ALP Dark Matter from Kinetic Fragmentation

Opening up the parameter window and observational consequences

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Based on **2206.14259** and **2207.10111**

Axions and Axion-Like-Particles (ALPs)

- One of the strongest BSM candidates: Strong CP problem, dark matter, ...
- At low energies, and high temperatures, it has the effective potential:

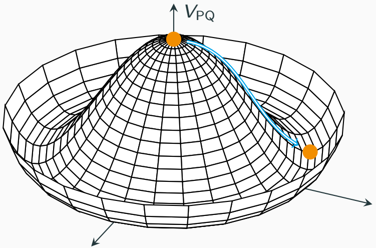
$$V_{\mathrm{ALP}} \supset m^2(T) f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right] = \Lambda_b^4(T)[1 - \cos(\theta)]$$

- The mass (barrier-height) is in general temperature-dependent:

$$m^2(T) \approx m_0^2 \times \begin{cases} \left(\frac{T_c}{T}\right)^{-\gamma} & , T \geq T_c \\ 1 & , T < T_c \end{cases}$$

QCD axion	Generic ALP
$m_0^2 f^2 \approx (76\,\mathrm{MeV})^4,\ \gamma \approx 8,\ T_c \approx 150\,\mathrm{MeV}$	m_0, f, γ, T_c are free parameters.

Pre- and post-inflationary scenario



Post-inflationary scenario

- Different initial angle in each Hubble patch.
- Inhomogeneous including topological defects.

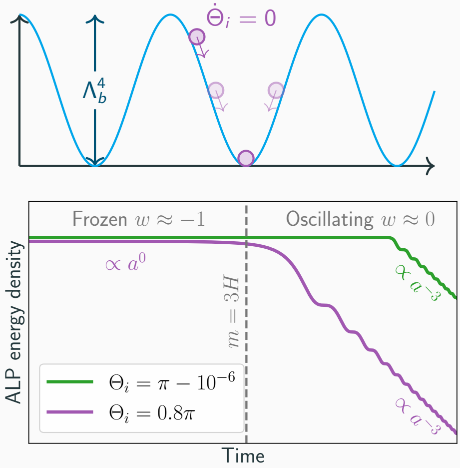
Pre-inflationary scenario (This work)

- Random initial angle in the observable universe.
- Initially homogeneous w/o topological defects.

Dark matter from ALPs: Misalignment mechanisms

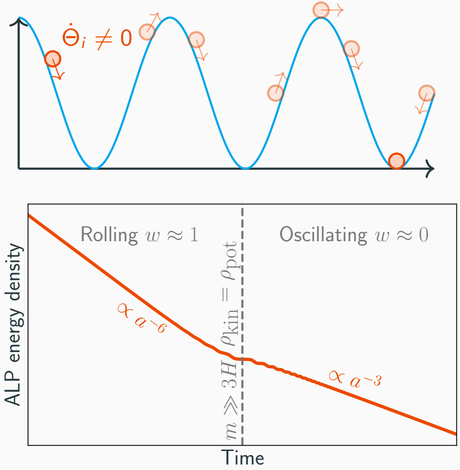
Standard (Large) misalignment

Zhang,Chiueh 1705.01439; Arvanitaki et al. 1909.11665

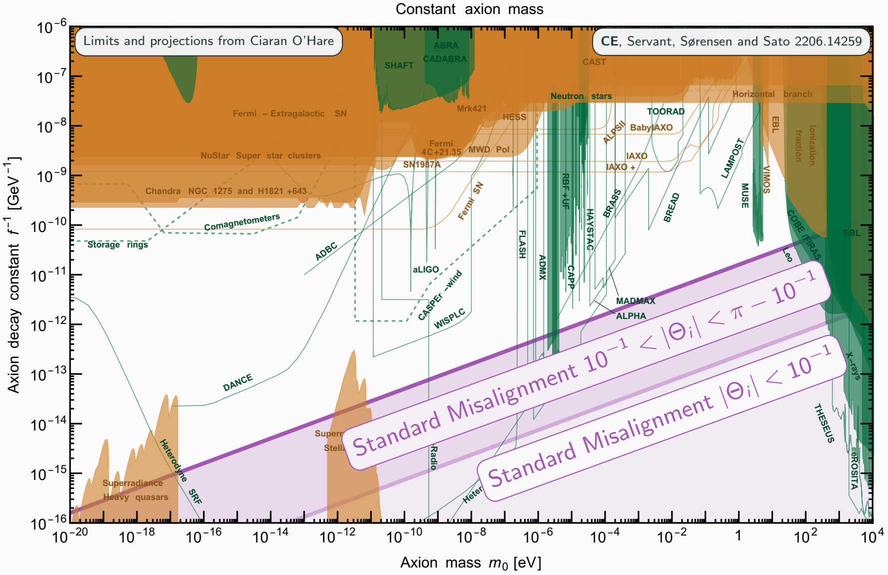


Kinetic misalignment

Co et al. 1910.14152; Chang et al. 1911.11885



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



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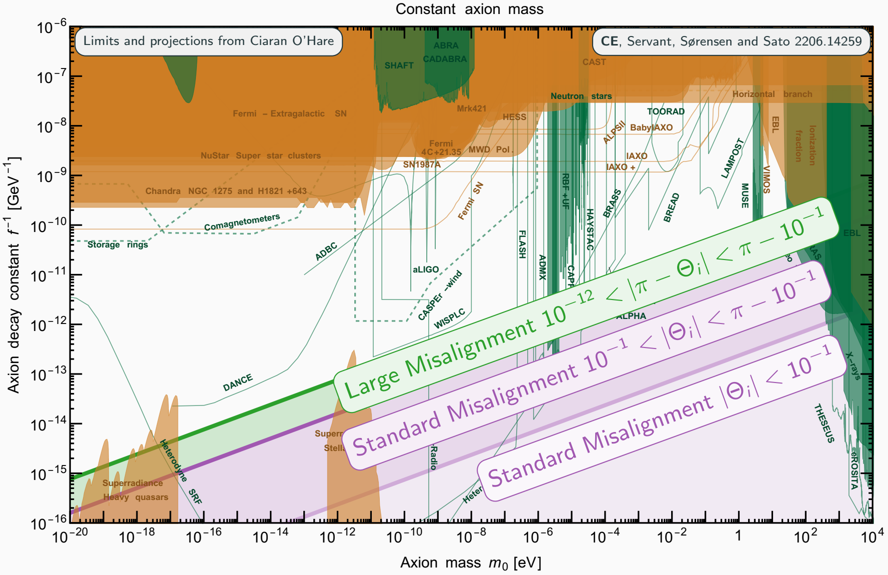

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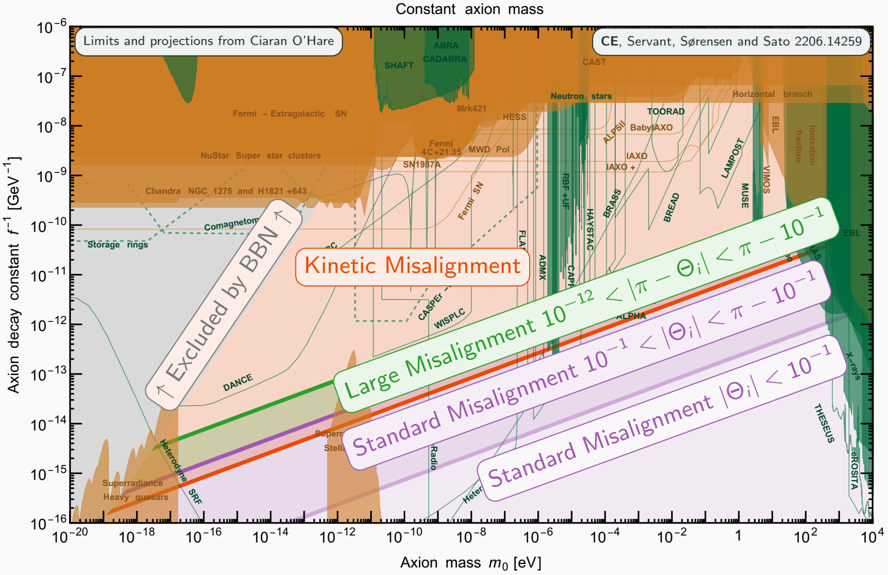


ALP fluctuations and the mode functions

- 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**.

Isocurvature perturbations

- If ALPs exist during inflation and are light $m \ll H_{\rm inf}$, they pick up quantum fluctuations:
- Can be avoided/suppressed if ALP has a large mass during inflation, or $f_{\rm inf} \gg f_{\rm today}$.

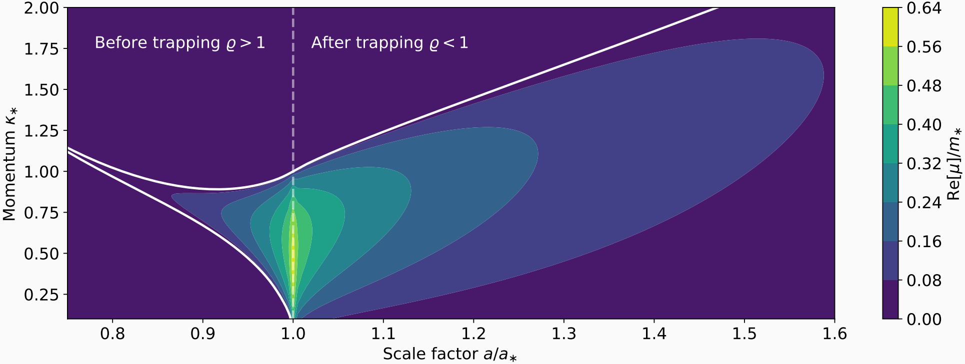
- Even though the fluctuations are small initially, they can be enhanced exponentially later via tachyonic instability and/or parametric resonance yielding to **fragmentation**.

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

Parametric resonance

CE, Servant, Sørensen, Sato 2206.14259



$$\theta_k(t) \sim \underbrace{\sqrt{P_\theta^{\mathrm{ini}}(k)}}_{\text{initial conditions}} \times \underbrace{\left(\frac{a_i}{a}\right)^{3/2}\left(\frac{\frac{k^2}{a_i^2}+m^2(T_i)}{\frac{k^2}{a^2}+m^2(T)}\right)^{1/4}}_{\text{redshift}} \times \underbrace{\exp\left(\int_{t_i}^{t}\mathrm{d}t'\ \overbrace{\mu(t')}^{\text{Floquet exp.}}\right)}_{\text{exponential growth}}$$

Initial conditions for the ALP mode functions

- To determine the power spectrum *after* the fluctuations, we need to specify the initial conditions *before* the fragmentation:

$$P_\theta^{\rm ini}(k) = \lim_{t\to t_i} \left|\theta_k^2(t)\right|$$

- At early times when the axion mass can be neglected the mode functions θ_k obey

$$\ddot{\theta}_k + 3H\dot{\theta}_k + \frac{k^2}{a^2}\theta_k = -4\dot{\Phi}_k\dot{\Theta}, \quad \Phi_k := \text{curvature perturbations in the radiation era}$$

- Assuming only adiabatic initial conditions, we analytically calculated the field power spectrum at early times as

$$P_\theta^{\rm ini}(k) \approx \frac{2\pi^2}{k^3}\left(\frac{1}{3}\right)^2 A_s \left(\frac{\dot{\Theta}}{H}\right)^2 \cos^2\left(\frac{k}{aH}\right), \quad A_s = 2.101\times 10^{-9}\ \text{(Planck 2018)}$$

Efficiency of fragmentation

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

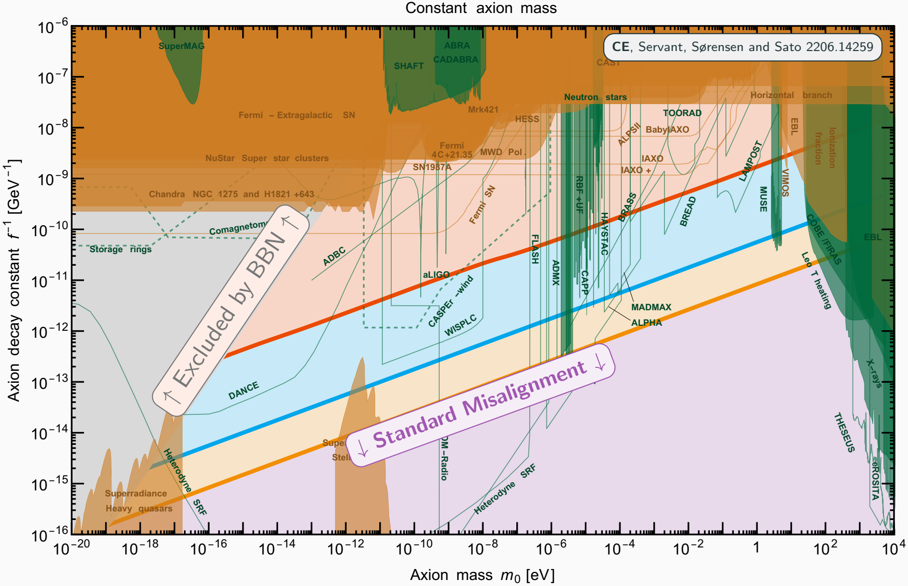
$$\Delta \equiv \frac{\rho_{\text{fluct}}}{\rho_{\Theta}} \propto \underbrace{A_s}_{\sim 10^{-9}} \int \mathrm{d}\kappa \exp\left(\frac{m_*}{H_*} \underbrace{\mathcal{B}_\kappa}_{\sim \mathcal{O}(1)}\right), \quad * := \text{quantities at trapping}, \quad \kappa \equiv \frac{k}{m_* a_*}$$

- The fragmentation is incomplete if $\Delta \lesssim 1$, and complete if $\Delta \gtrsim 1$.
- The boundary is mainly determined by m_*/H_* due to the exponential dependence:

$$\left.\frac{m_*}{H_*}\right|_{\text{boundary}} \sim \mathcal{O}(1) \times 40$$

where the $\mathcal{O}(1)$ factor depends mildly on the high-temperature scaling of the axion mass.

Fragmentation regions on the ALP parameter space



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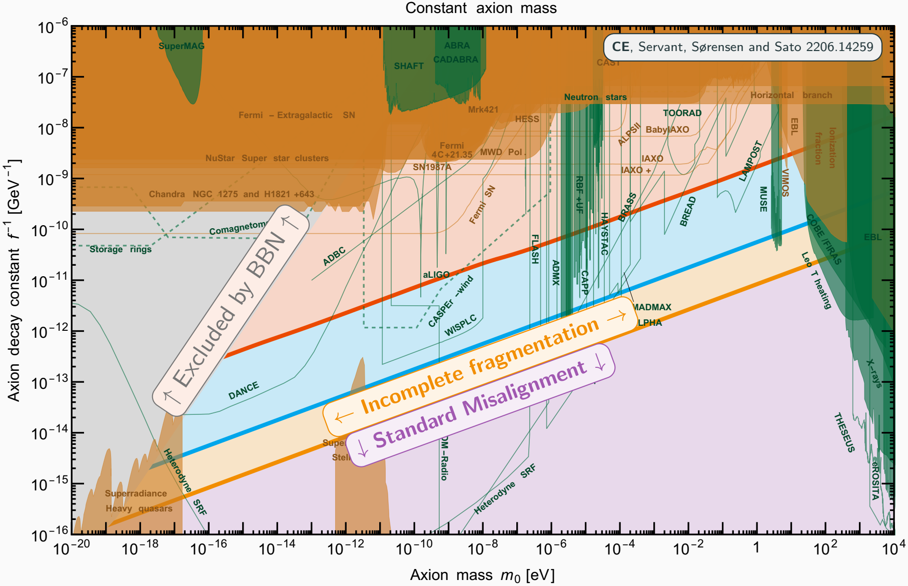

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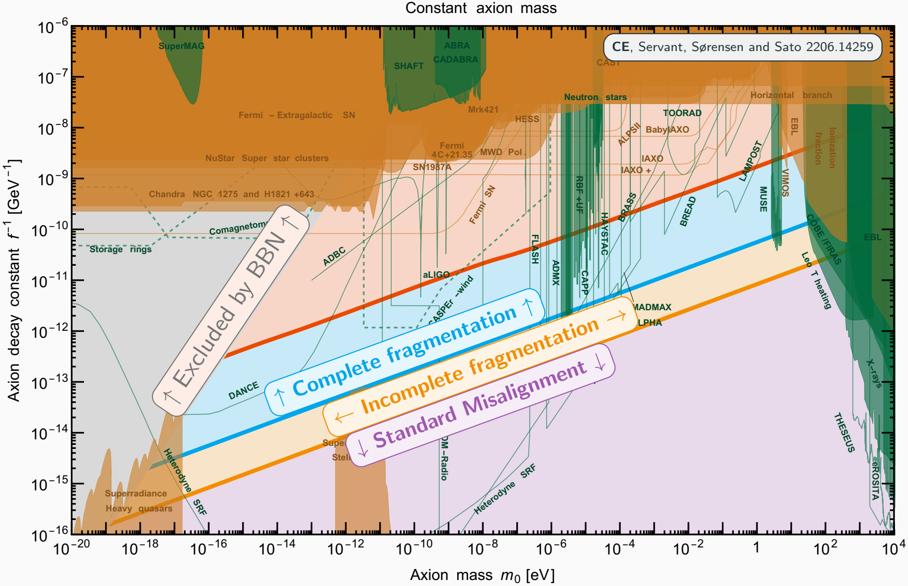
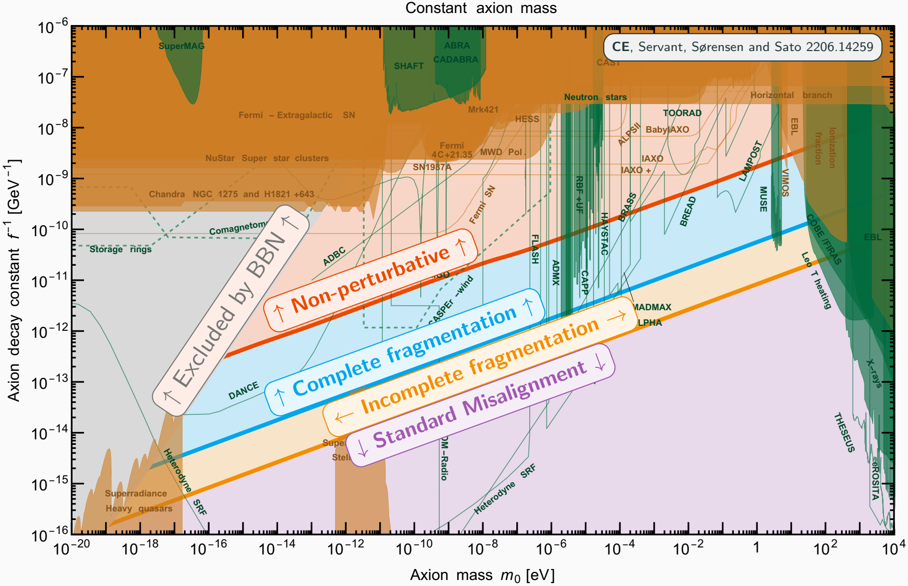
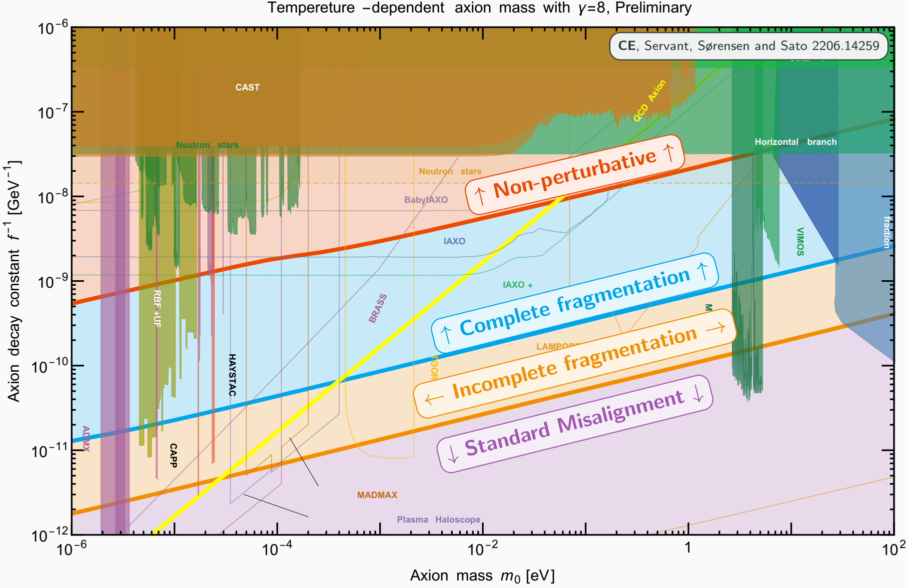


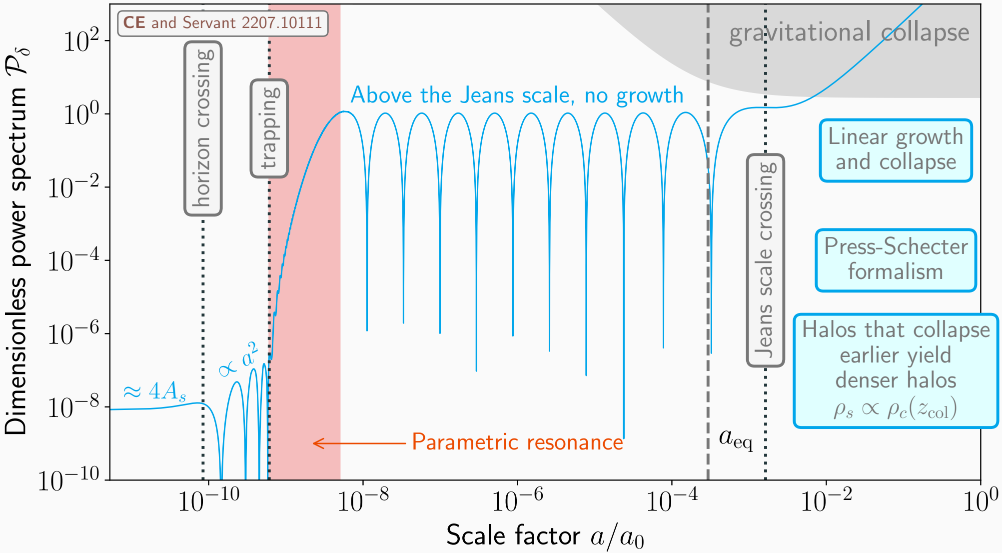
Fragmentation regions on the ALP parameter space



Fragmentation regions for the QCD axion



Lifetime of a fluctuation mode



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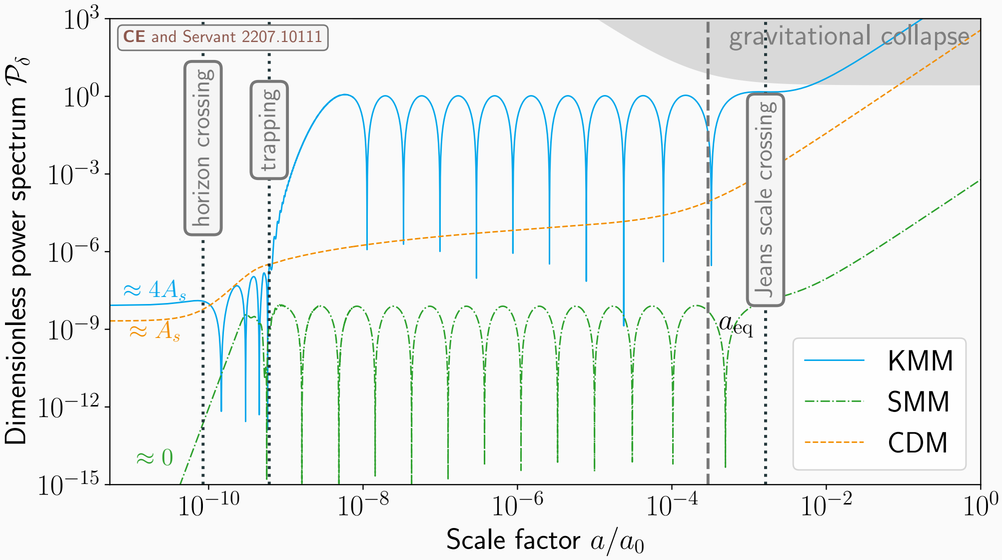
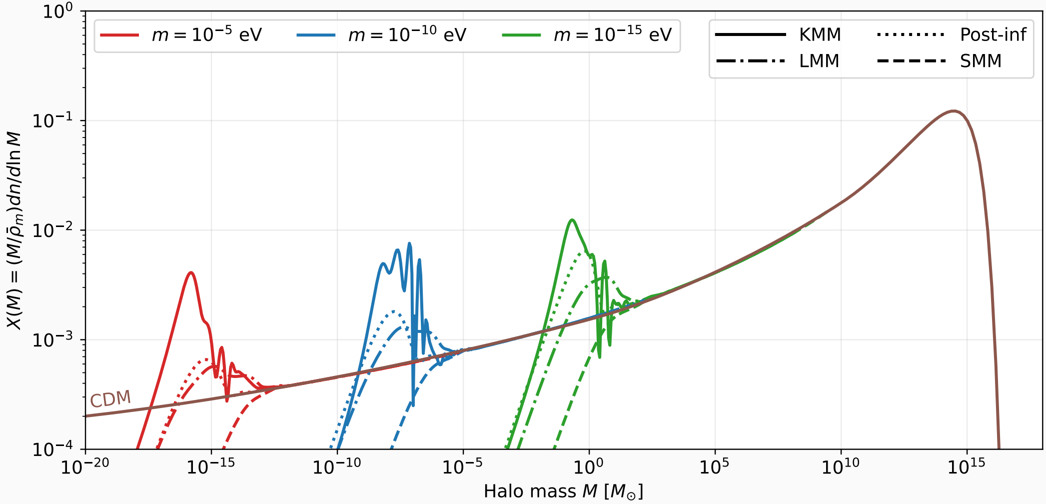
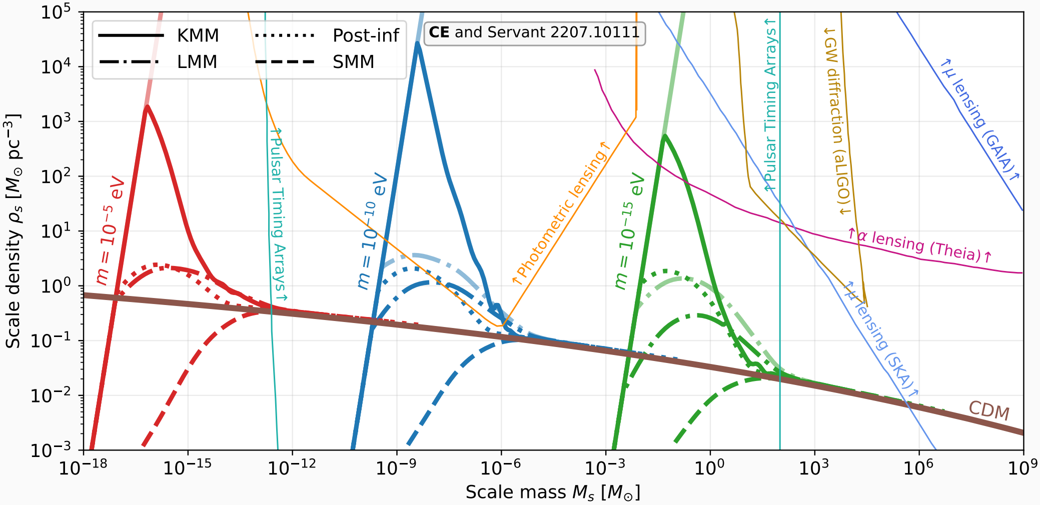


Halo mass function



Halo spectrum and gravitational observables



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

Conclusions

- In models where the ALP field has a large initial kinetic energy, ALP fluctuations play a prominent role, and can yield complete fragmentation.
- The efficiency of the fragmentation is mainly determined by the hierarchy of the axion mass and Hubble scale at trapping.
- After the fragmentation, the power spectrum becomes $\mathcal{O}(1)$ which leads to much denser dark matter halos.
- All the discussion is applicable to the QCD axion, to a generic ALP model, and also to other kind of potentials such as monodromy (Ongoing project with Aleksandr Chatrchyan, Matthias Koschnitzke, Géraldine Servant)
- The initial conditions can be motivated by various UV completions (**CE**, Servant, Sørensen, Sato. to appear), see also the talk by Keisuke Harigaya.

Thank you for listening!

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