Relaxion Fragmentation

EM, N. Fonseca, R. Sato, G. Servant

1911.08472, 1911.08473

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15. Kosmologietag, ~~Bielefeld~~ **cyberspace**

References

Talk based on

1. N. Fonseca, EM, R. Sato, G. Servant, *Axion fragmentation*, JHEP 04 (2020), 010 [arXiv:1911.08472 [hep-ph]]

2. N. Fonseca, EM, R. Sato, G. Servant, *Relaxion Fluctuations (Self-stopping Relaxion) and Overview of Relaxion Stopping Mechanisms*, JHEP (accepted), 010 [arXiv:1911.08473 [hep-ph]]

3. (EM, W. Ratzinger, R. Sato, B. Stefanek, *in preparation*)

Relaxion

Motivation

Cure the EW hierarchy problem without NP at the EW scale, in cosmology

Relaxion mechanism Graham, Kaplan, Rajendran 1504.07551, PRL

- ϕ a classically evolving pNGB
- Higgs – ϕ coupling (via a spurion $g\Lambda$)

$$\mu_h^2 h^2 = (\Lambda^2 - g\Lambda\phi)h^2$$

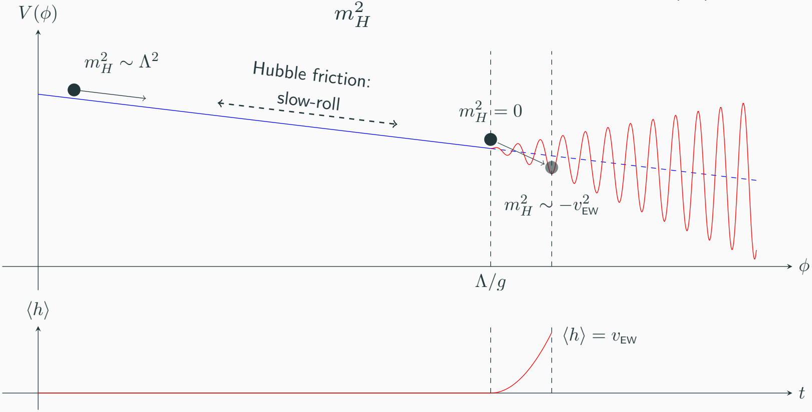
- Backreaction mechanism stops the evolution of ϕ when

$$\mu_h^2 \approx v_{\rm EW}^2 \ll \Lambda^2$$

The relaxion mechanism

Graham, Kaplan, Rajendran 1504.07551, PRL

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



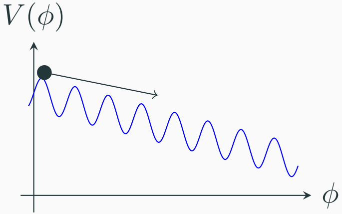
(Rel-)axion fragmentation

Relaxion fluctuations

So far, ϕ classical and uniform field. Include fluctuations:

$\phi \to \phi_0 + \delta\phi$

$$\ddot{\delta\phi}_k + (k^2 + V''(\phi_0))\delta\phi_k = 0$$



$V'' \sim \cos \omega t$

parametric resonance

growth of fluctuations

Growth of fluctuations

For $\ddot{\phi} = 0$ it's a Mathieu equation: exponentially growing solutions!

$$\ddot{\phi}_k + \left(k^2 + \frac{\Lambda_b^4}{f^2} \cos \frac{\dot{\phi}\, t}{f} \right) \phi_k = 0$$

Very well known equation (preheating, but also engineering)

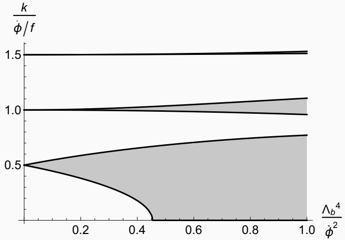
$$\frac{\mathrm{d}^2 y}{\mathrm{d}t^2} + (\delta + \varepsilon \cos t) y = 0 \quad \longrightarrow$$

First instability band:

$$\frac{\dot{\phi}^2}{4f^2} - \frac{\Lambda_b^4}{2f^2} < k^2 < \frac{\dot{\phi}^2}{4f^2} + \frac{\Lambda_b^4}{2f^2}$$

Exponential growth

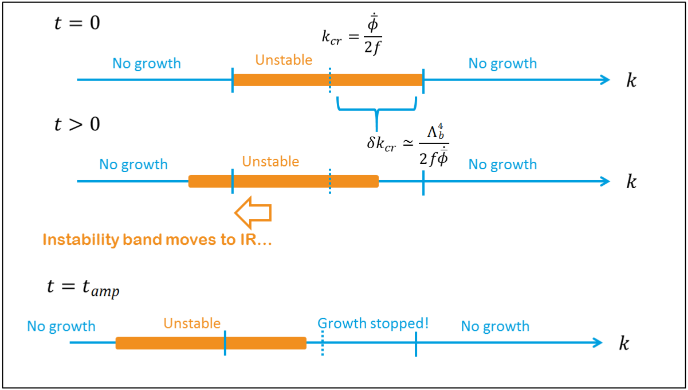
$$\phi_k \sim \exp\left[\sqrt{\delta k_{\rm cr}^2 - (k - k_{\rm cr})^2} \right] \sin(\dots)$$



Backreaction on the zero mode

Backreaction (at first order):

$$\ddot{\phi}_0 + V'(\phi_0) = \frac{1}{2} V'''(\phi_0) \int \frac{\mathrm{d}^3 x}{\mathrm{Vol}} \langle \delta\phi^2 \rangle$$



credit: R. Sato

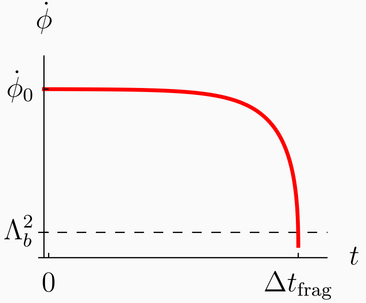
Compute the backreaction

The growth of fluctuations can be computed *analytically* at linear level*.

The relaxion stops in a finite time

$$\Delta t_{\text{frag}} \sim \frac{f\dot{\phi}_0^3}{\Lambda_b^8} \log \frac{f^4}{\dot{\phi}_0^2}$$

$$\Delta \phi_{\text{frag}} \sim \frac{f\dot{\phi}_0^4}{\Lambda_b^8} \log \frac{f^4}{\dot{\phi}_0^2}$$



* non-linear effects under control
(EM, Ratzinger, Stefanek, Sato, in preparation)

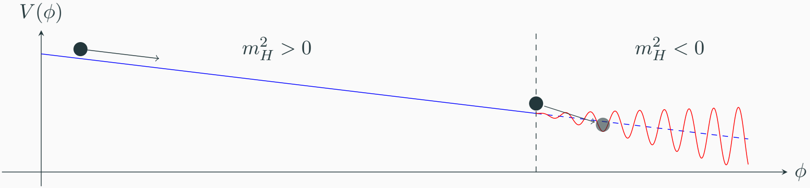
Consequences

Consequences

Growth of relaxion fluctuations can stop the relaxion field!

- If $\Lambda_b \sim h^n$, can provide an alternative friction source other than Hubble friction
- If Λ_b constant, ϕ stops at a random position: potentially very dangerous!

Relaxion with Higgs-dependent barriers



Original model (GKR)

The field goes over the barriers in more than 1 Hubble time

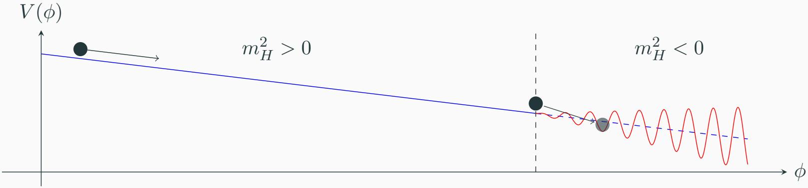
$$\Delta t_1 > H^{-1} \;\Rightarrow\; \dot{\phi} = \frac{V'}{3H}$$

ϕ stops when $V' = 0$

$$g\Lambda^3 \approx \frac{\Lambda_b^4}{f}$$

Crucially requires a **strong Hubble friction**

Relaxion with Higgs-dependent barriers



Fragmentation

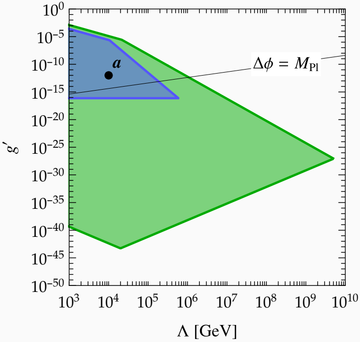
ϕ fast rolls over many barriers in more than 1 Hubble time

$$\Delta t_1 < H^{-1}$$

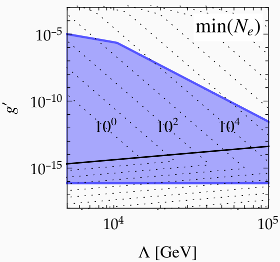
ϕ stops at $\Delta\phi_{\text{frag}}$ independently of Hubble friction

- opens new parameter space during inflation
- relaxation can take place **after inflation**

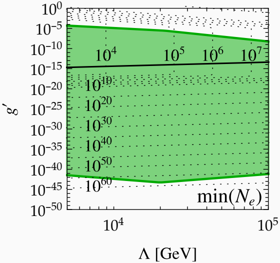
Parameter space



Fragmentation



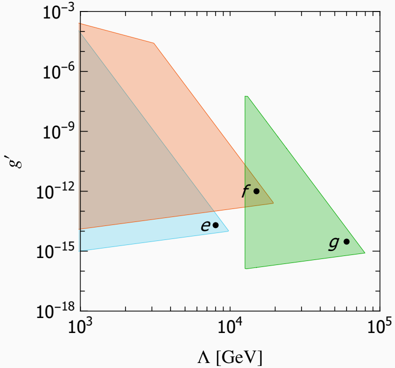
Hubble friction (GKR)



Relaxation after inflation

Hubble friction is not necessary to slow down the field

$$H \approx 0 \qquad \Rightarrow \qquad \dot{\phi} \sim \Lambda^2$$



- (blue) $\dot{\phi} = \sqrt{2\, g/g'}\, \Lambda^2$, $g/g' = 1$
- (orange) $\dot{\phi} = \sqrt{2\, g/g'}\, \Lambda^2$, $g/g' = 1/(4\pi)^2$
- (green) $\dot{\phi} = 10^{-2}\sqrt{2}\, \Lambda^2$

$\Rightarrow$ No need for large N_e

$\Rightarrow$ *in principle* observable

$\Rightarrow$ Think about cosmological history: Ω_ϕ, GW, . . .

Relaxion driving inflation?

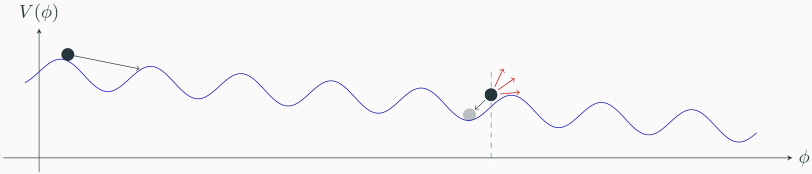
The relaxion can drive a period of inflation.

- Attempted in the original construction, but it was not possible to generate enough perturbations (1706.03072)
- With fragmentation, $N_e \sim 10$ is possible. It can be a "secondary" inflation period
- The cutoff can be pushed up to $\mathcal{O}(100)\,\mathrm{TeV}$

Relaxation with particle production

[Hook & Marques-Tavares 1607.01786, JHEP]

$$\mathcal{L} \supset -g\Lambda^3\phi - \frac{1}{2}(g\Lambda\phi - \Lambda^2)h^2 + \Lambda_b^4 \cos\frac{\phi}{f'} - \frac{\phi}{4f} Z_{\mu\nu}\widetilde{Z}^{\mu\nu} + \frac{\pi\alpha}{2} Z_\mu Z^\mu h^2$$



Fragmentation

Constant wiggles $\Rightarrow$ fragmentation is always active!

- Slow-down independent of the Higgs vev
- Need to avoid fragmentation (Hubble friction, steep potential)

Relaxation with particle production

During inflation [1607.01786, 1809.04534]

- Small velocity, low barriers
- Exclude some parameter space
- Model still alive (also Relaxion DM [1809.04534])

After inflation [1607.01786, 1805.04543]

- Fragmentation enhanced (large velocity)
- Cosmo/astro constraints
- Model is **excluded**

Summary

Fragmentation: a built-in effect with important consequences

- provides additional friction
- serious problem if barriers are constant
- new parameter space with viable inflationary scenario (N_e)
- relaxation after inflation
- observable features?

Thank you!

Effect of the expansion and of the slope

- Hubble friction suppresses the growth of fluctuations

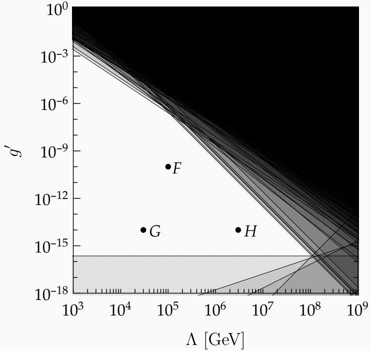
$$\ddot{u}_k + 3H\dot{u}_k + (k^2 + V'')u_k = 0$$

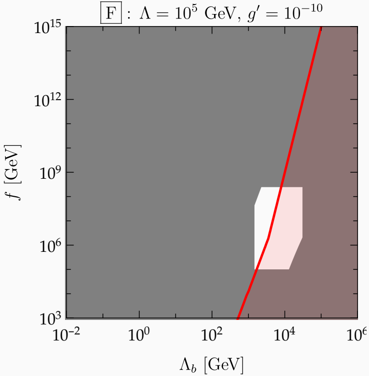
- The slope accelerates the field, contrasting fragmentation

Both must be suppressed

$$\begin{cases} H < \dfrac{\Lambda_b^4}{3f\dot{\phi}} \quad \Leftrightarrow \quad \dot{\phi} < \dfrac{\Lambda_b^4}{fg\Lambda^3}\dot{\phi}_{\rm SR} \qquad \text{trivial for } \dot{\phi} < \dot{\phi}_{\rm SR} \\ g\Lambda^3 < 2H\dot{\phi} + \dfrac{\pi\Lambda_b^8}{2f\dot{\phi}^2}\left[W_0\left(\dfrac{32\pi^2 f^4}{e\dot{\phi}_0^2}\right)\right]^{-1} \end{cases}$$

During inflation





After inflation