A CMB Millikan Experiment with Axion Strings

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[1912.02823]
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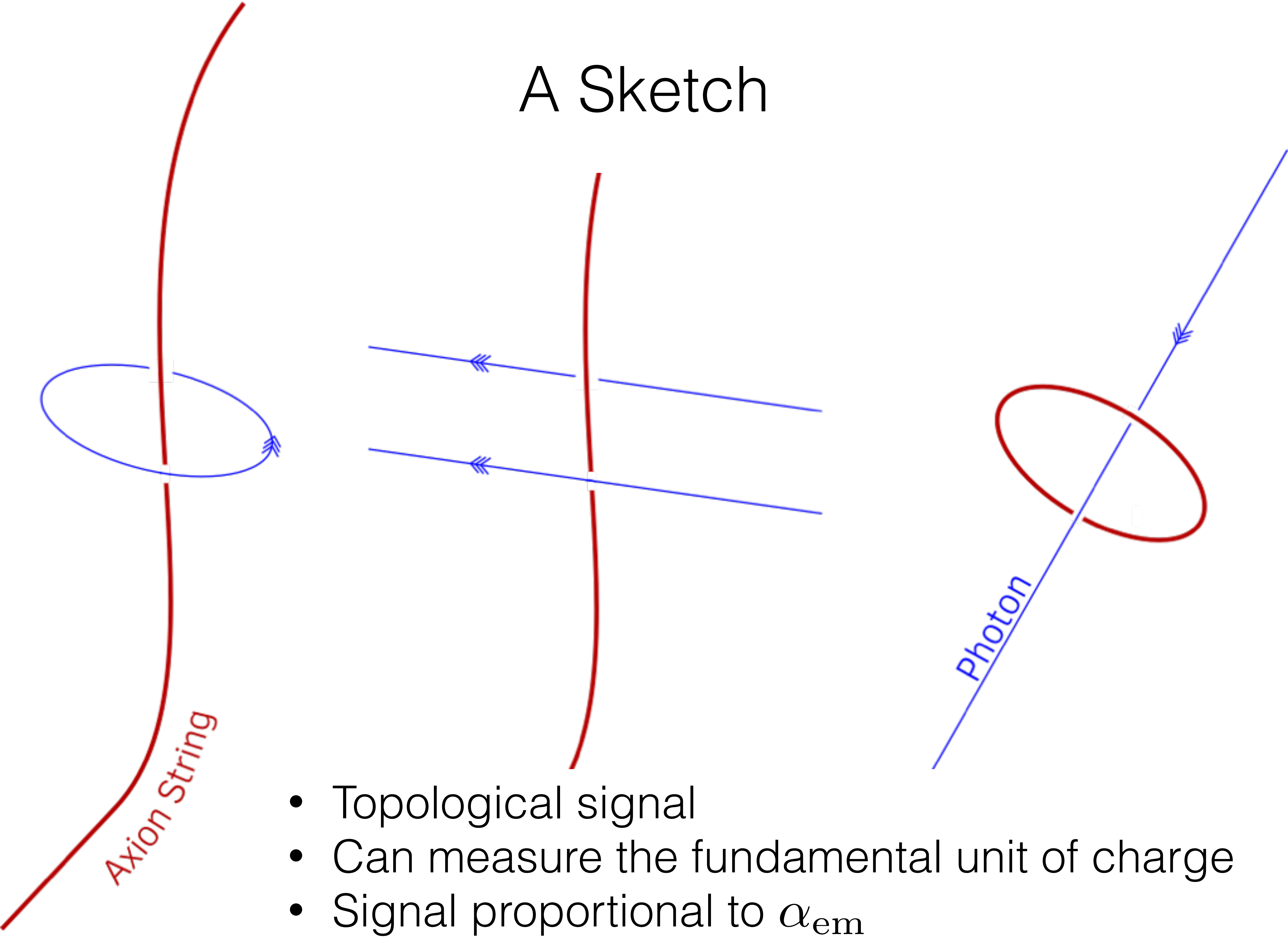
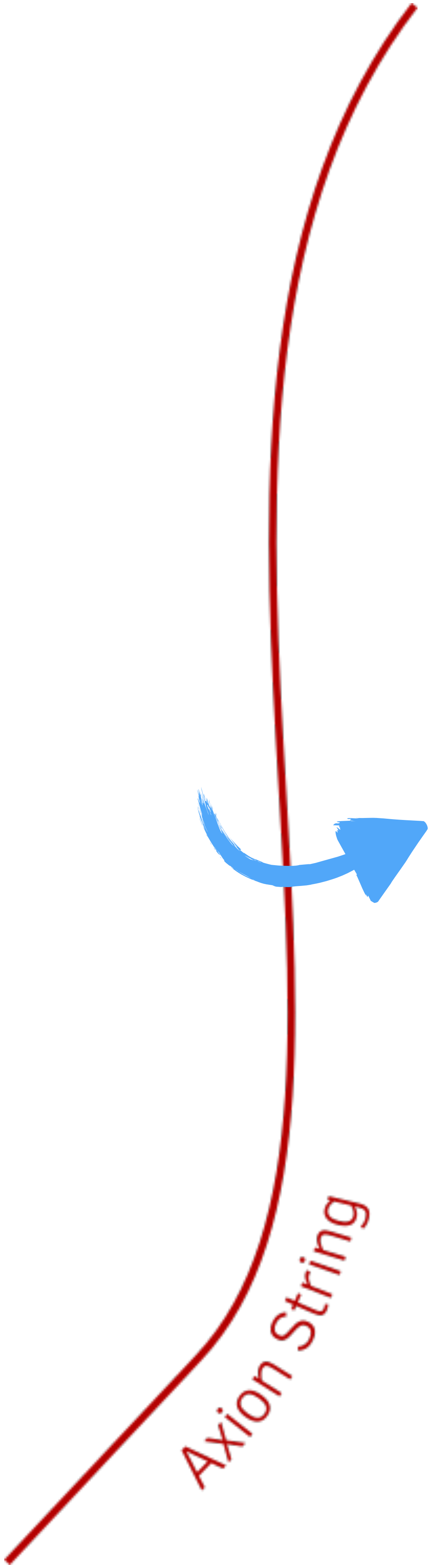
A Sketch

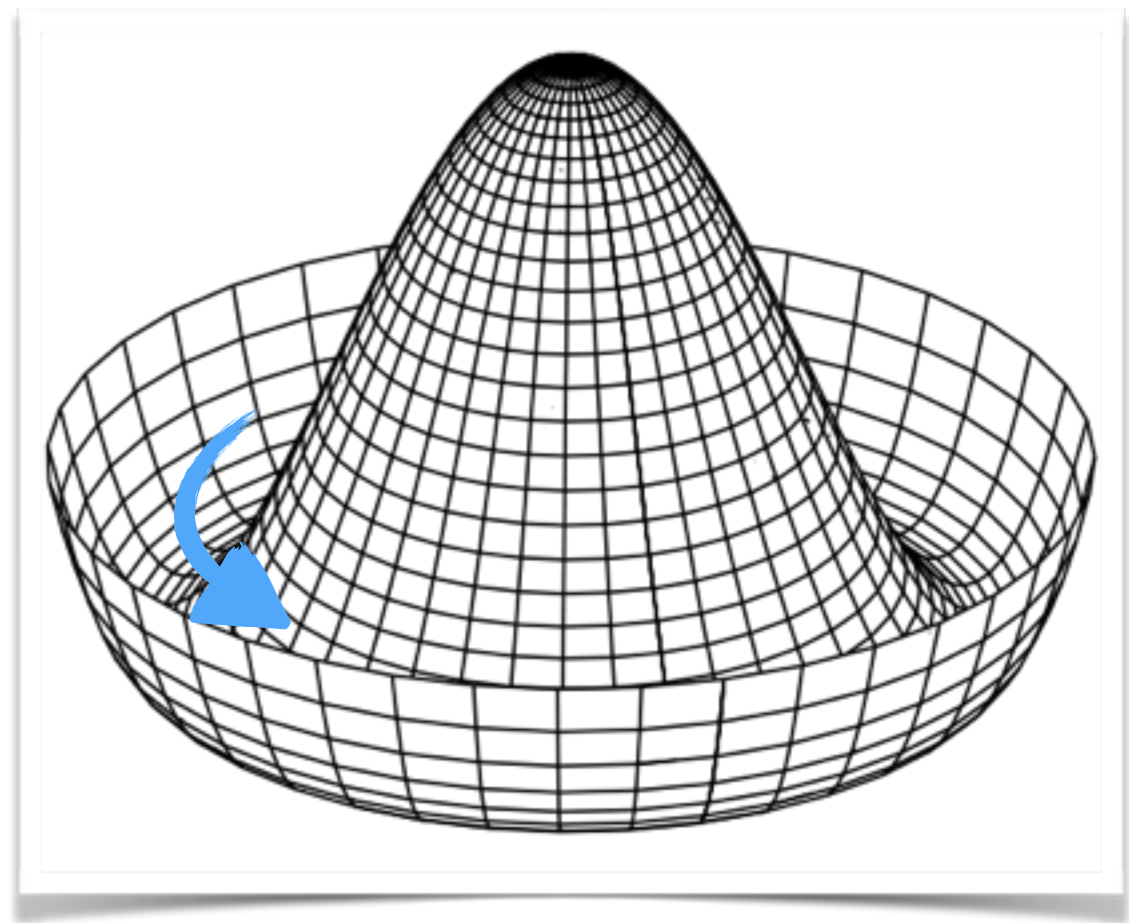


- Topological signal
- Can measure the fundamental unit of charge
- Signal proportional to $\alpha_{\rm em}$

Axion Strings

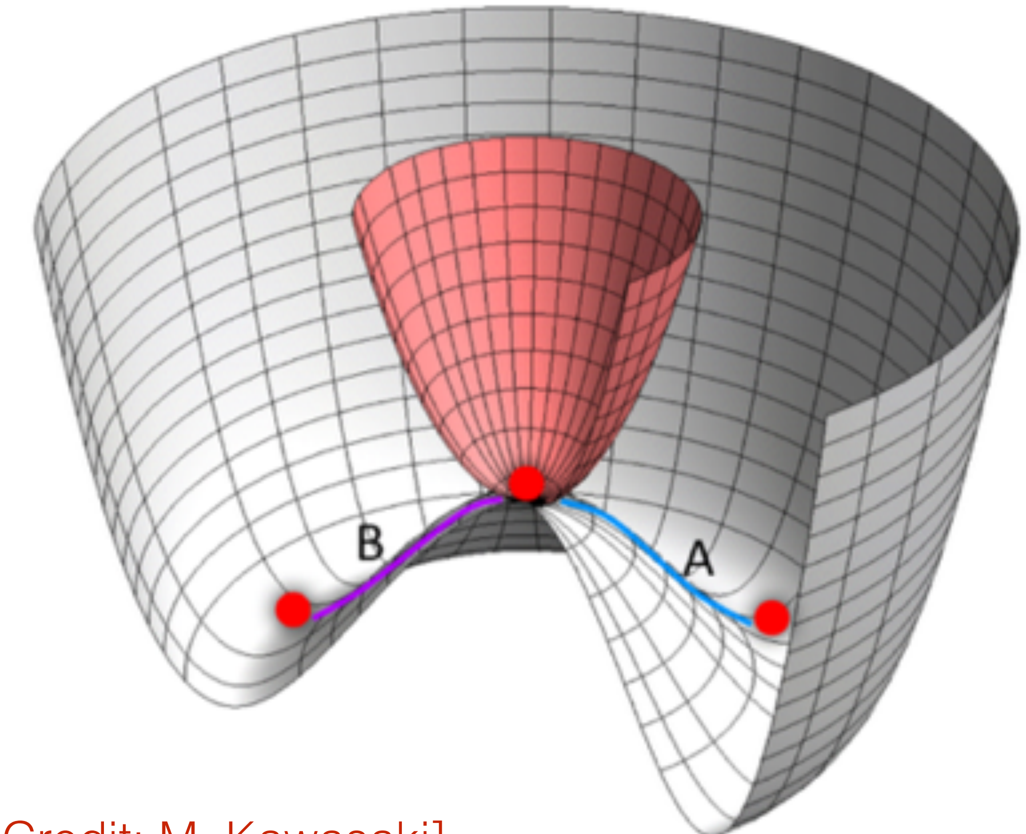


Spontaneously broken Peccei-Quinn symmetry



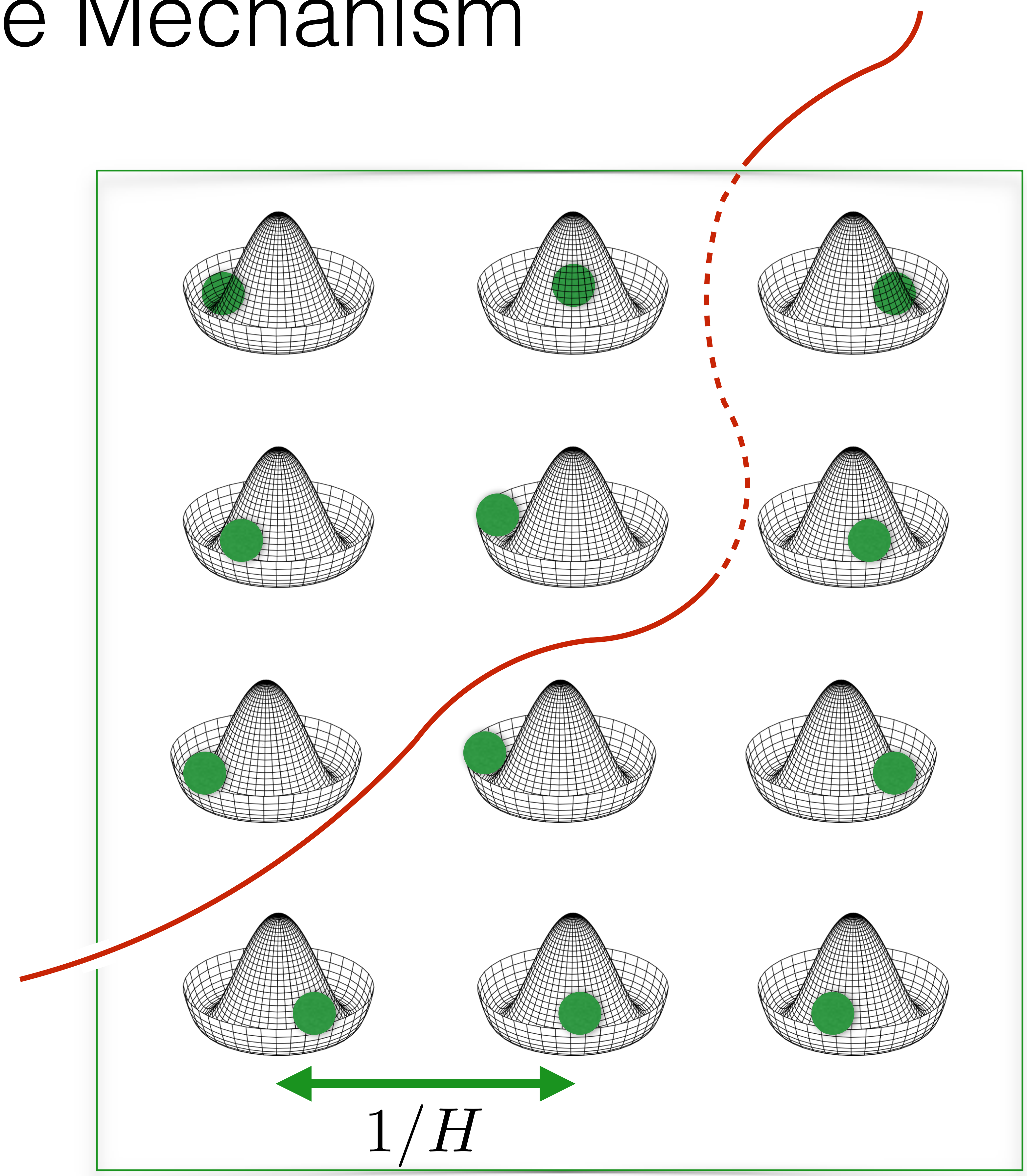
$$a \to a + 2\pi f$$

Kibble Mechanism

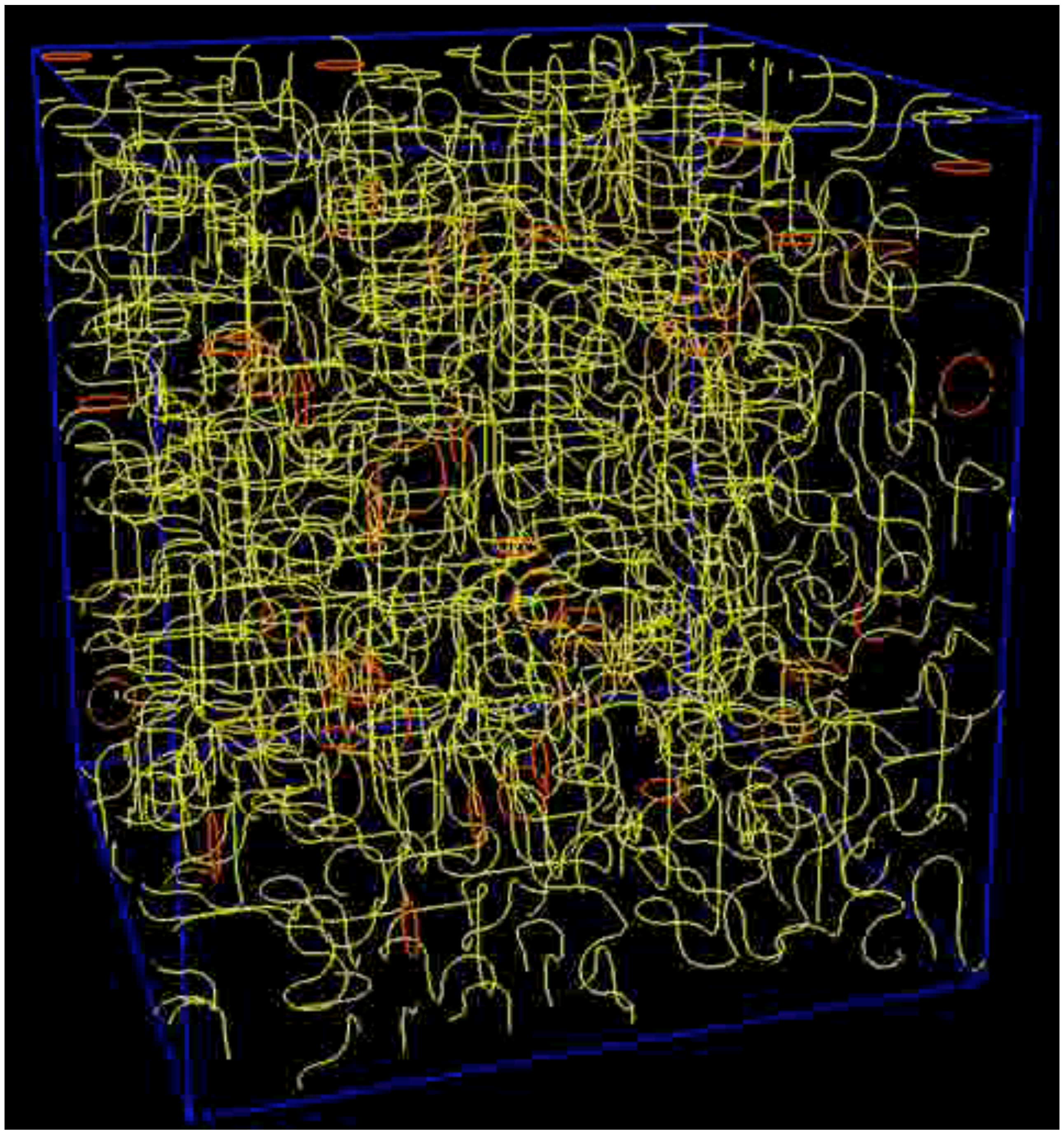


[Credit: M. Kawasaki]

Phase transition to the broken state in the early universe



The String Network



[C. Martins & E. P. Shellard]

String interactions are complicated, understood by numerical simulations

String energy density follows a scaling law

$$\rho_{\rm strings} \simeq \xi \mu H^2$$

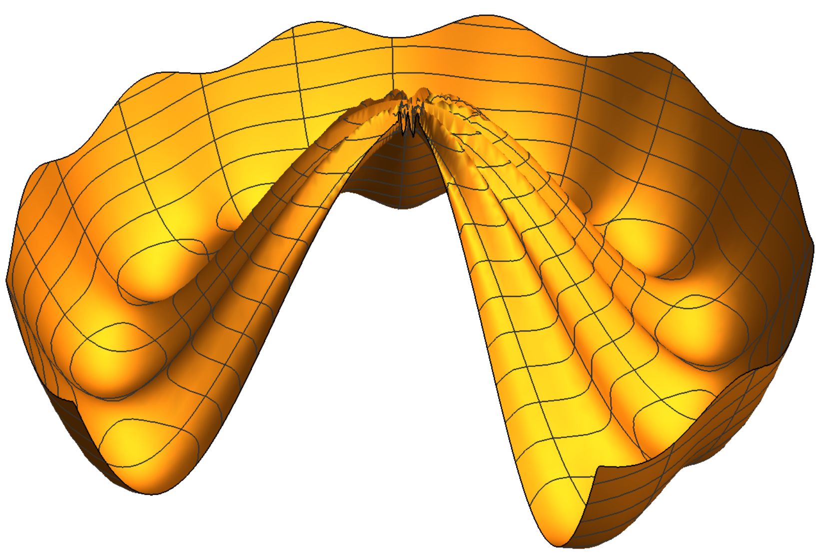
$$10^3 > \xi > 1$$

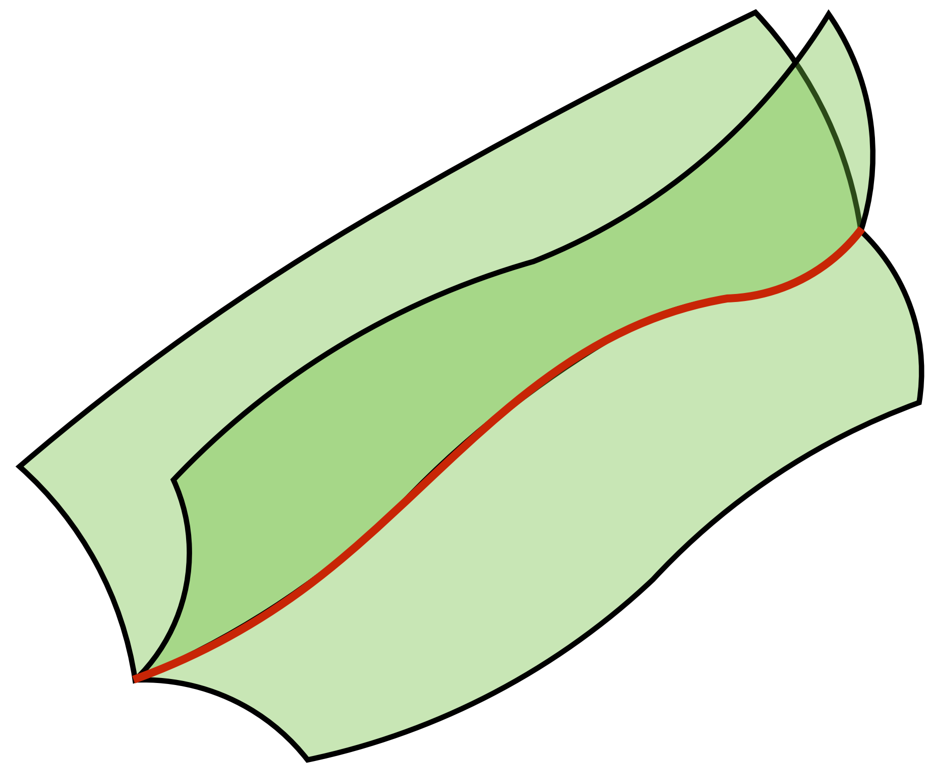
Equivalent to ξ strings per Hubble volume

Network is dominated by infinitely long strings with structure at scale 1/H

For massless axions:
Once formed, there are always a few strings per Hubble

Axion mass and domain walls



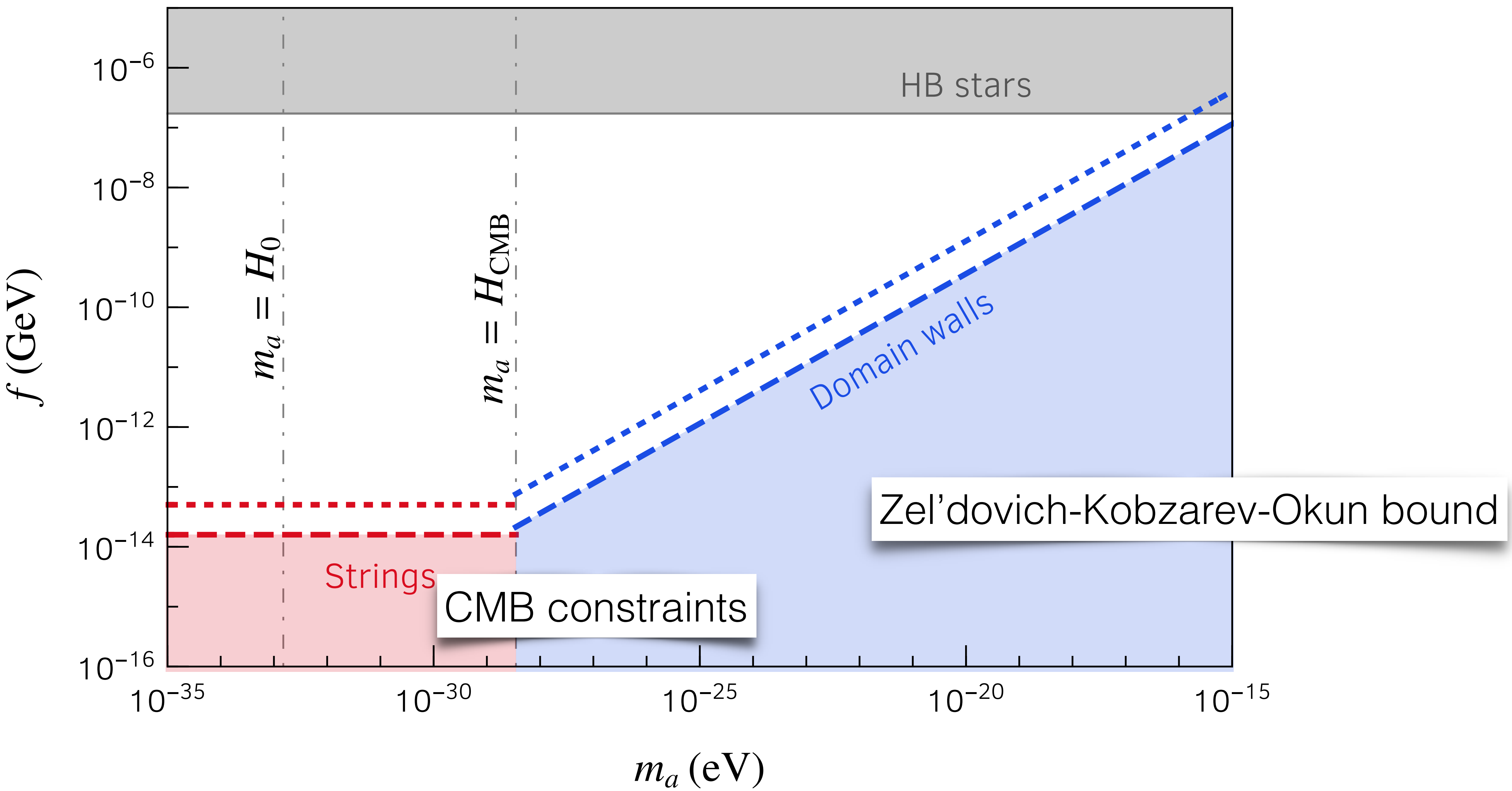


When $H < m_a$, domain walls ending on strings form

$N_{\mathrm{DW}} = 1$ String network disappears soon after

$N_{\mathrm{DW}} > 1$ String/domain wall network survives

Hyperlight axions



Not QCD axion, not dark matter

The String Axiverse

Hyperlight axions are ubiquitous in string compactifications

$$\mathcal{L} = \frac{\mathcal{A}\alpha_{\rm em}}{4\pi f} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

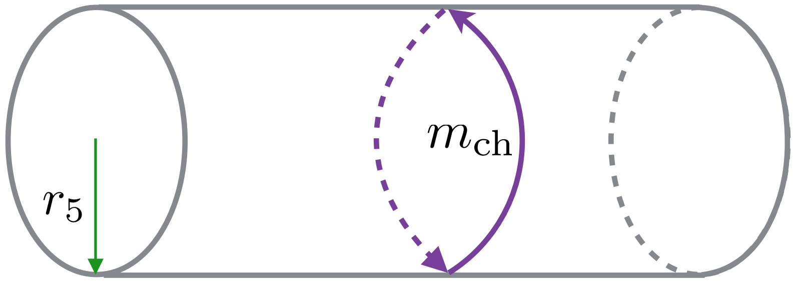
Axions are light, protected by an approximate shift symmetry

$$a \to a + c$$

Axions get a mass from instantons, can be exponentially suppressed

Toy example: Gauge theory in a theory with one extra dimension

$$A_M \equiv (A_\mu, A_5)$$



Only contribution to potential from charged particles around the circle

$$V(A_5) \sim \exp(-m_{\rm ch} r_5)\cos(A_5 r_5)$$

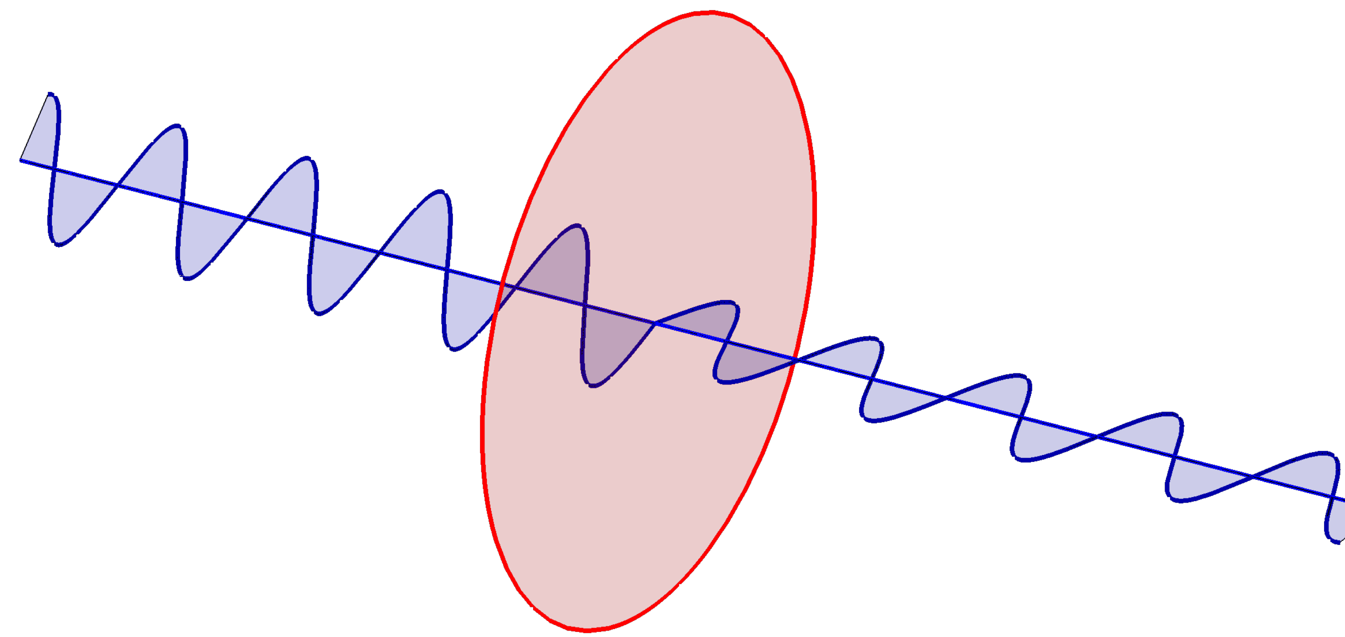
$$V(a) \sim \exp(-M_{\rm pl}/f)\cos(a/f)$$

"hundreds of axions, some of them massless"

[arXiv:1808.01282]
Demirtas, Long, McAllister, Stillman

Photons in Axion String Background

$$\mathcal{L} = \frac{\mathcal{A}\alpha_{\rm em}}{4\pi f} a F_{\mu\nu}\widetilde{F}^{\mu\nu} \propto a\vec{E}\cdot\vec{B}$$



Solve plane waves in axion electrodynamics

$$A_\pm(\eta, z) = A_\pm(0,0)e^{i(kz-\omega\eta)}e^{\pm i\Delta\Phi(\eta,z)}$$

$$\Delta\Phi(\eta, z) = \frac{\mathcal{A}\alpha_{\rm em}}{2\pi f}\left(a(\eta,z) - a(0,0)\right)$$

Rotation of linear polarization: axion birefringence

Aharanov-Bohm like effect for trajectory around a string $\Delta a = 2\pi f$

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

Access to measuring $\mathcal{A}$ directly!

Axions and charge quantization

In the SM, all gauge invariant states (leptons, hadrons) carry integer electric charge

$$\mathcal{L} = \frac{\mathcal{A}\alpha_{\rm em}}{4\pi f} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

The axion - photon coupling is quantized in units of fundamental EM charge

$$\mathcal{A} \in \frac{\mathcal{Q}_{\rm fund}}{\mathcal{Q}_e} \times \mathbb{Z}$$

Usually, this is only true up to mass mixing effects for particles.
E.g. for the QCD axion, in the mass basis

$$2\mathcal{A} = \frac{E}{N} - 1.92 \sim \frac{E}{N} - \frac{m_a^2 f_a^2}{m_\pi^2 f_\pi^2}$$

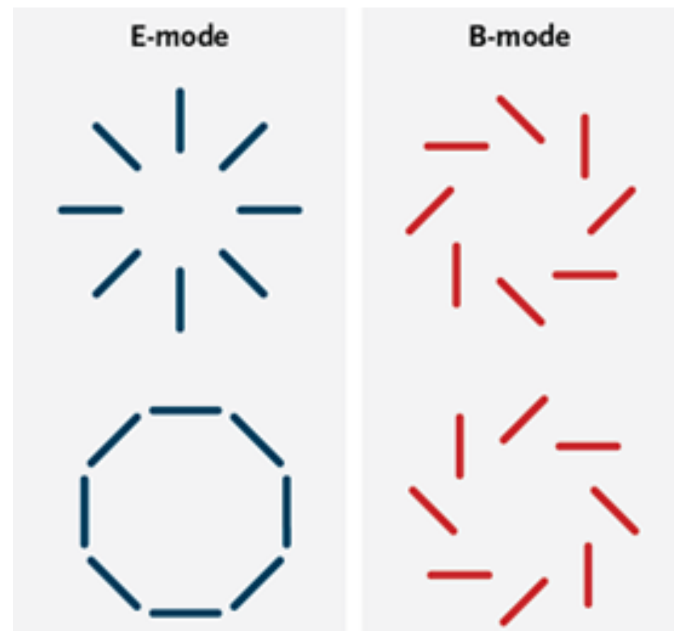
However, around axion strings, both the axion and the pion shift, so

$$\Delta\Phi = \mathcal{A}\alpha_{\rm em} \quad \text{with} \quad \mathcal{A} \in \frac{\mathcal{Q}_{\rm fund}}{\mathcal{Q}_e} \times \mathbb{Z}$$

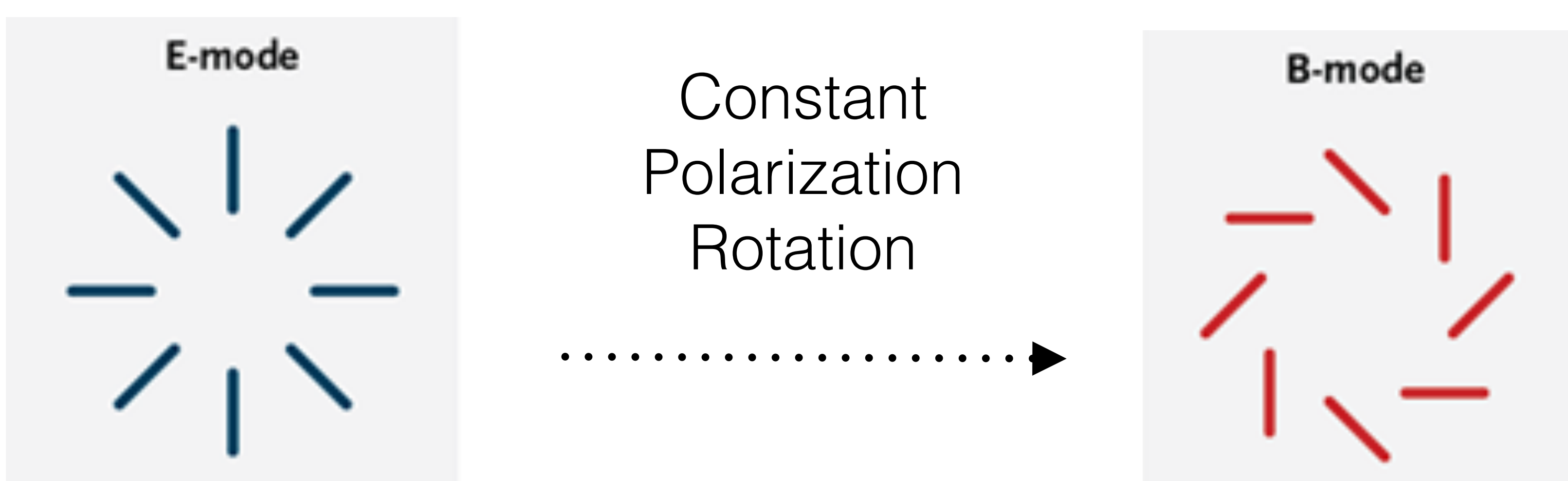
Measuring $\mathcal{A}$ can test the fundamental unit of electric charge

CMB Observables

CMB polarization can be decomposed in curl-free (E-mode) and divergence-free (B-mode)



Correlated B-modes generated from E-modes



Cosmic Birefringence

For angle dependent rotation $\Phi(\hat{n})$, B-modes are convolution of Φ_{LM} and E-modes

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

Functions of Clebsch-Gordan coefficients

Estimator for Φ_{LM} from E- and B-mode maps

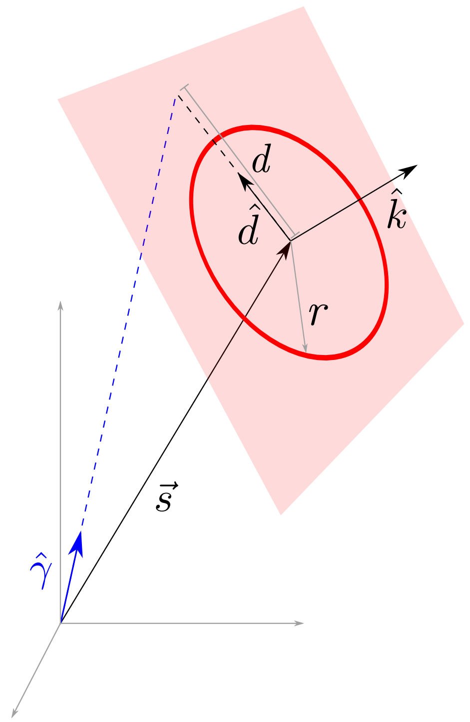
$$[\hat{\Phi}^{E^i B^j}_{LM}]_{ll'} = \frac{2\pi}{(2l+1)(2l'+1)C^{EE}_l H^L_{ll'}} \sum_{mm'} B^i_{lm} E^{j*}_{l'm'} \Xi^{LM}_{lml'm'}$$

Can be used to estimate the variance of the estimator from noise and background sources

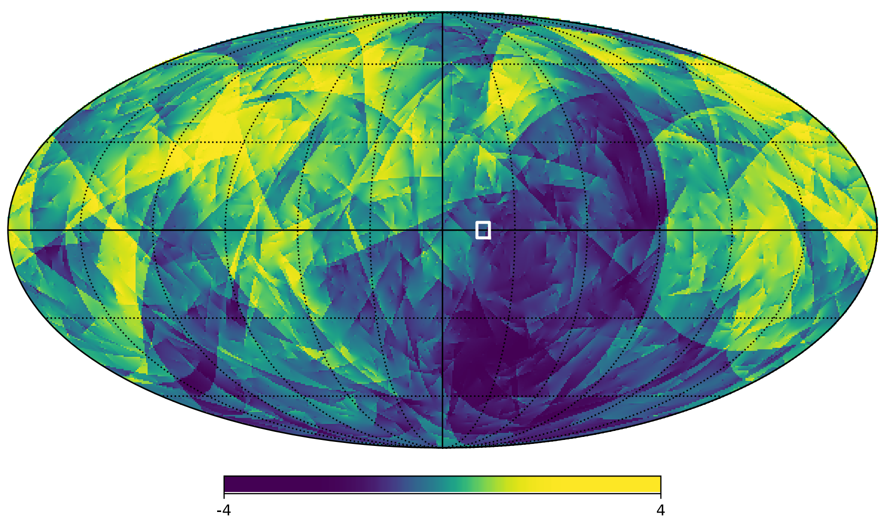
Theory predictions

Study the polarization rotation in two simplified settings

1. Semi-analytical approach



2. Simple numerical simulation

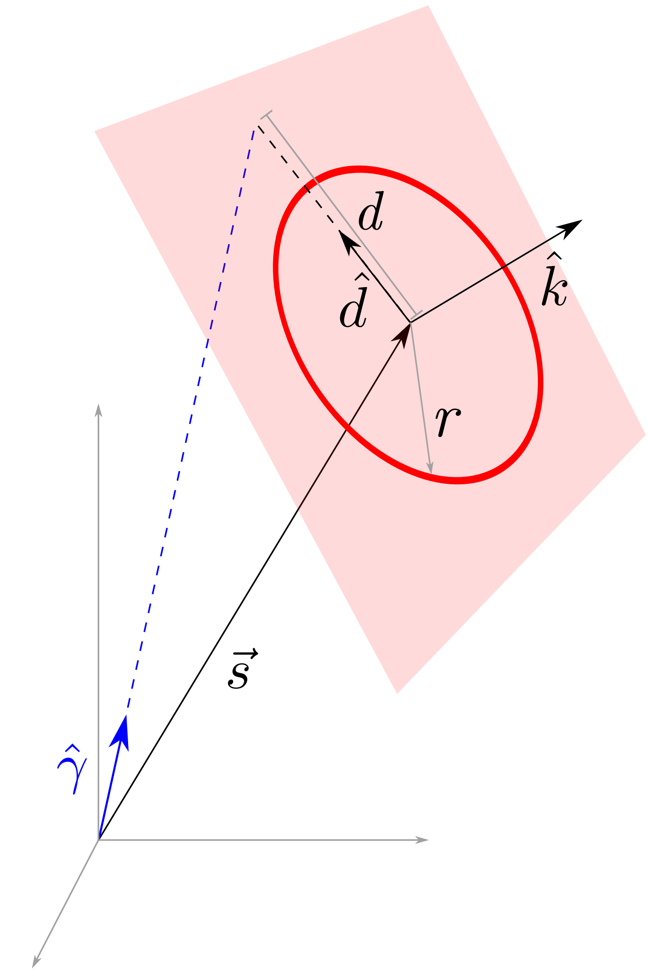


Future direction: Set up a string simulation for hyperlight axions combined with a CMB simulation

1. Semi-analytical approach

Model String network by

- Circular loops of comoving radius 1/aH
- Total number of strings follow scaling $\rho_{\rm strings} \simeq \xi \mu H^2$
- Spatially uniform, random orientation



Further assume that photons passing through the loop pick up rotation $\mathcal{A}\alpha_{\rm em}$, and 0 otherwise

- An ok assumption for loops at smaller angular scales

Two-point function for the polarization rotation

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

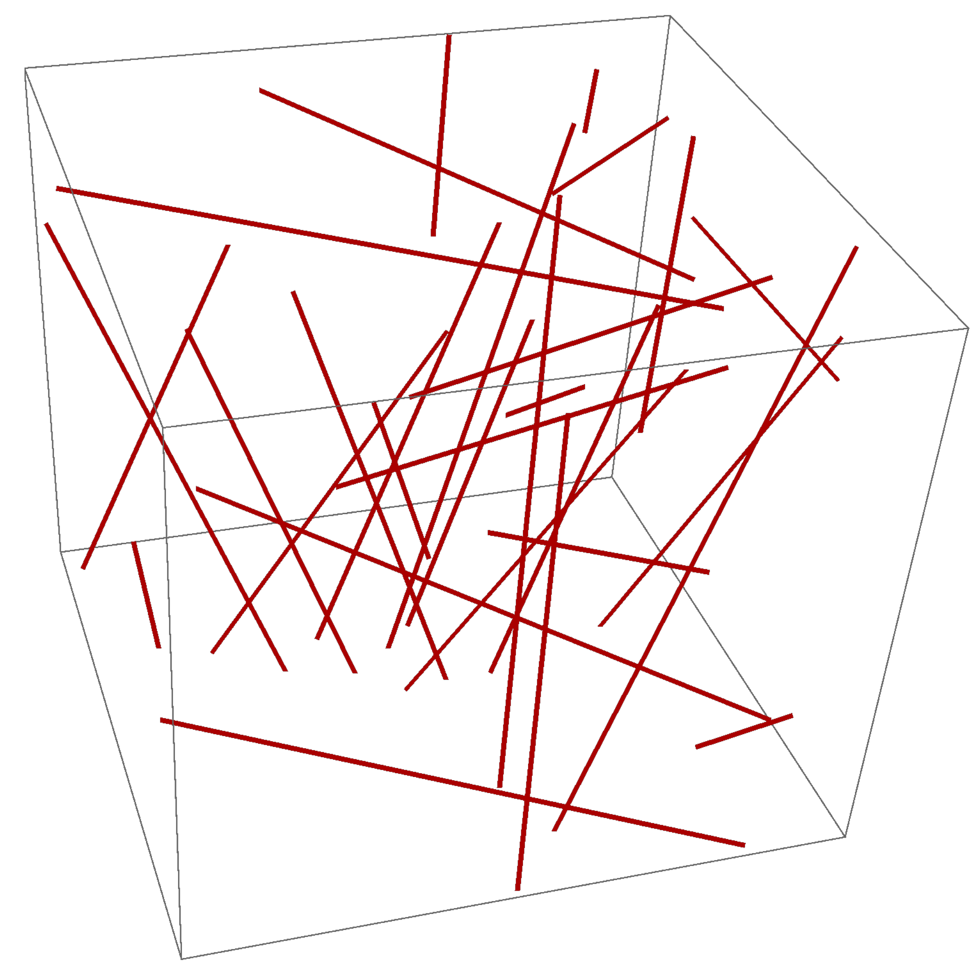
$$\langle \Phi(\hat{\gamma})\Phi(\hat{\gamma}')\rangle = (\mathcal{A}\alpha_{\rm em})^2 \int d[\text{string}] P([\text{string}]) \text{Pass}(\hat{\gamma})\ \text{Pass}(\hat{\gamma}')$$

Variance: $\langle \Phi(0)^2 \rangle \simeq (\mathcal{A}\alpha_{\rm em})^2 \xi \log\left(\frac{\eta_0}{\eta_{\rm CMB}}\right)$

2. Simple Simulation

Model String network by

- Infinitely long, straight strings
- Total number of strings follow scaling $\rho_{\rm strings} \simeq \xi \mu H^2$
- Spatially uniform, random orientation

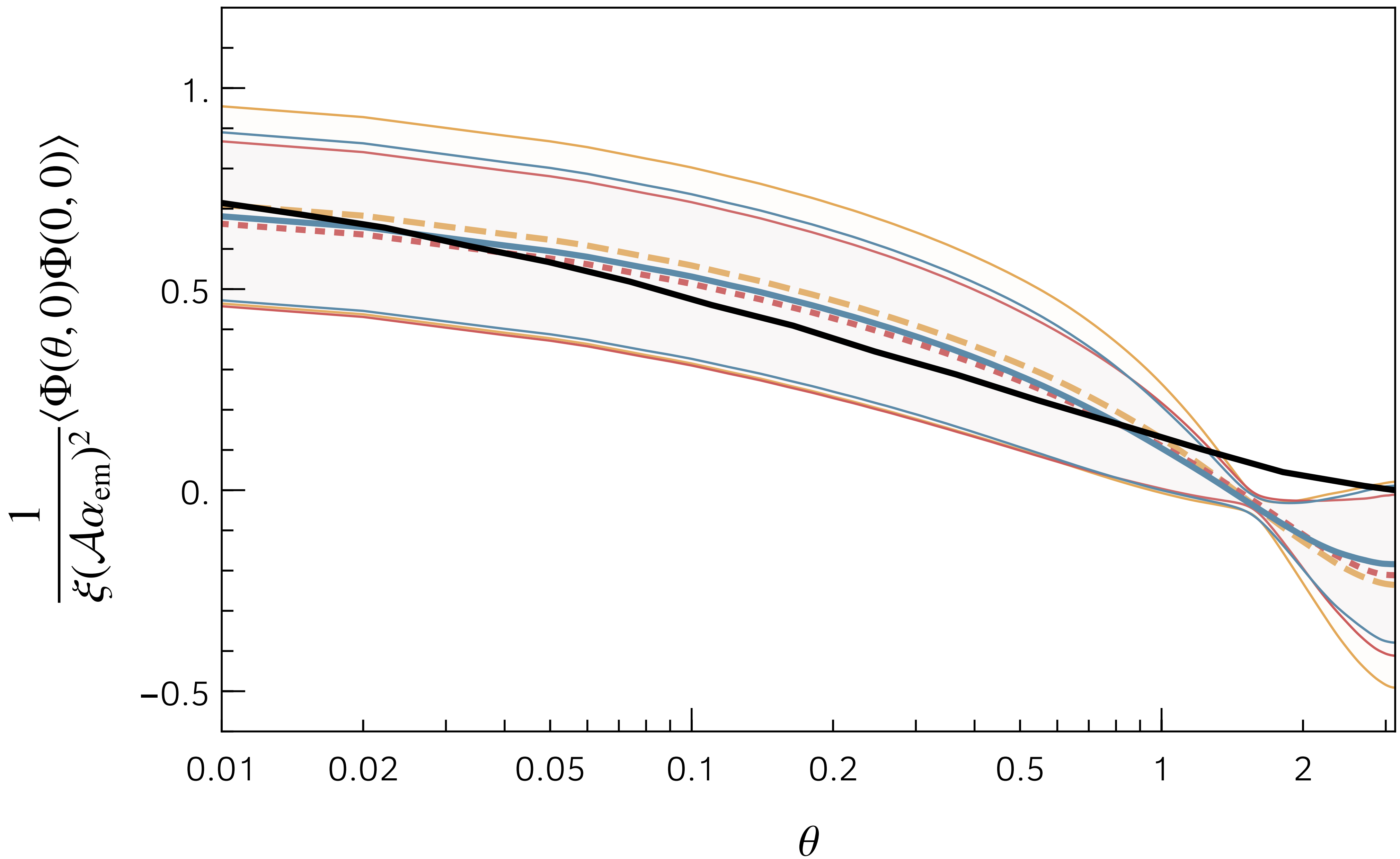


Strings are removed randomly to maintain scaling

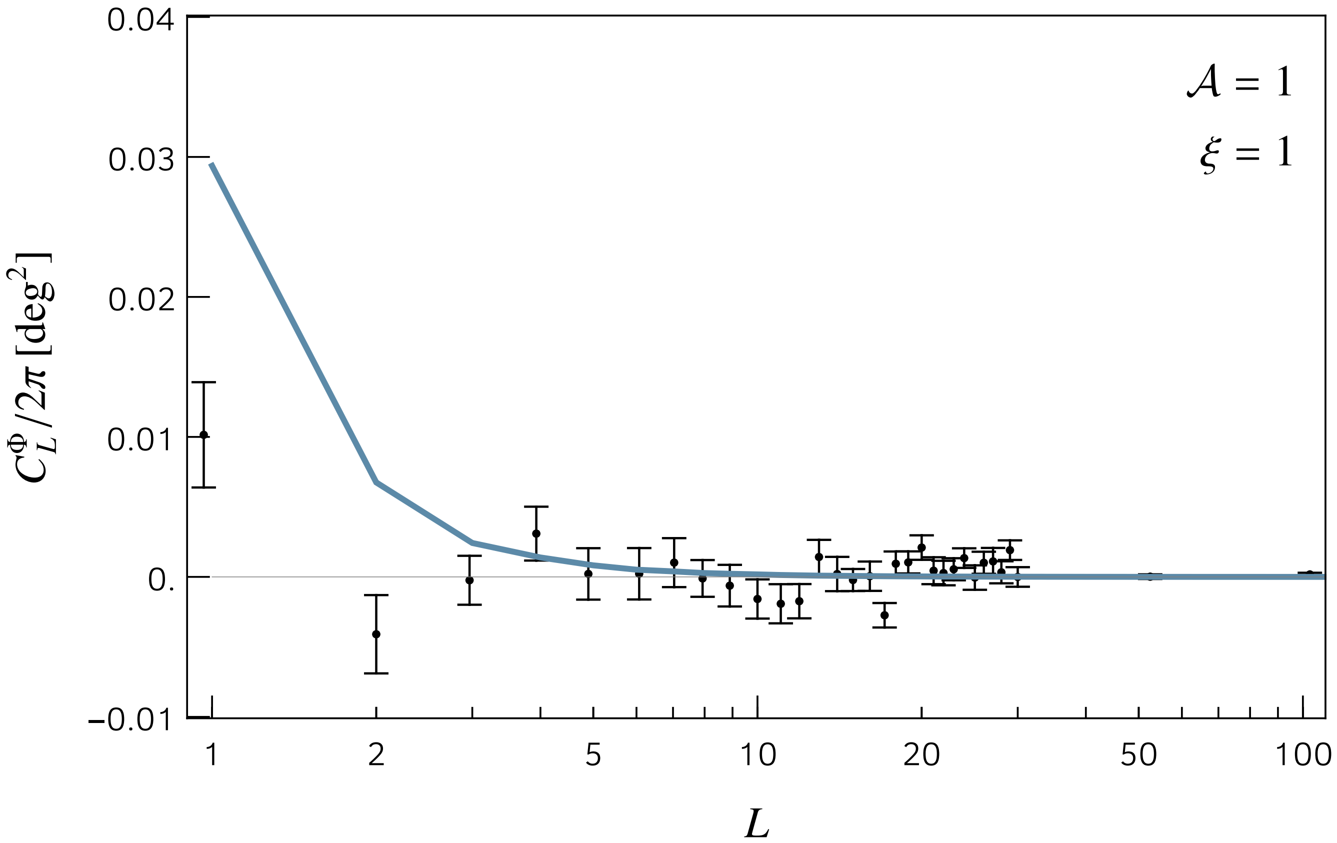
Pass photons through this network, adding up their polarization rotations along trajectory

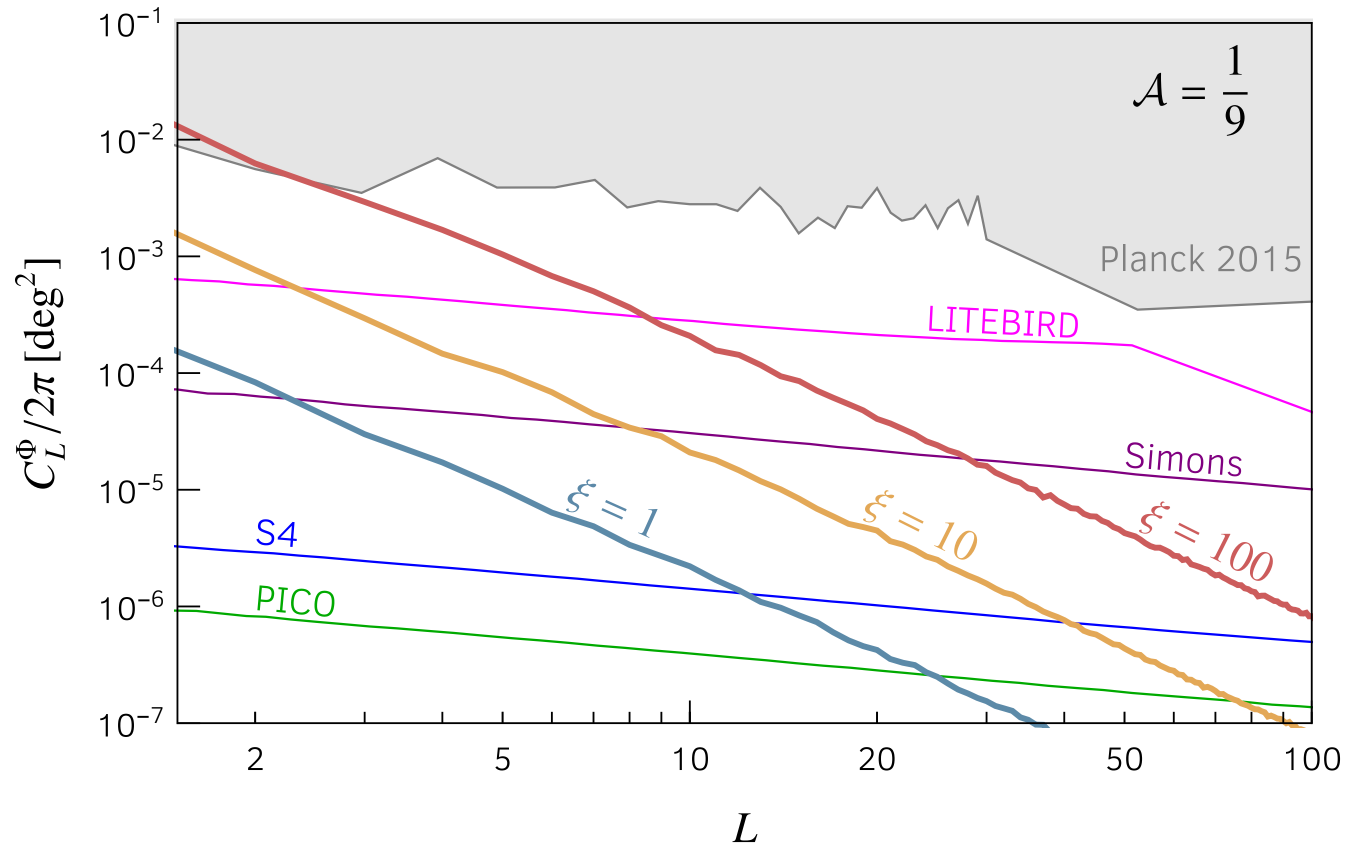
Captures larger angular scale correlations well

Two-point function



Angular power spectra

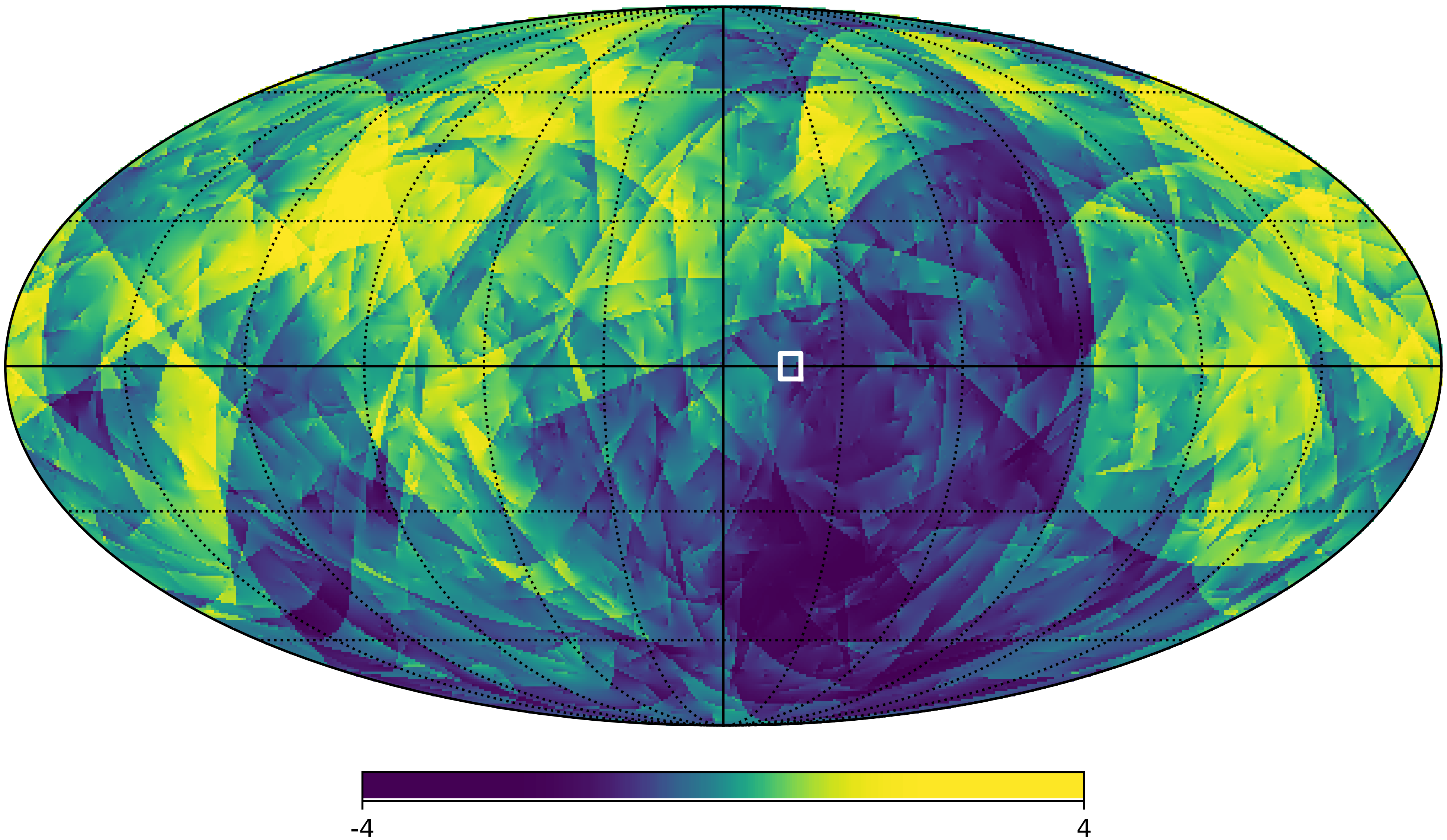




<u>Data points</u>
Planck 2015
Contreras, Boubel, Scott
[arXiv:1705.06387]

<u>Forecasts</u>
Pogosian et al
[arXiv:1904.07855]

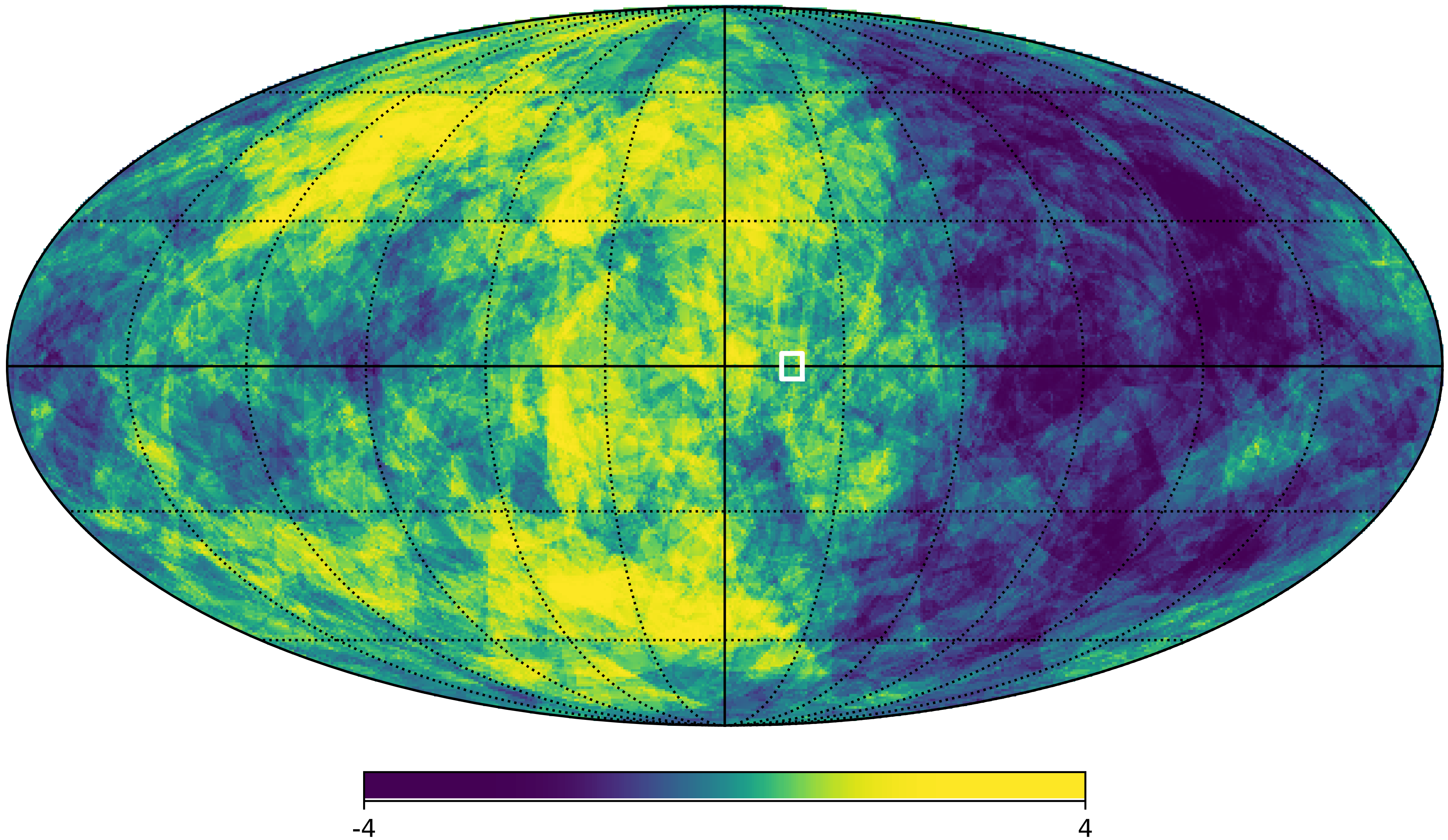
Sky maps



$$\frac{\Delta\Phi}{\sqrt{\xi}\mathcal{A}\alpha_{\rm em}}$$

$$\xi = 1$$

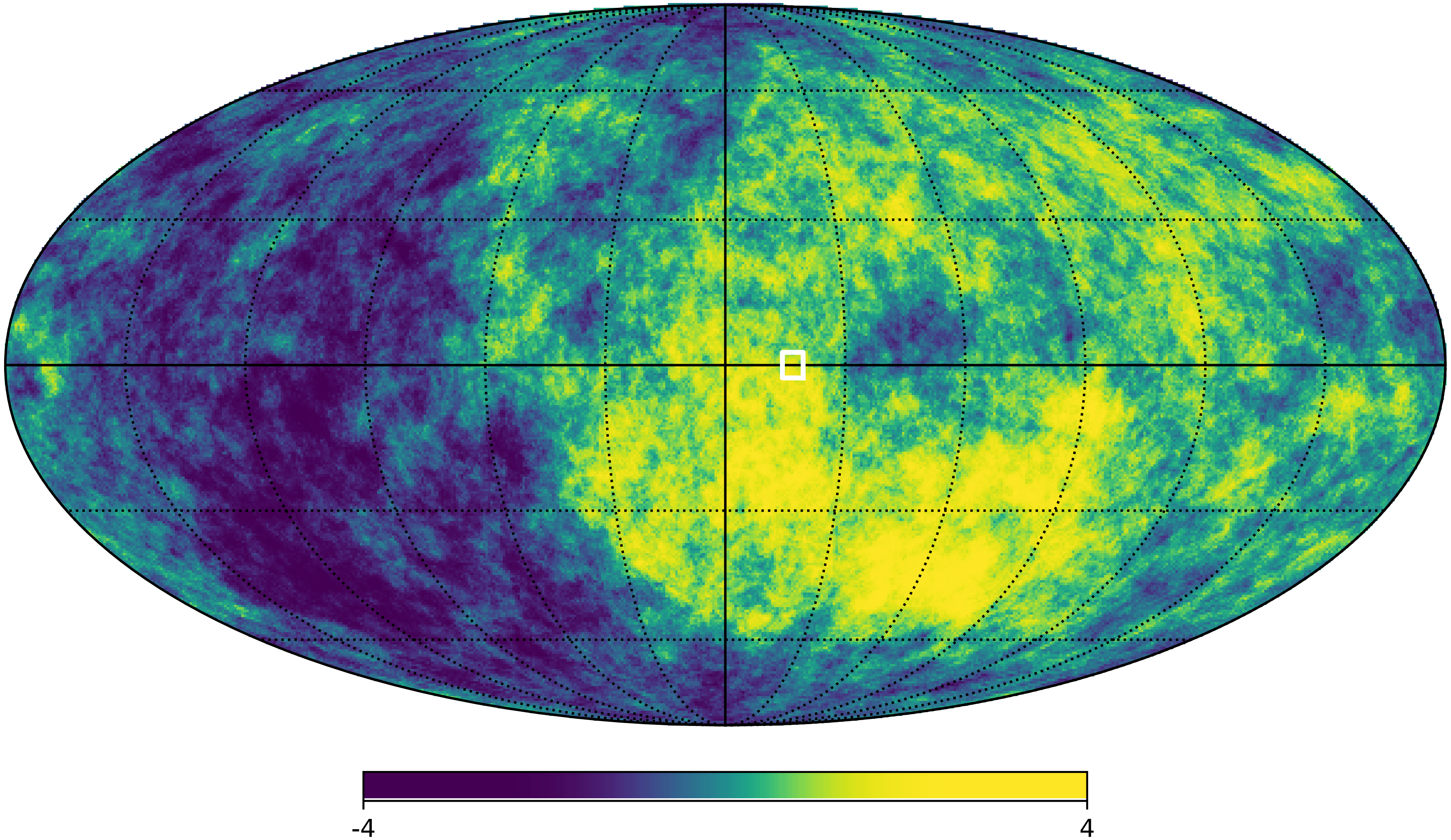
Sky maps



$$\frac{\Delta\Phi}{\sqrt{\xi}\mathcal{A}\alpha_{\rm em}}$$

$\xi = 10$

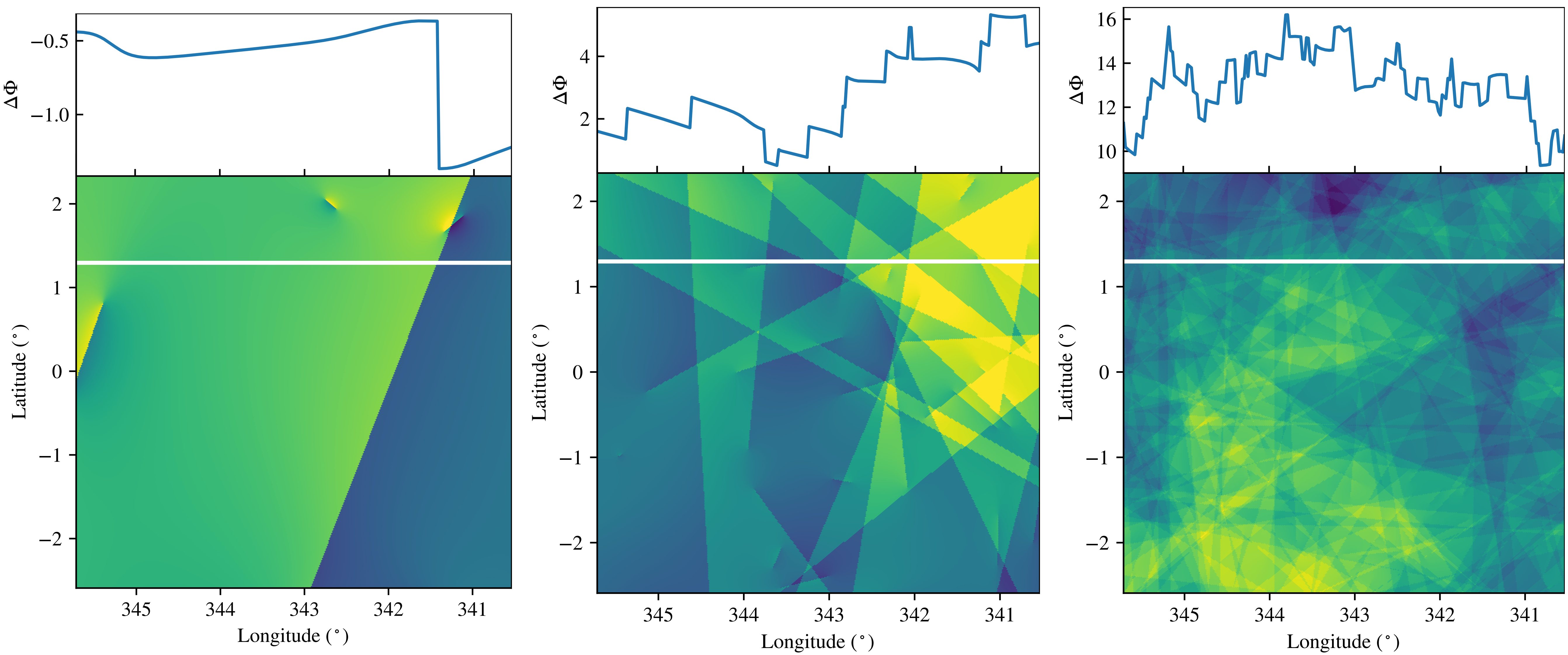
Sky maps



$$\frac{\Delta\Phi}{\sqrt{\xi}\mathcal{A}\alpha_{\rm em}}$$

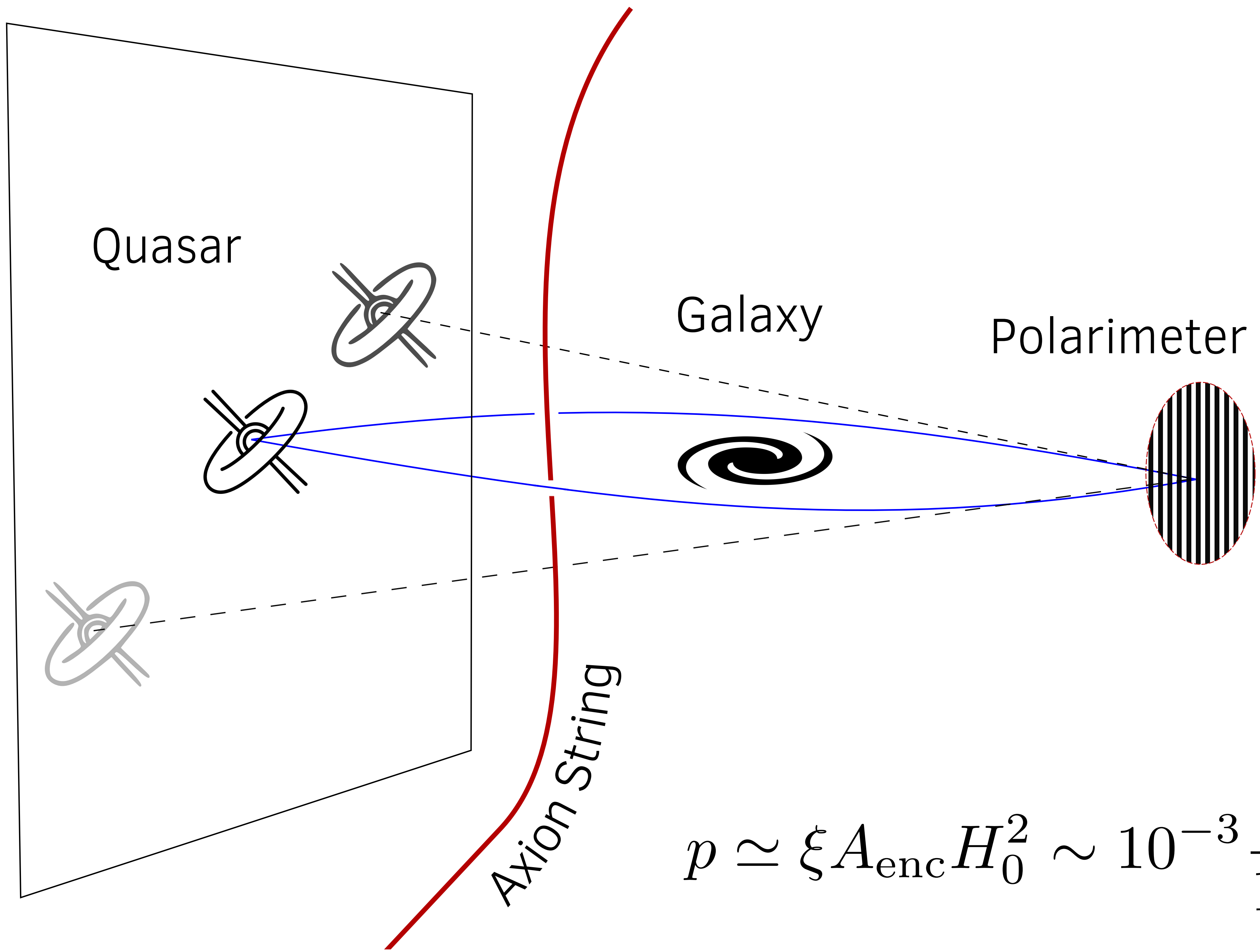
$$\xi = 100$$

Edge Detection



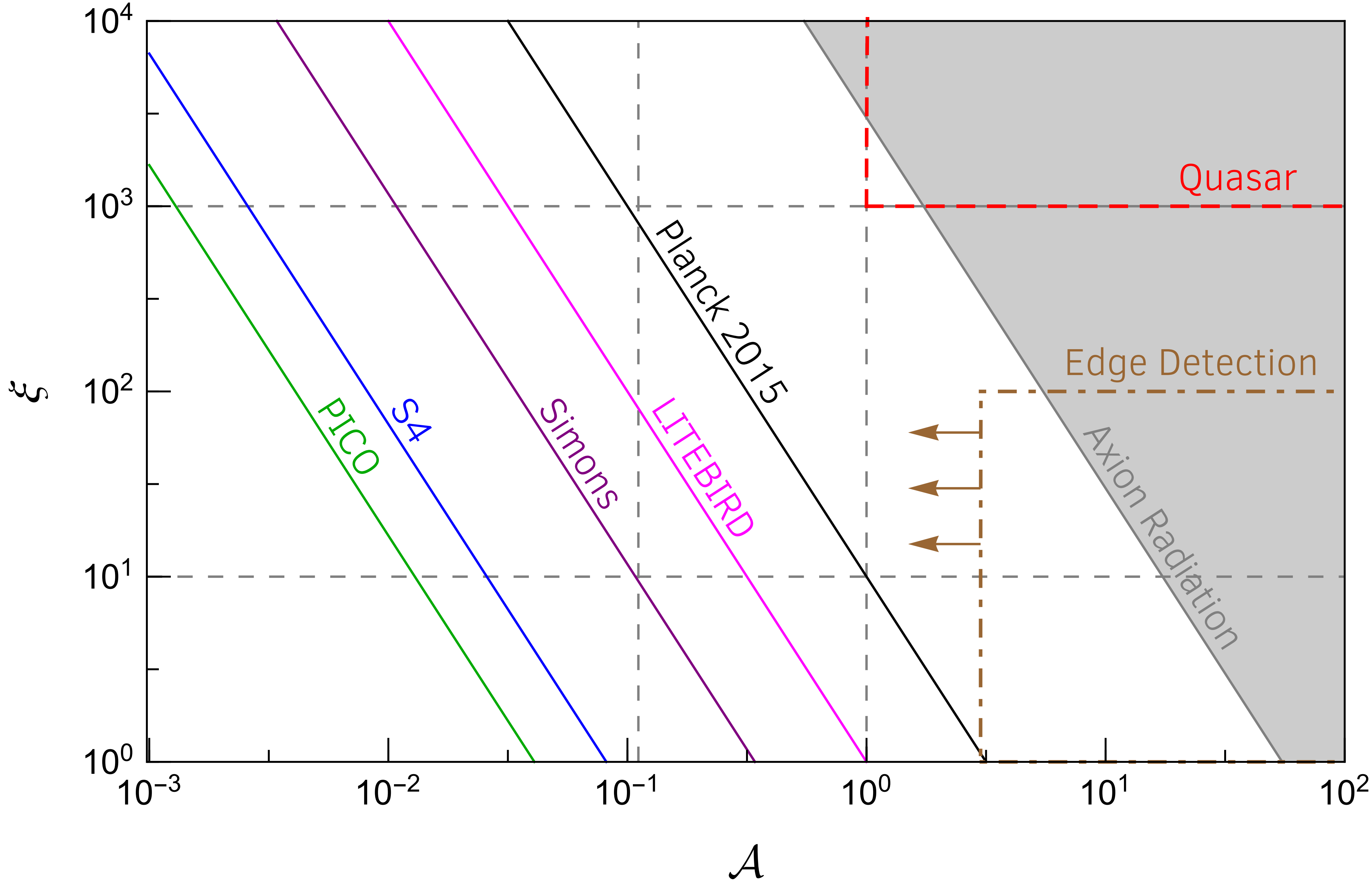
$\xi = 1$ $\xi = 10$ $\xi = 100$

Lensed Quasar systems



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

Reach Estimates



Thank You!