Berry phase from Axiverse string

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1912.02823
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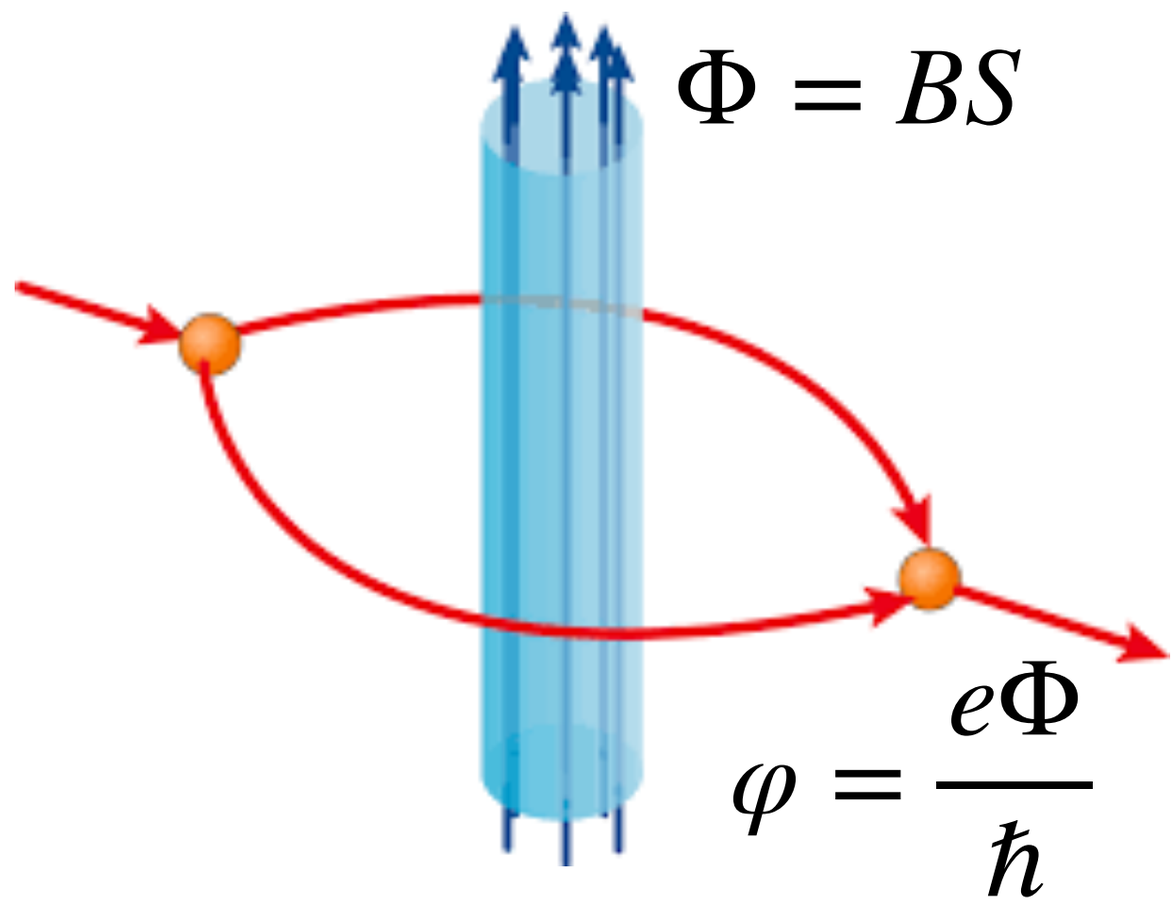
Topological effects



Aharonov-Bohm effect

Topological new physics

Topological defects

Topological interaction

Topological defects

Monopoles

Strings

Domain Walls

Magnetic monopoles

- Dirac Quantization: $eg = 2\pi n$

  Dirac 1931

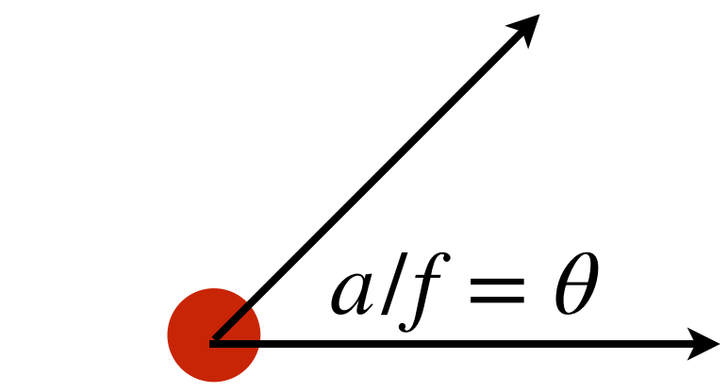
- A single monopole will teach us valuable information about charge quantization

$$eg = 2\pi \rightarrow \text{electron has unit charge}$$

- The monopole problem (Inflation)

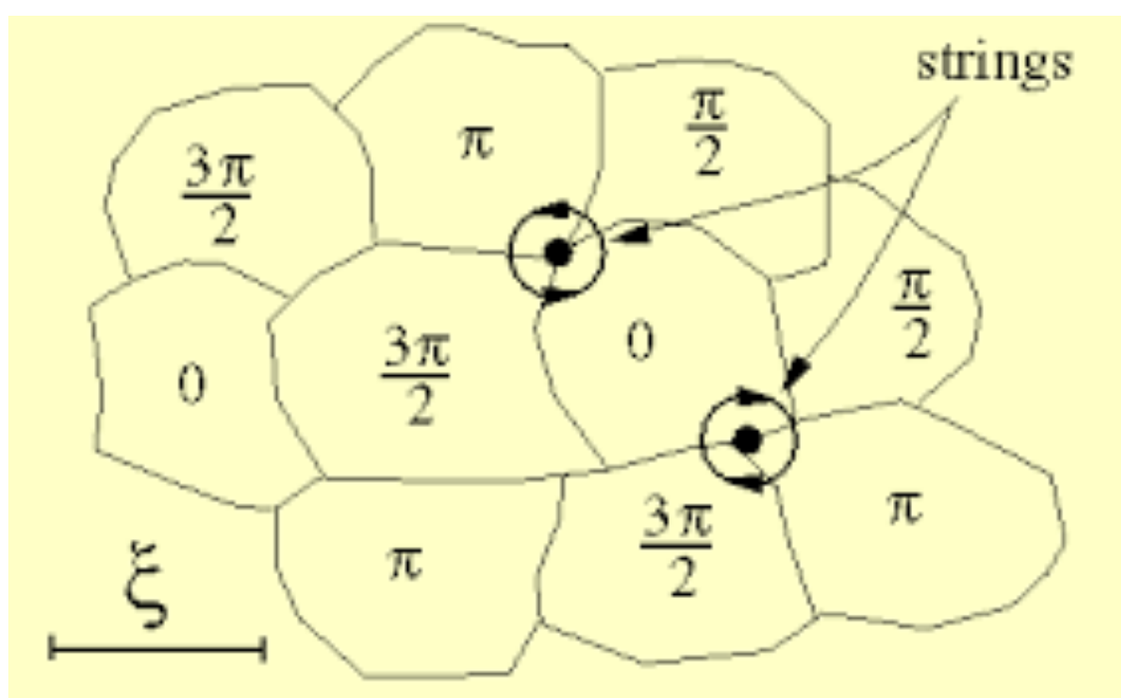
Topological defect

- Cosmic Axion string (defect)



$$a \to a + 2\pi f$$

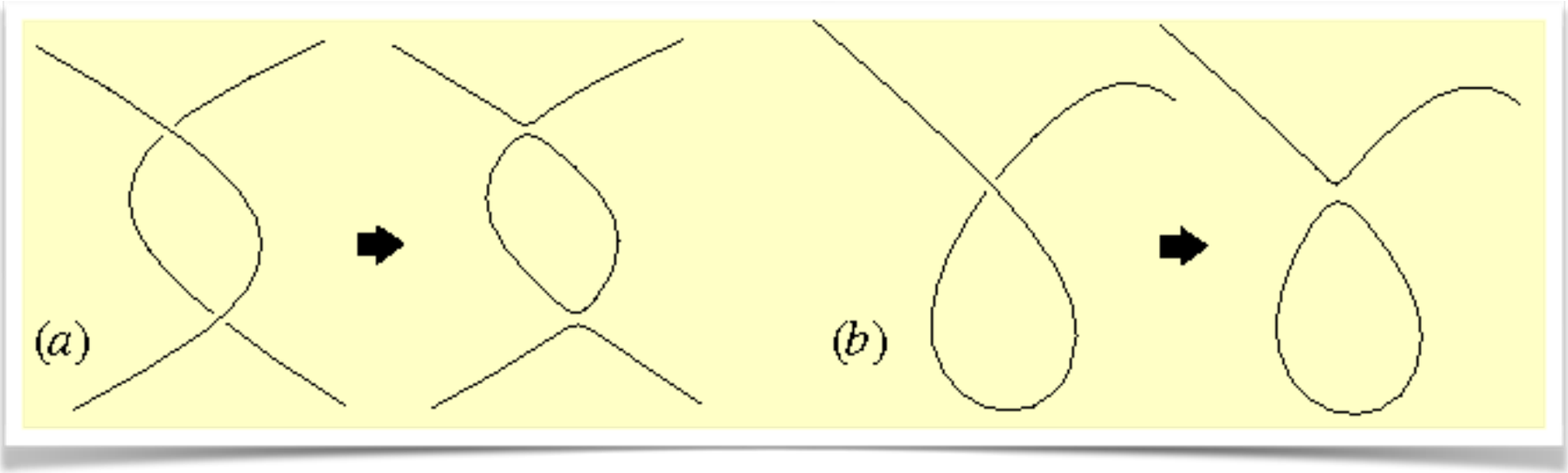
- Kibble Mechanism



Kibble 1976

Topological defect

- Strings interact by cutting each other open



- String network will reach a scaling solution

O(1) string/Hubble volume

Kibble 1976

- Logarithmic scaling violation

$$L \sim \xi / H \quad \xi \sim (1, 1000)$$

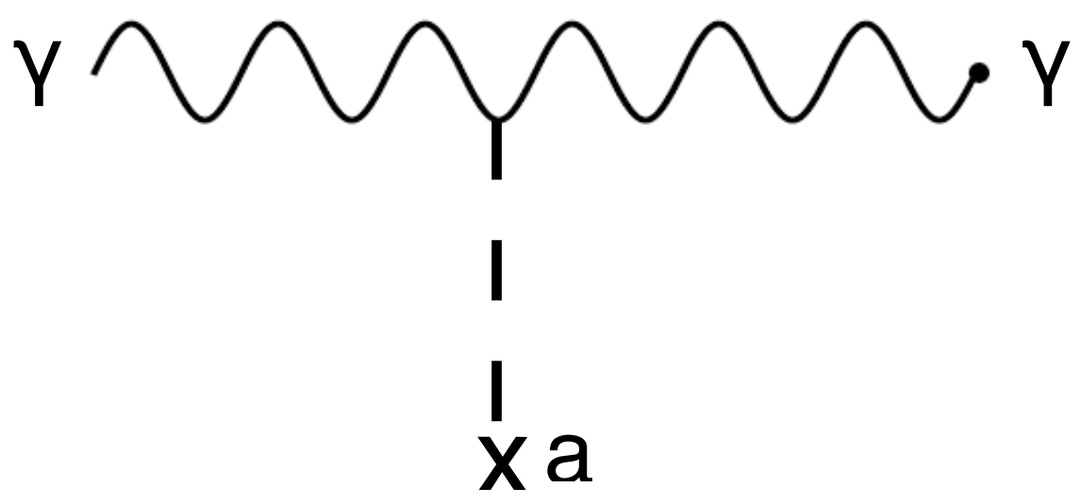
Gorghetto, Hardy, Villadoro, 1806.04677

Topological interactions

- Axion photon coupling (topological interaction)

$$g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

- Light propagation in Axion background?



Topological interactions

- Axion photon coupling (topological interaction)

$$g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

- Circularly polarized photon in axion background (phase accumulation)

$$A_\sigma(\eta, z) = A_\sigma(0,0) \times \exp\left[-i\omega\eta + ikz + i\sigma\Delta\Phi(\eta, z)\right]$$

$$\Delta\Phi(\eta, z) = g_{a\gamma\gamma}\left(a(\eta, z) - a(0,0)\right)$$

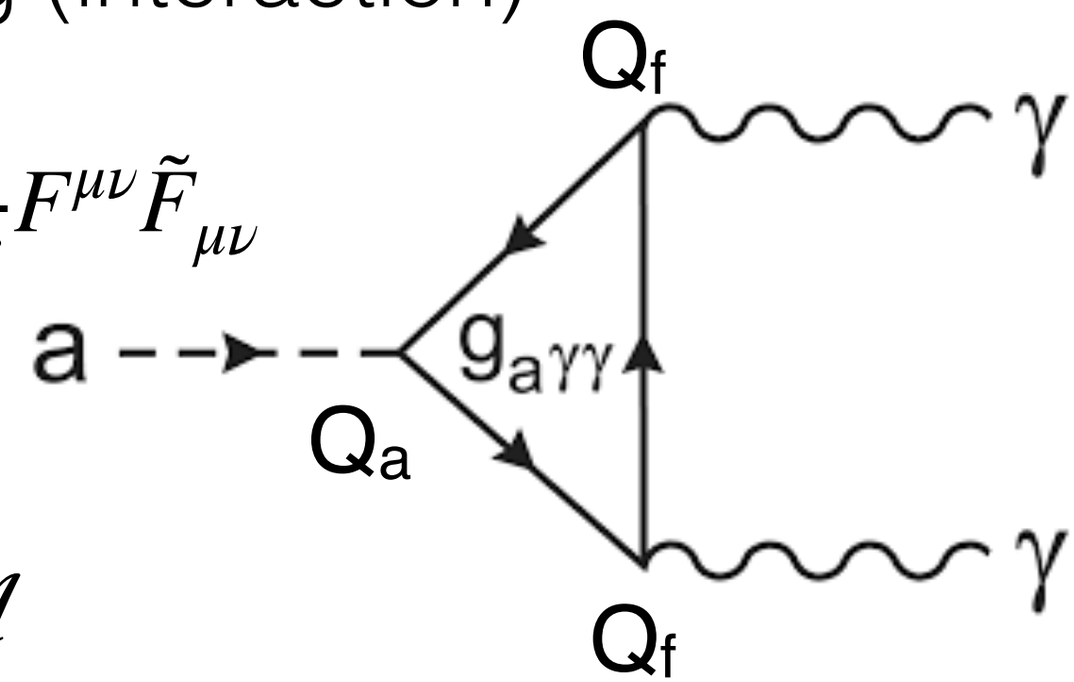
Fedderke, Graham, Rajendran, 1903.02666

- Linear polarization rotates

Topological interactions

- Axion photon coupling (interaction)

$$g_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu} \to \mathscr{A}\frac{\alpha_{\rm em}}{4\pi}\frac{a}{f}F^{\mu\nu}\tilde{F}_{\mu\nu}$$



- Anomaly coefficient $\mathscr{A}$

$$\mathscr{A} = \sum Q_f^2 Q_a =$$

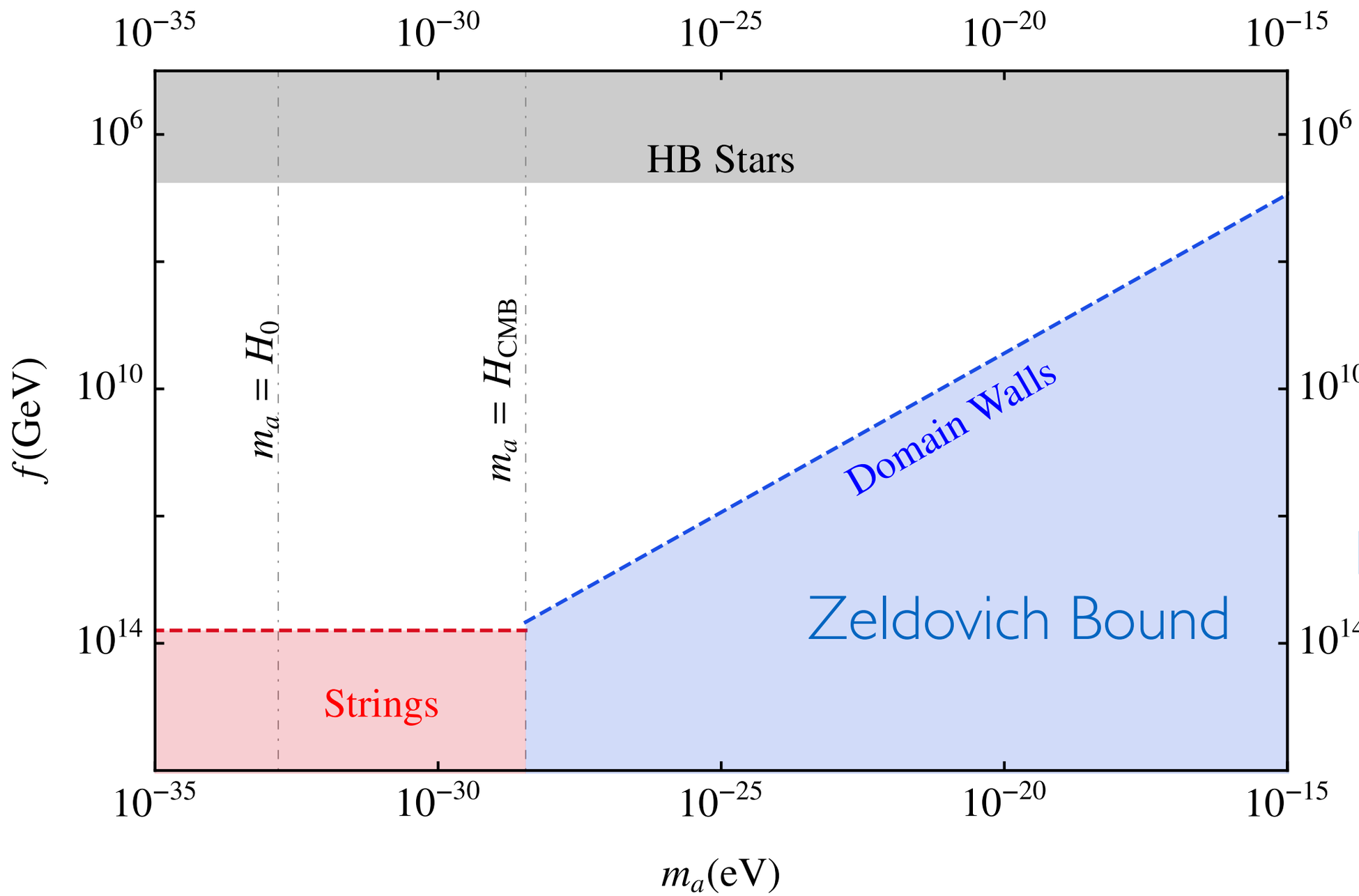
Minimal GUT: 4/3
Electron like: Int
Quark like: Int/9

- If axion is DM, CMB suggests: $\frac{\mathscr{A} a}{f} \lesssim 60$

Fedderke, Graham, Rajendran, 1903.02666

Parameter space

Our Berry Phase is independent of either m or f, no need for axion DM



hep-th/0605206

0905.4720

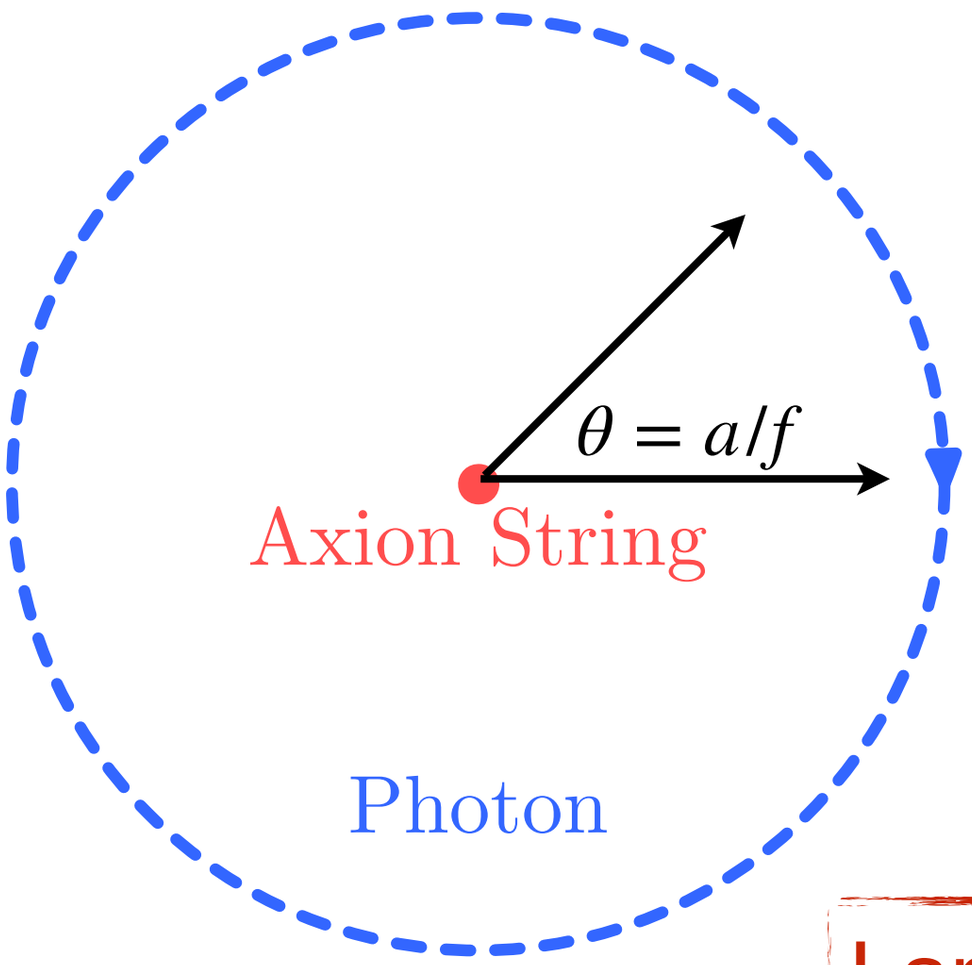
1808.01282

How to look for topological effect of topological defect?

Axion Berry Phase from A single string

A single string (1)

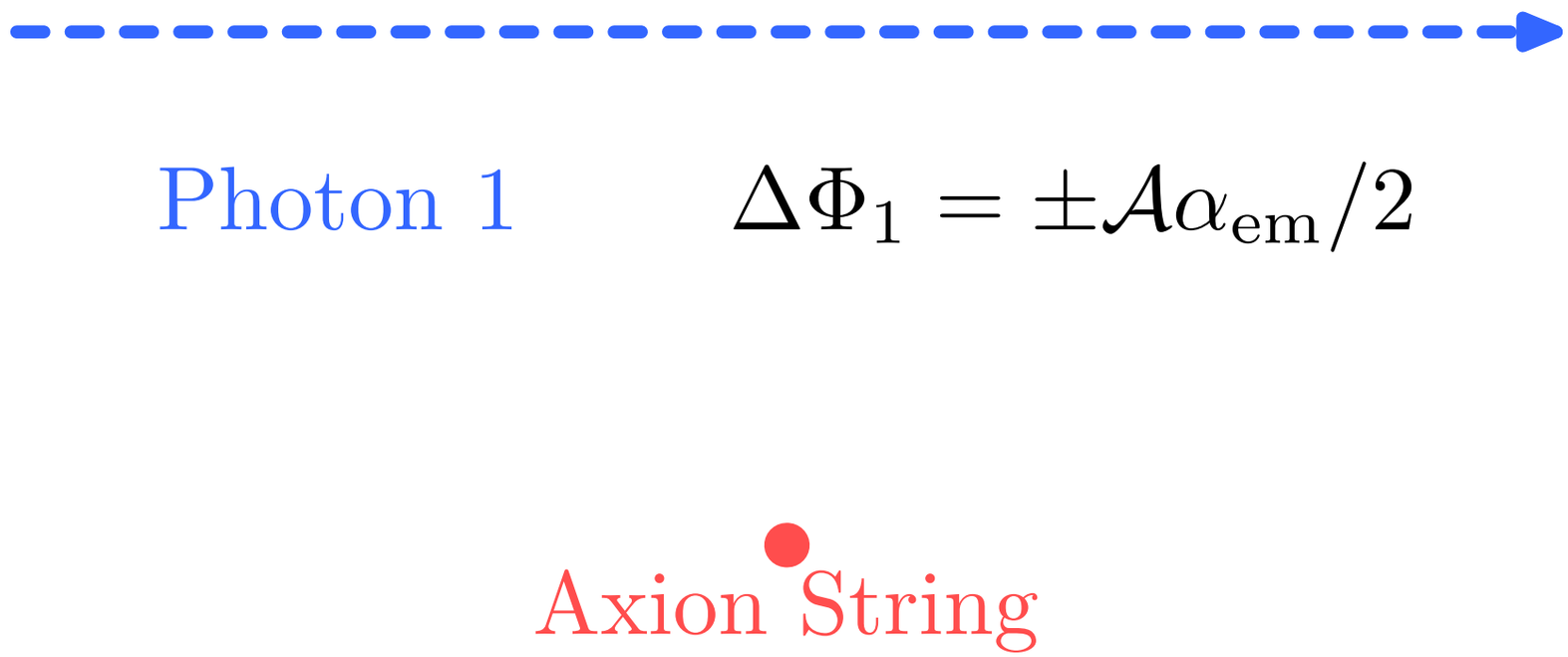
Berry Phase: $\Delta\Phi(\eta, z) = \mathscr{A}\alpha_{\rm em}\dfrac{a(\eta, z) - a(0,0)}{2\pi f}$



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

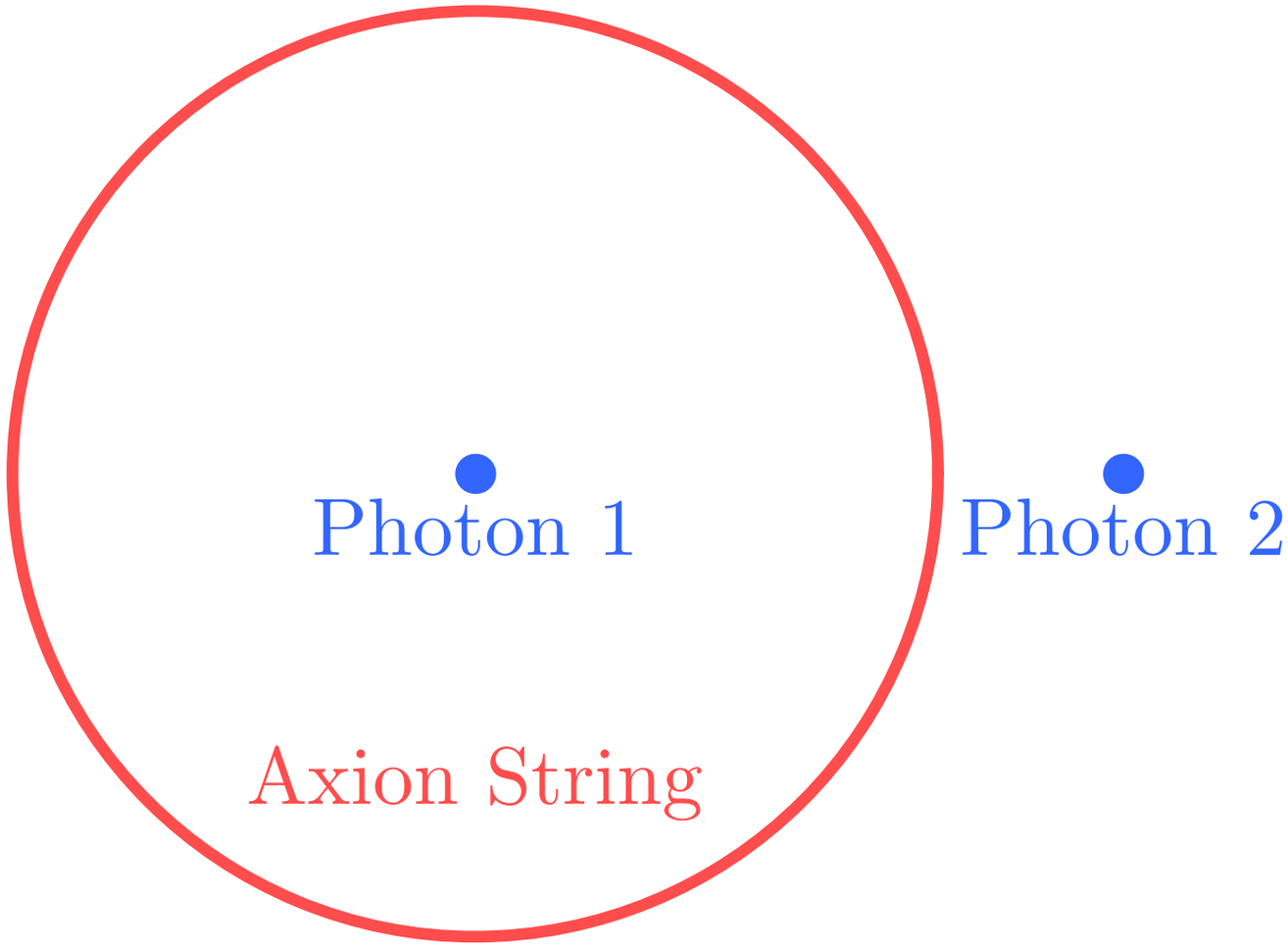
Large signal from large $\Delta a/f$!

A single string (2)



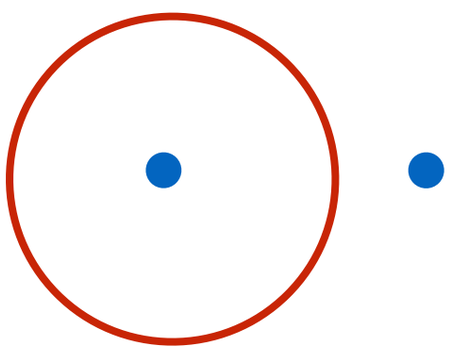
CMB (numerical method)

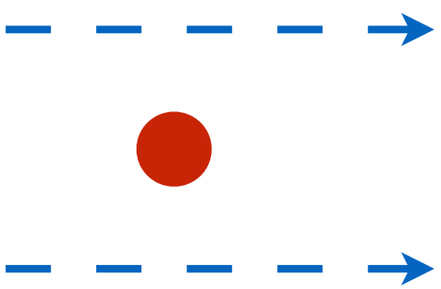
Axion string loop (3)



$$\Delta\Phi_1 = \pm\mathcal{A}\alpha_{\rm em} \qquad \Delta\Phi_2 = 0$$

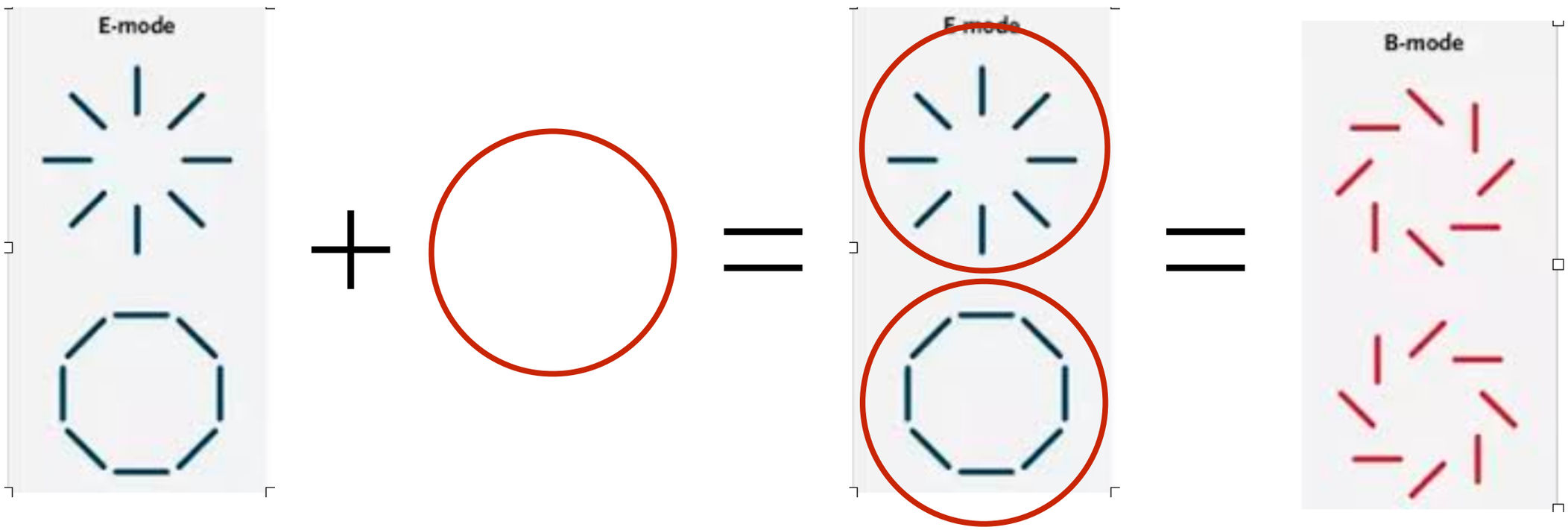
CMB (analytical method)





Polarization rotation correlations & CMB observables

CMB observable

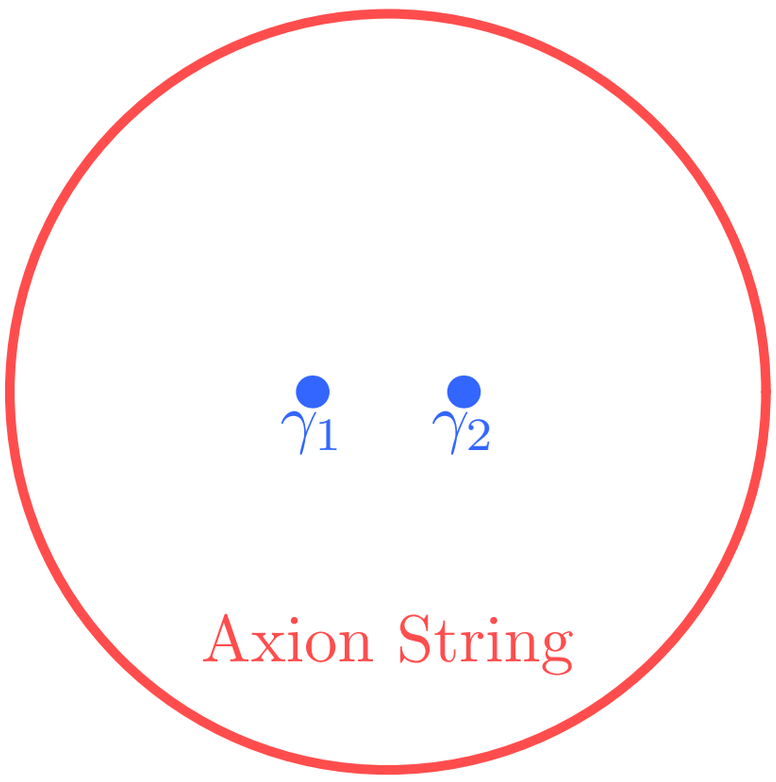


$$E + \Phi = B \quad \leftrightarrow \quad E + B \rightarrow \Phi \quad \left(\langle EBEB \rangle \rightarrow \langle \Phi\Phi \rangle\right)$$

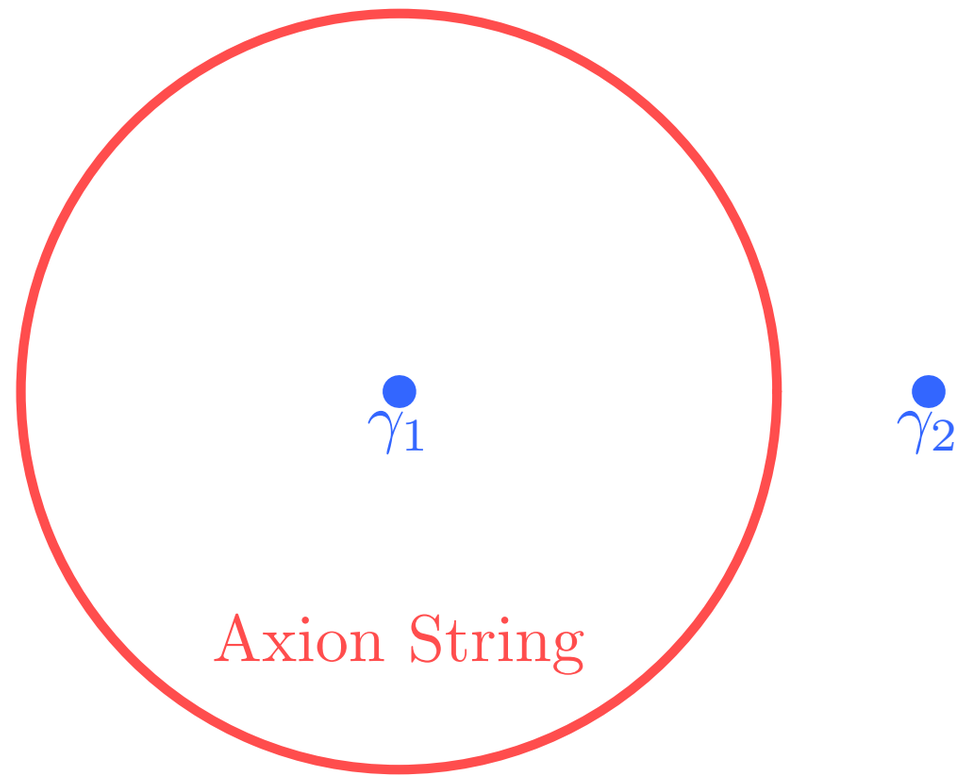
Topological => Frequency independent

$\Phi\Phi$ correlation (Analytical)

- The correlations are generated when



Correlation

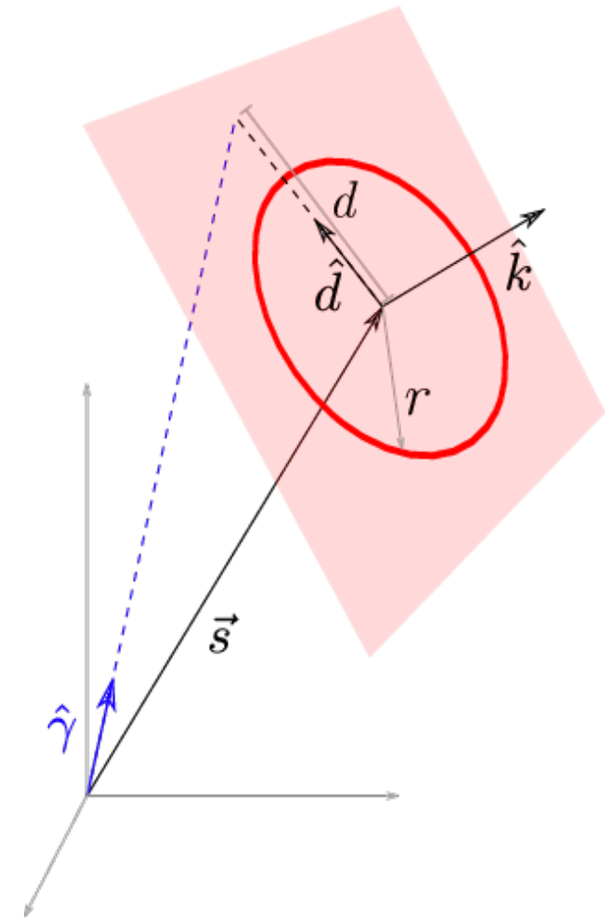


No correlation

- Same for higher point correlation functions

A toy analytical model

- We treat strings as loops with a radius of r=1/H(η)
- $\langle \Phi \rangle = 0$
- Two point functions:

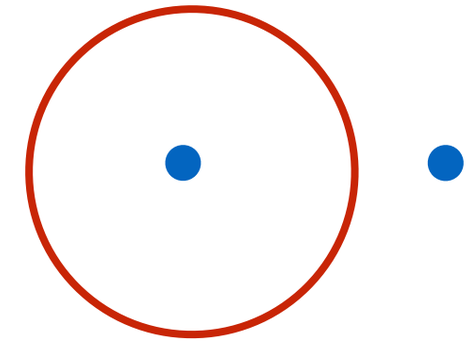


$$\langle \Phi(\hat{\gamma})\Phi(\hat{\gamma}') \rangle = (\mathcal{A}\alpha_{\rm em})^2 \int d\eta \int d^2\hat{s} \int d^2\hat{k}\,(\eta_0 - \eta)^2 f(\eta) \times \Theta\left(\frac{\eta}{2} - d(\hat{s},\hat{\gamma},\hat{k},\eta)\right)\Theta\left(\frac{\eta}{2} - d(\hat{s},\hat{\gamma}',\hat{k},\eta)\right)$$

Counting loops

Photon goes through the loop

Toy analytical model

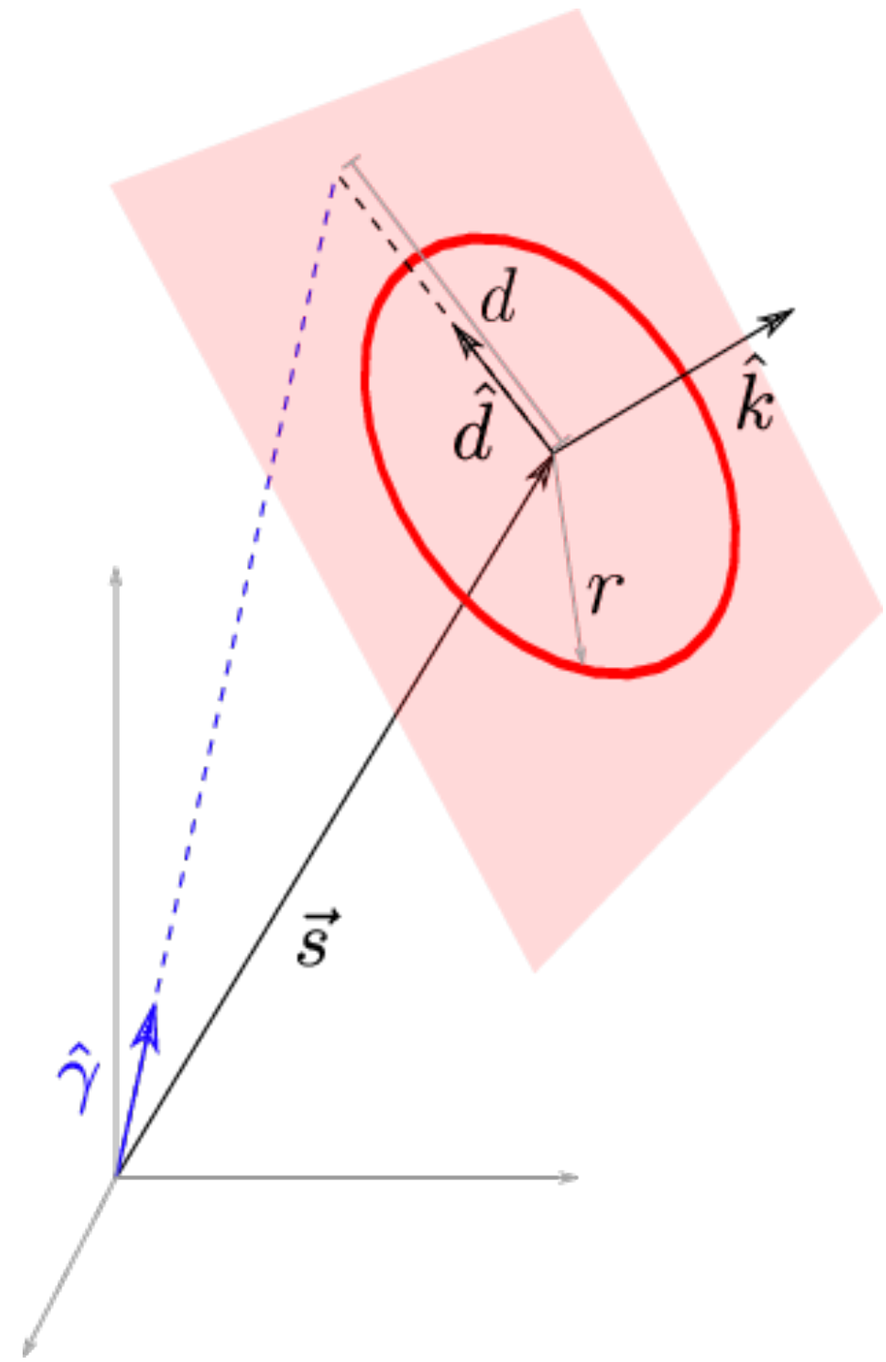


- The amplitude of the signal:

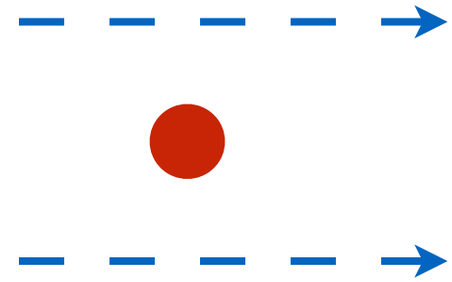
$$\langle \Phi(\hat{\gamma})\Phi(\hat{\gamma})\rangle \approx \xi \mathscr{A}^2 \alpha_{\rm em}^2 \log\left(\frac{\eta_0}{\eta_{CMB}}\right)$$

$$\sqrt{\Phi\Phi} \sim \mathscr{A}\alpha_{\rm em}\sqrt{N_{\rm string}}$$

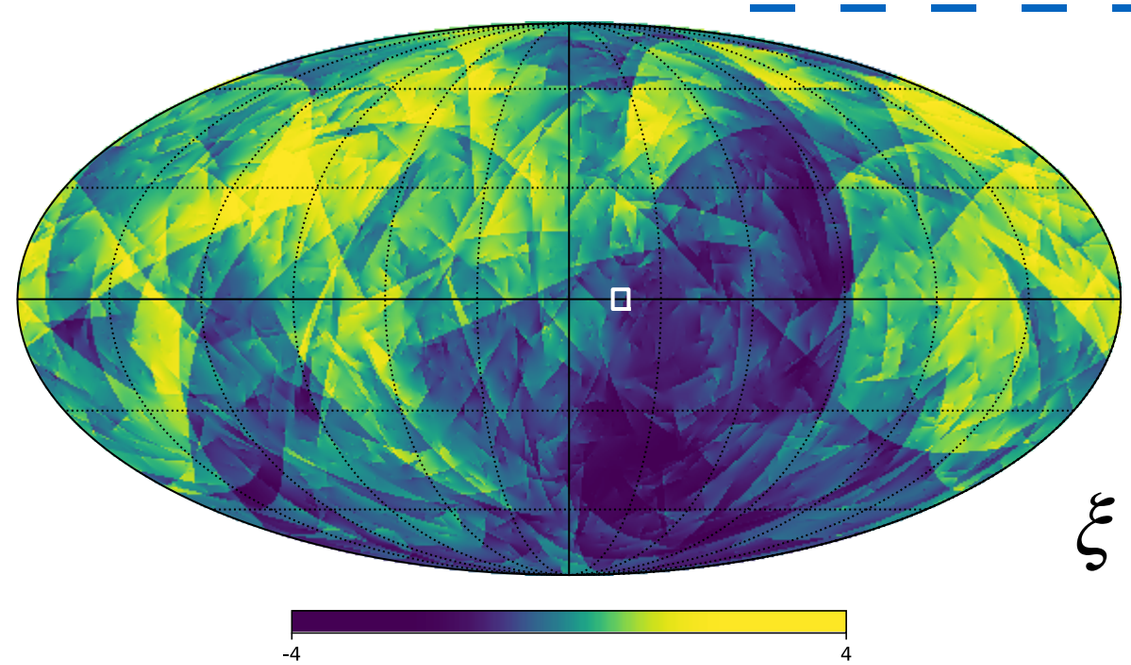
Large signal from random walk!



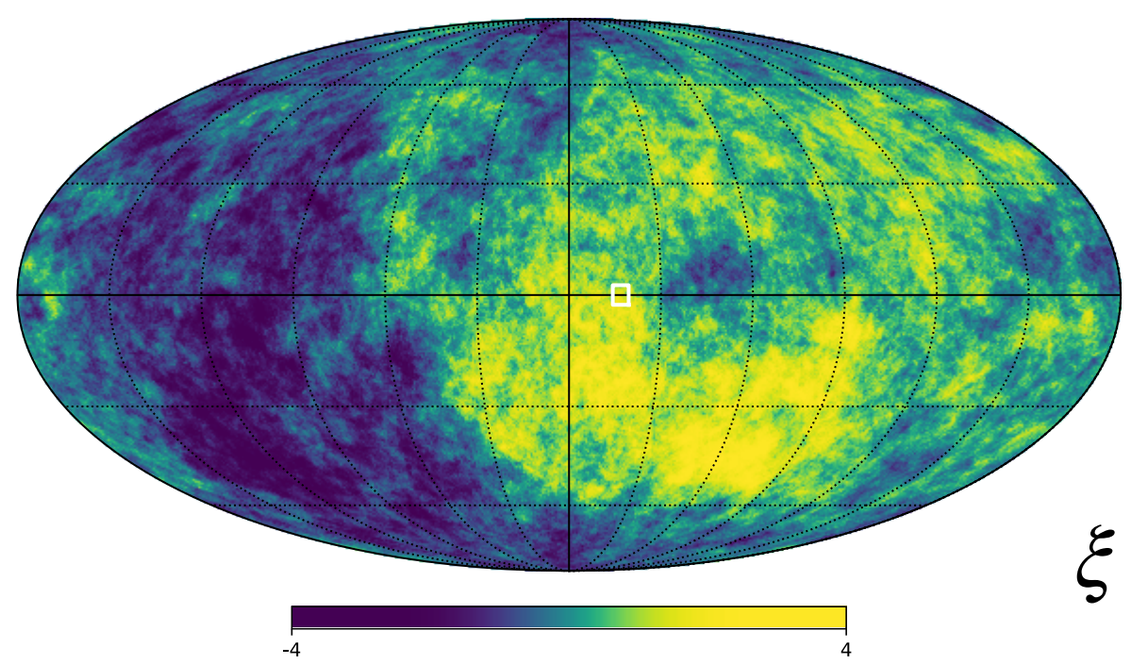
A toy simulation



- We treat strings as infinite lines in the Hubble patch
- We make strings randomly disappear as universe expand
- Photons accumulate phases as it pass the string networks



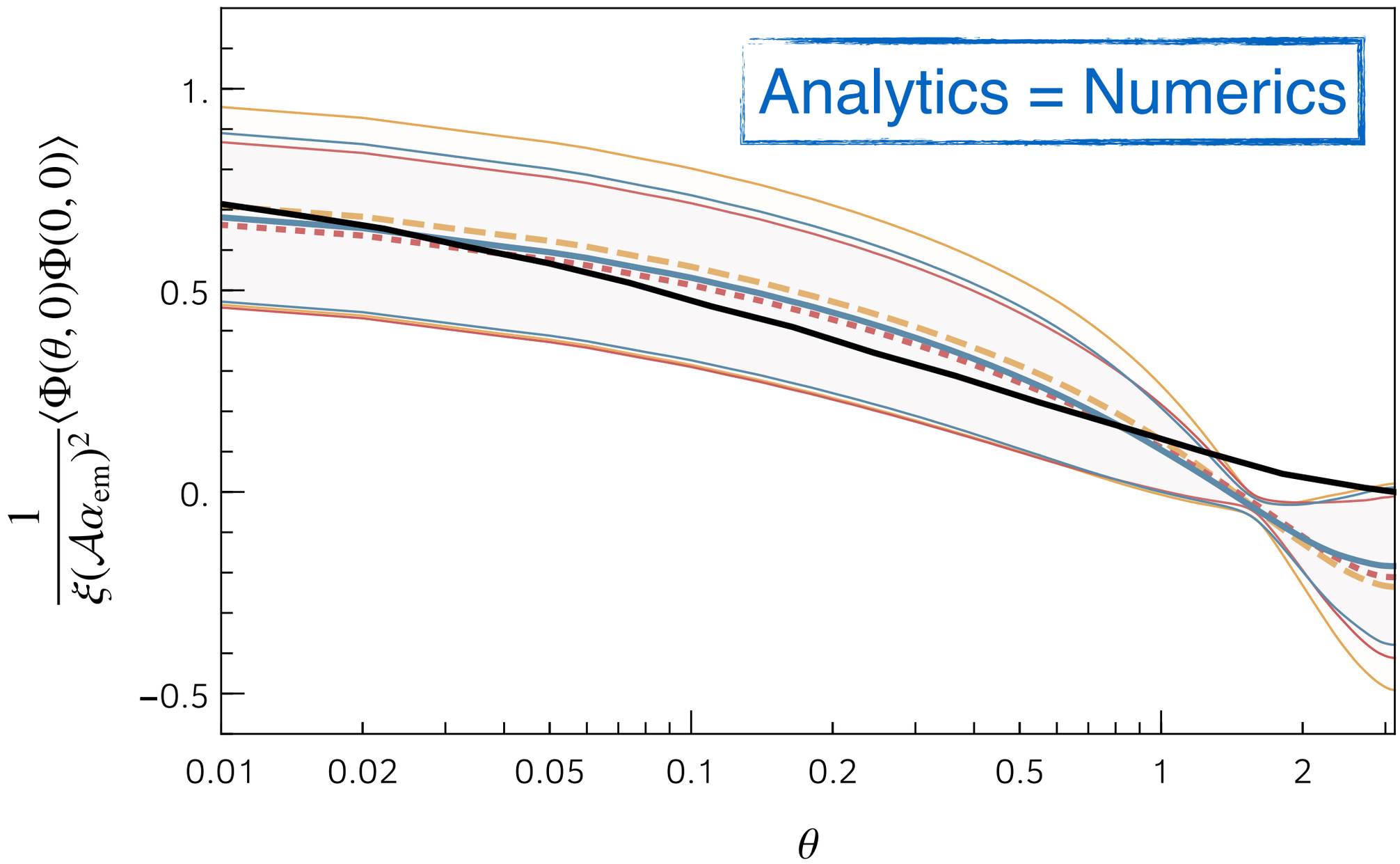
$\xi = 1$



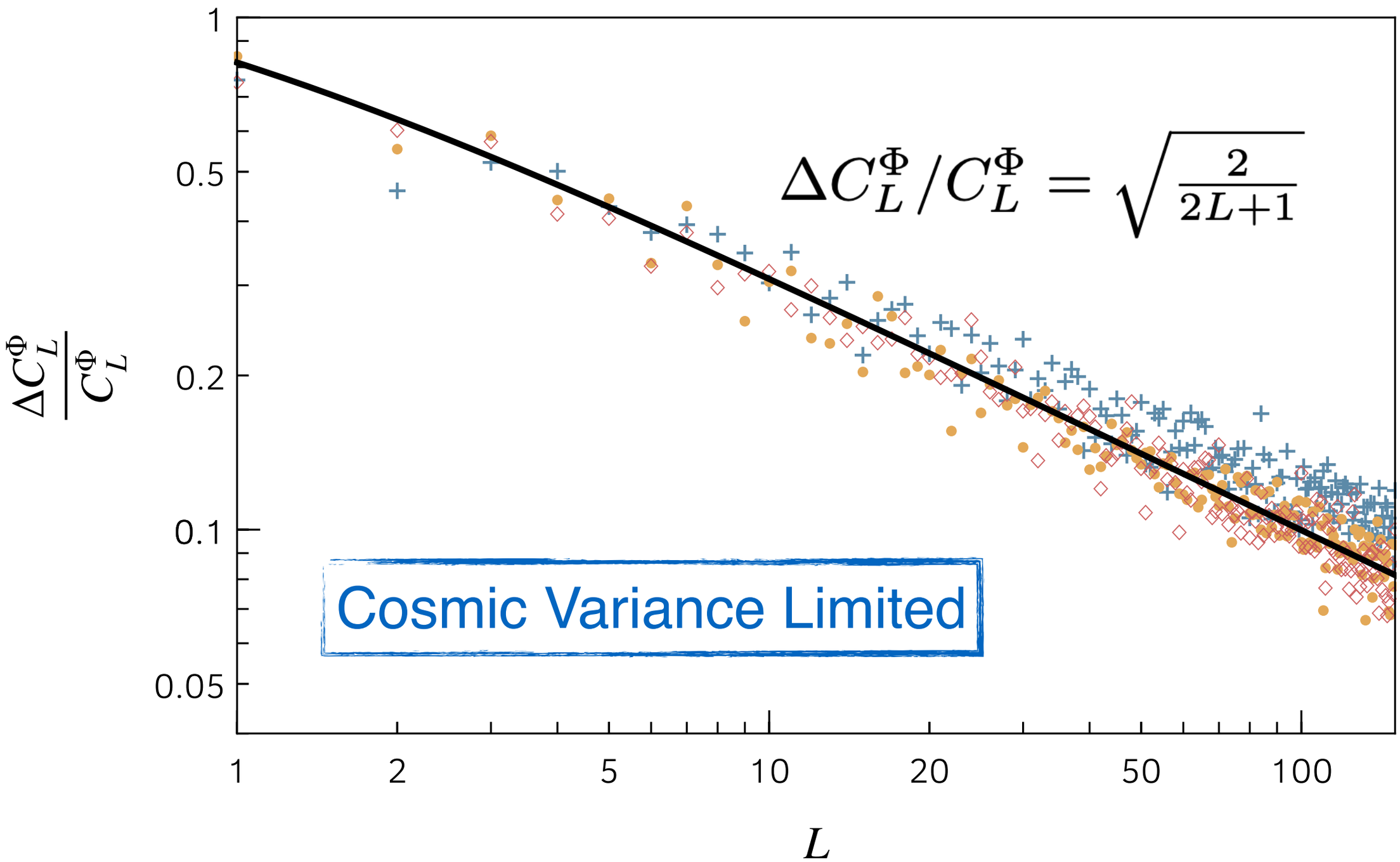
$\xi = 100$

Normalized to $(\xi \mathscr{A}^2)^{1/2}$

Power Spectrum

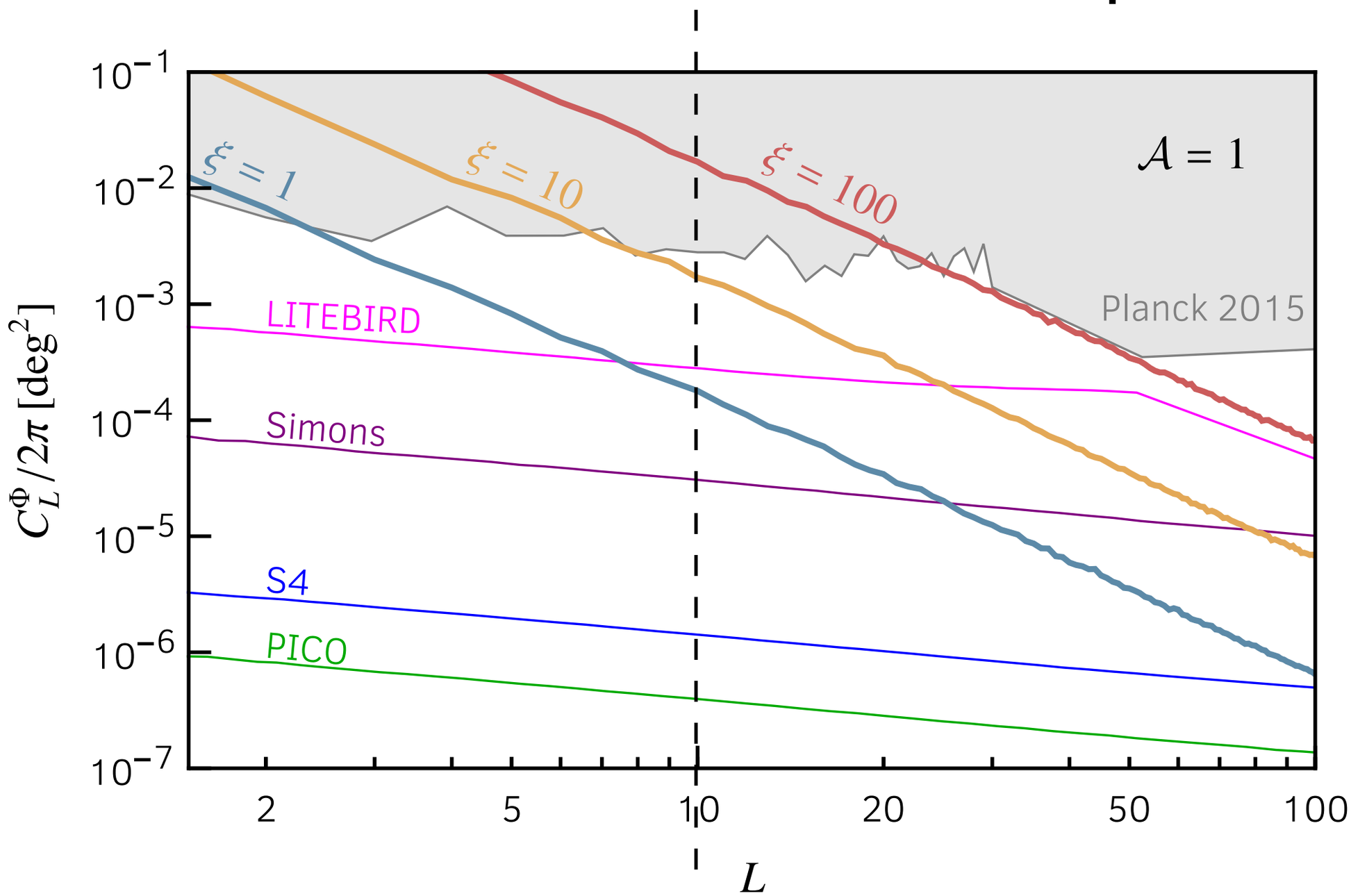


Cosmic Variance



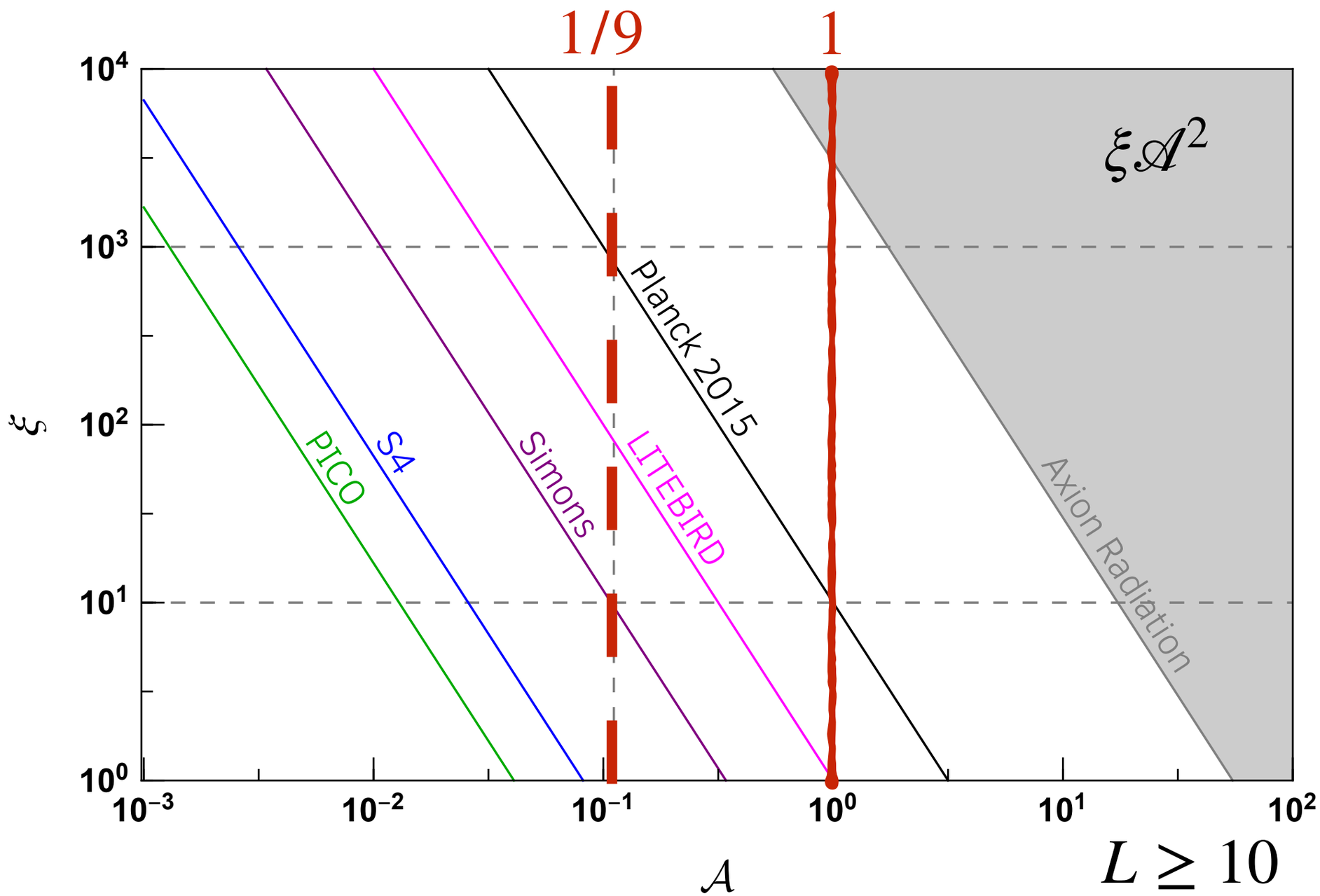
CMB spectrum
Constraint and Prospect

Constraint and Prospect



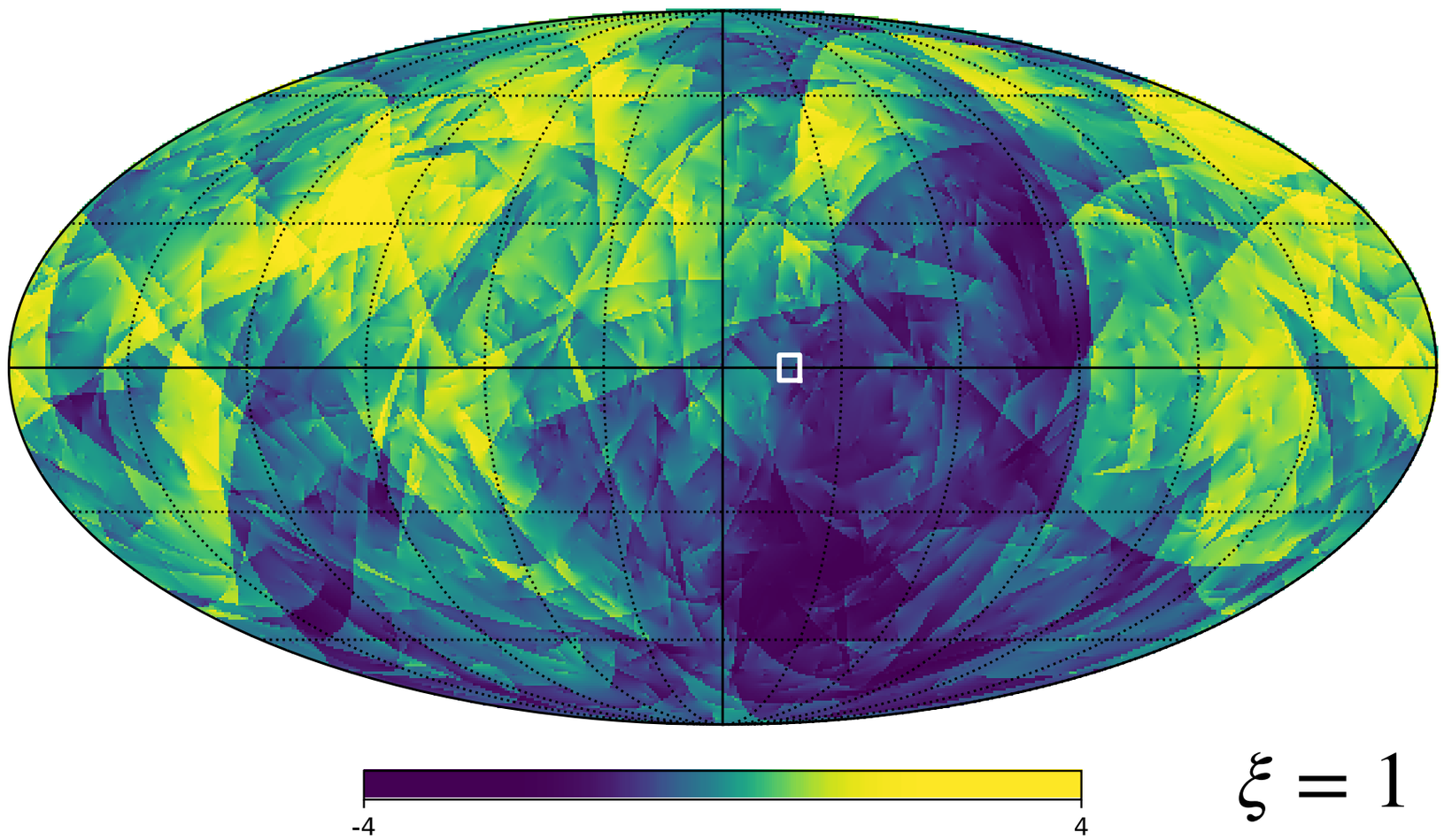
Scales as $\xi\mathcal{A}^2$

Searching for axion string



$L \geq 10$

Angular space

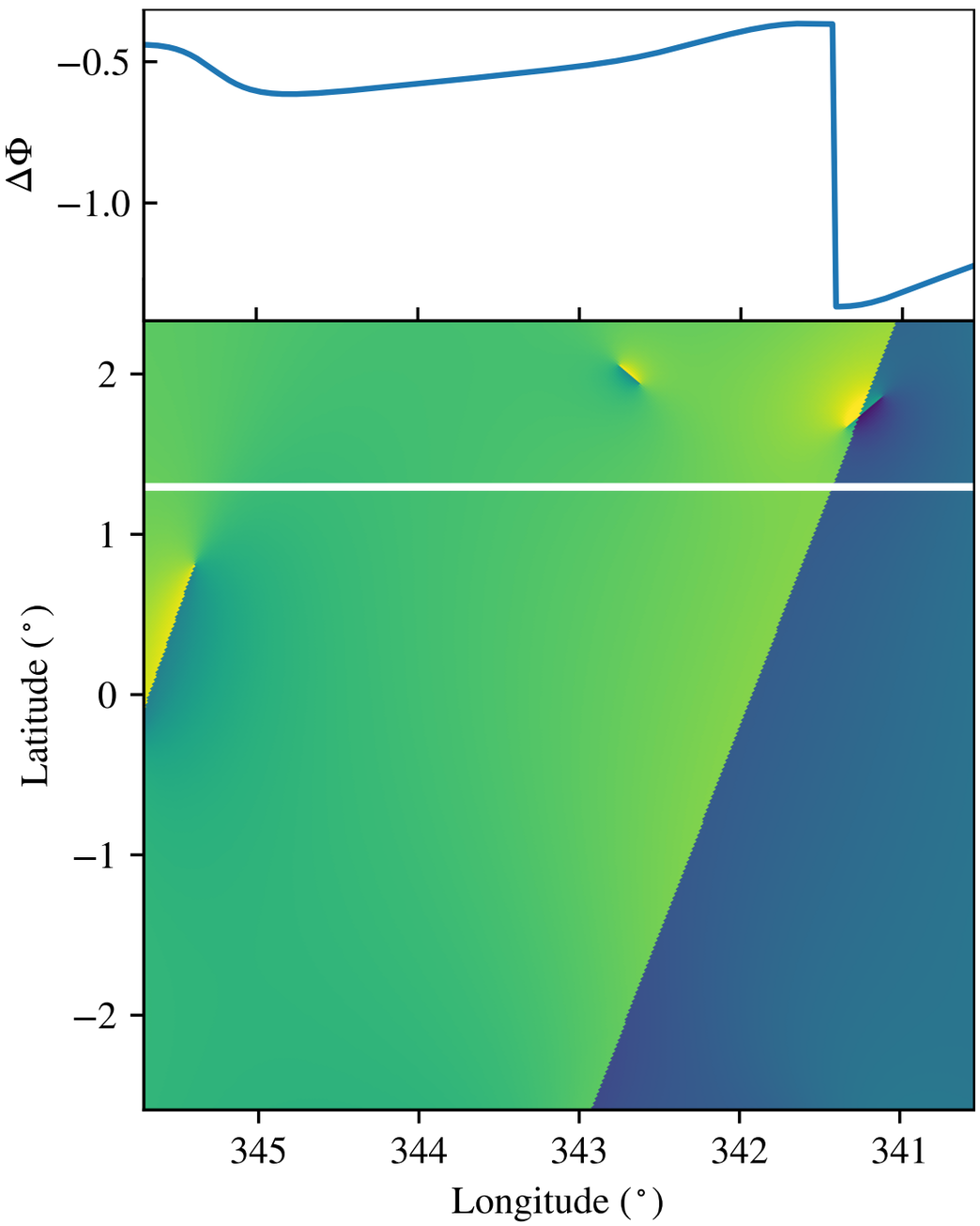


$\xi = 1$

We see long and short strings in our universe

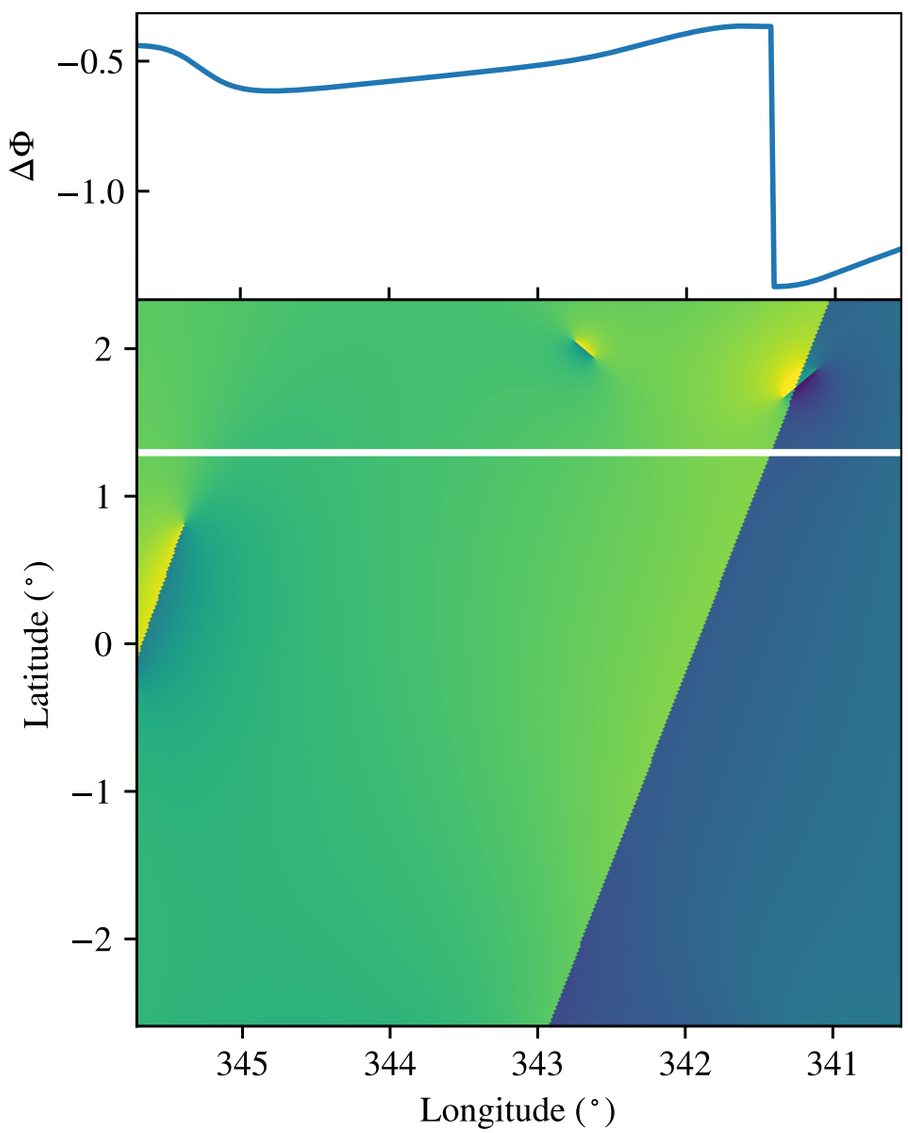
How to look for an axion string?

Edge detection



- The smallest string loop has a length of a few degree
- ACTpol/Simons/SPT:
  - Area of view: ~(100 deg)^2
  - Angular resolution: ~1’
- We can look for a string in CMB in position space!

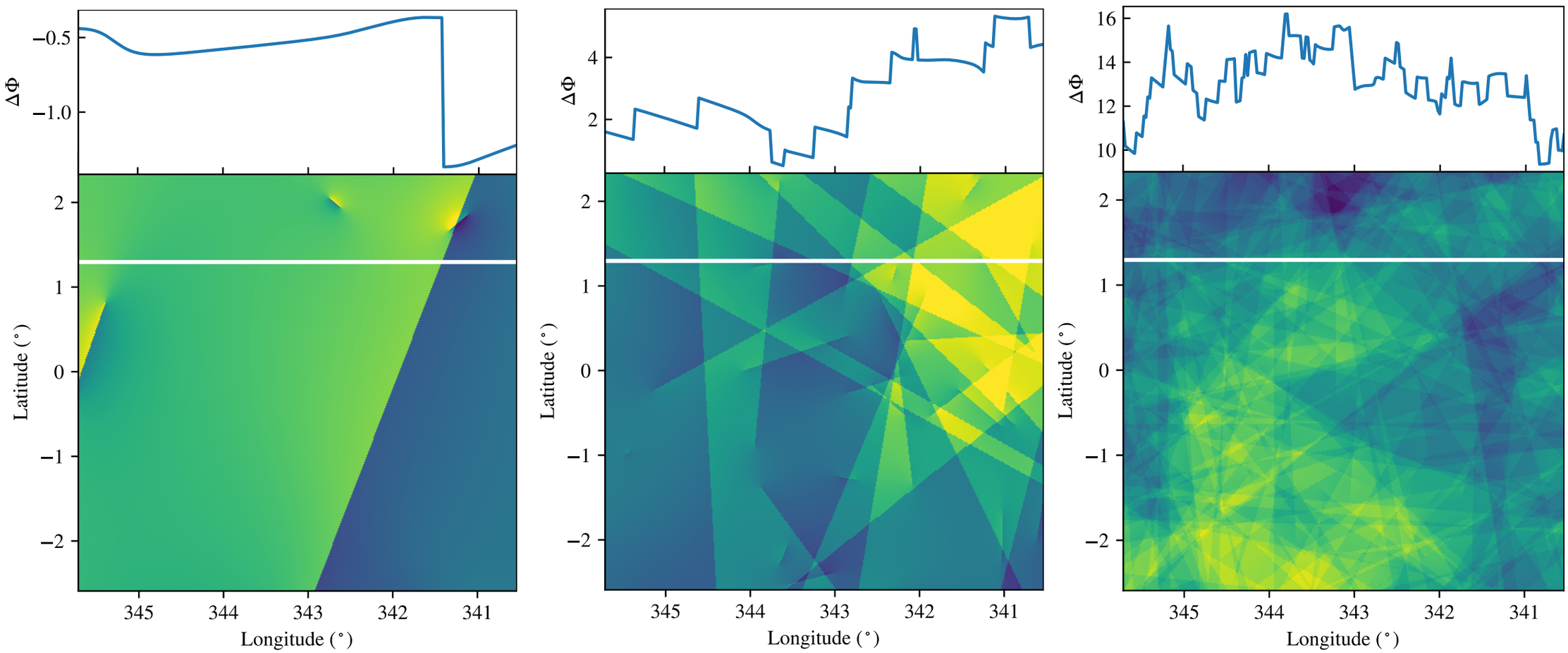
A single string in the Universe



$\xi = 1$

- For PQ symmetry broken before inflation, there can be one string in the whole Universe
- Edge detection can be sensitive to that string
- Implications for the duration and the beginning of inflation

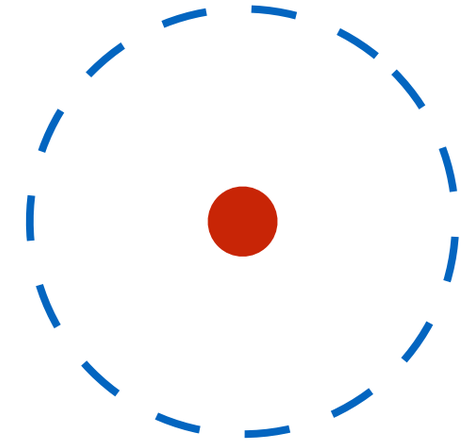
Edge detection



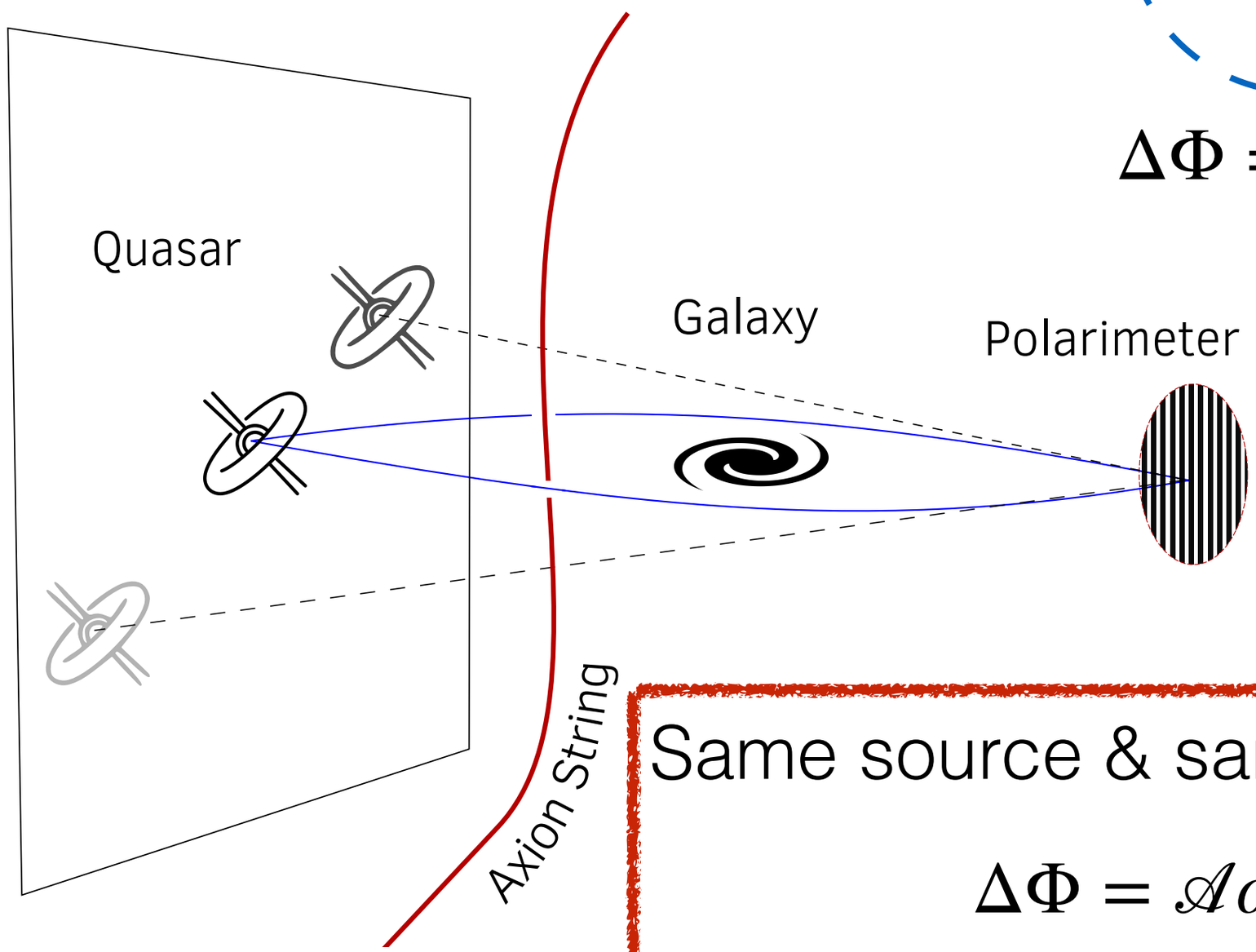
$\xi = 1$ $\xi = 10$ $\xi = 100$

Adding string = Blurring images

Lensed Quasar



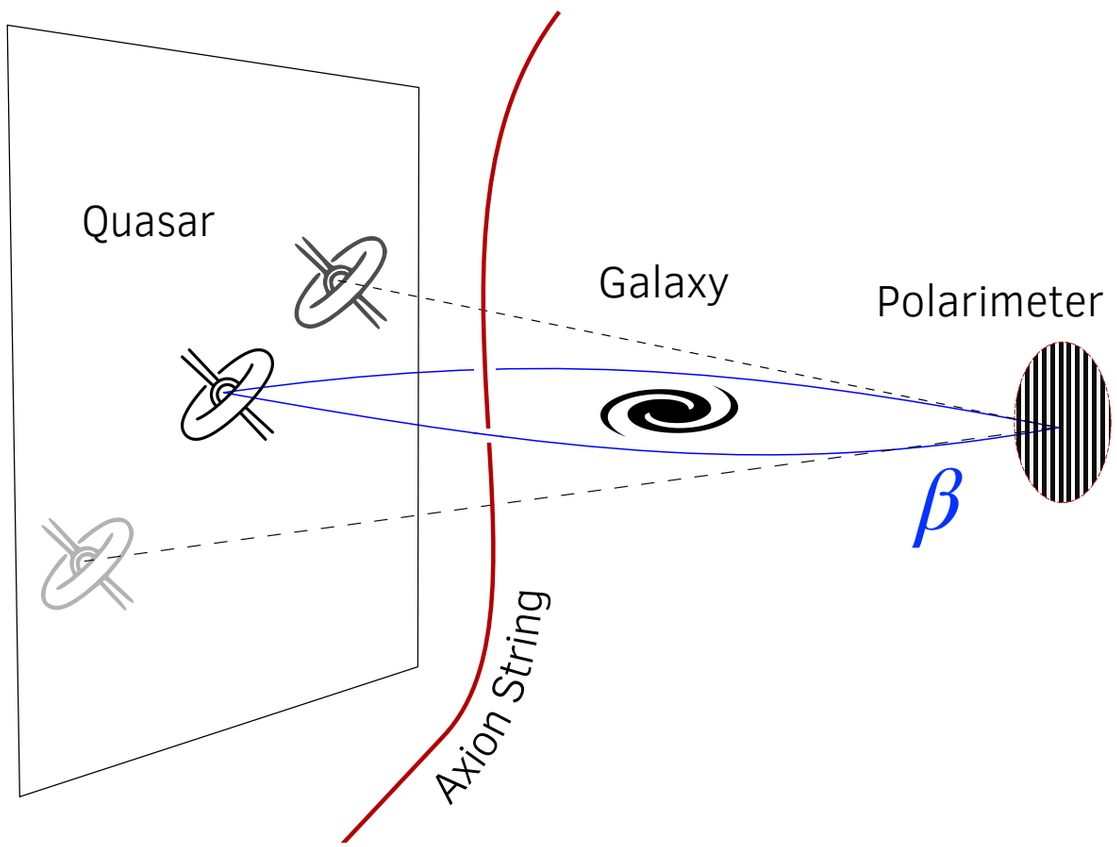
$$\Delta\Phi = \mathscr{A}\alpha_{\rm em}$$



Same source & same receiver

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

Quasar + String



- We have confirmed 205 gravitationally lensed Quasar systems
- Angular separation:

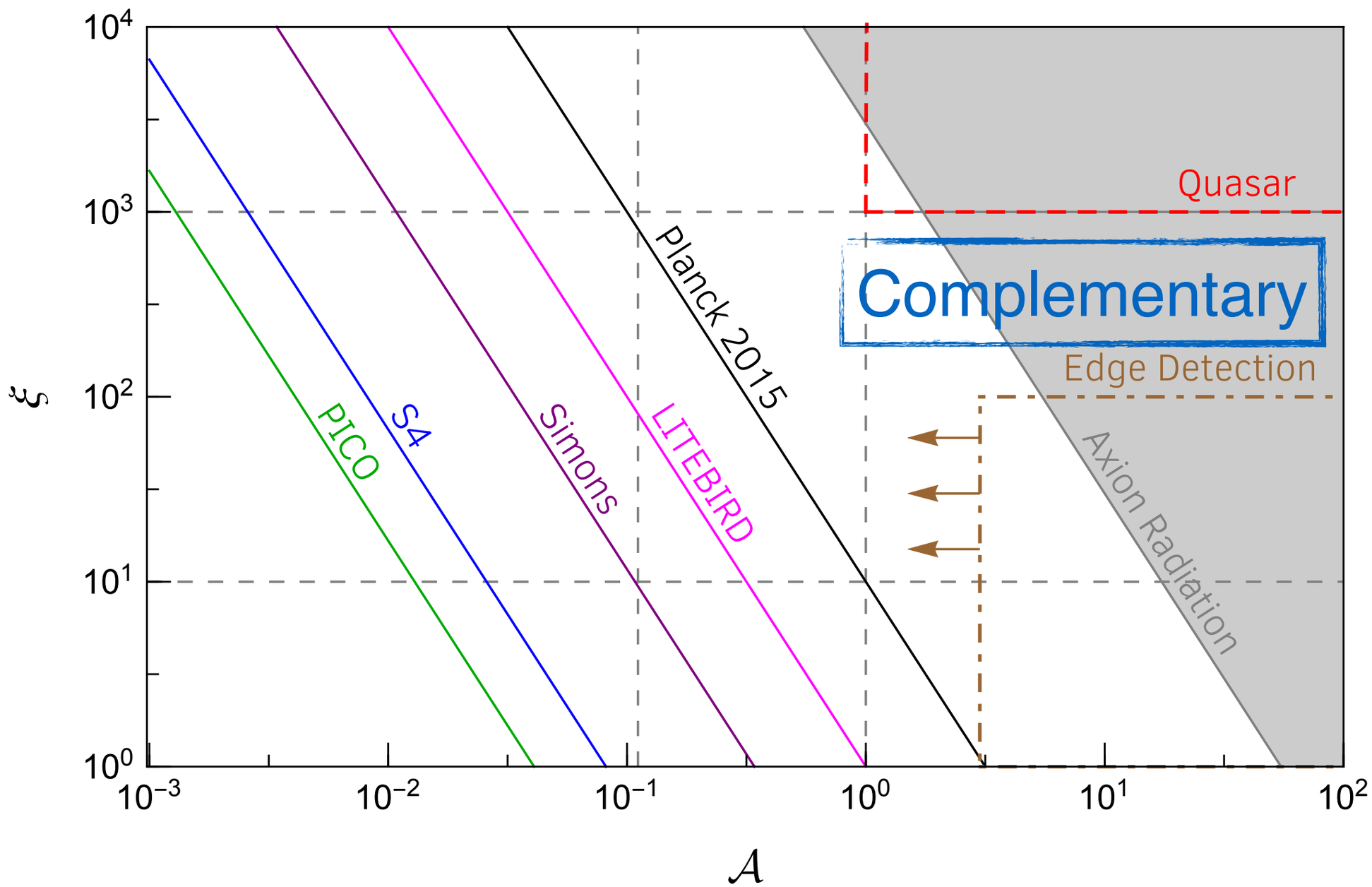
  Galaxy Cluster as a lens

  $$\beta \sim 10''$$
- Probability of a string:

$$p \simeq 10^{-3} \frac{\xi}{100} \frac{\beta}{10''}$$

Adding string = Increasing chances

Moving forward…



Implications
&
Remarks

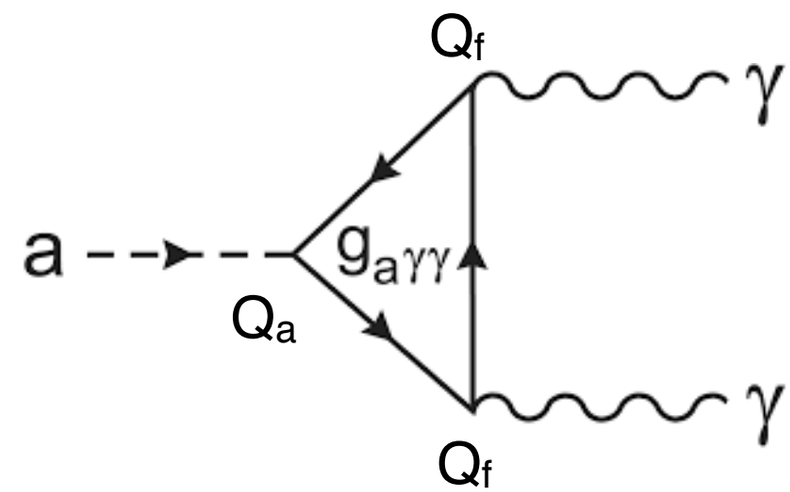
What will we learn?

- Axiverse axion
- Axion photon coupling ($\mathscr{A}$)
- Cosmic strings
- Scaling solution and scaling violation (ξ)
- Before inflation/Total duration of inflation
- Topological interaction & defect = UV knowledge?

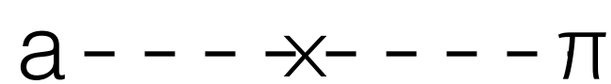
What can $\mathscr{A}$ be?

What can $\mathscr{A}$ be?

- Axion photon coupling
  - UV contribution:



  - IR contribution



- Example: QCD Axion?

$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left[\frac{E}{N} - \frac{2}{3}\,\frac{4m_d + m_u}{m_d + m_u}\right]$$

di Cortona, Hardy, Pardo Vega, Villadoro, 1511.02867

What can $\mathscr{A}$ be?

- (QCD Axion example) Pion rotates as the axion field rotates around a string

$$\left\langle \frac{\pi_0}{f_\pi} \right\rangle = \tan^{-1}\left(\frac{m_u - m_d}{m_u + m_d} \tan\left(\frac{a}{2f} \right) \right)$$

- The combined axion and “pion” anomaly remains an integer ratio
- Implications
  - Charge Quantization and the unit of electric charge
  - For massless axion, if $\mathscr{A} \neq \mathrm{Integer}$, electron is not fundamentally charged!

Excluding simple GUT!

  - Sensitivity to massless dark photon (Irrational $\mathscr{A}$)

Conclusion

- Cosmic axion strings can have topological interactions with photons,
- …this generates a Berry phase
- …that can be observable today!
- so, let’s go find it!

Thank you!