Axions

Reasons to Believe, Reasons to Explore

The Strong P,T Problem

The standard model divides into two sectors: the gauge sector and the flavor, or Higgs, sector.

The gauge sector is tightly principled and brilliantly successful.

The flavor sector is looser. It has had considerable success in correlating data, but it requires many phenomenological input parameters.

Its most striking success, I think, is the KM theory of T violation.

But there's a serpent in the garden:

The overall phase of quark mass matrix physically meaningful.

In the minimal standard model, this phase is a free parameter, theoretically. Experimentally, it is very small: $|\theta| < 10^{-9}$.

This is the most striking *unnaturality* of the standard model, aside from the cosmological term.

It does not seem susceptible of anthropic “explanation”.

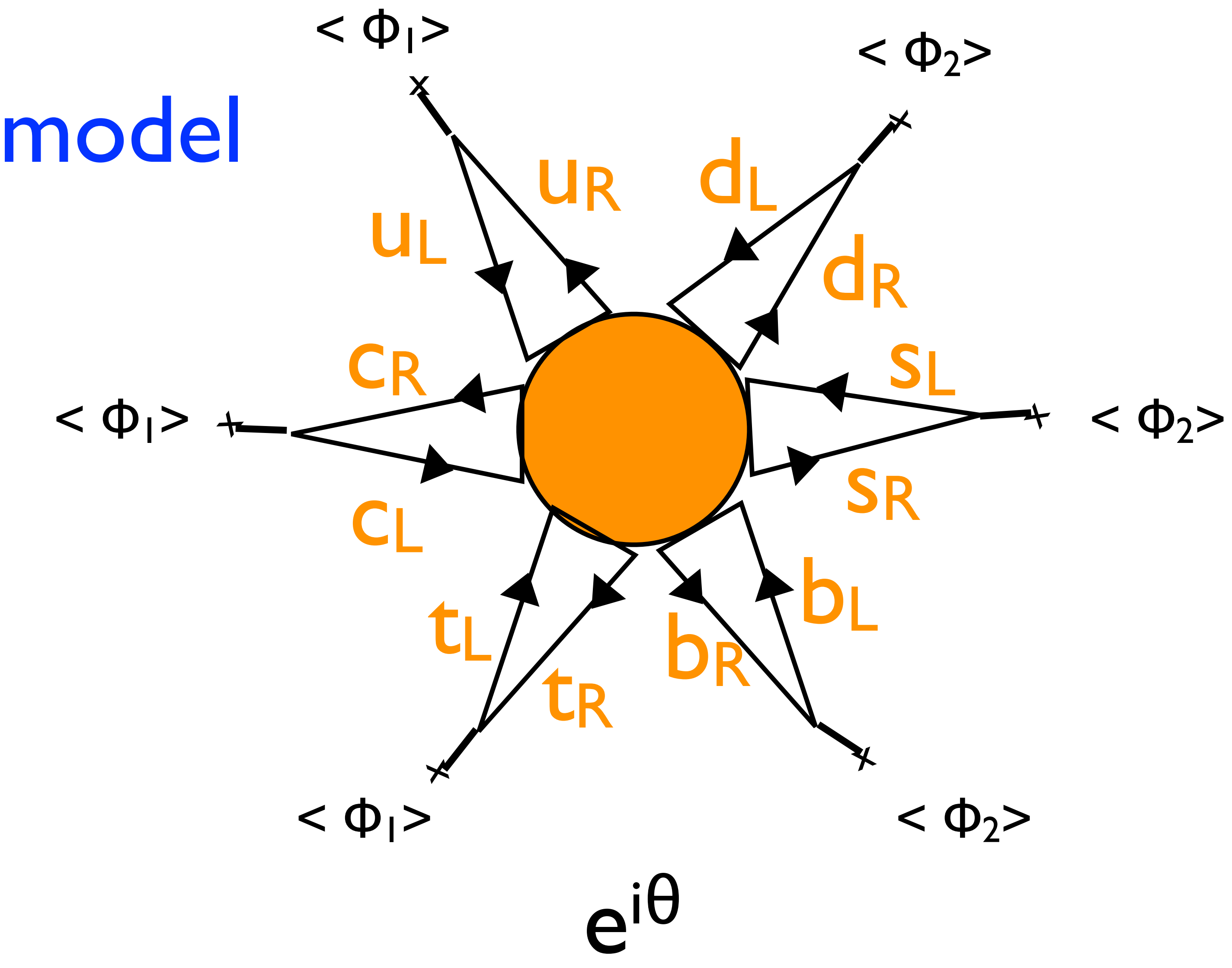
PQ Quasi-Symmetry

The most convincing response to this challenge: PQ "symmetry"

More precisely: We postulate an asymptotic or classical symmetry (perhaps accidental or approximate) under translations of θ, that is violated by QCD non-perturbatively, through instantons.

Small θ will be favored dynamically.

minimal PQ model



$$V(\alpha) \sim -\cos\alpha\, \Lambda_{\mathrm{QCD}}^4$$

$$m_a^2 \sim \frac{1}{F^2}\frac{d^2V(\alpha)}{d\alpha^2} \sim \frac{\Lambda_{\mathrm{QCD}}^4}{F^2}$$

Axions Defined

We can implement the general mechanism with a complex scalar order parameter field ϕ, and PQ charge assignments.

The axion field is established at the PQ transition, $<\phi> = F\ e^{i\theta} = F\ e^{ia/F}$.

a is an *approximate* Nambu-Goldstone boson.

It has a non-vanishing potential, and mass, as indicated previously.

Its main couplings are dictated by the broken symmetry, following standard NG-ology.

Laboratory Phenomenologies

Laboratory experiments following several strategies have searched for axions:

beam dumps

Hertz inspired

macroscopic forces

Astrophysical Phenomenologies

Solar radiation.

Stellar cooling: white dwarfs, neutron stars.

Taken as a whole, the experiments seem to constrain F $\geq 10^{10}$ GeV.

Conventional Axion Cosmology

The axion field is established at the PQ transition, $<\phi> = F\, e^{i\theta} = F\, e^{ia/F}$.

At the transition the energy associated with varying θ is negligible, and differences from the minimum $\theta \cong 0$ can be imprinted.

They store field energy that eventually materializes, with density roughly proportional to $F \sin^2\theta_0$ today.

If no inflation occurs after the PQ transition then the correlation length, which was no larger than the horizon at the transition, corresponds to a very small length in the present universe.

We therefore average over $\sin^2\theta_0$.

$F \sim 10^{12}$ GeV corresponds to the observed dark matter density.

Since experimental constraints require F $\geq 10^{10}$ GeV, axions are almost forced to be an important component of the astronomical dark matter, if they exist at all.

So it seems interesting to entertain the hypothesis that axions provide the bulk of the dark matter, and F $\cong 10^{12}$ GeV.

This has traditionally been regarded as the default axion cosmology. A cosmic axion background with $F \cong 10^{12}$ GeV might be detectable, in difficult experiments.

Searches are ongoing. $(a \rightarrow \underset{\overset{\uparrow}{= B_{\text{ext.}}}}{\gamma}\ \ \gamma)$

Inflationary Axion Cosmology

If inflation occurs after the PQ transition, things are very different.

Then the correlated volume inflates to include the entire presently observed universe, so we shouldn't average.

$F > 10^{12}$ GeV can be accommodated, by allowing "atypically" small $\sin^2\theta_0$.

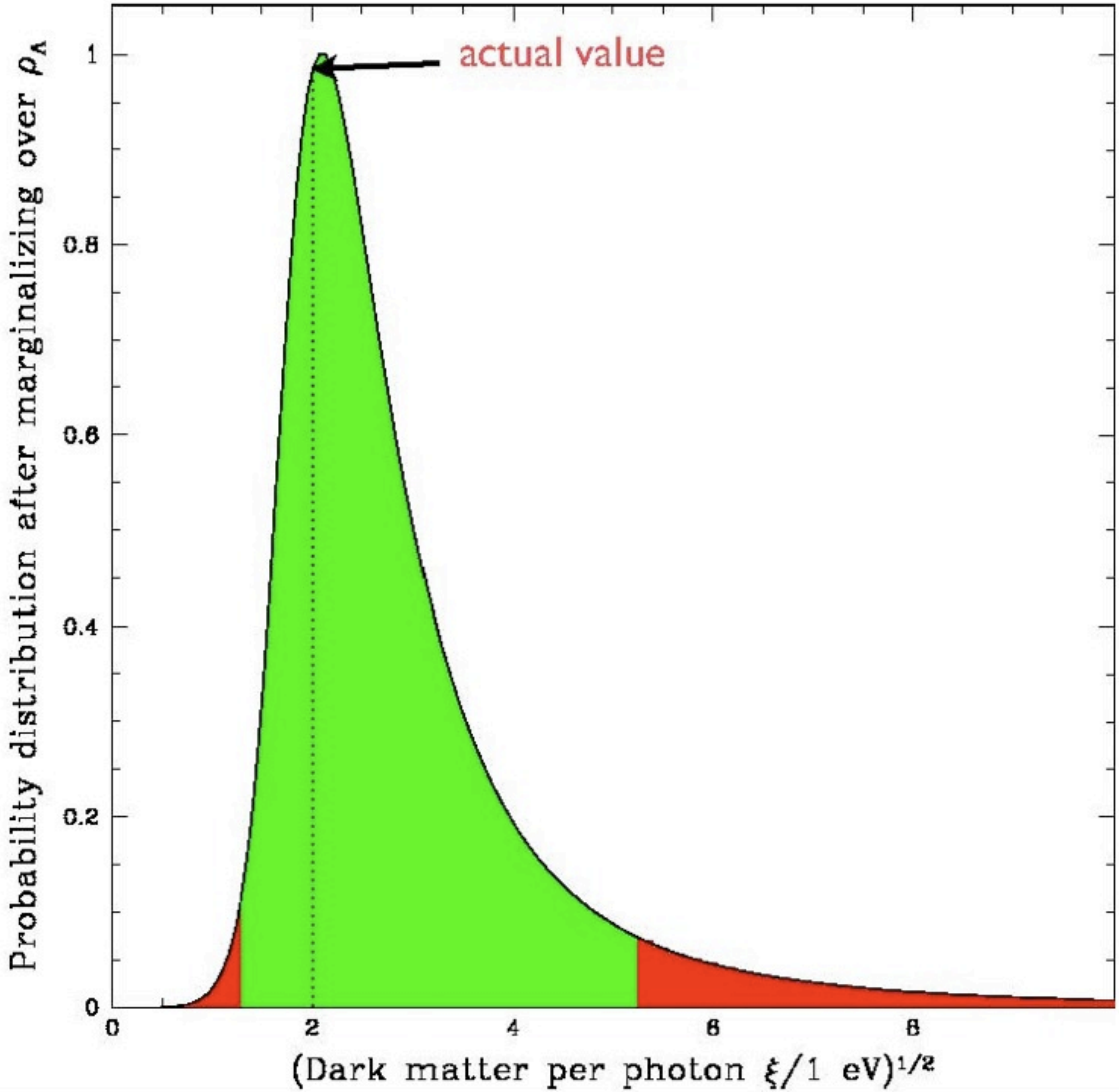
In the large-F scenario, most of the multiverse is overwhelmingly axion-dominated, and inhospitable for the emergence of complex structure, let alone observers.

Selection effects must be considered.

θ_0 controls the dark matter density, but it has little or no effect on anything else.

It is hard to imagine a clearer, cleaner case for applying anthropic reasoning.

The result appears encouraging:


actual value
Probability distribution after marginalizing over ρ_Λ
(Dark matter per photon $\xi/1$ eV$)^{1/2}$
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8

A canonically normalized boson field - graviton or axion - acquires fluctuations of amplitude $T_{GH} \sim \Lambda_{infl.}^2/M_{Pl}$.

For axions, this translates into jitter in θ_0, and thus ultimately into isocurvature density fluctuations.

Constraints on isocurvature fluctuations translate into constraints on $\Lambda_{\text{infl.,}}$ and thus on the gravity wave background.

Conversely, observation of isocurvature fluctuations, in the absence of gravity waves, would be encouraging for inflationary axion cosmology.

Very recently Arvanitaki and Dubovsky (elaborating A+D+Dimopoulos, Kaloper, March-Russell) have argued that axions whose Compton wavelength is a small multiple of the horizon size of a spinning black hole will form an atmosphere around that hole, populated by super-radiance.

This effect alters the gravitational wave and x-ray signals from such holes, possibly in spectacular ways.

Since

$(m_a)^{-1} \approx 2$ cm. $(F / 10^{12}$ GeV$)$

$R_{\text{Schwarzschild}} \approx 2$ km. (M / M_{Sun}),

this provides a possible window through which to view $F \geq 10^{15}$ GeV axions.