Phenomenology of relaxion-Higgs mixing

in the lab, in the sky and at colliders .

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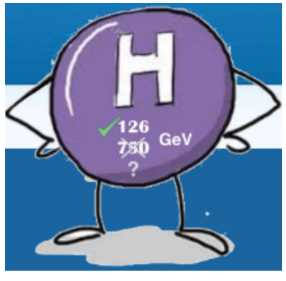
[1609:XXXX]

in collaboration with
Thomas Flacke, Claudia Frugiuele, Rick S. Gupta and Gilad Perez

DESY Mini-Workshop: BSM facing the Run-2 realities
September 13, 2016



Motivation: a dynamical Higgs mass (see also Gustavo's talk)

[Graham, Kaplan, Rajendran '15]

$$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi \text{ scans } M_h$$

1. $\phi \geq \Lambda/g \;\Rightarrow \mu^2 > 0$, no vev
2. $\phi < \Lambda/g \;\Rightarrow \mu^2 < 0$, sign flip, EWSB

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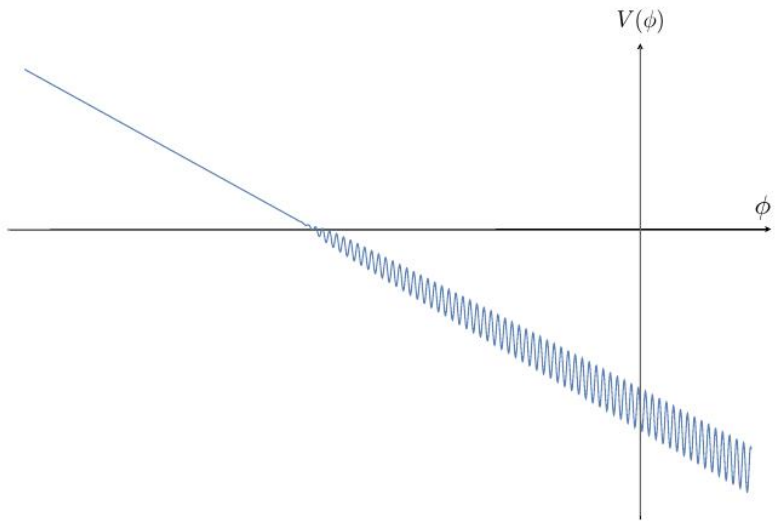
3. backreaction
   $\Delta V_{\rm br} = \tilde{M}^{4-j}\hat{h}^j \cos\left(\frac{\phi}{f}\right)$,
   $\hat{h} = \frac{1}{2}(v(\phi) + h)$,
   $j = 1$: QCD, $j = 2$: non-QCD
4. $\phi\searrow \;\Rightarrow |\mu^2(\phi)|, v^2 \nearrow \;\Rightarrow \Delta V_{\rm br}\nearrow$
5. until ϕ stopped by sufficient barrier



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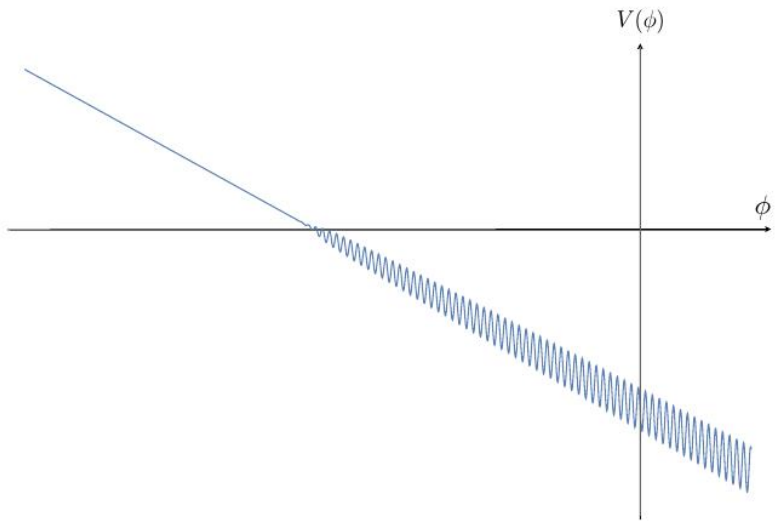

$\boldsymbol{V(h,\phi) \supset h\phi}$ **:** Measurable consequences of relaxion-Higgs mixing?

Outline

1. Relaxion-Higgs mixing
2. Relaxion properties
3. Probes of relaxion-Higgs mixing
   - 5th force
   - Cosmology and astrophysics
   - Rare B, K decays
   - Higgs production and decay
4. Implications for relaxion parameter space

Mixing term in the relaxion-Higgs potential

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

Mixing term

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

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$\boldsymbol{j = 1}$: QCD relaxion

- θ_{QCD} limits mixing
- $45\,\mathrm{GeV} \leq \tilde{M} \leq 100\,\mathrm{GeV}$
- see well-known axion bounds

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$j = 2$: non-QCD relaxion

- mixing can be large
- collect applicable bounds
- translate to relaxion space

Mixing angle and mass eigenstate

ϕ_0 stops at $\sin, \cos\left(\frac{\phi_0}{f}\right) \sim \mathcal{O}(1)$

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: $g_{\phi\psi,\phi V} = \sin\theta\, g_{h\psi,hV}$

Mixing angle and mass eigenstate

for definiteness: $\sin, \cos\left(\frac{\phi_0}{f}\right) = \frac{1}{\sqrt{2}}$

Small-mixing approximation

$$\sin\theta \approx \tan\theta \approx \frac{M^2_{h\hat{\phi}}}{M^2_{hh}} \approx \frac{v}{\sqrt{2}f}\frac{\tilde{M}^2}{m_h^2}$$

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

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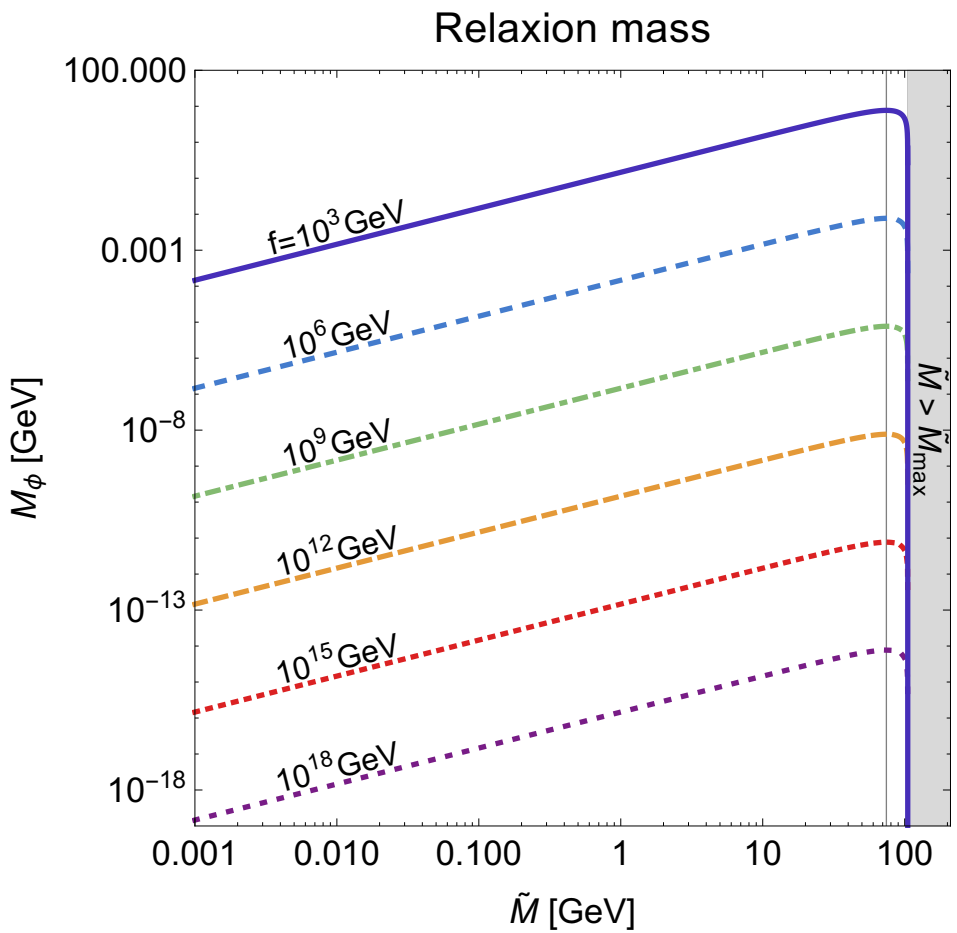
mass and mixing determined by f (oscillation) and $\tilde{M}$ (backreaction)

Relaxion mass



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

2 mechanisms for light ϕ:

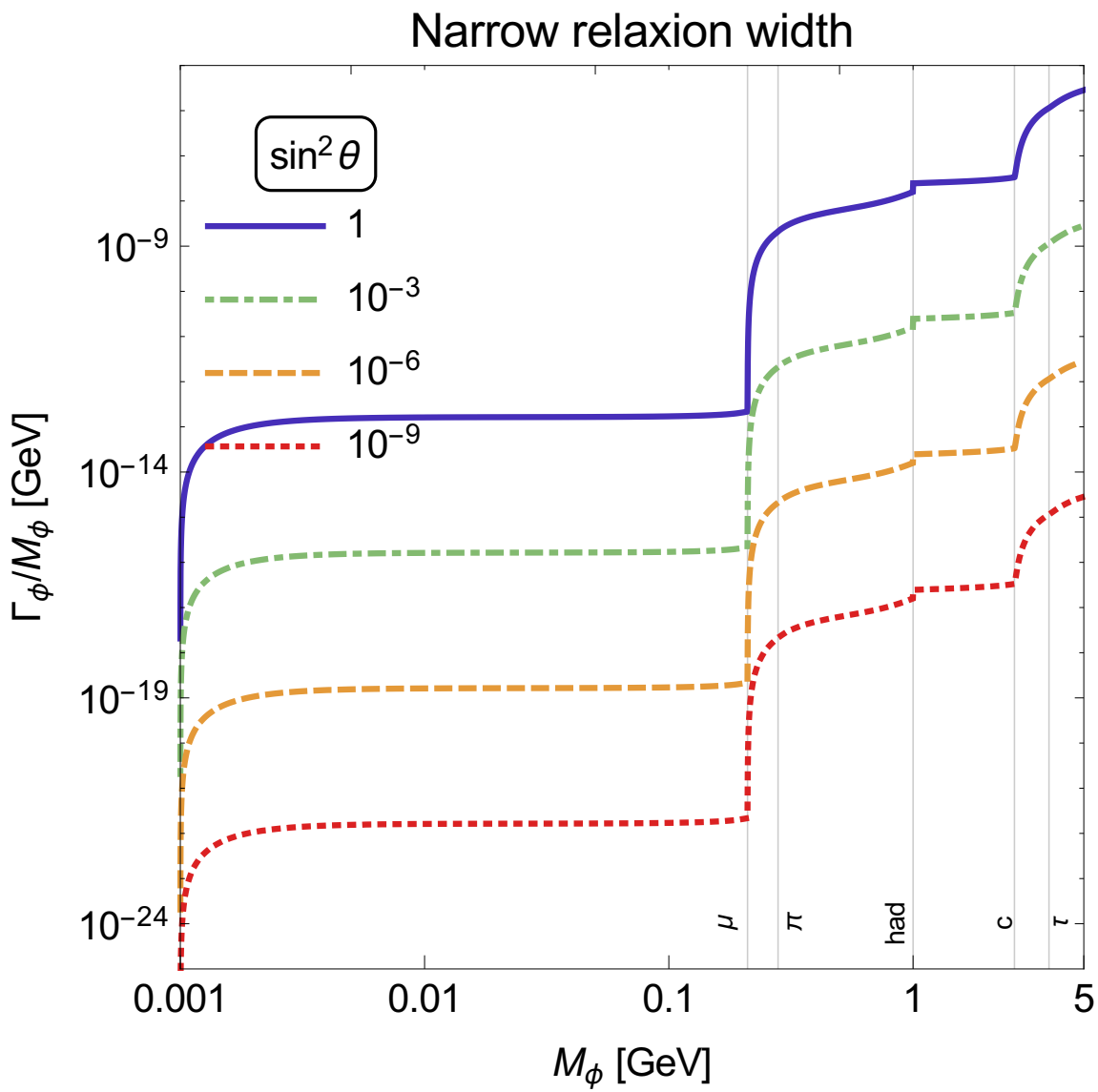
- ▷ high f
- ▷ tuned $\tilde{M}$

maximum m_ϕ
at $\tilde{M} = M_h \cdot 2^{-3/4} \simeq 74\,\mathrm{GeV}$

$\boldsymbol{m_\phi \geq 0} \Rightarrow$ upper bound on $\tilde{M}$:

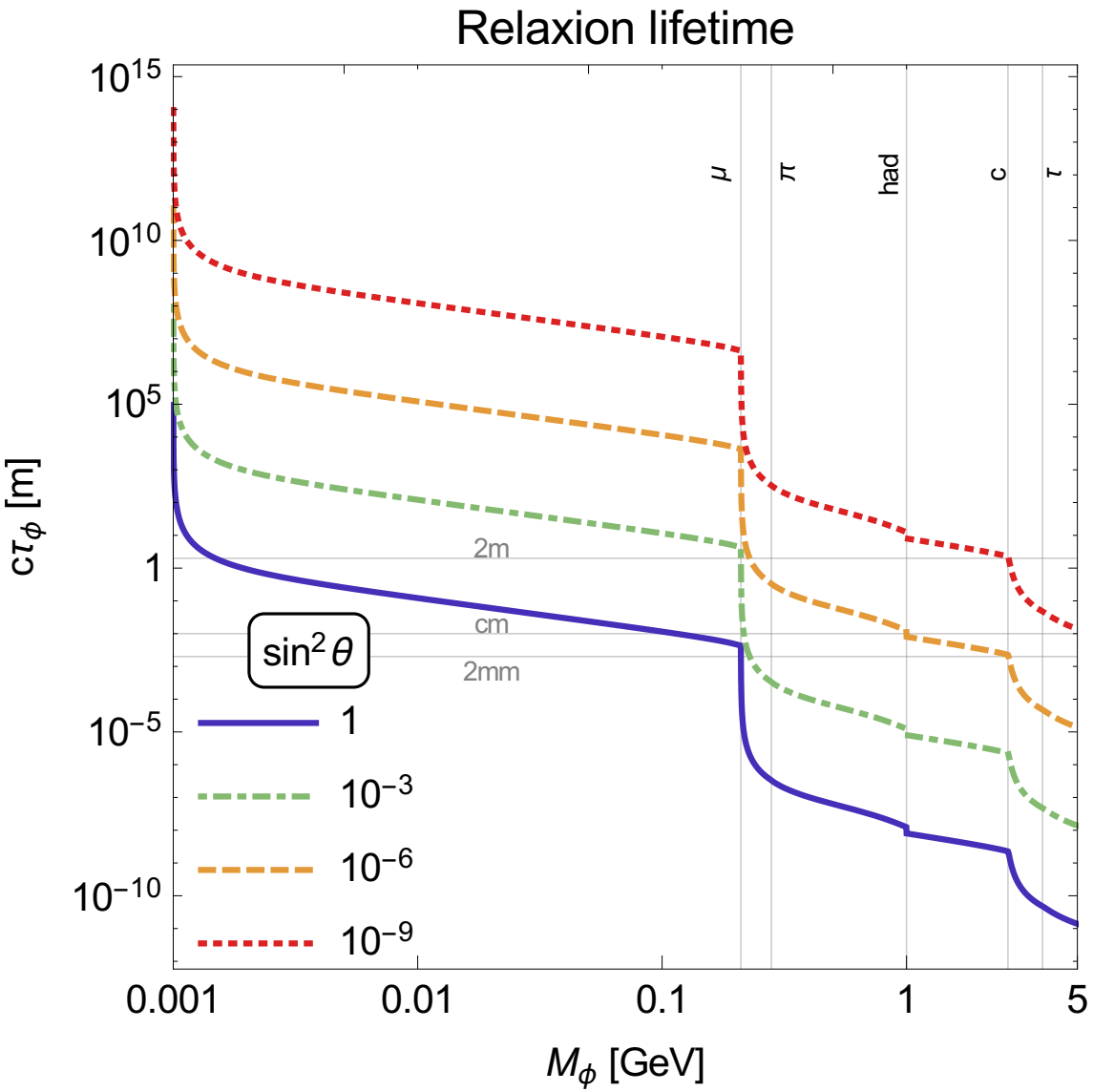
$$\boldsymbol{\tilde{M} \leq \tilde{M}_{max}} = M_h \cdot 2^{-1/4} \simeq 105\,\mathrm{GeV}$$

Narrow relaxion



relaxion very narrow $\longrightarrow$ lifetime?

Relaxion lifetime

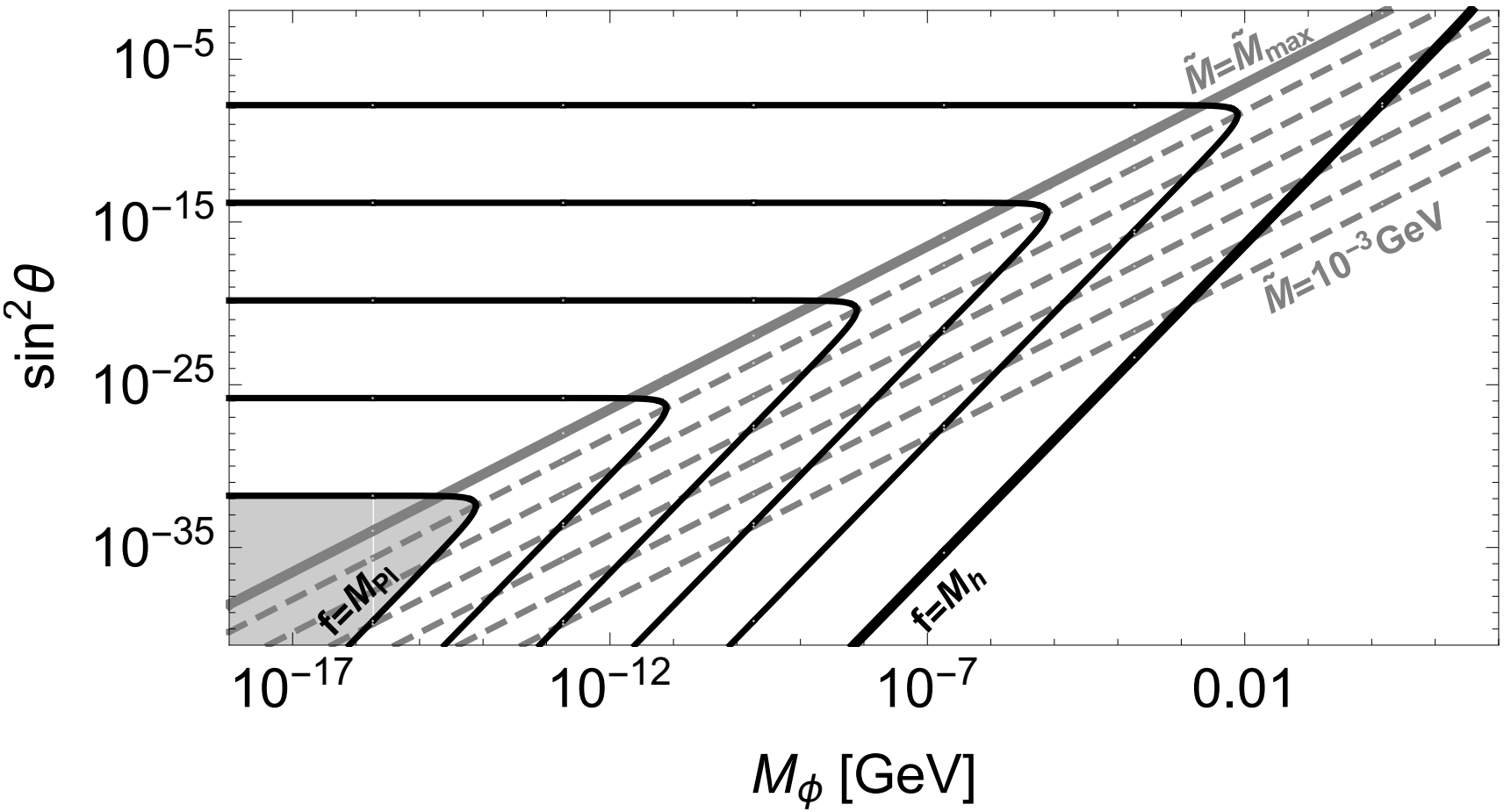


- threshold effects
- $c\tau_\phi \propto (\sin\theta)^{-2}$
- displaced vertex?
- decay outside detector?

ϕ possibly long-lived

"Higgs portal" vs relaxion

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



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

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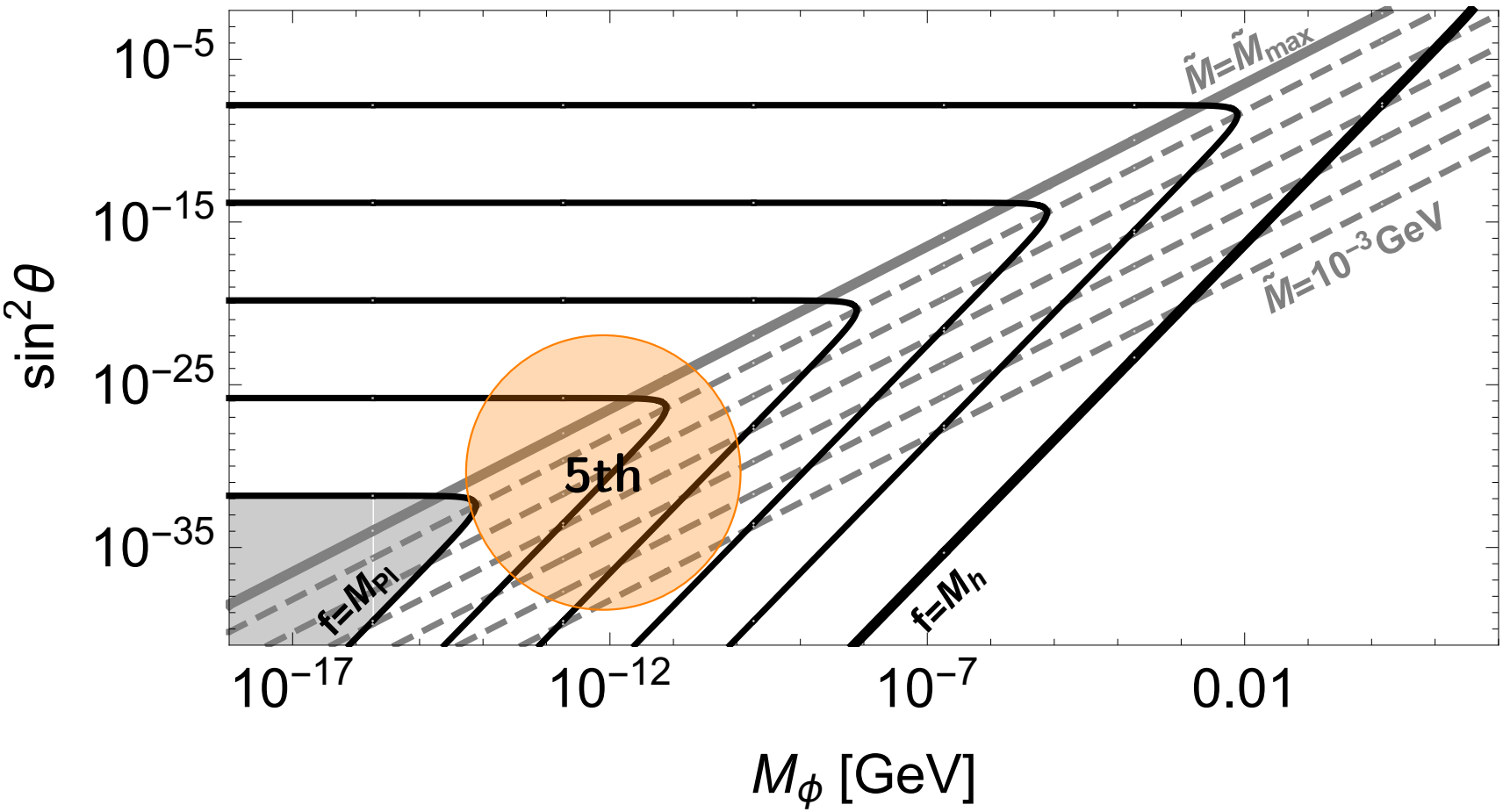

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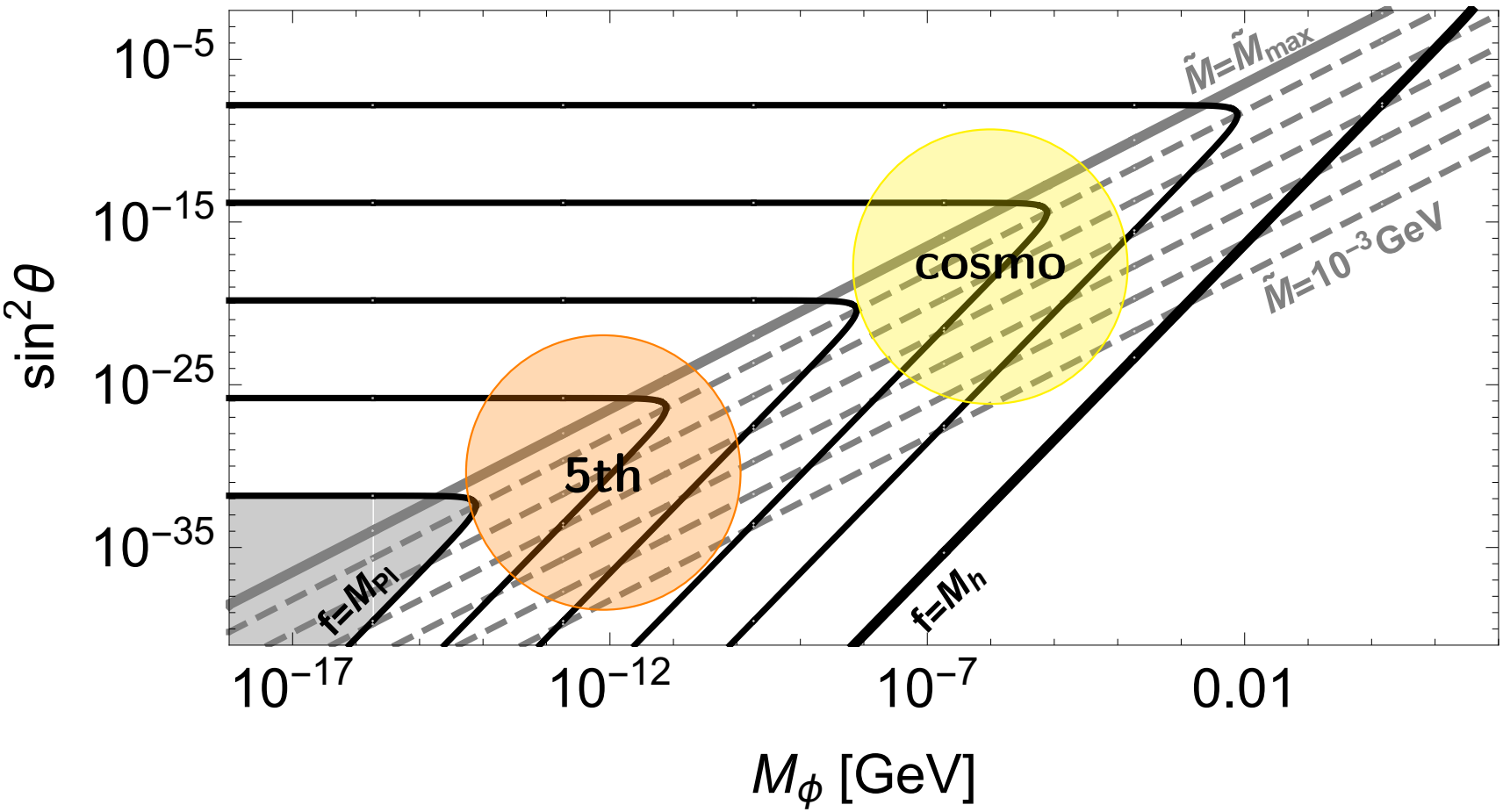

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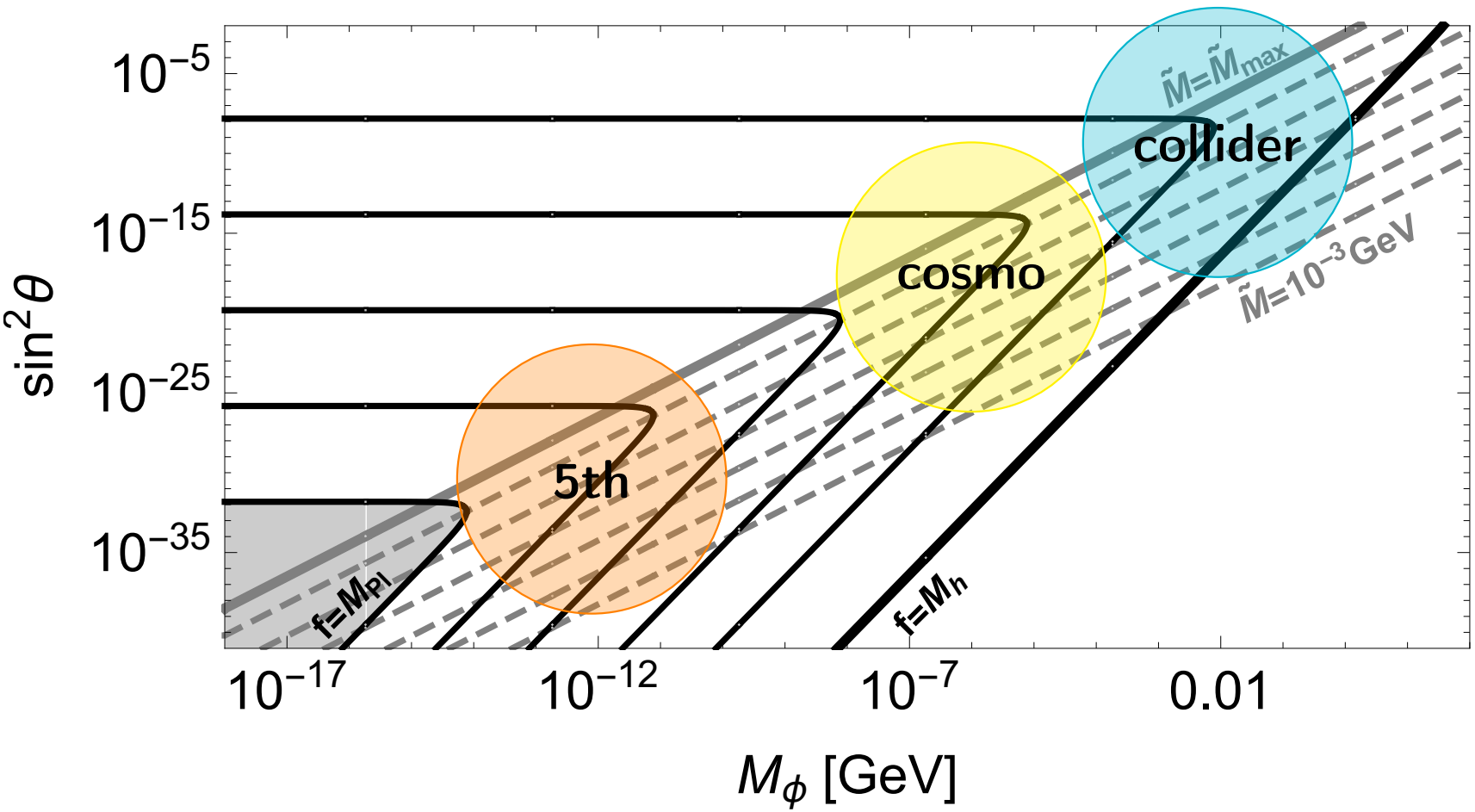

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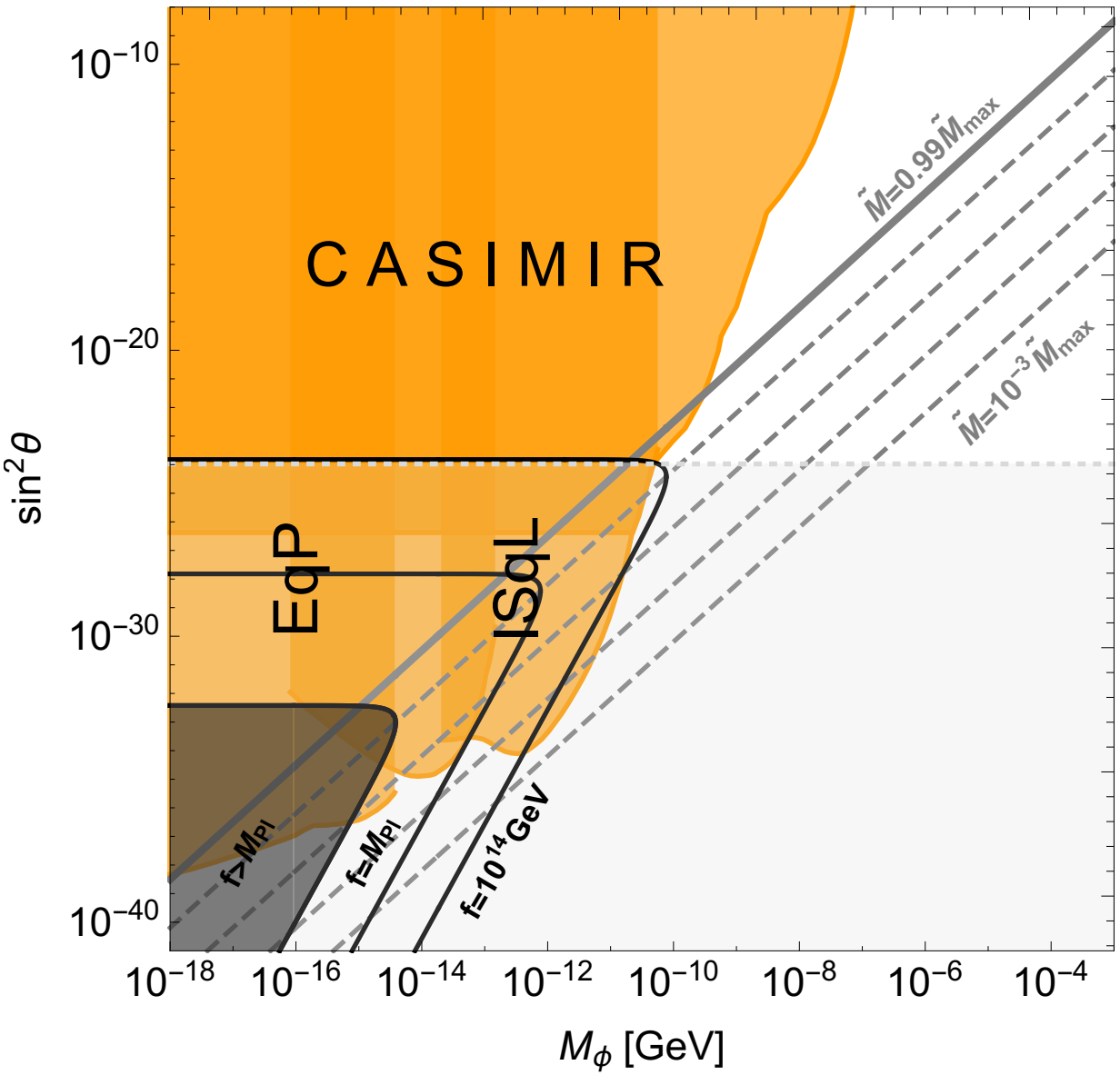
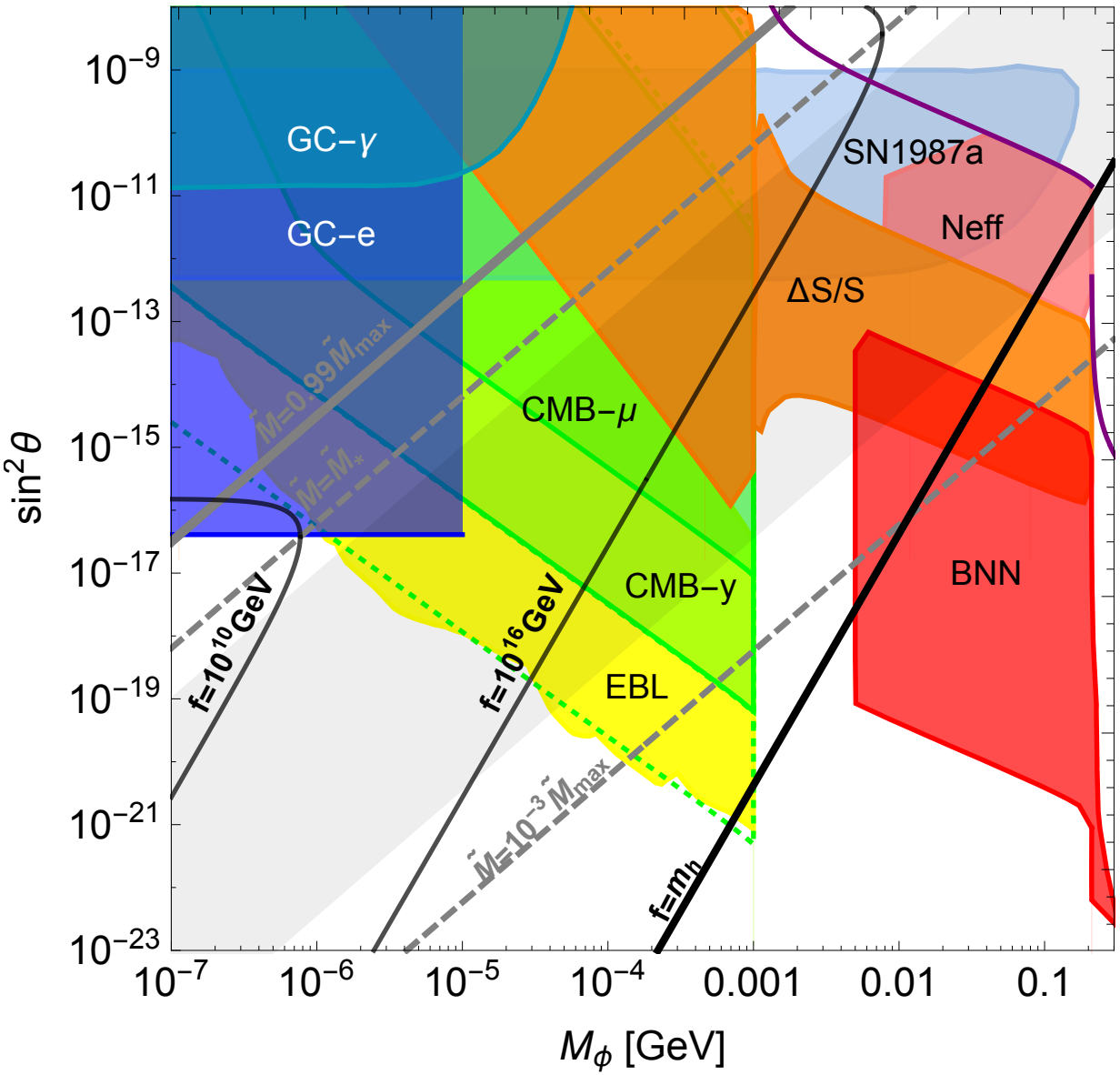
Relaxion sub-keV: 5th force



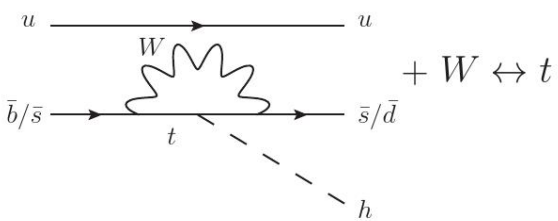
[Eöt-Wash group (Adelberger et al.)] [Bordag, Mohideen, Mostepanenko '01] [Piazza, Pospelov '10],...

Cosmological and astrophysical bounds

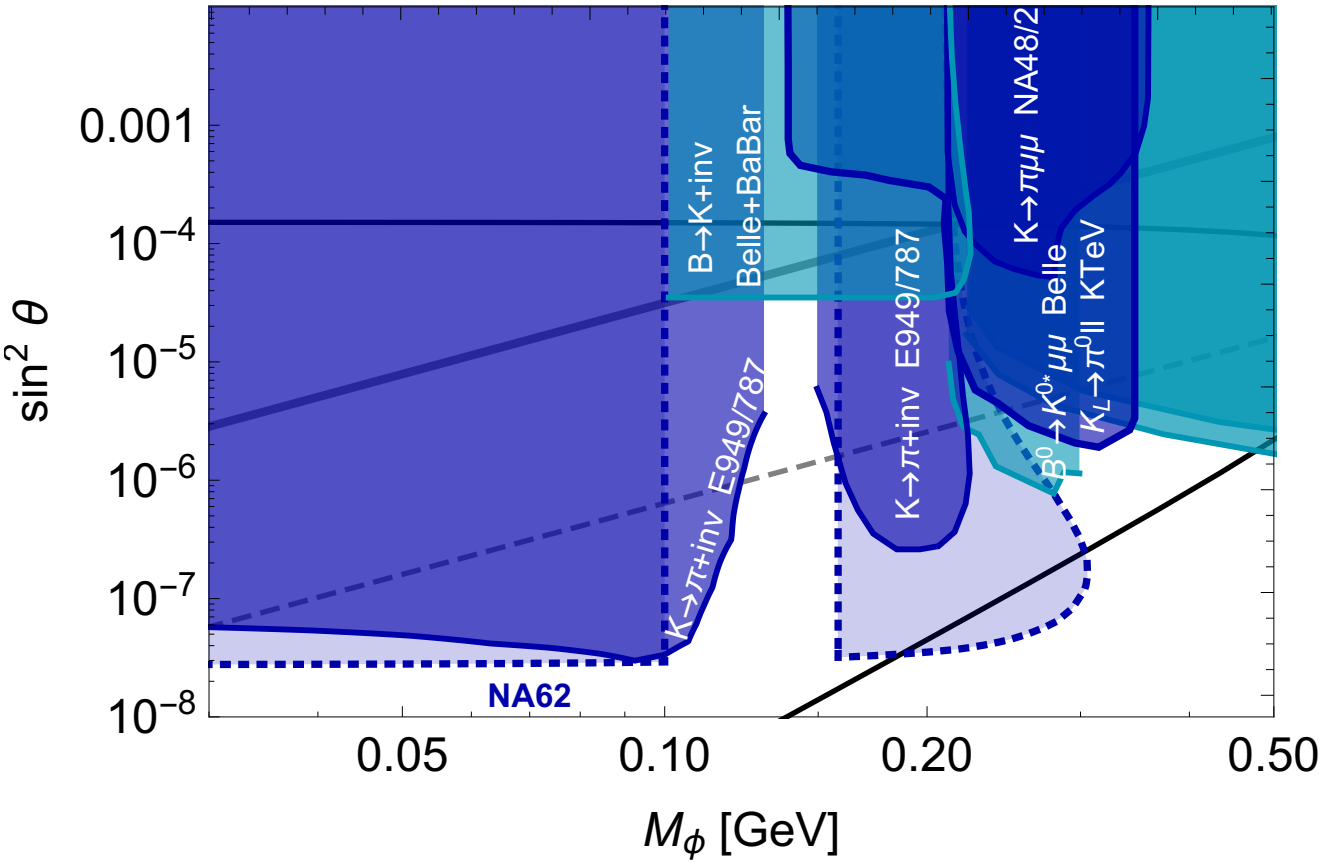


[Kolb, Turner] [Planck] [Cadamuro, Redondo '12] [Arias, Cadamuro, Goodsell, Jäckel, Redondo, Ringwald '12]

Relaxion-mediated rare B, K-decays



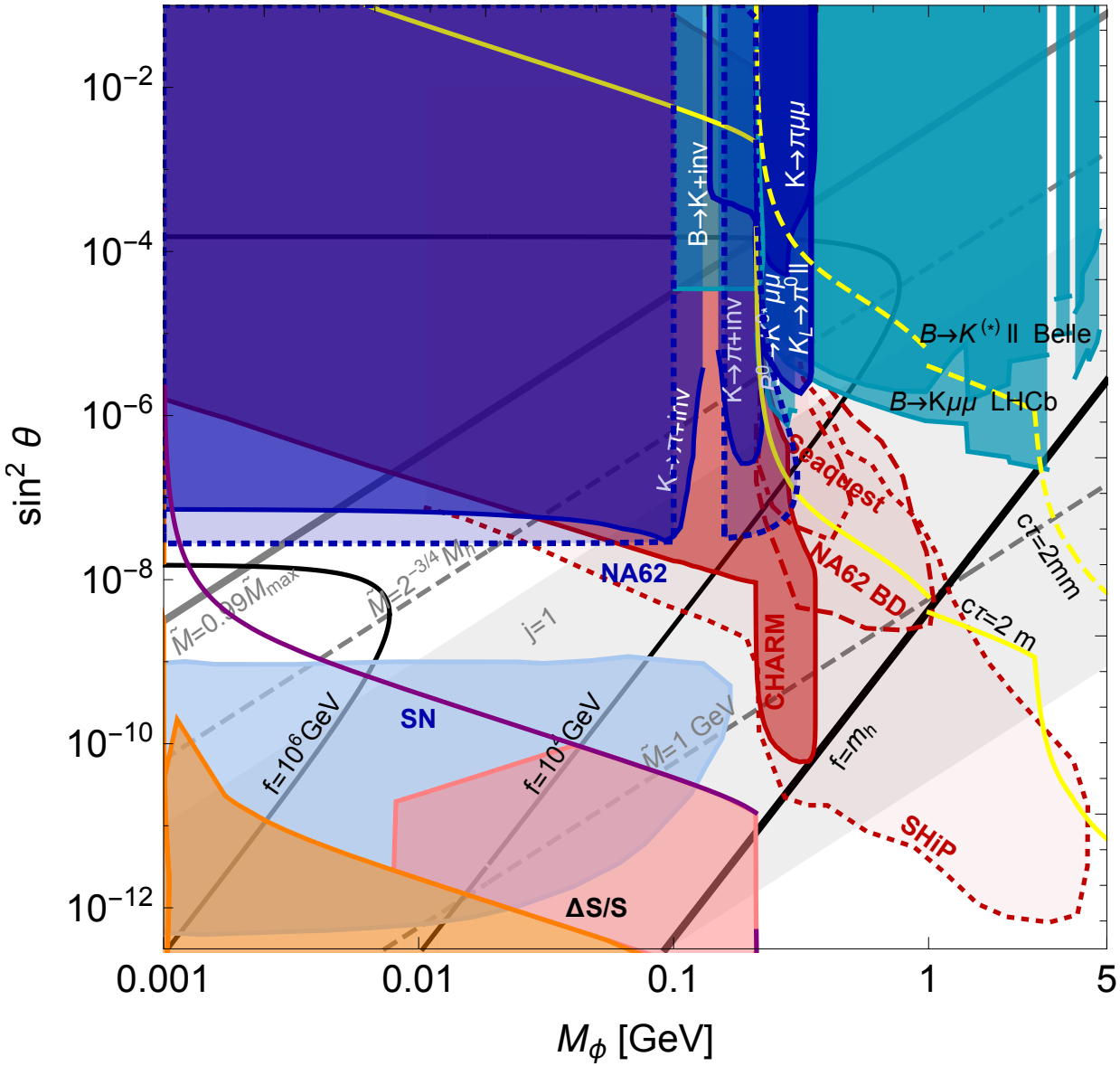
[Clarke, Foot, Volkas '13]



[Clarke, Foot, Volkas '13] [Schmidt-Hoberg, Staub, Winkler '13]

[Dolan, Kahlhoefer, McCabe, Schmidt-Hoberg '14] [Krnjaic '15]

Relaxion MeV - few GeV



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Higgs production and exotic Higgs decays

Higgs/relaxion strahlung at LEP

$\sigma(e^+e^- \to Z \to Z^*\phi)$

$\mathcal{S}_{95} = \sigma_{\rm max}/\sigma_{\rm SM} = \sin^2\theta_{\rm max}$

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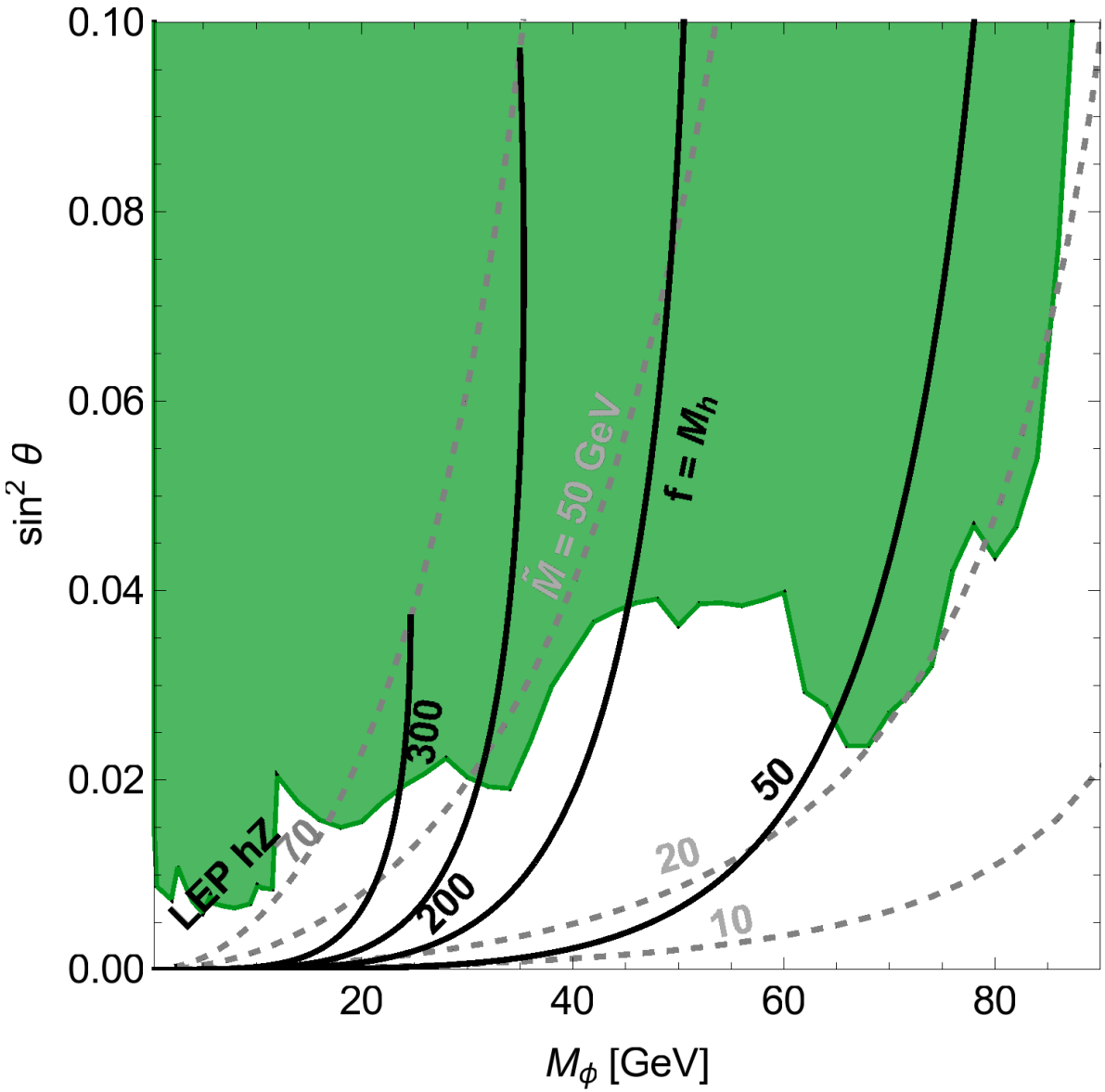
Higgs decays to relaxions

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

- fit of Higgs couplings, allowing for universal $\kappa \equiv \sin\theta$
  upper bound on $\Gamma_H^{\rm tot}$ bounds $\boldsymbol{\Gamma(H \to \text{NP}) < 20\%}$
- explicit searches by CMS, ATLAS for $H_{125} \to aa \to 4f/4\gamma$,
  $m_a \simeq 0.3\,\text{GeV} - M_h/2$; $\mu\mu bb$ promising
  $\curvearrowright$ reinterpreted for $H_{125} \to \phi\phi \to 4f/4\gamma$ decays

Relaxion above GeV: LEP and LHC



[L3] [LEP combination] [Bechtle, Heinemeyer, Stål, Stefaniak, Weiglein '14]

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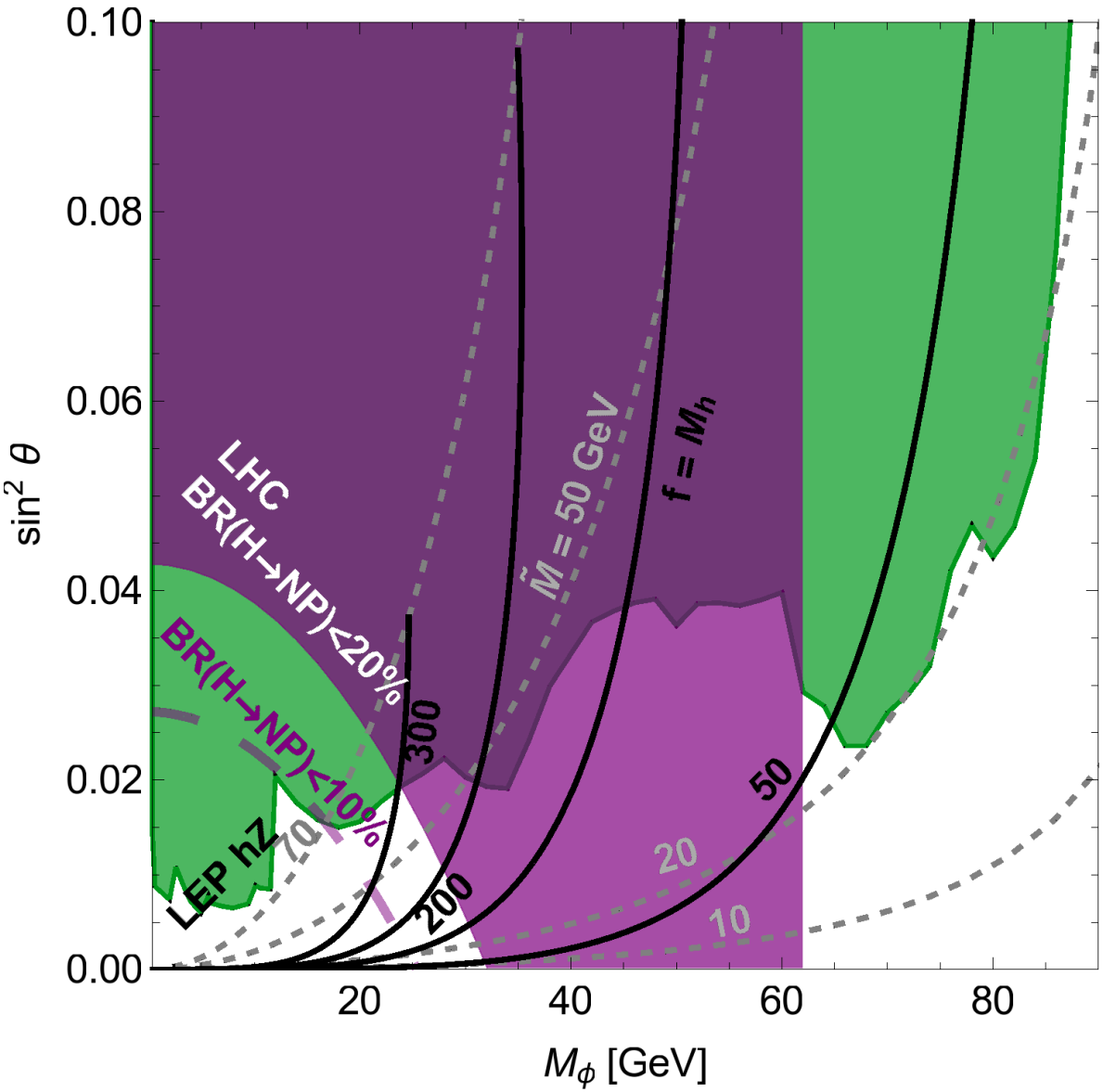

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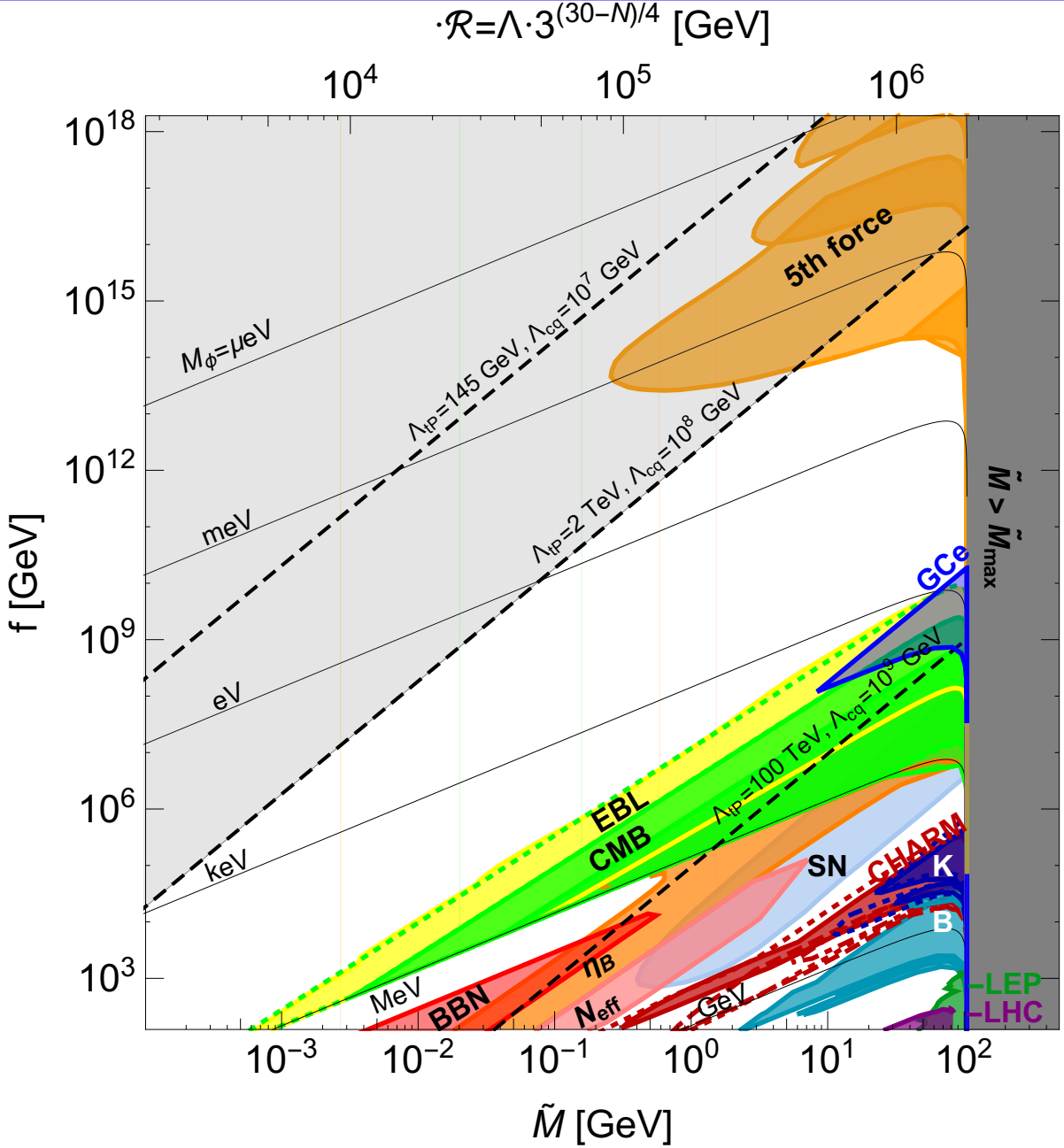
Relaxion parameter space: $\tilde{M}, f$



Prospects for future improvements

- Rare B, K decays
  - differential distributions
  - displaced vertices
  - ongoing data taking at NA62
- Beam dump experiments
  - SHiP, NA62 dump mode, SeaQuest
- Exotic Higgs decays
  - reduced uncertainty on Higgs couplings, total width
    $\Rightarrow$ stronger bound on $\Gamma(H \to \mathrm{NP})$
  - $H \to \phi\phi \to 4f$ at ATLAS and CMS (13 TeV update – Run III)

Conclusions

- considered relaxion in broad mass range sub-eV - weak scale
- scalar-portal like mixing can have observable effect
- probed by 5th force, B,K decays, cosmology, astrophysics and colliders
- relaxion mostly unconstrained for $m_\phi \simeq$ few meV - keV
- significant improvements of bounds possible
- theory: upper bound on $\tilde{M}$

THANK YOU!