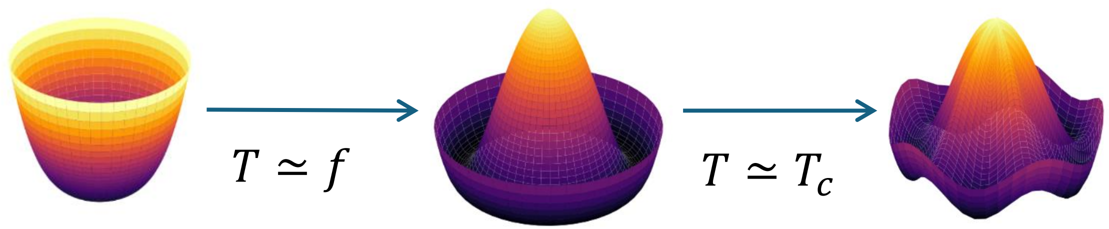
Kinetic Axion from non-minimally coupled PQ field

Enrico Morgante
Riccardo Natale

Misalignment Mechanism

When **non-perturbative effects** appear the initial axion field **may not be aligned** to the actual minimum.



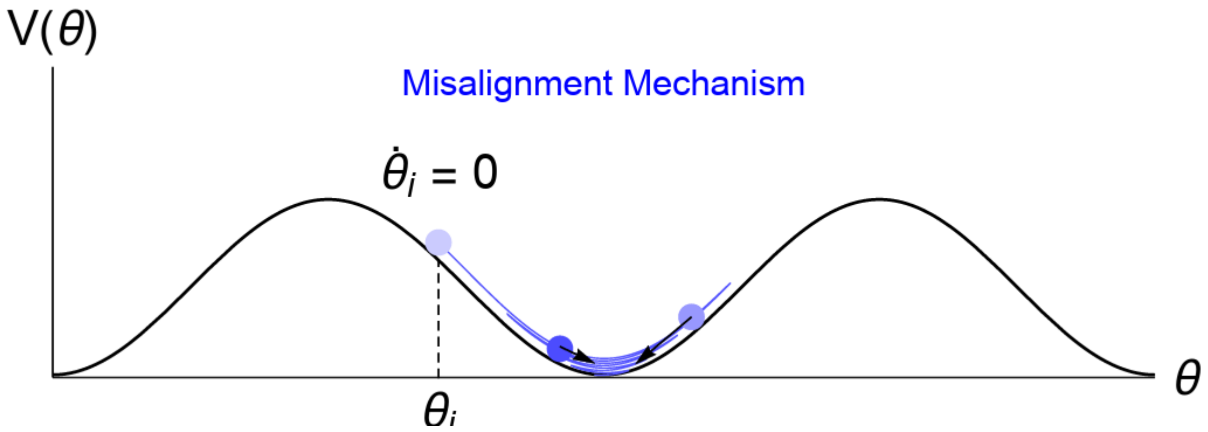


Fig. by «Harigaya et all, Axion Kinetic Misalignment Mechanism»

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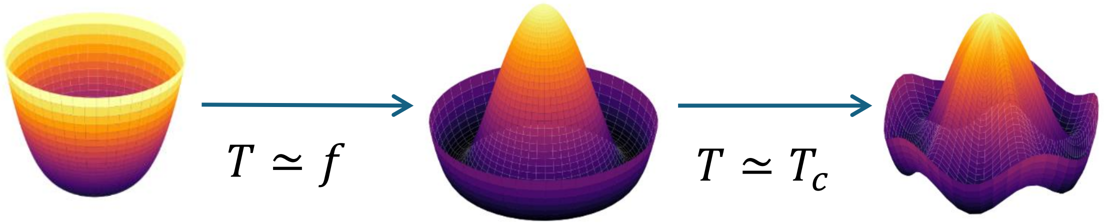

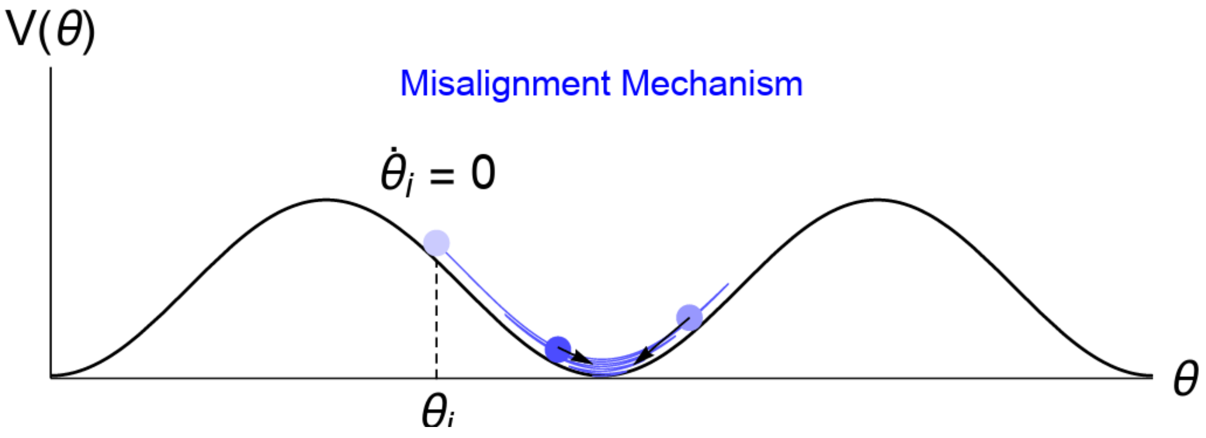

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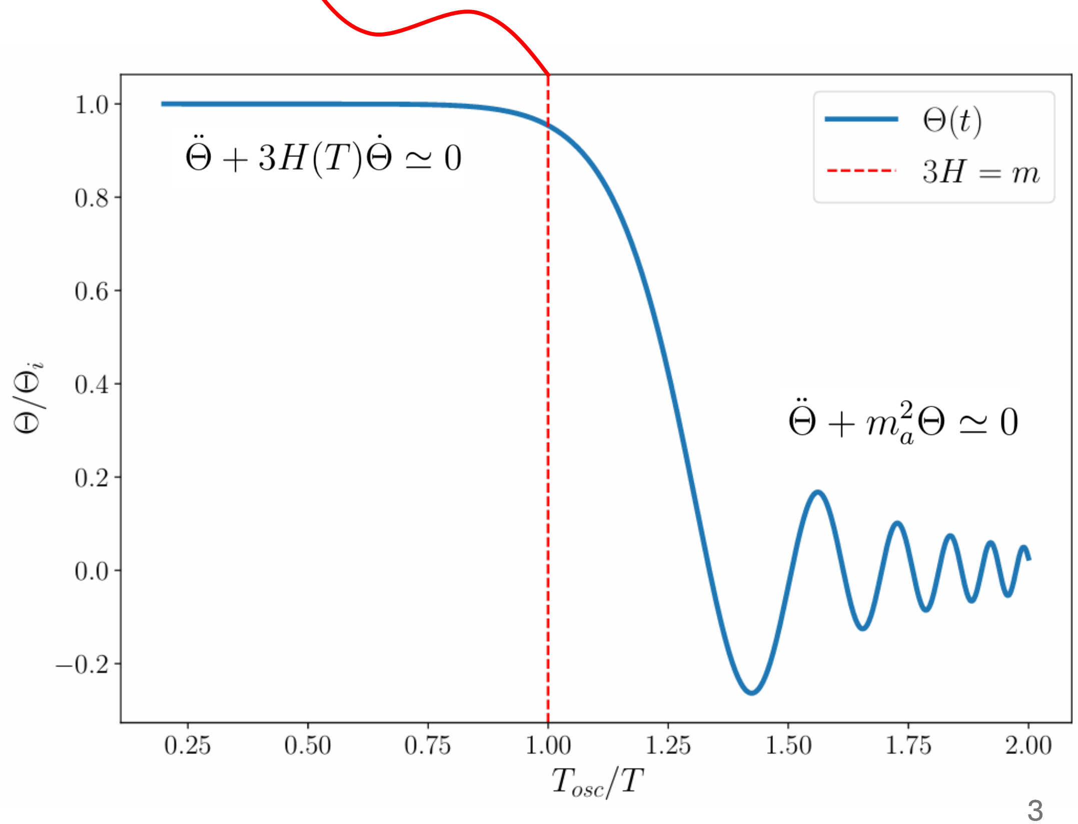
$$\ddot{\Theta} + 3H(T)\dot{\Theta} + m^2(T)\Theta = 0$$

$$3H(T_{\rm osc}) \simeq m(T_{\rm osc})$$



Kinetic Misalignment Mechanism

Axion Kinetic Misalignment Mechanism

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(Received 22 November 2019; revised manuscript received 6 April 2020; accepted 8 June 2020; published 26 June 2020)

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DOI: 10.1103/PhysRevLett.124.251802

New perspectives on axion misalignment mechanism

Chia-Feng Chang* and Yanou Cui†
Department of Physics and Astronomy, University of California, Riverside, California 92521, USA

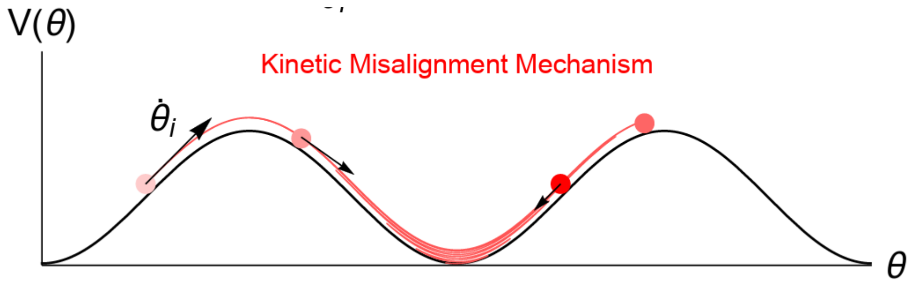
(Received 18 December 2019; accepted 23 June 2020; published 9 July 2020)

A zero initial velocity of the axion field is assumed in the conventional misalignment mechanism. We propose an alternative scenario where the initial velocity is nonzero, which may arise from an explicit breaking of the Peccei-Quinn (PQ) symmetry in the early Universe. We demonstrate that, depending on the specifics of the initial velocity and the time order of the PQ symmetry breaking vs inflation, this new scenario can either enhance or suppress the axion relic abundance relative to the conventional prediction. As a result, new viable parameter regions for axion dark matter may open up.

DOI: 10.1103/PhysRevD.102.015003

If the axion field has an initial **large velocity** it continues to **overcome the potential barrier** without being trapped

$$\frac{1}{2}\dot{\Theta}^2(T_{\rm osc})f^2 > 2m^2(T_{\rm osc})f^2$$



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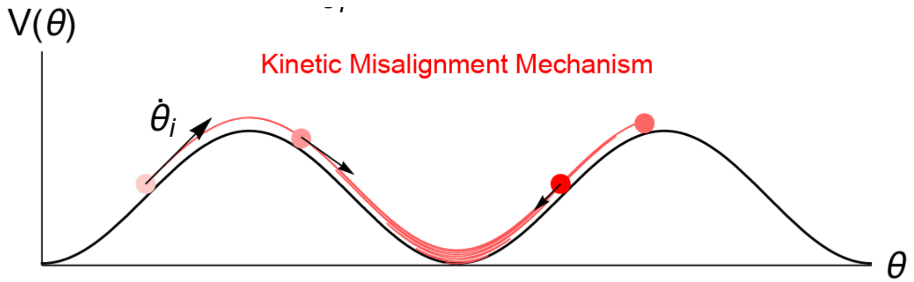
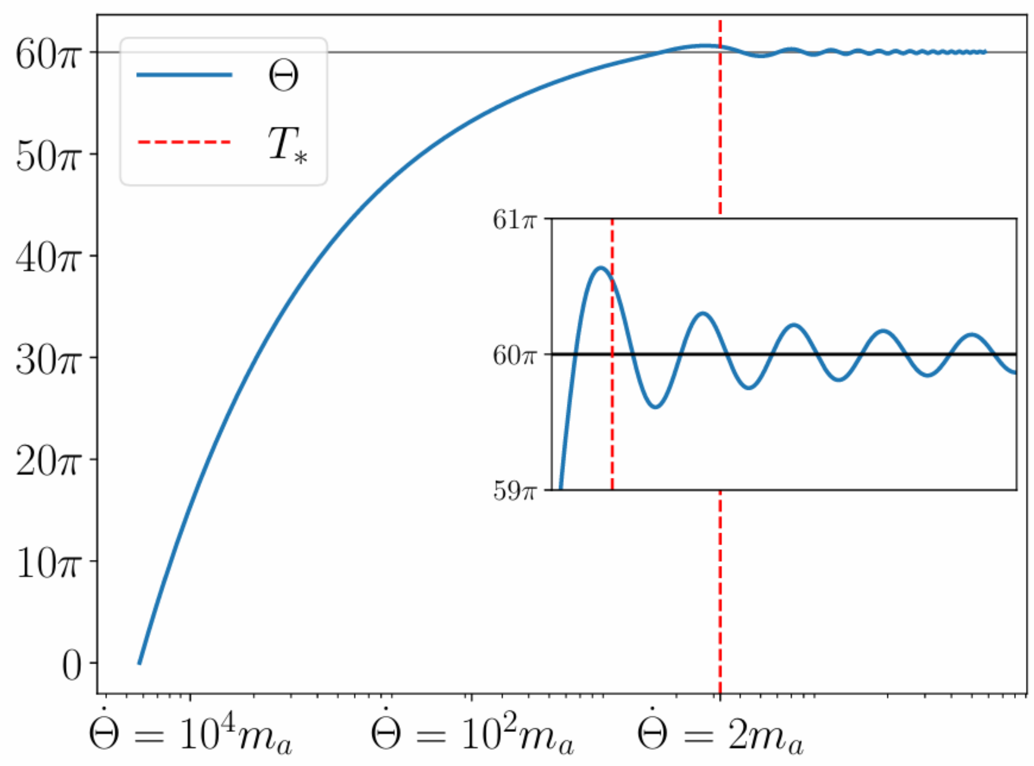


Fig. by «Harigaya et all, Axion Kinetic Misalignment Mechanism»

$$\dot{\Theta}(T_*) = 2m(T_*)$$



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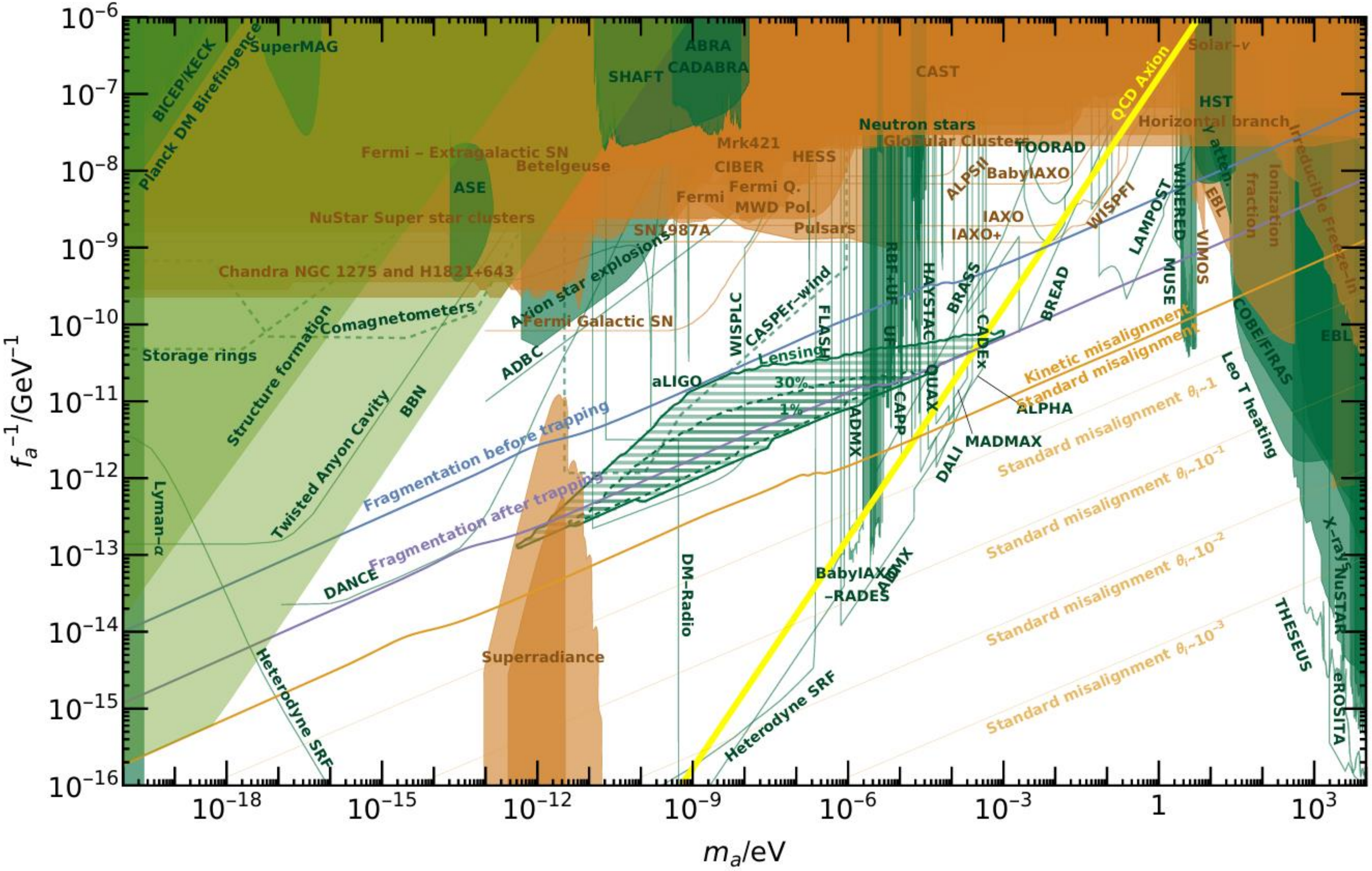

Fig by Eröncel et all «Model implementations of axion dark matter from kinetic misalignment»

How to generate a large axion velocity

Kinetic Misalignment can be generated by **high-order operators** producing an **explicit break of U(1) symmetry**

$$V_{\not{\mathrm{PQ}}} = 2^{\frac{n}{2}} \frac{A\Phi^n}{n M_{\mathrm{Pl}}^{n-3}} + \mathrm{h.c.}$$

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2408.17013 Lee, Menkara, Seong, Song
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2312.17730 Co, Yamada
2310.17710 Lee, Menkara, Seong, Song
2004.00629 Co, Hall, Harigaya, Olive, Verner

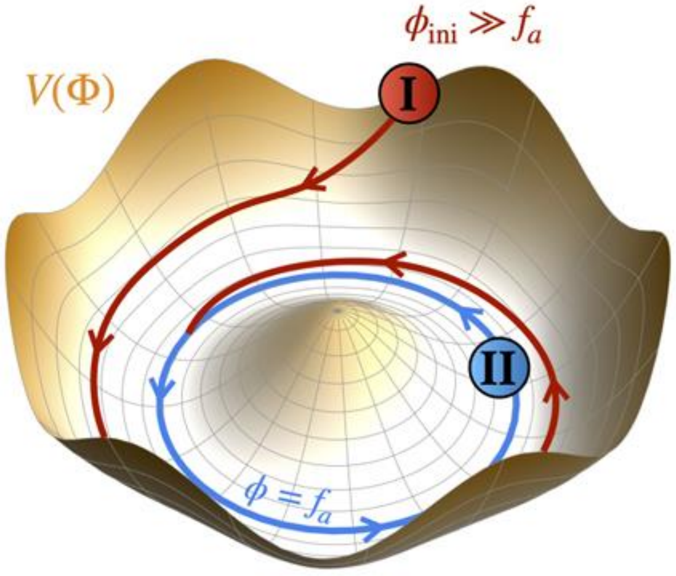

Fig. by Gouttenoire et all, «Kination Cosmology from scalar fields and gravitational waves signatures»

Kinetic Axion with NMC PQ field

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{Pl}}^2}{2}R + \mathcal{L}_{\mathrm{inf}} - g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi^\dagger - \xi R|\Phi|^2 - V_{\mathrm{PQ}}(|\Phi|) - V_{\cancel{\mathrm{PQ}}}(\Phi, \Phi^\dagger)\right]$$

- A **non-minimal coupling**
- A **stiff era**

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This transition generates a **tachyonic instability**

$$R = 3(1-3\omega)H^2$$

$m^2 \approx 12\xi H_I^2$ — During Inflation

$m^2 \propto -H^2$ — After Inflation

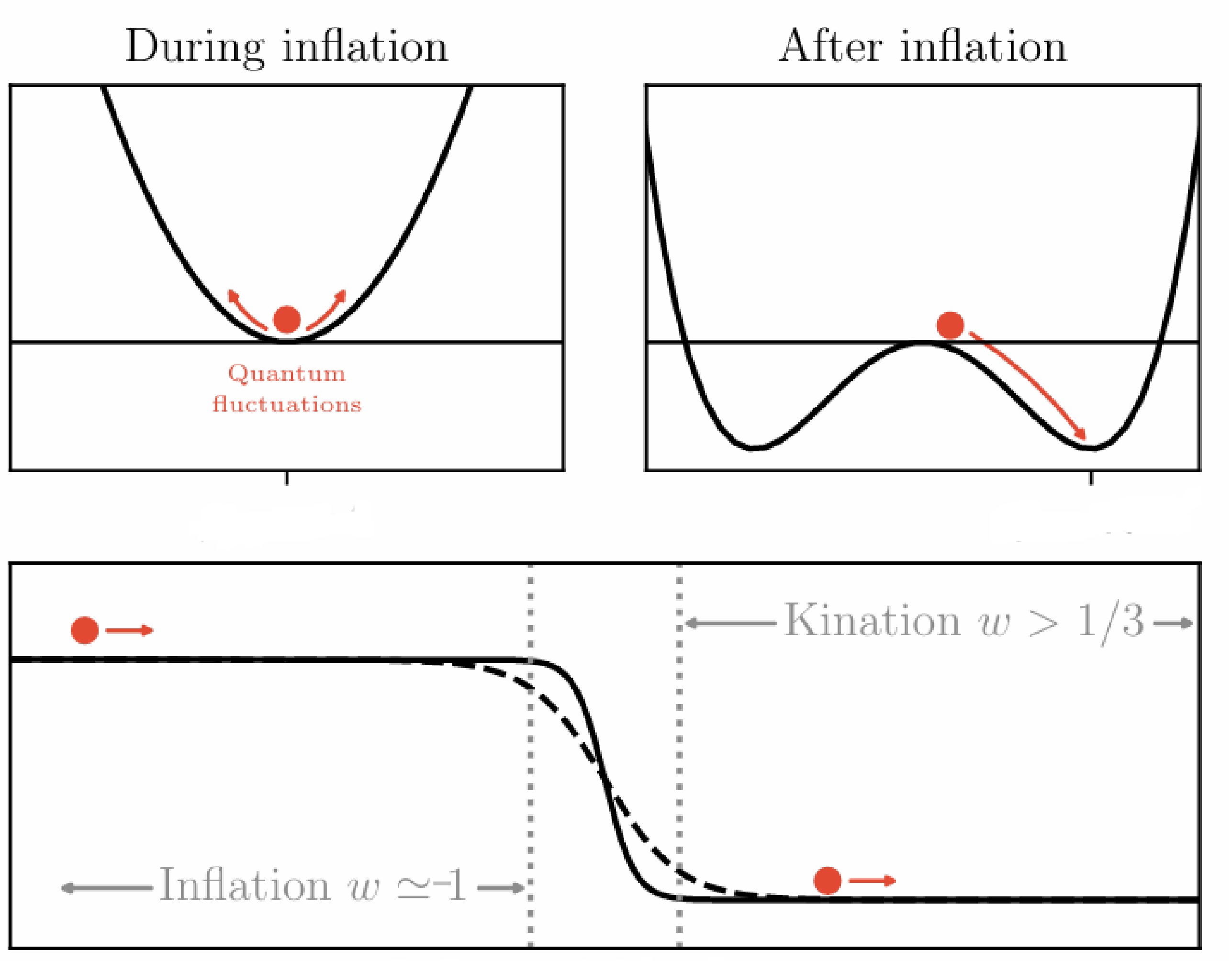

Fig. by Figueroa et all «Ricci Reheating on the Lattice»

PQ Field Dynamics

$$V_{U(1)} = \lambda \left(|\Phi|^2 - \frac{f_a^2}{2} \right)^2$$

$$V_{\cancel{U(1)}} = 2^{\frac{n}{2}} \frac{A\Phi^n}{n M_{\rm Pl}^{n-3}} + \text{h.c.}$$

$$\ddot{S} + 3H\dot{S} + (\xi R - \lambda f_a^2)S + \lambda S^3 + 2A\frac{S^{n-1}}{M_{\rm Pl}^{n-3}}\cos(n\theta) = S\dot{\theta}^2$$

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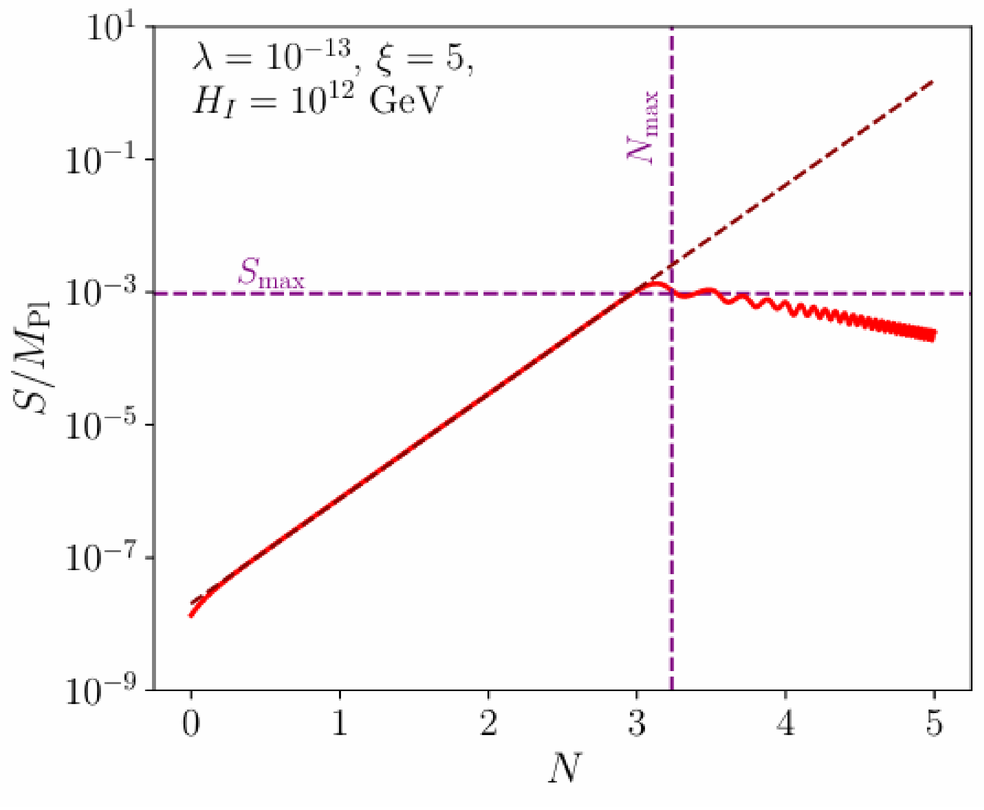

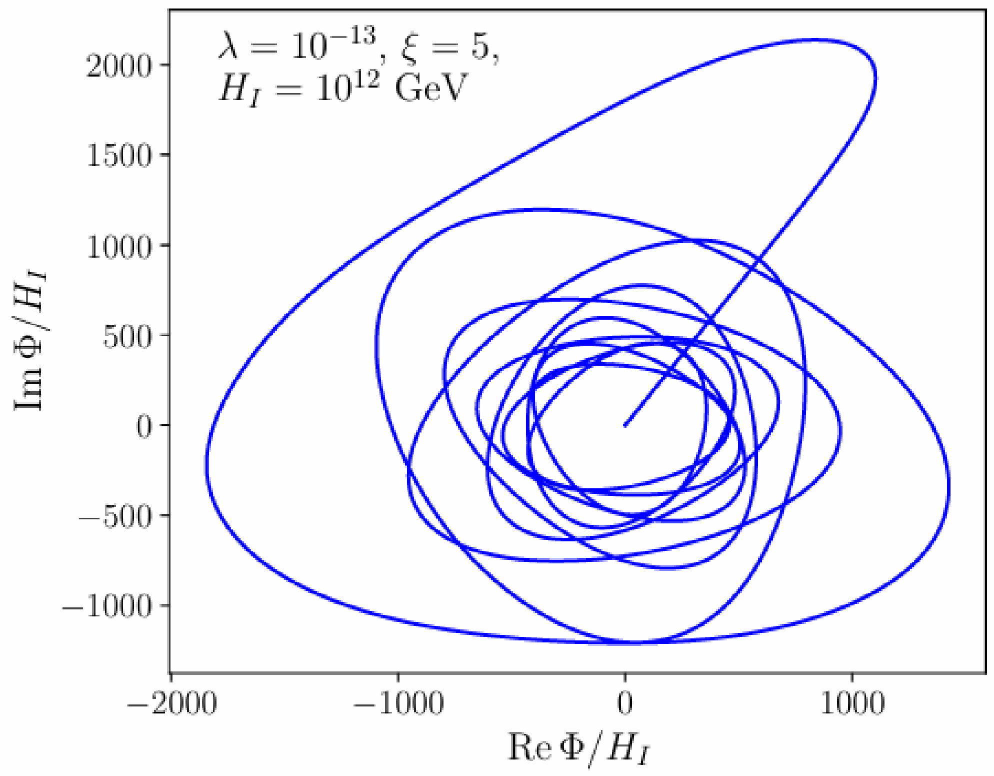

Post Inflationary Kinetic Axion

Because spontaneous symmetry breaking happens **after inflation**, the axion field takes on **different values** in separate regions of the universe.

$$\dot{\theta}_{\max} = \beta \sin(n\theta) \frac{A S_{\max}^{n-2}}{M_{\mathrm{Pl}}^{n-3} H_{\max}}$$

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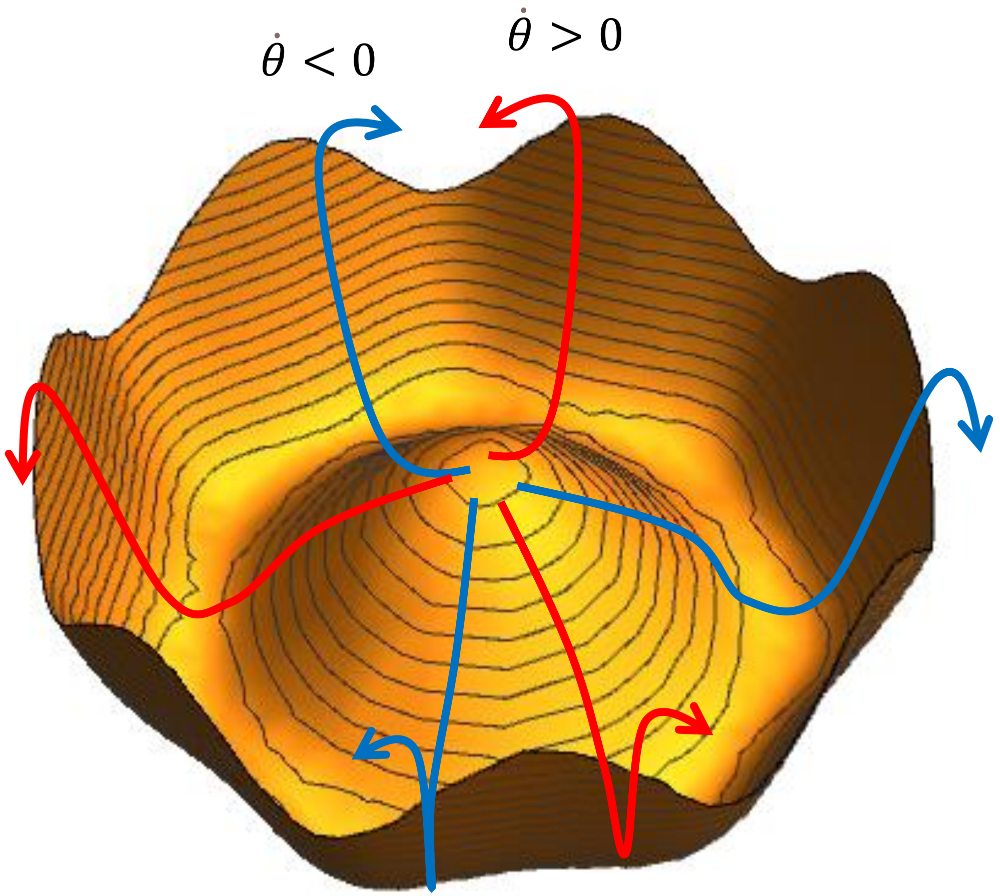

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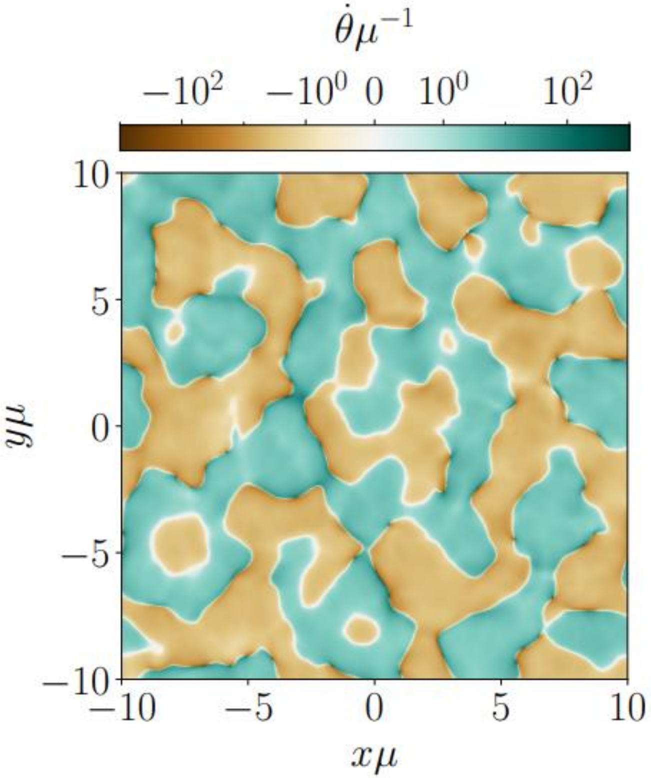

Once the kick is applied, the universe becomes **divided into multiple domains**, each carrying a U(1) charge of either **positive** or **negative** sign.

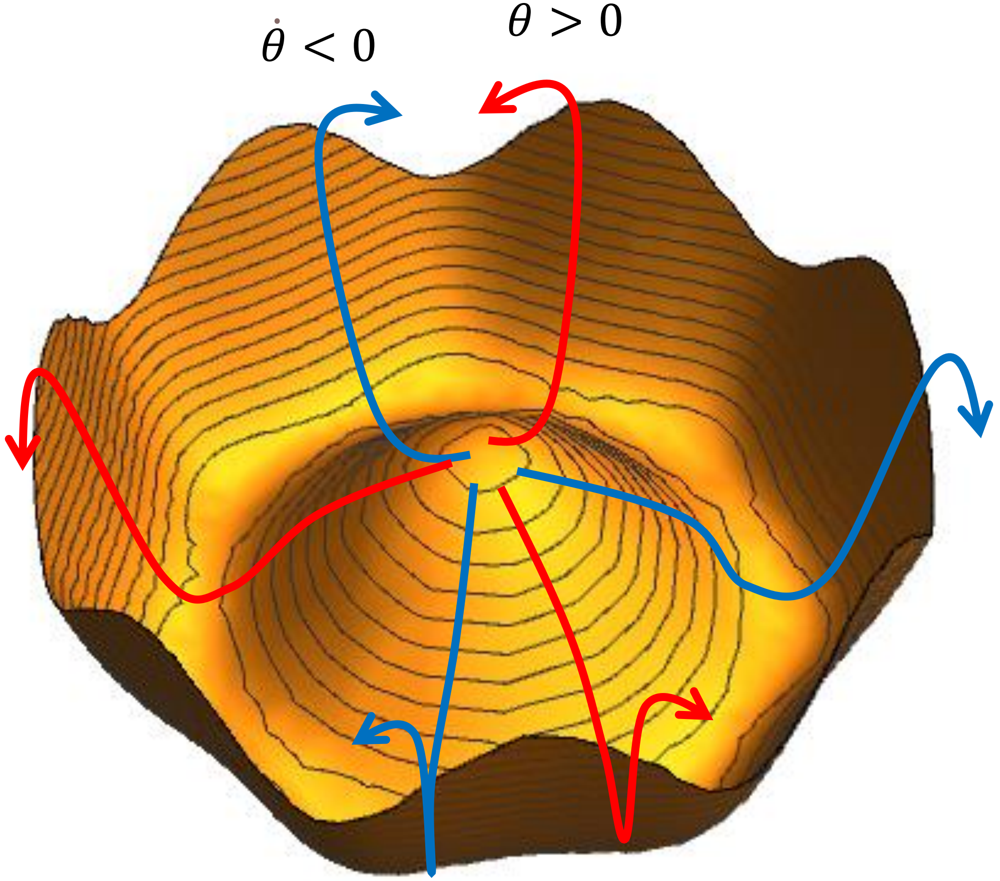

Fig. by Fedderke et all «Periodic Cosmic String Formation and Dynamics»

Post Inflationary Kinetic Axion

After the kick is imparted, our field rotates in the U(1) potential and because of Hubble expansion the **saxion vev shifts toward the minimum**

$$S \propto a^{-1} \longrightarrow V_{\cancel{U(1)}} \propto a^{-n}$$

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After a U(1) charge is produced in each domain, this is **conserved** in a comoving volume

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We can compute the RMS of the produced charge **averaging on several domains** inside a Hubble patch

$$\bar{n}_\theta = \left(\frac{1}{2\pi}\int_0^{2\pi} d\theta_i\, n^2_{\theta,\mathrm{dom}}(\theta_i)\right)^{\frac{1}{2}}$$

Dark Matter abundance

At the trapping moment, the U(1) charge is converted into **axion number density**

$$n_a \approx 2|n_\theta|$$

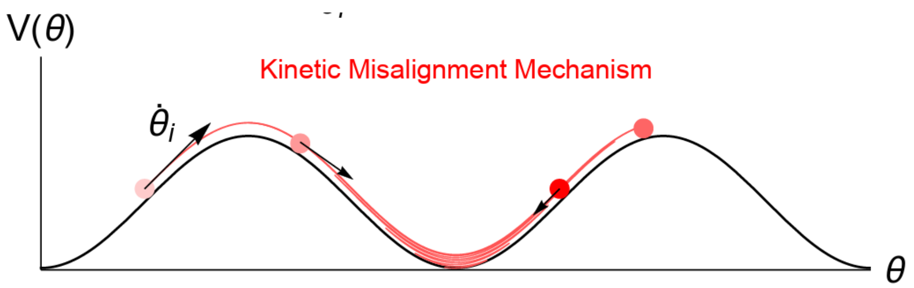

Fig. by «Harigaya et all, Axion Kinetic Misalignment Mechanism»

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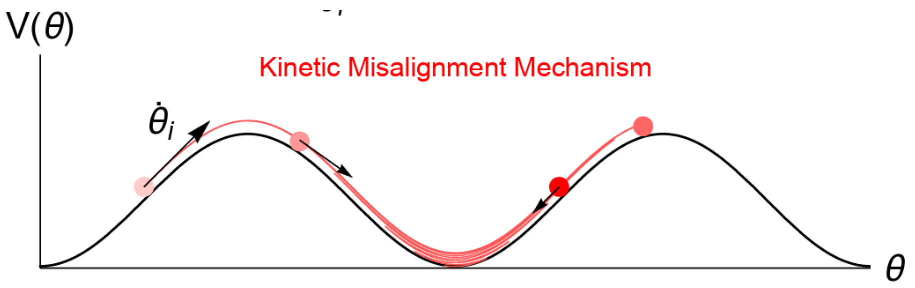
So, we can compute the **axion yield** and the **total relic abundance**

$$\bar{Y}_\theta = 167 \left(\frac{\bar{\epsilon}}{0.5}\right) \left(\frac{10}{g_s}\right)^{\frac{1}{4}} \left(\frac{10^{-10}}{\lambda}\right)^{\frac{1}{4}}$$

$$\frac{h^2\Omega_{\theta,0}}{h^2\Omega_{\rm CDM}} \approx \left(\frac{m_a}{5\times 10^{-3}\,{\rm eV}}\right)\left(\frac{\bar{Y}_\theta}{40}\right)$$



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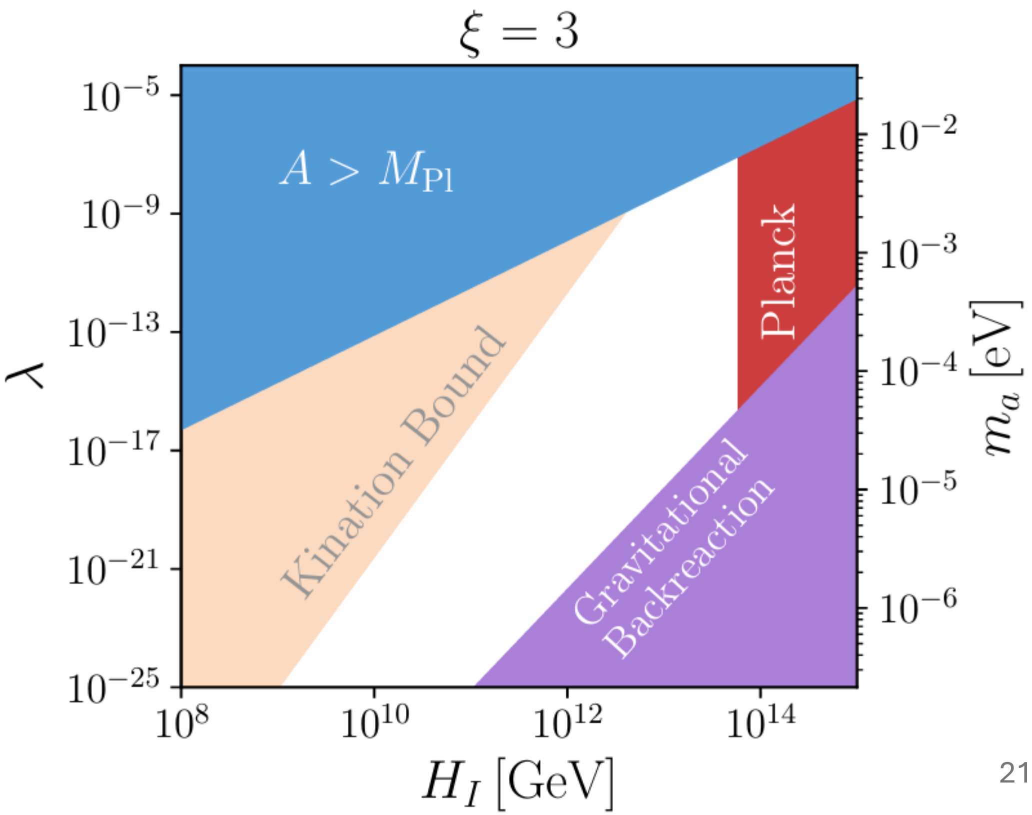
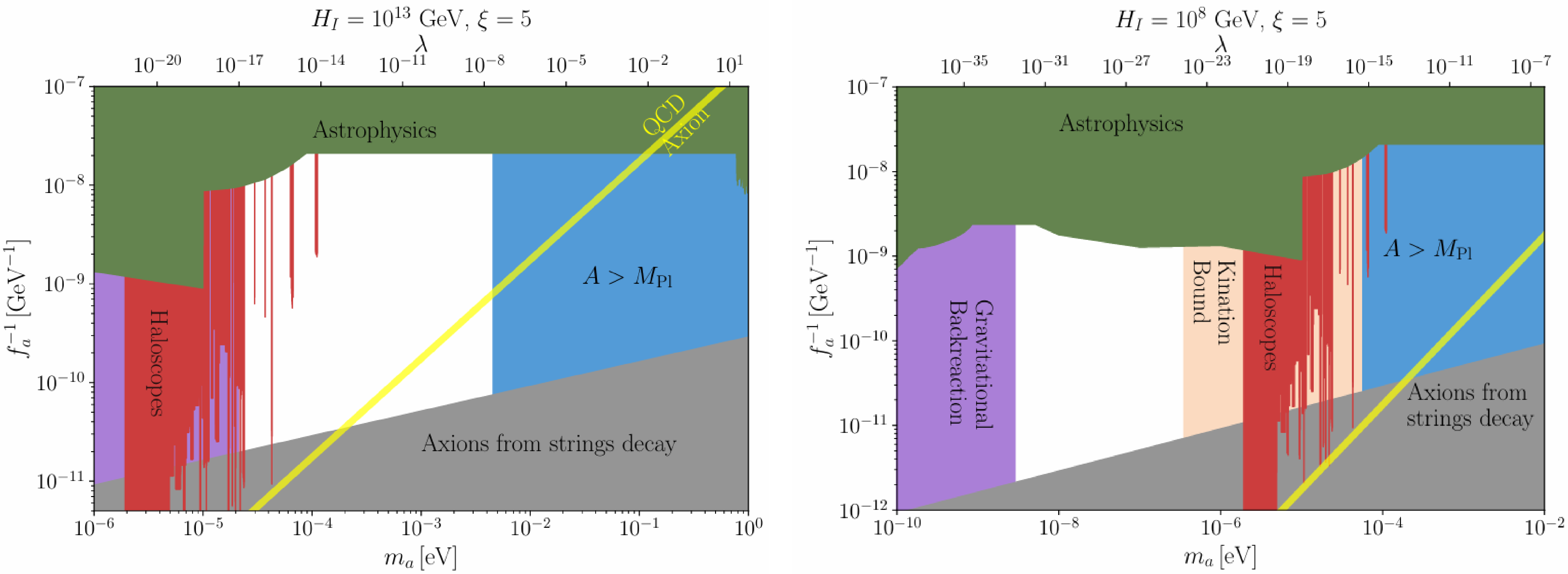


Parameter Space



What’s the fate of the saxion?

The saxion can realize different **couplings** to SM and BSM particles:

$$\mathcal{L} \supset y S \bar{\chi} \left(\frac{1-\gamma^5}{2} \right) \chi + h.c.$$

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If there is no radiation bath, the **decay of the saxion** is the actual **reaheating** of the universe

$$T_{\rm reh} = \begin{cases} 8.2 \times 10^9 \ {\rm GeV} \left(\frac{106}{g_{\rm reh}} \right)^{1/4} \left(\frac{y}{10^{-2}} \right)^2 \left(\frac{\lambda}{10^{-12}} \right)^{1/4} & \text{if} \quad S \gg f_a \\ 5.3 \times 10^7 \ {\rm GeV} \left(\frac{106}{g_{\rm reh}} \right)^{1/4} \left(\frac{y}{10^{-2}} \right) \left(\frac{\lambda}{10^{-12}} \right)^{1/4} \left(\frac{f_a}{10^9 \ {\rm GeV}} \right)^2 & \text{if} \quad S = f_a \end{cases}$$

Reheating via fermions charged under SU(3)

$$T_R = 10^6 \ {\rm GeV} \left(\frac{100}{g} \right)^{1/4} \left(\frac{\lambda}{10^{-10}} \right)^{1/4} \left(\frac{f_a}{10^9 \ {\rm GeV}} \right)$$

Reheating via SM Higgs

Summary and Conclusion

1. A **non-minimal coupling** combined to a transition **Inflation-Kination** is a good mechanism to drive your NMC field to high values.

2. Higher order operators, **violating U(1)**, may become relevant and produce an **angular rotation**.

3. This U(1) charge is then converted into **axions** at the trapping temperature.

4. The saxion can decay and be responsible of standard model **reheating.**

5. (Bonus) A rich phenomenology of **cosmic strings** and **gravitational waves** come out, because of the presence of a kination era and counter rotating domains.

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Thank you!