Gravitational imprints of monodromic axions

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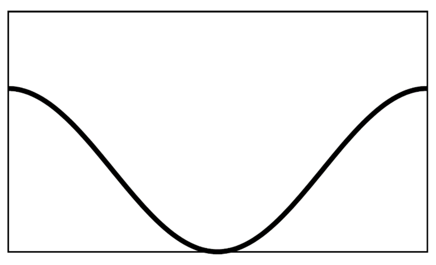
Axion-like particles (ALPs) and monodromy

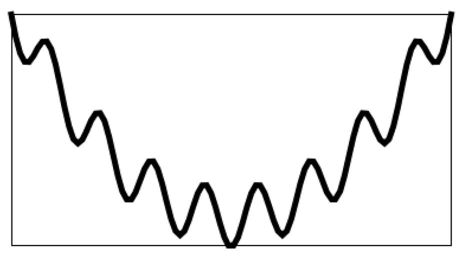
Standard ALPs: pseudo-Goldstone bosons, string axions
enjoy a discrete shift symmetry, $\varphi \to \varphi + 2\pi f$.

If the **discrete shift symmetry is broken**, ALP exhibits a **monodromy** [1].

- For string axions, monodromy can be induced by the presence of wrapped branes, fluxes etc.



The shape of the potential $U(\varphi)$ for standard (left) and monodromic (right) ALPs.



Misalignment production: Growth of fluctuations

ALPs can behave as dark matter if produced via the misalignment mechanism.

Equations of motion: $\ddot{\varphi} + 3H\dot{\varphi} - \frac{\Delta\varphi}{a^2} + m^2\varphi + \frac{\Lambda^4}{f}\sin\frac{\varphi}{f} = 0.$

Symmetry breaking part | Periodic part

For large misalignment angles ϕ_1/f, self-interactions can play a role [2].

· Oscillations start in a radiation-dominated universe, at $H_{\rm osc} \approx \frac{m_a}{3}$.

Parametric resonance instability → Amplification of fluctuations

Fragmentation of the (homogeneous) background field

As the ALP densitiy decreases, the interaction rates drop
→ The spectrum freezes

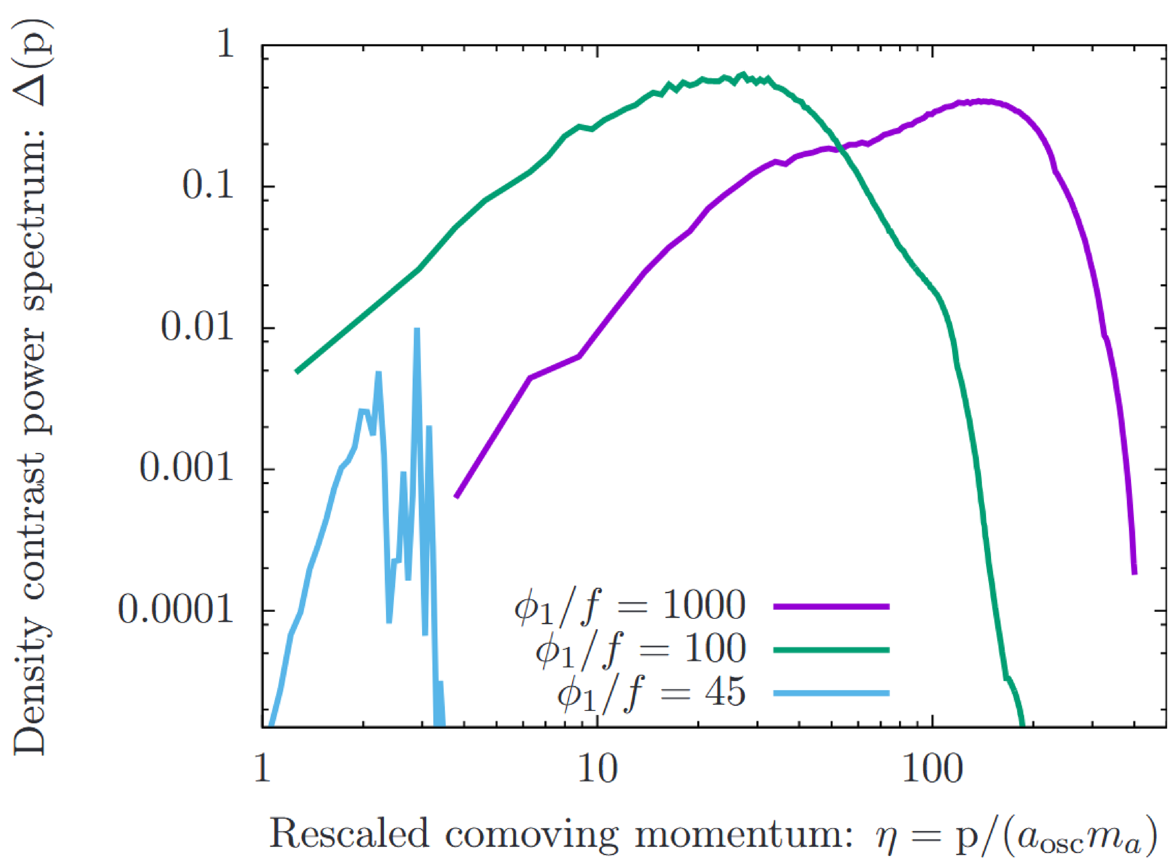
Axion miniclusters? Gravity versus pressure

Growth of fluctuations → ALPs can have $O(1)$ over-densities.

Characterized by the **density contrast power spectrum**:

$$\Delta_\delta(t,\mathrm{p}) = \frac{\mathrm{p}^3}{2\pi^2 V}\langle|\delta(\mathbf{p})|^2\rangle, \qquad \delta(\mathbf{x}) = \frac{\rho(\mathbf{x})-\langle\rho\rangle}{\langle\rho\rangle}.$$

Extracted from classical-statistical lattice simulations:



Spherical **collapse** of an over-density (including its pressure):

$$\frac{d^2r}{dt^2} = -\frac{8\pi G}{3}\rho_R r - \frac{GM}{r^2} - \frac{1}{\rho}\frac{dp}{dr}. \quad \longleftrightarrow \quad p \approx \frac{\langle \mathrm{p}^2\rangle}{3m_a^2}\rho$$

For pressureless matter ($p \approx 0$) the over-density collapses at $x \approx \frac{0.7}{\delta}$ [3], where $x = a/a_{\rm eq}$.

Pressure **prevents** the collapse (is stronger than gravity), if $x < 1.5\frac{\eta^4}{\delta}$ [2].

Fluctuations in the post-inflation scenario, QCD axion	$\eta < 1$	pressure is small, **miniclusters form**
Fluctuations from parametric resonance, monodromy axion	$\eta \sim$ few $\times 10 - 100$	over-densities **have not collapsed** yet

Expected typical size of over-densities today: $R_{\rm today} \sim (10^5 - 10^6)\mathrm{km}\sqrt{\frac{\mathrm{eV}}{m_a}}$

Production of gravity waves

Parametric resonance and subsequent non-linear dynamics generate a **stochastic gravitational wave (GW) background**.

The **frequency** of the signal is determined by the **mass**,

$$\nu = 3.2\times 10^{-3}\mathrm{Hz}\,\eta\,\sqrt{\frac{m}{\mathrm{eV}}}\left(g_{s,\rm emit}^{1/3} g_{\rm emit}^{1/4}\right)^{-1}.$$

The strength of the signal i.e. the **energy fraction,**

$$\Omega_{\rm GW,today}(\nu) = \frac{1}{\rho_c(t_{\rm today})}\frac{d\rho_{\rm GW}(t_{\rm today})}{d\ln(\nu)} = 2\times 10^{-4}\, g_{\rm emit}^{-1/3}\,\Omega_{\rm GW,emit}(\nu).$$

is determined by the **misalignment field value** ϕ_1**,**

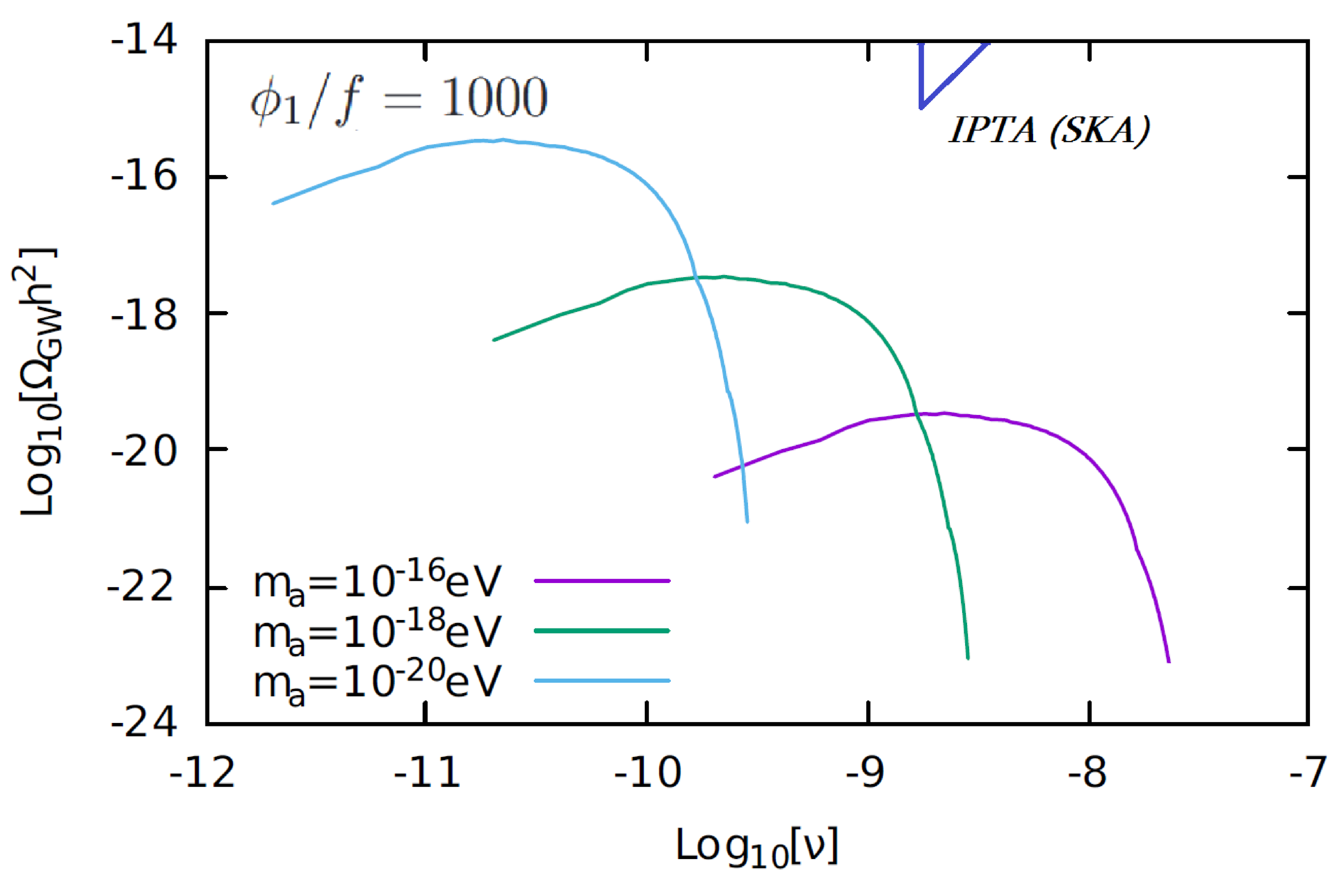
$$\Omega_{\rm emit} = \frac{\rho_{\rm GW}(t_{\rm emit})}{\rho_c(t_{\rm emit})}: \quad \propto \frac{\rho_\phi^2(t_{\rm osc})}{\mathrm{p}^2}, \quad \propto H_{\rm osc}^2 \approx m_a^2 \quad \Longrightarrow \quad \Omega_{\rm GW} \propto \phi_1^4.$$

Do not over-produce dark matter: $\sqrt{\frac{m_a}{\mathrm{eV}}}\left(\frac{\phi_1}{10^{11}\mathrm{GeV}}\right)^2 < 10^2.$

GW spectra from lattice simulation, using a modified version of HLATTICE [4] code,

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{\Delta h_{ij}}{a^2(t)} = \frac{16\pi}{M_{\rm Pl}^2}\Pi_{ij}, \qquad \Pi_{ij} = \frac{1}{a^2}\Big(\partial_i\varphi\partial_j\varphi - \delta_{ij}(\mathcal{L}) - \langle p\rangle\Big).$$

$$\rho_{\rm GW}(t) = \frac{M_{\rm Pl}^2}{32\pi V}\int_{\mathbf{k}}|\dot{h}_{ij}(t,\mathbf{k})|^2.$$



The signal can be **enhanced** if some of the ALP energy is converted into other degrees of freedom [5].

Axion as the inflaton: GW from preheating

ALPs can play the role of the inflaton i.e. axion monodromy inflation [1].

Preheating after inflation involves a **similar** dynamics, and generates gravity waves.

$m \approx 10^{-5}M_{Pl}$ required by observations, $\phi_1 \approx 0.25\, M_{pl}$, determined by the slow-roll attractor

- Frequency of the signal, $\nu \sim (10^7 - 10^9)$Hz.
- Energy fraction in GW, $\Omega_{\rm GW}h^2 \sim 10^{-9}$.

References

[1] E. Silverstein, A. Westphal, Phys. Rev. D78, 106003 (2008).
[2] J. Berges, A. Chatrchyan, J. Jaeckel, arxiv:1903.03116
[3] E. Kolb and I. Tkachev, Phys. Rev. D50, 769 (1994)
[4] Z. Huang, Phys. Rev. D83, 123509 (2011).
[5] S. Machado, W. Ratzinger, P. Schwaller, B. Stefanek, JHEP 1901 (2019) 053

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