The theoretical allure of the QCD Axion

The most general gauge invariant Lagrangian of a pure Yang-Mills theory (QCD):

Field strength tensor + dual

$$G^a_{\mu\nu}(x) = \partial_\mu A^a_\nu(x) - \partial_\nu A^a_\mu(x) + g\, f_{abc}\, A^b_\mu(x)\, A^c_\nu(x)$$

$$\tilde{G}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} G^{a\,\rho\sigma}$$

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

Two fundamental parameters:

Strong coupling $\alpha_s \sim O(1)$

Vacuum angle $\theta < 10^{-10}$

$$G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$$

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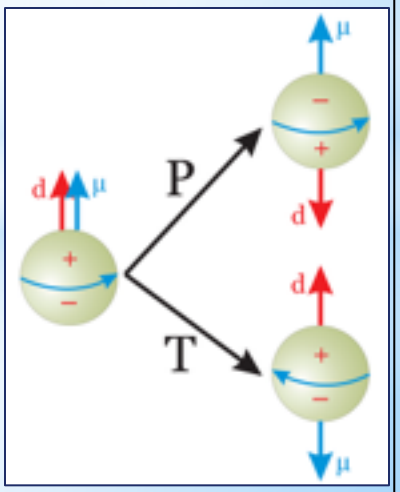

θ induces unseen processes like $\eta,\eta' \to 2\,\pi$ and a neutron EDM

$$d_n \sim e\theta \frac{m_*}{m_n^2} \sim 6 \times 10^{-17}\ \theta\ e\,\mathrm{cm};$$

$$|d_n^{\rm exp}| < 3.0 \cdot 10^{-26}\ e\ \mathrm{cm}$$

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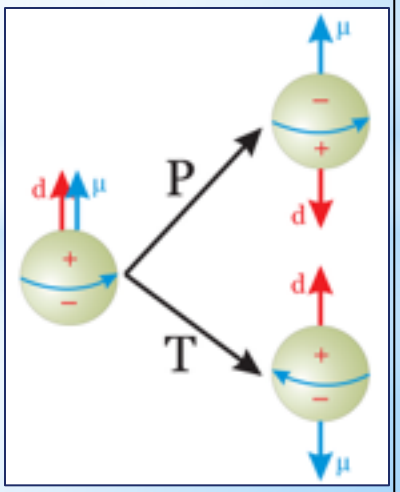

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$$\Rightarrow \quad |\bar{\theta}| \lesssim 10^{-10}\ ?$$

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The customary dictum to explain how the axion solves the strong CP problem:

"The axion turns θ into a dynamical field $\theta(x)$ that relaxes to zero at the minimum"

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I have amused myself in attempting to elaborate an analogy, which addresses the following points:

- CP violation is pervasive in nature, and strong CP violation is built-in QCD. But we do not see any signal of it… Why ?
- An accidental fine-tuning $\theta<10^{-10}$ is not a credible explanation.
- Attempts to find explanations based on anthropic selection, equally fail.
- However, there is a solution. It is cogent, elegant, and basically unique.
- And can be tested.

I hope it can help to convince you about the axion…

Imagine sailing upwind with a steady angle of heel

The deck,
the mast,
everything
is tilted…

Imagine sailing upwind with a steady angle of heel

The deck,
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Also in the cabin
everything is tilted,
the floor, the table,
the beds…

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However, the hob looks horizontal…

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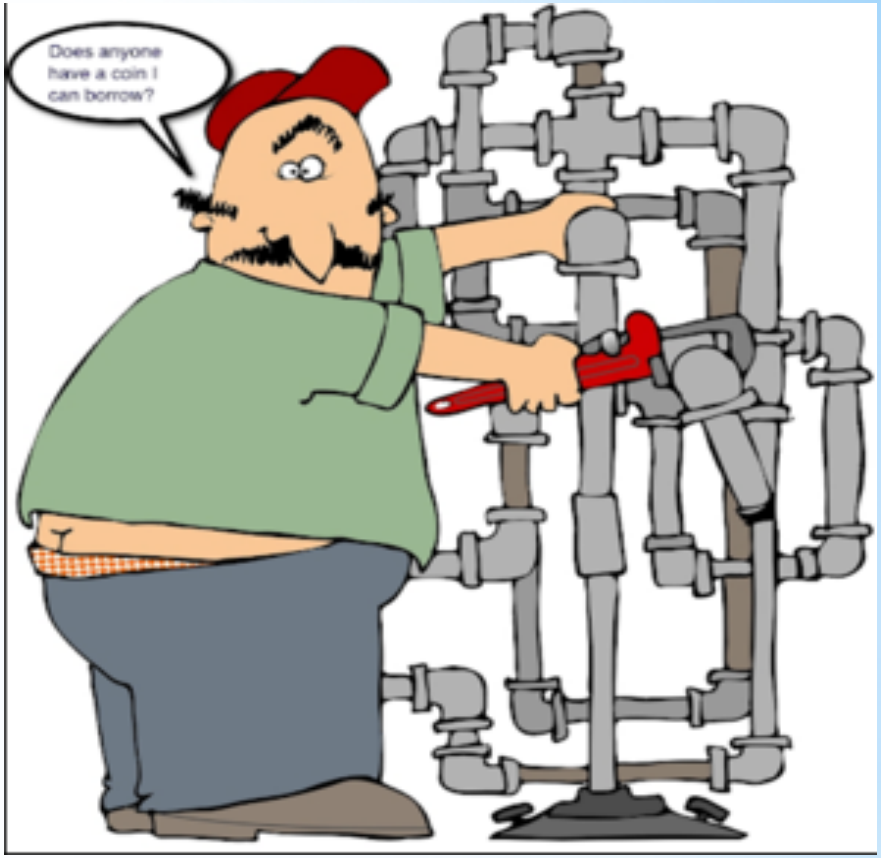
Yes, indeed it is horizontal !

An observer might conjecture that the hob was mounted not level by a drunk installer, at a random angle, that now is matching accidentally the angle of heel of the sailing boat…



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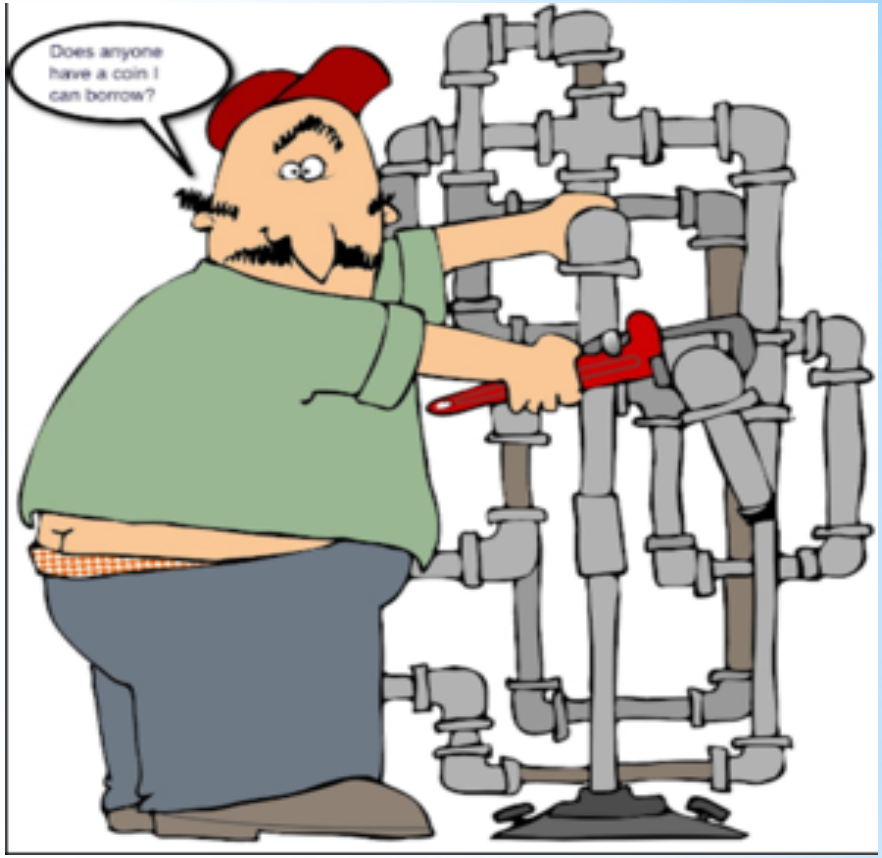

However, a very careful measurement returns that any angle of inclination is bounded to be less than 10^{-10}!!

Such an accident does not seem possible!

So maybe there are 10^{10} sailing boats out there, all with hobs mounted at random angles, and only the observer of this boat will be able to cook, survive to destination, and report his puzzling discovery…

Barcolana regatta, Trieste, 2 x10^3 boats

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However, the observer realizes that any hob with an angle of inclination smaller than 10^{-1} would work equally well.

So once more, why 10^{-10} ??

Eventually, the observer infers a convincing explanation: the hob is mounted on a gimbal that allows it to remain horizontal when the boat is heeled !
Gravity defines what is tilted and, with the help of the gimbal, gravity ensures that the hob will always remain level.

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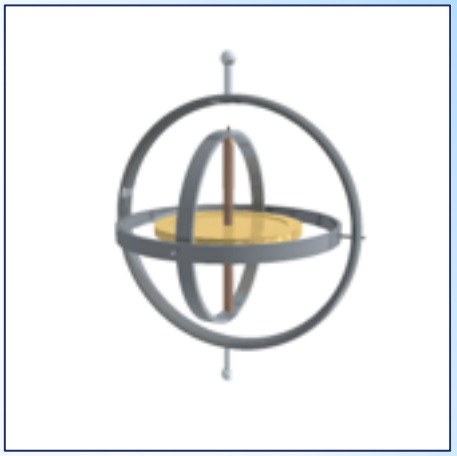

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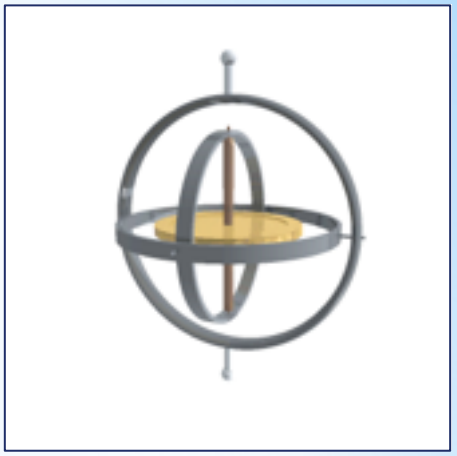

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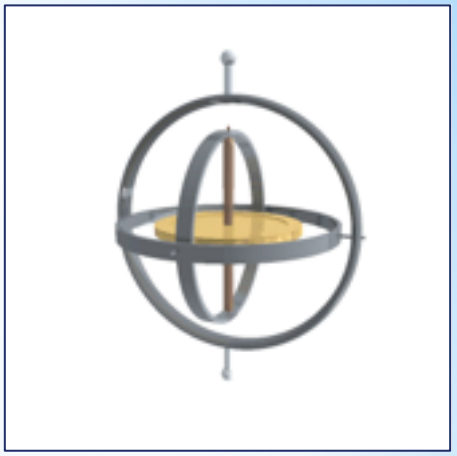

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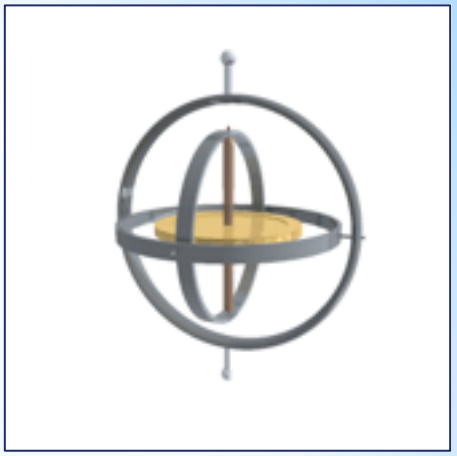

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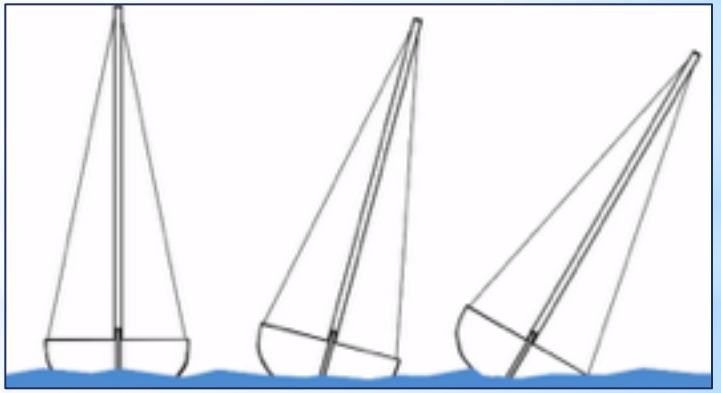
When the boat starts heeling, an initial static friction in the gimbal results in slightly lifting the hob cdm. If dynamical friction drops to zero when the gimbal starts oscillating, then almost imperceptible oscillations must still be going on



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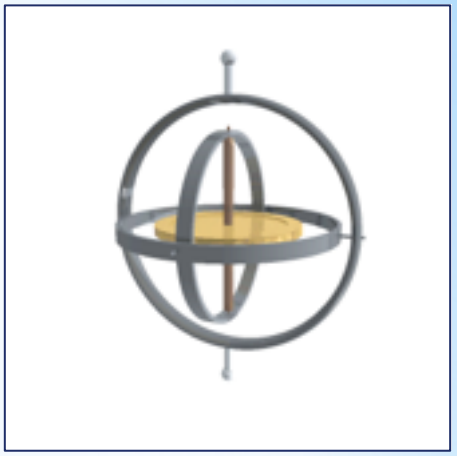

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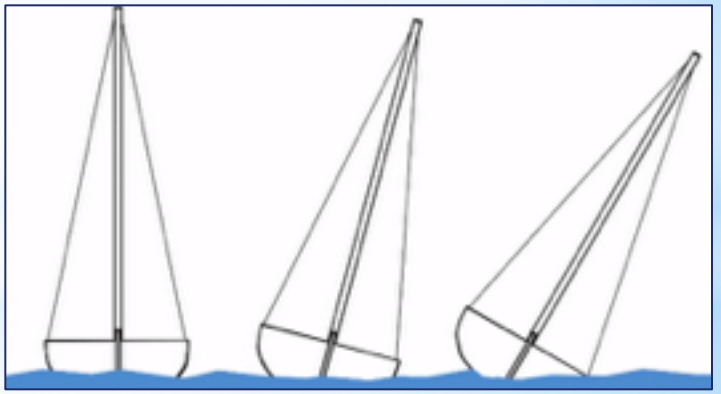

In the expanding Universe, 'Hubble friction' has precisely these properties. And the 'relic oscillations' that would prove the gimbal mechanism, are what axion DM searches with Haloscopes are aiming to detect.

THANK YOU FOR YOUR ATTENTION