Axion Kinetic Misalignment

What is it, what does it do, and how do you get it?

Philip Sørensen
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INFN PADOVA

Università degli Studi di Padova

Background

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The (standard) misalignment mechanism

QCD Axion Lagrangian

$$\mathcal{L} \supset \frac{f_a^2}{2}\partial_\mu\theta\partial^\mu\theta - m_a^2(T) f_a^2 (1 - \cos(\theta))$$

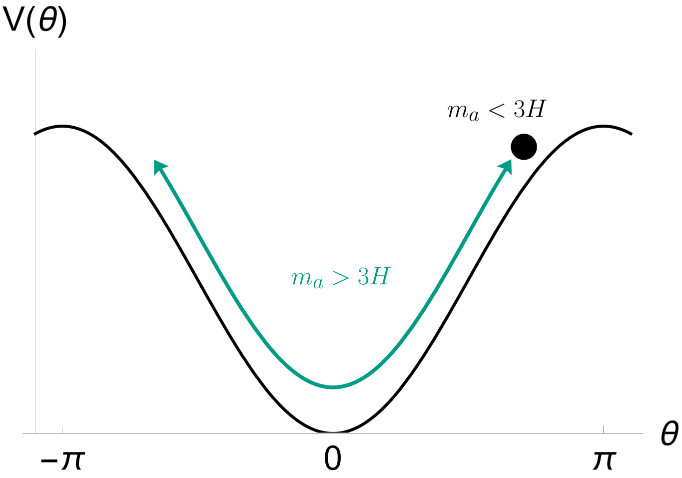
Equation of motion in an expanding spacetime:

$$\ddot{\theta} + \underbrace{3H\dot{\theta}}_{\text{friction}} + m_a^2(T)\theta = 0$$

Two regimes:

- $m_a(T) \ll 3H \iff \rho_a \propto a^0$ (Frozen)
- $m_a(T) \gg 3H \iff \rho_a \propto a^{-3}$ (Oscillating)

The (standard) misalignment mechanism



Initial conditions:

$$\theta \neq 0, \quad \text{and} \quad \dot{\theta} = 0$$

Relic density:

$$\rho_{\theta,0}^{SMM} \approx \frac{1}{2} m_* m_0 \theta_*^2 f_a^2 \left(\frac{a_*}{a_0} \right)^3$$

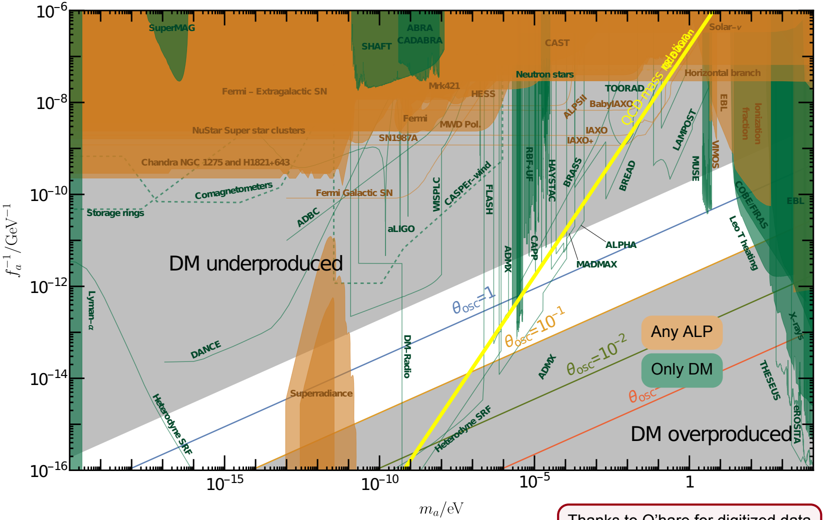
where

$_0$ = today,

$_*$ = time of onset of oscillations.

Axion (ALP) parameter space

Assuming KSVZ-like photon and neutron couplings:



Thanks to O'hare for digitized data

?

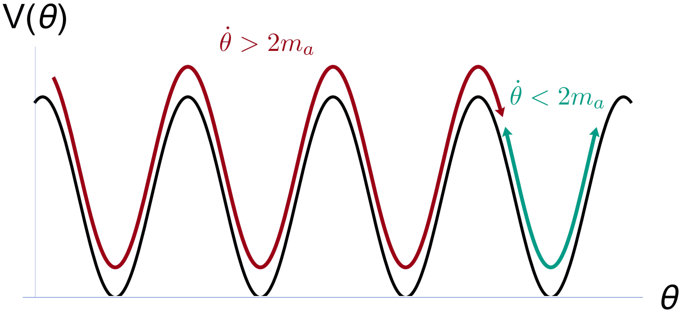
Can we produce ALP dark matter at low$-f_a$?

Kinetic misalignment
What is it?

Kinetic misalignment - What is it?

- New framework for axion DM production at low-f_a
- Proposed independently by Co et al. and Chang & Cui in 2019
- Key idea: $\dot{\theta} \neq 0$

Kinetic misalignment - What is it?



- Begins to oscillate at $\dot{\theta} \sim 2m_a$
- Delay oscillations
  $\Rightarrow$ less redshift
  $\Rightarrow$ more DM
  $\Rightarrow$ lower f_a

Kinetic misalignment
What does it do?

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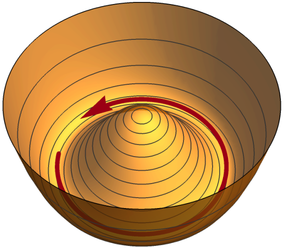
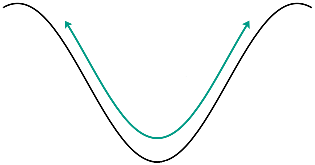
Kinetic misalignment - What does it do?





Dark matter production

Two types of conserved quantities:

Spinning: Noether charge: $n_{PQ} = \dot{\theta} f_a^2$

Oscillating: Conserved particle number: n_a

These are related as $n_a = 2n_{PQ}$

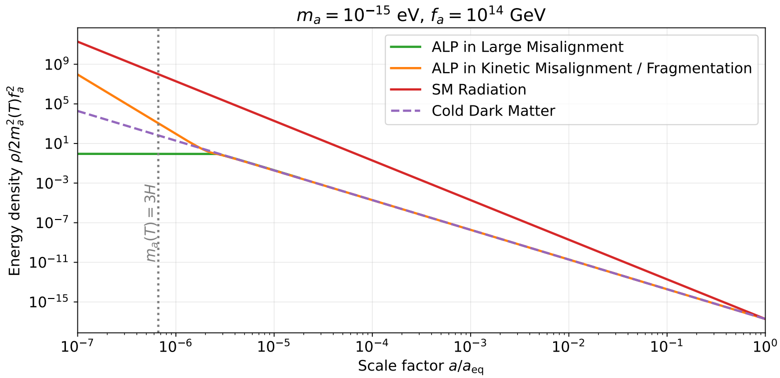
$$\Rightarrow \rho_{a,\text{today}} \approx 2 m_a \dot{\theta}_* f_a^2 \left(\frac{a_*}{a}\right)^3,$$

if $m_a(T_*) > H$.

Co et al. (1910.14152), Eröncel et al. (2206.14259)

Kinetic misalignment - What does it do?

Causing problems for BBN



Conserved charge:

$$f_a^2\dot{\theta} \propto a^{-3}$$

$$\downarrow$$

$$\rho_{a,\text{kin}} \propto a^{-6}$$

$$\downarrow$$

AlterBBN_v2

$$\downarrow$$

$$\frac{\rho_{a,\text{kin}}}{\rho_r}\Big|_{\text{BBN}} < 0.19$$

$$\downarrow$$

$T_* \gtrsim 20$ keV (inst. approx.)

Kinetic misalignment - What does it do?

Axion fragmentation - Fonseca et al. (1911.08472)

Expand into fluctuation:

$$\theta(t,x) = \Theta(t) + \delta\theta(t,x), \quad \text{where} \quad \delta\theta(t,x) = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \theta_k(t) e^{-ik\cdot x}$$

EOM is a Hills equation:

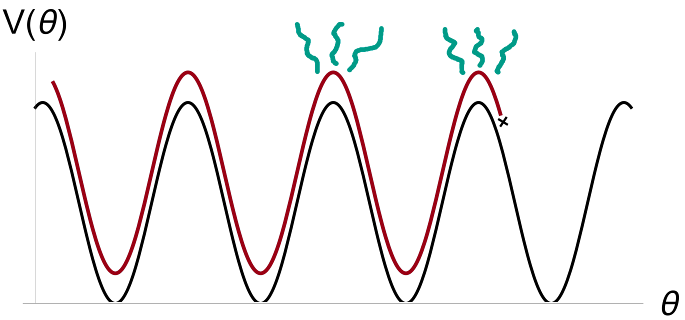
$$\ddot{\theta}_k + \left[\frac{k^2}{a^2} + m_a^2(T) \cos\Theta\right]\theta_k = 0$$

Solutions given by Floquet theorem:

$$\theta_k(t) = \theta_+(t;k)e^{\mu_k t} + \theta_-(t;k)e^{-\mu_k t} \quad \text{such that} \quad \mathrm{Re}\{\mu_k\} > 0 \to \text{exponential growth!}$$

Kinetic misalignment - What does it do?

Axion fragmentation



Fluctuations can disrupt the homogeneous mode
$=$ fragmentation

- No major impact on DM abundance
- Mini-clusters
- Weak GW signal

Eröncel et al. (2206.14259)

Eröncel and Servant (2207.10111)

Kinetic misalignment - What does it do?

Axion fragmentation

The ratio $m_a(T_*)/H(T_*)$ controls the efficiency:

$$\frac{m_a(T_*)}{H(T_*)} \lesssim 3 \quad \rightarrow \text{Standard misalignment}$$

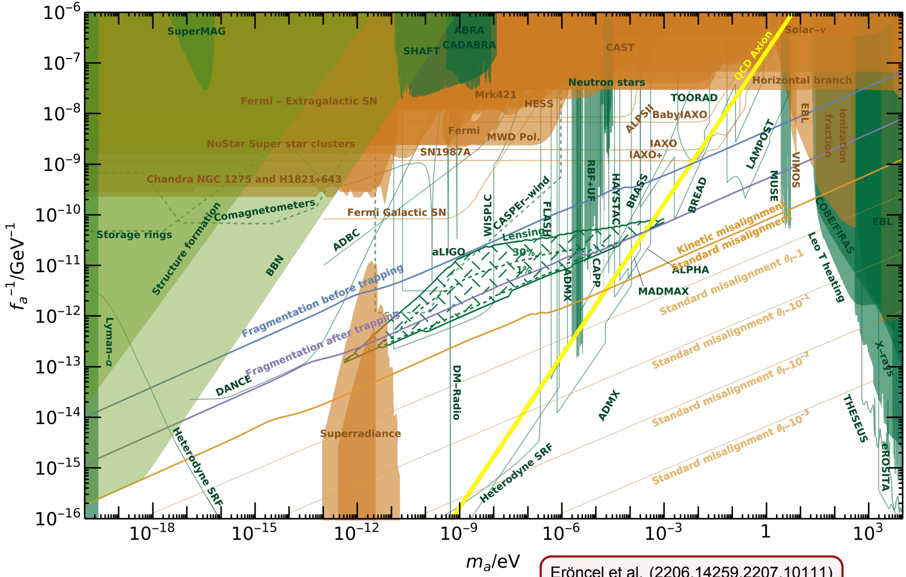
$$3 \lesssim \frac{m_a(T_*)}{H(T_*)} \lesssim 42 \quad \rightarrow \text{Kinetic misalignment with weak fragmentation}$$

$$42 \lesssim \frac{m_a(T_*)}{H(T_*)} \lesssim 900 \quad \rightarrow \text{Fragmentation after trapping}$$

$$900 \lesssim \frac{m_a(T_*)}{H(T_*)} \quad \rightarrow \text{Fragmentation before trapping}$$

Eröncel et al. (2206.14259)

Assuming KSVZ-like photon and neutron couplings:



Eröncel et al. (2206.14259,2207.10111)

Kinetic misalignment
How do you get it?

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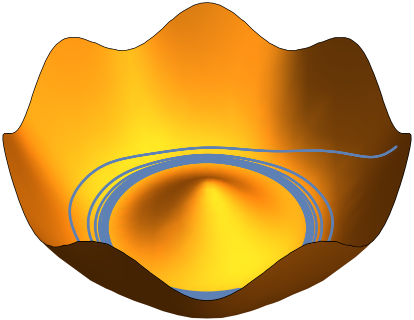
Kinetic misalignment - How do you get it?

Reuse Affleck-Dine baryogenesis!



Affleck & Dine 85: $n_{PQ} \to n_{\text{baryon}}$

Co et al. 19: $n_{PQ} \to n_a$

Full complex field (incl. radial dynamics)

$$P = \frac{1}{\sqrt{2}} \phi e^{i\theta}$$

Higher-dimensional terms

$$\frac{A}{n} \frac{P^n}{m_{\text{Pl}}^{n-3}} + \text{c.c.} = \frac{2A}{n 2^{n/2}} \cos(n\theta) \frac{\phi^n}{m_{\text{Pl}}^{n-3}}$$

Probed by a large VEV ϕ_{kick}

$$\to \dot{\theta}_{\text{kick}} = 2^{1-\frac{n}{2}} \frac{A \phi_{\text{kick}}^{n-2} \sin(n\theta_{\text{kick}})}{m_\phi m_{\text{Pl}}^{n-3}}$$

$$\to n_{PQ} = \dot{\theta}_{\text{kick}} \phi_{\text{kick}}^2$$

Kinetic misalignment - How do you get it?

Large radial VEV

SUSY motivated nearly-quadratic potential

$$V_{\text{late}} = m_\phi^2 |P|^2 \left(\frac{1}{2} \ln\left(\frac{2|P|^2}{f_a^2} \right) - \frac{1}{2} \right) + \frac{1}{4} m_\phi^2 f_a^2$$

Higher-dimensional terms (also SUSY motivated)

$$V_{\text{early}} = (\underbrace{\mathcal{O}(1) \times m_\phi^2}_{V_{\text{late}}} \underbrace{- c_H H^2}_{\text{Drive VEV}})|P|^2 + \underbrace{\frac{A + c_A H}{n} \frac{P^n}{m_{\text{Pl}}^{n-3}} + h.c.}_{\text{Angular gradient}} + \underbrace{\frac{|P|^{2n-2}}{m_{\text{Pl}}^{2n-6}}}_{\text{Stabilize } H^2\text{-term}}$$

Same terms used for Dine, Randal and Thomas (hep-ph/9507453)
Co et al. (1910.14152)

Kinetic misalignment - How do you get it?
Radial dynamics

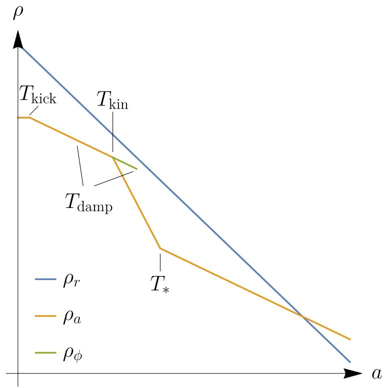
Radial equation of motion:

$$\ddot{\phi} + 3H\dot{\phi} + \underbrace{V'}_{\text{Potential}} = \underbrace{\dot{\theta}^2\phi}_{\text{Centrifugal}}$$

Radial oscillations about effective minimum at

$$\dot{\theta} = m_\phi \quad \text{where} \quad m_\phi \equiv \sqrt{\phi^{-1}V'}$$

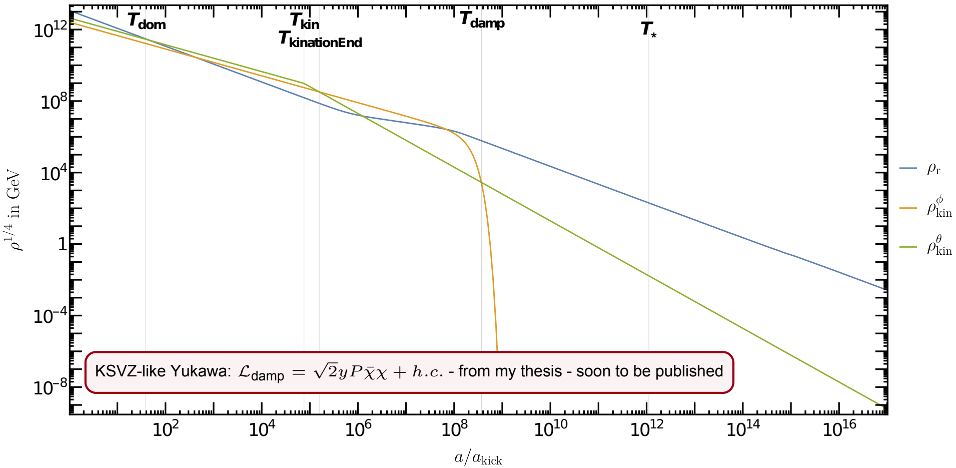
Must be damped!



Kinetic misalignment - How do you get it?

Numerical integration of Boltzmann equations

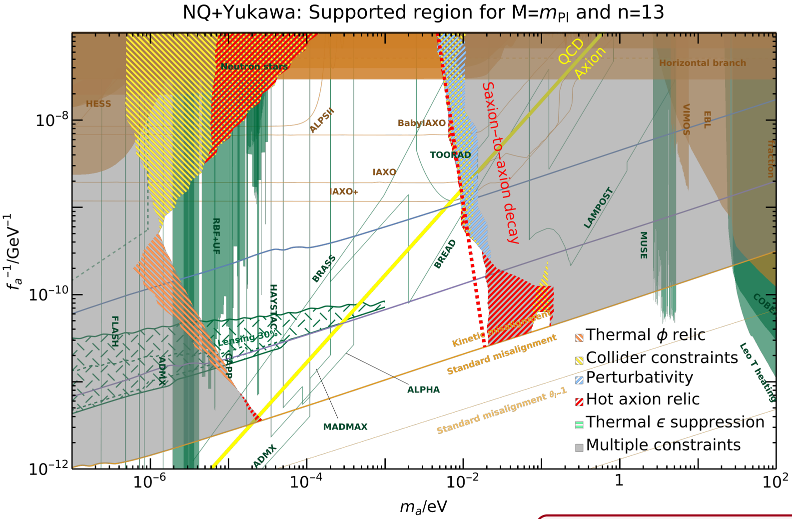
$m_a = 1.$ eV, $f_a = 10^{10}$ GeV, $m_\phi = 10^8$ GeV, $y = 10^{-6}$, $M = m_p$, $n = 13$,
$T_{\rm kick} = 5. \times 10^{12}$ GeV, $T_{\rm damp} = 2. \times 10^5$ GeV, $T_* = 80.$ GeV, Mechanism: $\Gamma_{\chi-\rm decay}$



KSVZ-like Yukawa: $\mathcal{L}_{\rm damp} = \sqrt{2} y P \bar{\chi}\chi + h.c.$ - from my thesis - soon to be published

Kinetic misalignment - How do you get it?

Supported ALP DM parameter space



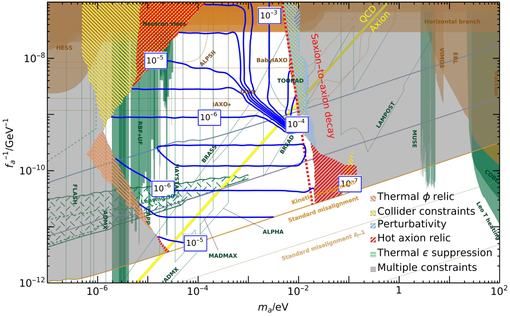
From my thesis - soon to be published

Kinetic misalignment - How do you get it?

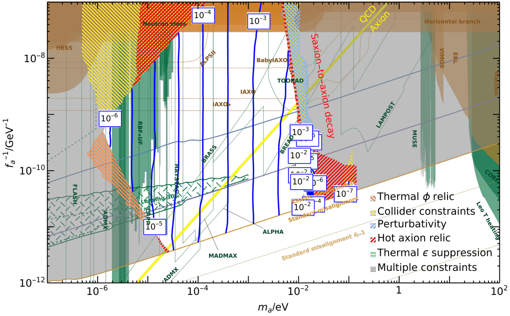
Required parameters

We map explicitly the required model parameters:

NQ with Yukawa: Lower bound on y for M=m_{Pl} and n=13



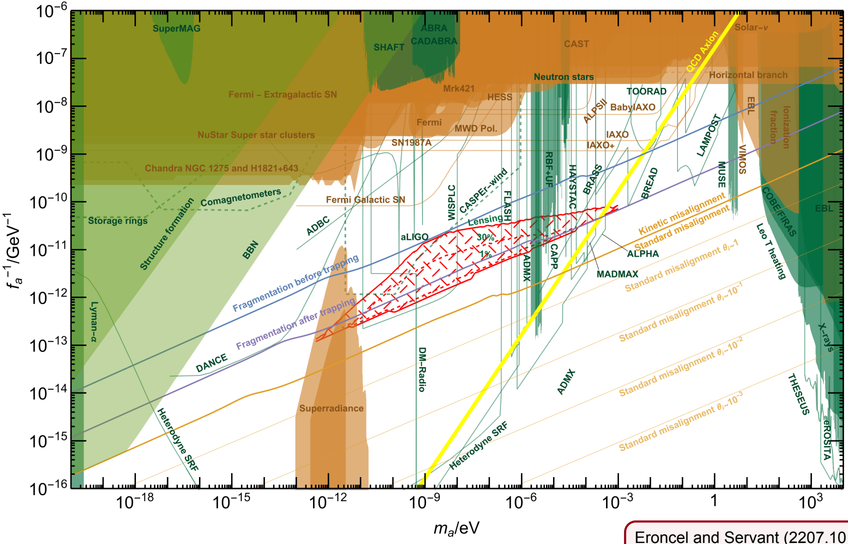
NQ with Yukawa: Upper bound on y for M=m_{Pl} and n=13



Preliminary - to be published soon

Signatures

Signature from fragmentation: Photometric lensing



Eroncel and Servant (2207.10111)

Signature from implementation: GWs amplified by kination

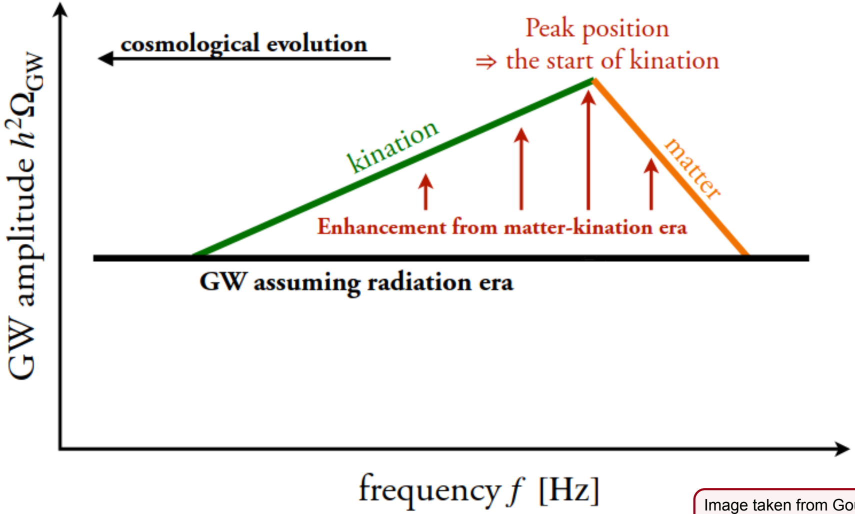
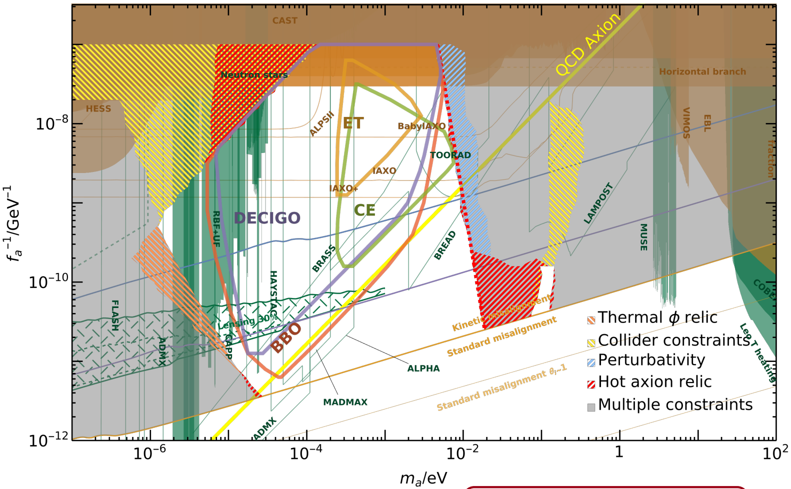


Image taken from Gouttenoire et al. (2111.01150)

Signature from implementation: GWs amplified by kination

Potential reach of GW experiments for $E_I = 1.6\times10^{16}$GeV, M=$m_{\rm Pl}$ and n=13



From my thesis, soon to be published

Summary

Axion kinetic misalignment implies that...

- Axion-like-particle dark matter can be motivated also in the low-f_a regime
- ALP DM in reach of upcoming experiments
- Much parameter space features fragmentation
  - GW signal from fragmentation is hard to observe (Eroncel et al., 2206.14259)
  - Minicluster formation is more promising (Eroncel et al., 2207.10111)
- Model implementations can be found (Co et al., our upcoming paper)
  - Model shown here: KSVZ-like ALP with Affleck-Dine-like terms
  - Supports QCD axion and ALP DM from $m_a \in [10^{-6}\text{eV}, 10^{-2}\ \text{eV}]$
  - Might imply GW signal from kination (our upcoming paper)

Thank you!

Contact
Philip Sørensen
0000-0003-4780-9088
University of Padova / INFN Padova
philip.soerensen@pd.infn.it
+4530897153

Thank you!

Questions?

Contact
Philip Sørensen
iD 0000-0003-4780-9088
University of Padova / INFN Padova
philip.soerensen@pd.infn.it
+4530897153

Kinetic misalignment - How do you get it?

List of assumptions:

- Assume SUSY
- $m_\phi \ll f_a$ from soft SUSY braking
- Higher-dim. terms from superpotential
  - Sufficiently large n to not void axion-quality
- Assume a coupling that makes the origin unstable $\rightarrow$ large radial VEV
- Small Yukawa (or Higgs portal) coupling
  - Small to limit thermal effects
  - Large enough to damp radial oscillations
- An inflation model with $T_{\text{reheat}} > T_{\text{kick}}$ and $A_s(k)/A_s(k_{\text{CMB}}) < 10^{-\text{few}}$ for large k

GW production directly by fragmentation (Frequency)

Frequency is determined by most amplified mode, which is $k \approx m_a(T_*)$.
Redshifts competes:

$$\nu \approx \frac{m_*}{2\pi} \underbrace{\kappa_*}_{\mathcal{O}(1)} \qquad \underbrace{\frac{a_*}{a_0}}_{\propto (m_a f_a)^{-\frac{1}{2}+\frac{1}{6+\gamma}}} \qquad \text{where} \quad \kappa_* \equiv \frac{k_*}{m_a(T_*)} \sim 1$$

Dependency from most amplified mode wins:

$$\nu_{\text{peak}} \sim 8 \times 10^{-11}\,\text{Hz} \left(\frac{m_a}{10^{-16}\,\text{eV}}\right)^{1/3} \left(\frac{f}{10^{14}\,\text{GeV}}\right)^{-2/3} \mathcal{Z}^{-1/3} \quad \text{for} \quad \gamma = 0$$

GW production directly by fragmentation (Amplitude)

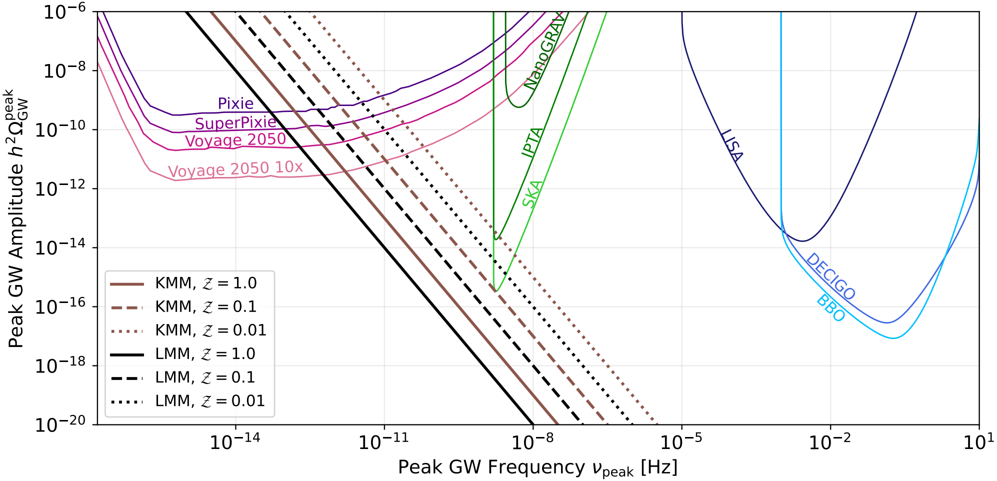
GW Amplitude at production:

$$\Omega_{\text{GW},*}^{\text{peak}} \sim \frac{256\pi^2}{3} \underbrace{\left(\frac{m_a(T_*)}{H_*}\right)^2}_{\sim k^2 H^2} \underbrace{\left(\frac{f_a}{m_P}\right)^4}_{\text{Grav. coupling}^2} \quad .$$

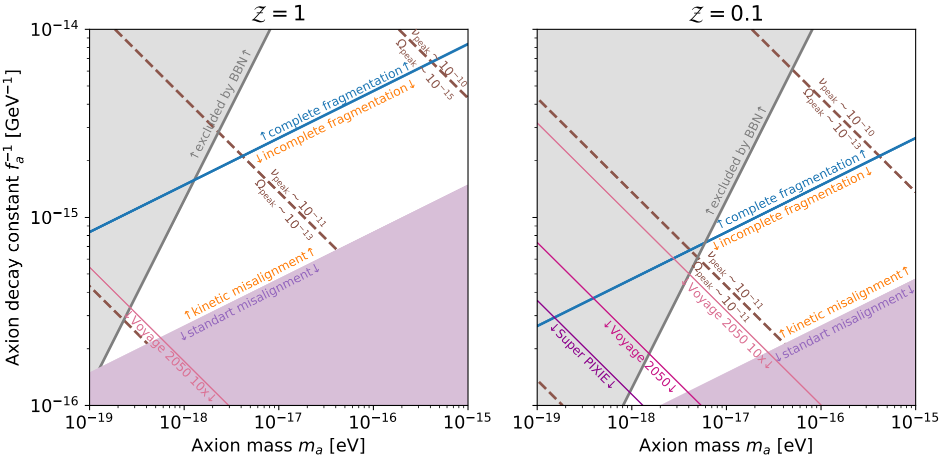
Including redshift:

$$\Omega_{\text{GW},0}^{\text{peak}} \sim 1.5 \times 10^{-15} \left(\frac{m_a(T_*)}{m_a}\right)^{2/3} \left(\frac{m_a}{10^{-16}\,\text{eV}}\right)^{-2/3} \left(\frac{f}{10^{14}\,\text{eV}}\right)^{4/3} \mathcal{Z}^{-4/3}.$$

GW production directly by fragmentation (Signal)



GW production directly by fragmentation ($[m_a, f_a]$)



Left: $\mathcal{Z} = 1$, Right: $\mathcal{Z} = 1$. Approximation unreliable below blue line.

Equivalence principle constraints

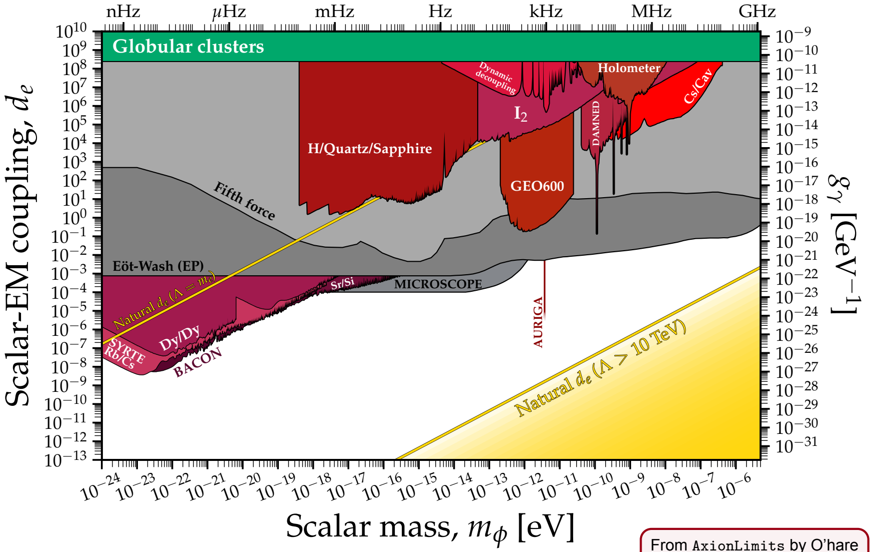
The radial (saxion) mode has a scalar EM coupling

$$\mathcal{L}_{\phi\gamma} = \frac{1}{4} g_{\phi\gamma\gamma} \phi F F$$

We generally expect $g_{\phi\gamma\gamma} \sim g_{\theta\gamma\gamma}$.

- Light scalar couplings are more strongly constrained
- Not a problem from heavy scalars
- EP applies for $m_\phi \lesssim 10^{-5}$ eV

Equivalence principle constraints



From AxionLimits by O'hare

Thermal ϕ relic constraints

- Damping interaction creates a thermal population of saxions
- Problematic if the interaction becomes inefficient while $T > m_\phi$
- Created as $\rho_{\phi,\text{thermal}} \sim \rho_r / g_*$, but $\rho_{\phi,\text{thermal}} / \rho_r$ grows after cooling

Large mass solution: Saxion-to-axion decay before cooling:

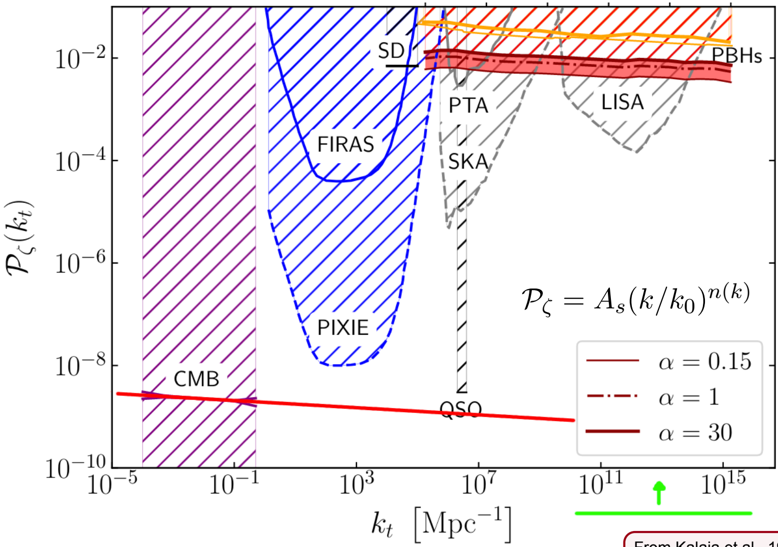
$$|\partial_\mu P|^2 \to \Gamma_{S\varphi} \sim \frac{m_\phi^3}{f_a^2} \quad \text{where} \quad S = \phi - f_a, \quad \varphi = \theta f_a$$

$$\mathcal{O}(1) \times \frac{f_a^2}{m_{\text{pl}}} < m_\phi$$

Low mass solution: Stay relativistic until after T_{eq}:

$$m_\phi < \mathcal{O}(1) \times T_{\text{eq}}$$

Constraints on the primordial curvature power spectrum



From Kalaja et al., 1908.03596

Quartic model: Specification

We also studied models with quartic potentials:

$$V_{\text{late}} = \lambda^2 \left(|P|^2 - \frac{f_a^2}{2} \right)^2$$

We mainly consider de Sitter fluctuation:

$$\phi_{\text{kick}}^2 \sim \frac{3}{8\pi^2} \frac{H_I^4}{m_\phi^2} \sim \frac{3}{8\pi^2} \frac{H_I^4}{\phi_{\text{kick}}^2 \lambda^2} \quad \text{where} \quad m_\phi \equiv \sqrt{\phi^{-1} V'}$$

This reduces sensitivity of m_ϕ to m_a:

$$\begin{aligned} \text{Higher-Dim.:} \quad & m_\phi \propto m_a^k \quad \text{where} \quad 2.8 \leq k \leq 8 \quad \text{for} \quad 7 \leq n \leq 13, \\ \text{de Sitter:} \quad & m_\phi \propto m_a^k \quad \text{where} \quad k = 4/5 \end{aligned}$$

Quartic does not naturally give light $m_\phi \to$ Tuning cannot be avoided