Axion Strings in the Sky

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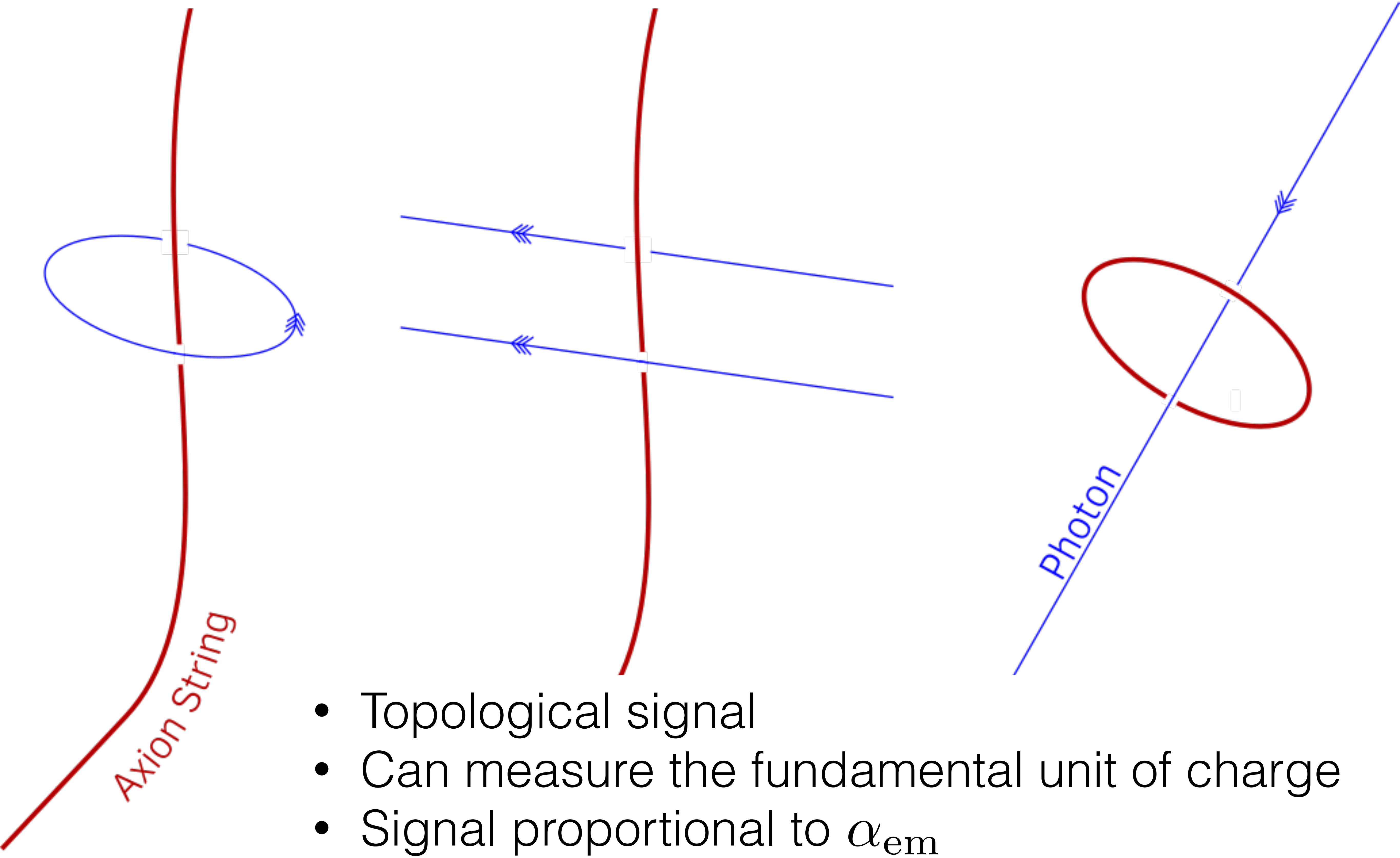
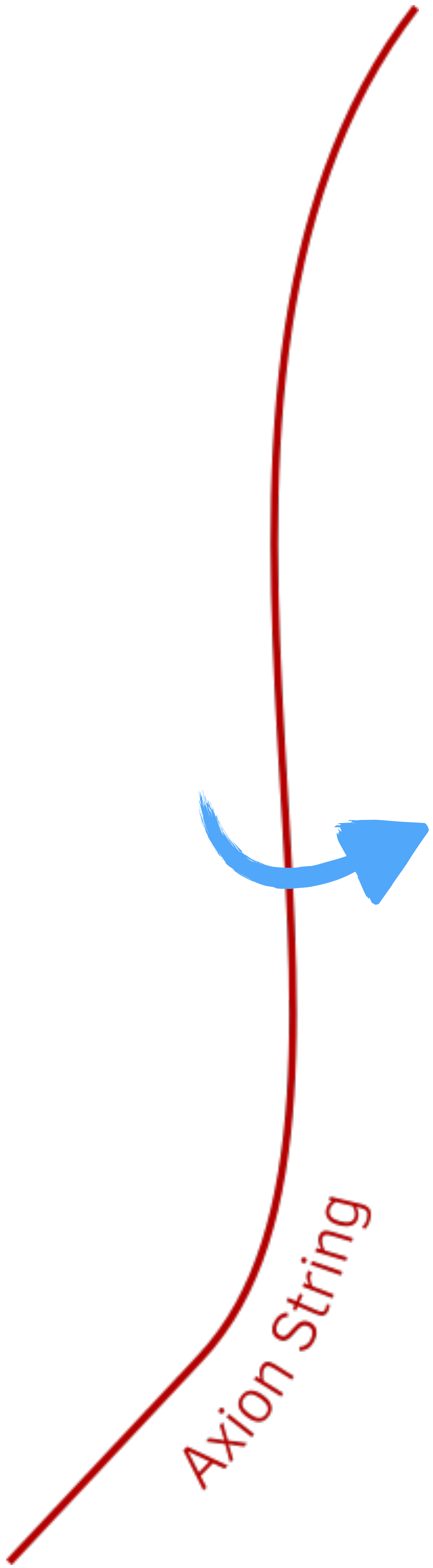
[1912.02823]
PA, Anson Hook, Junwu Huang
[2010.15848]
+Gustavo Marques-Tavares

A Cosmological Millikan Experiment

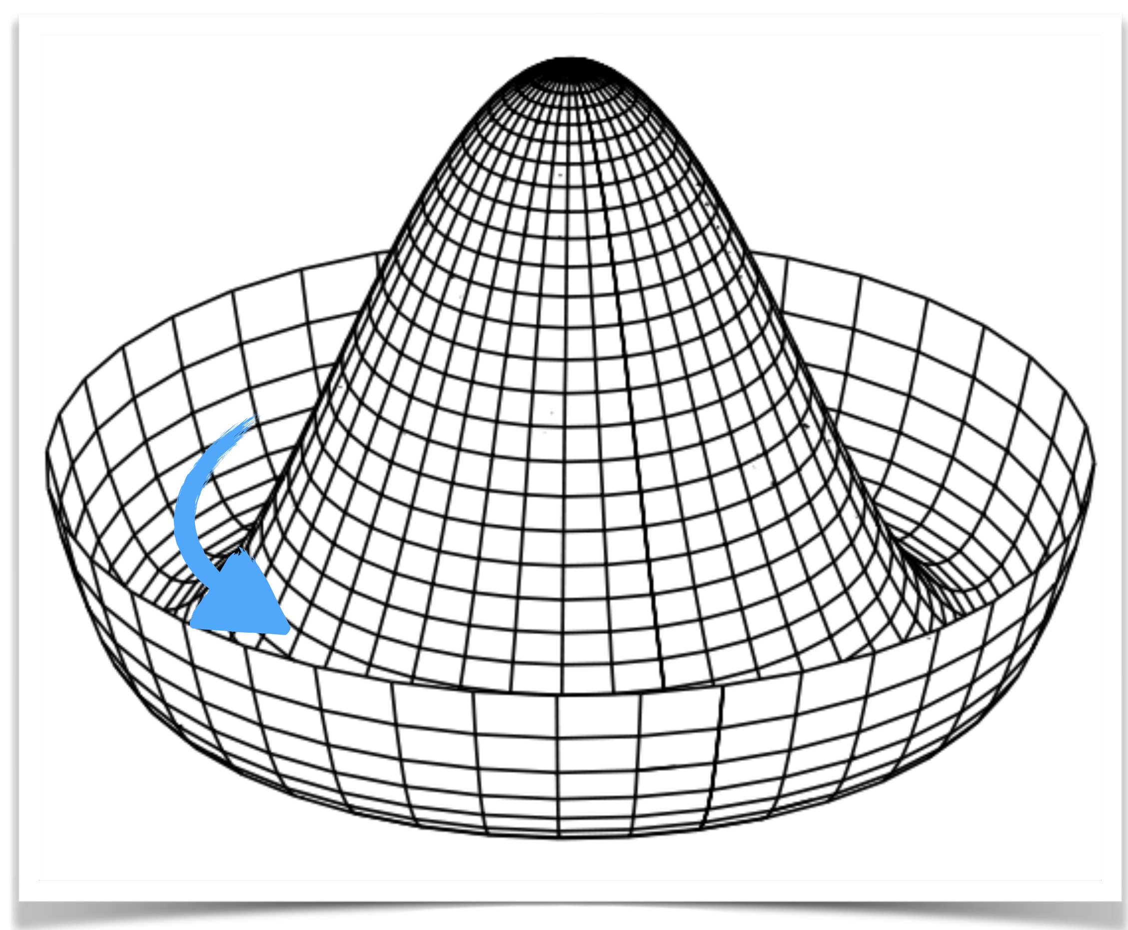


- Topological signal
- Can measure the fundamental unit of charge
- Signal proportional to $\alpha_{\rm em}$

Axion Strings

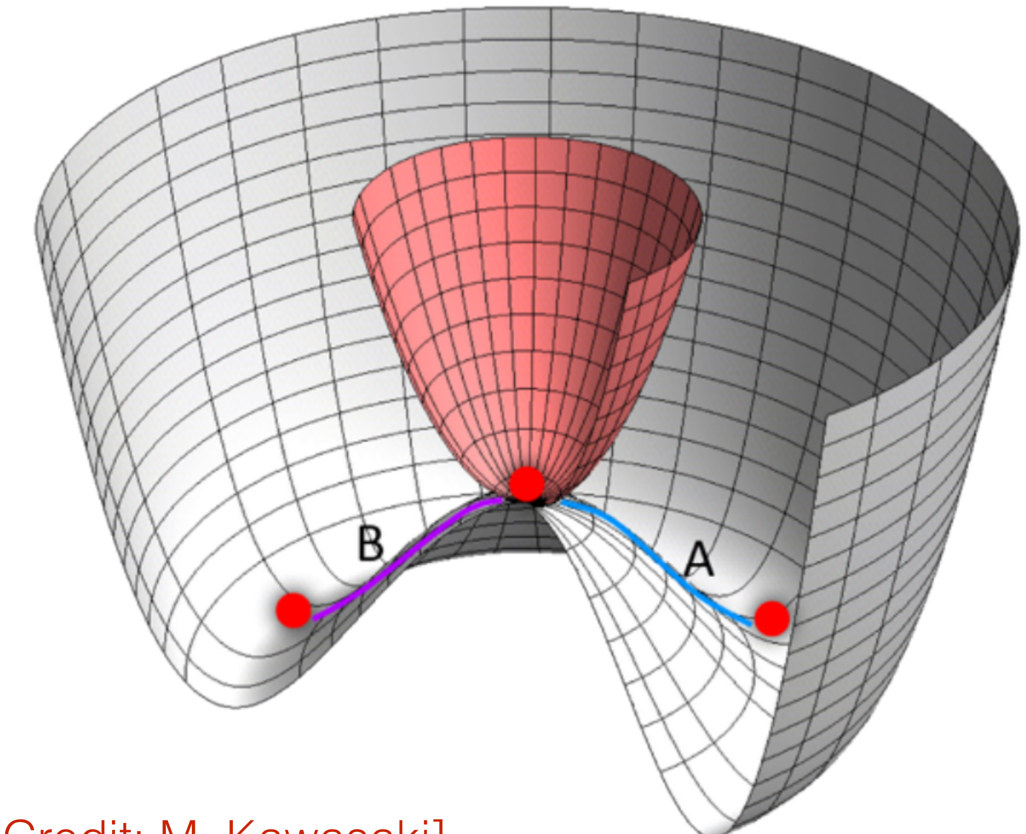


Spontaneously broken Peccei-Quinn symmetry

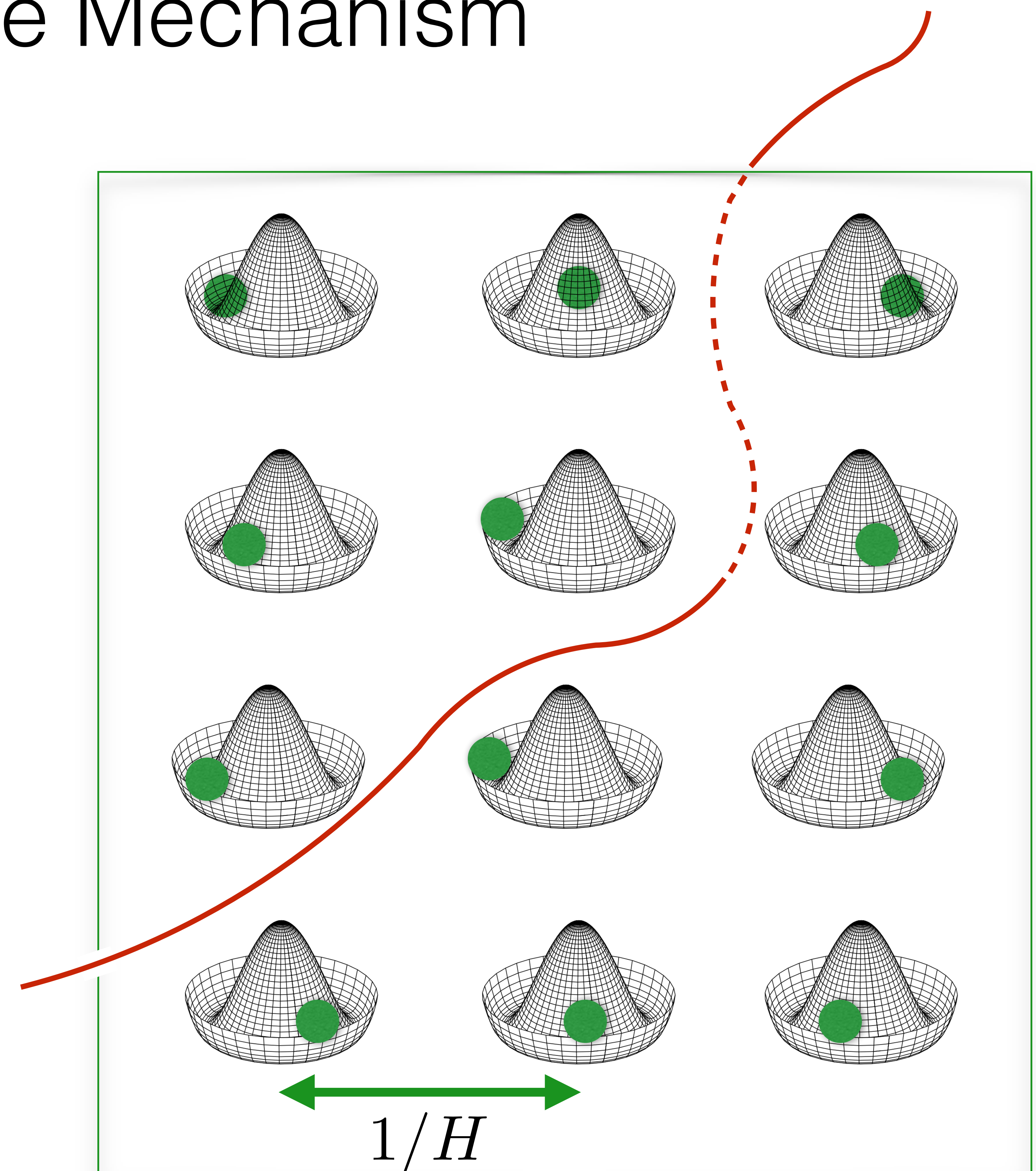


$$a \to a + 2\pi f$$

Kibble Mechanism

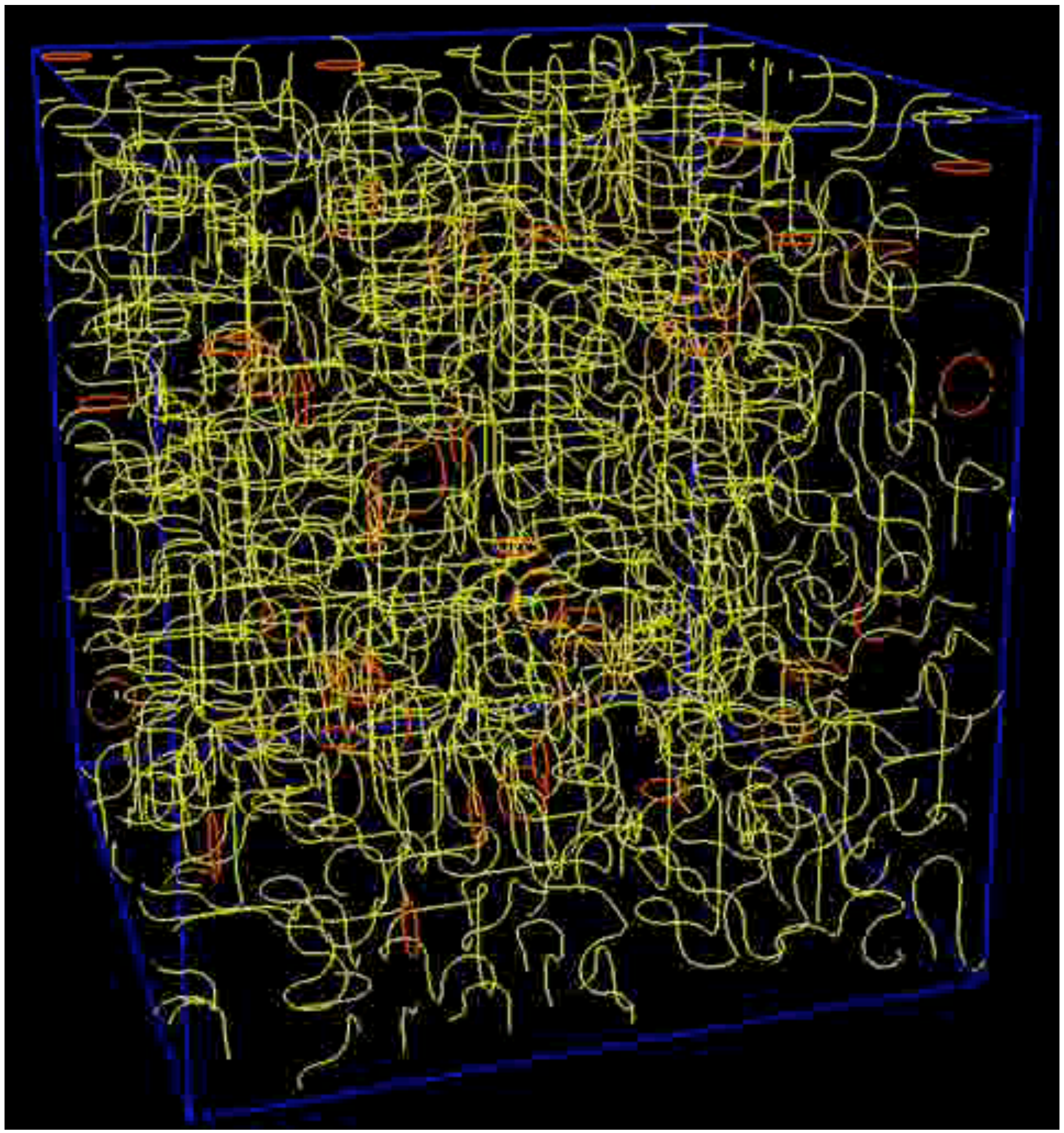


[Credit: M. Kawasaki]



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

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

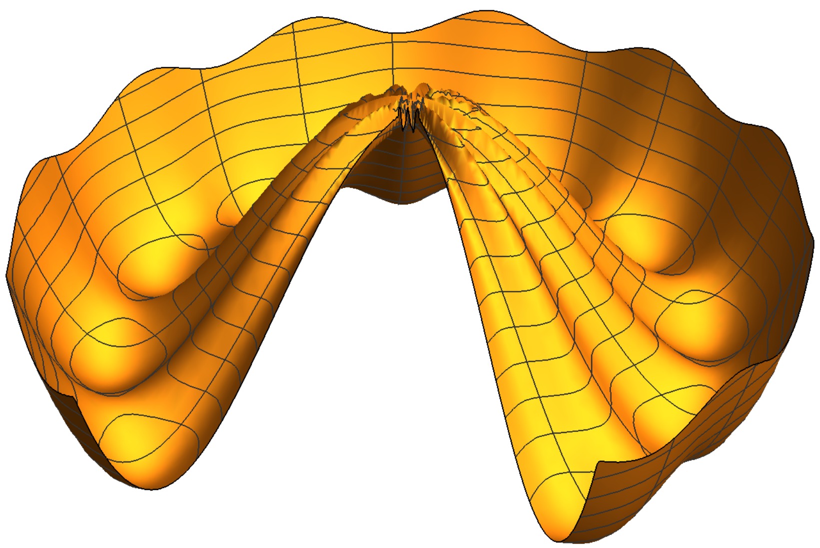
$$10^3 > \xi > 1$$

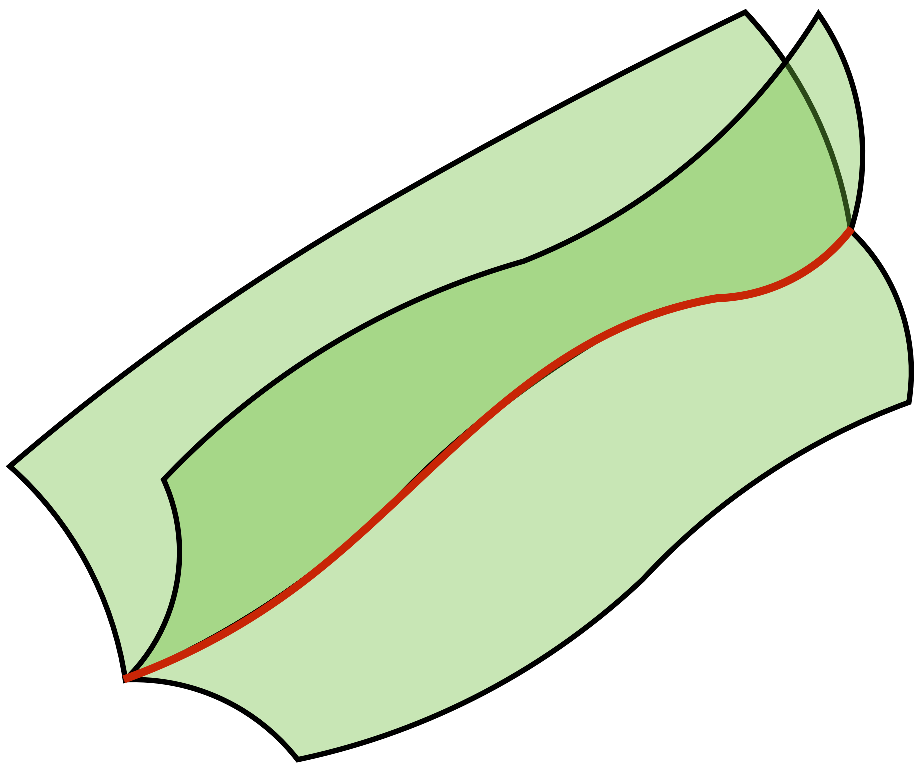
Equivalent to ξ strings per Hubble volume

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



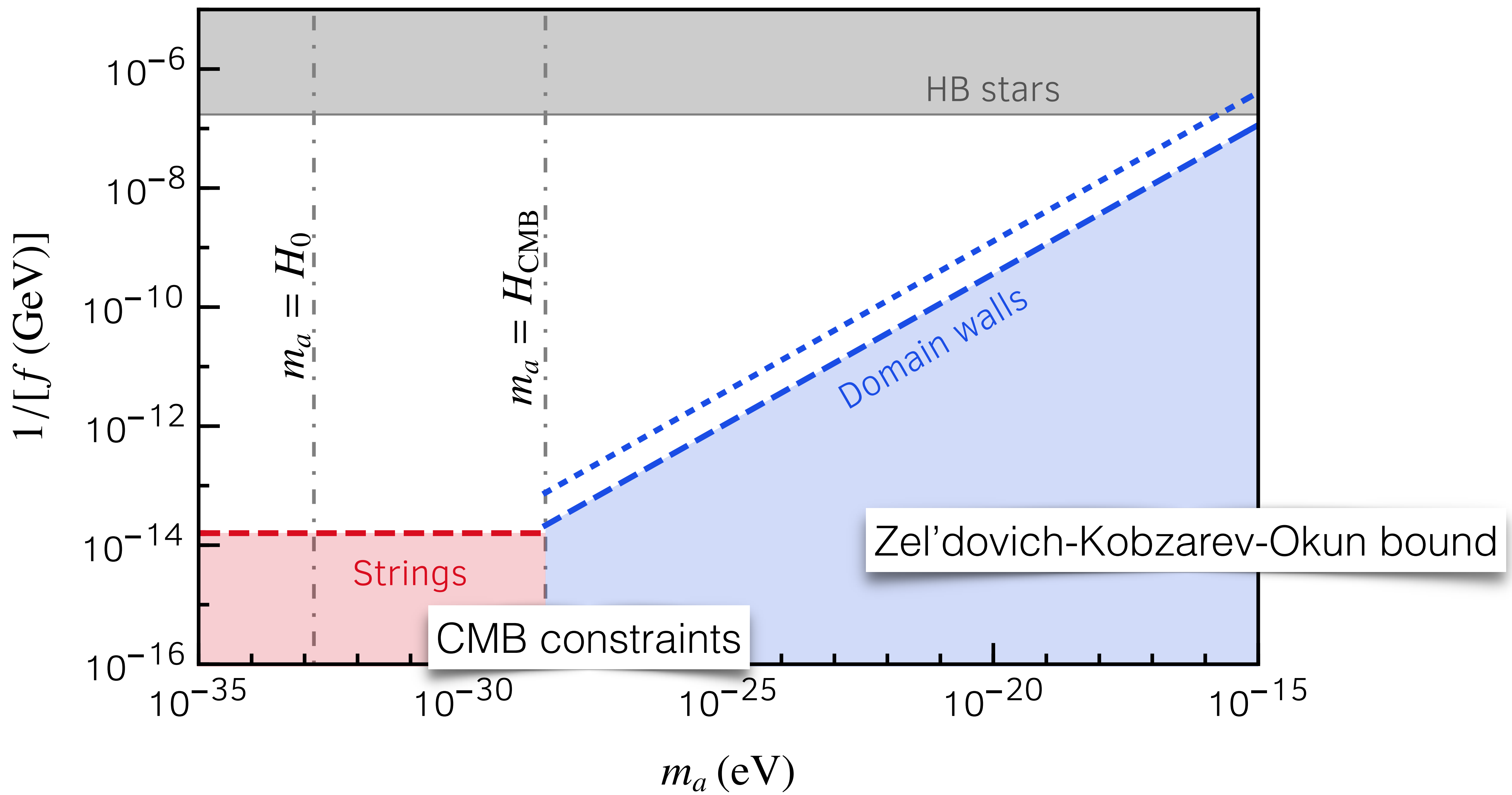


When $H < m_a$, domain walls ending on strings form

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

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

Hyperlight axions



Not QCD axion, not dark matter

The String Axiverse

Hyperlight axions are ubiquitous in string compactifications

[arXiv:0905.4720]
Arvanitaki, Dimopoulos,Dubovsky, Kaloper, March-Russell

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

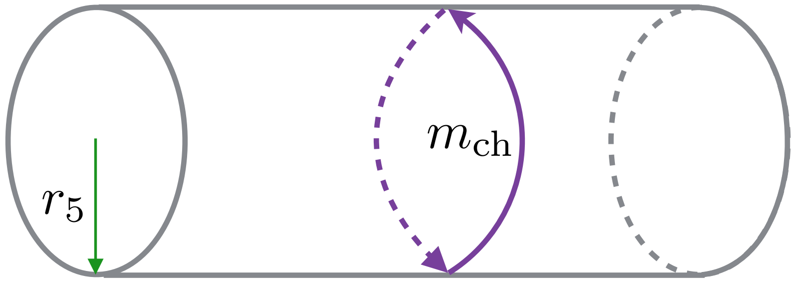
Axions are light, protected by an approximate shift symmetry

$$a \to a + c$$

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

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

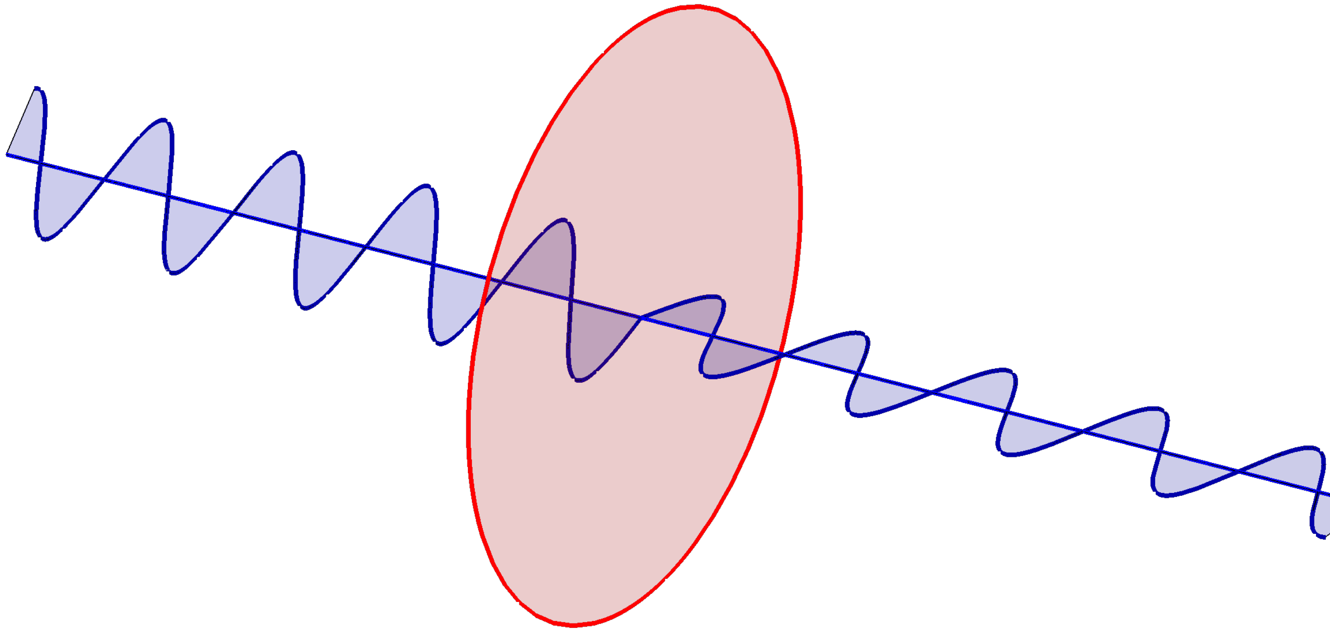
$$V(a) \sim \exp(-M_{\rm pl}/f)\cos(a/f)$$

"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

$$\mathcal{A} \in \left[\frac{\mathcal{Q}_{\rm fund}}{\mathcal{Q}_e} \times \mathbb{Z}\right]^2$$

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

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

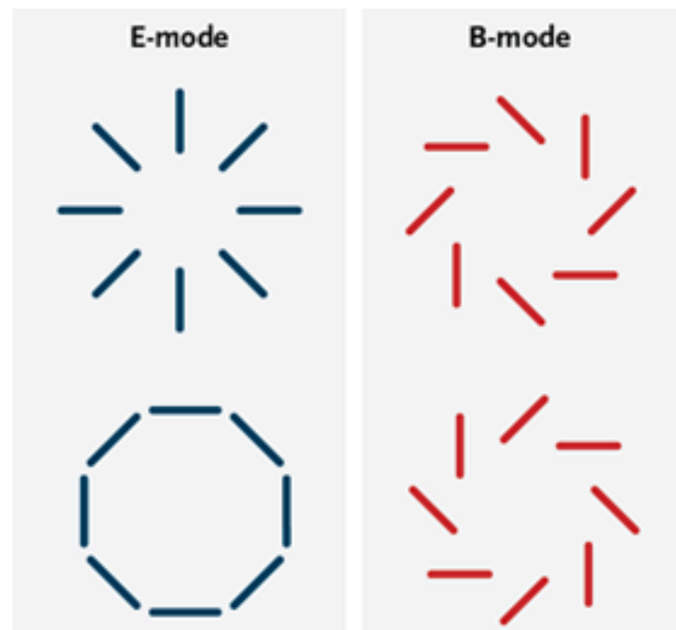
However, around axion strings, both the axion and the pion shift, so

$$\Delta\Phi = \mathcal{A}\alpha_{\rm em} \quad \text{with} \quad \mathcal{A} \in \left[\frac{\mathcal{Q}_{\rm fund}}{\mathcal{Q}_e} \times \mathbb{Z}\right]^2$$

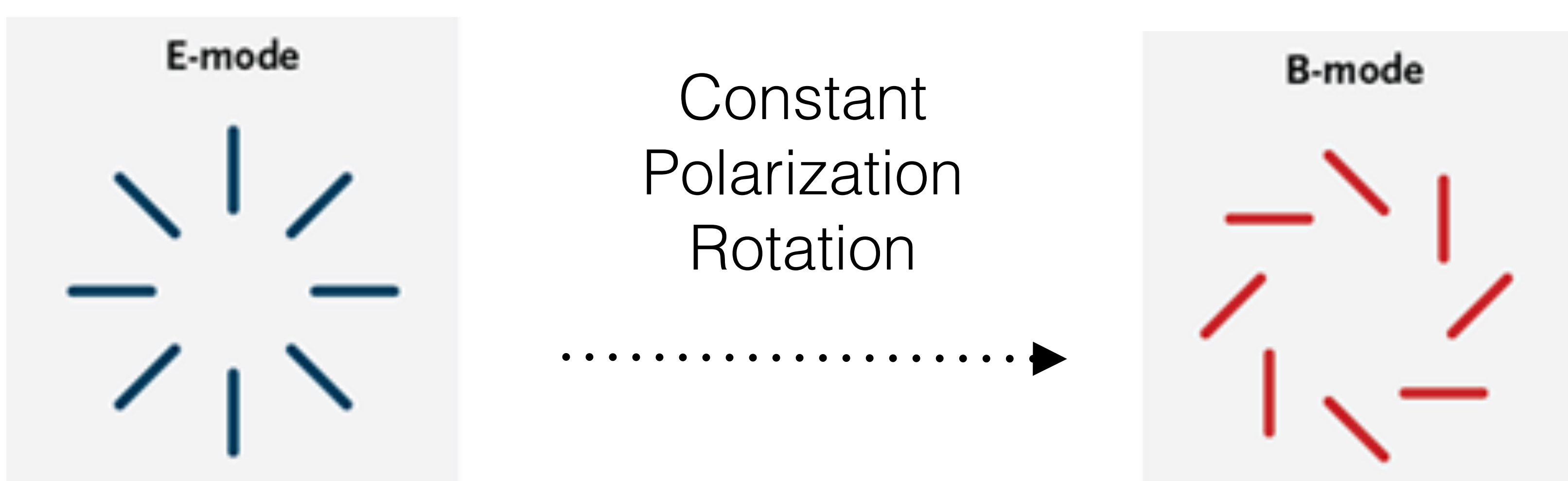
Measuring $\mathcal{A}$ can test the fundamental unit of electric charge

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

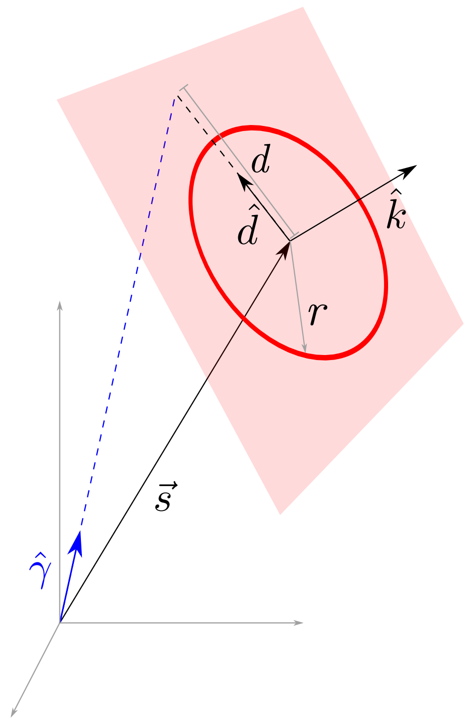
$$[\hat{\Phi}^{E^i B^j}_{LM}]_{ll'} = \frac{2\pi}{(2l+1)(2l'+1) C^{EE}_{l} H^{L}_{ll'}} \sum_{mm'} B^{i}_{lm} E^{j*}_{l'm'} \Xi^{LM}_{lml'm'}$$

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

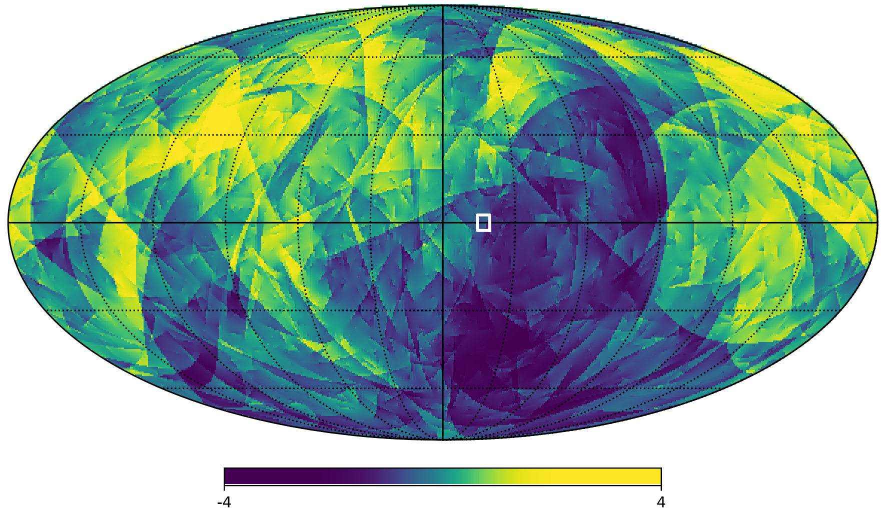
Theory predictions

Study the polarization rotation in two simplified settings

1. Semi-analytical approach



2. Simple numerical simulation

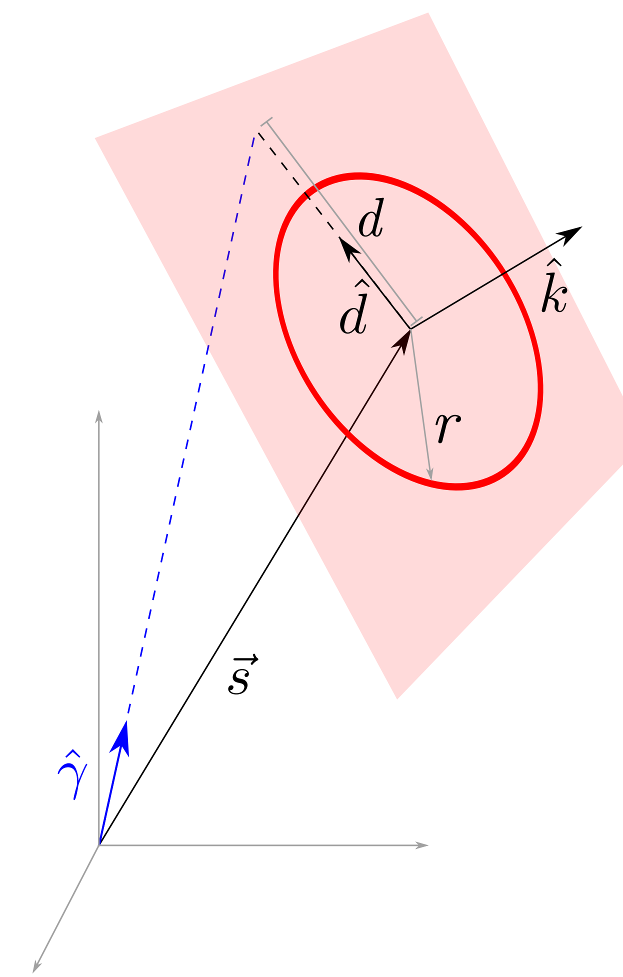


Future direction: Set up a string simulation for hyperlight axions combined with a CMB simulation

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

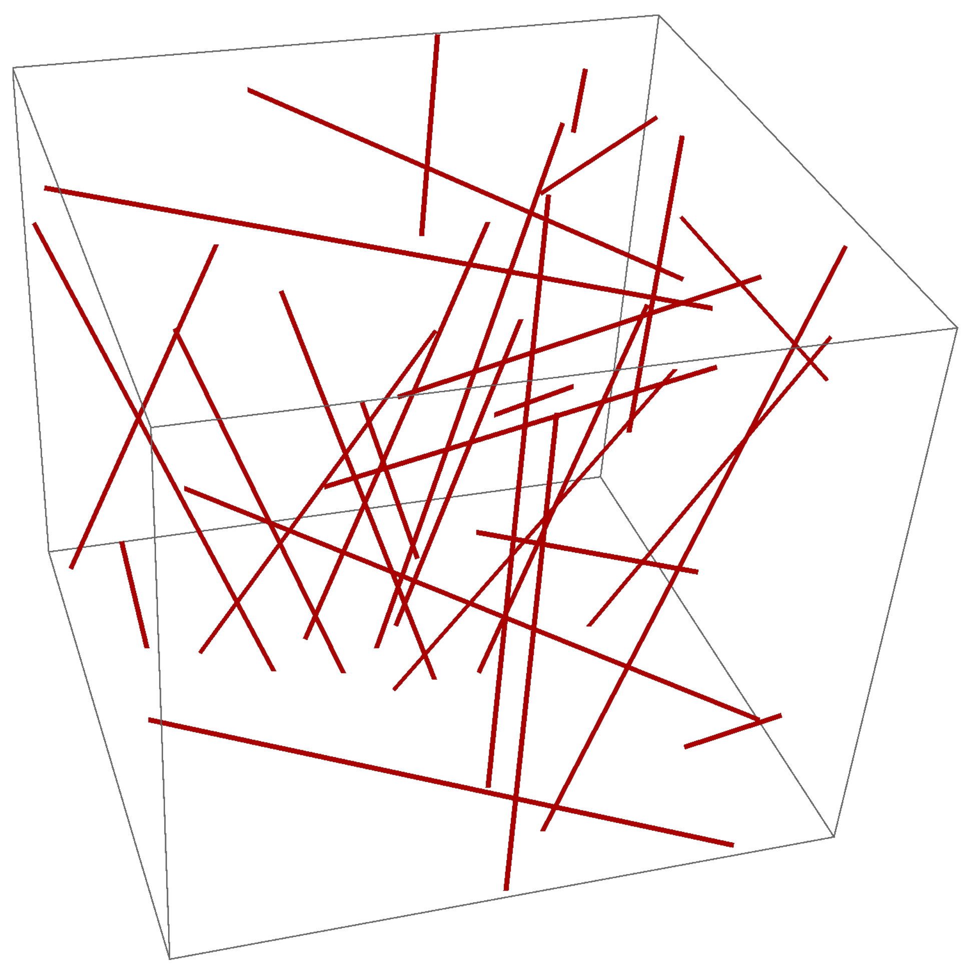
Model String network by

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

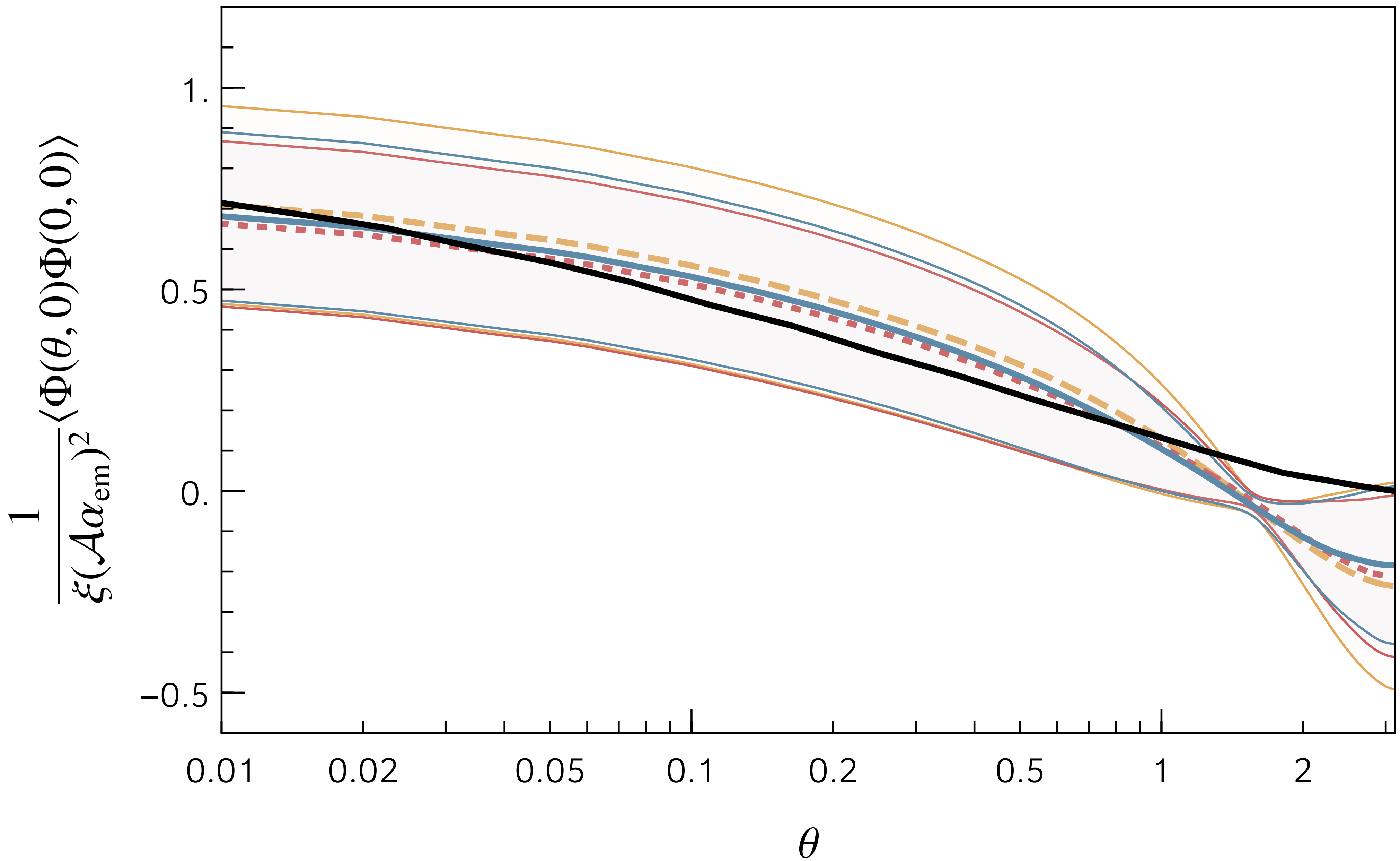
Strings are removed randomly to maintain scaling

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

Captures larger angular scale correlations well



Two-point function

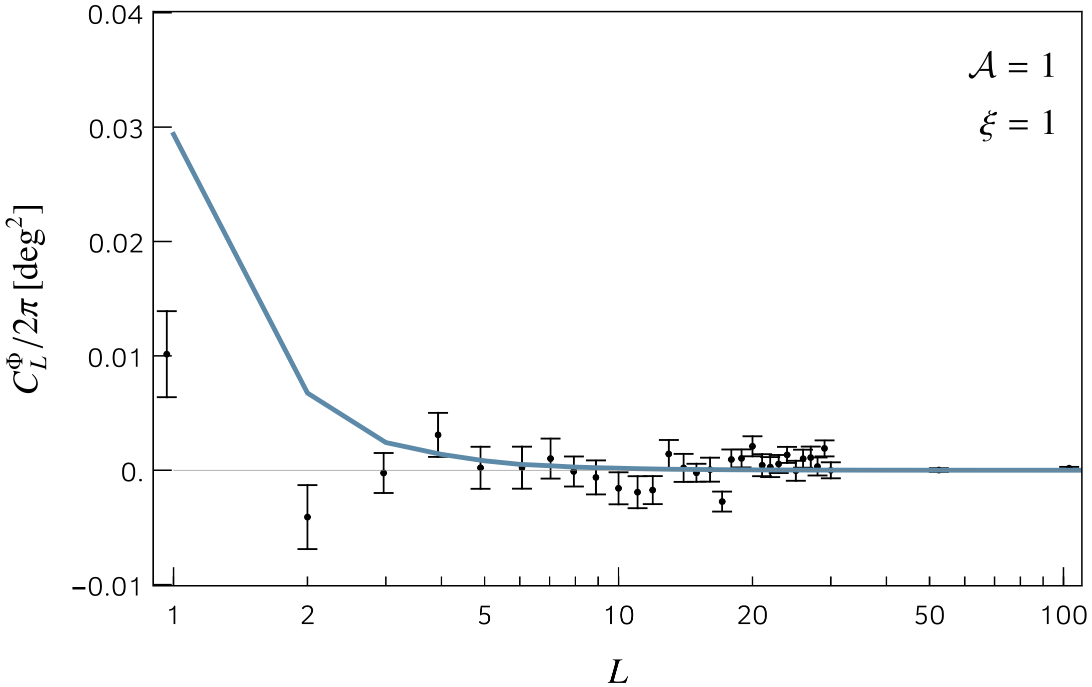


Constraints / Forecasts

Constraints

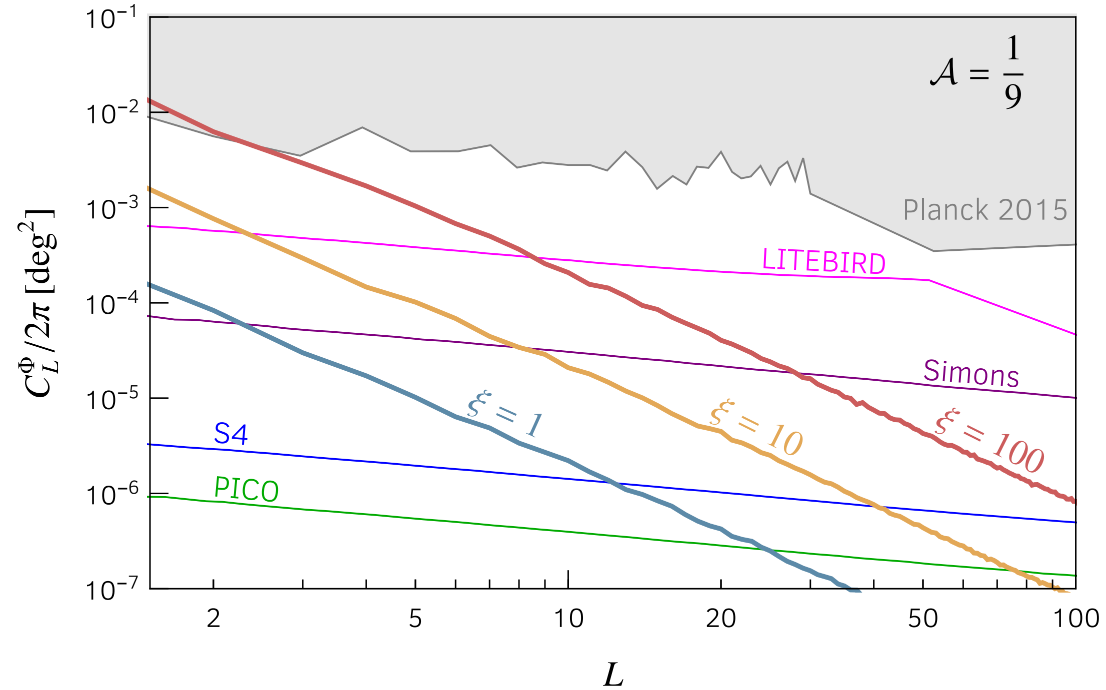
Planck 2015

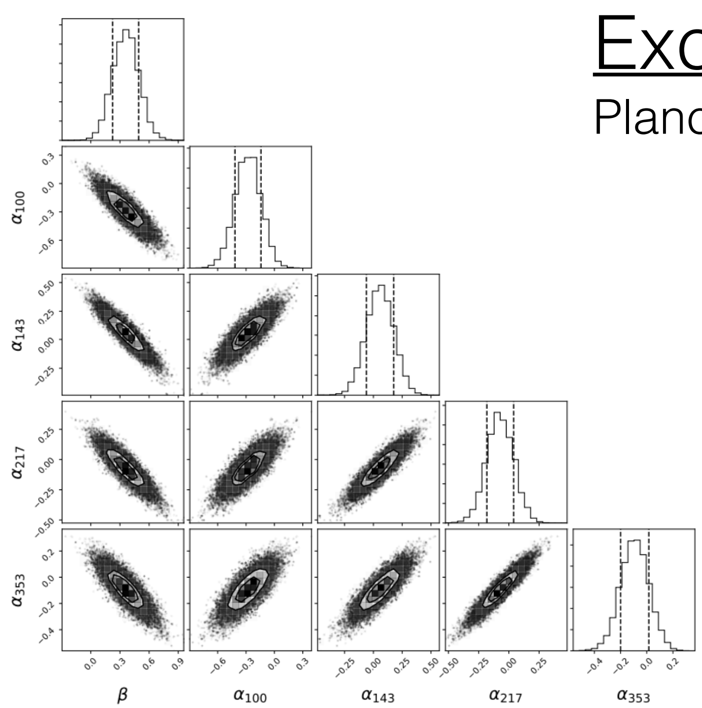
Contreras, Boubel, Scott
[arXiv:1705.06387]



Forecasts

Pogosian et al
[arXiv:1904.07855]





Excess in Birefringence (L = 0)

Planck 2018

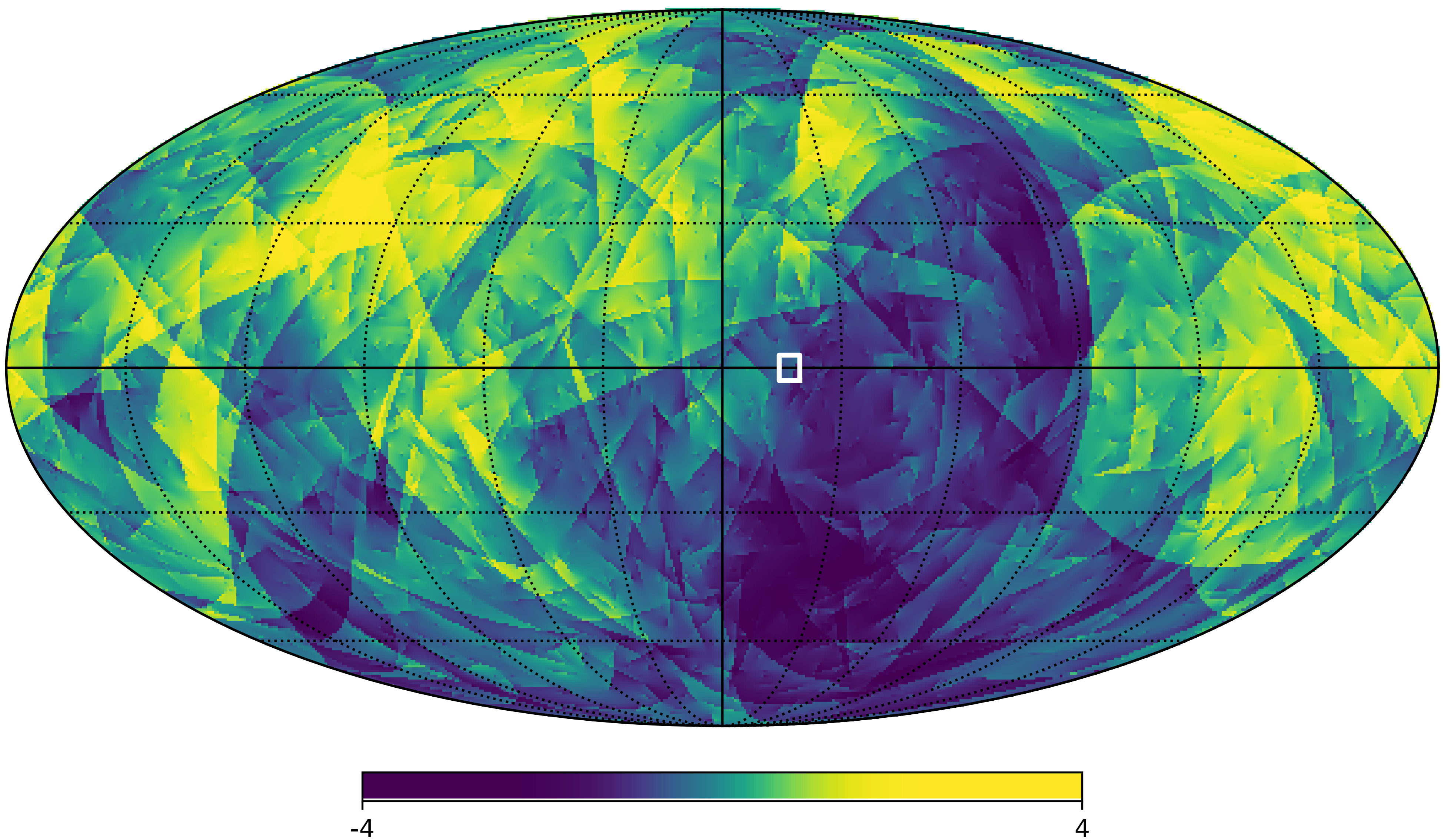
Stat: 2.4σ

$\beta = 0.35 \pm 0.14$ deg

$\alpha_{\rm em} = 0.42$ deg

Minami, Komatsu
[arXiv:2011.11254]

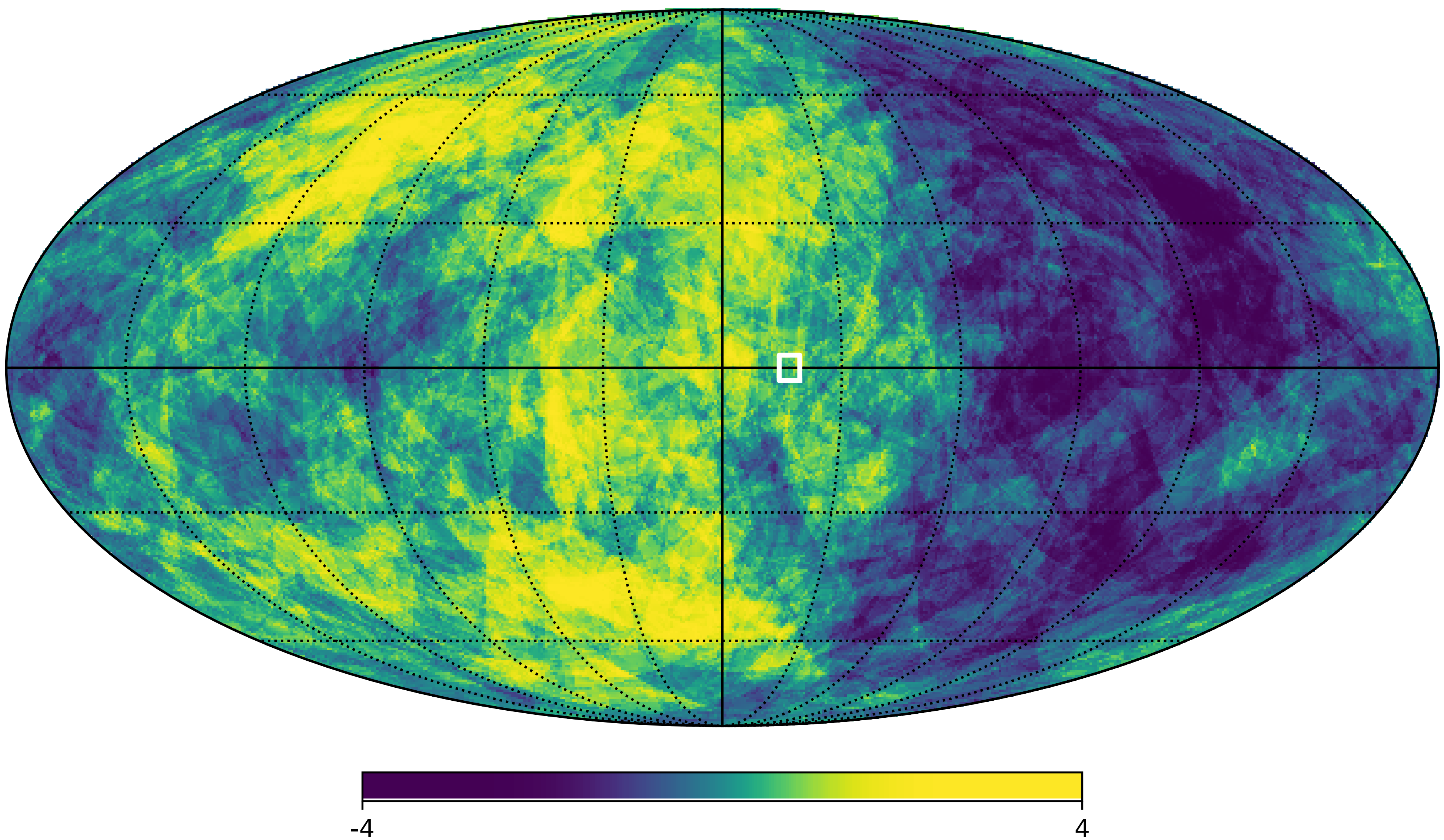
Sky maps



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

$\xi = 1$

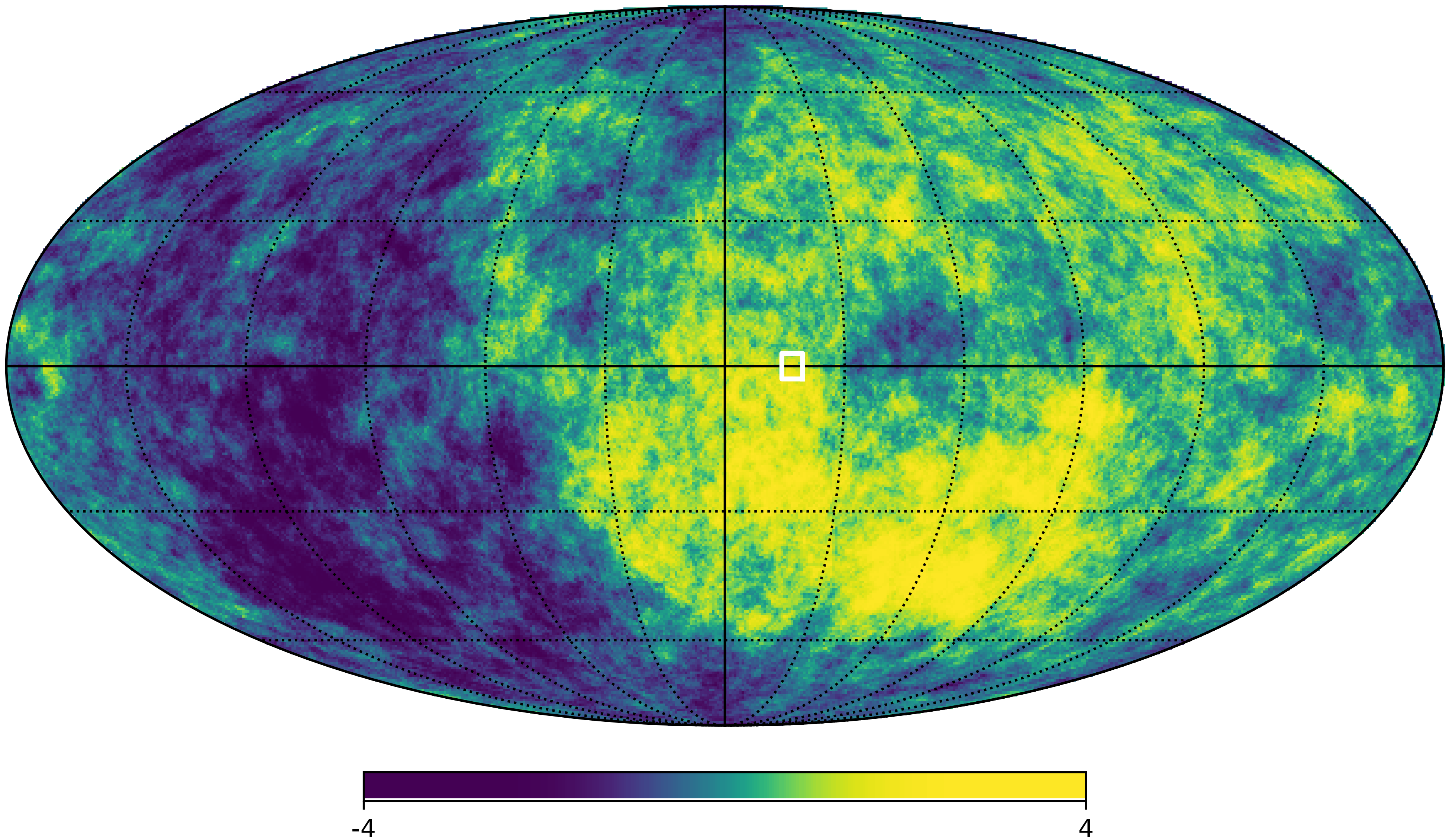
Sky maps



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

$\xi = 10$

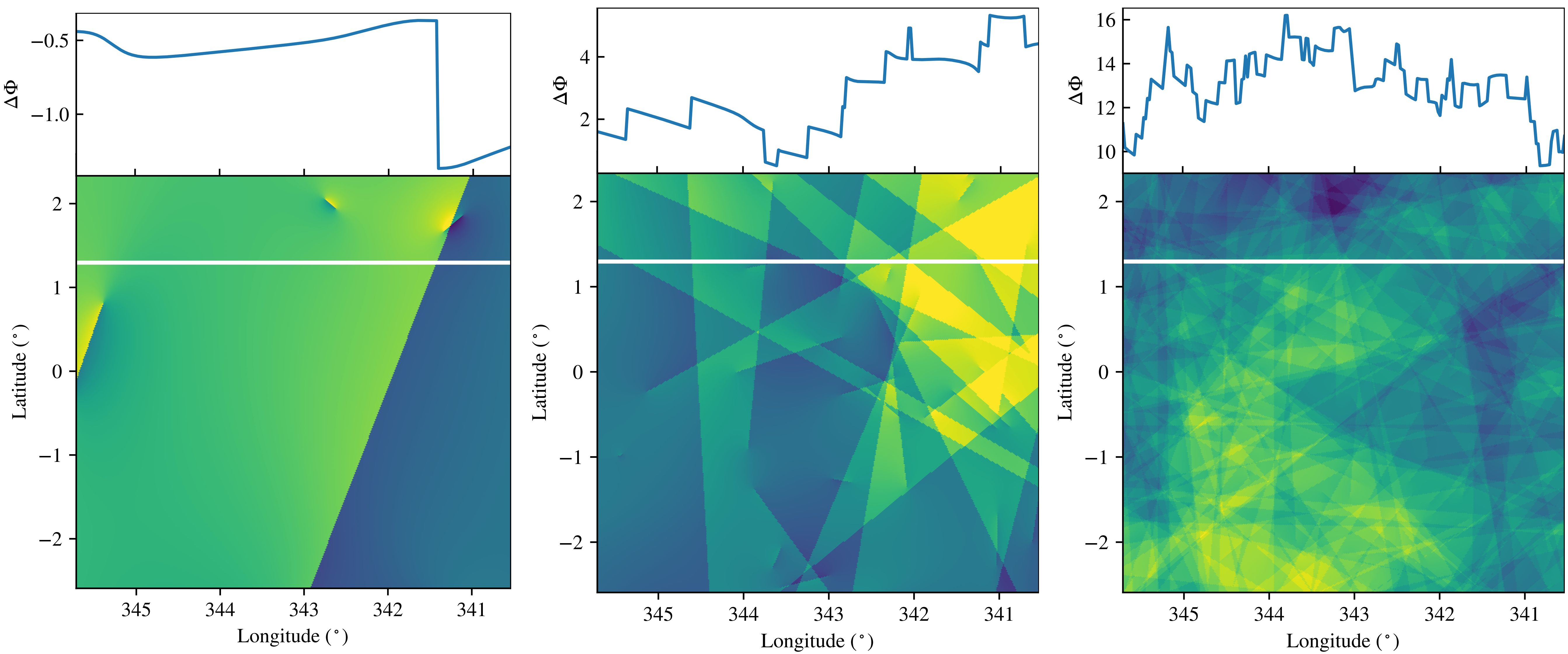
Sky maps



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

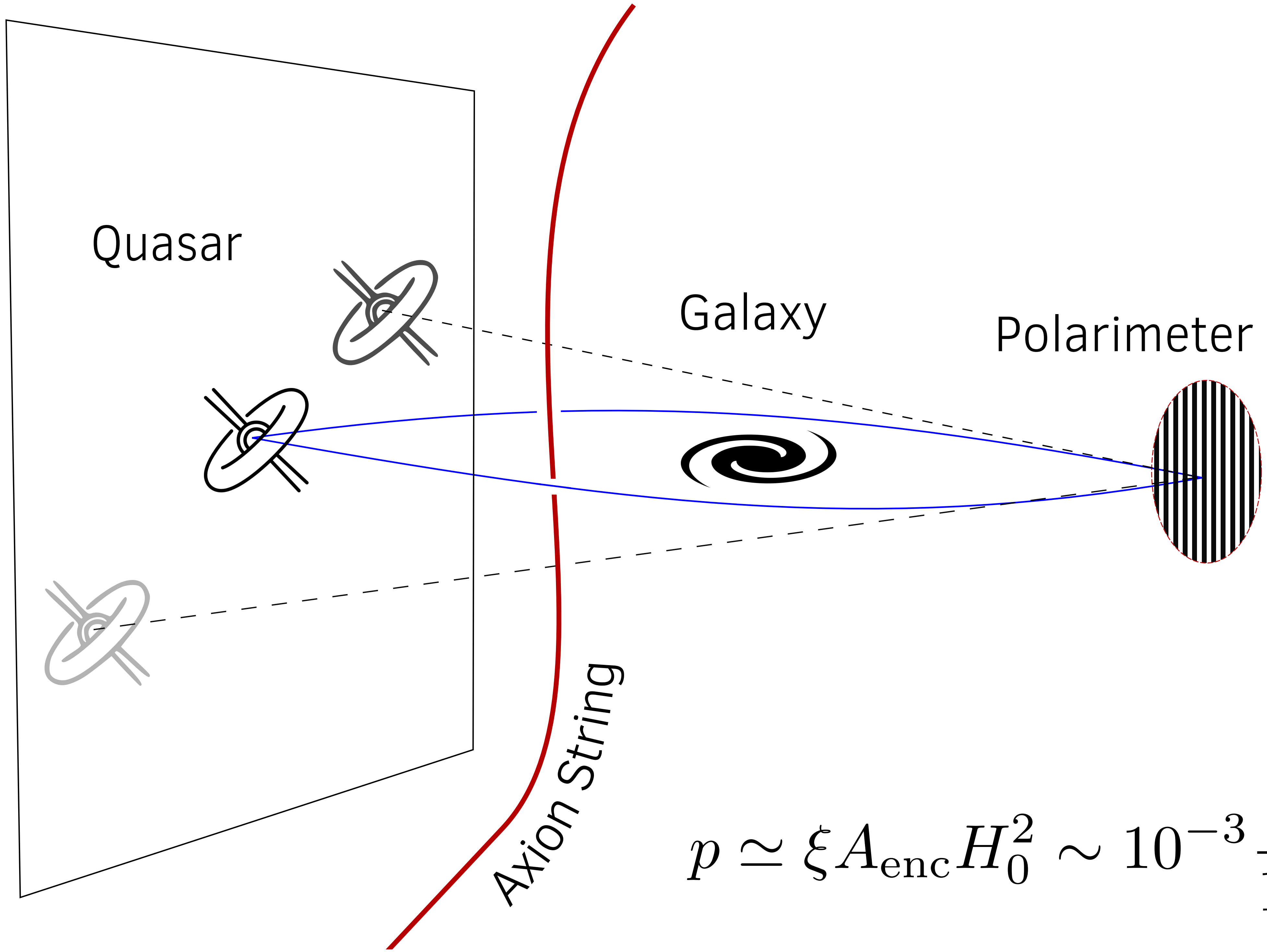
$\xi = 100$

Edge Detection



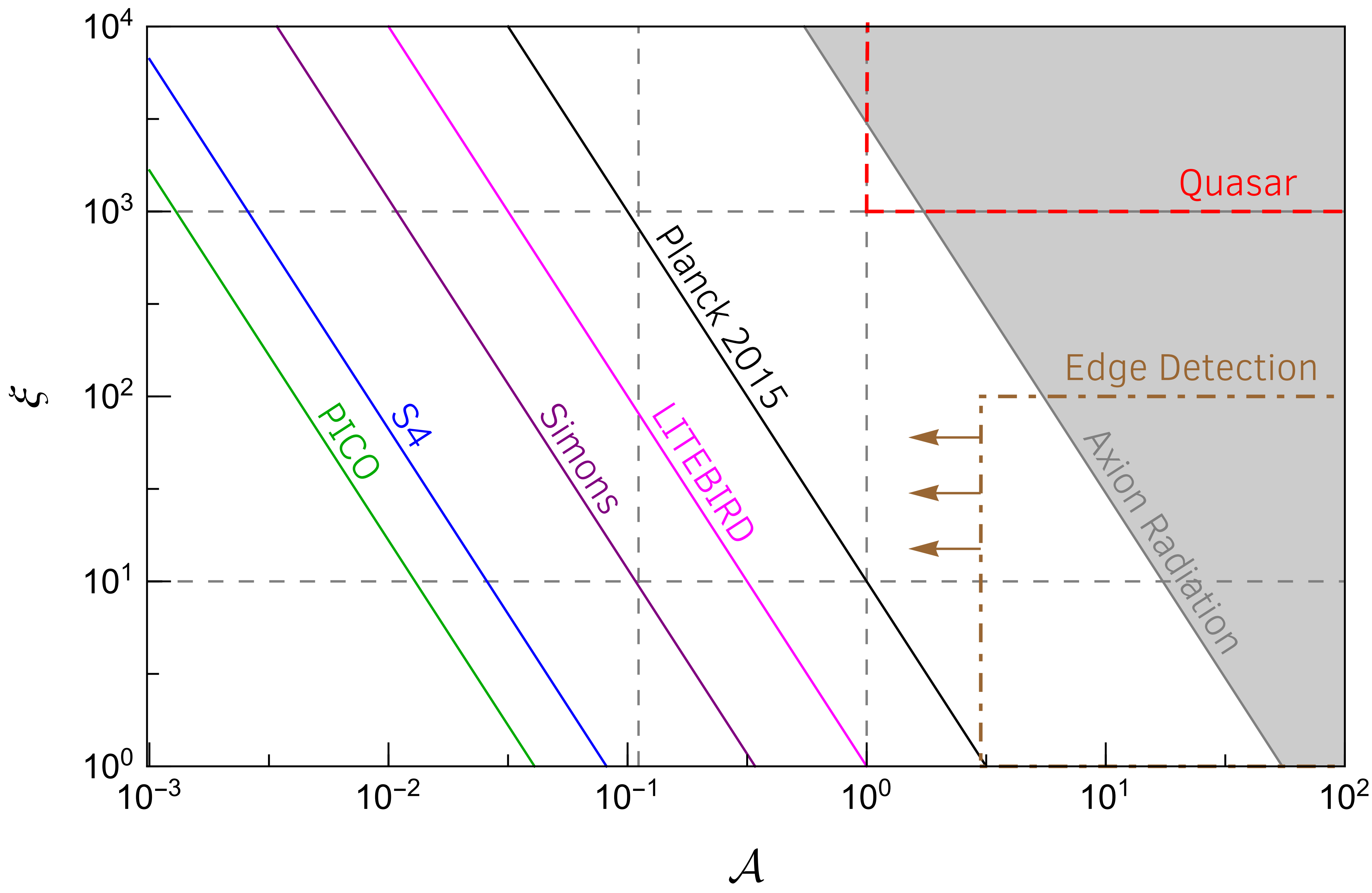
$\xi = 1$ $\xi = 10$ $\xi = 100$

Lensed Quasar systems



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

Reach Estimates



Electromagnetic properties

Axion strings are superconducting!

- Consequence of Atiyah-Singer index theorem and axion EM anomaly
- Chiral edge mode of PQ quark lives on the string
- Quantum Hall edge state
- E.g. only left-moving + charged state

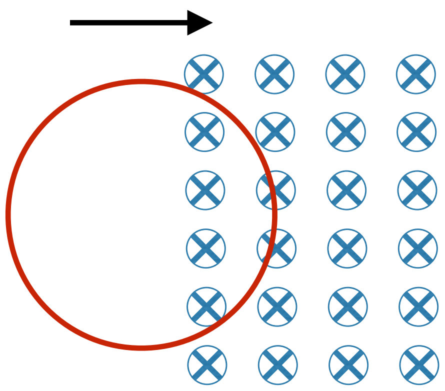
[Nucl.Phys.B 250 (1985)]
Callan, Harvey

Contrast with Witten's superconducting strings

- Witten strings are *local* strings (Abrikosov-Nielsen-Olesen strings)
- Non-chiral spectrum, equal number of + and - left-moving modes

[Nucl.Phys.B 249 (1985)]
Witten

Crossing magnetic flux induces charge + current on the axion string



Witten strings are magnetic: induced currents when they cross magnetic field
Axions strings are electric: both charges and currents are induced

Charging Up Axion strings

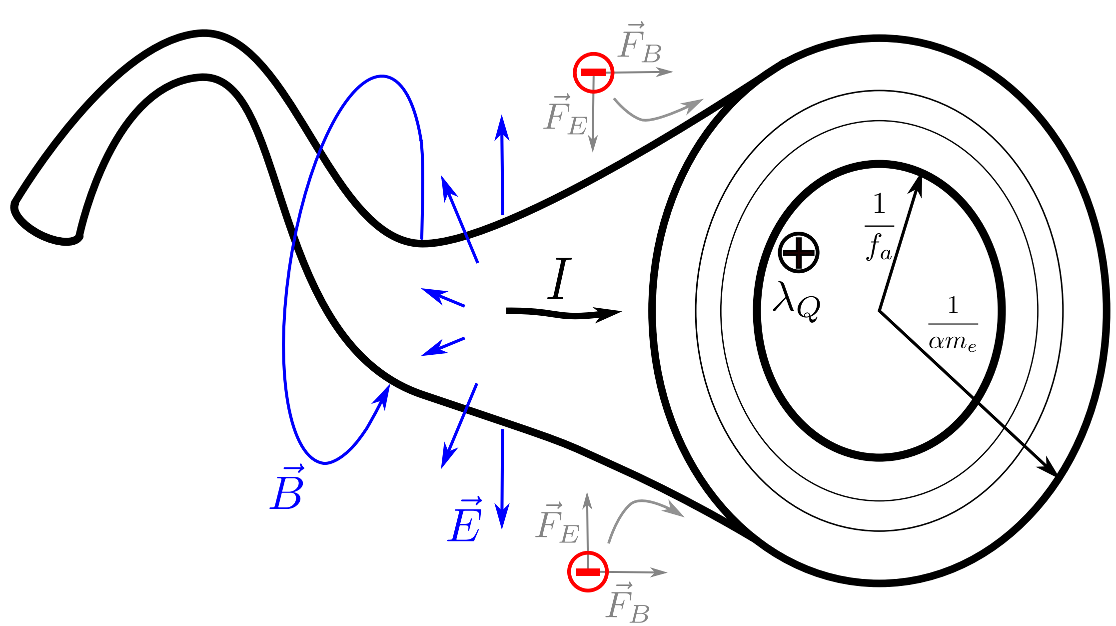
Axion strings encounter galaxies and galaxy clusters

$$N_K \simeq \xi H^3 L_{\rm string} N_{\rm galaxy} A_{\rm galaxy} \approx 100 \left(\frac{\xi}{10}\right)\left(\frac{N_{\rm galaxy}}{10^{12}}\right)\left(\frac{A_{\rm galaxy}}{(10\,{\rm kpc})^2}\right)$$

Galactic magnetic flux crossing the string charges up the string

$$\lambda_Q = \frac{e^2\mathcal{A}}{2\pi} B_{\rm galaxy} d_{\rm galaxy} v_s \approx 3\times 10^8\,{\rm GeV}\left(\frac{\mathcal{A}}{1}\right)\left(\frac{B_{\rm galaxy}}{5\,\mu{\rm G}}\right)\left(\frac{v_s}{0.1}\right)\left(\frac{d_{\rm galaxy}}{10\,{\rm kpc}}\right)$$

Electric (and magnetic) fields from the charge string result in a 1-d atom with SM plasma



A Plasma Collider in the Sky

SM plasma around the string travels and collides with other wavepackets at very high energies

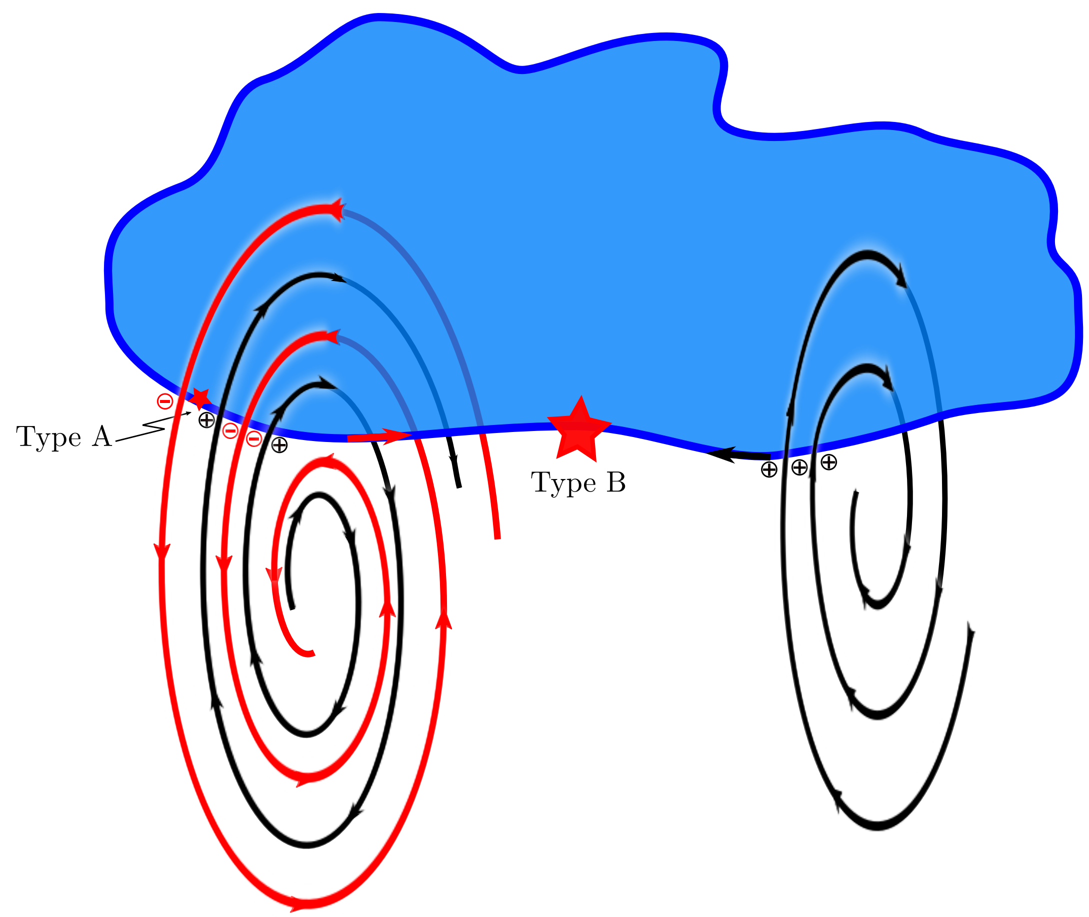
$$E \simeq \frac{e\lambda_Q}{2\pi} \log(f_a L)$$

Collisions can be as bright as 10 million suns

$$P \simeq \frac{\lambda_Q^2}{2\pi} \log(f_a L) \approx 10^{40}\,\mathrm{erg/s} \left(\frac{\lambda_Q}{10^9\,\mathrm{GeV}}\right)^2$$

Flux from the source at a cosmological distance

$$\frac{P}{A} \simeq 10^{-16}\,\mathrm{erg/s/cm^2} \left(\frac{\xi \mathcal{A}^2}{1}\right)$$

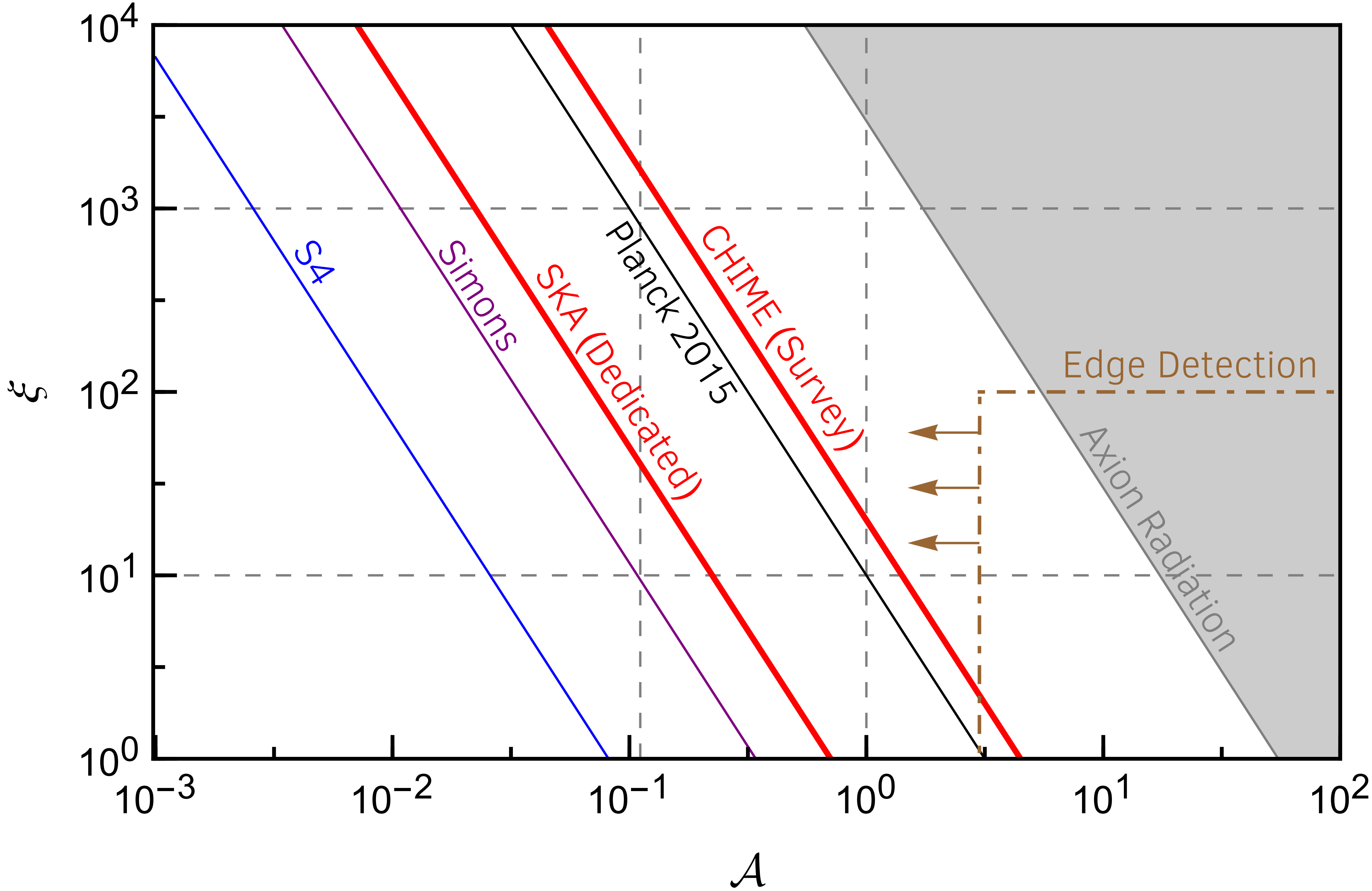


Details of the spectrum hard to model, high energy emission reabsorbed in the dense plasma

Radio Sensitivity

$$\begin{cases} 2\times 10^{-18}\mathrm{erg/s/cm^2}\left(\frac{\mathrm{SEFD}}{10^4\,\mathrm{Jy}}\right)\left(\frac{B}{\mathrm{GHz}}\right)^{1/2}\left(\frac{1000\,\mathrm{hr}}{t_{\mathrm{int}}}\right)^{1/2} & \text{(Survey)} \\ 5\times 10^{-20}\mathrm{erg/s/cm^2}\left(\frac{\mathrm{SEFD}}{10\,\mathrm{Jy}}\right)\left(\frac{B}{\mathrm{GHz}}\right)^{1/2}\left(\frac{\mathrm{hr}}{t_{\mathrm{int}}}\right)^{1/2} & \text{(Dedicated)} \end{cases}$$

Reach Estimates



Thank You!