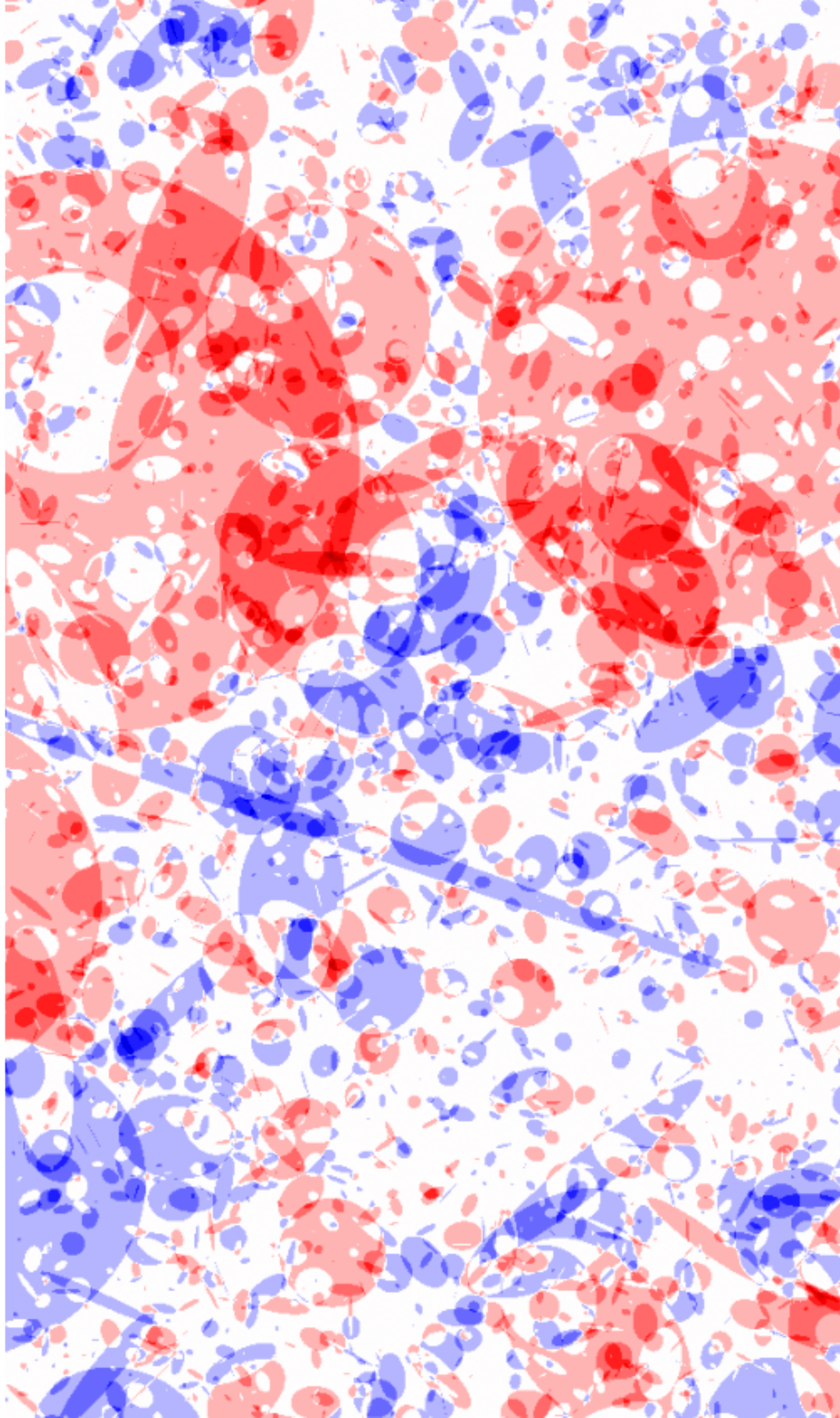
Charge quantisation, Axion strings, and Cosmic birefringence

arXiv:2305.02318 (2023)
arXiv:2111.12741 (2022)

Winston Yin, 2023-04-28



Charge quantisation

Charges beyond the Standard Model

- Electric charges in Standard Model (SM) are multiples of 1/3
- What are the charge assignments in beyond-the-SM theories?
- Any new fermions with charges less than 1/3?
- Axion-photon coupling can help us answer this question
- Observable: cosmic birefringence (in CMB) induced by axion strings
- P. Agrawal, A. Hook, J. Huang (2020)

Ultralight axion
(-like particles)

- Axions are pseudo-scalar fields, i.e. their values are periodic $a \in [0, 2\pi f_a)$
- Generic product of breaking of global $U(1)$ symmetry [Peccei-Quinn (PQ) symmetry] in models beyond SM
- Ultralight axions with mass $m_a \lesssim H_{\rm cmb} \simeq 3 \times 10^{-29}\,{\rm eV}$
  - ~~CP problem~~
  - ~~Dark matter~~
  - Potential as dark energy
  - Predicted in large numbers in string theory "axiverse" scenarios

Axion-photon coupling

After PQ symmetry breaking

- Induces a Chern-Simons (topological) axion-photon coupling

$$\mathscr{L} \supset \frac{\mathscr{A}\,\alpha_{\rm em}}{4\pi f_a}\, a\, F\, \tilde{F}$$

PQ-EM anomaly coefficient

fine structure constant

axion

EM field strength

axion periodicity / PQ symmetry breaking scale

Anomaly coefficient

$$\mathscr{L} \supset \frac{\mathscr{A}\alpha_{\mathrm{em}}}{4\pi f_a} a F \tilde{F}$$

- f_a is subject to renormalisation
- But $\mathscr{A}$ is not, so its value is fixed on all energy scales

$$\mathscr{A} = \sum_f Q_f^{\mathrm{PQ}} \left(Q_f^{\mathrm{EM}}\right)^2$$

all beyond-SM fermions

PQ charges, integers

electric charges

- $\mathscr{A}$ is integer multiple of square of the smallest electric charge beyond SM
- Beyond-the-SM theories predict different $\mathscr{A} = \mathscr{O}(1)$, e.g. 4/3 for minimal GUT
- Axion strings will allow us to measure $\mathscr{A}$ directly, unaffected by f_a

Cosmic birefringence

Induced by axion-photon coupling

$$\mathscr{L} \supset \frac{\mathscr{A}\alpha_{\rm em}}{4\pi f_a} a F \tilde{F}$$

- Polarisation of CMB photons is rotated by intervening axion field

$$\Delta\Phi = \frac{\mathscr{A}\alpha_{\rm em}}{2\pi f_a} \Delta a$$

- Rotation angle is proportional to net change in axion value along photon path
- Typically $a \ll 2\pi f_a$, so effect is very weak (naively)
- With axion strings, $\Delta a \approx n\, 2\pi f_a$ for integers n for any CMB photon, possible due to axion periodicity
- $\Delta\Phi \approx n\, \mathscr{A}\alpha_{\rm em} = n\, \mathcal{O}(\rm deg)$, rotation angle is macroscopic and quantised!

Axion strings

Axion strings

Topological defects in axion field

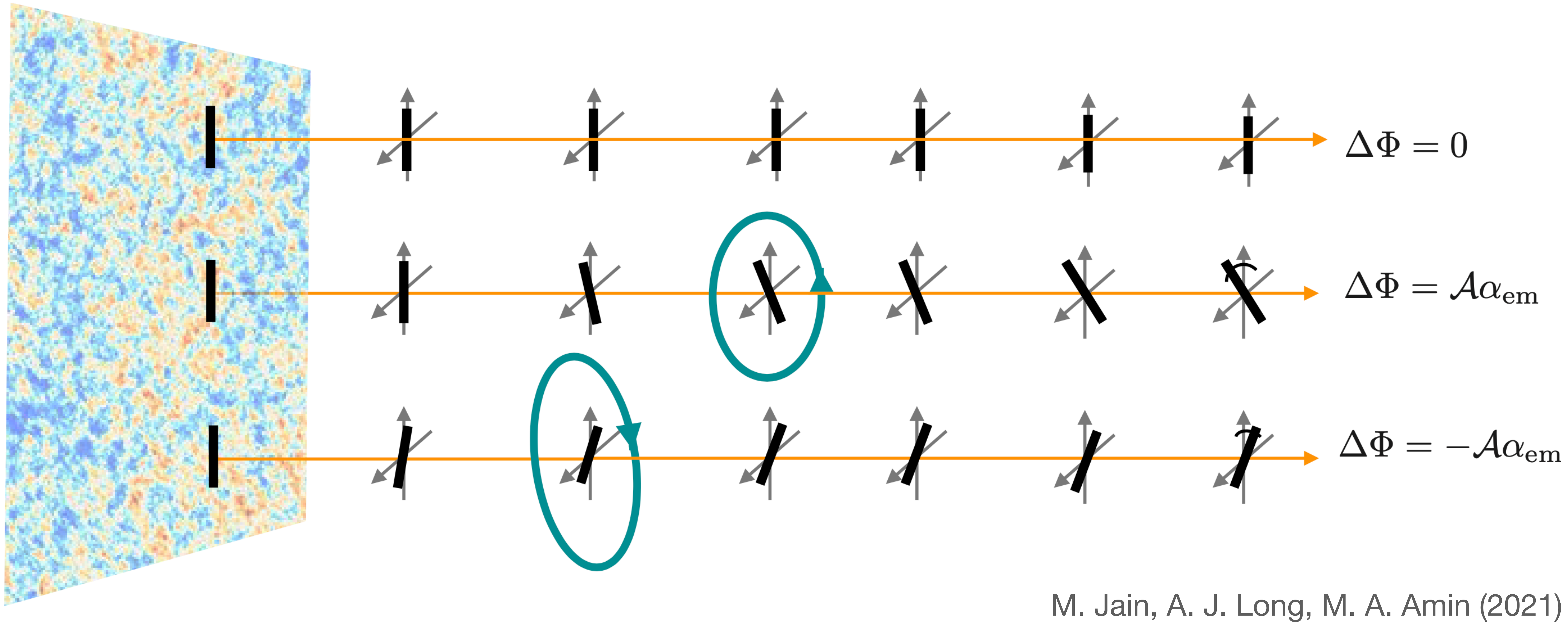
- a changes by exactly one period $2\pi f_a$ around a string
- Topologically stable (cannot be continuously deformed into vacuum)
- Formed in large numbers by Kibble mechanism if PQ symmetry breaking occurred after inflation
- Ultralight axion strings have no detectable gravitational effect

Cosmic birefringence

Induced by axion strings

$$\Delta\Phi = \frac{\mathscr{A}\alpha_{\rm em}}{2\pi f_a}\Delta a$$

- CMB polarisation rotates by $\Delta\Phi = \pm\mathscr{A}\alpha_{\rm em}$ if photon passes through a loop
- Observable: anisotropies in CMB polarisation rotation field

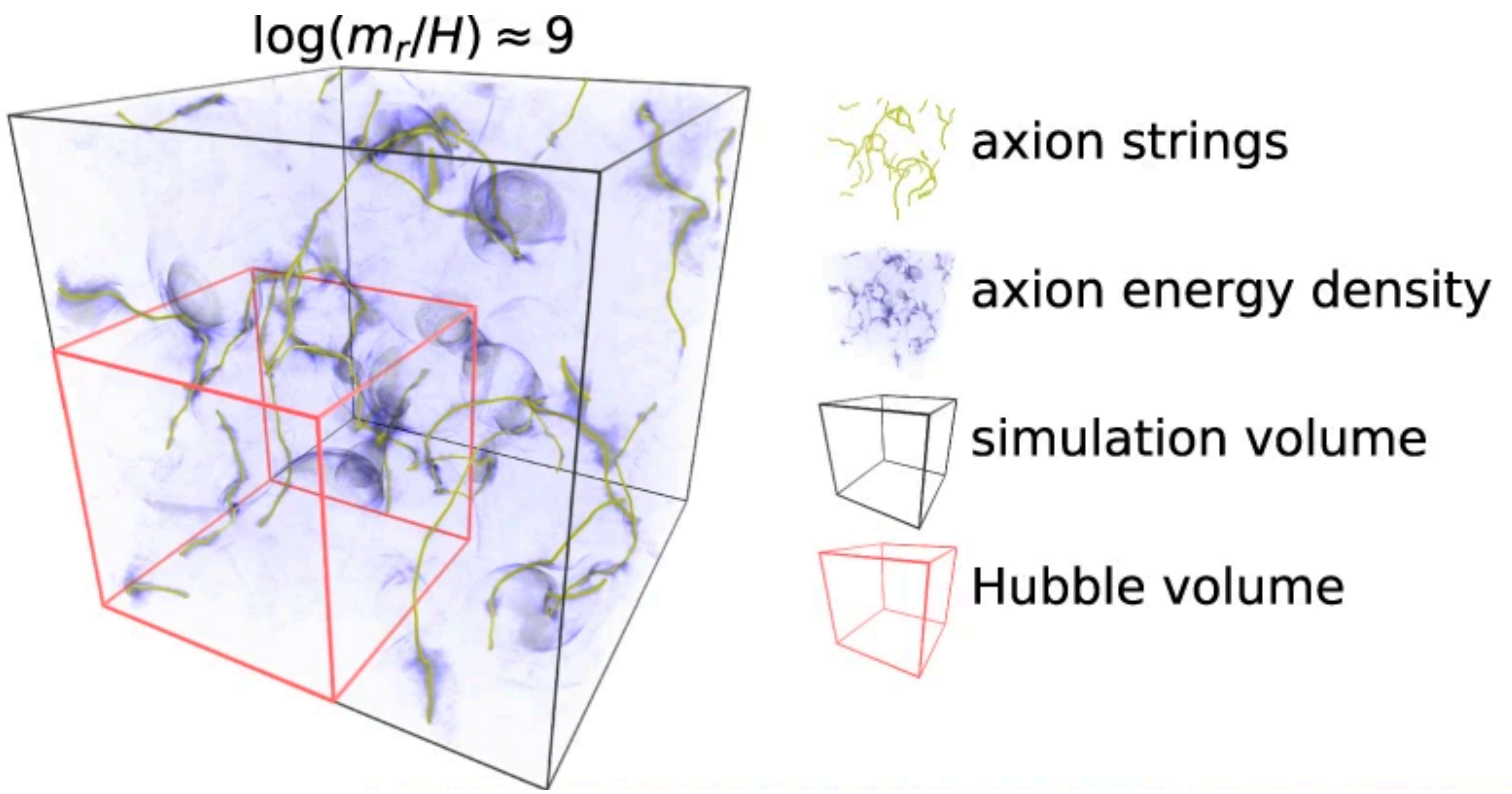


M. Jain, A. J. Long, M. A. Amin (2021)

Simulations

Of axion string networks

- String dynamics leads to the same loop length distribution
- Most strings (~80%) are Hubble or super-Hubble scale
- The rest are logarithmically distributed sub-Hubble scale



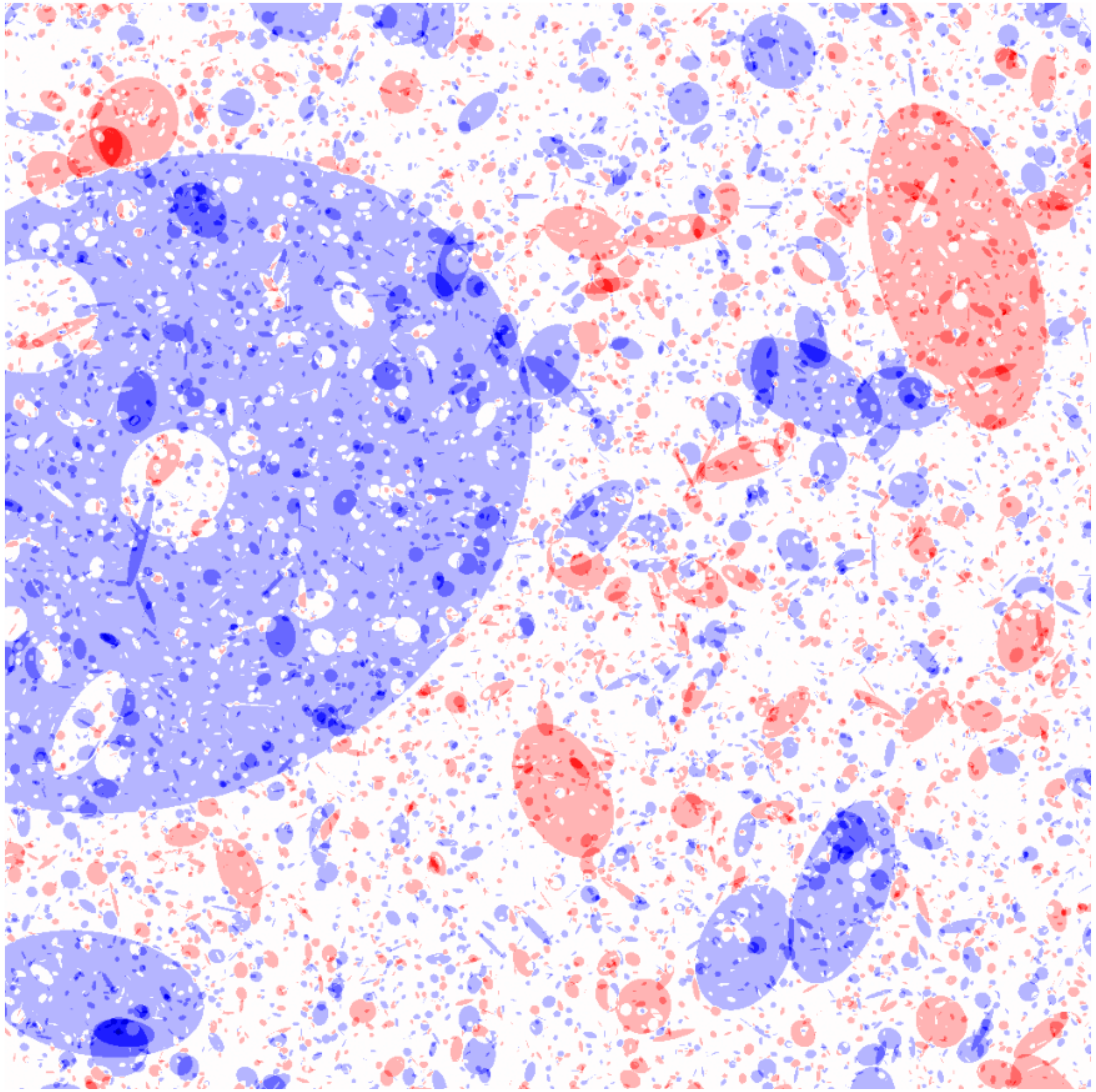
M. Buschmann, et al. (2022)

Loop-crossing model

A phenomenological string network model

- M. Jain, A. J. Long, M. A. Amin (2021)
- Circular string loops in random orientations scattered throughout the universe
- Loop radius distribution specified for one redshift then evolves via scaling law
- Each loop "paints" an ellipse on polarisation rotation field filled with $\pm\mathscr{A}\alpha_{\mathrm{em}}$

Simulated polarisation rotation field (red+, blue–)



W. W. Yin, L. Dai, S. Ferraro (2023)

Parameters

Of the loop-crossing model

- $\mathscr{A} = 0.1 \sim 1$
  Overall scaling of string-induced CMB polarisation rotation signal
- $\xi_0 = 1 \sim 100$
  Effective number of (Hubble-scale) string loops per Hubble volume
- Other parameters that control loop radius distribution at any given redshift

Cosmic birefringence

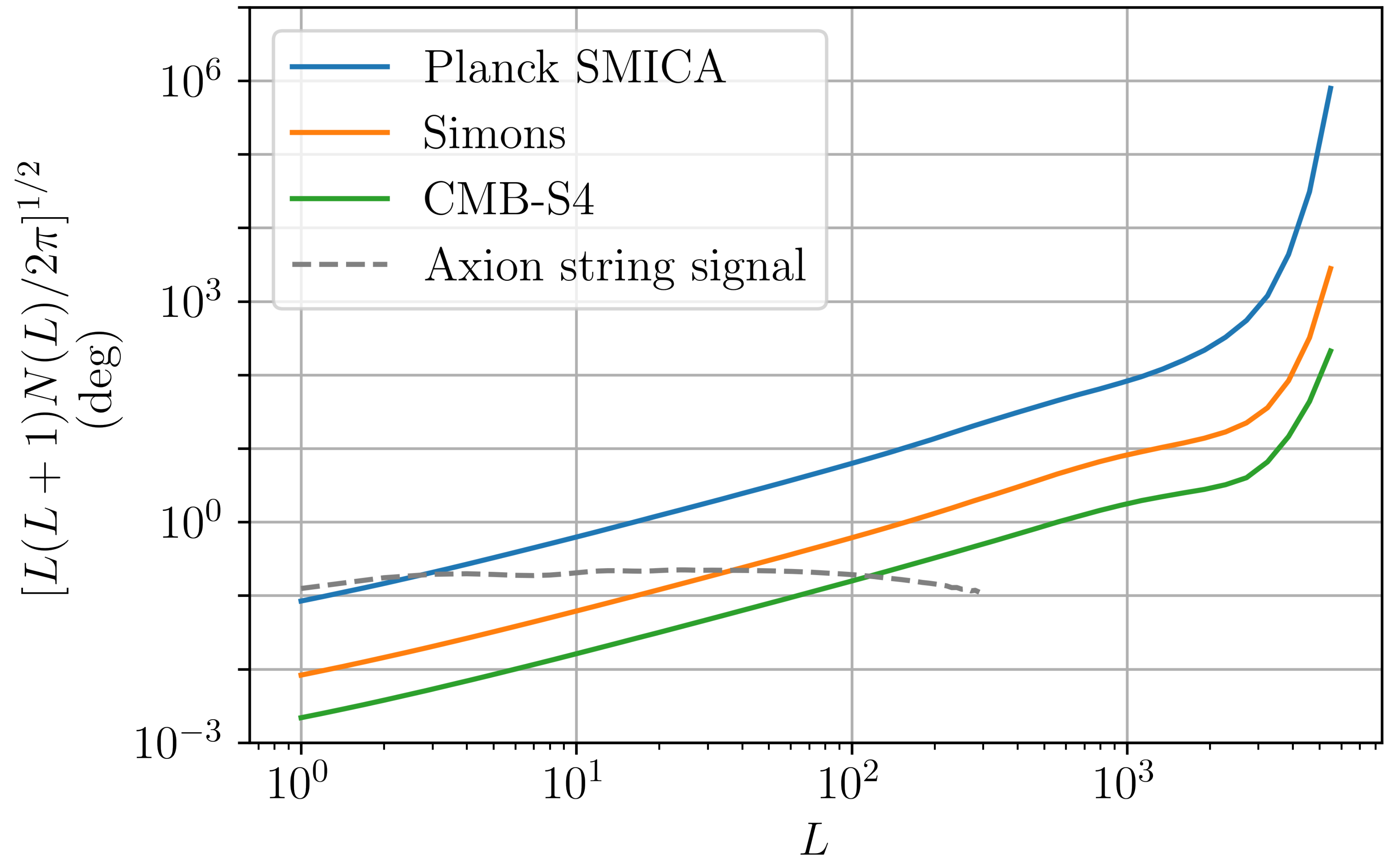
Quadratic estimators

- CMB polarisation rotation field must be estimated from cross-correlations between primary CMB observables T, E, and B
- Quadratic estimators (QE), well established for weak lensing, can be applied
- Lensing potential and polarisation rotation field can be simultaneously estimated via QEs
- Cannot resolve individual strings, need statistical detection of many strings
- Power spectrum of QEs well understood, use as summary statistics

QE sensitivity

To axion string signal

- Signal is dominated by $L \lesssim 100$ modes in the rotation field power spectrum
- CMB Stage III, IV will discover or falsify axion string-induced anisotropic polarisation rotation



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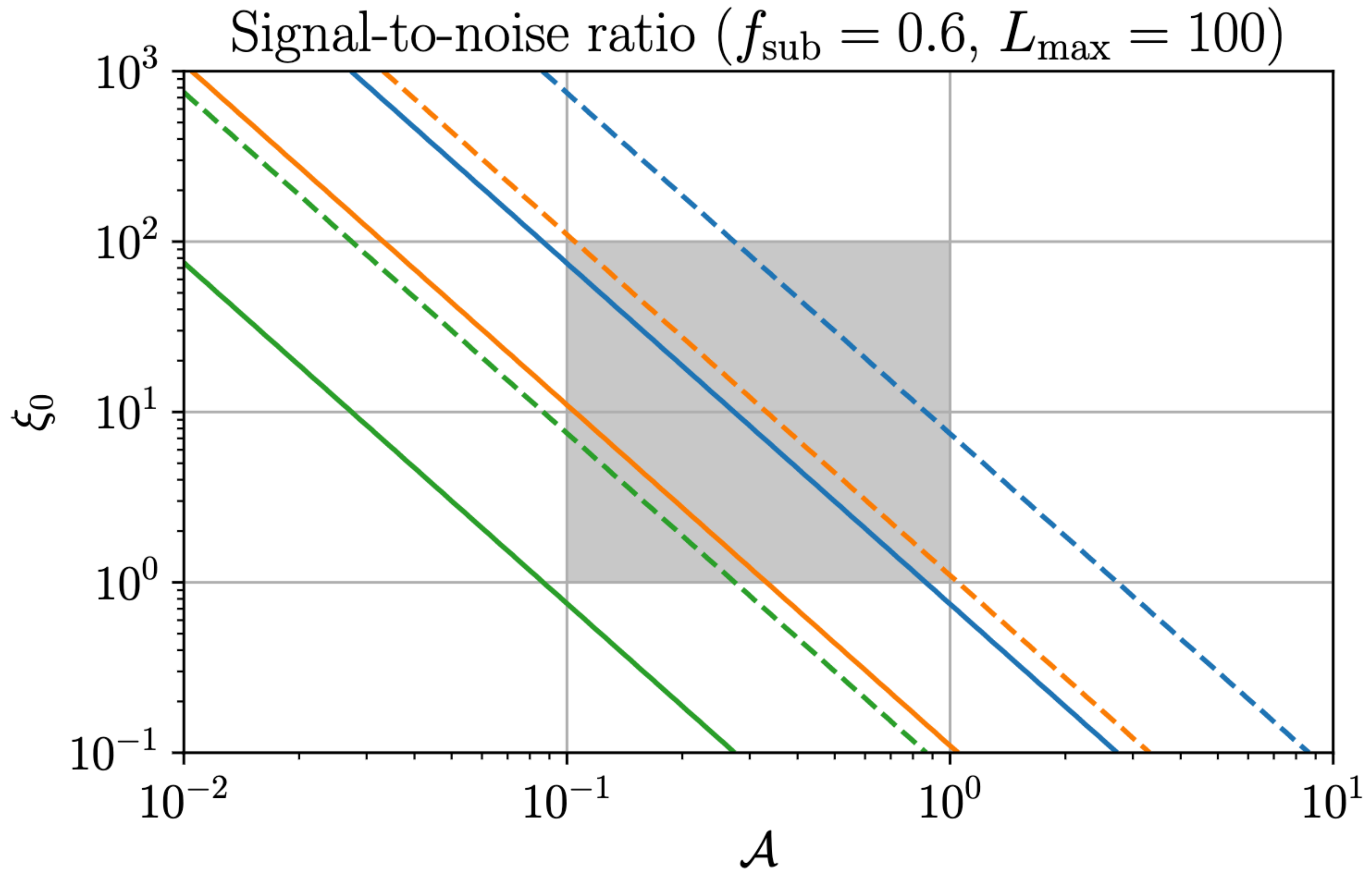

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Planck constraint

- For the loop-crossing model in which a fraction of string loops have logarithmically distributed sub-Hubble sizes
- Planck 2015 data gives constraint $\mathscr{A}^2\,\xi_0 < 0.93$ at 95% confidence
- Consistent with absence of axion strings

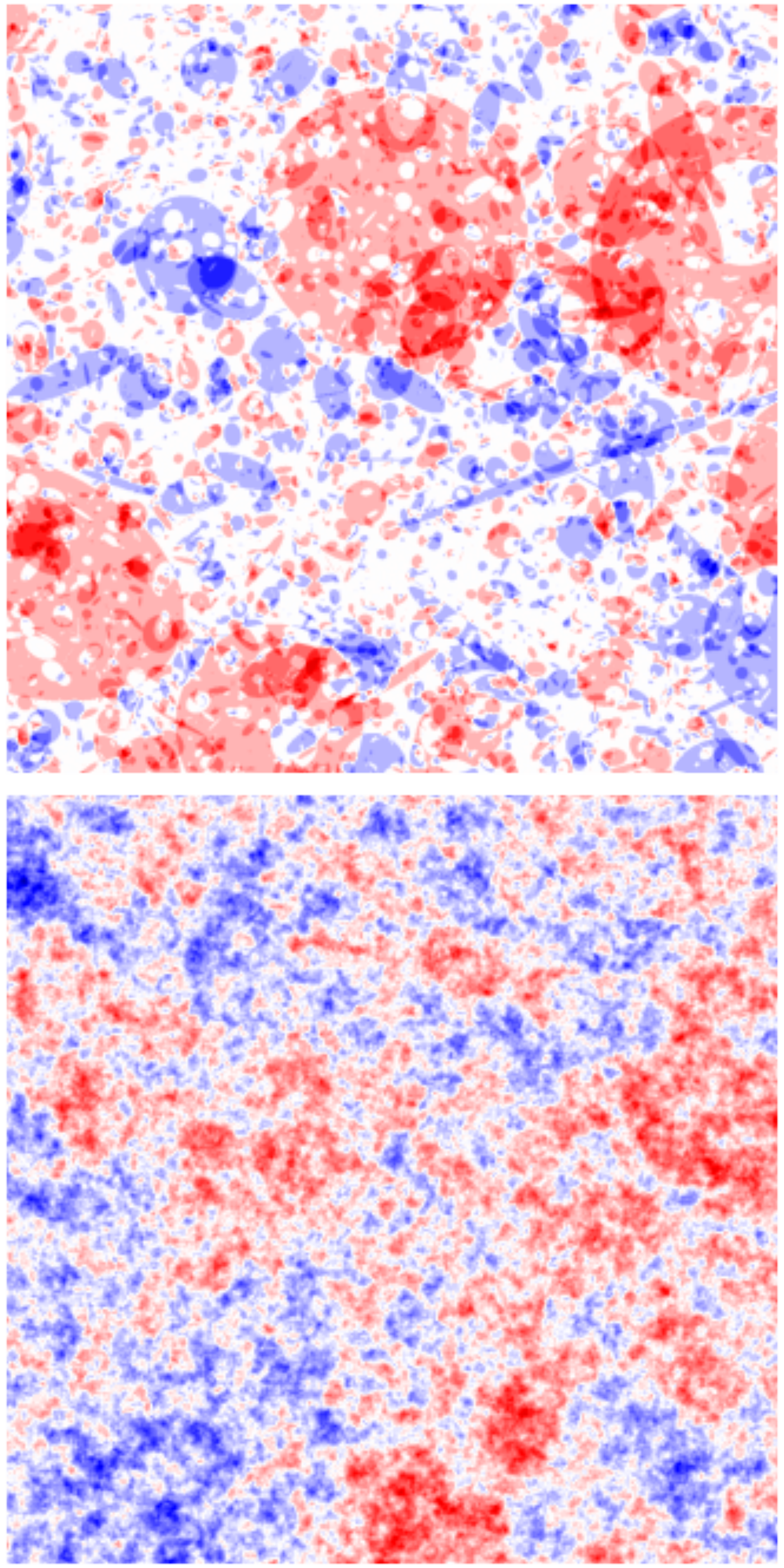
Beyond the power spectrum

Limitations

Of power spectrum

- Only captures Gaussian information
- Unable to distinguish between string networks with the same $\mathscr{A}^2 \xi_0$ but different $\mathscr{A}$
- Need to go beyond power spectrum
  - Bi-/trispectrum? CNN? *Scattering transform?* 🎉

Few strong strings



Many weak strings

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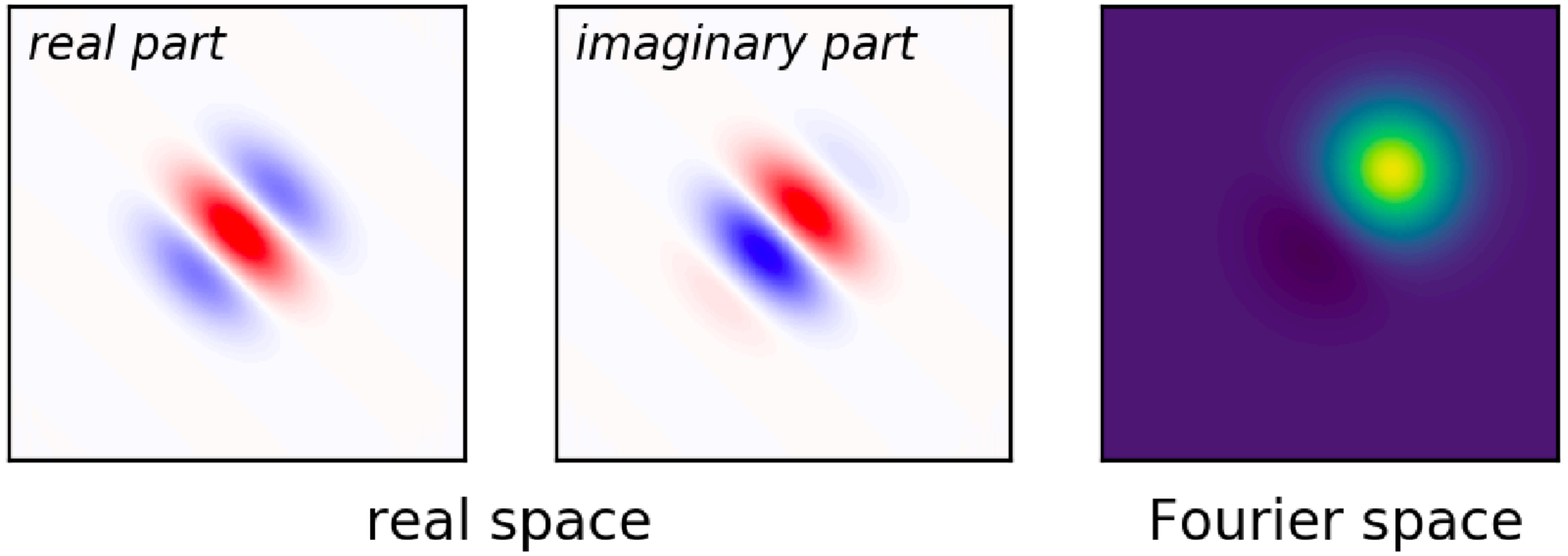
Scattering transform

- Convolve input field with Morlet wavelets (localised in real and Fourier space) of different scales and orientations



S. Cheng, et al. (2020)

- Similar to convolutional neural network but requires no training
- Non-linear transform (absolute value) after convolution ensures non-Gaussian info is extracted
- Can reduce to translationally and rotationally symmetric summary statistics

Advantages

Of scattering transform (ST)

- Over bi-/trispectra
  - Packs non-Gaussian info in small number of coefficients: for 128^2 input field, only 21 ST coefficients
  - Higher-order ST does not suffer from the increased sample variance from (input field)^(high power)
- Over convolutional neural network (CNN)
  - Requires no training
  - Reduced coefficients are inherently translationally and rotationally symmetric
  - Individual coefficients have interpretable meaning

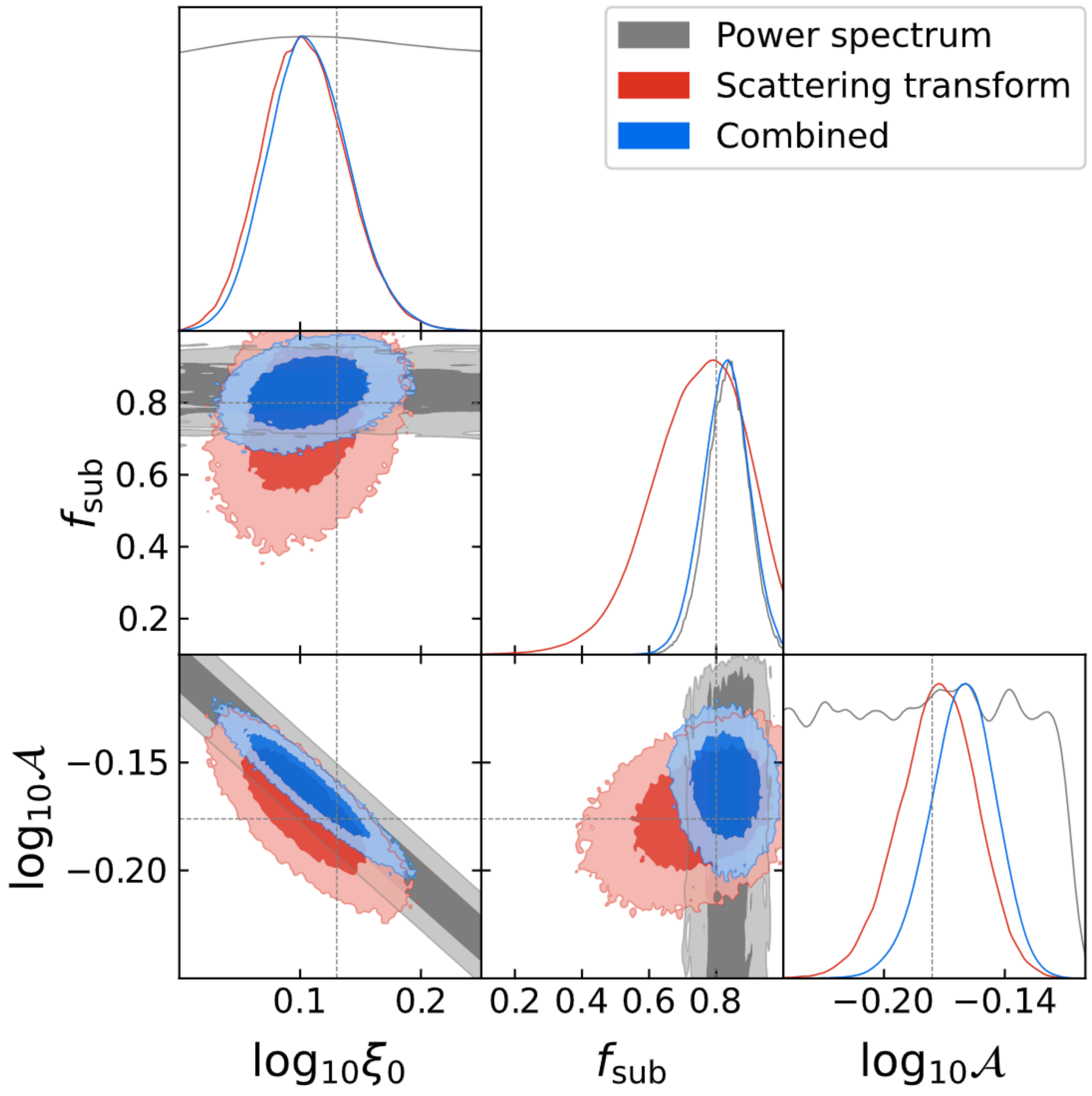
Parameter inference

Using scattering transform

- Generate a large number of polarisation rotation fields on the discretised parameter space of the loop-crossing model
- Compute their scattering transform coefficients (Kymatio Python package)
- Compute sample mean and covariance matrix at each parameter grid point
- Interpolate to obtain the "theory" against which actual CMB polarisation rotation field is compared
- Likelihood maximisation by MCMC

Evaluation

- Testing is done using mock polarisation rotation fields with known parameters as input fields
- Procedure repeated for both ideal noise-free case and QE reconstruction noise at future CMB-HD level
- Compared with power spectrum analysis



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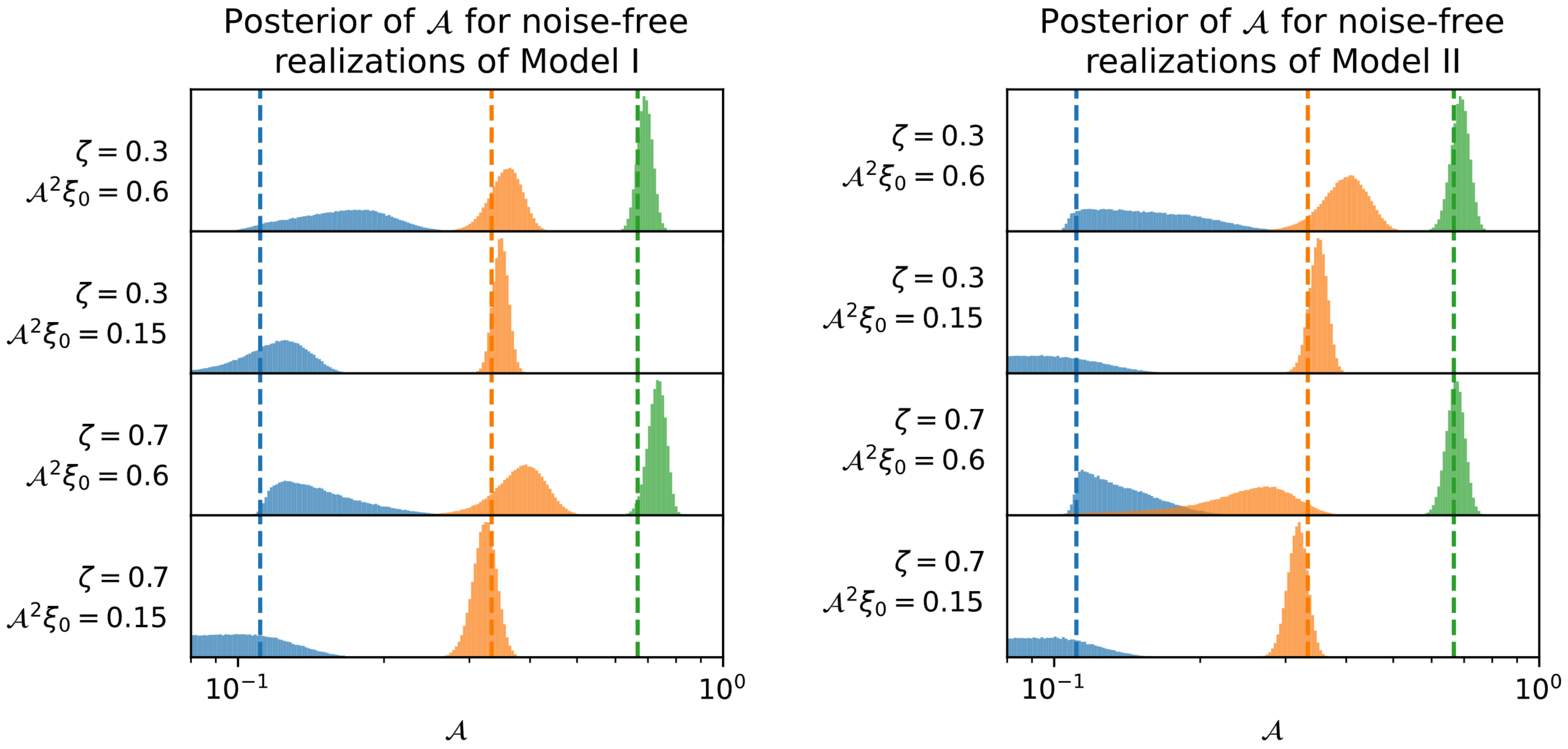
Ideal noise-free case

- Able to clearly distinguish between $\mathscr{A} = 1/9, 1/3, 2/3$



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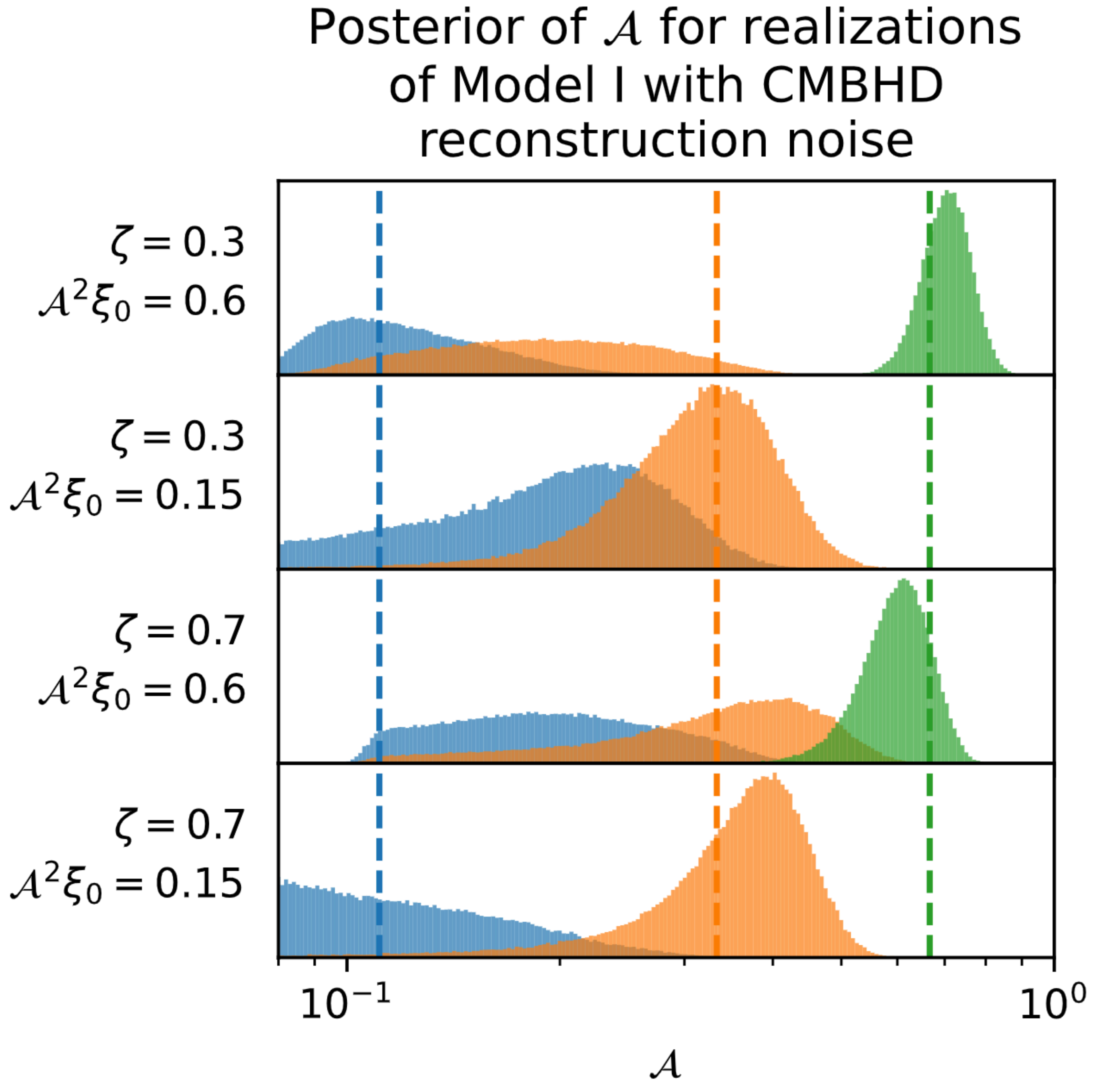
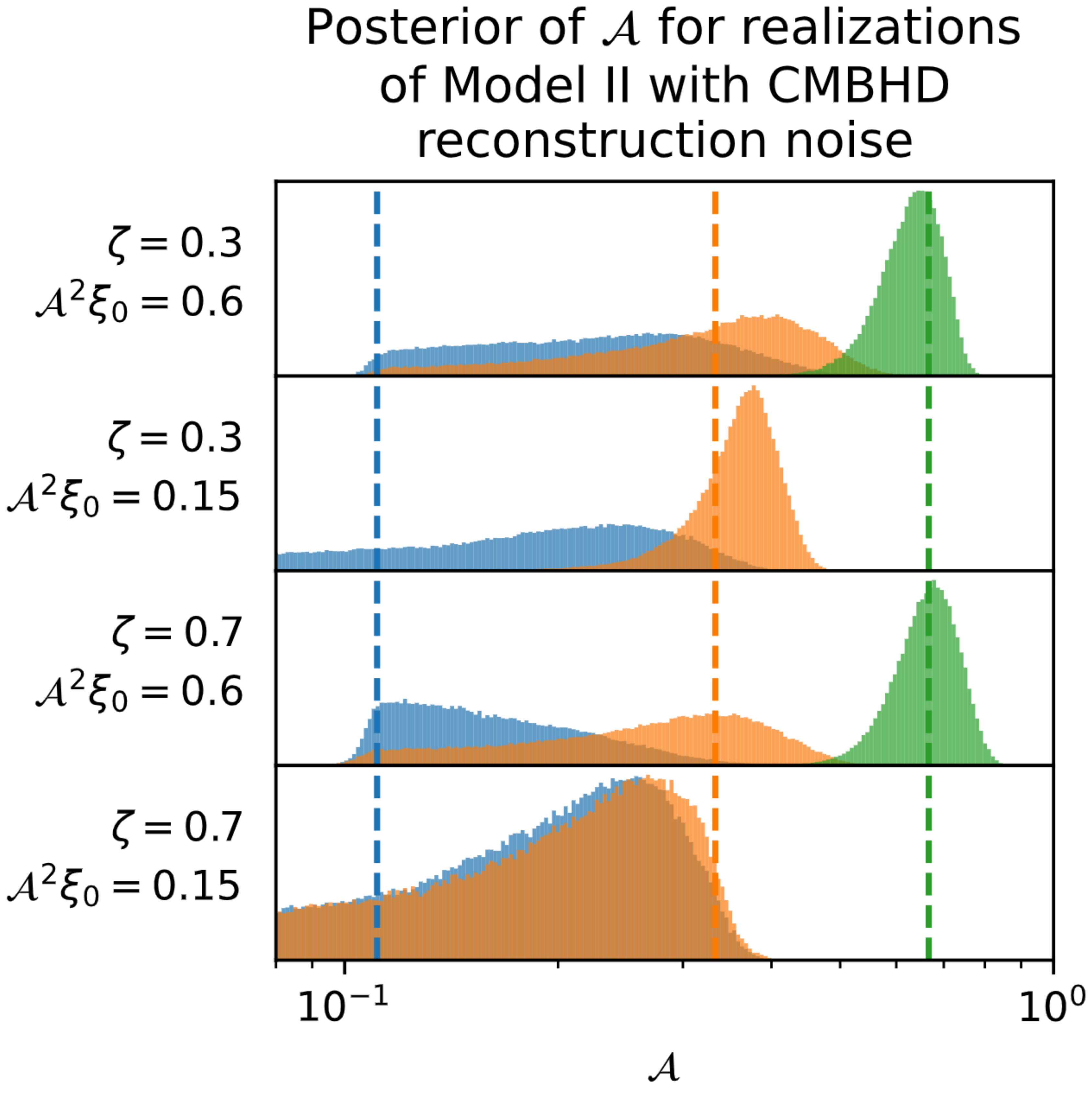
CMB-HD noise level

- Able to clearly distinguish $\mathscr{A} = 2/3$ from $\mathscr{A} = 1/9, 1/3$ and marginally between $\mathscr{A} = 1/9, 1/3$





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Summary

- Axion-photon coupling is proportional to anomaly coefficient $\mathscr{A}$
- $\mathscr{A}$ reveals charge assignments beyond the SM
- Axion strings induce quantised anisotropic rotation of CMB polarisation $\propto \mathscr{A}$
- CMB Stage III, IV will give us a conclusive answer on axion strings through power spectrum of QE
- Power spectrum analysis suffers from $\mathscr{A}^2\,\xi_0$ degeneracy
- If axion strings are discovered, scattering transform can measure $\mathscr{A}$ (at CMB-HD noise level) and rule out certain beyond-the-SM theories

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