# Cosmological relaxation of the EW scale

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based on **J.R. Espinosa, C. Grojean, G. P., A. Pomarol, O. Pujolàs, G. Servant arXiv:1506.09217**

# Introduction

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The origin of the **Hierarchy problem** can be equivalently understood as the requirement that Higgs potential satisfies two conditions near the same point

(i) a zero of the first derivative
(local minimum)

(ii) a zero of the second derivative
(Higgs mass and EW scale much smaller than the overall scale, $m_h, v \ll \Lambda$)

In a generic potential a **fine-tuning** is required to obtain the two conditions simultaneously.

# Introduction

"Classical" mechanisms to solve the Hierarchy problem

- **New physics at the** $\mathrm{TeV}$ **scale** stabilizes the EW scale (eg. low-scale Supersymmetry, Composite Higgs, ...)
  - Avoid condition (ii) by assuming that $\Lambda \sim v \sim m_h$
- Large **Landscape** with huge number of minima
  - Ensamble of realized vacua spans all possible EW scales
  - Anthropic selection of correct vacuum

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New solution

- **"Relaxation"** of the EW scale [Graham, Kaplan, Rajendran, 1504.07551]
  (see also earlier work by Abbott 85; Dvali, Vilenkin 04; Dvali 06)
  - condition (i) avoided by a potential with **vacua "everywhere"** (eg. oscillating function can have infinite set of minima)
  - "correct" **minimum selected dynamically** through a backreaction of EWSB

## The “minimal” realization

# The “Relaxation” mechanism

[Graham, Kaplan, Rajendran, 1504.07551]

Higgs mass parameter → **Field-dependent Higgs mass**

$m^2|H|^2$ $\qquad$ $m^2(\phi)|H|^2$

e.g. $m^2(\phi) = \Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right)$

- Higgs mass determined by the evolution of $\phi$
- $\phi$ must be stabilized where $|m^2(\phi)| \ll \Lambda^2$
- this structure can arise from a “clever” dynamical interplay between $H$ and $\phi$

# The "Relaxation" mechanism

The potential generate an interplay between the Higgs $h$ and an axion-like field $\phi$

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

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**"Kicking" term**

makes $\phi$ slide forward

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$\phi$ **"scans" the Higgs mass**

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$n = 1, 2, \ldots$

**“self-regulating” term**

stops $\phi$ when $h$ turns on

(periodic function of $\phi$
as for axion-like states)

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$\mathbf{\Lambda}$ cut off of the theory

$\mathbf{\Lambda_c}$ scale at which the periodic term originates

**Spurions:**

$g \ll 1$ breaking of the shift symmetry $\phi \to \phi + c$

$\varepsilon \ll 1$ further breaking of the shift symmetry, respecting $\phi \to 2\pi f$, $\phi \to -\phi$

# The "Relaxation" mechanism

Cosmological evolution

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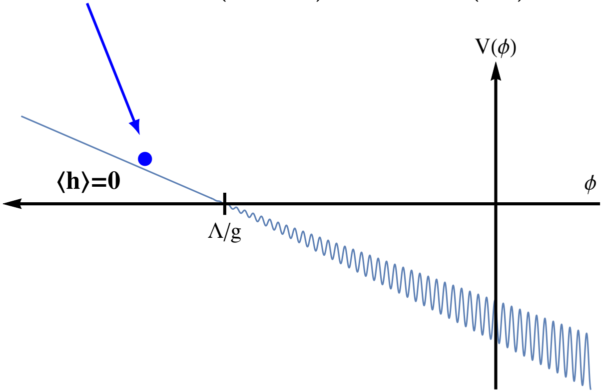

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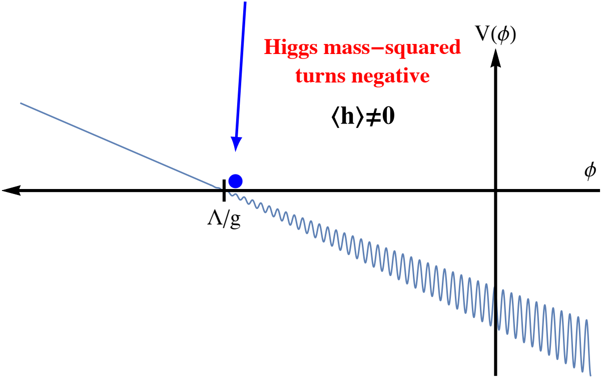

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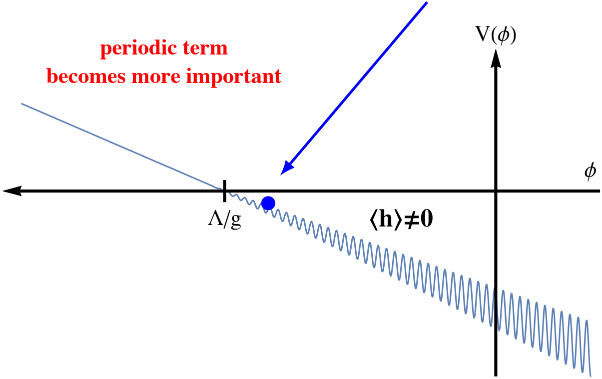

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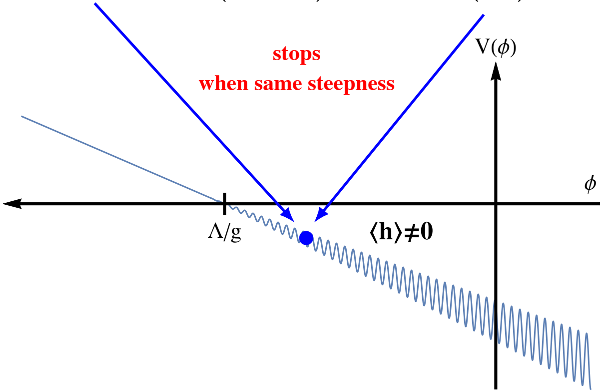

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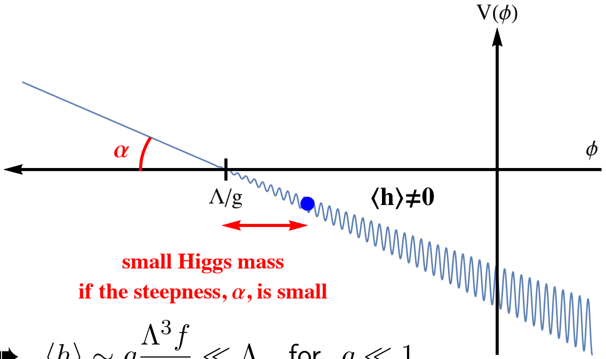


➠ $\langle h \rangle \sim g\frac{\Lambda^3 f}{\Lambda_c^3 \varepsilon} \ll \Lambda$ for $g \ll 1$

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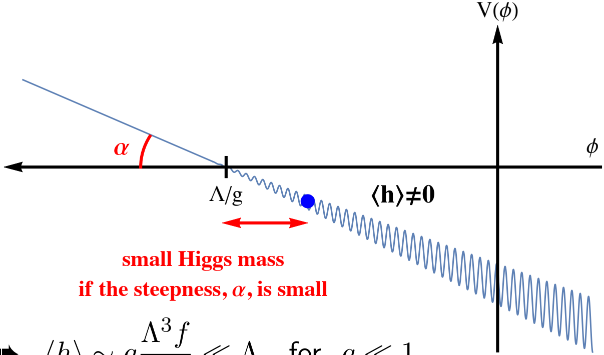


$$\Rightarrow \quad \langle h\rangle \sim g\frac{\Lambda^3 f}{\Lambda_c^3\varepsilon} \ll \Lambda \quad \text{for} \quad g \ll 1$$

- Notice that **large field excursions** for $\phi$ needed: $\phi \sim \Lambda/g \gg \Lambda$

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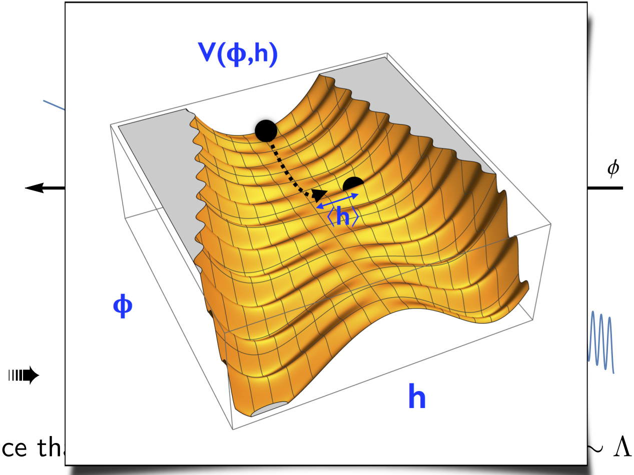


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How do we stop in the correct minimum? Should we **tune the initial conditions**?

**No**, if $\phi$ slow-rolls!

- ➢ possible if a friction is present

  (eg. during the **inflationary epoch**, through Hubble friction)

- ➢ $\phi$ must "scan" large ranges of the Higgs mass, a long period of inflation is needed

e-folds needed: $$N_e \gtrsim \frac{H_I^2}{g^2\Lambda^2} \sim 10^{40}$$

# The “Relaxation” mechanism

**Important constraint:**

$\phi$ must slow-roll **classically** so that quantum effects do not generate a large spreading

$$\Delta\phi_{class} \sim g\frac{\Lambda^3}{H_I^2} \quad \gtrsim \quad \Delta\phi_{quant} \sim H_I$$

$$\Downarrow$$

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

# Origin of the oscillating potential

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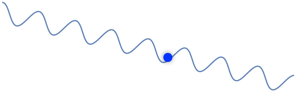
**problem:** too large $\theta_{\rm QCD} \sim 1$ due to linear tilt!

$\Lambda^3 g \phi$ ➠



can be solved if the tilt disappears after inflation

**Low cut-off**: $\Lambda \lesssim 30$ TeV

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Which is the origin of $\varepsilon \Lambda_c^4 \left( \frac{h}{\Lambda_c} \right)^n \cos(\phi/f)$ ?

$\boxed{n = 2}$ gauge invariant, generated by new-physics at scale $\Lambda_c$ (no need to rely on QCD)

$$\varepsilon \Lambda_c^2 |H|^2 \cos(\phi/f)$$

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**problem:** quantum corrections from Higgs loop

$$\Rightarrow \quad \varepsilon\Lambda_c^4\cos(\phi/f)$$

➢ "Relaxation" only works if Higgs barrier dominates

$$\Lambda_c \lesssim v$$

**New-dynamics must be around the EW scale!**

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**New-physics at the LHC is still required**
though it arises from an "unusual" motivation
(needed to generate the periodic potential)

Extra drawback: "coincidence problem" why $\Lambda_c \sim v$?

**Can we make the new-physics scale larger?**

# Raising the cut-off

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[Espinosa, Grojean, GP, Pomarol, Pujolàs, Servant, 1506.09217]

Add an additional field $\sigma$ "modulates" the periodic potential

**Field-dependent amplitude**

$$A\cos(\phi/f) \longrightarrow A(\phi,\sigma,H) = \varepsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\sigma}{\Lambda} + \frac{|H|^2}{\Lambda^2}\right)$$

**Two "scanners" potential**

$$V(\phi,\sigma,H) = \Lambda^4\left(\frac{g\phi}{\Lambda} + \frac{g_\sigma\sigma}{\Lambda}\right) + m^2(\phi)|H|^2 + A(\phi,\sigma,H)\cos(\phi/f)$$

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spurions

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- We take $\Lambda \sim \Lambda_c$ and see how much we can push it up

# The cosmological evolution

$$V(\phi,\sigma,H) = \Lambda^4\left(\frac{g\phi}{\Lambda}+\frac{g_\sigma\sigma}{\Lambda}\right) + m^2(\phi)|H|^2 + A(\phi,\sigma,H)\cos(\phi/f)$$

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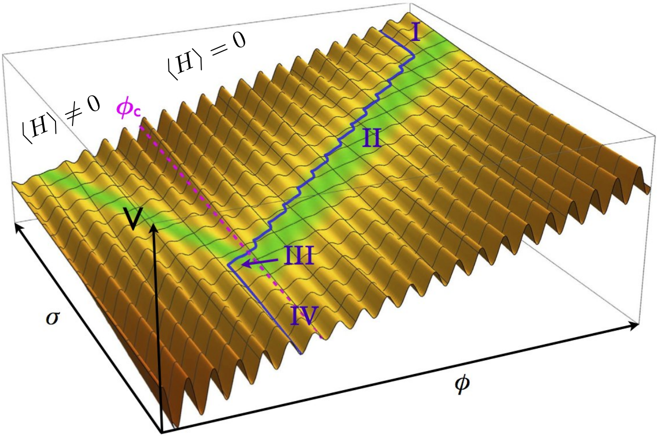

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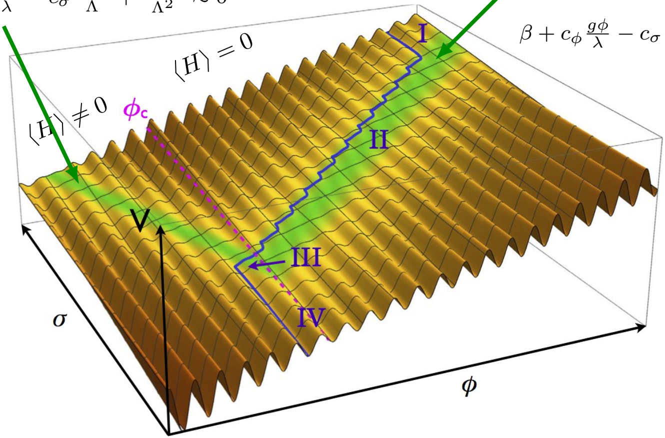
area where $A \approx 0$

$\beta + c_\phi \frac{g\phi}{\lambda} - c_\sigma \frac{g_\sigma \sigma}{\Lambda} + \frac{|H|^2}{\Lambda^2} \approx 0$

area where $A \approx 0$

($\phi$ can slow-roll)

$\beta + c_\phi \frac{g\phi}{\lambda} - c_\sigma \frac{g_\sigma \sigma}{\Lambda} \approx 0$



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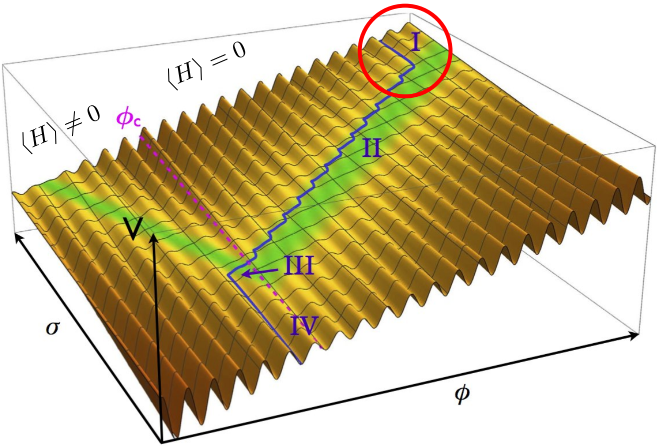


**Stage I:** $\phi$ “frozen”

# The cosmological evolution

$$V(\phi,\sigma,H) = \Lambda^4\left(\frac{g\phi}{\Lambda}+\frac{g_\sigma\sigma}{\Lambda}\right)+m^2(\phi)|H|^2+A(\phi,\sigma,H)\cos(\phi/f)$$

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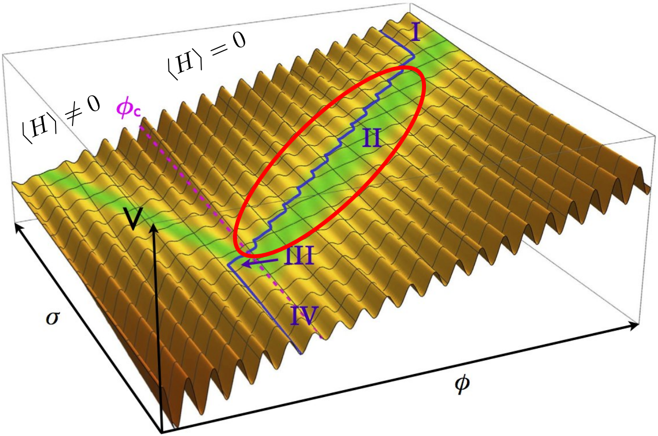


**Stage II:** $\phi$ "tracks" $\sigma$

# The cosmological evolution

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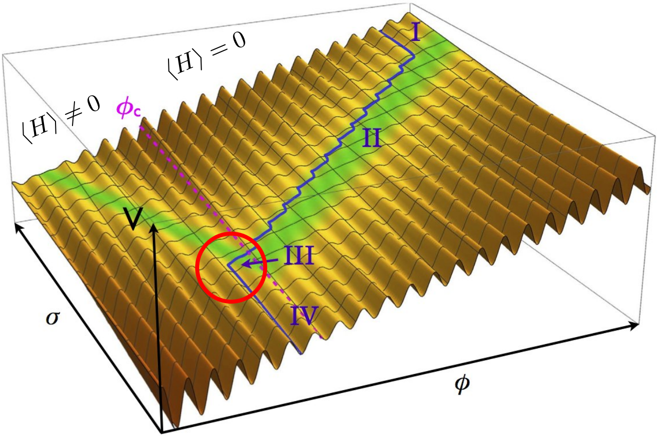


**Stage III:** $\phi$ enters the minimum

# The cosmological evolution

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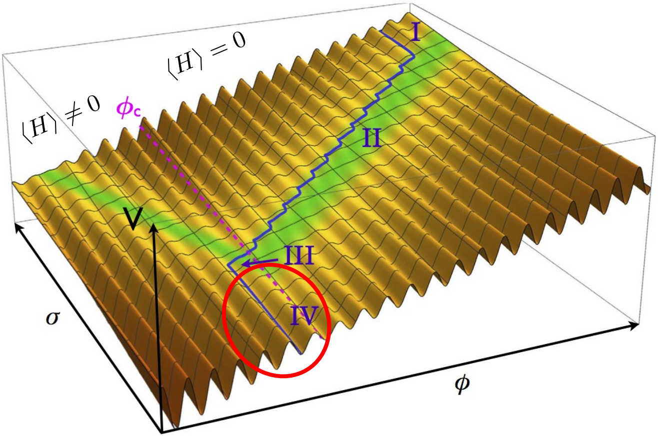
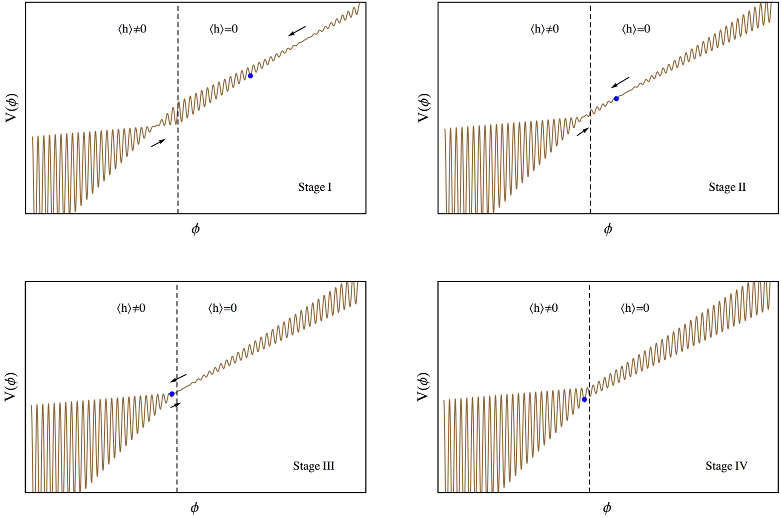



**Stage IV:** $\phi$ stabilized

# The cosmological evolution

Potential for $\phi$ in the four stages:



# Constraints

- $\varepsilon \lesssim v^2/\Lambda^2$ keep under control quantum corrections
- $H_I^3 \lesssim g_\sigma \Lambda^3$ avoid quantum effects spoiling classical rolling
- $g_\sigma \lesssim g$ allow $\phi$ tracking $\sigma$
- $\Lambda^2/M_{Pl} \lesssim H_I$ avoid backreaction of $\phi$ and $\sigma$ on inflation

Stabilization of the EW scale: $v^2 \simeq \frac{g\Lambda f}{\varepsilon}$

**upper bound on the cut-off**

$$\Lambda \lesssim (v^4 M_{Pl}^3)^{1/7} \simeq 2 \times 10^9 \text{ GeV}$$

# UV origin of the periodic term

**Strong sector**
a la QCD
(with light fermion, $N$)

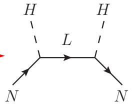
$+$ **Axion-like** $\phi$ → $\frac{\phi}{f} G'_{\mu\nu}\widetilde{G}'^{\mu\nu}$

**Axion potential:** $V \simeq \Lambda^3 m_N \cos(\phi/f)$

Gives the needed potential if the mass of $N$ is given by

$$m_N \simeq \varepsilon \left( \Lambda + g_\sigma \sigma + g\phi - \frac{|H|^2}{\Lambda} \right)$$

from integrating
a fermion doublet $L$



# Phenomenological implications

- ➢ No state detectable at the LHC
- ➢ $\phi$ and $\sigma$ are the only BSM states below $\Lambda$

  light scalars weakly-coupled to the SM

$$m_\phi \sim 10^{-20} - 10^{2}\ \mathrm{GeV}$$
$$m_\sigma \sim 10^{-45} - 10^{-2}\ \mathrm{GeV}$$

  mixing to the SM through the Higgs:

$$|H|^2 \cos\phi/f\,, \qquad g\phi|H|^2$$

- Bechmark values for $\Lambda \sim 10^9$ GeV

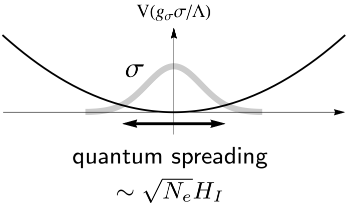
| | |
|---|---|
| $m_\phi \sim 100$ GeV | $m_\sigma \sim 10^{-18}$ GeV |
| $\theta_{\phi h} \sim 10^{-21}$ | $\theta_{\sigma h} \sim 10^{-50}$ |
| $\phi\phi hh$ coupling $\sim 10^{-14}$ | |

# Cosmological consequences

➢ Many **constraints from cosmology**

dark matter overabundance, late decays, BBN bounds, $\gamma$-rays, CMB, pulsar timing observations, ...

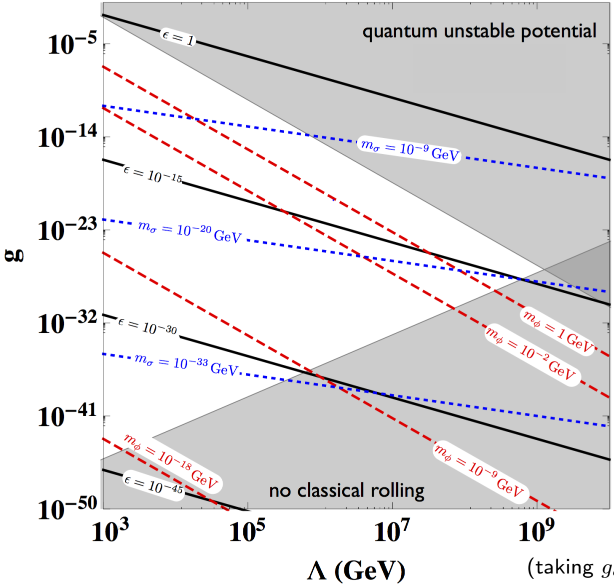
➢ Oscillations of $\sigma$ can provide a **Dark Matter candidate**




➠ $\rho_{ini}^{\sigma} \sim H_I^4$

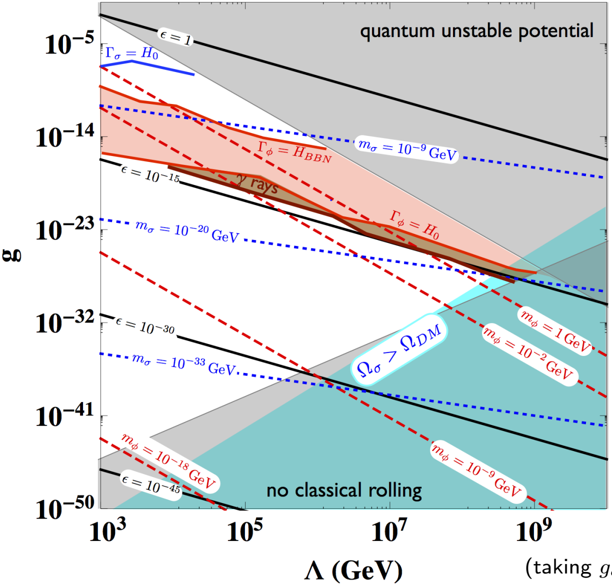
$$\rho_\sigma(T) \sim \rho_{ini}^{\sigma}(T/T_{osc})^3 \quad ➠ \quad \Omega_\sigma \gtrsim \left(\frac{10^{-27}}{g_\sigma}\right)^{3/2} \left(\frac{\Lambda}{10^8 \text{ GeV}}\right)^{13/2}$$

# Parameter space




(taking $g_\sigma \sim 0.1g$)

# Constraints on the parameter space

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# Conclusions

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The **“Relaxation” models** provide an “existence proof” of **natural theories** with a high cut-off scale $(\Lambda \sim 10^9 \text{ GeV})$

**Good features:**

Change of paradigm

- new physics is given by weakly-coupled light states
- not detectable at high-energy collider experiments

Other type of experiments needed

- astrophysics ($\gamma$-rays, pulsar timing, ...), CMB, fifth-force searches, ...

**Ugly features:**

Huge number of inflation e-folds $N_e > 10^{38}$

Super-Planckian field excursions

# Conclusions

**Future directions:**

- Are there ways to avoid the limit on the cut-off $\Lambda \lesssim 10^9~\mathrm{GeV}$?
- UV completion? How to get the double breaking of the shift symmetry in the "axion" potential?

  [see Gupta, Komargodski, Perez and Ubaldi, arXiv:1509.00047, Batell, Giudice, McCullough, arXiv:1509.00834]

- Find suitable inflationary models with huge $N_e$
- Alternative sources of friction, disentangling the "relaxation" mechanism from inflation
  - proposal to do this at finite temperature, see talk by Hardy