Aharonov-Bohm in the Sky : A CMB Millikan Experiment with Cosmic Axiverse Strings

Anson Hook
University of Maryland

Why CMB strings?

My goal : Find the UV theory of the Universe

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A) Find UV particles

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A) Find UV particles
B) Measure IR interactions
    1. Make assumptions about intervening physics
    2. Learn something about UV modulo assumptions

Why CMB strings?

My goal : Find the UV theory of the Universe

A) Find UV particles
B) Measure IR interactions
   1. Make assumptions about intervening physics
   2. Learn something about UV modulo assumptions

GUTs

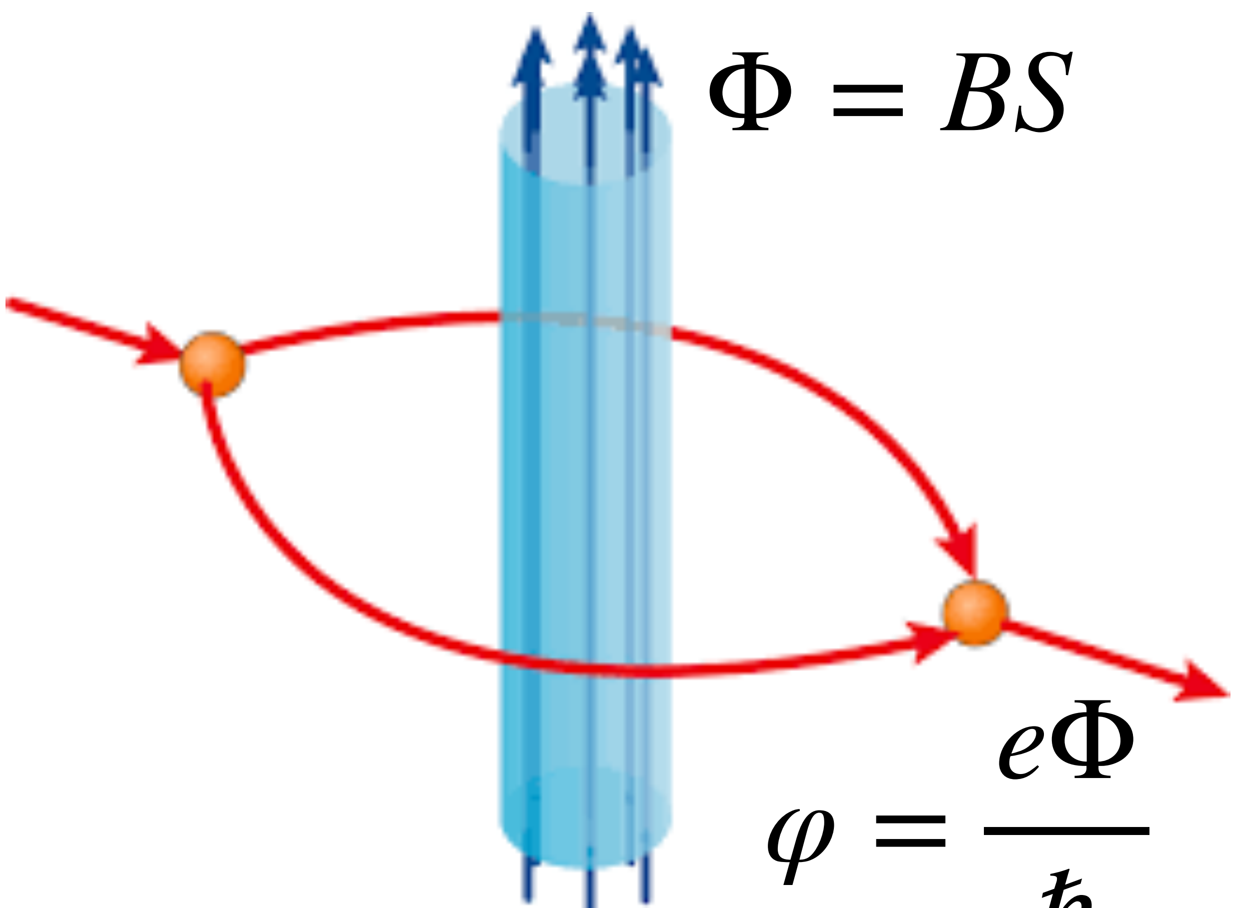
Topology is King

Most robust quantity in any theory is topological

Topology robust to new physics
between the UV and the IR

Measure topological quantities!

Aharonov-Bohm Effect



$$\Phi = BS$$

$$\varphi = \frac{e\Phi}{\hbar}$$

Electron acquire phase as it moves around a magnetic flux

Independent of path and mass of the electron

Topological interactions

Standard Model

$\theta F\tilde{F}$	Unphysical without monopoles
$\theta W\tilde{W}$	B+L violation
$\theta G\tilde{G}$	Strong CP problem

Topological interactions

Standard Model

$$\theta F\tilde{F}$$

$$\theta W\tilde{W}$$

$$\theta G\tilde{G}$$

BSM

$$\frac{a}{f}F\tilde{F}$$

't Hooft Anomaly

How to use the Axionic coupling

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

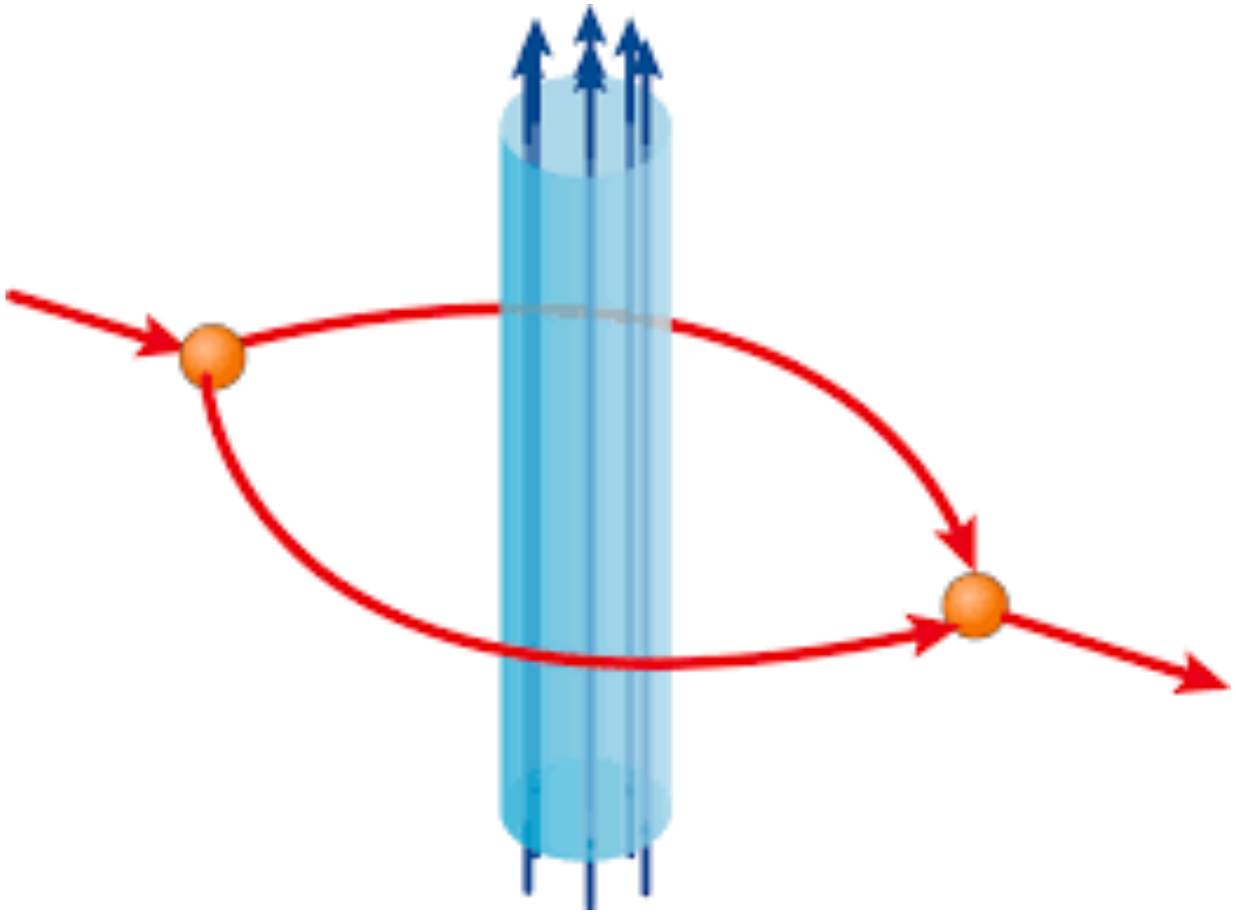
Particle approach **HARD**

Anomaly - decay constant ambiguity

Decay constant RG runs : Wavefunction renormalization

Need something independent of f

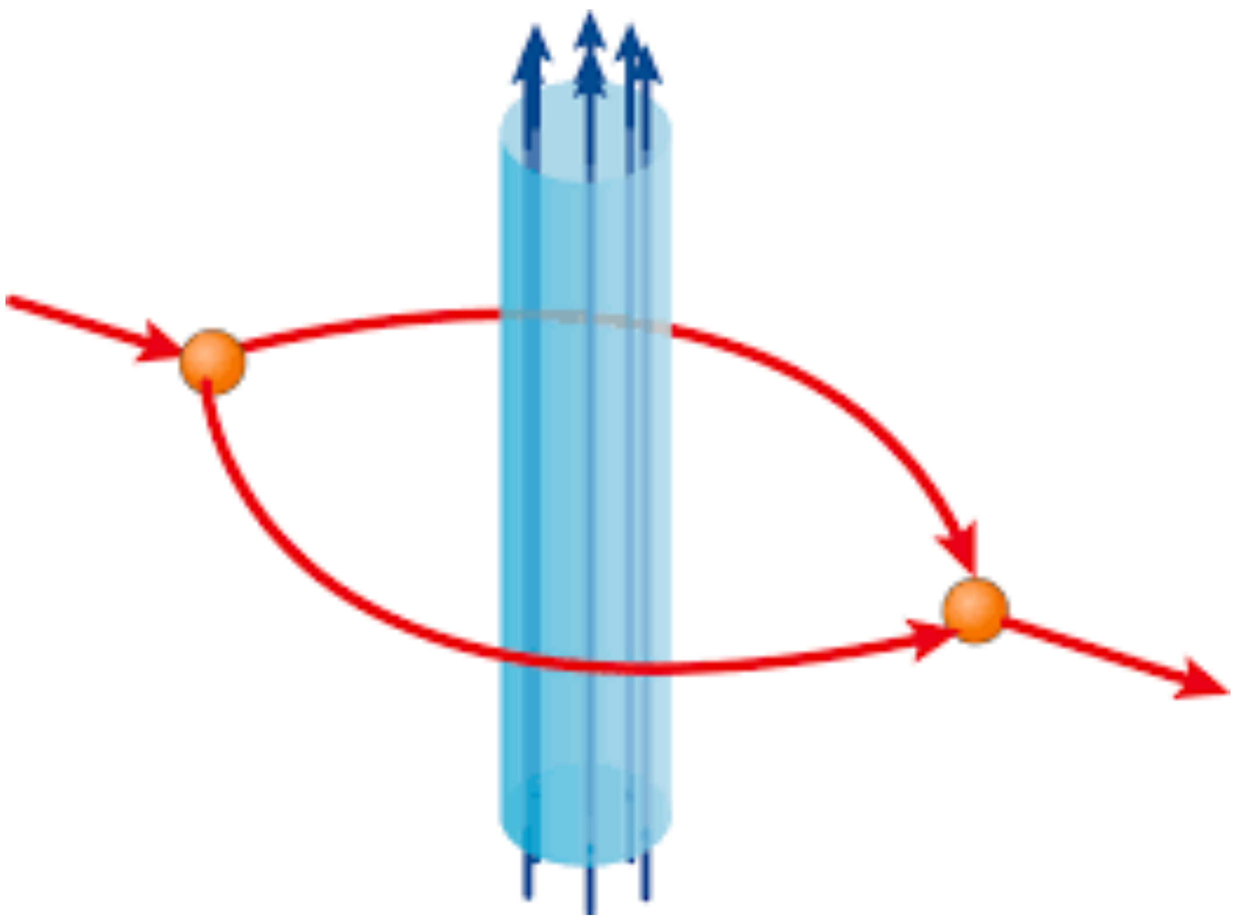
How to use the Axionic coupling



Strings!

$$\frac{a}{f} \to \frac{a}{f} + 2\pi\,(\mathbb{Z})$$

How to use the Axionic coupling



Aharonov-Bohm Effect

Photons acquire phase as it moves around an axion string

How to use the Axionic coupling

Strings

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

Unique opportunity to learn directly about 't Hooft anomalies!

Motivation?

Strings

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

String theory predicts many near massless axions with these couplings

Outline

- Millikan (What do we learn from anomalies)
- String Theory Review
- Basic Signature of a String
- (CMB) ways of looking for Strings

Anomalies

$$\frac{\alpha_{\rm em}}{4\pi}\left(\mathcal{A}\frac{a}{f}+\theta\right)F\tilde{F}$$

$\boldsymbol{A}$ is the 't Hooft anomaly of the axion

Axion is periodic but coupling is not

$$\frac{a}{f}=\frac{a}{f}+2\pi \qquad \longrightarrow \qquad \theta=\theta+2\pi\mathcal{A}$$

Periodicity of theta

What does this periodicity teach us? $$\theta = \theta + 2\pi\mathcal{A}$$

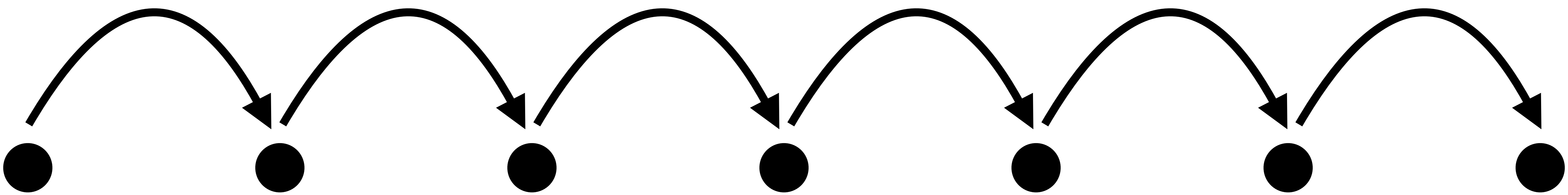
Witten effect $$q_e = \left(\frac{eg}{2\pi}\right)\frac{\theta e}{2\pi} = \frac{e}{e_{\rm min}}\frac{\theta e}{2\pi}$$

Not periodic!

Need many monopoles that are exchanged

Periodicity of theta

$$\theta \to \theta + 2\pi\mathcal{A}$$



$$q_{-2}(\theta) \quad q_{-1}(\theta) \quad q_0(\theta) \quad q_1(\theta) \quad q_2(\theta)$$

$$q_n(\theta + 2\pi\mathcal{A}) = q_{n+1}(\theta)$$

Periodicity of theta

$$q_n(\theta + 2\pi\mathcal{A}) = q_{n+1}(\theta)$$

Periodicity gives difference in charge between various monopoles

$$\Delta q_e = \frac{e}{e_{\rm min}}\mathcal{A}\, e$$

Fundamental electric charge of monopoles

$$\Delta q_e = e_{\rm min} = \sqrt{\mathcal{A}}\, e$$

Periodicity of theta

Without any assumptions

$$\mathcal{A} = \mathbb{Z}\, e_{\min}^2 = \sum_f N_f\, N_a\, Q_f^2$$

Fractional anomaly necessarily implies fractional electric charge is the minimal charge

Outline

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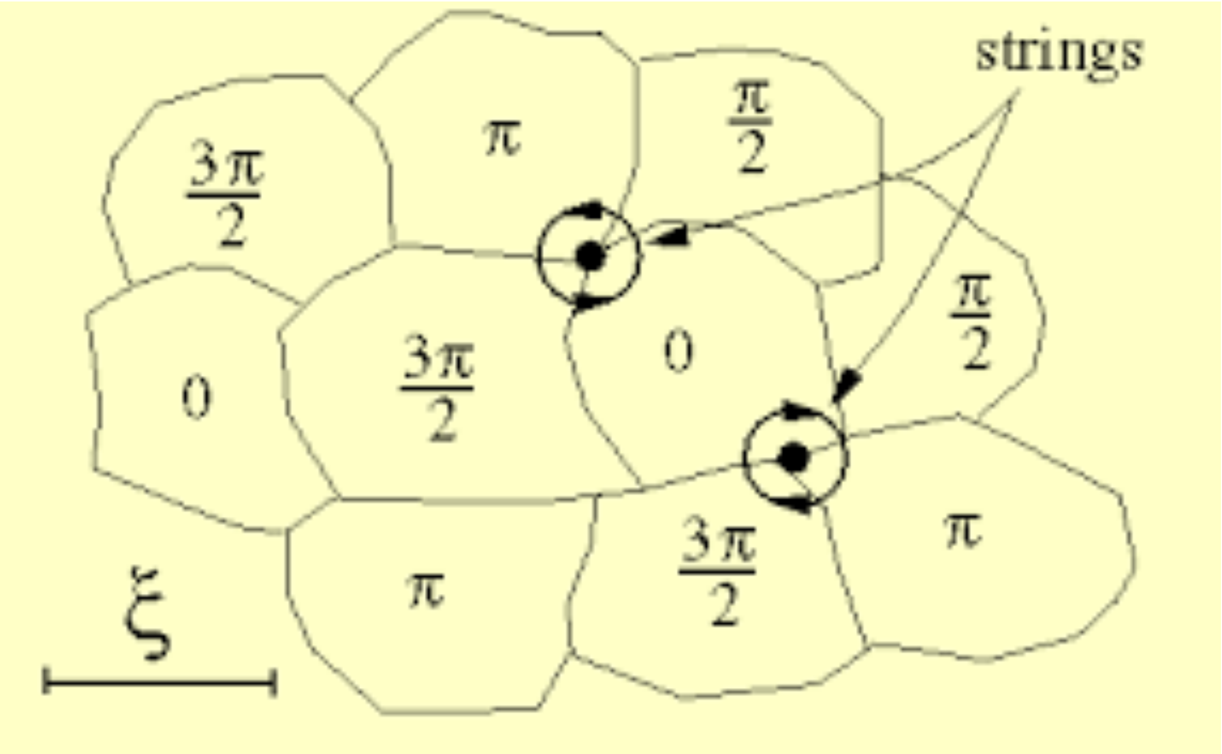
Kibble Mechanism

If the universe was hot enough that the symmetry was restored …..

Kibble Mechanism

If the universe was hot enough that the symmetry was restored ….. **Strings!**



Each Hubble patch randomly determines its own value of a/f

Strings by chance

String evolution

String density $\rho_{\text{string}} = \xi(t)\, H^2 f^2 \log\left(f/H\right)$

- Scaling solution : $\xi = \text{constant}$

- Scaling violation : $1 \lesssim \xi \lesssim 1000$

Outline

- ~~Millikan (What do we learn from anomalies)~~
- ~~String Theory Review~~
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Polarization Rotation

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

Dispersion relation of photon

$$\omega^2 = k^2 \pm k\frac{\mathcal{A}\alpha_{\rm em}}{\pi f}\frac{da}{dt}$$

$$v_{\rm phase} \approx 1 \pm \frac{\mathcal{A}\alpha_{\rm em}}{2\pi f}\frac{da}{dt}$$

Polarization Rotation

$$v_{\mathrm{phase}} \approx 1 \pm \frac{\mathcal{A}\alpha_{\mathrm{em}}}{2\pi f}\frac{da}{dt}$$

Phase rotation of circularly polarized light is a polarization rotation of linearly polarized light

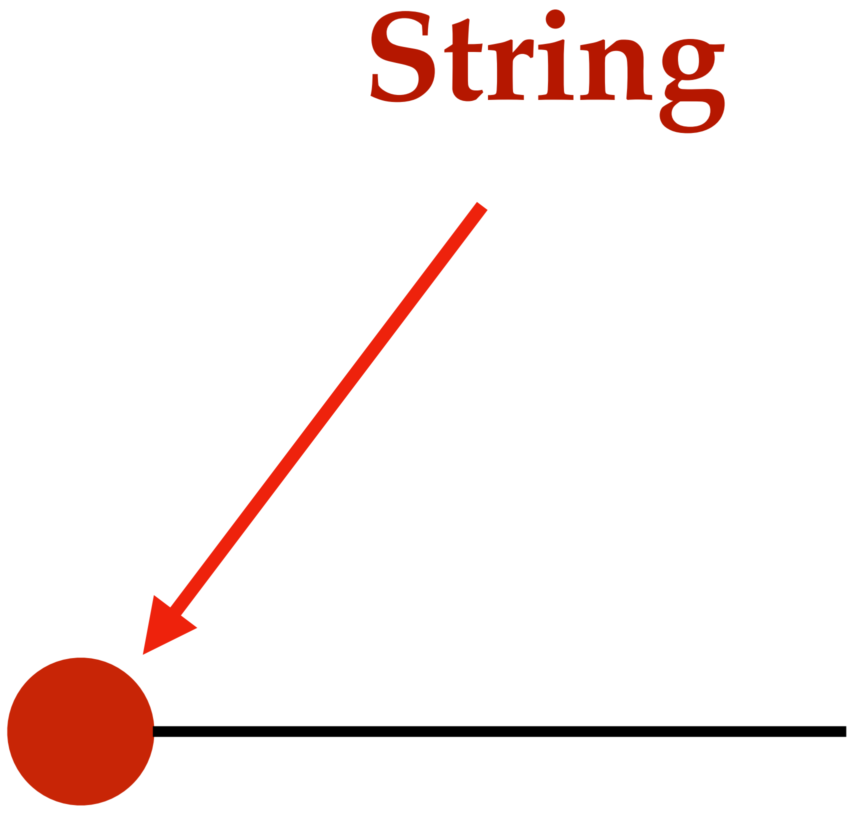
$$\Phi = \int v dt = \mathcal{A}\alpha_{\mathrm{em}}\frac{\Delta a}{2\pi f}$$

Topological - depends only on initial and final value of the axion

Apology

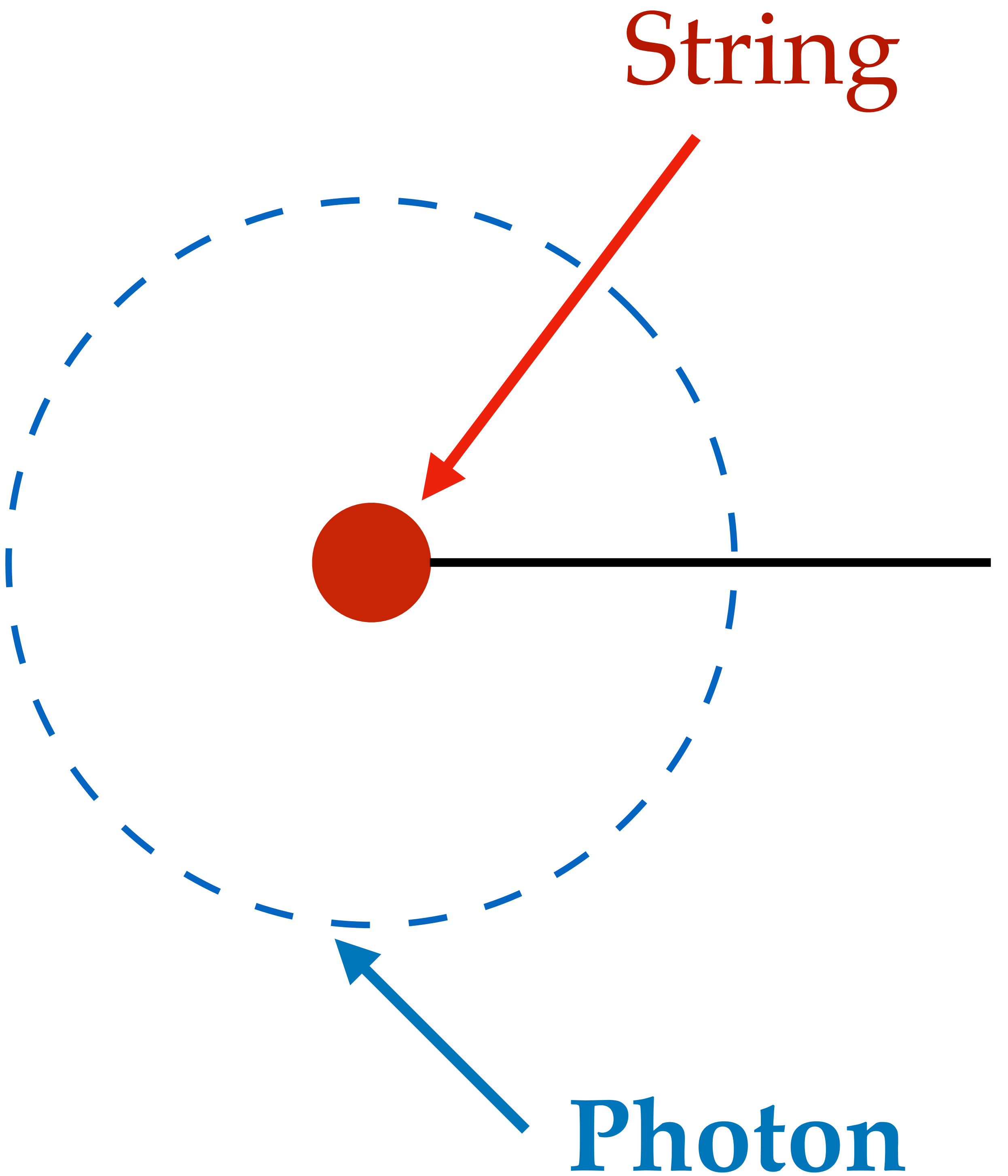
Φ	Phase rotation of linearly polarized light
α	CMB standard
α_{EM}	Photon coupling
$\alpha = \mathcal{A}\,\alpha_{\mathrm{EM}}$	Suggestive equation?

Strings and photons - a love story



$$\theta = \frac{a}{f}$$

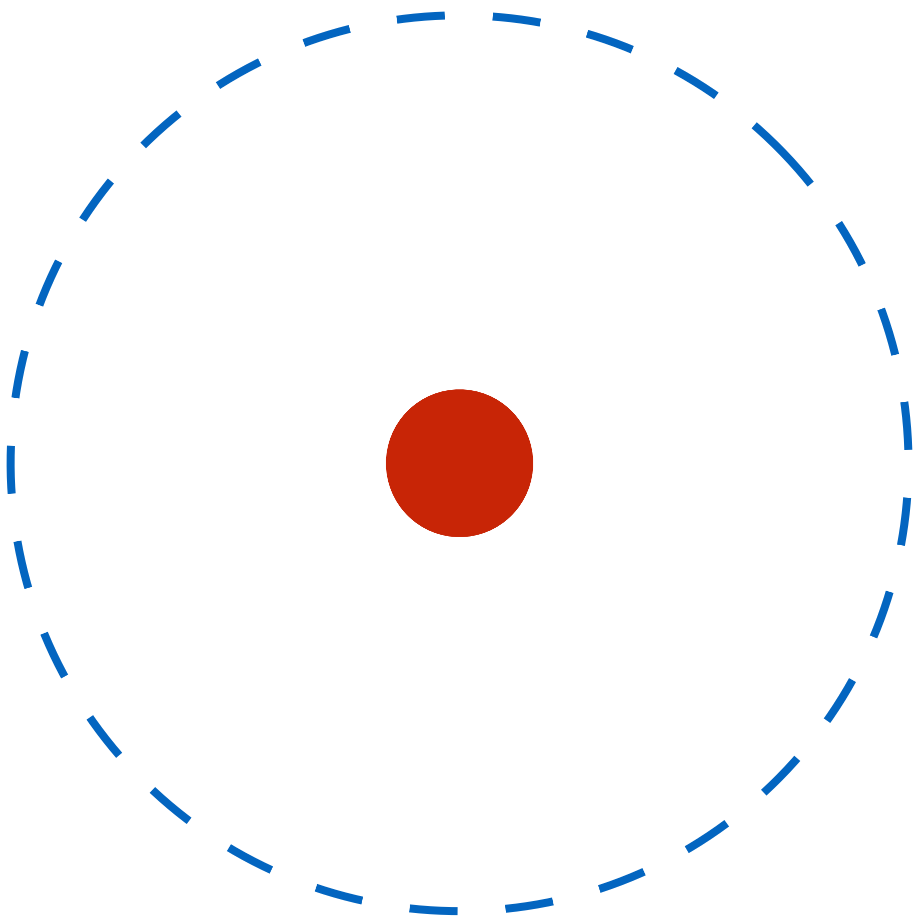
Strings and photons - a love story



$$\theta = \frac{a}{f}$$

Strings and photons - a love story

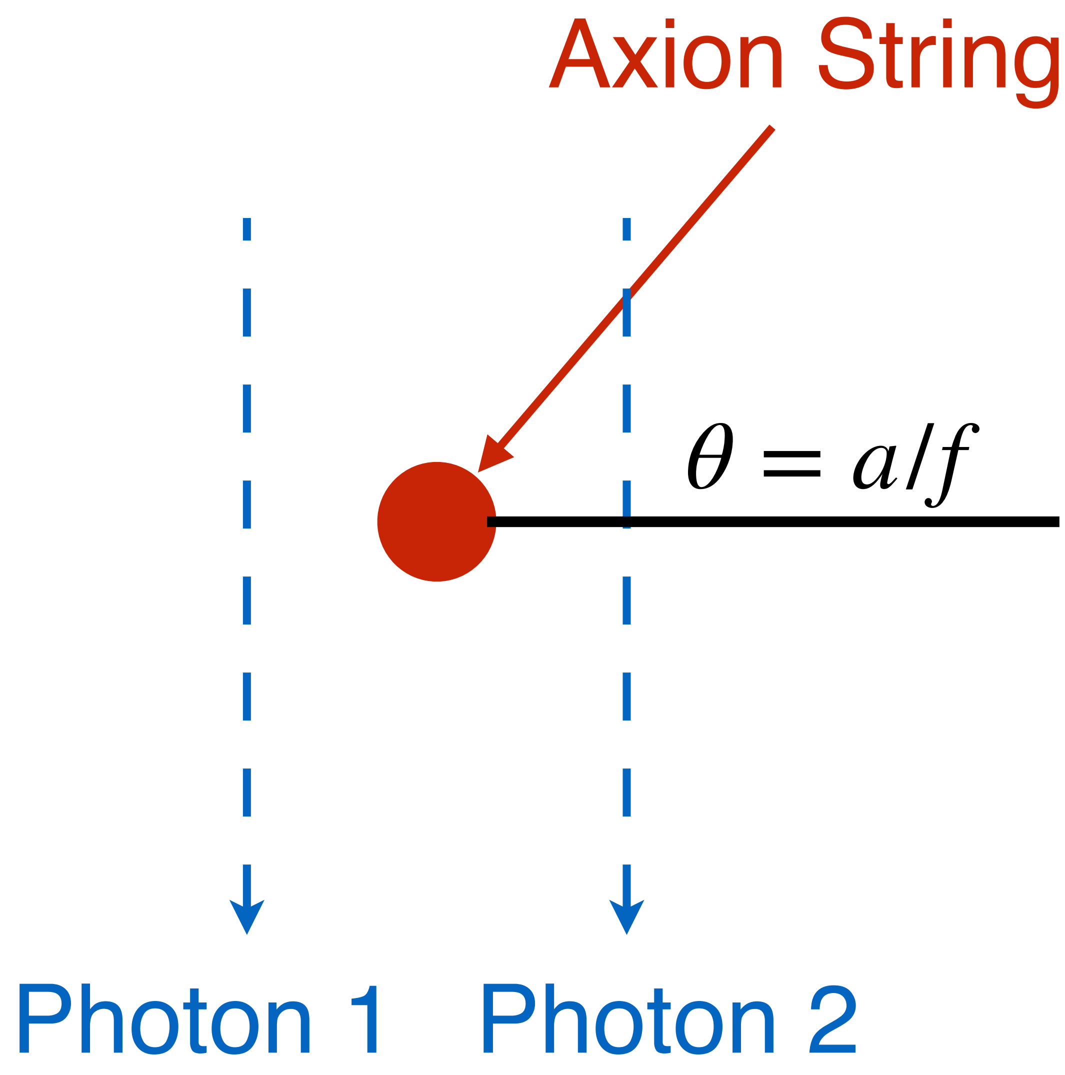
Topological effect



Large polarization rotation from traveling around a string!

$$\Phi = \frac{\mathcal{A}\alpha_{\rm em}}{2\pi}\frac{\Delta a}{f} = \mathcal{A}\alpha_{\rm em}$$

Strings and photons - a love story



$$\Phi_1 = \frac{\mathcal{A}\alpha_{\rm em}}{2\pi}\frac{\Delta a}{f} = \frac{\mathcal{A}\alpha_{\rm em}}{2}$$

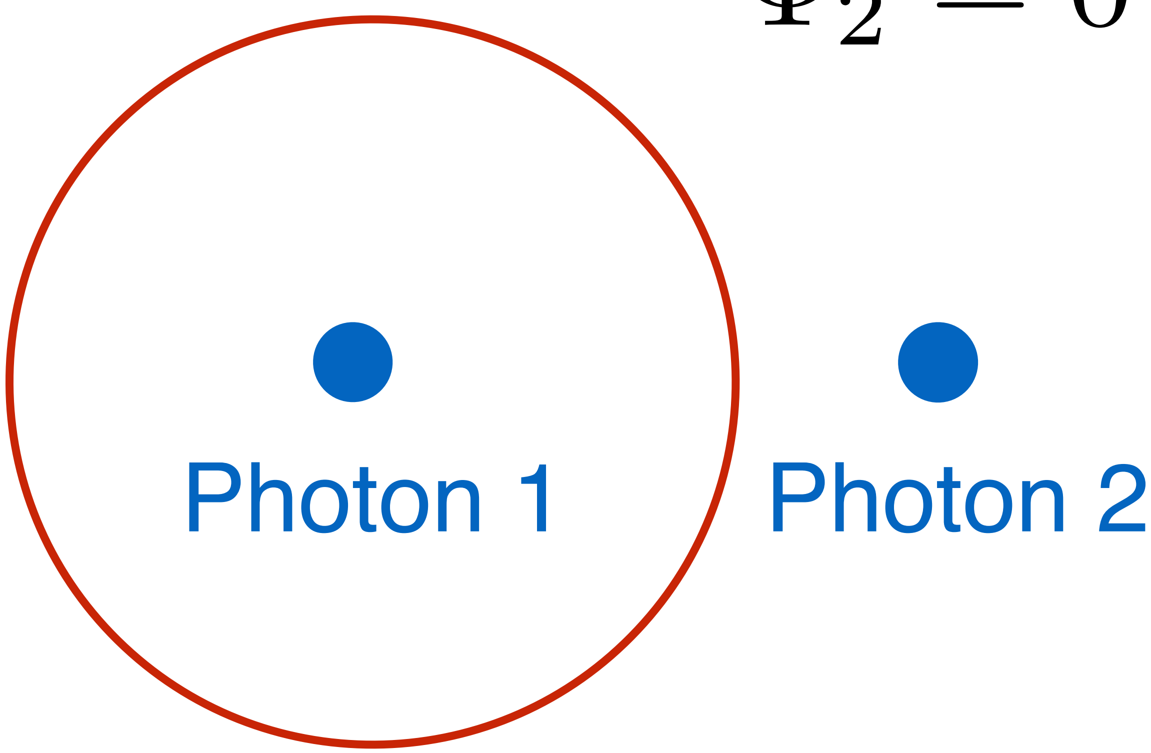
$$\Phi_2 = -\frac{\mathcal{A}\alpha_{\rm em}}{2}$$

$$\Delta\Phi = \mathcal{A}\alpha_{\rm em}$$

Strings and photons - a love story

String

$$\Phi_2 = 0$$



$$\Phi_1 = \pm \mathcal{A} \alpha_{\rm em}$$

Photons that go through a string loop acquire a rotation

Photons that do not go through a string loop do not acquire a rotation

Outline

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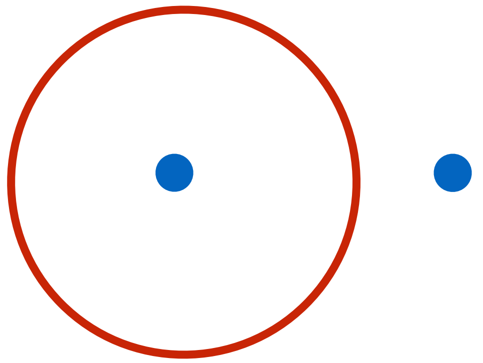
CMB

CMB acts as a backlight which is rotated by strings

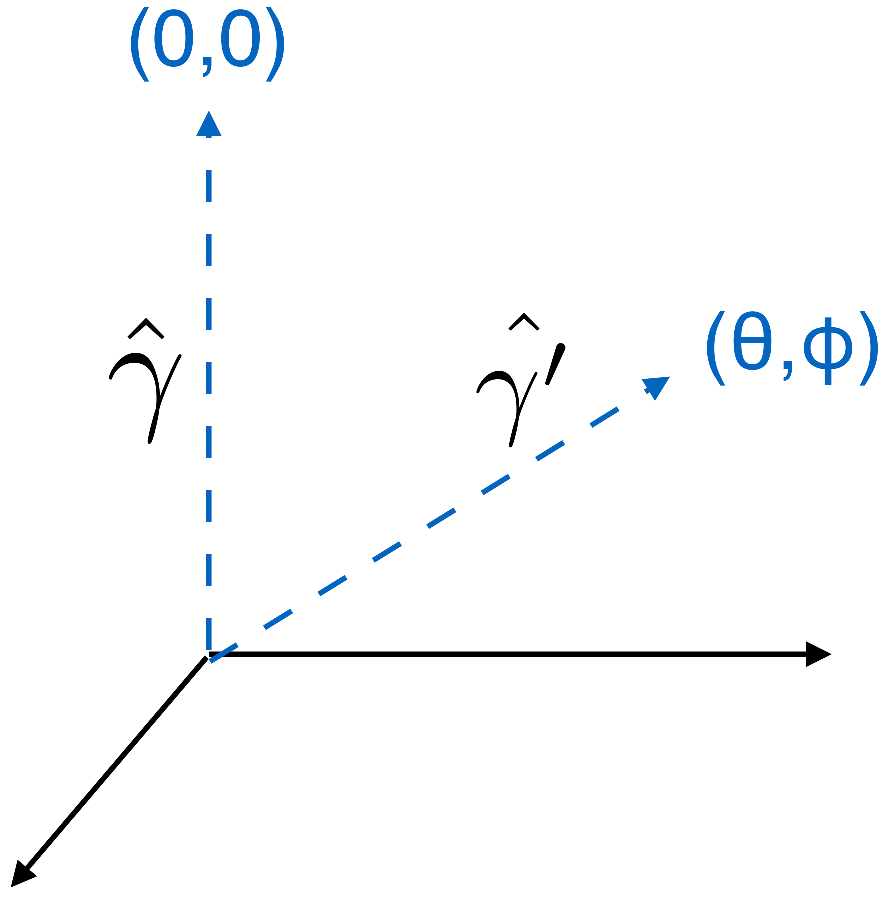
Power spectrum analysis

Look for discontinuous jumps
in the rotation angle

Toy analytics

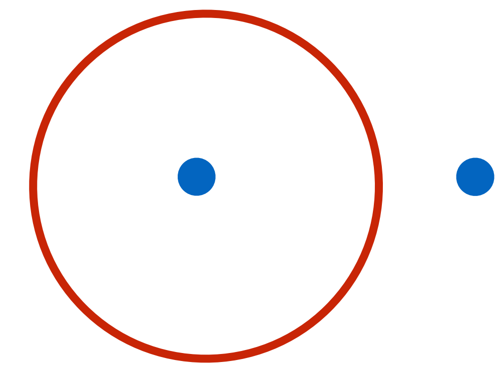


Two point function of the polarization rotation

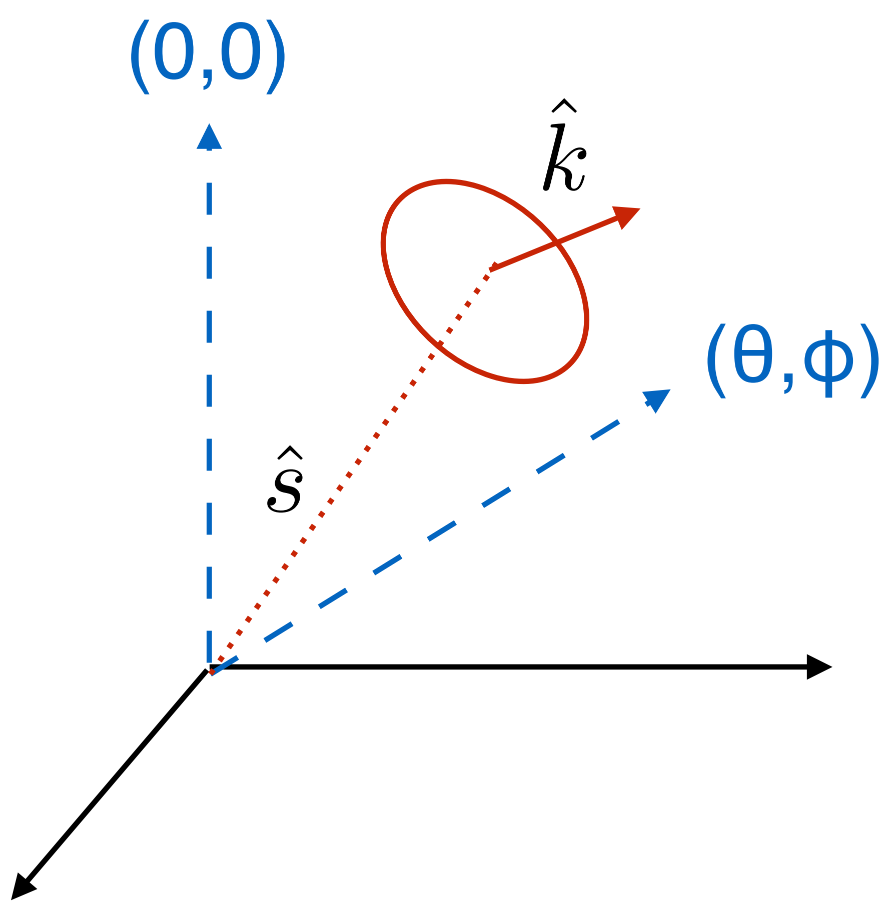


$$\langle \Phi(\theta, \phi)\Phi(0,0)\rangle$$

Toy analytics

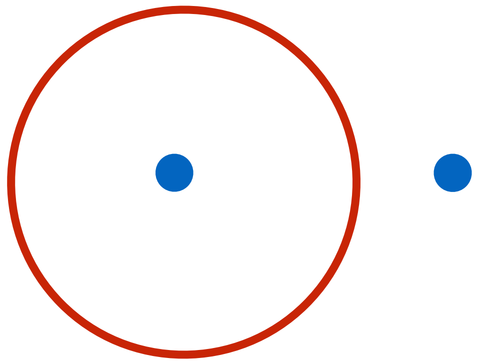


Two point function of the polarization rotation



- Take strings to be Hubble sized loops
- Pass through loop acquire a phase $\Phi = \pm \mathcal{A} \alpha_{\rm em}$
- Integrate over all orientations and directions

Toy analytics

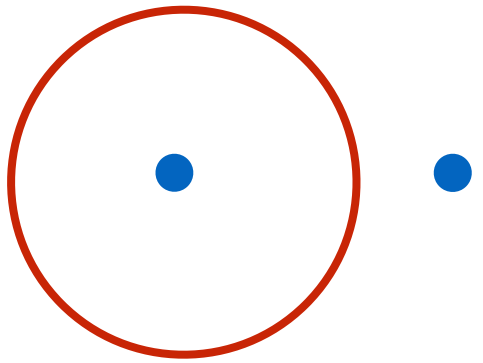


Number of strings at a particular redshift

$$\langle \Phi(\hat{\gamma})\Phi(\hat{\gamma}')\rangle = (\mathcal{A}\alpha_{\rm em})^2 \int d\eta \int d^2\hat{s} \int d^2\hat{k}\,(\eta_0-\eta)^2 f(\eta)$$
$$\times\,\Theta\left(\frac{\eta}{2} - d(\hat{s},\hat{\gamma},\hat{k},\eta)\right)\Theta\left(\frac{\eta}{2} - d(\hat{s},\hat{\gamma}',\hat{k},\eta)\right)$$

Both photons pass through string

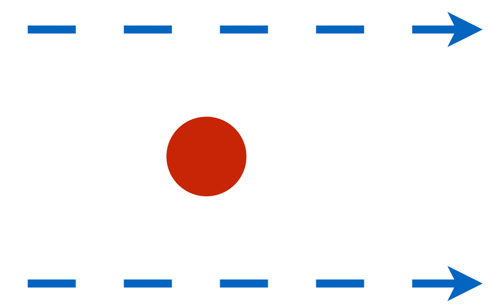
Toy analytics



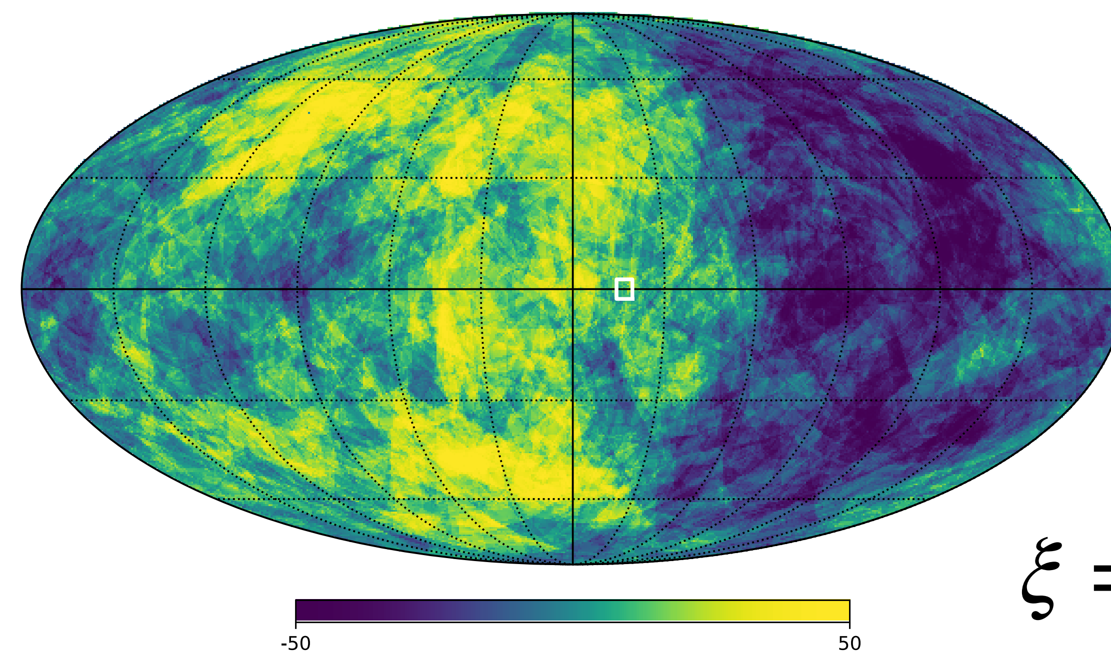
$$\langle\Phi(0,0)^2\rangle \approx \xi \left(\mathcal{A}\alpha_{\rm em}\right)^2 \log\left(\frac{\eta_0}{\eta_{\rm CMB}}\right) \sim \left(\mathcal{A}\alpha_{\rm em}\right)^2 N_{\rm string}$$

Polarization is undergoing a random walk

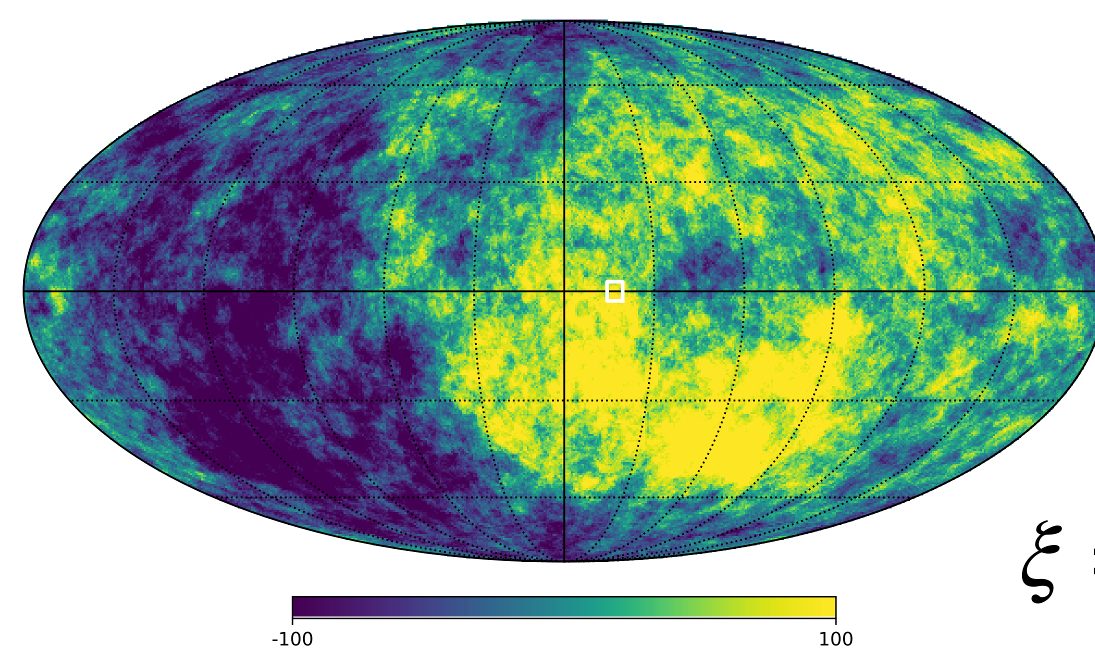
Toy simulation



- Randomly throw down infinitely long straight strings
- Remove strings as time goes on to maintain correct number density
- Trace CMB photon paths

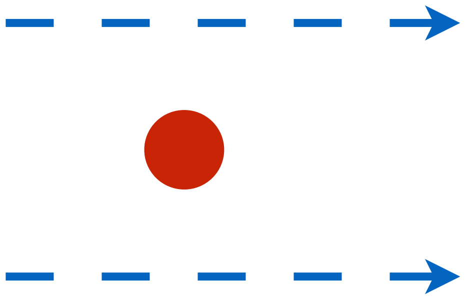


$\xi = 10$

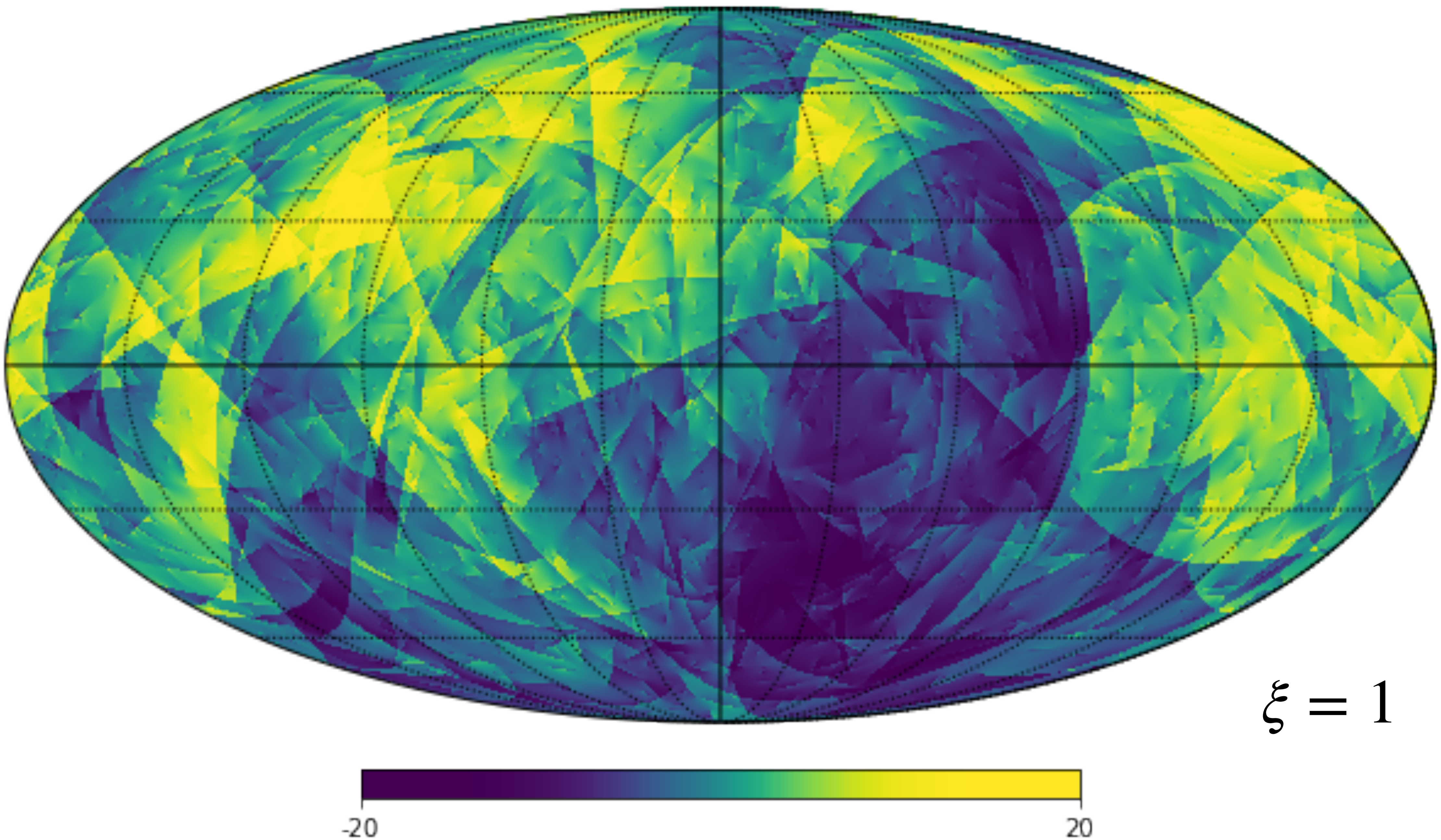


$\xi = 100$

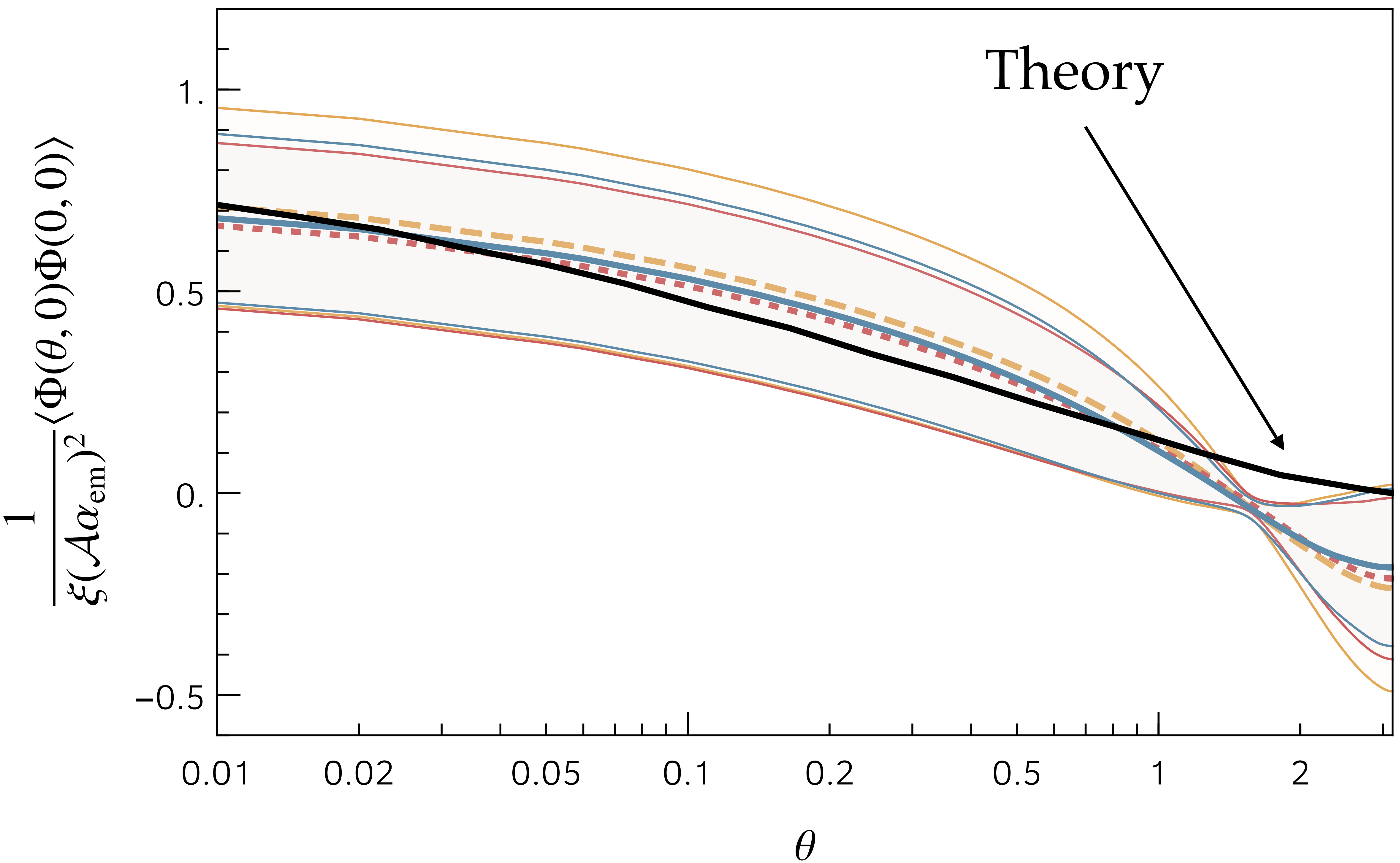
Toy simulation



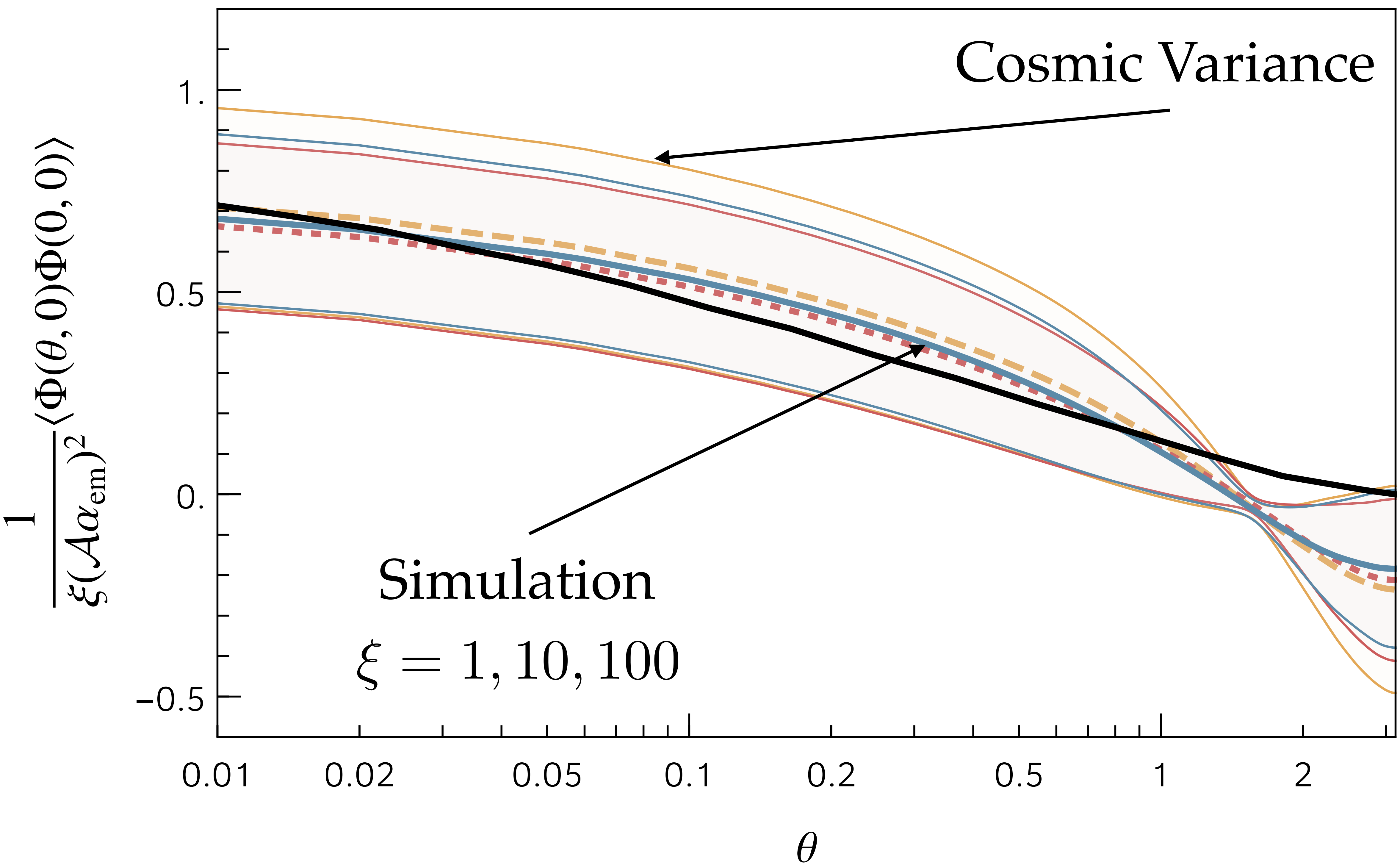
Can see both long and short strings



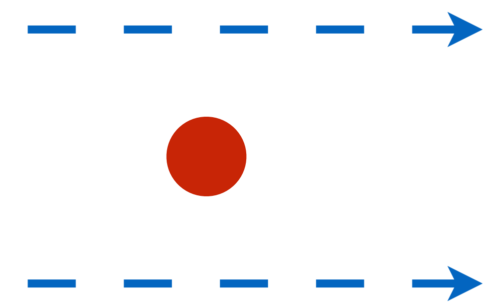
Simulation Comparison



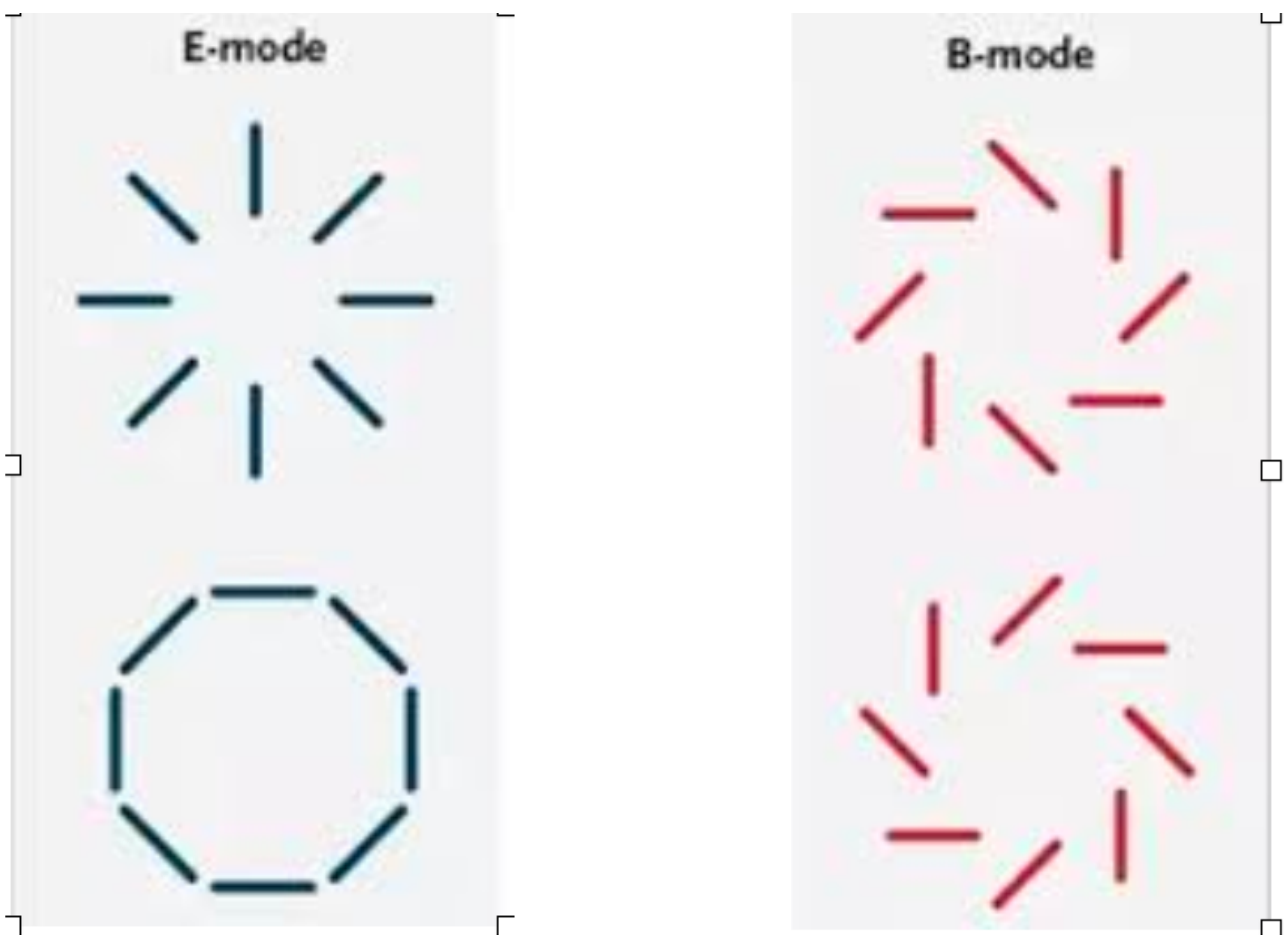
Simulation Comparison



CMB Constraints(ish)



Rotation takes E into B modes



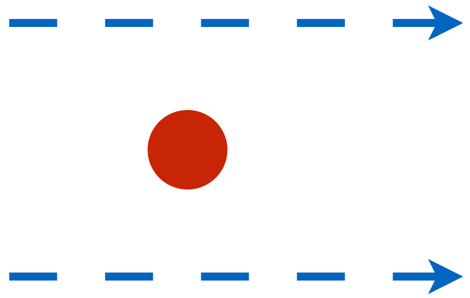
Use CMB to look for B modes correlated with E modes

Frequency Independent

Distinct feature in physical space

astro-ph/9812088, 1705.06387, 1904.07855

CMB Constraints(ish)



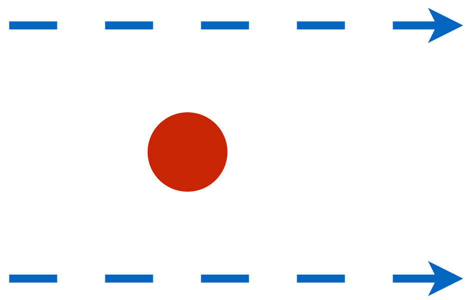
$$Q(\hat{\gamma}) \pm iU(\hat{\gamma}) = (\tilde{Q}(\hat{\gamma}) \pm i\tilde{U}(\hat{\gamma}))\exp(\pm 2i\Phi(\hat{\gamma}))$$

Polarization rotates Q and U into each other

$$p(\hat{\gamma}) = \sum_{lm}(E_{lm} + iB_{lm})_2 Y_{lm}(\hat{\gamma})$$

Typically Fourier transform into E and B modes

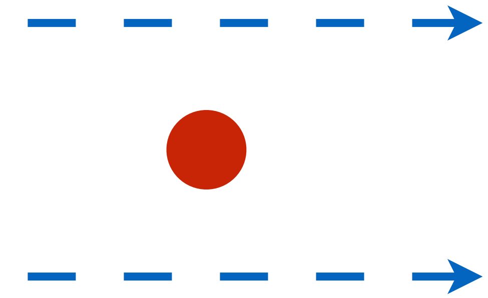
CMB Constraints(ish)



$$B_{lm} = 2 \sum_{LM} \sum_{l'm'} \Phi_{LM} E_{l'm'} \xi^{LM}_{lml'm'} H^{L}_{ll'}$$

Polarization rotates E and B into each other via Wigner-3j symbols

CMB Constraints(ish)



Build an estimator

$$[\hat{\Phi}^{E^i B^j}_{LM}]_{ll'} = \frac{2\pi \sum_{mm'} B^i_{lm} E^{j*}_{l'm'} \xi^{LM}_{lml'm'}}{(2l+1)(2l'+1)C^{EE}_l H^L_{ll'}}$$

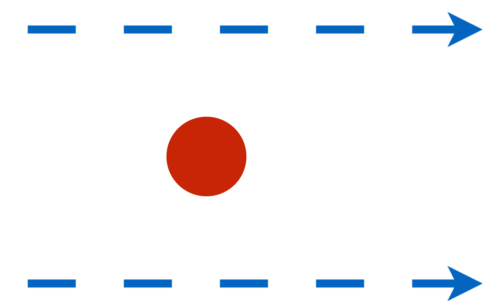
$$\langle \hat{\Phi}_{LM} \hat{\Phi}_{L'M'} \rangle = \delta_{LL'} \delta_{MM'} (C^{\Phi}_L + \sigma^2_{\Phi,L})$$

What we want → C^{Φ}_L

Noise → $\sigma^2_{\Phi,L}$

astro-ph/9812088, 1705.06387, 1904.07855

CMB Constraints(ish)



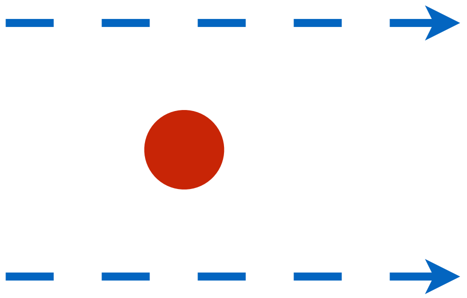
$$\langle \hat{\Phi}_{LM} \hat{\Phi}_{L'M'} \rangle = \delta_{LL'} \delta_{MM'} (C_L^{\Phi} + \sigma^2_{\Phi,L})$$

Forecast sensitivity

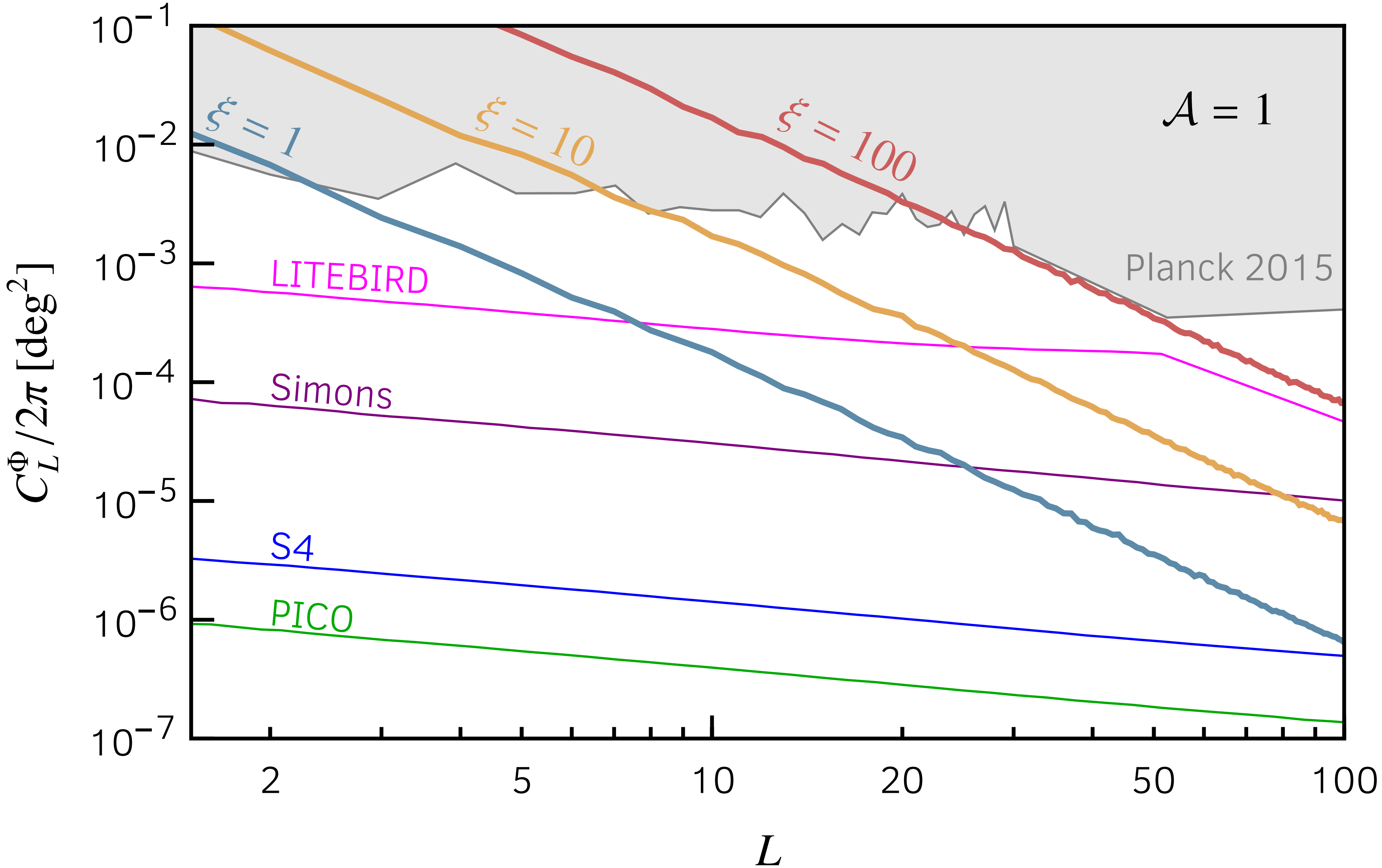
$$\sigma_{C_L^{\Phi}} = \frac{\sigma^2_{\Phi,L}}{f_{\rm sky}(2L+1)/2}$$

astro-ph/9812088, 1705.06387, 1904.07855

CMB Constraints(ish)



Constraints scale as $\xi \mathcal{A}^2$



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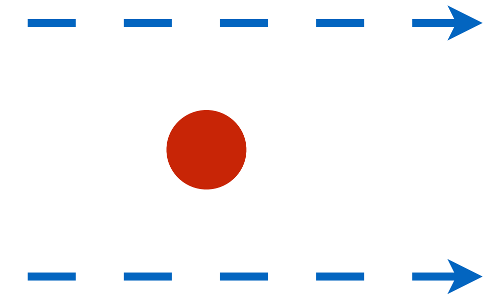

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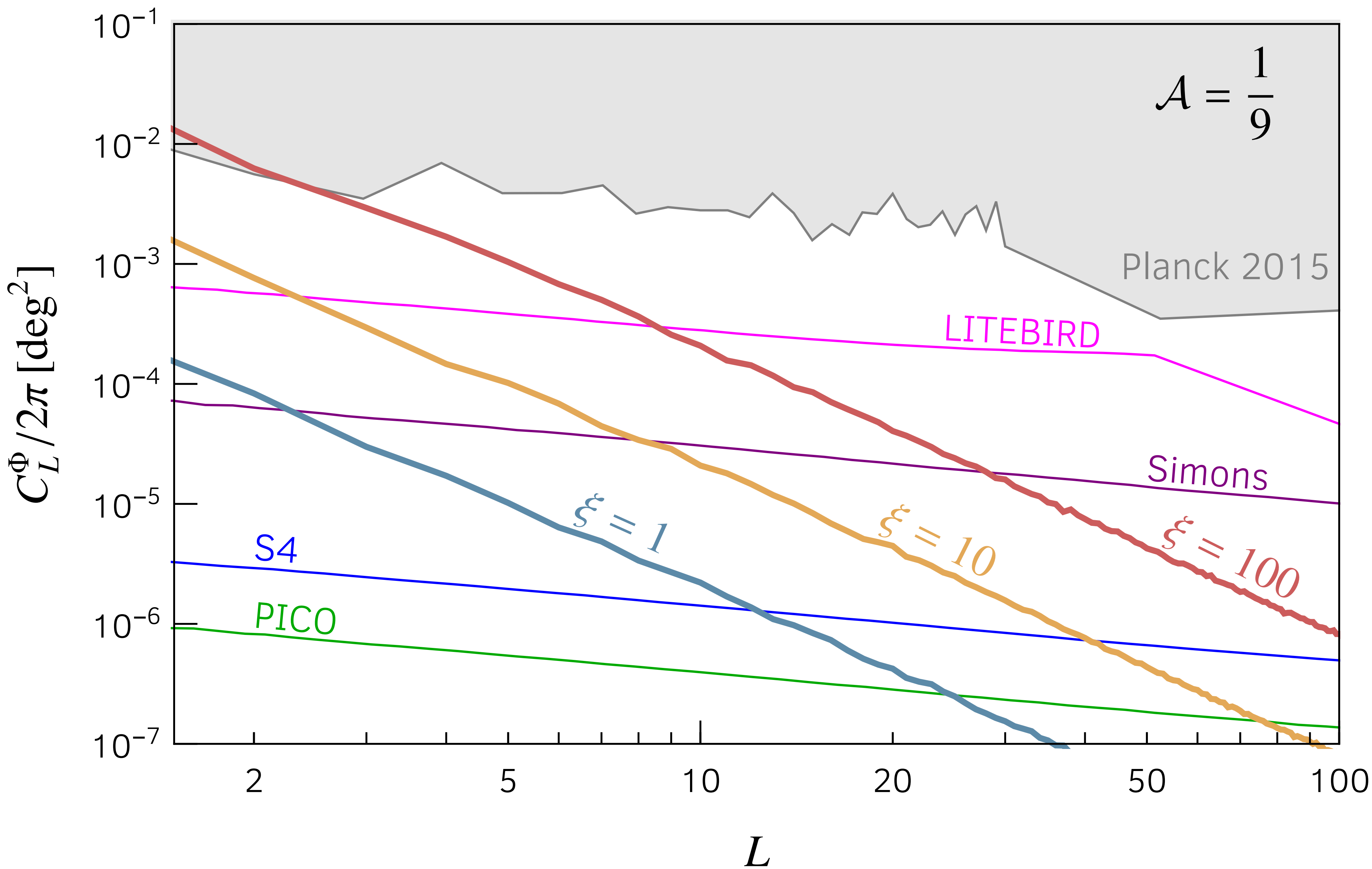
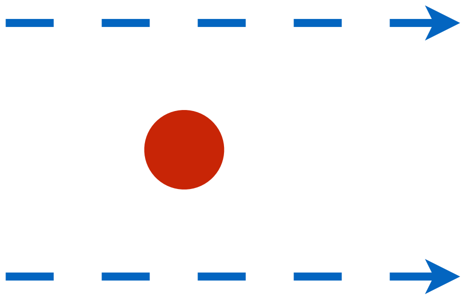
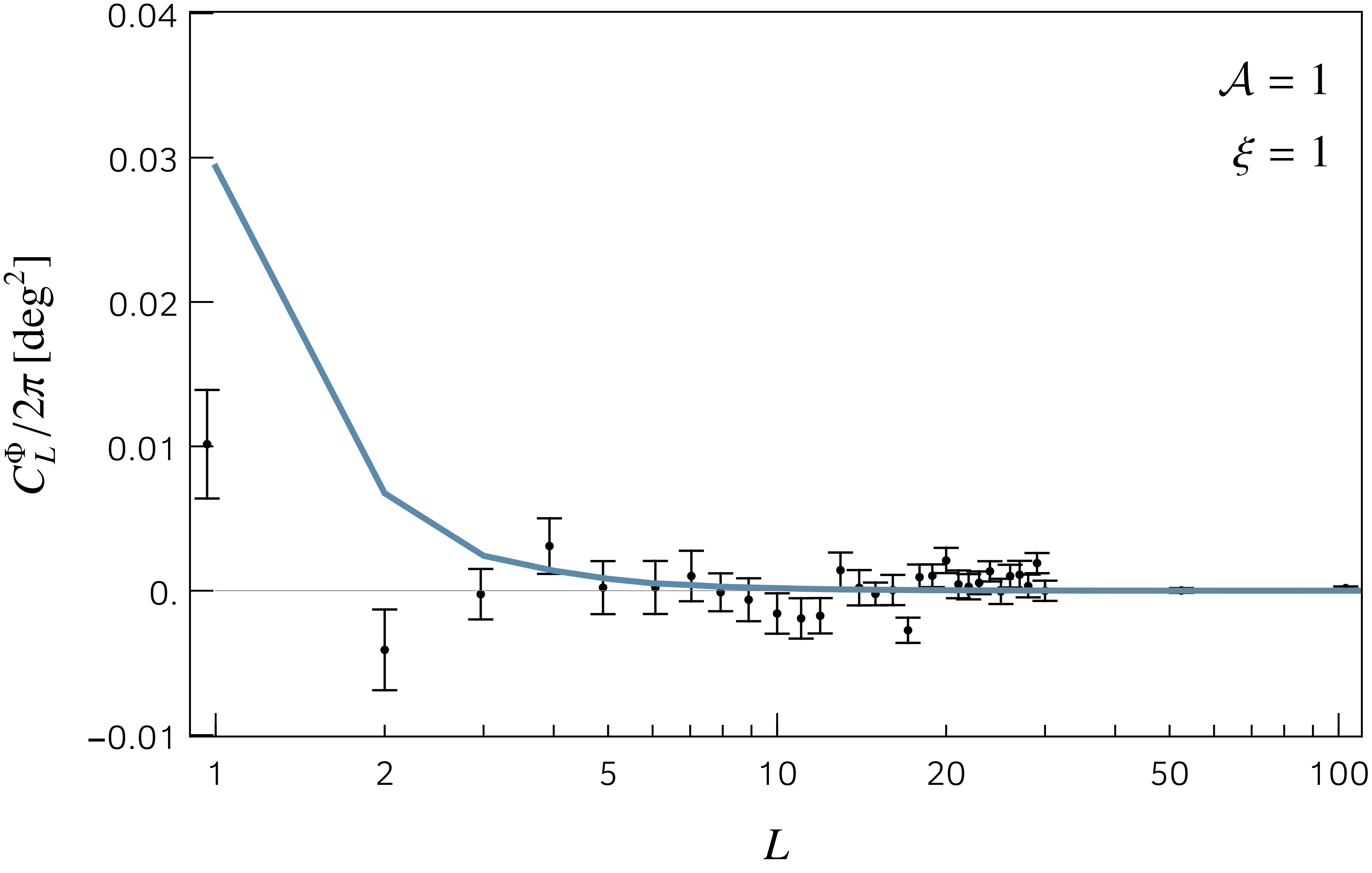
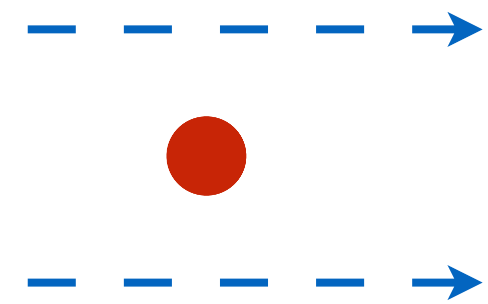


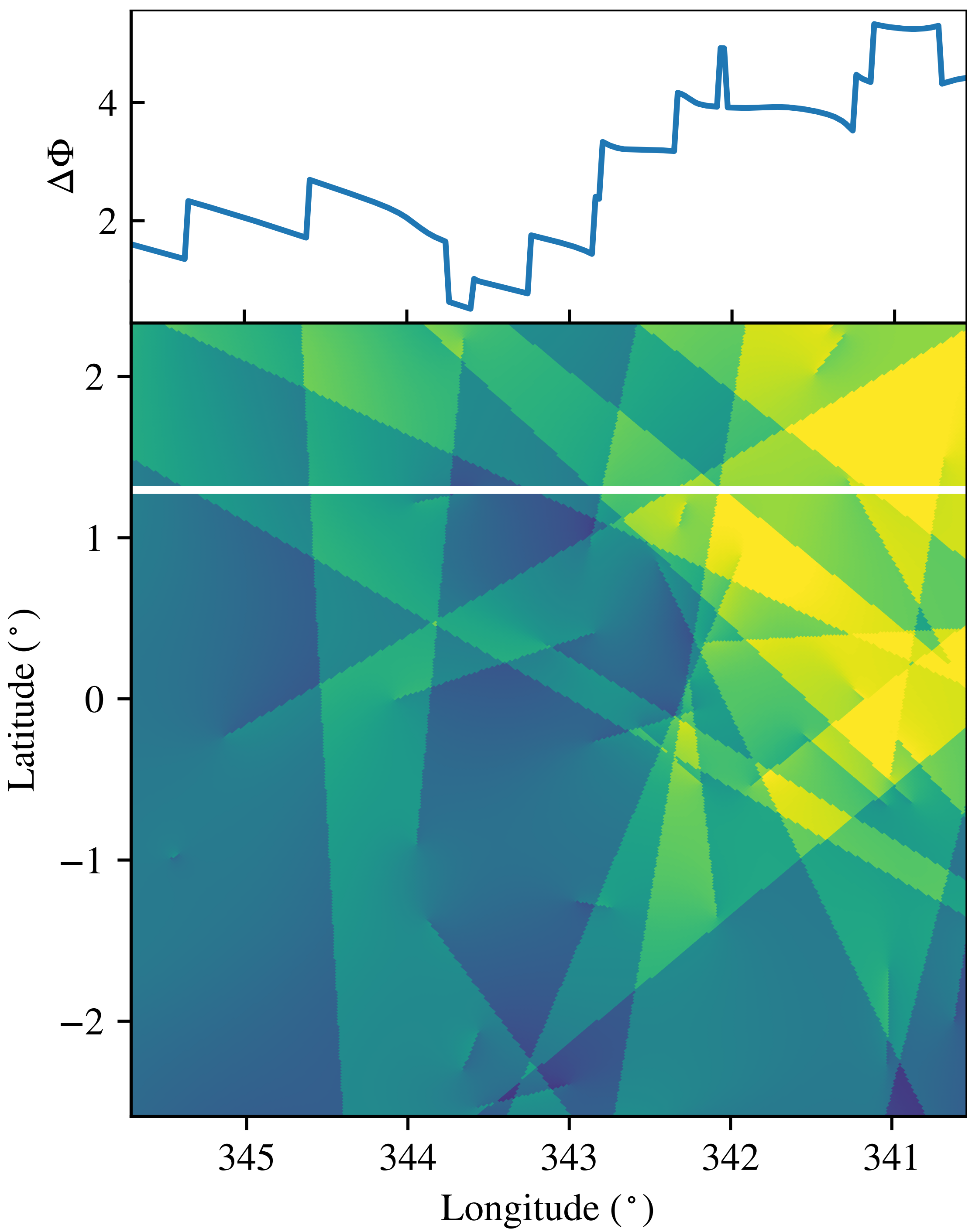
Power spectrum





Edge Detection

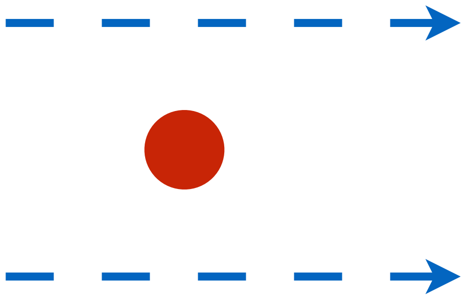


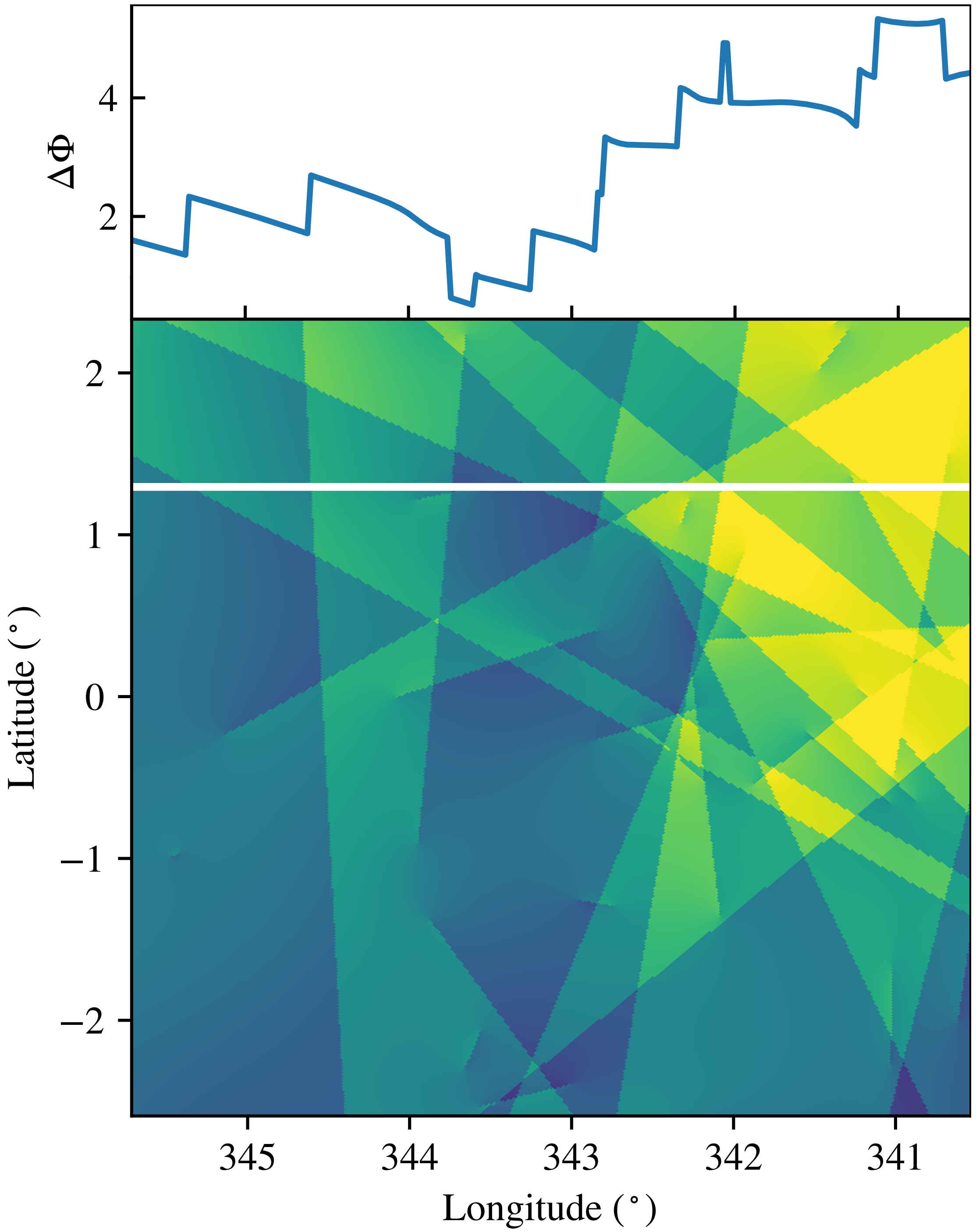


Coolest feature are the edges

- Position space search
- Important elements
  - Angular resolution $\xi \gg 1$
  - Accuracy $\mathcal{A} \ll 1$
- BICEP/KEK/SPT/Polarbear
  - Angular resolution ~ arcmin
  - Accuracy ~ percent

Edge Detection





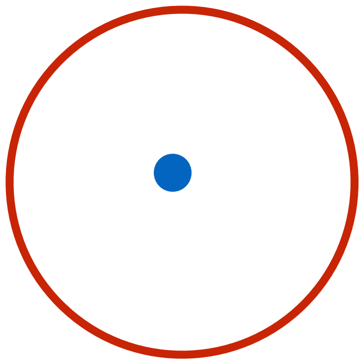
Coolest feature are the edges

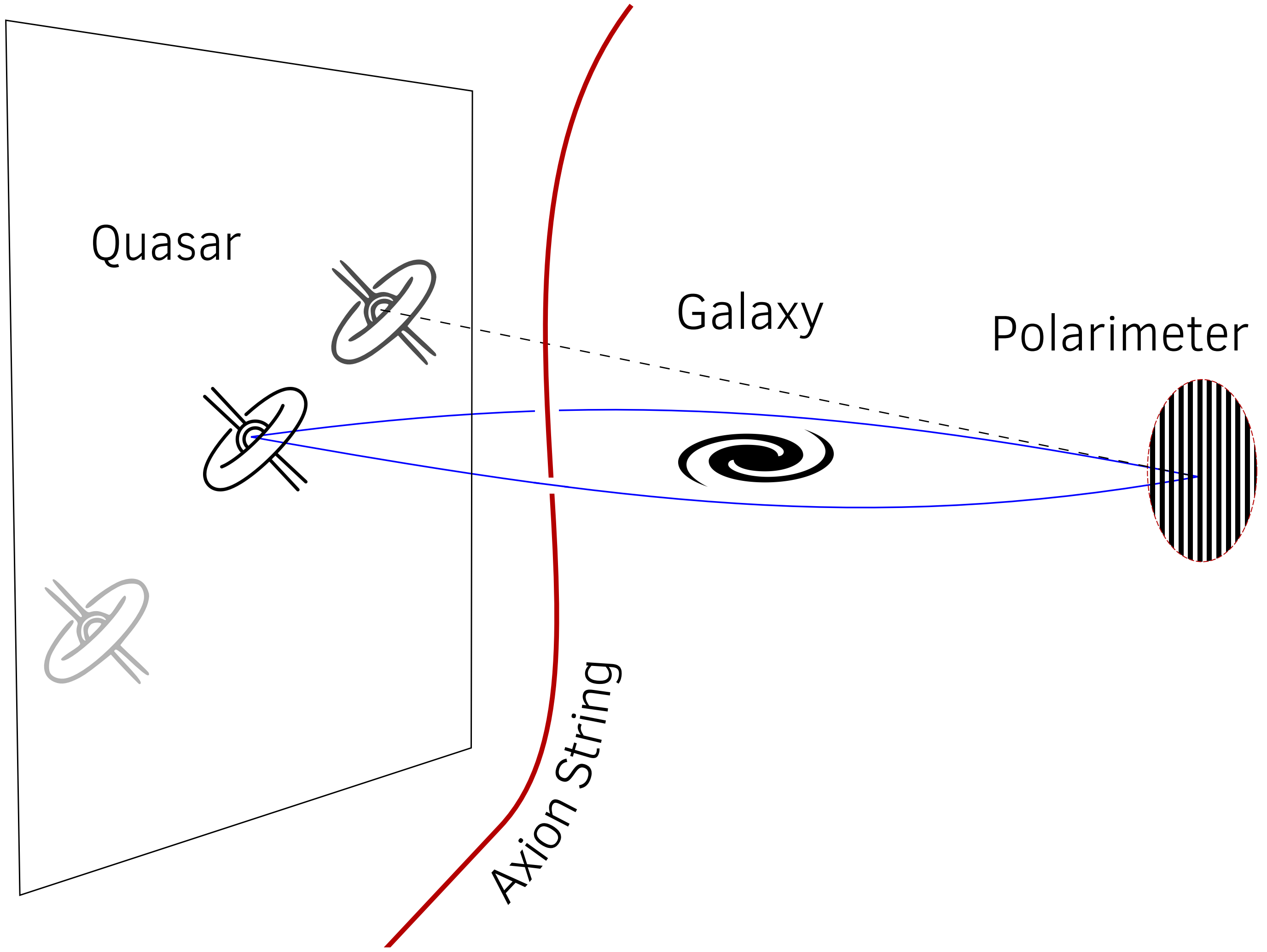
Likely edges are most useful when there are only a few strings

Few strings => production before/during inflation

Rare chance at testing pre-inflationary physics

Quasar

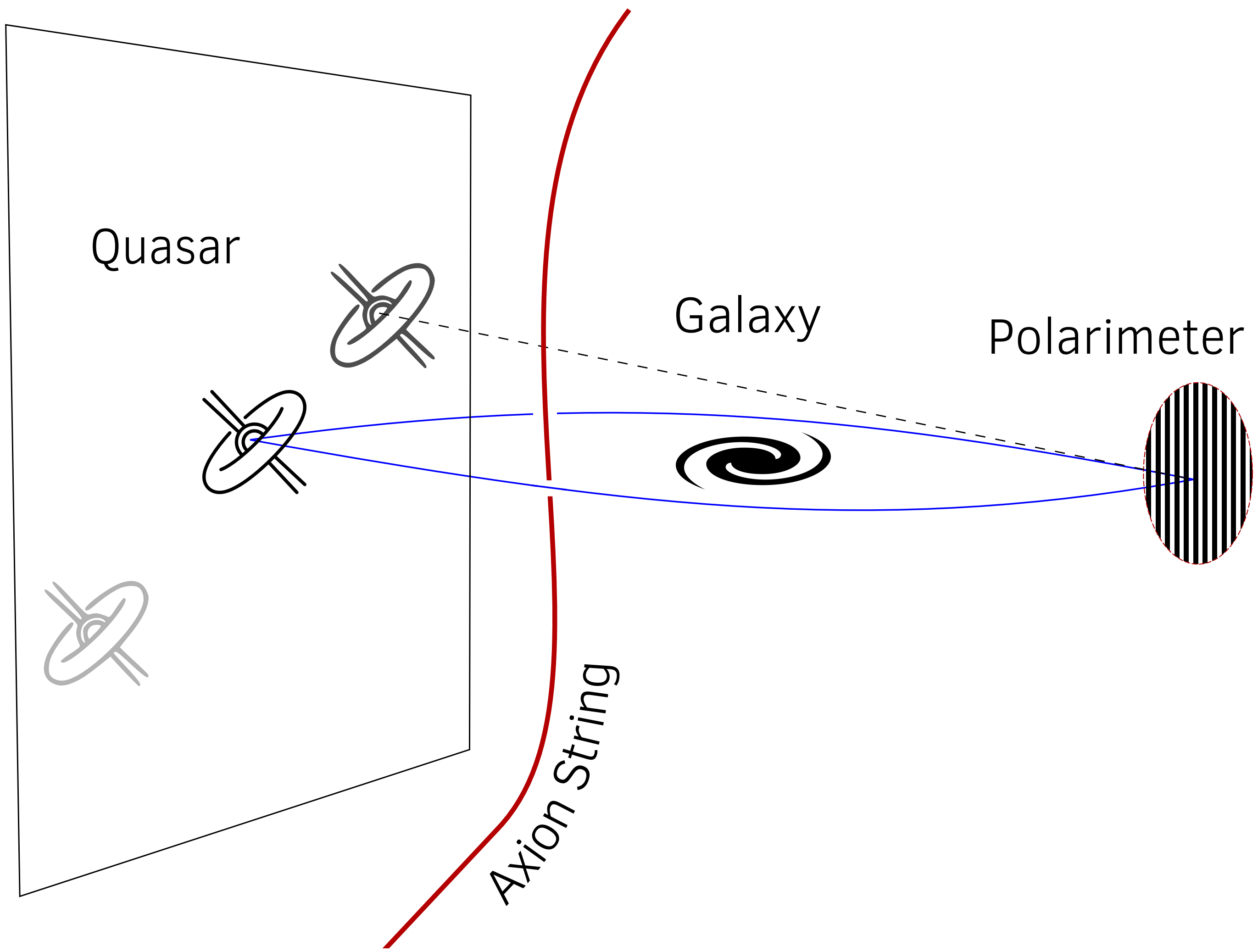




Quasar images have relative polarization rotations

$$\Delta\Phi = \mathcal{A}\alpha_{\rm em}$$

Quasar

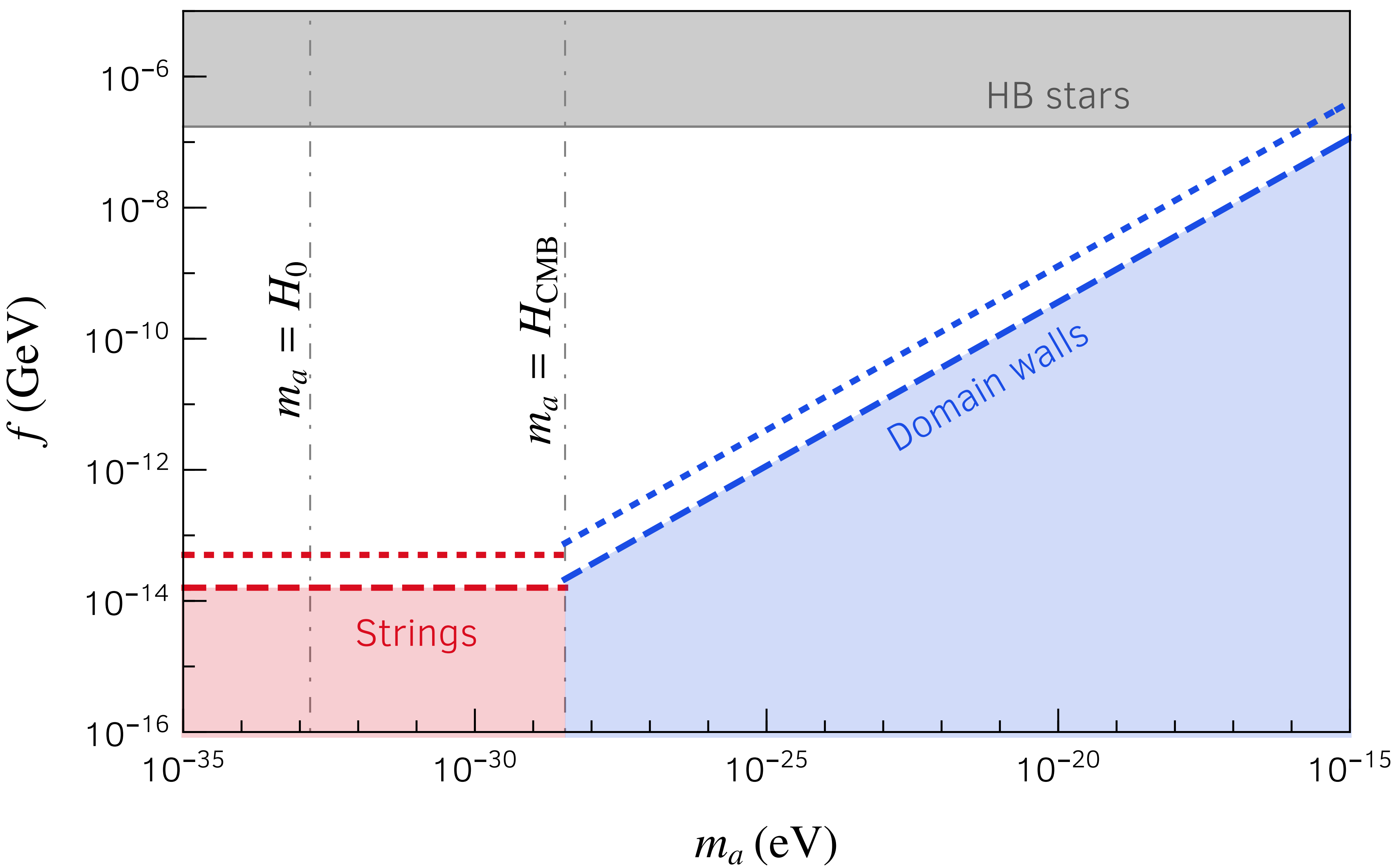


- 205 lensed quasars
- Angle between images can be as large as $\beta \sim 10''$
- Probability that a string is in between the two images

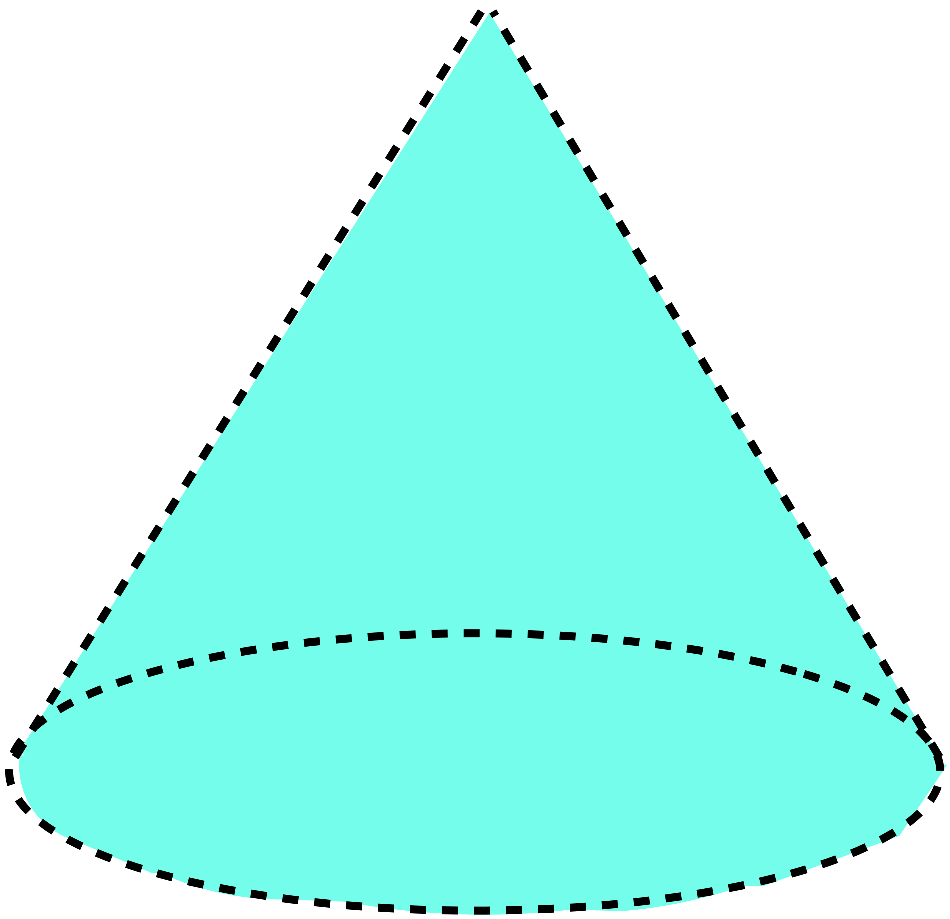
$$p \simeq \xi A_{\rm enc} H_0^2 \approx 10^{-3} \frac{\xi}{100} \frac{\beta}{10''}$$

Usual Constraints

Our results are completely independent of decay constant



Usual Constraints



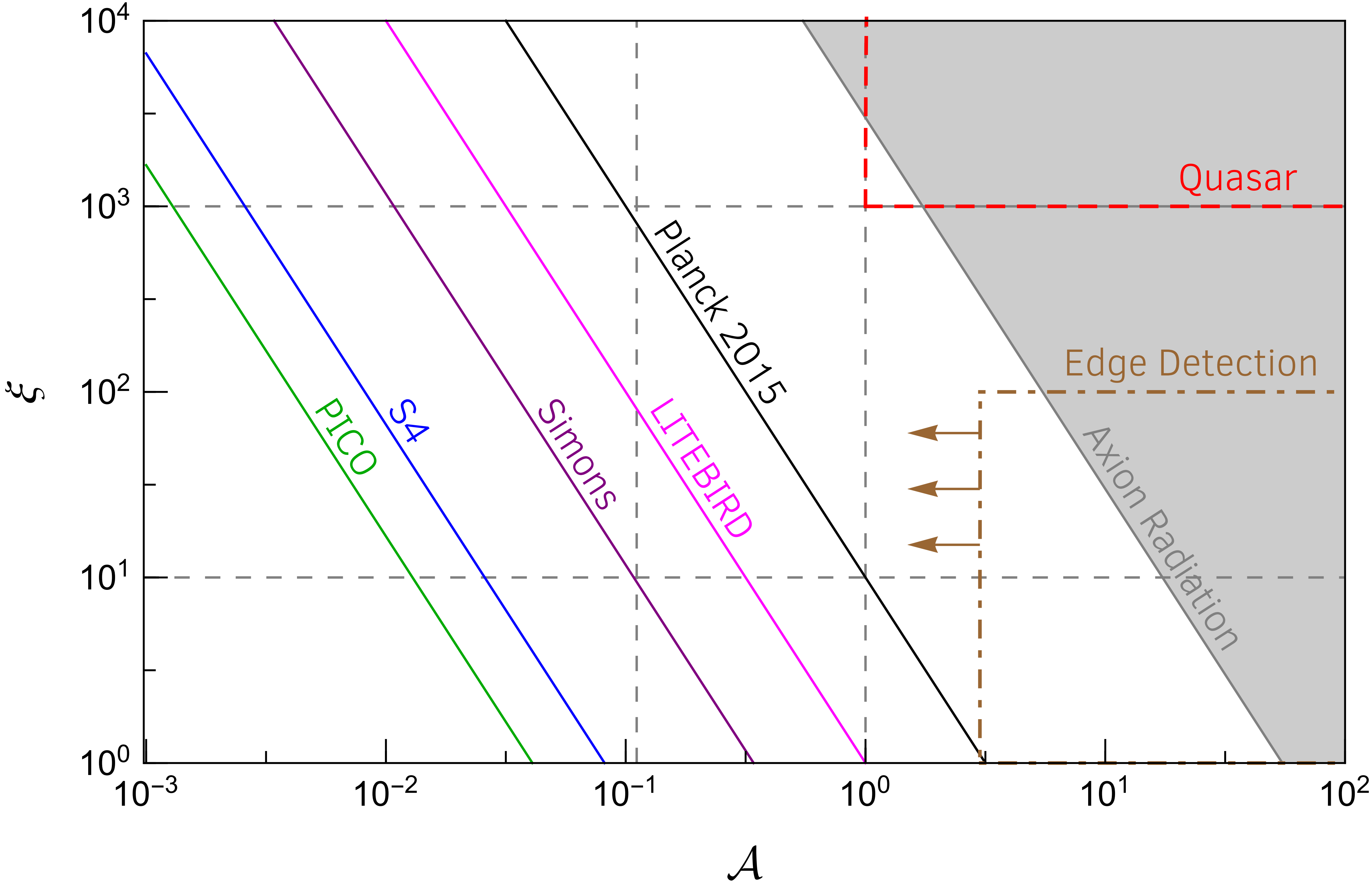
Deficit Angle

$$0 < \theta < 2\pi - 8\pi G\mu$$

$$G\mu \lesssim 10^{-7}$$

CMB Temperature anisotropy

Constraint(ish)



Conclusion

Strings

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

Match made in heaven

Topological way of causing polarization rotation

Super distinct features in the CMB

Power spectrum at the edge of sensitivity

Edges in the CMB

Quasars