Cosmological relaxation of the EW scale after inflation

EM, N. Fonseca, G. Servant, *in progress*

Enrico Morgante - DESY

Scalars 2017 - Warsaw - 01 Dec. 2017

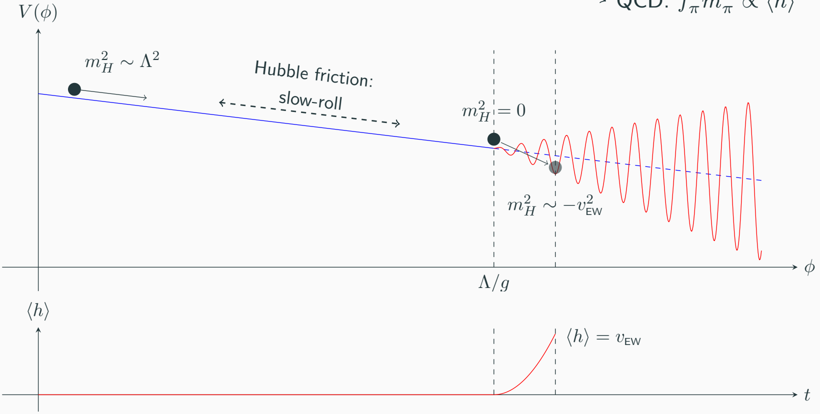
The relaxion mechanism

The relaxion mechanism

Graham, Kaplan, Rajendran 1504.07551

$$V(\phi,h) = -g\Lambda^3\phi + \frac{1}{2}\underbrace{(\Lambda^2 - g\Lambda\phi)}_{m_H^2}h^2 + \Lambda_c^{4-n}\langle h\rangle^n \cos\left(\frac{\phi}{f}\right) + \dots$$

QCD: $f_\pi^2 m_\pi^2 \propto \langle h\rangle$



Problems

This construction has its own issues:

- Generate a large hierarchy of scales ($F \gg f$) Kaplan+ 1511.01827 Choi+ 1511.00132
- Size of the barriers $\sim \langle h \rangle^n$:
  - $n = 1$ (QCD-axion): excluded by $\theta_{\rm QCD} \ll 1$
  - $n = 2$: requires new fermions at the EW scale not related to the Higgs (or more refined construction, Espinosa+ 1506.09217)
- Inflation: large number of efolds (10^{100}), small H_I (Λ_{QCD})
- Super-Planckian field excursions
- C.C. problem: does it get worse?

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- Super-Planckian field excursions $\Longleftarrow$
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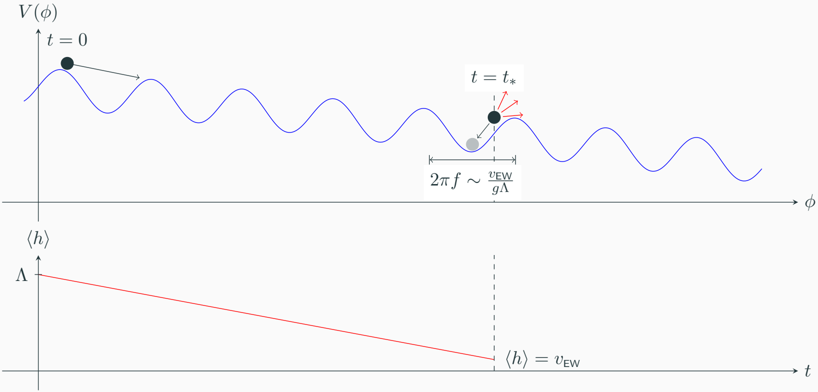
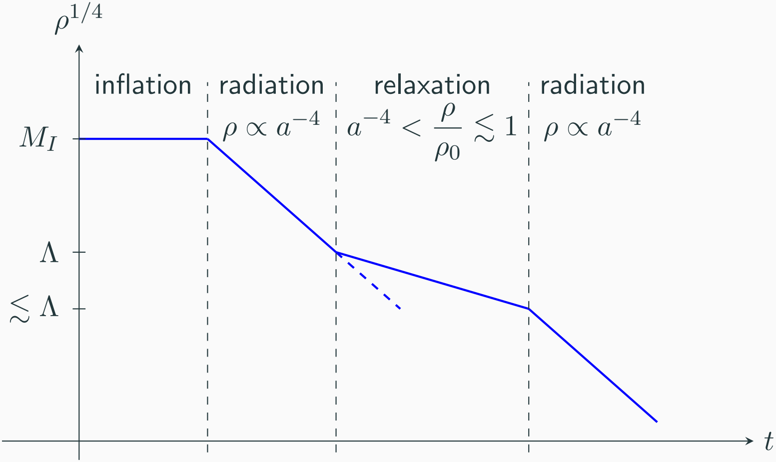
Relaxation after inflation

Relaxation with particle production

- We don't want to rely on inflation: no Hubble friction
- EW symmetry initially broken
- Barriers with constant amplitude



Timeline



EM, Fonseca, Servant, *in preparation*

Avoid slow-roll

Slow roll: ϕ generates a second period of inflation.

- If $N > 60$, this would wash out inflationary perturbations
- Impose $\epsilon \gtrsim 1$:

$$\epsilon = \frac{m_{\mathsf{Pl}}^2}{2}\left(\frac{V'}{V}\right)^2 = \frac{m_{\mathsf{Pl}}^2}{2}\frac{g^2}{\Lambda^2} \gtrsim 1$$

$$\boxed{\Rightarrow g \gtrsim \frac{\Lambda}{m_{\mathsf{Pl}}}}$$

- With no slow-roll, relaxation lasts

$$\Delta t_* \sim \frac{\Delta\phi}{\dot{\phi}} \sim \frac{\Lambda}{g}\frac{1}{\Lambda^2} = \frac{1}{g\Lambda}$$

Issue with reheating

Suppose SM is reheated to $T_{\text{RH}} > \Lambda$

- At $T = \Lambda$ the potential is generated and relaxation starts.
- Higgs mass $-\Lambda^2 + g\Lambda\phi + g_{\text{EW}}T^2 < 0$
- At the end of relaxation

$$\frac{T}{\Lambda} = e^{-\int H \mathrm{d}t} \approx 1 - H\Delta t_*$$

To have $T < v_{\text{EW}}$ one needs

$$g \lesssim \frac{\Lambda}{m_{\text{Pl}}}$$

Issue with reheating

Solutions:

- Small window at $g \sim \Lambda / m_{\mathsf{Pl}}$
- Reheating into a dark sector with $T_{\mathsf{SM}} < v_{\mathsf{EW}}$

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Particle production

Particle production: scalars

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}(\phi - \phi_\star)^2\chi^2$$

$$\ddot{\chi} + \underbrace{\left[k^2 + (\phi - \phi_\star)^2\right]}_{\omega^2}\chi = 0$$

Violate the adiabatic condition:

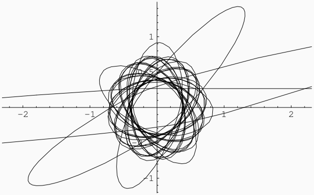
$$\dot{\omega}/\omega^2 \gtrsim 1 \qquad \Longrightarrow \qquad \langle\chi^2\rangle \text{ grows exponentially}$$

$$\ddot{\phi} + 3H\dot{\phi} + (\phi - \phi_\star)\langle\chi^2\rangle = 0$$

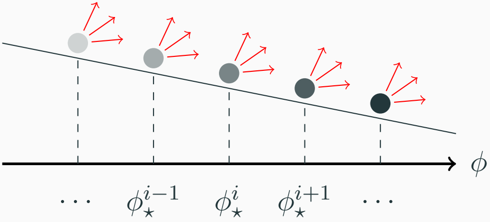
ϕ is "trapped" at the critical point $\phi_\star$.

Particle production: scalars

Moduli trapping at enhanced symmetry points (Kofman+ hep-th/0403001)



Trapped inflation (Green+ 0902.1006)



Stopping the relaxion with the Higgs

Decompose the Higgs as $h = h_0 + \chi$

$$\chi(t,\vec{x}) = \int \frac{d^3k}{(2\pi)^3} \left(a_k u_k(t) e^{i\vec{k}\cdot\vec{x}} + a_k^\dagger u_k^*(t) e^{-i\vec{k}\cdot\vec{x}} \right),$$

Equation of motion:

$$\ddot{u}_k + \left(k^2 + \underbrace{g\Lambda\phi - \Lambda^2}_{m_H^2} + 3\lambda h_0^2 \right) u_k = 0$$

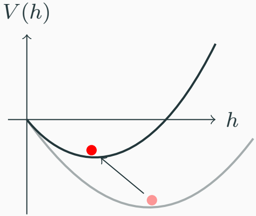
Particle production

- $\dot{\omega}/\omega^2 \gg 1$ for $(k^2 + g\Lambda\phi - \Lambda^2 + 3\lambda h_0^2) = 0$
- We want $h_0 = 0$ when $m_H = 0$: h_0 must track the minimum of the potential

Stopping the relaxion with the Higgs

The Higgs vev tracks the minimum as far as

$$h_0^2 = \frac{\Lambda^2 - g\Lambda\phi}{\lambda} \gtrsim \frac{1}{\lambda}(g\Lambda\dot{\phi})^{2/3}$$



Particle production is efficient for

$$\frac{\dot{\omega}}{\omega^2} \gtrsim 1 \Longrightarrow \dot{\phi} \gtrsim \frac{(\Lambda^2 - g\Lambda\phi)^{3/2}}{g\Lambda}$$

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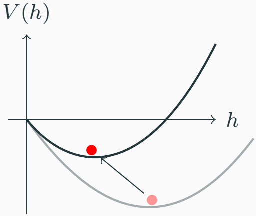

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No efficient particle production is possible

Particle production: vectors

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial h)^2 - \frac{1}{4}(F_{\mu\nu})^2 - V(\phi, h) - \frac{\phi}{4f} F_{\mu\nu}\widetilde{F}^{\mu\nu} + \frac{\pi\alpha}{2} A_\mu A^\mu h^2$$

The field A_μ experiences a tachyonic instability:

$$\ddot{A}_\pm + (k^2 + m_A^2 \mp k\frac{\dot{\phi}}{f})A_\pm = 0 \qquad m_A^2 = \pi\alpha h^2$$

The growth of $F\tilde{F}$ slows down the field ϕ

$$\ddot{\phi} - g\Lambda^3 + g'\Lambda h^2 + \frac{\Lambda_c^4}{f'}\sin\frac{\phi}{f'} + \frac{1}{4f}\langle F\widetilde{F}\rangle = 0$$

$$\langle F\widetilde{F}\rangle = \frac{1}{4\pi^2}\int_0^\Lambda \mathrm{d}k\, k^3 \frac{\mathrm{d}}{\mathrm{d}t}(|A_+|^2 - |A_-|^2)$$

Hook & Marques-Tavares, JHEP 1612 (2016) 101 (1607.01786)

Prediction for the weak scale

The electroweak scale is derived:

- Tachyonic growth should start only when $h \sim v_{\mathsf{EW}}$:

$$\dot{\phi} \sim v_{\mathsf{EW}} f,$$

- Field velocity: $\dot{\phi} \sim \Lambda^2$

We expect

$$v_{\mathsf{EW}} \sim \frac{\Lambda^2}{f}$$

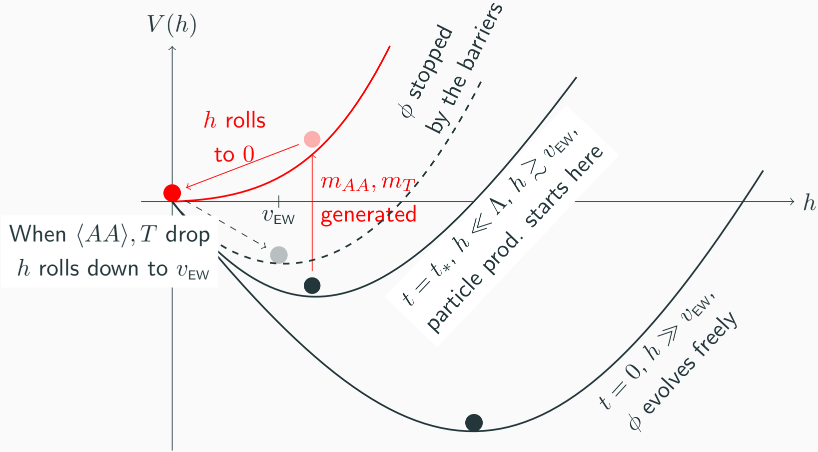
To be precise...

Two key points (but not enough time):

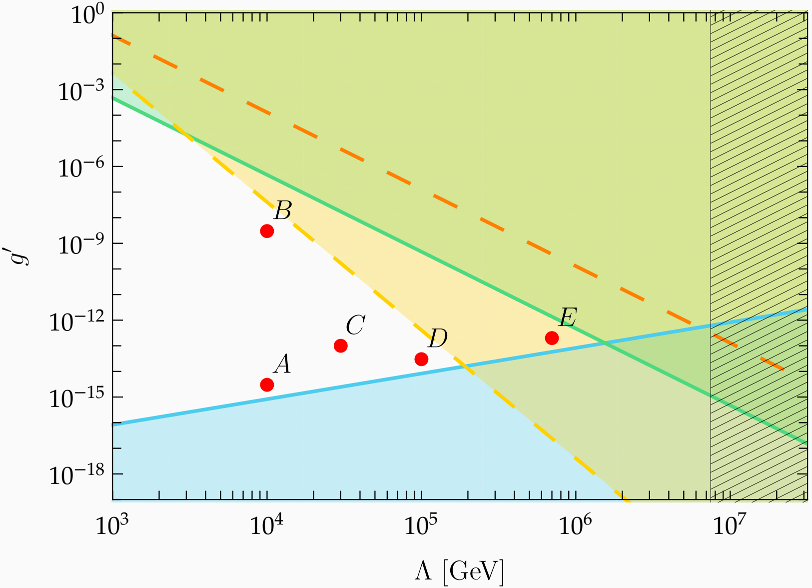
- $F\widetilde{F}$ should not contain $F_\gamma \widetilde{F}\gamma$
- Thermal effects modify the dispersion relation of the gauge bosons, reducing the efficiency of the mechanism

A closer look

$$V(h) = (-\Lambda^2 + g\Lambda\phi + |A_\pm|^2 + g_{\text{EW}}^2 T^2)h^2 + \frac{\lambda}{4}h^4$$

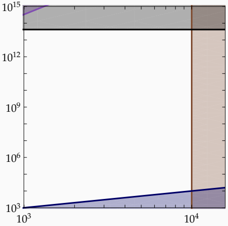


Constraints: g' *vs.* Λ

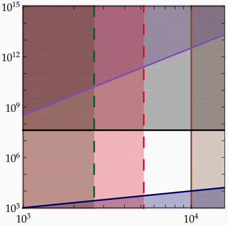


Constraints: f' *vs.* Λ_c

$\boxed{\text{A}}: \Lambda = 10^4,\ g' = 3\times 10^{-15},\ f \approx 10^6$



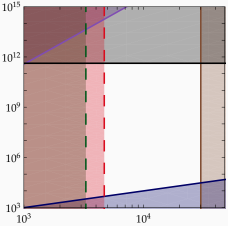
$\boxed{\text{B}}: \Lambda = 10^4,\ g' = 3\times 10^{-9},\ f \approx 10^6$



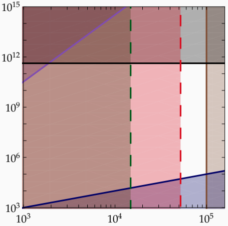
$$\Lambda_c \sim \Lambda$$

$$f' \sim 10^{4-13}\ \text{GeV}$$

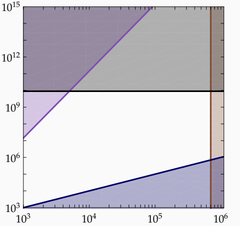
$\boxed{\text{C}}: \Lambda = 3\times 10^4,\ g' = 10^{-13},\ f \approx 10^7$



$\boxed{\text{D}}: \Lambda = 10^5,\ g' = 3\times 10^{-14},\ f \approx 10^8$

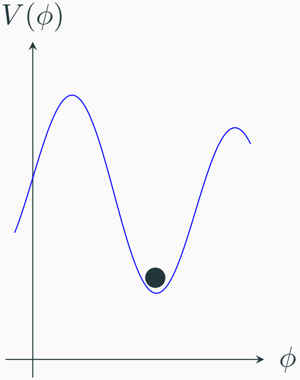


$\boxed{\text{E}}: \Lambda = 7\times 10^5,\ g' = 2\times 10^{-13},\ f \approx 5\times 10^9$



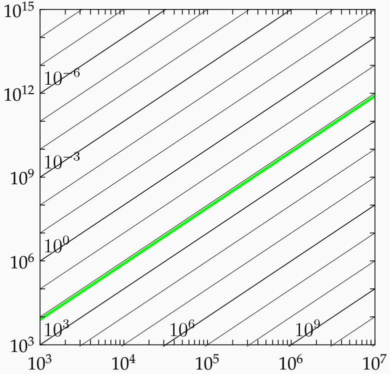
Phenomenology (in progress)

Relaxion mass



$$m_\phi = V''(\phi)^{1/2} = \frac{\Lambda_c^2}{f'}$$

Relaxion mass



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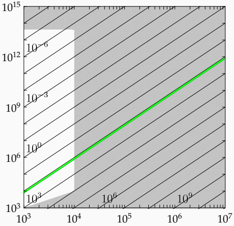

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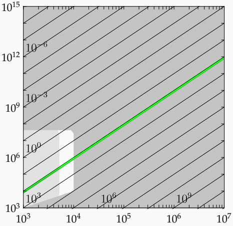

$$10^{-6} \lesssim \frac{m_\phi}{\text{GeV}} \lesssim 10^4$$

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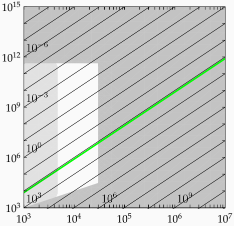

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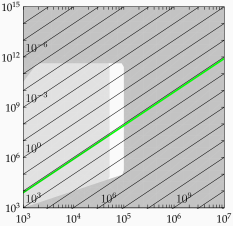

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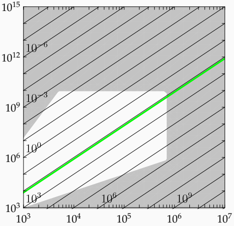
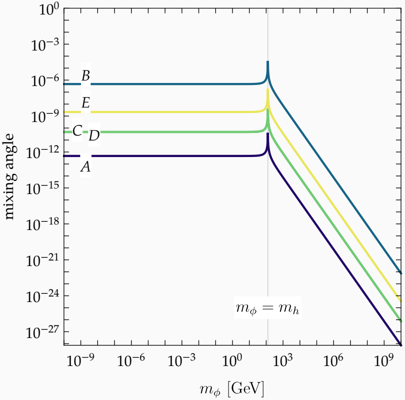


Relaxion - Higgs mixing

$$V(\phi, h) \sim -g\Lambda^3\phi + \frac{1}{2}(-\mu_h^2 + g'\Lambda\phi)h^2 + \frac{\lambda}{4}h^4 + \frac{1}{2}m_\phi^2\phi^2$$

Expand the Higgs $h \to v_{\mathsf{EW}} + \chi$

$$\theta = \frac{g'\Lambda v_{\mathsf{EW}}}{\sqrt{4g'^2\Lambda^2 v_{\mathsf{EW}}^2 + (m_h^2 - m_\phi^2)^2}}$$



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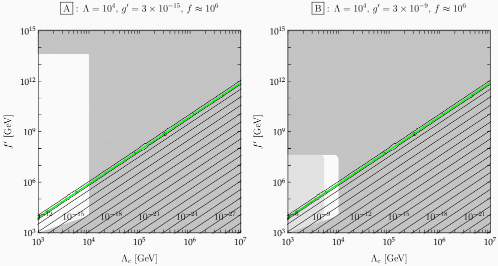
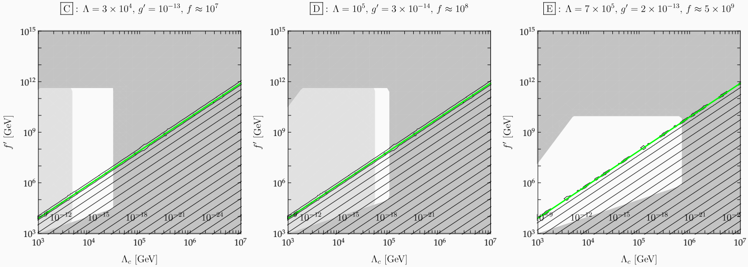
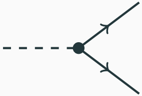


$$\theta \sim 10^{-(5-16)}$$



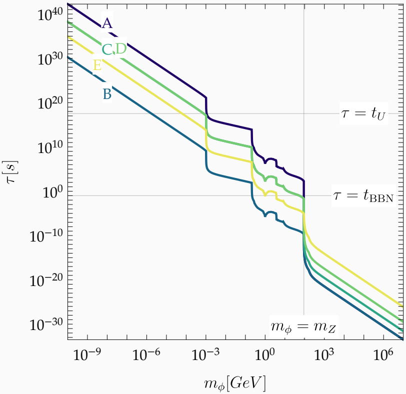
Relaxion decays:

- $m_\phi < m_Z$: Higgs mixing

$\propto \theta :$ 

- $m_\phi > m_Z$: through $\phi F\widetilde{F}$

$$\phi \to Z\gamma, ZZ, WW$$



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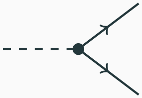
$\propto \theta :$ 

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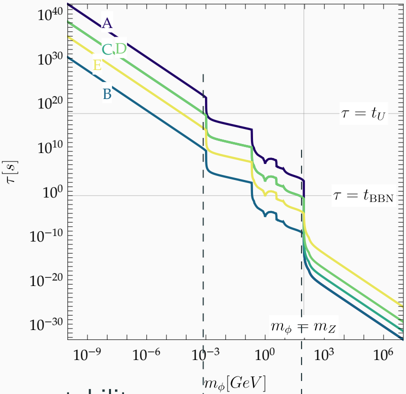


stability $\longleftarrow$

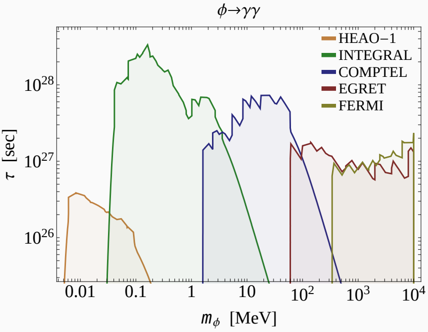
$$m_\phi \lesssim 10^{-(3-6)}\ \mathrm{GeV}$$

BBN $\longleftarrow$

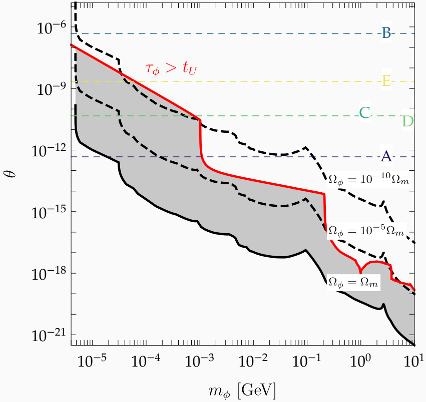
$$m_\phi \lesssim 10^{0-2}\ \mathrm{GeV}$$

Indirect detection

$\phi \to \gamma\gamma$ can give ID signals



Essig+ 1309.4091, diffuse γ rays



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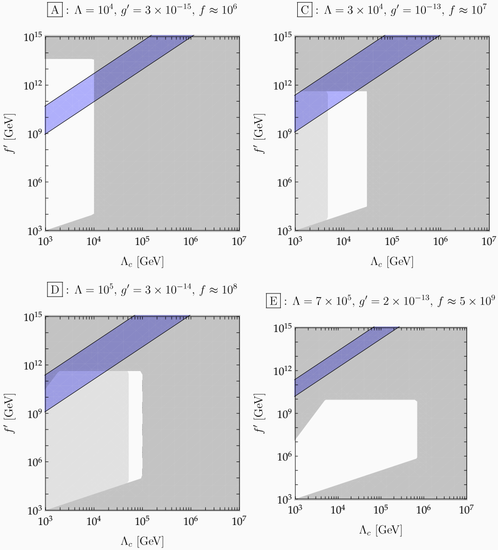

Bounds from BBN

- For $m_\phi \lesssim 1\,\mathrm{GeV}$ the relaxion decays after BBN.
- Light elements' abundance:

$$E < \mathcal{O}(\mathrm{MeV}) \quad \text{(energy injected per baryon)}$$

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- BBN abundances:

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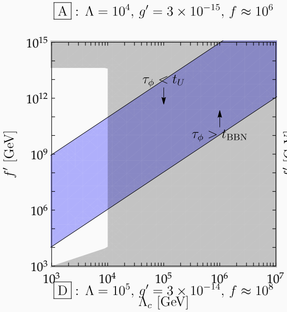
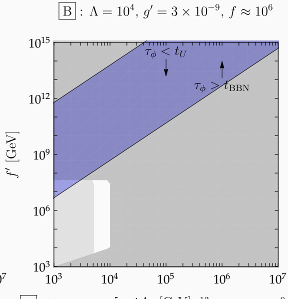
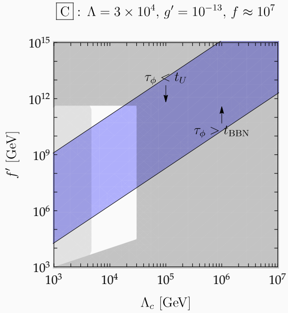
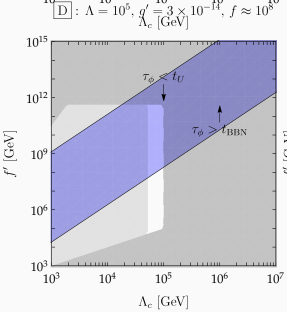
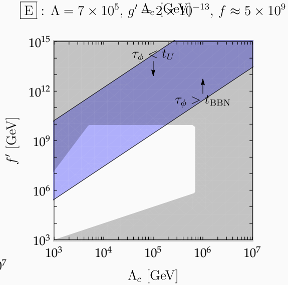










Work in progress

- Cosmology
  - Relic abundance
  - BBN, DM, ...
- Particle physics
  - Mass larger than in original model
  - Coupling to Z (not like the usual axion $a\gamma\gamma$)
- Correct treatment of the thermal effects

Conclusions

- Relaxion: a novel alternative way to save Naturalness
- This talk:
  - **Relaxion decoupled from inflation**
  - **Barriers independent of the Higgs vev**
  - **Automatic avoidance of super-Planckian field excursions**
  - **Cosmology further constraints the model**
- A new territory to explore!

BACKUP

Number of efolds

Slow roll: velocity controlled by H_I

- After N efolds

$$\Delta\phi \sim \dot{\phi}\frac{N}{H_I} \sim \frac{V'_\phi}{H_I^2}N \sim \frac{g\Lambda^3}{H_I^2}N$$

- Vacuum energy larger than V_ϕ

$$H_I > \frac{\Lambda^2}{m_{\mathsf{Pl}}}$$

The number of efolds is large:

$$N > \frac{\Lambda^2}{g^2 m_{\mathsf{Pl}}^2} \sim 10^{\mathsf{many}}$$

Moreover, $H_I < \Lambda_{\mathsf{QCD}}$ for the barriers to form.

Vector field

It is crucial that the relaxion does not couple to the photon $F_\gamma \widetilde{F}_\gamma$.

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + (\mathcal{D}_\mu H)^\dagger \mathcal{D}^\mu H - \frac{1}{2}\mathrm{Tr}[W_{\mu\nu}W^{\mu\nu}] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$
$$- \frac{\phi}{4f}\left(g_2^2 W^a_{\mu\nu}\widetilde{W}^{a\,\mu\nu} - g_1^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right) - V(\phi, H)$$

$$\longrightarrow -\frac{\phi}{f}\epsilon^{\mu\nu\rho\sigma}\Big(2g_2^2\partial_\mu W^-_\nu \partial_\rho W^+_\sigma + (g_2^2 - g_1^2)\partial_\mu Z_\nu \partial_\rho Z_\sigma$$
$$- 2g_1 g_2 \partial_\mu Z_\nu \partial_\rho A_\sigma\Big)$$

(Can be made consistent in a L-R symmetric model with a PQ symmetry)

Thermal effects on vector bosons

Gauge bosons thermalize after being produced

$$\omega^2 = k^2 + m_A^2 \mp \frac{k\dot{\phi}}{f} + \Pi_t[\omega, k]$$

where, in a hard thermal loop (*i.e.* high temperature) limit,

$$\Pi_t[\omega, k] = m_D^2 \frac{\omega}{k} \left(\frac{\omega}{k} + \frac{1}{2} \left(1 - \frac{\omega^2}{k^2} \right) \log \frac{\omega + k}{\omega - k} \right) .$$

Debye mass: $m_D^2 = g_{\mathsf{EW}}^2 T^2 / 6$

Thermal effects on vector bosons

For $\omega \ll k$

$$\Pi[\Omega, k] \approx \frac{\pi}{2}\frac{|\Omega|}{k}m_D^2$$

$\Omega = i\omega$ maximized for $k = 2\dot{\phi}/3f$:

$$\Omega_{\mathsf{max}} \approx \frac{8}{27\pi}\frac{\dot{\phi}^3}{f^3 m_D^2} = \frac{16}{9\pi g_{\mathsf{EW}}^2}\frac{\dot{\phi}^3}{T^2 f^3}$$

Timescale for the growth of A_μ:

$$\Delta t_{\mathsf{pp}} \sim \frac{9\pi g_{\mathsf{EW}}^2}{16}\frac{T^2 f^3}{\dot{\phi}^3} \sim \frac{\Lambda^2}{m_Z^2}m_Z^{-1}$$

whereas at zero temperature $\Delta t_{\mathsf{pp}} \sim m_Z^{-1}$.

Simplifying assumptions

$$\mathcal{L} \supset g\Lambda^3\phi - \frac{1}{2}(\Lambda^2 - g'\Lambda\phi)h^2 - \Lambda_c^{4-n}\langle h\rangle^n \cos\left(\frac{\phi}{f'}\right) + \frac{\phi}{4f}F\widetilde{F}$$

Six free parameters: $g, g', \Lambda, \Lambda_c, f, f'$. We assume

- $g = g'$
- $f = \Lambda^2/m_Z$

Conditions to make it work i

Conditions for particle production

1. Avoid slow roll
$$g' \gtrsim \frac{\Lambda}{m_{\mathsf{Pl}}}$$
2. Higgs tracks the minimum of the potential
$$g' \lesssim \left(\frac{v_{\mathsf{EW}}\sqrt{\lambda}}{\Lambda}\right)^3$$
3. Relaxion rolls over the barriers
$$\Lambda_c^2 \lesssim \dot{\phi} \sim \Lambda^2$$

Conditions to make it work ii

4. Barriers larger than the slope

$$\Lambda_c^4 \gtrsim g' \Lambda^3 f'$$

5. Higgs mass scanning $\Delta m_h^2 \lesssim v_{\mathsf{EW}}^2$

$$g' \lesssim \frac{m_h^2}{4\pi f' \Lambda}$$

6. Efficient slow-down

$$\Lambda_c^8 \gtrsim \frac{9\sqrt{2}\pi g_{\mathsf{EW}}^2}{128 g_*^{1/2}} \frac{g' \Lambda^{11}}{m_Z^3}$$

Conditions to make it work iii

7. Particle production faster than $\dot{m}_h/m_h^2$

$$\Lambda_c^4 \gtrsim \frac{9\sqrt{2}\pi g_{\mathsf{EW}}^2}{256 g_*^{1/2} m_h^2 m_Z^3} g' \Lambda^9$$

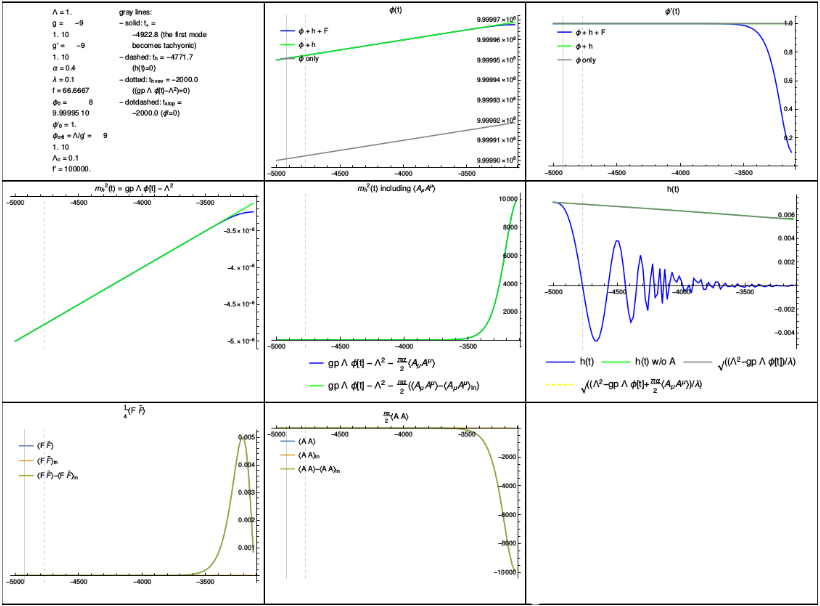
8. Condensation

$$\Lambda_c \lesssim f'$$

9. Combinations of the above

$$g' \lesssim \frac{128 g_*^{1/2}}{9\sqrt{2}\pi g_{\mathsf{EW}}^2} \frac{m_Z^3}{\Lambda^3} \qquad g' \lesssim \frac{256 g_*^{1/2} m_h^2 m_Z^3}{9\sqrt{2}\pi g_{\mathsf{EW}}^2 \Lambda^5}$$

Numerics


Λ = 1.
g = −9
1. 10
g' = −9
1. 10
α = 0.4
λ = 0.1
f = 66.6667
ϕ₀ = 8
9.99995 10
ϕ'₀ = 1.
ϕcrit = Λ/g' = 9
1. 10
Λc = 0.1
f' = 100000.
gray lines:
– solid: t* = −4922.8 (the first mode becomes tachyonic)
– dashed: th = −4771.7 (h(t)=0)
– dotted: thvev = −2000.0 ((gp Λ ϕ[t]−Λ²)=0)
– dotdashed: tstop = −2000.0 (ϕ'=0)
ϕ(t)
ϕ + h + F
ϕ + h
ϕ only
ϕ'(t)
mh²(t) = gp Λ ϕ[t] − Λ²
mh²(t) including ⟨AμA^μ⟩
gp Λ ϕ[t] − Λ² − πα/2 ⟨AμA^μ⟩
gp Λ ϕ[t] − Λ² − πα/2 (⟨AμA^μ⟩−⟨AμA^μ⟩in)
h(t)
h(t)
h(t) w/o A
√((Λ²−gp Λ ϕ[t])/λ)
√((Λ²−gp Λ ϕ[t]+ πα/2 ⟨AμA^μ⟩)/λ)
1/4 ⟨F F̃⟩
⟨F F̃⟩
⟨F F̃⟩in
⟨F F̃⟩−⟨F F̃⟩in
πα/2 ⟨A A⟩
⟨A A⟩
⟨A A⟩in
⟨A A⟩−⟨A A⟩in

Numerics 2