ALP Dark Matter: Beyond the Standard Paradigm

Based on 2206.14259, 2207.10111, 2305.03756, 23xx.xxxxx

Cem Eröncel, Istanbul Technical University

International Conference on Particle Physics and Cosmology (dedicated to Prof. Rubakov memory)

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

Funded by the 2236 Co-Funded Brain Circulation Scheme2 (CoCirculation2) of The Scientific and Technological Research Council of Turkey TÜBİTAK (Project No: 121C404).

QCD Axion and Axion-Like-Particles (ALPs)

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

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

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

$$\Lambda_b^4(T) \approx m_\phi^2 \times \begin{cases} \left(\frac{T_c}{T}\right)^\gamma & , T \geq T_c \\ 1 & , T < T_c \end{cases}$$

QCD axion	Generic ALP
$m_\phi^2 f^2 \approx (76\,\mathrm{MeV})^4$, $\gamma \approx 8$, $T_c \approx 150\,\mathrm{MeV}$ Couplings to photons, nucleons, electrons, etc...	m_ϕ, f, γ, T_c are free parameters. Might not have any coupling to SM.

This talk: A generic ALP with a constant mass, i.e. $\gamma = 0$.

QCD Axion and Axion-Like-Particles (ALPs)

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

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

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

$$\Lambda_b^4(T) \approx m_\phi^2 \times \begin{cases} \left(\frac{T_c}{T}\right)^\gamma & , T \geq T_c \\ 1 & , T < T_c \end{cases}$$

QCD axion

$m_\phi^2 f^2 \approx (76\,\mathrm{MeV})^4$, $\gamma \approx 8$, $T_c \approx 150\,\mathrm{MeV}$
Couplings to photons, nucleons, electrons, etc...

Generic ALP

m_ϕ, f, γ, T_c are free parameters.
Might not have any coupling to SM.

This talk: A generic ALP with a constant mass, i.e. $\gamma = 0$.

QCD Axion and Axion-Like-Particles (ALPs)

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

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

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

$$\Lambda_b^4(T) \approx m_\phi^2 \times \begin{cases} \left(\frac{T_c}{T}\right)^\gamma & , T \geq T_c \\ 1 & , T < T_c \end{cases}$$

QCD axion	Generic ALP
$m_\phi^2 f^2 \approx (76\,\mathrm{MeV})^4$, $\gamma \approx 8$, $T_c \approx 150\,\mathrm{MeV}$ Couplings to photons, nucleons, electrons, etc...	m_ϕ, f, γ, T_c are free parameters. Might not have any coupling to SM.

This talk: A generic ALP with a constant mass, i.e. $\gamma = 0$.

QCD Axion and Axion-Like-Particles (ALPs)

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

$$\Lambda_b^4(T) \approx m_\phi^2 \times \begin{cases} \left(\frac{T_c}{T}\right)^\gamma & , T \geq T_c \\ 1 & , T < T_c \end{cases}$$

QCD axion	Generic ALP
$m_\phi^2 f^2 \approx (76\,\mathrm{MeV})^4$, $\gamma \approx 8$, $T_c \approx 150\,\mathrm{MeV}$ Couplings to photons, nucleons, electrons, etc...	m_ϕ, f, γ, T_c are free parameters. Might not have any coupling to SM.

This talk: A generic ALP with a constant mass, i.e. $\gamma = 0$.

ALP dark matter: The standard paradigm

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: The standard paradigm

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: The standard paradigm

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: The standard paradigm

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

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

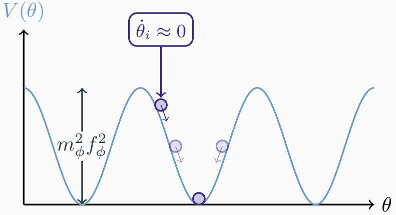
One also needs to specify the initial conditions that depends on the time of the symmetry breaking that has generated the ALP as the pNGB.

- **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.

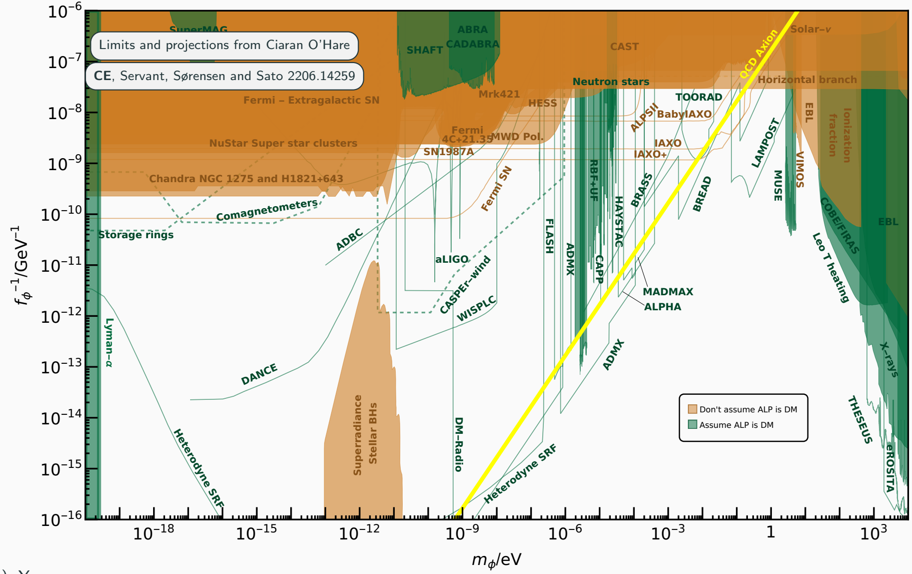
Assuming pre-inflationary scenario and negligible initial kinetic energy

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

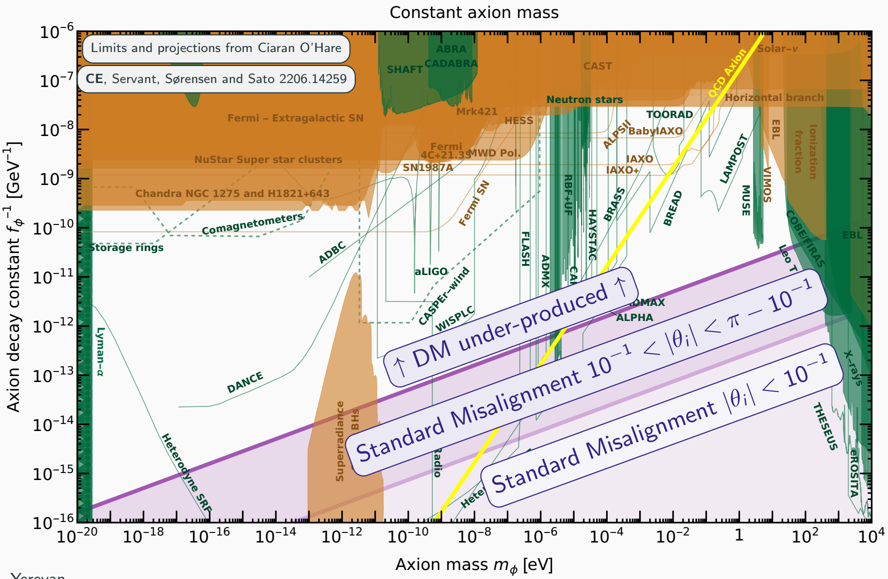
The relic density for ALP dark matter is determined by $0 \leq |\theta_i| < \pi$.



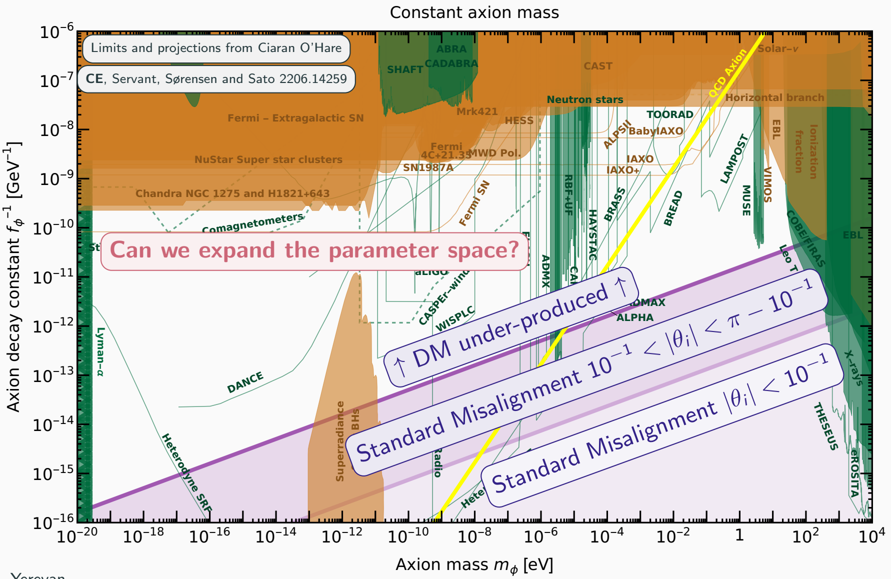
ALP dark matter parameter space in the standard paradigm (with $g_{\theta\gamma} = (\alpha_{\text{em}}/2\pi)(1.92/f_\phi)$)



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



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



Extending the parameter space to lower f_ϕ values

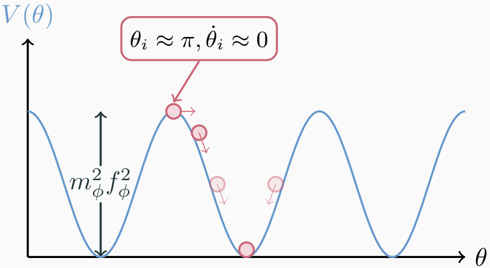
- Modify the initial conditions
  - **Large misalignment**: Choose the initial angle very close to the top, i.e. $|\pi - \theta_i| \ll 1$.
    Zhang,Chiueh 1705.01439; Arvanitaki et al. 1909.11665
  - **Kinetic misalignment:** Start with a large initial kinetic energy.
    Co et al. 1910.14152; Chang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

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

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

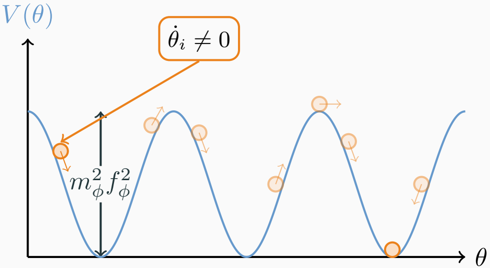
$$V(\theta) = \frac{m_\phi^2 f_\phi^2}{2p}\left[\left(1+\theta^2\right)^p - 1\right], \quad p < 1.$$



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

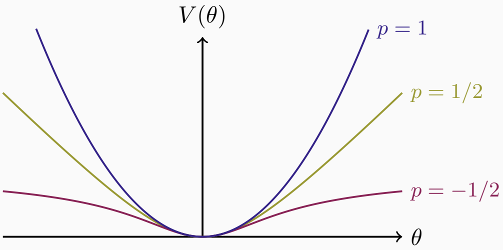
$$V(\theta) = \frac{m_\phi^2 f_\phi^2}{2p}\left[\left(1+\theta^2\right)^p - 1\right], \quad p < 1.$$



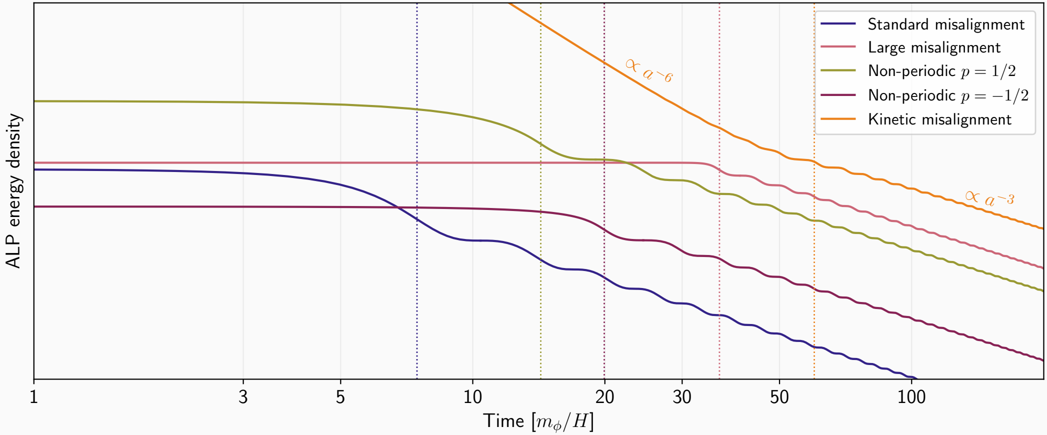
Extending the parameter space to lower f_ϕ values

- 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

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

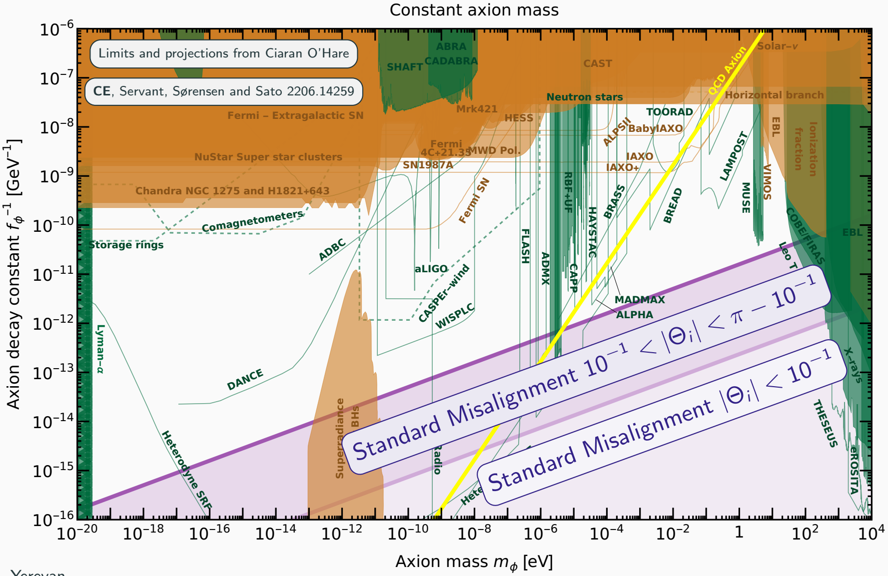


Expanding the parameter space to lower f_ϕ values

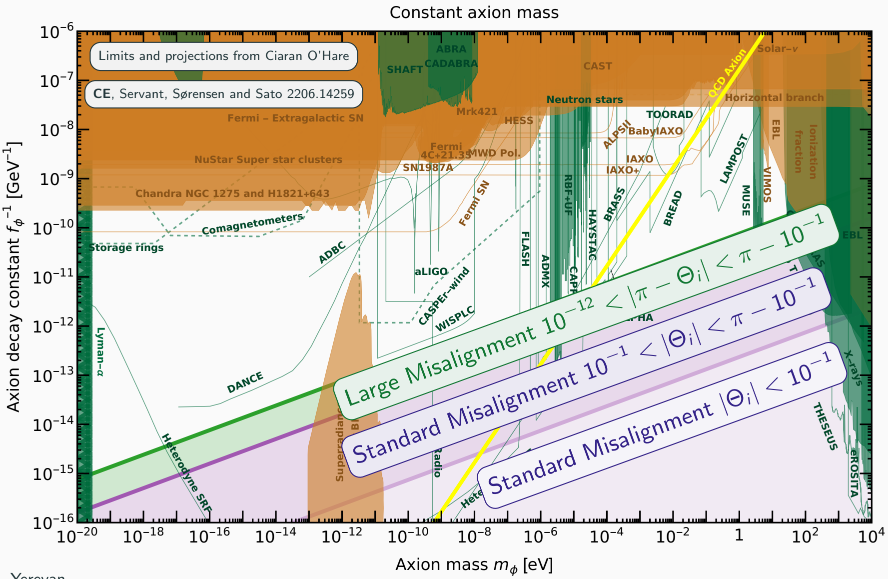


Common property of all these is that the onset of oscillations got delayed which boosts the dark matter abundance, and extends the ALP dark matter parameter space to lower decay constants.

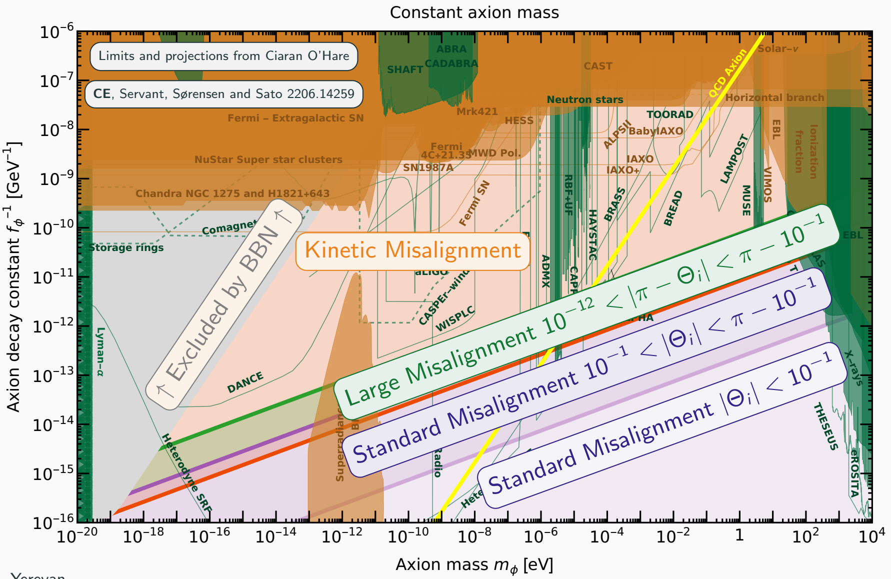
ALP parameter space (with KSVZ-like photon coupling $g_{\theta\gamma} = (\alpha_{em}/2\pi)(1.92/f_\phi)$)



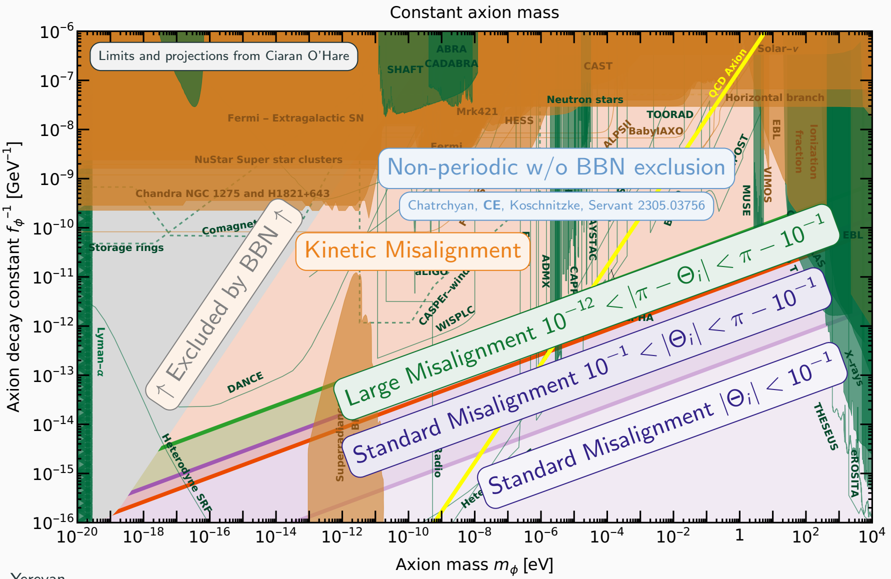
ALP parameter space (with KSVZ-like photon coupling $g_{\theta\gamma} = (\alpha_{\text{em}}/2\pi)(1.92/f_\phi)$)



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



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



How to get a large initial kinetic energy?

A large initial kinetic energy for the ALP field can be motivated in various UV completions:

- Explicit breaking of the PQ symmetry at very large energies. Co et al. 1910.14152; 2004.00629; 2006.05687
- Trapped misalignment Luzio et al. 2102.00012; 2102.01082

Today's ALP energy density is Co et al. 1910.14152

CE, Servant, Sørensen, Sato 2206.14259

$$h^2\Omega_{\phi,0} \approx 0.12\left(\frac{m_\phi}{5\times 10^{-3}\,\mathrm{eV}}\right)\left(\frac{Y}{40}\right), \quad Y = \frac{f_\phi \dot{\phi}(T)}{s(T)}$$

The yield parameter Y is conserved after the kick, and determines the ALP relic density today.

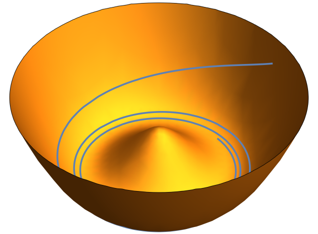
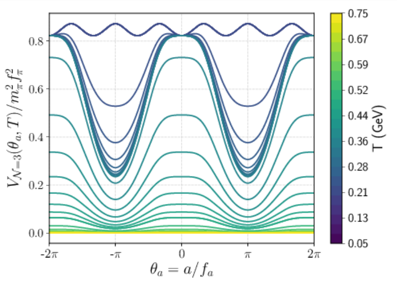
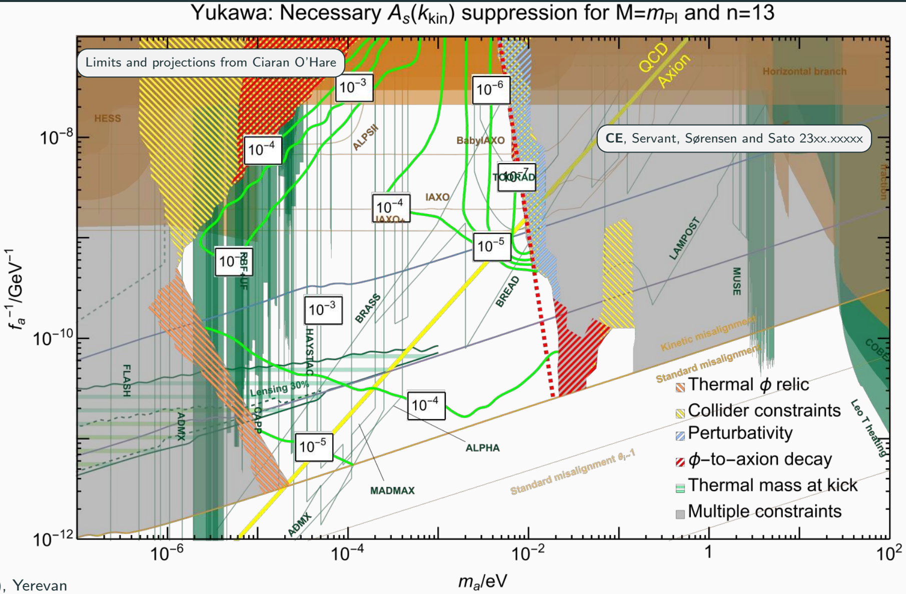


Figure credit: Philip Sørensen



Luzio et al. 2102.01082

Specific example of a UV completion with KSVZ fermions and nearly-quadratic potential



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

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

The EoM is unstable when the effective frequency

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

Kofman et al. hep-ph/9704452; Felder, Kofman hep-ph/0606256
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

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

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

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

The EoM is unstable when the effective frequency

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

Kofman et al. hep-ph/9704452; Felder, Kofman hep-ph/0606256

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

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

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

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

The EoM is unstable when the effective frequency

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

Kofman et al. hep-ph/9704452; Felder, Kofman hep-ph/0606256
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

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

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

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

The EoM is unstable when the effective frequency

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

Kofman et al. hep-ph/9704452; Felder, Kofman hep-ph/0606256
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

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

The size of fluctuations is determined by the density contrast:

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

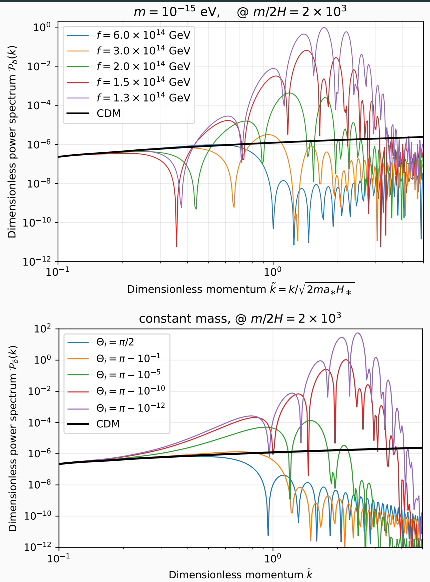
The power spectrum (two-point function) determines the distribution of structures today:

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

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!

Growth rate of the perturbations depend exponentially on $m_\phi / H\big|_{osc}$.



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.

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.

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.

For sub-horizon $k/a \gg H$ and non-relativistic $k/a \ll m$ modes, the density contrast evolution is

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \Bigg[\overbrace{\underbrace{\frac{1}{4}\frac{(k/a)^4}{m^2}}_{\text{"pressure" term}}}^{c_{s,\mathrm{eff}}^2 (k/a)^2} - \underbrace{4\pi G\bar{\rho}}_{\text{gravitational instability}} \Bigg]\delta_k = 0.$$

The scale at which the "pressure" term and gravitational instability becomes equal is called the Axion Jeans scale:

$$k_J(a) = (16\pi G a\bar{\rho})^{1/4}\sqrt{m} = 66.5 \times a^{1/4}\left(\frac{h^2\Omega_{\ominus}}{h^2\Omega_{\mathrm{DM}}}\right)\sqrt{\frac{m}{10^{-22}\,\mathrm{eV}}}\,\mathrm{Mpc}^{-1}.$$

The behavior of the density contrast depends whether the mode is above or below the Jeans scale:

- Modes above the Jeans scale oscillate with a frequency given by the effective sound speed both in matter- and radiation-domination.
- Modes below the Jeans scale behaves like CDM. They grow logarithmically during the radiation era, and linearly during the matter era.

For sub-horizon $k/a \gg H$ and non-relativistic $k/a \ll m$ modes, the density contrast evolution is

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \Bigg[\overbrace{\underbrace{\frac{1}{4}\frac{(k/a)^4}{m^2}}_{\text{"pressure" term}}}^{c_{s,\mathrm{eff}}^2 (k/a)^2} - \underbrace{4\pi G\bar{\rho}}_{\substack{\text{gravitational}\\ \text{instability}}}\Bigg]\delta_k = 0.$$

The scale at which the "pressure" term and gravitational instability becomes equal is called the Axion Jeans scale:

$$k_J(a) = (16\pi G a\bar{\rho})^{1/4}\sqrt{m} = 66.5 \times a^{1/4}\left(\frac{h^2\Omega_\ominus}{h^2\Omega_{\mathrm{DM}}}\right)\sqrt{\frac{m}{10^{-22}\,\mathrm{eV}}}\,\mathrm{Mpc}^{-1}.$$

The behavior of the density contrast depends whether the mode is above or below the Jeans scale:

- Modes above the Jeans scale oscillate with a frequency given by the effective sound speed both in matter- and radiation-domination.
- Modes below the Jeans scale behaves like CDM. They grow logarithmically during the radiation era, and linearly during the matter era.

Latetime evolution of the density contrast

For sub-horizon $k/a \gg H$ and non-relativistic $k/a \ll m$ modes, the density contrast evolution is

$$\ddot{\delta}_k + 2H\dot{\delta}_k + \Bigg[\underbrace{\overbrace{\frac{1}{4}\frac{(k/a)^4}{m^2}}^{c_{s,\mathrm{eff}}^2 (k/a)^2}}_{\text{"pressure" term}} - \underbrace{4\pi G\bar{\rho}}_{\substack{\text{gravitational}\\ \text{instability}}} \Bigg] \delta_k = 0.$$

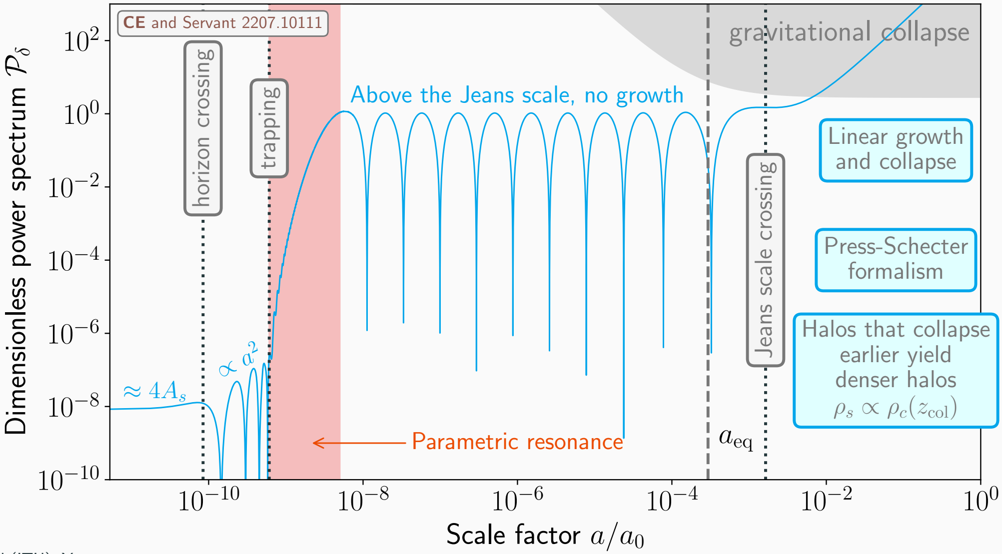
The scale at which the "pressure" term and gravitational instability becomes equal is called the Axion Jeans scale:

$$k_J(a) = (16\pi G a \bar{\rho})^{1/4}\sqrt{m} = 66.5 \times a^{1/4} \left(\frac{h^2\Omega_\ominus}{h^2\Omega_{\mathrm{DM}}}\right) \sqrt{\frac{m}{10^{-22}\,\mathrm{eV}}}\,\mathrm{Mpc}^{-1}.$$

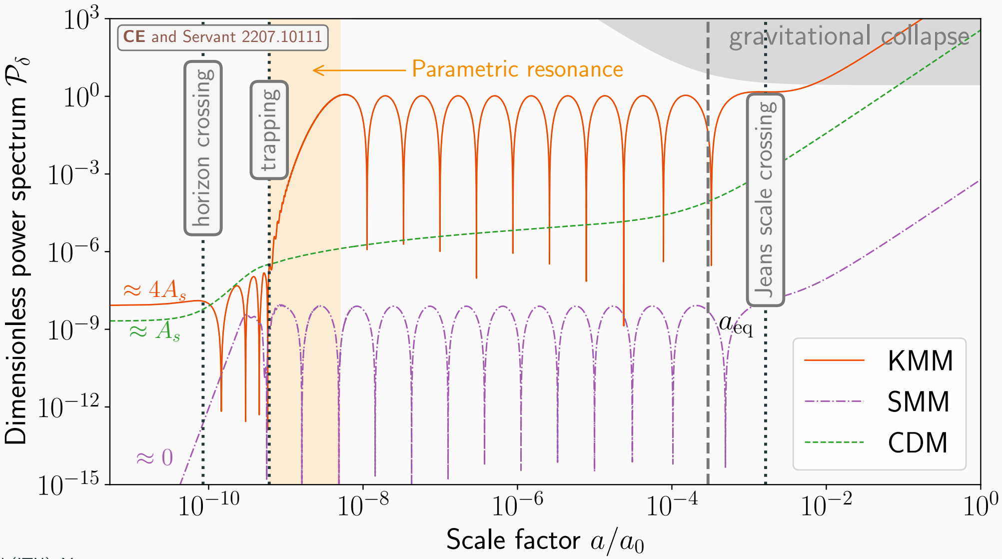
The behavior of the density contrast depends whether the mode is above or below the Jeans scale:

- Modes above the Jeans scale oscillate with a frequency given by the effective sound speed both in matter- and radiation-domination.
- Modes below the Jeans scale behaves like CDM. They grow logarithmically during the radiation era, and linearly during the matter era.

Lifetime of a fluctuation mode



Lifetime of a fluctuation mode



Density profiles of dark matter halos

- Useful parameters to describe the dark matter halos:

$$\underbrace{\left.\frac{\partial \ln \rho(r)}{\partial \ln r}\right|_{r=r_s} = -2}_{\text{scale radius}}, \quad \underbrace{\rho_s = \rho(r=r_s)}_{\text{scale density}}, \quad \underbrace{M_s = \int_0^{r_s} \mathrm{d}^3\vec{\mathbf{r}}\,\rho(r) = 16\pi\rho_s r_s^3\left(\ln 2 - \frac{1}{2}\right)}_{\text{scale mass}}.$$

- In order to determine these parameters, we need to know the density profile.

CDM

On all scales, the profile is well-approximated by the Navarro-Frenk-White (NFW) profile

Navarro et al. astro-ph/9611107

$$\rho_{\rm NFW}(r) = \frac{4\rho_s}{(r/r_s)(1+r/r_s)^2}.$$

ALP

The profile is scale dependent:

- **Large scales:** NFW
- **Small scales:** Soliton profile Schive et al. 1406.6586

$$\rho_{\rm sol}(r) \approx \frac{2.9\rho_s}{\left(1+\left(r/\sqrt{7}r_s\right)^2\right)^8} \Rightarrow \rho_s \propto m^6 M_s^4$$

- The scale density is closely related to the energy density at collapse:

$$\rho_s \propto \rho_c(z_{\rm col}) \Rightarrow \text{Fluctuations that collapse earlier create denser halos.}$$

Density profiles of dark matter halos

- Useful parameters to describe the dark matter halos:

$$\underbrace{\left.\frac{\partial \ln \rho(r)}{\partial \ln r}\right|_{r=r_s} = -2}_{\text{scale radius}}, \quad \underbrace{\rho_s = \rho(r = r_s)}_{\text{scale density}}, \quad \underbrace{M_s = \int_0^{r_s} \mathrm{d}^3\vec{\mathbf{r}}\,\rho(r) = 16\pi\rho_s r_s^3\left(\ln 2 - \frac{1}{2}\right)}_{\text{scale mass}}.$$

- In order to determine these parameters, we need to know the density profile.

CDM

On all scales, the profile is well-approximated by the Navarro-Frenk-White (NFW) profile

Navarro et al. astro-ph/9611107

$$\rho_{\mathrm{NFW}}(r) = \frac{4\rho_s}{(r/r_s)(1 + r/r_s)^2}.$$

ALP

The profile is scale dependent:

- **Large scales:** NFW
- **Small scales:** Soliton profile Schive et al. 1406.6586

$$\rho_{\mathrm{sol}}(r) \approx \frac{2.9\rho_s}{\left(1 + \left(r/\sqrt{7}r_s\right)^2\right)^8} \Rightarrow \rho_s \propto m^6 M_s^4$$

- The scale density is closely related to the energy density at collapse:

$$\rho_s \propto \rho_c(z_{\mathrm{col}}) \Rightarrow \text{Fluctuations that collapse earlier create denser halos.}$$

Density profiles of dark matter halos

- Useful parameters to describe the dark matter halos:

$$\underbrace{\left.\frac{\partial \ln \rho(r)}{\partial \ln r}\right|_{r=r_s} = -2,}_{\text{scale radius}} \quad \underbrace{\rho_s = \rho(r=r_s),}_{\text{scale density}} \quad \underbrace{M_s = \int_0^{r_s} \mathrm{d}^3\vec{\mathbf{r}}\,\rho(r) = 16\pi\rho_s r_s^3\left(\ln 2 - \frac{1}{2}\right)}_{\text{scale mass}}.$$

- In order to determine these parameters, we need to know the density profile.

CDM

On all scales, the profile is well-approximated by the Navarro-Frenk-White (NFW) profile

Navarro et al. astro-ph/9611107

$$\rho_{\mathrm{NFW}}(r) = \frac{4\rho_s}{(r/r_s)(1+r/r_s)^2}.$$

ALP

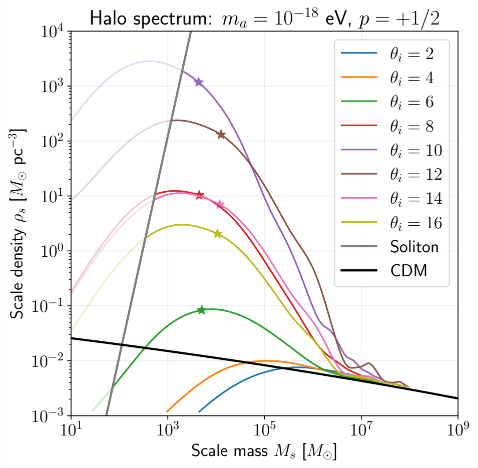
The profile is scale dependent:

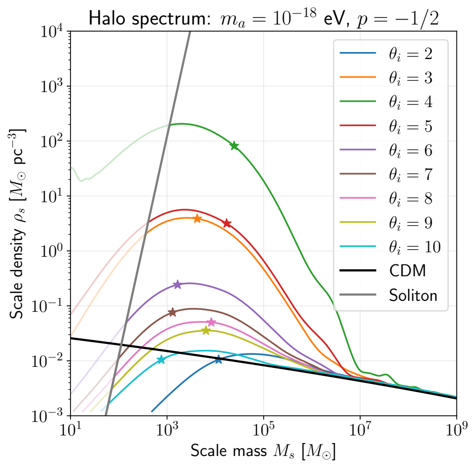
- **Large scales:** NFW
- **Small scales:** Soliton profile Schive et al. 1406.6586

$$\rho_{\mathrm{sol}}(r) \approx \frac{2.9\rho_s}{\left(1+\left(r/\sqrt{7}r_s\right)^2\right)^8} \Rightarrow \rho_s \propto m^6 M_s^4$$

- The scale density is closely related to the energy density at collapse:

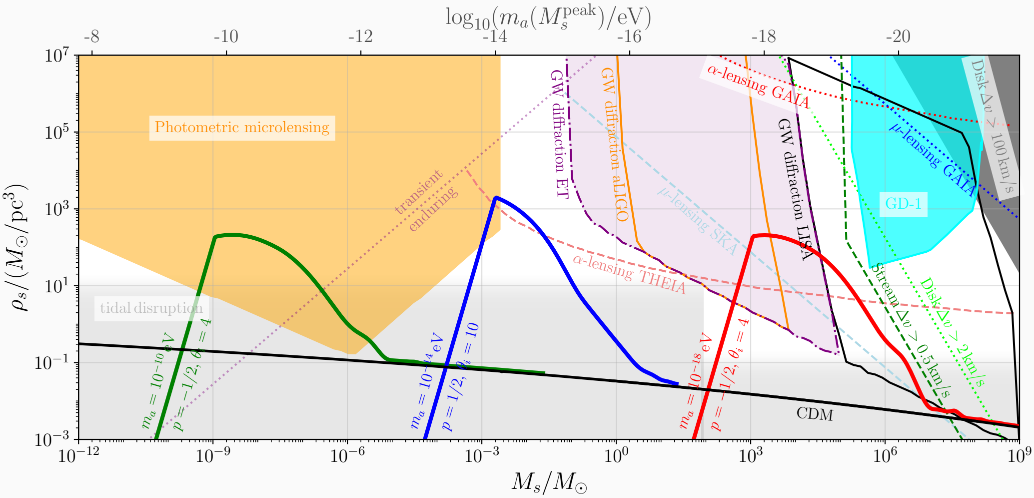
$\rho_s \propto \rho_c(z_{\mathrm{col}}) \Rightarrow$ Fluctuations that collapse earlier create denser halos.





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



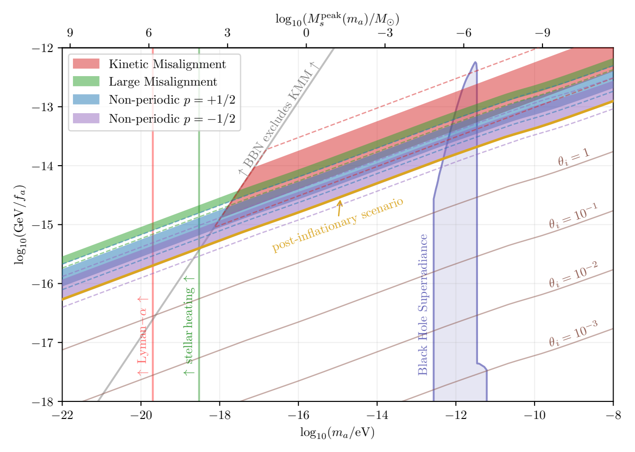
Experimental prospects from Tilburg et al. 1804.01991; Arvanitaki et al. 1909.11665; Ramani et al. 2005.03030

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.

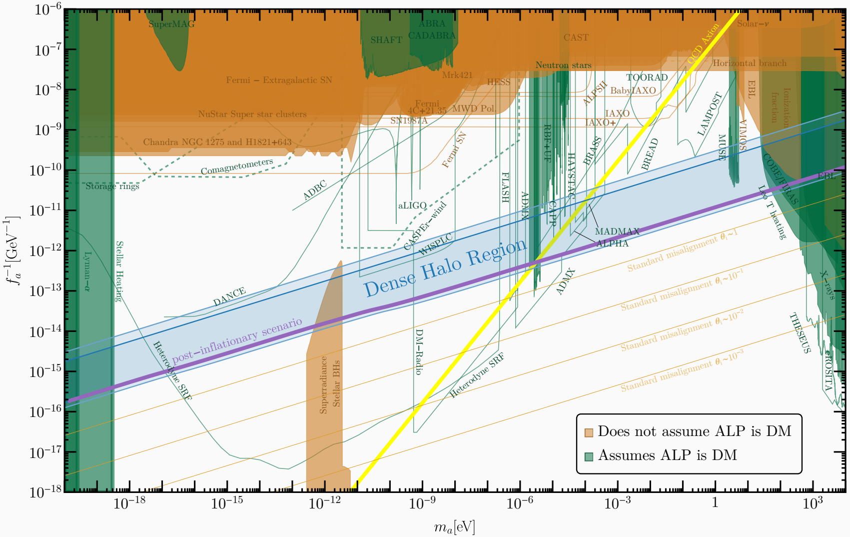
The "dense halo regions" in different production mechanisms mostly overlap with each other. So, it is difficult to infer the mechanism from observations.

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



Dense halo region in the ALP parameter space

Chatrchyan, CE, Koschnitzke, Servant 2305.03756



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 $m_{\text{osc}}/H_{\text{osc}} \sim 3$.
- 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!

Cem Eröncel

0000-0002-9308-1449

cem.eroncel@itu.edu.tr