RELAXION: A LANDSCAPE WITHOUT ANTHROPICS

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Nelson & CPW, Phys Rev D 96, 113007
arXiv: 1708.00010

Final takeaway:

The **relaxion** can solve Strong CP, dark matter, and electroweak hierarchy problems — if you take its temperature (into account).

Where Axions Come From

- Term can be added to QCD Lagrangian that break CP symmetry

$$-\frac{n_f g^2 \theta}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- No reason a priori this term should be zero
- Solvable by introducing Peccei-Quinn mechanism
- Side effect: the low mass pseudo Nambu-Goldstone boson, **the axion**

Cosmological Axion

$$V(\phi) = \Lambda^4(1 - cos(\phi/f_a))$$

Axion potential

The QCD scale ~ 0.1 GeV

The symmetry breaking scale/ axion decay constant

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

$m = \Lambda^2/f_a$

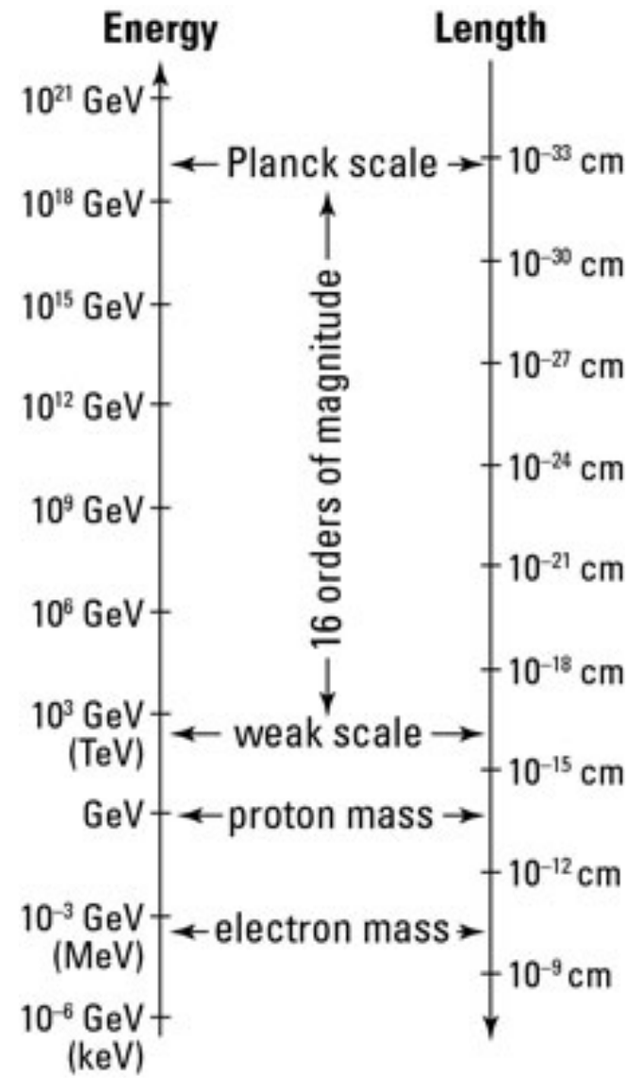
$\lambda = -\Lambda^4/f_a^4 < 0$

One Particle to Rule Them All?

- **Strong CP solution?**
- **Dark matter?**
- **Solving the electroweak hierarchy problem too??**

Electroweak Hierarchy Problem

- Electroweak Scale/Higgs Mass is ~ 10^{16} times smaller than Planck scale
- Why is the Higgs mass so light?
- Fine tuning problem
- Solvable with multiverse
- And now the **relaxion** (Graham et al.)



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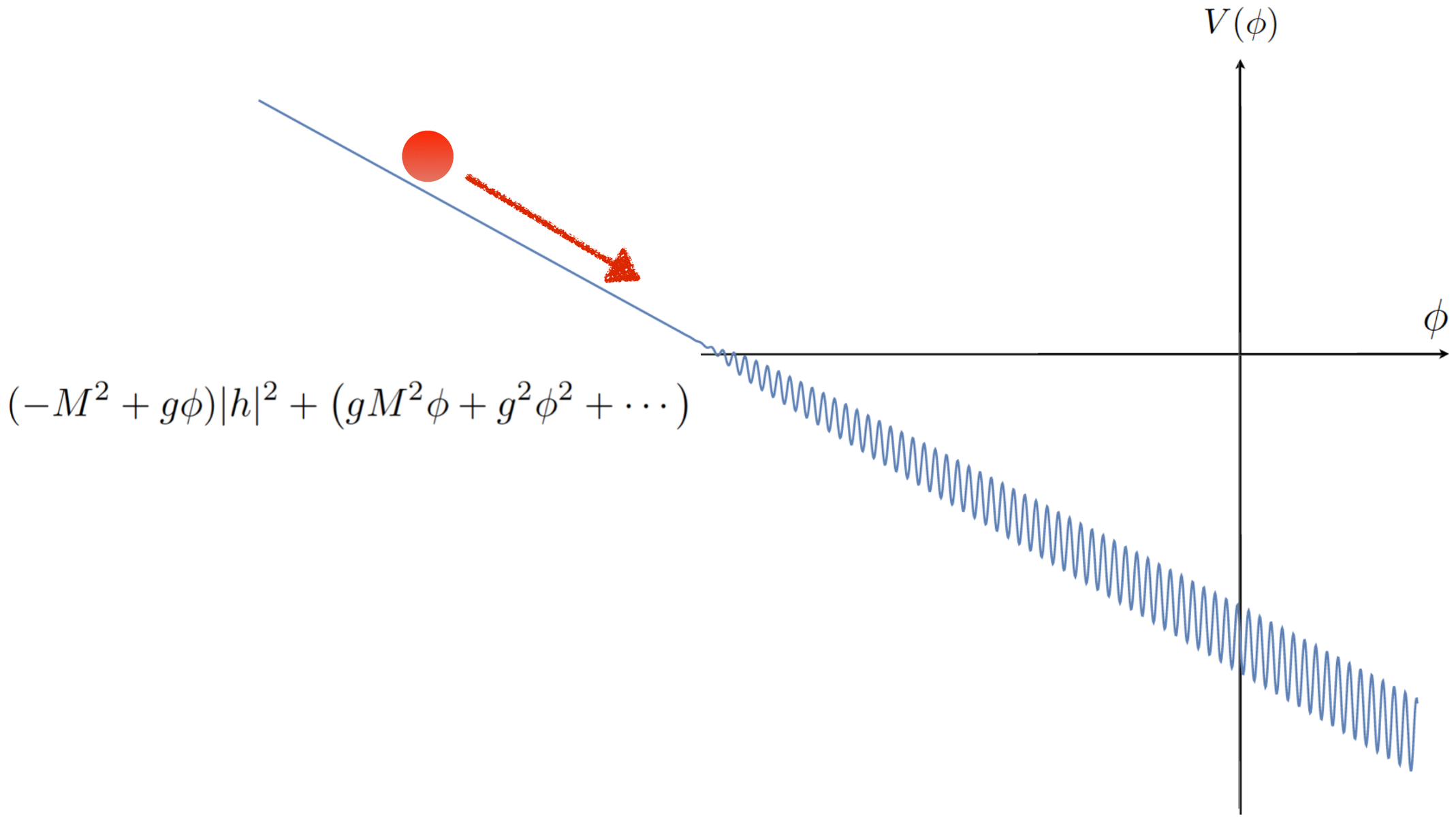
Relaxion:
Slow rolling during inflation



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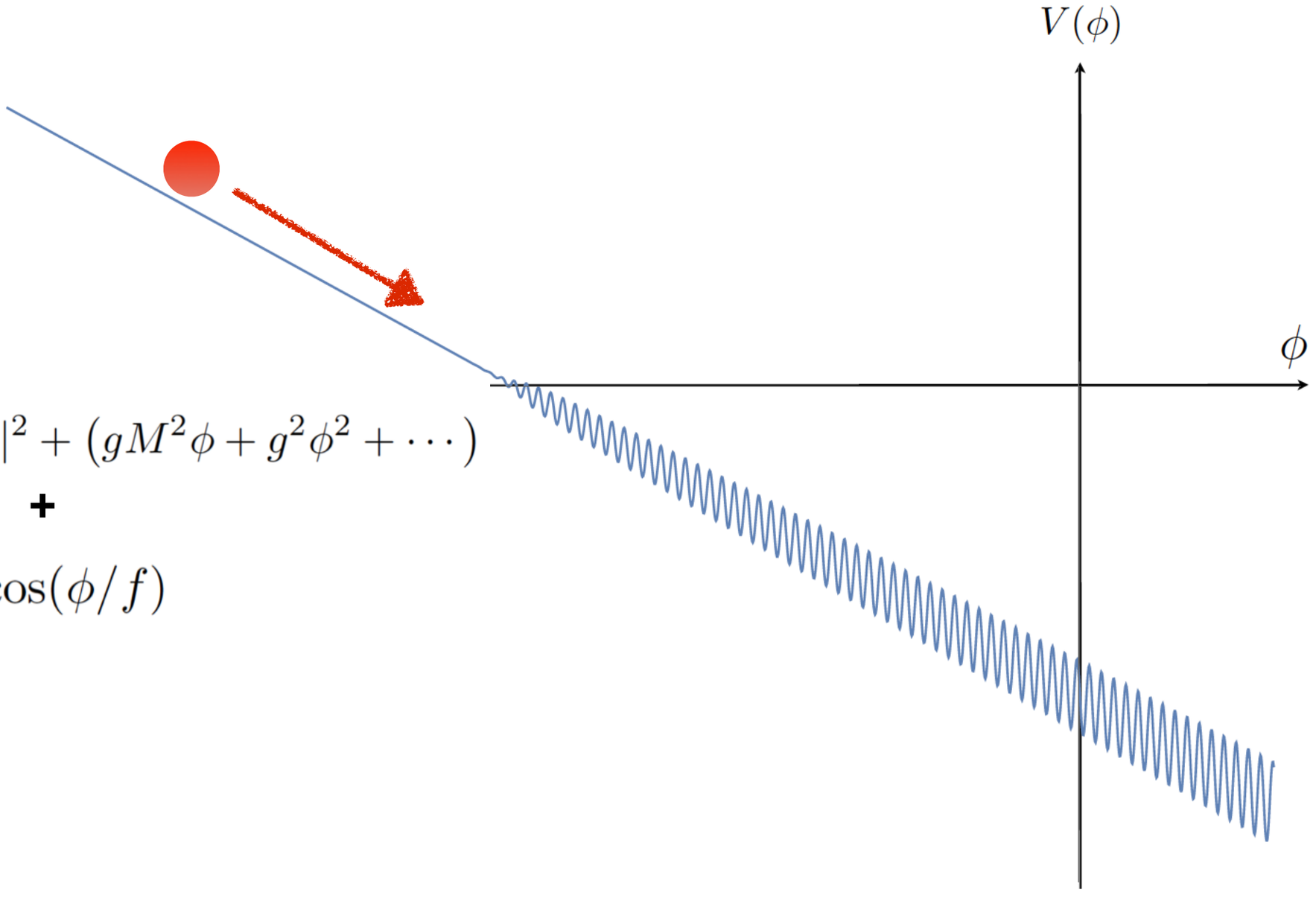

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right)$$

$$+$$

$$\Lambda^4 \cos(\phi/f)$$

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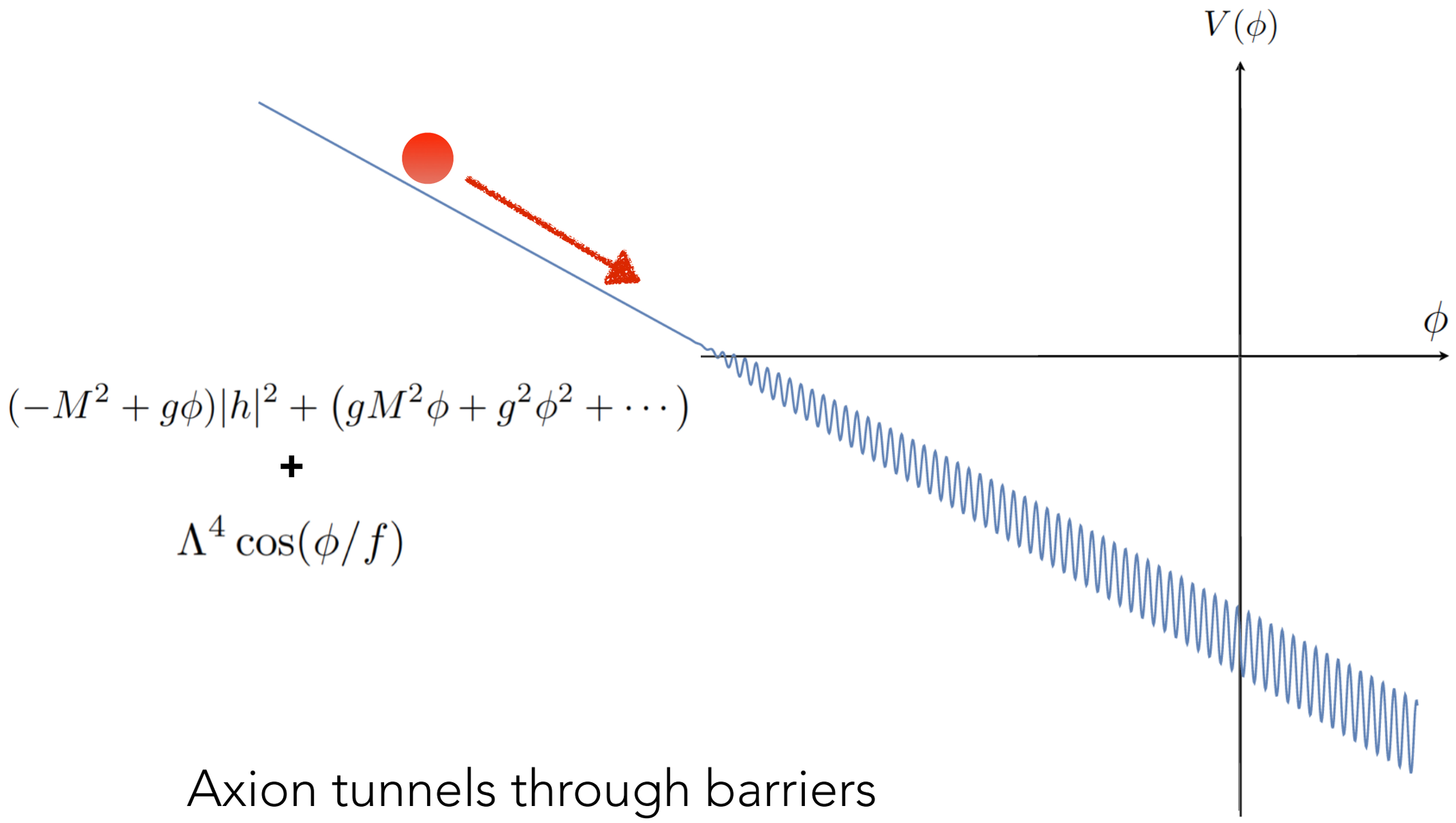

Axion tunnels through barriers
until it naturally lands at right Higgs scale

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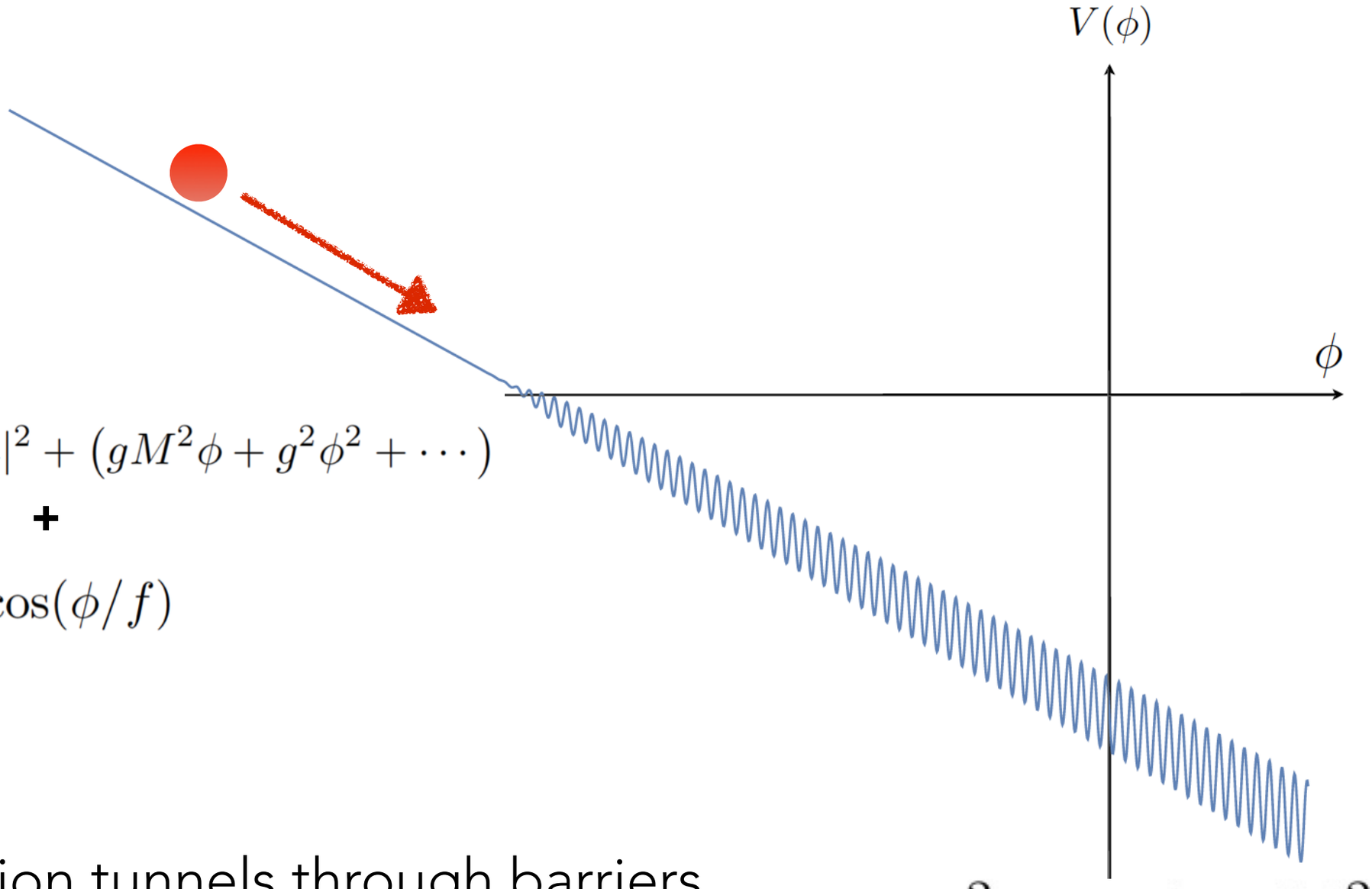

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$$\Lambda^4 \cos(\phi/f)$$

$$m_H^2 = g\phi - M^2$$

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The Relaxion

h = Higgs

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4 \cos(\phi/f)$$

$\propto v.e.v_H$

g is a spurion

cutoff scale

$$m_H^2 = g\phi - M^2$$

Constraints?

- H < Λ_{QCD} so **classical evolution dominates**
- H > $\frac{M^2}{M_{pl}}$ to prevent back reaction onto inflaton
- inflation must be long-lasting ~ 10^{50} e-folds
- the coupling *g* must be extremely small

SOLVED? PARTICLE PHYSICS PROBLEMS

- How do we solve the strong CP problem?
- What is the dark matter?
- How do we solve the hierarchy problem?

- What if we solved all three at once?
- Original relaxion mechanism **can't**.

$$- \frac{n_f g^2 \theta}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Chanda Prescod-Weinstein, Quark Dissemblement

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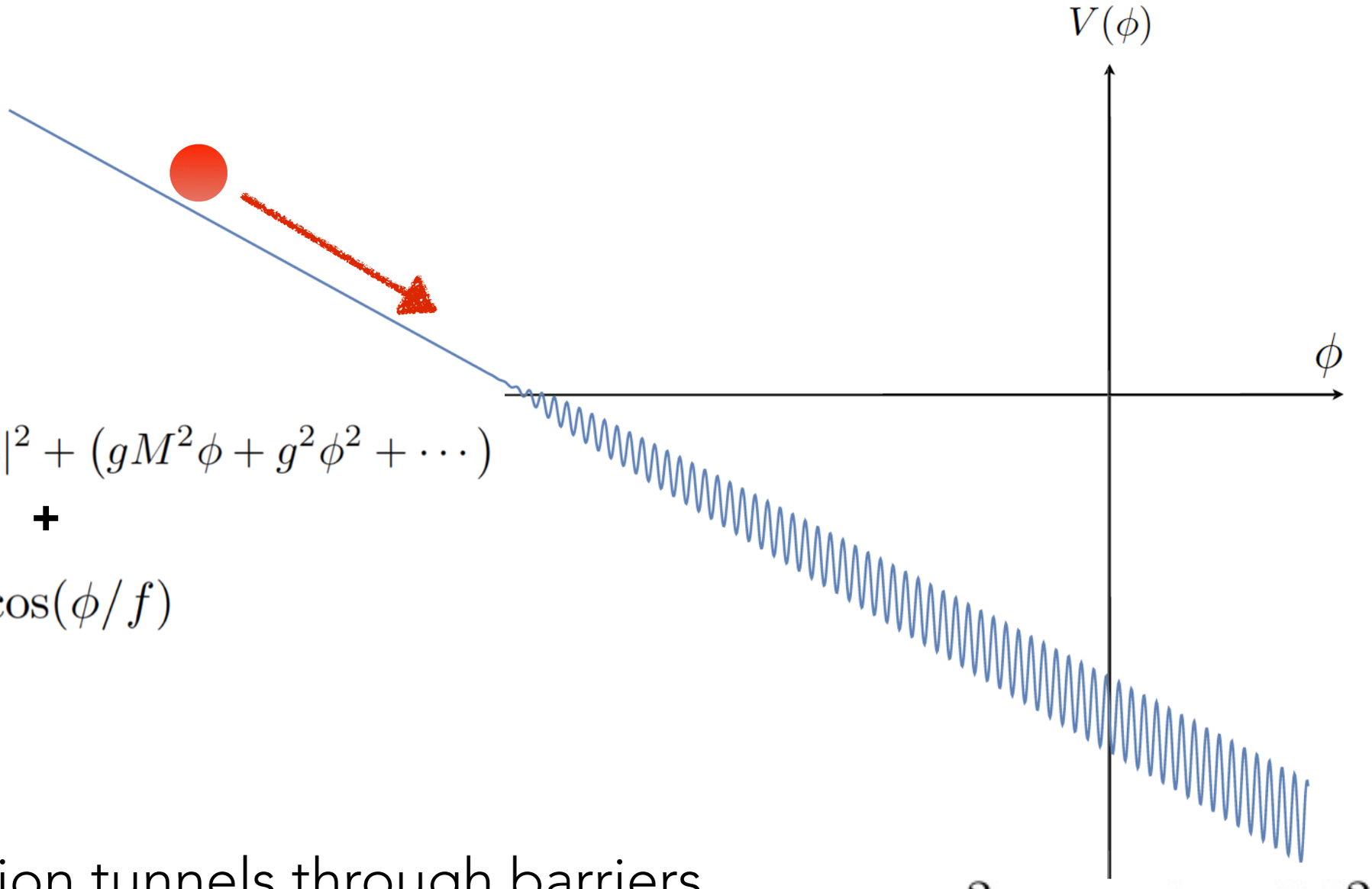

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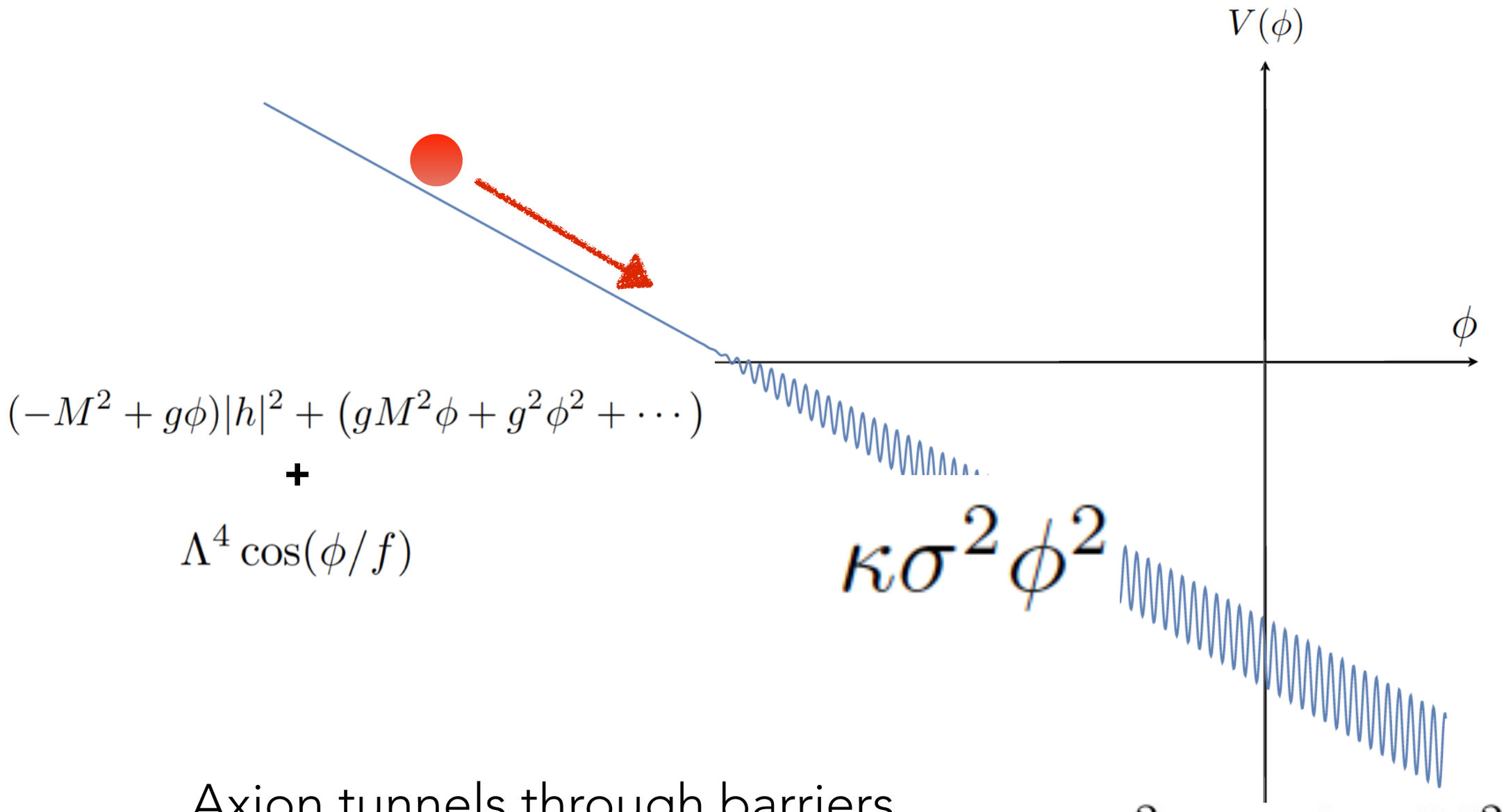

Axion tunnels through barriers
until it naturally lands at right Higgs scale

Can we achieve the same without resorting to arguments that aren't symmetry-based?

WHAT IF THE HUBBLE SCALE IS ABOVE QCD?
IS CLASSICAL EVOLUTION NECESSARY?

Chanda Prescod-Weinstein, U of Washington

A Thermal Universe

- So far, studied in zero-temperature regime
- BUT axion mass is temperature-dependent

High temperatures

$$m_\phi(T) = (2 \times 10^{-2}) \left(\frac{\lambda}{f_a}\right) \left(\frac{m_u m_d m_s}{\lambda^3}\right)^{1/2} \left(\frac{\lambda}{\pi T}\right)^4 [9 \ln(\frac{\pi T}{\lambda})]^3$$

“Low” temperature

$$m_\phi = \frac{1}{f_a} \frac{(m_u m_d)^{1/2}}{(m_u + m_d)} f_\pi m_\pi$$

CPW & Nelson arXiv:1708.00010

Account for Temperature-Dependence

$$-gM^2\phi + (M^2 - g\phi)|h^2| - (F(h)/r)(m_a^2 f_a^2)\cos(\phi/f_a)$$

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$\propto v.e.v_H$

r = m(T=0)/m(T)

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Temperature dependence means:
QCD contribution during inflation << after inflation

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$\propto v.e.v_H$ **r = m(T=0)/m(T)**

Temperature dependence means:
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Relaxion solves three problems in our patch if

$$r > 10^{10}$$

CPW & Nelson arXiv:1708.00010

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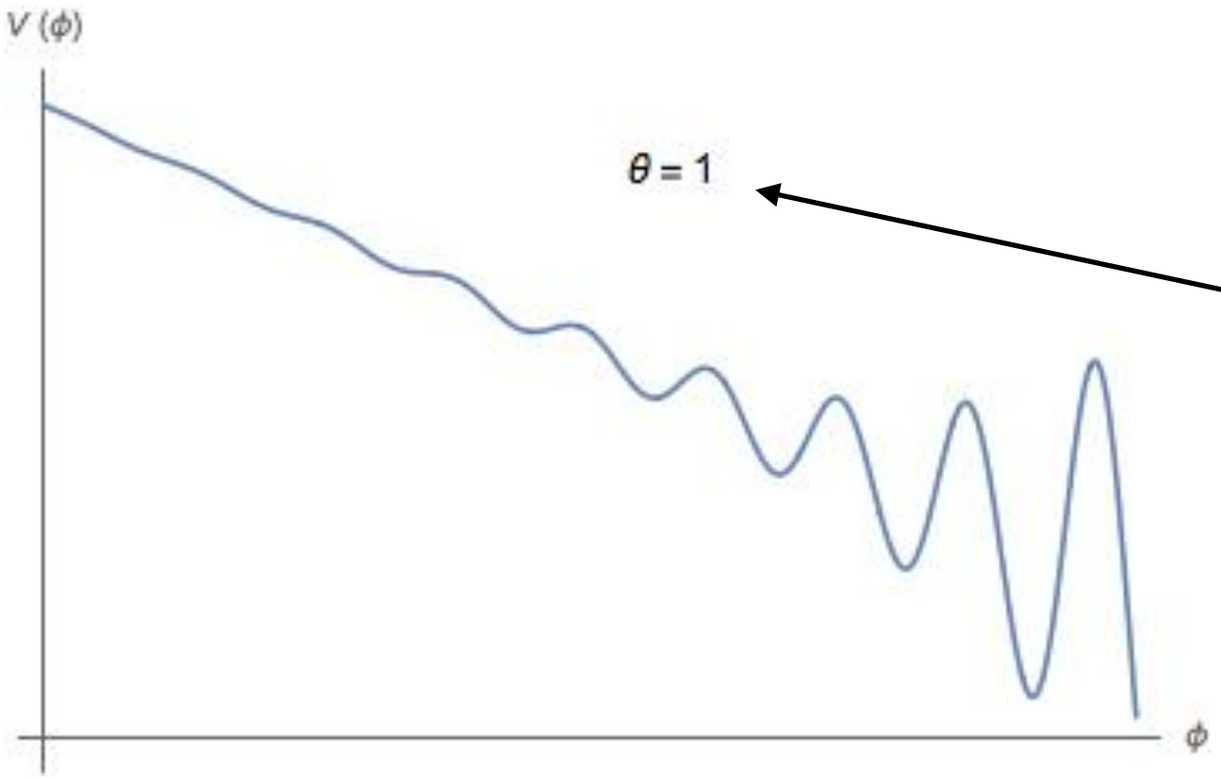
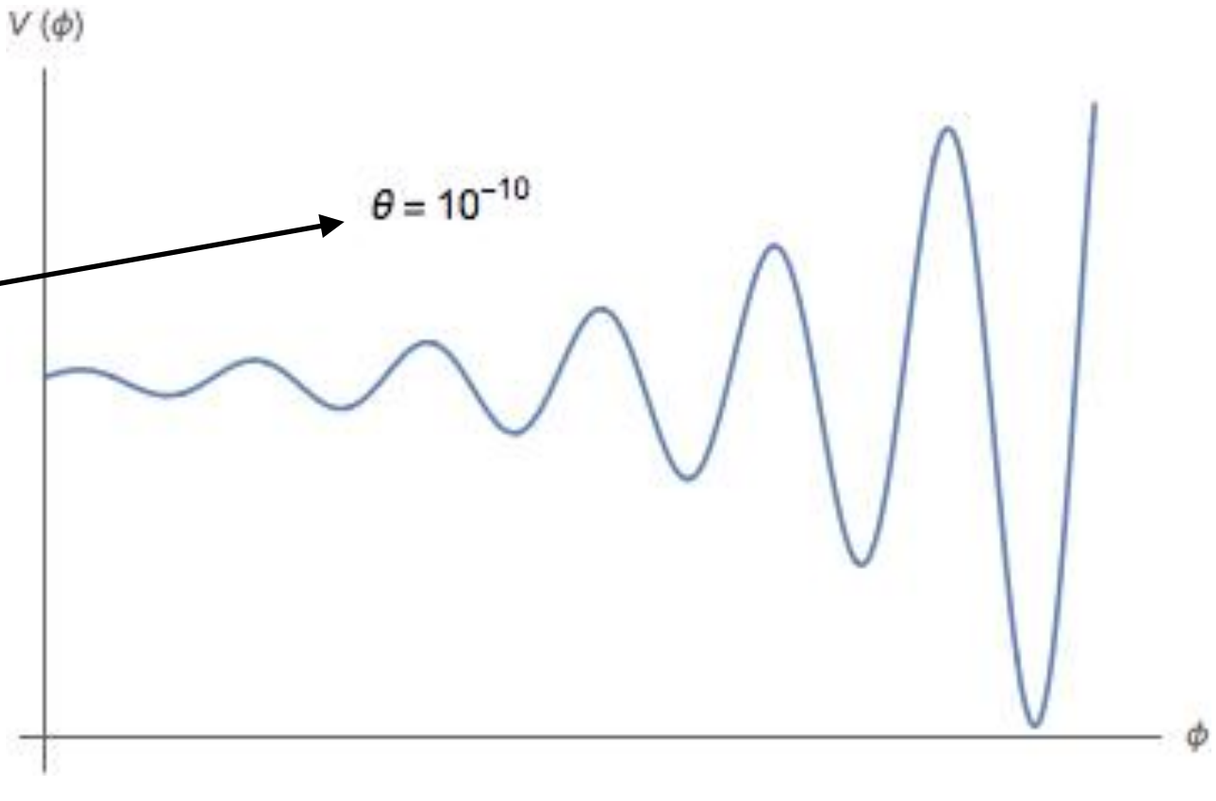


BAD

GOOD



Hubble/Temperature scale needs to be above QCD scale.

Problem: Extremely slow roll inflation means lots of patches

Solution: Statistical arguments show we usually get the right relaxion value

Classical evolution not necessary *+ landscape??*

CPW & Nelson arXiv:1708.00010

Open Questions

- **Measure problem:** Gupta (1805.09316) shows our proposed resolution to measure problem works!
- Can Hubble scale really be that small?
- Reheating picture
- Is this indeed a natural solution that avoids fine tuning?
- Relaxion origins?
- Observables?!

Final takeaway:

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