Relaxation from Particle Production

Anson Hook
Stanford

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A.H. & G. Marques-Tavares

Ultra Fast Relaxion Review

$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)hh^\dagger + \epsilon\Lambda^2\phi + \frac{\phi}{f}G\tilde{G}$$

- Relaxion field scans Higgs mass during inflation
- QCD generates a cosine potential for the relaxion whose magnitude is approximately linear in H
- Choose parameters such that minima start appearing when Higgs vev is 100 GeV

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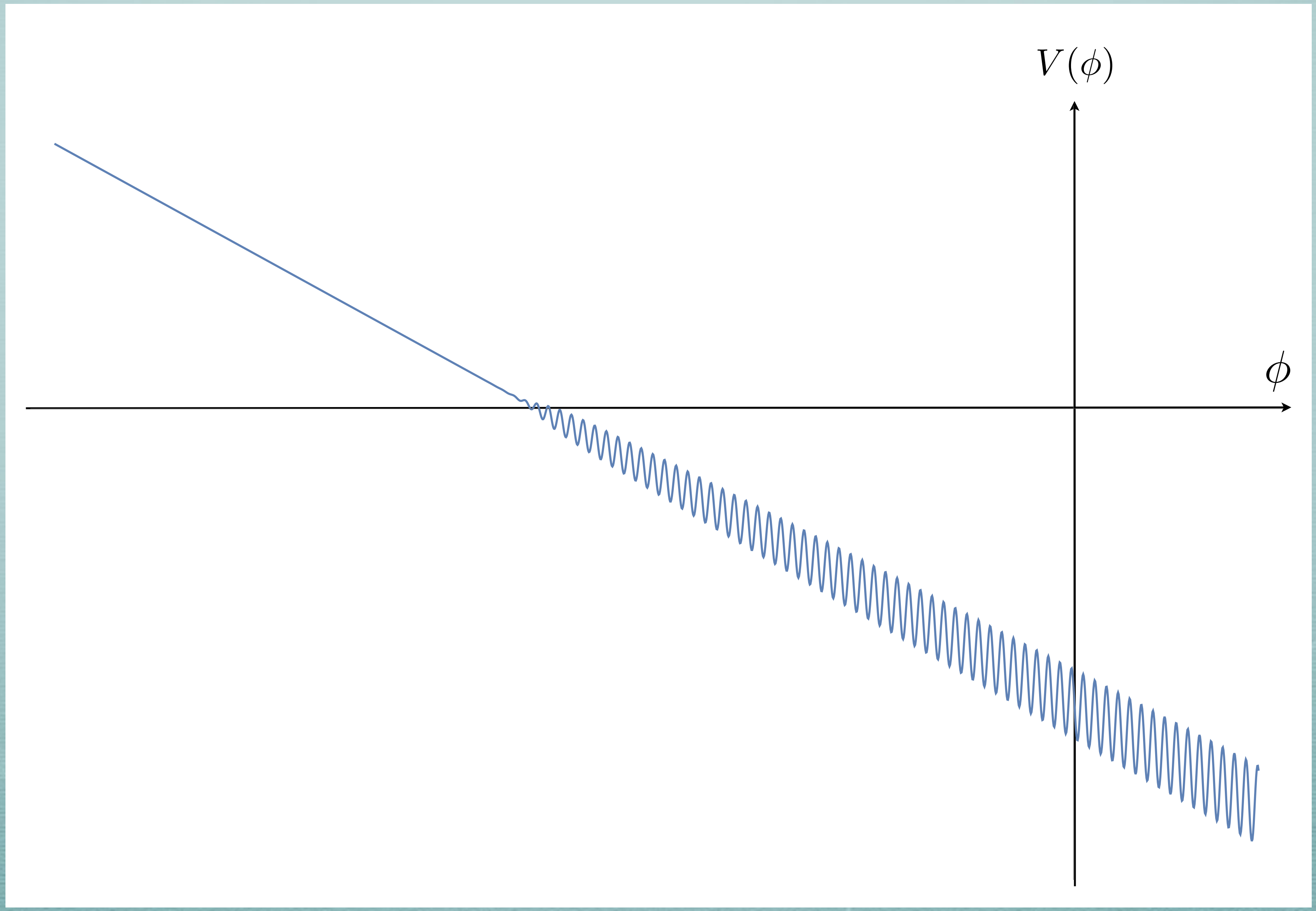


Ultra Fast Relaxion Review

- Relaxion has generated much controversy
- Many aesthetically (theoretically?) unappealing aspects
  - Super Planckian field excursions
  - Large Monodromy
  - Low scale inflaton
  - Large amount of inflation
  - … (c.c./why early time rather than late time)

Downsides

$$\Lambda \sim 10^7 \,\mathrm{GeV}$$

- Field excursions of relaxion are extremely super Planckian

$$\Delta\phi \sim \frac{\Lambda^2}{\epsilon} \sim 10^{22} M_p$$

- Super Planckian periodicity theoretically suspect
  - Giddings and Strominger showed gravitational instantons exist whose actions scale as Mp/period
  - Inherently untestable

. S. B. Giddings and A. Strominger, Nucl. Phys. B306, 890 (1988)

Downsides

- Super large number of e-foldings of inflation

$$N_e \gtrsim \frac{H^2}{\epsilon^2} \sim 10^{44}$$

- Requiring that you stop

$$N_e \gtrsim \frac{\Lambda^4}{m_\pi^2 f_\pi^2}$$

Downsides

$$N_e \lesssim \frac{M_p^2}{H^2} \sim 10^{44}$$

- If number of e-foldings is too large inflaton sector is automatically eternally inflating

$$n_s - 1 \sim 1/N_e$$

. N. Arkani-Hamed, S. Dubovsky, A. Nicolis, E. Trincherini, and G. Villadoro, JHEP 05, 055 (2007), 0704.1814

Downsides

- Small scale inflation

$$H \sim \frac{\Lambda^2}{M_p} \sim 10^{-4}\,\mathrm{GeV}$$

- Model building is difficult
  - Tends to be fairly fine tuned
  - Hard to reproduce density perturbations

Relaxion

- Have a minima with the correct Higgs vev
  - Large monodromy
- Select 100 GeV
- Friction
  - Inflation
  - This is why most of the downsides emerge

Relaxion

- Have a minima with the correct Higgs vev
  - Large monodromy
- Select 100 GeV
- Friction

Relaxion in the infinite Mp limit

  - Inflation
  - This is why most of the downsides emerge

Relaxation with Particle Production

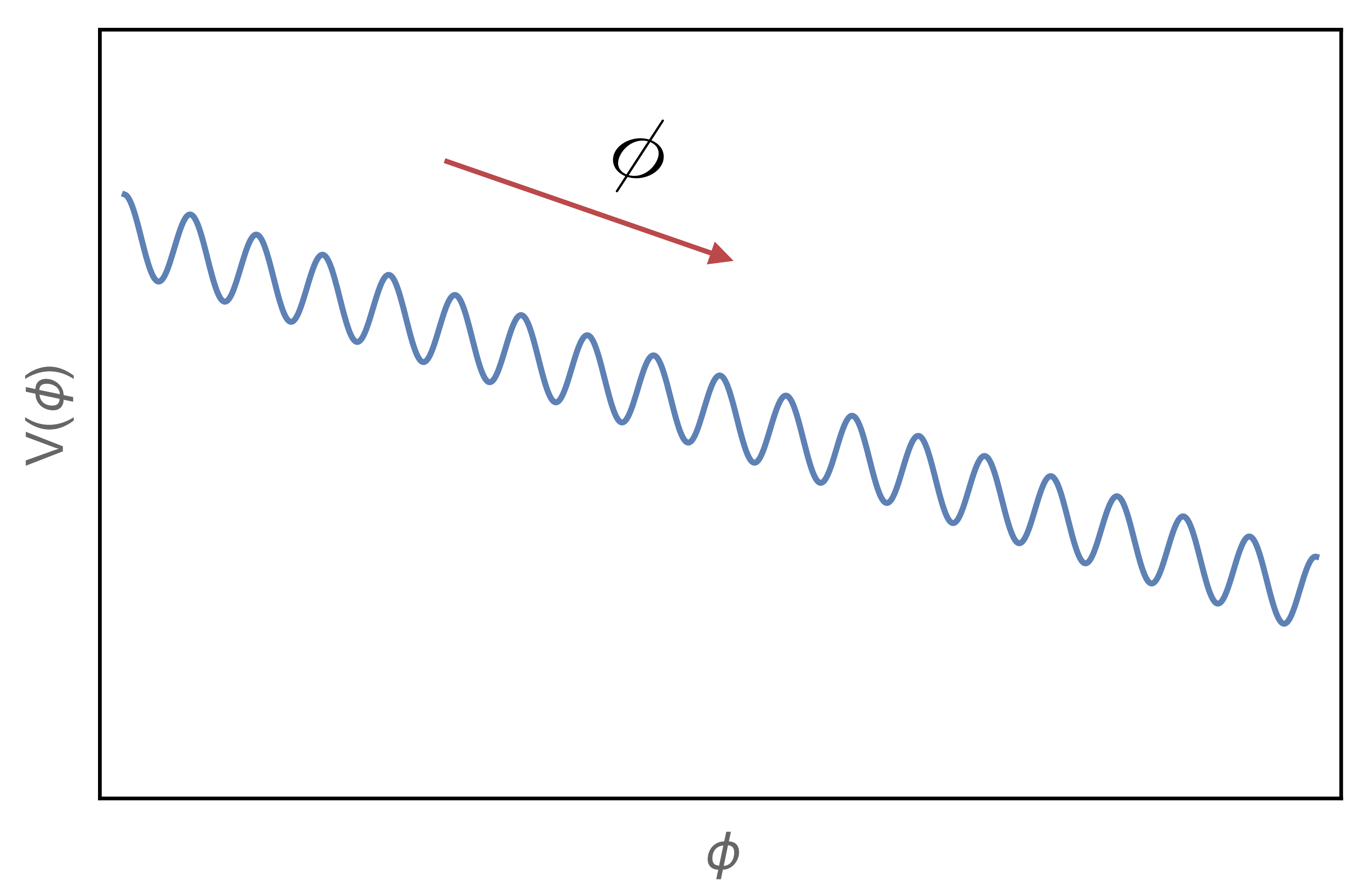
$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)hh^\dagger + \epsilon\Lambda^2\phi + \frac{\phi}{f}G\tilde{G}$$

$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)hh^\dagger + \epsilon\Lambda^2\phi + \frac{\phi}{f}(W\tilde{W} - B\tilde{B}) + \Lambda_c^4 \cos\frac{\phi}{f'}$$

Removes all previous problems!

Relaxation with Particle Production

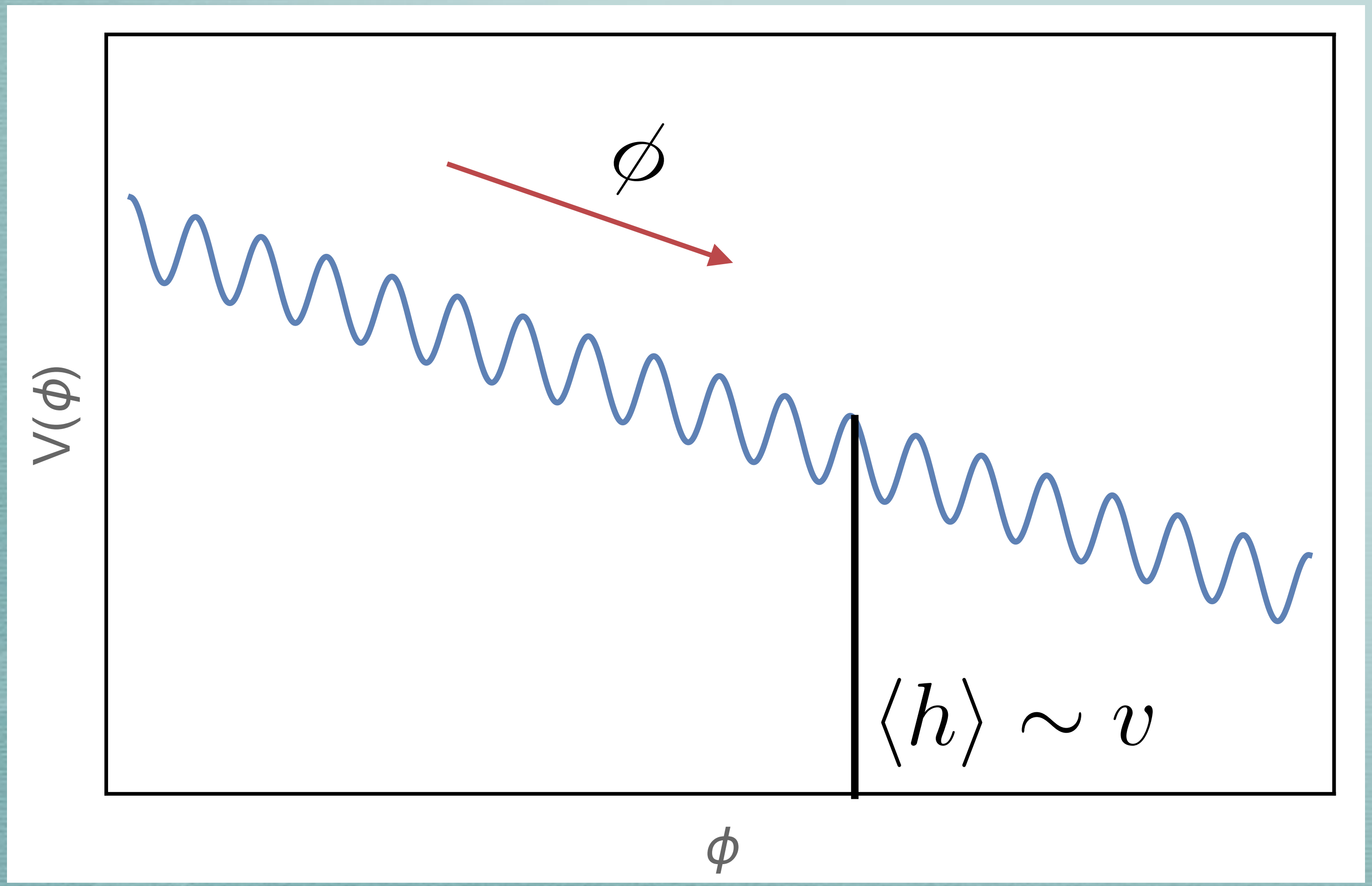
$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)hh^\dagger + \epsilon\Lambda^2\phi + \frac{\phi}{f}(W\tilde{W} - B\tilde{B}) + \Lambda_c^4 \cos\frac{\phi}{f'}$$



Initially relaxion has enough kinetic energy to fly over Higgs independent bumps

Relaxation with Particle Production

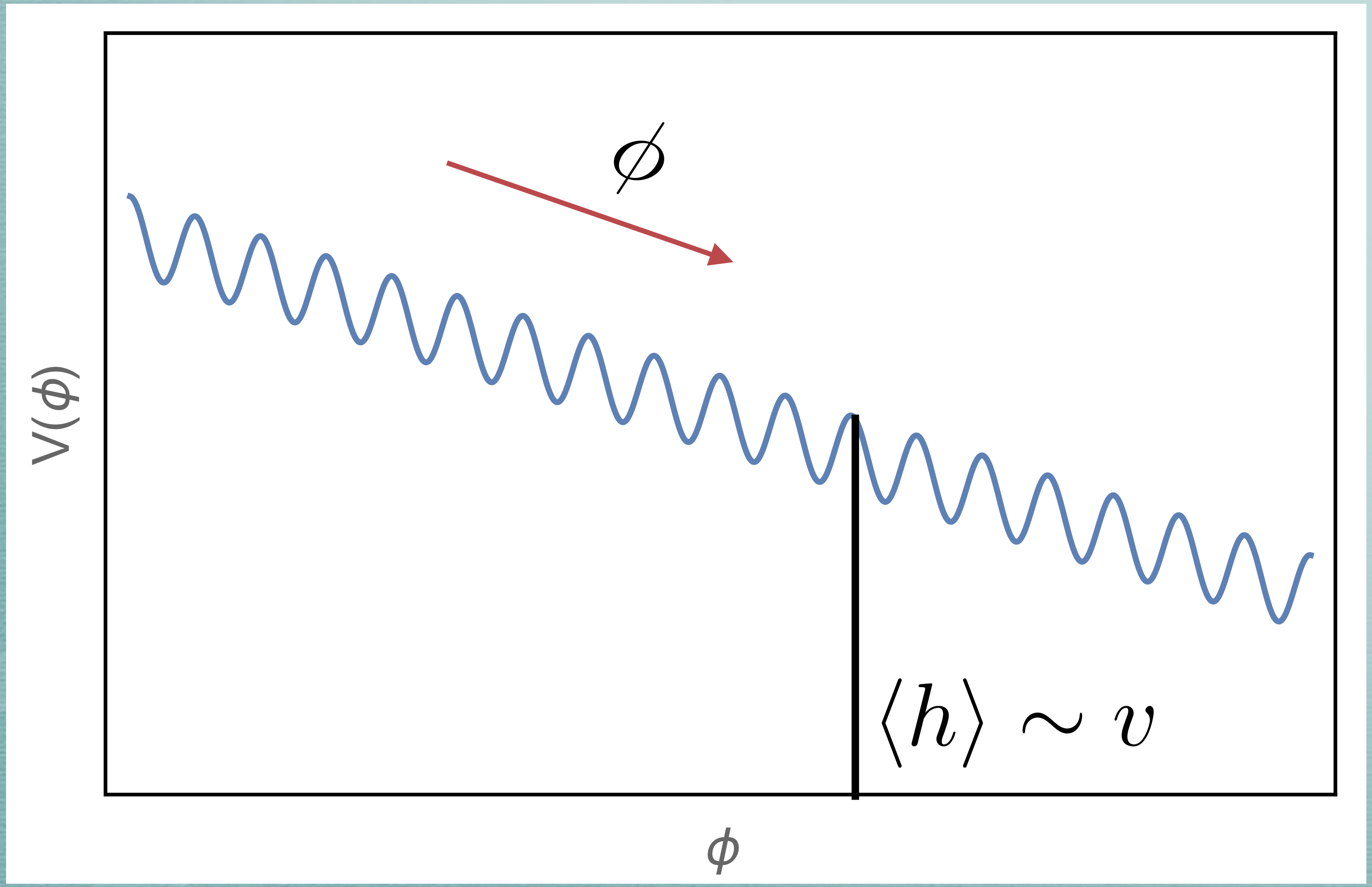
$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi) h h^\dagger + \epsilon \Lambda^2 \phi + \frac{\phi}{f}(W\tilde{W} - B\tilde{B}) + \Lambda_c^4 \cos\frac{\phi}{f'}$$



When h ~ v exponential production of electroweak gauge bosons occurs

Relaxation with Particle Production

$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)hh^\dagger + \epsilon\Lambda^2\phi + \frac{\phi}{f}(W\tilde{W} - B\tilde{B}) + \Lambda_c^4 \cos\frac{\phi}{f'}$$



Can happen before/during/after inflation

Particle Production

$$\mathcal{L} \supset -\frac{\phi}{4f} F\tilde{F}$$

- Consider an axion-like coupling
- Gauge boson equation of motion

$$\ddot{A}_\pm + (k^2 + m_A^2 \pm \frac{k\dot{\phi}}{f}) A_\pm = 0 \qquad |\dot{\phi}| \gtrsim 2 f m_A$$

- A tachyon for one of the transverse polarizations of the gauge boson!

Particle Production

$$\mathcal{L} \supset -\frac{\phi}{4f} F\tilde{F}$$

- Time scale for particle production is inverse tachyon frequency

$$t \sim \frac{f}{\dot{\phi}} \qquad \frac{\dot{\phi}}{f} \gtrsim m_A$$

Particle Production

- Particle production gives a thermal bath
- Repeat calculation at finite temperature
    - Use finite temperature self energy

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

$$\Pi_t(\omega, k) \approx \Pi_t(0, k) + \frac{\partial \Pi_t}{\partial \omega}(0, k)\omega + \cdots$$

- In order for there to be a tachyon, first term must vanish. i.e. no mass term

Particle Production

$$\Pi_t(\omega, k) \approx \Pi_t(0, k) + \frac{\partial \Pi_t}{\partial \omega}(0, k)\omega + \cdots$$

- First term is called magnetic mass
    - Unlike Debye mass, NOT a mass term!
- Vanishes for U(1) gauge fields
    - Solve gap equation : m = 0 consistent solution
    - Experimentally verified

Particle Production

$$\Pi_t(\omega, k) \approx \Pi_t(0, k) + \frac{\partial \Pi_t}{\partial \omega}(0, k)\omega + \cdots$$

- Non-zero for non-abelian gauge fields
  - Results from quartic couplings of gauge bosons
  - Perturbation theory fails if it doesn't exist
  - Existence confirmed via lattice
- Particle production occurs at finite T only for couplings to U(1) gauge fields

Particle Production

$$w^2 - k^2 \pm \frac{k\dot{\phi}}{f} = \frac{m_D^2}{2}\frac{w}{k}\left[\frac{1}{2}(1 - \frac{w^2}{k^2})\log\left(\frac{w+k}{w-k}\right) + \frac{w}{k}\right]$$

$$\approx \frac{|i\pi w| m_D^2}{4k}$$

- Written in terms of gauge fields, this is literally Ohm's law
  - 1-loop calculation of the conductivity
- Time scale associated with tachyon slower

$$t \sim \frac{f}{\dot{\phi}}\left(\frac{f m_D}{\dot{\phi}}\right)^2$$

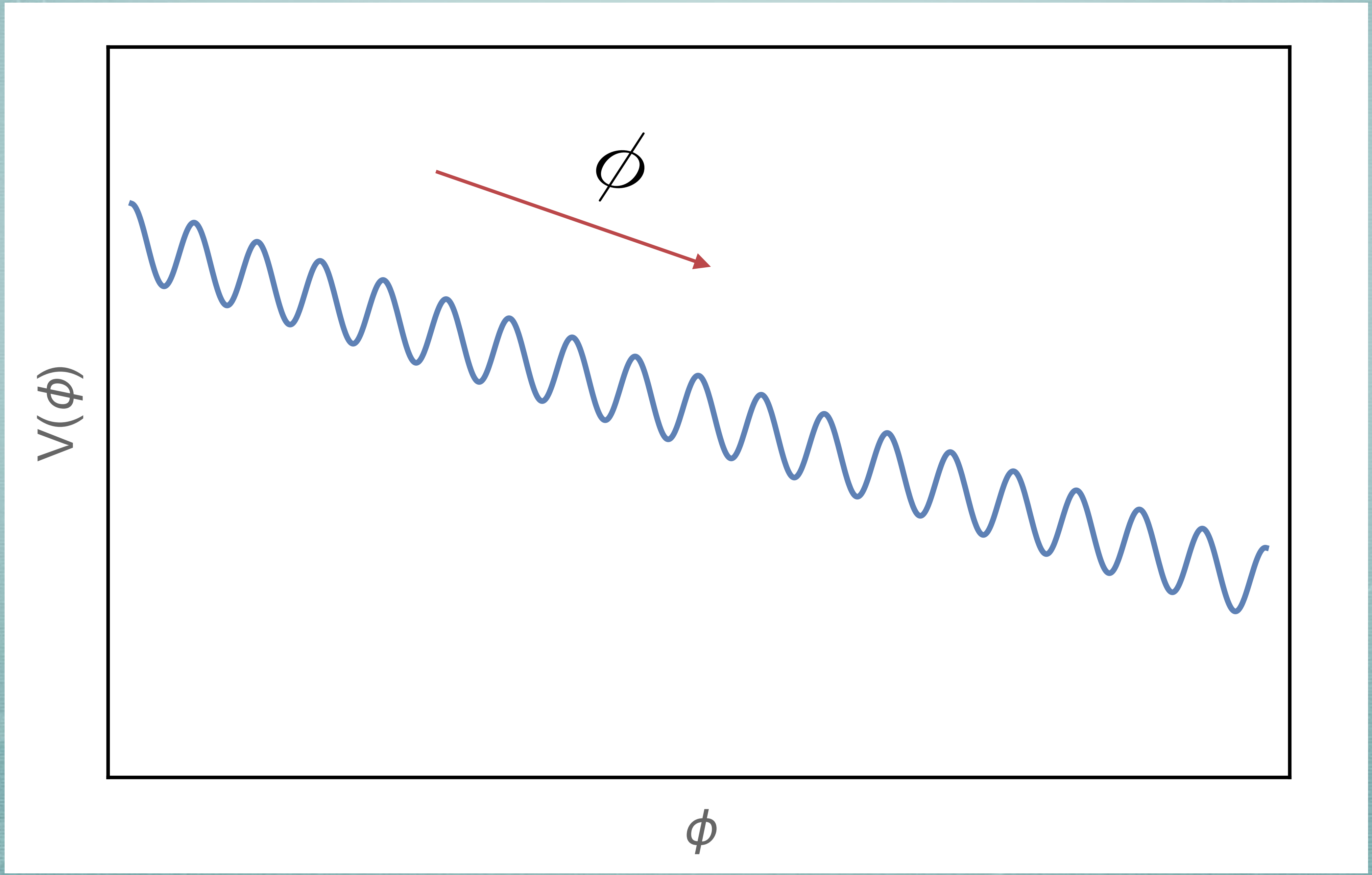
During Inflation

	Λ	H	ϵ	N_e	f	f'	Λ_c
Values in GeV	10^5	10^{-5}	10^{-6}	10^2	3×10^6	10^9	1.5×10^4

$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)hh^\dagger + \epsilon\Lambda^2\phi + \frac{\phi}{f}(W\tilde{W} - B\tilde{B}) + \Lambda_c^4 \cos\frac{\phi}{f'}$$

- Start in the attractive slow roll solution
- Higgs mass is large and negative

During Inflation



During Inflation

$$\dot{\phi} \sim \frac{\epsilon \Lambda^2}{3H} + \delta(t)$$

- Dimensional analysis
  - Small high frequency bumps cannot disrupt slow roll
- There still exists a pseudo slow roll attractive solution

During Inflation

- Attractive slow roll solution exists when
  - Slow roll velocity has enough kinetic energy to go over the bumps $$\frac{\epsilon\Lambda^2}{3H} \gtrsim \Lambda_c^2$$
  - Time scale to go over a bump fast compared to Hubble so they can be averaged away $$H < \sqrt{\frac{\epsilon\Lambda^2}{f'}}$$
  - Second weaker than first due to the requirement that minima exist

During Inflation

- Slow roll until Particle production kicks in

$$100\,\mathrm{GeV} \sim \frac{\dot{\phi}}{f} \lesssim m_W \lesssim v$$

- Zero temperature Higgs mass is the correct measured value
- As gauge bosons are produced, finite temperature/density effects decrease their mass

During Inflation

$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi)hh^\dagger + \epsilon\Lambda^2\phi + \frac{\phi}{f}(W\tilde{W} - B\tilde{B}) + \Lambda_c^4 \cos\frac{\phi}{f'}$$

- Exponential production occurs until relaxion has lost enough kinetic energy that it is stuck
- T = 0
  - EW gauge bosons produced
  - No couplings to photon
- T ≠ 0
  - B gauge boson being exponentially produced

Constraints

- Particle production happens much faster than Hubble
- Hubble < v
- Classical beats quantum
- Higgs mass does not change much in the time it takes for relaxion to get stuck
- SM fermion particle production from changing Higgs vev
- Higgs tracks minimum efficiently
- ...

During Inflation

	Λ	H	ϵ	N_e	f	f'	Λ_c
Values in GeV	10^5	10^{-5}	10^{-6}	10^2	3×10^6	10^9	1.5×10^4

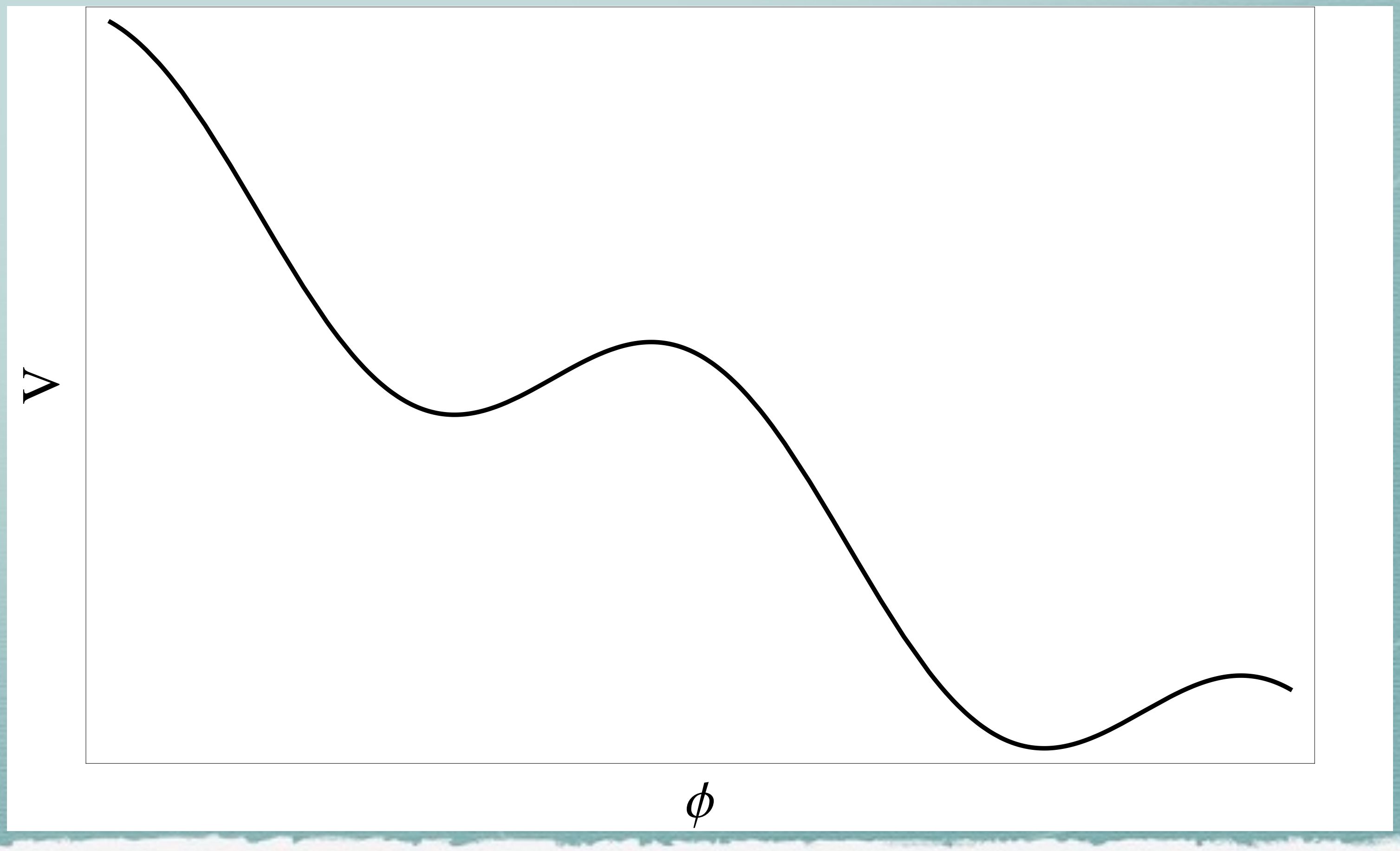
- Can satisfy all constraints
- Field excursion sub Planckian
- Number of e-folds small
- Hubble is still small

After Inflation

- Generic initial conditions after inflation
  - Relaxion at a random point in the potential
  - Relaxion at rest (slow roll)
  - $T = 0$
  - Energy in matter (inflaton) or dark radiation (inflaton decay product)

After Inflation

- Scanning of Higgs mass requires that relaxion does not get stuck in a minimum in the early universe
  - Exit inflation with pseudo-slow roll initial conditions
  - Coincidence of scales



After Inflation

- After inflation, sitting at a random point in the potential
- H ~ ϵ then the relaxion is able to scan O(1) of field space
- Only operational difference between during and after inflation is the speed

$$\dot{\phi} \sim \frac{\epsilon \Lambda^2}{H} \qquad \dot{\phi} \sim \Lambda^2$$

After Inflation

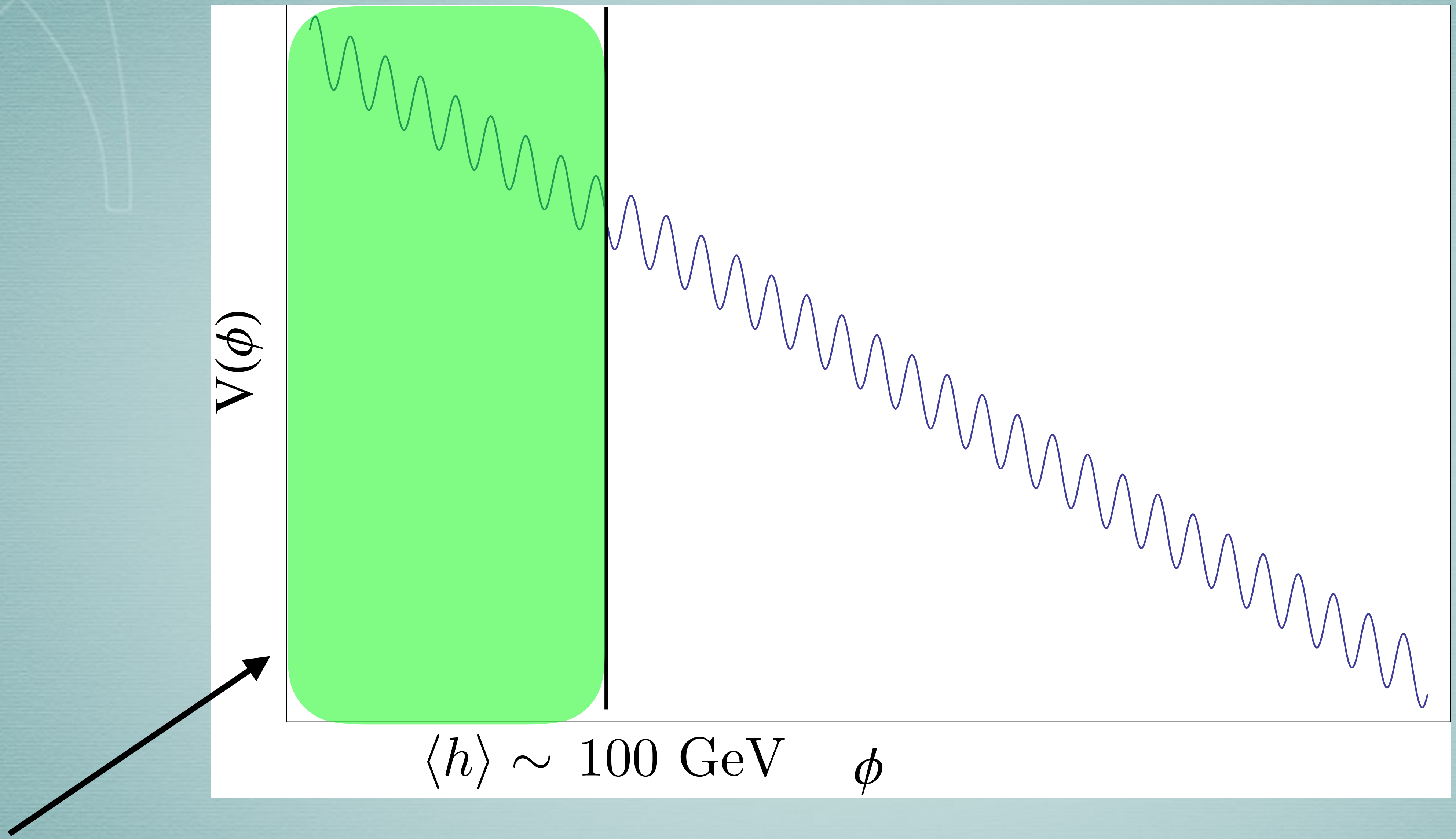
	Λ	ϵ	f	f'	Λ_c
Values in GeV	10^4	10^{-10}	10^6	10^{14}	10^3

- As this happens after inflation, completely insensitive to details of inflation
- High scale inflation allowed
- Arbitrary number of e-folds
- Sub-Planckian field excursions
- SM reheated by relaxion particle production

After Inflation

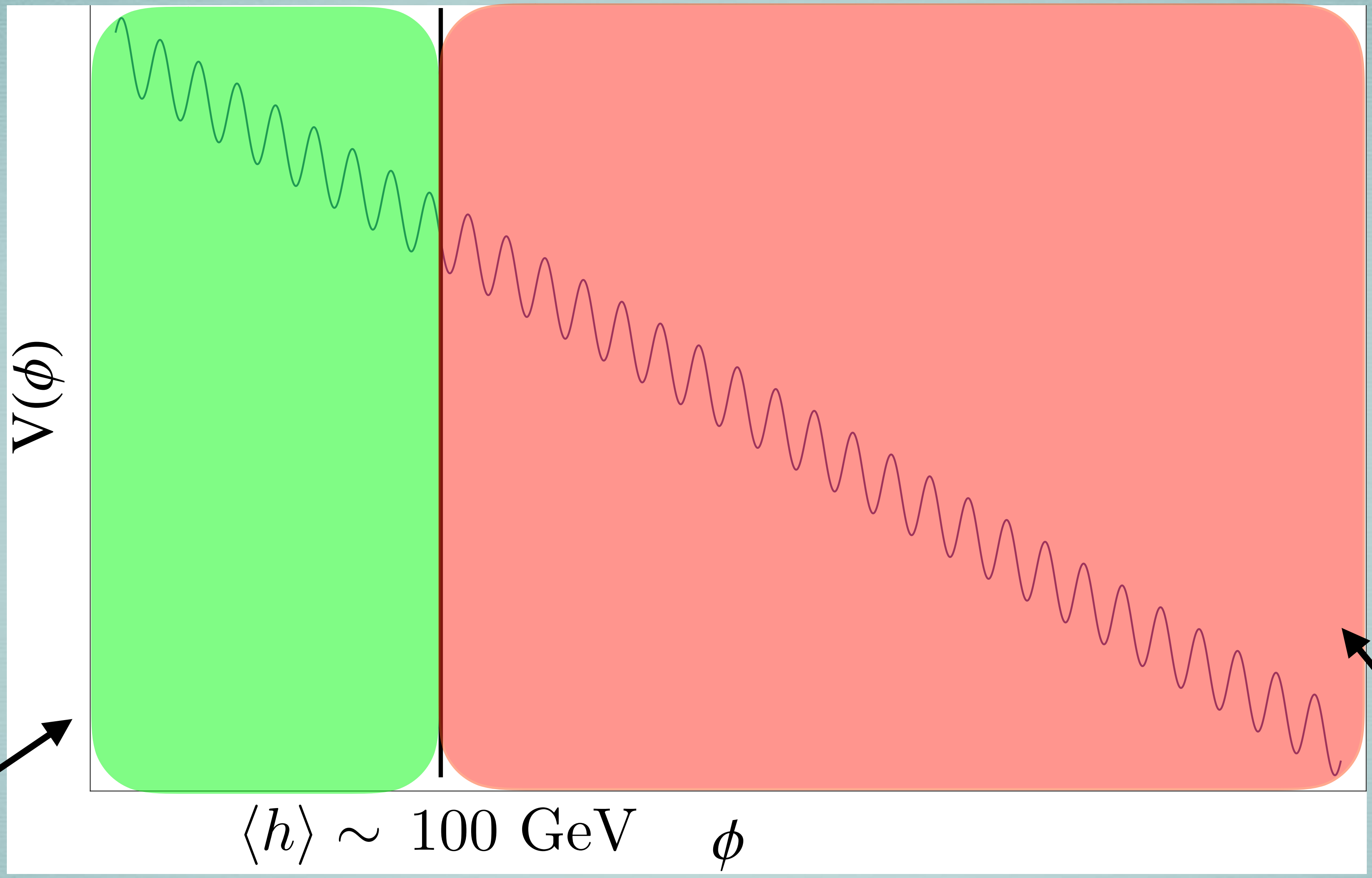
$\langle h \rangle \sim 100 \text{ GeV}$

After Inflation



- Higgs mass evolves to 100 GeV
- SM reheated by relaxion

After Inflation



- Higgs mass evolves to 100 GeV
- SM reheated by relaxion

- Higgs mass squared larger than -100^2 GeV
- Relaxion stops right away
- Much lower reheat temperature

Three interpretations

- If Higgs vev 100 GeV, reheat temperature much larger than if Higgs vev is not 100 GeV
    - Put Baryogenesis, Dark Matter … in between these two temperatures
- Three interpretations of the same model!

Three interpretations

- Relaxion approach
  - Initial conditions after inflation result in a large number of initial conditions giving the correct Higgs vev
  - Attractor solution
  - Makes things better by an amount that depends on your bias towards initial conditions

Three interpretations

- Anthropic approach
  - Reheating/Baryogenesis/Dark matter tied to Higgs vev
  - Presence of matter necessary for any anthropic arguments : Thus Higgs vev is 100 GeV

Three interpretations

$$P(\langle h \rangle = 100\,\mathrm{GeV}|\mathrm{matter\ existing}) = 1$$

- Conditional approach
  - Observed fact : Baryogenesis/Dark matter/Reheating has occurred
  - Higgs vev being 100 GeV is not a surprise
- Initially two question
  - Why is Higgs vev 100 GeV? Why is the universe reheated?
- After model, one question
  - Why is the universe reheated?

Conclusion

- Relaxion mechanism can be implemented completely separately from inflation
  - Solves several of the theoretically annoying issues
  - Super Planckian field excursions
  - Small Hubble
  - Huge amounts of inflation
- Reheating tied with obtaining correct Higgs vev
- Multiple conceptually different interpretations of the same model