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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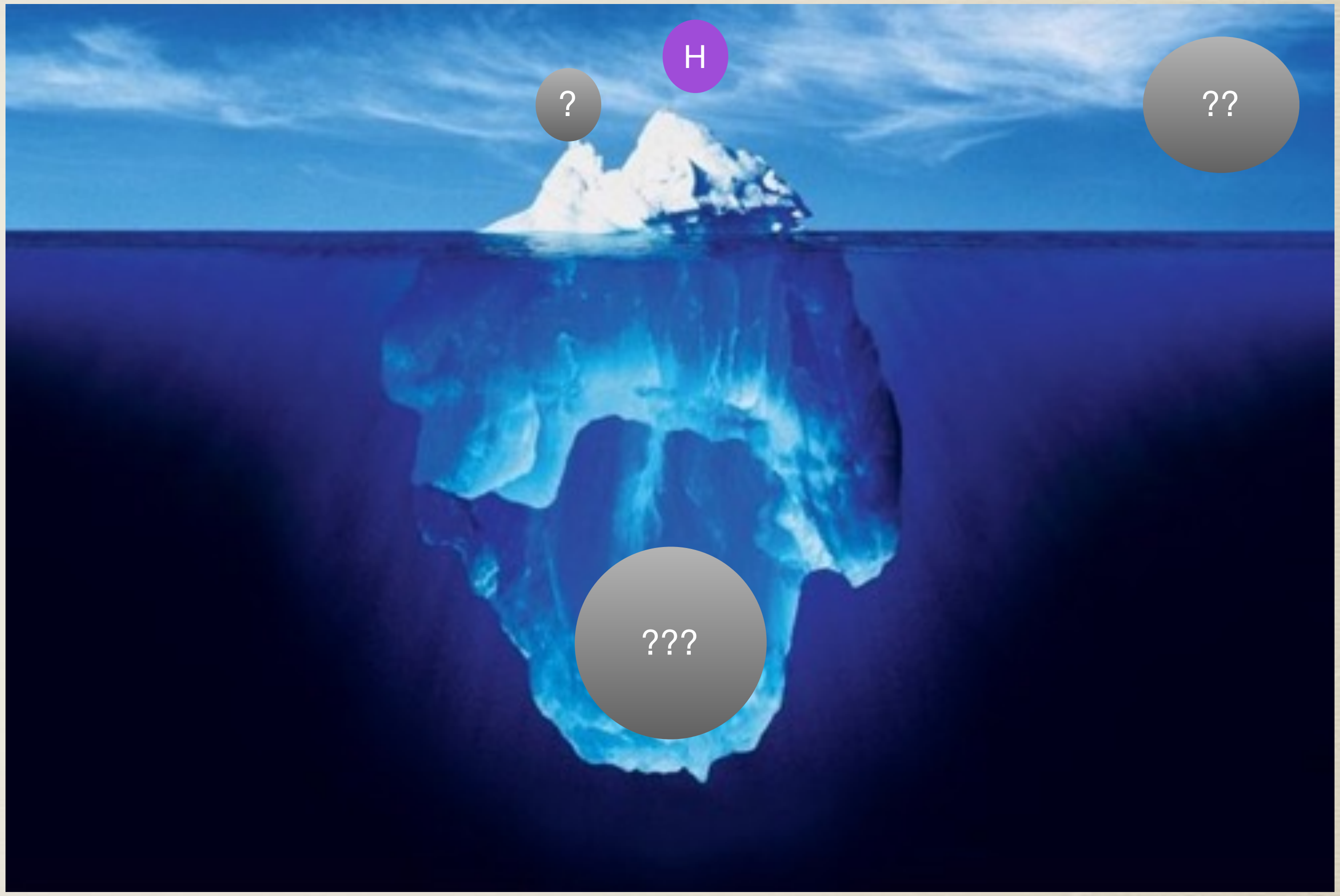
Outline

- Motivation
- Relaxions-Higgs mixing
- Relaxion-Higgs phenomenology
- Conclusions



Motivation

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, μ receives quadratically divergent corrections

$\Rightarrow$ the natural scale for μ is the cutoff Λ of the SM.

Some known (but still unconfirmed) solutions:

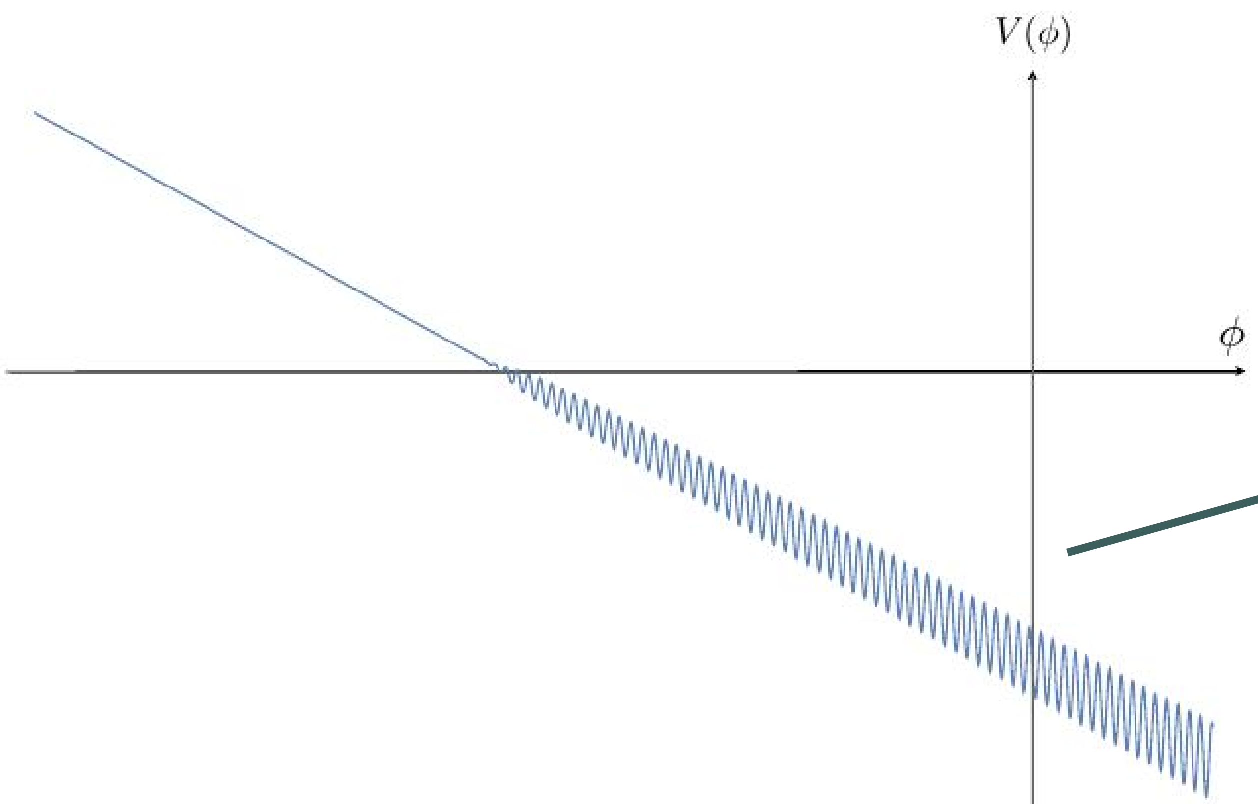
- Supersymmetry: "The divergence is not quadratic" (due to a symmetry)
- Composite Higgs Models: " The cutoff of the Higgs sector is a strong-coupling scale (like Λ_{QCD} but in the TeV regime)"

…

A different approach: Relaxion models attempt to couple the Higgs to a field which *dynamically* makes μ small.

Relaxions

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



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

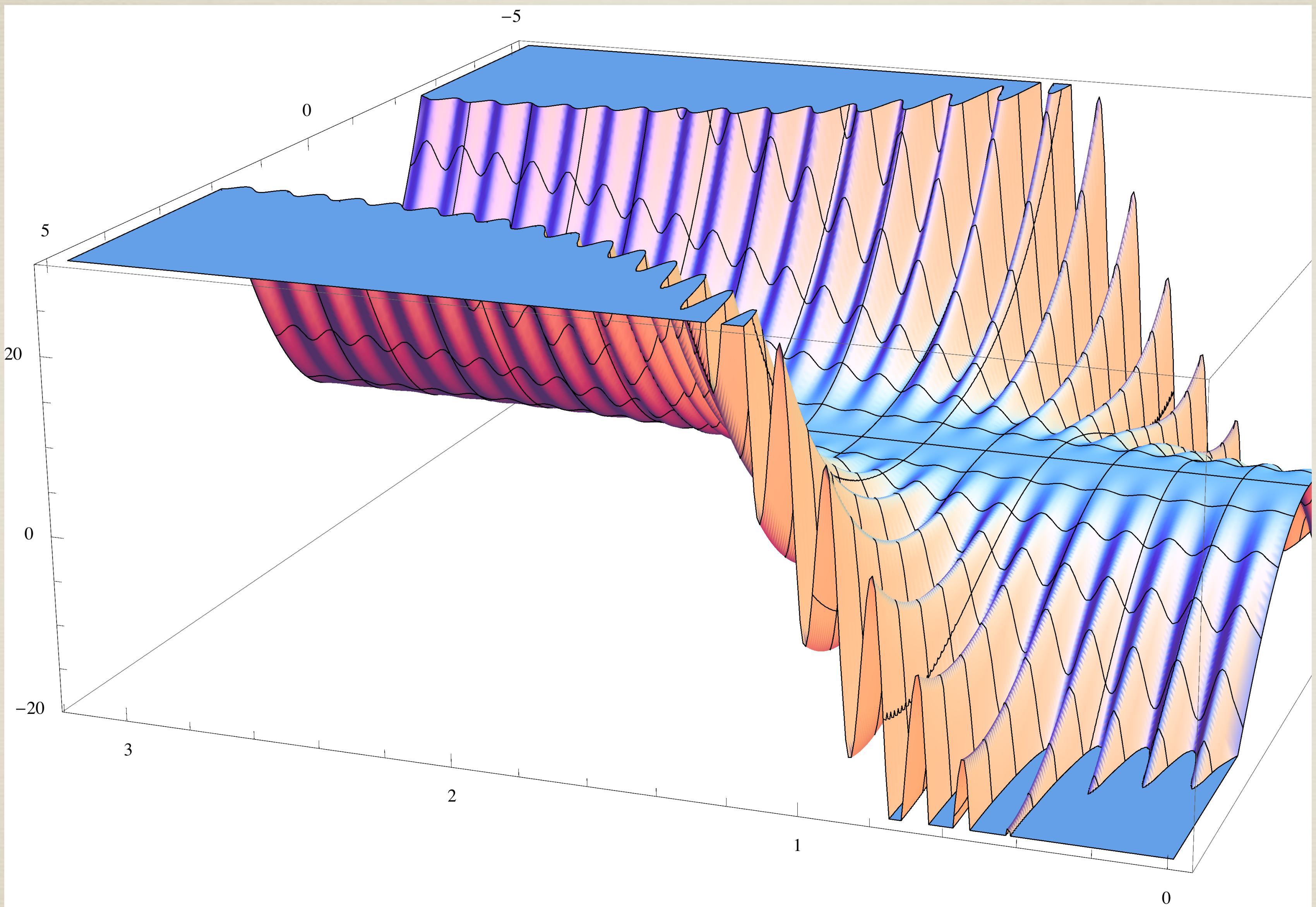
dynamical μ

$$
\begin{aligned}
V(H) &= -\mu^2(\phi) H^\dagger H + \lambda (H^\dagger H)^2 \\
\mu^2(\phi) &= -\Lambda^2 + g\Lambda\phi + \ldots \\
V(\phi) &= rg\Lambda^3\phi + \ldots \\
\Delta V_{br} &= \tilde{M}^{4-j}\hat{h}^j \cos\left(\frac{\phi}{f}\right)
\end{aligned}
$$

oscillating back-reaction term

unavoidable contribution to the ϕ potential

Real shape of the relaxion potential (with one relaxion field)



Relaxion - Higgs mixing

Mixing term (when expanding around the vacuum (ϕ_0,v))

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

Small-mixing approximation

$$\sin\theta \approx \tan\theta \approx \frac{M^2_{h\hat{\phi}}}{M^2_{hh}} \approx \frac{v}{f} \frac{\tilde{M}^2}{m_h^2} \sin\left(\frac{\phi_0}{f}\right)$$

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

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

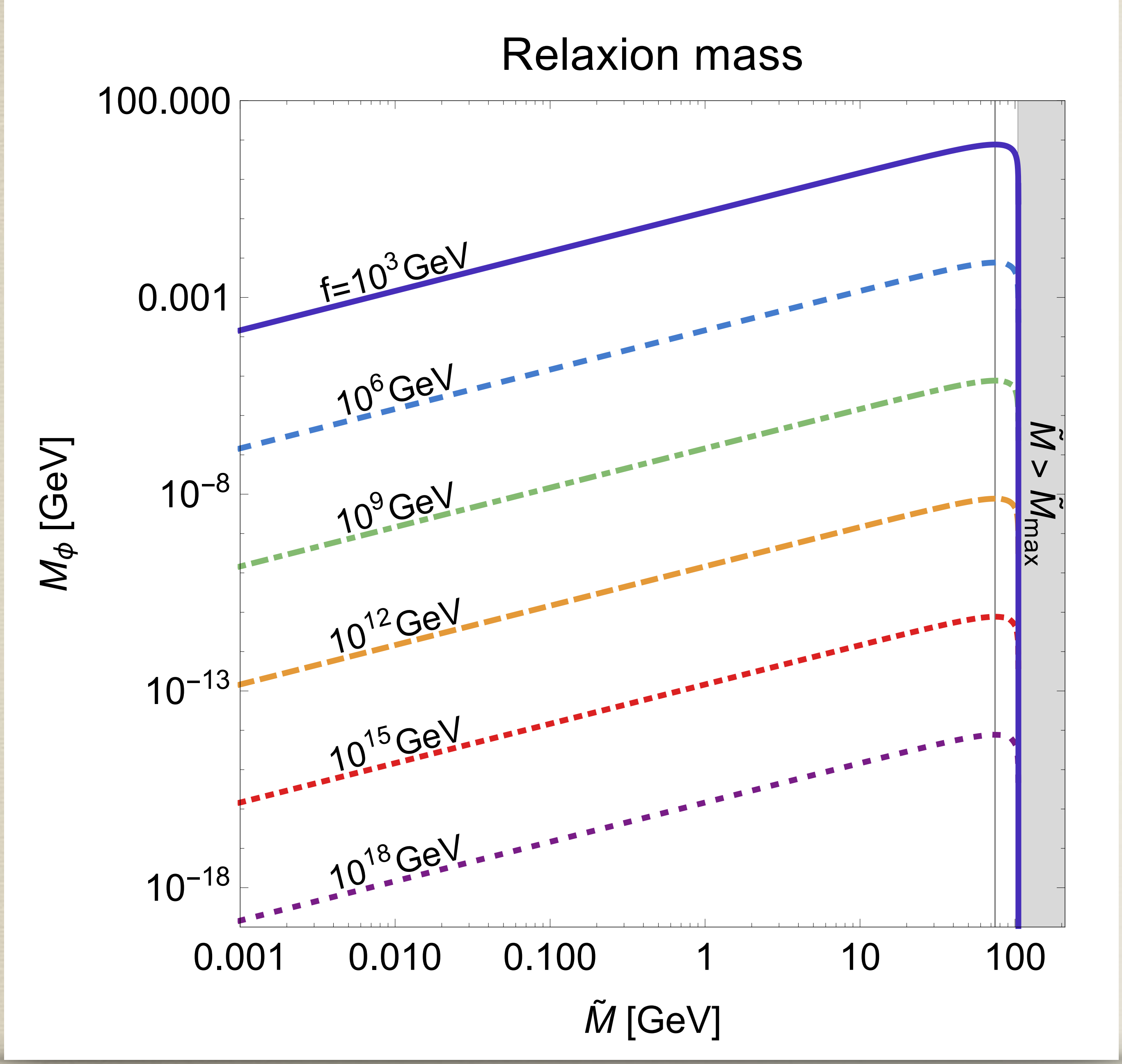
Note: In UV embeddings of relaxion models, additional couplings of the relaxion to the SM will be present. [c.f. e.g. Choi etal, 1610.00680]
In the following we focus on the "Higgs portal couplings" only.

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 $\Lambda_{\rm br}$ 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 $\Lambda_{\rm br}$ and f.

Translating Relaxion parameters



Setting $\sin(\frac{\phi_0}{f}) = \frac{1}{\sqrt{2}}$ for simplicity:

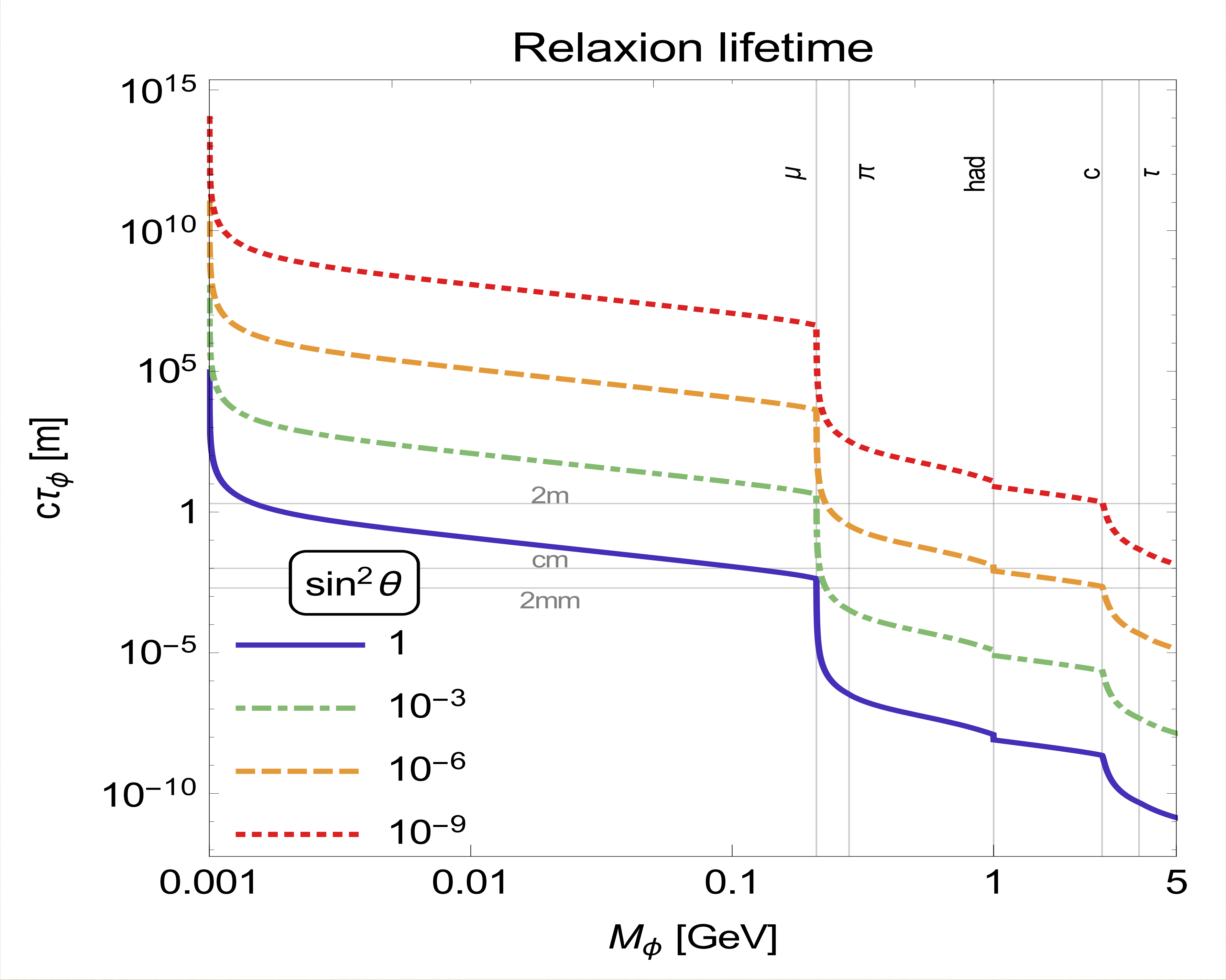
$$m_\phi^2 \approx \frac{\tilde{M}^2 v^2}{2f^2}\left(\frac{1}{\sqrt{2}} - \frac{\tilde{M}^2}{m_h^2}\right)$$

$$\sin\theta \approx \frac{v}{f}\frac{\tilde{M}^2}{m_h^2}$$

Note:

- two solutions for relaxion mass. The relaxion is light
  - if f is large or
  - if $\tilde{M}$ is tuned
- maximum m_ϕ at $\tilde{M} \simeq 74$ GeV
- $\tilde{M}_{max} = m_h/2^{1/4} \simeq 105$ GeV

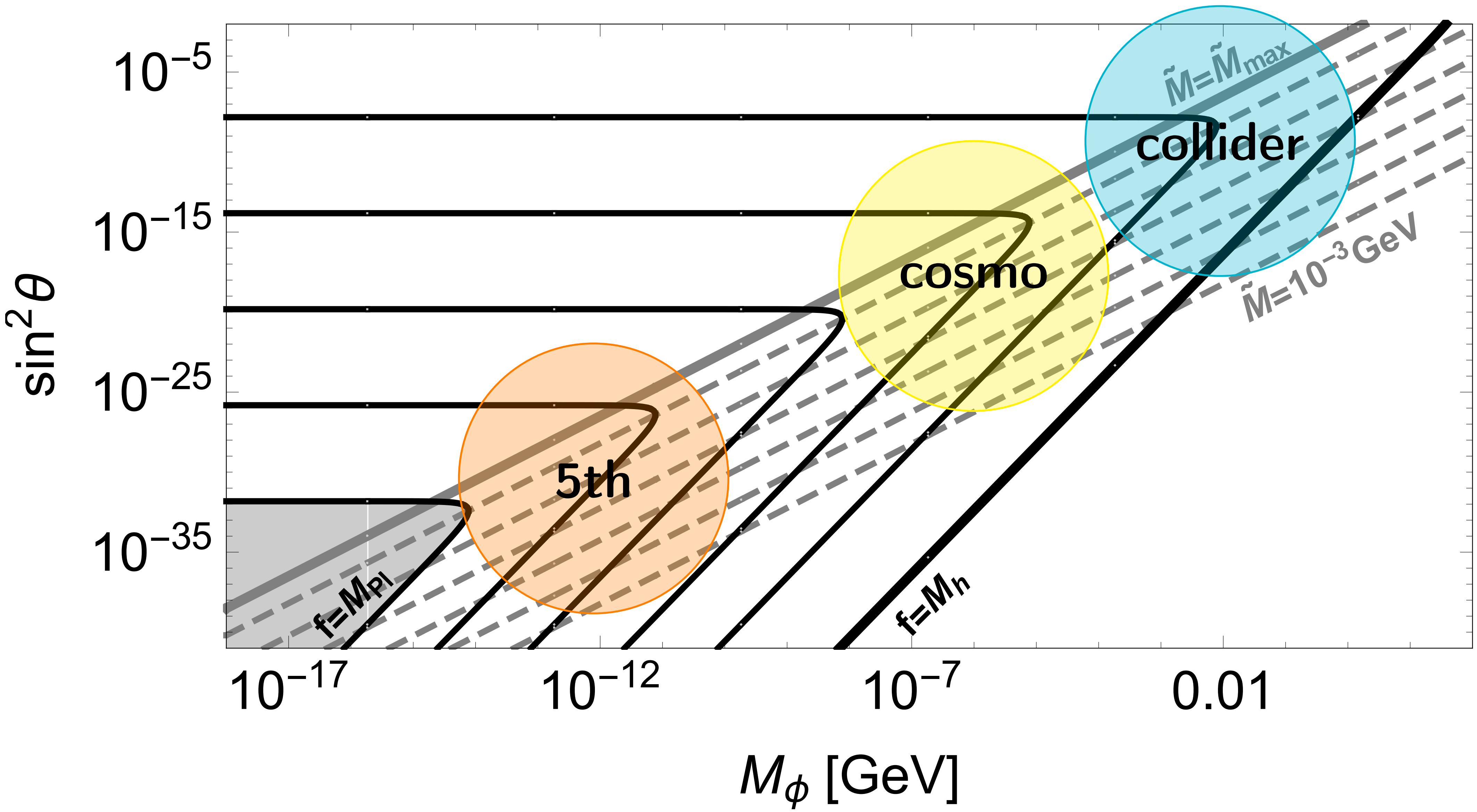
Relaxion lifetime and propagation lengths



$$\tau_\phi = \frac{1}{\Gamma_\phi} \propto \frac{1}{\sin^2\theta}$$

Relaxion parameters and bounds (schematically)

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



given $(m_\phi, f) \longrightarrow$ 2 solutions of $\tilde{M}$

[courtesy to E. Fuchs, talk at DESY]

Relaxion bounds for GeV scale masses (collider physics)

Higgs decays to relaxions can be calculated from the effective relaxion potential:

$$g_{h\phi\phi} \simeq \frac{\tilde{M}^2}{\sqrt{2}f}\left(-\frac{v^2 s_\theta c_\theta^2}{4f^2} + \frac{v c_\theta^3}{2f} - \frac{v s_\theta^2 c_\theta}{f} + \frac{s_\theta^3}{2} - s_\theta c_\theta^2\right) + 3\lambda v s_\theta^2 c_\theta$$

- Fit of Higgs couplings yield $\Gamma(h \to \text{new physics}) < 20\%$.

  [P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak and G. Weiglein, 2014]

  this can be reinterpreted as an upper bound on $g_{h\phi\phi}$ and hence s_θ, m_ϕ.
- The decays $h \to \phi\phi \to 4l$ and $h \to \phi\phi \to (2l)(2b)$ are being searched for at LHC.

Also: $e^+ e^- \to Z^* \to Z\,\phi$ is bound from LEP searches.

[L3 collaboration (1996), LEP working group (2006)]

Relaxion bounds for GeV scale masses (collider physics)

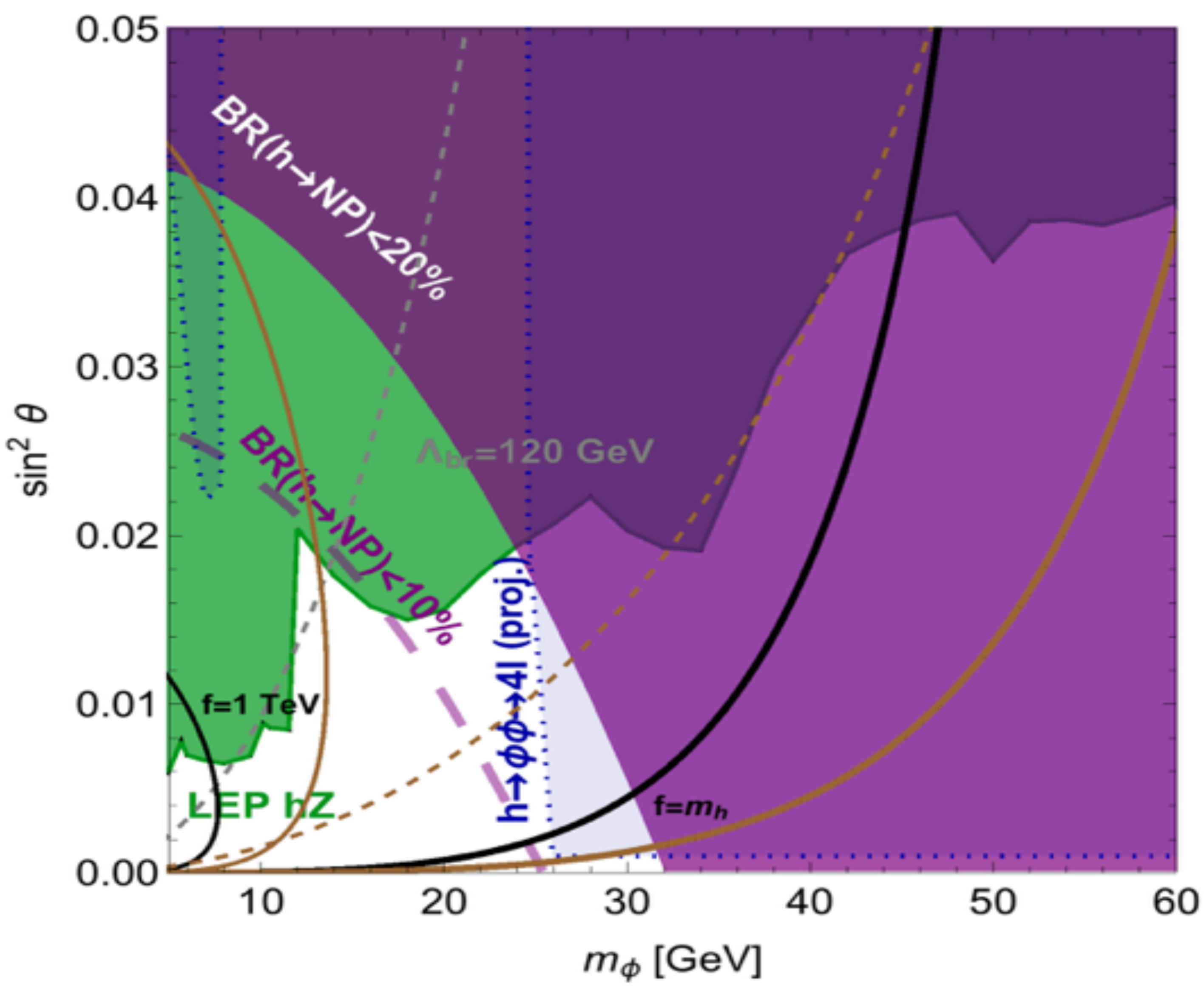
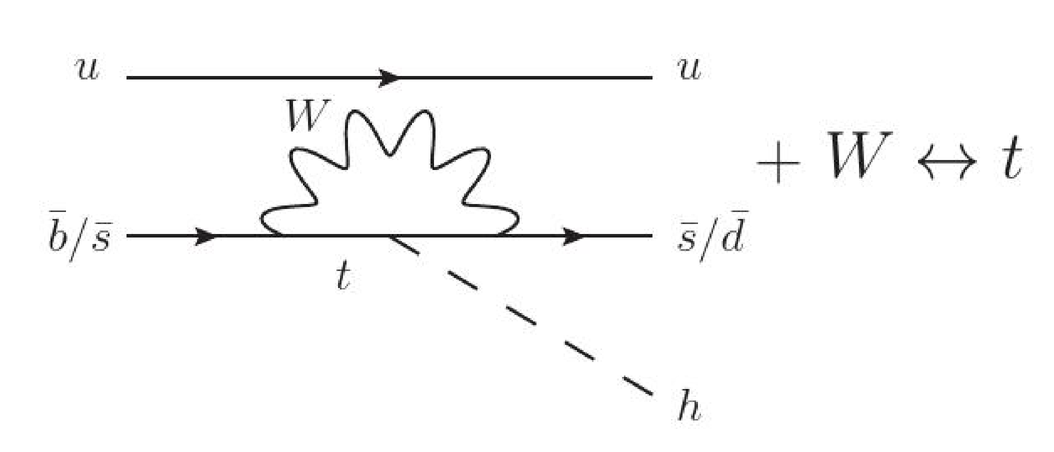


Figure 4. Constraints on the relaxion-Higgs mixing $\sin^2\theta$ for relaxions with m_ϕ between 5 GeV and 90 GeV from LEP and the LHC: 4-fermion final states from Higgs strahlung at LEP (green, labelled as LEP hZ); Higgs decays to NP with $\mathrm{BR}(\phi \to \mathrm{NP}) \leq 20\%$ at the LHC (purple, solid) as well as a projection for $\mathrm{BR}(\phi \to \mathrm{NP}) \leq 10\%$ (purple, dashed); explicit searches for $h \to \phi\phi$ with final states 4τ (dark blue, dotted, $m_\phi < 10$ GeV, Run 3 projection) and $2\mu 2b$ (dark blue, dotted, $m_\phi > 25$ GeV, Run 3 projection). Contours for $\Lambda_{br} = 120$ GeV (gray, dashed for $j = 2$; brown, dashed for $j = 1$), $f = m_h$ and $f = 1$ TeV (black for $j = 2$, brown for $j = 1$). [arXiv:1610.02025]

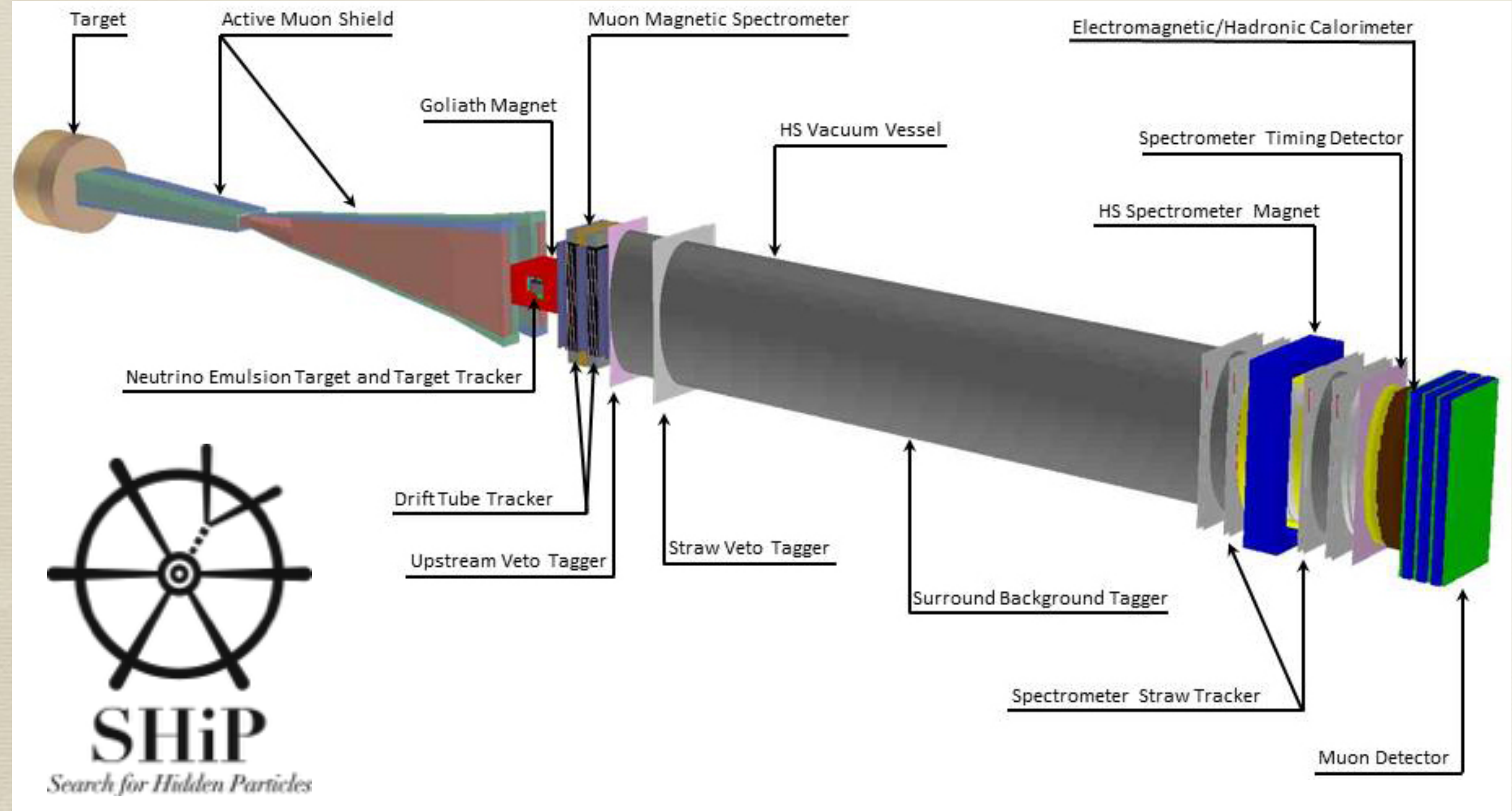
Relaxion bounds for MeV-GeV scale masses

Rare decays



In the SM, rare decays like B → K ll are extremely suppressed because the lepton pair comes from a highly virtual h or Z. If the Higgs mixes with a light state, the decay can happen on-shell.

Beam dump



Relaxions can be produced in rare meson decays from mesons produced in beam dumps. If they are long-lived, they can pass the beam dump and be detected when decaying far away.

Relaxion bounds for MeV - GeV masses
(collider physics, beam-dump, rare decays, astro physics / cosmology)

using and re-interpreting bounds from

[Clarke, Foot, Volkas] (2013)

Schmidt-Hoberg,etal] (2013)

[Dolan,Kahlhoefer etal] (2014)

[Krnjaic] (2012)

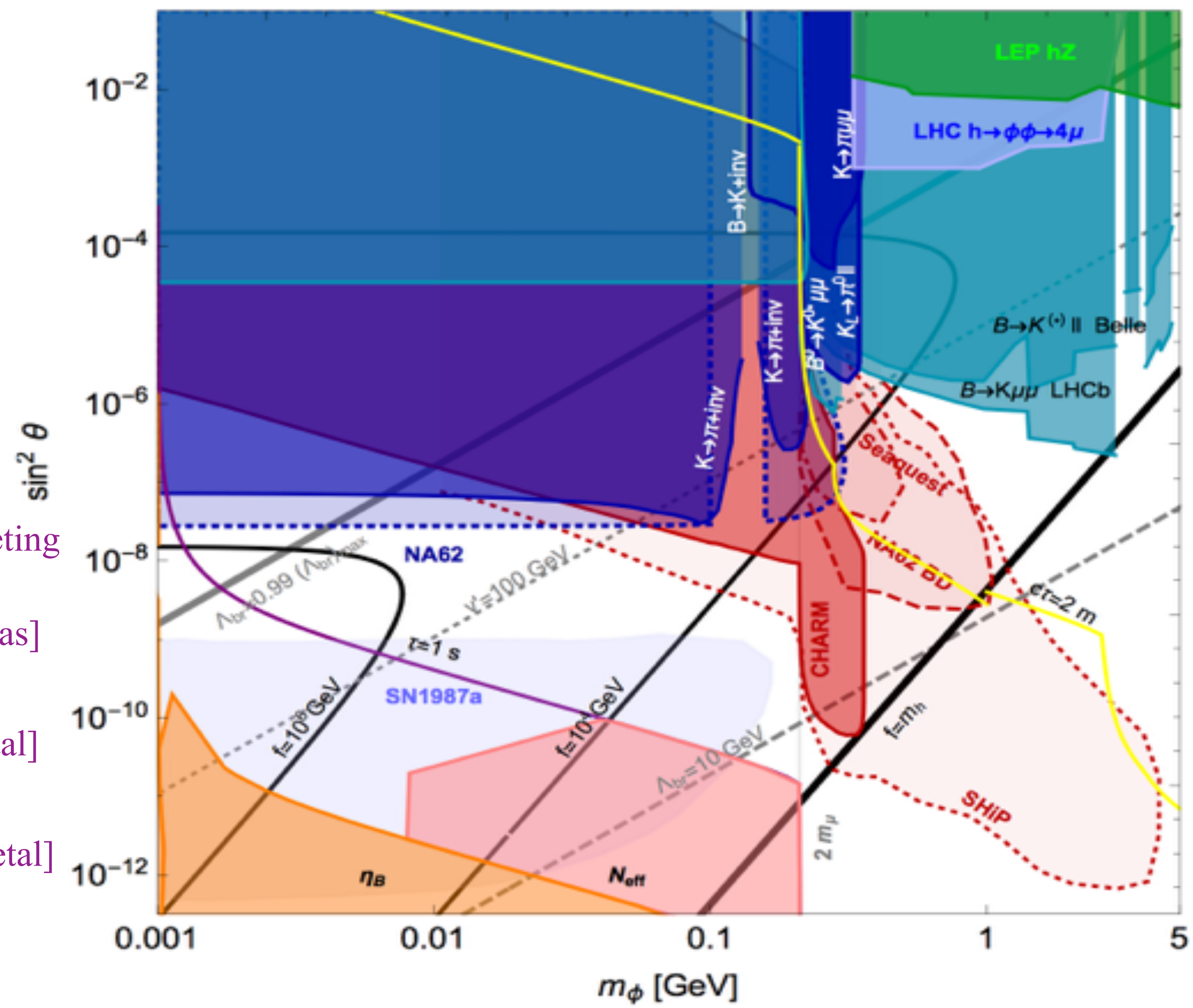
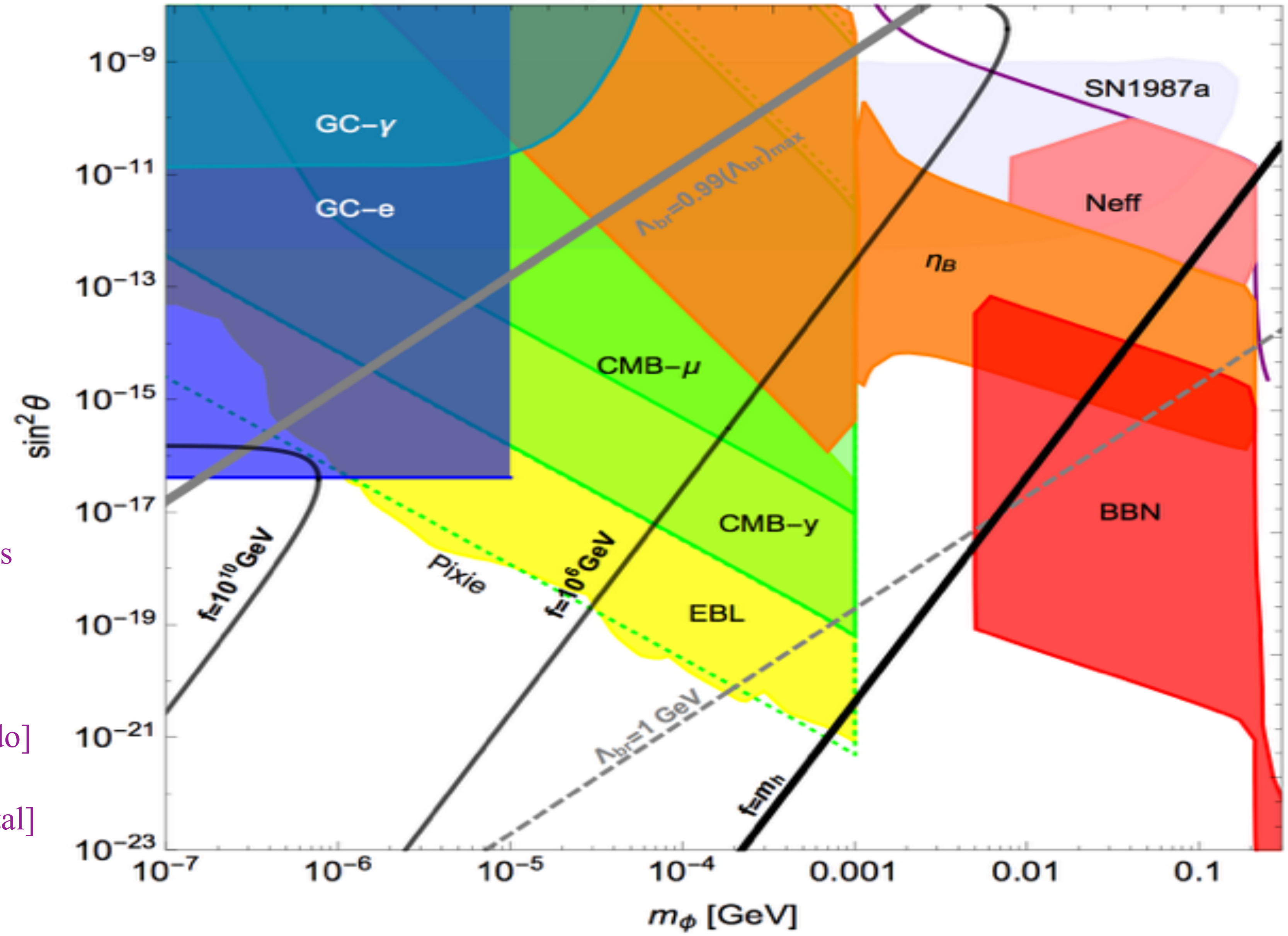


Figure 3. Constraints on the relaxion-Higgs mixing $\sin^2\theta$ for relaxions with m_ϕ between MeV and GeV by the CHARM beam dump experiment (dark blue), rare B- and K-meson decays (light blue, labelled by B, K and numbers 1-6), B-meson decays (labelled by B) at LHCb (turquoise) and Belle (turquoise, 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 $\tau_\phi = 1\,\mathrm{s}$. Contours of constant Λ_{br} (gray) for $\Lambda_{br} = 0.99(\Lambda_{br})_{\max} \simeq 104\,\mathrm{GeV}$ (gray, thick, solid), $\Lambda_{br} = \Lambda^*_{br} \simeq 74\,\mathrm{GeV}$ and $\Lambda_{br}/(\Lambda_{br})_{\max} = 10^{-1}, 10^{-2}$ (gray, dashed). Contours of constant $f/\,\mathrm{GeV} = 10^6, 10^5, 10^4, 10^3$ (black, solid).

[arXiv:1610.02025]

Light relaxions (astrophysics and cosmology)



using and re-interpreting bounds from

[Kolb, Turner]

[Planck]

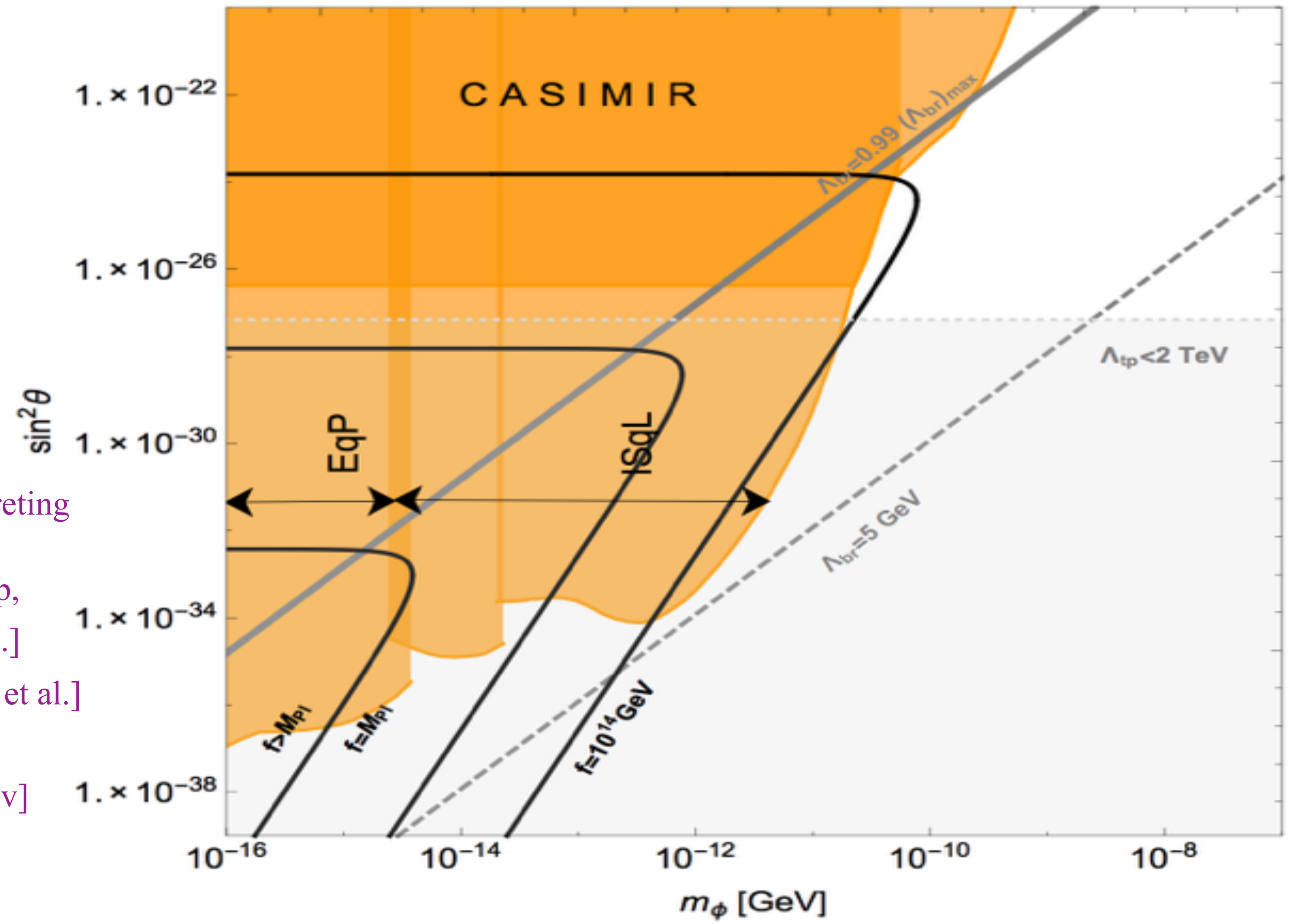
[Cadamuro, Redondo] (2012)

[Arias, Cadamuro etal] (2012)

Figure 5. Cosmological and astrophysical bounds on s_θ and m_ϕ 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 μ-distortion (green), entropy injection $\Delta S/S$ bounded by the baryon-to-photon ratio η_B (orange) and by $N_{\rm eff}$ (pink), BBN (red). The light gray band indicates the possible range of s_θ for $j = 1$, i.e. the QCD case. The gray lines (from top to bottom) are contours of constant $\Lambda_{br} = 0.99(\Lambda_{br})_{\rm max}$ (thick, solid), Λ^*_{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).

[arXiv:1610.02025]

very light relaxions (5th force and Eq. principle)



using and re-interpreting bounds from

[Eöt Wash group, Adelberger et al.]

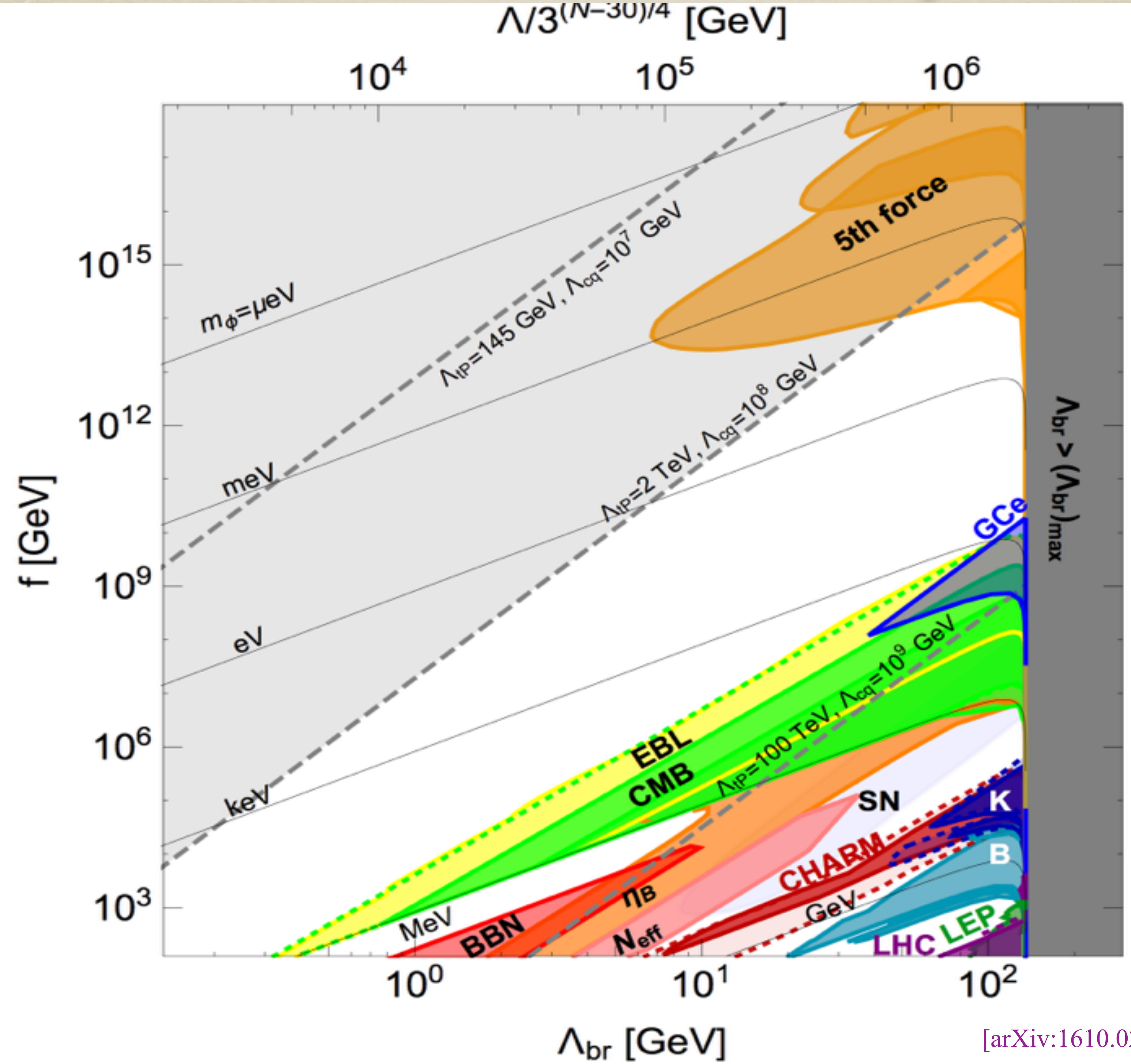
[Bordag, Mohideen, et al.] (2001)

[Piazza, Pospelov] (2010)

Figure 2. Constraints on the relaxion-Higgs mixing $\sin^2\theta$ for light relaxions with m_ϕ 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 Λ_{br} (gray) for $\Lambda_{br} = 0.99(\Lambda_{br})_{\max} \simeq 104\,\mathrm{GeV}$ (gray, thick, solid), $\Lambda_{br} = \Lambda^*_{br} \simeq 74\,\mathrm{GeV}$ and $\Lambda_{br}/(\Lambda_{br})_{\max} = 10^{-1}, 10^{-2}, 10^{-3}$ (gray, dashed). Contours of constant $f = M_{\mathrm{Pl}}, 10^{16}\,\mathrm{GeV}, 10^{14}\,\mathrm{GeV}$ (black, solid), the area of $f > M_{\mathrm{Pl}}$ is shaded in dark gray. The light gray region below the dotted gray line corresponds to trans-Planckian field excursions $\Delta\phi > M_{\mathrm{Pl}}$ for $\Lambda = 5\,\mathrm{TeV}$.

[arXiv:1610.02025]

Translation to relaxion model parameters



[arXiv:1610.02025]

Scalar vs. pseudo-scalar

In the bounds established, we made the implicit assumption that the relaxion is only (or at least dominantly) coupling to SM particles through the Higgs portal.

Other interactions, in particular pseudo scalar interactions can be present, in particular in axion-like relaxion models, axion like couplings

$$\mathcal{L} \supset \frac{\tilde{g}_{\phi\gamma}}{4} F\tilde{F} + \frac{\tilde{g}_{\phi g}}{4} G\tilde{G}$$

can be present, and they depend strongly on the precise UV embedding.

Three possible situations for models:

- Higgs portal couplings dominate → use bounds presented here
- axion-like couplings dominate → use bounds for axions-like particles [PDG]
- couplings are comparable → requires detailed analysis.
  Note: some bounds apply to both, Higgs portal and the axion-like models, but in many cases, they are complementary. E.g. 5th force, Solar axion search (CAST), shining light through walls, axion DM searches in resonance cavities …

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 couplings to SM particles which are to be determined from the UV-completion of the relaxion model. These coupling can lead to additional bounds, an interesting interplay … or ways to discover relaxions.

… and if you do not care about relaxions, just use this work as comprehensive collection of Higgs portal bounds.

THANK YOU