Higgs, Relaxion, and Dark Matter

(particle production, relaxation during/after inflation, relaxion as DM…)

Nayara Fonseca

DESY

borrowing from work with:

- **Morgante & Servant** (1805.04543)
- **Morgante** (1809.04534)

LBNL, Berkeley – 17 October 2018

Outline

Part 1: Higgs Relaxation after inflation

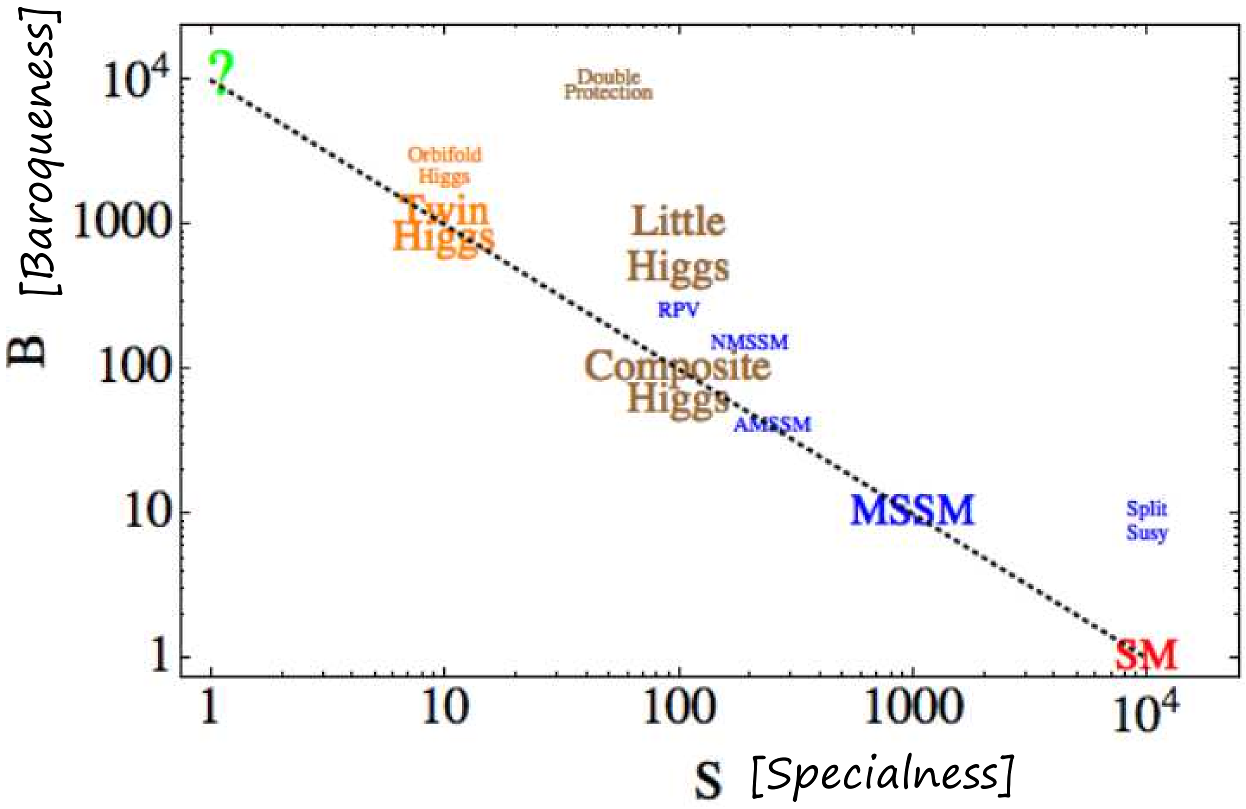
NF, Morgante & Servant (1805.04543)

Part 2: Relaxion as a DM candidate

NF & Morgante (1809.04534)

Minimum BS conjecture

Falkowski; '15
(http://resonaances.blogspot.com/)



For all models $\Lambda = 10^4$ GeV

$B_{SM} = 1$
$S_{SM} \sim (\Lambda/m_Z)^2 \sim 10^4$

Naturalness: $S \leq 10$, then B ↗

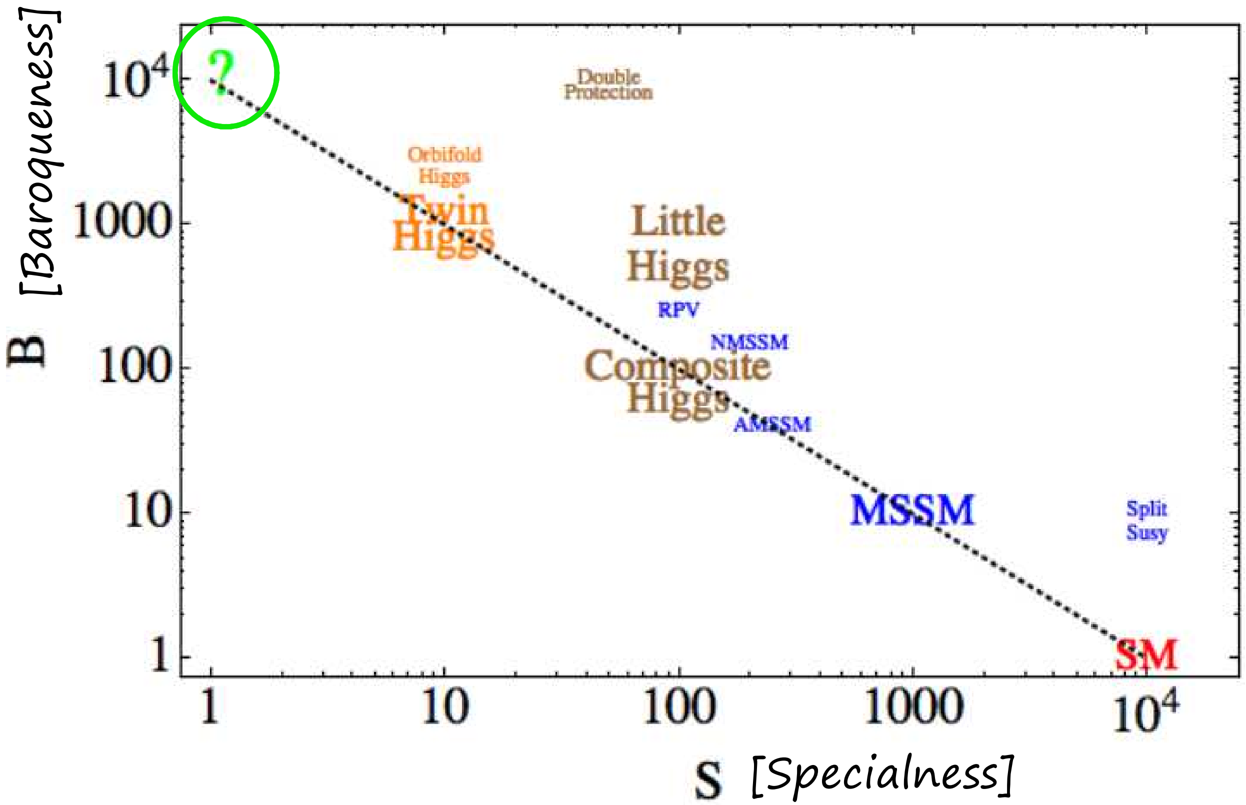
Conjecture

$BS \gtrsim 10^4$

- **B**: how complicated is the model relative to the SM;
- **S**: the fine-tuning needed to achieve EWSB with the observed Higgs boson mass.

Minimum BS conjecture

Falkowski; '15
(http://resonaances.blogspot.com/)



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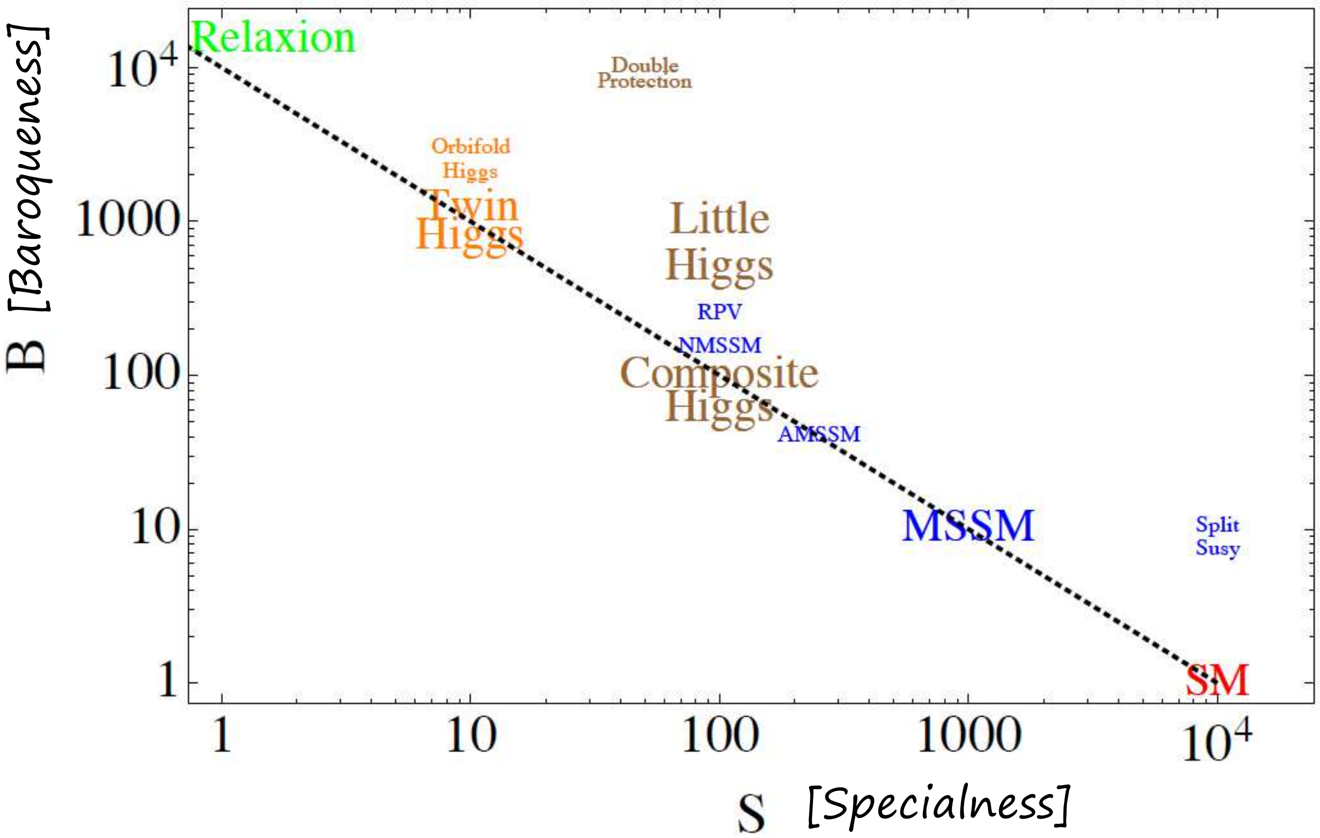
$BS \gtrsim 10^4$

Prediction: the existence of a complicated ($B=10^4$) yet to be discovered model with no fine-tuning.

Minimum BS conjecture



Falkowski; Swieca School; Sao Paulo ’17

Conjecture

$BS \gtrsim 10^4$

Prediction: the existence of a complicated ($B=10^4$) yet to be discovered model with no fine-tuning.

- The Relaxion Idea (Graham-Kaplan-Rajendran; 1504.07551 [hep-ph]) *inspired by Abbott's attempt to solve the CC problem, '85*

SM hierarchy problem: Relaxation mechanism of the EW scale

Warming up…

$$V(h,\phi) = \frac{1}{2} m_H^2(\phi) h^2 + \cdots = \frac{1}{2}(-\Lambda^2 + g\Lambda\phi) h^2 + \cdots$$

- ϕ scans $m_H^2(\phi)$ during the cosmological evolution;
- Arrange a mechanism so that ϕ stops where we want, precisely at the EW scale:

$$m_H^2(\phi_c) = -\Lambda^2 + g\Lambda\phi_c \ll \Lambda^2$$

○ The Relaxion Idea (Graham-Kaplan-Rajendran; 1504.07551 [hep-ph]) *inspired by Abbott's attempt to solve the CC problem, '85*

SM hierarchy problem: Relaxation mechanism of the EW scale

Warming up…

high scale

the new field

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small coupling

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small coupling

- ϕ scans $m_H^2(\phi)$ during the cosmological evolution;
- Arrange a mechanism so that ϕ stops where we want, precisely at the EW scale:
    - Originally, backreaction from Higgs-dependent potential

$$\sim \Lambda_b^4(\langle H \rangle)\cos\phi/f'$$

- The Relaxion Idea (Graham-Kaplan-Rajendran; 1504.07551 [hep-ph]) *inspired by Abbott's attempt to solve the CC problem, '85*

SM hierarchy problem: Relaxation mechanism of the EW scale

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high scale | the new field

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small coupling

- ϕ scans $m_H^2(\phi)$ during the cosmological evolution;
- Arrange a mechanism so that ϕ stops where we want, precisely at the EW scale:
  - $\Lambda \lesssim 10^8$ GeV, UV completions... eg.:

SUSY: Batell, Giudice, McCullough '15
Evans, Gherghetta, Nagata, Thomas '16

WED: NF, von Harling, Lima, Machado '17

Relaxation happens during inflation…

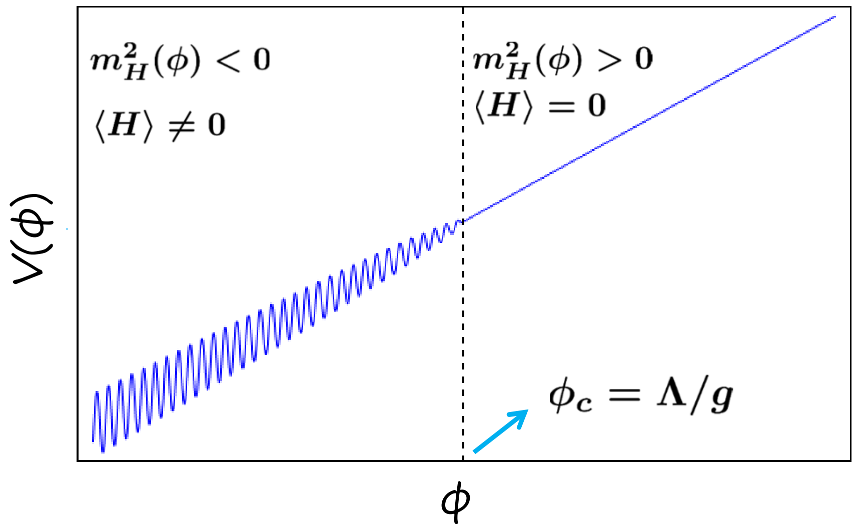
- Dissipation mechanism: Hubble friction during inflation

○ <u>Inflation sector:</u> largely unspecified, but we need:

- Low inflation scale
- Super-Planckian field excursions
- Large number of e-folds

ϕ does not overshoot the barriers…

Relaxation happens during a long period of inflation.



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  - **Low inflation scale**
  - **Super-Planckian field excursions**
  - **Large number of e-folds**

aesthetic or/and theoretical problems:
WGC ? Fine-tuning inflation sector ? Semi-classical description of inflation ?…

Relaxation happens during inflation…

- Dissipation mechanism: Hubble friction during inflation

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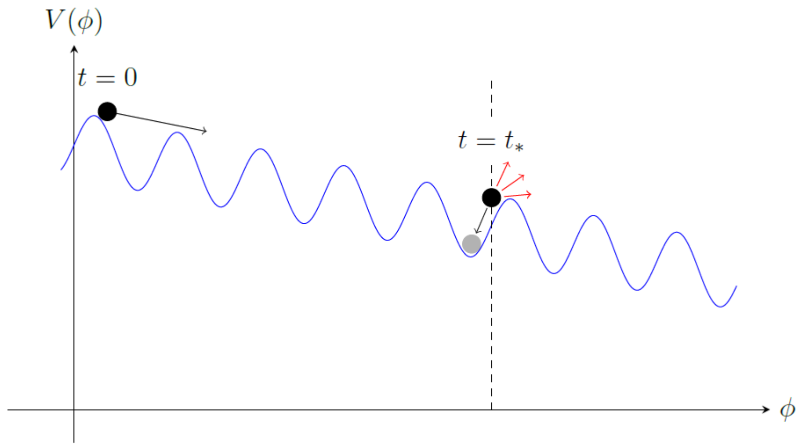
Alternative to Inflation: Particle production

Hook, Marques-Tavares ‘16



Particle production

Alternatives to Inflation

Anber-Sorbo '09

Dissipation from particle production friction (SM vectors)

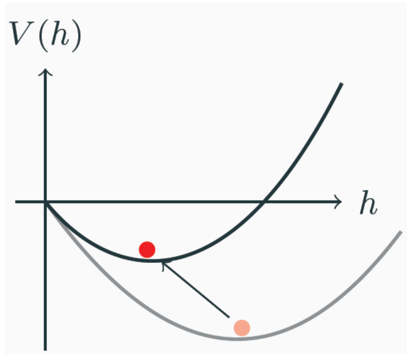
Hook, Marques-Tavares '16

SM massive V_μ

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}\partial_\mu h\partial^\mu h - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\phi}{4f}V_{\mu\nu}\widetilde{V}^{\mu\nu} + \frac{g_V^2}{2}V_\mu V^\mu h^2 - \mathcal{V}(\phi, h)$$

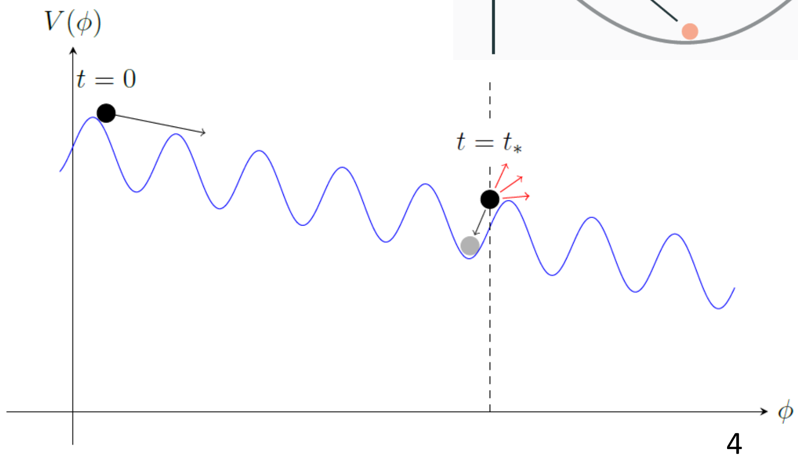
$$\mathcal{V} \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 - g\Lambda^3\phi + \frac{\lambda}{4}h^4 + \Lambda_b^4\cos\left(\frac{\phi}{f'}\right)$$

$m_h^2 < 0$



- the evolution starts in the broken phase, i.e. the vev is large: $\Phi_{ini} < \Lambda/g$.
- the relaxion is coupled to a massive SM vector field*;

$$-\frac{\phi}{4f}\left(g_2^2 W^a_{\mu\nu}\widetilde{W}^{a\,\mu\nu} - g_1^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right)$$



* see also Craig, Hook, Kasko '18

Alternatives to Inflation

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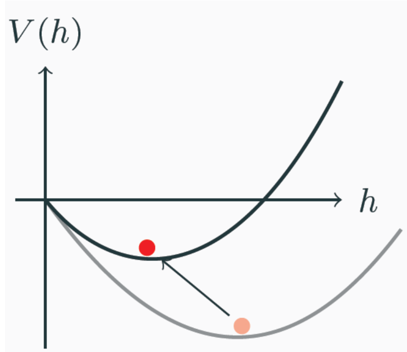
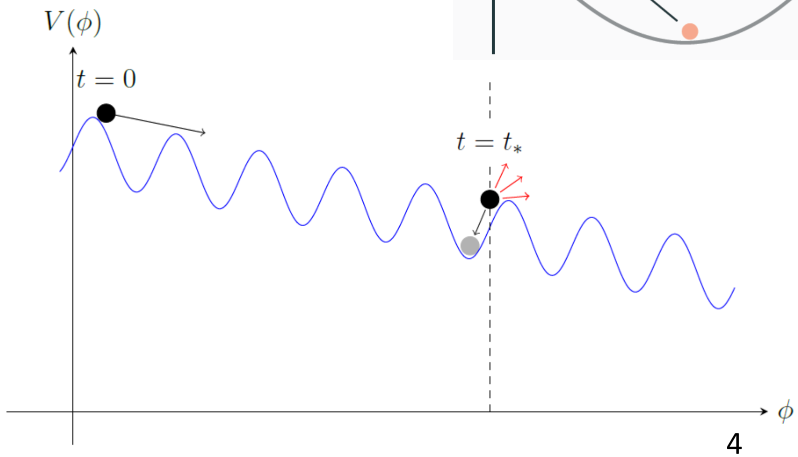


- the evolution starts in the broken phase, i.e. the vev is large: $\phi_{ini} < \Lambda/g$.
- the relaxion is coupled to a massive SM vector field;
- constant barriers, ϕ has enough $\dot{\phi}^2$ to jump Λ_b^4
- $-g\Lambda^3\phi$ makes the relaxion roll to larger values, decreasing the Higgs vev



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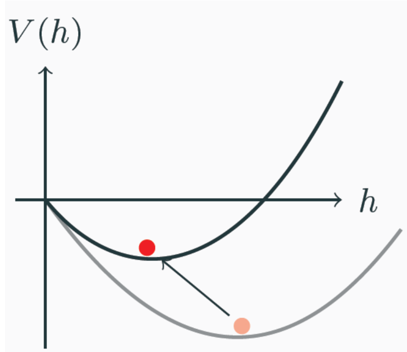
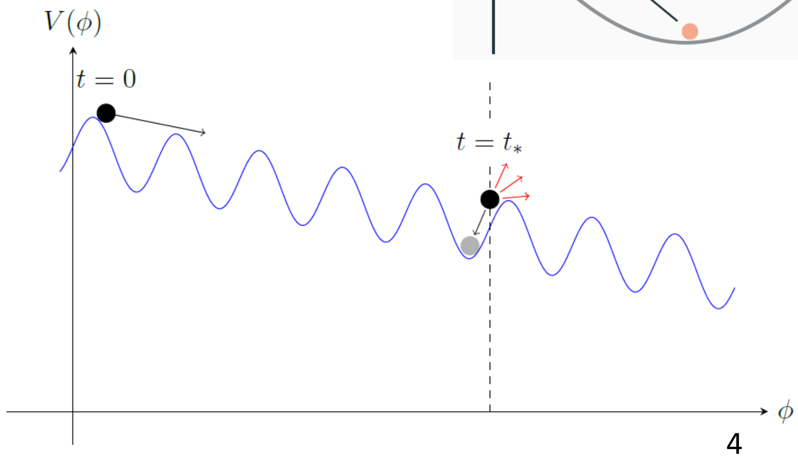


- Higgs vev is sufficiently small ↔ V_μ experiences a tachyonic instability

$$\ddot{V}_\pm + (k^2 + m_V^2 \mp k\frac{\dot{\phi}}{f})V_\pm = 0 \qquad m_V^2 = g_V^2 h^2$$

- When V_+ grows exponentially, the $V\tilde{V}$ term slows down the field ϕ



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

$$\langle V\widetilde{V}\rangle = \frac{1}{4\pi^2}\int_0^\Lambda dk\, k^3 \frac{d}{dt}(|V_+|^2 - |V_-|^2)$$

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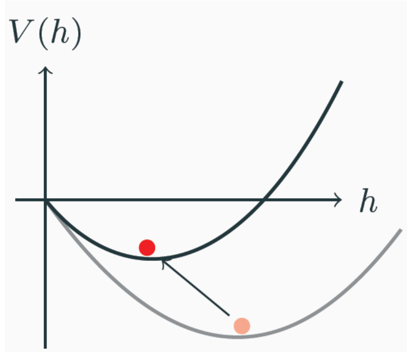

- Higgs vev is sufficiently small ↔ Vμ experiences a tachyonic instability

$(\omega_k)^2 < 0$ $\quad |\dot{\phi}| \gtrsim 2m_V f$

$$\ddot{V}_\pm + (k^2 + m_V^2 \mp k\frac{\dot{\phi}}{f})V_\pm = 0 \qquad m_V^2 = g_V^2 h^2$$

- When V_+ grows exponentially, the $V\widetilde{V}$ term slows down the field ϕ

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

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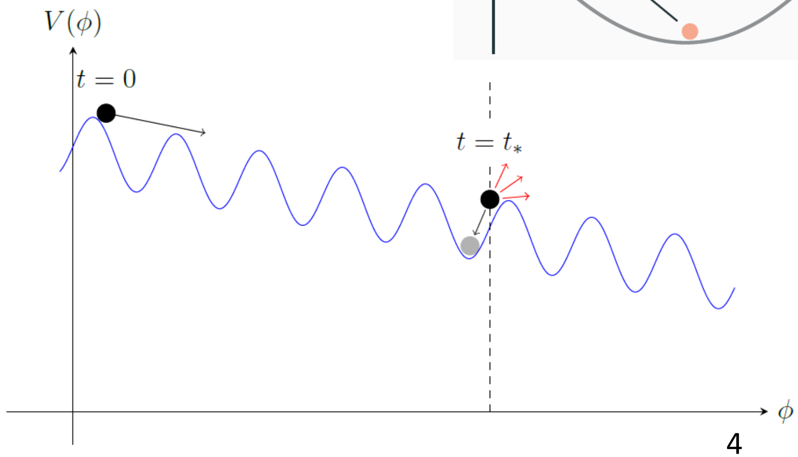


Higgs Relaxation after inflation

NF, E. Morgante, G. Servant (1805.04543)

I. **Relaxion-Higgs Cosmological Evolution after inflation**

II. **Relaxion properties**

III. **Parameter space**

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

I. Relaxion-Higgs Cosmological Evolution after inflation: Two distinct assumptions about the first reheating phase

A. High Temperature

Inflation

⇩

SM particles

⇩

radiation era

⇩

$T \sim \Lambda$: $V(\phi)$ is generated

Make sure we are not scanning the Higgs thermal mass

B. Low Temperature

Inflation

⇩

Most of its energy is transferred to a hidden sector

⇩

such that $T \ll v_{EW}$

⇩

$H \sim \Lambda^2/M_{Pl}$: $V(\phi)$ is generated

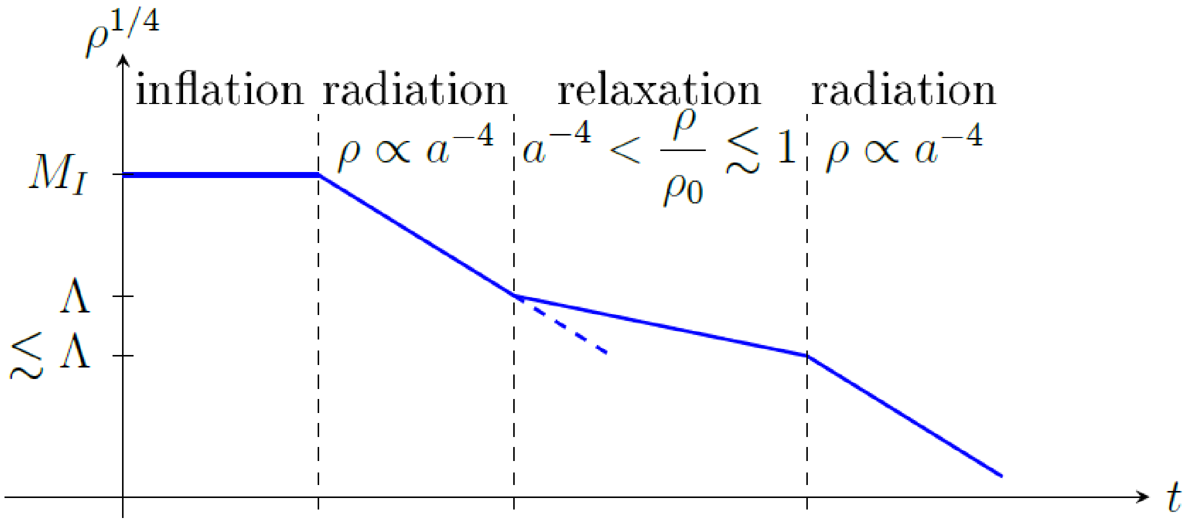
pp role:

- stops the relaxion
- reheats the visible universe

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

A. High Temperature

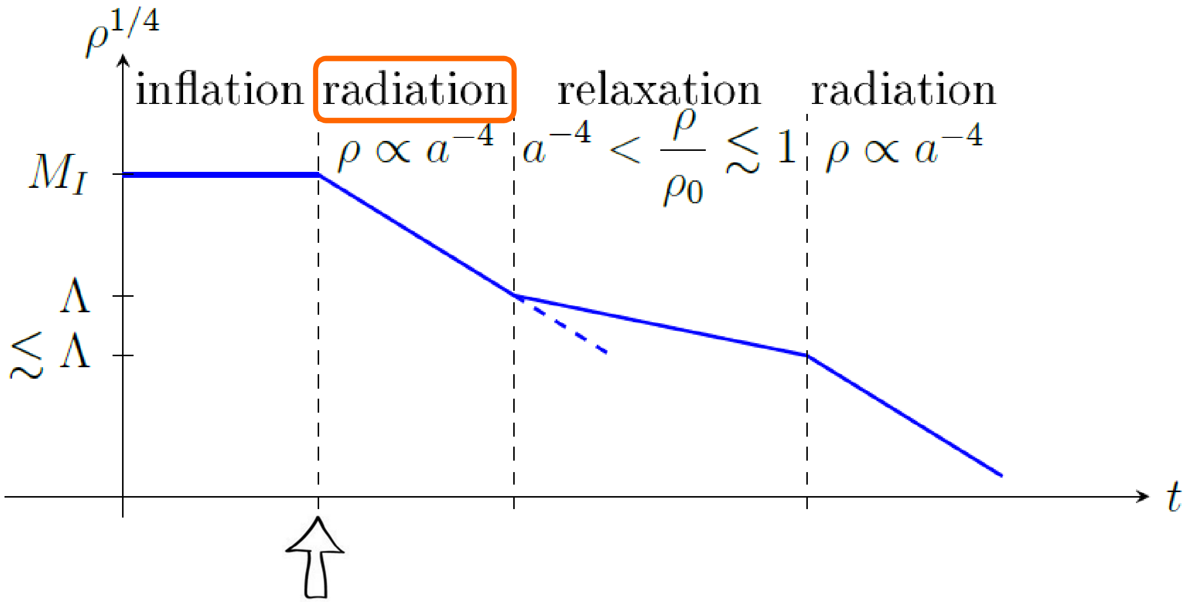


Sketch of the energy density evolution (ρ_0 is the energy density when the relaxation stars).

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

A. High Temperature

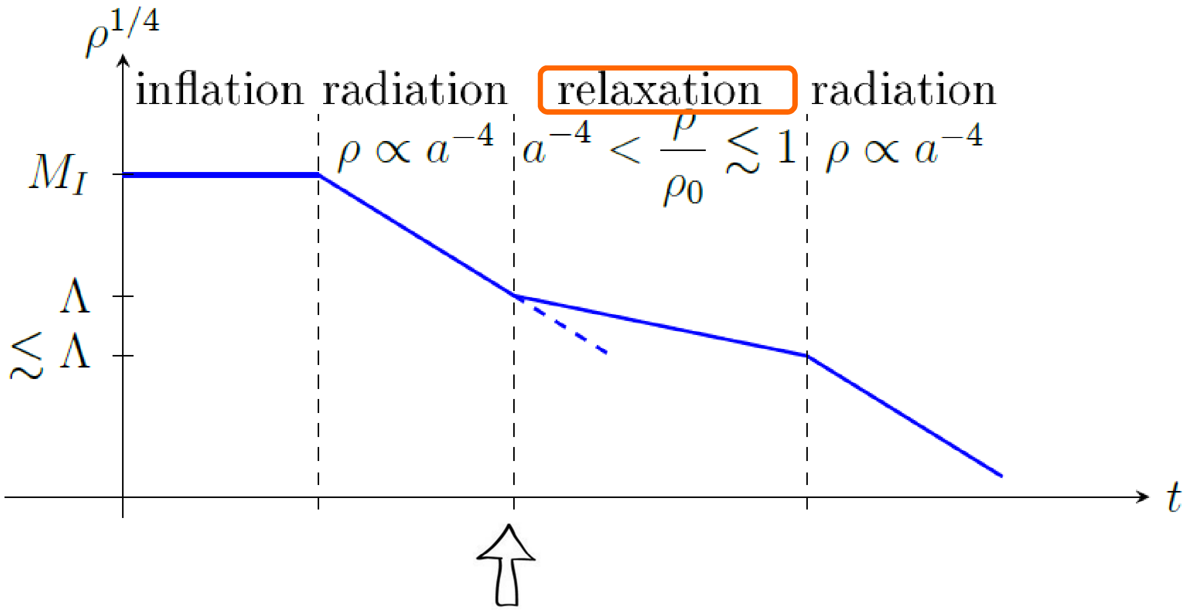


- **End of inflation: energy stored in the inflation is transferred to light particles**
- Radiation era starts

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

A. High Temperature



- **When H ~ Λ^2/M_{Pl} : V(ϕ) is generated**
- Scanning starts

Higgs Relaxation after inflation

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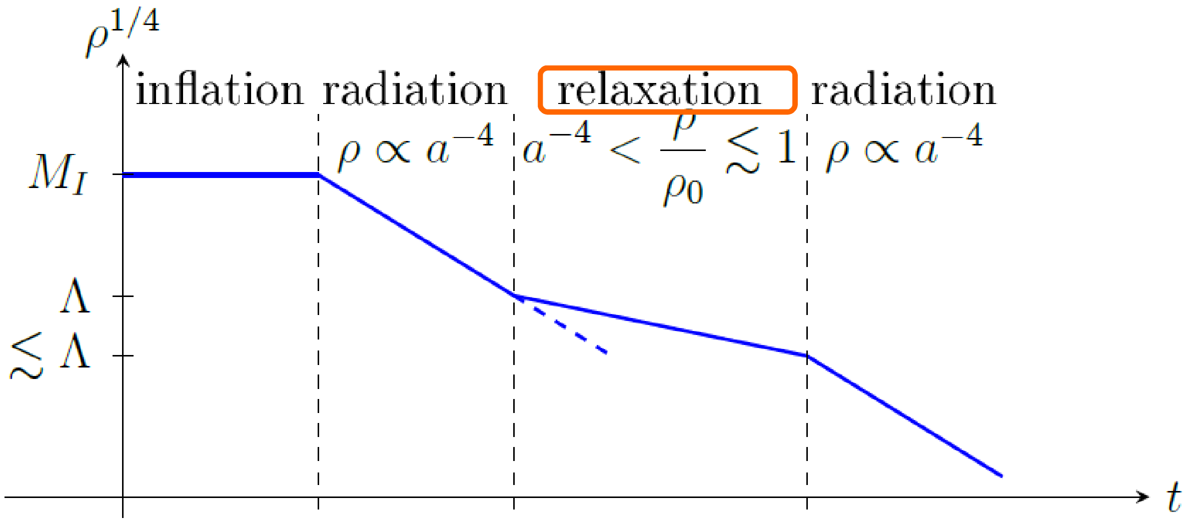
A. High Temperature



- **relaxion cannot generate a new period of inflation**
  (this would wash out the amplitude of perturbations produced during the inflationary era)

- $N_e \lesssim O(20)$

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant ‘18

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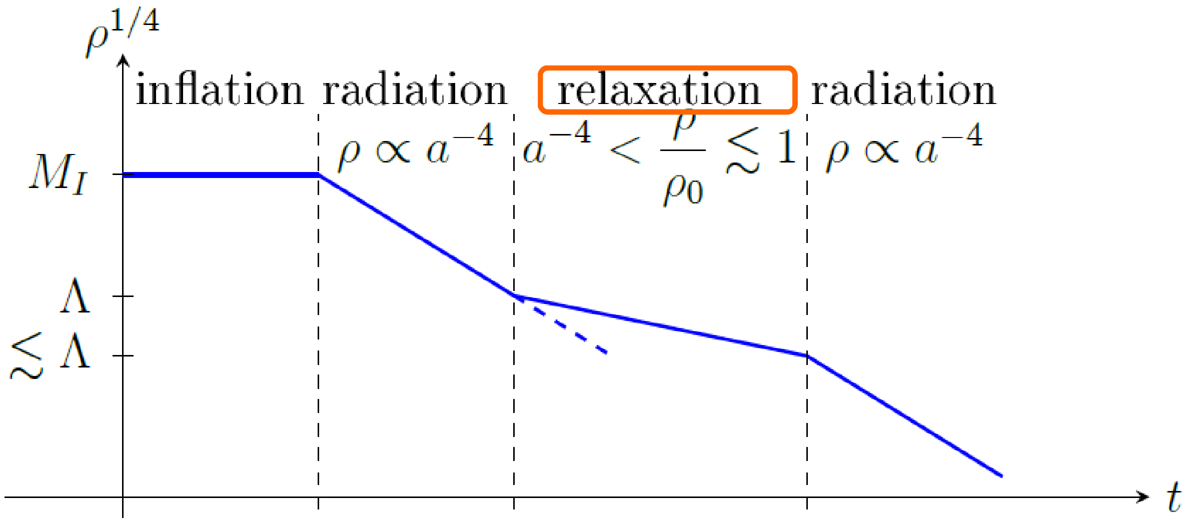

- ***relaxion cannot generate a new period of inflation***

  (this would wash out the amplitude of perturbations produced during the inflationary era)

- $N_e \lesssim O(20)$ ⇨ $g \gtrsim \frac{\Lambda}{20\sqrt{3}M_{\rm Pl}}$ $\quad V \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 + \cdots$

  Automatically avoids very large field excursions $\Delta\phi \sim \frac{\Lambda}{g}$

Higgs Relaxation after inflation

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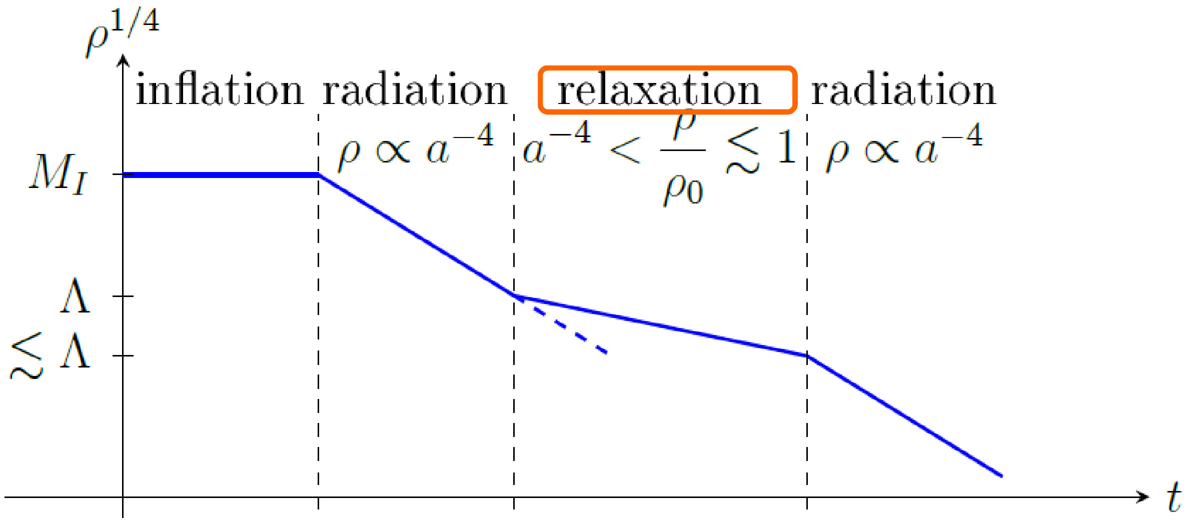
A. High Temperature



- **Reminder:**

In the minimal approach, the relaxion cannot be the inflaton as the linear slope does not generate the observed curvature perturbation amplitude (COBE normalization)

e.g.:Tangarife, Tobioka, Ubaldi, Volansky; arXiv:1706.03072

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

I. Relaxion-Higgs Cosmological Evolution after inflation

A. High Temperature ⇨ Make sure we are not scanning the Higgs thermal mass

$$V \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi + yT^2\right) h^2 + \cdots$$

This could spoil the relaxation mechanism: ϕ would stop in the wrong position

$$m_h^2 + yT^2 = 0$$

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$T_{end} \ll v_{EW}$

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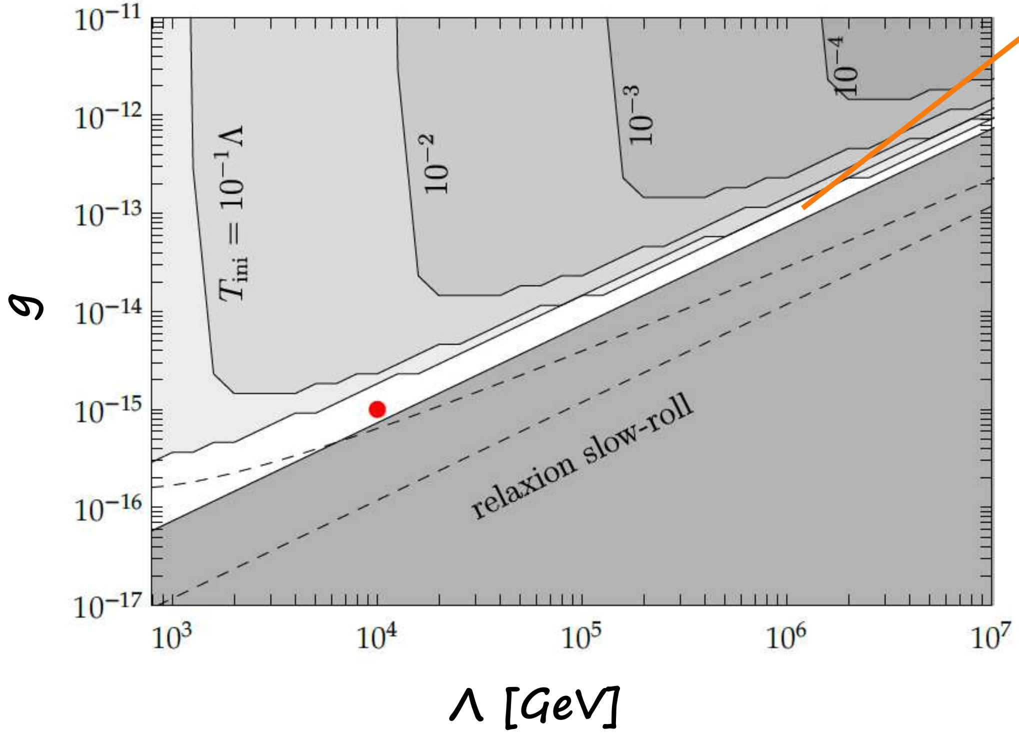

Allowed region without assuming transfer of energy to a hidden sector

Higgs Relaxation after inflation

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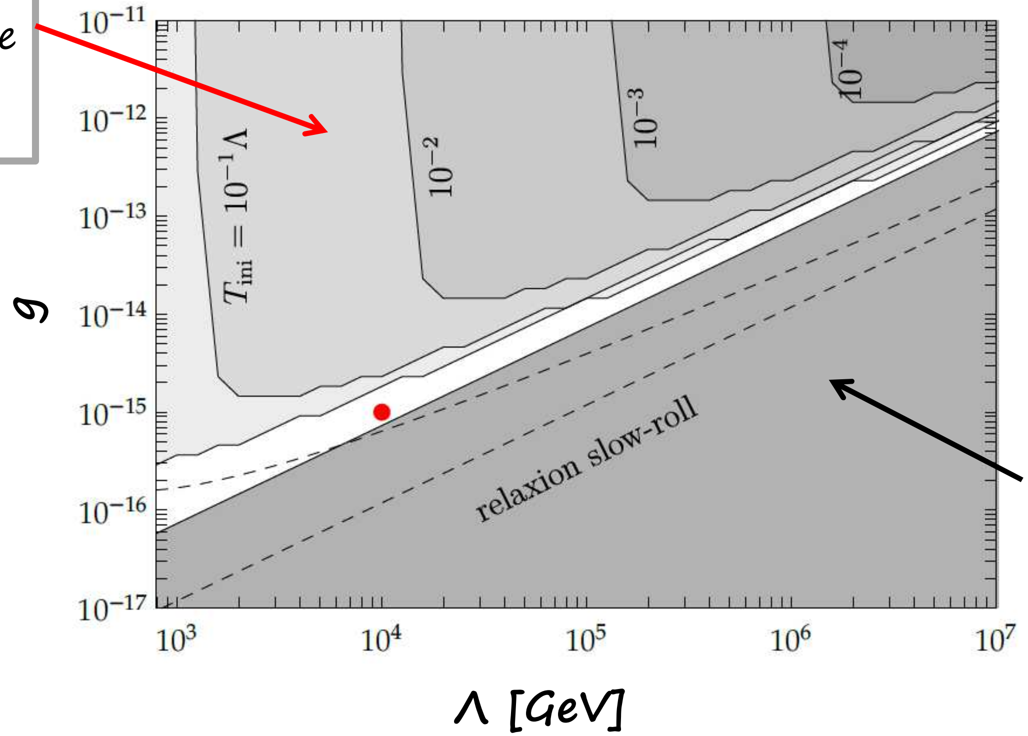
A. High Temperature

The parameter space opens up if the initial temperature is assumed to be a fraction of the cutoff: $T_{ini} \sim a\,\Lambda$



relaxion cannot generate a new period of inflation

$$g \gtrsim \frac{\Lambda}{20\sqrt{3}M_{\rm Pl}}$$

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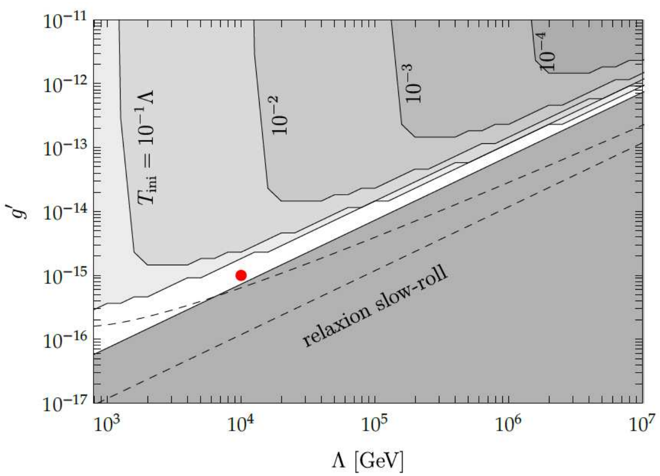
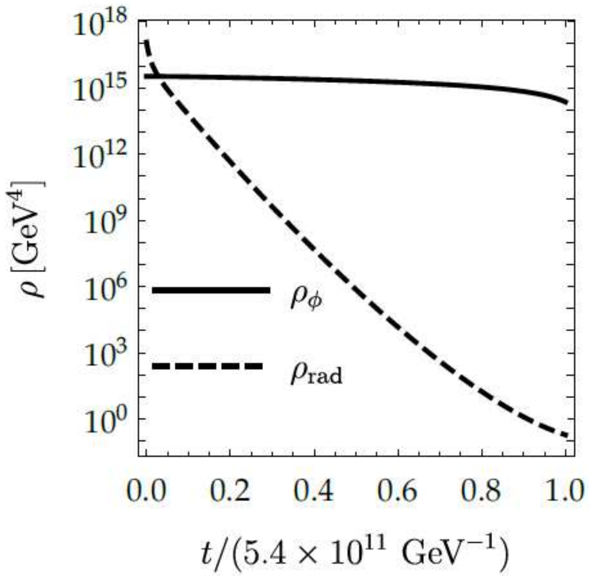
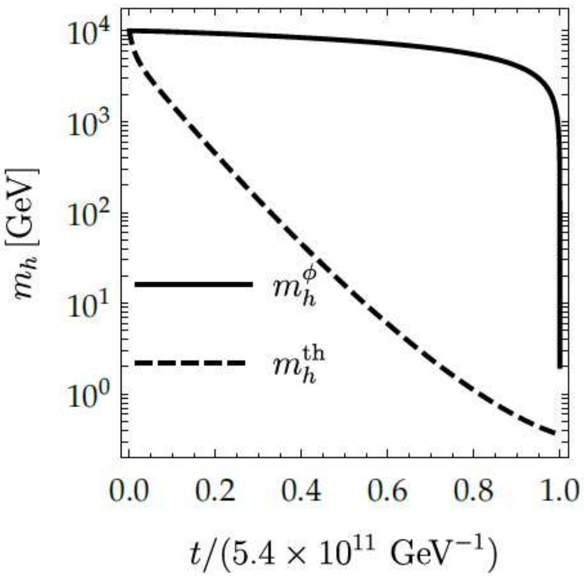
A. High Temperature

• $\Lambda = 10^4$ GeV; $g = 10^{-15}$







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Inflation

⇩

SM particles

⇩

radiation era

⇩

$T \lesssim \Lambda$: $V(\phi)$ is generated

Make sure we are not scanning the Higgs thermal mass

B. Low Temperature

Inflation

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Most of its energy is transferred to a hidden sector

⇩

such that $T \ll v_{EW}$

⇩

$H \sim \Lambda^2/M_{Pl}$: $V(\phi)$ is generated

pp role:

- stops the relaxion
- reheats the visible universe

Higgs Relaxation after inflation

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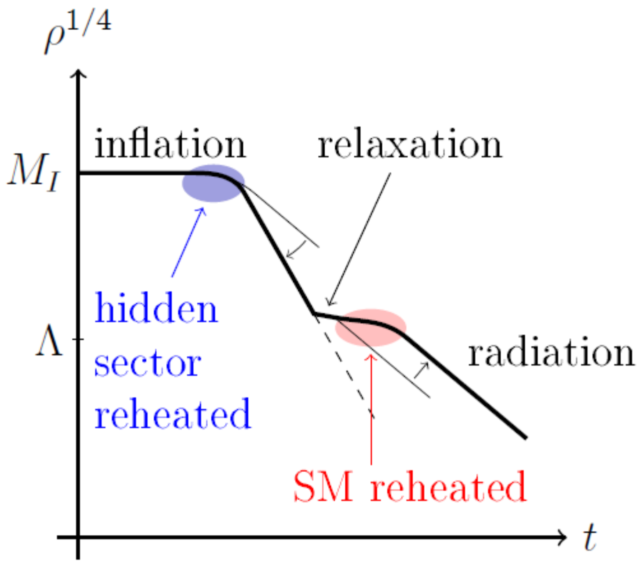

Eg.: period of **kinetic energy domination** in the dark sector or a prolonged reheating phase with a **matter-like** equation of state

- Or…. hidden sector decays into the SM model after the reheating phase and before the BBN epoch

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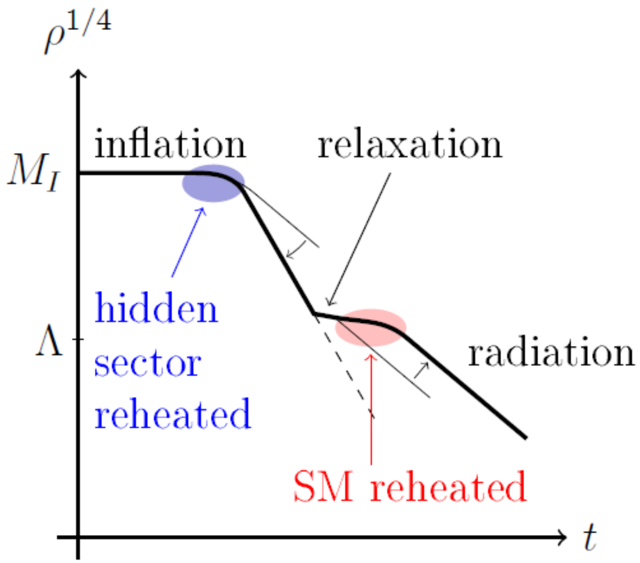

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NF, E. Morgante, G. Servant (1805.04543)

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II. **Relaxion properties**

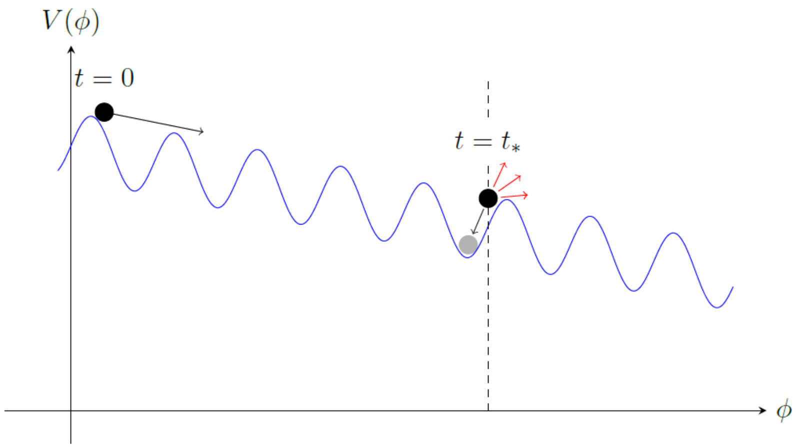
III. **Parameter space**

Higgs Relaxation after inflation

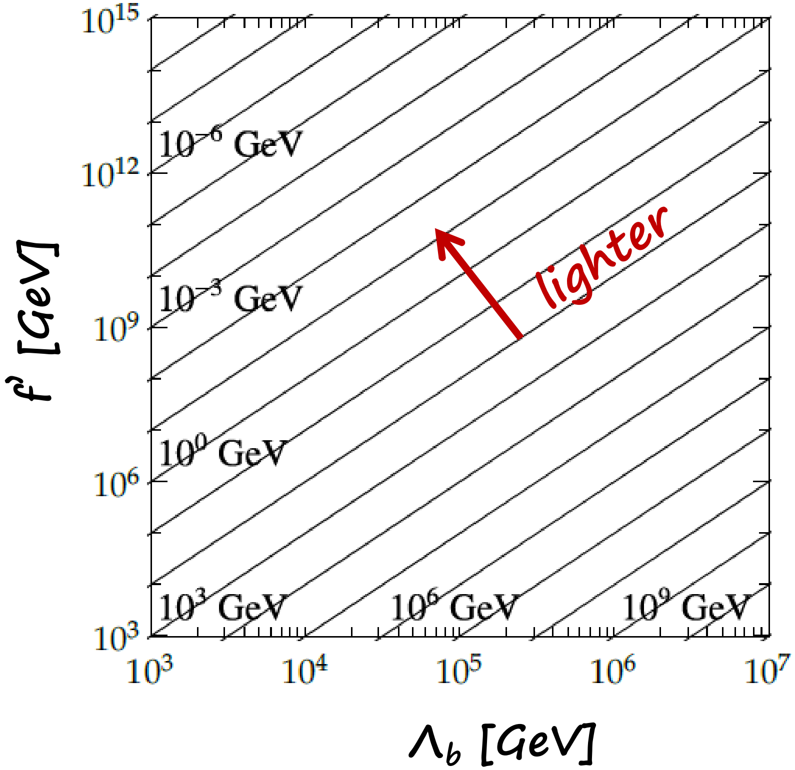
NF, E. Morgante, G. Servant '18

II. Relaxion properties: Relaxion mass

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



Contour plot for m_ϕ



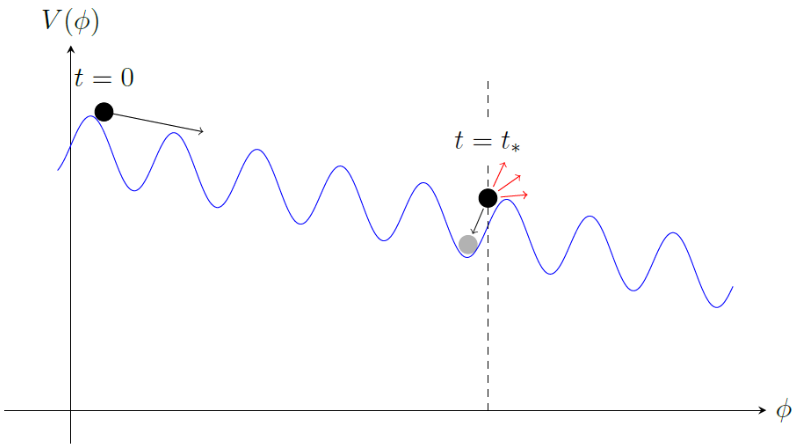
Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

For pp to work (depending on the benchmark): O(10) eV – O (100) TeV

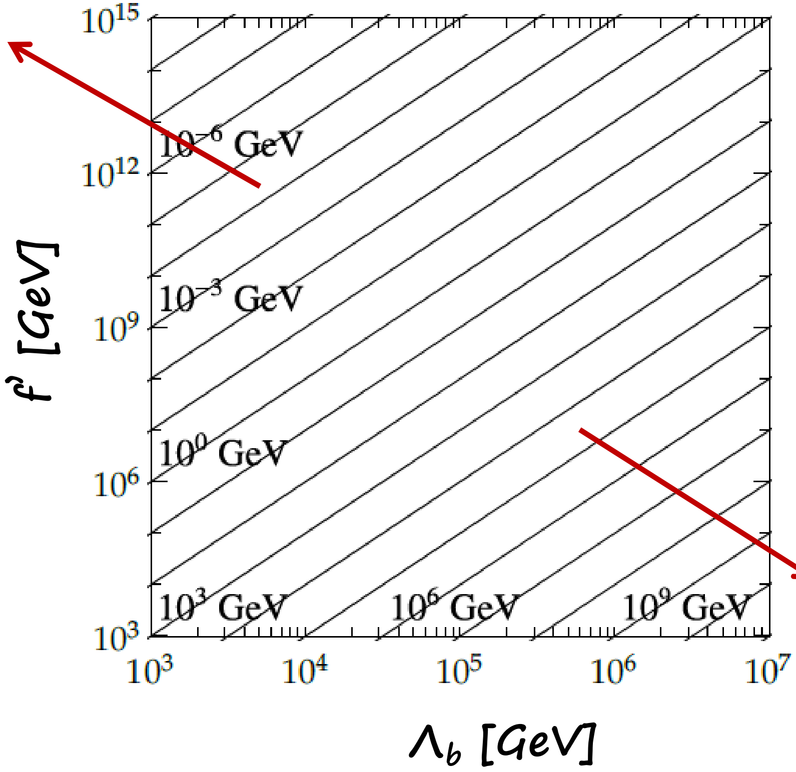
II. Relaxion properties: Relaxion mass

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



Very light: Astro constrained

Contour plot for m_ϕ



Very heavy: γ-coupling constrained

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

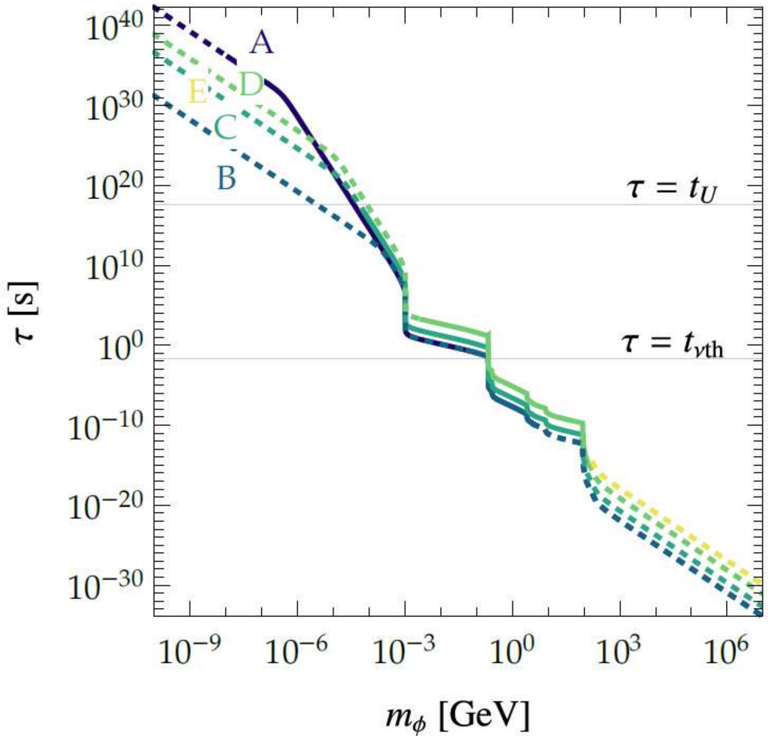
II. Relaxion properties: Relaxion lifetime

Relaxion decays:

- $m_\phi < m_Z$: Higgs mixing, loop induced (fermions and photons)
- $m_\phi > m_Z$: $\phi \tilde{V} V$

Benchmarks

scenario A:	$\Lambda = 10^4\,\text{GeV},$	$g' = 3 \times 10^{-15}$
scenario B:	$\Lambda = 10^4\,\text{GeV},$	$g' = 10^{-9}$
scenario C:	$\Lambda = 2 \times 10^4\,\text{GeV},$	$g' = 10^{-12}$
scenario D:	$\Lambda = 5 \times 10^4\,\text{GeV},$	$g' = 3 \times 10^{-14}$
scenario E:	$\Lambda = 10^5\,\text{GeV},$	$g' = 3 \times 10^{-14}$



Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

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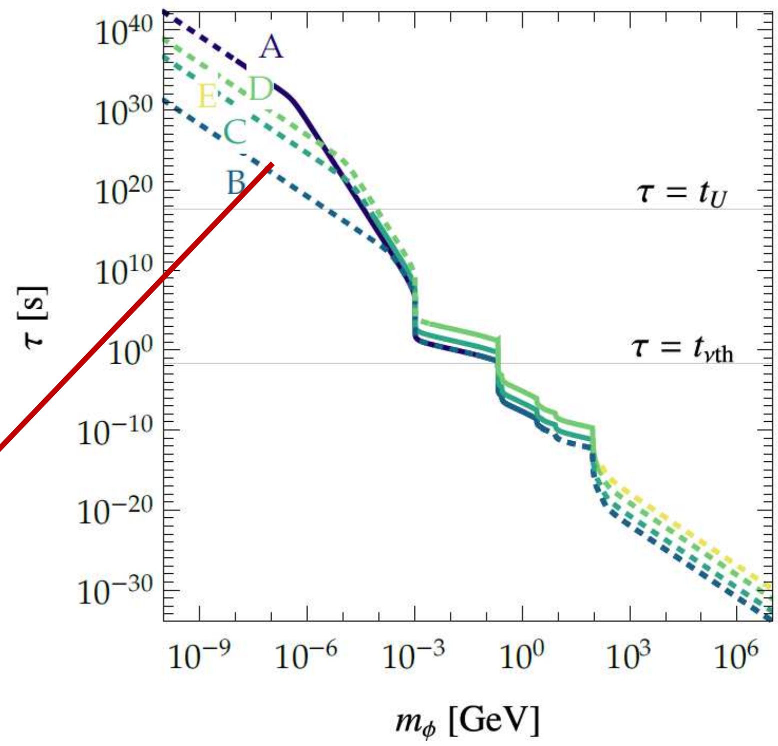


Long lived: overabundant

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant (1805.04543)

I. Relaxion-Higgs Cosmological Evolution after inflation

II. Relaxion properties

III. Parameter space

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

III. Parameter space

❖ **Requirements for relaxation through particle production**

- Relaxion does not generate a new period of inflation ✓
- Higgs field is efficiently tracking the minimum of V(h) Hook, Marques-Tavares '16
- **Photon coupling $\phi\tilde{\gamma}\gamma$ should be suppressed** Craig, Hook, Kasko '18
  see also Bauer, Neubert, Thamm '17

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

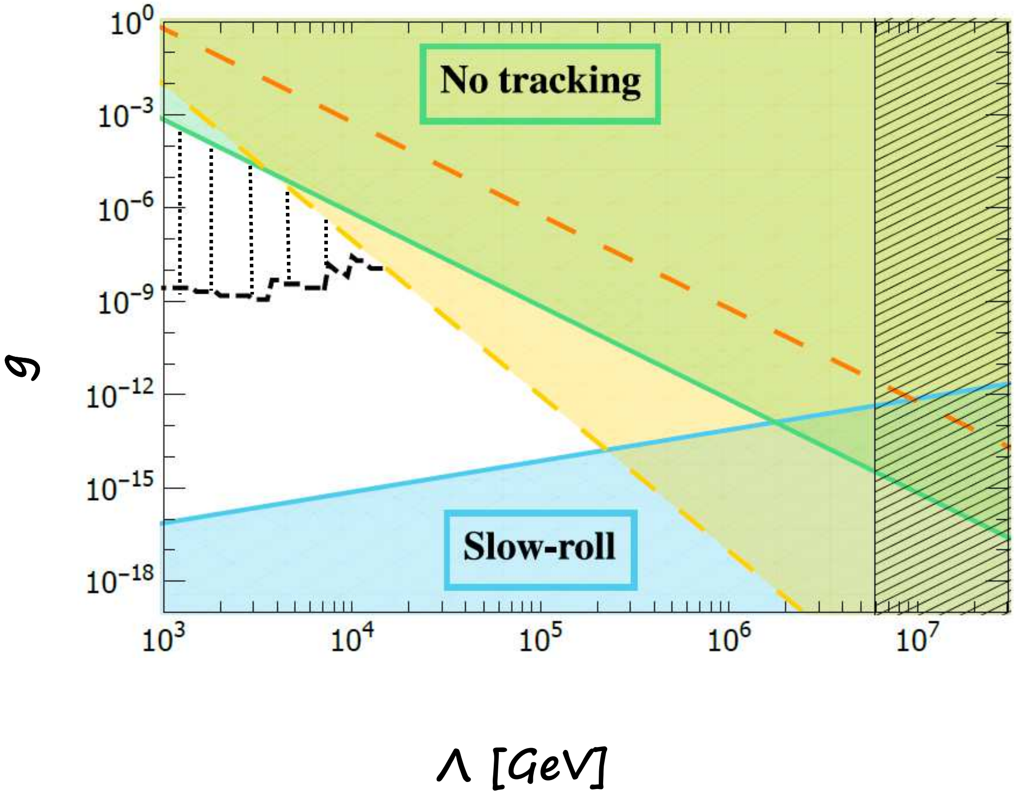
III. Parameter space

- **Requirements for relaxation through particle production**
  - Relaxion does not generate a new period of inflation ✓
  - Higgs field is efficiently tracking the minimum of V(h)
  - Photon coupling $\phi\tilde{\gamma}\gamma$ should be suppressed
  - Tachyonic growth should start only when $h \sim v_{EW}$
  - Barriers high enough to stop the rolling
  - Scanning precision
  - Time scale for particle production (massive V_μ) is fast (compared to H^{-1})
  - ...

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

III. Parameter space



$\Lambda, g, \Lambda_b, f'$

$$V \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 - g\Lambda^3\phi + \frac{\lambda}{4}h^4 + \Lambda_b^4\cos\left(\frac{\phi}{f'}\right)$$

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

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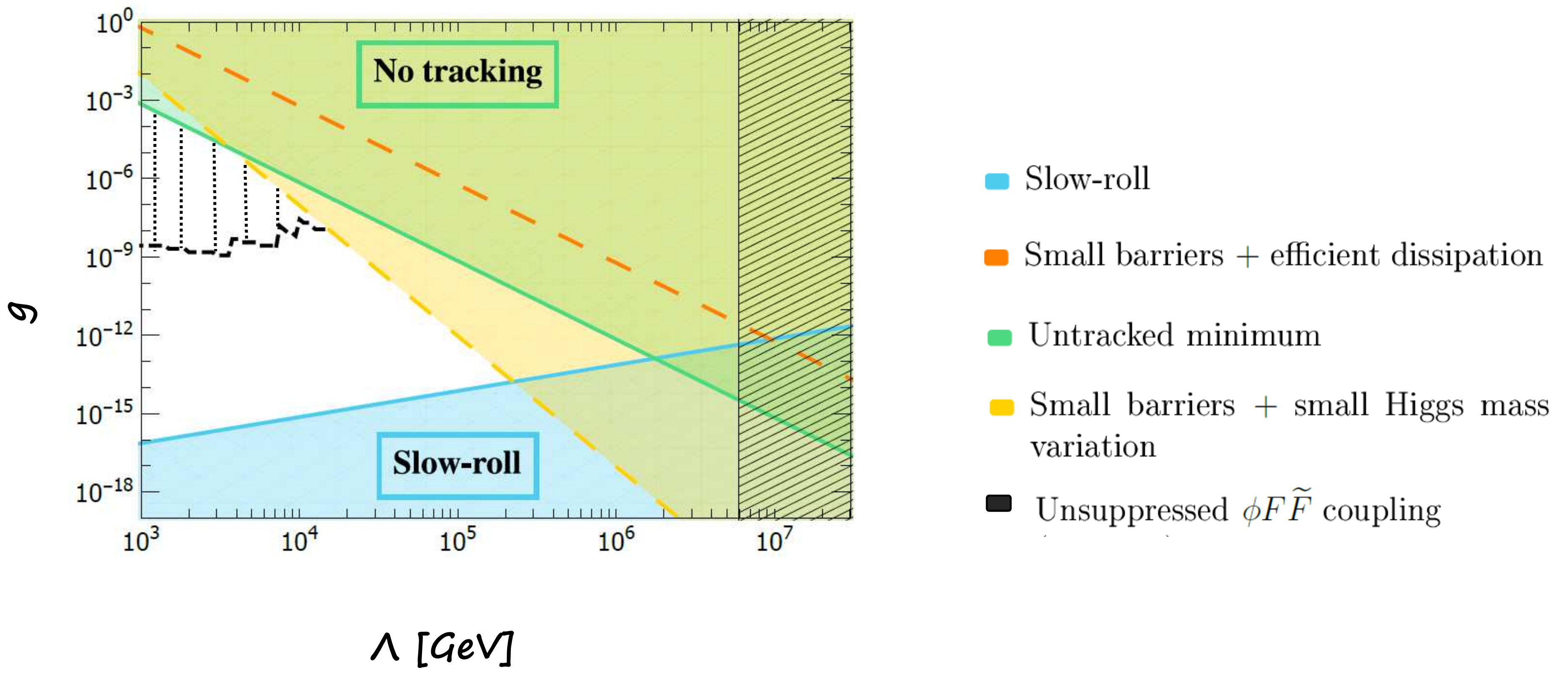

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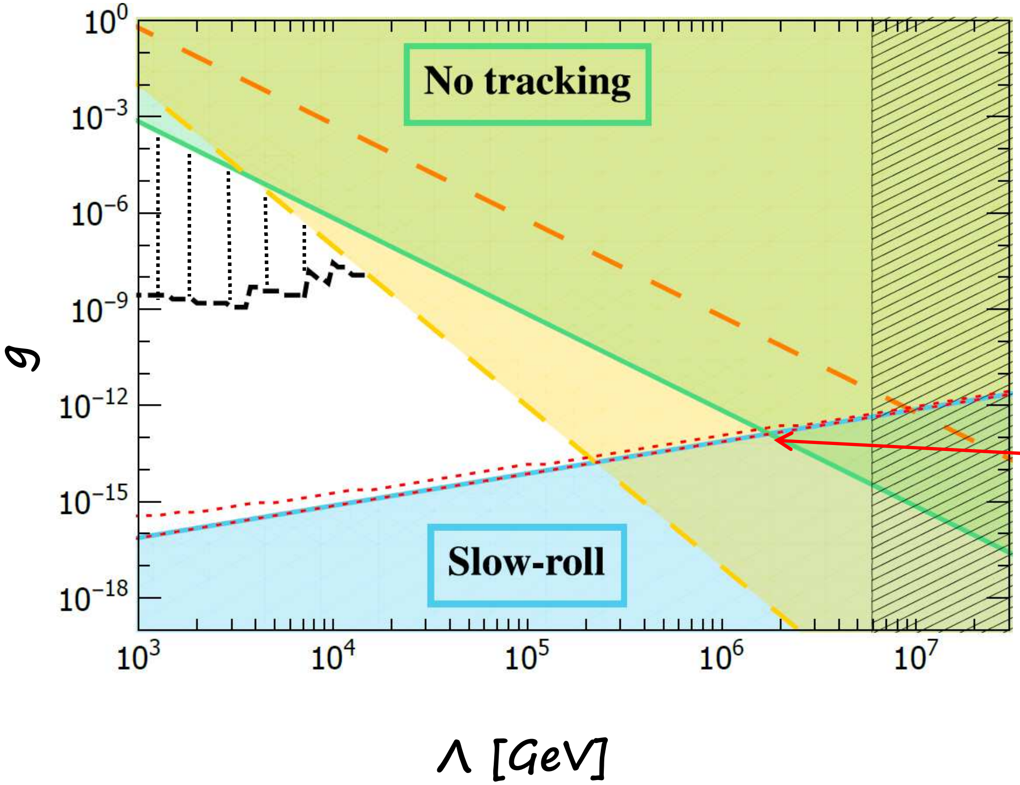

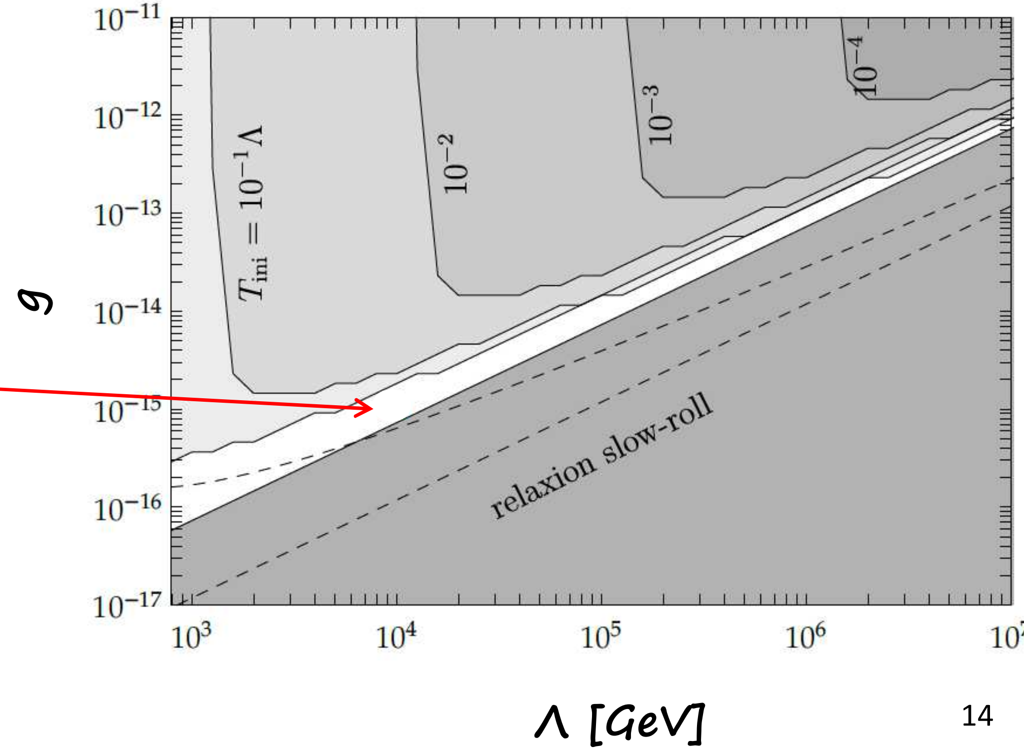

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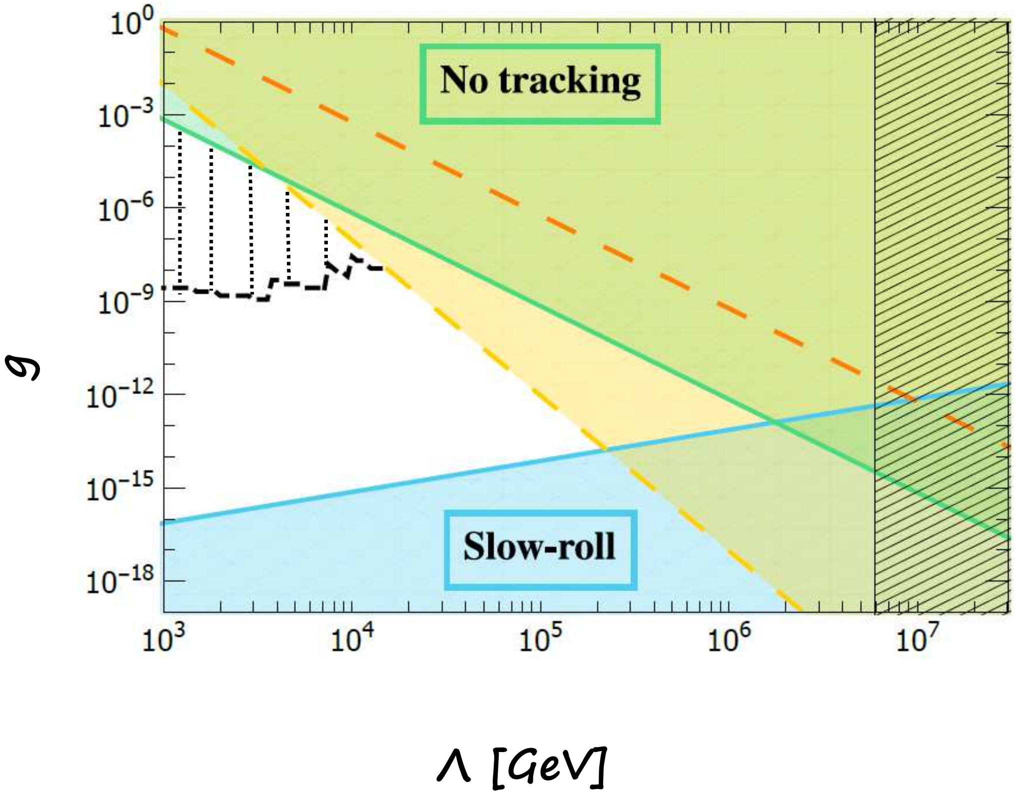
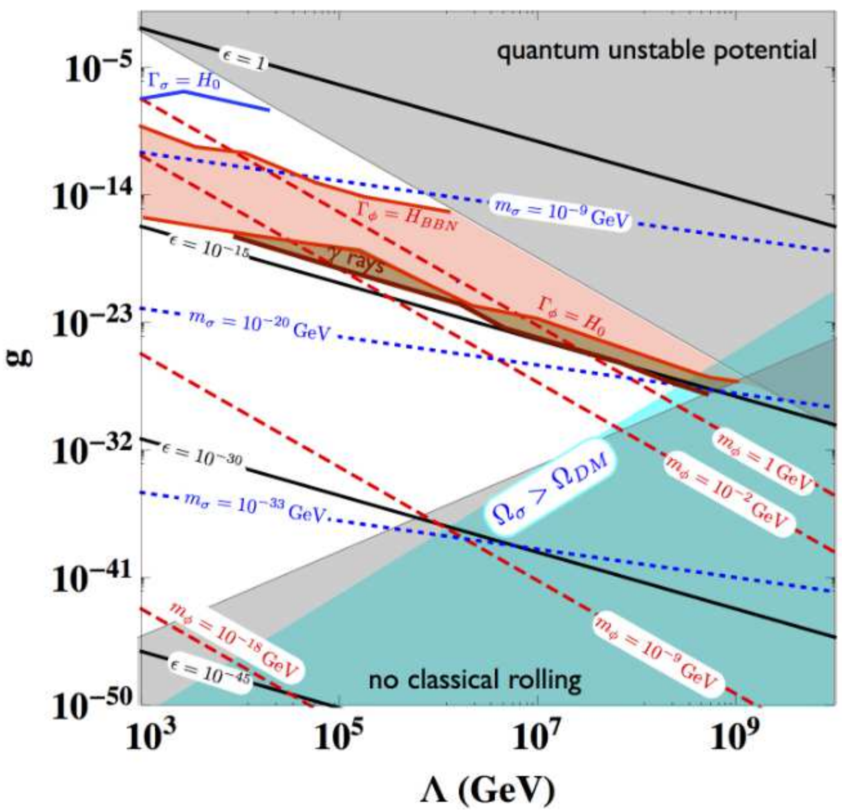


Espinosa-Grojean-Panico-Pomarol-Pujolàs-Servant; '15



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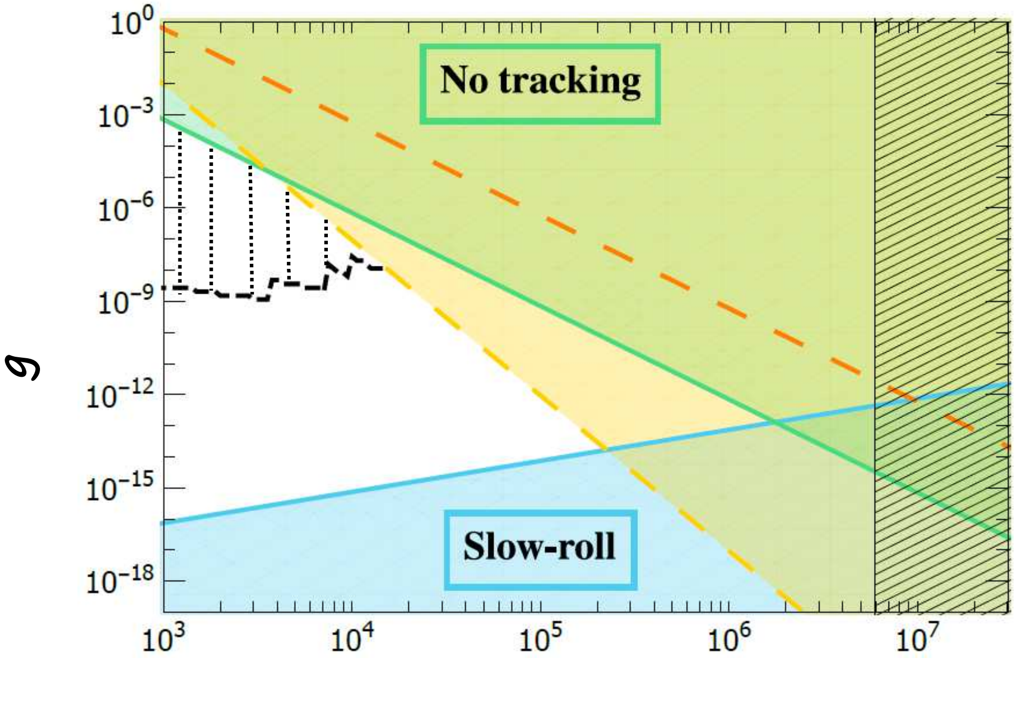

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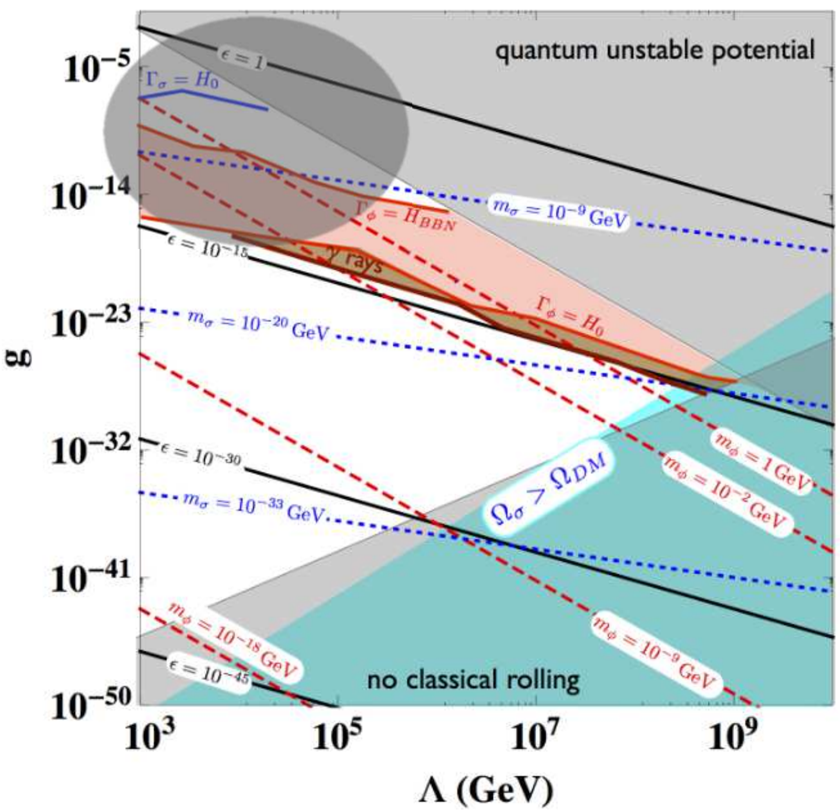


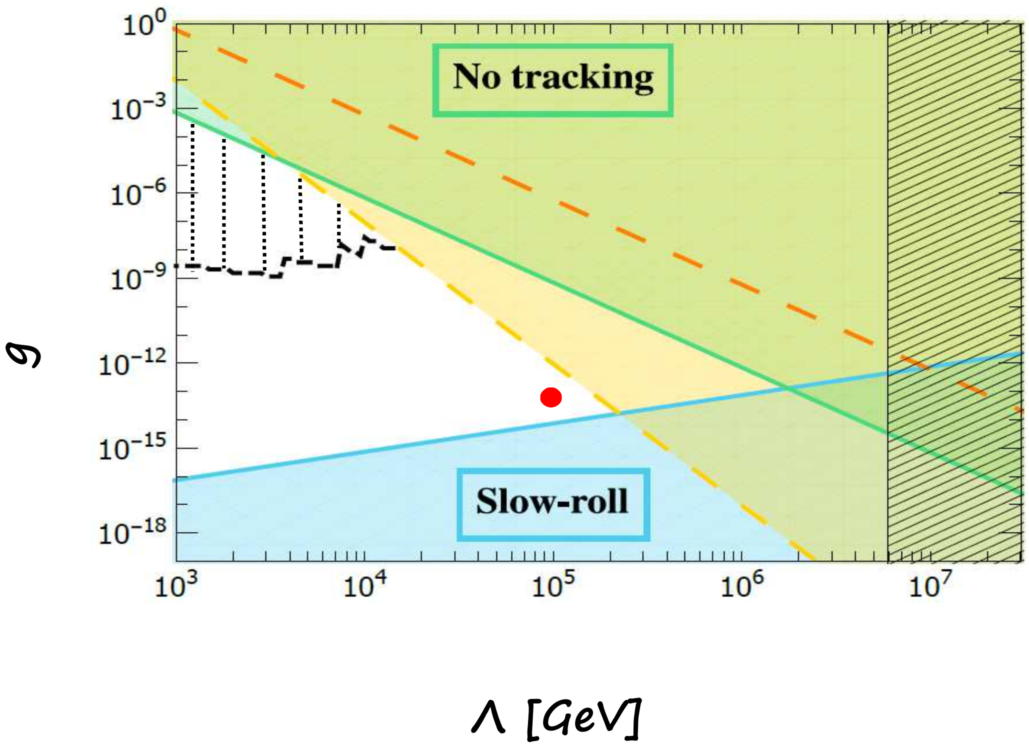
Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

III. Parameter space

- *Cosmological Probes*

$\Lambda = 10^5$ GeV; $g = 3 \times 10^{-14}$



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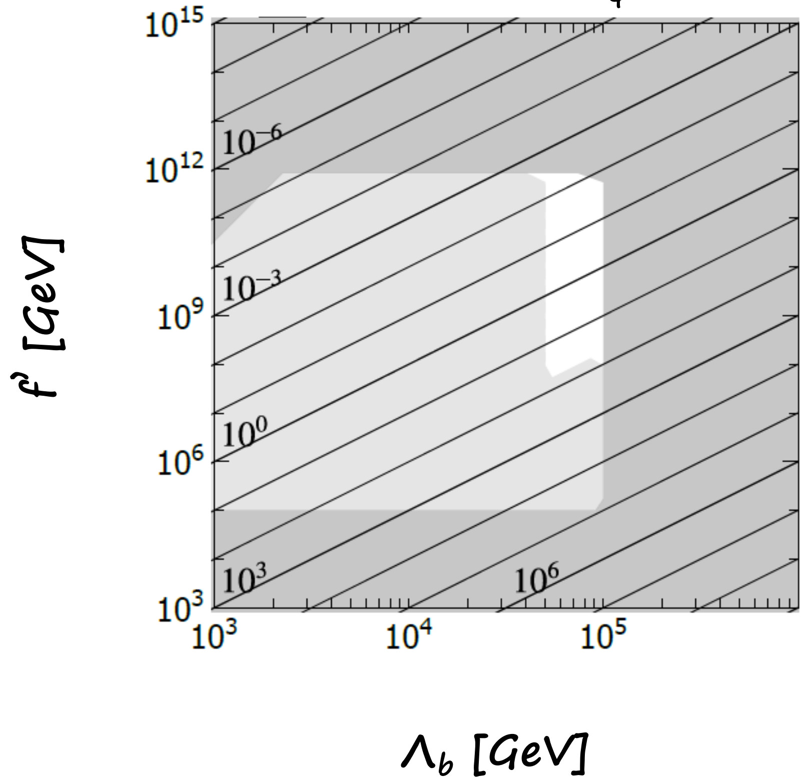
$$m_\phi \sim \frac{\Lambda_b^2}{f'}$$

Contours of m_ϕ



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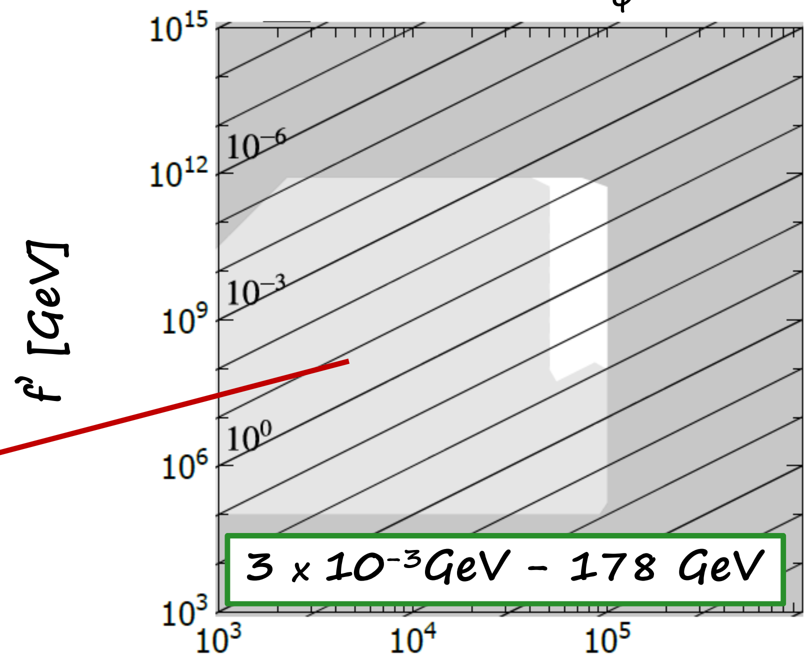

Λ_b [GeV]

Gray region: excluded just by requirements for the stopping mechanism from pp

Light gray may be alleviated by invoking an inefficient thermalization

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

Relaxion abundance — Huge! If the relaxion is stable, it is overabundant.

Relaxion late decays — If the relaxion decays after/during BBN, it is ruled out.

Overclosure

Light elements

III. Parameter space

- *Cosmological Probes*

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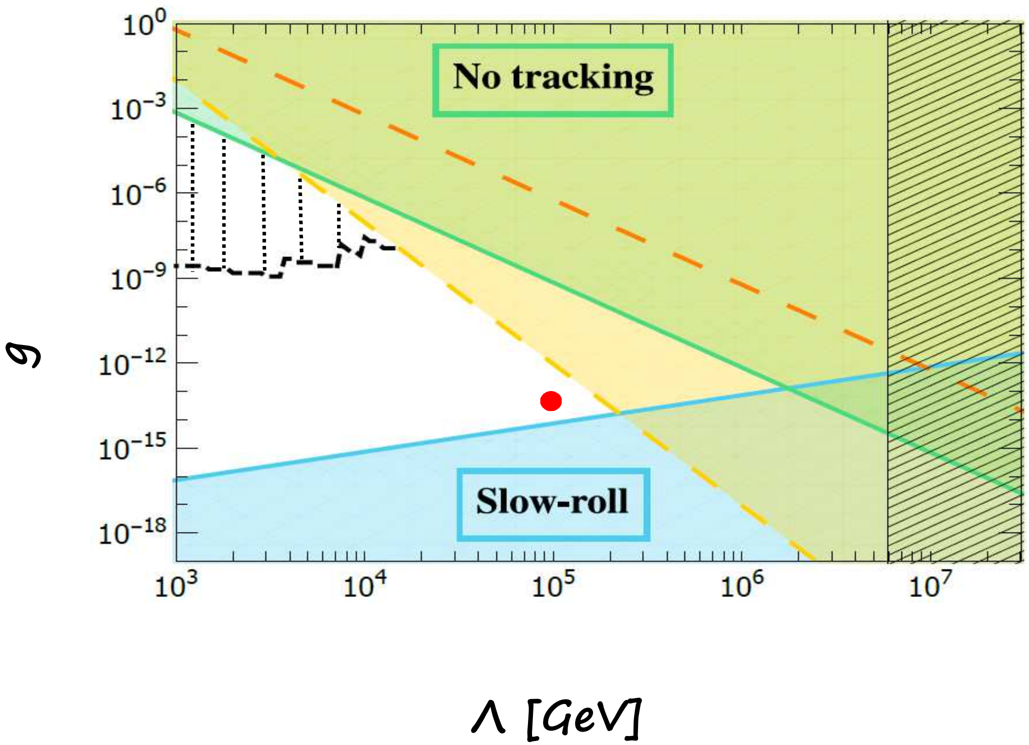

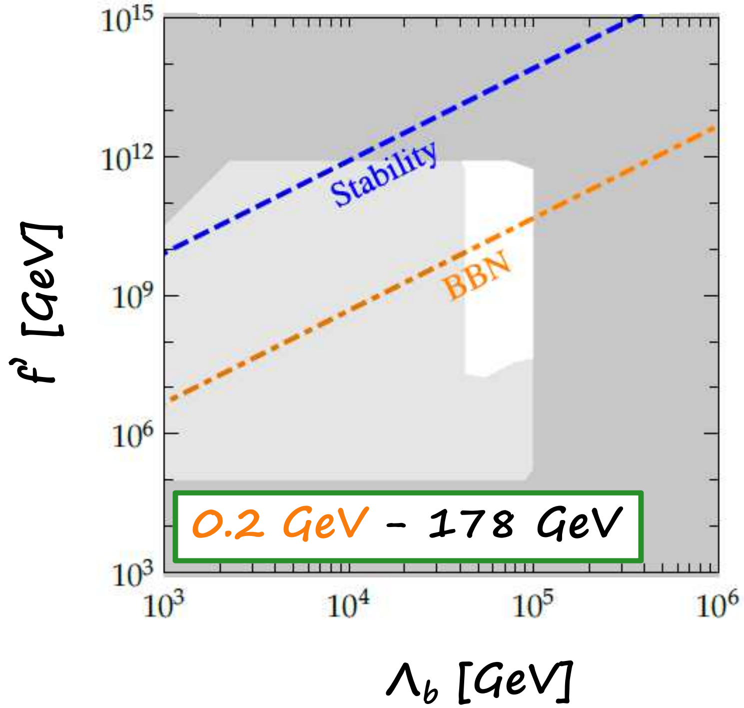

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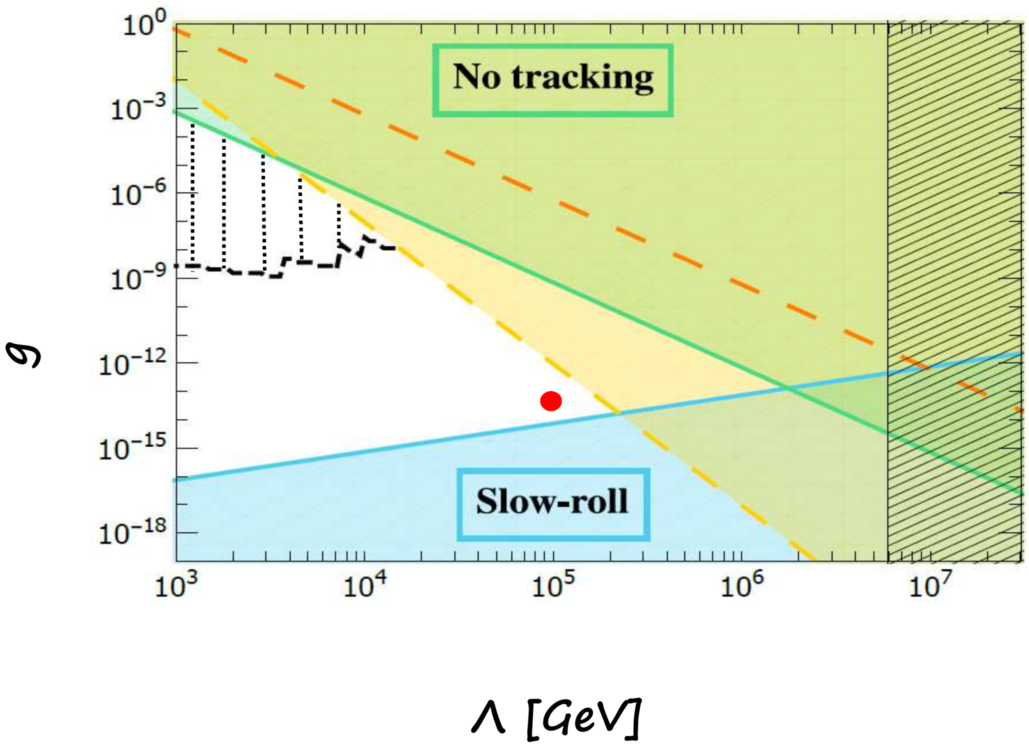
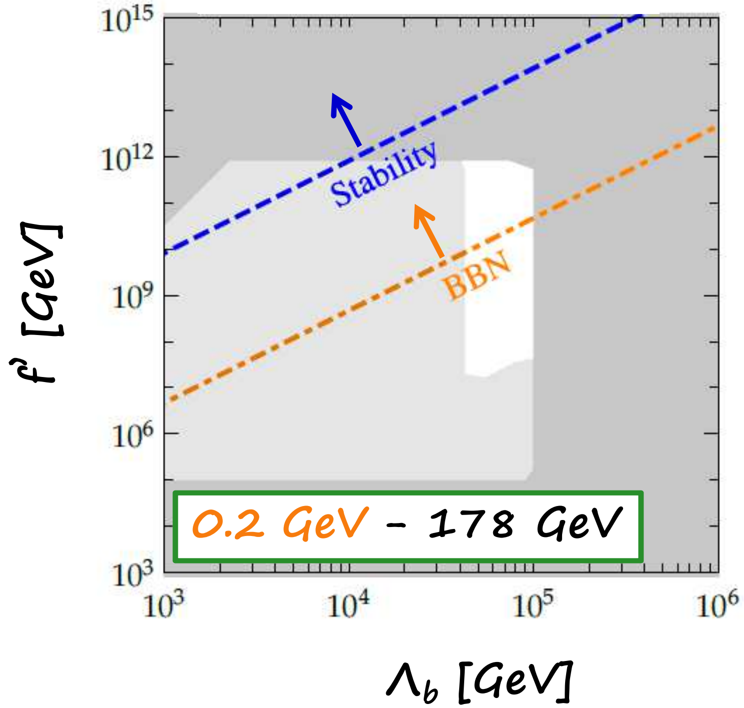
Overclosure

Light elements

Can be alleviated if there is some mechanism to dilute the abundance





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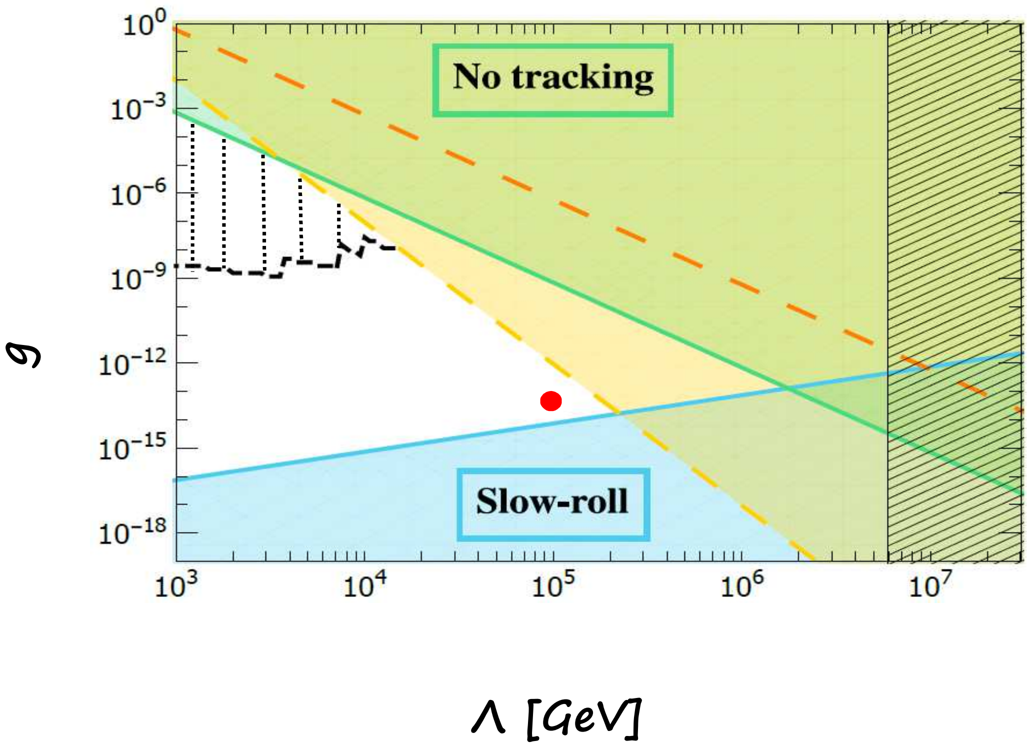

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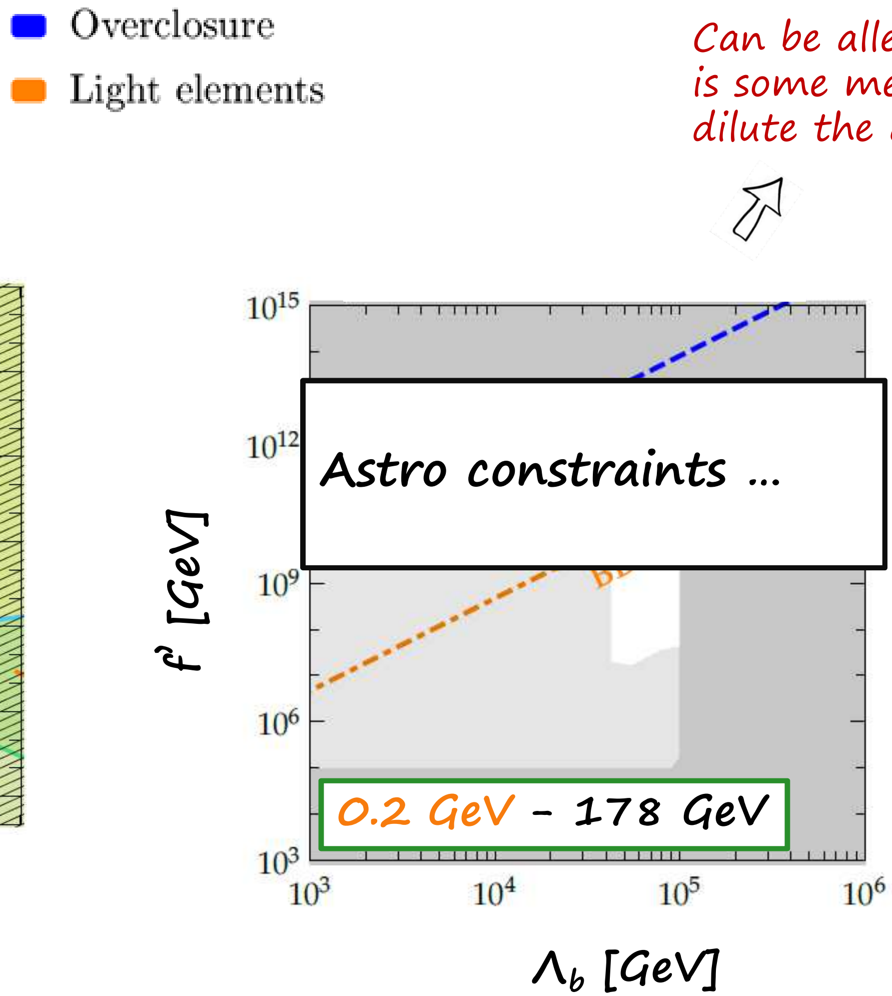

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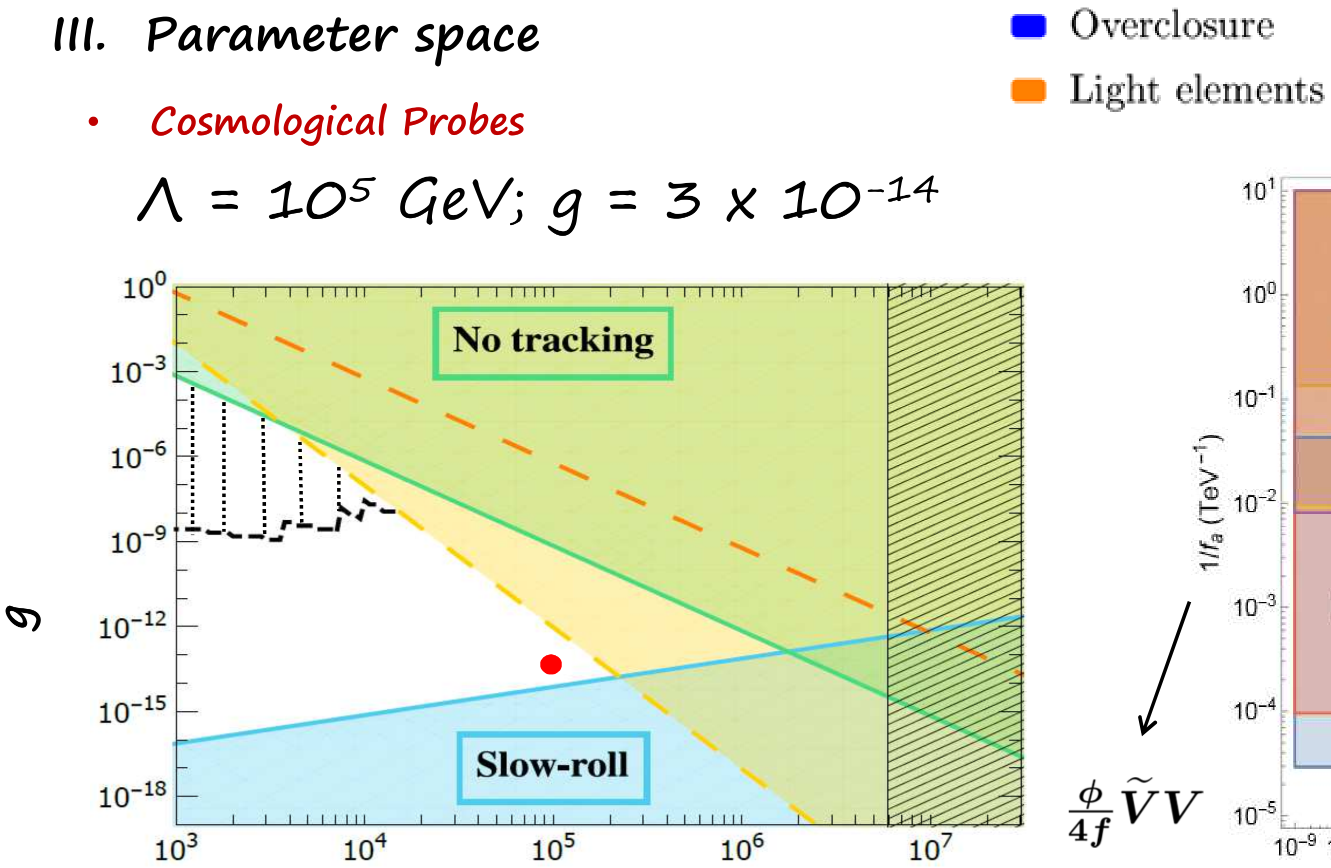
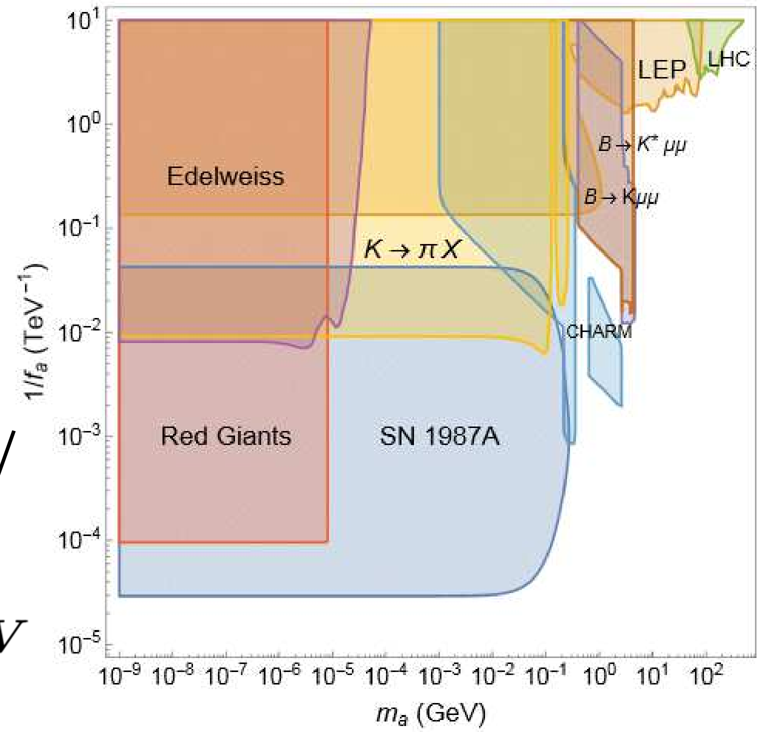


$\frac{\phi}{4f}\tilde{V}V$



Astro constraints

Craig, Hook, Kasko '18

Higgs Relaxation after inflation

NF, E. Morgante, G. Servant '18

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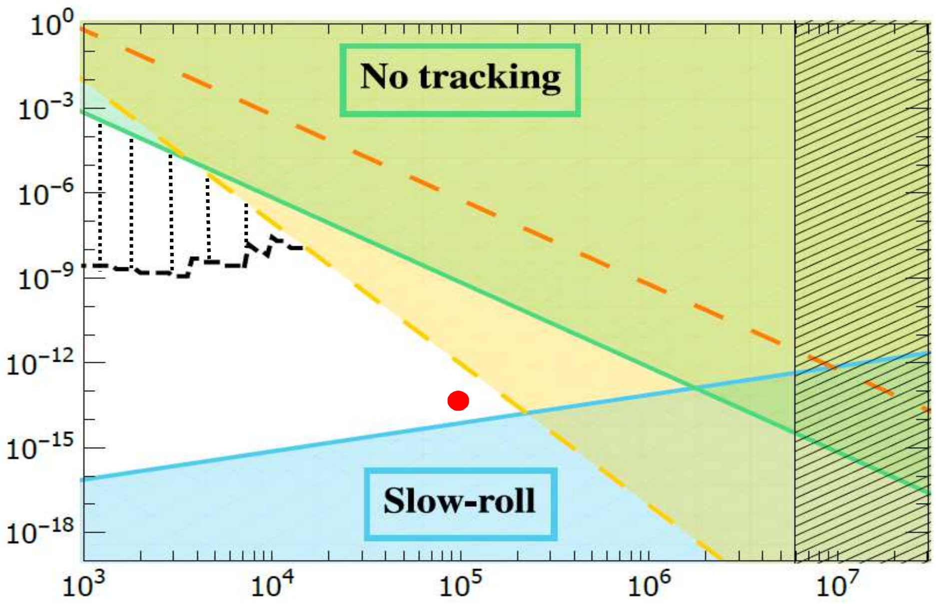
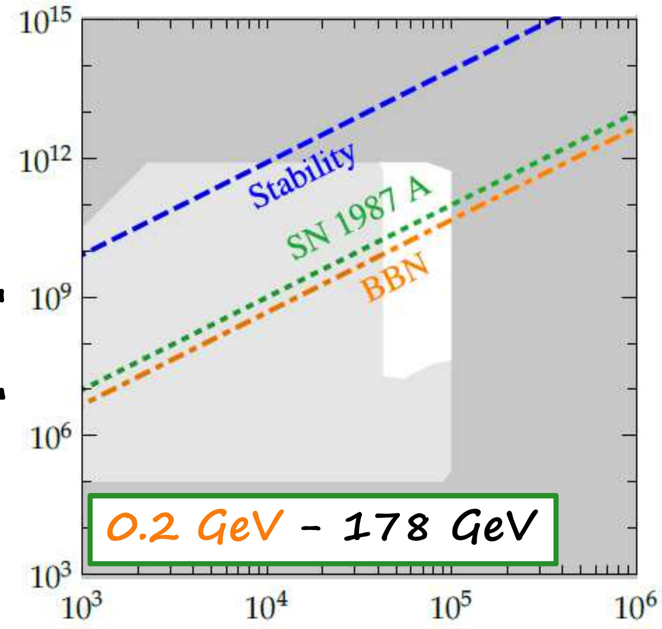


g

Λ [GeV]



$$m_\phi \sim \frac{\Lambda_b^2}{f'}$$

Part 2

Relaxion as Dark Matter

NF & E. Morgante (arXiv:1809.04534)

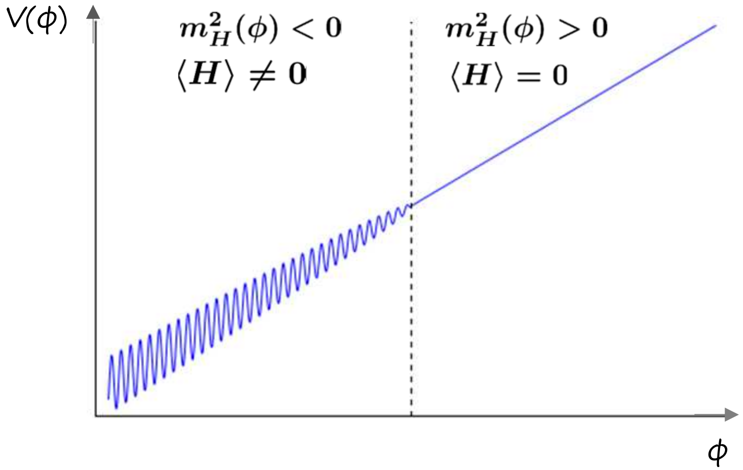
I. **Relaxion as a DM candidate**

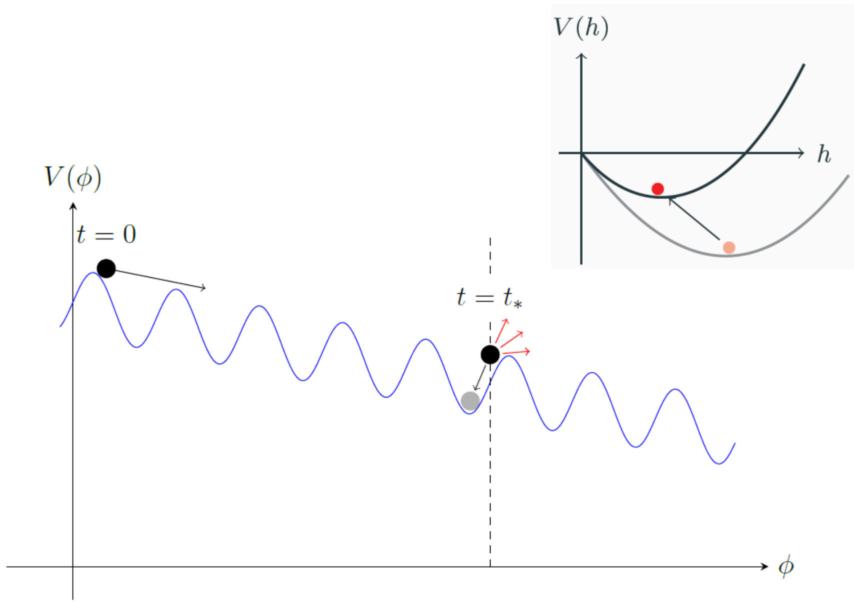
II. **Parameter space**

$\sim \Lambda_b^4(\langle H\rangle)\cos\phi/f'$

$\sim \frac{\phi}{f} V\widetilde{V}$

Stopping Mechanism	Higgs-dependent barrier	Particle Production



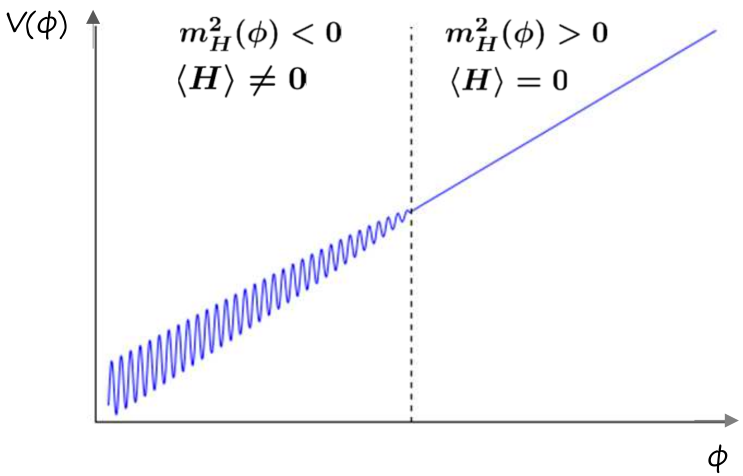


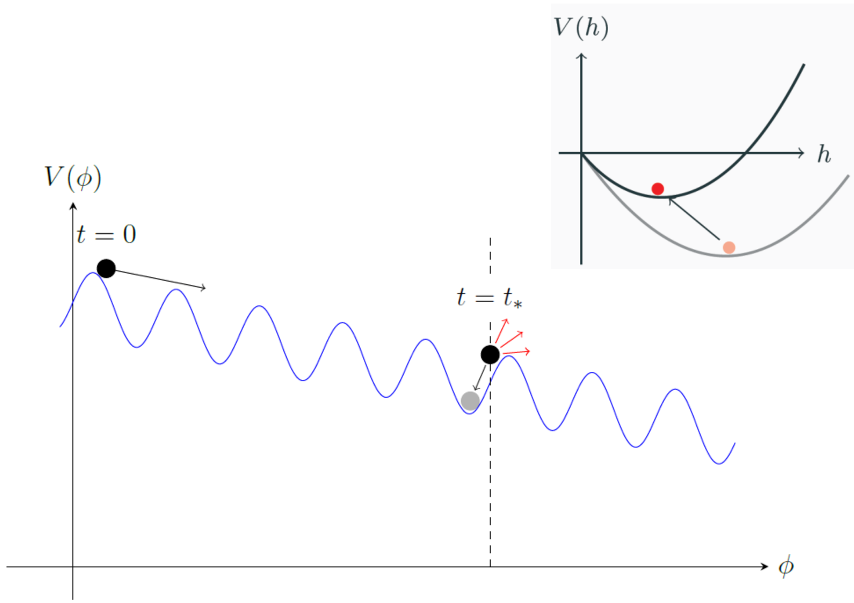
$$\sim \Lambda_b^4(\langle H\rangle)\cos\phi/f' \qquad\qquad \sim \frac{\phi}{f} V\widetilde{V}$$

Stopping Mechanism	Higgs-dependent barrier	Particle Production

Disclaimer: Focus on representative cases...

Apologies for hybrid models!





Relaxion as Dark Matter

$$\sim \Lambda_b^4(\langle H \rangle)\cos\phi/f'$$

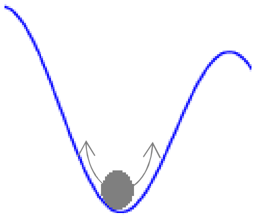
Stopping Mechanism	HIGGS-DEPENDENT BARRIER
When?	**During Inflation**

Stopping Mechanism	Higgs-dependent barrier
When?	**During Inflation**

Production: Misalignment & Thermal scattering

Stopping Mechanism	Higgs-dependent barrier
When?	During Inflation

Misalignment



At T_{osc}: Φ oscillates freely and contributes to ρ as CDM

$$Y = \frac{1}{m_\phi}\frac{\rho_\phi}{s} \approx \frac{m_\phi \phi_i^2/2}{2\pi^2 g_* T_{\rm osc}^3/45}$$

Espinosa, Grojean, Panico, Pomarol, Pujolàs, Servant; '15
Flacke, Frugiuele, Fuchs, Gupta, Perez; '16

Stopping Mechanism	HIGGS-DEPENDENT BARRIER
When?	**During Inflation**

Misalignment

- The initial misalignment angle is determined by the maximum spread displacement at the end of inflation:

$$\Delta\phi \approx \frac{3H_I^4}{8\pi^2 V'(\phi)} \lesssim \frac{3}{8\pi^2}\left(\frac{\Lambda_b^4}{f'}\right)^{1/3}$$

- Misalignment contribution is negligible: $\Omega_{mis} \ll 1$

Espinosa, Grojean, Panico, Pomarol, Pujolàs, Servant; '15
Flacke, Frugiuele, Fuchs, Gupta, Perez; '16

Stopping Mechanism	HIGGS-DEPENDENT BARRIER
When?	During Inflation

Thermal scattering

$$a + b \leftrightarrow \phi + c$$

$$\frac{dY_\phi}{dx} = -\frac{\Gamma}{xH}\left(Y_\phi - Y_\phi^{\mathrm{eq}}\right)$$

$$Y_\phi^{\mathrm{eq}} = n_\phi^{\mathrm{eq}}/s \approx 0.278/g_*$$

$$\Gamma = n_c\langle\sigma v\rangle$$

Espinosa, Grojean, Panico, Pomarol, Pujolàs, Servant; ‘15
Flacke, Frugiuele, Fuchs, Gupta, Perez; ‘16

Relaxion as Dark Matter

Stopping Mechanism	Higgs-dependent barrier
When?	**During Inflation**

Thermal scattering

$$\Lambda_b^4(\langle H \rangle) \cos\phi/f'$$

via Higgs

$$a + b \leftrightarrow \phi + c$$

$$\frac{dY_\phi}{dx} = -\frac{\Gamma}{xH}\left(Y_\phi - Y_\phi^{\rm eq}\right)$$

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Flacke, Frugiuele, Fuchs, Gupta, Perez; '16

Stopping Mechanism	Higgs-dependent barrier
When?	**During Inflation**

Thermal scattering

- Dominant production via the relaxion-Higgs mixing (θ) in the EW broken phase;
- Γ is dominated by:
  - Primakoff (ϕgg)
  - Compton (ϕqq)

$$Y_{th} \propto \theta^2$$

Flacke, Frugiuele, Fuchs, Gupta, Perez; '16

Stopping Mechanism	HIGGS-DEPENDENT BARRIER
When?	**During Inflation**

Thermal scattering

Can ϕ be DM?

- Lifetime: $\tau_{\phi} \propto 1/\Gamma_{\phi} \propto 1/\theta^2$
- In the region of the parameter space ϕ is stable, its abundance is suppressed ($\Omega_{th} \propto \theta^2$)
- It cannot explain the observed DM abundance

$$\Omega_{th} \ll 1$$

Flacke, Frugiuele, Fuchs, Gupta, Perez; '16

Stopping Mechanism	Particle Production $\nearrow \sim \frac{\phi}{f} V \widetilde{V}$	
When?	**After Inflation**	**During Inflation**

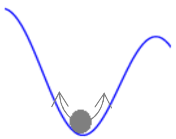
Production: Misalignment & Thermal scattering

Stopping Mechanism	PARTICLE PRODUCTION $\Leftarrow \sim \frac{\phi}{f} V \widetilde{V}$
When?	After Inflation

Production: Misalignment & Thermal scattering

Stopping Mechanism	PARTICLE PRODUCTION
When?	**After Inflation**

Misalignment



- *The initial misalignment angle is set by the time when particle production becomes inefficient and ϕ can oscillate freely;*

- *Naively,* $$\phi_i \lesssim \frac{\Lambda^2}{\Lambda_b^2}\frac{m_Z}{v_{\rm EW}} f'$$ *(Similar to the naïve expectation)*

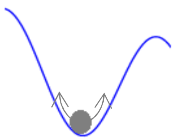
$$\frac{1}{2}\frac{\Lambda_b^4}{f'^2}\phi_i^2 = \frac{1}{2}\dot{\phi}_c^2 \lesssim 2f^2 m_Z^2$$

- *Huge!*

NF, Morgante, Servant; '18

Stopping Mechanism	Particle Production
When?	**After Inflation**

Misalignment



- The initial misalignment angle is set by the time when particle production becomes inefficient and ϕ can oscillate freely;
- **In general, ϕ abundance is too large (it has to decay).**

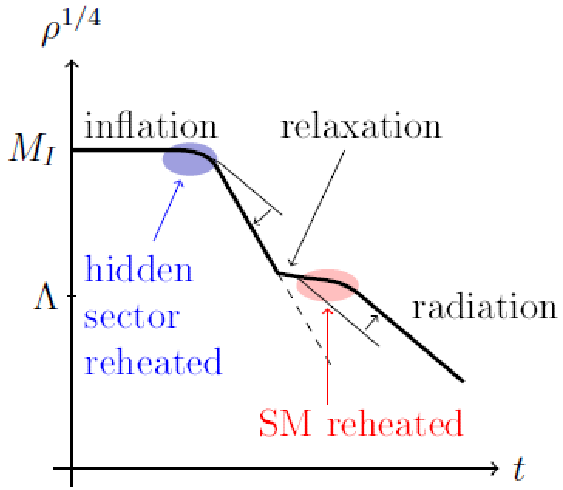
NF, Morgante, Servant; '18

Stopping Mechanism	PARTICLE PRODUCTION
When?	**After Inflation**

Thermal scattering

$a + b \to \phi + c$

- $\phi \to VV \Rightarrow$ Reheats the visible sector $\Rightarrow T_{ini} \sim \Lambda \gg v_{ew}$



NF, Morgante, Servant; '18

Stopping Mechanism	PARTICLE PRODUCTION
When?	**After Inflation**

Thermal scattering

$a + b \to \phi + c$

- $\phi \to VV$ ⇨ Reheats the visible sector ⇨ $T_{ini} \sim \Lambda \gg v_{ew}$;
- Dominant production via ϕVV;
- Γ is dominated by the Primakoff :
  - $\phi BB \quad (T > v_{ew})$
  - $\phi Z/\gamma \; (T < v_{ew})$
- $\Gamma/H > 1$ large such that: $Y_\phi(x) = Y_\phi^{\rm eq}\left[1 - \exp\left(-\int_1^x \frac{\Gamma}{x' H} dx'\right)\right] \to Y_\phi^{\rm eq}$

$x = T_{\rm ini}/T$

final abundance equal to the equilibrium value

NF, Morgante, Servant; '18

Stopping Mechanism	PARTICLE PRODUCTION
When?	**After Inflation**

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  - $\phi Z/\gamma$ $(T < v_{ew})$
- $\Gamma/H > 1$ large such that:

$$Y_{th} = Y^{eq}$$

NF, Morgante, Servant; '18

Stopping Mechanism	PARTICLE PRODUCTION
When?	**After Inflation**

Thermal scattering

$$a + b \to \phi + c$$

Why ϕ cannot be DM?

- Its abundance is too large (it has to decay)
- It cannot explain the observed DM abundance

$\Omega_{th} \gg 1$

NF, Morgante, Servant; '18

Stopping Mechanism	PARTICLE PRODUCTION
When?	During Inflation

Production: Misalignment & Thermal scattering

Stopping Mechanism	PARTICLE PRODUCTION
When?	During Inflation

Production: Misalignment & Thermal scattering

- As in the other cases during inflation, the misalignment contribution is negligible;
- The energy density stored in the field is diluted away.

Stopping Mechanism	PARTICLE PRODUCTION
When?	**During Inflation**

Thermal scattering

- If relaxation happens during inflation, the inflaton reheats the visible sector, then we can have:

$$1\ \text{MeV} < T_{ini} \ll v_{ew} \quad \text{such that } \Gamma/H < 1$$

DM is never in thermal equilibrium

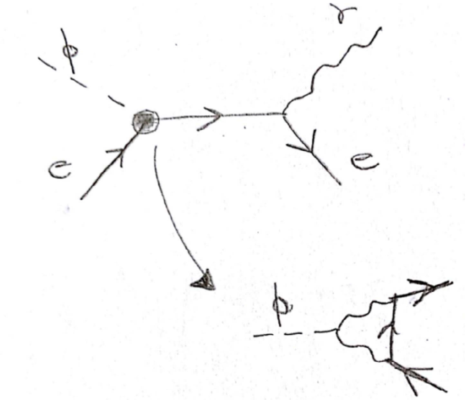
To avoid overabundance

NF, Morgante; '18

Stopping Mechanism	PARTICLE PRODUCTION
When?	**During Inflation**

Thermal scattering

- Production is then via **freeze-in mechanism**;
- Dominant production channel at low T (below m_π):
  - Compton scattering Γ_c (via $\phi\psi\psi$)



Relaxion stable + sizable abundance:

$\Omega_\phi = \Omega_{DM}$

NF, Morgante; '18

Relaxion as Dark Matter

NF & E. Morgante (arXiv:1809.04534)

I. Relaxion as DM

II. **Parameter space**

Relaxion as Dark Matter

NF, Morgante; '18

II. Parameter space

$\Lambda, g, \Lambda_b, f'$ $\quad + H_I$

$$V \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 - g\Lambda^3\phi + \frac{\lambda}{4}h^4 + \Lambda_b^4 \cos\left(\frac{\phi}{f'}\right)$$

During Inflation

Relaxion as Dark Matter

NF, Morgante; '18

II. Parameter space

$\frac{g'\Lambda}{3} \lesssim H_I$	slow-roll velocity
$\frac{g'^2\Lambda^4}{3v_{\rm EW}^3\lambda^{3/2}} \lesssim H_I$	Higgs tracking the minimum
$\frac{g'\Lambda^3}{3\Lambda_b^2} \gtrsim H_I$	overcome the wiggles
$(\frac{10^{-4}g'^5\Lambda^{15}}{\sqrt{g_*}m_Z^3\Lambda_b^8})^{1/4} \lesssim H_I$	efficient dissipation
$(\frac{10^{-4}g'^5\Lambda^{13}}{\sqrt{g_*}m_h^2m_Z^3\Lambda_b^4})^{1/4} \lesssim H_I$	small Higgs mass variation
$\mathrm{Min}[(\frac{5}{3}\frac{g'^2\Lambda^6}{g_*\pi^2\Lambda_b^4})^{1/2}, (\frac{230m_Z^8g'^2\Lambda^6}{g_*^5f'^8})^{1/6}] \lesssim H_I$	no symmetry restoration
$\frac{\Lambda^2}{M_{\rm Pl}} \lesssim H_I$	inflaton potential dominates
$(\frac{2\pi}{3})^{1/3} g'^{1/3}\Lambda \gtrsim H_I$	classical rolling dominates
$\frac{16}{9\pi^2 g_{\rm EW}^2}\frac{\dot\phi^3}{T^2 f_\gamma^3} \lesssim H_I$	photon dilution
$\frac{16}{9\pi^2 g_{\rm EW}^2}\frac{\dot\phi^3}{T^2 f^3} \gtrsim H_I$	particle production fast
$g' \lesssim \frac{\Lambda_b^4}{\Lambda^3 f'}$	stopping condition
$g' \lesssim \frac{m_h^2}{2\pi f'\Lambda}$	scanning with enough precision
$\Lambda_b, \Lambda \lesssim f'$ and $\Lambda \lesssim f$	consistency of the EFT

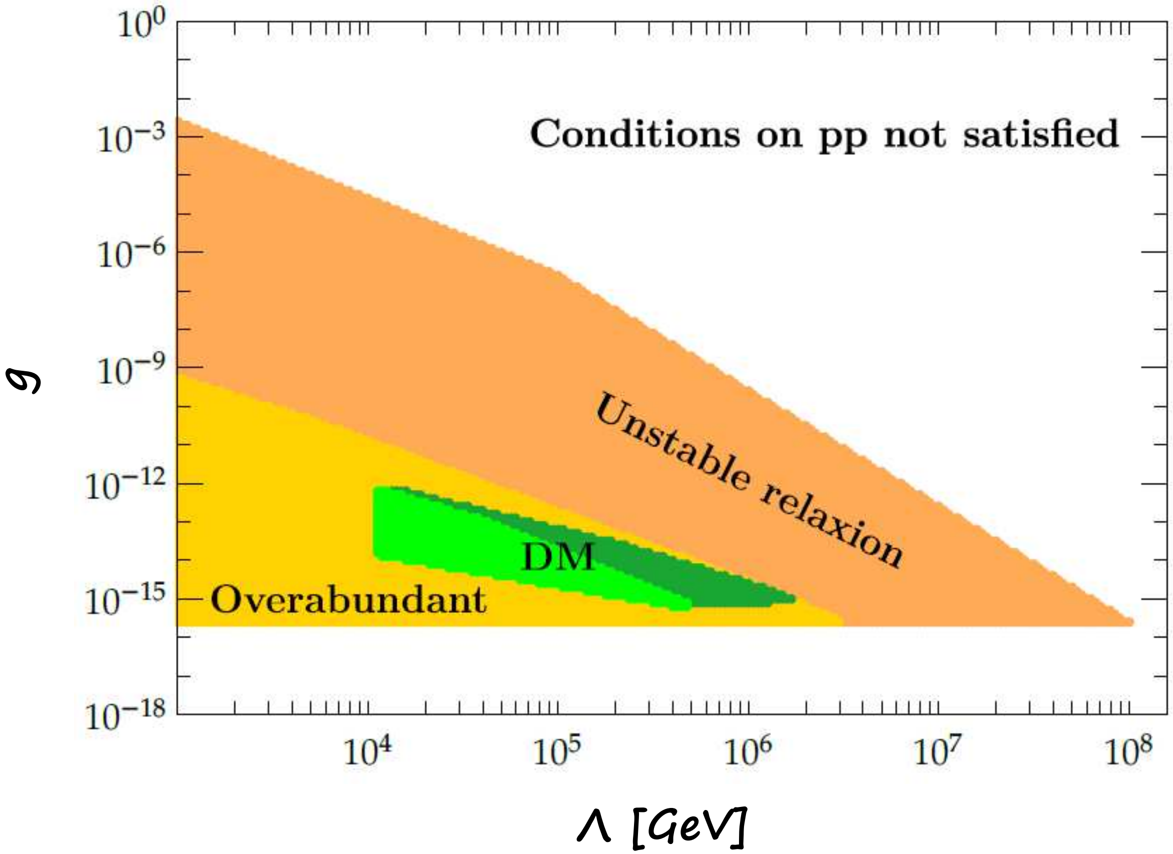
Relaxion as Dark Matter

NF, Morgante; '18

$\Lambda, g, \Lambda_b, f'$ + H_I

$$V \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 - g\Lambda^3\phi + \frac{\lambda}{4}h^4 + \Lambda_b^4 \cos\left(\frac{\phi}{f'}\right)$$

II. Parameter space



Relaxion as Dark Matter

NF, Morgante; '18

Λ, g, Λ_b , f' + H_I

$$V \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 - g\Lambda^3\phi + \frac{\lambda}{4}h^4 + \Lambda_b^4\cos\left(\frac{\phi}{f'}\right)$$

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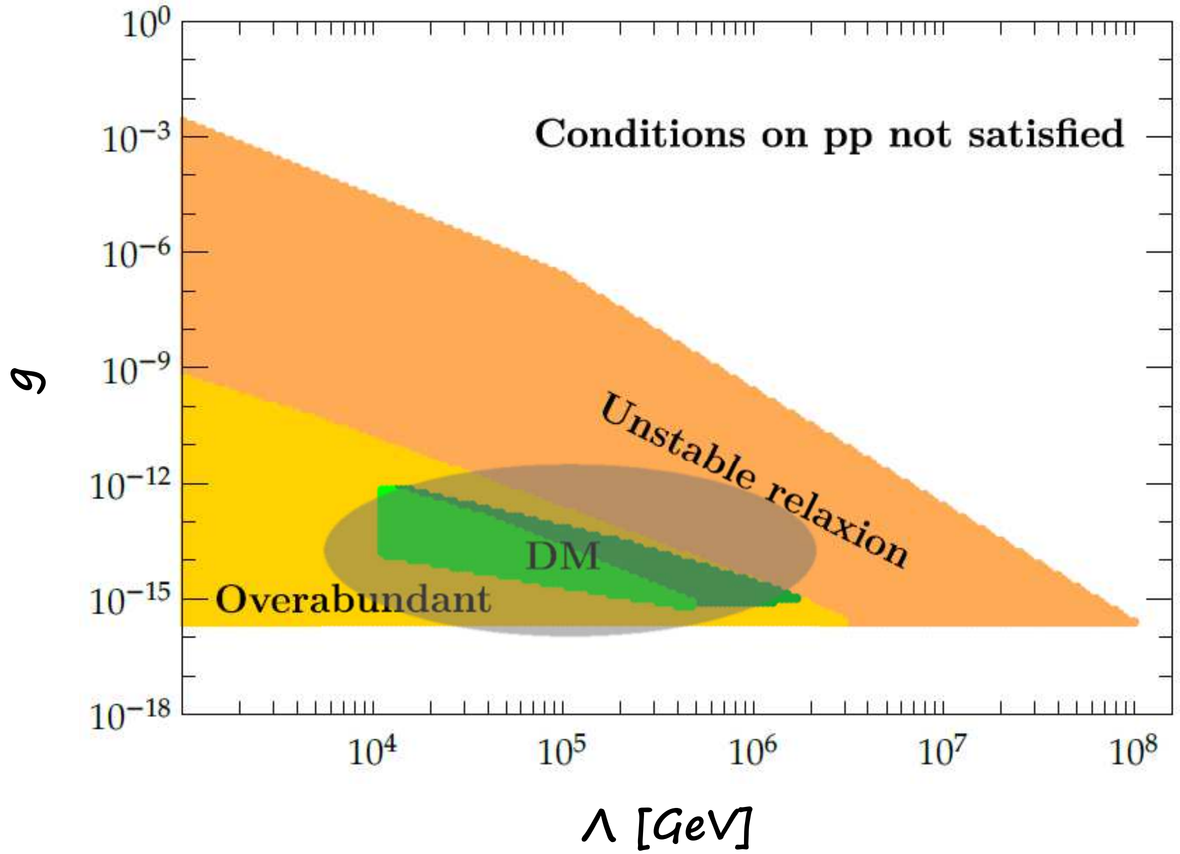


Relaxion as Dark Matter

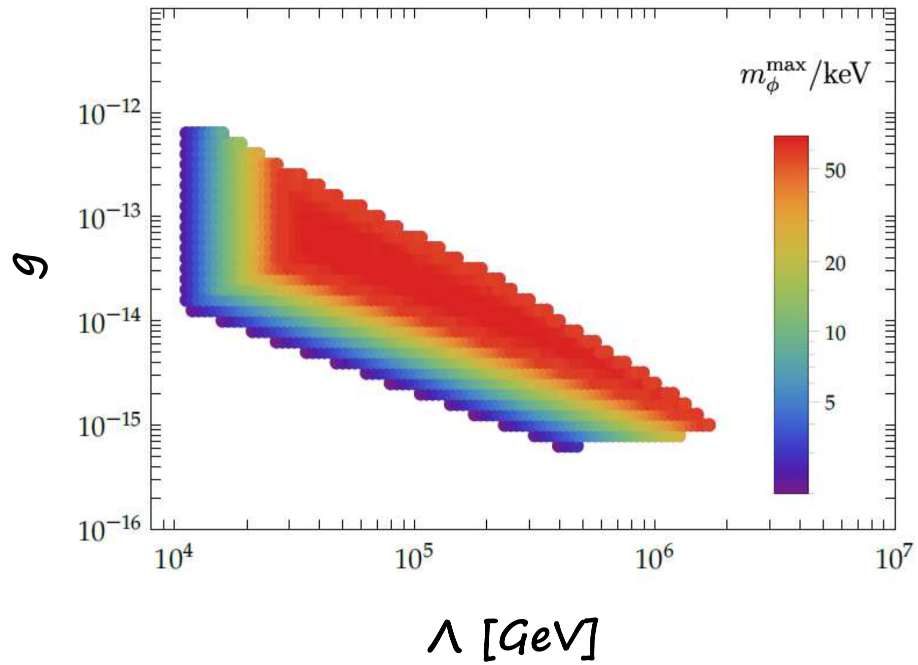
NF, Morgante; '18

$\Lambda, g, \Lambda_b, f' \quad + H_I$

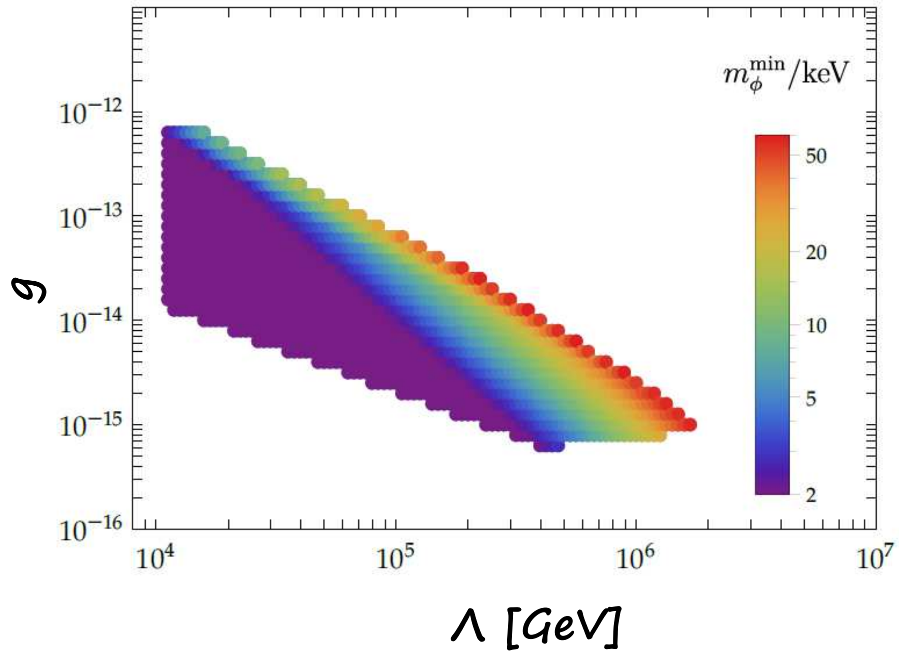
$$V \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 - g\Lambda^3\phi + \frac{\lambda}{4}h^4 + \Lambda_b^4 \cos\left(\frac{\phi}{f'}\right)$$

II. Parameter space

m_ϕ max



m_ϕ min



Relaxion DM: $m_\phi \sim$ 2 keV - 70 keV

Relaxion as Dark Matter

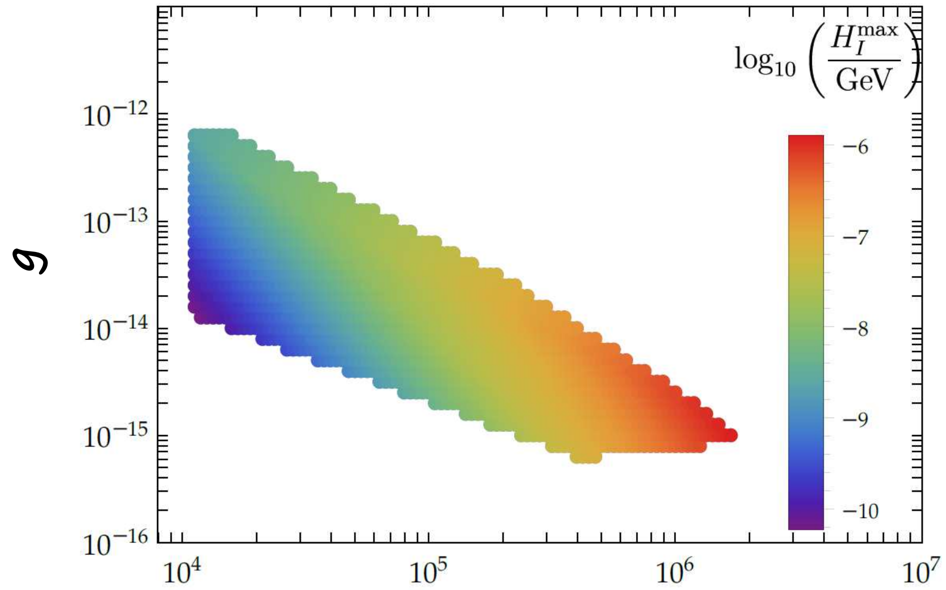
NF, Morgante; '18

$\Lambda, g, \Lambda_b, f'$ + H_I

$$V \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 - g\Lambda^3\phi + \frac{\lambda}{4}h^4 + \Lambda_b^4\cos\left(\frac{\phi}{f'}\right)$$

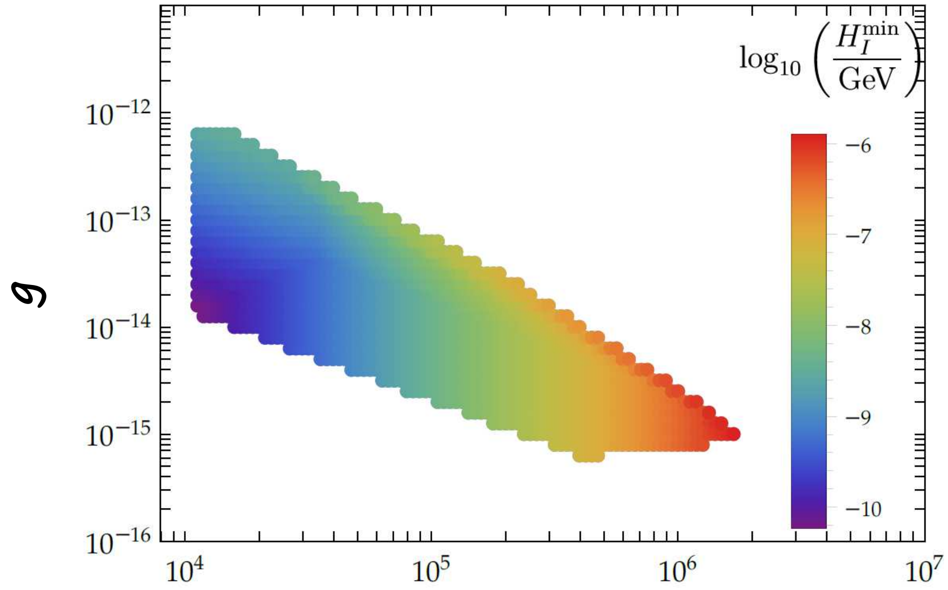
II. Parameter space

H_I max



Λ [GeV]

H_I min



Λ [GeV]

Hubble (H_I) : ~ 10^{-10} GeV – 10^{-6} GeV

M_I : ~ 10^4 GeV – 10^6 GeV

Relaxion as Dark Matter

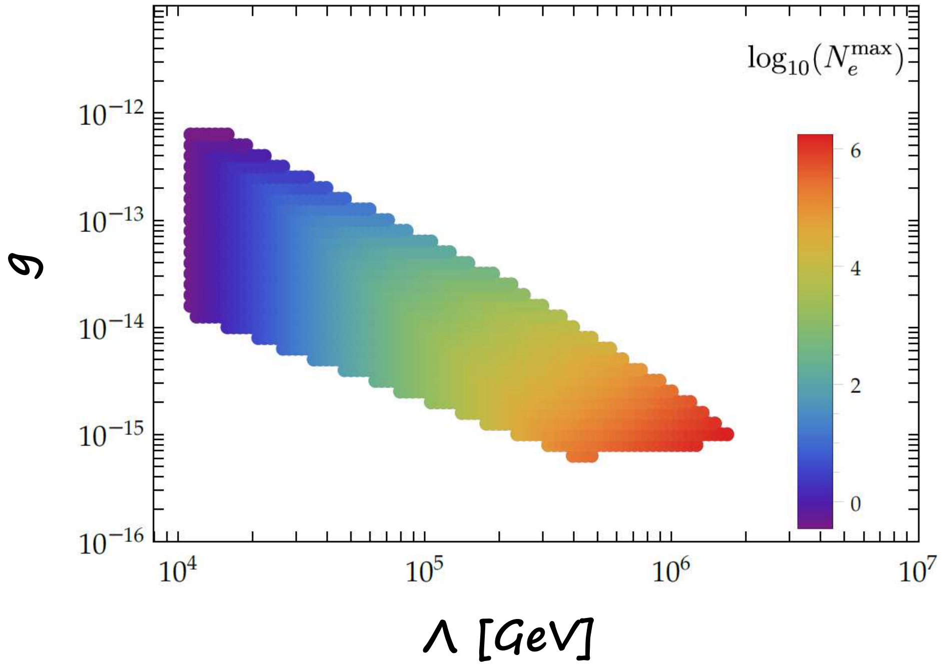
NF, Morgante; '18

$\Lambda, g, \Lambda_b, f'$ + H_I

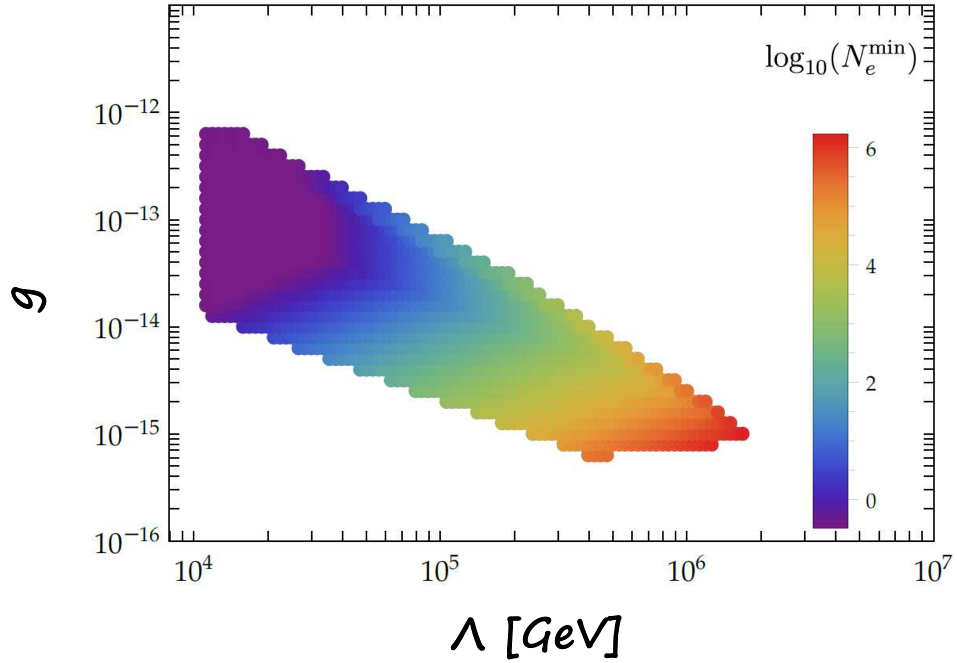
$$V \supset \frac{1}{2}\left(-\Lambda^2 + g\Lambda\phi\right)h^2 - g\Lambda^3\phi + \frac{\lambda}{4}h^4 + \Lambda_b^4 \cos\left(\frac{\phi}{f'}\right)$$

II. Parameter space

N_e max



N_e min



N_e necessary for relaxation: ~ O(1) - 10^6

Relaxion as Dark Matter

NF, Morgante; '18

II. Parameter space

How the allowed region depends on the initial T?

- If relaxation happens during inflation, the inflaton reheats the visible sector, then we can have:

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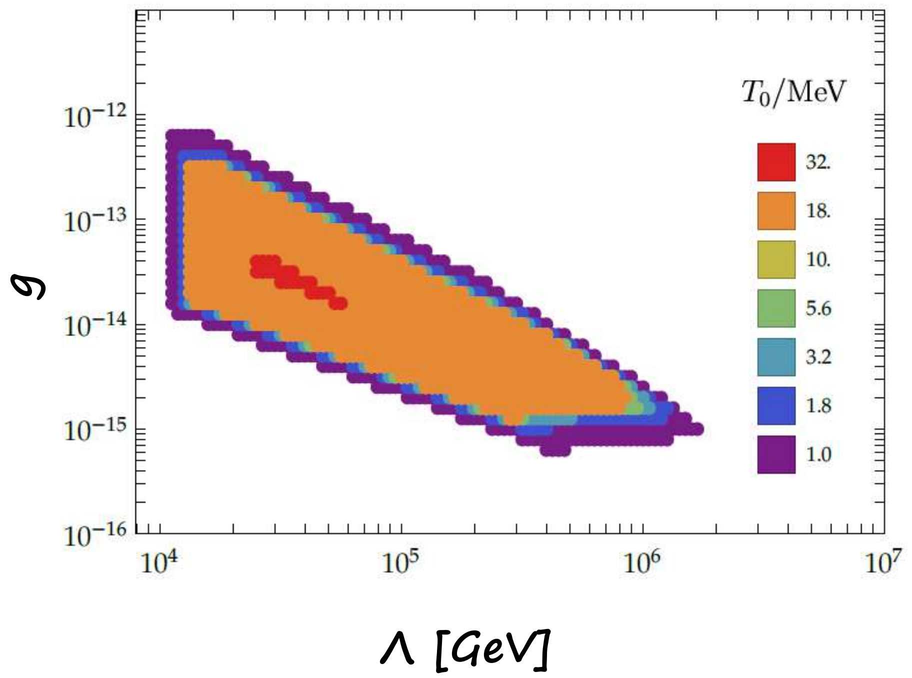
Relaxion as Dark Matter

NF, Morgante; '18

II. Parameter space

How the allowed region depends on the initial T?

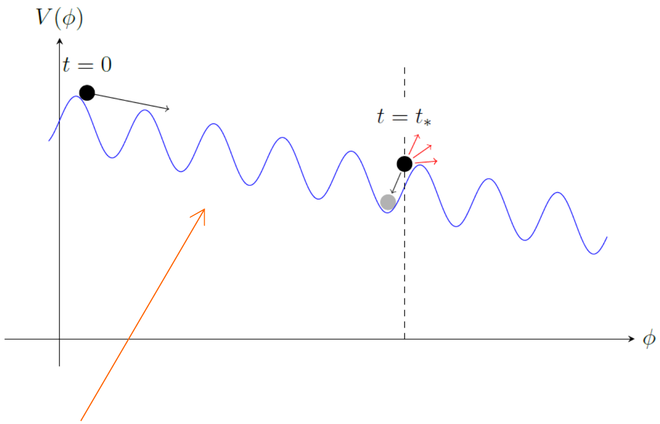


- T reheating can be larger than T_0 if a dilution mechanism is active (decay of unstable particles injecting entropy in the plasma, see e.g. Giudice, Kolb, Riotto, hep-ph/0005123);
- If thermal equilibrium is reached, in this mass range the relaxion would be overabundant by a factor of 10-1000.

Concluding Remarks and Outlook

- **Higgs Relaxation after inflation**
  NF, E. Morgante, G. Servant '18

  - No need for inflation input
  - Cutoff can be as high as $\Lambda \sim 10^5$ GeV
  - Relaxion can be heavy $m_\phi = \frac{\Lambda_b^2}{f'}$
  - Astro/Cosmo probes + self-consistency: very constrained



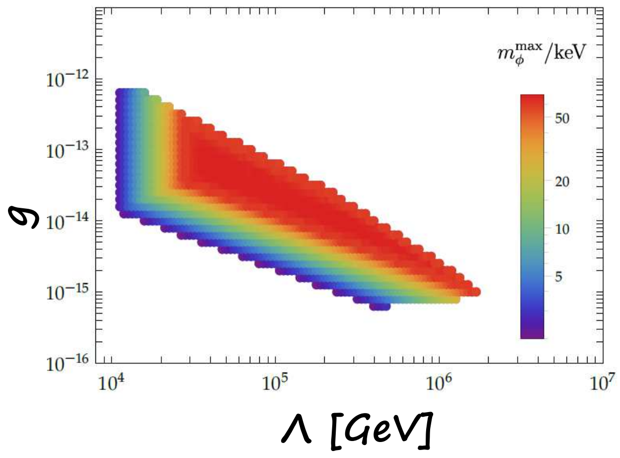
Barriers independent of the Higgs vev

Concluding Remarks and Outlook

- ## Relaxion as Dark Matter

  NF, Morgante; '18

- Hierarchy problem ⟷ DM sector;
- Phenomenologically viable DM candidate;
- Relaxion is warm;
- Dedicated studies on ID and on the impact on structure formation.



Concluding Remarks and Outlook

- **Relaxion as Dark Matter**

  NF, Morgante; '18

Thanks!

- Hierarchy problem ⟷ DM sector;
- Phenomenologically viable DM candidate;
- Relaxion is warm;
- Dedicated studies on ID and on the impact on structure formation.