Can cosmological relaxation be reconciled with high reheating temperature?

Toyokazu Sekiguchi (IBS-CTPU)

기초과학연구원
Institute for Basic Science

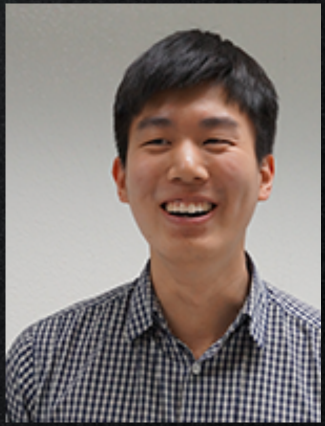
PASCOS2017
IFT, UAM, 20.06.2017

Outline

- High reheating temperature in cosmological relaxation
- Dynamics of relaxion with anomalous coupling with U(1)
- Parameter constraints
- Summary

References:

Hyunjing Kim, Kiwoon Choi, TS, arXiv:1611.08569



Hyunjing Kim

Introduction

Hierarchy problem

$$\delta m_H^2 = \left[3\lambda - 3y_t^2 + \frac{9g_2^2 + 3g_1^2}{8} \dots\right] \frac{\Lambda^2}{16\pi^2}$$

Fine tuning is required if Λ >> EW scale

Possible solutions

- New physics regulating the quadratic divergence around TeV

  supersymmetry, extra dimension, …

- ***Cosmological relaxation***

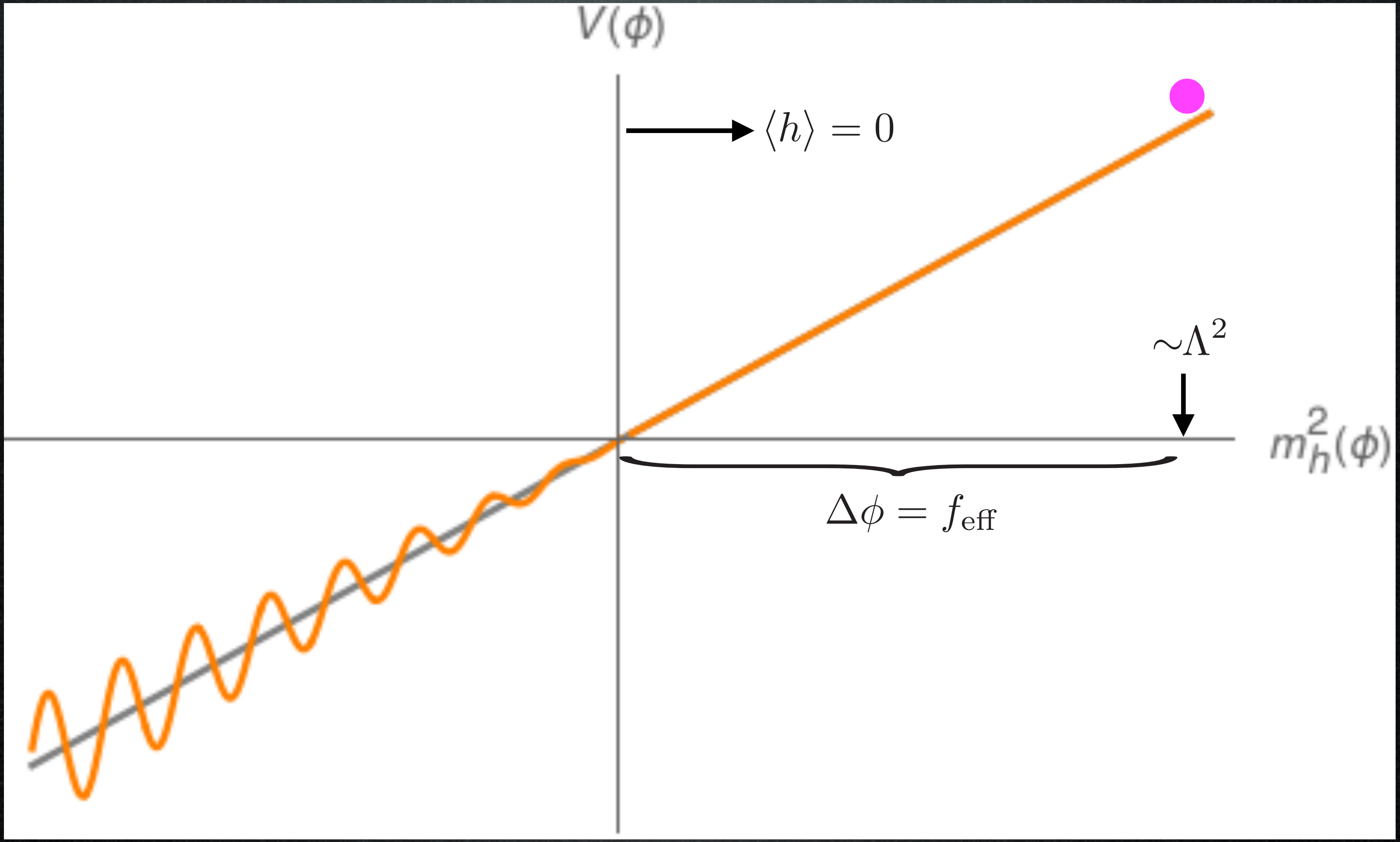
- Anthropic principle, …

Cosmological relaxation

Graham, Kaplan, Rajendran 2015

Dynamical solution for hierarchy problem

$$V(\phi) = \Lambda^2 \left(1 - \frac{\phi}{f_{\rm eff}}\right)|h|^2 + \Lambda^4 \frac{\phi}{f_{\rm eff}} + \Lambda_{\rm b}(\langle h \rangle)^4 \cos\left(\frac{\phi}{f}\right)$$

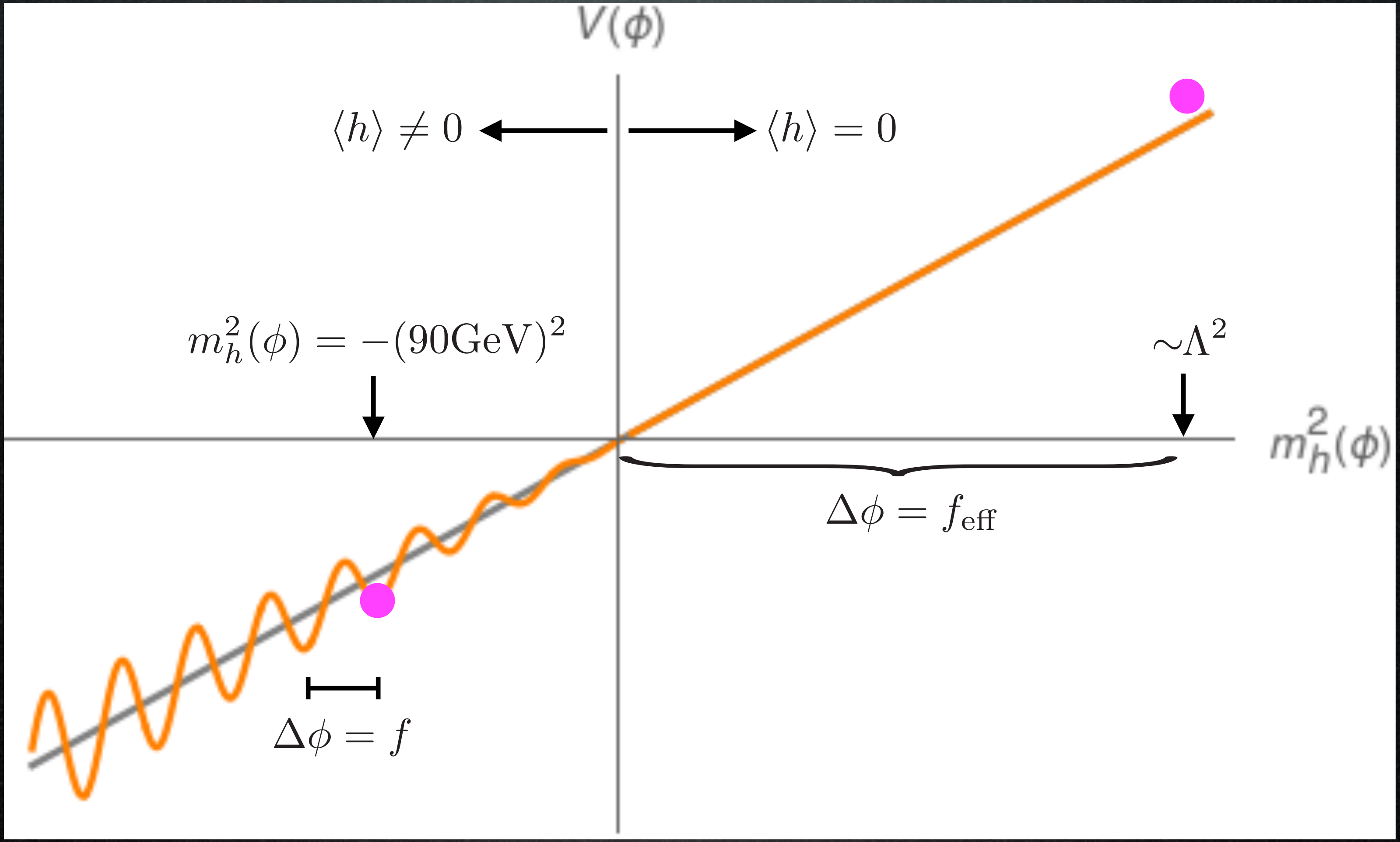


Cosmological relaxation

Graham, Kaplan, Rajendran 2015

Dynamical solution for hierarchy problem

$$V(\phi) = \Lambda^2 (1 - \frac{\phi}{f_{\mathrm{eff}}})|h|^2 + \Lambda^4 \frac{\phi}{f_{\mathrm{eff}}} + \Lambda_{\mathrm{b}}(\langle h \rangle)^4 \cos\left(\frac{\phi}{f}\right)$$



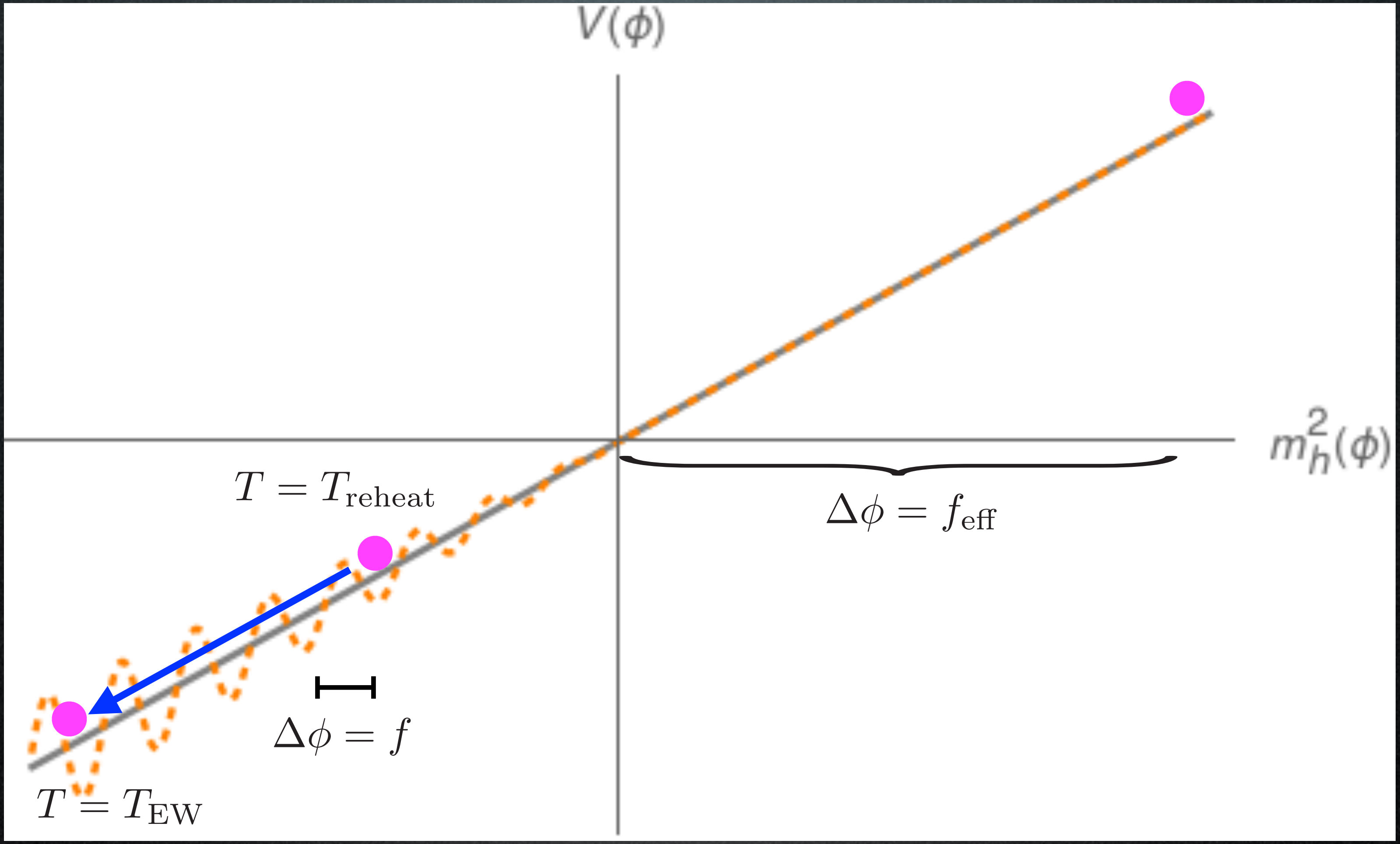
After inflation?

Two primary possibilities:

- $T_{reheat} < T_{EW}$
    - EW symmetry is never restored
    - Barrier potential persists
    - Realization of correct EW scale is maintained

- $T_{reheat} > T_{EW}$: **often required by e.g. baryogenesis**
    - EW symmetry is restored
    - Barrier potential disappears and relaxion starts rolling again
    - If relaxion overshoots the EW scale, cosmological relaxation fails …

Relaxion excursion after reheating



To stop relaxion within the EW scale, $d\phi/dt|_{T=T_{\rm EW}} < \Lambda_b^2$ is required.

Relaxion excursion after reheating

Problem: Hubble friction is not effective

→ slope should be extremely flat

$$\frac{f}{M_{\rm Pl}} \gtrsim \frac{\Lambda_b^2}{v^2} \sim \mathcal{O}(1)$$

On the other hand, for scanning of the EW scale to take place

$$f_{\rm eff} \gg f$$

→ This leads to relaxion scale >> Planck scale

Alternative possibility?

U(1) gauge field X_μ anomalously coupled to relaxion

$$\mathcal{L} \supset \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{\phi}{4F} X_{\mu\nu} \tilde{X}^{\mu\nu}$$

We assume X_μ is

- in hidden sector (i.e. dark radiation)
- out of thermal equilibrium

The possibility of X_μ = hyper U(1) will be examined later.

Gauge field production

Field equation of X_μ:

$$\ddot{X}_\pm + \left(k^2 \mp k\frac{\dot{\phi}}{F}\right) X_\pm = 0$$

One of helicity states is **tachyonic** at

$$k < \dot{\phi}/F$$

→ **Exponential production of gauge fields**

Amplification rate: $\Omega \simeq \dfrac{\dot{\phi}}{F}$

Relaxion motion

Backreaction: frictional force on the relaxion motion

$$\ddot{\phi} + 2\mathcal{H}\dot{\phi} - a^2 V'(\phi) = -\frac{1}{Fa^2}\langle X_{\mu\nu}\tilde{X}^{\mu\nu}\rangle$$

$$\propto \frac{\partial}{\partial\tau}\left[|X_-|^2 - |X_+|^2\right]$$

with $\quad |X_\pm|^2 \propto \exp\left[\pm\frac{\dot{\phi}}{F}\tau\right]$

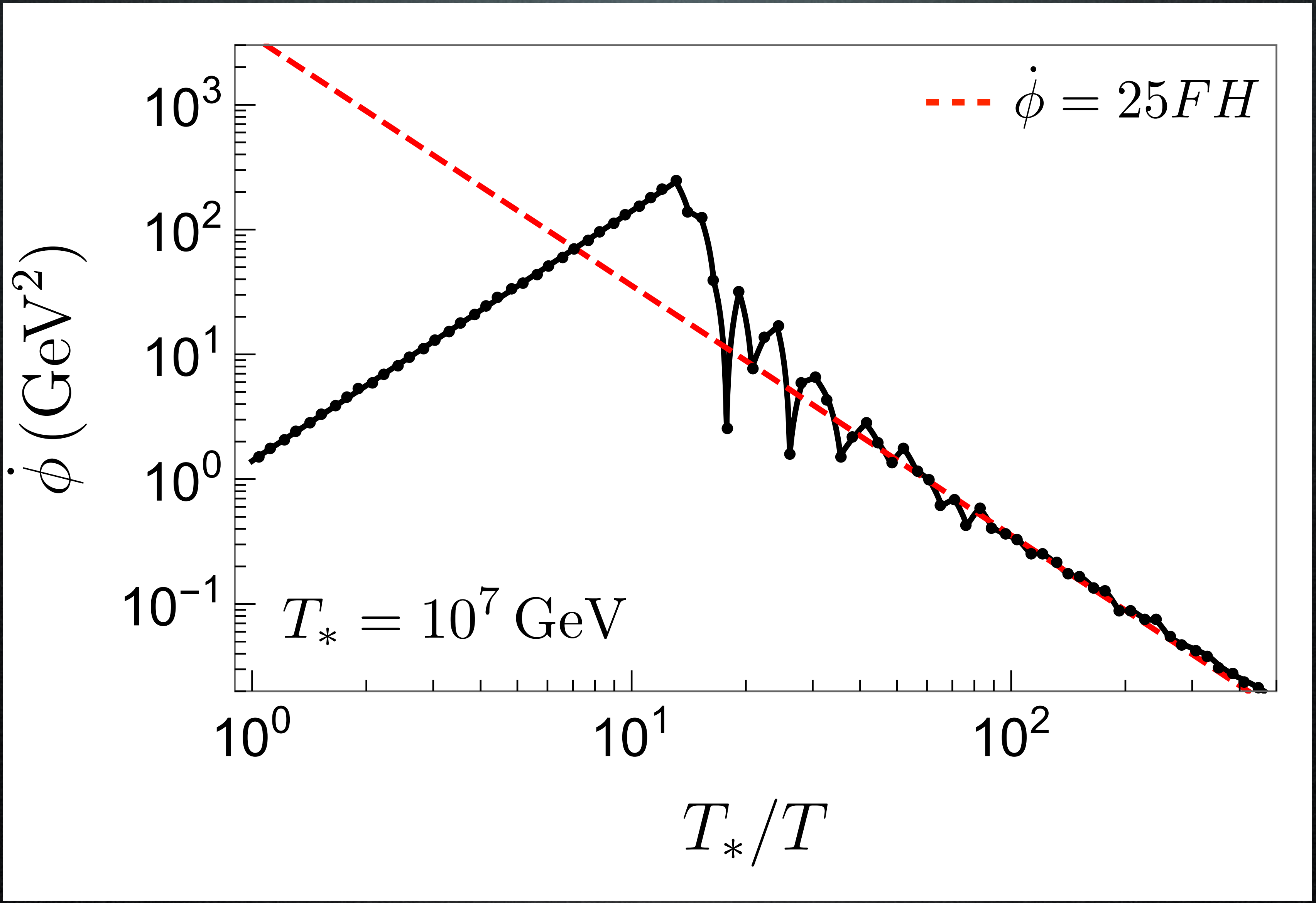
Terminal velocity is achieved when friction saturates

$$\dot{\phi} \simeq \xi F \mathcal{H}$$

→ **Relaxion velocity is decreasing function of time**

ξ is constant of O(10-100) with logarithmic dependences on e.g. model parameters and/or initial conditions etc.

Numerical calculation



When does relaxion stop?

Barrier potential develops at $T=T_{EW}$

- If $d\phi/dt|_{T=T_{\rm EW}} < \Lambda_b^2$

  Relaxion stops immediately at $T=T_{EW}$

- If $d\phi/dt|_{T=T_{\rm EW}} > \Lambda_b^2$

  Relaxion continues rolling but soon stops as velocity decreases $\dot{\phi} \propto T^2$

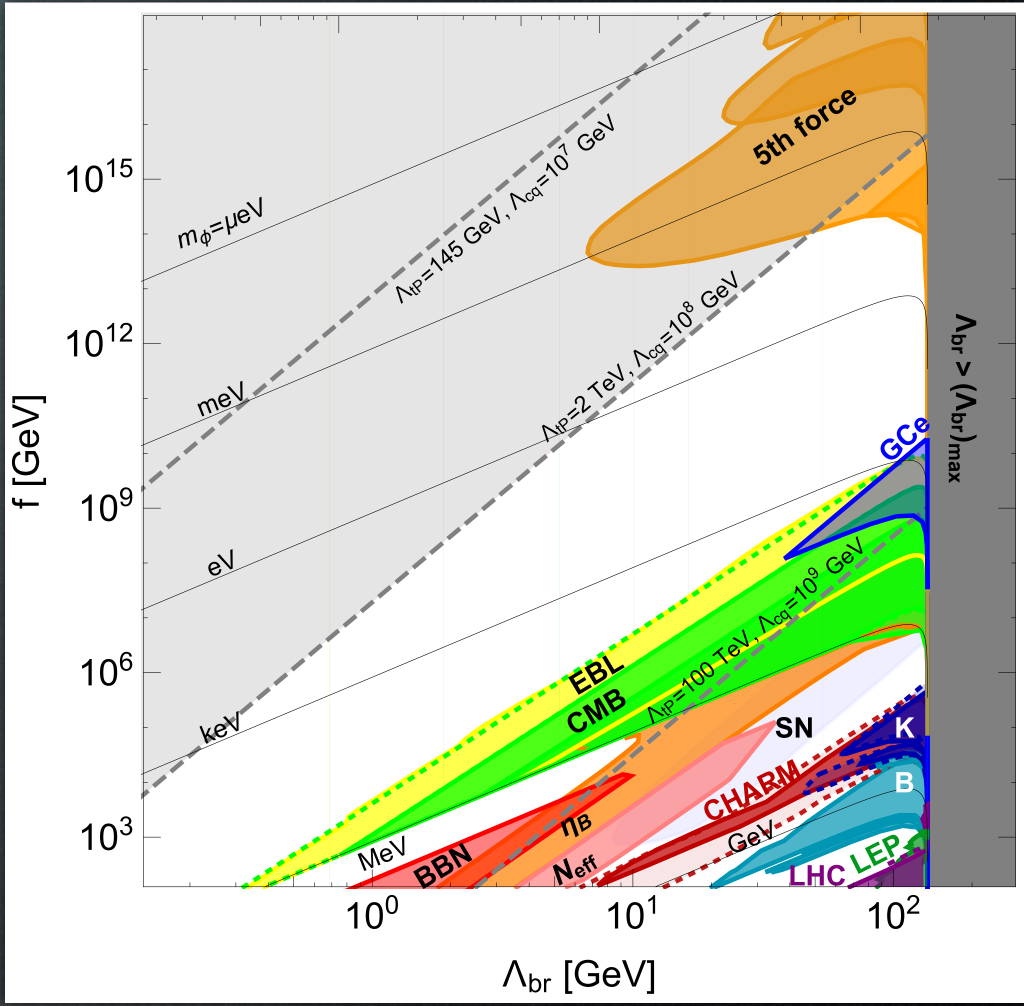
In most of parameter region, the former is the actual case

Constraints

Conventional relaxion is subject of a variety of constraints

Choi & Im (2016), Flacke et al. (2016)

- Fifth force & Casimir effect
- CMB, BBN, EBL
- SN1987A, globular clusters
- K- & B-meson decay, beam dump (CHARM)
- LEP, LHC



Flacke et al., arXiv:1610.02025

In our setup, however, relaxion can dominantly decay into X_μ

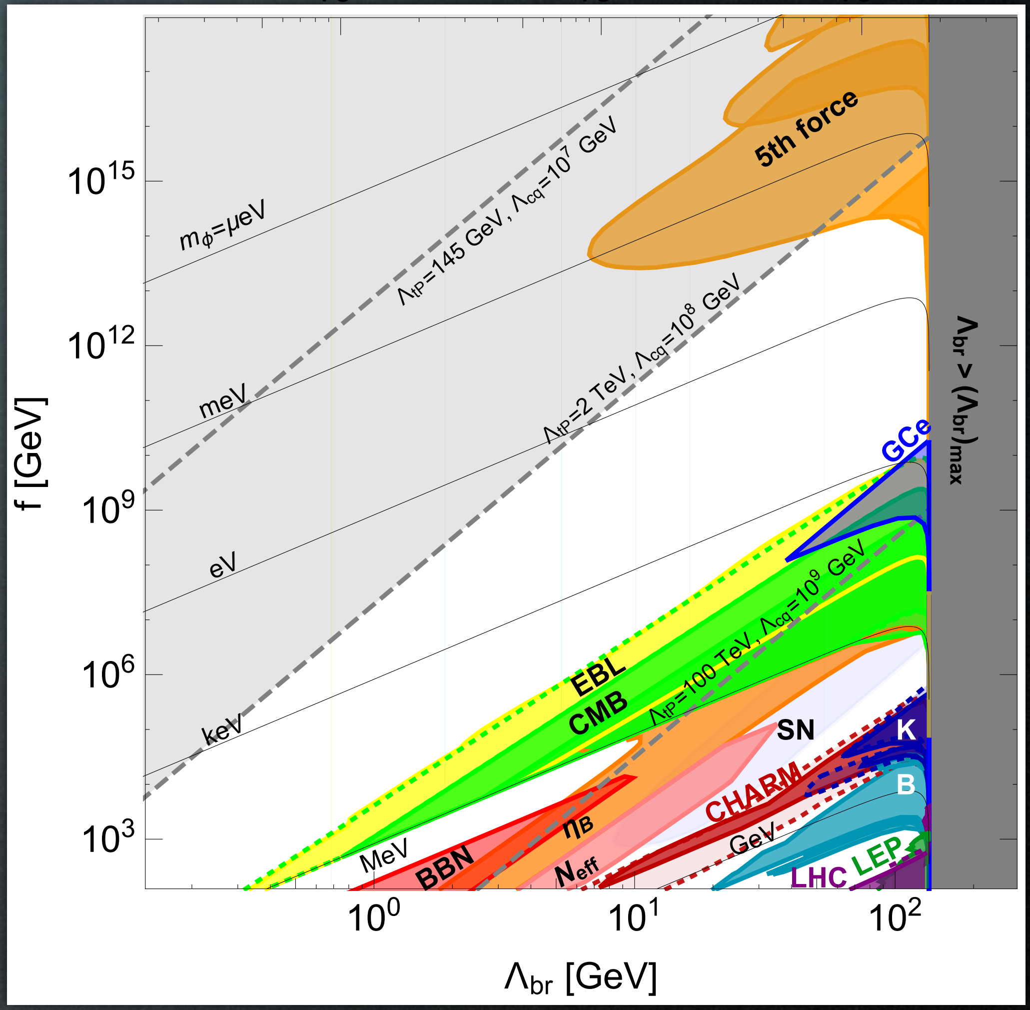
→ **Many of cosmological constraints (+beam dump) can be evaded**

Constraints

Conventional relaxion is subject of a variety of constraints

Choi & Im (2016), Flacke et al. (2016)

- Fifth force & Casimir effect
- ~~CMB~~, ~~BBN~~, ~~EBL~~
- SN1987A, globular clusters
- K- & B-meson decay, ~~beam dump (CHARM)~~
- LEP, LHC



Flacke et al., arXiv:1610.02025

In our setup, however, relaxion can dominantly decay into X_μ

→ **Many of cosmological constraints (+beam dump) can be evaded**

Additional constraints

Gauge field overproduction from relaxion

- During excursion

Produced X_μ should not dominate the Universe

$$\Delta V = \Lambda^4 \frac{\Delta\phi}{f_{\rm eff}} \simeq \Lambda_b^4 \frac{\Delta\phi}{f} \lesssim T_{\rm EW}^4$$

cf. constraint from Δm_h^2 turns out to be weaker

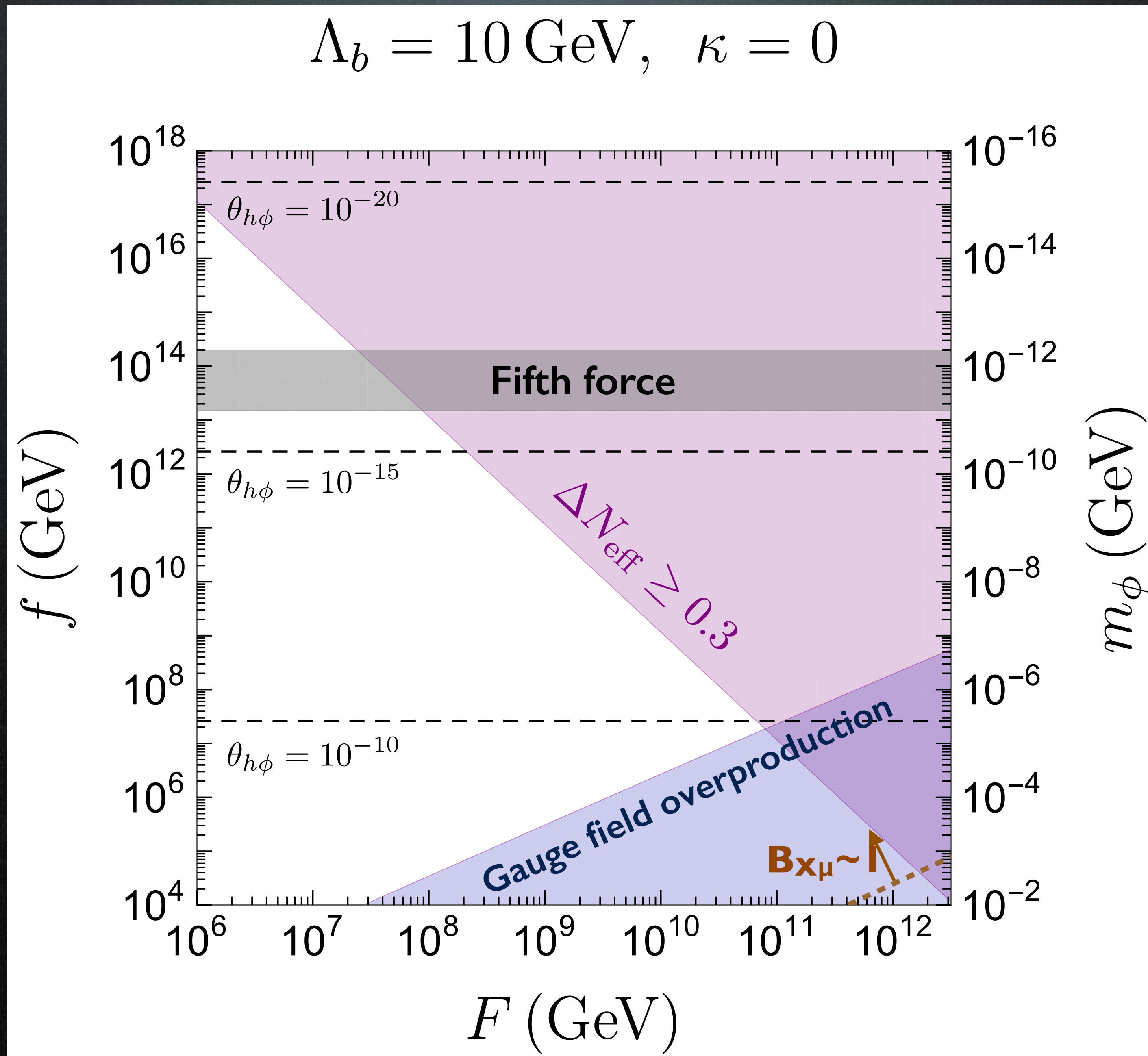
$$\Delta V \lesssim v^2 \Lambda^2$$

- Decay of coherent oscillation in the barrier potential

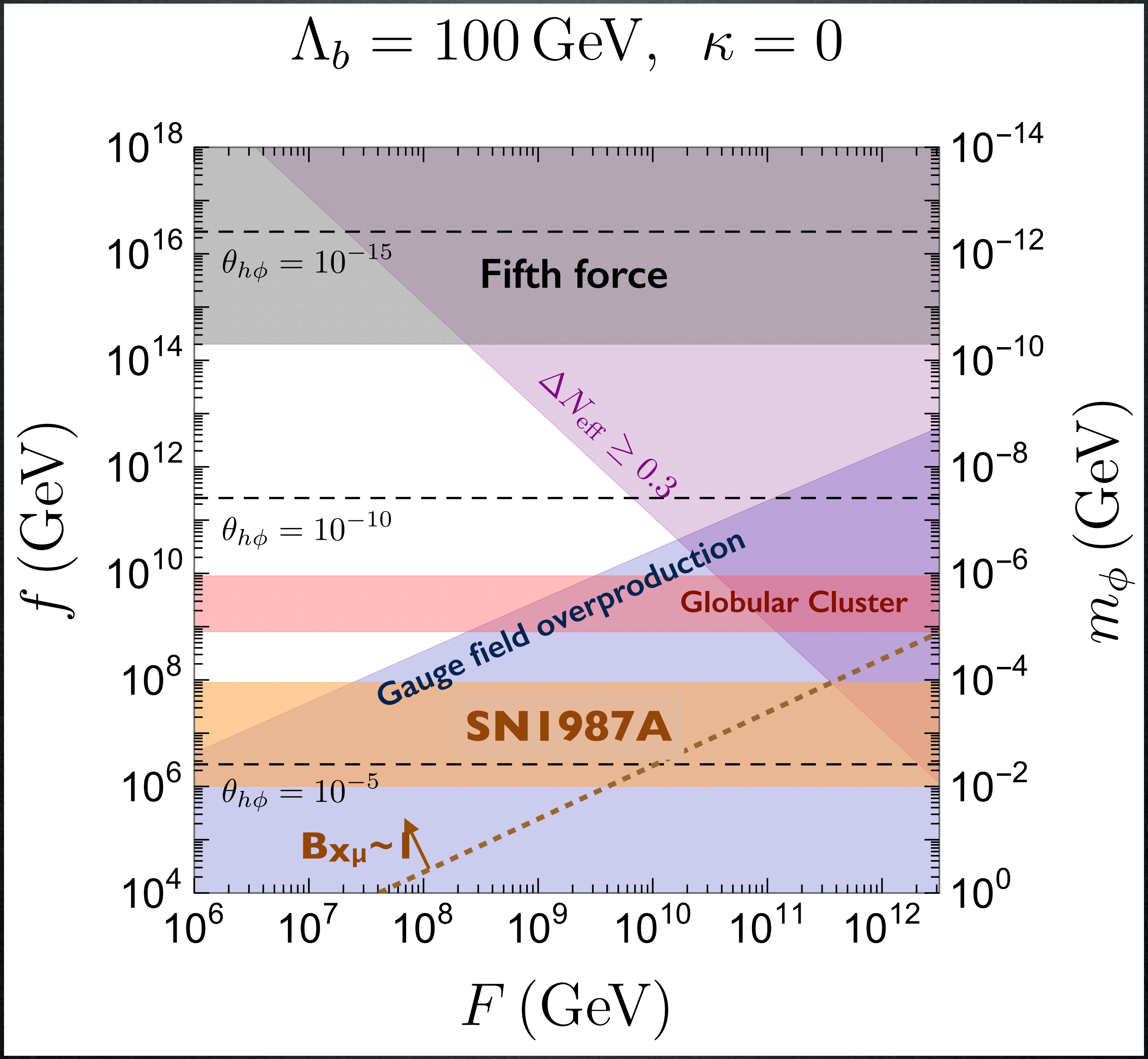
$$\rho_\phi \simeq \frac{1}{a^3} \frac{d\phi}{dt}\bigg|^2_{T=T_{\rm EW}}$$ → Late time decay into X_μ with $\Gamma \simeq \dfrac{m_\phi^3}{64\pi F^2}$

X_μ should not produce $\Delta N_{\rm eff}$>0.3 Planck 2015

Parameter constraints



Parameter constraints



Hyper U(1) can be X_μ?

Precluded by the following requirements

- Hyper U(1) is in thermal equilibrium with charged particles in SM
  - Due to landau damping, gauge field production is less efficient
  - Smaller 1/F is required
- Severe constraints from ALP search
  - 1/F is no more than 10^{-10} GeV^{-1} for m_φ of our interest

* Note that we don't exclude the possibility of relaxion domination

Issue of perturbations

- Gauge field production peaks at particular scales
  → Inhomogeneity in relaxion may develop through backreaction?

- This is unlikely at least at observably large scales (CMB, LSS)
  - Terminal behaviour is attractor solution.
  - Negative feedback works onto small deviations in velocity from terminal one.

- No additional large-scale perturbations

Summary

The cosmological relaxation is a novel solution for the hierarchy problem. However, the conventional setup is difficult to be compatible with T_{reheat} higher than the EW scale. Relaxion can easily overshoot the EW scale.

We extends the relaxion mechanism by incorporating anomalous relaxion coupling to a hidden U(1) gauge field. Relaxion motion causes tachyonic instability in the gauge field. As backreaction, frictional force effectively suppresses the relaxion excursion.

Many of cosmological constraints in the conventional relaxion model can be circumvented in our setup.

backup slides

X_μ in thermal equilibrium

Thermal correction to dispersion relaxion (1-loop)

$$\omega^2 - k^2 \pm k\frac{\dot{\phi}}{F} = \Pi_T(\omega, k)$$

$$\Pi_T(\omega, k) = m_D^2 \frac{\omega}{k}\left[\frac{\omega}{k} + \frac{1}{2}\left\{1 - \left(\frac{\omega}{k}\right)^2\right\}\ln\left(\frac{\omega + k}{\omega - k}\right)\right]$$

(conformal) Debye mass: $m_D^2 = \frac{g_X^2 a^2 T_X^2}{6}$

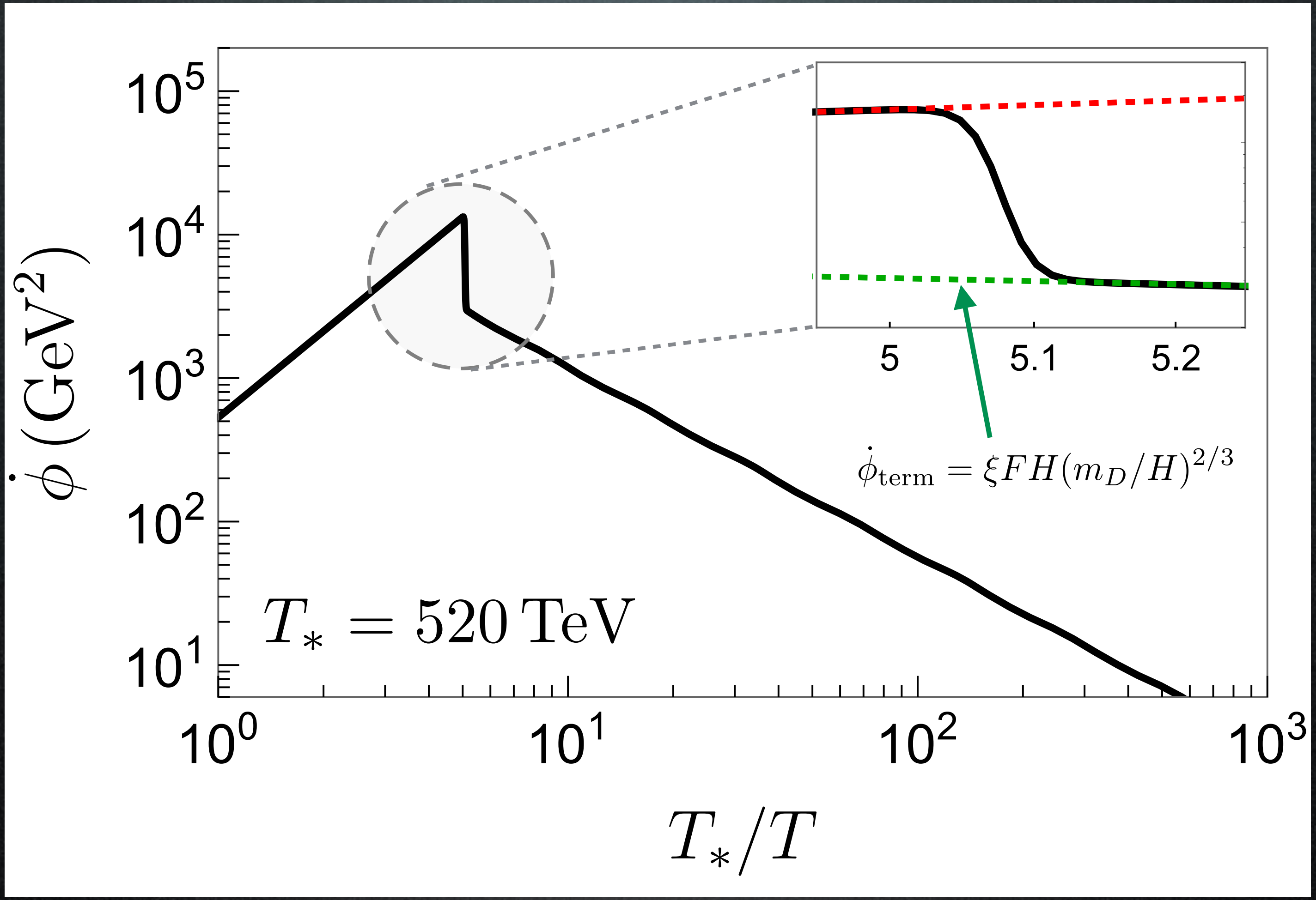
Tachyonic frequency

$$\Omega = \frac{k^2}{m_D^2}\frac{\dot{\phi}}{F} \ll \frac{\dot{\phi}}{F}$$

Tachyonic growth is suppressed by (k^2/T^2) compared to vacuum

Given availability of tachyonic modes: $|\omega| \ll k \ll aT_X$

X_μ in thermal equilibrium



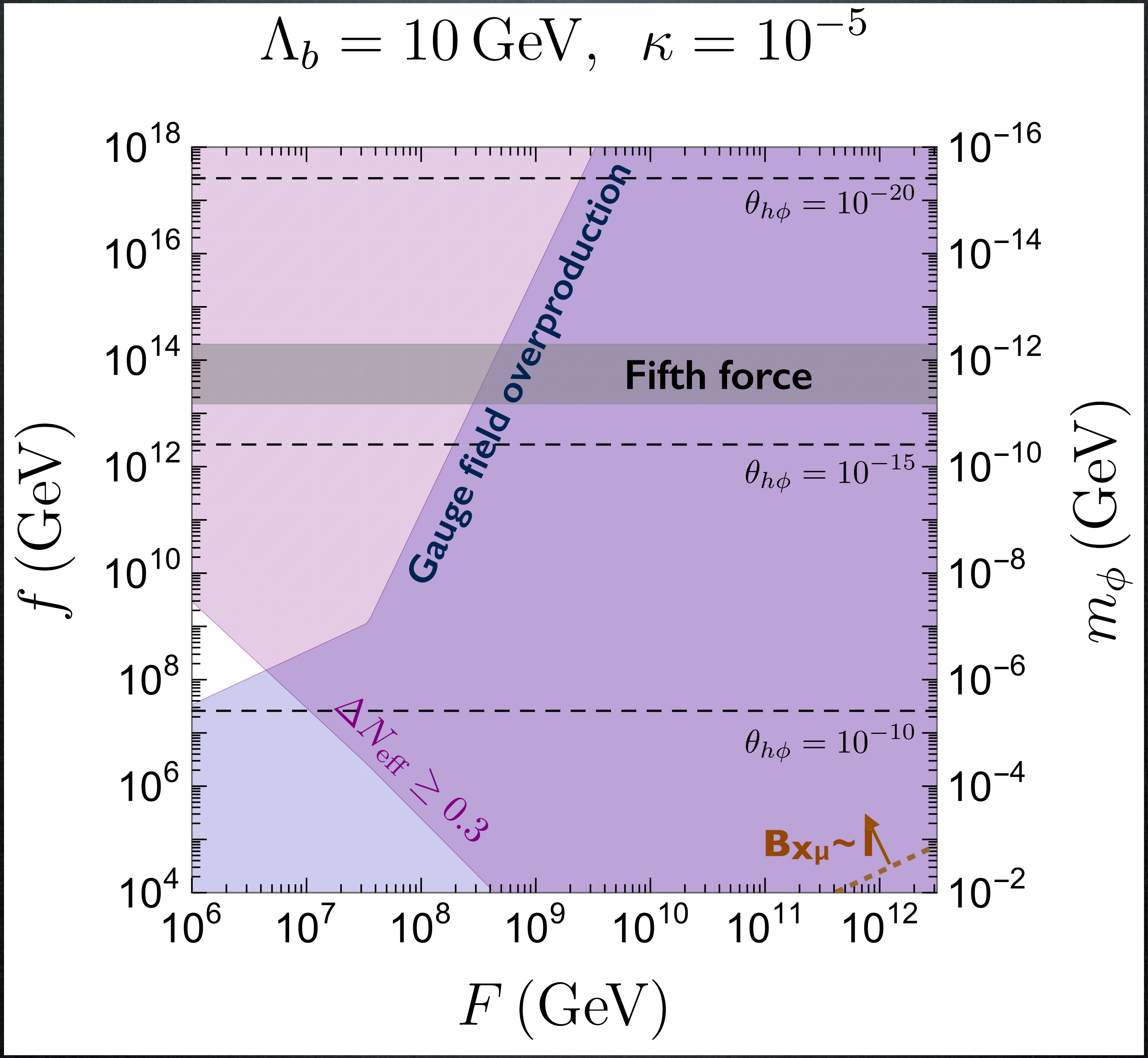
Terminal behaviour is available but with velocity much larger than vacuum

$$\dot\phi = \xi F \mathcal{H} (m_D/\mathcal{H})^{2/3} \gg F\mathcal{H}$$

→ Larger relaxion excursion & production of X_μ

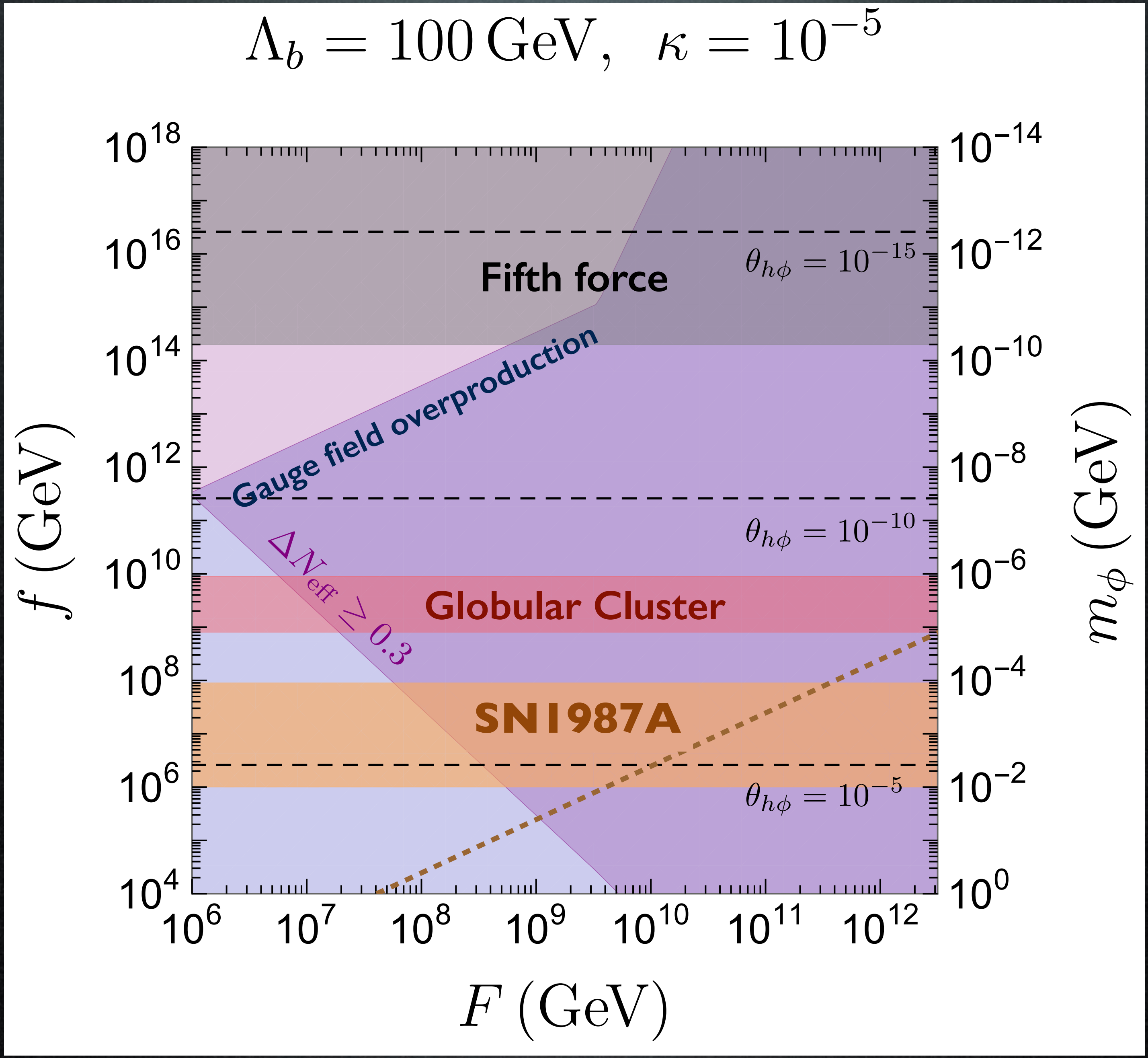
Parameter constraints

$$\kappa \equiv g_X \frac{T_X}{T}$$



Parameter constraints

$$\kappa \equiv g_X \frac{T_X}{T}$$



Dependence of terminal velocity