Out-of-the-box Baryogengesis;

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

[1810.05153]

Jakub Scholtz
(IPPP)
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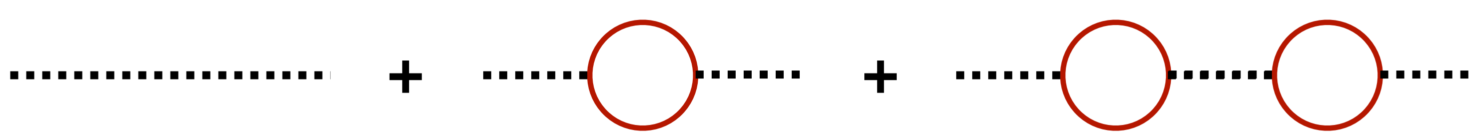
Work with S.A. Abel and R.S. Gupta

Contents

Hierarchy Problem

Scalars pick up the mass-scale of whatever they couple to
(probably the only accidentally well chosen name)

$$\delta\Pi(p \to 0) = \int_m^{m_{\rm pl}} \frac{dq^4}{(2\pi)^4} \frac{g}{q^2+m^2} \approx \frac{g}{16\pi^2}\left(m_{\rm pl}^2 - m^2\right) + \mathcal{O}(\log)$$



$$\frac{1}{p^2+m^2} + \frac{1}{p^2+m^2}\delta\Pi(0)\frac{1}{p^2+m^2} + \frac{1}{p^2+m^2}\delta\Pi(0)\frac{1}{p^2+m^2}\delta\Pi(0)\frac{1}{p^2+m^2} + \ldots = \frac{1}{p^2+m^2+\delta\Pi(0)}$$

Hierarchy Problem

$$\delta m_H^2 \sim \frac{\lambda}{16\pi}\Lambda_{\rm cut}^2$$

- Say I ignore the Planck corrections (claiming some quantum gravity magic/ ignorance), I am forced into either of three scenarios:

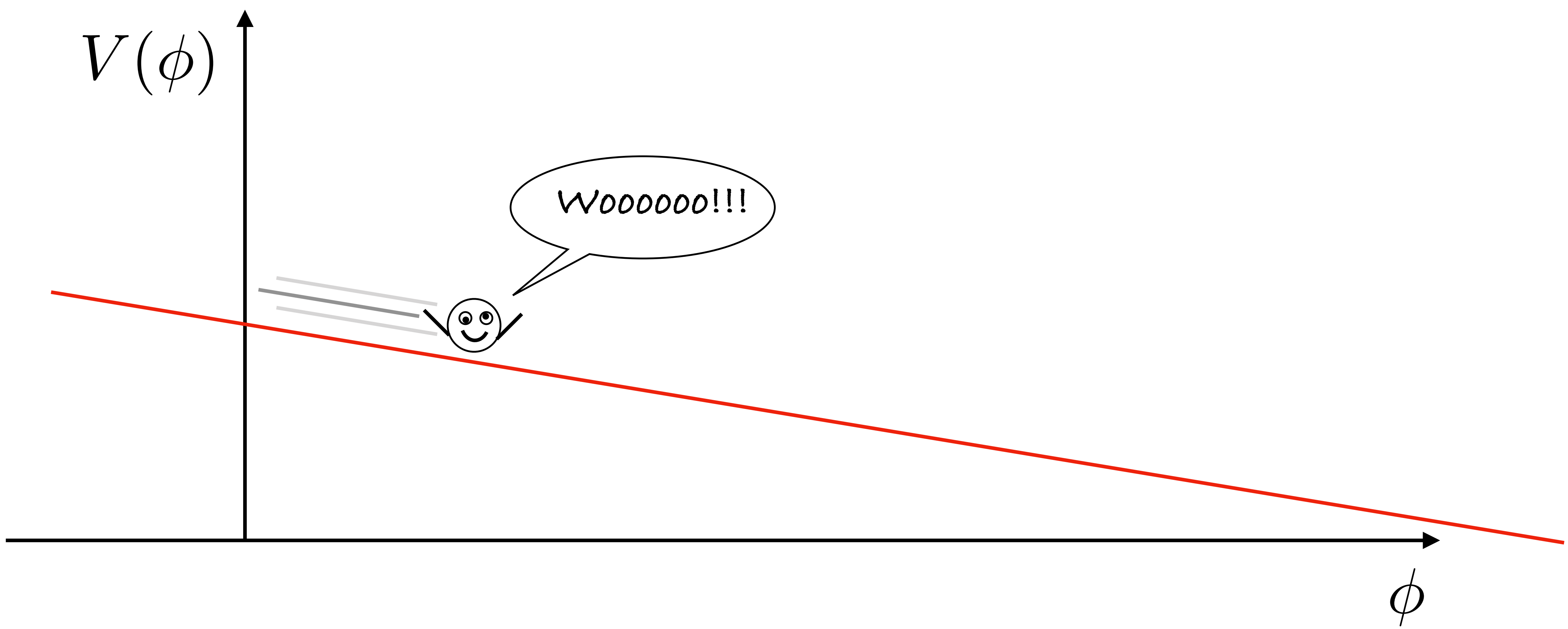
  A. There are no particles that couple to Higgs between the weak scale and Planck scale (at any appreciable loop level)

  B. I fine-tune the theory: at some UV scale I set the Higgs bare mass as to precisely cancel all the contributions from all the loops.

  C. If there any particles that couple to Higgs, they do so in a very peculiar way as to cancel/suppress the contribution to its mass: symmetries

  D. Let dynamics determine the Higgs mass : The Relaxion[1504.07551]

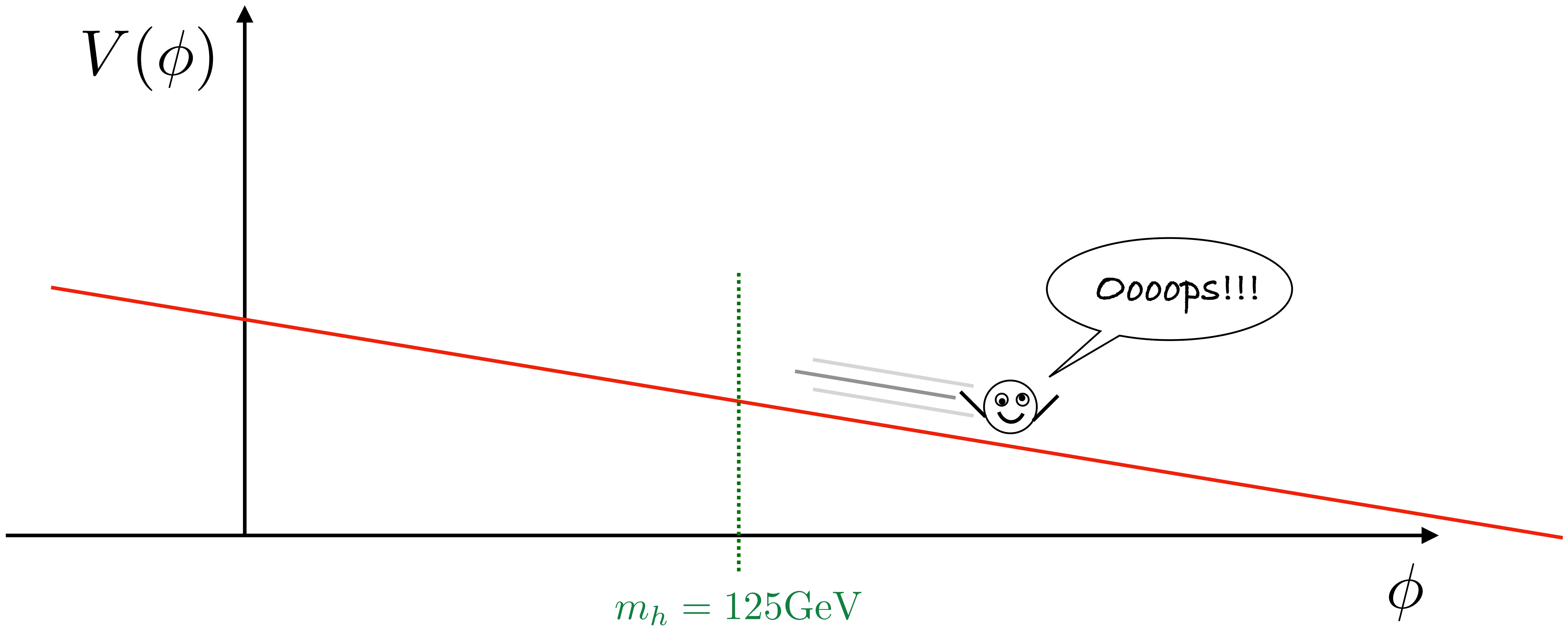
Relaxion — a fun toy model



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

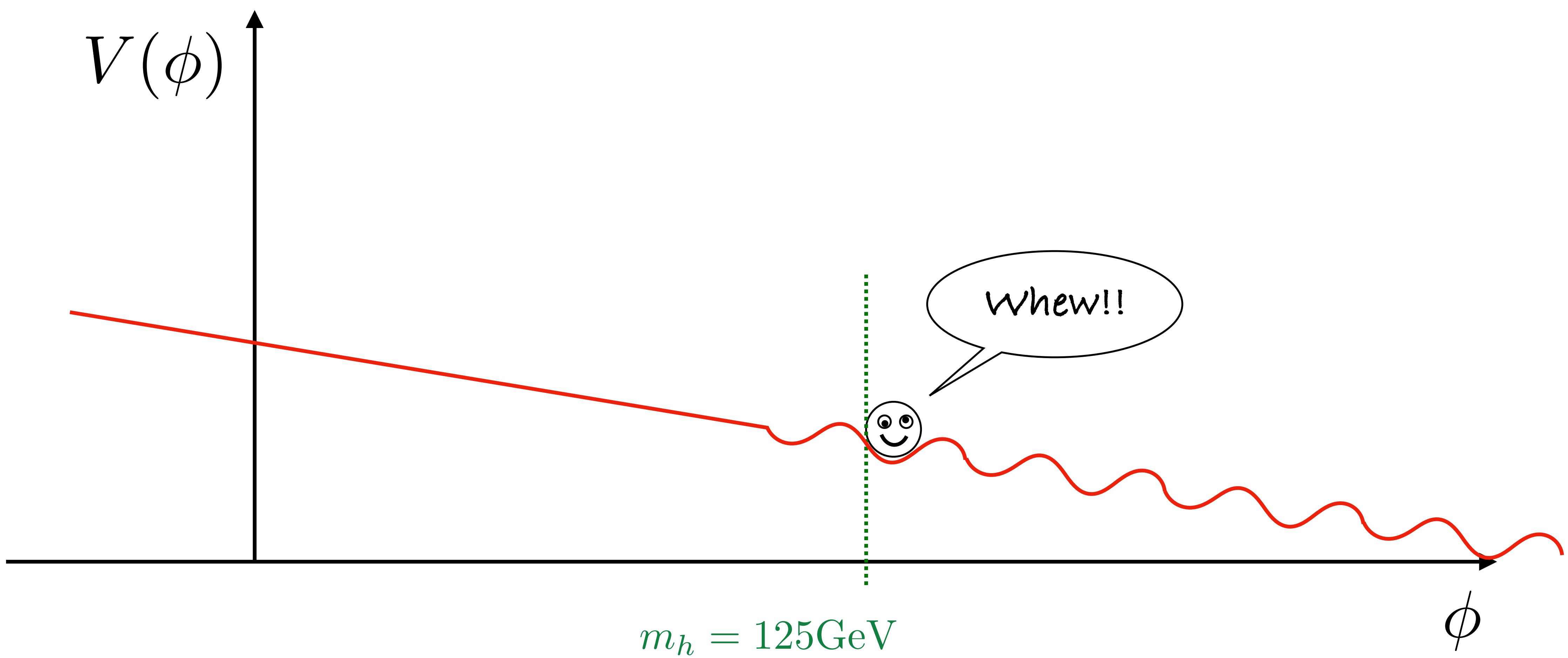
[1504.07551]

Relaxion — a fun toy model



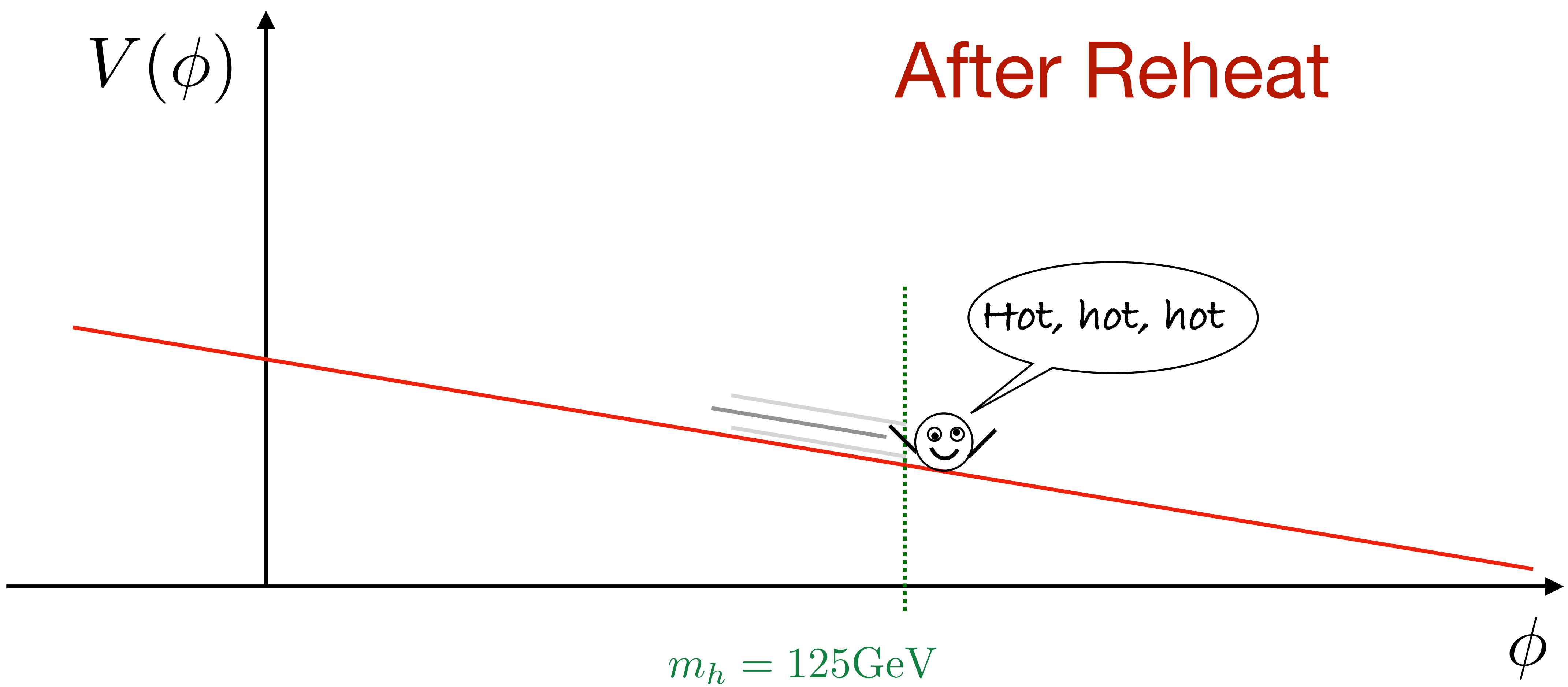
$$\mathcal{L} = \kappa\Lambda^3\phi + \left(\Lambda^2 - \phi^2\right)H^2$$

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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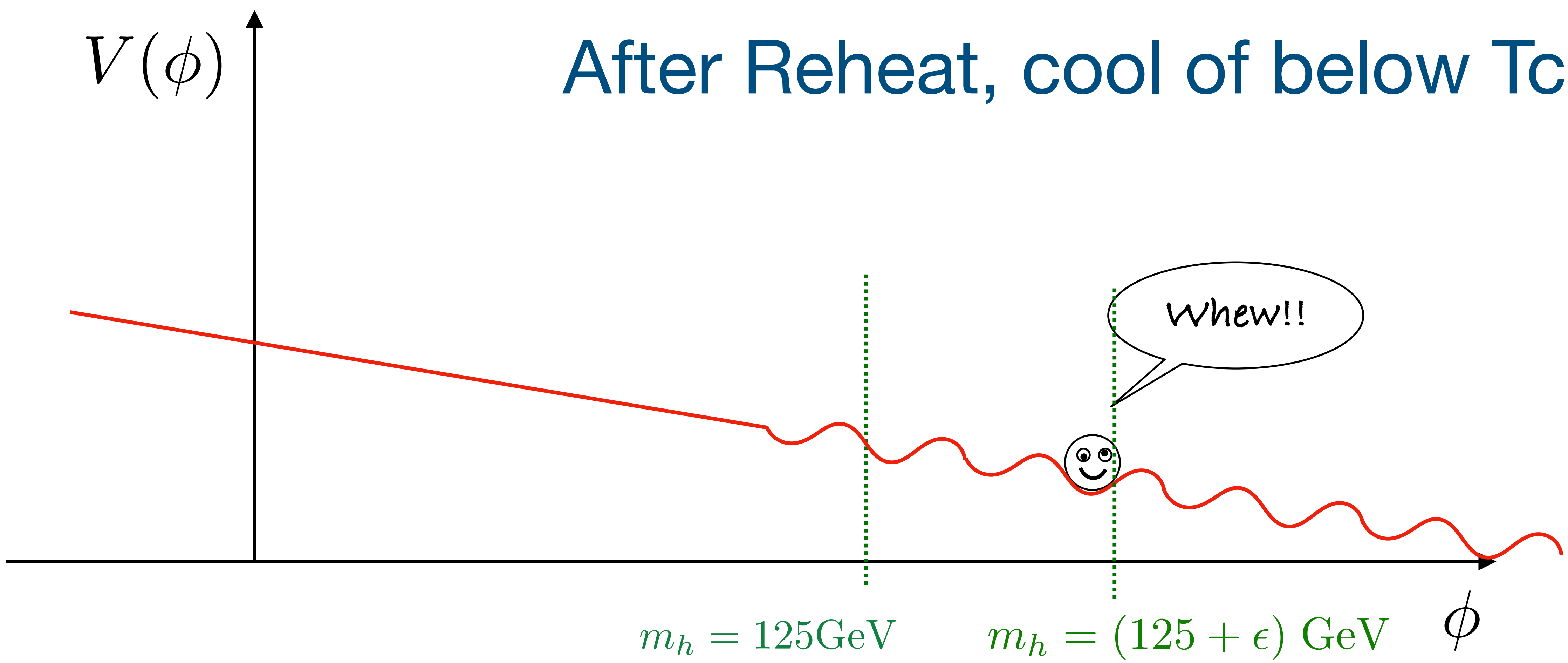
Relaxion — a fun toy model



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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.
- The relaxion naturally scans the CC, how is the EW vacuum so lucky to give the right CC?

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…

We live in an asymmetric world…

- The Standard Model sector is dominated by baryons (and not anti-baryons), at least by energy density.
- However, by particle count the Standard Model is barely asymmetric:

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 10^{-9}$$

- There are no pockets of anti-baryons (the boundaries would be very bright).
- The Standard Model prediction (as is), is significantly lower:

$$\eta_{\mathrm{SM}} = \frac{n_b + n_{\bar{b}}}{n_\gamma} < 10^{-20}$$

Sakharov Conditions

Condition 1: You need Baryon number violation.

If baryon number is conserved, then you cannot change baryon number, duh.

Condition 2: You need CP violation.

$$\langle B|H|i\rangle = \langle \bar{B}|H|i^*\rangle \quad \longrightarrow \quad n_B = n_{\bar{B}}$$

Condition 3: Must be out of equilibrium.

$$\Gamma(\mathrm{bath} \to \mathrm{bath} + B) = \Gamma(\mathrm{bath} + B \to \mathrm{bath})$$

Spontaneous Baryogenesis

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

[Cohen, Kaplan, Nelson]

Spontaneous Baryogenesis

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

Imagine that Cosmology gives me:

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

$\downarrow$

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

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

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Spontaneous Breaking of CPT by the background:

Sakharov Conditions don't apply.

[Cohen, Kaplan, Nelson]

Digression: Chemical Potential and net charge…

$$\Delta \mathcal{H} = \frac{\Lambda^2}{f} J^0 = \mu Q \quad \longrightarrow \quad n_Q = \int \frac{dp^3}{\exp\left(\frac{E+Q\mu}{T}\right) \pm 1}$$

$$n_Q - n_{-Q} = \int \frac{dp^3}{\exp\left(\frac{E+Q\mu}{T}\right) \pm 1} - \int \frac{dp^3}{\exp\left(\frac{E-Q\mu}{T}\right) \pm 1}$$

$$\approx \frac{\mu}{T} \int \frac{\exp\left(\frac{E}{T}\right) dp^3}{\left(\exp\left(\frac{E}{T}\right) \pm 1\right)^2} + \mathcal{O}(\mu^2/T^2)$$

$$\boxed{\propto \mu T^2}$$

Spontaneous Baryogenesis

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

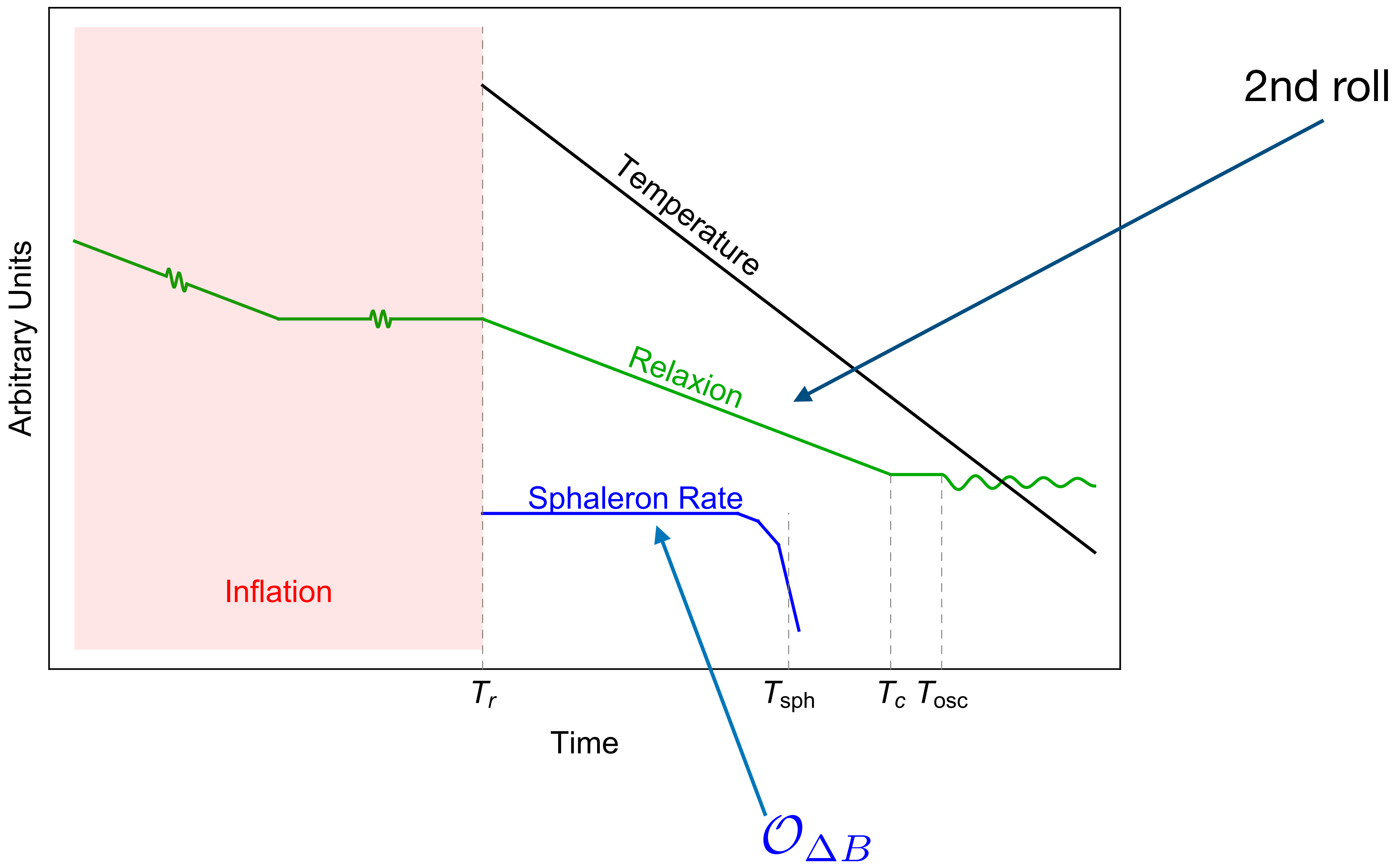
$\partial_t \phi = \Lambda^2 \neq 0, \;\; \text{but} \;\; \partial_i \phi = 0$ and $\mathcal{O}_{\Delta B}$ is in equilibrium

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

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

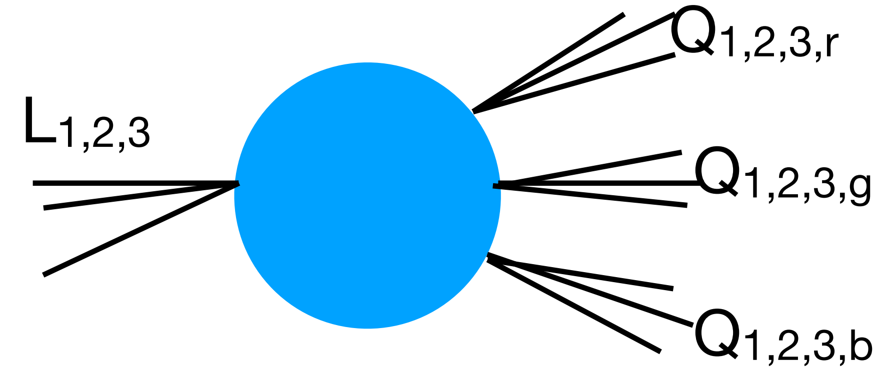
[Cohen, Kaplan, Nelson]

The big picture…

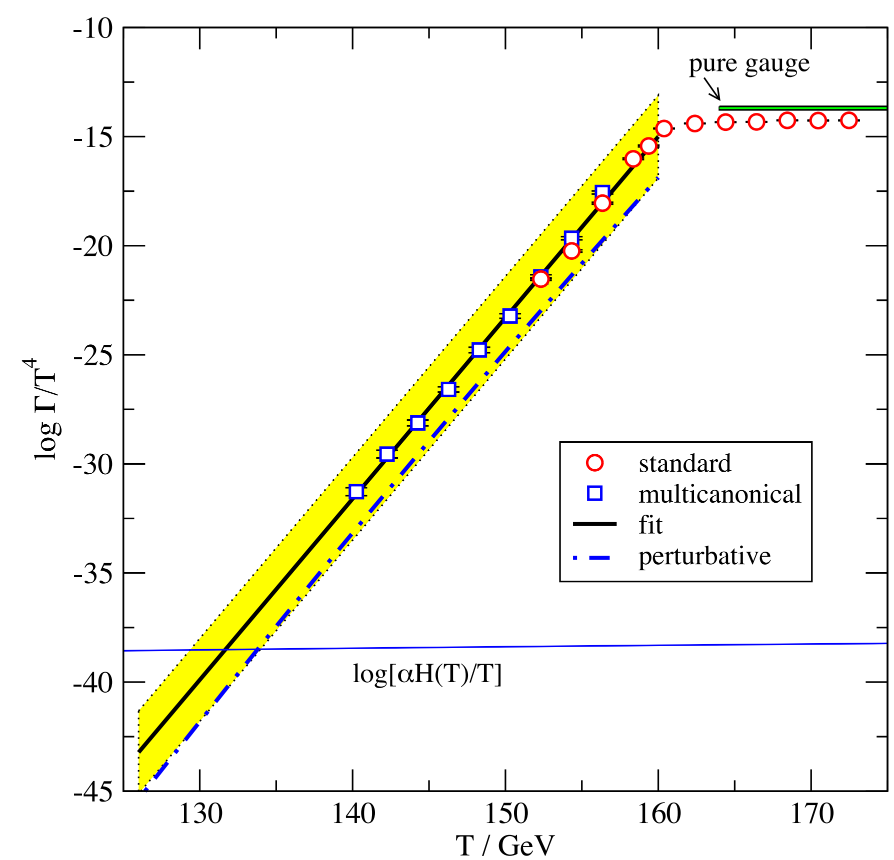


Digression: Sphalerons

- They are non-perturbative diffuse configurations of Electroweak fields. By definition they couple to all the left-handed quarks and leptons at once.
- One can think of them as a blob that can trade quarks for leptons.
- As a result, they conserve B-L, but violate B+L
- Below EW scale, they are very difficult to excite. But above EW temperatures, they are ever-present.
- Normally, they erase baryon number, here they help!



uu —> u ccc ttt ddd e τ μ



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

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

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

$$m_\phi^2 = \frac{\partial^2}{\partial\phi^2}\Lambda_c^4\cos(\phi/f_w)\Big|_{\phi\to 0}$$

$$\mu^2 = \frac{\partial}{\partial\phi}\frac{\partial}{\partial h}\Lambda_c^4\cos(\phi/f_w)\Big|_{\phi\to 0, h\to 0}$$

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

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

Coupling the Relaxion to the Standard Model

"Froggatt-Nielsen-like"

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

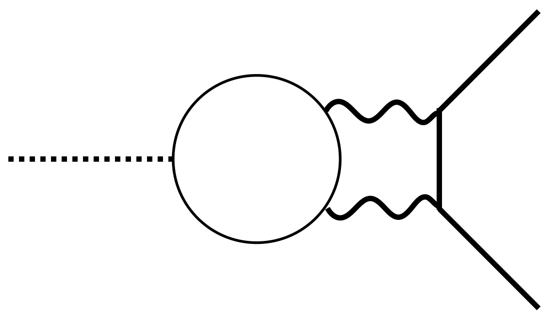
$$\frac{\partial_\mu \phi}{f}\bar{\Psi}\gamma^\mu\Psi$$

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

- 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]



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

- 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.

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

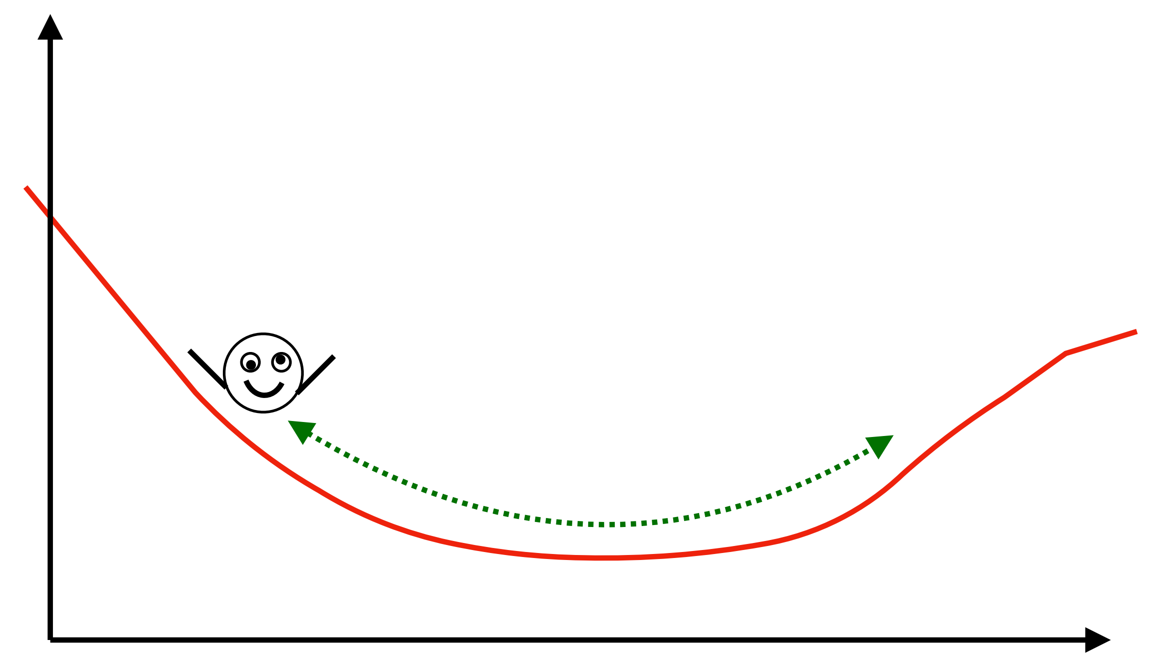
Constraints

- Overshooting —> if the relaxion is too heavy, the barrier might not stop it. [1611.08569]
- Loop Consistency —> we need to make sure that the dominant contribution to the wiggly potential comes after the Higgs vev is turned on. [1504.07551]
- Mixing with the Higgs —> produces fifth force between leptons, baryons. For light relaxion, this fifth force is severely constrained by torsion pendulum experiments like EotWash. [1610.02025]
- Coupling to matter in general —> allows hot SM particles to radiate a light relaxion away, and cool down. This could affect star evolution. [Raffelt]

Relaxion Dark Matter

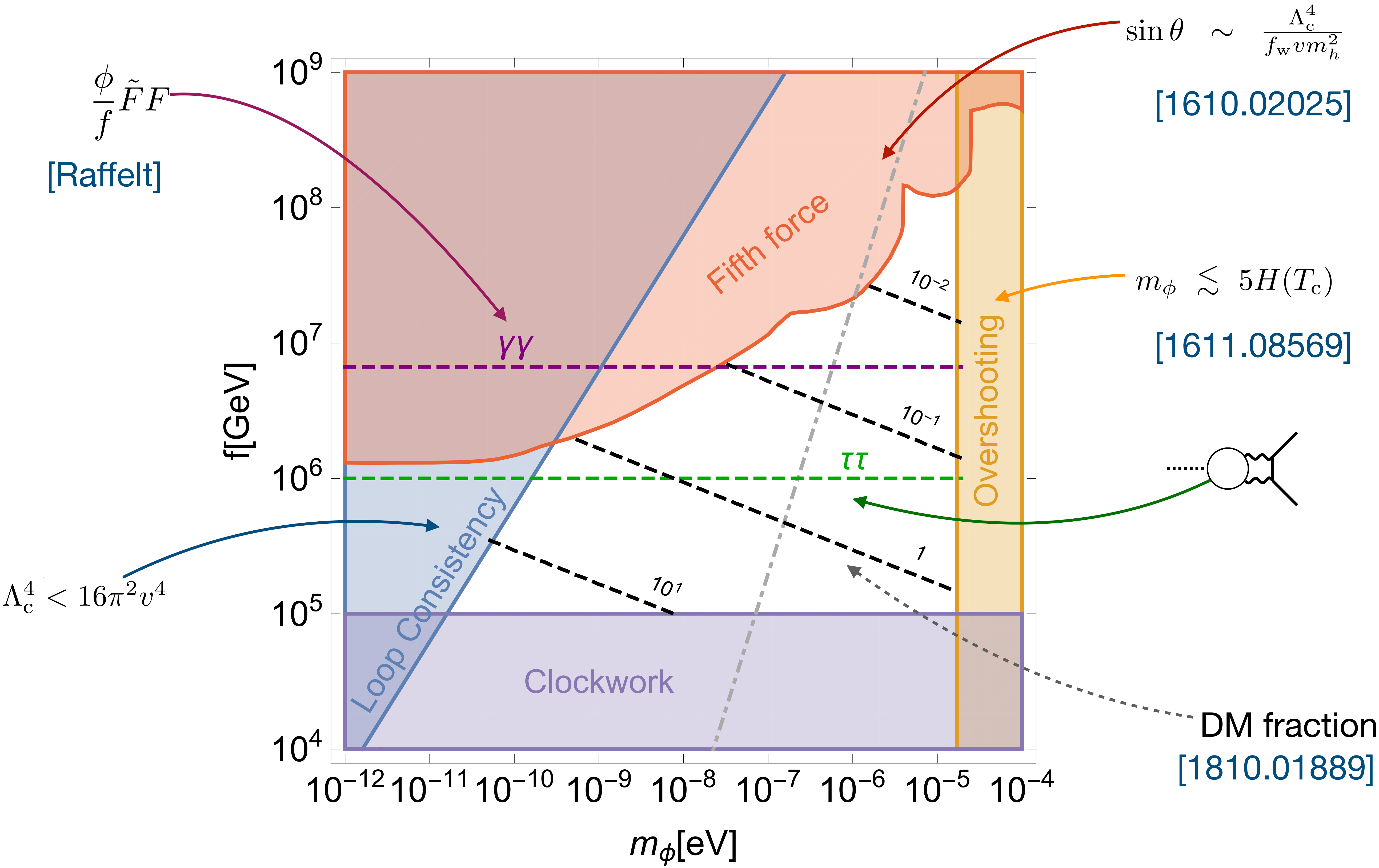
[1810.01889]

- The relaxion rolls with a certain speed and then ends up inside a minimum of a wiggle
- Oscillations around this minimum can be interpreted as a density of particles in a coherent state (like a BEC)
- There are regimes of parameter space, in which this density is the same as the necessary Dark Matter density.
- Coherently oscillating field acts as matter.



$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

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
Overshooting
Loop Consistency
Clockwork
$\gamma\gamma$
$\tau\tau$
10^{-2}
10^{-1}
1
10^{1}
f[GeV]
m_ϕ[eV]
10^4
10^5
10^6
10^7
10^8
10^9
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.
- 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…
- Ask me about Planet 9 being a Black Hole (about as speculative) or about CP violations in D—>ππ and D—>KK and BSM