Title: Biasing in the Lyman-alpha forest

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Abstract: I'll present a series of numerical experiments to test simple analytical predictions for large-scale Lyman-alpha forest bias parameters. Despite relying on second-order SPT, some of the predictions are surprisingly accurate, especially if thermal broadening is not taken into account. I'll also discuss details of using filtered and squared small-scale fields as robust tracers of large-scale structure that might be useful for non-Gaussianity measurements.

Inverse Dual Simulations

Anže Slosar, Brookhaven National Laboratory
w Andrew Pontzen, UCL

LSS Perimeter, 2015

Deeply non-linear regime

- N-body simulations are our only tool to understand deeply non-linear structure formation
- They are essentially Monte Carlo simulations, simulating a particle initial conditions.
- Note that this need not be so: one could write a hierarchical sets of equation for the time evolution of n-point function: one could imagine non-linear solver for correlators rather than field realization (but one can only imagine it).

Initial conditions duals

- We normally either run one large simulation or multiple smaller one with independent random seeds for IC
- Can we do better and learn something by running multiple simulations with cleverly correlated initial conditions?
- Here is one such proposal: run pairs of simulations with "inverse IC":

$$\delta(IC) \to -\delta(IC)$$

Inverse simulations

$$\delta \rightarrow -\delta$$

(both in real and Fourier space)
You get a pair of initial conditions, but

- Overdensities in correspond to underdensities in the other (and vice versa)
- Halos in one will correspond to voids in the other (and vice versa)
- Large scales are expected to evolve the same (up to a minus sign).
- Small scales will "decorrelate"

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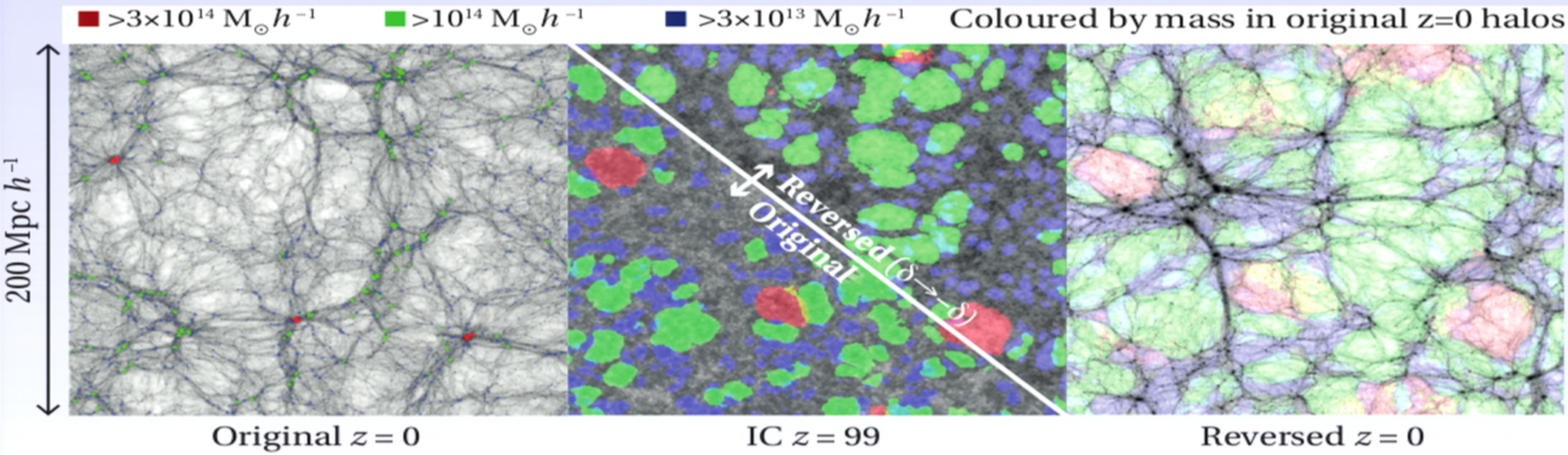
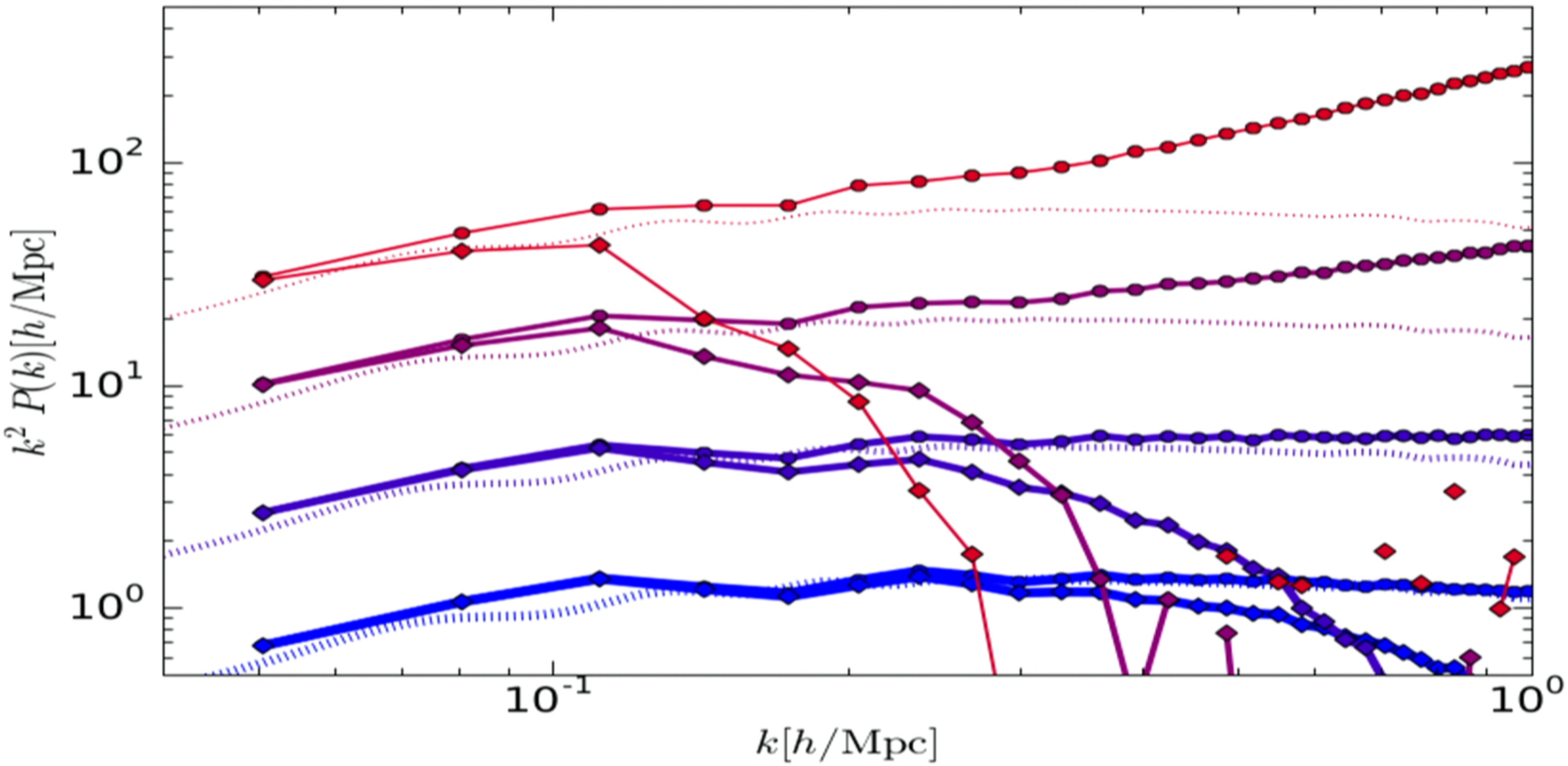
We run a pair

- w Andrew Pontzen (UCL)
- 200 Mpc, 512^3 particles, WMAP5 cosmology
- Run standard and inverse

Example



$>3\times10^{14}\ M_\odot h^{-1}$
$>10^{14}\ M_\odot h^{-1}$
$>3\times10^{13}\ M_\odot h^{-1}$
Coloured by mass in original z=0 halos
200 Mpc h^{-1}
Reversed ($\delta \to -\delta$)
Original
Original $z=0$
IC $z=99$
Reversed $z=0$


10^2
10^1
10^0
$k^2\,P(k)[h/\mathrm{Mpc}]$
10^{-1}
10^0
$k[h/\mathrm{Mpc}]$

Perturbation theory

There are many perturbation theory approaches. In SPT/RPT one expands in powers of δ:

$$\delta(\mathbf{k}) = \sum_{i=1}^{\infty} a^i \delta_i(\mathbf{k}), \tag{1}$$

where $a\delta_n$ term is a convolution of n initial fields δ_1 with a relevant perturbation theory kernel and where translational invariance reduces the dimensionality of the integral to $n-1$:

$$\delta_n(\mathbf{k}) = \iiint F_n(\mathbf{k}, \mathbf{k}', \mathbf{k}'' \ldots) d^3\mathbf{k}' d^3\mathbf{k}'' d^3\mathbf{k}''' \ldots d^3\mathbf{k}'^{(n-1)\mathrm{times}} \delta_1(\mathbf{k}')\delta(\mathbf{k}'') \tag{2}$$

It is immediately clear that for the inverse simulations, the orders in the evolved field are the same in magnitude, but that odd ones flip the sign:

$$\delta_j \rightarrow (-1)^j \delta_j \tag{3}$$

Perturbation theory

The standard auto-power spectrum is given by

$$P(k) = \langle \delta(\mathbf{k})\delta^*(\mathbf{k}) \rangle = P_{11}(k) + \sum_{ij;\ i+j \text{ is even}} P_{ij}(k)$$
$$= P_{11} + P_{1X} + P_{2X} + P_{3X} + \ldots$$

Therefore we have

$$\begin{aligned}
P_{\mathrm{IC}\times\mathrm{IC}} &= P_{11} \\
P_{\mathrm{IC}\times\mathrm{S}} &= P_{11} + \frac{1}{2}P_{1X} \\
P_{\mathrm{S}\times\mathrm{S}} &= P_{11} + P_{1X} + P_{2X} + P_{3X} \ldots \\
P_{\mathrm{S}\times\mathrm{R}} &= -P_{11} - P_{1X} + P_{2X} - P_{3X} \ldots
\end{aligned}$$

Can solve for 4 quantities from 4 measured power spectra

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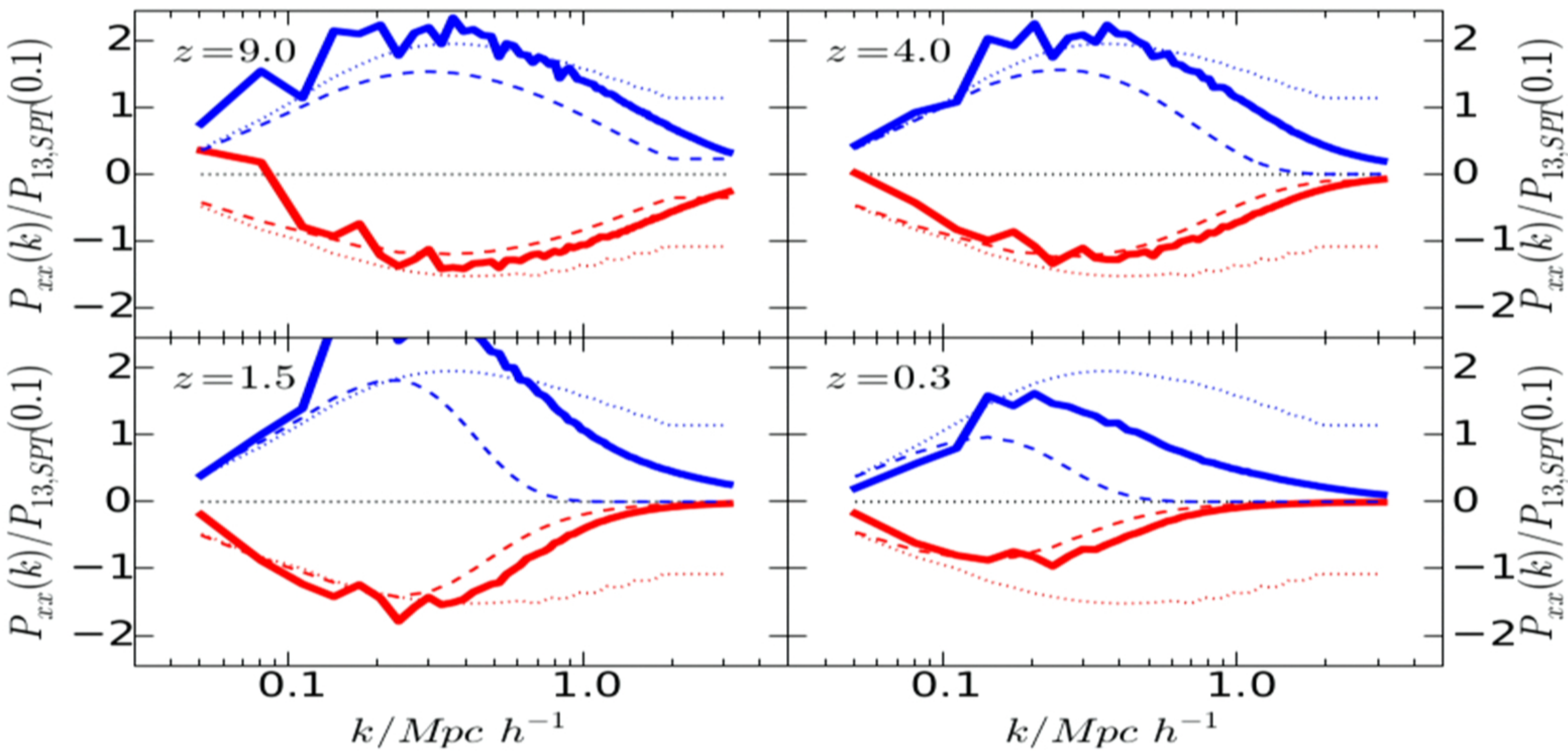
3 quantities with 3 PS



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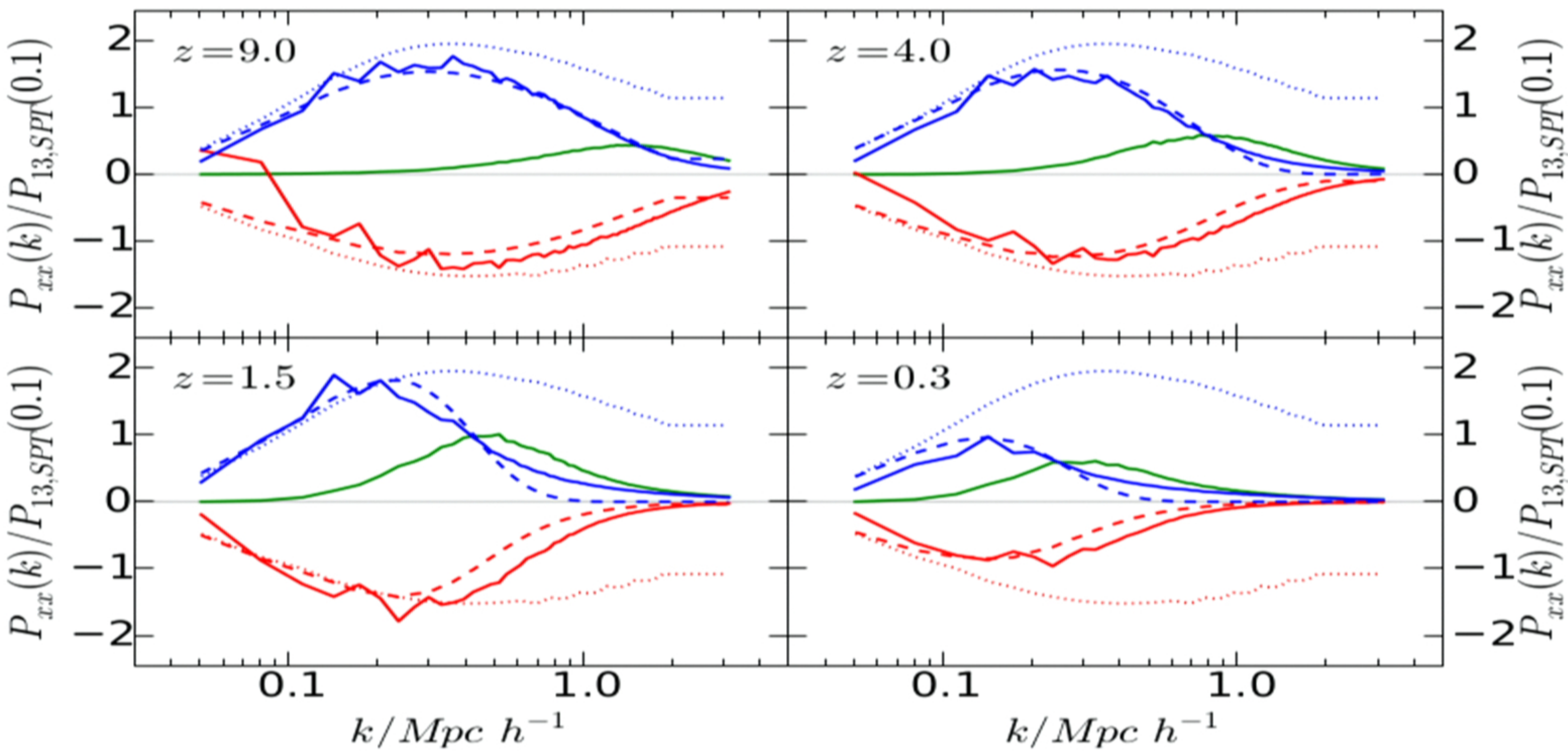
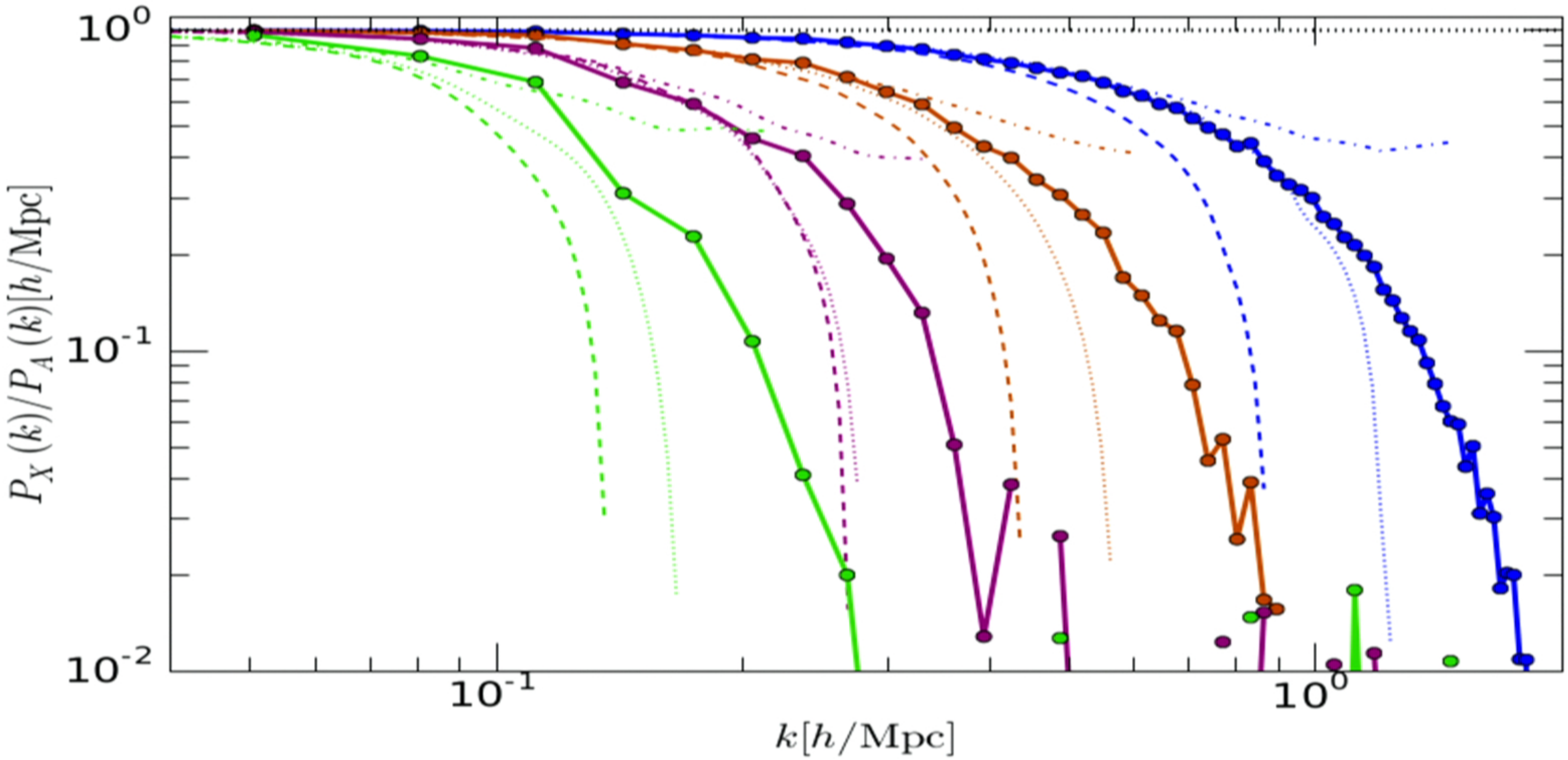


Supression: PT



Fitting supression

We fitted $P_x(k)/P_I(k)$ with the following functional form:

$$\frac{P_x(k)}{P_A(k)} = e^{-\left(\frac{k}{k_{\rm NL}}\right)^{-\alpha}} \quad (4)$$

redshift	$k_{\rm NL}$	α
9	0.89	**1.9998** $\leftarrow$ f'in daddy Gaussian
4	0.45	2.06
1.5	0.24	2.25
0.26	0.15	2.86

This is of course an idiotic form, but something like

$$\frac{P_x(k)}{P_A(k)} = e^{-\left(\frac{k}{k_{\rm NL}}\right)^{-2}} \left(1 + ak^2 + bk^4 \ldots\right) \quad (5)$$

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Phase rotation

This is a special case of a general transformation

$$\delta_1(\mathbf{k}) \rightarrow \ {}_A\delta_1 = \delta_1 A(\mathbf{k}), \tag{6}$$

If

$$\begin{aligned} AA^* &= 1, & (7) \\ A(\mathbf{k}) &= A^*(-\mathbf{k}). & (8) \end{aligned}$$

the rotated initial conditions are an equally likely realization of the same universe.

Two special cases:

- $A = \pm 1$, a constant
- $A = e^{i\mathbf{kr}}$, a translation

You could imagine that with $A = \exp(i2\pi/N)$ rotation, we could in principle tease out any order in δ expansion. But you need to work out how to do complex simulations first.

Helping sample variance

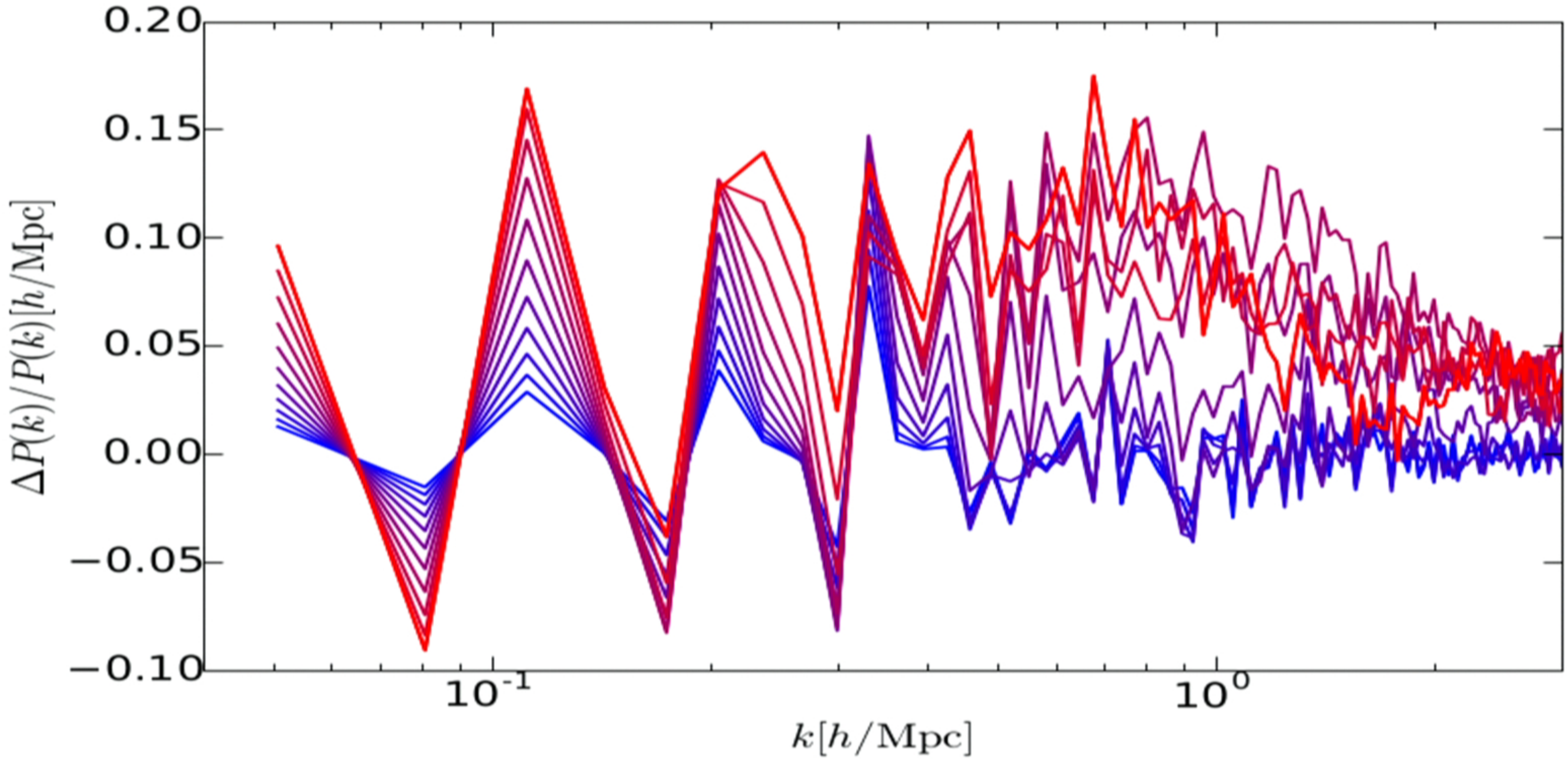
Another interesting aspect is that the pair of simulations have

- Exactly the same realization of even correlators
- Equal and opposite realizations of odd correlators

Hence, by averaging two IC n-point functions, the IC bispetrum is exactly zero. Since this is dominant in weakly non-linear scales, averaging over pairs of realizations *might* converge to ensemble average faster than if all realizations were independent.

But anyway, here is another intriguing plot...

Same IC module flipped sign



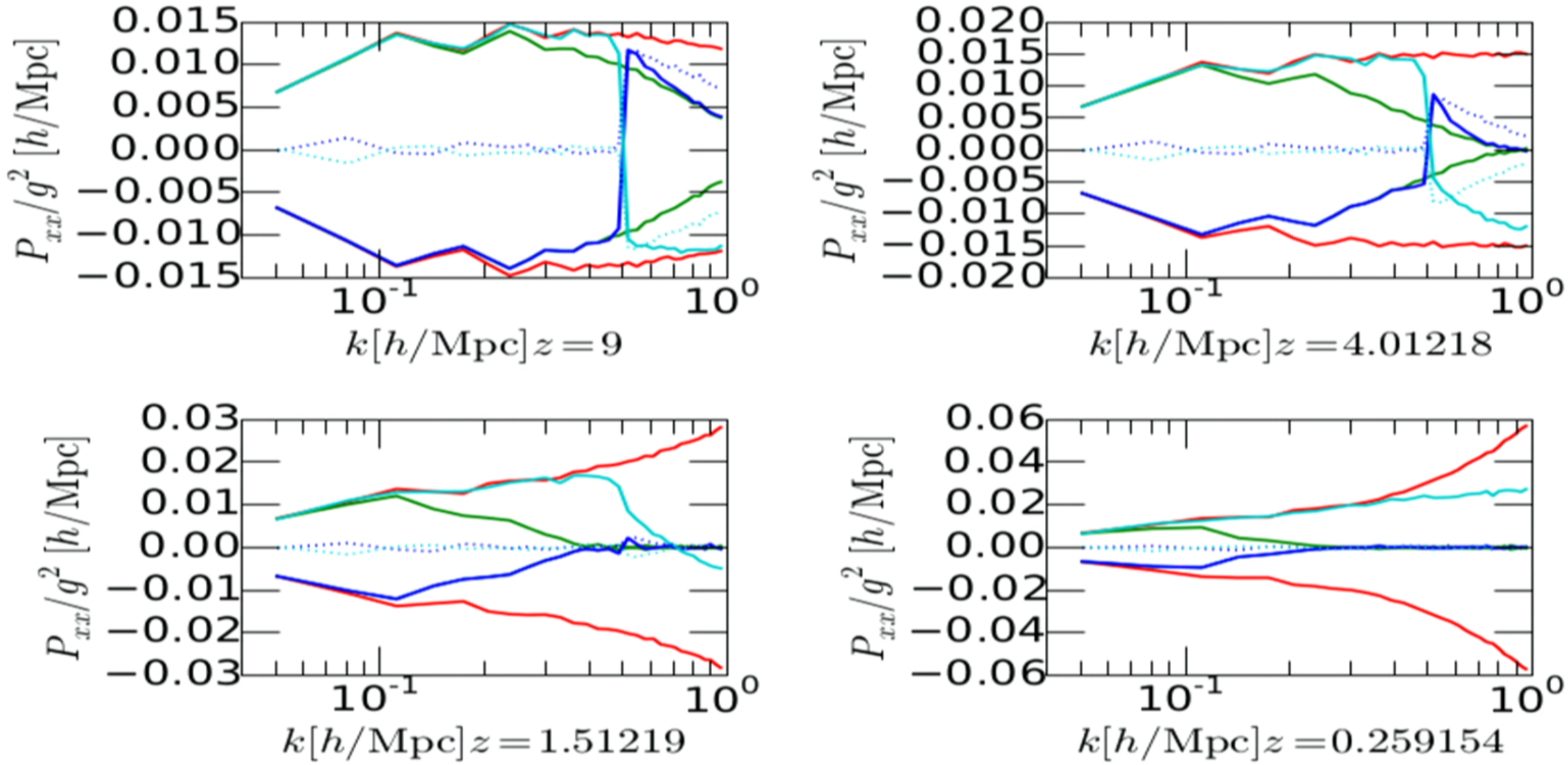
Partially inverted pairs

One can run a third simulation with

$$A = \begin{cases} -1 & k < k_x \\ 1 & k > k_x \end{cases} \tag{9}$$

Again, all three are equally valid realizations, but this can be used to measure the spread of information across scales.

Partially inverted pairs



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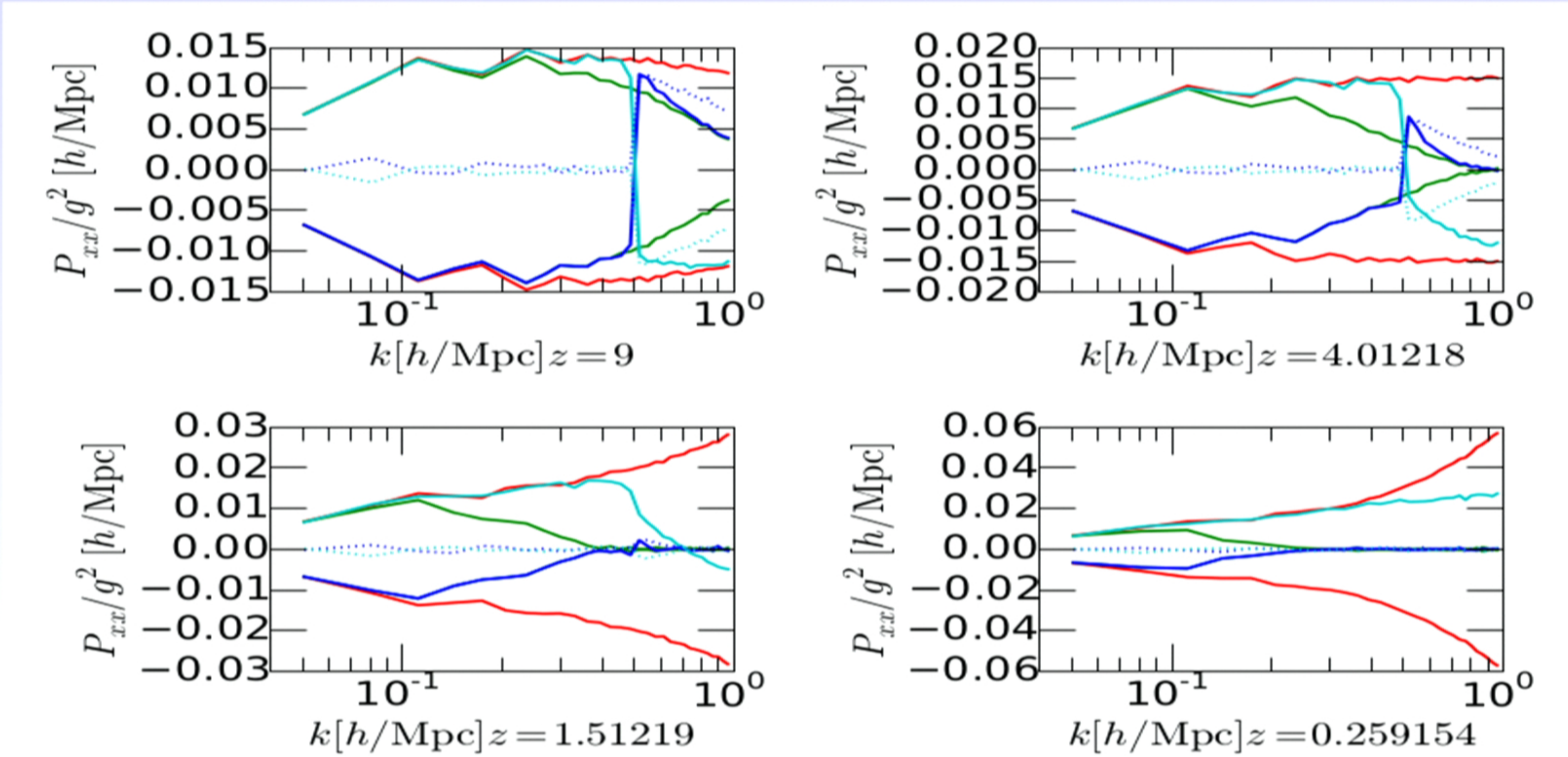

Large-scale bias in the Lyman-α forest

Anže Slosar w **Agnieszka Cieplak**,
Brookhaven National Laboratory

Introduction

- With BOSS we are finally able to measure 3D correlations in the forest
- We robustly measure large scale biasing parameters b_δ and b_η (modulo complications)
- We want to be able to unify the 3D and 1D power spectra into a single measurement.
- We want to be able to use the full shape of the 3D power spectrum in a similar manner we use 1D power spectrum (measure amplitude of primordial fluctuations, etc.)

What does Lyman-α forest measure?

Absorption done by neutral hydrogen in photo-ionization equilibrium:

$$\Gamma n_{\rm HI} = \alpha(T) n_p n_e$$

$$n_{\rm HI} = \frac{\alpha(T)\rho_b^2}{\Gamma} \ll 1$$

and so the absorbed flux fraction is given by

$$f = \exp\left(-\tau\right) \sim \exp\left(-A(1+\delta_b)^{1.7}\right)$$

- We are observing a very non-linear transformation of the underlying density field.
- **On small scales, physics can be understood from first principles.**
- **On large scales, Lyman-α forest is simply a biased tracer.**

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Flux as a tracer

- For a local transformation, expect

$$\delta_F = b_\delta \delta + b_\eta \delta_\eta + b_\Gamma \delta_\Gamma + \epsilon.$$

in Fourier space in $k \to 0$ limit. where δ_X are relative fluctuations in density ($X = \rho$), velocity gradient $X = \eta = dv_{||}/dr$ and photoionization fluctuations ($X = \Gamma$)

- Note equivalent for galaxies is $b_\eta = 1$ since numbers conserved under RSD transformation
- A peak-background split tells us:

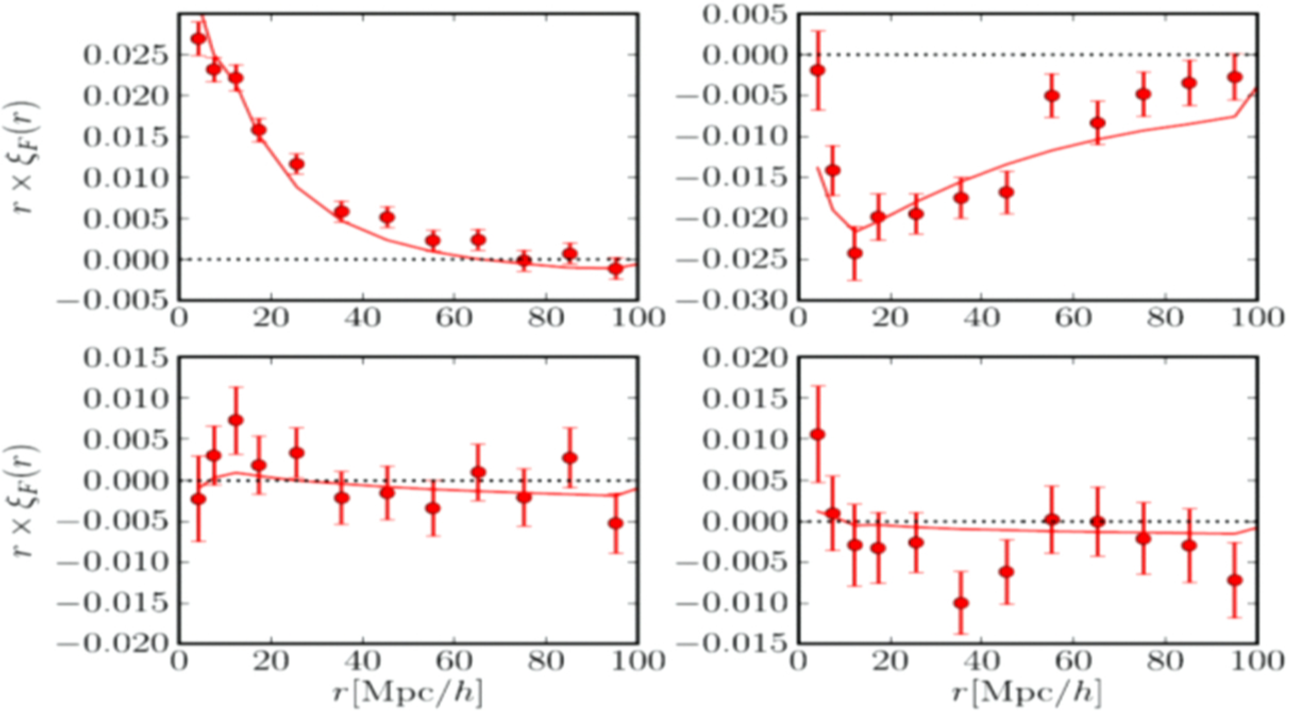
$$b_\delta = \frac{1}{\bar{F}} \frac{d\bar{F}}{d\delta}\bigg|_{\eta=0}, \qquad b_\eta = \frac{1}{\bar{F}} \frac{d\bar{F}}{d\eta}\bigg|_{\delta=0},$$

- Power spectra given by

$$P_{\delta_F}(\vec{k}) = b_\delta^2 \left(1 + \beta\mu^2\right)^2 P_\delta(k) + P_N$$

with $\beta = f b_\eta / b_\delta$

14k QSOs: ξ push



A paper in 2014: bias parameters were at face value inconsistent with measured $P_{1\mathrm{D}}$

- Clear detection of correlations with no significant contamination
- The measured correlation function is distorted due to continuum fitting
- Analysis is harder than galaxy analysis:
  - Redshift-space distortions always matter
  - Redshift-evolution does matter

Bias factors from data

- In 2014: $b_F(1+\beta) = 0.336 \pm 0.012$ with $b_F = -0.2 \pm 0.02$, $\beta < 1.2$
- When doing back of the envelope calculations, this was inconsistent with extrapolation of P1D:

$$P_{1D}(k_{\|}) = 2\pi \int_0^{\infty} P(k_{\|}, k_{\perp}) k_{\perp} \, dk_{\perp}$$

- Blomqvist et al, 2015: $b_F(1+\beta) = 0.336 \pm 0.012$ with $b_F = 0.374 \pm 0.007$, a 2.7σ shift; $\beta = 1.4 \pm 0.12$ from DR11 BOSS correlation function
- These numbers are in a much better agreement with what P_{1D} wants.
- The difference was in the fitting range, Blomqvist et al turned out due to fitting $r > 10\mathrm{Mpc}/h$ vs $r > 20\mathrm{Mpc}/h$.

Analytical predictions

Seljak wrote a very interesting paper in 2011, making analytical predictions for these bias parameters:

$$b_\delta = \alpha \langle F \ln F \rangle + \alpha(\nu_2 - 1) \left\langle F \ln F [1 - (-\ln F/A)^{-\alpha^{-1}}] \right\rangle$$
$$b_\eta = \langle F \ln F \rangle$$

Averages are over flux PDF, $\tau = A(1 + \delta_b)^\alpha$, $\nu_2 = 34/21$

Potentially very interesting:

- could use combination of measurements of flux PDF and large-scale structure to infer A,α
- could use combination of flux PDF and power spectrum to measure $f\sigma_8$ at $z > 2$ from the Lyman-α forest

Potentially very wrong:

- expression for b_δ is based on second order perturbation theory
- expression for b_η assumes no thermal broadening (but otherwise exact!)

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Deriving b_η

Aside note:

- Standard derivation of Kaiser formula relies on Jacobian transformation (e.g. Hamilton et al 1997)

$$(1+\delta_s)s^2 ds = (1+\delta_r)r^2 dr \tag{10}$$

with $s = r + \mathbf{v}\hat{r}$. This works, but for wrong reasons.

- A better derivation is to note that

$$b_\eta = \frac{1}{\bar{\rho}}\frac{d\rho}{d\eta}\bigg|_{\delta=0}, \tag{11}$$

and that since $\eta = dv/dr$ action of a constant η is $r \rightarrow r(1+\eta)$ and so for conserved tracers $b_\eta = 1$.

- Similar argument can be used to show that for Lyman-α forest:

$$b_\eta = \langle F \ln F \rangle \tag{12}$$

is *exact* modulo thermal broadening.

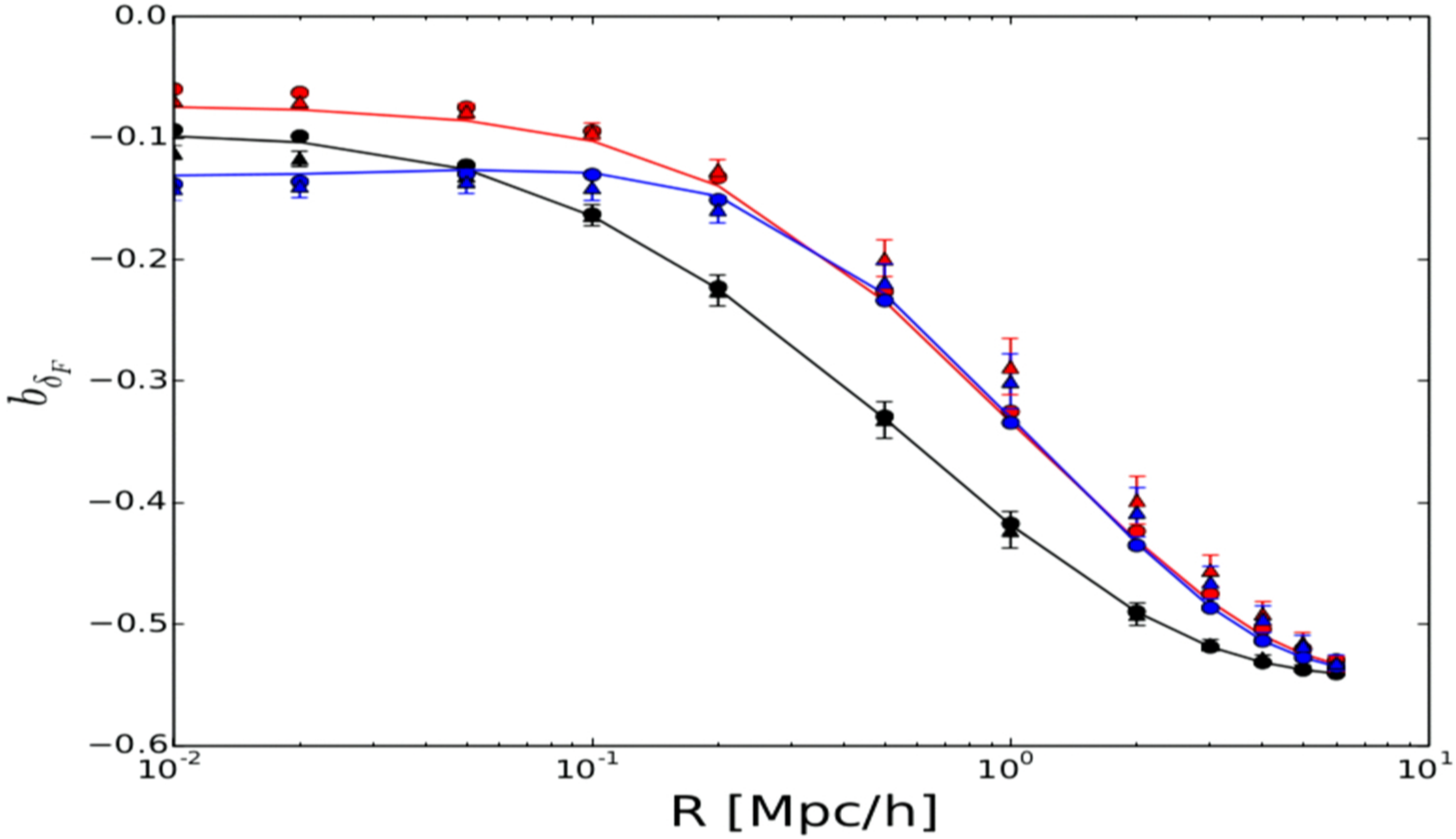
N-body tests

- We have a number of hydro sim boxes, $L = 40\mathrm{h/Mpc}$ with 2×512^3 particles.
- We start by smoothing total density field on scale R and then transforming it to τ and F using

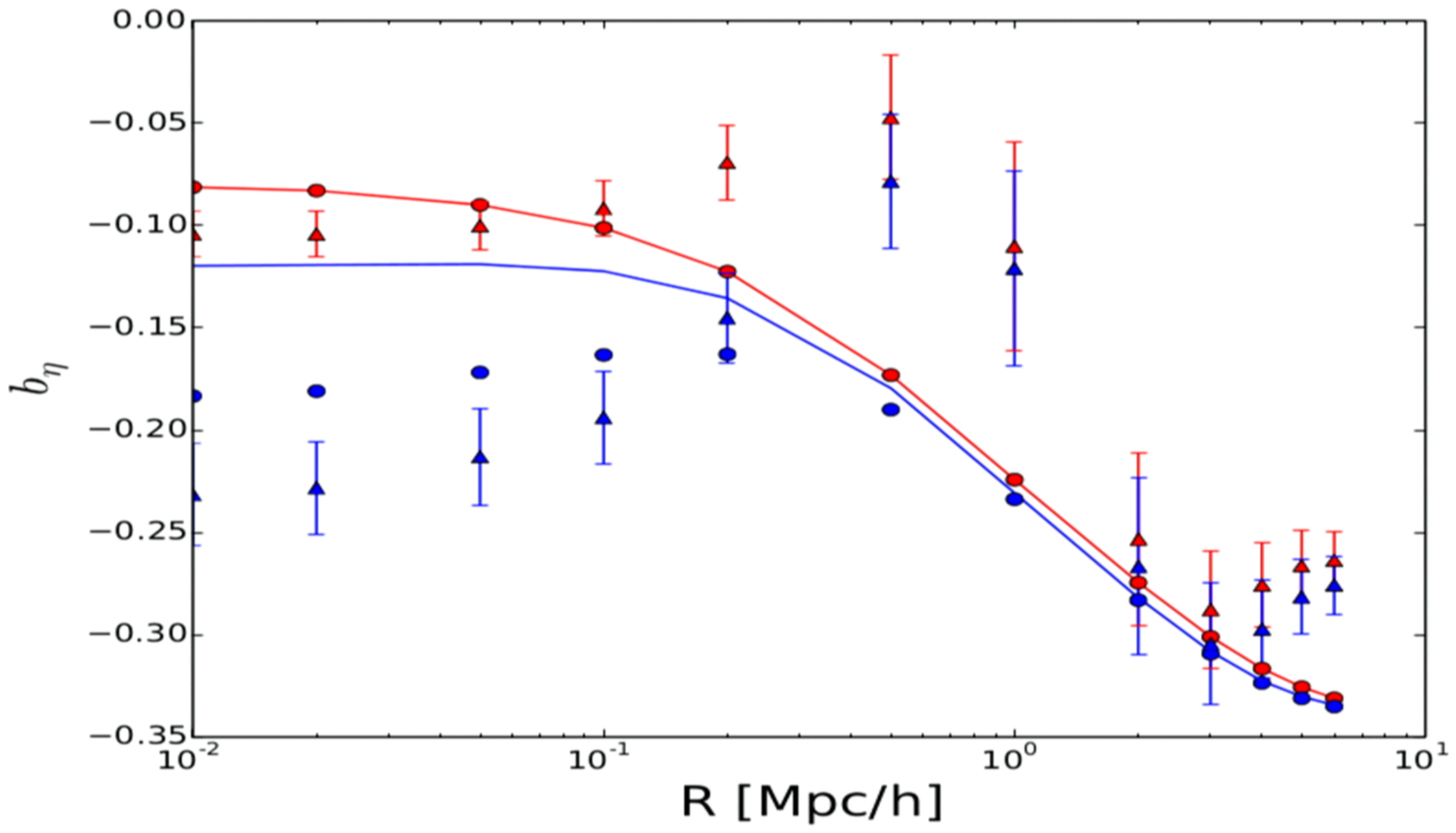
$$\begin{aligned} \tau &= A(1 + \delta_{\mathrm{smoothed}})^{\alpha} \\ F &= e^{-\tau} \end{aligned}$$

- Calculate bias using analytical predictions and using PB-split methods and using direct mode-by-mode estimation
- test in redshift-space
- test in redshift-space w smoothing
- test with hydro-fields

b_δ at $z = 2.5$



b_η at $z = 2.5$



Conclusions

Out of time. . .