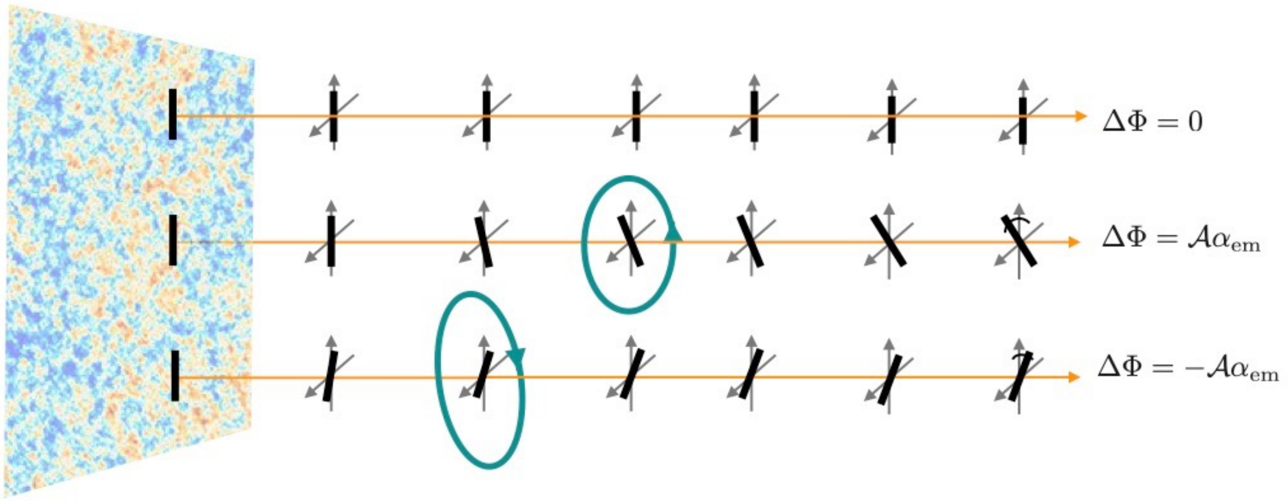
CMB Birefringence from Axion Strings



Andrew J. Long
Rice University
@ Mitchell Conference
May 26, 2024

Summary

- If a hyper-light axion-like particle exists in Nature, the associated cosmological network of axion strings can leave an imprint on CMB polarization through birefringence
- We use existing measurements of anisotropic birefringence (Planck, SPT, …) to place constraints on this scenario. Next-generation telescopes (CMB-S4) will probe O(1) electromagnetic anomaly coefficients and thereby probe the axion's UV embedding
- We argue that measurements of anisotropic birefringence could not only reveal the presence of a hyper-light ALP in Nature, but also lead to a measurement of its mass
- Our ongoing work (very early stages) seeks to use machine learning techniques (spherical CNN) to detect the subtle signal of axion strings in CMB polarization data

axion-like particles
& cosmic axion strings

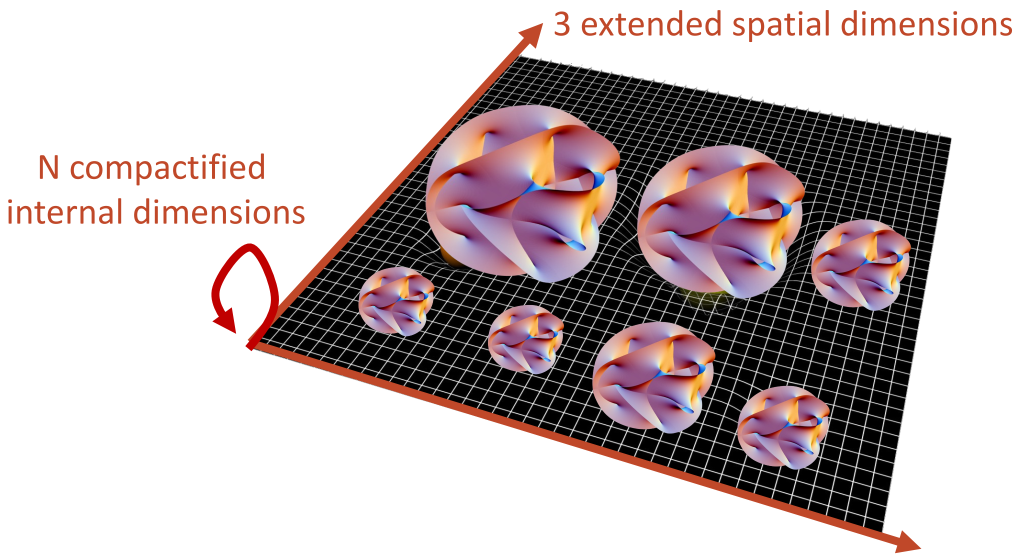
Theory landscape: axion-like particles

axion-like particles

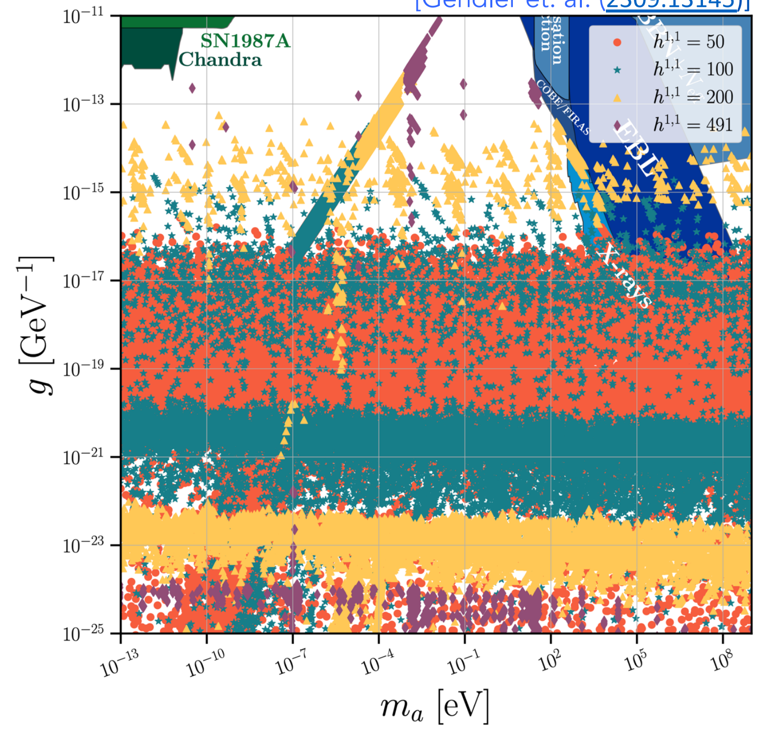
$$\mathcal{L} \supset \frac{1}{2}(\partial a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

ALPs from extra dimensions

(such as string theory)



[Gendler et. al. (2309.13145)]

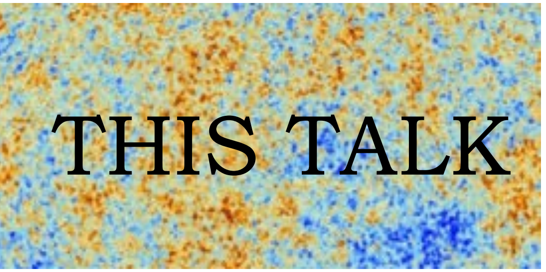


Theory landscape: axion-like particles

axion-like particles

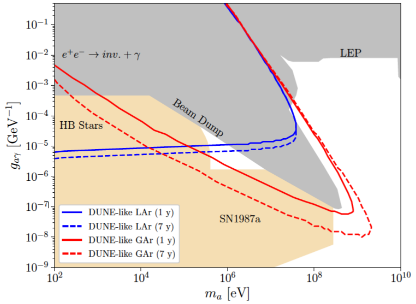
$$\mathcal{L} \supset \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

hyper-light axion-like particles (testable with cosmology)



ultra-light axion-like particles (dark mater candidate)

heavy axion-like particles (testable in the lab)



10^{-38} eV | 10^{-30} eV | 10^{-22} eV | 10^{-14} eV | 10^{-6} eV | 10^{2} eV | 10^{10} eV | m_a

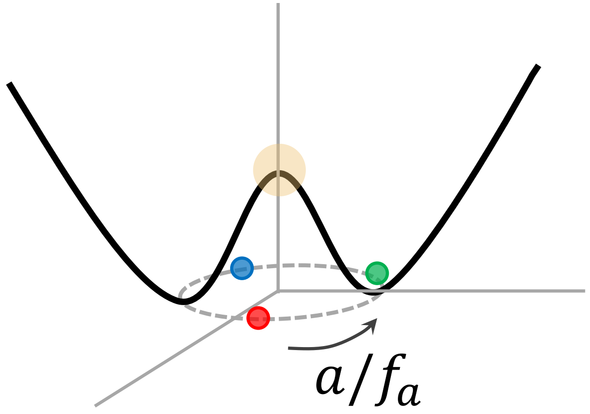
ALPs form axion strings

[Kibble (1976)]
[Vilenkin & Vachaspati (1987)]

string formation:
early-universe phase transition

Field space

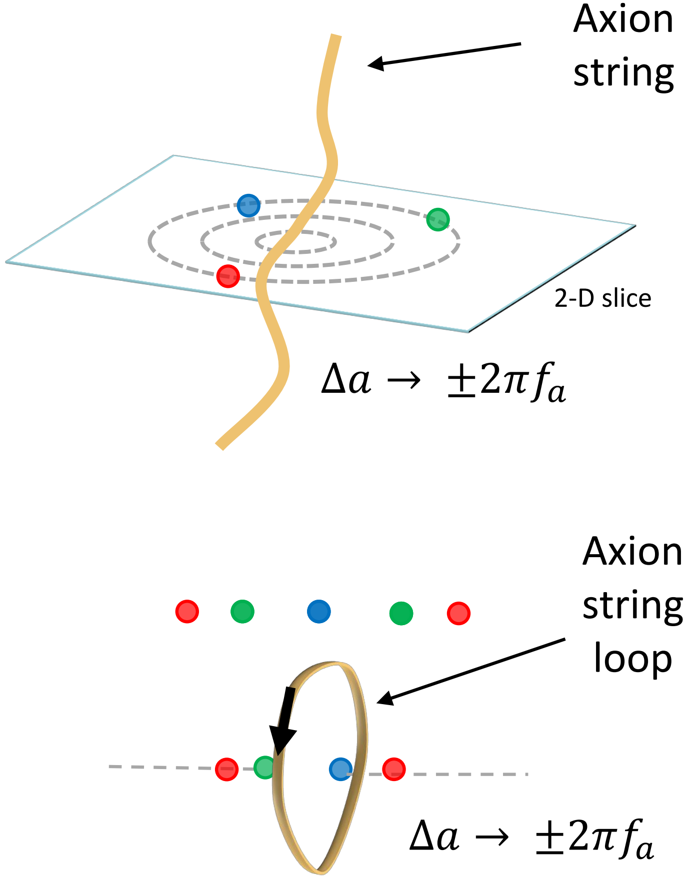
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



Clockwise (+); or
anti-clockwise (-)

↔

Physical space



string thickness = microscopic

string length = cosmological

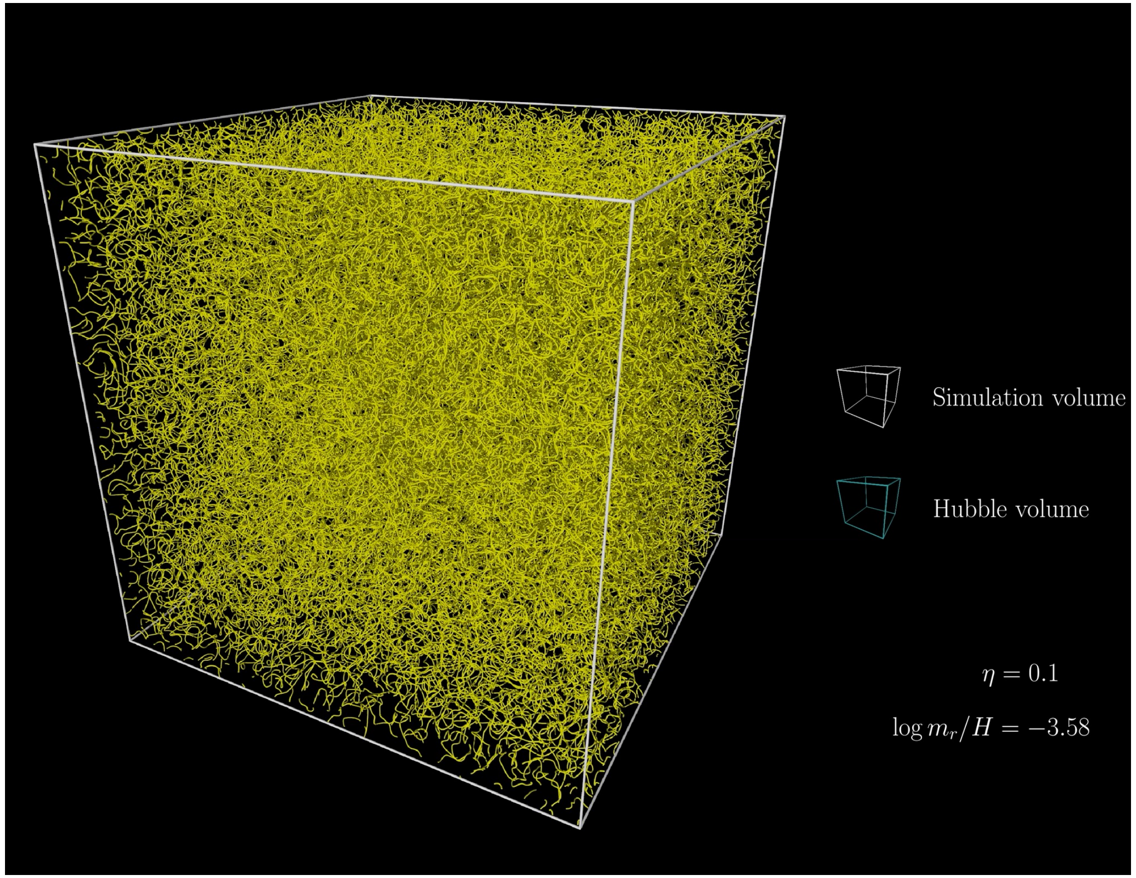
assume: $T_{\mathrm{RH}} > f_a$

image credit: Mudit Jain (2021)

A cosmic string network

[Buschmann et. al. (2022)]

string network simulation:



- string network is in scaling
- new loops are formed from reconnection
- loops emit axions and collapse
- typical string length tracks Hubble
- average energy density tracks Hubble
- today: O(1-10) strings per Hubble volume

How can we detect axion strings in the Universe today?

birefringence
from axion strings

How could we detect an axion string?

[Harvey & Naculich (1989)], [Carroll, Field, Jackiw (1990,91)], [Harari, Sikivie (1992)]
[Fedderke, Graham, Rajendran (2019)], [Agrawal, Hook, Huang (2019)]
[Yin, Dai, Ferraro (2021) & (2023)]

assume interaction
with electromagnetism:
standard Chern-Simons coupling

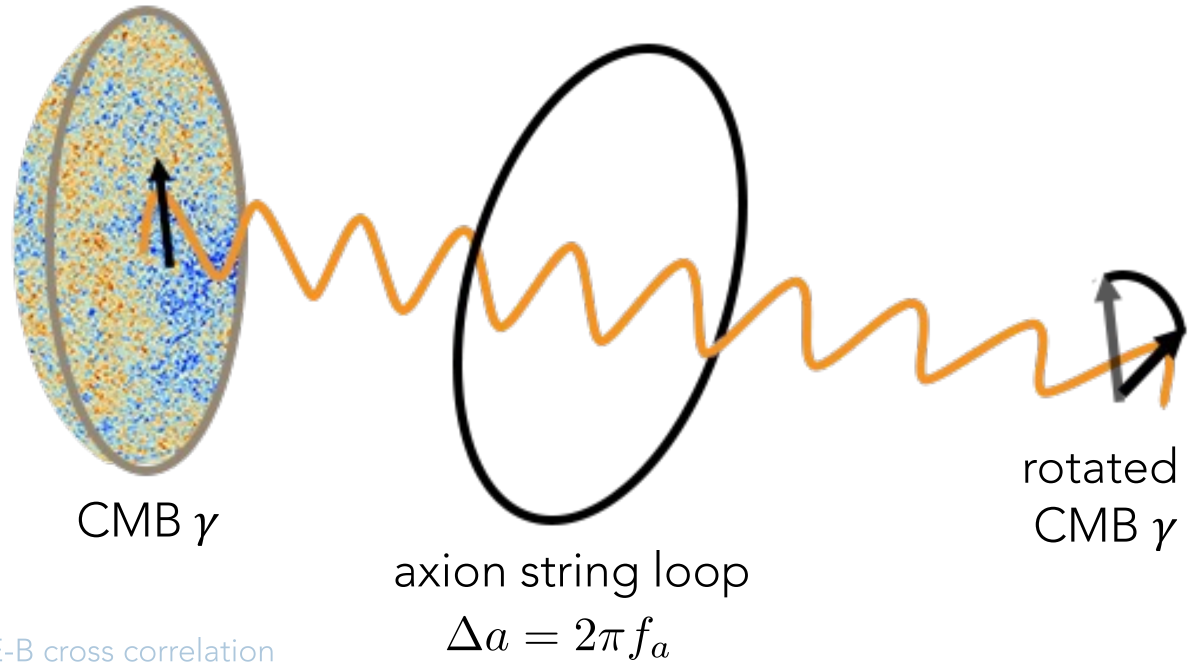
$$\mathscr{L}_{\rm int} = -\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$$

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

$$\mathcal{A} = \sum Q_{\rm PQ} \, Q_{\rm em}^2 \sim \#/9$$

axion-induced birefringence:
an electromagnetic wave
traveling through a varying axion field
has its plane of polarization rotated

$$\alpha = \frac{1}{2} g_{a\gamma\gamma} \int_C \mathrm{d}X^\mu \, \partial_\mu a(X)$$



rotation angle

$$\alpha = g_{a\gamma\gamma} \pi f_a$$
$$\equiv -\mathcal{A} \alpha_{\rm em}$$
$$\approx -0.42^\circ \, \mathcal{A}$$

* birefringence can be measured through E-B cross correlation

The loop-crossing model

Assumptions

- All loops are circles
- Randomize loop orientation
- Randomize loop location in space
- All loops same radius at any time
- Loop radius evolves tracking Hubble

$$R(t) = \zeta_0 / H(t)$$

- Number of loops tracks Hubble

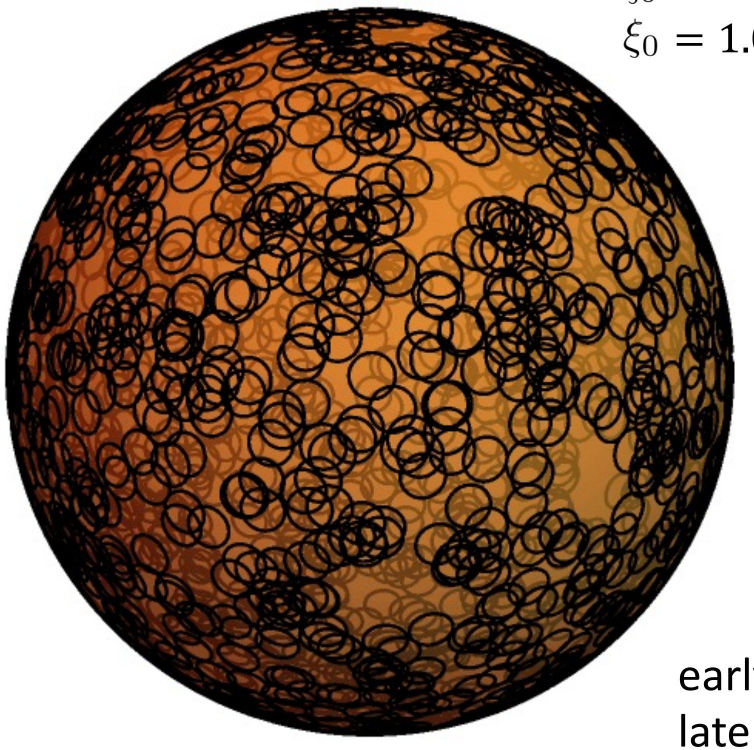
$$\rho(t) = \xi_0 \mu(t) H(t)^2$$

Model Parameters

$$\{m_a,\ \mathcal{A},\ \zeta_0,\ \xi_0\}$$

loop-crossing model

$\zeta_0 = 1.0$
$\xi_0 = 1.0$



early time -> small loops
late time -> large loops

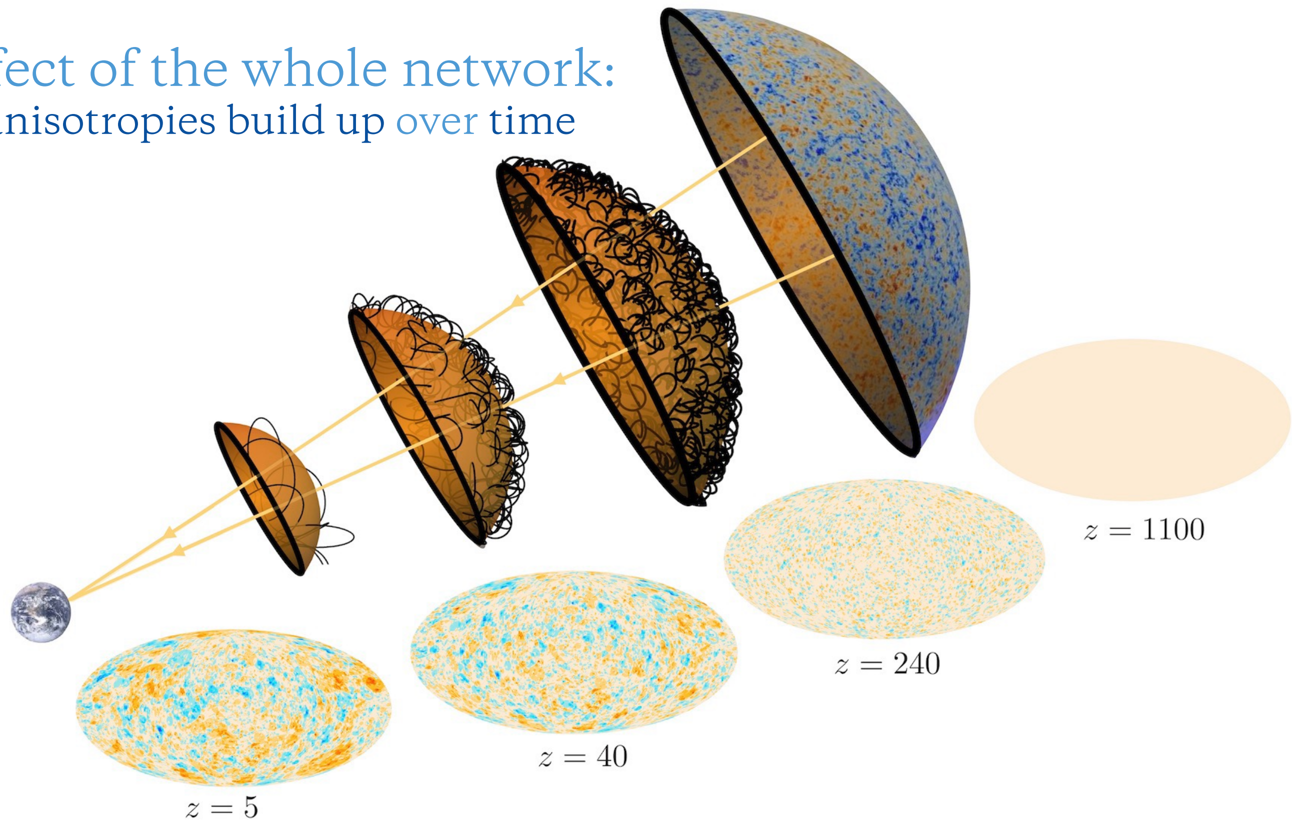
Expected birefringence signal

[Jain, AL, Amin, arXiv:2103:10962]
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

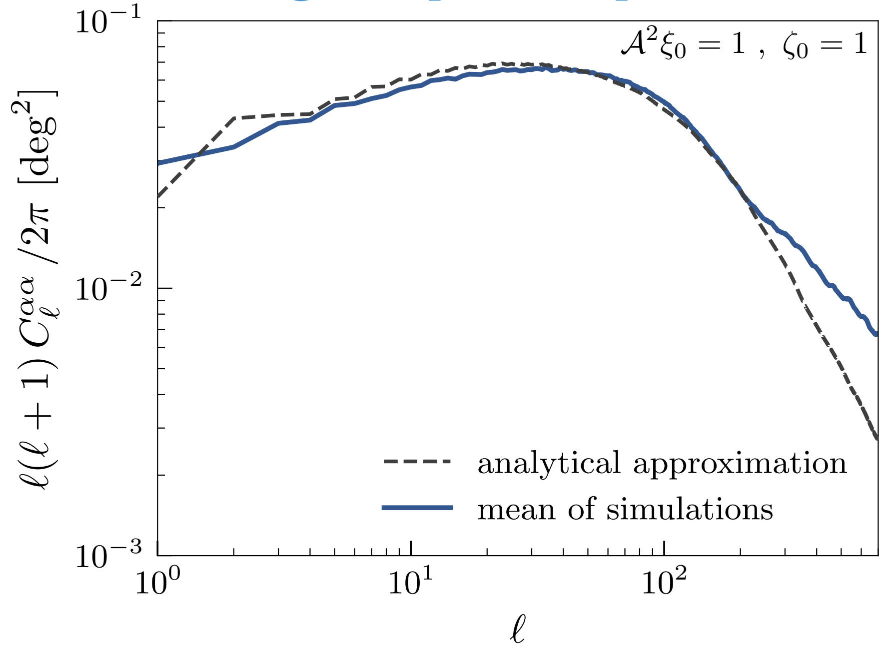
loop-crossing model:
a network of circular loops

$\mathcal{A}$ = dimensionless axion-photon coupling
ξ_0 = dimensionless loop density (Hubble units)
ζ_0 = dimensionless loop length (Hubble units)

effect of the whole network:
anisotropies build up over time



angular power spectrum:



approx. scale invariant up to l ~ 100

degeneracy: <αα> ~ $A^2\ \xi_0$

$*$ need $m_a \lesssim 3H_{\rm cmb} \approx 10^{-28}$ eV for the network to survive until after recombination

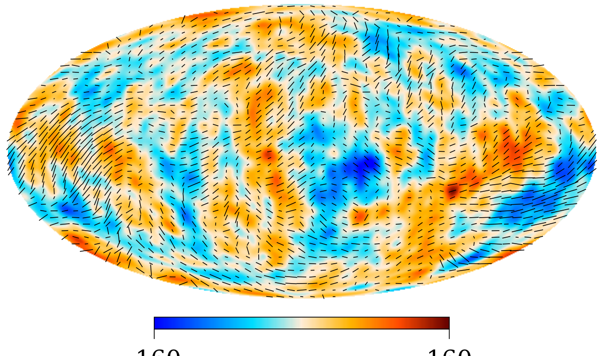
Effect on CMB polarization

How does birefringence affect the CMB's temperature and polarization?

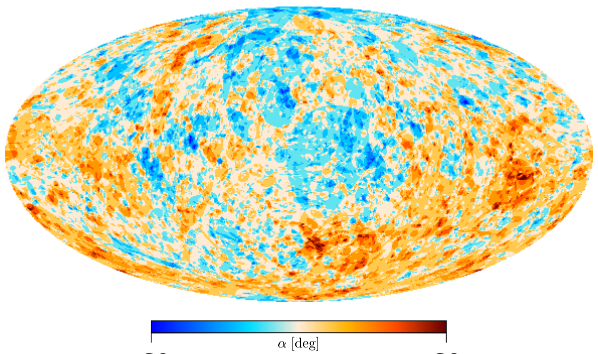
$$T(\hat{\boldsymbol{n}}) \to T(\hat{\boldsymbol{n}})$$

$$[Q \pm iU](\hat{\boldsymbol{n}}) \to [(Q \pm iU)e^{\pm 2i\Delta\Phi}](\hat{\boldsymbol{n}})$$

primordial CMB sky

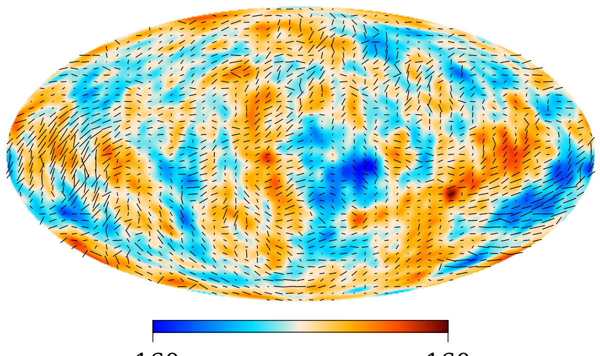


axion string -induced birefringence angle

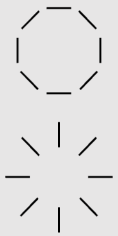


(exaggerated by ~30x)

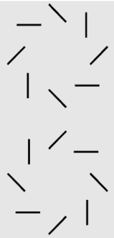
Planck's CMB sky



$E-mode$ pol pattern



$B-mode$ pol pattern



Signal of axion string-induced cosmological birefringence

$$\begin{cases} \langle TB \rangle \neq 0 \\ \langle EB \rangle \neq 0 \end{cases}$$

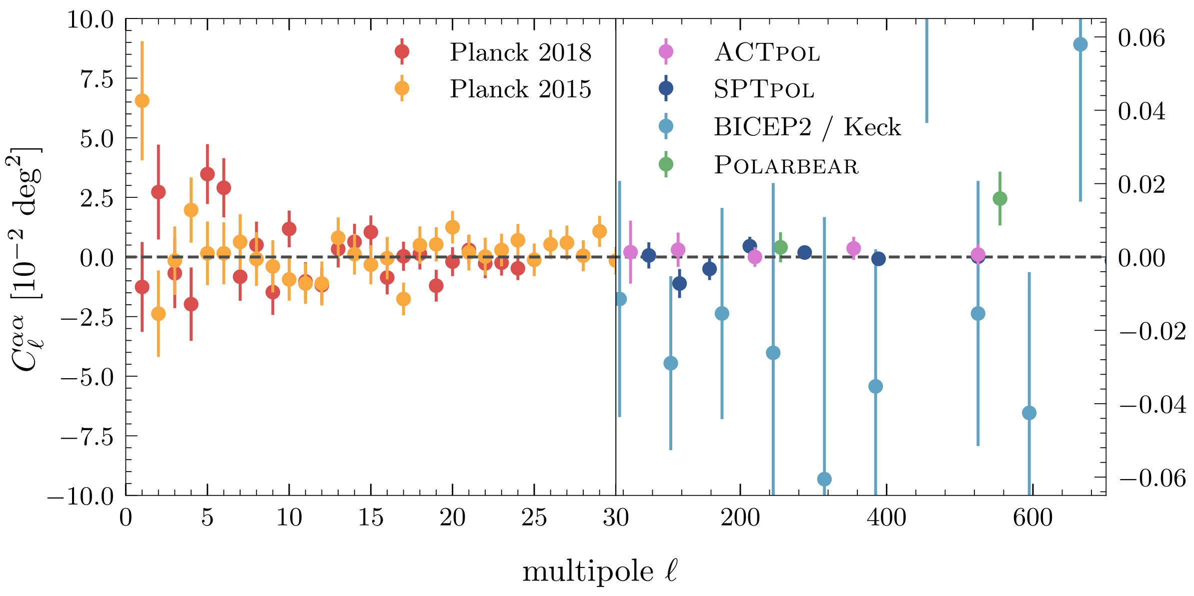
$$C_\ell^{\rm EB} \sim \sin(4\Delta\Phi)\left(C_\ell^{\rm EE} - C_\ell^{\rm BB}\right)$$

constraints
from CMB polarization data

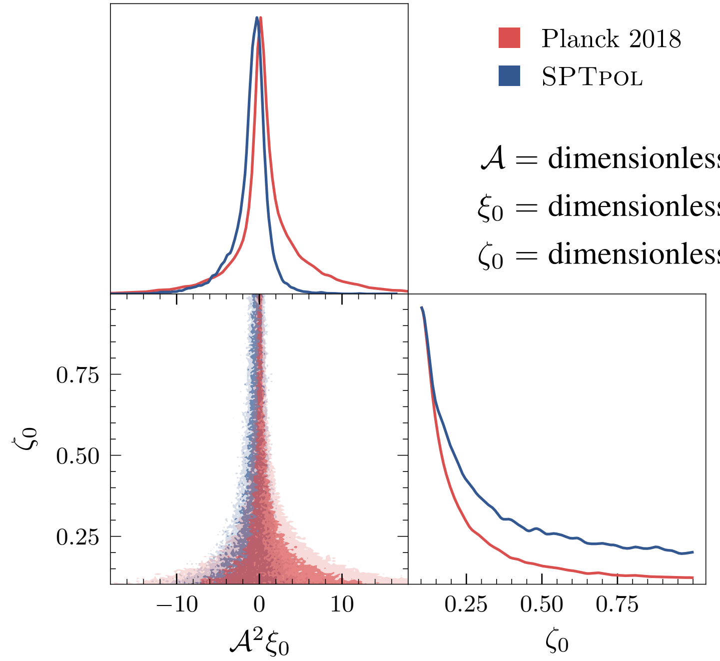
Constraints from anisotropic birefringence

[Jain, AL, Amin, arXiv:2103:10962]
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]
see also: Yin, Dai, & Ferraro (2111.12741)

measurements of CMB polarization:
no evidence for anisotropic birefringence



a constraint on axion strings networks
& their coupling to electromagnetism:



$\mathcal{A}$ = dimensionless axion-photon coupling
ξ_0 = dimensionless loop density (Hubble units)
ζ_0 = dimensionless loop length (Hubble units)

constraints:

SPTPOL: $\mathcal{A}^2\xi_0 < 3.7$ at 95% CL

Implications

CMB observations constrain:

$$\text{SPTPOL:}\;\; \mathcal{A}^2\xi_0 < 3.7 \text{ at } 95\% \text{ CL}$$

Typical axion-photon coupling:

$$\mathcal{A} = 1/3$$

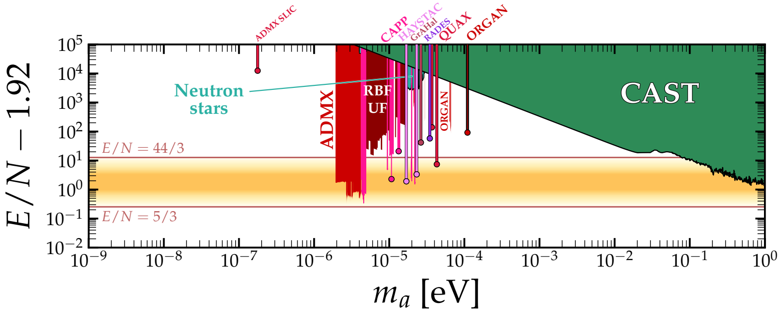
Typical loop abundance:

$$\xi_0 = 30$$

$$\mathcal{A}^2\xi_0 \approx 3.3$$

… already probing an O(1) anomaly coefficient!

… but still large uncertainties in ξ_0 (from sims)



Projected sensitivity

Pogosian et. al. (2019)

future telescopes

probes of isotropic + aniso. birefringence

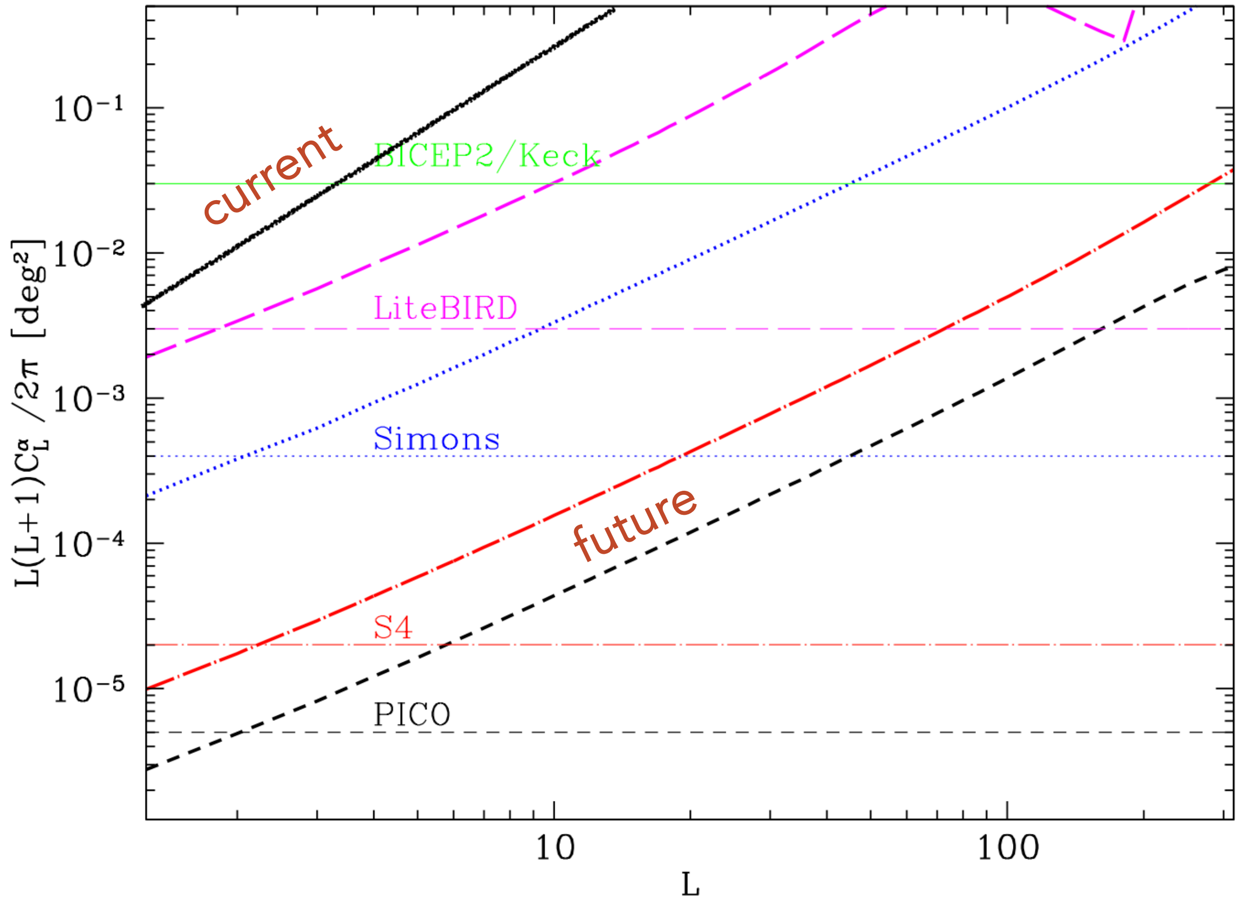
Current			LiteBIRD			SO			CMB-S4-like			PICO		
α $'$	A_α 10^{-2}deg^2	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ $'$	α $'$	A_α 10^{-3}deg^2	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ $'$	α $'$	A_α 10^{-4}deg^2	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ $'$	α $'$	A_α 10^{-5}deg^2	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ $'$	α $'$	A_α 10^{-5}deg^2	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ $'$
-	-	-	1.3	2.7	0.9	0.56	3	0.29	0.1	1.4	0.065	0.05	0.4	0.035
-	-	-	1.5	3.3	1.0	0.66	4	0.35	0.11	2.0	0.08	0.06	0.5	0.04
-	-	-	1.4	3.5	1.0	0.64	5.0	0.4	0.13	2.5	0.09	0.08	1.2	0.06
30	2	3	1.6	4.0	1.1	0.71	5.5	0.4	0.15	3.3	0.1	0.09	1.4	0.065

BLE II. Current and forecasted 68% CL bounds on the uniform and the anisotropic CPR parameters.

$$A_\alpha = L(L+1)C_L^\alpha/2\pi$$

future CMB polarization measurements will drastically improve sensitivity to axion-string induced anisotropic birefringence

diagonal = allows multipoles to vary independently
horizontal = restricts to a scale invariant spectrum



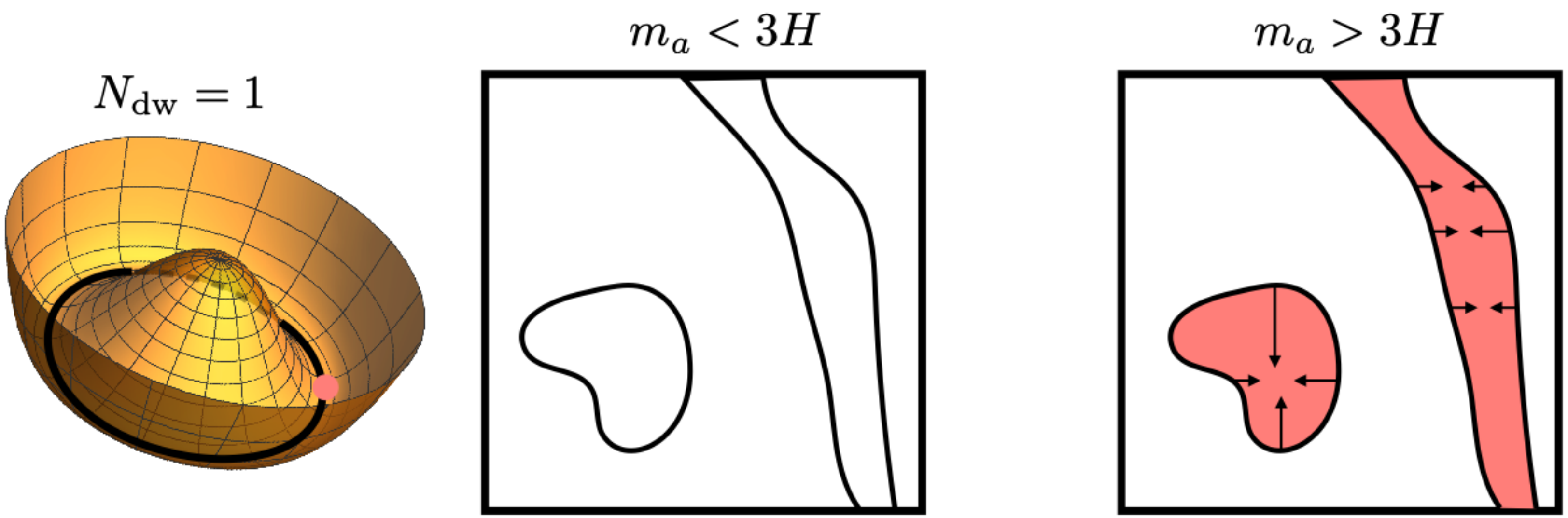
effect of
varying ALP mass

Collapse of the string-wall network

[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

Axion strings become connected together by domain walls

… the string-wall network collapses (for $N_{dw} = 1$)



let's consider: $\begin{cases} m_a \lesssim 3H_{\rm CMB} \simeq 3 \times 10^{-29}\ \mathrm{eV} \\ m_a \gtrsim 3H_0 \simeq 5 \times 10^{-33}\ \mathrm{eV} \end{cases}$

(string network survives until after recombination)

(string network collapses before today)

Impact on birefringence

(assuming $N_{\rm DW} = 1$)

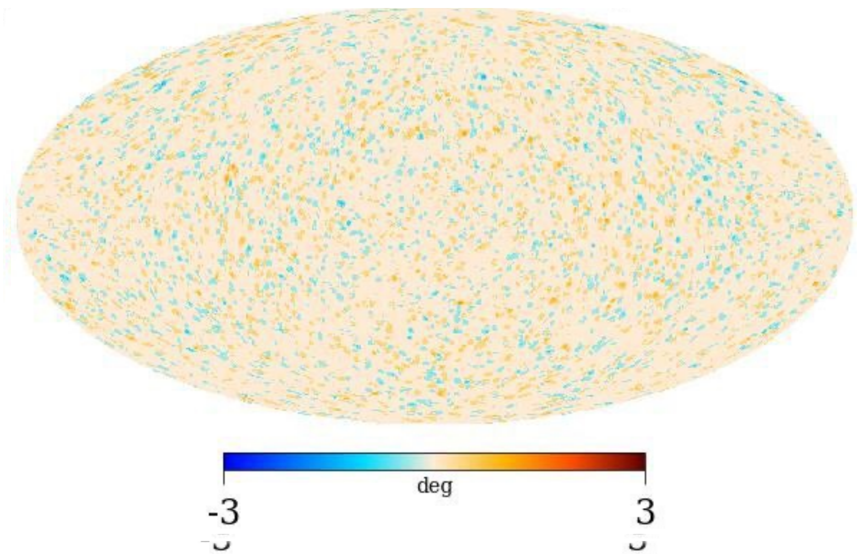
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

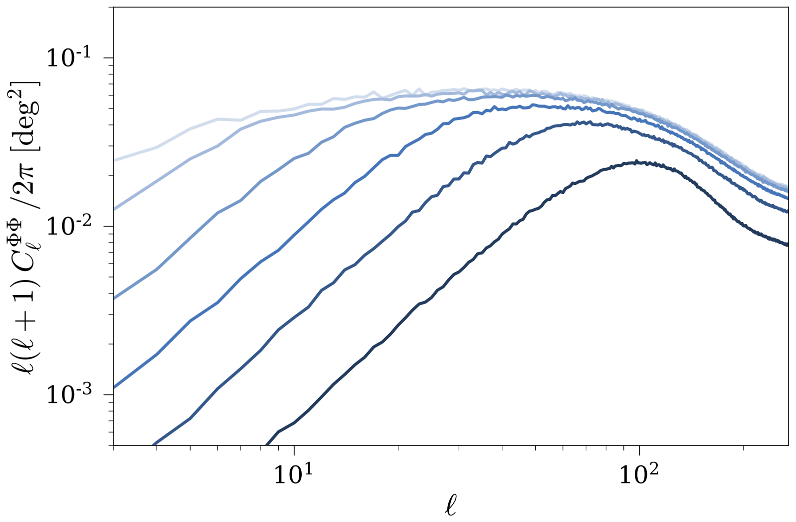
see also: [Ferreira, Gasparotto, Hiramatsu, Obata, & Pujolas (2023)]

raise the ALP mass

(network collapses earlier)

$$m_a = 2 \times 10^{-29}\ \mathrm{eV} \quad (z_c = 404)$$





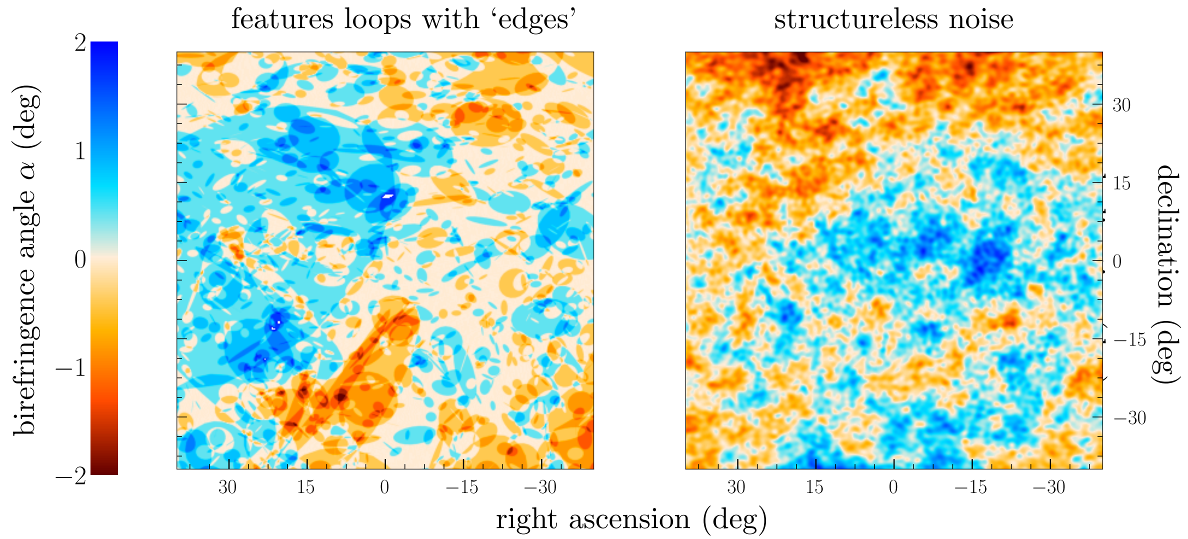
strong scale dependence ➔ possible to measure m_a

signatures of non-Gaussianity

Birefringence non-Gaussianity

[Hagimoto & AL, arXiv:2306:07351]
see also: Yin, Dai, Ferraro (2305.02318)

axion-string induced birefringence:
loop-like features are visibly non-Gaussian



Non-Gaussian axion birefringence map

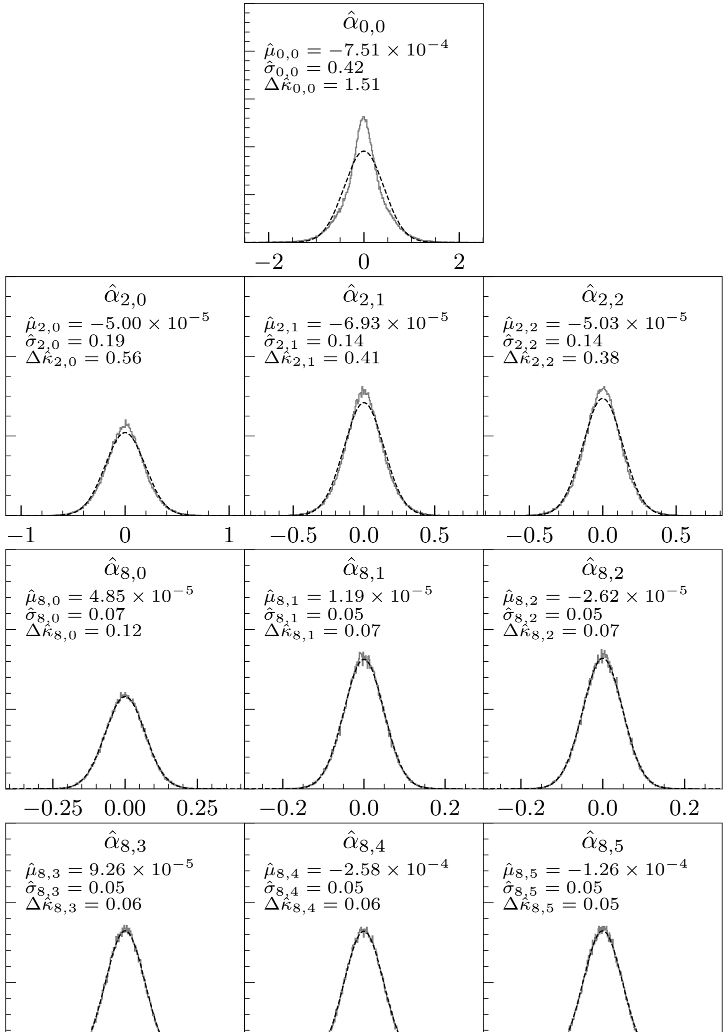
Gaussian random field with same power spectrum

How to best quantify the non-Gaussian birefringence and develop tests to extract these features from the data?

Measures of NG 1: kurtosis

[Hagimoto & AL, arXiv:2306:07351]

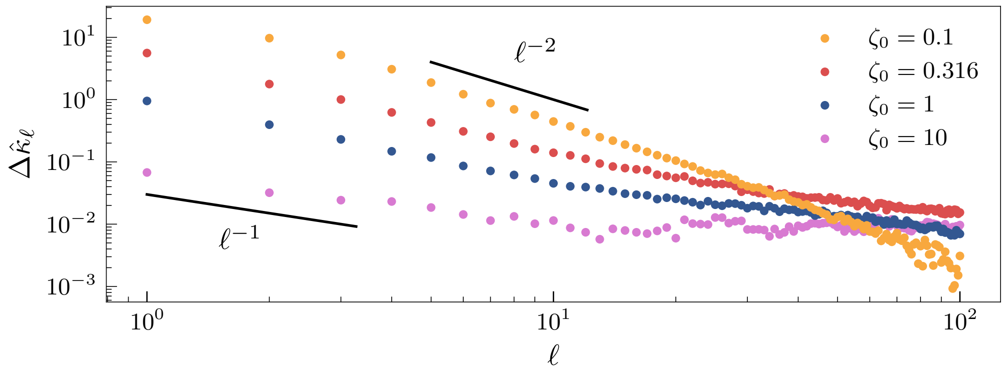
distribution over a_{lm}'s
less Gaussian at lower ell



kurtosis
a measure of Gaussianity

$$\kappa_{\ell m} = \frac{\left\langle \left| \hat{\alpha}_{\ell m} - \langle \hat{\alpha}_{\ell m} \rangle \right|^4 \right\rangle}{\left\langle \left| \hat{\alpha}_{\ell m} - \langle \hat{\alpha}_{\ell m} \rangle \right|^2 \right\rangle^2}$$ = 3 for Gaussian

scaling with multipole index
more Gaussian on smaller scales



analytical model
~ inverse with # loops

$$\Delta\hat{\kappa}_\ell \sim \frac{\zeta_0}{8\xi_0}\left(1 + \frac{\pi}{\lambda\zeta_0\ell}\right)^2$$

recall: $R(t) = \zeta_0 / H(t)$

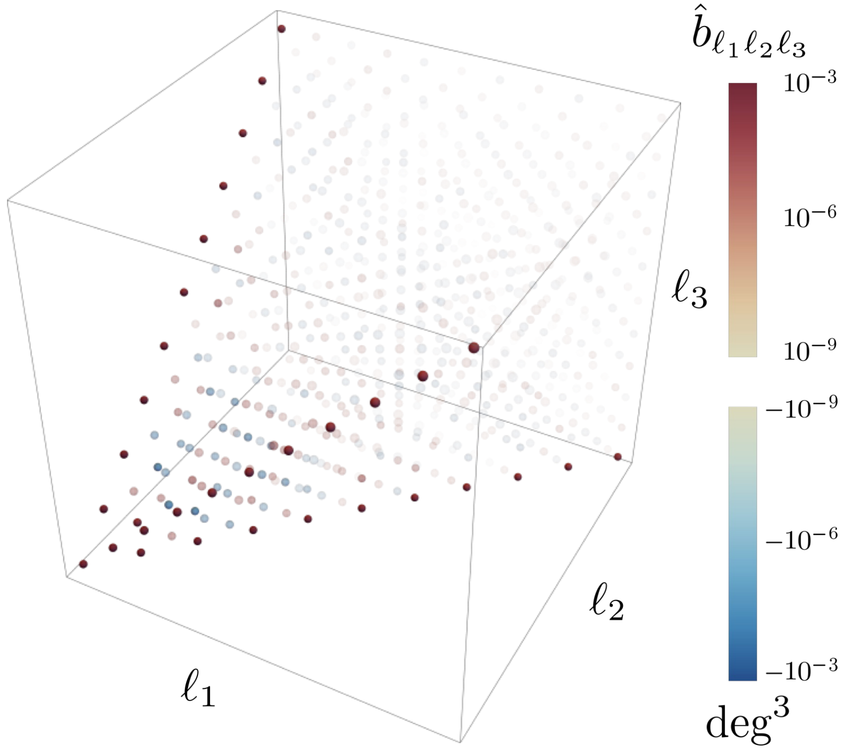
Measures of NG 2: bispectrum

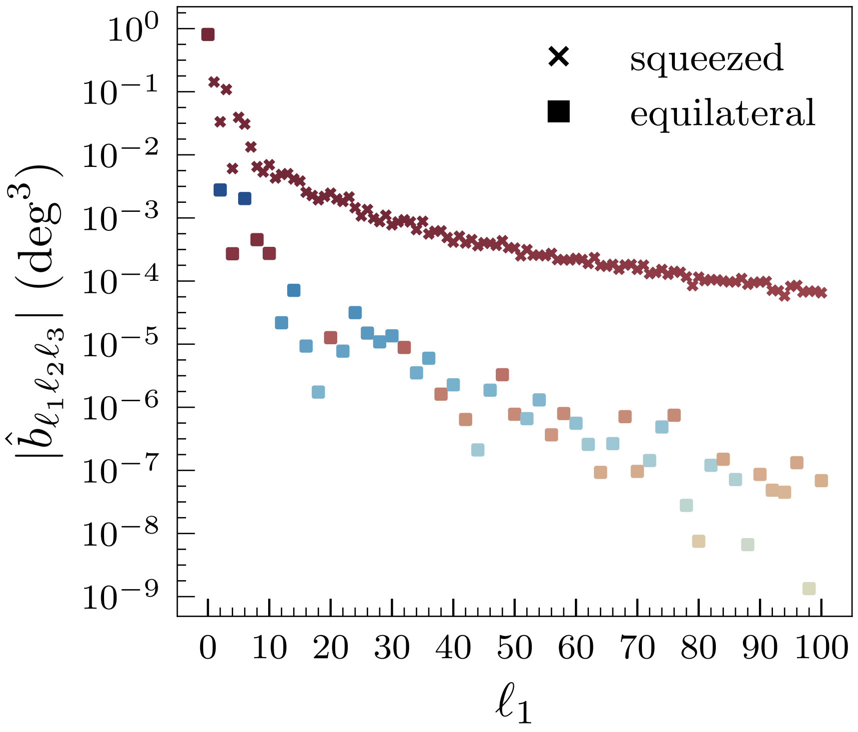
[Hagimoto & AL, arXiv:2306:07351]

bispectrum
3-point correlations

$$\hat{b}_{\ell_1\ell_2\ell_3} = h^{-1}_{\ell_1\ell_2\ell_3} \sum_{m_1=-\ell_1}^{\ell_1} \sum_{m_2=-\ell_2}^{\ell_2} \sum_{m_3=-\ell_3}^{\ell_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \hat{\alpha}_{\ell_1 m_1} \hat{\alpha}_{\ell_2 m_2} \hat{\alpha}_{\ell_3 m_3}$$

single realization
largest in squeezed triangle form





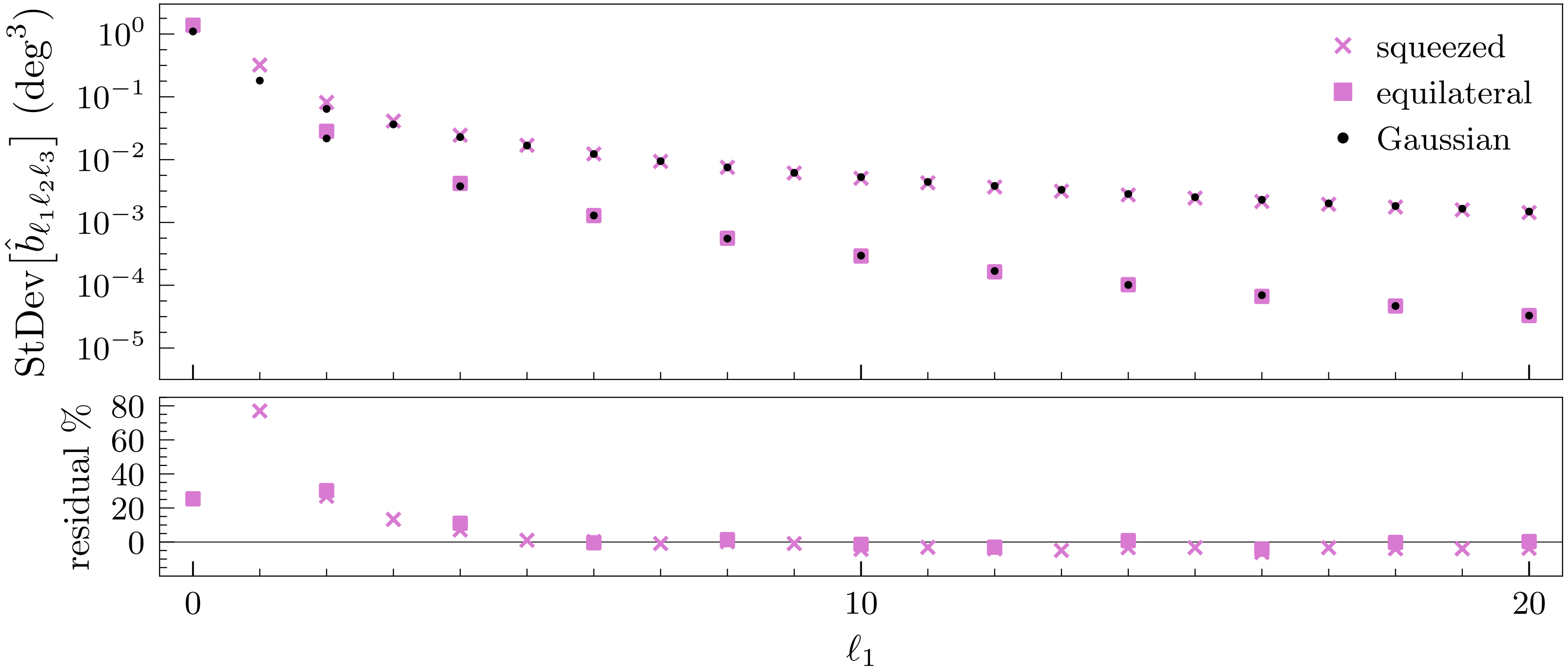
Measures of NG 2: bispectrum

[Hagimoto & AL, arXiv:2306:07351]

bispectrum
3-point correlations

$$\hat{b}_{\ell_1\ell_2\ell_3} = h^{-1}_{\ell_1\ell_2\ell_3} \sum_{m_1=-\ell_1}^{\ell_1} \sum_{m_2=-\ell_2}^{\ell_2} \sum_{m_3=-\ell_3}^{\ell_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \hat{\alpha}_{\ell_1 m_1} \hat{\alpha}_{\ell_2 m_2} \hat{\alpha}_{\ell_3 m_3}$$

average bispectrum
and comparison with Gaussian random field



Measures of NG 3: scattering transform

Yin, Dai, Ferraro (2023

std. method
power spectrum

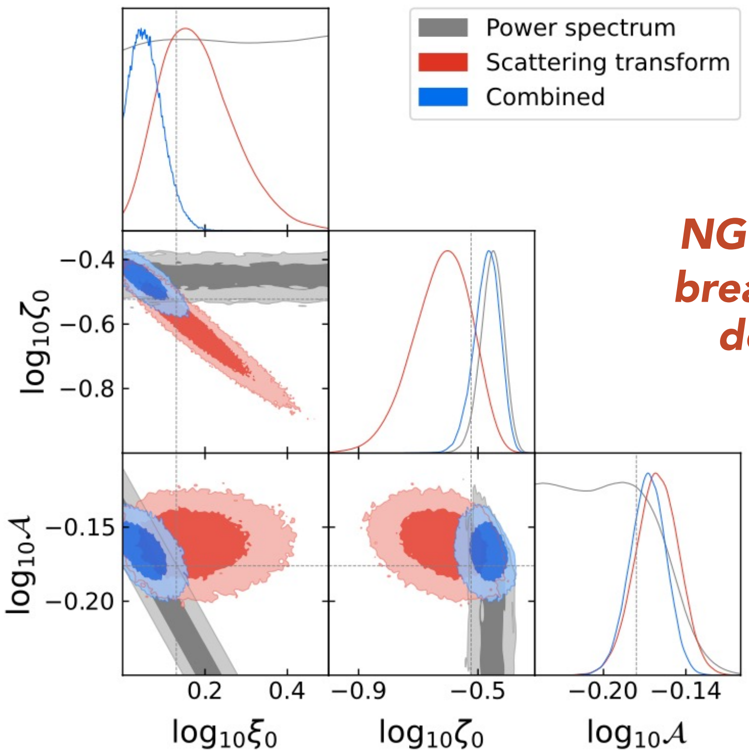
$$\text{signal:} \quad I_0(\mathbf{x})$$
$$\text{plane wave:} \quad \phi_{\mathbf{k}}(\mathbf{x})$$
$$P_{\mathbf{k}}(\mathbf{x}) = \langle |I_0 * \phi_{\mathbf{k}}|^2 \rangle(\mathbf{x})$$

new method
scattering transform

$$\text{wavelet:} \quad \psi^{j.l}(\mathbf{x})$$

$$I_1^{j,l}(\mathbf{x}) = \langle |I_0 * \psi^{j,l}|^2 \rangle(\mathbf{x})$$
$$I_2^{j_1,l_1,j_2,l_2}(\mathbf{x}) = \langle |I_1^{j_1,l_1} * \psi^{j_2,l_2}|^2 \rangle(\mathbf{x})$$
$$s_1^j = \langle I_1^{j,l} \rangle_{\mathbf{x},l}$$
$$s_2^{j_1,j_2} = \langle I_2^{j_1,l_1,j_2,l_2} \rangle_{\mathbf{x},l_1,l_2}$$

comparison
pow-spec vs. scatt-transform



(b) $\mathcal{A}^2\xi_0 = 0.6,\ \mathcal{A} = 2/3,\ \zeta_0 = 0.3$

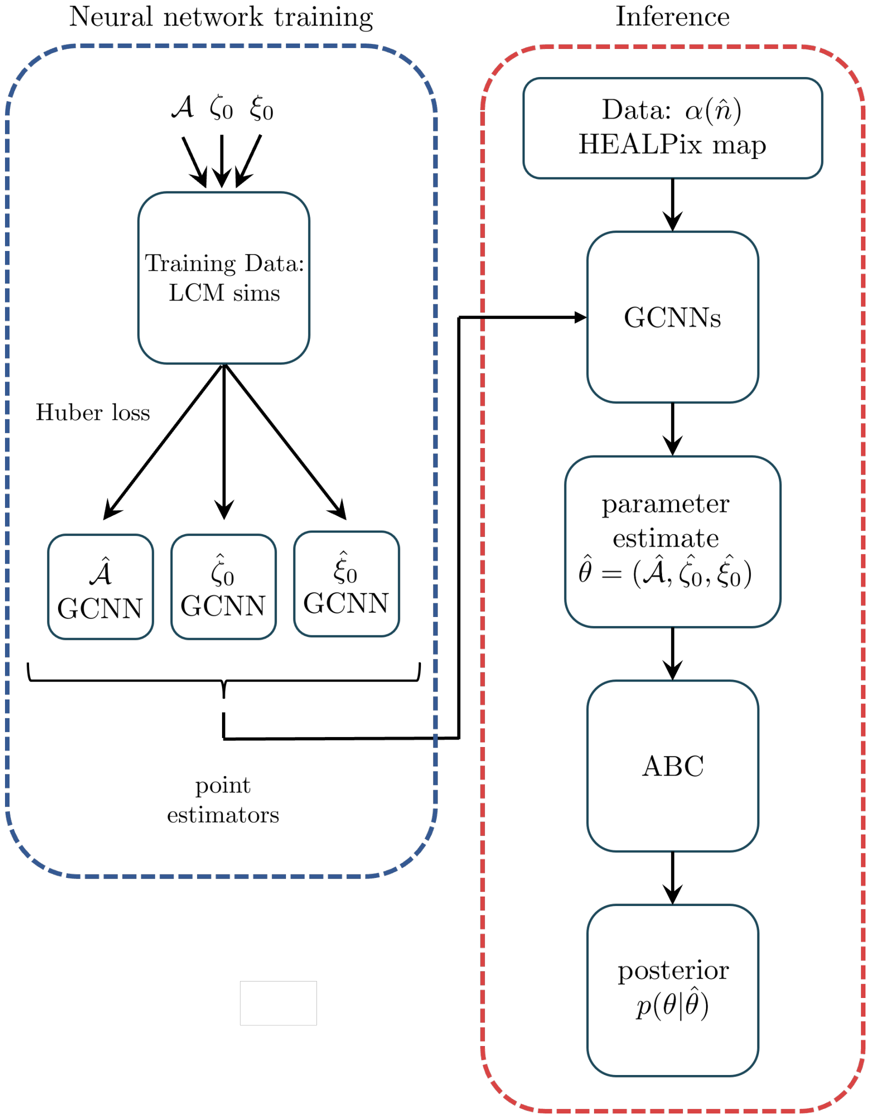
NG information breaks the $A^2\ \xi_0$ degeneracy

machine learning
for axion string identification

Machine learning for axion strings

--- early stages ---

goal: to train an AI to identify features of axion strings in CMB polarization maps

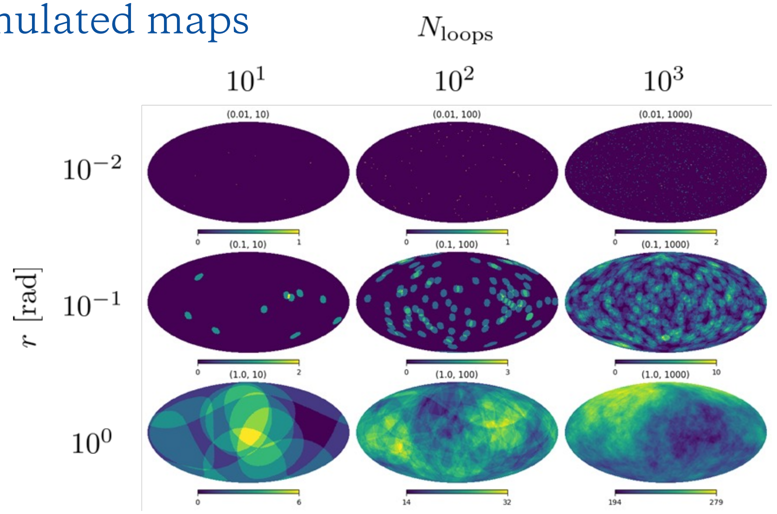


Ray Hagimoto (Rice U grad)

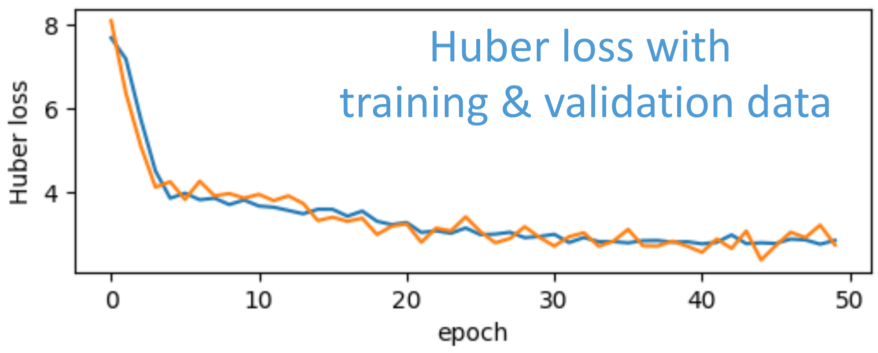
Machine learning for axion strings

--- early stages ---

simulated maps

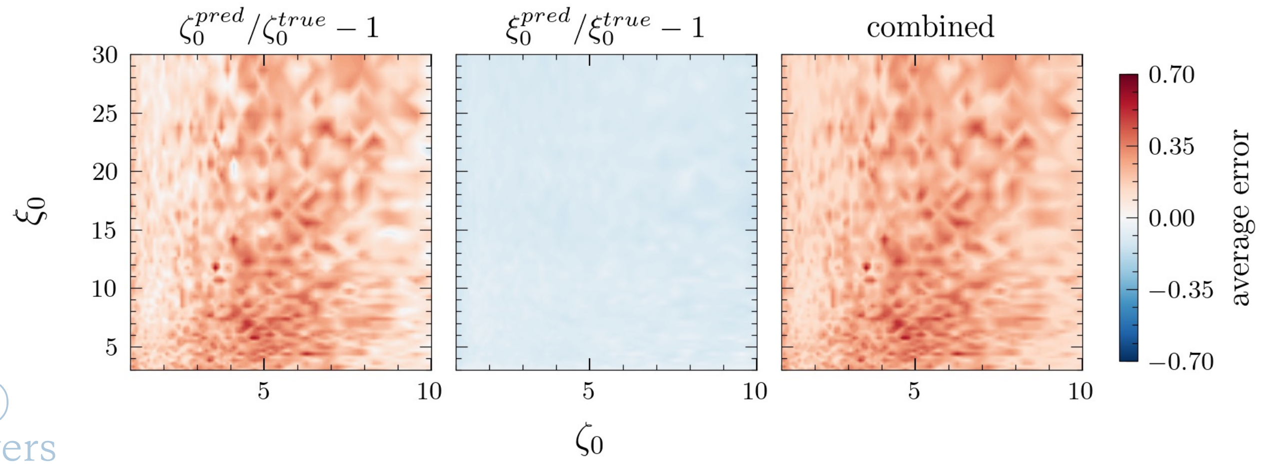


training




Ray Hagimoto
(Rice U grad)

how well is it working? … not bad!



things to do
& where we're going:
-- detector noise
-- beyond LCM sims
-- real CMB data
-- projections

package: DeepSphere (Python)
architecture: 3 conv + 3 pool layers

summary
& conclusion

Summary

- If a hyper-light axion-like particle exists in Nature, the associated cosmological network of axion strings can leave an imprint on CMB polarization through birefringence
- We use existing measurements of anisotropic birefringence (Planck, SPT, …) to place constraints on this scenario. Next-generation telescopes (CMB-S4) will probe O(1) electromagnetic anomaly coefficients and thereby probe the axion's UV embedding
- We argue that measurements of anisotropic birefringence could not only reveal the presence of a hyper-light ALP in Nature, but also lead to a measurement of its mass
- Our ongoing work (very early stages) seeks to use machine learning techniques (spherical CNN) to detect the subtle signal of axion strings in CMB polarization data