



QU Kickoff Meeting



# Higgs, Relaxion, and Dark Matter

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

Nayara Fonseca

DESY

DESY - 20 March 2019

- The slide you have seen **1000** times

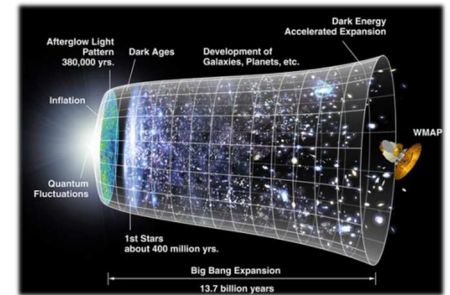
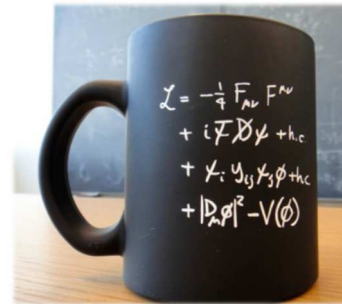
**SM hierarchy problem: New physics at the weak scale**

- **UV sensibility** to the Higgs mass: one of the leading motivations for new physics at the LHC;
- **The problem** and its **importance**: 170 of the 226 search channels at LHC tied to naturalness (Craig PPC '16)
- We need BSM at  $\sim$  **TeV** scale (Eg.: SUSY & Composite Higgs Models)
- **No compelling evidence of BSM at the LHC current data!**



## SM hierarchy problem

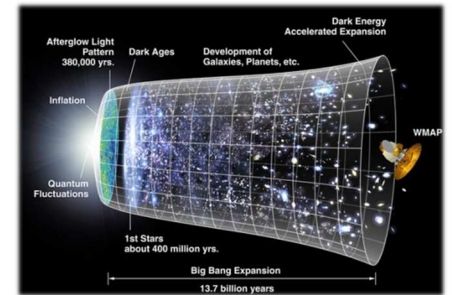
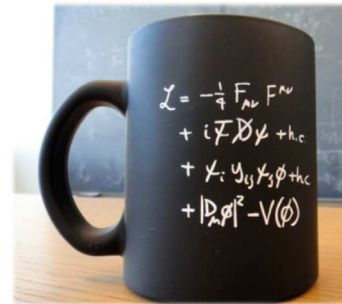
- Particle physics has been an essential ingredient in understanding the cosmological history...



Can **cosmology** be a key ingredient to understand the parameters in **particle physics** ?

## SM hierarchy problem

- Particle physics has been an essential ingredient in understanding the cosmological history...



Can **cosmology** be a key ingredient to understand the parameters in **particle physics** ?

How?  
What can make a **bridge**?



Venice @ Miniatur Wunderland

# Naturalness: The Relaxing Way

*SRtp workshop "BSM in direct, indirect and tabletop experiments"*  
*Weizmann Institute, November 12, 2017*



*Christophe Grojean*

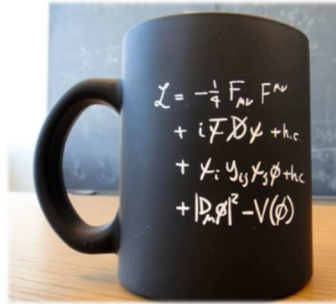
DESY (Hamburg)  
Humboldt University (Berlin)

( [christophe.grojean@desy.de](mailto:christophe.grojean@desy.de) )

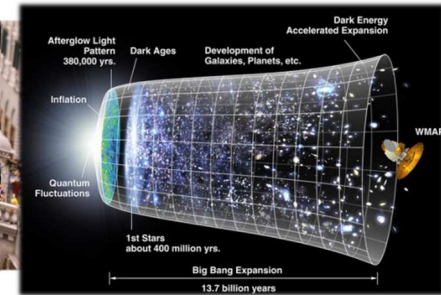
(unauthorized reproduction of C. Grojean, Weizmann - 2017)



# Outline



@ Miniatur Wunderland



1. Relaxion idea (super fast review)
  - Paradigm shift to solve the HP (no NP at TeV)
  - Particle-cosmology interplay

## 2. Concerns & Possible Solutions & Directions

- 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...

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

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SM hierarchy problem: Relaxation mechanism of the EW scale

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

high scale

the new field

small coupling

breaks  $\phi$  'axion-like' shift symmetry



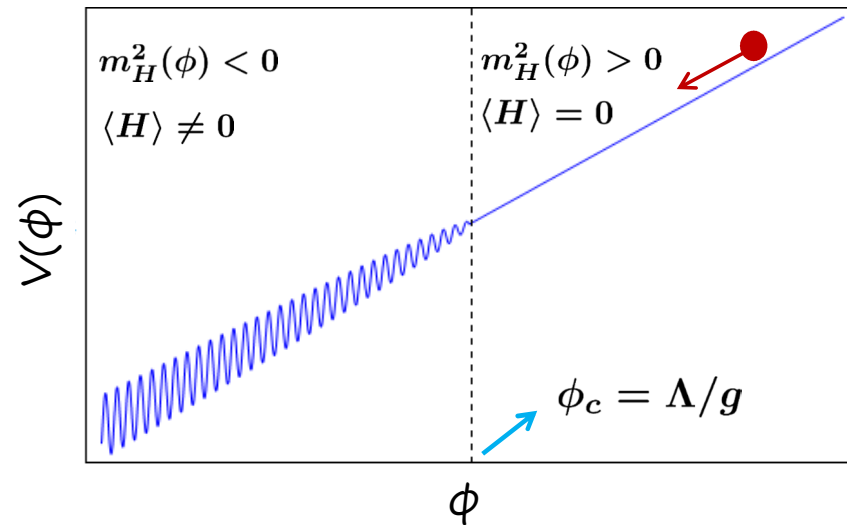
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## SM hierarchy problem: Relaxation mechanism of the EW scale

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

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

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



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

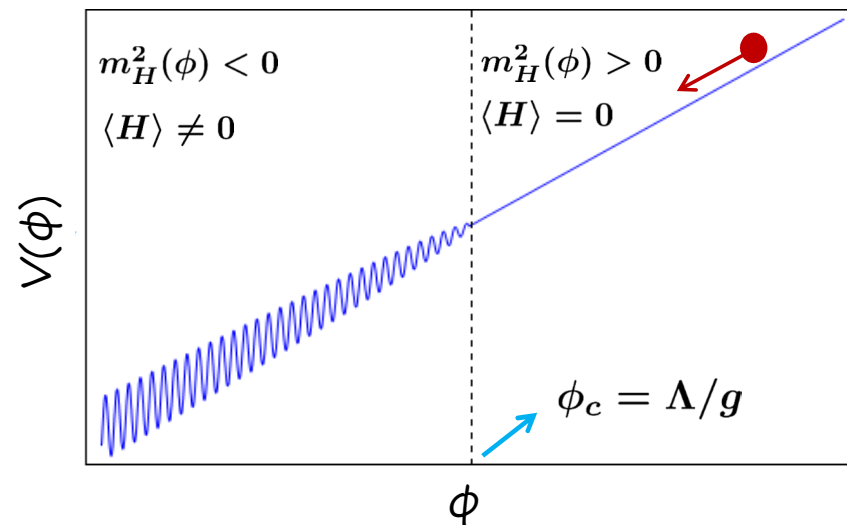
## SM hierarchy problem: Relaxation mechanism of the EW scale

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

- Originally, **backreaction** from Higgs-dependent potential

$$V(h, \phi) \supset \frac{1}{2}(-\Lambda^2 + g\Lambda\phi)h^2 + g\Lambda^3\phi$$

$$+ \underline{\Lambda_b^4(\langle H \rangle) \cos \phi / f'}$$



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

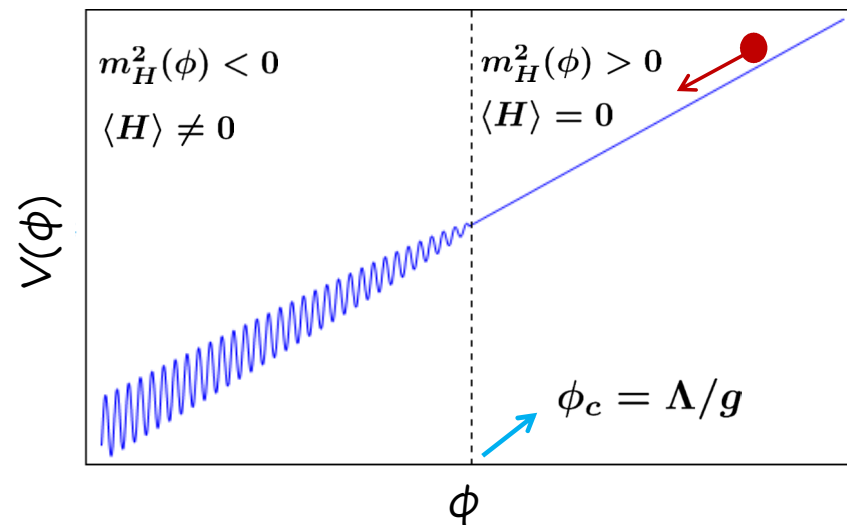
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### ▪ $\Lambda < 10^8$ GeV, UV completions... eg.:

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

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



## SM hierarchy problem: Relaxation mechanism of the EW scale

### Issues in the original proposal:

- Low inflation scale/Large number of  $e$ -folds
- Super-Planckian field excursions
- Fermions at EW to generate the wiggles
- Large hierarchies/UV completion
- Signatures
- Cosmological Constant
- ...



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

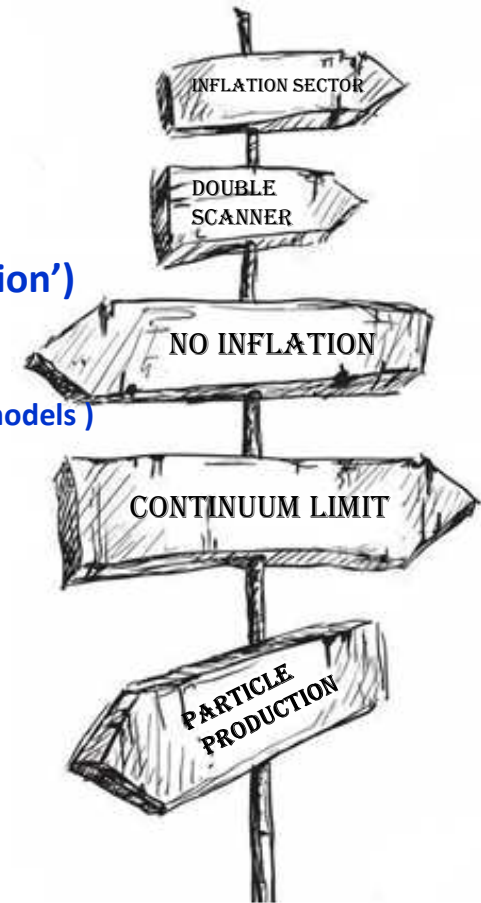
## SM hierarchy problem: Relaxation mechanism of the EW scale

### Issues in the original proposal:

- Low inflation scale/Large number of  $e$ -folds (particle production 'friction')
- Super-Planckian field excursions (particle production 'friction')
- Fermions at EW to generate the wiggles (double scanner or particle production models)
- Large hierarchies/UV completion (clockwork-like models)
- Signatures !?
- Cosmological Constant !?
- ...



Triggered a varied literature



*An incomplete list of relaxation possibilities which  
address some of these problems...*





## Cosmological Relaxation of the Electroweak Scale

# Related work that involved former/current DESY members:

### Dynamics during Inflation

- Reduce the  $N_e$ ;

Patil, Schwaller '15

### Double scanner mechanism

- No new fermions at TeV;

Espinosa, Grojean, Panico, Pomarol, Pujolàs, Servant '15

### Alternatives to Inflation

- Friction from particle production;

NF, E. Morgante, G. Servant '18

### Relaxion as DM

NF, E. Morgante '18

### Model building front

- ❖ 4D site models; NF, Lima, Machado, Matheus '16

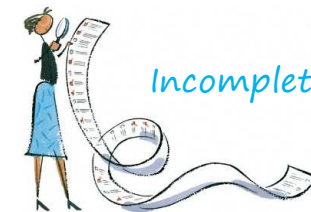
- ❖ String theory (Monodromy);

McAllister, Schwaller, Servant, Stout, Westphal '16

- ❖ Relaxion from Warped Space

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- ❖ Pole attractor Matsedonskyi, Montull '17



Incomplete list!

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$$\frac{\phi}{f} V_{\text{SM}} \tilde{V}_{\text{SM}}$$

### Relaxion as DM

NF, E. Morgante '18

Inflation +  
particle  
production

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Incomplete list!

○ **Higgs Relaxation after inflation** (Stopping mechanism: particle production )

NF, E. Morgante, G. Servant '18

$$\frac{\phi}{f} V_{\text{SM}} \tilde{V}_{\text{SM}} \swarrow$$

Is **Relaxation after inflation** cosmologically viable?  
What is the allowed parameter space?

**Far from clear!**

# ○ Higgs Relaxation after inflation (Stopping mechanism: particle production)

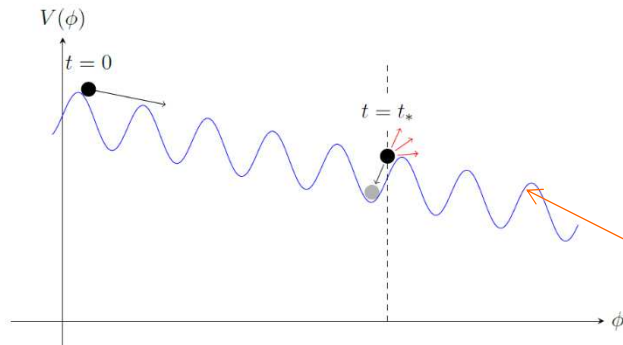
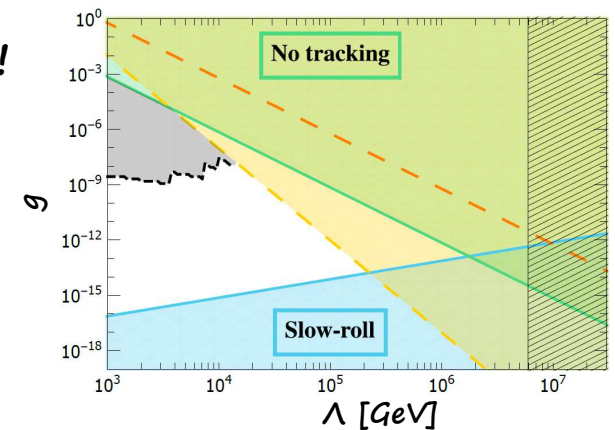
NF, E. Morgante, G. Servant '18

$$\frac{\phi}{f} V_{\text{SM}} \tilde{V}_{\text{SM}} \quad \swarrow$$

Is Relaxation after inflation cosmologically viable?  
What is the allowed parameter space?



- Very constrained (abundance, BBN, astro,...) but still viable!
- Cutoff can be as high as  $\Lambda \sim 10^5 \text{ GeV}$ ;
- Relaxion can be heavy!  $m_\phi \sim \frac{\Lambda_b^2}{f'}$



Barriers independent of the Higgs vev

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

## Cosmological Relaxation of the Electroweak Scale

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Incomplete list!



## ○ Relaxion as Dark Matter

NF, Morgante; '18

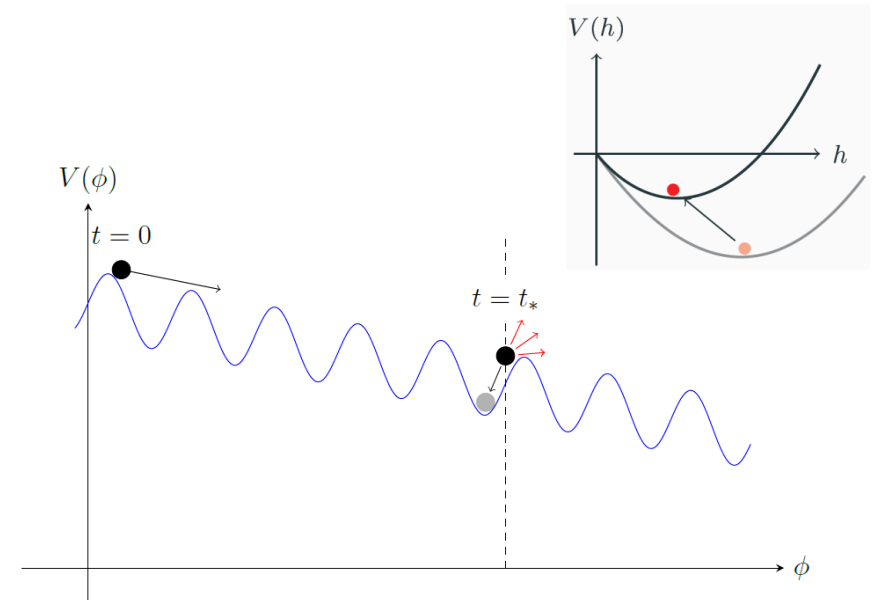
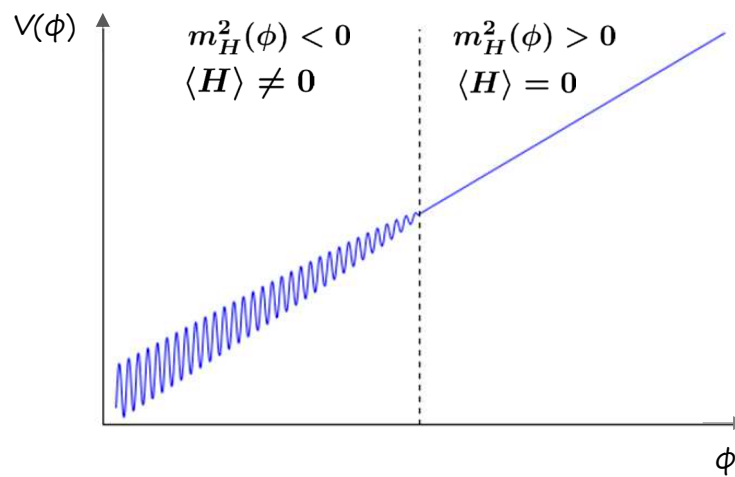
Stopping  
Mechanism

HIGGS-DEPENDENT BARRIER

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

PARTICLE PRODUCTION

$$\sim \frac{\phi}{f} V_{\text{SM}} \tilde{V}_{\text{SM}}$$



## ○ Relaxion as Dark Matter

NF, Morgante; '18

Stopping  
Mechanism

HIGGS-DEPENDENT BARRIER

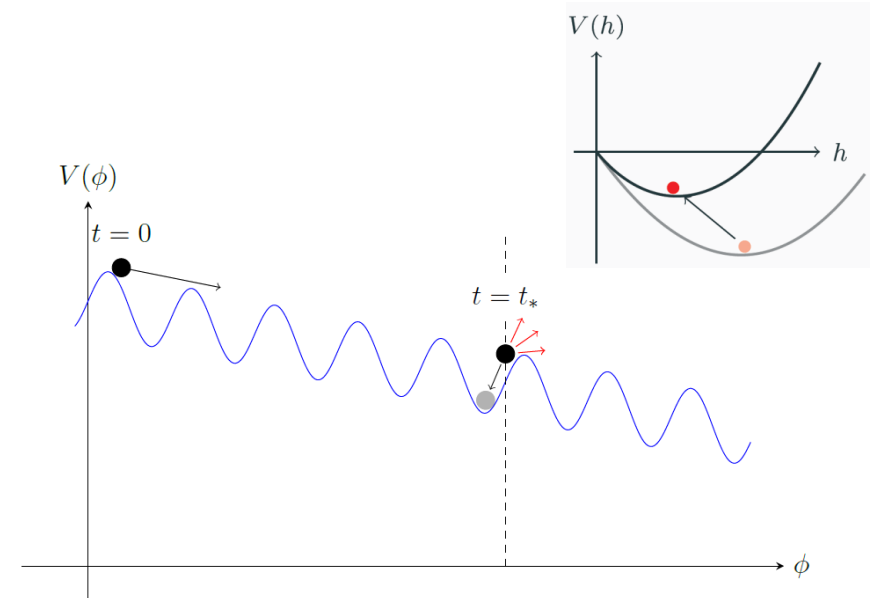
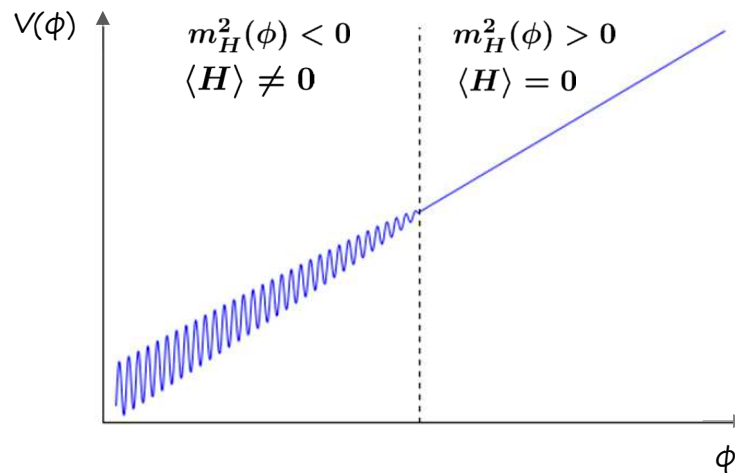
$$\sim \Lambda_b^4(\langle H \rangle) \cos \phi / f'$$

PARTICLE PRODUCTION

$$\sim \frac{\phi}{f} V_{\text{SM}} \tilde{V}_{\text{SM}}$$

**Disclaimer:** Focus on representative cases...

Apologies for **hybrid** models!



See also Banerjee, Kim, Perez '18; Abel, Gupta, Scholtz '18 ; Gupta, Reiness, Spannowsky '19, ...

## ○ Relaxion as Dark Matter

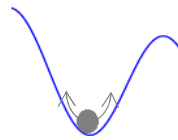
NF, Morgante; '18

		$\sim \Lambda_b^4(\langle H \rangle) \cos \phi / f'$	$\sim \frac{\phi}{f} V_{\text{SM}} \tilde{V}_{\text{SM}}$
Stopping Mechanism	HIGGS-DEPENDENT BARRIER	PARTICLE PRODUCTION	
When?	During Inflation	After Inflation	
Misalignment			
Thermal scattering			

Dark Matter

Relaxion  
Abundance:

Misalignment





Thermal scattering

$$a_{\text{SM}} + b_{\text{SM}} \rightarrow \phi + c_{\text{SM}}$$



## ○ Relaxion as Dark Matter

NF, Morgante; '18

NF, Morgante; '18		
	$\sim \Lambda_b^4(\langle H \rangle) \cos \phi / f'$	$\sim \frac{\phi}{f} V_{\text{SM}} \tilde{V}_{\text{SM}}$
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NF, Morgante; '18

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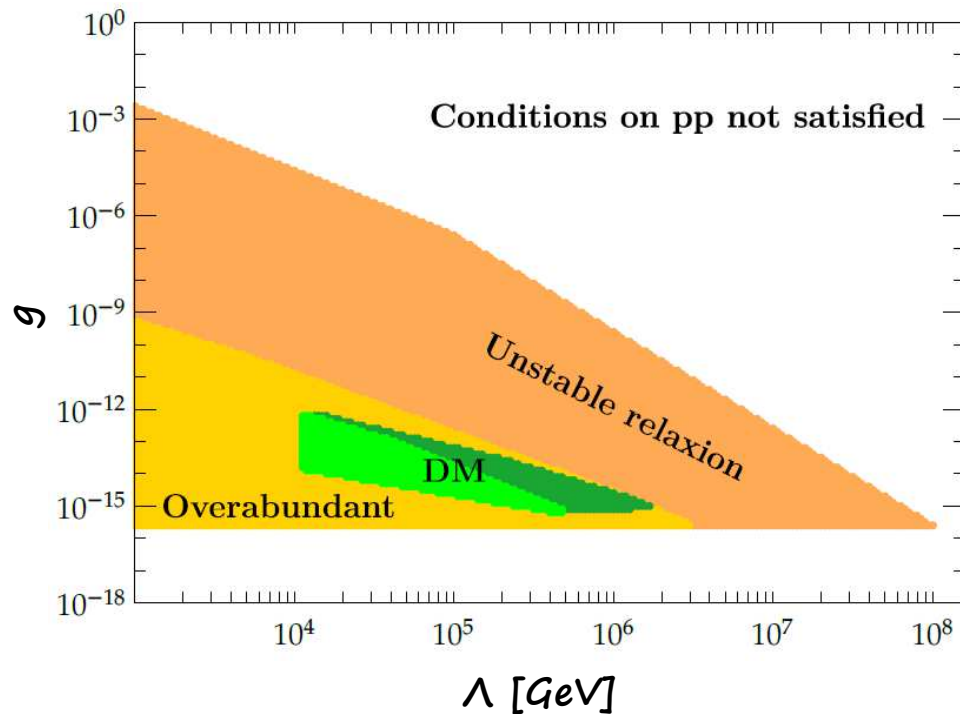
Particle production + inflation ➡

## ○ Relaxion as Dark Matter

NF, Morgante; '18

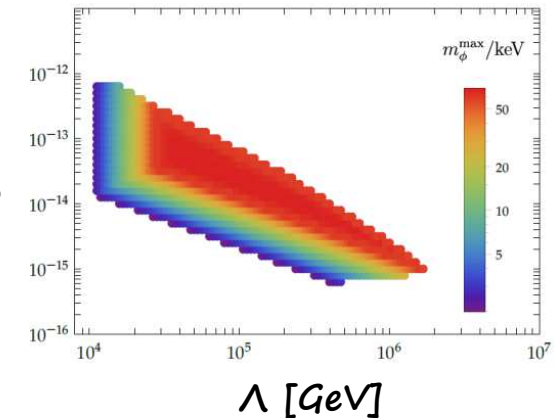
Particle production during inflation 

Inflation: dilute misalignment & more freedom for  $T_{RH}$



○ Phenomenologically viable DM candidate;

○ Relaxion is warm;  $g$



○ Motivate DM keV range: dedicated studies on ID and on the impact on structure formation.

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



Relax.



@ Miniatur Wunderland

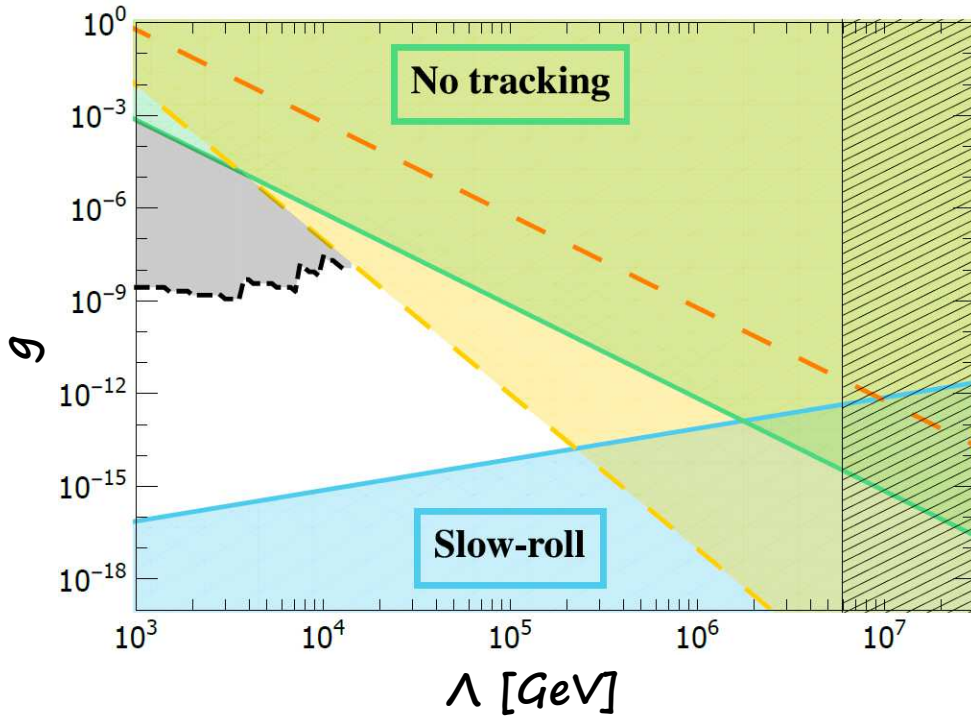
Thanks!

*Parameter space*

- *Parameter space*

## Relaxation after inflation

NF, E. Morgante, G. Servant '18



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

## Relaxation during inflation

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

