Cosmological relaxation of the EW scale

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IFAE, Barcelona

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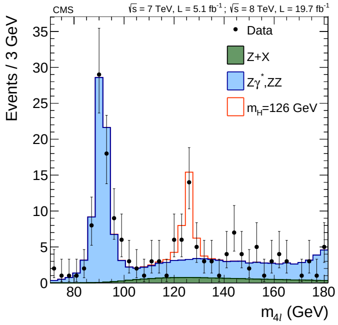
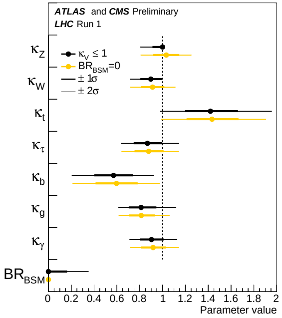
based on **J.R. Espinosa, C. Grojean, G. P., A. Pomarol, O. Pujolàs, G. Servant arXiv:1506.09217**

Introduction

Introduction

The Higgs discovery and the recent LHC measurements confirm that the Standard Model (i.e. the **Higgs mechanism**) correctly describes the main features of the **EW Symmetry Breaking** dynamics

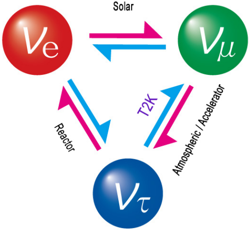




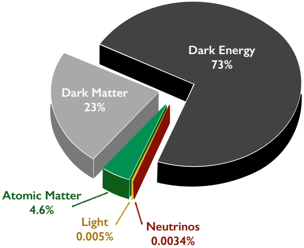
Introduction

The SM is not a complete theory, several phenomena unexplained

- origin of neutrino masses
- dark matter
- full description of gravity
- ...



Neutrino oscillation between three generations



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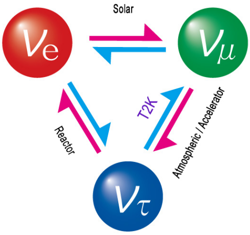

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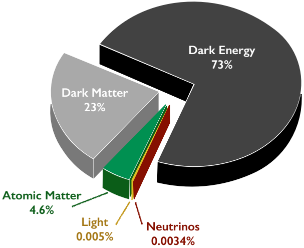


More fundamental theory necessarily present!

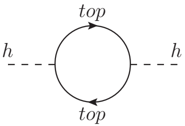
Introduction: the Hierarchy Problem

Obstruction to get a **predictive** extension of the SM:

the Hierarchy Problem

- the Higgs mass is highly sensitive to new physics
- its **natural** value of m_h is of the order of the new-physics scale Λ_{NP}

$$\delta m_h^2\big|_{1-loop} \sim$$



$$\sim -\frac{y_{top}^2}{8\pi^2}\Lambda_{NP}^2 \quad \gg \quad (125\ \mathrm{GeV})^2$$

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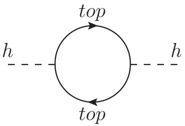


$$\sim -\frac{y_{top}^2}{8\pi^2}\Lambda_{NP}^2 \quad \gg \quad (125\ \text{GeV})^2$$

- **huge cancellation** needed to keep the Higgs mass small

$$m_h^2 = m_h^2\big|_{bare} + \delta m_h^2\big|_{1-loop} = (125\ \text{GeV})^2$$

➠ **loss of predictivity!**

Introduction: the Hierarchy Problem

Is the Higgs mass really **unnatural**?

➠ look for extensions of the SM that avoid the Hierarchy Problem

Introduction: the Hierarchy Problem

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, $m_h, v \ll \Lambda$)

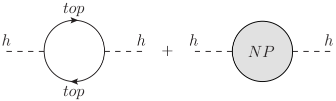
In a generic potential a **fine-tuning** is required to obtain the two conditions simultaneously.

Introduction: Solutions of the Hierarchy Problem

"Classical" mechanisms to solve the Hierarchy problem

- **New physics at the** TeV **scale** stabilizes the EW scale
  (eg. low-scale Supersymmetry, Composite Higgs, ...)
  - Avoid condition (ii) by assuming that $\Lambda \sim v \sim m_h$

$$\delta m_h^2\big|_{1-loop} \sim$$



$$\sim -\frac{y_{top}^2}{8\pi^2}\Lambda_{NP}^2 \lesssim (\mathrm{TeV})^2$$

- Large **Landscape** with huge number of minima
  - Ensamble of realized vacua spans all possible EW scales
  - Anthropic selection of correct vacuum

Introduction: Solutions of the Hierarchy Problem

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 ϕ
- ϕ must be stabilized where $|m^2(\phi)| \ll \Lambda^2$
- this structure can arise from a "clever" dynamical interplay between H and ϕ

The "Relaxation" mechanism

The potential generate an interplay between the Higgs h and an axion-like field ϕ

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

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"Kicking" term

makes ϕ slide forward

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ϕ **"scans" the Higgs mass**

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$n = 1, 2, \ldots$

"self-regulating" term

stops ϕ when h turns on

(periodic function of ϕ
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:

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

$g \ll 1$ full breaking of the shift symmetry

The "Relaxation" mechanism

Cosmological evolution

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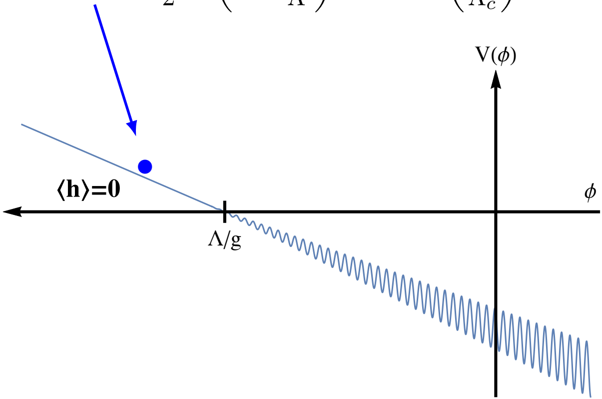

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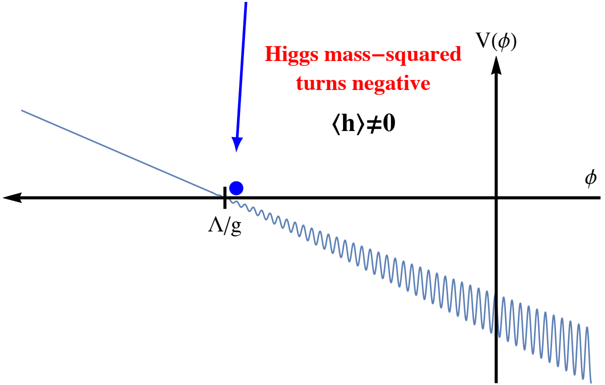

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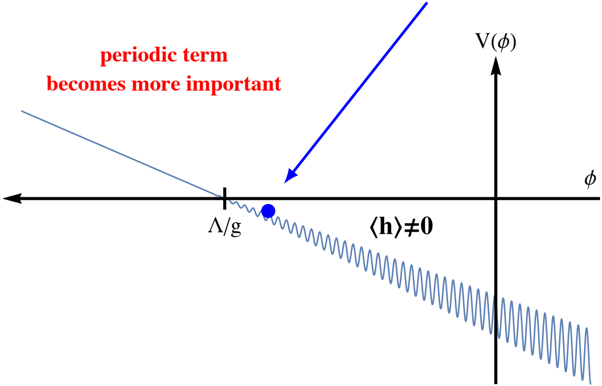

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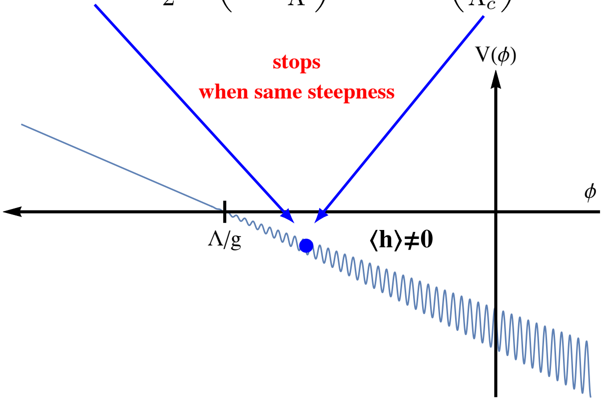

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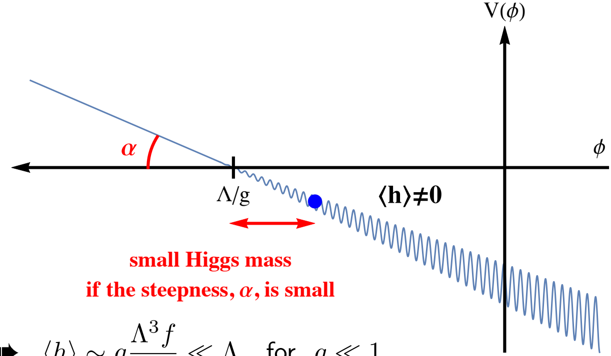

➠ $\langle h \rangle \sim g\frac{\Lambda^3 f}{\Lambda_c^3 \varepsilon} \ll \Lambda$ for $g \ll 1$

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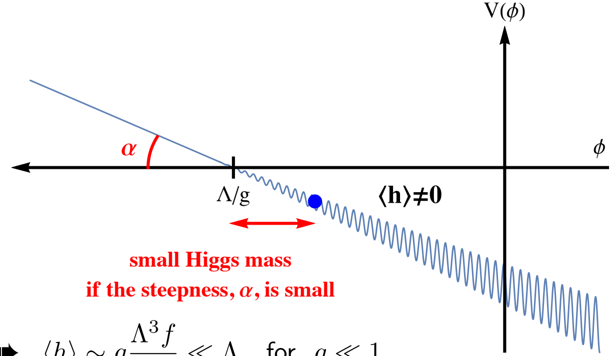

$$\Rightarrow \quad \langle h \rangle \sim g\frac{\Lambda^3 f}{\Lambda_c^3 \varepsilon} \ll \Lambda \quad \text{for} \quad g \ll 1$$

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

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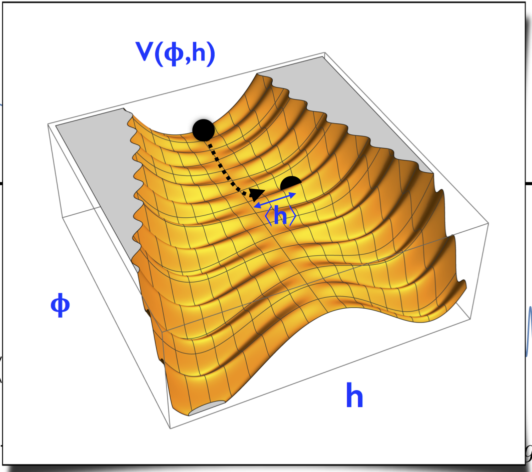

ϕ

• Notice tha ... $g \gg \Lambda$

The "Relaxation" mechanism

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

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

No, if ϕ slow-rolls!

- ➢ possible if a friction is present

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

- ➢ ϕ 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:

ϕ 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

[Graham, Kaplan, Rajendran, 1504.07551]

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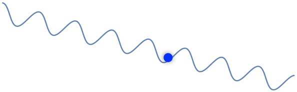
problem: too large $\theta_{\rm QCD} \sim 1$ due to linear tilt!

$\Lambda^3 g\phi$ ➠



can be solved if the tilt disappears after inflation

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

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[Graham, Kaplan, Rajendran, 1504.07551]

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 Λ_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 σ "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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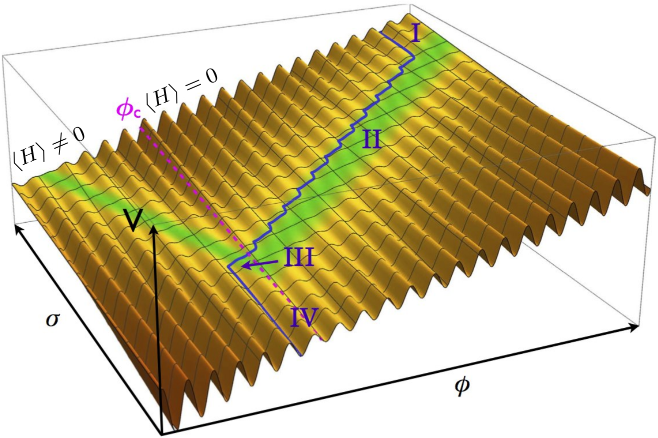

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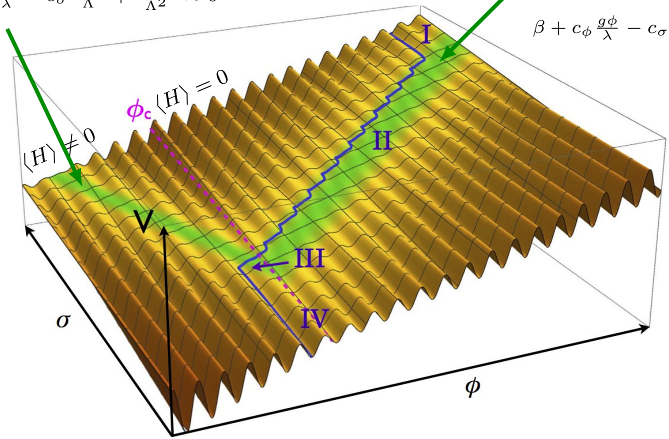
area where $A \approx 0$

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

area where $A \approx 0$

(ϕ can slow-roll)

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



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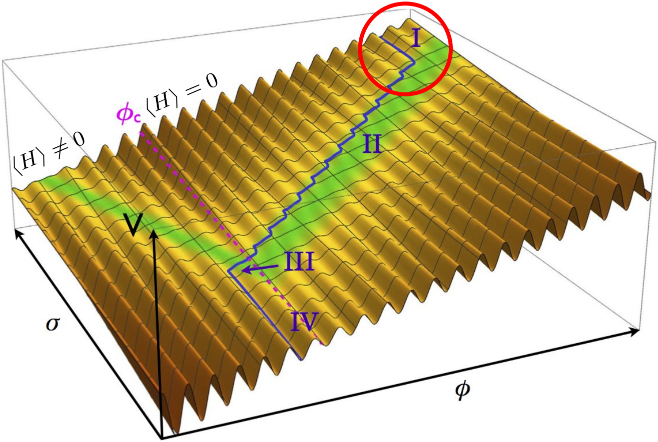

Stage I: ϕ “frozen”

The cosmological evolution

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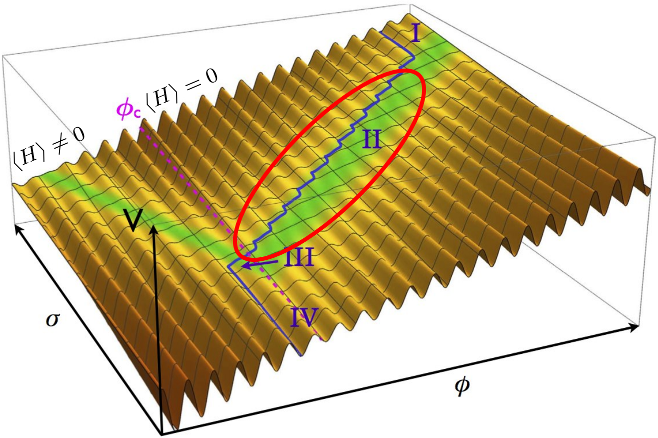

Stage II: ϕ "tracks" σ

The cosmological evolution

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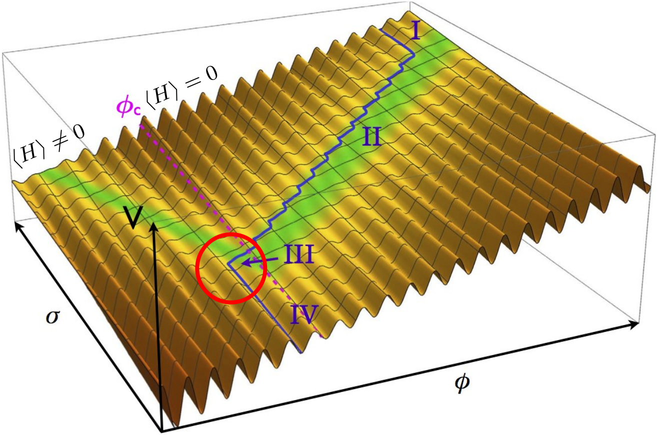

Stage III: ϕ enters the minimum

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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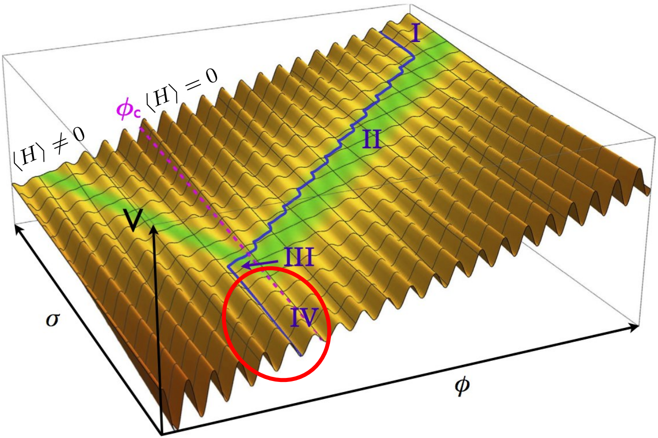
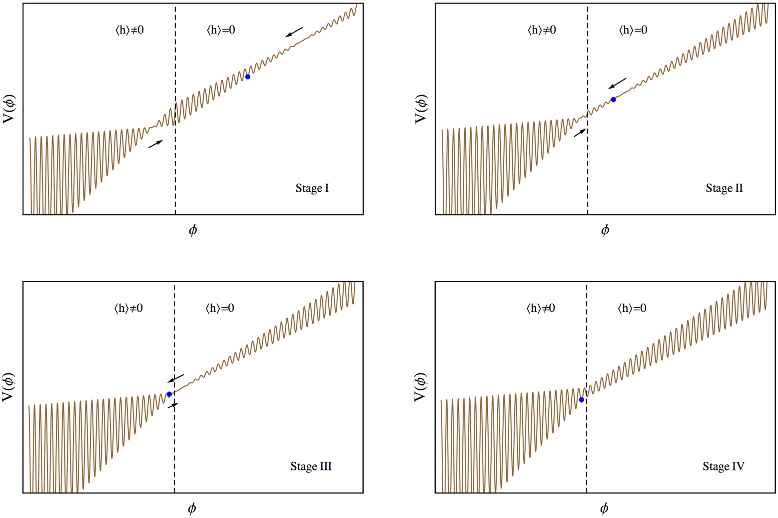


Stage IV: ϕ stabilized

The cosmological evolution

Potential for ϕ in the four stages:



Constraints

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

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

upper bound on the cut-off

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

UV origin of the periodic term

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

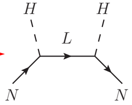
+ **Axion-like** ϕ → $\frac{\phi}{f} G'_{\mu\nu} \widetilde{G}'^{\mu\nu}$

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

➢ ϕ and σ are the only BSM states below Λ

light scalars weakly-coupled to the SM

$$m_\phi \sim 10^{-20} - 10^{2}\ \mathrm{GeV}$$
$$m_\sigma \sim 10^{-45} - 10^{-8}\ \mathrm{GeV}$$

mixing to the SM through the Higgs:

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

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

$m_\phi \sim 100\ \mathrm{GeV}$ $\qquad$ $m_\sigma \sim 10^{-18}\ \mathrm{GeV}$

$\theta_{\phi h} \sim 10^{-21}$ $\qquad$ $\theta_{\sigma h} \sim 10^{-50}$

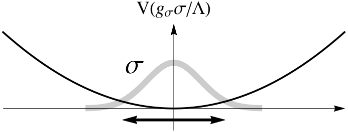
$\phi\phi hh$ coupling $\sim 10^{-14}$

Cosmological consequences

➢ Many **constraints from cosmology**

dark matter overabundance, late decays, BBN bounds,
γ-rays, CMB, pulsar timing observations, ...

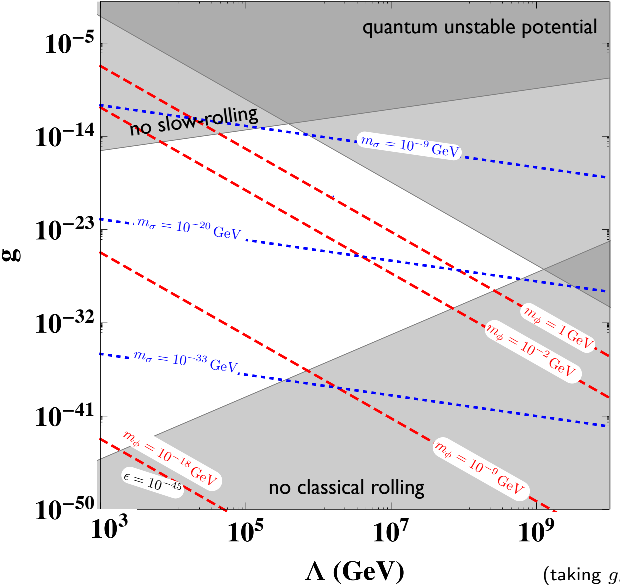
➢ Oscillations of σ can provide a **Dark Matter candidate**



$\Rightarrow \quad \rho^{\sigma}_{ini} \sim H_I^4$

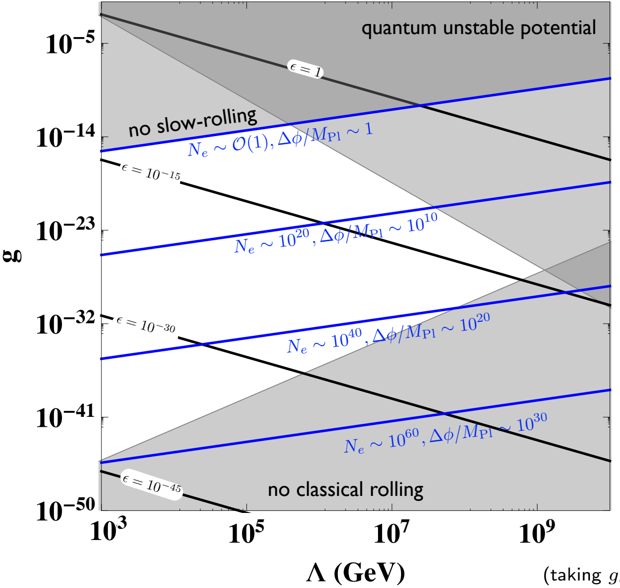
$$\rho_\sigma(T) \sim \rho^\sigma_{ini}(T/T_{osc})^3 \quad \Rightarrow \quad \Omega_\sigma \gtrsim \left(\frac{10^{-27}}{g_\sigma}\right)^{3/2} \left(\frac{\Lambda}{10^8 \text{ GeV}}\right)^{13/2}$$

Parameter space



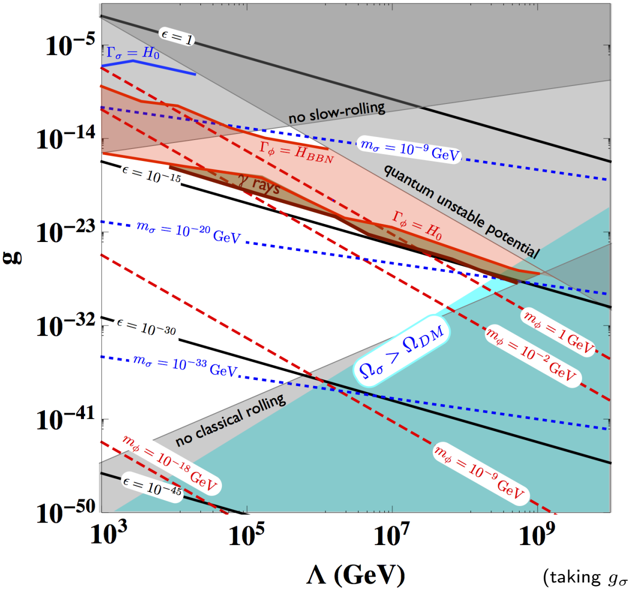
(taking $g_\sigma \sim 0.1g$)

Parameter space



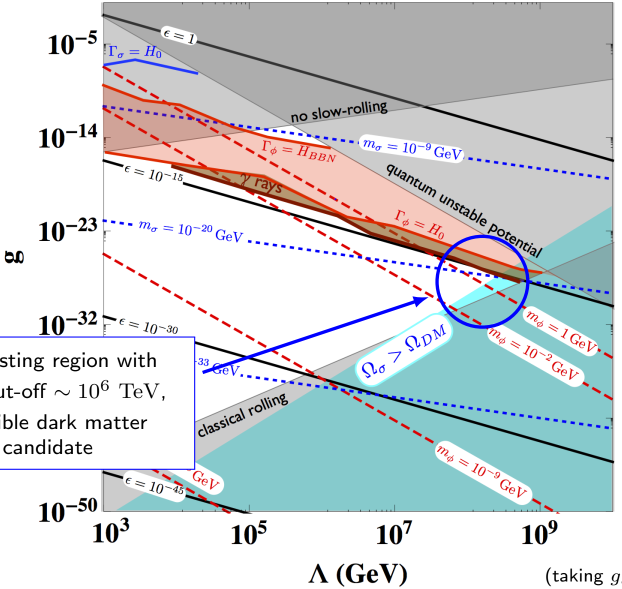
(taking $g_\sigma \sim 0.1g$)

Constraints on the parameter space



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

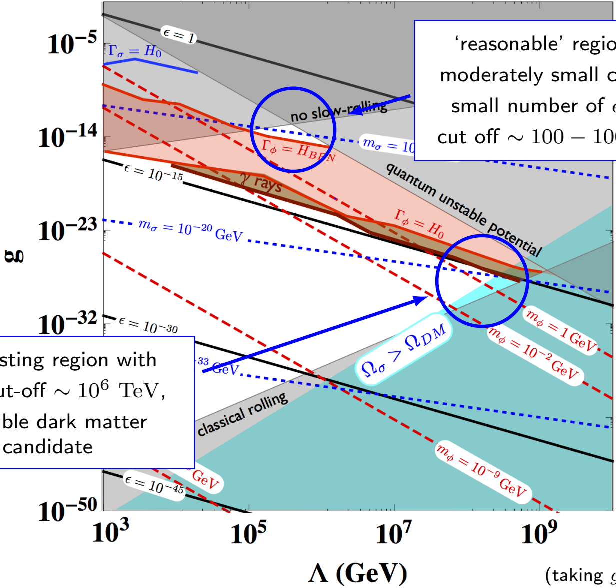
Constraints on the parameter space



Interesting region with high cut-off $\sim 10^6$ TeV, possible dark matter candidate

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

Constraints on the parameter space



'reasonable' region with moderately small coupling, small number of e-folds, cut off $\sim 100 - 1000$ TeV

Interesting region with high cut-off $\sim 10^6$ TeV, possible dark matter candidate

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

Conclusions

Conclusions

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 (γ-rays, pulsar timing, ...), CMB, fifth-force searches, ...

Ugly features:

Huge number of inflation e-folds $N_e > 10^{38}$ (if high cut-off is required)

Super-Planckian field excursions

Conclusions

Future directions:

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

  [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 [Hardy, arXiv:1507.07525]