Axion-like particle (ALP) dark matter

Beyond the standard paradigm

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ALP dark matter in the standard paradigm

An "axion-like-particle (ALP)" is defined as a scalar field ϕ with the following effective Lagrangian at low energies:

$$\mathcal{L}_{\rm ALP} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \Lambda_b^4(T)\left[1-\cos\left(\frac{\phi}{f_\phi}\right)\right] - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} + \ldots$$

The form of $\Lambda_b(T)$ and $m_\phi f_\phi$ are fixed for the QCD axion, while they are free parameters for an ALP.

$$\Lambda_b^4(T) \approx m_\phi^2 \times \begin{cases} \left(\frac{150\,\mathrm{MeV}}{T}\right)^{8.16} & , T \geq 150\,\mathrm{MeV} \\ 1 & , T < 150\,\mathrm{MeV} \end{cases} \quad , \quad m_\phi^2 f^2 \approx (76\,\mathrm{MeV})^4$$

The cosmological evolution depends whether the ALP was present during inflation or not:

- Post-inflationary: Different initial conditions in each Hubble patch.
  $\Rightarrow$ Inhomogeneous ϕ including topological defects, such as domain walls and strings.
- Pre-inflationary: Random initial angle $\theta \equiv \phi/f_\phi \in [0, 2\pi)$ in the observable universe.
  $\Rightarrow$ Initially homogeneous w/o topological defects. **Focus of this talk.**

Standard Misalignment Mechanism in the pre-inflationary scenario

During its cosmological evolution, the ALP field obeys the following equation of motion:

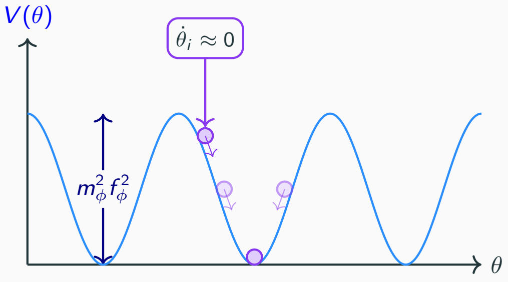
$$\ddot{\theta} + 3H\dot{\theta} - \underbrace{\frac{\nabla^2}{a^2}}_{\approx 0}\theta + \frac{1}{f_\phi^2}\frac{\mathrm{d}V}{\mathrm{d}\theta} = 0, \quad H = \frac{\dot{a}}{a}.$$

Assuming negligible initial kinetic energy, the early- and late-time limits are

$$\theta(t) \sim \begin{cases} \text{constant}, & 3H \gg m_\phi \\ a(t)^{-3/2}\cos(m_\phi t + \varphi), & 3H \ll m_\phi \end{cases}$$

The energy density at late times behaves as

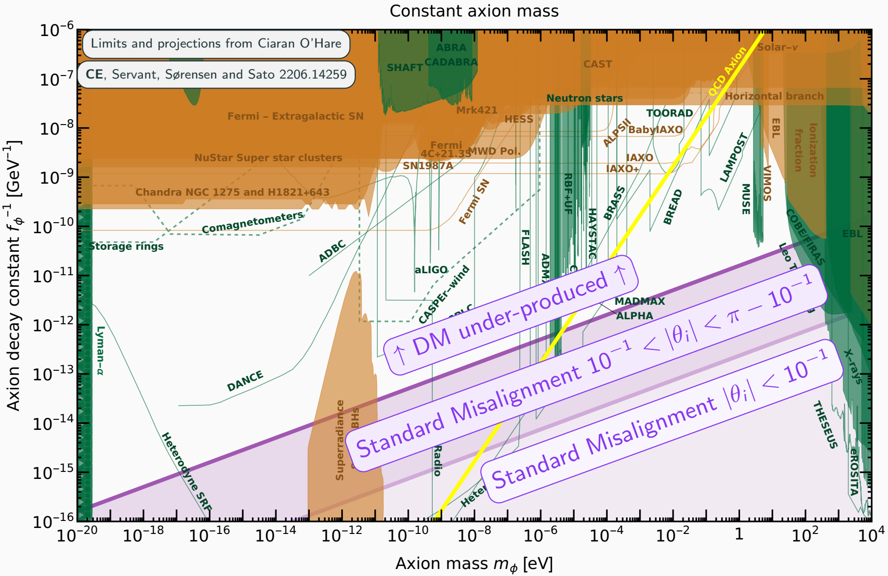
$$\rho(a) \sim \underbrace{V(\theta_i)}_{\text{initial energy}} \times \underbrace{\left(\frac{a_{\text{osc}}}{a}\right)^3}_{\text{redshift}} \propto a^{-3} \rightarrow \text{cold matter}$$



The relic density for ALP dark matter is determined by

$$0 \leq \theta_i < \pi.$$

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



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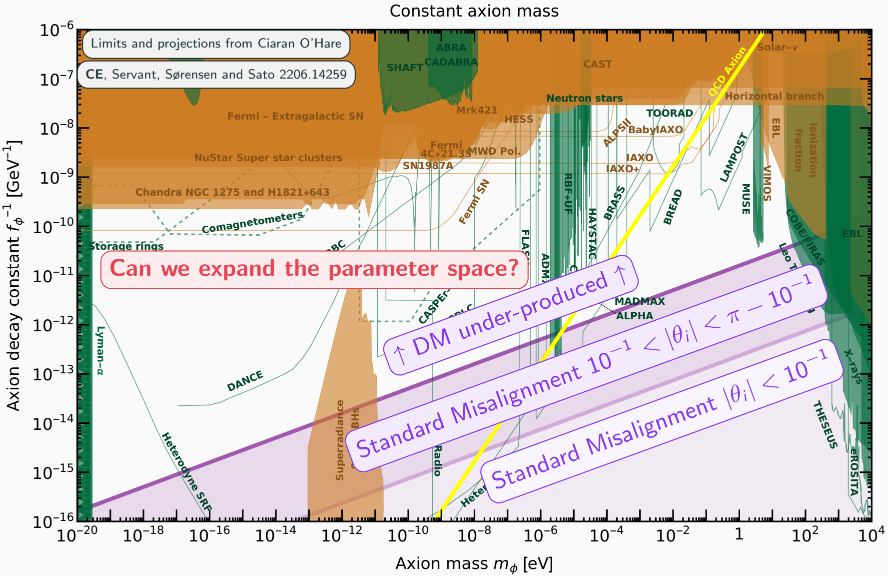


How to extend the parameter space?

In order to expand the parameter space to lower f_ϕ values, we need to boost the DM production.

$$\rho_{\phi,0} \sim \underbrace{\rho_{\phi,i}}_{\text{increase the initial energy}} \times \underbrace{\left(\frac{a_{\rm osc}}{a_0}\right)^3}_{\text{delay the oscillations}}$$

- Non-periodic potentials (Axion Monodromy): $\theta_i \gg \pi$ possible. Ollé et al. 1906.06352

  Chatrchyan, **CE**, Koschnitzke, Servant 2305.03756

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

- **Large misalignment:** Delay the onset of oscillations via $|\pi - \theta_i| \ll 1$ Zhang,Chiueh 1705.01439

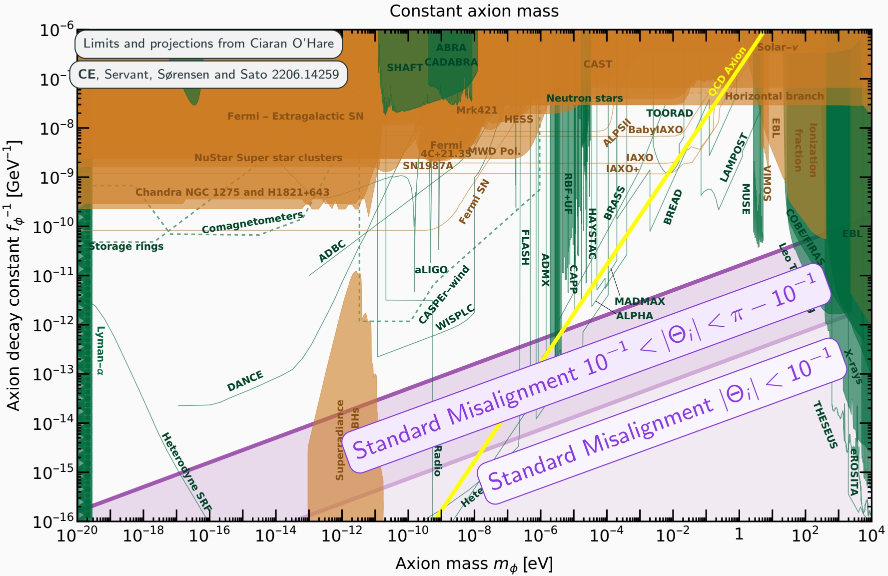
  Arvanitaki et al. 1909.11665

- **Kinetic misalignment:** Large initial kinetic energy and delay Co et al. 1910.14152; Chang et al. 1911.11885

  CE, Servant, Sørensen, Sato 2206.14259

$$\dot\phi^2(T_i) \gg 2\Lambda_b^4(T_i), \quad \frac{\dot\phi^2(T_{\rm osc})}{2} \approx 2\Lambda_b^4(T_{\rm osc}) \quad \Rightarrow \quad \frac{m(T_{\rm osc})}{H(T_{\rm osc})} \gg 1$$

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



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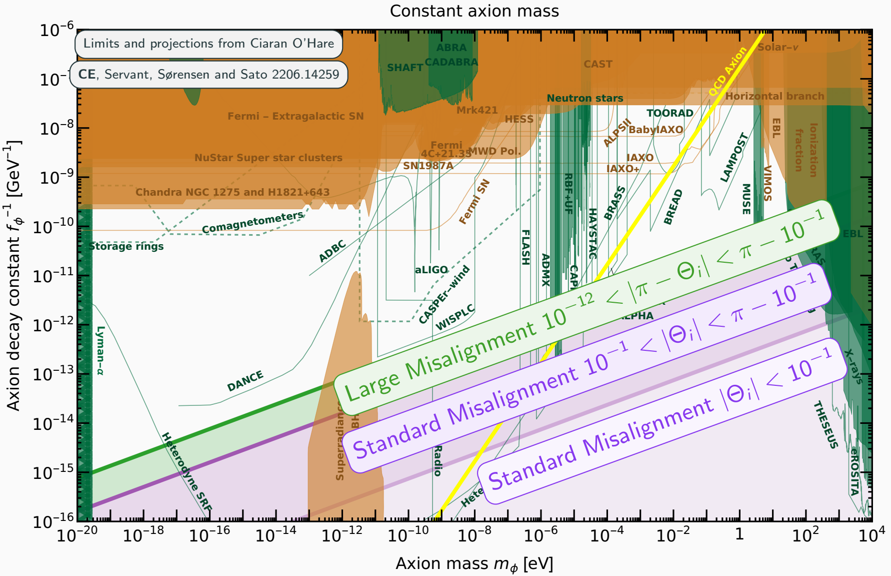

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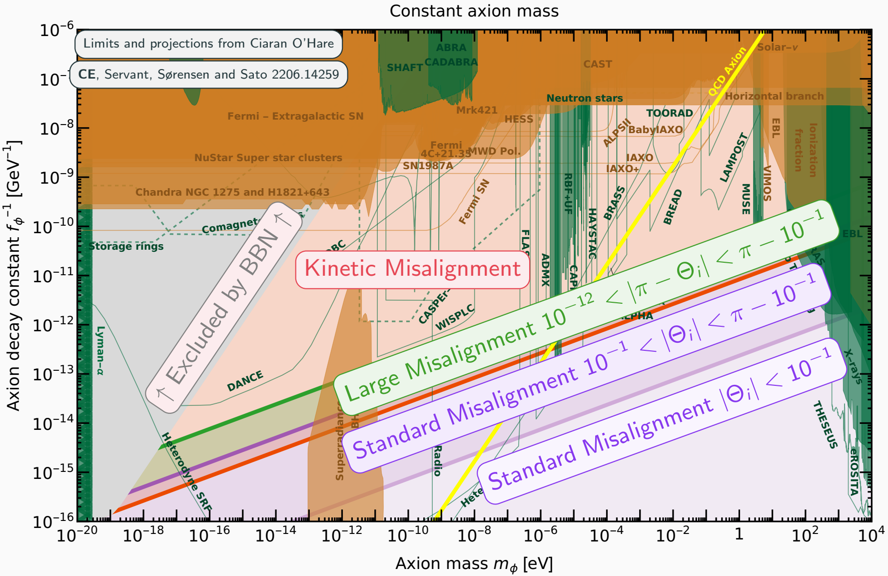

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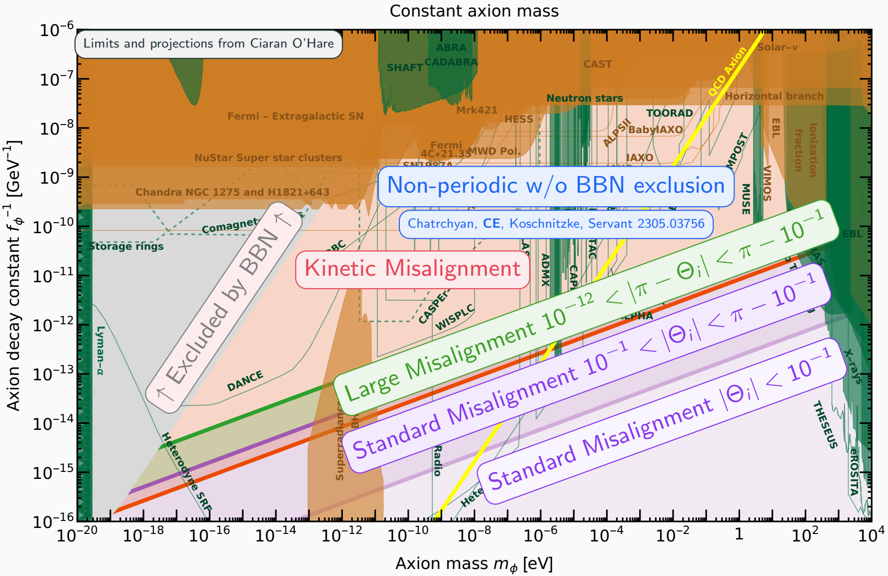


ALP fluctuations and the mode functions

- Even in the pre-inflationary scenario ALP field has some fluctuations on top of the homogeneous background which can be described by the mode functions in the Fourier space.

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

- These fluctuations are seeded by adiabatic and/or isocurvature perturbations:

Adiabatic perturbations (This work)

- Due to the energy density perturbations of the dominating component, **unavoidable**.
- Initial conditions in the super-horizon limit:

$$\delta_i/(1+w_i) = \delta_j/(1+w_j),$$

where δ is the density contrast, and w is EoS.

Isocurvature perturbations

- If ALPs exist during inflation and are light $m \ll H_{\rm inf}$, they pick up quantum fluctuations:

$$\delta\theta \sim H_{\rm inf}/(2\pi f_{\rm inf})$$

- Can be avoided/suppressed if ALP has a large mass during inflation, or $f_{\rm inf} \gg f_{\rm today}$.

- Even though the fluctuations are small initially, they can be enhanced exponentially later via tachyonic instability and/or parametric resonance yielding to **fragmentation**.

Greene et al. hep-ph/9808477; Jaeckel et al. 1605.01367; Cedeno et al. 1703.10180

Berges et al. 1903.03116; Fonseca et al. 1911.08472; Morgante et al. 2109.13823

Efficiency of parametric resonance

- The efficiency of the parametric resonance can be estimated by comparing the energy density in the fluctuations to the one in the homogeneous mode:

$$\Delta \equiv \frac{\rho_{\rm fluct}}{\rho_\Theta} \propto \underbrace{A_s}_{\sim 10^{-9}} \int \mathrm{d}\kappa \exp\left(\frac{m_{\rm osc}}{H_{\rm osc}} \underbrace{\mathcal{B}_\kappa}_{\sim \mathcal{O}(1)} \right), \quad \kappa \equiv \frac{k}{m_{\rm osc} a_{\rm osc}}$$

- The field dynamics becomes non-linear if $\Delta \gtrsim 1$. Lattice simulations are needed.
- The boundary is mainly determined by $m_{\rm osc}/H_{\rm osc}$ due to the exponential dependence:

$$\left.\frac{m_{\rm osc}}{H_{\rm osc}}\right|_{\rm boundary} \sim \mathcal{O}(10)$$

  where the exact value depends on the ALP model.
- $m_{\rm osc}/H_{\rm osc}$ increases as one goes to the upper region of the ALP parameter space, i.e. lower f_ϕ values.

Power spectrum at the end of parametric resonance

The size of fluctuations is determined by the density contrast:

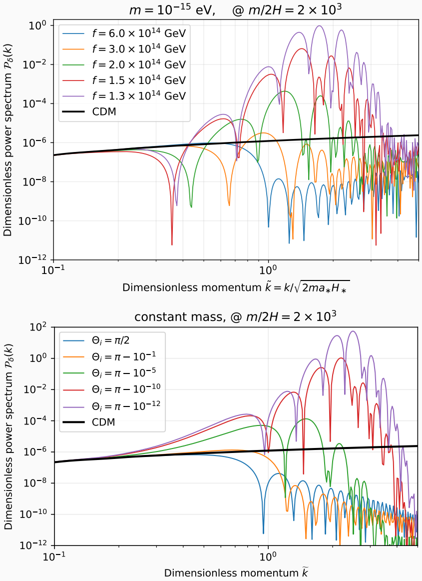
$$\delta_\rho(\vec{\mathbf{x}}, t) \equiv \frac{\rho(\vec{\mathbf{x}}, t) - \overline{\rho}(t)}{\overline{\rho}(t)}$$

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

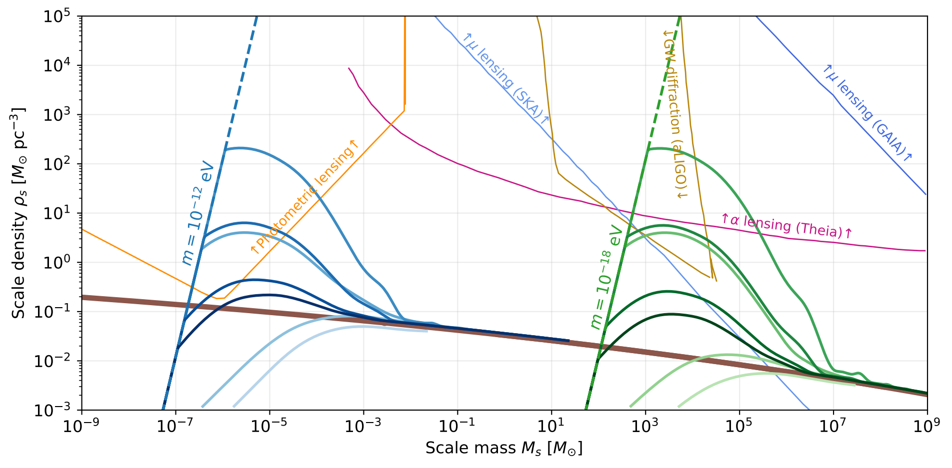
$$\mathcal{P}_\delta(k) = \frac{k^3}{2\pi^2} \left\langle \left| \tilde{\delta}_\rho(\vec{\mathbf{k}}, t) \right|^2 \right\rangle$$

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!



Halo spectra with Excursion Set Formalism (Non-periodic with $p = -1/2$)



Darker colors ⇒ Larger initial value ⇒ More delay ⇒ More efficient parametric resonance

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

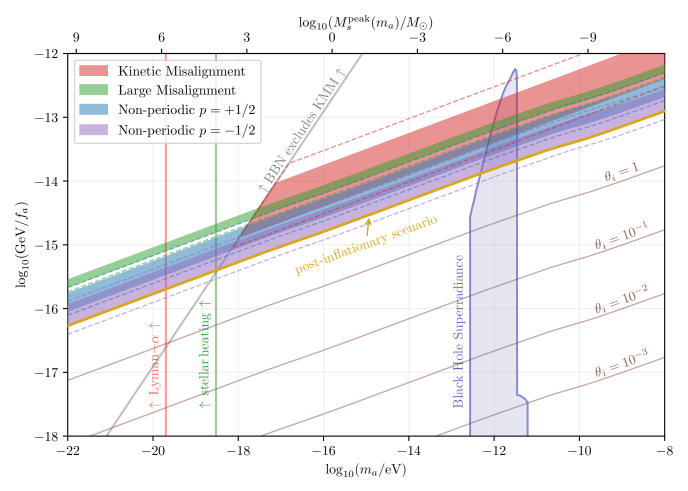
Dense halo region in the ALP parameter space

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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