Far-from-equilibrium dynamics of axion-like particles with broken shift symmetry

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DESY.

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ALPs with a broken shift symmetry

- ALPs can arise as pseudo Nambu-Goldstone bosons (e.g. QCD axion) or string theory axions

Peccei, Quinn, PRL 38, 1440. Weinberg, PRL 40, 223. Svrcek, Witten, JHEP 06, 051 (2006). Arvanitaki et al., PRD 81, 123530 (2010). Cicoli et al., JHEP **10**, 146 (2012).

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- ALPs enjoy an approximate shift symmetry, which can be broken by

nonperturbative (instanton) effects

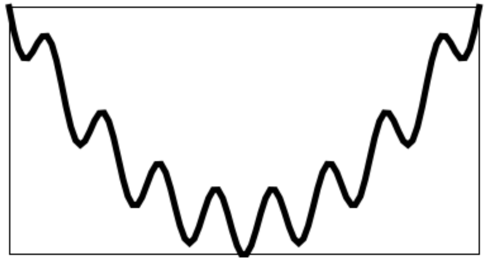
$$U(\varphi) = \Lambda^4\left[1 - \cos\left(\frac{\varphi}{f}\right)\right]$$

Callan Curtis et al., PRD 17, 2717 (1978).

monodromies (branes, fluxes), mixing

$$U(\varphi) = \mu^{4-m}\varphi^m$$

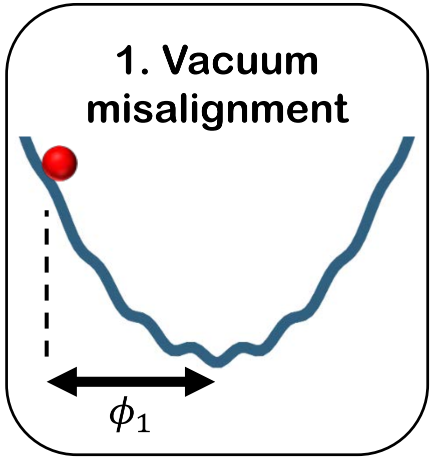
- Combination of both effects: wiggly potentials



Misalignment production of ALP dark matter

- Considered potential: $U(\varphi) = \frac{1}{2}m^2\varphi^2 + \Lambda^4\left(1 - \cos\frac{\varphi}{f}\right)$
- Homogenous initial conditions, $\langle\hat{\varphi}(\mathbf{x})\rangle = \phi_1$.

Preskill, et al.,
PLB 120, 127–132 (1983).
Arias et al.,
JCAP 1206, 013 (2012).



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- Homogenous initial conditions, $\langle\hat{\varphi}(\mathbf{x})\rangle = \phi_1$.
- Coherent oscillations around the minimum.

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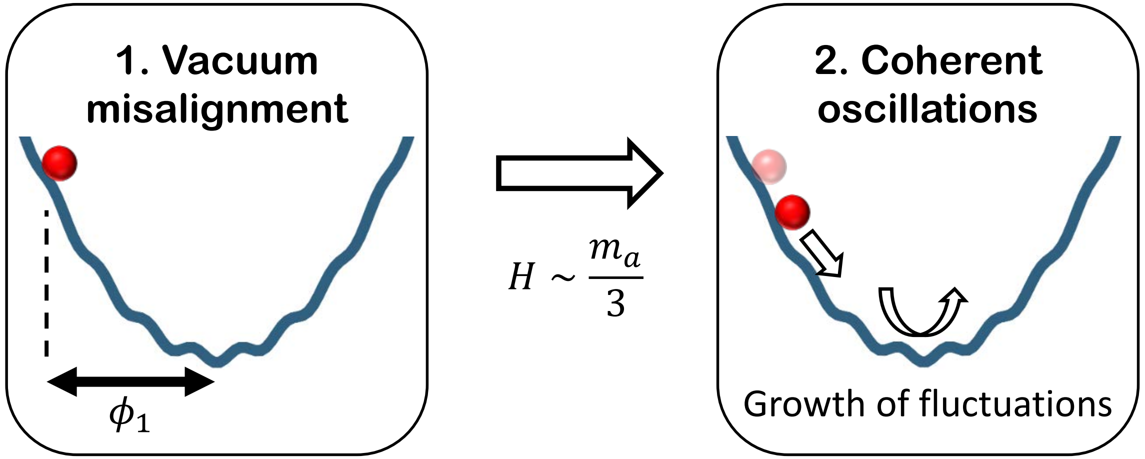
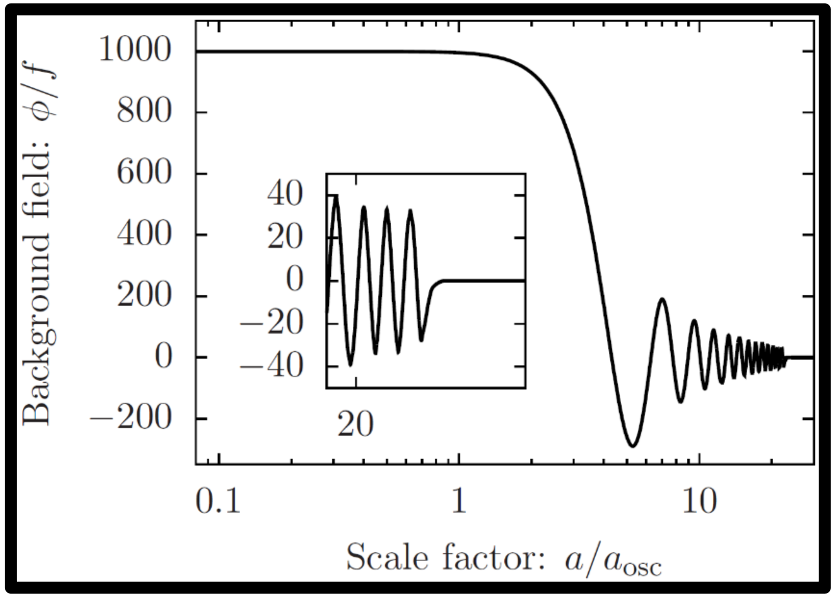


Jaeckel et al., JCAP 1701, 036 (2017).



Berges, AC, Jaeckel, JCAP 1908 (2019) 020
Fonseca et al., 1911.08473
Fonseca et al., JHEP 04, 010 (2020).

Gravitational wave production

- The frequency is determined by the mass, $\nu_\star \propto \sqrt{m_a}$

see also

Machado et. al, 1912.01007

Machado et al., JHEP 01, 053 (2019).

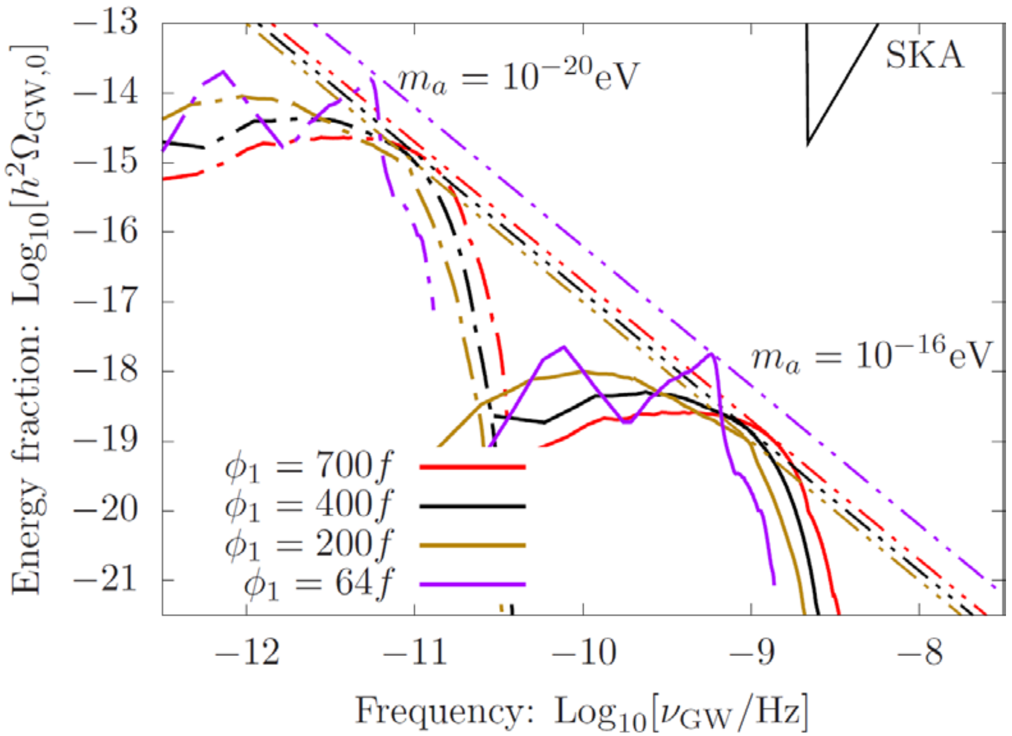
Kitajima et al., *JCAP* 10 (2018) 008.

- The strength of the signal

$$h_\star \propto \rho_\varphi(a_{\rm emit}) = \rho_\varphi(a_{\rm today})\left(\frac{a_{\rm today}}{a_{\rm emit}}\right)^3 \frac{1}{\mathcal{Z}}$$

Fixed

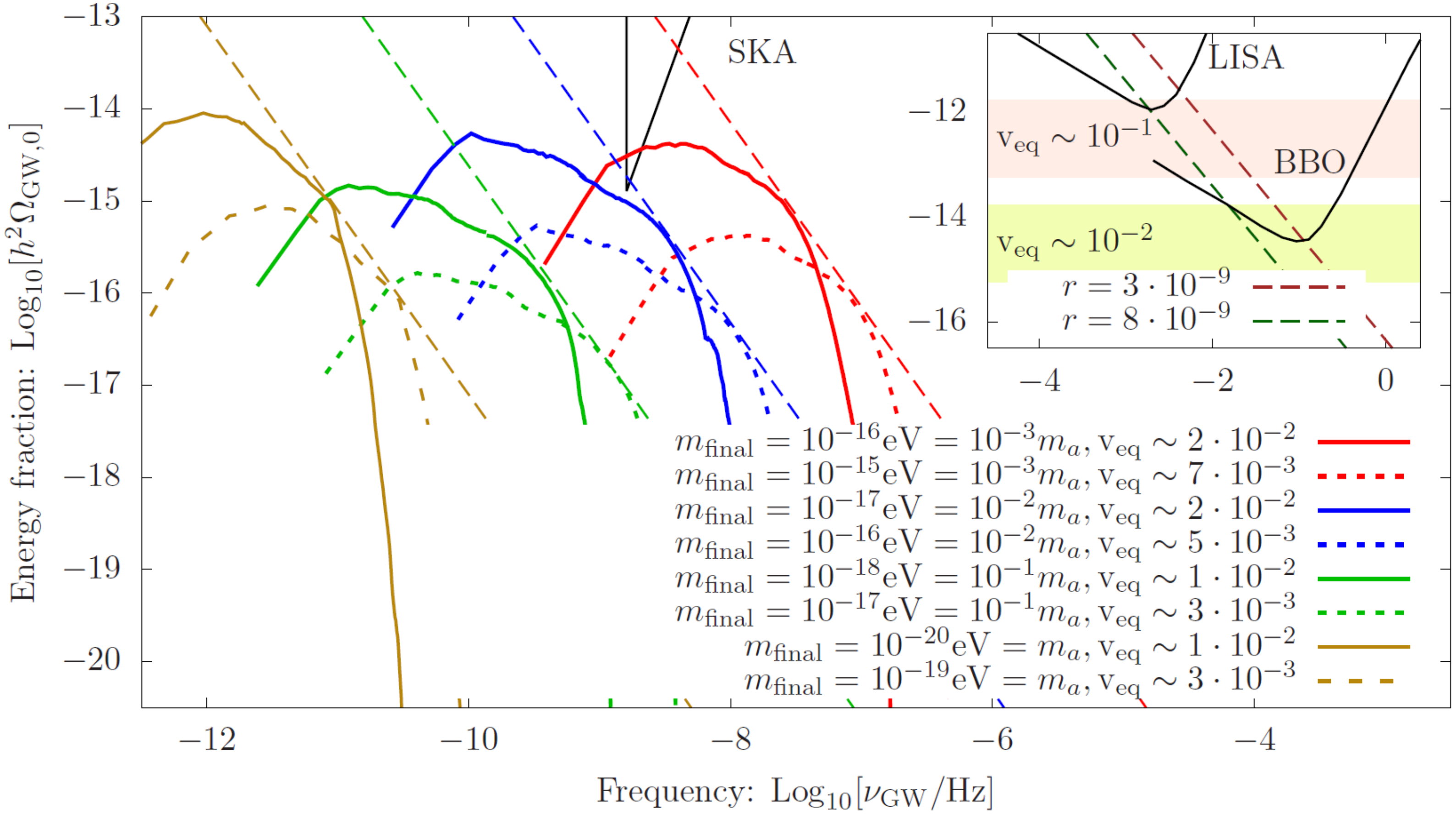
$$\mathcal{Z} = \exp\left(-3\int_{a_{\rm emit}}^{a_{\rm today}} w_\varphi(\tilde{a})\, d\ln\tilde{a}\right)$$



GWs from ALP dark matter

- Small final mass: extended relativistic phase after fragmentation, $\mathcal{Z} \ll 1$.

AC, Jaeckel
2004.07844



ALPs driving inflation: Preheating

- $m \sim 10^{-5} M_{\rm Pl}$, GW production during preheating at frequencies $\nu \sim (10^{7} - 10^{9})\rm Hz$.

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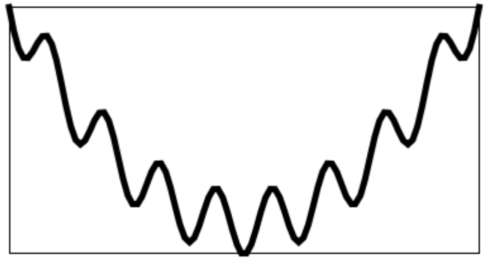
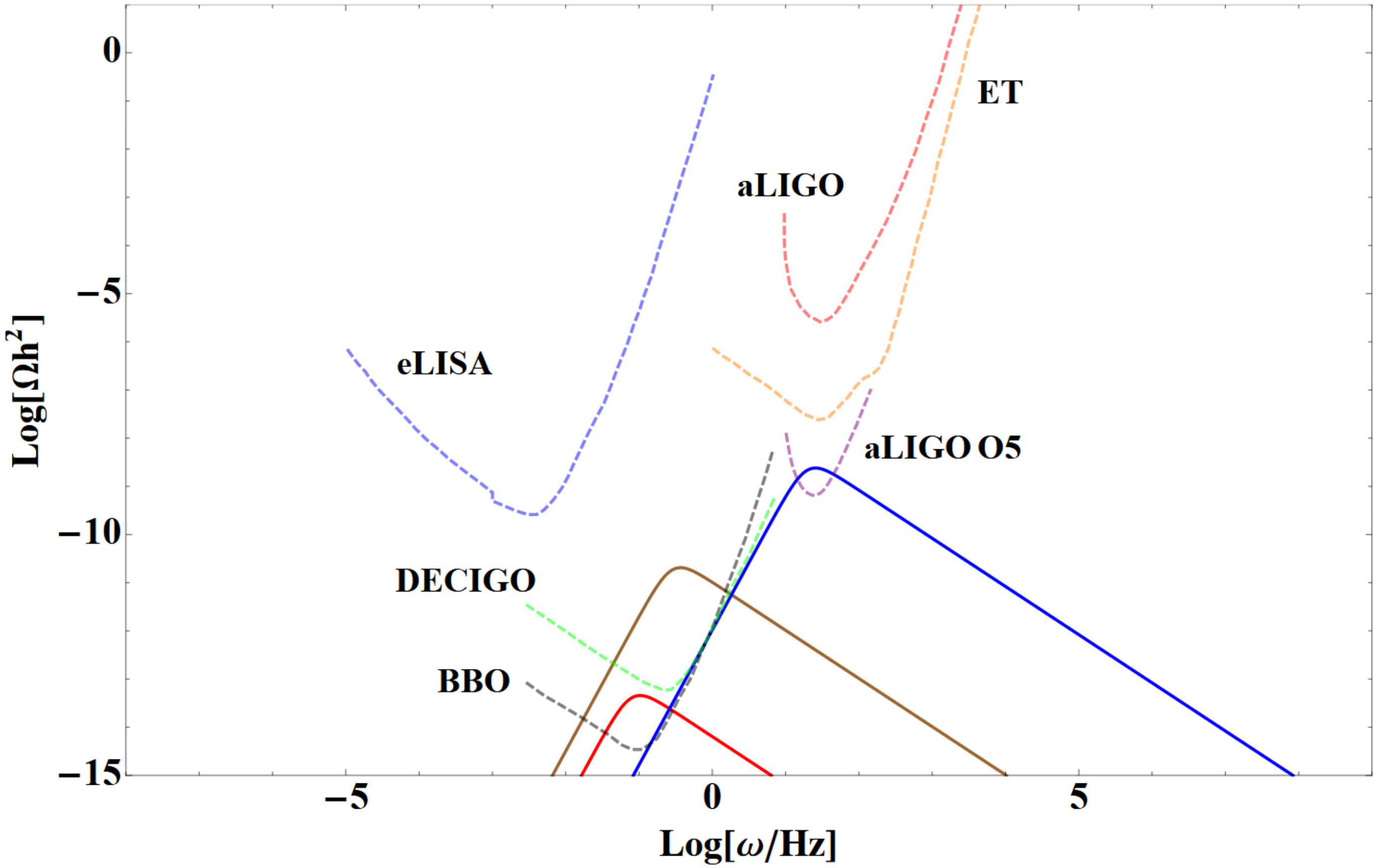
- Phase transitions between minima



- GW production from PTs

Figure taken from Hebecker et al. JCAP 11 (2016) 003



Bubble nucleation out of equilibrium

- Instanton (static) picture by Coleman, Callan, de Luccia and Linde.
  - Valid when the field is initially in vacuum or thermal state.
  - The nucleation rate is determined by the Euclidean action of the $O(4)$ or $O(3)$ bounce solution:

$$\Gamma_4 = A_4 \exp(-S_4), \qquad \Gamma_3 = A_3 T \exp(-S_3/T).$$

- **Not applicable** in our case
  - The spectrum of produced fluctuations is nonthermal.

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- Stochastic approach to tunneling, proposed by Linde
  - Based on classical-statistical approximation
  - (Classical) fluctuations randomly add up in position space to form a bubble

A. Linde
Nucl.Phys.B 372 (1992)

Braden et al.,
PRL 123 (2019)

Hertzberg, Yamada
PRD 100 (2019)

Stochastic (real-time) approach

- Analytical estimation:

$$\Gamma \sim \exp\left(-\frac{\varphi_b^2}{2\langle\varphi^2\rangle_{\mathrm{p}<1/\mathrm{r}}}\right); \qquad \text{where } \langle\varphi^2\rangle_{\mathrm{p}<1/\mathrm{r}} = \int_{\mathrm{p}<1/\mathrm{r}} \langle|\varphi_{\mathrm{p}}|^2\rangle$$

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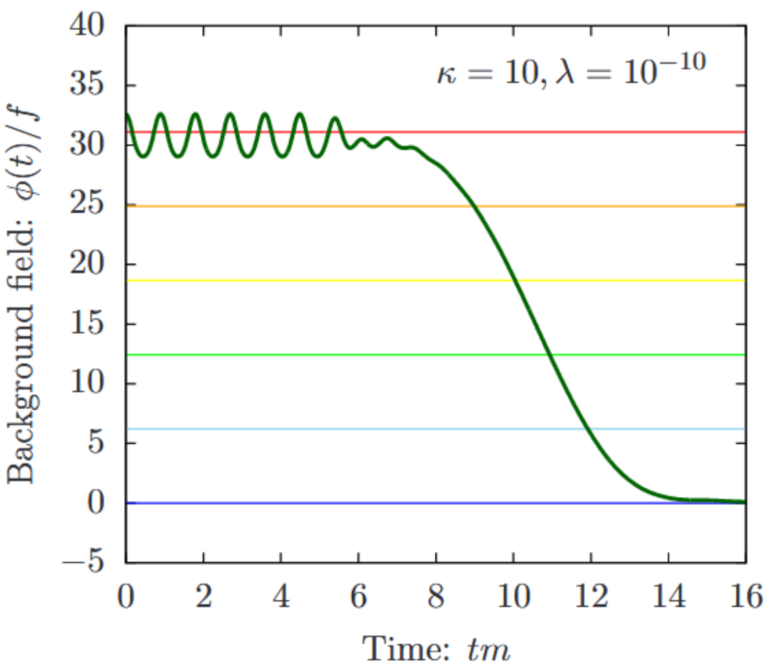
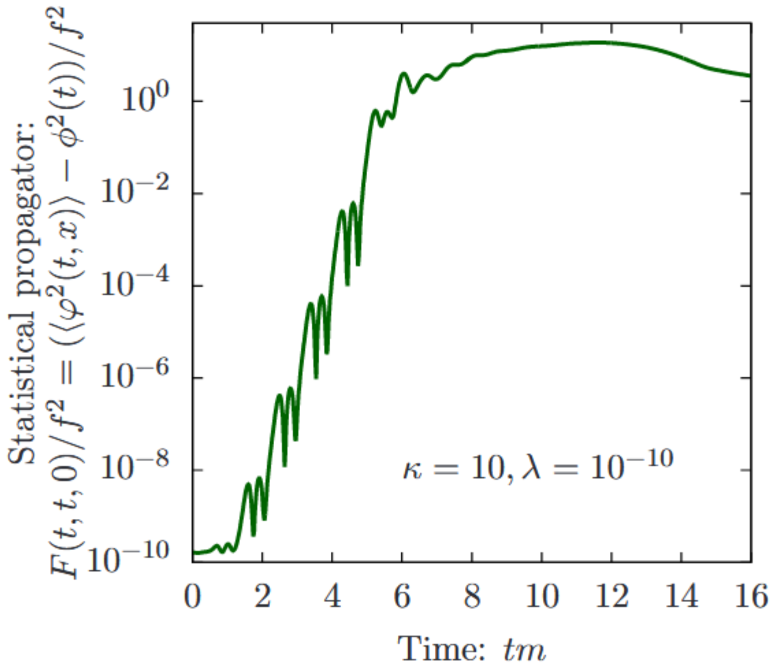
- Numerical simulations:





More details:
in preparation

Thanks for your attention!