Cosmological Relaxion Windows and Observational constraints

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Outline

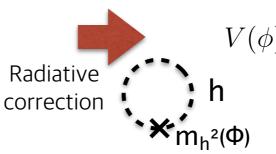
- Relaxion mechanism
 - : Transmutation of the weak scale hierarchy
 - i) Large separation of axion scales
 - ii) Large number of e-folding
- Cosmological Relaxion Windows
- Observational constraints
- Conclusions

Relaxion mechanism

Graham, Kaplan, Rajendran, '15

M: Natural Higgs mass scale

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



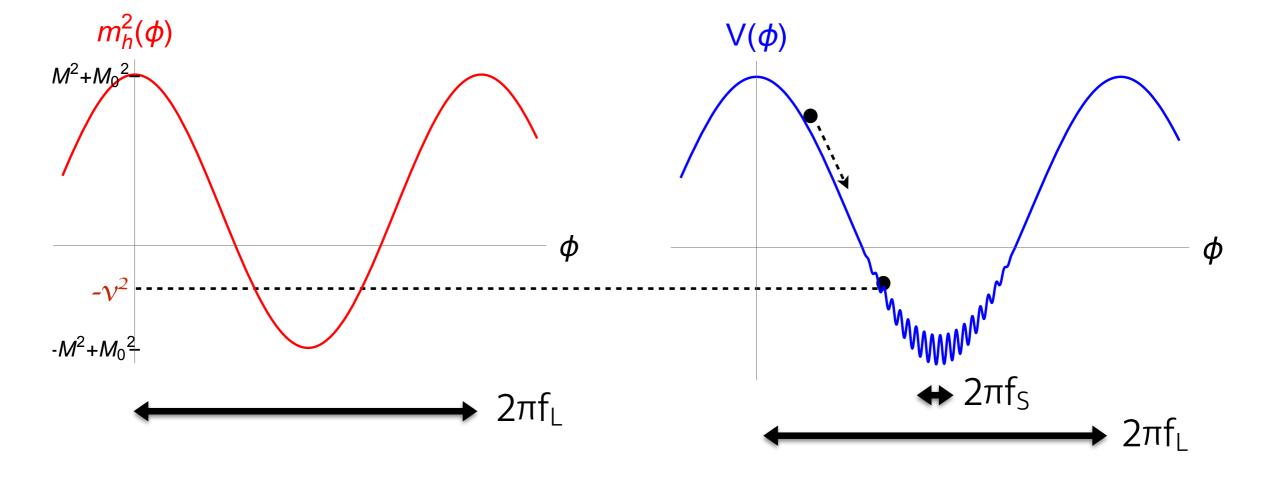
Higgs dependent barrier

$$V(\phi,h) = m_h^2(\phi)|h|^2 + \cdots$$
 Higgs dependent barrier
$$V(\phi,h) = \frac{c_0}{16\pi^2}M^2m_h^2(\phi) + \Lambda_b^4(h)\cos\left(\frac{\phi}{f_S} + \delta_b\right) + V_0$$
 Radiative correction
$$h$$

$$\Lambda_b^4(h) \sim h^n \neq 0 \text{ when } m_h^2(\phi) < 0$$



$$\frac{\partial V}{\partial \phi} = 0 \quad \to \quad \frac{f_L}{f_S} \sim \frac{c_0}{16\pi^2} \left(\frac{M}{\Lambda_b(h=v)}\right)^4 \frac{1}{\sin(\phi/f_S + \delta_b)}$$



Large separation of axion scales

$$\frac{f_L}{f_S} \sim \frac{c_0}{16\pi^2} \left(\frac{M}{\Lambda_b(h=v)}\right)^4 \frac{1}{\sin(\phi/f_S + \delta_b)} \gtrsim \frac{c_0}{(4\pi)^3} \frac{M^4}{v^4}$$

e.g.
$$f_L > 10^3 f_S$$
 for $M > 10 \,\text{TeV}$

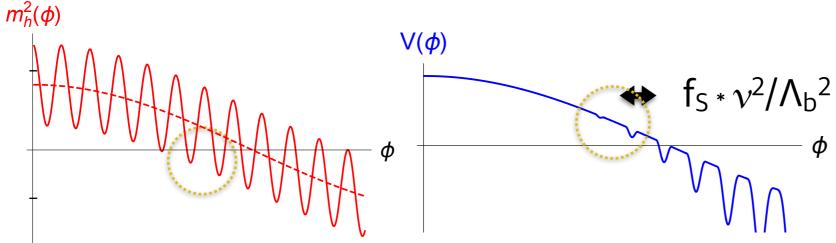
Naturalness limit on the barrier height

$$V_b(\phi, h) = \Lambda_b^4(h) \cos\left(\frac{\phi}{f_S} + \delta_b\right) = \left(\mu_b^2 |h|^2 + \mu_0^4\right) \cos\left(\frac{\phi}{f_S} + \delta_b\right)$$

For the barrier to depend on the Higgs VEV,
$$\mu_b^2 v^2 > \mu_0^4 \gtrsim \frac{1}{16\pi^2} \mu_b^4 \quad \to \quad \Lambda_b^4(h=v) < \mathcal{O}(16\pi^2 v^4)$$

Barrier shrinking effect when $\Lambda_b > v$: the barrier potential takes part in scanning the Higgs

mass m_h². Consequently, at the relaxion stabilisation point,



$$\sin\left(\frac{\phi}{f_S} + \delta_b\right) \sim \frac{v^2}{\Lambda_b^2 + v^2}$$

(114)(14)(14)(14)(14)(14)(14)(16)

Clockwork for $\frac{\partial f}{\partial \phi_1} = \frac{\partial f}{\partial \phi_2} = \frac{\partial f}{\partial f_1} = \frac{\partial f}{\partial f_2} = \frac{\partial f}{\partial f_2}$

(115) (115)(115) $\Delta \phi/f \gtrsim 100$ (Maching Smith of the property of the property

$$\Delta \phi / f \text{ MACON Filtration of the Macon Filter of the Macon Fi$$

Large number of e-folding

$$\mathcal{N} \sim \frac{f_L}{\dot{\phi}/H_I} \sim \left(\frac{c_0}{16\pi^2}\right)^{-1} \frac{f_L^2 H_I^2}{M^4} \sim \frac{c_0}{16\pi^2} \frac{f^2 M^4}{\Lambda_b^8 \sin^2(\phi_0/f)} H_I^2$$

- * Lower bound on H_I
 - i) slow roll

of back
$$\begin{array}{c|c}
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ii)
$$\rho_{inflaton} > \rho_{\Phi}$$

ii)
$$\rho_{\text{inflaton}} > \rho_{\Phi}$$
 $H_I^2 > \frac{\rho_{\phi}}{3M_{\text{Pl}}^2} \sim \frac{c_0}{16\pi^2} \frac{M^4}{M_{\text{Pl}}^2}$



$$\mathcal{N} \gtrsim \max \left[\frac{1}{16\pi^2} \frac{M^4}{\Lambda_{\rm b}^4}, \frac{1}{(16\pi^2)^2} \frac{f^2}{M_{\rm Pl}^2} \frac{M^8}{\Lambda_{\rm b}^8} \right] \left(1 + \frac{\Lambda_{\rm b}^2}{v^2} \right)^2 > \frac{1}{16\pi^2} \frac{M^4}{v^4} \sim \left(\frac{M}{\rm TeV} \right)^4$$

the right of the activities are the large from the large from the second control of the

this is estimated as

 $\mathcal{N}_{\rm NP} \sim \frac{f_{\rm eff}}{\dot{\phi}/H_I} \sim \frac{f_{\rm eff}^2 H_I^2}{M^4} \sim \frac{f^2 M^4 H_I^2}{\Lambda_b^8} \gtrsim \max\left[\frac{M^4}{\Lambda_b^4}, \frac{f^2}{M_{\rm Pl}^2} \frac{M^8}{\Lambda_b^8}\right],$ • Number of e-folding

problem [1]. Taking into account the different problem [1] where $\Lambda_b < \mathcal{O}(\sqrt{4\pi}v)$ (1) which was introduced in [1] to a wide M_b and M_b where M_b where M_b where M_b where M_b where M_b and M_b where M_b where M_b where M_b in M_b where M_b is a coupling during inflation, which was introduced in [1] to a wide M_b where M_b is a coupling during inflation, which was introduced in [1] to a wide M_b where M_b is a coupling during inflation, which was introduced in [1] to a wide M_b where M_b is a coupling during inflation, M_b in M_b in Me-foldings is estimated as

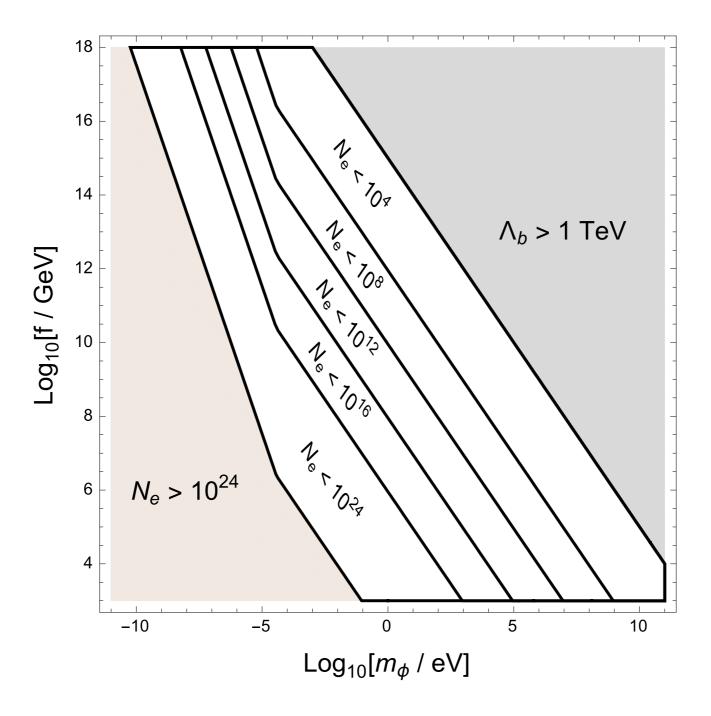
 $\mathcal{N}_{\text{QCD}} \sim \frac{1}{\theta_{\text{QCD}}} \frac{f^2 M^4 H_{\text{P}}^2}{f^2} \underbrace{\mathcal{V}}_{\text{Max}} \underbrace{\frac{\partial \mathcal{V}}{\partial x^2} \mathcal{V}_{\text{max}}^2}_{\text{Max}} \underbrace{\frac{\partial \mathcal{V}}{\partial x^2} \mathcal{V}_{\text{P}}^2}_{\text{Max}} \underbrace{\frac{\partial \mathcal{V}}{\partial x^2} \mathcal{V}_{\text{Max}}^4}_{\text{Max}} \underbrace{\frac{\partial \mathcal{V}}{\partial x^2} \mathcal{V}_{\text{Max}}^4$ a fine-tuning in the new physics sector to generate the barrier potential sit is bounded as $\Lambda_b^4 \lesssim \mathcal{O}(1000) \frac{10^{26} \text{ max}^2}{10^{26} \text{ level}} \frac{10^{26} \text{ level}}{10^{26} \text{ level}} \times 10^{23} \times 1$ $\mathcal{N}_e = \mathcal{O}(10^4).$

SFI with such a large e-folding would imply a fine-tuning on the inflation sector $\sim 10^{-10}$.

- Adthoughurat scingriorisce or eargument bit is clikely that eaching befolding number bigger
- # Anahalle? [28-30]. To avoid this potential problem, in the following we will focus on the scenario that the barrier potential

An important quantity of melaxion cosmology is the than acceptable e-f for the important quantity over a field distantes M is the fight distantes M is the important quantity of $M_1/4$ the weak scale. For the case that the barrier potential $V_{\rm b}$ is generated by frew physics, $\Lambda_b^4 \simeq f_\pi^2 m_\pi^2 \sim (0.1 \,\text{GeV})^4, \quad f \gtrsim 4 \times 10^8 \,\text{GeV}$ this is estimated as where we \mathcal{M}_{SP} again $f_{\pi I}^{\text{eff}}$ $f_{\pi I}^{2}$ $f_{\pi I}$ Although not being a prigorous priguing at it is likely that a huge's in the hough of the hough than 10^{26} causes $f_{s}^{2} = 4H_{f}^{2}$ returning problem if the inflaton sector [24] 30 from potential problem, in the following we will be scenario that the barrier potential M is generated by the whole which the property of the second consistency, and XFrom inthe up set bounded any of the first the new physics sector to generate the bound (16) is translated to $\Lambda_b (\underline{h} = \underline{b})$ where \underline{h} is the respective terms of the cosmological relaxion where the stabilization enimistry with the property of the property of the stabilization enimistry where the stabilization enimistry where the stabilization enimistry with the property of th Asswelnavenacticed, adequisitate fathebeaboier policitativation, ibe telecitatibily lagely. Alisa volidation id ggs mass cut off is the new private street of the theory of the property in the delimeted 7 nbers Aft establings and Cripothinewalascalener of the Color of the this burne ound come can raise the Higgs the relaxion to the relaxion of the relaxion of the raise the Higgs the relaxion of the relaxi is $\mathcal{N}_{\phi} = \mathcal{N}_{\phi}$ in the wind wind where theoretical consistency, and $\Lambda_b \lesssim \mathcal{O}(\sqrt{4\pi}v)$ to avoid a fine-tuning problem in the new physics sector to generate the barrier potential. The (1 TeV) 3×107^8 AV $(1 + \frac{1}{4})^2$ (LeV) $(1 + \frac{1}{4})^2$ $(1 + \frac{1}{4})^2$ $(1 + \frac{1}{4})^2$ $(1 + \frac{1}{4})^2$ range corresponds to the Asmological least on window for the Higgs mass cutoff M, the barrier height Λ_b , and the relaxion decay constant f, expressed in In Fig 26(1), we depict the cosmological relaxion window in terms of the relaxion mass

Cosmological relaxion windows



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

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

For a given m_{ϕ} , the required N_e is smaller as f is larger (due to a higher barrier).

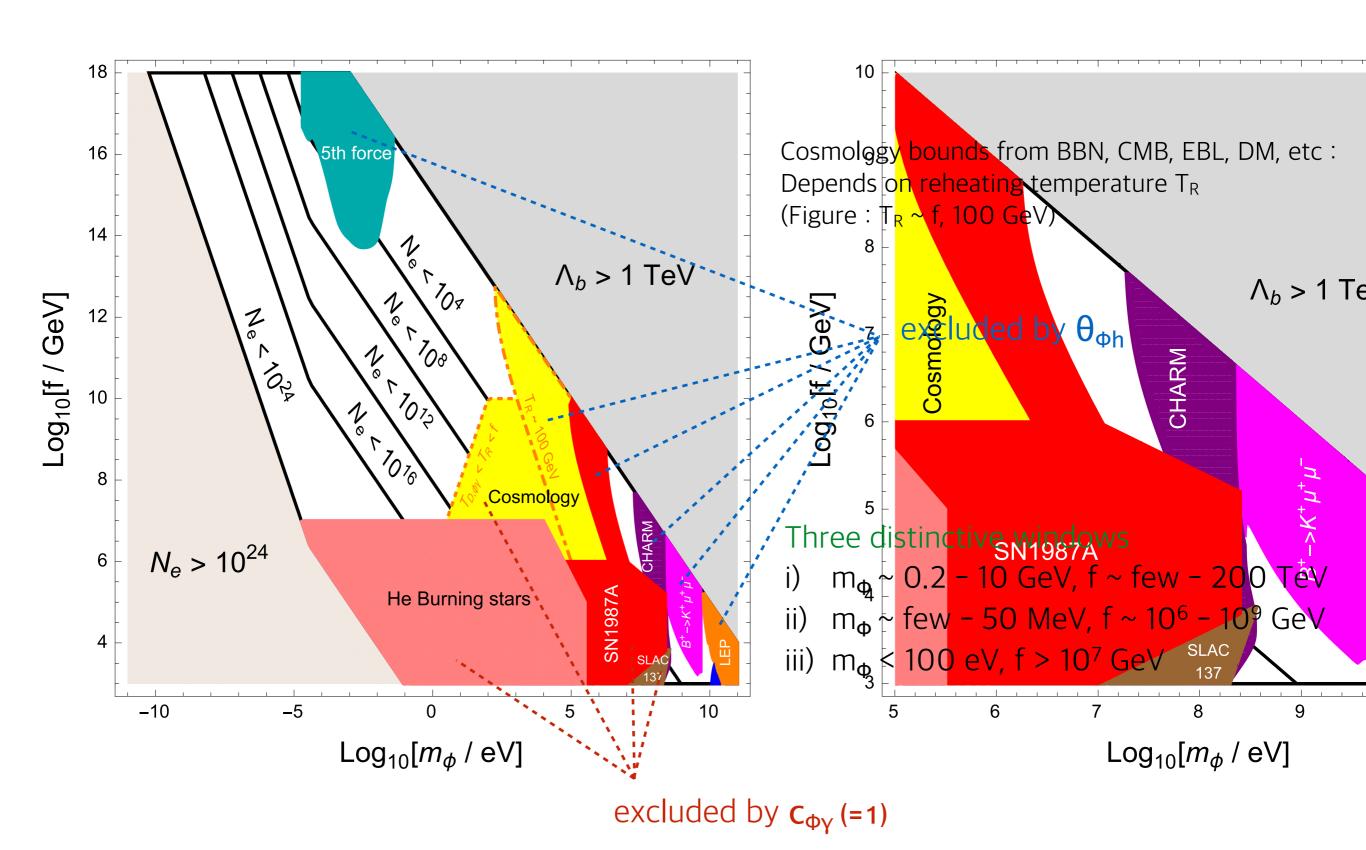
If relaxion is a τ set of Nambu-Goldstone Boson (PNGB), f_{eff} must be interpreted as FIG. 1: Cosmological relaxion window in terms of the relaxion mass m_{ϕ} and the relaxion decay another axion scale for a long periodic potential [4] 1 and such different, axion scales for Exionstante fictorsified algoring terms of the acceptable enfolding number A. The gray region with in sterms of the acceptable e-folding number N_e . The gray region with Sasritic dynamics $(\arcsin \sqrt{\tau})$ to generate the barrier potential. lly disfavoured as it requires a fine puning in the winderlying dynamics $a\Delta\phi \leq v^2$ (10)otentiage of \mathcal{N}_{e} . At any rate, the barrier potential (27), provides the relaxion mass and also i) Note that here we are workside the are latively simple situation and 3 that the relaxion a relaxion-Higgs mixing, which are estimated as té, 414 bather notification (27) estimates emalles personnais, but causses to the electroweak gauge which are estimated as through the new ϕ physics sector to generate $V_{\rm b}$, and also to ϕ gluon kinetic operator GG through the mixing with the Higgs boson. $H_{I} \gtrsim \max \left(\frac{\Lambda^{2}}{f}, \frac{M^{2}}{M^{2}} \right) \mu_{b} \nu_{b} \nu$ region. We then need the low energy relaxion couplings at scale below the OCD cale. Starting from (27) and (28), one can derive the effective coupling xion-Higgs mixing Starting Hold (27) and (292) one can derive the energy realizations of the QCD operators that appears that appears that appears the energy relaxion phenomenously, which inchede [31]₁₀-28 cm (100 picks) nuc (100 picks) nuc (100 picks) and the following low energy relaxion couplings to the picks) nuc and (28), page gar derive the effective complings relevant for low.

For a given meaning angle is sizeable of f, is large t region will be nearly which the mixing angle is sizeable of f, is large t region will be nearly which the first one of the first of the firs The relaxion photon botton by the relaxion seed in the relaxion seed ario if the relaxion $\bar{\psi}_{t}\psi_{t}^{\mu\nu}+s_{\theta}$ which is the relaxion seed ario if the relaxion $\bar{\psi}_{t}\psi_{t}$ (32)is to be stabilized during the primoridal inflation due to the Hubble friction. l=E in t $\frac{ds}{dr}$ all the constant support $\frac{ds}{dr}$ of $\frac{ds}{dr}$ and $\frac{ds}{dr}$ inflationary Hubble scale in order for the classical

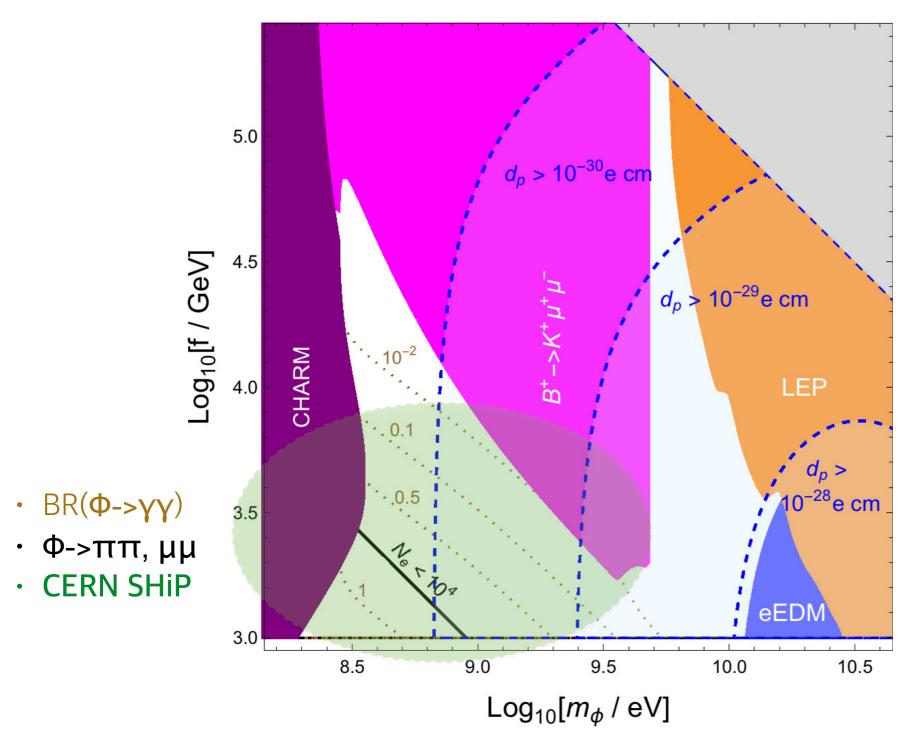
The cosmological relax-(9)(9)distavoured as it requires a fine-tining to the time ty in the light of the light o The policy of the property of the diverse (13)

Solve of the property of the p the phenomenon strained to the constraint of the öldings we olgings ght a given (31)(32)

Observational constraints on the relaxion windows



Enlarged picture for the first window



- EDM with $C_{\Phi Y} = 1$
- Proton EDM estimated by the QCD sum rule

$$d_p = 0.78 \, d_u(\mu_*) - 0.20 \, d_d(\mu_*)$$
 where $\mu_* = 1 \; {\rm GeV}$

- 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 transmuting the hierarchy to a large separation between two axion scales.
- The separation between two axion scales can be addressed by the clockwork mechanism with multiple axions.
- The large separation also leads to the requirement of a large number of e-folding for the relaxion dynamics, assuming the Hubble friction is the main source of dissipation of relaxion kinetic energy.
- The cosmological relaxion window identifies the favored relaxion parameter space in terms of the required number of e-folding.
- After imposing various observational constraints, three distinctive windows remain viable, all of which include the relatively small number of e-folding region below 10⁴.
- The first window ($m_{\Phi} \sim 0.2$ 10 GeV, f ~ few 200 TeV) can be probed by future EDM experiments and CERN SHiP.