Axion dark matter from frictional misalignment

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*Based on arXiv:2206.01129

Misalignment Mechanism

Assuming a pre-inflationary scenario for the scale of Peccei-Quinn breaking the value of the axion after inflation would be homogeneous $\frac{a_i}{f} \equiv \theta_i = \mathcal{O}(1)$
and follows the eom

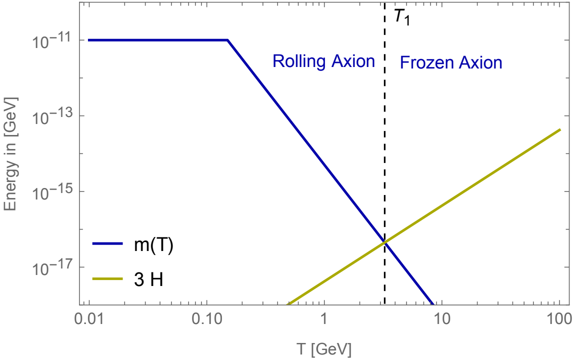
$$\ddot{\theta} + 3H\dot{\theta} + m(T)^2 \sin(\theta) = 0 \qquad (1)$$

At early times $3H \gg m(T)$ the axion is frozen at it's initial value

$$\theta(T) = \theta_i \qquad (2)$$

At around $3H \sim m(T)$ the axion is released starts oscillating around the bottom of the potential.

Misalignment Mechanism



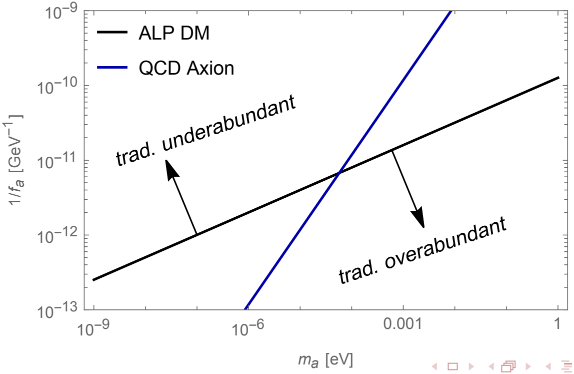
At late times the axion behaves as dark matter

$$A = \frac{a^3\,\rho_a}{m(T)} = \mathrm{ct} \to \rho_a \propto a^{-3} \tag{3}$$

Misalignment Mechanism

Axion dark matter abundance

$$\frac{\rho_{a,0}}{\rho_{\rm DM}} \simeq 28\sqrt{\frac{m_a}{\rm eV}}\sqrt{\frac{m_a}{m_{\rm osc}}}\left(\frac{\theta_i f_a}{10^{12}\,\rm GeV}\right)^2 \mathcal{F}(T_{\rm osc}) \qquad (4)$$



Kinetic misalignment as an alternative?

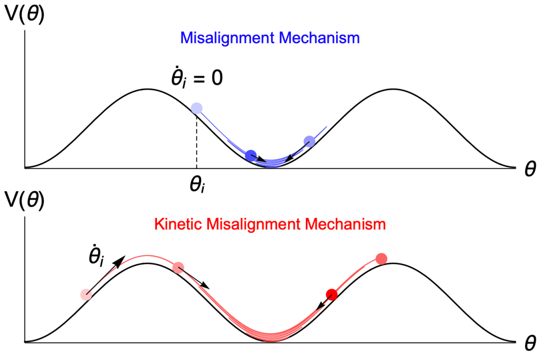


Figure 1: Taken from 1910.14152: Co, Hall, Harigaya

Kinetic misalignment as an alternative?

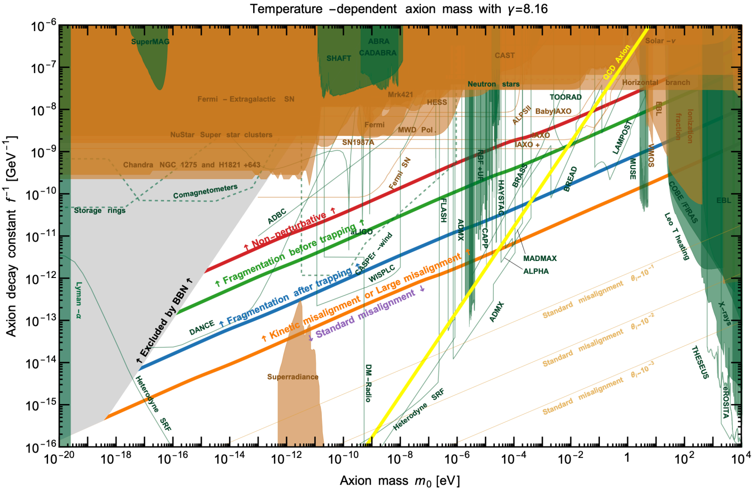


Figure 2: Taken from 2206.14259: Eroncël, Sato, Servant, Sorensen

Axions in a thermal bath

We assume an axion coupled to a dark non-Abelian gauge field which forms a thermal bath of temperature T'

$$\mathcal{L} \supset \frac{\alpha}{8\pi} \theta F^b_{\mu\nu} \widetilde{F}^{b\mu\nu} \,, \tag{5}$$

The effective EOMs for the axion background and gauge field are

$$\ddot{\theta}_a + \left[3H + \Upsilon(T')\right] \dot{\theta}_a = -\frac{1}{f_a^2} V'(\theta_a) \,, \tag{6}$$

$$\dot{\rho}_{\mathrm{dr}} + 4H\rho_{\mathrm{dr}} = f_a^2 \, \Upsilon(T') \, \dot{\theta}_a^{\,2} \tag{7}$$

Properties of the thermal bath

Friction coefficient for $\alpha < 0.1$

$$\Upsilon(T') = \frac{\Gamma_{\rm sph}}{2T' f_a^2} \simeq 1.8 \times \frac{N_c^2 - 1}{N_c^2} \frac{(N_c \alpha)^5 \, T'^3}{2 f_a^2} \tag{8}$$

by McLerran et al.

For QCD there is an additional Yukawa suppression factor due to the presence of light states charged under QCD.

$$\Upsilon(T') = \frac{\Gamma_{\rm sph}}{2T' f_a^2} \left(\frac{\Gamma_{\rm ch}}{\Gamma_{\rm ch} + \frac{24 T_R^2}{d_R T'^3} \Gamma_{\rm sph}} \right) \tag{9}$$

Where $\Gamma_{\rm ch} = \frac{N_c \, \alpha \, m_f^2}{T}$

Properties of the thermal bath

- Recently revived by Berghaus et al assuming there are no light states charged under the non-Abelian gauge field which lifts the Yukawa suppression. They applied this idea to warm inflation, warm dark energy and early dark energy.
- In their case the gauge coupling α can be taken to be constant because the temperature is slow-rolling.
- For axion dark matter the running of the coupling is important

$$\alpha\left(T'\right) = \frac{4\pi}{\bar{b}_0 N_c} \frac{1}{\ln\left(T'^2/\Lambda^2\right)} \tag{10}$$

where $\bar{b}_0 = \frac{11}{3}$ for confinement or $\frac{10}{3}$ spontaneous symmetry breaking.

Properties of the thermal bath

$\rho_X \equiv$ energy of dark gauge field and its decay byproducts

$$\Delta N_{\mathrm{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_X}{\rho_\gamma}\bigg|_{T=T_{\mathrm{rec}}} < 0.3 \text{ at } 95\%\text{C.L.} \qquad (11)$$

We define $\xi \equiv \frac{T_0'}{T_0}$

$$\Delta N_{\mathrm{eff}} = 0.016 \times n^{-1/3} \left(2N_c^2 - 2\right)^{4/3} \xi^4 \,, \qquad (12)$$

For $SU(3)$ we get $\xi < 0.86$

Properties of the thermal bath

The temperature of the dark thermal bath can be related to the standard model temperature through their respective entropy conservation.

$$T' = \xi \left(\frac{g_{\mathrm{s,SM}}(T)\, g'_{\mathrm{s}}(T'_0)}{g_{\mathrm{s,SM}}(T_0)\, g'_{\mathrm{s}}(T')} \right)^{1/3} T \tag{13}$$

Motion of the axion at early times

For $m(T) \equiv m_0 \left(\frac{\Lambda}{T}\right)^{\beta}$, if $3H \gg \Upsilon(T')$

$$\theta_a(T) \simeq \theta_i \mathrm{e}^{-\frac{m_a(T)^2}{6(2+\beta)H(T)^2}} , \tag{14}$$

whereas if $\Upsilon(T') \gg 3H$

$$\theta_a(T) \simeq \theta_i \mathrm{e}^{-\frac{m_a(T)^2}{(5+2\beta)\Upsilon(T')H(T)}} , \tag{15}$$

The onset of rolling is given by

$$m_a(T_{\rm osc}) \simeq \begin{cases} 4\, H(T_{\rm osc}) & , \; 3H > \Upsilon \\ \dfrac{10\Upsilon(T'_{\rm osc})\, H(T_{\rm osc})}{m_a(T_{\rm osc})} & , \; 3H < \Upsilon \end{cases} \tag{16}$$

Motion of the axion at late times

We derive a new adiabatic invariant for generic friction coefficient $\Gamma(T)$

$$A = \frac{\rho_\theta\,(t)}{\omega(t)}\,\exp\left[\int^t d\tilde{t}\,\Gamma(\tilde{t})\right] = \mathrm{const}\,, \tag{17}$$

Which recreates the correct result when $\Gamma(T) = 3H(T)$

$$A = \frac{\rho_\theta\,(T)}{m_a(T)}\,\exp\left[\int_{t_{\rm osc}}^t d\tilde{t}\,3H(\tilde{t})\right] = \frac{\rho_\theta\,a^3}{m_a} = \mathrm{const}. \tag{18}$$

and yields a new result when one considers both Hubble and thermal friction

$$A_{\rm fr} = \frac{\rho_\theta\,(T)\,a^3\,(T)}{m_a(T)}\,\exp\left[\int^t d\tilde{t}\,\Upsilon(\tilde{t})\right] = \mathrm{const}\,. \tag{19}$$

DM abundance in the presence of friction

$$\frac{\rho_{a,0}}{\rho_{\rm DM}} \simeq \underbrace{28\sqrt{\frac{m_a}{\rm eV}}\sqrt{\frac{m_a}{m_{\rm osc}}}\left(\frac{\theta_i\, f_a}{10^{12}\,\rm GeV}\right)^2 \mathcal{F}}_{\text{standard result}}\ \underbrace{{\rm e}^{-D}}_{\text{suppression}}\ \underbrace{\left(\frac{m_{\rm osc}}{4\,H_{\rm osc}}\right)^{3/2}}_{\text{enhancement}} \tag{20}$$

where

$$D \simeq 6.3\left(\frac{10^8\ \rm Gev}{f_a}\right)^2\left(\frac{\Lambda}{150\ \rm MeV}\right) \times\left[\frac{\tau^3+\tau^2+2\tau+6}{\tau^4}\,e^{\tau}-{\rm Ei}\left(\tau\right)\right]_{\tau_{\rm osc}}^{\tau_{\rm end}} \tag{21}$$

and $\tau \equiv \ln\left(\frac{T'}{\Lambda}\right)$

Basic mechanism

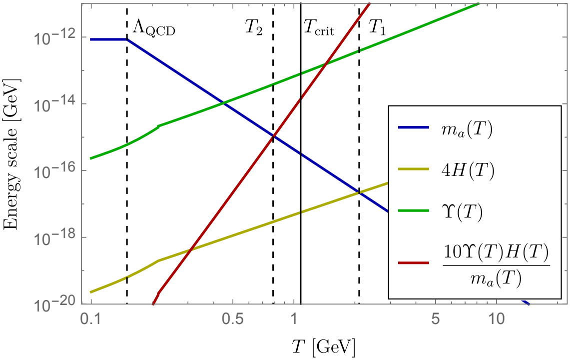


Figure 3: Example for the QCD axion

Minimal ALP scenario

We assume a single gauge group that gives rise to the mass through instanton effects and friction through sphaleron transitions. In that case $m_0 = \frac{\Lambda^2}{f_a}$

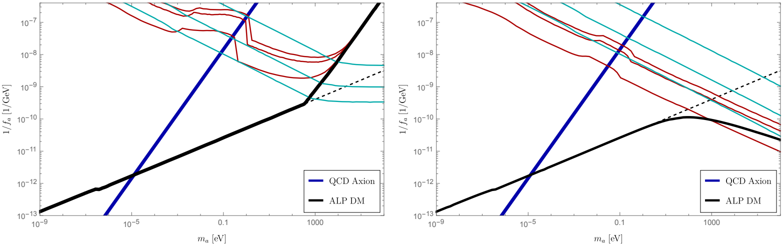


Figure 4: Left panel for $\alpha_{\rm thr} = 0.2$ and right panel for $\alpha_{\rm thr} = 0.4$

Minimal ALP scenario

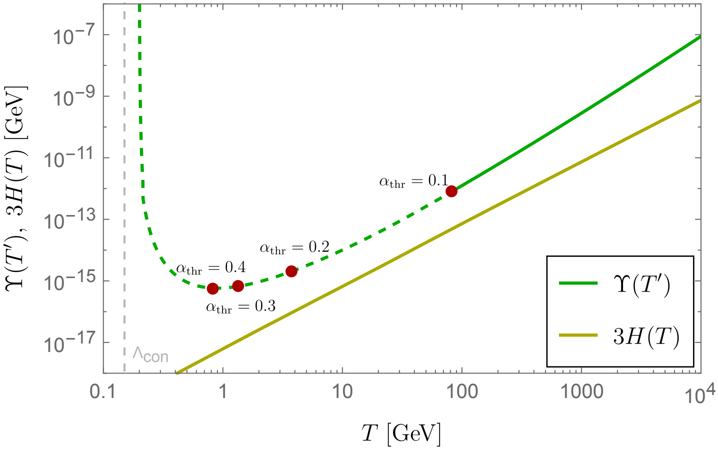


Figure 5: Evolution of the friction close to the confinement scale.

ALP coupled to two gauge groups

The model under consideration is

$$\mathcal{L}_{\rm int} = \frac{\alpha_G}{8\pi}\theta_a G^b_{\mu\nu}\widetilde{G}^{b\mu\nu} + \lambda\frac{\alpha}{8\pi}\theta_a F^b_{\mu\nu}\widetilde{F}^{b\mu\nu}\,, \tag{22}$$

In this case $m_0 = \frac{\Lambda_G^2}{f_a}$, we define the enhancement parameter

$$\lambda \equiv \text{enhancement parameter} \tag{23}$$

which we assume may be very large. Such largeness can be justified by alignment (Kim et al) or clockwork mechanism (Kaplan et al) in which case $\lambda = 3^N$.

ALP coupled to two gauge groups (underabundant case)

$$\frac{\rho_{a,0}}{\rho_{\rm DM}} \simeq \left(\frac{m_a f_a}{T_{\rm osc}^2}\right)^4 \theta_i^2 \left(\frac{T_{\rm osc}}{4.53\cdot 10^{-10}\,{\rm GeV}}\right) \frac{\mathcal{F}}{g_{\rho,{\rm SM}}(T_{\rm osc})^{3/4}} \tag{24}$$

where $T_{\rm crit} \simeq 21.6\,{\rm GeV}\left(\frac{m_a f_a}{{\rm GeV}^2}\right)^{4/7} \frac{\mathcal{F}^{1/7}}{g_{\rho,{\rm SM}}(T_{\rm crit})^{3/28}}$

Condition for opening the underabundant regime:

$$T_2 \leq T_{\rm crit} \tag{25}$$

Simplifies to

$$\frac{\mathcal{F}_a \left(\frac{m_a f_a}{17.0\,{\rm GeV}^2}\right)^{10/7} \lambda^2}{\left[1 + 0.17\left(\ln\left[\mathcal{F}_b\left(\frac{m_a f_a}{{\rm GeV}^2}\right)^{1/7}\right] + \ln\left[\Lambda_G^2/\Lambda^2\right]\right)\right]^5} > 1 \tag{26}$$

ALP coupled to two gauge groups (overabundant case)

- We simply demand that the axion dilutes sufficiently enough after it starts to roll so that its abundance matches the observed one.
- The minimum value of λ in this case is when the friction is the minimum possible over the longest possible time

ALP DM parameter space

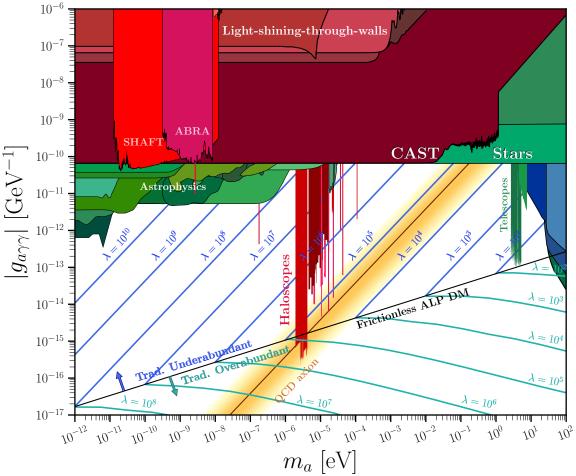


Figure 6: Minimum enhancement parameter λ for ALP DM. https://cajohare.github.io/AxionLimits/

What about the QCD axion?

The same results apply for the QCD axion with two important differences

- Our conclusions require a small correction due to the presence of light degrees of freedom charged under QCD.
  ~~$m_a^{\mathrm{QCD}} f_a = \Lambda^2_{\mathrm{QCD}}$~~ instead

$$m_a^{\mathrm{QCD}} f_a = m_\pi f_\pi \frac{\sqrt{z}}{1+z}, \quad \text{where } z \equiv \frac{m_u}{m_d} \tag{27}$$

- The only possible fate of the hidden sector is spontaneous breaking so that the axion potential is not affected and the strong CP problem is solved.

Underabundant regime for the QCD axion

$$\frac{\rho_{a,0}}{\rho_{\rm DM}} \simeq \left(\frac{m_a f_a \theta_i}{T_{\rm osc}^2}\right)^2 \left(\frac{104\,{\rm GeV}}{T_{\rm osc}}\right)^3 \frac{\mathcal{F}}{g_{\rho,{\rm SM}}(T_{\rm osc})^{3/4}} \tag{28}$$

I can set the left hand side to one and solve for a unique temperature that is independent on the QCD axion mass and decay constant.

$$T_{\rm crit} \simeq 1.08\ {\rm GeV} \quad \longleftrightarrow \quad \rho_{\rm a,0} \simeq \rho_{\rm DM}\,. \tag{29}$$

Conclusions

- We call this mechanism "Frictional misalignment". We hope to add it to a short list of other modifications of the standard mechanism such as "Kinetic misalignment" Co et al, "Trapped misalignment" Di Luzio et al etc.
- It can open up both the traditional over and underabundant regimes.
- Most of the parameter space requires the clockwork mechanism to justify the large scale hierarchy.
- It mostly evades constraints from axion fragmentation.
- Works for the QCD axion.
- Alters the picture in the minimal model for axion masses greater than $10^2\ \mathrm{eV}$

Thank You