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Dark Matter from Axion Fragmentation

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1. Motivation

Axions and the more general concept of axion-like-particles (ALPs) appear naturally in a broad range of theories and make for compelling dark matter (DM) candidates. Unfortunately, the standard misalignment mechanism has difficulties producing the observed DM relic in the low-f_a regime which is becoming increasingly accessible to dedicated ALP experiments. We here explore how both QCD-axion and ALP DM can be produced by axion fragmentation even in the low-f_a regime, which motivates the possibility of detecting ALP as DM.

2. Misalignment mechanisms

We first review the usual misalignment mechanism. Consider an ALP with the usual periodic potential:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \Lambda_b^4(1-\cos(\phi/f_a)) \quad \text{where} \quad \Lambda_b^4 = m^2(T)f_a^2. \tag{1}$$

A DM relic of such an ALP can be produced by the misalignment mechanism. This mechanism assumes that the field is initially frozen by Hubble friction with some $\phi_i \neq 0$ generally set by inflation. Naturally, we expect $\theta_i = \phi_i/f_a = \mathcal{O}(1)$ if the field is frozen at a random phase. As the expansion of the universe slows down and the condition $m_a \sim 3H$ is eventually satisfied the field begins oscillating. This results in a DM relic[1]:

$$\rho_\phi^{mis} \approx \frac{1}{2}m_* m_0 \theta_*^2 f_a^2 \left(\frac{a_*}{a_0}\right)^3 \quad \text{where} \quad \begin{matrix} {}_0 = \text{today}, \\ {}_* = \text{time of onset of oscillations}. \end{matrix} \tag{2}$$

For large values of f_a the DM tends to be overproduced, so that tuning of $\theta_i \to 0$ becomes necessary as f_a is increased. For smaller values of f_a dark matter tends to be under-produced, unless θ_i is tuned near π as in [2].

Because the low-f_a parameter space can be probed by a long list of upcoming experiments attempts have been made to extend the reach of ALP DM into this region. One such mechanism is kinetic misalignment[3]. In this framework a kicking mechanism, taken to be Affleck-Dine-like, delivers initial velocity, $\dot\phi \neq 0$. If $\dot\phi > 2\Lambda_b^2$ the kinetic energy makes the field roll over potential barriers. When Hubble friction reduces $\dot\phi$ to $\sim 2\Lambda_b^2$ the field becomes trapped and begins oscillating if $m_a > 3H$. The motion of ϕ corresponds to a conserved PQ charge $n_{PQ} \sim \dot\phi f_a$, which determines the present day relic density:

$$\rho_\phi^{kin} \approx m_a f_a \dot\phi_* \left(\frac{a_*}{a_0}\right)^3 \quad \text{where} \quad {}_* = \text{time of stopping}. \tag{3}$$

Kinetic misalignment extends the standard misalignment ALP-DM parameter in the direction of lower-f_a. However, in this work we stress that as f_a is decreased further, axion fragmentation disrupts the field before KMM can take place.

3. Axion Fragmentation

Axion fragmentation[4] arises when fluctuations are taken into account and the field passes through many wiggles due to large initial kinetic energy. To see this, expand the field into mode function u_k:

$$\phi(x,t) = \phi(t) + \left(\int \frac{d^3k}{(2\pi)^3}\hat a_k u_k(t) e^{ikx} + \text{h.c.}\right). \tag{4}$$

In the $H \to 0$ limit the equation of motion for these modes is given by a Mathieu eq:

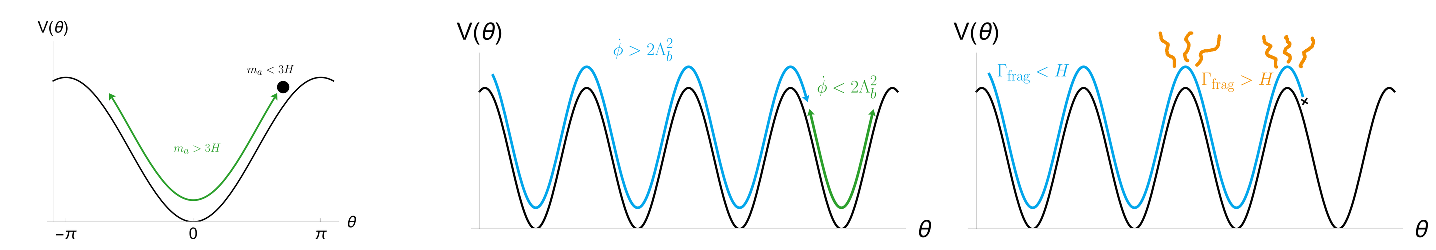
$$\ddot u_k + \left[k^2 - \frac{\Lambda_b^4}{f_a^2}\cos\left(\frac{\phi}{f_a}\right)\right]u_k = 0. \tag{5}$$

Mathieu equations are characteristic of parametric resonance, in which a band of mode functions are exponetially amplified when the zero mode $\phi(x)$ moves across peaks in the potential. This corresponds to rapid particle production which slows down ϕ and eventually transfers all energy to excitations. The energy lost to particle production by fragmentation corresponds to a friction on the zero mode[4]:

$$\Gamma_{\text{frag}} = \frac{\pi\Lambda_b^8}{2 f_a \dot\phi^3}\left(\ln\frac{32\pi^2 f_a^4}{\dot\phi^2}\right)^{-1}, \tag{6}$$

The particle production becomes efficient once it overcomes Hubble at $\Gamma_{\text{frag}} \sim H(a_*)$, after which the field quickly stops. If this takes place before Hubble friction stops the field, then KMM is prevented and a DM relic is produced by fragmentation. Because the present day relic is also fixed by the conserved PQ charge the present day relic density is identical to that of KMM.

A visual summary of the three mechanisms discussed above:



Standard misalignment — Kinetic misalignment — Axion Fragmentation

4. Parameter space

The m_a-f_a parameter space can be populated by ALP dark matter. At highest f_a the relic can be produced by the standard misalignment mechanism, although the initial displacement from the minimum has to be tuned close zero. At intermediate f_a kinetic misalignment (KMM) can take place. At low f_a axion fragmentation disrupts the zero-mode before KMM takes place. The results are summarized in the following figures:

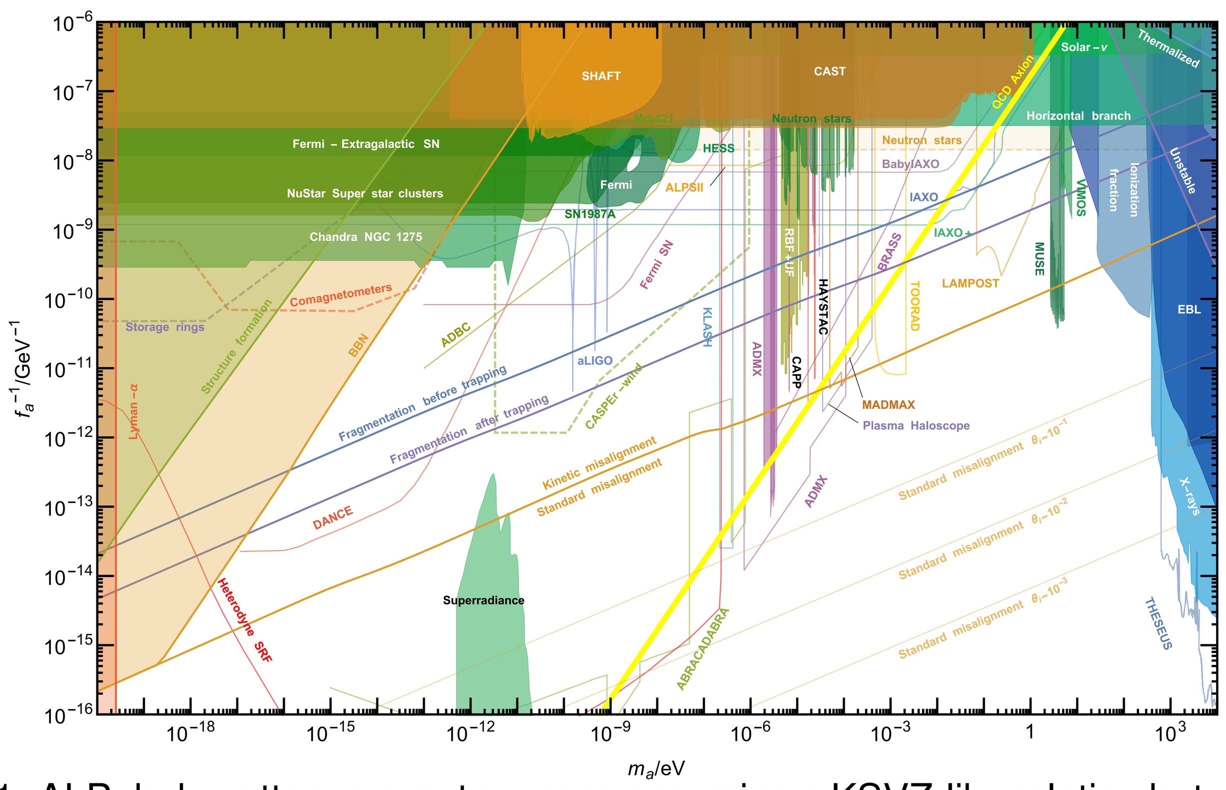


Fig 1: ALP dark matter parameter space assuming a KSVZ-like relation between f_a and the photon/neutron couplings. The white region is viable and the correct relic abundance is reproduced in every point of this region. Proposed/future experiments are given by lines without filling.

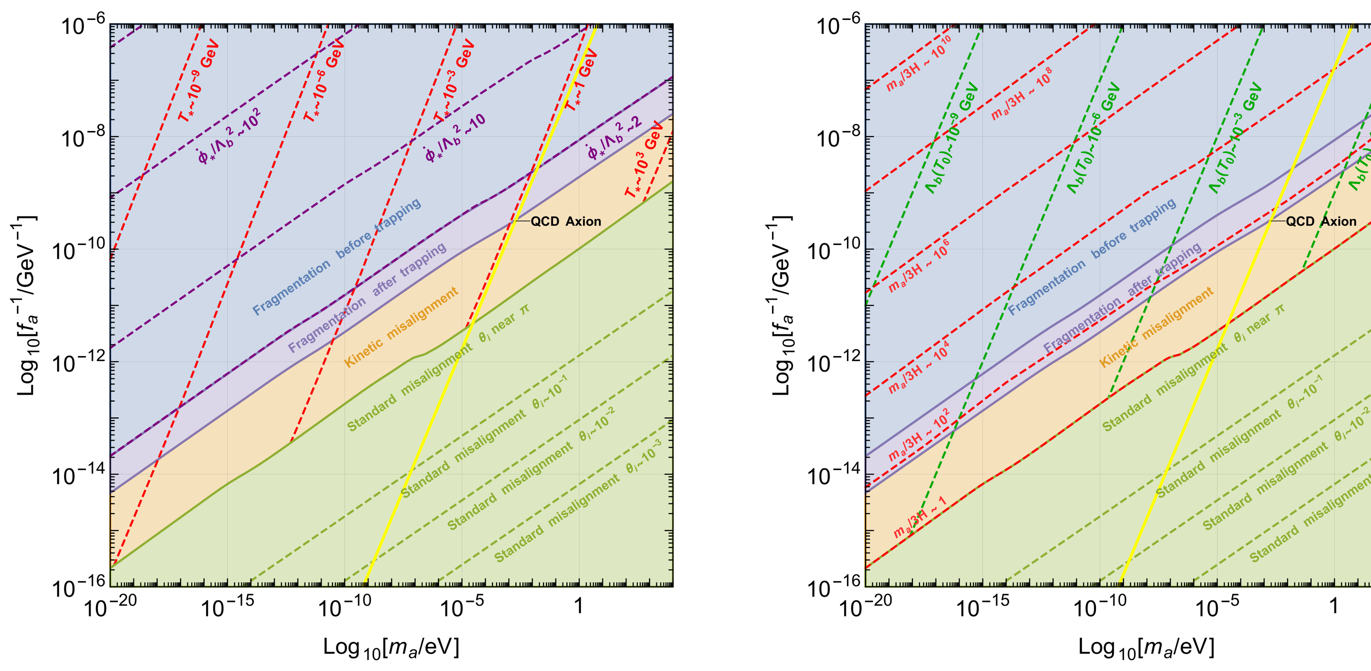


Fig 2: Regions of different ALP DM production mechanisms as well as contours of the fragmentation temperature T_*, the hidden sector confining scale Λ_b and ratios $\dot\phi_*/\Lambda_b^2$ and $m_*/3H_*$.

5. Signatures

ALP experiments: The search for axions and axion-like-particles is carried out by a diverse collection of experiments. Given that the ALP couplings to the SM generally are proportional to f_a^{-1}, the low-f_a ALP DM produced by axion fragmentation is very suitable for experimental detection.

Axion miniclusters: Axion fragmentation distinguishes itself by producing an ALP relic corresponding to a gas of particles with a momentum spectrum rather than the oscillating homogenous field of the (kinetic) misalignment mechanism. Although the gas can be cold enough to allow for CDM structure formation, the momentum distribution affects the growth of structure and in particular can lead to the formation of axion miniclusters, which could be detected by lensing and would also affect the sensitivity of haloscopes.

Gravitational waves: Parametric resonance is a source of anisotropic stress that can drive the production of gravitational waves. This is well known in the context of preheating after inflation and has also been studied in the context of an axion field fragmenting into dark photons[5]. Future work will determine if a detectable signature can also be produced by pure axion fragmentation.

6. Conclusion

Axion fragmentation extends the realm of ALP dark matter into the low-f_a regime, which allows for the possibility of detectable ALP DM. In particular, QCD-axion DM could be detected by IAXO. Axion fragmentation takes place when the field is given a non-zero initial velocity and efficient particle production disrupts the zero-mode before kinetic misalignment can take place.

7. References

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