Axion Dark Matter

Second lecture 9.7.21

Recap:

- Strong CP problem: Why is CP conserved in the strong sector ($\theta = 0$)?
- Axion provides a mechanism to explain this.

  $\Rightarrow$ new light boson

  $$m_a = 5.70(7)\ \mu eV \left(\frac{10^{12}\,GeV}{f_a}\right)$$

- Axion couples to all or some gauge bosons through $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$.

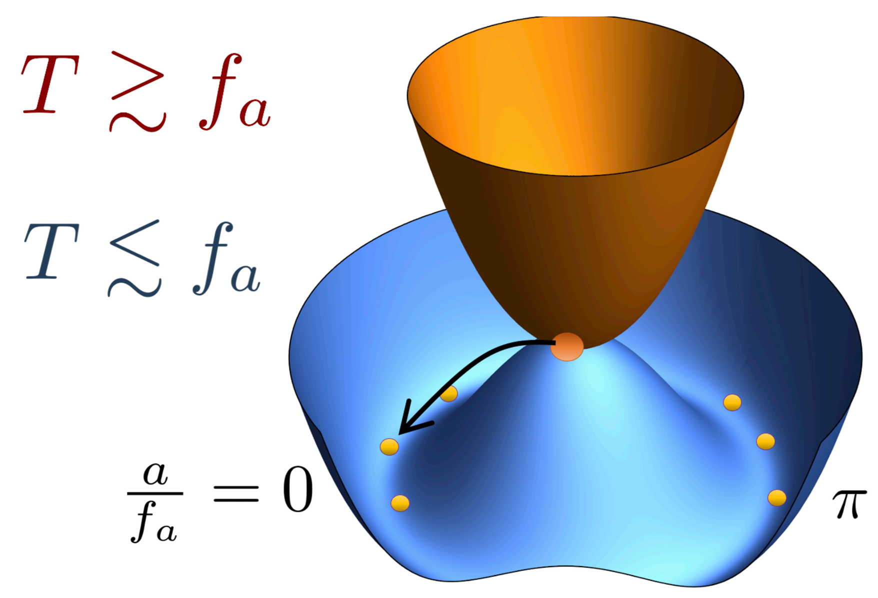
3. A glimpse at axion models

$\frac{a}{f_a} G\tilde{G}$ is a dimension 5 operator. $\Rightarrow$ Not UV complete.

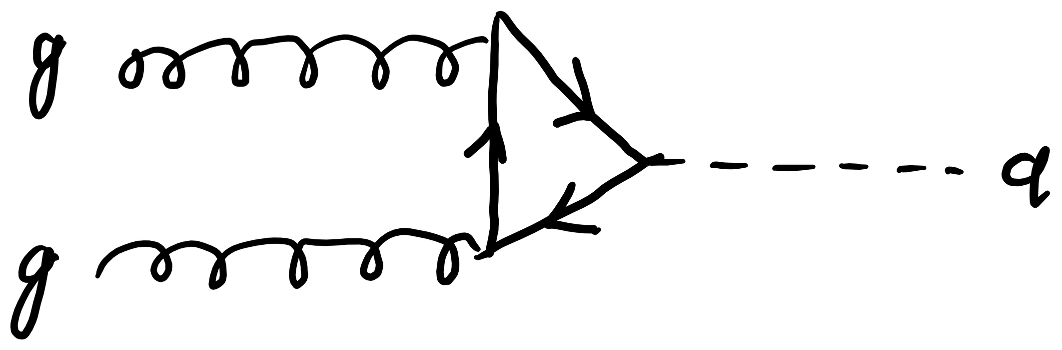
All possible UV completions are called axion models.

(Almost) All QCD axion models introduce a complex scalar field ϕ with a SSB potential.

When ϕ obtains a vev: $\phi = (\langle\phi\rangle + \rho)\cdot e^{i\frac{a}{f_a}}$ ← axion



The required coupling to $G\tilde{G}$ is generated by a loop:



$\sim \frac{a}{f_a} G\tilde{G}$

All QCD axion models have this $a\,G\tilde{G}$ interaction.

They differ in their couplings to the SM

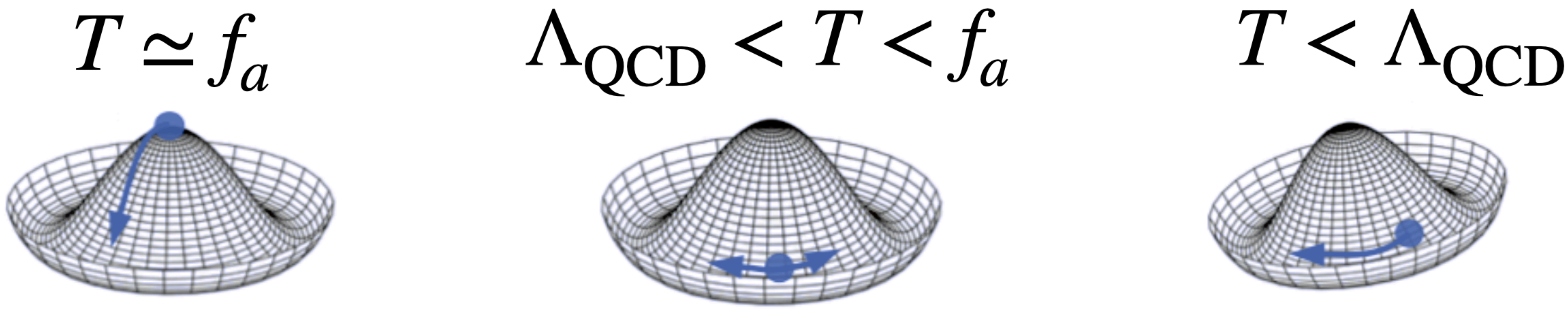
e.g. $c_f \frac{\partial_\mu a}{f_a} \bar{f}\gamma^\mu\gamma^5 f$ or $c_{FF} \frac{a}{f_a} F\tilde{F}$

4. Vacuum realignment production

Common prejudice: DM particles can't be light ($\lesssim$ keV)
Relies on at least one of two assumptions
- DM is fermionic → axion is a boson
- DM is thermally produced → we need a non-thermal production mechanism

Cosmic history of axions

1. The PQ scalar ϕ obtains a vev at $T \simeq f_a$.
   $\frac{a}{f_a}$ takes a random value from $-\pi$ to π.
2. Axion obtains a significant mass at $T \simeq \Lambda_{QCD}$.
3. Axion field starts to oscillate.



Dynamics of cosmological axion field.

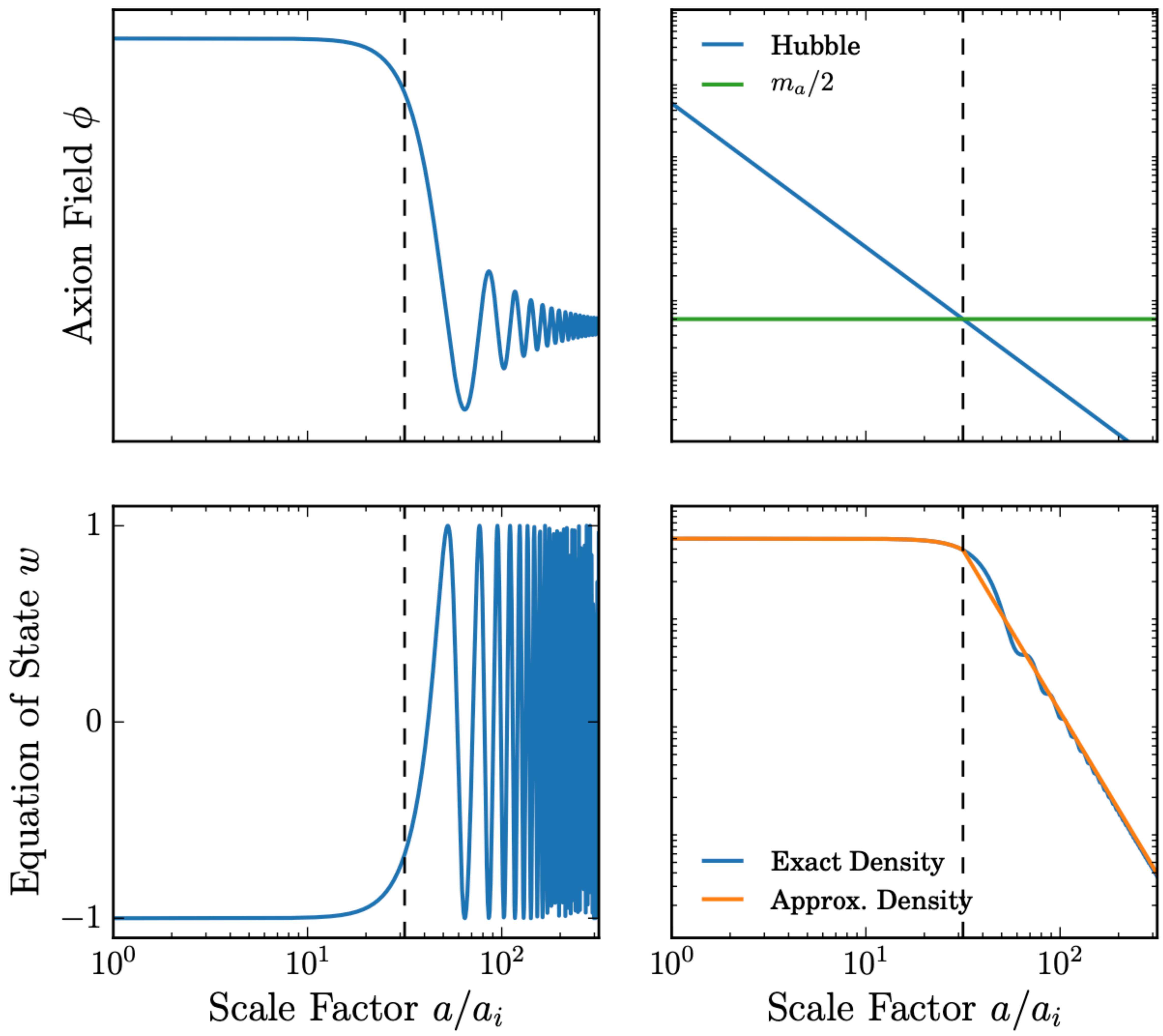
$$S = \int d^4x \sqrt{-g} \left[g^{\mu\nu} (\partial_\mu a)(\partial_\nu a) - \frac{1}{2} m_a^2 a^2 \right]$$

(↑ FLRW metric)

$\xRightarrow{a \text{ homogenous}}$ $$\ddot{a} + \underbrace{3H\dot{a}}_{\text{Hubble damping}} + m_a^2 a = 0$$

H decreases as the universe expands.
⟹ Overdamped oscillator becomes underdamped. → oscillations

Oscillations behave as DM.



Amount of produced DM

$$\Omega_a \approx 8 \left(\frac{\mu eV}{m_a}\right)^{1.175} \theta_{init}^2$$

↑ initial misalignment angle ≃ order 1

We need $\Omega_{DM} = 0.23$

⇒ typical mass scale for axion DM : few-hundreds μeV

<u>Pre- and Postinflationary scenario</u>

So far we have assumed a homogenous axion field in the whole universe.

This is justified in the <u>preinflationary scenario</u>:

The SSB happens <u>before</u> cosmic inflation.

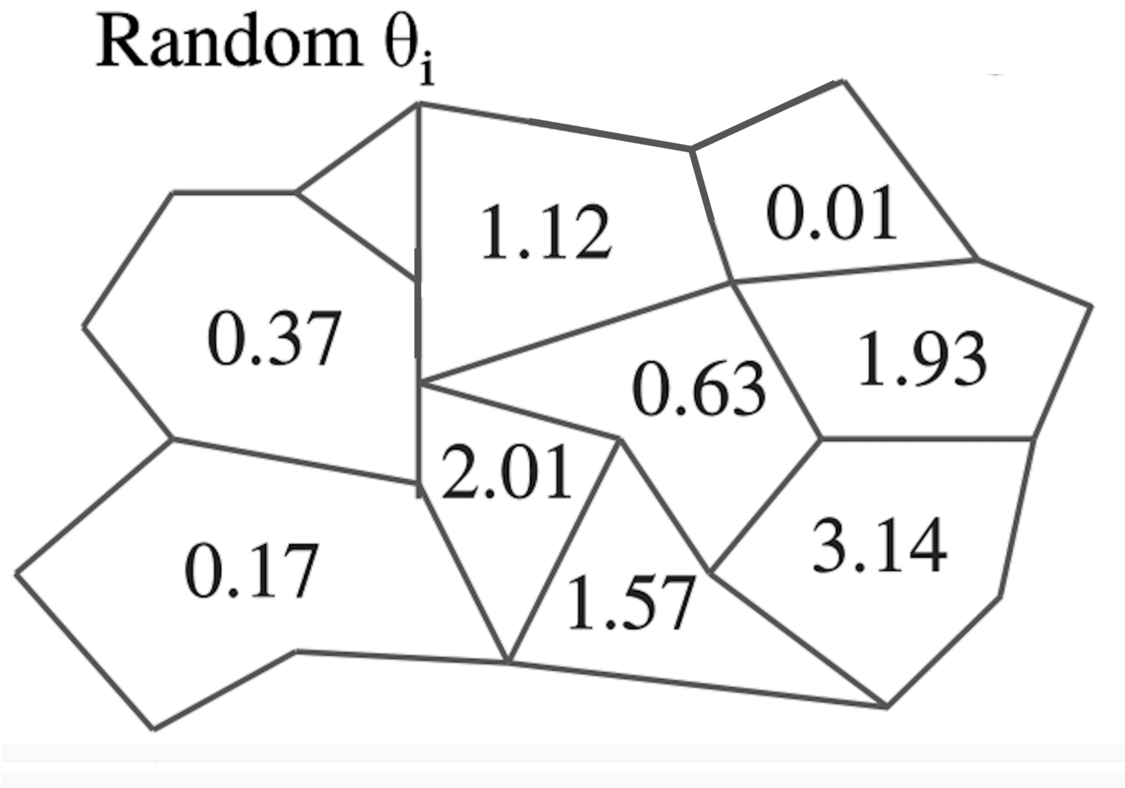
⇒ Axion field is stretched until it is constant throughout the observable universe.

This is the simplest scenario, but it does not predict a specific abundance since θ_{init} is random.

Postinflationary scenario

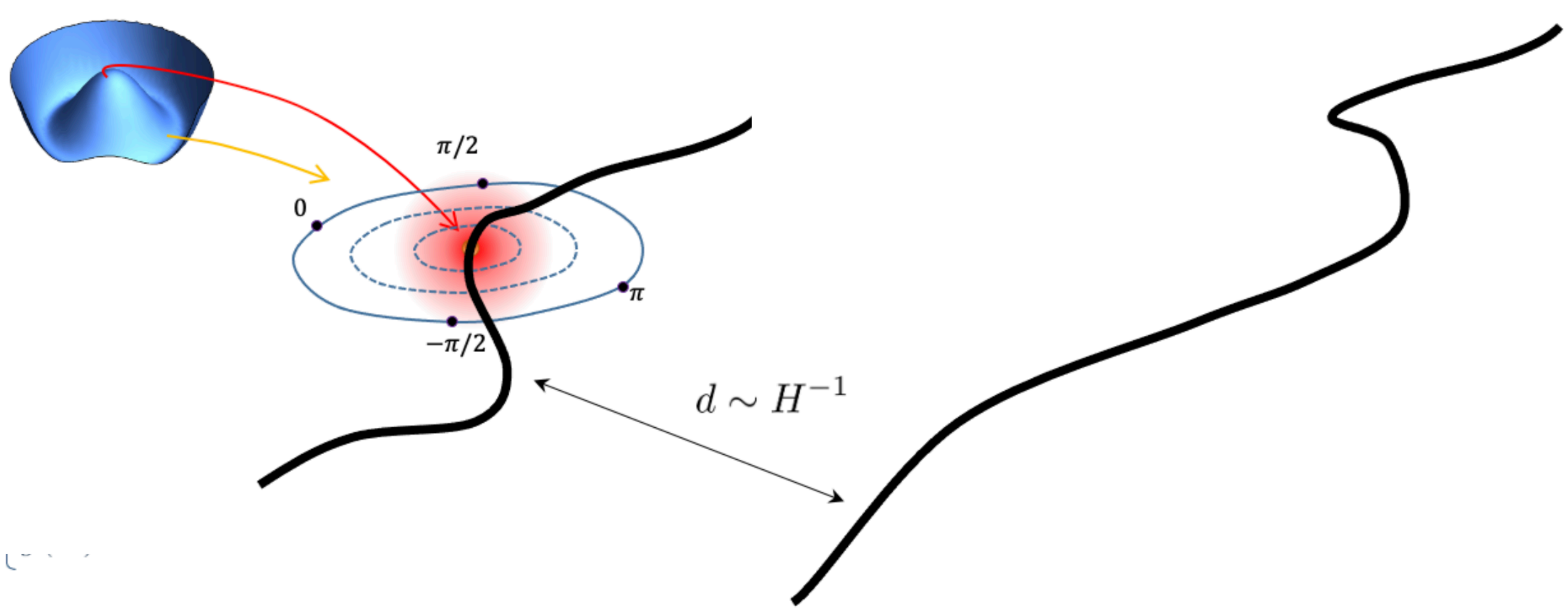
When the PQ symmetry is broken after inflation, the initial misalignment angle is different in different patches of the universe.

$\Rightarrow$ We can average over all initial angles to get a prediction for the abundance $\theta^2_{init} \longrightarrow \langle \theta^2_{init} \rangle$



This scenario is more predictive. However, topological defects like axion strings will appear.

A cosmic axion string is a trajectory through space around which the axion field winds from $-\pi$ to π.



Strings will be dilated as the universe expands but also decay into axions.

$\Rightarrow$ additional abundance

This is hard to calculate numerically.

$\Rightarrow$ Axion dark matter window: $\mu eV \lesssim m_a \lesssim meV$