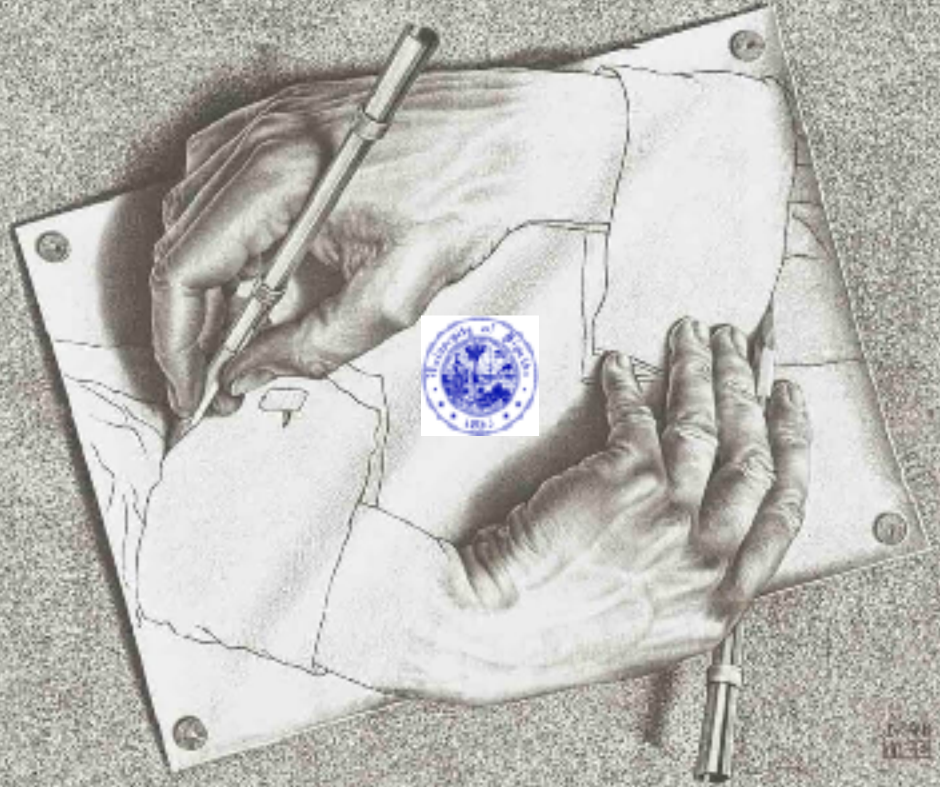
Parity Violation and the Galaxy 4-Point Correlation Function



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UF, WCA, PI

Outline

1. How: in principle
2. How: in practice
3. DESI 2, 3PCF
4. Even 4PCF
5. The Odd

How can we search for P violation in the early Universe?

Let's start with us

Imagine tracing your hands . . .

A 2D tracing can be rotated (in 3D) into its mirror image

But you can tell left from right!

Use this Idea for Parity Search

Need a 3D statistic

2PCF—no

3PCF—no

4PCF—YES!

Galaxy 4-Point Correlation Function

lowest-order 3D statistic—

excess of tetrahedra over spatially random distribution

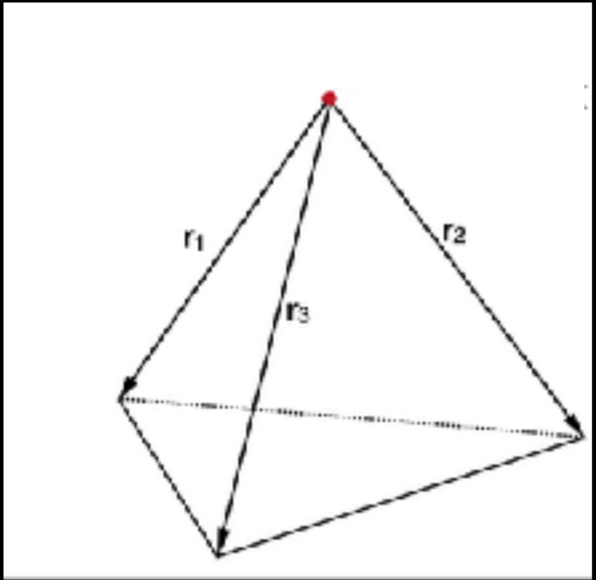
Rotation and translation invariant—isotropy and homogeneity

Cahn Slepian Hou 2021, PRL (2022)

What's the right math to describe tetrahedra (the 4PCF)?

Use the Isotropic Basis!

$$\text{4PCF} = \sum_{\ell_i} \boxed{\zeta_{\ell_1\ell_2\ell_3}(r_1, r_2, r_3)} \underline{\mathcal{P}_{\ell_1\ell_2\ell_3}(\hat{r}_1, \hat{r}_2, \hat{r}_3)}$$



Radial coefficient (red box) times
angular basis function (yellow underline)

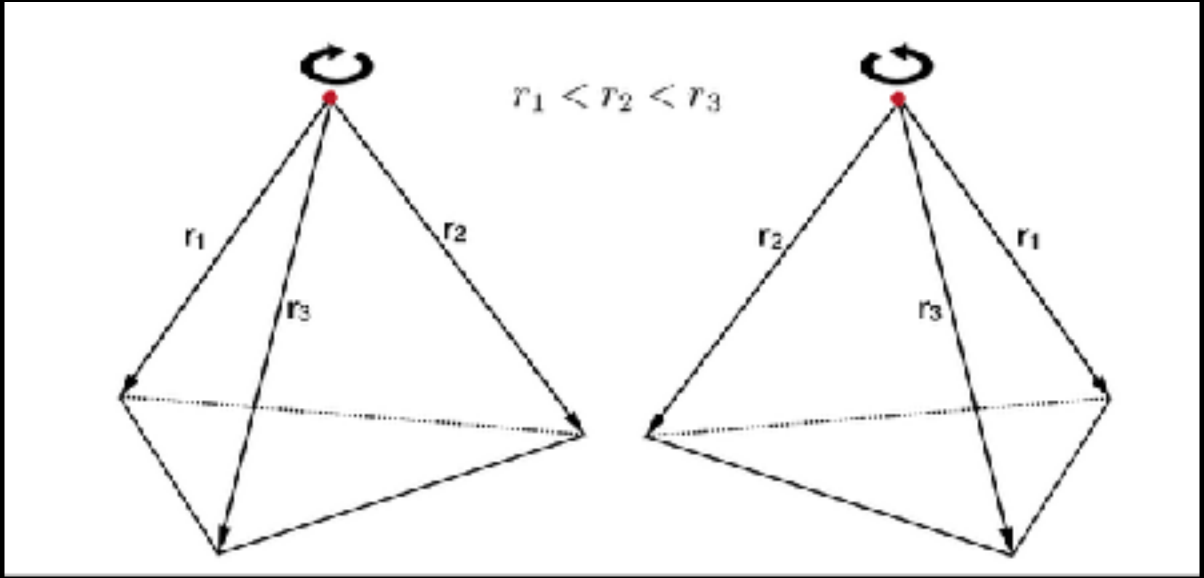
All information is now in the radial coefficient

$$\mathcal{P}_{\ell_1\ell_2\ell_3}(\hat{r}_1, \hat{r}_2, \hat{r}_3) = \sum_{m_i} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} Y_{\ell_1 m_1}(\hat{r}_1) Y_{\ell_2 m_2}(\hat{r}_2) Y_{\ell_3 m_3}(\hat{r}_3)$$

Cahn & Slepian: Isotropic N-point basis functions and their properties Journal of Physics A, 2023

Also: generating function: arXiv:2406.15385, J. Phys. A 2024

Basis splits into even and odd



Odd modes capture *imbalance* of tetrahedra and their mirror images

Odd modes all proportional to the *signed* volume of tetrahedron (scalar triple product)

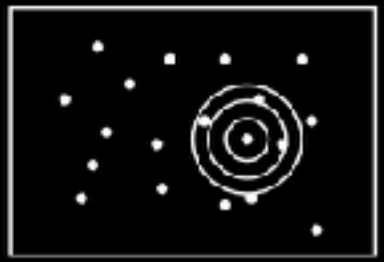
Cahn & Slepian 2023, Cahn Slepian Hou PRL 2022

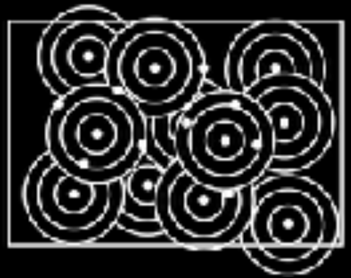
Algorithm?

Use orthogonality to project densities onto our basis by integrating against it

$$\mathcal{P}_{\ell_1\ell_2\ell_3}(\hat{r}_1,\hat{r}_2,\hat{r}_3) = \sum_{m_i} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} Y_{\ell_1 m_1}(\hat{r}_1) Y_{\ell_2 m_2}(\hat{r}_2) Y_{\ell_3 m_3}(\hat{r}_3)$$

Exploit factorization: bin galaxies into shells, do angular integral against harmonic on each shell, and then only look at combinations of 3 *shells* around the primary



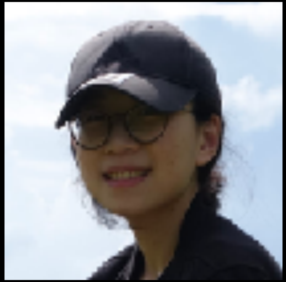


Accelerate Measurement with GPUs

High arithmetic intensity (FLOPS)

CADENZA:
code for 2-6PCF optimized for GPUs

140X speed up over CPU



4PCF for all 1M galaxies (+32X randoms) in SDSS BOSS CMASS in 30 minutes on 1 core, ~45 minutes for DESI Y1

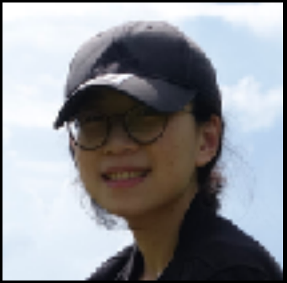
CPU: ENCORE: Philcox, Slepian, Warner, Hou, Cahn, Eisenstein
CADENZA: Slepian, Warner, Hou, Cahn

How to assess significance?

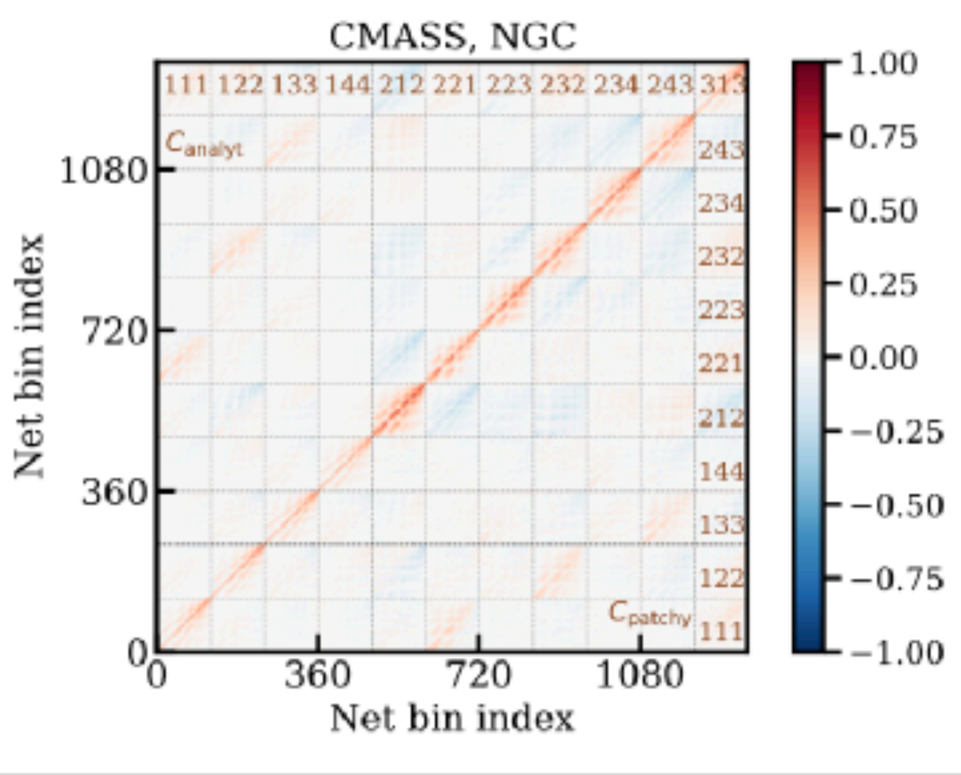
Covariance matrix!

Cannot use gold standard, estimation from mock catalogs: data vector (~18,000 d.o.f.) >> number of mocks (~2,000)

Not enough constraints to give an invertible covariance matrix



-> Analytic template based on Gaussian Random Field



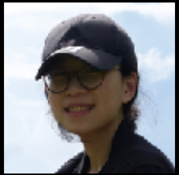
Hou Cahn Philcox Slepian 2021

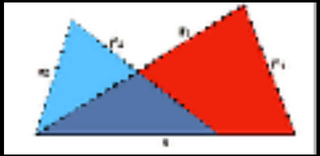
Analytic Covariance

$$\mathrm{Cov}_{\Lambda,\Lambda'}(r_1,r_2,r_3;r_1',r_2',r_3') = \mathrm{Cov}^{\mathrm{I}}_{\Lambda,\Lambda'}(r_1,r_2,r_3;r_1',r_2',r_3') + \mathrm{Cov}^{\mathrm{II}}_{\Lambda,\Lambda'}(r_1,r_2,r_3;r_1',r_2',r_3').$$

$$\begin{aligned}\mathrm{Cov}^{\mathrm{I}}_{\Lambda,\Lambda'}(r_1,r_2,r_3;r_1',r_2',r_3') \;=\; & (4\pi)^4 \sum_{G} (-1)^{\Sigma(\Lambda)(1-\epsilon_G)/2} \sum_{L_1L_2L_3} \mathcal{D}^{\mathrm{P}}_{L_1L_2L_3} \mathcal{C}^{L_1L_2L_3}_{000} \begin{Bmatrix} \ell_{G1} & \ell_{G2} & \ell_{G3} \\ \ell_1' & \ell_2' & \ell_3' \\ L_1 & L_2 & L_3 \end{Bmatrix} \\ & \times \int \frac{s^2 ds}{V} \prod_{i=1}^{3} \left[(-1)^{(-\ell_{Gi}-\ell_i'+L_i)/2} \mathcal{D}^{\mathrm{P}}_{\ell_{Gi}\ell_i'L_i} \mathcal{C}^{\ell_{Gi}\ell_i'L_i}_{000} \xi(s) f_{\ell_{Gi}\ell_i'L_i}(r_{Gi}, r_i', s)\right],\end{aligned}$$

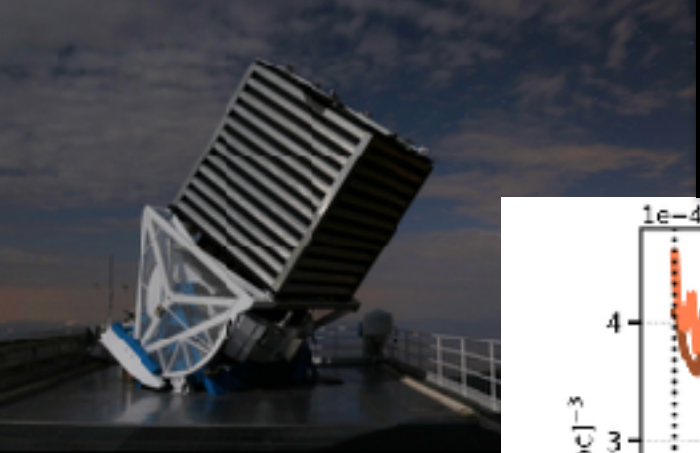
$$\begin{aligned}\mathrm{Cov}^{\mathrm{II}}_{\Lambda,\Lambda'}(r_1,r_2,r_3;r_1',r_2',r_3') \;=\; & (4\pi)^4 \sum_{G,H} (-1)^{\Sigma(\Lambda')(1-\epsilon_H)/2} \sum_{L_1L_2L_3} \mathcal{D}^{\mathrm{P}}_{L_1L_2L_3} \mathcal{C}^{L_1L_2L_3}_{000} \begin{Bmatrix} \ell_{G1} & \ell_{G2} & \ell_{G3} \\ \ell'_{H1} & \ell'_{H2} & \ell'_{H3} \\ L_1 & L_2 & L_3 \end{Bmatrix} \\ & \times \int \frac{s^2 ds}{V} \prod_{i=1}^{3} \left[(-1)^{(-\ell_{Gi}-\ell'_{Hi}+L_i)/2} \mathcal{D}^{\mathrm{P}}_{\ell_{Gi}\ell'_{Hi}L_i} \mathcal{C}^{\ell_{Gi}\ell'_{Hi}L_i}_{000}\right] \\ & \times f_{\ell_{G1}0\ell_{G1}}(r_{G1},0,s) f_{0\ell'_{H1}\ell'_{H1}}(0,r'_{H1},s) f_{\ell_{G2}\ell'_{H2}L_2}(r_{G2},r'_{H2},s) f_{\ell_{G3}\ell'_{H3}L_3}(r_{G3},r'_{H3},s).\end{aligned}$$

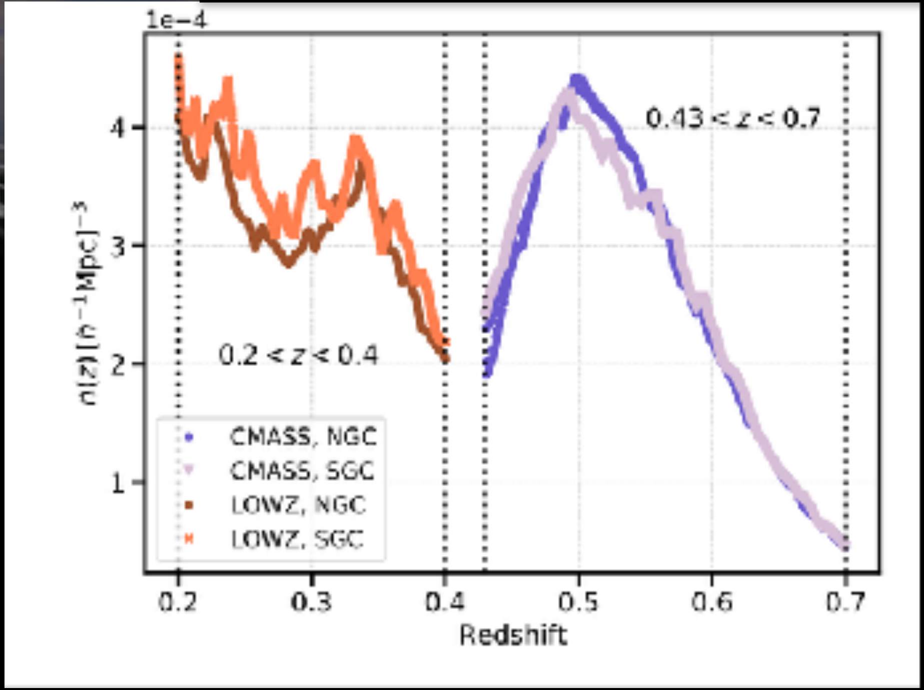




Chellino, Greco, Slepian 2025, arXiv:2504.21133
Hou, Cahn, Philcox, Slepian 2022

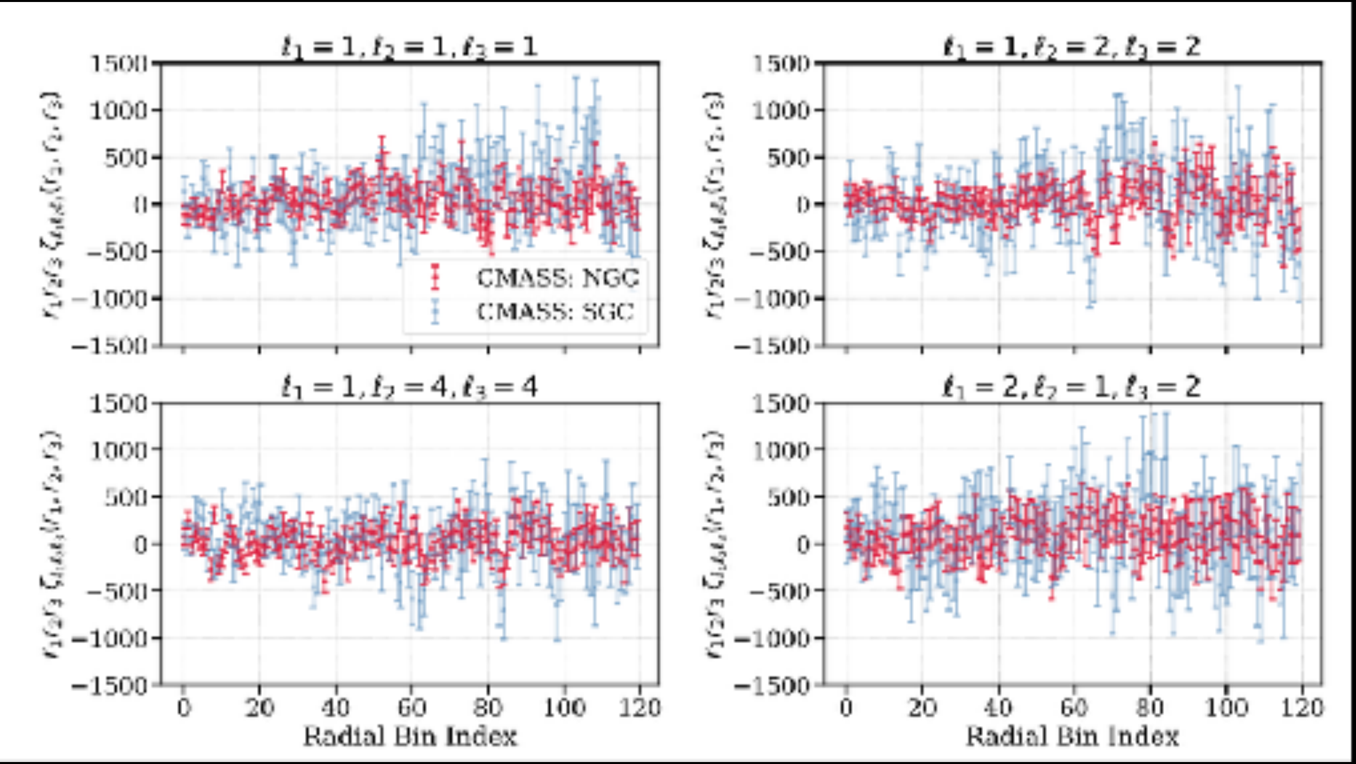
Data time!

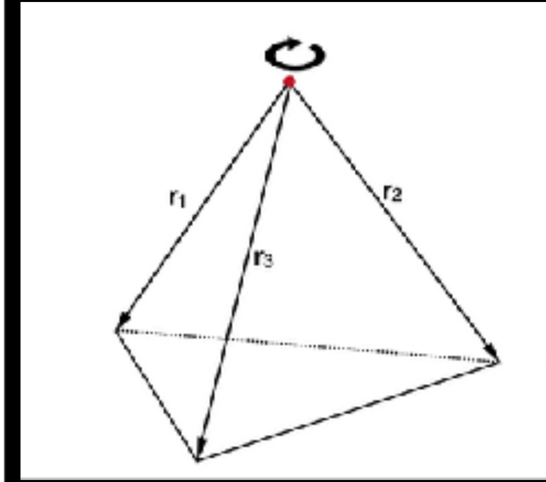




SDSS DR12 BOSS CMASS and LOWZ samples

How does the measured 4PCF look in our basis?





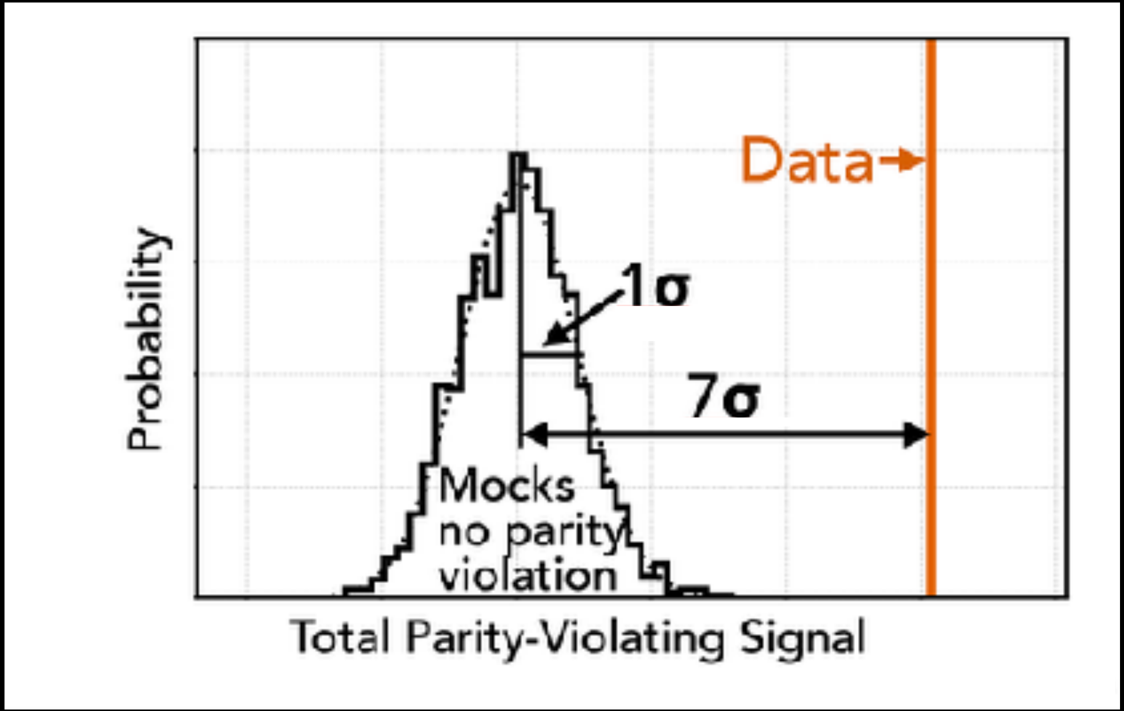
23 "angular" channels, 10 radial bins here in each side -> 1D index

$r_1 < r_2 < r_3$ is why 120 in total

For legibility; our fiducial analysis uses finer bins

Hou Slepian Cahn 2023

BOSS CMASS Results



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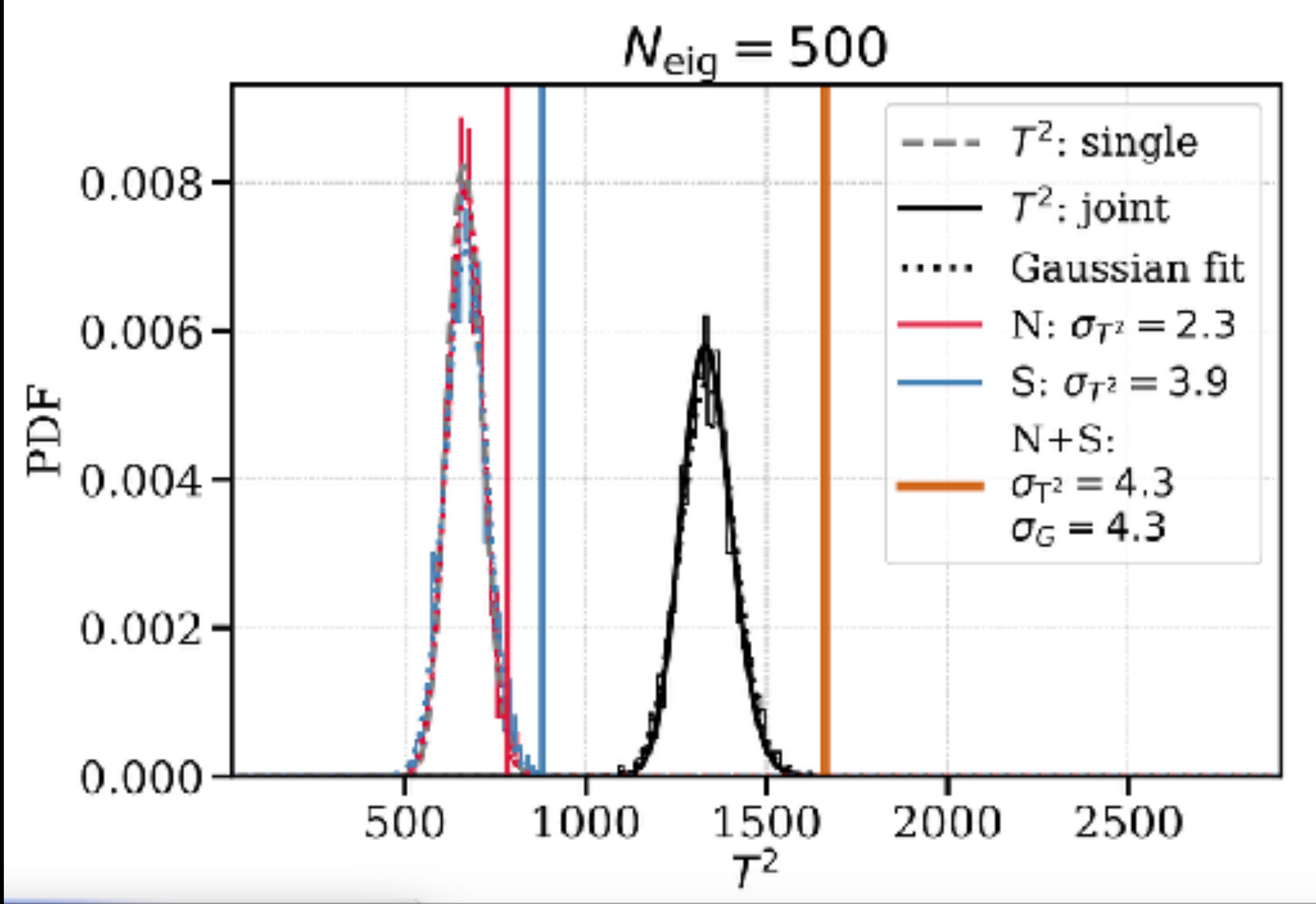
"Compressed" analysis

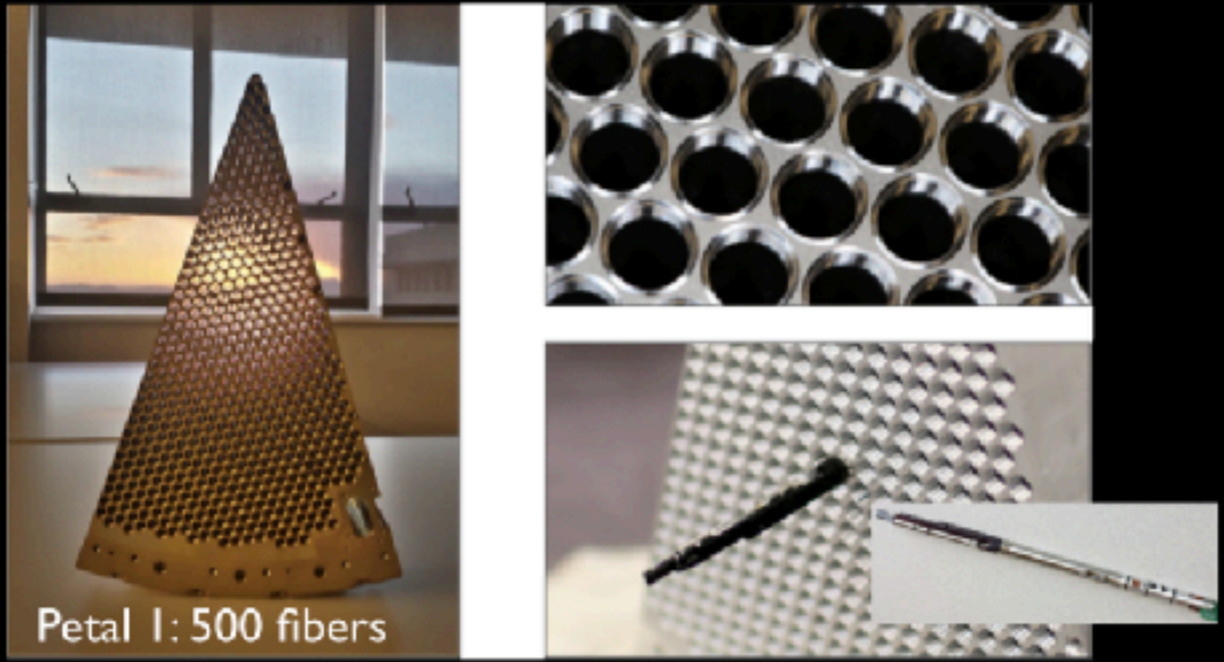


Hou
Slepian
Cahn 2022

Kitt Peak National Observatory

SDSS BOSS: ~1 M galaxies (to 2016)

DESI: ~30 M galaxies, quasars (2021-2025)



5k robotic positioners: reconfigure in ~1 minute

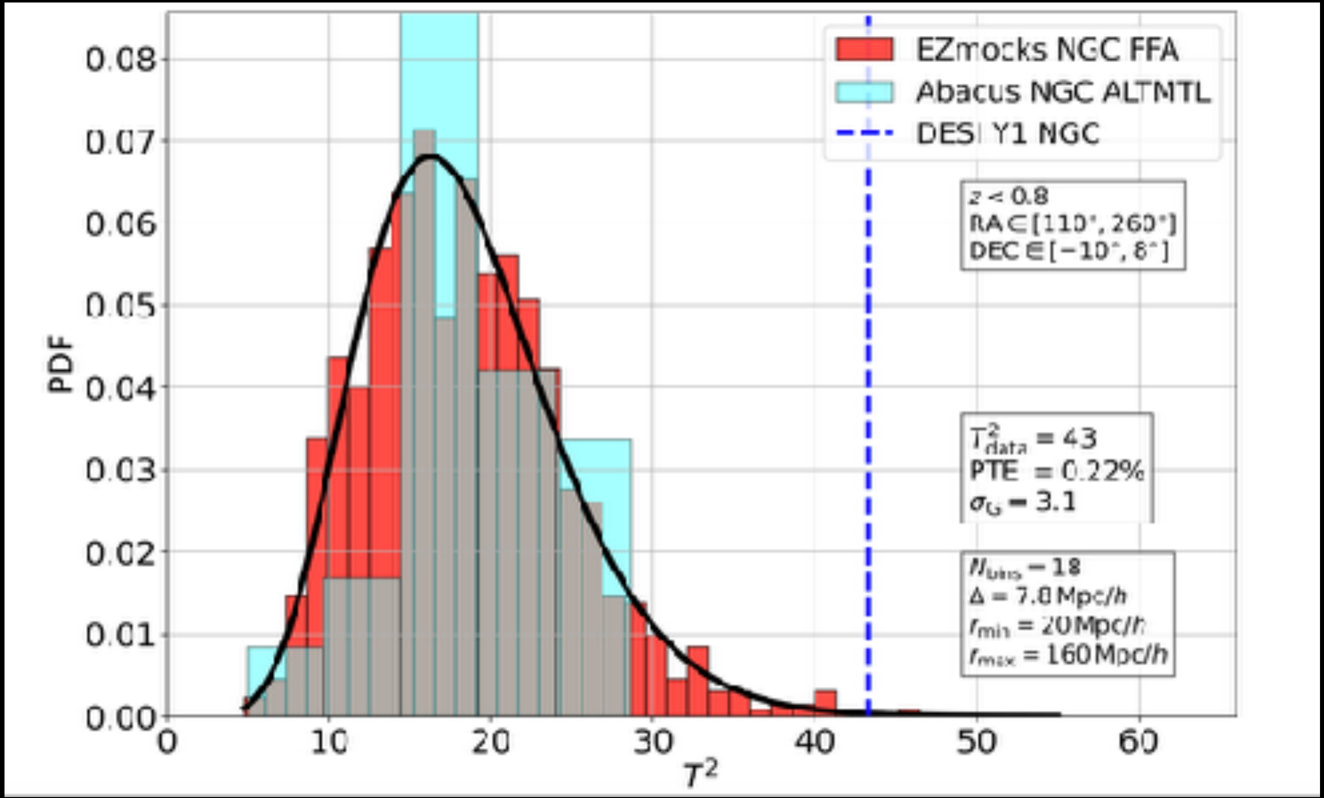

YONDR

DESI Y1 Luminous Red Galaxies (LRGs):
$0.4 < z < 1.1$

$n(z)$ ~ constant >~ 3e-4 [Mpc/h]$^{-3}$ to z = 0.8, linearly declining thereafter

2PCF, 3PCF:
checks of data-mock consistency, and some modeling

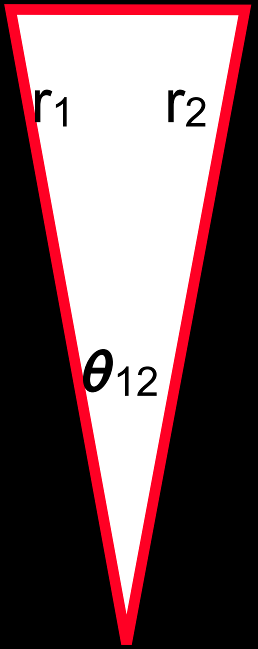
2PCF



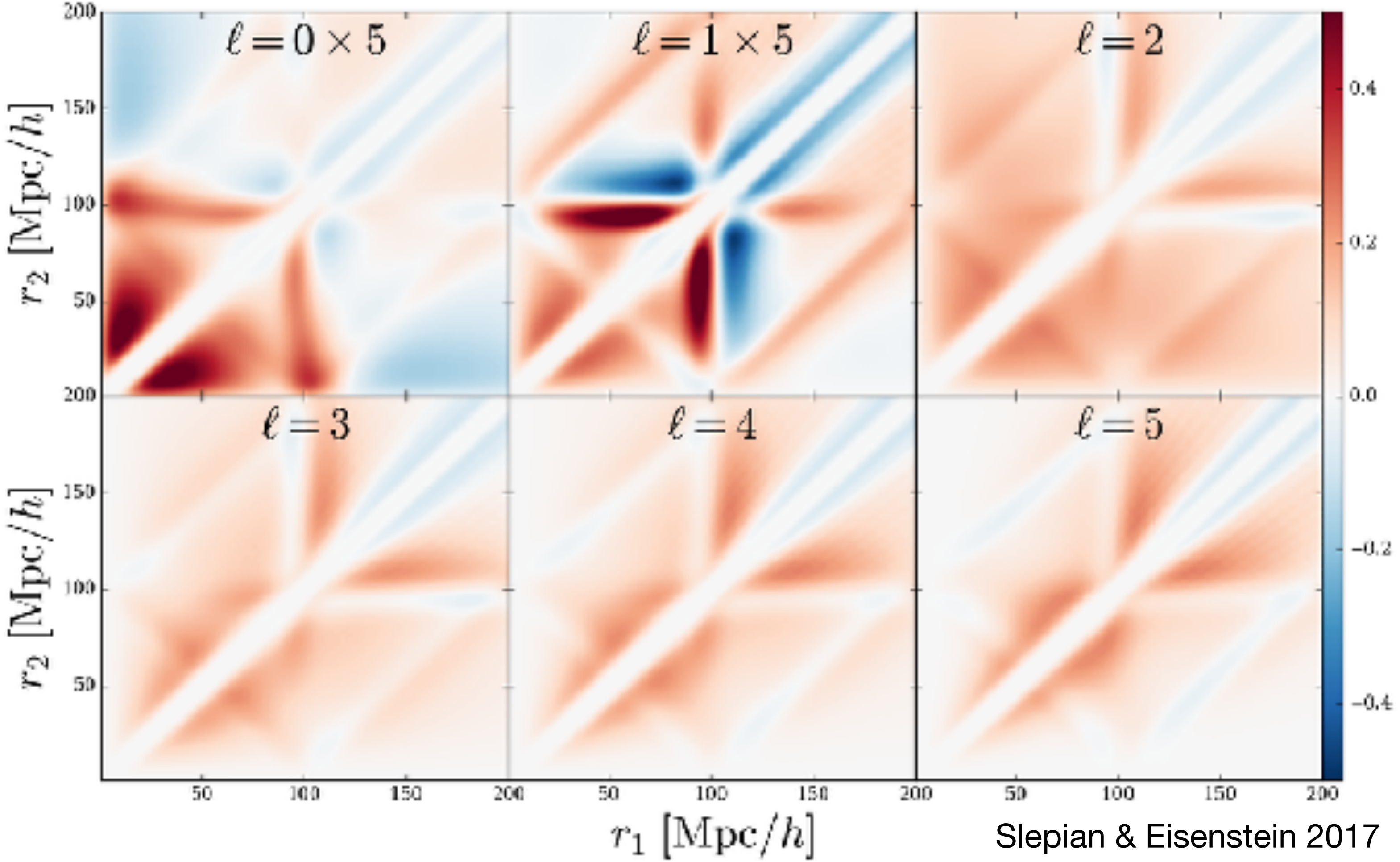
2 minutes on 1 A100 GPU: thank you HiPerGator!

3PCF signal

3PCF Model in Legendre basis



ℓ —> Legendre polynomial of cos θ_{12}



Slepian & Eisenstein 2017

3PCF consistency

3PCF modeling

4PCF connected even-parity

4PCF even: detection significances

Auto (χ^2), compressed

A brief pause in our scheduled programming…

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No evidence for parity violation in BOSS

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Abstract: Recent studies have found evidence for parity violation in the BOSS spectroscopic galaxy survey, with statistical significance as high as 7σ. These analyses assess the significance of the parity-odd four-point correlation function (4PCF) with a statistic called χ^2. This

arXiv: 2407.03397

Take patches, spatially separated—>
uncorrelated *noise*

Real signal: same everywhere (isotropy)
—> survives cross-correlation
Standard in CMB

So let’s do this in the *even* sector first, to see how it does , while we are still “blind” to the odd ;)

Cross, compressed

4PCF odd parity

Summary

Galaxy 4PCF is sensitive to parity violation

Developed fast algorithm to compute it, and exploited the GPU

Measured it on largest currently-extant spectroscopic samples, ~1M galaxies of SDSS BOSS and ~1M LRGs of DESI Y1

We live in exciting times.