THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

Searching for axions as dark matter

Ciaran O'Hare

U. Sydney

ACAMAR meeting on Astroparticle physics, 23rd June 2022

Axions

An **axion** is an extremely light and feebly-coupled boson that can interact with the SM in the following ways…

$$\mathcal{L} = \ \dots \ - \frac{g_{a\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu} + \partial_\mu a \sum_\psi \frac{g_{a\psi}}{2m_\psi} \left(\bar{\psi} \gamma^\mu \gamma^5 \psi \right)$$

Why should we believe such a particle exists?

Axions

An **axion** is an extremely light and feebly-coupled boson that can interact with the SM in the following ways…

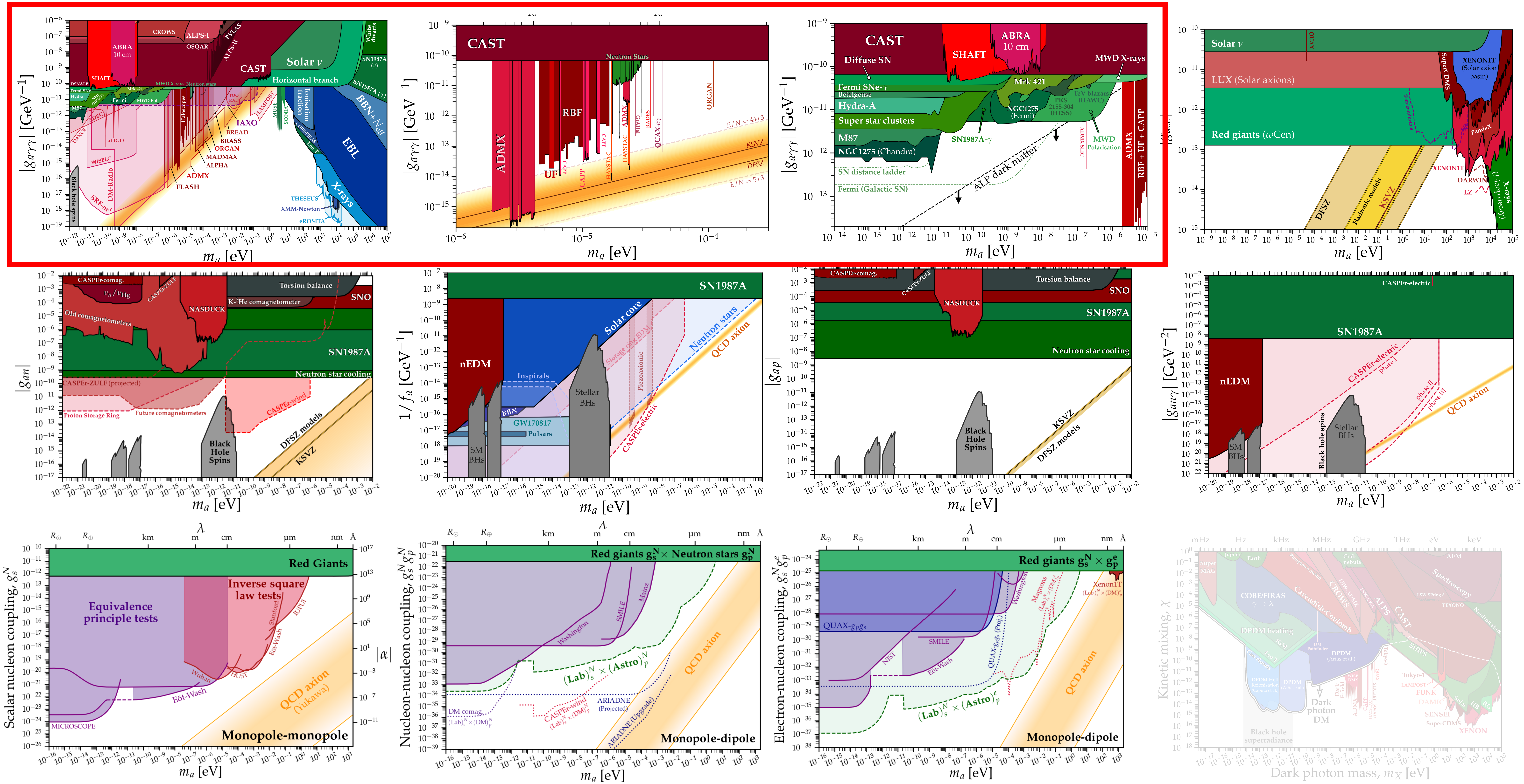
$$\mathcal{L} = \ \dots \ - \frac{g_{a\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu} + \partial_\mu a \sum_\psi \frac{g_{a\psi}}{2m_\psi} \left(\bar{\psi}\gamma^\mu \gamma^5 \psi\right)$$

Why should we believe such a particle exists?

- ✓ Solves the Strong CP problem → "QCD axion"
- ✓ Can be 100% of cosmological dark matter
- ✓ Appears generically in string theory constructions

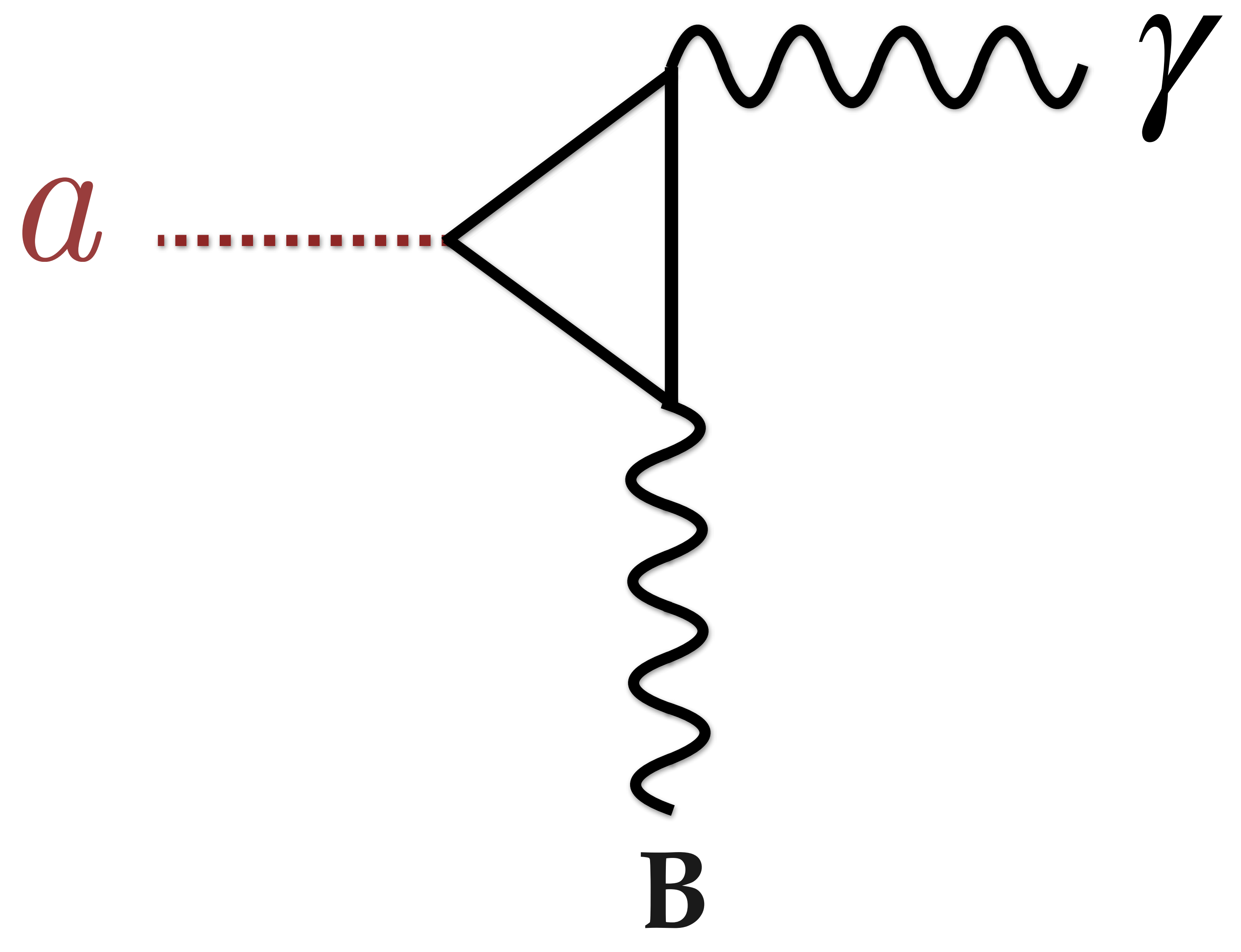
Lots of attempts, but so far no axions have been found…

For more, see cajohare.github.io/AxionLimits/ → Now lists results from >200 publications!

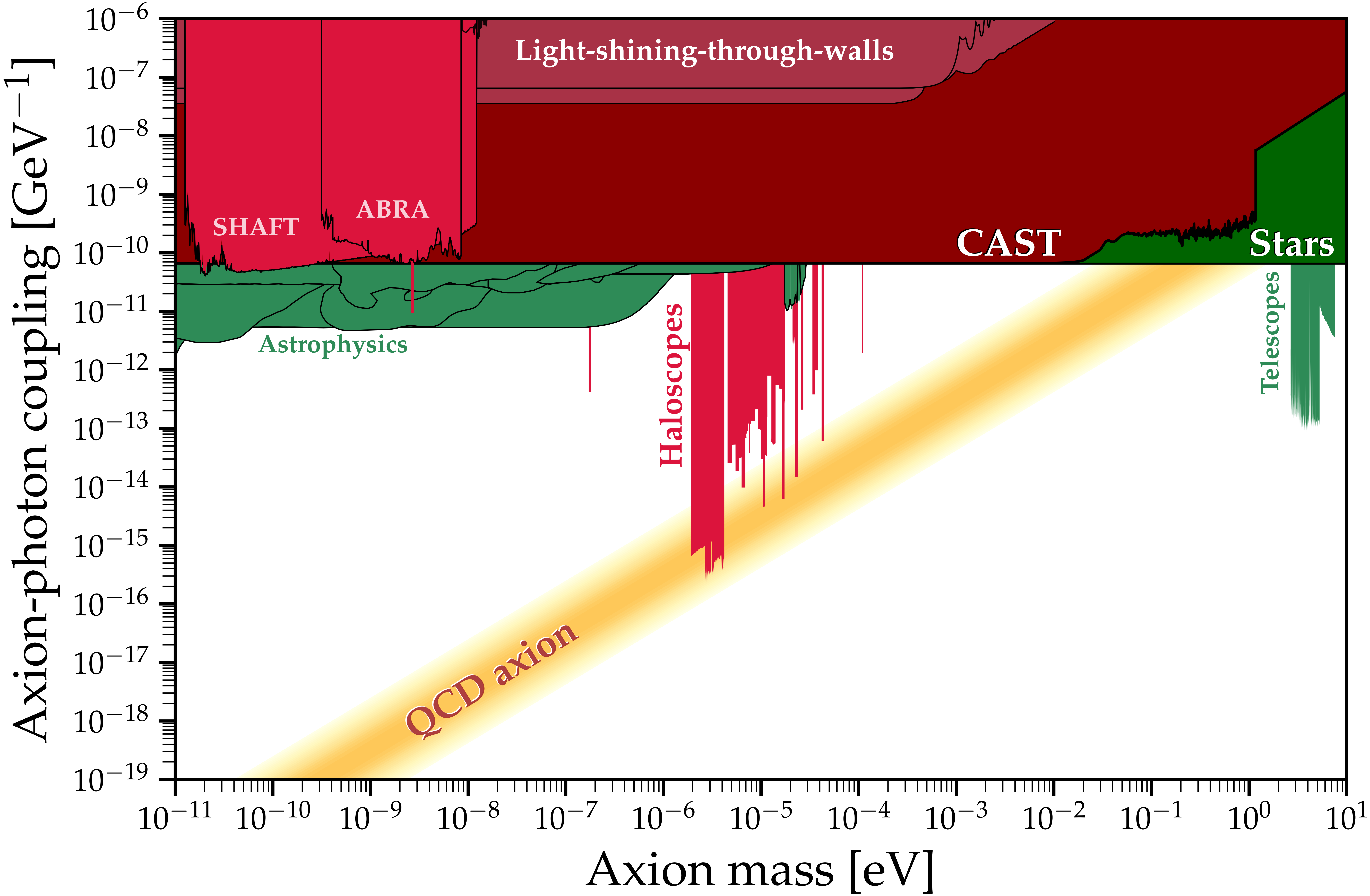


Coupling to the photon

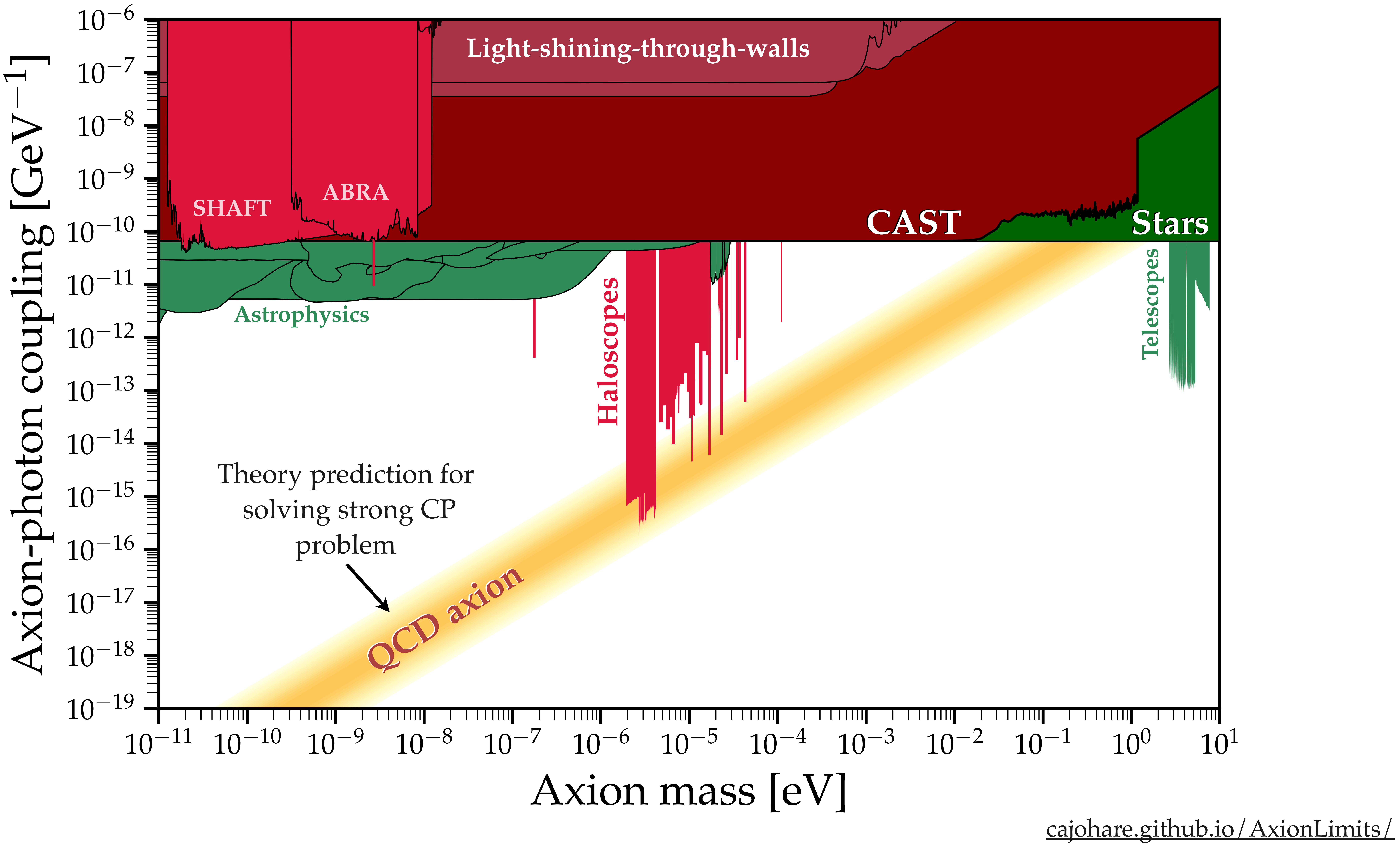
→ axions convert into photons in the presence of magnetic field

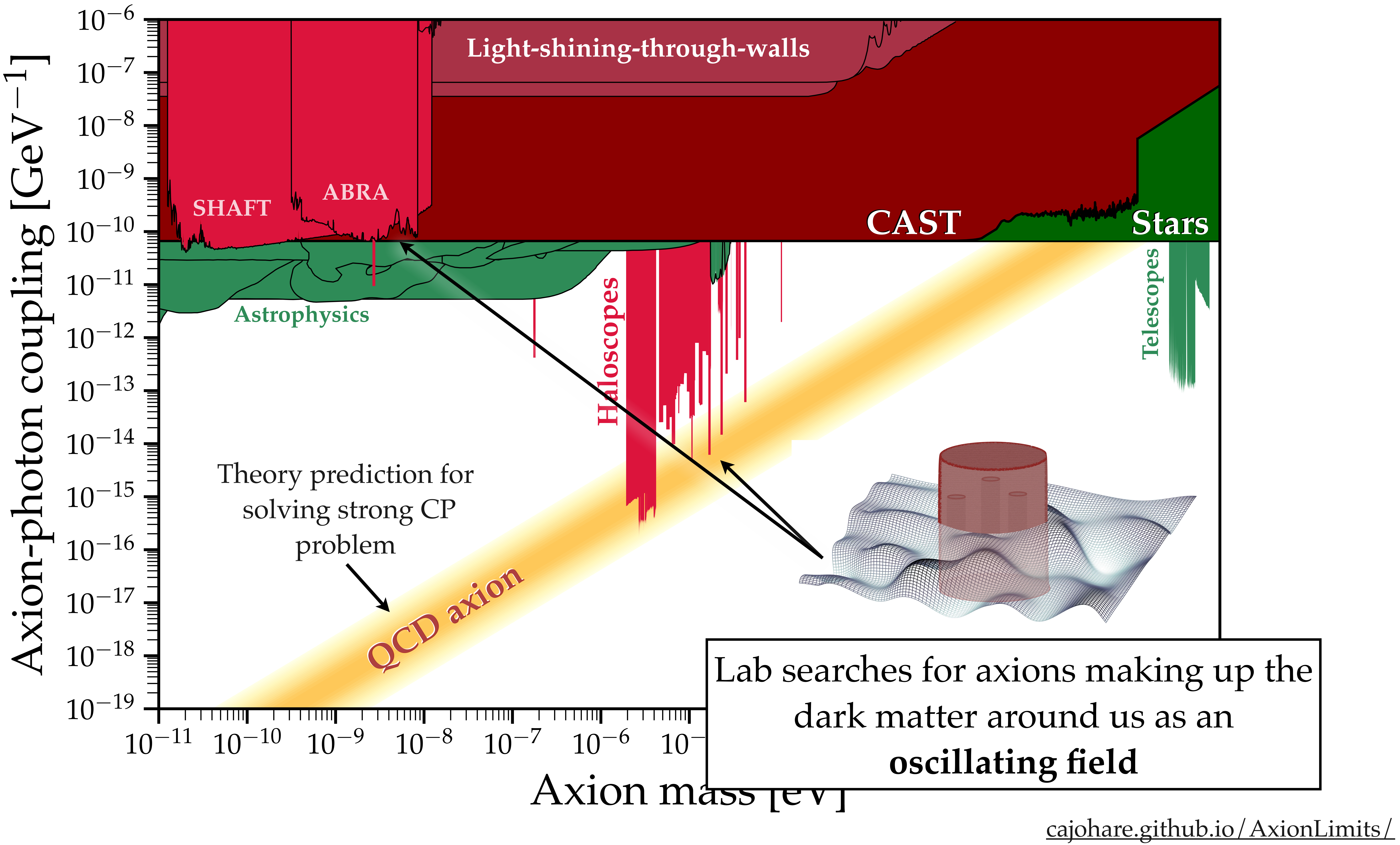


Search over parameter space: $(m_a, g_{a\gamma})$



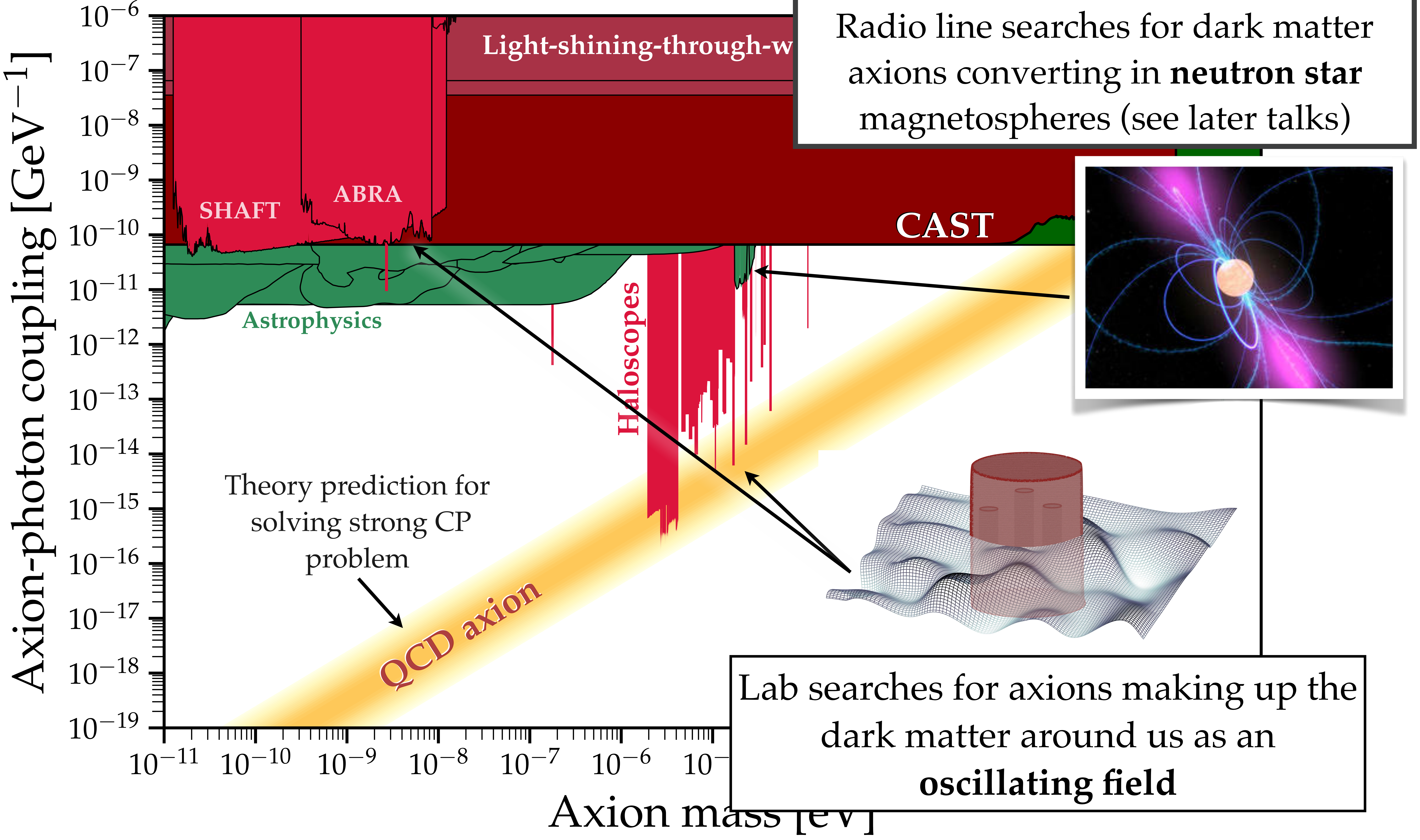
cajohare.github.io/AxionLimits/


Light-shining-through-walls
SHAFT
ABRA
CAST
Stars
Astrophysics
Haloscopes
Telescopes
Theory prediction for solving strong CP problem
QCD axion
Axion-photon coupling [GeV^{-1}]
Axion mass [eV]
cajohare.github.io/AxionLimits/



Light-shining-through-walls
SHAFT
ABRA
CAST
Stars
Astrophysics
Haloscopes
Telescopes
Theory prediction for solving strong CP problem
QCD axion
Axion-photon coupling [GeV^{-1}]
Axion mass [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6}
Lab searches for axions making up the dark matter around us as an **oscillating field**
cajohare.github.io/AxionLimits/

Radio line searches for dark matter axions converting in **neutron star** magnetospheres (see later talks)



Lab searches for axions making up the dark matter around us as an **oscillating field**

cajohare.github.io/AxionLimits/

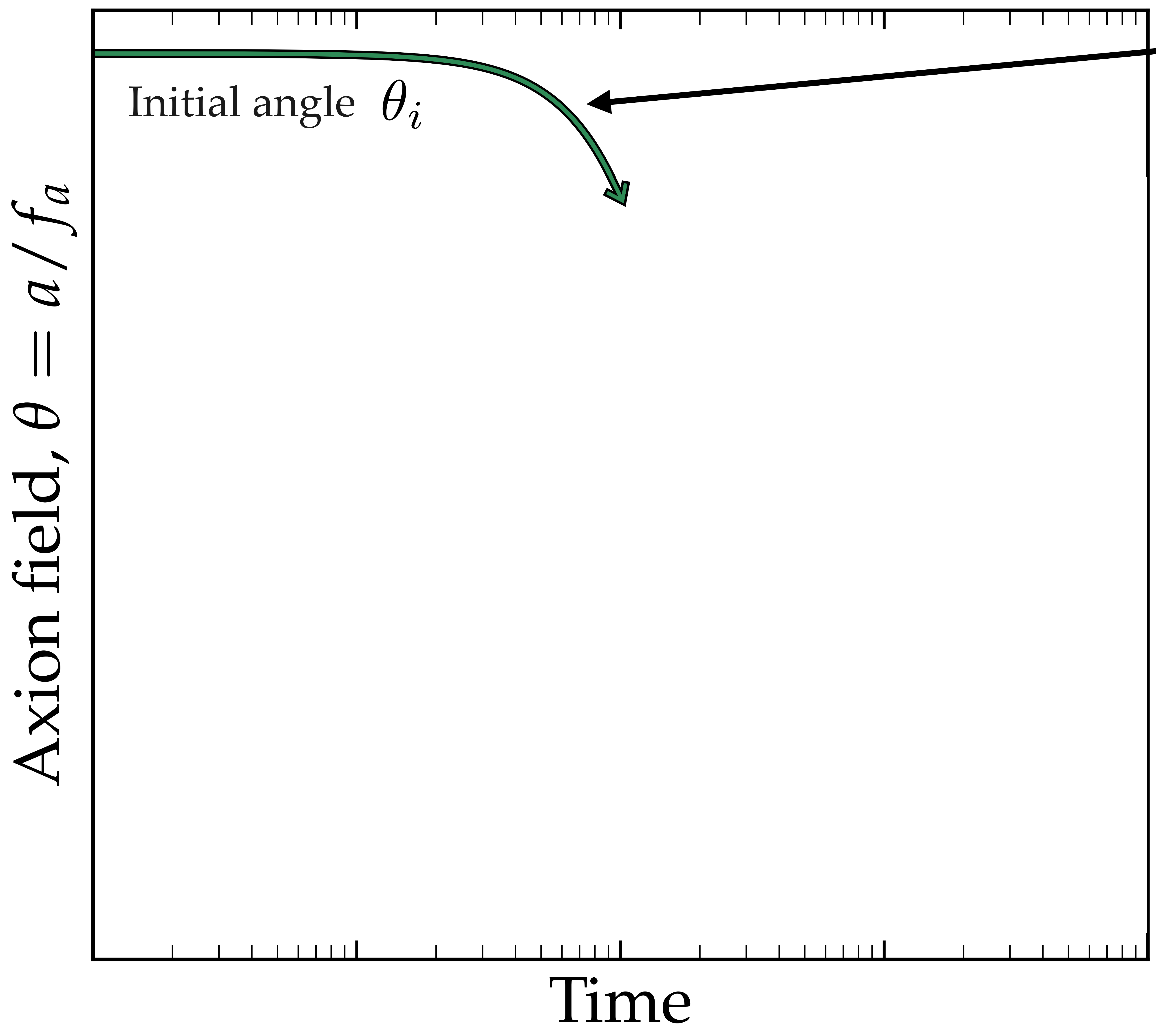
The experiment or observation that will one day detect the axion may have been proposed.

However without any prior on the axion's mass, the chances of them bumping into it in such a vast parameter space seem very low.

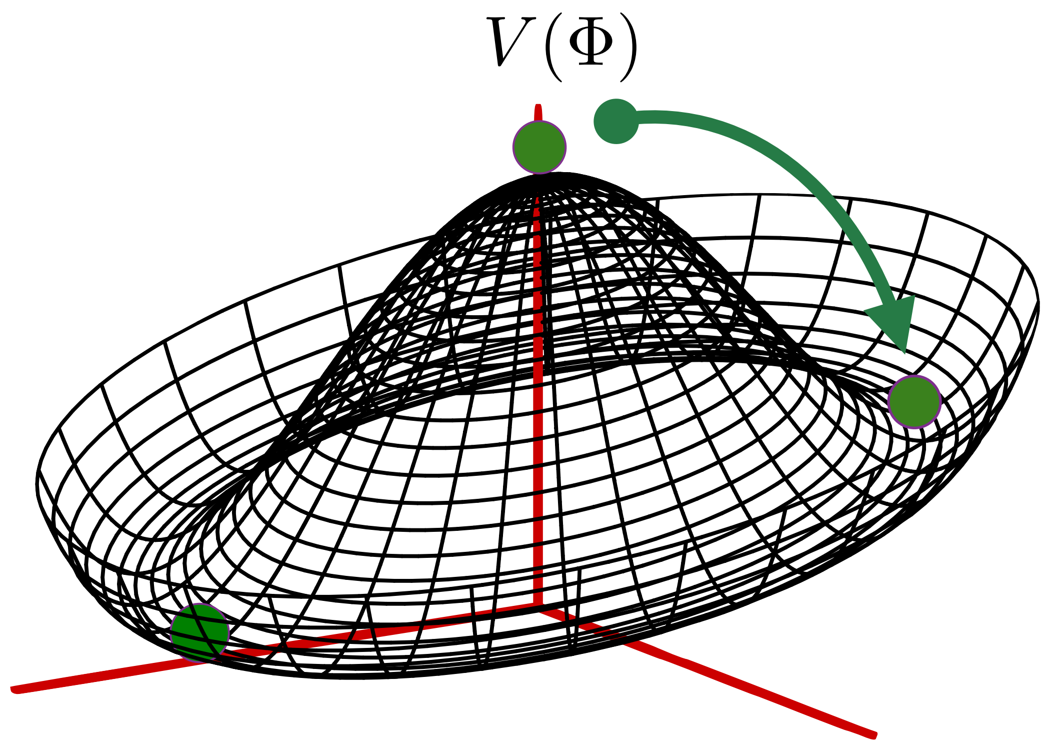
Is there anything we can do to light the way?

Yes, if we impose that the axion makes up dark matter

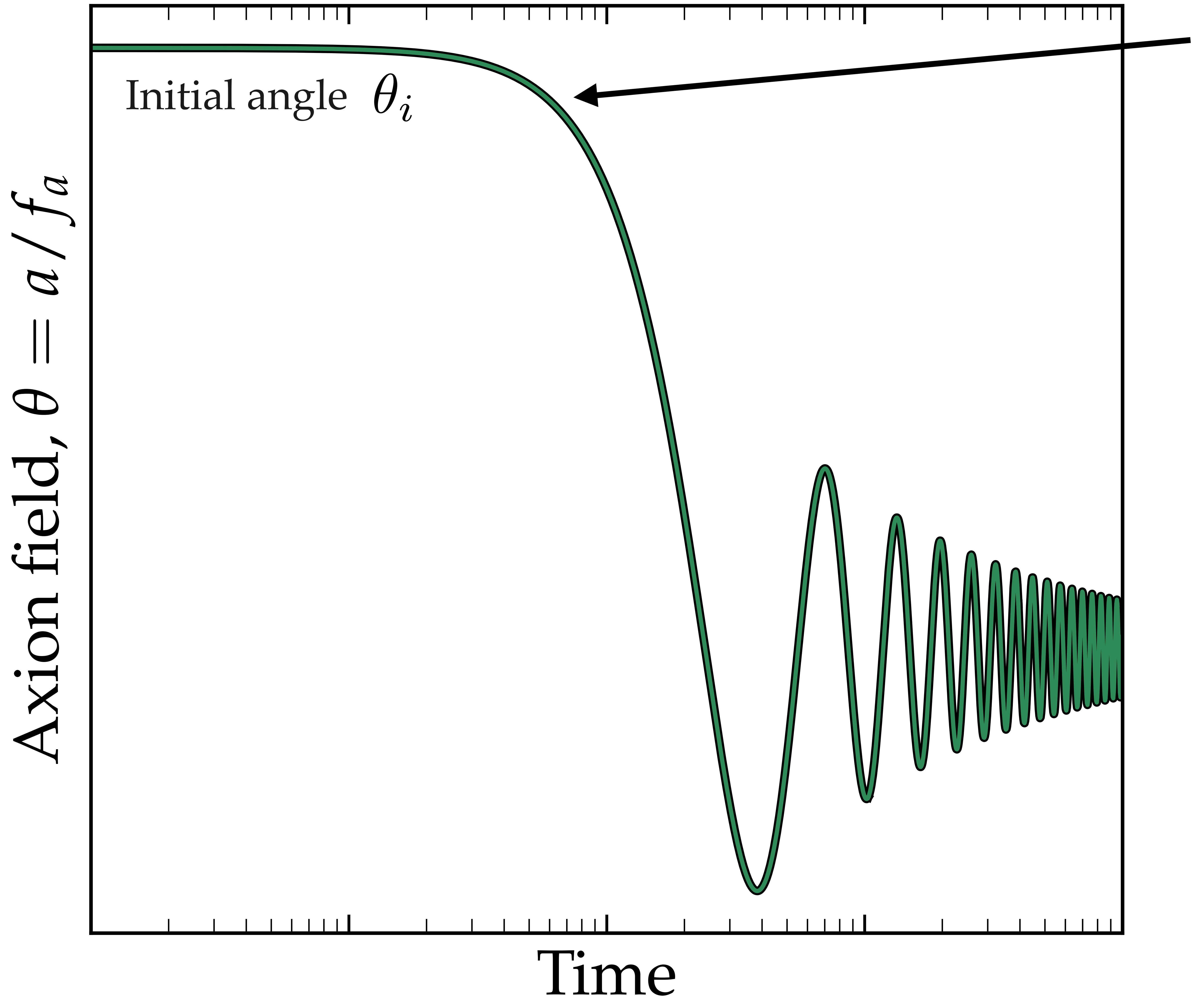
Axion dark matter: the misalignment mechanism



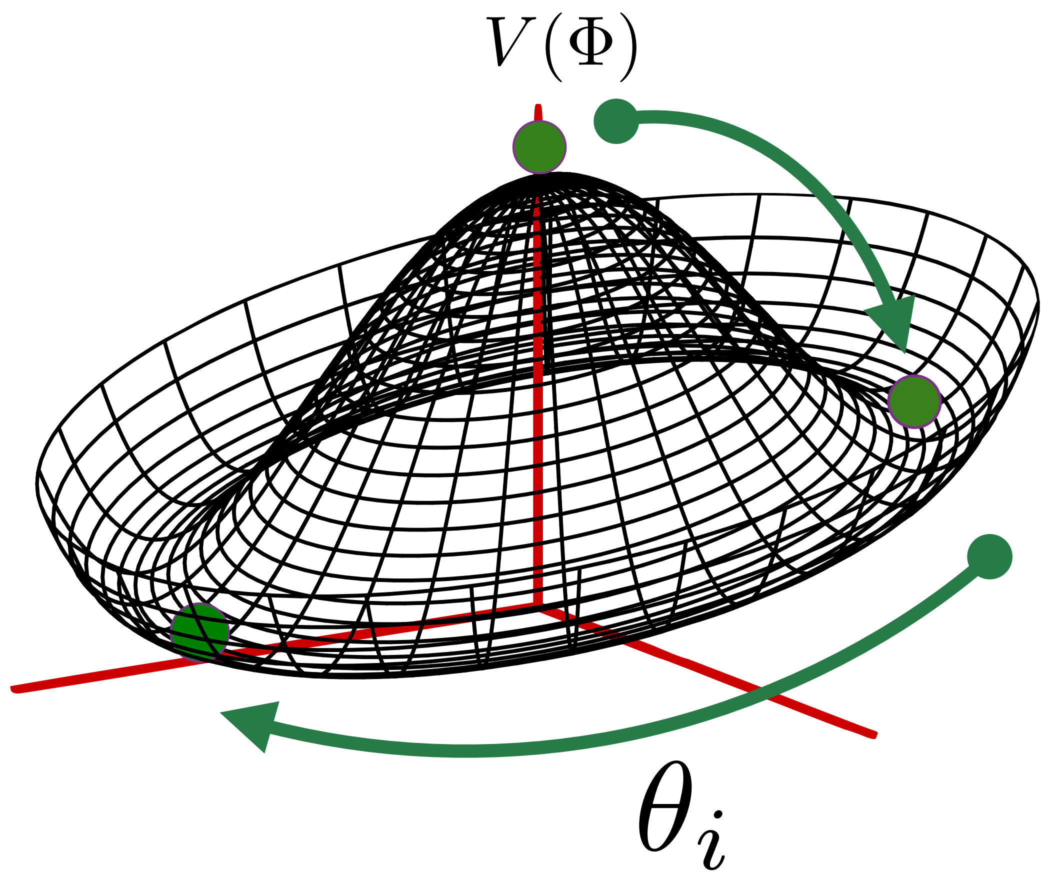
Axion is the phase of a complex scalar field governed by a tilted potential.



Axion dark matter: the misalignment mechanism

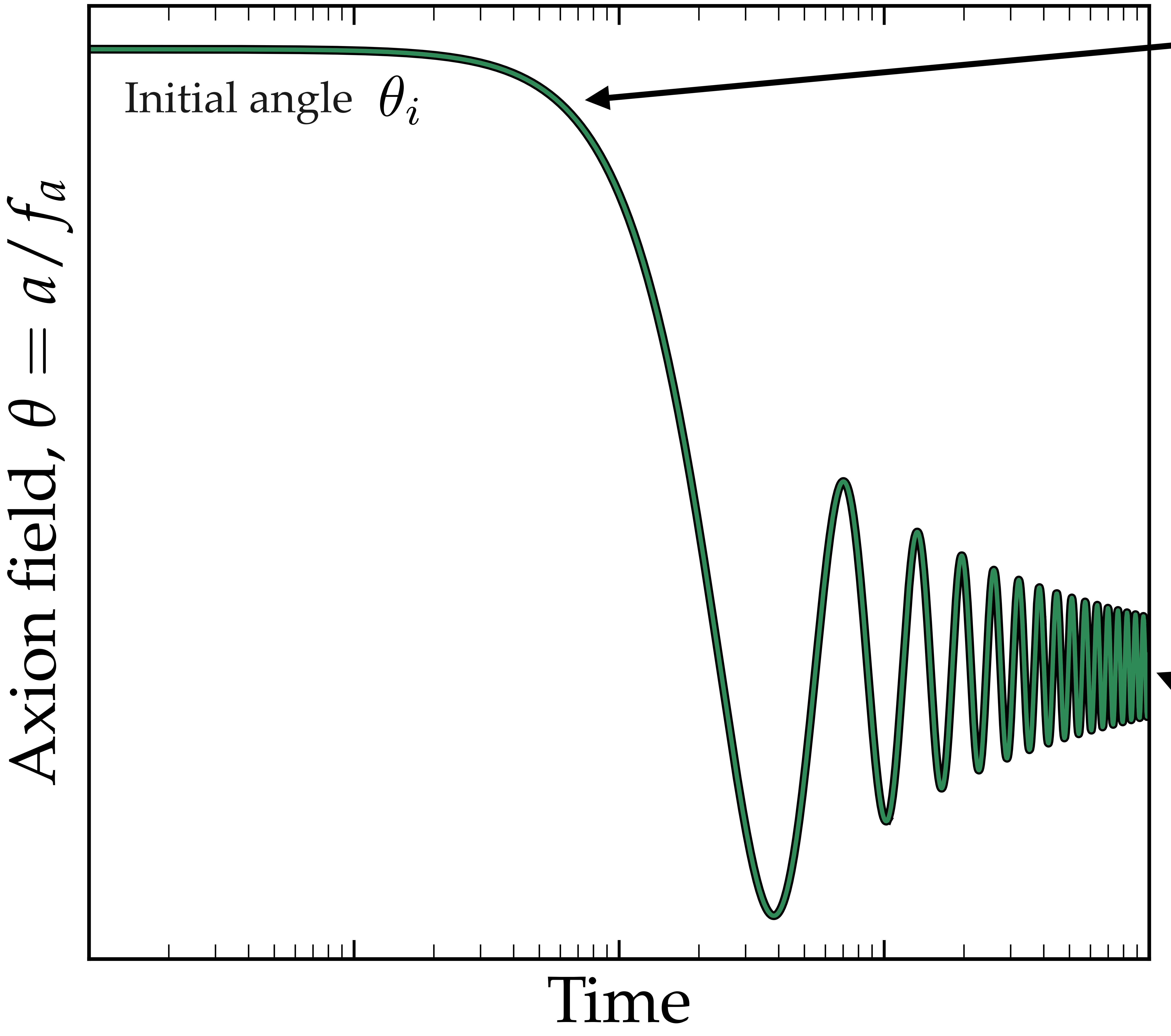


Axion is the phase of a complex scalar field governed by a tilted potential.

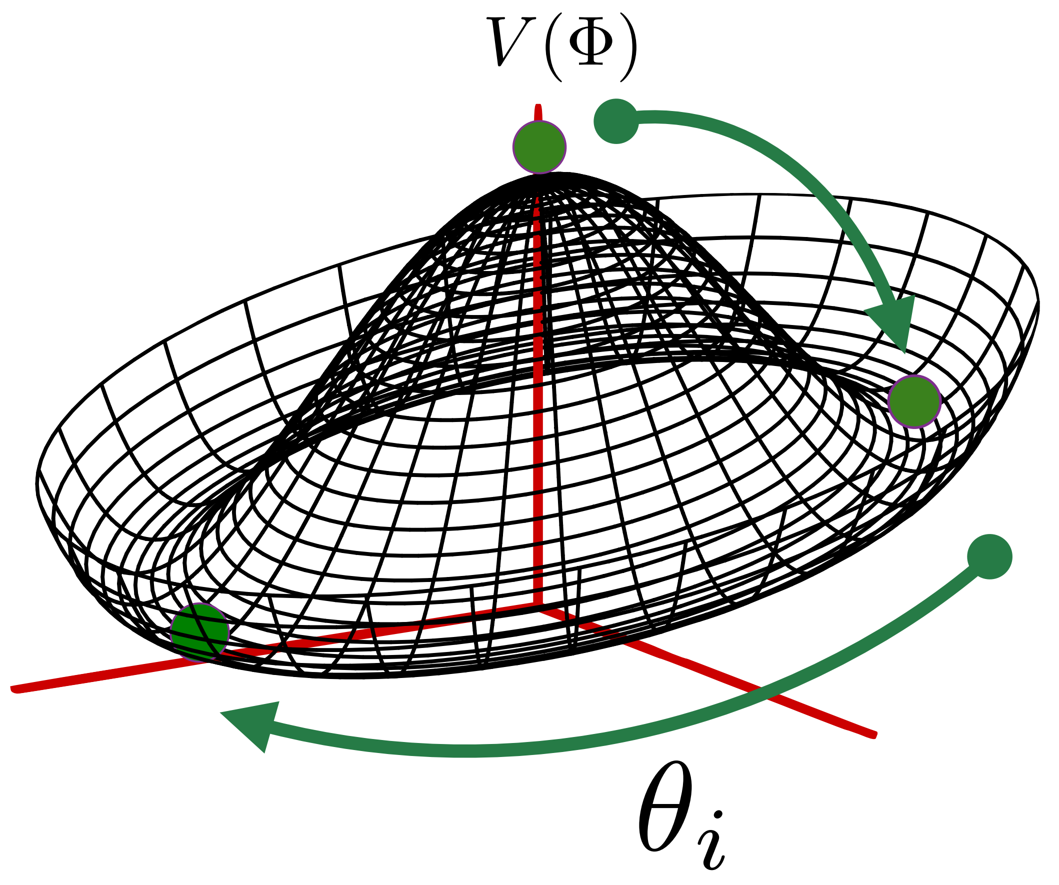


$$\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$$

Axion dark matter: the misalignment mechanism



Axion is the phase of a complex scalar field governed by a tilted potential.



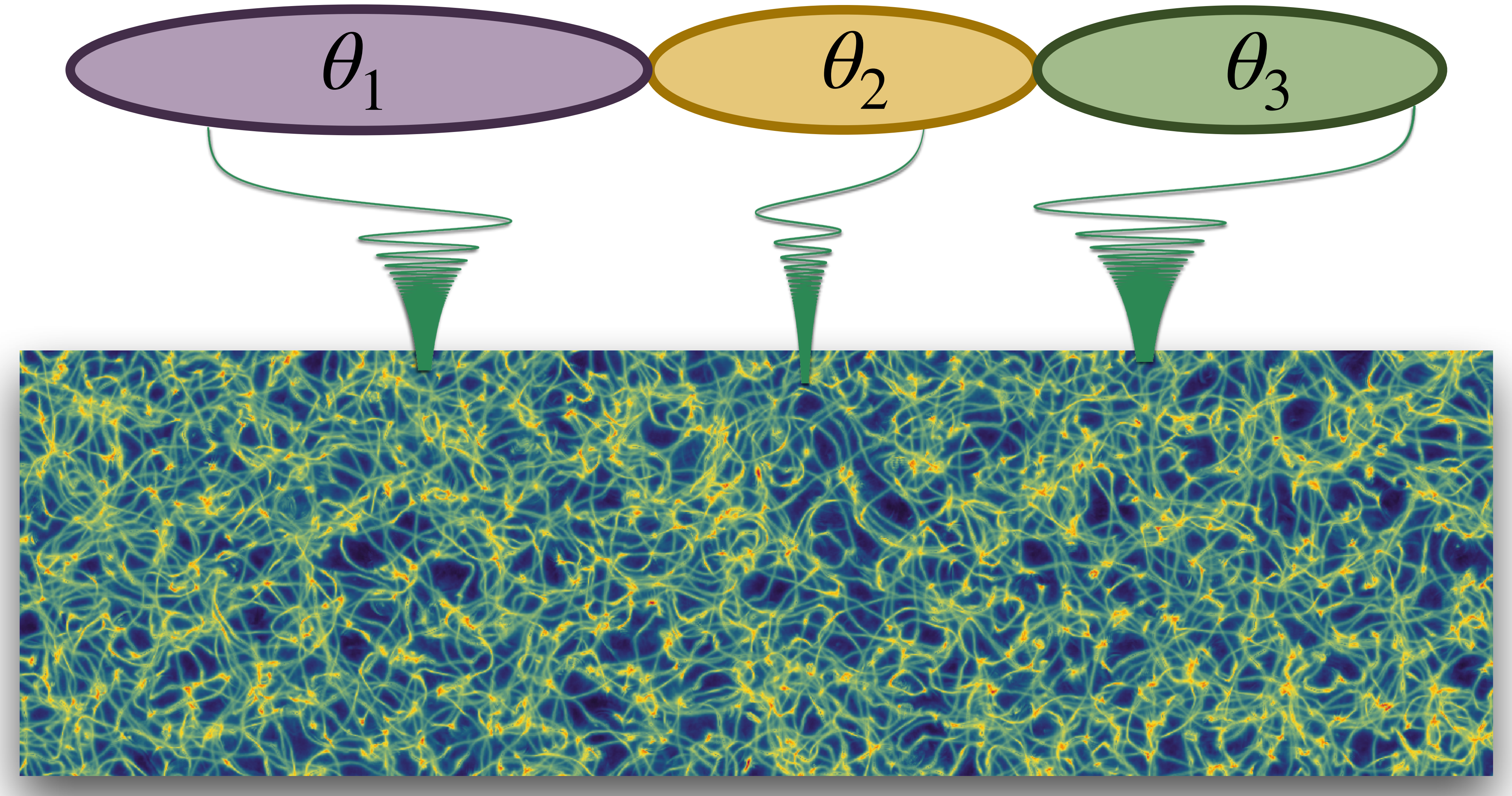
$$\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$$

Axion field rolls down to minimum and starts damped oscillations

→ **cold dark matter with predictable abundance:**

$$\Omega_a h^2 \propto \theta_i^2$$

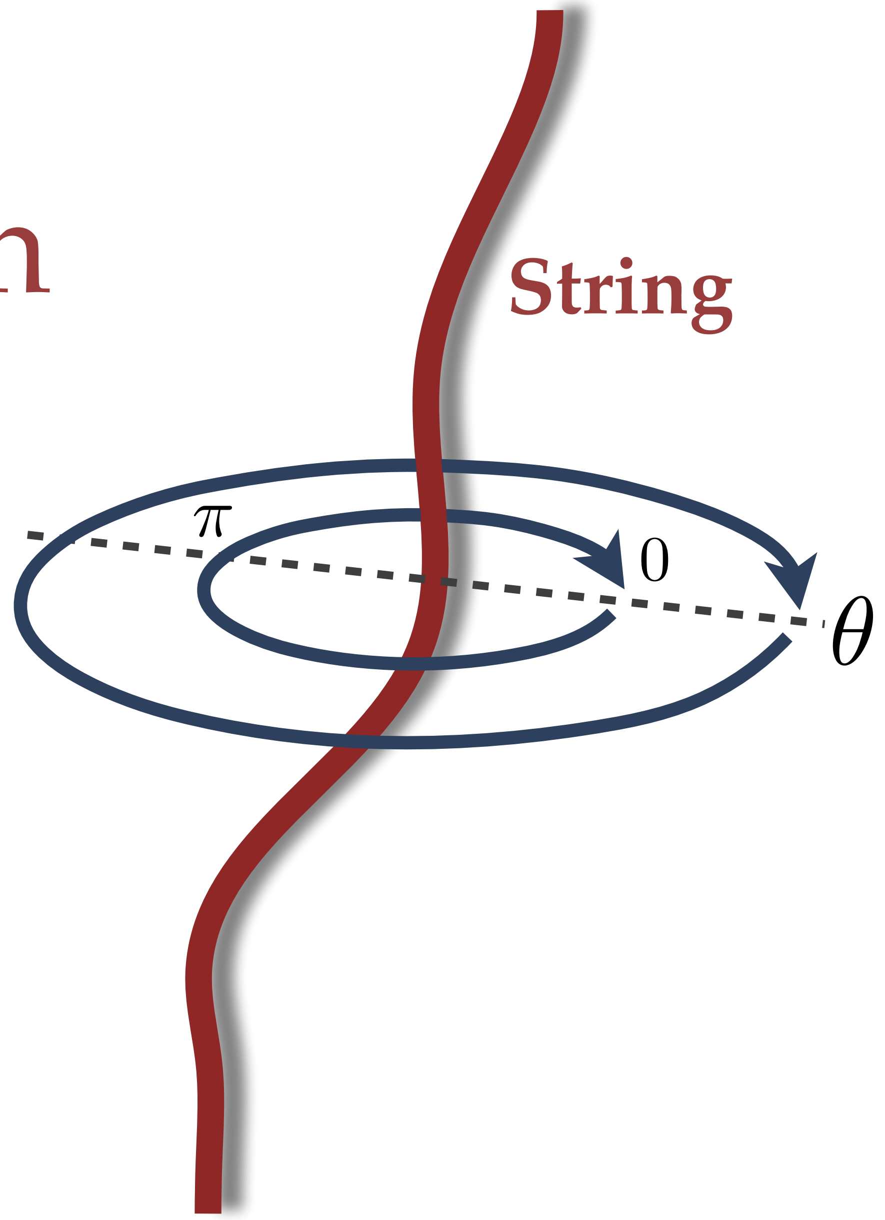
But there's a complication: what about $\nabla\theta$?



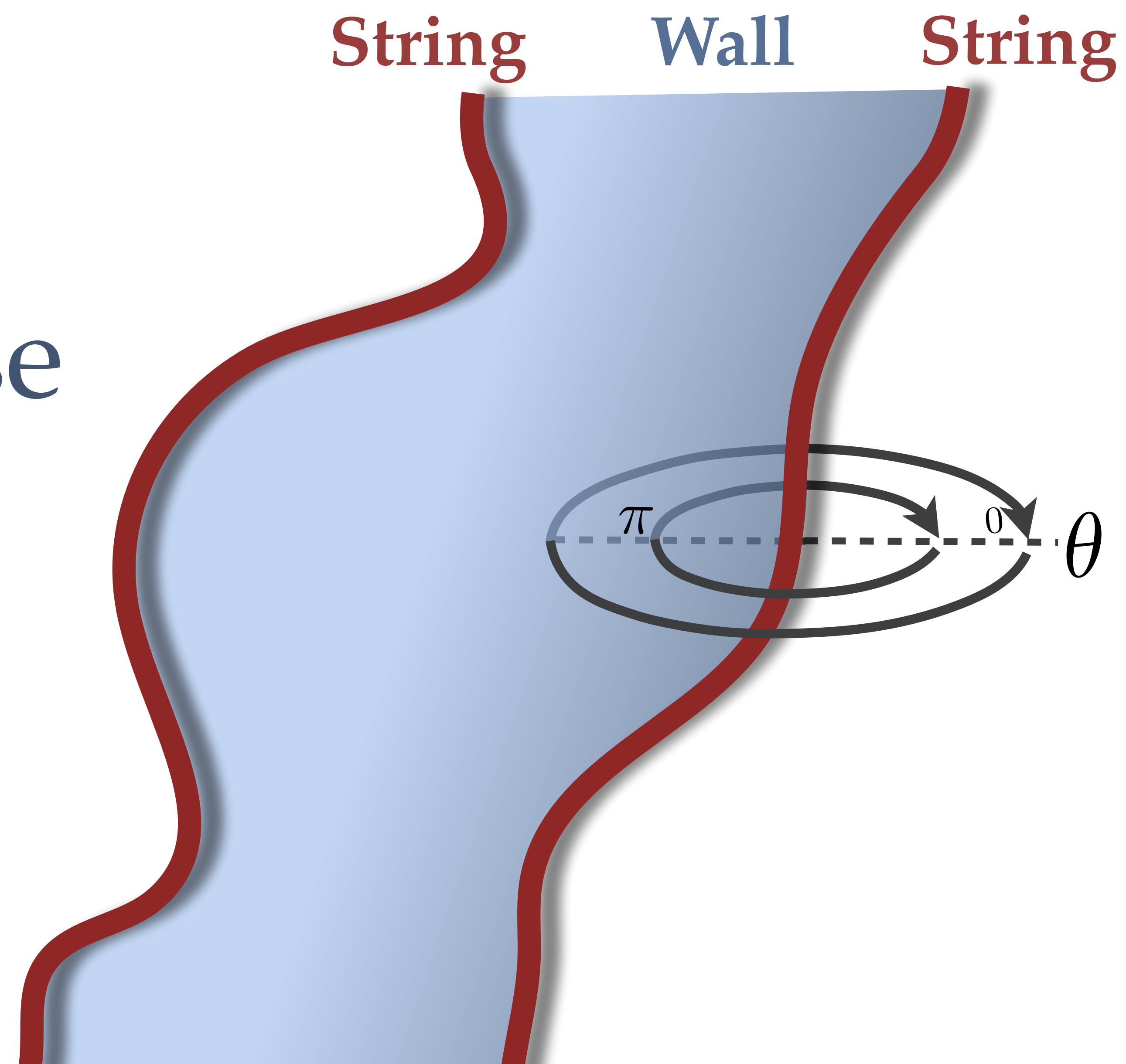
Different causal patches take on different initial angles
→ Field gradients!

$$\leftarrow \quad \ddot{\theta} + 3H\dot{\theta} \boxed{- \frac{1}{R^2}\nabla^2\theta} + m_a^2\theta = 0$$

⇒ **Cosmic strings** from axion field winding around 2π

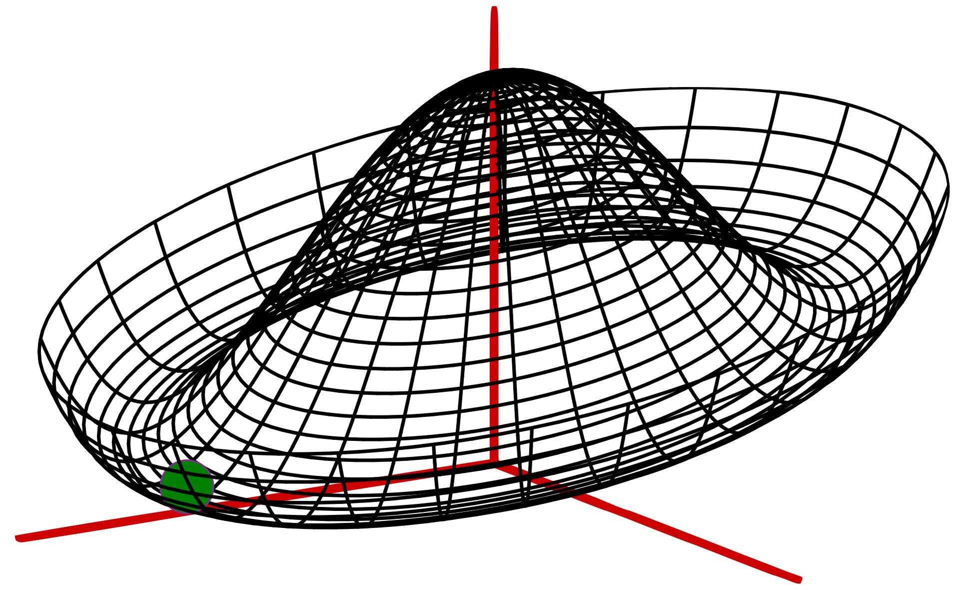


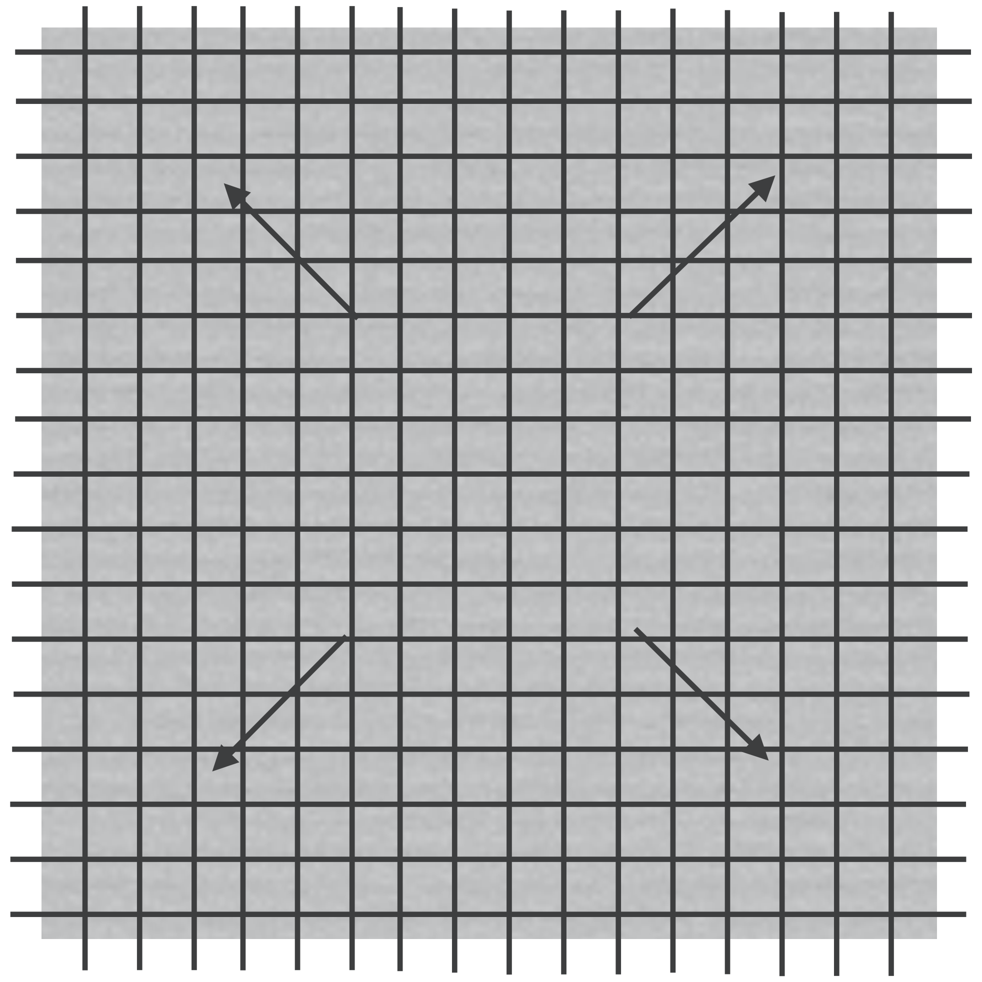
⇒ **Domain walls** between true/false vacuum (0 and π)

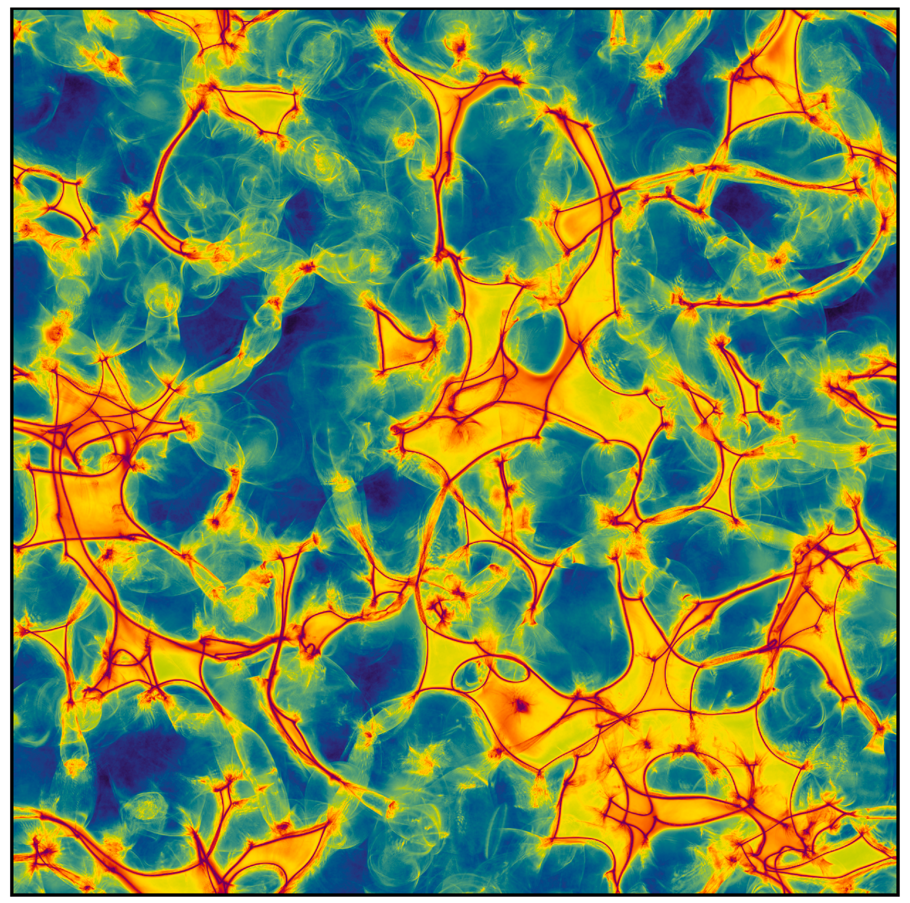


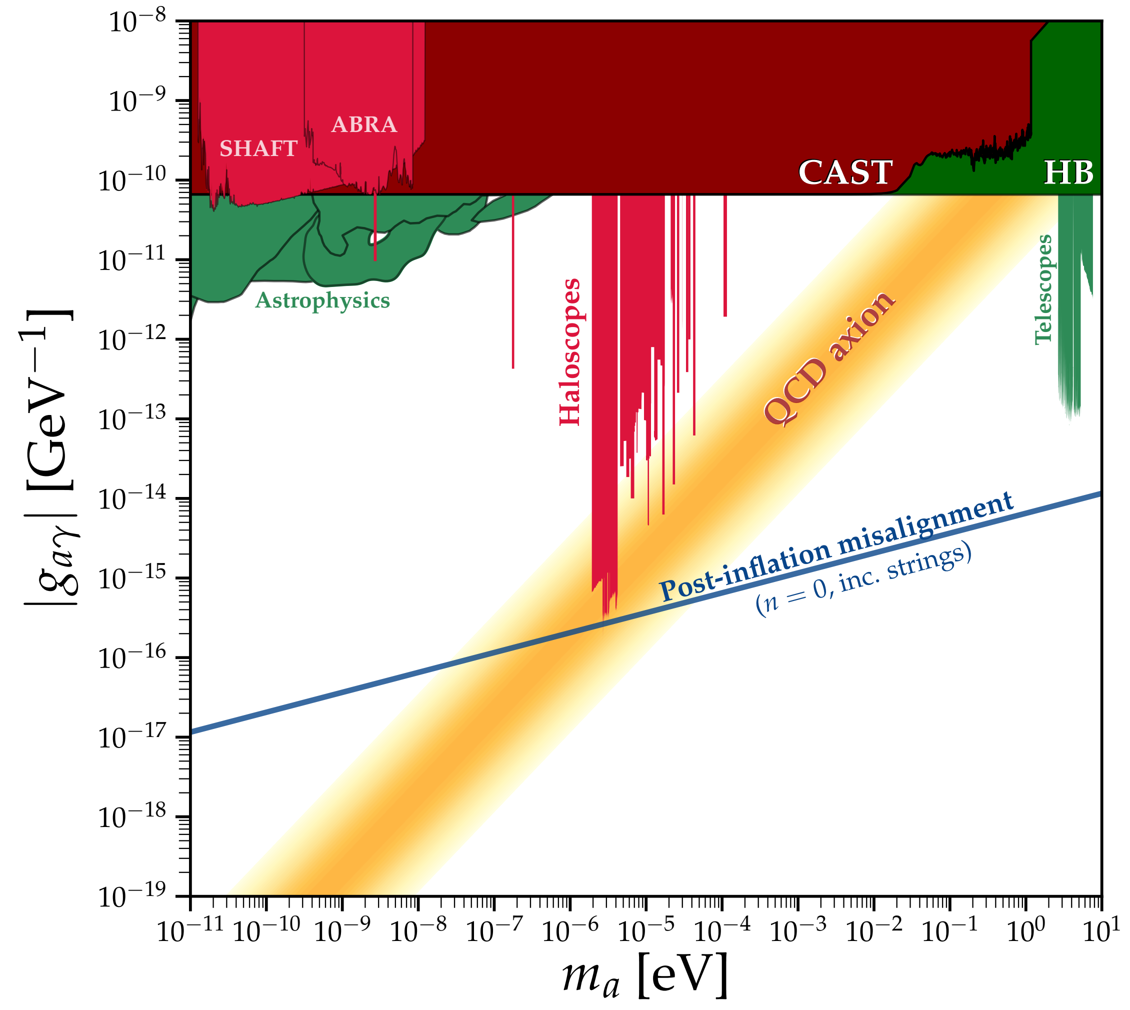
Numerical simulations of the cosmological axion

What do we want to do?









Solve the evolution of the axion field…

…on an expanding lattice…

…to measure the relic abundance of axions…

… and find the parameters that reproduce $\Omega h^2 = 0.12$

The axion potential

$$V(\phi) = \frac{\lambda_\phi}{8}\left(|\phi|^2 - f_a^2\right)^2 + \chi(T)(1 - \cos\arg\phi)$$

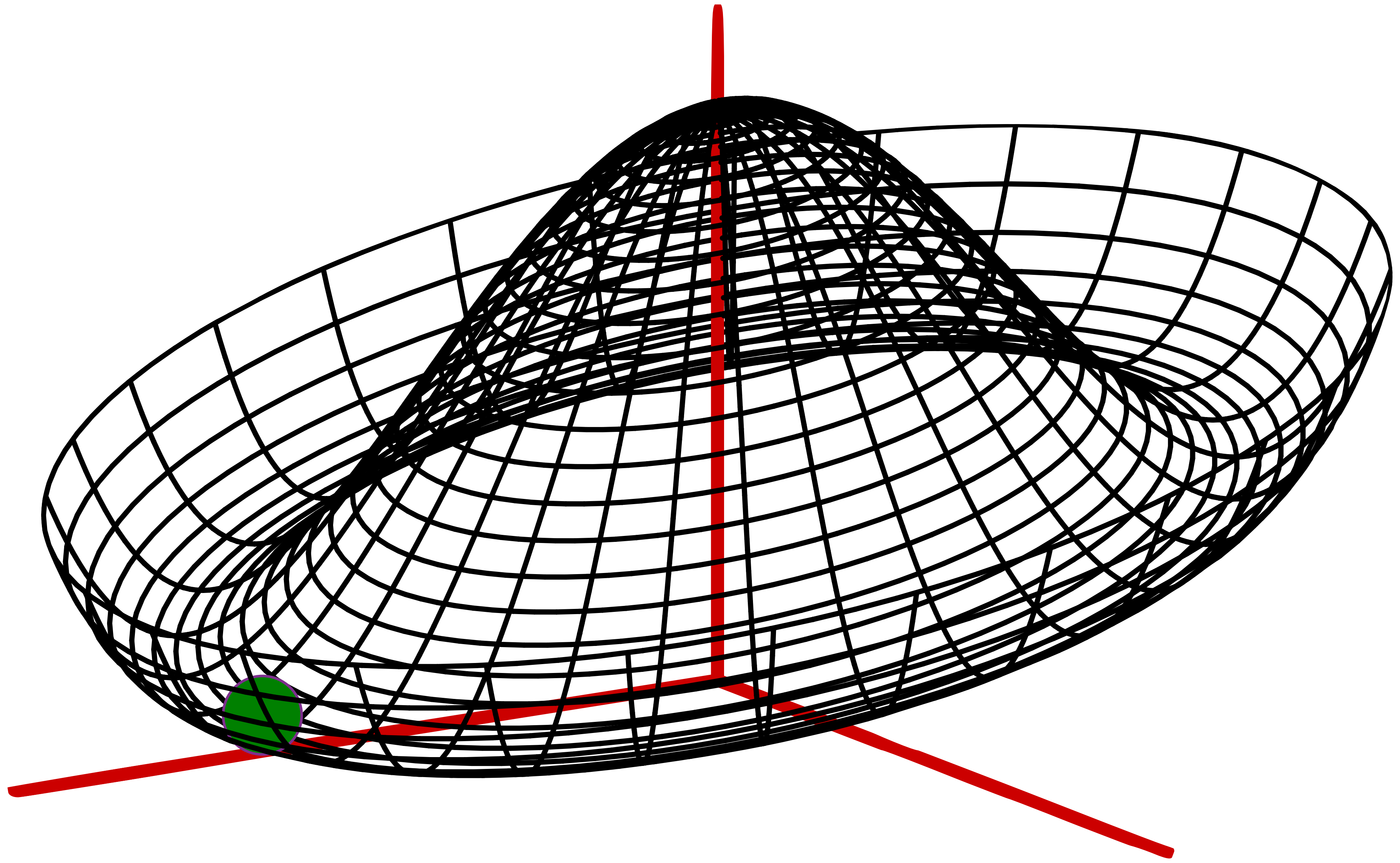
Wine bottle part — Governs → $|\phi(\mathbf{x})|$

Radial dof: "saxion"
Sets string width

Tilting part — Governs → $\theta(\mathbf{x}) = a(\mathbf{x})/f_a$

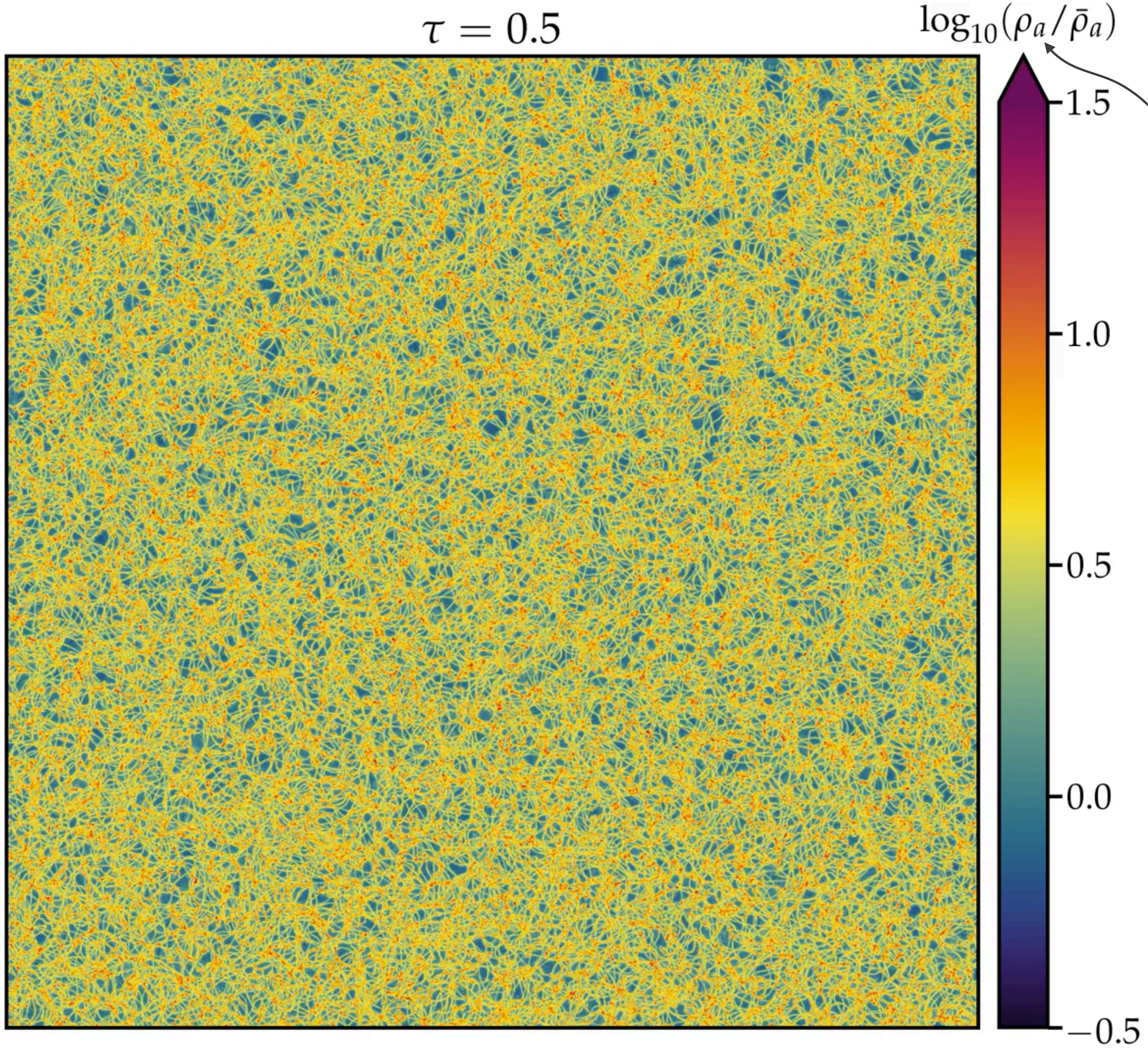
Angular dof: "axion"
Sets domain wall width

(this mode is the dark matter)



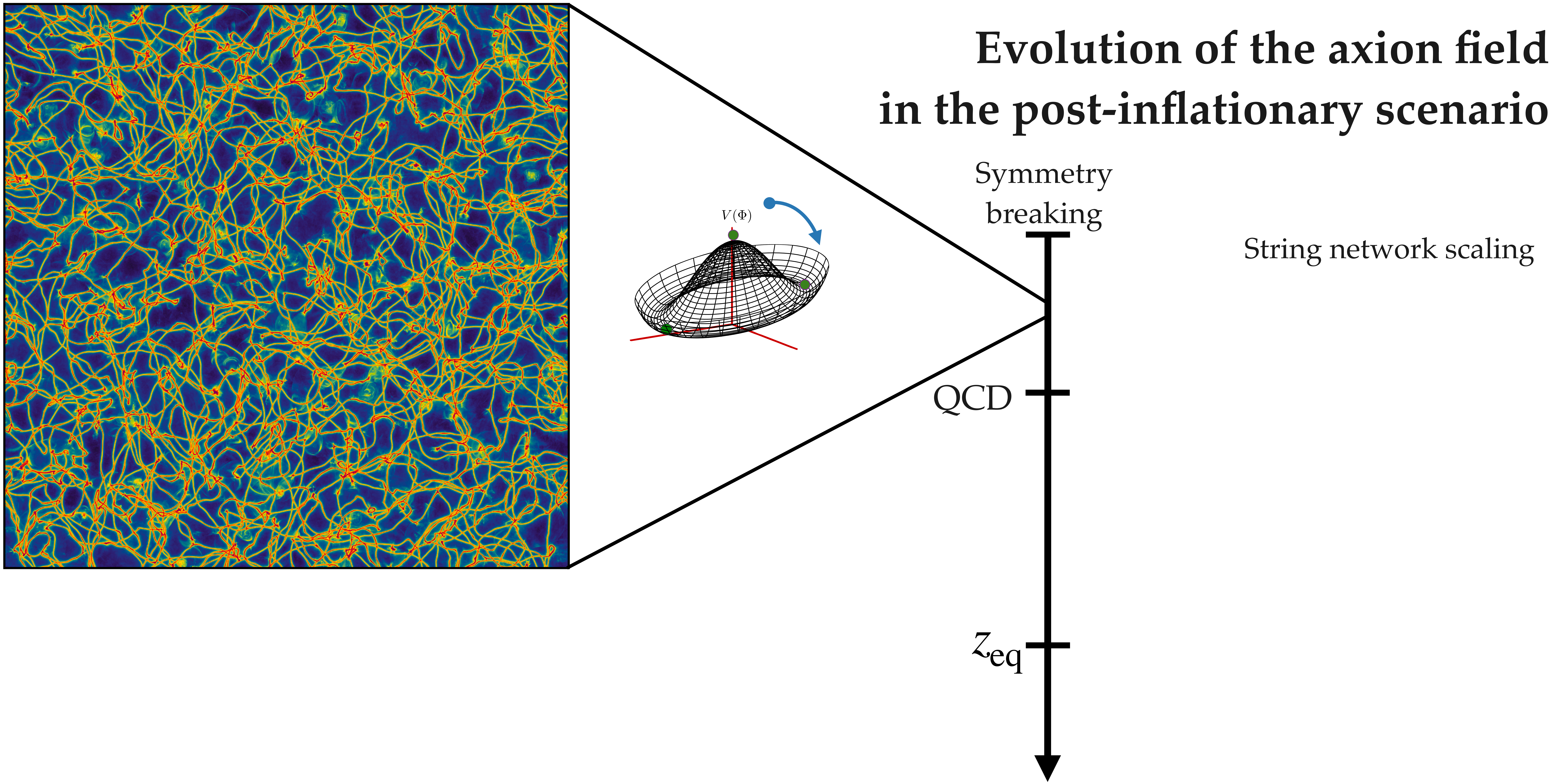
$$\phi(\mathbf{x}) \sim |\phi(\mathbf{x})|e^{i\theta(\mathbf{x})}$$

Evolution of the axion field in the post-inflationary scenario

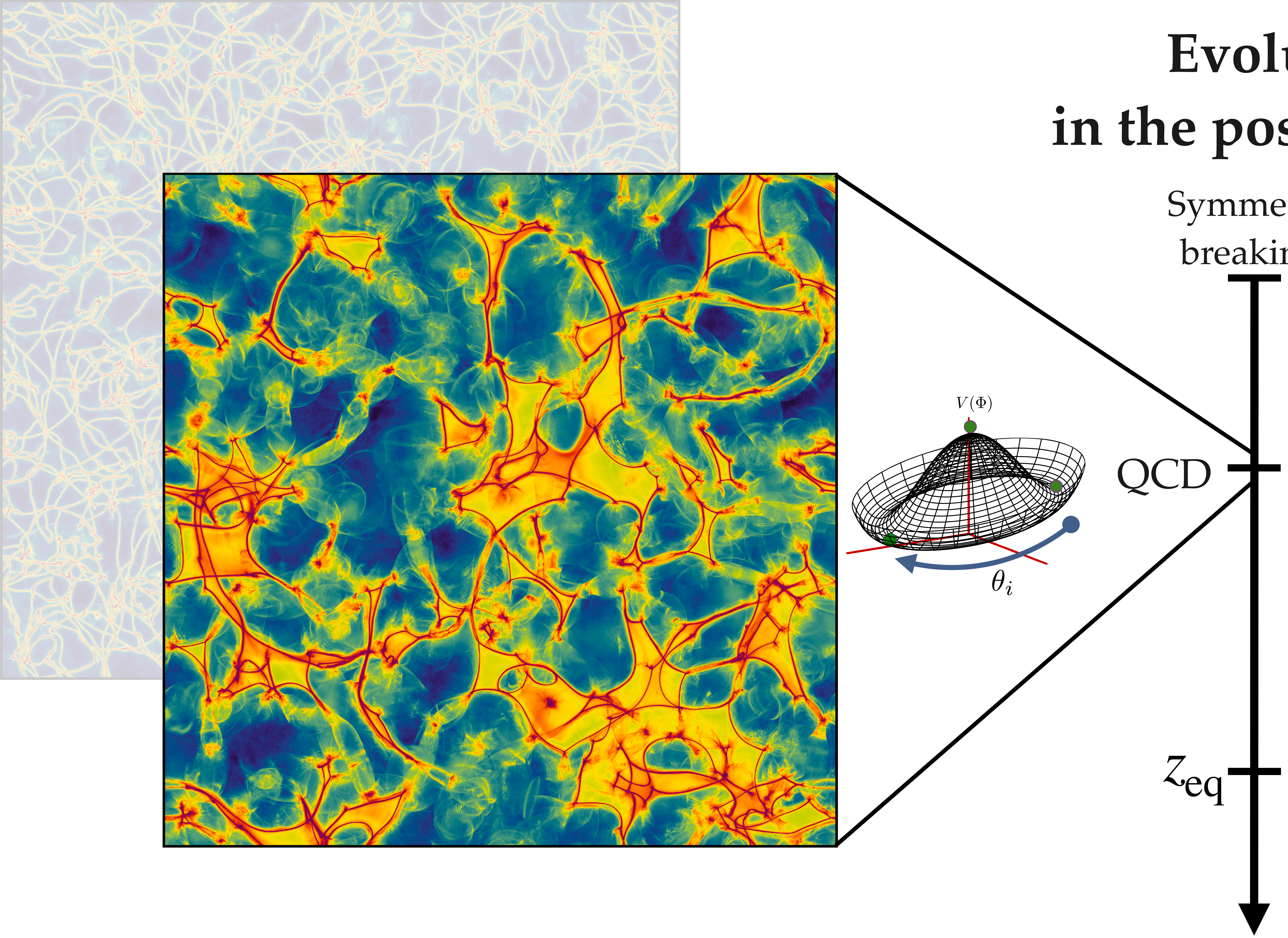


$$\rho_a = \frac{1}{2}\dot{a}^2 + \frac{1}{2R^2}(\nabla a)^2 + \chi\,(1 - \cos a/f_a)$$

(movie)


Evolution of the axion field
in the post-inflationary scenario
Symmetry
breaking
V(Φ)
String network scaling
QCD
$z_{\rm eq}$

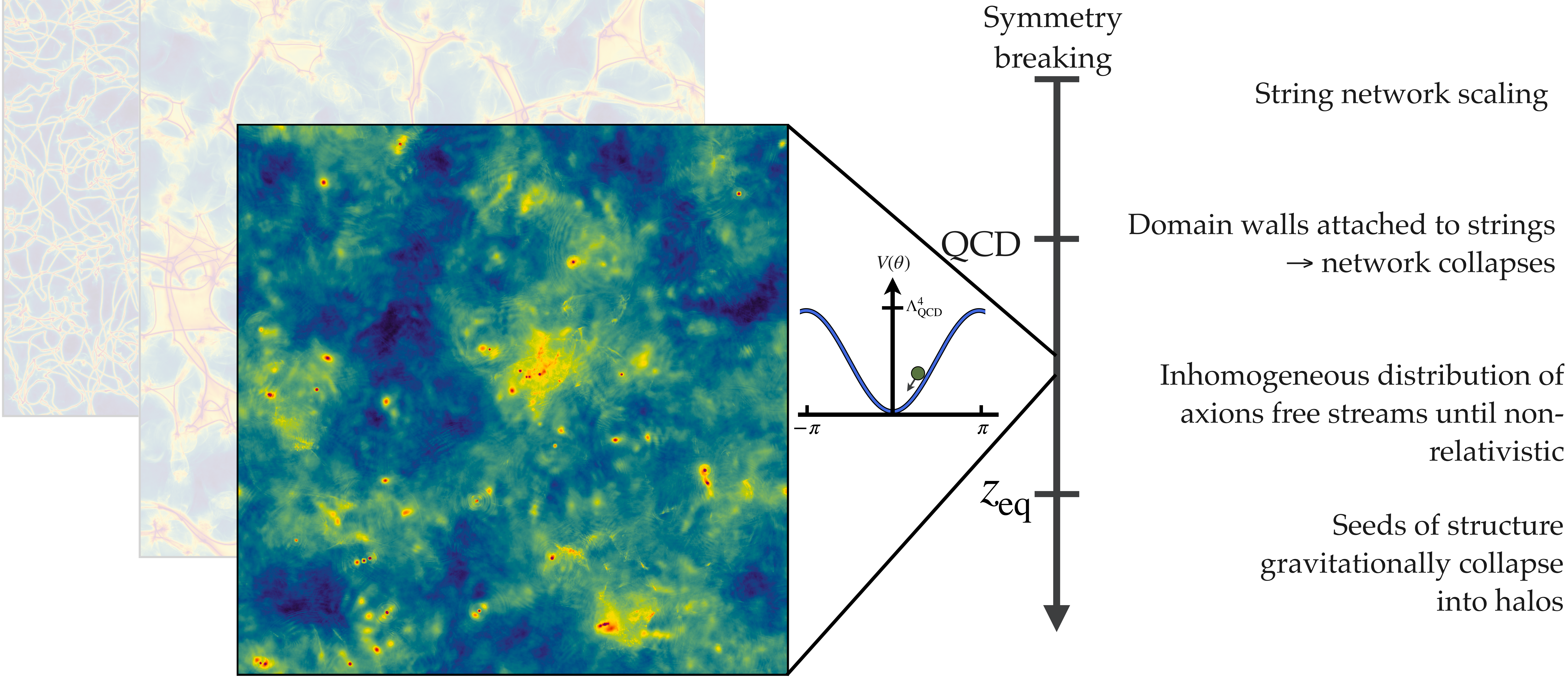
Evolution of the axion field in the post-inflationary scenario

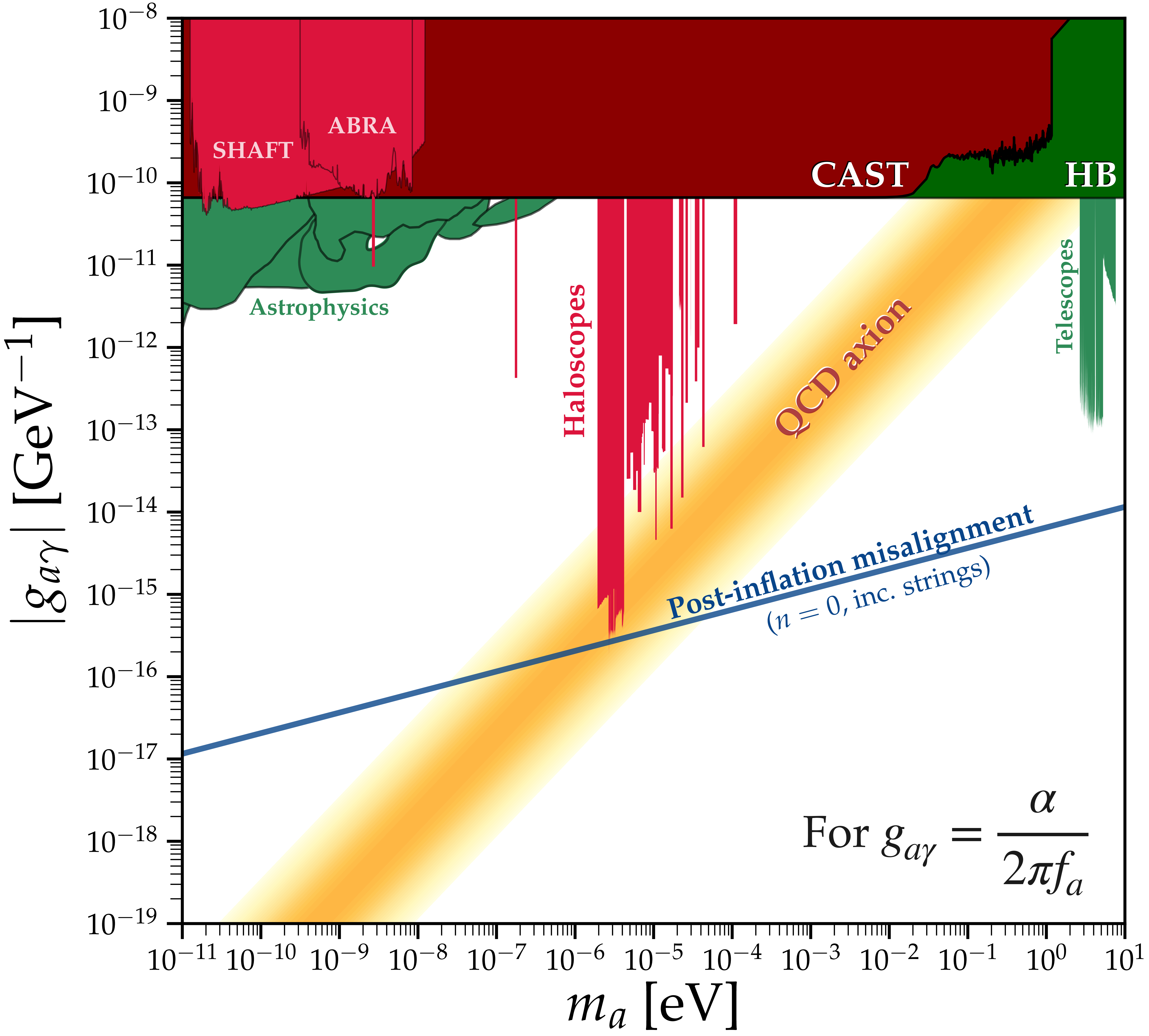


String network scaling

Domain walls attached to strings
→ network collapses

Evolution of the axion field in the post-inflationary scenario





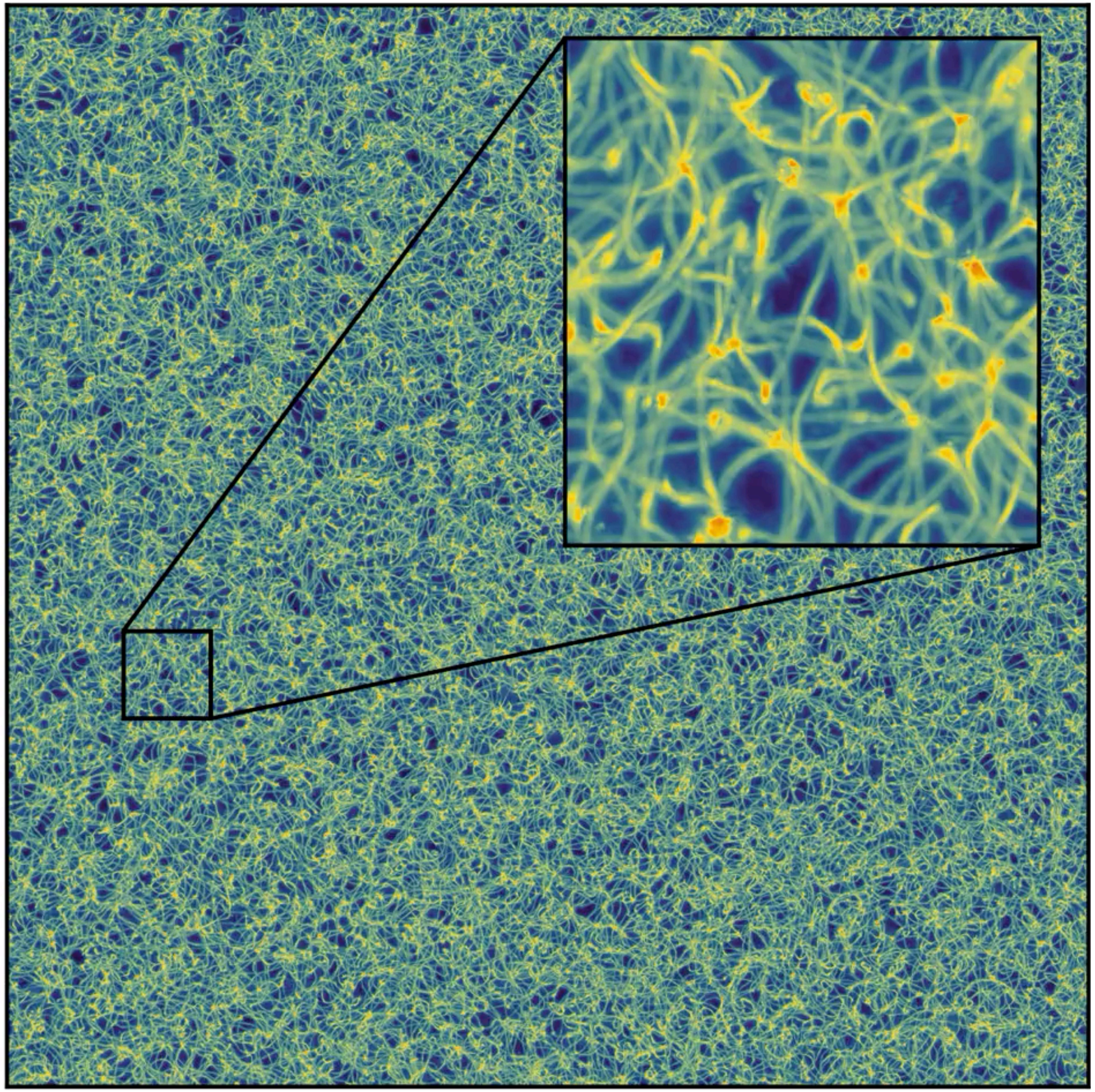
CAJO+[2112.05117]

Now simply take the density of axions at the end of the simulation and figure out the density today:

$$\rho_a\left(T_0\right) = m_a n_a(T) \frac{g_{*s}\left(T_0\right)}{g_{*s}(T)} \left(\frac{T_0}{T}\right)^3$$

From this can find which axion parameters reproduce $\Omega_a h^2 = 0.12$

i.e. which axions give the correct relic abundance?



(Movie)

Large numbers of high-density oscillating lumps are seeded towards the end of the simulation

"**Axitons**"

Axion stars

Axion miniclusters

Additional astrophysics signatures…

Summary

- Axions are the best candidates for dark matter

- One could be found tomorrow, or in 20 years time. Theoretical progress is desperately needed for the experimental community to know what experiments to run

- Simulations are beginning to firm up predictions for the axion's properties that make it consistent with 100% of the Dark Matter

- However, we need further simulations including N-body simulations to study the beyond-CDM clumping of axions in our galaxy and determine any further astrophysical signatures

THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER