Out-of-the-box Baryogengesis;

Or how the relaxion already has a built-in baryogensis mechanism

[1810.05153]

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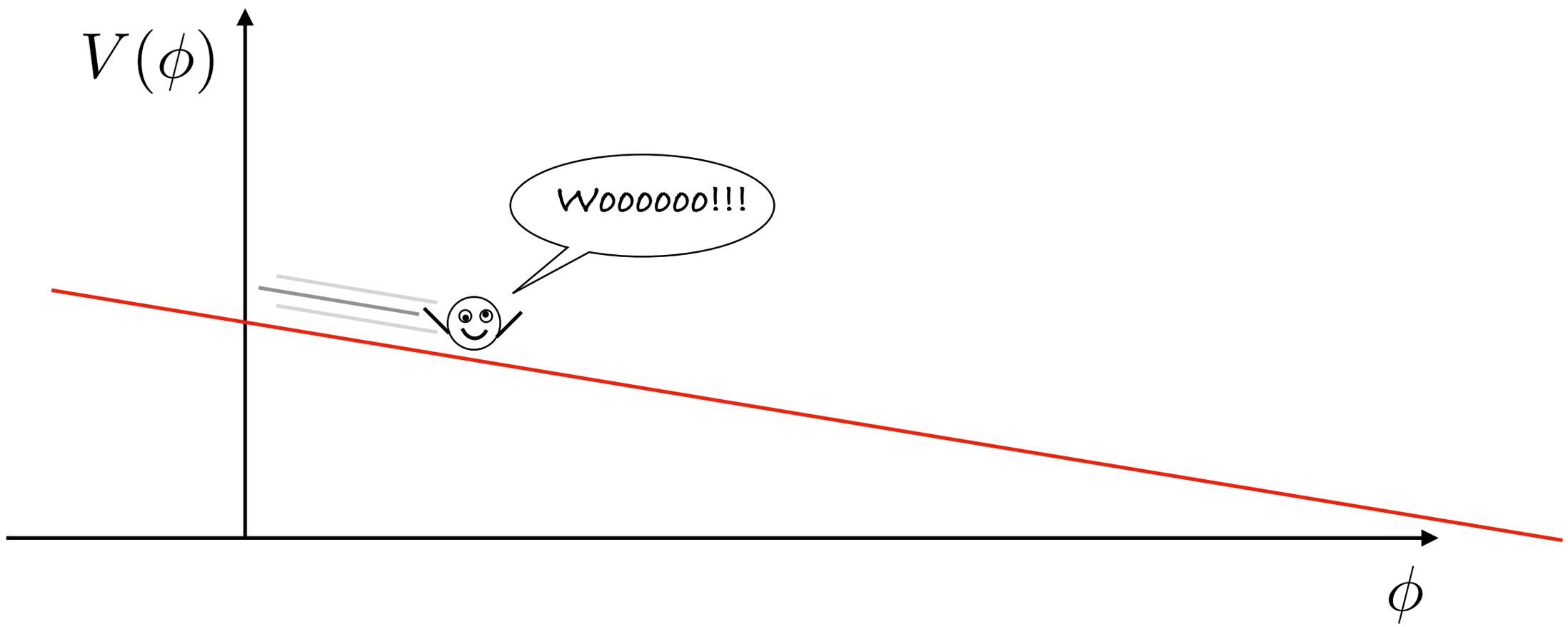
Work with S.A. Abel and R.S. Gupta

Contents

- Relaxion [1504.07551]
- Spontaneous Baryogenesis [Cohen, Kaplan, Nelson]
- They were meant to be together. [1810.05153]
- Coupling between the Standard Model fermions and the Relaxion
- Conclusions

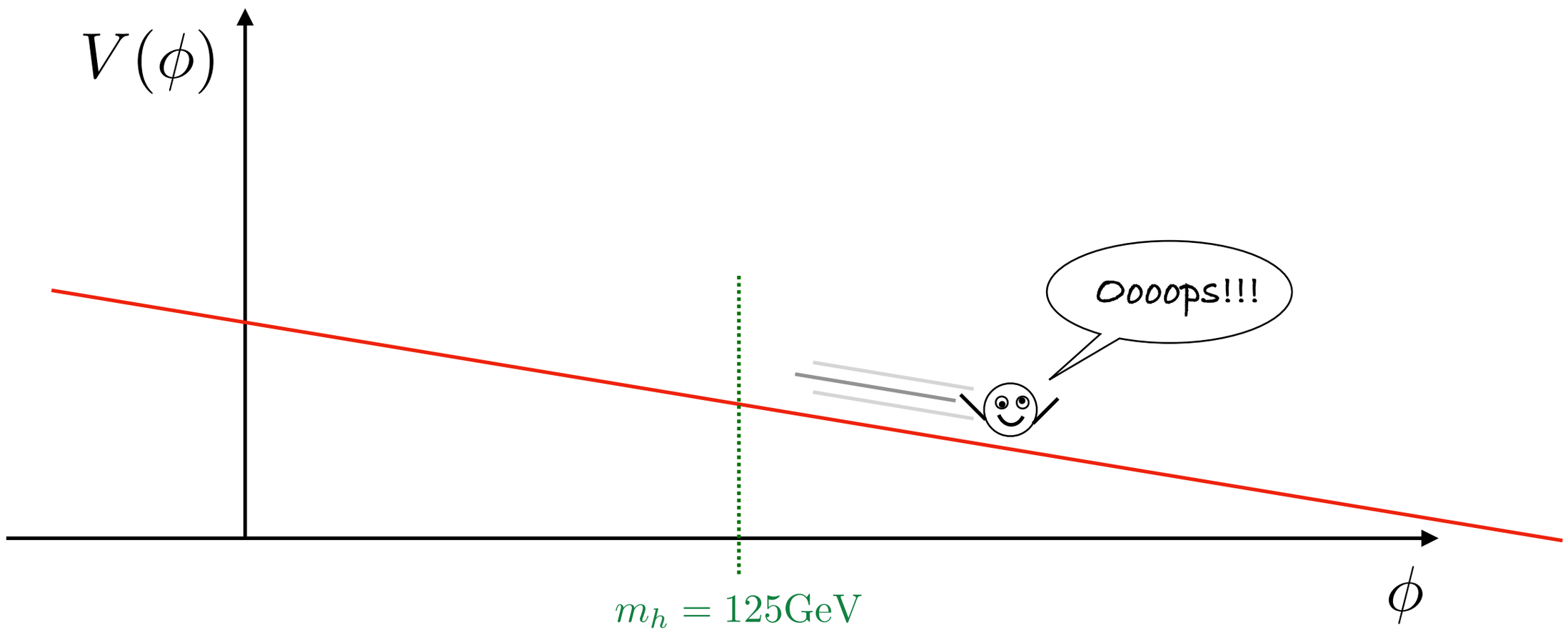
Relaxion — a fun toy model



$$\mathcal{L} = \kappa \Lambda^3 \phi$$

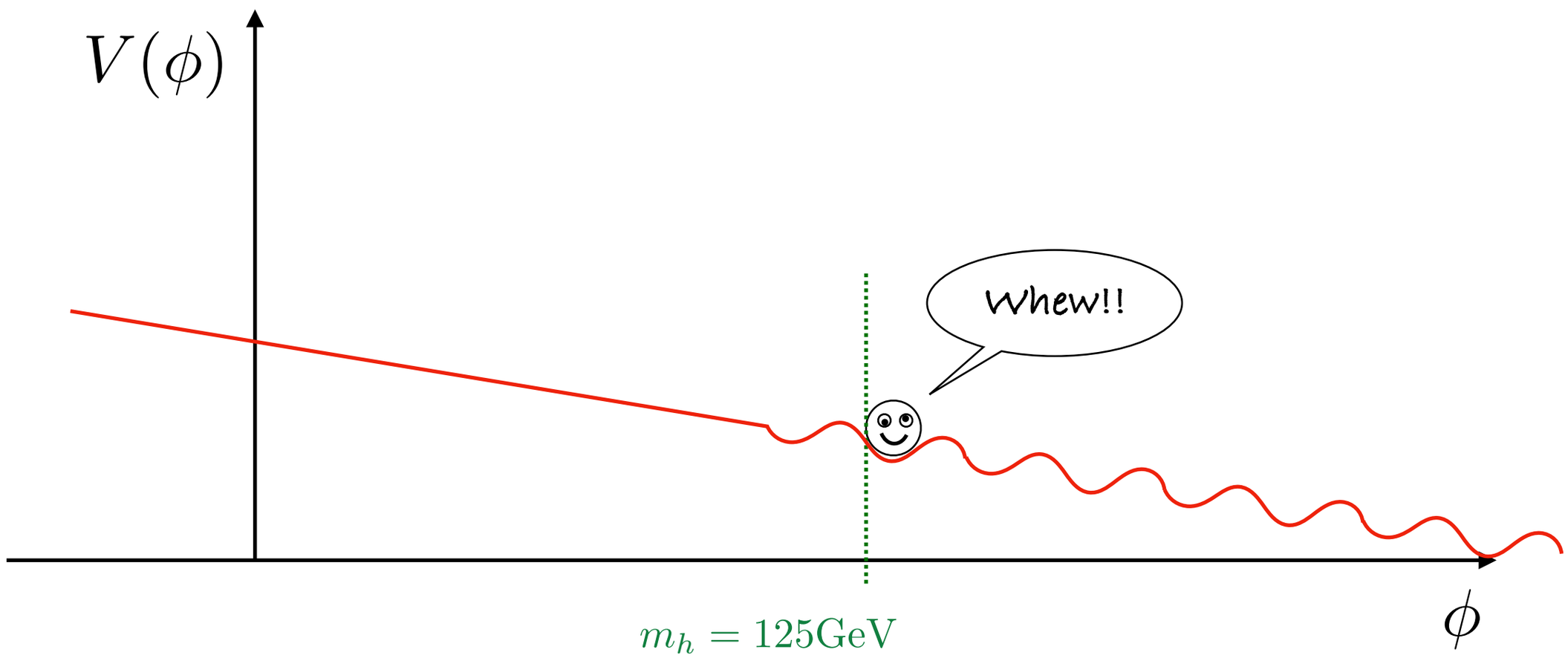
[1504.07551]

Relaxion — a fun toy model



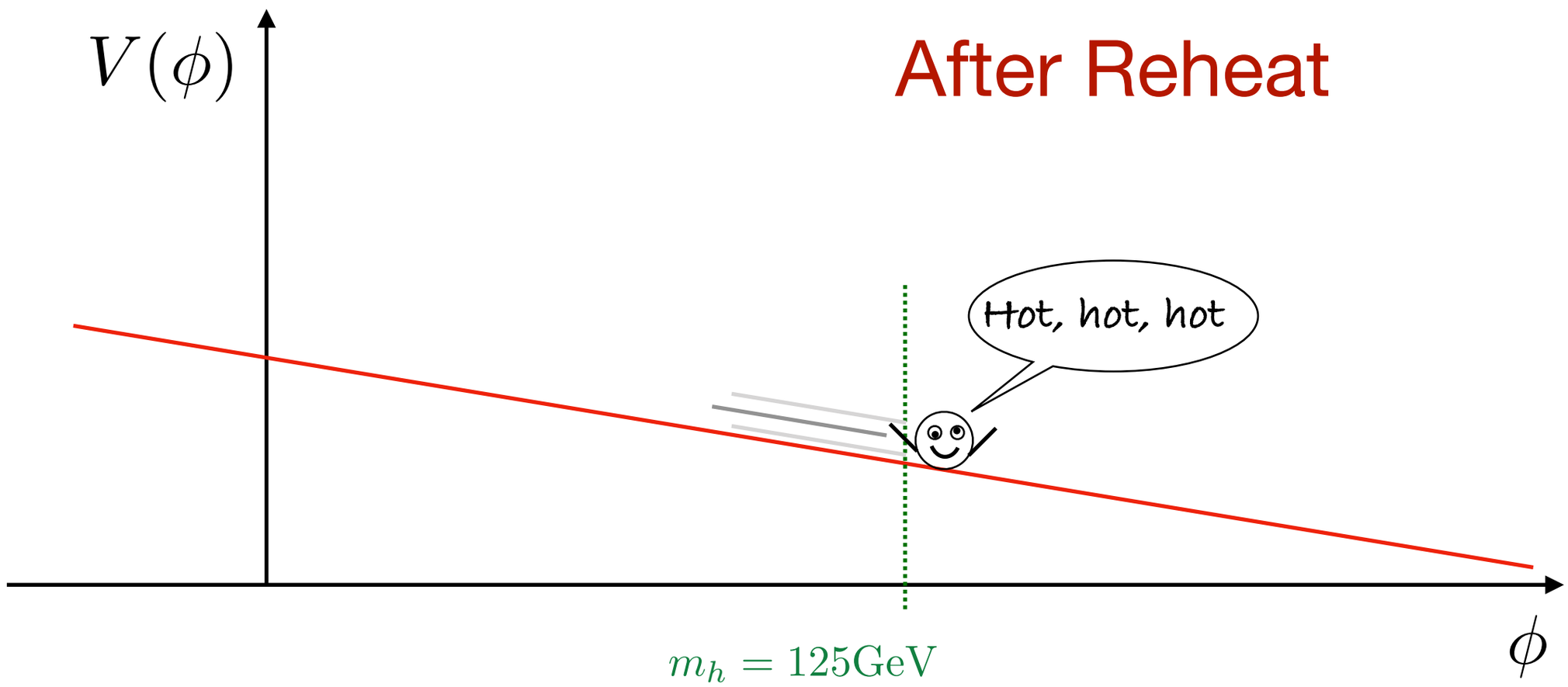
$$\mathcal{L} = \kappa\Lambda^3\phi + (\Lambda^2 - \phi^2)H^2$$

Relaxion — a fun toy model



$$\mathcal{L} = \kappa\Lambda^3\phi + (\Lambda^2 - \phi^2)H^2 + \Lambda_{QCD}(\langle H\rangle)\cos(\phi/f)$$

Relaxion — a fun toy model



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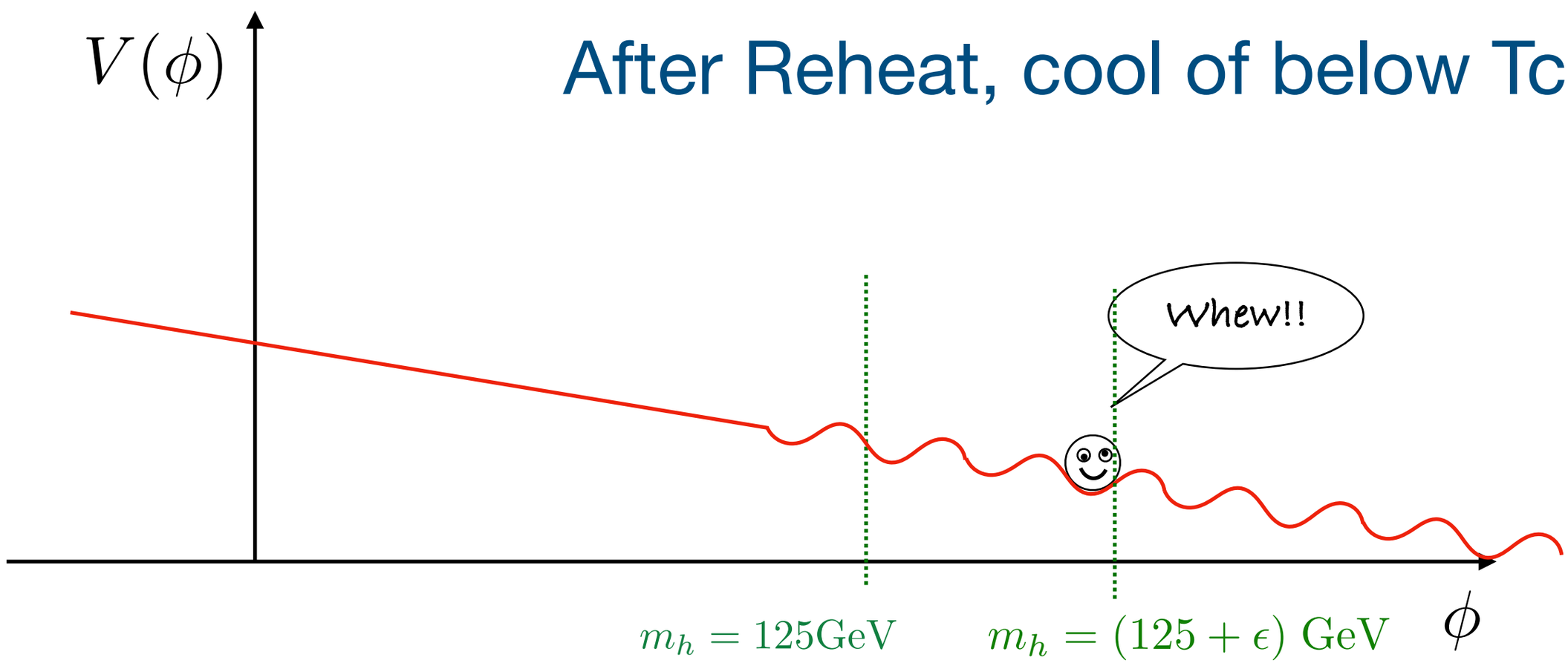
Relaxion — a fun toy model



$$\mathcal{L} = \kappa\Lambda^3\phi + (\Lambda^2 - \phi^2)H^2 + \Lambda_{QCD}(\langle H \rangle)\cos(\phi/f)$$

Relaxion — a fun toy model

There are issues:

- There is a large hierarchy between the linear term and the relaxion scale. (Though there are clockwork solutions)
- If the strongly coupled dynamics is SM QCD, then we generate too large theta_QCD, because of the additional slope. This implies we require a new strongly coupled sector.
- In order to relax the EW scale, the relaxion has to perform a huge field excursion >> Mpl.

And some solutions:

- There are other ways to stop the relaxion: by particle production.
- The clockwork mechanism relieves the hierarchies.

This is why it is best to think of these as toy models for proof of concept…

Spontaneous Baryogenesis

$$\mathcal{L} = V(\phi) + \frac{\partial_\mu \phi}{f} J^\mu$$

[Cohen, Kaplan, Nelson]

Spontaneous Baryogenesis

$$\mathcal{L} = V(\phi) + \frac{\partial_\mu \phi}{f} J^\mu$$

$$\partial_t \phi = \Lambda^2 \neq 0, \quad \text{but} \quad \partial_i \phi = 0 \quad \longrightarrow \quad \Delta\mathcal{H} = \frac{\Lambda^2}{f} J^0 = \mu Q$$

$$\downarrow$$

If I were to also turn on some Q-violating operator then I would start producing net Q number.

This is happening in equilibrium. (You ~~might~~ should be worried)

[Cohen, Kaplan, Nelson]

Spontaneous Baryogenesis

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Spontaneous Breaking of CPT by the background:

Sakharov Conditions don't apply.

[Cohen, Kaplan, Nelson]

Spontaneous Baryogenesis

$$\mathcal{L} = V(\phi) + \frac{\partial_\mu \phi}{f} J_B^\mu + \mathcal{O}_{\Delta B}$$

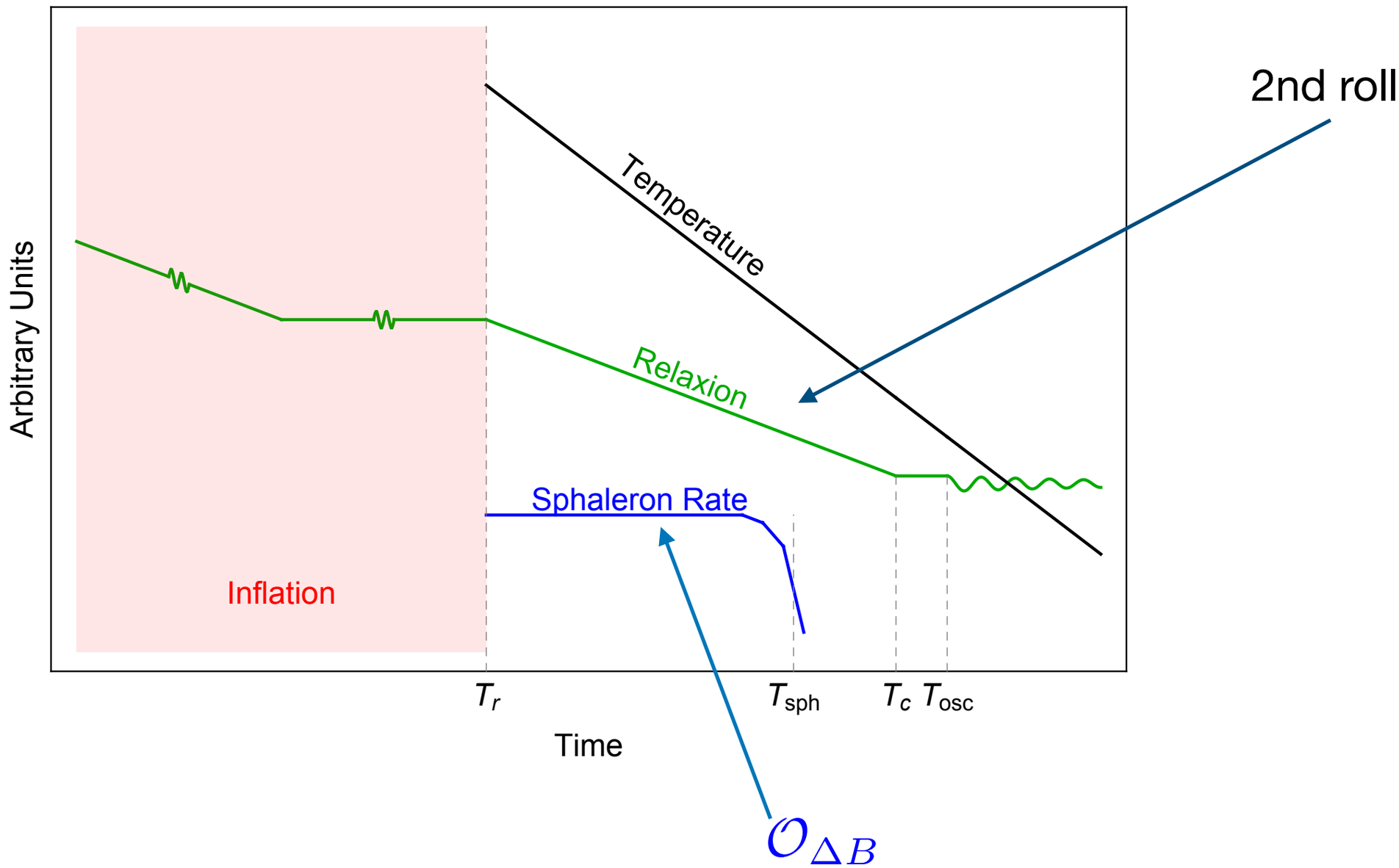
$\partial_t \phi = \Lambda^2 \neq 0, \;\; \text{but} \;\; \partial_i \phi = 0$ and $\mathcal{O}_{\Delta B}$ is in equilibrium

$$\Delta n_B \propto \mu T^2 = \frac{\Lambda^2 T^2}{f}$$

If $\mathcal{O}_{\Delta B}$ decouples before the field stops rolling, this asymmetry is 'locked in' at that temperature.

[Cohen, Kaplan, Nelson]

The big picture…



Lagrangian Description

$$\mathcal{L} = \kappa\Lambda^3\phi + (\Lambda^2 - \phi^2)H^2 + \Lambda_c(|H|)\cos(\phi/f_w) + \frac{\partial_\mu\phi}{f}J^\mu + \mathcal{O}_{sph}$$

Relaxion

New

SM

$$\eta = \frac{15}{4\pi^2}\frac{g_{\rm SB}}{g_*^{3/2}}\frac{m_\phi^2 m_{\rm pl}}{T_{\rm sph}^3}\frac{f_{\rm w}}{f}$$

$$m_\phi^2 = \Lambda_{\rm c}^4/f_{\rm w}^2$$

$$\Lambda_c(|H|)\cos(\phi/f_w) \to \mu^2 h\phi$$

Coupling the Relaxion to the Standard Model

$$\frac{\partial_\mu \phi}{f} \bar{\Psi} \gamma^\mu \Psi$$

"Froggatt-Nielsen-like"

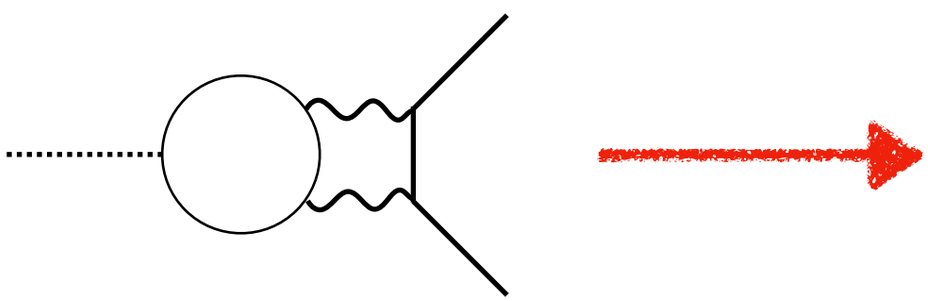
$$\Phi \bar{\Psi} \Psi \longleftrightarrow \lambda \exp(i\phi/f) \bar{\Psi} \Psi$$

$$\frac{\phi}{f} \tilde{F}_{\mu\nu} F^{\mu\nu}$$

- Fields redefinitions allow us to trade between the operators. Typically two are always present.
- "Clever" choice of charges can remove the anomaly coupling.
- But, the couplings run…

Running couplings

- The anomalous current can have a non-zero anomalous dimension [hep-ph/9302240]

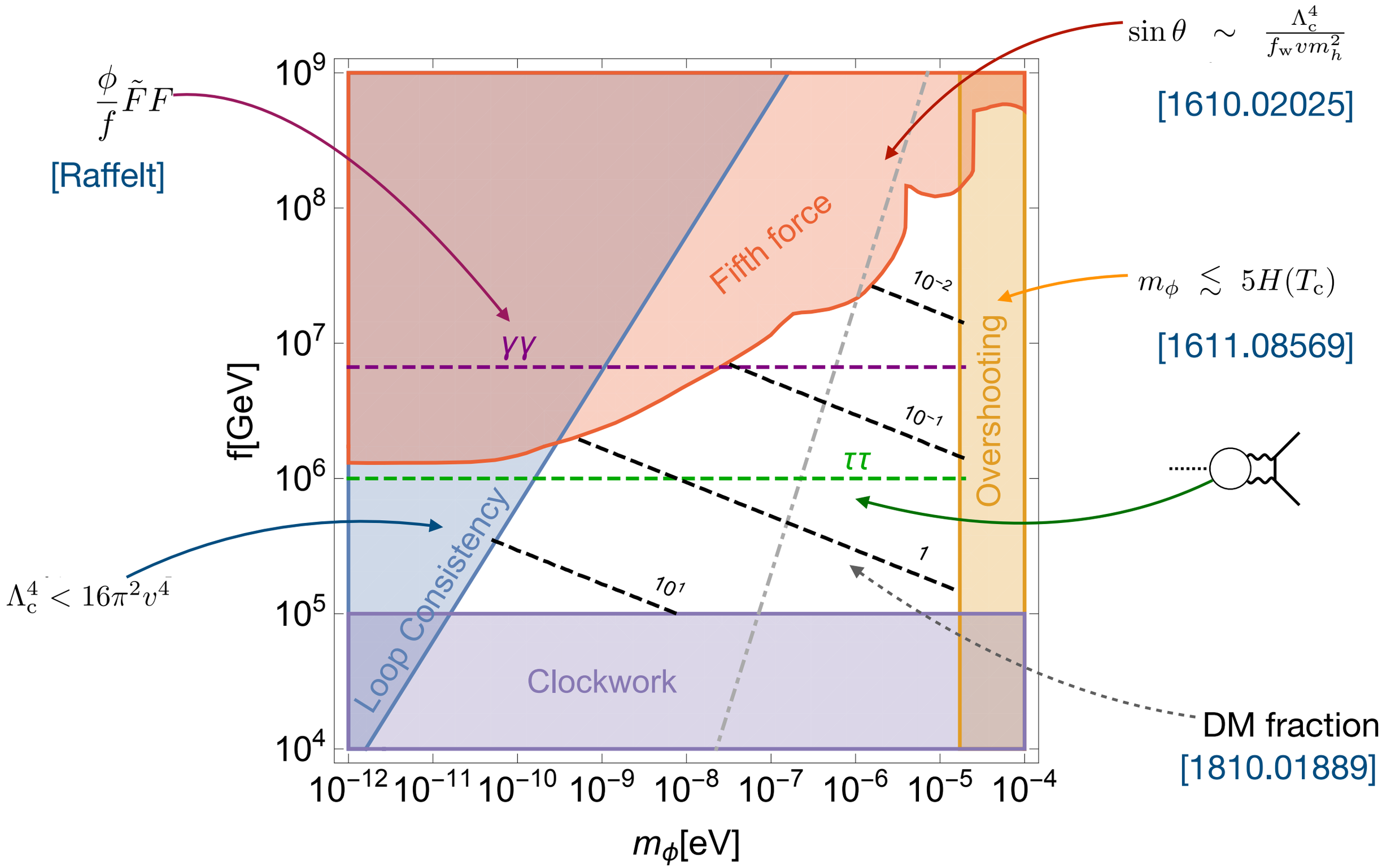


$$\frac{d\log Z}{d\log\mu} = \gamma_A = \frac{3n_F C_F}{8}\left(\frac{\alpha_i}{\pi}\right)^2 + \dots$$

- This is a well known two-loop effect for quarks
- It applies to leptonic couplings as well through the loops of Ws. Funnily enough, partly because there are four SU(2) fundamentals per generation, this effect is not as small.
- For example: if we couple to just tau at some high scale we still generate significant-ish couplings to all other fermions.

$$c_i = \frac{9n_g}{32\pi^2} c_\tau(f)\alpha_2^2(m_Z)\log f/m_Z = 8\times 10^{-4}\Big|_{f=10^6\,\mathrm{GeV}}$$

Is it safe?


$\frac{\phi}{f}\tilde{F}F$
[Raffelt]
$\sin\theta \sim \frac{\Lambda_c^4}{f_w v m_h^2}$
[1610.02025]
$m_\phi \lesssim 5H(T_c)$
[1611.08569]
$\Lambda_c^4 < 16\pi^2 v^4$
DM fraction
[1810.01889]
Fifth force
Loop Consistency
Clockwork
Overshooting
$\gamma\gamma$
$\tau\tau$
10^{-2}
10^{-1}
1
10^{1}
f[GeV]
m_ϕ[eV]
10^9
10^8
10^7
10^6
10^5
10^4
10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4}

Conclusions

- If you couple the Relaxion to a SM model current that carries lepton/ baryon number you get a pretty natural baryogensis scenario.
- This may be dangerous: this coupling allows for cooling of stars. However, not insurmountable.
- This does come at a cost: You need an additional hierarchy between the relaxion scale and the scale that suppresses this new operator. But this hierarchy was already present…
- It is consistent with axion being a DM candidate. [Banerjee, after coffee]
- Interesting extension into neutrino sector already exists [1902.08633]
- We should keep playing with the relaxion scenario and see if we can make it work better…