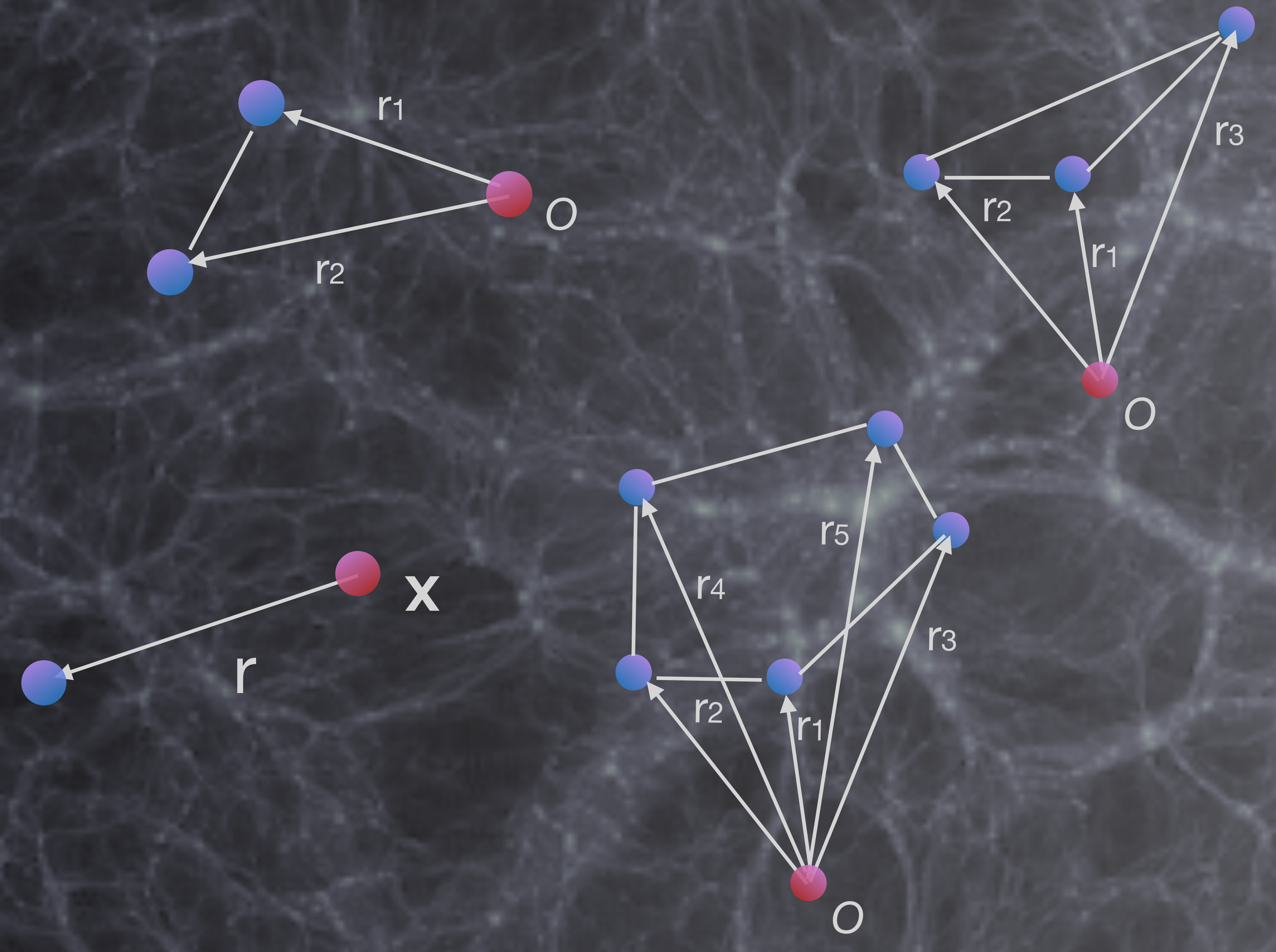
Max-Planck-Institut für
extraterrestrische Physik

N-Point Statistics of Large-Scale Structure and Parity-Violation Search

CIPANP
August 31 2022



Jiamin Hou

Marie Curie Fellow at the University of Florida

(with support from the Max Planck Institute for Extraterrestrial Physics)

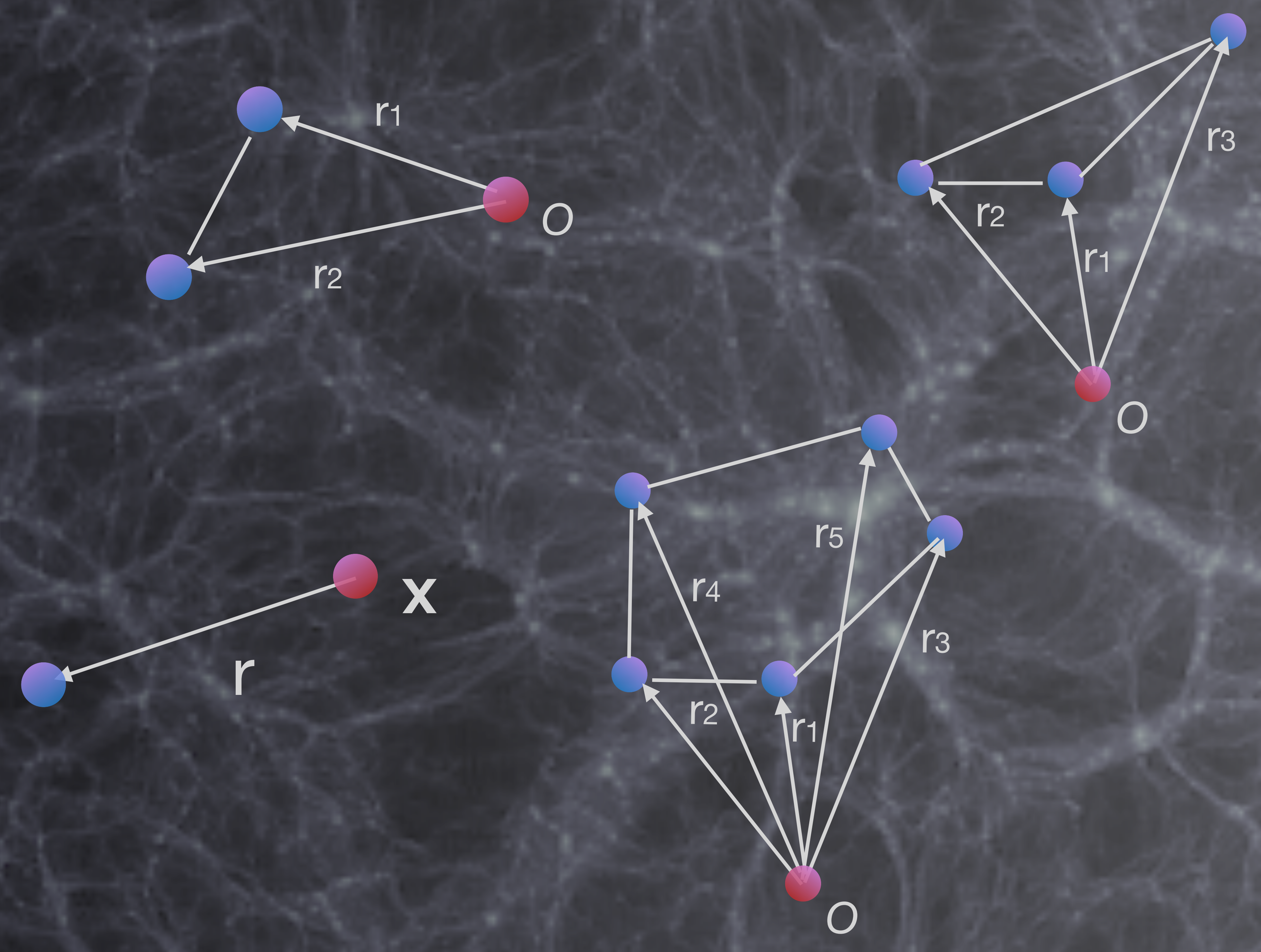
Background Image: O. Hahn

Max-Planck-Institut für extraterrestrische Physik

N-Point Statistics of Large-Scale Structure and Parity-Violation Search

Zachary Slepian (UF)

Robert Cahn (Berkeley)



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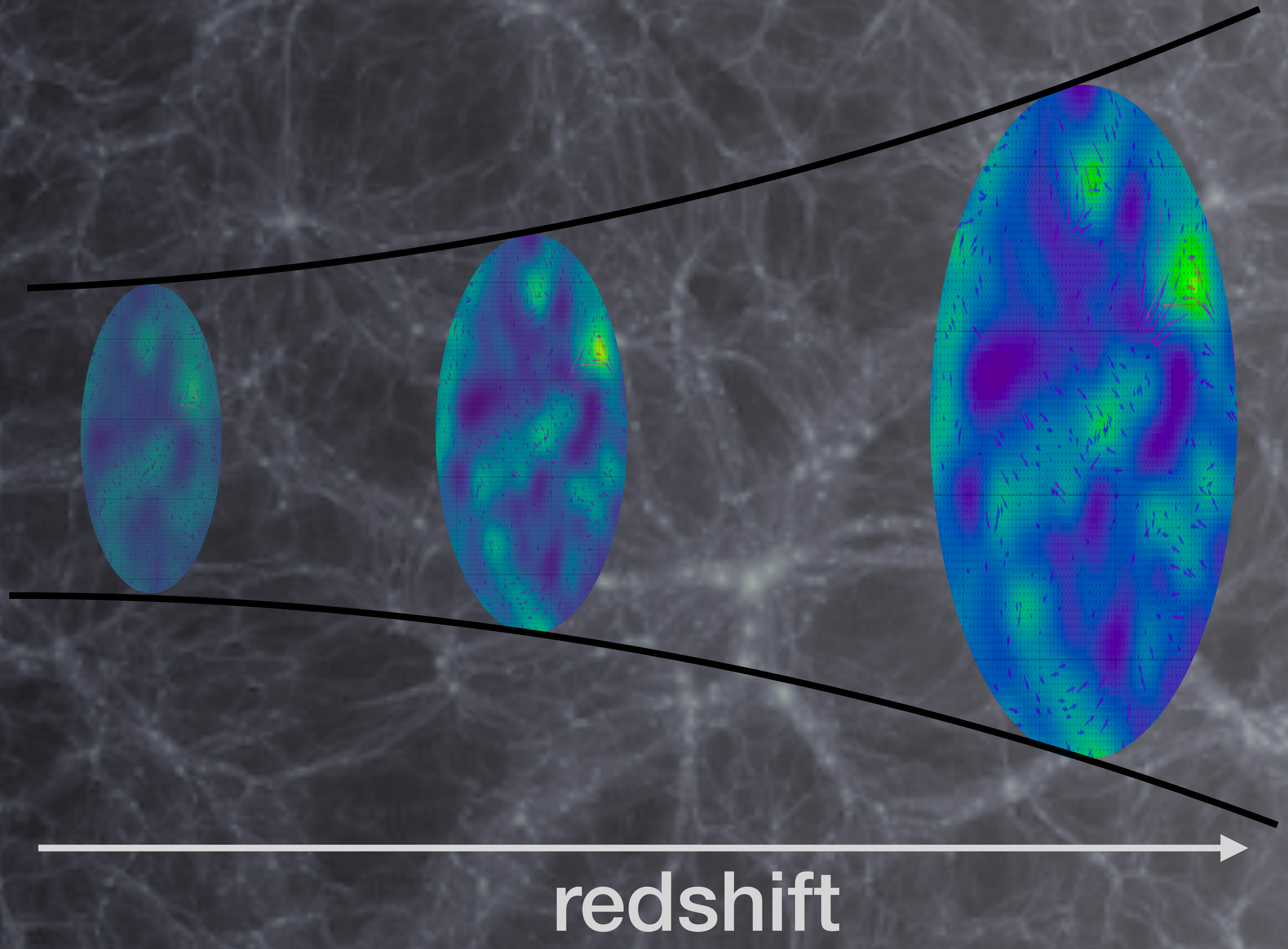
Information in Galaxies' 3D distribution

- Map the expansion history
- Probe growth of cosmic structure
- Origin of the Universe

➡ **Standard** cosmological paradigm

- Inflation
- Cosmological constant
- CDM



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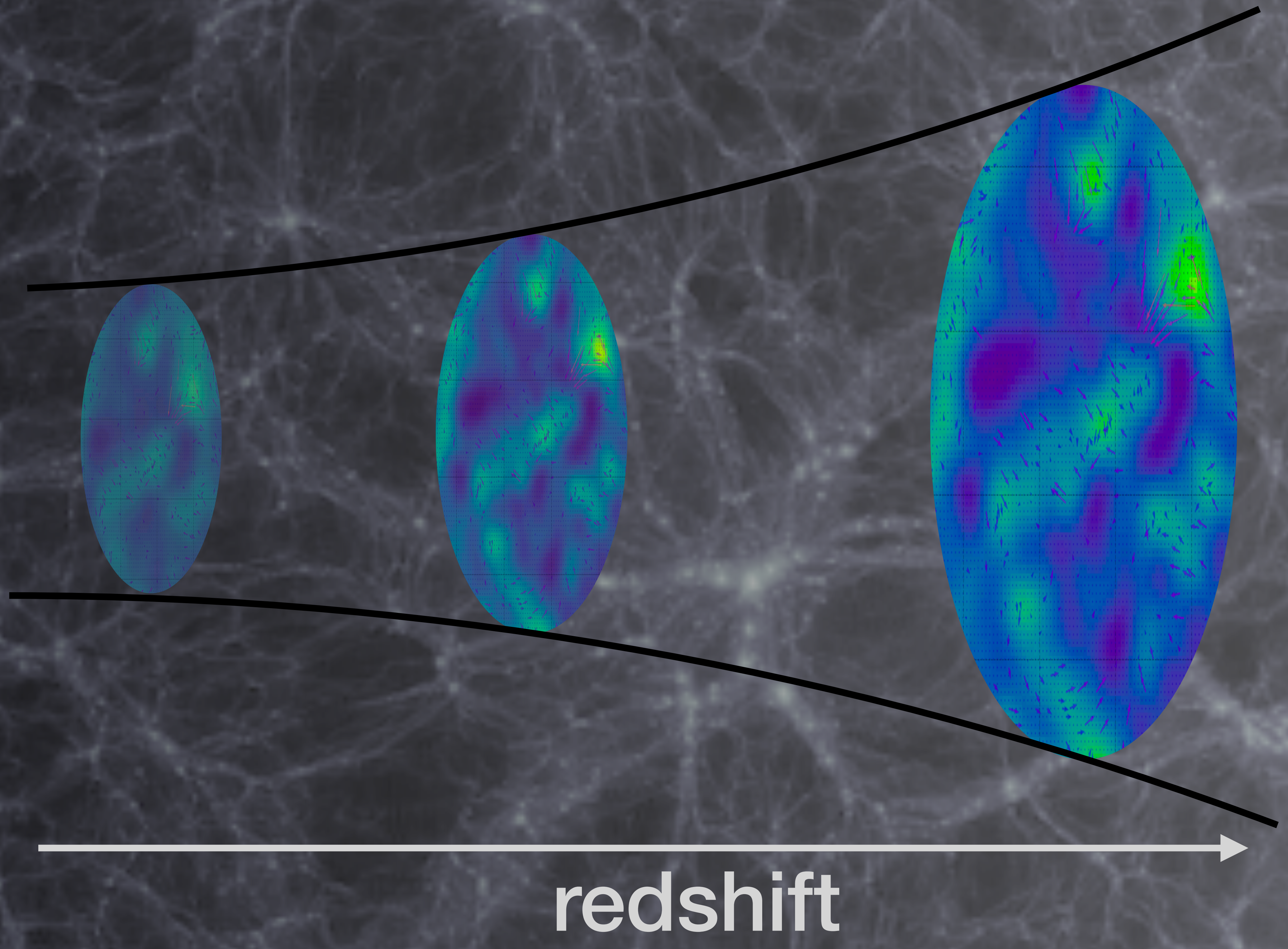
- Inflation ?
- Cosmological constant ?
- CDM ?




SDSS I-II + BOSS + eBOSS
(1998-2019)
Lookback time [Gyrs]
13.8
13.5
12.0
10.0
5.0
0.0
• 340k Quasars from LSS
0.8 < z < 2.2
• 300k Luminous Red Galaxies (LRGs)
0.6 < z < 1.0
• 200k Emission Line Galaxies (ELGs)
0.7 < z < 1.1
Light from background galaxies
Cosmic web gas in foreground
To Earth
• 60k Quasars from Lyα-Forest
2.1 < z < 3.5
Image:
A. Raichoor,
A. J. Ross,
and SDSS collaboration

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To Earth
declination J2000 (degrees)
20°N
10°N
0°
10°S
140°
160°
180°
200°
220°
right ascension J2000 (degrees)
0.5
0.6
0.7
0.8
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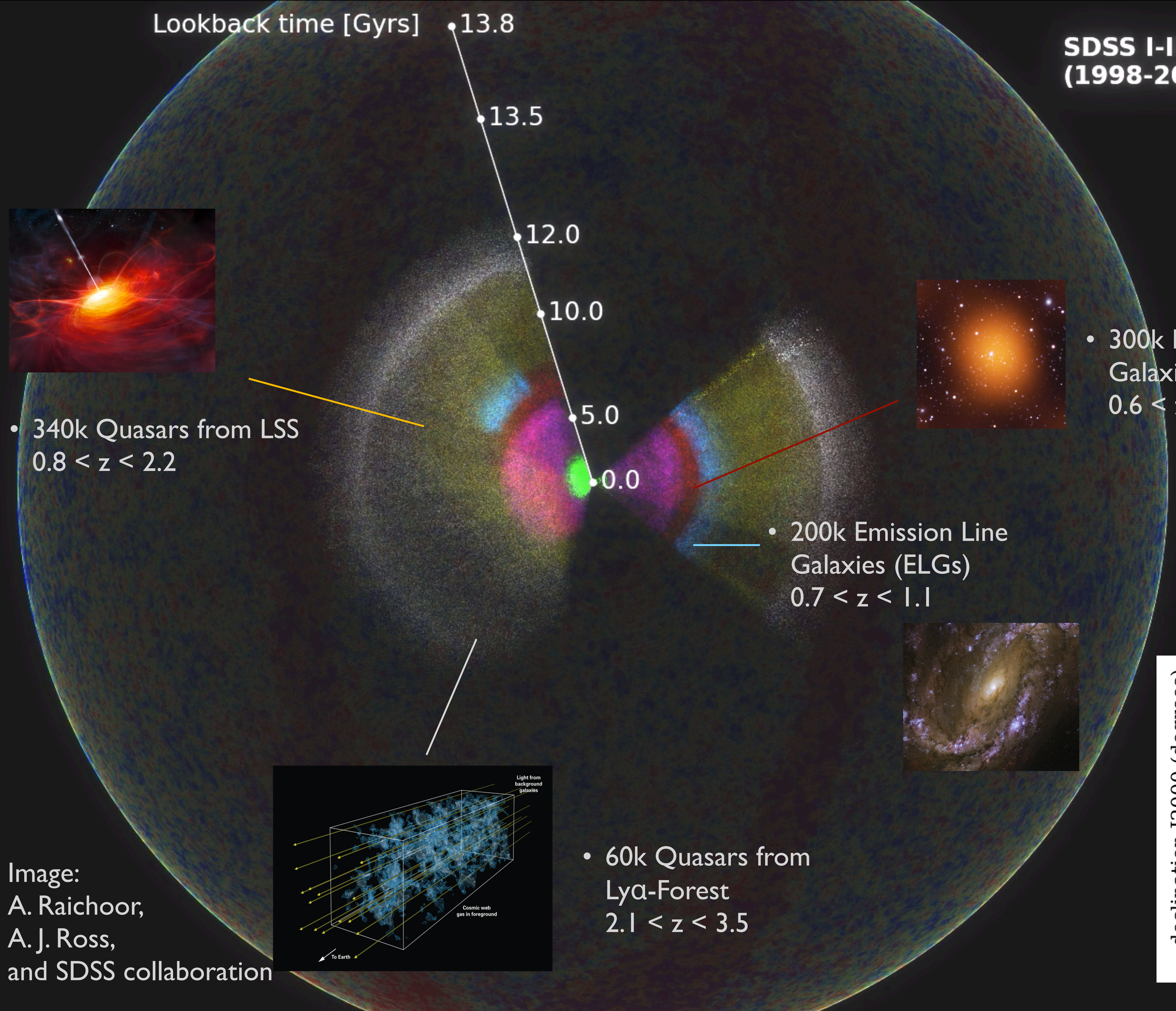
1.0
Image:
A. Raichoor,
A. J. Ross,
and SDSS collaboration

SDSS I-II + BOSS + eBOSS (1998-2019)



$$\xi(\mathbf{r}) \equiv \langle \delta(\mathbf{x}) \delta(\mathbf{x}+\mathbf{r}) \rangle$$

$$\delta(\mathbf{x}) = \rho(\mathbf{x})/\bar{\rho} - 1$$

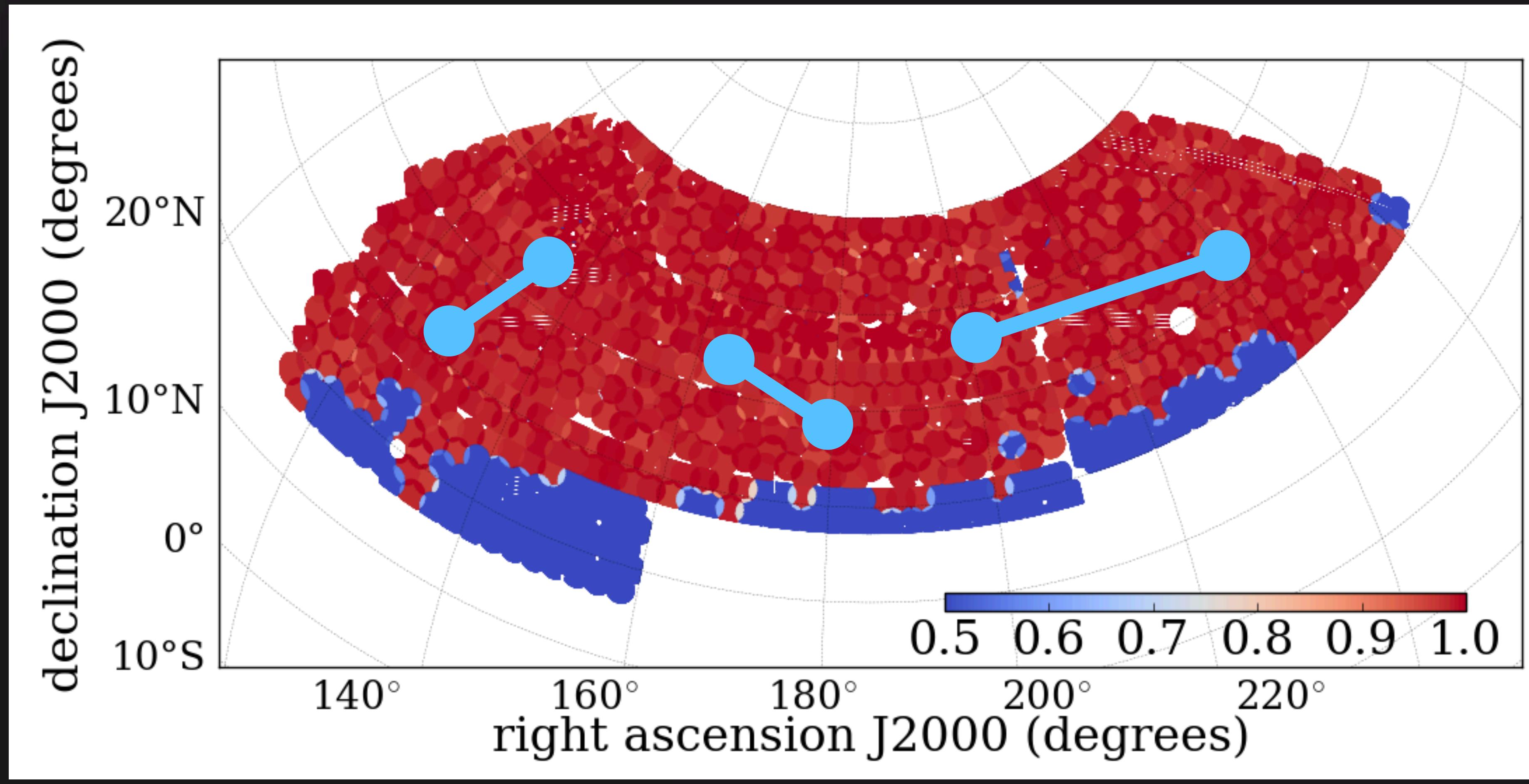
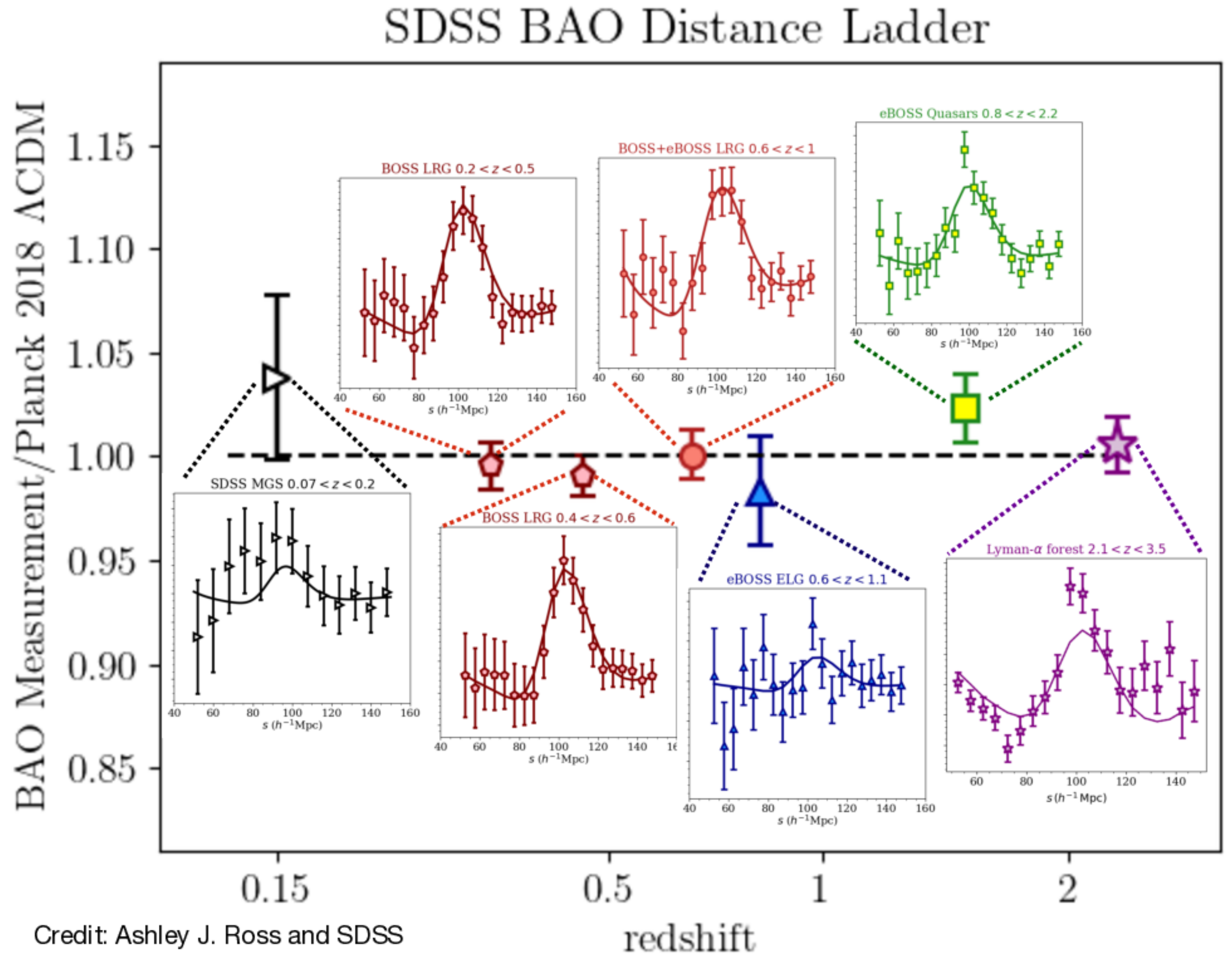
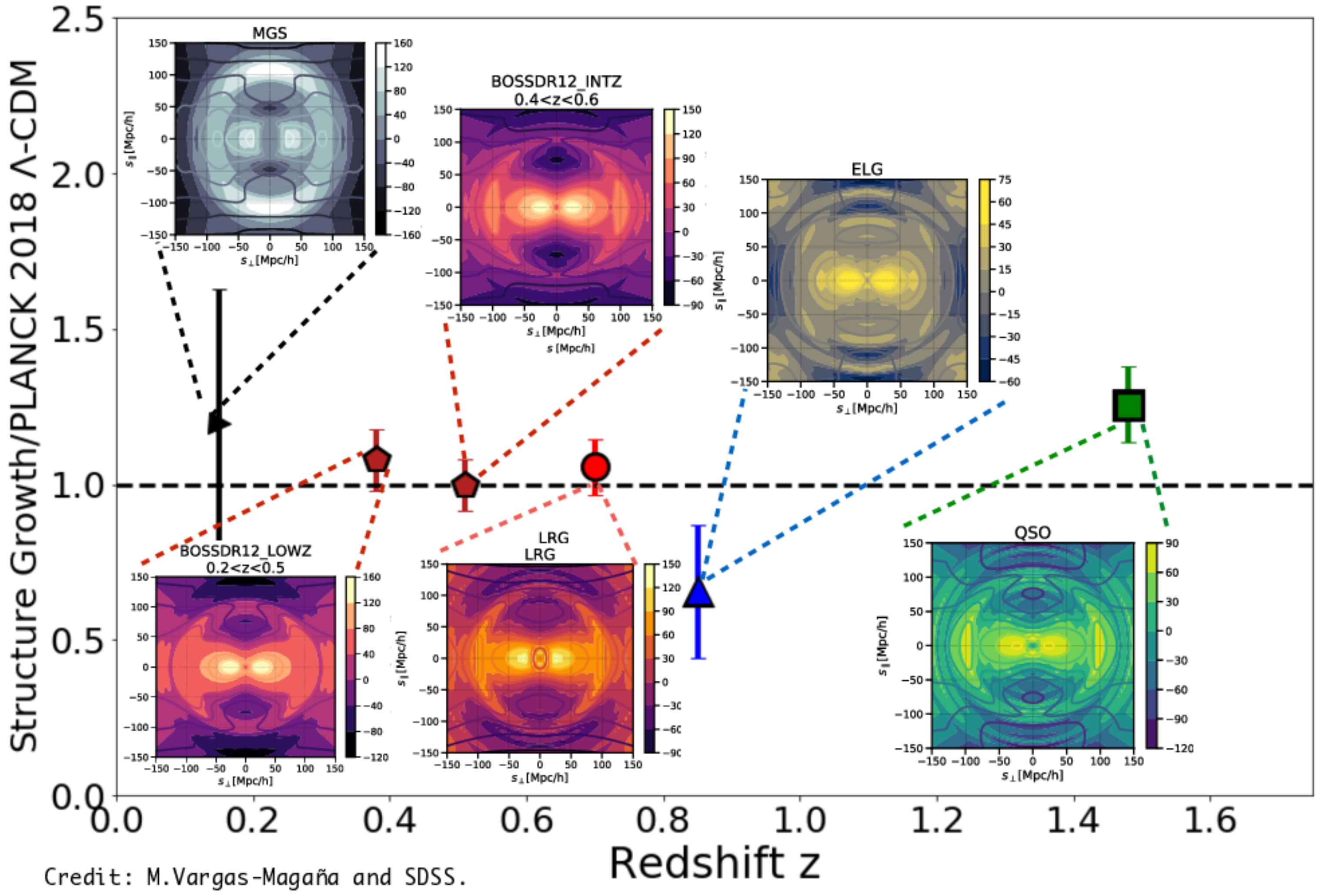


Image:
A. Raichoor,
A. J. Ross,
and SDSS collaboration

Recent Developments in 2-Point Statistics



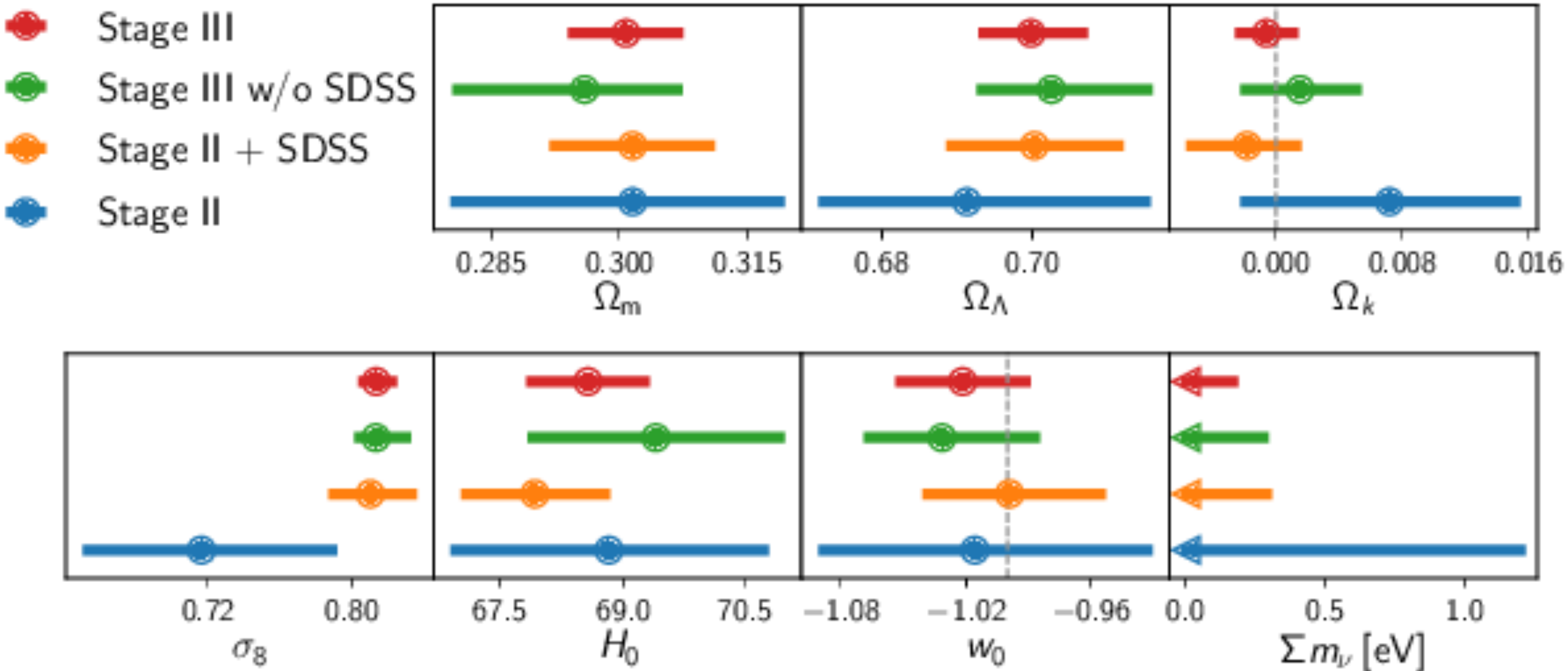
Credit: Ashley J. Ross and SDSS



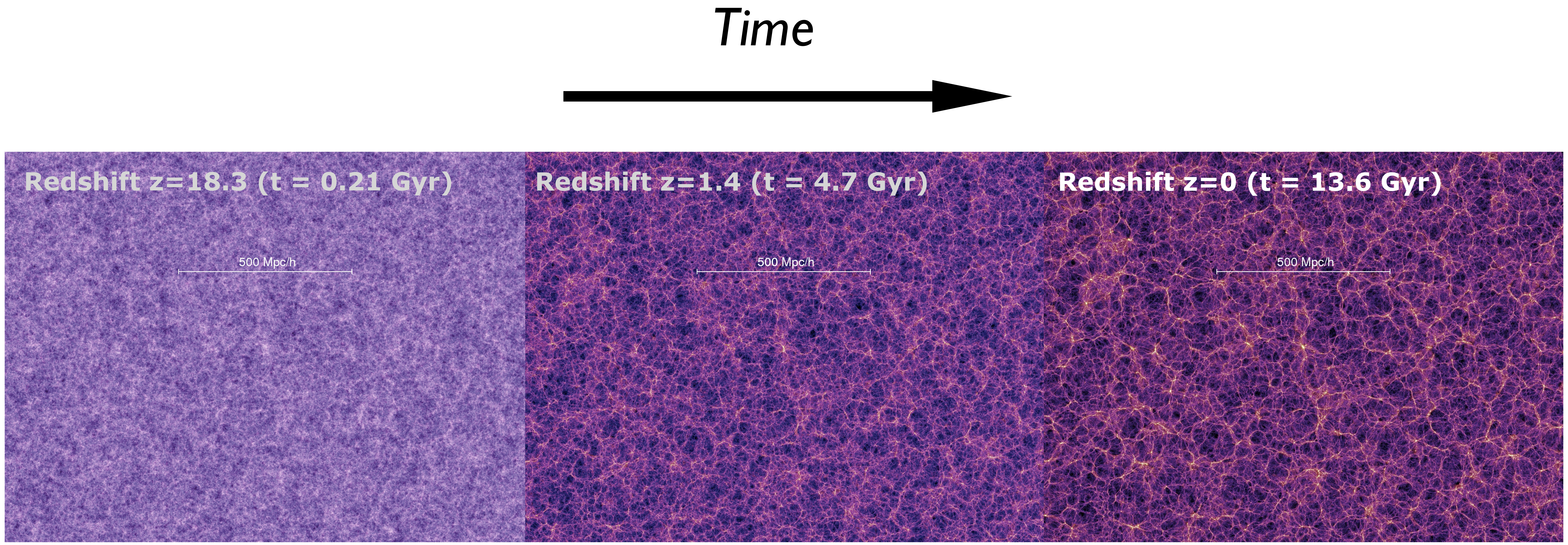
Credit: M.Vargas-Magaña and SDSS.

Stage II: WMAP, JLA SN, SDSS DR7 (2010)

Stage III: Planck, Pantheon SNe Ia, DES (2020)



Information in higher-order statistics?

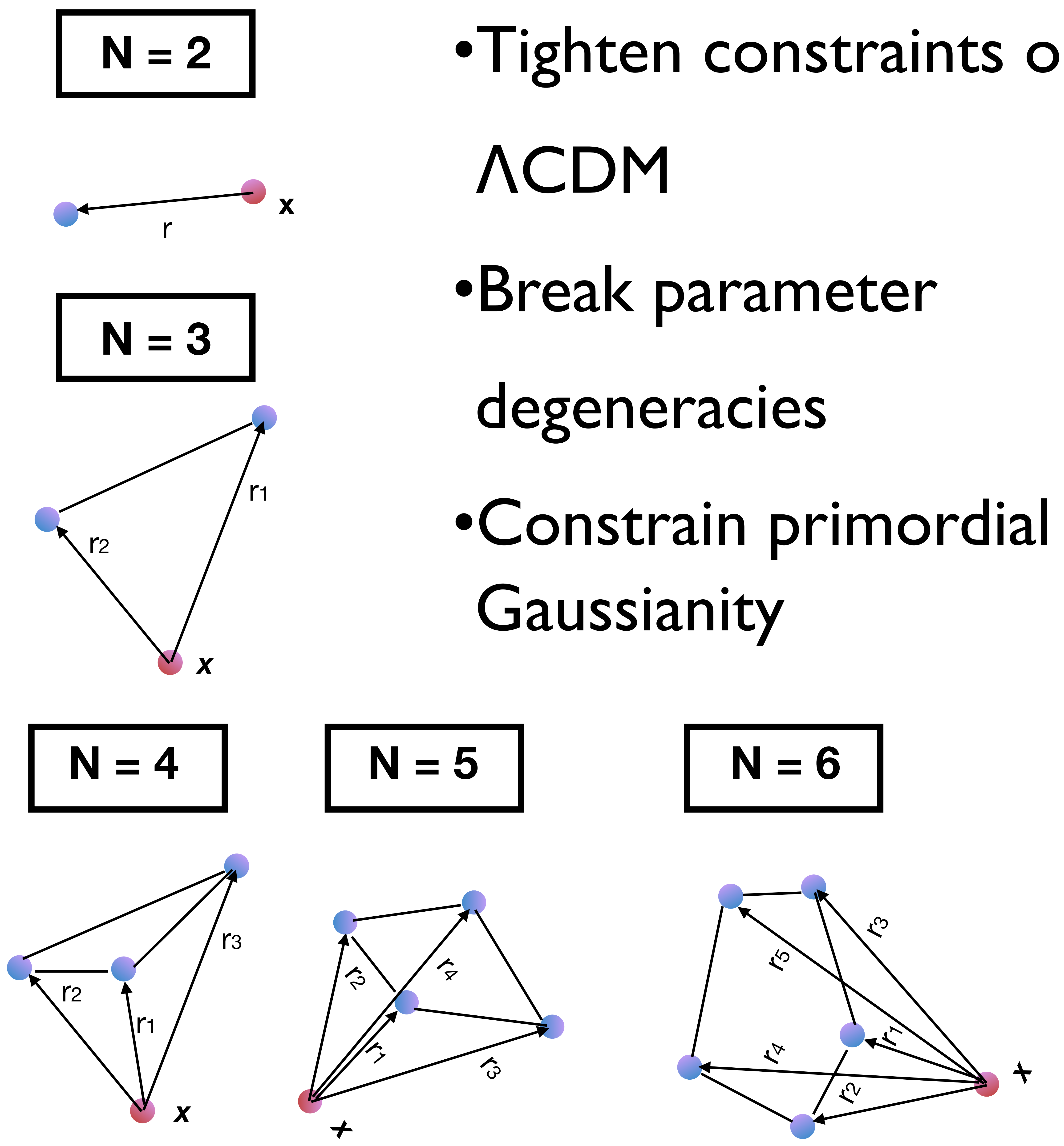


- **Gaussian initial conditions**

- **Nonlinearities are not fully captured by 2-point statistics**
- Unique window on different inflationary models
- Break parameter degeneracies

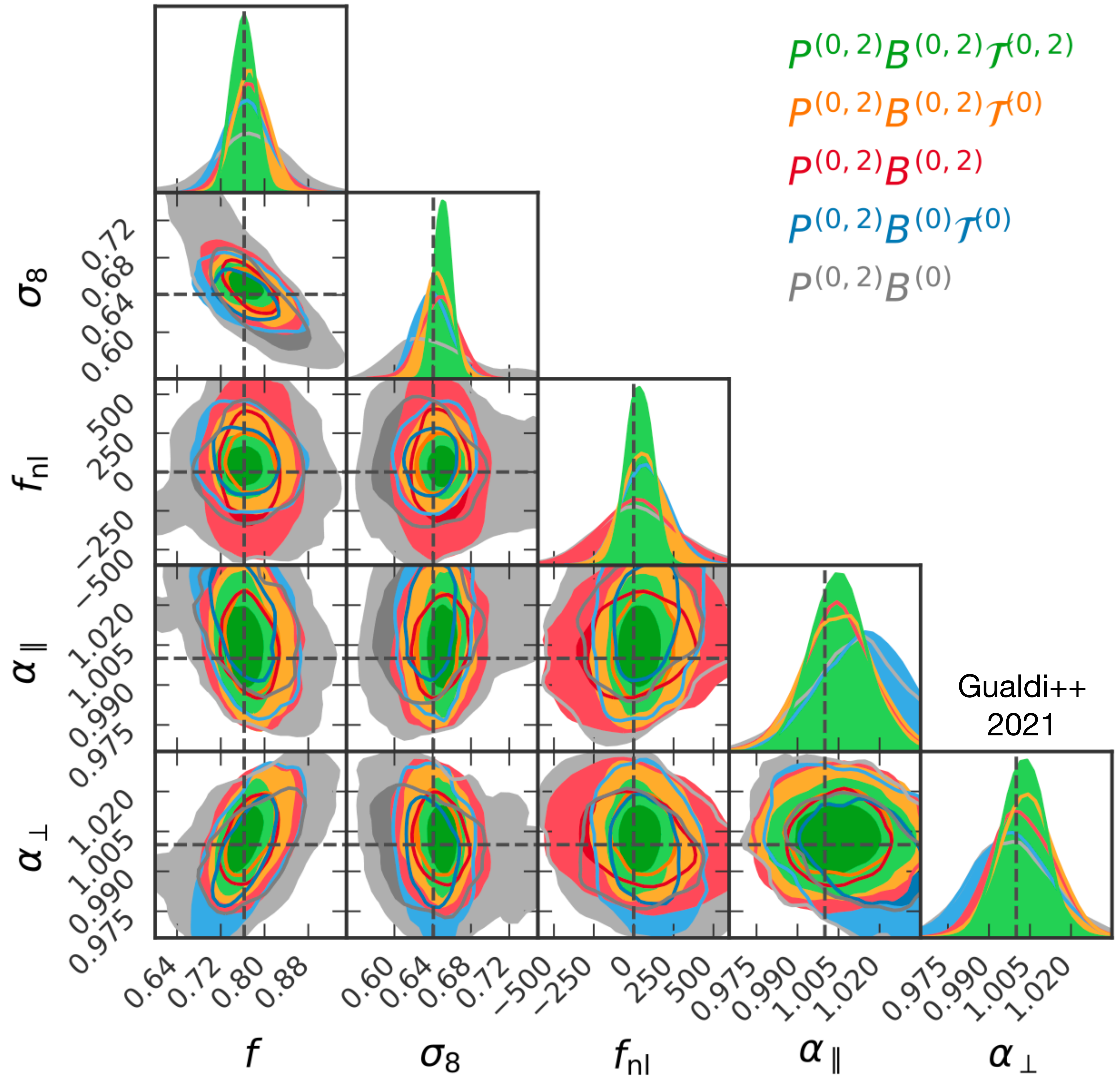
Image: Millenium Simulation Project

Go beyond 2-point statistics?



- Tighten constraints on ΛCDM
- Break parameter degeneracies
- Constrain primordial non-Gaussianity

P = Power Spectrum
B = Bispectrum
T = Trispectrum



NPCFs in the Isotropic Basis

$$\zeta(\mathbf{R}) \equiv \left\langle \prod_i \delta(\mathbf{r}_i) \right\rangle = \sum_\Lambda \zeta_\Lambda(R)\mathcal{P}_\Lambda(\hat{R})$$

$$\mathbf{R} = \{\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_{n-1}\}$$

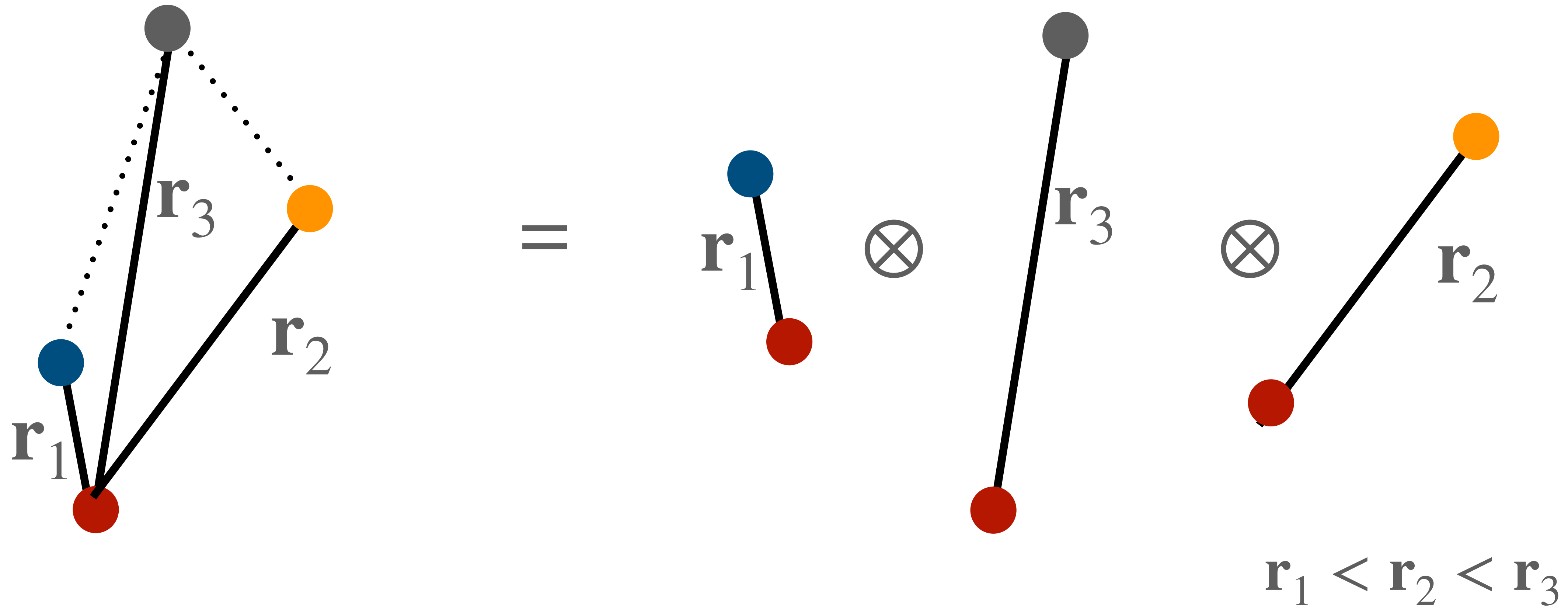
$$\mathcal{P}_\Lambda(\hat{R}) = \sum_M \mathcal{C}_M^\Lambda \prod_i Y_{\ell_i m_i}$$

- $$\mathcal{C}_{\mathrm{M}}^{\Lambda} = \mathcal{E}(\Lambda)\sqrt{2\ell_{12}+1} \times \cdots \times \sqrt{2\ell_{12}\ldots N-3}+1$$
$$\times \sum_{m_{12\ldots}} (-1)^\kappa \begin{pmatrix} \ell_1 & \ell_2 & \ell_{12} \\ m_1 & m_2 & -m_{12} \end{pmatrix} \ldots \begin{pmatrix} \ell_{12\ldots N-3} & \ell_{N-2} & \ell_{N-1} \\ m_{12\ldots N-3} & m_{N-2} & m_{N_1} \end{pmatrix}$$

- Complete orthonormal basis
- Given isotropy:
  - An efficient approach to sort information
- Separable angular basis:
  - offers a speed boost to measure it

Cahn and Slepian, arXiv: 2010.14418

Efficient N-point Correlator Estimation (ENCORE)



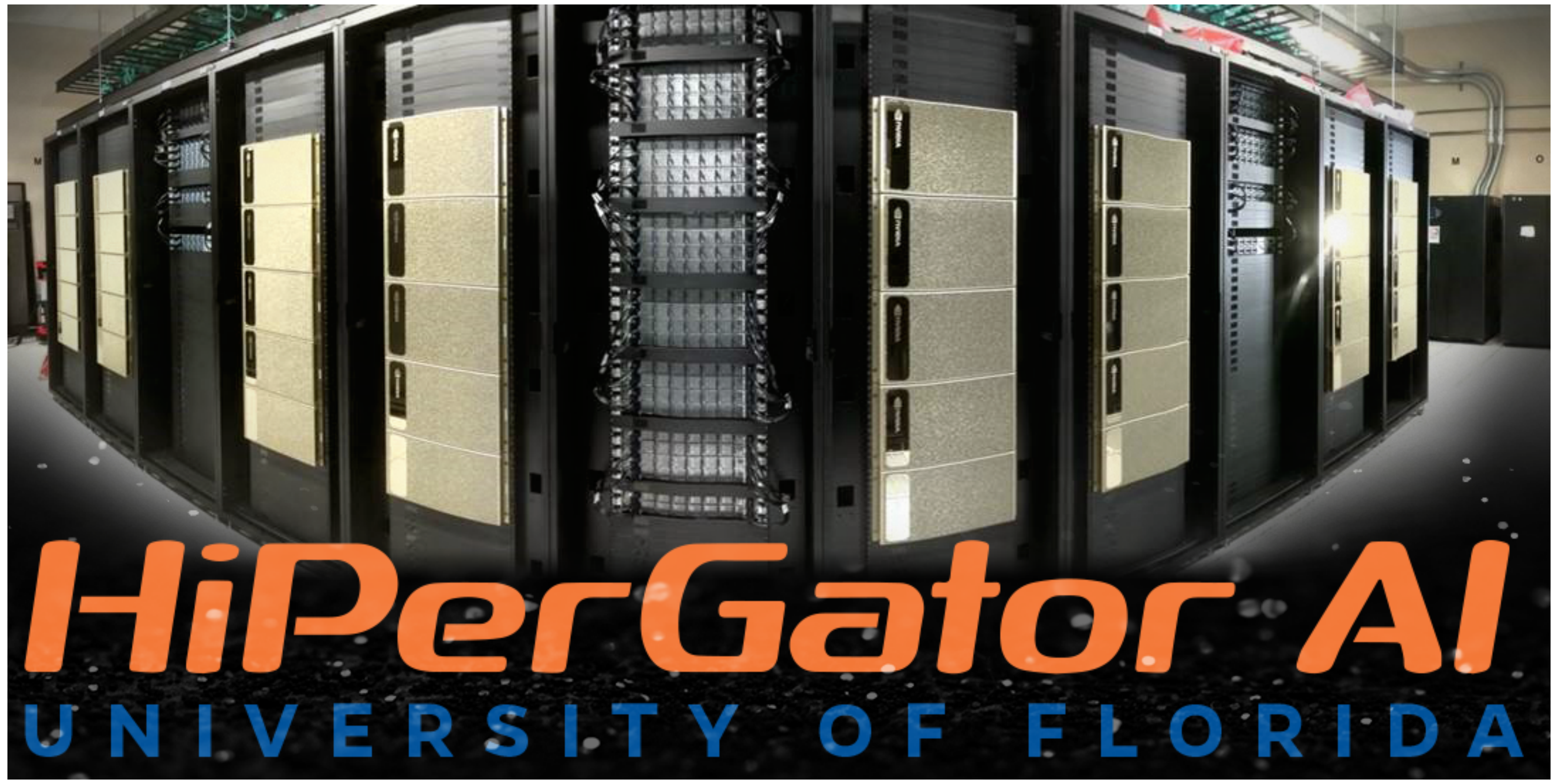
- Algorithm based on Slepian & Eisenstein 2015
- Survey geometry induces angular momentum coupling
  - Edge-correction is included
- "Connected-only" estimator

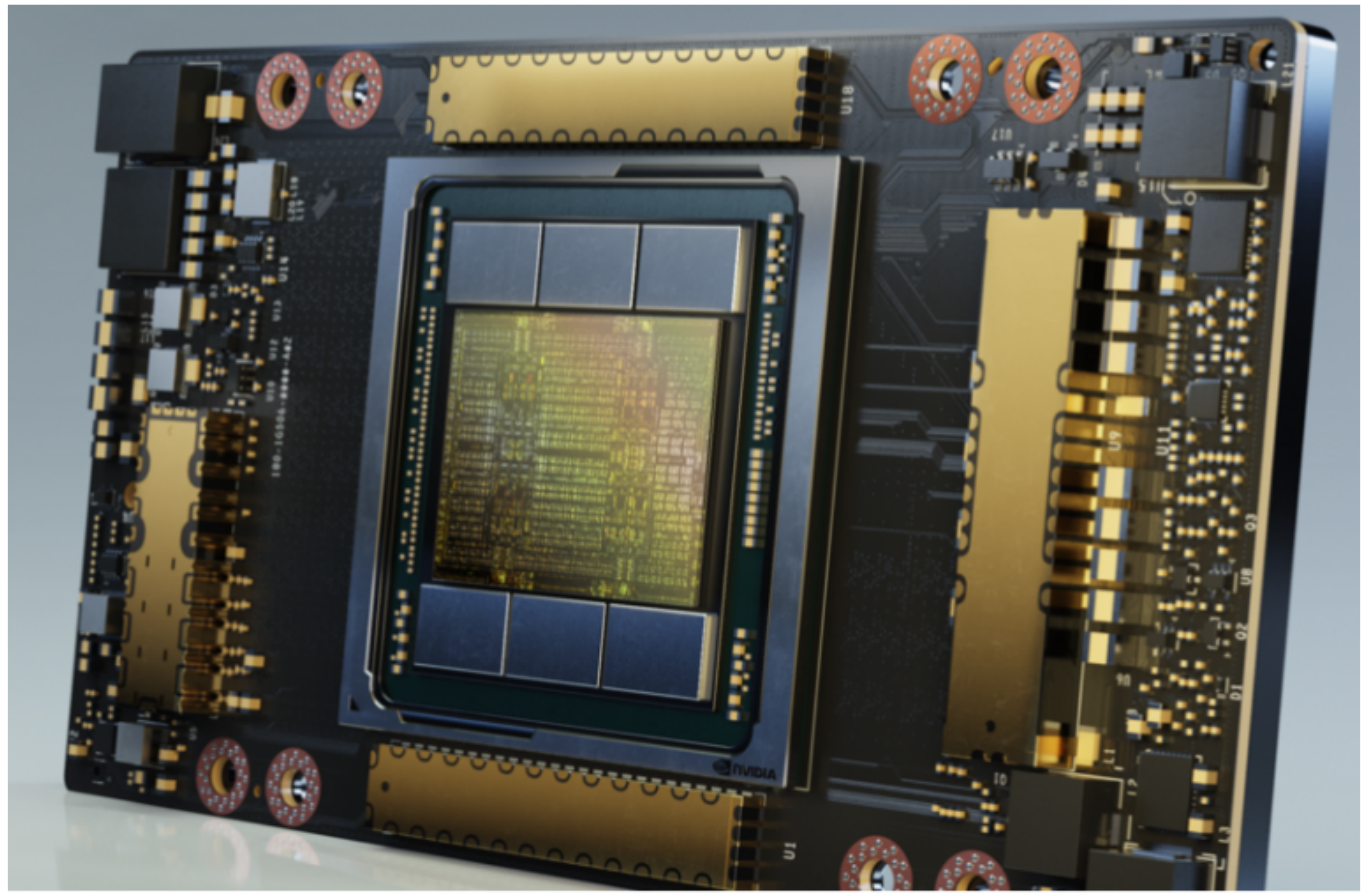
$$\zeta\left(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3\right) = \xi\left(\mathbf{r}_1\right)\xi\left(\mathbf{r}_2 - \mathbf{r}_3\right) + \text{cyc.} \boxed{+\,\zeta^{(c)}\left(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3\right)}$$

https://github.com/oliverphilcox/encore

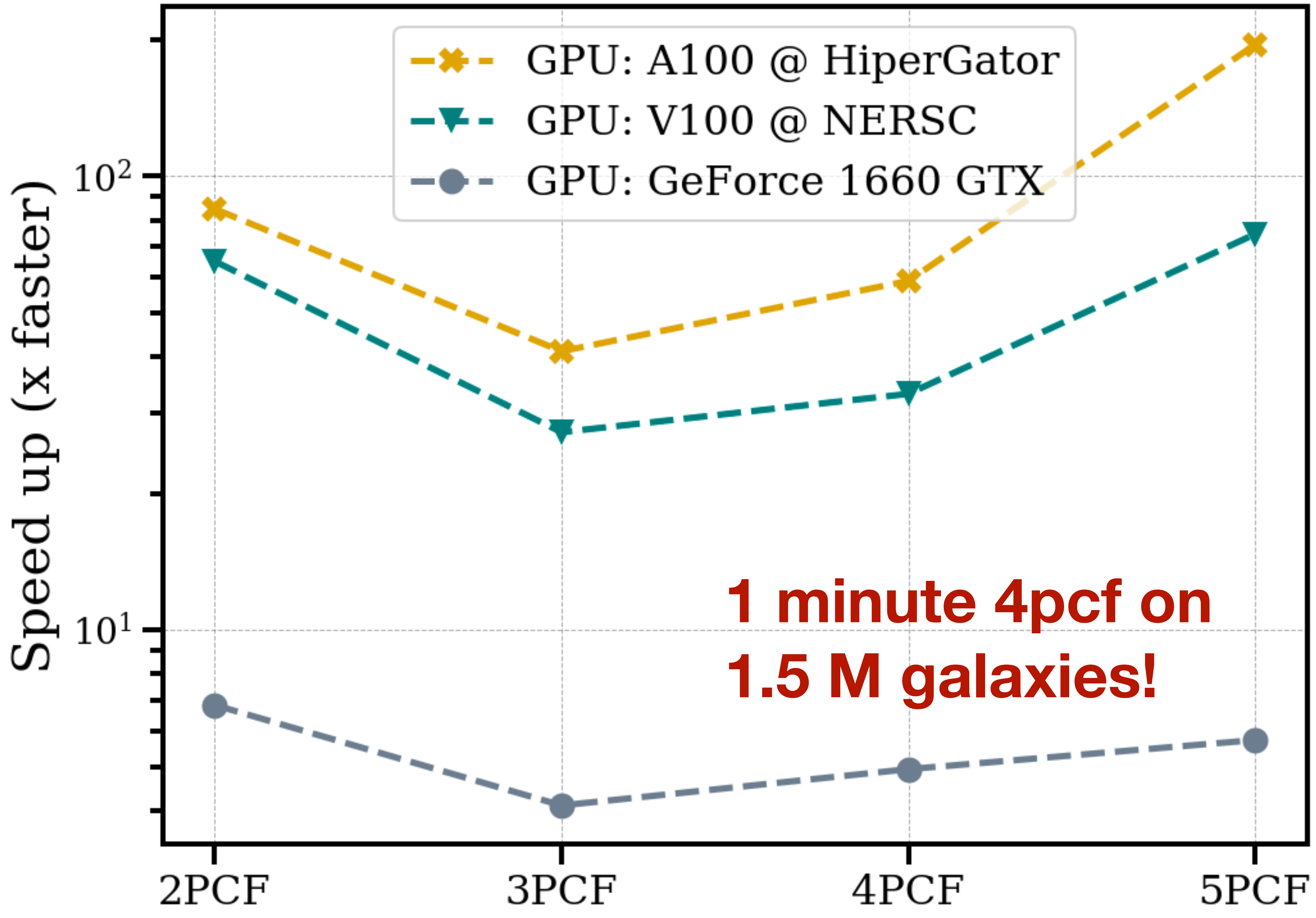
Philcox, Slepian, **JH,** Cahn, Warner, Eisenstein arXiv: 2105.08722

GPU for N-point Correlator Estimation (CADENZA)





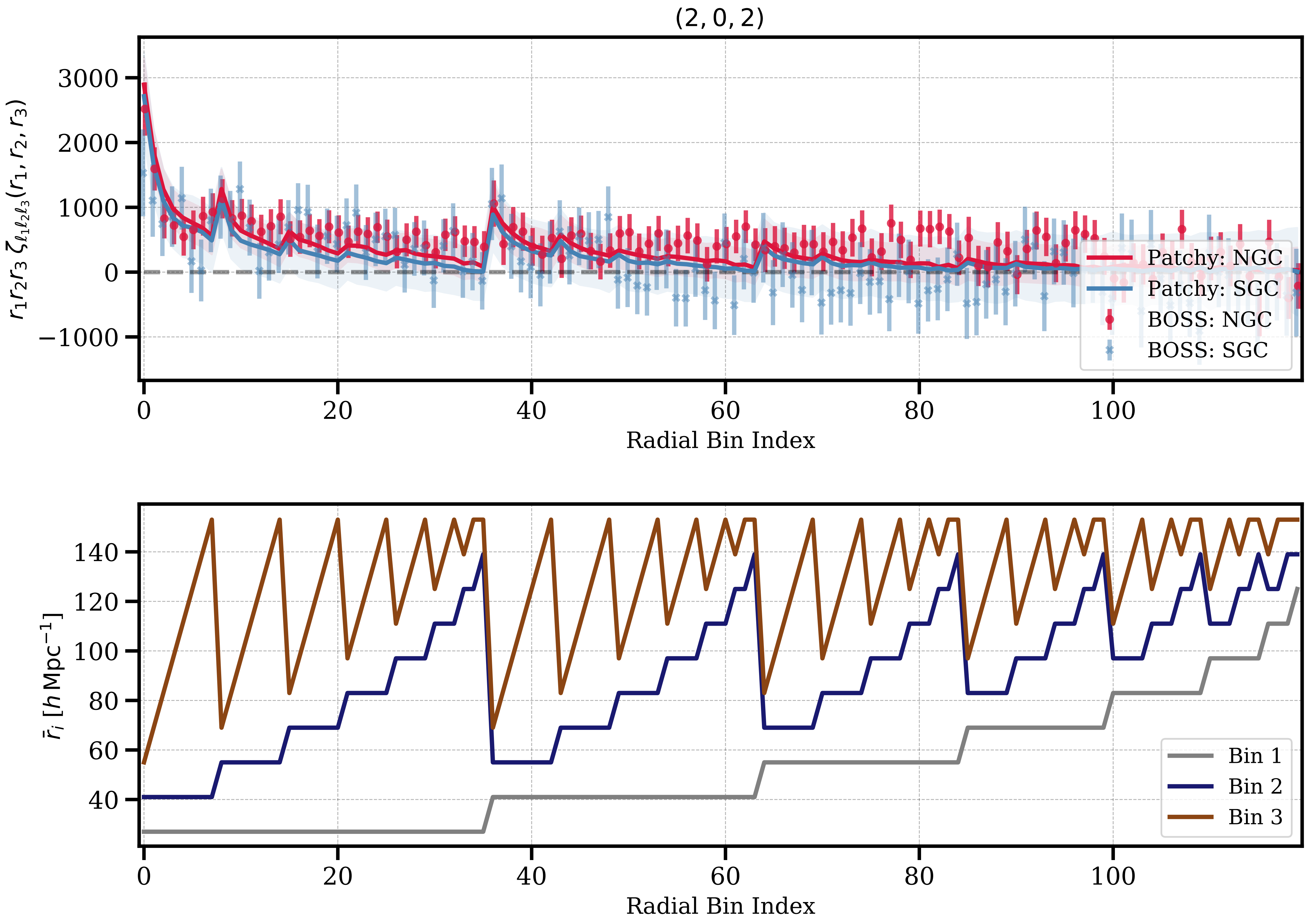
GPU vs. single thread CPU

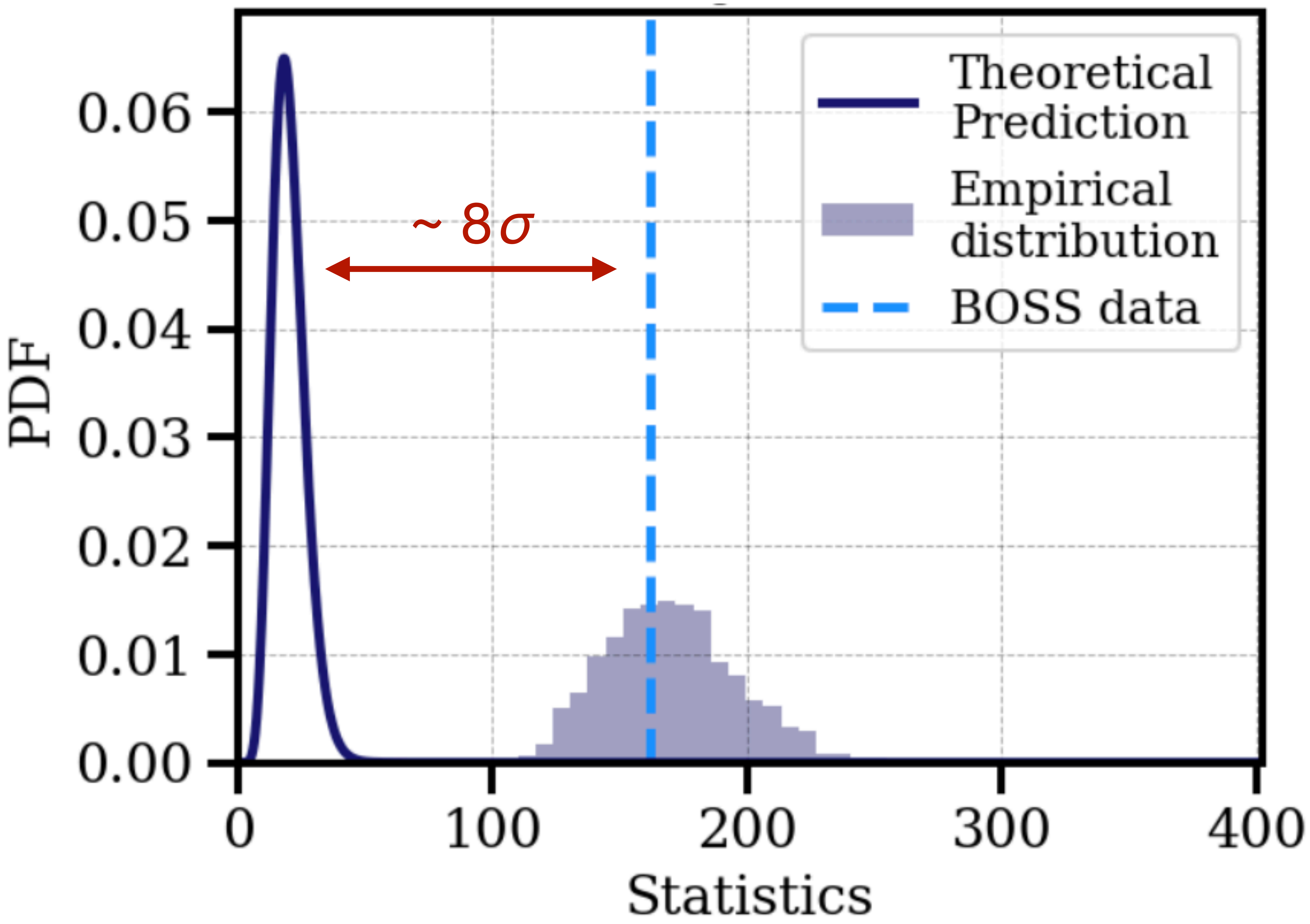


CADENZA: Slepian, Warner, Hou, Cahn in prep.

First Detection of Gravitationally-induced non-Gaussianity with BOSS data using 4PCF

4PCF from BOSS data

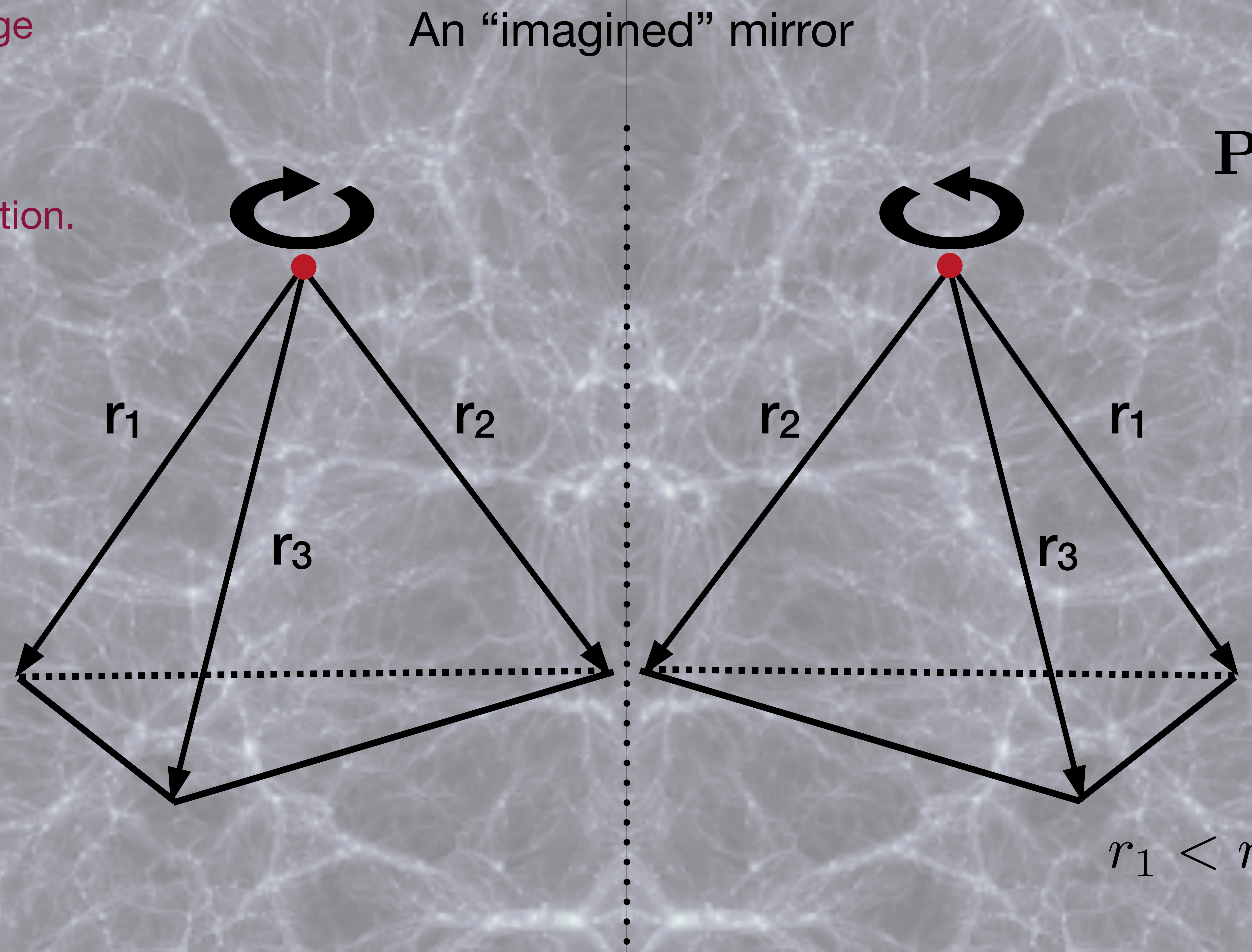




O. Philcox, JH, Z. Slepian, arXiv: 2108.01670

Parity Violation with the 4PCF of LSS

- A tetrahedron and its mirror image cannot be superimposed in 3D.
- The 4PCF is the lowest order statistics sensitive to parity violation.



$$\mathbf{P}: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

$r_1 < r_2 < r_3$

$$\mathcal{P}_{\ell_1\ell_2\ell_3}\left(-\hat{\mathbf{r}}_1, -\hat{\mathbf{r}}_2, -\hat{\mathbf{r}}_3\right) = (-1)^{\ell_1+\ell_2+\ell_3}\mathcal{P}_{\ell_1\ell_2\ell_3}\left(\hat{\mathbf{r}}_1, \hat{\mathbf{r}}_2, \hat{\mathbf{r}}_3\right)$$

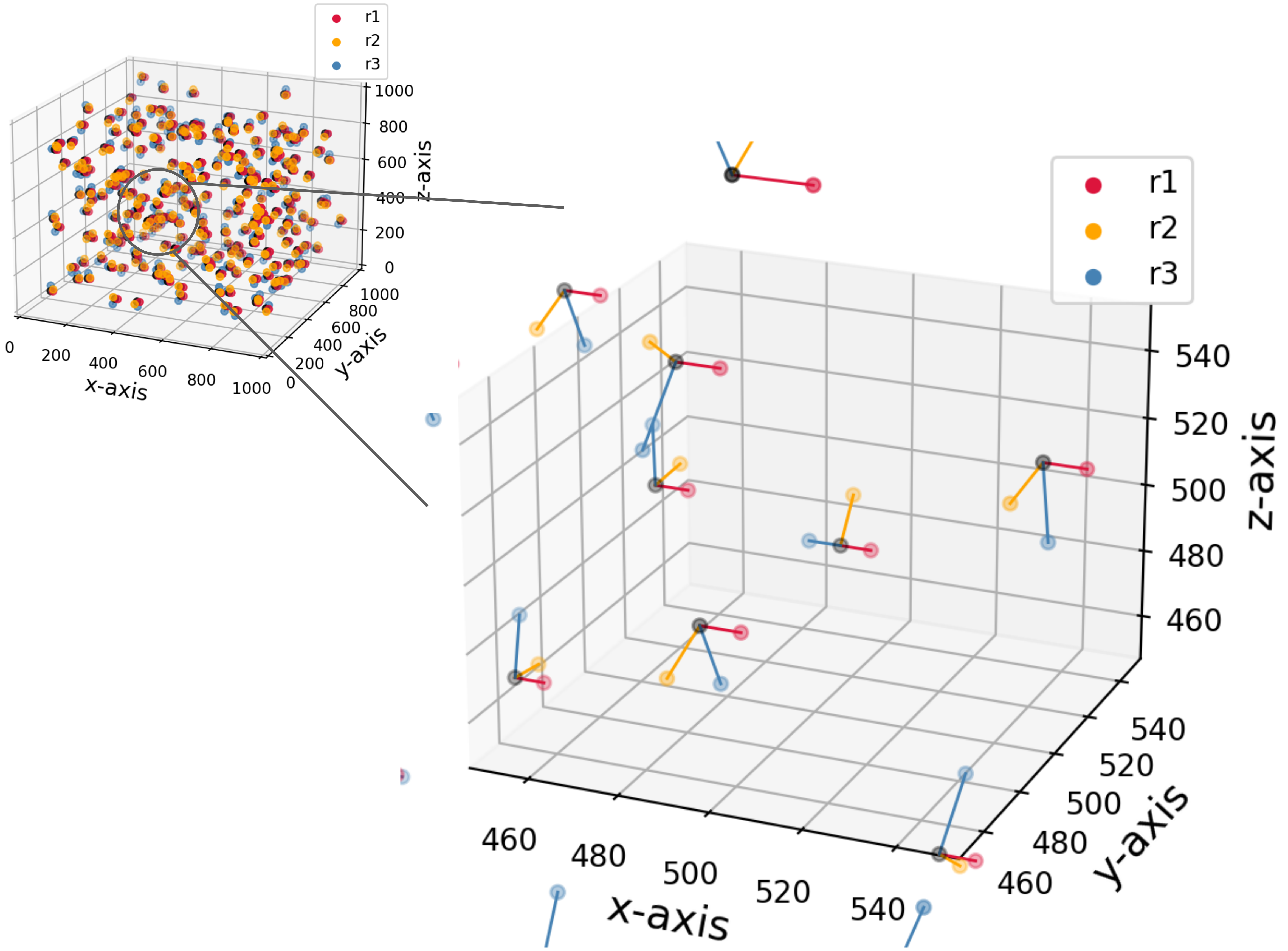
Background Image credit: O.Hahn

Cahn, Slepian, **JH** 2021

Parity Violation on Cosmological Scale

- Standard single-field inflation preserves parity
- Gravity is parity-conserving
    - *Sources* for parity violation?
        - Chern-Simons like interaction
            - e.g. axion coupled to gauge field (Kim+ 2005, Namba+ 2015)
        - Primordial vorticity (Vilenkin 1978)
        - Broken symmetry during phase transition (G.'t Hooft 1974, Quashnock+1989; Baym+1996)
        - String-sourced perturbations (Pogosian & Wyman 2008)
        - ...

A Toy Simulation for the Parity-Odd 4PCF



$$\mathcal{P}_{111}(\hat{\mathbf{r}}_1, \hat{\mathbf{r}}_2, \hat{\mathbf{r}}_3) = -i\frac{3}{\sqrt{2}}(4\pi)^{-3/2}\, \hat{\mathbf{r}}_1 \cdot (\hat{\mathbf{r}}_2 \times \hat{\mathbf{r}}_3)\,,$$

$$\mathcal{P}_{122}(\hat{\mathbf{r}}_1, \hat{\mathbf{r}}_2, \hat{\mathbf{r}}_3) = i\sqrt{\frac{45}{2}}(4\pi)^{-3/2}\, \hat{\mathbf{r}}_1 \cdot (\hat{\mathbf{r}}_2 \times \hat{\mathbf{r}}_3)\,(\hat{\mathbf{r}}_2 \cdot \hat{\mathbf{r}}_3)\,,$$

$$\mathcal{P}_{133}(\hat{\mathbf{r}}_1, \hat{\mathbf{r}}_2, \hat{\mathbf{r}}_3) = -i\frac{15}{4}\sqrt{7}(4\pi)^{-3/2}\, \hat{\mathbf{r}}_1 \cdot (\hat{\mathbf{r}}_2 \times \hat{\mathbf{r}}_3)\left[(\hat{\mathbf{r}}_2 \cdot \hat{\mathbf{r}}_3)^2 - \frac{1}{5}\right]$$

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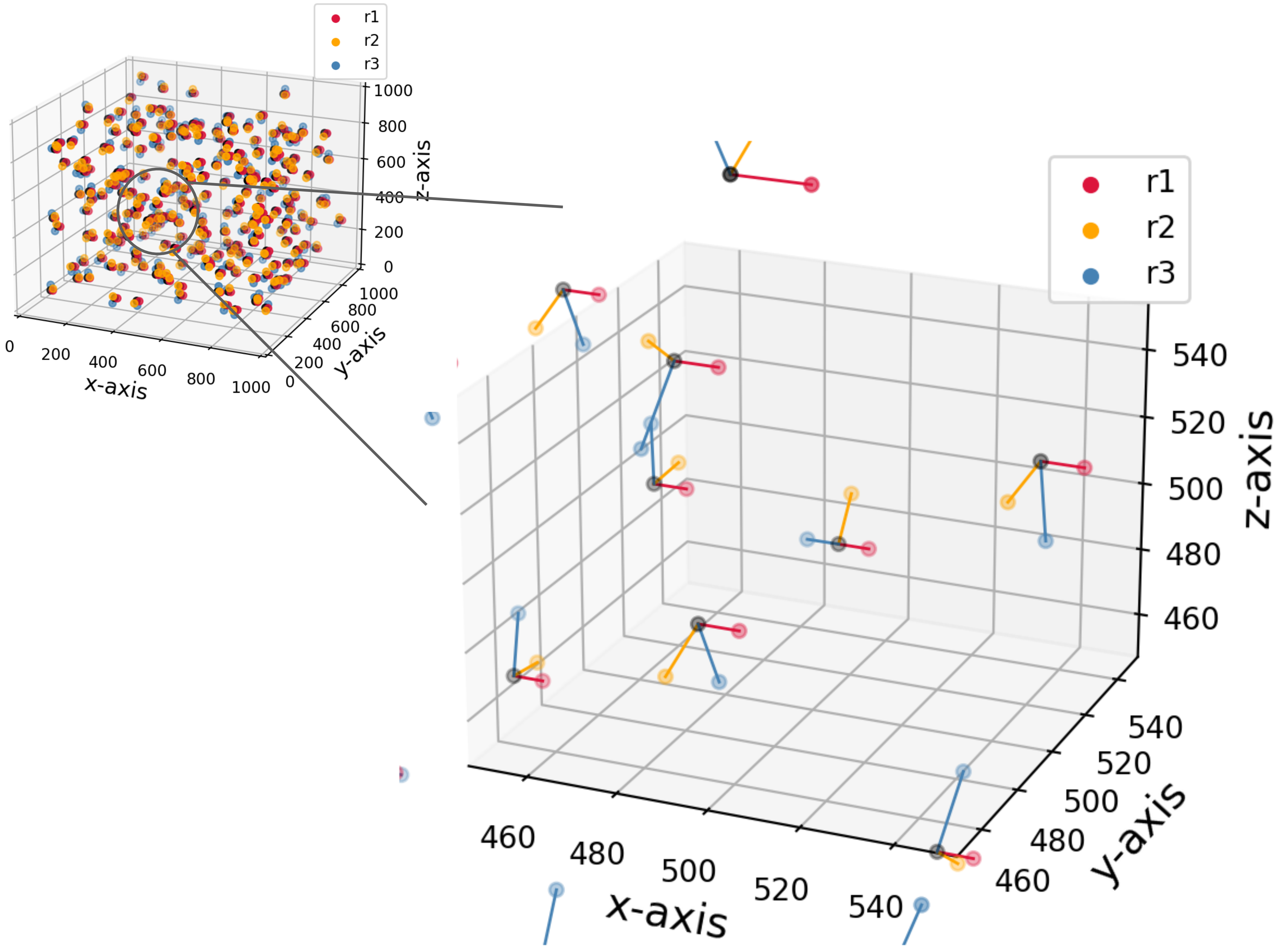
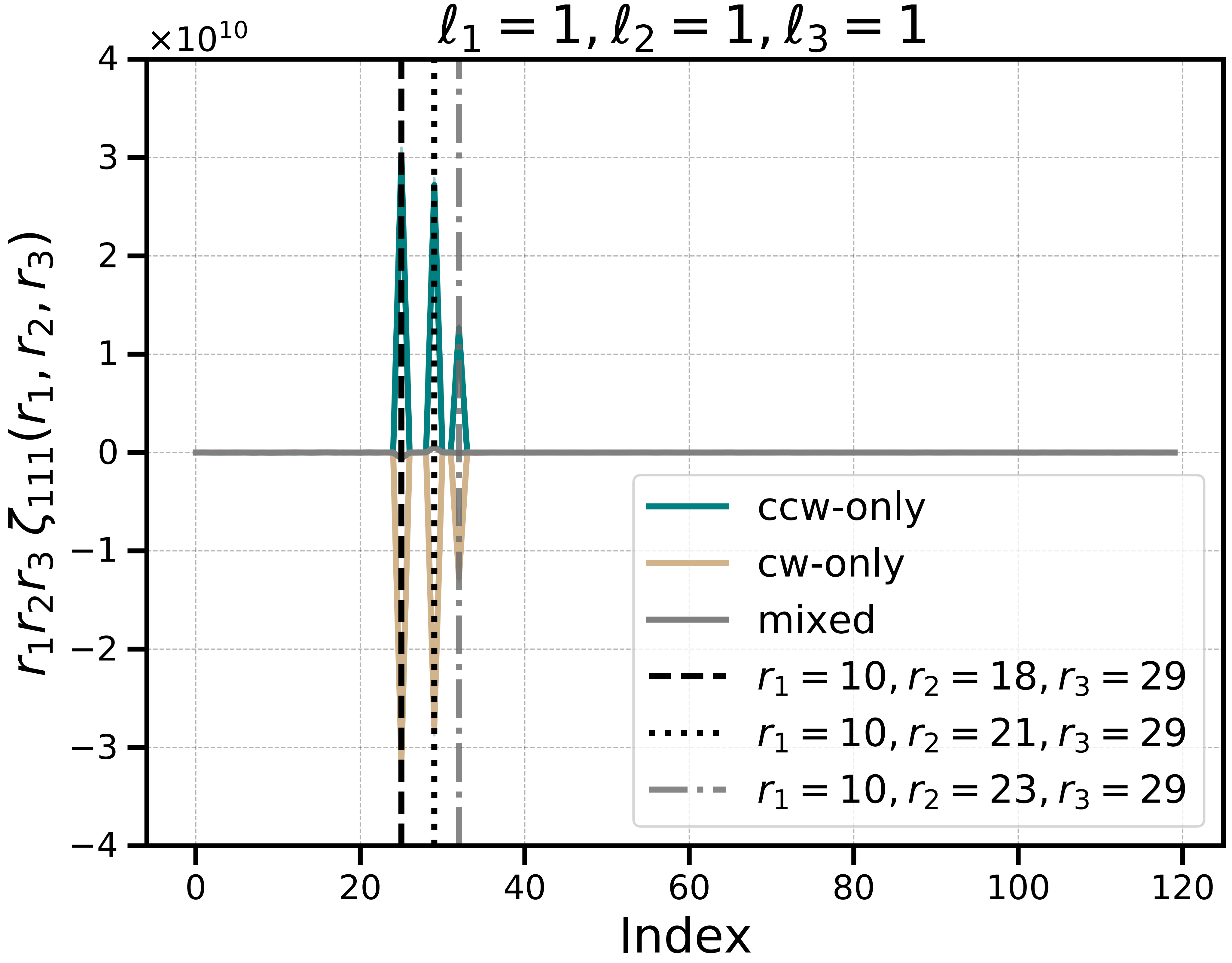
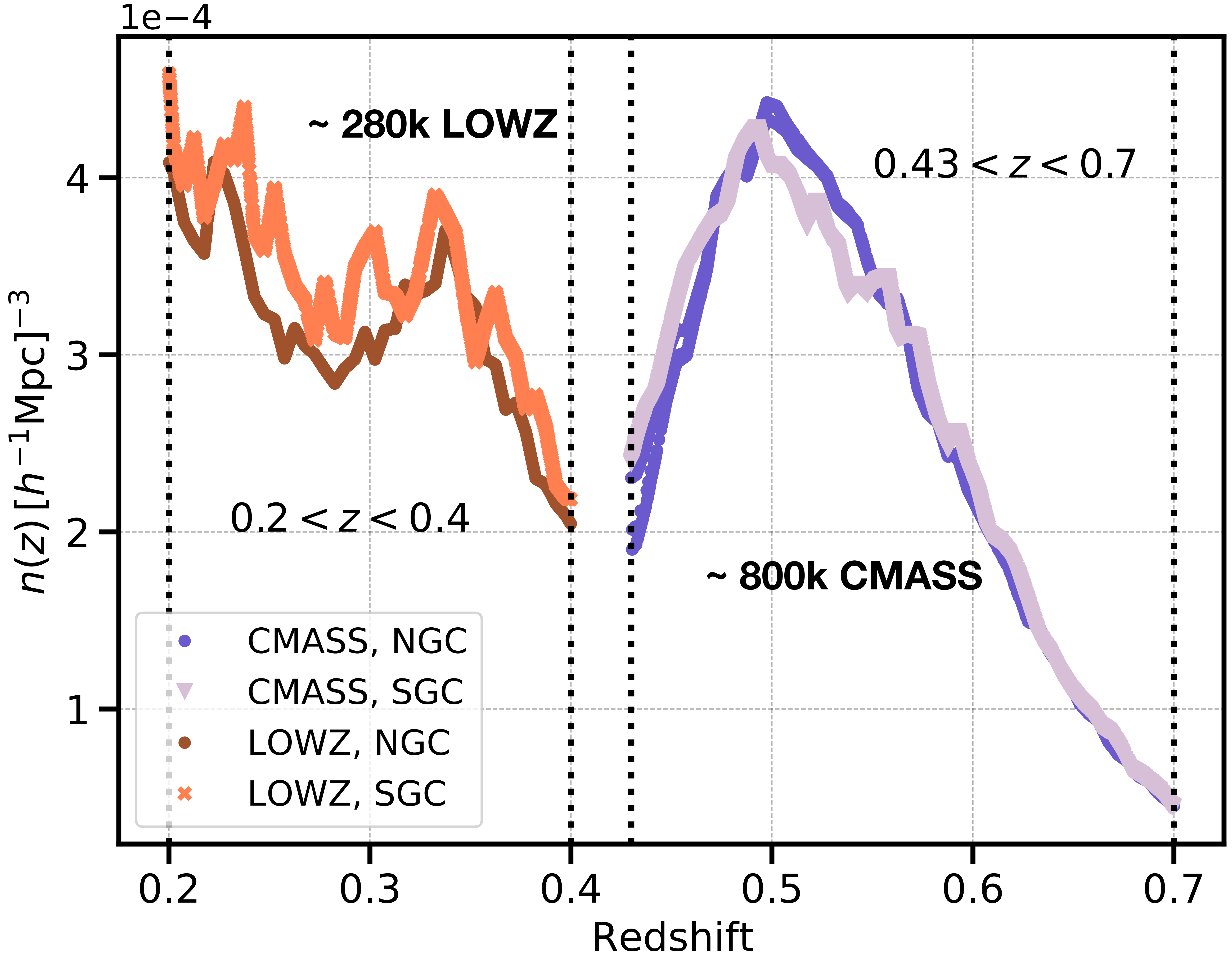


$$P_{111}(\hat{r}_1, \hat{r}_2, \hat{r}_3) \propto -i\hat{r}_1 \cdot (\hat{r}_2 \times \hat{r}_3)$$



Measurement of Parity-Odd Modes in the 4PCF of SDSS BOSS DR12 CMASS and LOWZ



JH, Slepian, Cahn (arXiv: 2206.03625)

Challenges

- **Statistical fluctuation estimation**
  - Gaussian analytic covariance
  - Compressed data vector[1]
  - Direct: reduced d.o.f.
- **Systematics study**
  - Survey-related effects
  - Observer-induced effects
  - Algorithm-related effects

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- **Statistical fluctuation estimation**
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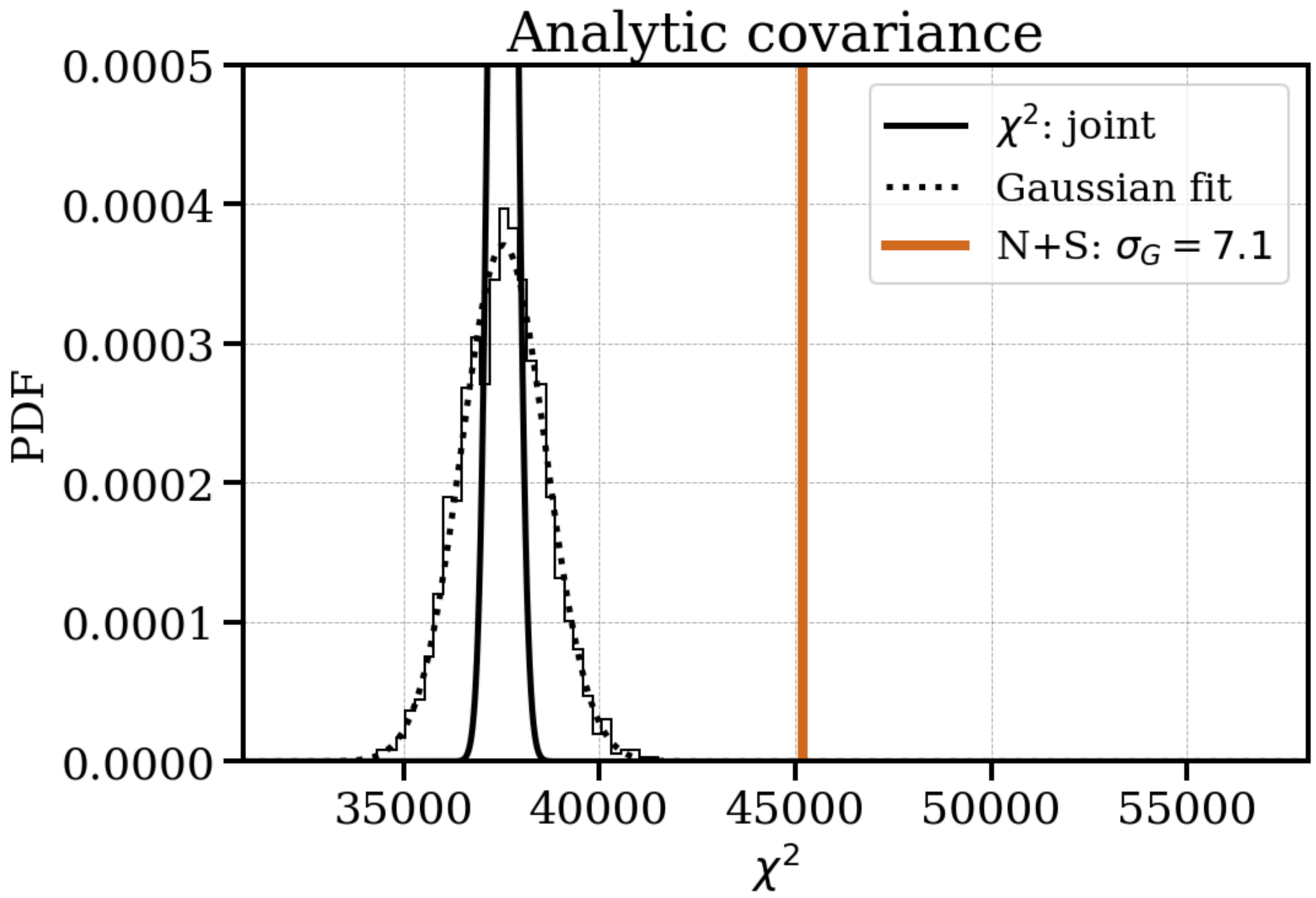
  - Observer-induced effects
  - Procedure/Algorithm-related effects

Detection significance in the CMASS sample



CMASS, 18 bins, $\ell_{max} = 4$

JH, Slepian, Cahn 2022

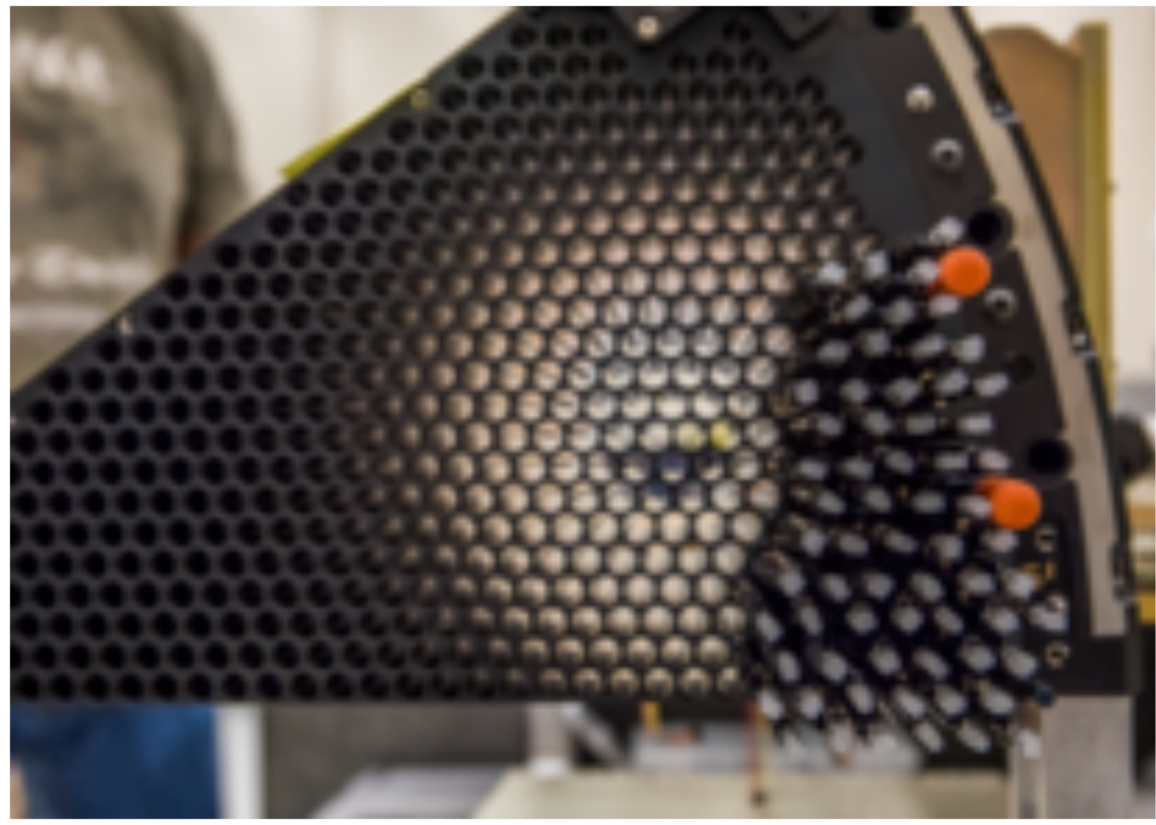
Potential question list and implications

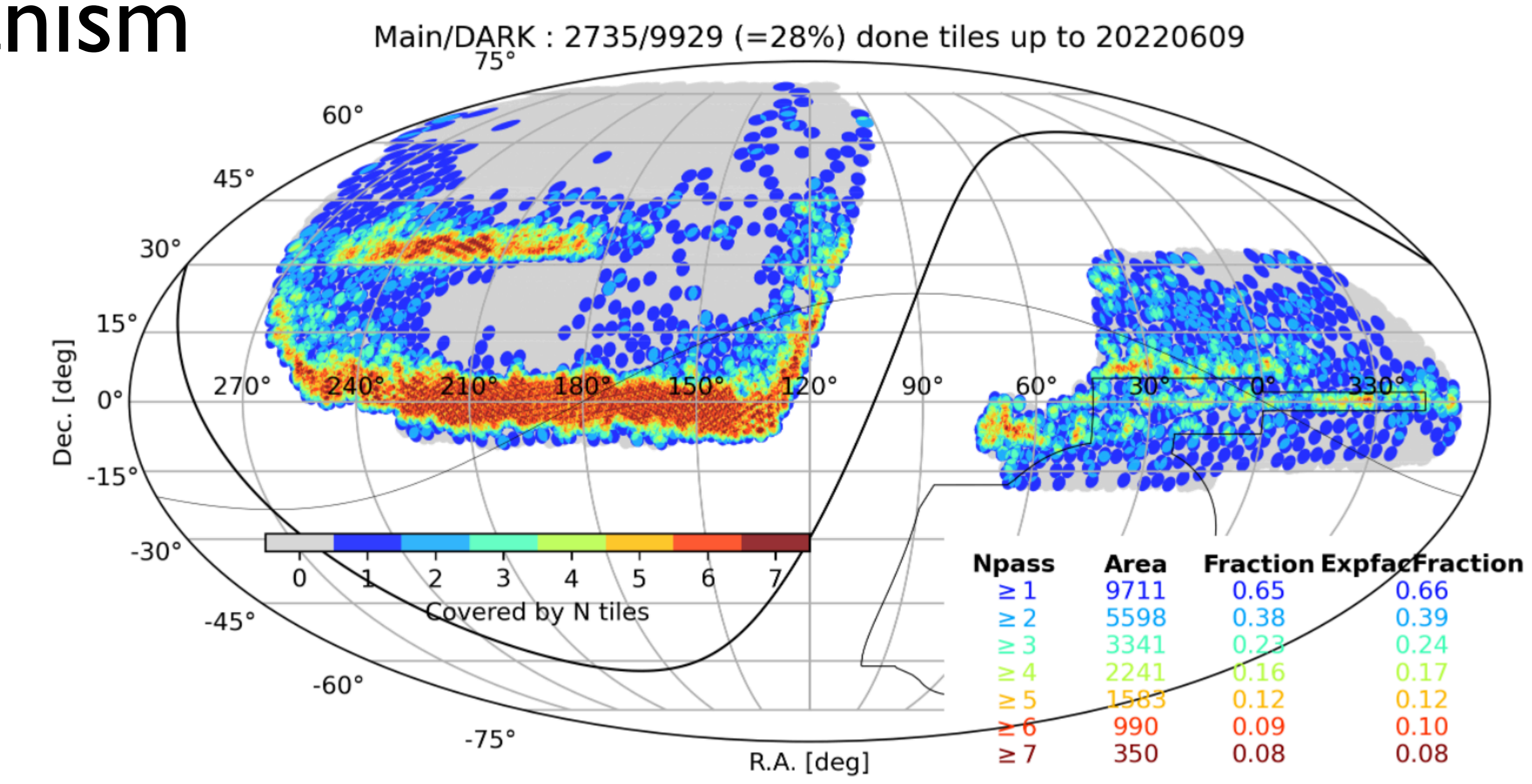
- ➡ Correlation across NGC/SGC
- ➡ Additional data variance
- ➡ Consistency between CMASS and LOWZ
- ➡ …

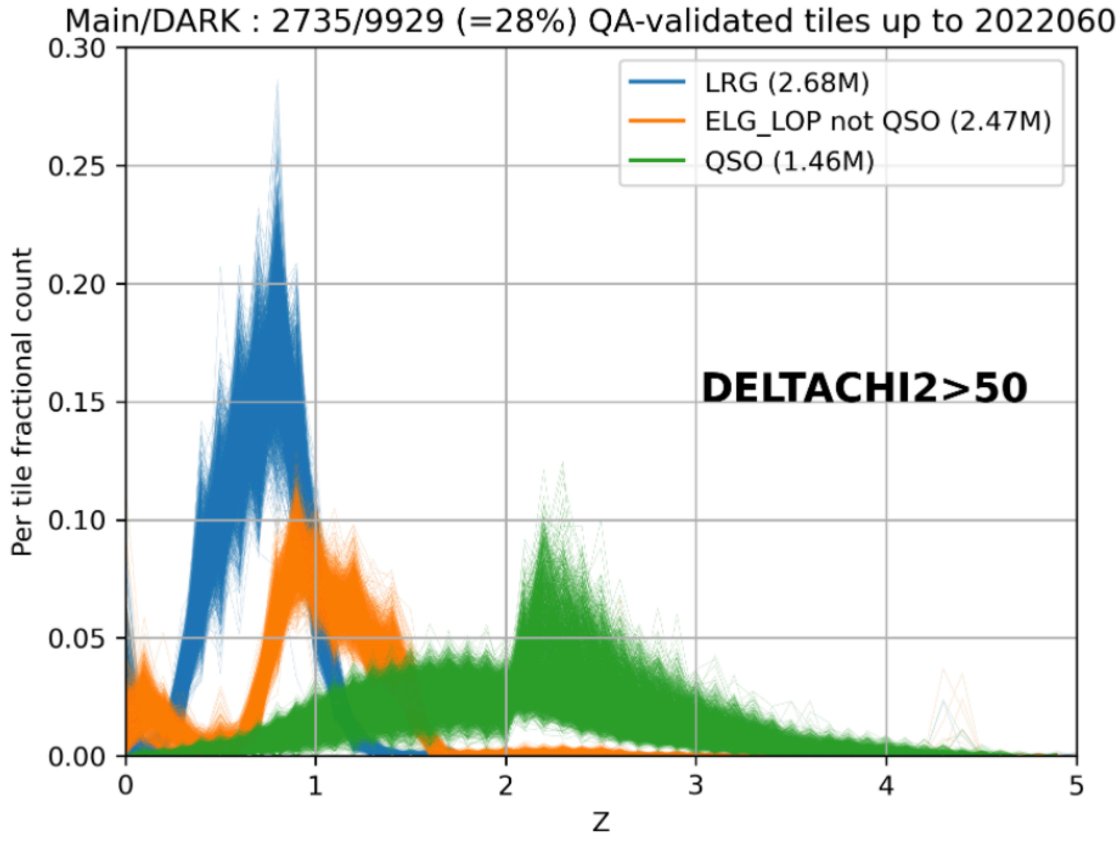
➡ Open an avenue to study P.V. with LSS

Next steps

- Dark Energy Spectroscopic Instrument (DESI)
  - Started 5-year survey on May 17, 2021
  - Collected ~18 M galaxies' spectra (2.7 M LRGs)
- Models for parity-odd signal
- Simulations with parity-violating mechanism
- Residual systematics



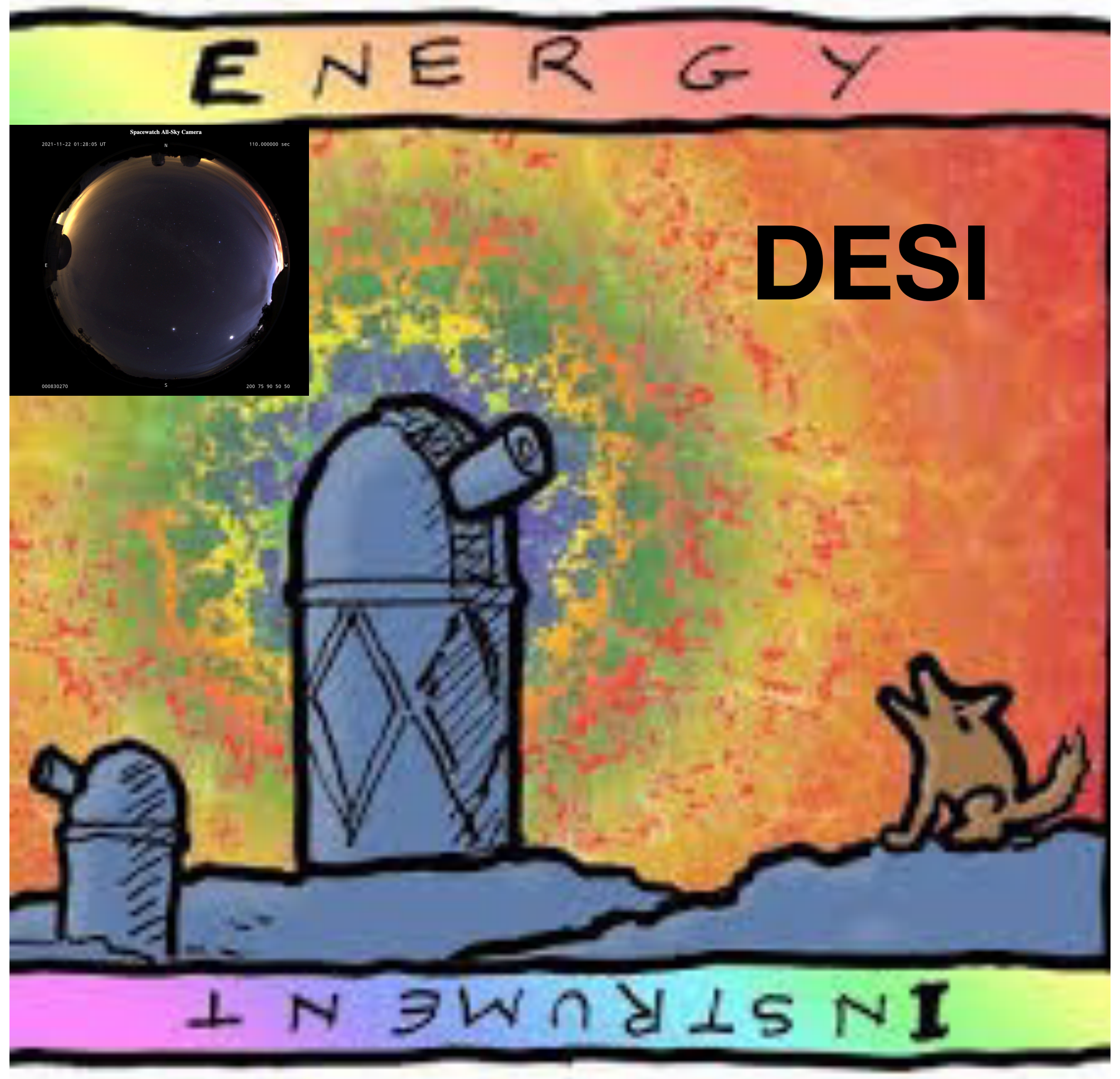




Next-stage Galaxy Surveys

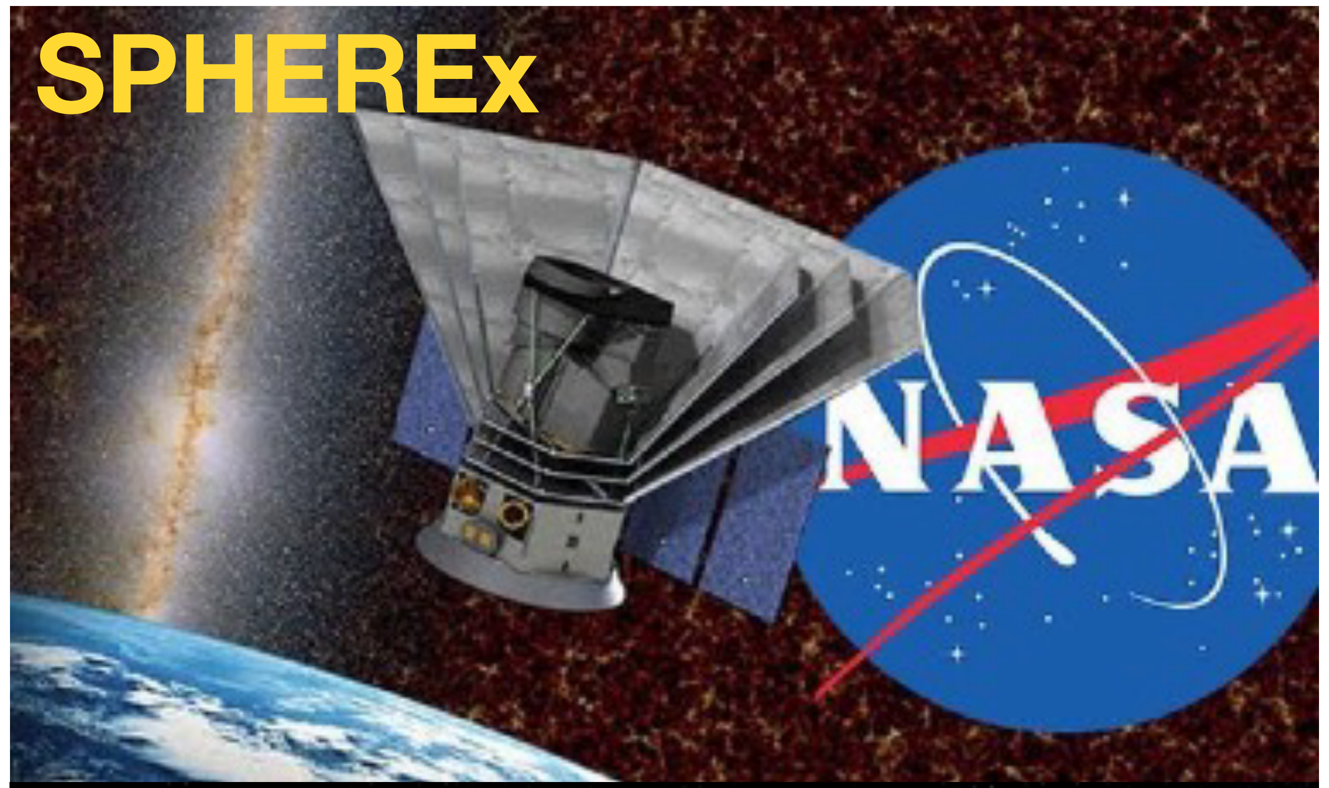
4MOST

DARK ENERGY SURVEY



SuMIRe

Prime
Focus
Spectrograph



Vera Rubin Observatory

LSST

Large Synoptic Survey Telescope

HETDEX

Hobby-Eberly Telescope Dark Energy Experiment