Fragmentation of the axion field in the early universe

Parametric resonance effects in novel models

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Misalignment mechanism

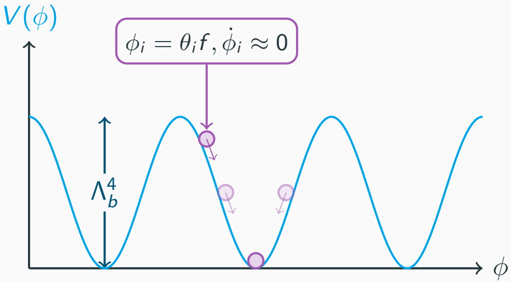
PQ breaking during inflation ⇒ almost homogeneous θ in observable universe.

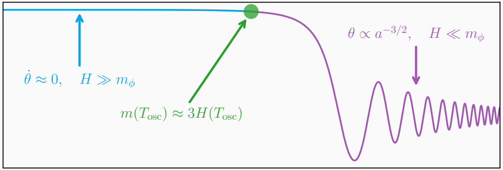
The fluctuations of the axion field are usually neglected; $\theta(t, \mathrm{x}) \rightarrow \theta(t)$

$$\ddot{\theta} + 3H\dot{\theta} + m^2(T)\sin(\theta) \approx 0$$

The field is Hubble frozen at the initial angle θ_i, starts oscillating around $m \approx 3H$, then redshifts as $\theta \propto a^{-3/2}$.

Relic density is determined by the initial angle θ_i and the oscillation temperature T_{osc}.





The Large Misalignment mechanism

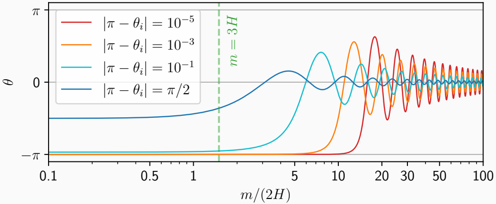
The fluctuations become important if the initial angle is tuned to the hill top, $\theta_i - \pi \ll 1$

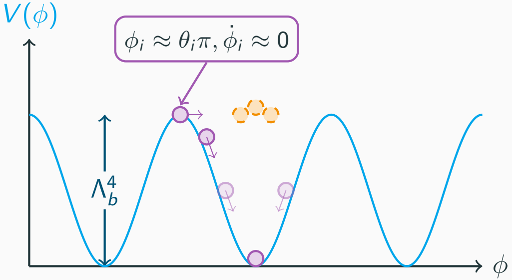
hep-ph/9808477, 1909.11665

This delays the onset of oscillations, so the amplitude of the oscillations decay at a much slower rate.

This allows the axion to probe the non-quadratic parts of the potential yielding to parametric resonance.

There are also mechanisms which can make this apparent tuning natural. 1812.11192





Axion fragmentation

In the axion has a large initial kinetic energy, then it travels many barriers before it stops.

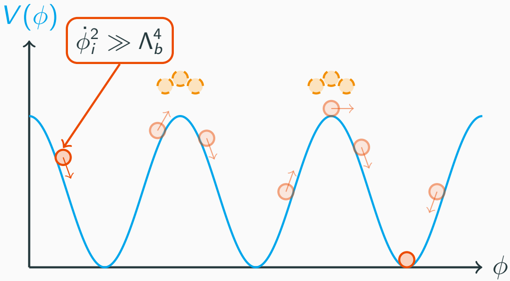
This can arise from

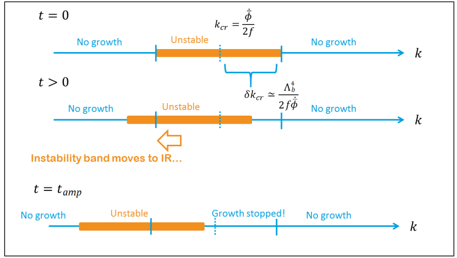
- Axion receives a kick from explicit PQ breaking in the UV see Peera Simakachorn's talk
- Trapped misalignment 2102.00012, 2102.01082

During the rolling, modes inside the instability band experiences exponential growth.

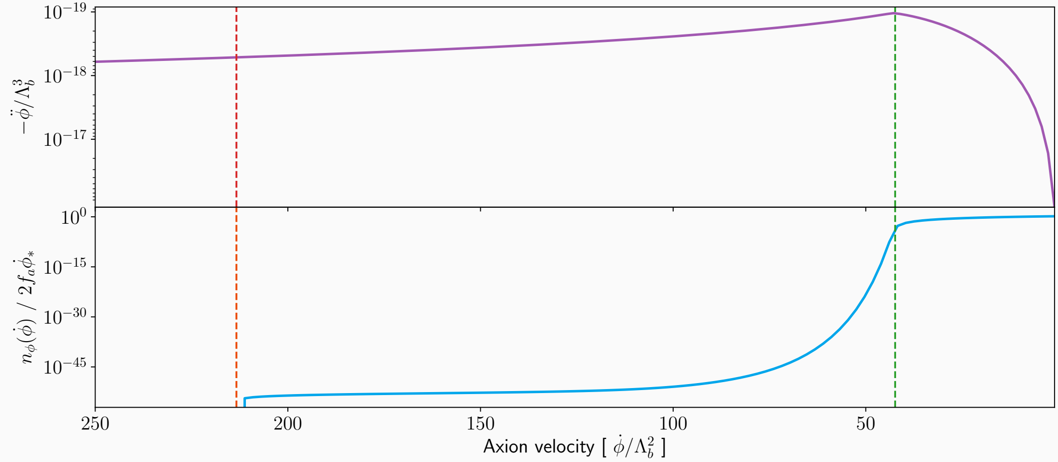
1911.08472, 1911.08473

$$\frac{\dot\phi^2(t)}{4f^2} - \frac{\Lambda_b^4}{2f^2} < \frac{k^2}{a^2(t)} < \frac{\dot\phi^2(t)}{4f^2} + \frac{\Lambda_b^4}{2f^2}$$





Axion fragmentation in a nutshell



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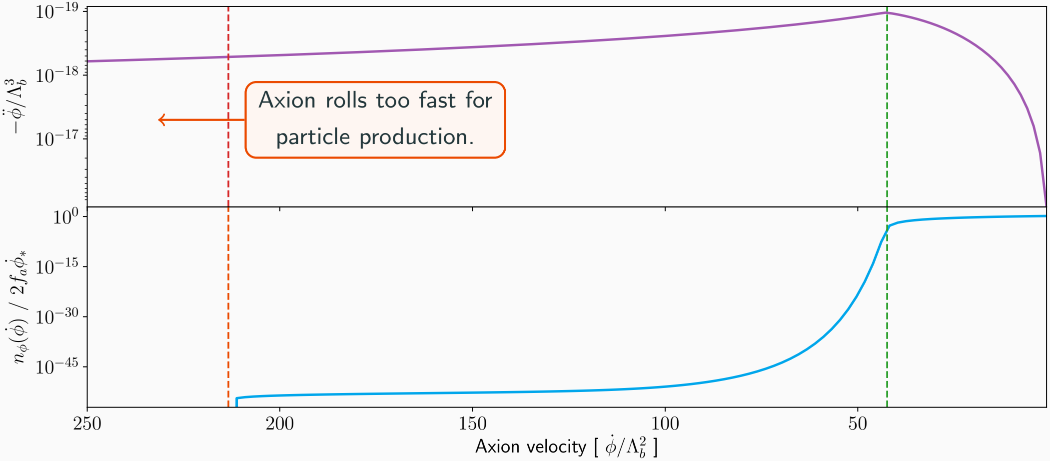
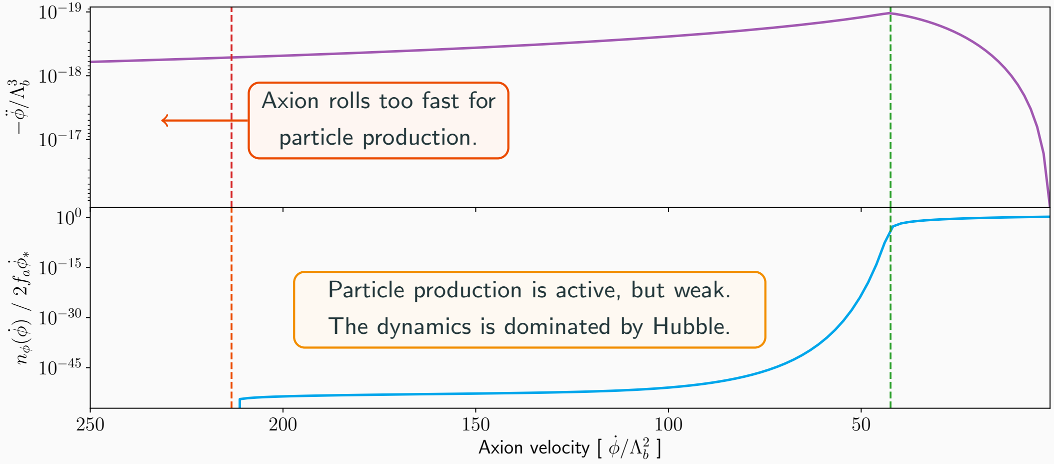


Axion rolls too fast for particle production.

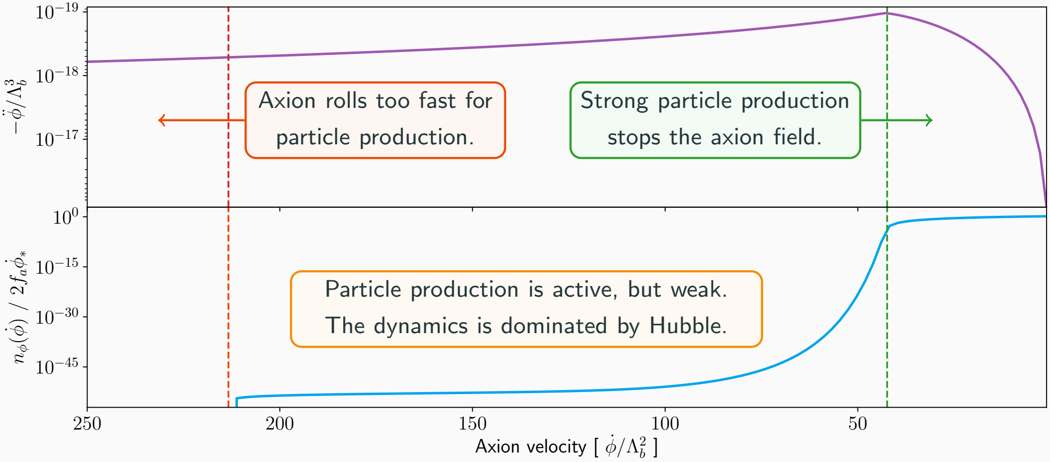
Axion fragmentation in a nutshell



Axion rolls too fast for particle production.

Particle production is active, but weak.
The dynamics is dominated by Hubble.

Axion fragmentation in a nutshell

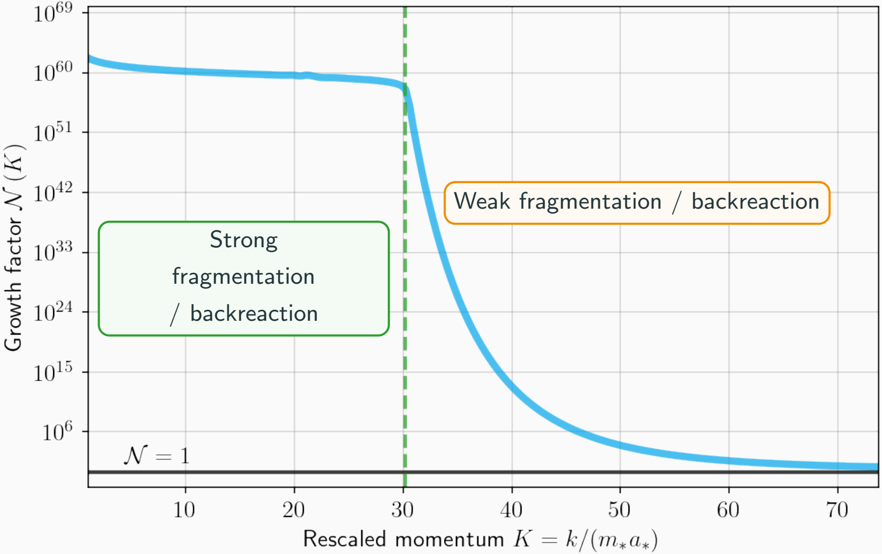


Axion rolls too fast for particle production.

Strong particle production stops the axion field.

Particle production is active, but weak. The dynamics is dominated by Hubble.

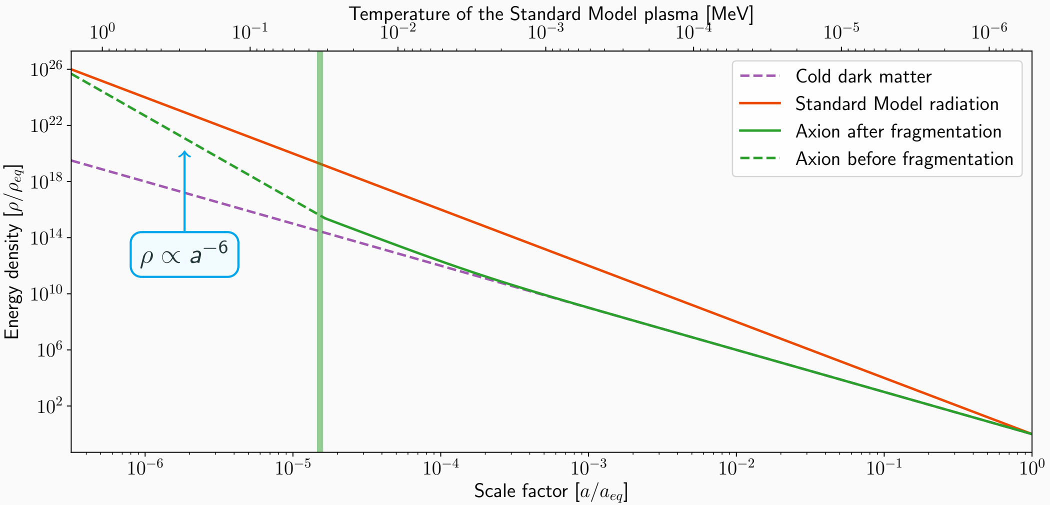
Exponential growth of the mod functions



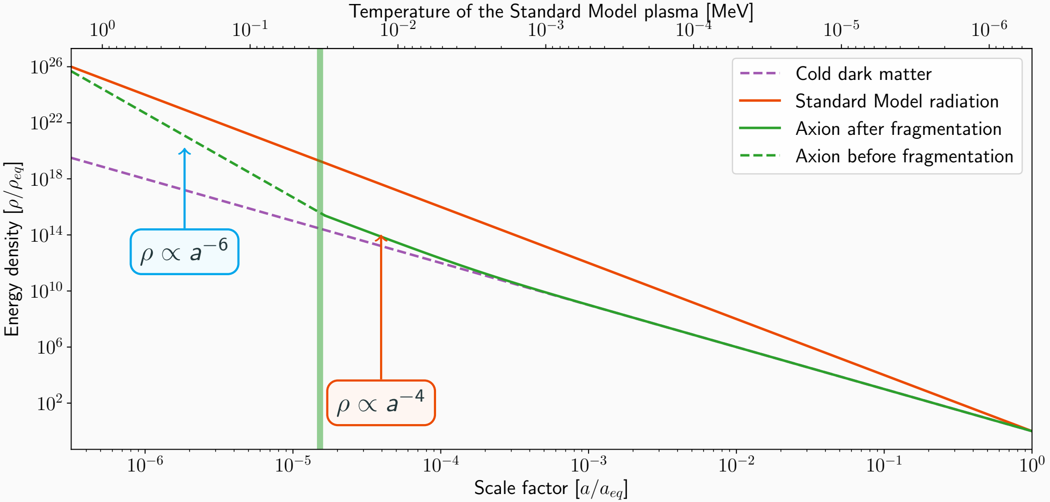
Strong fragmentation / backreaction

Weak fragmentation / backreaction

Evolution of the axion energy density



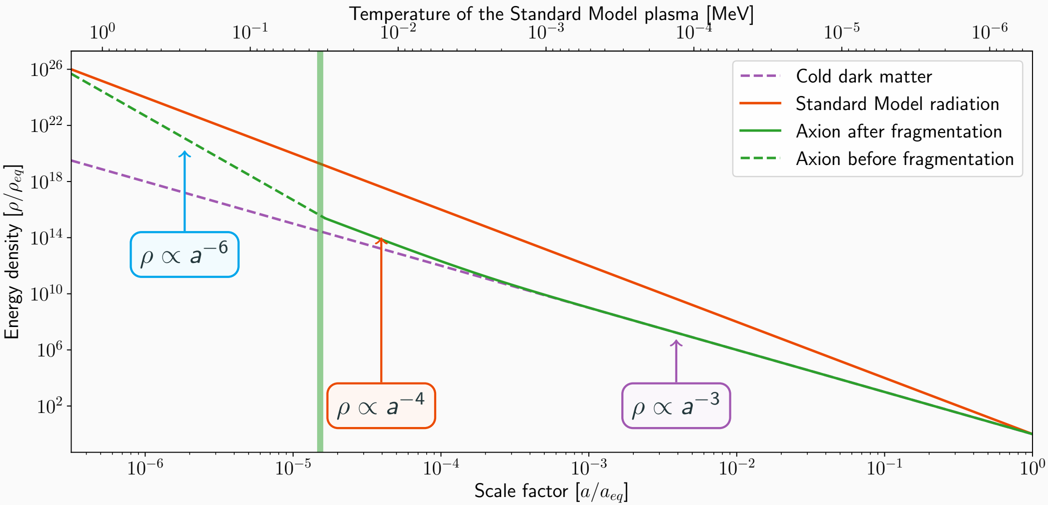
Evolution of the axion energy density



$\rho \propto a^{-6}$

$\rho \propto a^{-4}$

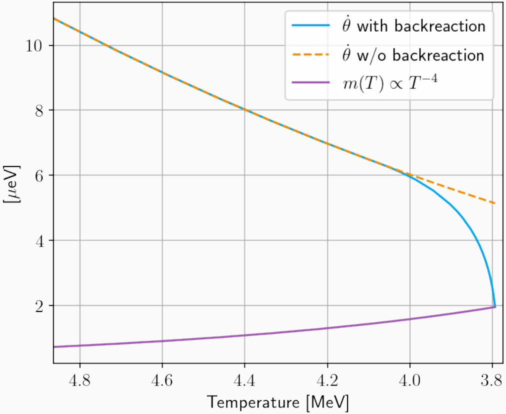
Evolution of the axion energy density



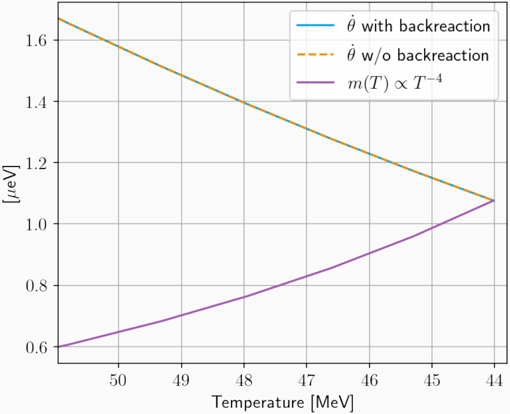
What if fragmentation cannot stop the rolling of the axion?

The axion field is trapped when $\frac{1}{2}\dot{\phi}^2(T_*) \approx 2\Lambda_b^4(T_*)$ or $\dot{\theta}(T_*) \approx 2m(T_*)$.

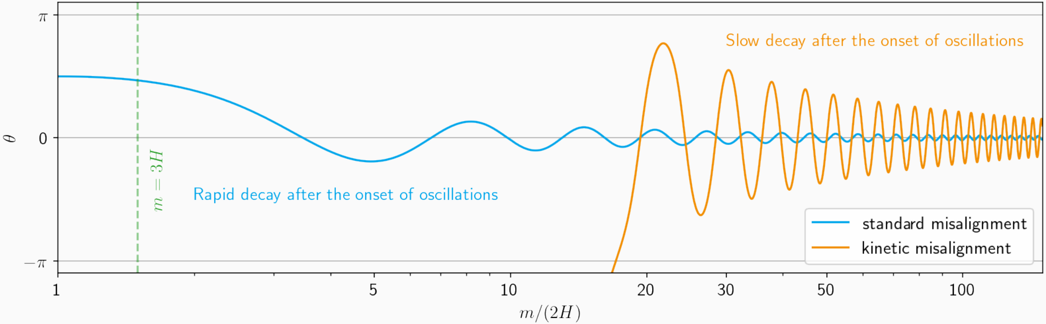
Fragmentation is complete before trapping



Fragmentation is not complete before trapping



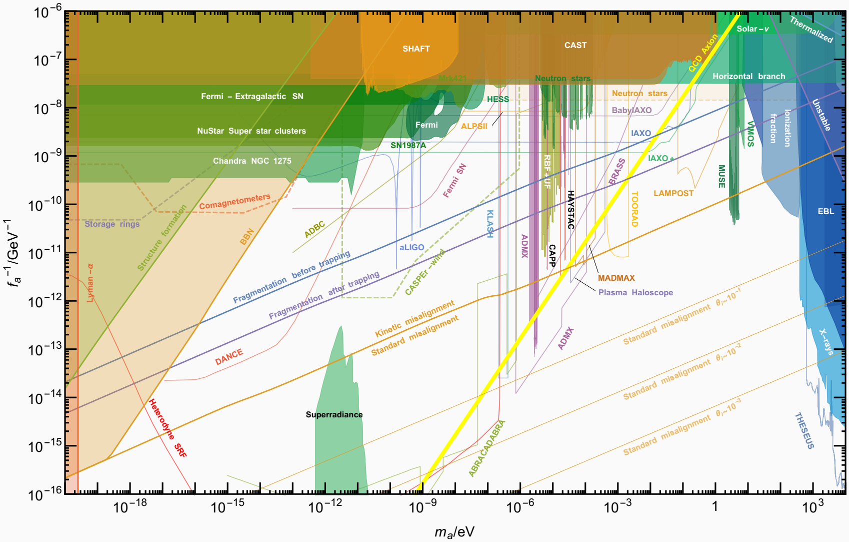
Axion fragmentation after trapping



Even in the absence of fragmentation during rolling, the onset of oscillations are delayed which can lead to efficient fragmentation even after trapping:

$$\frac{n_{\text{fluct}}}{n_{\text{zero-mod}}} \sim \left(\frac{m(T_*)}{f}\right)^2 \int \mathrm{d}\kappa\, \kappa^2 \exp\left\{\frac{m(T_*)}{H(T_*)} \underbrace{\mathcal{B}(\kappa)}_{\sim\mathcal{O}(1)}\right\}, \quad \kappa = \frac{k/a_*}{m_*}.$$

Reminder for the paramater space of ALP dark matter with fragmentation



Observational prospects (in progress)

After the fragmentation, the power spectrum of the axion fluctuations becomes $\mathcal{O}(1)$:

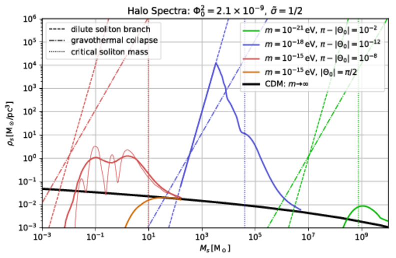
$$\mathcal{P}_\phi(k \sim m_* a_*) = \frac{2\pi^2}{k^3}|\delta_\phi(k)|^2\Big|_{k\sim a_* m_*} \sim \mathcal{O}(1)$$

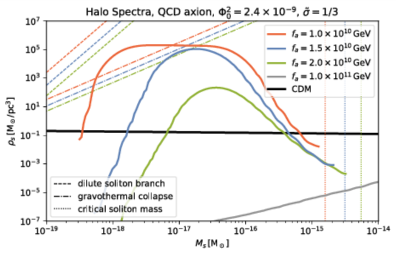
When these fluctuations reach to a critical density, they experience gravitational collapse:

$$\delta_c^2(z_{\rm col}) \simeq \sigma_R^2(z_{\rm col}) = \int \mathrm{d}\ln k\, \mathcal{P}_\phi(k, z_{\rm col})|W(k,R)|^2$$

Large fluctuations do collapse earlier yielding much denser dark matter halos:

$$\rho_s \sim 200\rho_\phi(z_{\rm col}) \propto \rho_{\phi,0}(1+z_{\rm col})^3$$





Arvanitaki et al. 1909.11665

Conclusions

- In models where the axion field has a large initial kinetic energy, axion fluctuations play a prominent role, and can yield complete fragmentation.
- Under suitable conditions, the fragmentation can be effective before the axions gets trapped by the potential, so that the rolling is stopped by the backreaction of the fluctuations.
- Even if the fragmentation is not efficient prior to trapping, it can become efficient after since the large initial kinetic energy delays the onset of oscillations allowing the axion to probe non-quadratic parts of its potential.
- After the fragmentation, the power spectrum becomes $\mathcal{O}(1)$ which leads to much denser dark matter halos.
- All the discussion is applicable to the QCD axion, to a generic ALP model, and also to other kind of potentials such as monodromy (Ongoing project with Aleksandr Chatrchyan, Matthias Koschnitzke, Géraldine Servant)

Stay tuned for our upcoming paper(s) for much more details!

Thank you for your attention!

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