Searching for Relaxions through the Higgs Portal

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based on:

T. Flacke, C. Frugiuele, E. Fuchs, R. S. Gupta, G. Perez,
“Phenomenology of relaxion-Higgs mixing”
[arXiv:1610.02025]

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Outline

• Motivation
• Relaxions-Higgs mixing
• Relaxion-Higgs phenomenology
• Conclusions
The Standard Model works tremendously well, but we still have no indication what sets its mass scale.

\[ V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \]

Within the SM, \( \mu \) receives quadratically divergent corrections

\[ \Rightarrow \text{the natural scale for } \mu \text{ is the cutoff } \Lambda \text{ of the SM.} \]

Some known (but still unconfirmed) solutions:

- Supersymmetry: “The divergence is not quadratic” (due to a symmetry)
- Composite Higgs Models: “The cutoff of the Higgs sector is a strong-coupling scale (like } \Lambda_{\text{QCD} \text{ but in the TeV regime})”

…

A different approach: Relaxion models attempt to couple the Higgs to a field which dynamically makes \( \mu \) small.
Relaxions

[Graham, Kaplan, Rajendran, PRL 115 (2015), 221801]

Motivation: a dynamical Higgs mass


\[
\mu^2 = \mu_0^2 + g \mu_0 + \ldots
\]

1. \(\mu^2 > 0\), no vev
2. \(\mu^2 < 0\), sign flip, EWSB
3. backreaction


\[
V_{br} = \tilde{M}^4 - \hat{h}^j \cos \left( \frac{\phi}{f} \right)
\]

dynamical \(\mu\)

unavoidable contribution to the \(\phi\) potential

osc. backreaction term

\[
V(H) = -\mu^2(\phi)H^\dagger H + \lambda (H^\dagger H)^2
\]

\[
\mu^2(\phi) = -\Lambda^2 + g\Lambda \phi + \ldots
\]

\[
V(\phi) = r g \Lambda^3 \phi + \ldots
\]
Relaxion - Higgs mixing

**Mixing term** (when expanding around the vacuum \((\phi_0, v)\))

\[
V(\phi, h) \supset \frac{\tilde{M}^{4-j} v^{j-1}}{\sqrt{2^{j} f}} \sin \left( \frac{\phi_0}{f} \right) h \phi
\]

**Small-mixing approximation**

\[
\sin \theta \approx \tan \theta \approx \frac{M_{h\phi}^2}{M_{hh}^2} \approx \frac{v \tilde{M}^2}{f \frac{m_h^2}{m_h}} \sin \left( \frac{\phi_0}{f} \right)
\]

\[
m_{\phi}^2 \approx \frac{\tilde{M}^2 v^2}{2f^2} \left( \cos \left( \frac{\phi_0}{f} \right) - \frac{2\tilde{M}^2}{m_h^2} \sin^2 \left( \frac{\phi_0}{f} \right) \right)
\]

relaxion inherits Higgs couplings: \(g_{\phi \psi, \phi V} = \sin \theta g_{h\psi, hV}\)

Note: In UV embeddings of relaxion models, additional couplings of the relaxion to the SM will be present. [c.f. e.g. Choi et al, 1610.00680 ]

In the following we focus on the “Higgs portal couplings” only.
Relaxion - Higgs mixing

Note:

- The relaxion is typically thought of as “axion-like” (and thus a pseudo-scalar). The mixing with the Higgs shows that it has a scalar component.
- If the relaxion couples dominantly to the SM through the mixing with the Higgs, all its couplings are inherited from the Higgs, and its phenomenology depends only on the relaxion mass and the mixing angle (it is a Higgs-portal model, then).
- The mass and mixing angle are related to the relaxion model parameters $f$ and $\Lambda_{br}$ where $\Lambda_{br}^{4} = \tilde{M}^{4-j} \left( \frac{v}{\sqrt{2}} \right)^{j}$. The Higgs portal bounds on relaxion mass and mixing can thus be translated into bounds on $\Lambda_{br}$ and $f$. 

\[ V(H) = \frac{\mu^2}{2} H^\dagger H + \frac{1}{2} (H^\dagger H)^2 \]
Relaxion mass and lifetime in relation to relaxion parameters
Relaxion parameters and bounds (schematically)

translation \((m_\phi, s_\theta) \leftrightarrow (\tilde{M}, f)\)

\[
\tilde{M} = \tilde{M}_{\text{max}} = 10^{-3} \text{GeV}
\]

\[
f = M_{\text{Pl}}
\]

\[
\sin^2 \theta = 10^{-5}
\]

[courtesy to E. Fuchs, talk at DESY]
Figure 4. Constraints on the relaxion-Higgs mixing $\sin^2 \theta$ for relaxions with $m_\phi$ between 5 GeV and 90 GeV from LEP and the LHC: 4-fermion final states from Higgs strahlung at LEP (green, labelled as LEP hZ); Higgs decays to NP with $\text{BR}(\phi \rightarrow \text{NP}) \leq 20\%$ at the LHC (purple, solid) as well as a projection for $\text{BR}(\phi \rightarrow \text{NP}) \leq 10\%$ (purple, dashed); explicit searches for $h \rightarrow \phi \phi$ with final states $4\tau$ (dark blue, dotted, $m_\phi < 10 \text{ GeV}$, Run 3 projection) and $2\mu 2b$ (dark blue, dotted, $m_\phi > 25 \text{ GeV}$, Run 3 projection). Contours for $\Lambda_{br} = 120 \text{ GeV}$ (gray, dashed for $j = 2$; brown, dashed for $j = 1$), $f = m_h$ and $f = 1 \text{ TeV}$ (black for $j = 2$, brown for $j = 1$).
Relaxion bounds for MeV - GeV masses
(collider physics, beam-dump, flavor physics, astro physics / cosmology)

Figure 3. Constraints on the relaxion-Higgs mixing $\sin^2 \theta$ for relaxations with $m_\phi$ between MeV and GeV by the CHARM beam dump experiment (dark blue), rare $B$- and $K$-meson decays (light blue, labelled by $B$, $K$ and numbers 1-6), $B$-meson decays (labelled by $B$) at LHCb (turquoise) and Belle (turquoise, dashed), the Supernova 1987a (red, labelled as SN) and by the future experiment SHiP as a projection (yellow, dotted). The green line (labelled by 1 s) indicates a lifetime of $\tau_\phi = 1$ s. Contours of constant $\Lambda_{br}$ (gray) for $\Lambda_{br} = 0.99(\Lambda_{br})_{\text{max}} \simeq 104$ GeV (gray, thick, solid), $\Lambda_{br} = \Lambda_{br}^* \simeq 74$ GeV and $\Lambda_{br}/(\Lambda_{br})_{\text{max}} = 10^{-1}, 10^{-2}$ (gray, dashed). Contours of constant $f/\text{GeV} = 10^6, 10^5, 10^4, 10^3$ (black, solid).
Figure 5. Cosmological and astrophysical bounds on $s_\theta$ and $m_\phi$ from 100 eV to 0.3 GeV: globular cluster via coupling to electrons (blue) or coupling to photons (turquoise), supernova 1987a (light blue), extragalactic background light (EBL, yellow), CMB $y$-distortion (light green) and $\mu$-distortion (green), entropy injection $\Delta S/S$ bounded by the baryon-to-photon ratio $\eta_B$ (orange) and by $N_{\text{eff}}$ (pink), BBN (red). The light gray band indicates the possible range of $s_\theta$ for $j = 1$, i.e. the QCD case. The gray lines (from top to bottom) are contours of constant $\Lambda_{br} = 0.99(\Lambda_{br})_{\text{max}}$ (thick, solid), $\Lambda^*_\text{br}$, 0.01 GeV (dashed). The black lines (from left to right) are contours of constant $f = 10^{10}$ GeV, $10^6$ GeV (thin) and $f = M_h$ (thick).
very light relaxions (5th force and Eq. principle)

**Figure 2.** Constraints on the relaxion-Higgs mixing $\sin^2 \theta$ for light relaxions with $m_\phi$ between $10^{-16}$ GeV and $10^{-7}$ GeV. Fifth-force experiments (orange) probe the lightest mass range via the equivalence principle (labelled as EqP), the inverse square law (ISqL) and the Casimir effect (Casimir). Contours of constant $\Lambda_{br}$ (gray) for $\Lambda_{br} = 0.99(\Lambda_{br})_{max} \simeq 104$ GeV (gray, thick, solid), $\Lambda_{br} = \Lambda_{br}^* \simeq 74$ GeV and $\Lambda_{br}/(\Lambda_{br})_{max} = 10^{-1}, 10^{-2}, 10^{-3}$ (gray, dashed). Contours of constant $f = M_{Pl}, 10^{16}$ GeV, $10^{14}$ GeV (black, solid), the area of $f > M_{Pl}$ is shaded in dark gray. The light gray region below the dotted gray line corresponds to trans-Planckian field excursions $\Delta \phi > M_{Pl}$ for $\Lambda = 5$ TeV.
Translation to relaxion model parameters
Conclusions and Outlook

• Relaxions might be able to provide a new approach to the hierarchy problem.
• Relaxions mix with the Higgs and can have interesting phenomenology in cosmology, astro physics and “low energy - high precision physics”.
• Relaxions will have additional (pseudo-scalar) couplings to SM particles which are to be determined from the UV-completion of the relaxion model. These coupling can lead to additional bounds … or ways to discover relaxions.