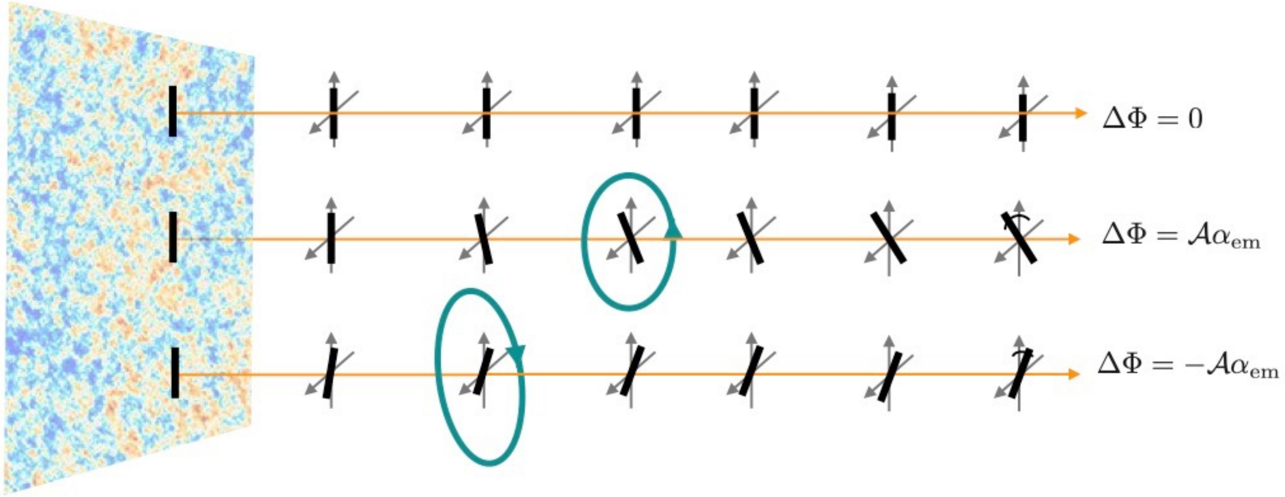
Looking through loops: CMB birefringence from axion strings



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June 6, 2025

RICE

[2103.10962, 2208.08391, 2306.07351, 2411.05002]

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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
- Machine learning methods (spherical CNN) may prove useful to help to detect the subtle non-Gaussian signal of axion strings in next-generation CMB polarization data

axion-like particles
& cosmic axion strings

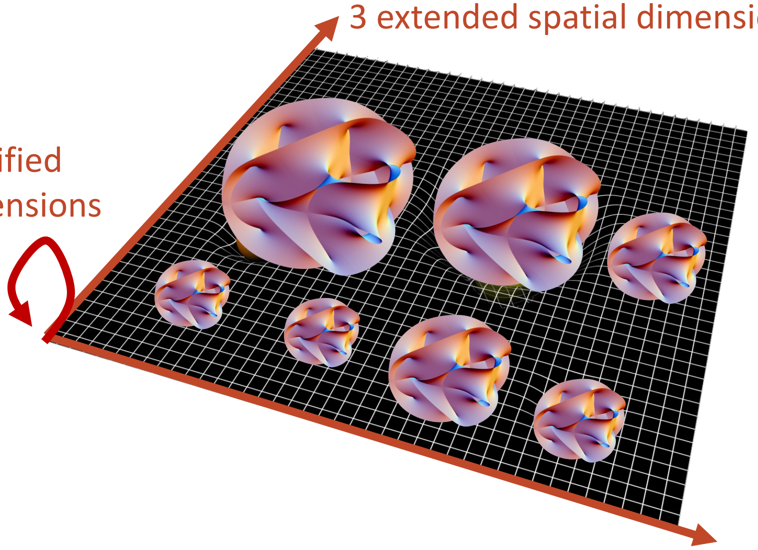
Theory landscape: axion-like particles

axion-like particles

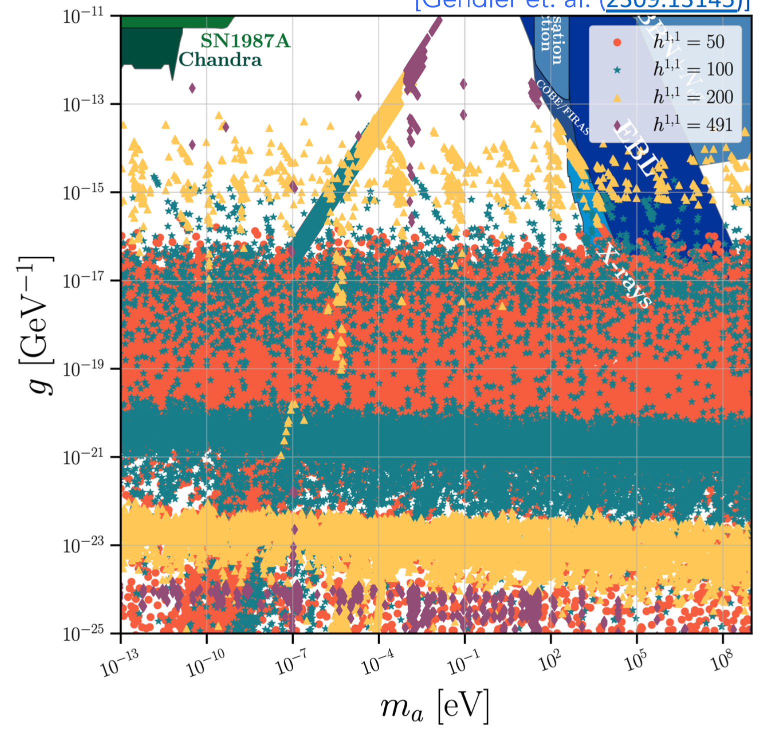
$$\mathcal{L} \supset \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

ALPs from extra dimensions

(such as string theory)



[Gendler et. al. (2309.13145)]



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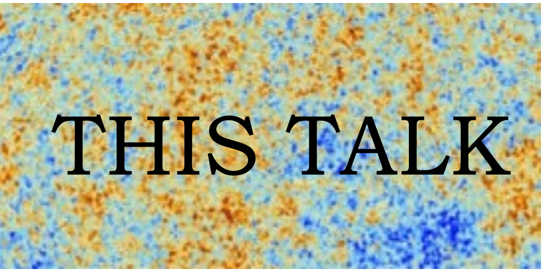
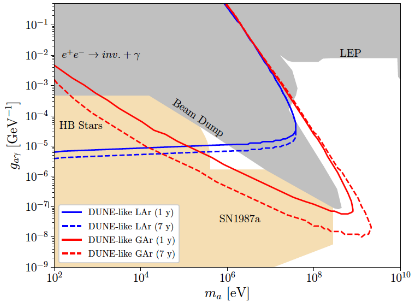
hyper-light axion-like particles (testable with cosmology)



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

heavy axion-like particles (testable in the lab)



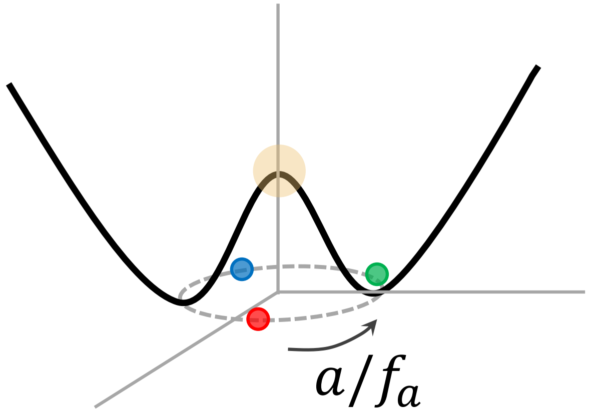
10^{-38} eV — 10^{-30} eV — 10^{-22} eV — 10^{-14} eV — 10^{-6} eV — 10^{2} eV — 10^{10} eV → m_a

ALPs can form axion strings

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

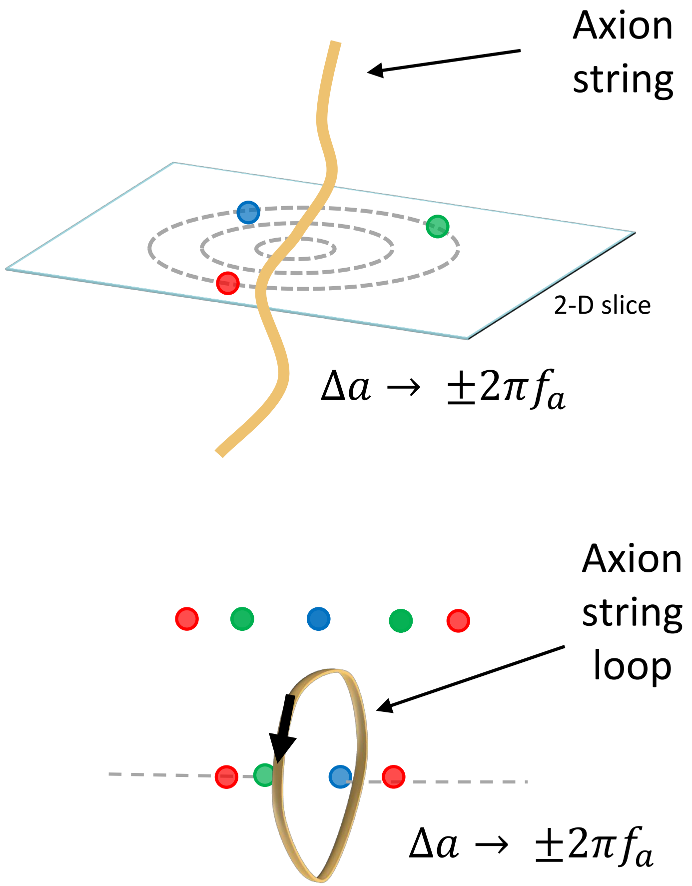
Field space

$$V(\phi) = \lambda(\phi^*\phi - f_a^2)^2$$



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

Physical space



string thickness = microscopic

string length = cosmological

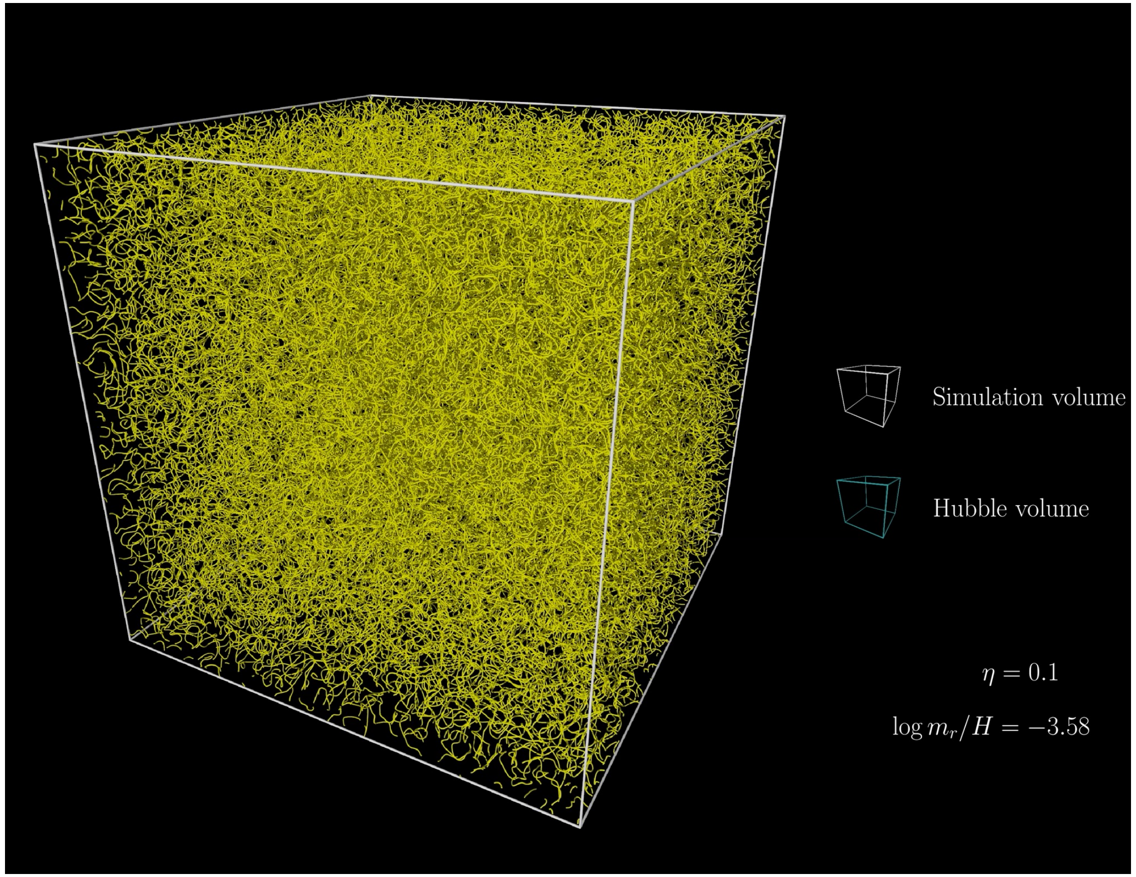
assume: $T_{\rm RH} > f_a$

image credit: Mudit Jain (2021)

A cosmic string network

[Buschmann et. al. (2022)]

string network simulation:



simulations show:

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

so, the network evolves into the scaling regime:

- typical string length tracks Hubble
- average energy density tracks Hubble

so, in the universe today we expect:

- order 10 strings per Hubble volume
- string loops with length ~ Hubble scale

How can we detect axion strings in the Universe today?

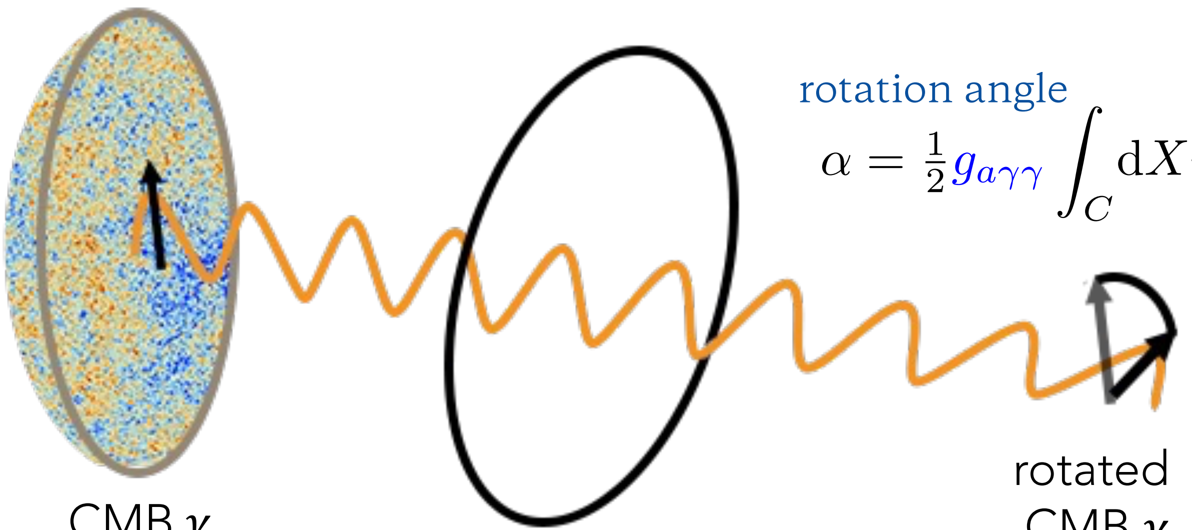
birefringence
from axion strings

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)]

axion-induced birefringence:

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



rotation angle

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

assume interaction with electromagnetism:

standard Chern-Simons coupling

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

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

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

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

* birefringence can be measured through E-B cross correlation

Modeling anisotropic birefringence from strings

[Jain, AL, Amin (2021)]

The loop-crossing model

- Circular & planar loops
- Randomize loop orientation
- Randomize loop location in space
- All loops same radius at any time
- Loop radius evolves tracking Hubble

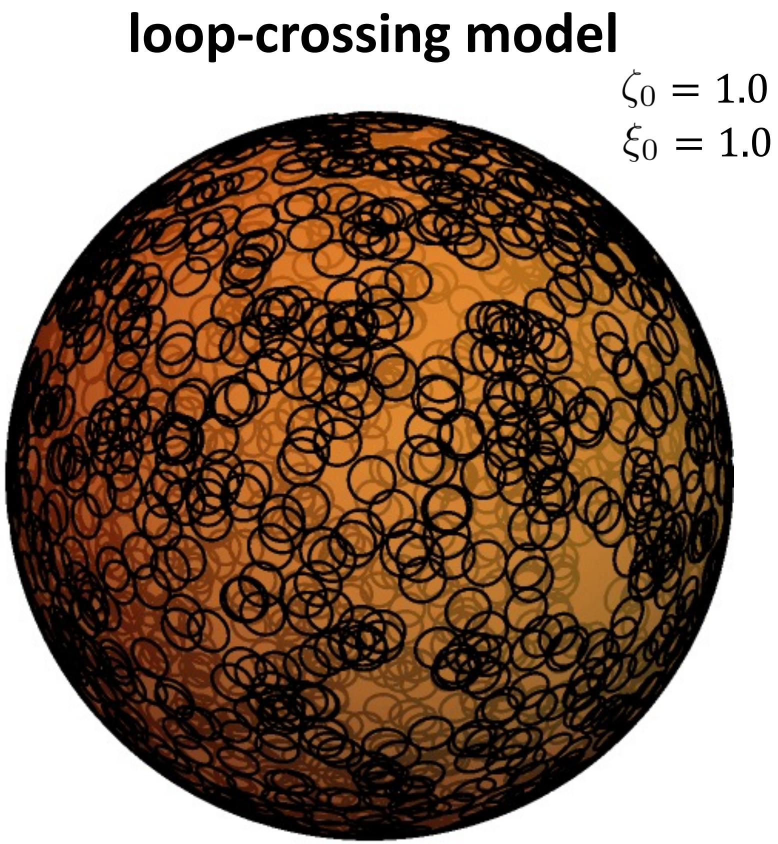
$$R(t) = \zeta_0 / H(t)$$

- Number of loops tracks Hubble

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

Model Parameters

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

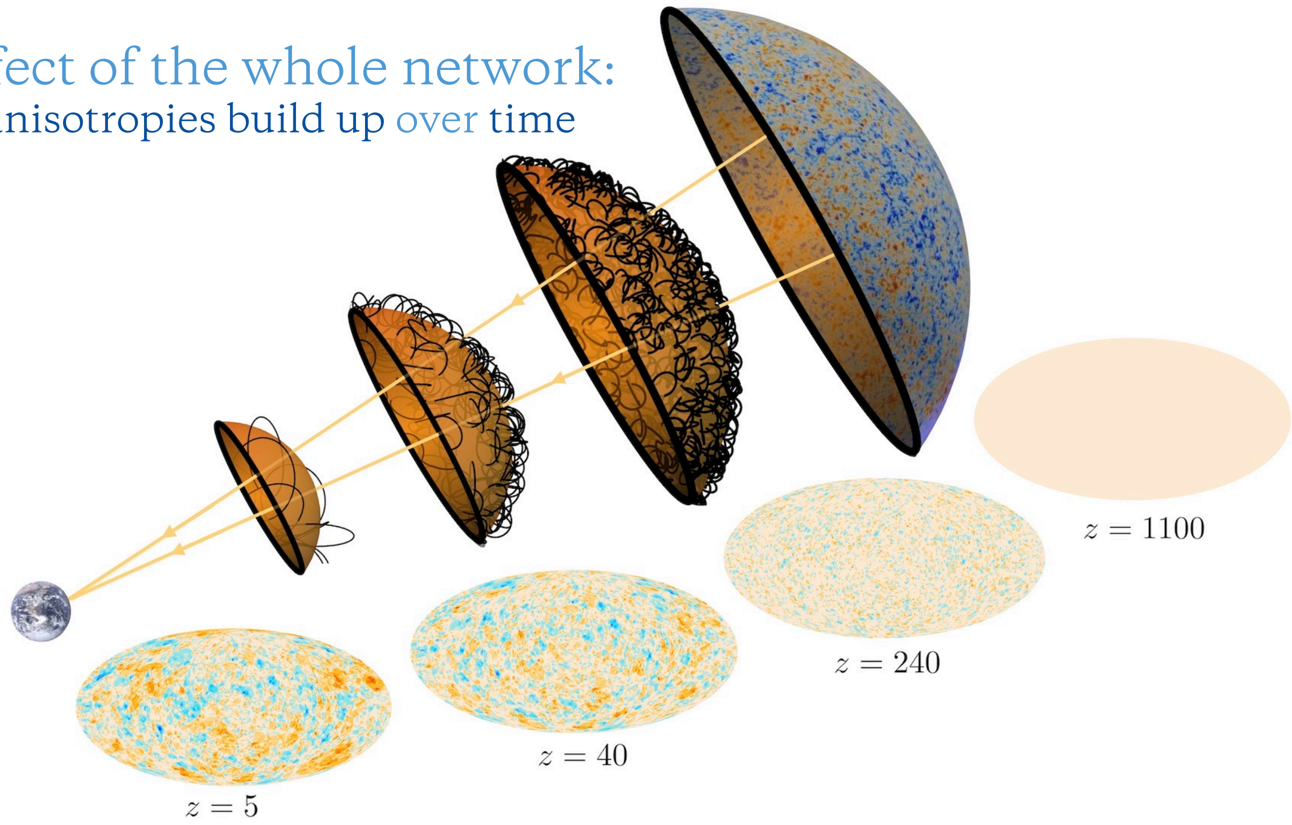


early time -> small loops
late time -> large loops

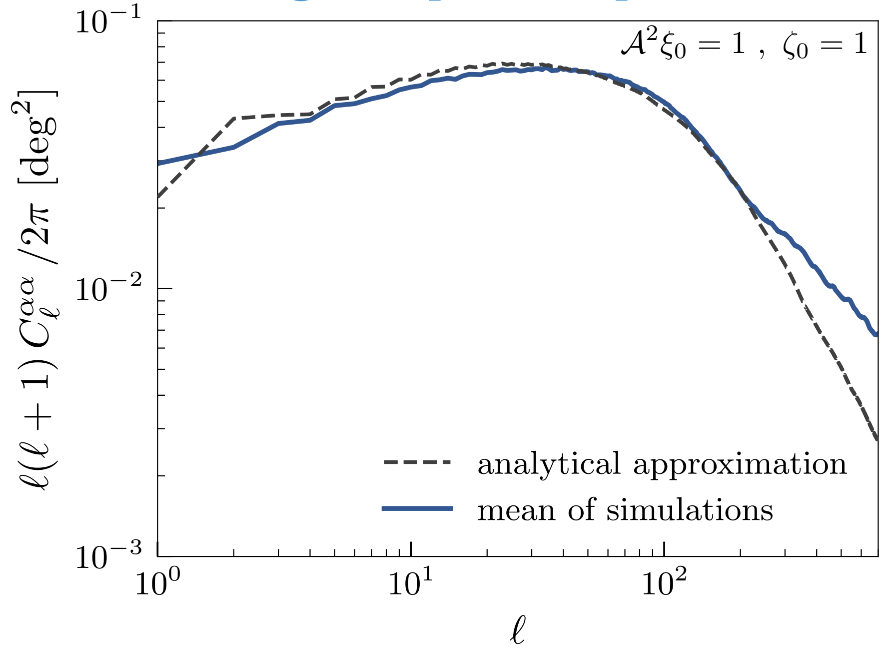
Expected birefringence signal

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

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

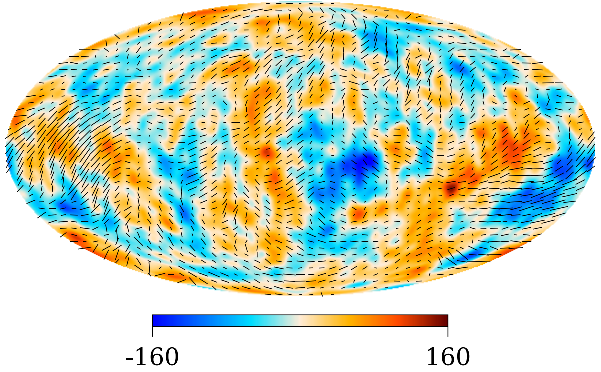
Effect on CMB polarization

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

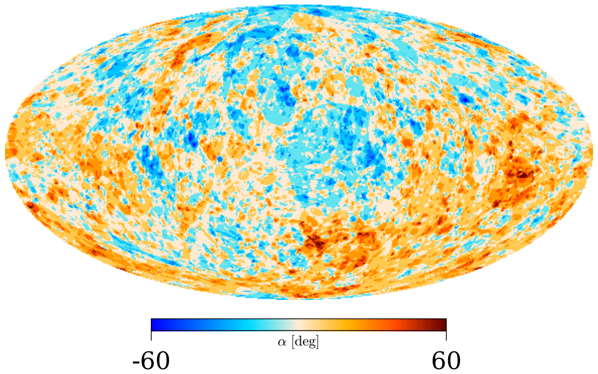
$$T(\hat{\boldsymbol{n}}) \to T(\hat{\boldsymbol{n}})$$

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

primordial CMB sky

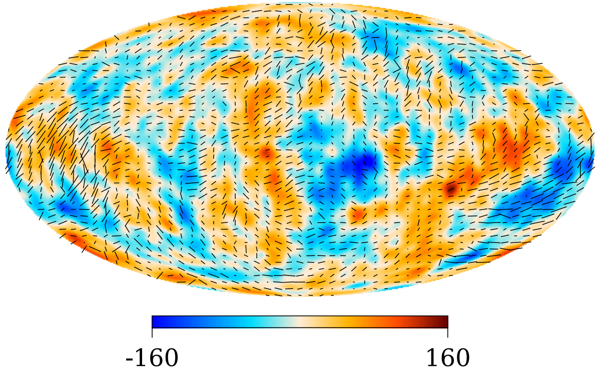


axion string -induced birefringence angle

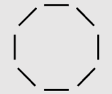


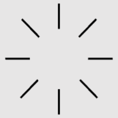
(exaggerated by ~30x)

Planck's CMB sky

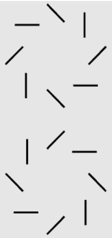


$E-mode$ pol pattern





$B-mode$ pol pattern



Signal of axion string-induced cosmological birefringence

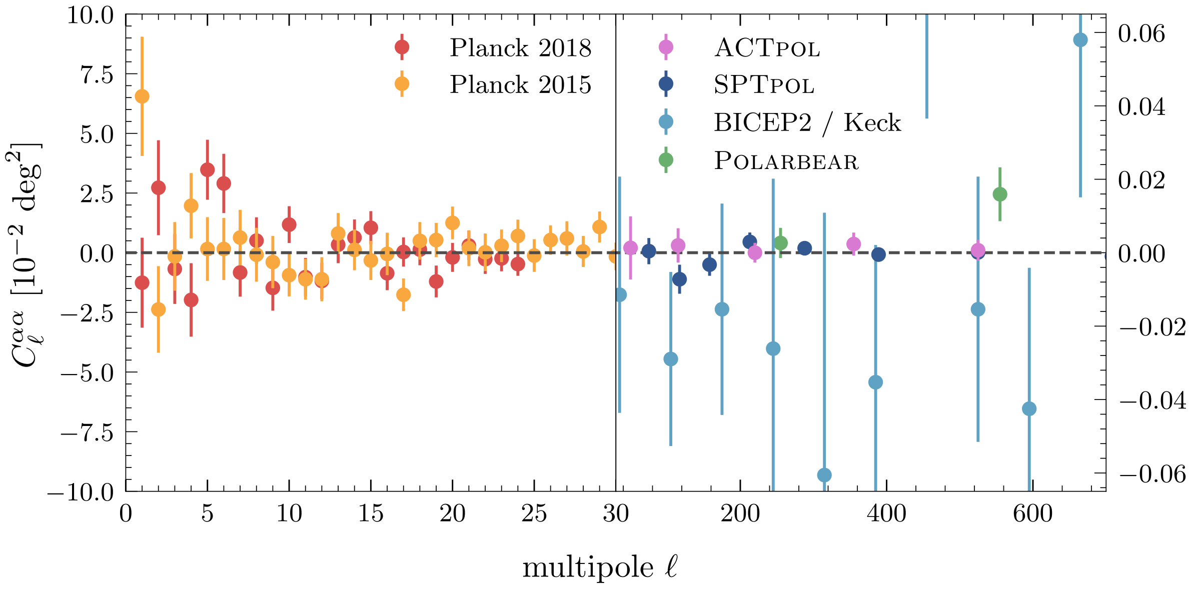
$$\begin{cases} \langle TB \rangle \neq 0 \\ \langle EB \rangle \neq 0 \end{cases}$$

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

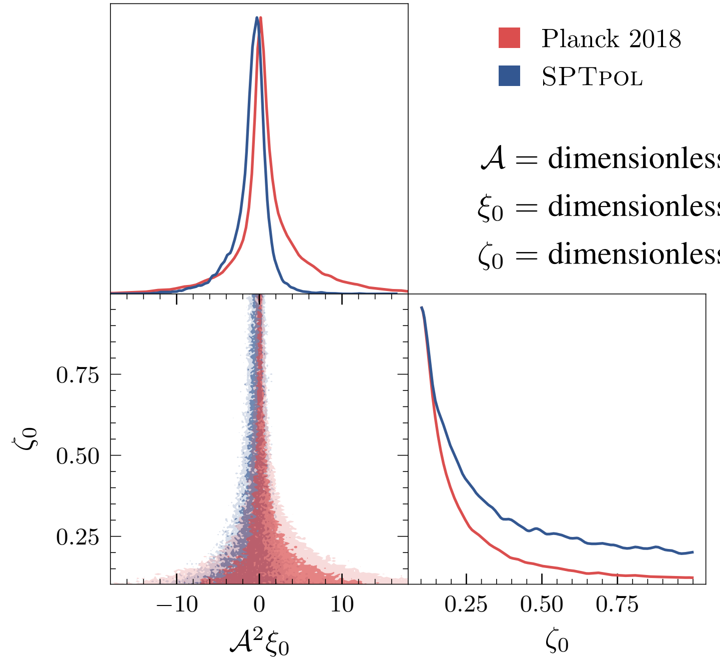
Constraints from anisotropic birefringence

[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:

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

Pogosian et. al. (2019)

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

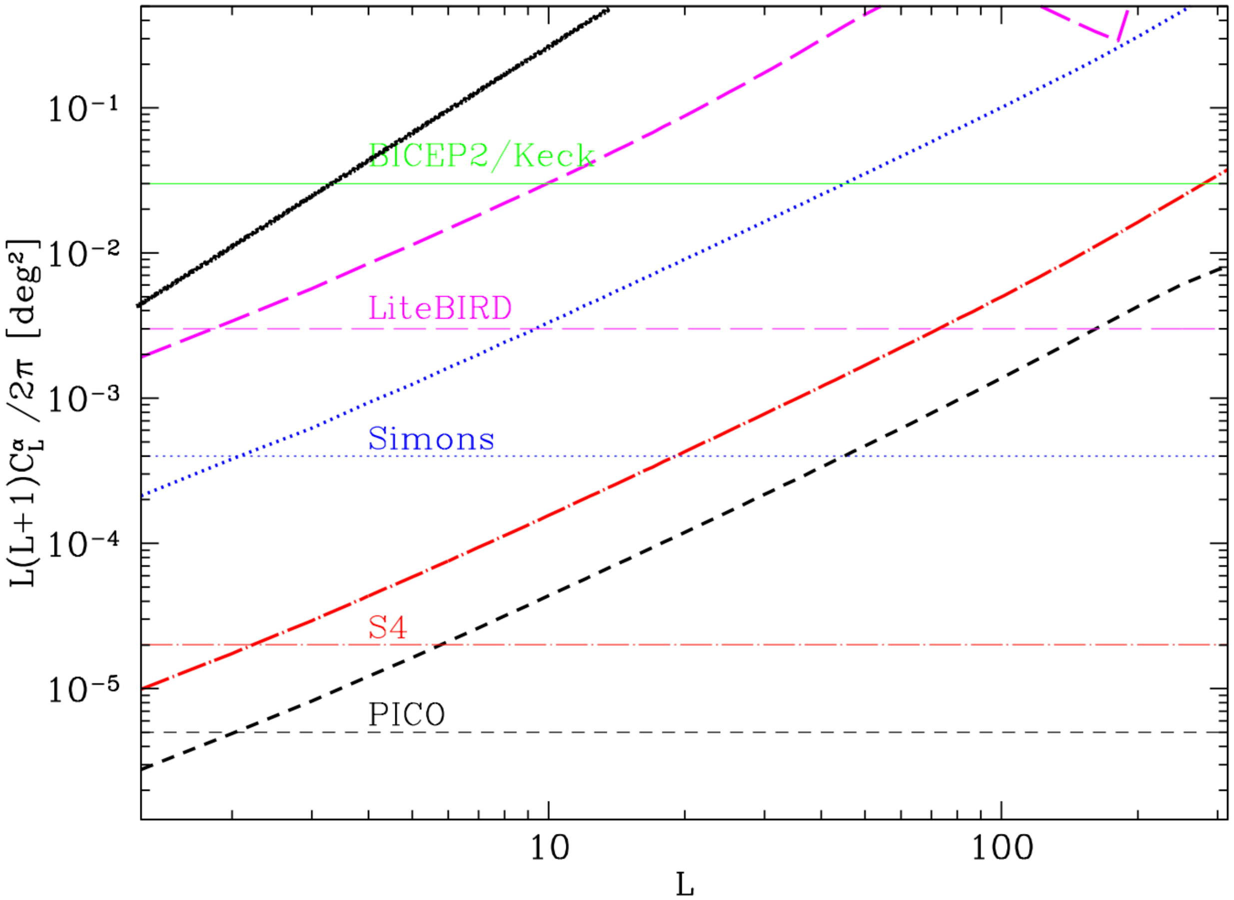
future telescopes

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.

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



what about
isotropic
birefringence

Are strings responsible for isotropic birefringence?

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

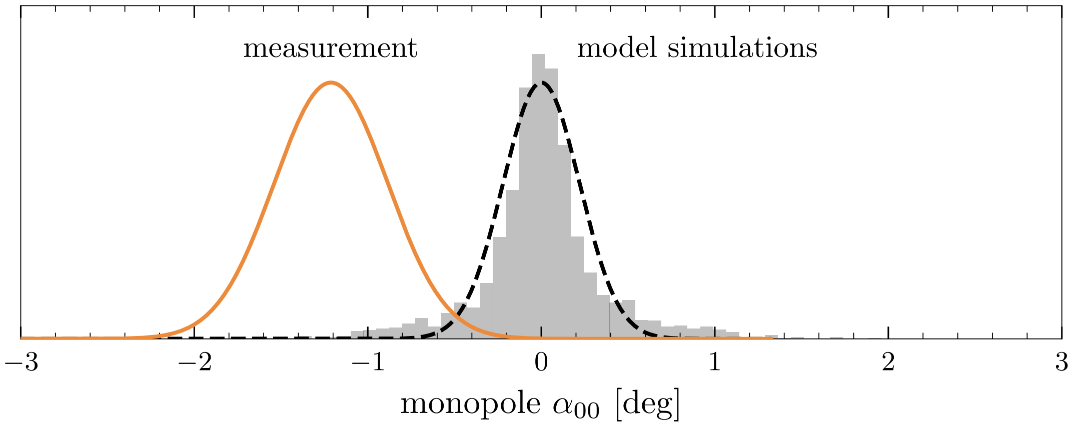
reported detection of isotropic birefringence:

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

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

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

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

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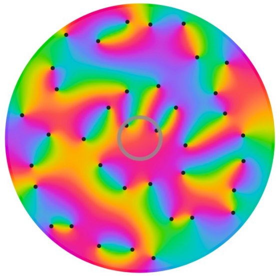
loopholes allowing large iso-BF

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

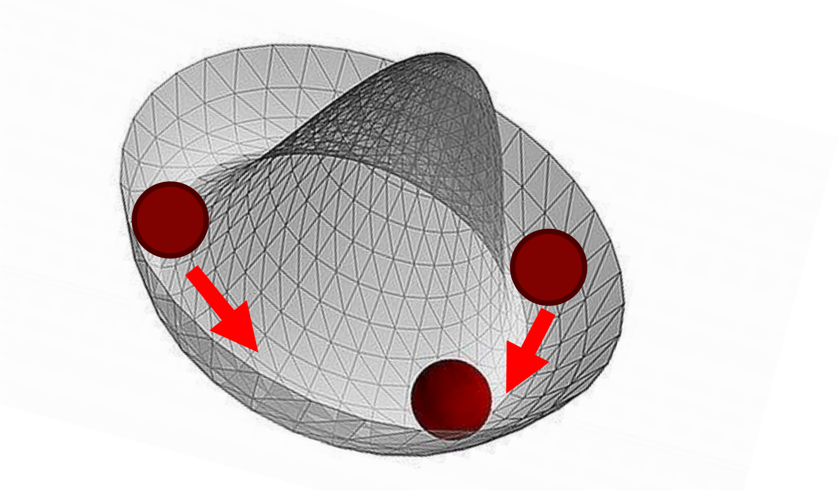
effect of
varying ALP mass

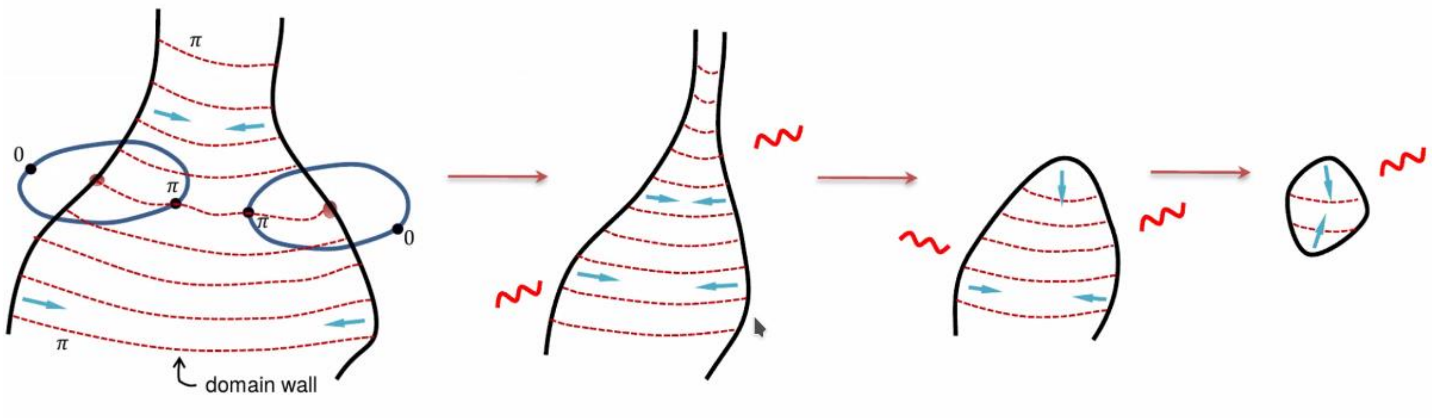
Collapse of the string-wall network

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

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

Impact on birefringence

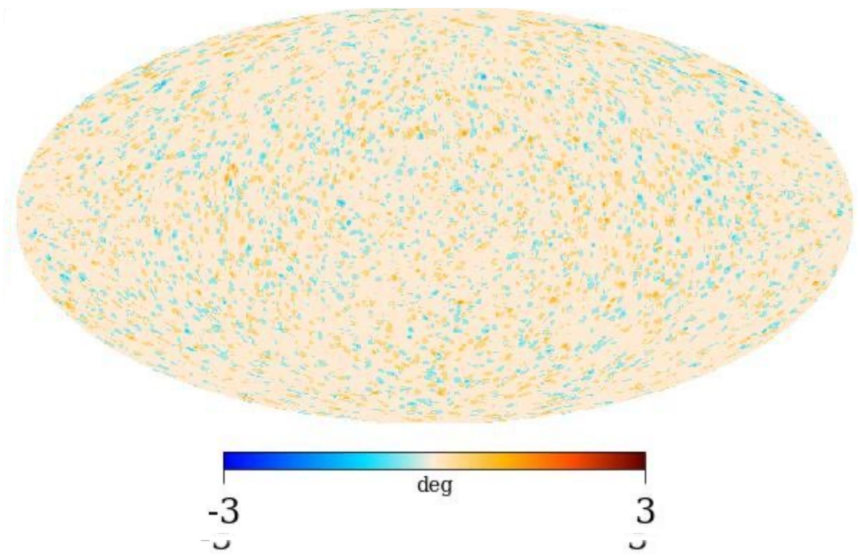
$\left(\text{assuming } N_{\text{DW}} = 1\right)$

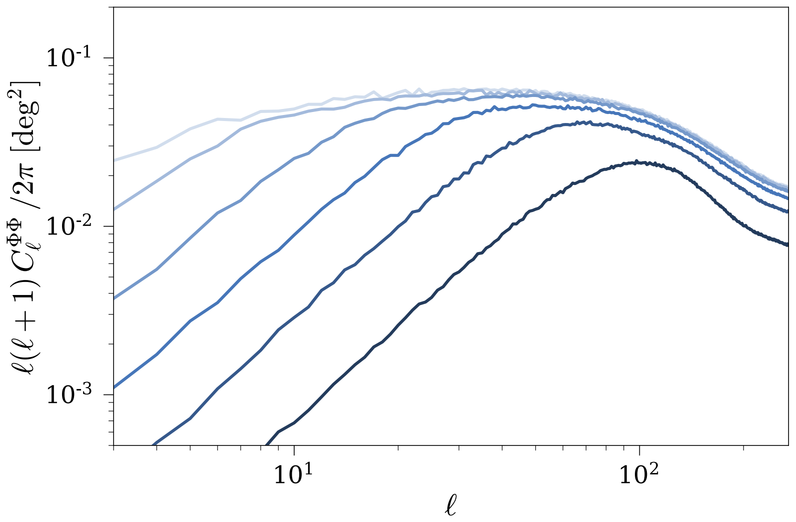
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

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

Implications

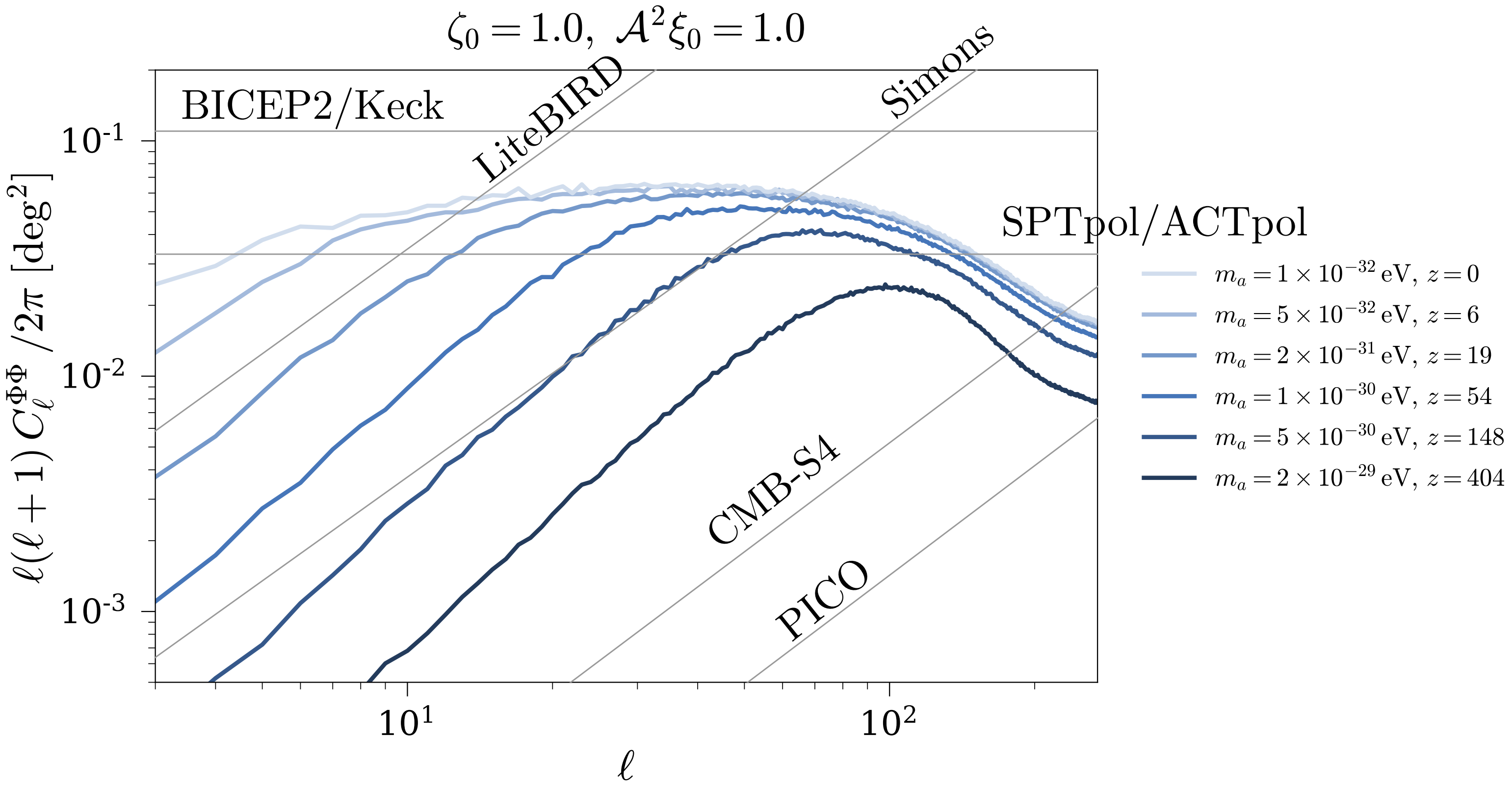
(assuming $N_{\text{DW}} = 1$)

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

projections: [Pogosian et. al. (2019)]

raise the ALP mass

(network collapses earlier)



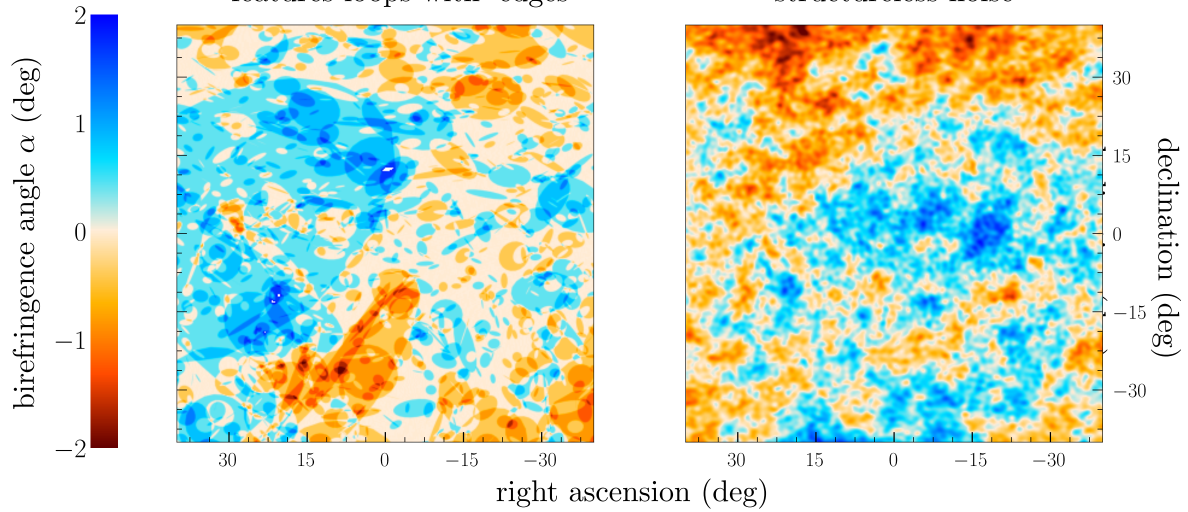
strong scale dependence ➔ possible to measure m_a

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?

Probing non-Gaussianity with scattering transform

[Yin, Dai, Ferraro (2023)]

std. method
power spectrum

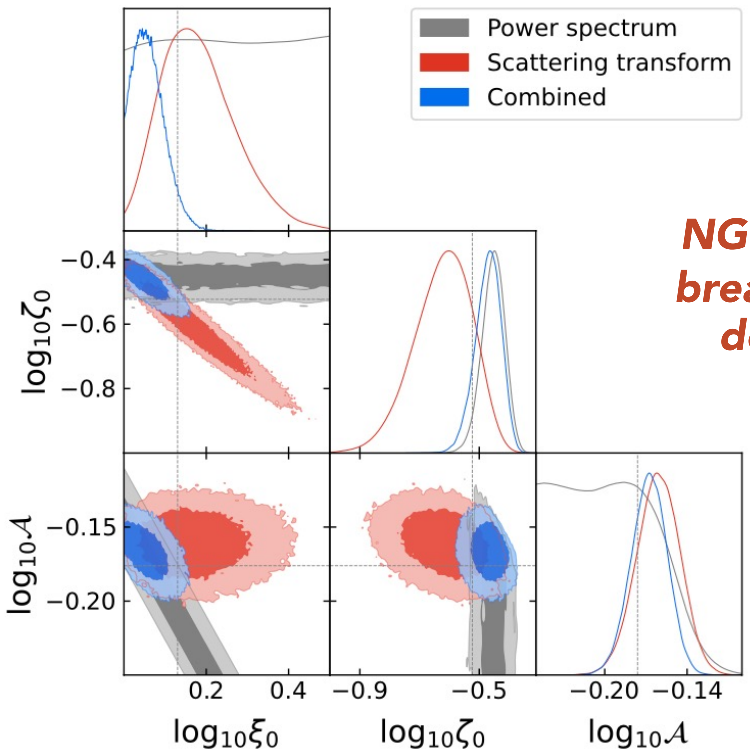
$$\text{signal:} \quad I_0(\mathbf{x})$$
$$\text{plane wave:} \quad \phi_{\mathbf{k}}(\mathbf{x})$$
$$P_{\mathbf{k}}(\mathbf{x}) = \langle |I_0 * \phi_{\mathbf{k}}|^2 \rangle(\mathbf{x})$$

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

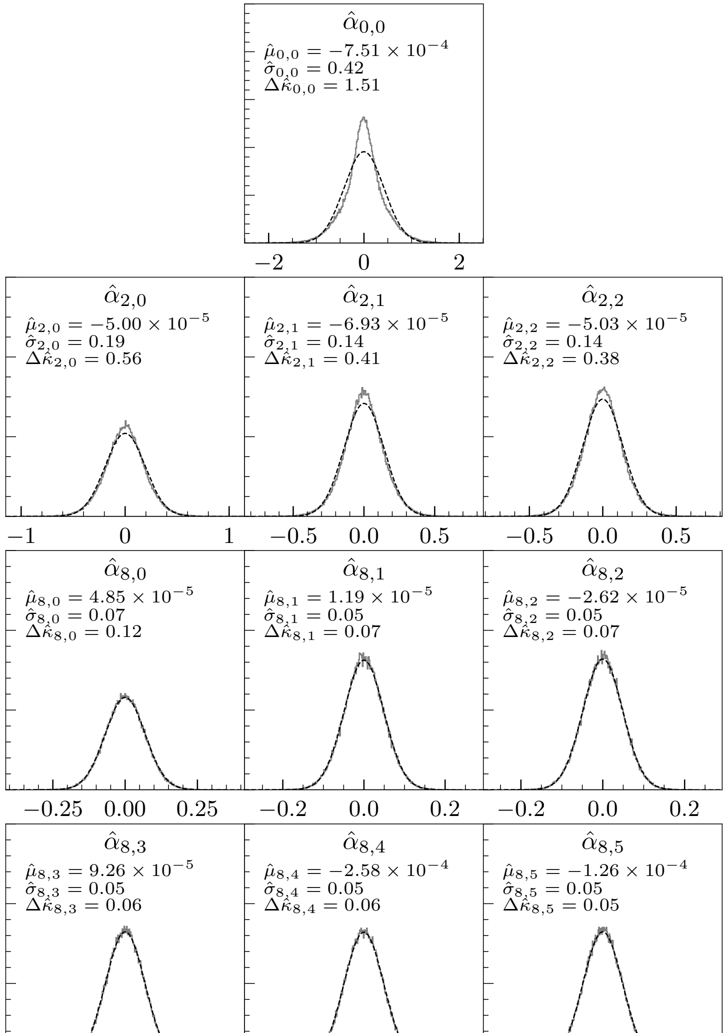
NG information breaks the $A^2\ \xi_0$ degeneracy

Birefringence non-Gaussianity

[Hagimoto & AL, arXiv:2306:07351]

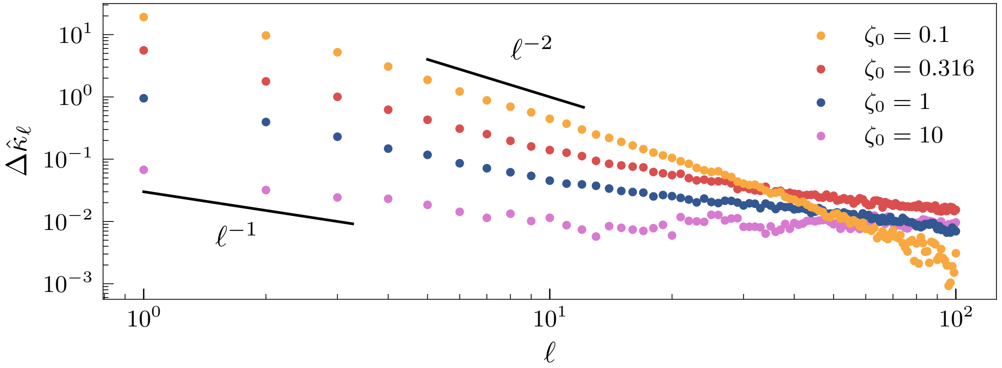
excess kurtosis

can be O(1) at low multipoles



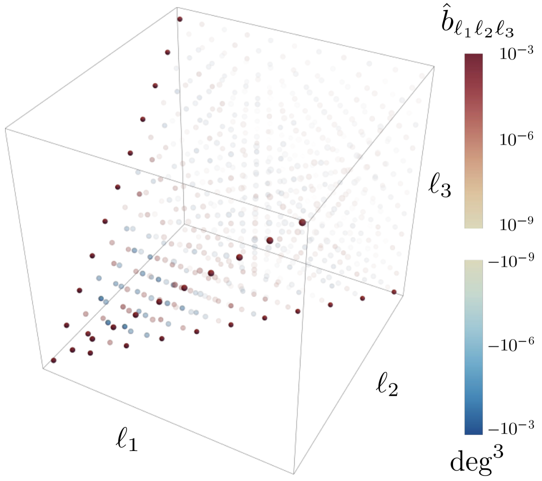
scaling with multipole index

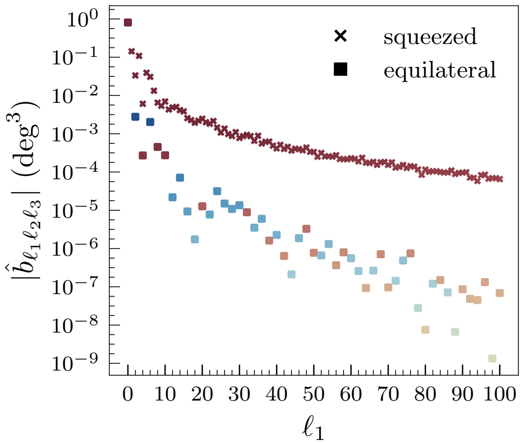
matches well an analytic toy model



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

Machine learning for axion strings

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

train 3 SCNN's to identify 3 LCM parameters

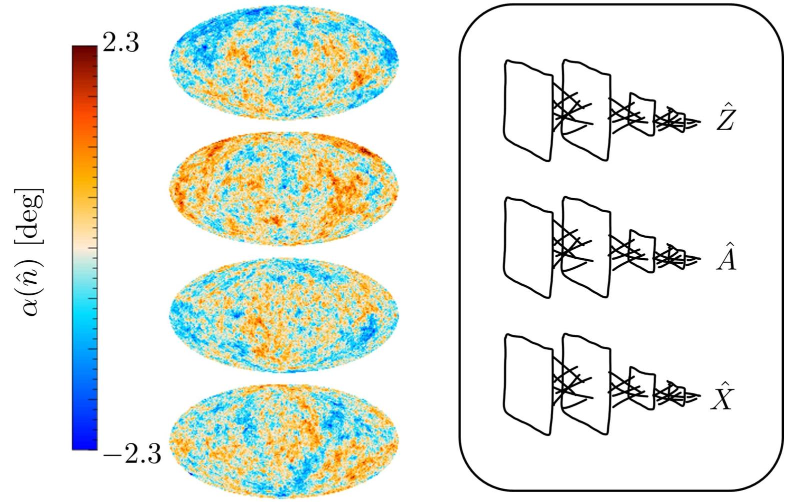
$$Z = \log_{10}(\zeta_0)\,, \qquad A = \log_{10}(\mathcal{A}^2\xi_0)\,, \qquad X = \log_{10}(\xi_0^2/\mathcal{A})$$

model parameters

$Z = 0$
$A = 0$
$X = 2.5$

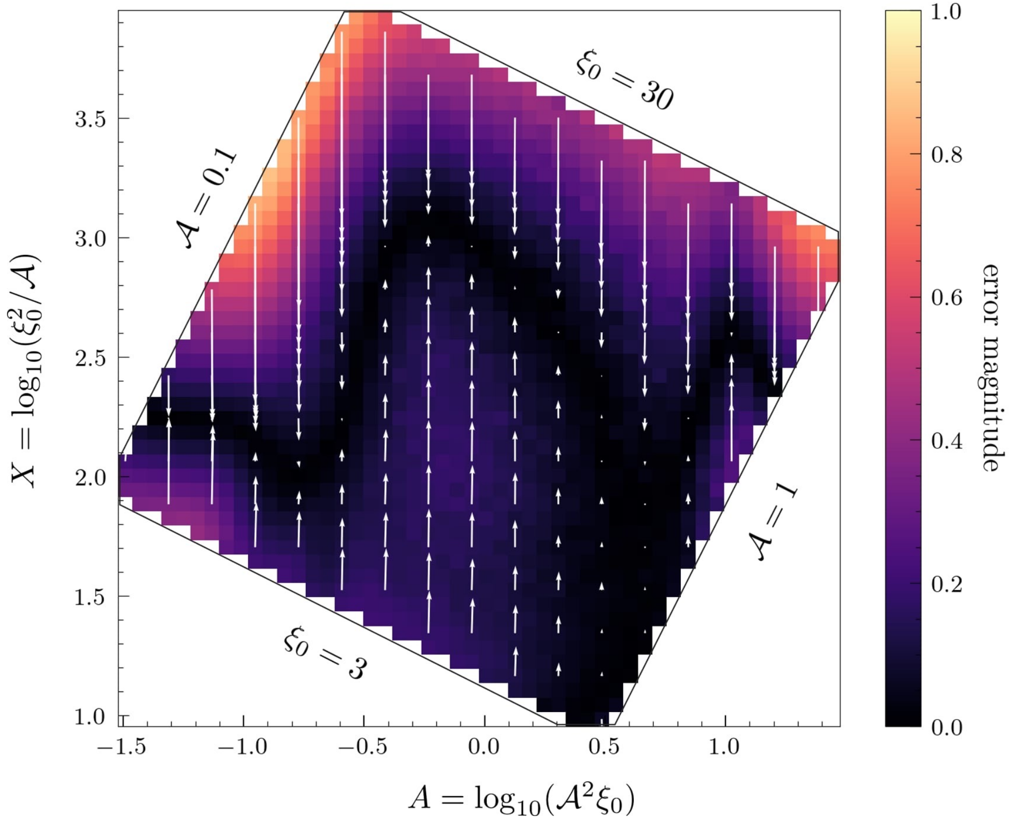
mock data

SCNN



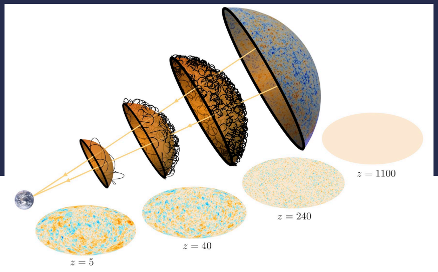
SCNN estimates

$\hat{Z}$	$\hat{A}$	$\hat{X}$
0.038	−0.003	2.23
0.074	−0.015	2.94
−0.030	0.020	2.88
0.031	−0.022	2.51



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
- Machine learning methods (spherical CNN) may prove useful to help to detect the subtle non-Gaussian signal of axion strings in next-generation CMB polarization data

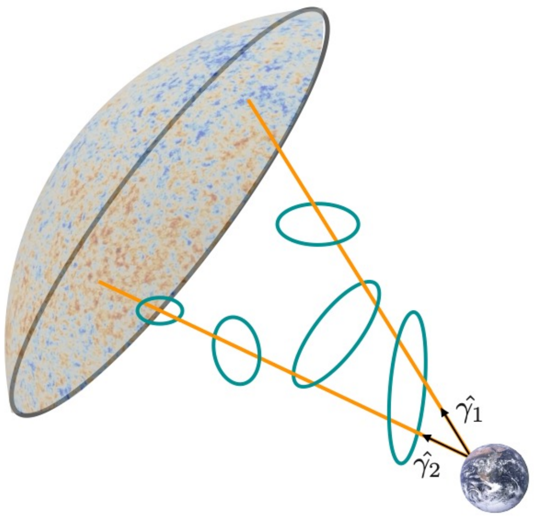
backup slides

Analytical understanding

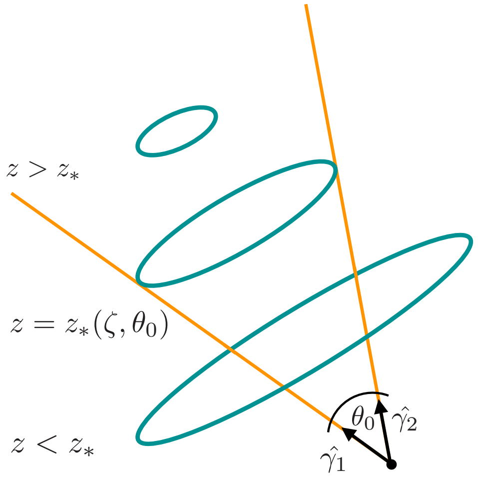
[Jain, AL, Amin, arXiv:2103:10962]

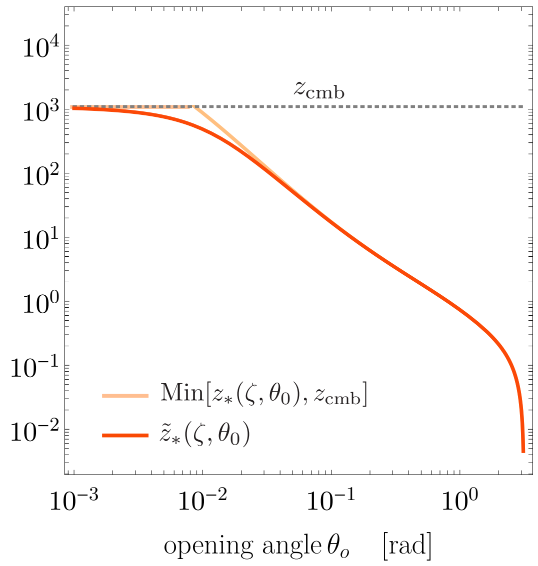
correlations accumulate
when both photons pass
through the same loops

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



large-angle correlations are
established later (small z)



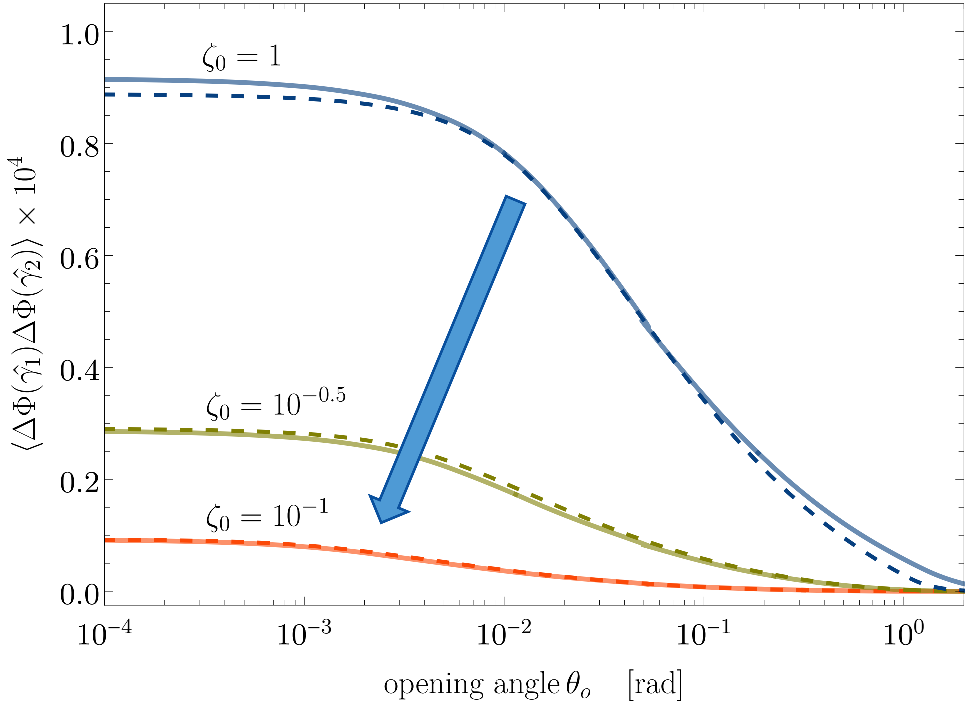


Analytical understanding

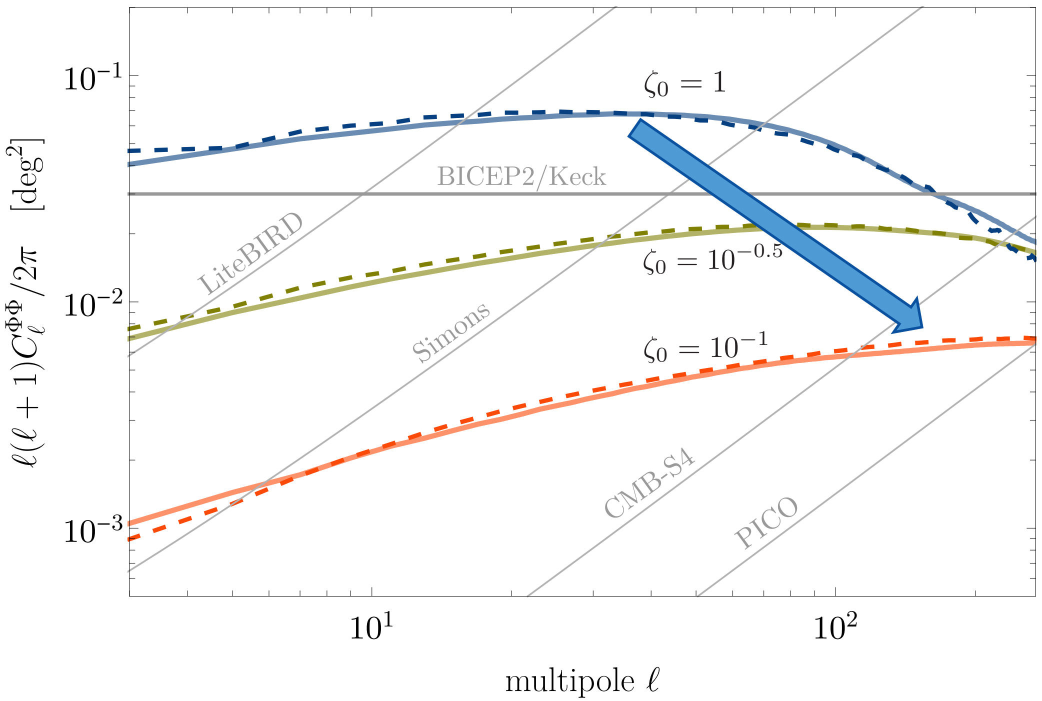
[Jain, AL, Amin, arXiv:2103:10962]

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

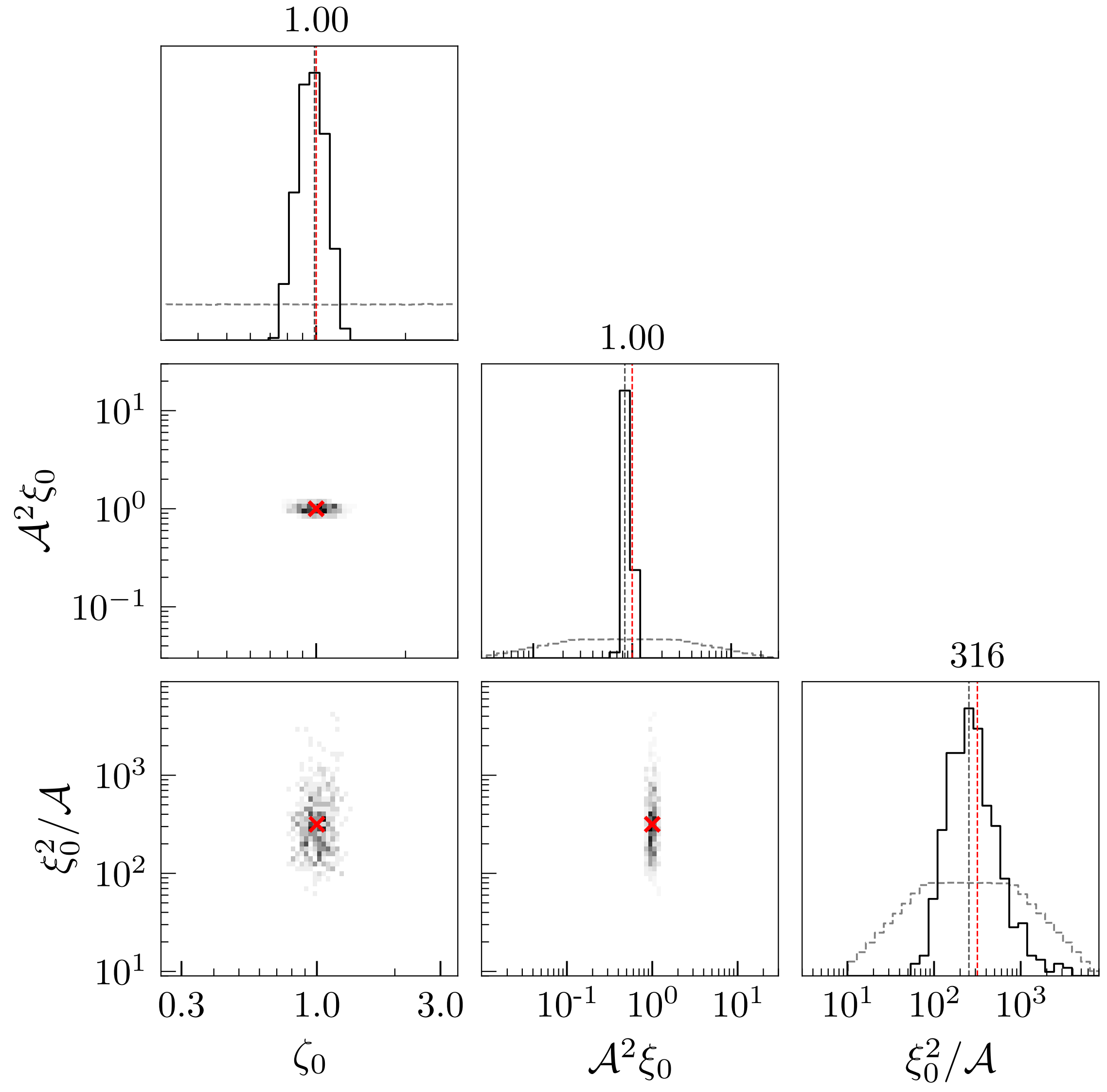
correlation function



angular power spectrum



Machine learning for axion strings



How well does the SCNN reproduce a known input?

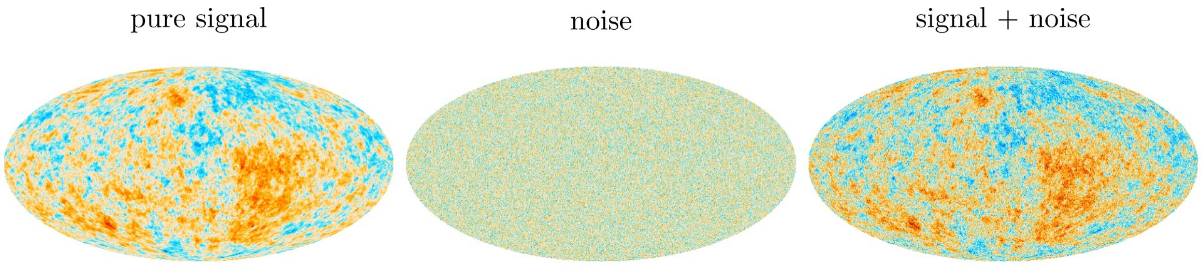
SCNN's for Z & A work well

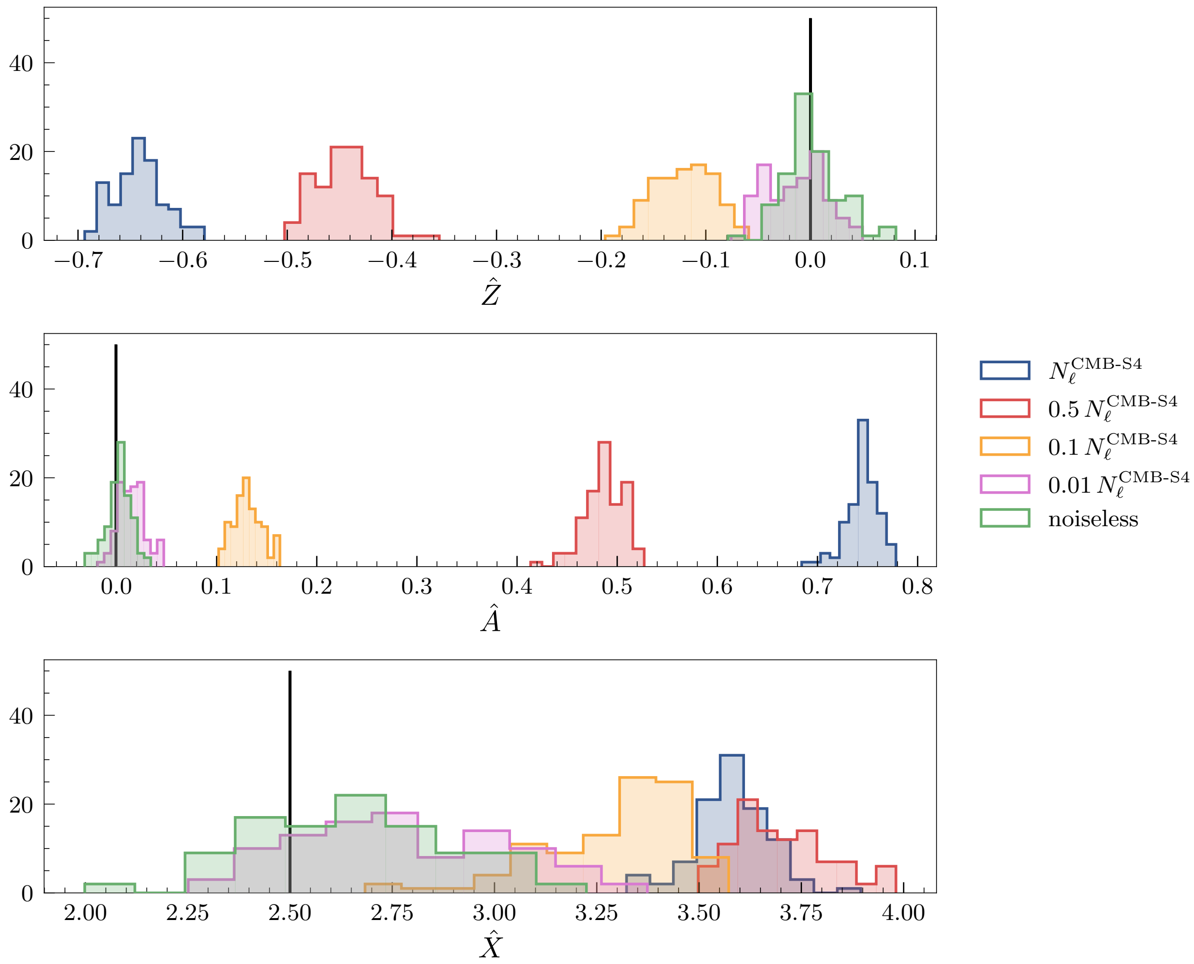
SCNN for X struggles

Machine learning for axion strings

How well would the SCNN perform on noisy data?

SCNN trained on noise-less sims … then shown sim + Gaussian noise





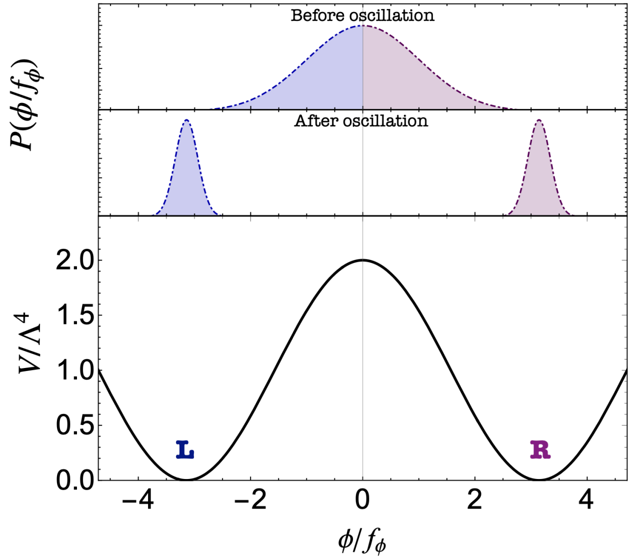
an SCNN trained on noise-less sims would require noise reduction to a level below the CMB-S4 projection to function (needs to be trained on noisy sims)

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 $H_{inf} \sim\sim f_a$



possible to evade DW problem

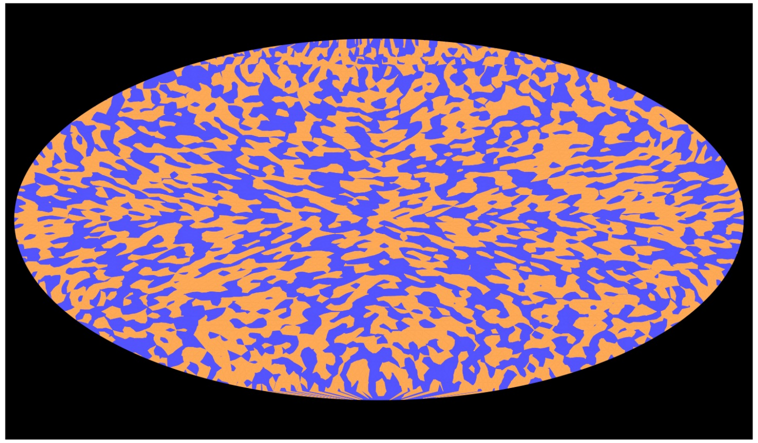
imposes bound on mass & decay constant

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

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

birefringence signal

independent of propagation



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

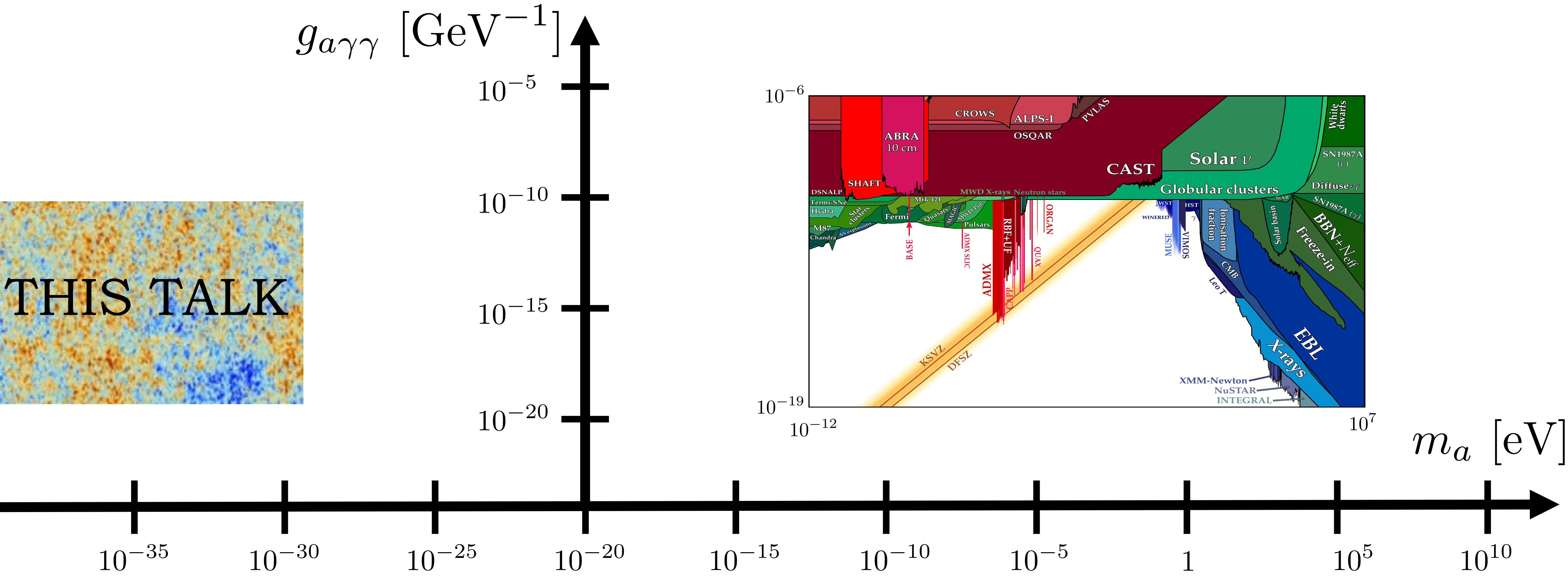
$\Delta\Phi = c_\gamma \alpha$ if LSγ is from the vacuum L.

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

(no random-walk enhancement)

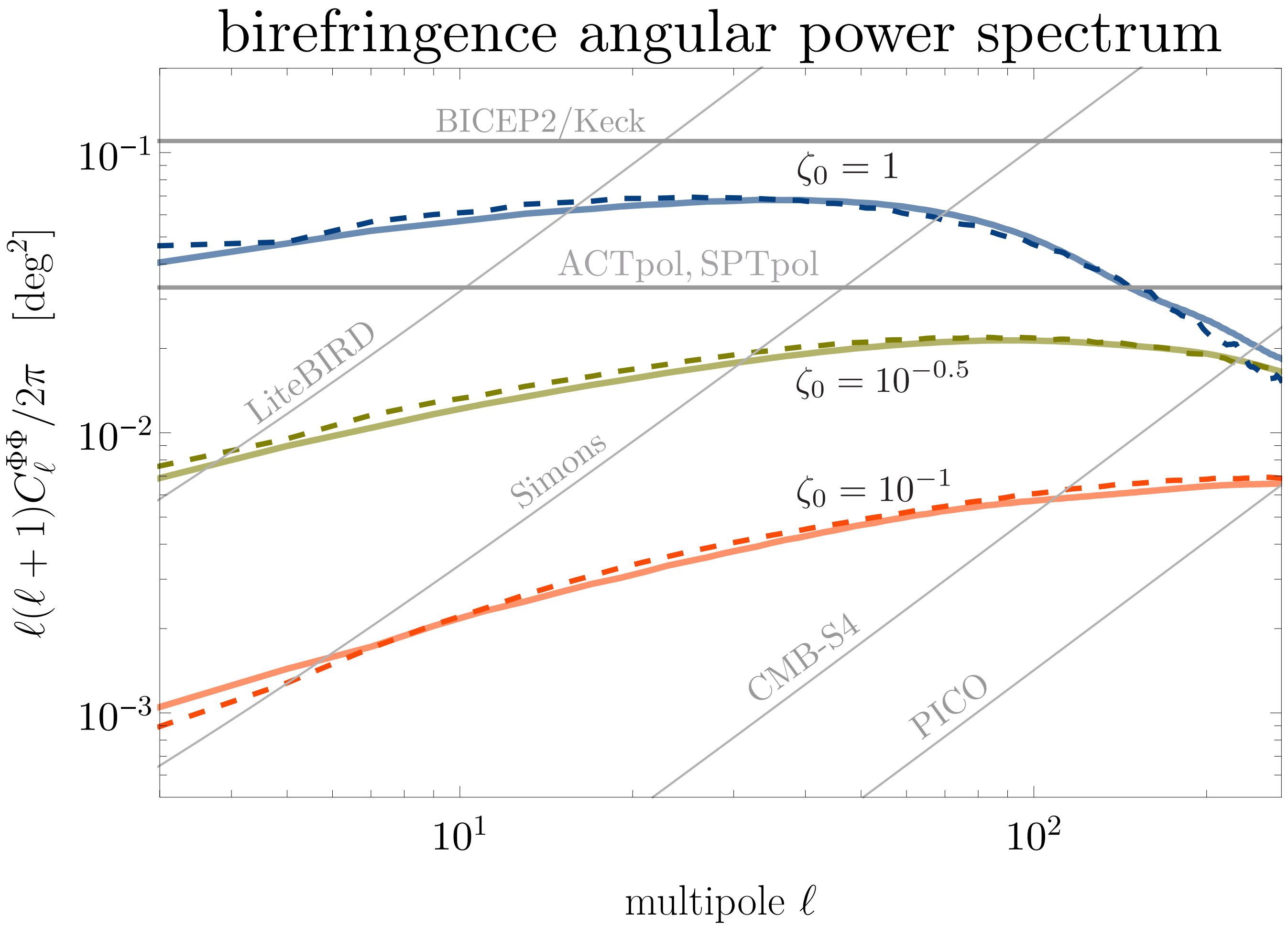
Theory landscape: axion-like particles

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



Axion-string induced birefringence signal

[Jain, AL, Amin (2103.01962)]



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

Key features

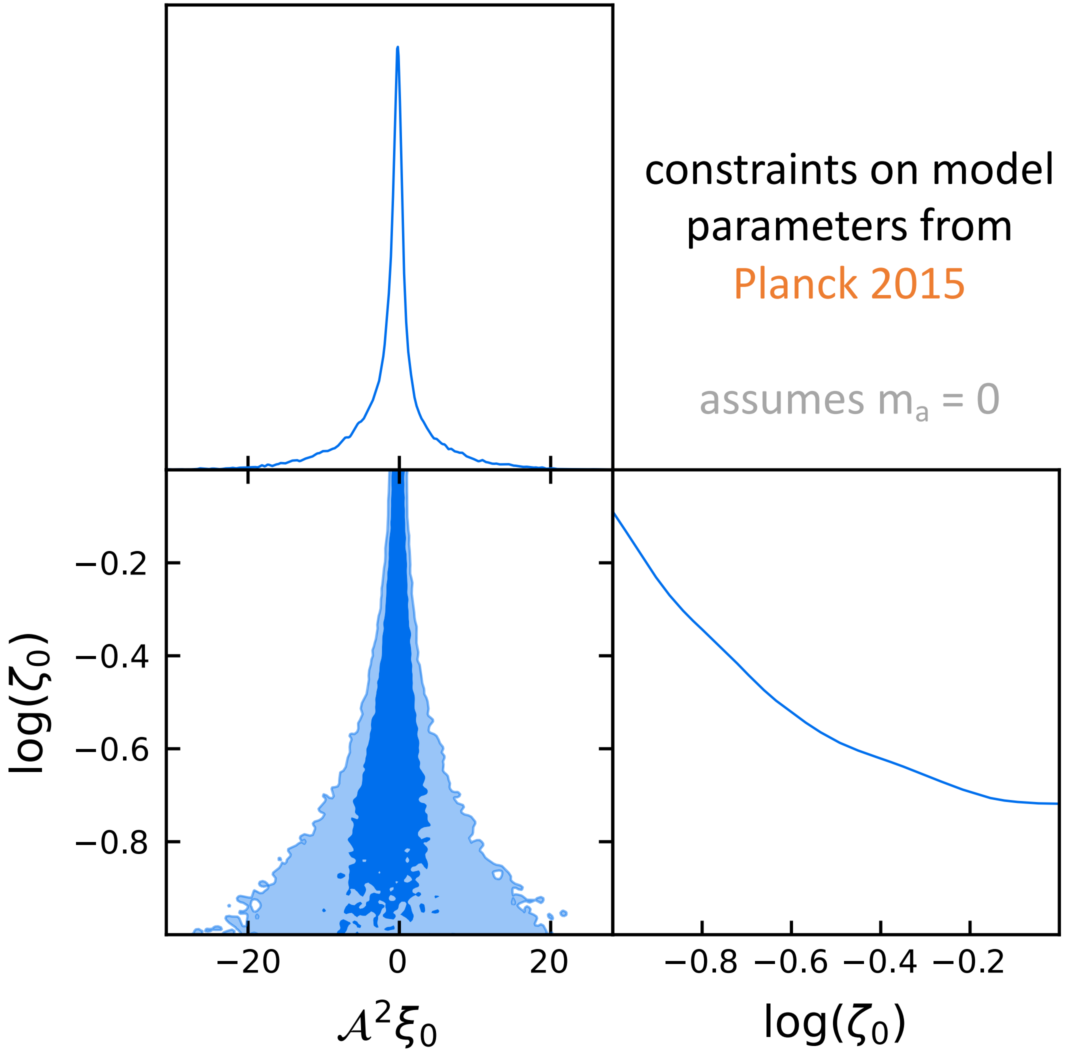
- Power spectrum is almost scale invar.
- Characteristic scale (l @ the peak) set by loop size at LSS
- Smaller loops (ζ_0) => weaker signal
- Trivial dependence on loop density (ξ_0) and anomaly coefficient (A) … power scales with ξ_0 A^2

Testability

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

CMB probes of axion strings: constraints

[Yin, Dai, Ferraro (2111.12741)]



constraints on model parameters from Planck 2015

assumes $m_a = 0$