AXIONS IN STRING THEORY

THE STRONG INTERACTIONS COULD VIOLATE CP

$$\Delta \mathcal{L} = \theta \cdot \frac{1}{16\pi^2} \int d^4x \, \mathrm{Tr}\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

BUT THEY DON'T.

EXPERIMENTALLY, $\theta \lesssim 10^{-10}$

EXPLAINING WHY IS THE STRONG CP PROBLEM

THREE SOLUTIONS HAVE BEEN PROPOSED:

1. THE AXION ... A SPIN ZERO FIELD a
   WITH COUPLING

$$\frac{a}{16\pi^2}\int d^4x \, \mathrm{Tr}\, F\tilde{F}$$

   θ BECOMES DYNAMICAL

2. $m_u = 0$ ... REMOVE THETA DEPENDENCE
   BY CHIRAL ROTATION OF UP QUARKS

3. CP ASYMMETRY AT HIGH ENERGIES
   SOFTLY BROKEN

OPTION 3 REQUIRES SOME SLIGHTLY CLEVER MODEL-BUILDING AND HASN'T BEEN MUCH EMBEDDED IN STRING THEORY ... WHICH HOWEVER HAS ONE OF THE KEY INPUTS:

CP CAN BE INTERPRETED AS A SPONTANEOUSLY BROKEN SYMMETRY

OPTION 2 — $m_u = 0$ — APPEARS TO CONTRADICT LOW ENERGY PHENOMENOLOGY

$$\frac{m_u}{m_d} \cong \frac{1}{1.8}$$

THERE IS A POSSIBLE LOOPHOLE...

WITH THREE LIGHT FLAVORS, THE QUARK MASS MATRIX M TRANSFORMS AS $(3,\bar{3})$ OF $SU(3) \times SU(3)$ AND

$$M^i{}_j \sim \epsilon^{i i' i''} \epsilon_{j j' j''} \bar{M}^{j'}{}_{i'} \bar{M}^{j''}{}_{i''}$$

SO $$m_u \sim \frac{\overline{m_d}\,\overline{m_s}}{\Lambda_{QCD}}$$

WHAT APPEARS TO BE m_u MIGHT BE

REALLY $$\frac{m_d m_s}{\Lambda_{QCD}}.$$

NO WAY TO TELL FROM PHENOMENOLOGY

ALONE; NEED LATTICE GAUGE THEORY.

LATEST RESULTS (MILC) DISFAVOR $m_u = 0$.

WHAT PRECISELY DOES $m_u = 0$ MEAN?

NO ENHANCED SYMMETRY, MEASURE m_u IN OPE's'

$$\bar{u}\gamma_\mu u(x)\,\bar{u}\gamma^\mu u(y) \sim \ldots + \frac{1}{|x-y|^2} m_u \bar{u}u$$

$$+ \frac{\Lambda_{QCD}^{1+\lambda}}{|x-y|^{2+\lambda}} e^{i\theta} \bar{u}u + \ldots$$

WITH CLEVERNESS ONE CAN CONSTRUCT A MODEL THAT SOLVES THE STRONG CP PROBLEM VIA $m_u = 0$

THE OTHER APPROACH TO THE STRONG CP PROBLEM IS OPTION 1 - THE AXION.

AN AXION IS SIMPLY A SCALAR FIELD a (WHICH I TAKE TO BE DIMENSIONLESS) WITH A (PECCEI-QUINN) SYMMETRY

$$a \to a + \text{CONSTANT}$$

THAT IS BROKEN ONLY, OR MAINLY, BY QCD INSTANTONS

THE EFFECTIVE ACTION IS

$$\mathcal{L}_a = \int d^4x \left[\frac{1}{2} F_a^2 (\partial a)^2 + \frac{a}{16\pi^2} \mathrm{Tr}\, F\tilde{F} \right]$$

F_a IS A CONSTANT WITH DIMENSIONS OF MASS – THE AXION COUPLING PARAMETER.

THE NORMALIZED SCALAR FIELD $\phi = a/F_a$ COUPLES AS

$$\frac{\phi}{F_a} \frac{1}{16\pi^2} \mathrm{Tr}\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

AXIONS AND $m_u = 0$ HAVE SOMETHING IN COMMON:

THEY ARISE FROM AN ANOMALOUS SYMMETRY THAT IS

i) BROKEN $\rightarrow$ AXION

ii) UNBROKEN $\rightarrow$ $m_u = 0$

BUT IS THIS NATURAL?

WHY INTRODUCE A "SYMMETRY"

IF IT IS GOING TO BE

ANOMALOUS?

UNDOUBTEDLY, OPINIONS HAVE DIFFERED

ON HOW NATURAL THESE SOL'NS OF THE

STRONG CP PROBLEM REALLY ARE

ARGUABLY, THE STRONGEST EVIDENCE THAT ANOMALOUS SYMMETRIES ARE NATURAL IS STRING THEORY, WHICH WITHOUT ANY CONTRIVANCE ON OUR PART GENERATES THEM – IN ESSENTIALLY ALL COMPACTIFICATIONS

USUALLY BROKEN (→ AXIONS)

SOMETIMES UNBROKEN

FOR EXAMPLE, IN HETEROTIC STRING THEORY, ANOMALOUS SYMMETRIES COME FROM THE MECHANISM BY WHICH GAUGE ANOMALIES ARE CANCELED.

THIS MECHANISM RELIES, OF COURSE, ON THE B-FIELD

"MODEL-INDEPENDENT" AXION

$$B_{\mu\nu} \qquad \mu,\nu = 1 \cdots 4$$

IS DUAL TO A SCALAR,

VIA

$$da = * dB$$

SUGRA COUPLINGS

$$(dB + \omega)^2 \qquad \omega = \mathrm{Tr}\left(A dA + \tfrac{2}{3} A^3\right)$$

BECOME $\qquad a \, \mathrm{Tr} \, F_{\mu\nu} \tilde{F}^{\mu\nu}$

"MODEL-DEPENDENT" AXIONS

$B_{\mu\nu}$ $\quad \mu, \nu = 5 \cdots 10$

$$B_{\mu\nu} = \sum_{\alpha=1}^{s} \phi_\alpha \, b^\alpha_{\mu\nu} \qquad s = b_2(K)$$

b^α = HARMONIC 2-FORMS ON K

THE ϕ_α HAVE AXIONIC COUPLINGS BECAUSE OF THE GREEN-SCHWARZ INTERACTION

$$\int B \wedge (\mathrm{Tr} F^2 \wedge \mathrm{Tr} F^2 + \cdots)$$

SO A MODEL OF GIVEN b_2 HAS

$b_2 + 1$ AXIONS

THEIR SYMMETRIES ARE VIOLATED BY

QCD INSTANTONS

WORLD SHEET INSTANTONS

GRAVITATIONAL INSTANTONS

INSTANTONS OF SECOND E8 ...

STRONG CP PROBLEM SOLVED IF QCD

INSTANTONS ARE DOMINANT FOR ONE

OF THE AXIONS

IF AXIONS DO EXIST, WHAT IS F_a?

$$\mathcal{L}_a = \int d^4x \left[\frac{1}{2} F_a^2 (\partial a)^2 + a \, \mathrm{Tr} \, F\tilde{F} \right]$$

LOWER BOUNDS ON F_a FROM, e.g.,
THE FACT THAT RED GIANTS COOL TOO
QUICKLY IF F_a IS TOO SMALL.

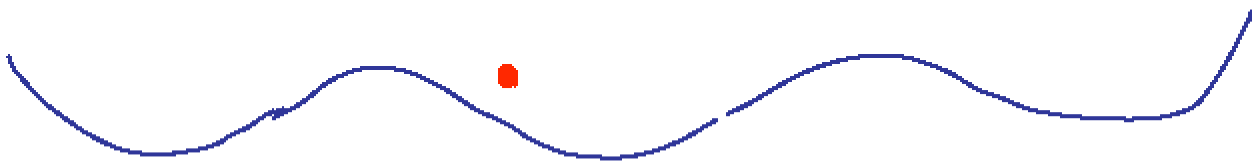
$$F_a \gtrsim 10^9 \text{ GeV}$$

MORE SURPRISINGLY, ALSO AN UPPER
BOUND ON F_a FROM COSMOLOGY

TOO MUCH DARK MATTER UNLESS

$$F_a \lesssim 10^{12}\ \mathrm{GeV}$$

START AXION AT A RANDOM VALUE



EVENTUALLY THE AXION STARTS TO OSCILLATE AS THE UNIVERSE COOLS. THE LARGER IS F_a, THE LATER THE OSCILLATIONS BEGIN AND THE MORE AXIONS ONE ENDS WITH.

EXPERIMENTAL SEARCHES FOR AXIONS USE THE COUPLING $a\gamma\gamma$

$$a F_{\mu\nu} \tilde{F}^{\mu\nu} \Big|_{\text{electromagnetism}}$$

TO PROBE THE "FAVORED" REGION

$$10^9 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV}$$

HOWEVER, THE COSMOLOGICAL UPPER BOUND IS NOT BULLETPROOF

LOOPHOLES HAVE BEEN PROPOSED

* ANTHROPIC
* QCD strongly coupled IN EARLY UNIVERSE
* INFLATION AT LOW ENERGIES
* ??

IT IS IMPORTANT TO PROBE EXPERIMENTALLY THE REGION $F_a > 10^{12}$ GeV

(ROMALIS, CABRERA)

WHAT HAPPENS IN STRING THEORY?

P. SVRCEK AND I HAVE UPDATED THE CONSIDERATIONS OF 20 YEARS AGO BY ESTIMATING F_a IN A VARIETY OF COMPACTIFICATIONS

THE QUALITATIVE RESULT IS AS IT WAS IN THE PAST:

AN AWFUL LOT OF MODELS, BUT NOT ALL, HAVE $f_a \gtrsim 10^{16}\,\mathrm{GeV} = M_{GUT}$

EXPERIMENTAL SEARCHES FOR AXIONS IN THE "FORBIDDEN" RANGE ABOVE $10^{12}\,\mathrm{GeV}$ WOULD BE ILLUMINATING

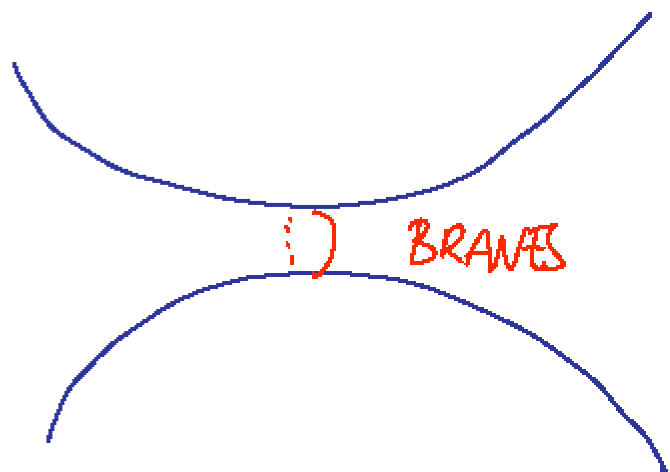
ALL PERTURBATIVE HETEROTIC STRING MODELS WITH PECCEI-QUINN SYMMETRY BROKEN AT TREE LEVEL HAVE $F_a \gtrsim 10^{16}$ GeV ... THE SAME IS TRUE OF MOST MODELS WITH GUT-LIKE PHENOMENOLOGY.

EXCEPTION: HETEROTIC STRING WITH ANOMALOUS GAUGE U(1) AND PQ SYMMETRY UNBROKEN AT TREE LEVEL ... MAY BE BROKEN AT LOWER ENERGIES, LEADING TO SMALLER F_a.

MANY MODELS WITH GAUGE SYMMETRY FROM D-BRANES, SINGULARITIES, ETC. ALSO HAVE $F_a \gtrsim 10^{16}$ GeV, ESSENTIALLY BECAUSE THE AXIONS ARE BULK MODES.

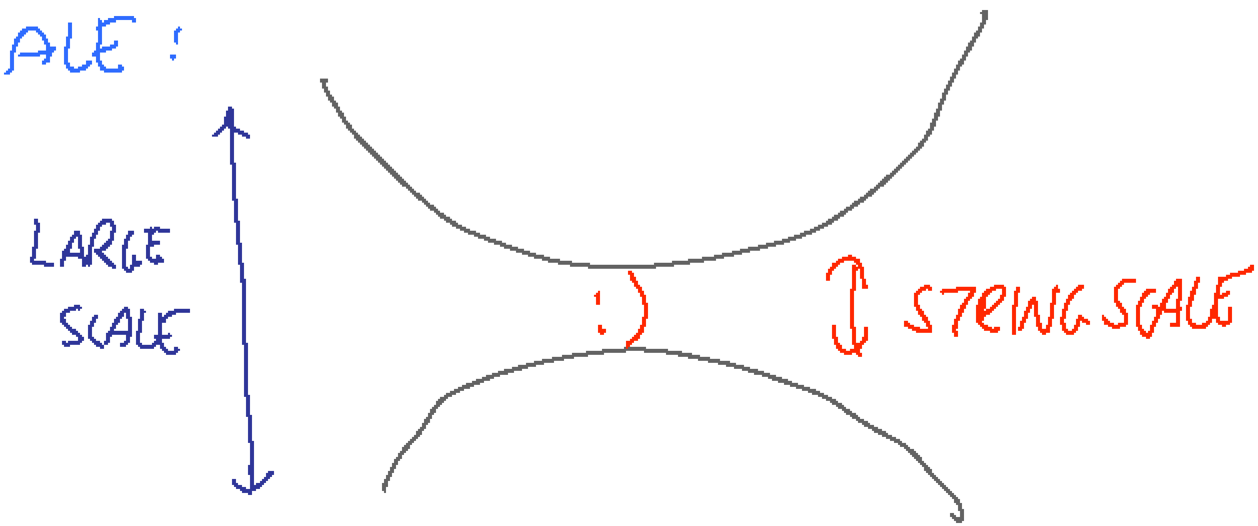
EXAMPLE: GAUGE THEORY ON D3-BRANES $\therefore$ LEADS TO $F_a \gtrsim 10^{16}$ GeV IRRESPECTIVE OF WARPING

BUT GAUGE THEORY ON Dp-BRANES FOR $p>3$ CAN GIVE SMALLER F_a IF THE BRANES ARE WRAPPED ON VANISHING CYCLES



NEED $p>3$ AS THERE ARE NO VANISHING 0-CYCLES

ONE NEEDS A COMPACTIFICATION SCALE WHICH IS LARGE (RELATIVE TO THE STRING SCALE) WITH A CYCLE WHOSE SIZE IS CLOSE TO THE STRING SCALE!



IT WOULD CERTAINLY HELP
A LOT IF WE COULD MEASURE
F_a !