Extracting Non-Gaussian Information from Large-scale Structure

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Theoretical and Observational Progress
on Large-scale Structure of the Universe

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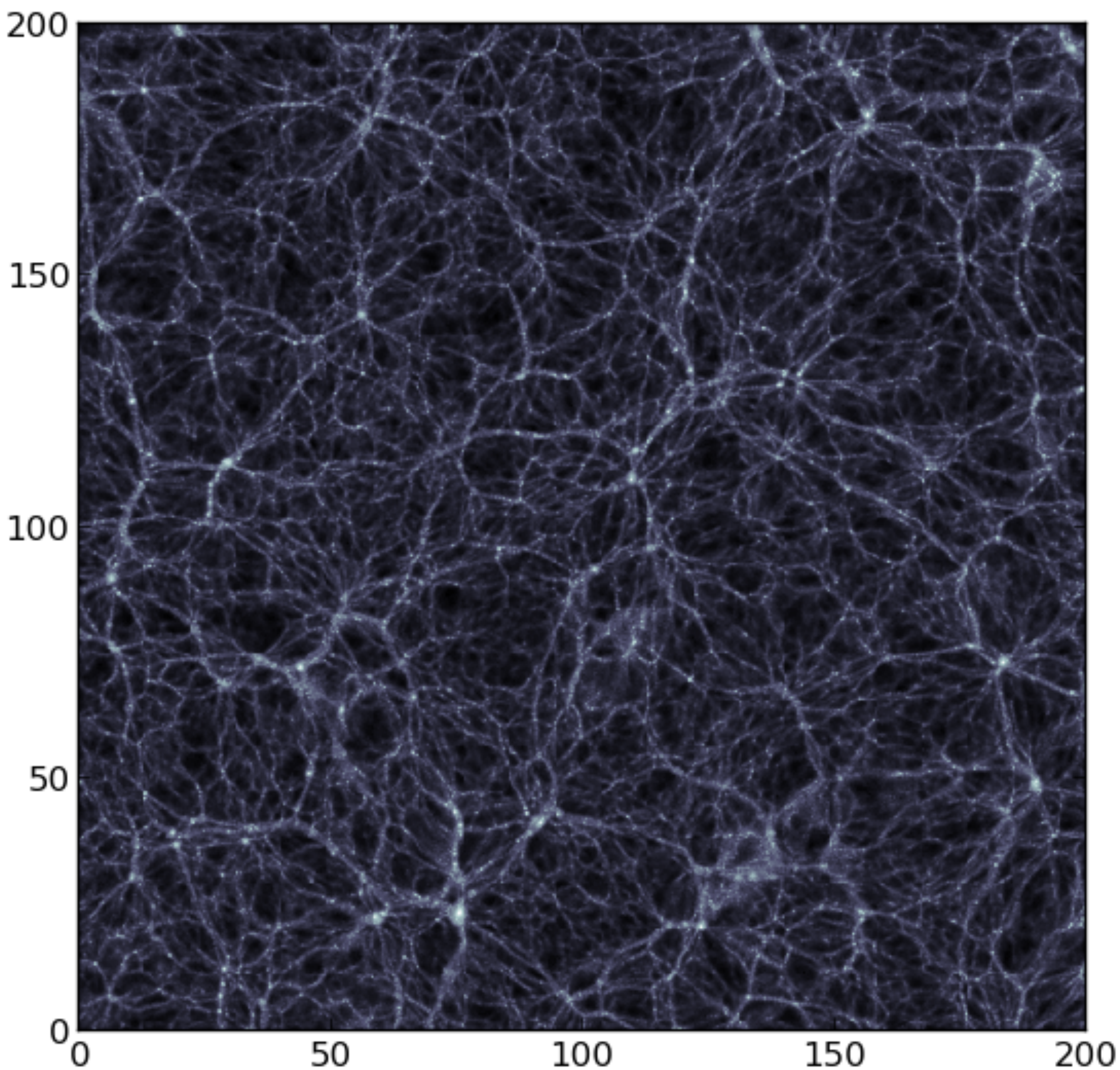
With: Alex Szalay, Donghui Jeong, Felipe Marin

Outline

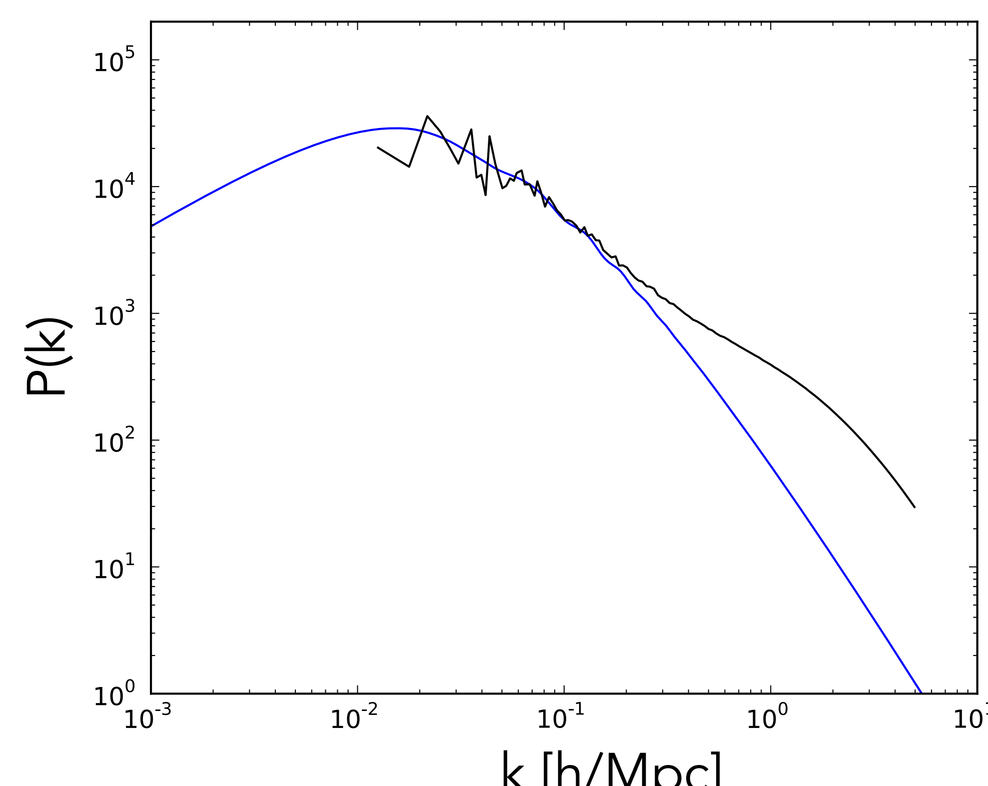
- Large-scale structure as a cosmological probe
- Beyond Gaussianity: higher-point statistics
    - Tree-level 3-point function from LPT
    - Modeling systematics
- Summary and future work

Large-scale Structure



Systematics:

- Time evolution of matter distribution (nonlinearity)
- Galaxy bias
- Redshift-space distortions



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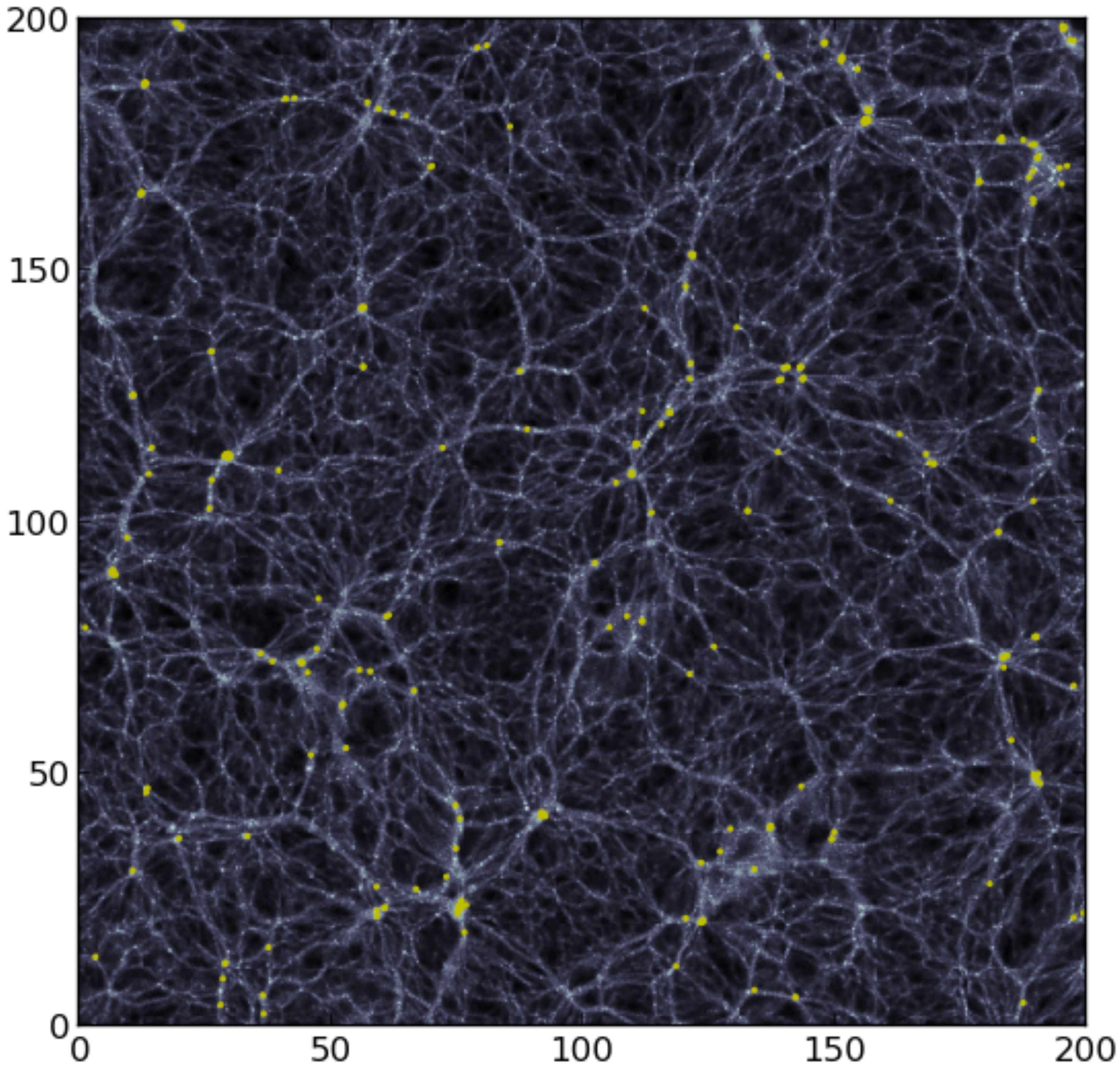

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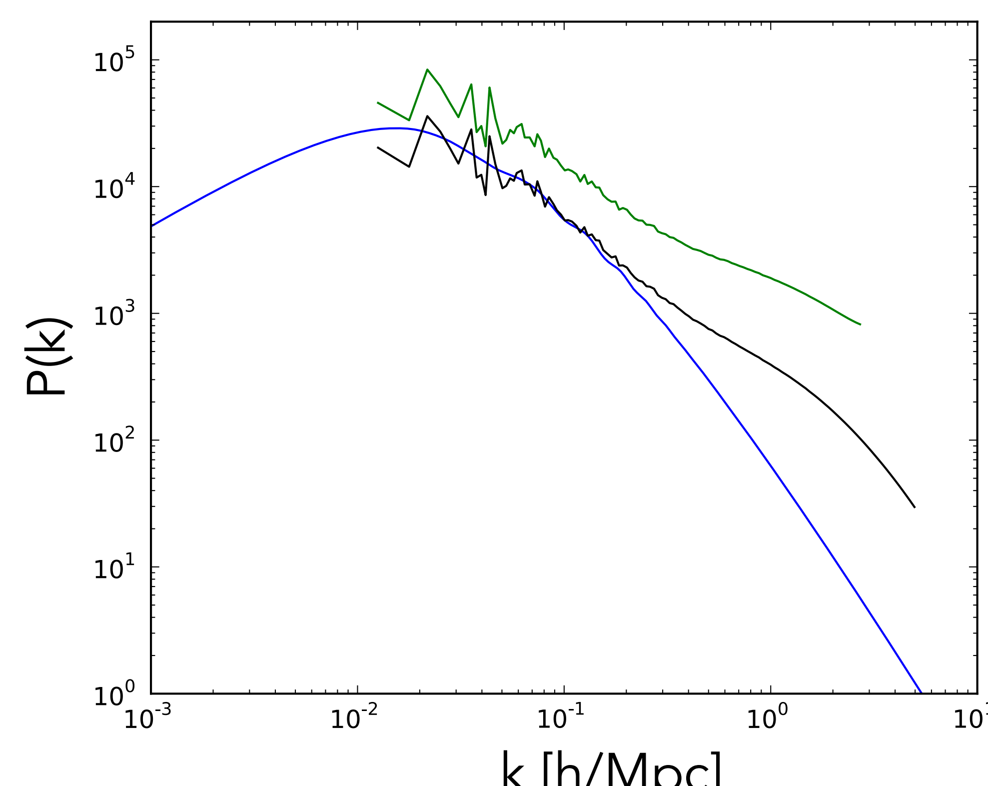

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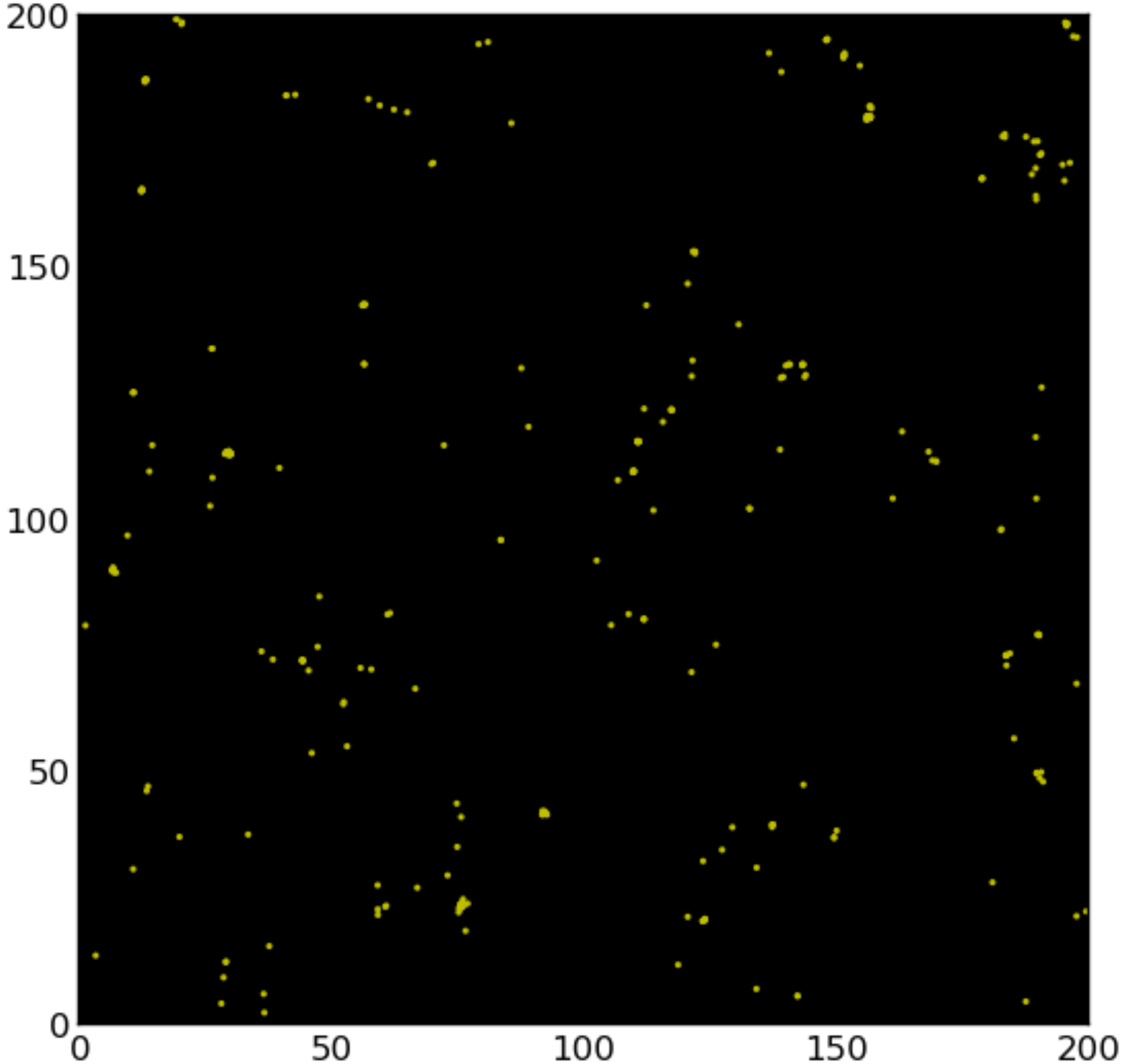

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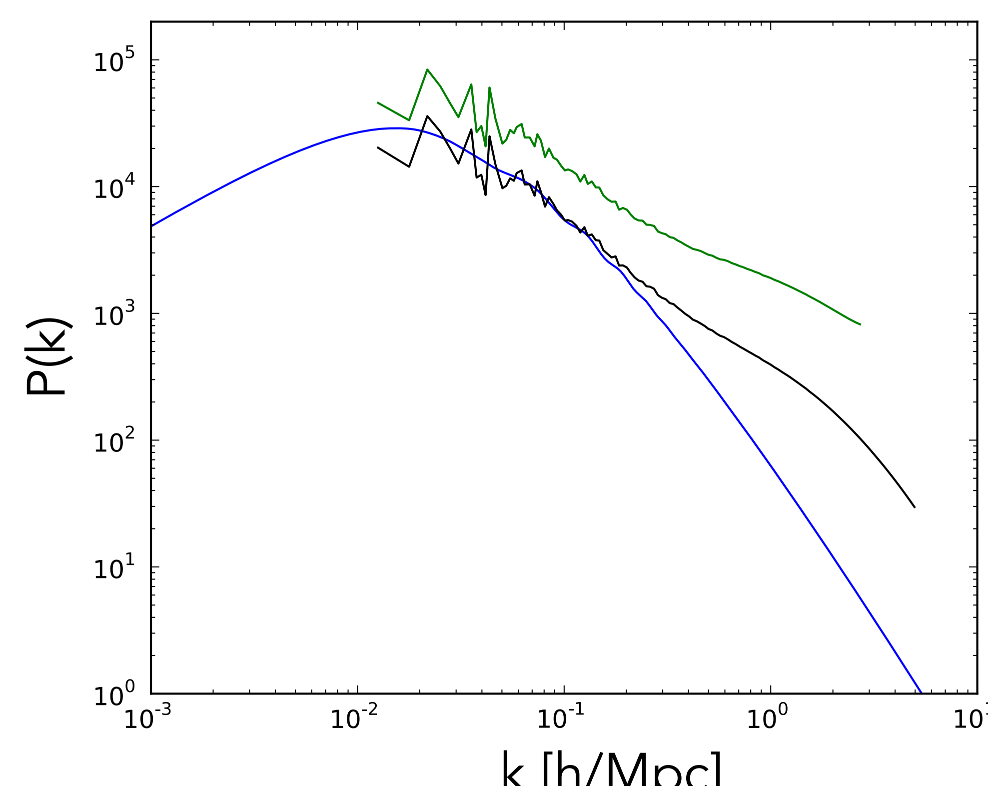

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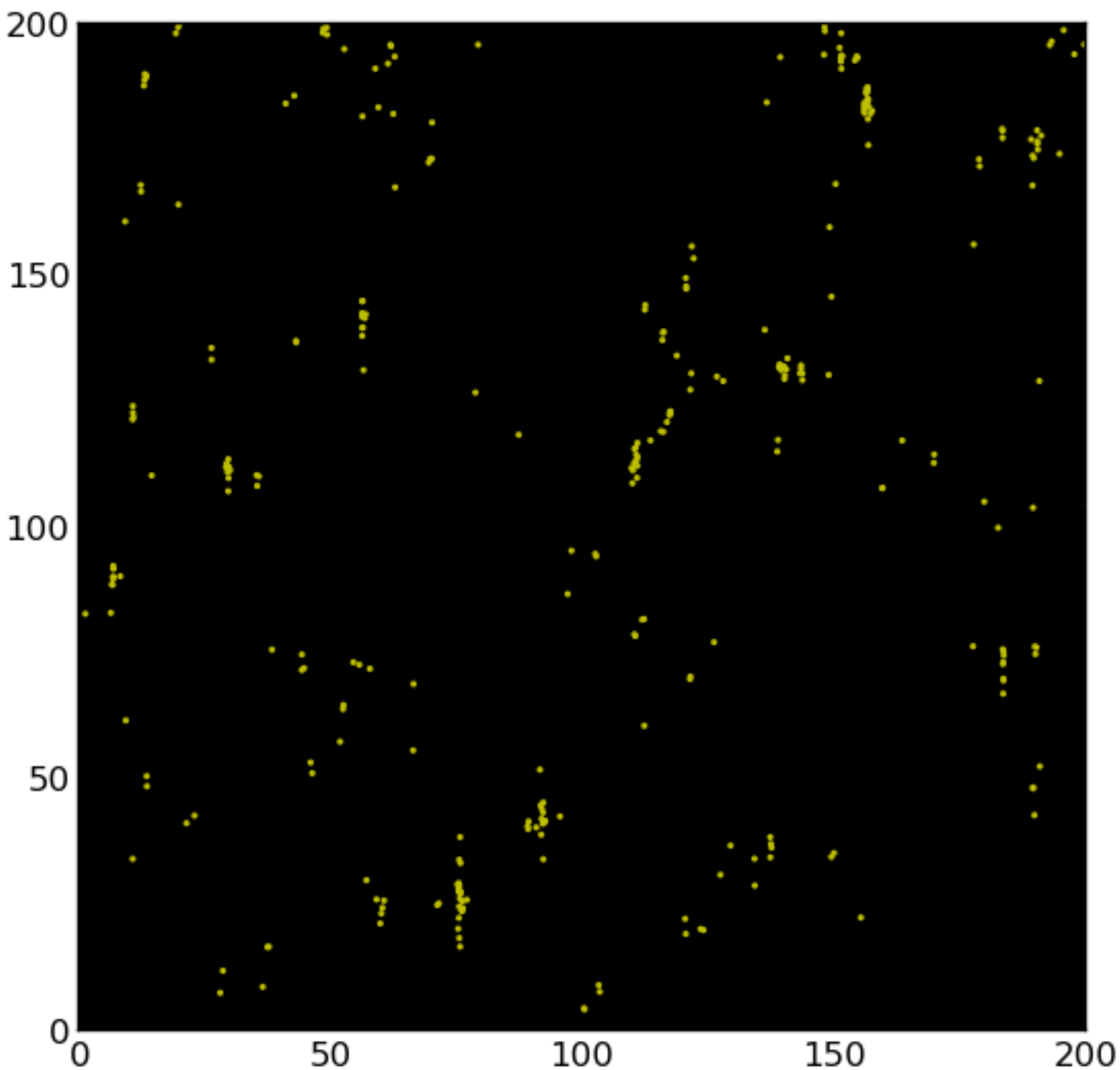

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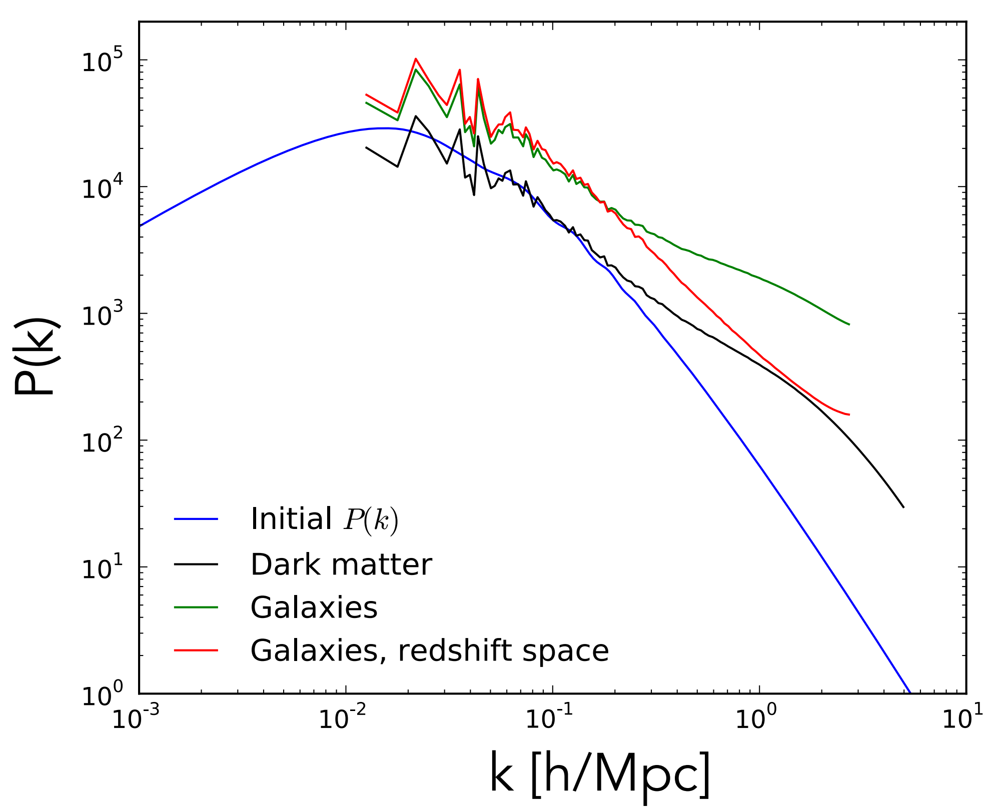
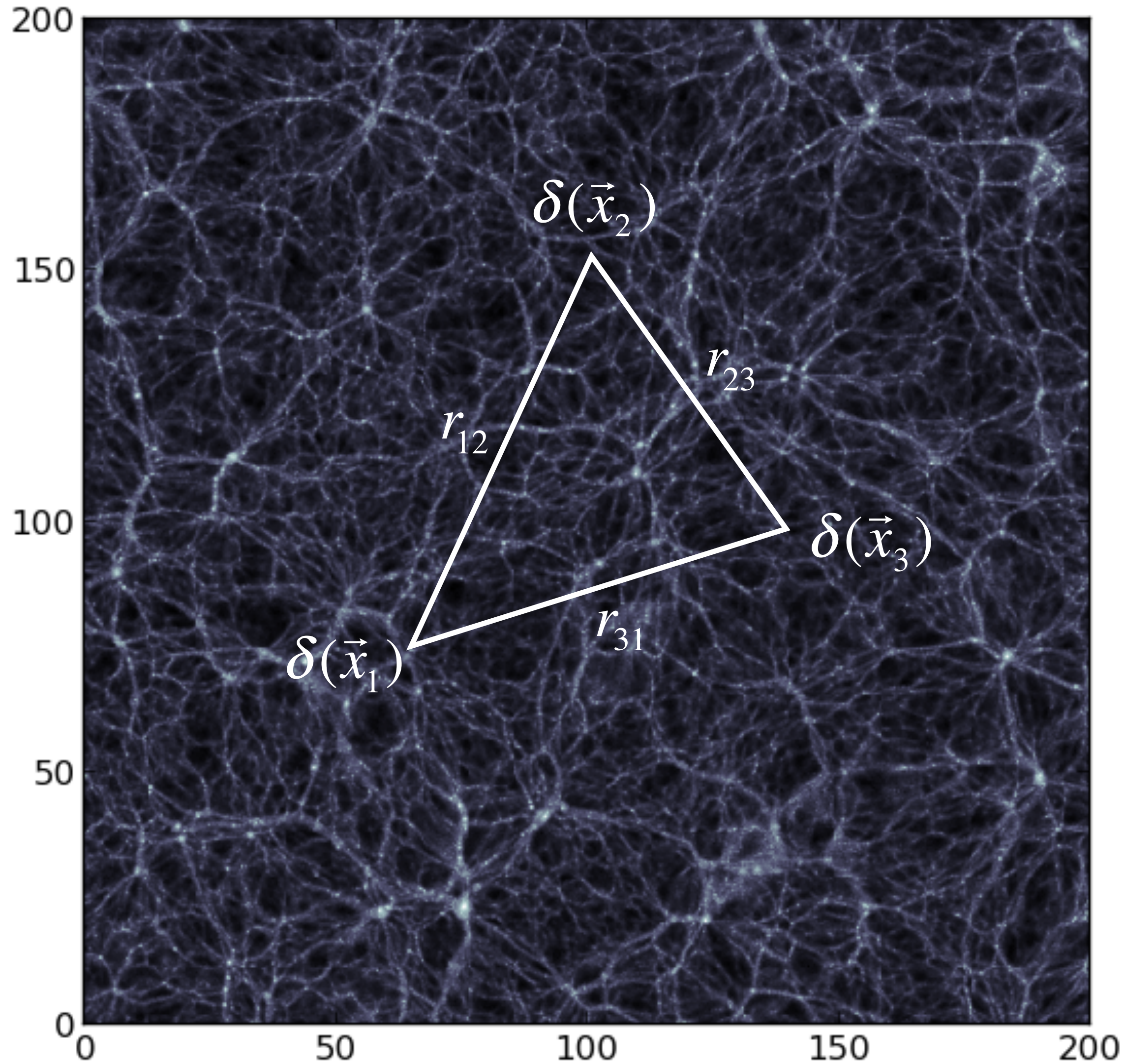


3-point Statistics

$$\zeta(r_{12}, r_{23}, r_{31}) = \langle \delta(\vec{x}_1)\delta(\vec{x}_2)\delta(\vec{x}_3) \rangle$$ ← *3-point correlation function*

$$\left\langle \hat{\delta}(\vec{k}_1)\hat{\delta}(\vec{k}_2)\hat{\delta}(\vec{k}_3) \right\rangle = (2\pi)^3 B(k_1, k_2, k_3)\delta_D(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)$$ ← *Bispectrum*



Galaxy 3-point correlation function/bispectrum contains information about:

- Galaxy bias
- Primordial non-Gaussianity
- Growth of structure / gravity

Modeling the 3-point correlation function

Lagrangian Perturbation Theory

$$\vec{x}(\tau) = \vec{q} + \vec{\Psi}(\vec{q},\tau)$$

$$\vec{\Psi}(\vec{q},\tau) = \vec{\Psi}^{(1)}(\vec{q},\tau) + \vec{\Psi}^{(2)}(\vec{q},\tau) + \ldots$$

$$\rho(\vec{x},\tau) d^3\vec{x} = \bar{\rho} d^3\vec{q}$$

$$1 + \delta(\vec{x},\tau) = \frac{1}{J(\vec{q})} = \left|\frac{\partial x_i}{\partial q_j}\right|^{-1}$$

$$\delta(\vec{x},\tau) = D(\tau)\delta^{(1)} + D(\tau)^2 \delta^{(2)} + \ldots$$

$$\zeta(r_{12}, r_{23}, r_{31}) = \left\langle \delta(\vec{x}_1)\delta(\vec{x}_2)\delta(\vec{x}_3) \right\rangle$$

$$= D(\tau)^4 \left\langle \delta^{(1)}(\vec{x}_1)\delta^{(1)}(\vec{x}_2)\delta^{(2)}(\vec{x}_3) \right\rangle$$

$$+\ 2 \text{ cyclic terms} + \ldots$$

Modeling the 3-point correlation function

Zel'dovich Approx:

$$\zeta(r_1, r_2, r_3) = D^4\Bigg(\frac{4}{3}\xi_0^0(r_1)\xi_0^0(r_3) - \cos\theta_{31}\left(\xi_1^1(r_1)\xi_1^{-1}(r_3) + \xi_1^{-1}(r_1)\xi_1^1(r_3)\right) + \frac{1}{6}\left(1 + 3\cos 2\theta_{31}\right)\xi_2^0(r_1)\xi_2^0(r_3) \; + 2 \text{ cyclic}\Bigg)$$

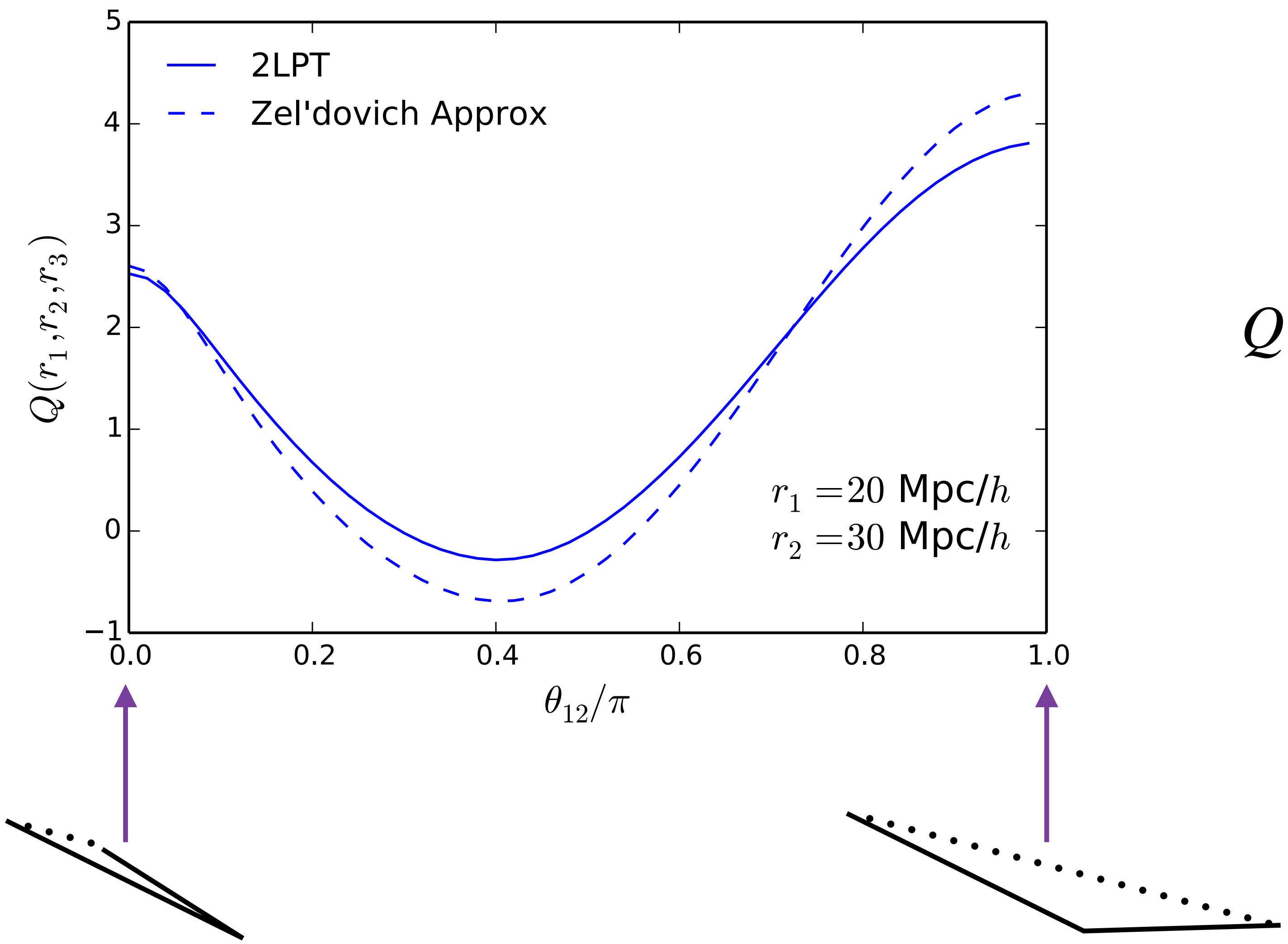
2LPT:

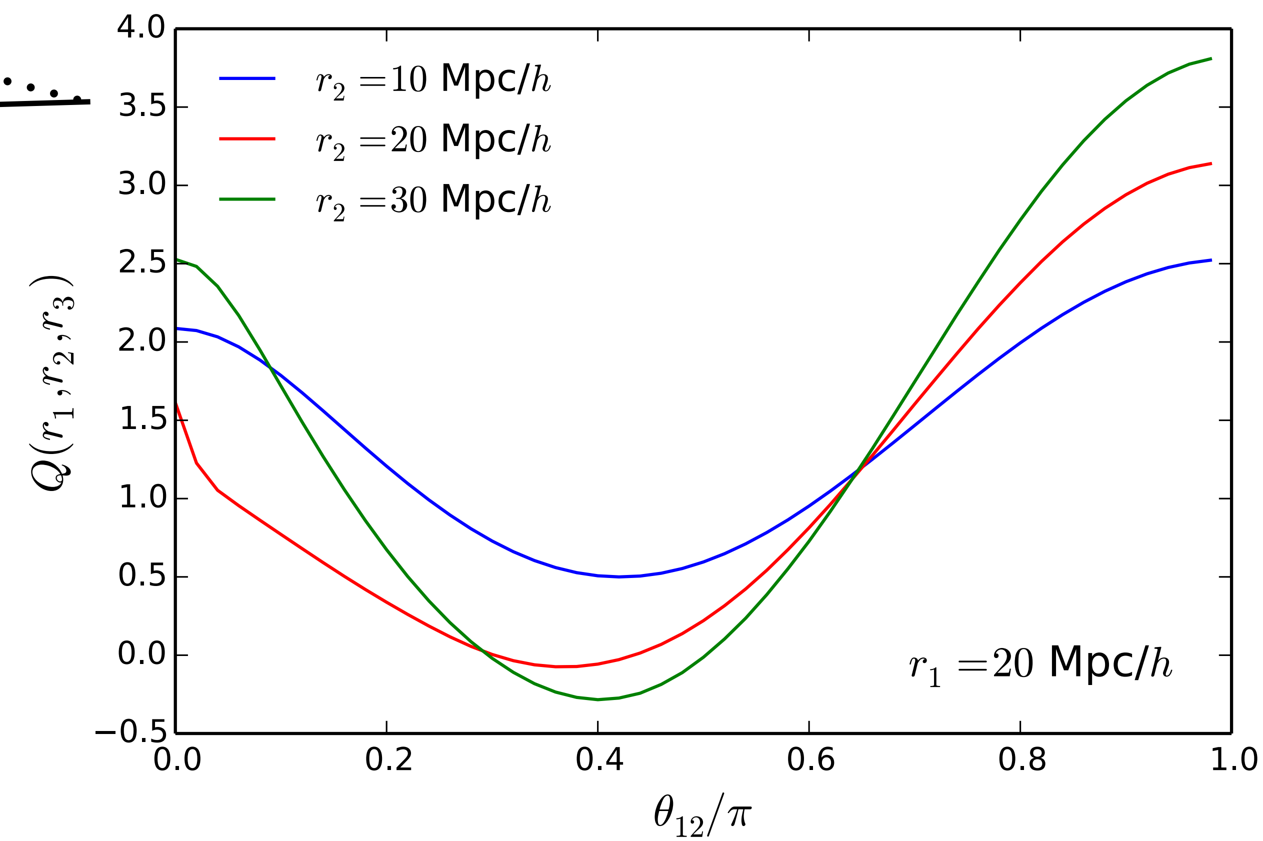
$$\zeta(r_1, r_2, r_3) = D^4\Bigg(\frac{34}{21}\xi_0^0(r_1)\xi_0^0(r_3) - \cos\theta_{31}\left(\xi_1^1(r_1)\xi_1^{-1}(r_3) + \xi_1^{-1}(r_1)\xi_1^1(r_3)\right) + \frac{2}{21}\left(1 + 3\cos 2\theta_{31}\right)\xi_2^0(r_1)\xi_2^0(r_3) \; + 2 \text{ cyclic}\Bigg)$$

$$\xi_n^m(r) = \frac{1}{2\pi^2}\int_0^\infty P_L(k) j_n(kr) k^{m+2} dk$$

Reduced 3-point function

$$Q(r_1,r_2,r_3)=\frac{\zeta(r_1,r_2,r_3)}{\xi(r_1)\xi(r_2)+\xi(r_1)\xi(r_3)+\xi(r_2)\xi(r_3)}$$





Modeling systematics

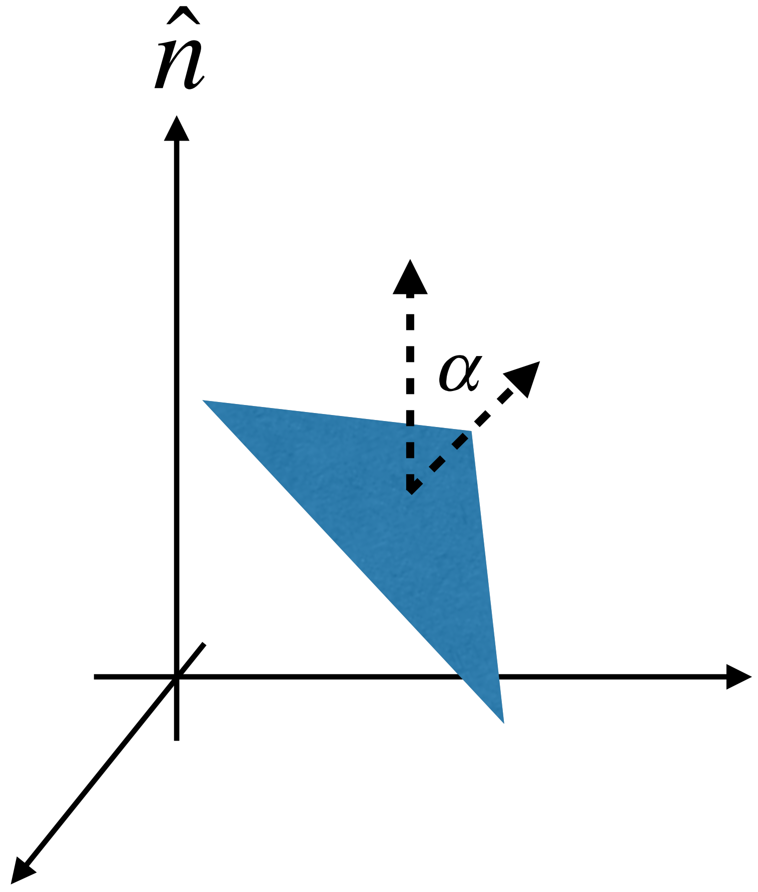
Redshift-space distortions:

$$\vec{s} = \vec{x} + \frac{\vec{u} \cdot \hat{n}}{aH} \hat{n}$$

Galaxy bias:

$$\delta_g(\vec{x}) = b_1 \delta_{DM}(\vec{x}) + \frac{b_2}{2}\left(\delta_{DM}(\vec{x})^2 - \sigma^2\right)$$

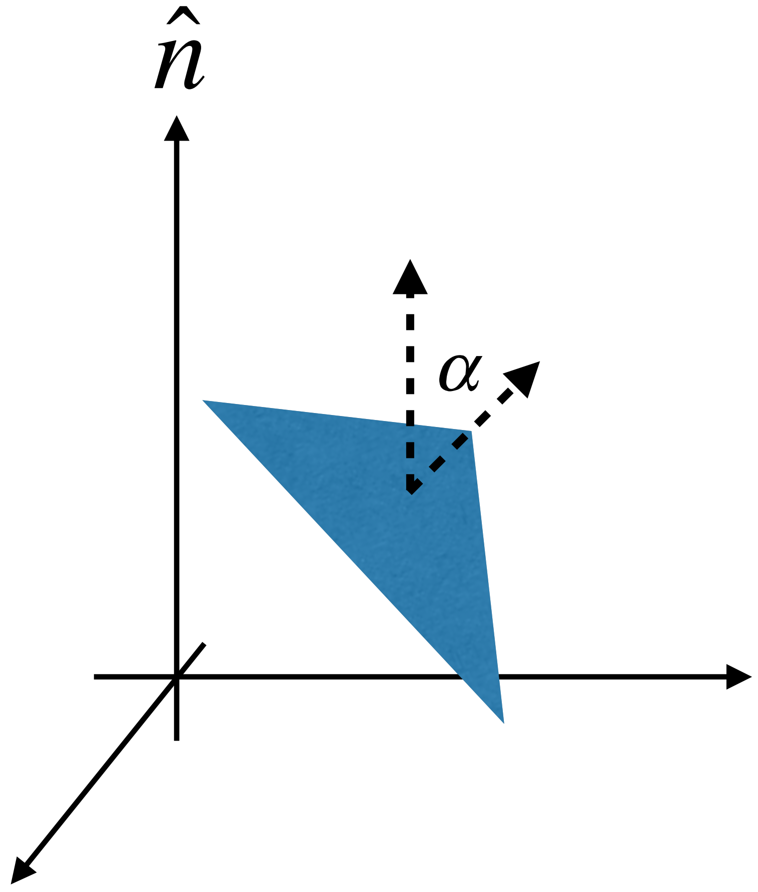
$$+ \frac{b_{s^2}}{2}\left(s^2(\vec{x}) - \left\langle s^2 \right\rangle\right)$$



$$(1 + \delta_s(\vec{x}, \tau))d^3\vec{s} = (1 + \delta_x(\vec{x}, \tau))d^3\vec{x}$$

Modeling systematics

$$\zeta_\alpha(r_1, r_2, r_3, \alpha) = \sum_{\ell=0}^{8} \sum_{m=-1}^{1} \sum_{n_1,n_2=0}^{5} f^{\ell/2} A^{\ell,m}_{n_1,n_2}(b_1, b_2, f, x) \times \xi^m_{n_1}(r_1)\xi^{-m}_{n_2}(r_2)\mathcal{P}_\ell(\cos\alpha) + (2\text{ cyclic}) ,$$



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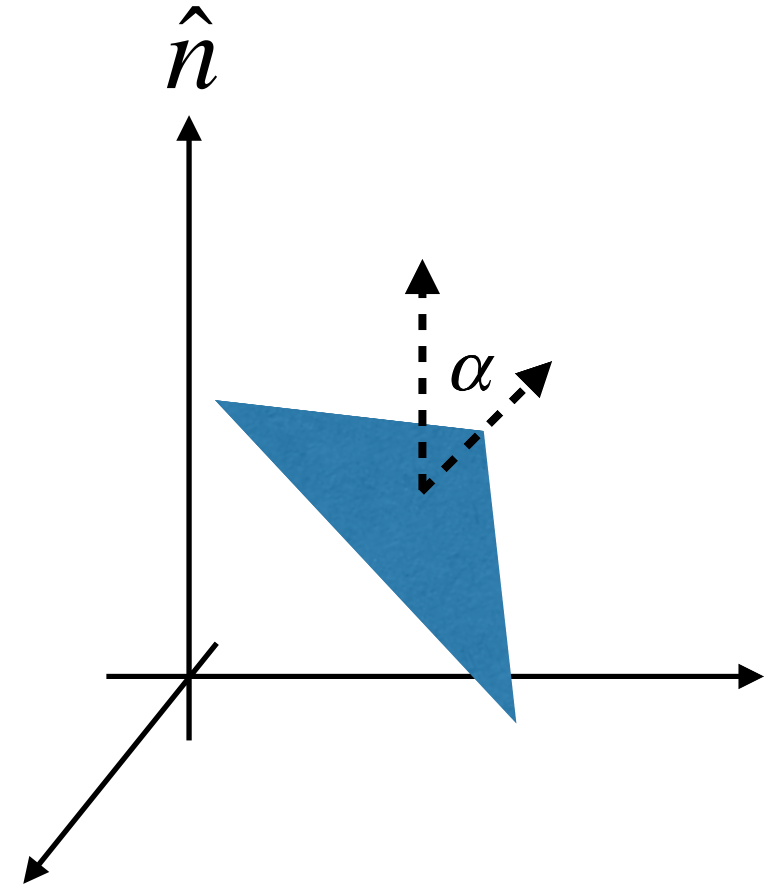
[+integral term]



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$$\times\, \xi^{m}_{n_1}(r_1)\xi^{-m}_{n_2}(r_2)\mathcal{P}_\ell(\cos\alpha) + (2 \text{ cyclic}) \,,$$

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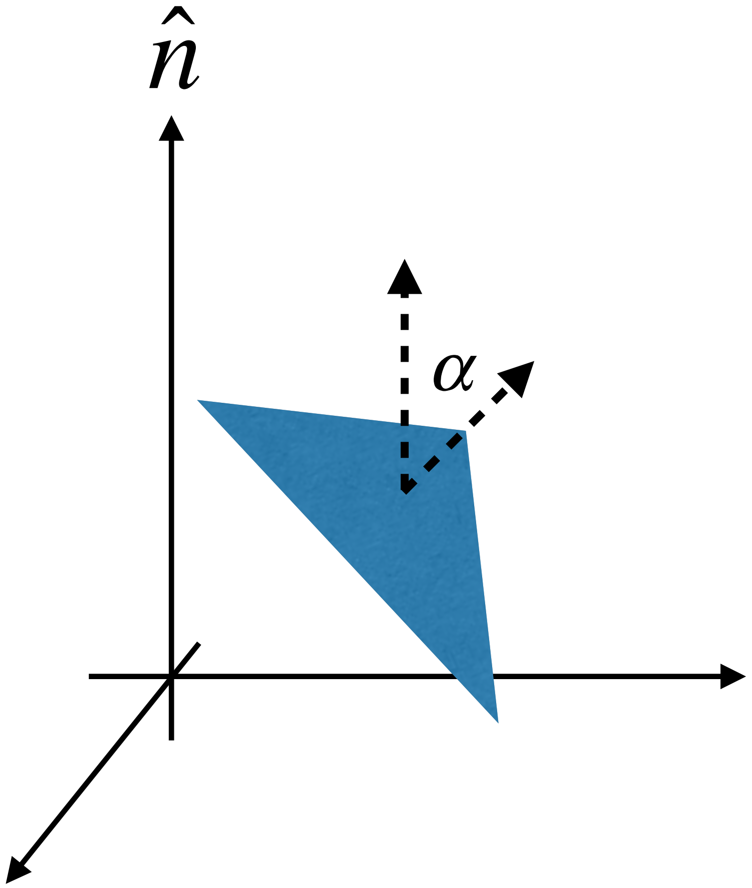
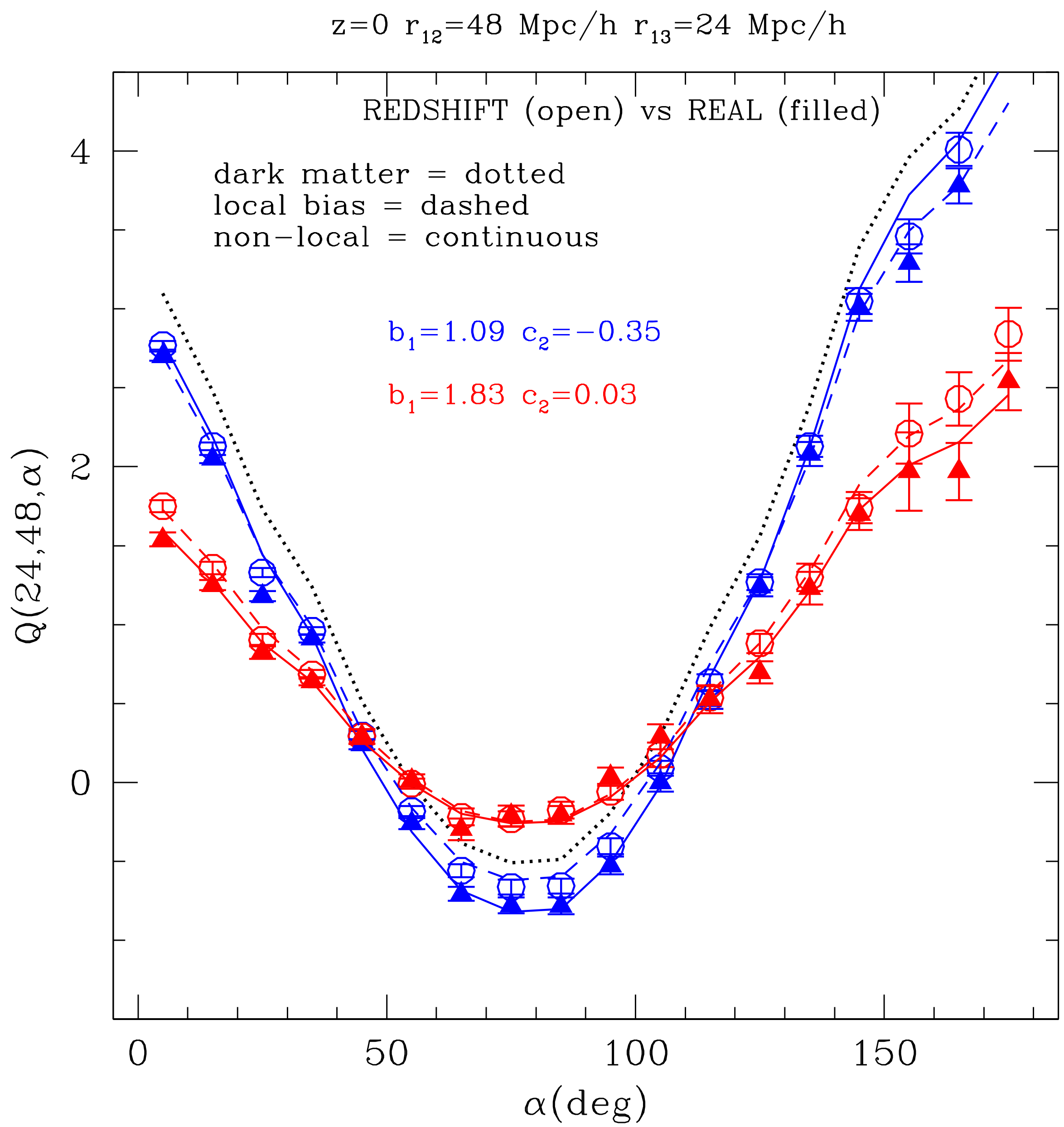
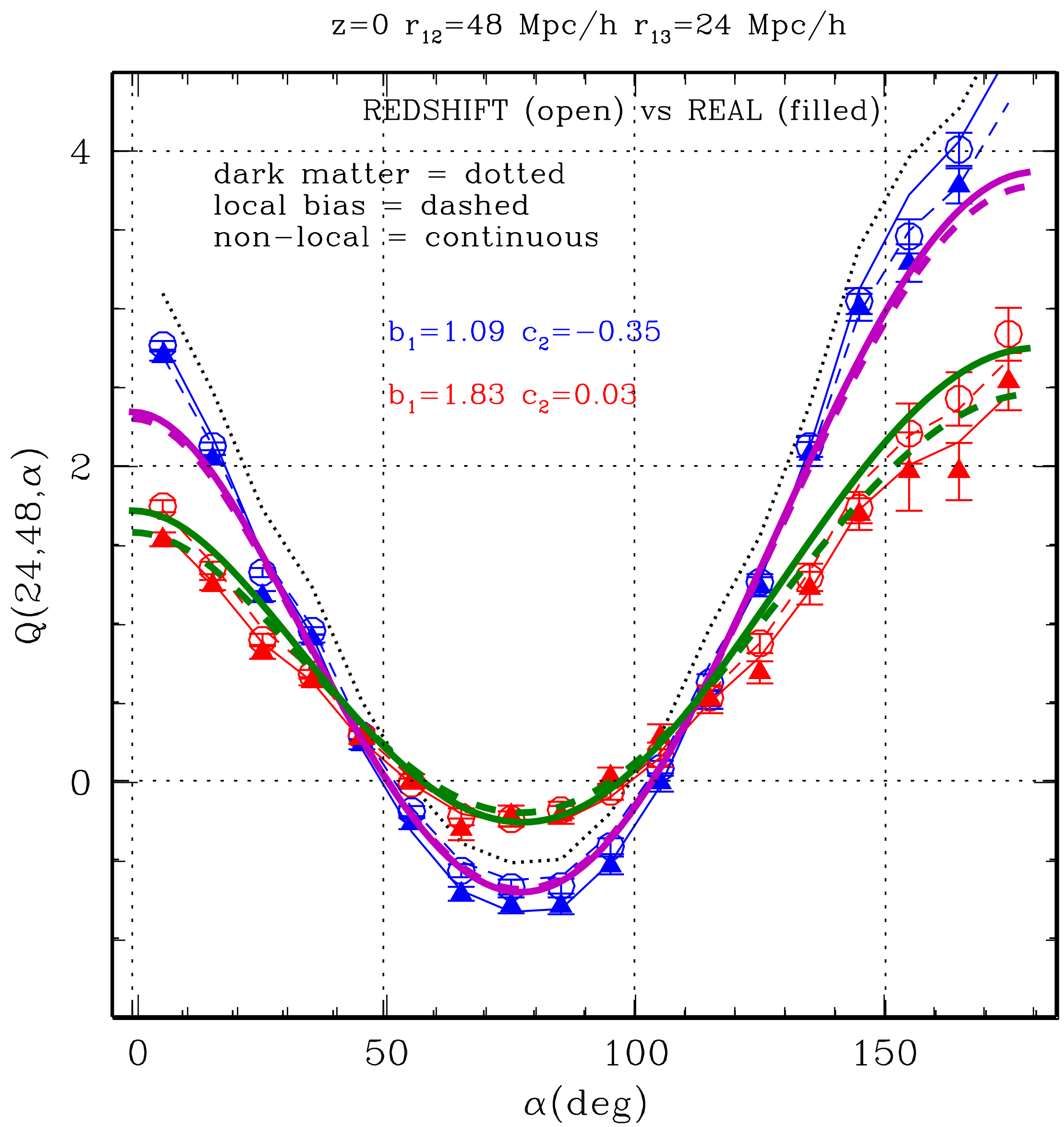


$$A^{0,0}_{0,0} = \frac{34b_1^3}{21} + b_1^2 b_2 + \left(\frac{8b_1}{15} - \frac{32b_1^2}{675}\right) f^3$$
$$+ f^2\left(-\frac{16b_1^3}{225} + \frac{794b_1^2}{675} + \frac{50b_1}{189} + \frac{b_2}{9} - \frac{8}{189}\right)$$
$$+ f\left(\frac{52b_1^3}{63} + \frac{88b_1^2}{63} + b_1\left(\frac{2b_2}{3} - \frac{16}{63}\right)\right) + \frac{2f^4}{25}$$



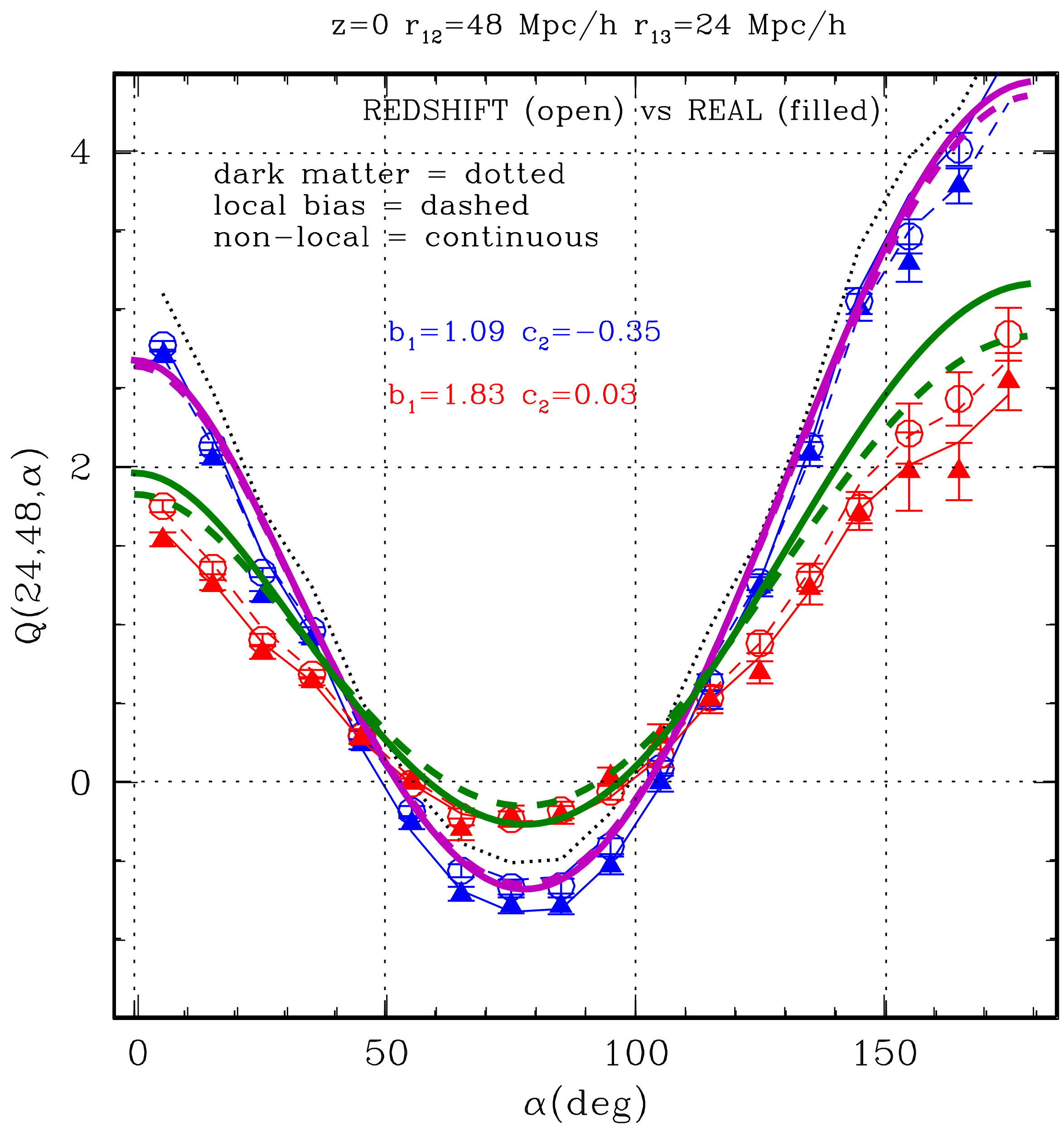
From K. Hoffmann, et al (2014) arXiv:1403.1259

Real Space Model



From K. Hoffmann, et al (2014) arXiv:1403.1259

Redshift Space Model



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Summary and future work

- Usual 2-point statistics of galaxies do not capture full cosmological information
- LPT approach to modeling 3-point correlation function
  - Galaxy bias and RSD can be included in configuration-space model
  - Test against N-body simulations on various scales / in different triangular configurations
  - Possibilities for extending model beyond tree-level PT, including fingers of god, etc, for better agreement on small scales

Thank you!