QCD axion dark matter from parametric resonance

Speaker: Riccardo Natale
Collaborators: Marco Gorghetto, Mariachiara Ingicco, Geraldine Servant

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

Initial Field Displacement

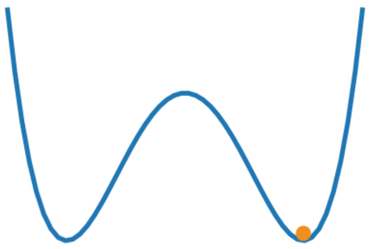
$$\Phi = \frac{\phi}{\sqrt{2}} e^{i\theta}$$

$$S = \int d^4x \sqrt{-g} \left(\partial_\mu \Phi \partial^\mu \Phi^* + cH^2|\Phi|^2 - V_{PQ}(|\Phi|)\right)$$

Peccei-Quinn Field

Hubble-induced mass

Peccei-Quinn Symmetry Breaking Potential



During Inflation the Hubble-induced mass provides a minimum at high field values.

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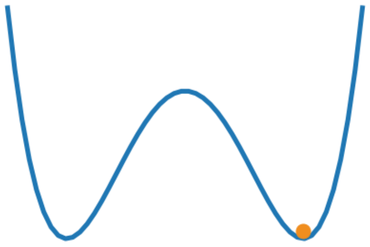

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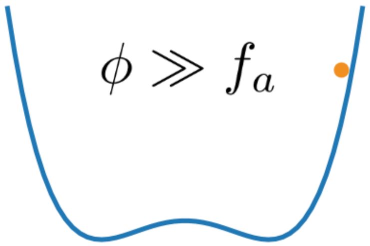

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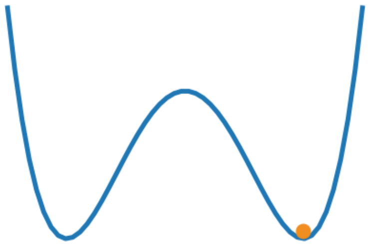

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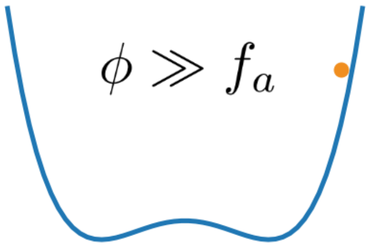

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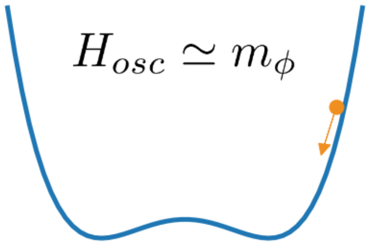
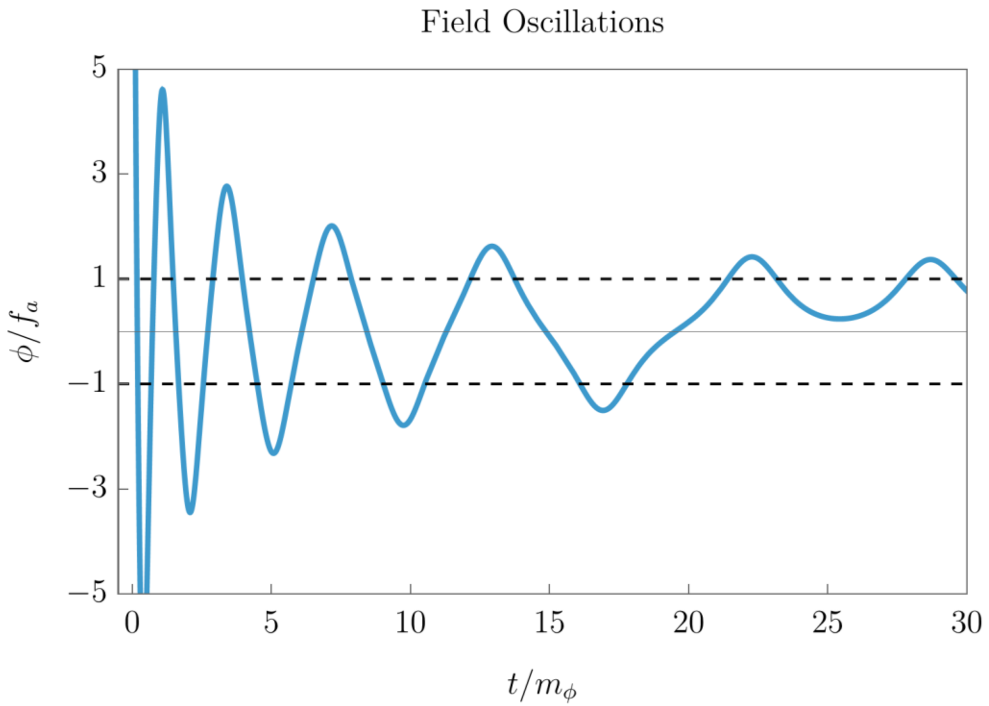


When the Hubble friction is weak enough, around $H_{osc} \simeq m_\phi$, the field **starts oscillating**

Parametric Resonance



We can decompose the Peccei-Quinn field in a ***homogenous component*** + ***spatial perturbations***

$$\phi(t,x) = \bar{\phi}(t) + \delta\phi(t,x)$$

Letting the homogeneous field oscillating and treating it as a background field, we can now study the dynamics of **perturbations**

Decomposing perturbations into Fourier modes we notice the arising of a **Hill differential equation**

$$\delta\ddot{\phi}_k + [k^2 + F(t)]\delta\phi_k = 0$$

$F(t+T) = F(t)$ periodic function

This equation admits **exponentially growing solutions** for those modes whose wave numbers resonate with the oscillation frequency of the background field

Parametric Resonance (Quartic Potential Example)

Let's take the case of a **quartic potential** and decompose the field into its ***real*** and ***imaginary*** components

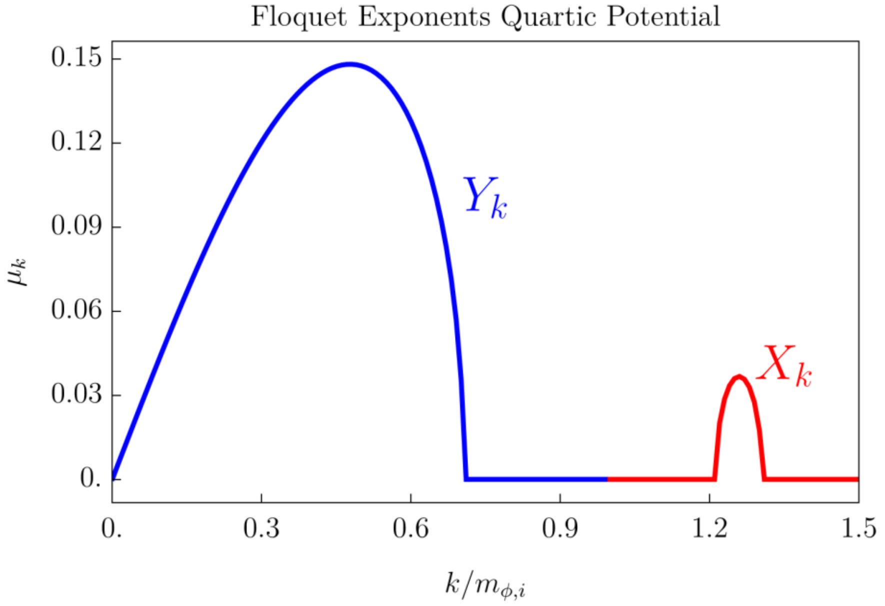
$$\Phi = X + iY \qquad \frac{\lambda}{4}\left(|\Phi|^2 - f_a^2\right)^2$$

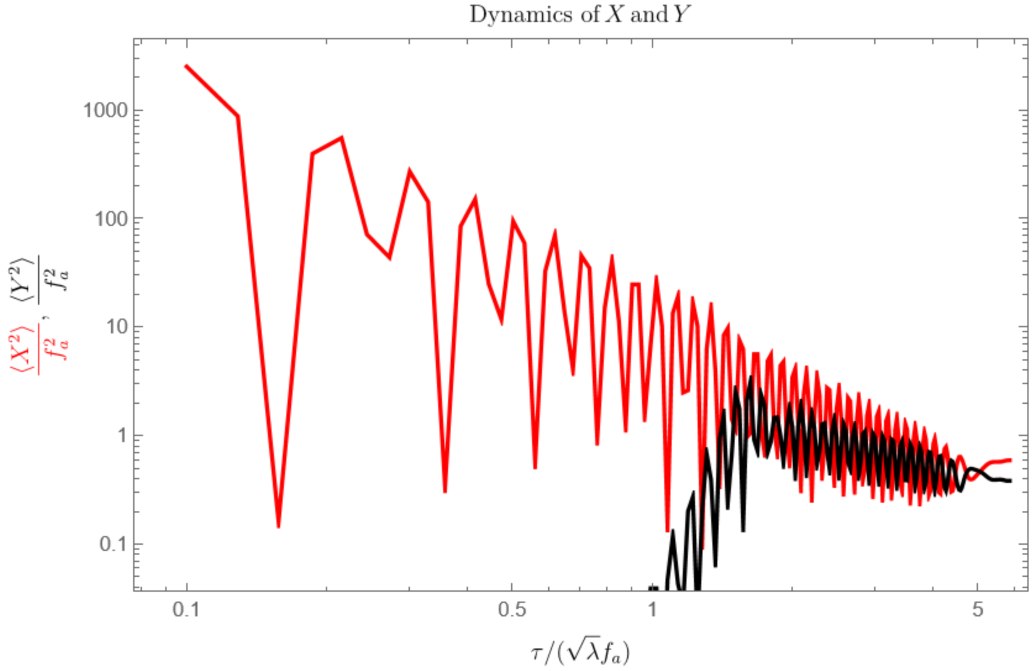
Perturbations follow a particular case of Hill equation, called Mathieu equation:

$$\ddot{y}_k + [k^2 + \lambda\phi_i^2\cos(\omega_\phi\tau)]y_k = 0$$

This equation has **bands of instability** in which **solutions grow exponentially**

$$y_k \sim \exp\left(\mu_k\tau\right)$$

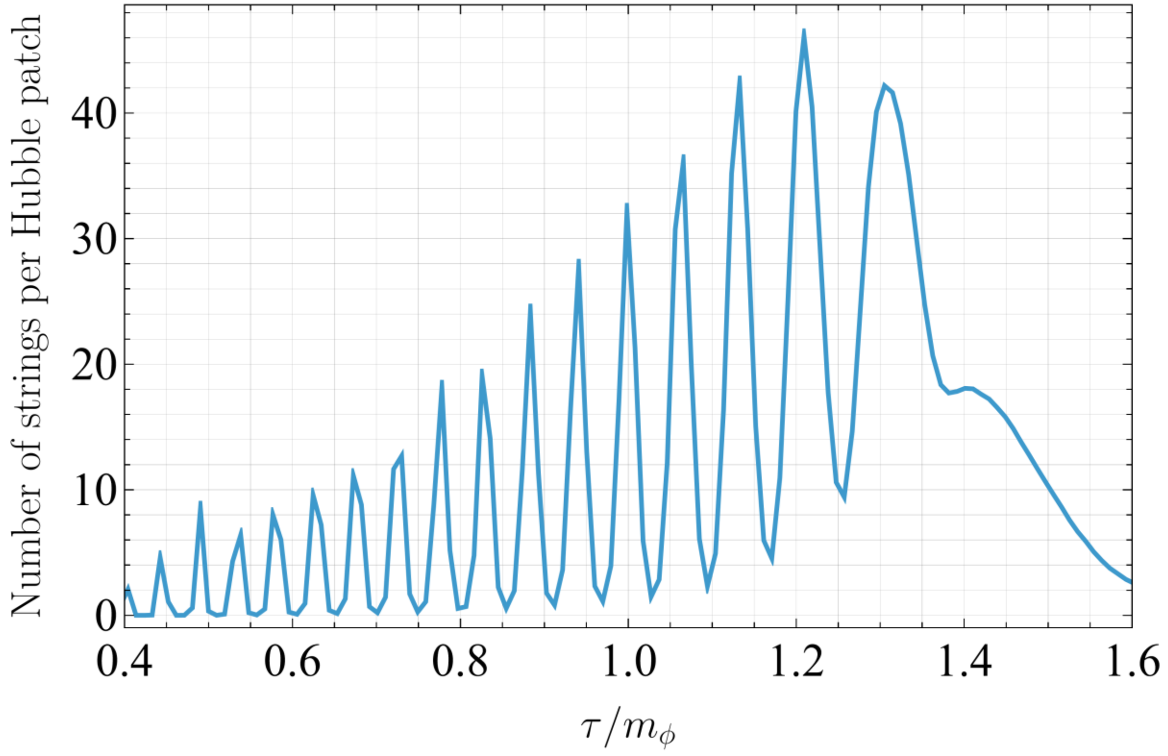


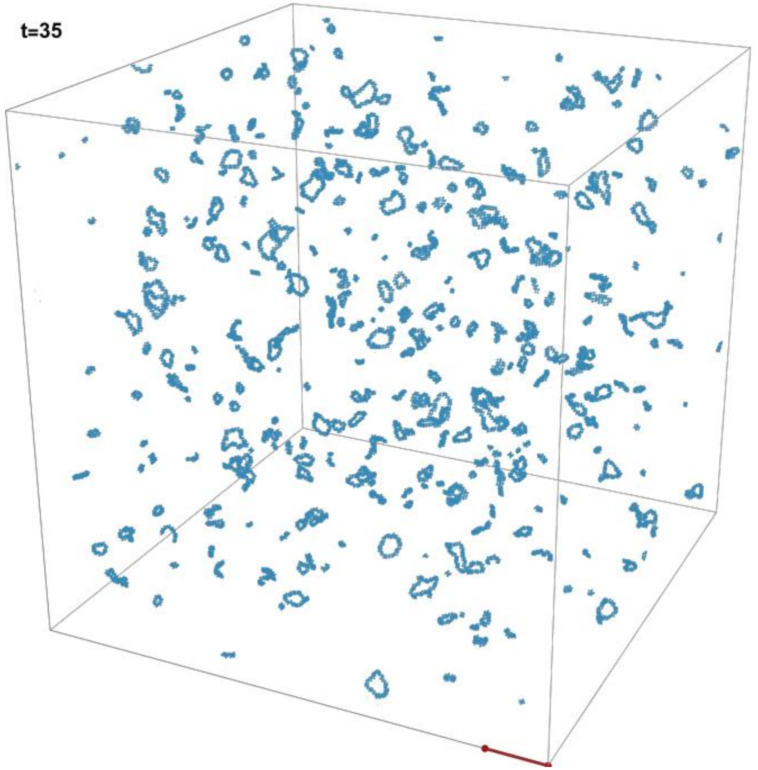


Axion Strings Formation

The growth of perturbations leads soon to a non-linear dynamics which has to be tackled via **lattice simulations**.

What we observe is the **periodic formation of axion string loops**, with a period fixed by the radial mode oscillation:

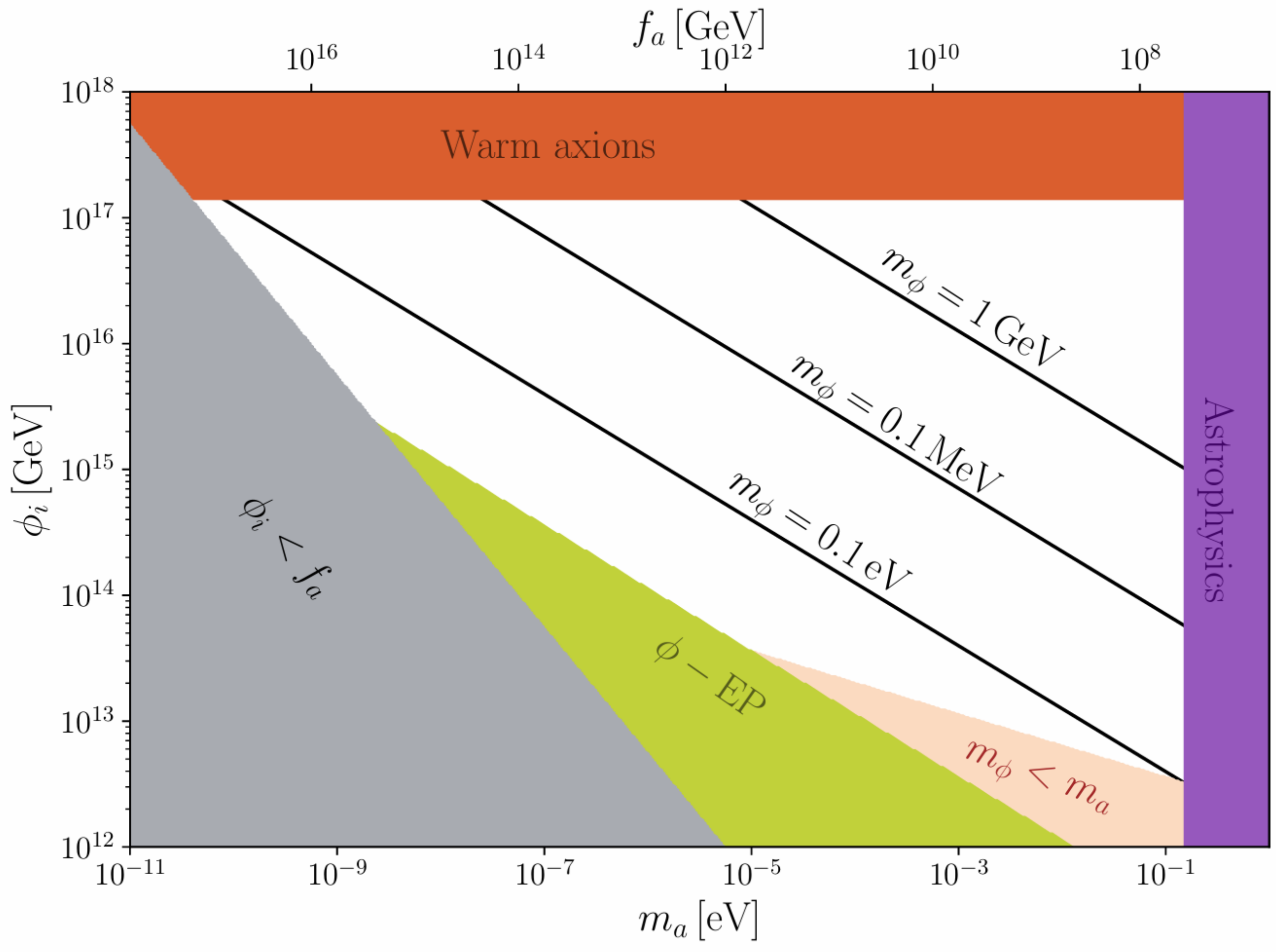




Axion Dark Matter

In conclusion, the relic axion abundance, produced by parametric resonance can account to cold dark matter via the relation:

$$h^2\Omega_{axion} \simeq 0.12 \left(\frac{\phi_i}{10^{-2} M_{Pl}}\right)^2 \left(\frac{m_a}{10^{-3}\, eV}\right) \left(\frac{10^2\, GeV}{m_{\phi_i}}\right)^{1/2}$$



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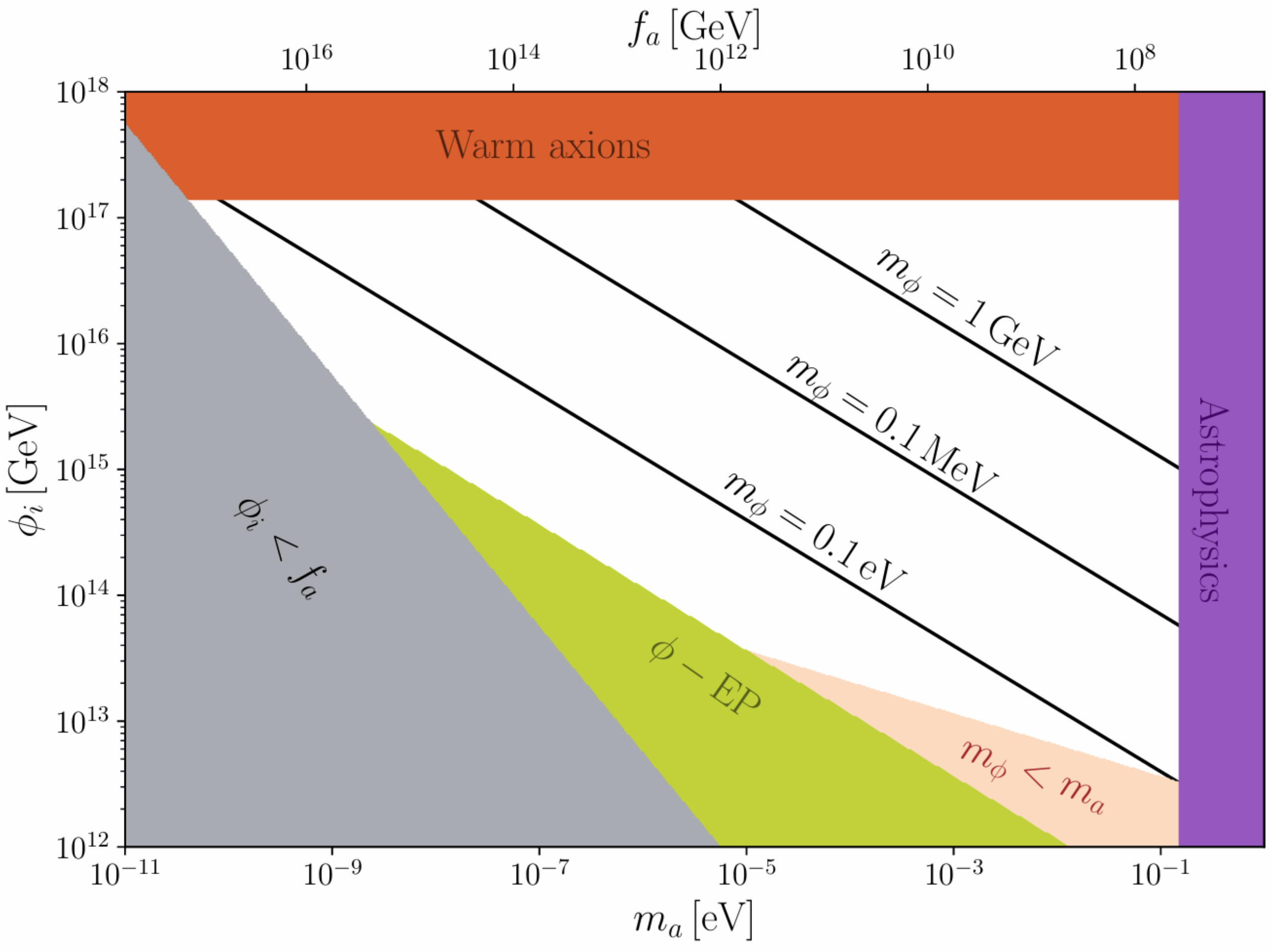
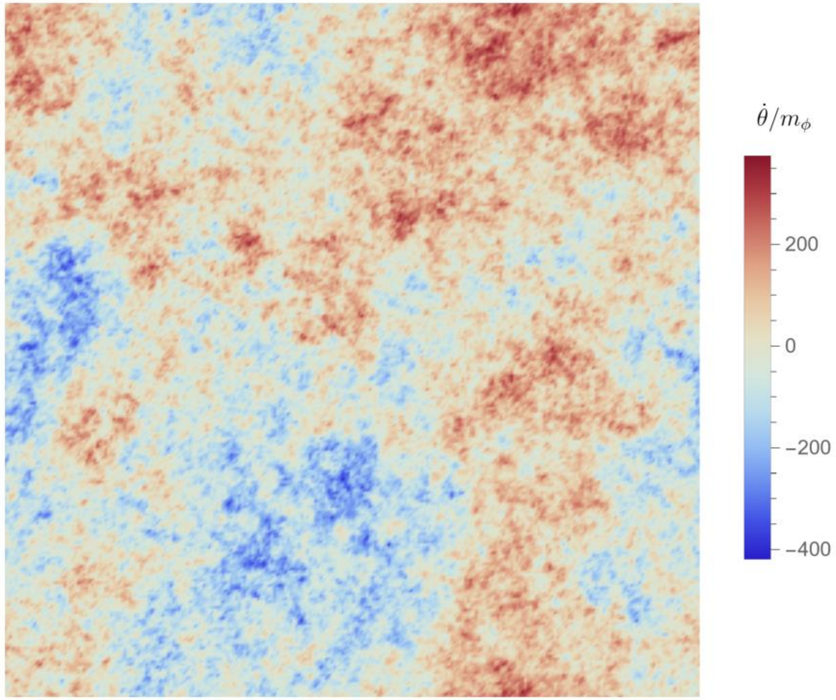


Thank you!

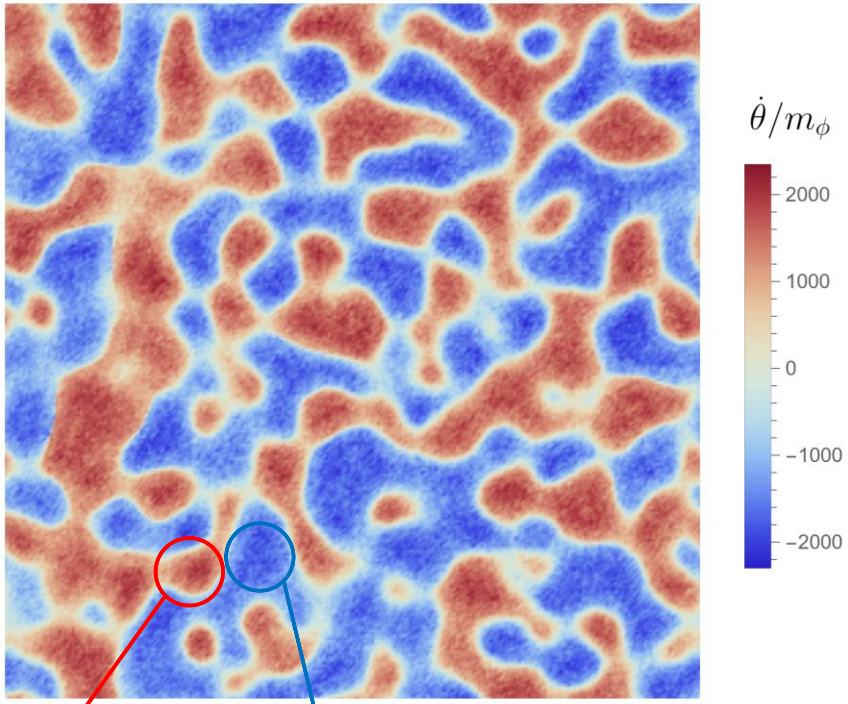
Backup slides

Axion Strings Formation

What we observe is the formation of many well-defined **domains**, in which the axion field is either rotating **clockwise** or **counterclockwise**.



Initial randomized axion field



Counterclowise rotation

Clockwise rotation