Axion Strings in the Sky

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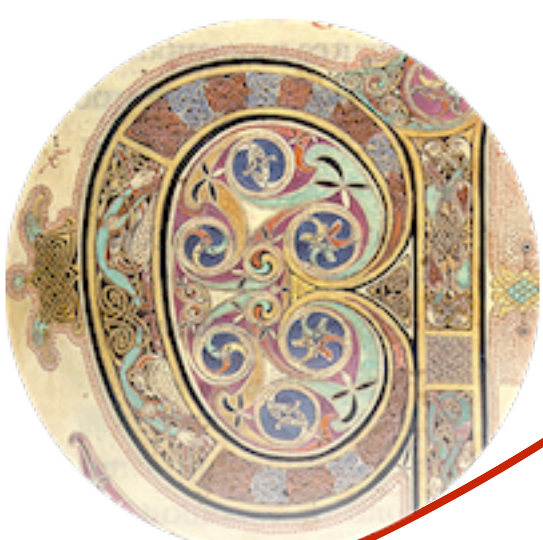
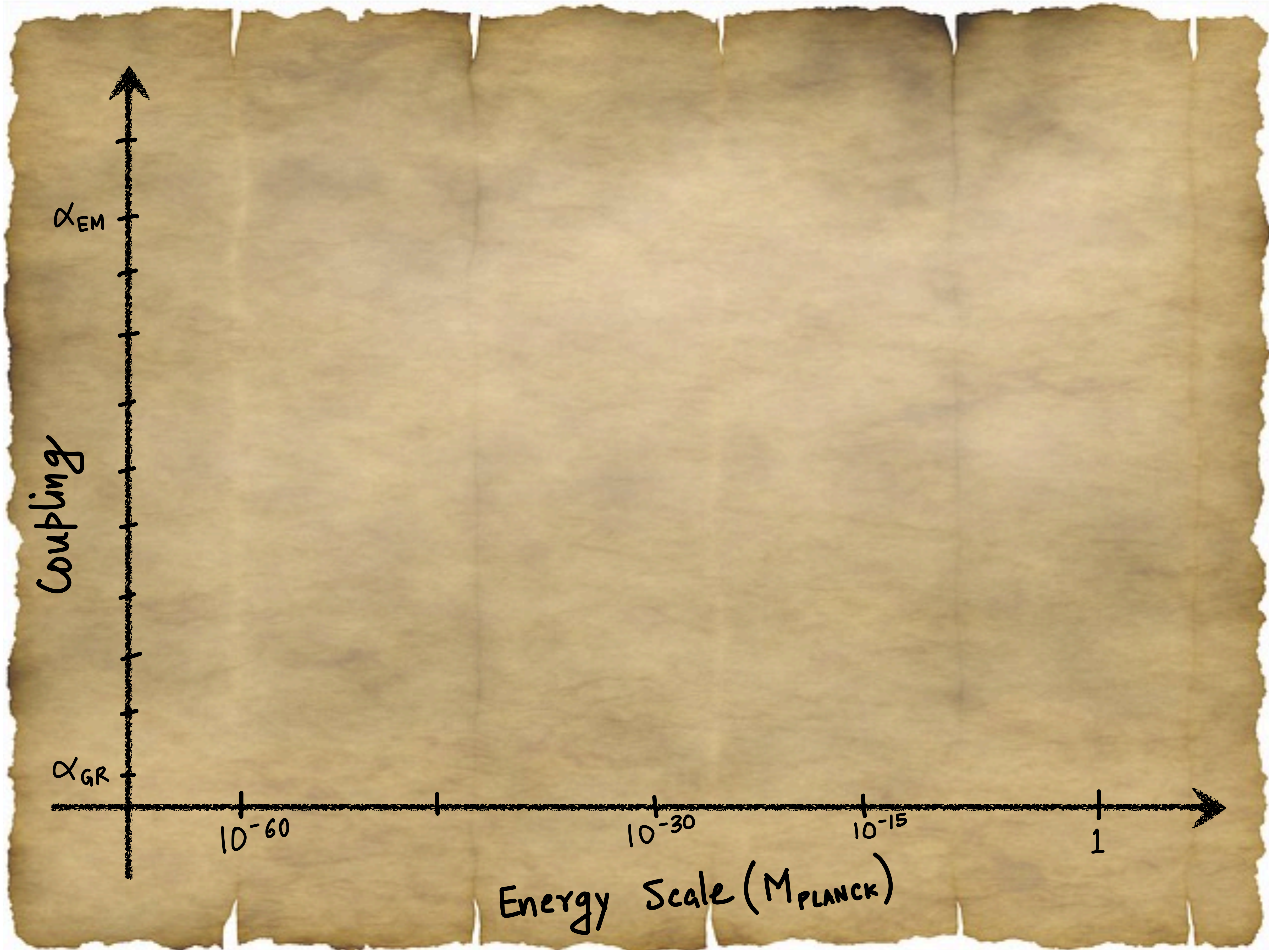
University of Oxford



Planck 2021

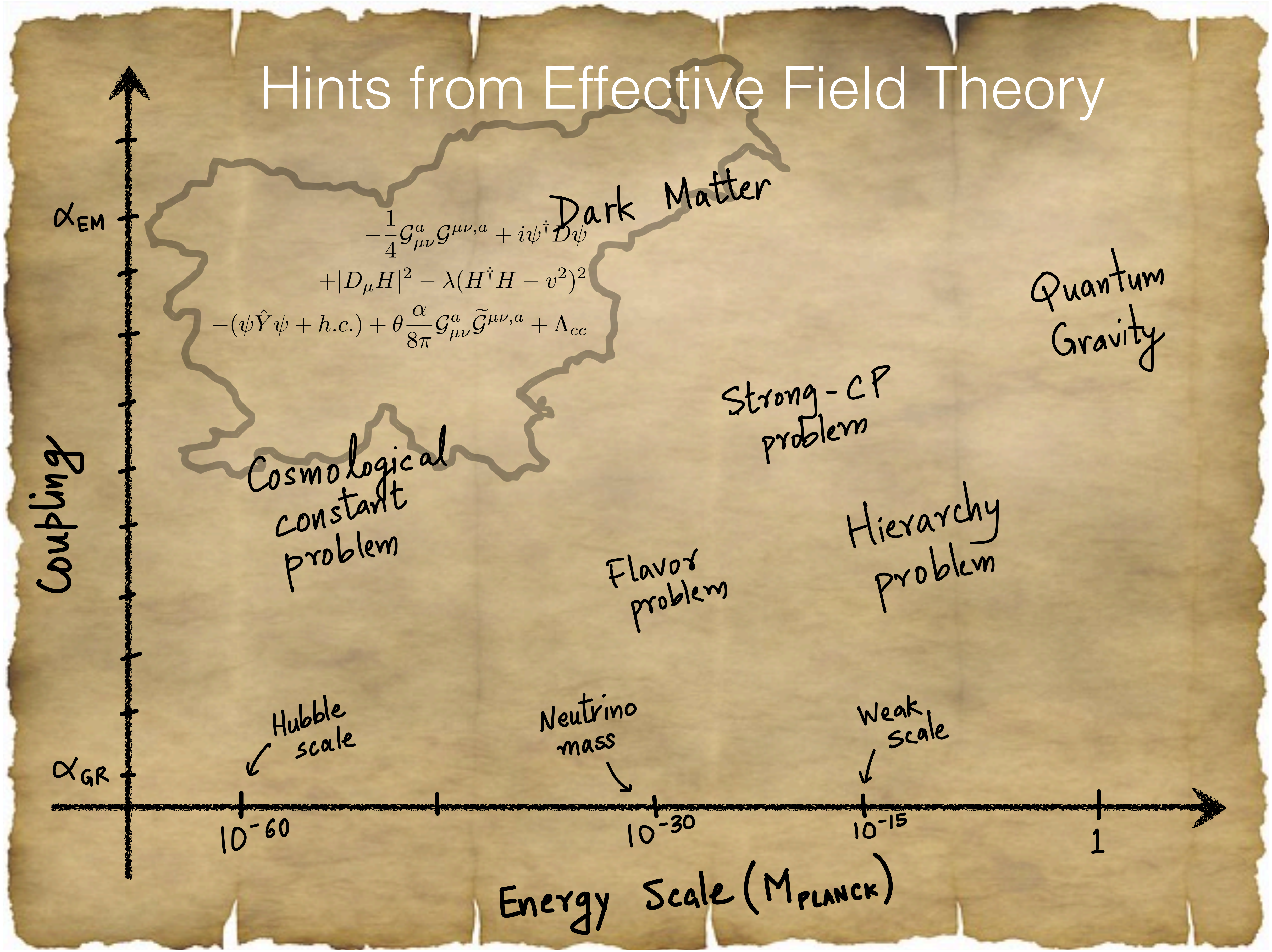
[1912.02823]
PA, Anson Hook, Junwu Huang
[2010.15848]
+Gustavo Marques-Tavares

FANTASTIC BEASTS AND WHERE TO FIND THEM



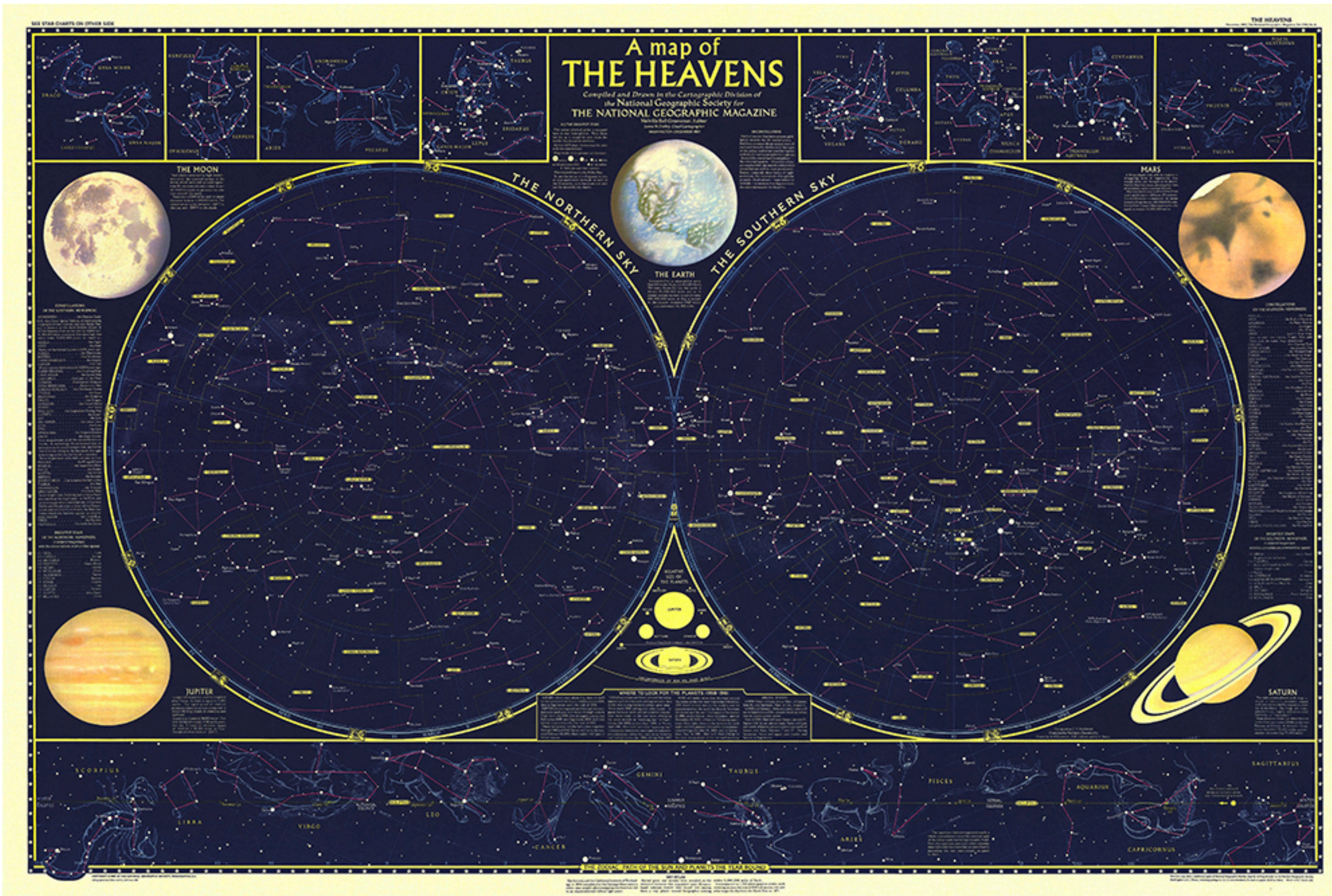
Coupling
α_{EM}
α_{GR}
10^{-60}
10^{-30}
10^{-15}
1
Energy Scale (M_{PLANCK})

Coupling
α_{EM}
α_{GR}
Hubble scale
Neutrino mass
Weak scale
10^{-60}
10^{-30}
10^{-15}
1
Energy Scale (M_{PLANCK})


Hints from Effective Field Theory
$-\frac{1}{4}\mathcal{G}^{a}_{\mu\nu}\mathcal{G}^{\mu\nu,a} + i\psi^{\dagger}D\psi$
$+|D_{\mu}H|^2 - \lambda(H^{\dagger}H - v^2)^2$
$-(\psi\hat{Y}\psi + h.c.) + \theta\frac{\alpha}{8\pi}\mathcal{G}^{a}_{\mu\nu}\widetilde{\mathcal{G}}^{\mu\nu,a} + \Lambda_{cc}$
Dark Matter
Quantum Gravity
Strong-CP problem
Cosmological constant problem
Hierarchy problem
Flavor problem
Coupling
α_{EM}
α_{GR}
Hubble scale
Neutrino mass
Weak scale
10^{-60}
10^{-30}
10^{-15}
1
Energy Scale (M_{PLANCK})

Hints from Effective Field Theory

New Guides from Cosmology & Quantum Gravity

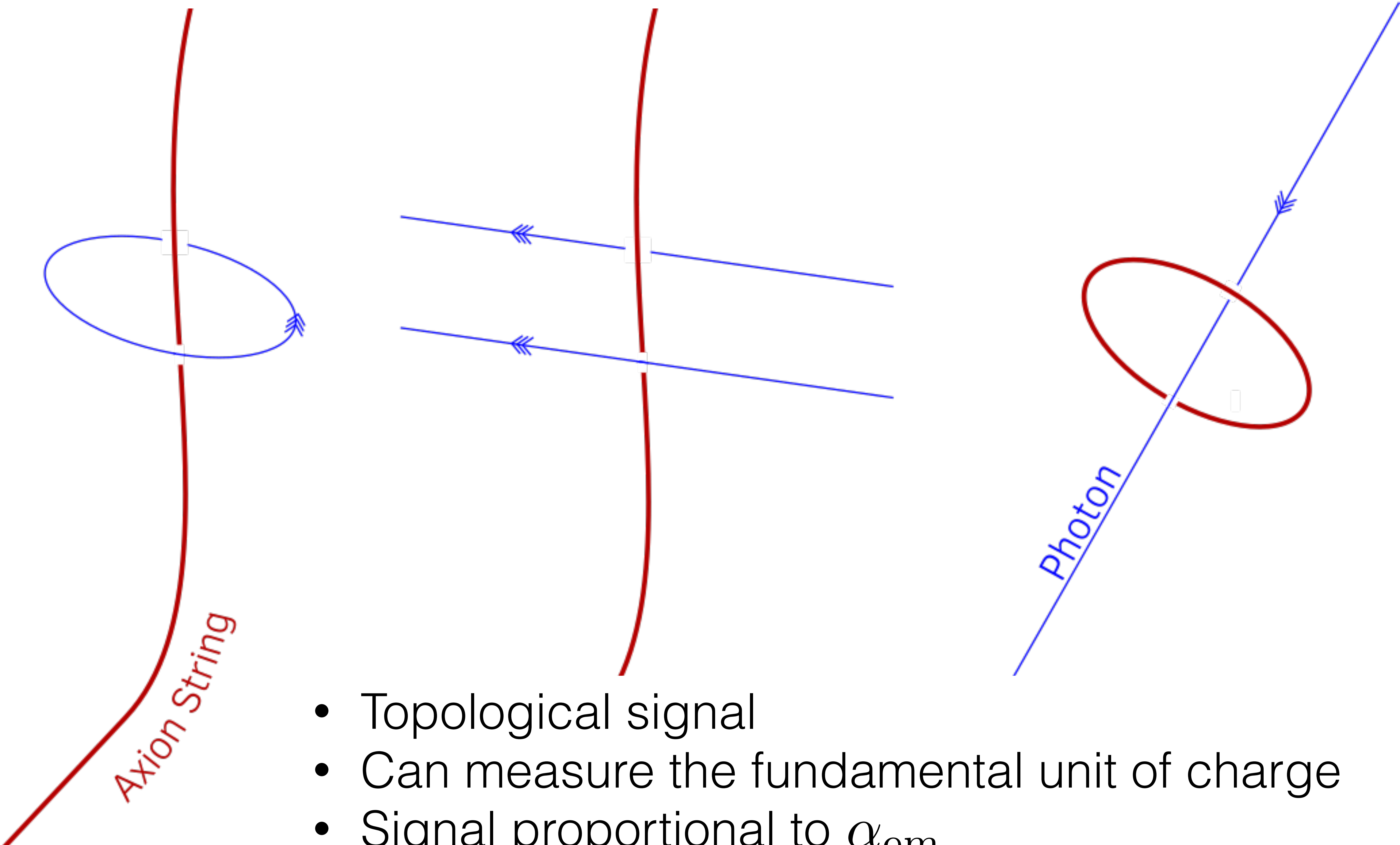


New pheno opportunities from the String Landscape and the Swampland

Vafa [hep-th/0509212]

see also talk by Irene Valenzuela

Millikan Experiment in the Sky



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

Axions

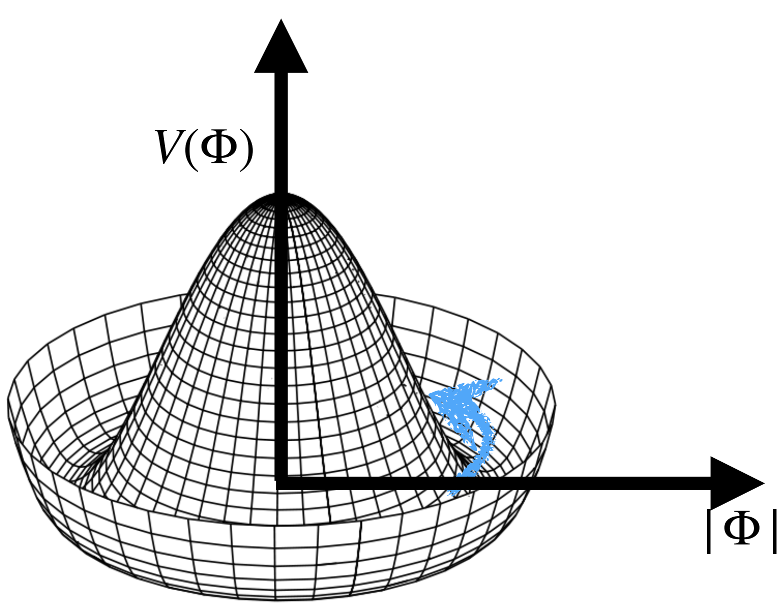
Axions are compelling new physics candidates

Light due to their nature as (pseudo)-Nambu-Goldstone Bosons (pNGBs)

Associated with spontaneous breaking of a global U(1) Peccei-Quinn symmetry

Naturally coupled to gauge fields in the Standard Model

Peccei, Quinn (1977)
Weinberg (1978)
Wilczek (1978)



$$\Phi = f e^{ia/f}$$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{a}{f} \frac{\mathcal{A}\alpha_{\rm em}}{8\pi} F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

$$\left(\widetilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\alpha\beta\mu\nu} F_{\alpha\beta} \right)$$

No-Global Symmetries in Quantum Gravity

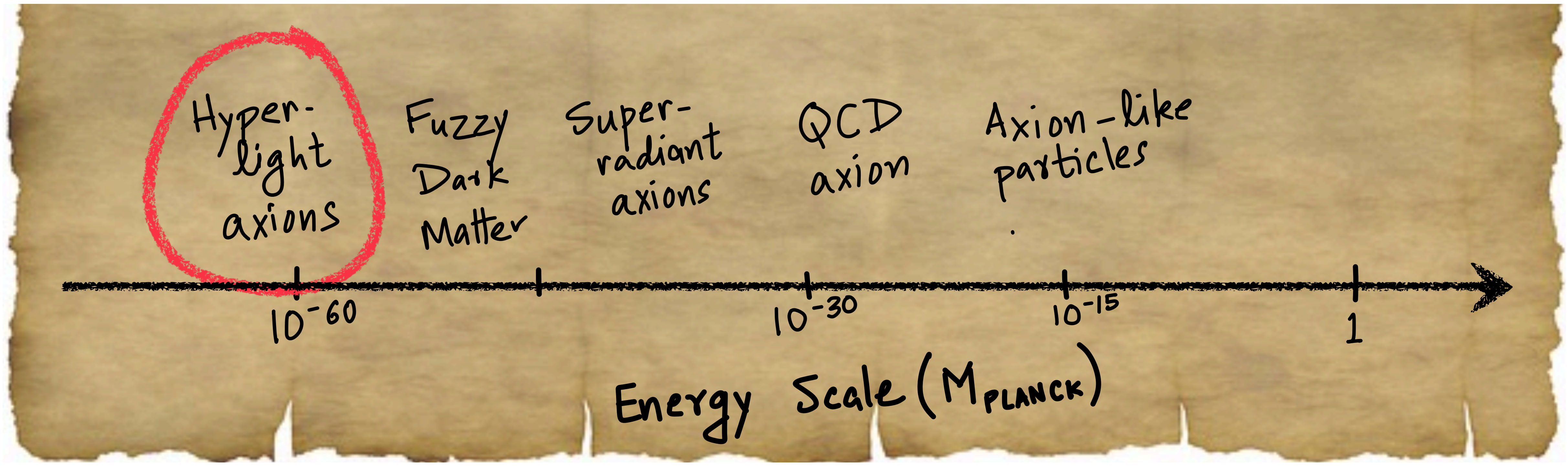
PQ symmetry must be explicitly broken
Expect some mass from instantons / quantum gravity effects

The mass can be exponentially suppressed ~ $\exp(-S_E)$
A wide range of masses

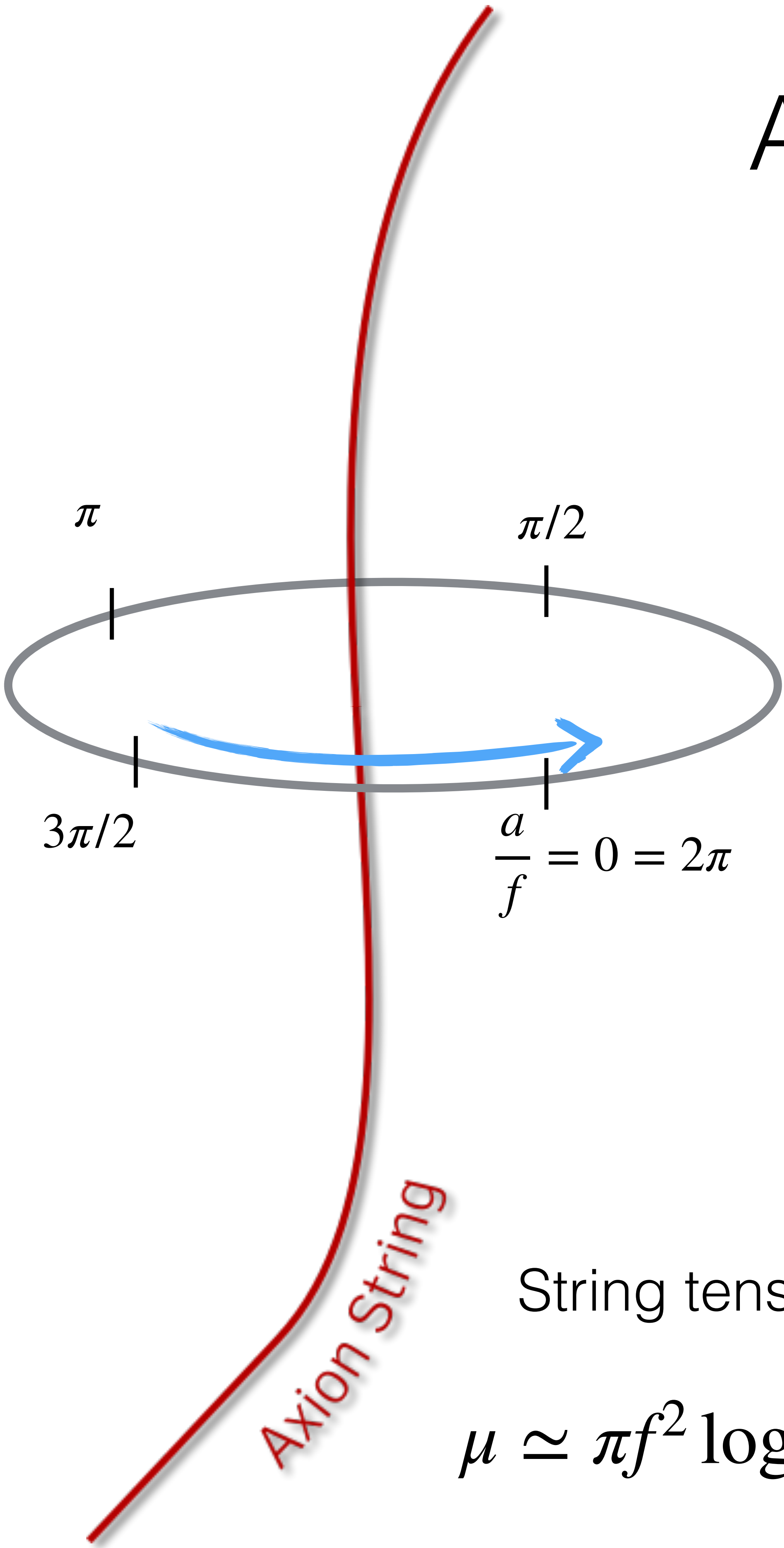
The String Axiverse
String theory predicts a plethora of axions
"hundreds of axions, some of them massless"

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

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



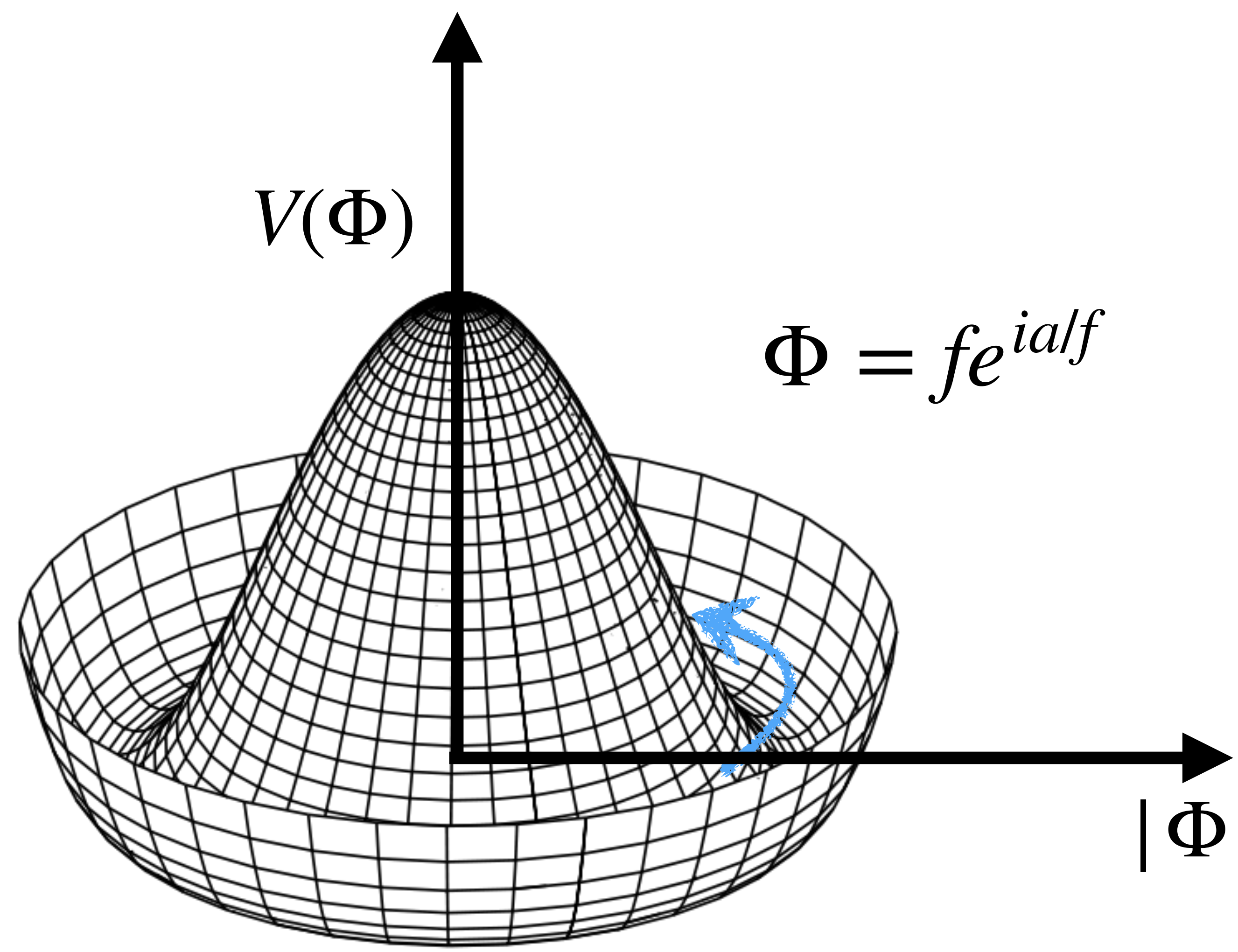
Axion Strings



Compact scalar field

$$a = a + 2\pi f$$

axion decay constant

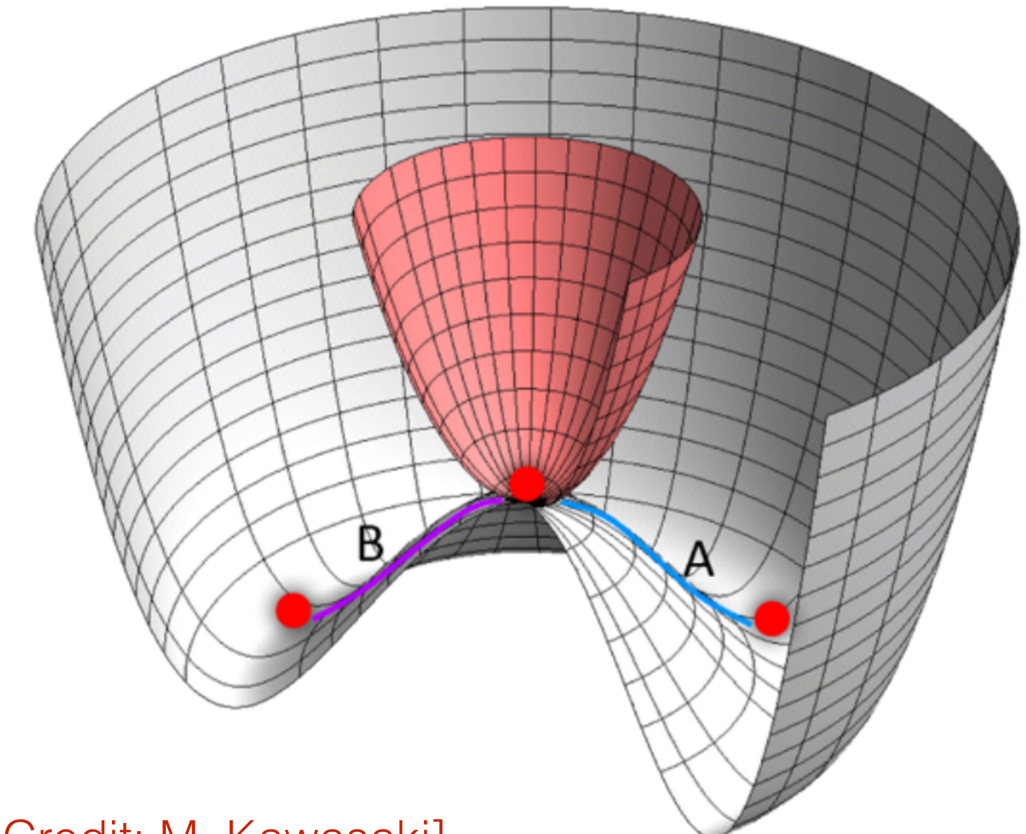


$$\Phi = f e^{ia/f}$$

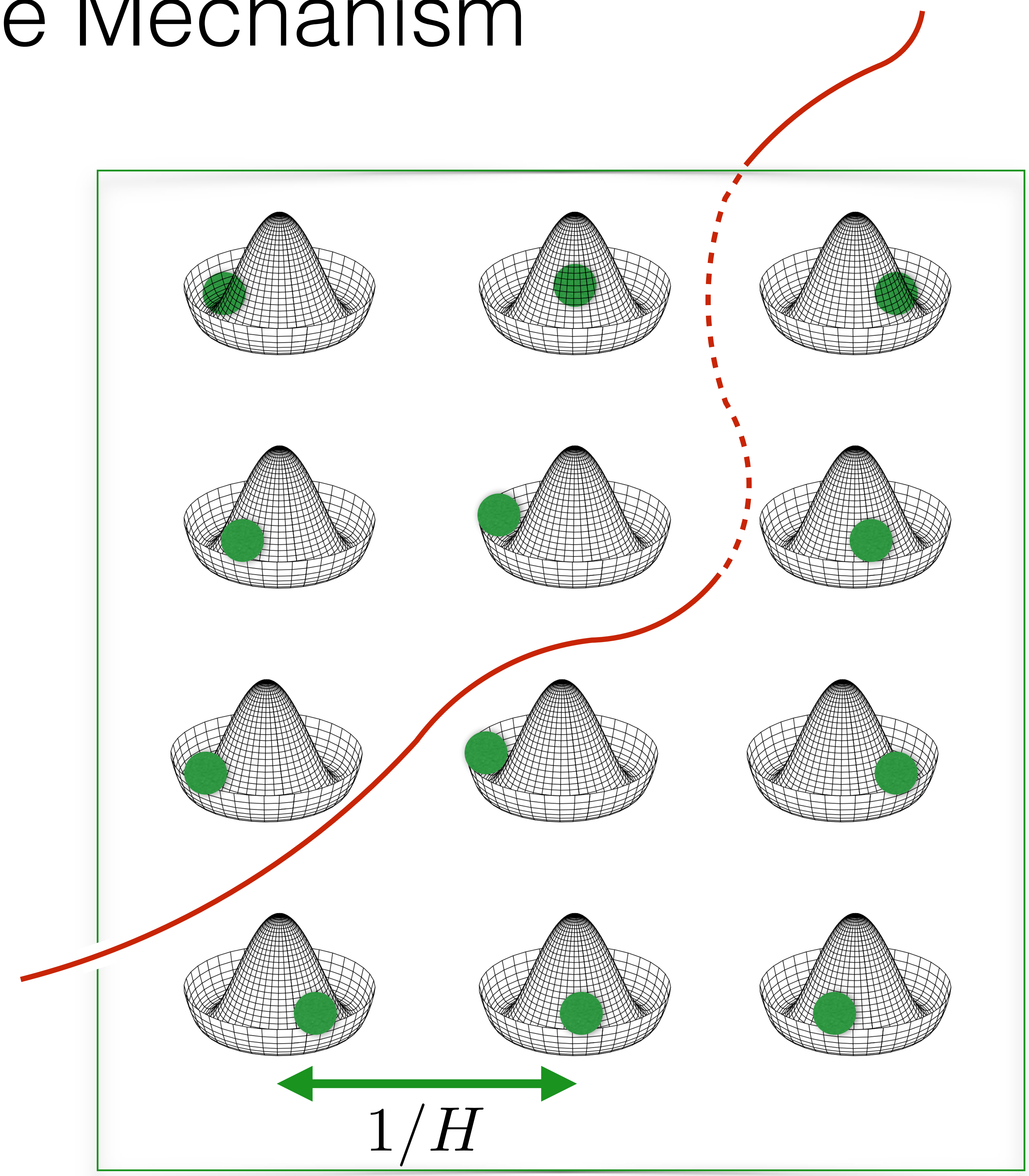
String tension

$$\mu \simeq \pi f^2 \log \frac{\Lambda_{uv}}{\Lambda_{ir}}$$

Kibble Mechanism

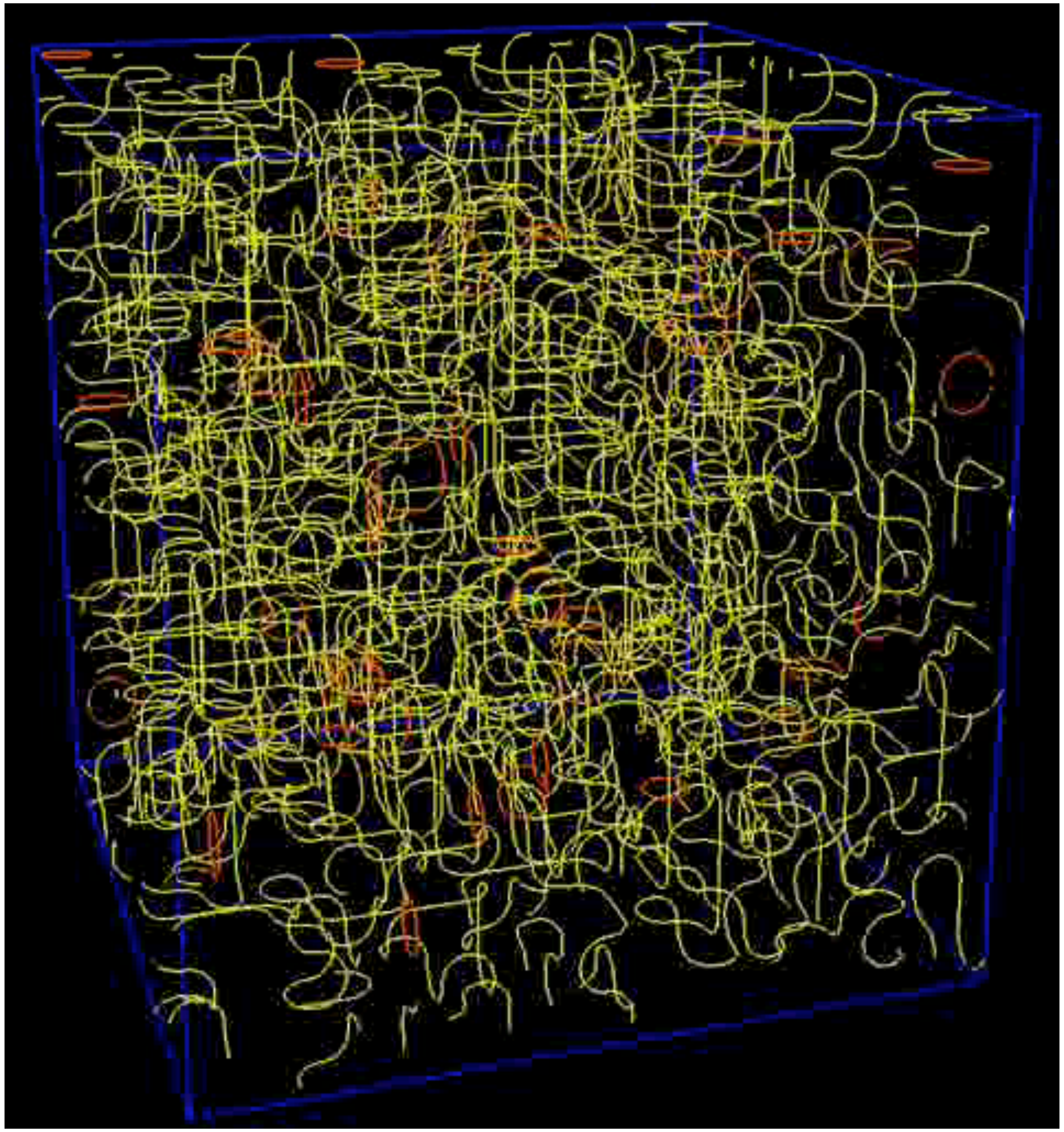


[Credit: M. Kawasaki]



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 Electrodynamics

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{a}{f}\frac{\mathcal{A}\alpha_{\rm em}}{8\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Axion-photon coupling modifies Maxwell equations

$$\nabla\cdot\mathbf{E} = \tilde{\rho} - \kappa\nabla a\cdot\mathbf{B},$$

$$\nabla\times\mathbf{E} = -\partial\mathbf{B}/\partial t,$$

$$\nabla\cdot\mathbf{B} = 0,$$

$$\nabla\times\mathbf{B} = \partial\mathbf{E}/\partial t + \tilde{\mathbf{j}} + \kappa(\dot{a}\mathbf{B} + \nabla a\times\mathbf{E}),$$

new charge and currents in axion gradients in background magnetic field

$$\left(\kappa = \frac{\mathcal{A}\alpha_{\rm em}}{2\pi f}\right)$$

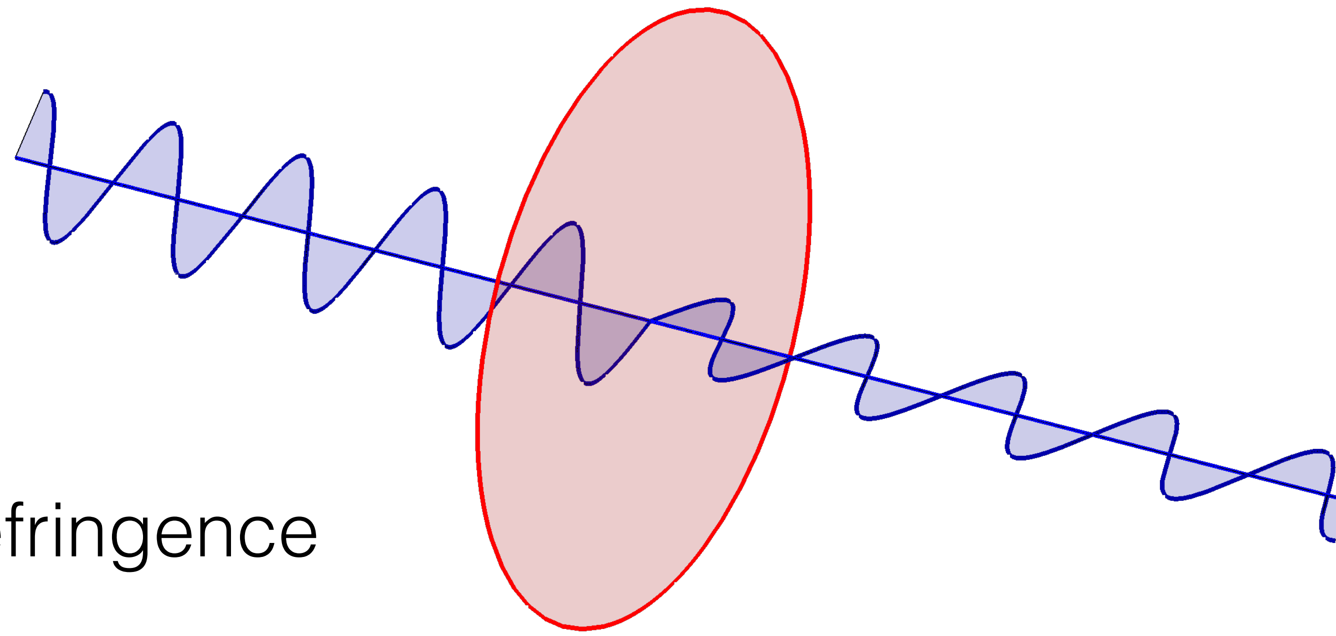
Wilczek [Phys. Rev. Lett. **58**, 1799, (1987)]

Photons in Axion String Background

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

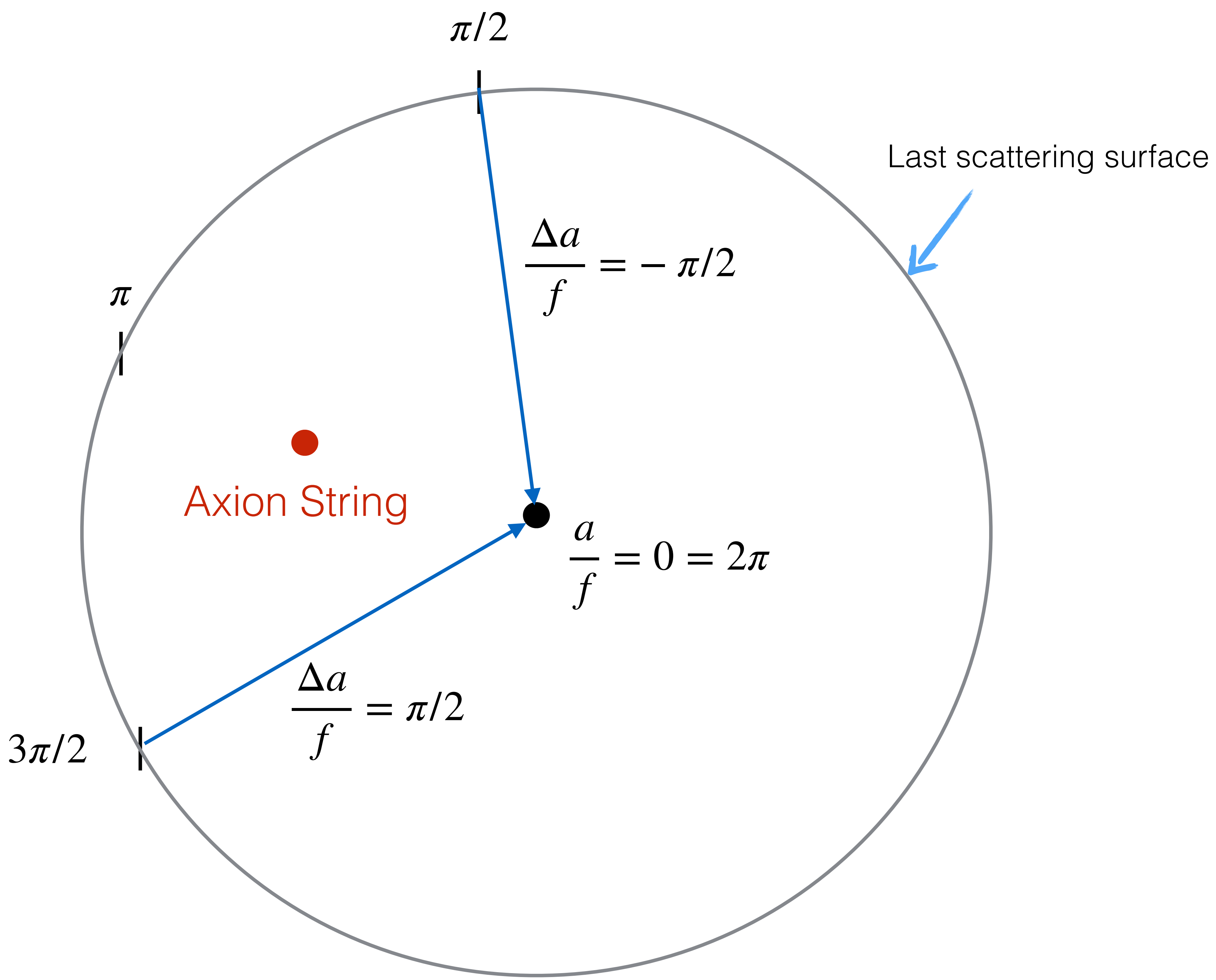
Aharanov-Bohm like effect for trajectory around a string $\Delta a = 2\pi f$

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

$\mathcal{A}$ is quantized in units of fundamental quantum of charge

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

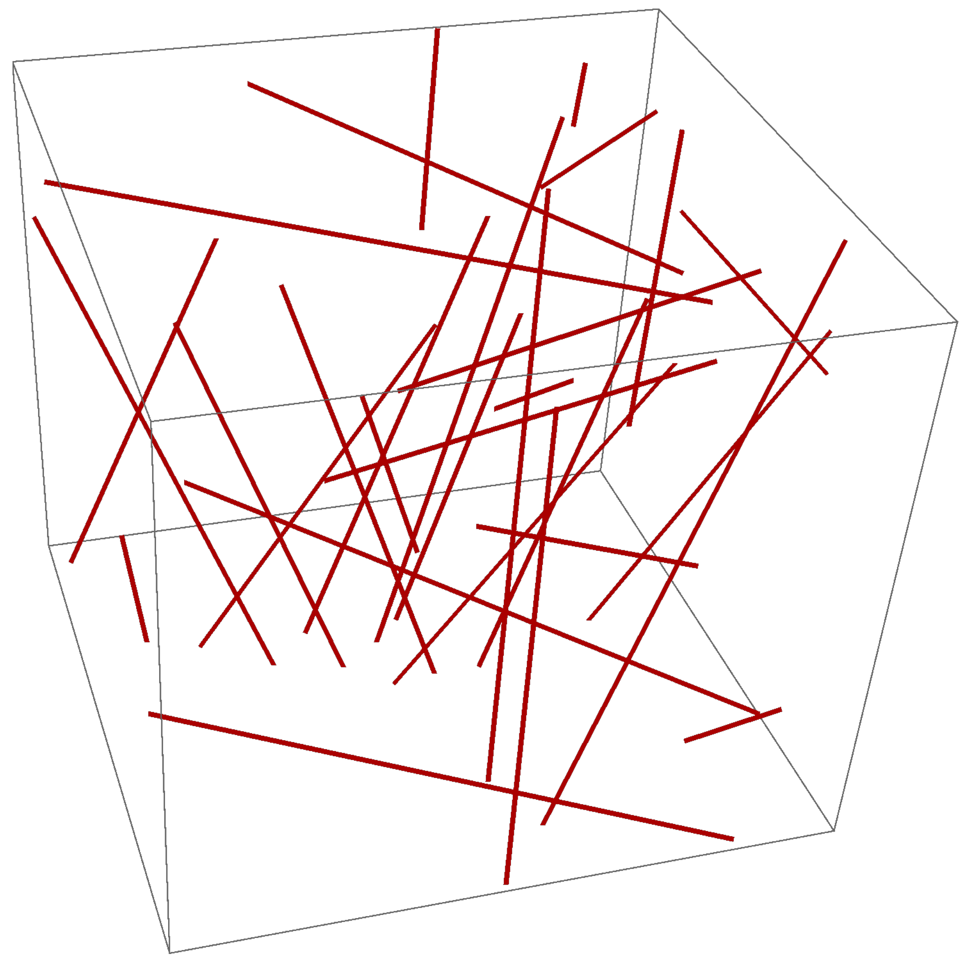
Polarization Rotation of CMB Photons



A Toy 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

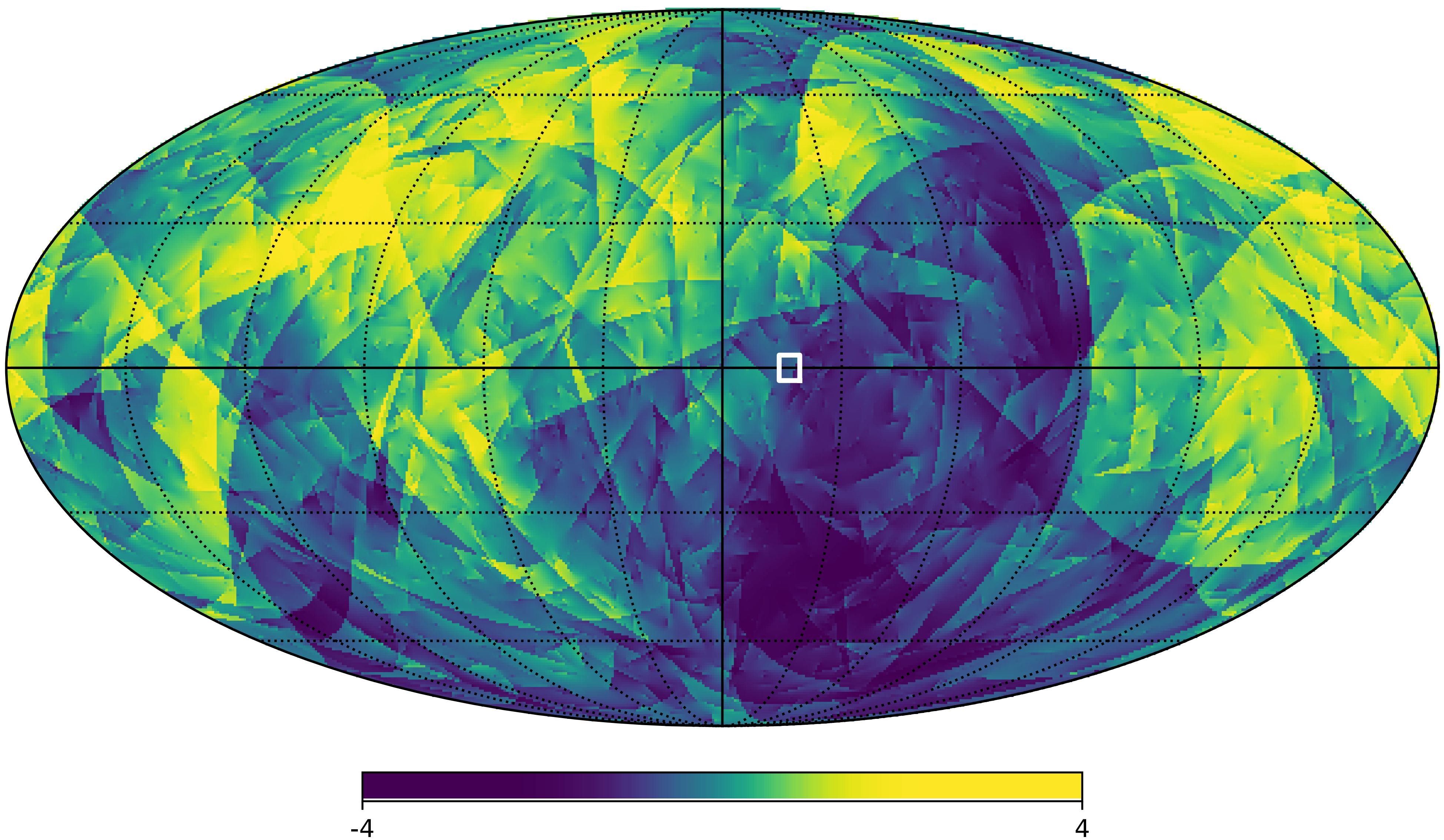


Strings are removed randomly to maintain scaling

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

Captures larger angular scale correlations well

Sky map

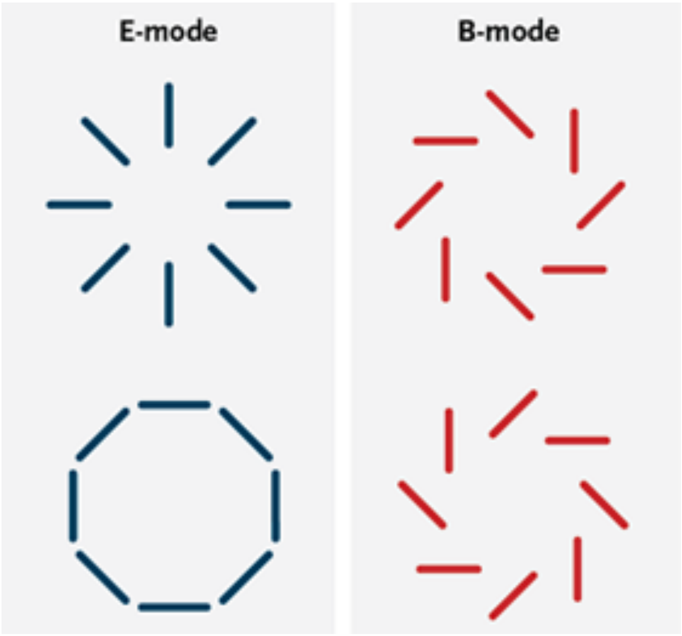


$$\frac{\Delta\Phi}{\sqrt{\xi}\mathcal{A}\alpha_{\rm em}}$$

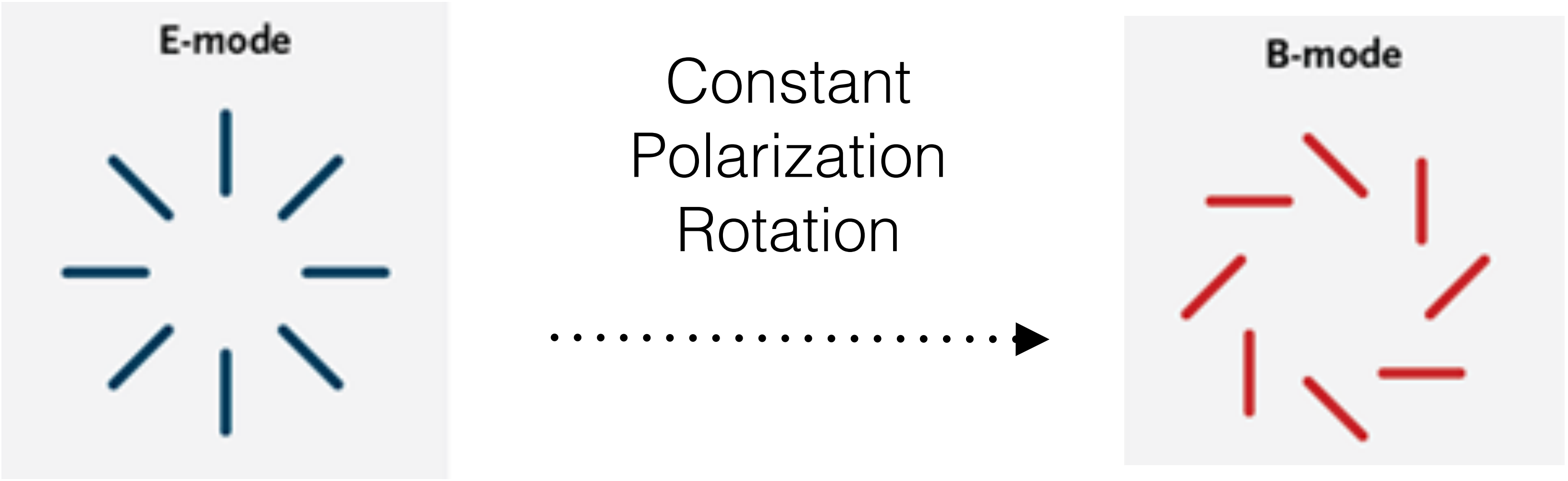
$\xi = 1$

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

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

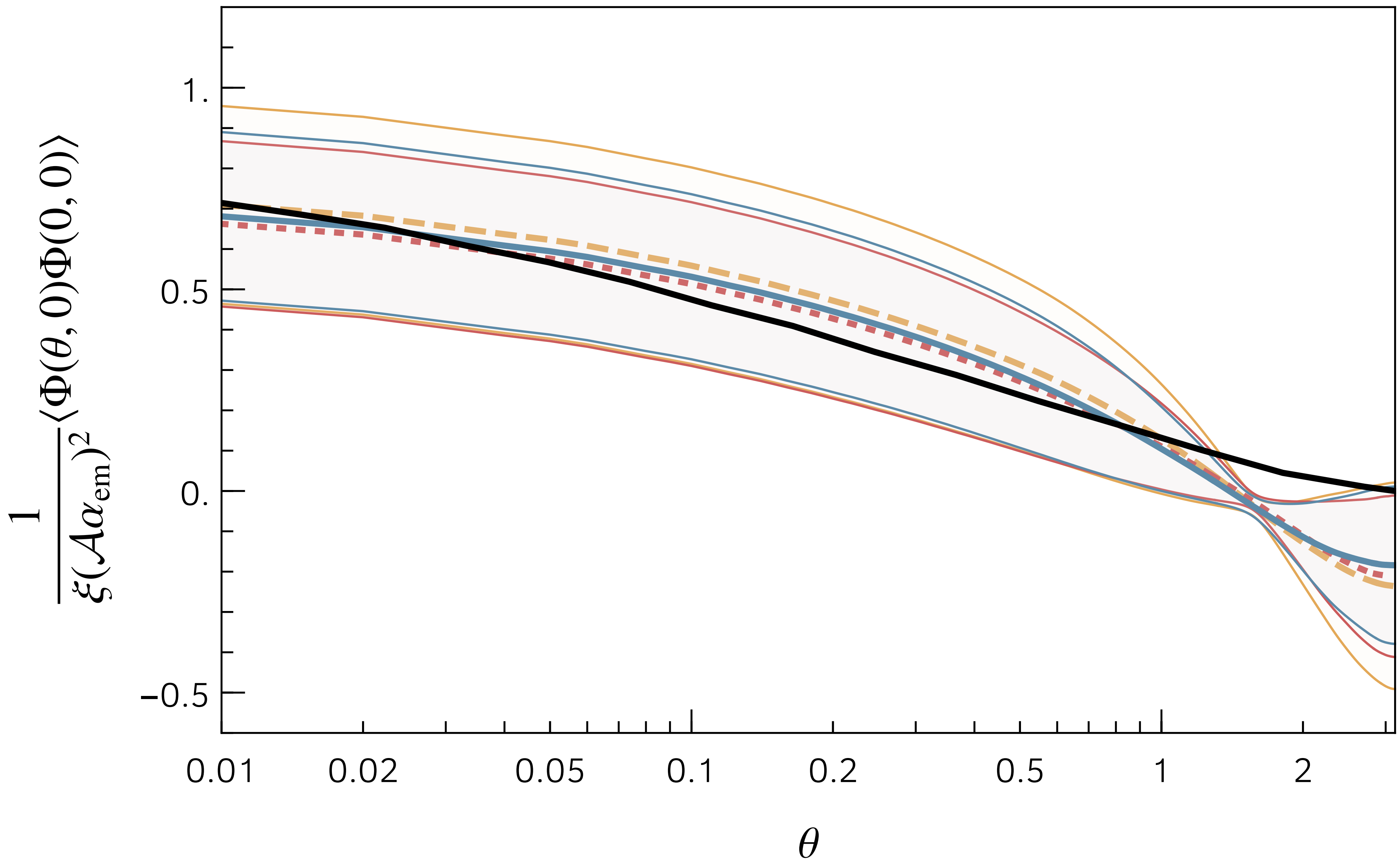
Functions of Clebsch-Gordan coefficients

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

Two-point function

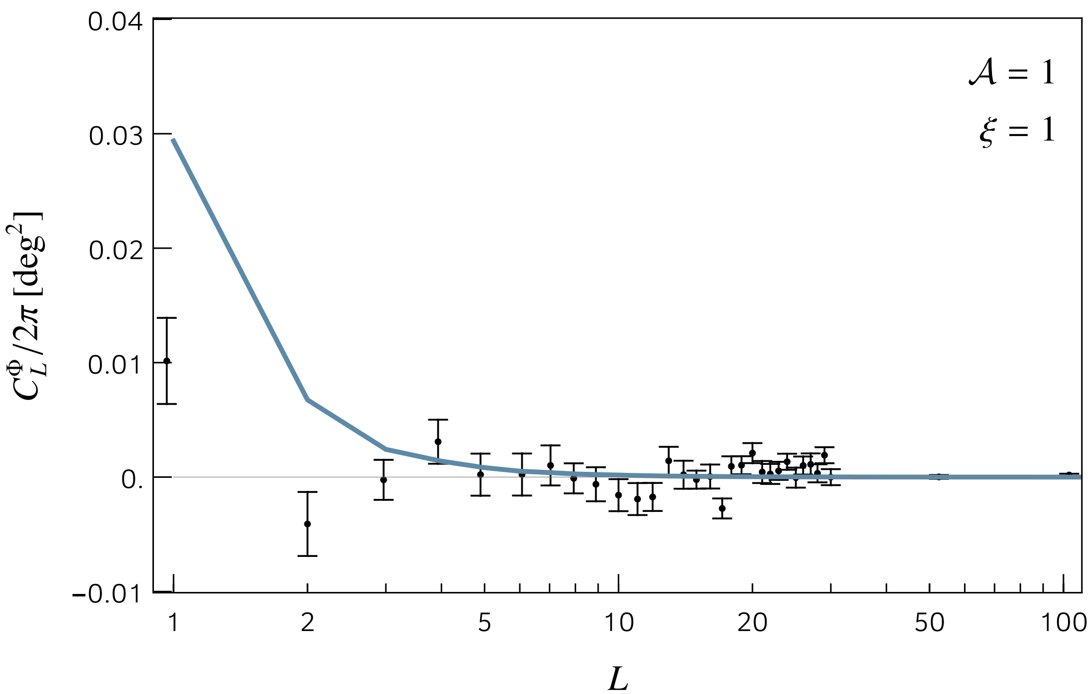


Constraints / Forecasts

Constraints

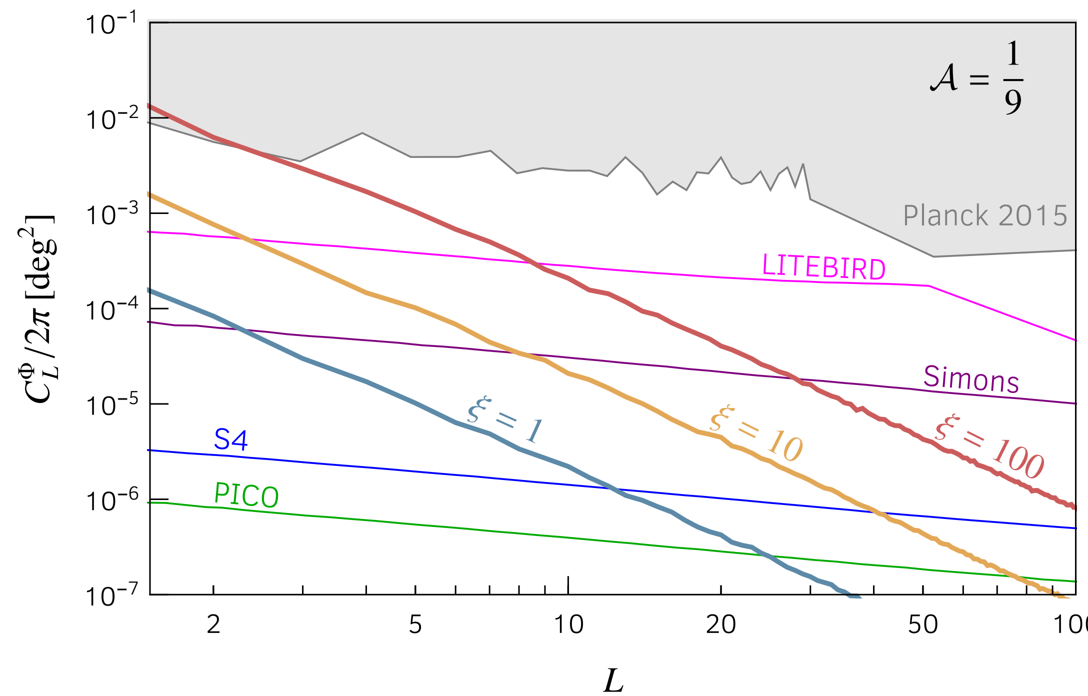
Planck 2015

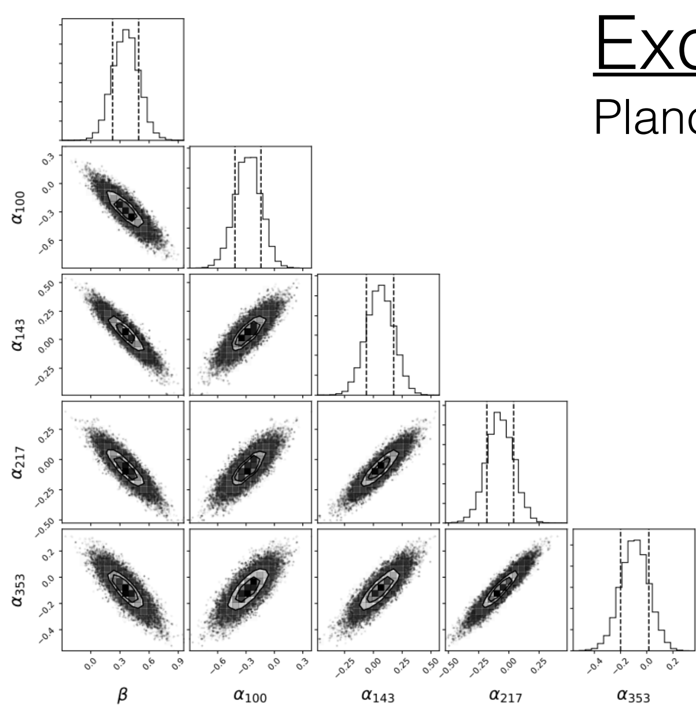
Contreras, Boubel, Scott
[arXiv:1705.06387]



Forecasts

Pogosian et al
[arXiv:1904.07855]





Excess in Birefringence (L = 0)

Planck 2018

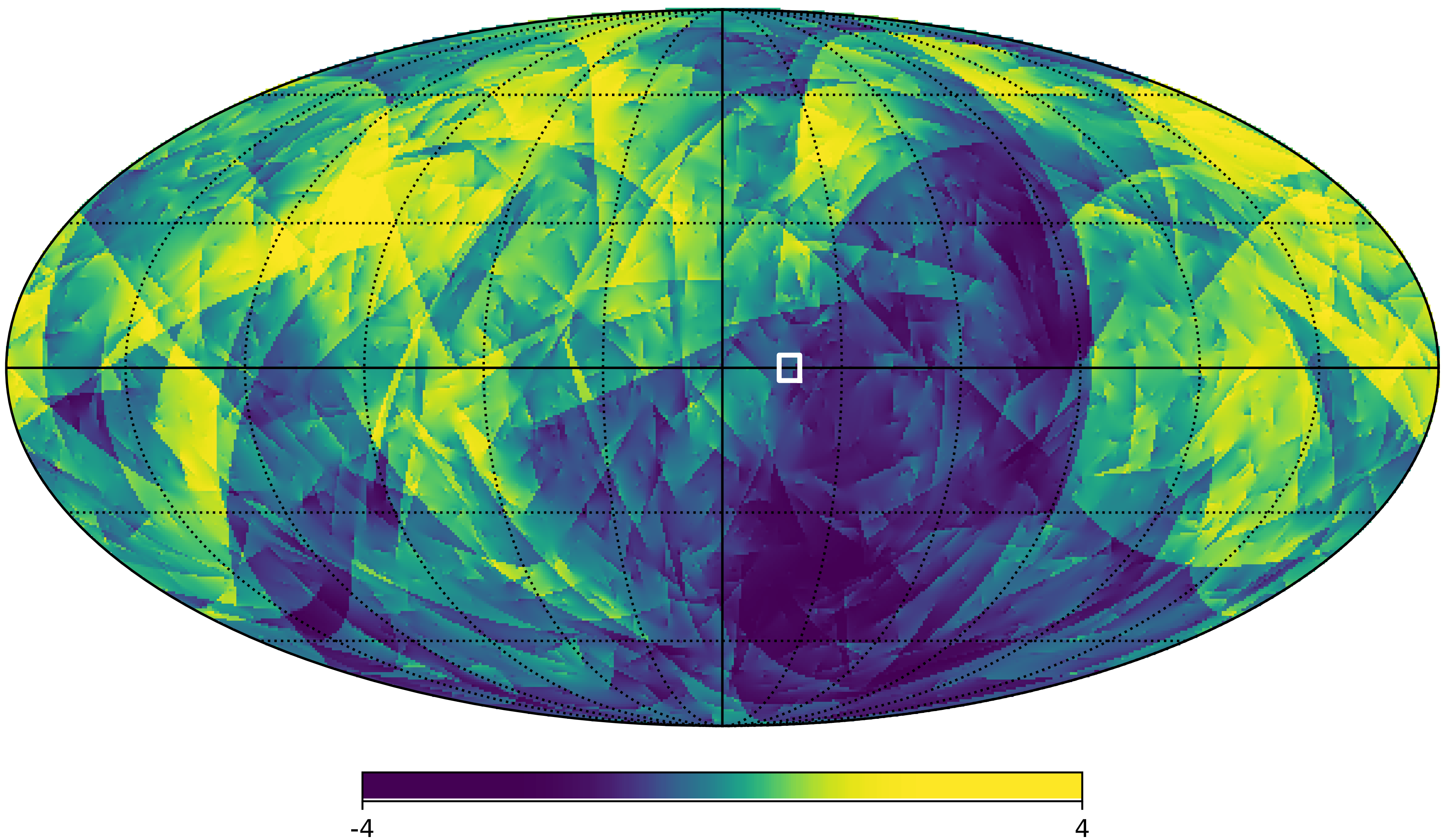
Stat: 2.4σ

$$\beta = 0.35 \pm 0.14\ \mathrm{deg}$$

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

Minami, Komatsu
[arXiv:2011.11254]

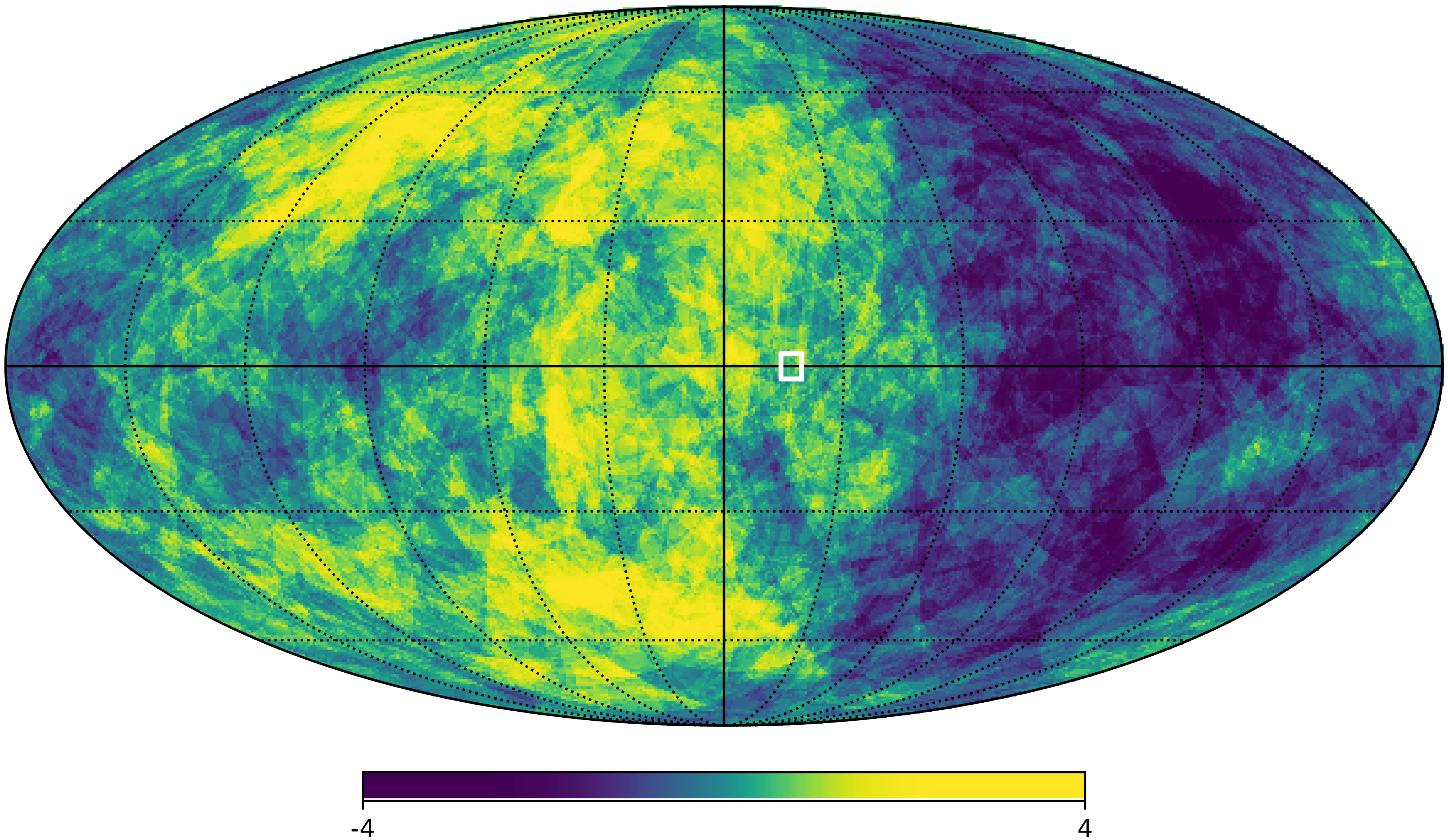
Sky maps



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

$\xi = 1$

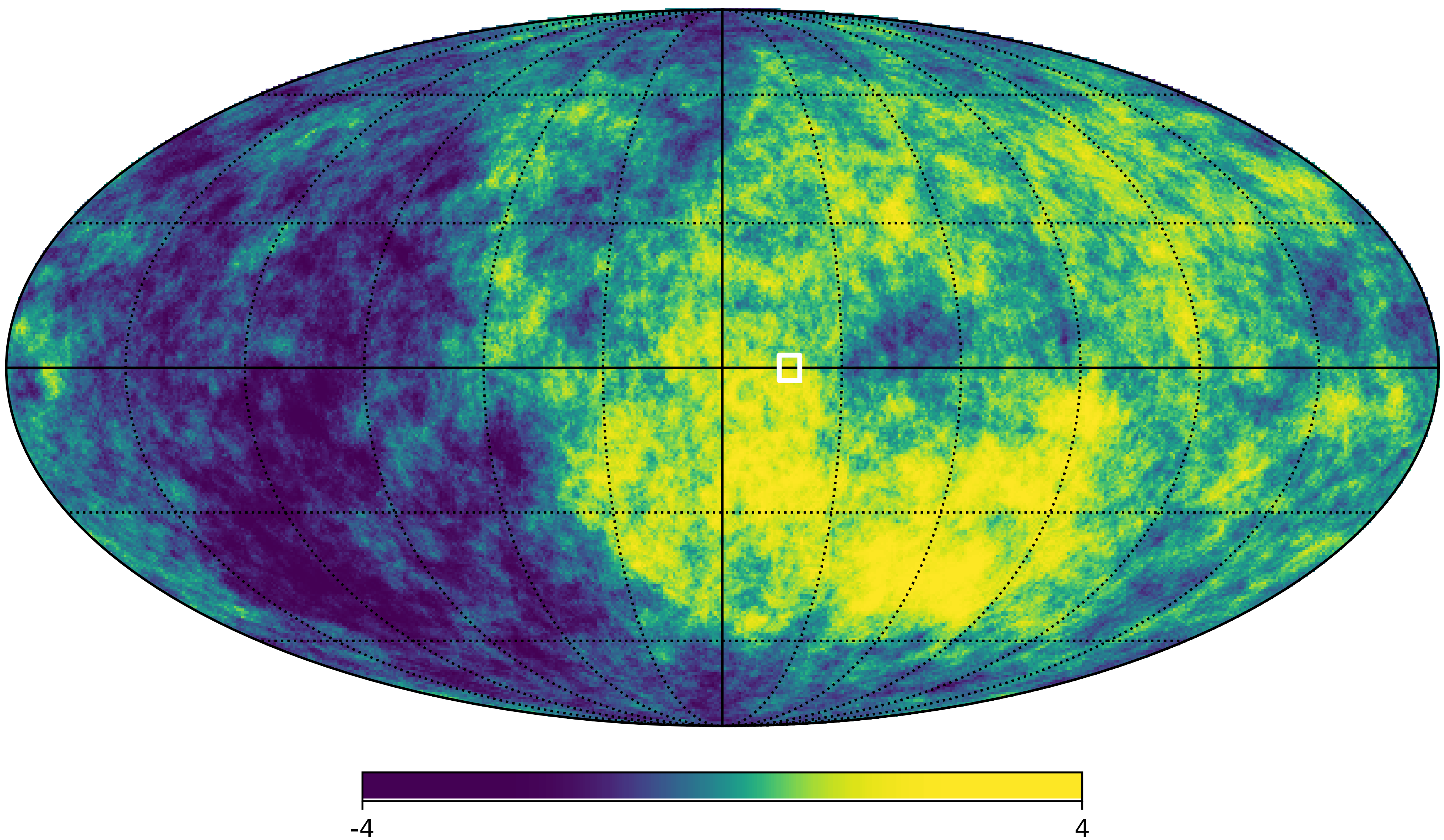
Sky maps



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

$\xi = 10$

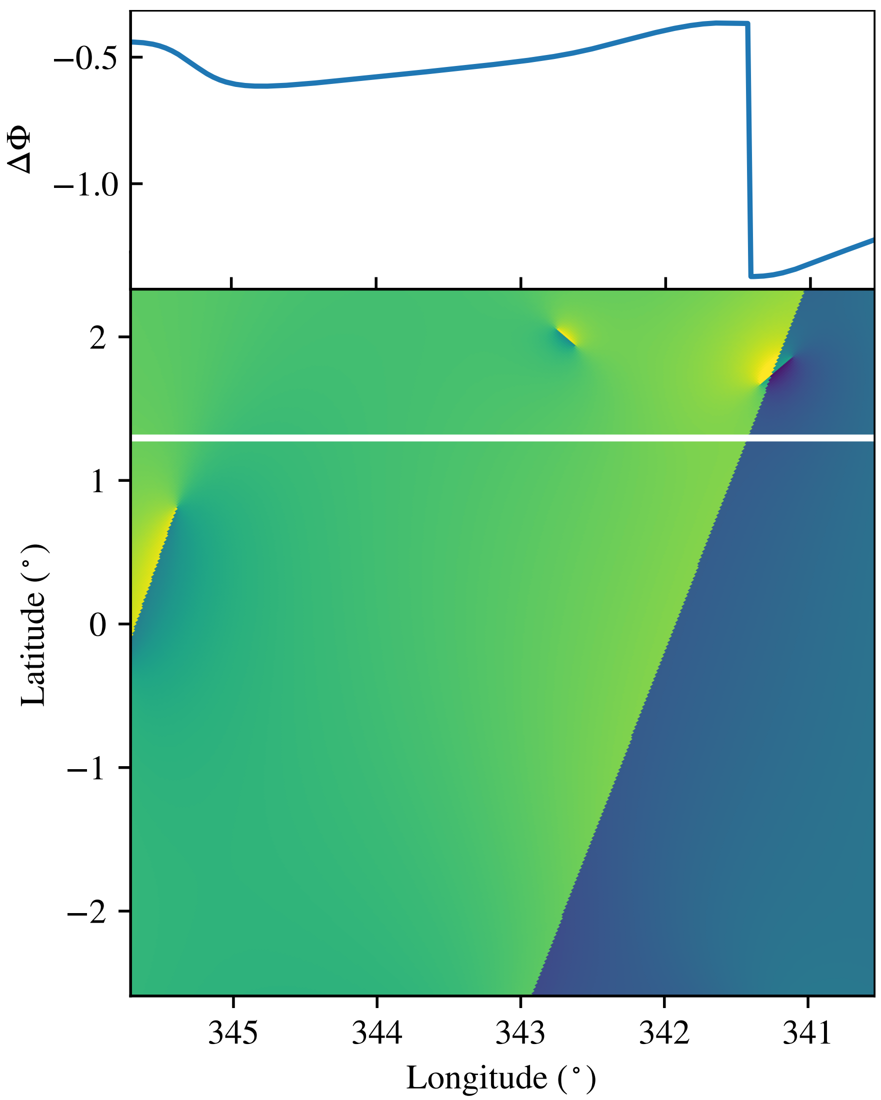
Sky maps



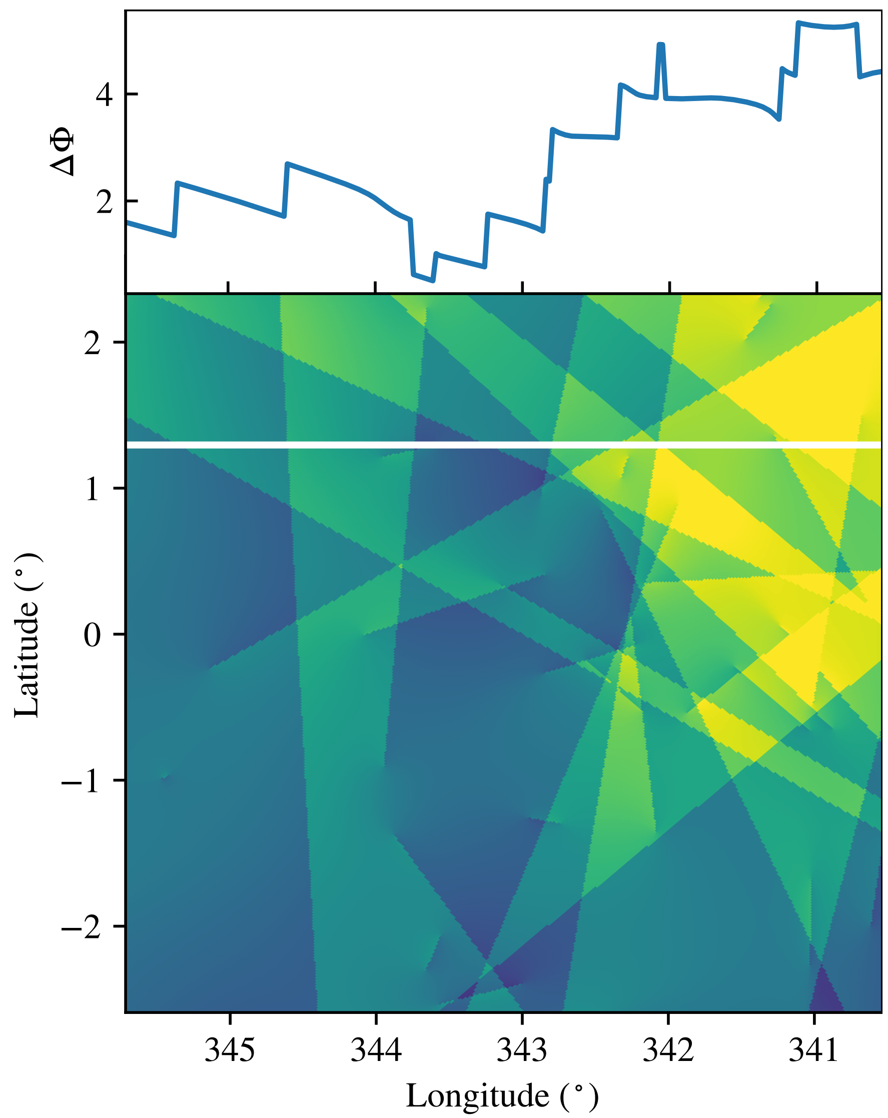
$$\frac{\Delta\Phi}{\sqrt{\xi}\mathcal{A}\alpha_{\rm em}}$$

$\xi = 100$

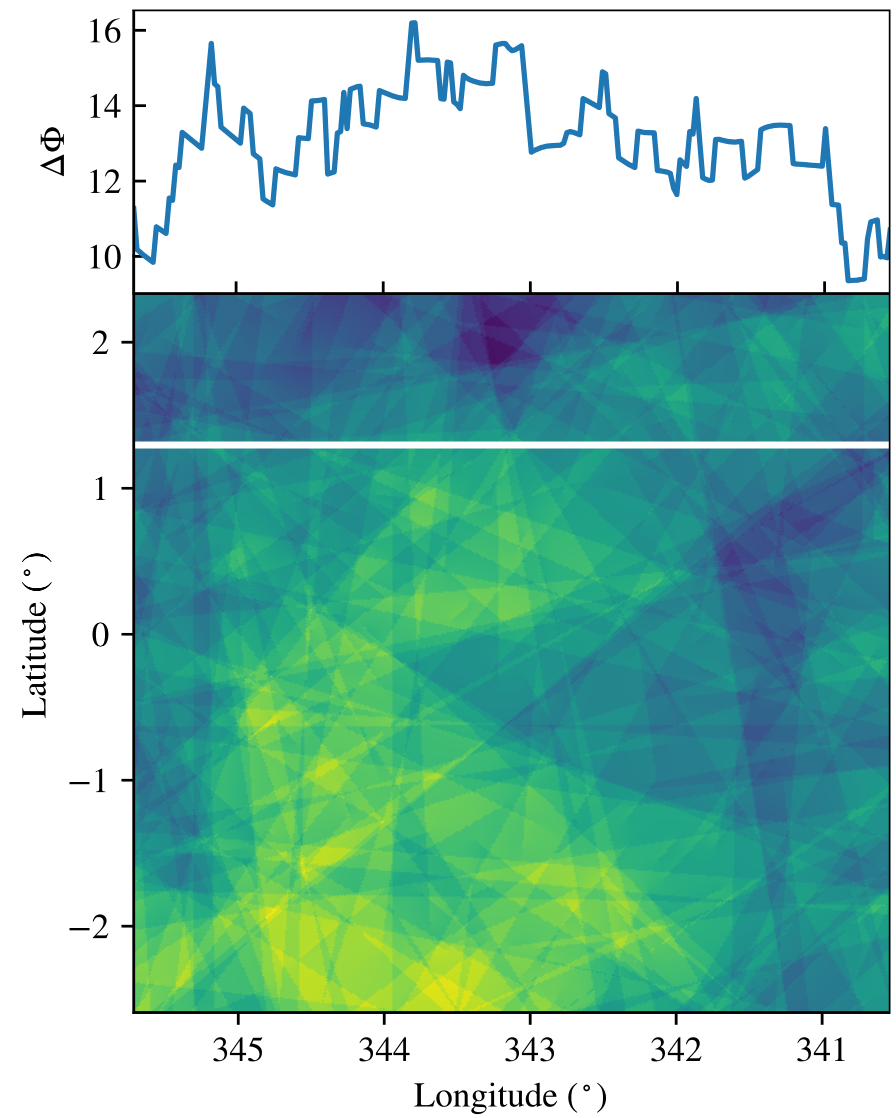
Edge Detection



$\xi = 1$

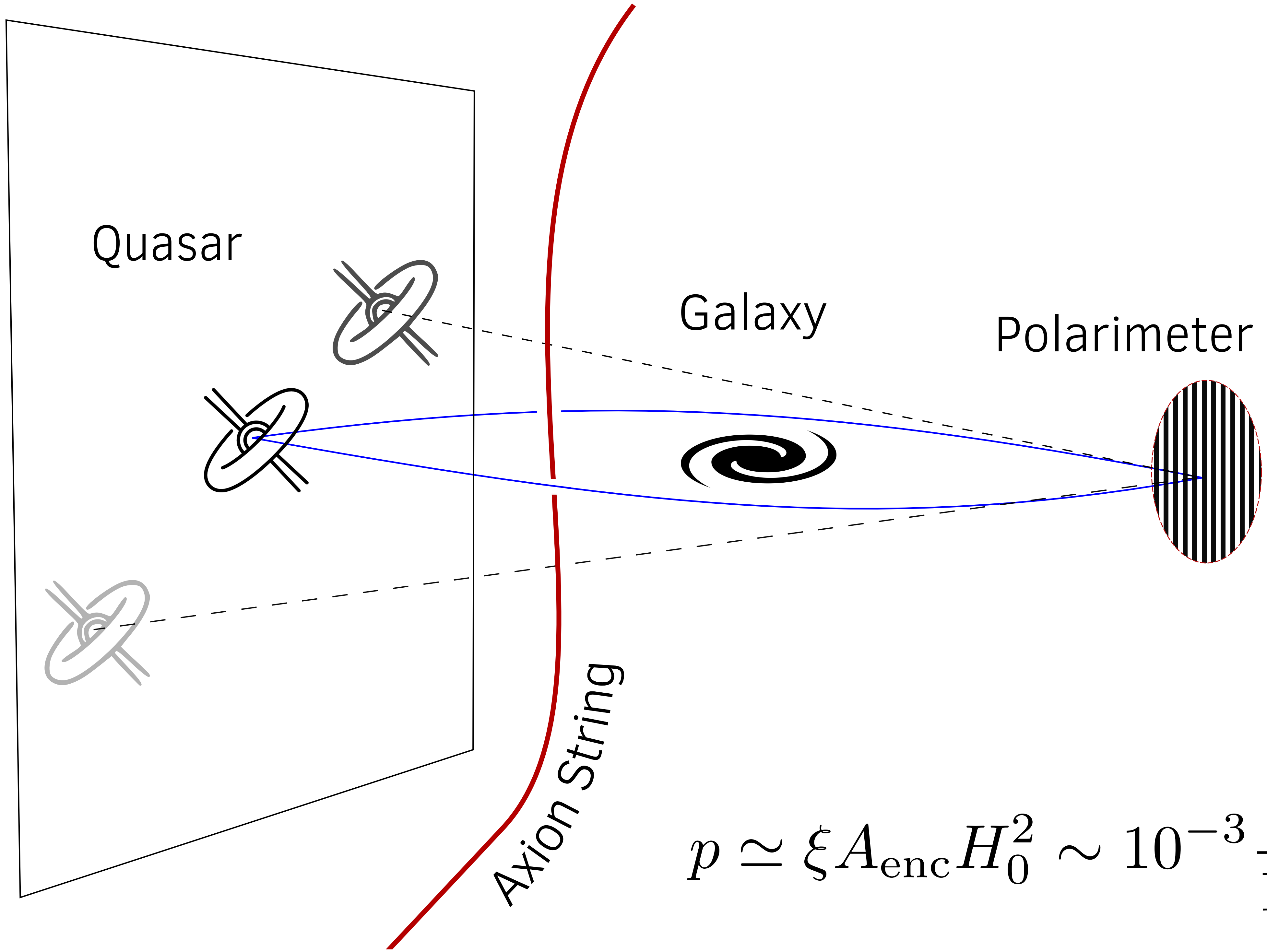


$\xi = 10$



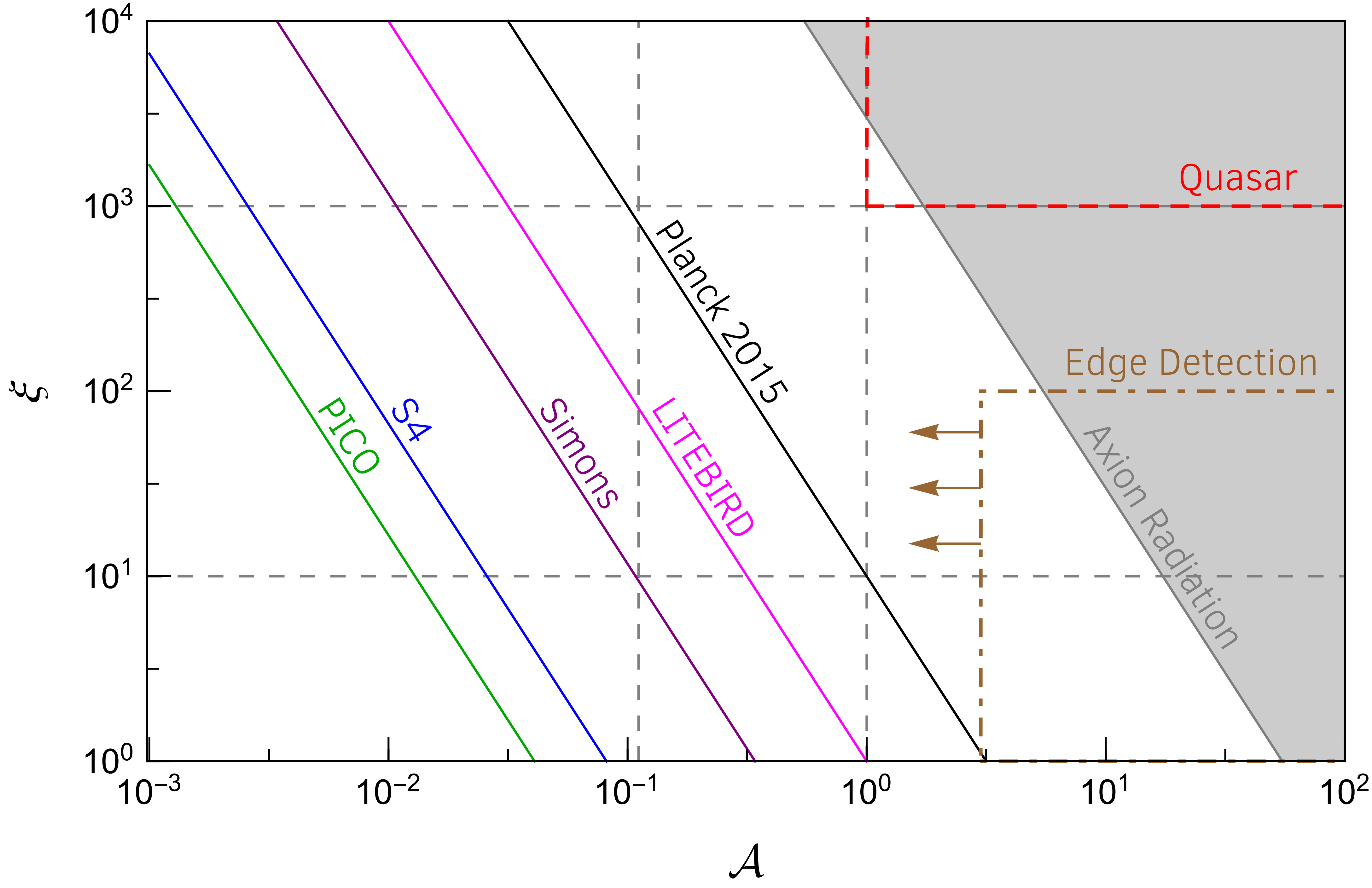
$\xi = 100$

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!

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

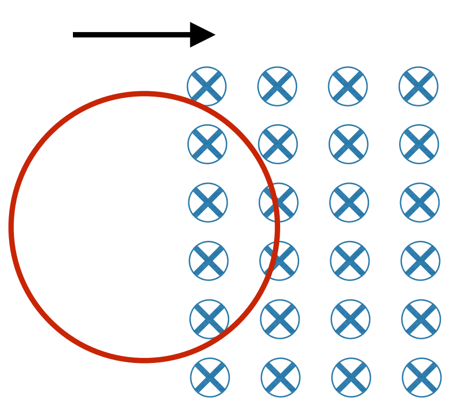
- Consequence of Atiyah-Singer index theorem and axion EM anomaly
- Chiral edge mode of PQ quark lives on the string
- Quantum Hall edge state
- E.g. only left-moving + charged state

Contrast with Witten's superconducting strings

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

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

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

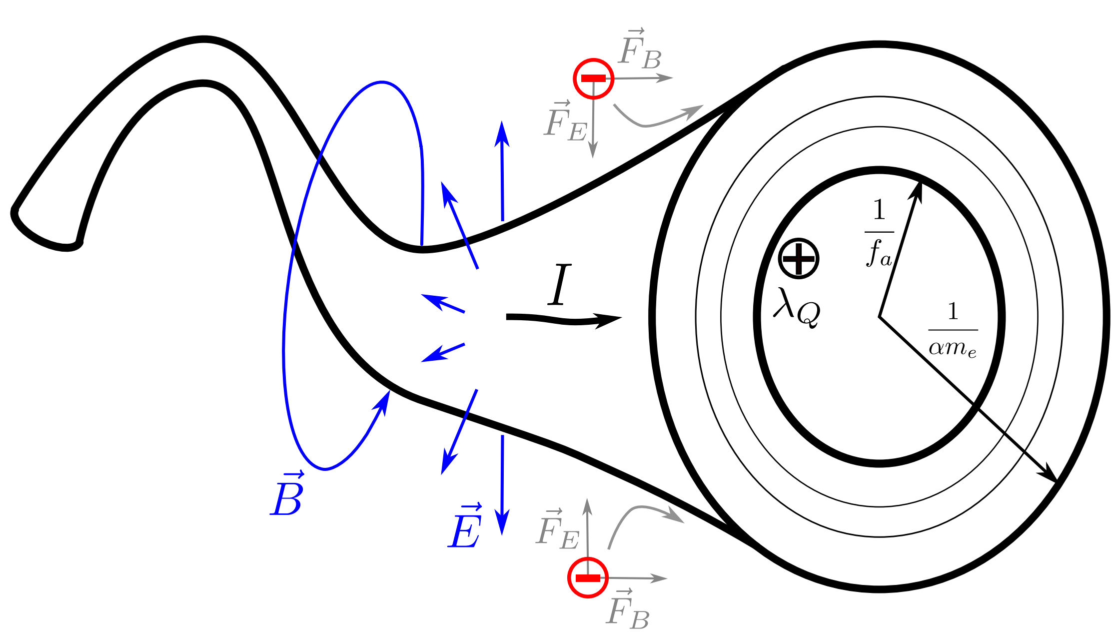
Axion strings encounter galaxies and galaxy clusters

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

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

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

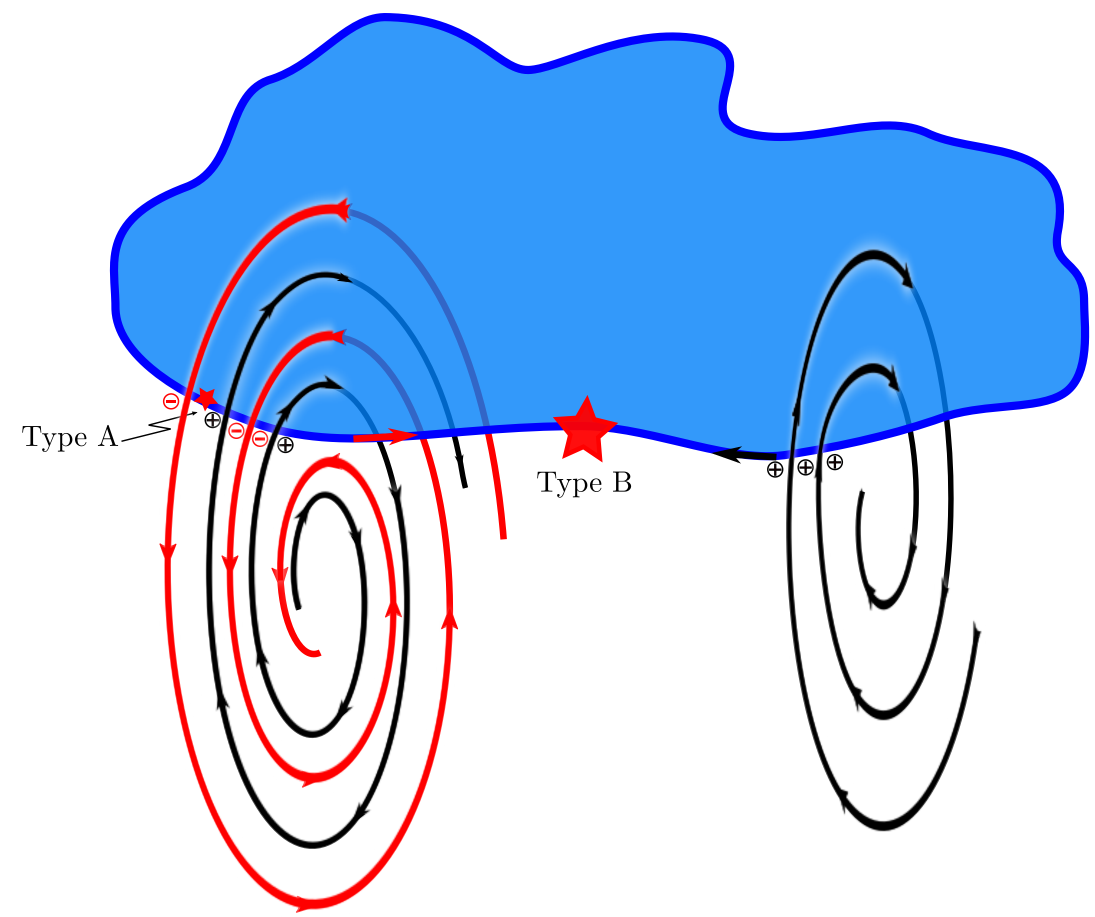
Collisions can be as bright as 10 million suns

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

Flux from the source at a cosmological distance

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

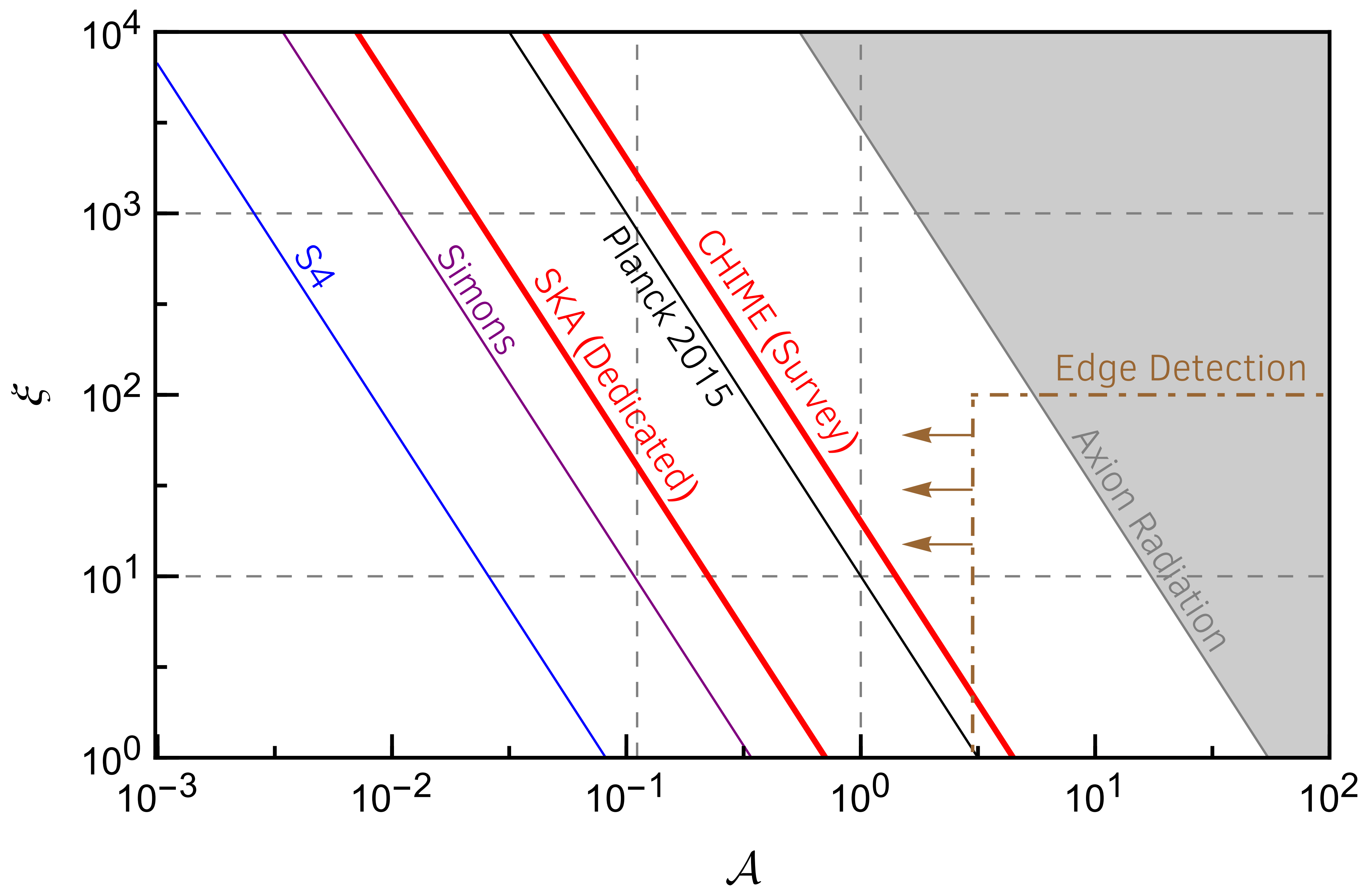
Details of the spectrum hard to model, high energy emission reabsorbed in the dense plasma



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!