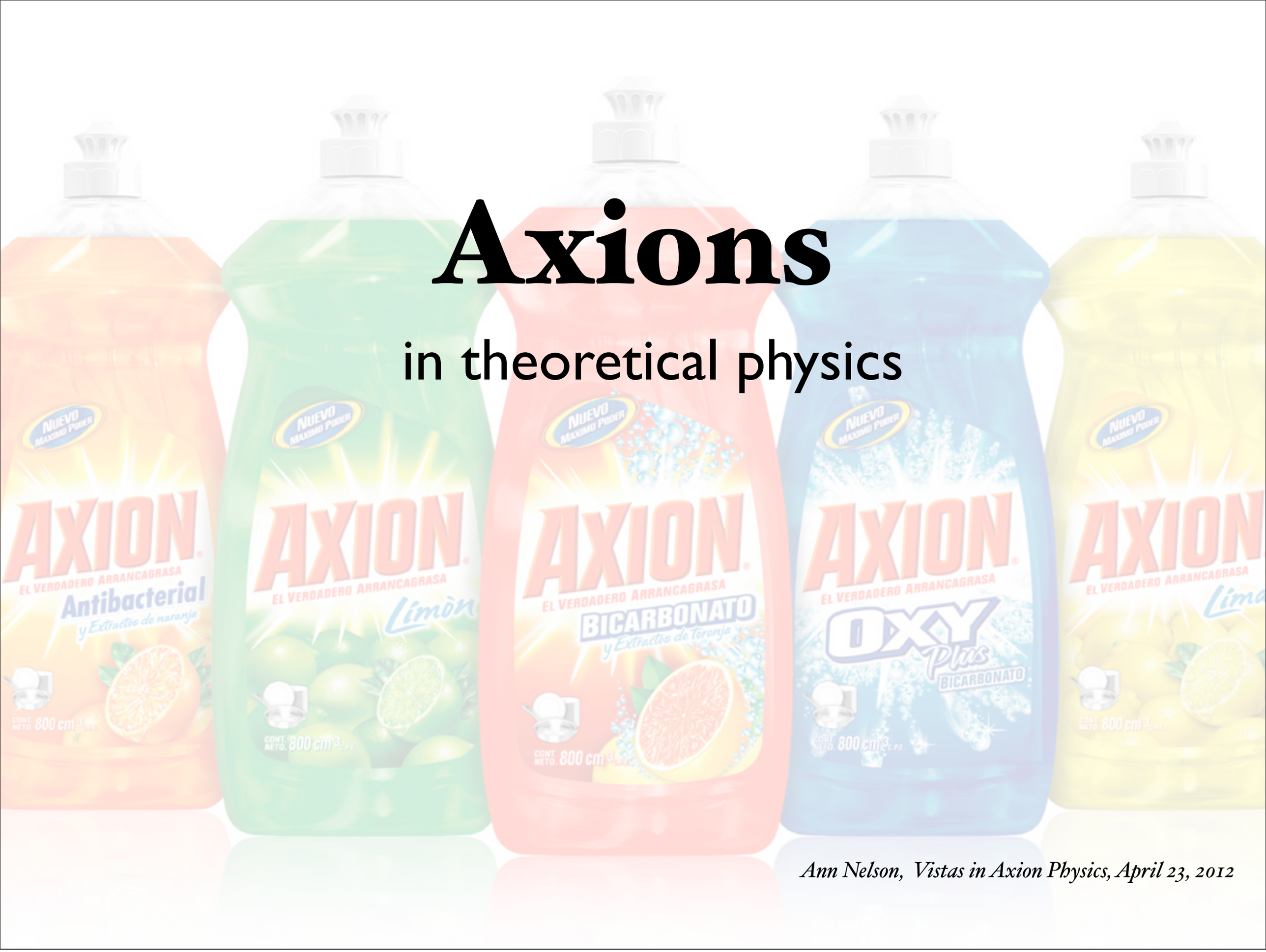
Axions

in theoretical physics



Ann Nelson, Vistas in Axion Physics, April 23, 2012

Over 5000 papers

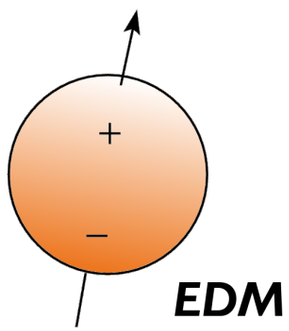
- why so much fascination with a speculative idea?
- “a perfect storm”
  - potential to solve 2 major problems
  - “model independent” in string theory
  - potential to create several major problems
  - lots of compelling, cool theory
  - some compelling, cool, feasible experiments

Strong CP Problem

- QCD theta term violates P, T, CP

$$\mathcal{L}_{CPV} = \bar{\theta}\frac{\alpha_s}{8\pi}G\tilde{G}$$

- renormalized in Standard Model, short distance sensitive ("divergent")

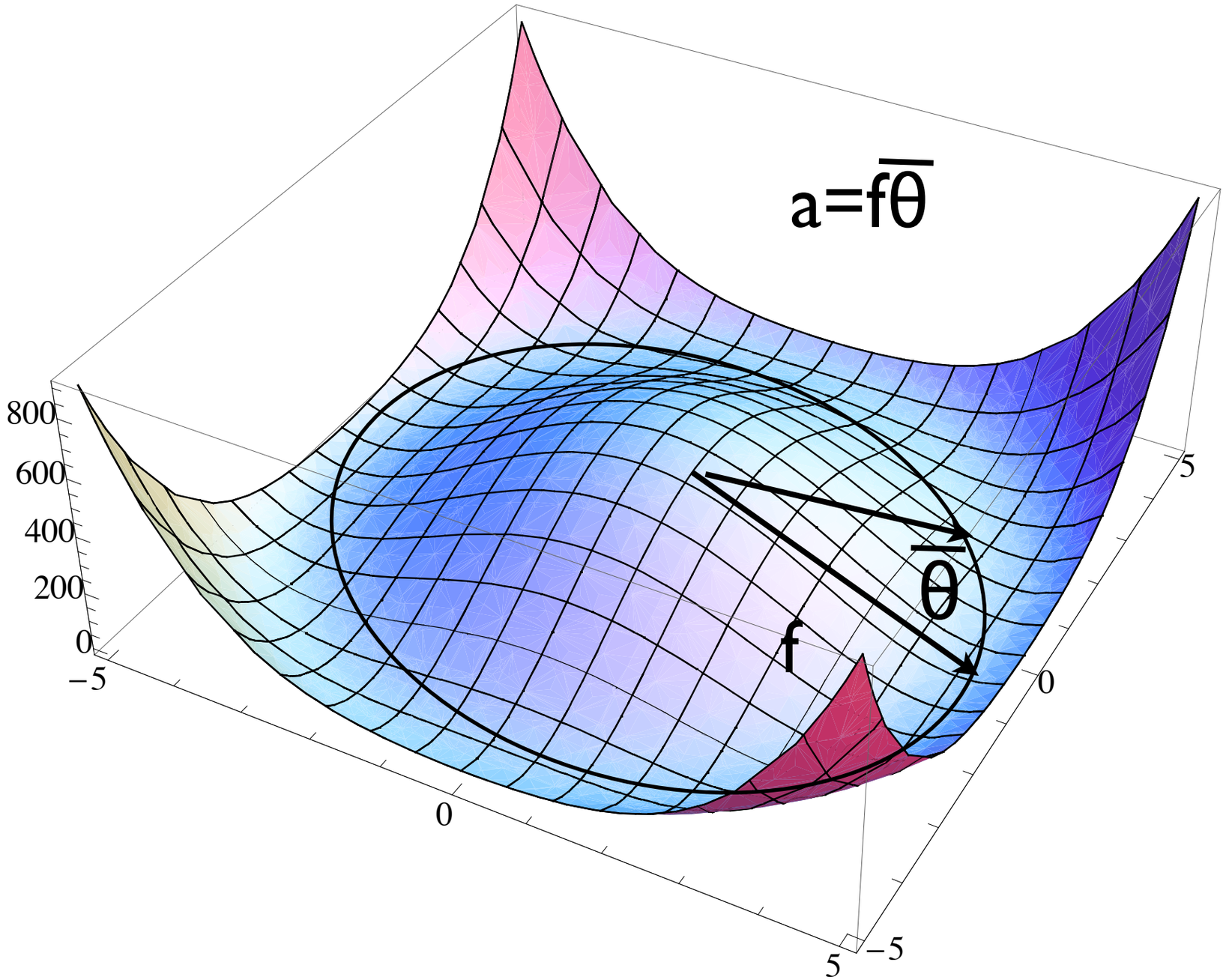


- Electric dipole moment of neutron ~ $3 \times 10^{-16}\bar{\theta}$ forces fine-tuning to part in ~10^{-9} to satisfy experimental bound

- elegant solution by Peccei and Quinn: $\bar{\theta}$ dynamical, ≈ 0 $\quad \mathcal{L}_{axion} = \frac{a}{f}\frac{\alpha_s}{8\pi}G\tilde{G}$

- Weinberg, Wilczek: PQ mechanism requires a new light, weakly coupled, ***axion***

Axion is pseudo-Nambu-Goldstone boson from spontaneously breaking anomalous Peccei-Quinn symmetry



Theory Origin of Axion

- Could have "accidental" Peccei-Quinn approximate symmetry
  - corrections to axion potential from PQ symmetry breaking highly constrained
  - String theory predicts "model independent axion"

(in large class of models) with $f_a \sim 10^{16}$ GeV

- String theory compatible with any $f_a < 10^{19}$ GeV
- string theory axion solves strong CP problem in large class of models

Alternatives to Axions

- No anthropic explanation for size of strong CPV!
- massless up quark incompatible with lattice, chiral sym
- alternative solution to strong CP problem: spontaneously broken P or CP plus some mechanism for weak CP without large strong CP (e.g. Nelson-Barr)
- axion is only solution to strong CP problem compatible with nonminimal flavor or CP violation at weak scale

Axion implies Axion Cold Dark Matter

Preskill, Wise, Wilczek; Abbot, Sikivie; Dine, Fischler

- Cosmological Axion equation of motion

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

- resembles damped Harmonic Oscillator
- $H > m_a \Rightarrow$ overdamped, a~ constant
- $H < m_a \Rightarrow$ underdamped, a oscillates and loses energy to cosmological "Hubble friction"
- $H < m_a \Rightarrow$ axion is pressureless Cold Dark Matter!
  - potentially too much for $f > 10^{12}$ GeV, $m_a < \mu$eV

Axion dark matter continued

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

- $a \sim a_{initial}$ until $H(T_i) \sim m_a(T_i)$ at redshift "z_i"
- larger $f_a \Rightarrow$ smaller $m_a(T_i) \Rightarrow$ smaller z_i (Note: axion mass temperature dependence currently estimated, could be computed on lattice)
- "typical" size of $a_{initial} \sim f_a$
- "typical" initial energy density $a^2_{initial} m_a^2 \sim m_\pi^2 f_\pi^2$
- $\alpha_i \equiv a_{initial}/f_a$ (Note: axion+inflation$\Rightarrow$"landscape" of initial conditions)
- subsequent energy density: $\alpha_i^2 m_\pi^2 f_\pi^2 (1/(1+z_i))^3$
- Assuming $\alpha_i \sim 1$, obtain observed dark matter abundance for $f_a \sim$ few 10^{11} GeV

Cosmological constraint on f_a

- Axion+ inflation+f_a>inflation scale⇒misalignment angle $\alpha_i \approx$ constant in our horizon
- Axion dark matter density $\propto \alpha_i^2$
- Cosmological bound $f_a < 10^{12}$ assumes "typical" $\alpha_i \sim 1$
- Logically possible for any value of α_i *(Pi; Turner; Linde)*, small value usually discounted as improbable
- Fine tuned selection of α_i in probable location of observers? *(Tegmark,Aguirre, Rees,Wilczek)*
- axion + high inflation scale⇒cosmological isocurvature fluctuations
- Evidence for high inflation scale from cosmo experiments, if seen, could conceivably eliminate possibility of $f_a > 10^{12}$

Viable Theories

Natural and Elegant Theories