DOMAIN WALLS AND THE COMPANION AXION MODEL

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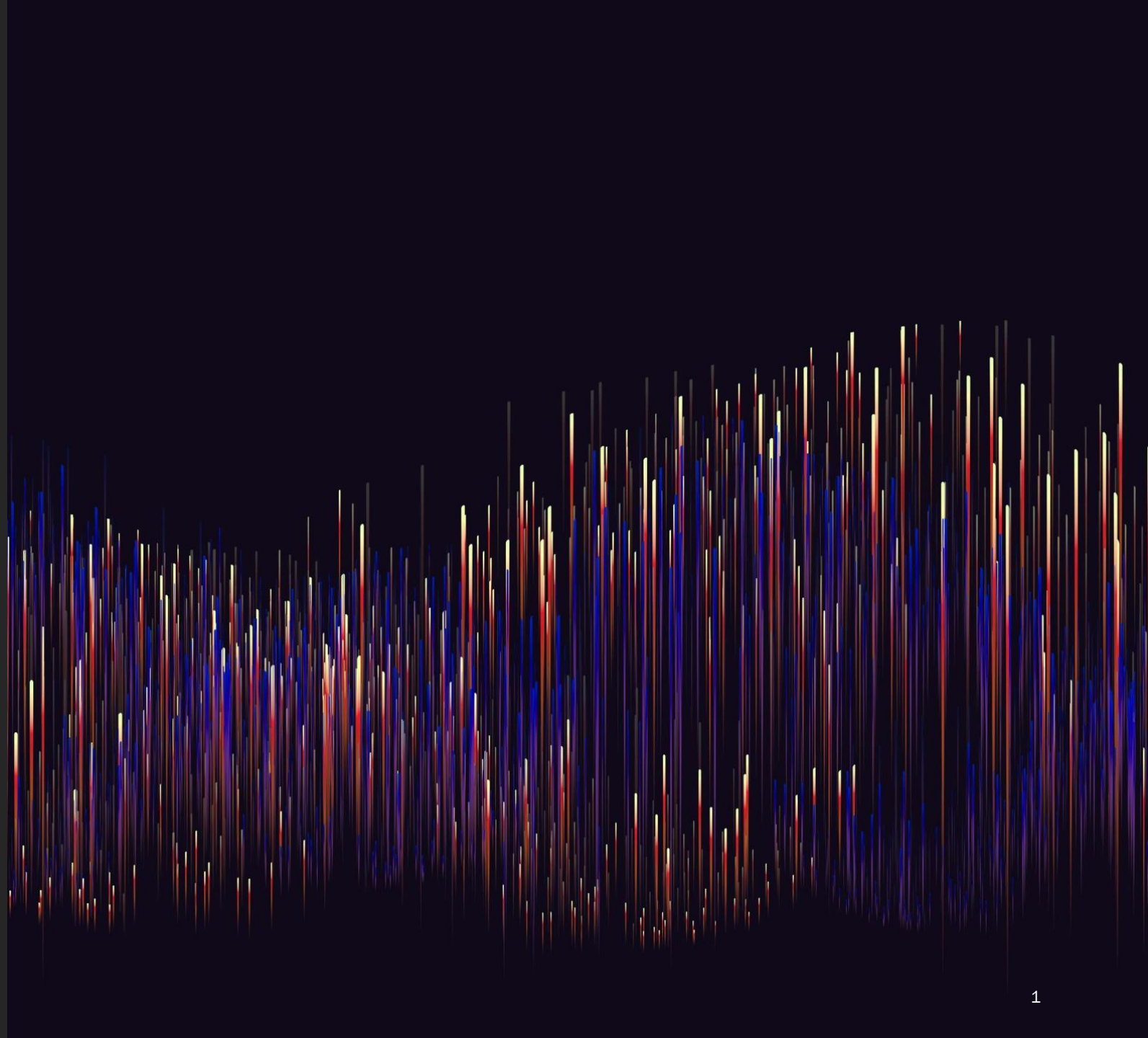
IN COLLABORATION WITH CIARAN O'HARE

SYNDEY CPPC MEETING



BACKGROUND: AXIONS

- A theoretical elementary particle, first introduced as the solution to the strong CP problem by Peccei and Quinn in 1977[1].
- Interesting as a cold dark matter candidate:
  - Non-zero mass
  - Weak couplings to other SM particles
- Yet to be observed.

1. PECCEI, R. D. & QUINN, H. R. CP CONSERVATION IN THE PRESENCE OF PSEUDOPARTICLES. PHYS. REV. LETT. 38,

AXION MODELS

- The first axion model consists of a complex scalar field with the Lagrangian
  - $L = (\partial_\mu \phi)(\partial^\mu \phi^*) - \frac{\lambda}{4}(|\phi|^2 - \eta^2)^2 + 2K\cos\big(N arg(\phi)\big)$
- Since then there other axion models have been proposed for a variety of reasons, forming a class of axion-like particles.

SIMULATING FIELDS (PRS TRICK)

- As axions are estimated to be very light, their occupancy numbers are high i.e. fields can be treated classically.
- The expansion of the universe shrinks features in the field, shortening the length of simulations.
- Using the PRS trick, named after Press, Ryden and Spergel (1989)[2] , simulations can be run for longer.
- For a field ϕ, modify the equation of motion by adding a parameter α, equal to the number of spatial dimensions
  - $\frac{\partial^2 \phi}{\partial \tau^2} + \alpha \frac{\partial \ln a}{\partial \tau} \frac{\partial \phi}{\partial \tau} - \nabla^2 \phi = -\frac{\partial V}{\partial \phi}$
- This can then be solved with a second order leapfrog numerical scheme.

2. PRESS, W., RYDEN, B., SPERGEL, D., AP. J., 347, 590-604 (1989).

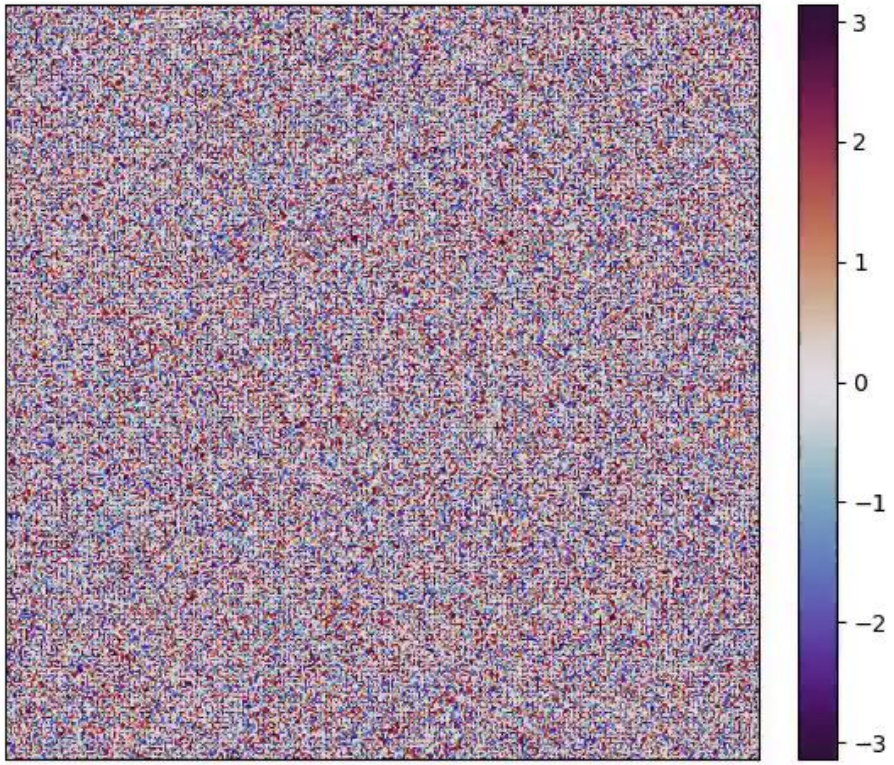


Figure 1a: Axion field simulation for N = 1

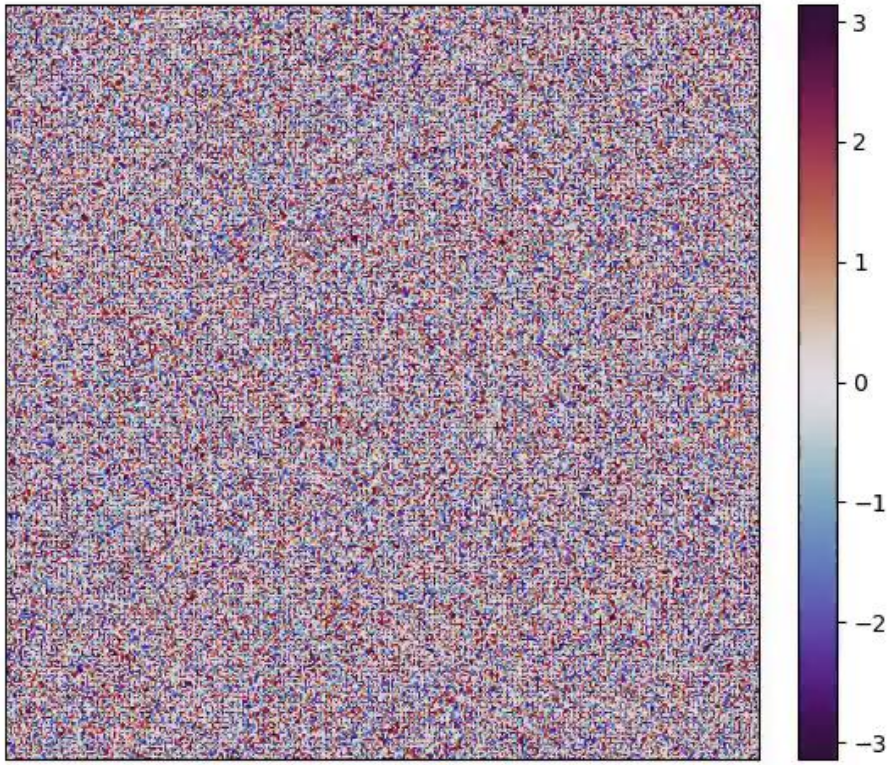


Figure 1b: Axion field simulation for N = 4

TOPOLOGICAL DEFECTS

- Topological defects occur during spontaneous symmetry breaking.
- Domain walls are a type of topological defect.
- The energy density of domain walls would dominate the energy of the Universe. This is not observed however.
- Other types of cosmological defects include:
  - Cosmic strings
  - Textures

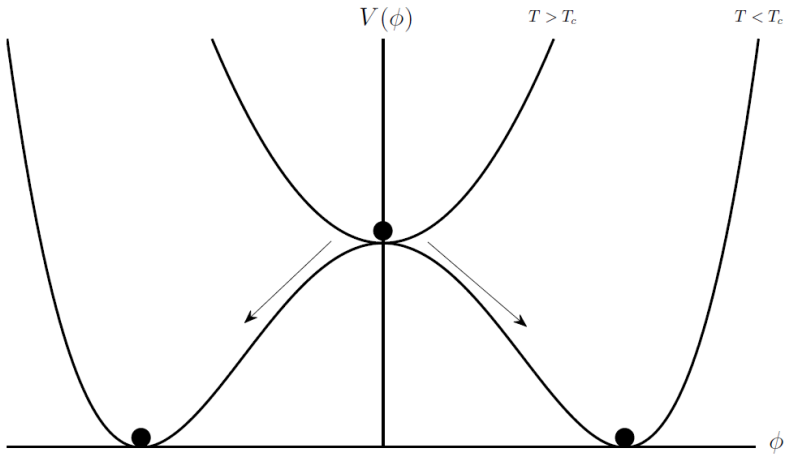


Figure 2: Spontaneous symmetry breaking of Z_2 symmetry[3]

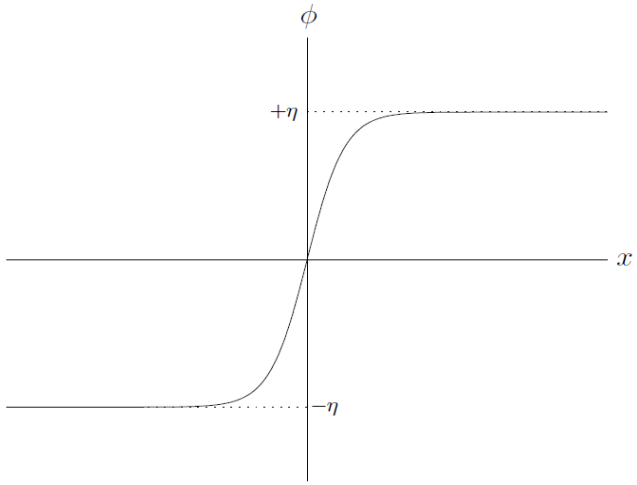


Figure 3: Kink solution of domain wall[3]

3. DIAGRAMS ARE TAKEN FROM CIARAN O'HARE'S NOTES ON DOMAIN WALLS

AXION POTENTIAL

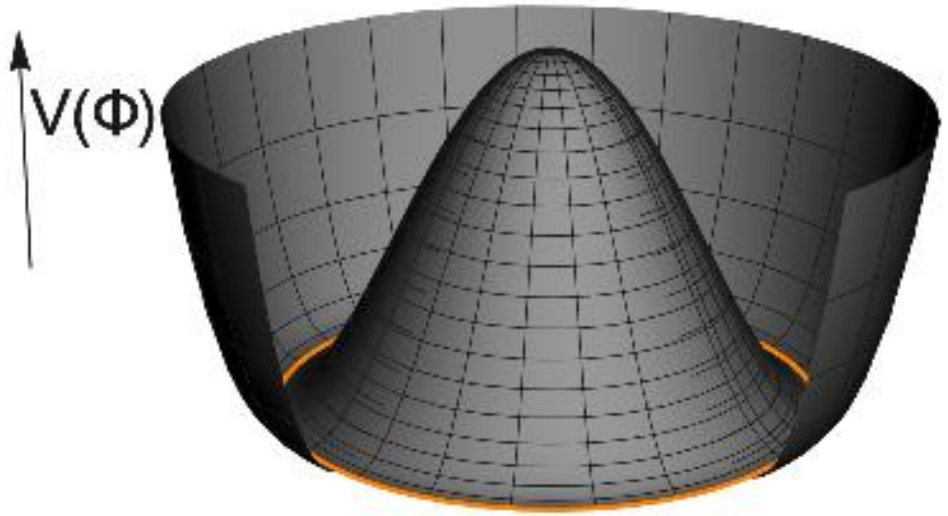


Figure 4: Peccei-Quinn potential before symmetry breaking

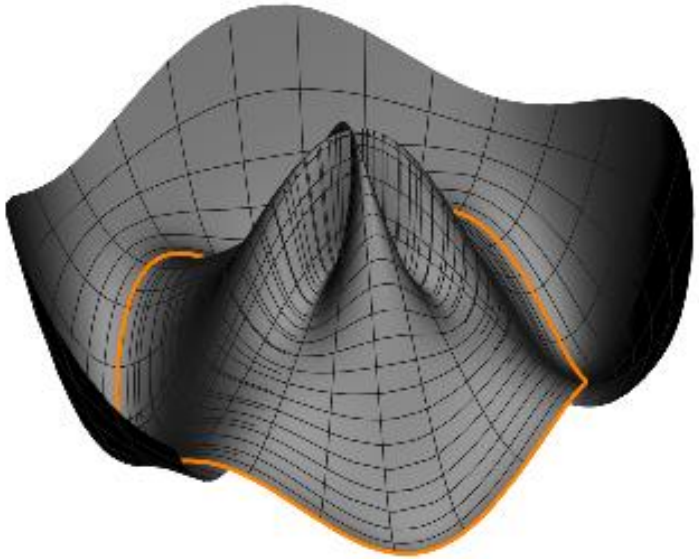


Figure 5: Symmetry broken potential for N = 4

COMPANION AXION MODEL

- The companion axion model is a new axion model introduced by Chen and Kobakhidze in 2021[1] in order to rescue the Peccei-Quinn axion from coloured gravitational instantons (an additional source of CP violation).
- The added potential
  - $V(\theta, \theta') = -2K\cos(N\theta + N'\theta') - 2\kappa K\cos\left(N_g\theta + N_g'\theta'\right)$
- Introduces a second axion field.
- This second field is believed to help disperse domain walls[2].

1. Z. CHEN AND A. KOBAKHIDZE, COLOURED GRAVITATIONAL INSTANTONS, THE STRONG CP PROBLEM AND THE COMPANION AXION SOLUTION
2. Z. CHEN ET AL., COSMOLOGY OF THE COMPANION-AXION MODEL: DARK MATTER, GRAVITATIONAL WAVES, AND PRIMORDIAL BLACK HOLES

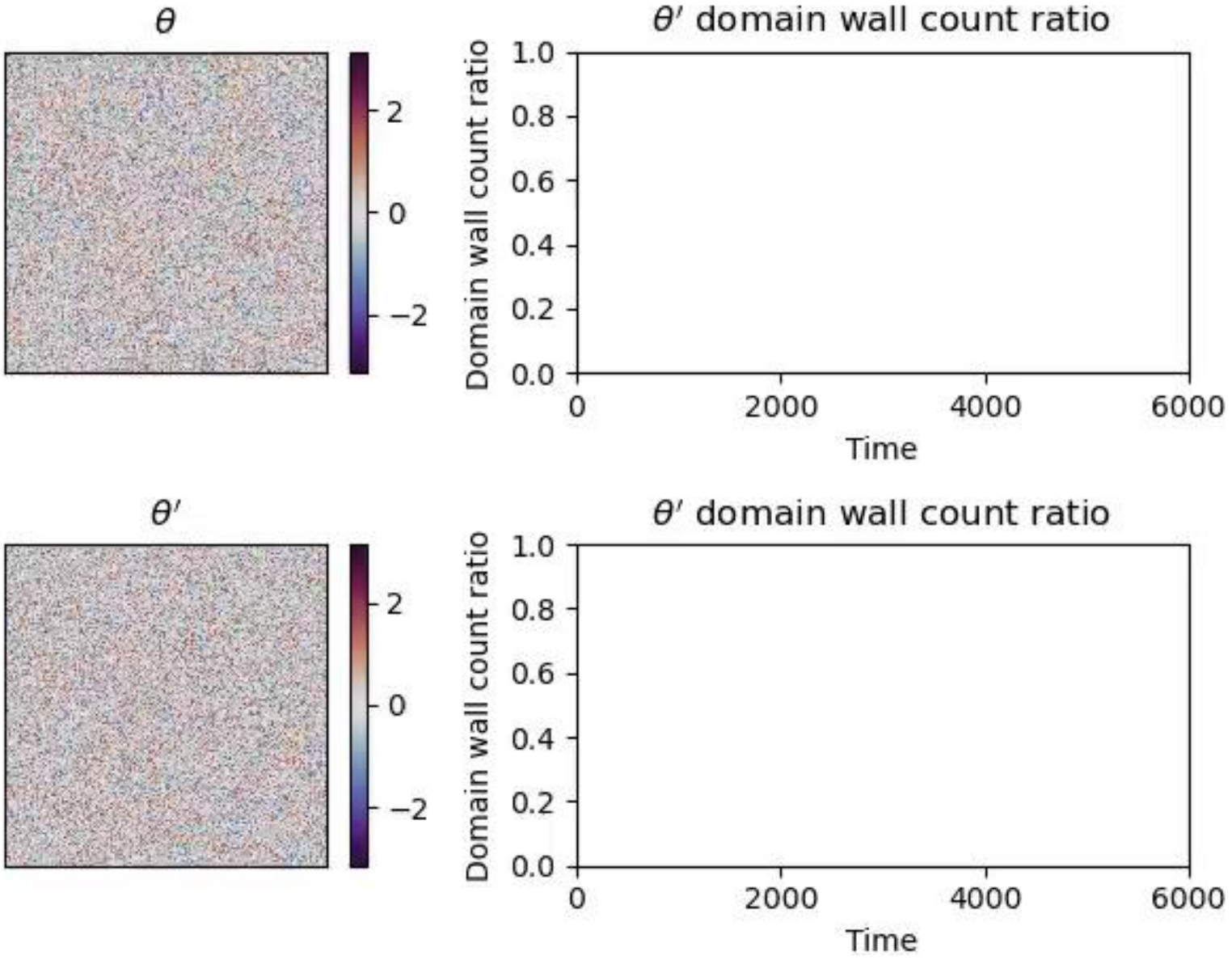
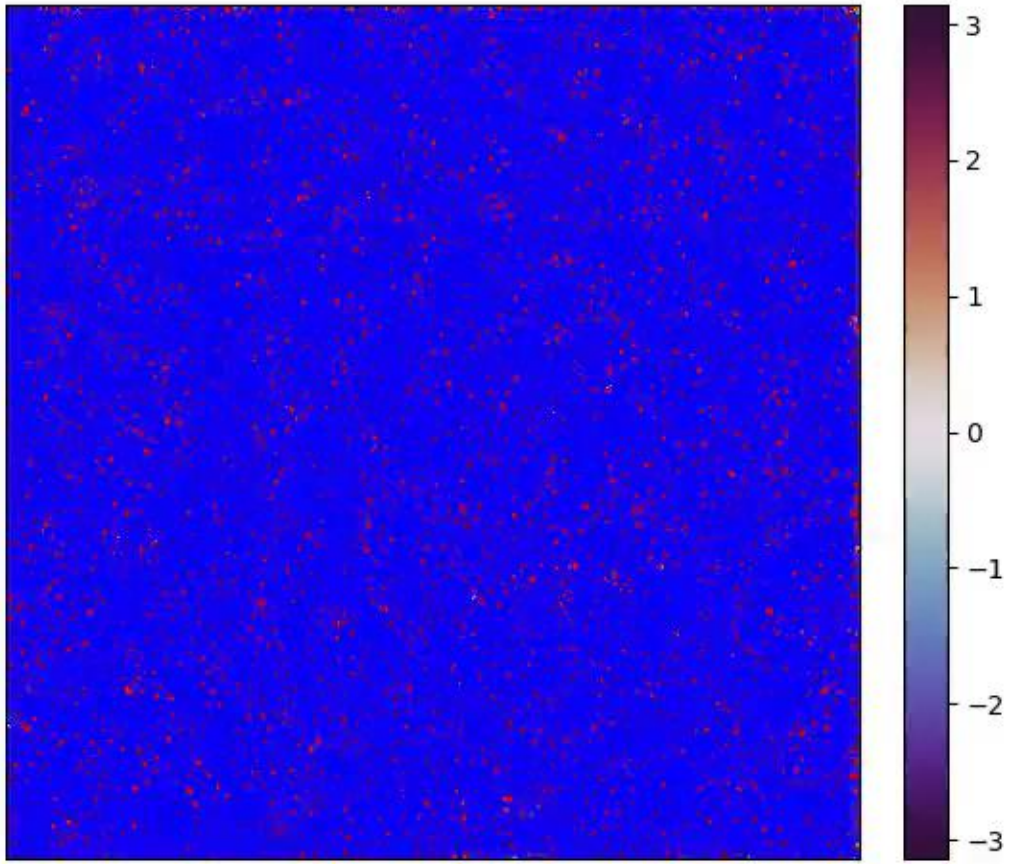


Figure 6: Companion axion simulation for $N = 3, N' = 1, N_g = 1, N_g{}' = 1$

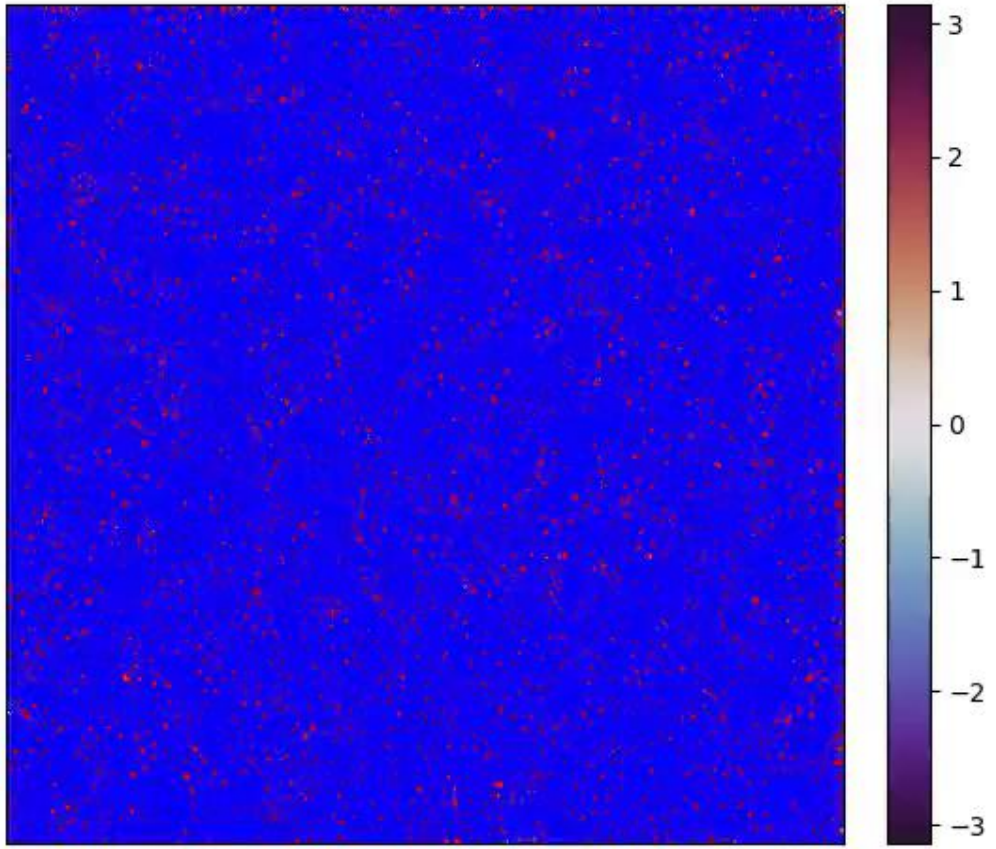
PLANS FOR THE FUTURE

- The companion axion model has many parameters to consider:
  - Color anomaly coefficients - $N, N', N_g, N_g{}'$
  - The K and κ coefficients and their temperature scaling
- Explore the phase space of parameters for domain wall dispersal.
- Currently, simulations are quite slow, ~20 mins per run, limiting the ability to do statistical analysis.
- Numerical artifacts can also occur for some parameter configurations.

APPENDIX: SINGLE AXION HIGHLIGHTING



N=1



N=4

APPENDIX: COMPANION AXION HIGHLIGHTING