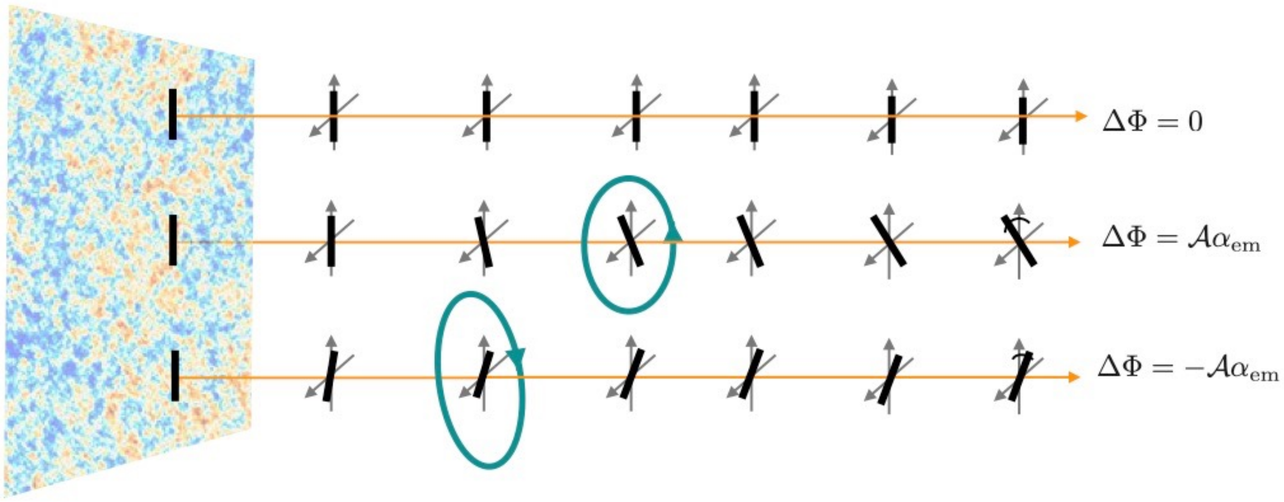
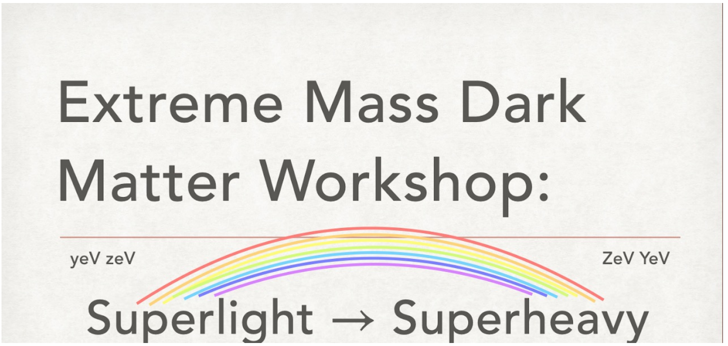
CMB Birefringence from Axion Strings





Andrew J. Long
Rice University

@ YITP
March 8, 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 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

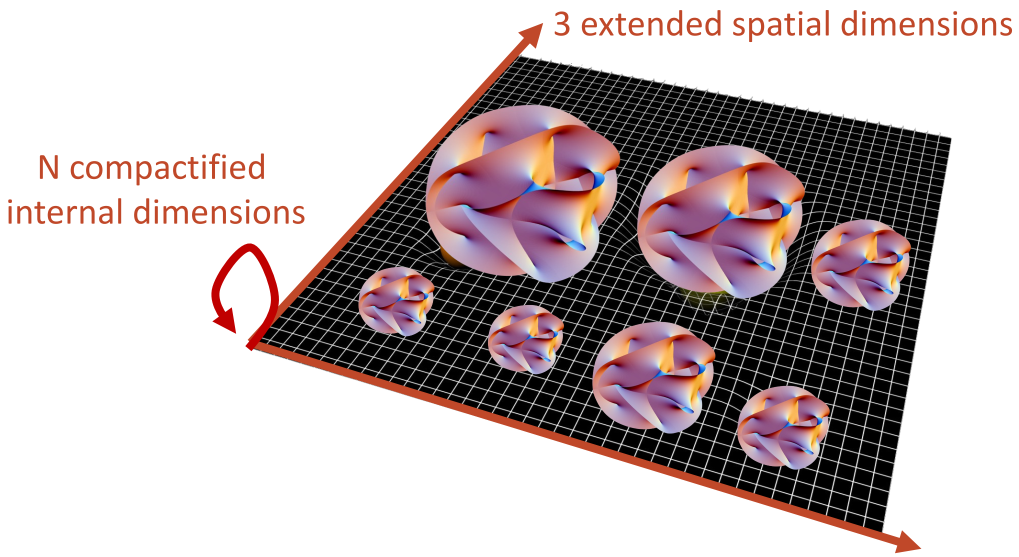
Theory landscape: axion-like particles

axion-like particles

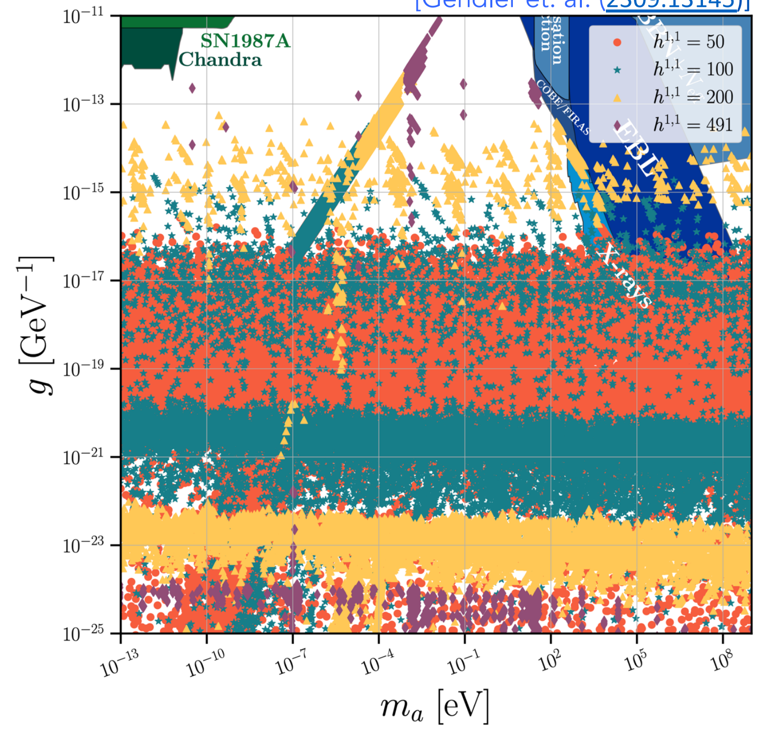
$$\mathcal{L} \supset \frac{1}{2}(\partial a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

ALPs from extra dimensions

(such as string theory)



[Gendler et. al. (2309.13145)]



Theory landscape: axion-like particles

axion-like particles

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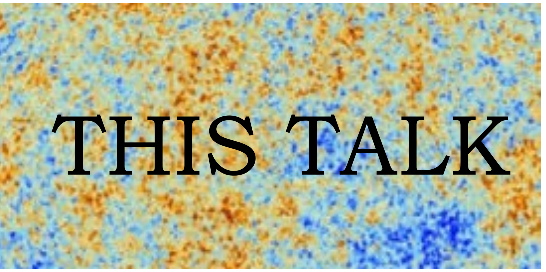
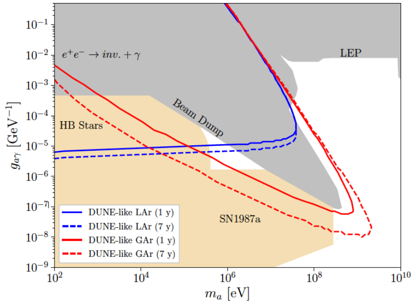
hyper-light axion-like particles (testable with cosmology)



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

heavy axion-like particles (testable in the lab)



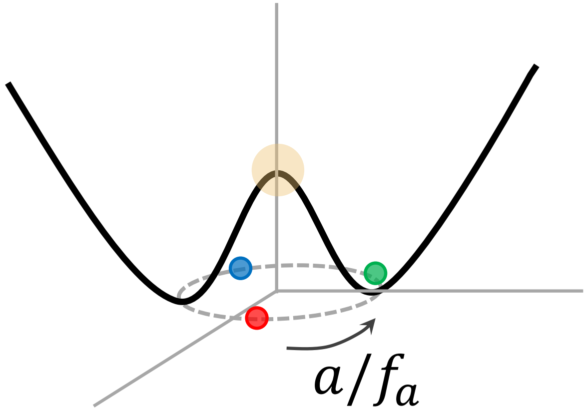
10^{-38} eV — 10^{-30} eV — 10^{-22} eV — 10^{-14} eV — 10^{-6} eV — 10^{2} eV — 10^{10} eV → m_a

ALPs form axion strings

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

string formation:
early-universe phase transition

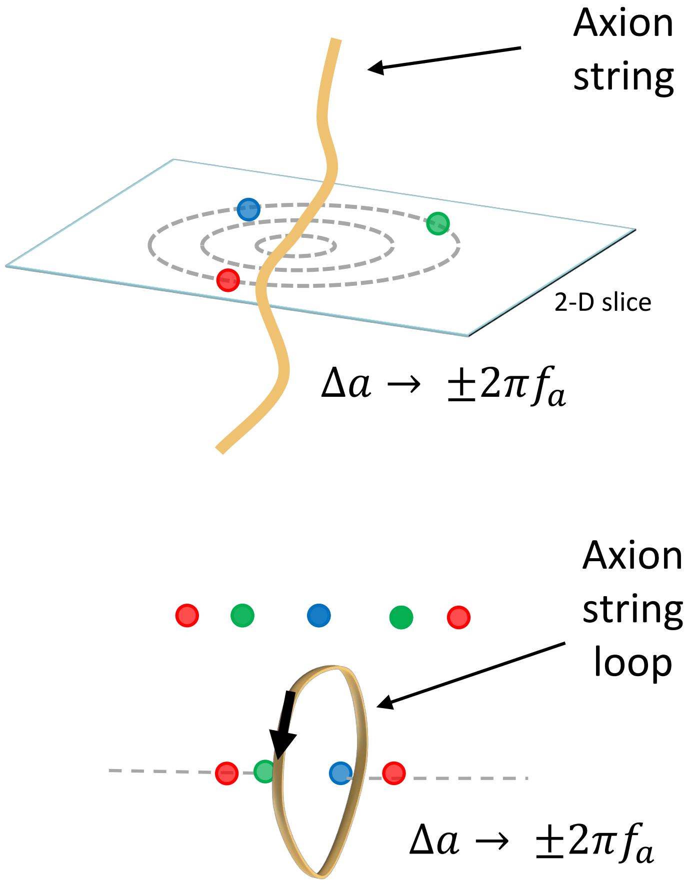
Field space



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

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

Physical space



string thickness = microscopic

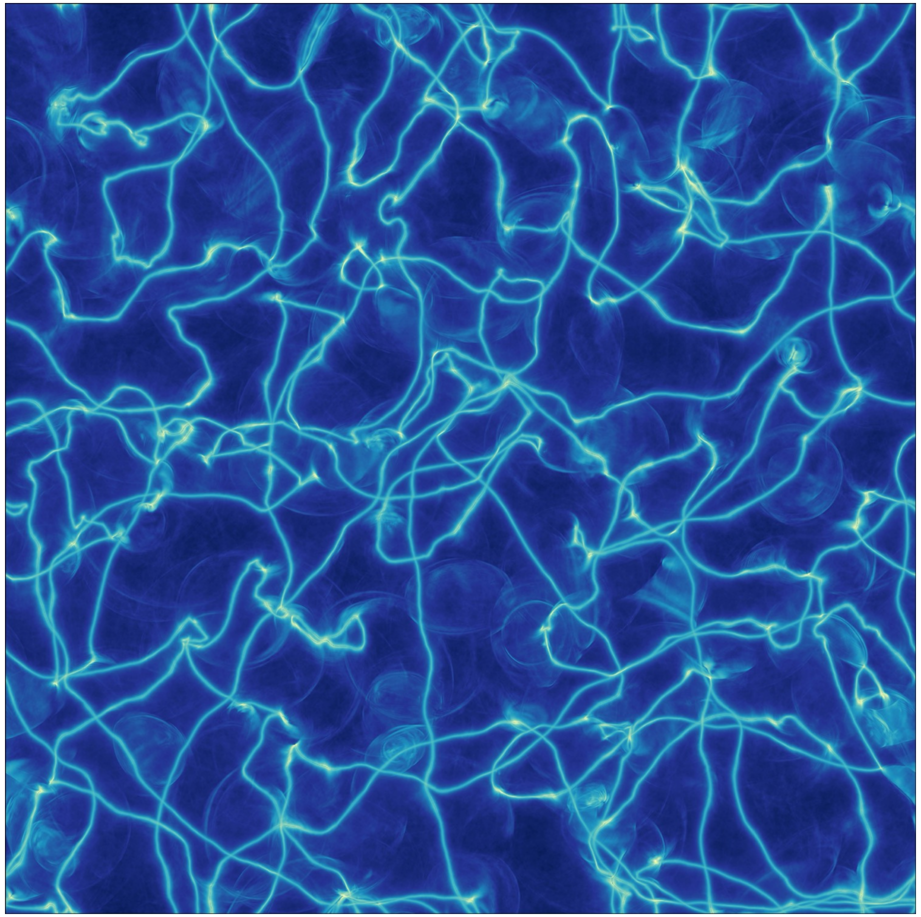
string length = cosmological

image credit: Mudit Jain (2021)

A cosmic string network

[Saikawa et. al. (2024)]

string network simulation:



see talk by : Ken'ichi Saikawa

- 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(10) strings per Hubble volume

How can we detect axion strings in the Universe today?

[image credit: Ken'ichi Saikawa]

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

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

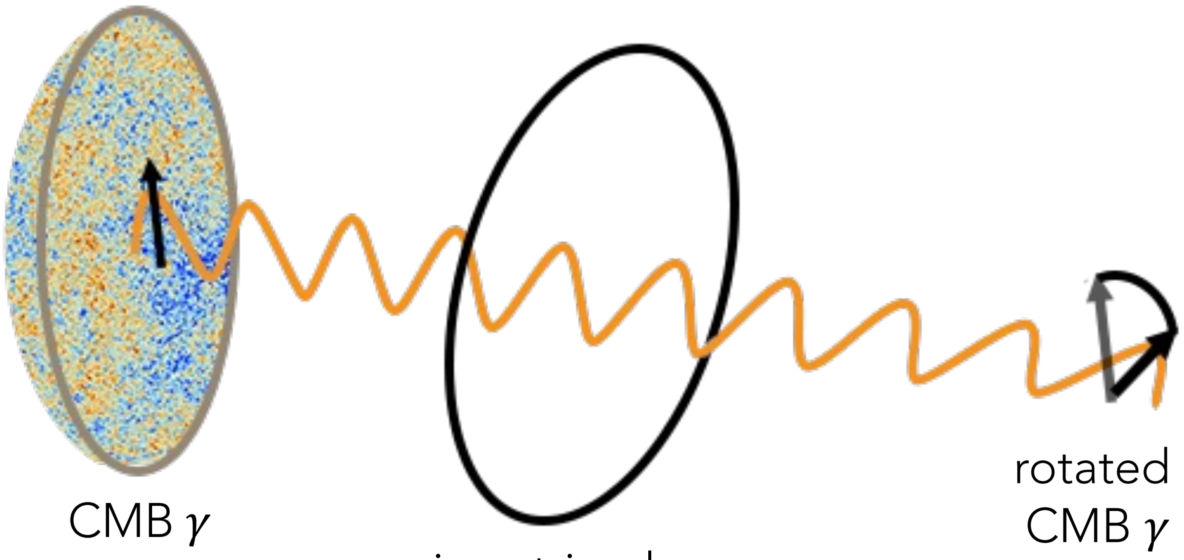
$$g_{a\gamma\gamma} = -\mathcal{A} \frac{\alpha_{\text{em}}}{\pi f_a}$$

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

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

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

* 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

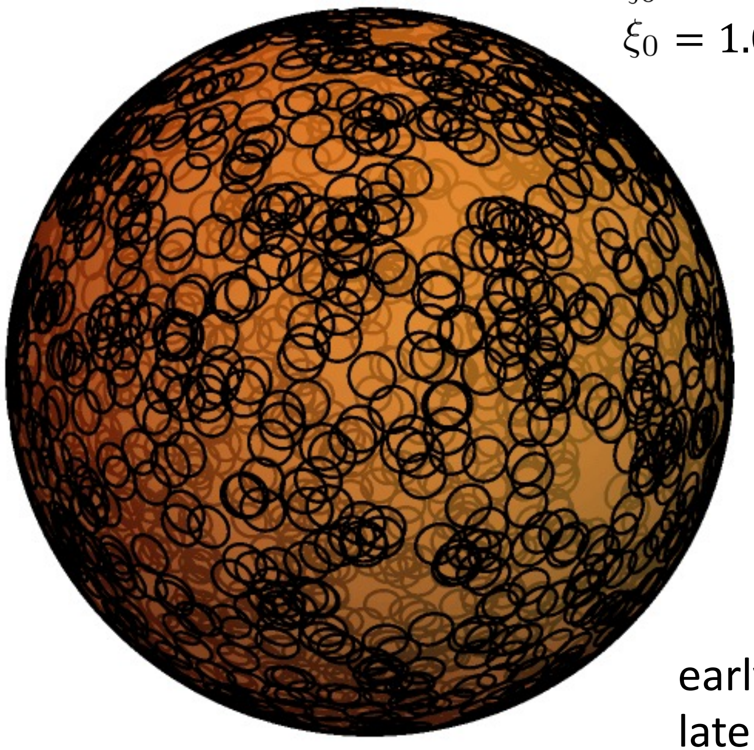
$$\rho(t) = \xi_0 \mu(t) H(t)^2$$

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

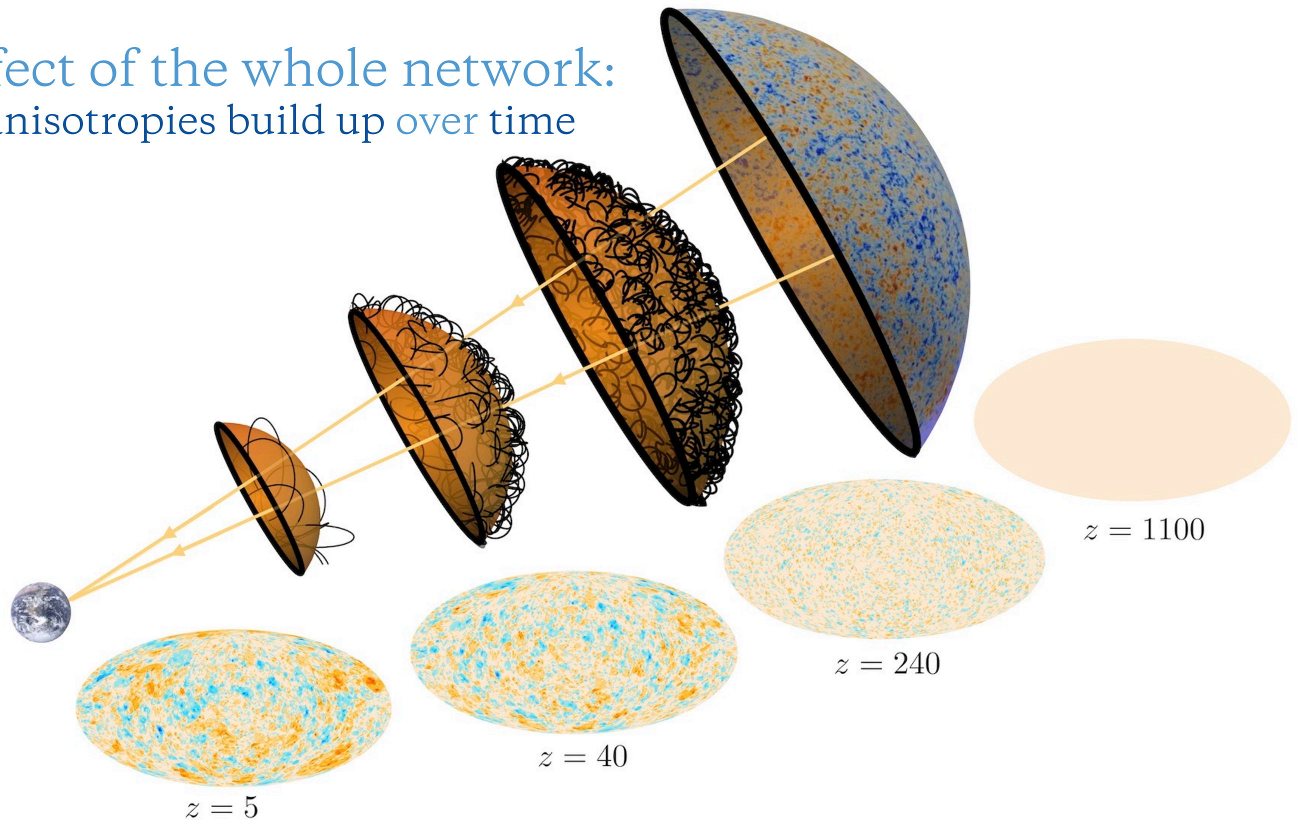
Expected birefringence signal

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

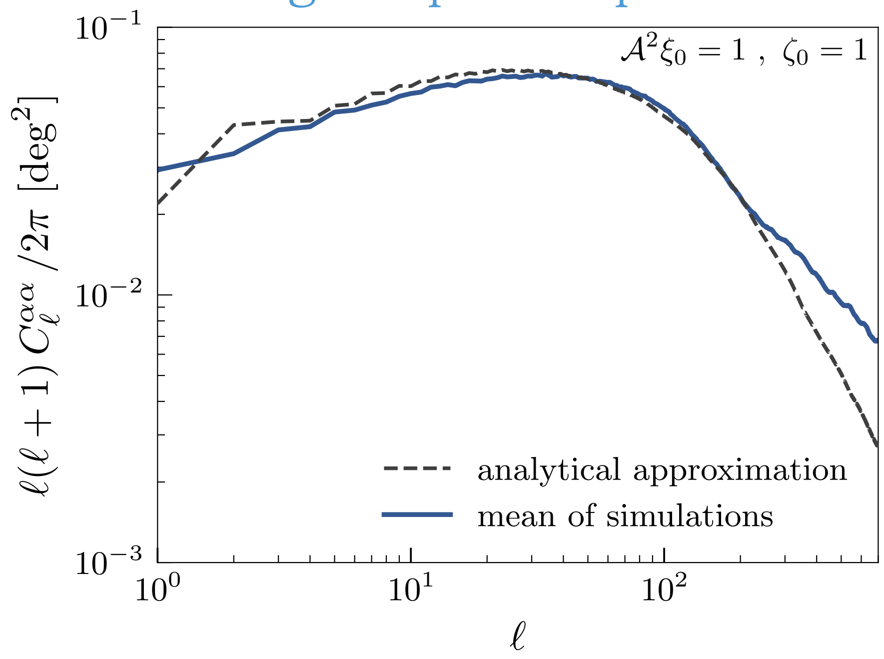
loop-crossing model:
a network of circular loops

$\mathcal{A}$ = 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> ~ A² ξ_0

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

Effect on CMB polarization

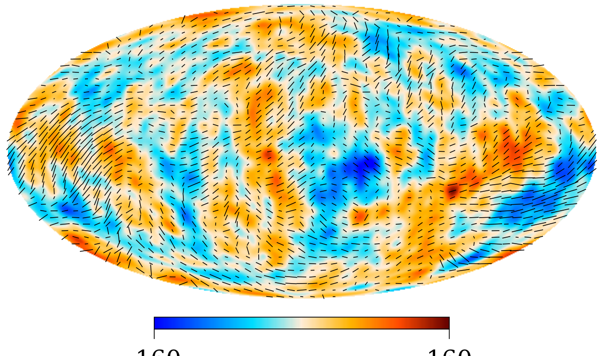
How does birefringence affect the CMB's temperature and polarization?

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

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

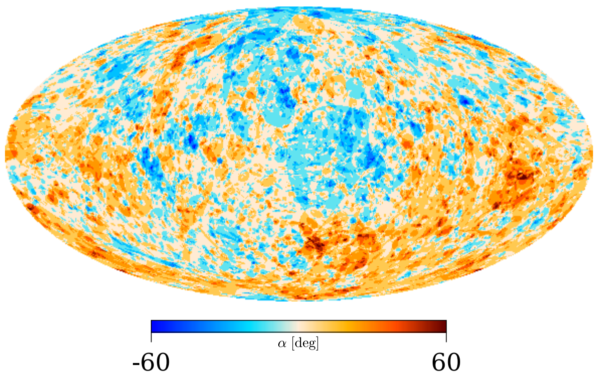
see talk by : Fumihiro Naokawa

primordial CMB sky



+

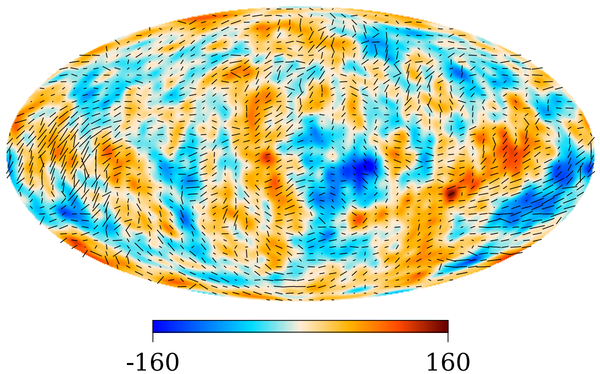
axion string -induced birefringence angle



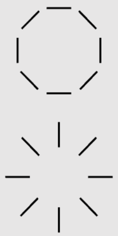
(exaggerated by ~30x)

=

Planck's CMB sky

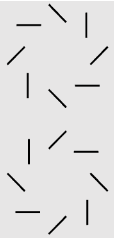


$E - mode$ pol pattern



→

$B - mode$ pol pattern



Signal of axion string-induced cosmological birefringence

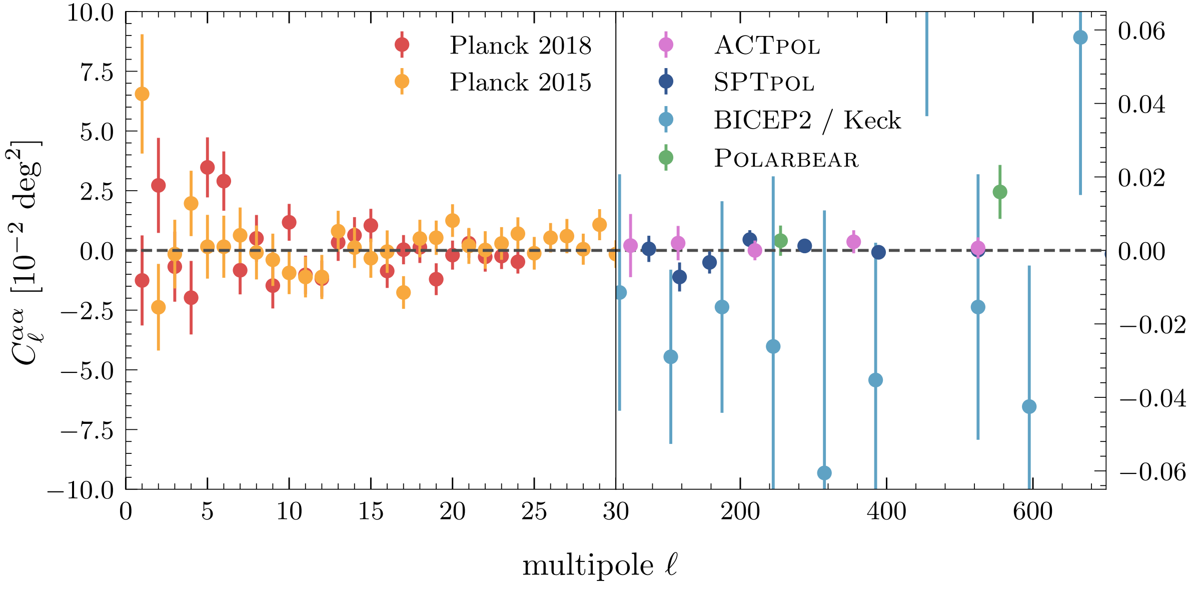
$$\begin{cases} \langle TB \rangle \neq 0 \\ \langle EB \rangle \neq 0 \end{cases}$$

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

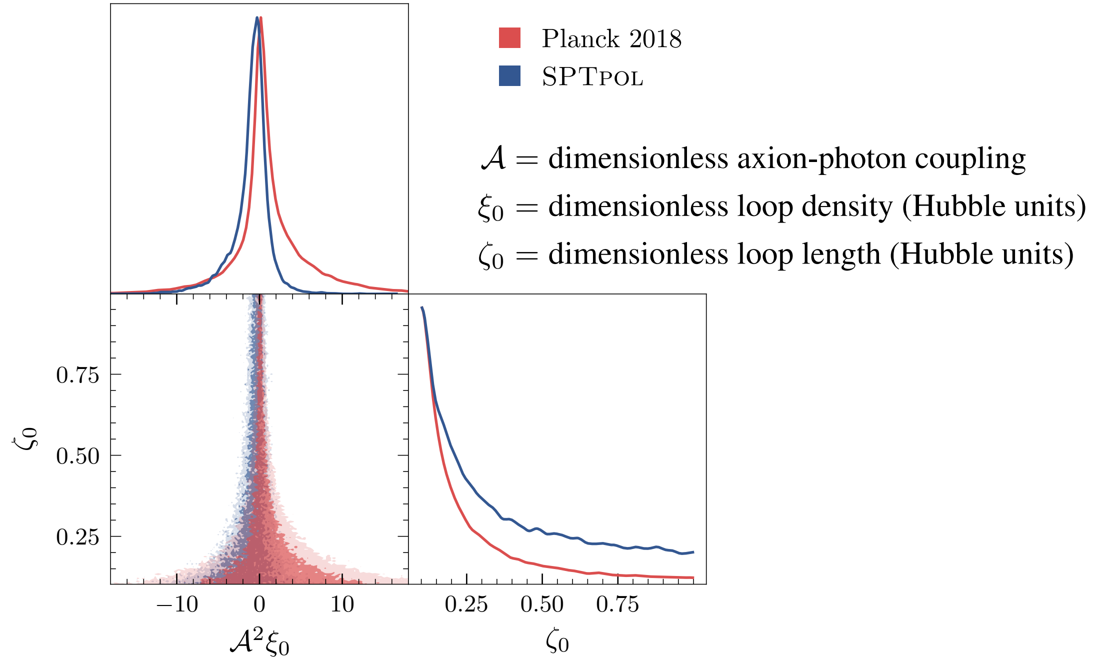
Constraints from anisotropic birefringence

[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:



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

already valuable!
if $\mathcal{A} = \frac{1}{3}$ and $\xi_0 = 30$ then $\mathcal{A}^2\xi_0 \approx 3.3$

what about
isotropic
birefringence

Are strings responsible for isotropic birefringence?

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

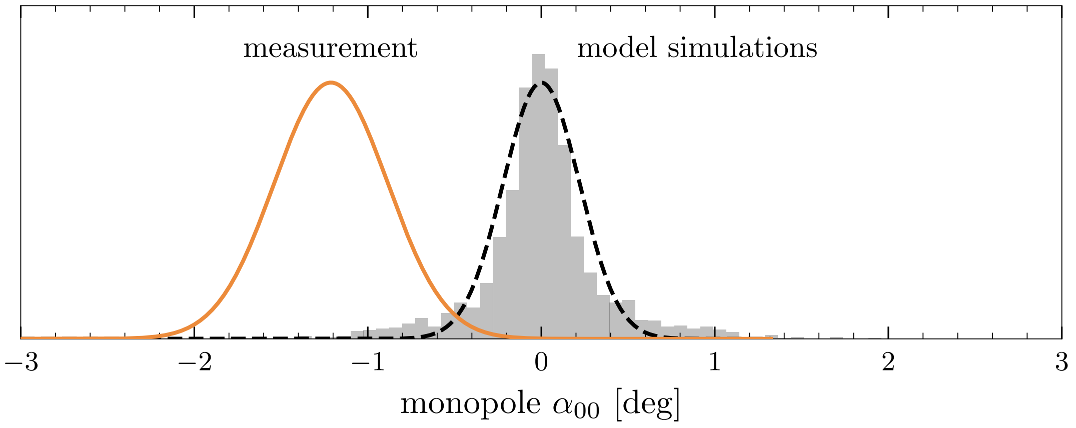
see talk by : Eiichiro Komatsu

reported detection of isotropic birefringence:
same rotation angle across the whole sky
(using *Planck* & *WMAP* data)

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

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

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



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

Are strings responsible for isotropic birefringence?

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

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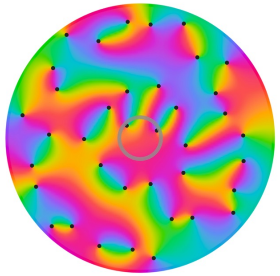
[Eskilt (2022)], [Eskilt & Komatsu (2022)]
[Eskilt et. al. (2023)]

loopholes allowing large iso-BF

please ask: Ippei Obata

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

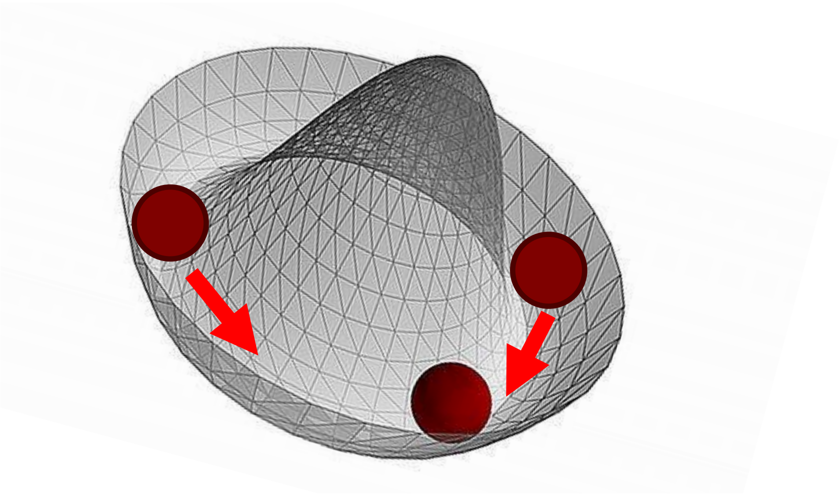
effect of
varying ALP mass

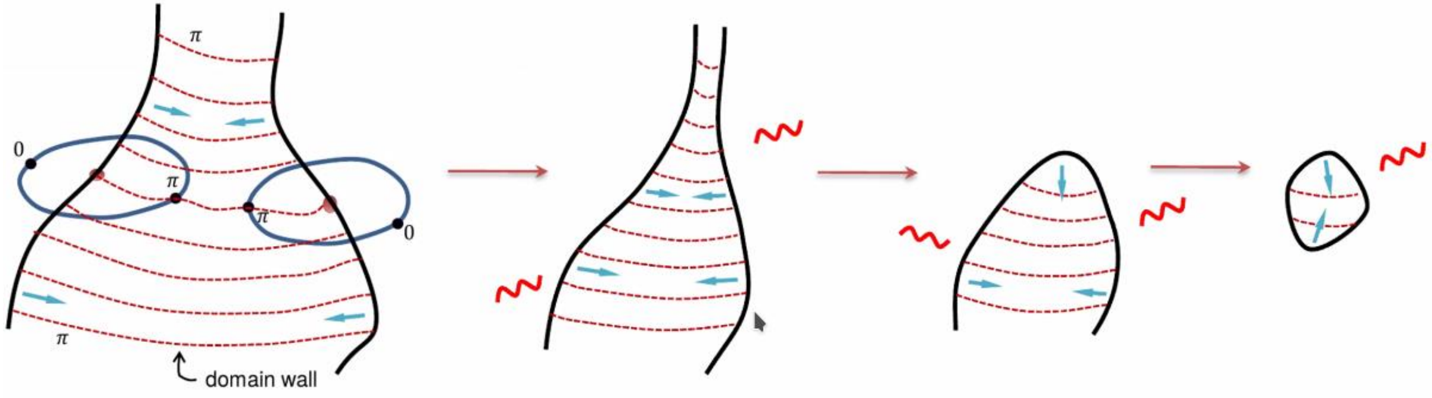
Collapse of the string-wall network

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

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

Impact on birefringence

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

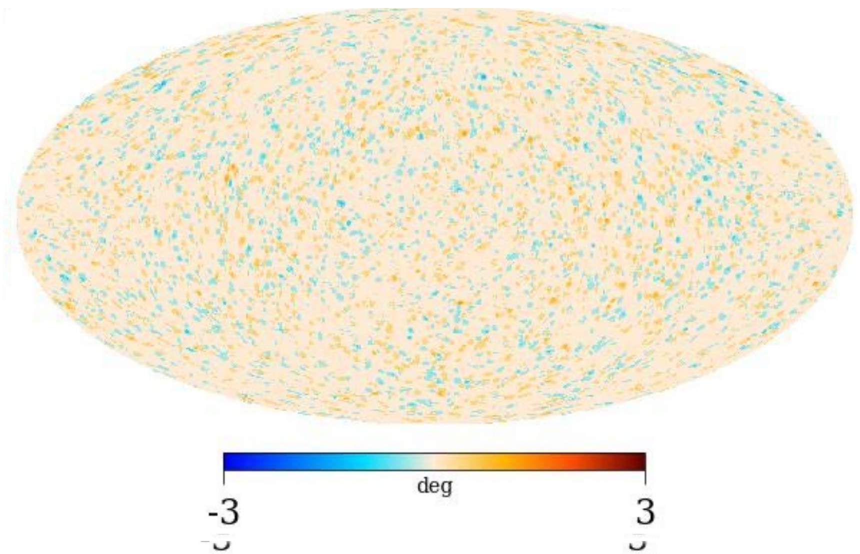
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

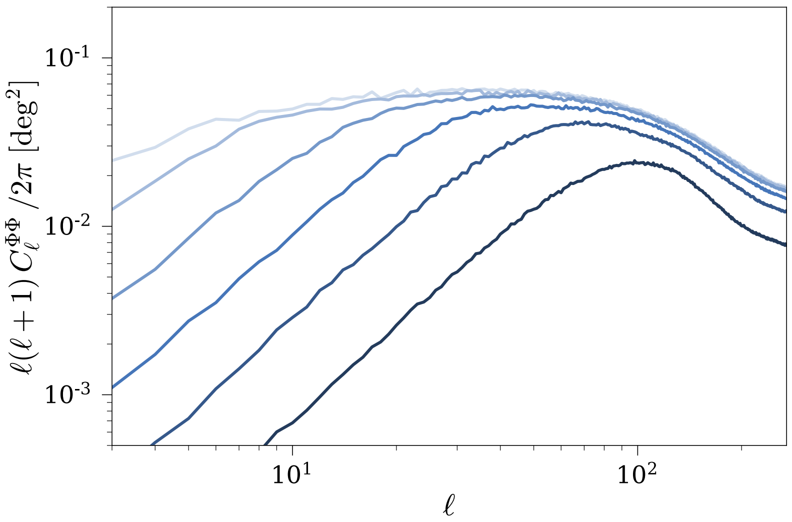
see also: [Ferreira, Gasparotto, Hiramatsu, Obata, & Pujolas (2023)]

raise the ALP mass

(network collapses earlier)

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





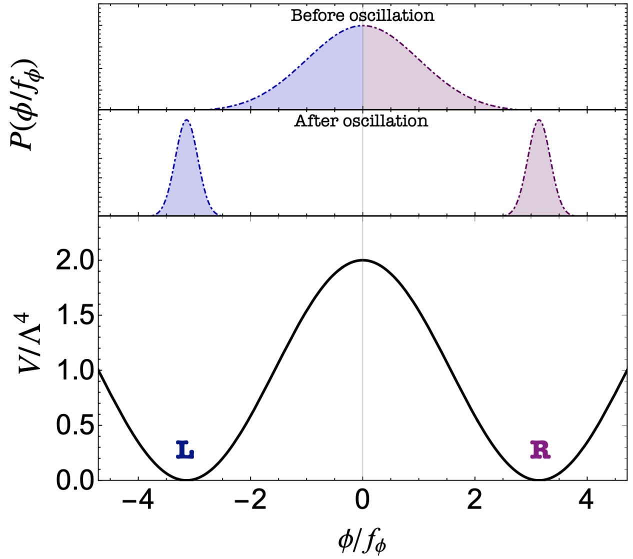
strong scale dependence ➔ possible to measure m_a

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

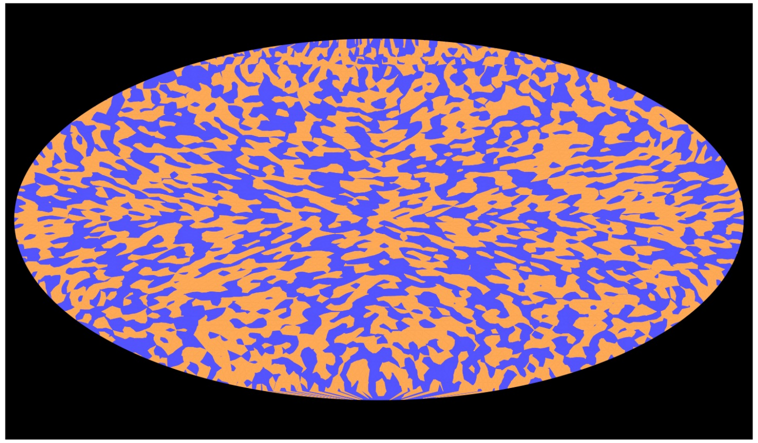
imposes bound on mass & decay constant

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

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

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.

please ask:
Fuminobu Takahashi
Diego Gonzalez
Naoya Kitajima
Shota Nakagawa
Masaki Yamada
Wen Yin

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

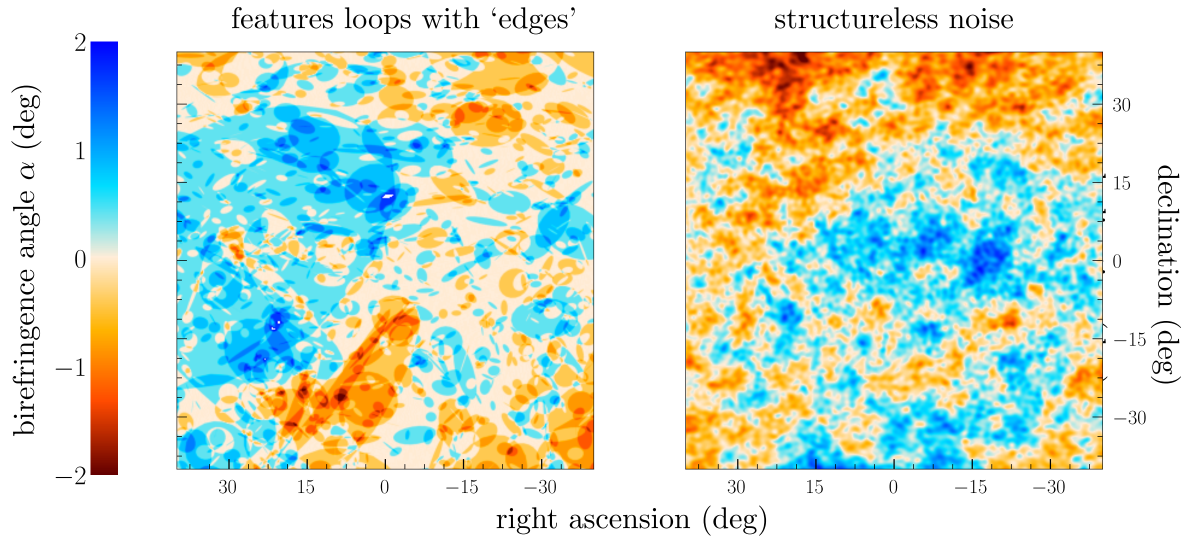
(no random-walk enhancement)

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

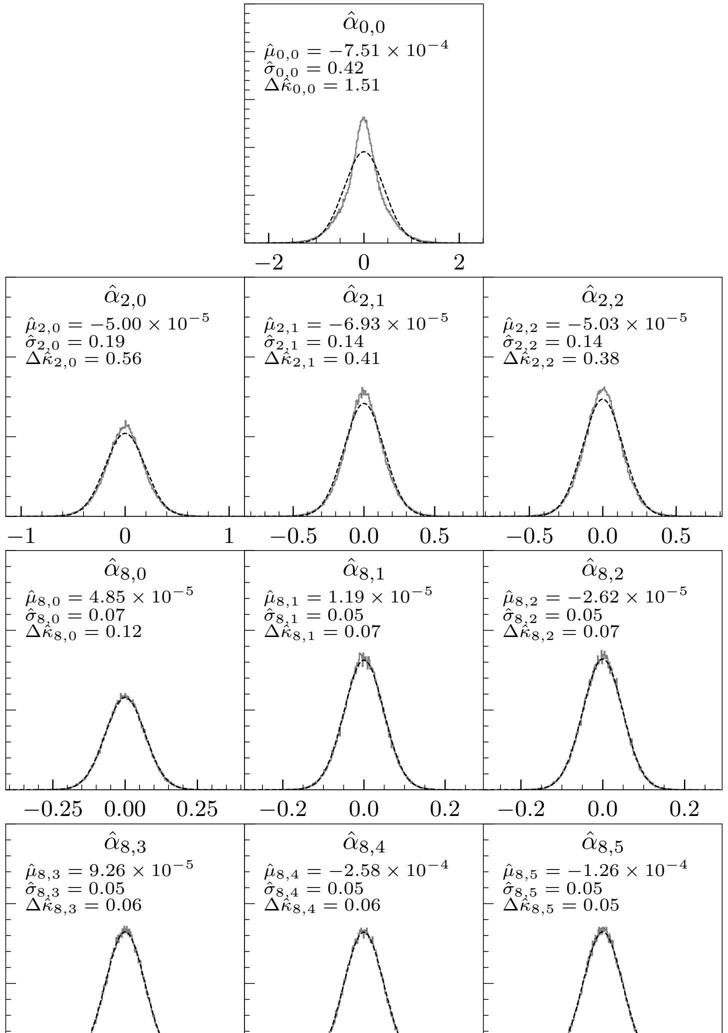
Gaussian random field with same power spectrum

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

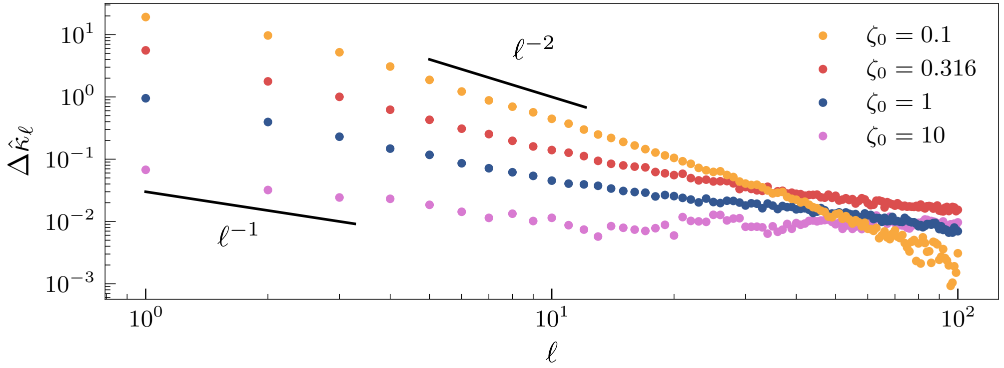
Birefringence non-Gaussianity

[Hagimoto & AL, arXiv:2306:07351]

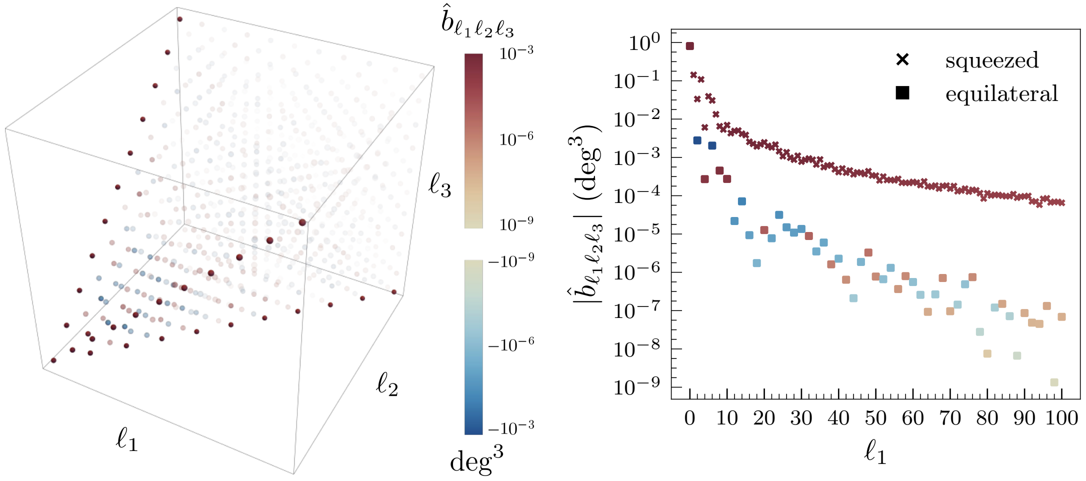
excess kurtosis
can be O(1) at low multipoles



scaling with multipole index
matches well an analytic toy model



bispectrum
largest in squeezed triangle form



smaller NG on smaller scales (b/c of central limit theorem)

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

a measurement of non-G will help to tell apart axion strings & other sources of birefringence

Probing non-Gaussianity with scattering transform

Yin, Dai, Ferraro (2023

std. method
power spectrum

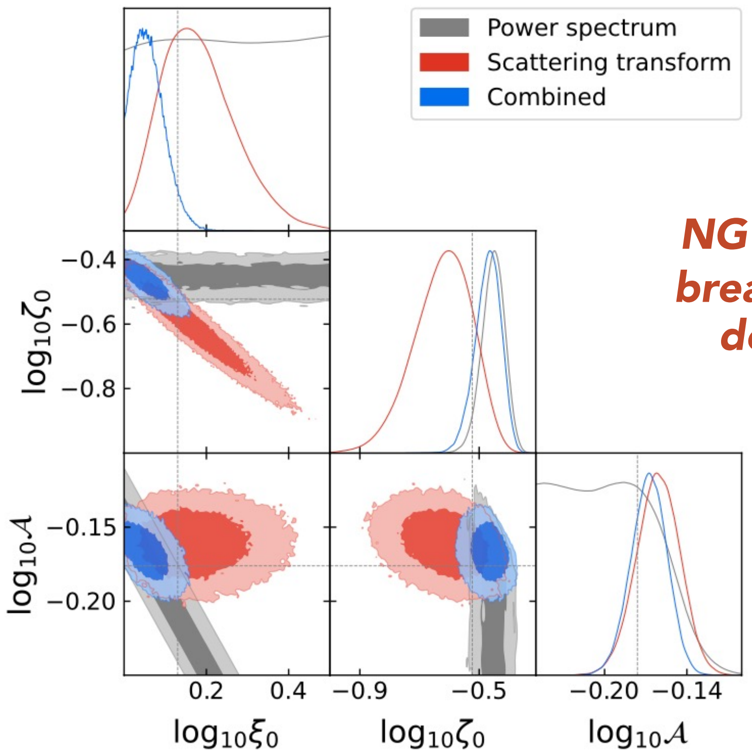
$$\text{signal:} \quad I_0(\mathbf{x})$$
$$\text{plane wave:} \quad \phi_{\mathbf{k}}(\mathbf{x})$$
$$P_{\mathbf{k}}(\mathbf{x}) = \langle |I_0 * \phi_{\mathbf{k}}|^2 \rangle(\mathbf{x})$$

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



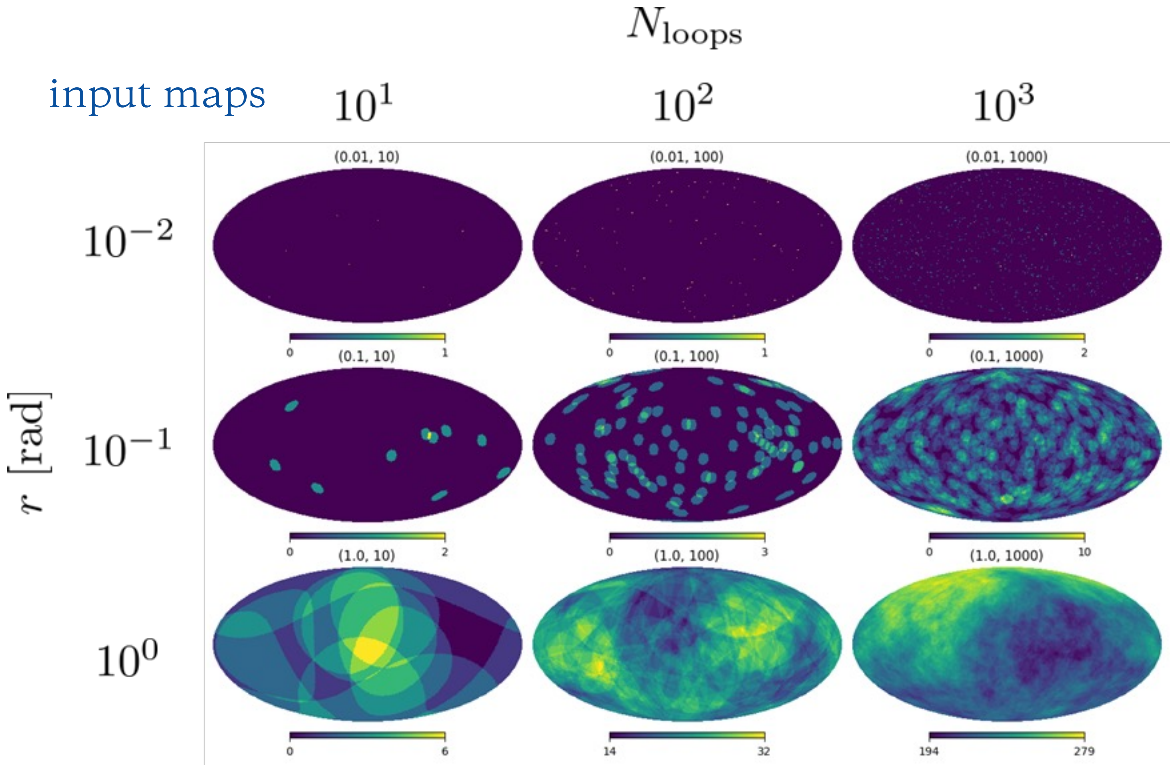
(b) $\mathcal{A}^2\xi_0 = 0.6, \ \mathcal{A} = 2/3, \ \zeta_0 = 0.3$

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

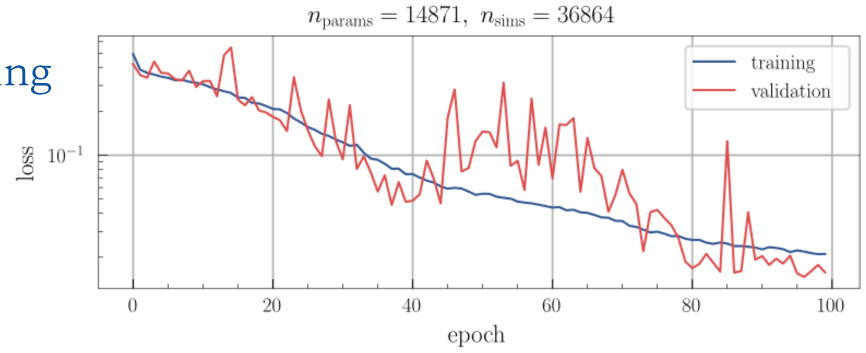
Machine learning for axion strings

--- early stages ---

input maps



training

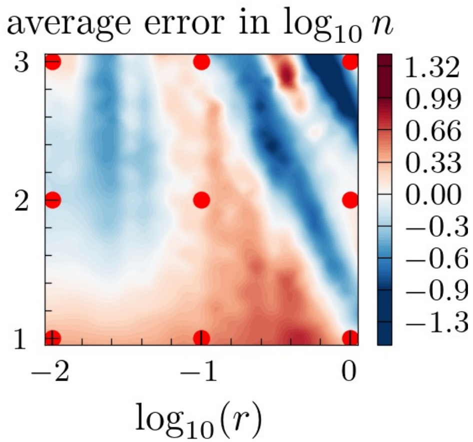


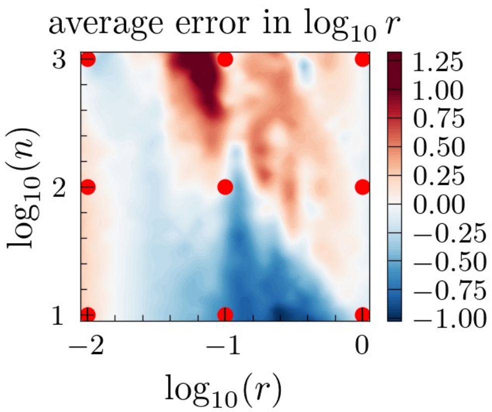
package: DeepSphere (Python)
architecture: 3 conv+pool layers

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

backup slides

Projected sensitivity

Pogosian et. al. (2019)

future telescopes

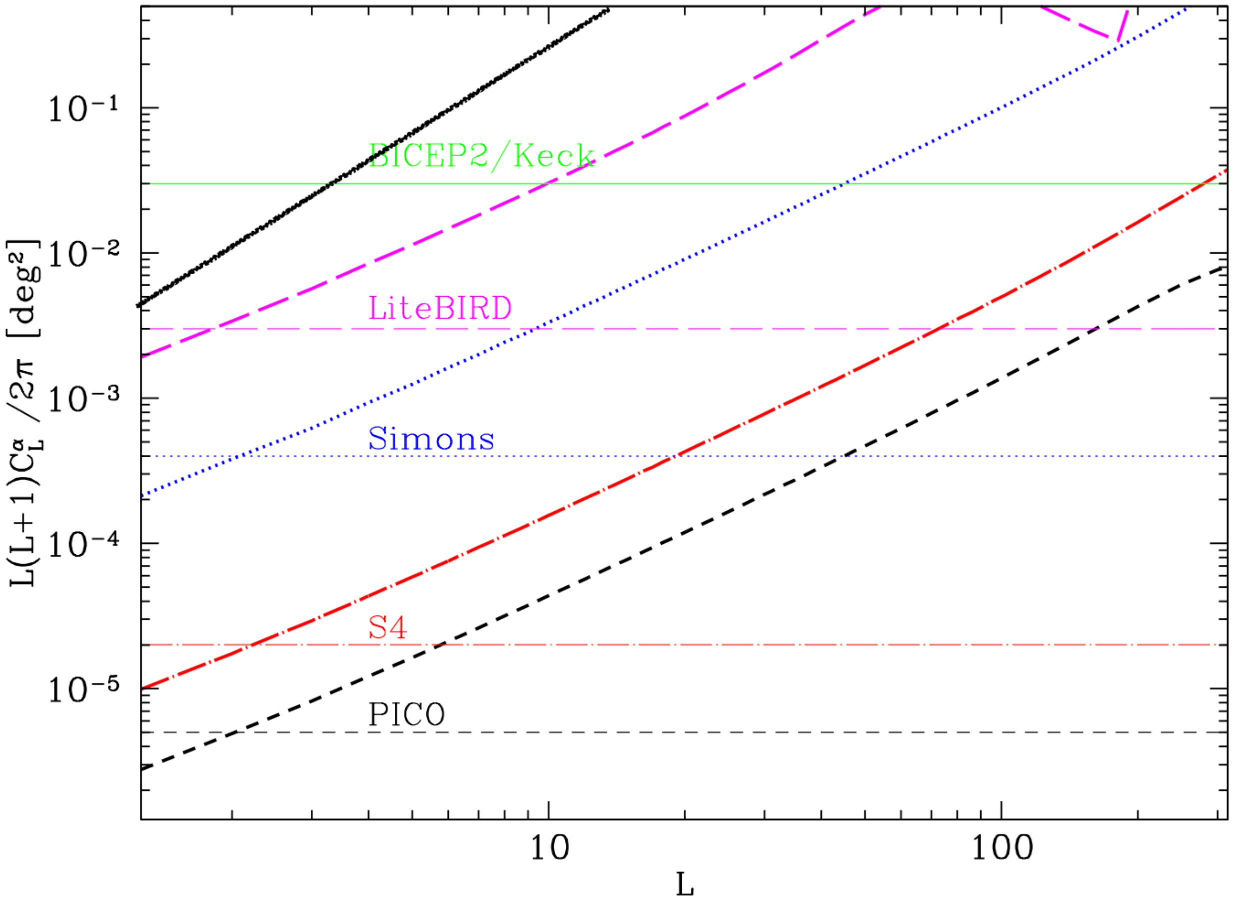
probes of isotropic + aniso. birefringence

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

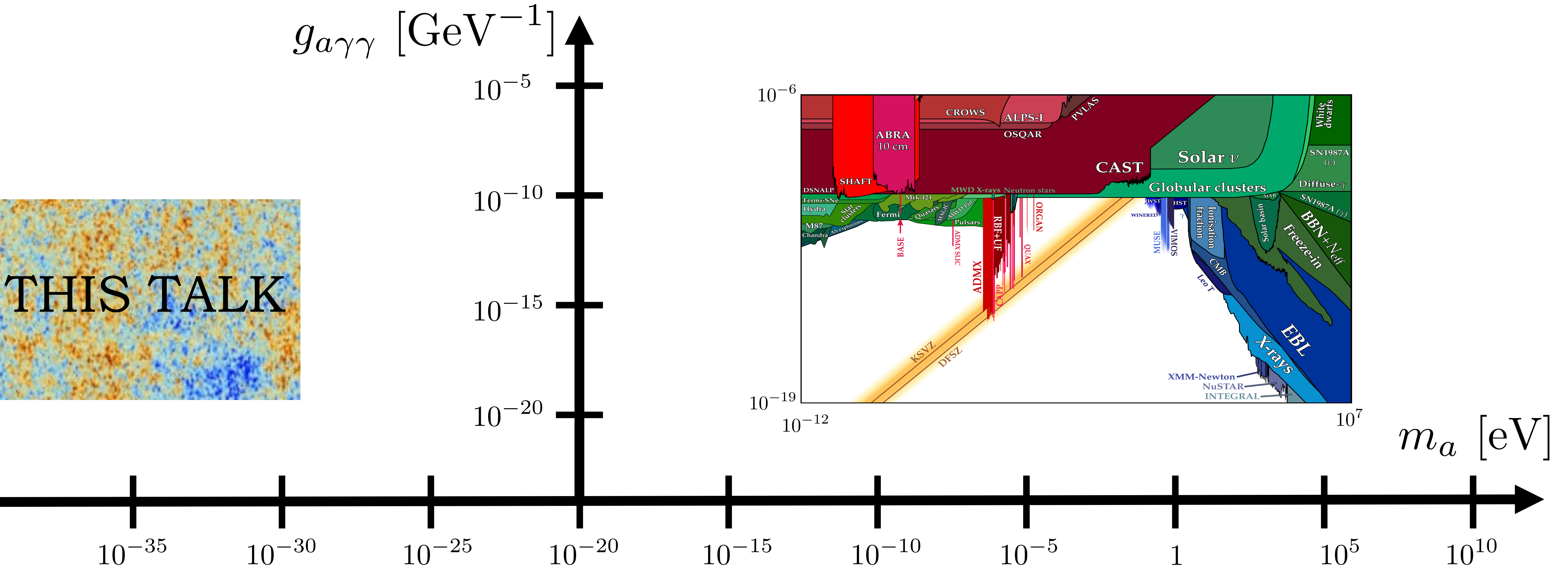
$$A_\alpha = L(L+1)C_L^\alpha/2\pi$$

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



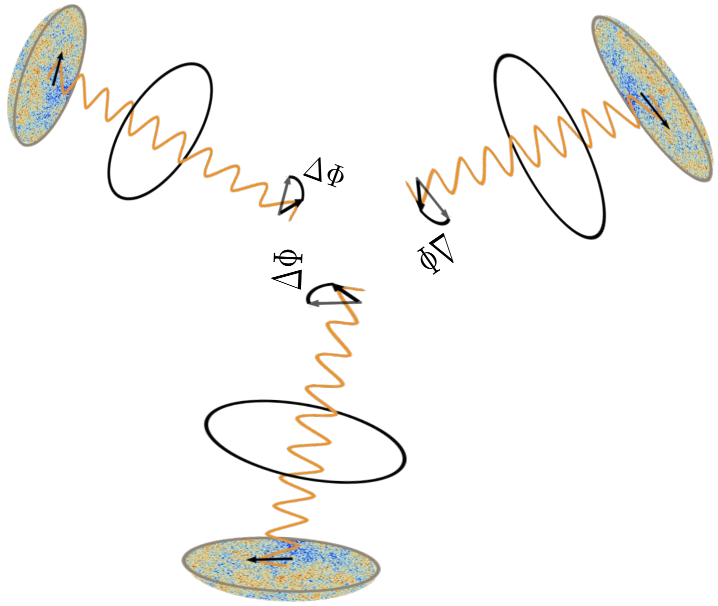
Theory landscape: axion-like particles

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

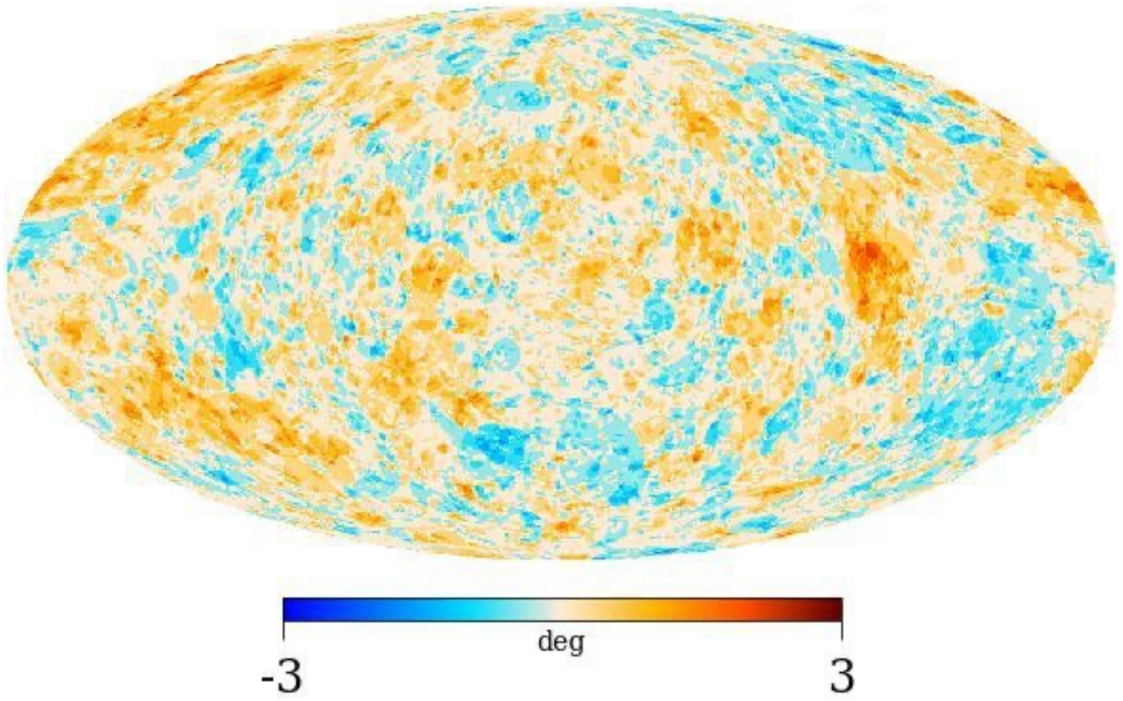


Net birefringence from the whole string network

[Ray Hagimoto (2022)]



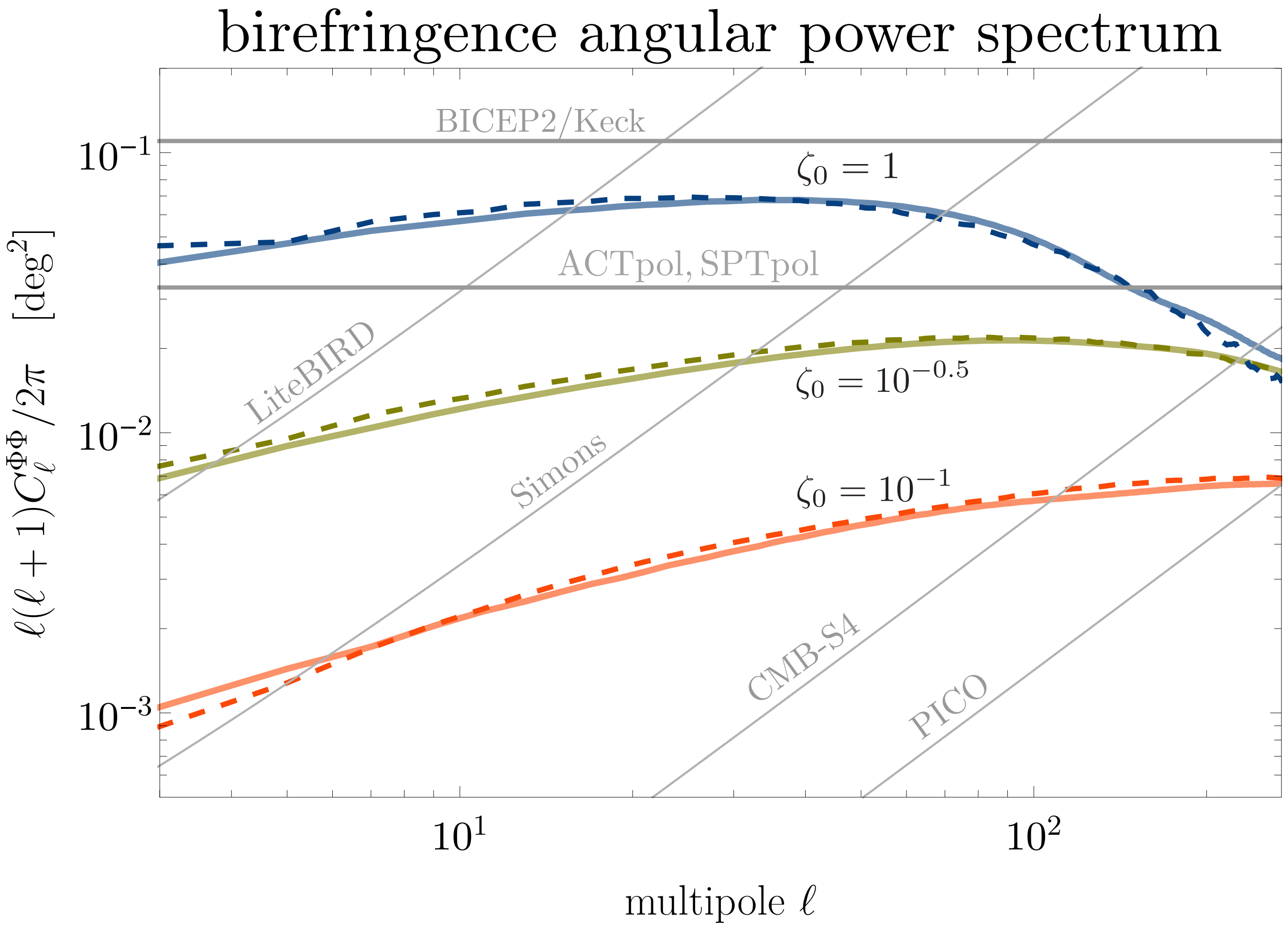
a map of $\Delta\Phi$ over the sky



parameters: $\begin{cases} m_a = 0 \\ \mathcal{A} = 1 \\ \zeta_0 = 1 \\ \xi_0 = 1 \end{cases}$

Axion-string induced birefringence signal

[Jain, AL, Amin (2103.01962)]



assumes: $m_a = 0$ and $\xi_0 \mathcal{A}^2 = 1$

Key features

- Power spectrum is almost scale invar.
- Characteristic scale (l @ the peak) set by loop size at LSS
- Smaller loops (ζ_0) => weaker signal
- Trivial dependence on loop density (ξ_0) and anomaly coefficient (A) … power scales with ξ_0 A^2

Testability

- Current telescopes (SPT/ACT) are already sensitive enough to test large loops (ζ_0=1)
- Future suveys will be very powerful