Dynamics of cosmological relaxation after reheating

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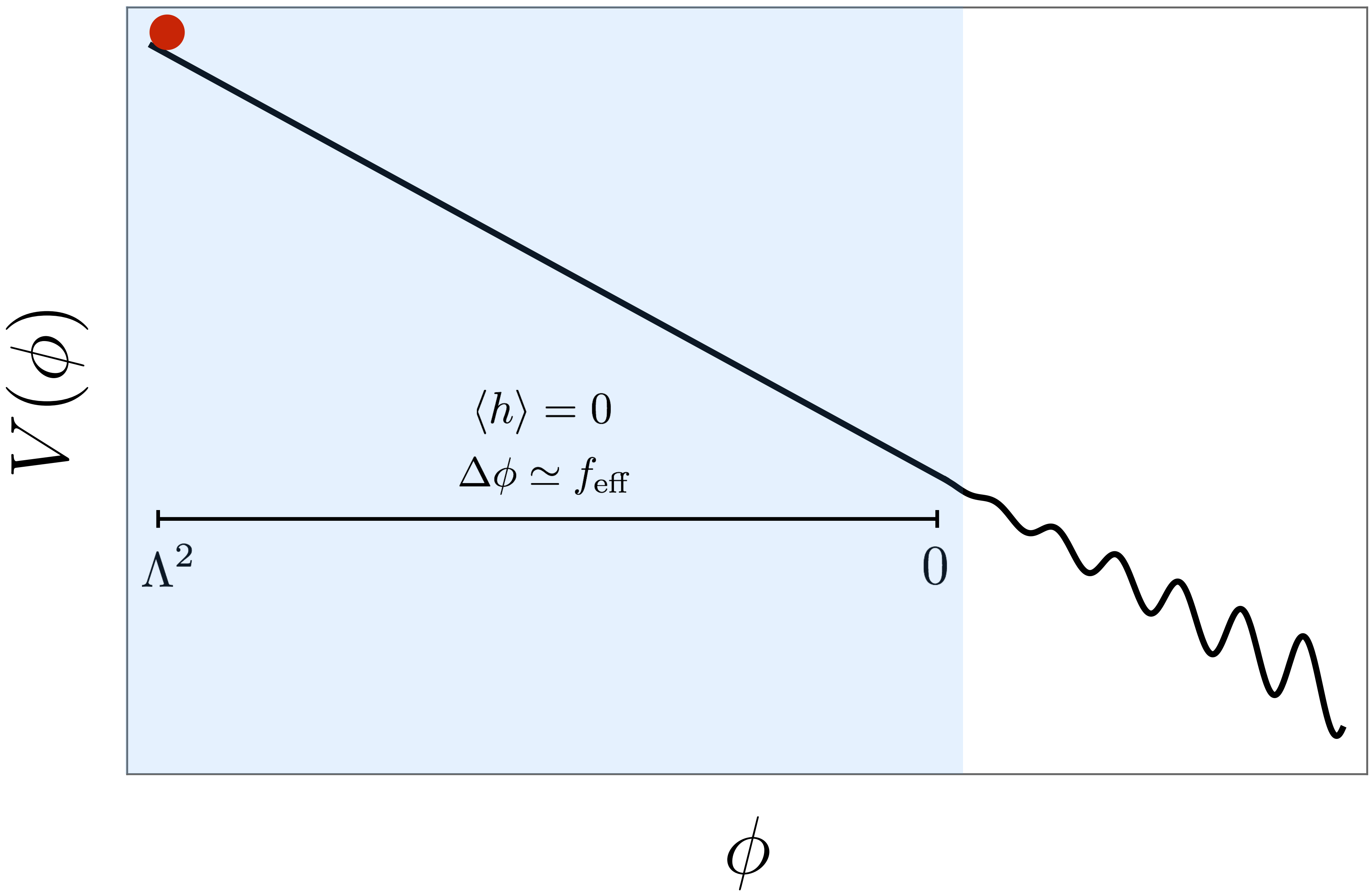
$$V(\phi) = \left(\Lambda^2 - \frac{\Lambda^2}{f_{\rm eff}}\phi\right)|h|^2 - \frac{\Lambda^4}{f_{\rm eff}}\phi + \Lambda_{\rm br}^4(\langle h\rangle)\cos(\phi/f)$$



[Graham, Kaplan, Rajendran 15]

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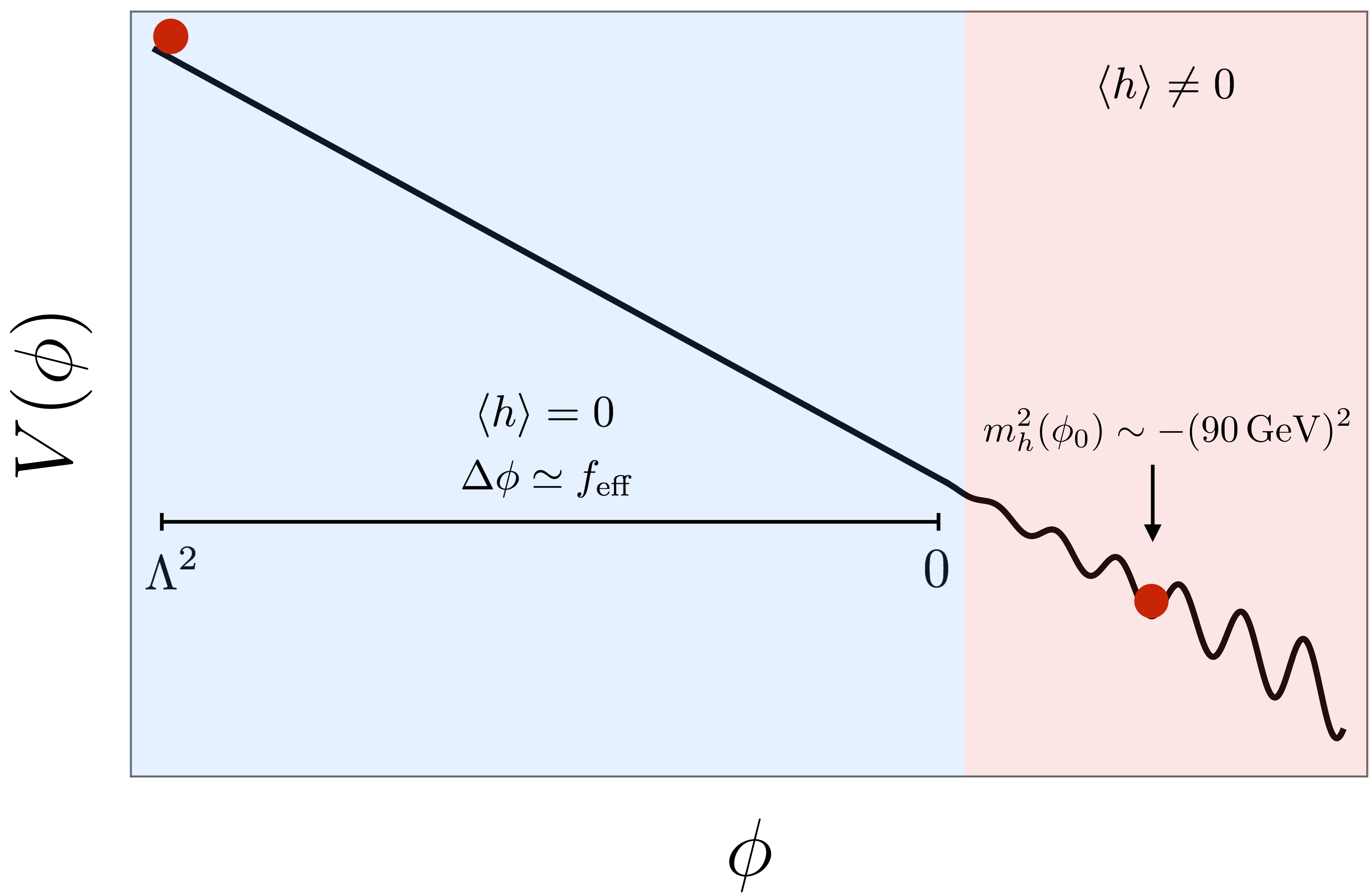

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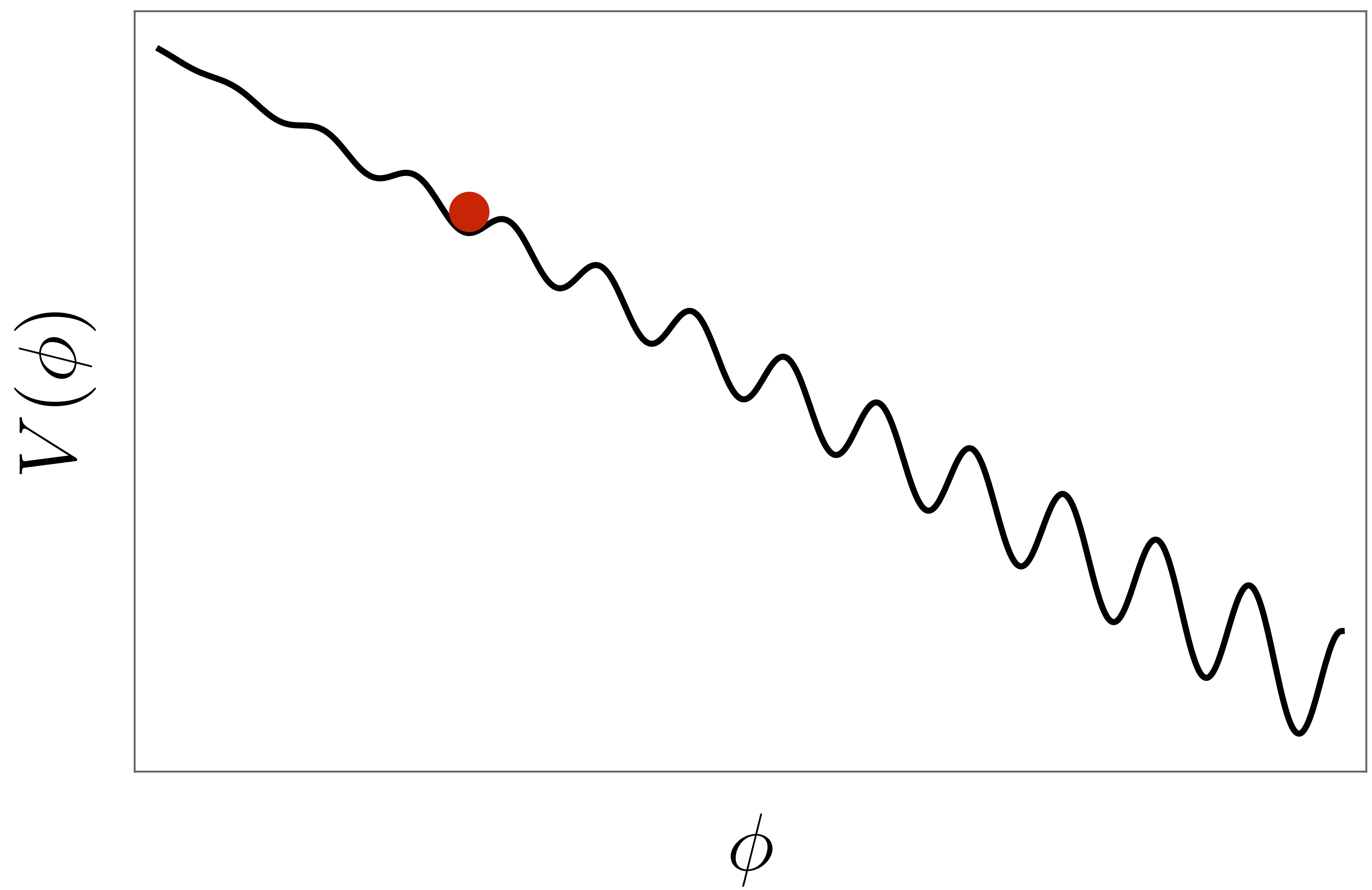
Necessary ingredients for relaxion are

- Relaxion dependent Higgs mass
- Higgs vev dependent Back-reaction potential
- Inflationary Hubble friction

[Graham, Kaplan, Rajendran 15]

Whole scanning process take place ***during inflation***



What happens ***after the reheating ?***

Two possible scenarios

- **Reheating temperature** ***lower*** than electroweak scale

- **Reheating temperature** ***higher*** than electroweak scale

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    - thermal correction is small
    - barrier is still there
    - relaxion does not evolve
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- **Reheating temperature *lower*** than electroweak scale
    - thermal correction is small
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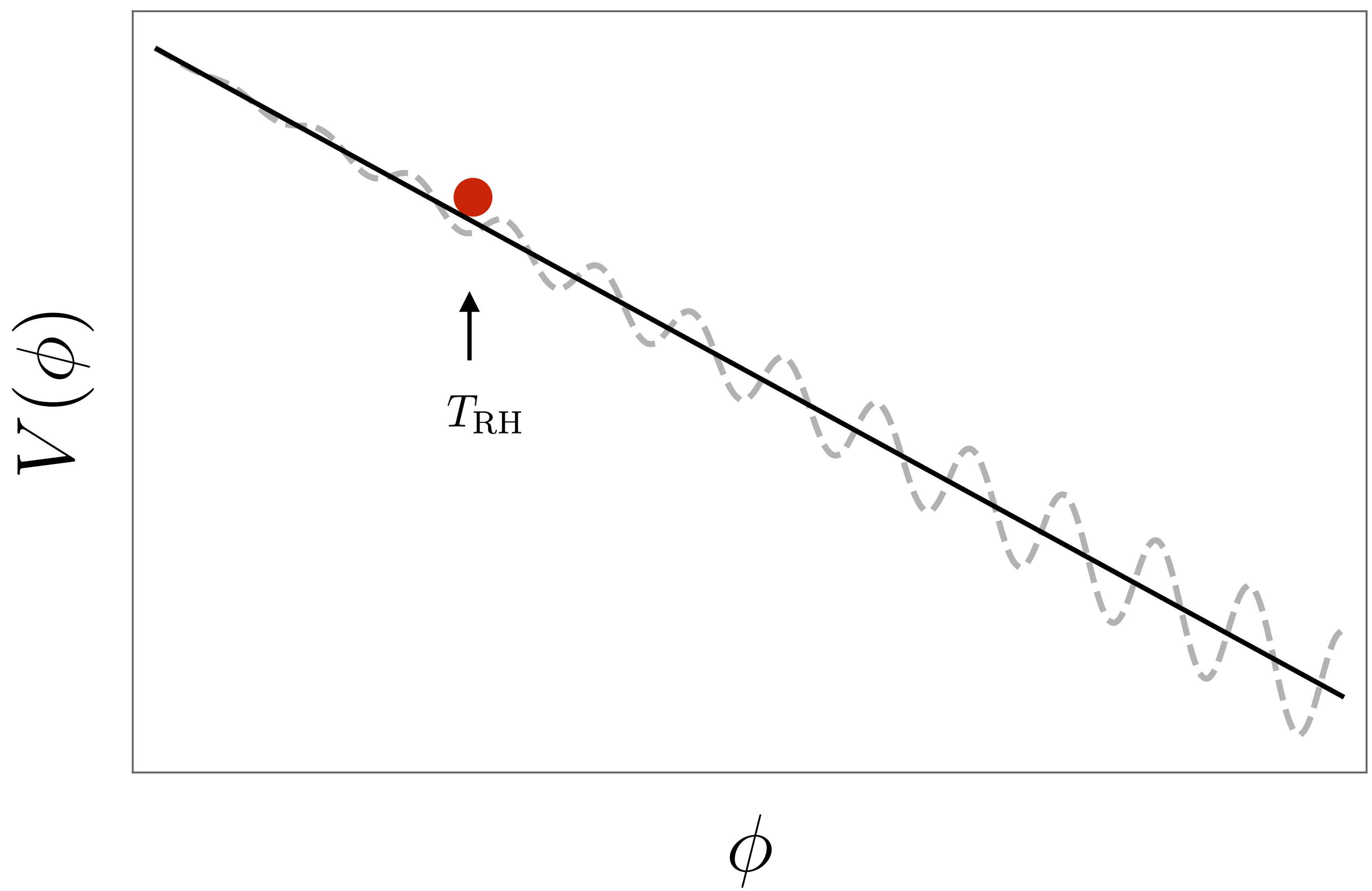
    - relaxion does not evolve

- **Reheating temperature *higher*** than electroweak scale
    - thermal correction is large
    - gauge symmetry is restored
    - barrier disappears
    - ***relaxion evolves!***

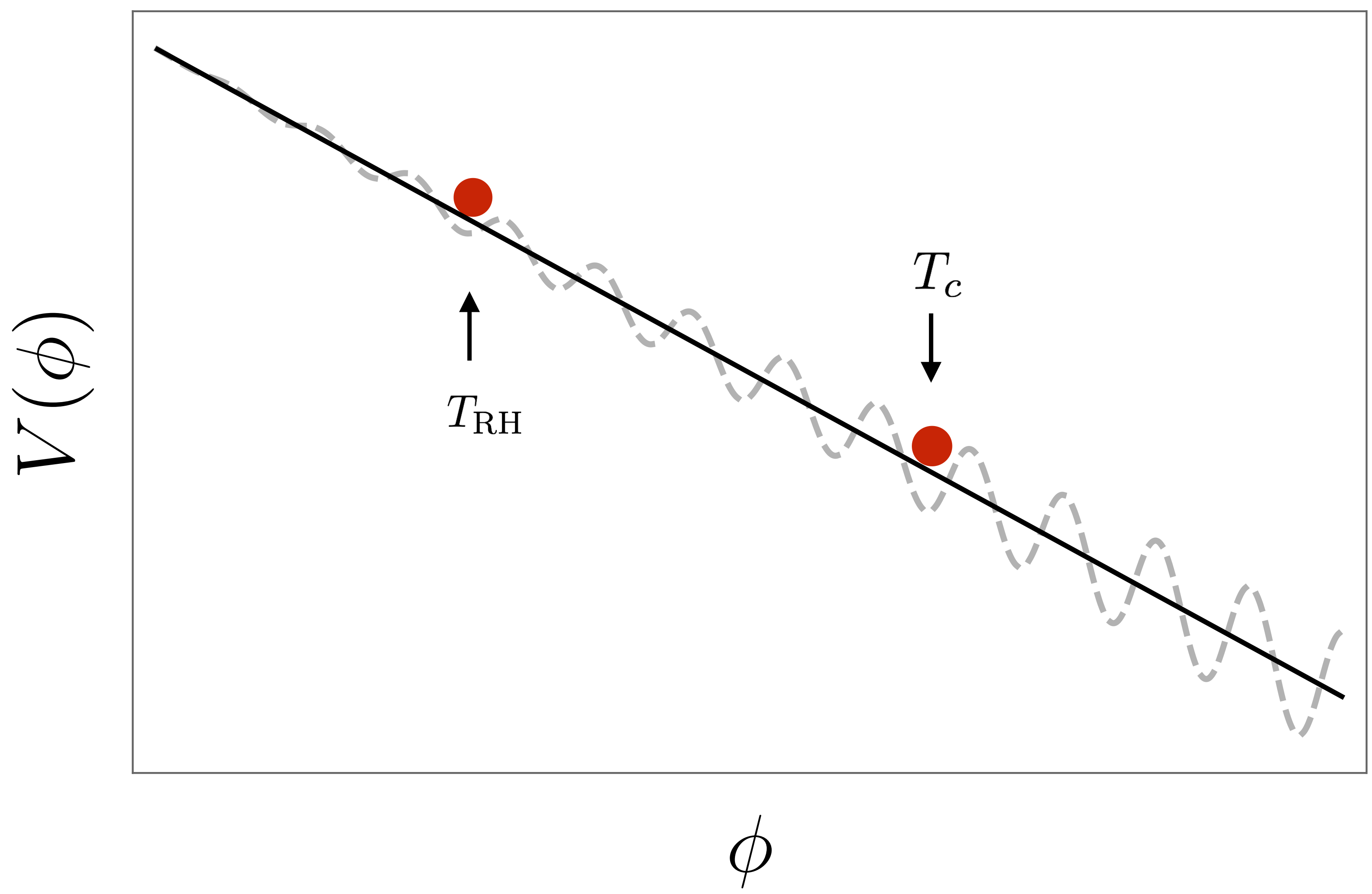
$$T_{\rm RH} > T_c$$



$$V(\phi) = [m_h^2(\phi) + m_T^2]|h|^2 + \cdots$$

(positive)

$$T_{\mathrm{RH}} > T_c$$



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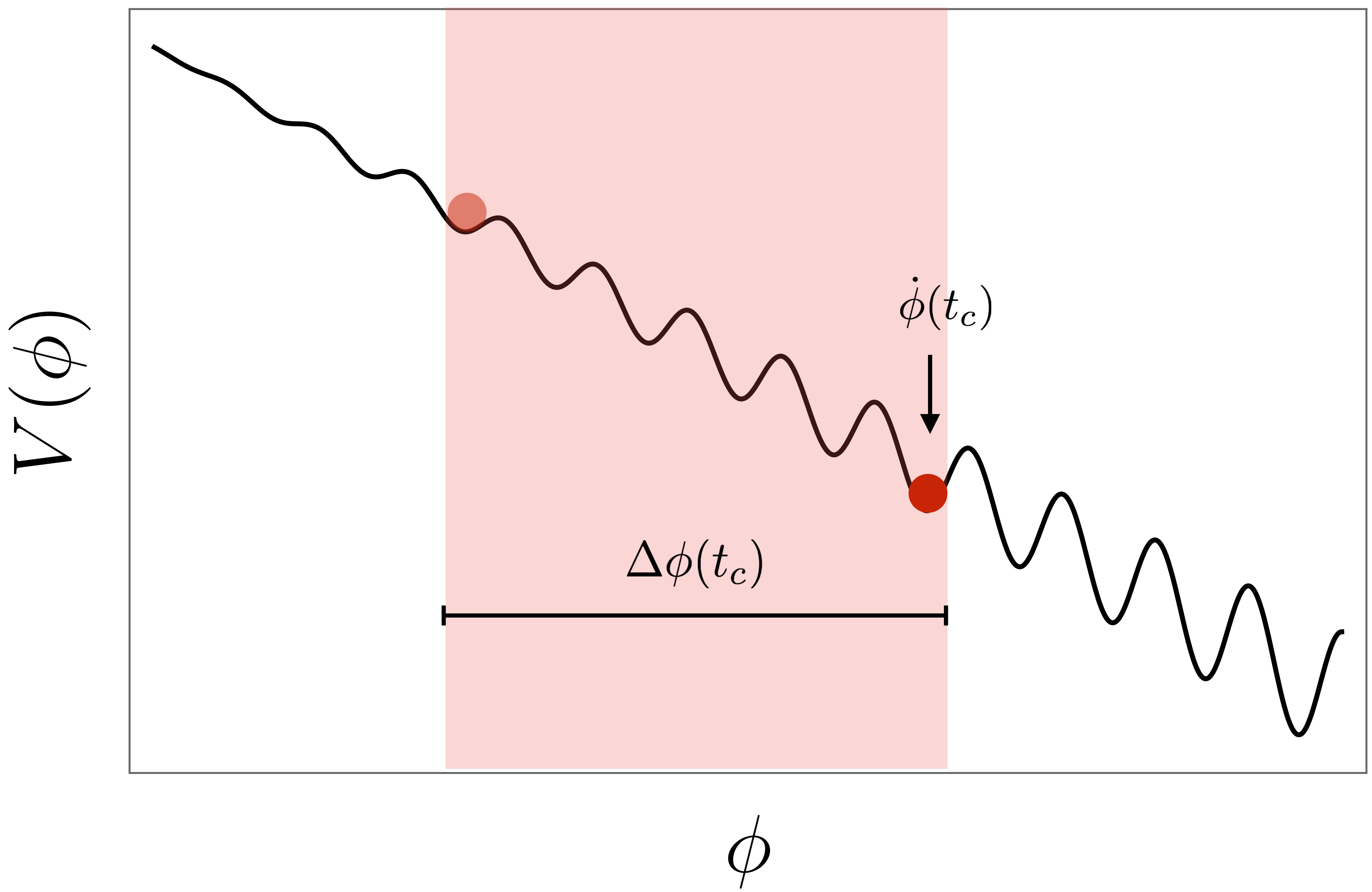
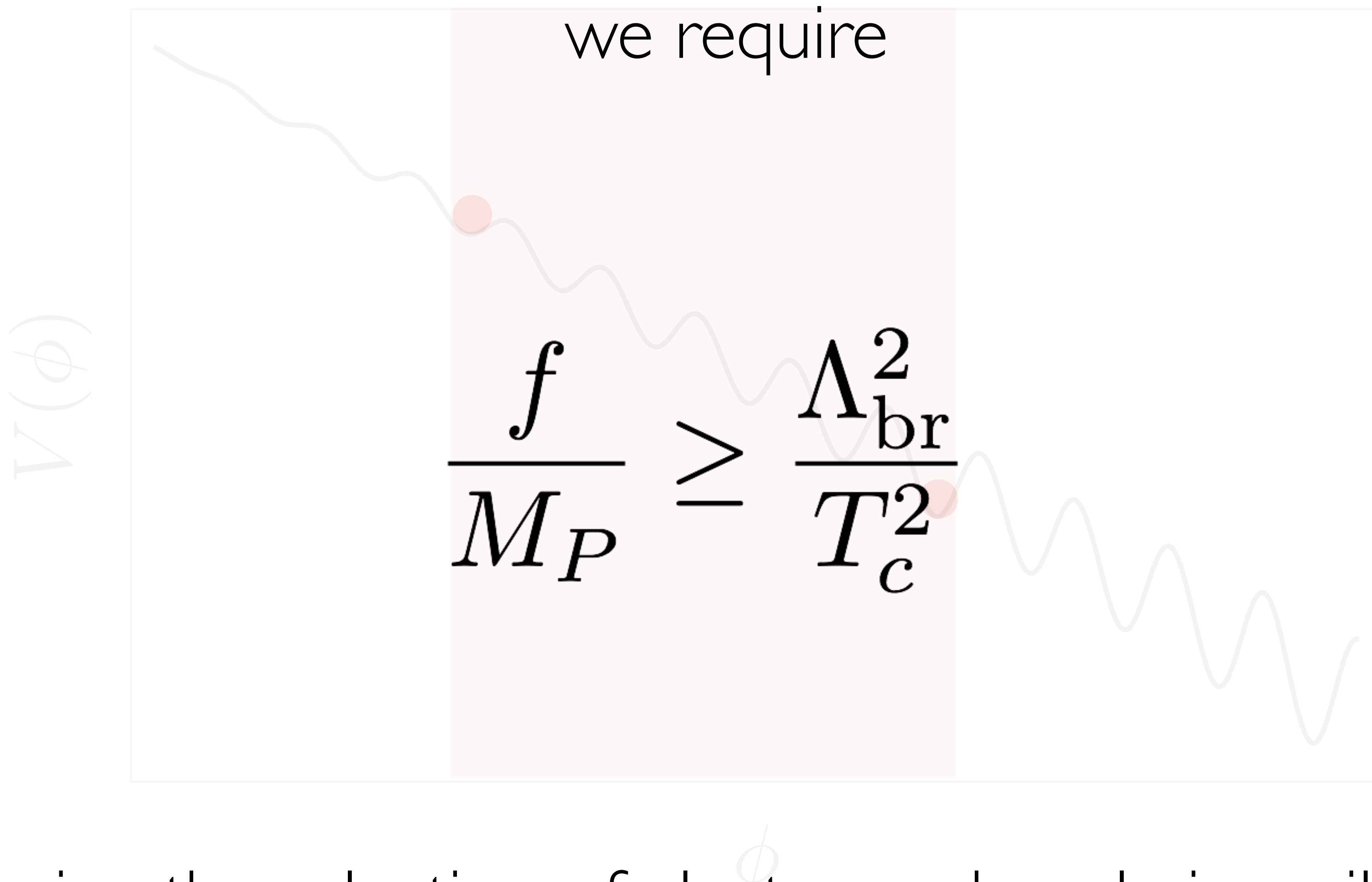
To preserve successful selection of electroweak scale



we need ***small enough field velocity*** $\dot\phi(t_c) \leq \Lambda_{\rm br}^2$

To preserve successful selection of electroweak scale,

we require



$$\frac{f}{M_P} \geq \frac{\Lambda_{\rm br}^2}{T_c^2}$$

otherwise, the selection of electroweak scale is easily ruined

$$\dot\phi(t_c) \sim (\Lambda^4/f_{\rm eff})(M_P/T_c^2) \leq \Lambda_{\rm br}^2$$

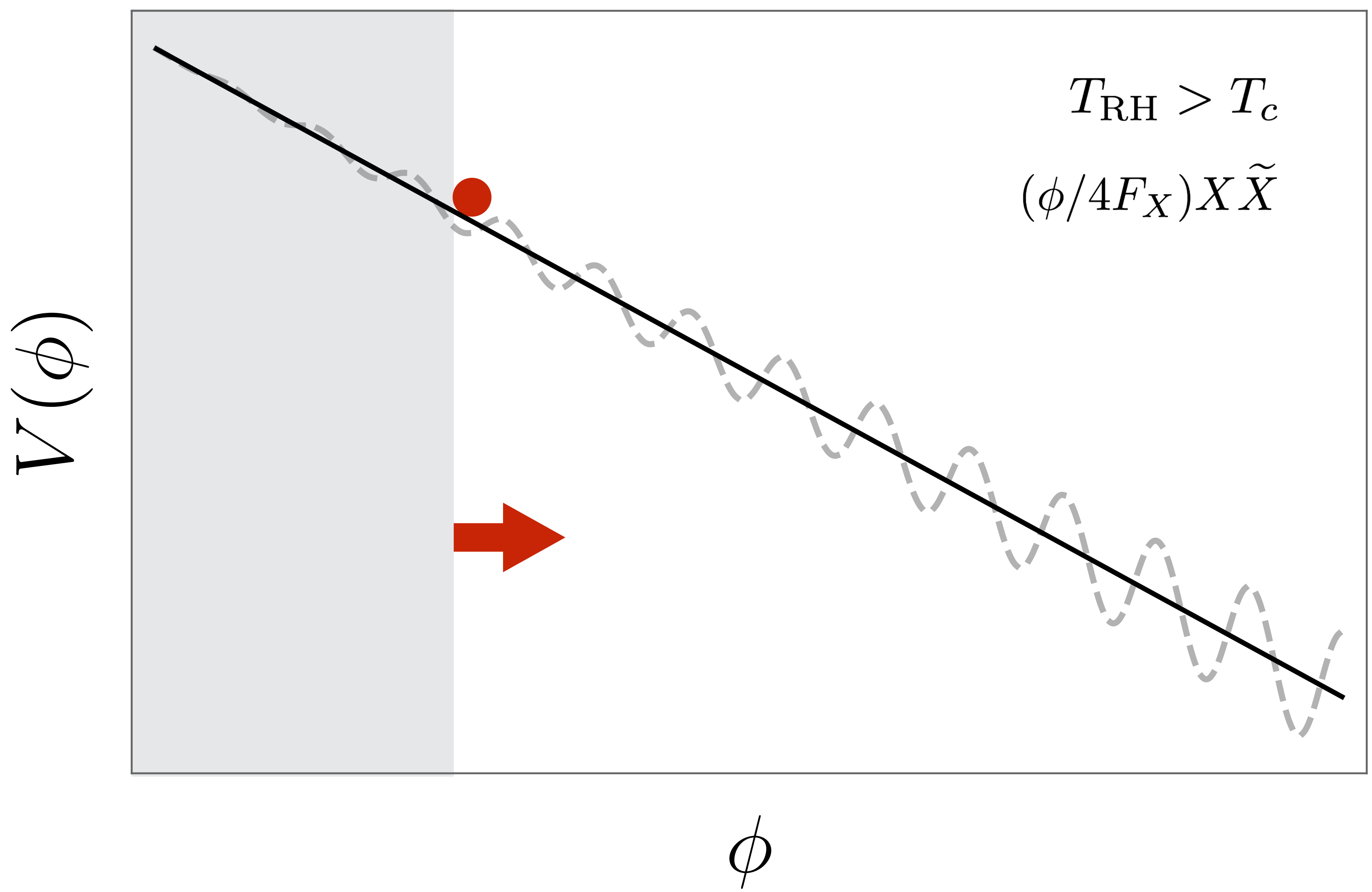
$$\Delta\phi(t_c) \sim (\Lambda^4/f_{\rm eff})(M_P^2/T_c^4) \leq (v/\Lambda)^2 f_{\rm eff}$$

Dynamically selected EW scale is ***not stable***
against ***high reheating temperature***

Alternative possibility?

A possibility:

A new frictional force from Abelian gauge boson



[Choi, HK, Toyokazu; Work in progress]

A possibility:

A new frictional force from Abelian gauge boson

- **Friction** from *Hubble*

- **Friction** from ***gauge field production***

[Choi, HK, Toyokazu; Work in progress]

A possibility:

A new frictional force from Abelian gauge boson

$$\ddot{\phi} + 3H\dot{\phi} + (\partial V/\partial\phi) = -\frac{1}{4F_X a^4} X_{\mu\nu}\widetilde{X}^{\mu\nu}$$

$$\partial_\mu X^{\mu\nu} + \frac{\partial_\mu \phi}{F_X}\widetilde{X}^{\mu\nu} = 0$$

[Choi, HK, Toyokazu; Work in progress]

Anomalous coupling

$$\mathcal{L} \supset -\frac{\phi}{4F_X} X_{\mu\nu}\widetilde{X}^{\mu\nu}$$

time-dependent coupling breaks conformal invariance

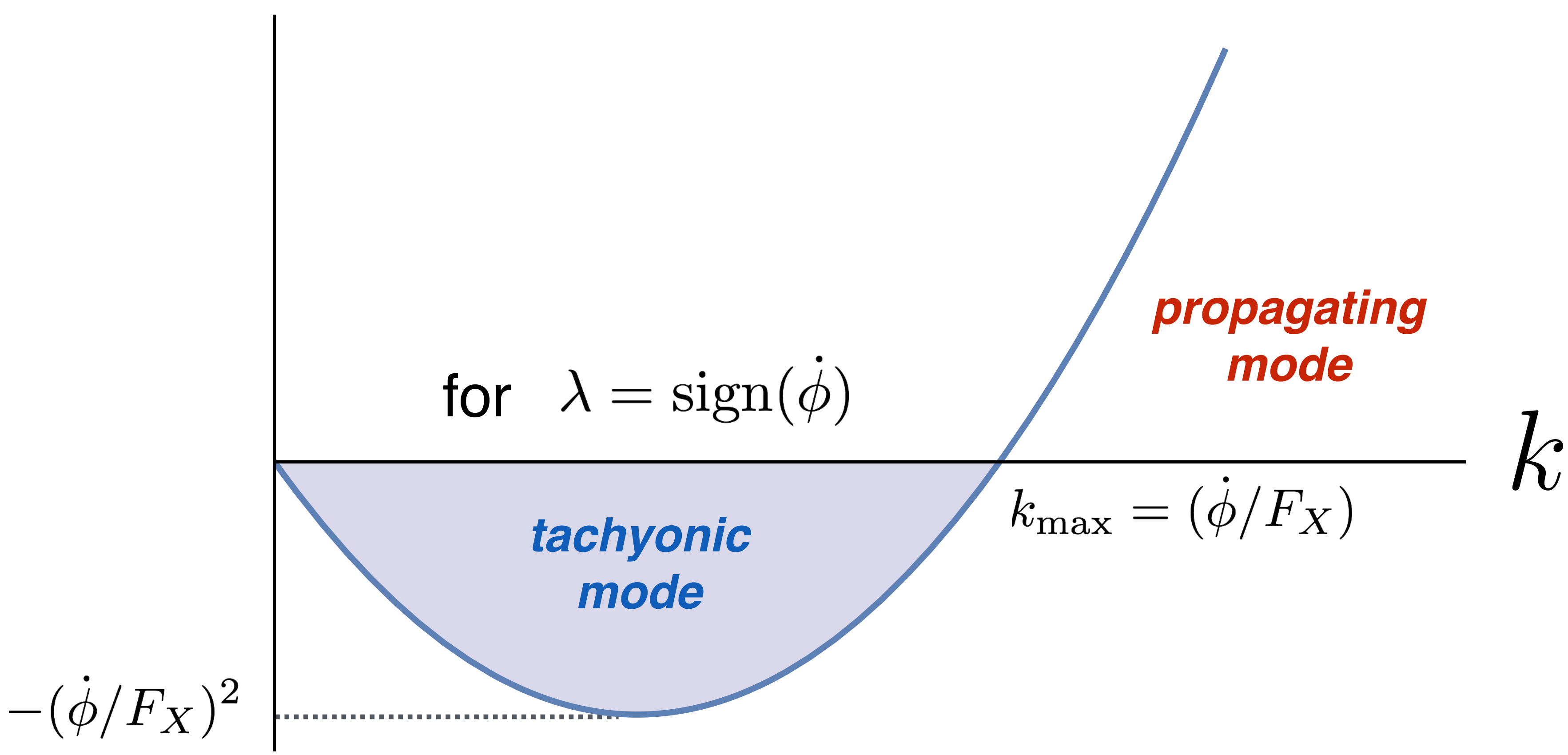
and develops ***instability of gauge boson***

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

[Anber & Sorbo, 09]

Dispersion relation

$$\omega^2 = \left(k^2 - \lambda k \frac{\dot{\phi}}{F_X}\right)$$



Dispersion relation

$$\omega^2 = \left(k^2 - \lambda k \frac{\dot{\phi}}{F_X}\right)$$

tachyonic mode exists for

$$\lambda = \mathrm{sign}(\dot{\phi}) \quad \textbf{\&} \quad k < k_{\mathrm{max}} = |\dot{\phi}/F_X|$$

and ***exponentially grows*** in time

$$X_\lambda(k) \propto \exp[(|\dot{\phi}|/F_X)t]$$

Background evolution of scalar field develops instability

and ***exponentially produces gauge bosons***

$$
\begin{tikzcd}
\dot{\phi} \arrow[rr, bend right, "\textbf{\textit{Produce X}}"'] & & X
\end{tikzcd}
$$

Background evolution of scalar field develops instability

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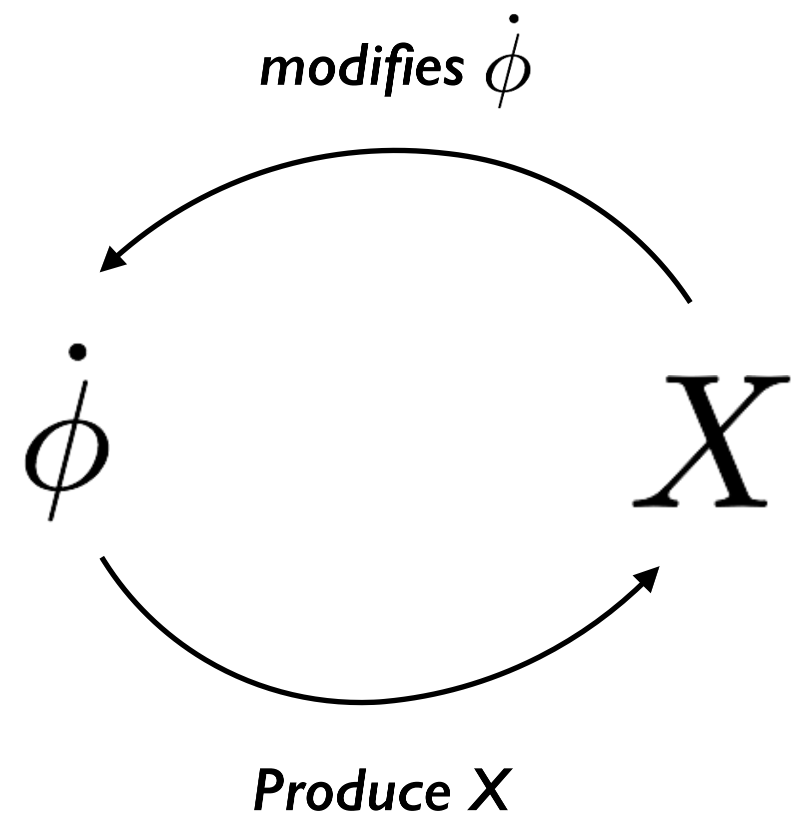

How does X field modify the field velocity of relaxion ?

Evolution of scalar field

$$\ddot{\phi} = -\partial V/\partial\phi - 3H\dot{\phi} - \frac{1}{4F_X a^4}\langle X_{\mu\nu}\widetilde{X}^{\mu\nu}\rangle$$

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force

Evolution of scalar field

$$\ddot{\phi} = -\partial V/\partial\phi \underbrace{- 3H\dot{\phi}}_{\substack{\text{velocity-dependent} \\ \textbf{friction}}} - \frac{1}{4F_X a^4}\langle X_{\mu\nu}\widetilde{X}^{\mu\nu}\rangle$$

Evolution of scalar field

$$\ddot{\phi} = -\partial V/\partial\phi - 3H\dot{\phi} \boxed{- \frac{1}{4F_X a^4}\langle X_{\mu\nu}\widetilde{X}^{\mu\nu}\rangle}$$

"gauge"
friction

Evolution of scalar field

$$\ddot{\phi} = -\partial V/\partial\phi - 3H\dot{\phi} - \frac{1}{4F_X a^4}\langle X_{\mu\nu}\widetilde{X}^{\mu\nu}\rangle$$

terminal velocity is determined as

$$\dot{\phi} = \xi F_X H$$

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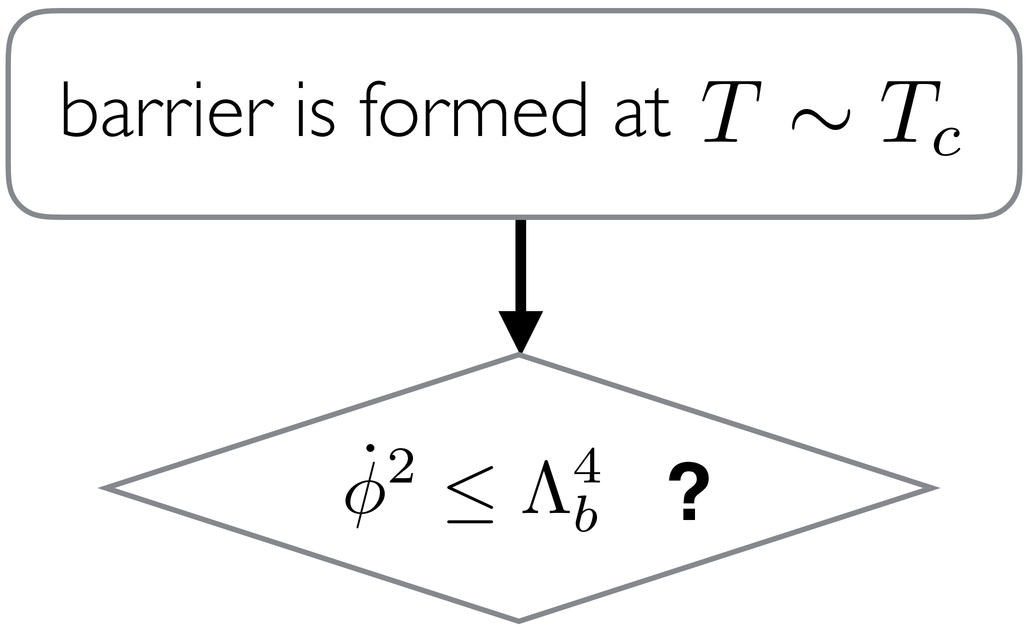
decreasing function in time!

When does it stop?



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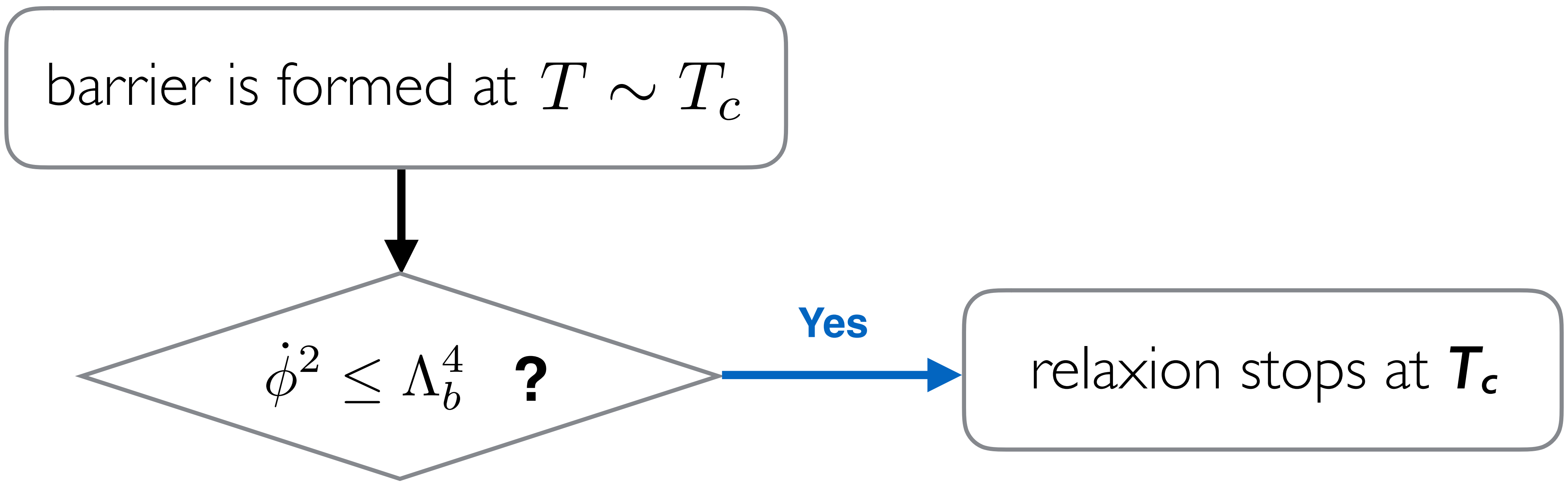

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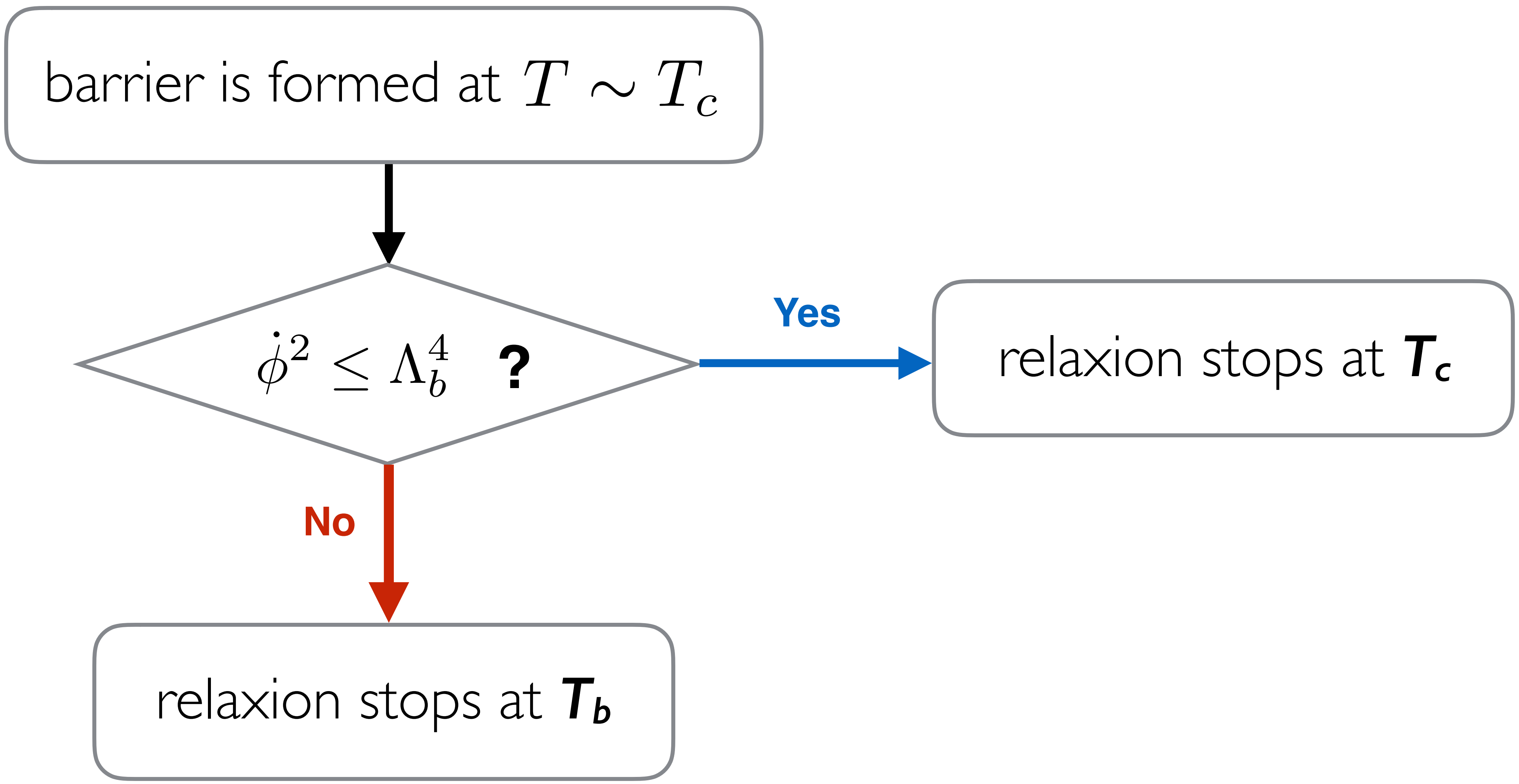

$*$ $\boldsymbol{T_b}$ *is when* $\dot{\phi}^2(T_b) \sim \Lambda_b^4$

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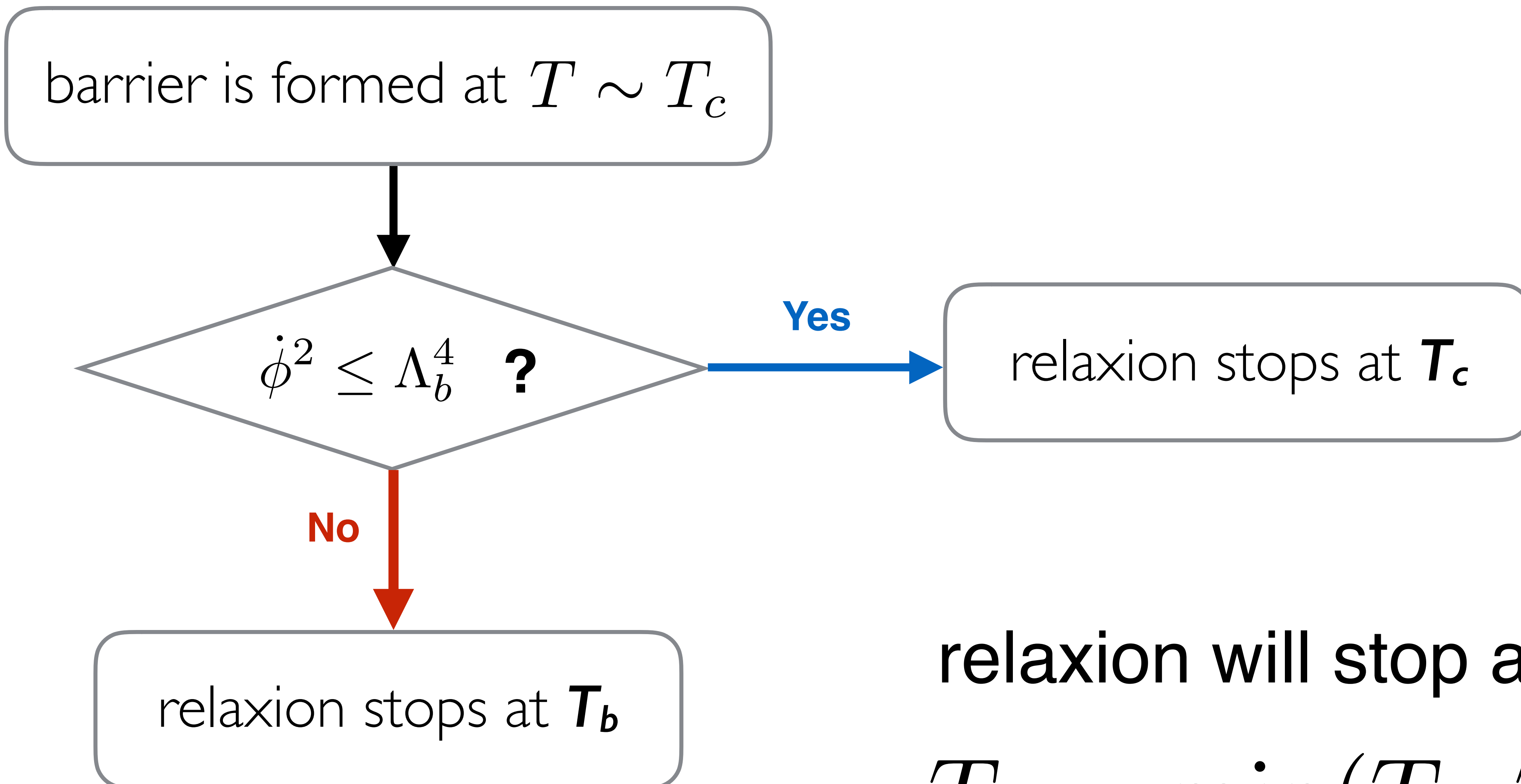
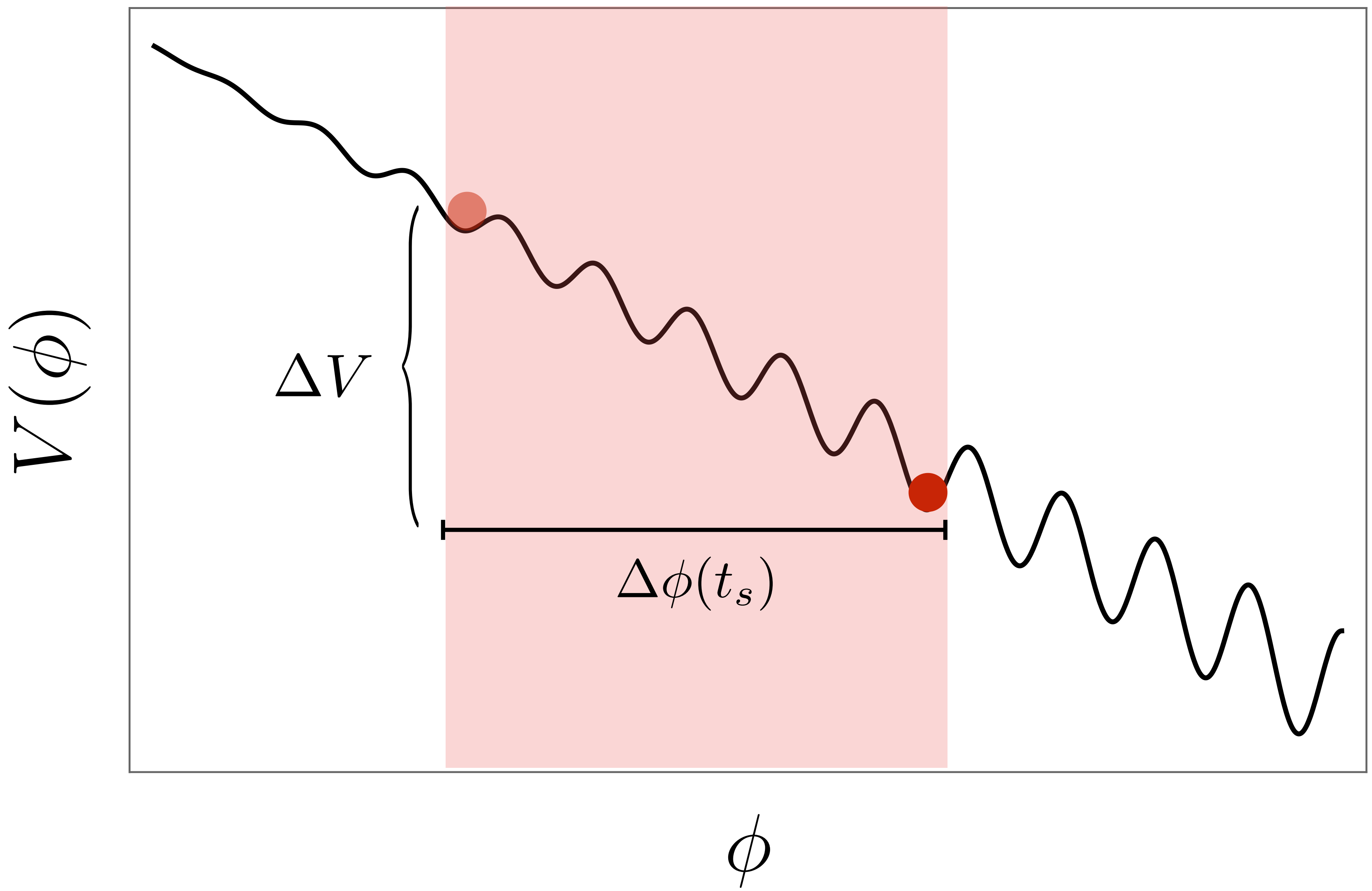


$*$ $\boldsymbol{T_b}$ *is when* $\dot{\phi}^2(T_b) \sim \Lambda_b^4$

relaxion will stop at

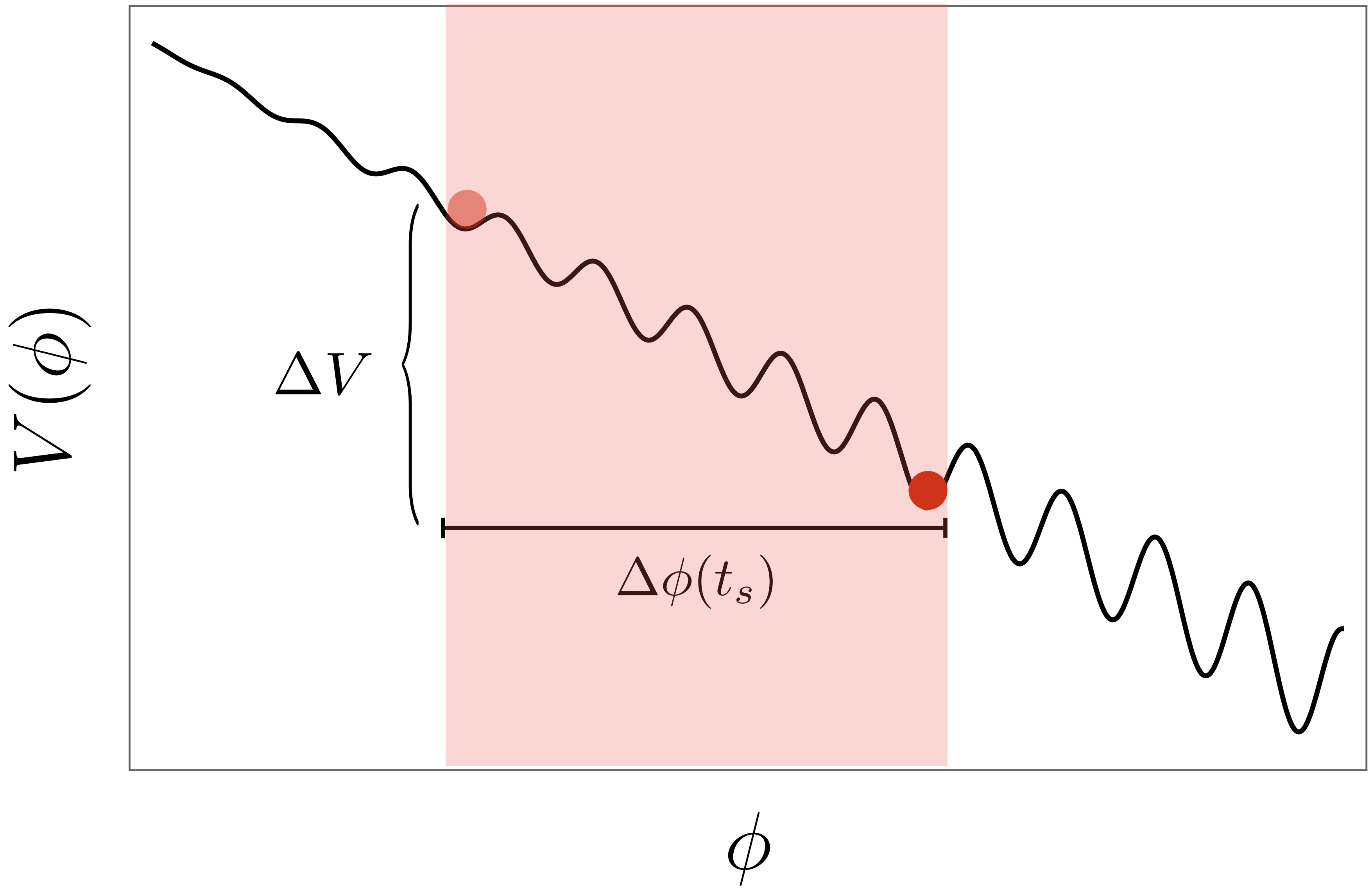
$$T_s = \min(T_c, T_b)$$

To preserve successful selection of electroweak scale



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

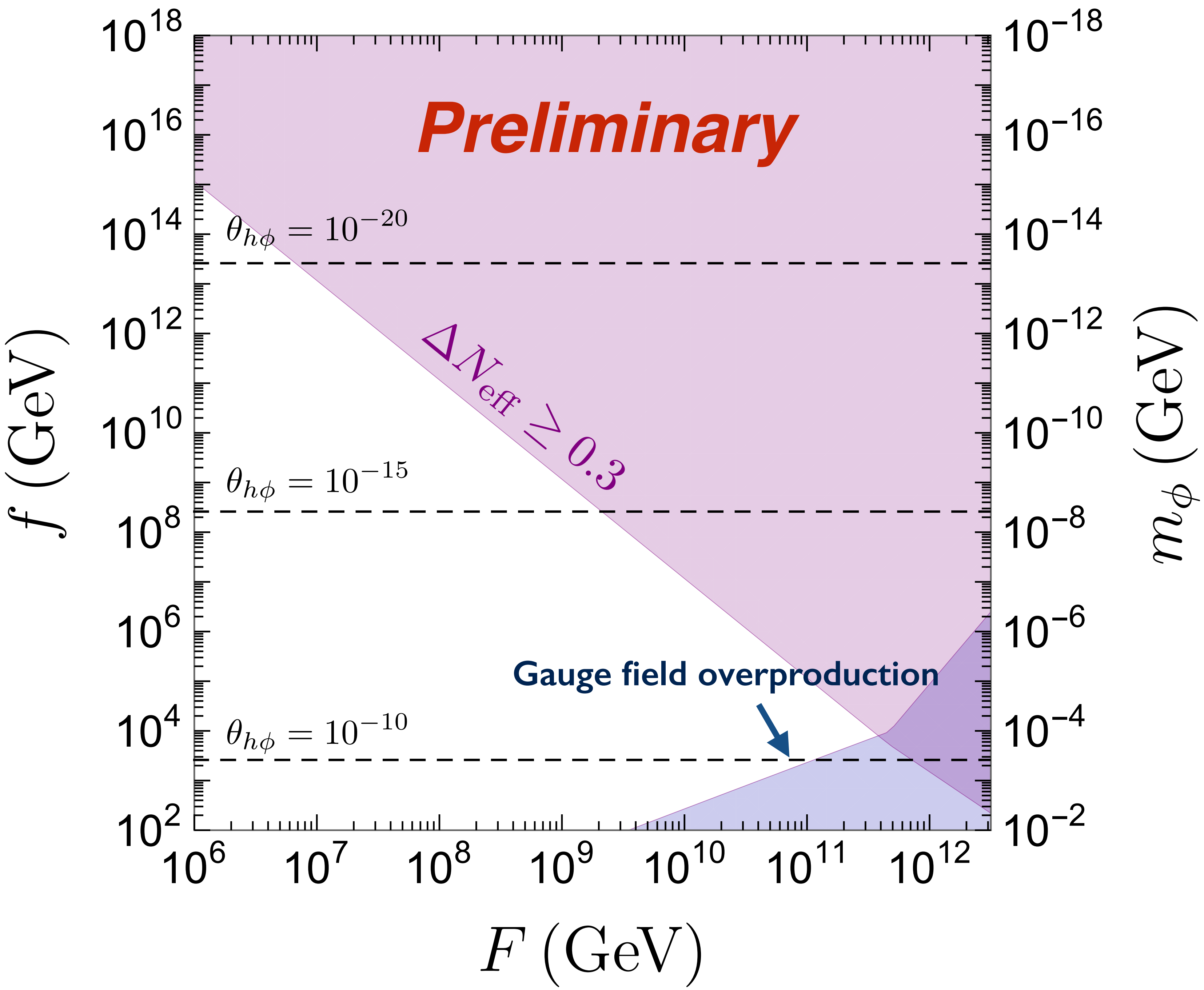
To preserve successful selection of electroweak scale



$$\boxed{\Delta V \le T_s^4} \le \Lambda^2 v^2$$

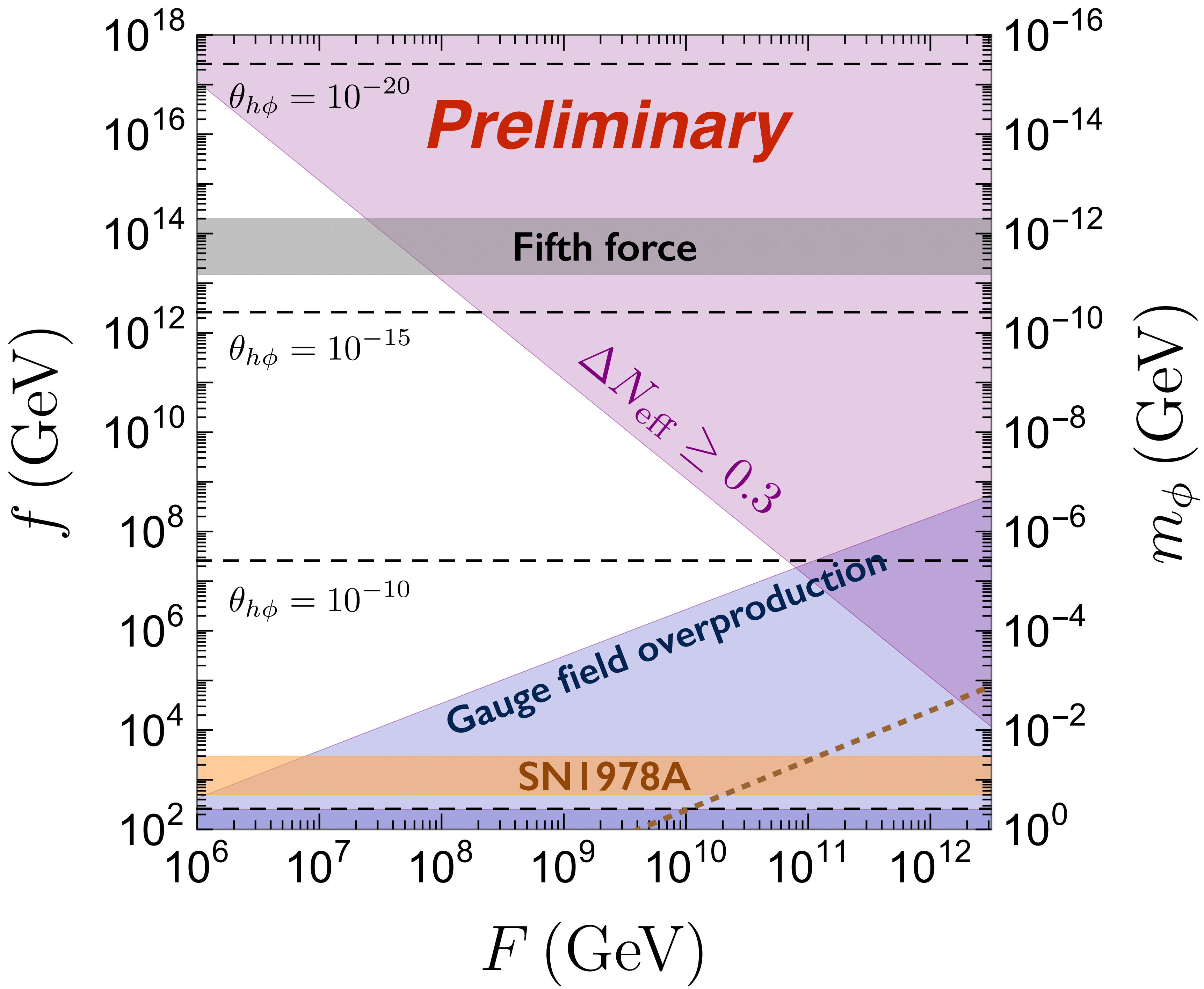
To prevent overproduction of dark gauge boson

$$\Lambda_b = 1\,\mathrm{GeV}, \quad \kappa = 0$$



[Choi, HK, Toyokazu; Work in progress]

$$\Lambda_b = 10\,\mathrm{GeV}, \quad \kappa = 0$$



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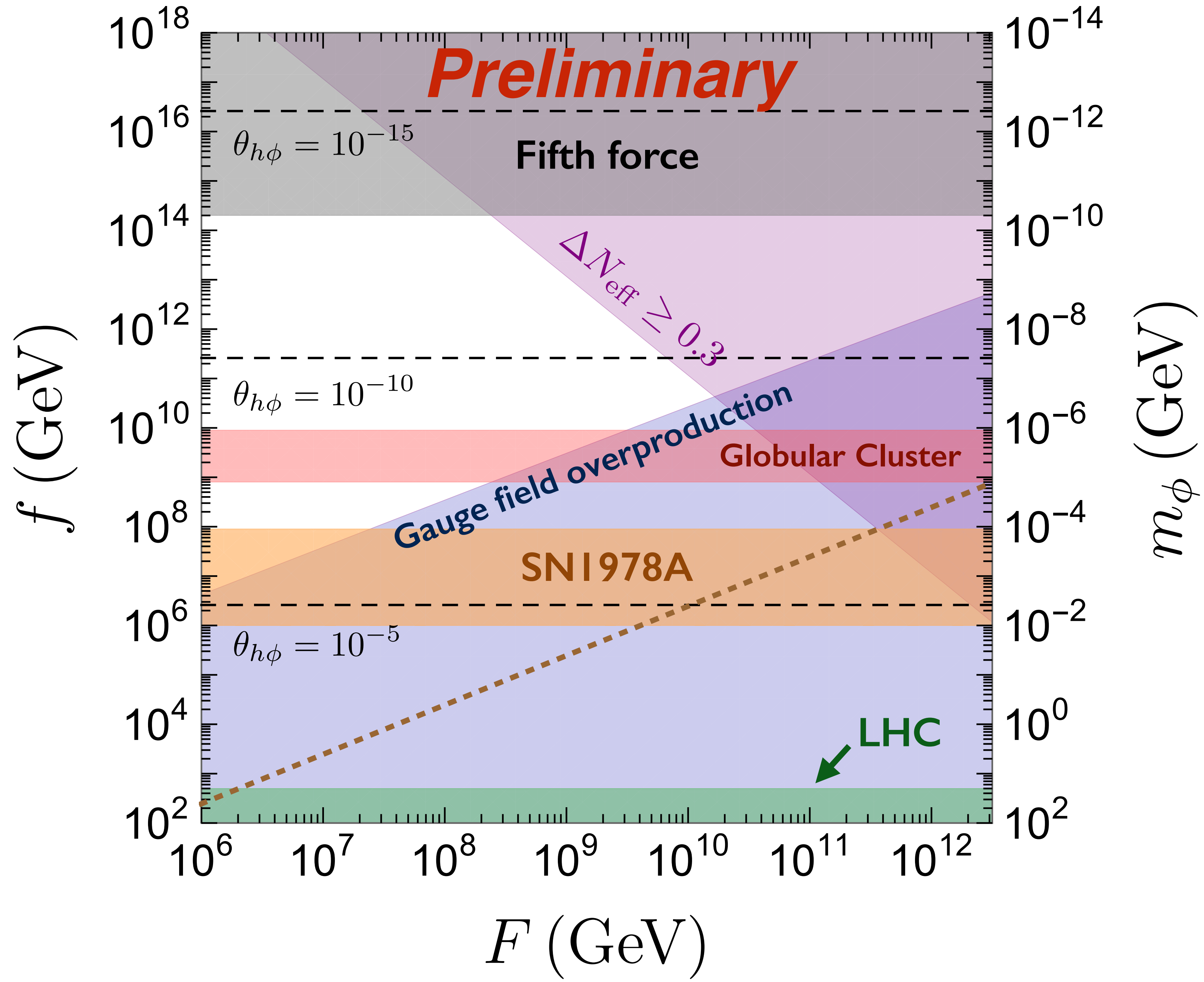

regarding constraints on relaxion scenario

[Choi & Im 16]

[Flacke et. al. 16]

Conclusion

1. High reheating temperature is dangerous for cosmological relaxation

2. If relaxion has anomalous coupling to Abelian gauge boson,

   it transfer its kinetic energy into gauge bosons

3. Field velocity approaches to terminal velocity,

4. The relaxion can be re-captured by back-reaction potential at EWPT

   under reasonable choice of parameters