ALP Dark Matter: Beyond the Standard Paradigm

Based on 2206.14259, 2207.10111, 2305.03756

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Axions++ — 27.09.2023

In collaboration with Aleksandr Chatrchyan (DESY → Stockholm), Matthias Koschnitzke (DESY), Géraldine Servant (DESY), Philip Sørensen (Padova) and Ryosuke Sato (Osaka)

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The cosmology of an ALP field ϕ is determined by the evolution equation:

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2}{a^2}\phi + V'(\phi) = 0, \quad V(\phi, T) = m_\phi^2(T) f_\phi^2 \left[1 - \cos\left(\frac{\phi}{f_\phi}\right)\right].$$

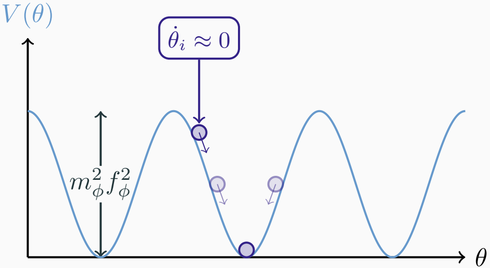
One also needs to specify the initial conditions that depends on the time of the symmetry breaking that has generated the ALP as the pNGB.

- **Post-inflationary:** Different initial conditions in each Hubble patch. Inhomogeneous.
- **Pre-inflationary:** Random initial angle $\theta \equiv \phi/f_\phi \in [-\pi, \pi)$ in observable universe. Homogeneous.

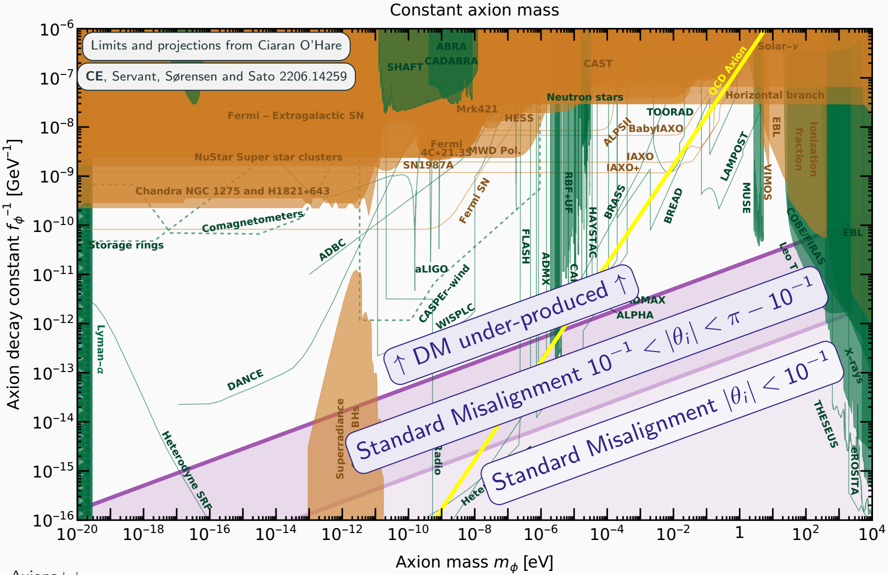
Assuming pre-inflationary scenario and negligible initial kinetic energy

$$\rho_\phi \propto \begin{cases} \text{constant}, & m(T) \ll H(T) \\ a^{-3}, & m(T) \gg H(T) \end{cases}.$$

The relic density for ALP dark matter is determined by $0 \leq |\theta_i| < \pi$.



ALP dark matter parameter space in the standard paradigm (with $g_{\theta\gamma} = (\alpha_{\text{em}}/2\pi)(1.92/f_\phi)$)



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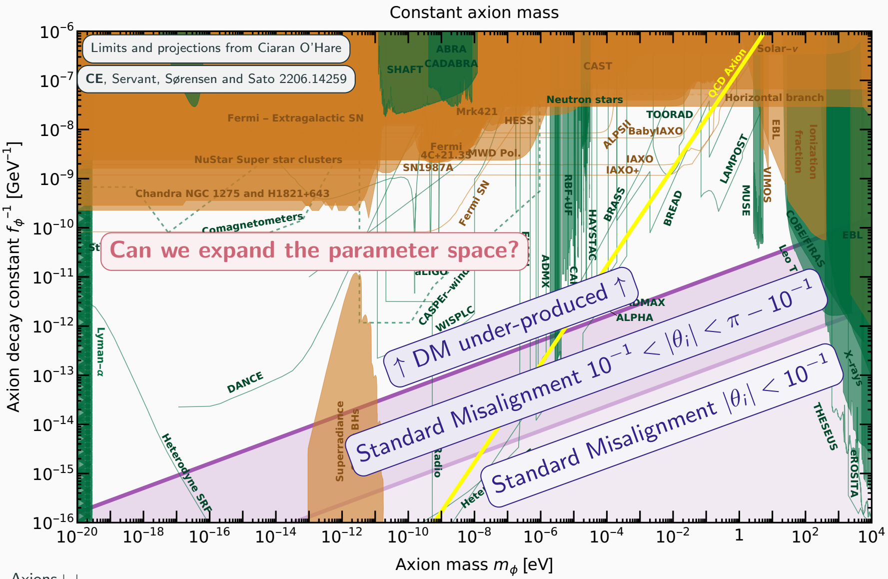

Extending the parameter space to lower f_ϕ values

- Modify the initial conditions
  - **Large misalignment:** Choose the initial angle very close to the top, i.e. $|\pi - \theta_i| \ll 1$.
    Zhang,Chiueh 1705.01439; Arvanitaki et al. 1909.11665
  - **Kinetic misalignment:** Start with a large initial kinetic energy.
    Co et al. 1910.14152; Chang et al. 1911.11885
- Modify the potential to a non-periodic one:
  Ollé+. 1906.06352; Chatrchyan, **CE**, Koschnitzke, Servant 2305.03756

$$V(\theta) = \frac{m_\phi^2 f_\phi^2}{2p}\left[\left(1+\theta^2\right)^p - 1\right], \quad p < 1.$$

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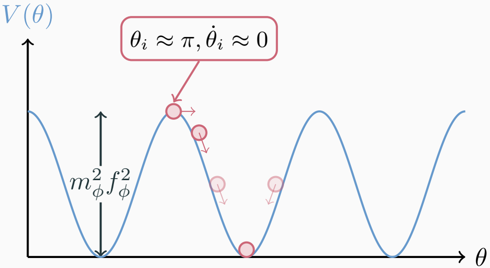

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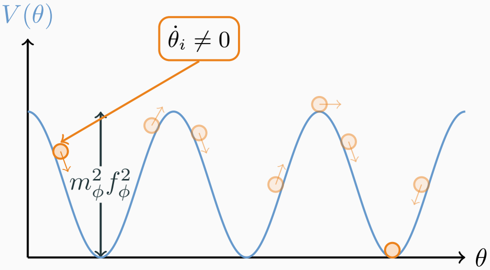

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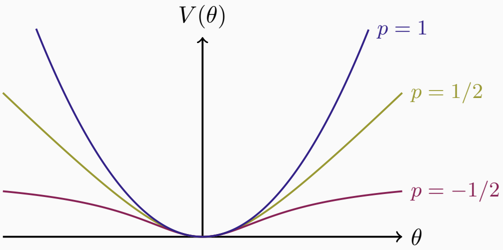
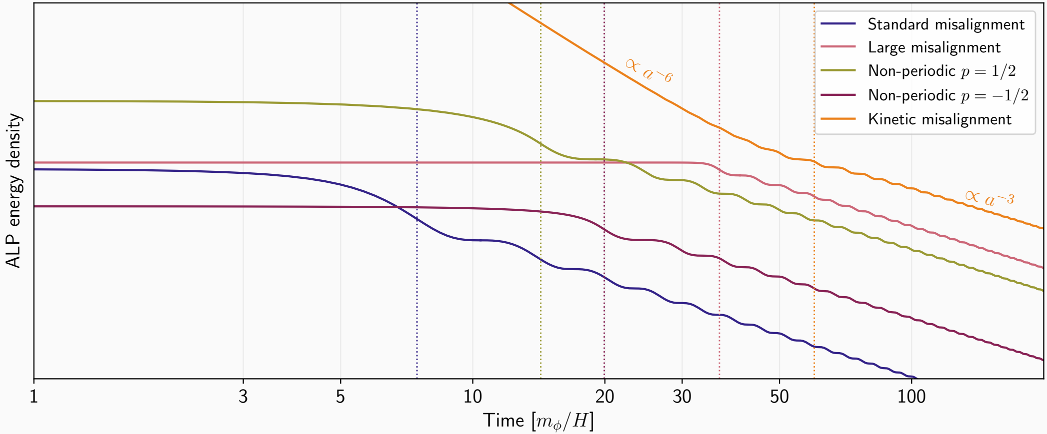
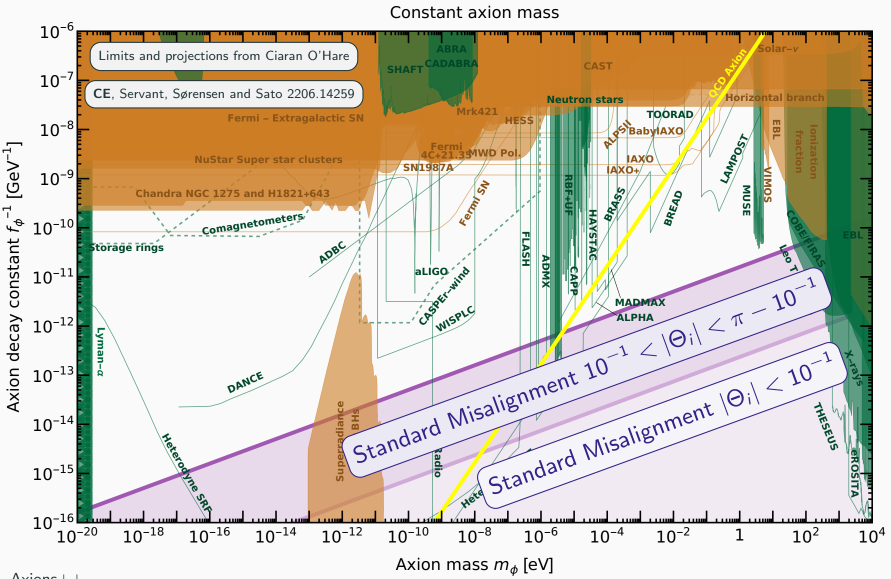


Expanding the parameter space to lower f_ϕ values



Common property of all these is that the onset of oscillations got delayed which boosts the dark matter abundance, and extends the ALP dark matter parameter space to lower decay constants.

ALP parameter space (with KSVZ-like photon coupling $g_{\theta\gamma} = (\alpha_{\text{em}}/2\pi)(1.92/f_\phi)$)



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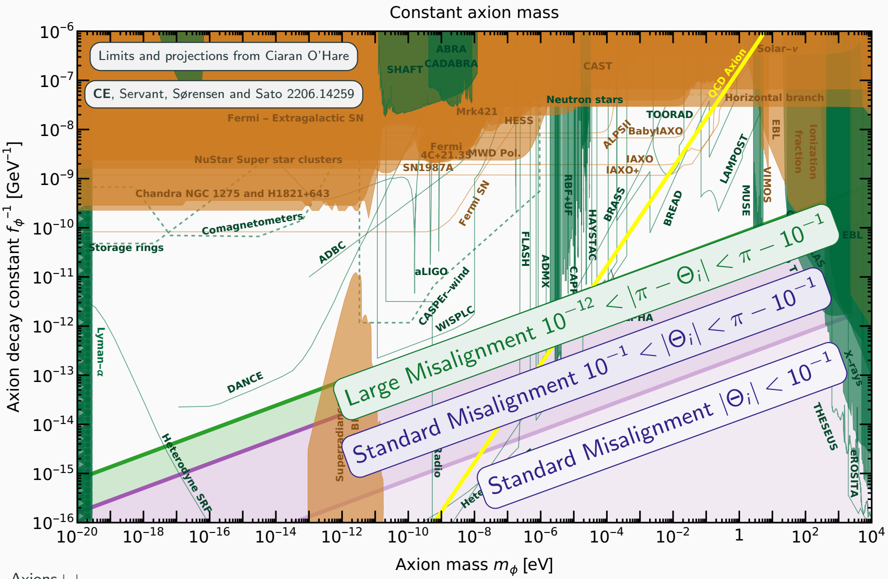

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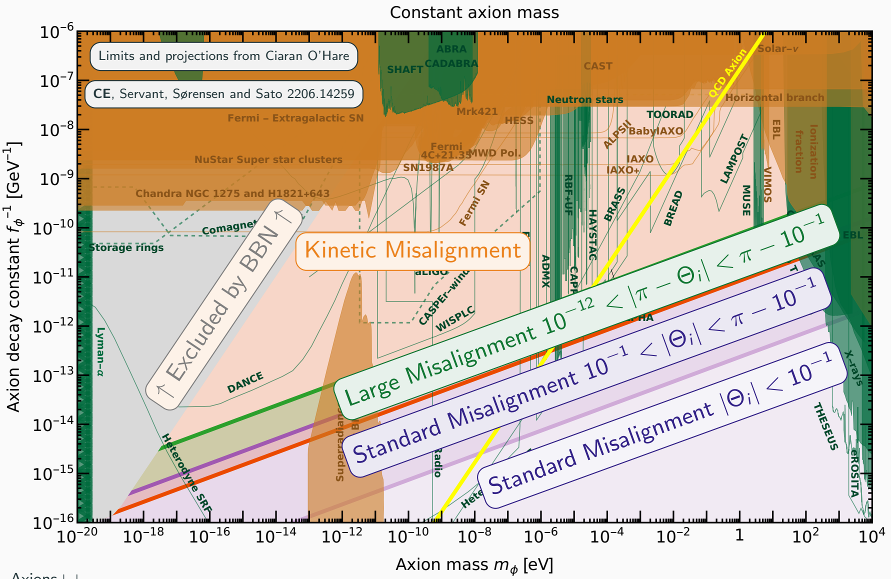

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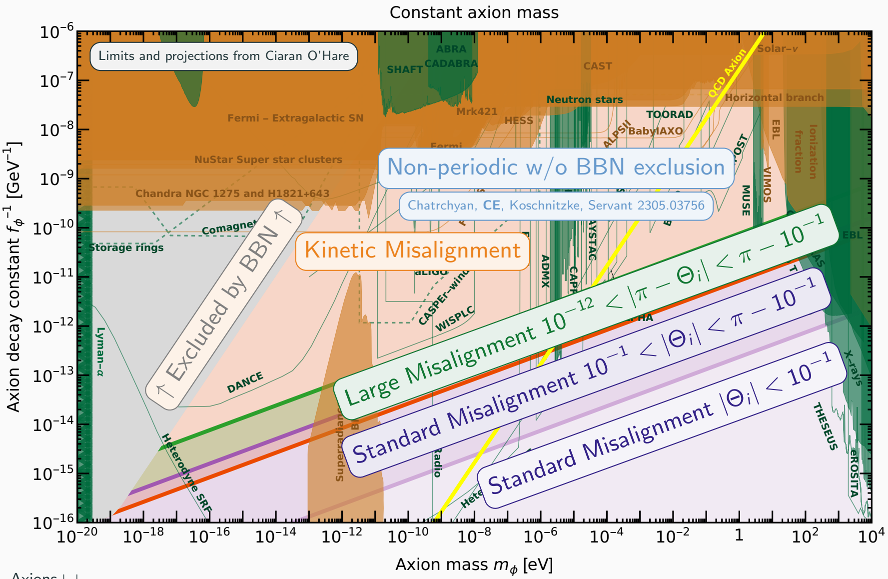

Fluctuations of the ALP field

Even in the pre-inflationary scenario ALP field has some fluctuations on top of the homogeneous background, that are seeded by the adiabatic and/or isocurvature perturbations.

$$\phi(t,\mathbf{x}) = \bar{\phi}(t) + \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \phi_k e^{i\vec{\mathbf{k}}\cdot\vec{\mathbf{x}}} + \text{h.c.}$$

The EoM for the unavoidable adiabatic perturbations are

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \underbrace{\left[\frac{k^2}{a^2} + V''(\phi)\Big|_{\bar{\phi}}\right]}_{\text{eff. frequency}} \phi_k = \underbrace{2\,\Phi_k\, V'(\phi)\Big|_{\bar{\phi}} - 4\dot{\Phi}_k \dot{\bar{\phi}}}_{\text{source term}}$$

The EoM is unstable when the effective frequency

- becomes negative $\Rightarrow$ tachyonic instability
- is oscillating $\Rightarrow$ parametric resonance

Instability exists except for a free theory where $V''(\phi) = m^2$.

Growth rate of the perturbations depend exponentially on $\left.\frac{m_\phi}{H}\right|_{\text{osc}}$.

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The size of fluctuations is determined by the density contrast:

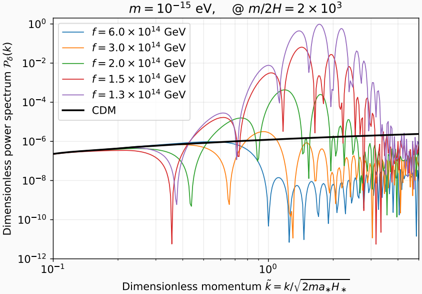
$$\delta_\rho(\vec{\mathbf{x}}, t) \equiv \frac{\rho(\vec{\mathbf{x}}, t) - \overline{\rho}(t)}{\overline{\rho}(t)}$$

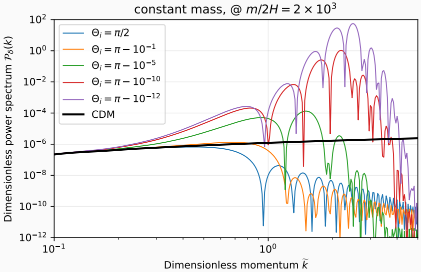
The power spectrum (two-point function) determines the distribution of structures today:

$$\mathcal{P}_\delta(k) = \frac{k^3}{2\pi^2} \left\langle \left| \tilde{\delta}_\rho(\vec{\mathbf{k}}, t) \right|^2 \right\rangle$$

After the parametric resonance the power spectrum can reach to $\mathcal{O}(1)$ values:

Dense and compact ALP mini-clusters can also be formed in the pre-inflationary scenario!





Breakdown of linearity and complete fragmentation

When the power spectrum becomes $\mathcal{O}(1)$, the linear perturbation theory breaks down, and the ALP field becomes completely fragmented. This regime can be studied by

- Semi-analytically via an energy conservation argument. Used for the Kinetic misalignment.
  Fonseca et al. 1911.08472; **CE**, Servant, Sørensen, Sato 2206.14259
- Fully numerically using lattice simulations. Used for the non-periodic potentials.
  Morgante et al. 2109.13823; Chatrchyan, **CE**, Koschnitzke, Servant 2305.03756

The non-linear effects smoothens out the power spectrum, so in the non-linear regime more efficient parametric resonance yields a power spectrum with smaller peaks.

For a given ALP mass m_ϕ and a production mechanism such as SMM, KMM, non-periodic etc..., there is a critical f_ϕ that yields the most peaked power spectrum, hence most dense structures.

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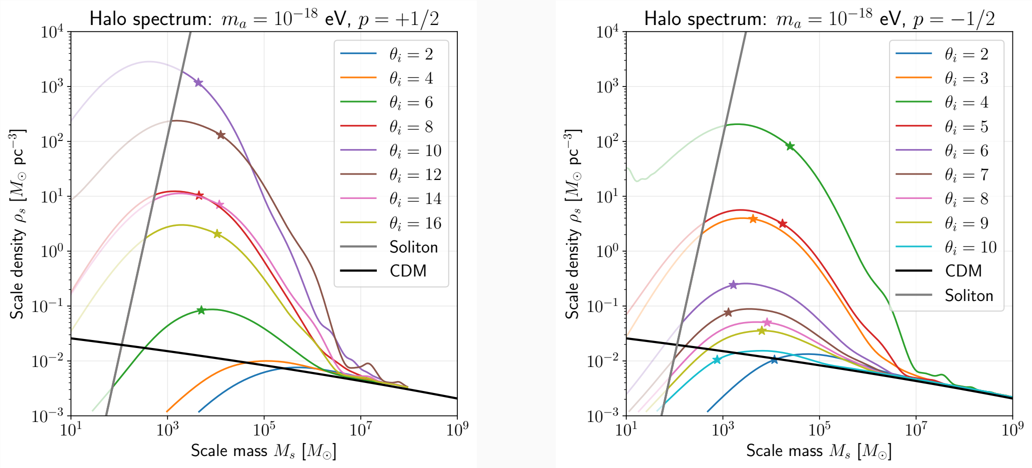
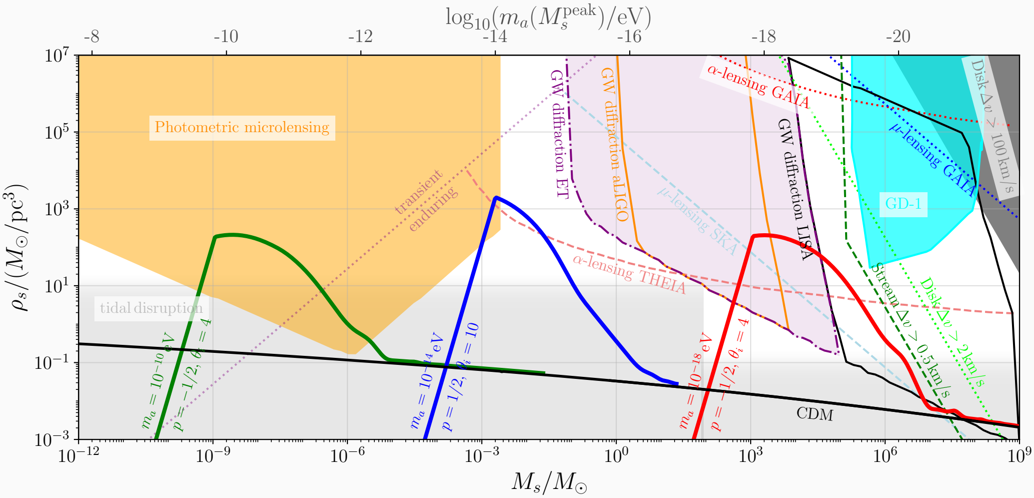
Chatrchyan, CE, Koschnitzke, Servant 2305.03756



Calculated semi-analytically using the Excursion Set Formalism assuming NFW profile, but setting the soliton line as a cutoff. Stars denote the local maxima of the Halo mass function.

Observational prospects



Experimental prospects from Tilburg et al. 1804.01991; Arvanitaki et al. 1909.11665; Ramani et al. 2005.03030

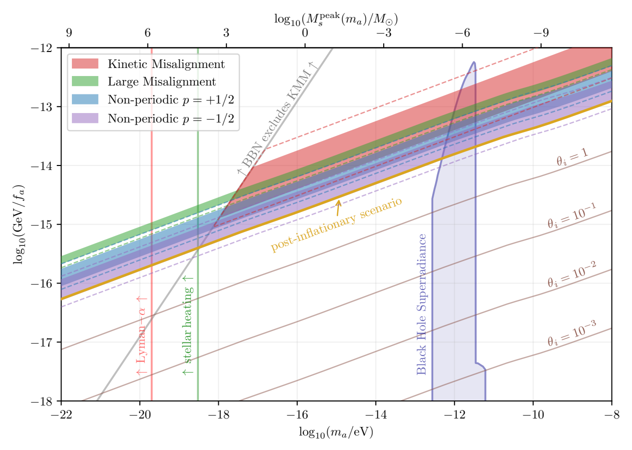
Dense halo region in the ALP parameter space

Shaded regions indicate the parameter space where parametric resonance might create halos with $\rho_s \gtrsim 10\, M_\odot\, \mathrm{pc}^{-3}$ which are more likely to survive tidal stripping

Arvanitaki et al. 1909.11665.

The "dense halo regions" in different production mechanisms mostly overlap with each other. So, it is difficult to infer the mechanism from observations.

However, observation of dense structures gives us information about the decay constant even when ALP does not couple to SM!



Conclusions and Outlook

- The Standard Misalignment Mechanism is not sufficient to account for the correct dark matter abundance in the ALP parameter space where the experiments are most sensitive.
- This parameter space can be opened by considering models where the initial energy budget is increased, and the onset of oscillations is delayed from the conventional value $m_{\rm osc}/H_{\rm osc} \sim 3$.
- In these models which go beyond the standard paradigm, the fluctuations can grow exponentially, and dense ALP mini-clusters can be formed even in the pre-inflationary scenario.
- Our semi-analytical study predicts that there is a band on the (m_ϕ, f_ϕ)-plane where the dense structures can be formed, and the location of this band does not depend drastically on the production mechanism.
- The existence of this band allows us to obtain information about the decay constant, even if ALP does not couple to the Standard Model.

Thank you for listening!

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