TAKING THE RELAXION'S TEMPERATURE

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The temperature-dependence of the relaxion mass matters!

YOU CAN HAVE A LARGE HUBBLE SCALE & HAVE YOUR RELAXION TOO

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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?
- Enter the relaxion.

(Graham, Kaplan & Rajendran arXiv:1504.07551)

The Strong CP Problem

- 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 pseudo Nambu-Goldstone boson, the axion

QCD 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

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

$m = \Lambda^2/f_a$

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

Axion Dark Matter Candidate

- Small mass + mostly gravitational interactions =

Dark Matter Candidate

- Nicely motivated by particle physics

- No charge & mass is not given a priori

- Fun astrophysical phenomenology: compact phase-correlated object or ***macroscopic quantum state***

CPW, Guth & Hertzberg,
arXiv:1412.5930

Electroweak Hierarchy Problem

- Electroweak Scale/Higgs Mass is ~ 10^{16} times smaller than Planck scale

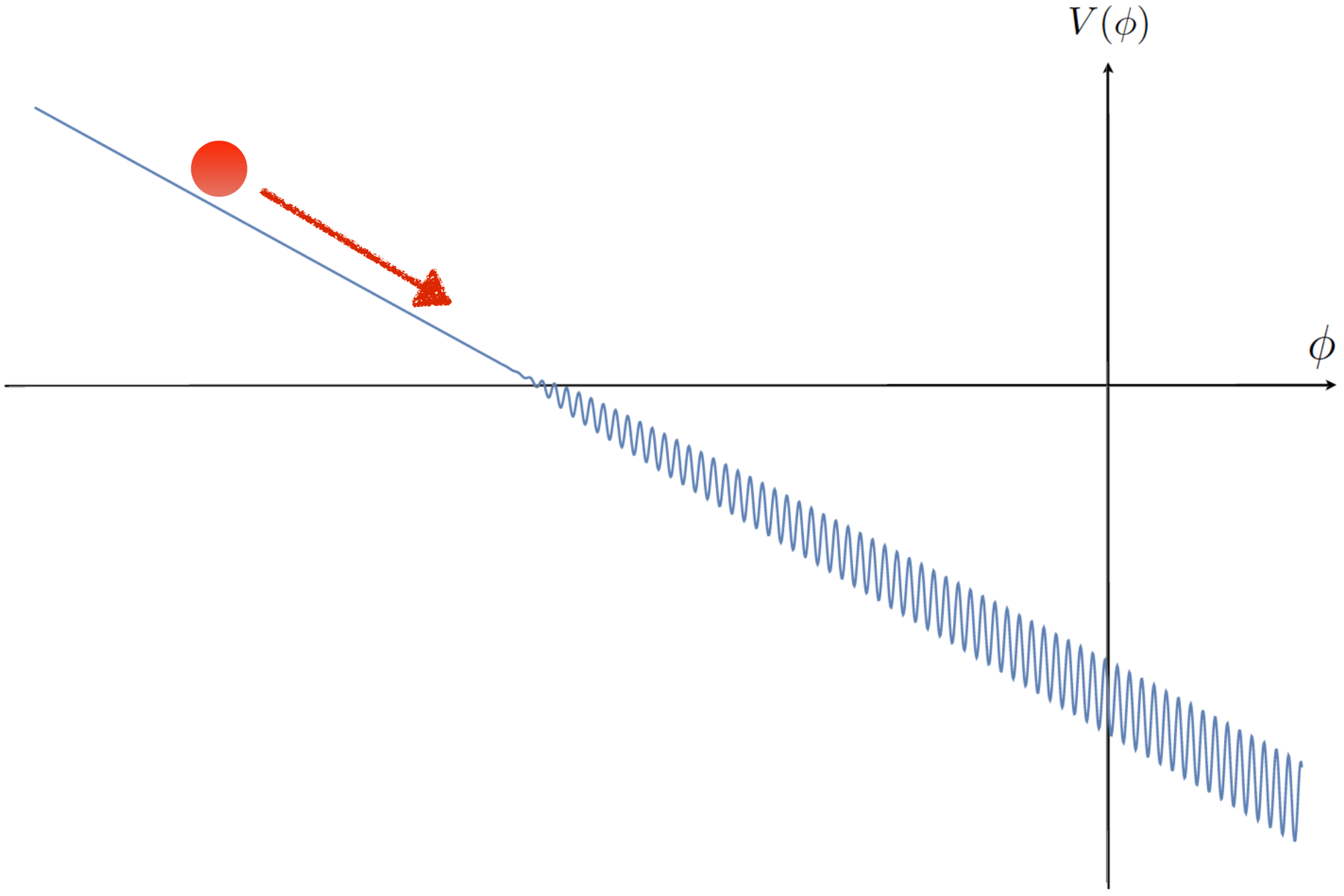
- Why is the Higgs mass so light?

- Fine tuning problem

- Solvable with Anthropics

- And now the relaxion . . .

Relaxion: Slow rolling during inflation



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

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

M is the cutoff

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

Stages of Relaxion

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

$$+$$

Higgs mass goes imaginary, VEV acquired

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

$$=$$

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

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 spurion 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.

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

Stages of Relaxion

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

$$+$$

Higgs mass goes imaginary, VEV acquired

$$\Lambda^4 \cos(\phi/f) \quad + \quad \kappa\sigma^2\phi^2$$

← **Couple to inflaton**

$$=$$

Axion tunnels through barriers until it naturally lands at right Higgs scale AND solves strong CP problem

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?

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A Hot Universe

- So far, studied in low-temperature regime
- BUT Axion mass is temperature-dependent

High temperatures

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

Below QCD scale

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

Hot Relaxion

h = Higgs

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

$\propto v.e.v_H$

g is a spurion

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

M is the cutoff

THANKS TO QUARK MASS-TEMP DEPENDENCE
(REL)AXION POTENTIAL DEPENDS
ON RATIO OF ZERO-TEMP MASS
& FINITE TEMP MASS DURING INFLATION

Only thermal fluctuations from last 60 e-folds matter, and they are sufficiently small.

Classical evolution not necessary.

Temperature-dependent physics allows us to consider these nuances.

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?
- **Relaxion can solve all three in our patch if**

$$r > 10^{10}$$

Temperature-dependent physics matters!

The original constraint on the Hubble scale is too restrictive!

GOOD NEWS FOR THE RELAXION

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Open Questions

- A more detailed inflationary model?
- Understanding preheating
- Are there other assumptions that are flexible?
- Is this indeed a natural solution that avoids fine tuning?
- Relaxion origins?