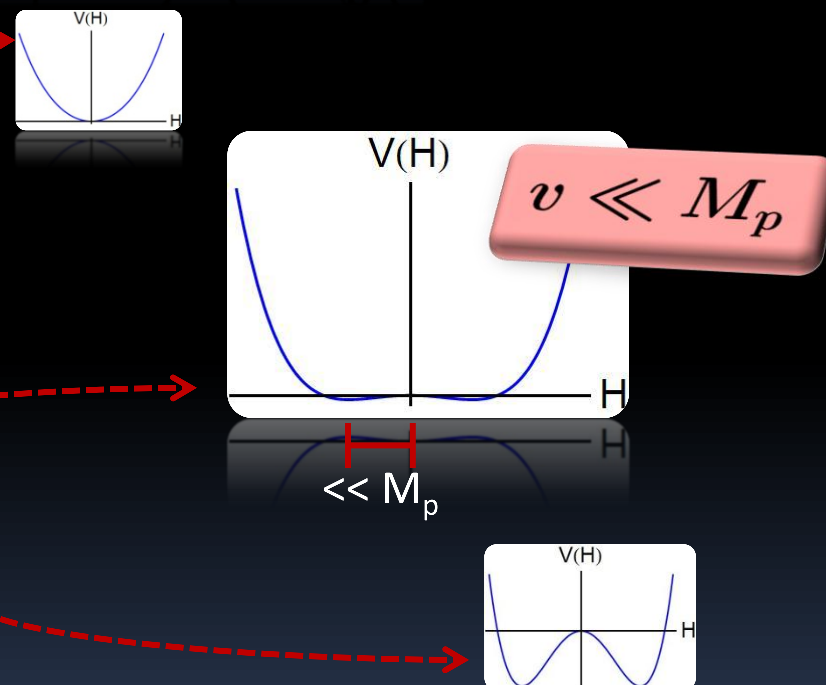




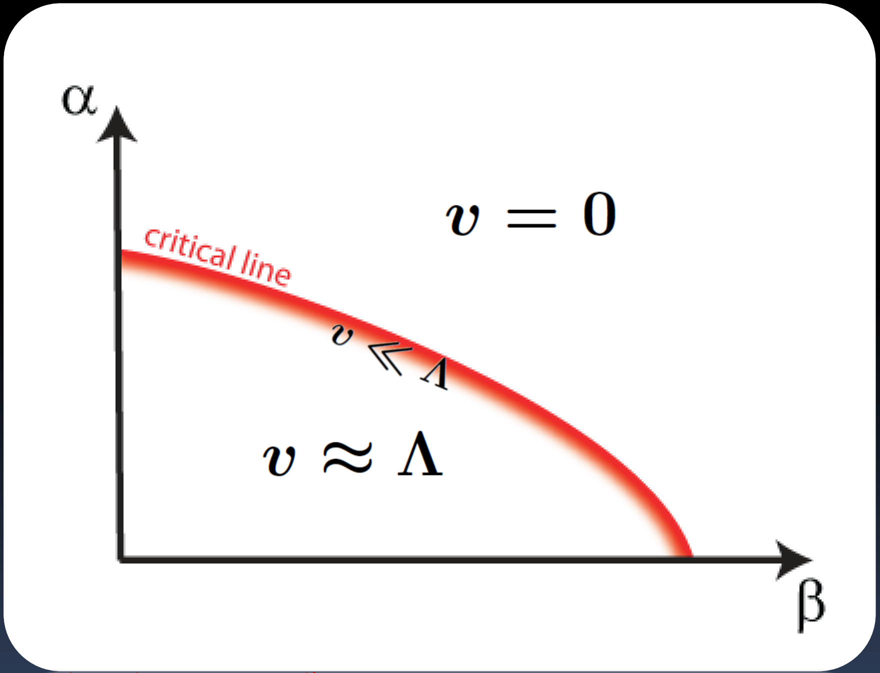
(inspired by Alex Pomarol)

Solving the Hierarchy Problem

Question: how come we live so close to the line?

Two answers: (1) Some symmetry forces it! (SUSY)

(2) The cut-off Λ, is not really M_p. In fact $\Lambda << M_p$ and Λ ~ 1 TeV
(Composite Models, Extra Dimensions et al.)



Both DEMAND new physics @ ~TeV

From a 2016 perspective:
WHERE IS THE F**KING
NEW PHYSICS!?

(inspired by Alex Pomarol)

Solving the Hierarchy Problem

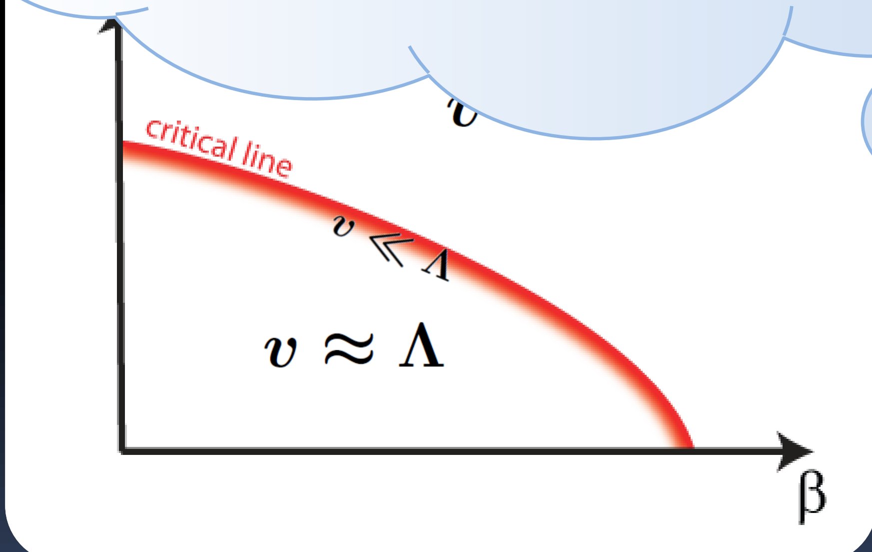
Questio... e line?

Tw... USY)

...$_p$ and Λ ~ 1 TeV

Excess of diphoton events
with
750 GeV ?

DEMAND new physics @ ~TeV



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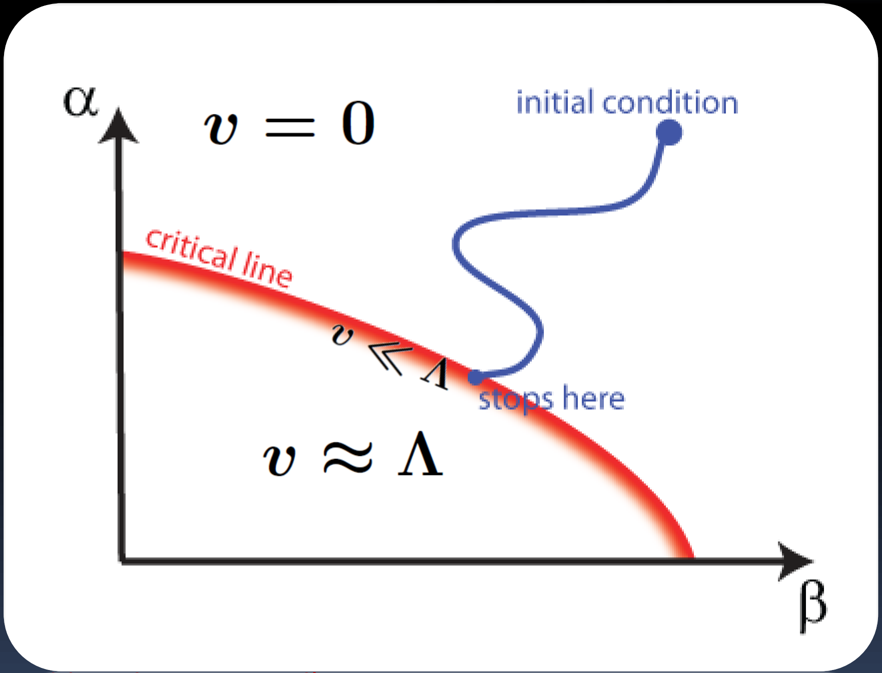
A New Hope

Question: how come we live so close to the line?

The Third Way: (3) History! Make α and β dynamical (fields in fact)

(stupid) Example: $m_H^2(\alpha,\beta)H^2 \rightarrow \alpha\beta H^2$ $\quad m_H^2 = \langle\alpha\rangle\langle\beta\rangle$



But how does the evolution stop?

(inspired by Alex Pomarol)

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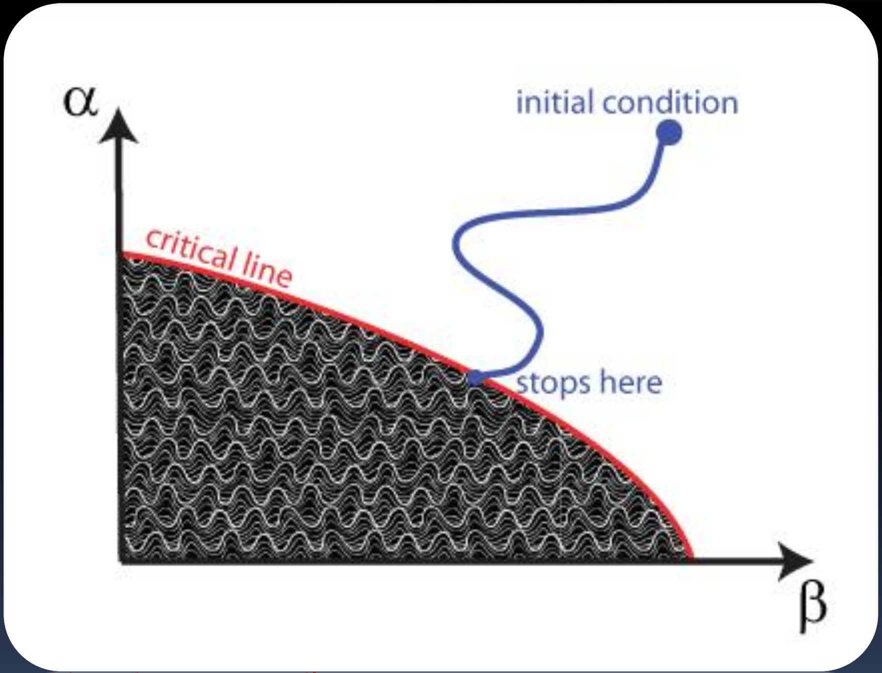


But how does the evolution stop?

Local Minima! A whole LOT OF local minima!

Can it be done in a (technically) natural way?

(spoiler: yes! But…)

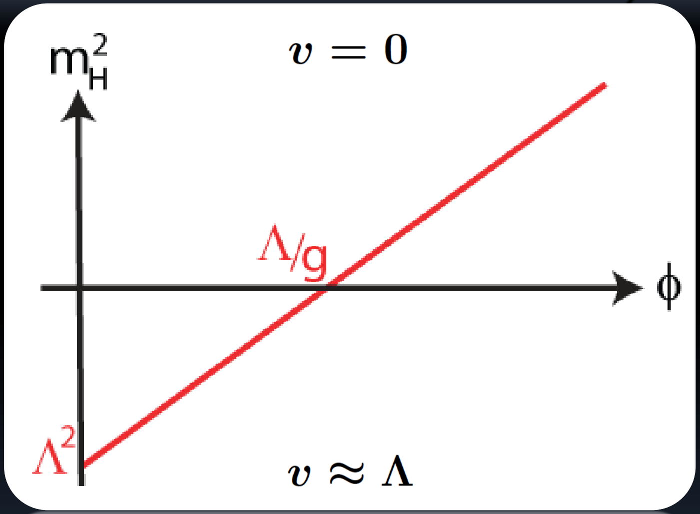
(inspired by Alex Pomarol)

Graham, Kaplan, Rajendran
arXiv:1504.07551

The Relaxion

Introduce one scalar field ϕ, and:

$$m_H^2 \to m_H^2(\phi) = -\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right)$$



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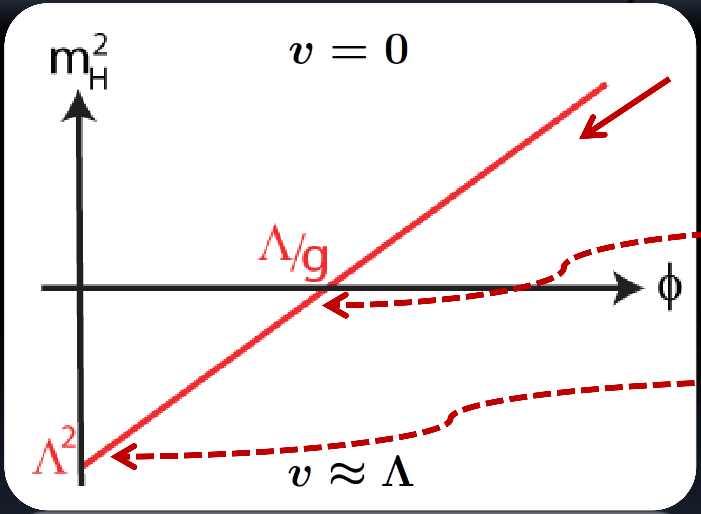

"rolls" down

Must stop here...

... not here

Graham, Kaplan, Rajendran
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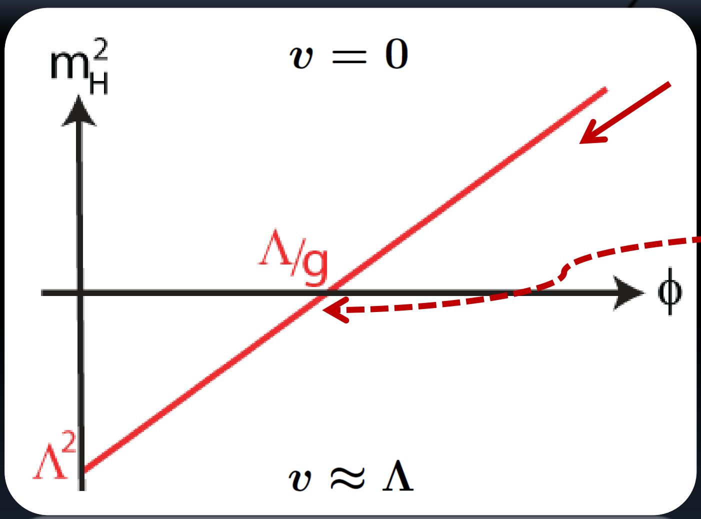

"rolls" down

Must stop here...

Large Field Excursions!

$\phi_c \equiv \Lambda/g$ If $g \ll 1$ $\rightarrow$ $\phi \approx \Lambda/g \gg \Lambda$

Espinosa et al.
arXiv: 1506.09217

The Relaxion

The minimal model:

$$V(\phi, H) = \underbrace{\Lambda^3 g\phi}_{\text{Linear slope for } \phi} \underbrace{- \frac{1}{2}\Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right)}_{\frac{1}{2} m_H^2} H^2 + \underbrace{\epsilon\Lambda_c^2 H^2 \cos(\phi/f)}_{\text{Local minima in } \phi}$$

Both *g* and ε break shift symmetries (more about that later) and can be naturally small !

Λ is the cut-off for the SM

Λ_c is the scale at which the periodic potential is generated

Espinosa et al.
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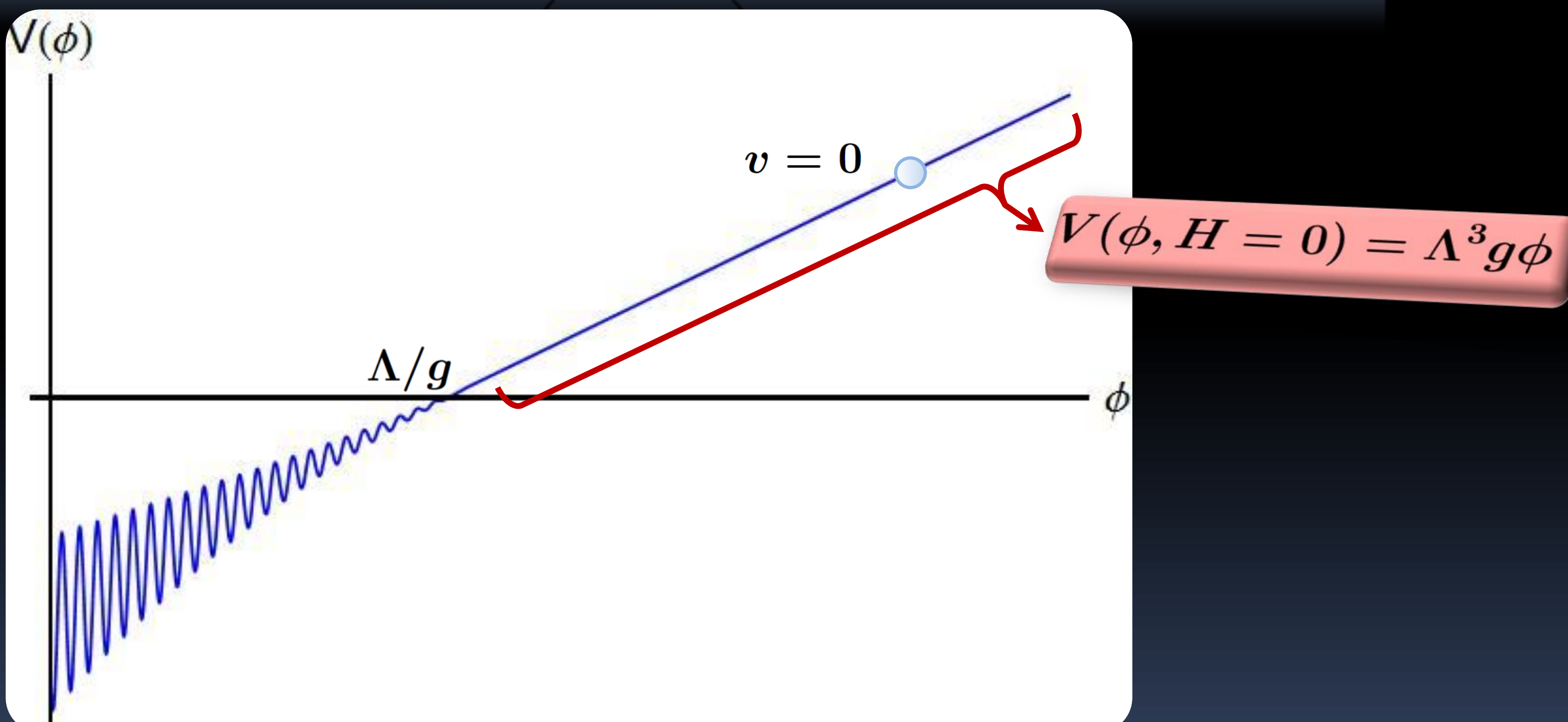

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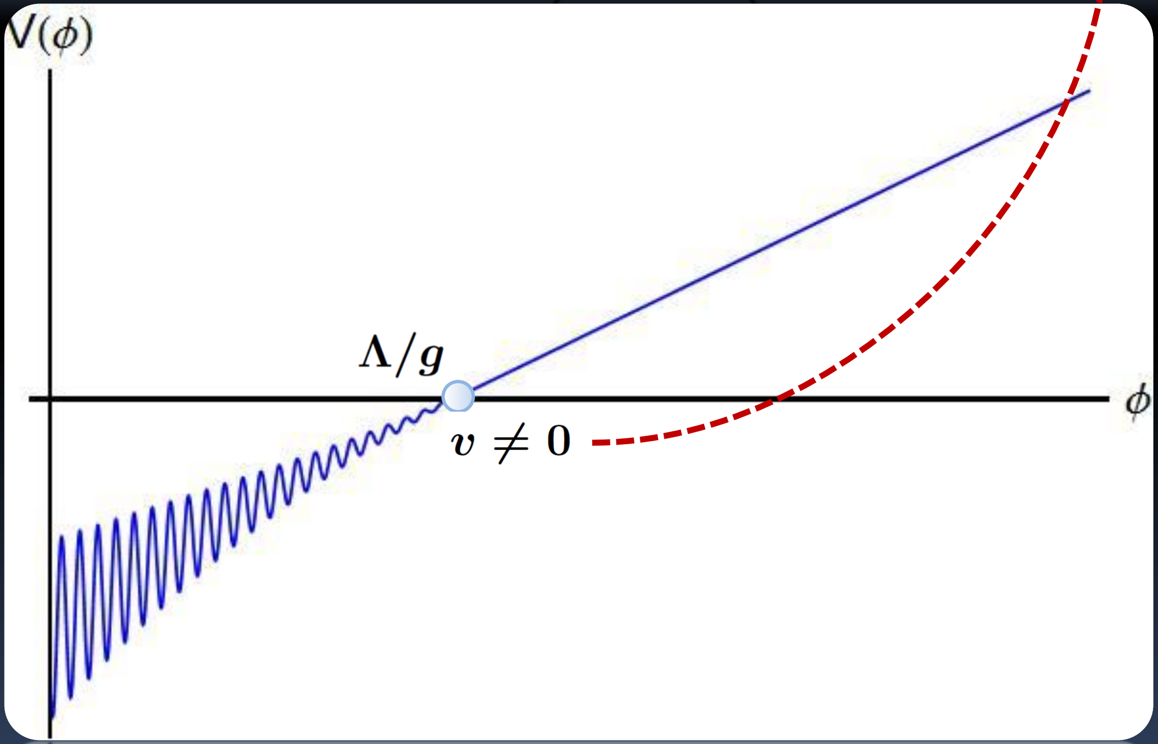

Becomes more important as *v* grows

Espinosa et al.
arXiv: 1506.09217

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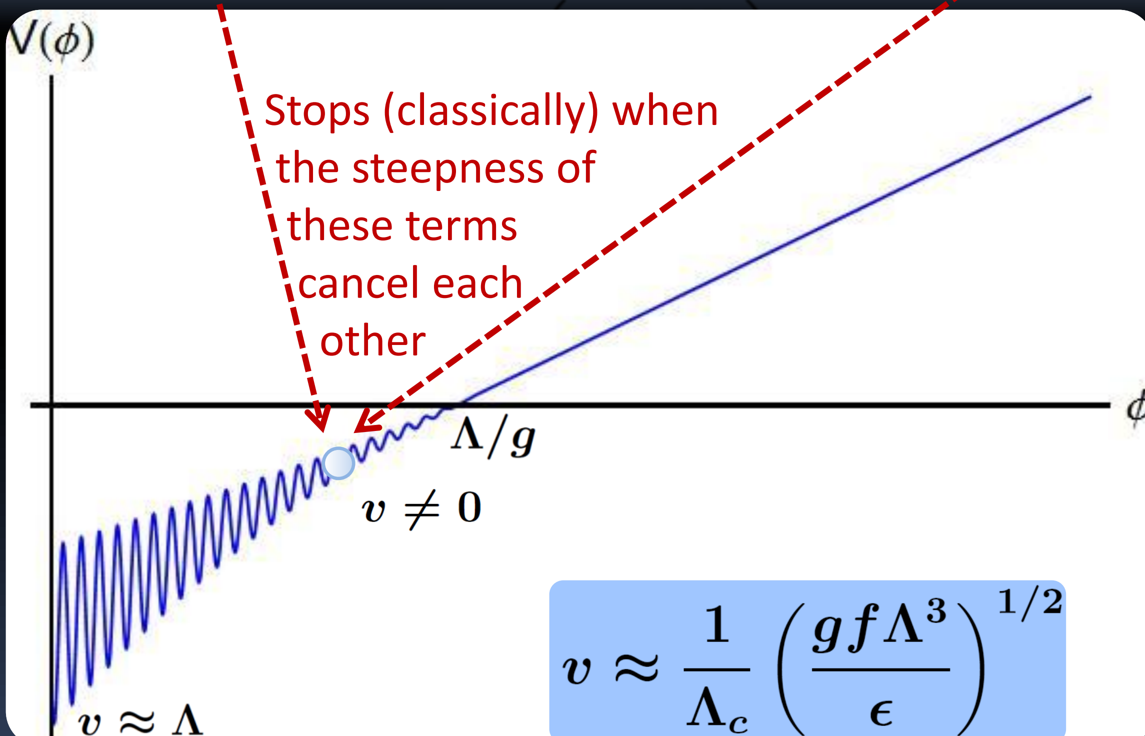

$$v \approx \frac{1}{\Lambda_c}\left(\frac{gf\Lambda^3}{\epsilon}\right)^{1/2}$$

The overall slope is controlled by *g*.

$$v \ll \Lambda$$

$\Updownarrow$

$$g \ll 1$$

Technically Natural!

NO NEW PHYSICS close to *v*

Espinosa et al.
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The Relaxion

The minimal model:

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

Originally the QCD axion:

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

$$\Lambda_c = \Lambda_{QCD} \quad \epsilon = Y_u$$

Does not work, mainly because Λ_c too low leads to low Λ, also: $\theta_{QCD} \sim 1$

The overall slope is controlled by *g*.

$v \ll \Lambda$

⇕

$g \ll 1$

Technically Natural!

NO NEW PHYSICS close to v

Espinosa et al.
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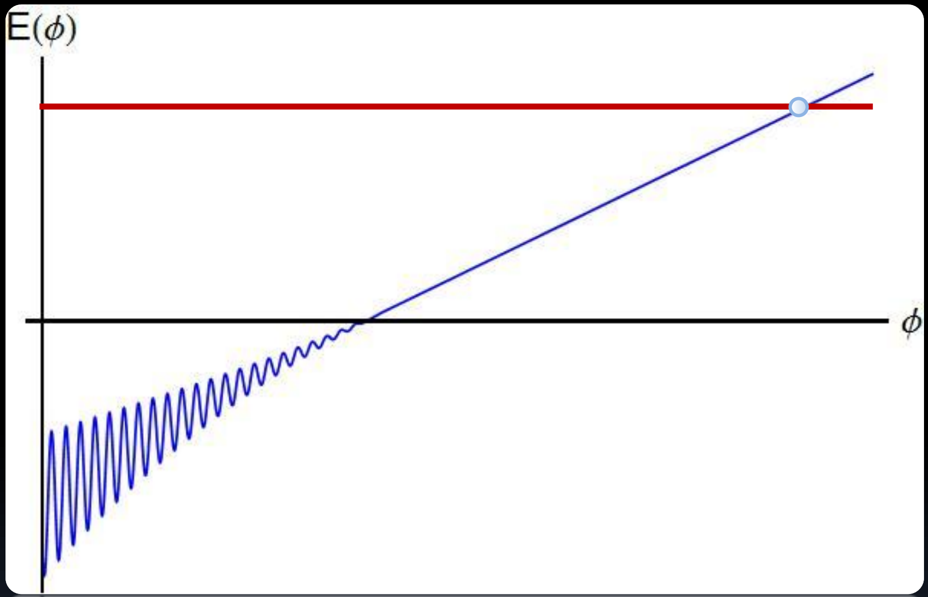
The Relaxion

So far, so good. Now on to the little dirty details:

Do we risk overshooting? Do we need to start close to ϕ_c?



NO, if slow rolling (during an inflationary epoch). Inflation introduces Hubble friction:

$$\cancel{\ddot{\phi}} + 3H_I\dot{\phi} = -\partial_\phi V(\phi)$$

(ϕ is not the inflaton)

Consequence: homework for cosmologists as a long period of inflation is needed ($N_e \sim 10^{40}$, smaller if H_I is not constant – Patil, Schwaller, arXiv:1507.08649)

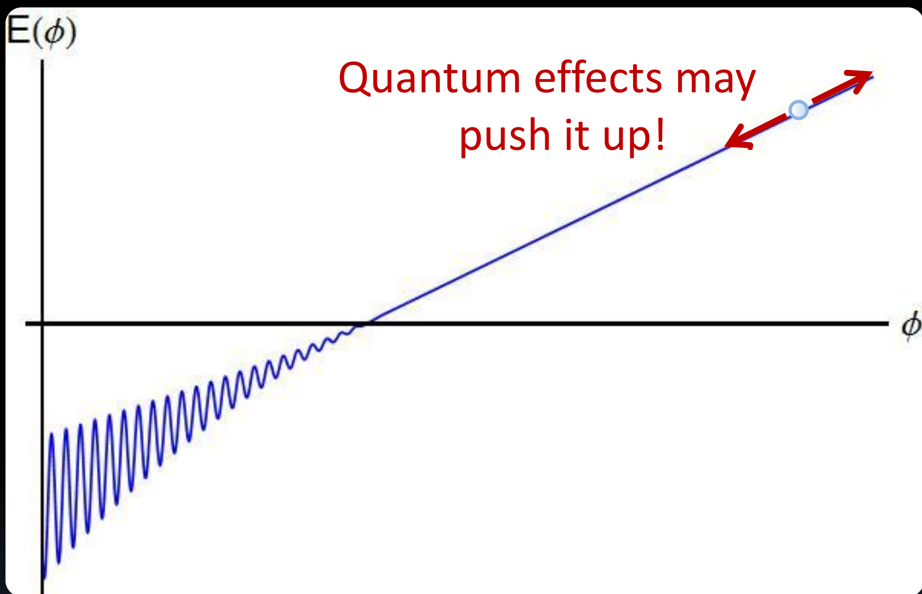
(Optional approach: no inflation, temperature dependent potential. E. Hardy, arXiv:1507.07525)

Espinosa et al.
arXiv: 1506.09217

The Relaxion

So far, so good. Now on to the little dirty details:

Limitations: Inflation ⇨ de Sitter space ⇨ Temperature (from Horizon)



$$\Delta\phi_{\text{class}} \sim \frac{V'(\phi)}{H_I^2} = \frac{g\Lambda^3}{H_I^2}$$

$$\Delta\phi_{\text{quant}} \sim H_I$$

$$\Delta\phi_{\text{class}} > \Delta\phi_{\text{quant}}$$

$$g > (H_I/\Lambda)^3$$

ϕ is not the inflaton

$$V(\phi \sim \Lambda/g) \approx \Lambda^4$$

$$V(\phi) < V_I \approx H_I^2 M_p^2$$

$$H_I > \frac{\Lambda^2}{M_p}$$

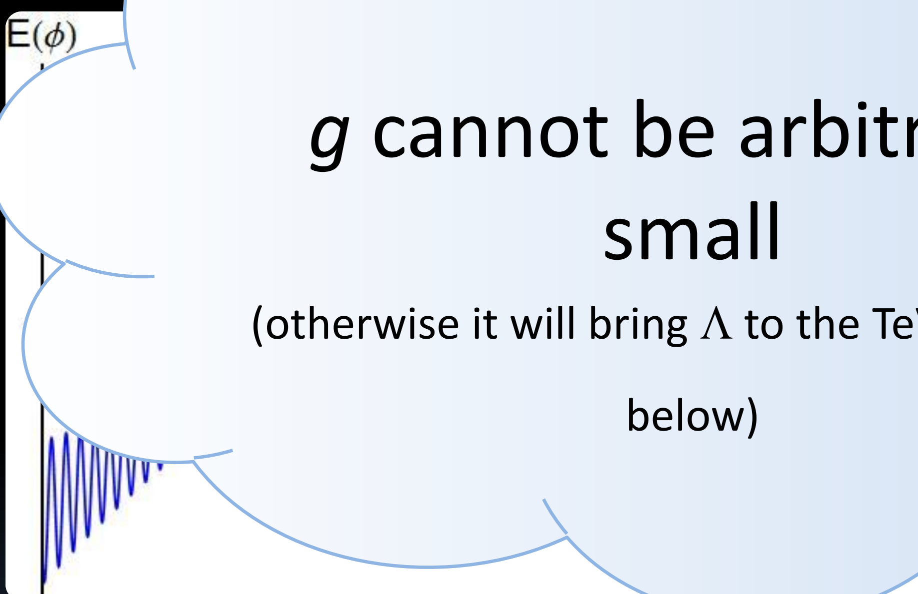
$$g > (\Lambda/M_p)^3$$

Espinosa et al.
arXiv: 1506.09217

The Relaxion

So far, so good. No…

Limit… (from Horizon)



$g < 1 \rightarrow \Lambda$ is not M_p

g cannot be arbitrarily small

(otherwise it will bring Λ to the TeV scale and below)

$$\frac{g\Lambda^3}{H_I^2}$$

$$\Delta\phi_{\text{class}} > \Delta\phi_{\text{quant}}$$

$$g > (H_I/\Lambda)^3$$

$$g > (\Lambda/M_p)^3$$

ϕ is not the inflaton

$$V(\phi \sim \Lambda/g) \approx \Lambda^4$$

$$V(\phi) < V_I \approx H_I^2 M_p^2$$

$$H_I > \frac{\Lambda^2}{M_p}$$

Espinosa et al.
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The Relaxion

So far, so good. Now on to the little dirty details:

Is this potential "all it can be"?

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

Even with g, $\varepsilon << 1$ we still have to guarantee the potential is radiatively stable. Similar question to: have I included all terms allowed by symmetry?

Espinosa et al.
arXiv: 1506.09217

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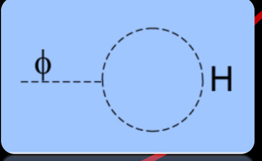

$$g\frac{\Lambda^3}{16\pi^2}\phi$$

Small correction to first term

Espinosa et al.
arXiv: 1506.09217

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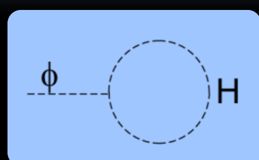

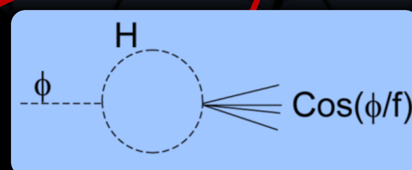

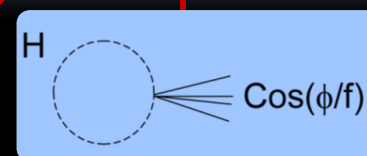

$$g\frac{\Lambda^3}{16\pi^2}\phi$$

$$\epsilon g\frac{\Lambda_c^2\Lambda}{16\pi^2}\phi\cos(\phi/f)$$

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DANGER! Local minima everywhere, even when *v = 0*.

Espinosa et al.
arXiv: 1506.09217

The Relaxion

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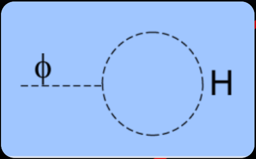

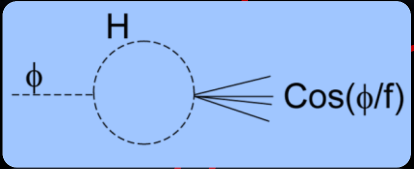

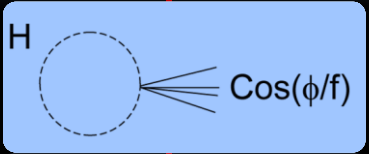

$$g\frac{\Lambda^3}{16\pi^2}\phi$$

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DANGER! Local minima everywhere, even when *v = 0*.

Also: $$g^n\epsilon^m\Lambda^{4-m-2m}\Lambda_c^{2m}\phi^n\cos^m(\phi/f)\left(1 + \frac{1}{2}\frac{H^2}{\Lambda^2} + \ldots\right)$$

Espinosa et al.
arXiv: 1506.09217

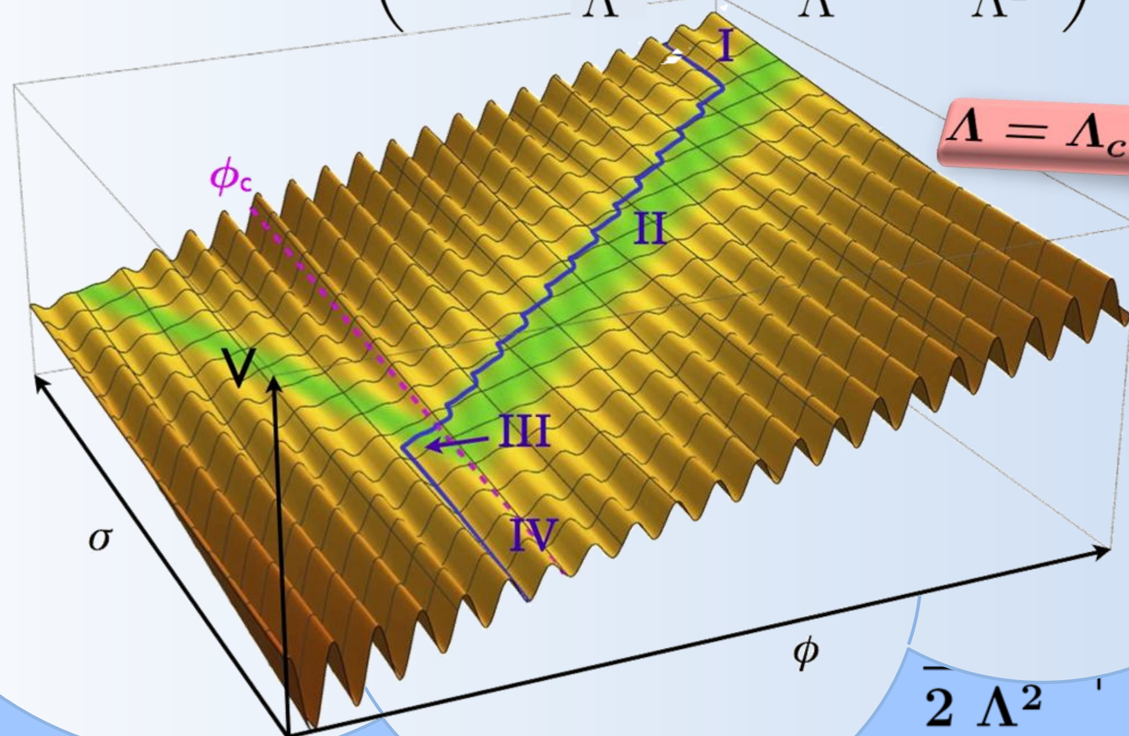
The Relaxion

Is this potenti… "all it c…

$V(\phi,$ …

Double scanner mechanism: $A\cos(\phi/f)$

$$A(\phi,\sigma,H) \equiv \epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\,\sigma}{\Lambda} + \frac{|H|^2}{\Lambda^2}\right)$$



$\Lambda = \Lambda_c \simeq 10^9 GeV$

Also: $g^n\epsilon$ … $\frac{\ }{2\,\Lambda^2} + \dots\Big)$

Symmetries

What are the symmetries involved? Is there a UV completion to this thing?

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \Lambda^3 g\phi - \frac{1}{2}\Lambda g\phi H^2 - \epsilon\Lambda_c^2 H^2\cos(\phi/f)$$

$g = 0$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \epsilon\Lambda_c^2 H^2\cos(\phi/f)$$

symmetric under $\phi \to \phi + 2n\pi f$ — Discrete shift symmetry

$\epsilon = 0$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$

symmetric under $\phi \to \phi + c, \forall c$

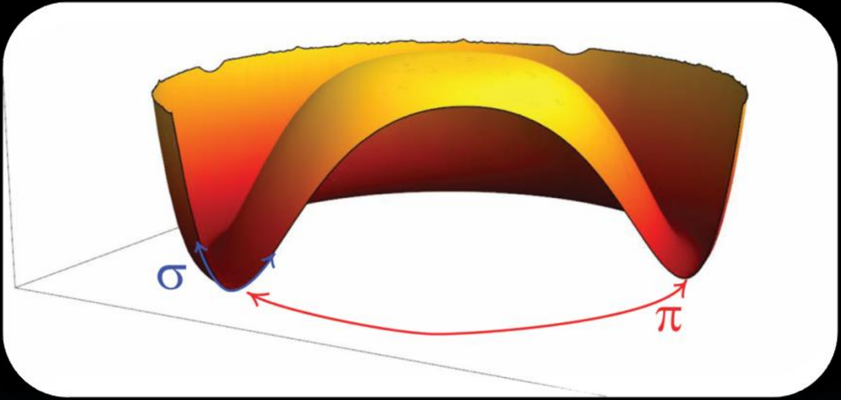
Continuous shift symmetry

Naturalness $\to$ $g \ll \epsilon$

Symmetries

Shift symmetries eh? Where do we normally find those?

Spontaneous breaking of a Global Symmetry



Nambu-Goldstone Bosons (NGB)

$\mathcal{L}(\pi) = \mathcal{L}(\pi + c), \forall c$ $\quad$ $V(\pi) = 0$

Compact Field Space ($2\pi f$)

Continuous shift symmetry

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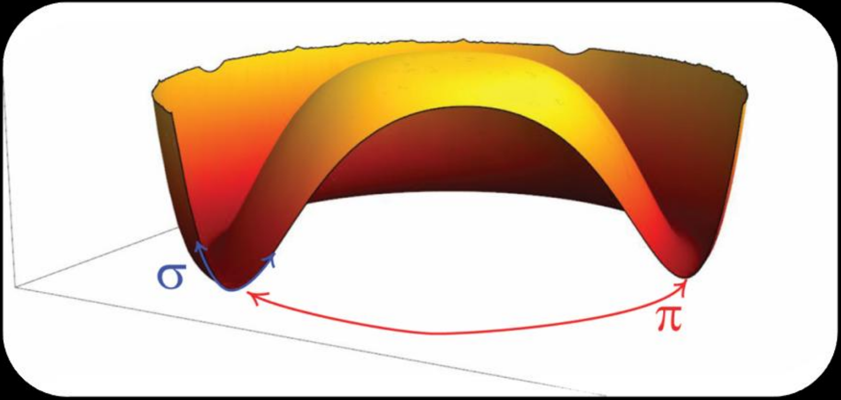

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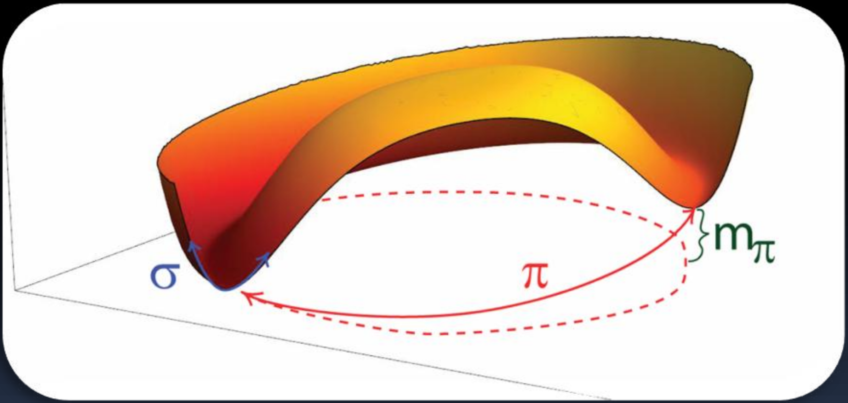

Pseudo-NGB (pNGP)

$$\mathcal{L}(\pi) = \mathcal{L}(\pi + 2n\pi f)$$

Compact Field Space ($2\pi f$)

Discrete shift symmetry

Allowed potential MUST be periodic in the field!

Symmetries

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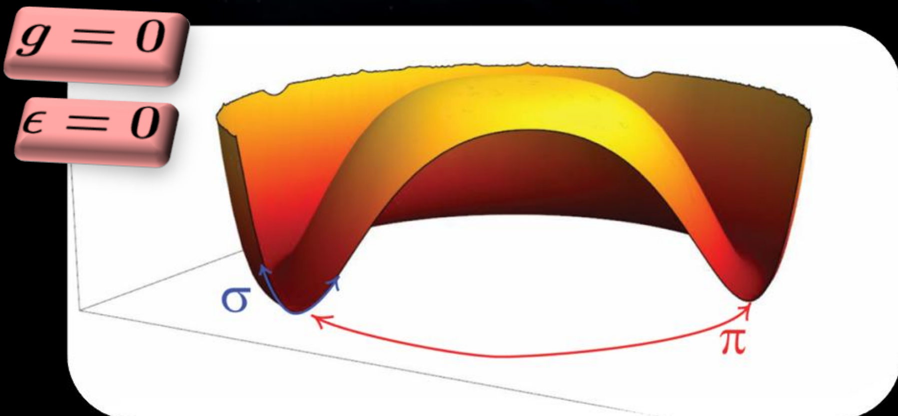

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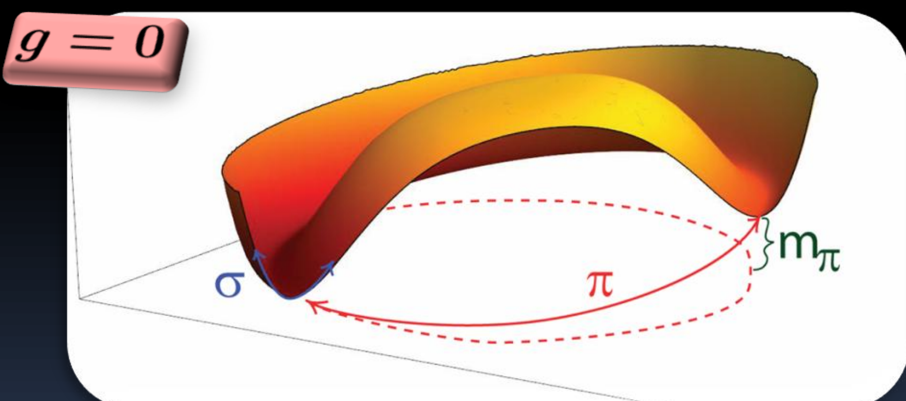

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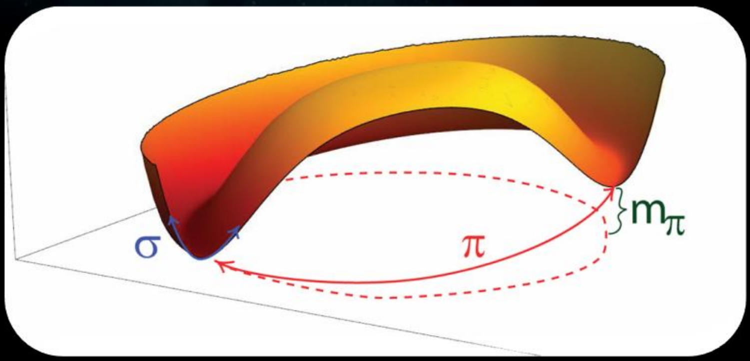


pNGP ➡ $m_\pi < m_\sigma$

Effective theory below m_σ: non-linear sigma model

$$\Sigma = e^{i\frac{T^a\pi^a}{f}} = \cos\left(\frac{\pi}{f}\right) + i\frac{T^a\pi^a}{\pi}\sin\left(\frac{\pi}{f}\right)$$

$$\pi = \sqrt{\pi^a\pi^a}$$

What about *g ≠ 0*? (non-periodic terms) $-\Lambda^3 g\phi - \frac{1}{2}\Lambda g\phi H^2$

→ Makes the field space non-compact

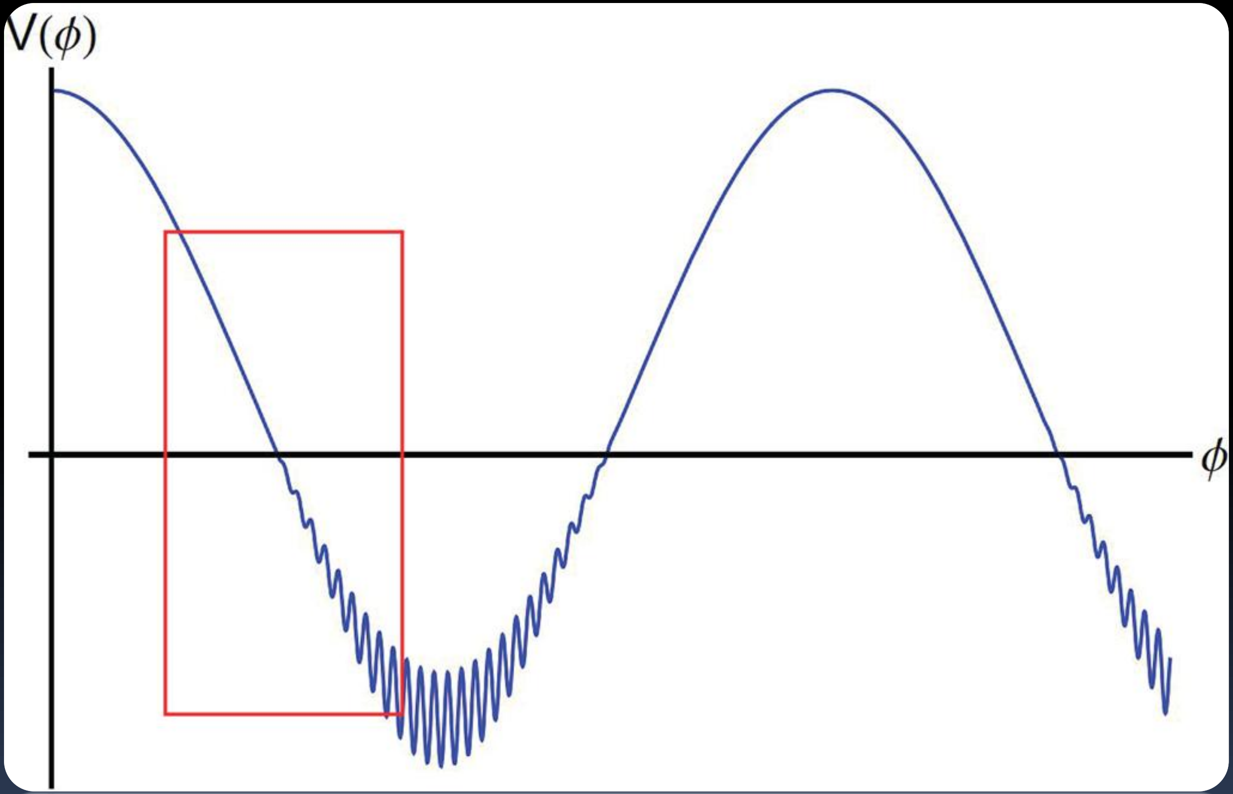
→ The discrete shift symmetry cannot be broken by local operators (it is a redundancy in the description, a gauge symmetry)

Symmetries

$$V(\pi, H) \sim \kappa_1(H^2)\cos\left(\frac{\pi}{F}\right) + \kappa_2(H^2)\cos\left(\frac{\pi}{f}\right)$$

$$F \gg f$$

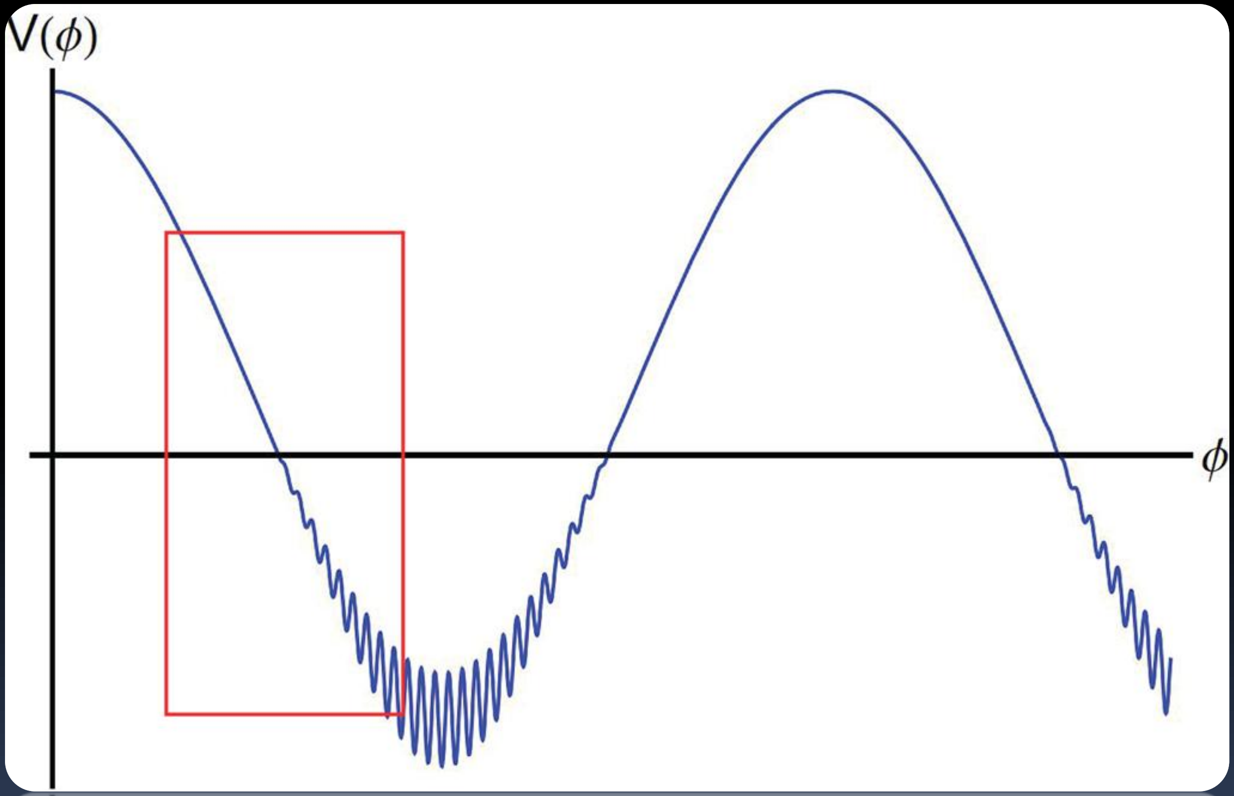
appropriate functions



Symmetries

$$V(\pi, H) \sim \kappa_1(H^2)\cos\left(\frac{\pi}{F}\right) + \kappa_2(H^2)\cos\left(\frac{\pi}{f}\right)$$

$F \gg f$



But how can we get the same pNGB to have two very different periods (compact field spaces) ?

Clockwork Relaxion

A Clockwork Axion
Kaplan, Rattazzi,
arXiv:1511.01827

Key element: many pNGBs with the same decay constant f:

$$\mathcal{L}_{pNGB} = \underbrace{f^2 \sum_{j=0}^{N} \partial_\mu U_j^\dagger \partial^\mu U_j}_{\mathrm{U(1)^{N+1}}} + \left(\underbrace{\epsilon f^4 \sum_{j=0}^{N-1} U_j^\dagger U_{j+1}^3 + h.c.}_{\mathrm{U(1)^{N+1} \to U(1)}} \right) + \cdots$$

$$U_j \equiv e^{i\pi_j/(\sqrt{2}f)}$$

$$Q_{j+1} = Q_j/3$$

$$\mathcal{L}_{pNGB} = \frac{1}{2} \sum_{j=0}^{N} \partial_\mu \pi_j \partial^\mu \pi_j + \underbrace{\epsilon f^4 \sum_{j=0}^{N-1} e^{i(3\pi_{j+1} - \pi_j)/(\sqrt{2}f)} + h.c.}_{} + \cdots$$

$$V^{(2)} = \frac{1}{2} \epsilon f^2 \sum_{j=0}^{N} (q\pi_{j+1} - \pi_j)^2 \Rightarrow \pi^{(0)} \sim \left(\pi_0 + \frac{1}{3}\pi_1 + \frac{1}{9}\pi_2 + \ldots + \frac{1}{3^N}\pi_N \right)$$

$$V(\pi^{(0)}) \sim \Lambda_N^4 \cos(\pi^{(0)}/F) + \Lambda_0^4 \cos(\pi^{(0)}/f) \rightarrow F = 3^N f$$

Clockwork Relaxi

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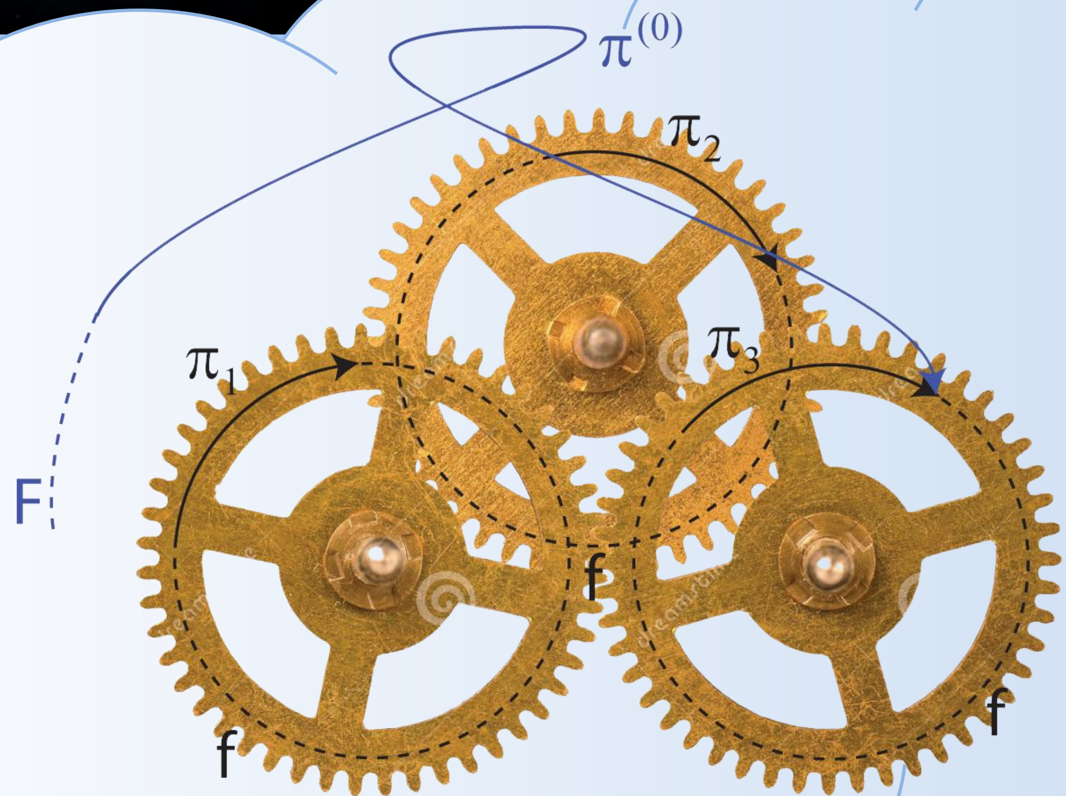
Key element: many pNGBs with the sa

$\mathcal{L}_{pNGB}$

$f)$



V $\ldots + \frac{1}{3^N}\pi_N \Big)$

$V(\pi^{(0)}) \sim \Lambda_N^4 \cos(\pi^{(0)}/F)$ $/f)$

$$F = 3^N f$$

Quick Recap

• pNGBs have the low energy potential needed to realize the relaxion mechanism

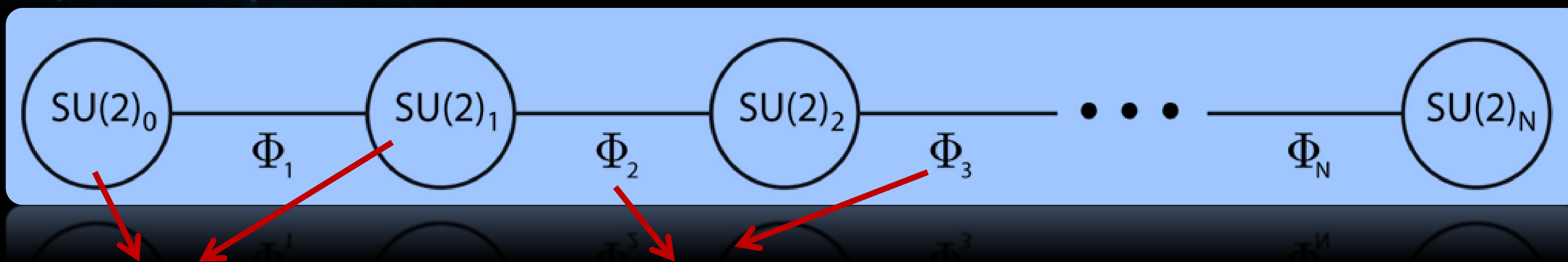
• radiative stability demands at least two fields (π and σ) to ensure no oscillations trap the relaxion field before the critical line (double scanner scenario)

• more copies of the two fields are needed to generate oscillations of longer period F from a theory with scale f, but the relation between F and f is exponential.

→ Also makes the theory compatible with the needed Large Field Excursions, and the compact space for the field is now $2\pi F$

The N-site model & extra dimensions

Arkani-Hamed, Cohen, Georgi, arXiv:hep-th/0104005v1



Gauge groups

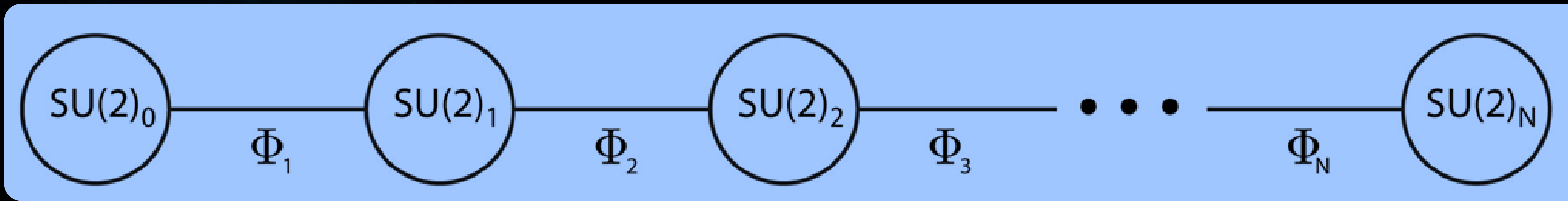
Non-linear sigma bi-doublets

$$S_4 = \int d^4x \left\{ -\frac{1}{2} \sum_{j=0}^{N} \mathrm{Tr}[F_{\mu\nu,j} F_j^{\mu\nu}] + \sum_{j=1}^{N} \mathrm{Tr}[(D_\mu \Phi_j)^\dagger (D^\mu \Phi_j)] - V(\Phi) \right\}$$

This is exactly the same as discretizing a 5$^{\text{th}}$ dimension (same as lattice field theory, with the Φ being the link variables).

The N-site model & extra dimensions

Arkani-Hamed, Cohen, Georgi, arXiv:hep-th/0104005v1



f_1 f_2 f_3 f_N

$$S_4 = \int d^4x \left\{ -\frac{1}{2}\sum_{j=0}^{N} \mathrm{Tr}[F_{\mu\nu,j}F_j^{\mu\nu}] + \sum_{j=1}^{N} \mathrm{Tr}[(D_\mu \Phi_j)^\dagger (D^\mu \Phi_j)] - V(\Phi) \right\}$$

Large *N* limit: SU(2) gauge theory in five dimensions.

Choice of scales determines metric:

$f_j = f, \quad \forall j$ ⇨ Flat extra dimension

$f_j = f q^j, \quad 0 < q < 1$ ⇨ AdS$_5$

Nayara Fonseca, Leonardo de Lima, Camila S. Machado, R.D.M.
arXiv: 1601.07183

N-Relaxion

Kaplan-Rattazzi clockwork axion:

$$\epsilon f^4 \sum_{j=0}^{N-1} U_j^\dagger U_{j+1}^3$$

$$Q_{j+1} = Q_j/3$$

$$\Downarrow$$

$$F = 3^N f$$

No continuum limit!

Goals:

- Find a model closer to a dimensional deconstruction that: (i) has a relaxion and (ii) provides a effective scale *F* much greater than *f*.

- Emulate the discretization of AdS_5 (which is motivated by dualities to strongly coupled theories). This is tricky, since we are taking $f_j = f$

- Generalize to non-abelian symmetries

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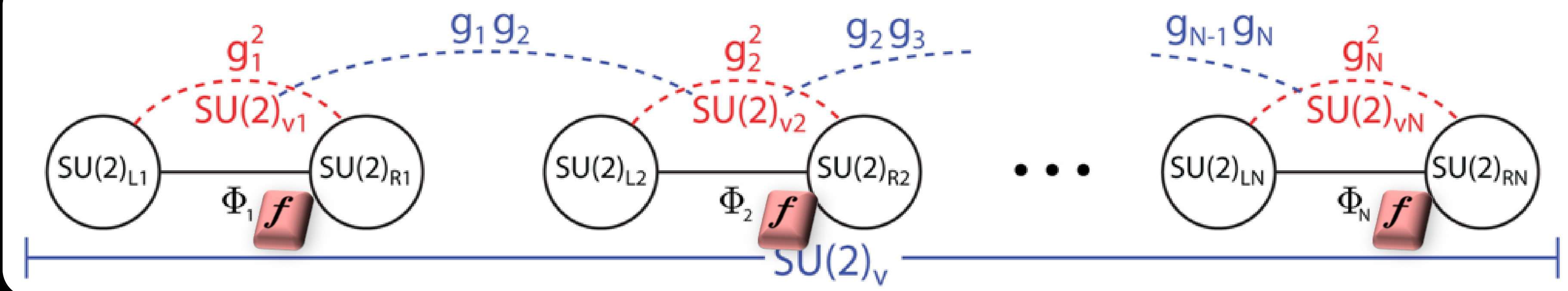
N-Relaxion



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

Small symmetry breaking parameters

(will be hierarchical to emulate AdS_5)

AdS_5

$f_j = f q^j$

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

$$q = \frac{g_{j+1}}{g_j}$$

$$\sum_{j=1}^{N}\left[\frac{1}{2}\partial_\mu \vec{\pi}_j \cdot \partial^\mu \vec{\pi}_j + f^4 (2-\delta_{j,1}-\delta_{j,N})\, g_j^2 \cos\left(\frac{\pi_j}{f}\right)\right] + f^4 \sum_{j=1}^{N-1} g_j g_{j+1} \frac{\vec{\pi}_j \cdot \vec{\pi}_{j+1}}{\pi_j \pi_{j+1}} \sin\left(\frac{\pi_j}{f}\right) \sin\left(\frac{\pi_{j+1}}{f}\right)$$

Quadratic (mass) terms everywhere, diagonalization needed

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N-Relaxion

$$M_\pi^2 = f^2 \begin{pmatrix} q^2 & -q^3 & 0 & \dots & 0 & 0 \\ -q^3 & 2q^4 & -q^5 & \dots & 0 & 0 \\ 0 & -q^5 & 2q^6 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 2q^{2(N-1)} & -q^{2N-1} \\ 0 & 0 & 0 & \dots & -q^{2N-1} & q^{2N} \end{pmatrix} \Rightarrow \vec{\eta}_0 = \sum_{j=1}^{N} \frac{q^{N-j}}{\sqrt{\sum_{k=1}^{N} q^{2(k-1)}}} \vec{\pi}_j$$

(massless at tree level, loops induce: $m = f^2 q^{2N}$)

Same as the Wilson Line in AdS$_5$!

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

New scales for oscillation

$$f_j \equiv f q^{j-N} \mathcal{C}_N$$

$\mathcal{C}_N \approx 1$ (small q or big N)

$$\to f_N \approx f$$

$$\to F = f_1 \approx f/q^{N-1}$$

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N-Relaxion

$$M_\pi^2 = f^2 \begin{pmatrix} q^2 & -q^3 & 0 & \dots & 0 & 0 \\ -q^3 & 2q^4 & -q^5 & \dots & 0 & 0 \\ 0 & -q^5 & 2q^6 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 2q^{2(N-1)} & -q^{2N-1} \\ 0 & 0 & 0 & \dots & -q^{2N-1} & q^{2N} \end{pmatrix}$$

$$\Rightarrow \quad \vec{\eta}_0 = \sum_{j=1}^{N} \frac{q^{N-j}}{\sqrt{\sum_{k=1}^{N} q^{2(k-1)}}} \vec{\pi}_j$$

(massless at tree level, loops induce: $m = f^2 q^{2N}$)

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

Amplitudes are also controlled by *q*

Bigger frequencies ↔ smaller amplitudes

(only the first few really matter)

$$f_j \equiv f q^{j-N} \mathcal{C}_N \qquad \mathcal{C}_N \approx 1$$

$$f_N \approx f$$

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

$V(\eta_0)$ gets flat for $q \ll 1$

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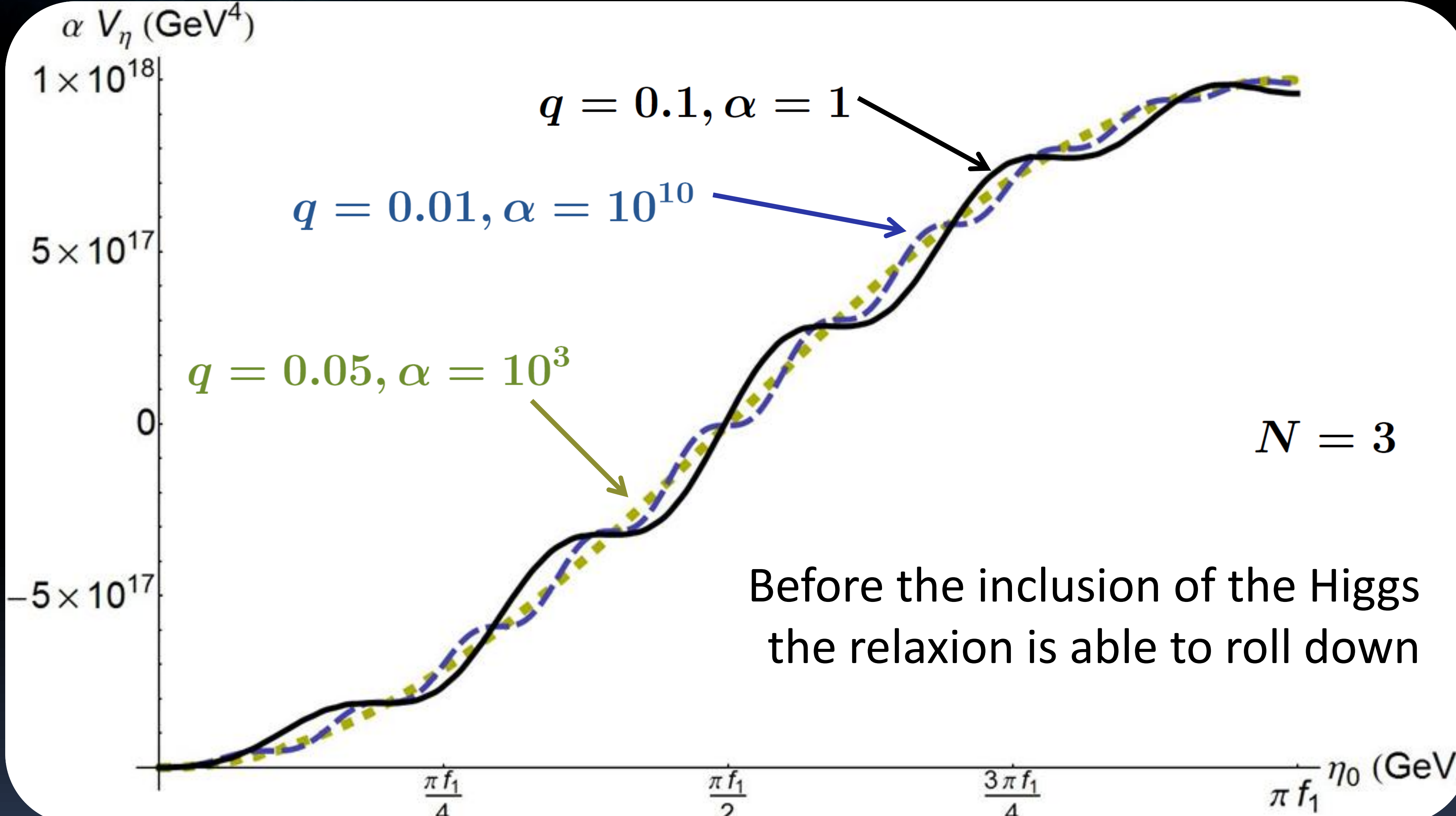
N-Relaxion



Before the inclusion of the Higgs the relaxion is able to roll down

Nayara Fonseca, Leonardo de Lima, Camila S. Machado, R.D.M.
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N-Relaxion

Interaction with the Higgs:

$$\mathcal{L}_{\eta,H} = \underbrace{\left(1+\frac{|H|^2}{\Lambda^2}\right)\mathcal{L}_\eta}_{\text{Most general thing you can do}} + \underbrace{|D_\mu H|^2 + \frac{\Lambda^2}{2}|H|^2 - \frac{\lambda_H}{4}|H|^4}_{V_H^{SM}} + \underbrace{\epsilon\frac{\Lambda_c}{16\pi}\mathrm{Tr}[\Phi_N + \Phi_N^\dagger]|H|^2}_{\text{New explicit breaking at site N}}$$

Most general thing you can do

Generates the linear terms

$$-\Lambda^3 g\phi - \frac{1}{2}\Lambda g\phi H^2$$

New explicit breaking at site N

$$\epsilon f^2|H|^2\cos\frac{\eta_0}{f_N}$$

Generates high frequency oscillations once *v ≠ 0*

- Also generates high frequency oscillations everywhere, double scanner needed!
- Modification of AdS_5 near the infrared brane (IR), enforces that the SM Higgs should be IR localized

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N-Relaxion

Interaction with the Higgs:

$$\mathcal{L}_{\eta,H} = \left(1 + \frac{|H|^2}{\Lambda^2}\right)\mathcal{L}_\eta + |D_\mu H|^2 + \frac{\Lambda^2}{2}|H|^2 - \frac{\lambda_H}{4}|H|^4 + \epsilon\frac{\Lambda_c}{16\pi}\mathrm{Tr}[\Phi_N + \Phi_N^\dagger]|H|^2$$

Solving for the classical stopping of the rolling: $v^2 \sim \dfrac{f^2}{\epsilon} q^{N+1}$

$q^{N+1} < \epsilon < 1$

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N-Relaxion

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Solving for the classical stopping of the rolling: $v^2 \sim \dfrac{f^2}{\epsilon} q^{N+1}$

$$q^{N+1} < \epsilon < 1$$

Constraints:

"not the inflaton" $\Rightarrow$ $H_I M_p > \Lambda^2$

"classical rolling vs quantum fluctuations" $\Rightarrow$ $q^{N+1} > H_I^3/f^3$

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$$\mathcal{L}_{\eta,H} = \left(1 + \frac{|H|^2}{\Lambda^2}\right)\mathcal{L}_\eta + |D_\mu H|^2 + \frac{\Lambda^2}{2}|H|^2 - \frac{\lambda_H}{4}|H|^4 + \epsilon\frac{\Lambda_c}{16\pi}\mathrm{Tr}[\Phi_N + \Phi_N^\dagger]|H|^2$$

Solving for the classical stopping of the rolling: $v^2 \sim \frac{f^2}{\epsilon} q^{N+1}$

$q^{N+1} < \epsilon < 1$

Constraints:

"not the inflaton"

"classical rolling vs quantum fluctuations"

$$q^{N+1} > \frac{\Lambda^6}{f^3 M_p^3}$$

"suppressing terms like ε *Cos^2*" $\epsilon < v^2/f^2$

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N-Relaxion

Interaction with the Higgs:

$$\mathcal{L}_{\eta,H} = \left(1 + \frac{|H|^2}{\Lambda^2}\right)\mathcal{L}_\eta + |D_\mu H|^2 + \frac{\Lambda^2}{2}|H|^2 - \frac{\lambda_H}{4}|H|^4 + \epsilon\frac{\Lambda_c}{16\pi}\mathrm{Tr}[\Phi_N + \Phi_N^\dagger]|H|^2$$

Solving for the classical stopping of the rolling: $v^2 \sim \frac{f^2}{\epsilon} q^{N+1}$

$$q^{N+1} < \epsilon < 1$$

Constraints:

$$q^{N+1} > \frac{\Lambda^6}{f^3 M_p^3} \Rightarrow \frac{\Lambda^6}{f^3 M_p^3} \lesssim q^{N+1} \lesssim \frac{v^4}{f^4}$$

$$q \lesssim 10^{-23/(N+1)}$$

$$\epsilon < v^2/f^2 \Rightarrow f \lesssim 10^8 \text{ GeV}$$

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N-Relaxion

Interaction with the Higgs:

$$\mathcal{L}_{\eta,H} = \left(1 + \frac{|H|^2}{\Lambda^2}\right)\mathcal{L}_\eta + |D_\mu H|^2 + \frac{\Lambda^2}{2}|H|^2 - \frac{\lambda_H}{4}|H|^4 + \epsilon\frac{\Lambda_c}{16\pi}\mathrm{Tr}[\Phi_N + \Phi_N^\dagger]|H|^2$$

Solving for the classical stopping of the rolling: $v^2 \sim \frac{f^2}{\epsilon} q^{N+1}$

$q^{N+1} < \epsilon < 1$

$$\frac{\Lambda^6}{f^3 M_p^3} \lesssim q^{N+1} \lesssim \frac{v^4}{f^4}$$

$$q \lesssim 10^{-23/(N+1)}$$

$$f \lesssim 10^8 \text{ GeV}$$

Co

$q = 10^{-24/(N+1)}$ & $\epsilon = 10^{-12}$

$$f \approx 10^8 \text{ GeV}$$

$$N = 2 \rightarrow m_{\eta_0} \approx 10^{-7} \text{ eV}$$

$$N = 3 \rightarrow m_{\eta_0} \approx 10^{-11} \text{ eV}$$

Conclusions

- The relaxation models are a proof of concept. If we come to the conclusion that they are self-consistent, then the hierarchy problem ceases to be an argument for new physics at the TeV scale.

- We manage to build an N-site relaxion model with a well defined continuum limit. Some improvements are needed and/or interesting:
  - To build the double scanner sector (or another solution to the high frequency oscillations induced by the Higgs)
  - To explore other symmetry breaking patterns. Can any of the possible patterns allow us to increase the cut-off? Or do away with the double scanner?
  - What about the continuum limit? What theory do we get in AdS_5?

Thank You!