Axions

SM Lagrangian should in principle have a term of the form

$$\mathcal{L}_\Theta = \frac{\Theta}{16\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

↳ gluon field strength

Generated by CP violation in quark ~~terms~~ sector of SM – no reason for $\Theta = 0$.

But induces neutron electric dipole moment (EDM)

$$d_n = 5.2 \times 10^{-16}\, \Theta \ e\,\text{cm}$$

Experimentally, $d_n < 3\times 10^{-26}$ e cm $\Rightarrow \Theta \lesssim 10^{-10}$

Why so small?

Axion solution: replace Θ by dynamical field $\frac{a}{f_a}$, a = axion field, $\frac{1}{f_a}$ = coupling

Need to explain why a evolves to small value

There is an effective potential for a (for derivation, see e.g. Dine's TASI lectures hep-ph/0011376):

$$V(a) = -m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} \cos(a/f_a).$$

$f_\pi \approx 93$ MeV – pion decay const

$m_\pi \approx 135$ MeV – pion mass

Minima at $\frac{a}{f_a} = 2n\pi$, let's examine $n=0$.

Coefficient of a^2 term gives axion mass, &

$$+V(a) \approx -m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u+m_d} + \frac{1}{2} a^2 \left(\frac{f_\pi}{f_a}\right)^2 m_\pi^2 \frac{\sqrt{m_u m_d}}{m_u+m_d} \Rightarrow m_a = \frac{f_\pi m_\pi}{f_a} \left(\frac{m_u m_d}{(m_u+m_d)^2}\right)^{1/4} \approx 0.6\ \text{meV} \left(\frac{10^{10}\,\text{GeV}}{f_a}\right)$$

Thus $\frac{1}{f_a}$ controls coupling of axions to SM fields

("DFSZ axion" = couplings to photons, gluons, leptons, quarks

"KFSZ/hadronic axion" = couplings to photons/gluons only

Axion mass also $\propto \frac{1}{f_a}$ − the lighter the axion, the more weakly it couples.

As we discussed earlier sub-keV axions can't be thermal − need to be much colder than SM (or would violate warm DM bounds)

But this meshes well with being v/ weakly coupled − interactions don't keep them in equilibrium w/ SM.

− Were they ever in equilibrium? Can they decay? (no symmetry keeps them stable)

Timescale for decay to photons $\tau \sim 10^{24}\,s \left(\frac{m_A}{eV}\right)^{-5}$. Age of universe $\sim 10^{10}$ yr $\sim 3\times 10^{17}$ s

Axion DM $\Rightarrow m_A \leq 20$ eV

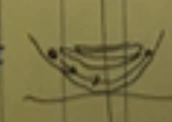
If $m_A \gtrsim 10^{-3} - 10^{-2}$ eV, can attain thermal equilibrium with SM, become HDM

$\Omega_{axions} \sim O\left(\frac{m_A}{100\,eV}\right)$ $m_A \leq 1$ eV OK for HDM limits ($O(1\%)$ contribution)

Cannot be 100% of DM.

For 100% of DM, need non-thermal ~~DM~~ axion, mass $\leq 10^{-3}$ eV

Consider axions as classical scalar field, $\Theta(t) = \langle a(t) \rangle$, evolving in potential



EOM: $\frac{d^2\Theta}{dt^2} + 3H\frac{d\Theta}{dt} + m_a^2\Theta = 0$ ~~(a = scalar field, not scale factor)~~

↳ shape of potential near minimum

For $m_a \ll H$, $\frac{d\Theta}{dt} \approx 0$ is soln − field is "frozen" at constant value Θ_0

For $m_a > H$, field begins to oscillate in potential, $\Theta(t) = \Theta_0 f(t) \cos(m_a t)$ ↑ fast oscillations

Θ_0: initial condition; $f(t) \propto (\text{scale factor})^{-3/2}$

To see scaling of energy density, note

$\dot{\Theta}(t) \approx \Theta_0 f(t) (-m_a \sin(m_a t))$ (+ terms depending on slow oscillation of $f(t)$)

i.e $\langle \dot{\Theta}(t)^2 \rangle \approx \langle \Theta(t)^2 \rangle m_a^2$

Write EOM as

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

$$\Rightarrow \frac{1}{2}\frac{d}{dt}(\dot{\Theta}^2) + 3H\dot{\Theta}^2 + \frac{m_a^2}{2}\frac{d}{dt}\Theta^2 = 0$$

Replace $\dot{\Theta}^2$, Θ^2 with their expectation values; & $\langle \Theta^2 \rangle = \frac{1}{m_a^2}\langle \dot{\Theta}^2 \rangle$

$$\frac{1}{2}\frac{d}{dt}\langle \dot{\Theta}^2 \rangle + 3H\langle \dot{\Theta}^2 \rangle + \frac{1}{2}\frac{d}{dt}\langle \dot{\Theta}^2 \rangle = 0$$

$$\Rightarrow \frac{d}{dt}\langle \dot{\Theta}^2 \rangle = -3H\langle \dot{\Theta}^2 \rangle$$

Energy density is $PE + KE = \frac{1}{2}m_a^2\Theta^2 + \frac{1}{2}\dot{\Theta}^2$

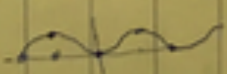
$$\approx \frac{1}{2}\left(m_a^2 \Theta_0^2 f(t)^2 \cos^2(m_a t) + m_a^2 \Theta_0^2 f(t)^2 \sin^2(m_a t)\right)$$

$$= \frac{1}{2}\langle \dot{\Theta}^2 \rangle$$

So $\frac{d\rho}{dt} = -3H\rho \Rightarrow \rho \propto a^{-3}$, eqn of state for matter

$\Rightarrow$ can act as CDM

Now Θ_0 = initial value of $\langle a \rangle$ varies between $\pm f_a \pi$ (at least, if closest minimum is at $\Theta = 0$)



Write $\Theta = \frac{\Theta_0}{f_a}$ - "misalignment angle"] Initial $\rho = \frac{1}{2}m_a^2\Theta_0^2$

$= \frac{1}{2}\theta^2 m_a^2 f_a^2$

Careful relic density calculation gives:

$$\frac{\Omega_{axions}}{\Omega_{DM}} \approx \theta^2 \left(\frac{f_a}{5\times 10^{11}\ \text{GeV}} \right)^{1.184}$$

Lighter axions $\rightarrow$ higher f_a $\rightarrow$ larger relic density (smaller m_a $\rightarrow$ oscillations start later, ρ starts redshifting later)

(Can always suppress Ω_{axions} by small initial misalignment angle θ. But θ is an angle, cannot be $\gg 1$.

$\Rightarrow$ To be 100% of DM, must have $f_a \gtrsim 10^{11}$ GeV - high-scale physics

Also implies $m_a \lesssim \frac{f_\pi m_\pi}{f_a} \sim 0.1$ meV to be all DM

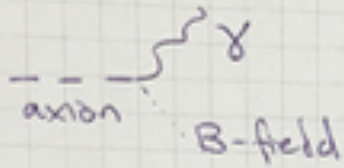
What value should θ have?

* If axions are produced/misalignment angle is set after inflation, $H_I \gg f_a$, then different patches of cosmos have different misalignment angles - take average of random sample, get $O(1)$ number

* If misalignment angle is set before inflation, same everywhere in our Hubble volume. Could take any value. Anthropic axion?

Axion searches

(good review by Graham et al 1602.00039)



- Axions/photons can interconvert in B-field
  - photons can travel through regions that should be opaque to them ~~~---~~

$$\mathcal{L} = G_{a\gamma\gamma}\, a F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$= G_{a\gamma\gamma}\, a \vec{E}\cdot\vec{B}$$

couplings $G_{a\gamma\gamma}$ scale as $1/f_a$

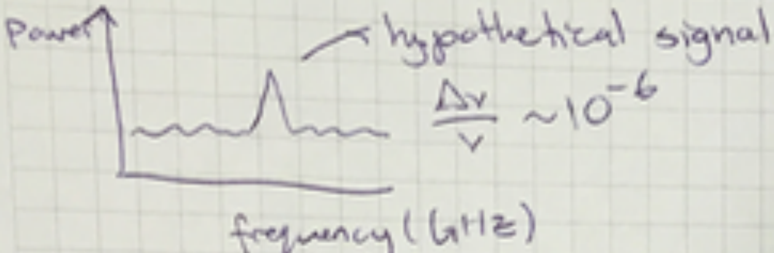
- could "catch" cosmological axions using B-fields, creating photons / inducing EM fields

- Axions can also induce nuclear electric dipole moments (CASPEr, 1306.6089)
- " " change proton-neutron mass splitting, affecting nucleosynthesis (1401.6460)
- + other neat QCD effects..

But focusing on axion-photon interconversion:

- in astrophysics - can enhance stellar cooling, axions escape more easily than photons (e.g 0806.2807)
- in the lab, "light shining through a wall", e.g 1009.4875
- in cosmology - could allow us to see photons from higher redshifts than otherwise possible
  - ↳ pair production on extragalactic background light absorbs photons when $E_\gamma E_{EBL} \gtrsim m_e^2$. Depends sensitively on EBL
- converting cosmological axions in resonant cavities
  - ADMX experiment, measure output power from microwave resonant cavity w/ strong B-field
    - axion-photon conversion will enhance power if B-field frequency matches axion energy. Vary frequency, look for a bump.

ADMX



$\frac{\Delta\nu}{\nu} \sim 10^{-6}$

Current limits just miss the CDM window for QCD axion (see 1310.8642)

ADMX-Gen2 hopes to cover CDM region for QCD axion for $\nu \lesssim 10$ GHz, IF $\exists$ $O(1)$ misalignment angle, in next few years

- CAST looks for conversions using B-field of Sun (e.g Arik et al PRL 112, 091302)
  IAXO next-gen, 1302.3273
- ABRACADABRA looks for induced effective electric current in a large toroidal magnet (1602.01086)
- MADMAX looks for axion-photon conversion at interface between different dielectric materials (1611.04549)

Axion-photon coupling limits: