PRINCETON UNIVERSITY

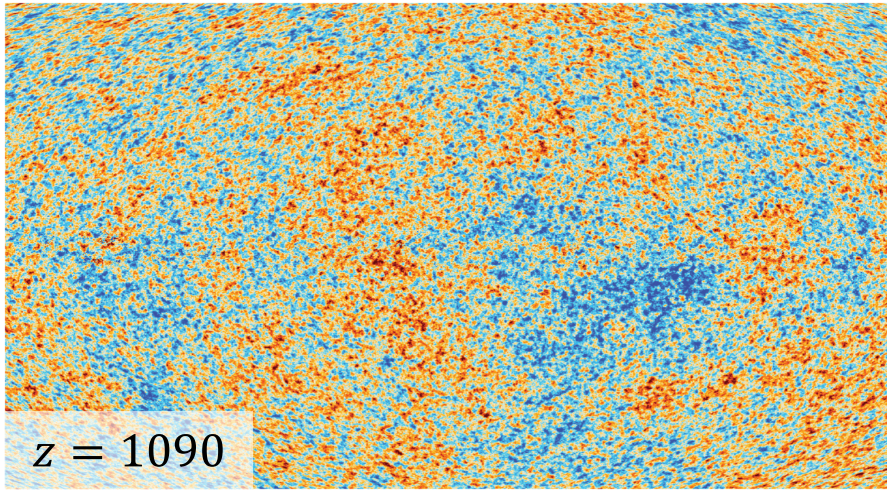
IAS INSTITUTE FOR ADVANCED STUDY

Large Scale Structure Beyond the Two-Point Function

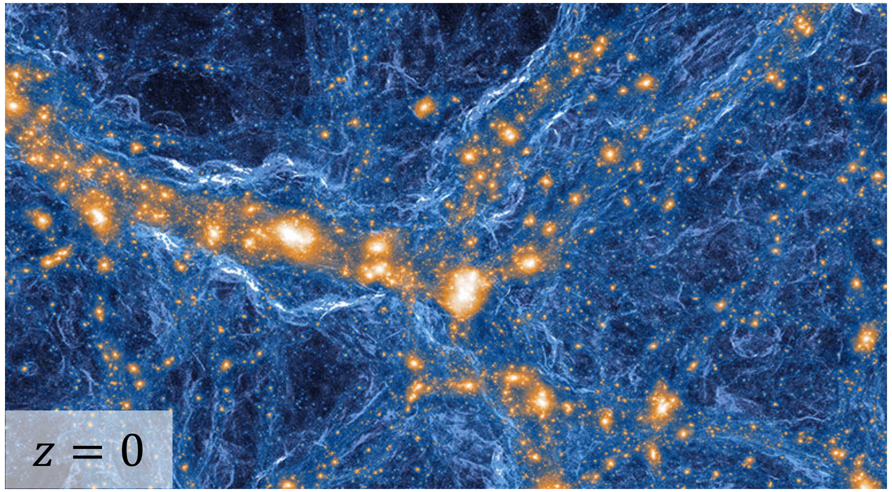
Oliver Philcox (Princeton / IAS)

BCCP Cosmology Seminar 9/21/21

THE LATE UNIVERSE IS NOT GAUSSIAN



Gravitational Collapse



$$\boxed{\delta(\mathbf{k}) \sim \mathcal{N}\left(0, P_L(\mathbf{k})\right)}$$

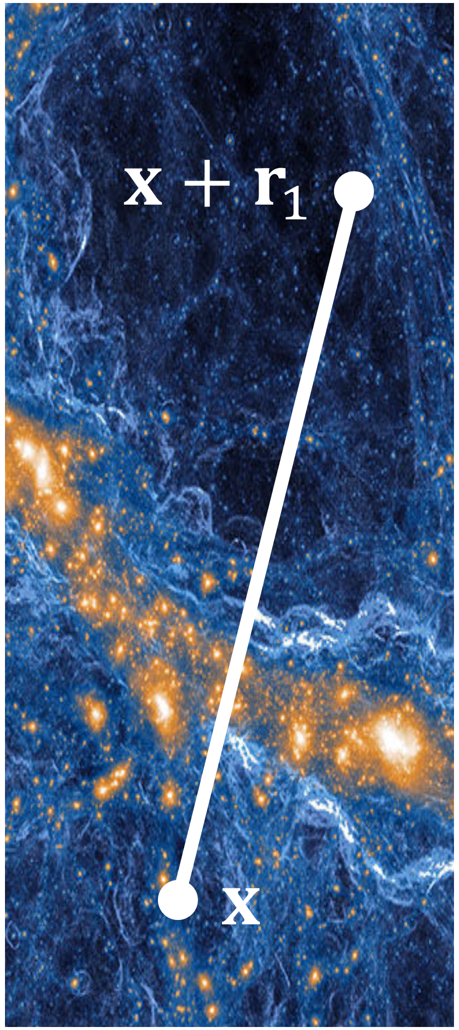
- All information contained in the power spectrum
- **No** higher order statistics needed!

$$\boxed{\delta(\mathbf{k}) \not\sim \mathcal{N}\left(0, P_L(\mathbf{k})\right)}$$

- **Not** all information contained in the power spectrum
- Higher-order statistics needed!

Planck 2018, IllustrisTNG

NON-GAUSSIAN DENSITY ⇒ NON-GAUSSIAN STATISTICS



Gaussian

1. Power Spectrum:

$$P(\mathbf{k}_1) = \langle \delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\rangle'$$

2. 2-Point Correlation Function:

$$\xi(\mathbf{r}_1) \equiv \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r}_1)\rangle$$

Non-Gaussian

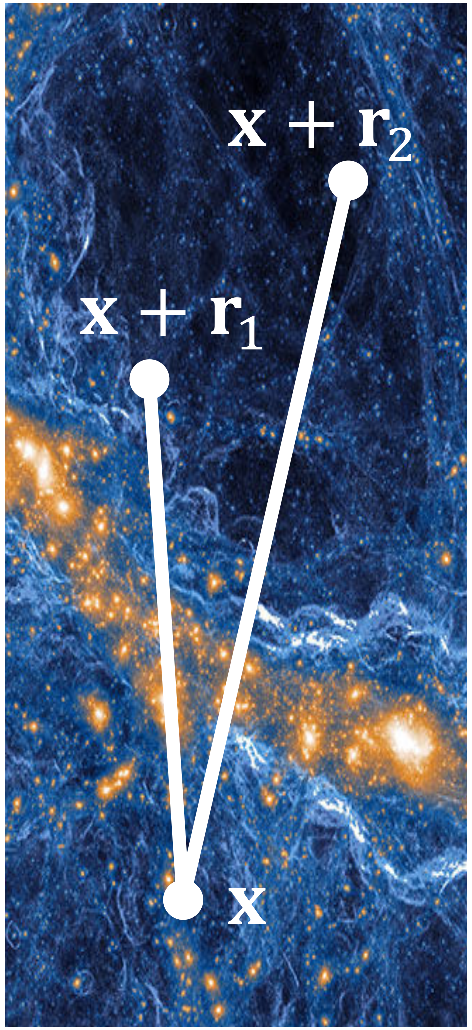
1. Bispectrum:

$$B(\mathbf{k}_1,\mathbf{k}_2) = \langle \delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\delta(\mathbf{k}_3)\rangle'$$

2. 3-Point Correlation Function:

$$\zeta_3(\mathbf{r}_1,\mathbf{r}_2) \equiv \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r}_1)\delta(\mathbf{x}+\mathbf{r}_2)\rangle$$

And beyond…



INFORMATION LEAKS INTO HIGHER-ORDER STATISTICS

$$B_g(\mathbf{k}_1,\mathbf{k}_2) = \left[2b_1^3 F_2(\mathbf{k}_1,\mathbf{k}_2) + b_2 b_1^2 + 2b_{s^2} b_1^2 \left(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2 - 1/3\right)\right] P_L(k_1) P_L(k_2) + 2 \text{ perms.}$$

The galaxy bispectrum depends on galaxy formation physics, gravity, and early-Universe cosmology.

▷ To obtain **all** the large-scale information in the initial conditions, we need:*

- Power Spectra / 2-Point Functions $\sim P_L(k)$
- Bispectra / 3-Point Functions $\sim P_L^2(k)$
- Trispectra / 4-Point Functions $\sim P_L^3(k)$
- *etc.*

*ignoring initial condition reconstruction

e.g. Schmittfull+15

THE CURRENT STATE OF PLAY

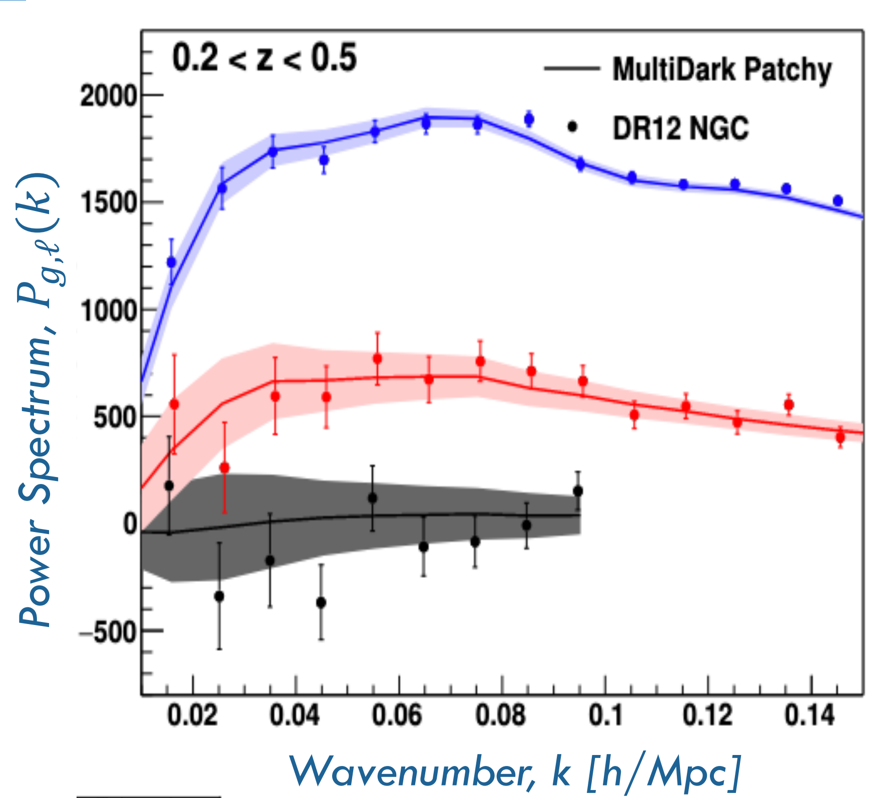
- Only the galaxy **power spectrum** is analyzed

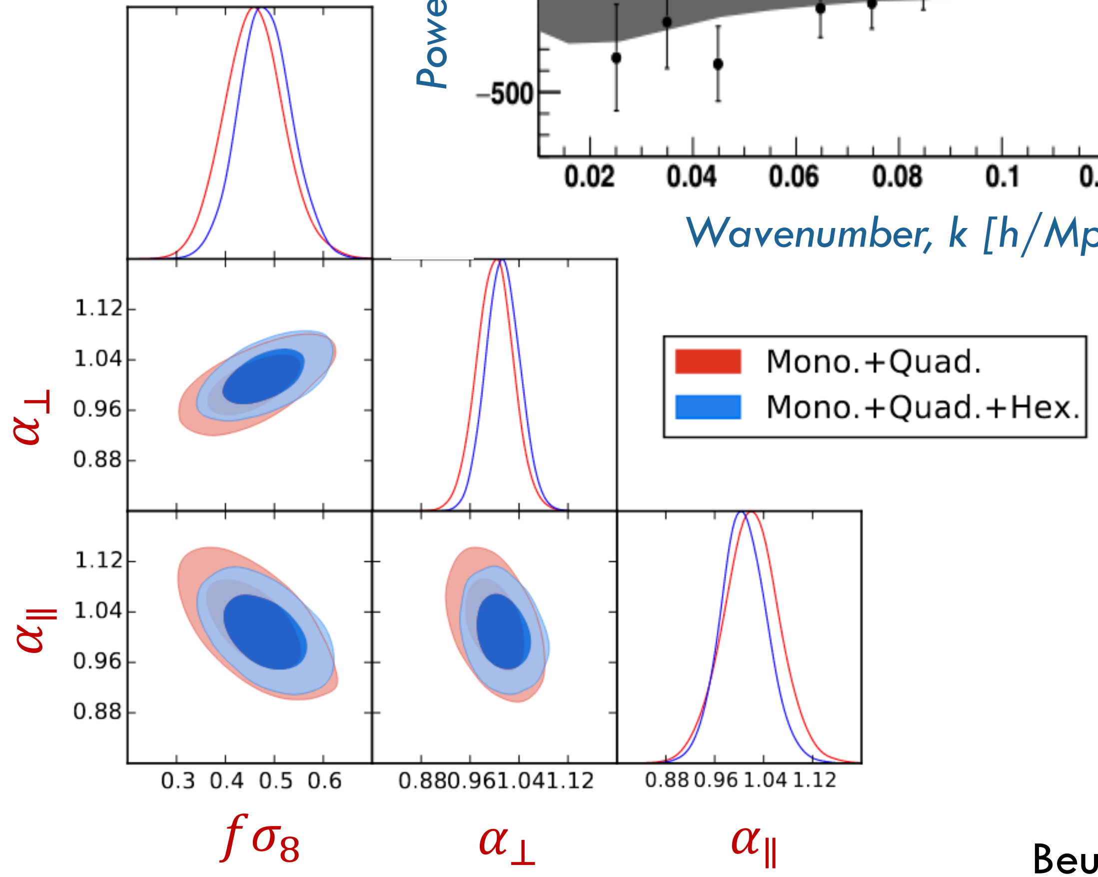
- Fit to $P_{g,\ell}(k)$ to a simple template searching for **wiggle positions** and **overall amplitudes,** *i.e.* $[\alpha_\parallel, \alpha_\perp, f\sigma_8]$

- 3- and 4-point functions ignored

With a few exceptions…

[e.g. Ivanov+19,20, d'Amico+19,20, Philcox+20, Gil-Marin+15,16]





Beutler+16

MORE STATISTICS = MORE INFORMATION

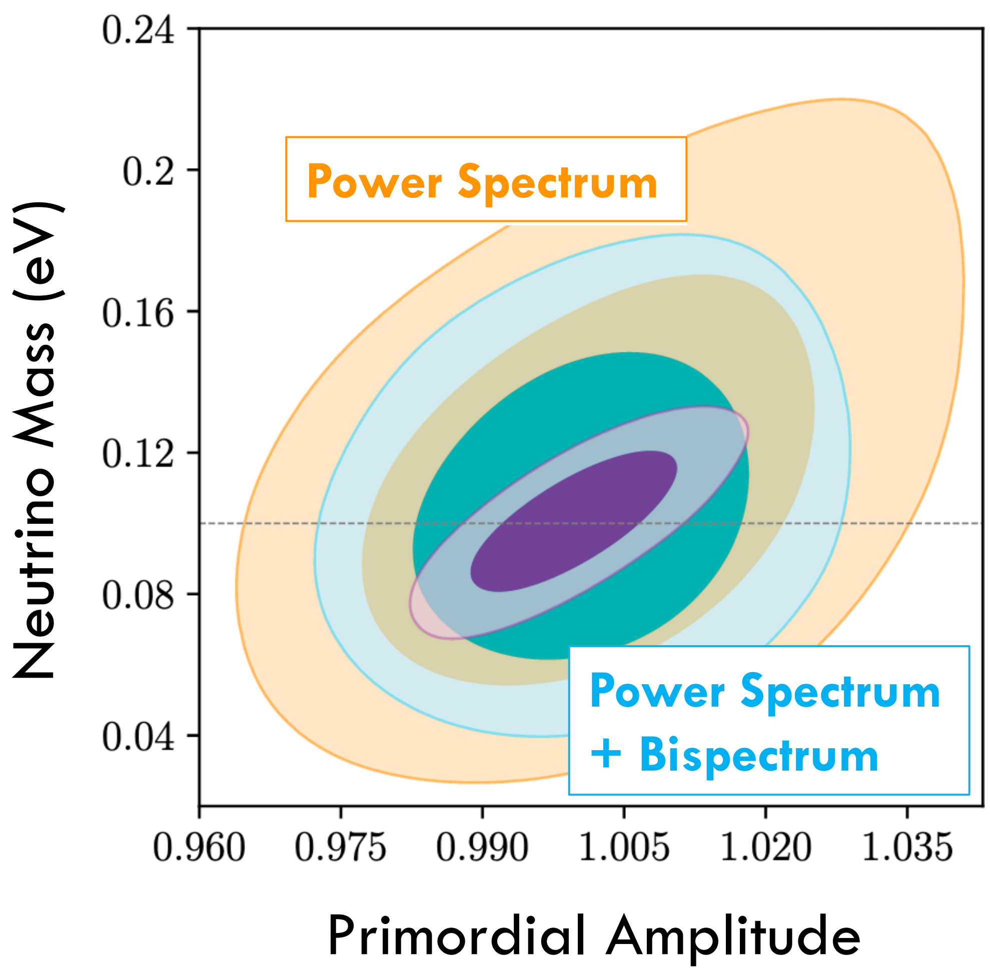
- **Break** parameter **degeneracies**!

  [e.g. $P_g \sim b_1^2\sigma_8^2,\ B_g \sim b_1^3\sigma_8^4$]

- **Sharpen** cosmological **constraints**!

Euclid Forecast [perturbative]

- Bispectrum improves constraints by $\approx 40\%$
- 1σ constraint of $\sigma_{M_\nu} = 0.013$ eV [including *Planck*]



Euclid Forecast, Chudaykin+19

MORE STATISTICS = MORE INFORMATION

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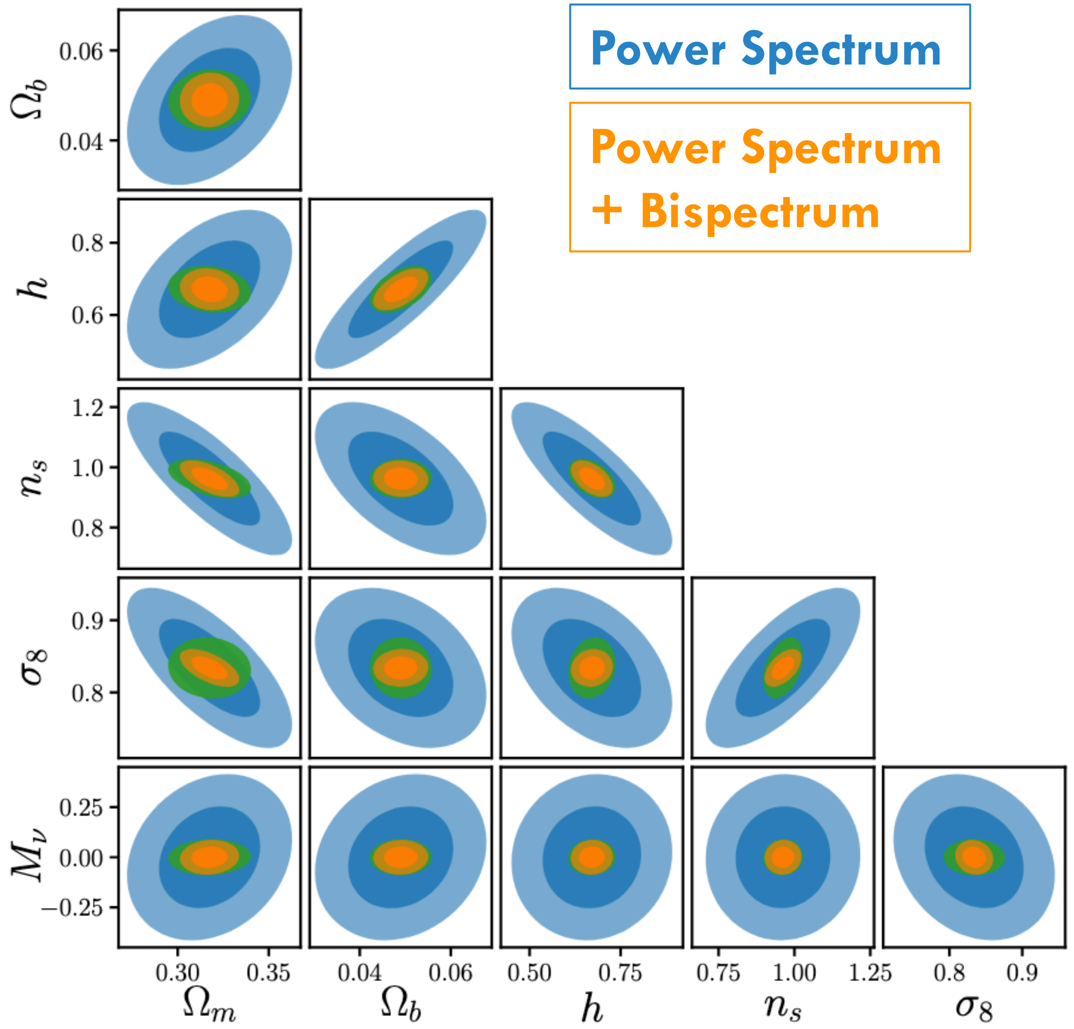
- **Sharpen** cosmological **constraints**!

<u>Simulation-Based Forecast</u>

- Bispectrum improves constraints by $> 2\times$

- Neutrino constraint improves by $5\times$



$1h^{-3}\mathrm{Gpc}^3$ *volume*, Hahn+20

*Marginalizing over HODs, with $k_{\max} = 0.5h\ \mathrm{Mpc}^{-1}$.

NON-GAUSSIAN INFLATION

*Are the primordial perturbations **Gaussian** and **adiabatic**?*

Standard Model of Inflation:

- Scalar field ϕ rolling down a potential $V(\phi)$

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)\right]$$

Gravity *Kinetic Energy* *Potential*

- Action, S, encodes **statistics** of the **primordial** curvature perturbations, ζ

Second Order ⇒ Power Spectrum

$$S^{(2)} \Rightarrow P_\zeta(k) \approx A_s k^{n_s-4}$$

Third Order ⇒ Bispectrum

$$S^{(3)} \Rightarrow B_\zeta(\mathbf{k}_1, \mathbf{k}_2) \approx \frac{6}{5} f_{\mathrm{NL}} P_\zeta(k_1) P_\zeta(k_2) + 2 \text{ perms.}$$

Generates **non-Gaussianity** proportional to f_{NL}

NON-GAUSSIAN INFLATION

$$B_\zeta(\mathbf{k}_1, \mathbf{k}_2) \approx \frac{6}{5} f_{\rm NL} P_\zeta(k_1) P_\zeta(k_2) + 2 \text{ perms.}$$

The **consistency condition** states that

$$\lim_{k_1 \to 0} B_\zeta(\mathbf{k}_1, \mathbf{k}_2) = (1 - n_s) P_\zeta(k_1) P_\zeta(k_2)$$

$$f_{\rm NL} \sim (1 - n_s) \ll 1$$

Non-Gaussianity is too small to be detected!

Non-standard inflation can beat this, e.g.

- Multifield Inflation [Local Bispectrum]
- New Kinetic Terms [Equilateral Bispectrum]
- New Vacuum States [Folded Bispectrum]

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} R - \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - V(\phi) \right]$$

Maldacena 03, Creminelli+04

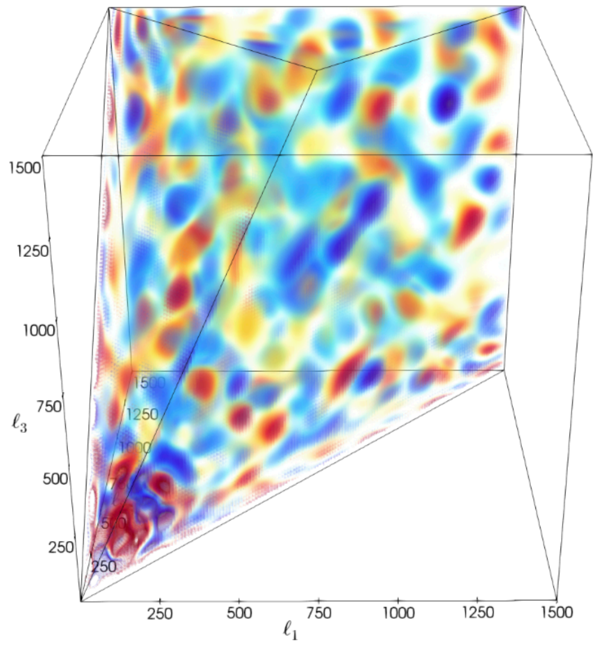
NON-GAUSSIAN INFLATION

$$B_\zeta(\mathbf{k}_1, \mathbf{k}_2) \approx \frac{6}{5} f_{\rm NL} P_\zeta(k_1) P_\zeta(k_2) + 2 \text{ perms.}$$

How do we measure Primordial non-Gaussianity?

1. **CMB Bispectrum**

Planck TTT Bispectrum



$f_{\rm NL}$ Constraints

Local	6.7 ± 5.6
Equilateral	6 ± 66
Orthogonal	−38 ± 36

Planck 2018 IX

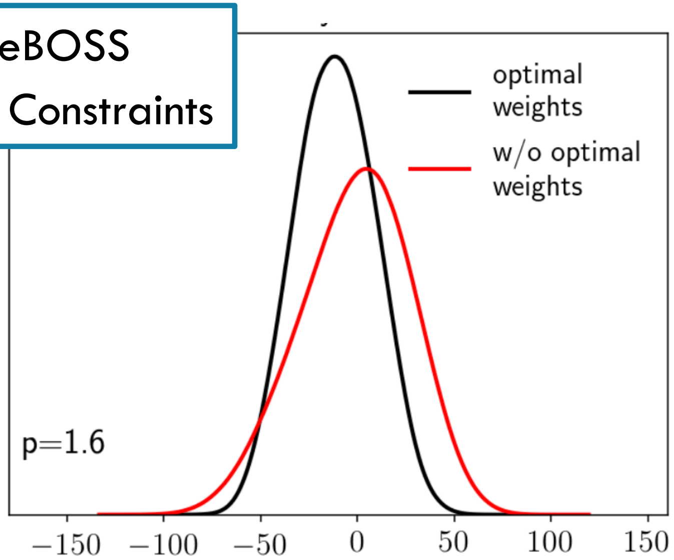
NON-GAUSSIAN INFLATION

$$B_\zeta(\mathbf{k}_1,\mathbf{k}_2) \approx \frac{6}{5} f_{\mathrm{NL}} P_\zeta(k_1) P_\zeta(k_2) + 2 \text{ perms.}$$

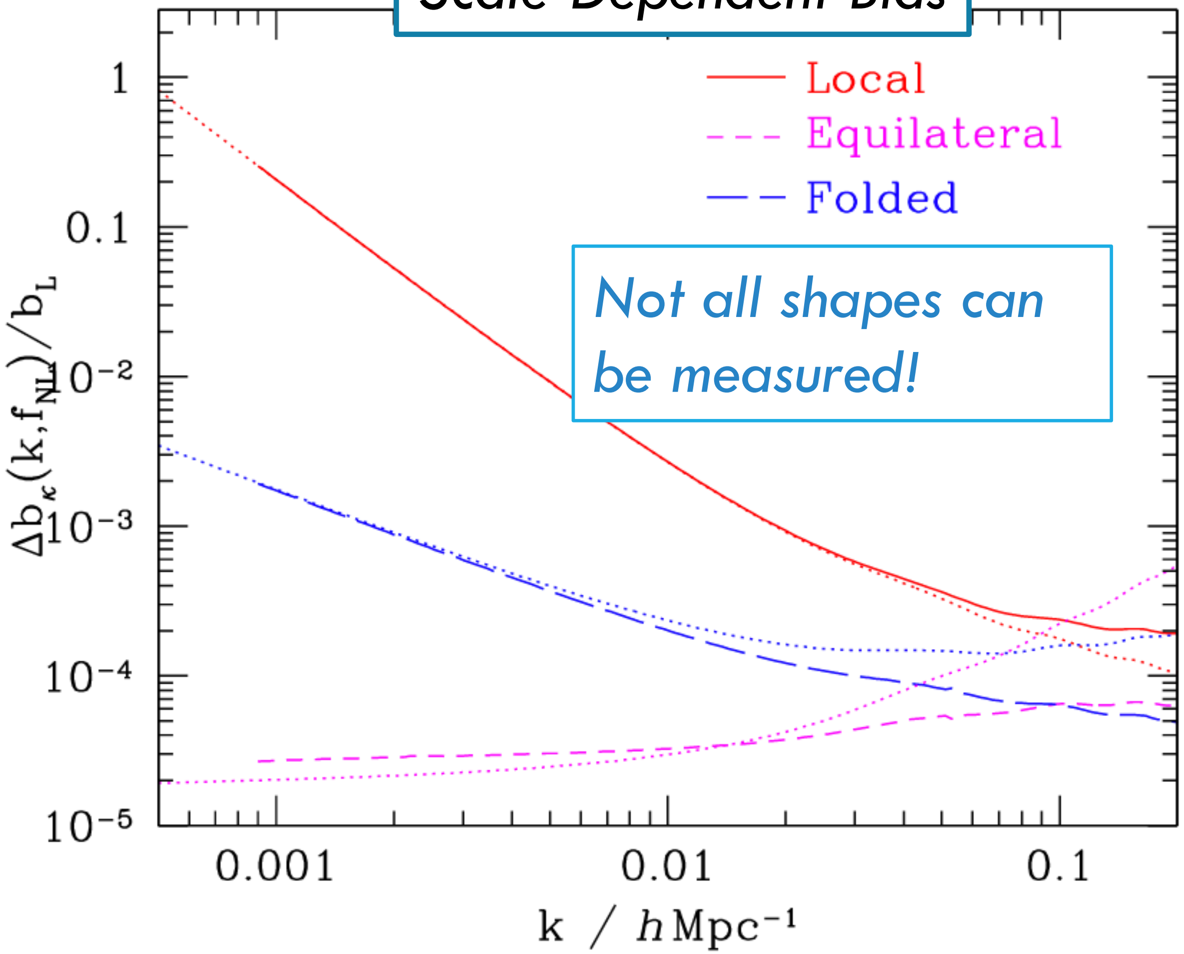
How do we measure this?

1. CMB Bispectrum
2. **Galaxy Power Spectrum**

eBOSS
$f_{\mathrm{NL}}^{\mathrm{loc}}$ Constraints



Scale-Dependent Bias



Not all shapes can be measured!

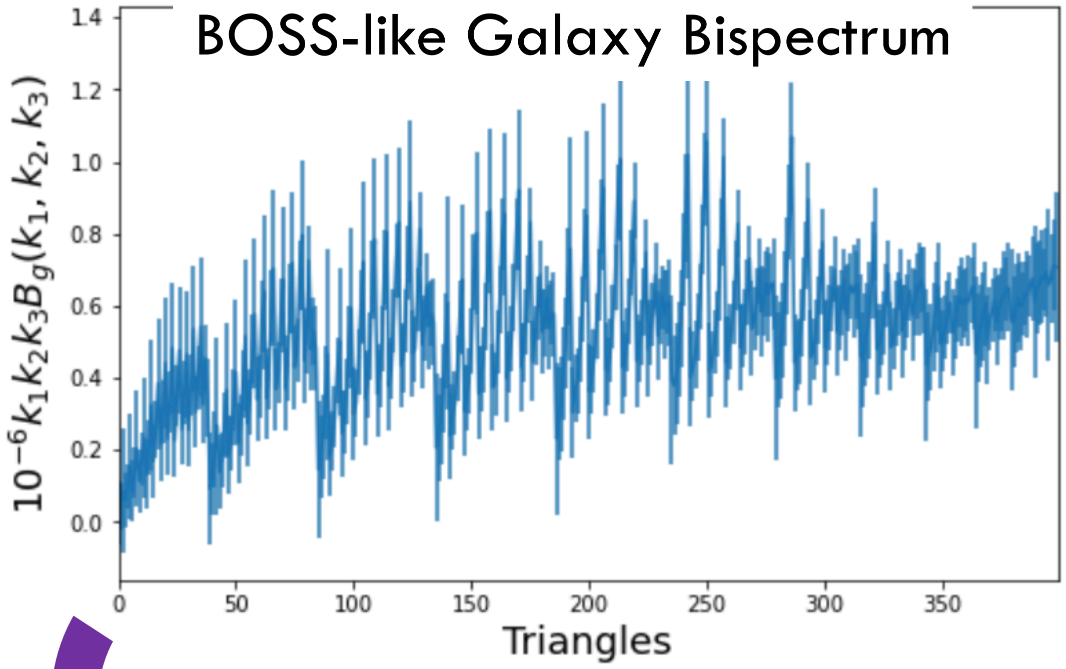
Desjacques & Seljak 10, eBOSS 21

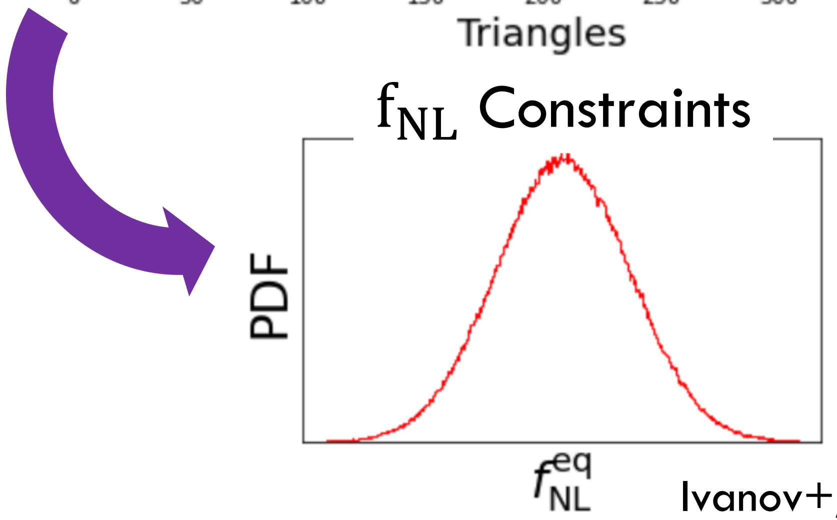
NON-GAUSSIAN INFLATION

$$B_\zeta(\mathbf{k}_1, \mathbf{k}_2) \approx \frac{6}{5} f_{\rm NL} P_\zeta(k_1) P_\zeta(k_2) + 2 \text{ perms.}$$

How do we measure this?

1. CMB Bispectrum
2. Galaxy Power Spectrum
3. **Galaxy Bispectrum**





Ivanov+, Philcox+ (in prep.)

CHERN-SIMONS INTERACTIONS VIOLATE PARITY

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) - \frac{1}{4}f(\phi)F_{\mu\nu}F^{\mu\nu} + \frac{\gamma}{4}f(\phi)F_{\mu\nu}\tilde{F}^{\mu\nu}\right]$$

- Add a **gauge field** A_μ to the inflationary action, via $F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$
- This can include a **Chern-Simons coupling** to the (pseudo-)scalar ϕ [motivated by baryogenesis]
- $f(\phi)F_{\mu\nu}\tilde{F}^{\mu\nu}$ violates **parity symmetry** ⇒ parity-violating correlators!

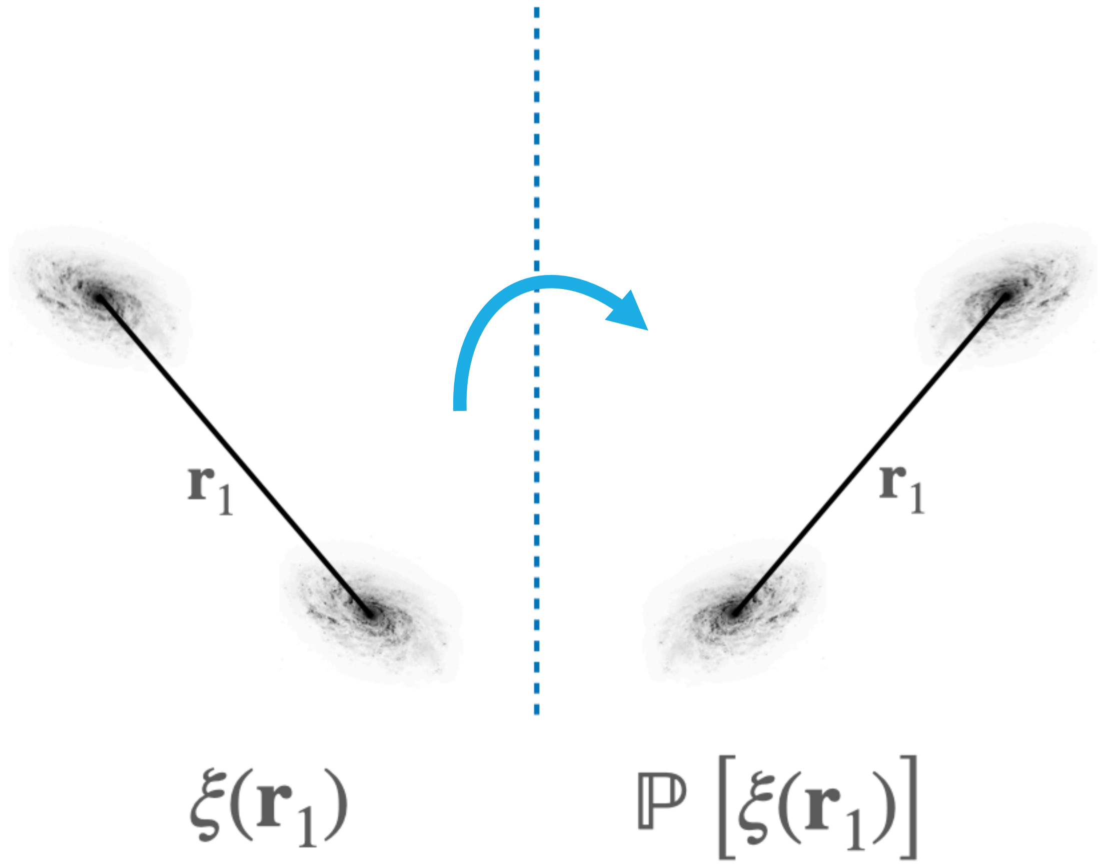
Where should we look for these signatures?

e.g. Lue+98, Alexander+11, Shiraishi 16

THE 2PCF + 3PCF ARE NOT SENSITIVE TO PARITY*

2-Point Correlation Function (2PCF):

Parity Inversion = Rotation



**Except for the polarized CMB, and redshift-space effects*

Shiraishi 16, Cahn+, Philcox+ (in prep.)

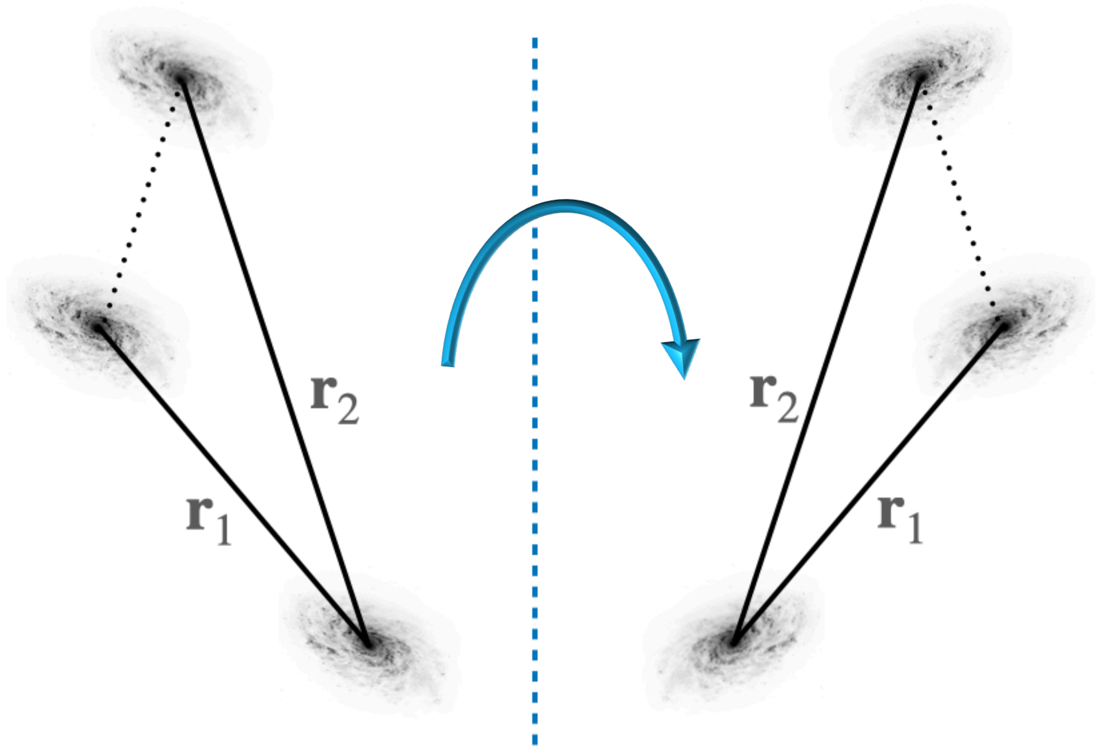
THE 2PCF + 3PCF ARE NOT SENSITIVE TO PARITY

2-Point Correlation Function (2PCF):

Parity Inversion = Rotation

3-Point Correlation Function (3PCF):

Parity Inversion = Rotation



$\zeta_3(\mathbf{r}_1, \mathbf{r}_2)$ $\quad$ $\mathbb{P}\left[\zeta_3(\mathbf{r}_1, \mathbf{r}_2)\right]$

*Except for the polarized CMB, and redshift-space effects

Shiraishi 16, Cahn+, Philcox+ (in prep.)

THE 2PCF + 3PCF ARE NOT SENSITIVE TO PARITY

2-Point Correlation Function (2PCF):

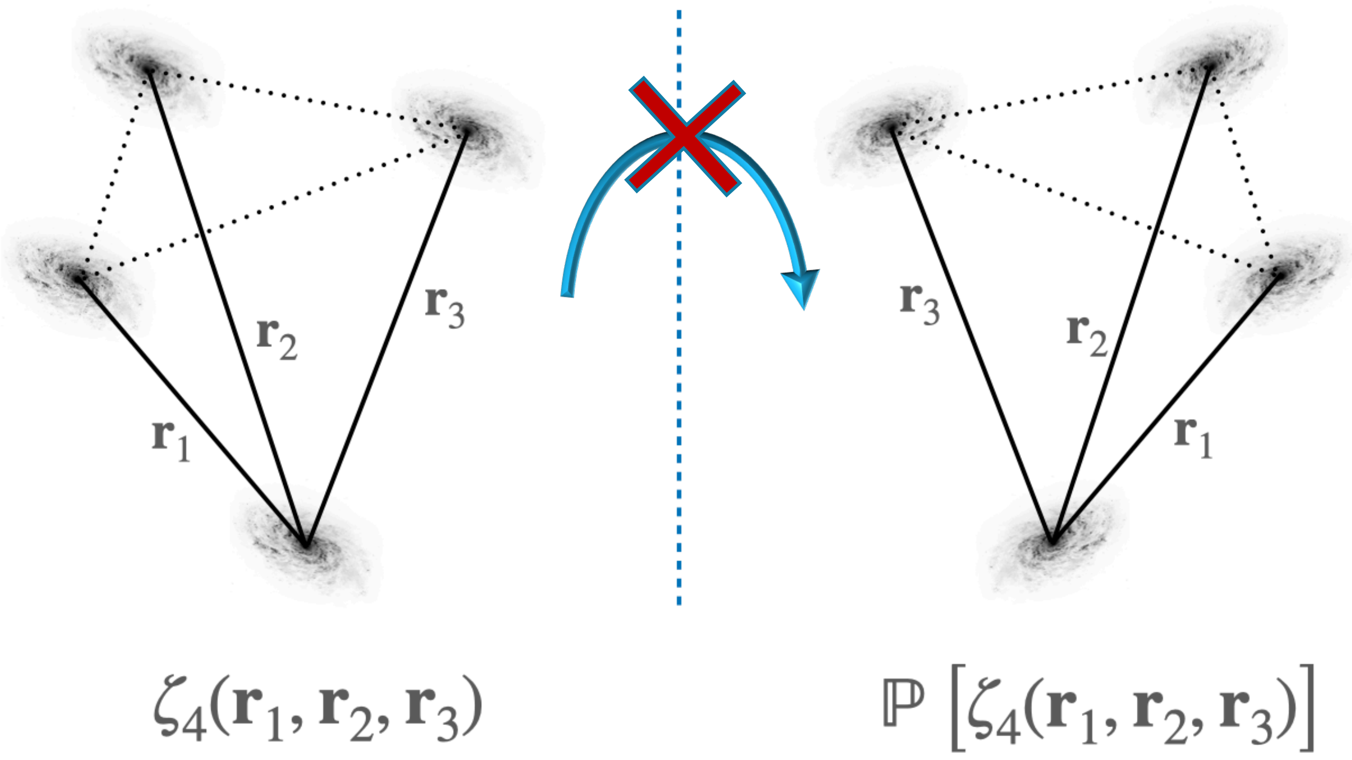
Parity Inversion = Rotation

3-Point Correlation Function (3PCF):

Parity Inversion = Rotation

4-Point Correlation Function (4PCF):

Parity Inversion ≠ Rotation



Use the 4PCF to search for Chern Simons terms!

Except for the polarized CMB, and redshift-space effects

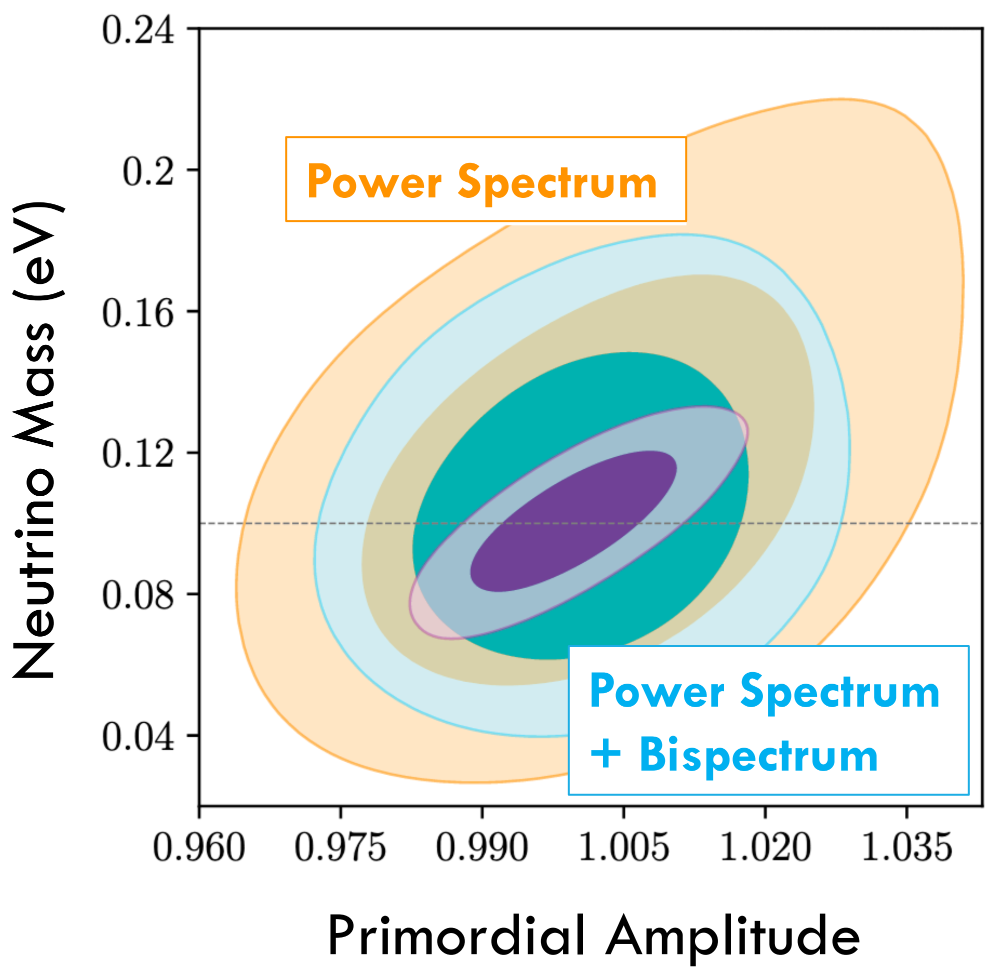
Shiraishi 16, Cahn+, Philcox+ (in prep.)

WHY USE HIGHER-ORDER STATISTICS?

- **Sharpen** parameter constraints!
- **Break** parameter **degeneracies**!
- Test **non-standard** physics models!

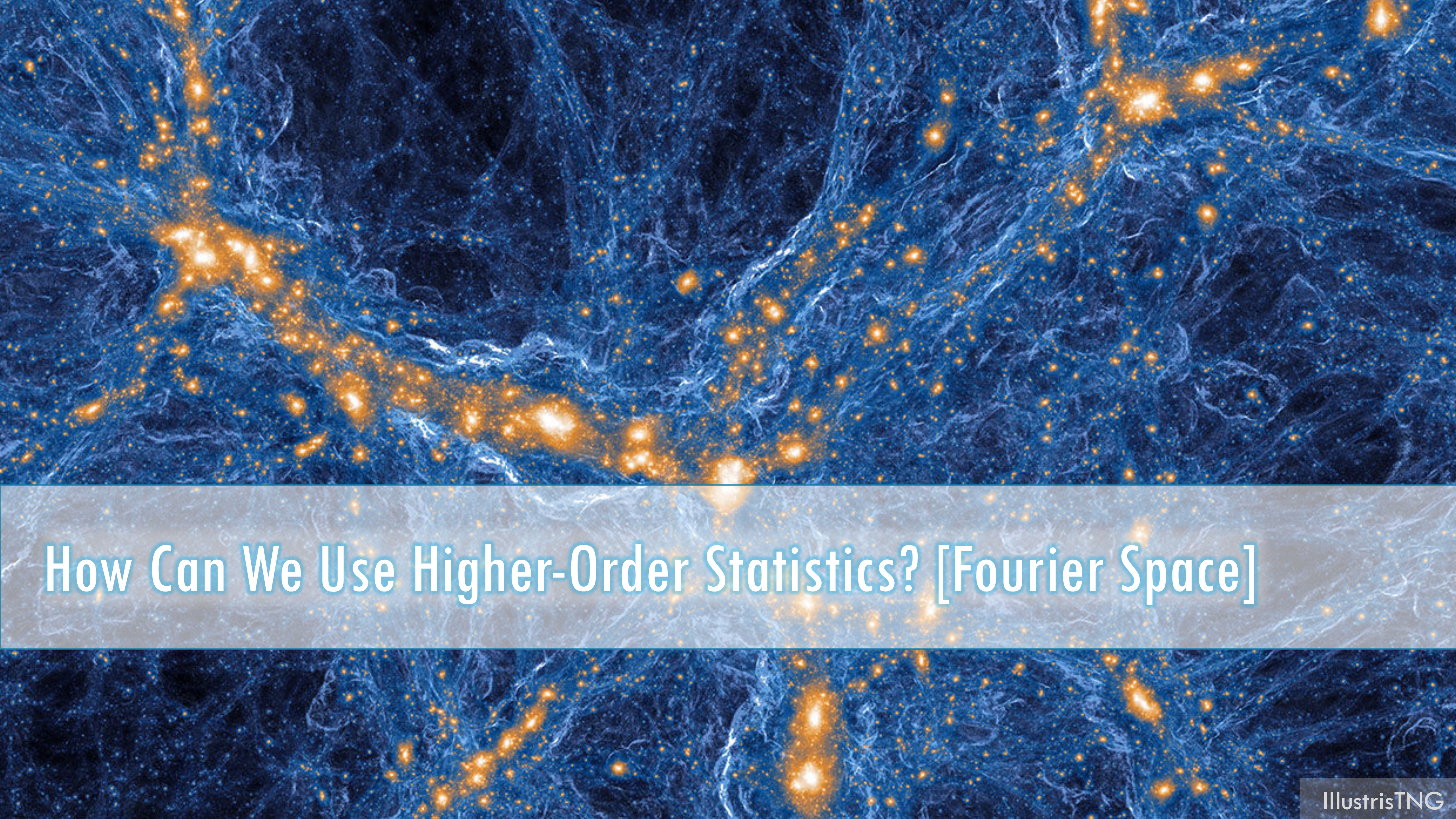
Why Use Large Scale Structure?

- Signal-to-Noise $\sim k_{\mathrm{max}}^3$, unlike $\sim \ell_{\mathrm{max}}^2$ for CMB
- New physics constraints **don't** dilute with redshift



Euclid Forecast, Chudaykin+19

How Can We Use Higher-Order Statistics? [Fourier Space]



HOW TO MEASURE A BISPECTRUM

Problem: We don't measure the density field directly.

$$\delta_g(\mathbf{r}) \to W(\mathbf{r})\delta_g(\mathbf{r}) \qquad \delta(\mathbf{k}) \to \int \frac{d\mathbf{p}}{(2\pi)^3} W(\mathbf{k}-\mathbf{p})\delta(\mathbf{p})$$

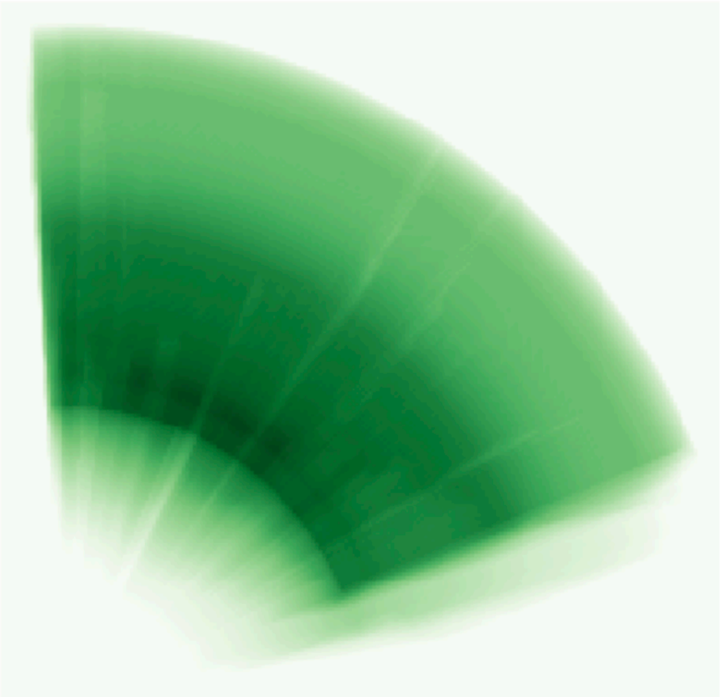
Window Function

The measured bispectrum is a triple **convolution**

$$B_g(\mathbf{k}_1,\mathbf{k}_2) \to \int_{\mathbf{p}_1\mathbf{p}_2} W(\mathbf{k}_1-\mathbf{p}_1)W(\mathbf{k}_2-\mathbf{p}_2)W(\mathbf{p}_1+\mathbf{p}_2-\mathbf{k}_1-\mathbf{k}_2)B_g(\mathbf{p}_1,\mathbf{p}_2)$$

Solution: Convolve the **theory model** too

$$\hat{B}_g(k_1,k_2,k_3) = \int_{\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3\in\mathrm{bins}} \delta_g(\mathbf{k}_1)\delta_g(\mathbf{k}_2)\delta_g(\mathbf{k}_3)(2\pi)^3\delta_{\mathrm{D}}\left(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3\right)$$



Survey Window Function

BOSS DR12, Low-z NGC
Sugiyama+18, Philcox 21

CONVOLUTION IS EXPENSIVE

$$B_g^{\mathrm{win}}(\mathbf{k}_1,\mathbf{k}_2) = \int_{\mathbf{p}_1\mathbf{p}_2} W(\mathbf{k}_1-\mathbf{p}_1)W(\mathbf{k}_2-\mathbf{p}_2)W(\mathbf{p}_1+\mathbf{p}_2-\mathbf{k}_1-\mathbf{k}_2)B_g(\mathbf{p}_1,\mathbf{p}_2)$$

- Window convolution is too costly to do repeatedly!

- Common approximation: apply the window **only** to the power spectrum

$$B_g(\mathbf{k}_1,\mathbf{k}_2) \supset P_L(k_1)P_L(k_2)$$

But:

- This gives **systematic shifts** on large scales
- Spectra cannot be used to search for new physics!

Gil-Marin 15,17, Sugiyama+18, Philcox 21

BISPECTRA WITHOUT WINDOWS

New Approach

- Start from the **likelihood** for data **d,** using an Edgeworth expansion

$$L[\mathbf{d}](\mathbf{b}) = L_G[\mathbf{d}](\mathbf{b}) \left[1 + \frac{1}{3!}\mathsf{B}^{ijk}\left\{\left[\mathsf{C}^{-1}\mathbf{d}\right]_i \left[\mathsf{C}^{-1}\mathbf{d}\right]_j \left[\mathsf{C}^{-1}\mathbf{d}\right]_k - \left(\mathsf{C}^{-1}_{ij} d_k + 2 \text{ perms.}\right)\right\} + \cdots\right]$$

Gaussian Piece   Three-Point Function, $\mathsf{B}^{ijk} \equiv \langle d^i d^j d^k \rangle$ Covariance, $\mathsf{C}^{ij} = \langle d^i d^j \rangle$

- This depends on **survey geometry** through C^{ij} and **bispectrum** through B^{ijk}

$$\boxed{\nabla_{\mathbf{b}} \log L[\mathbf{d}](\mathbf{b}) = \mathbf{0}}$$

- Optimize for true bispectrum, **b:** $\boxed{\hat{b}^{\mathrm{ML}}_\alpha = \sum_\beta F^{-1,\mathrm{ML}}_{\alpha\beta} \hat{q}^{\mathrm{ML}}_\beta,}$

$$\boxed{\hat{q}^{\mathrm{ML}}_\alpha = \frac{1}{6}\mathsf{B}^{ijk}_{,\alpha}\left[\mathsf{C}^{-1}\mathbf{d}\right]_i \left(\left[\mathsf{C}^{-1}\mathbf{d}\right]_j \left[\mathsf{C}^{-1}\mathbf{d}\right]_k - 3\mathsf{C}^{-1}_{jk}\right)}$$

Cubic Estimator

$$\boxed{F^{\mathrm{ML}}_{\alpha\beta} = \frac{1}{6}\mathsf{B}^{ijk}_{,\alpha}\mathsf{B}^{lmn}_{,\beta}\mathsf{C}^{-1}_{il}\mathsf{C}^{-1}_{jm}\mathsf{C}^{-1}_{kn},}$$

Fisher Matrix

Philcox 20, 21

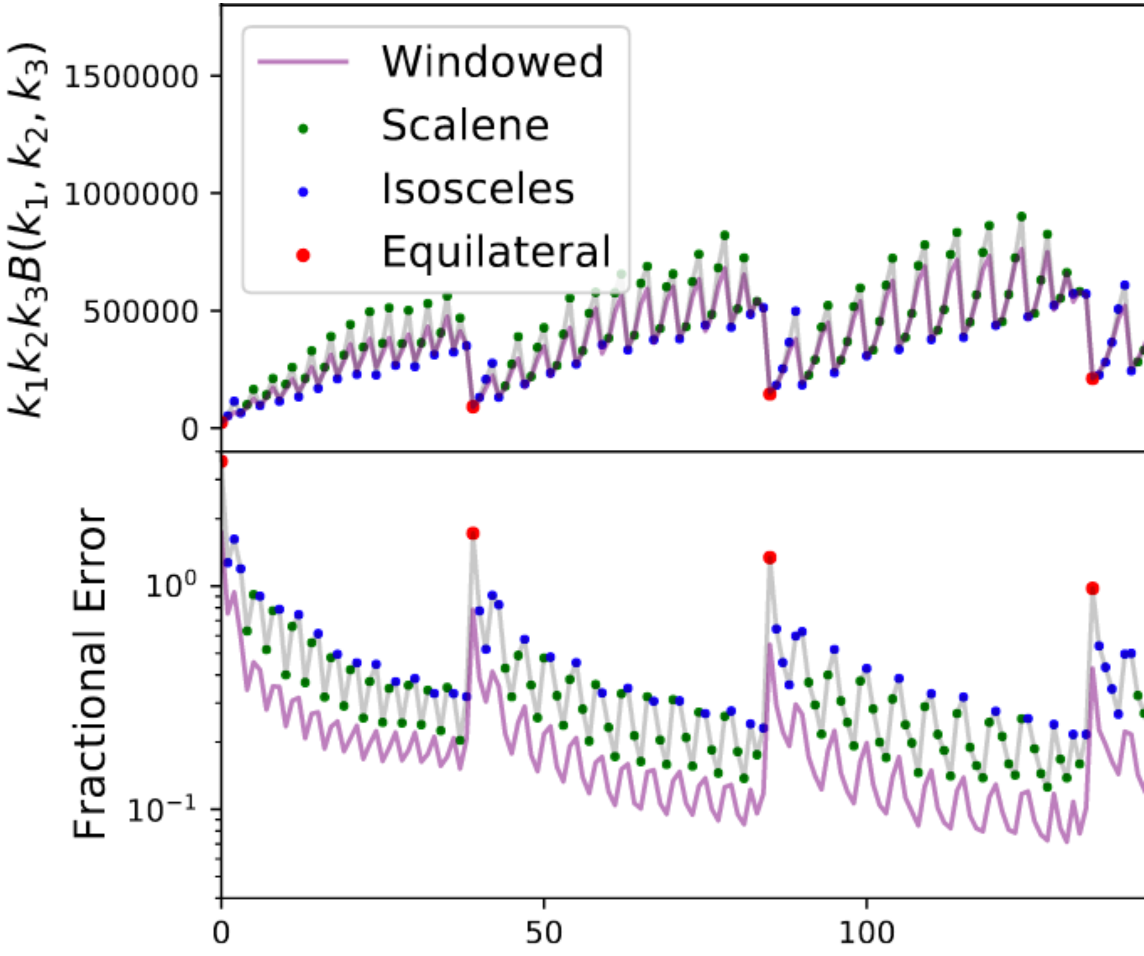
BISPECTRA WITHOUT WINDOWS

$$\hat{b}_\alpha^{\mathrm{ML}} = \sum_\beta F_{\alpha\beta}^{-1,\mathrm{ML}} \hat{q}_\beta^{\mathrm{ML}},$$

Properties of the **cubic estimator:**

1. Unbiased
2. Minimum variance [as $B(k_1, k_2, k_3) \to 0$]
3. Window-free [effectively a deconvolution]

▷ Requires various tricks for dealing with high-dimensional data [e.g. conjugate gradient descent, Monte Carlo estimation etc.]



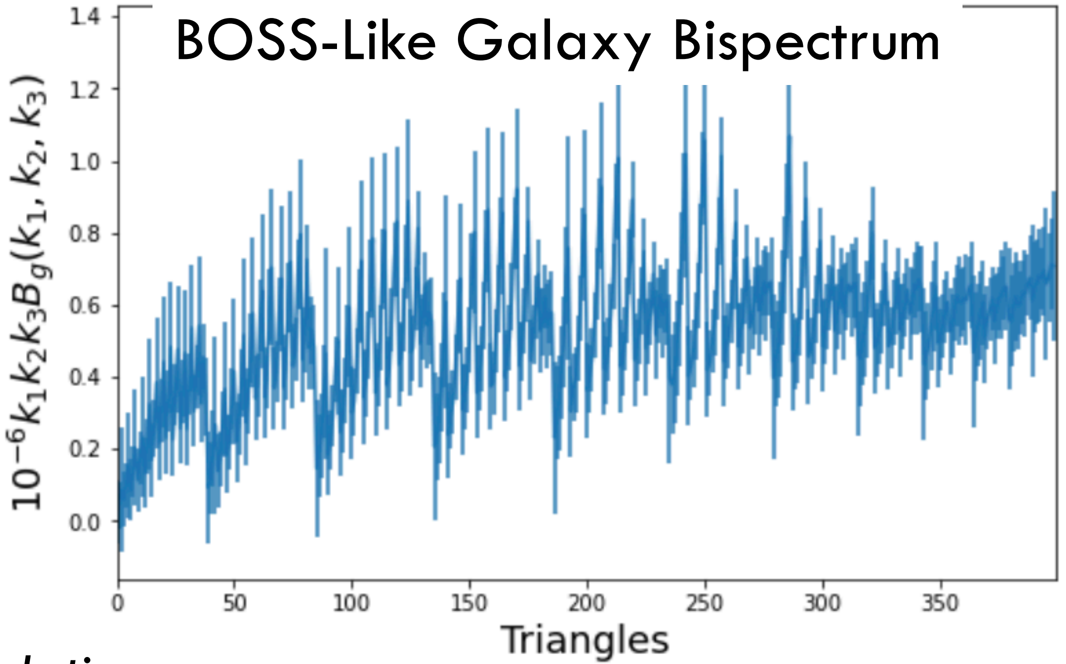
See GitHub.com/oliverphilcox/BOSS-Without-Windows

Philcox 20, 21

TOWARDS A ROBUST BISPECTRUM ANALYSIS

Bispectrum Model Ingredients:

- ~~Window Function~~
- Tree-Level Perturbation Theory
- Redshift-Space Distortions
- Alcock-Paczynski Effects
- Infrared Resummation
- Discreteness Effects



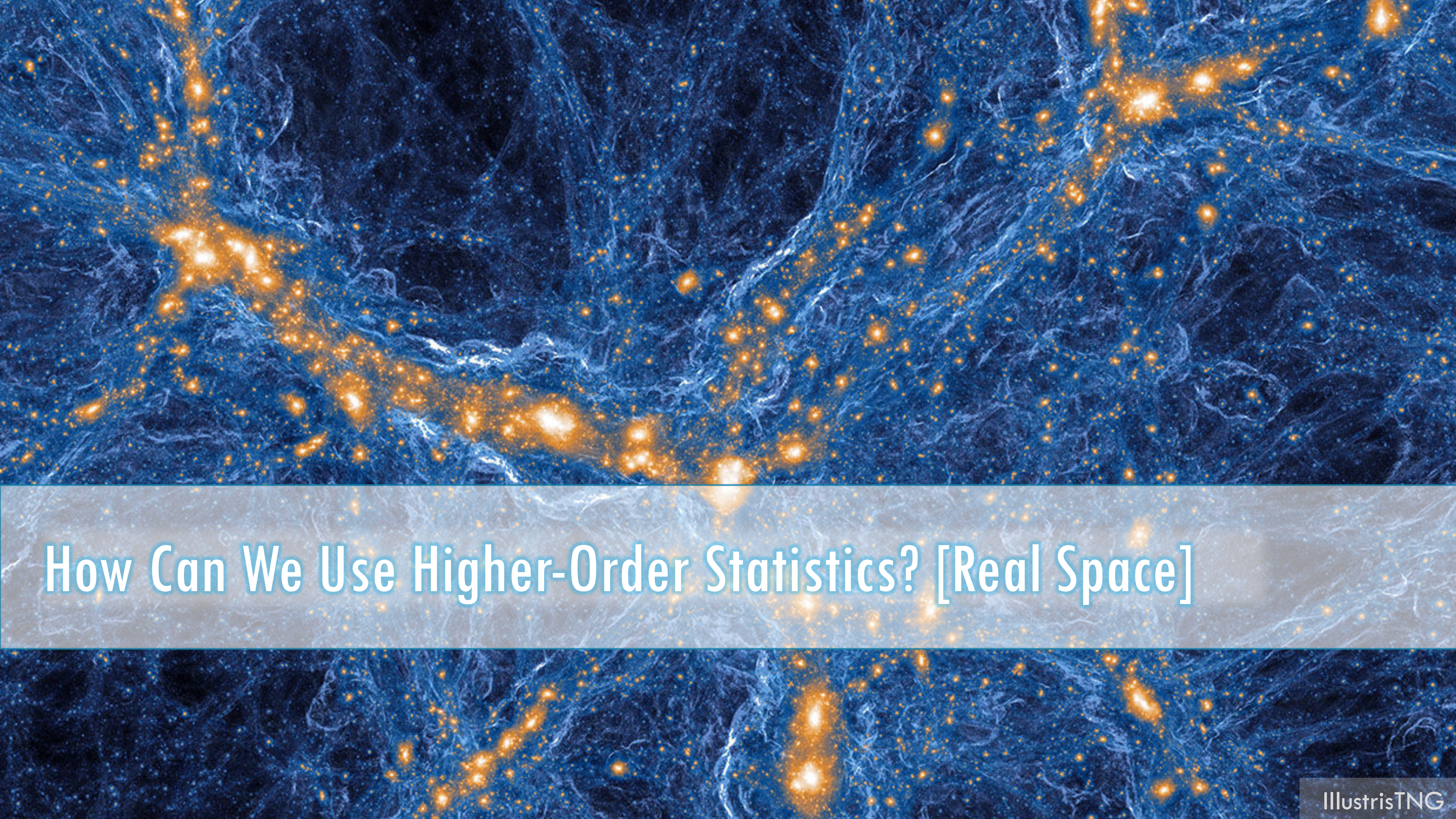
Theory model under development using high-resolution simulations

Applications:

1. Sharper constraints on cosmological parameters ($\approx 20\%$)
2. Primordial Non-Gaussianity Measurements, e.g. $\sigma_{f_{\rm NL}^{\rm eq}} \approx 500$

Patchy Simulations, NGC-z1 Region
Ivanov+, Philcox+ (in prep.)

How Can We Use Higher-Order Statistics? [Real Space]



IllustrisTNG

HOW TO MEASURE A CORRELATION FUNCTION

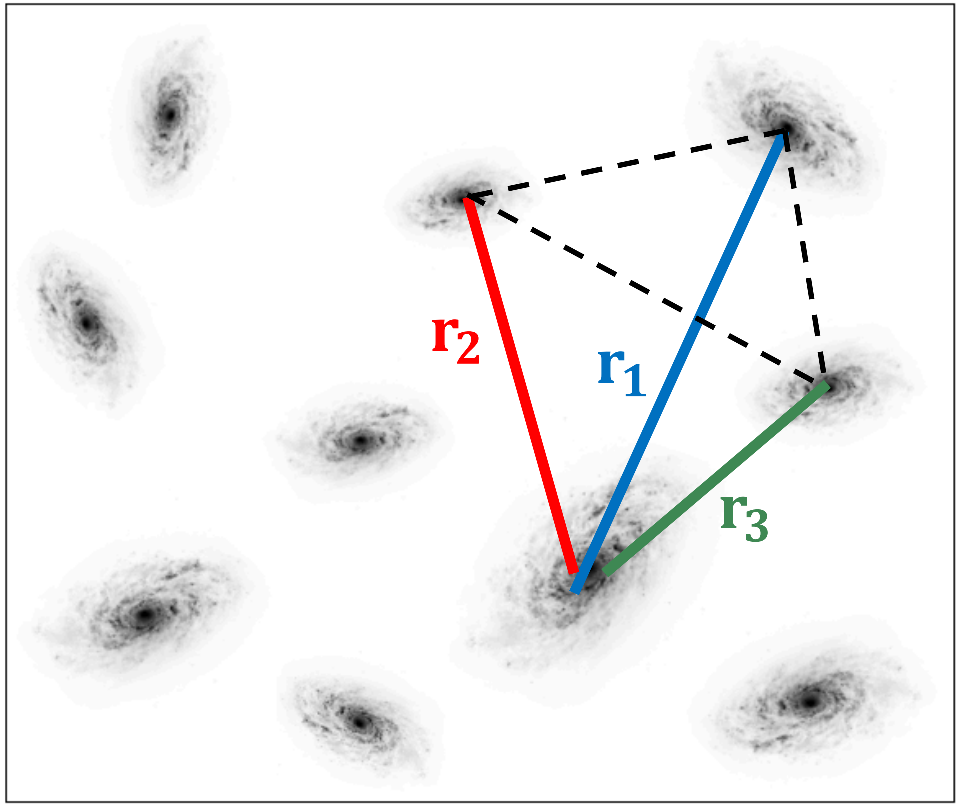
$$\hat{\zeta}_{g,4}(r_1, r_2, r_3, \hat{\mathbf{r}}_1 \cdot \hat{\mathbf{r}}_2, \hat{\mathbf{r}}_1 \cdot \hat{\mathbf{r}}_3, \hat{\mathbf{r}}_2 \cdot \hat{\mathbf{r}}_3) = \int \frac{d\mathbf{x}}{V} \int_{\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3 \in \mathrm{bins}} \delta_g(\mathbf{x})\delta_g(\mathbf{x}+\mathbf{r}_1)\delta_g(\mathbf{x}+\mathbf{r}_2)\delta_g(\mathbf{x}+\mathbf{r}_3)$$

Measuring the 4PCF involves counting **quadruplets** of galaxies

Total number of quadruplets:

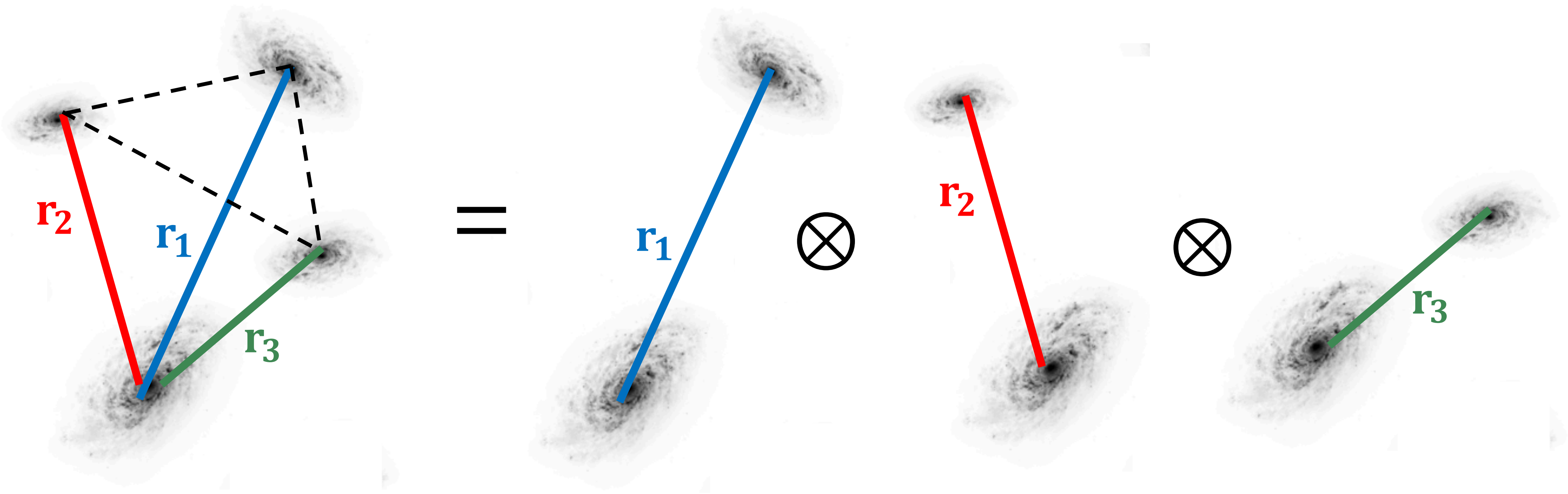
$$\mathcal{O}(N_{\mathrm{gal}}^4)$$

This is too many to count…



Philcox+21

ONE TETRAHEDRON $=$ THREE VECTORS



3 lengths + 3 angles

$(r_1, r_2, r_3, \hat{\mathbf{r}}_1 \cdot \hat{\mathbf{r}}_2, \hat{\mathbf{r}}_1 \cdot \hat{\mathbf{r}}_3, \hat{\mathbf{r}}_2 \cdot \hat{\mathbf{r}}_3)$

1 length + 1 direction

$(r_1, \hat{\mathbf{r}}_1)$

1 length + 1 direction

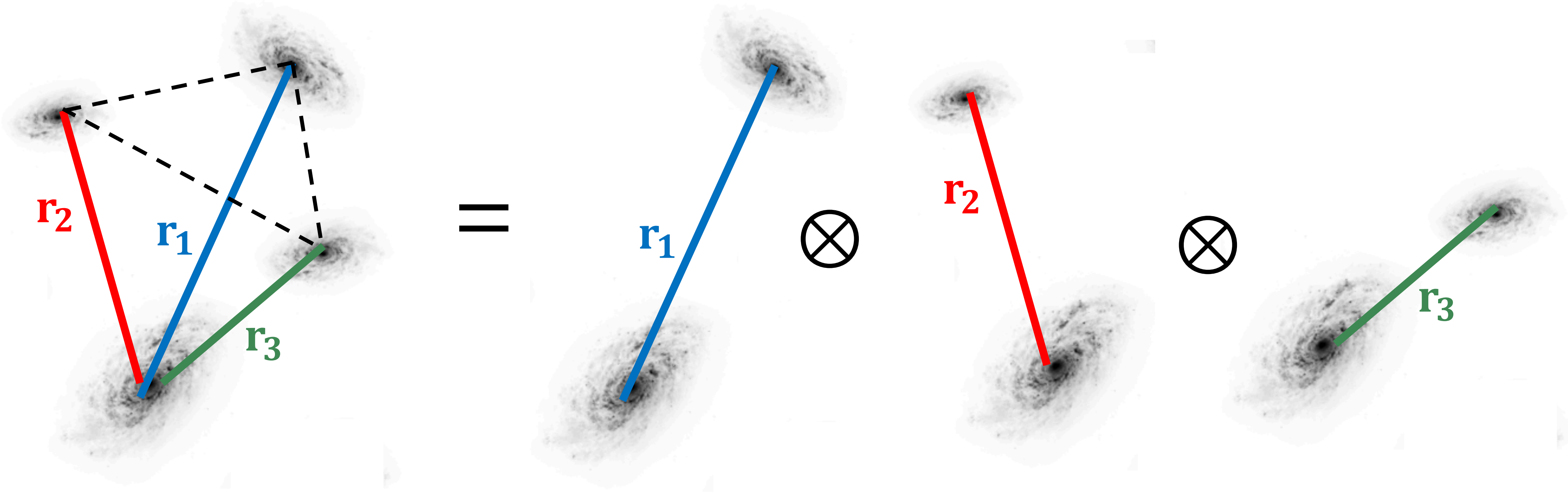
$(r_2, \hat{\mathbf{r}}_2)$

1 length + 1 direction

$(r_3, \hat{\mathbf{r}}_3)$

Philcox+21

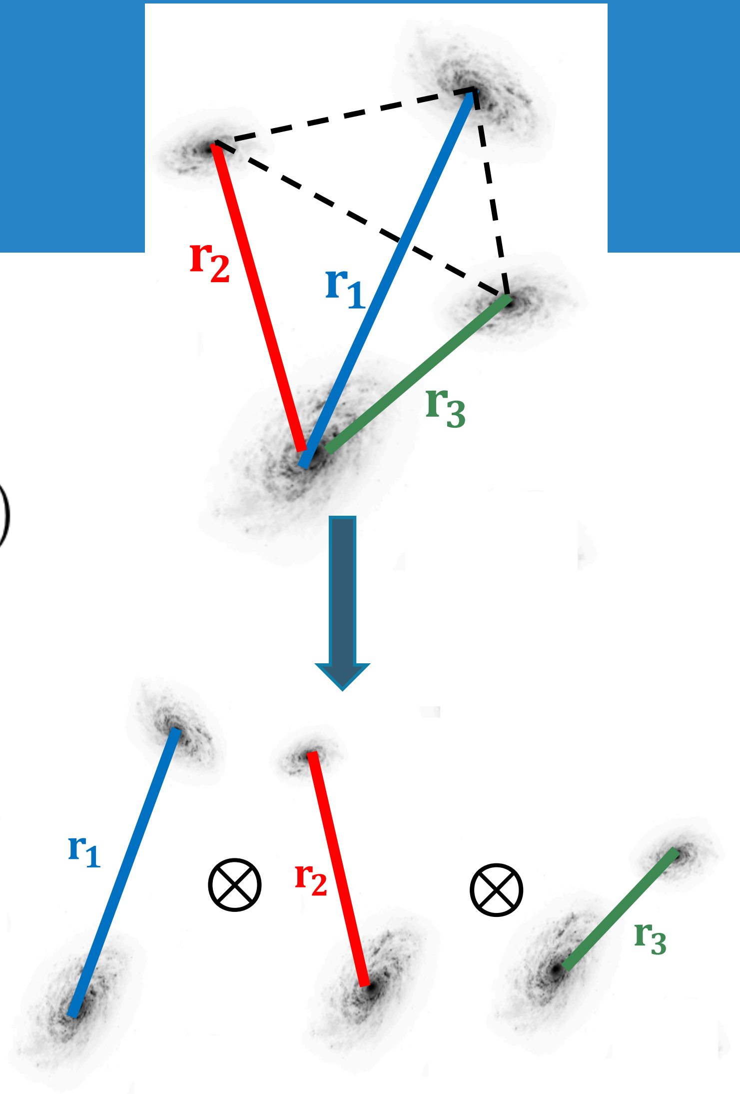
ONE TETRAHEDRON = THREE VECTORS



3 lengths + 3 multipoles	*1 length + 2 multipoles*	*1 length + 2 multipoles*	*1 length + 2 multipoles*
$(r_1, r_2, r_3, \ell_1, \ell_2, \ell_3)$	(r_1, ℓ_1, m_1)	(r_2, ℓ_2, m_2)	(r_3, ℓ_3, m_3)

Philcox+21

ANGULAR MOMENTUM BASIS



Expand (isotropic) 4PCF in basis of **isotropic functions**

$$\zeta_4(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = \sum_{\ell_1\ell_2\ell_3} \underbrace{\zeta_{\ell_1\ell_2\ell_3}}_{\text{Coefficients}}(r_1,r_2,r_3)\underbrace{\mathcal{P}_{\ell_1\ell_2\ell_3}}_{\text{Basis Functions}}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2,\hat{\mathbf{r}}_3)$$

Basis formed from **angular momentum addition** in 3D

$$\mathcal{P}_{\ell_1\ell_2\ell_3}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2,\hat{\mathbf{r}}_3) = \sum_{m_1m_2m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} Y^*_{\ell_1m_1}(\hat{\mathbf{r}}_1)Y^*_{\ell_2m_2}(\hat{\mathbf{r}}_2)Y^*_{\ell_3m_3}(\hat{\mathbf{r}}_3)$$

This is **separable** in $\hat{\mathbf{r}}_1$, $\hat{\mathbf{r}}_2$, $\hat{\mathbf{r}}_3$

Cahn+20, Philcox+21

A SEPARABLE BASIS ⇒ A QUADRATIC ESTIMATOR

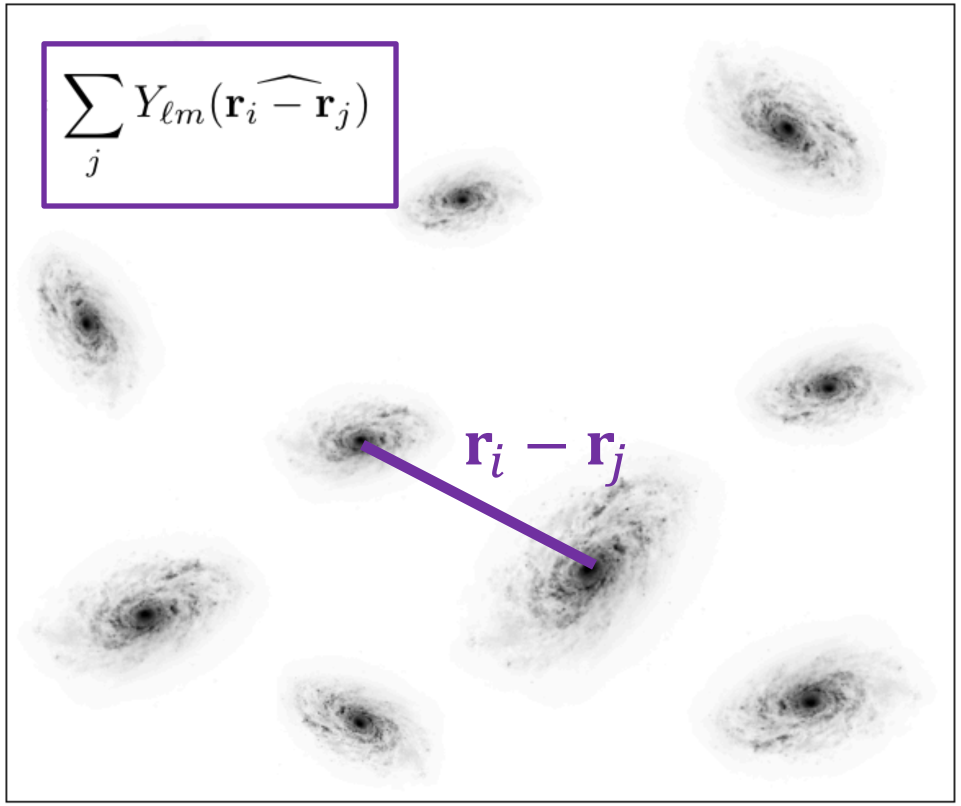
$$\hat{\zeta}_{\ell_1\ell_2\ell_3}(r_1,r_2,r_3) = \sum_{m_1m_2m_3}\begin{pmatrix}\ell_1 & \ell_2 & \ell_3\\ m_1 & m_2 & m_3\end{pmatrix}\int d\mathbf{x}\,\delta_g(\mathbf{x})\left[\int_{\mathbf{r}_1}\delta_g(\mathbf{x}+\mathbf{r}_1)Y_{\ell_1m_1}(\hat{\mathbf{r}}_1)\right]\left[\int_{\mathbf{r}_2}\delta_g(\mathbf{x}+\mathbf{r}_2)Y_{\ell_2m_2}(\hat{\mathbf{r}}_2)\right]\left[\int_{\mathbf{r}_3}\delta_g(\mathbf{x}+\mathbf{r}_3)Y_{\ell_4m_3}(\hat{\mathbf{r}}_3)\right]$$

The estimator **factorizes** into **independent** pieces

To compute the 4PCF: count *pairs* of galaxies

Total number of pairs: $\mathcal{O}\left(N_{\mathbf{gal}}^2\right)$

This *can* be computed!



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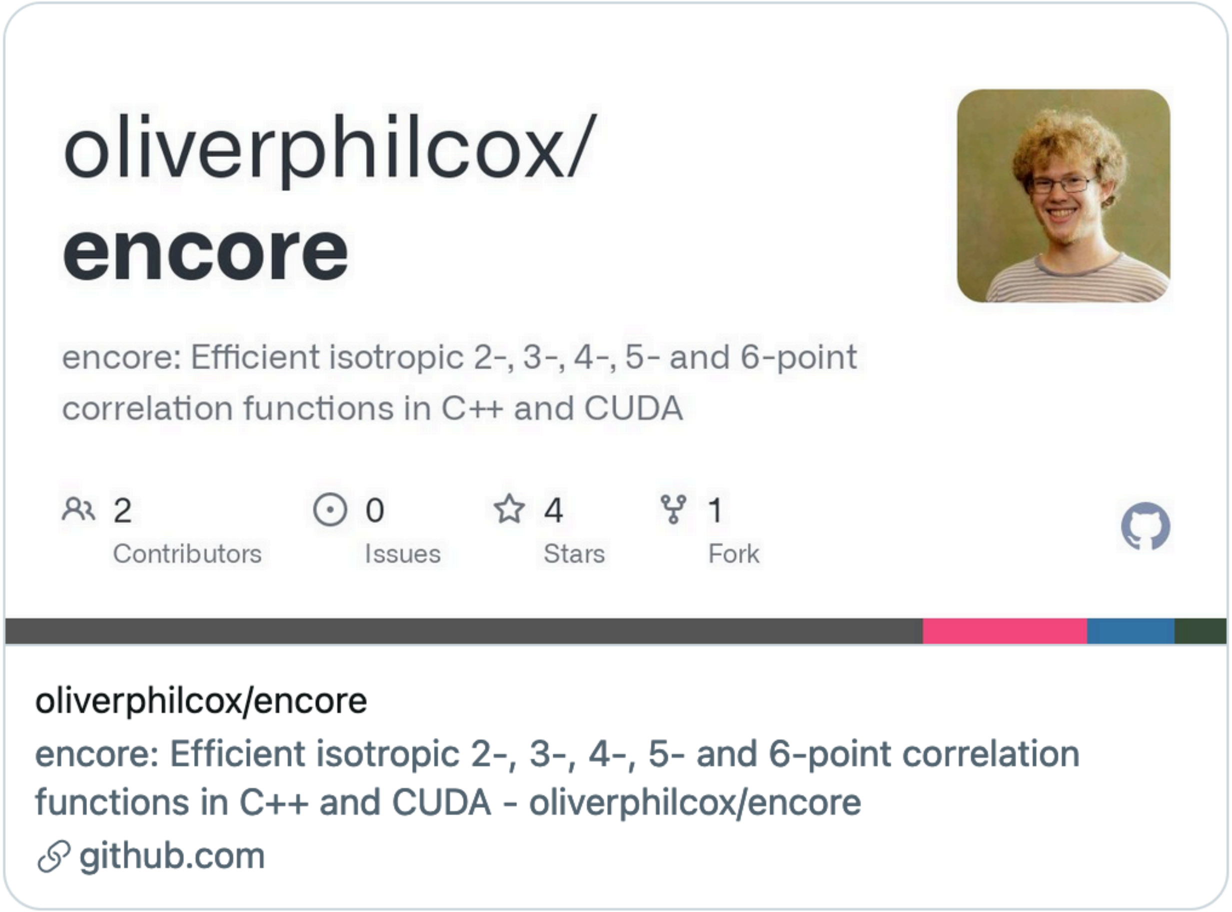
ENCORE: ULTRA-FAST N-POINT FUNCTIONS

- Public C++/CUDA code

- Computes isotropic 2-, 3-, 4-, 5- and 6-point correlation functions

- Corrects for **survey geometry**

- Requires ~ 10 CPU-hours to compute 4PCF of current data



See [GitHub.com/oliverphilcox/encore](https://github.com/oliverphilcox/encore)

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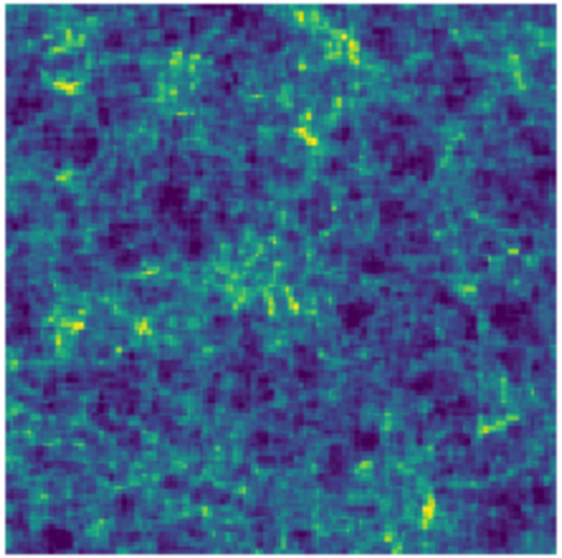
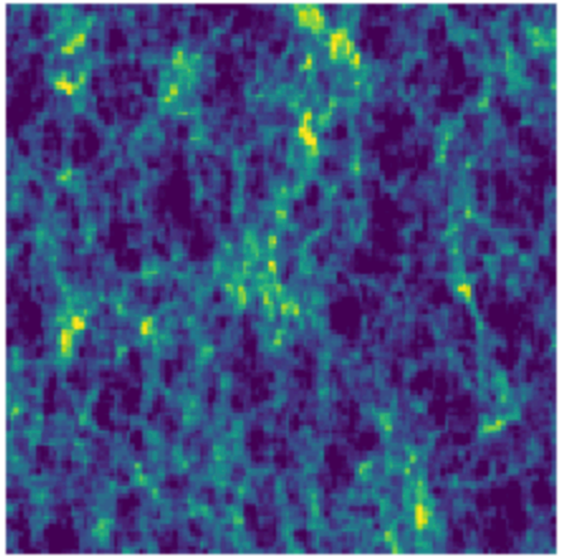
BEYOND THE 4-POINT FUNCTION

This generalizes **beyond** the 4PCF

- 5PCF, 6PCF, …
- **Anisotropic** correlation functions
- Non-Flat Universes
- Two, Three, Four, … Dimensions



Real Space



Redshift Space

Requires the addition of N angular momenta in D dimensions [*i.e.* $\mathfrak{so}(D)$ *Lie algebra*]

See GitHub.com/oliverphilcox/NPCFs.jl

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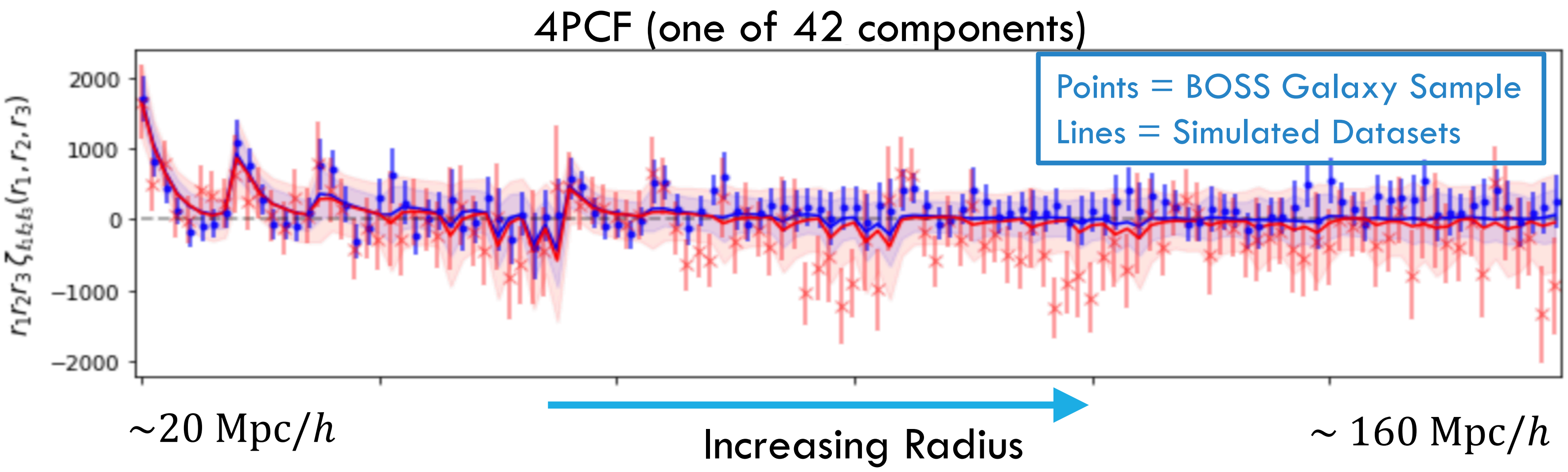
MEASURING THE 4-POINT FUNCTION

- Compute the connected 4PCF from $\sim 10^6$ **BOSS CMASS galaxies**

- Must remove **Gaussian** contribution 4PCF at the estimator level:

$$\zeta_{g,4}^{(c)} \sim \langle \delta_g \delta_g \delta_g \delta_g \rangle - [\langle \delta_g \delta_g \rangle \langle \delta_g \delta_g \rangle + 2 \text{ perms.}]$$

Do we detect a signal?



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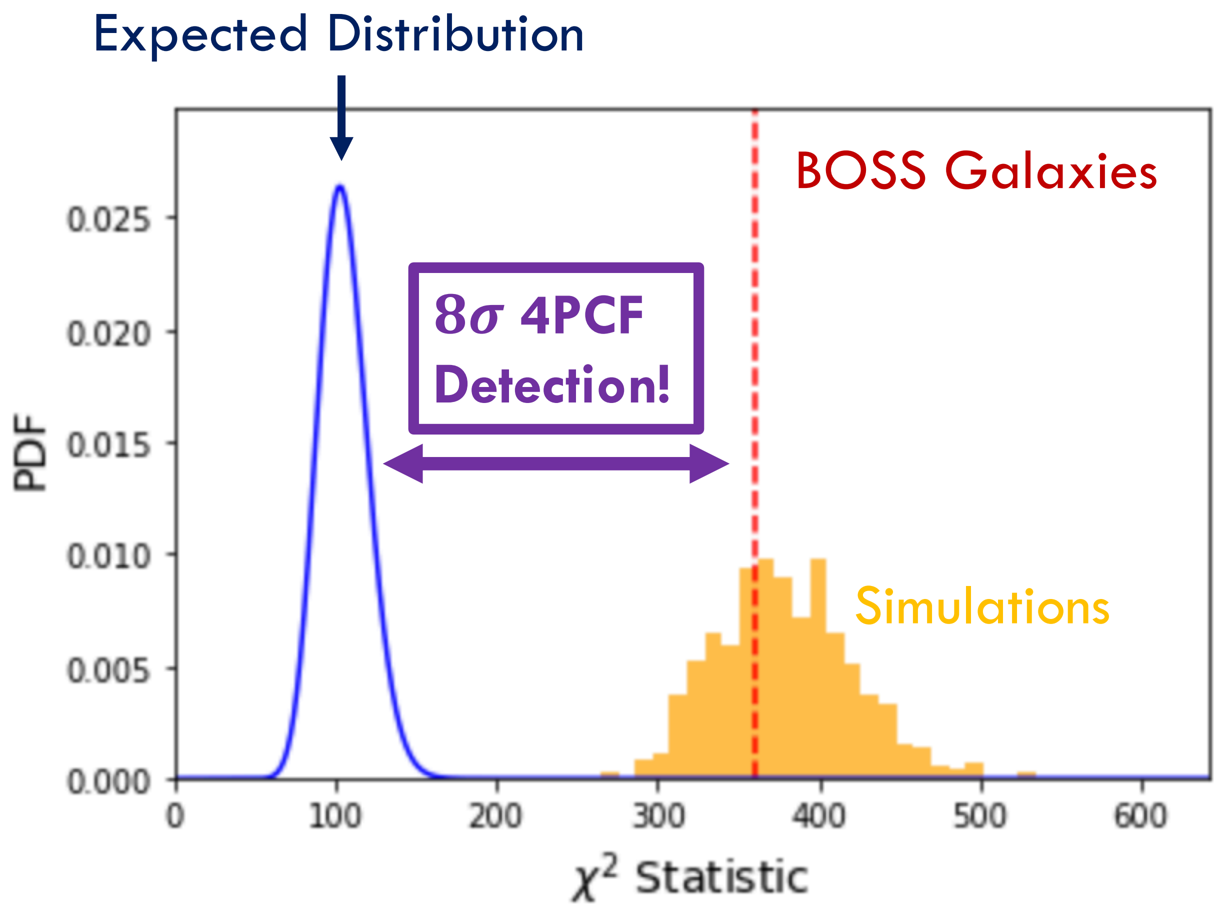
CAN WE DETECT THE GRAVITATIONAL 4PCF?

- Perform a χ^2-test to search for a **gravitational** 4PCF

- Null Hypothesis: **4PCF = 0.**

- **Strong** detection of non-Gaussianity!

- Most information is on short scales: **5σ detection for $r > 14h^{-1}$ Mpc**



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EXTRACTING INFORMATION FROM THE 4PCF

In configuration space, **windows** are easy, but **perturbation theory** is hard

- Formulate theory in Fourier-space then FT

$$\zeta_{g,4}(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = \int_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3} e^{i(\mathbf{k}_1\cdot\mathbf{r}_1+\mathbf{k}_2\cdot\mathbf{r}_2+\mathbf{k}_3\cdot\mathbf{r}_3)} T_{g,4}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

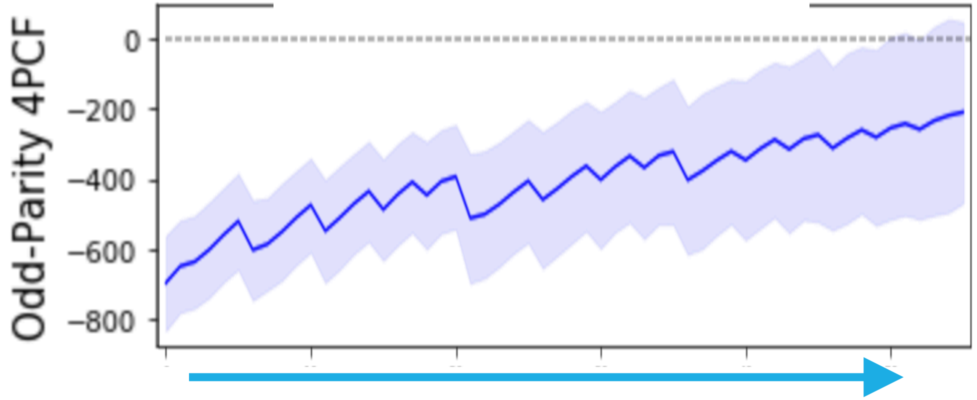
- Requires *many* coupled integrals, even at tree-level

Example: Chern-Simons 4PCF

Odd-Parity 4PCF

$$\zeta_4(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) - \mathbb{P}[\zeta_4(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)]$$

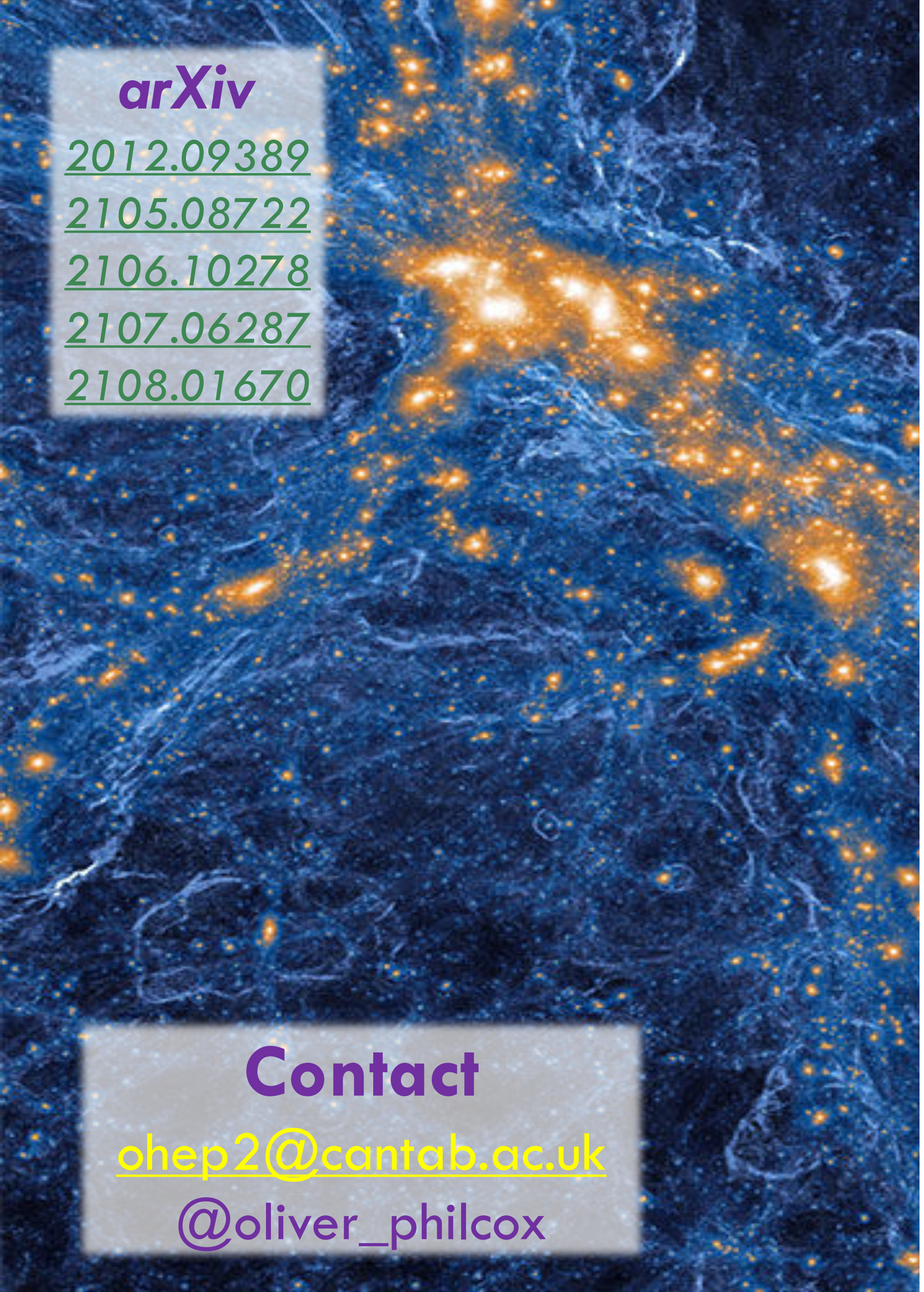
Chern-Simons 4PCF



Increasing Radius

$\sim$20 Mpc/h — $\sim$ 160 Mpc/h

Shiraishi 2016, Cahn+, Philcox+, (in prep.)



arXiv

2012.09389
2105.08722
2106.10278
2107.06287
2108.01670

CONCLUSIONS

- Non-Gaussian statistics:
  1. **Sharpen** cosmological constraints
  2. Probe **new physics** in the early Universe, e.g. f_{NL}, Chern-Simons couplings

- New methods allow statistics to be used in practice:
  1. **Bispectra** computed without **windows**
  2. **Correlation** functions compute at $\mathcal{O}(N_{gal}^2)$

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