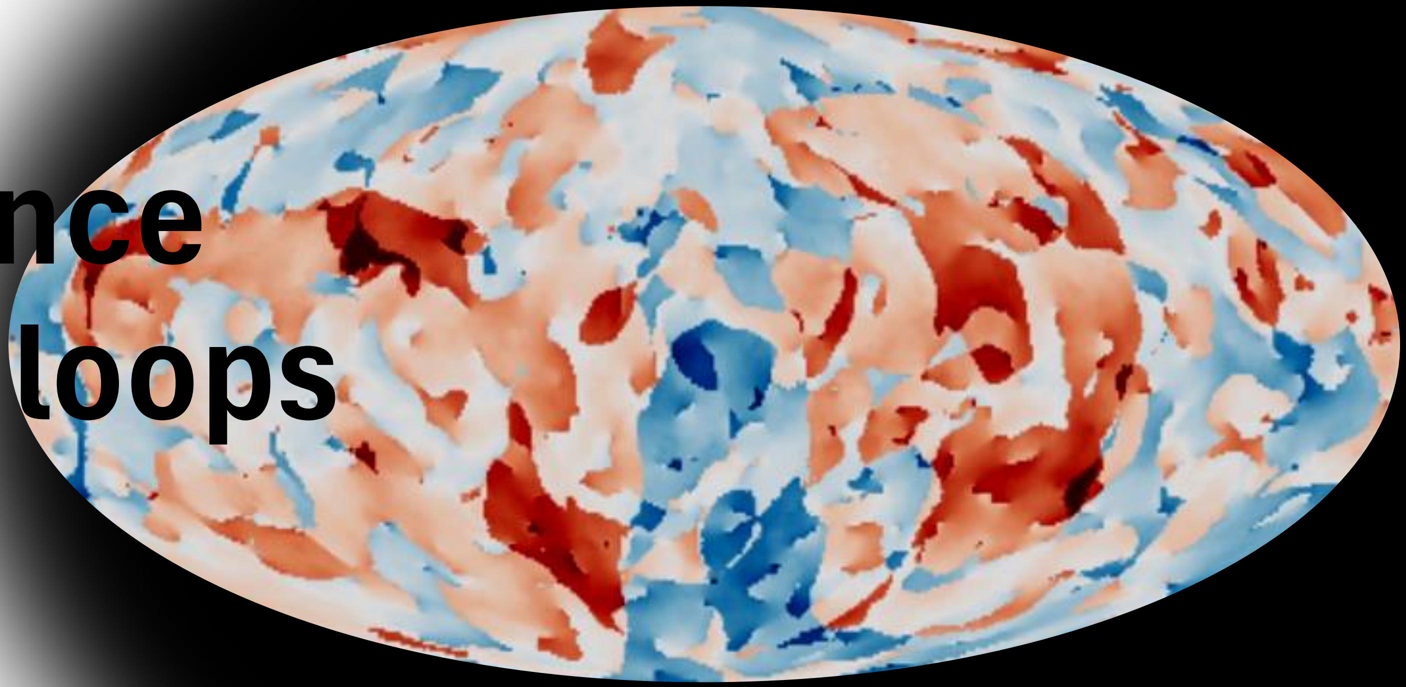
RICE UNIVERSITY

CMB birefringence by axion string loops



In collab. With

Mustafa Amin, Mudit Jain, Andrew J. Long,
Aden Pugsley and Magdalena Whelley

Moira Venegas

LIGHT DARK WORLD 2026

July 28th - July 31st
Carleton University
Ottawa, Canada

Cosmic birefringence

- Rotation of the CMB polarization plane by an angle $\alpha(\hat{\boldsymbol{n}})$ during propagation
- The rotation-angle is decomposed into spherical harmonics:

Isotropic birefringence

monopole: uniform rotation across the sky

Anisotropic birefringence

higher multipoles: direction – dependent rotation across the sky

Cosmic birefringence

- Rotation of the CMB polarization plane by an angle $\alpha(\hat{\boldsymbol{n}})$ during propagation
- The rotation-angle is decomposed into spherical harmonics:

Isotropic birefringence

monopole: uniform rotation across the sky

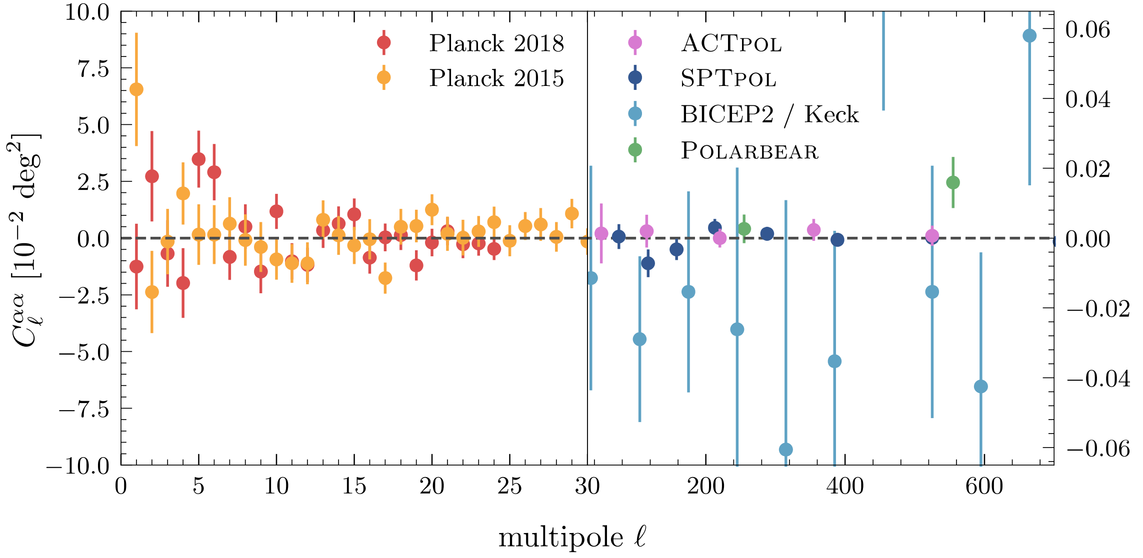
$$\bar{\alpha} = 0.264° \pm 0.058°$$

WMAP9 + Planck + ACT

Diego Palazuelos & Komatsu (2025)
Eskilt & Komtsu (2022)

Anisotropic birefringence

higher multipoles: direction – dependent rotation across the sky



Jain, Hagimoto, Long, Amin [2208.08391]

Cosmic birefringence by hyperlight axion strings

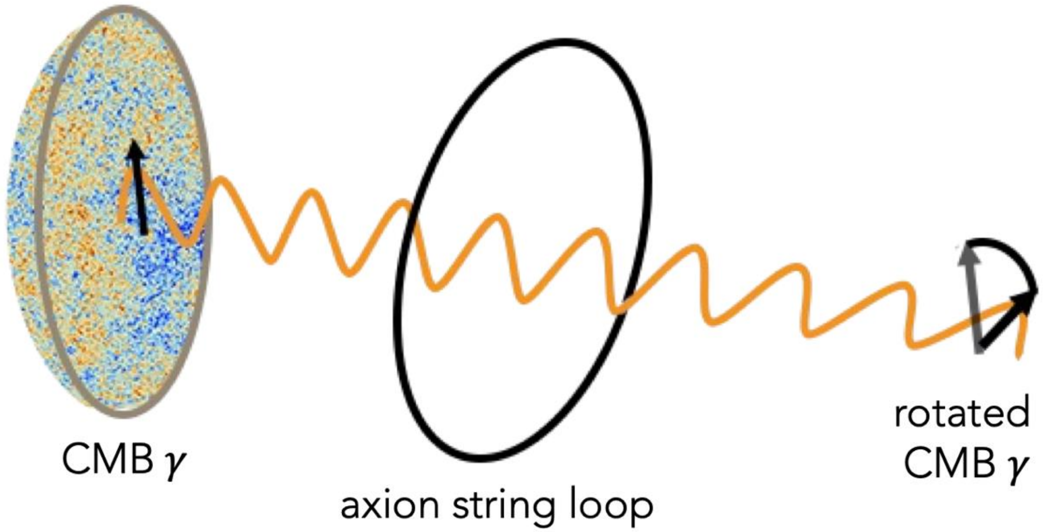
Agrawal, Hook, Huang [arXiv:1912.02823]

Interaction with electromagnetism $\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$

$$g_{a\gamma\gamma} = -\mathcal{A}\,\frac{\alpha_{em}}{\pi f_a}$$

anomaly coefficient

A CMB photon propagates from the last scattering surface to us



maximal field excursion $\boldsymbol{\Delta a = \pm 2\pi f_a}$

rotation angle after passing though one loop

$$\alpha = \frac{g_{a\gamma\gamma}}{2} \int dX^\mu \partial_\mu a(X)$$

$$\alpha \approx \pm 0.42° \mathcal{A}$$

Figure adapted from Jain, Hagimoto, Long, Amin [2208.08391]

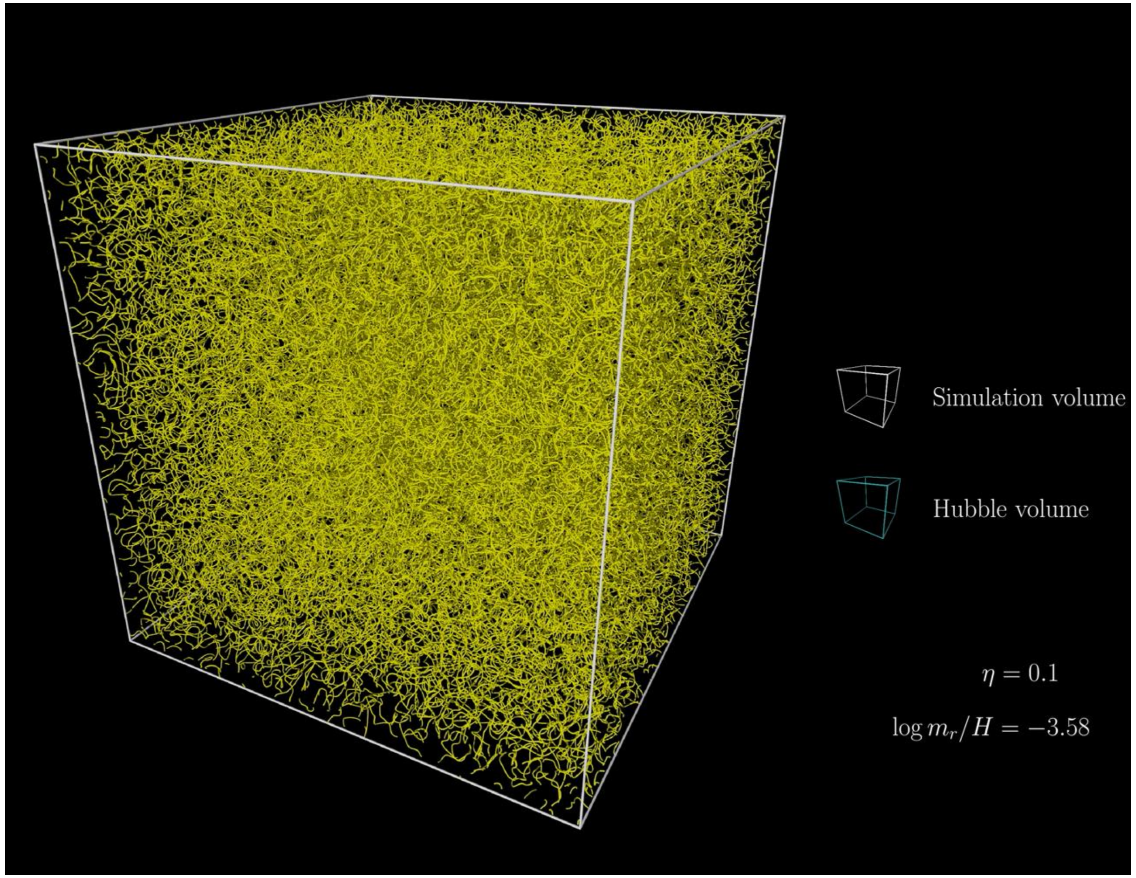
How evolve an axion string network?

Benabou, Buschmann, Foster, Safdi [2412.08699]
Buschmann, Foster, Foster + [2108.05368]
Video: Youtube @MalteBuschmann

string network simulation :

Adaptive Mesh Refinement (AMR) simulations

- **3D lattice:** 1024^3 grid
- **Fields:** complex PQ field $\Psi = \phi_1 + i\phi_2$
- **Evolution:** 117 conformal-time snapshots in radiation dom
- **Periodic boundary conditions**



Also shown in Katelin Schultz's talk yesterday

Simulations show:

- long strings intersect and reconnect
- reconnections form loops
- loops emit axions and collapse

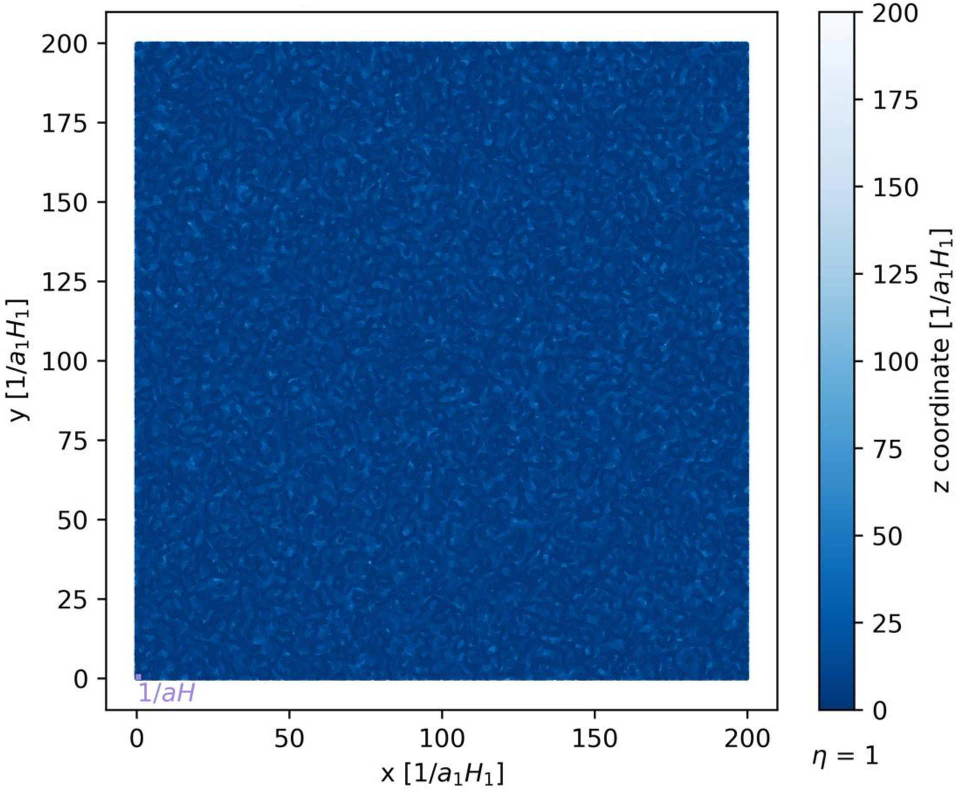
Polarization rotation in each simulation snapshot

For each snapshot, photons propagate from the top to the bottom of the simulation box

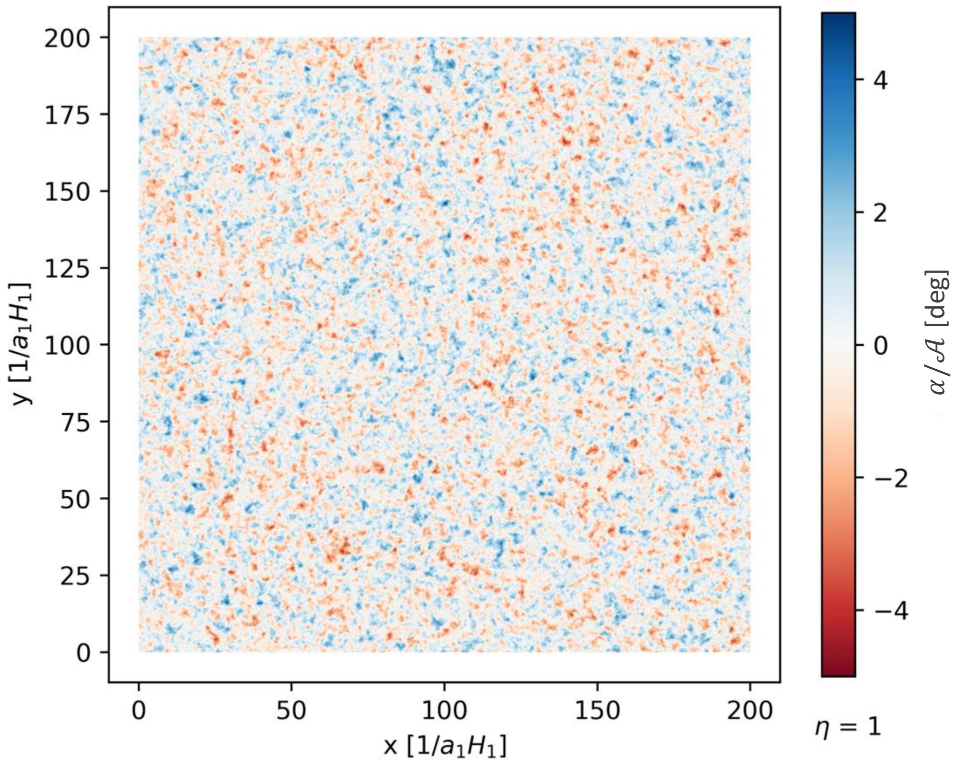
$$\alpha = \frac{\mathcal{A}\ \alpha_{em}}{2\ \pi f_a} \int dX^{\mu} \partial_{\mu} a(X)$$

$\eta = 1$

string network



birefringence $\alpha/\mathcal{A}$

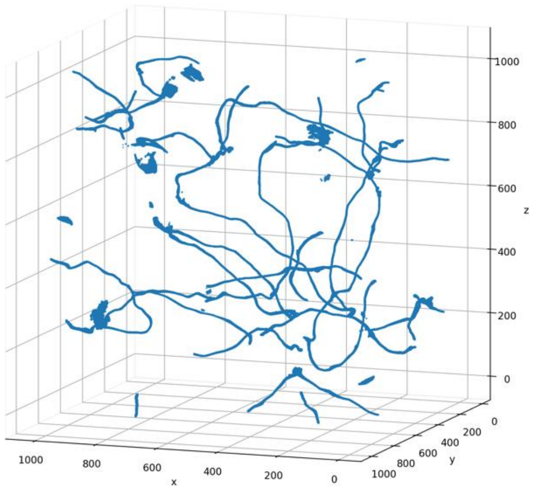


* The right panel is not showing the accumulation of birefringence over time

Can we use AMR to predict the CMB birefringence?

Numerical AMR simulations

Benabou, Buschmann, Foster, Safdi [2412.08699]
Buschmann, Foster, Foster + [2412.08699]



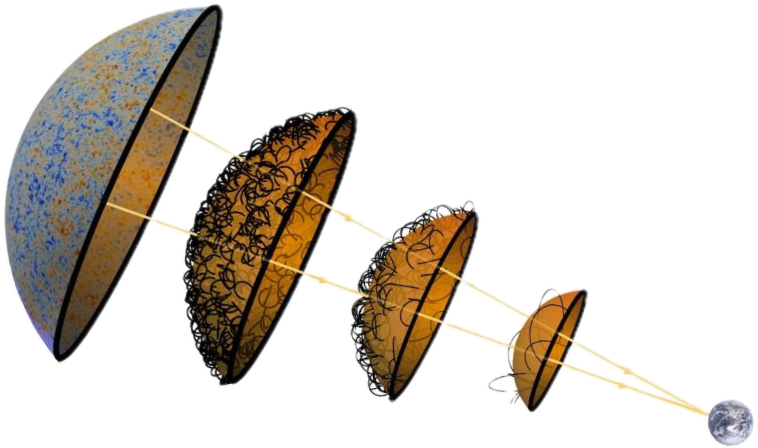
Pros: • Realistic 3D evolution of the string network

Cons: • The simulation covers a shorter time interval than the elapsed time from LSS to today

Cannot directly predict the CMB birefringence

Loop-Crossing Model (LCM)

Jain, Long, Amin [2103.10962]
Jain, Hagimoto, Long, Amin [2208.08391]



Pros: • Fast analytical predictions for any cosmology
• Predicts the CMB birefringence Power Spectrum

Cons: • Relies on 2 phenomenological network parameters

String number density $\xi(\eta)$
Characteristic loop size $\zeta(\eta)$

Can we determine these two parameters from AMR simulations?

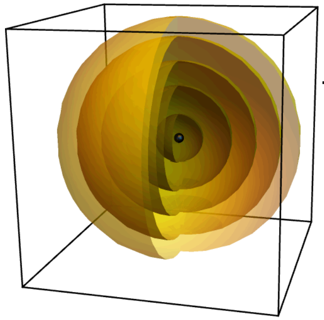
This work

Step 1. Use the realistic AMR simulations to **determine** the free parameters ξ and ζ of LCM

Step 2. **Predict** CMB anisotropic birefringence

Use the validated LCM to compute the CMB birefringence from last scattering $\longrightarrow$ today

To complete step 1: We need to compute the Power Spectrum using AMR simulations



Represent a simulation snapshot = Spherical shell

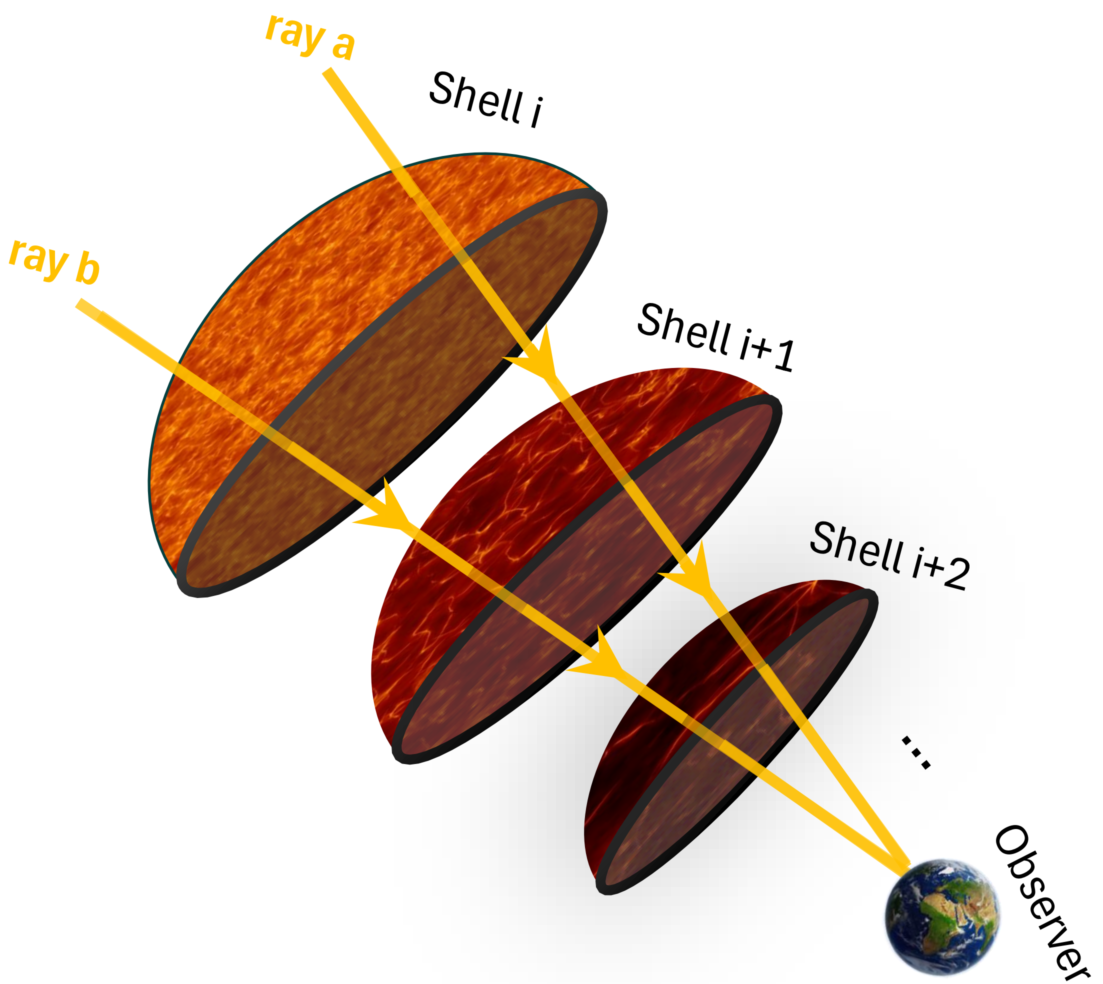
Each pixel on the outer shell defines a ray traveling inward

Sample the axion field a(x) along each ray

Compute axion gradient ∇a

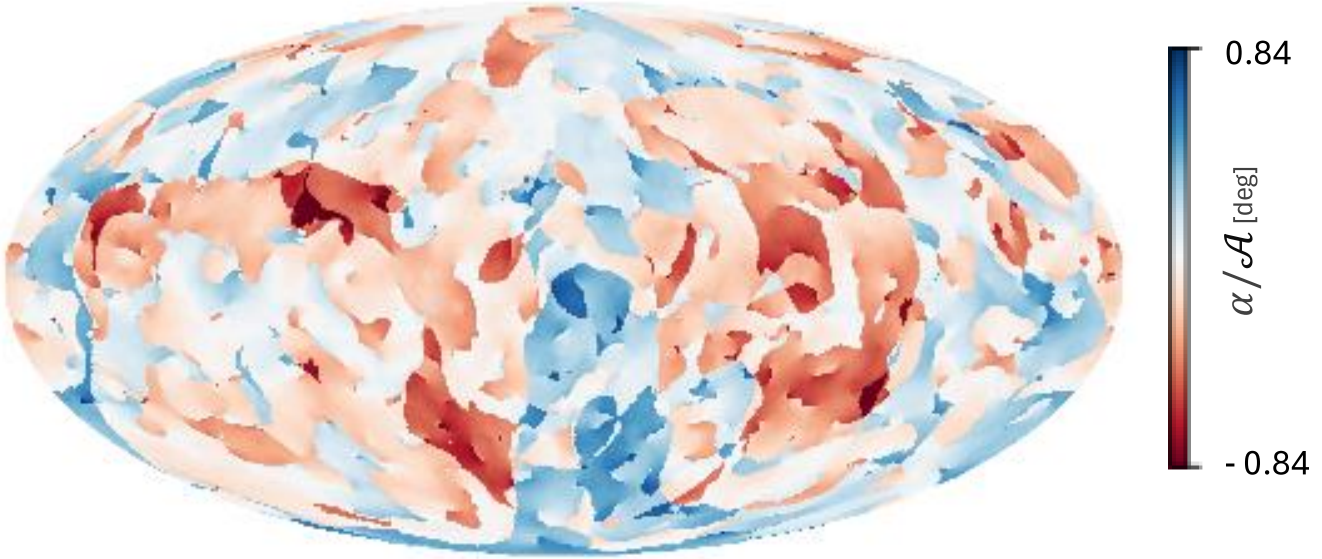
Integrate along LOS

Repeat over all directions to get $\alpha(\hat{n})$ HEALPix map



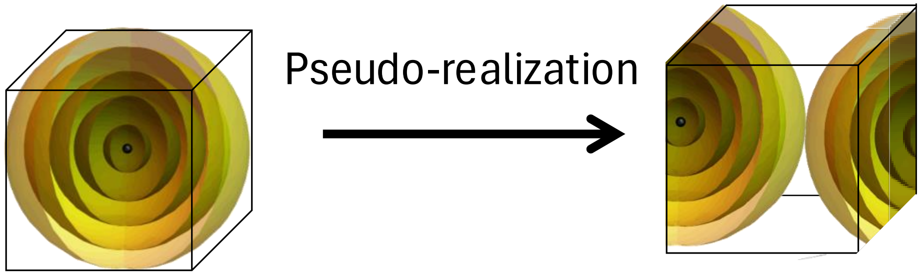
Generating Multiple Realizations

Example of $\alpha(\hat{n})$ map



We want the ensemble-average power spectrum
But only one simulation box is available

Solution: Randomly shift the observer within the periodic simulation box



Now, each pseudo-realization produces one C_ℓ

Results

1. Calibration of the LCM
2. Anisotropic Birefringence CMB Prediction

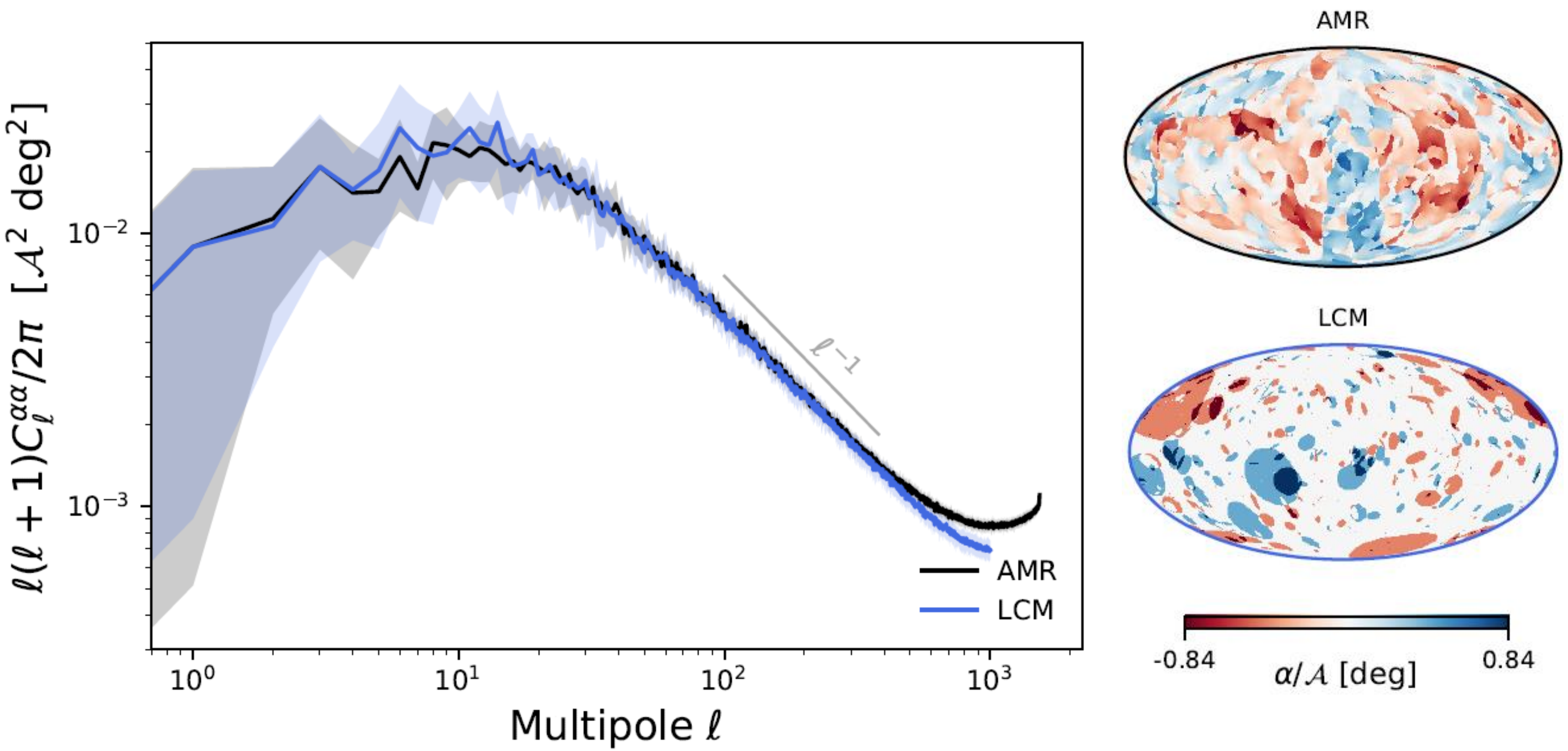
1. Calibration of the LCM

Characteristic loop size $\zeta(\eta)$:

- Calibrated against the AMR power spectrum
- Logarithmic loop-size distribution
- $\zeta_{\min} = 0.003$, $\zeta_{\max} = 0.55$

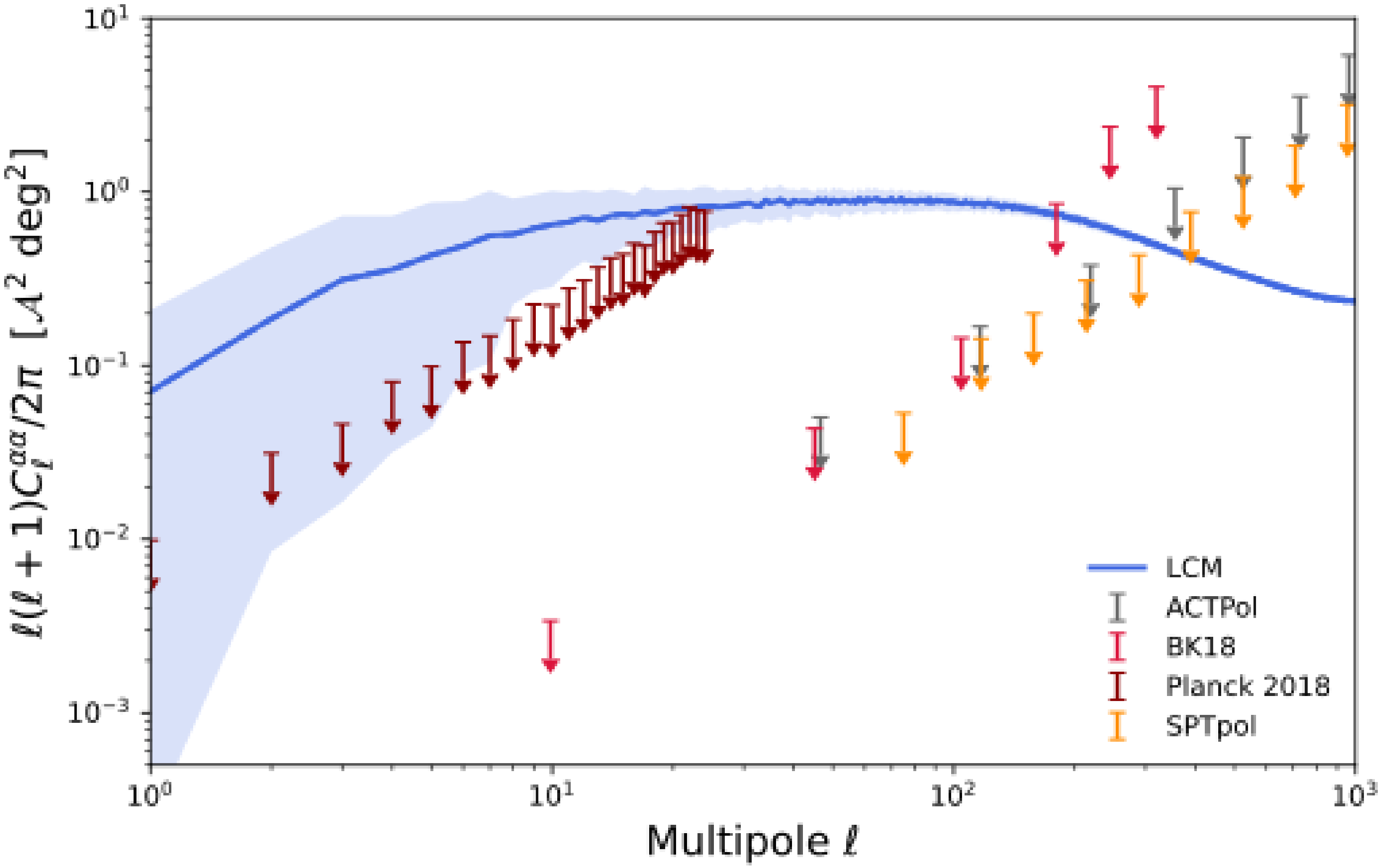
String number density $\xi(\eta)$:

- Taken from the AMR simulation fit [2412.08699]
- $\xi_{17} = 0.5529$, $\xi_{117} = 1.3345$



2. Anisotropic Birefringence CMB Prediction

Preliminary



Current data: no detection of anisotropic birefringence

Prediction must remain below observational limits

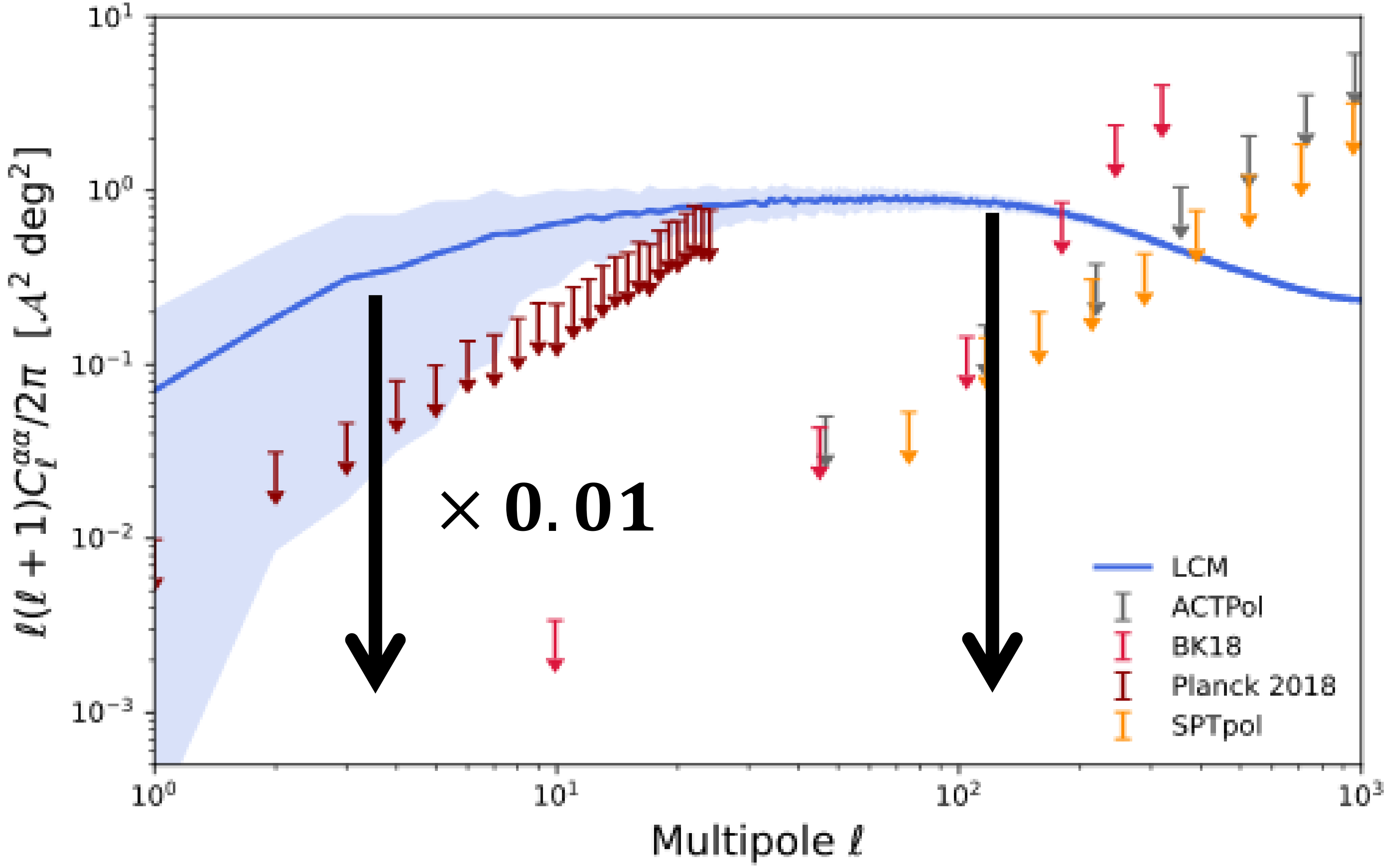
Upper bound on the anomaly coeff:

$$C_\ell^{\alpha\alpha} \propto \mathcal{A}^2$$

*Data: Jain, Hagimoto, Long, Amin [2208.08391]

2. Anisotropic Birefringence CMB Prediction

Preliminary



Current data: no detection of anisotropic birefringence

Prediction must remain below observational limits

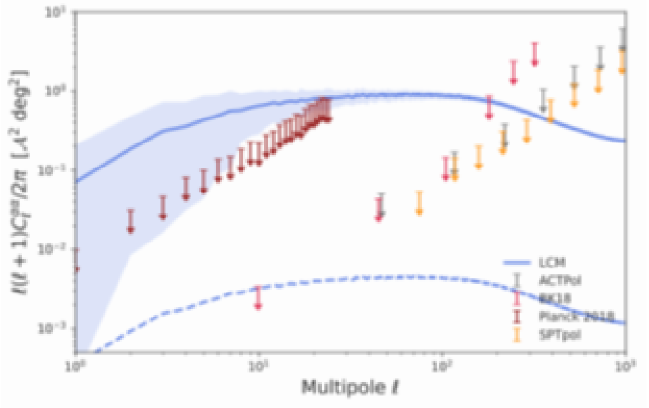
Upper bound on the anomaly coeff:

$$C_\ell^{\alpha\alpha} \propto \mathcal{A}^2$$

$$\mathcal{A} < 0.1 \qquad \text{(Crude estimate)}$$

Likelihood analysis in progress!

Conclusion



- Axion string network leaves an imprint on the CMB through cosmic birefringence
- Using AMR simulations, we calibrate the Loop-Crossing Model (LCM)
- The calibrated LCM predicts the anisotropic birefringence signal from recombination to today
- Using LCM we can constrain $\mathcal{A} < 0.1$ (precise value TBD)
- Can the axion string network explain the measured isotropic birefringence? (work in progress... Let's chat in the coffee break)

Backup

Cosmology

$H_{\mathrm{PQ}} = 10^{12}\mathrm{GeV}$ we are assuming radiation domination

$H_{\mathrm{BBN}} = 2 \times 10^{-18}$ eV

$H_{\mathrm{equality}} = 2 \times 10^{-28}$ eV

$H_{\mathrm{LSS}} = 3 \times 10^{-29}$ eV

$H_0 = 1.3 \times 10^{-33}$ eV

* We are considering $m_a < H_0$

* For dark matter axions $m_a > 10^{-19}$ eV

Scaling regime

The number of strings per Hubble patch remains order unity as a function of time

$\xi \;= \text{constant}$

AMR simulations

[2108.05368]
[2412.08699]

- Logarithmic deviation from the scaling solution
- The simulations find that ξ slowly increases with time

$$\xi(t) = c_0 + c_1 \log\big(m_r/H(t)\big) + \frac{c_{-1}}{\log\big(m_r/H(t)\big)} + \frac{c_{-2}}{\log\big(m_r/H(t)\big)^2}$$

Our work

phenomenological extrapolation to matter era

$$\xi(\eta) = \xi_{17} \; + \frac{\xi_{117} - \xi_{17}}{\ln(117/17)} \ln\left(\frac{\eta}{17}\right)$$

$\xi_{17} = 0.5529$ $\qquad$ $\xi_{117} = 1.3345$

$\longrightarrow$

$$\xi(z = 110) \simeq 22.46$$

$$\xi(z = 10) \simeq 23.59$$

$$\xi(z = 0) \simeq 24.05$$

* Keeping $\xi = \xi(z_{\rm LSS})$ constant instead changes the predicted amplitude by only 7%

The loop-crossing model

Description

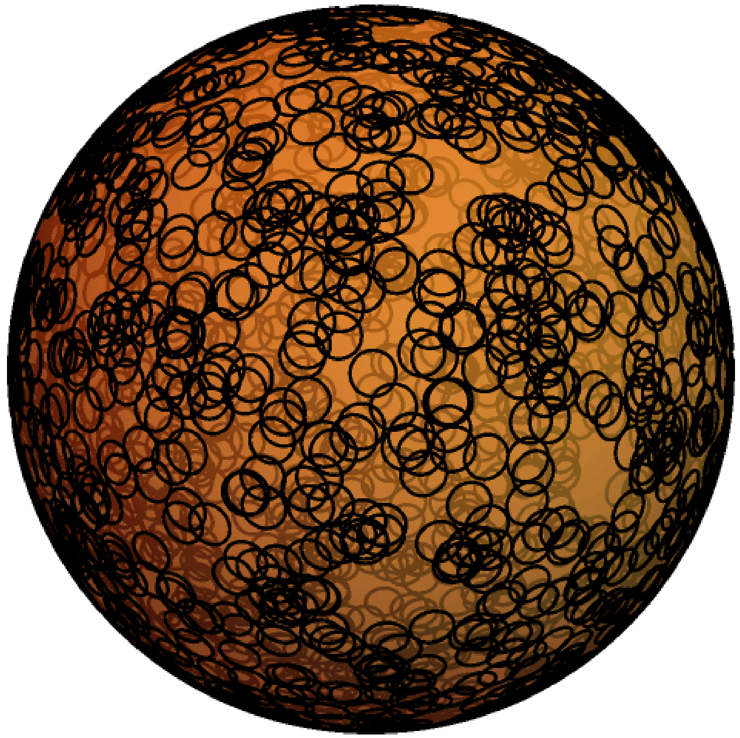
- Circular & planar loops
- Randomize loop orientation
- Randomize loop location in space
- Radius are uniformly logarithmic distribute

Loop radius $R(\eta) = \zeta \, d_H(\eta)$

Number of loops $\rho(\eta) = \dfrac{\xi(\eta)\mu(\eta)}{d_H(\eta)}$

Model Parameters $\{ m_a, \mathcal{A}, \ \zeta \, , \xi(\eta) \ \}$

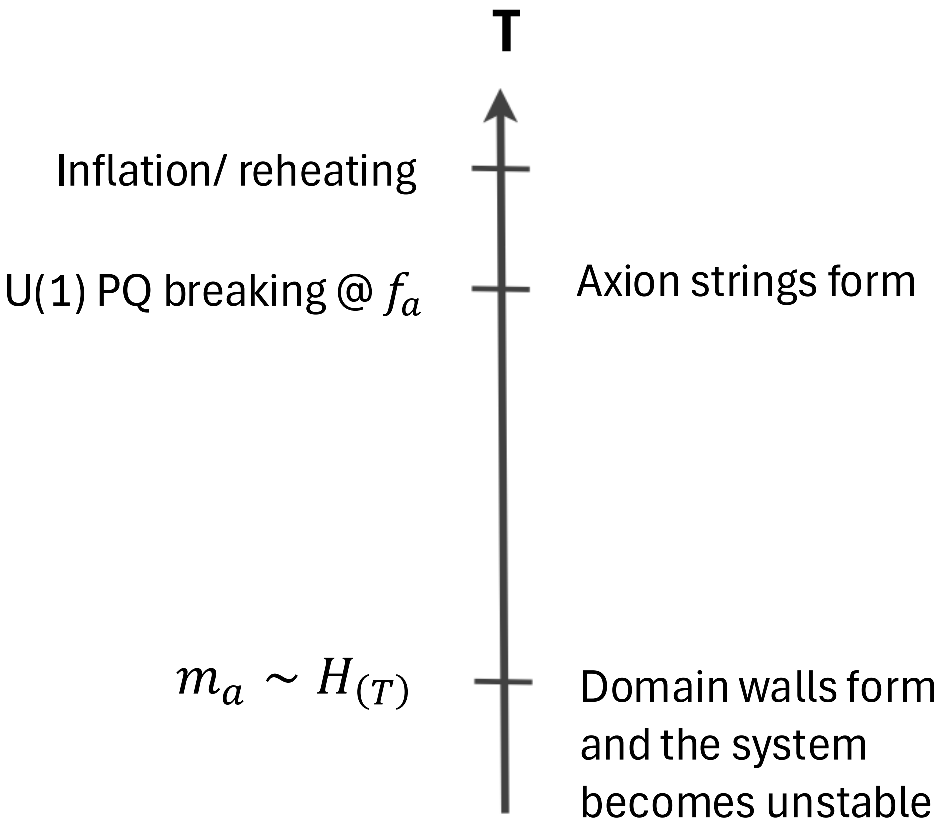
LCM

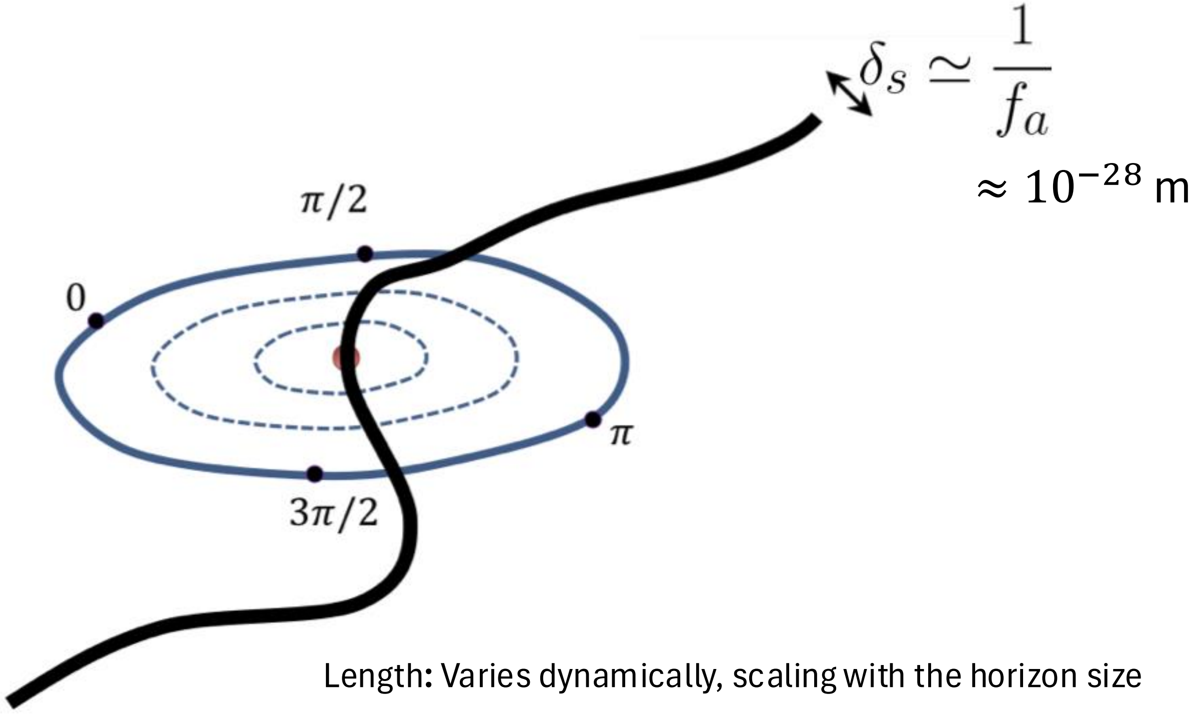


$\zeta = 1.0$
$\xi = 1.0$

Animation from Andrew Long's talk

Axion strings





Length: Varies dynamically, scaling with the horizon size

$$L(\eta) \sim \mathrm{d_H}(\eta)$$

Figures adapted from Ed Hardy's talk