Title: Higher-order Correlation Function of Large-Scale Structures and Parity-Violation Search

Speakers: Jiamin Hou

Series: Cosmology & Gravitation

Date: July 18, 2022 - 12:00 PM

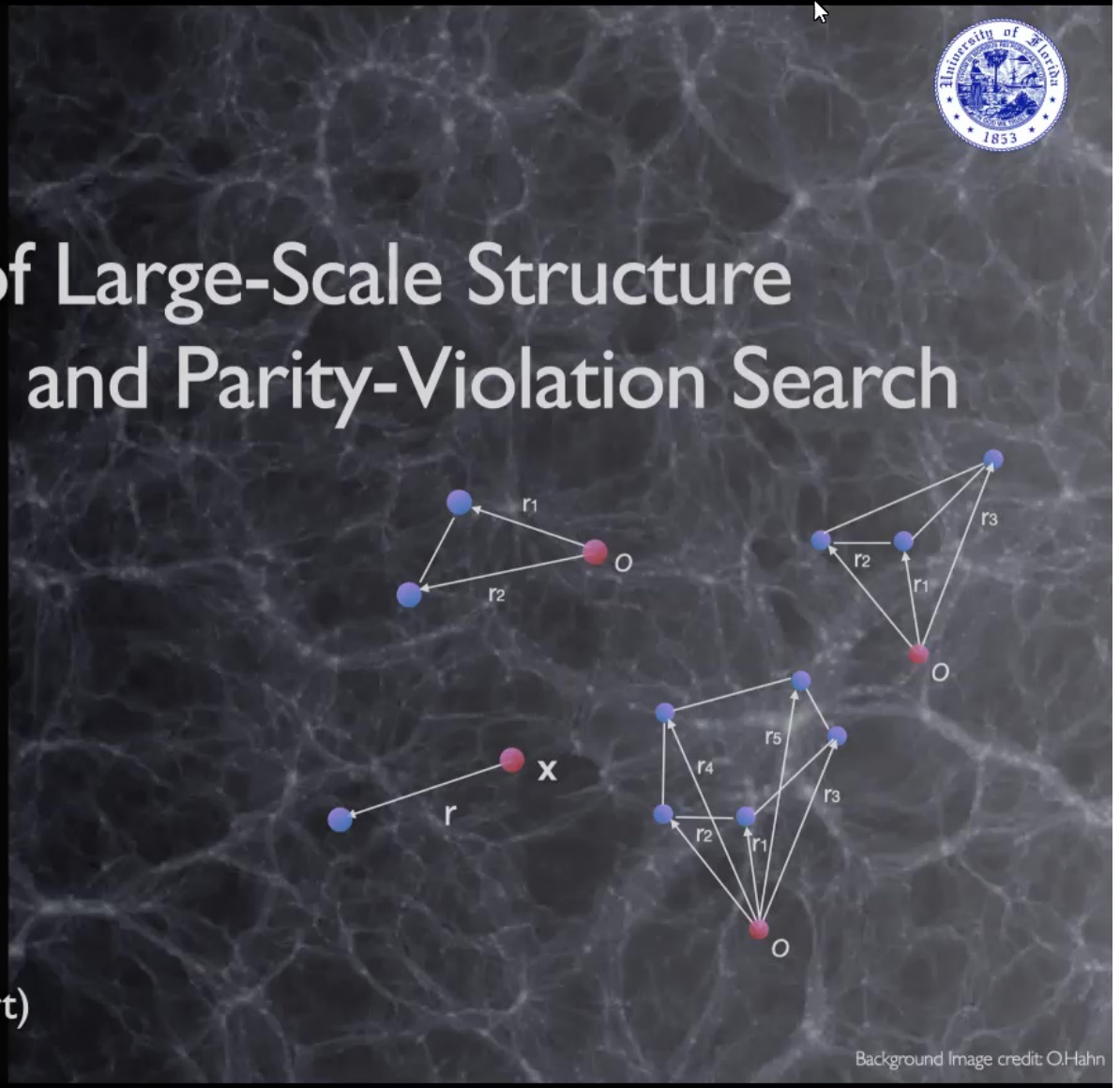
URL: https://pirsa.org/22070026

Abstract: In the standard cosmological paradigm, the initial condition follows Gaussian statistics. At later times, gravitational evolution induces nonlinearities in the large-scale structure, information that was fully captured by the two-point statistics at the early times gets spread into higher-order statistics. Whilst current standard cosmological analyses have focused on two-point statistics, higher-order statistics help further to tighten constraints by breaking parameter degeneracies as well as to probe the primordial Universe. In this talk, I will present our recent progress on the N-point Correlation Function (NPCF), including an analytical Gaussian covariance formalism, a first detection of the 4-point correlation function from nonlinear structure formation. Finally, I will focus on our recent analysis of parity-odd mode using the data from Baryon Oscillation Spectroscopic Survey (BOSS) and discuss the implication of parity-search at cosmological scales with large scale structure.

Zoom Link: https://pitp.zoom.us/j/92321535422?pwd=VlF4cHpvUit4bmR0eXYyczI5Qmw4dz09

Max-Planck-Institut für extraterrestrische Physik

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



Perimeter Institute

July 18 2022

Jiamin Hou

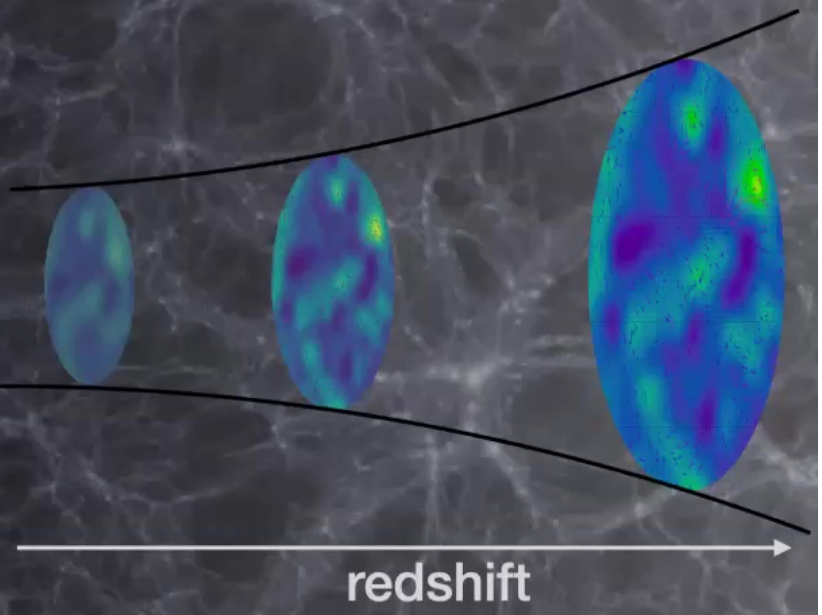
Marie Curie Fellow @UF (with MPE support)

Information in Galaxies' 3D distribution

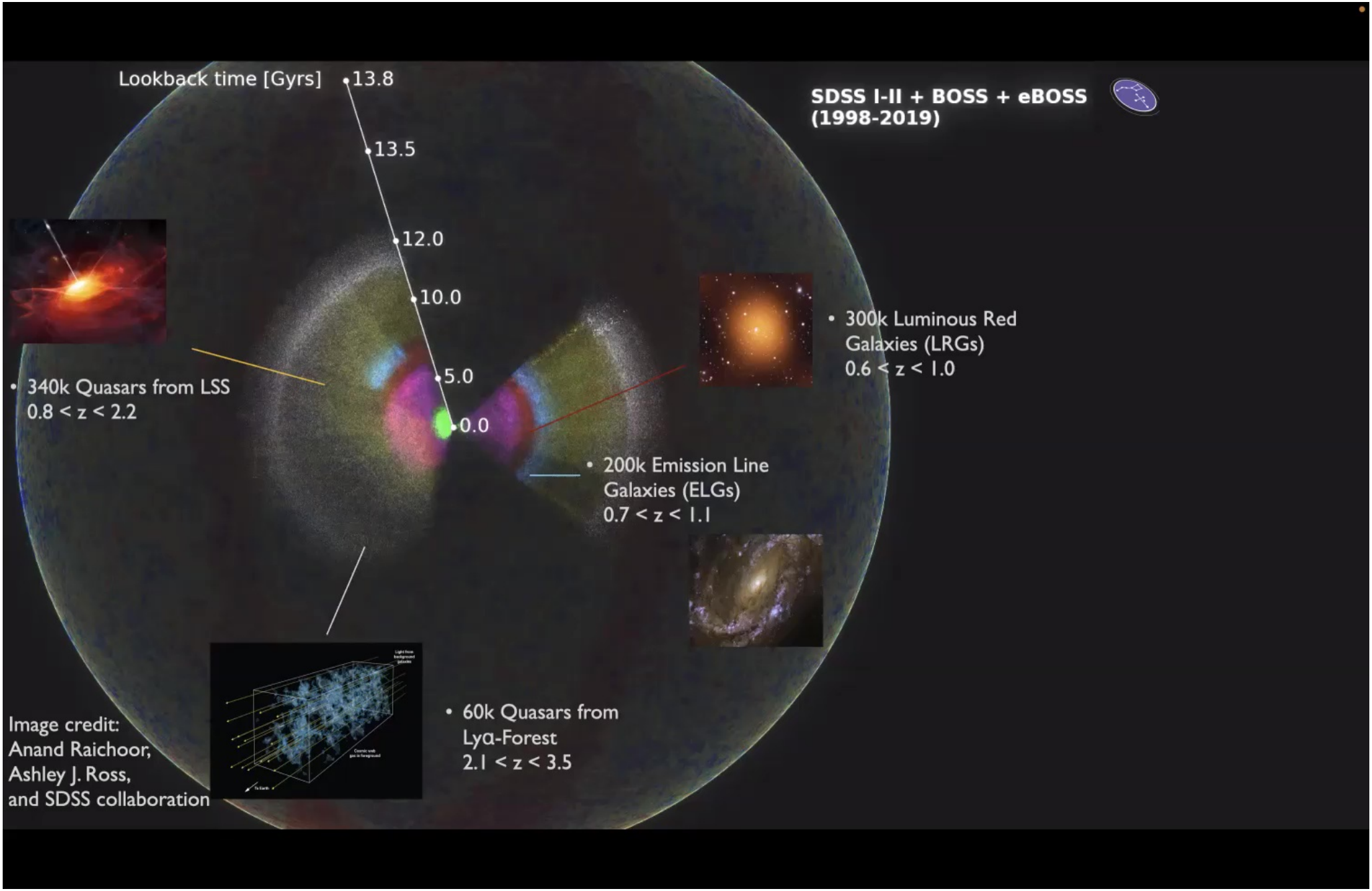
- Map the expansion history
- Probe growth of cosmic structure
- Origin of the Universe

➡ **Standard** cosmological paradigm

- Cosmic inflation
- w = -1
- CDM



Background Image credit: O.Hahn


Lookback time [Gyrs]
13.8
13.5
12.0
10.0
5.0
0.0
SDSS I-II + BOSS + eBOSS
(1998-2019)
• 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
• 60k Quasars from
Lyα-Forest
2.1 < z < 3.5
Image credit:
Anand Raichoor,
Ashley J. Ross,
and SDSS collaboration

Lookback time [Gyrs] 13.8 13.5 12.0 10.0 5.0 0.0

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

- 340k Quasars from LSS
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- 200k Emission Line Galaxies (ELGs)
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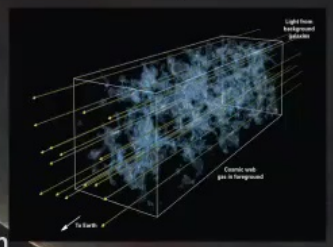
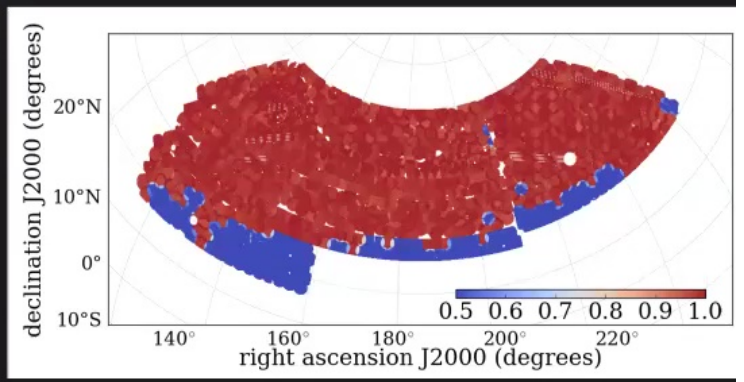


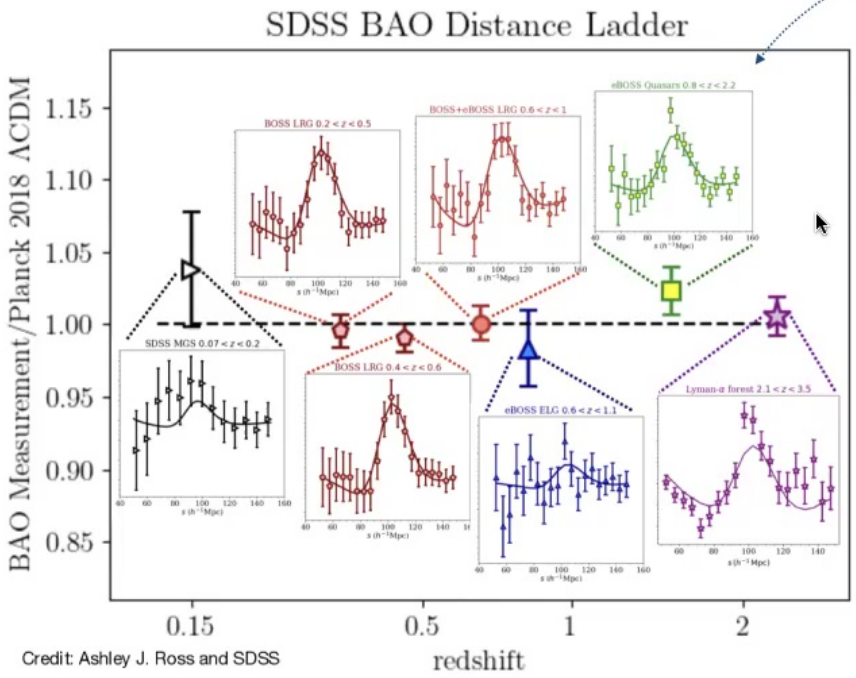
- 60k Quasars from Lyα-Forest
  2.1 < z < 3.5

Image credit:
Anand Raichoor,
Ashley J. Ross,
and SDSS collaboration

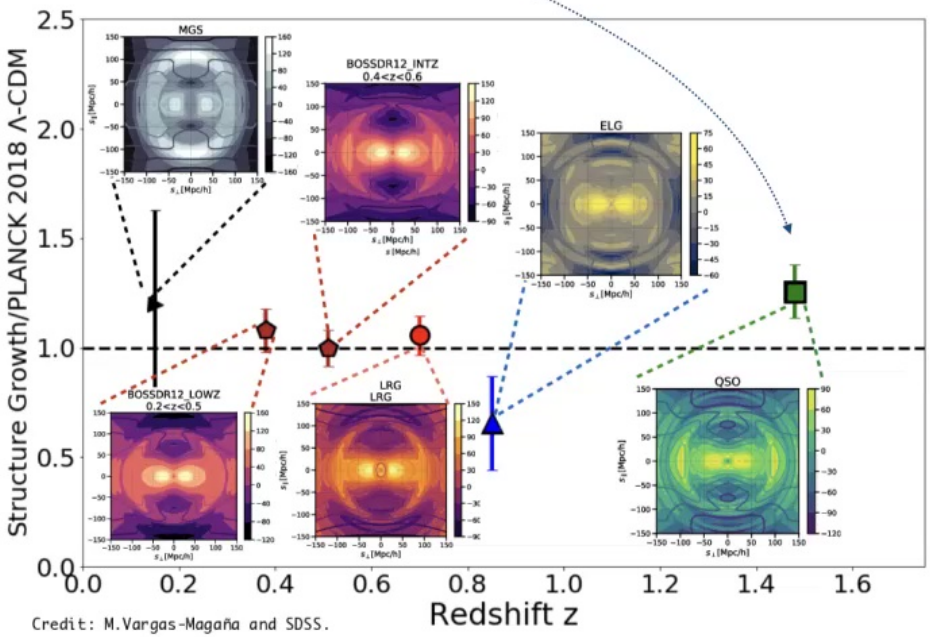
$$\xi(\mathbf{r}) \equiv \langle \delta(\mathbf{x}) \delta(\mathbf{x}+\mathbf{r}) \rangle$$



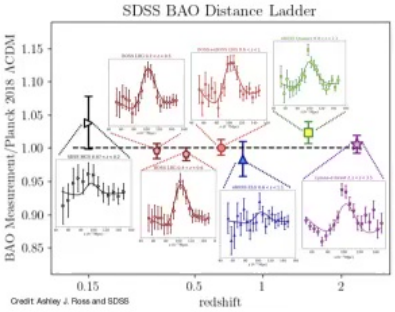
2-point statistics and Developments in the Last Decade

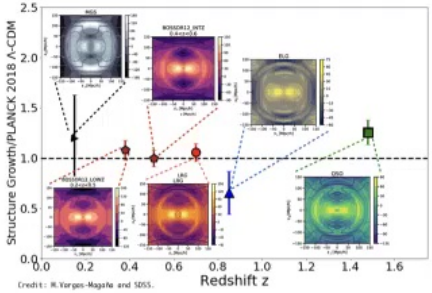


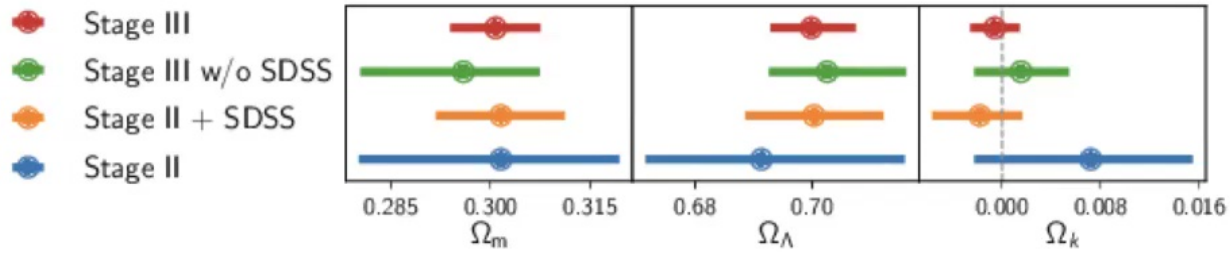
JH ++ 2020,
Neveux ++ 2020



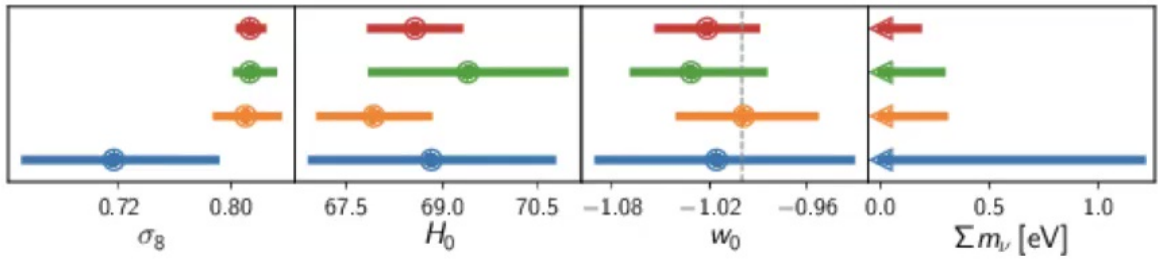
2-point statistics and Developments in the Last Decade





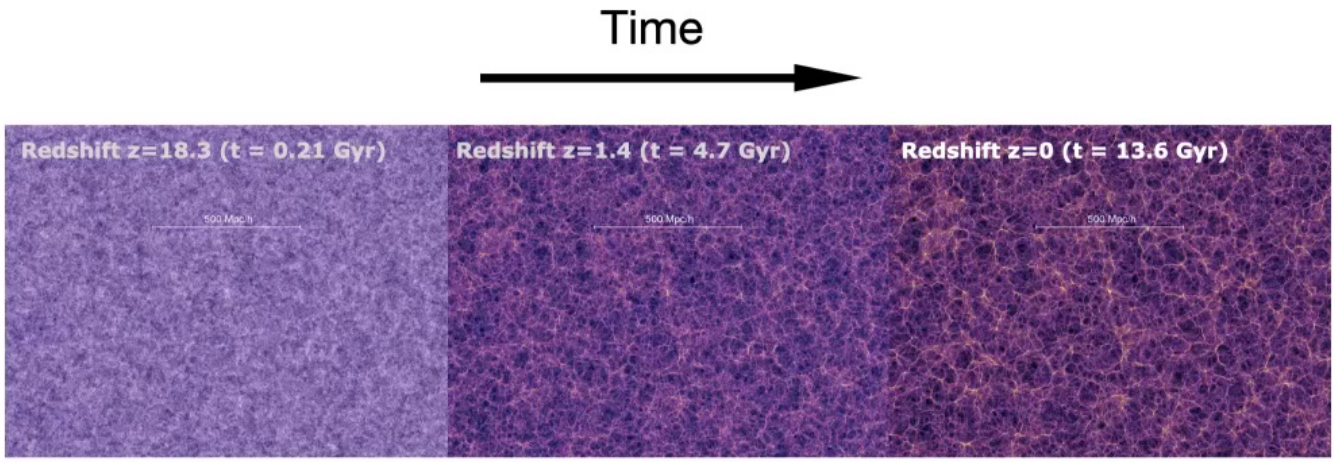


Stage II: WMAP, JLA SN, SDSS DR7 (2010)
Stage III: Planck, Pantheon SNe Ia, DES (2020)



Credit: eBOSS collaboration (2020)

Information in higher-order statistics?



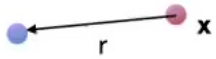
Credit: Millenium Simulation Project

- Gaussian initial conditions

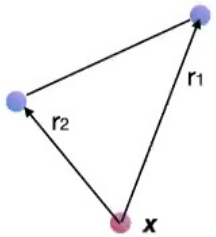
- Nonlinearities are not fully captured by 2-point statistics
- Unique window to different inflationary models
- Break parameter degeneracies

Go beyond 2-point statistics?

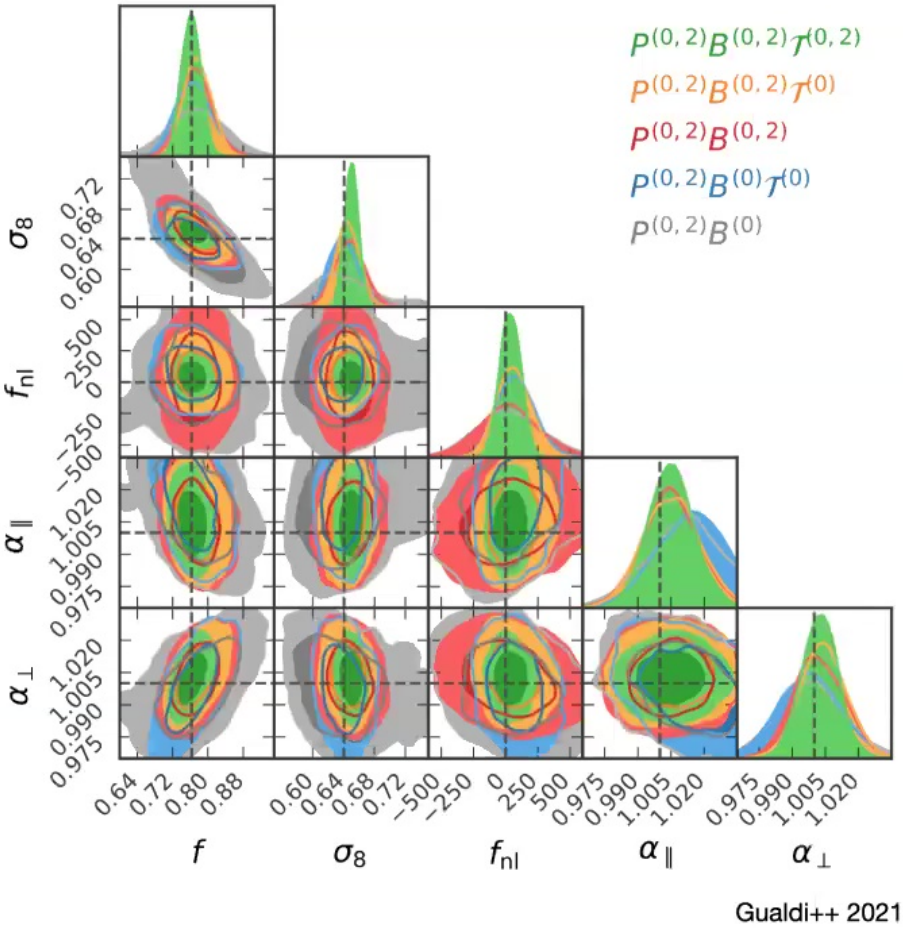
N = 2



N = 3

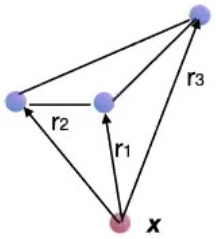


- Tighten constraints on ΛCDM
- Break parameter degeneracies
- Constrain primordial non-Gaussianity

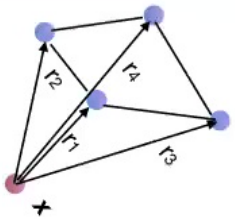


Gualdi++ 2021

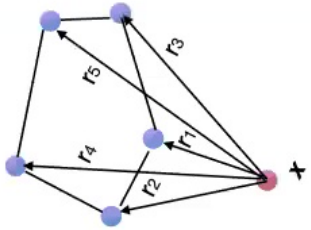
N = 4



N = 5



N = 6



NPCFs in the Isotropic Basis

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

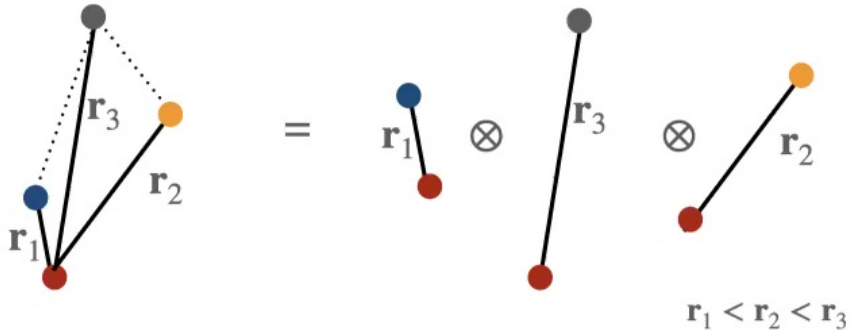
- $\mathcal{P}_\Lambda(\hat{R}) = \sum_M \mathcal{C}_M^\Lambda \prod_i Y_{\ell_i m_i}$
  - $\mathcal{C}_{\mathrm{M}}^{\Lambda} = \mathcal{E}(\Lambda)\sqrt{2\ell_{12}+1} \times \cdots \times \sqrt{2\ell_{12}\ldots N-3}+1$
    $\times \sum_{m_{12}\ldots} (-1)^\kappa \begin{pmatrix} \ell_1 & \ell_2 & \ell_{12}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

- 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)

https://github.com/oliverphilcox/encore

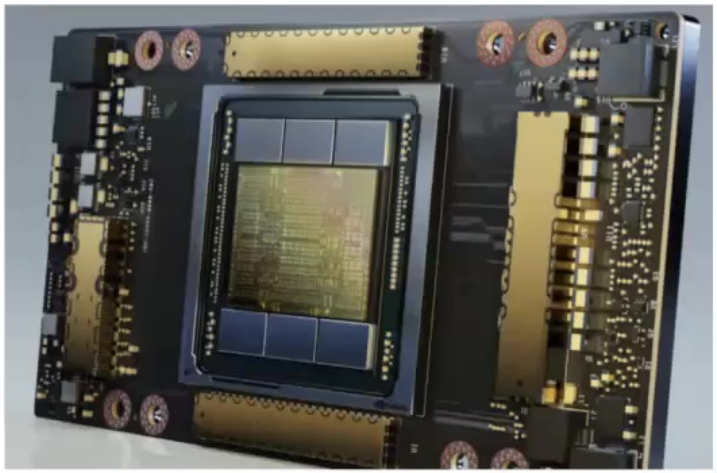


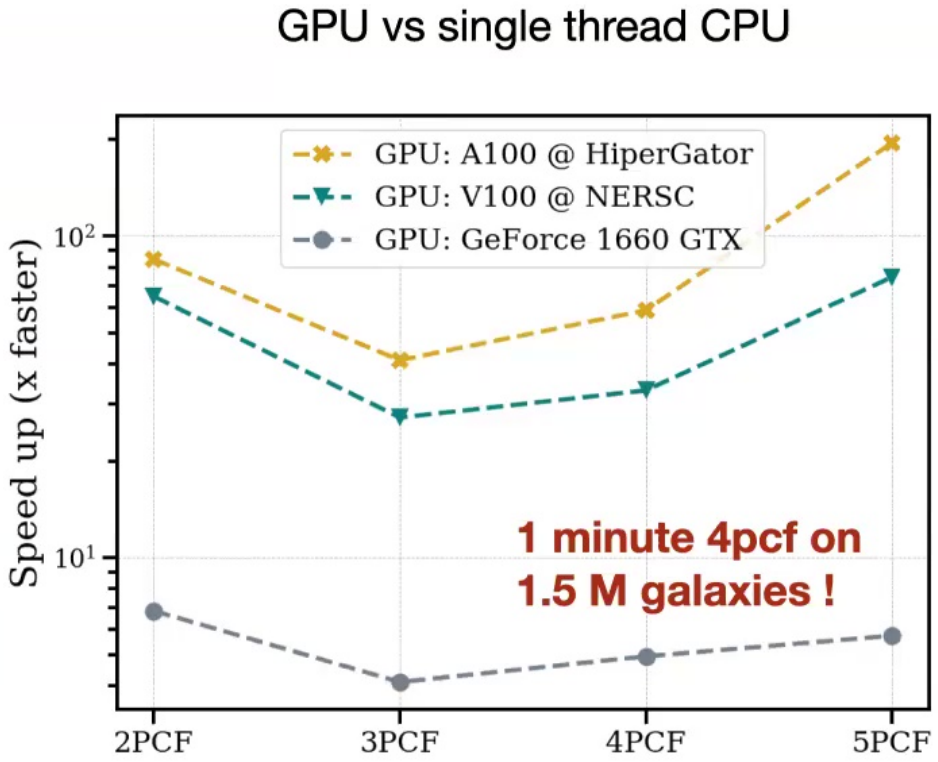
- Algorithm based on Slepian & Eisenstein 2015
- Survey geometry induces angular momentum coupling
  - Edge correction is included
- "Connected-only" estimator

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

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

GPU for N-point Correlator Estimation (Cadenza)

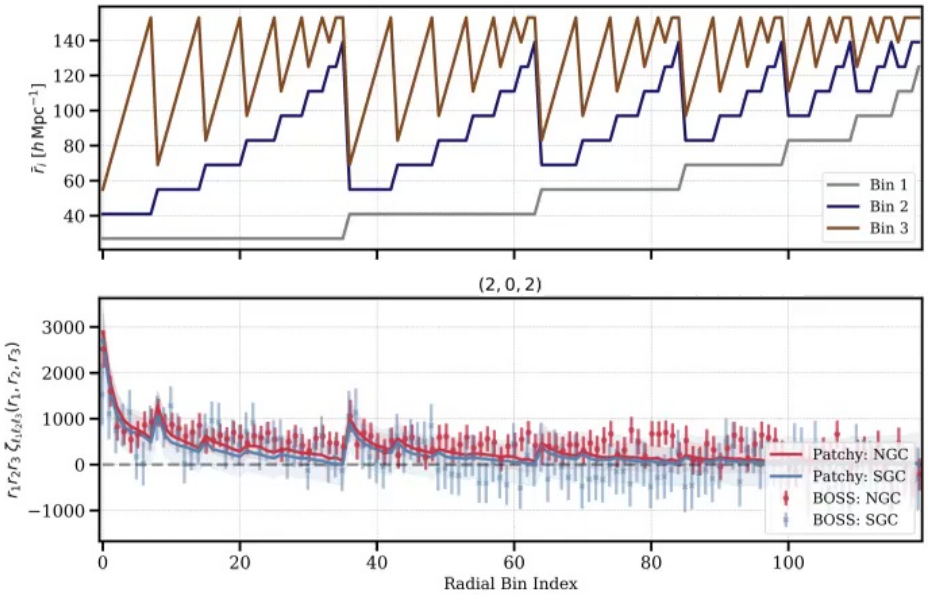


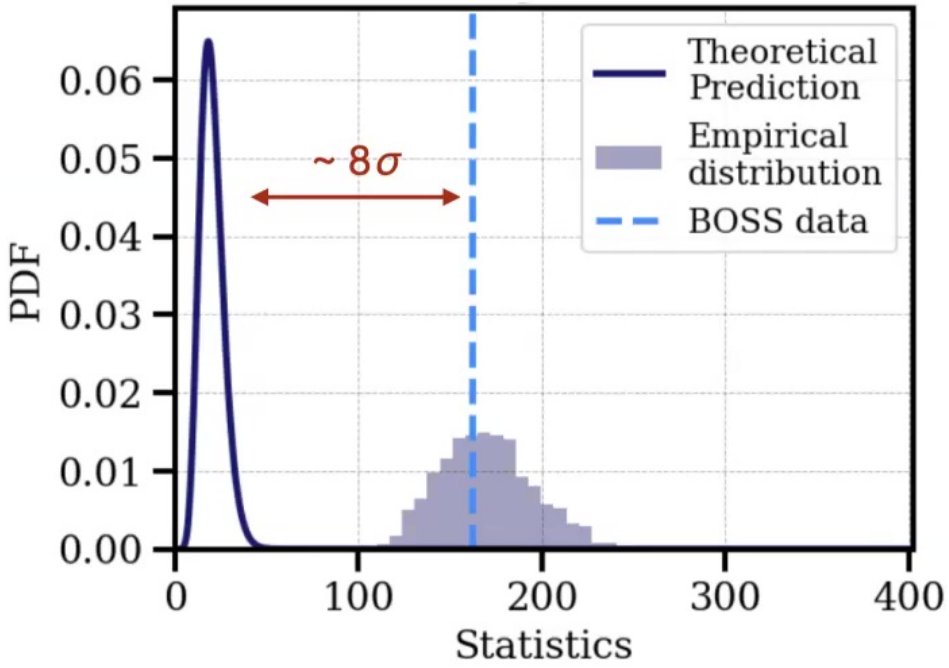


CADENZA: Slepian, Warner, Hou, Cahn in prep.

First Detection of Gravitationally-induced non-Gaussianity with BOSS CMASS

4PCF from BOSS CMASS



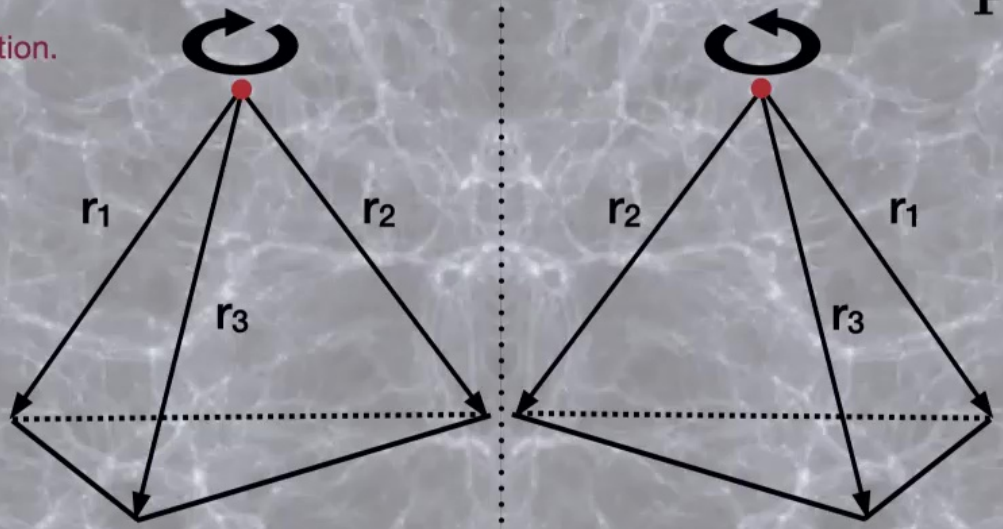


O. Philcox, JH, Z. Slepian, arXiv: 2108.01670

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.

An "imagined" mirror



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

$$r_1 < r_2 < r_3$$

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

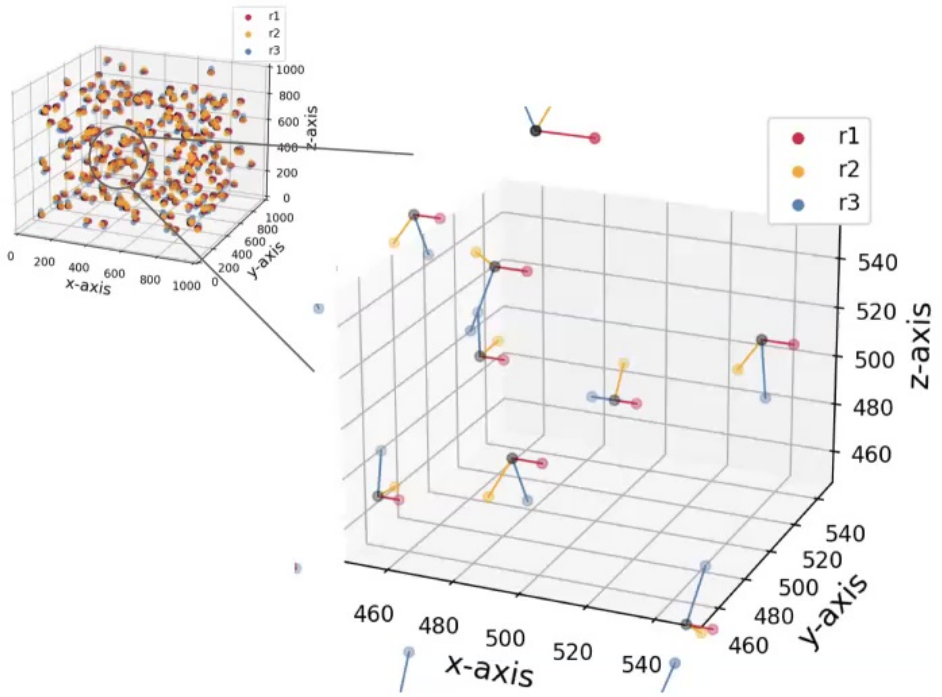
Background Image credit: © Hahn

Cahn, Slepian, **JH** 2021

Parity Violation at 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

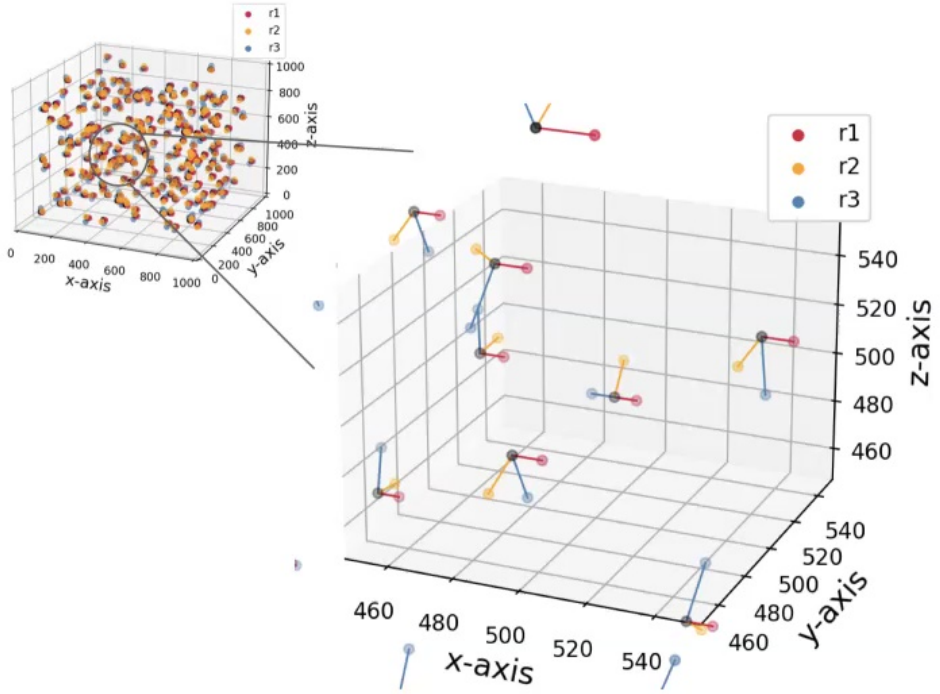


$$\mathcal{P}_{111}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2,\hat{\mathbf{r}}_3) = -i\frac{3}{\sqrt{2}}(4\pi)^{-3/2}\,\hat{\mathbf{r}}_1\cdot(\hat{\mathbf{r}}_2\times\hat{\mathbf{r}}_3)\,,$$

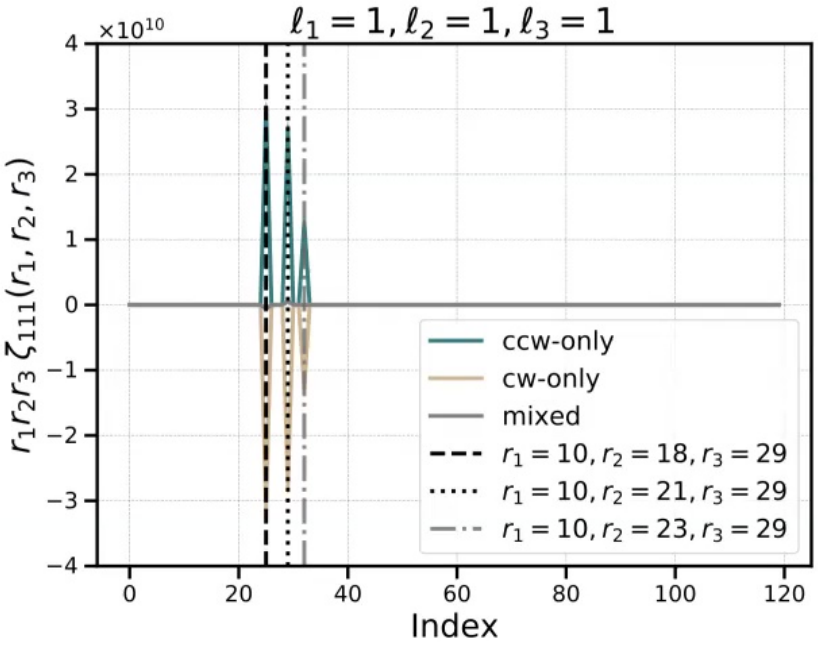
$$\mathcal{P}_{122}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2,\hat{\mathbf{r}}_3) = i\sqrt{\frac{45}{2}}(4\pi)^{-3/2}\,\hat{\mathbf{r}}_1\cdot(\hat{\mathbf{r}}_2\times\hat{\mathbf{r}}_3)\,(\hat{\mathbf{r}}_2\cdot\hat{\mathbf{r}}_3)\,,$$

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

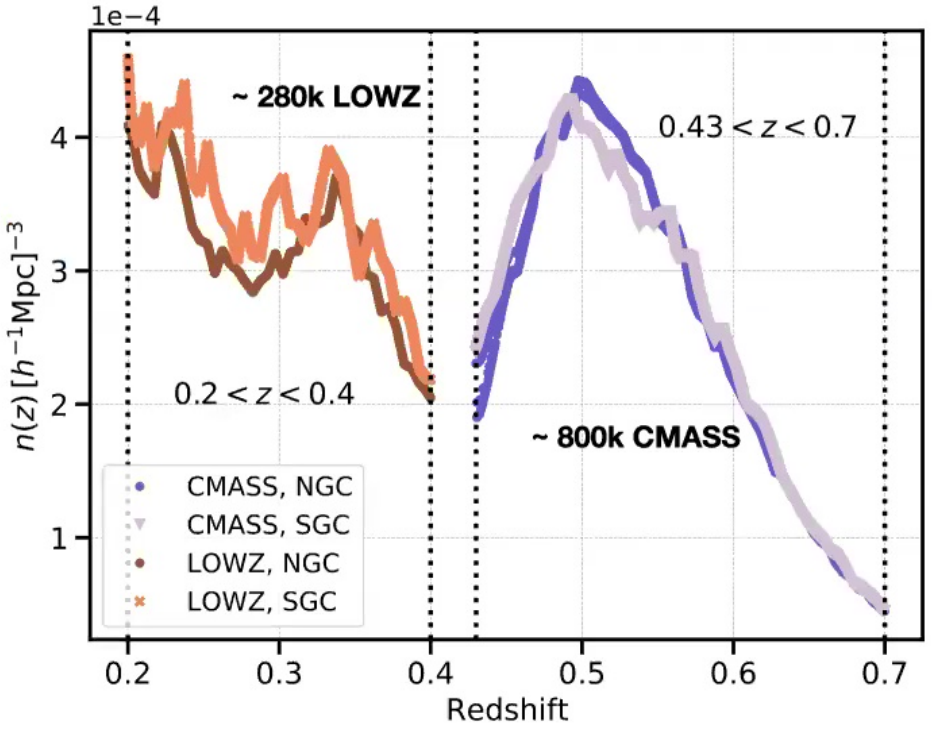
A Toy Simulation for the Parity-Odd 4PCF



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



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



JH, Slepian, Cahn (arXiv: 2206.03625)

Statistical Background Estimation

Model-independent search, null hypothesis

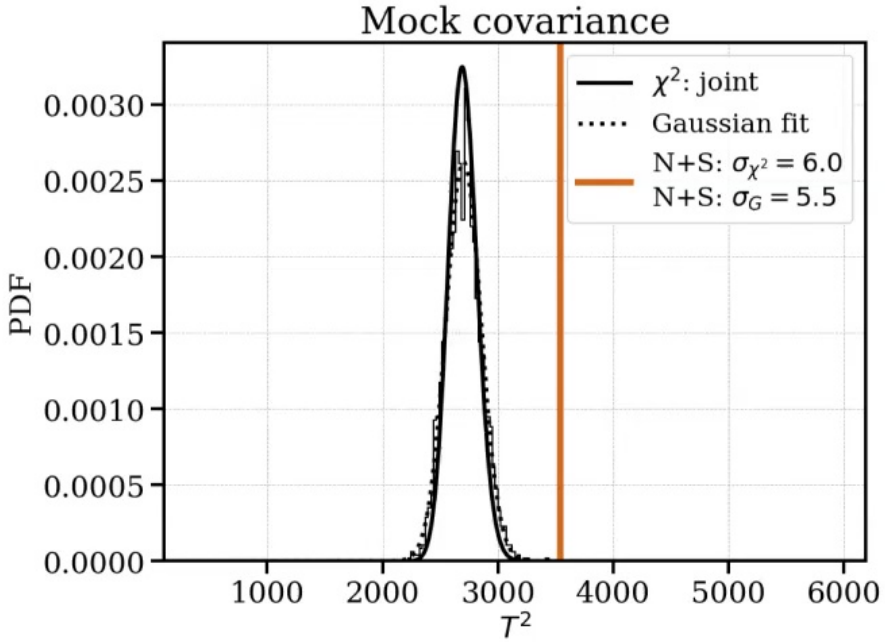
- Challenge: high dimensionality for 4PCF
  — NO sampling covariance from mocks

- Gaussian analytic covariance
- Compressed data vector[1]
- Direct: restrict angular momentum and/or radial bin to reach reduced d.o.f.

[1] Scoccimarro 1999

Detection Significance and Statistical Convergence test

Reduced data vector in radial binning

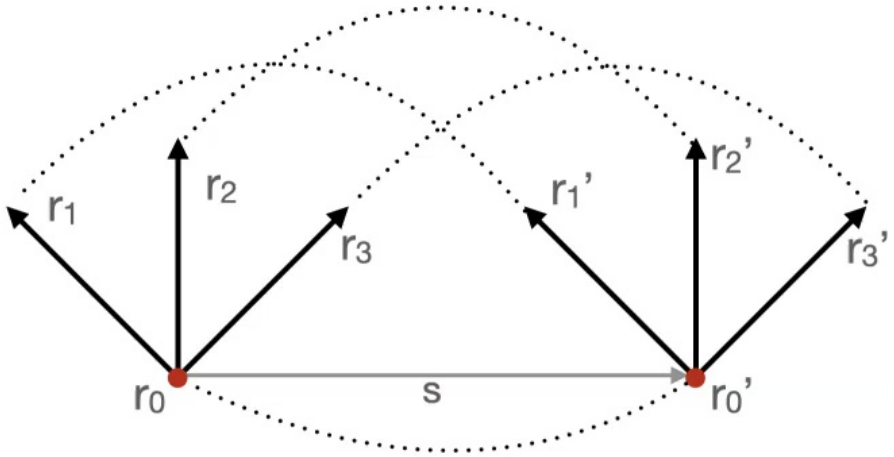


JH+2022

CMASS, 18 bins, $(\Delta r_{\rm min}, r_{\rm max}) = (15, 90)\left[h^{-1}{\rm Mpc}\right], \ell_{\rm max} = 4$

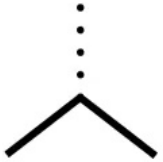
Analytic NPCF covariance in the Gaussian limit

Couple density fields from two tetrahedra, one for each



$$\langle \delta(\mathbf{x}+\mathbf{r}_i)\delta(\mathbf{x}+\mathbf{s}+\mathbf{r}'_j)\rangle \equiv \xi(|\mathbf{r}'_j+\mathbf{s}-\mathbf{r}_i|)$$

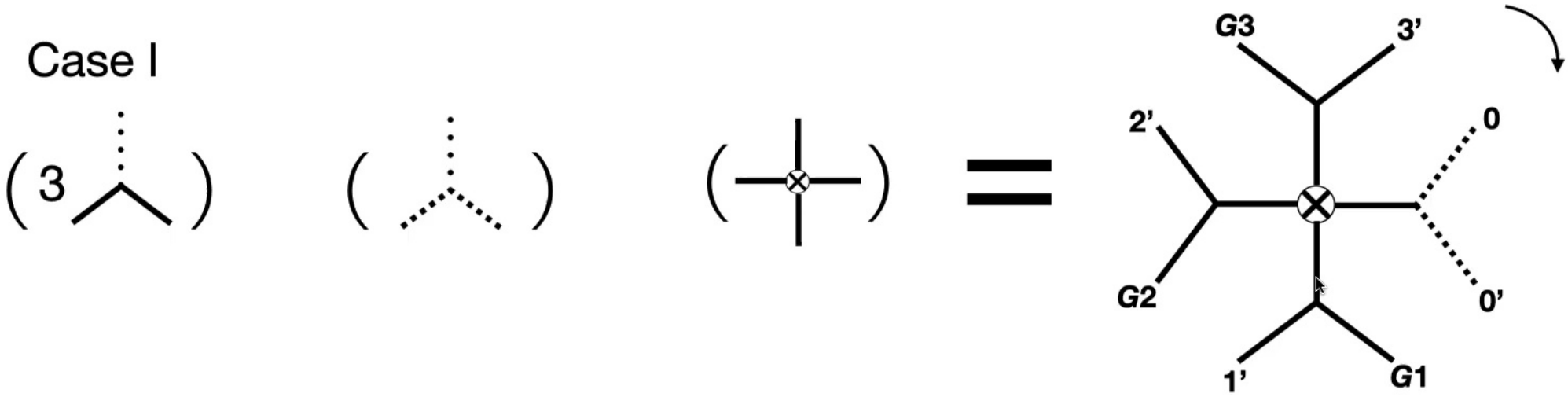
$$\longrightarrow \quad (4\pi)^{3/2}\sum_{\ell_i\ell'_jL} i^{\ell_i-\ell'_j-L} f_{\ell_i\ell'_jL}(r,r',s)\,\mathcal{D}^{\mathrm{P}}_{\ell_i\ell'_jL}\mathcal{C}^{\ell_i\ell'_jL}_{000}$$



- "Real space" covariance — Ignore higher multipole coupling

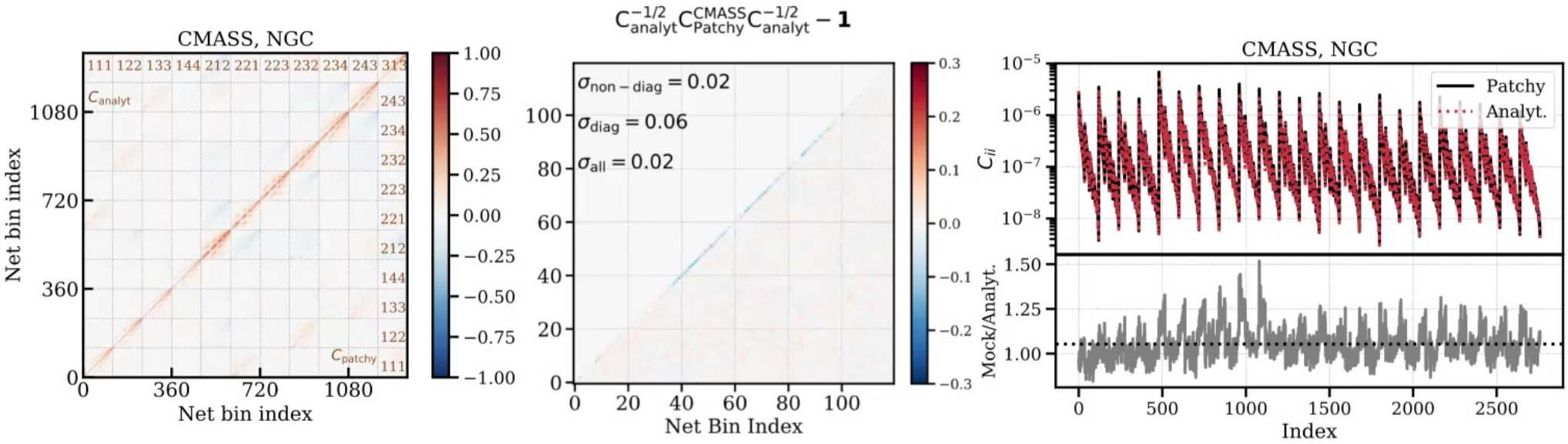
Analytic 4PCF covariance in the isotropic basis

Case I



Comparison to simulations

- Gaussianity
- "Isotropy"
- Uniform window

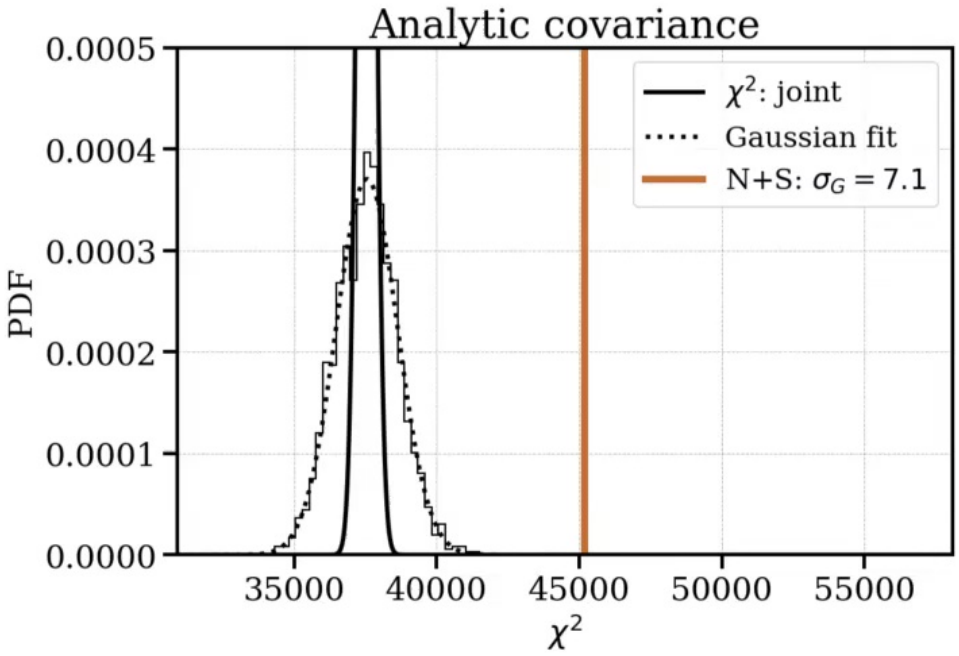


- Include higher order statistics,
  i.e. <332>, <44> types;
- Include window function
- "Anisotropy"
- Extended formalism for N > 4

JH, R.Cahn, O. Philcox, Z.Slepian 2022 PRD

Detection Significance and Statistical Convergence test

Full data vector



- Vary radial bin interval:
  - dr = {8, 14, 24} [Mpc/h]
  - Detection significance drops as interval increases
  - Conjecture:
    - internal cancellation

JH+2022

CMASS, 18 bins, $(\Delta r_{\rm min}, r_{\rm max}) = (0, 160)\left[h^{-1}{\rm Mpc}\right], \ell_{\rm max} = 4$

Impact of Systematics on Parity-odd Modes

- Survey-related effects
- Observer-induced effects
- Algorithm-related effects

Impact of Systematics on Parity-odd Modes

- Survey-related effects
  - redshift failure …

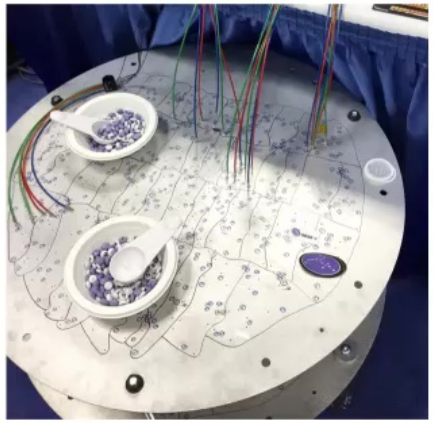


Photo taken at AAS 2020, Honolulu

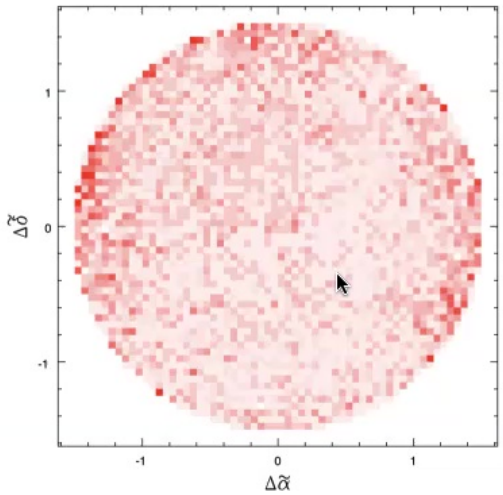
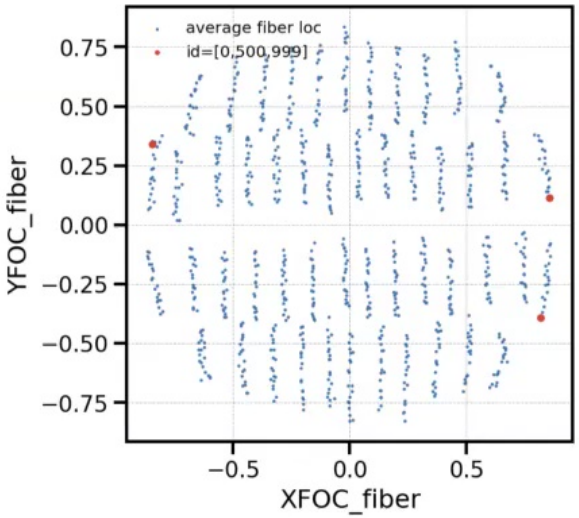


Image credit: Ross+ 2012



Impact of Systematics on Parity-odd Modes

- Observer-induced effects
  - Tidal alignment

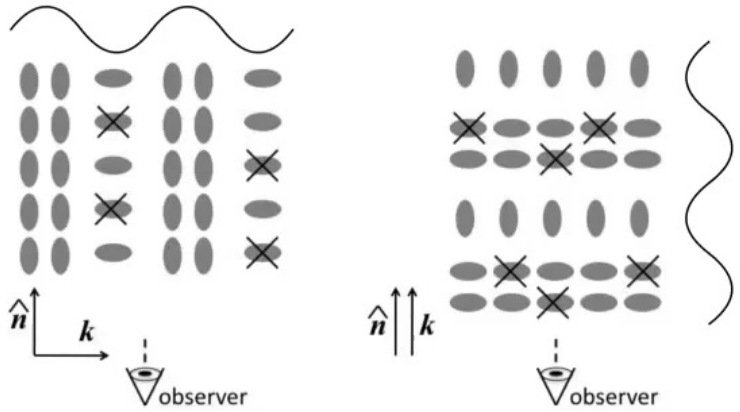


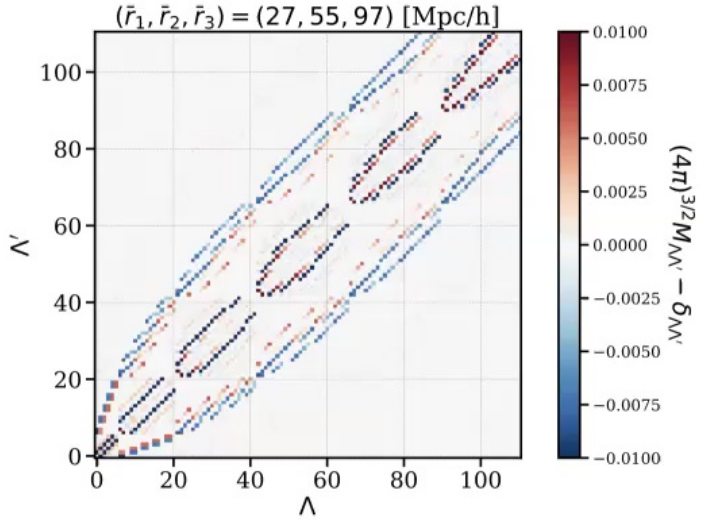
Image credit: Hirata 2009

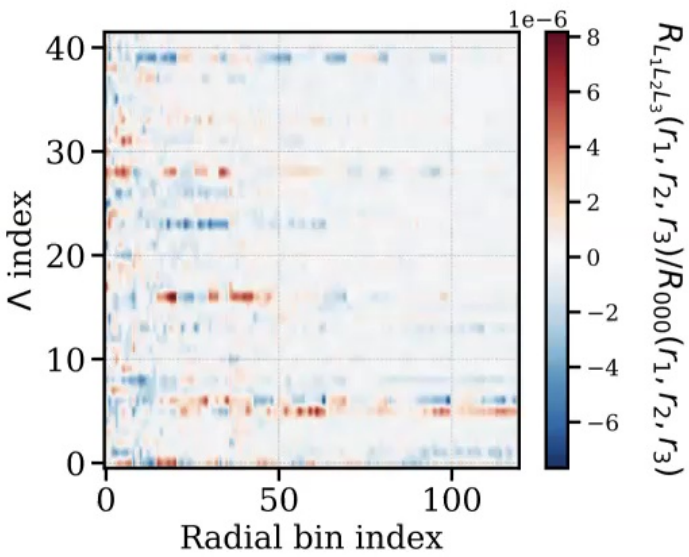
$$\delta_{\rm g}^{\rm obs} + 1 = \left(\delta_{\rm g}^{\rm true} + 1\right)\left(1 + \epsilon(\hat{\mathbf{n}} \mid \mathbf{x})\right)$$

$$\epsilon(\hat{\mathbf{n}} \mid \mathbf{k}) = A\left[(\hat{\mathbf{n}} \cdot \hat{\mathbf{k}})^2 - \frac{1}{3}\right]\delta_{\rm m}(\mathbf{k}) \qquad \textbf{Parity-even}$$

Impact of Systematics on Parity-odd Modes

- Algorithm-related effects
  - edge-correction



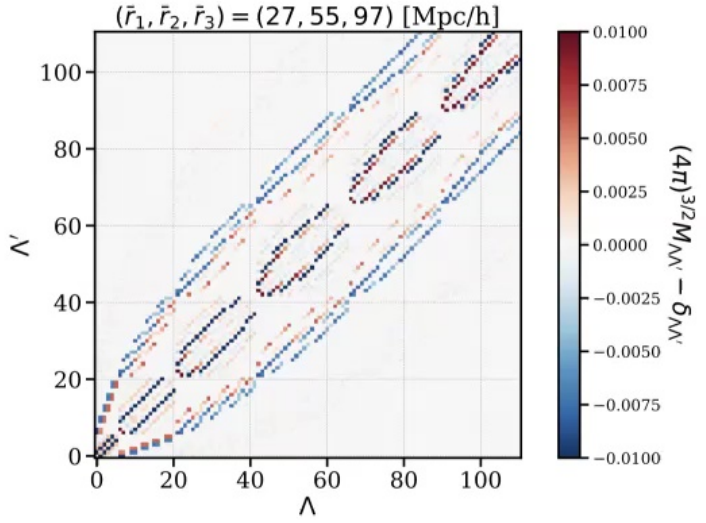


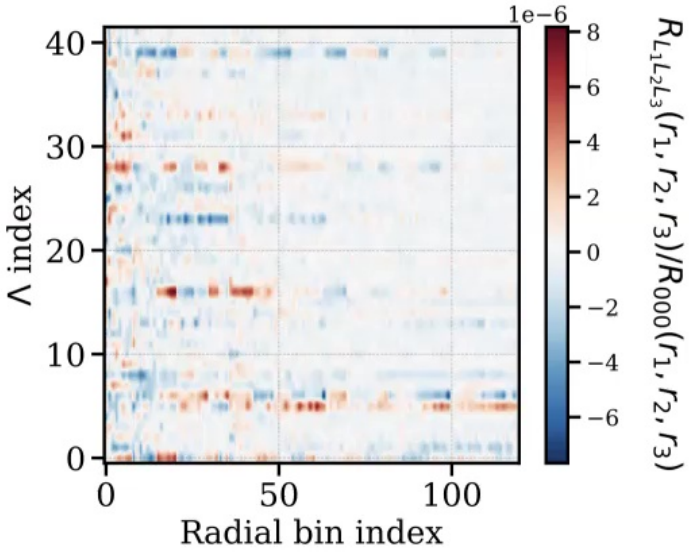
$$\hat{\zeta}_\Lambda \sim \sum_{\Lambda'} \mathbf{M}^{-1}_{\Lambda\Lambda'} (D - R)^4_{\Lambda'}.$$

$$\mathbf{M}_{\Lambda\Lambda'} \sim (-1)^{\ell_1' + \ell_2' + \ell_3'} \sum_{L_1 L_2 L_3} \frac{\mathcal{R}_{L_1 L_2 L_3}}{\mathcal{R}_{000}} \prod_{i=1}^{3} D^{\mathrm{P}}_{\ell_i L_i \ell_i'} \mathcal{C}^{\ell_i L_i \ell_i'}_{000} \begin{Bmatrix} \ell_1 & L_1 & \ell_1' \\ \ell_2 & L_2 & \ell_2' \\ \ell_3 & L_3 & \ell_3' \end{Bmatrix}$$

Impact of Systematics on Parity-odd Modes

- Algorithm-related effects
  - edge-correction





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Impact of Systematics on Parity-odd Modes

- fiber collision
- veto mask
- selection function

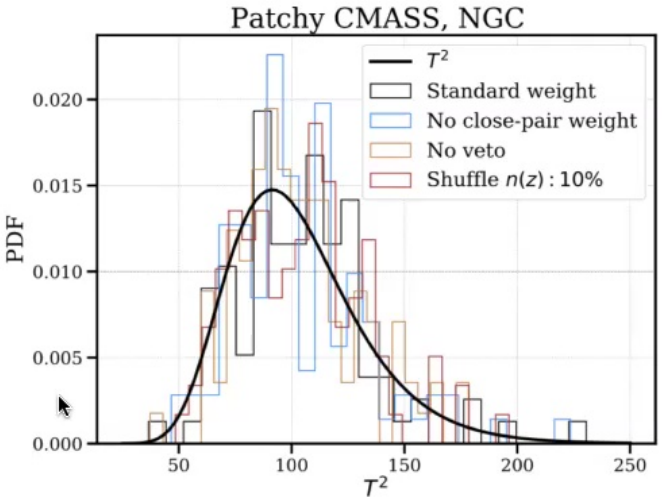
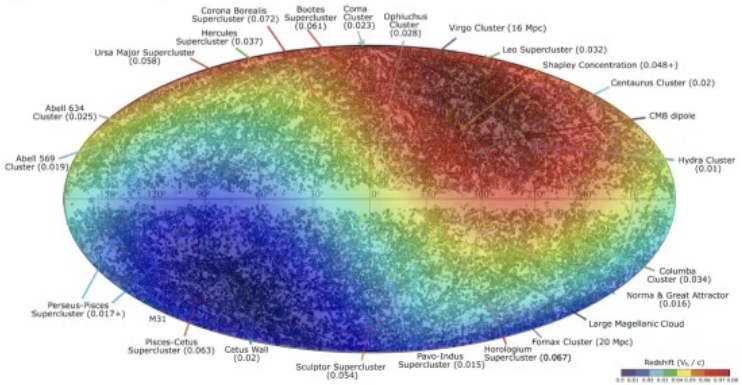
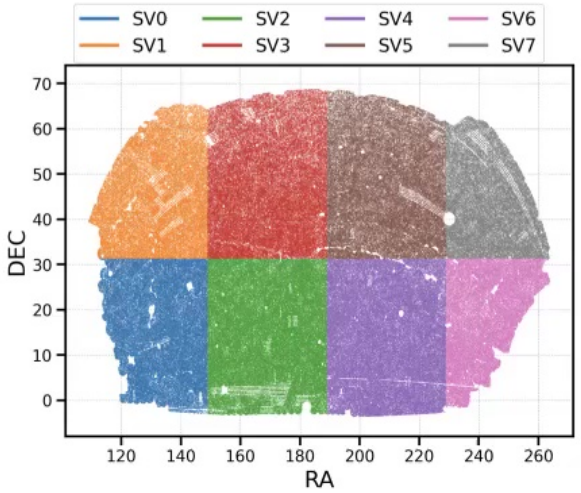


Image credit: reproduced from Huchra et al. 2012



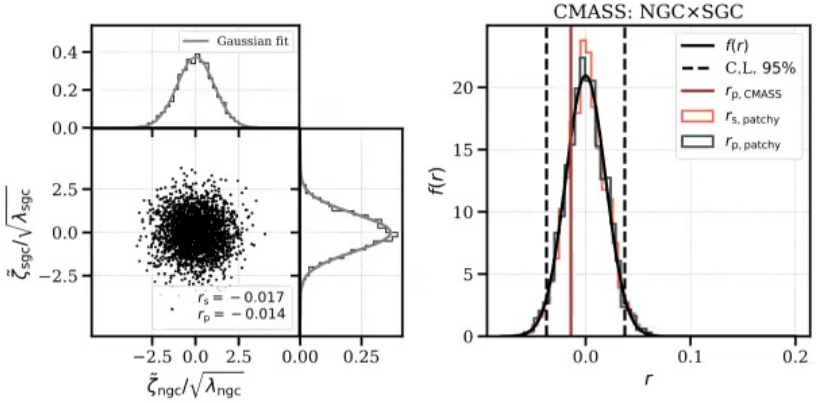
- Split sky test



- Kaiser-rocket effect

A non-exhaustive list for Potential Questions

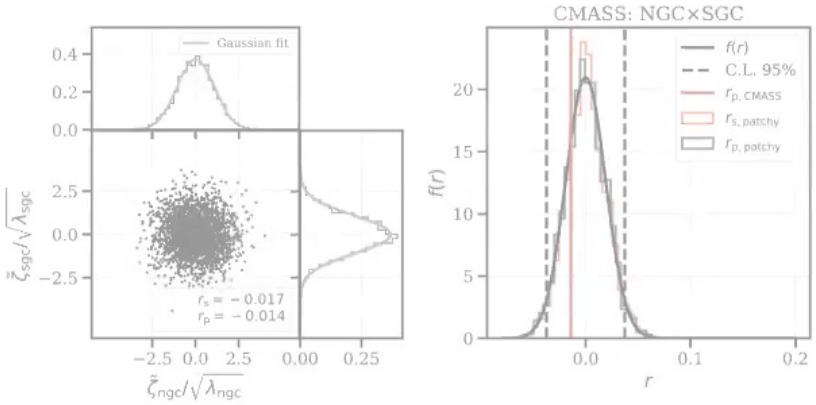
Correlation across the Sky?



- Low signal-to-noise ratio
- Toy model: possible to have statistically significant detection but low correlation.

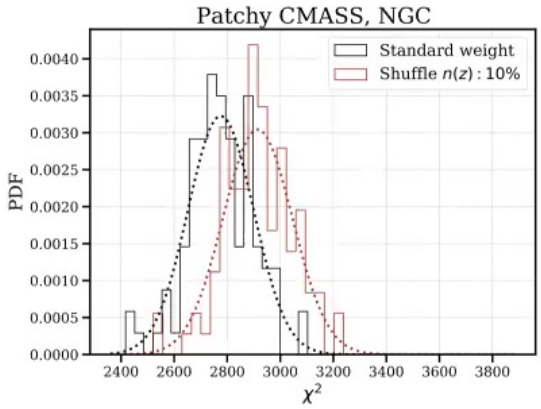
A non-exhaustive list for Potential Questions

Correlation across the Sky?



Consistency in Even-Parity Sector	CMASS 18 bins	Rescaling Factor	Rescaled Odd Detection Significance
1 standard deviation	Analytic Covariance	0.88	2.0σ
	$N_{\rm eig} = 800$	0.98	4.0σ
3 standard deviation	Analytic Covariance	0.94	4.6σ
	$N_{\rm eig} = 800$	-	4.4σ

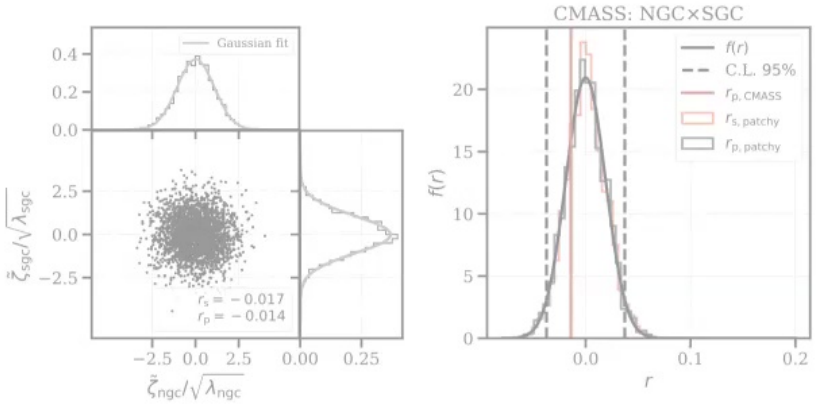
Systematics-induced variance?



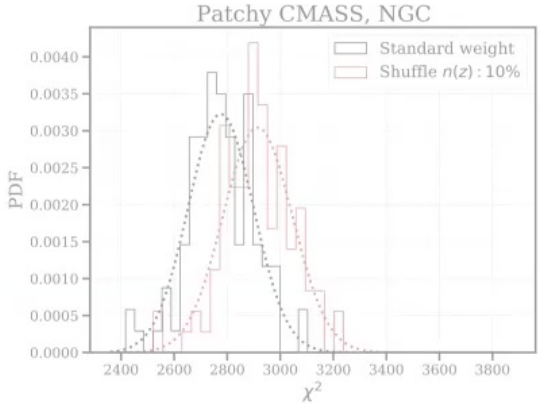
- Under-estimate covariance
- Self calibration with parity-even mode

A non-exhaustive list for Potential Questions

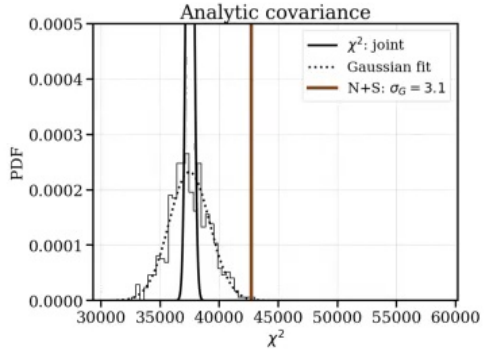
Correlation across the Sky?



Systematics-induced variance?



Consistency with LOWZ?



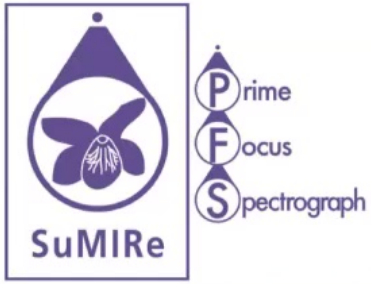
- Smaller volume?
- Different galaxy properties than CMASS (population, n(z) …)?

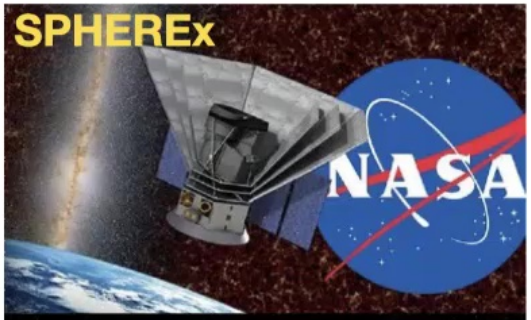
Summary

- NPCF algorithm
- First detection of connected 4PCF
- Analytical covariance matrix in the Gaussian limit
- 4PCF of LSS as a test for parity violation

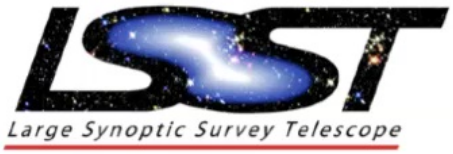
➡ Statistically significant detection
  ➡ If true: likely non-Gaussian initial condition
  ➡ To be validated on future datasets
  ➡ Open an avenue to study parity violation with LSS

Next-stage Galaxy Surveys





Vera Rubin Observatory



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