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Predicting the Axion Mass with large String Tension

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Klaer and Moore, arXiv:1708.07521 and arXiv:1707.05566

Contents

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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

Axion Cosmology

Lagrangian

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

f_a is unknown

$\chi(T)$ strong function of T

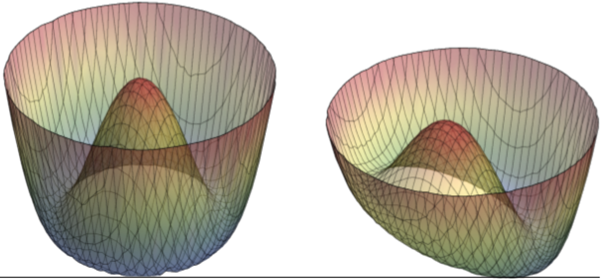
- $\chi(T) \approx (76\mathrm{MeV})^4$ if $T \ll T_C$

  Cortona *et al*, arXiv:1511.02867

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

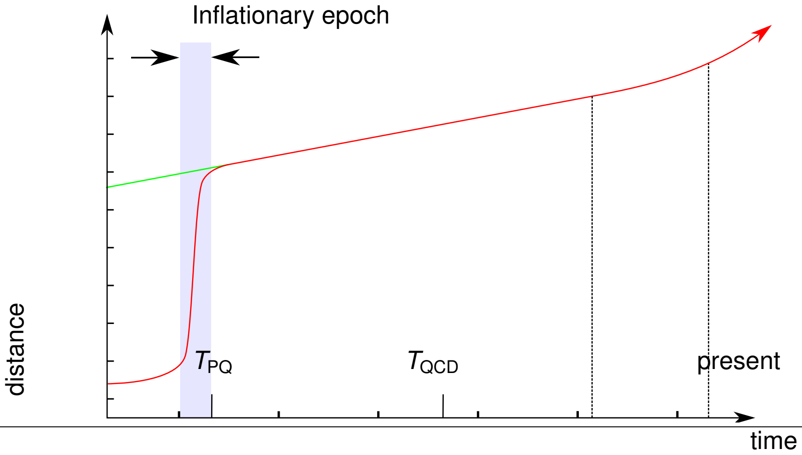
  Gross ,Rev.Mod.Phys.53,43(1981)

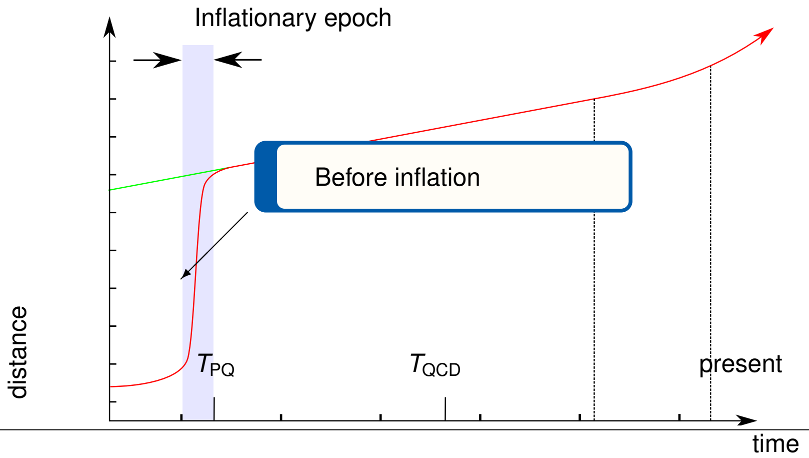
$T_{PQ} > T > T_C$ $\qquad$ $T_{PQ} > T_C > T$



Axion Cosmology

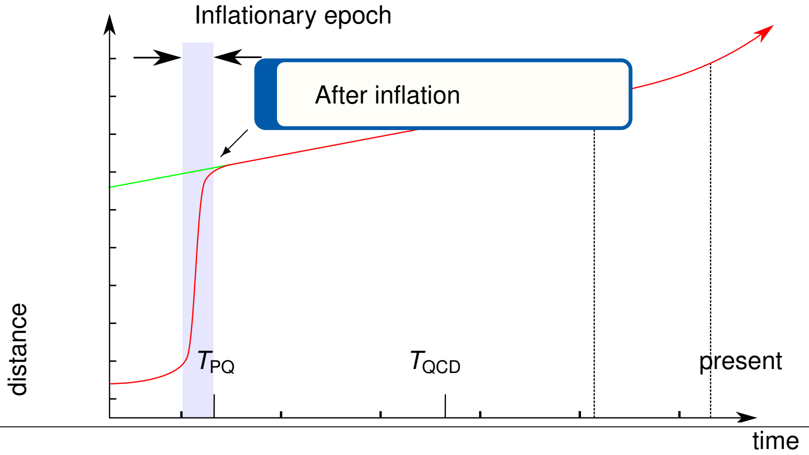
Evolution





Inflationary epoch
Before inflation
distance
T_{PQ}
T_{QCD}
present
time

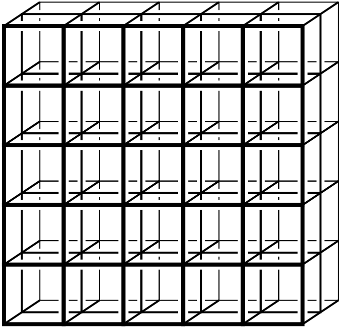
Axion Cosmology
Evolution



Axion Cosmology

Solving on Lattice

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



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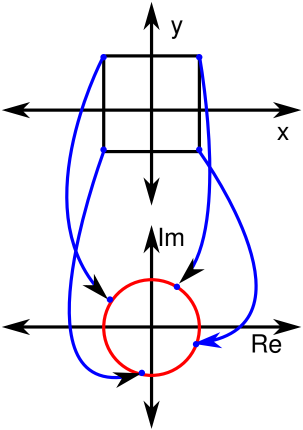
String arises when the spontaneous symmetry gets broken

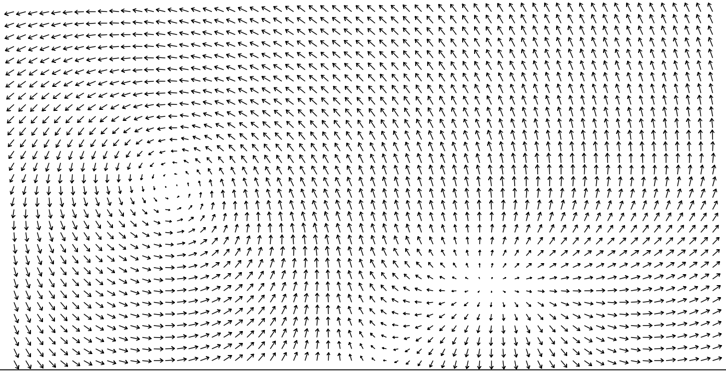
- ϕ is a complex number
- θ can take values between $[-\pi, \pi]$
- θ is undefined in the center of the string



Axion Cosmology

String

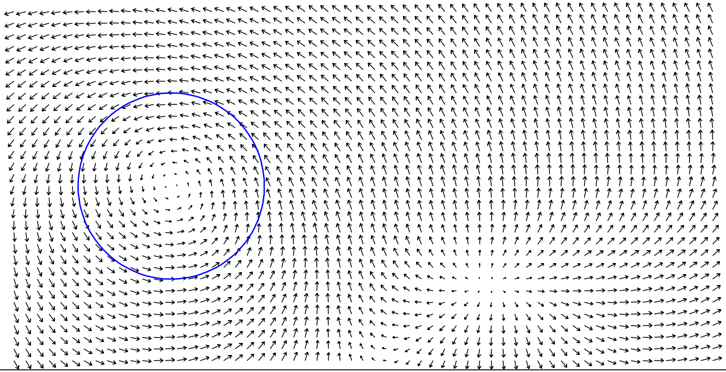
- 2D slice of an Axion field
- Field generically has **vortices** (**strings**)



Axion Cosmology

String

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

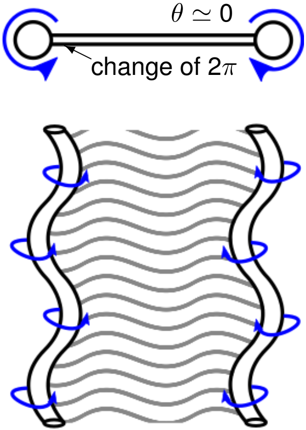


Axion Cosmology

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 θ happens in domain wall
- Domain walls pull strings



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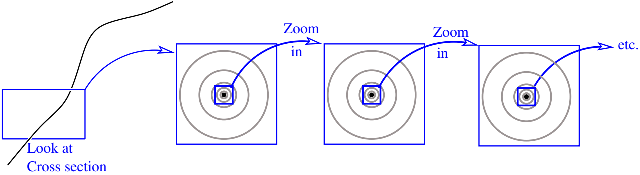
Evolution of the Axion field, when the potential tilts

Evolution of a string Network

Axion Cosmology

String Energy

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



- **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 κ = 6 and not κ = 70

Things which scale as κ

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

Things which do not scale with κ

- 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 κ 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

Hybrid Theory

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Using two complex scalars and A_μ

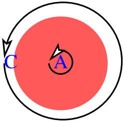
$$\mathcal{L}(\phi_1, \phi_2, A_\mu) = \frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)^2 + \frac{\lambda}{8}[(2\phi_1^*\phi_1 - f^2) + (2\phi_2^*\phi_2 - f^2)] + \left|(\partial_\mu - iq_1 eA_\mu)\phi_1\right|^2 + \left|(\partial_\mu - iq_2 eA_\mu)\phi_2\right|^2$$

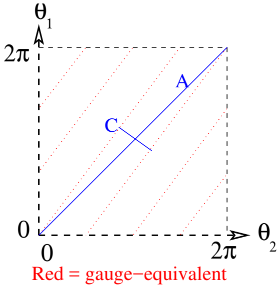
- Pick $q_1 \neq q_2$
- Two rotation symmetries $\phi_1 \to e^{i\theta_1}\phi_1$ and $\phi_2 \to e^{i\theta_2}\phi_2$
- $q_1\theta_1 + q_2\theta_2$ gauged, $q_2\theta_1 - q_1\theta_2$ global

Axionic String Networks

Global String, Local Core

- B-Field almost compensates gradients outside string
- $f_a^2 = f^2/(q_1^2 + q_2^2)$

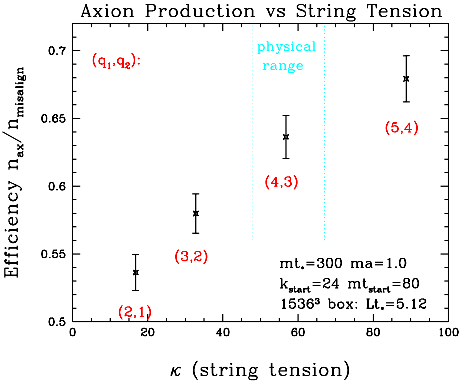




- Tension $T \simeq 2\pi f^2$
- string-string interaction $\frac{dF}{dl} = \frac{f^2}{(q_1^2+q_2^2)r}$
- $\kappa_{\text{eff}} = 2(q_1^2 + q_2^2)$
- κ_{eff} has **no log-scale**

Results

Axion Production Rate



Axion production changes **only a little**

Results

Calculating the mass

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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
- $\frac{\rho_{dm}}{s} = \frac{n_{ax}(T=T_*) \cdot m_a(T=0)}{s}$

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
- $m_a = 26.2 \pm 3.4\mu$eV

Results

- 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 $\rightarrow$ energy lost for axions
- Strings **bad at making axions**

Conclusion

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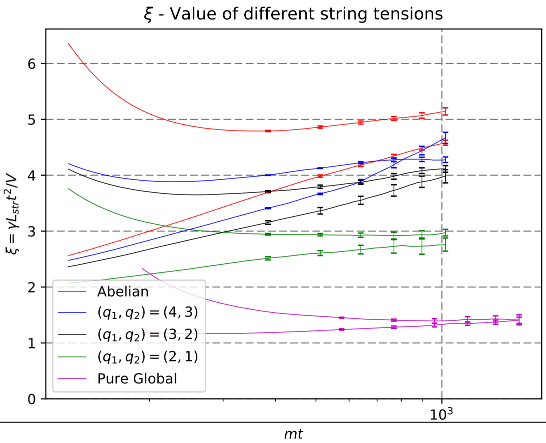
- Axion can explain the **CP-problem** and the **dark matter**
- In early Universe the Axion dynamics are **string defects**
- With the **two-field-model** we get the string defect physics right
- We find **Axion mass** $m_a = 26.2 \pm 3.4 \mu\text{eV}$
  - Assuming Axions make **all** DM
  - θ is chosen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

Thank You for your attention!

Results

String Density



Results

Starting Density

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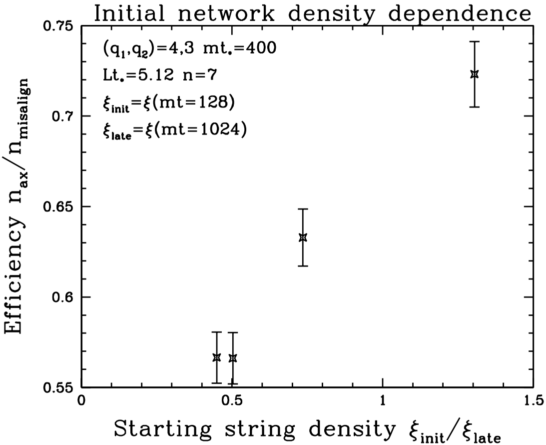

Results

Volume Dependence