Gravity waves from nonlinear axion-like particle dynamics

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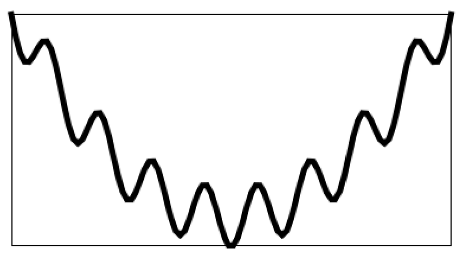
Axion-like particles (ALPs) and nonlinear dynamics

Axions and ALPs play an important role in cosmology, including dark matter and inflationary model building.

Wiggly potentials: A characteristic feature of ALPs is the cosine-type potential, which conserves the discrete shift symmetry. In the more general case, nonperiodic, wiggly potentials are possible (e.g. via monodromy in string theory [1]).



Homogeneity: Inflation sets almost homogeneous initial conditions for the field. At the same time, the post-inflationary evolution over the nonquadratic regions of the potential leads to the amplification of fluctuations, via parametric/tachyonic instabilities.

This impacts the dynamics, by possibly leading to the **fragmentation** of the field [2,3], **bubble nucleation** and transitions between local minima, and by sourcing **gravity waves**.

Production of gravity waves: the misalignment mechanism

The rapid conversion of energy from the homogeneous field into fluctuations is accompanied by the production of a stochastic GW background, peaked at similar wavelengths, determined by the mass of the scalar field (or, in the case of a phase transition, by the typical bubble distance).

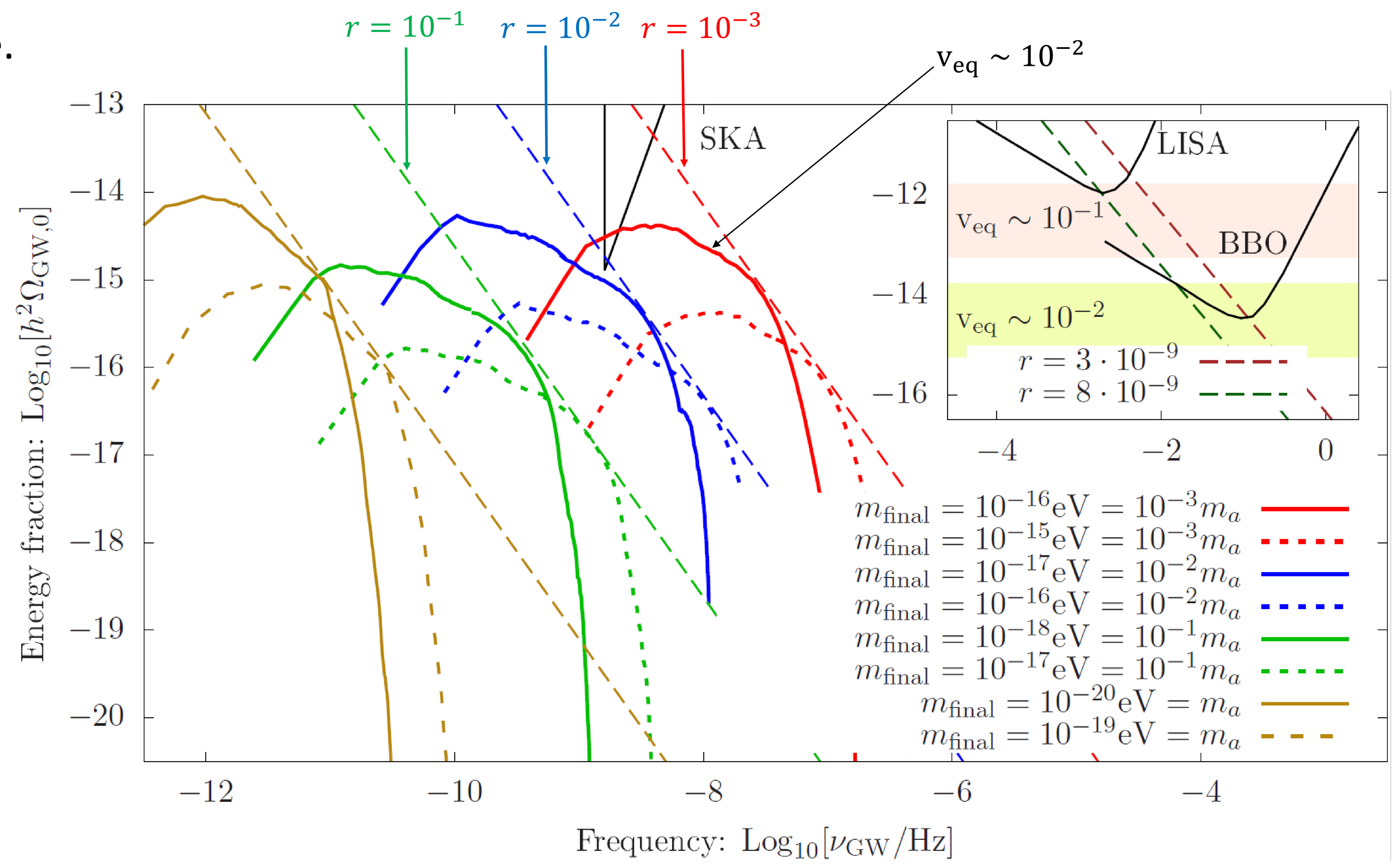
ALP DM from the misalignment mechanism: Light ALPs with masses from a wide range, $(10^{-21} - 10^{3})$eV, can behave as dark matter. The resulting GW background was investigated by means of numerical lattice simulations, using a modified version of the "Hlattice" code [4], for the ALP potential $U(\varphi) = \frac{1}{2}m^2\varphi^2 + \Lambda^4\left(1-\cos\frac{\varphi}{f}\right)$, with a large misalignment angle $\varphi_1/f \gg 1$.

Strong bounds on the signal (gold line) imposed by the DM abundance.

Weaker bounds are possible, if the field remains relativistic for a longer period after fragmentation, so that the field would dilute its energy more efficiently. This can be achieved if the mass near the minimum is small.

Modified potential, $U \rightarrow U + \xi\Lambda^4\left(1-\cos\left(\frac{2\varphi}{f}\right)\right)$, can lead to a smaller final mass, $m_{final} = rm_a, r \ll 1$ (green, blue, red lines), which extends the parameter space for the signal.

Constraints on ALP velocities: typical velocities at matter-radiation equality v_{eq} slightly higher than for typical warm dark matter.



Nonequilibrium bubble nucleation

The field can get trapped in one of the local minima, and perform a transition to a lower minimum by means of **bubble nucleation**.

Instabilities produce strong fluctuations at small momenta. This can strongly modify the transition from the usual thermal case.

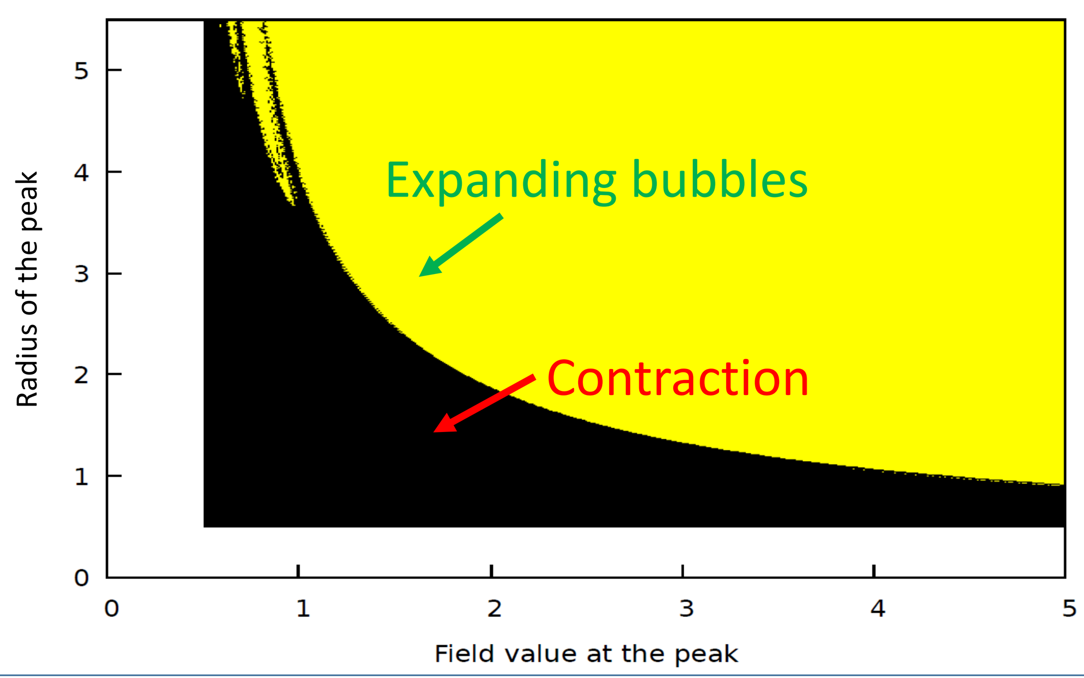
This "nonequilibrium" regime of bubble nucleation was explored using a real-time approach, based on the classical-statistical approximation [5], for the simple case of an asymmetric double well potential.

A semi-analytical method to compute the transition time/average bubble distance:

- Estimate the number density of peaks in the field (depends on the spectrum via the variance and the first few moments)

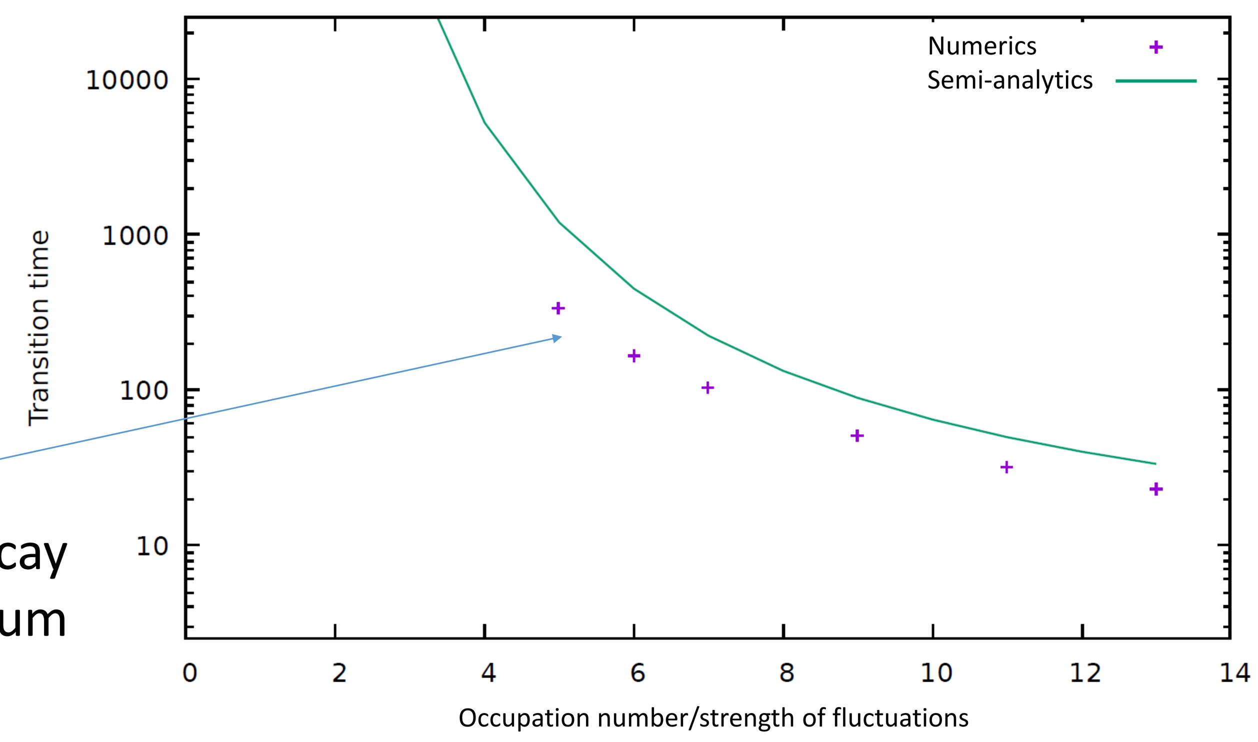
  e.g. for a gaussian random field $n_{peak}(\nu) \approx \frac{1}{8\pi^2}\left(\frac{\langle|\nabla\varphi|^2\rangle}{3\langle\varphi^2\rangle}\right)^{\frac{3}{2}}\nu^2 e^{-\frac{\nu^2}{2}}, \qquad \nu^2 = \frac{\varphi^2_{peak}}{\langle\varphi^2\rangle}$

- Determine which peaks turn into expanding bubbles,



Good agreement with the 3D lattice simulation

Deviations for slower decay
- Evolution of the spectrum
- Nongaussianities



Summary

- Axions and ALPs can exhibit very rich dynamics in the early universe, accompanied by the production of a stochastic GW background, potentially within reach of future experiments.
- Nonlinear effects can be important for the dynamics and should be taken into account.

References

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