Recent insights into halo and void formation and clustering

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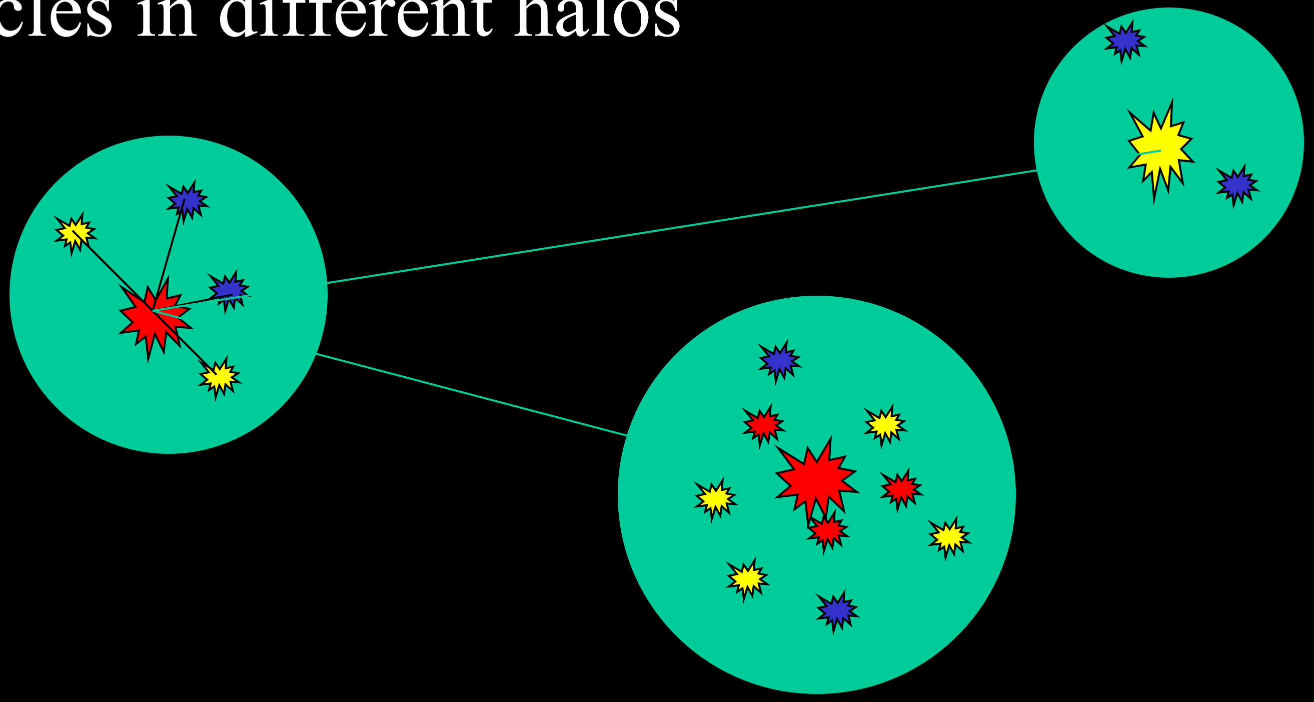
The halo-model of galaxy clustering

- Two types of particles: central + ‘satellite’
- Two types of pairs: both particles in same halo, or particles in different halos



- $1+\xi_{obs}(r) = 1+\xi_{1h}(r) + 1+\xi_{2h}(r)$

$$1+\xi_{1h}(r) = 1+\xi_{cs}(r) + 1+\xi_{ss}(r)$$

The halo-model of galaxy clustering

- Write as sum of two components:
  - $1+\xi_{1h}(r) = \int dm\, n(m)\, g_2(m)\, \xi_{dm}(m|r)/\rho_{gal}^2$
  - $\xi_{2h}(r) \approx [\int dm\, n(m)\, g_1(m)\, b(m)/\rho_{gal}]^2\, \xi_{dm}(r)$
  - $\rho_{gal} = \int dm\, n(m)\, g_1(m)$: number density of galaxies
  - $\xi_{dm}(m|r)$: fraction of pairs in m-halos at separation r
- Think of mean number of galaxies, $g_1(m)$, as a weight applied to each dark matter halo
  - Galaxies ‘biased’ if $g_1(m)$ not proportional to m, …, $g_n(m)$ not proportional to m^n
  - To generate mock catalog, pre-compute pairs once and for all, then re-weight as desired

The halo-model of galaxy clustering

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- Handle ‘assembly bias’ easily by treating m as vector (mass, concentration, formation time, …)
  - Statements that halo model cannot treat assembly bias are based on the assumption that m is scalar = halo mass
  - While this common assumption simplifies the analysis, it is *not* required by the formalism/approach
  - Problem is to identify elements of vector ‘m’

Ignorance:

- To parametrize?
  - Make model as complicated as possible (i.e. as allowed by symmetries, etc.)
  - Result is 'a ton' of nonlinear bias parameters (depends what you call a parameter, etc)
- Or reduce?
  - Study which subset of parameters are important
  - Look for relations between parameters

Ignorance: Parameterize or Reduce?

- Traditionally two approaches:
  - Eulerian: relate today's biased tracers to properties of today's field
  - Lagrangian: relate today's tracers to properties of initial field (e.g. CMB) + subsequent evolution (typically using some version of perturbation theory – spherical collapse, Zeldovich, etc.)

Recent progress:

merge peaks theory
(fixed smoothing scale; BBKS 1986)
with
excursion set approach
(multi-scale; Bond et al. 1991)

(Musso et al. 2012; Paranjape et al. 2013)

Tracer $n(m) = \int d\delta \ldots g(\delta,\delta',\delta'',\text{shear},\ldots)$

Bias from $n(m|\Delta,\Sigma)/n(m)$

$= \int d\delta \ldots g(\delta,\delta',\ldots|\Delta,\Sigma)/n(m)$

But $\langle\Delta|\text{halo}\rangle$

$= \int d\delta \ldots g(\delta,\delta',\ldots)\,\langle\Delta|\delta,\delta',\ldots\rangle/n(m)$

so close connection between bias and profile around bias tracers

Presence of δ' yields ‘velocity bias’

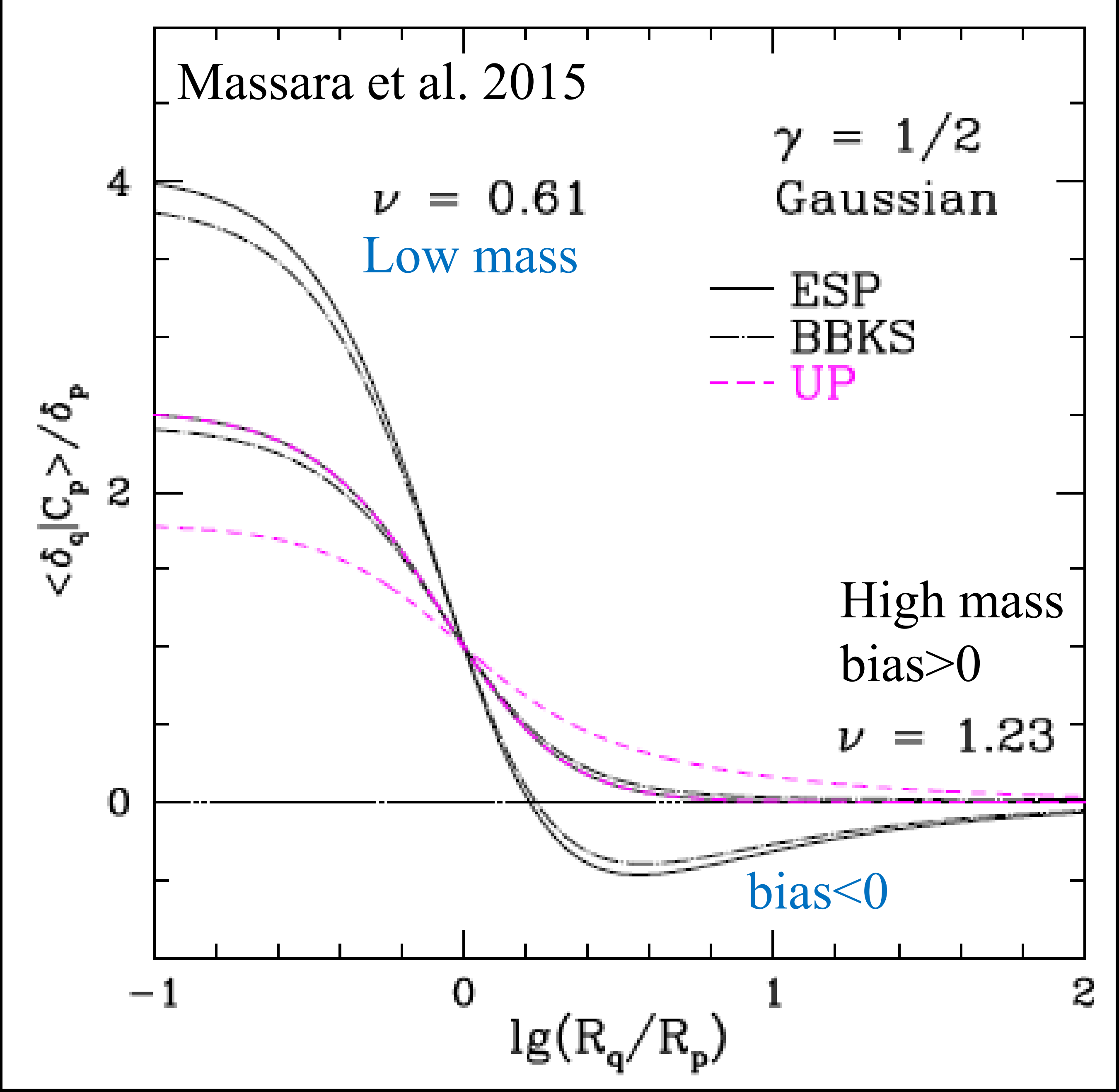
N.B. Environment = effective cosmology built-in

(e.g.Martino-Sheth 2009 for density; Desjacques 2013 for shear)

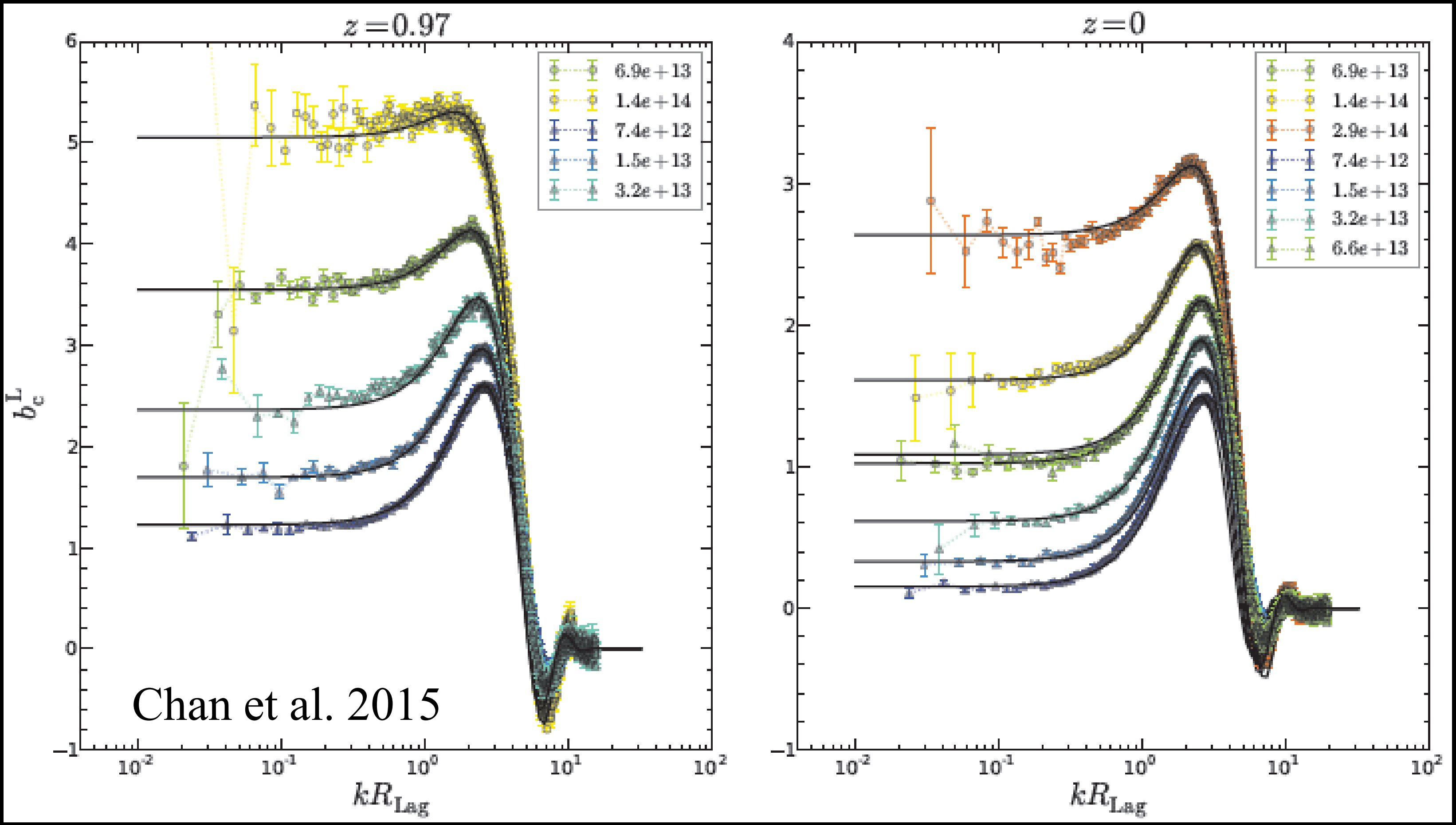
Density profile = cross correlation between peak and mass

Generic: Low mass = more concentrated

Lagrangian bias is scale dependent



Scale dependent bias depends on tracer type (halo mass + …)



Scale dependence of bias depends on the properties of a proto-halo patch which determine halo formation

E.g., if protohalo is (i) a sufficiently overdense initial patch which is (ii) a local maximum, and which is (iii) less dense when smoothed on a larger scale, then linear bias is

$$\mathrm{bias}(k) = [b_{100} + b_{010}\, k^2 R_h^{\,2} + b_{001}\, \mathrm{d}\ln W(kR_h)/\mathrm{d}\ln R_h]\; W(kR_h)$$

Coefficients depend on halo mass (R_h), density (i), steepness (iii), isolation (ii); Common to 'marginalize' over (ii) and (iii)

Woe to any approach which assumes W is sharp in k!

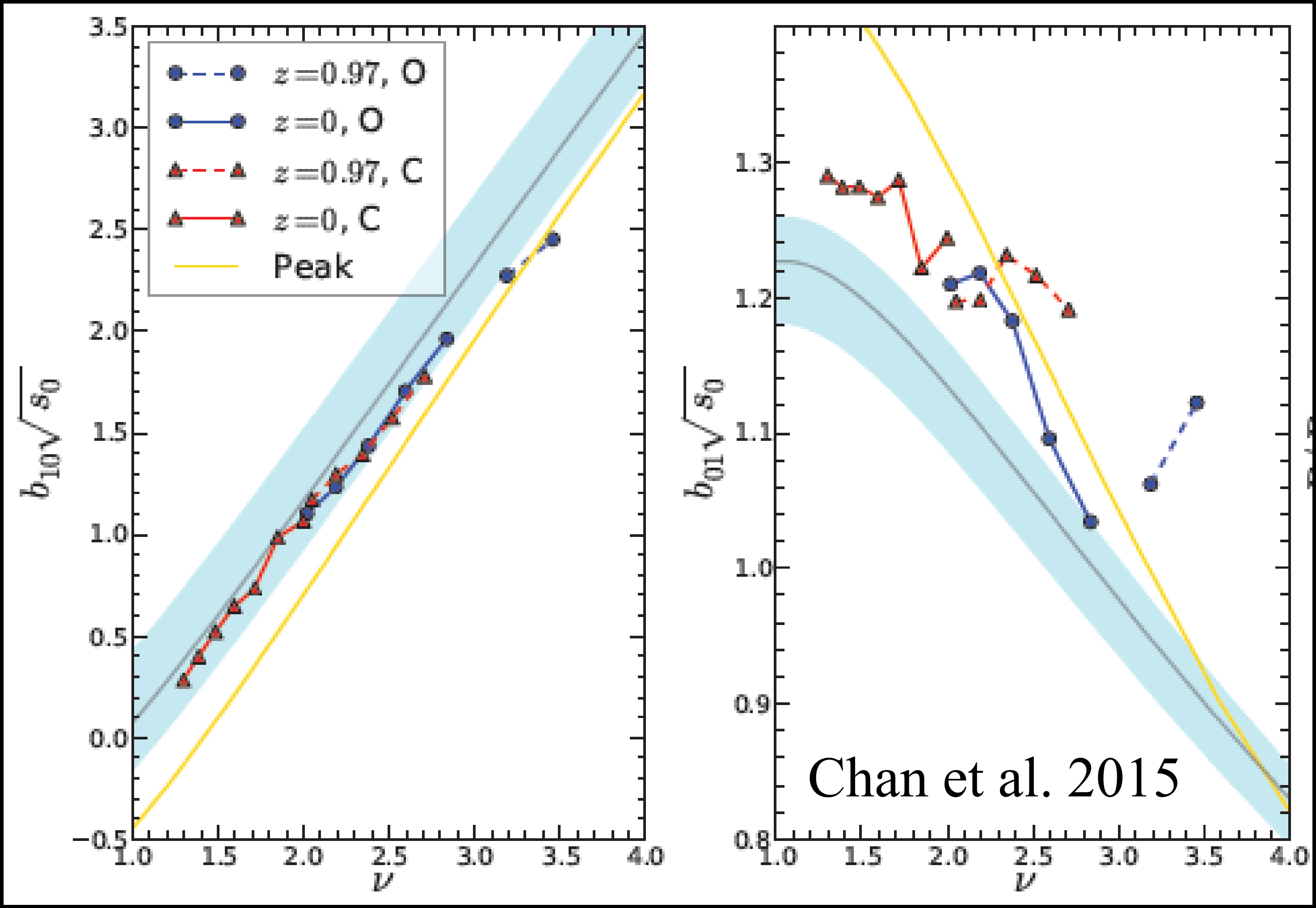
N.B. This is just linear bias; there are even more ('a ton of') coefficients for quadratic and higher order bias …

There are 'consistency relations' between coefficients:

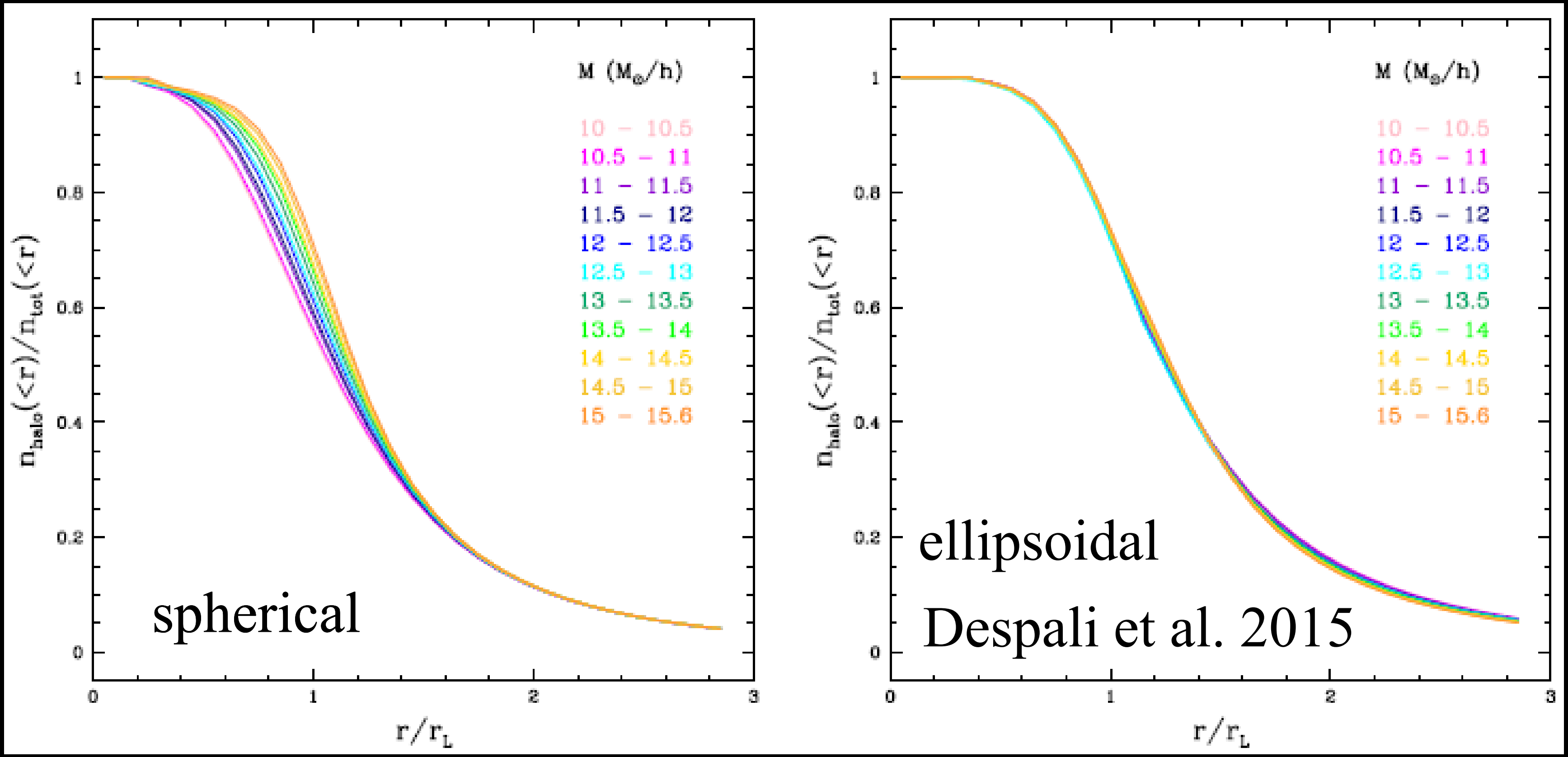
- $b_{100} + b_{010} + b_{001} = \delta_c(s)/s$ (Musso et al. 2012)
- If stochasticity (e.g. from shear), then

  $b_{10\ldots} + \ldots + b_{\ldots 01} = \langle\delta_c(s)\rangle/s$ (Castorina et al. 2015)
- Similar relations for higher order bias coefficients; bias coefficients associated with shear, etc.
- But … must know mass-dependence of δ_c
- Alternatively, can use large scale bias measurements to estimate this mass-dependence

Measure bias parameters from P_{hm}



More precision from including fact that initial patch not quite Tophat

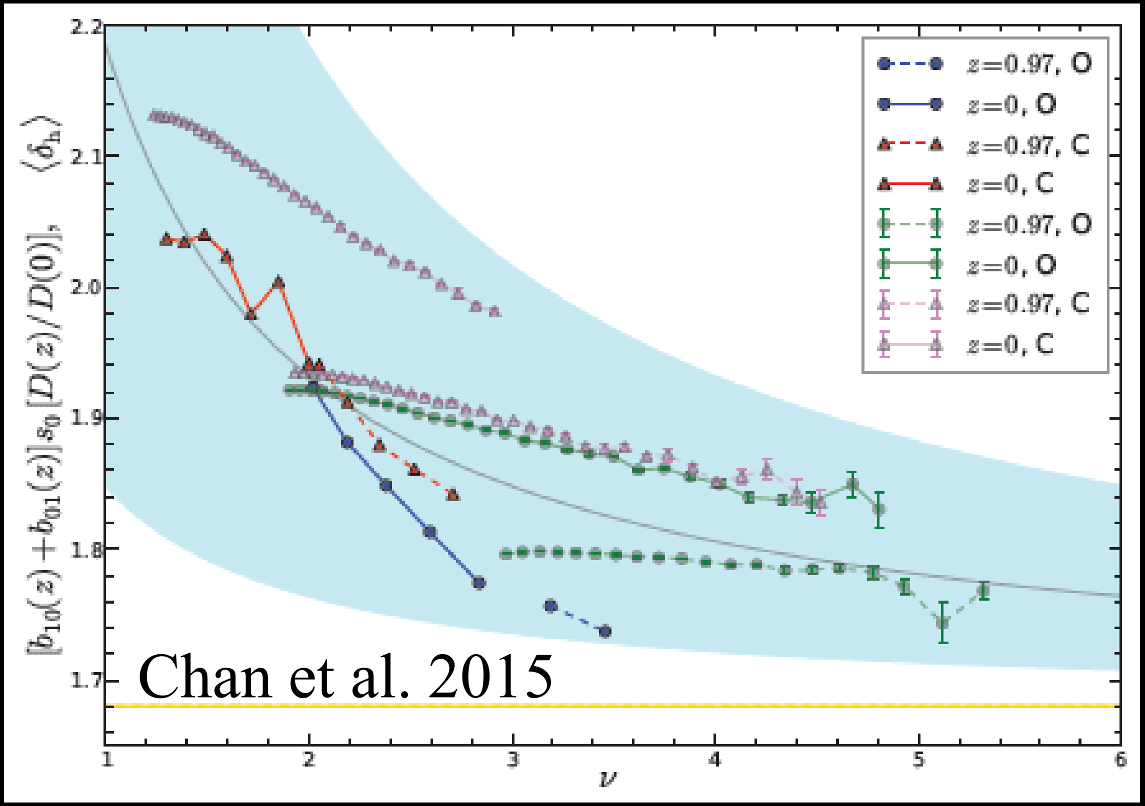


$W_{eff}(kR) = W_{th}(kR)\exp[-k^2(R/5)^2/2]$: escape velocity/'propagator'

W is clearly neither sharp in r nor in k!

Mass-dependence of collapse threshold δ_c

- … inferred from large scale bias
- … agrees with direct measurement in proto-halo patches



Evolution

- To relate to 'observations' must account for Lagrangian → Eulerian evolution of bias coefficients
- In general: $b^{Eul} = b_{vel} + b^{Lag}$
  - Usually b_{vel}=1, but k-dependent for peaks (Desjacques-Sheth 2010)
  - This results in (Desjacques et al. 2010)

$$b^{Eul}(k,t) = b^{Lag}_{10}+D(t) + [b^{Lag}_{01}-D(t)]\ (s_0/s_1)\ k^2$$

$$= b^{Eul}_{10} + b^{Eul}_{01}\ (s_0/s_1)\ k^2$$

  - Consistency relation survives!

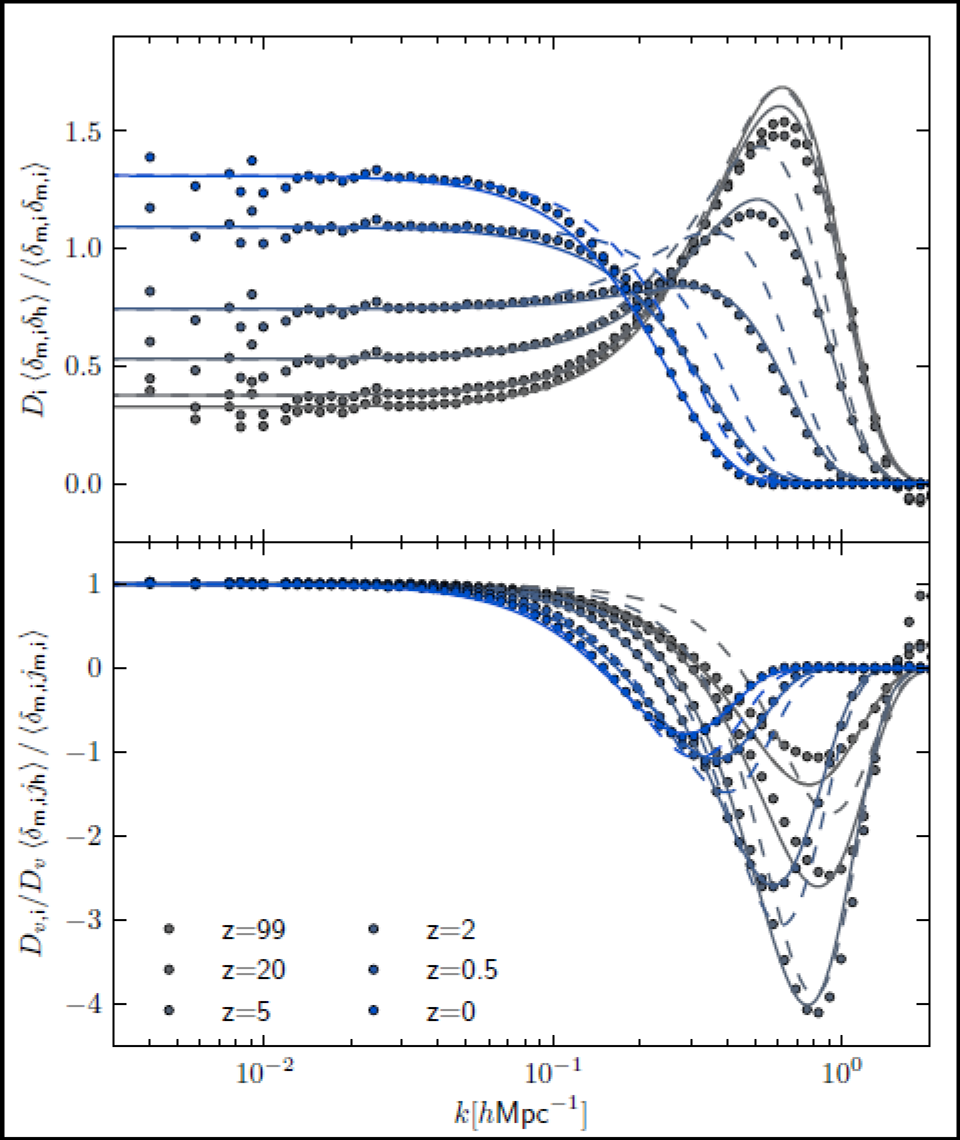
Evolution

$b = b_{vel} + b_{Lag}$

differs from usual prediction because of k-dependent velocity bias

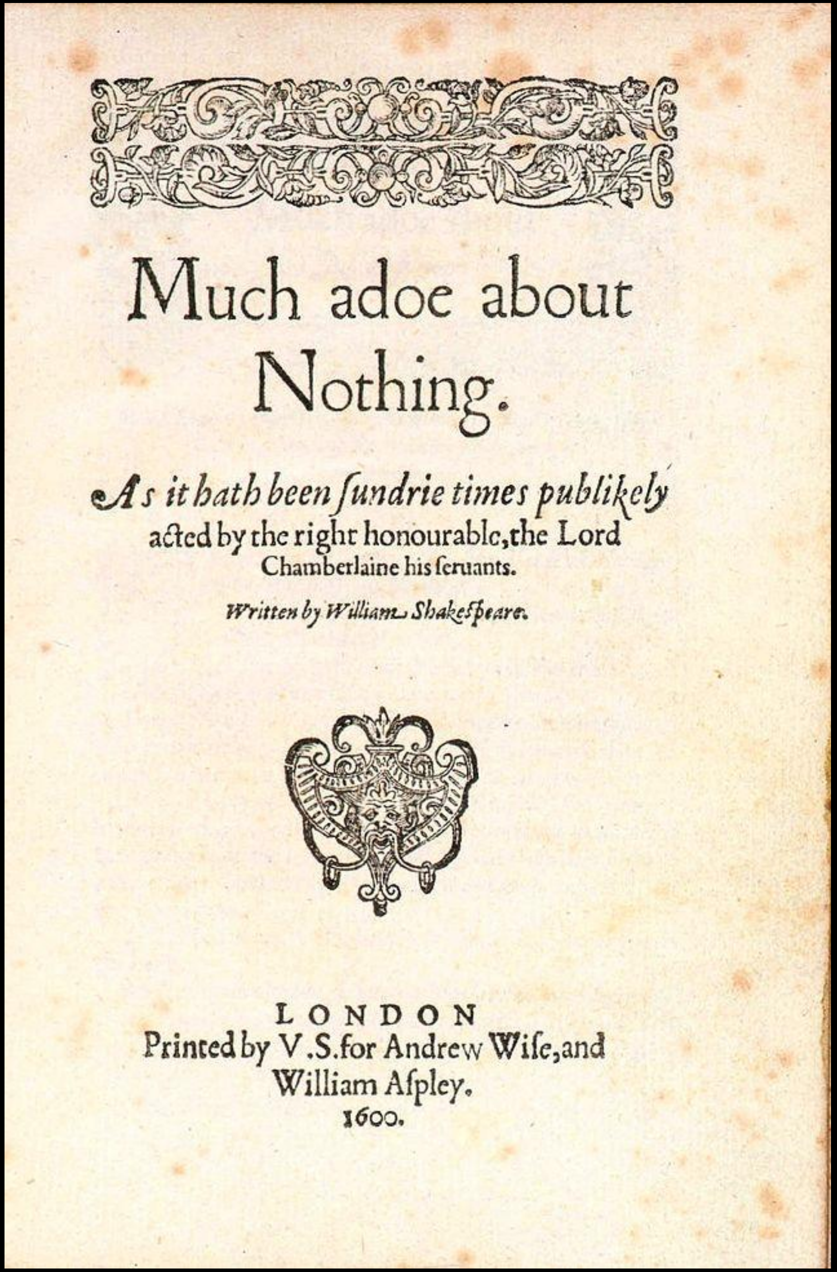
(Desjacques-Sheth 2010; Desjacques et al. 2010)

N.B. This preserves the consistency relation



Baldauf et al 2014

A victory is twice itself when the achiever brings home full numbers.



Much adoe about Nothing.

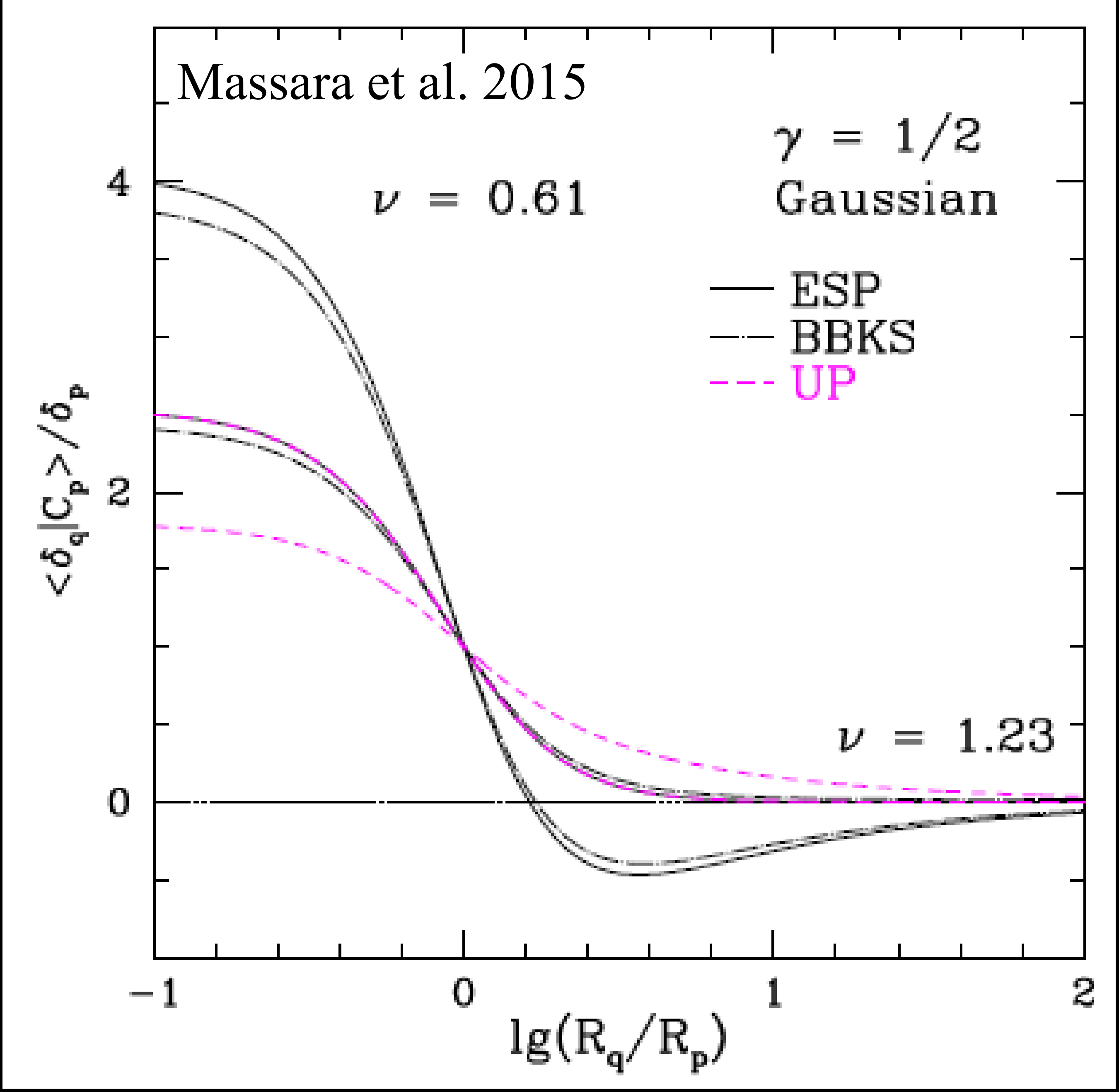
As it hath been ſundrie times publikely acted by the right honourable, the Lord Chamberlaine his ſeruants.

Written by William Shakeſpeare.

LONDON
Printed by V.S. for Andrew Wiſe, and William Aſpley.
1600.

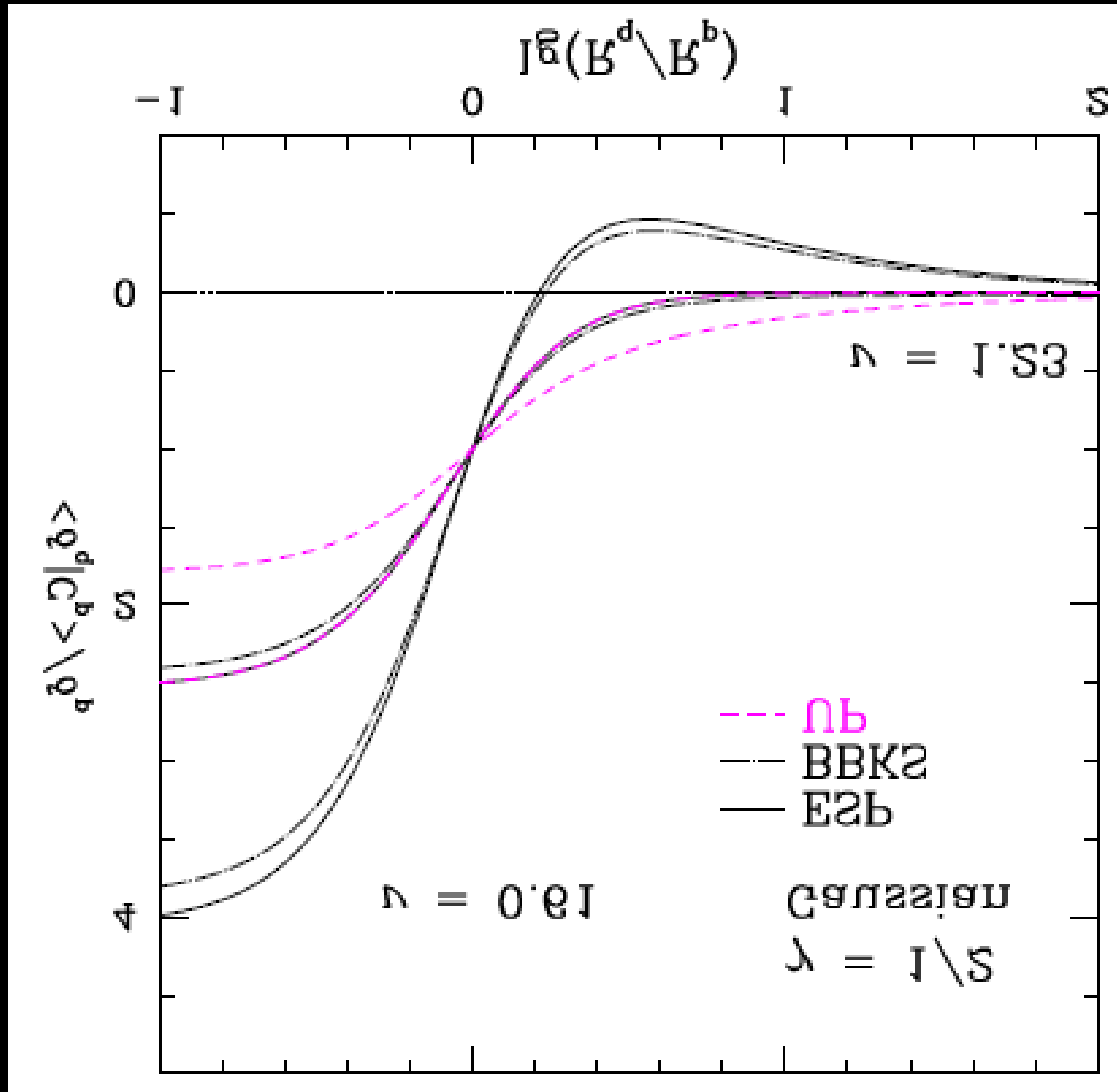
Density profile = cross correlation between peak and mass

Generic: Low mass = more concentrated



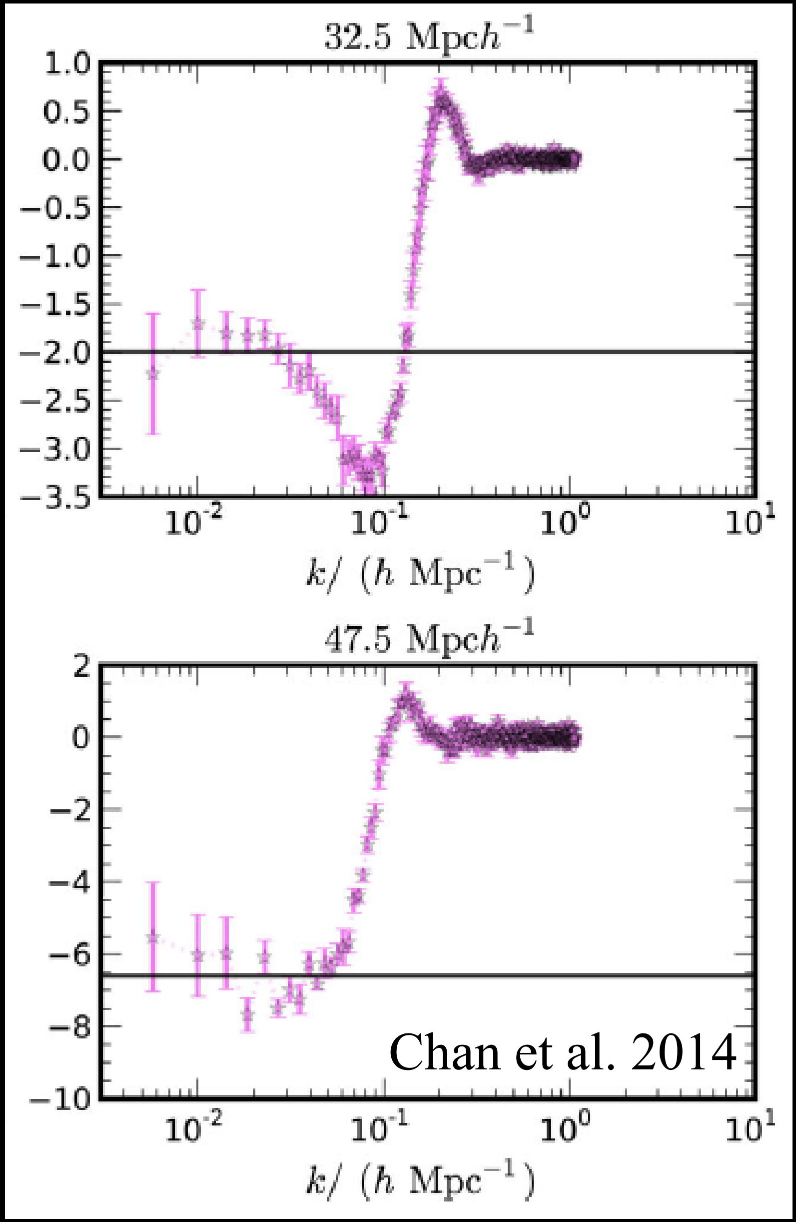
Density profile = cross correlation between void and mass

Generic: Small void = obvious wall

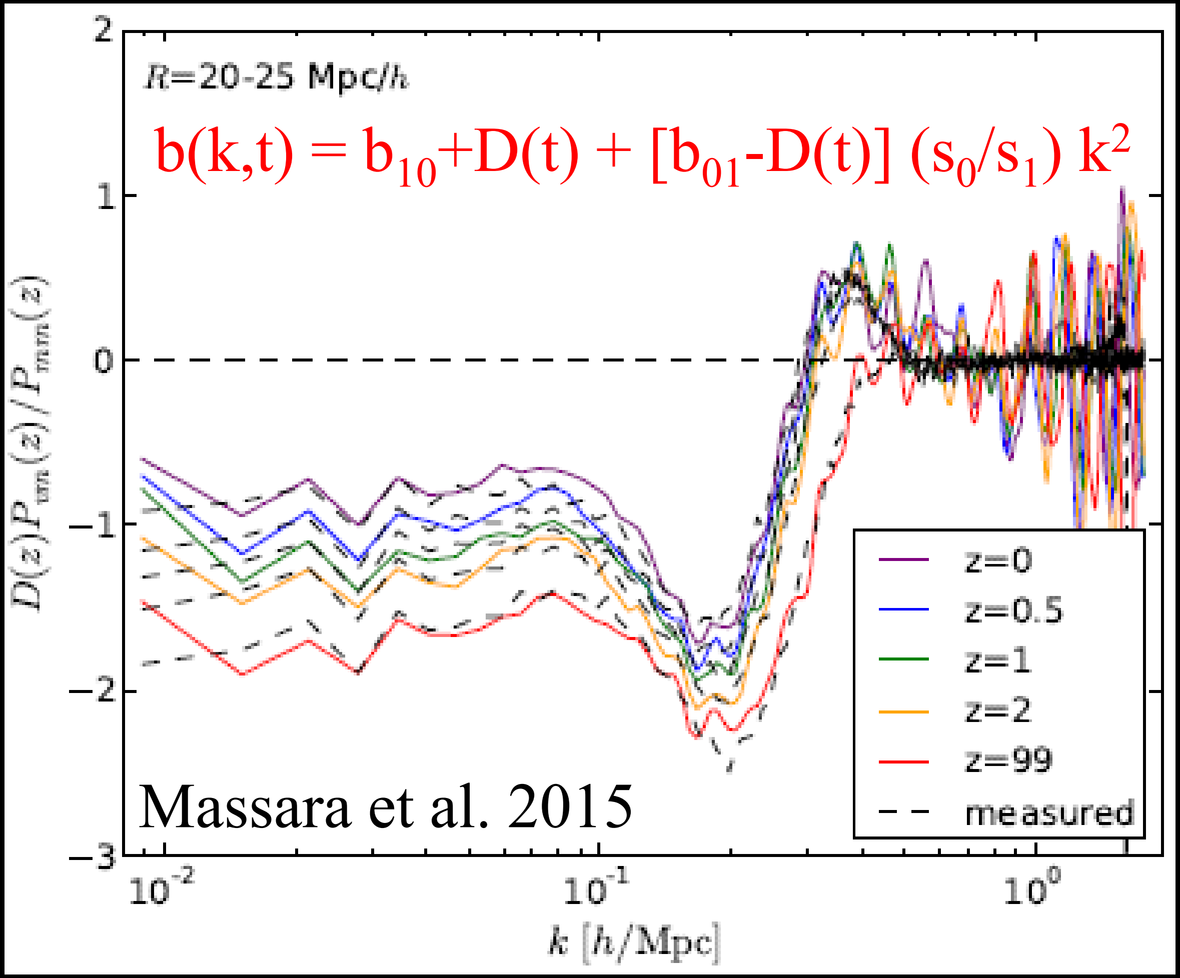


Voids ≈ halos, albeit usually negatively biased with respect to mass (i.e. profile = damped tophat)

One potentially interesting difference: voids can have b=0



Evolution of large scale void bias ~ same as for halos



Since some voids have $b>0$
and others $b<0$,
some ‘voids’ have bias = 0.

Generically, bias=0 is possible for sufficiently large sufficiently underdense regions.

Some interest in using b=0 objects as standard rods (Hamaus et al. 2013)

- These will depend on tracer population.
- SDSS Main Galaxy sample in Abbas-Sheth had b~1, so underdense patches of size 8Mpc/h in this sample had b_{void}=0.
- In LRG sample, galaxies have b~2, so b_{void}=0 for voids of size 20 Mpc/h.

Puzzle

- Predicted evolution of bias, which simulations confirm, says

$$b(k,t) = b_{10}+D(t) + [b_{01}-D(t)]\ (s_0/s_1)\ k^2$$

- If b=0 at one time, it does not have b=0 always
- Not obvious that b=0 rods remain standard

- Bias is scale dependent – understanding this allows (substantially) larger fraction of data (halos and voids) to constrain models
- Scale dependence encodes information about physics of halo formation
  - This connection can be obscured in symmetry motivated expansions
  - Smoothing window is always present; cures many PT divergences; is not sharp in k
- Consistency relations between bias factors potentially reduce parameter space
  - Large scale clustering ↔ small scale physics