Accuracy of Bias Measurements from 3-point Galaxy Correlations

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arXiv: 1607.01024, 1503.00313, 1504.02074, 1403.1259

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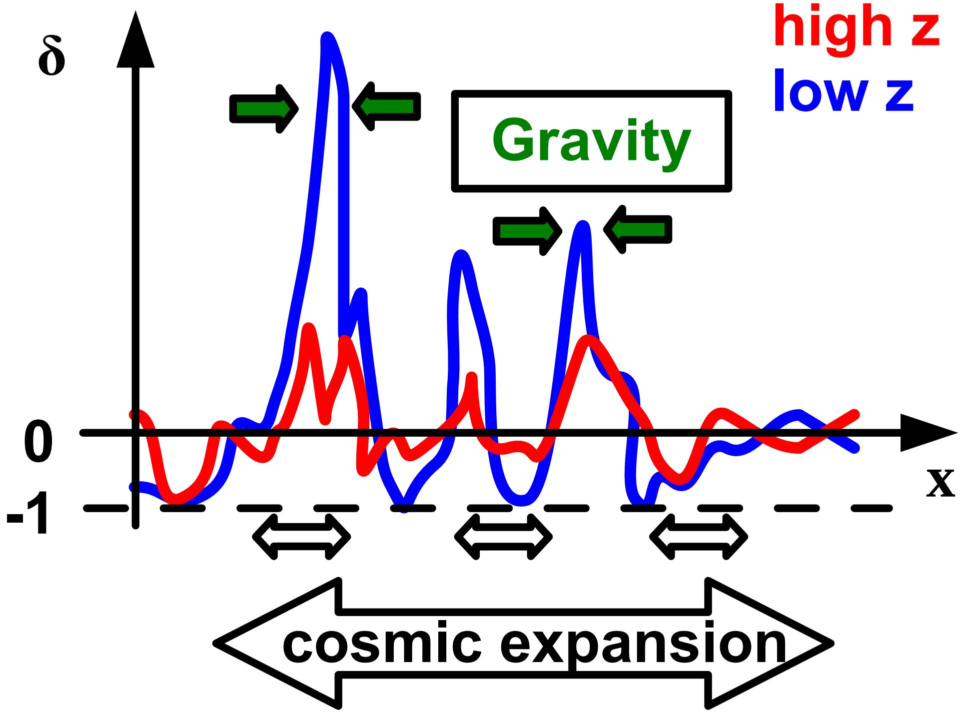
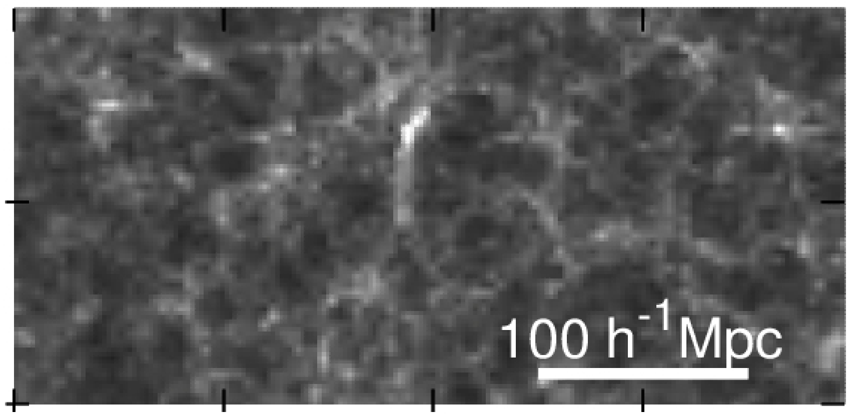
growth of matter fluctuations

matter fluctuations

$$\delta(x) \equiv (\rho(x) - \bar{\rho})/\bar{\rho}$$



z = 1.5



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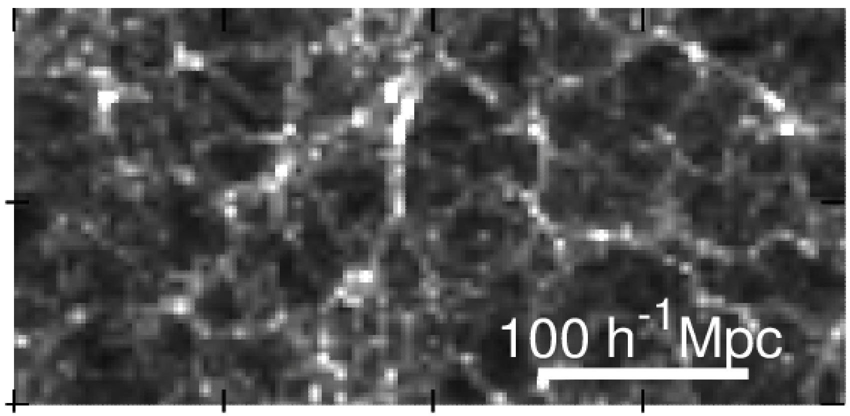


MICE Grand Challenge simulation

growth depends on cosmology

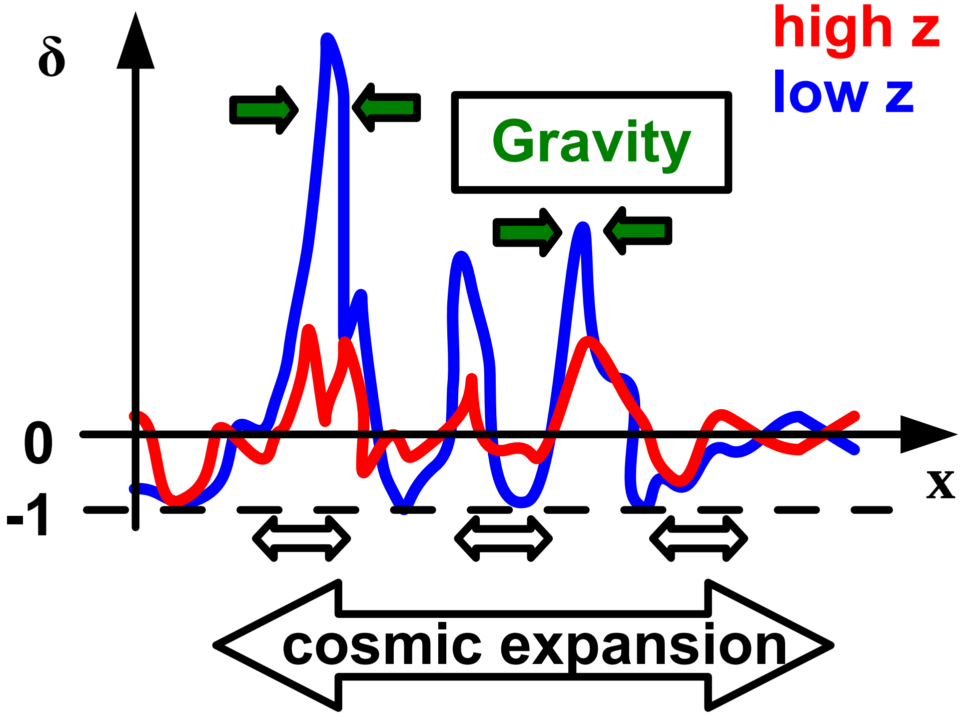
matter fluctuations

$$\delta(x) \equiv (\rho(x) - \bar{\rho}) / \bar{\rho}$$

linear growth factor

$$D(z) \simeq \delta_m(z) / \delta_m(z_0)$$

(large scale approximation)



growth sensitive to:

- expansion
- gravity
- matter density
- particle characteristics

two-point correlation depends on growth

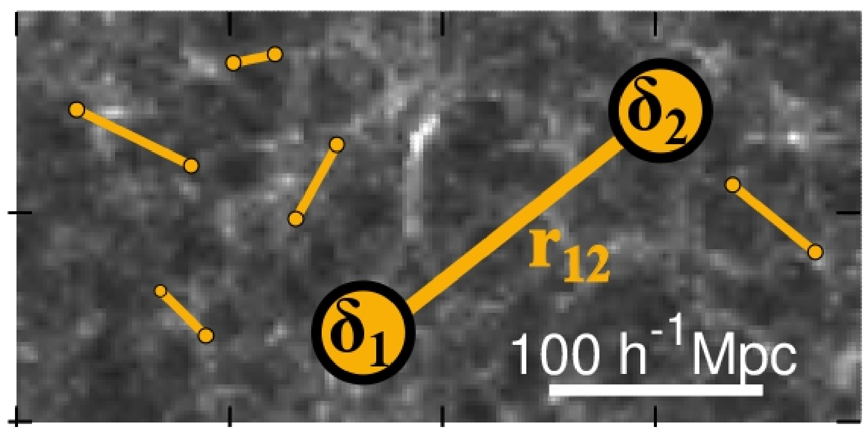
two-point correlation (2pc)

$$\xi(r_{12}) \equiv \langle \delta_1 \delta_2 \rangle (r_{12})$$

linear growth factor

$$D(z) \simeq \delta_m(z) / \delta_m(z_0)$$

(large scale approximation)



- study in 3D config. space
- ξ is isotropic

cosmology with large-scale structure

two-point correlation (2pc)

$$\xi(r_{12}) \equiv \langle \delta_1 \delta_2 \rangle (r_{12})$$

linear growth factor

$$D(z) \simeq \delta_m(z) / \delta_m(z_0)$$

(large scale approximation)

$$D_0^2(z) \simeq \xi_m(z) / \xi_m(z_0)$$

2pc growth measurement

compare with theory predictions, e.g. ΛCDM

(constrain free parameters, discriminate models)

$$D(a) \propto \frac{H(t)}{H(0)} \int_0^a \frac{da'}{\left[\Omega_m / a' + \Omega_\Lambda a' - (\Omega_m + \Omega_\Lambda - 1)\right]^{3/2}} \qquad a \equiv 1/(1+z)$$

cosmology with large-scale structure

two-point correlation (2pc)

$$\xi(r_{12}) \equiv \langle \delta_1 \delta_2 \rangle (r_{12})$$

linear growth factor

$$D(z) \simeq \delta_m(z) / \delta_m(z_0)$$

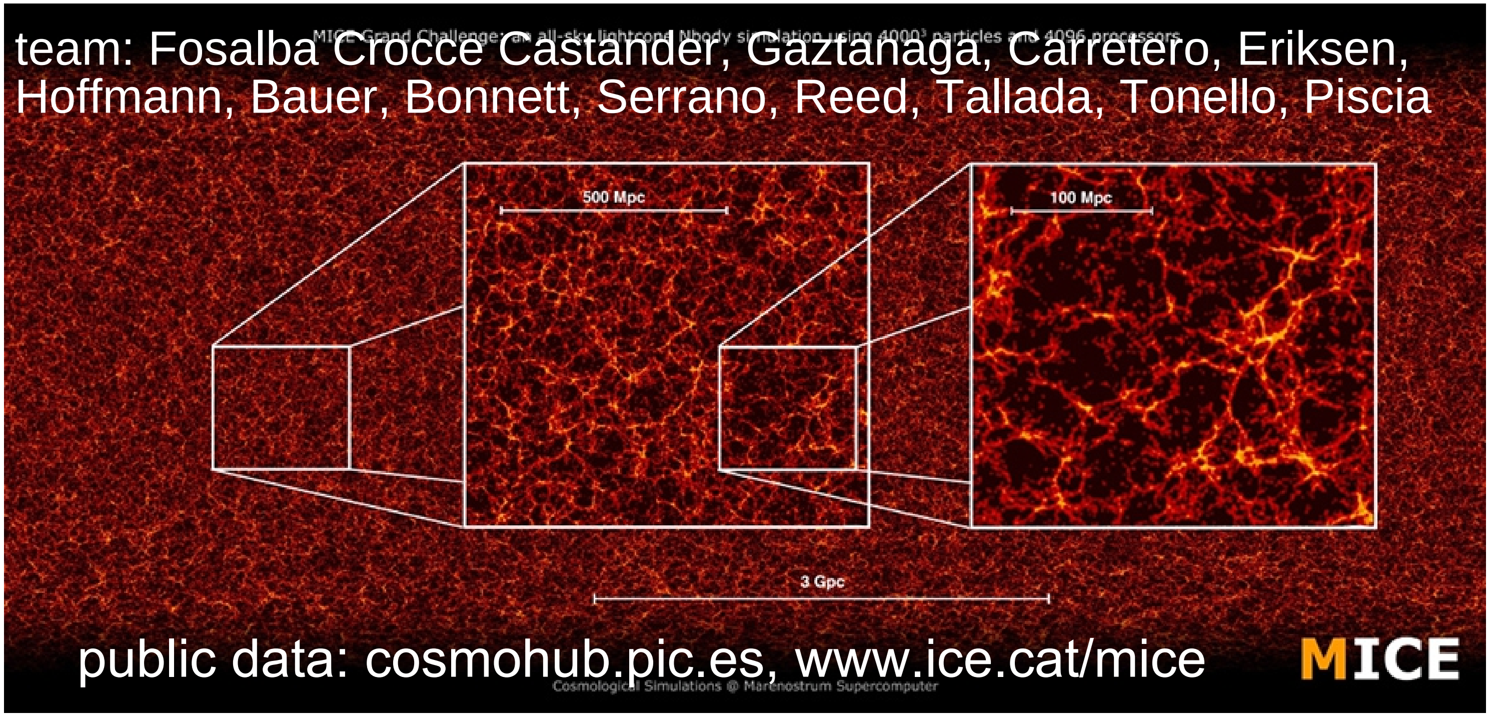
(large scale approximation)

$$D_0^2(z) \simeq \xi_m(z) / \xi_m(z_0)$$

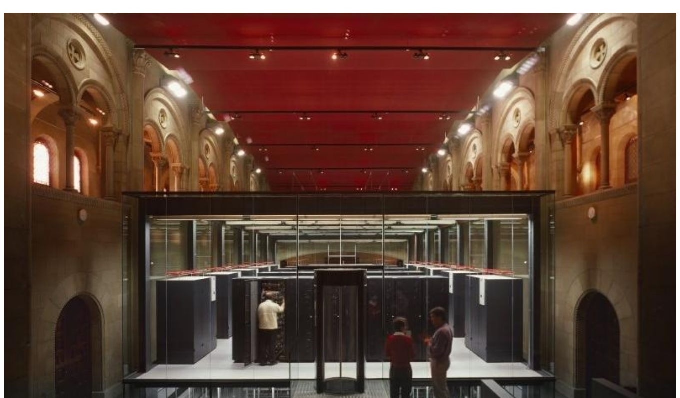
2pc growth measurement

problem: matter 2pc not directly observable!

MICE Grand Challenge simulation



MareNostrum super computer

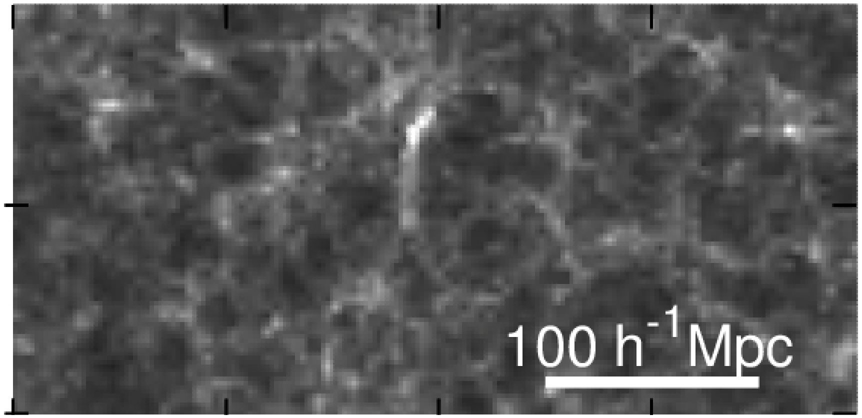


- 4096^3 ($7\ 10^{10}$) particles
- particle mass = $3\ 10^{10}$ Msun/h
- simulation box $(3\ \mathrm{Gpc/h})^3$
- ΛCDM cosmology:

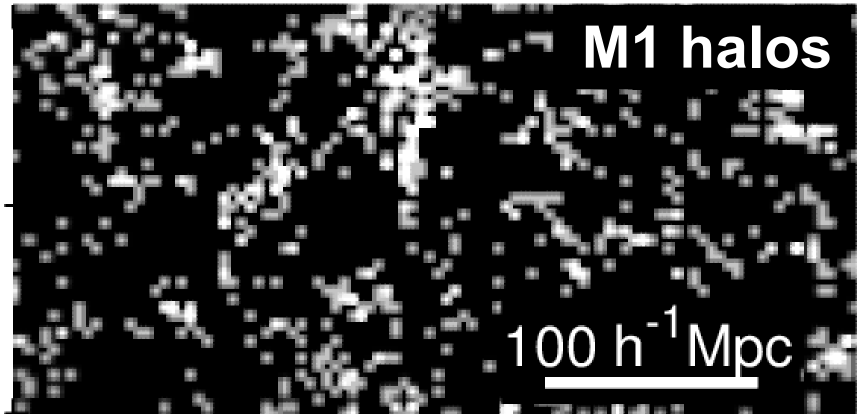
$$\Omega_m = 0.25, \Omega_\Lambda = 0.75\, \Omega_b = 0.044, \sigma_8 = 0.8\, n_s = 0.95, h = 0.7$$

galaxies trace matter density field

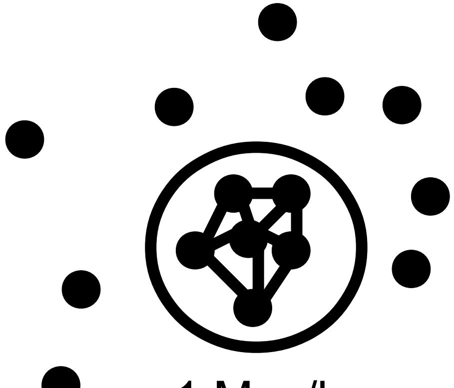
matter density



galaxy density



friends-of friends halo detection:

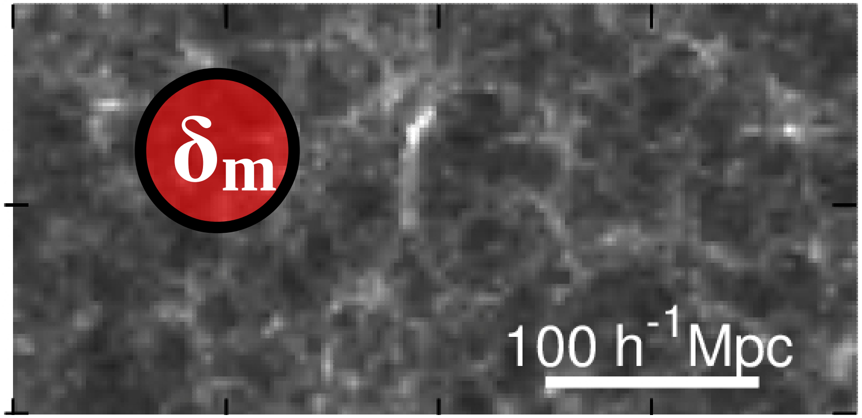


halo mass samples

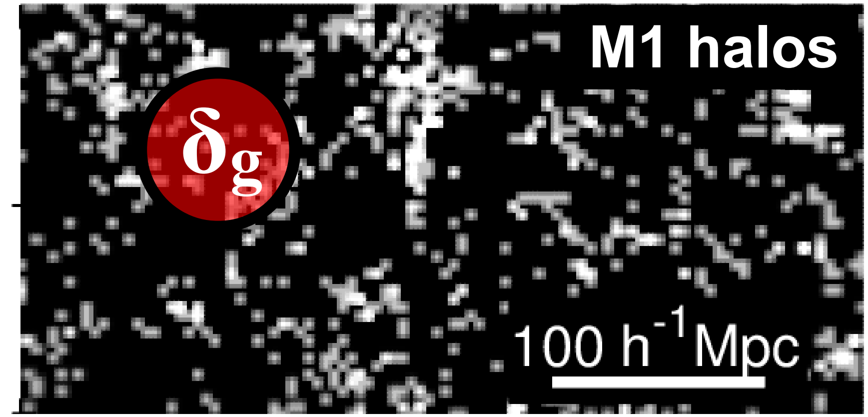
sample	mass range [10^{12} M_{sun}/h]
M0	0.58 - 2.32
M1	2.32 - 9.26
M2	9.26 - 100
M3	>100

galaxies bias model

matter density



galaxy density

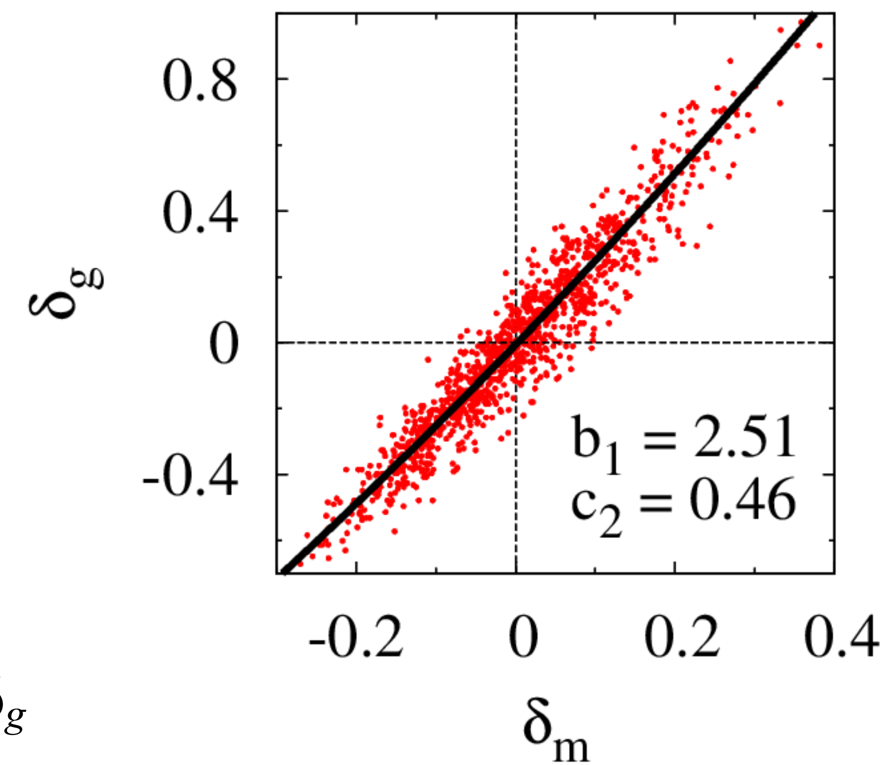


Fry & Gaztanaga (1993)

local quadratic bias model

$$\delta_g \simeq b_1 \left\{ \delta_m + (c_2/2)\left(\delta_m^2 - \langle \delta_m^2 \rangle\right) \right\}$$

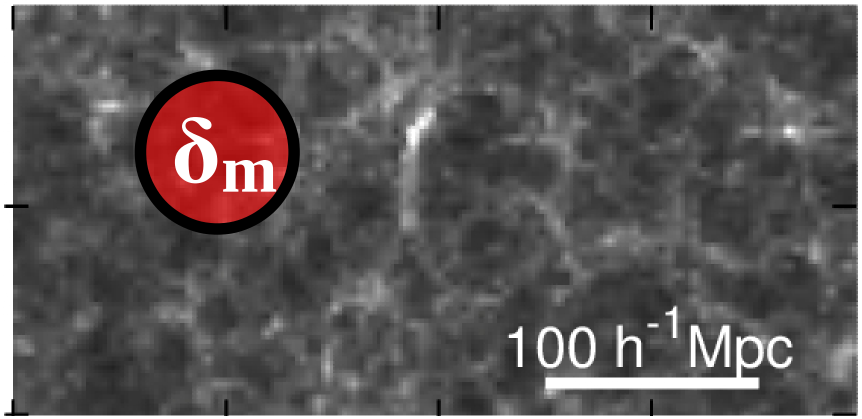
- b_1: linear bias parameter
- c_2: quadratic bias parameter



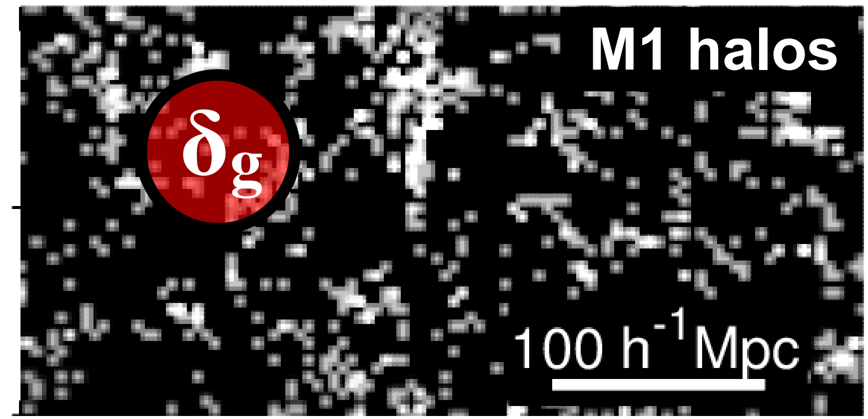
assumption: δ_m determines δ_g

galaxies bias model

matter density



galaxy density



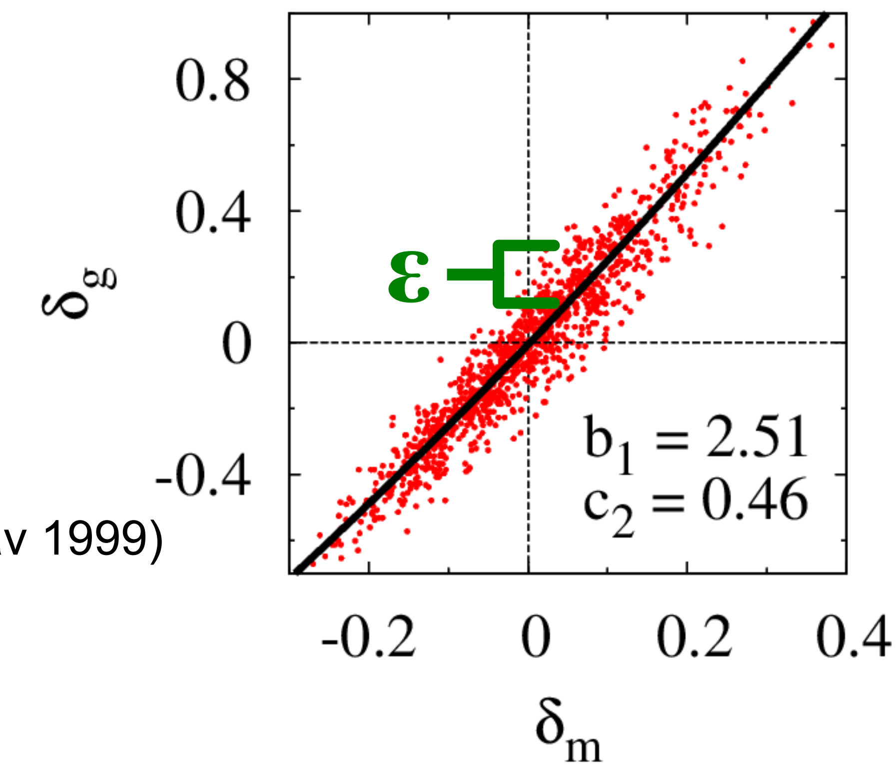
Fry & Gaztanaga (1993)

local quadratic bias model

$$\delta_g \simeq b_1 \left\{ \delta_m + (c_2/2)\left(\delta_m^2 - \langle \delta_m^2 \rangle\right) \right\}$$

+ ε **residual** from

- stochasticity (e.g. Dekel, Lahav 1999)
- “non-local” contributions (Chan 2012, Baldauf 2012)



bias in galaxy 2-point correlations

local quadratic bias model

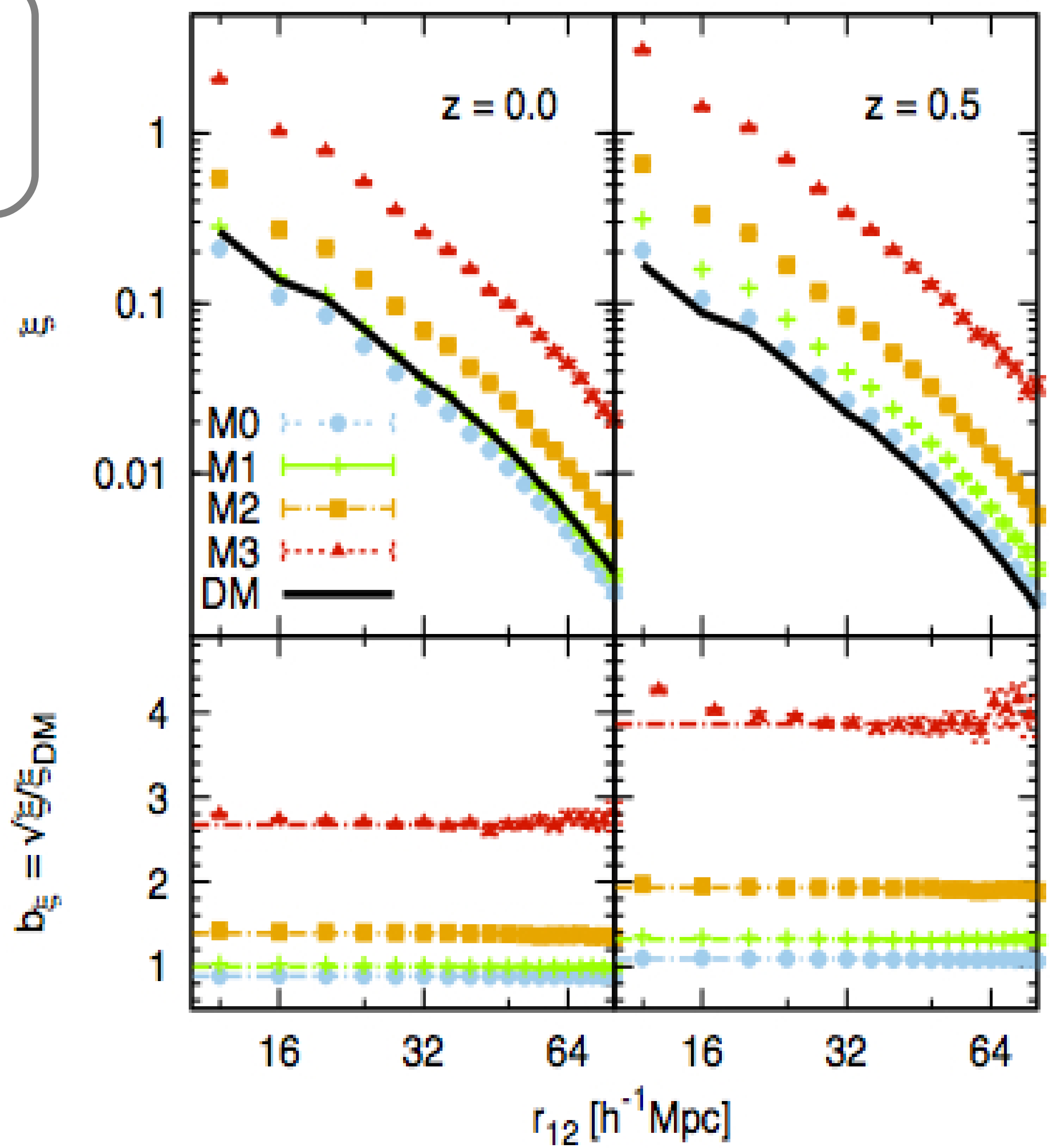
$$\delta_g \simeq b_1 \left\{ \delta_m + (c_2/2)(\delta_m^2 - \langle \delta_m^2 \rangle) \right\}$$

2-point correlation

$$\xi(r_{12}) \equiv \langle \delta_1 \delta_2 \rangle (r_{12})$$

leading order approximation for large scales

$$\xi_g \simeq \boxed{b_1^2} \xi_m$$

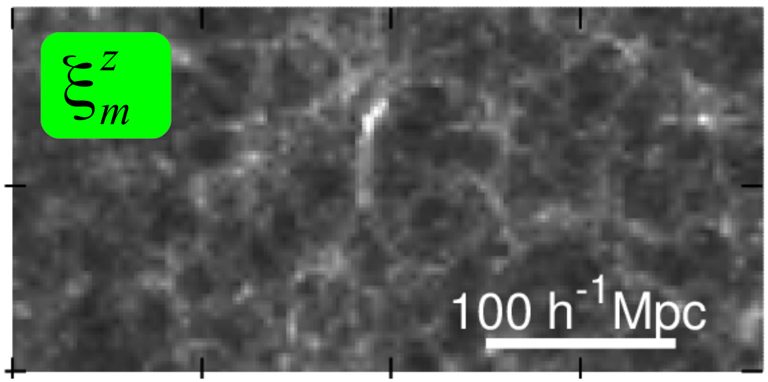


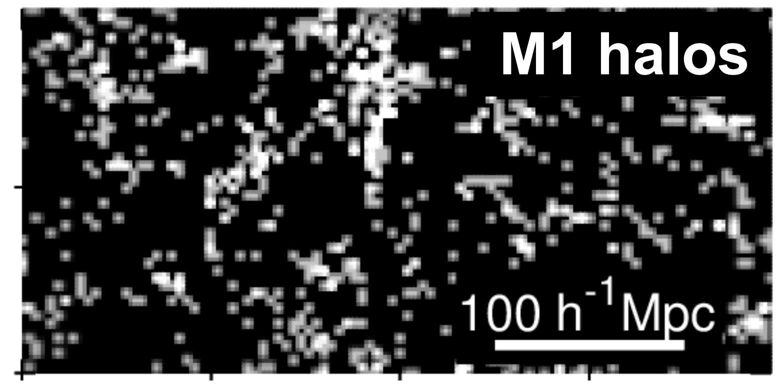
linear bias factor² (depends on redshift and halo mass)

growth – bias degeneracy

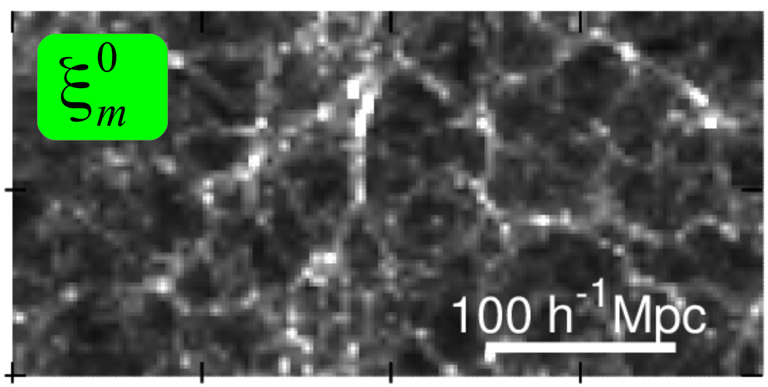
matter (theory) **galaxies (observations)**

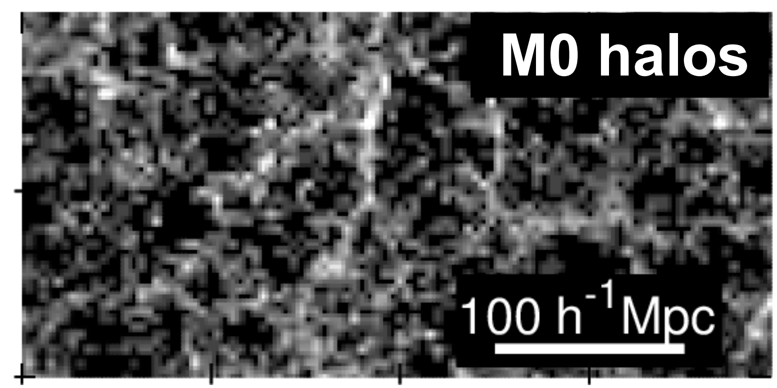
z = 1.0





z = 0.0





linear growth

$$D_0(z) = \sqrt{\frac{\xi_m(z)}{\xi_m(0)}}$$

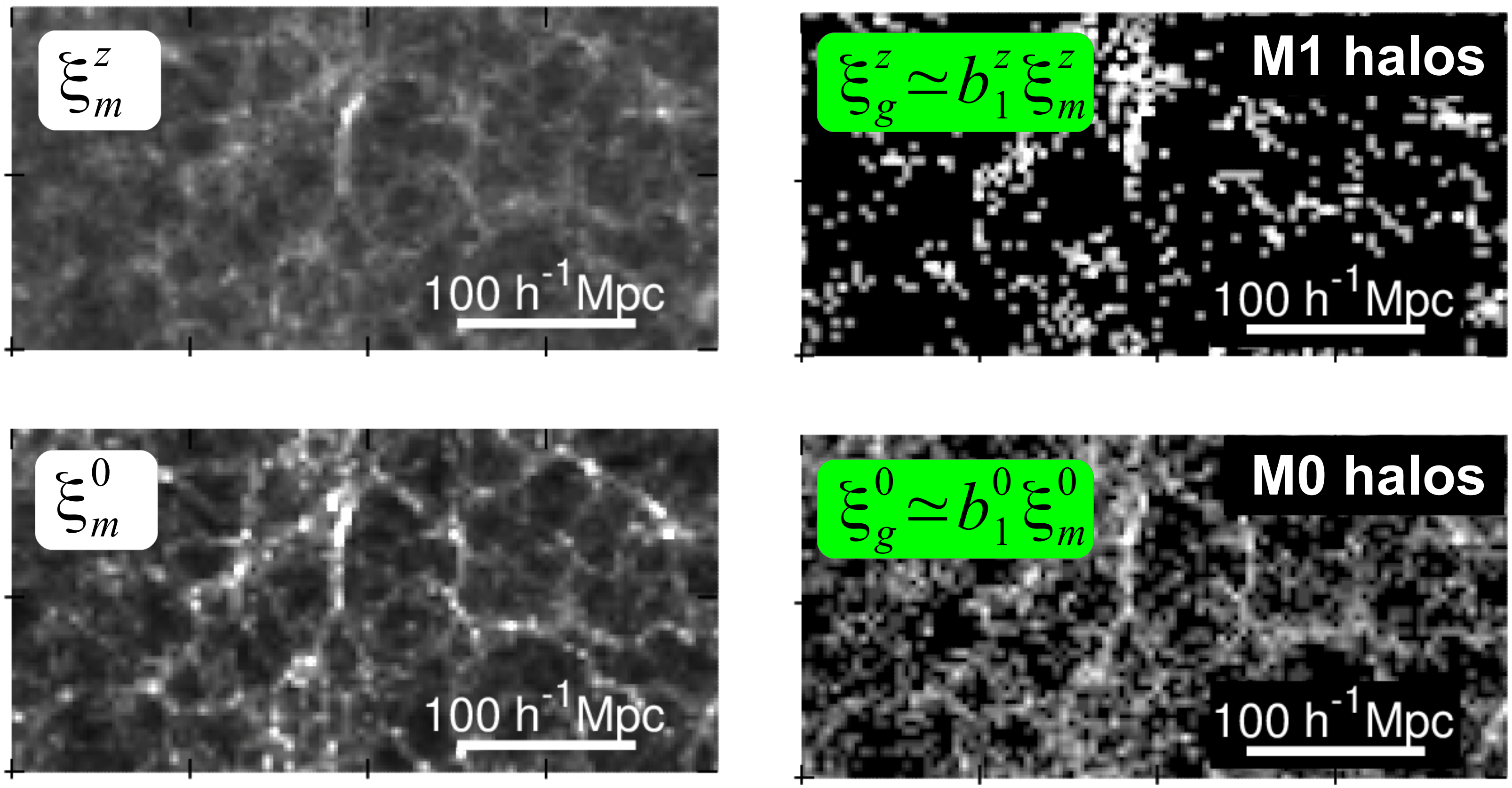
what we would like to observe

growth – bias degeneracy

matter (theory) **galaxies (observations)**

z = 1.0

z = 0.0



linear growth

$$D_0(z) = \sqrt{\frac{\xi_m(z)}{\xi_m(0)}} = \frac{b(0)}{b(z)} \sqrt{\boxed{\frac{\xi_g(z)}{\xi_g(0)}}}$$

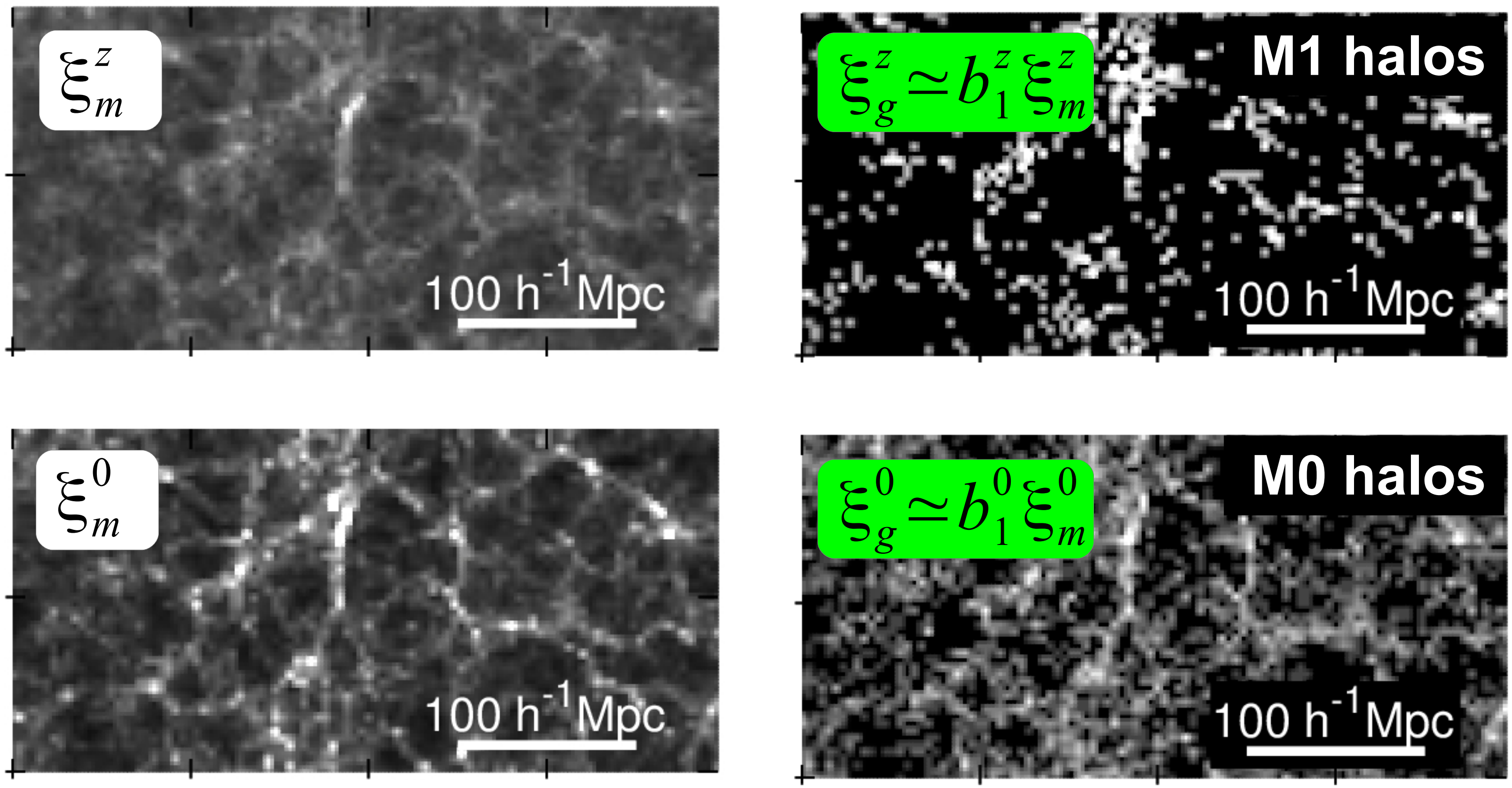
what we can observe

growth – bias degeneracy

matter (theory) **galaxies (observations)**

z = 1.0

z = 0.0



growth-bias degeneracy

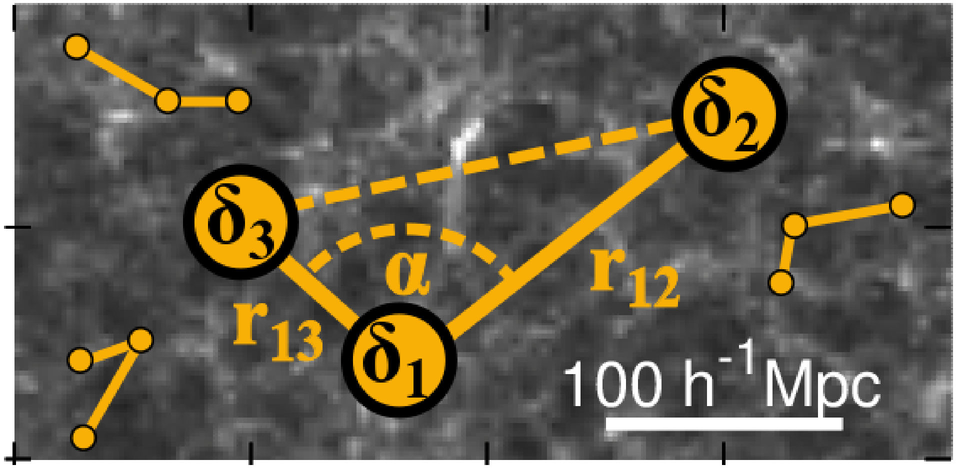
$$\boxed{D_0(z)\frac{b(z)}{b(0)}} = \sqrt{\frac{\xi_g(z)}{\xi_g(0)}}$$

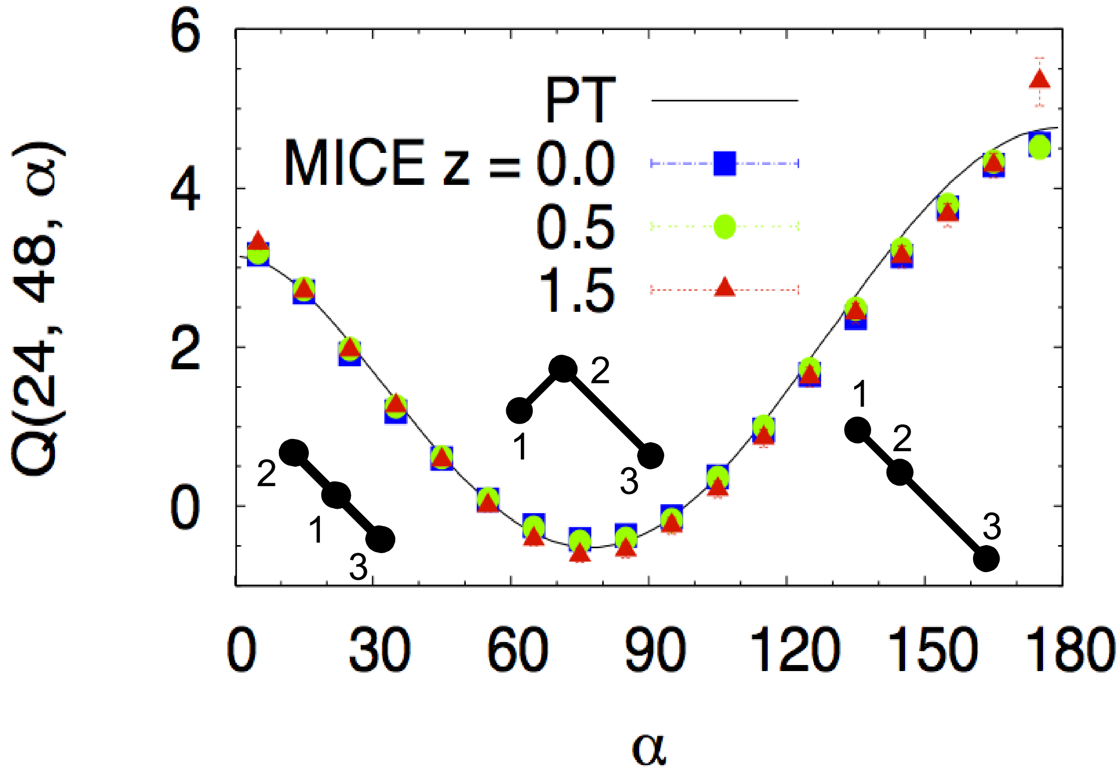
3-point correlation Q

reduced 3-point correlation:

$$Q \equiv \frac{\langle \delta_1 \delta_2 \delta_3 \rangle (r_{12}, r_{13}, \alpha)}{\langle \delta_1 \delta_2 \rangle \langle \delta_1 \delta_3 \rangle + 2\, perm.}$$

- **probes shape of LSS**





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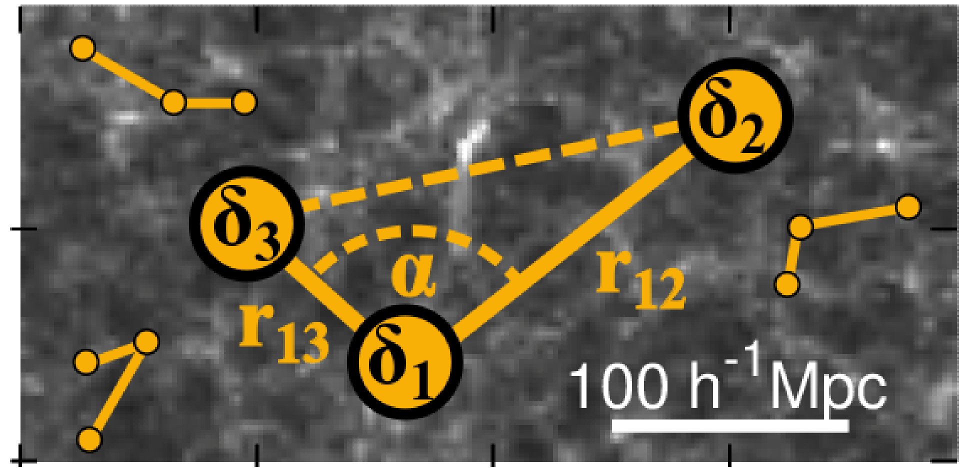
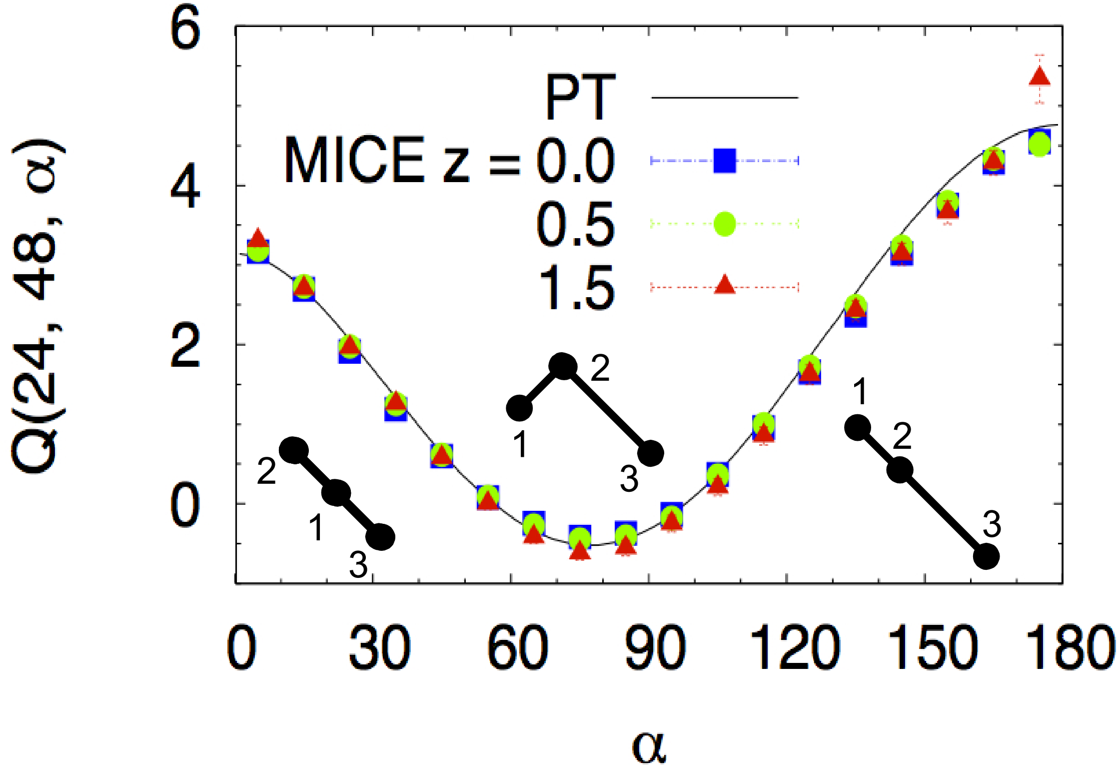
- probes shape of LSS
- **independent of redshift**





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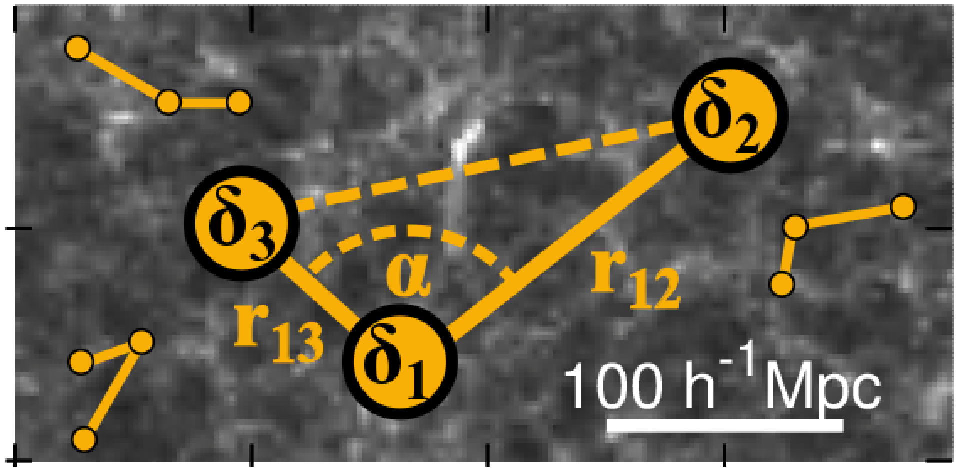
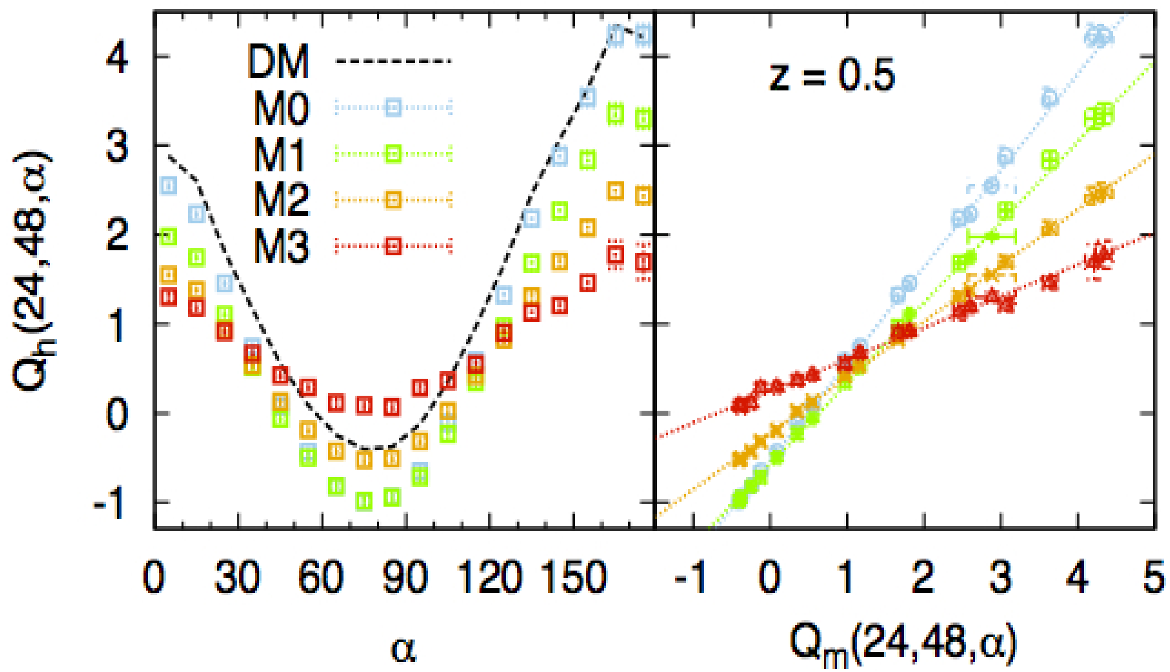
- probes shape of LSS
- independent of redshift
- **depends on bias**

$$\boxed{Q_g \simeq \frac{1}{b_1}(Q_m + c_2)}$$

- **large scale approximation**
- **based on local bias model**





Bel, Hoffmann, Gaztanaga 2015, arXiv:1403.1259

3-point correlation Q

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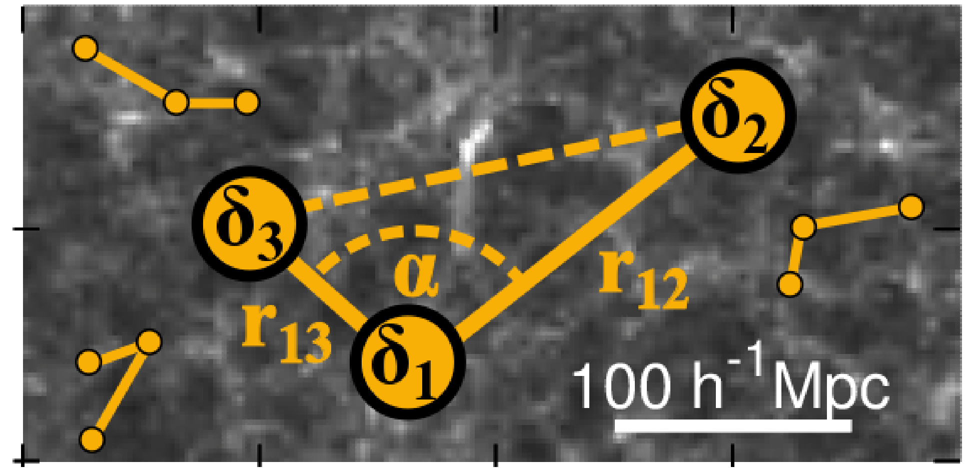
- probes shape of LSS
- independent of redshift
- depends on bias



growth - bias degeneracy broken with Q

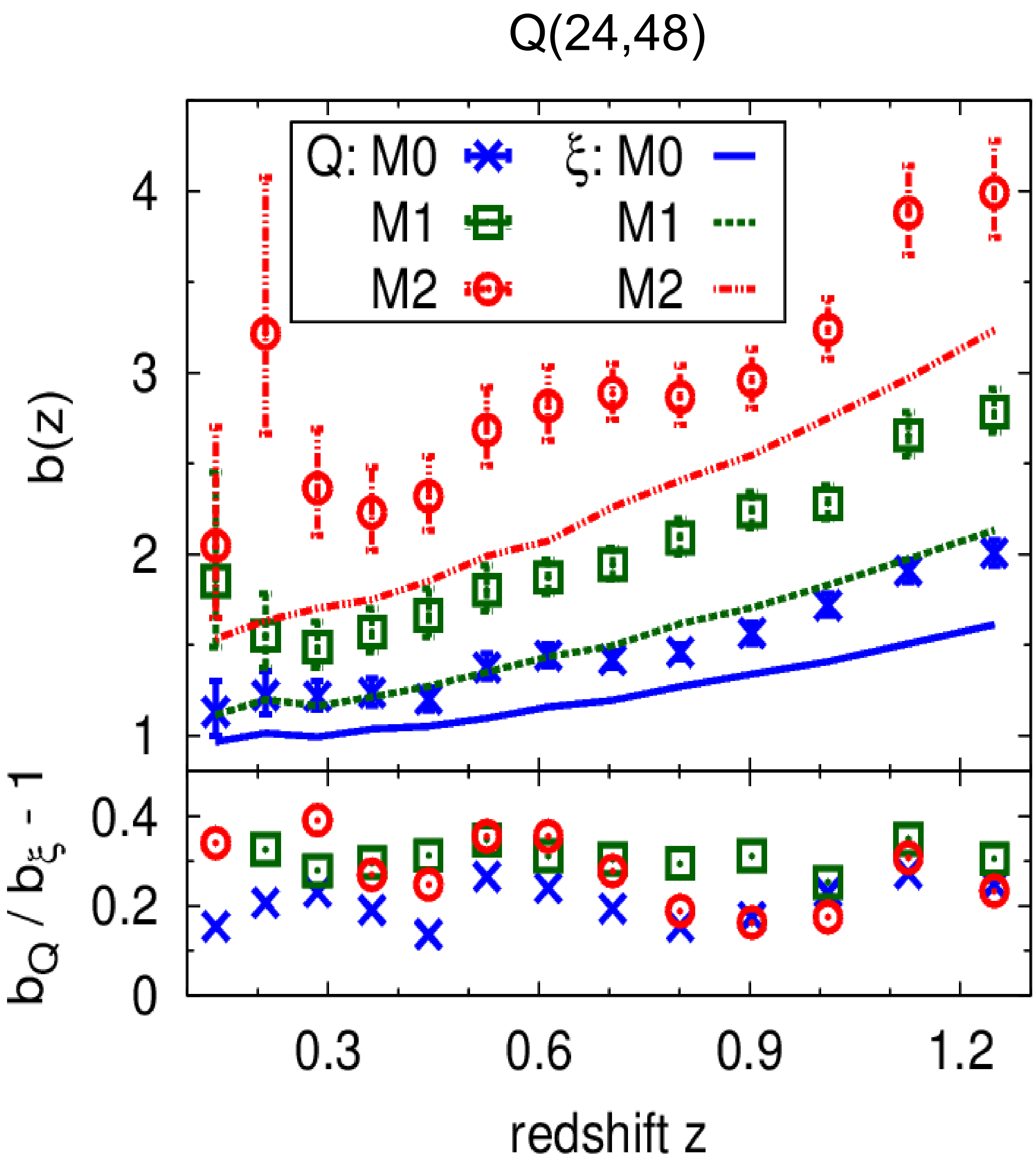
$$\boxed{Q_g \simeq \frac{1}{b_1}(Q_m + c_2)}$$

- **large scale approximation**
- **based on local bias model**

condition:

$$\frac{b_Q(0)}{b_Q(z)} = \frac{b_\xi(0)}{b_\xi(z)}$$

bias from Q ~30% too high



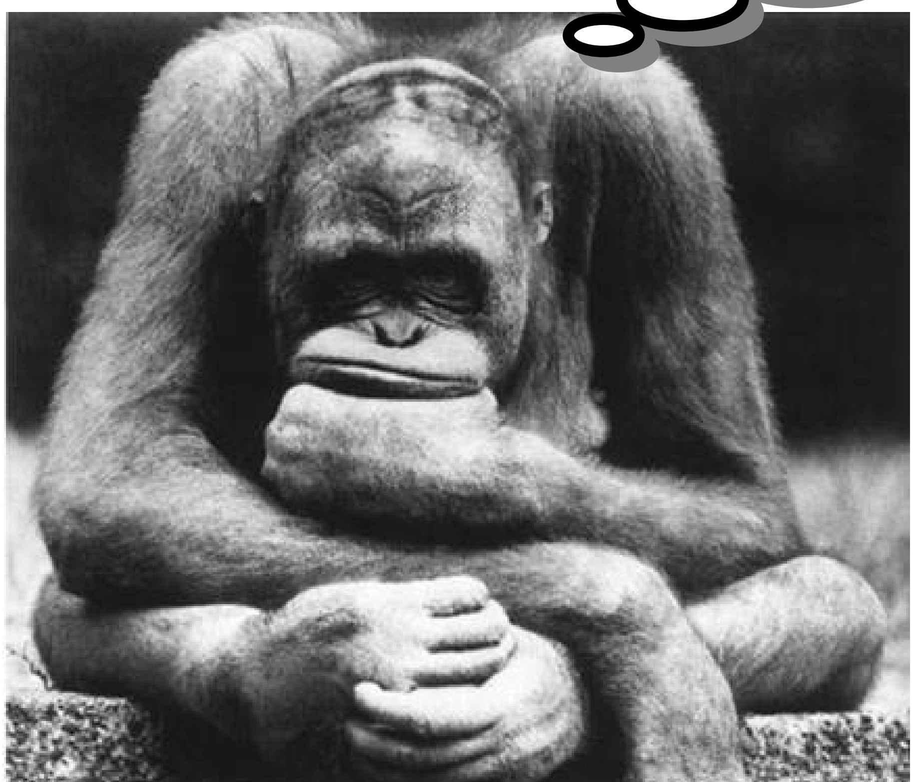
bias from ξ (lines)

- good estimate of linear bias

bias from Q (symbols)

- **~30 % overestimation**
- overestimation similar for different halo mass samples and redshifts
- overestimation appears also very large scales, i.e. Q (36,72)

bias from Q ~30% too high



- missing higher-order terms in Q_g ?
  (Pollack, Smith & Porciani, 2012)

- non-local bias ?
  (Chan, Scoccimarro & Sheth, 2012
  Baldauf et al. 2012)

non-local bias

local quadratic bias model:

$$\delta_g \simeq b_1 \delta_m + (b_2/2)(\delta_m^2 - \langle \delta_m^2 \rangle)$$

non-local bias

non-local quadratic bias model:

$$\delta_g \simeq b_1 \delta_m + (b_2/2)(\delta_m^2 - \langle \delta_m^2 \rangle)$$
$$+ \gamma_2 G_2(\Phi_v)$$

non-local contributions

$$G_2(\Phi_v) = (\nabla_{ij} \Phi_v)^2 - (\nabla^2 \Phi_v)^2$$

Chan, Scoccimarro & Sheth (2012)
Baldauf et al. 2012)

velocity potential: Φ_v

non-local bias: $\gamma_2 = g_2\, b_1/2$

non-local bias in 3-point correlation

non-local quadratic bias model

$$\delta_g \simeq b_1 \delta_m + (b_2/2)(\delta_m^2 - \langle \delta_m^2 \rangle)$$
$$+ \gamma_2 G_2(\Phi_v)$$

Q auto: galaxy-galaxy-galaxy

$$Q_g \simeq \frac{1}{b_1}(Q_m + [c_2 + g_2 Q_{nloc}])$$

non-local contributions

$$G_2(\Phi_v) = (\nabla_{ij}\Phi_v)^2 - (\nabla^2 \Phi_v)^2$$

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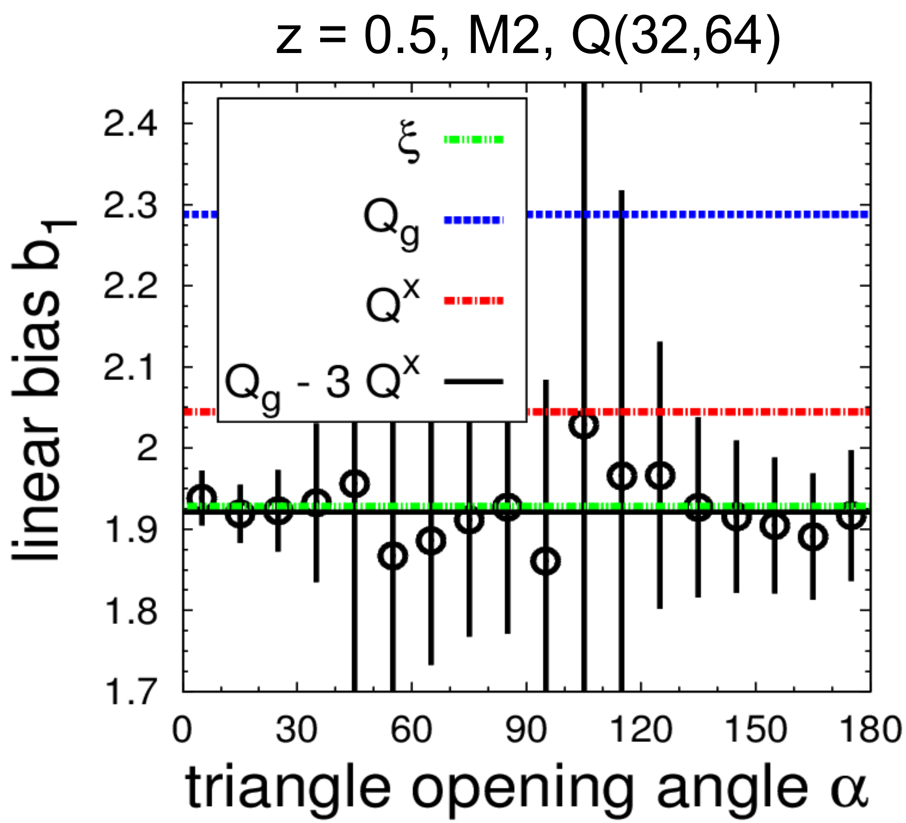
$$Q_g \simeq \frac{1}{b_1}(Q_m + [c_2 + g_2 Q_{nloc}])$$

non-local contributions

Q cross: galaxy-matter-matter

$$Q^x \simeq \frac{1}{b_1}(Q_m + \frac{1}{3}[c_2 + g_2 Q_{nloc}])$$

non-local bias in 3-point correlation



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non-local contributions

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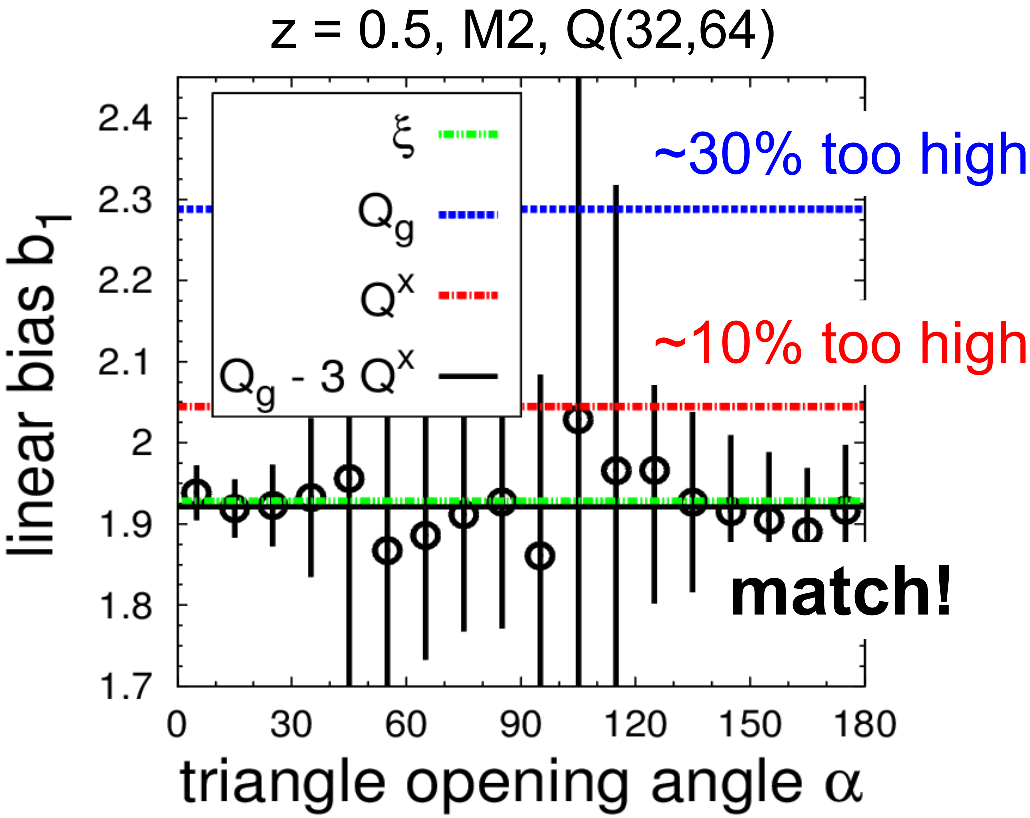
new linear bias estimator

Q auto – 3 Q cross:

$$b_1 = -2\,Q_m / \left(Q_h - 3\,Q^x\right)$$

- independent of quadratic and non-local contributions ($c_2 + g_2 Q_{nloc}$)
- **excellent match with "true" b_1 from ξ**
- possible application in galaxy-lensing cross-correlation

non-local bias in 3-point correlation



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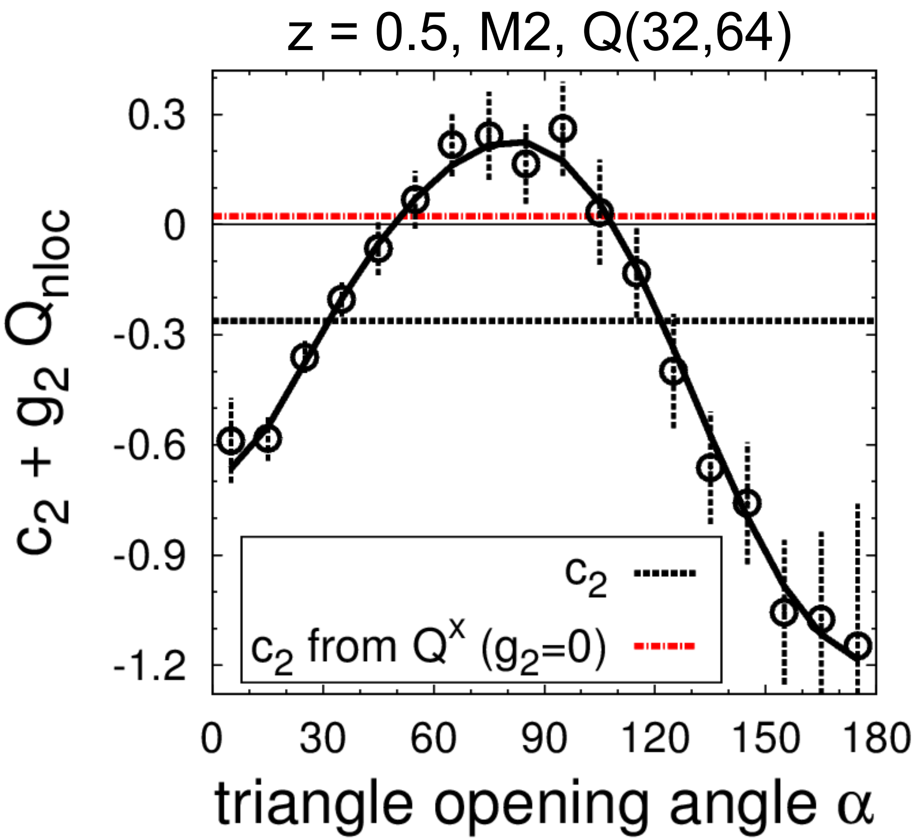

Q auto: galaxy-galaxy-galaxy

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non-local contributions

Q cross: galaxy-matter-matter

$$Q^x \simeq \frac{1}{b_1}\left(Q_m + \frac{1}{3}\left[c_2 + g_2 Q_{nloc}\right]\right)$$

Q auto – Q cross:

$$b_\xi (3/2)(Q_h - Q^x) = c_2 + g_2 Q_{nloc}$$

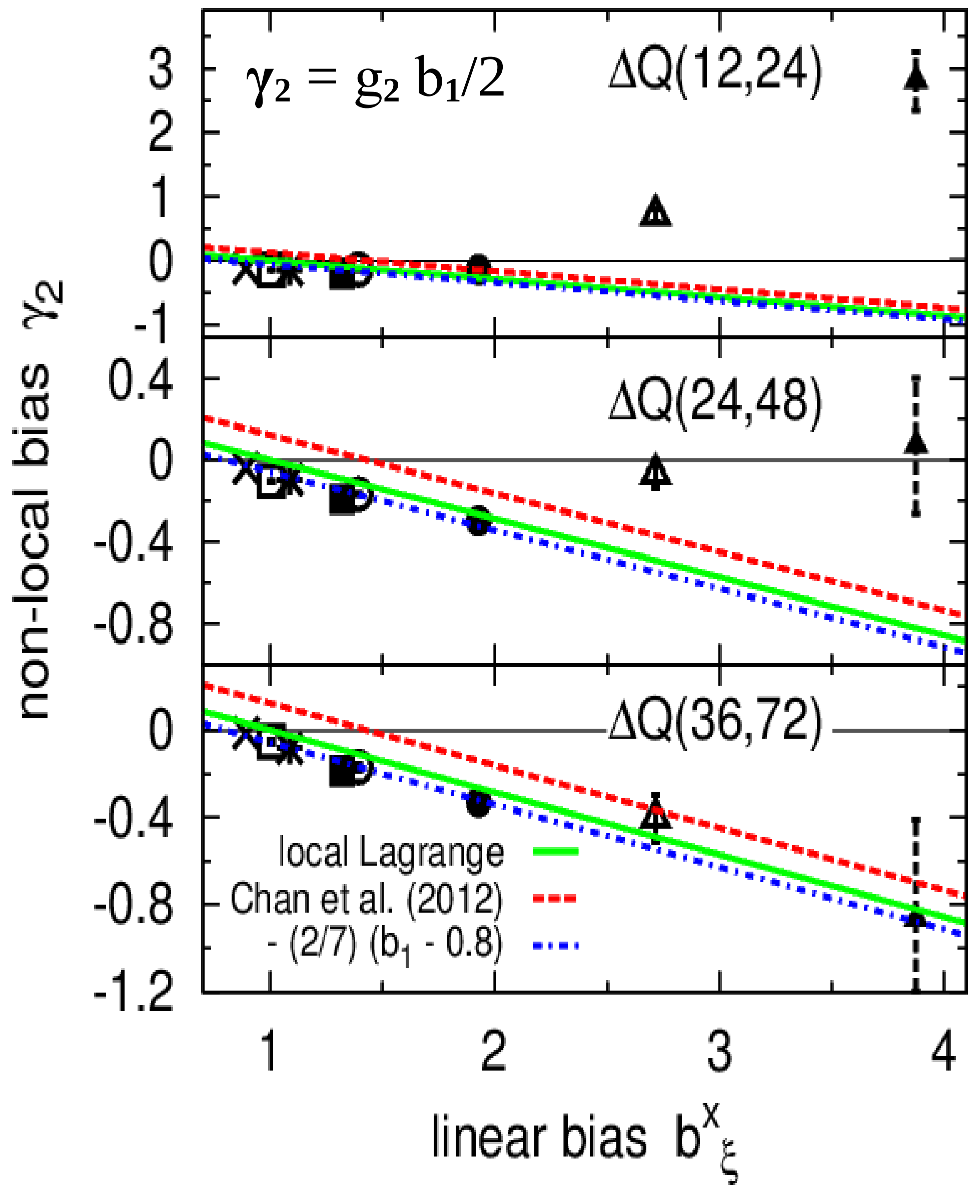
- independent of Q_m
- depends on triangle configuration
  → **local quadratic bias model (g_2 = 0) fails**
- agreement with Q_{nloc} prediction
- can be used to measure c_2 and g_2

non-local bias in 3-point correlation

Bel, Hoffmann, Gaztanaga (2015, arXiv:1504.02074)

symbols:
- measurements from $\Delta Q = Q - Q^X$

lines:
- **fit to measurements**
- local Lagrangian prediction
- fit from Chan, Scoccimarro, Sheth (2012)



strong scale dependence of non-local bias $\gamma_2 = g_2\, b_1/2$

- possibly caused by higher-order terms (local and non-local)

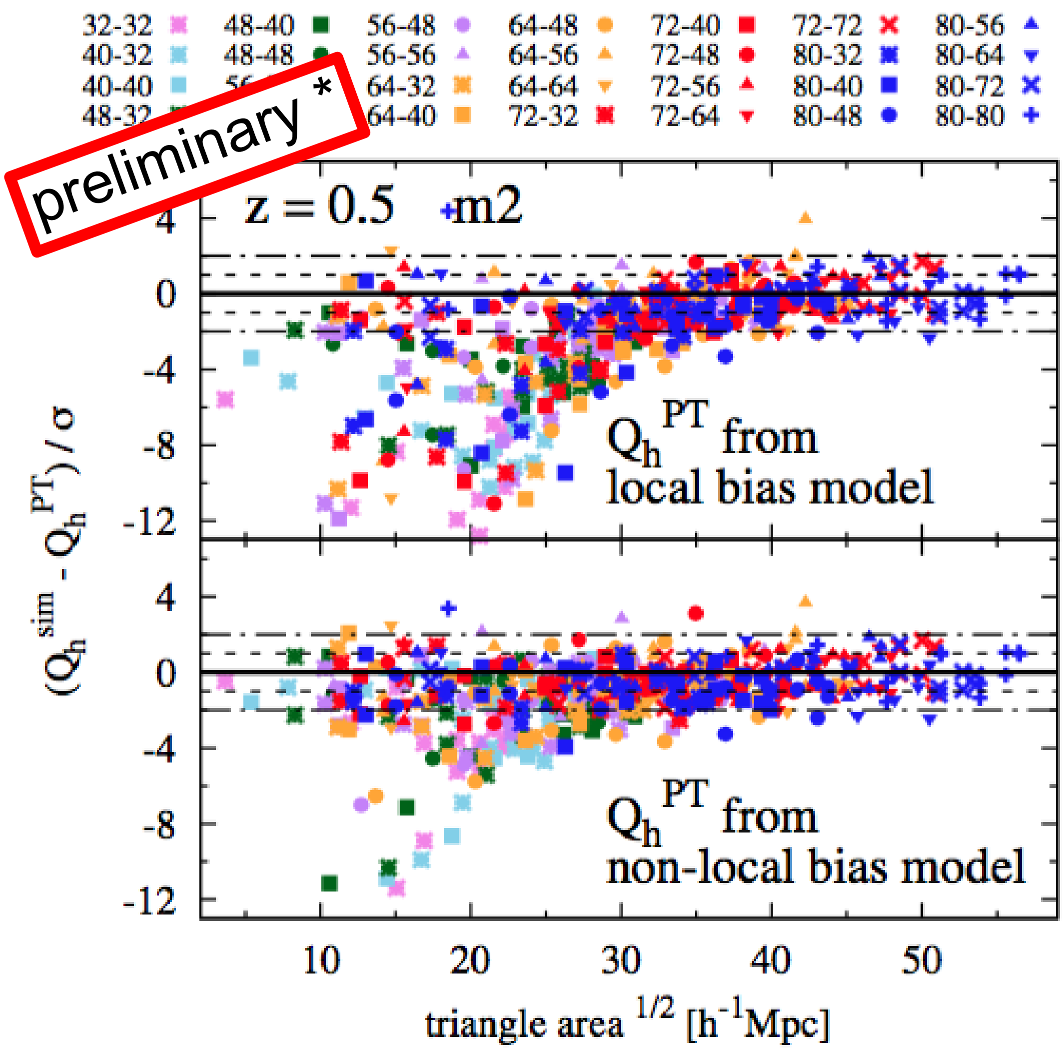
linear b_1-γ_2 relation at r > 35 Mpc/h

- close to local Lagrangian prediction

differences to Chan et al. 2012

- config. vs. Fourier space
- different measurement (B vs. Q)
- different simulation

3pc in Fourier and config. space



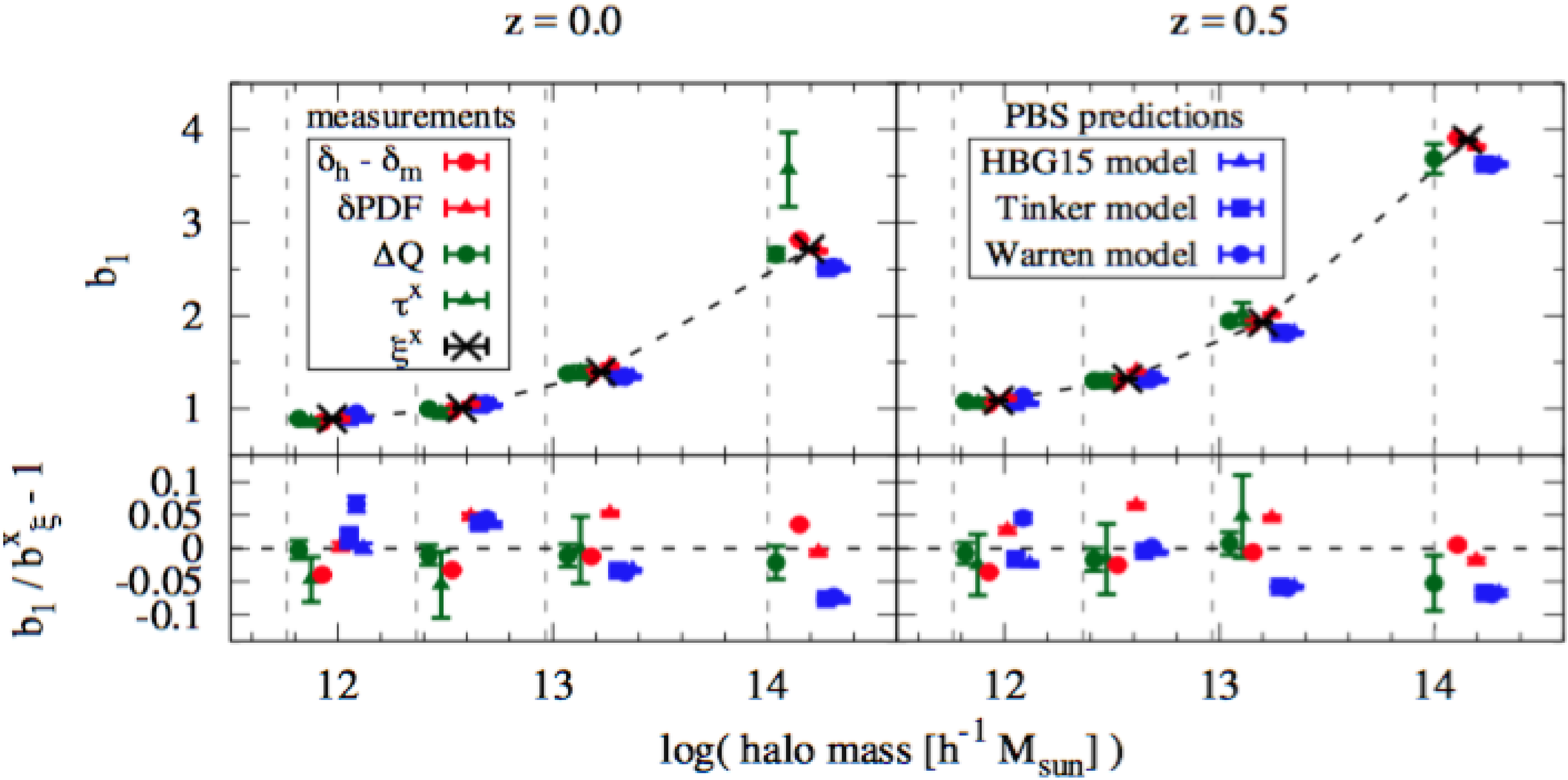
$$\overbrace{Q_h}^{\text{measurement}} \simeq \underbrace{\frac{1}{b_1}\left(Q_m + [c_2 + g_2 Q_{nloc}]\right)}_{\text{model}}$$

- Qm & Qnloc from leading order perturbation theory
- b1, c2, g2 from Fourier space measurements using the same simulations (Chan, Sheth, Scoccimarro, 2012)

- measurements better described by non-local model
- convergence between 30-40 Mpc/h

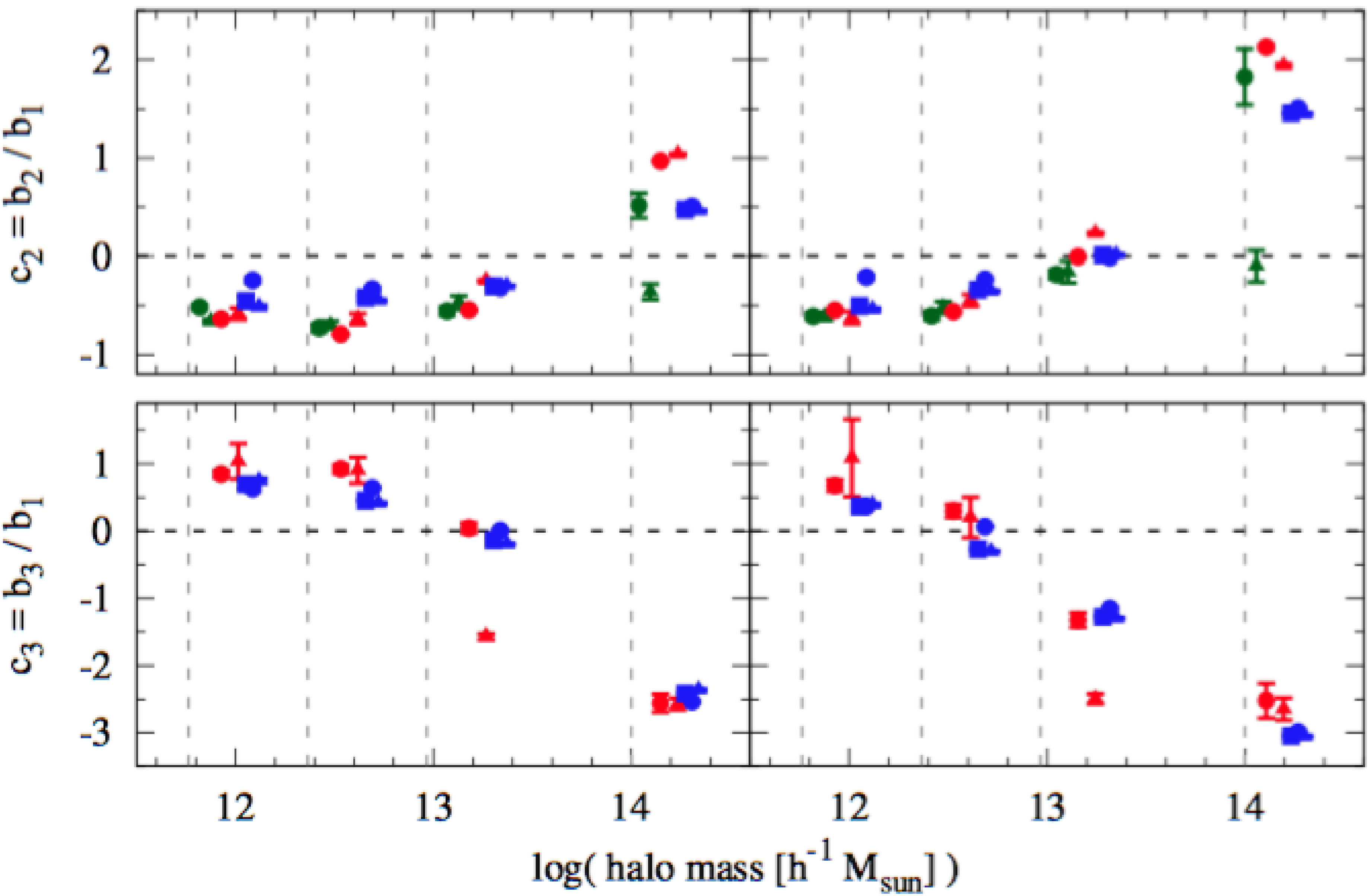
*Hoffmann, Gaztanaga, Scoccimarro, Crocce in prep.

linear bias comparison



Hoffmann, Bel, Gaztanaga 2016, arXiv:1607.01024

non-linear bias comparison



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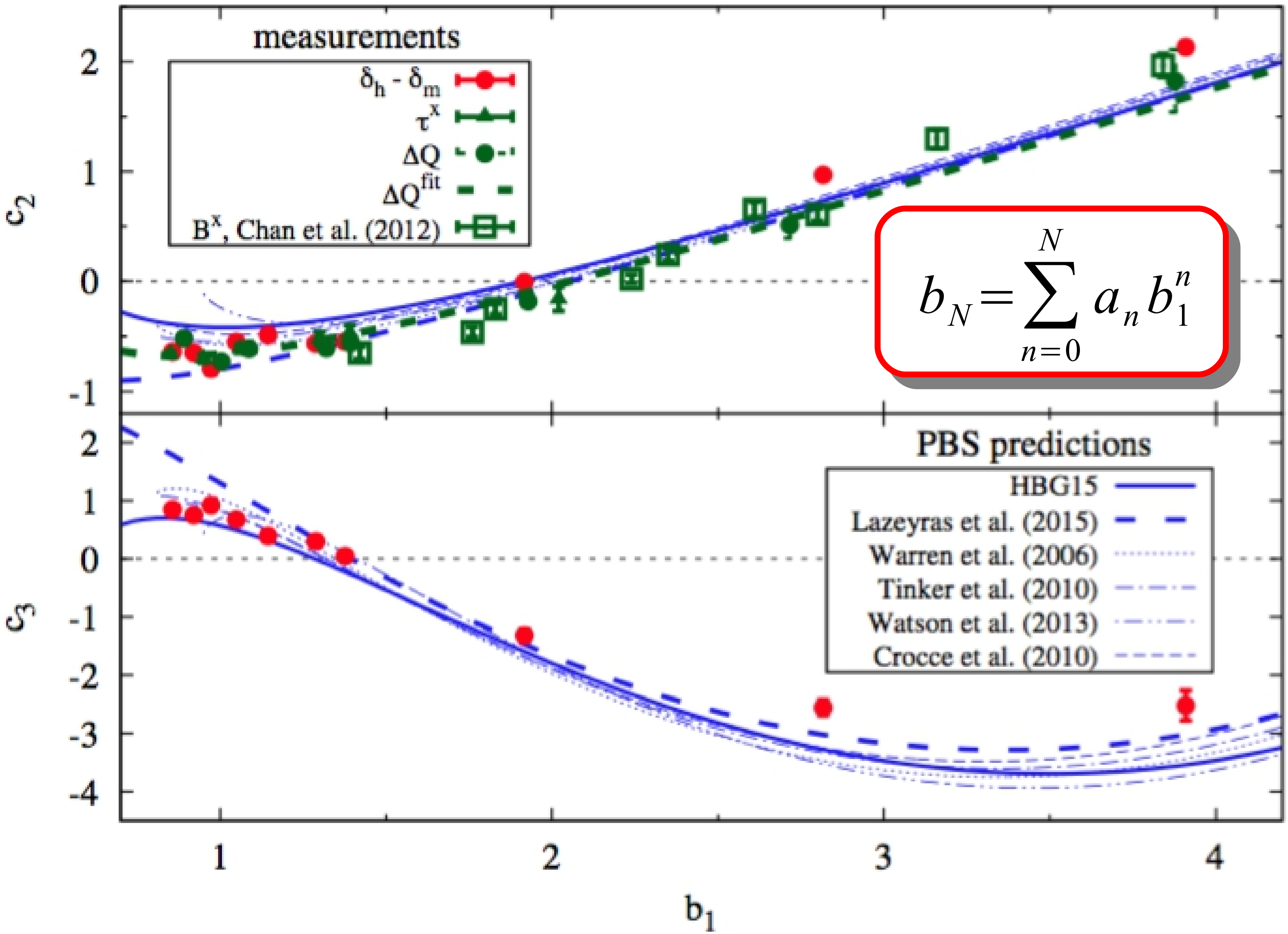
universal relation between b1, b2, b3



$$b_N = \sum_{n=0}^{N} a_n b_1^n$$

Hoffmann, Bel, Gaztanaga (2015, 2016, arXiv:1503.00313, 1607.01024)

Conclusions

- constraints on cosmological models limited by growth–bias degeneracy
- growth–bias degeneracy broken with 3pc
- 3pc is affected by non-local contributions to bias function
- agreement with Fourier space results only at > 40 Mpc/h
- accurate bias from combining 3pc & 3pcc
- nearly universal relation between b2(b1) and b3(b1)