THE ALMIGTHY AXION

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Content

Theoretical preliminaries

Axions in cosmology

Axion-photon oscillations in high energy astrophysics

Summary

The Strong CP problem

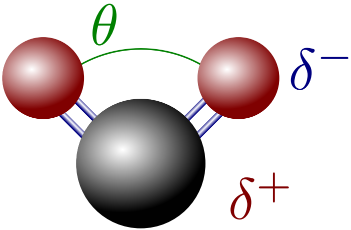
$$\mathcal{L}_{\mathrm{SM}} \supset \frac{\vartheta g^2}{8\pi^2} G\tilde{G}, \quad \vartheta \in [0, 2\pi)$$

- $G\tilde{G} = \partial_\mu K^\mu$ is a four divergence
- Arises from (1) non-trivial topology of the ground state, and (2) diagonalising the quark mass matrix
- Measurements of the neutron dipole moment $\Rightarrow |\vartheta| \lesssim 10^{-10}$

Fine tuning: Why not $\vartheta = \mathcal{O}(1)$?!

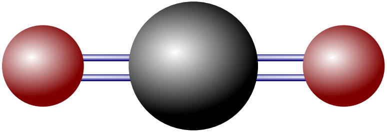
The Strong CO_2 problem

Problem:



But measurements show that $\vartheta = \pi$...

Solution:



ϑ is relaxed to zero by minimising the energy!

The Peccei-Quinn solution

$$\mathcal{L}_{\rm SM} \supset \frac{\vartheta g^2}{8\pi^2} G\tilde{G}$$

- **Idea:** Make the angle ϑ dynamically relax to 0 (Peccei, Quinn 1977)
- **How:** Add a global U(1) chiral symmetry that is spontaneously broken at an energy scale f_a

$$\Rightarrow \mathcal{L} \supset \mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{g^2}{16\pi^2}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- The field a is a pseudo-Goldstone boson (Wilczek 1978; Weinberg 1978)

Peccei and Quinn overlooked an important, testable consequence of their idea. The particles produced by their neutralizing field – its quanta – are predicted to have remarkable properties. Since they didn't take note of these particles, they also didn't name them. That gave me an opportunity to fulfill a dream of my adolescence.
Frank Wilczek (Quanta Magazine 2016)

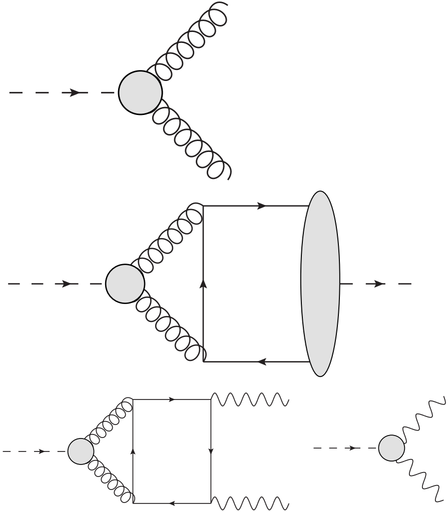
A few years before, a supermarket display of brightly colored boxes of a laundry detergent named Axion had caught my eye. It occurred to me that "axion" sounded like the name of a particle and really ought to be one. So when I noticed a new particle that "cleaned up" a problem with an "axial" current, I saw my chance.

Frank Wilczek (Quanta Magazine 2016)

Properties of the axion

$$\mathcal{L} \supset \frac{g^2}{16\pi^2}\frac{a}{f_a}G\tilde{G}$$

- Gluon coupling
- Mass, $m_a f_a \approx m_\pi f_\pi$
- Photon-coupling
- ...



Axion-like particles (ALPs)

$$\mathcal{L}_{\rm SM} \supset \frac{1}{2}\partial^{\mu} a \partial_{\mu} a - \frac{1}{2} {m_a}^2 a^2 \left[1 - \cos(a/f_a)\right] - \frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

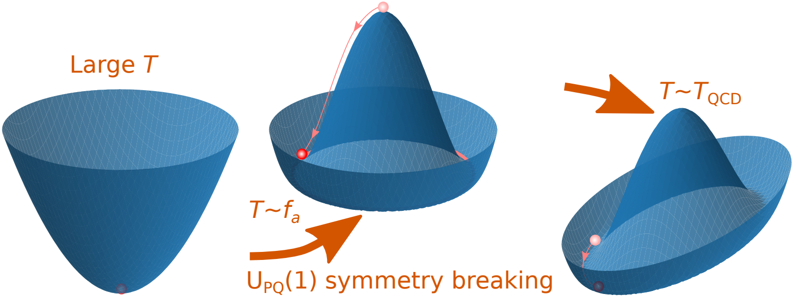
- Common in theories with spontaneous symmetry breakings
- QCD axion: $g_{a\gamma} \approx 10^{-19} m_a/\mathrm{eV}^2$

Axion almighty

1. Strong CP problem
2. Baryogenesis
3. **Dark matter**
4. **Inflation**
5. **Dark energy**
6. $g-2$ anomaly
7. ...

Idea: In the early Universe (high temperatures), the $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry is unbroken.

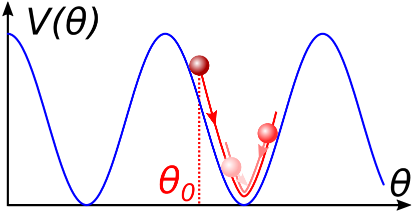
Axion field evolution



3. Axionic dark matter

Problem: What is the identity of cold dark matter?

- Thermal production: $\pi\pi \leftrightarrow \pi a$
- But the axion is light $\Rightarrow$ Thermal production gives hot dark matter
- Misalignment mechanism! (Preskill, Wise, Wilczek 1983)

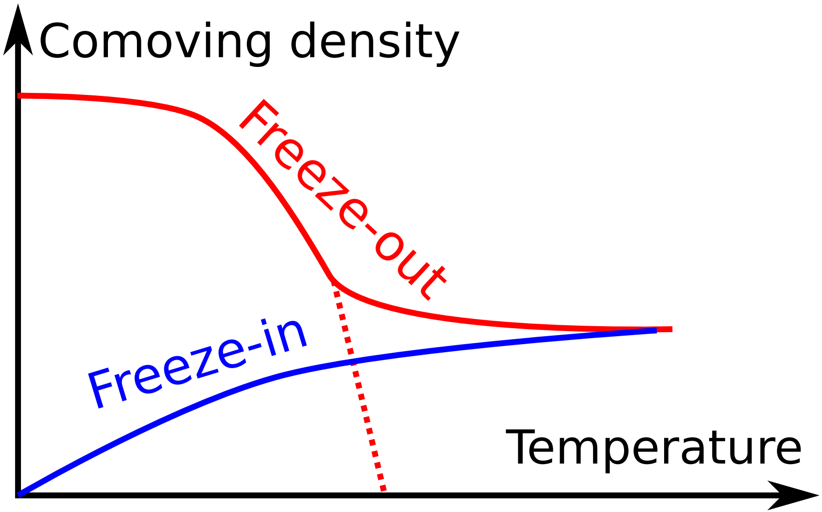


$$\langle \ddot{a}\rangle + 3H\langle \dot{a}\rangle + m_a^2\,\langle a\rangle = 0;\ \langle a\rangle = A(t)\cos(m_a t);\ \rho_a = \frac{1}{2}m_a^2 A(t)^2$$

$$\frac{1}{m_a A^2}\frac{\mathrm{d}(m_a A^2)}{\mathrm{d}t} = -3H \Rightarrow m_a A^2 \propto R^{-3} \Rightarrow \rho_a V = const.$$

- The axion field oscillates coherently and looses energy by producing physical axions

3. Axionic dark matter



4. Axionic inflation

Problem: What is the origin of inflation?

- Single field inflation:

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$

- Standard single field inflation scenario is similar to the misalignment mechanism
- The axion can take the role of the inflaton!
- The field oscillates coherently and looses energy by accelerating the expansion of the Universe

5. Axionic dark energy

Problem: What is the origin of the Dark Energy that accelerates the present day Universe?

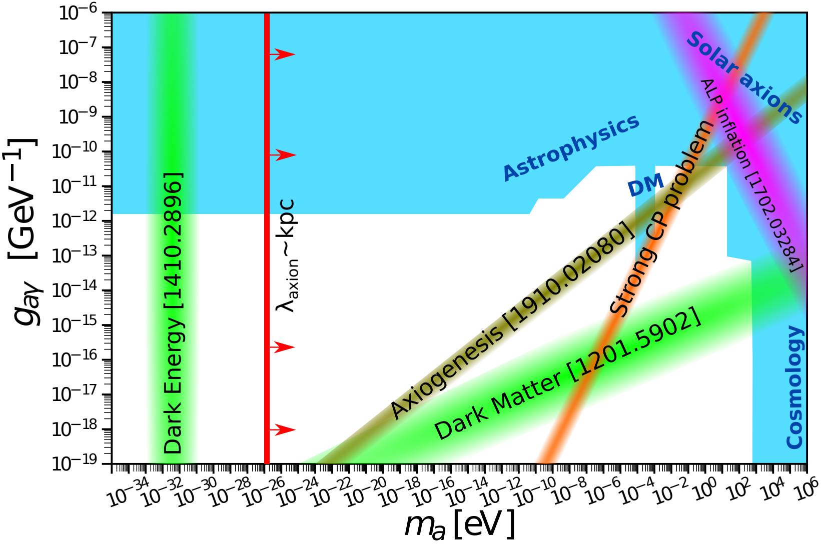
- Use the inflation mechanism and shift the onset of oscillations

$\Rightarrow$ Need small m_a

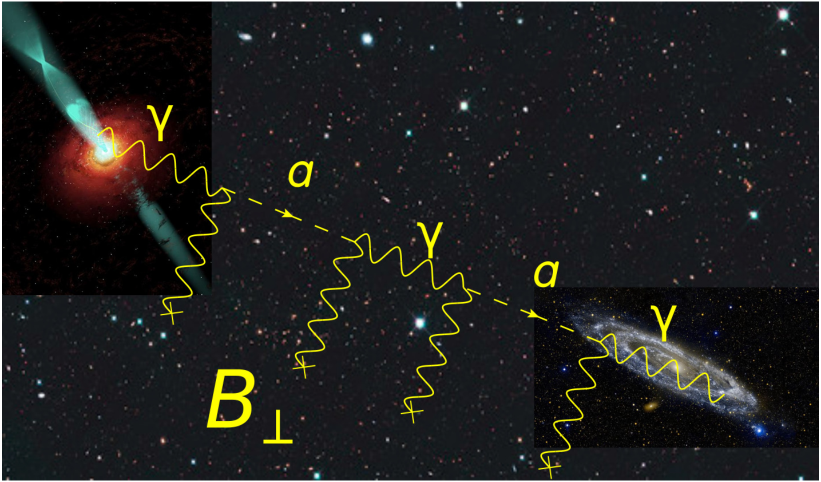
Is the axion almighty?

No.

The Axion Parameter space



Photon-axion oscillations



Divergence free Gaussian turbulence, Kolmogorov spectrum,
$B \sim \mathrm{nG}$, $L_{\mathrm{coh}} \sim \mathrm{Mpc}$, $g_{a\gamma} \sim 10^{-20}\ \mathrm{eV}^{-1}$

Photon-axion oscillations

$$\begin{pmatrix} \gamma \\ a \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

Free particle solution:

$$|\psi_i(t)\rangle = |\psi_i(0)\rangle\, \mathrm{e}^{\mathrm{i}\vec{p}_i\cdot\vec{x}-\mathrm{i}E_i t}; \quad \vec{p}_i\cdot\vec{x} - E_i t \approx -\frac{m_i^2}{2E}L$$

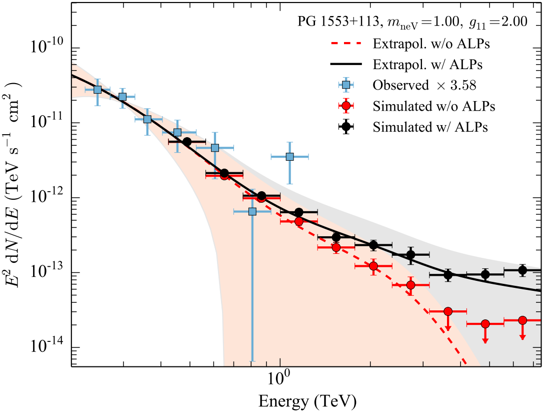
Photon mass eigenstate:

$$|\Psi(t)\rangle = \mathrm{e}^{-\mathrm{i}Ht}\,|\gamma\rangle = |\psi_1\rangle \cos\vartheta \mathrm{e}^{-\mathrm{i}m_1^2 L/2E} + |\psi_2\rangle \sin\vartheta \mathrm{e}^{-\mathrm{i}m_2^2 L/2E}$$

$$\Rightarrow P_{\gamma\to a} = |\langle a|\Psi(t)\rangle|^2 = \sin^2(2\vartheta)\sin\left(\frac{L}{2E}\left(m_1^2 - m_2^2\right)\right)$$

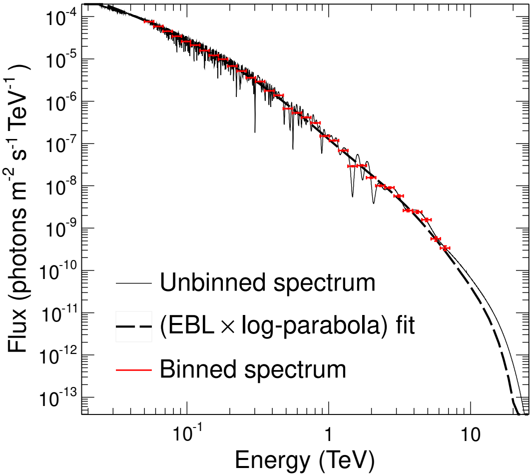
$\Rightarrow$ Oscillation due to a mass difference between two mass eigenstates

Increased opaqueness of the Univere



(Adapted from [1406.5972])

“Irregularities” in photon spectra



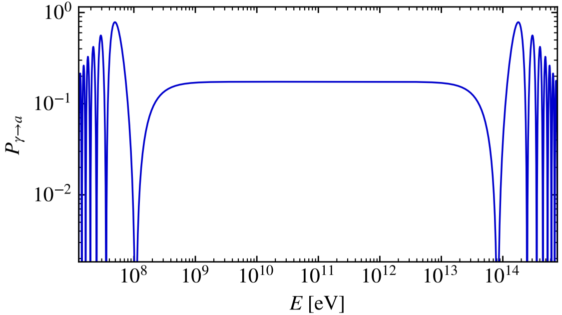
(Adapted from [1205.6428])

Energy dependence in a homogeneous field

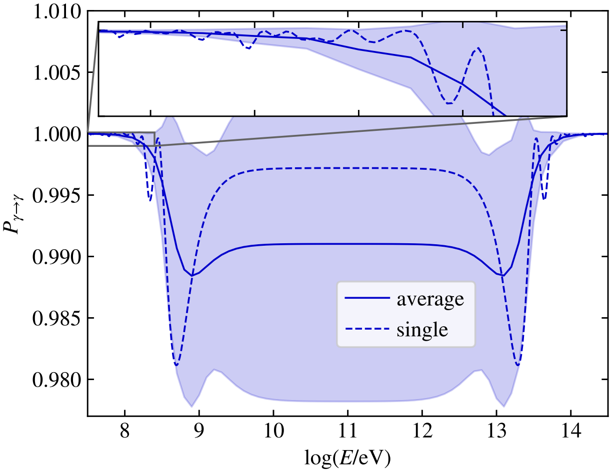
$$P_s(\gamma \to a) = \left|\langle A_\parallel(0)|a(s)\rangle\right|^2 = \left(\Delta_{a\parallel} s\right)^2 \frac{\sin^2(\Delta_{\rm osc} s/2)}{(\Delta_{\rm osc} s/2)^2},$$

$$\Delta_{\rm osc}^2 = (\Delta_\gamma - \Delta_a)^2 + 4\Delta_{a\gamma}^2; \qquad \Delta_{a\gamma} = \frac{g_{a\gamma} B_\perp}{2}$$

$$\Delta_\gamma = \Delta_\gamma^{\rm QCD} + \Delta_\gamma^{\rm CMB} + \Delta_\gamma^{\rm pl}$$



Energy dependence in a turbulent field



Preliminary

A direct detection of axion wiggles

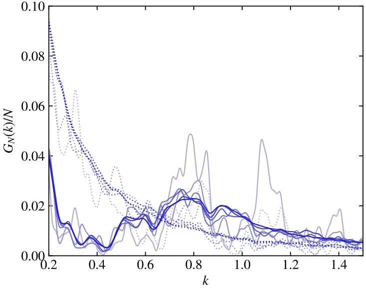
- **Idea:** Use the energy dependence of the wiggles as observable

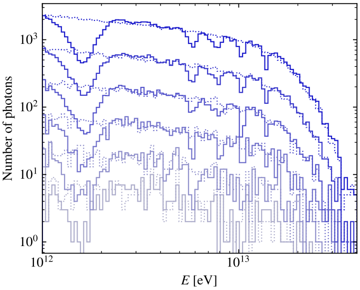
$$G(k) = \left| \int_{\eta_{\min}}^{\eta_{\max}} \mathrm{d}\eta \, q(\eta) \mathrm{e}^{\mathrm{i}\eta k} \right|^2 \approx \left| \frac{1}{N} \sum_{\text{events}} \exp\left\{ \mathrm{i}\eta k \right\} \right|^2$$

- Observables:
  - Peak in $G(k)$ for $\eta \sim E$ at “low” energies
  - Peak in $G(k)$ for $\eta \sim E^{-1}$ at “high” energies
  - No systematic signal otherwise
- The signal can be used to infer information about the magnetic field

Preliminary

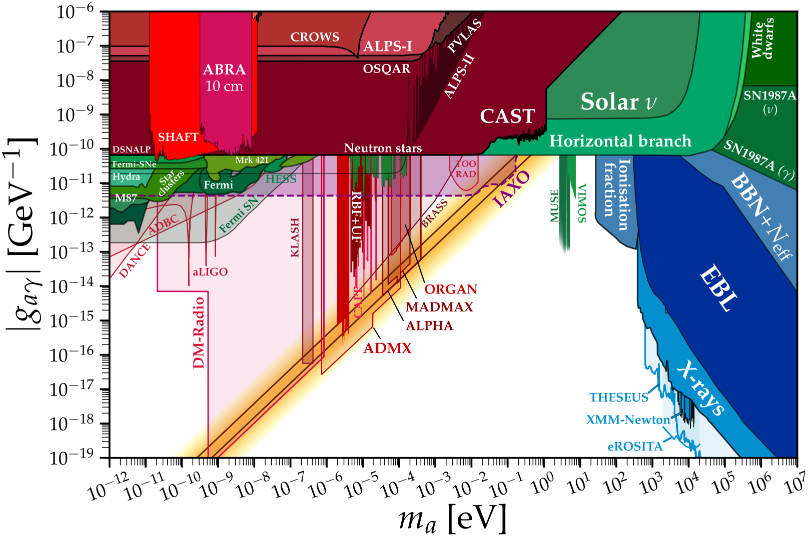
Example: detecting axion wiggles





Preliminary

The ALP parameter space



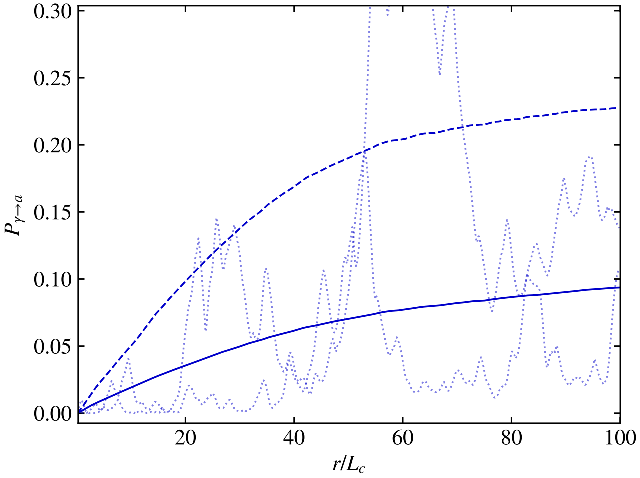
(adapted from [10.5281/zenodo.3932430])

Summary

- The axion was postulated to clean up a problem with an axial current
- Axions/ALPs can describe e.g. dark matter, dark energy, inflation, the strong CP proble, but it is not almighty
- Photon-axion oscillations lead to regular wiggles in photon spectra
- Axion wiggles can be detected using the discrete power spectrum

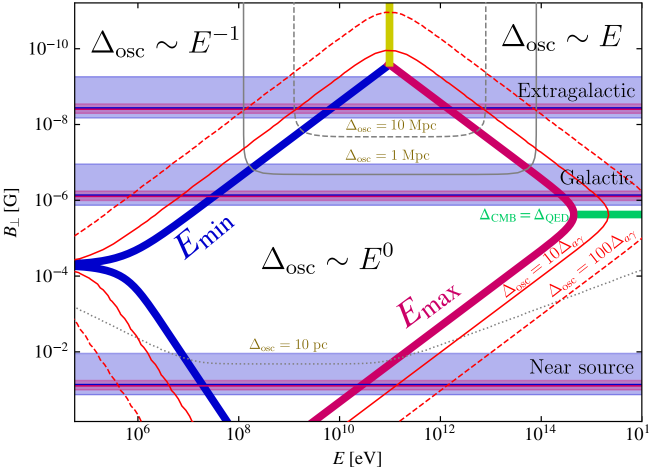
BACKUP SLIDES

Distance dependence



Preliminary

The parameter space of axion wiggles



Preliminary