Strong Hidden Fermion Production and Relaxation

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Outline

- Introduction
- Models
- Further analysis and questions
- Summary

Introduction

- After Higgs was discovered in 2012, particle contents seem to be complete.
- Unsolved: naturalness, dark matter (DM), etc

$$m_h \ll M_P$$

Introduction

Naturalness

- Solution (i): + symmetry, e.g. SUSY

Higgs mass: sensitive to large UV corrections

SUSY near EW scale solves hierarchy prob.

- Solutions (ii): via **dynamics**, e.g. **cosmological relaxation** of EW scale

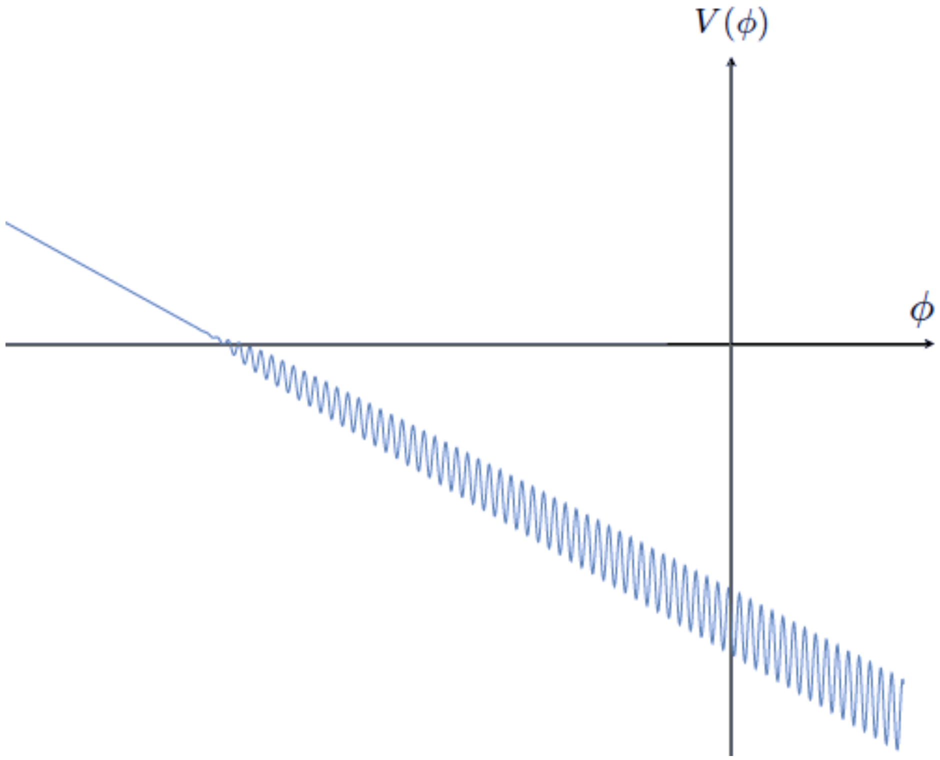
Due to the null result @ LHC, this is an increasingly motivated scenario

Introduction: relaxation

- Relaxion: axion-like particle (ALP) whose periodic symmetry is **softly** and explicitly broken by a **small** coupling to Higgs (and also small self-coupling)

[Graham, Kaplan, Rajendran (GKR), 1504.07551]

- Smallness of Higgs mass: cosmological evolution



EW unbroken -> EW broken

$$\Delta V = \left(\underbrace{-\Lambda^2}_{\text{cutoff}} + \underbrace{g}_{\text{small mass-dim parameter}}\phi\right)|h|^2 + \left(g\Lambda^2\phi + \cdots\right) + \underbrace{\Lambda_c^4}_{\text{Propto to Higgs vev <h>}}\cos\left(\phi/f\right)$$

Trapping: $g\Lambda^2 = \frac{\Lambda_c^4}{f}$

Introduction: relaxation

Conditions

$$\boxed{\Delta V = \left(-\Lambda^2 + g\phi\right)|h|^2 + \left(g\Lambda^2\phi + \cdots\right) + \Lambda_c^4 \cos\left(\phi/f\right)}$$

- Long enough slow-roll s.t. relation **can scan O(1) of its entire field range** => lower bound on number of efolds

Entire scan $\Delta\phi \sim \dot{\phi}\Delta t \sim \dot{\phi}\, N_e/H \underset{\uparrow}{\sim} (g\Lambda^2/H^2)\, N_e \gtrsim \Lambda^2/g \longrightarrow N_e \gtrsim H^2/g^2$

Slow-roll $3H\dot{\phi} + \frac{d\Delta V}{d\phi} \sim 0.$

- **Vac energy > change in the relation potential energy**

$$H^2 M_P^2 \gtrsim \Lambda^4$$

- **Barriers w/in Hubble sphere** $H^{-1} > \Lambda_c^{-1}$

- **Classical > Quantum**

slow-roll

Hubble time

$$\Delta\phi \sim \dot{\phi}\Delta t \sim \overset{\downarrow}{\frac{V'}{H}}\,\overset{\swarrow}{\frac{1}{H}} > H$$

Introduction: relaxation

Conditions

- After relaxion stops rolling and **reheating** occurs, the reheating temperature must be low enough s.t. barriers don’t melt or the traveling distance of the **2nd rolling** leads to a change in Higgs mass smaller than EW scale

Introduction: relaxation

Problems

$$\Delta V = \left(-\Lambda^2 + g\phi\right)|h|^2 + \left(g\Lambda^2\phi + \cdots\right) + \Lambda_c^4 \cos\left(\phi/f\right)$$

- QCD relaxion: O(f) shift of the local min of the QCD part => **O(1) theta parameter!**

Solutions

- + additional mech.

Introduction: relaxation

Problems

- **Tiny coupling**: e.g. g~ 10^-31 GeV for QCD relaxion
- => severe fine-tuning, exponentially large number of efolds, super-Planckian field excursion $N_e \gtrsim H^2/g^2$

  Contradicting with some gravity argument $\Delta\phi \geq \Lambda^2/g^2$

Solutions

- Tiny coupling / Large efolds / Super-Planckian: **inefficient** energy dissipation of the relaxion by **Hubble friction**
- **More efficient energy dissipation**: e.g. **particle production** sourced by rolling relaxion

Introduction: particle production

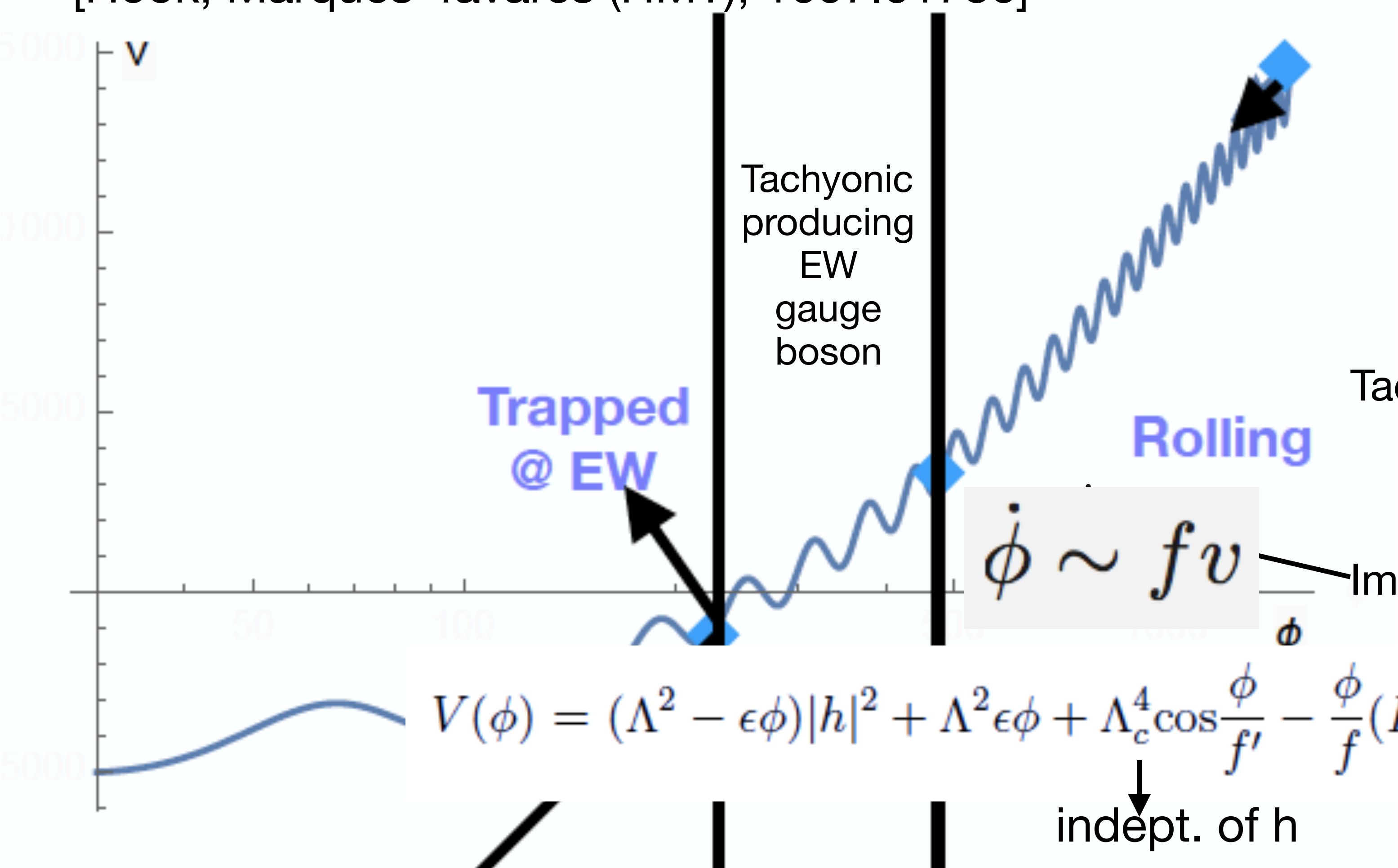
- Particle production is an efficient way of dissipating energy
- Various applications in pheno and cosmology
- Exponentially producing bosons: example in reheating: preheating

Introduction: particle production

- Exponentially producing bosons: example in relaxion models: tachyonic production of gauge bosons to stop relaxion

Fixed barrier height; h-dependence in the cond. to trigger tachyonic production

[Hook, Marques-Tavares (HMT), 1607.01786]



$$\dot{\phi} \sim f v$$

$$V(\phi) = (\Lambda^2 - \epsilon\phi)|h|^2 + \Lambda^2\epsilon\phi + \Lambda_c^4 \cos\frac{\phi}{f'} - \frac{\phi}{f}(B\tilde{B} - W\tilde{W}),$$

indept. of h

Start:
EW-broken
with ***very negative*** Higgs mass-square;
sufficient speed to pass min

Tachyonic production of gauge bosons when

$$\ddot{A}_\pm + (k^2 + m^2 \pm k\frac{\dot{\phi}}{f})A_\pm = 0 \quad \dot{\phi} \geq fm$$

Impose: tachyonic production starts at **m ~ v**

Introduction: particle production

HMT

- HMT solved problems in GKR. A specific UV needed.
- Cutoff in HMT: <~ 10^{4~5} GeV
- Tachyonic production is so strong that the slow-roll can't really be maintained ("quasi-slow-roll")
- Can we **maintain slow-roll with particle production** as the friction?

Introduction: particle production

- **Fermion production**?
- **Can't be exponential** due to Pauli blocking
- But may be **sufficient to support** a (“steep-slope”) **slow-roll**

[Adshead, Pearce, Peloso, Robers, Sorbo, 1803.04501]

Potential slope ~ fermion back reaction >> Hubble term

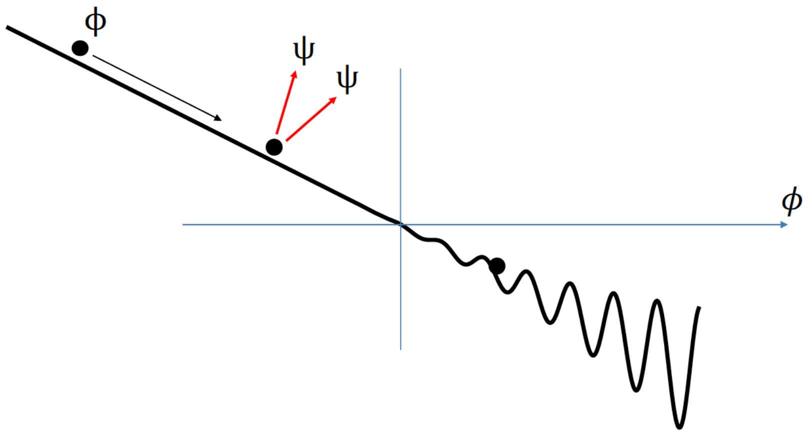
Introduction

Goals

- To maintain slow-roll
- To explain (little) hierarchy
- To use **fermion production** as the major friction
- No extremely small parameter
- To explore pheno. of such a scenario, eps. of the fermion produced by relaxion if it’s BSM

Inflaton: containing the most energy during inflation,
assumed to be a separate sector s.t. not too much
inflationary dynamics involved

Models



Fermion production

- Assume a flat FRW background for simplicity

$$ds^2 = dt^2 - a^2 d\mathbf{x}^2 = a^2\left(d\tau^2 - d\mathbf{x}^2\right)$$

- Couple relaxion to fermion via derivative coupling

- $\Delta S = \int d^4x\sqrt{-g}\left[\bar{\psi}\left(i\, e^{\mu}{}_{a}\,\gamma^a D_\mu - m_\psi - \frac{1}{f_\psi} e^{\mu}{}_{a}\,\gamma^a\gamma^5\partial_\mu\phi\right)\psi\right]$

Massless fermion => free field => production should be off

$\downarrow$

If scanning starts in EW-sym phase,
the produced fermion can’t be any SM fermion which is massless then.

The produced fermion must be BSM if scanning starts in EW-sym phase

Models

Hidden fermion production

$$\Delta S = \int d^4x\sqrt{-g}\left[\bar{\psi}\left(i\,e^{\mu}{}_{a}\,\gamma^{a}D_{\mu} - m_{\psi} - \frac{1}{f_{\psi}}e^{\mu}{}_{a}\,\gamma^{a}\gamma^{5}\partial_{\mu}\phi\right)\psi\right]$$

Number operator not well-defined in this basis due to the derivative coupling

[Adshead, Pearce, Peloso, Robers, Sorbo, 1803.04501]

[Min, Son, Suh, 1808.00939]

- New basis

$$\psi \to a^{-3/2}\psi \qquad \psi \to e^{-i\,\gamma^5\phi/f_\psi}\psi$$

$$\Delta\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m_R + i\,m_I\gamma^5\right)\psi \qquad \mathcal{H} = \bar{\psi}\left(-i\gamma^{i}\partial_{i} + m_R - i\,m_I\gamma^5\right)\psi$$

$$m_R = m_\psi a\,\cos(2\phi/f_\psi)\ \text{and}\ m_I = m_\psi a\,\sin(2\phi/f_\psi).$$

Fermion: creation and annihilation operators
=> occupation number, energy density,
backreaction onto the relaxion, etc

Models

Strong back reaction supported slow-roll

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi(\phi) = \mathcal{B}$$

$$\dot{\phi} \equiv \partial\phi/\partial t, \; V_\phi \equiv \partial V/\partial\phi$$

$$\mathcal{B} = \frac{2m_\psi}{fa^3}\langle\bar{\psi}\left[\sin(2\phi/f) + i\,\gamma^5\cos(2\phi/f)\right]\psi\rangle$$

$$\mu \equiv m_\psi/H \ll \xi, \qquad \mathcal{B} \sim -\frac{1}{f_\psi}H^4\mu^2\xi|\xi|$$

$$\boxed{\xi \equiv \frac{1}{2H}\frac{\dot{\phi}}{f_\psi}}$$

Fermions with heavier (but not too heavy) masses can also be produced,
but this simple expression for backreaction is no longer valid

Strong production: adiabaticity stongly violated

speed large enough, or coupling strength large enough

Models

Strong back reaction supported slow-roll

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi(\phi) = \mathcal{B}$$

Strong back reaction

$$V_\phi(\phi)(= g\Lambda^2) \sim \mathcal{B} \quad \rightarrow \quad \dot{\phi} \sim 2\,\frac{g^{1/2}\Lambda f_\psi^{3/2}}{m_\psi} \sim \text{constant}$$

Sizable relaxion speed <=> not-too-small linear slope

Not-too-small g

$$\Delta V = \left(-\Lambda^2 + g\phi\right)|h|^2 + \left(g\Lambda^2\phi + \cdots\right) + \Lambda_c^4 \cos\left(\phi/f\right) \; + \frac{\partial_\mu \phi}{f_\psi} J_\psi^{5\mu}$$

Models

Constraints

- Slow-roll: Hubble friction must be small enough s.t. the slow-roll is maintained by slope compensated by the back reaction

$$V_\phi(\phi) > 3H\dot{\phi} \quad \rightarrow \quad m_\psi > 6\,\frac{H}{\Lambda}\frac{f_\psi^{3/2}}{g^{1/2}}$$

- Validity of EFT

$$\dot{\phi} \lesssim \Lambda^2 \quad \rightarrow \quad m_\psi \gtrsim 2\,\frac{g^{1/2} f_\psi^{3/2}}{\Lambda}$$

- Hidden fermion energy density small enough

$$\rho_\psi \sim 16\pi^2 H^4 \mu^2 \xi^3 \lesssim H^2 M_P^2 \rightarrow m_\psi \gtrsim \frac{\Lambda^3}{H^3}\frac{g^{3/2} f_\psi^{3/2}}{M_P^2}$$

Models

Constraints

- Relaxion kinetic energy < total energy

$\dot{\phi}^2 \lesssim H^2 M_p^2 \quad \rightarrow \quad m_\psi \gtrsim 2\,\frac{\Lambda}{H}\frac{g^{1/2} f_\psi^{3/2}}{M_p}$ Automatically when $\Lambda^4 \lesssim H^2 M_p^2$.

- Sufficient scanning, not-too-large efolding, sub-Planckian

$$\Delta\phi \gtrsim \frac{\Lambda^2}{g} \quad \rightarrow \quad m_\psi \lesssim 2N_e\,\frac{g^{3/2} f_\psi^{3/2}}{H\Lambda} \qquad \Delta\phi = \dot{\phi}\Delta t = \dot{\phi}\,(N_e/H)$$

$$N_e \lesssim \mathcal{O}(10^{1\sim 3})$$

$$M_p > \Delta\phi \quad \rightarrow \quad m_\psi > 2N_e\frac{\Lambda}{H}\frac{g^{1/2} f_\psi^{3/2}}{M_p}$$

Models

Constraints

- Classical rolling > quantum spreading

$$\dot{\phi}\Delta t \gtrsim H \quad \rightarrow \quad m_\psi \lesssim \frac{g^{1/2} f_\psi^{3/2} \Lambda}{H^2}$$

- Barriers within Hubble sphere $H \lesssim \Lambda_c.$

- Precision of scanning $\Delta m_h^2 \sim g\Delta\phi \sim g\, 2\pi f \lesssim m_h^2$

- Temperature in the SM sector during scanning << v s.t. we're not scanning the thermal Higgs mass (ensured during inflation) (and we don't consider any fermion in a plasma to be produced by relaxion during scanning)

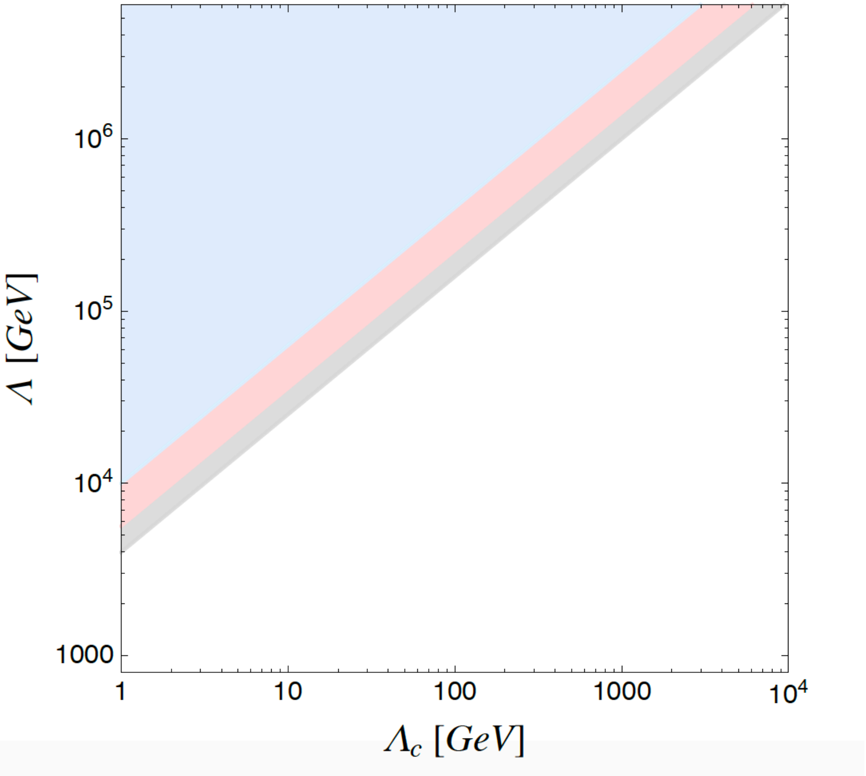
Models

Arrange those inequalities in terms of bounds on fermion mass

Combine upper bounds and lower bounds on fermion mass

$$f > \Lambda \text{ and } H > \Lambda^2/M_p$$

$$\Lambda < \min\left[\,(N_e/3)^{1/10}\, M_p^{1/5}\Lambda_c^{4/5}\ ,\ (1/6)^{1/7}\, M_p^{3/7}\Lambda_c^{4/7}\ ,\ N_e^{1/5}M_p^{1/5}\Lambda_c^{4/5}\right]$$



Excluded regions for N_e ~ 100, 1: colored

Focus on $\Lambda \sim 10^{4\sim5}$ GeV

Models

Forming periodic potential: model-dependent

Single extra scalar (relaxion)

QCD relaxion: need extra mech. to solve strong CP, barrier height fixed

non-QCD relaxion: extra strong dynamics near EW scale

2 extra scalars: double scanner

Models

A single non-QCD relaxion $(\phi/f)\, G'_{\mu\nu} G'^{\mu\nu}$

$$\Delta\mathcal{L}_{non\text{-}QCD} = m_L L L^c + m_N N N^c + y h L N^c + \tilde{y} h^\dagger L^c N$$

New fermions >~ EW scale

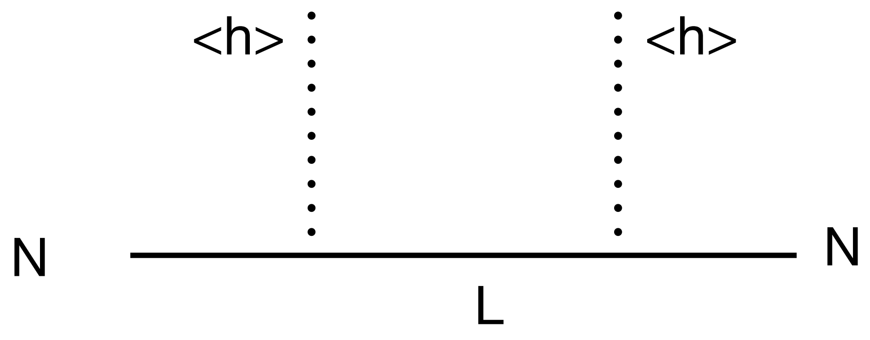
$$m_L \gg f_{\pi'} \gg m_N$$

Lighter fermion N responsible for forming condensate b/l confinement scale

$$m_N e^{i\phi/f} N N^c + \text{h.c.} = m_N N N^c \cos\frac{\phi}{f}$$

$$\langle N N^c \rangle \sim 4\pi f_{\pi'}^3$$

$$\Lambda_c^4 = 4\pi f_{\pi'}^3 m_N \sim 4\pi f_{\pi'}^3 \frac{y\tilde{y}\langle h\rangle^2}{m_L}$$

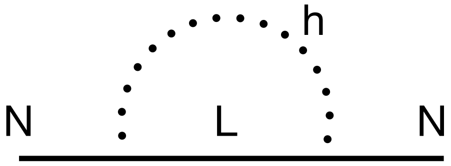


Models

A single non-QCD relaxion

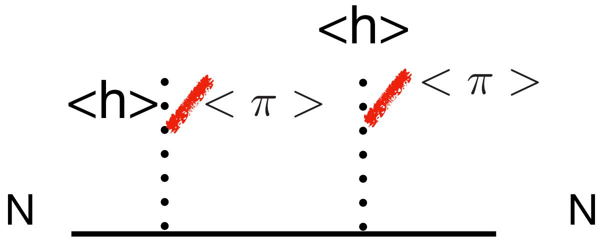
- For relaxation to work, **h-independent** contribution to the N mass must be **subdominant**

$$f_{\pi'} < \langle h \rangle \quad \text{and} \quad m_L < \frac{4\pi\langle h \rangle}{\sqrt{\log \Lambda / m_L}}$$



m_L ~ a few O(100) GeV

Constrained



- N should be light enough compared to confinement scale

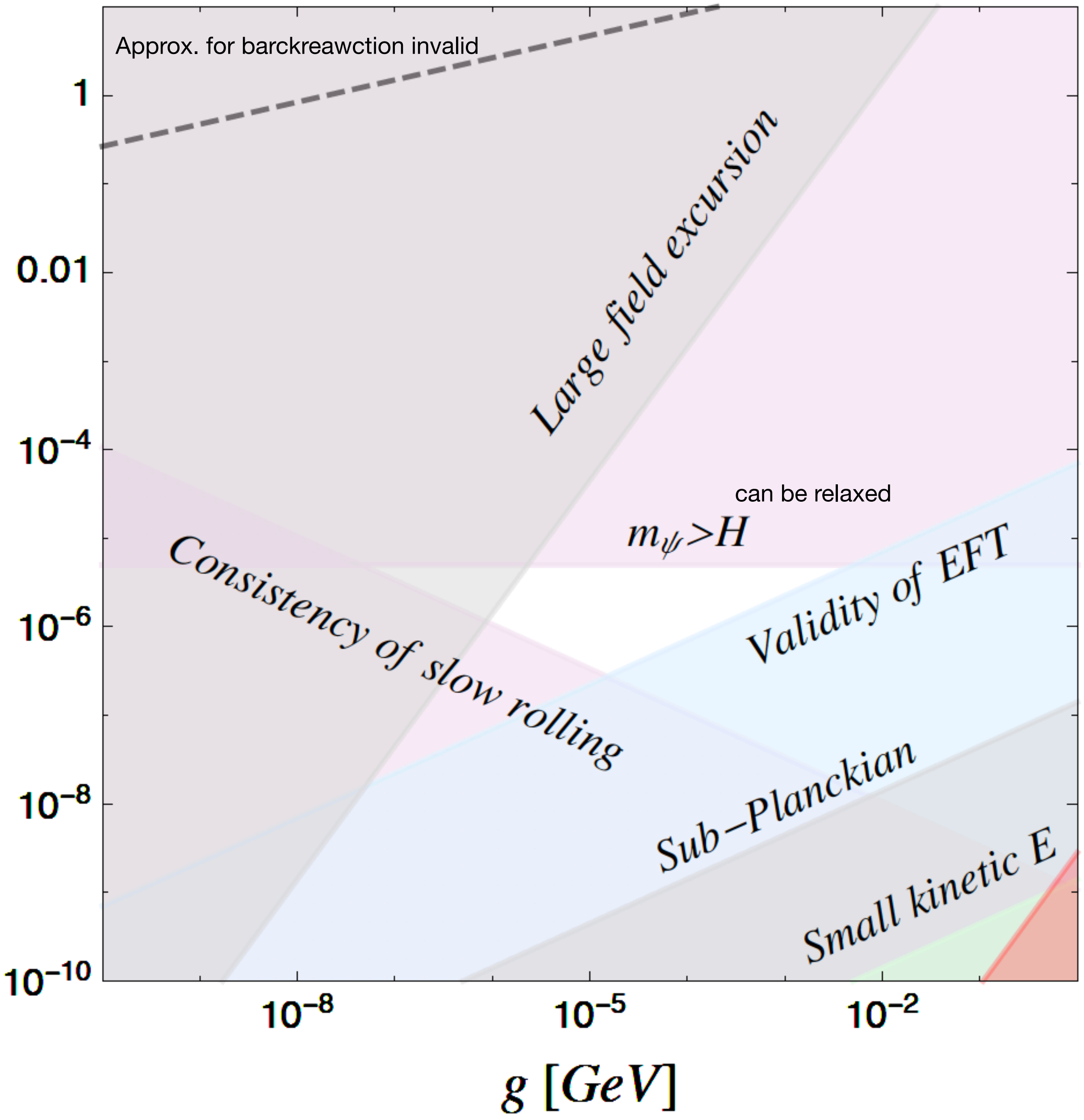
$$4\pi f_{\pi'} > \frac{y\tilde{y}\langle h \rangle^2}{m_L}$$

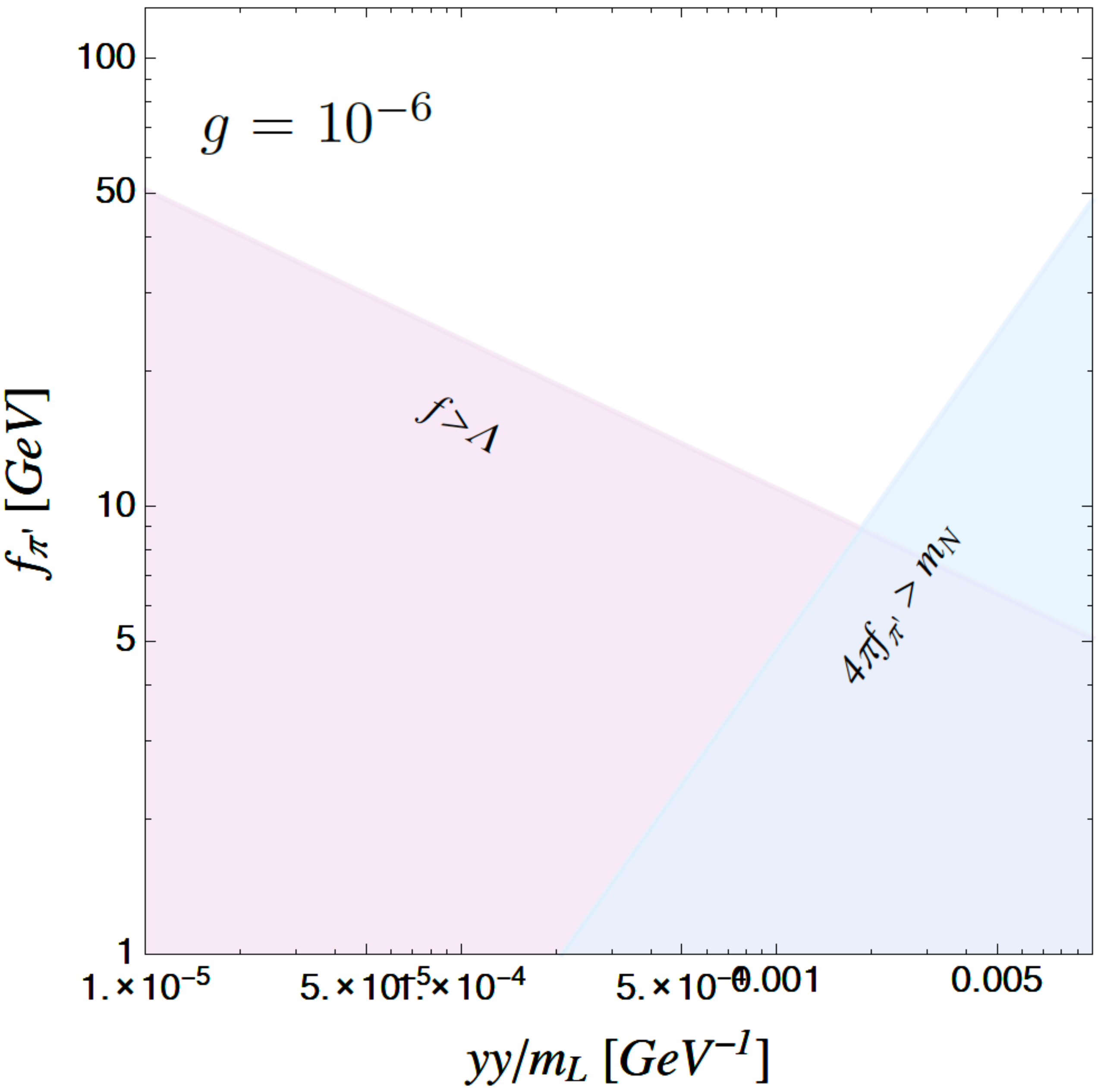
- EFT consistency: $f \gtrsim \Lambda$

Other constraints:
Higgs decay, EWPT etc

Models

A single non-QCD relaxion





$$\Lambda = 10^4 \text{ GeV}, \ H = 5 \times 10^{-6} \text{ GeV}, \ f_\psi = 0.5 \text{ GeV}, \text{ and } N_e = 100$$

Models

A single non-QCD relaxion

A typical solution

$$f_{\pi'} = 45\,\mathrm{GeV}\ , \quad m_L = 300\,\mathrm{GeV}\ , \quad y\tilde{y} = 1.5 \times 10^{-2}$$

$$\underline{f_\psi = 1\,\mathrm{GeV}}\ , \quad H = 5 \times 10^{-6}\,\mathrm{GeV}\ , \quad g = 10^{-6}\,\mathrm{GeV}\ , \quad \underline{\Lambda = 10^4\ \mathrm{GeV}}$$

$$f \sim 3.4 \times 10^4\ \mathrm{GeV} \qquad m_\phi \sim 5 \times 10^{-2}\ \mathrm{GeV} \qquad m_\psi \sim 10^{-6}\ \mathrm{GeV}$$

A scale much smaller than the cutoff scale: $f_\psi \ll \Lambda$

Generic issue;
to be solved
separately

Can't be solved by tuning…

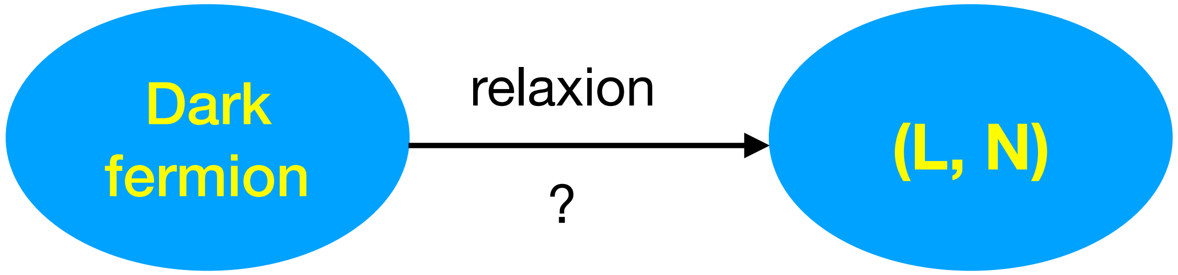
strong back reaction

This issue is even worse in [Adshead, Pearce, Peloso, Robers, Sorbo, 1803.04501]

Maybe explained by e.g. clockwork

Models

A single non-QCD relaxion



Dark fermion

relaxion

?

(L, N)

- One more problem: can the energy in the fermion sector be transferred to the (L,N)-sector?

- If so, the reheating temperature in the (L,N)-sector may be high enough to erase the barriers! => 2nd rolling may ruin relaxation

- Very non-trivial constraints to prevent this to happen

Models

Double scanner [Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant, 1506.09217]

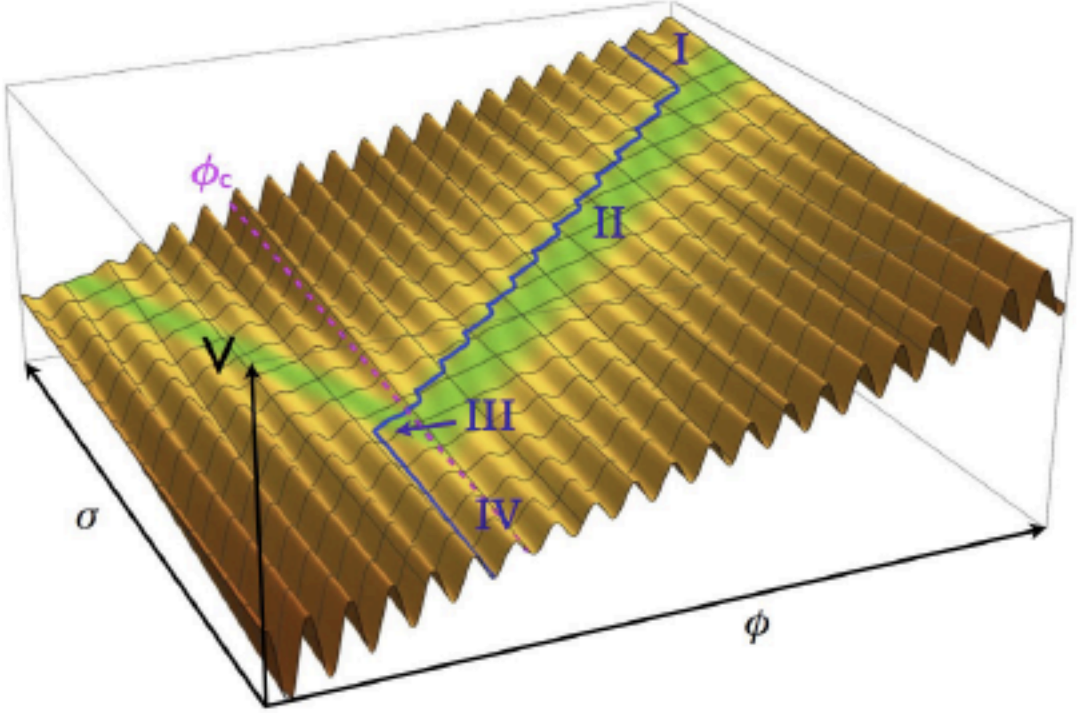
$$\Delta V = g\Lambda^2\phi + g_\sigma\Lambda^2\sigma + \left(-\Lambda^2 + g\phi\right)|h|^2 + A(\phi,\,\sigma,\,h)\cos\left(\phi/f\right)$$
$$+\frac{\partial_\mu\phi}{f_\psi}\bar{\psi}\gamma^\mu\gamma^5\psi + \frac{\partial_\mu\sigma}{f_\sigma}\bar{\psi}\gamma^\mu\gamma^5\psi + m_\psi\bar{\psi}\psi\ ,$$

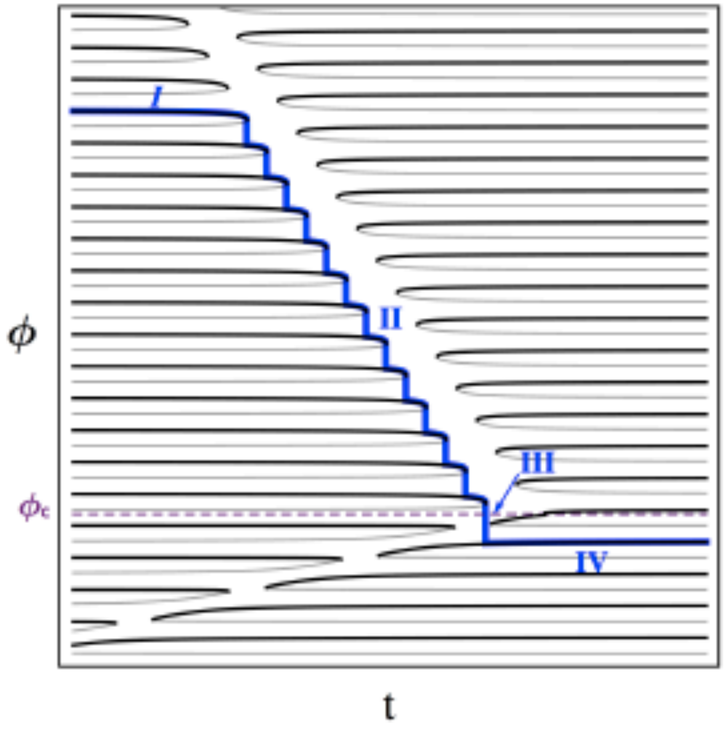
Confinement scale ~ cutoff

Barriers won't be erased during reheating

$$A(\phi,\,\sigma,\,h) = \epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda^2} - c_\sigma\frac{g_\sigma\sigma}{\Lambda^2} + \frac{|h|^2}{\Lambda^2}\right)$$

[Figures from 1506.09217]

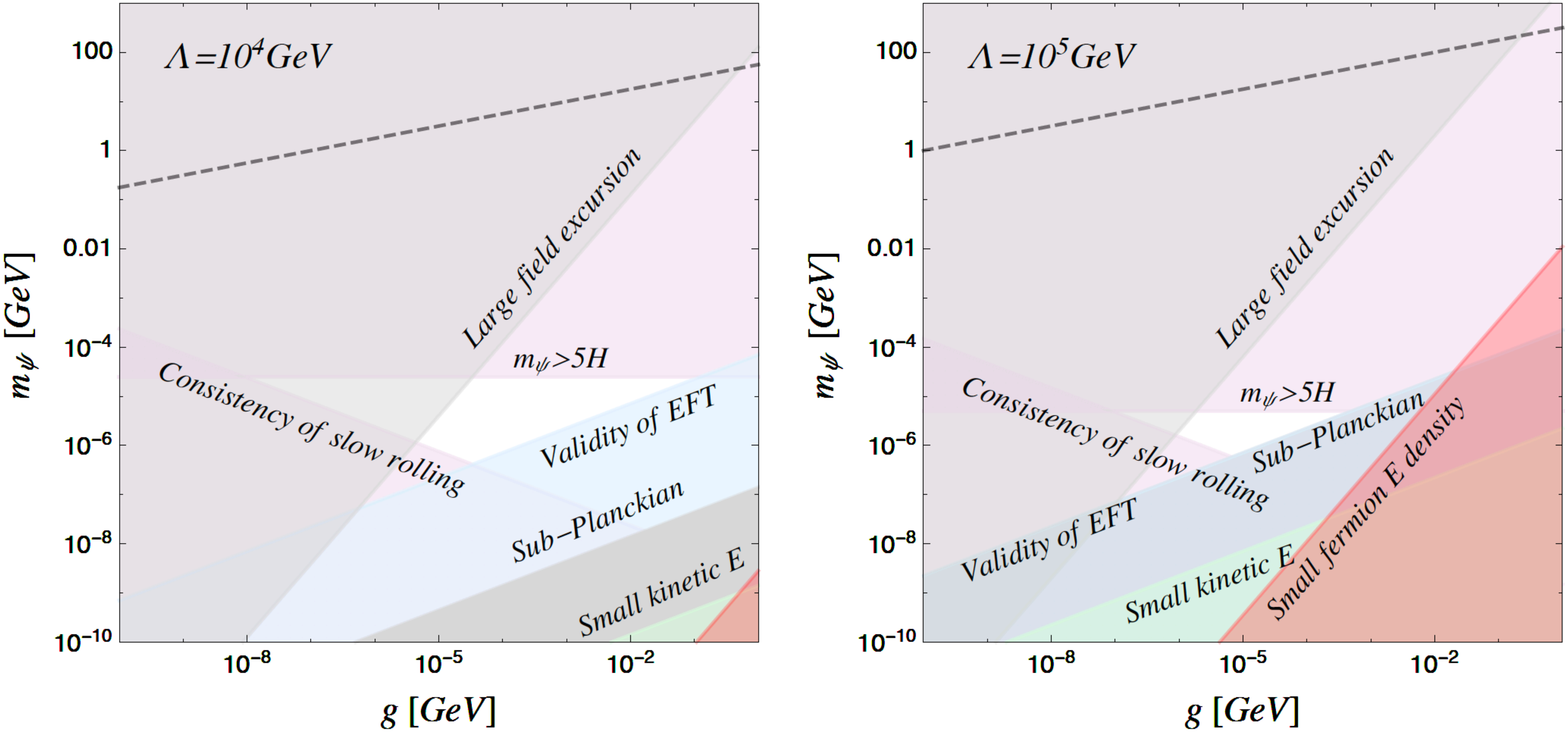




Conditions need to be satisfied for the mech. to work…

Models

Double scanner $f_\psi = f_\sigma$



$H = 10^{-6}$ GeV, $f_\psi = 0.5$ GeV, $\epsilon = 2. \times 10^{-6}$, $N_e = 100$, and $g_\sigma = 0.2\,g$. $\Lambda = 10^5$ GeV

Further analysis and questions

Relic abundances for scalars

Benchmark pt $m_\phi \sim \mathcal{O}(100)\ \mathrm{GeV}$

$m_\psi \sim\ \mathrm{KeV}$

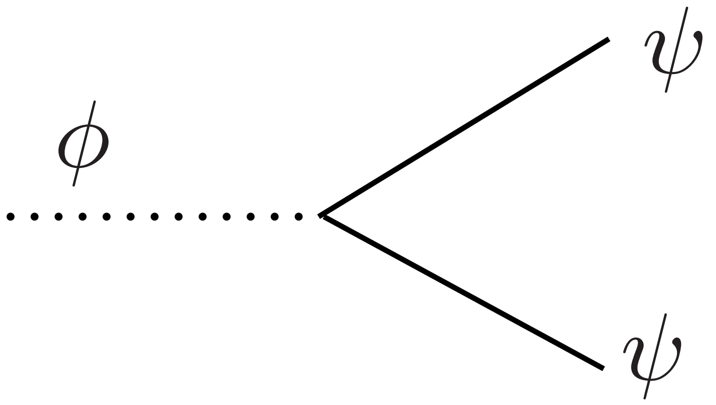
ϕ mixing w/ h, w/ mixing angle $\theta_{\phi h} \sim 2gv/m_h^2.$

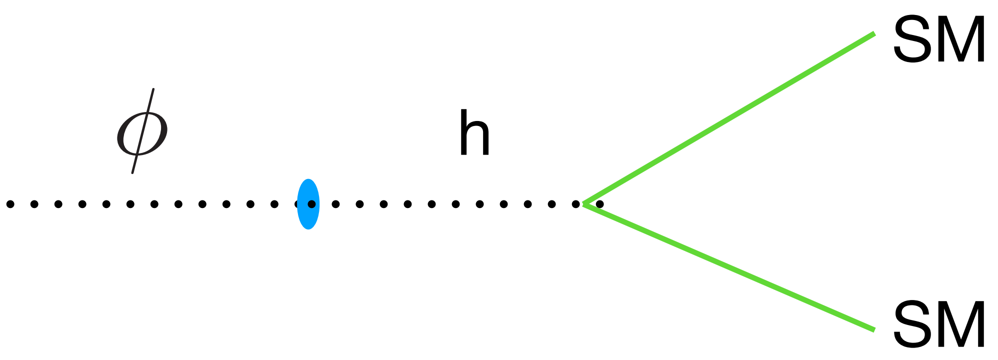
can decay into hidden fermion before BBN

$$\Gamma_\phi = \theta_{\phi h}^2 \Gamma_h(m_\phi) + \Gamma_{\phi\to\psi\psi}(m_\phi)$$

$$\Gamma_{\phi\to\psi\psi} = \frac{1}{2m_\phi}\frac{8m_\psi^2 m_\phi^2}{f_\psi^2}\frac{1}{8\pi}\sqrt{1-\frac{4m_\psi^2}{m_\phi^2}} = \frac{1}{2\pi}\frac{m_\psi^2}{f_\psi^2}m_\phi\sqrt{1-\frac{4m_\psi^2}{m_\phi^2}}$$

$$m_\phi^2 = \frac{\epsilon\Lambda^4}{f^2} \sim \frac{g}{v^2}\frac{\Lambda^4}{f} = \frac{g}{f}\left(\frac{\Lambda}{v}\right)^4 v^2$$





Further analysis and questions

Relic abundances for scalars

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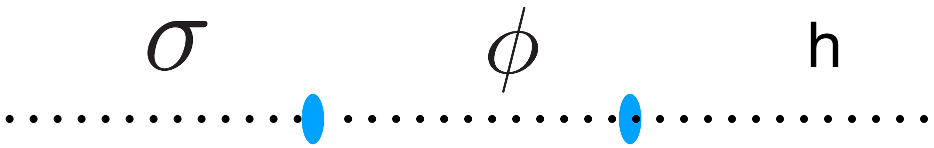
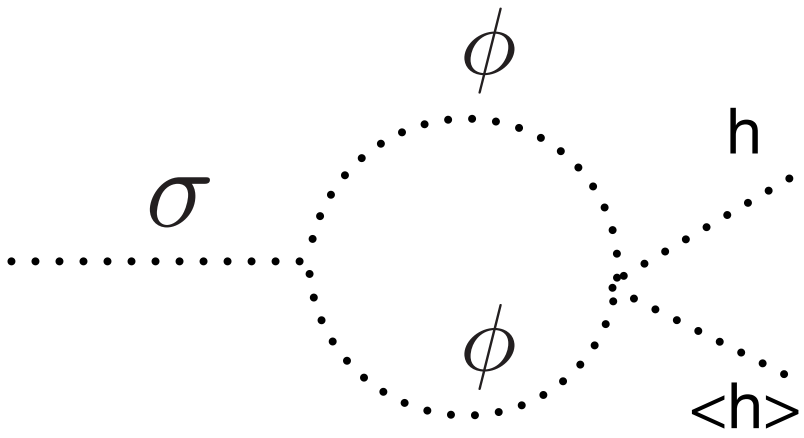
$m_\psi \sim$ KeV

$$\theta_{\phi h} \sim 2gv/m_h^2.$$





σ $$\theta_{\sigma\phi} \sim \frac{g_\sigma f v^2}{\Lambda^4}, \quad \theta_{\sigma h} \sim \text{Max}\left(\theta_{\sigma\phi}\theta_{\phi h}, \ \frac{g^2}{16\pi^2}\frac{g_\sigma \Lambda^4}{f^2 v^3 m_h^2}\right)$$

$m_\sigma^2 \sim g_\sigma^2$

$m_\sigma \sim$ KeV for our benchmark pt

If $\sigma \to \psi\psi$ is turned on, decay into hidden fermion before BBN

If $\sigma \to \psi\psi$ is turned off, only decay into SM fields vis h-mixing w/ small rate Need to worry about its abundance

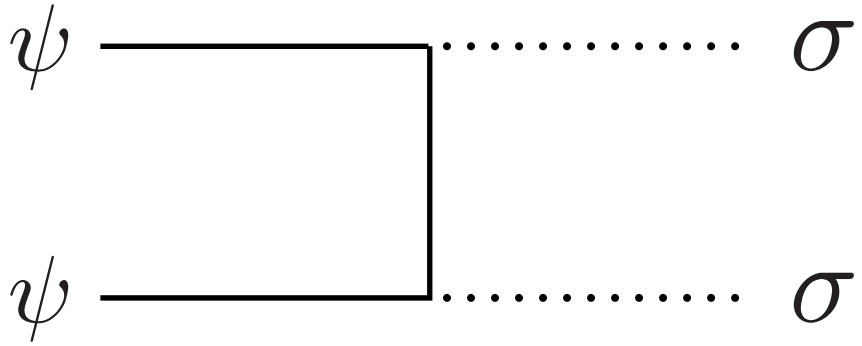
Non-thermal: misalignment

$m_\sigma^2(\Delta\sigma)^2 \quad \Delta\sigma \sim \sqrt{N_e}H$

$$\Omega_0^\sigma = \frac{\rho_0^\sigma}{\rho_c} \sim \frac{1}{\rho_c} m_\sigma^2 N_e H^2 \left(\frac{T_0}{\sqrt{m_\sigma M_p}}\right)^3 \ll 1 \qquad T_{osc} = \sqrt{m_\sigma M_p}$$

Further analysis and questions

Relic abundances for scalars



σ $\theta_{\sigma\phi} \sim \frac{g_\sigma f v^2}{\Lambda^4}, \; \theta_{\sigma h} \sim \mathrm{Max}\left(\theta_{\sigma\phi}\theta_{\phi h}, \frac{g^2}{16\pi^2}\frac{g_\sigma \Lambda^4}{f^2 v^3 m_h^2}\right)$

$m_\sigma^2 \sim g_\sigma^2$

$m_\sigma \sim \text{KeV for our benchmark pt}$

If $\sigma \to \psi\psi$ is turned on, decay into hidden fermion before BBN

If $\sigma \to \psi\psi$ is turned off, only decay into SM fields vis h-mixing w/ small rate

Need to worry about its abundance

Thermal: $\Gamma_{\psi\psi\to\sigma\sigma}(T) \sim \frac{m_\psi^2}{f_\psi^4}T^3$ $\quad T_d \sim \frac{f_\psi^4}{M_p}\frac{1}{m_\psi^2}$

More precise calculation:

$T_0 \sim \mathcal{O}(10^{-13})\ \text{GeV}$

$$T_d \sim 10^{-4}\text{GeV} \gg m_\sigma \xrightarrow{\text{decoupled while relativistic}} \Omega_0^\sigma \sim m_\sigma\, T_0^3\, g_{*S}(T_0)/\rho_C\, g_{*S}(T_d)$$

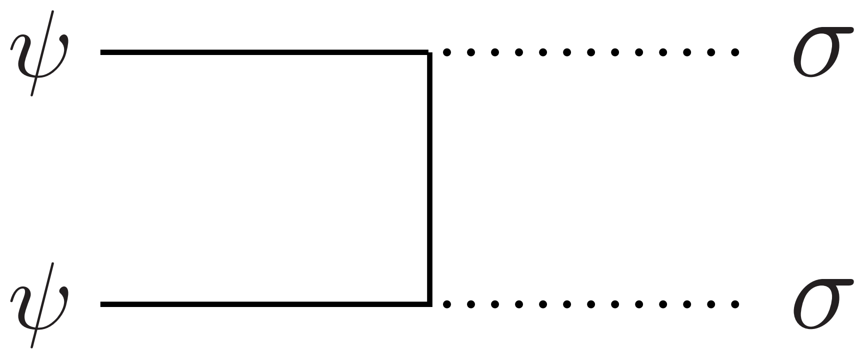
~ O(10)

Over production!

Further analysis and questions

Relic abundances for scalars

$$\Omega_0^{\psi} \sim \frac{m_\psi T_0^3}{\rho_c}\,\frac{g_{*S}(T_0)}{g_{*S}(T_d)}$$



σ $\quad \theta_{\sigma\phi} \sim \frac{g_\sigma f v^2}{\Lambda^4}, \; \theta_{\sigma h} \sim \mathrm{Max}\left(\theta_{\sigma\phi}\theta_{\phi h}, \; \frac{g^2}{16\pi^2}\,\frac{g_\sigma \Lambda^4}{f^2 v^3 m_h^2}\right)$

$m_\sigma^2 \sim g_\sigma^2$

$m_\sigma \sim$ KeV for our benchmark pt

If $\sigma \to \psi\psi$ is turned on, decay into hidden fermion before BBN

If $\sigma \to \psi\psi$ is turned off, only decay into SM fields vis h-mixing w/ small rate

Need to worry about its abundance

Thermal: $\quad \Gamma_{\psi\psi\to\sigma\sigma}(T) \sim \frac{m_\psi^2}{f_\psi^4} T^3 \qquad T_d \sim \frac{f_\psi^4}{M_p}\frac{1}{m_\psi^2}$ decoupled while relativistic

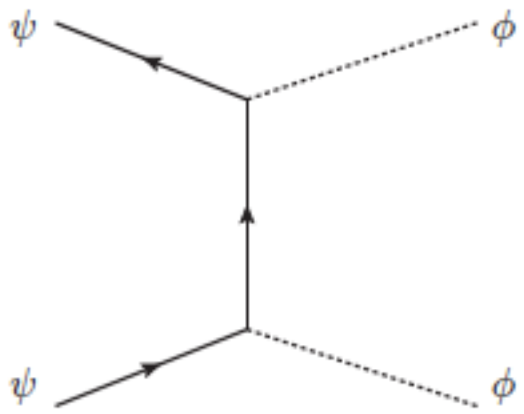
Non-universal coupling: $\quad f_\psi \to f_\sigma = \Lambda \gg f_\psi \qquad T_d \sim \mathcal{O}(10^{1-2})\mathrm{GeV}$

$T_0 \sim \mathcal{O}(10^{-13})$ GeV

$\Omega_0^\sigma \sim m_\sigma\, T_0^3\, g_{*S}(T_0)/\rho_C\, g_{*S}(T_d)$ ~ O(10^-1)

Further analysis and questions

Relic abundances for the fermion



Benchmark pt: $m_\phi \sim \mathcal{O}(100)\ \mathrm{GeV}$

$m_\psi \sim\ \mathrm{KeV}$

Hidden fermion decouples @ T ~ O(100) GeV
(not able to produce relaxion on shell => 2-step stops to be valid;
chain process not in thermal equilibrium)

Hidden fermion decouples while highly relativistic

$$\Omega_0^\psi \sim \frac{m_\psi T_0^3}{\rho_c} \frac{g_{*S}(T_0)}{g_{*S}(T_d)}$$

$T_0 \sim \mathcal{O}(10^{-13})\ \mathrm{GeV}$

WDM?

Constraints for KeV-scale WDM: precise calculation needed

Summary

- Achieved cosmological **relaxation with strong back reaction from hidden fermion production**
- **No extremely small parameter/large number of efolds/ super-Planckian**
- The models require a **relatively strong coupling between the relaxion and the hidden fermion** => seemingly EFT inconsistency? Explained by clockwork etc?
- **Thermal disconnection** may be an easy cure to the inconsistency: independent EFTs with independent cutoffs
- Further: thermal disconnection, more precise calculations of pheno of KeV-scale hidden fermion, gravitational waves from fermion production, etc

Thank you!

Backup

Introduction: relaxation

$$\Delta V = \left(-\Lambda^2 + g\phi\right)|h|^2 + \left(g\Lambda^2\phi + \cdots\right) + \Lambda_c^4 \cos\left(\phi/f\right)$$

cutoff

small mass-dim parameter

Propto to Higgs vev <h>

By NP effect, QCD or non-QCD

- Initial: relaxion has a very large field value (s.t. **positive Higgs mass-squared**) and **slowly rolls** down from its potential

$$\phi \gtrsim \Lambda^2/g \qquad \mu^2 \equiv -\Lambda^2 + g\phi > 0$$

- Rolling of relaxion => scanning Higgs mass
- At some pt: Higgs mass = 0. After this pt, <h> starts to develop, height of the periodic barrier increases
- When the height of the barrier is enough to compensate the linear slope and trap the relaxion, <h> is set to the correct EW VEV v.

Stopping condi: linear slope matches the barrier slope

Introduction: relaxation

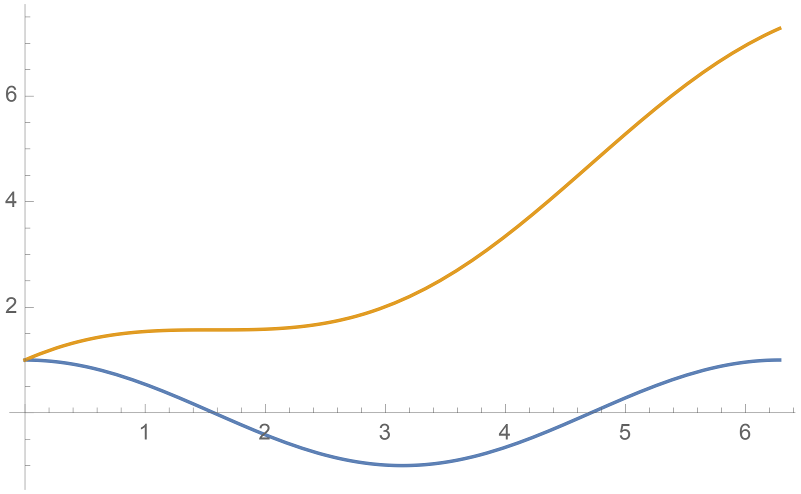
Problems

$$\Delta V = \left(-\Lambda^2 + g\phi\right)|h|^2 + \left(g\Lambda^2\phi + \cdots\right) + \Lambda_c^4 \cos\left(\phi/f\right)$$

- QCD relaxion: O(f) shift of the local min of the QCD part => **O(1) theta parameter!** => Sol: + additional mech. (e.g. a separate inflaton)

Near $\phi \sim \Lambda^2/g$,

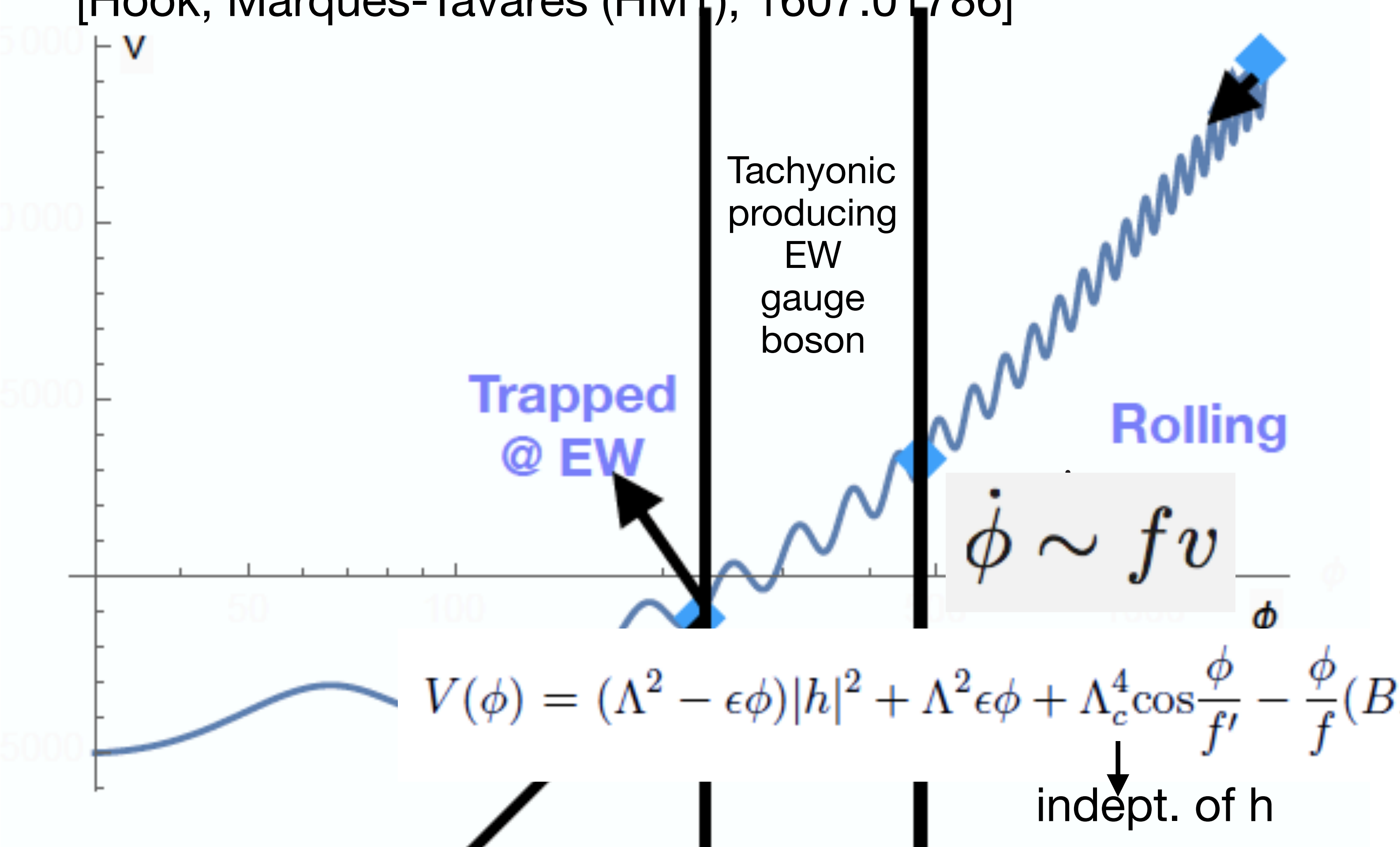
$$\Delta V \sim g\Lambda^2\phi + \Lambda_c^4 \cos(\phi/f)$$
$$\sim \Lambda_c^4\left[\frac{\phi}{f} + \cos\left(\frac{\phi}{f}\right)\right]$$



Introduction: particle production

- Exponentially producing bosons: example in relaxion models: tachyonic production of gauge bosons to stop relaxion

[Hook, Marques-Tavares (HMT), 1607.01786]



$$\dot{\phi} \sim f v$$

$$V(\phi) = (\Lambda^2 - \epsilon\phi)|h|^2 + \Lambda^2\epsilon\phi + \Lambda_c^4 \cos\frac{\phi}{f'} - \frac{\phi}{f}(B\tilde{B} - W\tilde{W}),$$

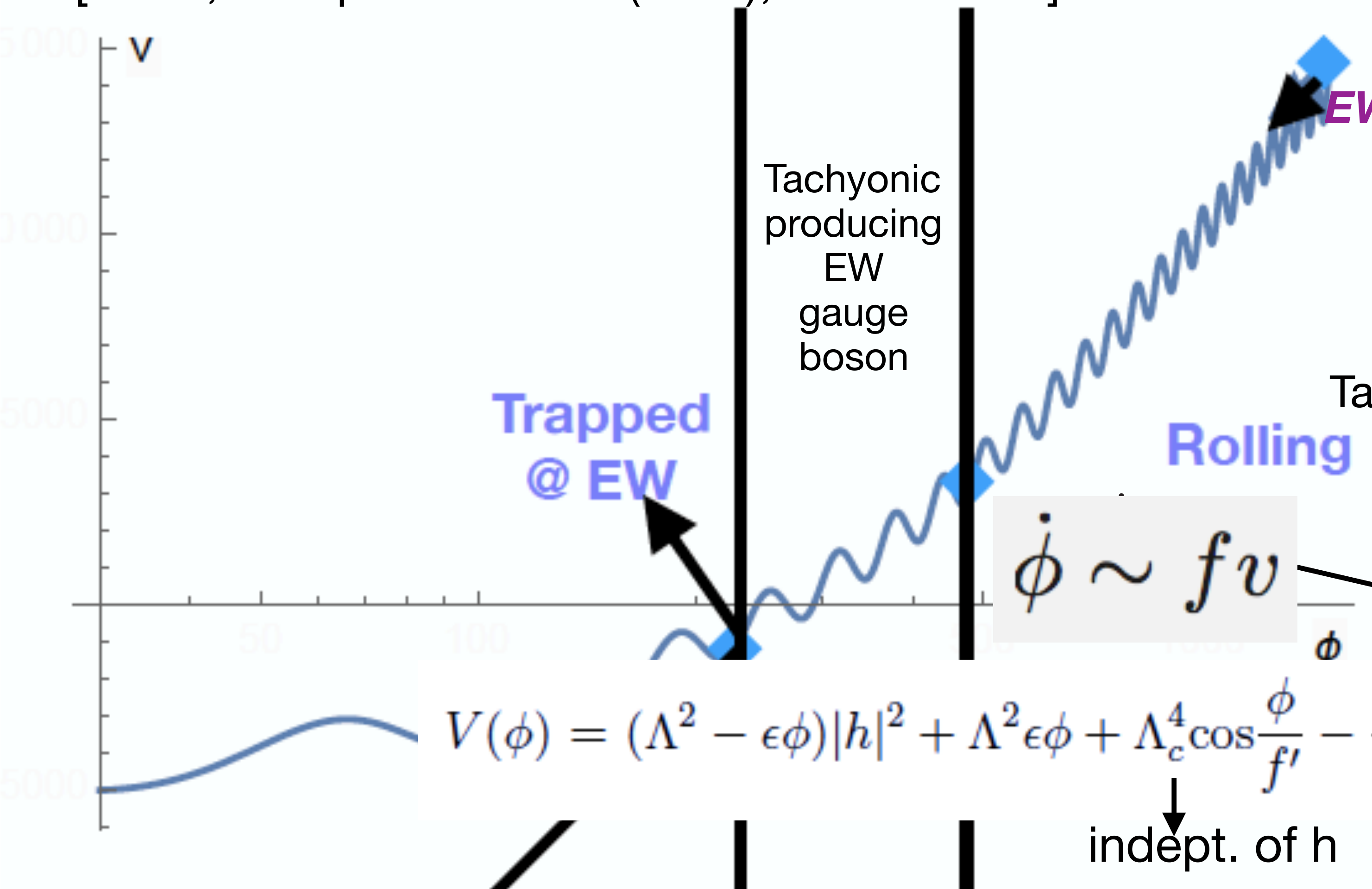
indept. of h

Introduction: particle production

- Exponentially producing bosons: example in relaxion models: tachyonic production of gauge bosons to stop relaxion

Fixed barrier height; h-dependence in the cond. to trigger tachyonic production

[Hook, Marques-Tavares (HMT), 1607.01786]



$$\dot{\phi} \sim f v$$

$$V(\phi) = (\Lambda^2 - \epsilon\phi)|h|^2 + \Lambda^2\epsilon\phi + \Lambda_c^4 \cos\frac{\phi}{f'} - \frac{\phi}{f}(B\tilde{B} - W\tilde{W}),$$

indept. of h

Start:
EW-broken phase with ***very negative*** Higgs mass-square
relatively fast relaxion ***speed*** to pass min

Scan <h> => scan gauge boson mass m

Tachyonic production of gauge bosons exists when

$$\ddot{A}_\pm + (k^2 + m^2 \pm k\frac{\dot{\phi}}{f})A_\pm = 0 \quad \dot{\phi} \geq fm$$

Impose: tachyonic production starts at **m ~ v**

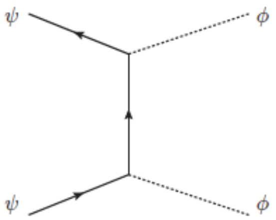
Tachyonic production quickly drains relaxion energy and stabilizes it

Models

A single non-QCD relaxion

- One more problem: reheating temperature in the (L,N)-sector can’t be too high

- Strong u/t-channel to make relaxion thermal



For $T \gg m_\phi, m_\psi,$

if such interactions are in eq.

$$\Gamma \sim \frac{m_\psi^2}{f_\psi^4} T^3 > H \sim \frac{T^2}{M_P}$$

- $\Rightarrow$

$$T > \frac{f_\psi^4}{M_P m_\psi^2} \sim 10^{-6}\mathrm{GeV}(\frac{f_\psi}{1\mathrm{GeV}})^4 \left(\frac{10^{18}\mathrm{GeV}}{M_P}\right) \left(\frac{10^{-6}\mathrm{GeV}}{m_\psi}\right)^2$$

Assume:
inflaton energy dilutes faster than radiation after inflation
s.t. now the universe is radiation-dominated

Double-scanner

$$\Delta V = g\Lambda^2\phi + g_\sigma\Lambda^2\sigma + \left(-\Lambda^2 + g\phi\right)|h|^2 + A(\phi,\,\sigma,\,h)\cos\left(\phi/f\right)$$
$$+\frac{\partial_\mu\phi}{f_\psi}\bar{\psi}\gamma^\mu\gamma^5\psi + \frac{\partial_\mu\sigma}{f_\psi}\bar{\psi}\gamma^\mu\gamma^5\psi + m_\psi\bar{\psi}\psi\ ,$$

$$A(\phi,\,\sigma,\,h) = \epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda^2} - c_\sigma\frac{g_\sigma\sigma}{\Lambda^2} + \frac{|h|^2}{\Lambda^2}\right)$$

Constraints

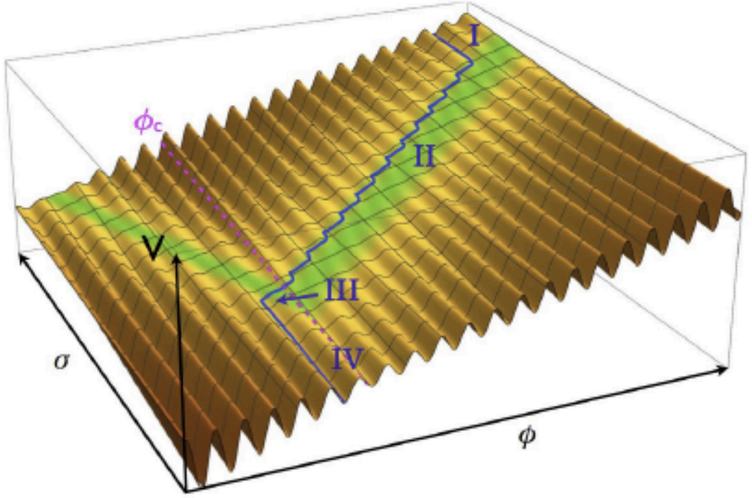
I: sigma rolling, relaxion trapped $A \sim \epsilon\Lambda^4$

II: relaxion needs to scan before reaching the critical pt.

$A \sim 0$

$$d\phi(t)/d\sigma(t) = (g/g_\sigma)^{1/2} > d\phi_*/d\sigma \qquad c_\phi\, g^{3/2} > c_\sigma\, g_\sigma^{3/2}$$

$$g > g_\sigma \text{ for } c_\phi \sim c_\sigma \sim \mathcal{O}(1).$$



III: Relaxion exits the trajectory (periodic slope << linear slope) to evolve along the path where A grows as h grows $A \sim \epsilon\Lambda^2 h^2$

$$d\phi(t)/d\sigma(t) < d\phi_*/d\sigma \qquad (c_\phi - 1/(2\lambda))\, g^{3/2} > c_\sigma\, g_\sigma^{3/2}$$

Relaxion trapped when slope condi.

$$g\Lambda^2 = \frac{A}{f} \sim \frac{\epsilon\Lambda^2 v^2}{f}.$$

IV: Sigma keeps moving until it finds its min Eventually $A \sim \epsilon\Lambda^4$ $m_\phi^2 = \frac{\epsilon\Lambda^4}{f^2} \sim \frac{g}{v^2}\frac{\Lambda^4}{f} = \frac{g}{f}\left(\frac{\Lambda}{v}\right)^4 v^2$

Sigma mass given by its self polynomial interaction $m_\sigma^2 \sim g_\sigma^2$

Double-scanner

$$\Delta V = g\Lambda^2\phi + g_\sigma\Lambda^2\sigma + \left(-\Lambda^2 + g\phi\right)|h|^2 + A(\phi,\,\sigma,\,h)\cos\left(\phi/f\right)$$

$$+\frac{\partial_\mu\phi}{f_\psi}\bar{\psi}\gamma^\mu\gamma^5\psi + \frac{\partial_\mu\sigma}{f_\psi}\bar{\psi}\gamma^\mu\gamma^5\psi + m_\psi\bar{\psi}\psi\ ,$$

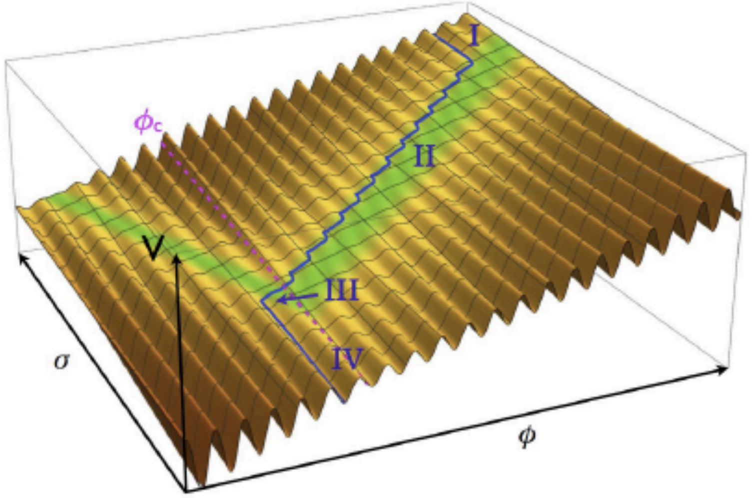
$$A(\phi,\,\sigma,\,h) = \epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda^2} - c_\sigma\frac{g_\sigma\sigma}{\Lambda^2} + \frac{|h|^2}{\Lambda^2}\right)$$

Constraints

Periodic potential contribution to h mass-squared < v^2

$$\Delta m_h^2 \sim \epsilon\Lambda^2\cos\left(\frac{\phi}{f}\right)_{final} \sim \epsilon\Lambda^2 \lesssim v^2$$

$$\Rightarrow g \lesssim \frac{v^4}{f\Lambda^2}$$

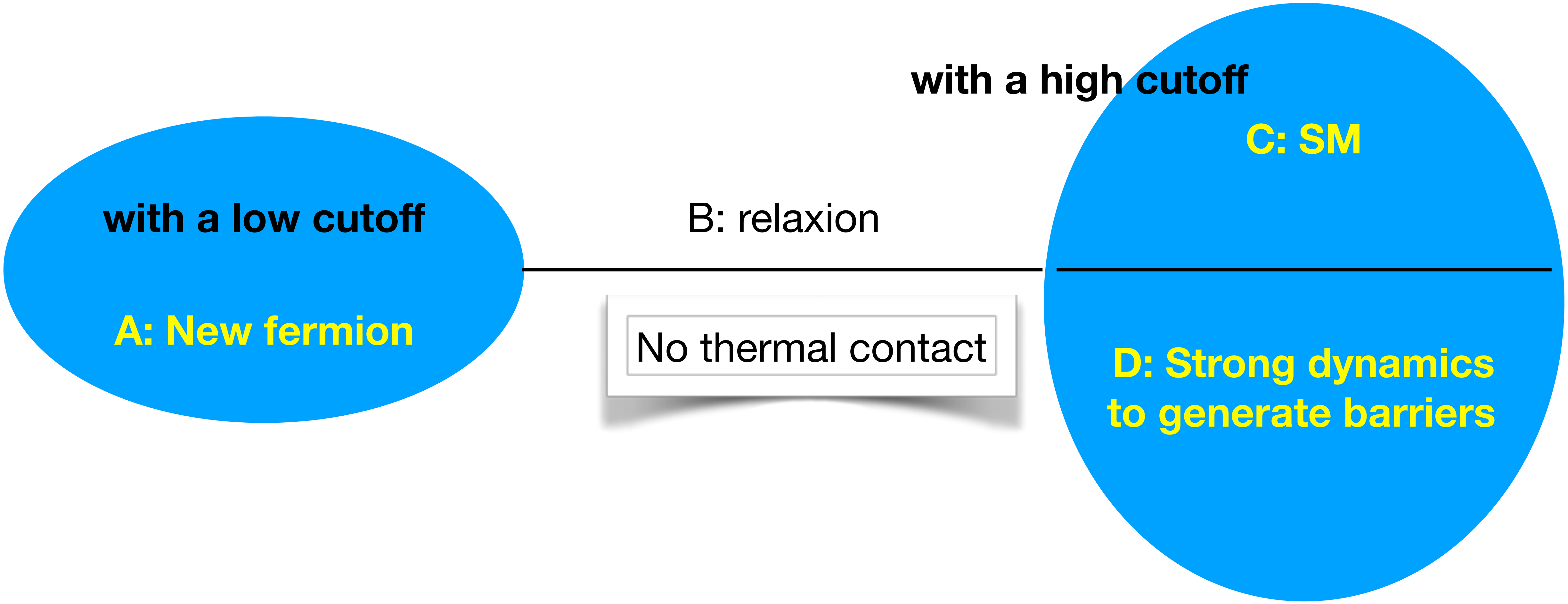


Dangerous corrections to the potential must be small

$\epsilon^2\Lambda^4\cos^2(\phi/f)$ => $\epsilon \lesssim v^2/\Lambda^2$

Further analysis and questions

$f_\psi \ll \Lambda$ universal in strong-fermion-production-supported slow-roll models



with a high cutoff

C: SM

with a low cutoff

B: relaxion

A: New fermion

No thermal contact

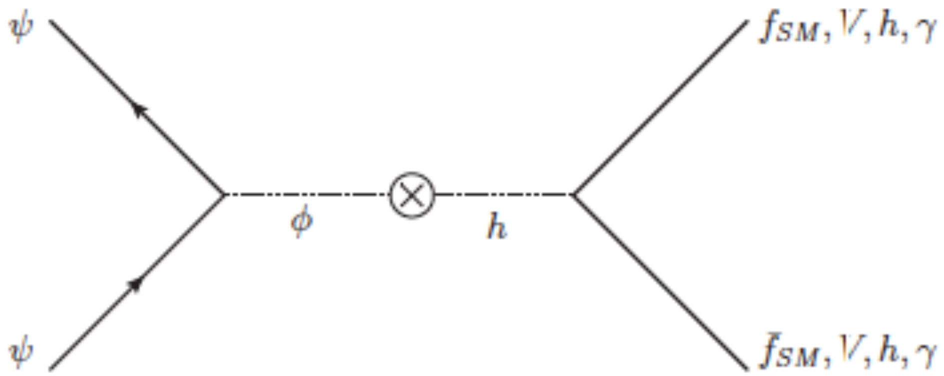
D: Strong dynamics to generate barriers

Further analysis and questions

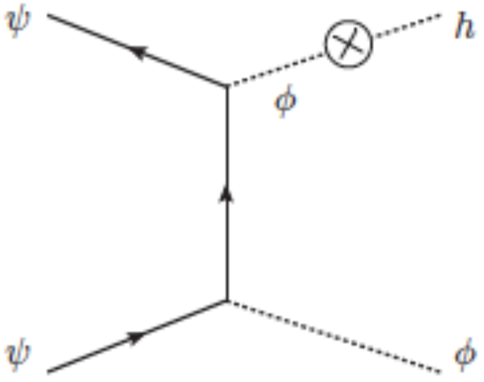
- Can **thermal disconnection** really be true in double scanner w/o new mech.?

- An interesting question:

Chain processes: **double suppression** -> rate enough (<H)



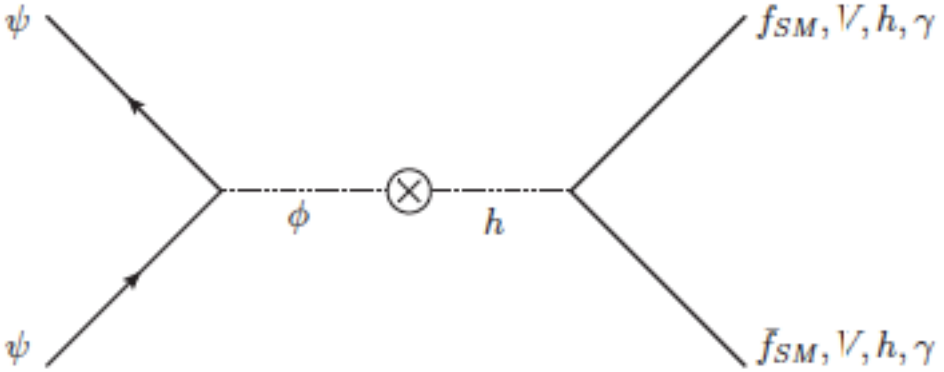
$$\Gamma \propto \mathcal{O}(g^2 v^2) \cdot \mathcal{O}(\frac{m_\psi^2}{f_\psi^2})$$



$$\Gamma \propto \mathcal{O}(g^2 v^2) \cdot \mathcal{O}(\frac{m_\psi^2}{f_\psi^4})$$

Further analysis and questions

An example of NDA analysis for a chain process



If this process is in thermal eq. when T > v (i.e. all particles are relativistic)

$$\Gamma \sim g^2 v^2 \frac{m_\psi^2}{f_\psi^2} T^{-3} > H \sim \frac{T^2}{M_P}$$

=>

$$T < \left(g^2 v^2 \frac{m_\psi^2}{f_\psi^2} M_P \right)^{1/5}$$

$$\sim 1\mathrm{GeV} \left(\frac{g}{10^{-6}\mathrm{GeV}} \right)^{2/5} \left(\frac{v}{10^2\mathrm{GeV}} \right)^{2/5} \left(\frac{m_\psi}{10^{-6}\mathrm{GeV}} \right)^{2/5} \left(\frac{1\mathrm{GeV}}{f_\psi} \right)^{2/5} \left(\frac{M_P}{10^{18}\mathrm{GeV}} \right)^{1/5}$$

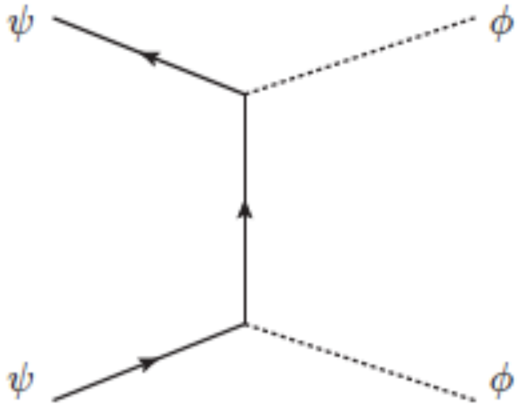
Assume:
inflaton energy dilutes faster than radiation after inflation
s.t. now the universe is radiation-dominated

$\downarrow$

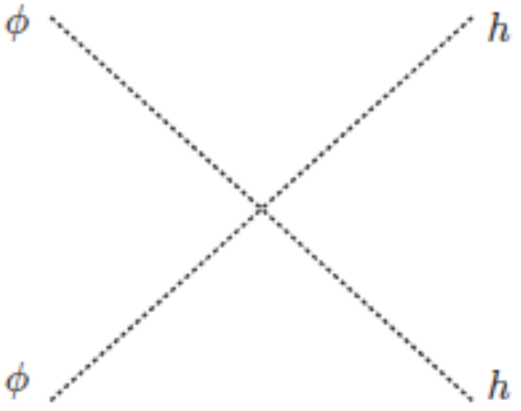
contradicting w/ T > v ⟶ This chain process is not in thermal eq.

Further analysis and questions

2-step processes: **single suppression** in each step, allowing each rate > H



$$\Gamma \propto \mathcal{O}\left(\frac{m_\psi^2}{f_\psi^4}\right)$$



$$\epsilon h^2 \Lambda^2 \cos\left(\frac{\phi}{f}\right)$$

$$\Gamma \propto \mathcal{O}\left(\epsilon^2 \frac{\Lambda^4}{f^4}\right)$$

2-step process seems to be able to make the hidden fermion and SM in eq.

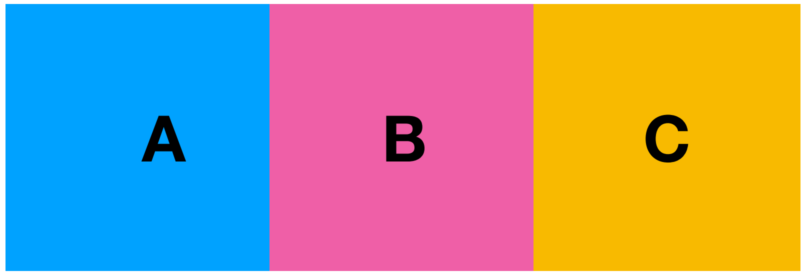
Chain VS 2-step: seemingly inconsistency

Further analysis and questions

A Chain Process VS N Processes

Further analysis and questions

- The 0th law in thermal dynamics



A <-> B, B <-> C
=>
A <->C

- But the pre-condition is, the **intermediate state** is “real”, i.e. **stable enough**
- **If B can only be off-shell, or short-lived (compared to its interaction timescales with A/C), the 2-step analysis is incorrect**

Further analysis and questions

- In our current double scanner model, T > O(100) GeV, the relaxion can be produced “on-shell” by the new fermion, and its lifetime is long enough compared to the timescales for the interactions with fermion and w/ Higgs. 2-step analysis is correct. No thermal disconnection :(

- However, the idea of “thermal-disconnection” may be applied to other models :)

- Similar problems exist in e.g. Higgs portal models. But in those models only T < (mass of intermediate particle) is interested s.t. the 2-step analysis is invalid.

Effective temperature of decoupled particles

- The momentum space distribution function after freezing-out

$$f(\vec{p}, t) = \left[\exp\left(\frac{E-\mu}{T} \pm 1\right)\right]^{-1}$$

$$f \sim \frac{d^3n}{dp^3}$$

$$n \sim a^{-3}$$

$$|\vec{p}| \sim a^{-1}$$

$$f \sim a^0$$

- A particle species decoupled while highly relativistic

$$E \sim |\vec{p}| \sim a^{-1}$$

$$\mu \sim 0$$

$$T \sim a^{-1}$$

$$T_{eff} \sim T_d \left(\frac{a_d}{a}\right)$$

- A particle species decoupled while highly non-relativistic

$$E \sim \vec{p}^2/2m \sim a^{-2}$$

$$T \sim a^{-2}$$

$$T_{eff} \sim T_d \left(\frac{a_d}{a}\right)^2$$

$$\mu_{eff} = m + (\mu_d - m)\frac{T_{eff}}{T_d}$$

	Pros	Cons
GKR	Start w/ EW-sym phase	Extremely small parameter, extremely large number of efolds, super-Planckian field excursion
HMT	No extremely small parameter, moderate number of efolds, sub-Planckian field excursion	specific UV needed
Ours	No extremely small parameter, moderate number of efolds, sub-Planckian field excursion, start w/ EW-sym phase	EFT consistency issue (new mech needed)

Introduction: relaxation

Problems

- Tiny coupling: e.g. g~ 10^-31 GeV for QCD relaxion
- => severe fine-tuning, exponentially large number of efolds, super-Planckian field excursion

$$\Delta\phi \geq \Lambda^2/g^2$$

Contradicting with some gravity argument

Giddings and Strominger

- A free periodic scalar w/ period f has gravitational instantons S ~ M_P/f

non-negligible NP effects if f >= M_P

Whether this applies to interacting scalars: open question

Monodromy induced potential

$F_4 = dC_3$ in 4-dimensional spacetime not dynamic

$$\mathcal{L} = -\frac{1}{2}(da)^2 - V_{KS}(a) - V_{NP}(a),$$

$$V_{KS}(a) \equiv \frac{1}{2}F_4 \wedge \star_4 F_4 - mF_4 a \underset{\overset{\uparrow}{\star_4 F_4 = f_0 + ma,}}{\Rightarrow} V_{KS}(a) = \frac{1}{2}(f_0 + ma)^2.$$

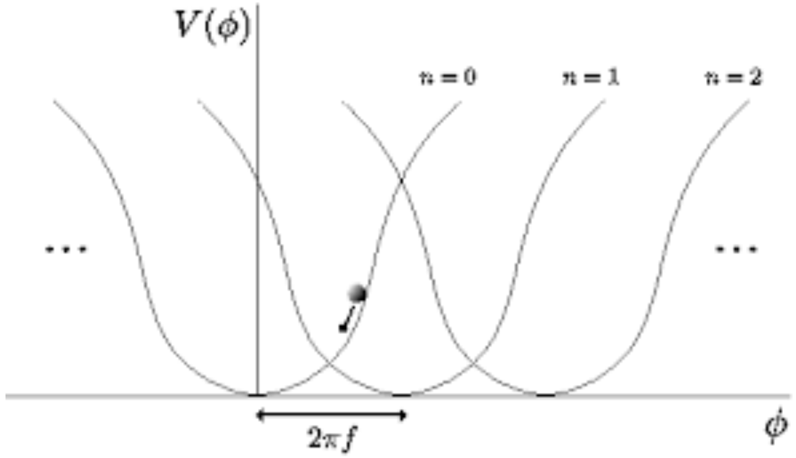
Dirac quantization of a gauge field $f_0 = n\Lambda_k^2, \quad n \in Z,$

where Λ_k is of mass dimension and the index k is associated with a combined discrete shift symmetry of the lagrangian:

$$a \to a + 2\pi f, \quad f_0 \to f_0 - 2\pi m f.$$

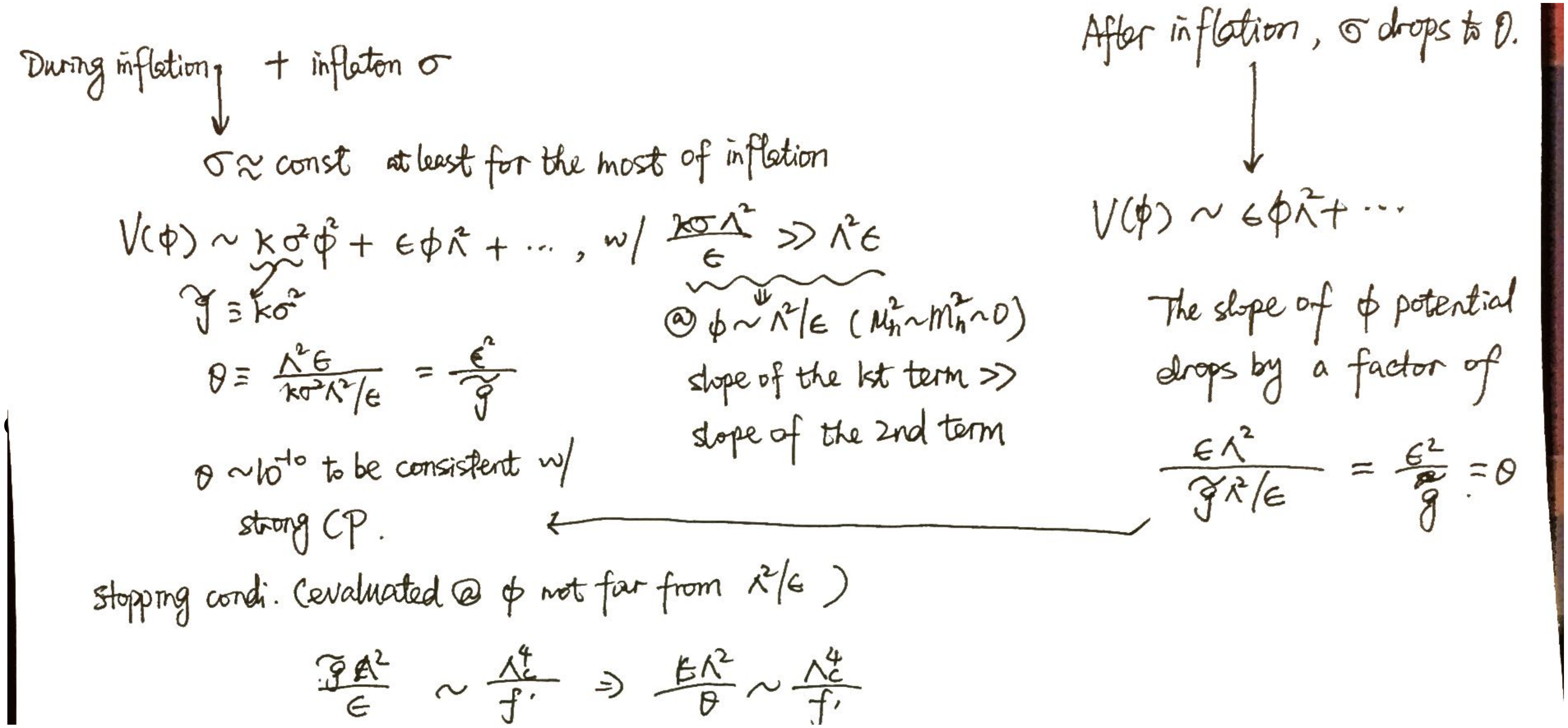
consistency condi. $2\pi m f = k\Lambda_k^2, \quad k \in Z.$

Thus the axion potential $V_{KS}(a)$ is multi-branched, with each branch (namely, a membrane) labelled by a value of f_0. When crossing a membrane, f_0 shifts by an integer times the charge of the membrane. Therefore, starting from a specific branch, the axion can go up in the potential away from its minimum and travel a distance Δa in its field space greater than the intrinsic periodicity f.



GKR's relaxion models

- Sol: e.g. + separate inflaton, or consider non-QCD relaxion



During inflation + inflaton σ

$\downarrow$

$\sigma \approx$ const at least for the most of inflation

$V(\phi) \sim \underbrace{k\sigma^2}\phi^2 + \epsilon\phi\Lambda^2 + \cdots$, w/ $\underbrace{\frac{k\sigma\Lambda^2}{\epsilon} \gg \Lambda^2\epsilon}$

$\tilde{g} \equiv k\sigma^2$

$\theta \equiv \frac{\Lambda^2\epsilon}{k\sigma^2\Lambda^2/\epsilon} = \frac{\epsilon^2}{\tilde{g}}$

$\theta \sim 10^{-10}$ to be consistent w/ strong CP.

@ $\phi \sim \Lambda^2/\epsilon$ ($M_h^2 \sim m_h^2 \sim 0$)

slope of the 1st term $\gg$ slope of the 2nd term

After inflation, σ drops to 0.

$\downarrow$

$V(\phi) \sim \epsilon\phi\Lambda^2 + \cdots$

The slope of ϕ potential drops by a factor of

$\frac{\epsilon\Lambda^2}{\tilde{g}\Lambda^2/\epsilon} = \frac{\epsilon^2}{\tilde{g}} = \theta$

stopping condi. (evaluated @ ϕ not far from Λ^2/ϵ)

$$\frac{\tilde{g}\Lambda^2}{\epsilon} \sim \frac{\Lambda_c^4}{f'} \Rightarrow \frac{\epsilon\Lambda^2}{\theta} \sim \frac{\Lambda_c^4}{f'}$$