



## Predicting the Axion Mass with large String Tension

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Klaer and Moore, [arXiv:1708.07521](#) and [arXiv:1707.05566](#)

Motivation

Axion Cosmology

Axionic String Networks

Results

## Why are we investigating the Axion

- ▶ The **Axion** can solve the strong CP problem
- ▶ **Dark Matter** is still a **mystery**

We know so far that it is

- ▶ **matter** : makes up 25% of the density of the Universe
- ▶ **dark** : interaction is feeble (except gravitationally)
- ▶ **cold** : almost pressureless

The **Axion** is also a **possible Dark Matter** candidate

$$\mathcal{L}_a = \partial^\mu \phi^* \partial_\mu \phi + \frac{\lambda}{8} (2\phi^* \phi - f_a^2)^2 + \chi(T) \text{Re} \phi$$

$f_a$  is unknown

$\chi(T)$  strong function of  $T$

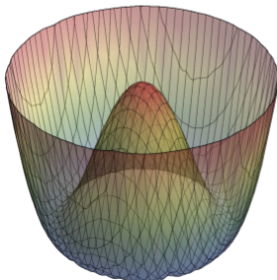
- ▶  $\chi(T) \approx (76\text{MeV})^4$   
if  $T \ll T_C$

Cortona *et al*, arXiv:1511.02867

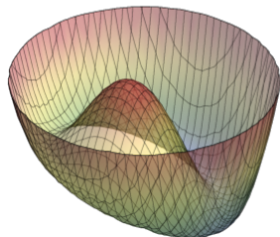
- ▶  $\chi(T) \propto T^{-8}$   
if  $T \gg T_C$ , with  
much **larger error**

Gross, *Rev.Mod.Phys.*53,43(1981)

$T_{PQ} > T > T_C$

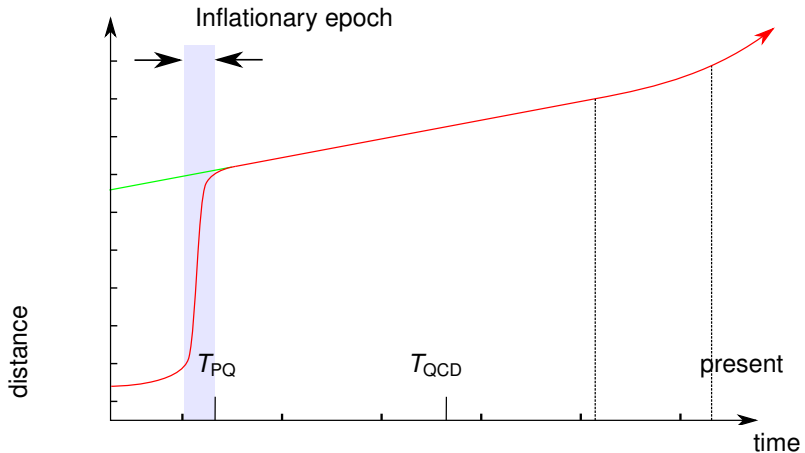


$T_{PQ} > T_C > T$



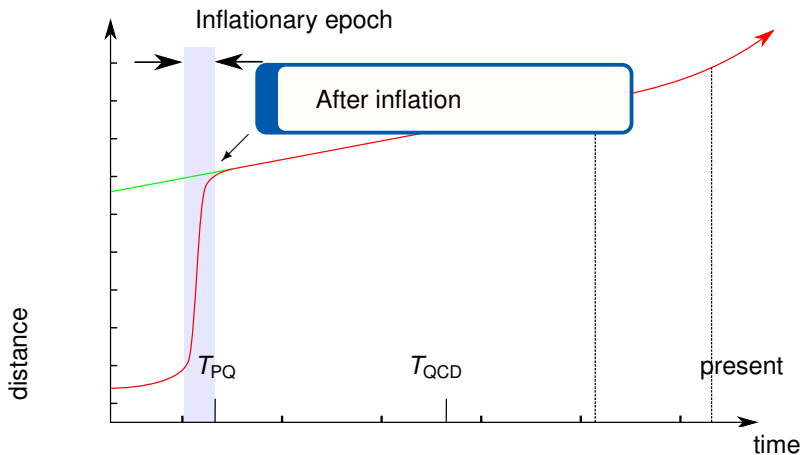
# Axion Cosmology

## Evolution



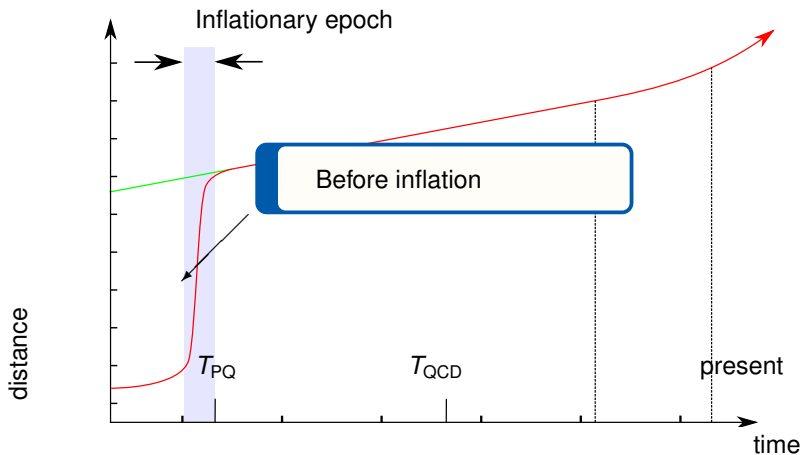
# Axion Cosmology

## Evolution



# Axion Cosmology

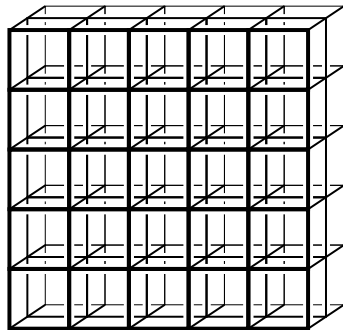
## Evolution



# Axion Cosmology

## Solving on Lattice

- ▶ Put  $\mathcal{L}_a$  as classical field theory on **lattice**
- ▶ Simulation starts **after Inflation**
- ▶  $\phi$  is a complex field
- ▶  $\theta$  is chosen randomly
- ▶ Topological defects will arise
- ▶ Simulate with **Hubble drag**
- ▶ Count axions at the end



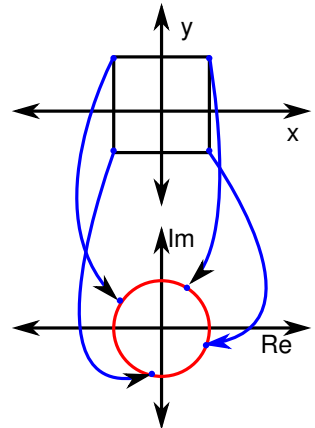


# Axion Cosmology

## String

String arises when the spontaneous symmetry gets broken

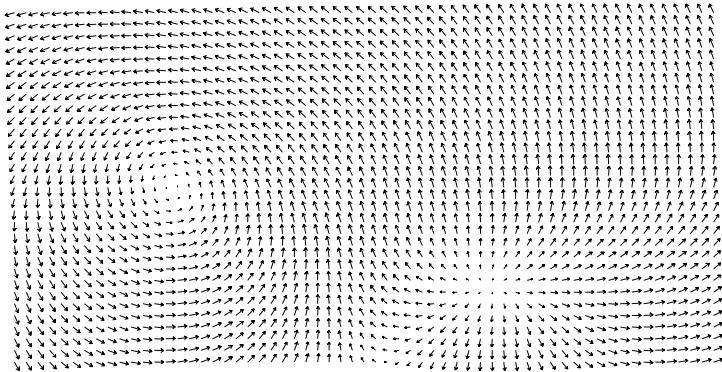
- ▶  $\phi$  is a complex number
- ▶  $\theta$  can take values between  $[-\pi, \pi]$
- ▶  $\theta$  is undefined in the center of the string



# Axion Cosmology

## String

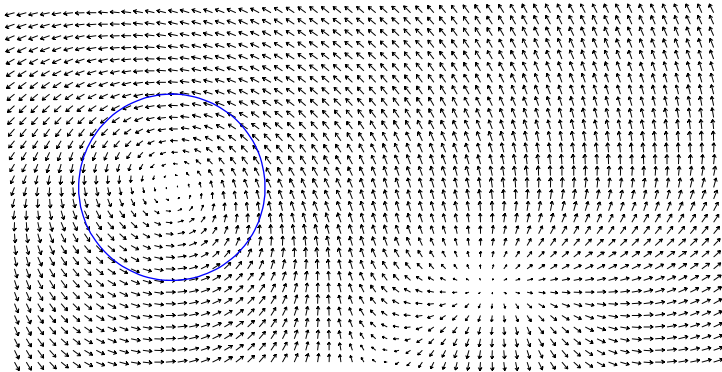
- ▶ 2D slice of an Axion field
- ▶ Field generically has **vortices (strings)**



# Axion Cosmology

## String

- ▶ Circling around the string,  $\theta$  varies by  $\pm 2\pi$
- ▶ In the center of the string  $\theta$  is **undefined**  $\rightarrow \phi = 0$

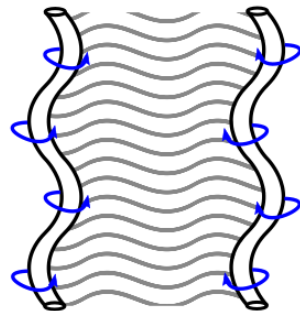
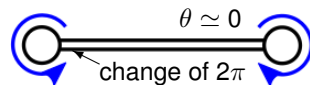


# Axion Cosmology

## Domain Wall

Domain walls arise when the potential tilts

- ▶ Each string is connected to a domain wall
- ▶ Domain walls can appear without strings
- ▶ Change of  $\theta$  happens in domain wall
- ▶ Domain walls pull strings

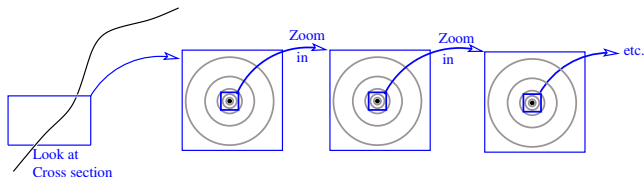




Evolution of the Axion field, when the potential tilts

### Evolution of a string Network

$$E_{str} = \iiint r dr dz d\phi (\nabla\phi^* \nabla\phi \simeq f_a^2/2r^2) \simeq \pi f_a^2 \int_{\sim f_a^{-1}}^{\sim H^{-1}} \frac{r dr}{r^2}$$



- ▶ **Log-large** string tension  $T_{str} = \pi f_a^2 \ln(f_a/H)$
- ▶  $f_a/H \simeq 10^{30}$
- ▶ Equal energy in each x2 scale
- ▶ Scale range is  $10^{30} \rightarrow \kappa = \ln(10^{30}) \simeq 70$ , **achievable is**  $\kappa = 6$



Should we care that  $\kappa = 6$  and not  $\kappa = 70$

Things which scale as  $\kappa$

- ▶ String tension  $T_s tr \simeq \pi \kappa f_a^2$
- ▶ Energy in network  $E \sim L_{\text{network}} \pi \kappa f_a^2$

Things which do not scale with  $\kappa$

- ▶ string-string interaction  $dF/dl \sim f_a^2/r_{\text{sep}}$
- ▶ power radiated from strings  $dE/dldt \sim f_a^2 R_{\text{curv}}^{-1}$

Small  $\kappa$  leads to **wrong physics**



## What must an effective model contain

- ▶ **Long-range** (light) degree of freedom to be the axion
- ▶ **Thin cores** with high tension  $T \simeq 70\pi f_a^2$
- ▶ Correct **string-field interactions**

Any modified **high-mass physics** which does this is OK

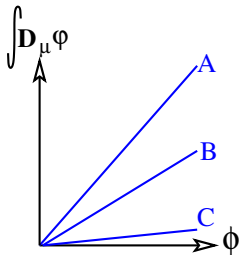
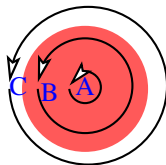
# Axionic String Networks

## Abelian Higgs

$$\mathcal{L}(\phi, A_\mu) = \frac{1}{4}(\partial_m u A_\nu - \partial_\nu u A_m)^2 + (D_\mu \phi)^*(D^\mu \phi) + \frac{\lambda}{8}(2\phi^* \phi - f_a^2)^2$$

with the covariant derivative  $D_\mu = \partial_\mu - ieA_\mu$

- ▶ Magnetic flux centered on string
- ▶ Outside the core  $D\phi \rightarrow 0$



Finite tension  $T \simeq \pi f_a^2$ , **no long-range interactions**

Using two complex scalars and  $A_\mu$

$$\begin{aligned}\mathcal{L}(\phi_1, \phi_2, A_\mu) &= \frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)^2 \\ &+ \frac{\lambda}{8}[(2\phi_1^* \phi_1 - f^2) + (2\phi_2^* \phi_2 - f^2)] \\ &+ |(\partial_\mu - iq_1 e A_\mu)\phi_1|^2 + |(\partial_\mu - iq_2 e A_\mu)\phi_2|^2\end{aligned}$$

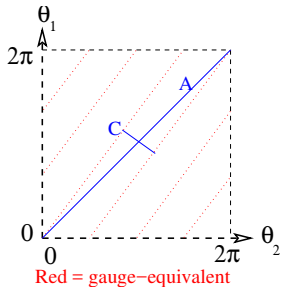
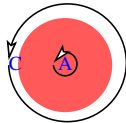
- ▶ Pick  $q_1 \neq q_2$
- ▶ Two rotation symmetries  $\phi_1 \rightarrow e^{i\theta_1} \phi_1$  and  $\phi_2 \rightarrow e^{i\theta_2} \phi_2$
- ▶  $q_1 \theta_1 + q_2 \theta_2$  gauged,  $q_2 \theta_1 - q_1 \theta_2$  global

# Axionic String Networks

## Global String, Local Core

- ▶ B-Field almost compensates gradients outside string

- ▶  $f_a^2 = f^2 / (q_1^2 + q_2^2)$



- ▶ Tension  $T \simeq 2\pi f^2$
- ▶ string-string interaction  $\frac{dF}{dl} = \frac{f^2}{(q_1^2 + q_2^2)r}$
- ▶  $\kappa_{\text{eff}} = 2(q_1^2 + q_2^2)$
- ▶  $\kappa_{\text{eff}}$  has **no log-scale**

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# Axionic String Networks

## Different String Tensions

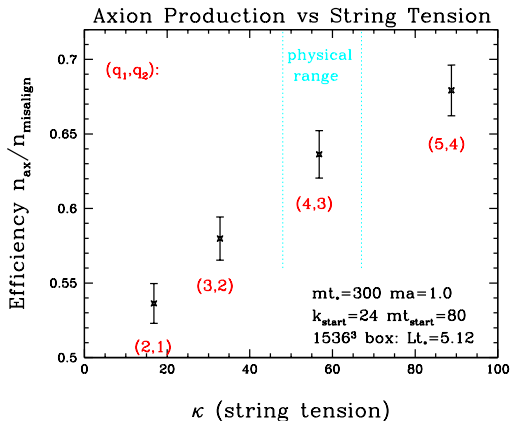


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# Results

## Axion Production Rate



Axion production changes **only a little**

# Results

## Calculating the mass



### Using

- ▶  $n_{ax}(T = T_*) = KH(T_*)f_a^2$
- ▶  $K$  is a constant and determines the produced density
  - ▶  $K = 13.0 \pm 2.0$  lattice result
  - ▶  $K = 16.61$  for Misalignment
- ▶  $\frac{\rho_{dm}}{s} = \frac{n_{ax}(T=T_*) * m_a(T=0)}{s}$

Ade et al, arXiv:1502.01589 ; Borsányi et al, arXiv:1606.07494 and Cortona et al arXiv:1511.02867

### We predict

- ▶  $f_a = (2.21 \pm 0.29) \times 10^{11}$  GeV
- ▶  $m_a = 26.2 \pm 3.4 \mu\text{eV}$

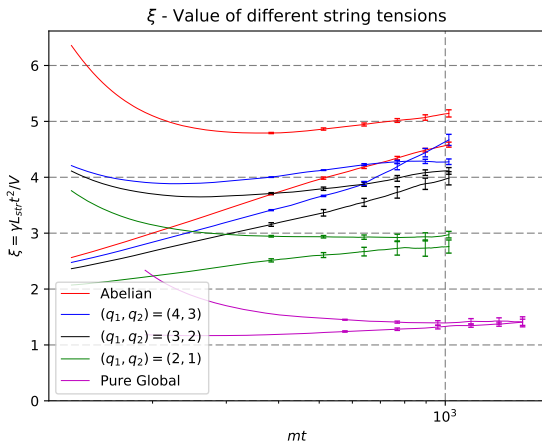
- ▶ 10x string tension leads to 3x denser networks
- ▶ Only 40% more axions than with axion-only simulation
- ▶ Energy in "walls" is part of misalignment energy
- ▶ Walls get "eaten" by strings → energy lost for axions
- ▶ Strings **bad at making axions**



- ▶ Axion can explain the **CP-problem** and the **dark matter**
- ▶ In early Universe the Axion dynamics are **string defects**
- ▶ With the **two-field-model** we get the string defect physics right
- ▶ We find **Axion mass**  $m_a = 26.2 \pm 3.4 \mu\text{eV}$ 
  - ▶ Assuming Axions make all DM
  - ▶  $\theta$  is chosen randomly

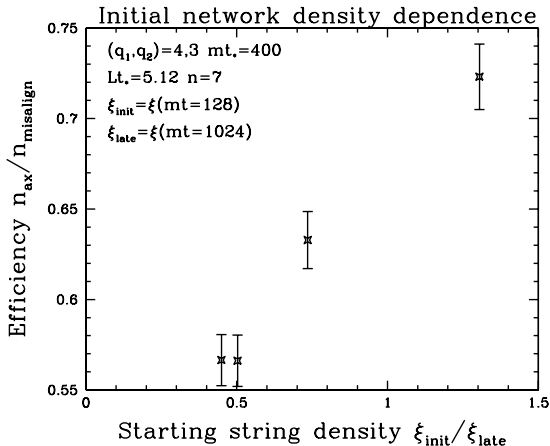
# Results

## String Density



# Results

## Starting Density



# Results

## Volume Dependence

