# Non-adiabatic particle production in the dynamical relaxation

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in collaboration with Z. Lalak (paper in preparation)

# Outline

- Dynamical relaxation: what it is all about?
- Particle production as an energy dissipation mechanism
  - Vector case
  - Scalar case

# Motivation

- Quantum corrections to the Higgs' mass are quadratically divergent. If there is no new physics Higgs mass should be of the order of the Planck scale
- Most protection mechanisms (SUSY, extra dimensions) predict new physics close to the electroweak scale, but we don't see one in experiments
- Can we devise a model that predicts a hierarchy of scales, but is natural (no fine tuning)?

# How relaxation works?

Graham, Kaplan, Rajendran, 2015

Drives relaxion towards smaller values

Higgs-relaxion interaction

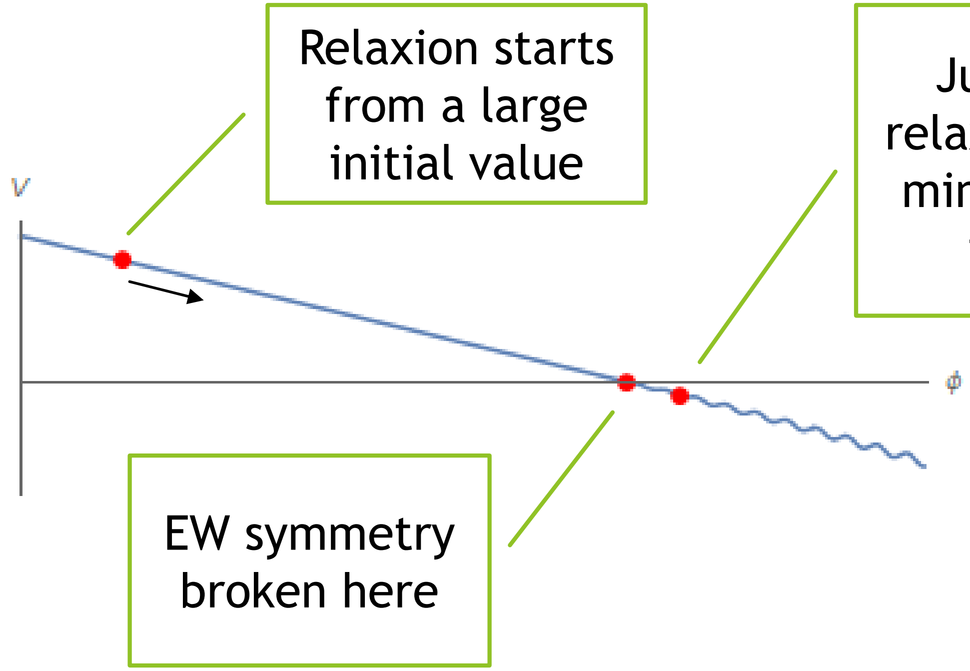
Higgs quartic interaction

$$V(\phi, h) = g_1 \Lambda^3 \phi + (\Lambda^2 - g_2 \Lambda \phi) h^2 + \frac{\lambda}{4} h^4 + v^n \Lambda_b^{4-n} \cos\left(\frac{\phi}{f}\right)$$

Quantum-corrected Higgs mass term

Effective potential from relaxion's anomalous coupling

# How relaxation works?




$$v = \sqrt[n]{\frac{g_2 \Lambda^3 f}{\Lambda_b^{4-n}}}$$

# Problems

- Quantum corrections can spoil the relaxation process

$$\Lambda_b^4 \cos\left(\frac{\phi}{f}\right) \qquad g_2\phi\Lambda_b^3 \cos\left(\frac{\phi}{f}\right)$$

Solution: CHAIN [Espinosa et al., 2015]

- Requires an ongoing inflation to dissipate relaxion's energy
- Inflation must be very slow and very long

$$H_I^3 < g_1\Lambda^3 \qquad N_e > \frac{H_I^2}{g_1^2\Lambda^2}$$

- Are transplanckian field excursions possible?

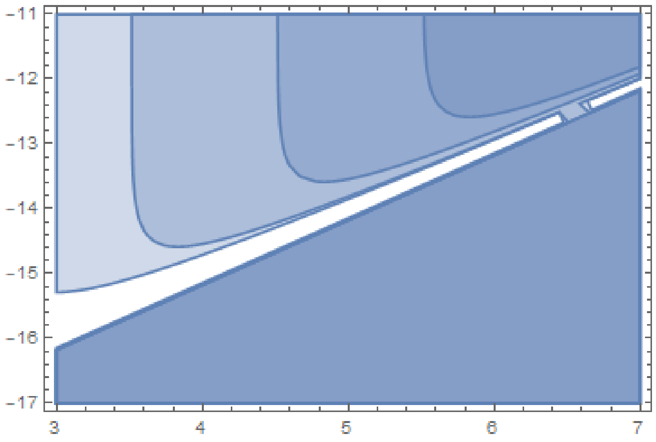
# Energy dissipation by particle production

- Relaxation starts in a broken phase. Higgs and all particles coupled to it are heavy
- Periodic barriers independent from the EW scale and always present. Initial relaxion's kinetic energy sufficient to cross the barriers
- Relaxion rolls towards higher values
- Close the EW symmetry recovery massive states coupled to relaxion would become light and would be produced in abundance ($\dot{\omega}_k/\omega_k^2 \gg 1$)
- Produced light states take away relaxion's kinetic Energy, causing it to stop in one of the minima

# Benefits

- Relaxation independent from inflation,
- Relaxation is fast ($\dot{\phi} \approx \Lambda^2$) and requires no transplanckian field excursions
- Rich phenomenological consequences which can be used to constrain the model

# Generic constraints




- Not to many e-folds ($N_e < 20$) to ensure that the primordial fluctuations are not washed out

- Temperature must be controlled, to make sure EW symmetry is not recovered before relaxation is complete

- It is best to start in a cold Universe (e.g. inflation decays into a hidden sector)

# Production of vector bosons

[Hook, Marques-Tavares, 2016]

$$V(\phi, h) = -g_1 \Lambda \phi + (-\Lambda^2 + g_2 \Lambda \phi) h^2 + \frac{\lambda}{4} h^4$$
$$+ \frac{\phi}{f} V_{\mu\nu} \tilde{V}^{\mu\nu} + \Lambda_b^4 \cos\left(\frac{\phi}{f'}\right)$$

- No new states required beyond the SM and the relaxion
- Consistent with experimental constraints [Fonseca, Morgante, Servant, 2018]
- Requires very specific coupling to exclude relaxion-photon interaction

$$V_{\mu\nu} \tilde{V}^{\mu\nu} = g_W^2 W_{\mu\nu}^a \tilde{W}^{a\,\mu\nu} - g_B^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$$

# Higgs production

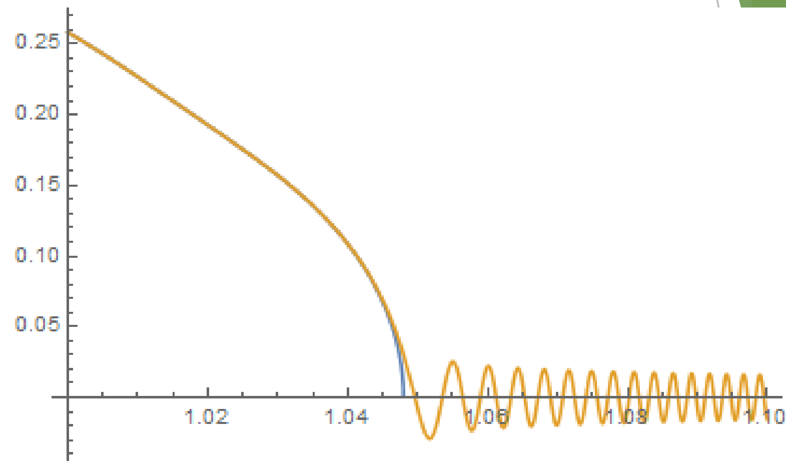
$$V(\phi, h) = -g_1\Lambda\phi + (-\Lambda^2 + g_2\Lambda\phi)h^2 + \frac{\lambda}{4}h^4 + \Lambda_b^4 \cos\left(\frac{\phi}{f}\right)$$

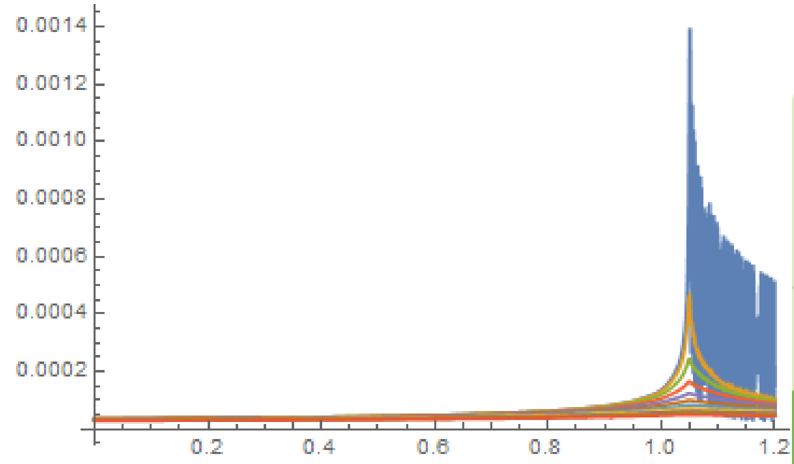
- Higgs follows its minimum if

$$\dot{\phi} < (g_2\Lambda)^{1/2}\left|\phi - \frac{\Lambda}{g_2}\right|^{3/2}$$

- Effective production if

$$\dot{\phi} > 2\sqrt{2}(g_2\Lambda)^{1/2}\left|\phi - \frac{\Lambda}{g_2}\right|^{3/2}$$



# Higgs production

- Production rate surprisingly independent from model's parameters
- Particle production is never effective enough to stop the relaxation

$$\frac{\dot{\omega}_0}{\omega_0^2} < 0.7$$

- The same happen if an additional scalar field is coupled to relaxion and Higgs

# Scalars vs vectors

- Higgs case

$$\omega_k = \sqrt{k^2 + (g_2 \Lambda \phi - \Lambda^2 + 3\lambda h_0^2)}$$

- Vector case

$$\omega_k = \sqrt{k^2 + g_V^2 h^2 - \frac{\dot{\phi}}{f} k}$$

- Mass of vector bosons depends on $\dot{\phi}$. Production is self-reinforcing
- Derivative coupling  necessary (?)

# Conclusions

- Relaxation provides an interesting solution to the hierarchy problem, where a hierarchy of scales is generated naturally
- Using particle production as an energy dissipation mechanism avoids major issues of the original proposal
- Production of vector bosons works, and is consistent with experimental constraints
- Production of scalar particles is insufficient to stop the relaxation