

# Domain walls of string theory axions

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TeVPA 2024



# Introduction

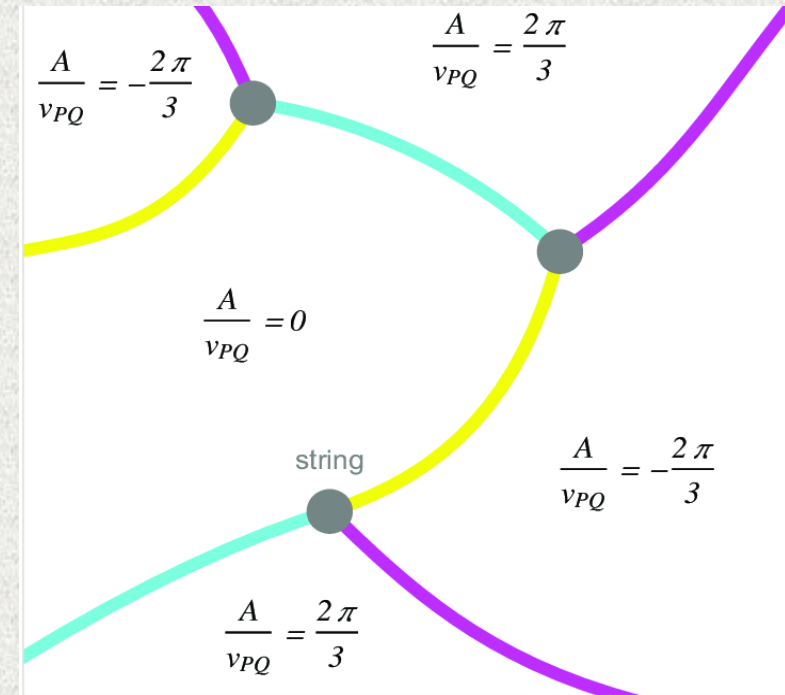
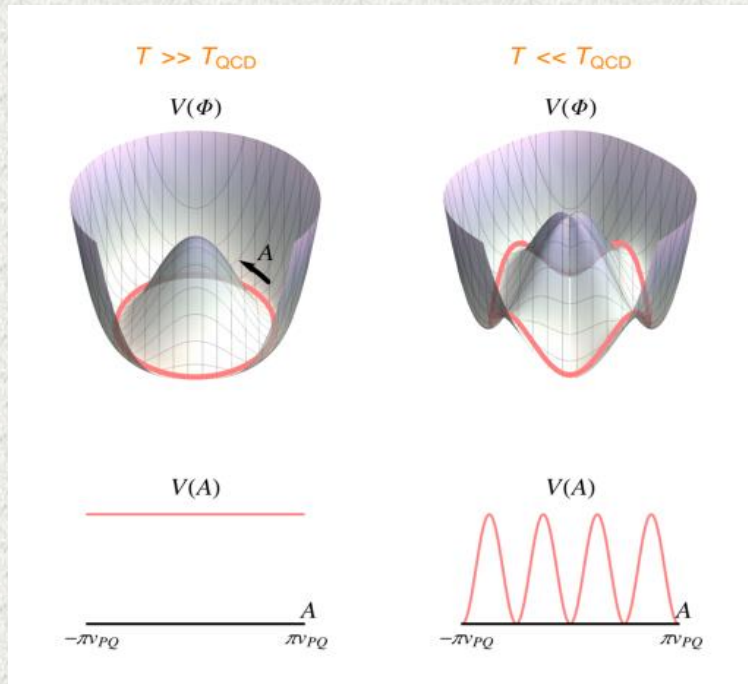
Axions domain walls are created after QCD phase transition.

If the QCD axions have multiple degenerate minima, the string domain wall network is stable.

Domain walls quickly dominate the energy density of the universe, unless they decay.  $\rho_{DW} \sim \frac{1}{t}$

The collapse of domain walls can create axion DM, GWs.

# Introduction



# Multiple axions

In general, it is imperative to consider multiple axion scenario

The axions are generally coupled

$$\mathcal{L} \subset -\frac{K_{ij}}{2} \partial_\mu a_i \partial^\mu a_j - \Lambda_n^4 \left[ 1 - \cos \left( Q_{ni} \frac{a_i}{f_i} + \delta_n \right) \right]$$

$K_{ij}$  is the kinetic mixing matrix which we assume to be diagonal

$Q_{ni}$  are the integer instanton charges

$$\Lambda_n \sim \Lambda_{string} \exp(-S_n)$$

# Unstable domain walls

String theory axions strings are different than field theory axion strings.

If the string domain wall network is unstable, the strings overproduce QCD axion DM.

In the case of multiple axion, it is possible to populate the observed abundance of DM.

What happens if the string domain wall network is stable for a long time?

# Domain wall annihilation

$$V_1(a_1, a_2) = \Lambda_1^4 \left[ 1 - \cos \left( N_{11} \frac{a_1}{f_1} + N_{12} \frac{a_2}{f_2} + \delta_1 \right) \right]$$

If the strings source  $a_1$ , the domain walls are 'formed' when Hubble crosses wall thickness.

$N_{11} = 1$  The string domain wall network is unstable and decays quickly.

$N_{11} \neq 1$  The network is stable for a long time.

# Domain wall annihilation

$$V_2(a_1, a_2) = \Lambda_2^4 \left[ 1 - \cos \left( N_{21} \frac{a_1}{f_1} + N_{22} \frac{a_2}{f_2} + \delta_2 \right) \right] \quad \Lambda_1 > \Lambda_2$$

$V_1$  and  $V_2$  fixes the classical minima for the axions if  $\frac{|N_{11}N_{22} - N_{12}N_{21}|}{\text{gcd}(N_{12}, N_{22})} = 1$

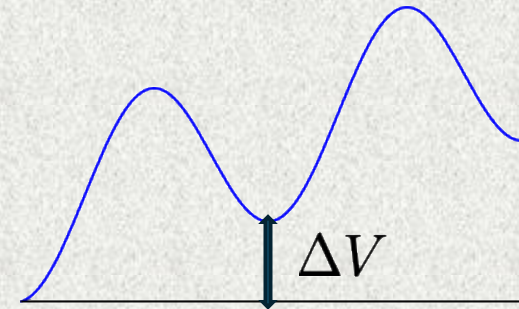
$$N_{11} = 2 \quad N_{12} = N_{21} = N_{22} = 1 \quad f_1 = f_2 = f$$

# Domain wall annihilation

$$V_1 \sim 1 - \cos(2\theta_1 + \theta_2) \quad V_2 \sim 1 - \cos(\theta_1 + \theta_2)$$

Only minimum at the origin.

Domain wall decay when  $\Delta V \approx \rho_{DW}$



To avoid domain wall domination

$$\Lambda_2 > \Lambda_1 \sqrt{\frac{f}{M_{pl}}}$$



# Emission of Gravitational waves

$$P \sim G \ddot{Q}_{ij} \ddot{Q}_{ij} \quad E \sim Pt \sim G \sigma^2 t^3$$

Gravitational wave emission is enhanced for late decays.

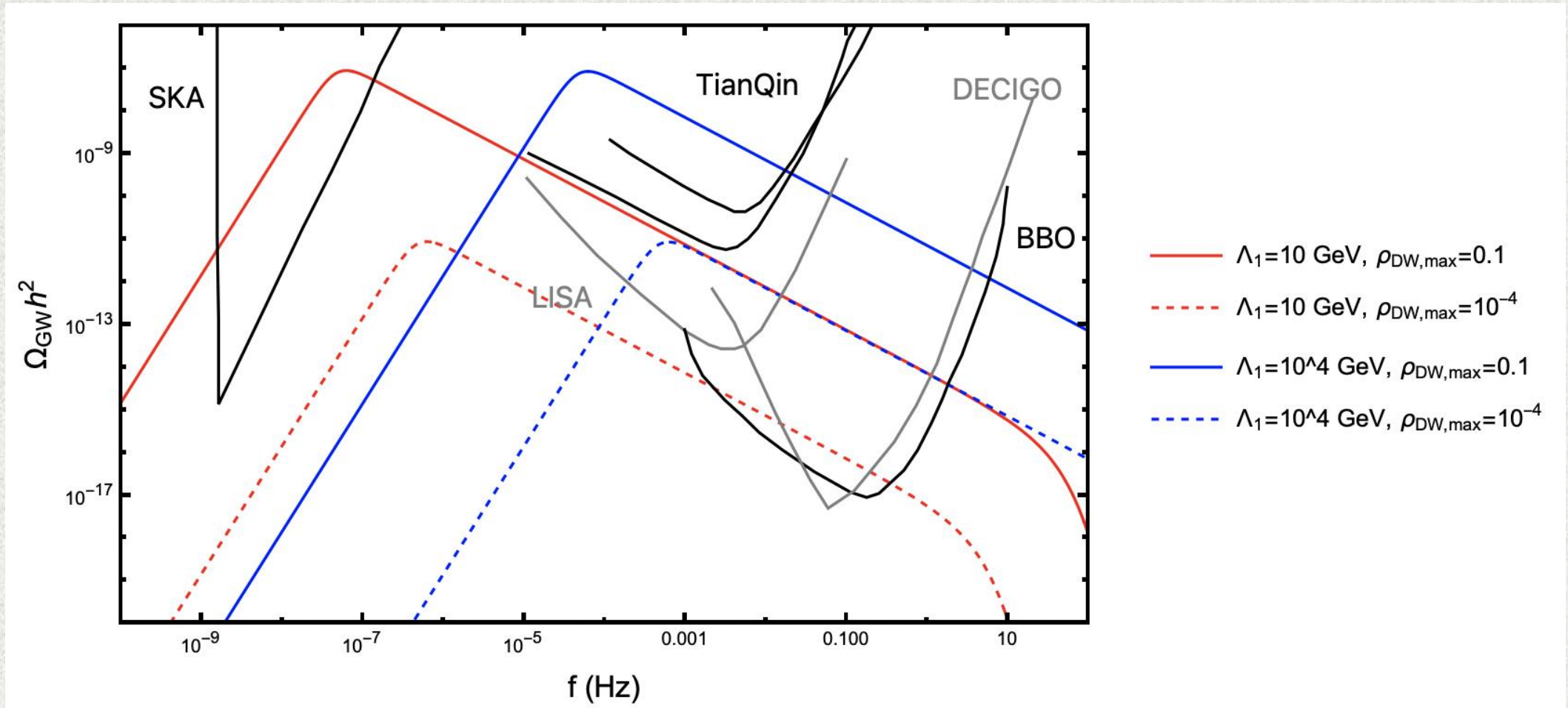
$$f_{peak} = H(t_{ann}) \frac{R(t_{ann})}{R(t_0)} = H(t_{ann}) \frac{T_0}{T(t_{ann})}$$

The characteristic frequency is higher if decayed earlier.

Only frequencies below the (inverse of) wall width is produced.

$$f_{max} = \delta^{-1} \frac{R(t_{ann})}{R(t_0)} = \delta^{-1} \frac{T(t_{ann})}{T_0}$$

# Emission of Gravitational waves



# Axion dark matter

The mass eigenstates are related to the flavor states.

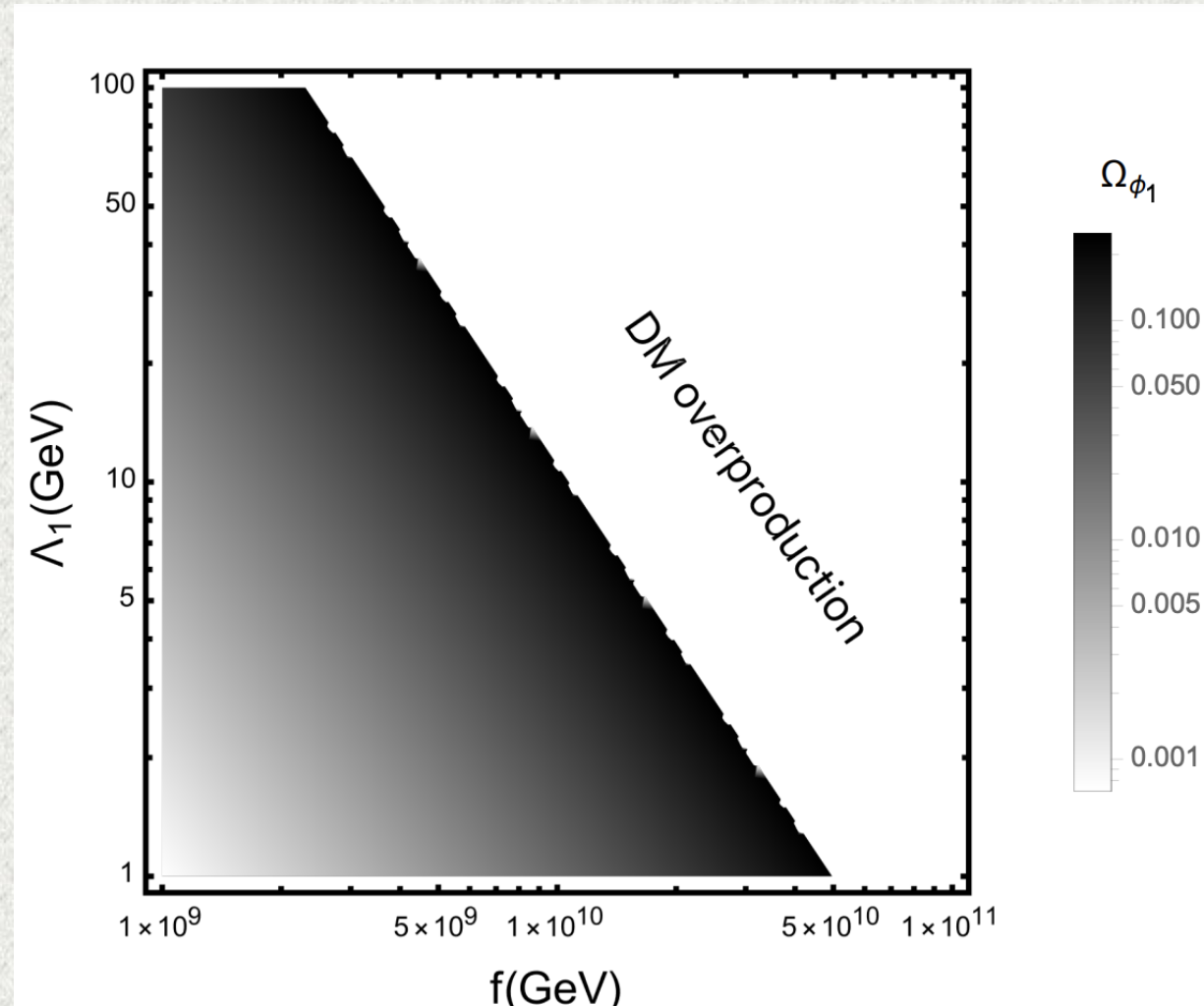
$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = R(\theta) \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad R(\theta) = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \quad m_{\phi_1} > m_{\phi_2}$$

The wall emits the flavor state it couples to.

The collapse can thus produce more than one type of relic axion abundance. However, the DM abundance is dominated by misalignment contribution.

For a large part of parameter space, the heavier axion creates EMD era and decays subsequently.

# Axion dark matter



# Summary

Stable axion string domain wall network can be produced before QCD phase transition.

Collapse of the same can leave observable gravitational wave background.

The production of multiple type of axion mass eigenstate can be probed.

Thank you