Nature loves us, loves us not…

Oriol Pujolàs

IFAE, UAB

IFT Madrid 11/2/2016

PLAN

1) Loves us not: **no-show @ LHC**

- Relaxions

2) Loves us: **present(s) @ LHC**

PLAN

1) Loves us not: **no-show @ LHC**

- Relaxions

2) Loves us: **present(s) @ LHC**

- Dilaton

1) Cosmological Relaxation mechanisms

A long long time ago,
in a far far away place,
the scale of the EW forces
(the Higgs mass)
were suppressed... by...
a cosmic conspiracy...

Motivation

- A new type of solution to the Hierarchy Problem has been identified (Graham, Kaplan & Rajendran ‘15)
- It doesn’t require new particles @ TeV energies
- Instead, a fantastic cosmological history

Idea

Relaxation mechanism

Abbot '85

Dvali & Vilenkin'2004

Graham, Kaplan, Rajendran '15

$$M^2 H^2 \quad \rightarrow \quad M^2(\phi)\, H^2$$

ϕ rolls, scans, and stops when M small

Stopping can be linked to EWSB

$$M^2 < 0$$

Cosmological Relaxation

$$V_{SM+PQ}(\phi, H) = M^2 H^2 + \lambda H^4 + \underbrace{\varepsilon H \Lambda^3 \cos(\phi / f)}_{m_q \langle \bar{q}_R q_L \rangle}$$

Cosmological Relaxation

$$V_{SM+PQ}(\phi, H) = M^2 H^2 + \lambda H^4 + \varepsilon H \Lambda^3 \cos(\phi / f)$$

(Graham, Kaplan, Rajendran'15)

$$V_{GKR} = M^2(\phi) H^2 + \lambda H^4 + \varepsilon H \Lambda^3 \cos(\phi / f) + V_0(\phi)$$

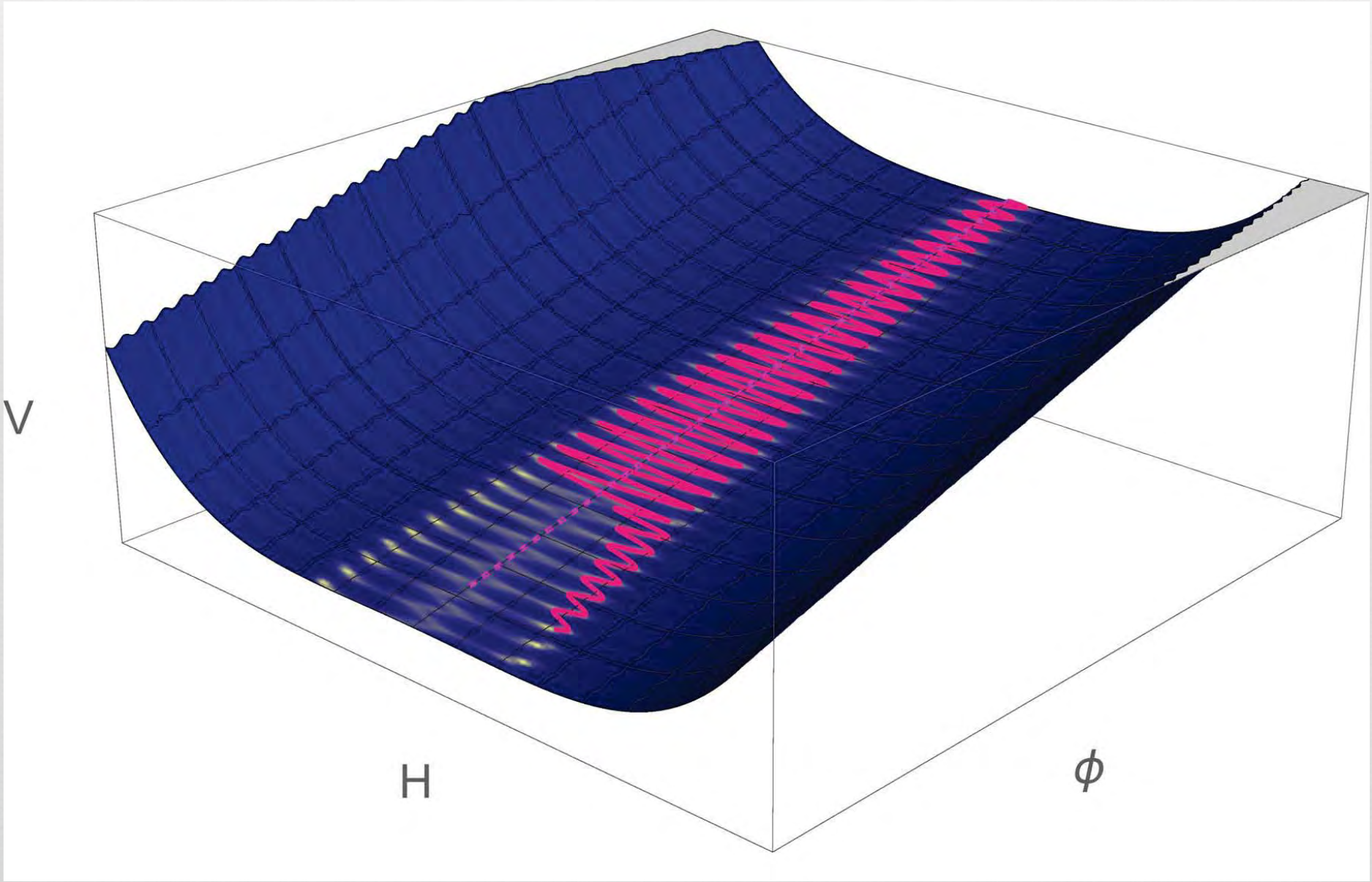
scanning stopping rolling

Technically natural !!

$$V_0(\phi) = \Lambda^4 F(g\phi / \Lambda)$$

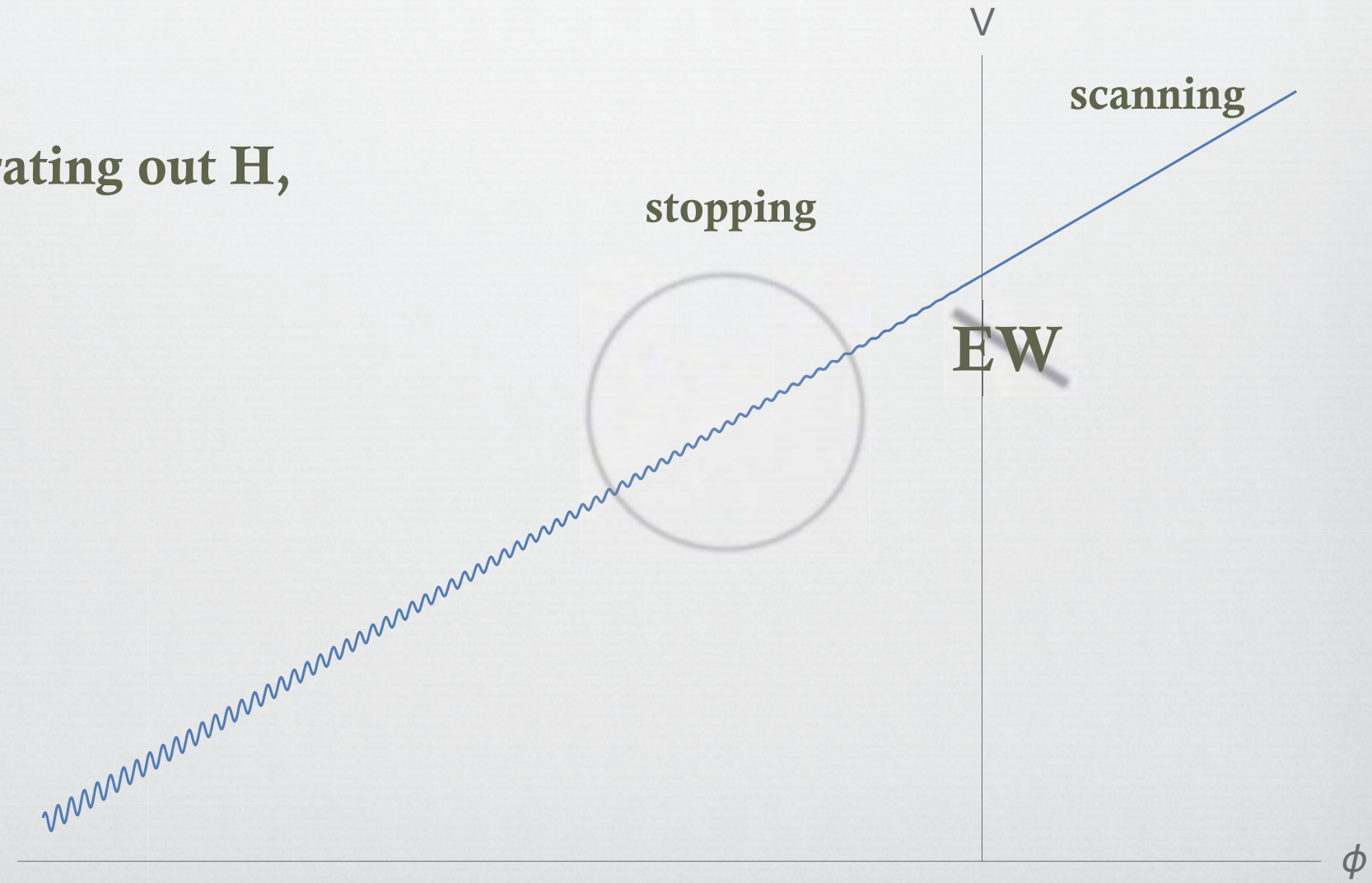
$$M^2(\phi) = \Lambda^2 F(g\phi / \Lambda)$$

GKR Relaxion



GKR Relaxion

Integrating out H,



GKR Relaxion

- conditions:

solve HP

- full scan => $\Delta\phi \geq \Lambda / g$
- many vacua $(\Delta M_H \ll \Lambda)$ => $gf \ll \Lambda$
- right ew scale => $g \sim \varepsilon\, v/f$

inflation

- friction => inflation (maybe more options…)
- subleading to inflaton => $\Lambda^4 < H_I^2 M_P^2$
- classical motion => $H_I^3 < g\Lambda^3$

$\Lambda^3 < g M_P^3$

GKR Relaxion

- **results:**
- **raises NP scale to** $\Lambda \leq 30\text{-}1000$ TeV
- **Long inflation epoch** $N_{efolds} \sim 10^{40}$
- **Long field excursion** $\Delta\phi \gg \Lambda$
- **low inflation scale** $g^{1/3}\Lambda^2 M_P^2$

(Reminder) Ingredients below Λ **= { SM + QCD axion + expl. breaking of PQ + few assumptions on inlfation}**

Cosmological Higgs-Axion Interplay – CHAIN

Cosmological Higgs-Axion Interplay for a Naturally Small Electroweak Scale

J. R. Espinosa, C. Grojean, G. Panico, A. Pomarol, O. Pujolàs, and G. Servant

Phys. Rev. Lett. **115**, 251803 – Published 16 December 2015

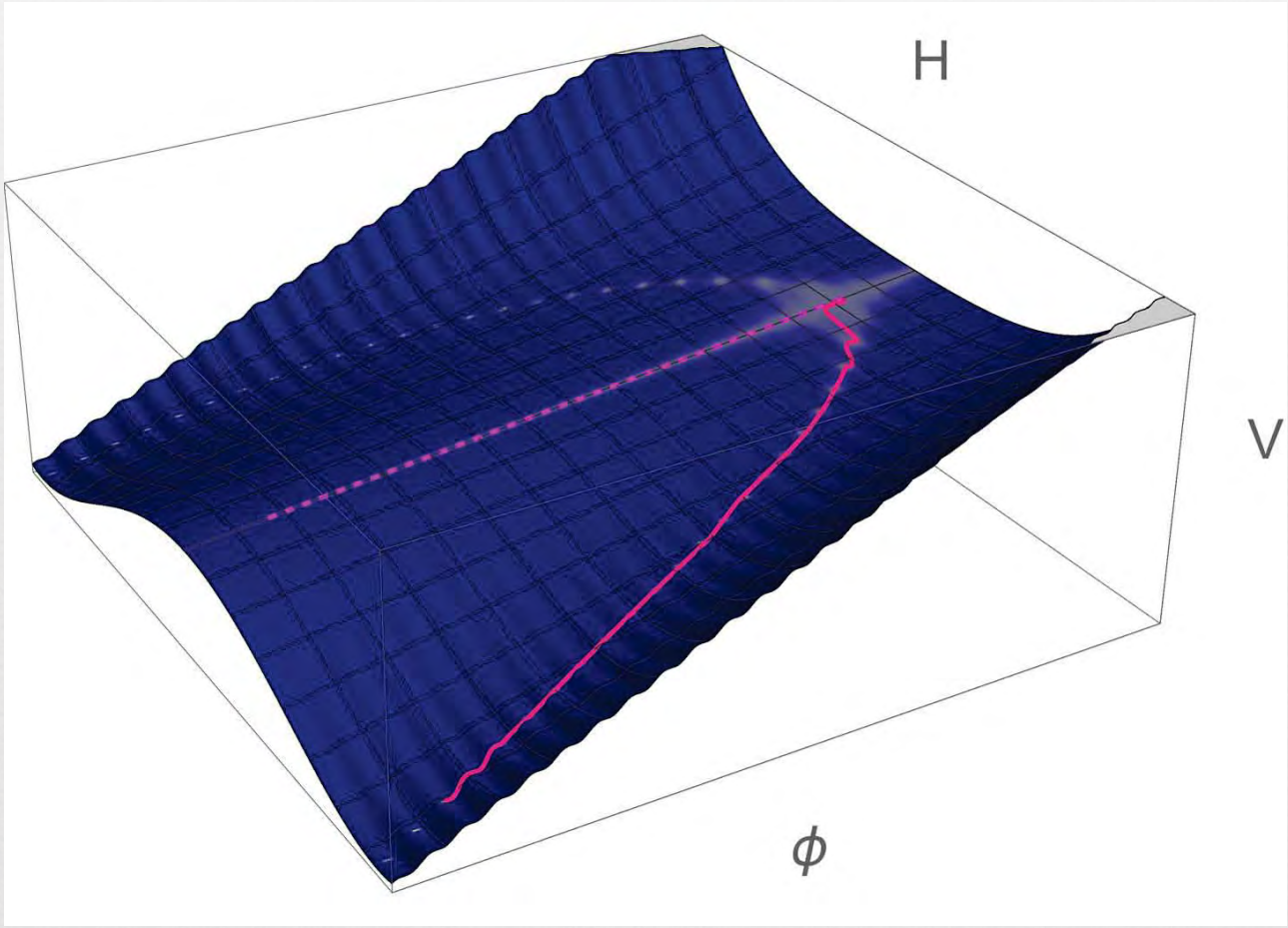
CHAIN

$$V(H,\phi) = M^2(\phi)\, H^2 + \lambda H^4 + V_0(\phi) + H^n \Lambda^{4-n} \cos(\phi/f)$$

scanning **driving** **stopping**

$$V_{stopping} = |H|^2 \Lambda^2 \cos(\phi/f)$$ **??**

CHAIN



$$V_{stopping} = H^2 \Lambda^2 \cos(\phi / f)$$

CHAIN

$$V(H,\phi) = M^2(\phi)\, H^2 + \lambda H^4 + V_0(\phi) + H^n \Lambda^{4-n} \cos(\phi/f)$$

scanning **driving** **stopping**

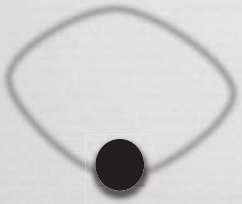
$$V_{stopping} = |H|^2 \Lambda^2 \cos(\phi/f)$$ **??**

CHAIN

$$V(H,\phi) = M^2(\phi)\,H^2 + \lambda H^4 + V_0(\phi) + H^n \Lambda^{4-n} \cos(\phi/f)$$

scanning **driving** **stopping**

$$V_{stopping} = |H|^2 \Lambda^2 \cos(\phi/f)$$ **??**



$$V_{stopping} = (|H|^2 \Lambda^2 + \Lambda^4) \cos(\phi/f)$$ **!!**

CHAIN

Resolution:

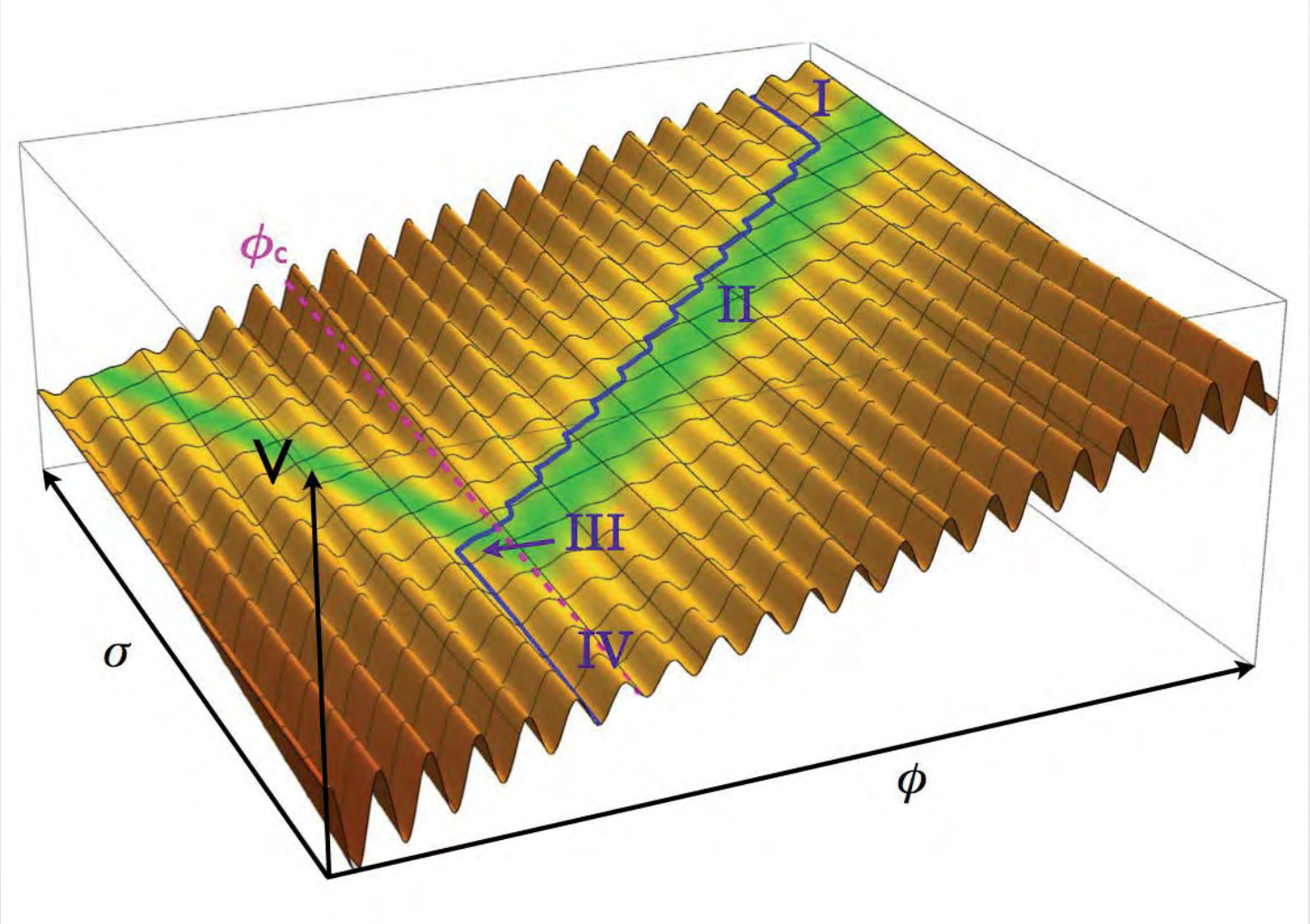
Technically natural !!

$$V(H,\phi,\sigma) = M^2(\phi)\, H^2 + \lambda H^4$$

$$+ A(H,\phi,\sigma)\cos(\phi/f) + V_0(\phi,\sigma)$$

$$= \varepsilon\Lambda^2\left(\Lambda^2 + |H|^2 + g\Lambda\sigma + g\Lambda\phi + \ldots\right)$$

CHAIN



CHAIN

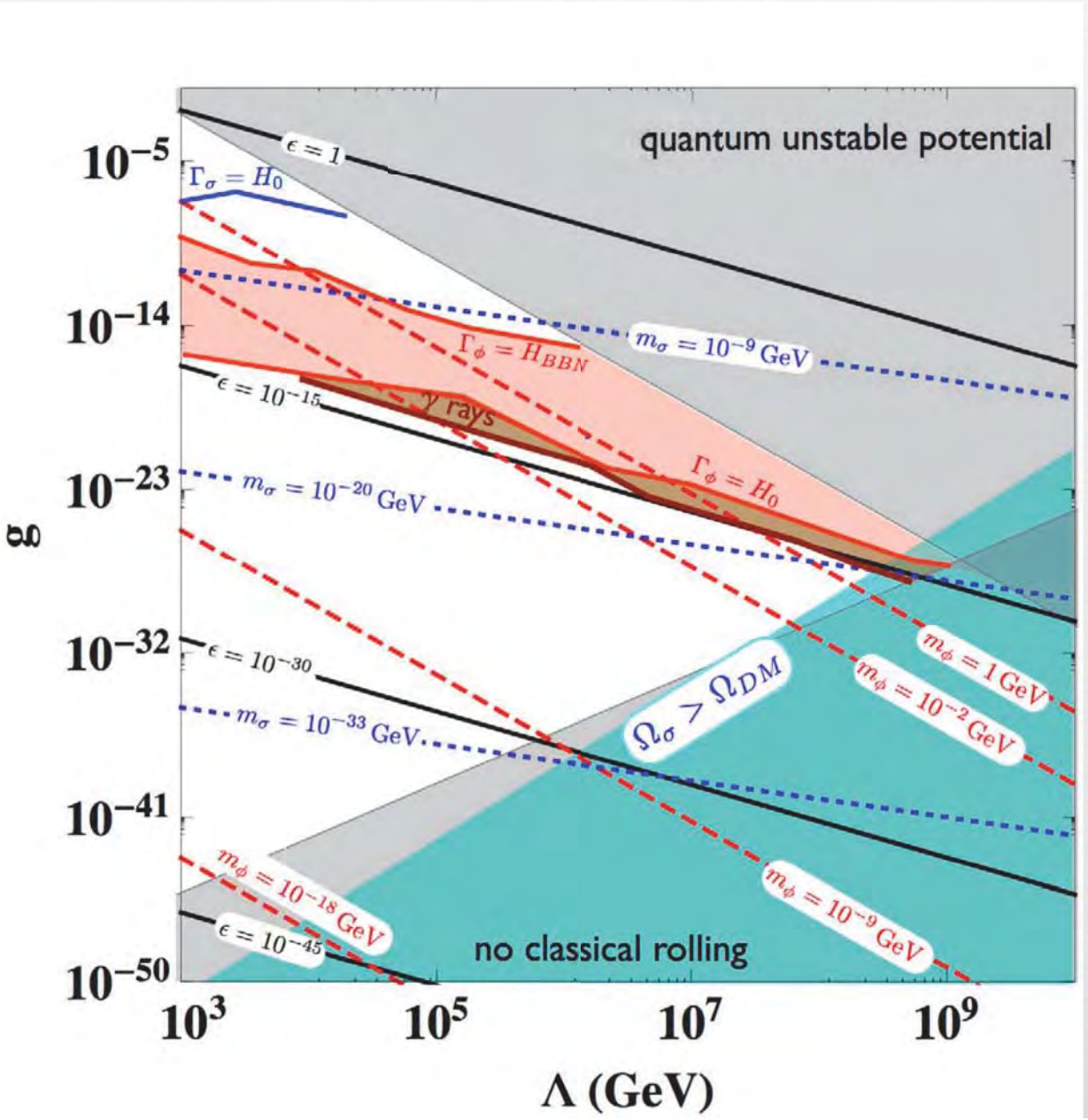
- 2 light scalars,

  ϕ axion-like
  $m_\phi \sim$ sub-GeV-ish
  moderate weakly coupled (thermally produced)
  impact on BBN

  σ ultra-light scalar, ultra weakly coupled
  DM candidate (from 'vac. misalignment')

- No new particles until $10^5 - 10^9$ GeV

CHAIN



BBN constraints can be evaded if

$$T_{reh} < m_H$$

Cosmological Relaxation

- Can raise the New Physics (NP) scale to ~10^9 GeV
- => *Partial* Solution to the Hierarchy problem
- => No new particles @ EW scale, but implications in cosmo
- Only remnant: 2 light and weakly coupled scalar singlets
- Long excursions/periods a problem?

Cosmological Relaxation

- Long excursions/periods a problem?

- Weak Gravity Conjecture(hep-th/0601001) suggests $f < M_p$

Gupta Komargodski Perez Ubaldi 1509.00047

- However, the argument is naïve/quick

Choi & Im 1511.00132
Kaplan & Rattazzi 1511.01827
Ibanez Montero Uranga Valenzuela 1512.00025

Monodromy in Large N QCD
Witten 80's

Cosmological Relaxation

- Long excursions/periods a problem?

Exponentially large field periods can be realized in models with:
- order-few fields
- order-few charge assignments

$$\Delta\phi \sim e^N f$$

Choi & Im 1511.00132
Kaplan & Rattazzi 1511.01827

Open questions (?):
tension with Quantum Gravity/Weak Gravity Conjecture?

From EFT perspective, I see
i) no problem ii) no deviation from QFT framework, and
iii) WGC and alike are *assumptions* about QG

Cosmological Relaxation

- Long excursions/periods a problem?

  It seems not (at least yet).

  Rather, it makes relaxion-ology a probe of QG.

2) What if Nature loves us?

A nice present would be…

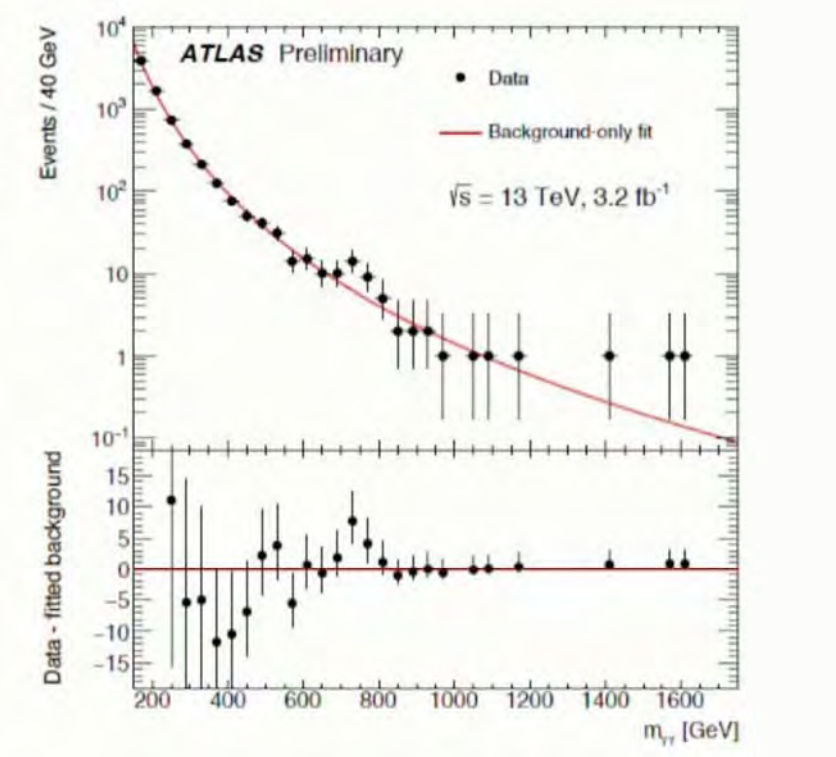
2) What if Nature loves us?

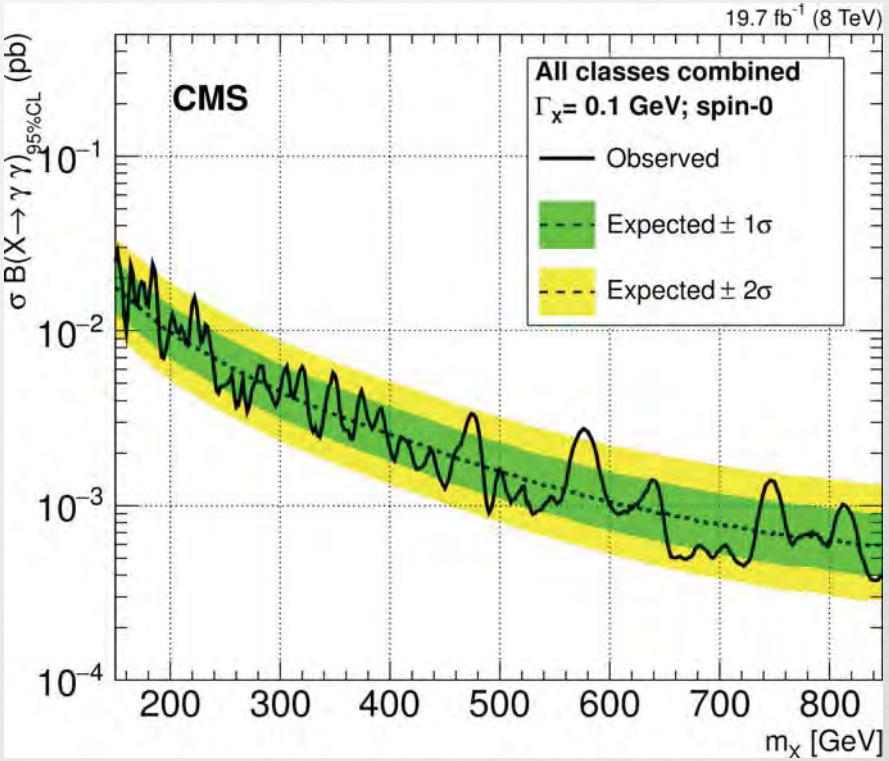
A nice present would be…

a *dilaton* !

“Naturally light dilatons”
w/ Eugenio Megías and Mariano Quirós

Diphoton excess





Dilaton?

- Goldstone Boson of Spontaneously Broken Conformal Invariance (SBCI)
- Contino-Pomarol-Rattazzi '2010 showed how to realize naturally SBCI and a light dilaton
- Now we have examples of such beasts arising from (holographic) strong dynamics

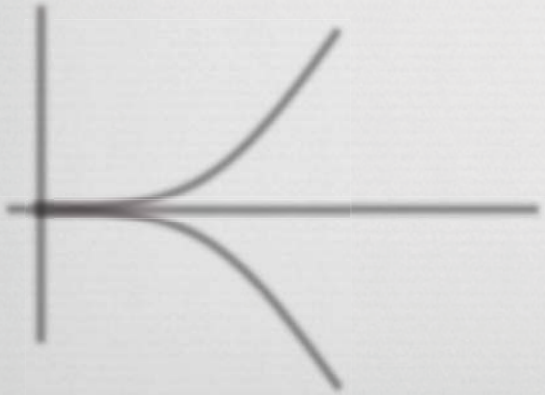
Dilaton?

- EFT of SBCI

$$\phi \to s\phi \qquad \langle \phi \rangle \neq 0$$

$$x \to s^{-1} x$$

$$L = \phi^4 F\left[\frac{(\partial\phi)^2}{\phi^4}\right] = (\partial\phi)^2 - \lambda\phi^4 + \ldots$$



Expected to be large (~ 1) => no natural SBCI

Analogous to Cosmological Constant problem

Dilaton?

- Simplest example: IR brane in Randall Sundrum

$$\phi = \text{warp factor at IR brane location}$$

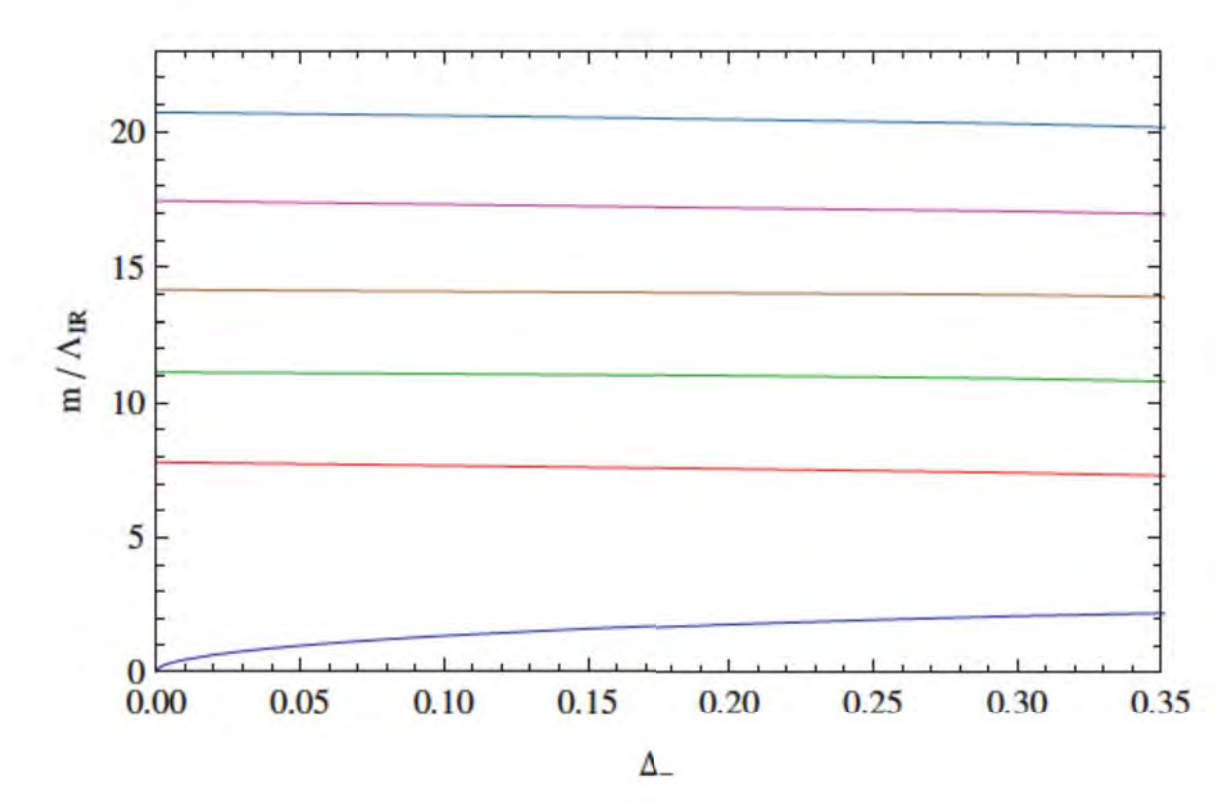
$$\lambda \sim \ell \Lambda_5 - \Lambda_4$$

- CPR solution: add small explicit breaking (by *nearly marginal deformation*)
- λ gets dynamically suppressed in the ground state and a (naturally) light dilaton appears

Dilaton?

w/ Eugenio Megías 1401.4998

Also in
1305.3919
1306.4601



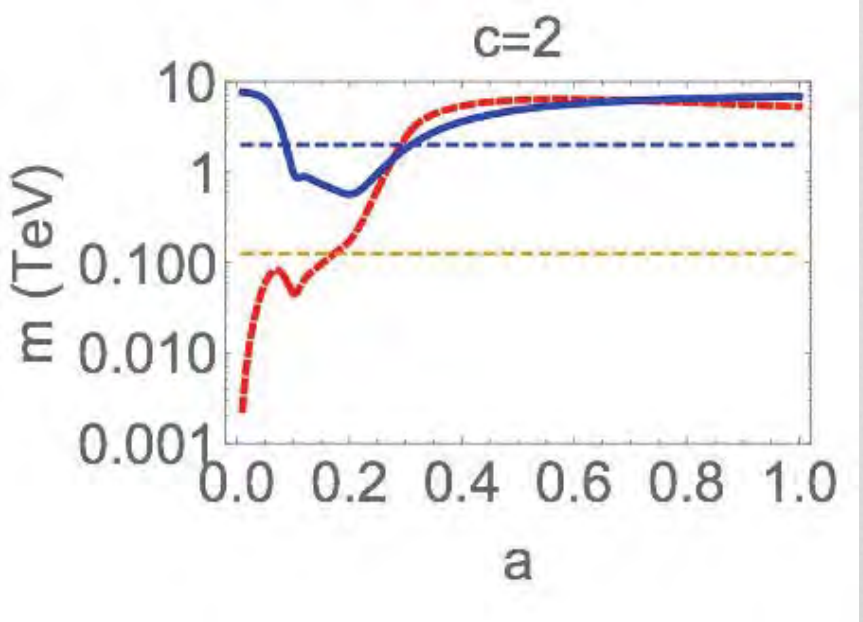
$$m_{dil}^2 \sim \beta_{IR}\,\Lambda_{IR}^2$$

Diphoton as a dilaton?

Explicit & minimal Soft-Wall model with:

- KK resonances at most at 2 TeV
- *light* dilaton ~ 750 GeV
- large enough couplings to $\gamma\,\gamma$ and gg
- pass EWPT tests

'*diphoton-dilaton*' is light naturally stands as a possibility



w/ E. Megías and M. Quirós
1512.06106

Conclusions

- Interesting times ahead…

- If she loves us => happy family, lots of children
- Loves us not =>

Conclusions

- Interesting times ahead…

- If she loves us => happy family, lots of children

- Loves us not => keep working on her, learning how to lover her – eventually she'll love us back!

Thanks!

(and apologies for many missing refs)