How Much Can We Trust the Galaxies?

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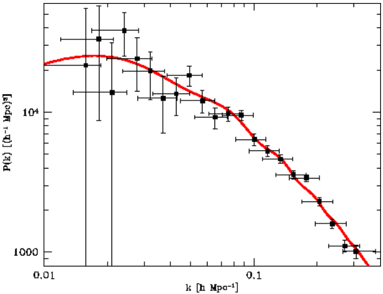
Outline

1. **Introduction**
   - What can galaxies teach us?
   - Relative galaxy bias framework
2. **Methods**
   - Counts-in-cells: comparing pairs of galaxy samples
   - A test for stochasticity and a fit for bias parameters
3. **Results**
   - Luminosity-dependent bias
   - Stochasticity
4. **How much can we trust the galaxies?**

What can galaxies teach us?



- Distribution of galaxies traces large-scale structure of the universe
- The clumpiness of the matter distribution (power spectrum $P(k)$) depends on cosmological parameters: $P(k)$ movies

Need assumption about how galaxies trace dark matter

- Simplest assumption: deterministic linear bias
- Means that bias is a normalization factor for $P(k)$
- But bias could be much more complicated: scale-dependent, nonlinear, and/or stochastic

Relative bias

- Hard to measure dark matter directly —
  so study *relative bias* between different types of galaxies
  e.g. bright vs. dim, red vs. blue
- If they are perfectly correlated with dark matter, they will be perfectly correlated with each other
- Probe size scale where gastrophysics becomes important
- Bright galaxies are more clustered than dim galaxies
  Need a correction to $P(k)$ from flux-limited surveys
- Relative bias also tells us about galaxy formation physics

Relative bias equations

Relate overdensities $\delta(\vec{x}) \equiv \frac{(\rho(\vec{x}) - \langle\rho\rangle)}{\langle\rho\rangle}$ of two types of galaxies:

- Simplest: deterministic linear bias: $\delta_2(\vec{x}) = b_{\mathrm{rel}}\delta_1(\vec{x})$

  Type 1 galaxies can be more or less clumpy than type 2 galaxies, but their peaks and valleys coincide

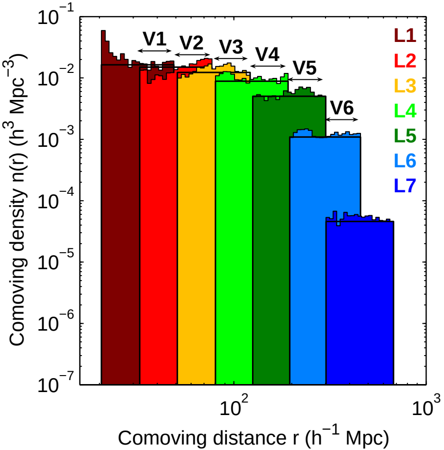
- Stochastic linear bias: $\delta_2(\vec{x}) = b_{\mathrm{rel}}\delta_1(\vec{x}) + \epsilon(\vec{x})$

  If peaks and valleys don't line up, add additional random field $\epsilon(\vec{x})$ to model relative distribution

Relative bias parameters b_{rel} and r_{rel}:

- Auto-corr: $\langle\delta_2(\vec{x})\,\delta_2(\vec{x}+\vec{r})\rangle = b_{\mathrm{rel}}^2\langle\delta_1(\vec{x})\,\delta_1(\vec{x}+\vec{r})\rangle$
- Cross-corr: $\langle\delta_1(\vec{x})\,\delta_2(\vec{x}+\vec{r})\rangle = b_{\mathrm{rel}}r_{\mathrm{rel}}\langle\delta_1(\vec{x})\,\delta_1(\vec{x}+\vec{r})\rangle$

Volume-limited samples

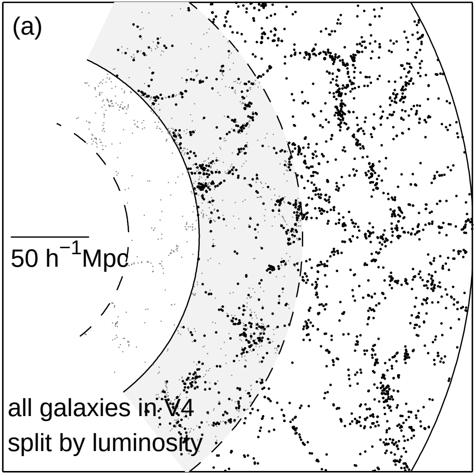


- SDSS DR5 galaxies
- Luminosity bins L1-L7
  - L1: $-17 < M_r < -16$
  - L7: $-23 < M_r < -22$
- Volume-limited samples using redshift cuts defined by apparent magnitude limits
- Compare samples in overlapping volumes V1-V6 (neighboring luminosity bins)
- Find bias between bright and dim, red and blue galaxies
- Test stochasticity and scale dependence

Pairwise comparisons

- Make four pairwise comparisons:

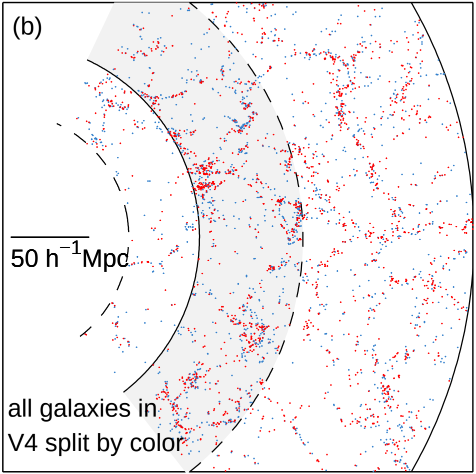
Pairwise comparisons



- Make four pairwise comparisons:

(a) bright vs. dim

Pairwise comparisons

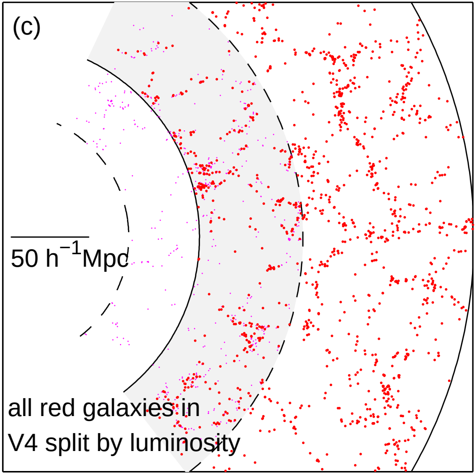


- Make four pairwise comparisons:

(a) bright vs. dim

(b) red vs. blue

Pairwise comparisons



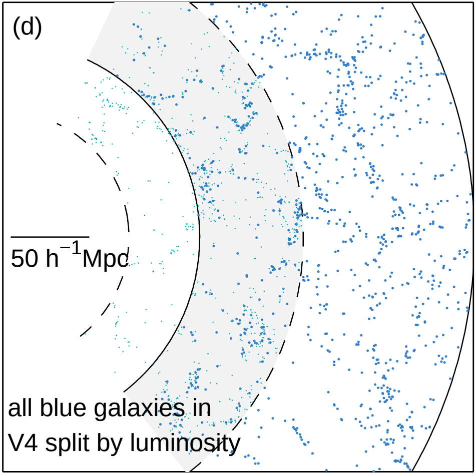
- Make four pairwise comparisons:

(a) bright vs. dim

(b) red vs. blue

(c) bright red vs. dim red

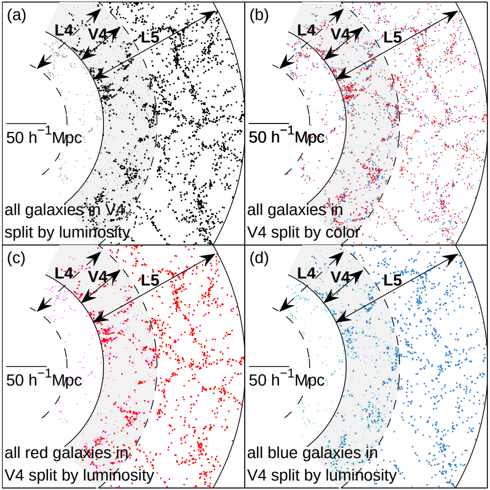
Pairwise comparisons



- Make four pairwise comparisons:

(a) bright vs. dim
(b) red vs. blue
(c) bright red vs. dim red
(d) bright blue vs. dim blue

Pairwise comparisons



- Make four pairwise comparisons:

(a) bright vs. dim

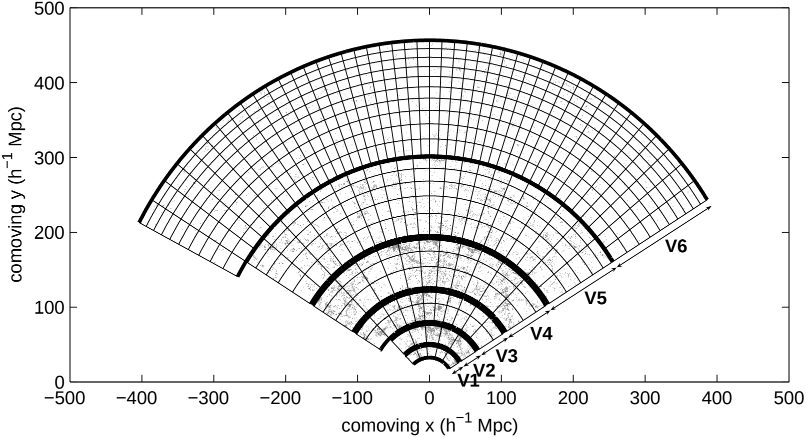
(b) red vs. blue

(c) bright red vs. dim red

(d) bright blue vs. dim blue

- Repeat for each overlapping comparison volume

Counts-in-cells



- Counts of two different types of galaxies in each cell
- Cell sizes of $2 - 164\ h^{-1}$Mpc probe scale dependence

Analysis methods

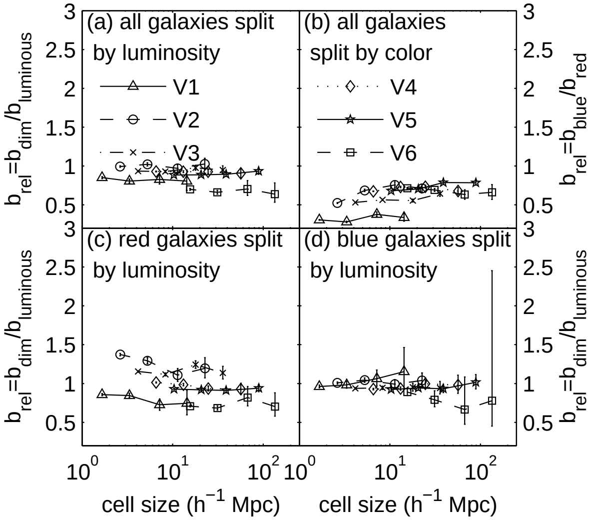
Nullbuster Test

- Generalized χ^2 statistic developed in Tegmark 1999
- Most sensitive test to rule out null hypothesis of deterministic linear bias
- Number of "sigmas" at which null hypothesis is ruled out

Maximum Likelihood Fitting

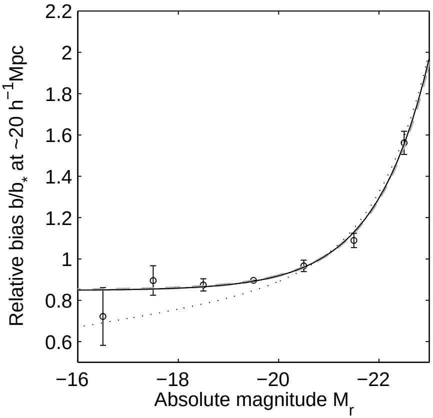
- Measure best-fit values of bias parameters b_{rel} and r_{rel}
- Deterministic linear bias: $r_{\mathrm{rel}} = 1$
- Stochastic bias: $r_{\mathrm{rel}} < 1$

Bias from nullbuster method



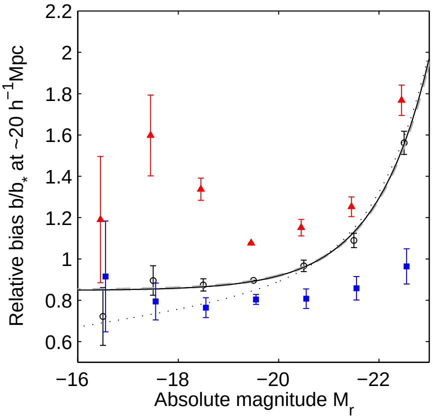
- Relative bias is scale-independent at $\gtrsim 5\ h^{-1}\mathrm{Mpc}$
- Can use relative bias between neighboring luminosity bins to calculate bias vs. luminosity

Luminosity-dependent bias



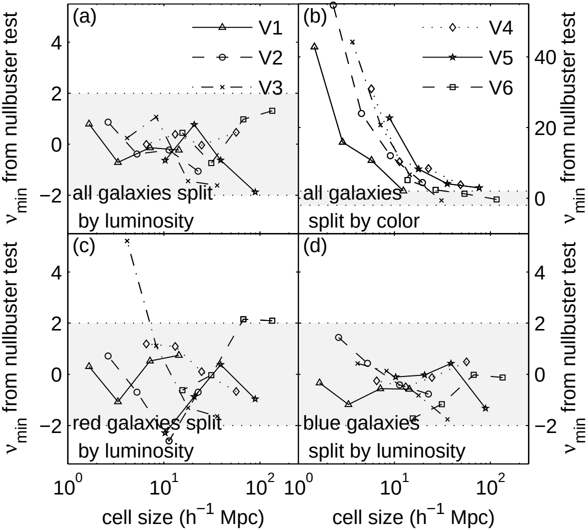
- Black circles: all galaxies
- Solid black line: best fit model for b/b_* vs. magnitude
- Compare to previous fits: Norberg et al. 2001 (dashed), Tegmark et al. 2004 (dotted)
- Agrees with Zehavi et al. 2005

Luminosity-dependent bias



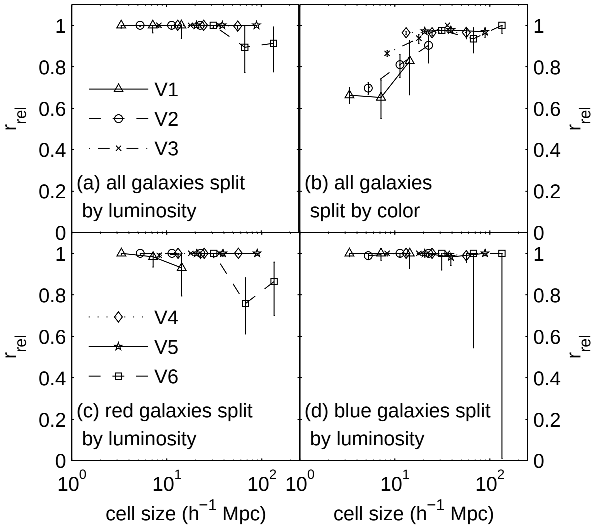
- Black circles: all galaxies
- Solid black line: best fit model for b/b_* vs. magnitude
- Compare to previous fits: Norberg et al. 2001 (dashed), Tegmark et al. 2004 (dotted)
- Agrees with Zehavi et al. 2005
- Red galaxies: L_* galaxies are the least clustered
- Blue galaxies: no strong luminosity dependence
- Faint red galaxies are mostly satellites in high-mass halos

Nullbuster results



- Luminosity-dependent bias *consistent* with deterministic linear bias
- But *ruled out* quite strongly in color-dependent case!
- Red and blue galaxies sample different regions of the universe

Stochasticity from likelihood method



- Luminosity-dependent bias consistent with $r_{\rm rel} = 1$
- Color-dependent bias has $r_{\rm rel} < 1$, especially at smaller scales
- Agrees with nullbuster results
- Agrees with Wild et al. 2005, Wang et al. 2007

Summary of results

Conclusions

- Relative bias factor b_{rel} not strongly scale dependent down to $\sim 5\,h^{-1}\mathrm{Mpc}$ ($\sim$ size of big galaxy cluster)
- Luminosity-dependent bias depends strongly on color:
    - Blue galaxies show little luminosity dependence
    - Bright and dim red galaxies more biased than L_* galaxies
- Deterministic linear bias model:
    - OK for luminosity-dependent bias
    - Ruled out for color-dependent bias, esp. at $\lesssim 20\,h^{-1}\mathrm{Mpc}$ ($\sim$ distance between clusters)

How much can we trust the galaxies?

- Luminosity-dependent bias is pretty trustworthy
  - Can be modeled with simplest model
  - Straightforward correction for flux-limited surveys
  - But need to be aware of color dependence
- Color-dependent bias is a little more sketchy
  - Stochasticity implies that red and blue galaxies occupy different regions of the universe
  - Still OK for large scales in linear clustering regime $\gtrsim 60\,h^{-1}$Mpc for SDSS LRGs (Tegmark et al. 2006)
  - But next-generation surveys will need to account for this

For more details: Swanson et al. 2007, `astro-ph/0702584`

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