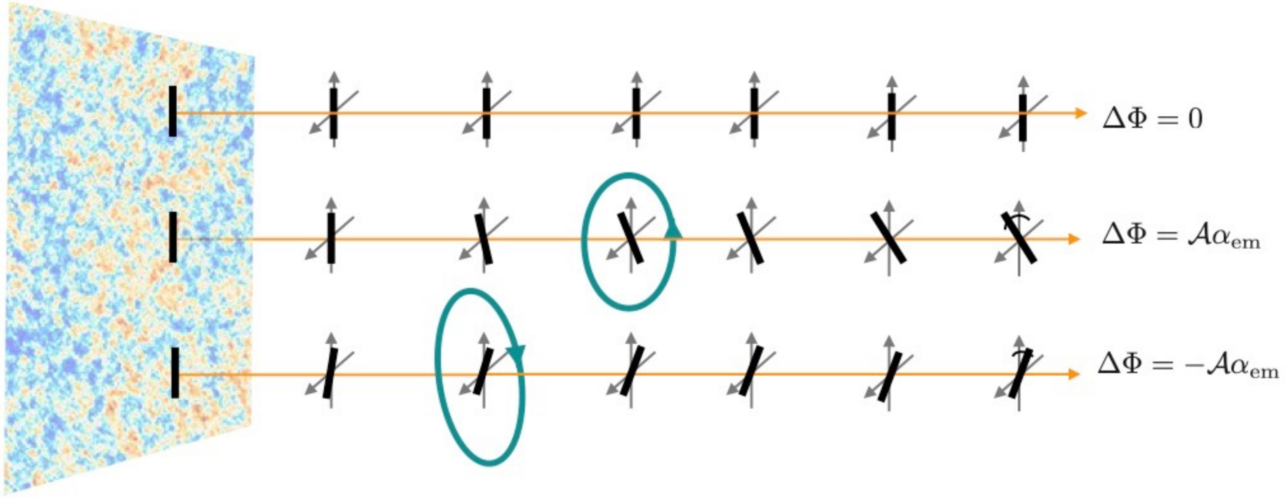
Looking through loops: CMB birefringence from axion strings



Andrew Long
Rice University
@ Axions in Stockholm
June 30, 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

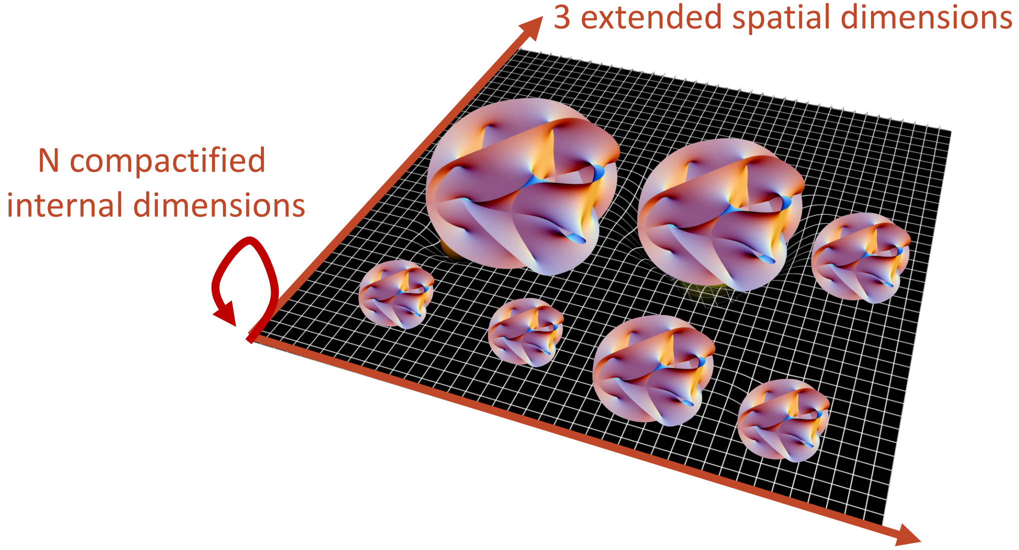
Theory landscape: axion-like particles

axion-like particles

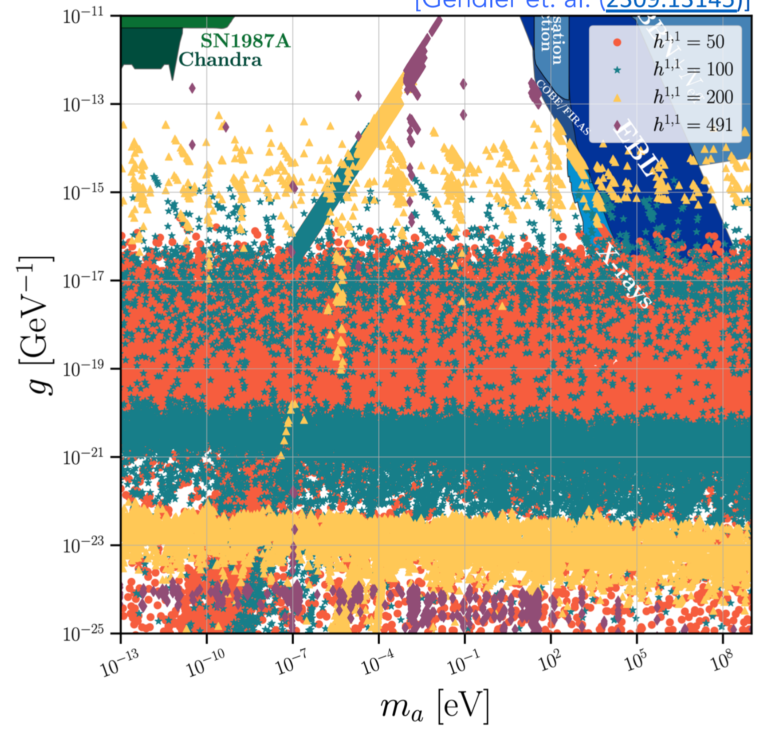
$$\mathcal{L} \supset \frac{1}{2}(\partial a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

ALPs from extra dimensions

(such as string theory)



[Gendler et. al. (2309.13145)]



Theory landscape: axion-like particles

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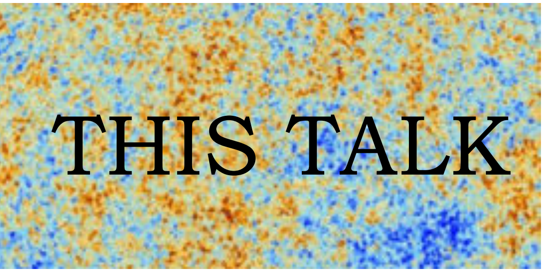
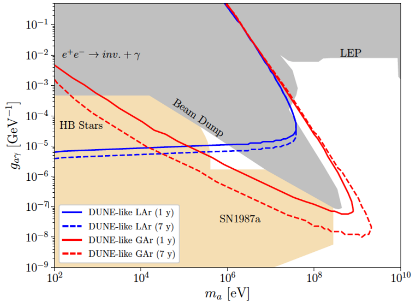
hyper-light axion-like particles (testable with cosmology)

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

heavy axion-like particles (testable in the lab)





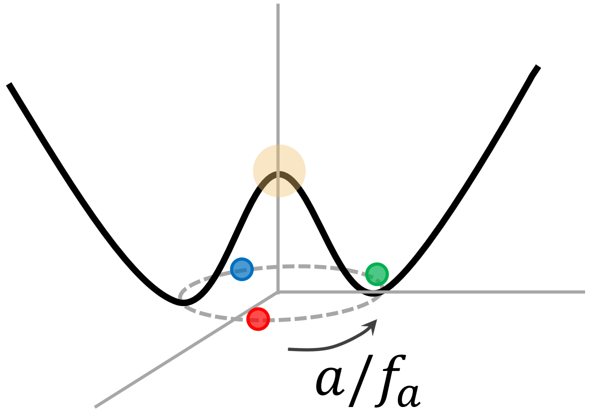
10^{-38} eV | 10^{-30} eV | 10^{-22} eV | 10^{-14} eV | 10^{-6} eV | 10^{2} eV | 10^{10} eV — m_a

ALPs can form axion strings

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

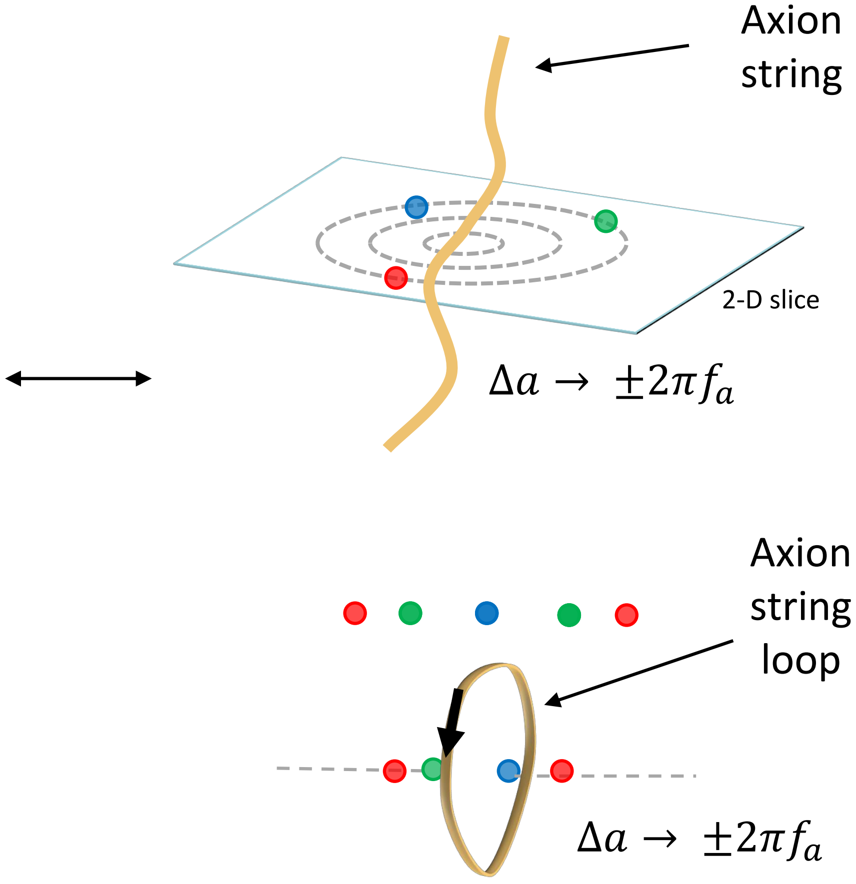
Field space

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



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

Physical space



string thickness = microscopic

string length = cosmological

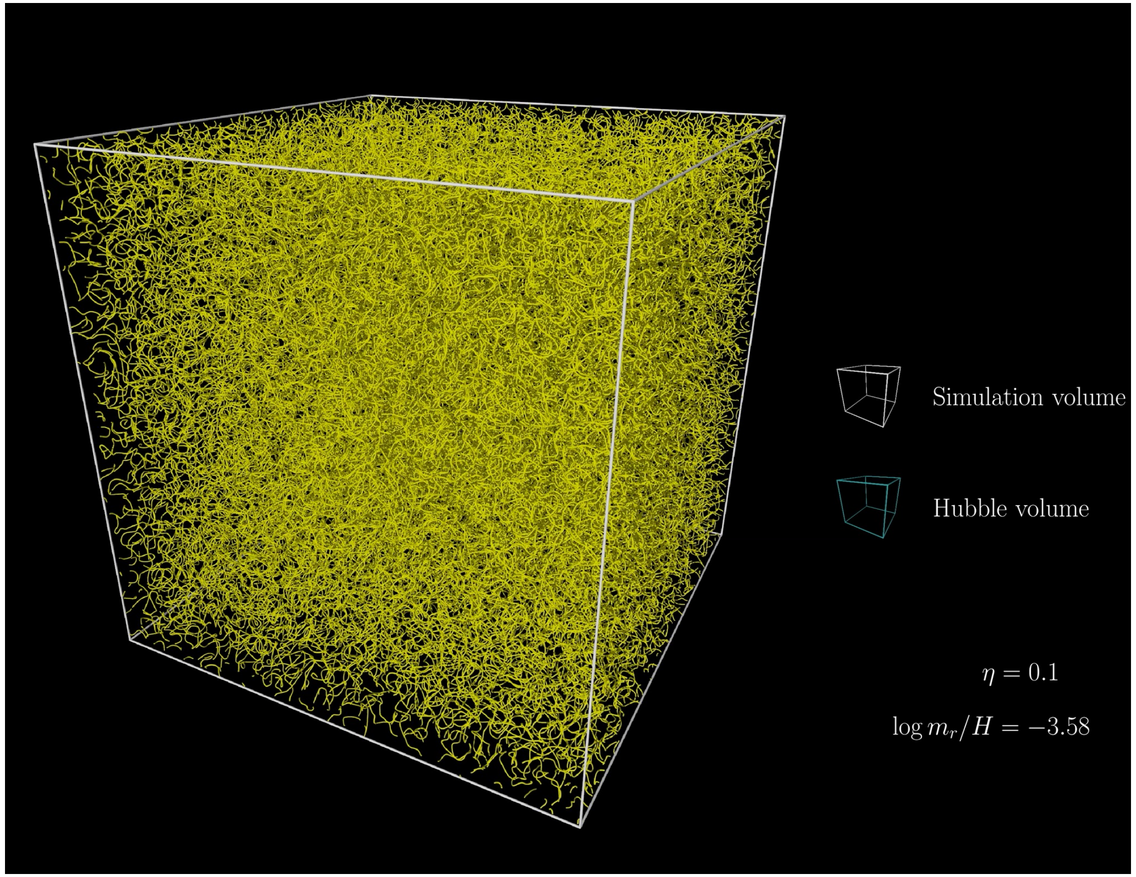
assume: $T_{\mathrm{RH}} > f_a$

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?

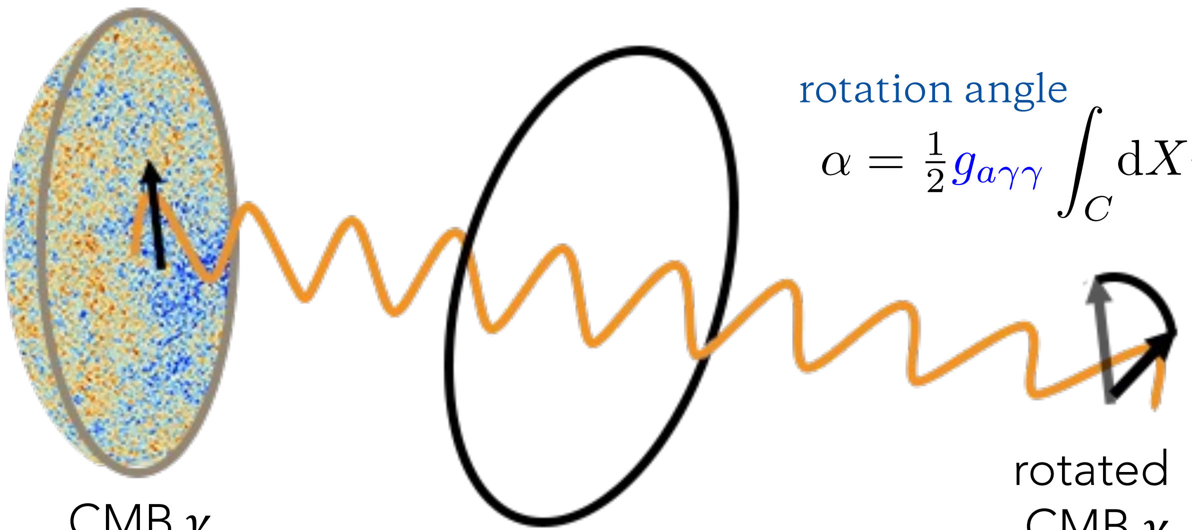
birefringence
from axion strings

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

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

assume interaction with electromagnetism:

standard Chern-Simons coupling

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

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

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

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

* birefringence can be measured through E-B cross correlation

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

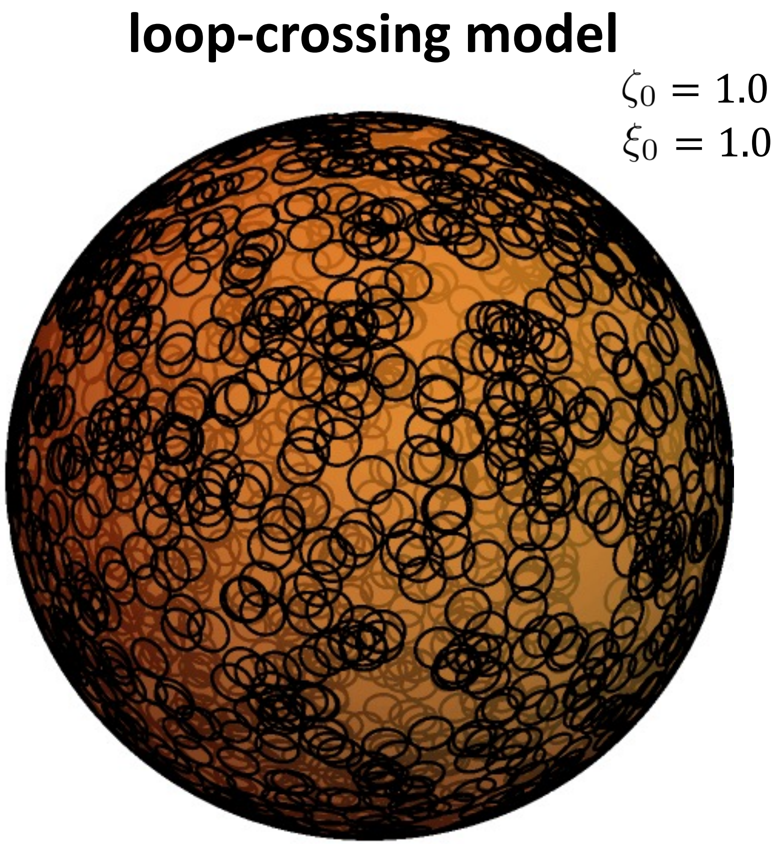
$$R(t) = \zeta_0 / H(t)$$

- Number of loops tracks Hubble

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

Model Parameters

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

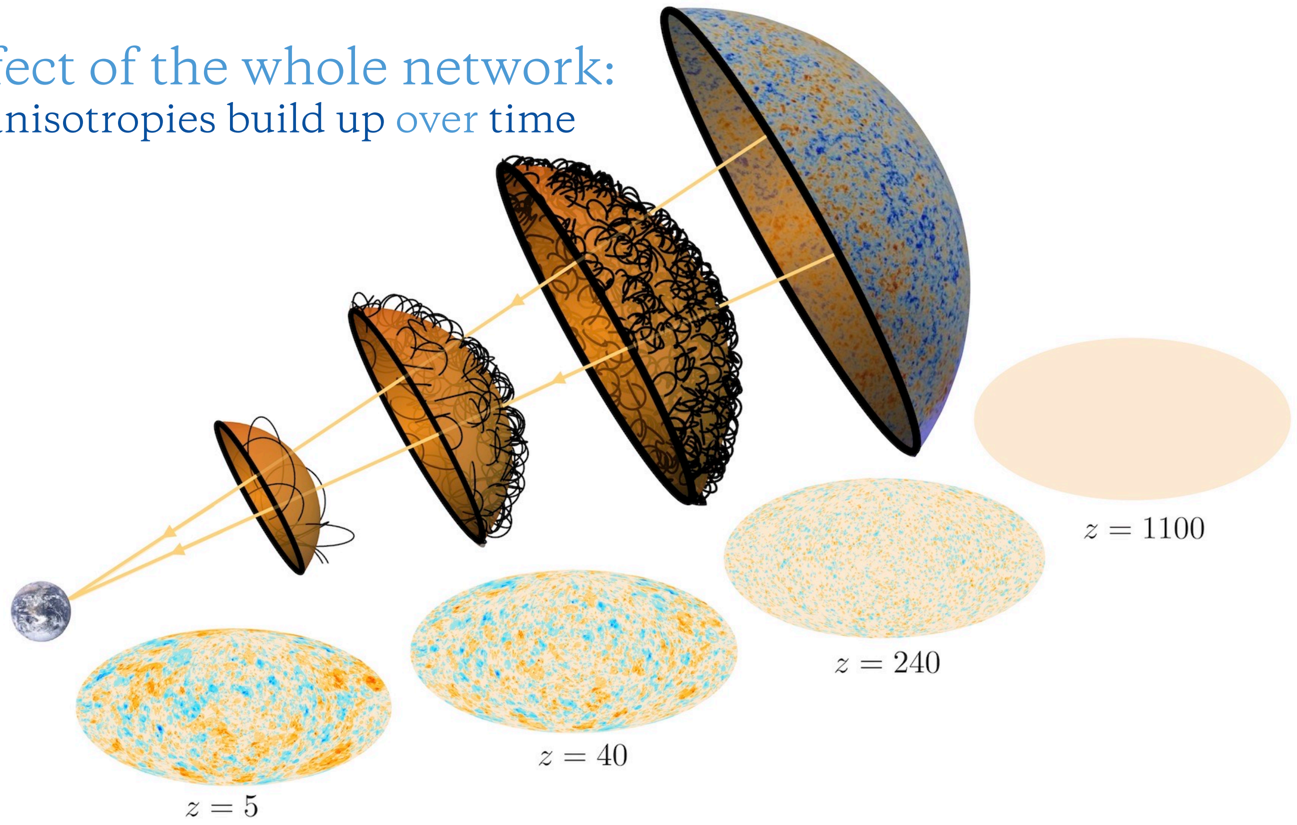


early time -> small loops
late time -> large loops

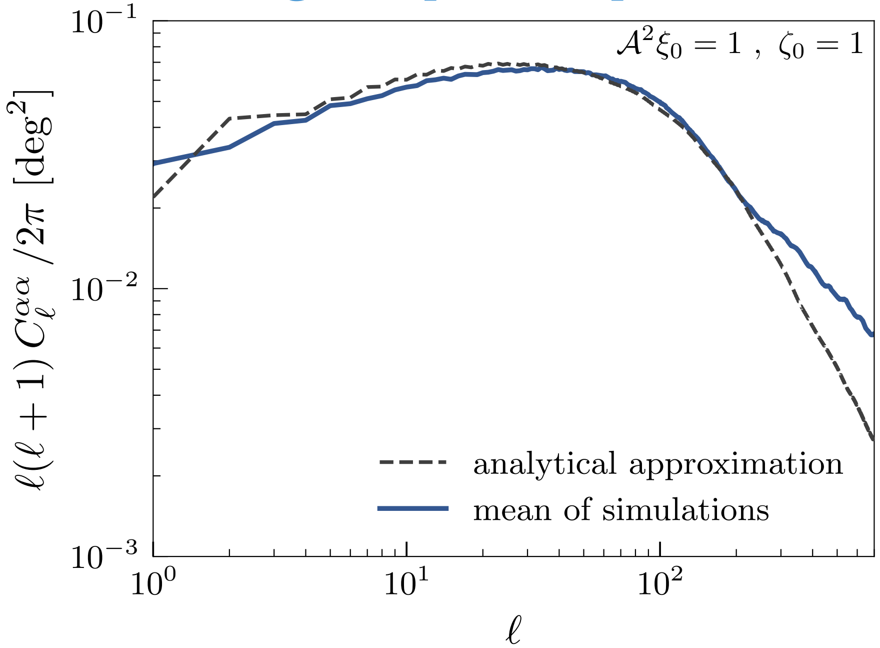
Expected birefringence signal

[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: $\langle\alpha\alpha\rangle \sim A^2\,\xi_0$

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

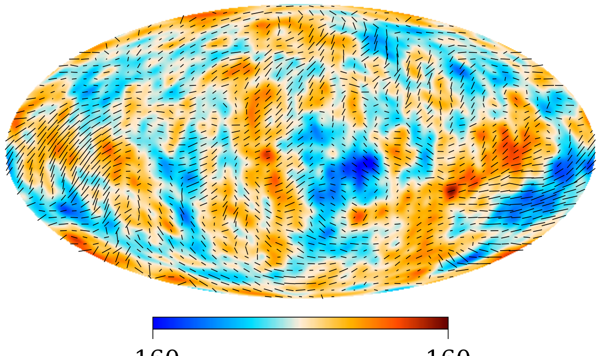
Effect on CMB polarization

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

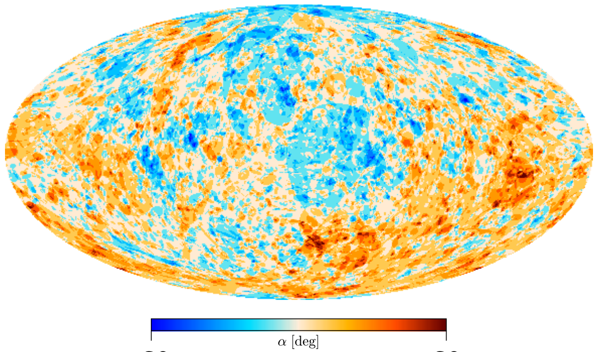
$$T(\hat{\boldsymbol{n}}) \to T(\hat{\boldsymbol{n}})$$

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

primordial CMB sky

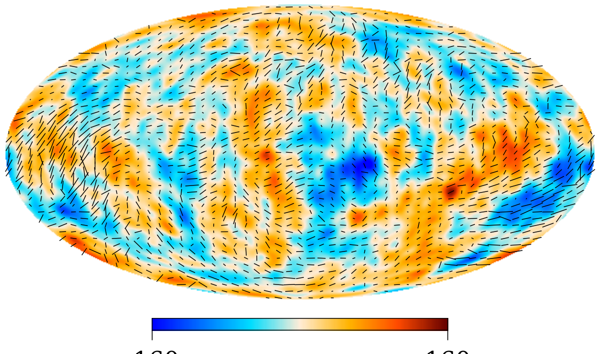


axion string -induced birefringence angle

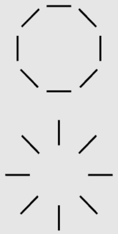


(exaggerated by ~30x)

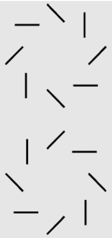
Planck's CMB sky



$E-mode$ pol pattern



$B-mode$ pol pattern



Signal of axion string-induced cosmological birefringence

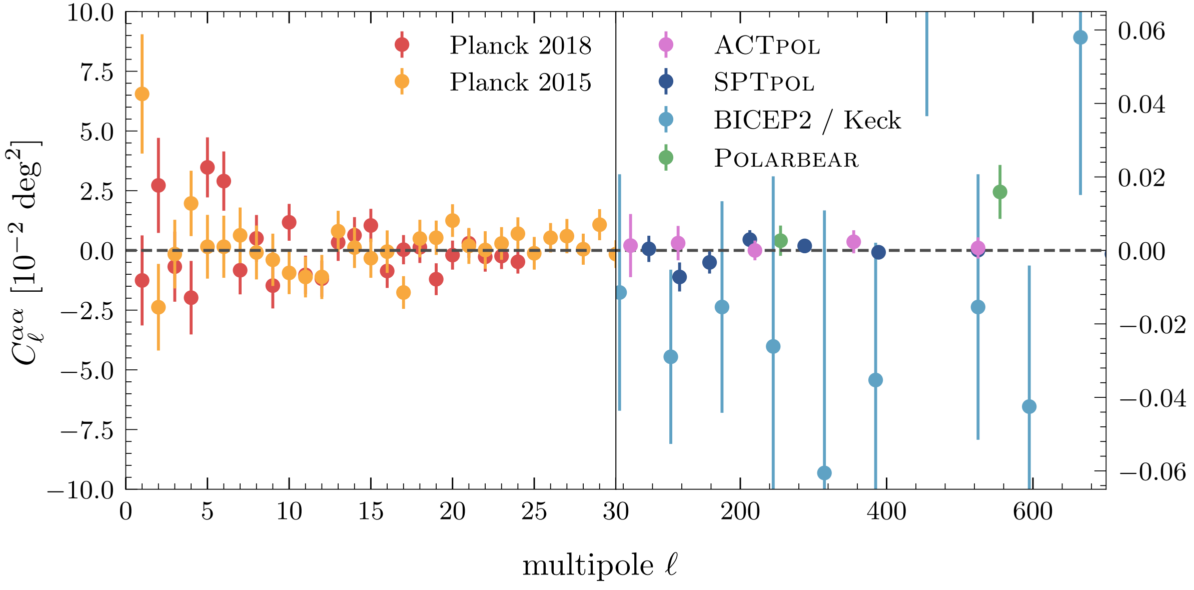
$$\begin{cases} \langle TB \rangle \neq 0 \\ \langle EB \rangle \neq 0 \end{cases}$$

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

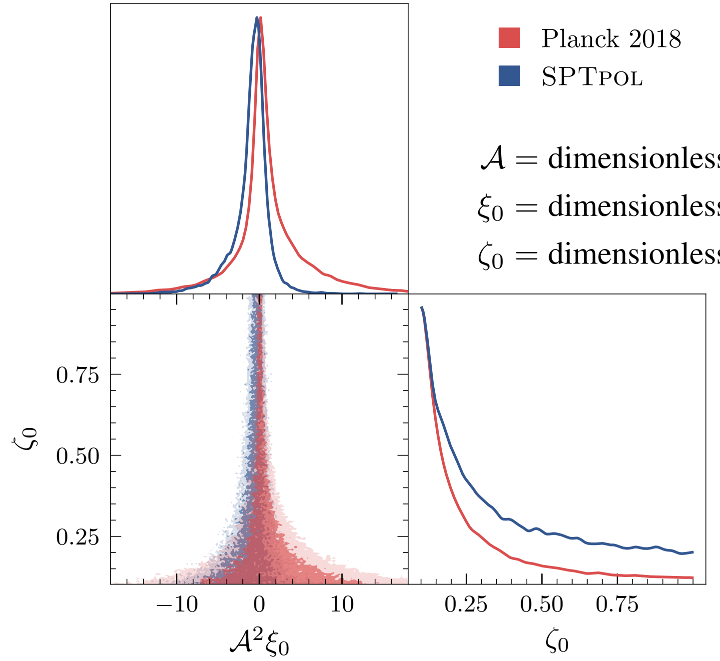
Constraints from anisotropic birefringence

[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:



$\mathcal{A}$ = 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)

future telescopes

probes of isotropic + aniso. birefringence

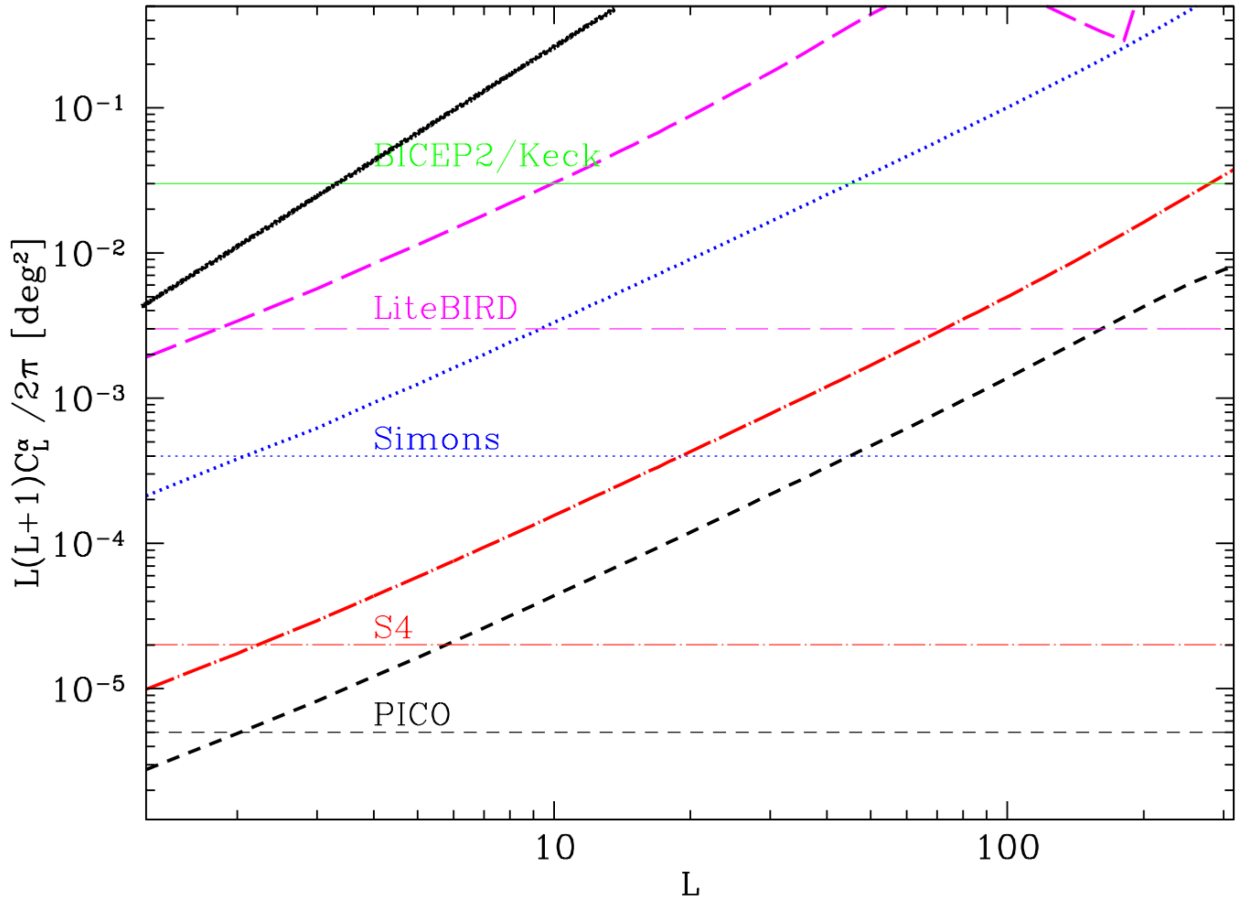
Current			LiteBIRD			SO			CMB-S4-like			PICO		
α ′	A_α $10^{-2}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ ′	α ′	A_α $10^{-3}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ ′	α ′	A_α $10^{-4}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ ′	α ′	A_α $10^{-5}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$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



what about
isotropic
birefringence

Are strings responsible for isotropic birefringence?

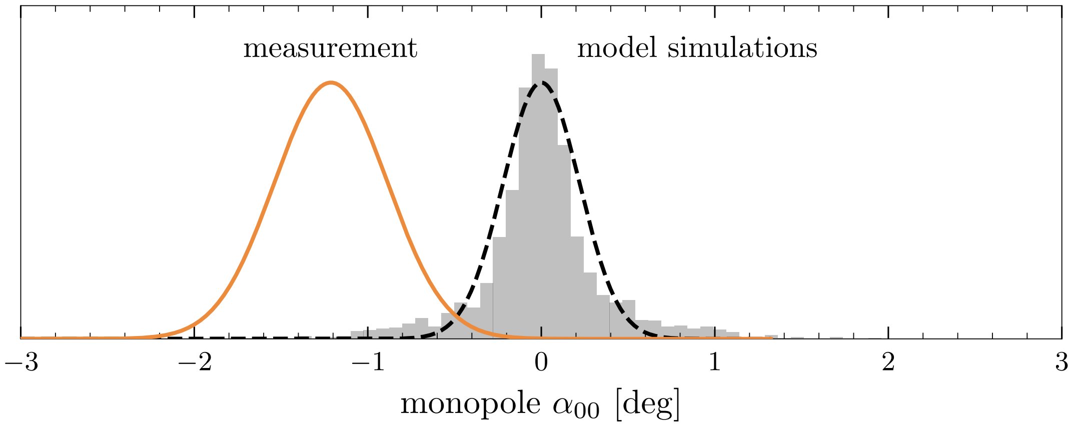
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

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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[Eskilt (2022)], [Eskilt & Komatsu (2022)]
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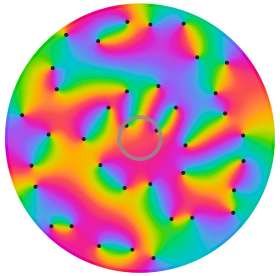
loopholes allowing large iso-BF

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

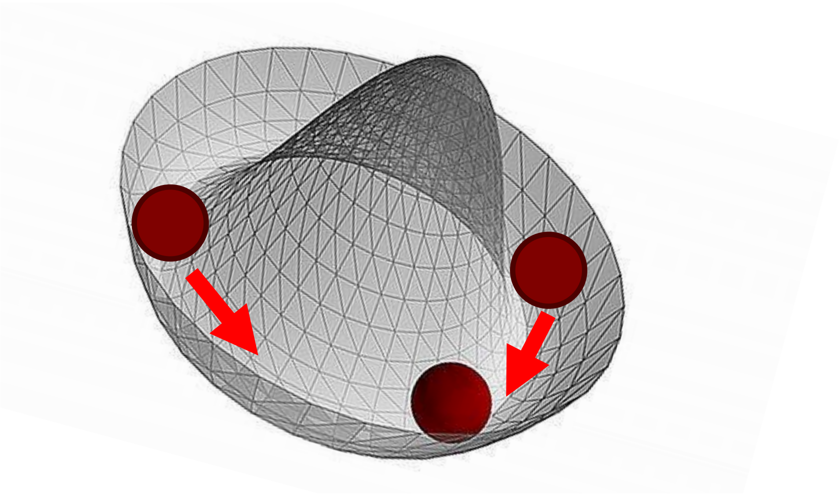
effect of
varying ALP mass

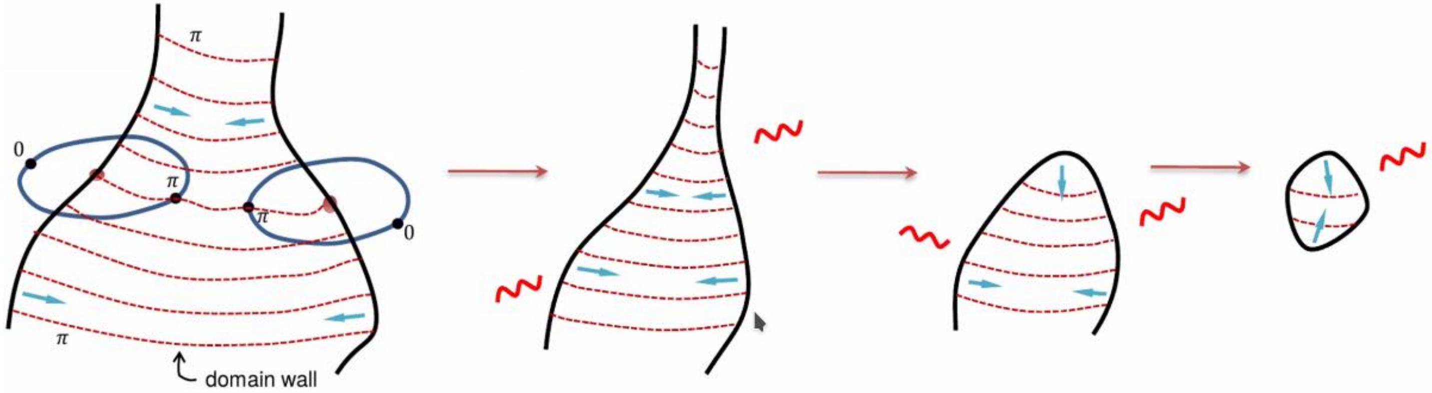
Collapse of the string-wall network

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

(string network survives until after recombination)

(string network collapses before today)

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

Impact on birefringence

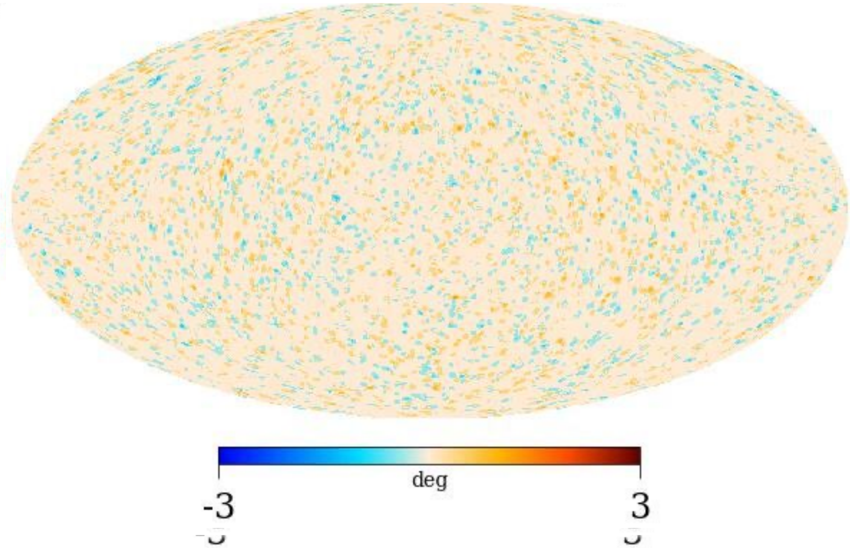
(assuming $N_{\rm DW} = 1$)

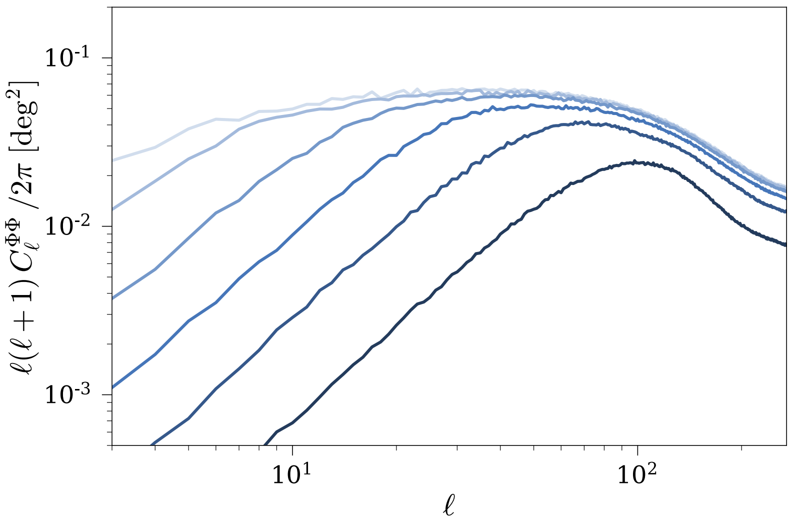
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

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

raise the ALP mass
(network collapses earlier)

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





strong scale dependence ➔ possible to measure m_a

Implications

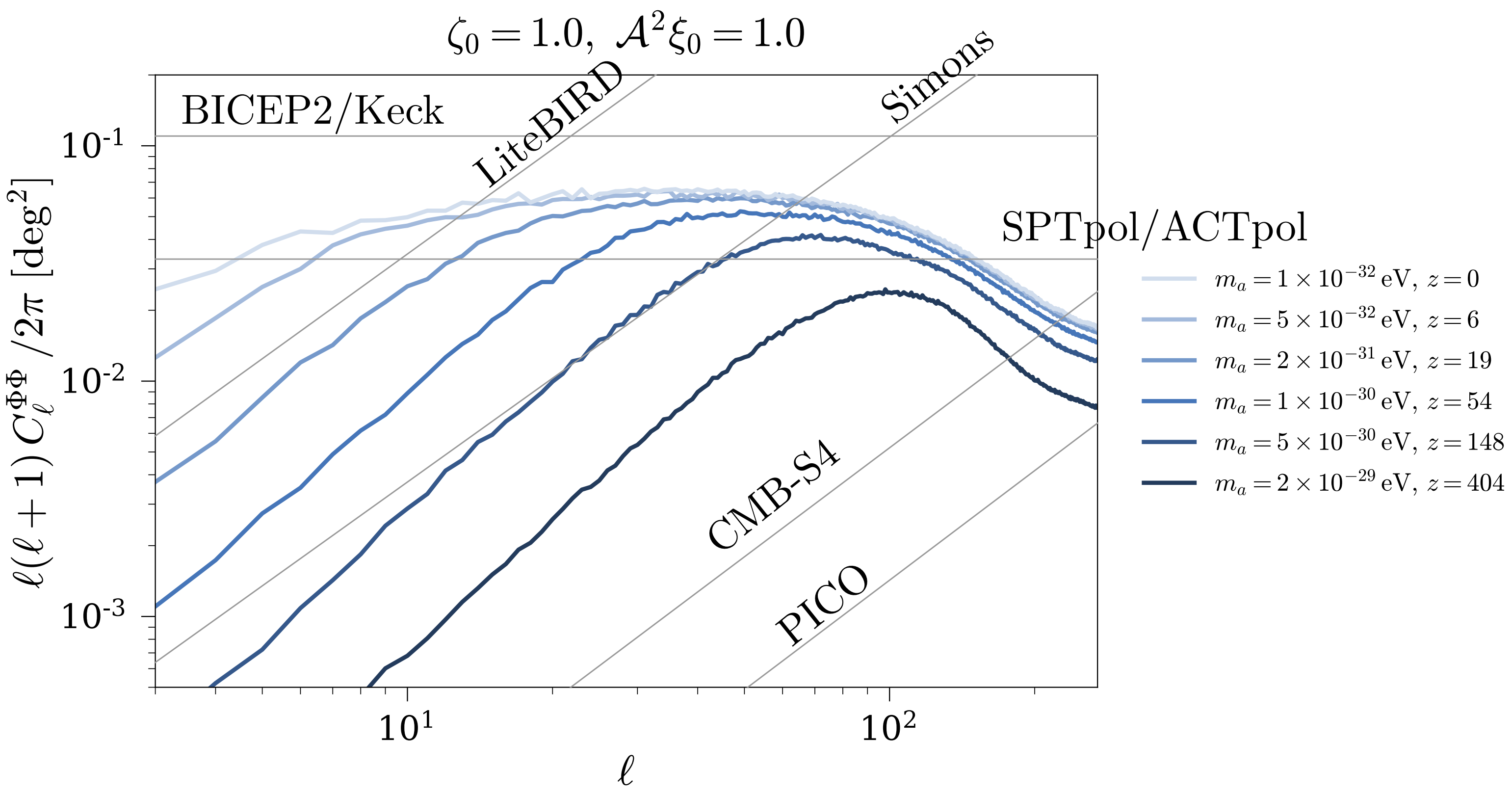
(assuming $N_{\text{DW}} = 1$)

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

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

raise the ALP mass

(network collapses earlier)



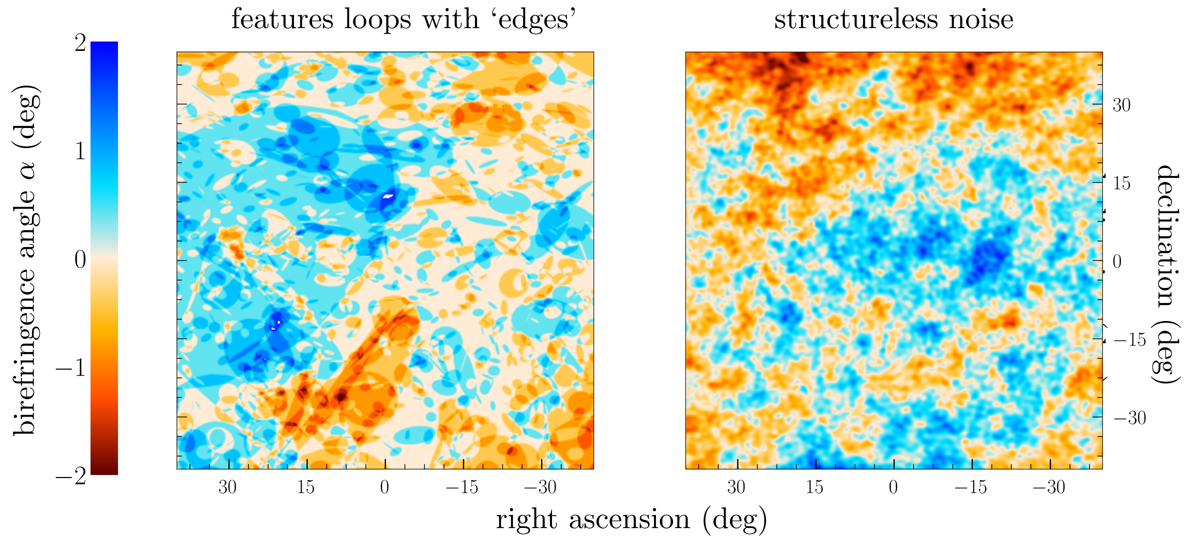
strong scale dependence ➔ possible to measure m_a

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

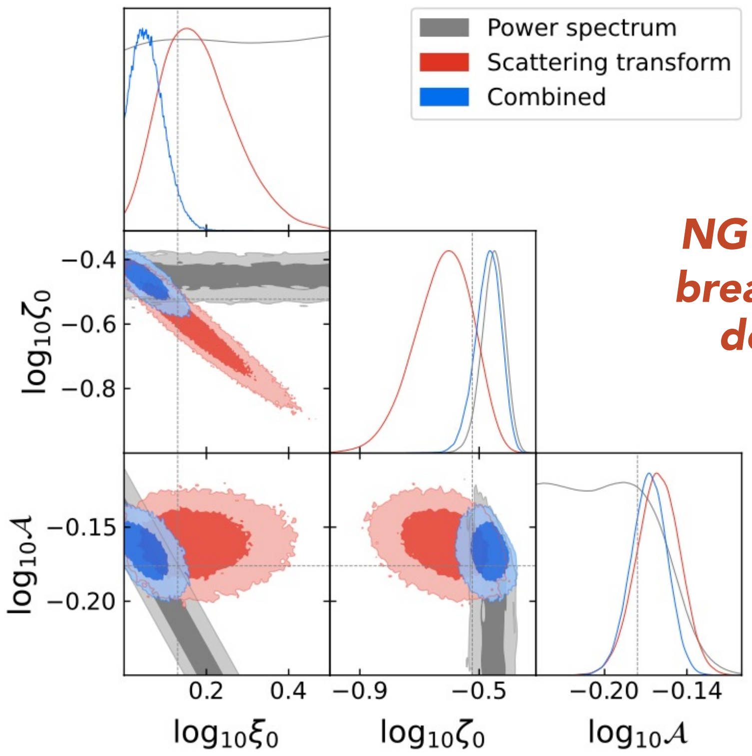
$$\text{signal:} \quad I_0(\mathbf{x})$$
$$\text{plane wave:} \quad \phi_{\mathbf{k}}(\mathbf{x})$$
$$P_{\mathbf{k}}(\mathbf{x}) = \langle |I_0 * \phi_{\mathbf{k}}|^2 \rangle(\mathbf{x})$$

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

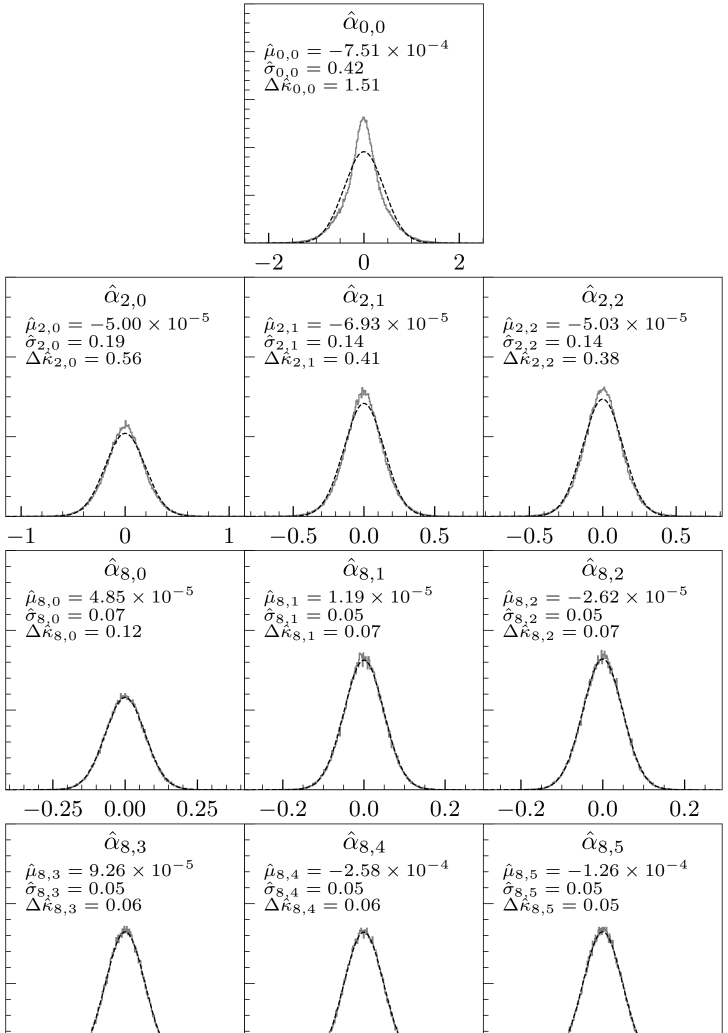
NG information breaks the $A^2\ \xi_0$ degeneracy

Birefringence non-Gaussianity

[Hagimoto & AL, arXiv:2306:07351]

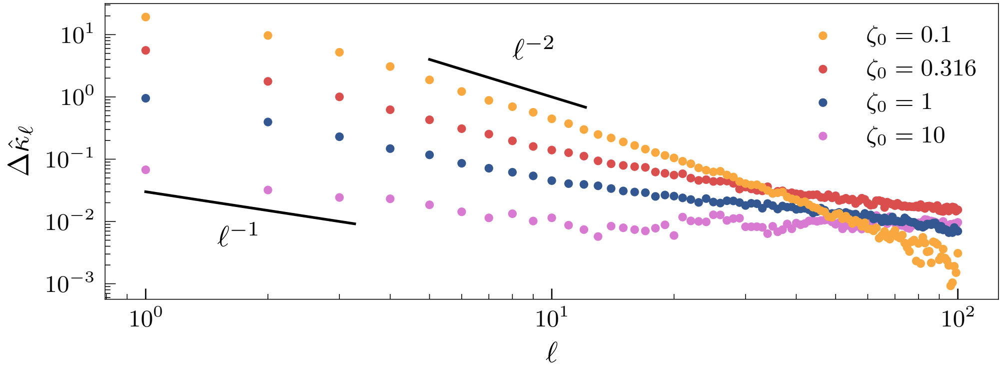
excess kurtosis

can be O(1) at low multipoles



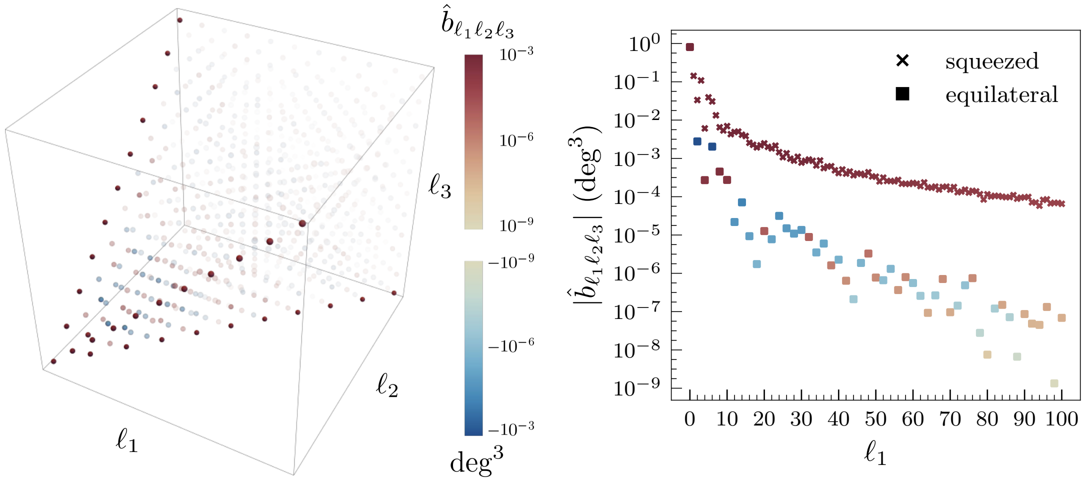
scaling with multipole index

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

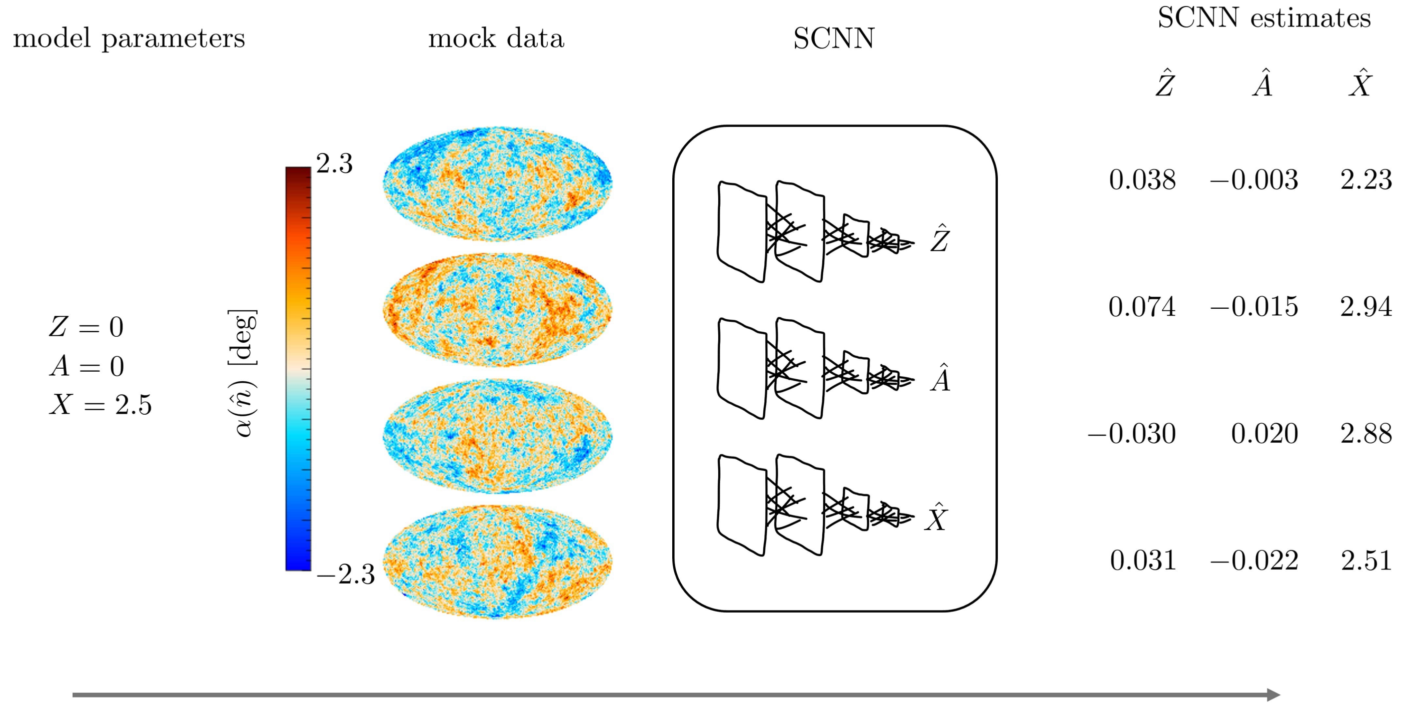
a measurement of non-G will help to tell apart axion strings & other sources of birefringence

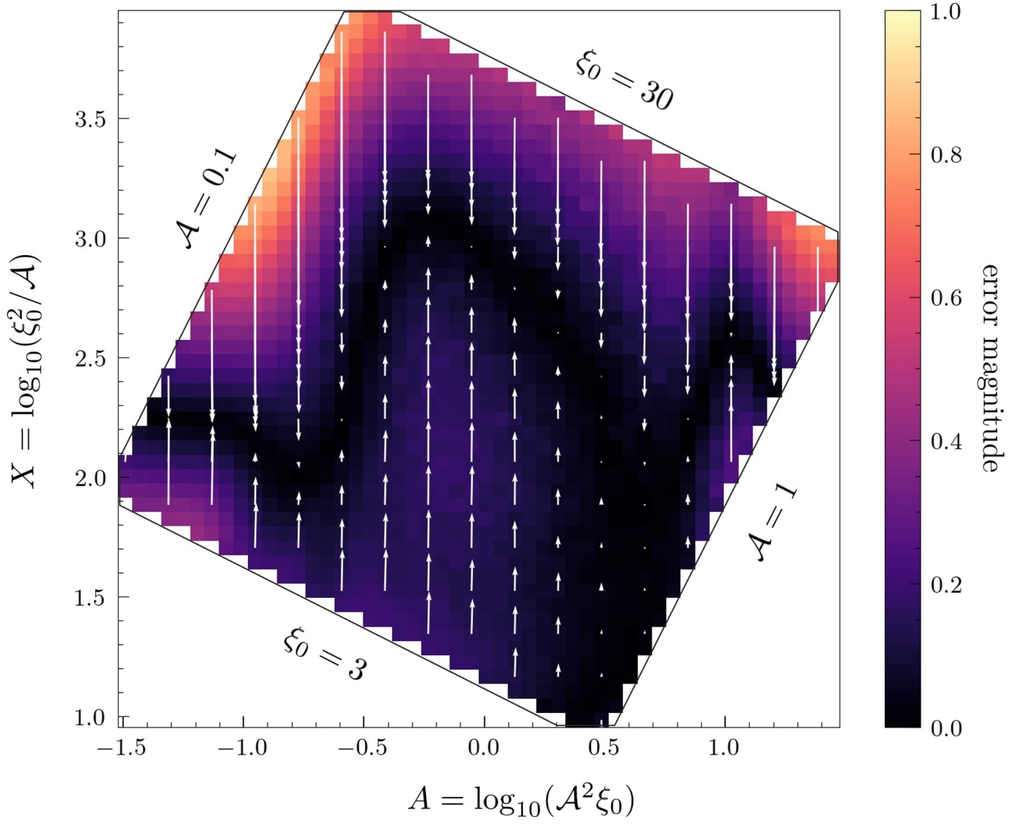
Machine learning for axion strings

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

train 3 SCNN's to identify 3 LCM parameters

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





summary
& conclusion

Terahertz-Radiometer for Axions (T-RAx)

something completely different: a proposal to search for axion dark matter in the THz gap


Andrey Baydin (Rice)

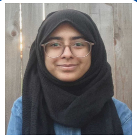

Henry Everitt (Rice)


Shengxi Huang (Rice)


Junichiro Kono (Rice)

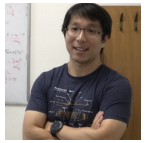

Michael Manfra (Purdue)


Andrew Long (Rice)

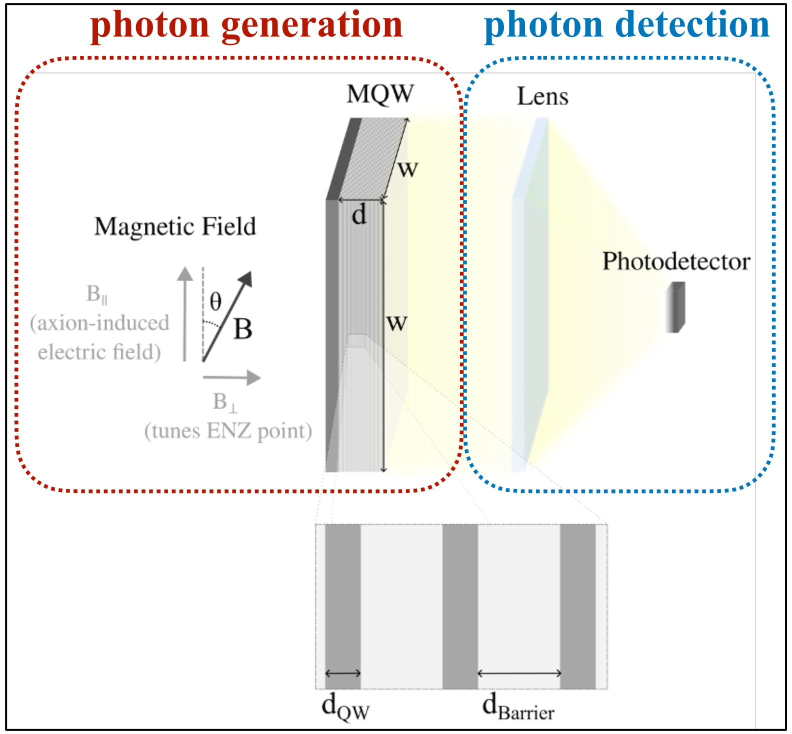

Jaanita Mehrani (Rice)

lead author

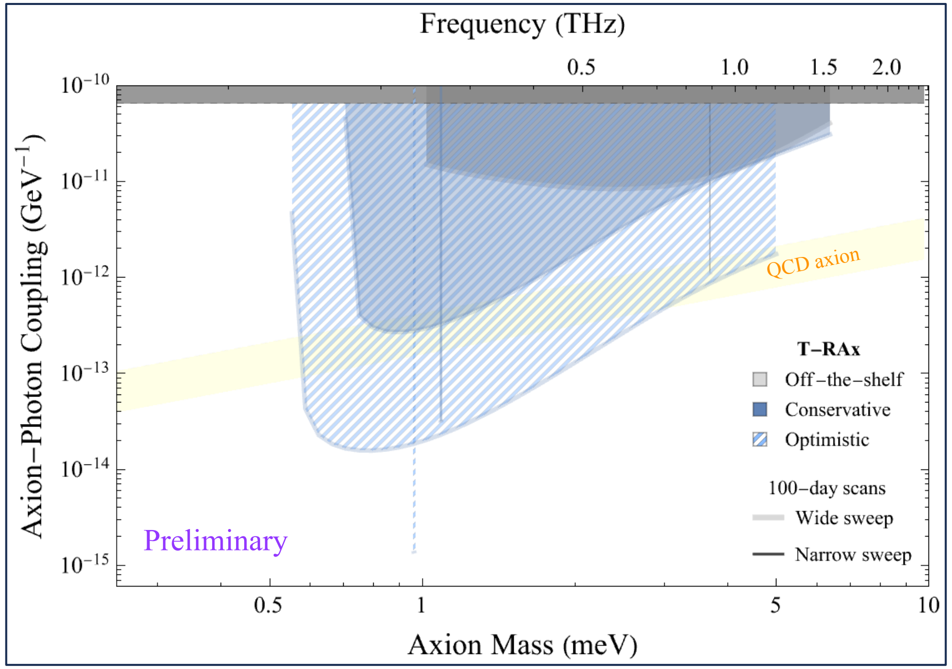

Kuver Sinha (Oklahoma)


Tao Xu (Oklahoma)

to appear on arXiv later this summer



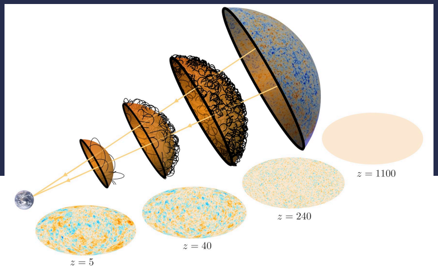
Epsilon-Near-Zero (ENZ) material
- ➔ small permittivity ➔ boosts E-field
- ➔ realized w/ multiple quantum wells
- ➔ B-field tunes ENZ resonant freq.



Projected sensitivity
- ➔ easily beats CAST limit
- ➔ with low-enough DC rate and

strong-enough B-field, T-RAx will probe QCD axion dark matter at m_a ~ meV

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

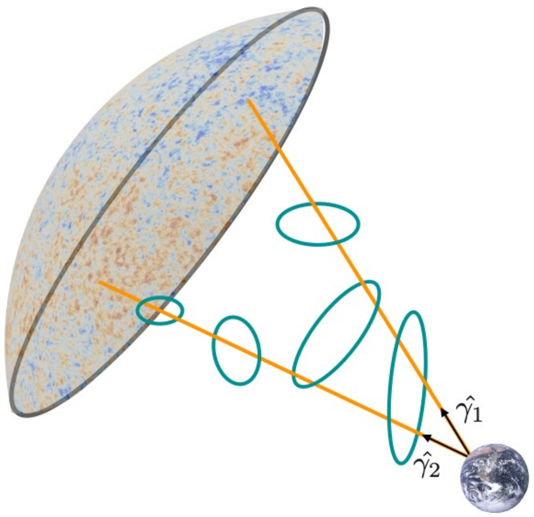
backup slides

Analytical understanding

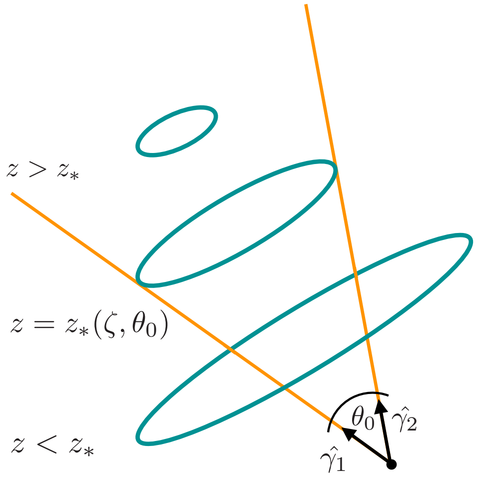
[Jain, AL, Amin, arXiv:2103:10962]

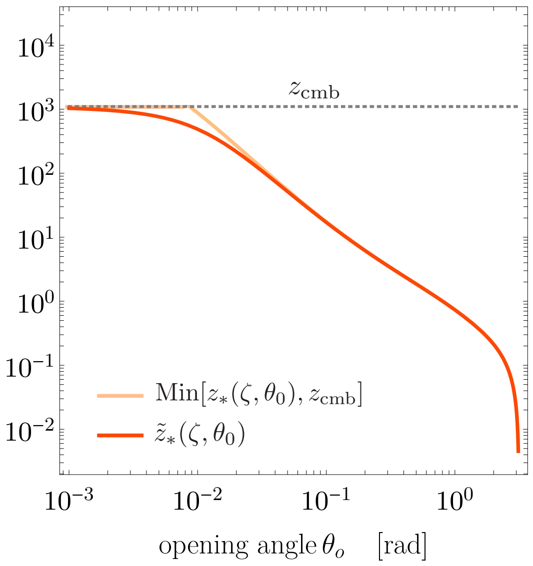
correlations accumulate
when both photons pass
through the same loops

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



large-angle correlations are
established later (small z)



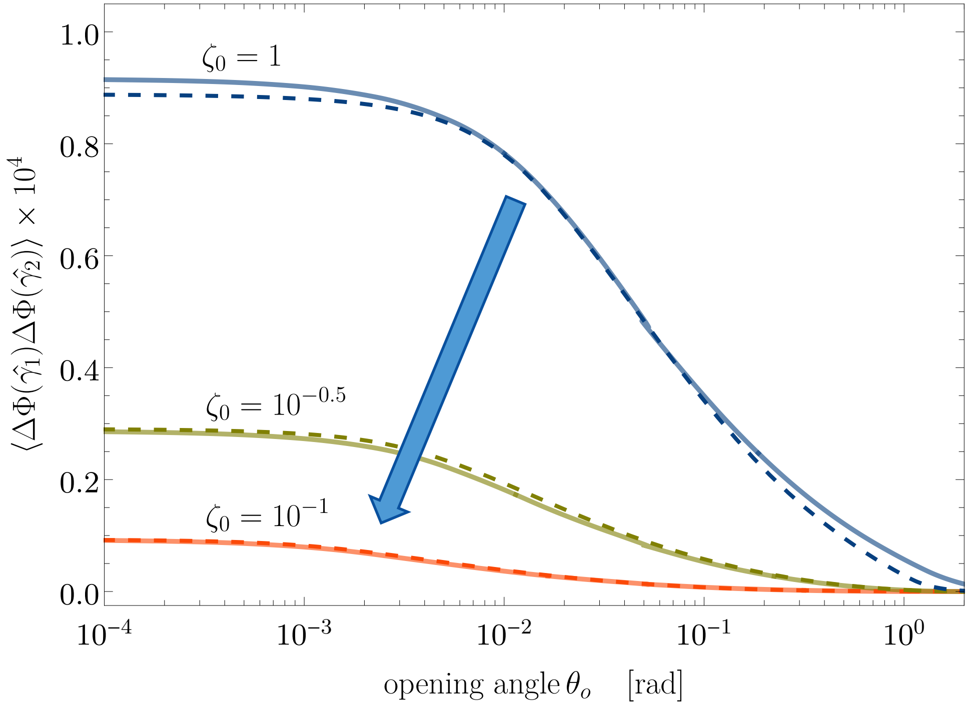


Analytical understanding

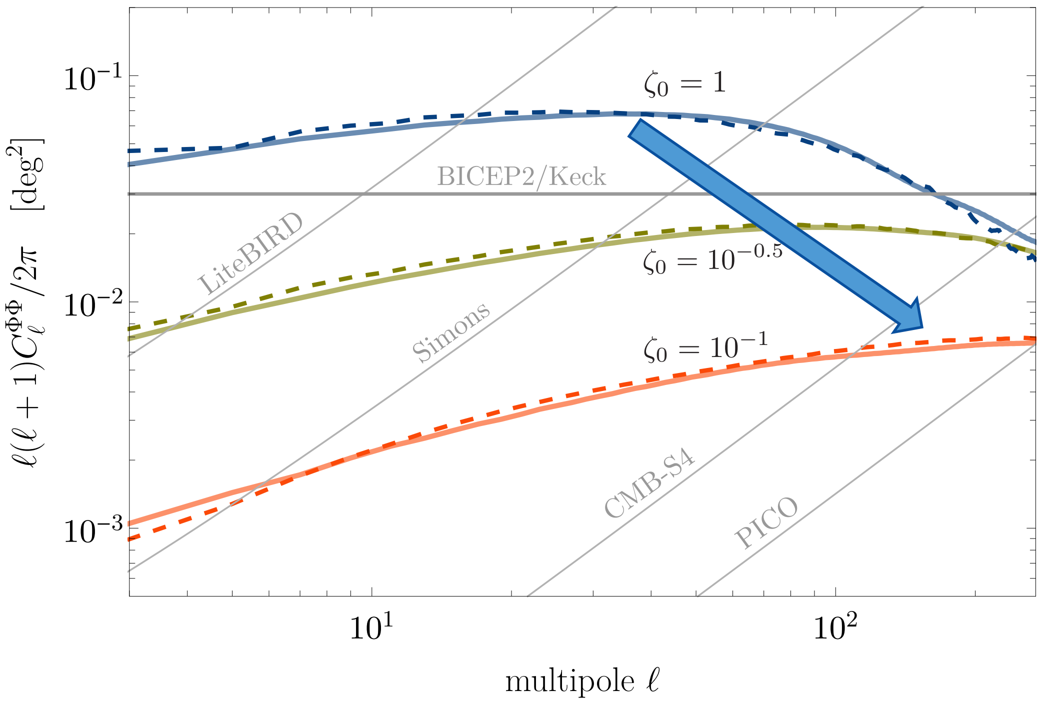
[Jain, AL, Amin, arXiv:2103:10962]

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

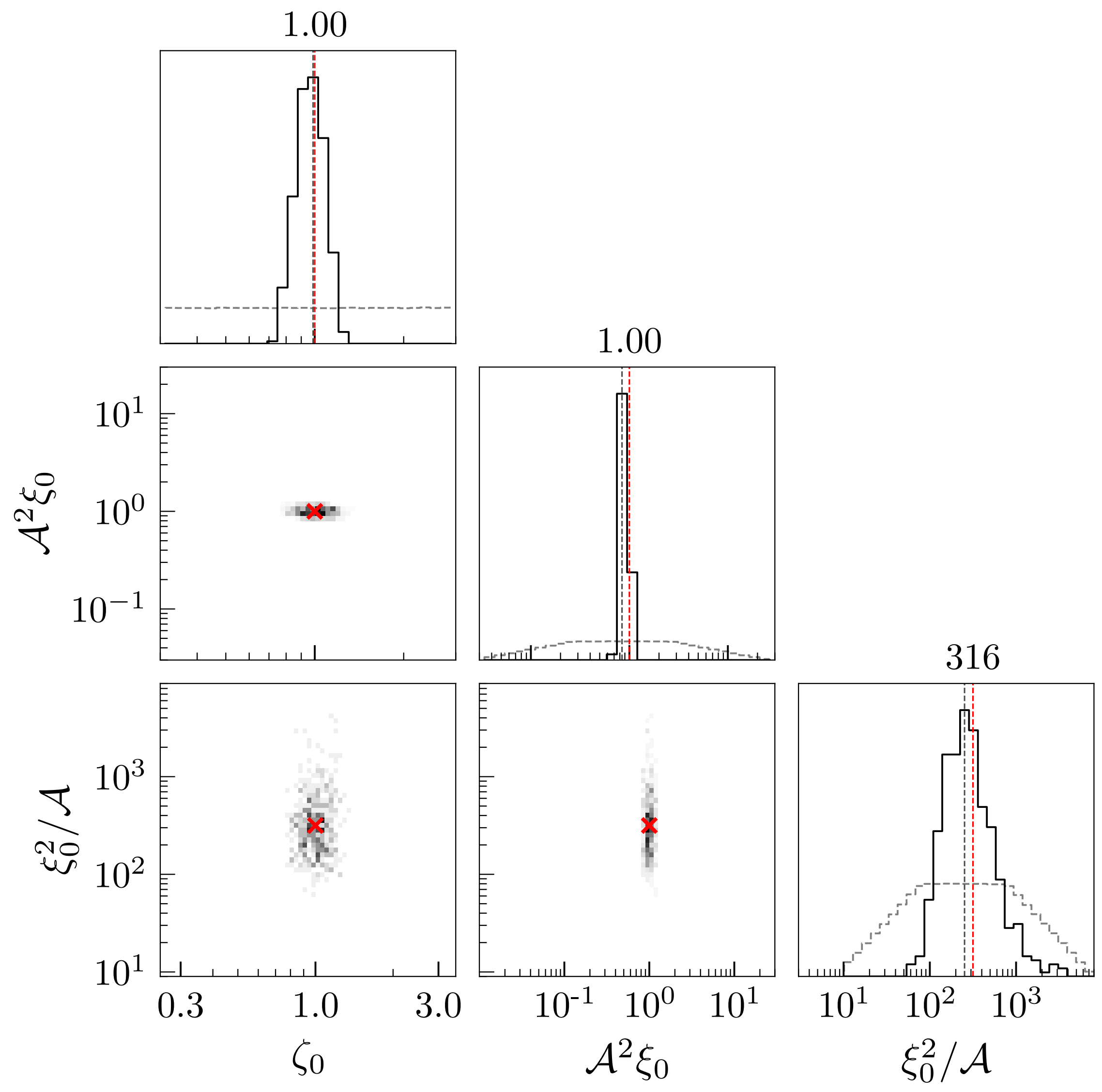
correlation function



angular power spectrum



Machine learning for axion strings



How well does the SCNN reproduce a known input?

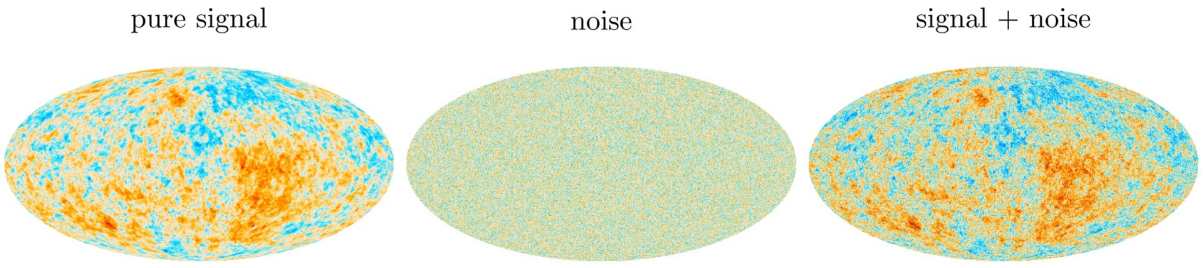
SCNN's for Z & A work well

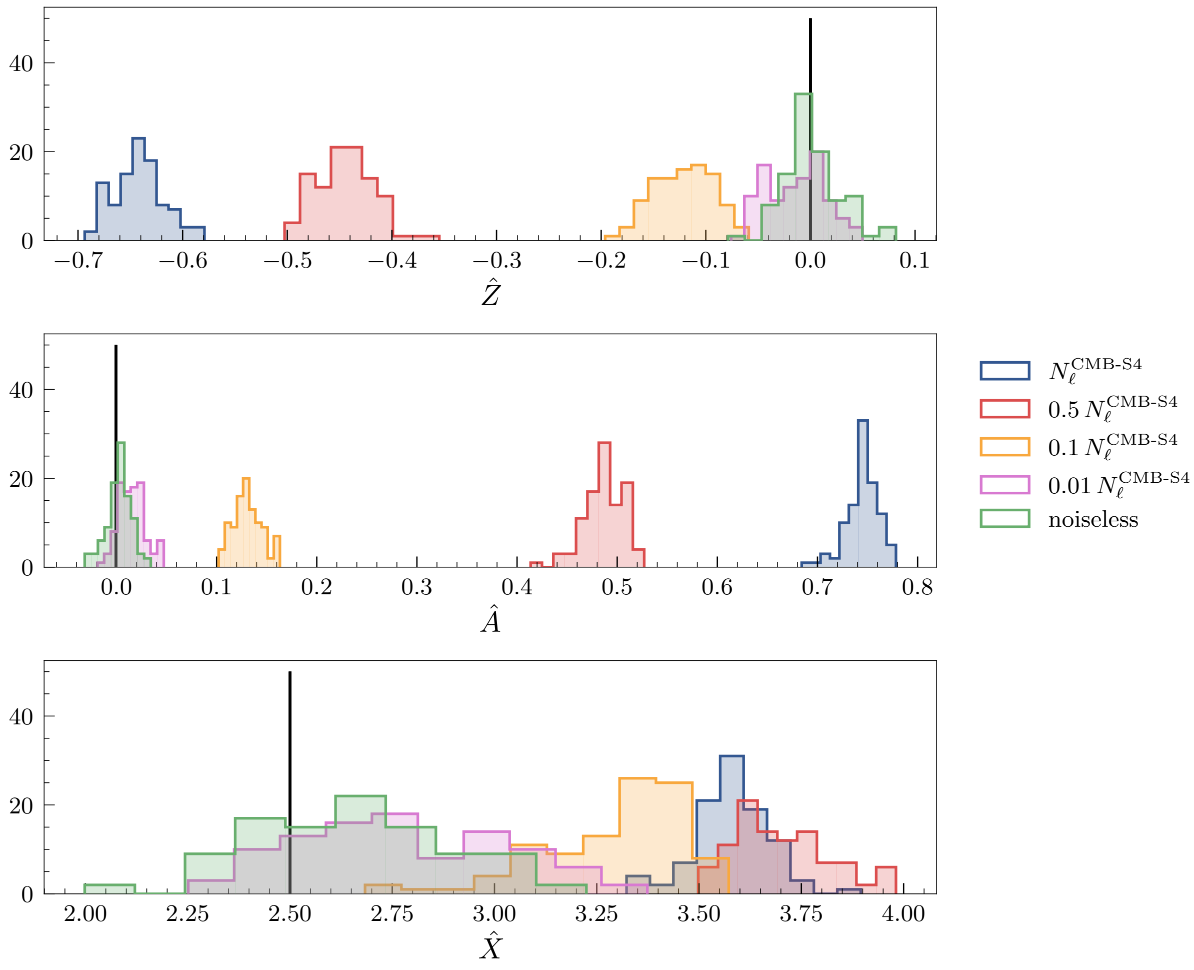
SCNN for X struggles

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





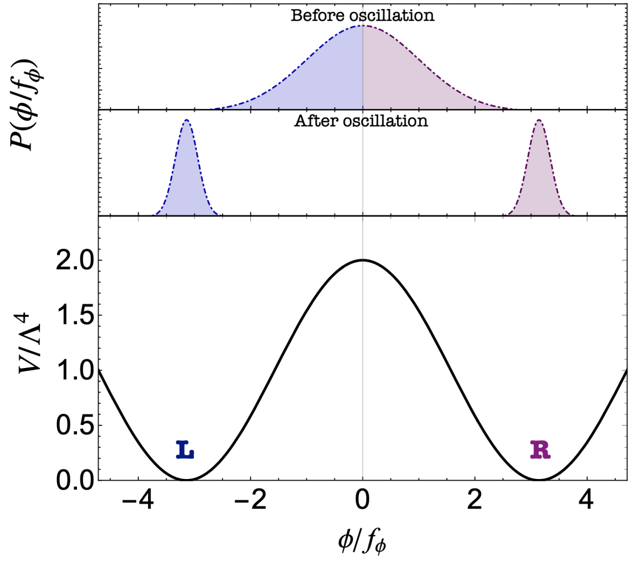
an SCNN trained on noise-less sims would require noise reduction to a level below the CMB-S4 projection to function (needs to be trained on noisy sims)

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

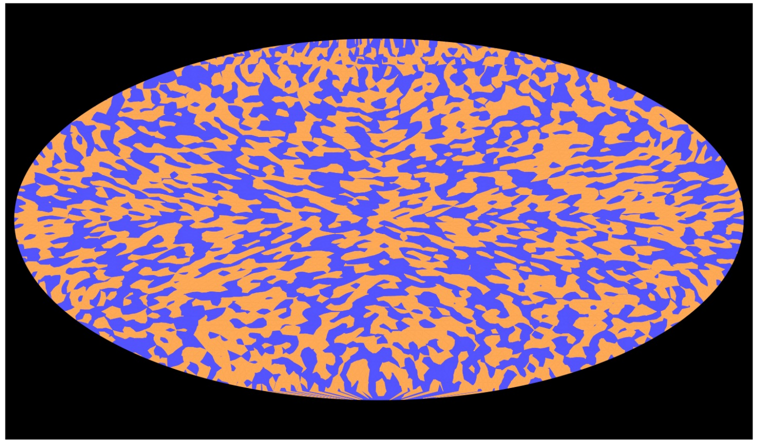
imposes bound on mass & decay constant

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

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

birefringence signal

independent of propagation



$$\Delta\Phi = 0 \qquad \text{if LS}\gamma \text{ is from the vacuum } R$$

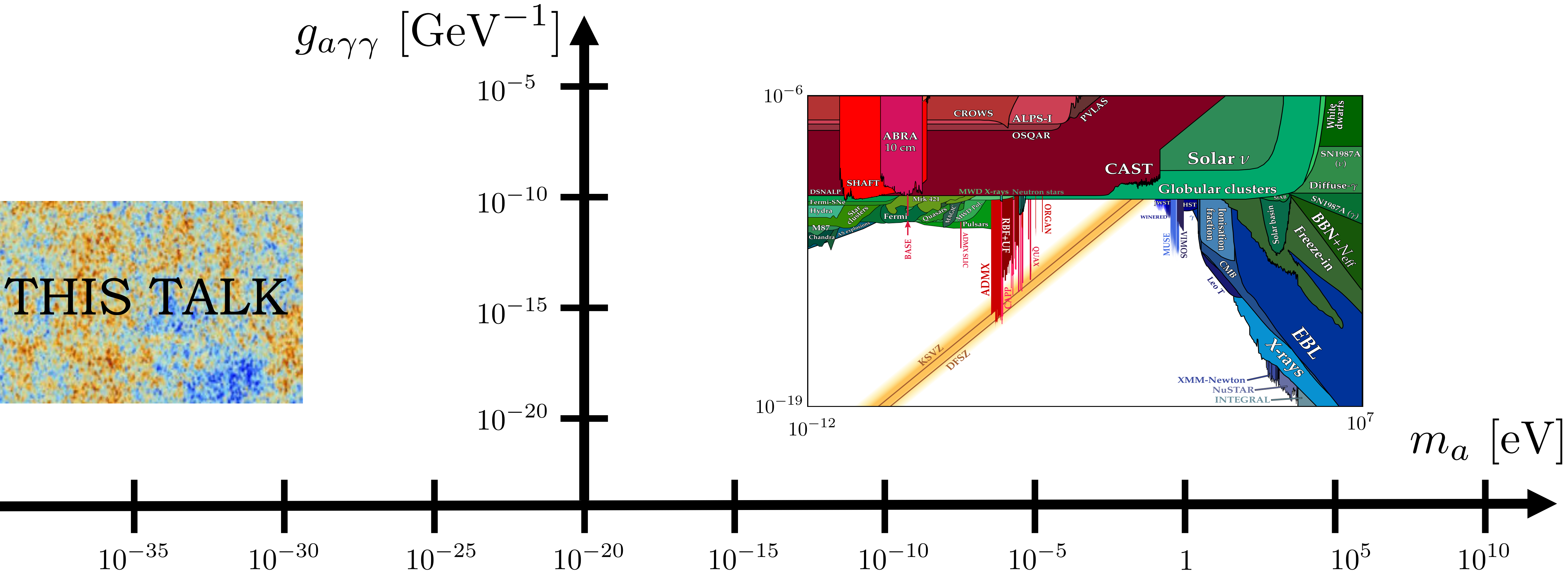
$$\Delta\Phi = c_\gamma \alpha \qquad \text{if LS}\gamma \text{ is from the vacuum } L.$$

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

(no random-walk enhancement)

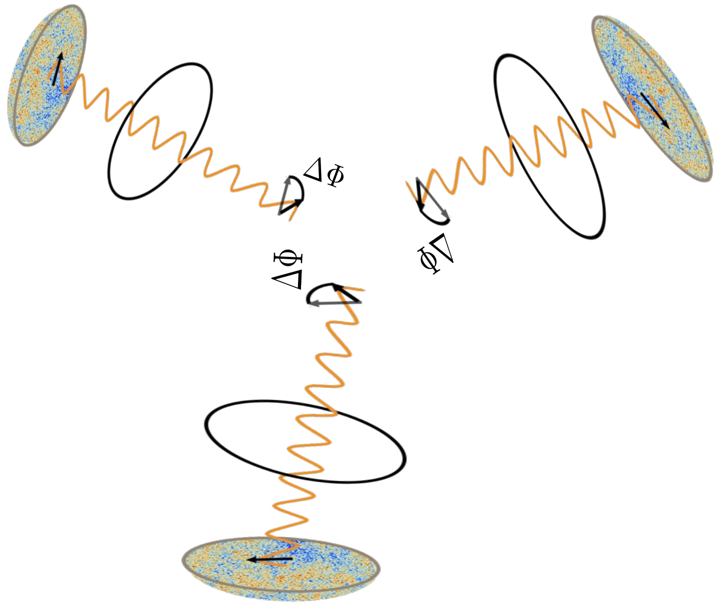
Theory landscape: axion-like particles

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



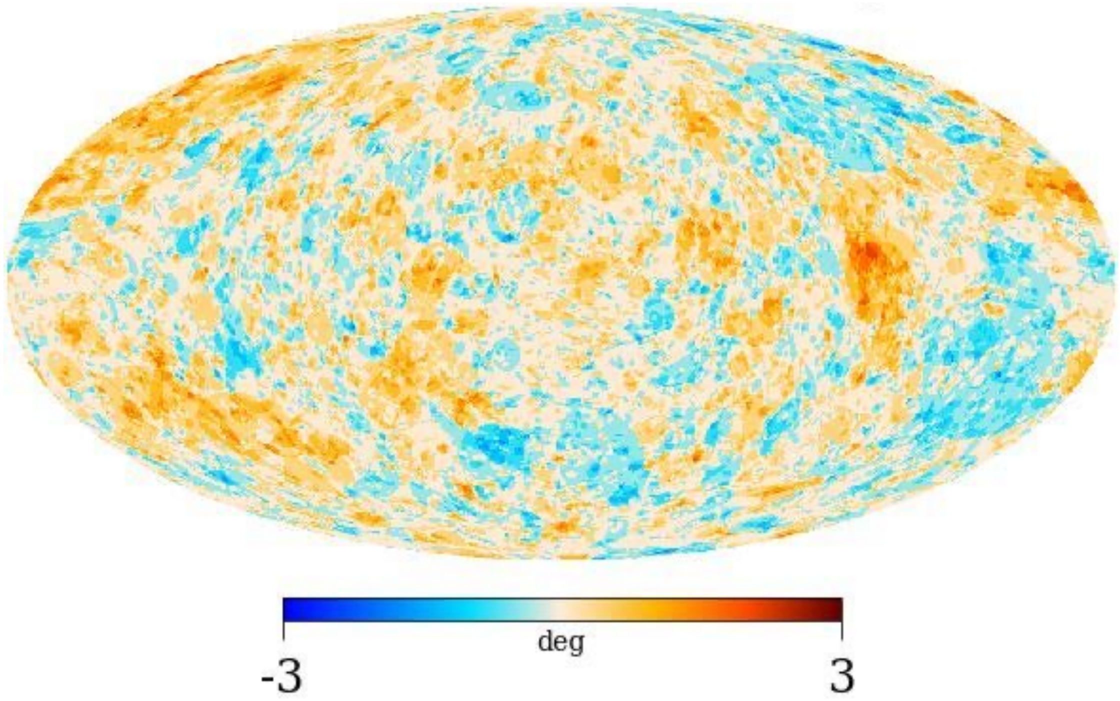
Net birefringence from the whole string network

[Ray Hagimoto (2022)]



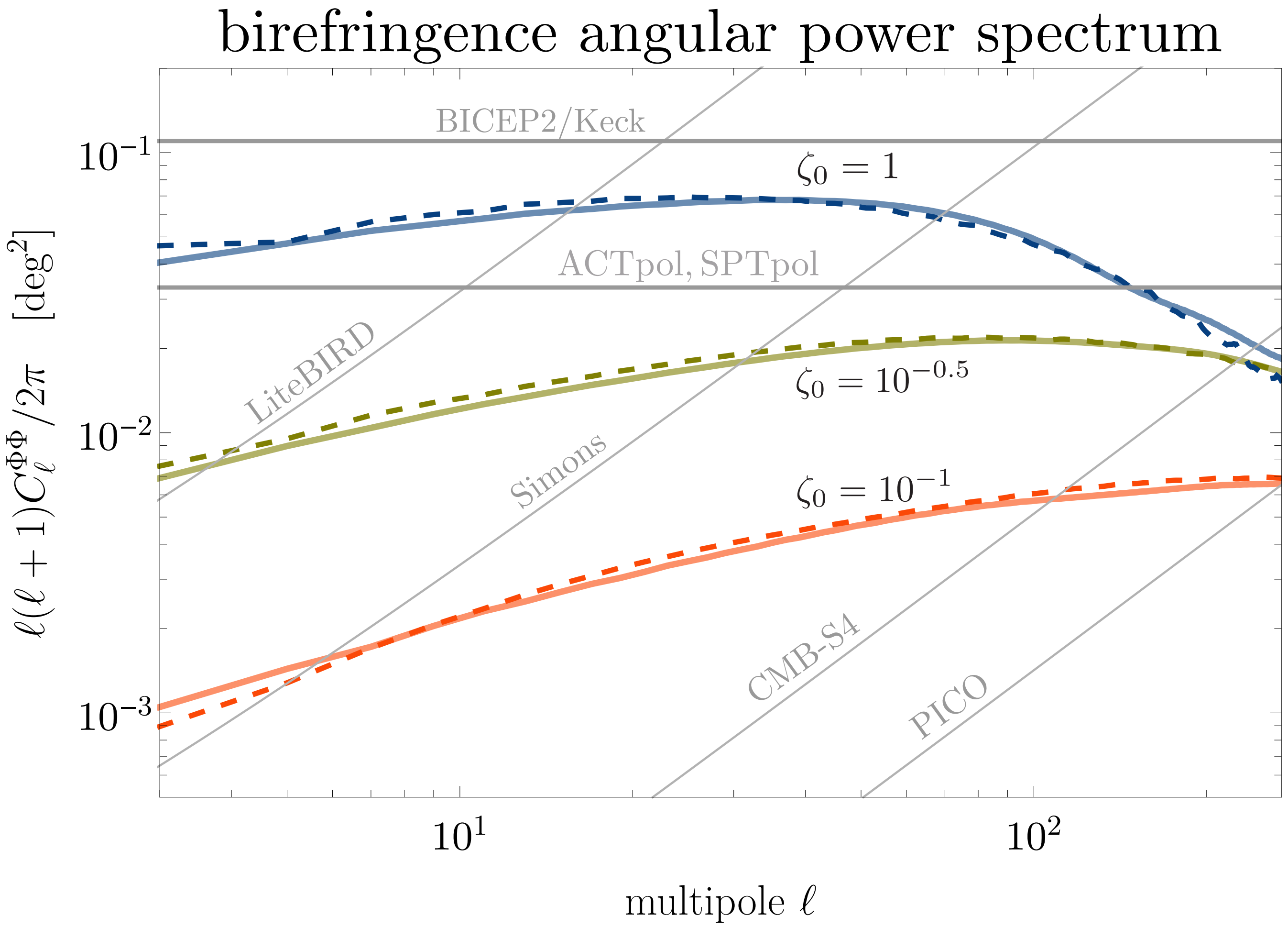
parameters: $\begin{cases} m_a = 0 \\ \mathcal{A} = 1 \\ \zeta_0 = 1 \\ \xi_0 = 1 \end{cases}$

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



Axion-string induced birefringence signal

[Jain, AL, Amin (2103.01962)]



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

Key features

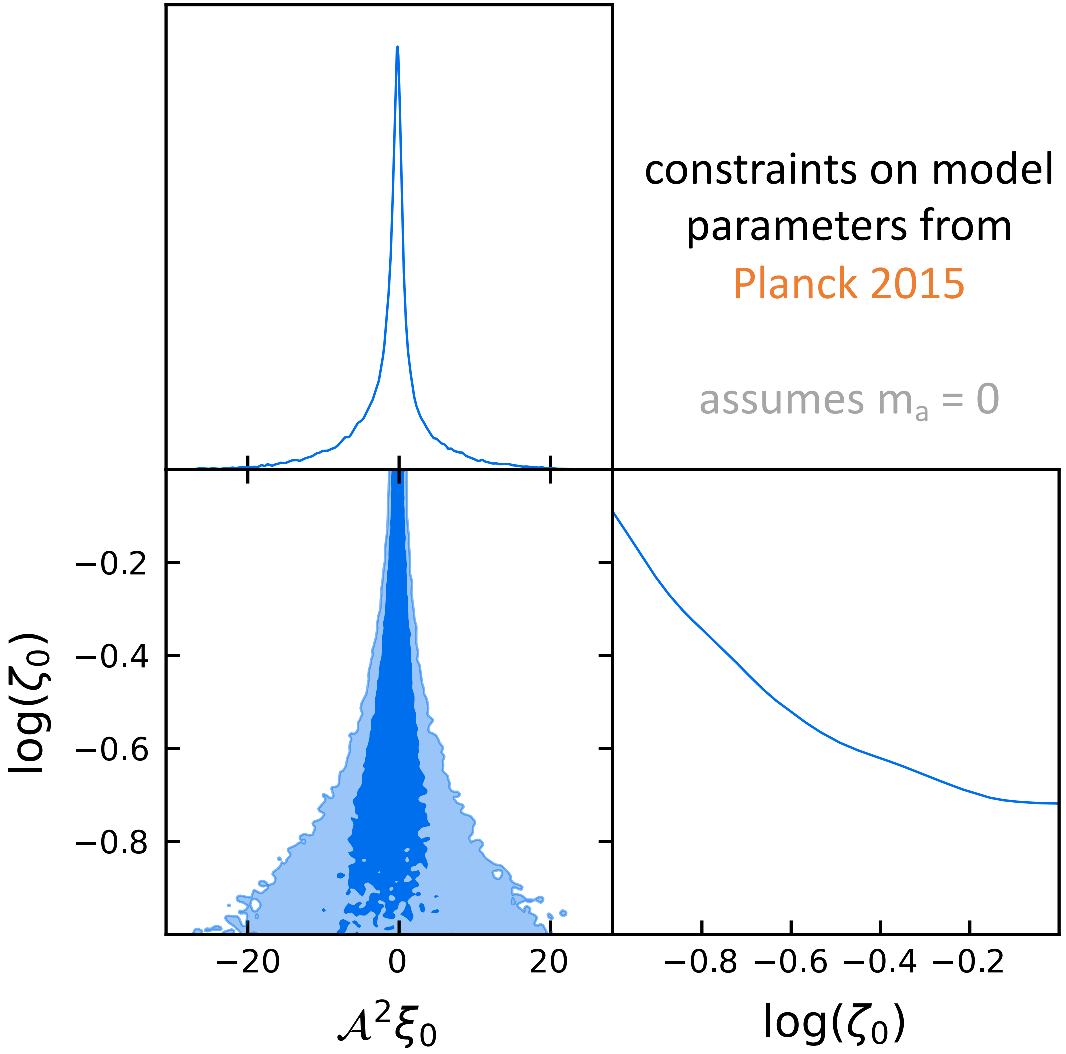
- Power spectrum is almost scale invar.
- Characteristic scale (l @ the peak) set by loop size at LSS
- Smaller loops (ζ_0) => weaker signal
- Trivial dependence on loop density (ξ_0) and anomaly coefficient (A) … power scales with ξ_0 A^2

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 $m_a = 0$

Projected sensitivity

Pogosian et. al. (2019)

future telescopes

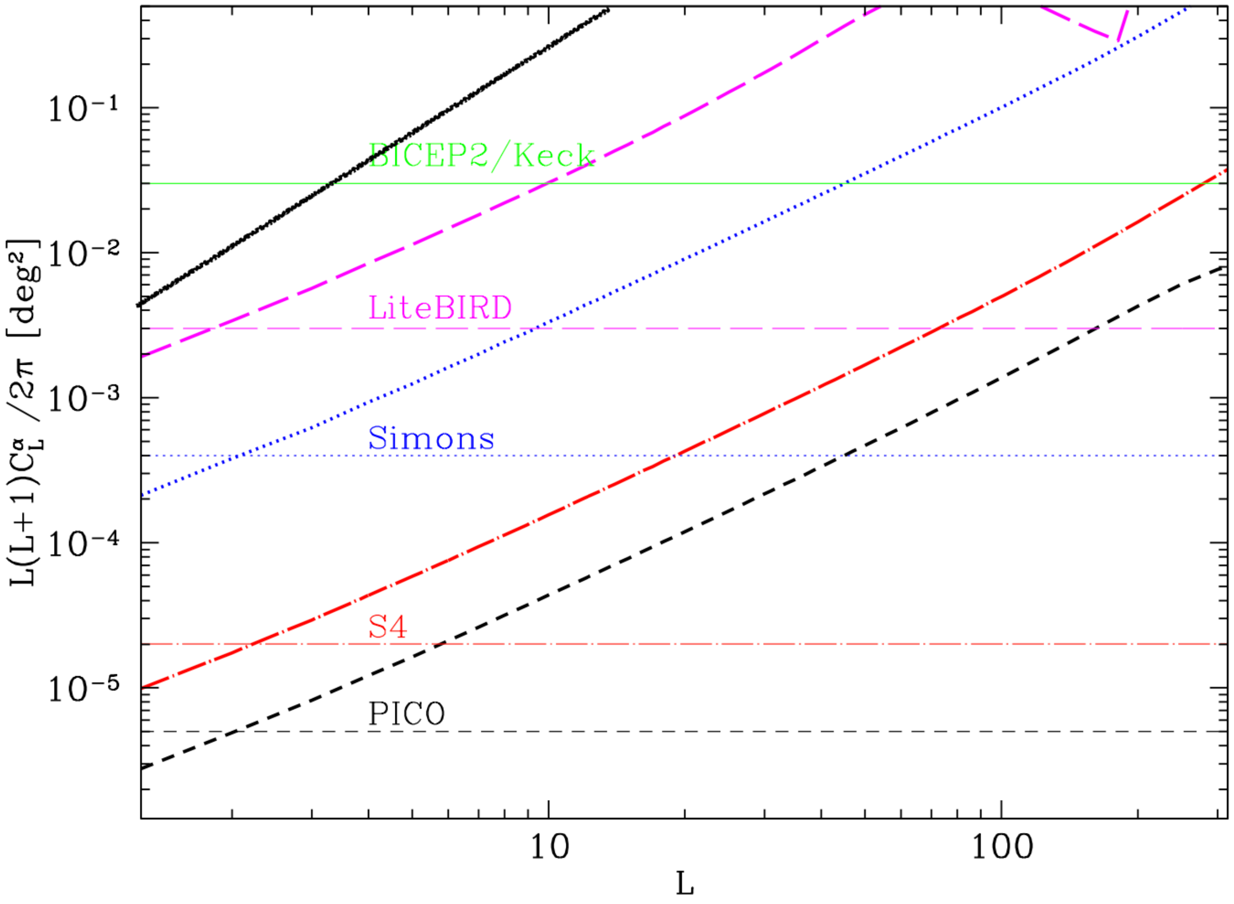
probes of isotropic + aniso. birefringence

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.

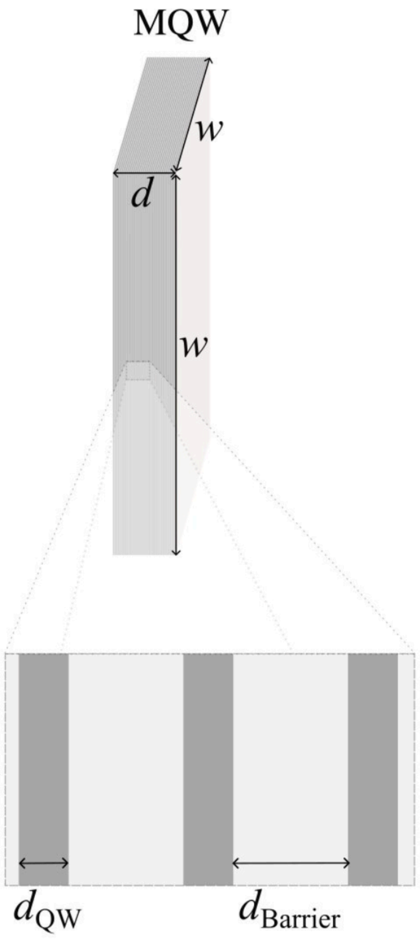
$$A_\alpha = L(L+1)C_L^\alpha/2\pi$$

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



T-RAx

Photon generation: MQW emitter



- Doping density about $O(10^{11})$ cm^{-2}
- MQW layer at nm thickness
- T-RAX emitter at mm thickness
- Emission area of cm scale is viable

Parameter	Off-shelf	Conservative	Optimistic
n (10^{11}cm^{-2})	3	3	3
d (mm)	0.2	1	2
Area (cm^2)	3×3	3×3	5×5
d$_{QW}$ (nm)	30	30	10

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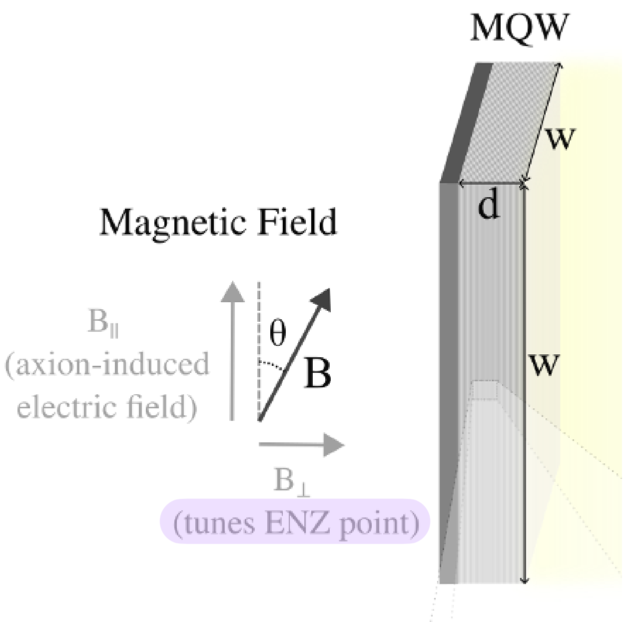
See https://indico.cern.ch/event/1488822/contributions/6480040/ for his full talk.

Photon generation: Magnetic field

- Considering the 36-T NMR magnetic field at National Magnetic Lab
- Magnetic field in two directions responsible for conversion and tuning



NATIONAL HIGH MAGNETIC FIELD LABORATORY

Parameter	Off-shelf	Conservative	Optimistic
Temp. (K)	0.3	0.3	0.3
B (T)	36	36	50

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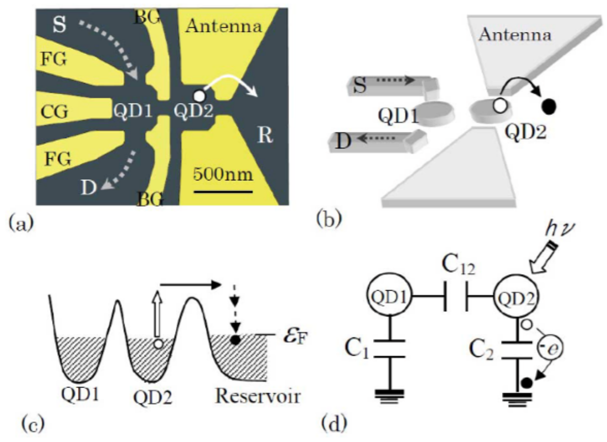
Photon detection: single-photon detector

- Quantum dot photodetector made of GaAs/AlGaAs
  - Measure changes in capacitance
  - **Works in high magnetic fields**

Will also consider single-photon detector options capable of operating in a strong magnetic field.



Parameter	Off-shelf	Conservative	Optimistic
Γ_{dark} (Hz)	10^{-2}	10^{-3}	10^{-4}
η	7%	20%	90%

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