Parity Violation on Cosmological Scales

New Physics from Galaxy Clustering, GGI

9 September, 2025

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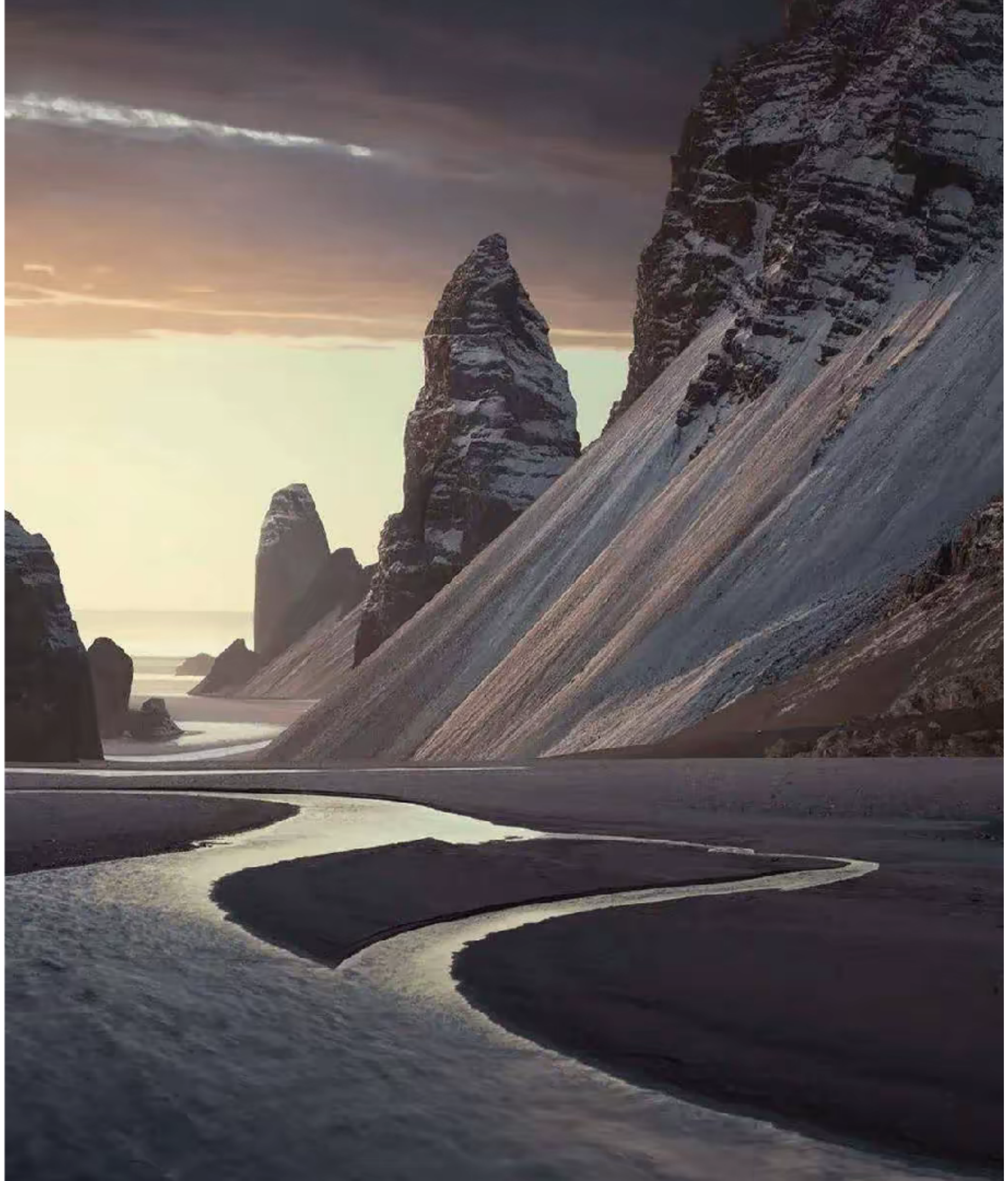
B. Everett
@ South Iceland



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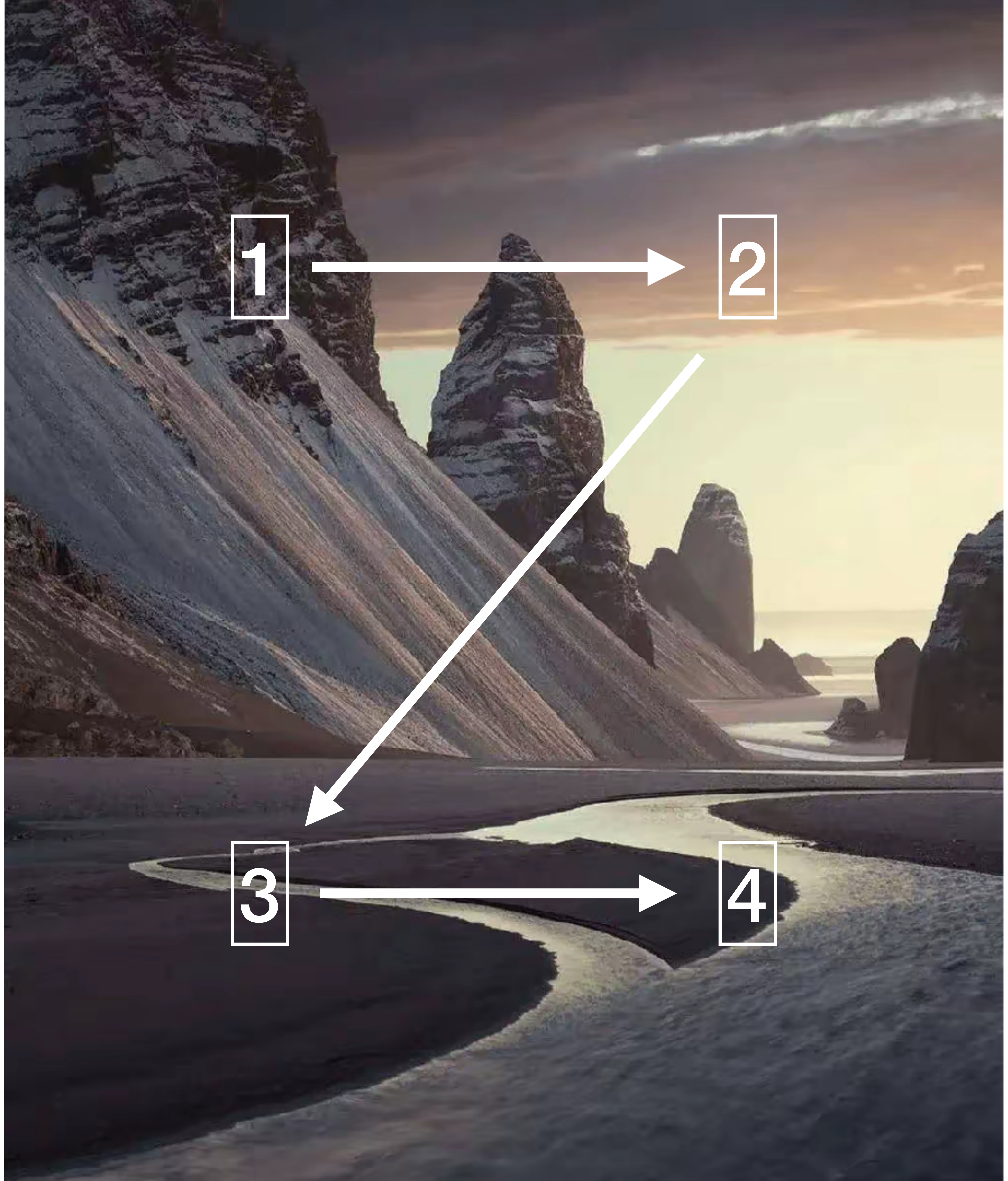
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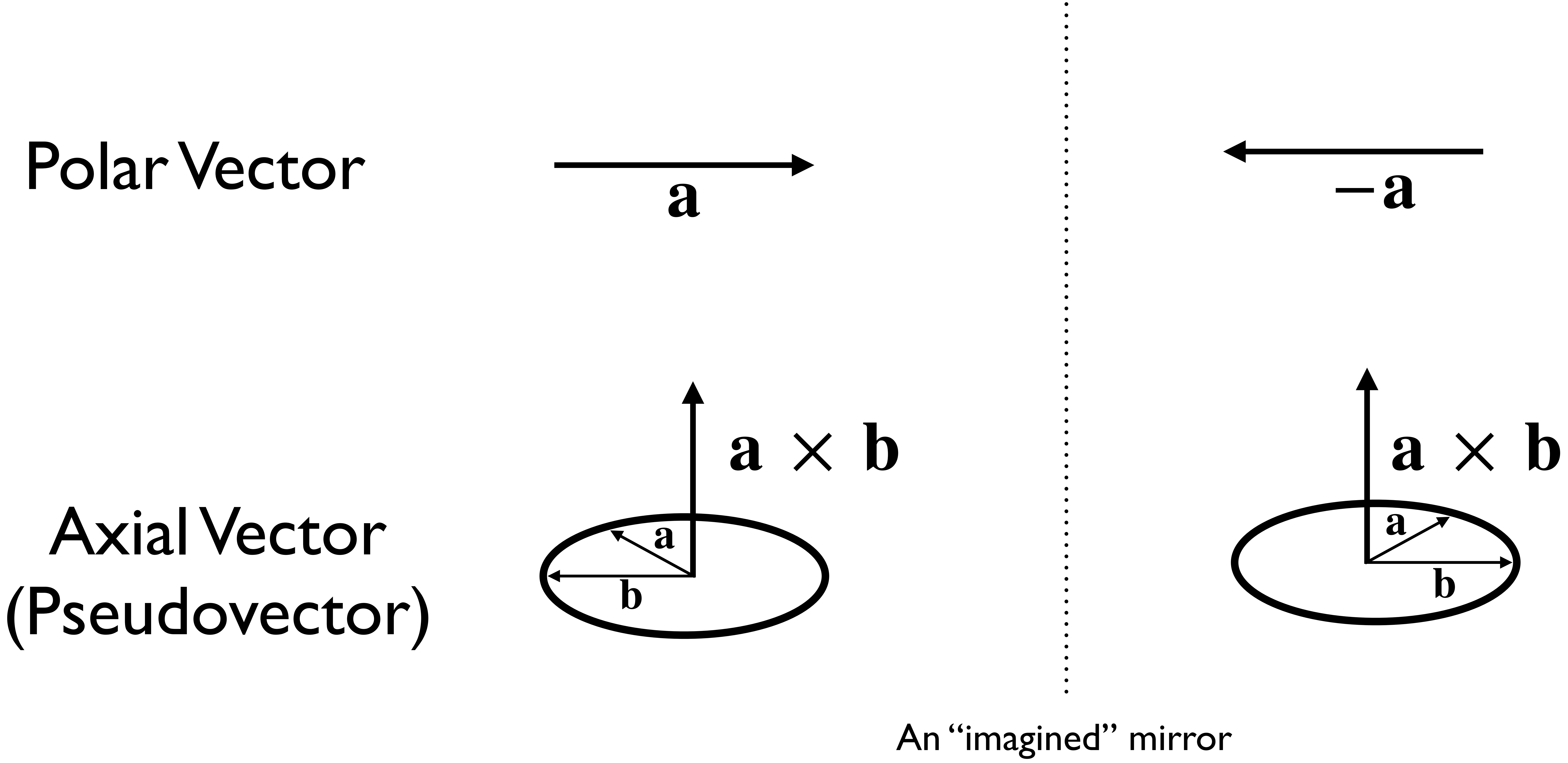
Parity Transformation

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \stackrel{\hat{\mathbb{P}}}{\mapsto} \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

How to extract parity information from scalar field?

$$\Phi(\mathbf{x}) \longrightarrow \Phi(-\mathbf{x})$$

Parity Transformation for Vectors

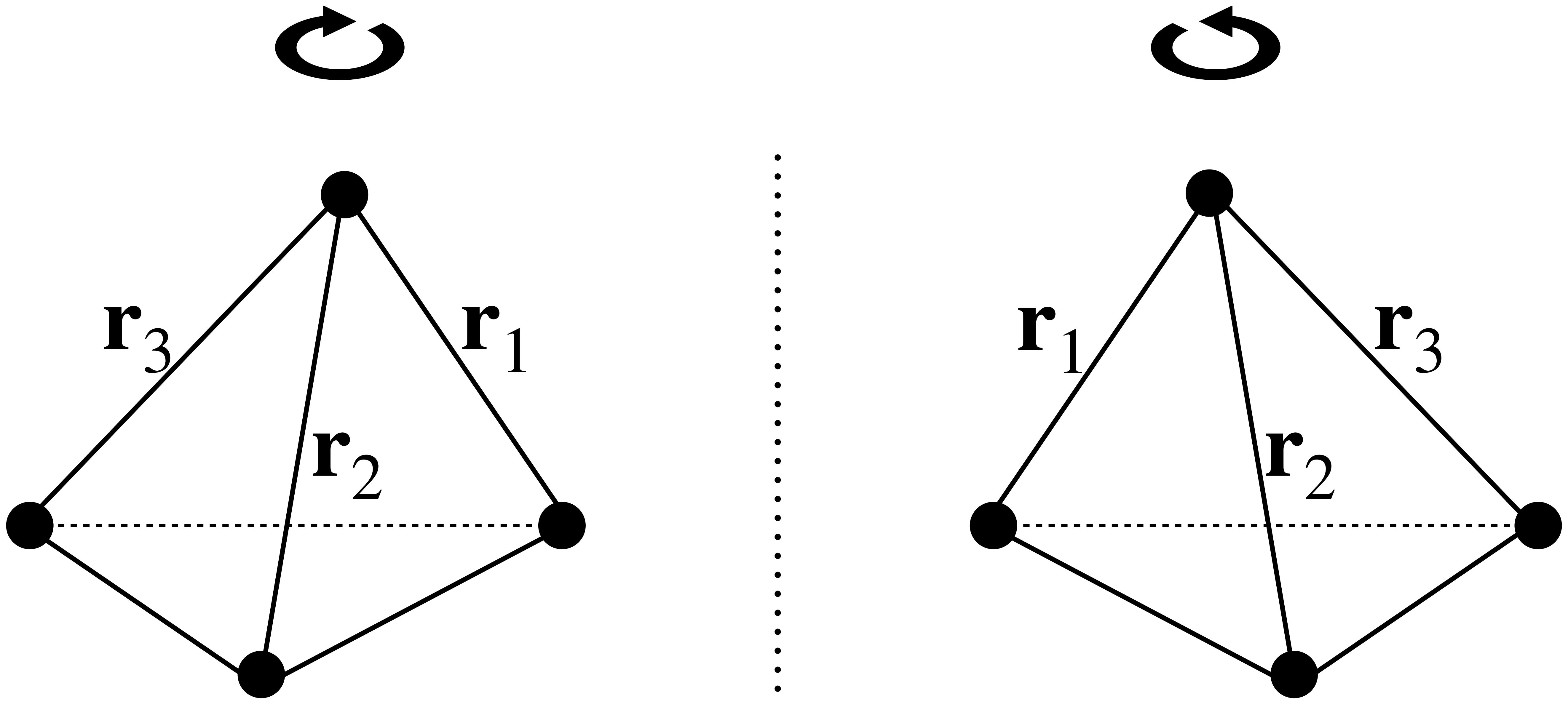


Polar Vector $\times$ Axial Vector (Pseudovector) $=$ Pseudoscalar

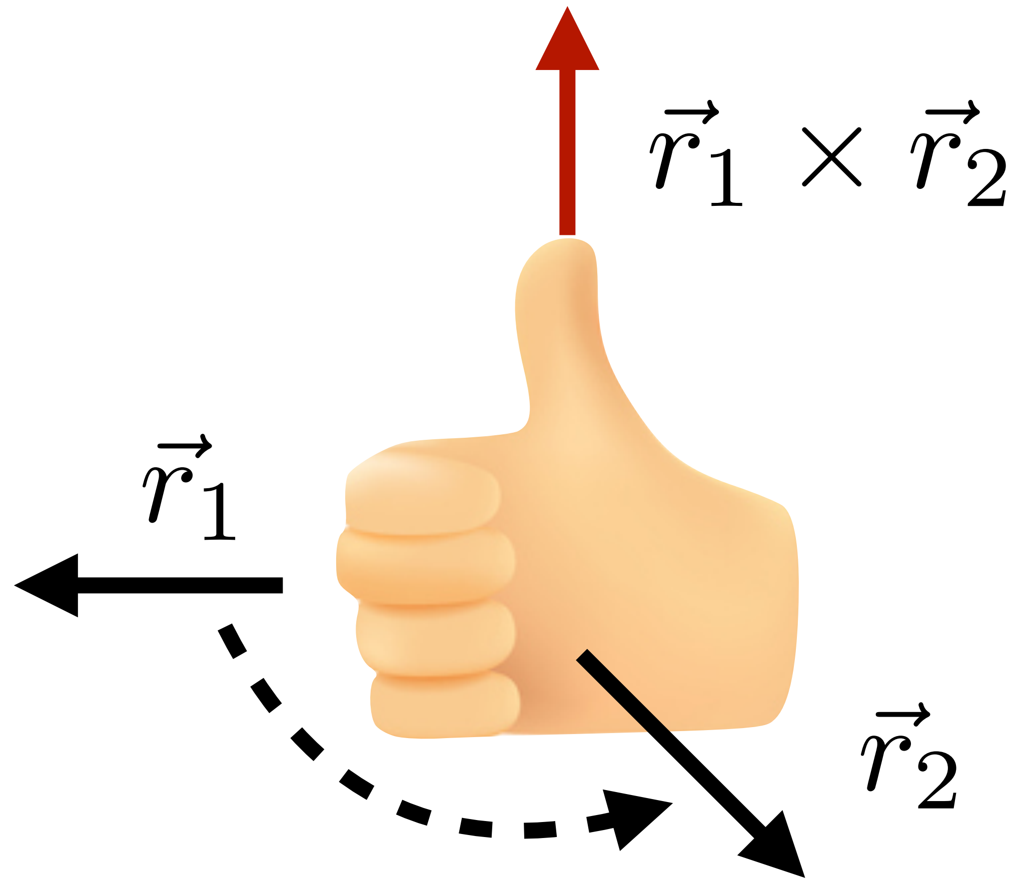
$$\mathbf{r}_1 \cdot (\mathbf{r}_2 \times \mathbf{r}_3) \longrightarrow -\mathbf{r}_1 \cdot (\mathbf{r}_2 \times \mathbf{r}_3)$$

Test of Parity Symmetry with Tetrahedra

$$\mathbf{r}_1 \cdot (\mathbf{r}_2 \times \mathbf{r}_3)$$



An “imagined” mirror

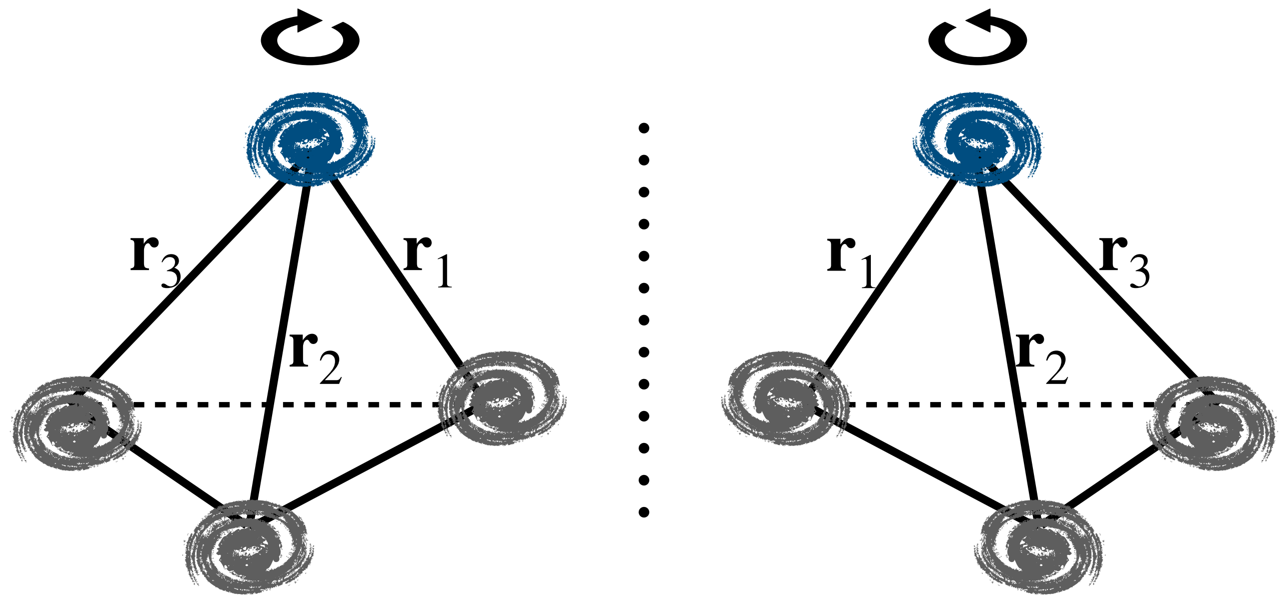


Need at least
4 points
to probe parity

Parity-Sensitive Cosmological Probes

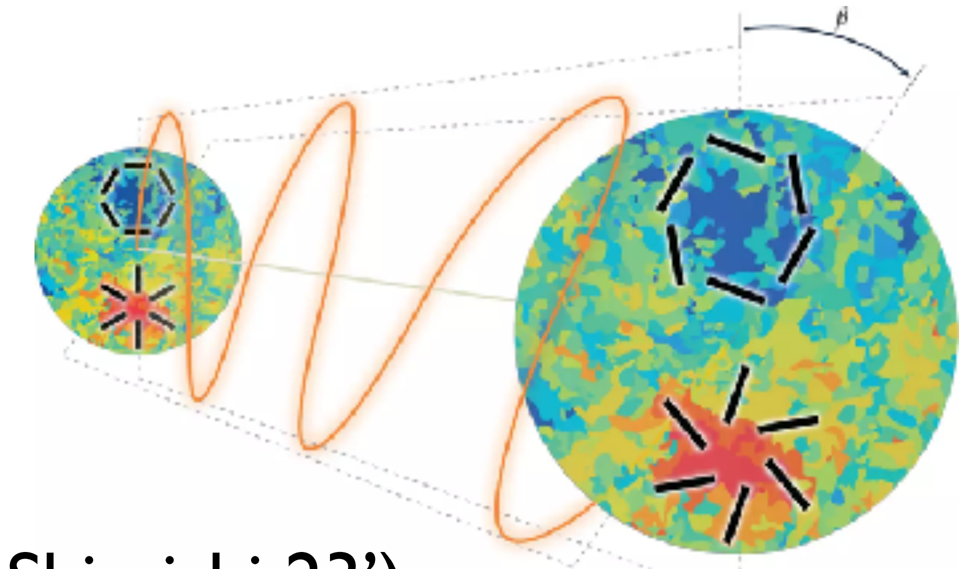
Scalar

- Galaxy 3D distribution (Hou+ 23', Philcox 22')
- CMB Temperature (Shiraishi 16', Philcox 23'), CMB lensing (Grecco++**JH**++, 25')



Vector/ Tensor

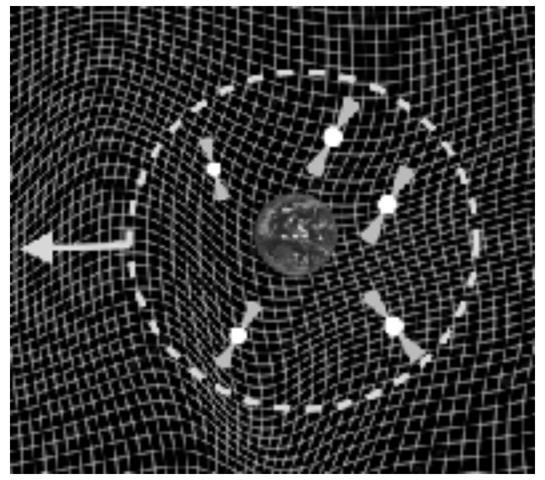
- Galaxy spin (Yu+ 20', Shim+ 24'), Intrinsic alignment (Kurita+, in prep), Shear & Shape (Philcox+, 23')
- CMB birefringence (Minami & Komatsu 20'; Eskilt & Komatsu 20'; Diego-Palazuelos+22')
- CMB polarisation (Lue+ 99', Saito+ 07', Kamionkowski & Souradeep 10', Masui + 17', Philcox & Shiraishi 23')



Credit: Minami

Tensor

- GW birefringence (Yagi+ 12', Berti+ 18', Qiao+ 19', Zhao+ 19', Alexander & Yunes 18', Yamada & Tanaka 20', Jenks+ 23', Ng+ 23'), Stochastic fore/background (Liang+ 24' Keisuke+ 24', Sato-Polito & Kamionkowski 24')



Credit: astrobites

Parity-violating Mechanisms

- Early-time: inflation
- Late-time: dark energy / dark matter

Parity-violating Mechanism and No-go theorem

Liu ++ 20'; Cabass ++ 22';

- Bunch Davis vacuum (Cabass, Ivanov, Philcox 23')
- Scale invariance (Creque-Sarbinowski ++ 23'; Niu ++ 23'; Reinhard++ **JH** ++ 24')
- Unitarity & Locality (Stefanyszyn, Tong, Zhu 22')
- Tree-level (Lee, McCulloch, Pajer 23')

4PCF can be decomposed into a parity-even and parity-odd component

$$\zeta = \zeta_+ + i\zeta_-$$

Even: gravity-induced non-Gaussianity

Odd: beyond standard model physics

$$\zeta_- = \mathbf{k}_1 \cdot (\mathbf{k}_2 \times \mathbf{k}_3)\, \tau_-(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)$$

Extract Parity Violation from Scalar field and Choice of Basis

Rotational invariant — statistical isotropy

Sensitive to parity transformation

Allow to construct fast algorithms

Spherical Harmonics as a Convenient Choice

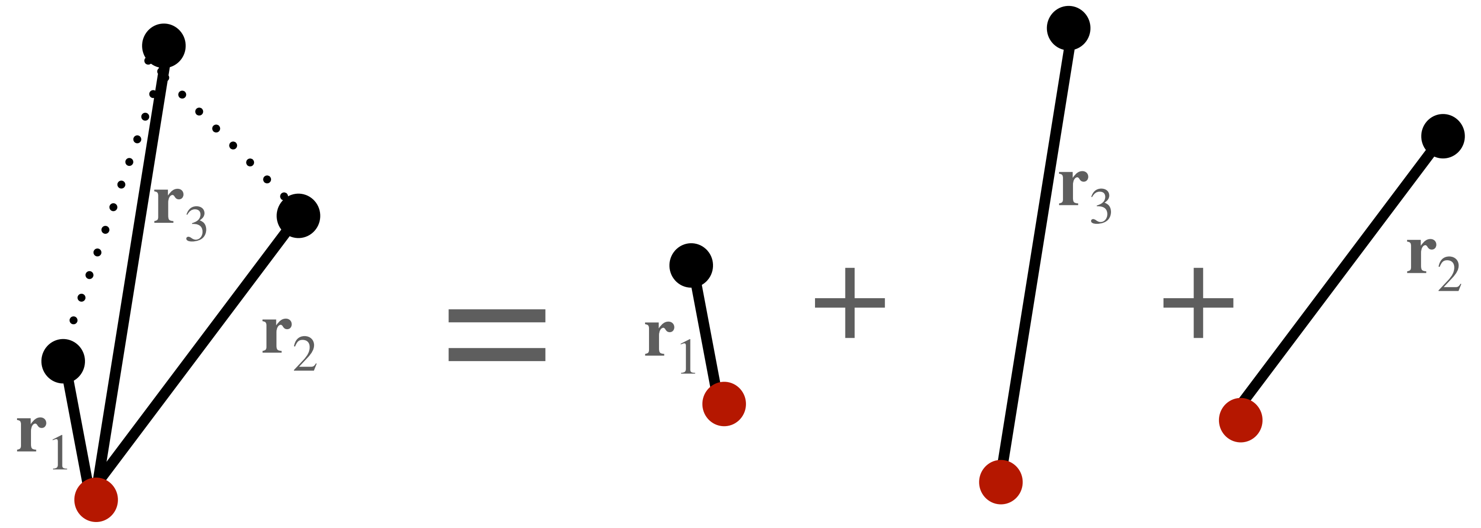
Rotational invariant

$$V^{(\ell_1)} \otimes V^{(\ell_2)} = \bigoplus_{L=|\ell_1-\ell_2|}^{\ell_1+\ell_2} V^{(L)}$$

Sensitive to parity transformation

$$\mathbb{P}[Y_{\ell m}(\hat{n})] \rightarrow (-1)^{\ell} Y_{\ell m}(\hat{n})$$

Speed and Factorizability



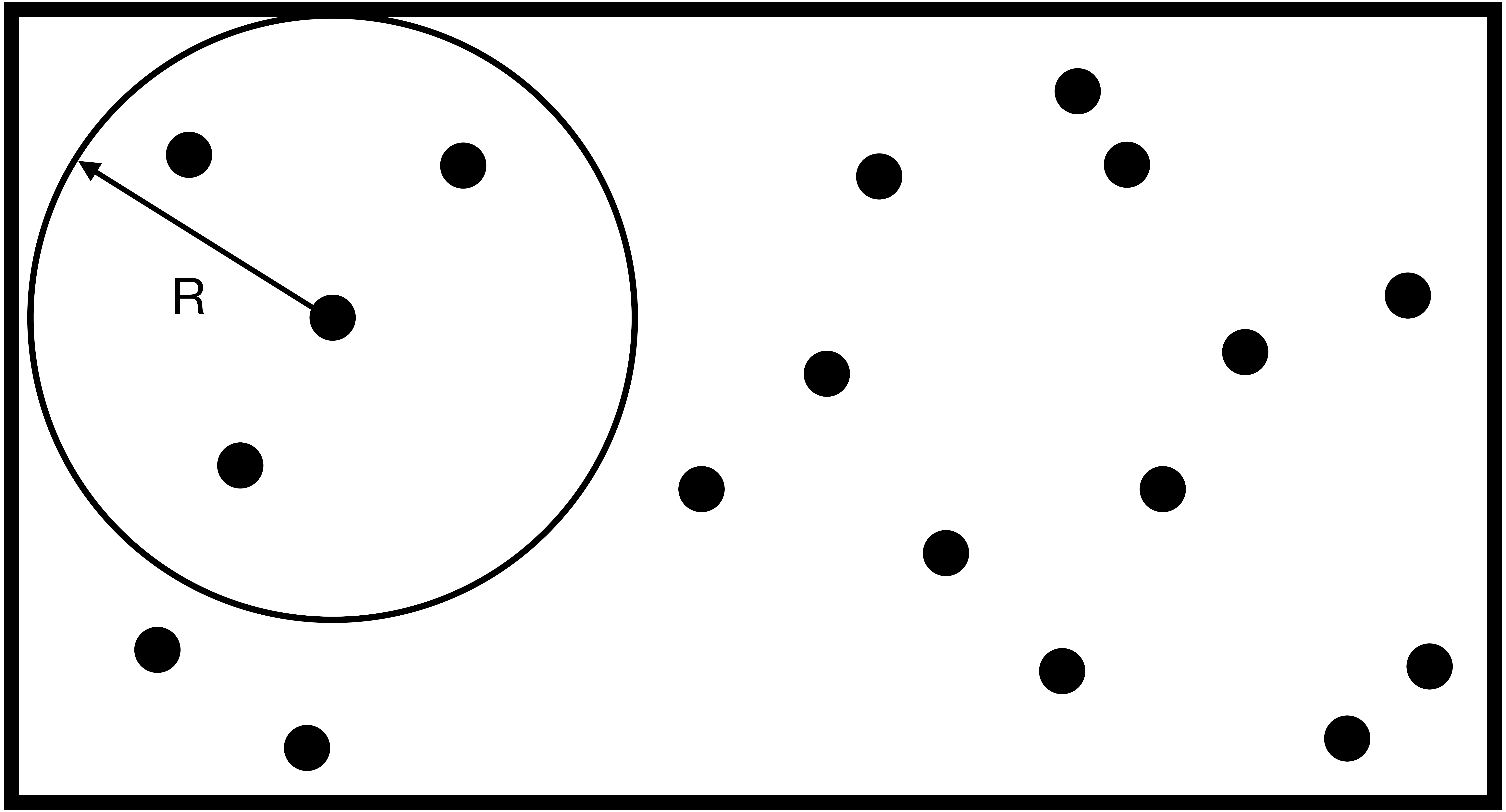
Harmonic Basis for 4-Point Function

$$\mathscr{P}_{\ell_1\ell_2\ell_3}(\hat{r}_1, \hat{r}_2, \hat{r}_3)$$

$$\equiv \sum_{m_1,m_2,m_3} (-1)^{\ell_1+\ell_2+\ell_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} Y_{\ell_1 m_1}(\hat{r}_1) Y_{\ell_2 m_2}(\hat{r}_2) Y_{\ell_3 m_3}(\hat{r}_3)$$

Tripolar Spherical Harmonics (Hu 04'; Shiraishi 17'; Sugiyama 18')
Isotropic basis function (Cahn & Slepian 22')

How are spherical harmonics related to galaxies?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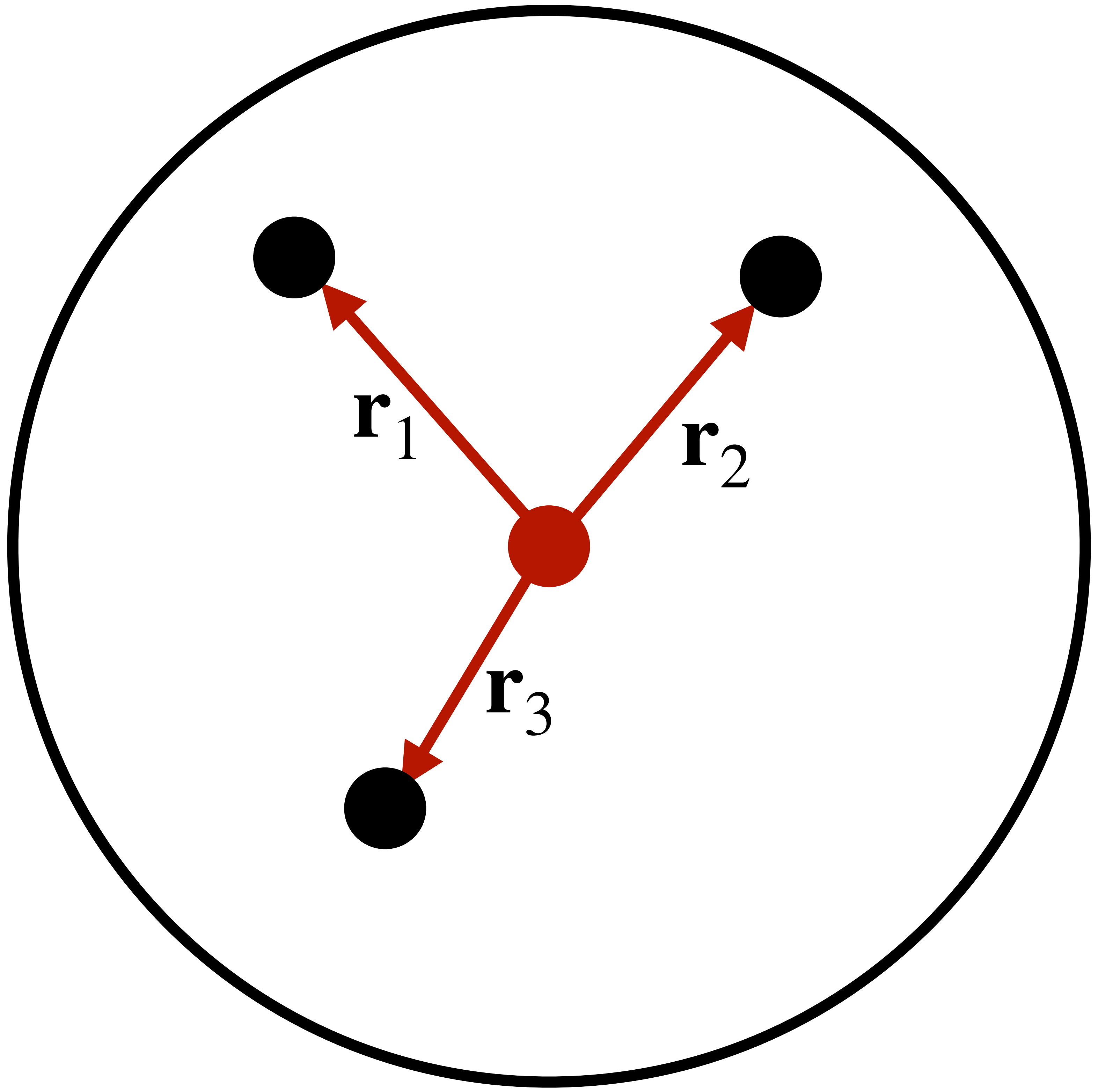


Single density field

$$\delta(\mathbf{x}+\mathbf{r}_i) = \sum_{\ell_i m_i} a_{\ell_i m_i}(r_i\,|\,\mathbf{x}) Y_{\ell_i m_i}(\hat{r}_i)$$

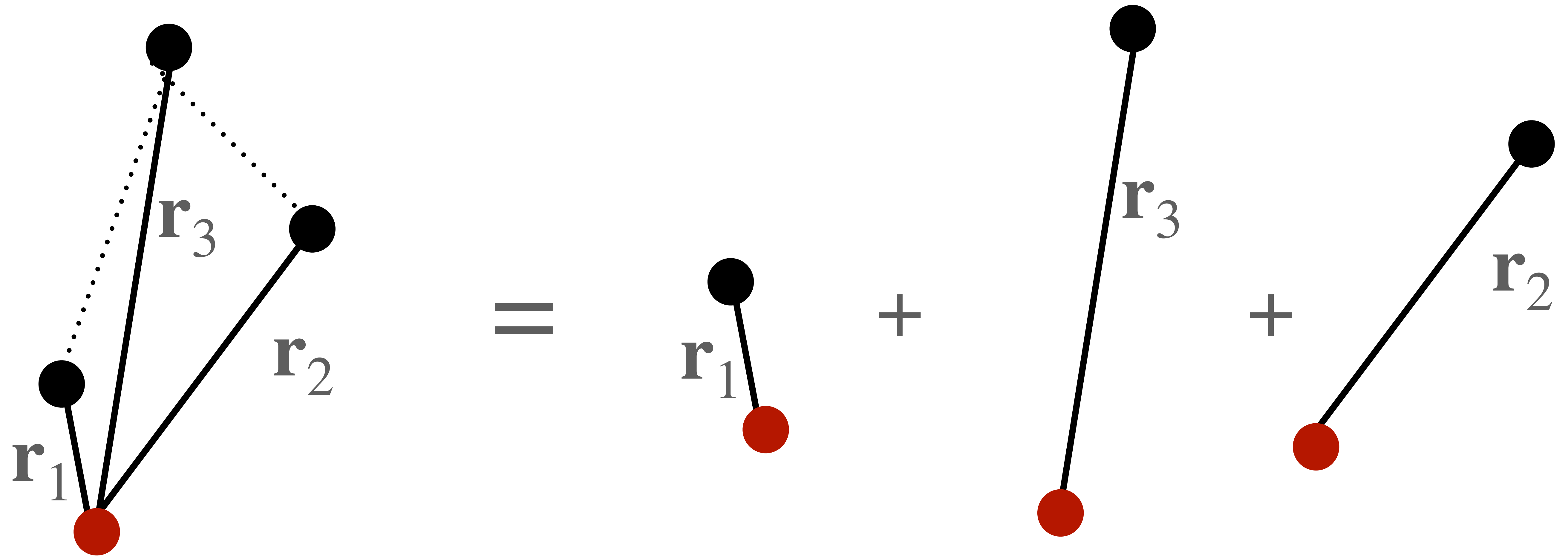
↓

N-density fields

$$\langle \delta(\mathbf{x}) \prod_{i=1}^{N-1} \delta(\mathbf{x}+\mathbf{r}_i) \rangle$$

$$= \sum_{\ell_1,\ldots\ell_{N-1}} \zeta_\Lambda(r_1,\ldots,r_{N-1}) \mathscr{P}_\Lambda(\hat{r}_1,\ldots,\hat{r}_{N-1})$$

Angular Basis is Factorizable



$N_g^4 \longrightarrow N_g^2$

Reduce the scaling from
"quartet" to "pair"

Measurement of 4-point function for $\mathcal{O}(10^6)$ Galaxies

~ 10^{24} galaxy quartets

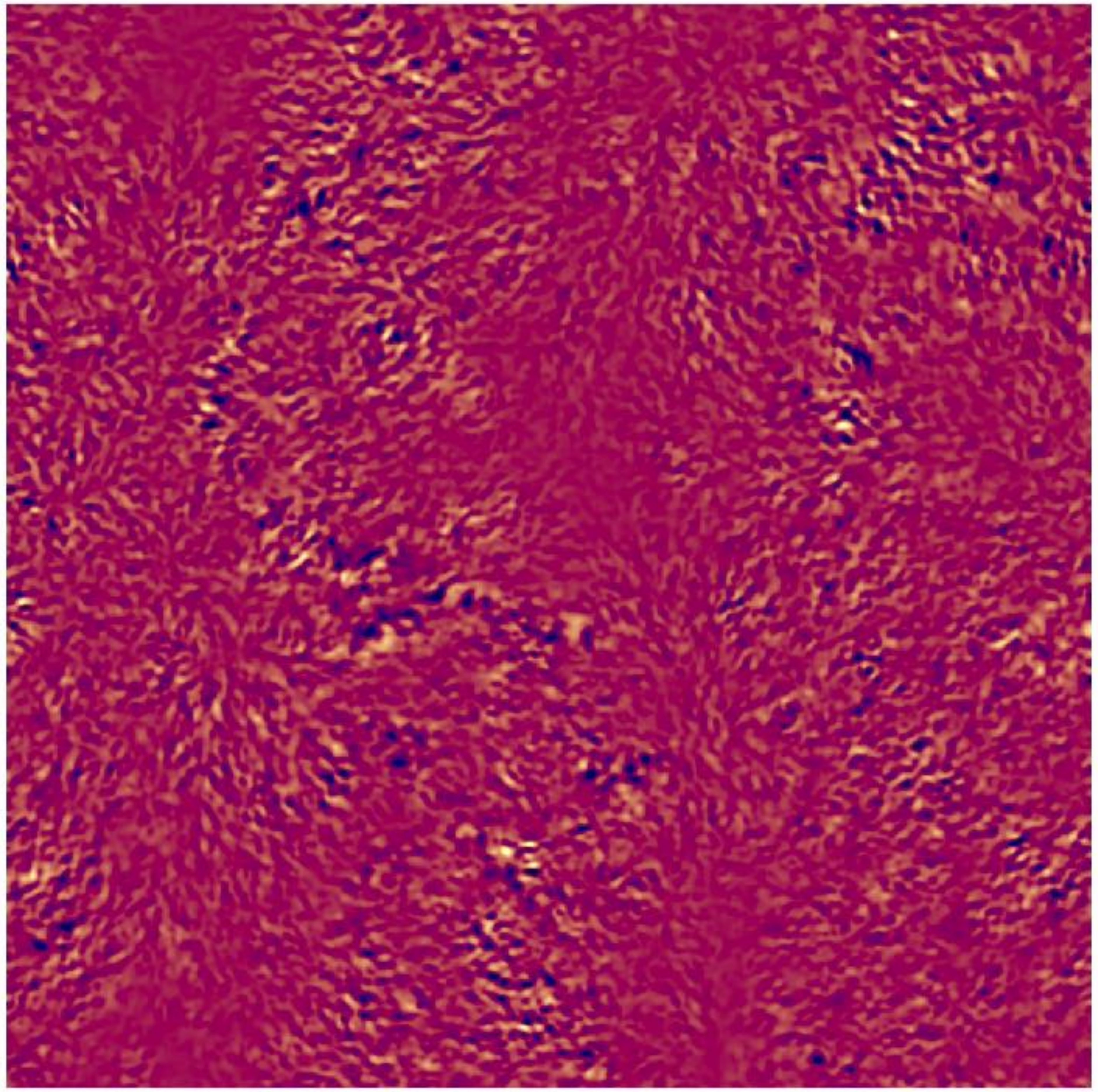
Centuries of calculation $\rightarrow$ **One minute**!*

*4PCF, with Graphics Processing Unit (GPU) acceleration

Philcox++**JH**++ (22')

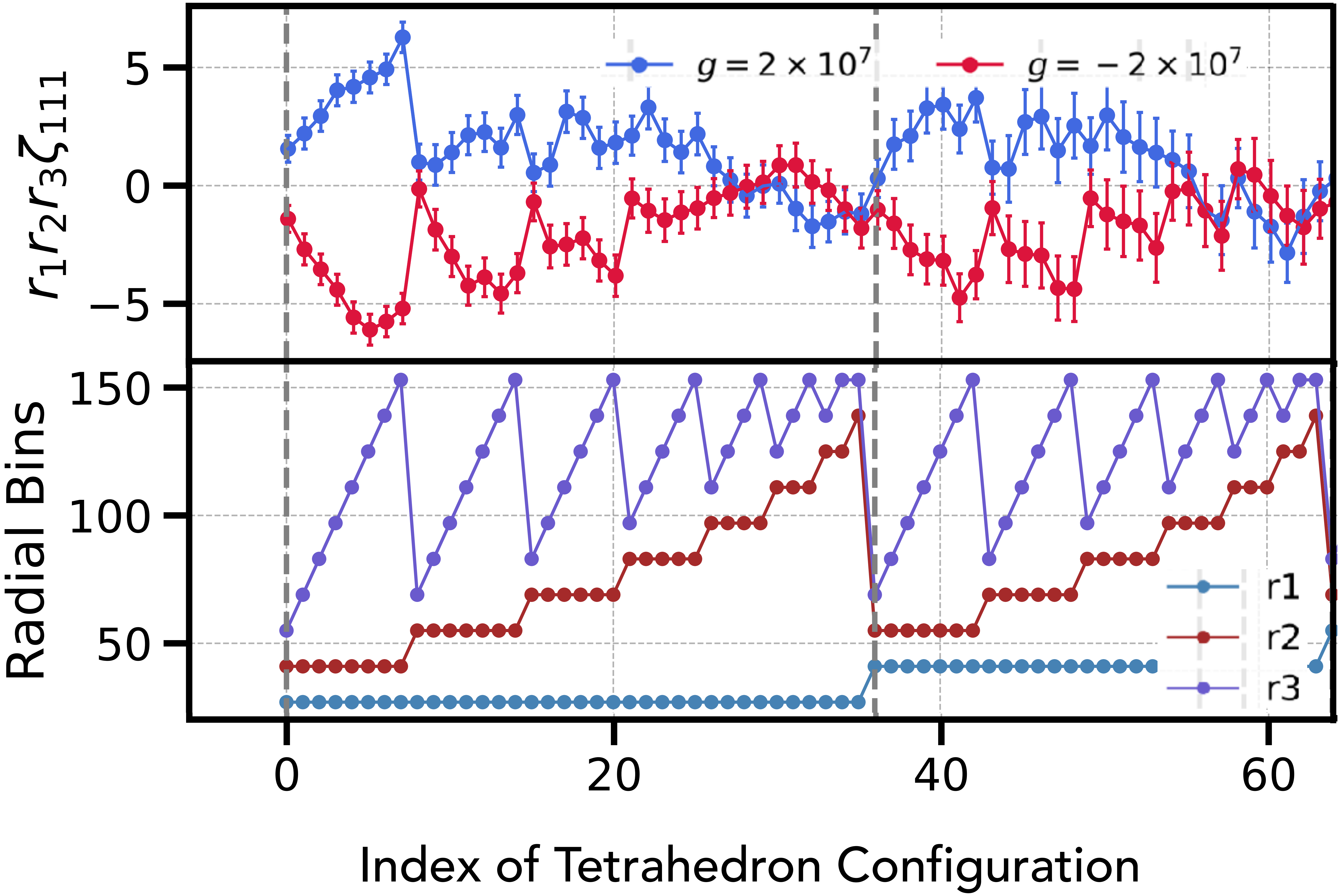
Parity Violation in Density Field

$$\Phi_{\mathrm{NG}} = \nabla\Phi_{\mathrm{G}}^{[\alpha]} \cdot \left[\nabla\Phi_{\mathrm{G}}^{[\beta]} \times \nabla\Phi_{\mathrm{G}}^{[\gamma]}\right]$$



JH, Slepian, Jamieson (2024)
Jamieson, Caravano, **JH** ++ (2024)
Also see Coulton ++ (2023)

Measured Odd 4-Point Function from Simulation

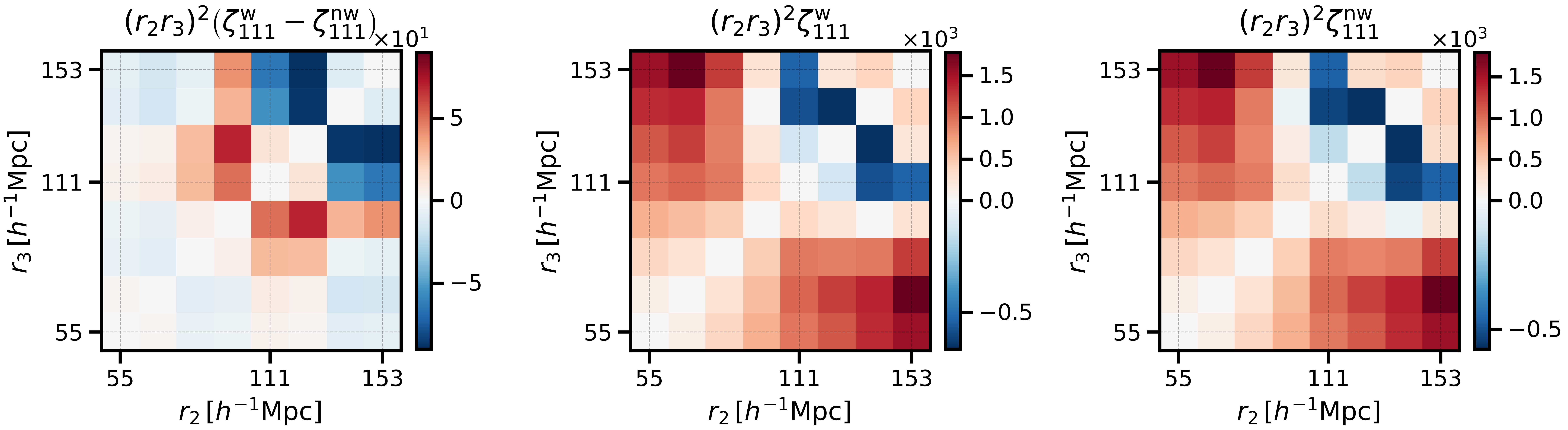


$$\zeta_\Lambda(R) = \int d\hat{R}\, \zeta(\mathbf{R})\, \mathscr{P}^*_\Lambda(\hat{R})$$

JH, Slepian, Jamieson (24')

Can we find baryon acoustic oscillations in the odd sector?

Baryon Acoustic Oscillation in the Odd 4-Point Correlation Function



JH, Slepian, Jamieson (24')

For scalar (spin-0) field, what are the necessary ingredients for probing the parity transformation?

- 4 fields: $\Phi_1, \Phi_2, \Phi_3, \Phi_4$
- Scalar triple product: $\hat{\mathbf{k}}_1 \cdot (\hat{\mathbf{k}}_2 \times \hat{\mathbf{k}}_3)$

Group and Weight the Fields

$\langle \Phi \, \Phi \, \Phi \, \Phi \rangle$ Trispectrum / 4PCF

4 Fields:

$\langle \Phi \, \Phi, \Phi \, \Phi \rangle$

$\langle \Phi, \Phi \, \Phi \, \Phi \rangle$

} Compressed 4-point statistics

A Different Way for Extracting Parity: Parity-odd Power Spectra (*POP*)

$$\left\langle \tilde{\mathbf{V}}(\mathbf{k}) \cdot \tilde{\mathbf{A}}\,(\mathbf{k}') \right\rangle \equiv (2\pi)^3 \delta_{\mathrm{D}}^{(3)}(\mathbf{k} + \mathbf{k}') P_{\mathrm{V}}(k)$$

$$\tilde{\mathbf{A}}(\mathbf{k}) \propto i\mathbf{k} \times \tilde{\mathbf{V}}(\mathbf{k})$$

Pseudovector (Even)

Vector (Odd)

Jamieson, Caravano, **JH** ++ (24')

Also see:
Jeong & Kamionkowski (12'), Schmittfull ++ (14'), Munshi (21'), Gao ++ (in prep.)

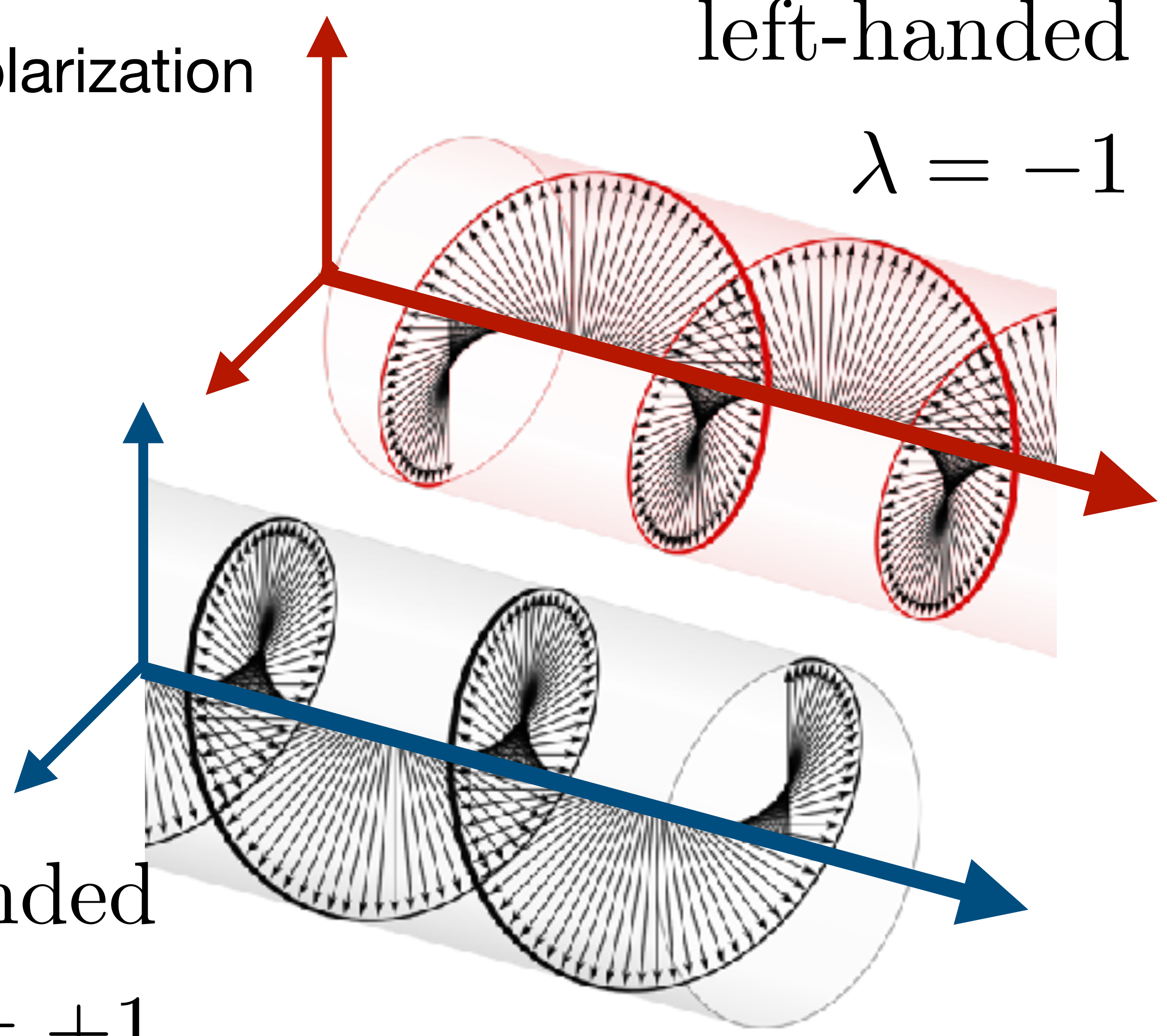
POP and Polarization Basis

$$\mathbf{V}(\mathbf{x}) = -\nabla\psi(\mathbf{x}) + \nabla\times\mathbf{A}(\mathbf{x})$$

$$= v_{\|}\hat{\epsilon}_{\|}(\mathbf{x}) + \underbrace{v_{+}\hat{\epsilon}_{+}(\mathbf{x}) + v_{-}\hat{\epsilon}_{-}(\mathbf{x})}$$

$\hat{\epsilon}_{\{+,-\}}$: Polarization vectors

Helicity $\lambda = \pm 1$ describe photons' circular polarization

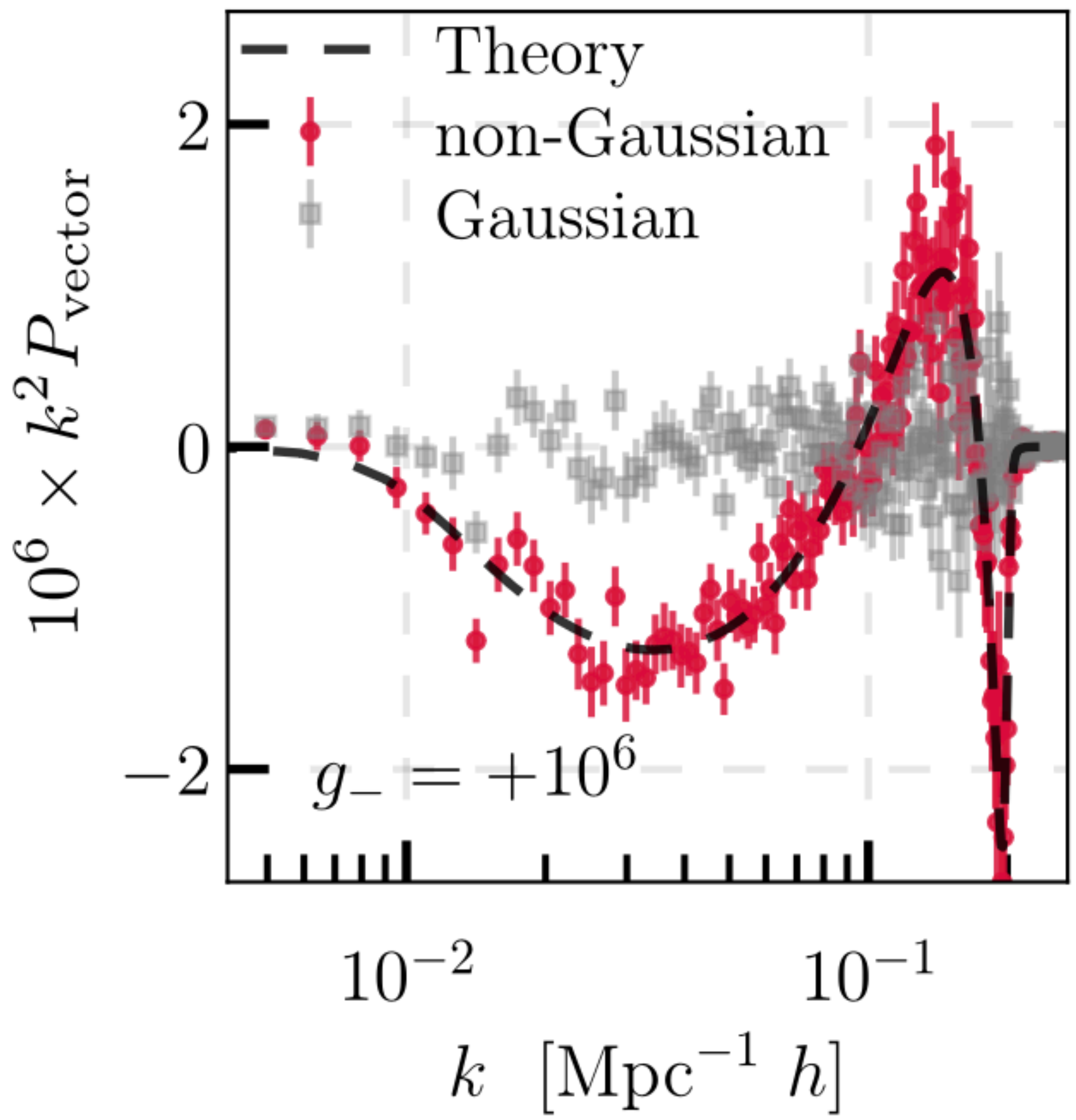


Credit: Adapted from Wikipedia

$$\left\langle \tilde{\mathbf{V}}(\boldsymbol{k}) \cdot \tilde{\mathbf{A}}\left(\boldsymbol{k}'\right) \right\rangle = ik^{-1}\left\langle v_{+}(\boldsymbol{k}) v_{-}\left(\boldsymbol{k}'\right)\right\rangle + \text{cyc.}$$

$$\rightarrow P_{\mathrm{V}}(k) \propto P_{+-}(k) + \text{cyc.}$$

Measured *POP* from Parity-Violating Simulations



Jamieson, Caravano, **JH** ++ (24')

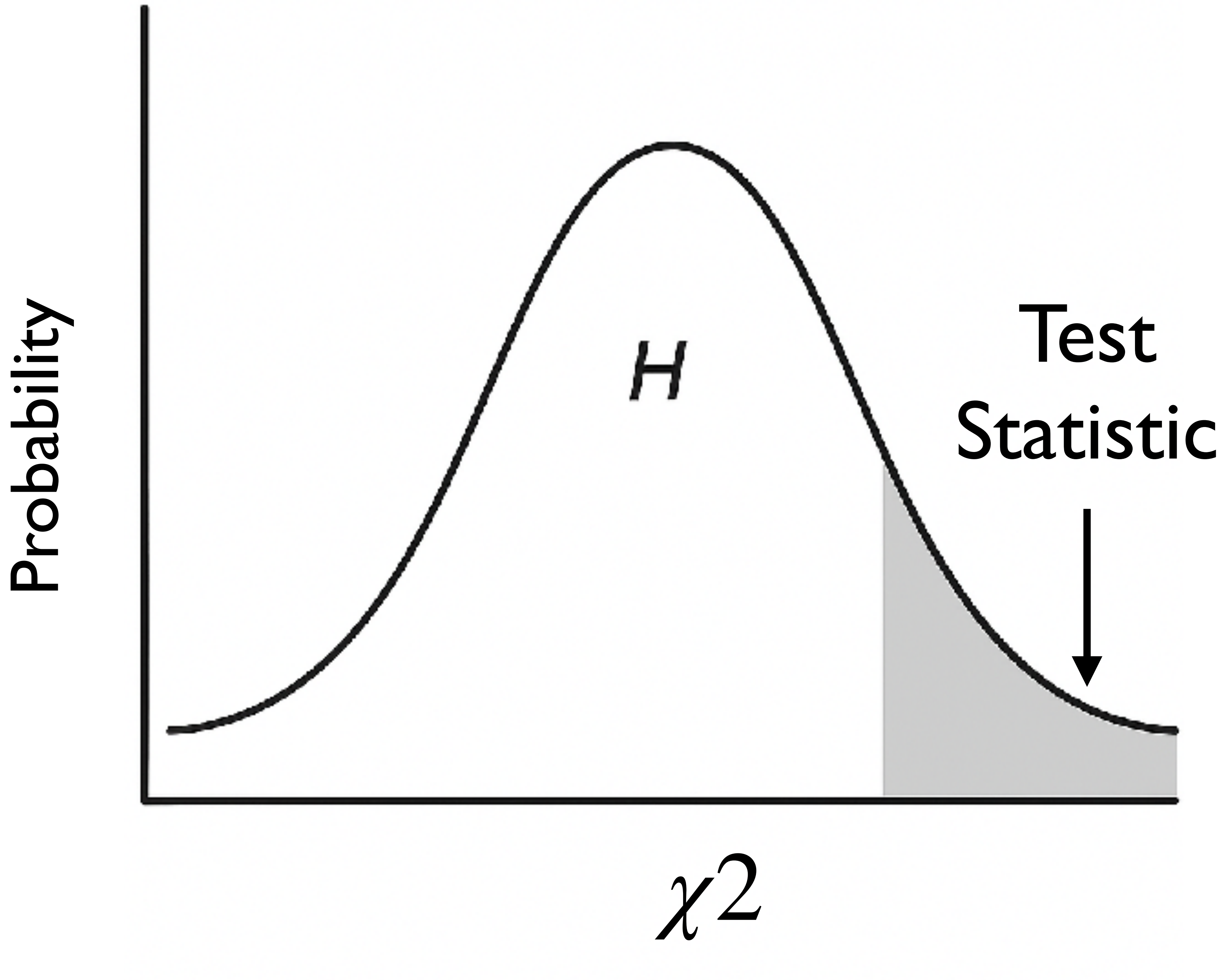
Measurements on the Real Galaxy Data

Signal, Uncertainties, and Significance

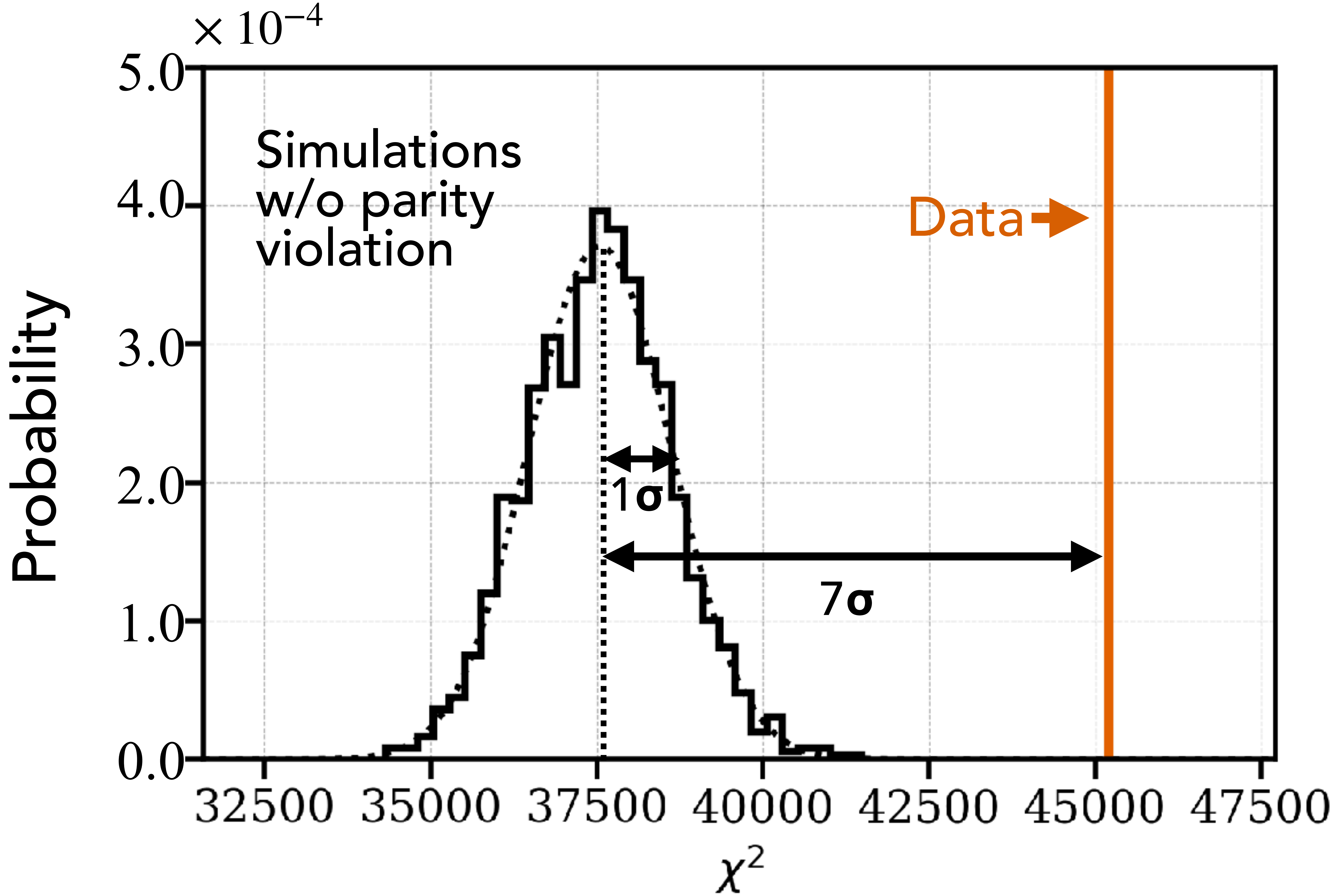
Observed data compose several components:

$\hat{\zeta} = \zeta + \hat{\epsilon}$ — signal, cosmic variance

Often, use $\chi^2 = \hat{\zeta}^{\mathrm{T}}\ \hat{\mathbb{C}}^{-1}\ \hat{\zeta}$ to quantify significance with null hypothesis



Intriguing Measurement of Parity Violation in Real Galaxy Data from SDSS

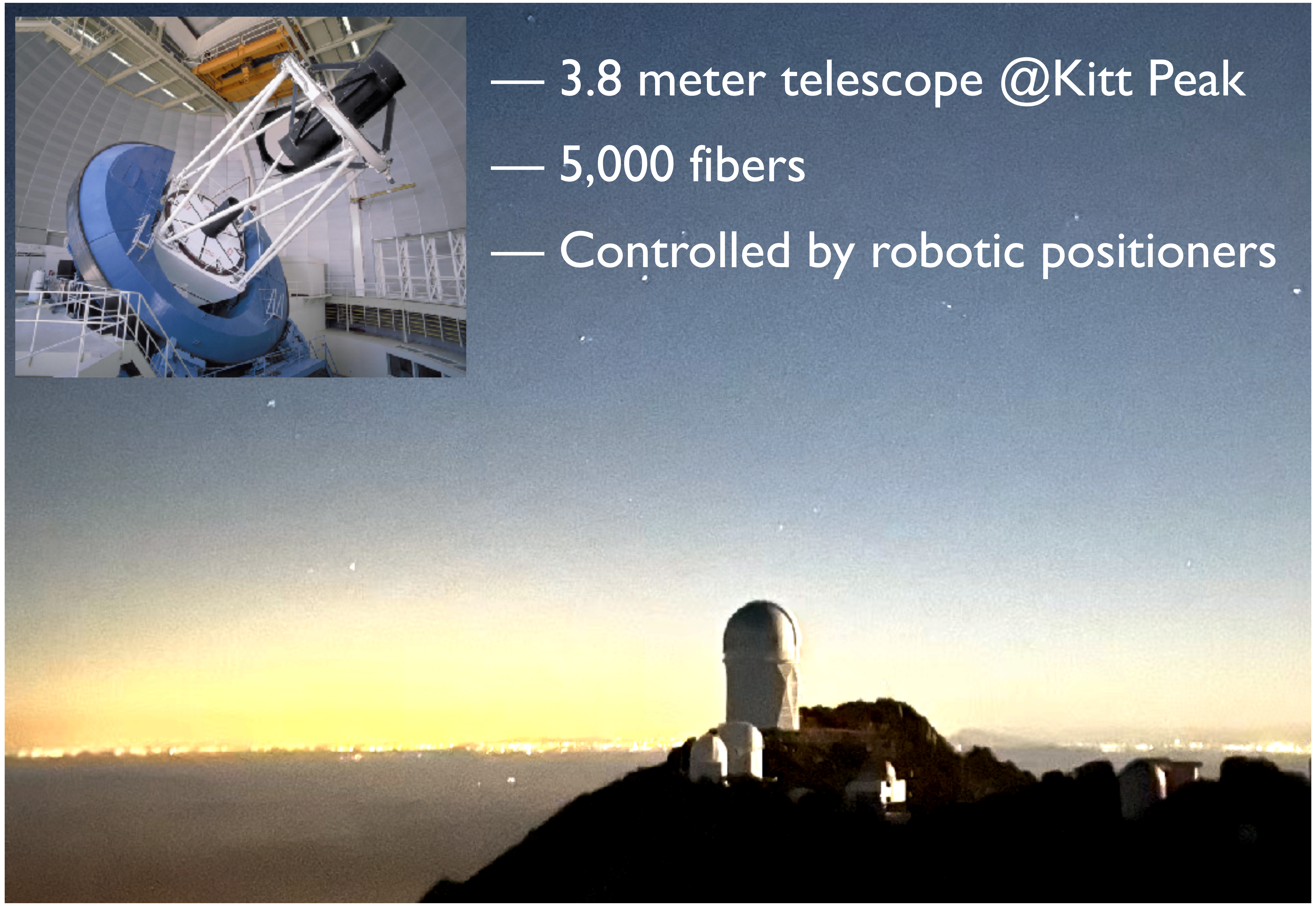


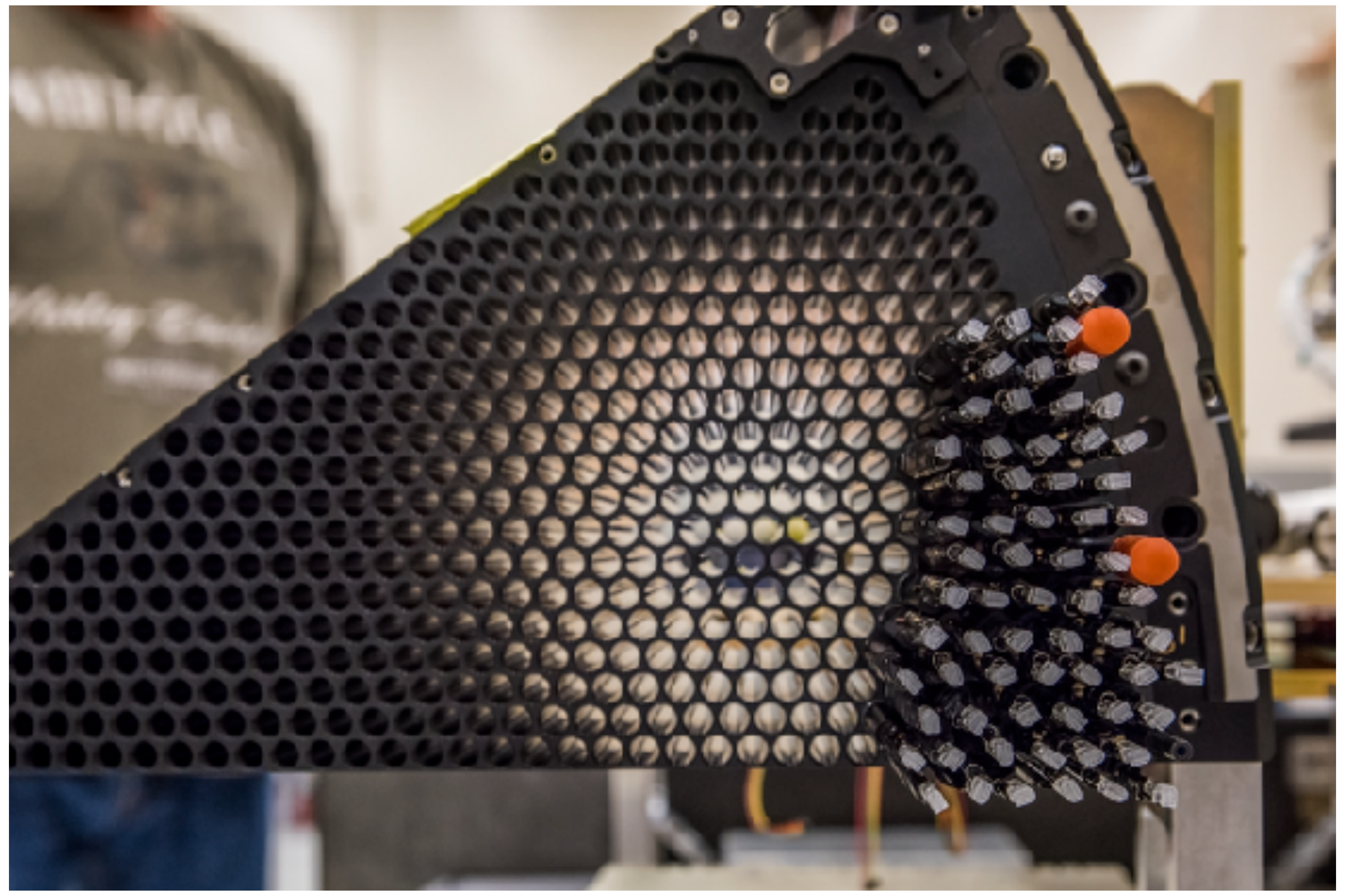
Total Parity-Violating Signal

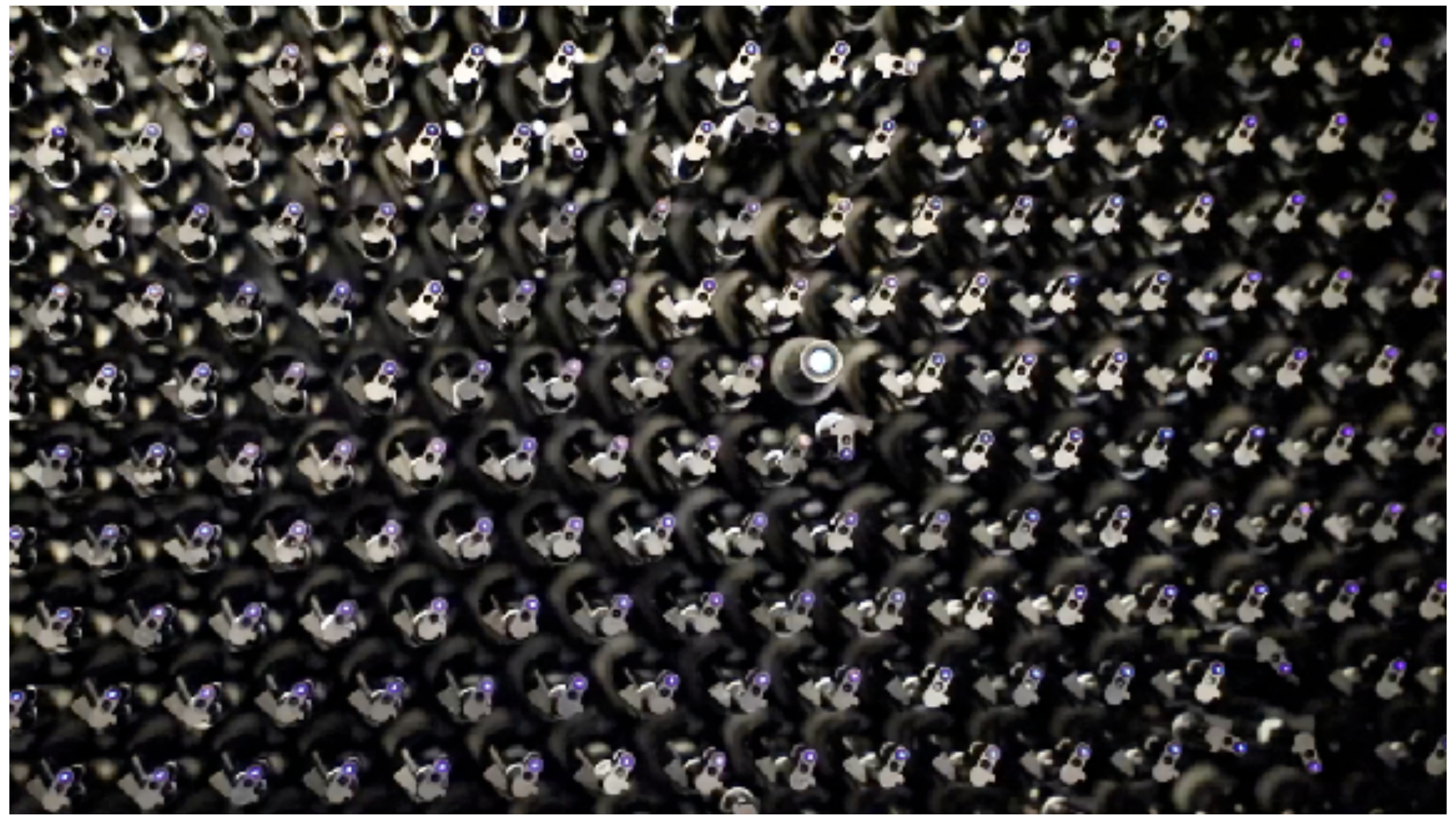
SDSS BOSS: Baryon Oscillation Spectroscopic Survey

JH, Slepian, Cahn (22')
Philcox (22')

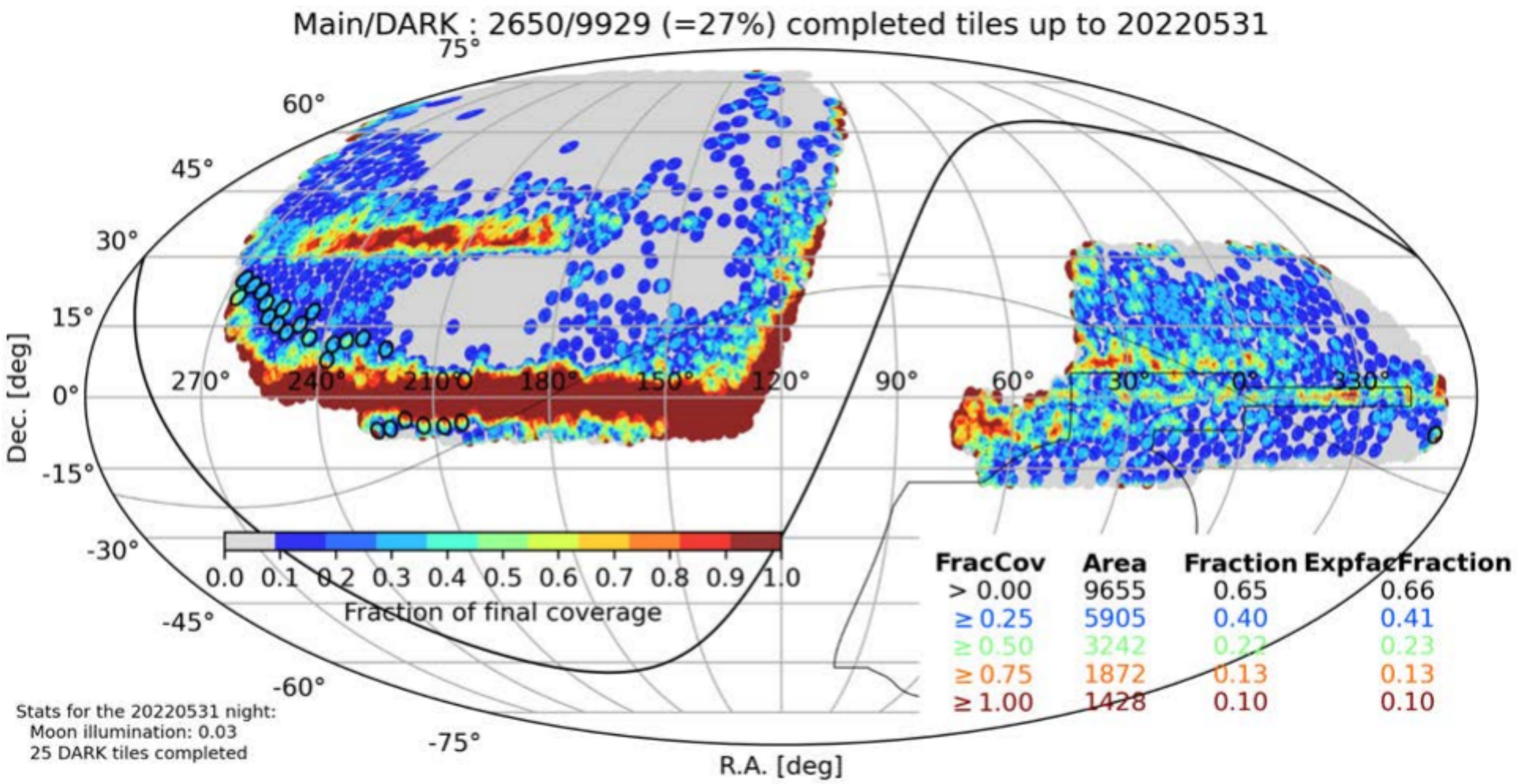
Dark Energy Spectroscopic Instrument (DESI)







DESI Data Release 1 (DR1)



13 months of observation

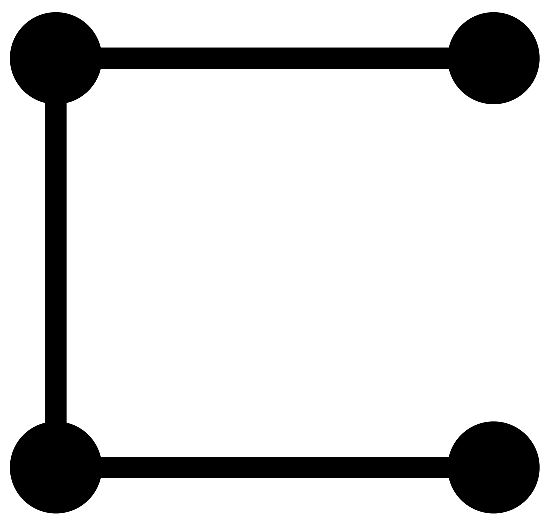
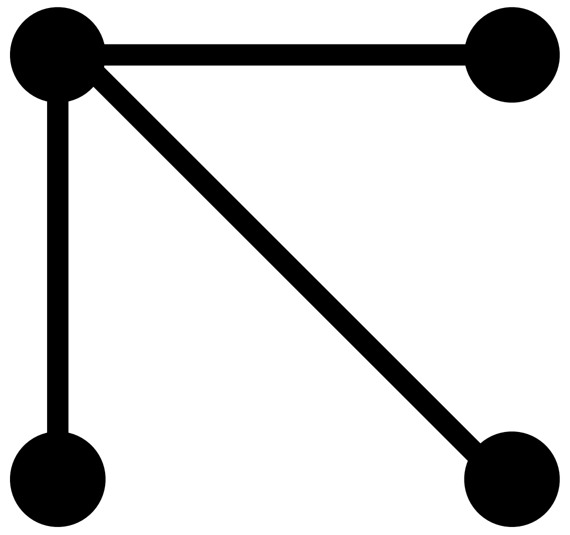
5.7M galaxy and quasar spectra

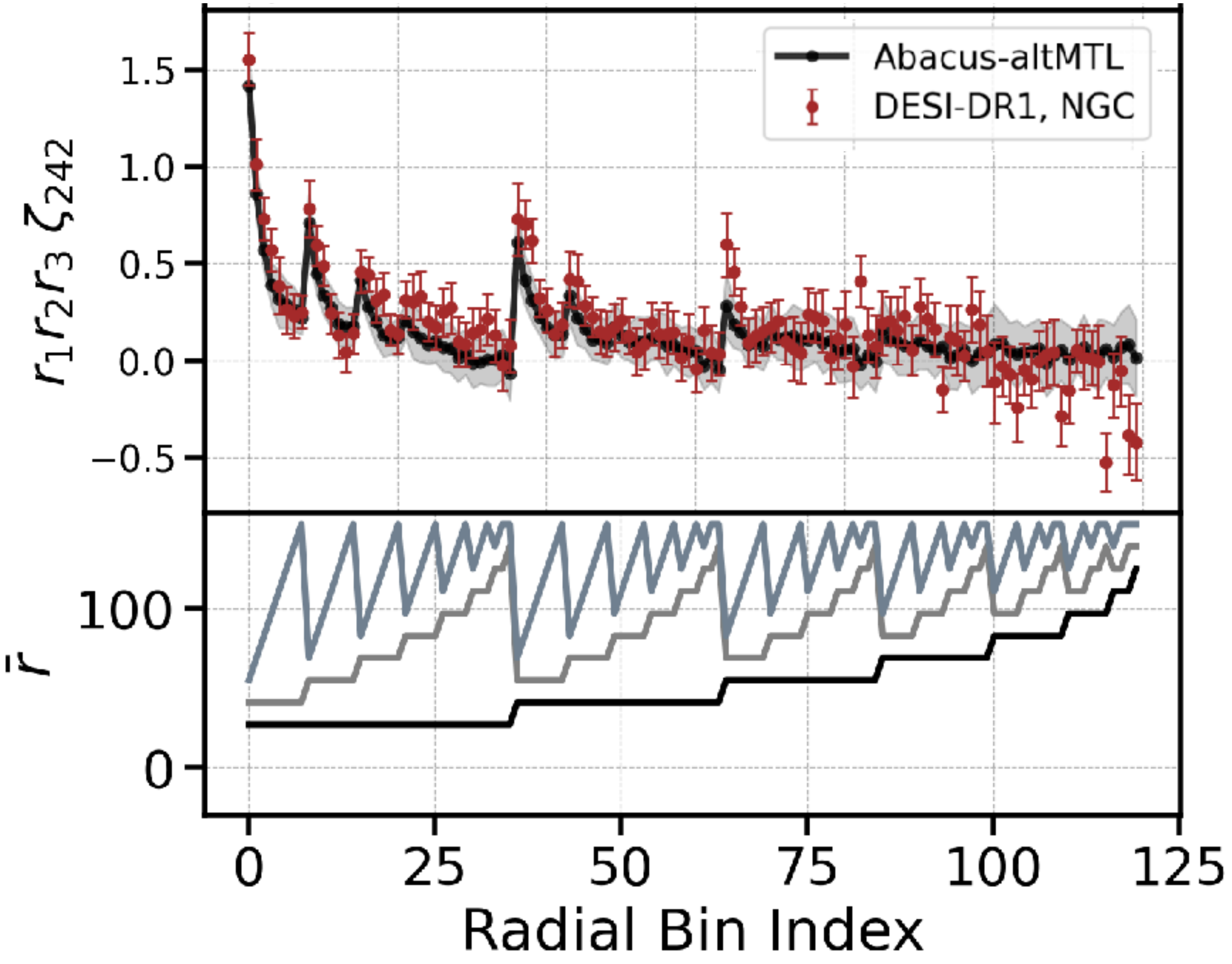
~ 50 % completeness

Gravity-induced Connected 4PCF from DESI

$$\zeta_+ = \zeta_+^{\rm dc} + \zeta_+^{\rm c}$$

Gravity-induced Connected 4-Point Function $\zeta_+^{\rm c}$

=  + 



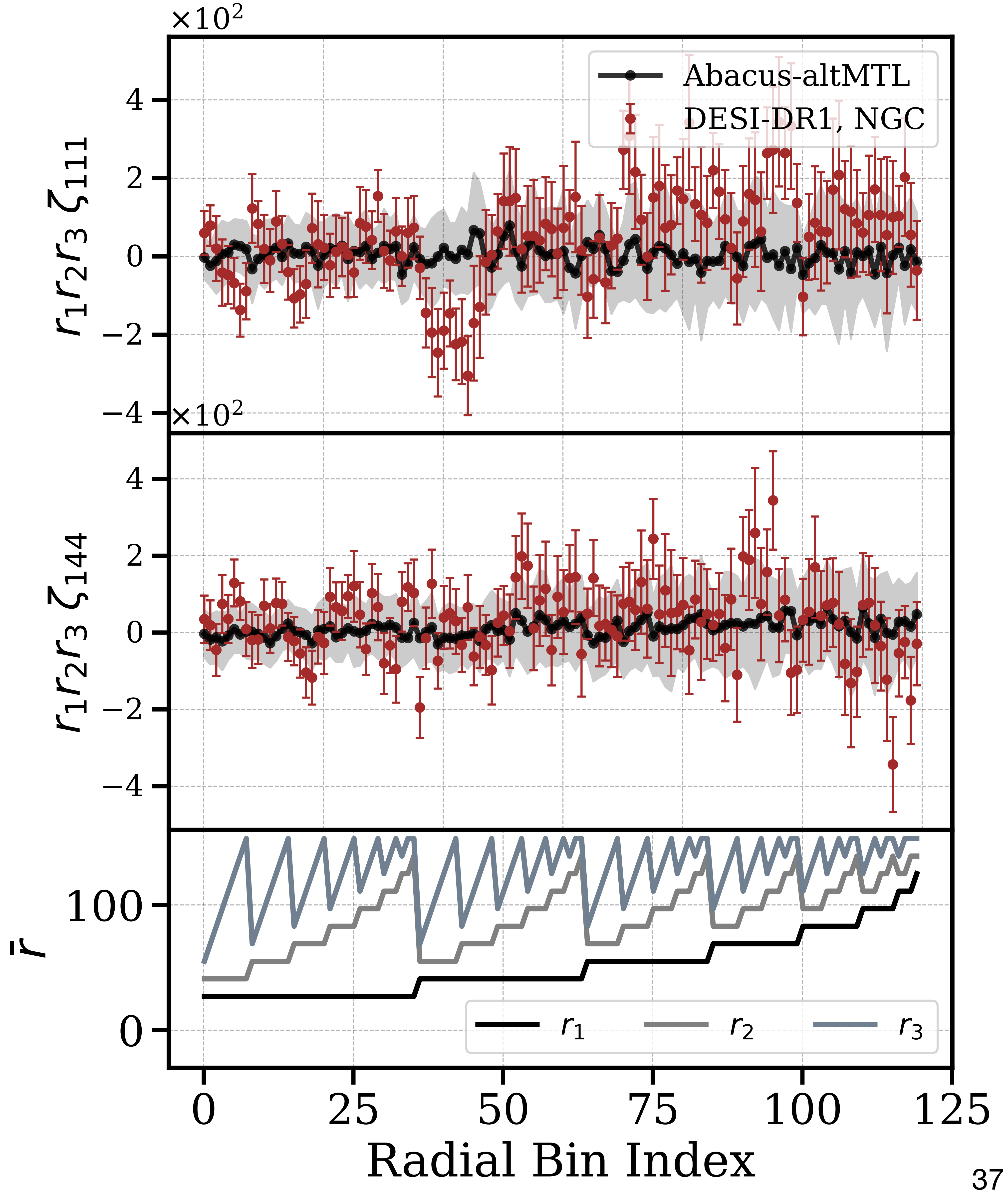
Larger than 14σ in Gravity-induced even 4PCF in DESI Y1

JH, Cahn ++ (25')

Parity-odd Measurements of DESI DR1

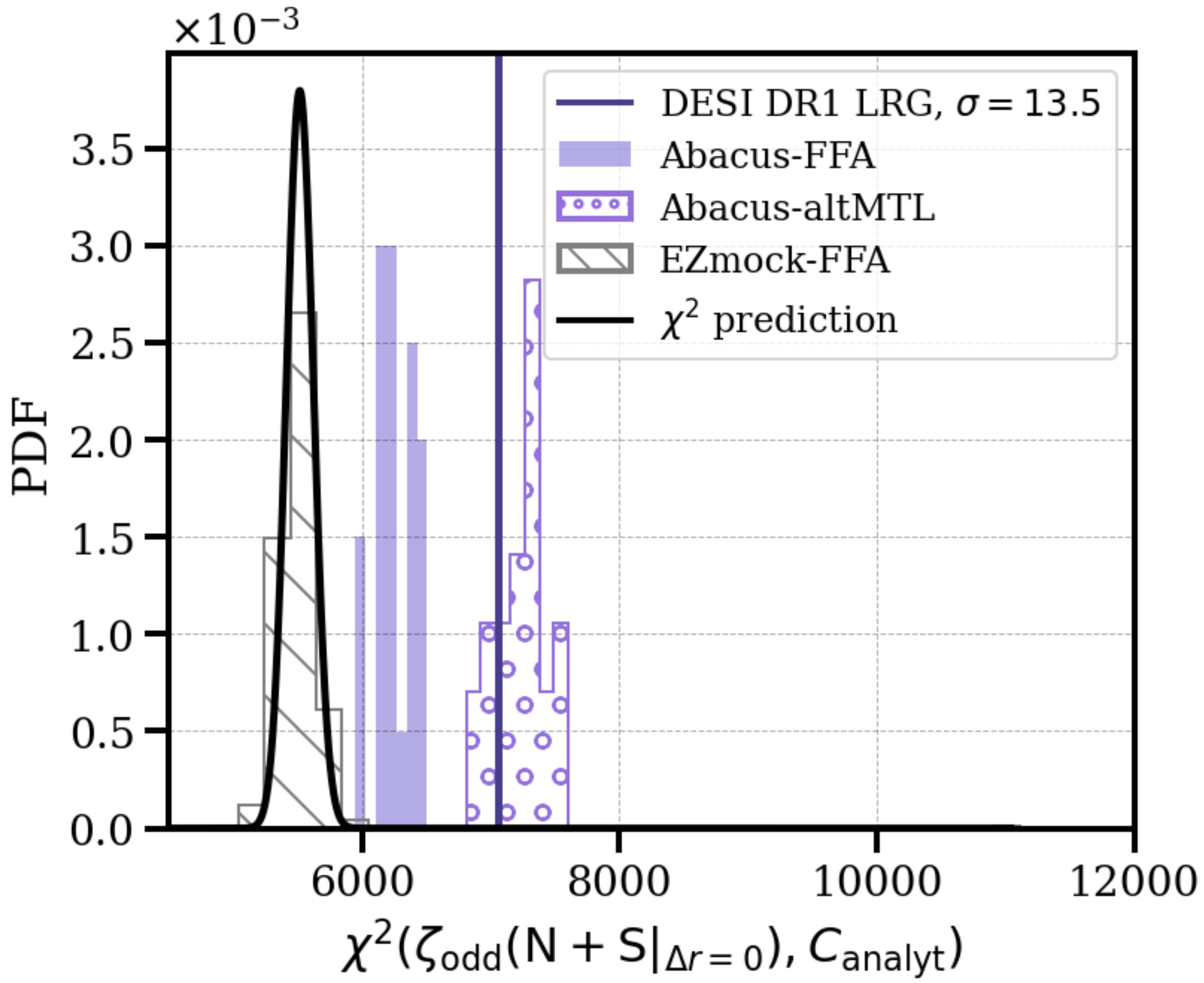
Compared to the even parity, odd sector is noise dominated

Observed data:
$\hat{\zeta} = \zeta + \hat{\zeta}_s + \hat{\epsilon}$ — signal, systematics, cosmic variance



JH & Cahn (in prep.)

Significance of Parity-Odd 4PCF before Calibration



Two effects on the covariance :

Sample incompleteness due to limited fiber

Volume replication due to box size of N-body simulation

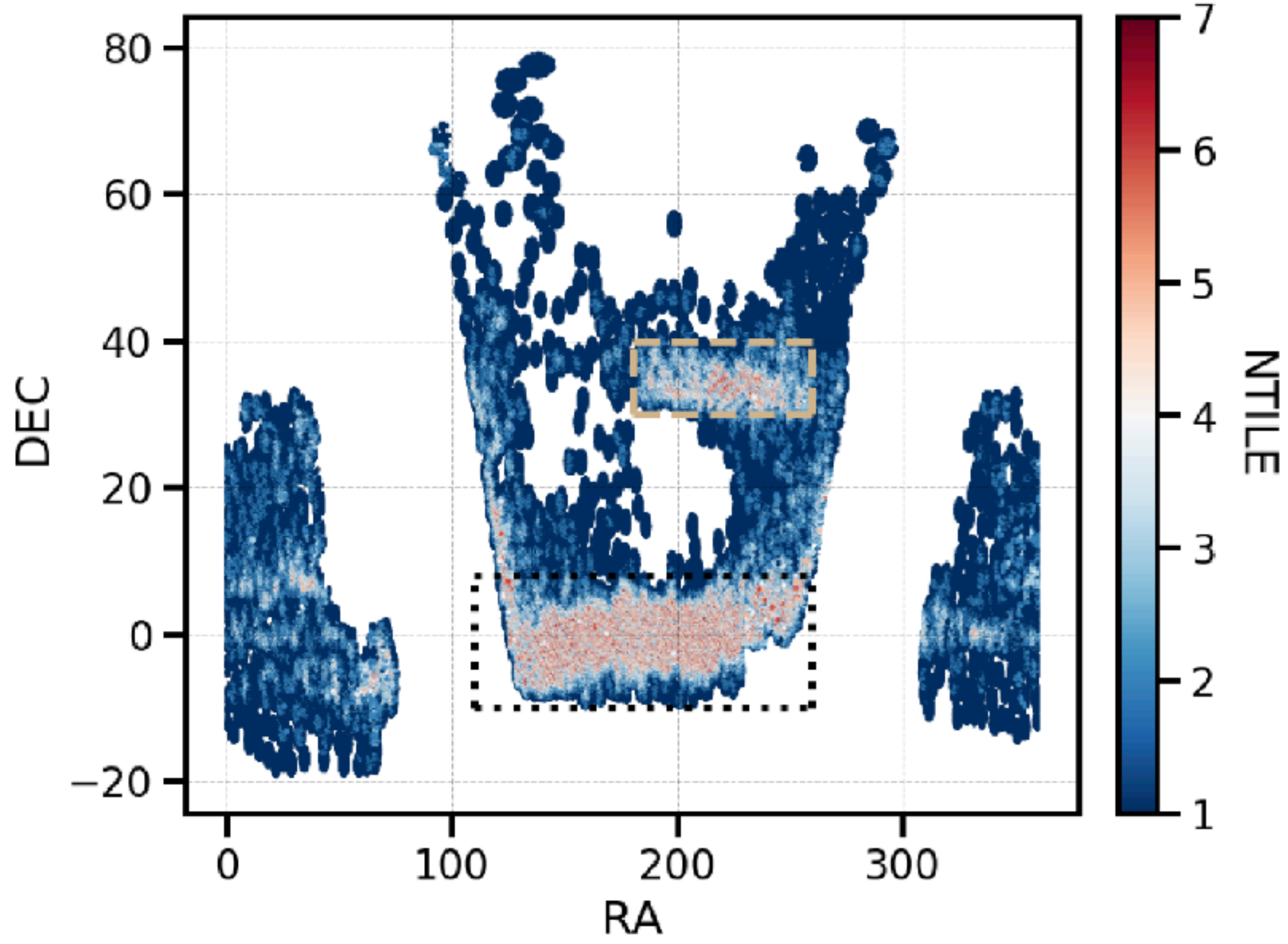
JH & Cahn (in prep.)

Cross-correlation as Consistency Test

Cross-correlate different sky patches

$\chi^2_\times \propto \hat{\zeta}^{\mu,i}\,(\hat{\mathbb{C}}^{-1})_{ij}\,\hat{\zeta}^{\nu,j}$

$\longrightarrow$ deterministic contributions

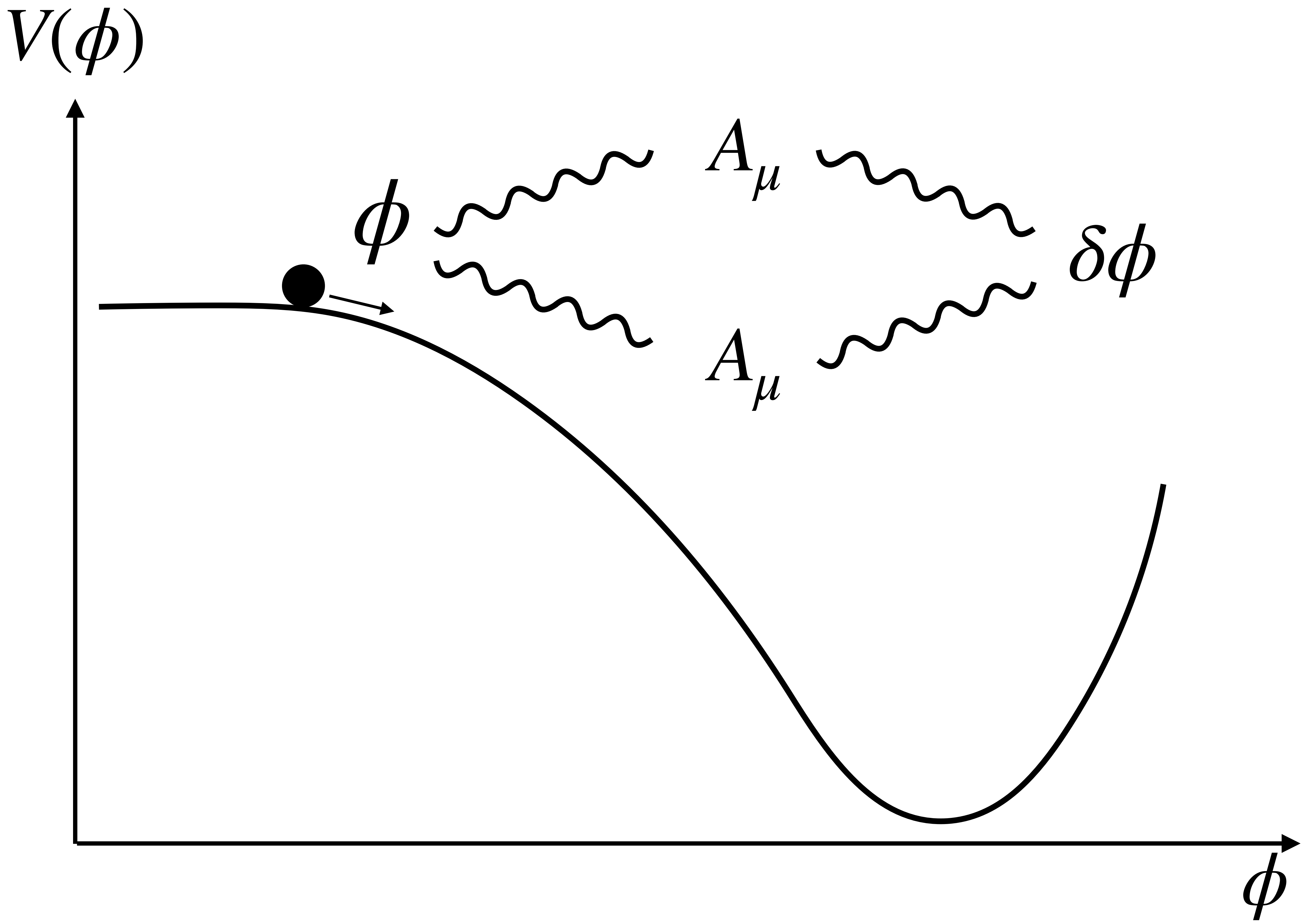


c.f. Krolewski++ (24')

** μ and ν: indices of different sky patches

Beyond Single-field Inflation

Axion-U(1) Inflation $\mathscr{L} \supset -\frac{1}{4\Lambda}\phi\tilde{F}^{\mu\nu}F_{\mu\nu}$



Barnaby+11'; Niu+23'

Equations of Motion

Gauge field

$$A''_{\pm}(\tau, k) + k^2 A_{\pm}(\tau, k) \mp \frac{2k\xi}{\tau} A_{\pm}(\tau, k) = 0$$

Inflaton perturbation

$$\delta\phi'' + 2\mathscr{H}(\tau)\delta\phi' - \nabla^2\delta\phi + a(\tau)^2 \frac{\mathrm{d}^2 V}{\mathrm{d}\bar{\phi}^2}\delta\phi = \frac{a(\tau)^2}{\Lambda}(J - \langle J \rangle)$$

Source

$J \equiv \mathbf{E} \cdot \mathbf{B}$

Primordial Curvature Trispectrum

$$\left\langle \prod_{i=1}^{4} \zeta\left(\tau, \mathbf{k}_i\right) \right\rangle \supset \prod_{i=1}^{4} \int d\tau_i G(\tau, \tau_i, k_i) \int d^3\mathbf{q}_i \, q_i \, [\hat{\epsilon}(\mathbf{q}_i) \cdot \hat{\epsilon}(\mathbf{k}_i - \mathbf{q}_i)] \, A'_+(\tau_i, |\,\mathbf{k}_i - \mathbf{q}_i\,|\,) \, A_+(\tau_i, q_i)$$
$$\times \, \delta_{\mathrm{D}}(\mathbf{q}_2 + \mathbf{k}_4 - \mathbf{q}_4) \, \delta_{\mathrm{D}}(\mathbf{q}_1 + \mathbf{k}_3 - \mathbf{q}_3) \, \delta_{\mathrm{D}}(\mathbf{k}_1 + \mathbf{q}_1 - \mathbf{q}_4) \, \delta_{\mathrm{D}}(\mathbf{k}_2 + \mathbf{q}_2 - \mathbf{q}_3)$$

16-D integral

Parity-Odd and Even Trispectrum from Axion Inflation

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Abstract. The four-point correlation function of primordial scalar perturbations has parity-even and parity-odd contributions and the parity-odd signal in cosmological observations is opening a novel window to look for new physics in the inflationary epoch. We study the distinct parity-odd and even prediction from the axion inflation model, in which the inflaton couples to a vector field via a Chern-Simons interaction, and the vector field is considered to be either approximately massless ($m_A \ll$ Hubble scale H) or very massive ($m_A \sim H$). The parity-odd

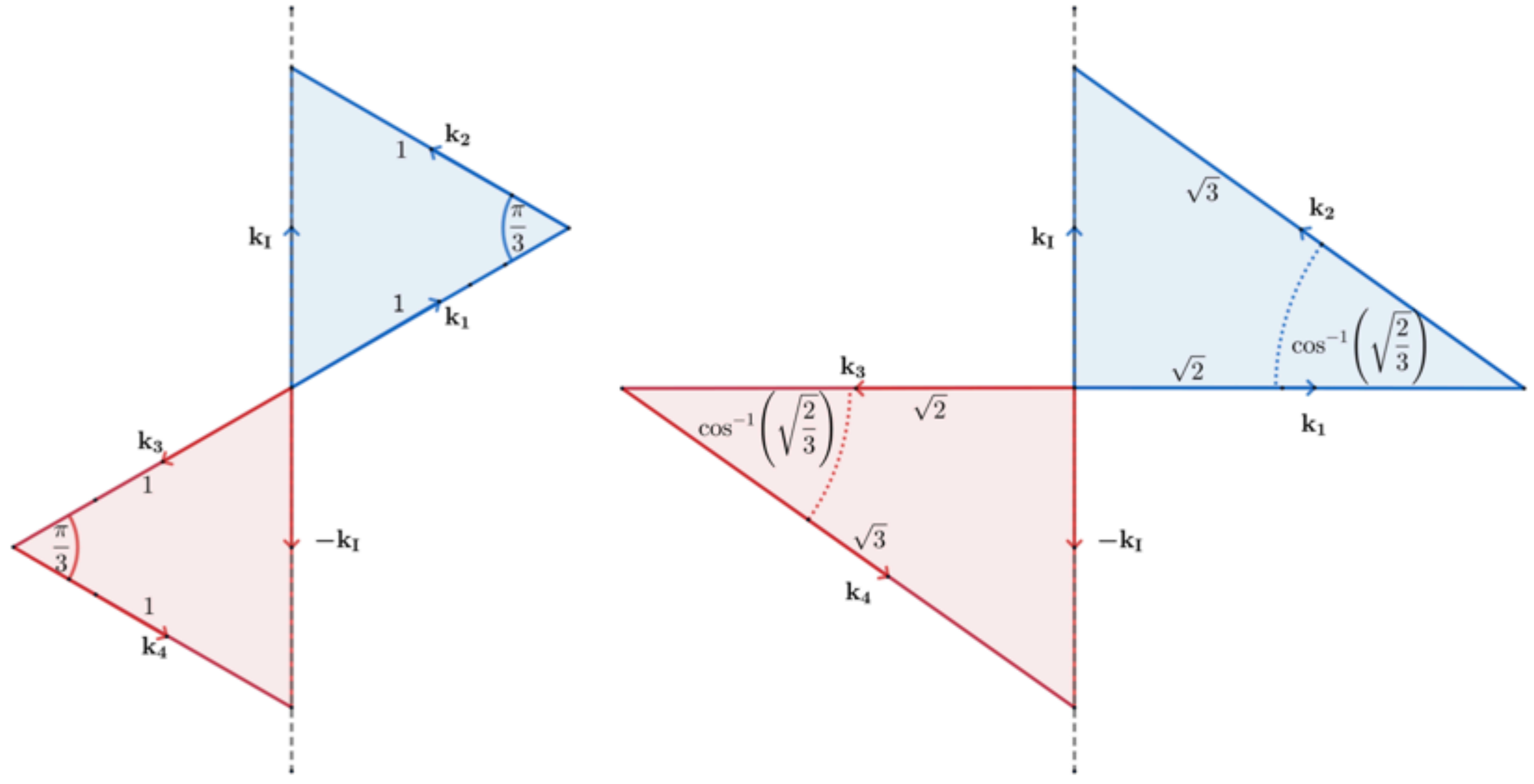
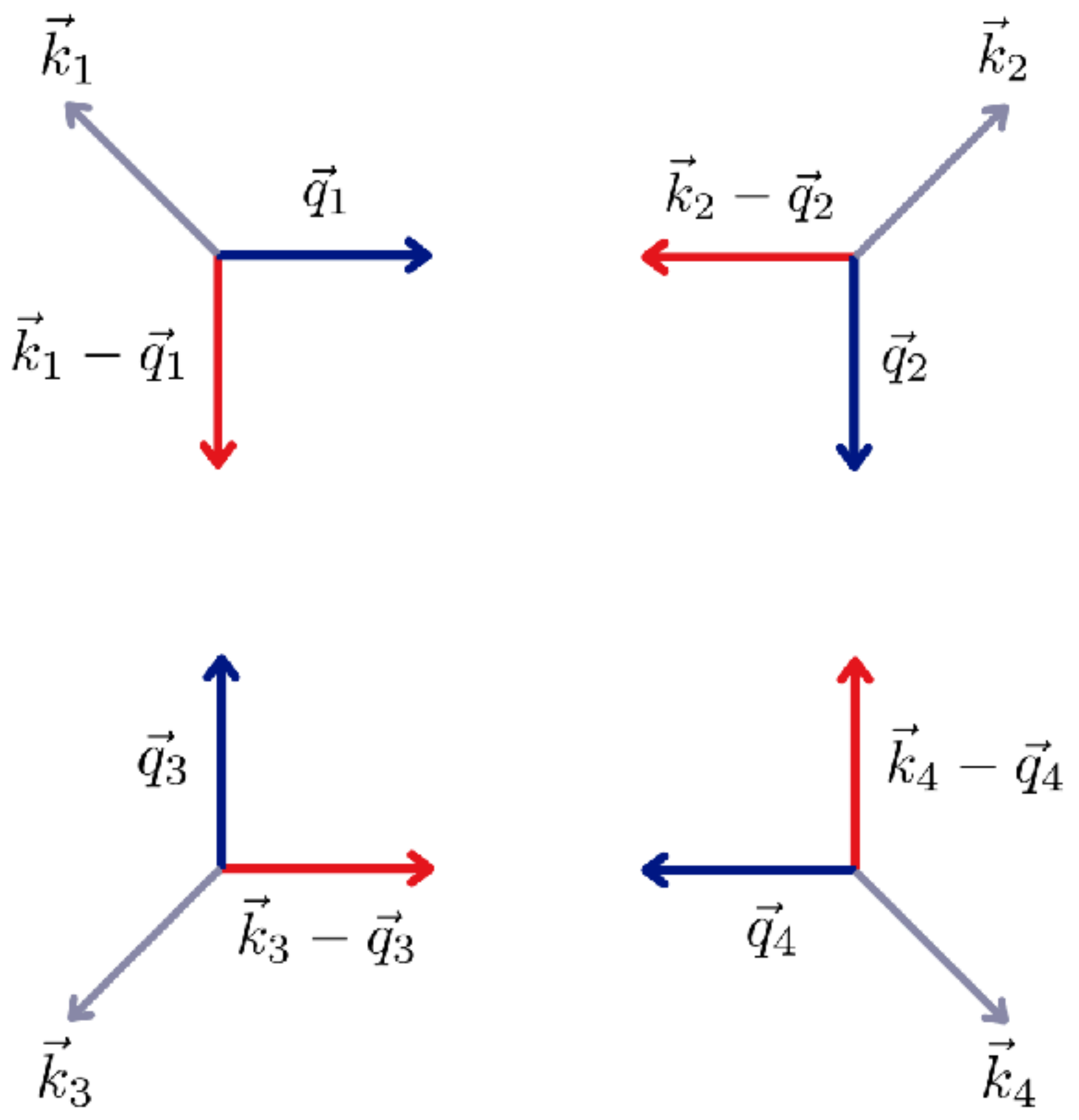


Figure 5. Momentum configurations I (left) and II (right). The red and the blue triangles are in different planes.

Can we simplify the calculation?

Angular Structure of the Integral



At each vertex:

- Momentum conservation — Convolutional structure
- Polarization state of gauge field

Across the vertices:

- Wick theorem: 3-dimensional Dirac delta distribution

Reduced Trispectrum Calculation

$$\left\langle \prod_{i=1}^{4} \zeta\left(\tau, \mathbf{k}_i\right) \right\rangle \supset \prod_{i=1}^{4} \int d\tau_i G(\tau, \tau_i, k_i) \int d^3\mathbf{q}_i \, q_i \left[\hat{\epsilon}(\mathbf{q}_i) \cdot \hat{\epsilon}(\mathbf{k}_i - \mathbf{q}_i)\right] A'_+(\tau_i, |\,\mathbf{k}_i - \mathbf{q}_i\,|\,) \, A_+(\tau_i, q_i)$$

$$\times \, \delta_{\mathrm{D}}(\mathbf{q}_2 + \mathbf{k}_4 - \mathbf{q}_4) \, \delta_{\mathrm{D}}(\mathbf{q}_1 + \mathbf{k}_3 - \mathbf{q}_3) \, \delta_{\mathrm{D}}(\mathbf{k}_1 + \mathbf{q}_1 - \mathbf{q}_4) \, \delta_{\mathrm{D}}(\mathbf{k}_2 + \mathbf{q}_2 - \mathbf{q}_3)$$

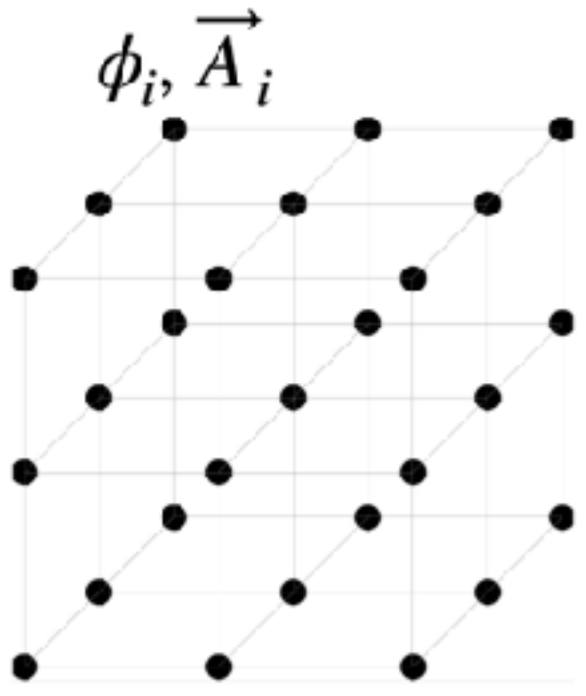
Matthew Reinhard
PhD@UF

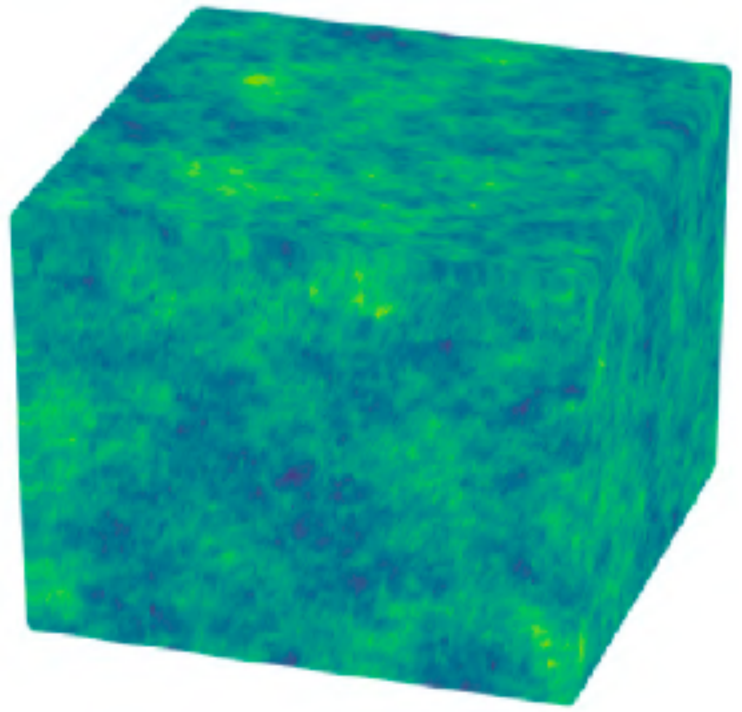
After the angular reduction

$$\supset \sum_{\boldsymbol{\ell},\mathbf{m}} \sum_{\boldsymbol{\lambda},\boldsymbol{\mu}} \sum_{\boldsymbol{\lambda}',\boldsymbol{\mu}'} (4\pi)^{12} \left[\prod_{j=1}^{4} i^{\ell_j+\lambda_j+\lambda'_j} (-1)^{\lambda'_j+\mu_j+\mu'_j} Y_{\ell_j}^{m_j *}(\hat{\mathbf{k}}_j) \sum_{\Lambda_j M_j} (-1)^{M_j} \mathcal{G}^{-\mu'_j-\mu_j-M_j}_{\lambda'_j \lambda_j \Lambda_j} \right]$$

$$\times \, \mathcal{G}^{\mu_2 m_4 \mu'_4}_{\lambda_2 \ell_4 \lambda'_4} \mathcal{G}^{\mu_1 m_3 \mu'_3}_{\lambda_1 \ell_3 \lambda'_3} \mathcal{G}^{m_1 \mu'_1 \mu_4}_{\ell_1 \lambda'_1 \lambda_4} \mathcal{G}^{m_2 \mu'_2 \mu_3}_{\ell_2 \lambda'_2 \lambda_3} \mathcal{T}^{(1)\boldsymbol{M}}_{\boldsymbol{\ell\Lambda\lambda}}(k_1, k_2, k_3, k_4).$$

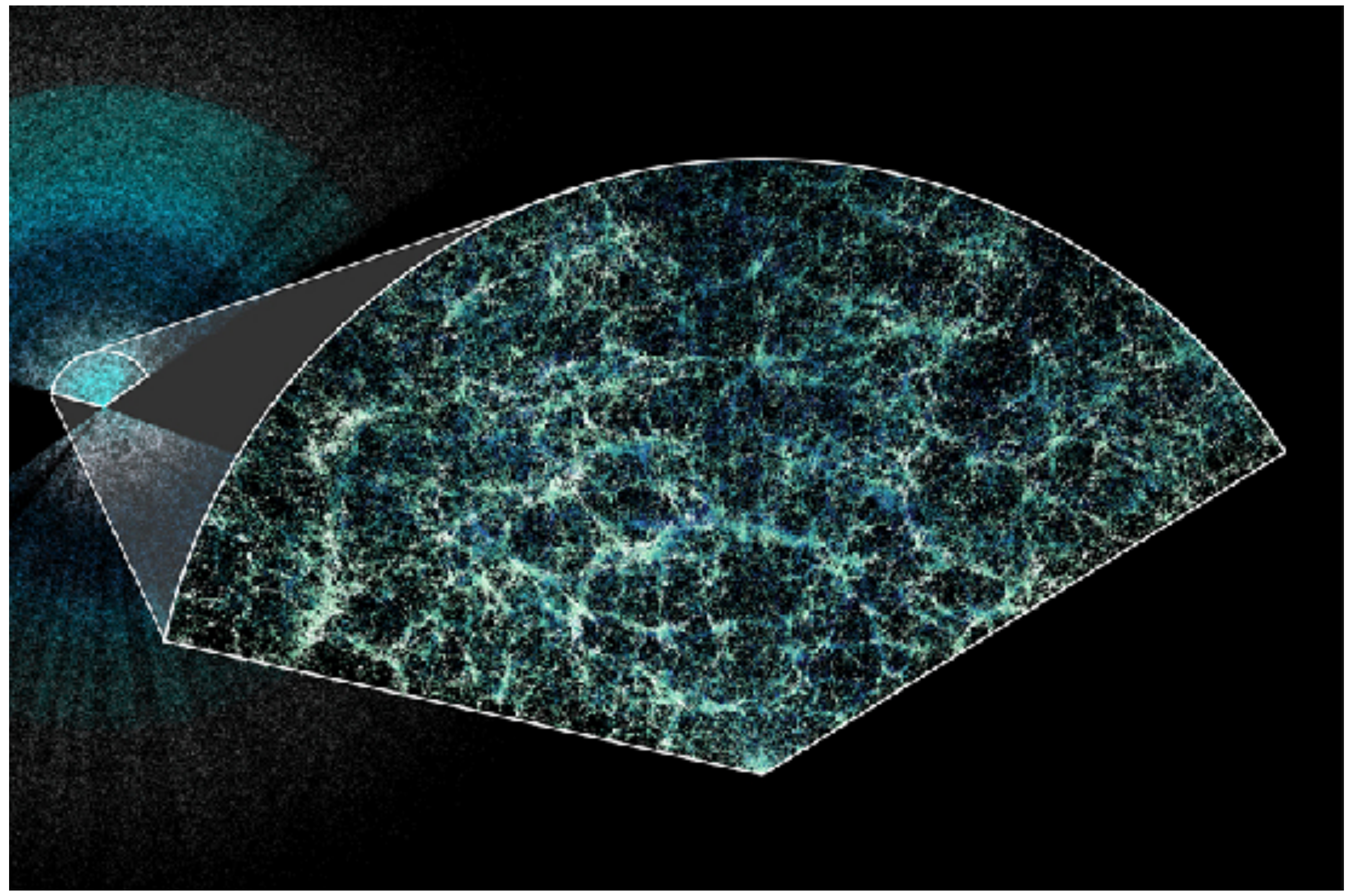
Reinhard, Slepian, **JH**, Grecco (24')





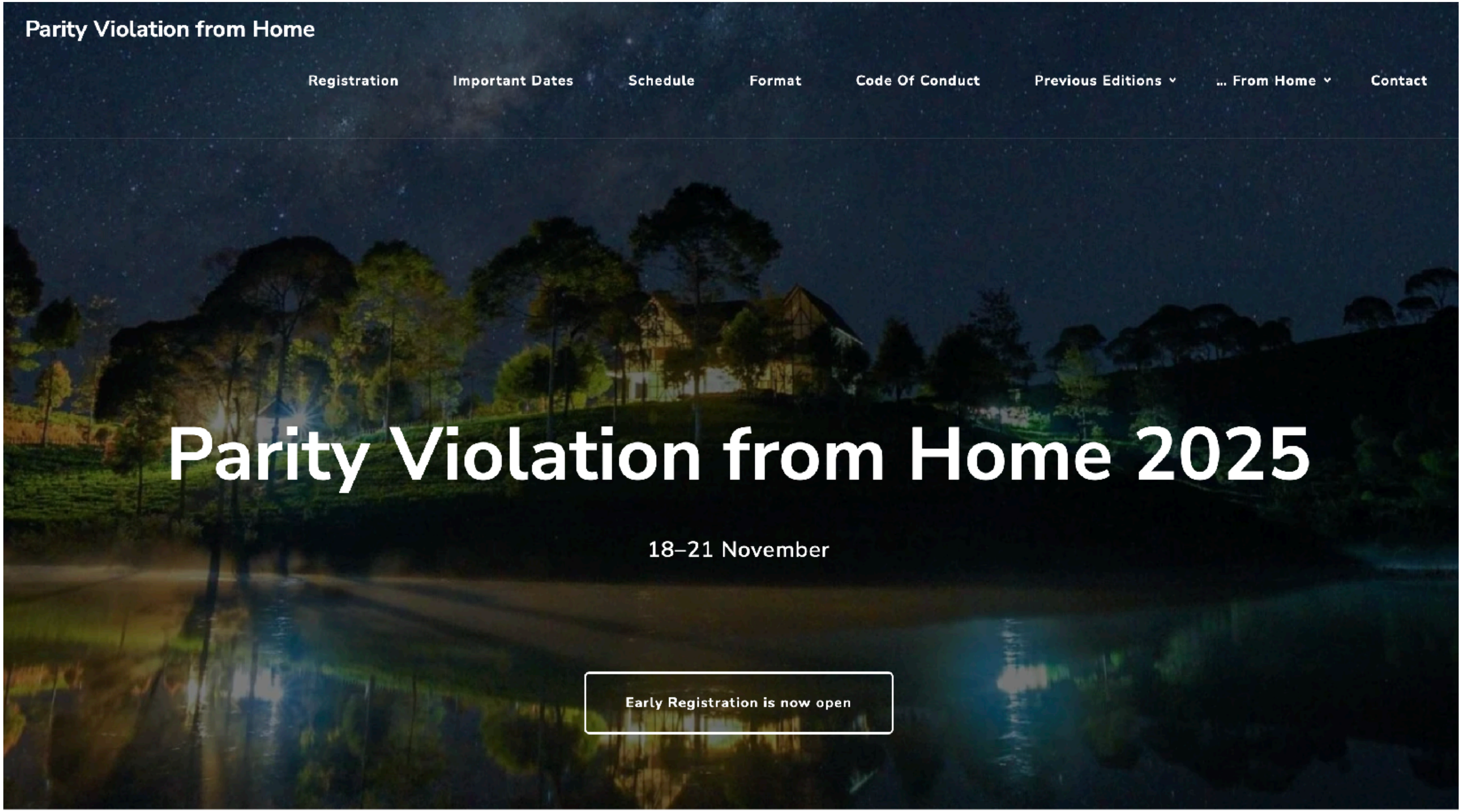
Compare the analytic calculation of primordial trispectra to lattice simulations (Caravano+ 23', Jamieson+25')

- Trispectrum shape from axion inflation
- Limits in the analytic calculation
- Renormalizability (?) — slow-roll regime



Parity-violating simulations for galaxies

- Impact of gravity, observational effects on initial conditions



https://parity.cosmodiscussion.com/

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

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