Simulating axion string-wall networks

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Goal

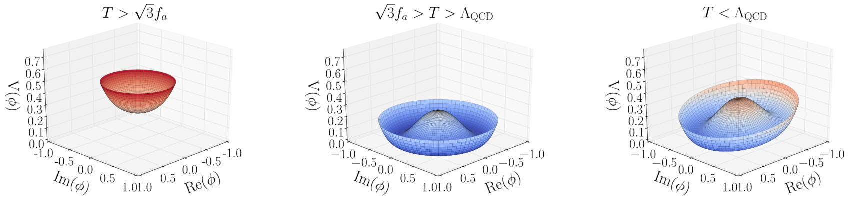
- Simulate cosmological evolution of axion field
- Find relationship between present-day axion energy density and mass
- Use measured dark matter energy density to bound axion mass

Axion Cosmology

$$-\mathcal{L} = \partial_\mu \phi \partial^\mu \phi^* + \frac{\lambda}{8}(2\phi\phi^* - f_a^2)^2 + \chi(T)(1 - \cos\theta_A)$$

Axion field: $\theta_A = \mathrm{Arg}(\phi)$
Topological susceptibility: $\chi(T) = m_a(T)^2 f_a^2$
$\Lambda_{QCD} \sim 1 \ \mathrm{GeV}$

$$f_a \sim 10^9 - 10^{12} \ \mathrm{GeV} \quad \longleftrightarrow \quad m_a(0) \sim 10^{-5} - 10^{-2} \ \mathrm{eV}$$



Contributions to Axion Energy Density

Assume PQ symmetry broken after inflation

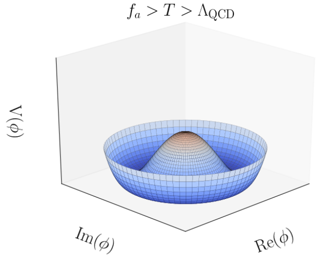
Misalignment Mechanism

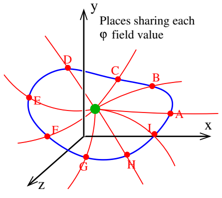
- Straightforward to calculate energy density
- $m_a > 10^{-5}\ \mathrm{eV}$

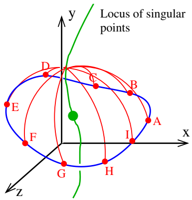
Topological Defects (Strings, Walls)

- Regions where ϕ is forced leave vacuum configuration
- Expected to raise lower limit on m_a

Formation of Strings







- If θ_A varies by 2π around a loop in physical space, θ_A must be singular ($\phi = 0$) somewhere within loop = vortex
- In 3D, there is a **string** of singular points
- **Core** = region where ϕ has left vacuum

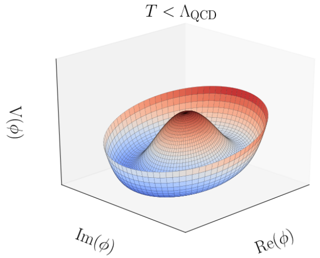
Strings and Walls

$f_a < T < \Lambda_{QCD}$:
Strings move and sometimes annihilate. String network scales

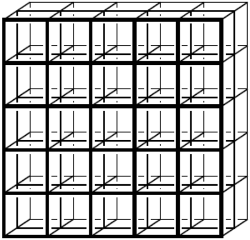
$T \sim \Lambda_{QCD}$:
V tilts $\Rightarrow \theta_A = 0$ becomes only minimum.

Other θ_A values now correspond to higher-than-vacuum energy = domain wall

Wall attaches neighbouring pair of strings and pulls them together.
$\Rightarrow$ String-wall network annihilates.



Traditional Lattice Simulations



Lattice simulations:

- $\mathrm{Re}(\phi)$ and $\mathrm{Im}(\phi)$ live at discrete points
- **Need string core $\gtrsim$ lattice spacing**

Some numbers:

- String separation $\ell \sim H^{-1} \sim 10^{18}\ \mathrm{GeV}^{-1}$
- Core radius: $r_0 \sim f_a^{-1} \sim 10^{-11}\ \mathrm{GeV}^{-1}$
- $\boxed{\ell/r_0 \sim f_a/H \sim 10^{30}}$ $\longleftrightarrow$ latt sims can do: $\sim 10^3$
- **Very large scale disparity**

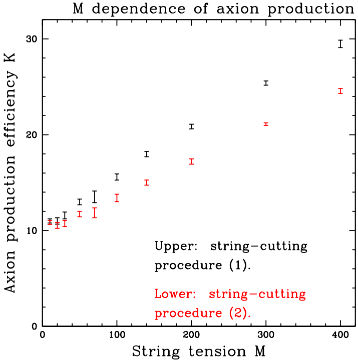
String energy: $\epsilon \propto \int_{r_0}^{\ell} \frac{rdr}{r^2} = \ln(\ell/r_0)$

A Different Approach

- Cut out string cores (only evolve θ_A on lattice)
- Solve core physics separately, with strings as explicit objects
- Sew it back together by including interactions between lattice field and explicit cores

Sounds difficult; but it currently works in 2+1D

Axion Production vs. Scale Hierarchy



y-axis: Dimensionless efficiency of axion production

Realistic value: $M \sim 200$

Lattice sims go up to $M \sim 20$

Axion number doubles from fields-only M value to physical value
$M = 200 \;\Rightarrow\; f_a = 1.6 \times 10^{11}\ \mathrm{GeV}\ ,\ m_a = 36\mu\ \mathrm{eV}$

Conclusion

- Want to simulate axion string-wall networks to determine axion energy density and bound mass
- Difficult because of large scale disparity between string separation and core size
- Traditional lattice methods insufficient; need new methods
- Proposal: Treat string cores as explicit objects and keep θ_A on lattice, enforcing interactions between cores and θ_A
- Works in 2+1D; still working on 3+1D