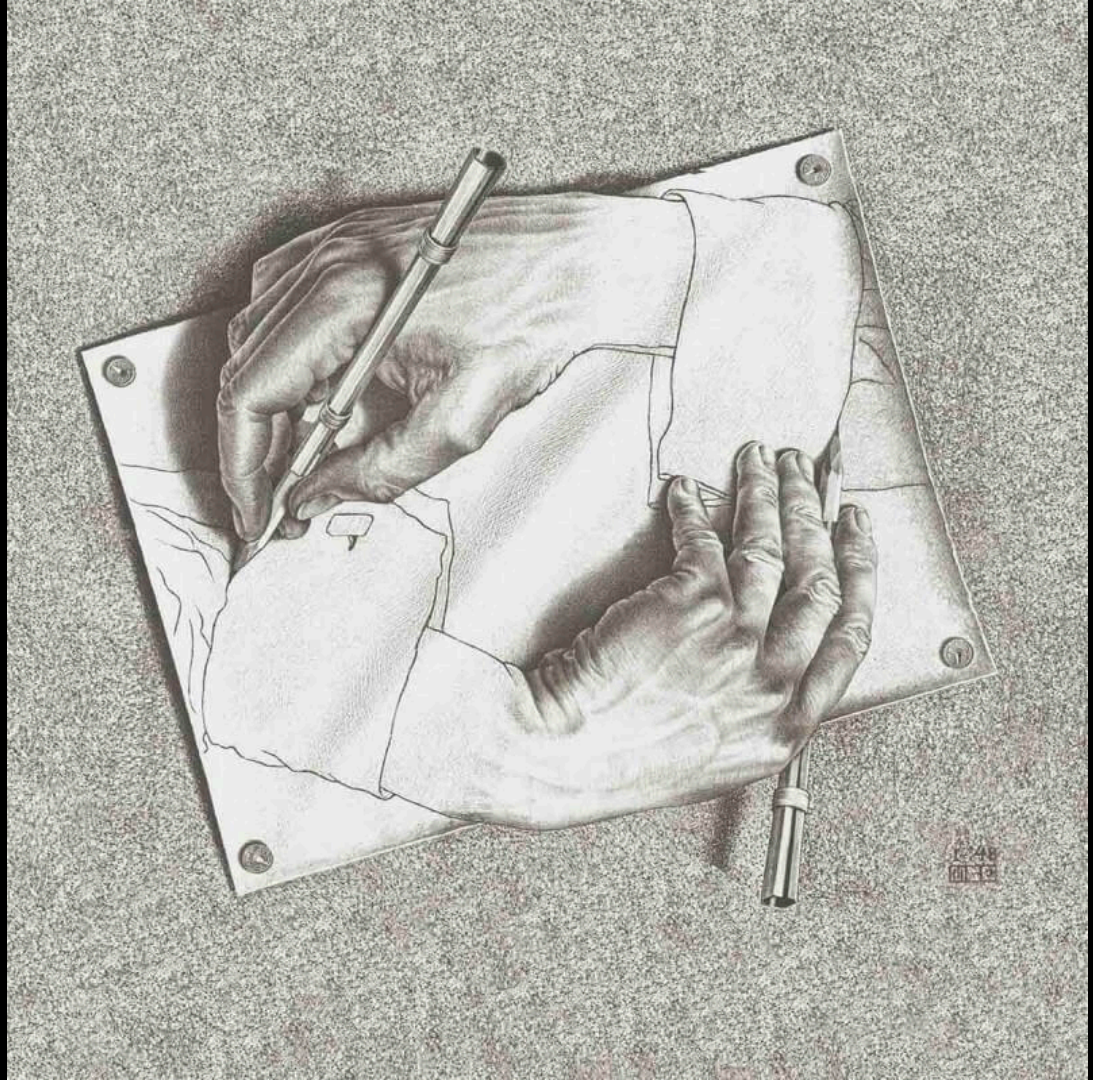
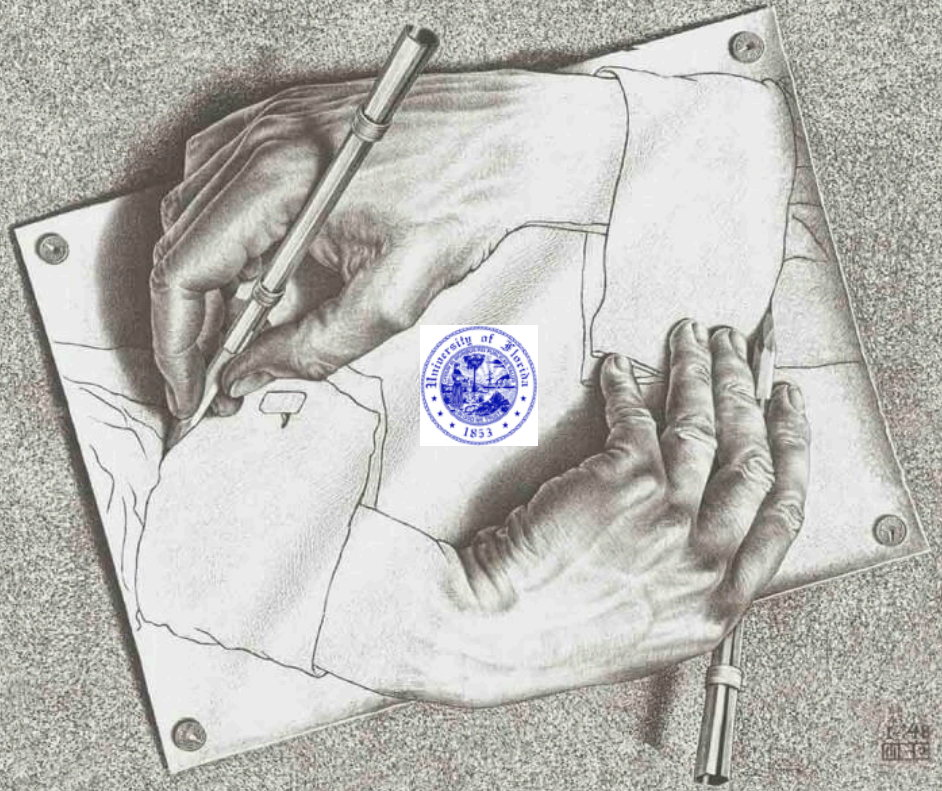


High Energy Physics at the High Number Density Frontier: Parity Violation with the Galaxy 4-Point Function



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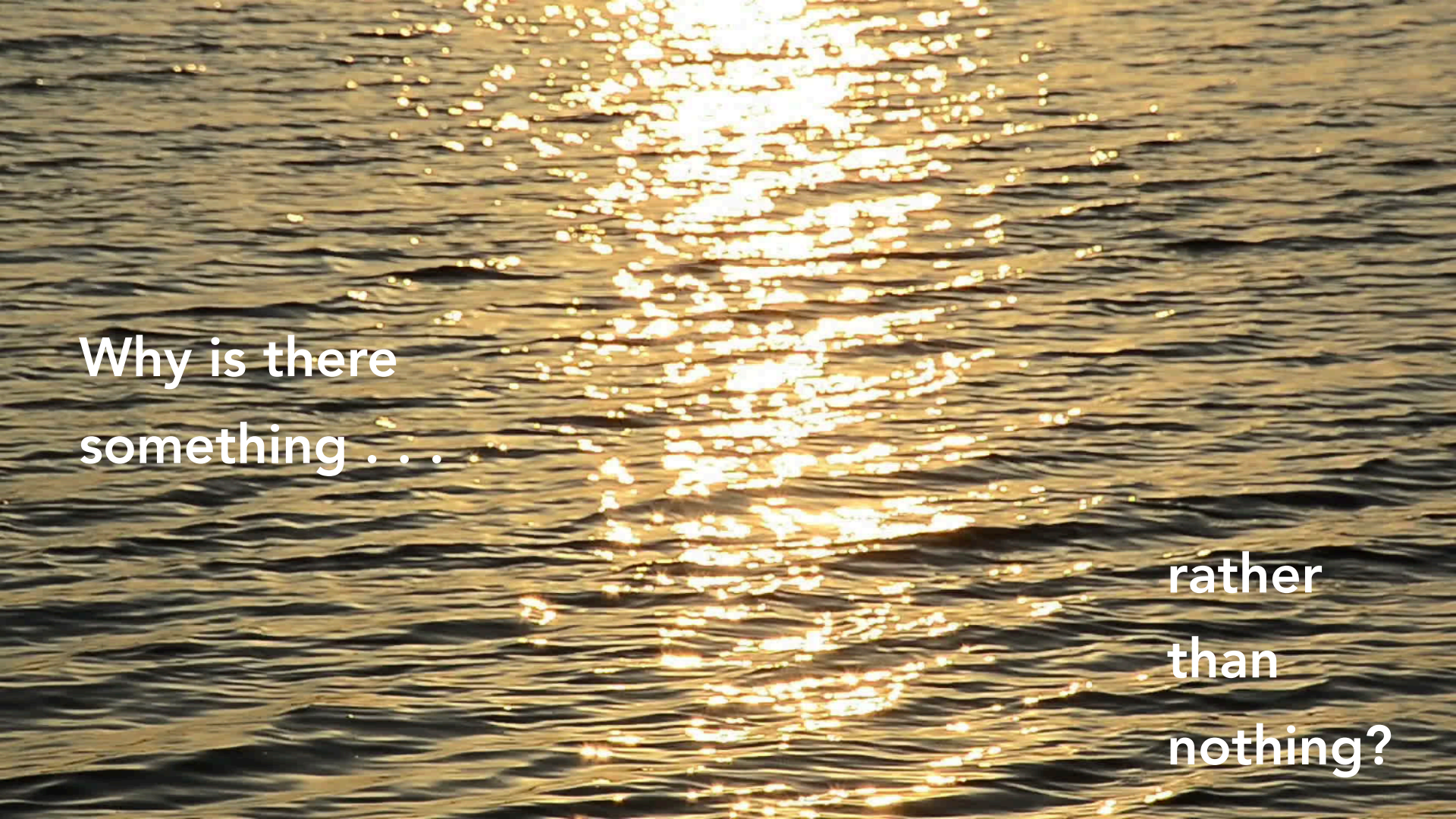

Why is there
something . . .
rather
than
nothing?

More precise question:

Why isn't our Universe filled with equal amounts of matter and anti-matter?

(which would then annihilate, leading to nothing)

Standard Model argues this should happen

Need for CP Violation

But in fact: 1 extra baryon for every 1 billion anti-baryons
—explained by hypothesized “baryogenesis”

Sakharov: baryogenesis requires breaking of CP
(charge-parity) symmetry

No physics we know gives nearly enough!

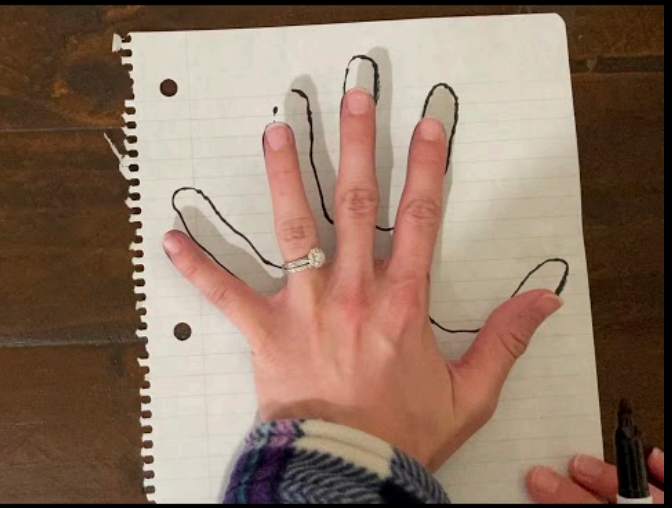
Perhaps just P violation?

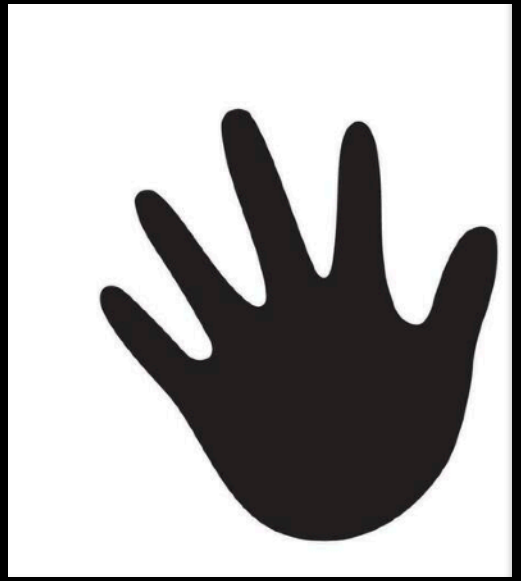
Parity: *(x, y, z)* to *(-x, -y, -z)*: mirroring + rotation


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

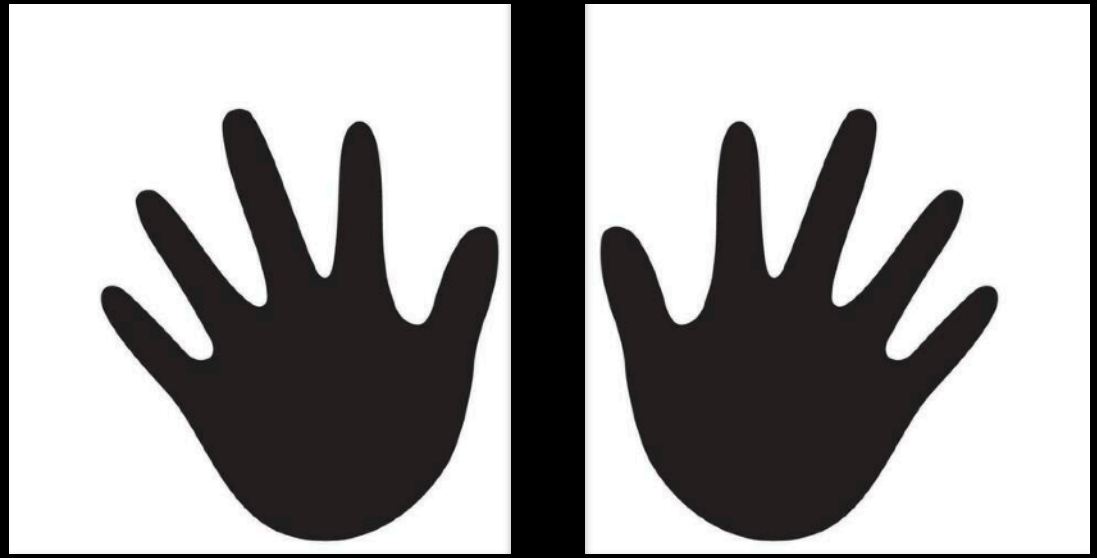
Let’s start with us

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:

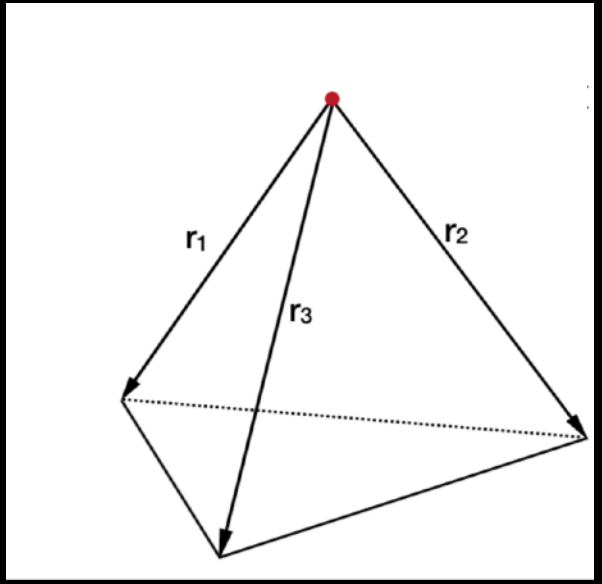
lowest-order 3D statistic: excess of tetrahedra over spatially random distribution

Rotation and translation invariant—isotropy and homogeneity

Cahn Slepian Hou PRL 2022

Use the Isotropic Basis!

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



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

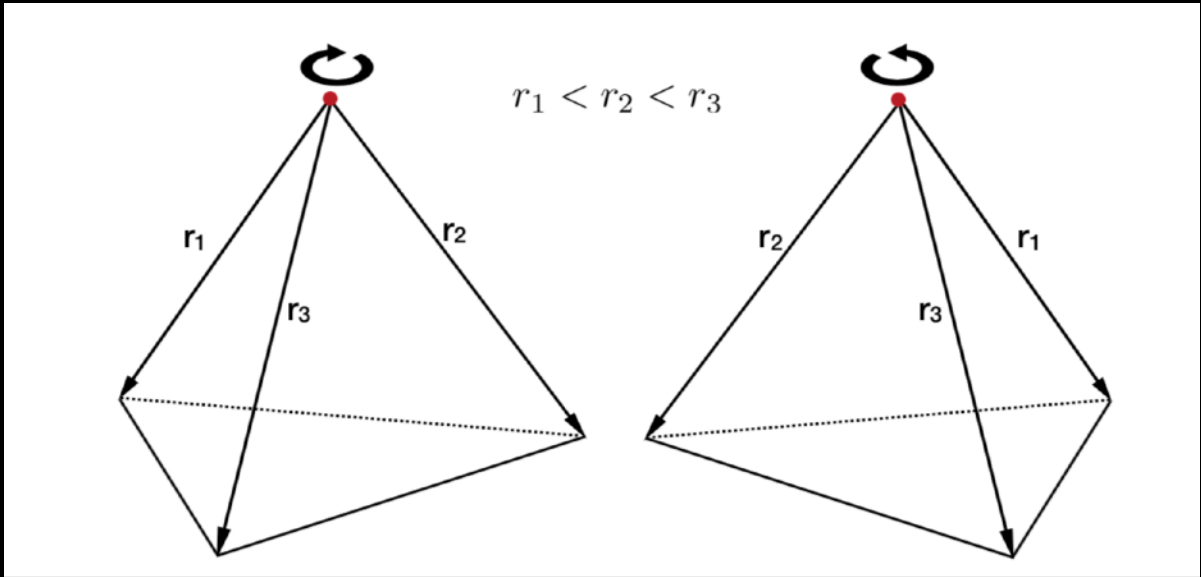
All information is now in the radial coefficient

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

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

Also: generating function: arXiv:2406.15385

Basis splits into even and odd

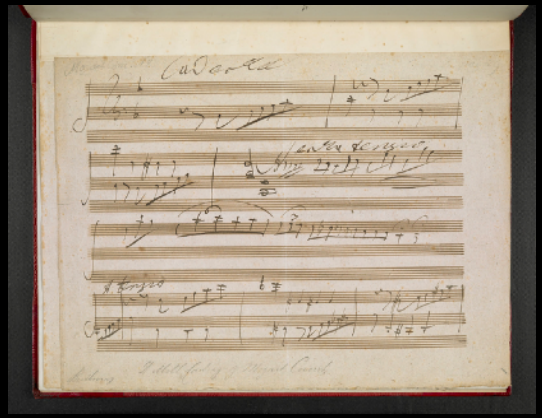


Odd modes capture imbalance of tetrahedra and their mirror images

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

Cahn & Slepian 2023, Cahn Slepian Hou PRL 2022

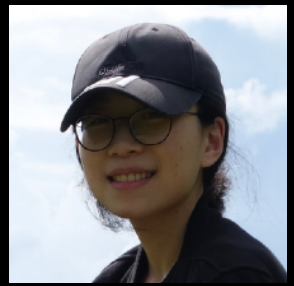
Accelerate Measurement with GPUs



High arithmetic intensity (FLOPS)

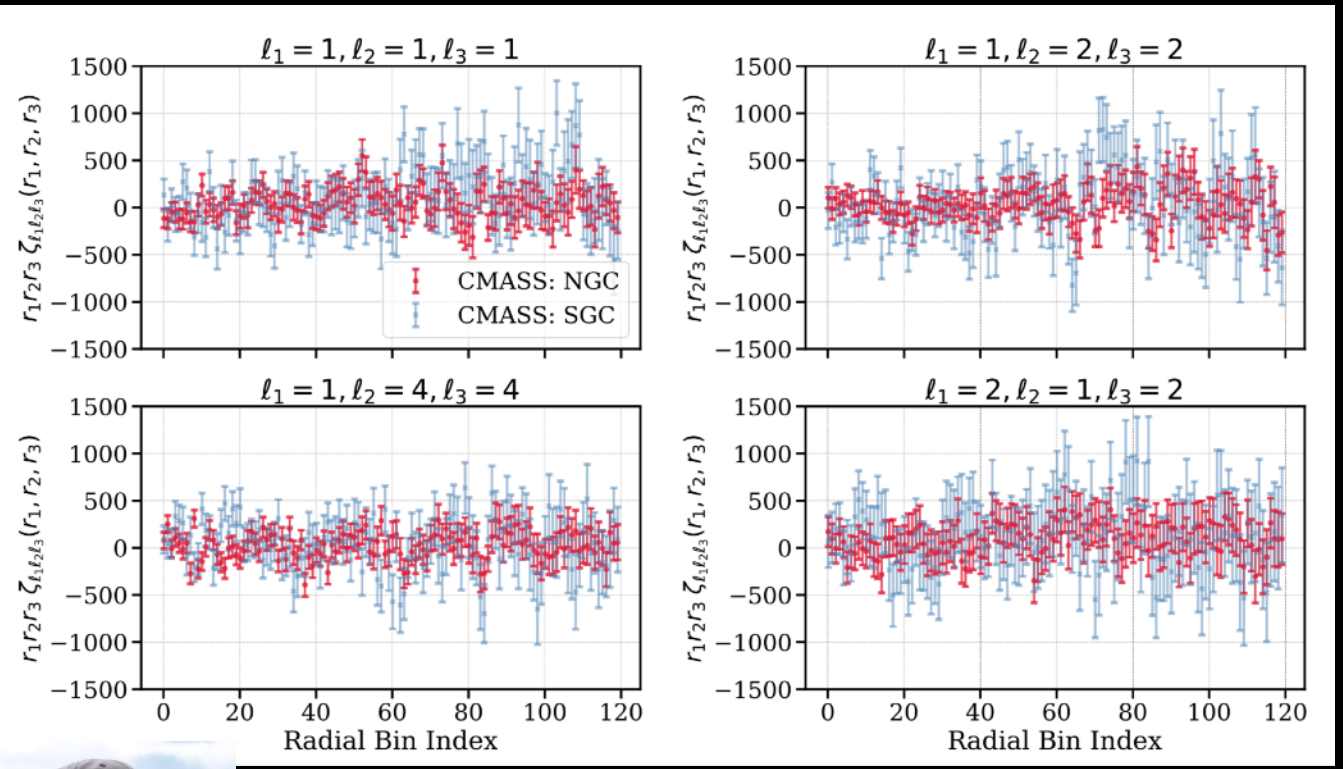
CADENZA:
code for 2-6PCF optimized for GPUs

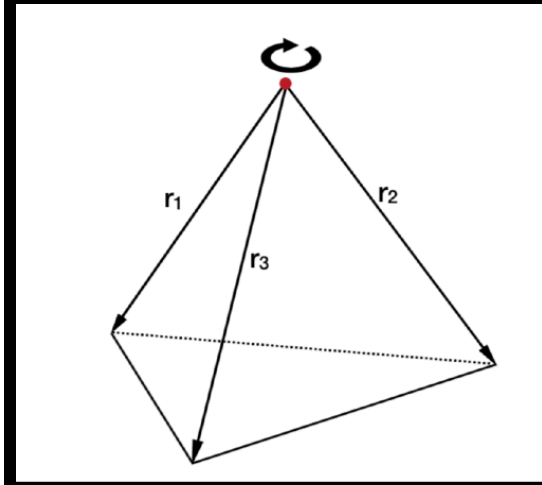
140X speed up over CPU



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

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





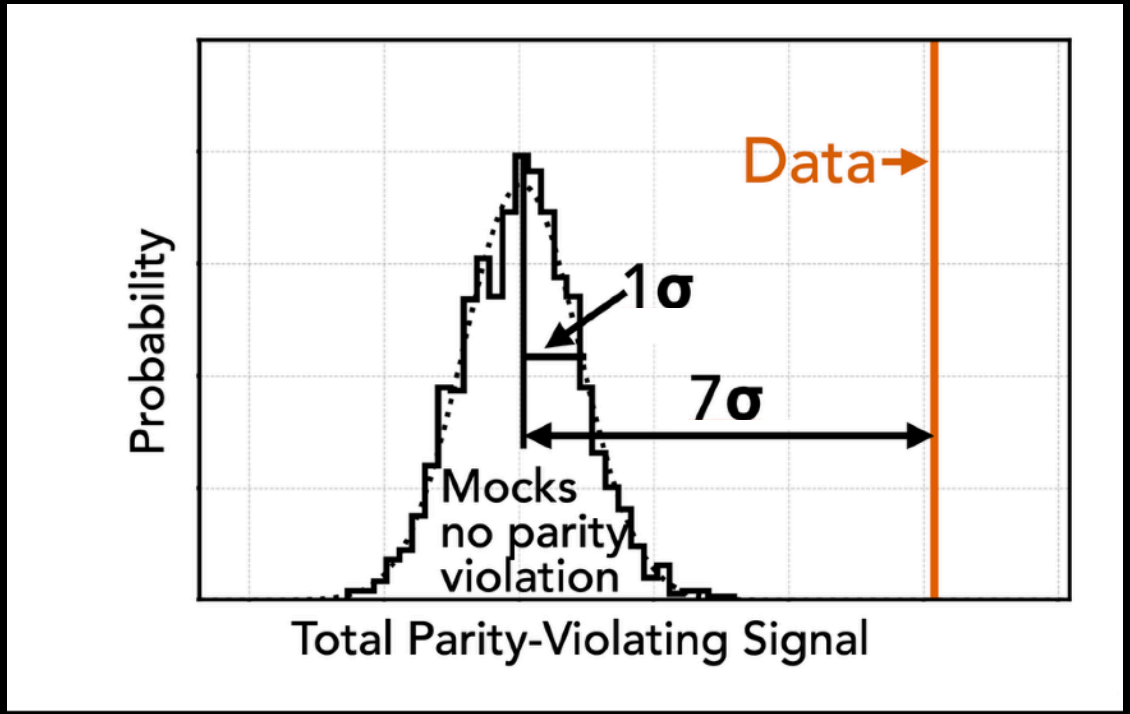
23 “angular” channels, 10 radial bins here in each side -> 1D index

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

For legibility; our fiducial analysis uses finer bins

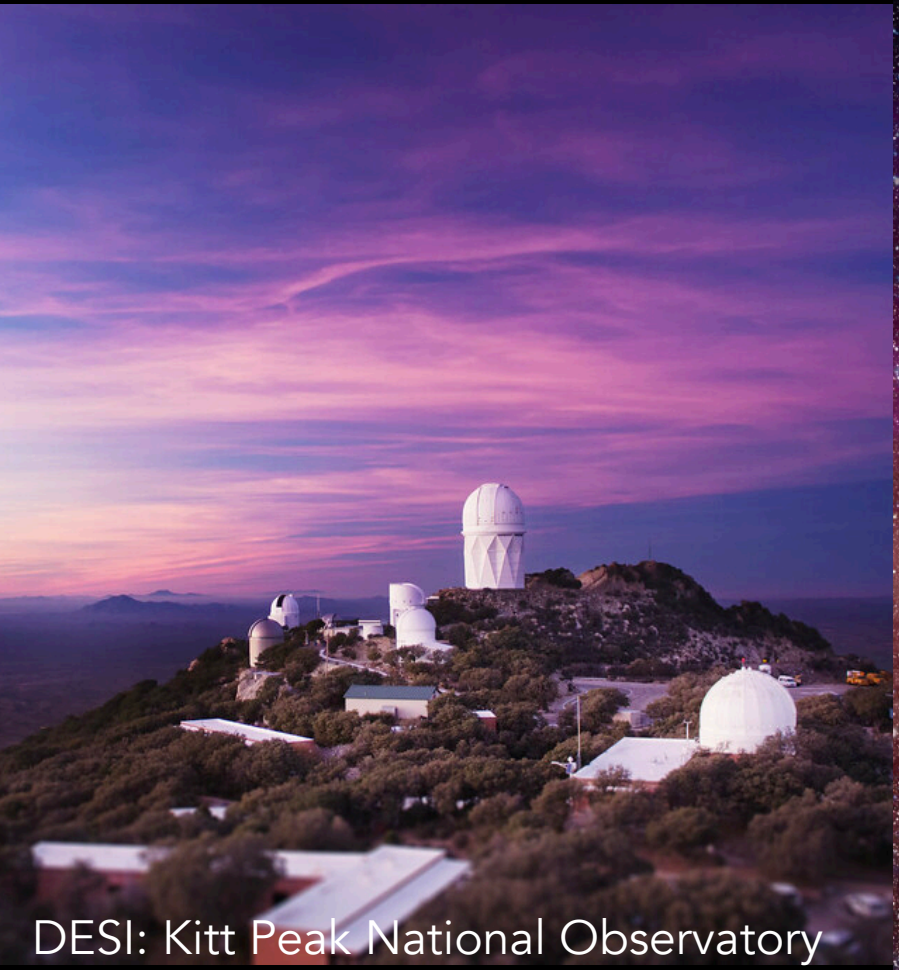
Hou Slepian Cahn 2023

BOSS CMASS Results

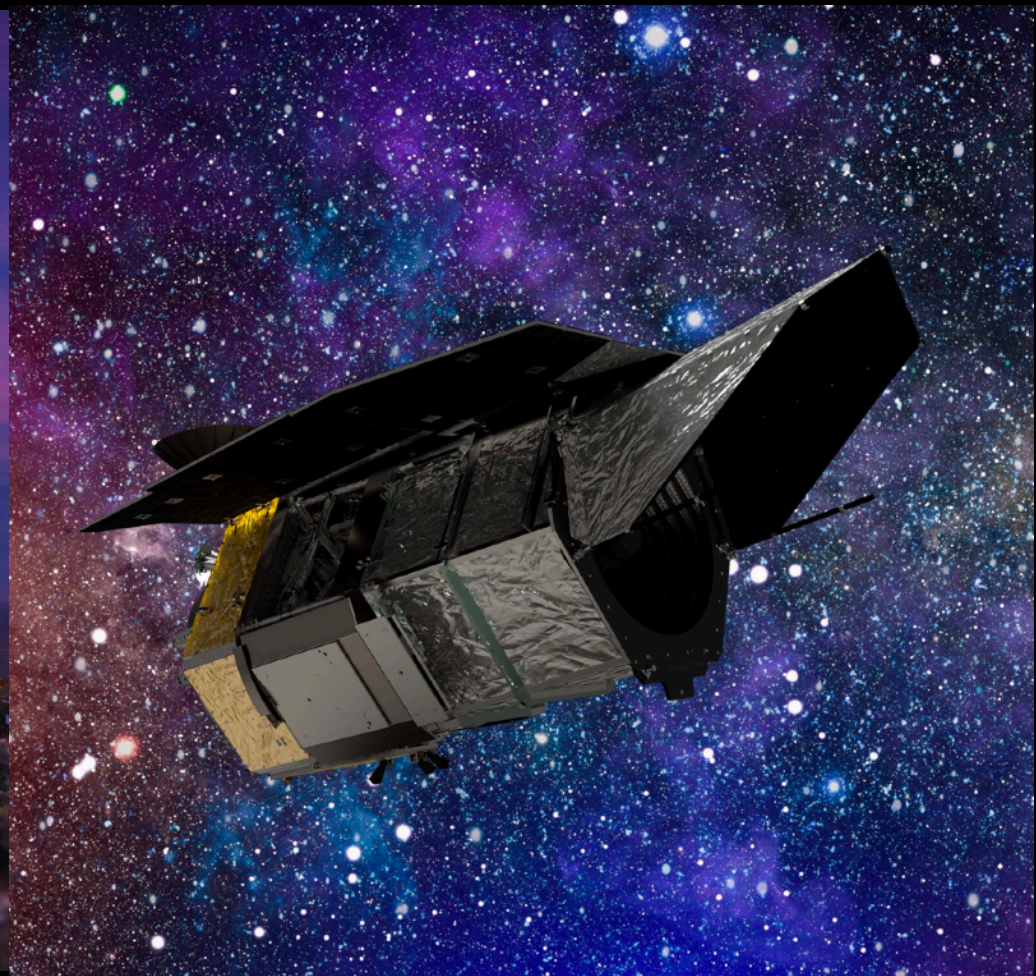


Hou Slepian Cahn 2023

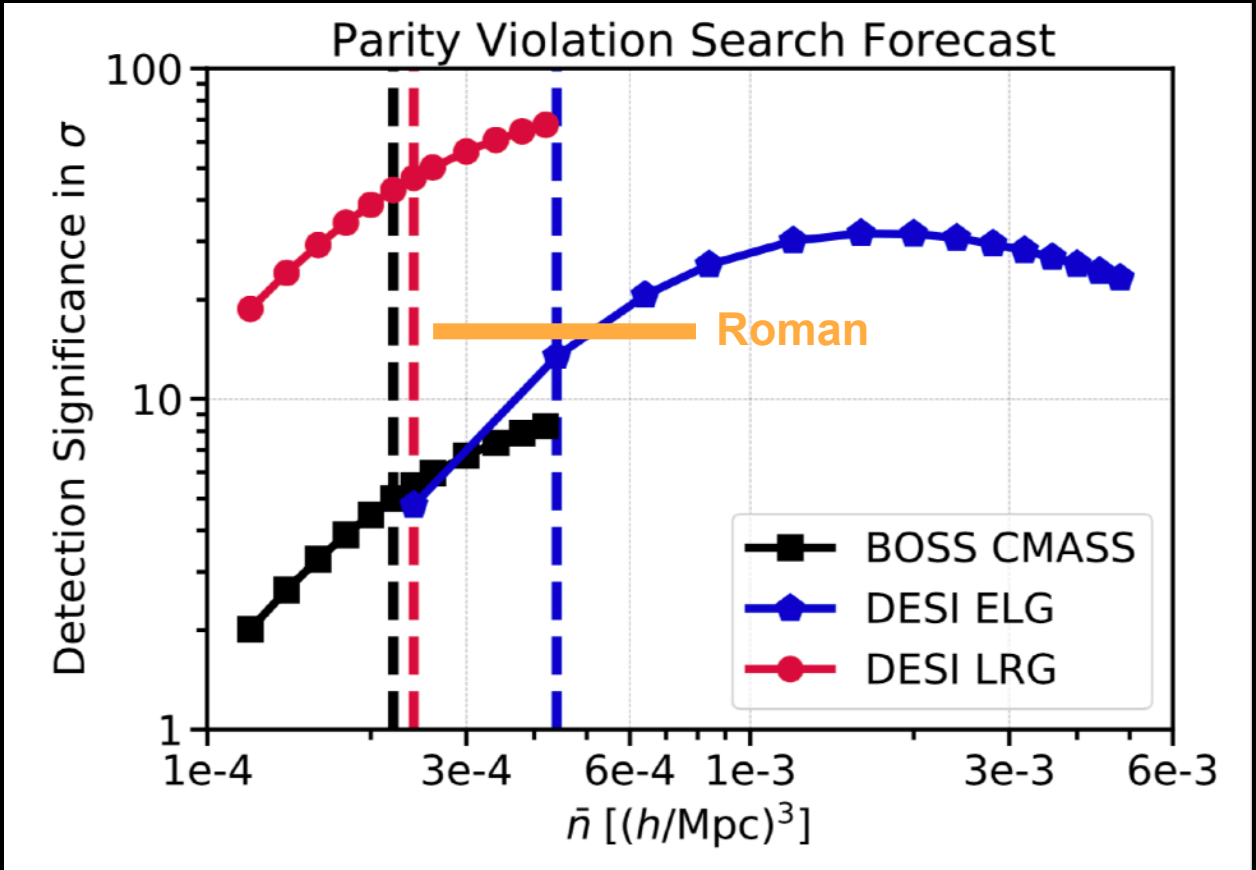
What comes next?



DESI: Kitt Peak National Observatory



Forecasts for DESI & Roman



Cahn Slepian Hou 2022, PRL

Roman's unique role

Roman can detect this at high significance

But what's most important—
totally different method from ground-based, fiber-fed spectrograph (BOSS & DESI)

Different systematics

Different "unknown unknowns'

Roman's unique role

Different, higher redshift galaxy population from BOSS and DESI

Good because:
1—adds confidence the signal is not some strange population evolution effect

2—higher redshift —> less nonlinearity —> better-controlled covariance matrix

What could it all mean?

Axions?

-axion field can produce parity-violation during inflation

$$\mathcal{L} = \frac{M_{\rm P}^2}{2} R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu - \frac{1}{4\Lambda}\phi\tilde{F}^{\mu\nu}F_{\mu\nu} - V(\phi)$$

$$\mathbf{A}'' - \nabla^2\mathbf{A} - \frac{\phi'}{\Lambda}\boldsymbol{\nabla}\times\mathbf{A} = 0$$

$$\mathbf{B} = a^{-2}\boldsymbol{\nabla}\times\mathbf{A}, \qquad \mathbf{E} = -a^{-2}\mathbf{A}'$$

$$\delta\phi'' + 2\mathcal{H}\delta\phi' - \nabla^2\delta\phi + a^2\frac{\mathrm{d}^2V}{\mathrm{d}\phi^2} = \frac{a^2}{\Lambda}\left(\mathbf{E}\cdot\mathbf{B} - \langle\mathbf{E}\cdot\mathbf{B}\rangle\right).$$

Matthew Reinhard

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 sample, ~1M galaxies of SDSS BOSS

Found statistically significant (7σ) evidence for it

Could indicate new physics during inflation:
Roman has a unique role to play in confirming this signal