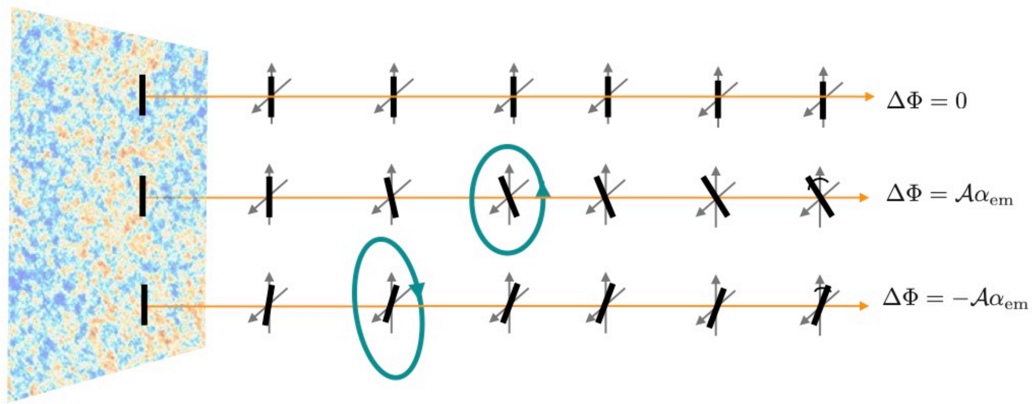
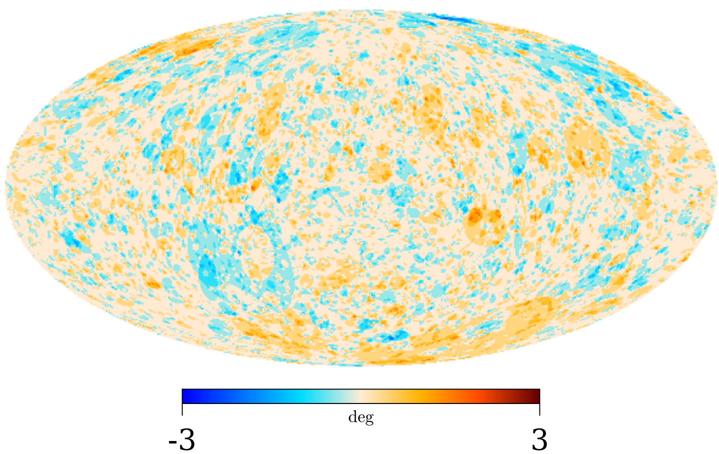
CMB Birefringence from Hyper-Light Axion String Networks





Andrew J. Long
Rice University

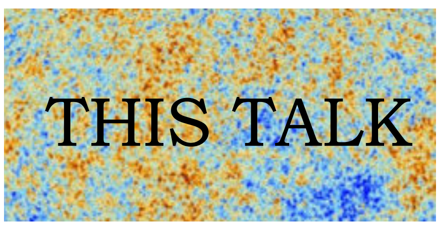
@ Mitchell Conference
May 26, 2022

ALPs again

axion-like particles

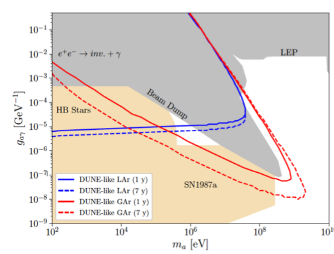
$$\mathcal{L} \supset \frac{1}{2}(\partial a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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



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

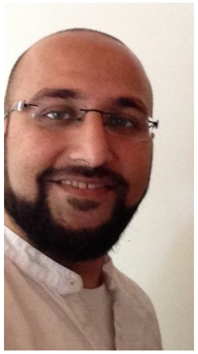
axion-like particles (testable in the lab)



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

What can *cosmology*
(particularly, CMB polarization)
teach us about
hyper-light axion-like particles?

work with … **Mustafa Amin** … **Ray Hagimoto** …. & **Mudit Jain**



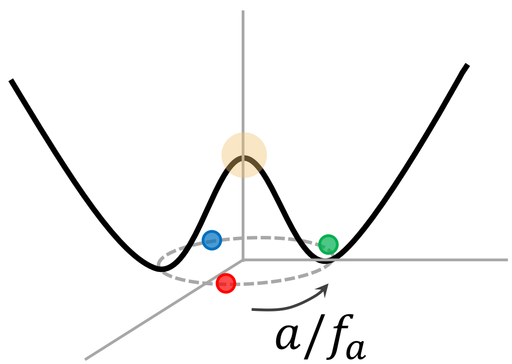
[Jain, AL, Amin (2103.01962)]
[Amin, Hagimoto, Jain (2208.XXXXX)]

ALPs form axion strings

[Kibble (1976)]
[Vilenkin & Vachaspati (1987)]
[graphic thanks to Mudit Jain (2021)]

assume: $T_{RH} > f_a$

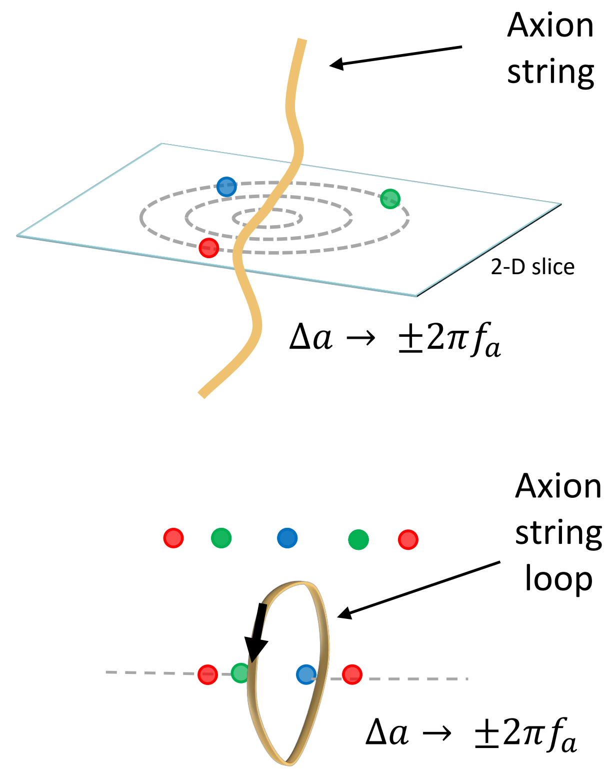
Field space



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

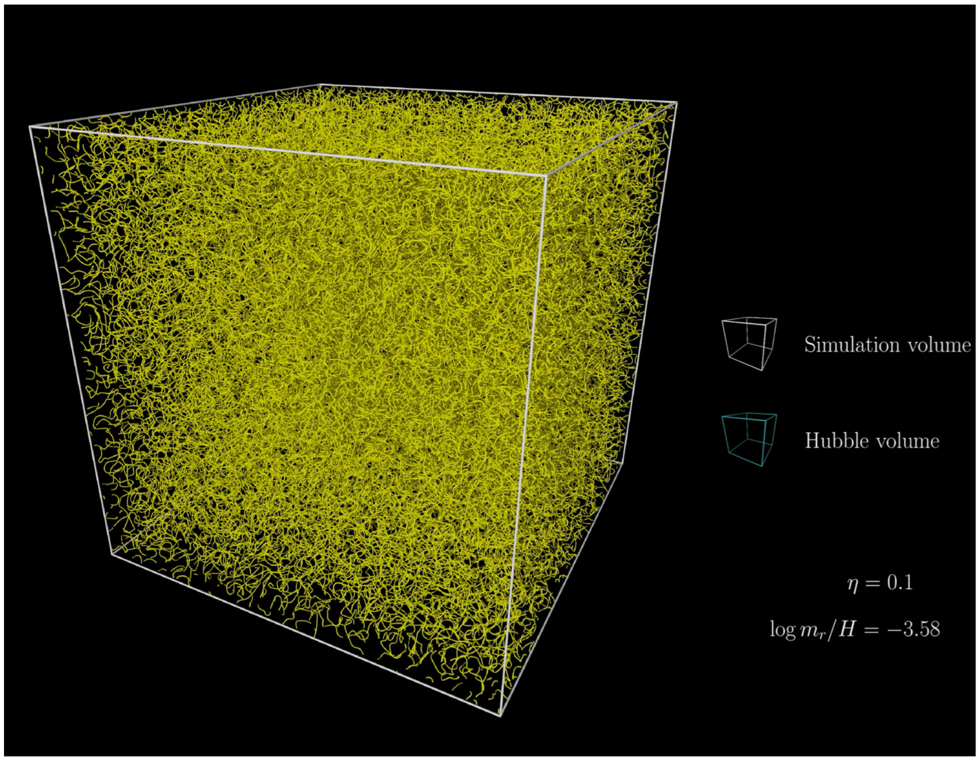
$\longleftrightarrow$

Physical space



A cosmological network of axion strings

[Buschmann et. al. (2022)]



String network evolution

- Long strings reconnect to form loops
- Loops evaporate by emitting axions
- Typical string length tracks Hubble:

$$\langle l \rangle \approx d_H(t)$$

- Average energy density tracks Hubble:

$$\rho \sim f_a^2 H^2$$

Open questions

- A log deviation from scaling?
- Energy spectrum of axion radiation?

Birefringence from axion strings

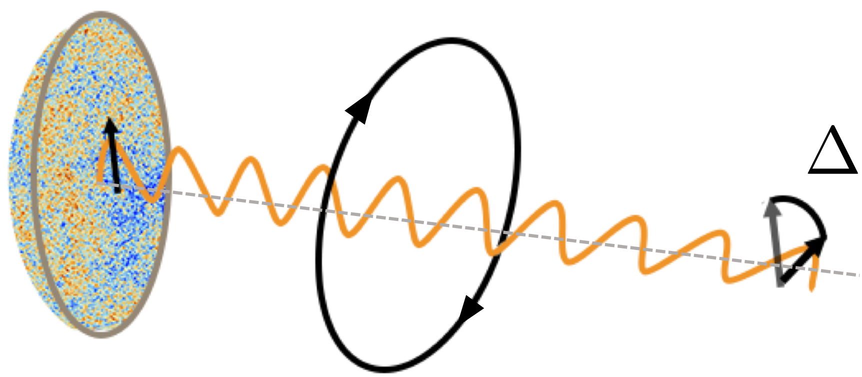
[Carroll, Field, Jackiw (1990,91)]
[Harari, Sikivie (1992)]
[Fedderke, Graham, Rajendran (1903.02666)]
[Agrawal, Hook, Huang (1912.02823)]

axion-photon coupling

$$\mathcal{L}_{\mathrm{int}} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

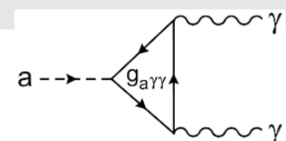
rotation angle (pol. axis)

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



$$\Delta\Phi = g_{a\gamma\gamma} \pi f_a \equiv -\mathcal{A} \alpha_{\mathrm{em}}$$

insensitive to PQ scale f_a
direct probe of anomaly coefficient A



Status of CMB probes of cosmo birefringence

if rotation angle is uniform across the sky:

$$|\Delta\Phi| < \begin{cases} 1.5^\circ \ (68\% \ \mathrm{CL}) & , \quad \text{WMAP 7-yr} \\ 0.5^\circ \ (68\% \ \mathrm{CL}) & , \quad \text{Planck 2015} \\ 0.35^\circ \pm 0.14^\circ & , \quad \text{Minami \& Komatsu (2020)} \end{cases}$$

if signal has a scale-invariant power spectrum:

$$\langle \Delta\Phi\Delta\Phi \rangle < \begin{cases} 0.1 \ \mathrm{deg}^2 \ (95\% \ \mathrm{CL}) & , \quad \text{Planck 2018} \\ 0.11 \ \mathrm{deg}^2 \ (95\% \ \mathrm{CL}) & , \quad \text{BICEP2/Keck} \\ 0.033 \ \mathrm{deg}^2 \ (95\% \ \mathrm{CL}) & , \quad \text{SPTpol} \\ 0.033 \ \mathrm{deg}^2 \ (95\% \ \mathrm{CL}) & , \quad \text{ACTpol} \end{cases}$$

How do we calculate the effect
of axion strings
on CMB polarization?

A simplification: the loop-crossing model

[graphic sthanks to Ray Hagimoto (2022)]

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

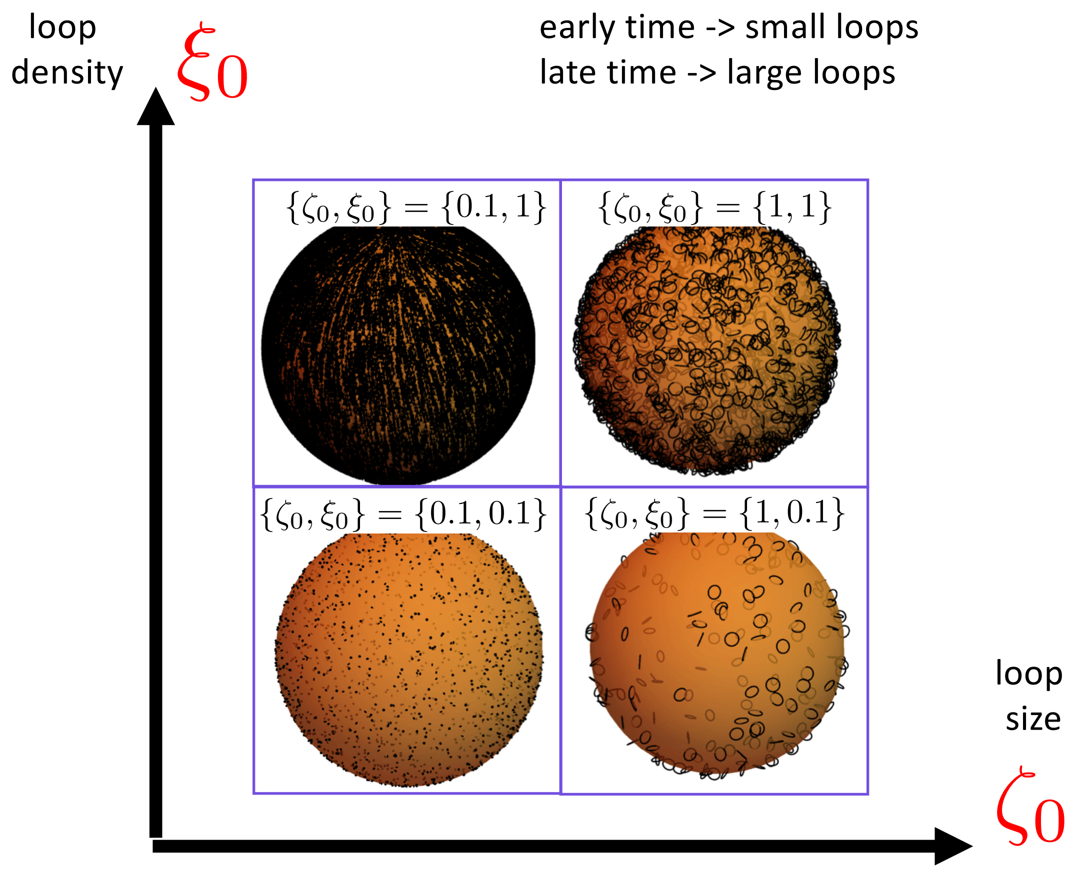
$$R(t) = \zeta_0 \, d_H(t)/2$$

- Number of loops tracks Hubble

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

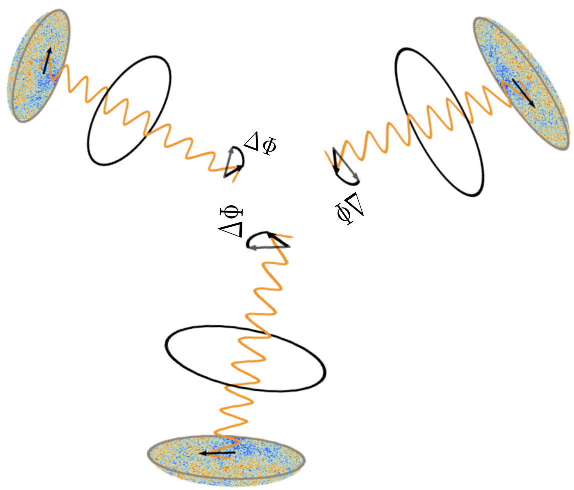
Model parameters

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



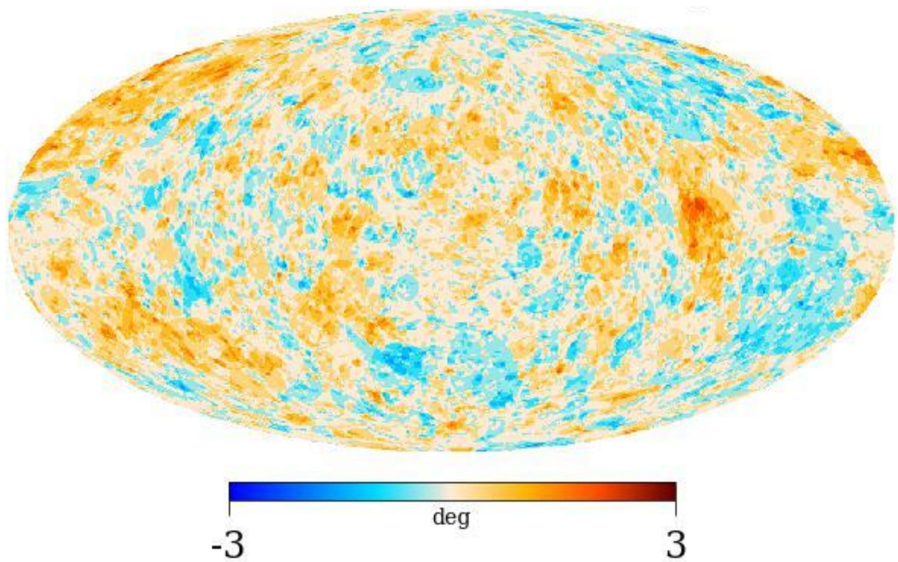
Net birefringence from the whole string network

[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



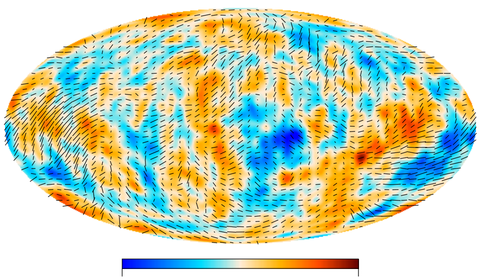
Effect on CMB polarization

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

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

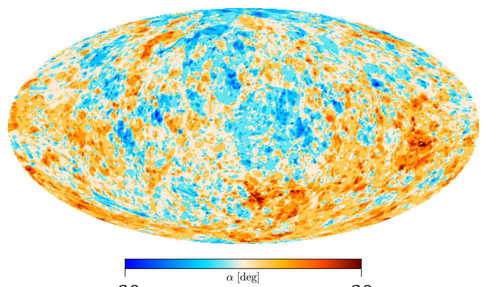
$$[Q \pm iU](\hat{\boldsymbol{n}}) \to [(Q \pm iU)e^{\pm 2i\Delta\Phi}](\hat{\boldsymbol{n}})$$

primordial CMB sky



-160 160

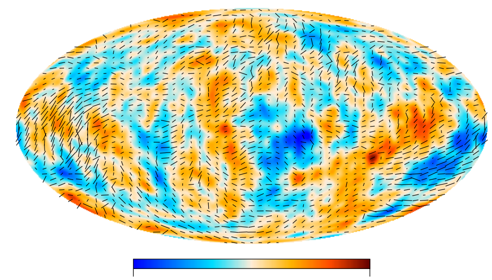
axion string -induced birefringence angle



-60 60

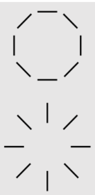
(exaggerated by ~30x)

Planck's CMB sky



-160 160

$E - mode$
pol pattern



$B - mode$
pol pattern

Signal of axion string-induced cosmological birefringence

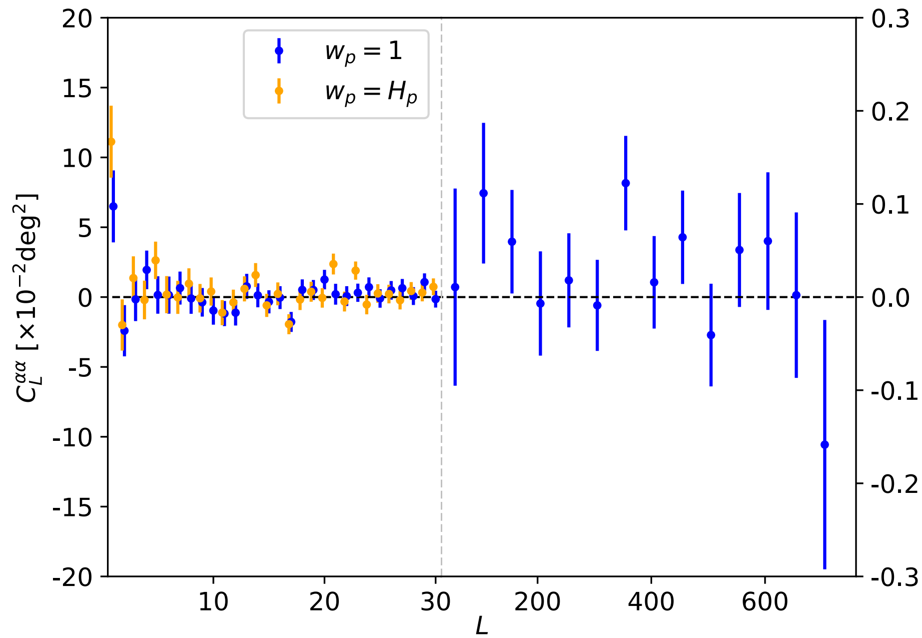
$$\begin{cases} \langle TB \rangle \neq 0 \\ \langle EB \rangle \neq 0 \end{cases}$$

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

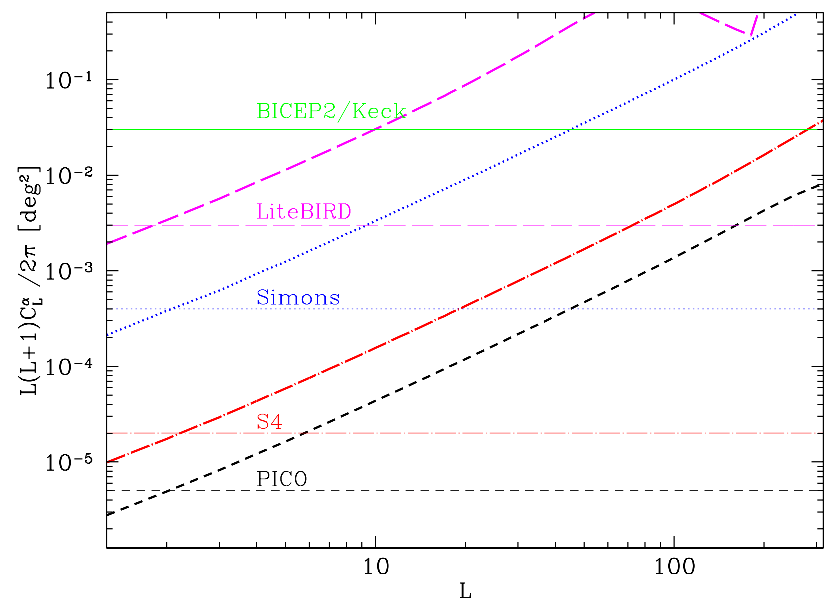
Interfacing with CMB data

[Contreras, Boubel, Scott (1705.06387)]
[Pogosian , Shimon Mewes, Keating(1904.07855)]

Planck 2015 is consistent with zero birefringence

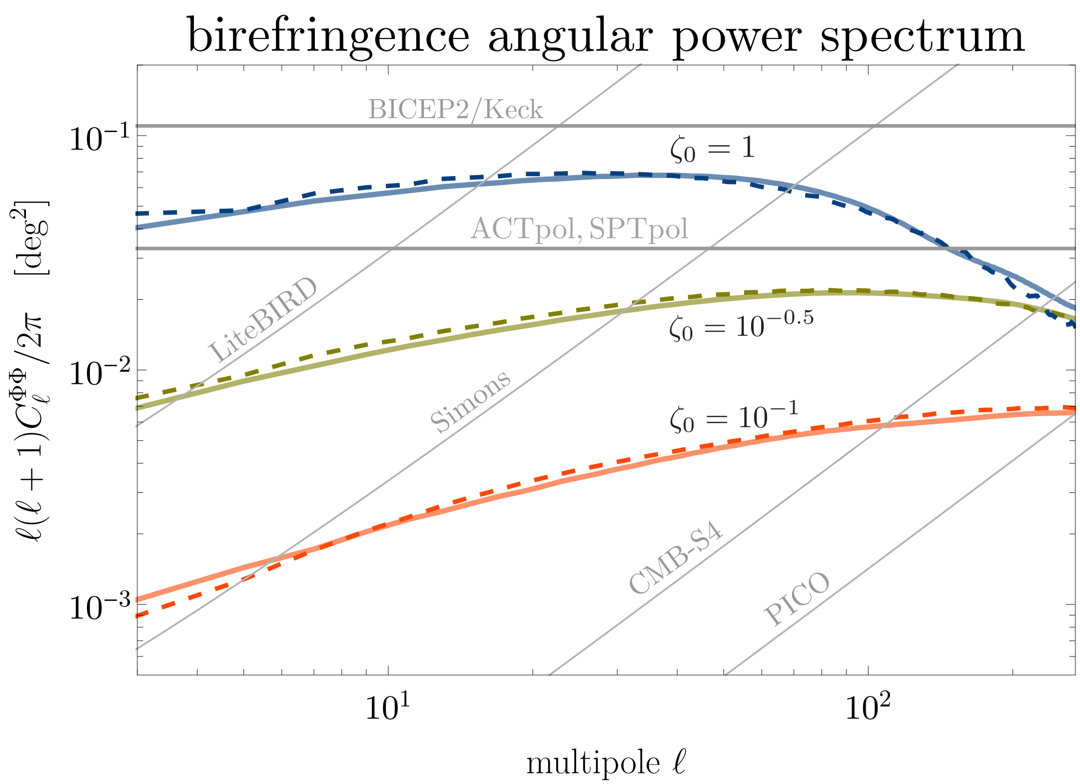


Future CMB telescopes will do much better



Axion-string induced birefringence signal

[Jain, AL, Amin (2103.01962)]



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

Key features

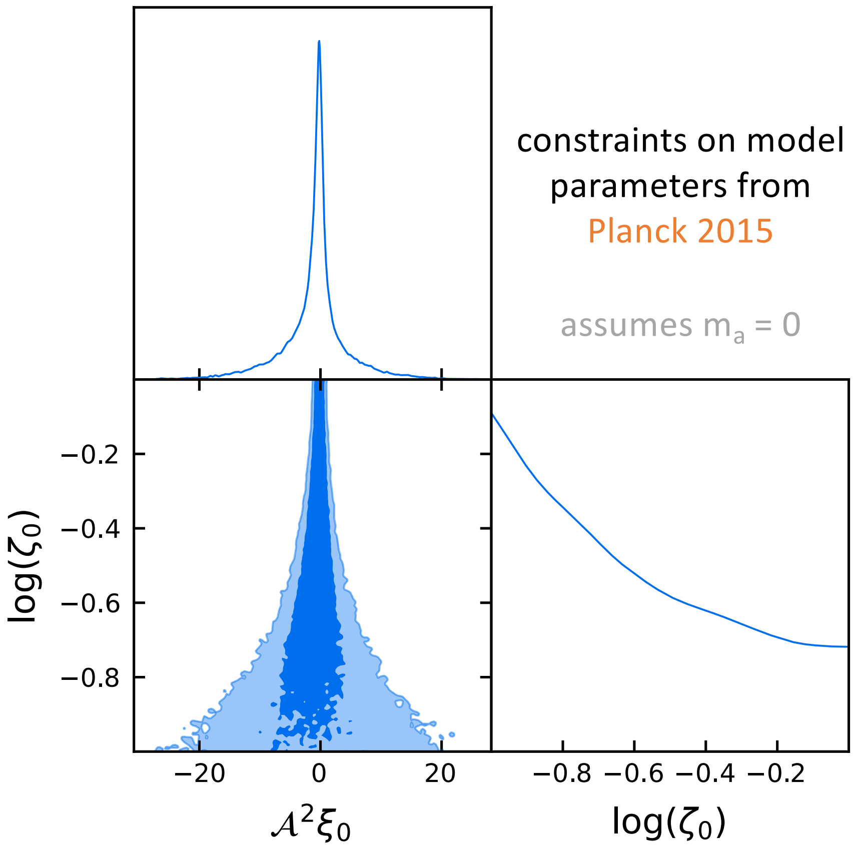
- Power spectrum is almost scale invar.
- Characteristic scale (l @ the peak) set by loop size at LSS
- Smaller loops (ζ_0) => weaker signal
- Trivial dependence on loop density (ξ_0) and anomaly coefficient (A) … power scales with ξ_0 A^2

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 $m_a = 0$

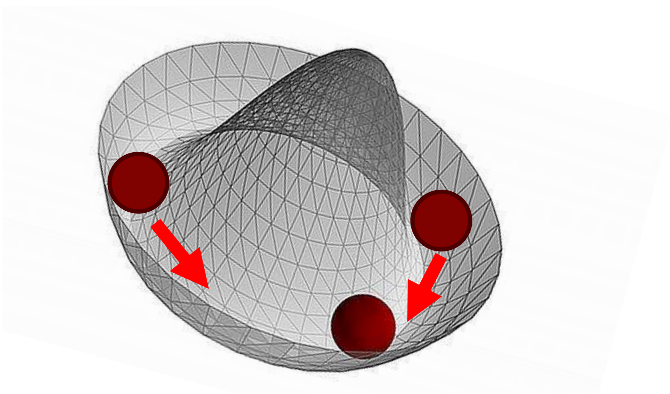
What about m_a?

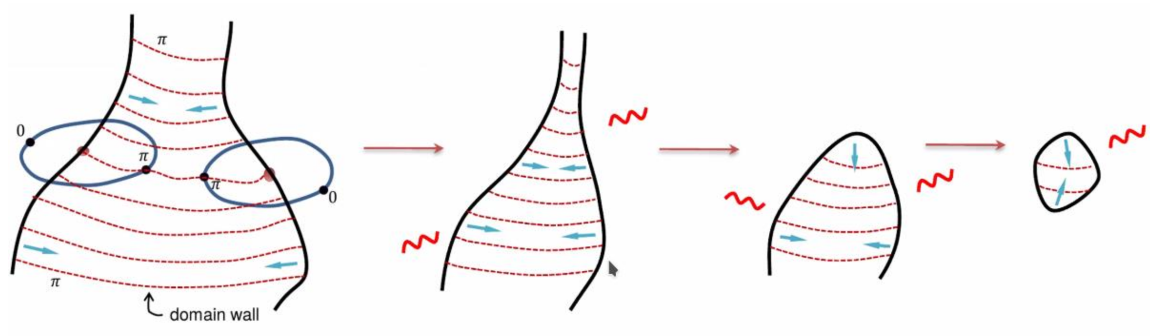
Impact of nonzero axion mass

[Amin, Hagimoto, Jain, AL (2208.XXXXX)]

Axion strings become connected together by domain walls

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





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

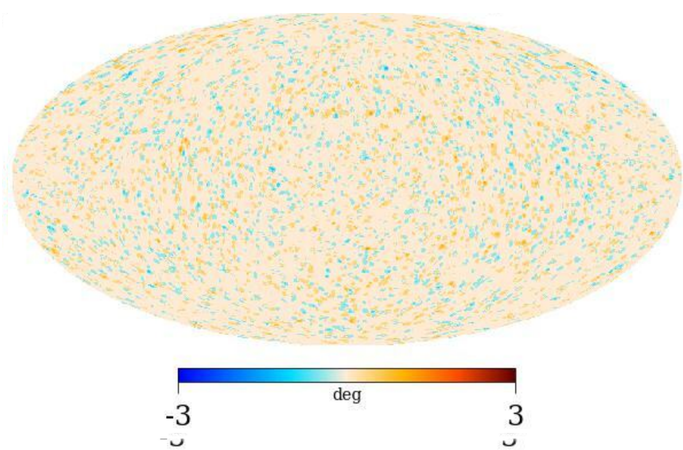
after the network collapses at redshift z_c the accumulation of birefringence is shut off

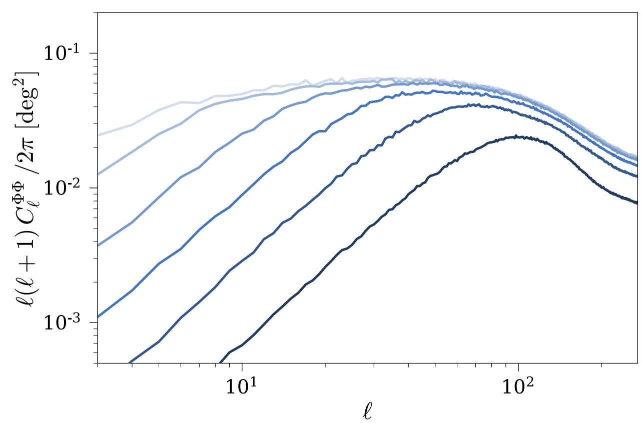
Impact of nonzero axion mass

[Amin, Hagimoto, Jain, AL (2208.XXXXX)]

$$\mathcal{A} = 1, \quad \zeta_0 = 1, \quad \xi_0 = 1$$

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

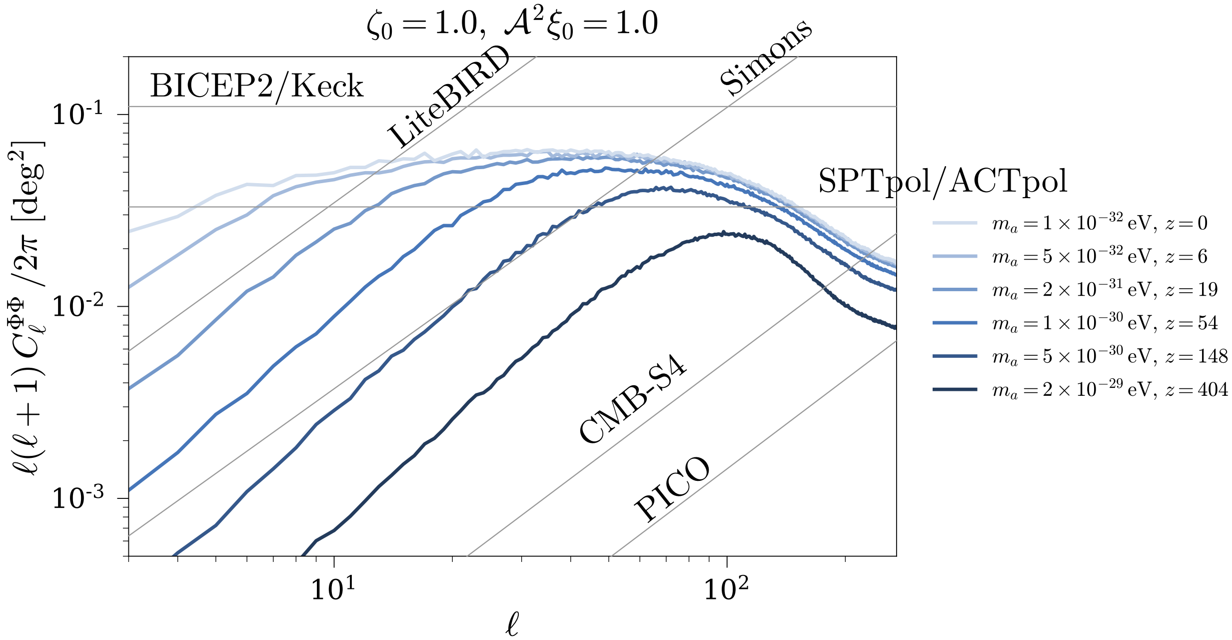




axion mass induces strong scale dependence

larger m_a ➔. suppresses power on large angular scales

Implications / context



Key messages

- The axion mass sets a new scale in the power spectrum
- Detection of this signal would not only provide evidence for ALPs in nature + axion strings, but also inform us about the ALP mass scale!

Get ready for coffee …

Summary

Hyper axion-like particles may manifest themselves in our Universe as a network of axion strings

… such particles arise in theories with compactified extra dimensions

An axion-photon coupling leads to the phenomenon of axion-string-induced cosmological birefringence

… and leaves a distinctive imprint on the cosmic microwave background radiation

We generate birefringence sky maps and calculate the power spectrum for a variety of string network models

… current CMB telescopes + future suveys will probe O(1) values of the anomaly coefficeint

Axions with $H_0 < m_a < H_{cmb}$ leave a very distinctive imprint on CMB & are exceptionally testable

… the string network collapses when $H=m_a$ suppressing power on large angular scales

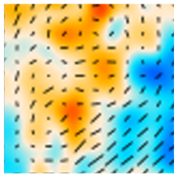
… these observations are an avenue for discovering ALPs and measuring their mass

BACKUP SLIDES

QUADRATIC ESTIMATORS

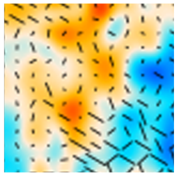
Want to: Convert $T, Q, U \rightarrow \alpha$.

Suppose we knew *primordial* CMB $\tilde{T}, \tilde{Q}, \tilde{U}$.



Under birefringence these transform like

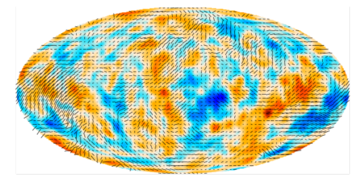
$$\tilde{T} \rightarrow T = \tilde{T}$$
$$\tilde{Q} \pm i\,\tilde{U} \rightarrow Q \pm iU = (\tilde{Q} \pm i\tilde{U})e^{\pm 2i\alpha}.$$



or, since α is small:

$$(\tilde{Q} \pm i\tilde{U})e^{\pm 2i\alpha} \approx (\tilde{Q} \pm i\tilde{U})(1 \pm 2i\alpha)$$

QUADRATIC ESTIMATORS

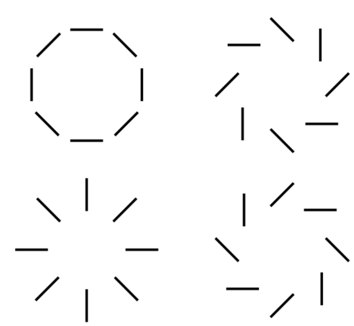


After some maths (and introducing E-modes, and B-modes)

$$T(\mathbf{l}) = \tilde{T}(\mathbf{l})$$

$$E(\mathbf{l}) = \tilde{E}(\mathbf{l}) - \int \frac{\mathrm{d}^2 l'}{(2\pi)^2} 2\alpha(\mathbf{L}) \left\{ \tilde{E}(\mathbf{l}') \sin 2\phi_{l'l} + \tilde{B}(\mathbf{l}') \cos 2\phi_{l'l} \right\} |_{\mathbf{L}=\mathbf{l}-\mathbf{l}'}$$

$$B(\mathbf{l}) = \tilde{B}(\mathbf{l}) + \int \frac{\mathrm{d}^2 l'}{(2\pi)^2} 2\alpha(\mathbf{L}) \left\{ \tilde{E}(\mathbf{l}') \cos 2\phi_{l'l} - \tilde{B}(\mathbf{l}') \sin 2\phi_{l'l} \right\} |_{\mathbf{L}=\mathbf{l}-\mathbf{l}'}$$



Now we have a statistical relationship between α and a pair of the observables ($X, Y \in \{T, E, B\}$)

$$\langle X(\mathbf{l}_1) Y^*(\mathbf{l}_2) \rangle = \langle \tilde{X}(\mathbf{l}_1) \tilde{Y}^*(\mathbf{l}_2) \rangle + f_{XY}(\mathbf{l}_1, \mathbf{l}_2) \alpha(\mathbf{l}_1 - \mathbf{l}_2)$$

XY	$f_{XY}(\mathbf{l}_1, \mathbf{l}_2)$
TT	0
TE	$-2\tilde{C}_{l_1}^{TE} \sin 2\varphi_{12}$
TB	$2\tilde{C}_{l_1}^{TE} \cos 2\varphi_{12}$
EE	$-2\left(\tilde{C}_{l_1}^{EE} - \tilde{C}_{l_2}^{EE}\right) \sin 2\varphi_{12}$
EB	$2\left(\tilde{C}_{l_1}^{EE} - \tilde{C}_{l_2}^{BB}\right) \cos 2\varphi_{12}$
BB	$-2\left(\tilde{C}_{l_1}^{BB} - \tilde{C}_{l_2}^{BB}\right) \sin 2\varphi_{12}$

$\langle\ \rangle \equiv$ ensemble average over CMB realisations.

QUADRATIC ESTIMATORS

Maybe we can estimate α with something of the form (Hu & Okamoto, 2002)

$$\hat{\alpha}_{XY}(\mathbf{L}) = \lambda_{XY}(\mathbf{L}) \int \frac{\mathrm{d}^2 l_1}{(2\pi)^2} X(\mathbf{l}_1) Y(\mathbf{l}_1) F_{XY}(\mathbf{l}_1, \mathbf{l}_2)\Big|_{\mathbf{l}_2 = \mathbf{L} - \mathbf{l}_1}$$

where $\hat{\alpha}$ must satisfy $\langle \hat{\alpha}_{XY}(\mathbf{L}) \rangle = \alpha(\mathbf{L})$.

Minimising the variance of $\hat{\alpha}$:

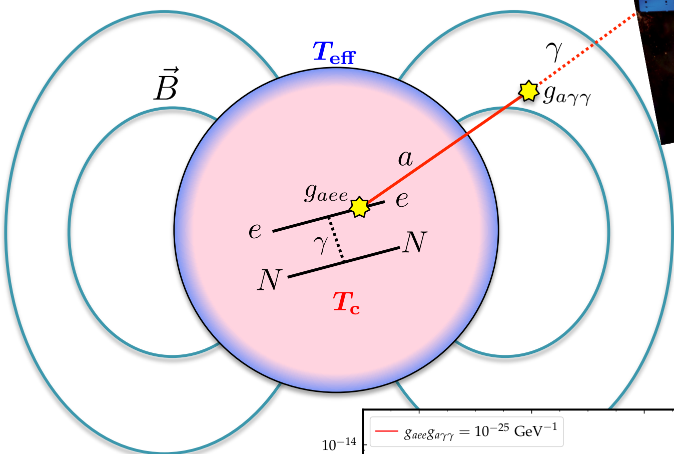
$$\lambda^{-1}_{XY}(\mathbf{L}) = \int \frac{\mathrm{d}^2 l_1}{(2\pi)^2} f_{XY}(\mathbf{l}_1, \mathbf{l}_2) F_{XY}(\mathbf{l}_1, \mathbf{l}_2)\Big|_{\mathbf{l}_2 = \mathbf{L} - \mathbf{l}_1}$$

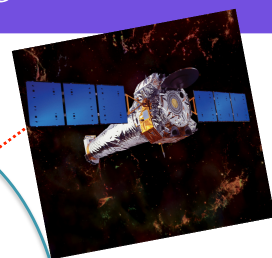
$$F_{XY}(\mathbf{l}_1, \mathbf{l}_2) = \frac{f_{XY}(\mathbf{l}_1, \mathbf{l}_2)}{(1 + \delta_{XY}) C^{XX}_{l_1} C^{YY}_{l_2}} \quad (XY \neq TE)$$

XY	$f_{XY}(\mathbf{l}_1, \mathbf{l}_2)$
TT	0
TE	$-2\tilde{C}^{TE}_{l_1} \sin 2\varphi_{12}$
TB	$2\tilde{C}^{TE}_{l_1} \cos 2\varphi_{12}$
EE	$-2\left(\tilde{C}^{EE}_{l_1} - \tilde{C}^{EE}_{l_2}\right) \sin 2\varphi_{12}$
EB	$2\left(\tilde{C}^{EE}_{l_1} - \tilde{C}^{BB}_{l_2}\right) \cos 2\varphi_{12}$
BB	$-2\left(\tilde{C}^{BB}_{l_1} - \tilde{C}^{BB}_{l_2}\right) \sin 2\varphi_{12}$

Astrophysical limits

[Dessert, AL, Safdi (1903.05088)]
[Dessert, AL, Safdi (2104.12772)]





Chandra X-ray Observatory