Title: CMB birefringence from axion strings

Speakers: Andrew Long

Series: Particle Physics

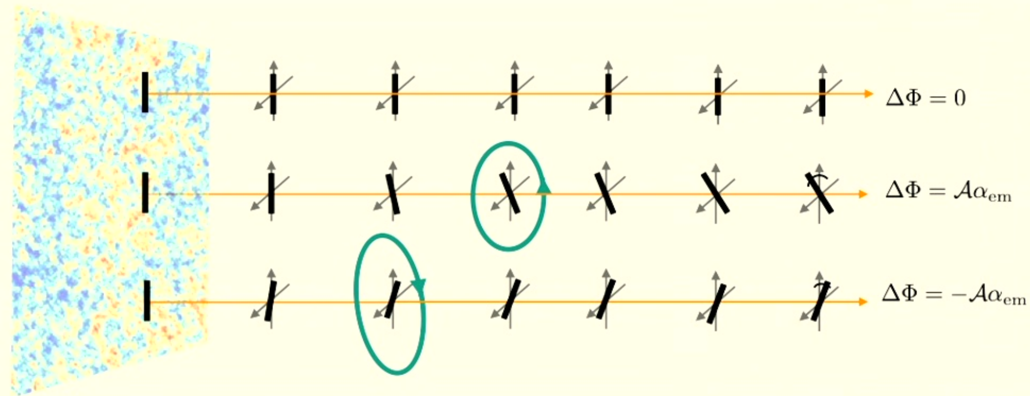
Date: March 26, 2024 - 1:00 PM

URL: https://pirsa.org/24030125

Abstract: A cosmological network of axion strings in our Universe today may leave its imprint on the polarization pattern of the cosmic microwave background radiation through the phenomenon of axion-string-induced birefringence. I will explain how this signal arises, discuss how it depends on the properties of the string network and the axion-photon coupling, describe how existing measurements of anisotropic birefringence place constraints on axion strings, and discuss how the non-Gaussian nature of this signal could be leveraged in searches with future data.

Zoom link

CMB Birefringence from Axion Strings

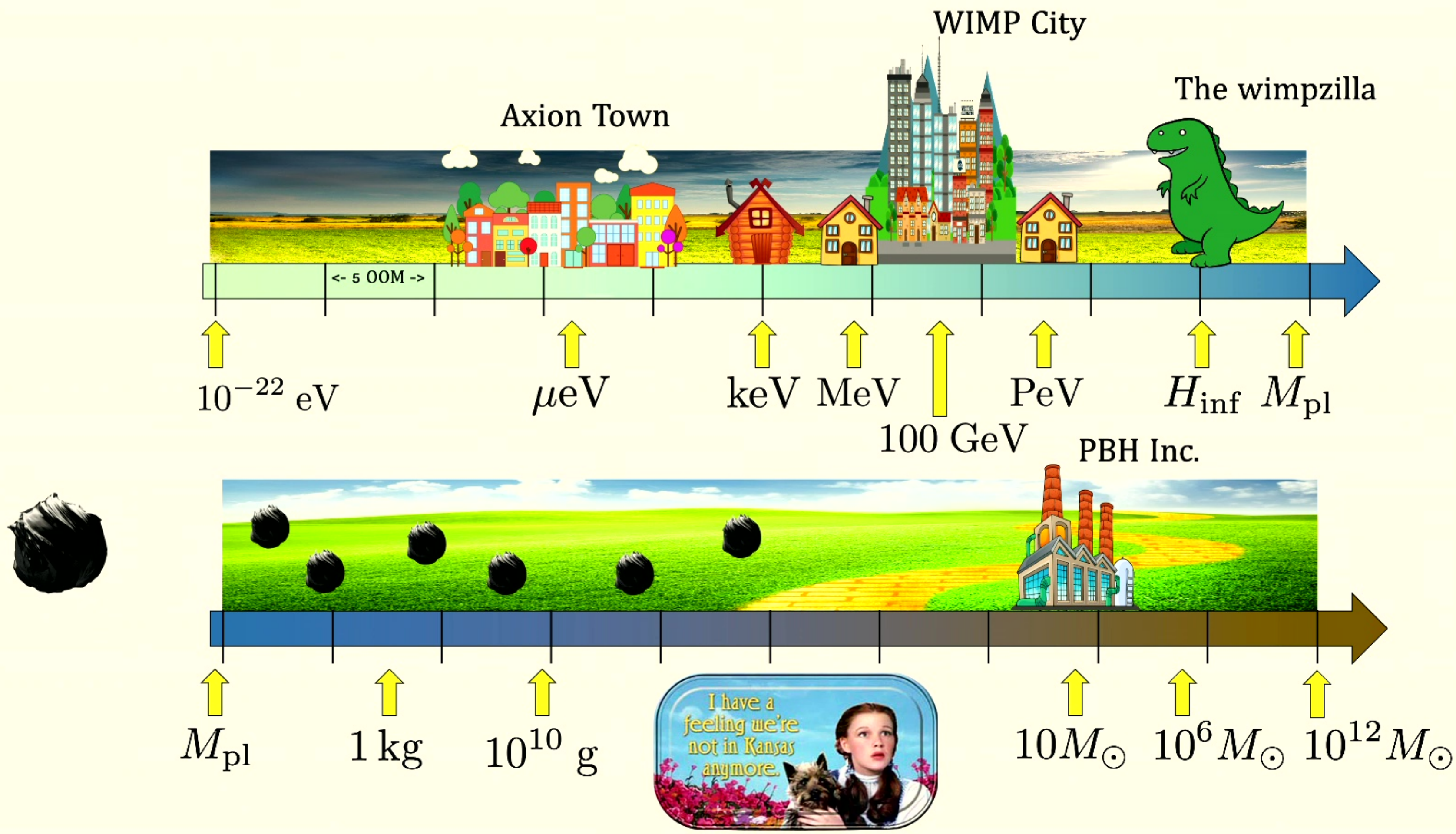


Andrew J. Long
Rice University

@ Perimeter Institute
March 26, 2024

RICE

NOT THIS TALK



$1\,{\rm g} \simeq 6 \times 10^{23}\ {\rm GeV}/c^2$ $\quad$ $1 M_\odot \simeq 1 \times 10^{57}\ {\rm GeV}/c^2$

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 find that it is difficult (but not impossible!) to reconcile the detection of isotropic birefringence with strong limits on anisotropic birefringence coming from axion strings
- 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

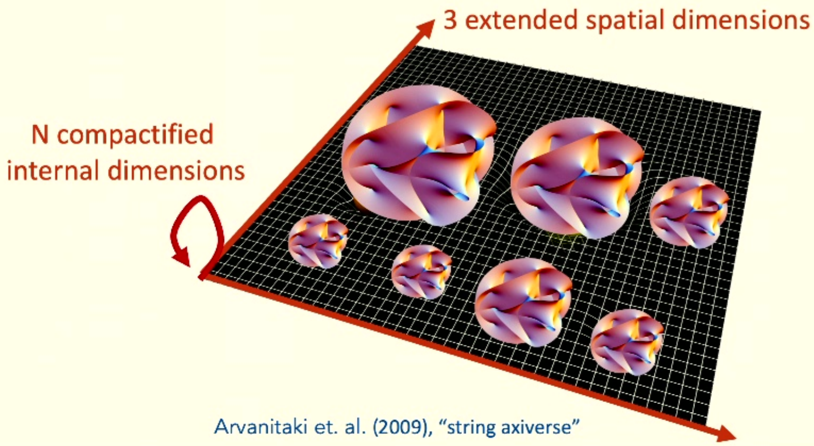
axion-like particles
& cosmic axion strings

Theory landscape: axion-like particles

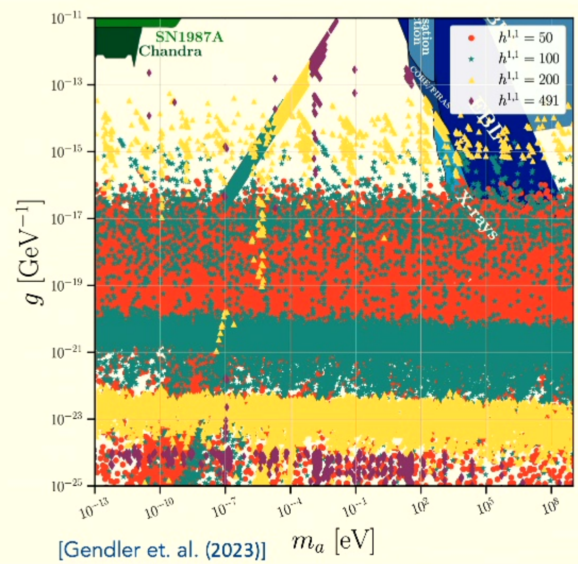
axion-like particles

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

ALPs from extra dimensions
(such as string theory)



Arvanitaki et. al. (2009), "string axiverse"



[Gendler et. al. (2023)]

Theory landscape: axion-like particles

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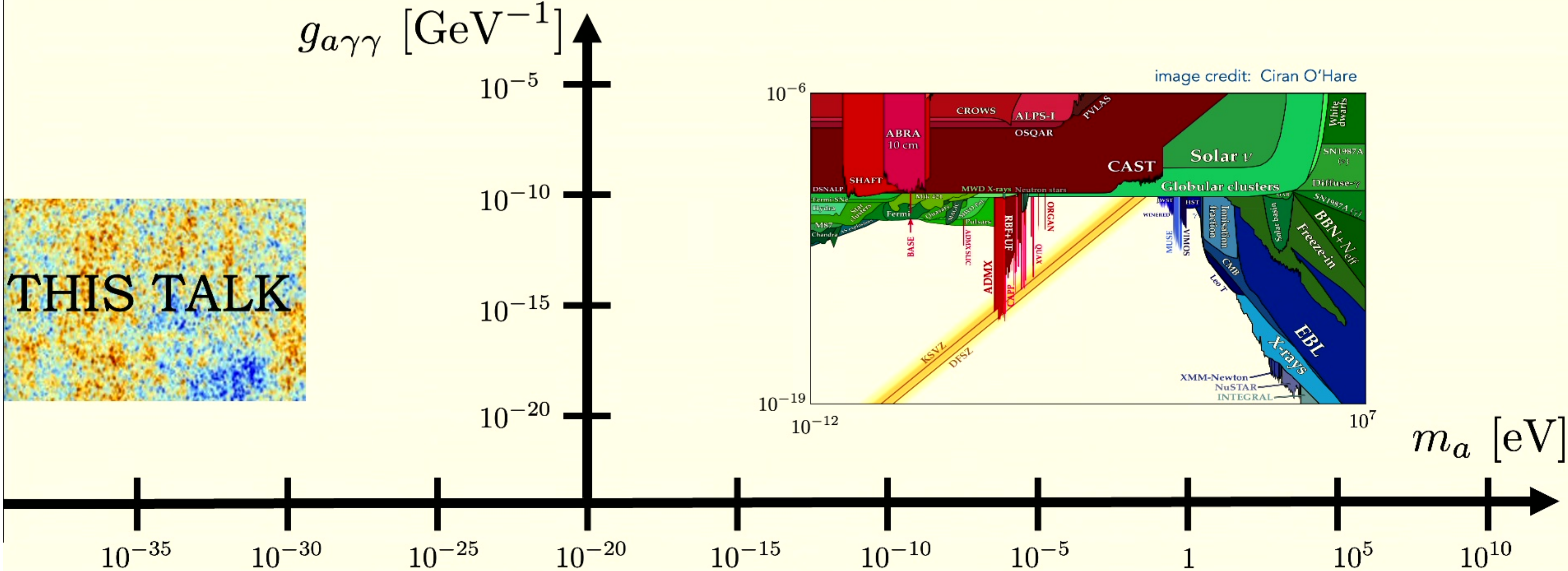


Axion strings from ALPs

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

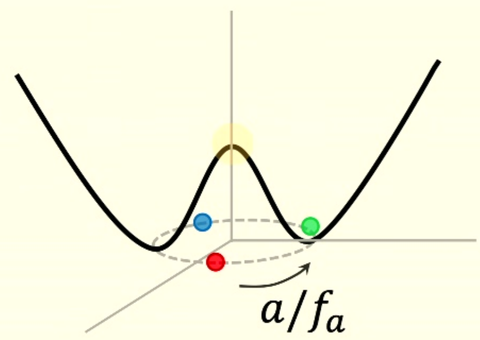
string formation:

early-universe phase transition

Field space

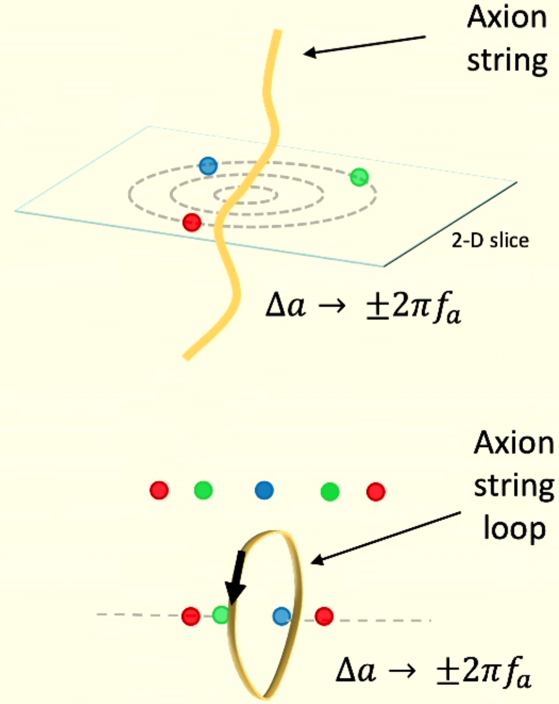
$$\mathscr{L} = |\partial\Phi|^2 - \lambda\left(|\Phi|^2 - f^2/2\right)^2$$

$$\Phi(x) = \frac{f+s(x)}{\sqrt{2}}\, e^{ia(x)/f}$$



$\longleftrightarrow$

Physical space



string thickness = microscopic

string length = cosmological

"post-inflation scenario"

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

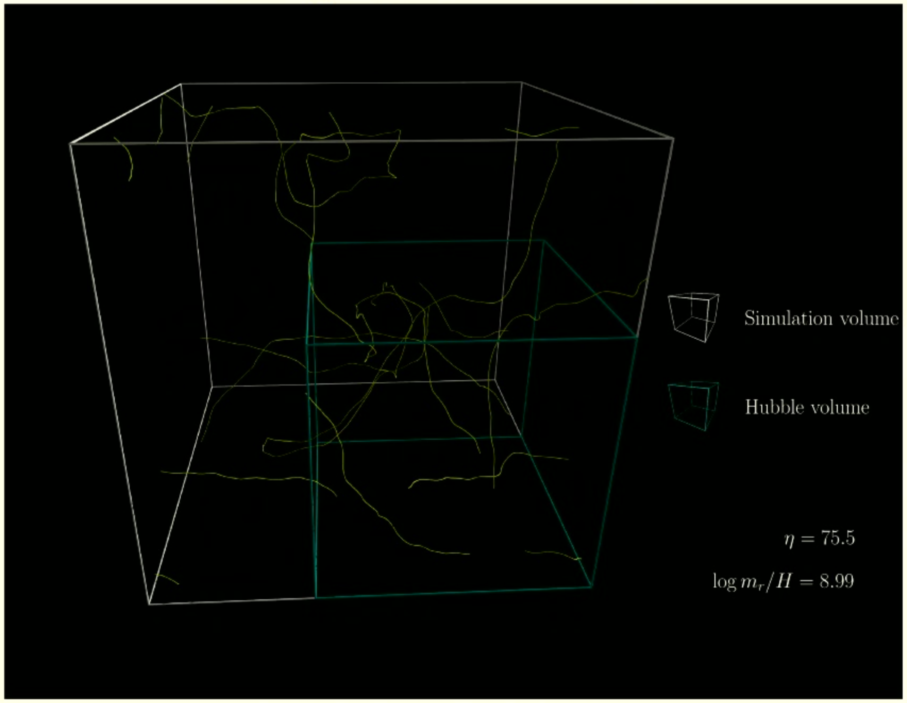
Clockwise (+); or anti-clockwise (-)

image credit: Mudit Jain (2021)

A cosmic string network

[Buschmann et. al. (2022)]
see also: [Saikawa et. al. (2024)]

string network simulation:



things we have learned:

- the network contains long strings & string loops
- string tension pulls bent string segments ($L < d_H$)
- string segments cross & reconnect
- reconnections forms new loops
- loops ($L < d_H$) emit axions and collapse
- distribution over loop lengths tracks Hubble
- average energy density tracks Hubble

things we want to know:

- what's the energy spectrum of axion emission?
- how many strings in the universe today?
  - does the network maintain scaling?
  - should be O(10) strings per Hubble volume
- distribution over loop lengths

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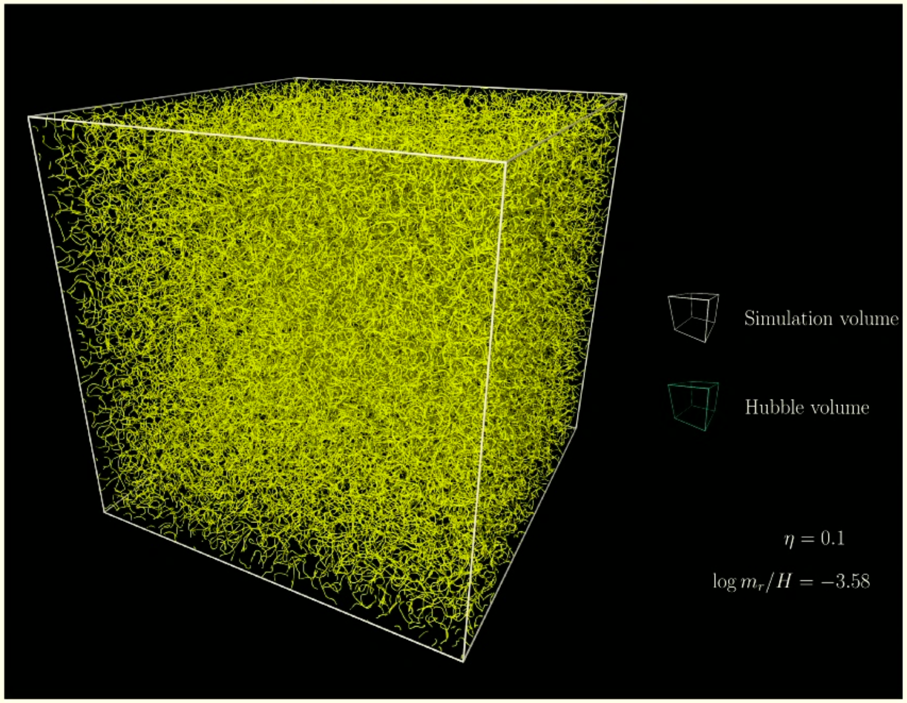

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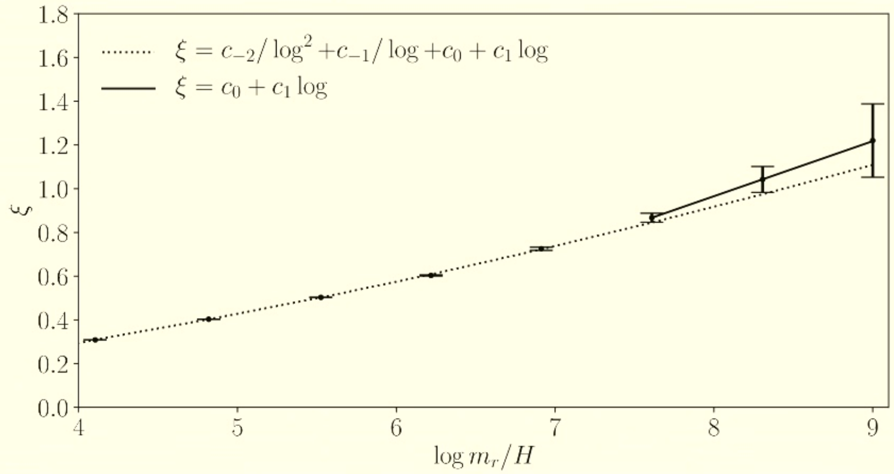
To scale or not to scale?

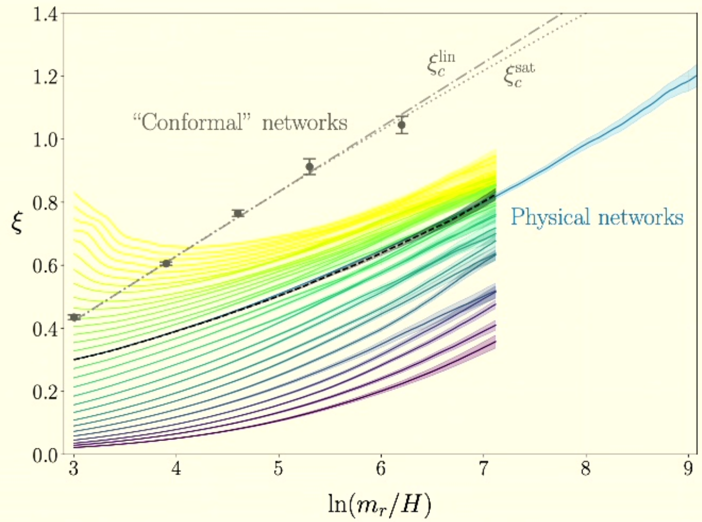
see also: [Gorghetto et. al. (2021)]

string abundance parameter: $\xi \equiv l_s t^2 / \mathcal{V}$ so $\rho_s \sim \xi \mu H^2$

Buschmann et. al. (2022)
adaptive mesh refinement



Saikawa et. al. (2024)
fixed lattice 11264³ sites



extrapolating till today: $\log \sim 120$ and $\xi \sim 25$

Cosmological probes of axion strings

How can we detect axion strings in the Universe today?

Gravitational Probes

Kaiser-Stebbins effect ➔ CMB

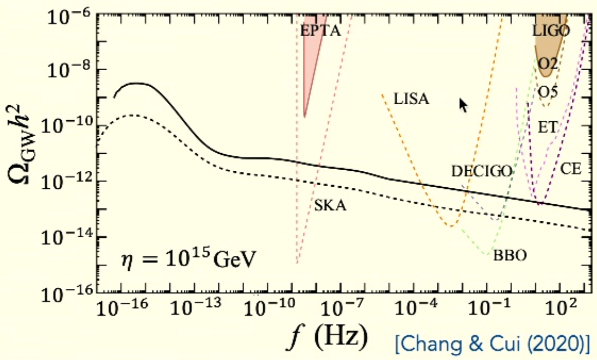
string wakes ➔ LSS

grav wave emission ➔ PTA, LVK, LISA

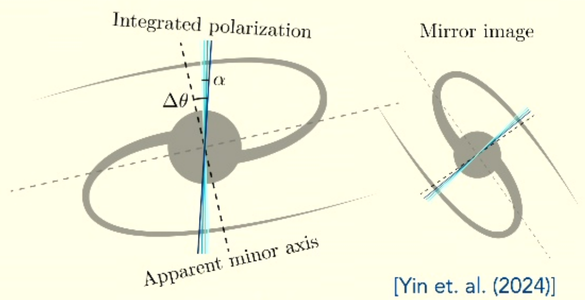
Non-Gravitational Probes

particle emission ➔ dark radiation … BBN … cosmic rays … CMB effects

birefringence ➔ CMB … galaxy polarization/shape



[Chang & Cui (2020)]



[Yin et. al. (2024)]

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

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

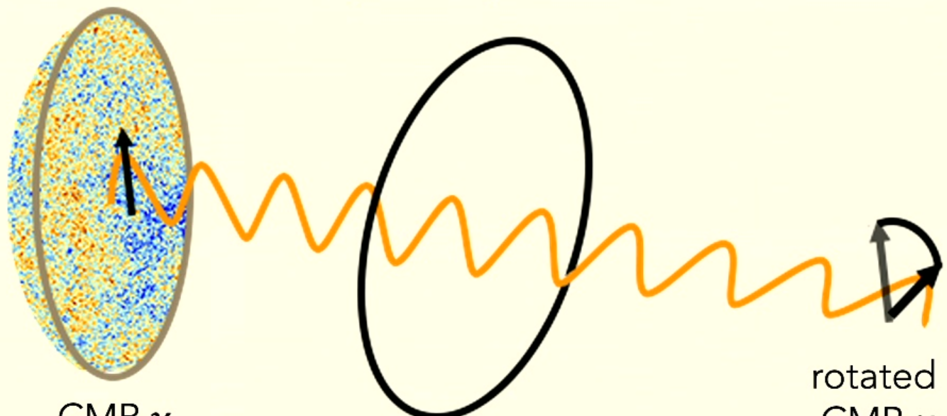
$$g_{a\gamma\gamma} = -\mathcal{A} \frac{\alpha_{\rm em}}{\pi f_a}$$

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

axion-induced birefringence:

an electromagnetic wave
traveling through a varying axion field
has its plane of polarization rotated

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



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 strings are circular loops
- Randomize loop orientation
- Randomize loop location in space
- All loops same radius at any time
- Loop radius tracks Hubble

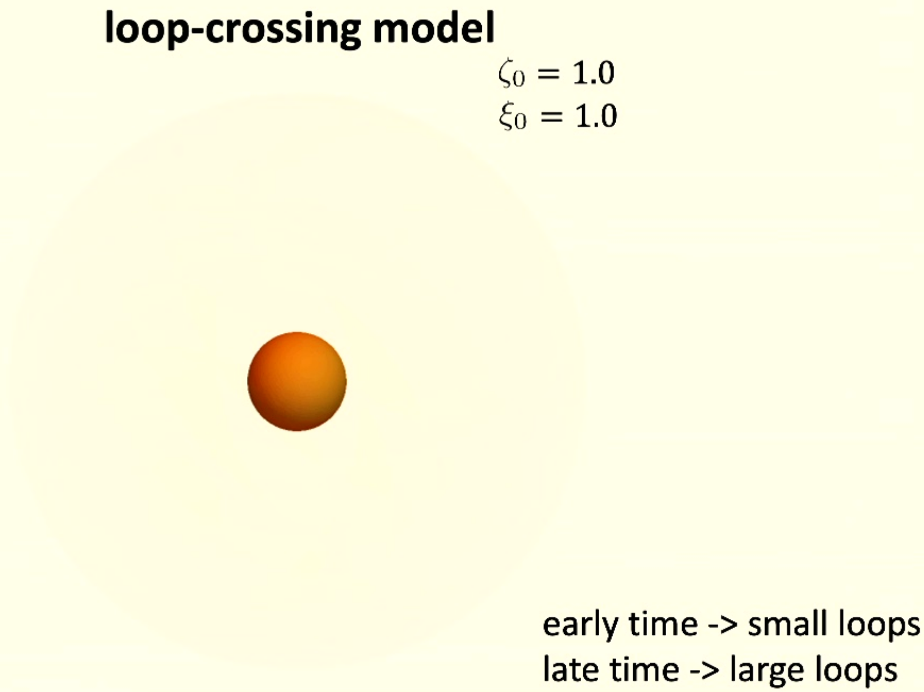
$$R(t) = \zeta_0 / H(t)$$

- Number of loops tracks Hubble

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

Model Parameters

$$\{m_a,\ \mathcal{A},\ \zeta_0,\ \xi_0\} \quad g_{a\gamma\gamma} = -\mathcal{A}\frac{\alpha_{\rm em}}{\pi f_a}$$



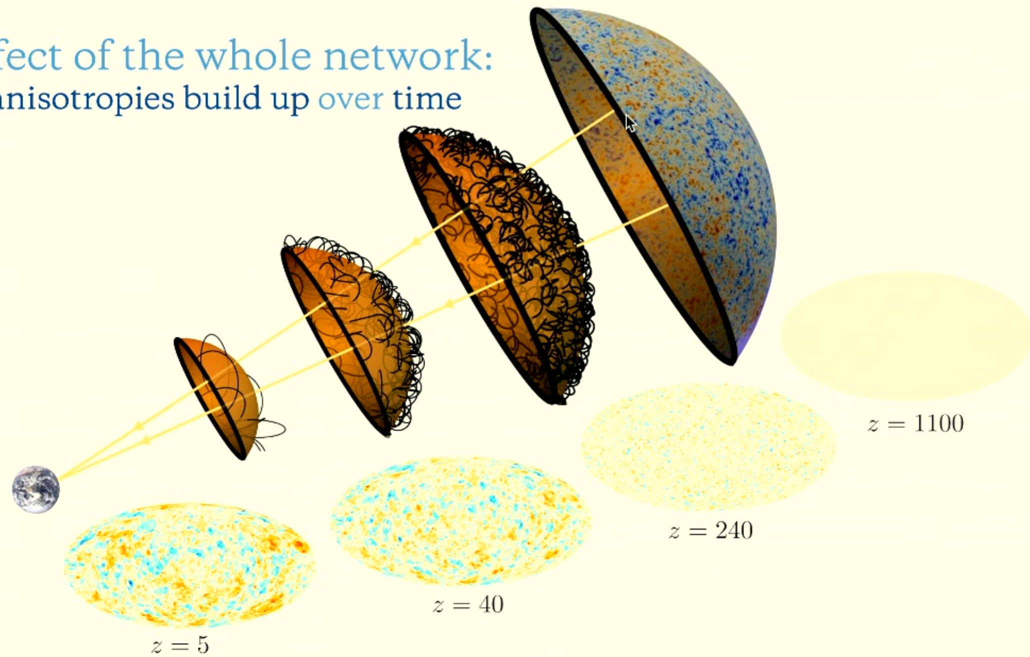
Expected birefringence signal

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

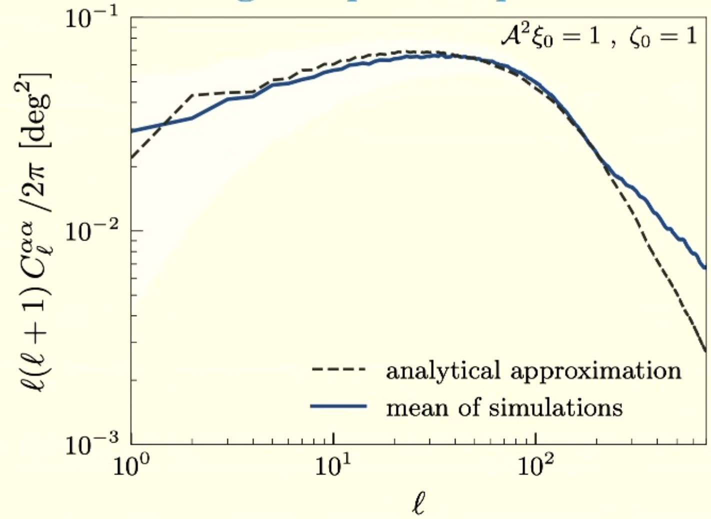
loop-crossing model:
a network of circular loops

$\mathcal{A}$ = 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: <$\alpha\alpha$> ~ $A^2\ \xi_0$

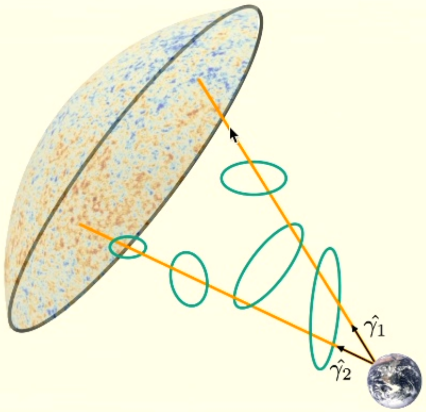
$*$ need $m_a \lesssim 3H_{\rm cmb} \approx 10^{-28}$ eV for the network to survive until after recombination

Analytical understanding

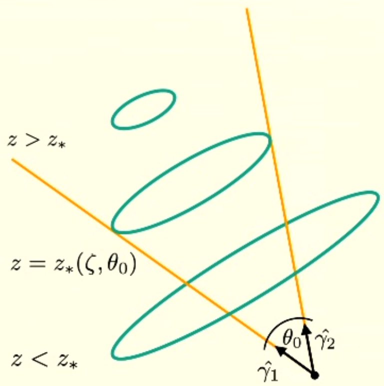
[Jain, AL, Amin, arXiv:2103:10962]

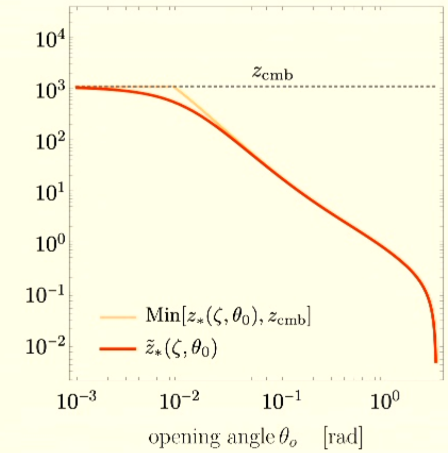
correlations accumulate
when both photons pass
through the same loops

$$\langle \alpha(\hat{\gamma}_1)\,\alpha(\hat{\gamma}_2)\rangle = \left(\mathcal{A}\alpha_{\rm em}\right)^2 N_{\rm both}(\hat{\gamma}_1 \cdot \hat{\gamma}_2)$$



large-angle correlations are
established later (small z)



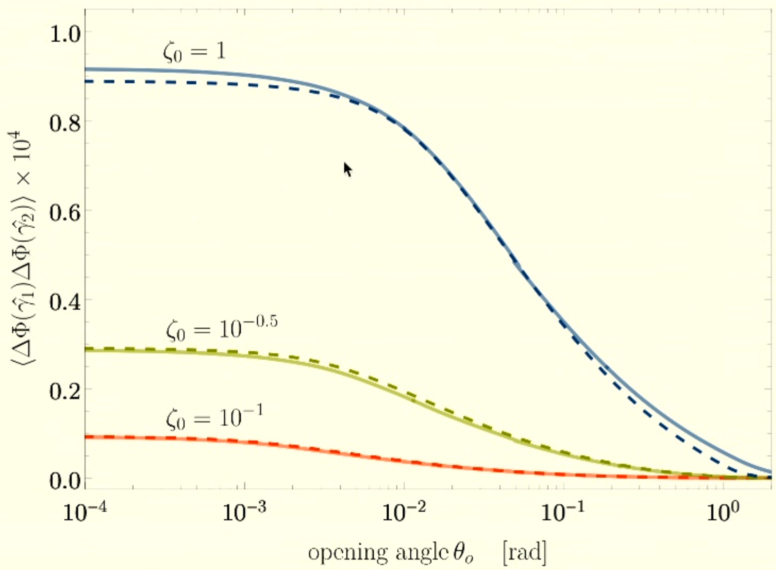


Analytical understanding

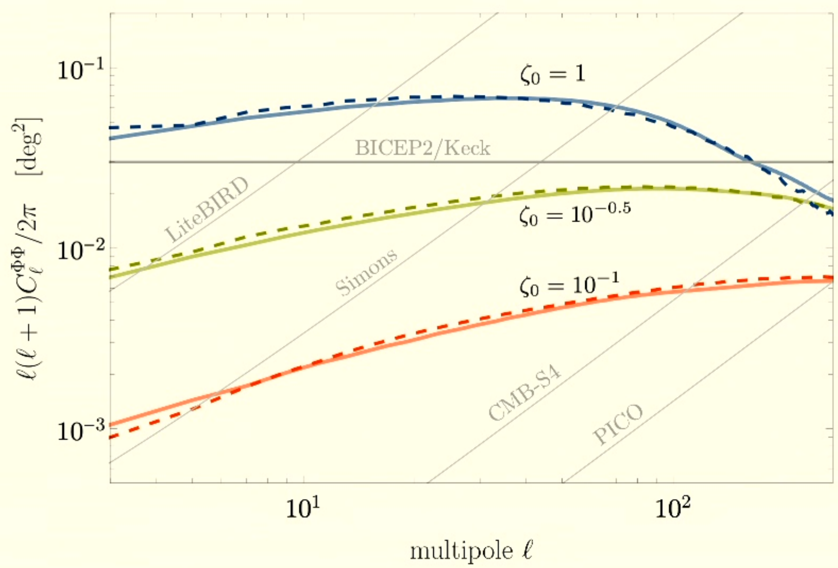
[Jain, AL, Amin, arXiv:2103:10962]

vary the loop radius: $R(t) = \zeta_0 / H(t)$

correlation function



angular power spectrum



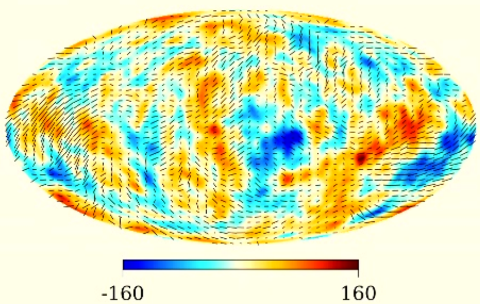
Effect on CMB polarization

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

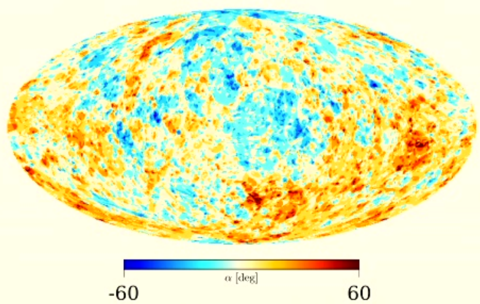
$$T(\hat{\boldsymbol{n}}) \to T(\hat{\boldsymbol{n}})$$

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

primordial CMB sky

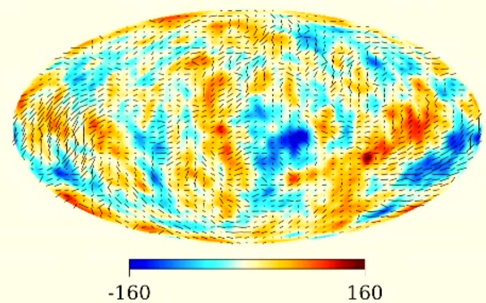


axion string-induced birefringence angle

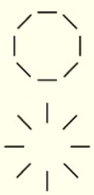


(exaggerated by ~30x)

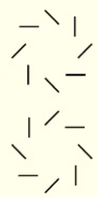
Planck's CMB sky



$E - mode$ pol pattern



$B - mode$ pol pattern



Signal of axion string-induced cosmological birefringence

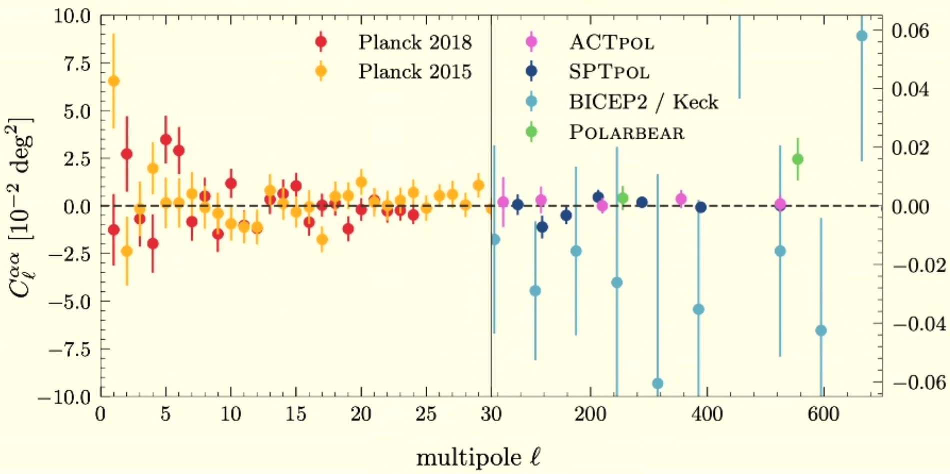
$$\begin{cases} \langle TB \rangle \neq 0 \\ \langle EB \rangle \neq 0 \end{cases}$$

$$C_\ell^{\mathrm{EB}} \sim \sin(4\Delta\Phi)\big(C_\ell^{\mathrm{EE}} - C_\ell^{\mathrm{BB}}\big)$$

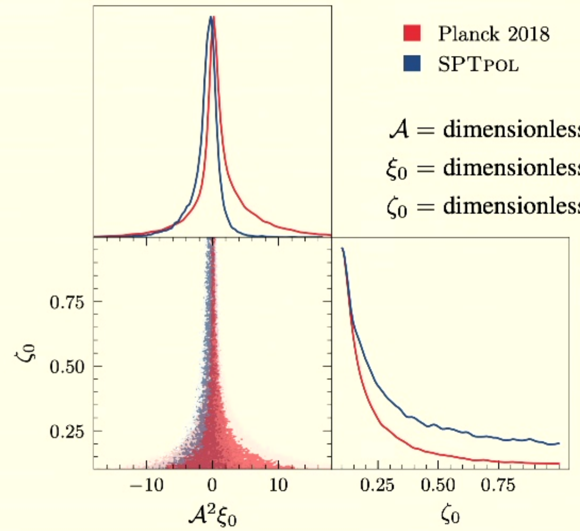
Constraints from anisotropic birefringence

[Jain, AL, Amin, arXiv:2103:10962]
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]
see also: Yin, Dai, & Ferraro (2021)

measurements of CMB polarization:
no evidence for anisotropic birefringence



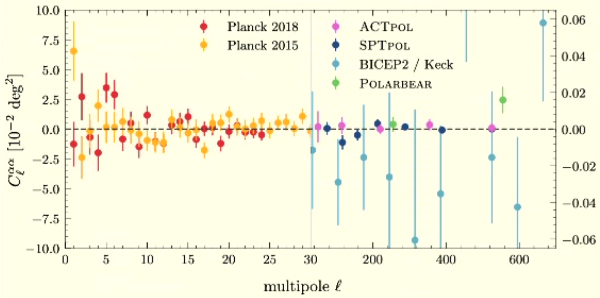
a constraint on axion strings networks
& their coupling to electromagnetism:

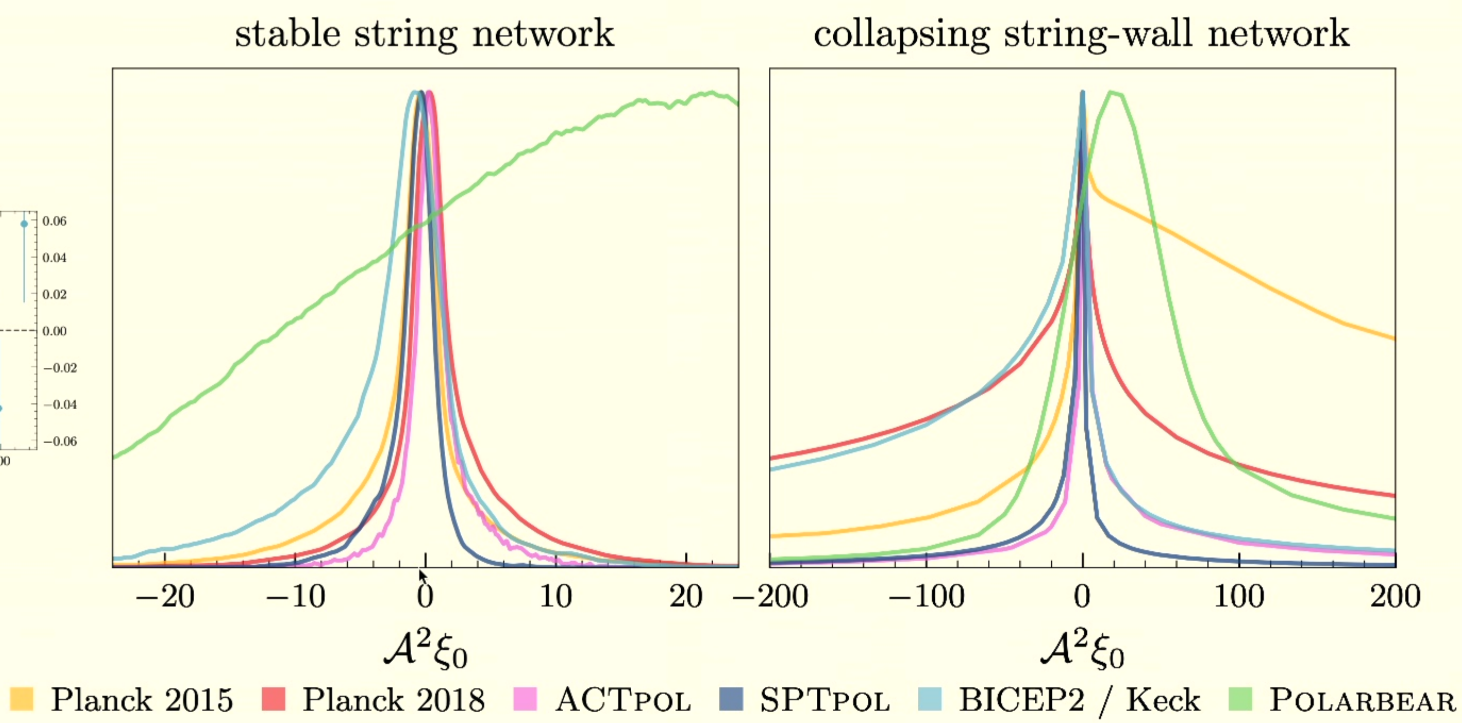


$\mathcal{A}$ = dimensionless axion-photon coupling
ξ_0 = dimensionless loop density (Hubble units)
ζ_0 = dimensionless loop length (Hubble units)

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

Constraints from anisotropic birefringence





Implications

CMB observations constrain:

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

future telescopes

probes of isotropic + aniso. birefringence

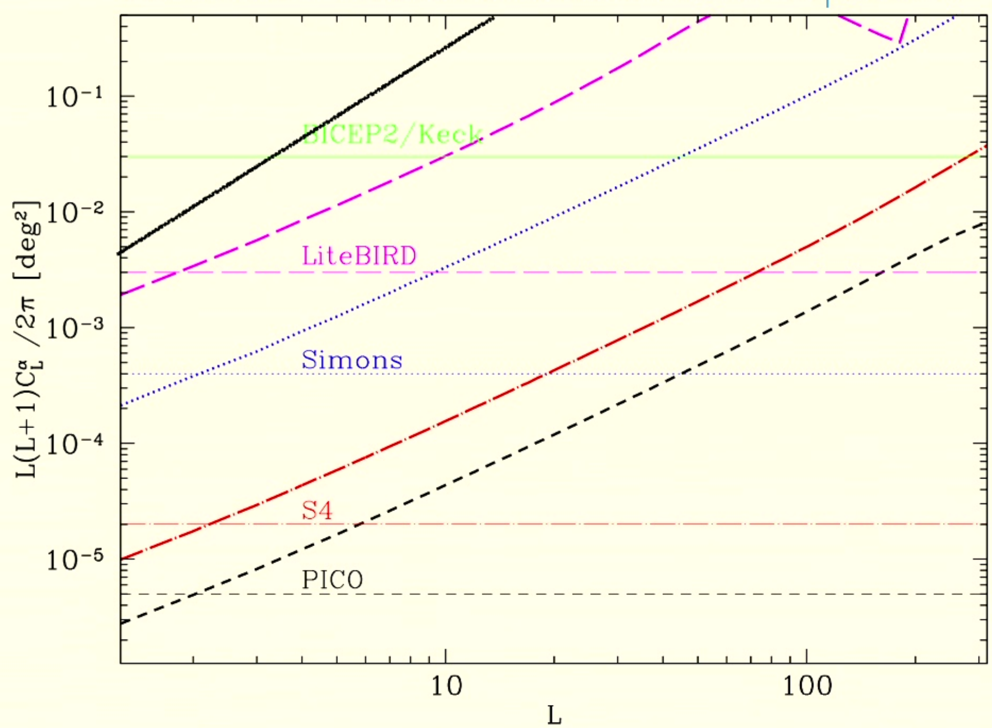
Current			LiteBIRD			SO			CMB-S4-like			PICO		
α ′	A_α $10^{-2}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ ′	α ′	A_α $10^{-3}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ ′	α ′	A_α $10^{-4}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ ′	α ′	A_α $10^{-5}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ ′	α ′	A_α $10^{-5}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ ′
-	-	-	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.

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

Pogosian et. al. (2019)

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



what about

isotropic birefringence

Are strings responsible for isotropic birefringence?

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

reported detection of isotropic birefringence:

same rotation angle across the whole sky
(using *Planck* & *WMAP* data)

$$\alpha_{00} = -1.21^{\circ}{}^{+0.33^{\circ}}_{-0.32^{\circ}} \ (68\% \ \mathrm{CL})$$

[Minami & Komatsu (2020)]
[Diego-Palazuelos et. al. (2022)]
[Eskilt (2022)], [Eskilt & Komatsu (2022)]
[Eskilt et. al. (2023)]

note that: $\beta = -\alpha_{00}/\sqrt{4\pi} \approx 0.34^{\circ}$

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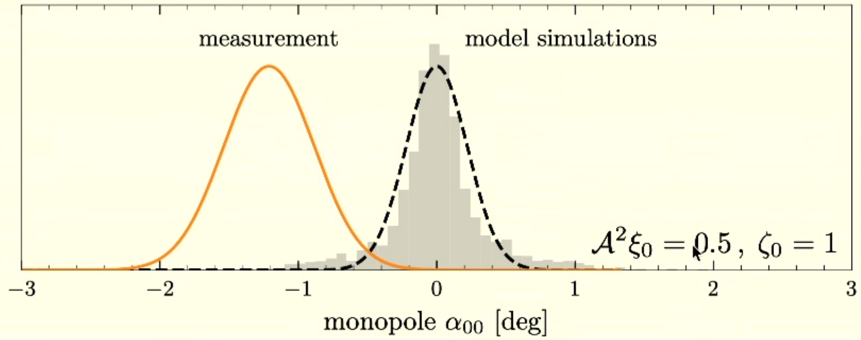
our conclusion: the isotropic signal is in tension with limits on anisotropic BF if they both arise from axion-string induced birefringence



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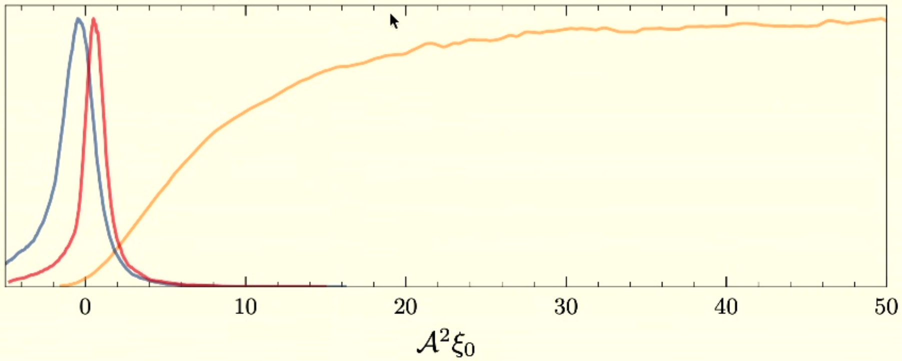

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Are strings responsible for isotropic birefringence?

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

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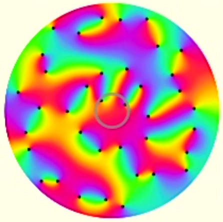
[Eskilt (2022)], [Eskilt & Komatsu (2022)]
[Eskilt et. al. (2023)]

loopholes allowing large iso-BF

(1) environmental effects
a nearby loop in our Hubble volume would dominate the isotropic signal

(2) Hubble-scale gradients
the massless axion field is expected to be inhomogeneous on the Hubble scale



(3) late-forming network
if the string network is not present just after recombination, the small-scale BF is suppressed

note that: $\beta = -\alpha_{00}/\sqrt{4\pi} \approx 0.34^\circ$

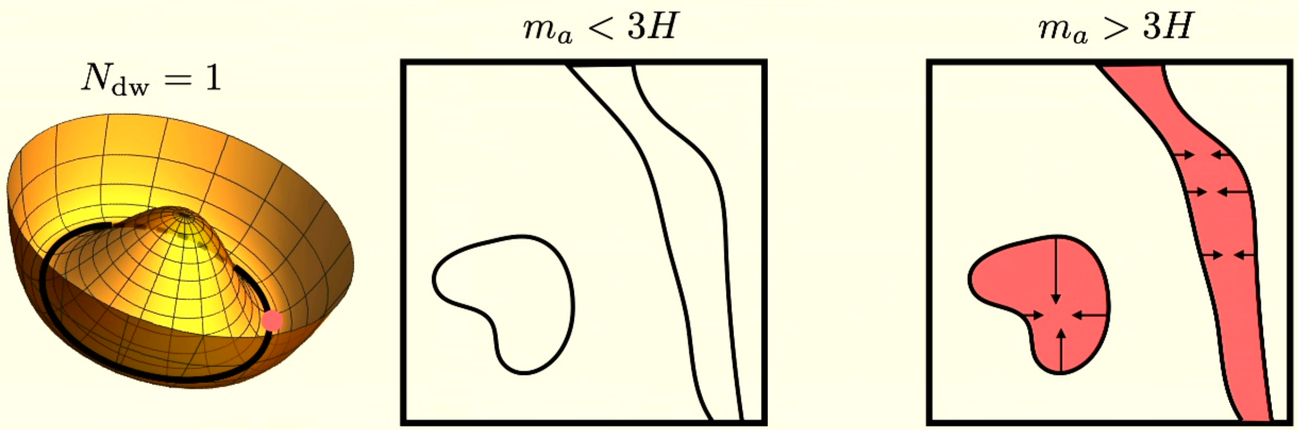
effect of
varying ALP mass

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:

$$\begin{cases} m_a \lesssim 3H_{\rm CMB} \simeq 3 \times 10^{-29}\ \text{eV} & \text{(string network survives until after recombination)} \\ m_a \gtrsim 3H_0 \simeq 5 \times 10^{-33}\ \text{eV} & \text{(string network collapses before today)} \end{cases}$$

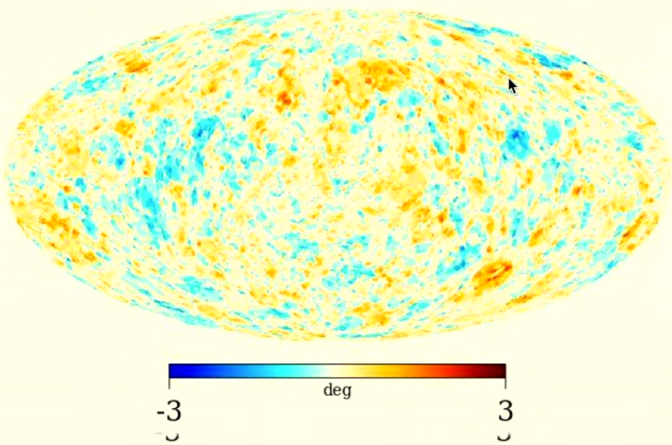
Impact on birefringence

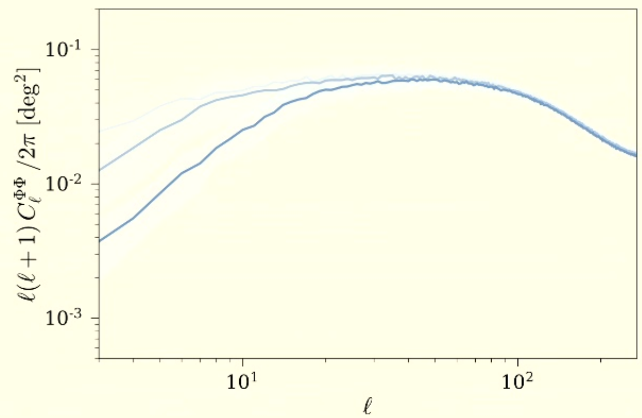
$\left(\text{assuming } N_{\rm DW} = 1\right)$

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

raise the ALP mass
(network collapses earlier)

$$m_a = 2 \times 10^{-31}\ \text{eV} \quad (z_c = 19)$$





after the network collapses at redshift z_c the accumulation of birefringence is shut off

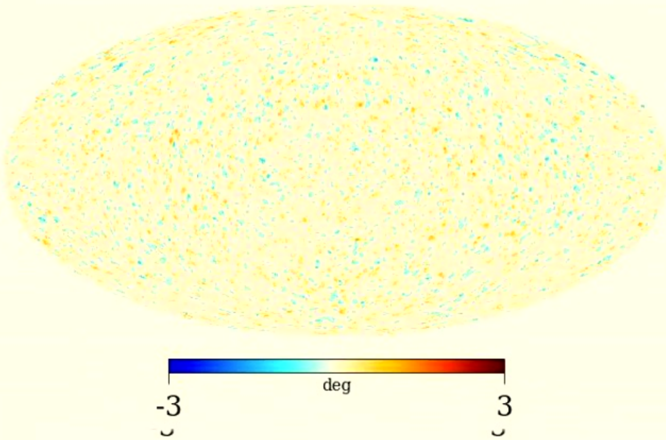
Impact on birefringence

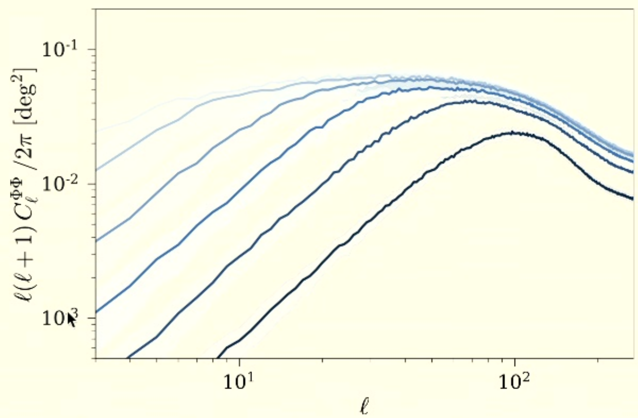
(assuming $N_{\mathrm{DW}} = 1$)

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

raise the ALP mass
(network collapses earlier)

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





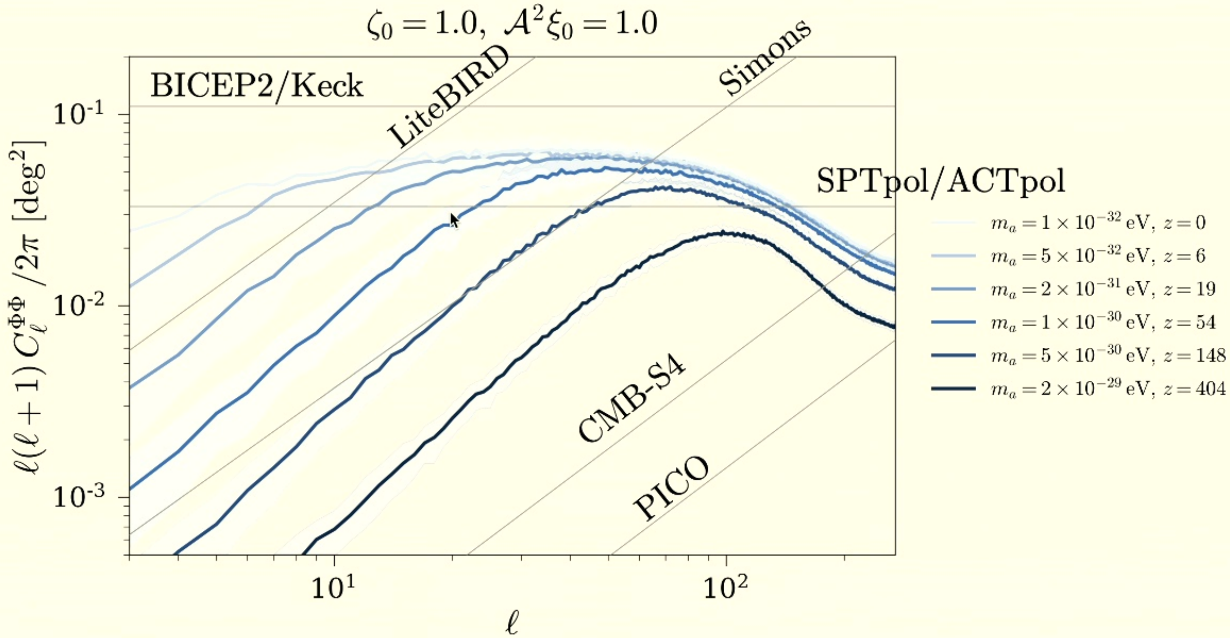
after the network collapses at redshift z_c the accumulation of birefringence is shut off

Implications

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

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

raise the ALP mass
(network collapses earlier)



strong scale dependence → possible to measure m_a

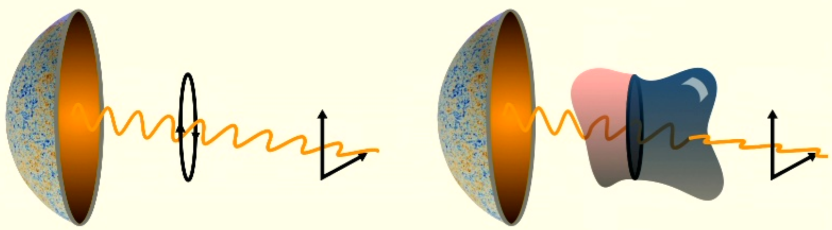
Similar results for stable string-wall networks

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

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

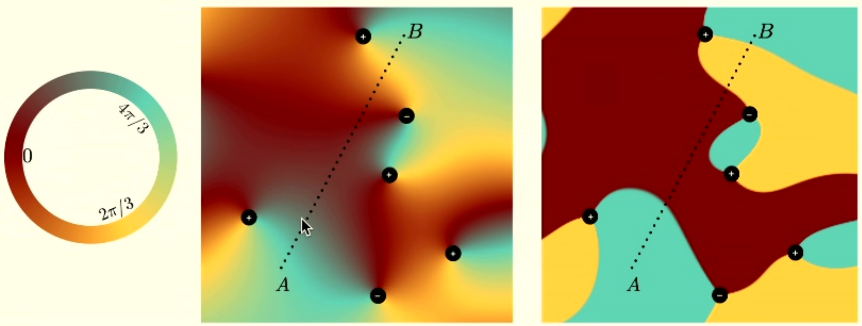
birefringence

due to string versus string-wall



birefringence builds up across many defects

similar behavior to string network

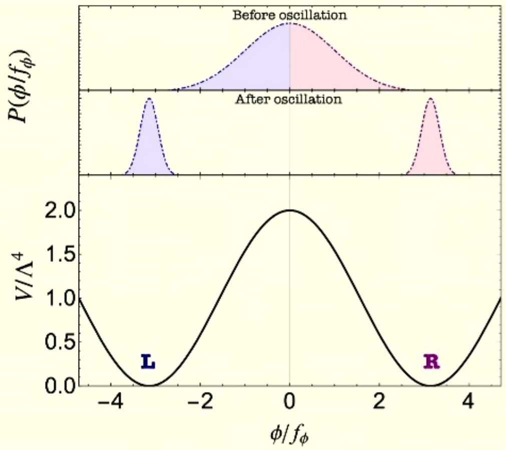


Complementary studies: stable axion domain walls

[Takahashi & Yin (2020)]
[Nakagawa, Takahashi, & Yamada (2021)]
[Kitajima, Kozai, Takahashi, & Yin (2022)]
[Gonzalez, Kitajima, Takahashi, & Yin (2022)]

domain walls without strings

expected if H_{inf} ~~ f_a



possible to evade DW problem

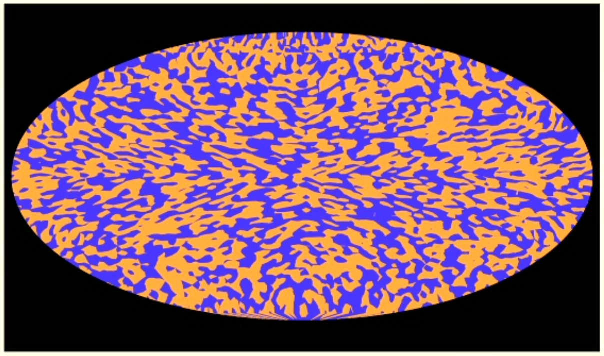
imposes bound on mass & decay constant

$$\sigma_{\rm DW} \simeq 8 f_\phi^2 m_\phi \lesssim (1\,{\rm MeV})^3,$$

$$f_\phi \lesssim 4\times 10^9\,{\rm GeV}\sqrt{\frac{10^{-20}\,{\rm eV}}{m_\phi}}.$$

birefringence signal

independent of propagation



$\Delta\Phi = 0$ if LSγ is from the vacuum R

$\Delta\Phi = c_\gamma \alpha$ if LSγ is from the vacuum L.

possible to accommodate detection of isotropic BF and evade limits on anisotropic BF

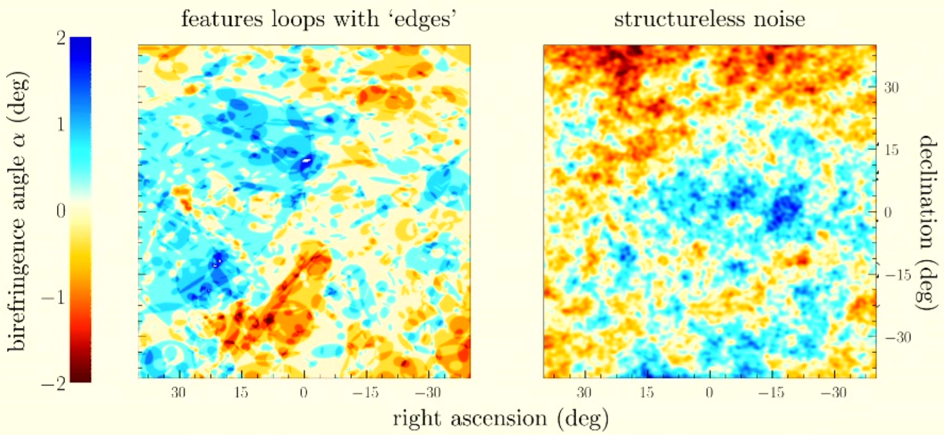
(no random-walk enhancement)

signatures of non-Gaussianity

non-Gaussianity in birefringence maps

[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

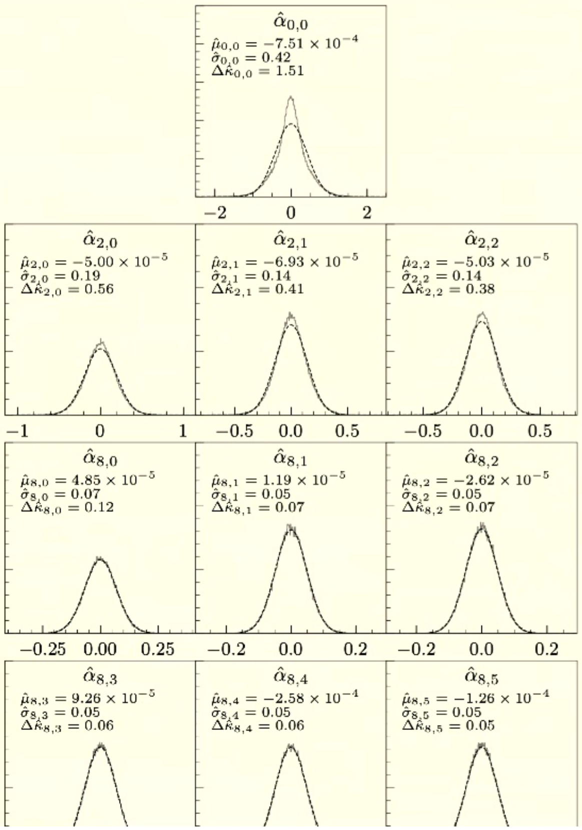
Gaussian random field with same power spectrum

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]

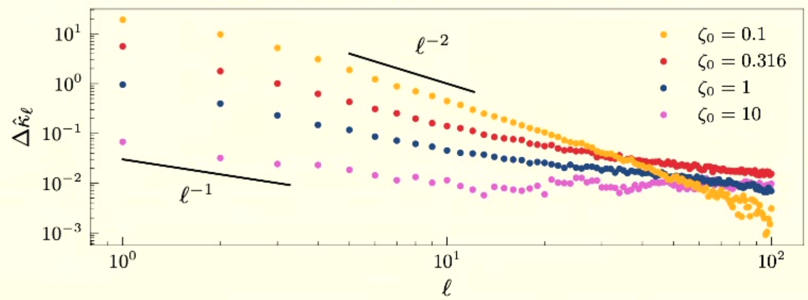
distribution over a_{lm}'s
less Gaussian at lower ell



kurtosis
a measure of Gaussianity

$$\kappa_{\ell m} = \frac{\langle |\hat{\alpha}_{\ell m} - \langle \hat{\alpha}_{\ell m} \rangle|^4 \rangle}{\langle |\hat{\alpha}_{\ell m} - \langle \hat{\alpha}_{\ell m} \rangle|^2 \rangle^2}$$ = 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: $R(t) = \zeta_0/H(t)$

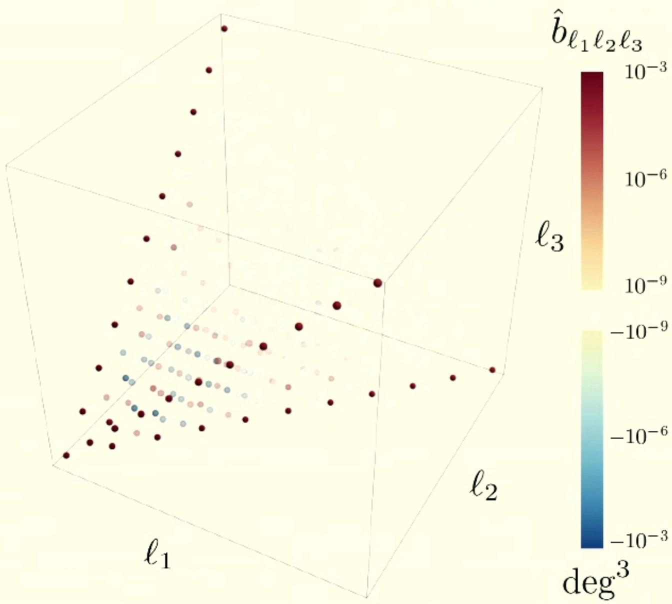
Measures of NG 2: bispectrum

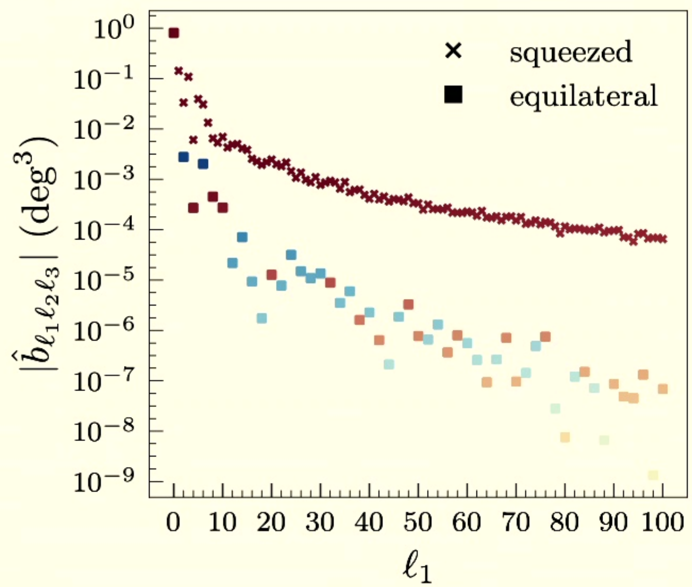
[Hagimoto & AL, arXiv:2306:07351]

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





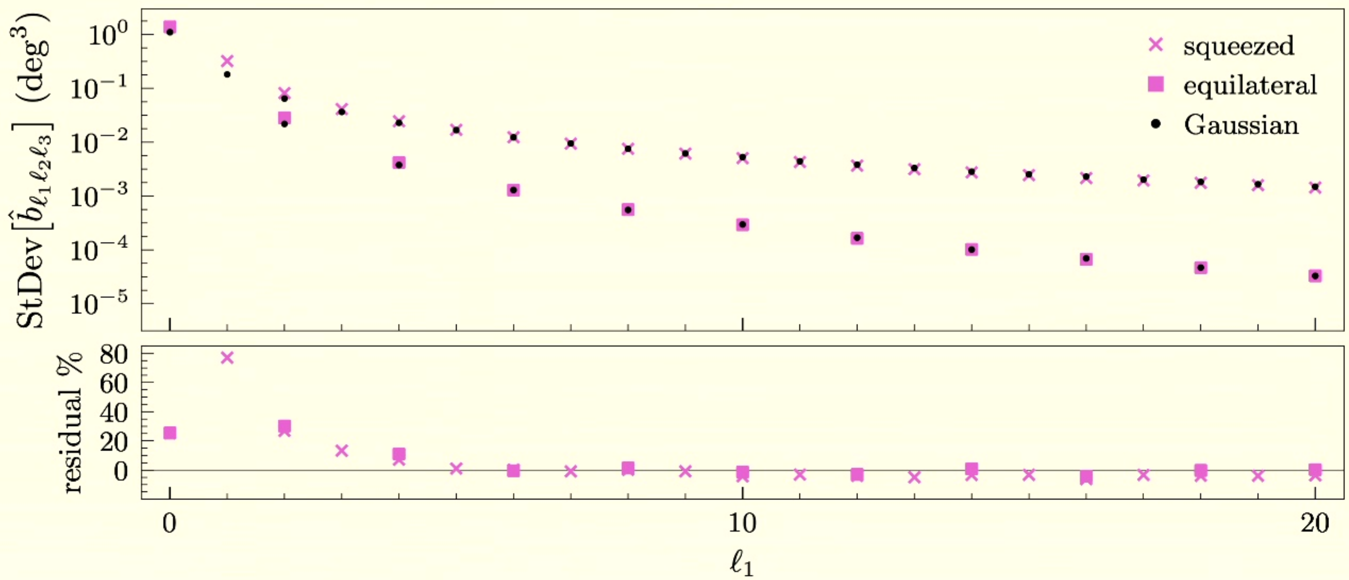
Measures of NG 2: bispectrum

[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

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

$$I_1^{j,l}(\mathbf{x}) = \langle |I_0 * \psi^{j,l}|^2 \rangle(\mathbf{x})$$

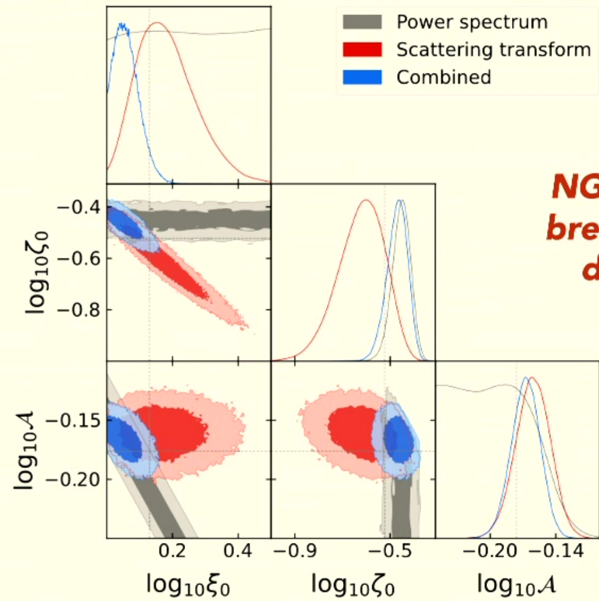
$$I_2^{j_1,l_1,j_2,l_2}(\mathbf{x}) = \langle |I_1^{j_1,l_1} * \psi^{j_2,l_2}|^2 \rangle(\mathbf{x})$$

$$s_1^j = \langle I_1^{j,l} \rangle_{\mathbf{x},l}$$

$$s_2^{j_1,j_2} = \langle I_2^{j_1,l_1,j_2,l_2} \rangle_{\mathbf{x},l_1,l_2}$$

comparison

pow-spec vs. scatt-transform



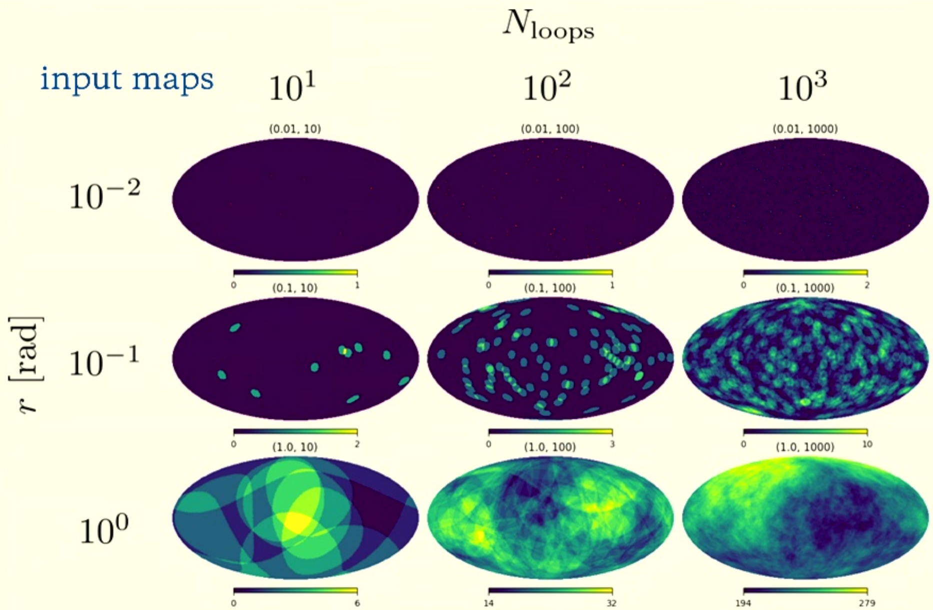
(b) $\mathcal{A}^2\xi_0 = 0.6,\ \mathcal{A} = 2/3,\ \zeta_0 = 0.3$

NG information breaks the A² ξ_0 degeneracy

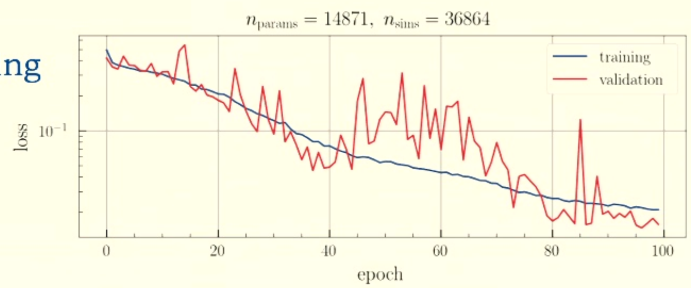
Machine learning for axion strings

--- early stages ---

input maps



training

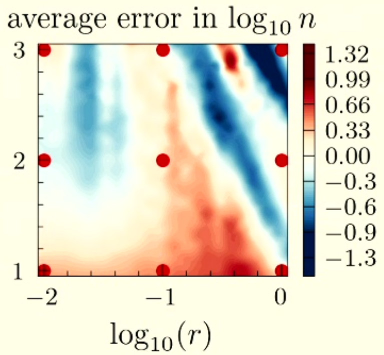


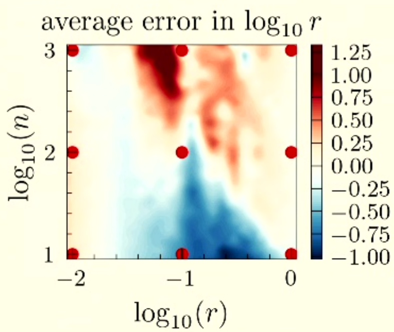
package: DeepSphere (Python)
architecture: 3 conv+pool layers

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

Ray Hagimoto
(Rice U grad)

how well is it working? … not bad!





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 find that it is difficult (but not impossible!) to reconcile the detection of isotropic birefringence with strong limits on anisotropic birefringence coming from axion strings
- 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