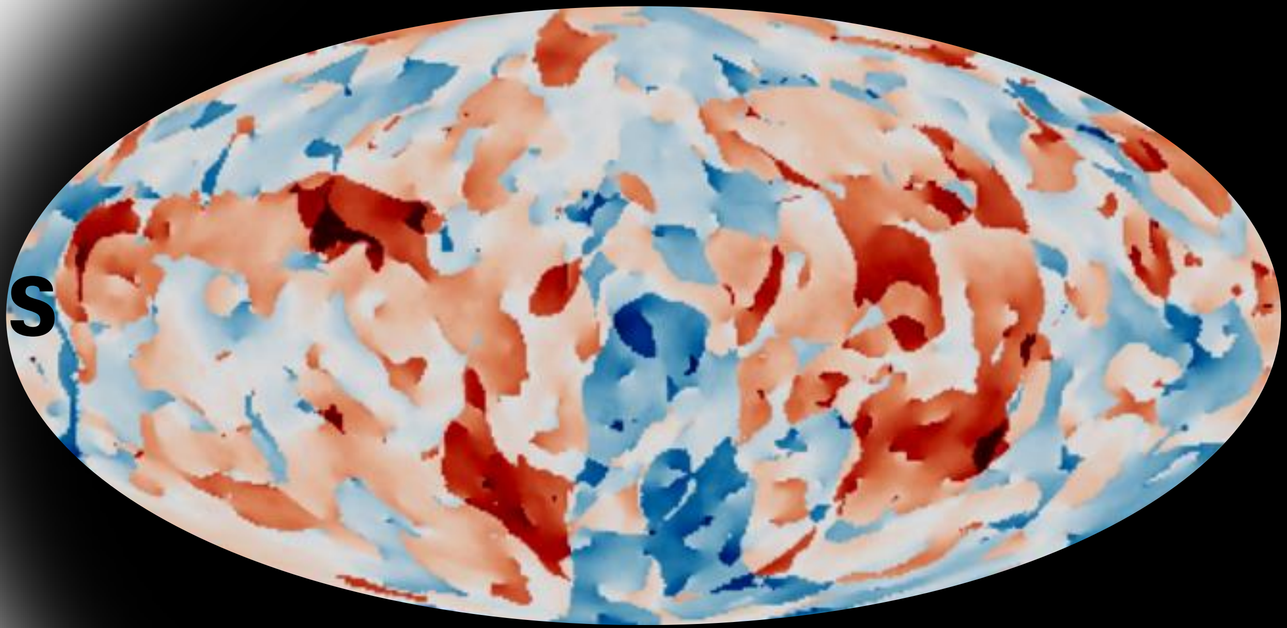
RICE UNIVERSITY

based on [2608.24456]

CMB birefringence by axion string loops



Moira Venegas

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

COSMO 26

Cosmic birefringence

- Rotation of the CMB polarization plane by an angle $\alpha(\hat{\boldsymbol{n}})$ as the photons propagate
- The rotation angle is expanded in spherical harmonics:

Isotropic birefringence

monopole α_{00} : uniform rotation across the sky

Anisotropic birefringence

higher multipoles $\alpha_{\ell m}$: direction-dependent rotation across the sky

Cosmic birefringence

- Rotation of the CMB polarization plane by an angle $\alpha(\hat{\boldsymbol{n}})$ as the photons propagate
- The rotation angle is expanded in spherical harmonics:

Isotropic birefringence

monopole α_{00} : uniform rotation across the sky

sky-averaged isotropic rotation $\beta = -\alpha_{00}/\sqrt{4\pi}$

C4/C5 14:45–15:30

Plenary 5 Eiichiro Komatsu

$$\beta = 0.215° \pm 0.074°$$

ACT DR6

Diego Palazuelos & Komatsu (2025)

Anisotropic birefringence

higher multipoles $\alpha_{\ell m}$: direction-dependent rotation across the sky

Cosmic birefringence

- Rotation of the CMB polarization plane by an angle $\alpha(\hat{\boldsymbol{n}})$ as the photons propagate
- The rotation angle is expanded in spherical harmonics:

Isotropic birefringence

monopole α_{00} : uniform rotation across the sky

sky-averaged isotropic rotation $\beta = -\alpha_{00}/\sqrt{4\pi}$

C4/C5 14:45–15:30

Plenary 5 Eiichiro Komatsu

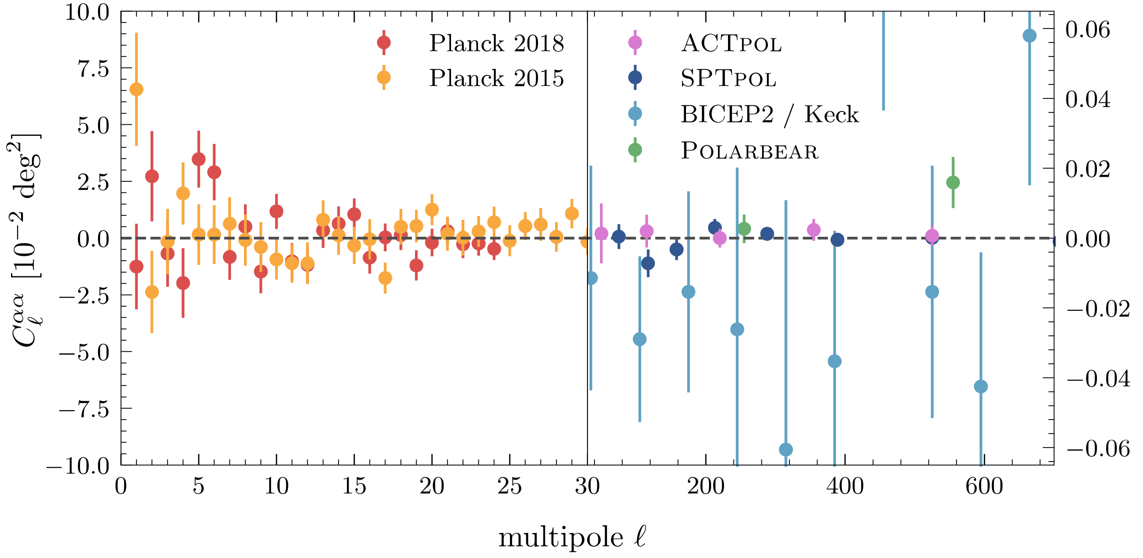
$$\beta = 0.215° \pm 0.074°$$

ACT DR6

Diego Palazuelos & Komatsu (2025)

Anisotropic birefringence

higher multipoles $\alpha_{\ell m}$: direction-dependent rotation across the sky



Jain, Hagimoto, Long, Amin [2208.08391]

are axion-like particles behind the cosmic birefringence?

Axion-like particles

- QCD axion: proposed to solve the strong CP problem
  pseudo-Nambu–Goldstone boson of a spontaneously broken $U(1)_{PQ}$ symmetry

- Axion-like particles (ALPs): similar pseudoscalars arising in extensions of the Standard Model

- **This talk:** hyperlight ALPs $m_a \ll H_0 \sim 10^{-33}\mathrm{eV}$

Interaction with electromagnetism

$$\mathcal{L} \supset \frac{1}{4}\frac{\mathcal{A}\,\alpha_{em}}{\pi\, f_a}\, a\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}$$

$\mathcal{A}$: anomaly coefficient

is generally expected to be an order-one rational number

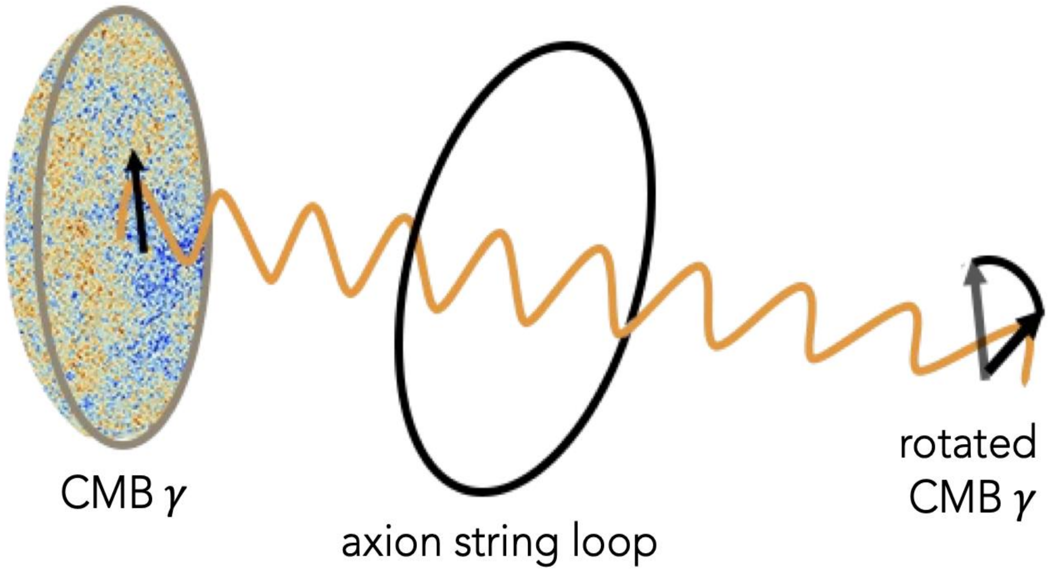
for instance, minimal Grand Unified Theories predict an integer multiple of **4/3**

Cosmic birefringence by hyperlight axion strings

Agrawal, Hook, Huang [arXiv:1912.02823]

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

A CMB photon propagates from the last scattering surface to us



$$\mathcal{L} \supset \frac{1}{4}\frac{\mathcal{A}\,\alpha_{em}}{\pi\, f_a}\, a\, F_{\mu\nu}\ \tilde{F}^{\mu\nu}$$

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

for an axion string loop , the axion field reaches its maximal excursion $\Delta a = \pm 2\pi f_a$

rotation angle after passing though one loop

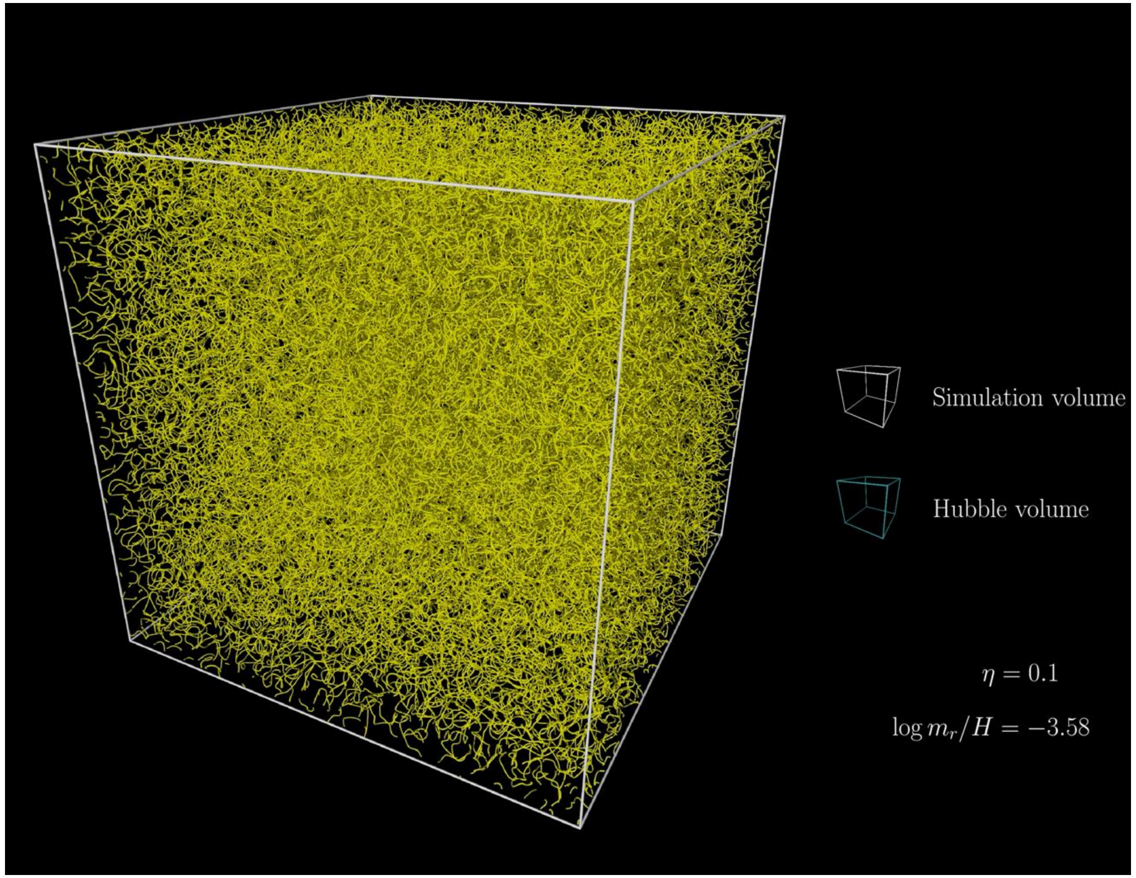
$$\alpha \approx \pm 0.42°\mathcal{A}$$

How evolve an axion string network?

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**



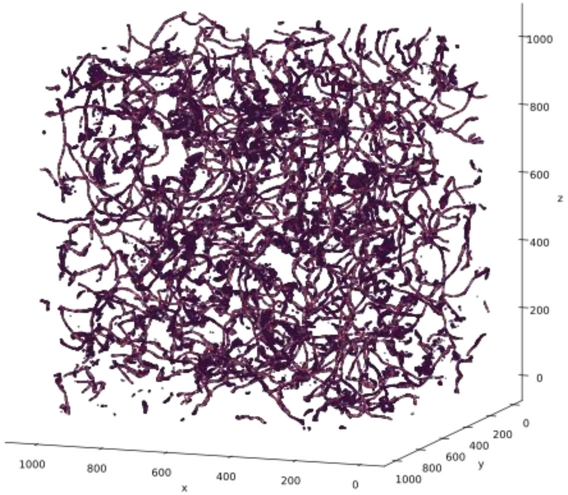
Simulations show:

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

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

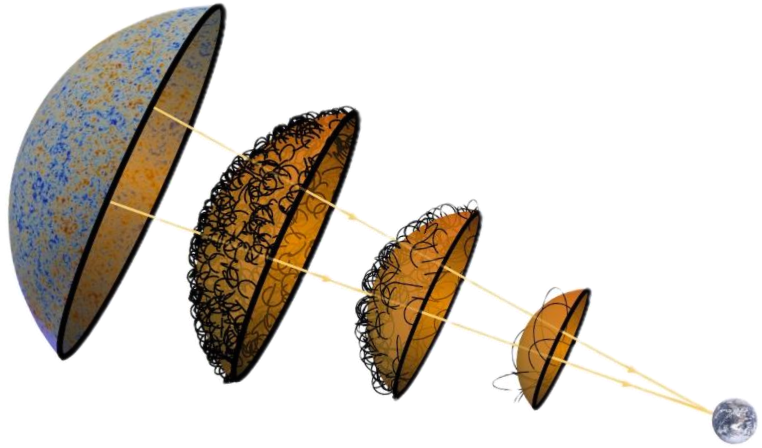
Cons: • The simulation covers a shorter time interval than the elapsed time from LSS to today

Cannot directly predict the CMB birefringence

+

Loop-Crossing Model (LCM)

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



- Fast analytical predictions for any cosmology
- The network is represented as a collection of randomly distributed planar circular loops
- Relies on 2 phenomenological network parameters

ξ_d: dimensionless string density parameter
ζ : Characteristic loop size

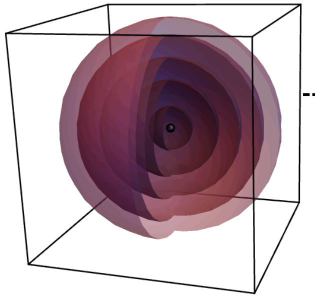
This work

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

Step 2. **Predict** CMB birefringence with LCM

Use the validated LCM to compute the CMB birefringence from last scattering until today

Computing the power spectrum from AMR simulations



Represent a simulation snapshot as a spherical shell

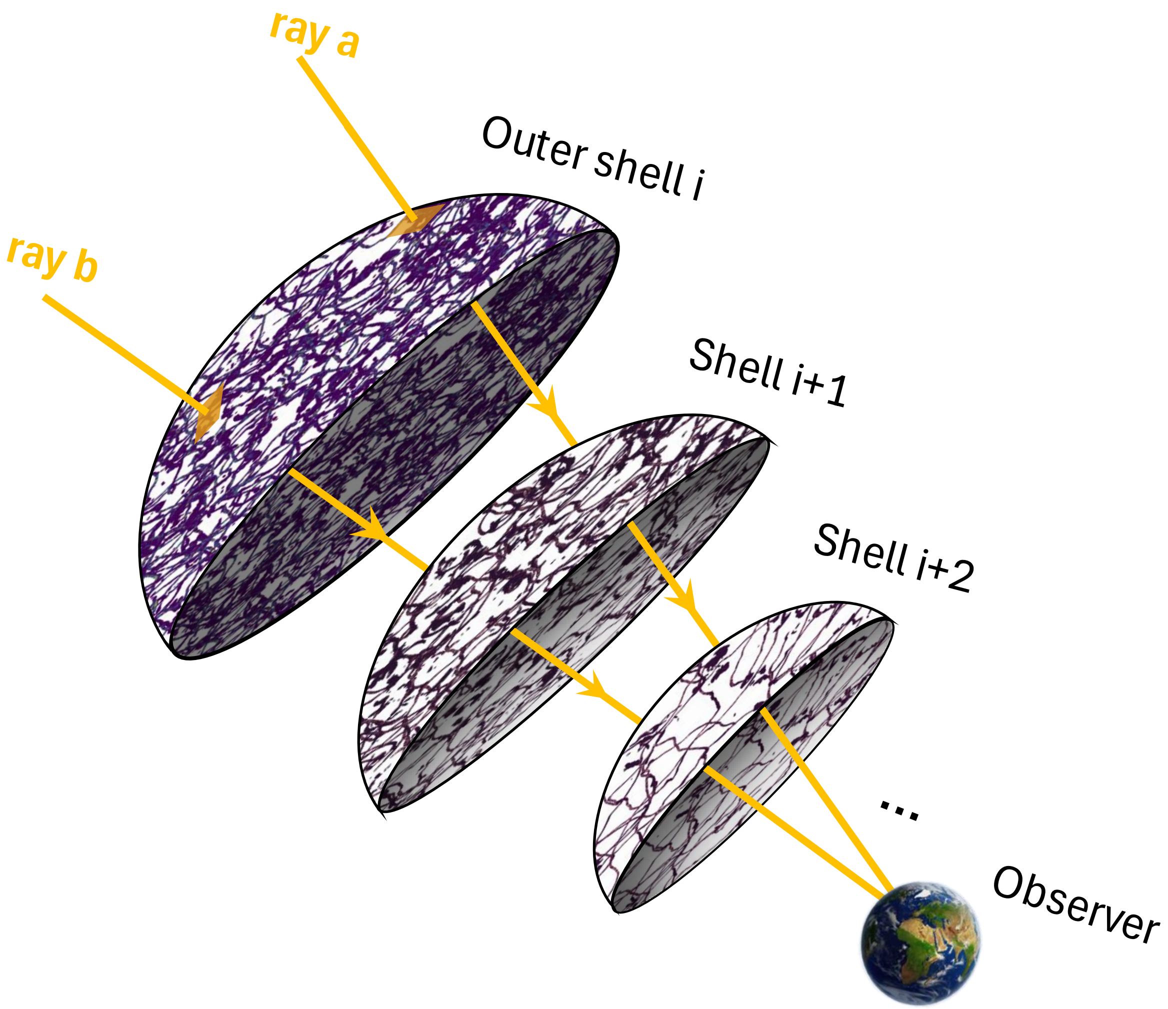
Each pixel on the outer shell defines a ray propagating inward

Sample the axion field $a(x)$ along each ray

Compute axion gradient ∇a

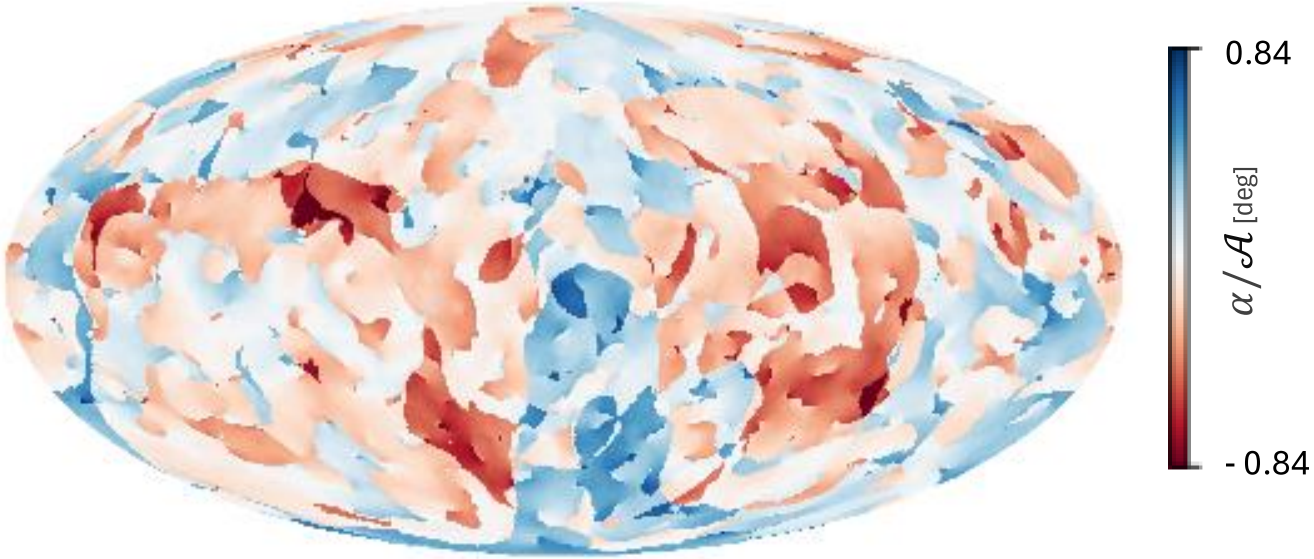
Integrate along the line of sight

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



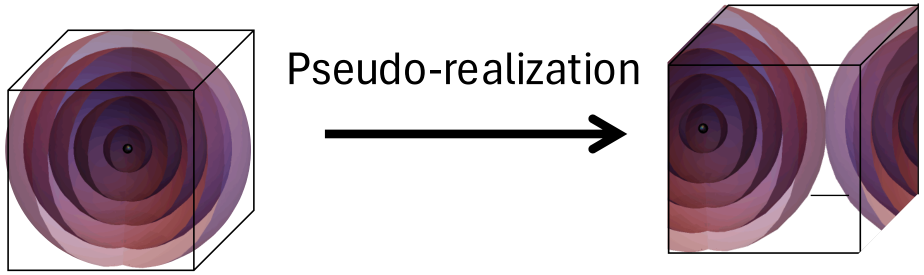
Generating Multiple Realizations

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



We want the ensemble-averaged power spectrum,
but only one simulation box is available.

Solution: Randomly shift the observer's position within the periodic simulation box

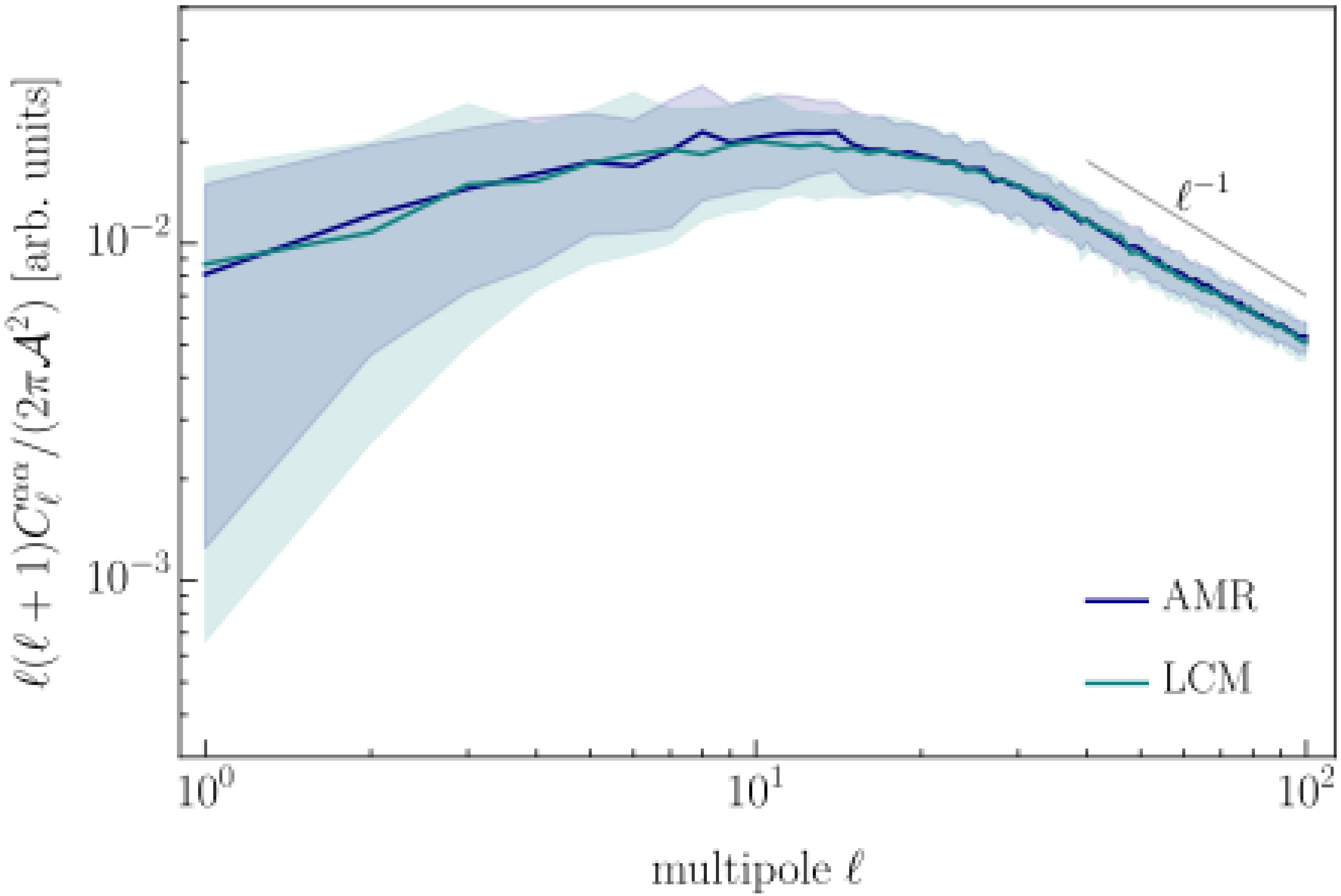


Each pseudo-realization then yields one C_ℓ

Results

1. Calibration of the LCM
2. Anisotropic birefringence CMB Prediction
3. Isotropic birefringence CMB Prediction

1. Calibration of the LCM against AMR



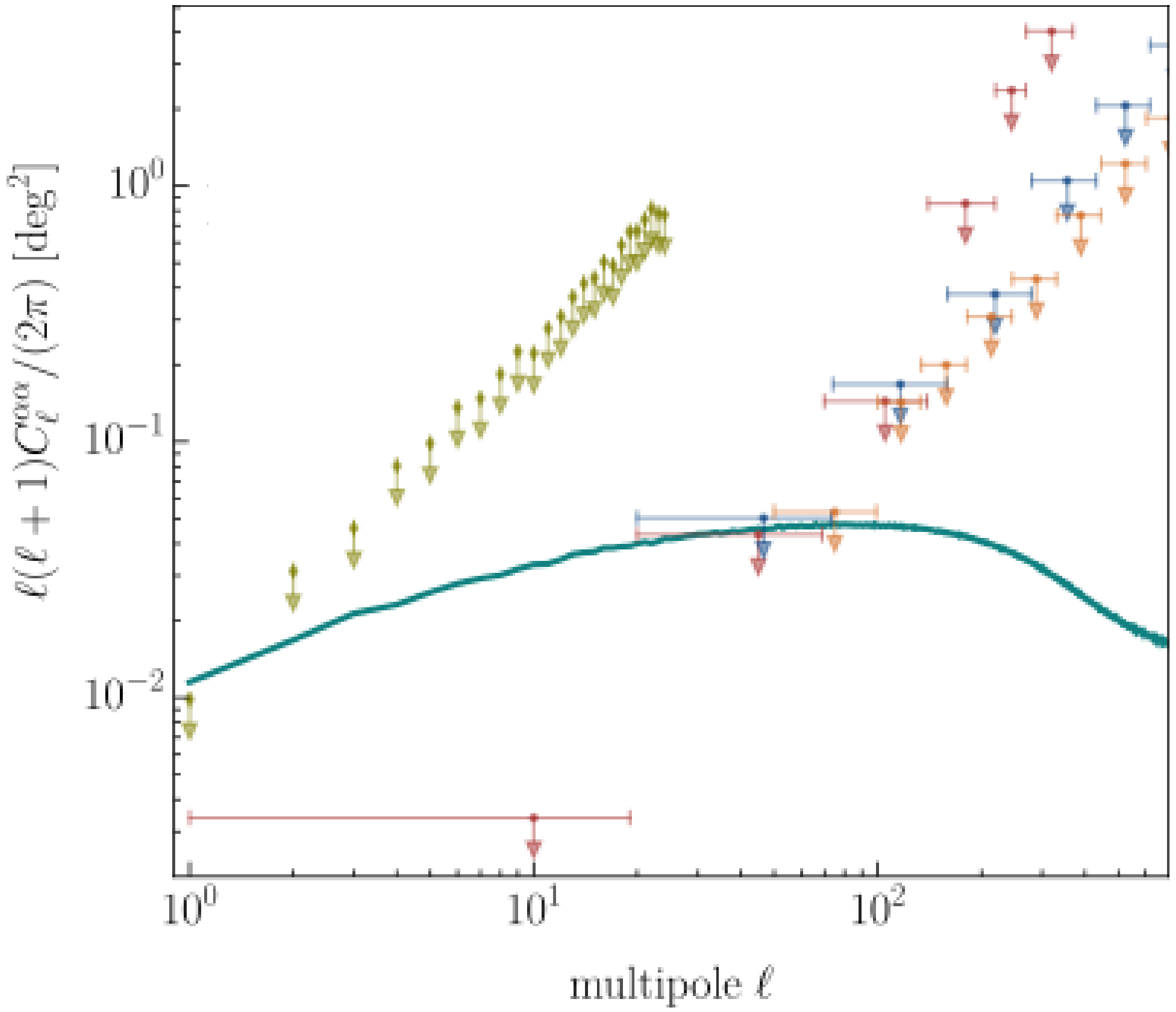
LCM Parameters:

1. dimensionless string density parameter $\xi_d(\eta)$:
   - Taken from the AMR simulation fit [2412.08699]

     $\xi_{\mathrm{d},17} = 2.2, \qquad \xi_{\mathrm{d},117} = 5.16$

2. Characteristic loop size ζ:
   - Calibrated against the AMR power spectrum
   - Logarithmic loop-size distribution
   - $\zeta_{\mathrm{min}} = 0.003$, $\zeta_{\mathrm{max}} = 0.35$

2. Anisotropic Birefringence CMB Prediction using LCM



$C_\ell \sim \mathcal{A}^2$

Upper bound on the anomaly coefficient $|\mathcal{A}| < \mathcal{A}_{95}$

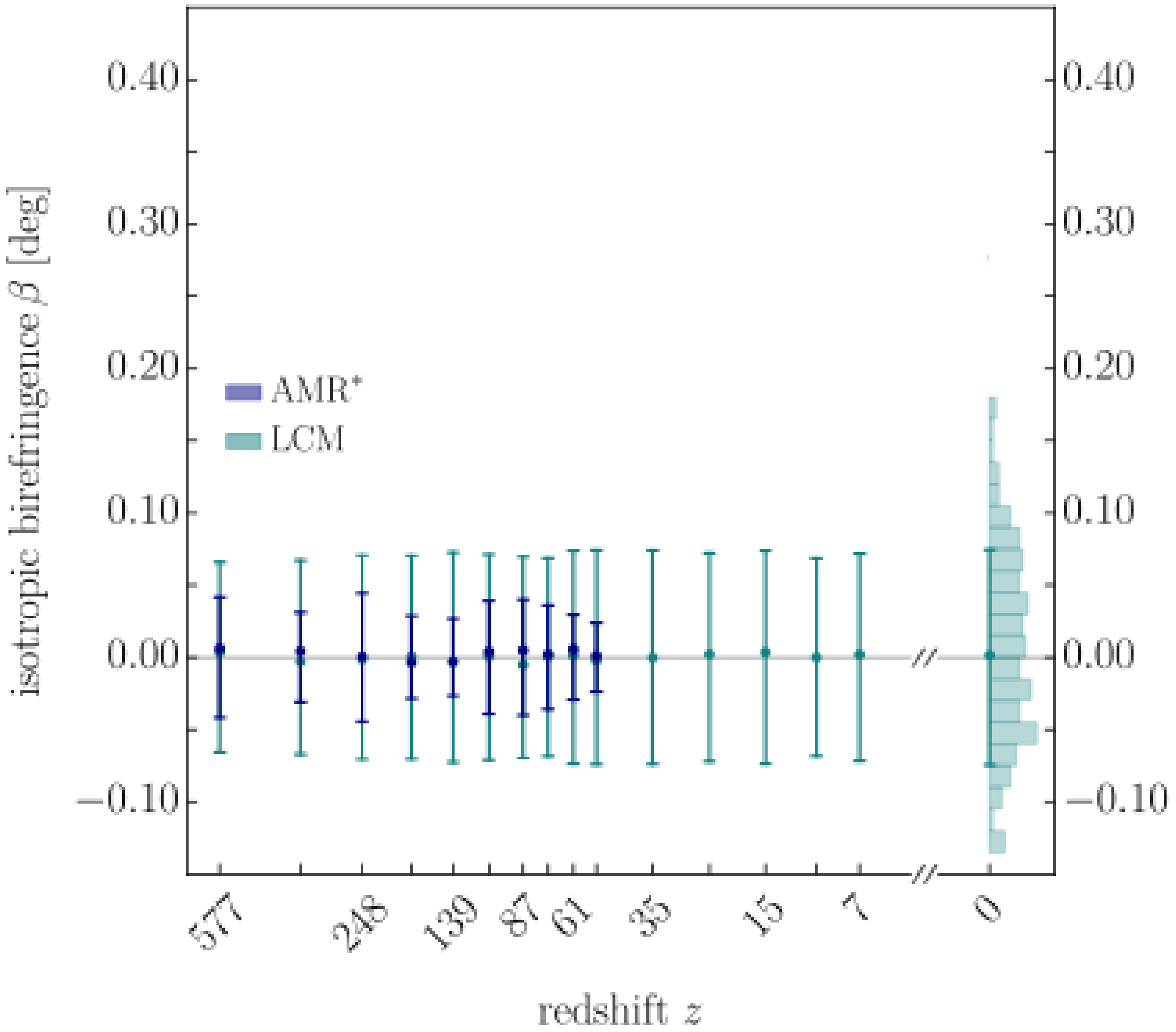
telescope	$\mathcal{A}_{95}$
Planck18	0.36
ACTpol	0.44
SPTpol	0.38
BICEP/Keck	0.30
joint	0.24

Largest value of $\mathcal{A}$ that would still be consistent with each telescope's non-detection at 95% C.L.

Powerful limit!

Theories of fundamental physics in which axions couple to photons generally predict $\mathcal{A}$ to be an order-one rational number.

3. Isotropic Birefringence CMB Prediction using LCM



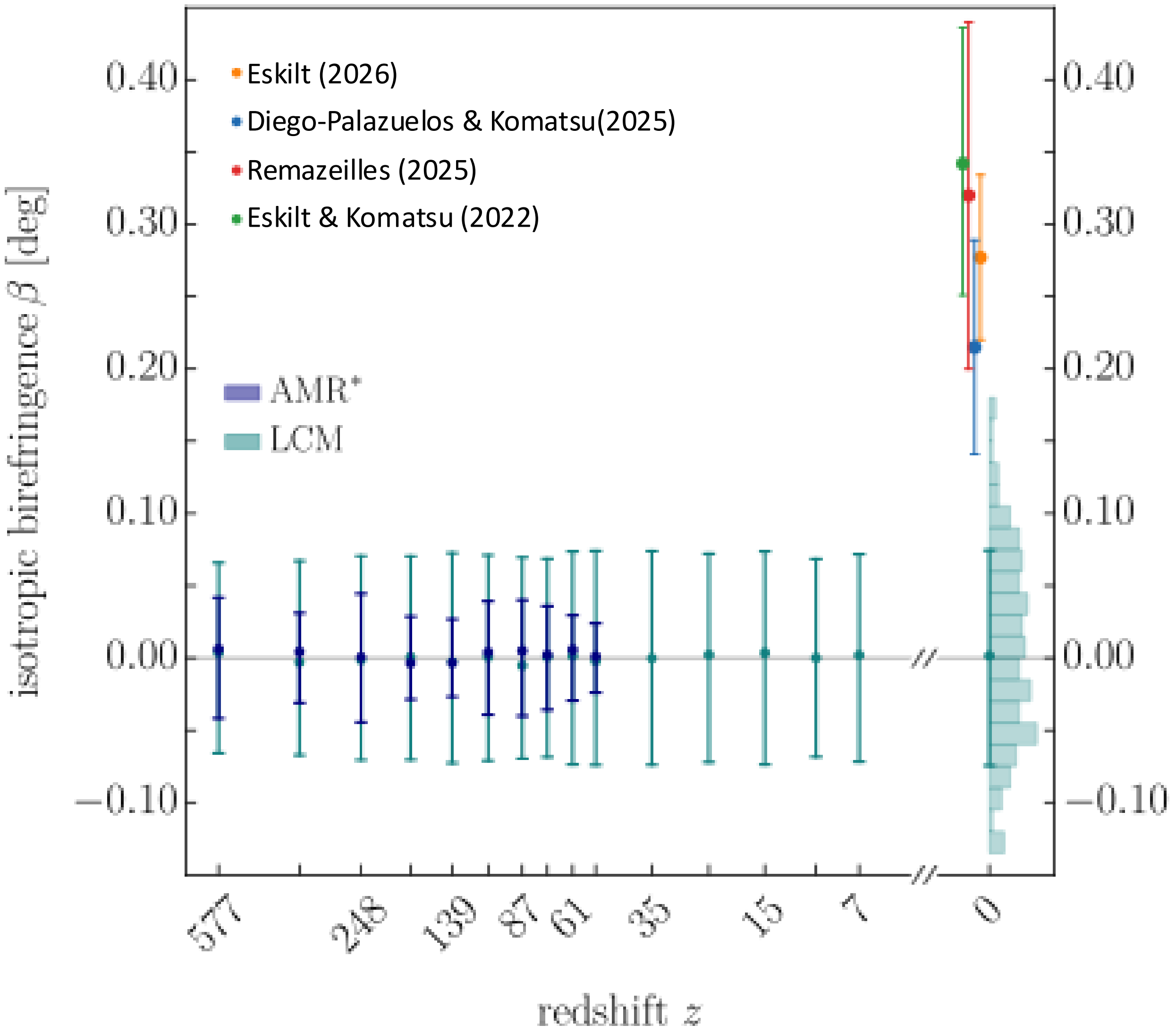
we fit $\mathcal{A} = 0.24$

and the isotropic birefringence prediction gives:

symmetrically distributed around $\beta = 0$

with a standard deviation $\beta_{\mathrm{rms}} = 0.075°$

3. Isotropic Birefringence CMB Prediction



we fit $\mathcal{A} = 0.24$

and the isotropic birefringence prediction gives:

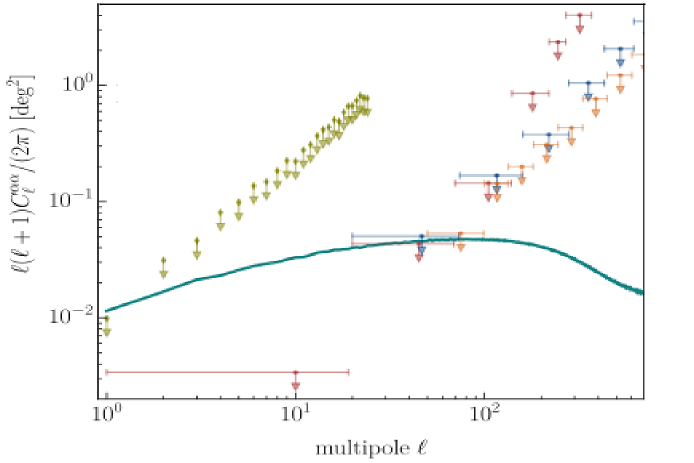
symmetrically distributed around $\beta = 0$

with a standard deviation $\beta_{\rm rms} = 0.075°$

The reported measurements lie in the tail of the predicted distribution.

The axion string network is an unlikely explanation for the observed isotropic birefringence.

Summary



- 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 $|\mathcal{A}| < 0.24$
- axion string network is an unlikely explanation for the observed isotropic birefringence.

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

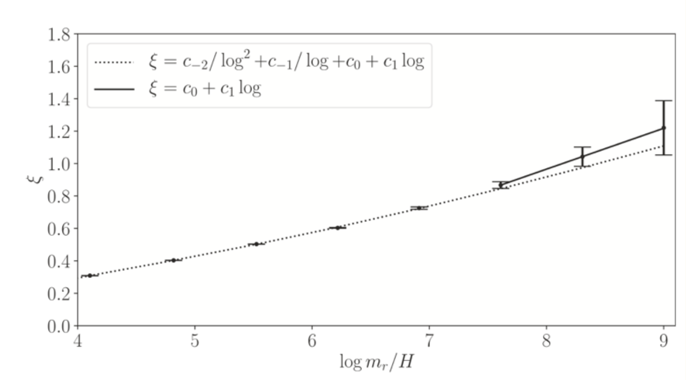
$H_0 = 1.3 \times 10^{-33}$ eV

* We are considering $m_a < H_0$

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

Extrapolating ξ

In radiation [2108.05368] [2412.08699]



AMR simulations shows a Logarithmic deviation from the scaling solution

$$\xi_d(z) = C_{-2}L^{-2} + C_{-1}L^{-1} + C_0 + C_1 L$$

After matter-rad equality

We consider the fit found in radiation era remains applicable

$$\text{at } z = 1100 \quad : \quad \xi_d = 92.4$$
$$\text{at } z = 0 \quad : \quad \xi_d = 100.9$$

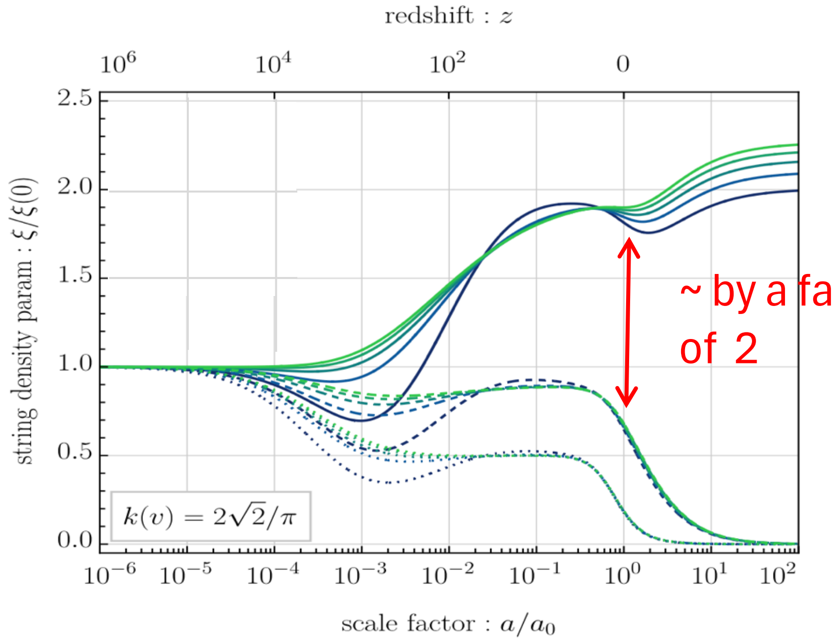
Extrapolation uncertainty (EU)

To quantify the theoretical uncertainty in our extrapolation, we follow the semi-analytical model Velocity One-Scale (VOS)

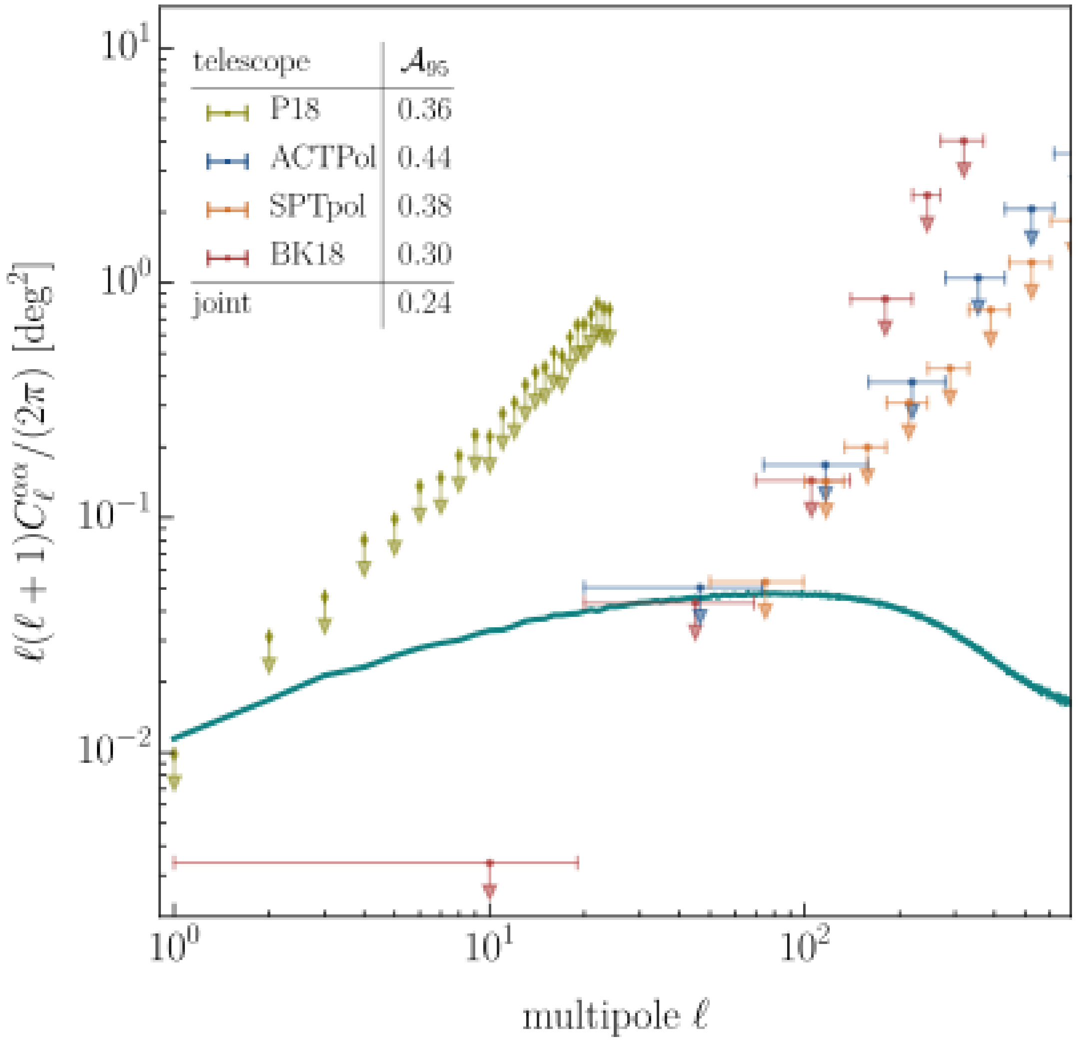
We find that ξ_d can increase or decrease by as much as a factor of 2 from the early universe till today, depending on the values of the VOS parameters.

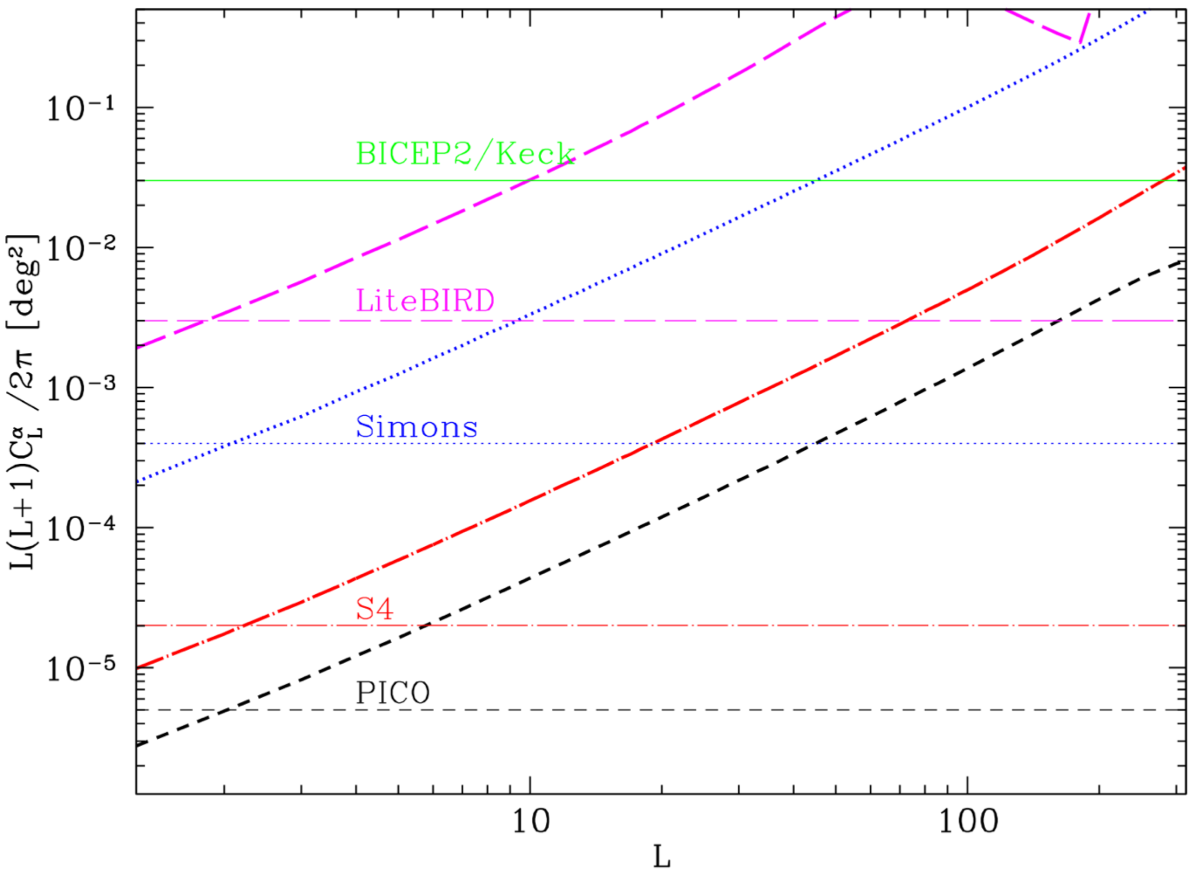
We account for this EU as a scale-independent nuisance parameter

$$C_\ell^{\alpha\alpha} \to \kappa C_\ell^{\alpha\alpha}$$



Future telescopes





The loop-crossing model

Description

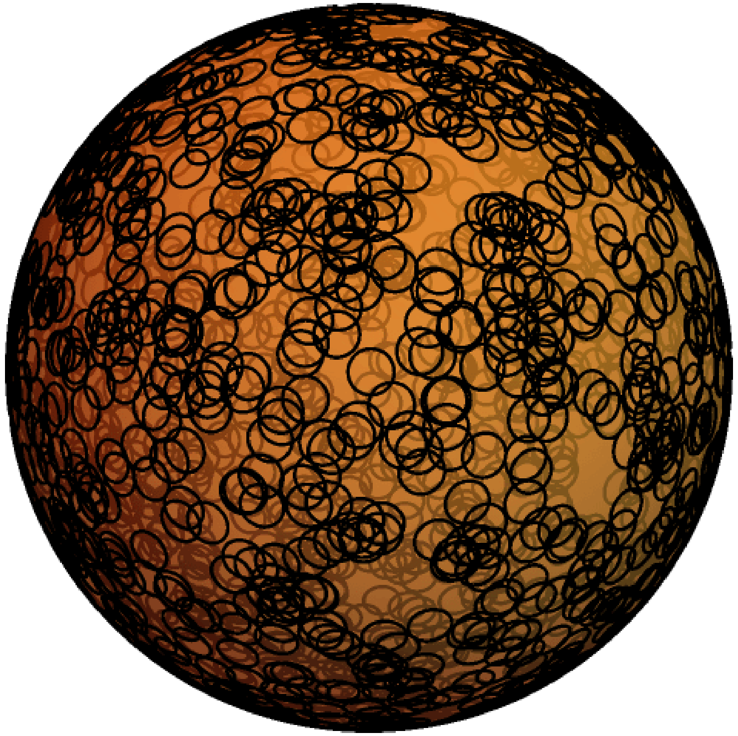
- Circular & planar loops
- Randomize loop orientation
- Randomize loop location in space
- Radius are uniformly logarithmic distribute

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

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

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

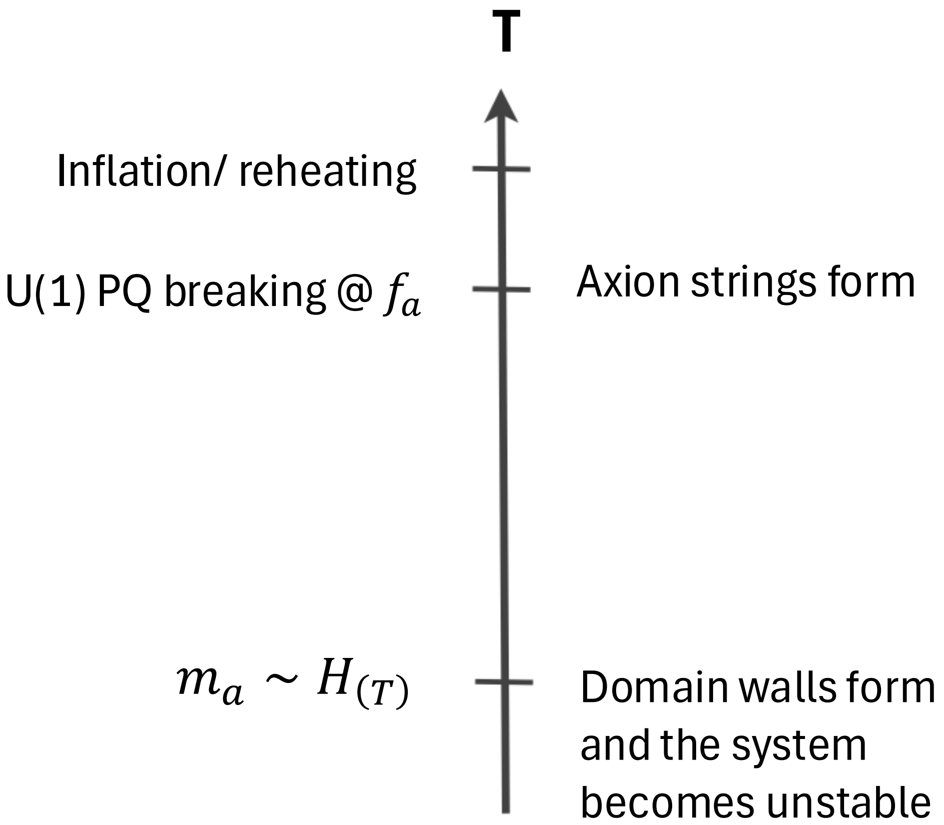
LCM

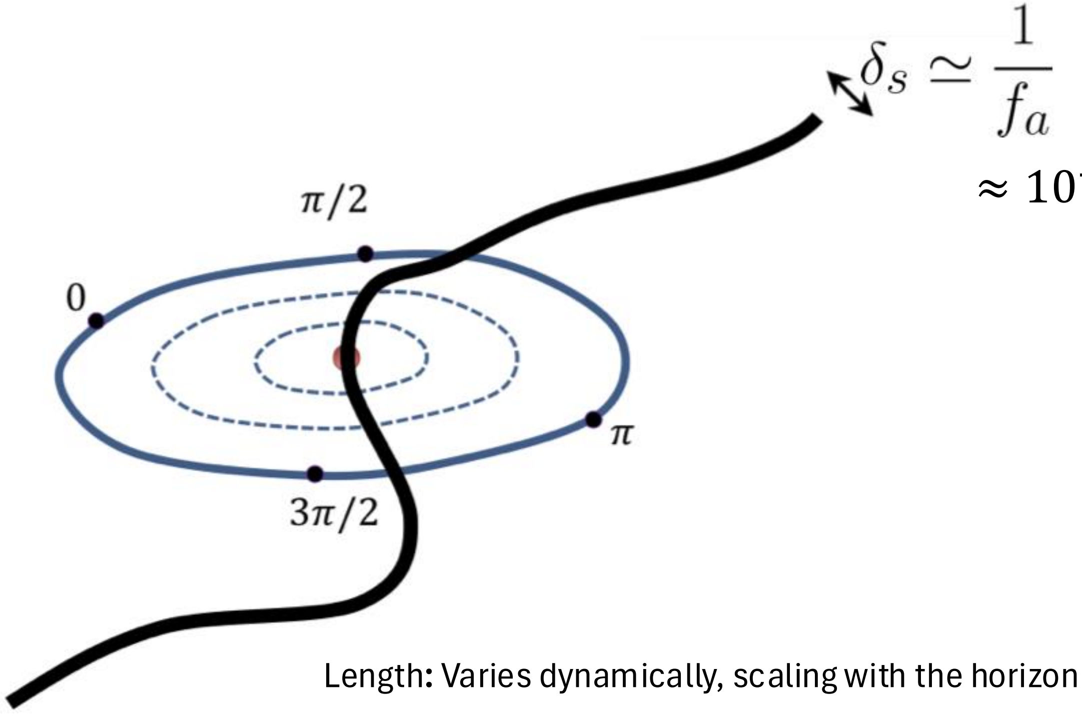


$\zeta\ = 1.0$
$\xi\ = 1.0$

Animation from Andrew Long's talk

Axion strings





$\approx 10^{-28}$ m

Length: Varies dynamically, scaling with the horizon size

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

Figures adapted from Ed Hardy's talk

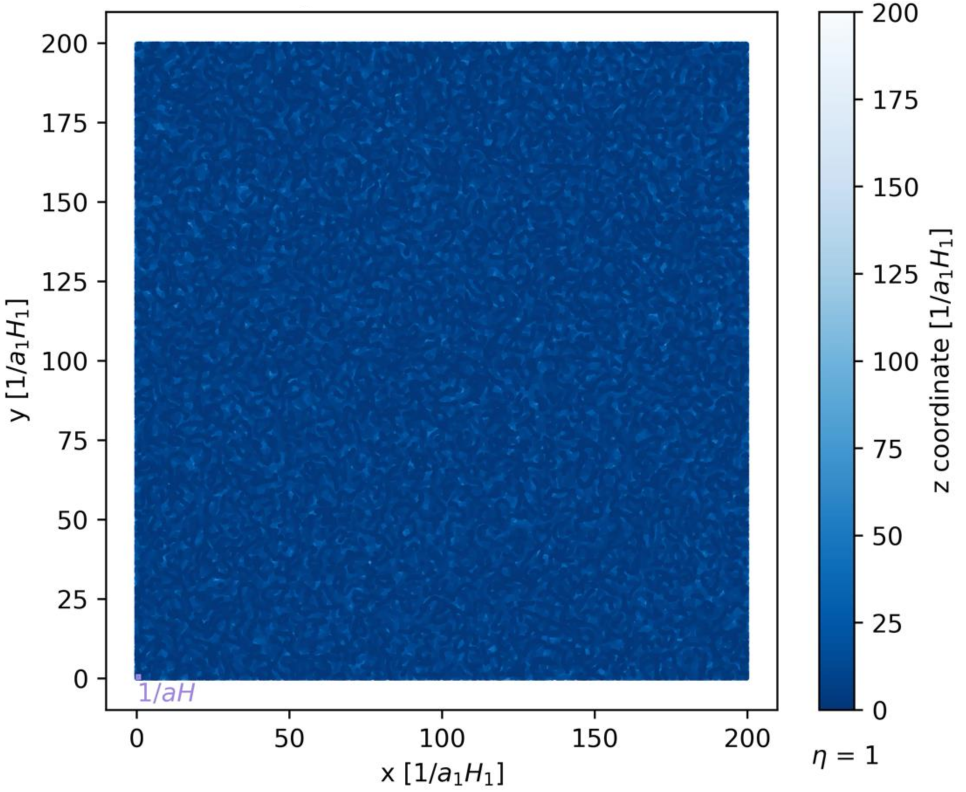
Visualizing the polarization imprint of axion strings

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

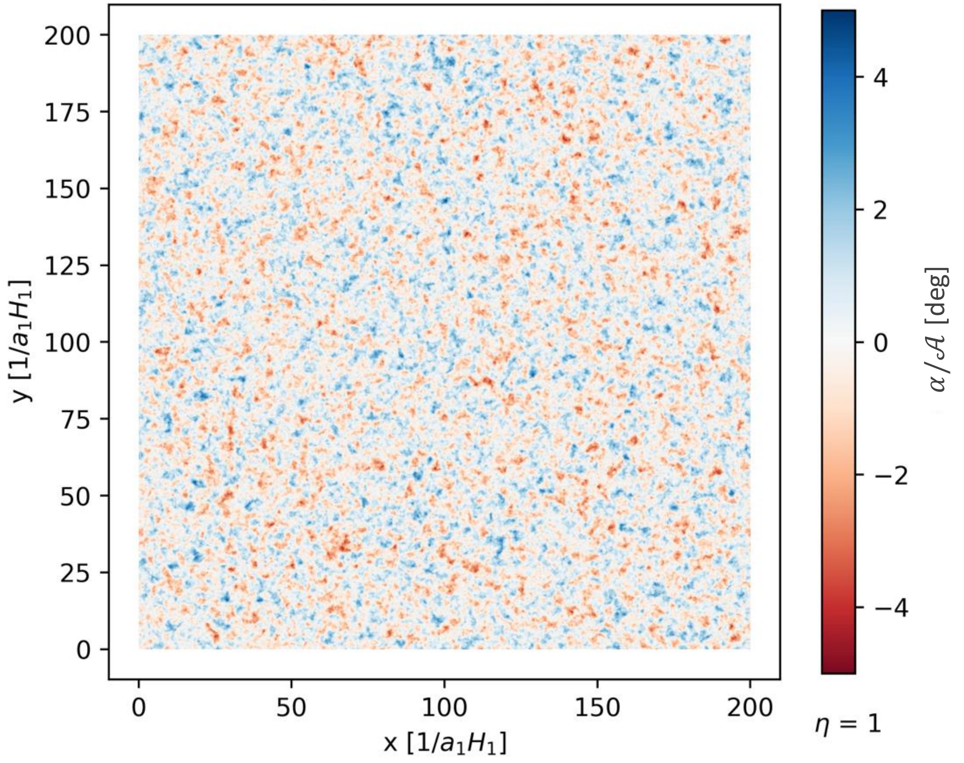
$$\alpha = \frac{\mathcal{A}\ \alpha_{em}}{2\ \pi f_a} \int dX^\mu \partial_\mu a(X)$$

$\eta = 1$

string network



birefringence $\alpha/\mathcal{A}$



* Right panel: each frame shows the birefringence from a single snapshot, not accumulated over time.