Constraints on Relaxion Window

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Kiwoon Choi, SHI : 1610.00680 [JHEP 1612:093 (2016)]

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Outline

- Relaxation of the Electroweak scale
  : Axion scale hierarchy problem

- Large number of e-folding
  : Cosmological Relaxion Window

- Low energy phenomenology with minimal couplings
  : Constraints on Relaxion Window

- Conclusions

Relaxation of the Electroweak scale

Graham, Kaplan, Rajendran, '15

Higgs mass as a dynamical field
: Relaxion

$$\mathcal{L} = -m_H^2(\phi)|H|^2 - \frac{1}{4}\lambda_H |H|^4 + \cdots$$

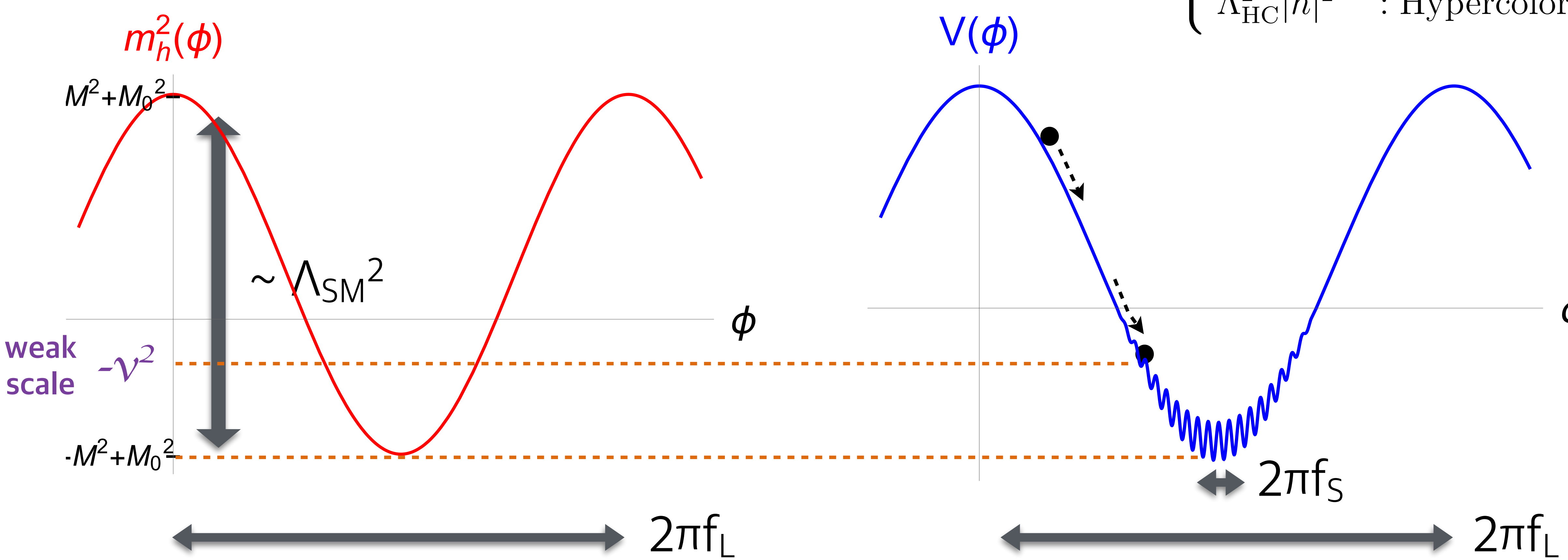
$$m_H^2(\phi) = M^2 \cos\left(\frac{\phi}{f_L}\right) + M_0^2$$

where $M \sim M_0 \sim \Lambda_{SM}$

Relaxion potential
: Radiative correction + Higgs dependent modulation (barrier)

$$V(\phi) = \frac{c_0}{16\pi^2}\Lambda_{SM}^4 \cos\left(\frac{\phi}{f_L}\right) + \Lambda_b^4(h) \cos\left(\frac{\phi}{f_S} + \delta_b\right)$$

$$\Lambda_b^4(h) \to \begin{cases} y_u \Lambda_{QCD}^3 h & : \text{QCD} \\ \Lambda_{HC}^2 |h|^2 & : \text{Hypercolor} \end{cases}$$



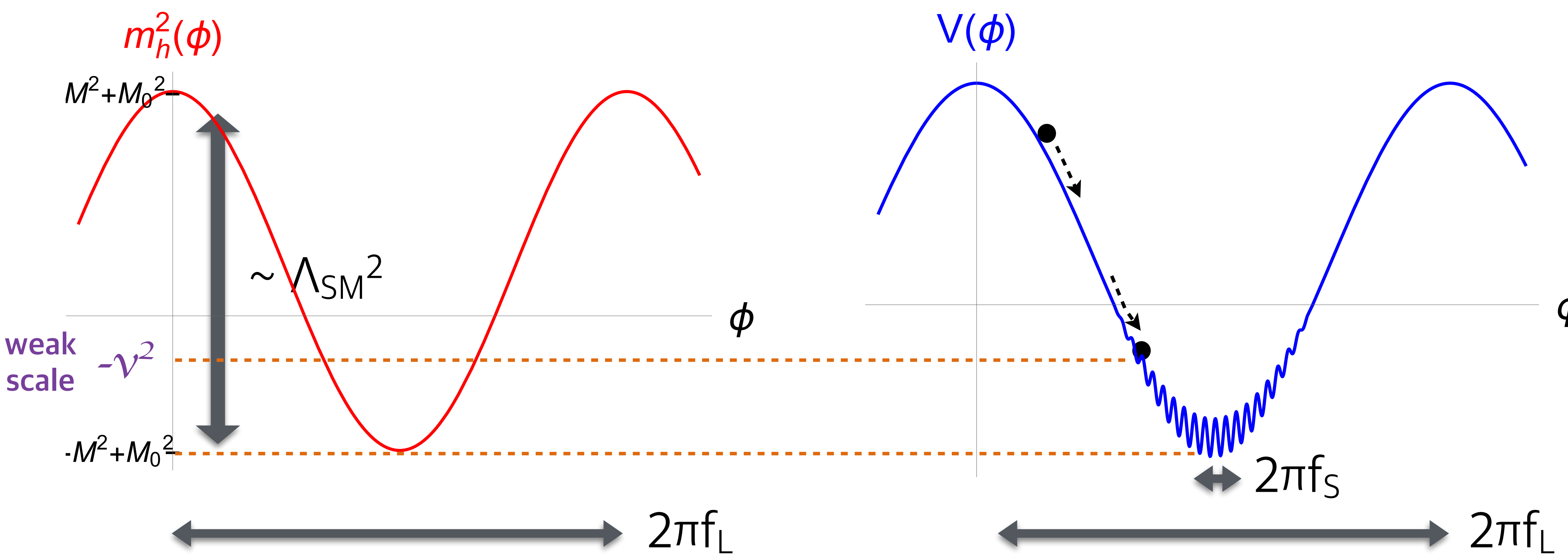
$$V(\phi) = V_0(\phi) + V_b(\phi) = \frac{c_0}{16\pi^2}\Lambda_{\rm SM}^4 \cos\left(\frac{\phi}{f_L}\right) + \Lambda_b^4(h)\cos\left(\frac{\phi}{f_S} + \delta_b\right)$$

$$\frac{\partial V}{\partial \phi} = 0 \quad \Rightarrow \quad \boxed{\frac{f_L}{f_S}} \sim \frac{c_0}{16\pi^2}\frac{\Lambda_{\rm SM}^4}{\Lambda_b^4(h=v)}\frac{1}{\sin(\phi/f_S + \delta_b)} \gtrsim \frac{1}{(4\pi)^3}\frac{\Lambda_{\rm SM}^4}{v^4} \sim \boxed{10^3\left(\frac{\Lambda_{\rm SM}}{10\,{\rm TeV}}\right)^4}$$

In order to stabilise the relaxion at the point $\langle h \rangle = v = 246$ GeV,
the ratio between the two periodicities f_L and f_S must be larger than the above ratio.

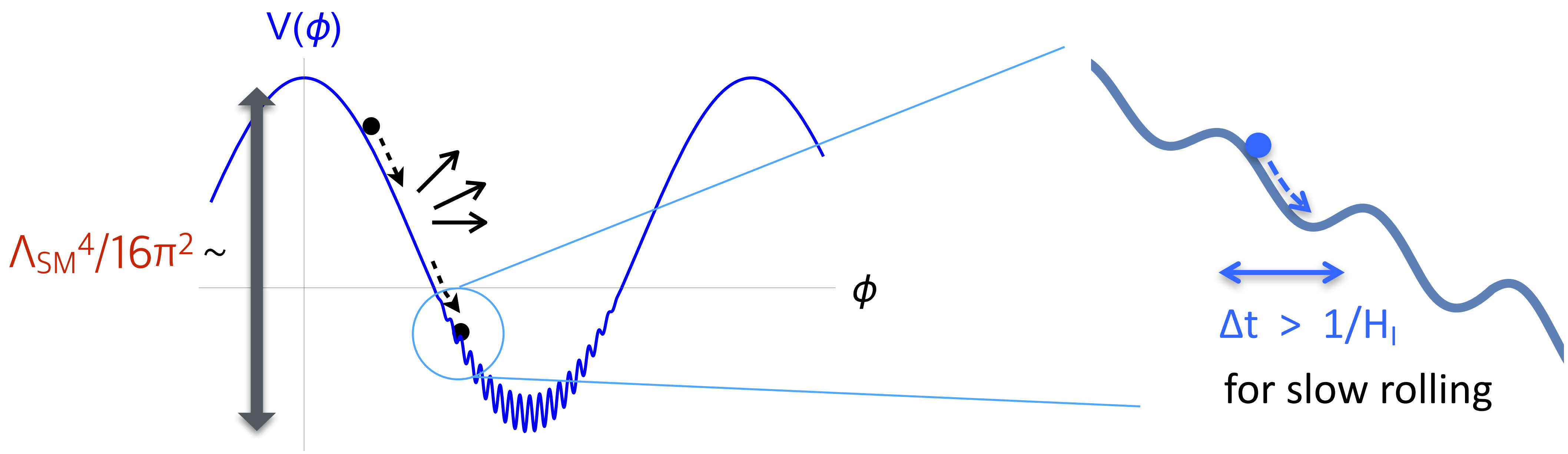
➡ Axion scale hierarchy problem : clockwork

K. Choi, H.J. Kim, S.H. Yun '14
K. Choi, SHI '15
Kaplan, Rattazzi '15



Cosmological relaxion evolution : Long e-folding

The relaxion kinetic energy should be efficiently dissipated away to stop the relaxion before going into the global minimum.



If the relaxion dynamics occurs during inflation, **the Hubble friction** can be responsible for the dissipation.

- Slow roll : $H_I > \dfrac{\Lambda_b^2}{f_S} \sim m_\phi$
- Inflaton energy density > Relaxion energy density : $H_I^2 M_{\rm Pl}^2 > \dfrac{1}{16\pi^2}\Lambda_{\rm SM}^4$

$$\mathcal{N} \sim \frac{f_L}{\dot\phi} H_I \sim 16\pi^2 \frac{f_L^2 H_I^2}{\Lambda_{\rm SM}^4} \gtrsim \max\left[\frac{f_L}{f_S}\left(1+\frac{\Lambda_b^2}{v^2}\right), \frac{f_L^2}{M_{\rm Pl}^2}\right] > \frac{1}{16\pi^2}\frac{\Lambda_{\rm SM}^4}{v^4} \sim \left(\frac{\Lambda_{\rm SM}}{1\,{\rm TeV}}\right)^4$$

Necessary number of e-folding

- Necessary e-folding for the QCD barrier

$$\frac{f_L}{f_S} \sim \frac{1}{16\pi^2}\frac{\Lambda_{\rm SM}^4}{\Lambda_b^4}\left(1+\frac{\Lambda_b^2}{v^2}\right) \quad \Rightarrow \quad \mathcal{N} \gtrsim \max\left[\frac{1}{16\pi^2}\frac{\Lambda_{\rm SM}^4}{\Lambda_b^4}, \frac{1}{(16\pi^2)^2}\frac{f_S^2}{M_{\rm Pl}^2}\frac{\Lambda_{\rm SM}^8}{\Lambda_b^8}\right]\left(1+\frac{\Lambda_b^2}{v^2}\right)^2$$

Barrier from QCD $\Downarrow$ $\Lambda_b^4 \simeq f_\pi^2 m_\pi^2 \sim (0.1\,{\rm GeV})^4$

$$\mathcal{N}_{\rm QCD} \gtrsim \max\left[10^{24}\left(\frac{\Lambda_{\rm SM}}{1\,{\rm TeV}}\right)^4, 10^{19}\left(\frac{f_S}{10^9\,{\rm GeV}}\right)^2\left(\frac{\Lambda_{\rm SM}}{1\,{\rm TeV}}\right)^8\right]\left(\frac{10^{-10}}{\theta_{\rm QCD}}\right)$$

- de Sitter Quantum fluctuation < Classical rolling

$$H_I < V'(\phi)^{1/3} < \left(\frac{\Lambda_b}{f_S}\right)^{1/3}\Lambda_b < \mathcal{O}(\sqrt{4\pi}v)$$

Low scale inflation

Such a long e-folding in a low scale inflation would imply a fine-tuning on the inflaton sector.

$\Rightarrow$ For a natural scenario, we need a new physics for the barrier sector.

Cosmological relaxion windows

Requiring $\mathcal{N} < \mathcal{N}_e$ (a certain acceptable number of e-folding) ,

$$\Lambda_{\rm SM} < \min\left[9\,{\rm TeV}\left(\frac{\mathcal{N}_e}{10^4}\right)^{1/4},\ 10^{11}\,{\rm GeV}\left(\frac{\rm TeV}{f}\right)^{1/6}\right]$$

$$30\,{\rm GeV}\left(\frac{\Lambda_{\rm SM}}{1\,{\rm TeV}}\right)\left(\frac{10^4}{\mathcal{N}_e}\right)^{1/4} < \Lambda_b \lesssim \mathcal{O}(\sqrt{4\pi}v)$$

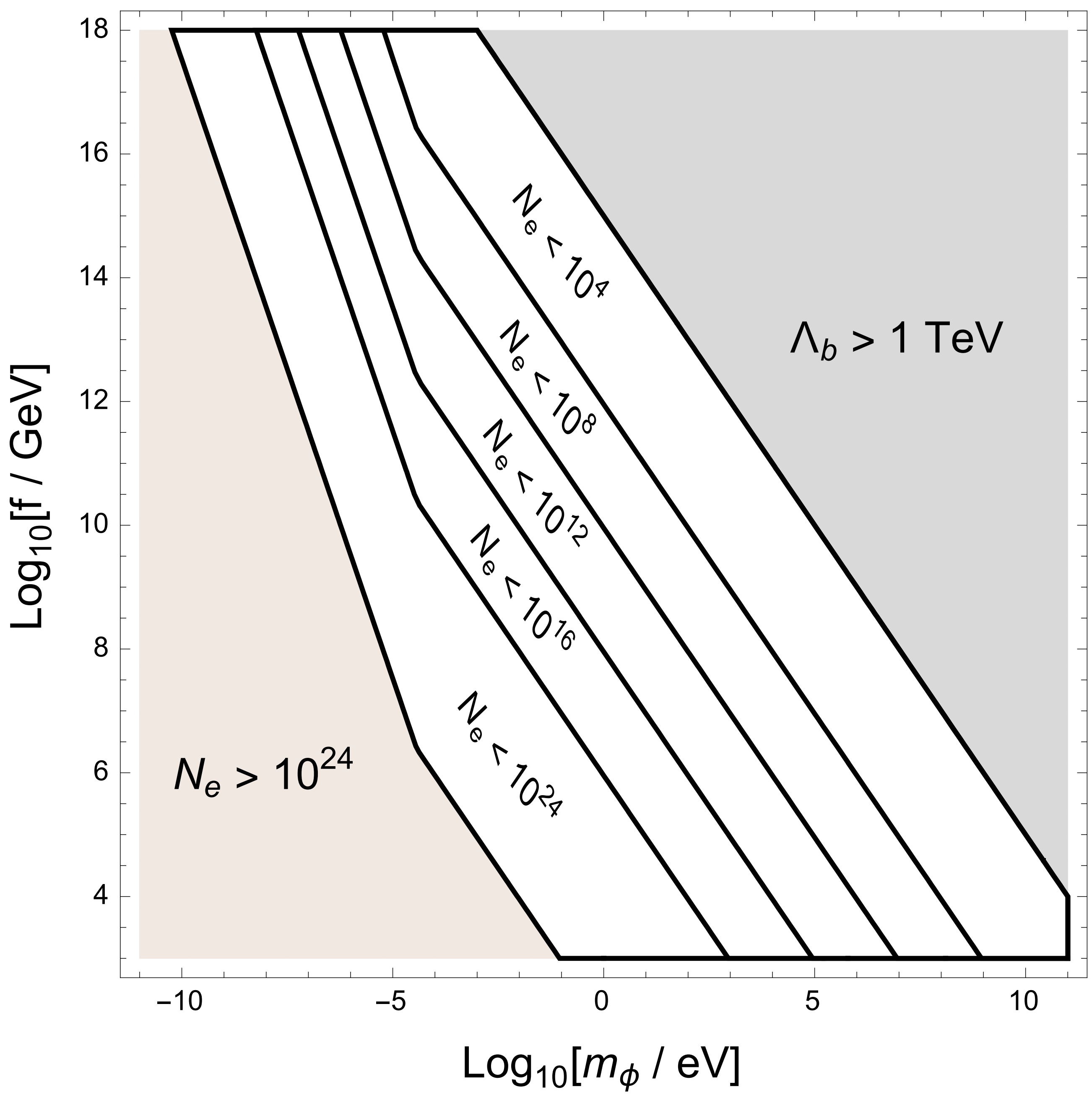
$$\Lambda_{\rm SM} < f < 3\times 10^{22}\,{\rm GeV}\left(\frac{1\,{\rm TeV}}{\Lambda_{\rm SM}}\right)^4\left(\frac{\Lambda_b}{1\,{\rm TeV}}\right)^4\left(\frac{\mathcal{N}_e}{10^4}\right)^{1/2}\left(1+\frac{\Lambda_b^2}{v^2}\right)^{-1}$$

$m_\phi \sim \Lambda_b^2/f$

$$3\times 10^{-8}\,{\rm eV}\left(\frac{\Lambda_{\rm SM}}{\rm TeV}\right)^4\left(\frac{1\,{\rm TeV}}{\Lambda_b}\right)^2\left(\frac{10^4}{\mathcal{N}_e}\right)^{1/2}\left(1+\frac{\Lambda_b^2}{v^2}\right) < m_\phi < \min\left[v,\ 1\,{\rm TeV}\left(\frac{1\,{\rm TeV}}{\Lambda_{\rm SM}}\right)\left(\frac{\Lambda_b}{1\,{\rm TeV}}\right)^2\right]$$

$H_I < O(v)$

Cosmological relaxion windows



- $\Lambda_b > 1$ TeV : theoretically disfavored (naturalness bound on the barrier height)
- N_e : required number of e-folding for the relaxion dynamics with the Hubble friciton
- $N_e \sim 10^{24}$: lowest e-folding for the QCD barrier

$1\ \mathrm{TeV} < f < M_{Pl}$

$10^{-10}\ \mathrm{eV} < m_\Phi < v_{EW}$

The smaller e-folding corresponds to the higher barrier. $\Lambda_b > 30\,\mathrm{GeV}\left(\frac{\Lambda_{\rm SM}}{1\,\mathrm{TeV}}\right)\left(\frac{10^4}{\mathcal{N}_e}\right)^{1/4}$

Phenomenology of the Relaxion
: Minimal couplings

- Relaxion-Higgs coupling   Flacke, Frugiuele, Fuchs, Gupta, Perez '16

$$\Lambda_b^4(h)\cos\left(\frac{\phi}{f}+\delta_b\right) \Rightarrow$$

$$m_\phi \sim \frac{\Lambda_b^2}{f} \qquad \Lambda_b \equiv \Lambda_b(h=v)$$

$$\theta_{\phi h} \sim \frac{\Lambda_b^4}{vf}\sin\left(\frac{\langle\phi\rangle}{f}+\delta_b\right)\times\frac{1}{m_h^2-m_\phi^2} \sim \boxed{\frac{m_\phi^2}{m_h^2-m_\phi^2}\frac{f}{v}\left(1+\frac{fm_\phi}{v^2}\right)^{-1}}$$

The relaxion-Higgs mixing **$\theta_{\phi h}$** is determined in terms of **m_ϕ** and **f**.

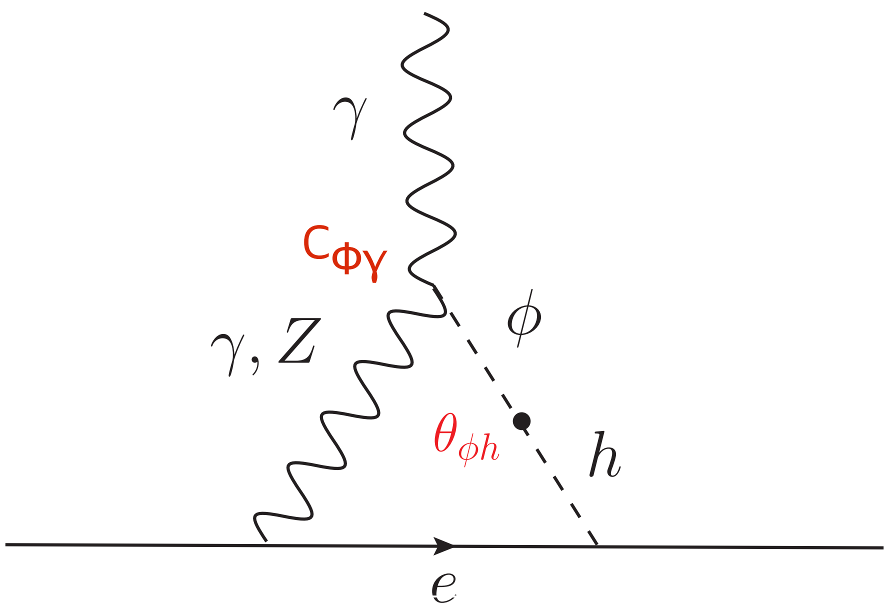
- Relaxion-Photon coupling

The Higgs dependent barrier sector generally includes the electroweak charged fermions.
→ relaxion-photon coupling through the anomaly

$$c_{\phi\gamma}\frac{\alpha}{4\pi f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \text{with} \quad c_{\phi\gamma}=\mathcal{O}(1)$$

The simultaneous presence of those two couplings means that CP is spontaneously broken by the relaxion VEV.

EDM and sub-GeV relaxion couplings



$$d_f \simeq 4\frac{e^3}{(4\pi)^4}\frac{m_f}{v}\frac{c_{\phi\gamma}}{f}\sin\theta_{\phi h}\cos\theta_{\phi h}\ln\left(\frac{m_h^2}{m_\phi^2}\right)$$

$$d_e \sim 7\times 10^{-29} c_{\phi\gamma}\left(\frac{m_\phi}{10\,\mathrm{GeV}}\right)^2\ln\left(\frac{10\,\mathrm{GeV}}{m_\phi}\right)\left(1+\frac{f m_\phi}{v^2}\right)^{-1} e\cdot\mathrm{cm}$$

$$d_e < 8.7\times 10^{-29}\, e\cdot\mathrm{cm}$$: $m_\Phi > 10/\sqrt{c_{\Phi\gamma}}$ GeV is excluded.

ACME '13

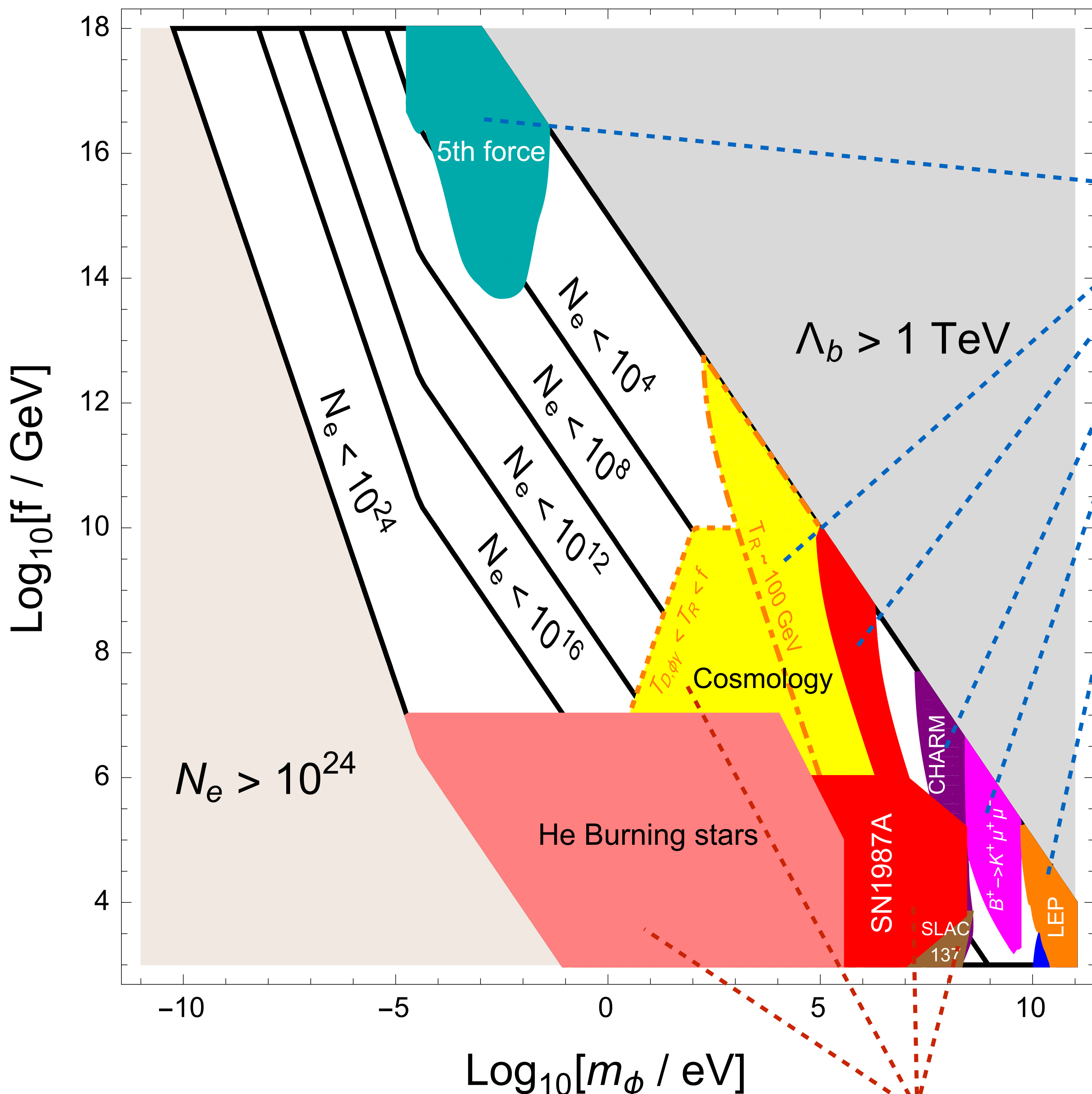
- The future EDM experiment like the proton storage ring experiment can probe the relaxion mass region below about 10 GeV.

- For m_Φ < 1 GeV, the **relaxion couples to pions and nucleons** through the relaxion-Higgs mixing.

$m_\phi < 1\,\mathrm{GeV}$

$$\mathcal{L}_{\rm eff} = 2 s_\theta \kappa\frac{\phi}{v}\left(\frac{1}{2}\partial_\mu\pi^0\partial^\mu\pi^0+\partial_\mu\pi^+\partial^\mu\pi^-\right)-\frac{5 s_\theta}{3}\frac{\phi}{v}m_\pi^2\left(\frac{1}{2}\pi^0\pi^0+\pi^+\pi^+\right)$$
$$-\frac{s_\theta}{6}\frac{g_2 m_N}{m_W}\phi\bar{N}N + s_\theta\frac{c_{h\gamma}\alpha}{4\pi v}\phi F^{\mu\nu}F_{\mu\nu}+\frac{c_{\phi\gamma}\alpha}{4\pi f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}+s_\theta\sum_{l=e,\mu}\frac{m_l}{v}\phi\,\bar{\psi}_l\psi_l$$

Phenomenological constraints on the relaxion windows



Excluded by $\theta_{\Phi h}$

$$\sim \frac{m_\phi^2}{m_h^2 - m_\phi^2}\frac{f}{v}\left(1 + \frac{f m_\phi}{v^2}\right)^{-1}$$

(large f region for a given m_Φ)

Three distinctive viable windows

i) $m_\Phi \sim 0.2 - 10$ GeV, f ~ few – 200 TeV

ii) $m_\Phi \sim$ few – 50 MeV, f ~ $10^6 - 10^9$ GeV

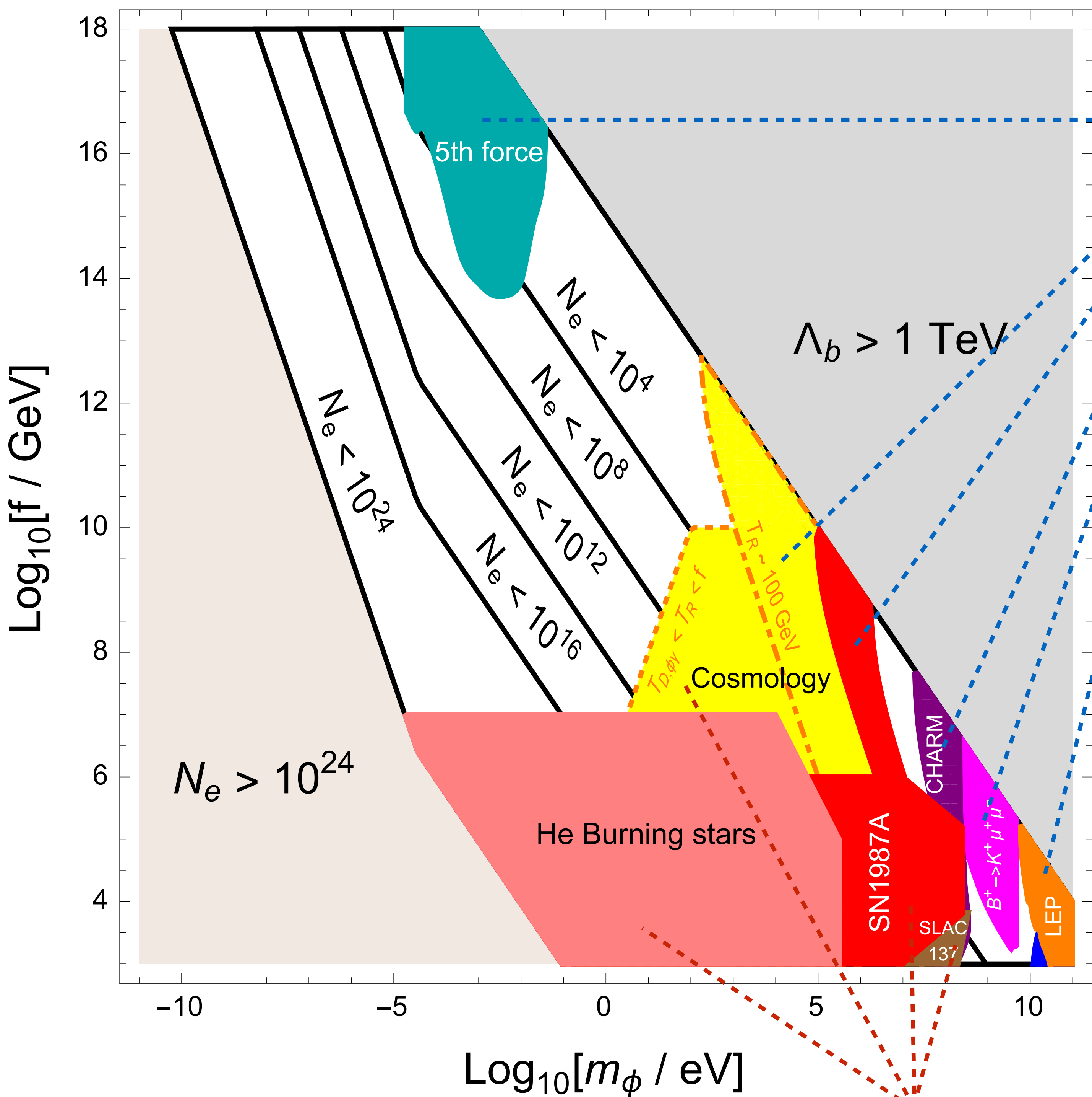
iii) $m_\Phi < 100$ eV, f > 10^7 GeV

All of them include the small e-folding region below 10^4.

Excluded by $c_{\Phi\gamma}$ (=1)
(small f region for a given m_Φ)

$$c_{\phi\gamma}\frac{\alpha}{4\pi f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Phenomenological constraints on the relaxion windows



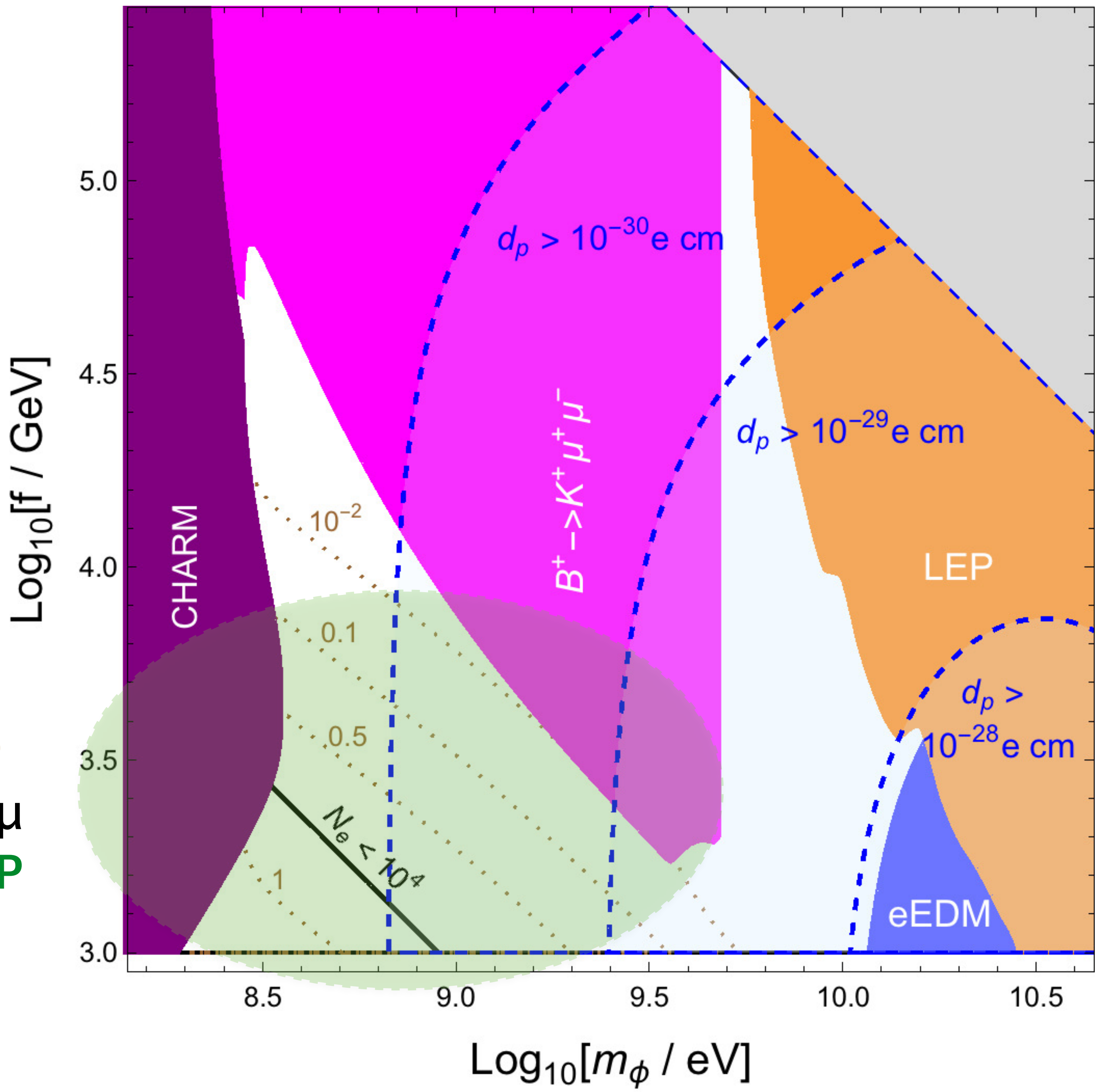
Excluded by $\theta_{\Phi h}$

- LEP : $e^+e^- \to Z \to Z\Phi$
- Rare meson decay : $B^+ \to K^+\Phi$ ($\Phi \to \mu^+\mu^-$) [$m_\Phi < 5$ GeV]
- CHARM Beam dump : $K \to \pi\,\Phi$ ($\Phi \to$ SM)
- SN1987A : Nucleon bremsstrahlung from ΦNN
- Cosmology (BBN, CMB, DR, DM, etc) : relaxion production from thermal equilibirium through the Higgs mixing ; depends on T_R
- 5th force : inverse square law

Excluded by $c_{\Phi\gamma}$ (=1)

- SLAC 137 Beam dump
- SN1987A : Primakoff process
- **He Burning stars : Primakoff process**
- Cosmology (BBN, CMB, DR, DM, etc) : relaxion production from the photon coupling ; depends on T_R

Enlarged picture for the first window



- BR(Φ->γγ)
- Φ->ππ, μμ
- **CERN SHiP**

- EDM with **$c_{\Phi\gamma}$ =1**
- Proton EDM estimated by the QCD sum rule

$$d_p = 0.78\, d_u(\mu_*) - 0.20\, d_d(\mu_*)$$

where $\mu_* = 1$ GeV

- NDA with s quark : an order of magnitude larger

- **Storage ring experiment for proton EDM**

Conclusions

- The relaxion mechanism can explain the weak scale in a technically natural way by converting the weak scale hierarchy to the axion scale hierarchy, which can be addressed by the clockwork mechanism.

- The hierarchy is also responsible for a large number of e-folding for the relaxion dynamics with the Hubble friction.

- The cosmological relaxion window identifies the favored relaxion parameter space in terms of the necessary number of e-folding.

- The model-independent low energy relaxion phenomenology can be studied by the relaxion-Higgs mixing and relaxion-photon coupling.

- After imposing various phenomenological constraints, three distinctive windows remain viable, all of which can accommodate a relatively small number of e-folding below 10^4.

- The first window ($m_\Phi \sim 0.2 - 10$ GeV, $f \sim$ few - 200 TeV) can be probed by future EDM experiments and CERN SHiP.