SubHalo Abundance Matching for eBOSS Galaxies

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- Introductions
  - Galaxy Bias
  - SubHalo Abundance Matching Method
  - Two-point Correlation Function
- SHAM Implementation
- Results
- Conclusions and Outlooks

Introductions: Galaxy Bias

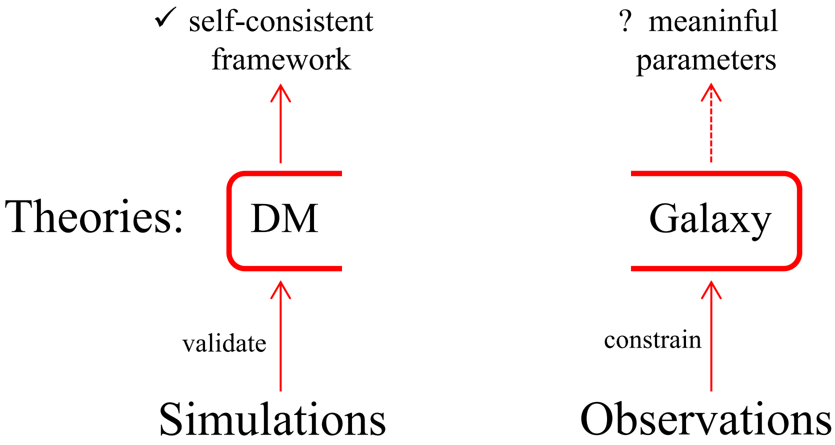
✓ self-consistent framework

Theories: DM

validate

N-body Simulations

Introductions: Galaxy Bias



Introductions: Galaxy Bias

✓ self-consistent framework

? meaninful parameters

Theories: DM + Galaxy Bias =Galaxy

validate

constrain

Simulations

Observations

Introductions: Galaxy Bias

✓ self-consistent framework

✓ reliable link

✓ meaningful parameters

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✓ self-consistent framework

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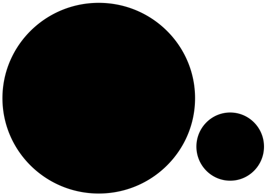
Simulations **SHAM** Observations

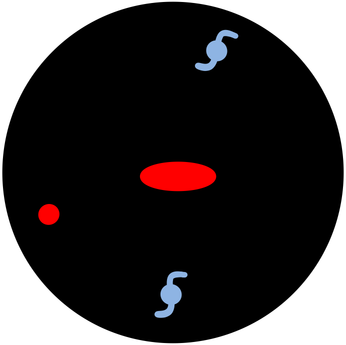
Introductions: Galaxy Bias Models



Halo/Subhalo
N-body Simulations

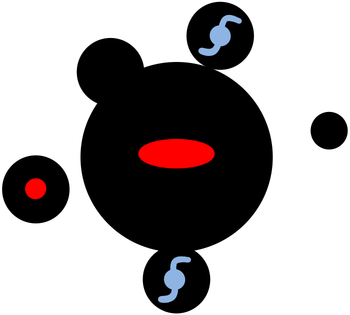
ELG/LRG
Observations

Introductions: Galaxy Bias Models



HOD

$P(N|M_{halo})$



SHAM

$P(M_{(sub)halo})$

Introductions: SHAM Method

Select halos (i.e., galaxies) so that they:

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Select halos (i.e., galaxies) so that they:

- Have **the same number density** as observations

Introductions: SHAM Method

Select halos (i.e., galaxies) so that they:

- Have **the same number density** as observations
- Match the **galaxy probability distribution function** (P.D.F)

$$\frac{\text{selected}}{\text{total}}$$

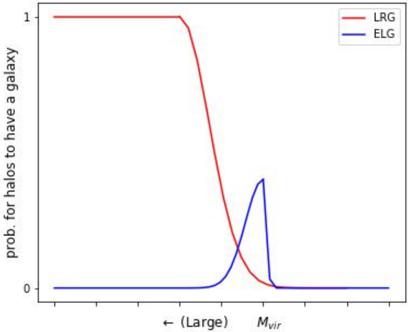


Fig 1. The ideal probability distribution function for halos with a certain mass to have a galaxy inside

Introductions: SHAM Method

The most massive halos: all have an LRG, no one hosts an ELG

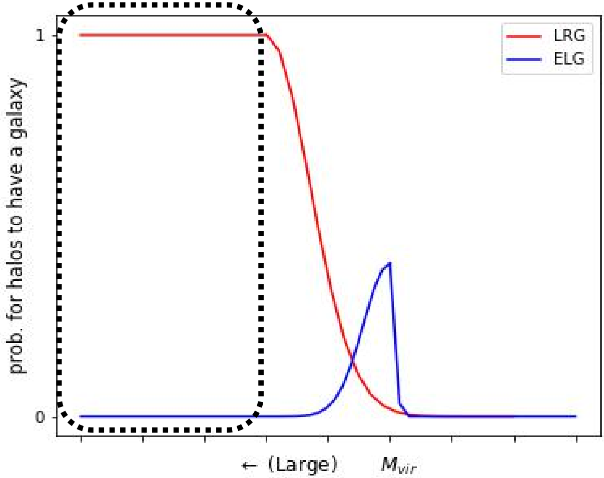


Fig 1. The ideal probability distribution function for halos with a certain mass to have a galaxy inside

Introductions: SHAM Method

The lightest halos: no galaxy

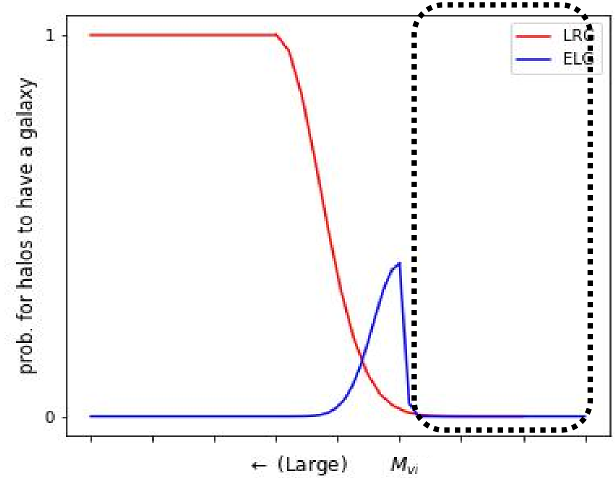


Fig 1. The ideal probability distribution function for halos with a certain mass to have a galaxy inside

Introductions: SHAM Method

Intermediate halos: smooth transition in between

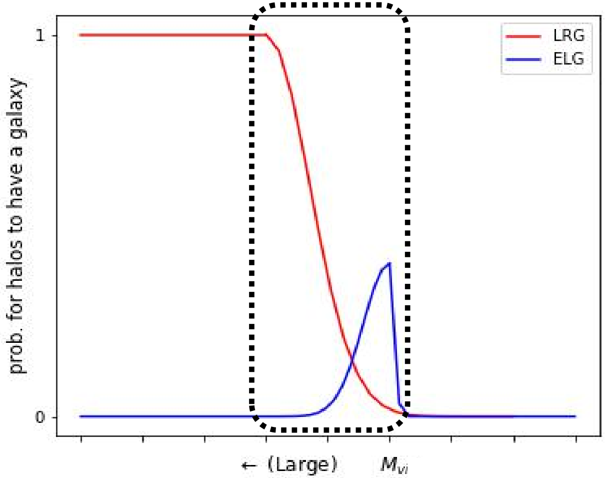


Fig 1. The ideal probability distribution function for halos with a certain mass to have a galaxy inside

Introductions: SHAM Method

Select halos (i.e., galaxies) so that they:

- Have **the same number density** as observations
- Match the **galaxy probability distribution function** (P.D.F)
- Agree with the observed **two-point correlation functions** (2PCF) on small scales

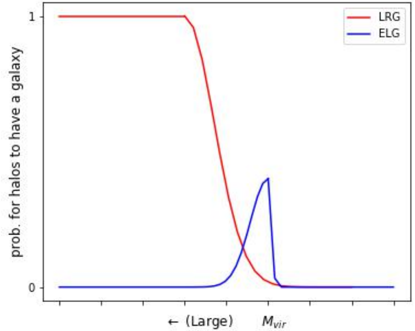


Fig 1. The ideal probability distribution function for halos with a certain mass to have a galaxy inside

Introductions: 2PCF

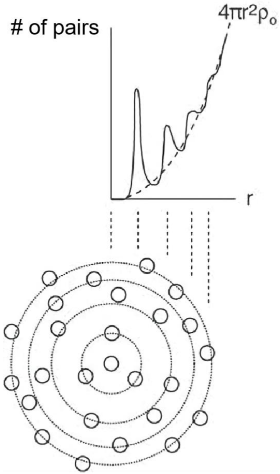
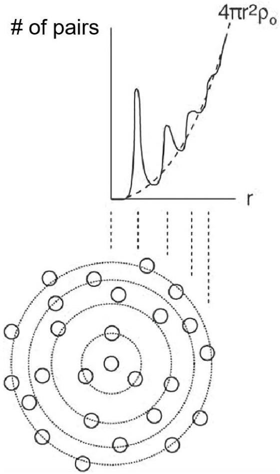


Figure from LASTRO Tea-Time Talk: Cosmology with large-scale structures

Introductions: 2PCF



For SHAM galaxies:

$$\xi_{\mathrm{PH}}(\boldsymbol{s}) = \frac{DD(\boldsymbol{s})}{RR(\boldsymbol{s})} - 1$$

(Peebles & Hauser 1974)

For eBOSS galaxies:

$$\xi_{\mathrm{LS}}(\boldsymbol{s}) = \frac{DD(\boldsymbol{s}) - 2DR(\boldsymbol{s}) + RR(\boldsymbol{s})}{RR(\boldsymbol{s})}$$

(Landy & Szalay 1993)

Figure from LASTRO Tea-Time Talk: Cosmology with large-scale structures

Ref 1. Peebles, P. J. E., & Hauser, M. G. 1974, The Astrophysical Journal Supplement Series, 28, 19
Ref 2. Landy, S., & Szalay, A. 1993, the astropysical journal, 412, 64

Introductions: 2PCF(b) with RSD

density contrast in the real space:

$$\delta(\boldsymbol{x}) = \frac{\rho(\boldsymbol{x}) - \bar{\rho}(\boldsymbol{x})}{\bar{\rho}(\boldsymbol{x})}$$

density contrast in the redshift space:

peculiar velocity's effect

$$\delta_{obs}(\boldsymbol{x}) = \delta(\boldsymbol{x}) - \frac{\partial_d \boxed{(\boldsymbol{v} \cdot \boldsymbol{n})}}{H}$$

(Kaiser 1987)

the linear galaxy bias in the real space:

$$\delta_{gal}(\boldsymbol{x}) = b \times \delta_{halo}(\boldsymbol{x})$$

Ref 1. Kaiser, N. 1987, Monthly Notices of the Royal Astronomical Society, 227, 1

Introductions: 2PCF(b) with RSD

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the linear galaxy bias in the real space:

$$\delta_{gal}(\boldsymbol{x}) = b \times \delta_{halo}(\boldsymbol{x})$$

$$\Downarrow$$

correlation function in the redshift space:

$$\xi_{gal}(\boldsymbol{s}) = <\delta_{obs}(\boldsymbol{x})\delta_{obs}(\boldsymbol{x}-\boldsymbol{s})>$$

stronger bias impacts on the monopoles

$$\boxed{\begin{aligned} \xi_0(\boldsymbol{s}) &\propto f(b^2, b) \\ \xi_2(\boldsymbol{s}) &\propto f(b) \end{aligned}}$$

(Hamilton 1992)

Ref 1. Kaiser, N. 1987, Monthly Notices of the Royal Astronomical Society, 227, 1
Ref 2. Hamilton, A. J. S. 1992, The Astrophysical Journal, 385, L5

Contents:

- Introductions
  - Galaxy Bias: the link of DM and galaxies
  - SHAM: select halos with bias models and calibrate them
  - 2PCF = 2PCF(bias,v_{pec})
- SHAM implementation
- Results
- Conclusions and Outlooks

Contents:

- Introductions
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  - Data Descriptions
  - SHAM using V_{peak}
  - SHAM model Calibration
- Results
- Conclusions and Outlooks

SHAM Implementation: Data Description

the (Sub)Halo catalogue:

the UNIT simulation

Box size: 1^3 (Gpc/h)^3

Employed snapshots z=0.859 and z=0.702

V_{peak}: the peak maximum circular velocity over the mass accretion history

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Employed snapshots z=0.859 and z=0.702

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eBOSS observations:

PIP+ANG weighted galaxy pair counts (Mohammad et al. (2020))

ELGs at $0.6<z<1.1$, $z_{eff}=0.845$, $n_{eff}= 2.93e^{-4}$ $(\mathrm{Gpc}/h)^{-3}$

LRGs at $0.6<z<1.0$, $z_{eff}=0.698$, $n_{eff}= 6.26e^{-5}$ $(\mathrm{Gpc}/h)^{-3}$

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Covariance matrices:

EZmocks

1000 realisations for one tracer in one galactic cap

SHAM Implementation: SHAM using V_{peak}

Massive Truncation: probable absence of eBOSS heavy galaxies

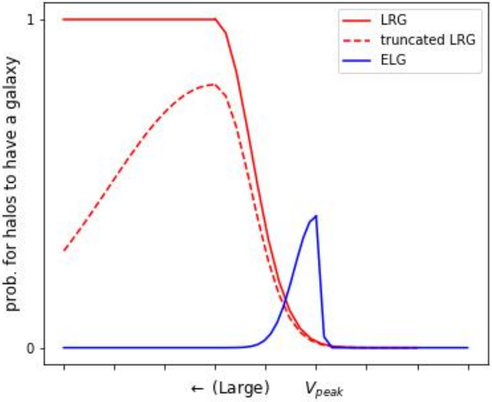


Fig 2. The eBOSS galaxy P.D.F compared with the ideal one

SHAM Implementation: SHAM using V_{peak}

the same SHAM model for eBOSS LRGs and ELGs

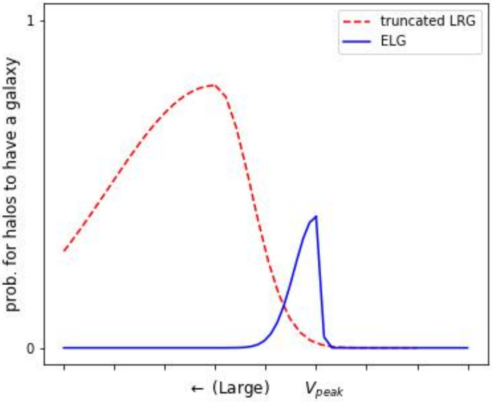
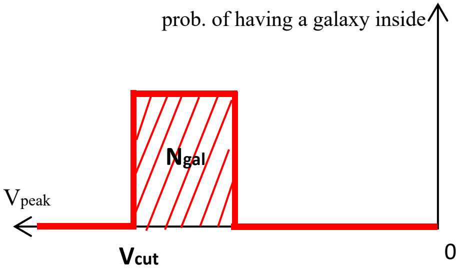


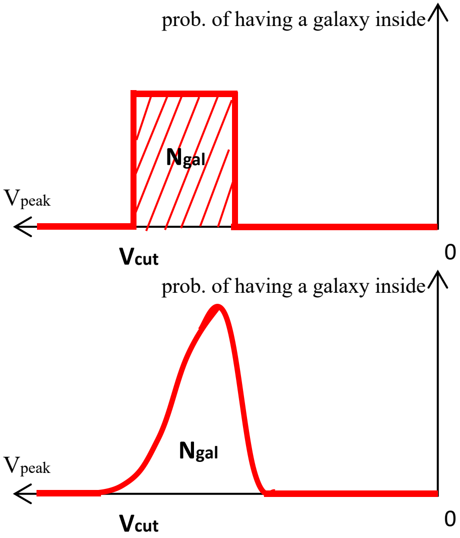
Fig 3. The eBOSS galaxy P.D.Fs

SHAM Implementation: SHAM using V_{peak}



Simply Cut at V_{cut}

SHAM Implementation: SHAM using V_{peak}



Simply Cut at V_{cut}

Scattering with $N\,(0, \sigma^2)$
Massive-end cut at V_{cut}

SHAM Implementation: SHAM using V_{peak}

SHAM processes:

- Scatter V_{peak} by $V_{peak}^{scat} = V_{peak}(1+N(0,\boxed{\sigma^2}))$
- Truncate the massive end of V_{peak}^{scat} at $\boxed{V_{cut}}$
- Assign N_{gal}-th galaxies to the remaining halos

that have the largest $V_{peak}^{scat,cut}$

SHAM Implementation: SHAM using V_{peak}

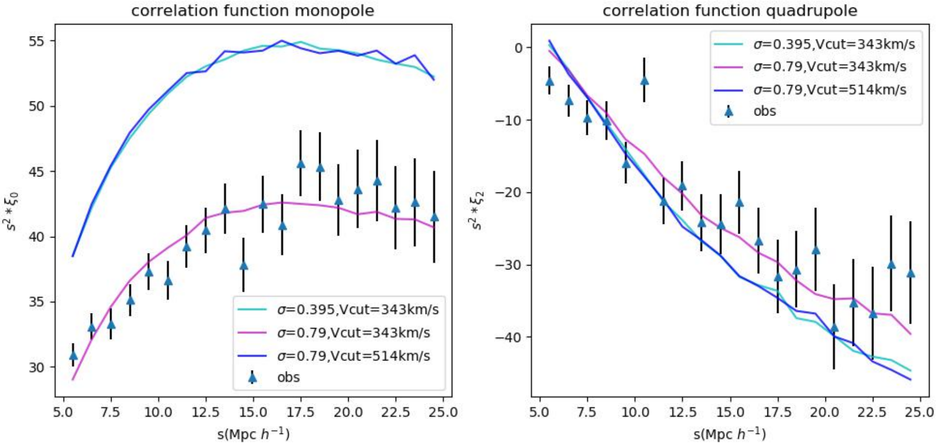


Fig 4. The impacts of σ and Vcut on the 2PCF monopole (left), quadrupole (right) and the Vpeak PDF (the next page)

SHAM Implementation: SHAM using V_{peak}

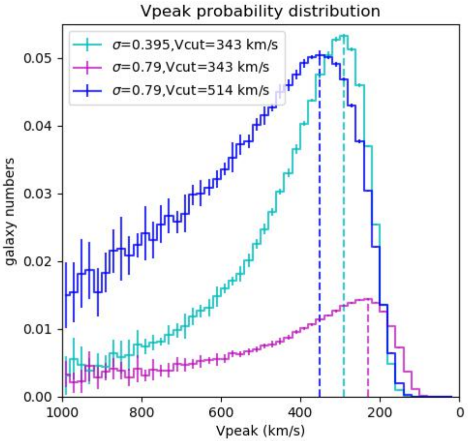


Fig 4. The impacts of σ and Vcut on the Vpeak PDF

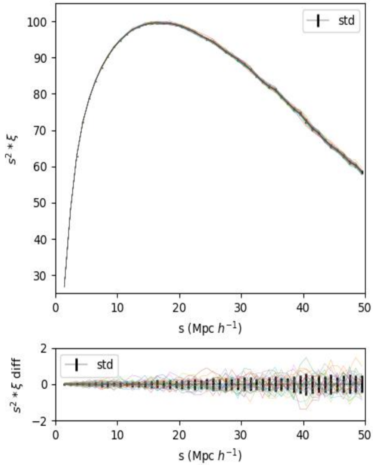
SHAM Implementation: Calibration

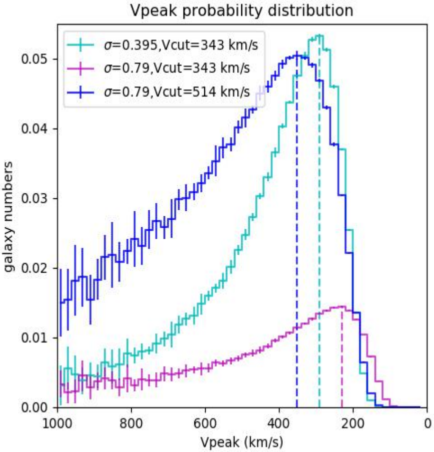
(Sub)Halos

↓ SHAM selection (σ, V_{cut})

SHAM galaxy catalogue & 2PCF

SHAM Implementation: Calibration





SHAM Implementation: Calibration

(Sub)Halos

↓ SHAM selection (σ, V_{cut})

SHAM galaxy catalogue & 2PCF

↓ Reduce the statistical fluctuation from $N(0,\sigma^2)$

Average over the 2PCFs of 20 catalogues for a single (σ, V_{cut})

SHAM Implementation: Calibration

(Sub)Halos

$\downarrow$ SHAM selection (σ, V_{cut})

SHAM galaxy catalogue & 2PCF

$\downarrow$ Reduce the statistical fluctuation from $N(0,\sigma^2)$

Average over the 2PCFs of 20 catalogues for a single (σ, V_{cut})

$\downarrow$ calculate χ^2 with the observations

Monte-Carlo Nested Samping (Multinest) to obtain the best parameters

(iminuit as a contrast)

Contents:

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- SHAM Implementation
- Results
  - SHAM Models for ELGs
  - SHAM Models for LRGs
  - LRG Improvement: the Redshift Uncertainty
- Conclusions and Outlooks

Results: ELG NGC 2PCF

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.513^{+0.433}_{-0.081}$	268^{+124}_{-30}	52.296	1.376

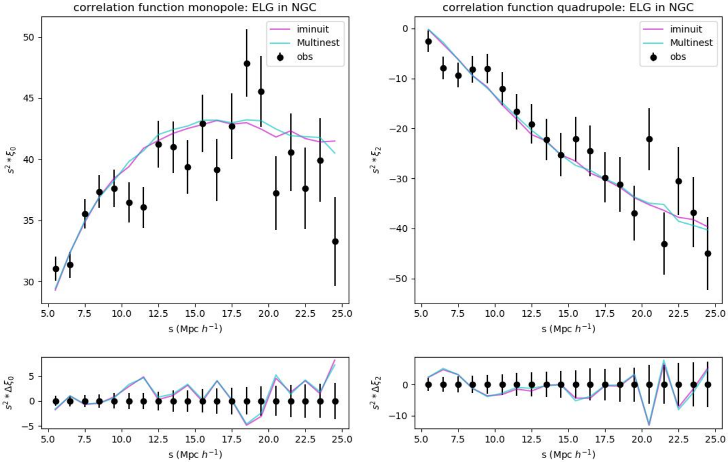


Fig 5. The correlation functions of eBOSS SHAM ELGs in NGC

Results: ELG NGC P.D.F

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.513^{+0.433}_{-0.081}$	268^{+124}_{-30}	52.296	1.376

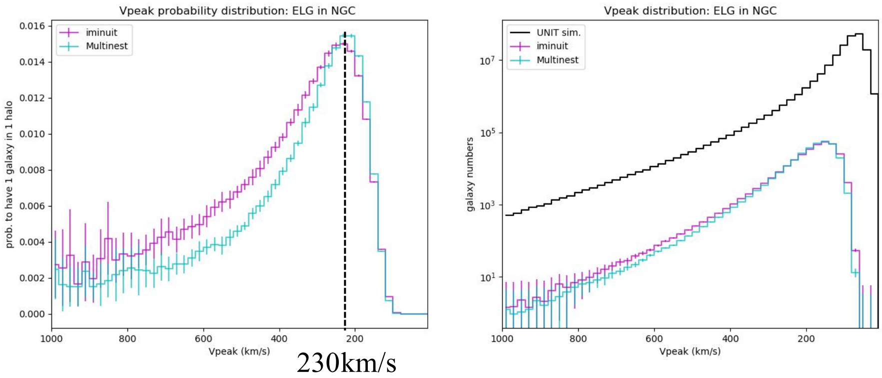


Fig 6. The probability distribution function of eBOSS SHAM ELGs in NGC

Results: ELG NGC Posterior

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.513^{+0.433}_{-0.081}$	268^{+124}_{-30}	52.296	1.376

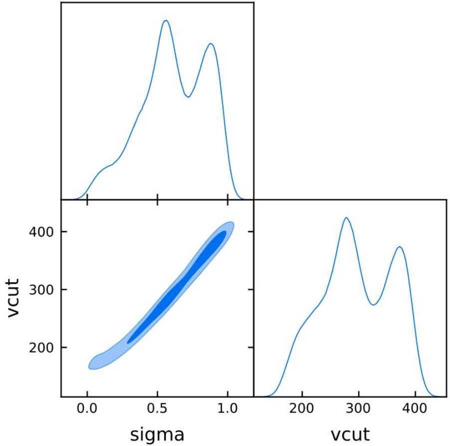


Fig 7. The posterior distributions of eBOSS SHAM ELGs in NGC

Results: ELG SGC 2PCF

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.790^{+0.200}_{-0.285}$	342^{+58}_{-61}	51.526	1.356

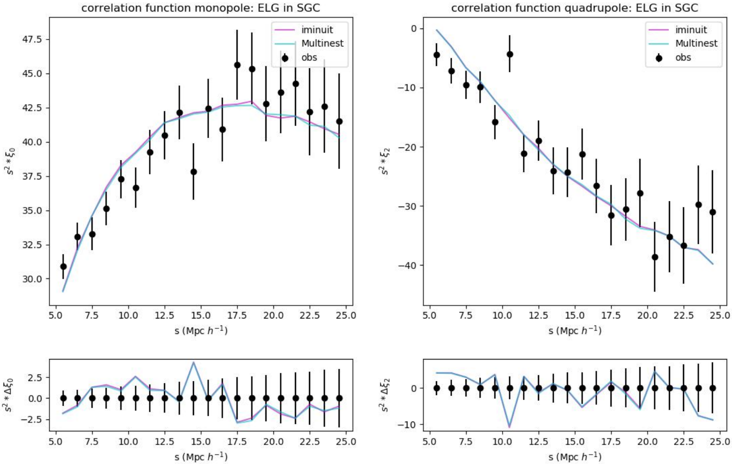


Fig 8. The correlation functions of eBOSS SHAM ELGs in SGC

Results: ELG SGC P.D.F

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.790^{+0.200}_{-0.285}$	342^{+58}_{-61}	51.526	1.356

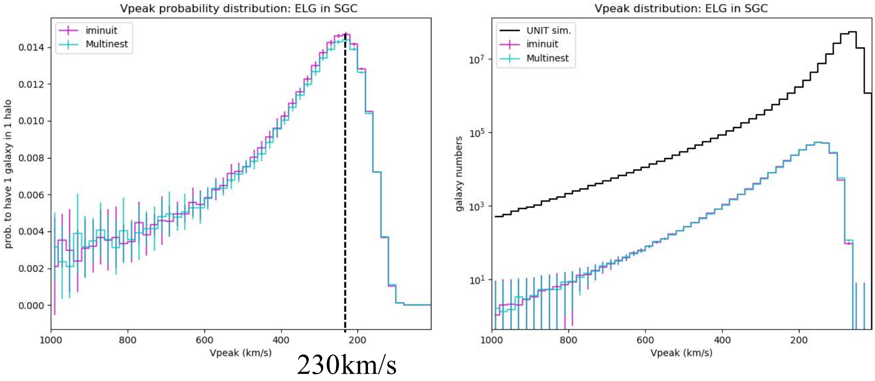


Fig 9. The probability distribution function of eBOSS SHAM ELGs in SGC

Results: ELG SGC Posterior

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.790^{+0.200}_{-0.285}$	342^{+58}_{-61}	51.526	1.356

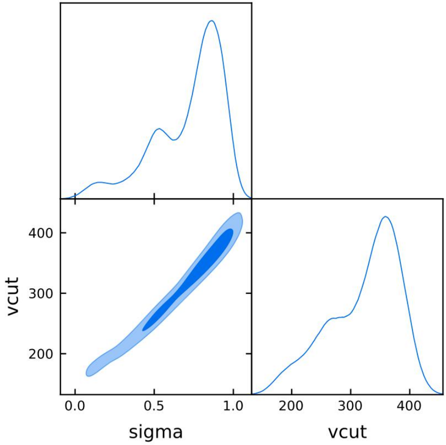


Fig 10. The posterior distributions of eBOSS SHAM ELGs in SGC

Results: LRG NGC 2PCF

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.800^{+0.035}_{-0.056}$	1167^{+29}_{-63}	72.785	1.915

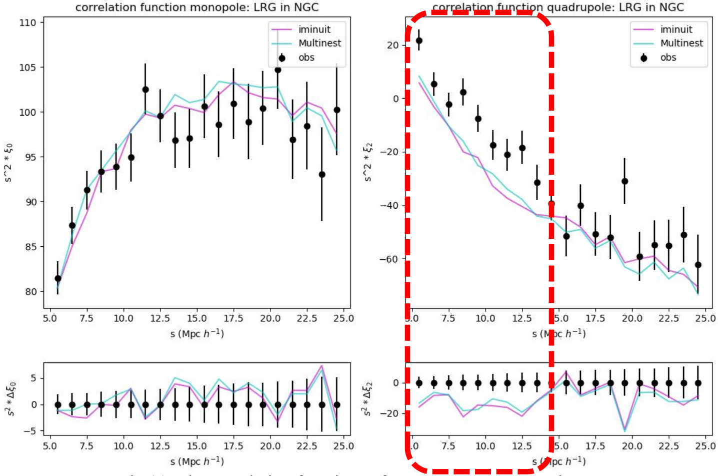


Fig 11. The correlation functions of eBOSS SHAM LRGs in NGC

Results: LRG NGC P.D.F

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.800^{+0.035}_{-0.056}$	1167^{+29}_{-63}	72.785	1.915

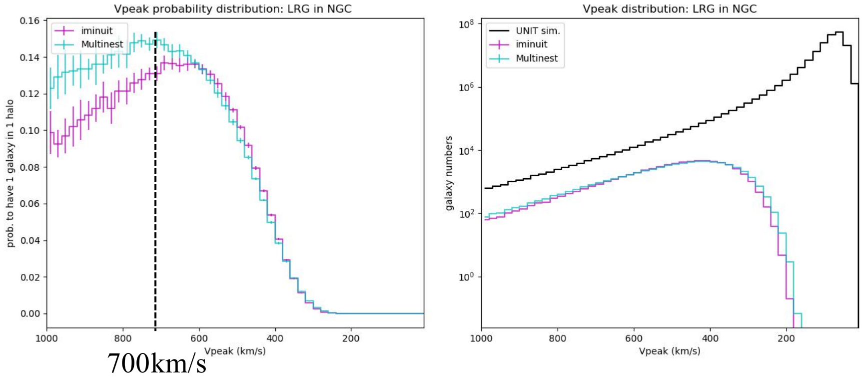


Fig 12. The probability distribution function of eBOSS SHAM LRGs in NGC

Results: LRG NGC Posterior

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.800^{+0.035}_{-0.056}$	1167^{+29}_{-63}	72.785	1.915

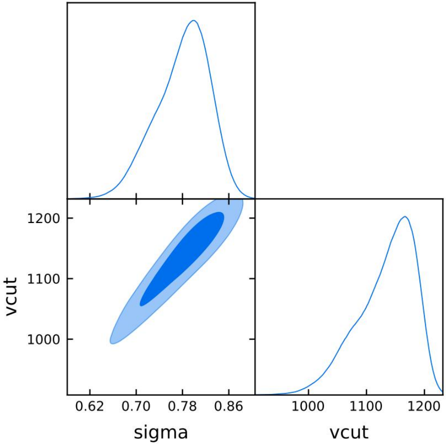


Fig 13. The posterior distributions of eBOSS SHAM LRGs in NGC

Results: LRG SGC 2PCF

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.710^{+0.144}_{-0.029}$	994^{+167}_{-12}	54.593	1.437

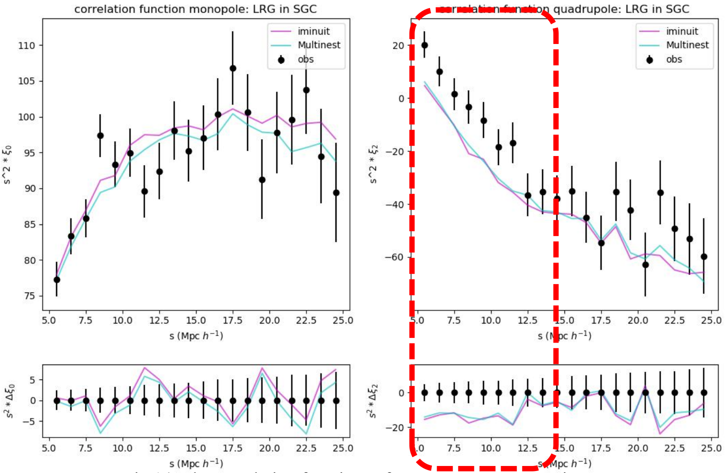
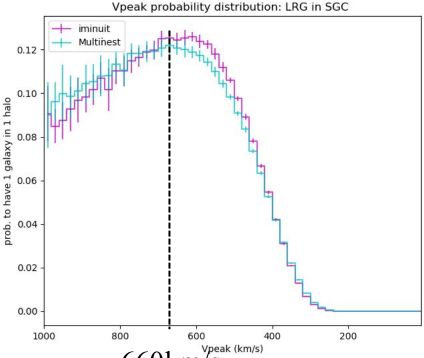
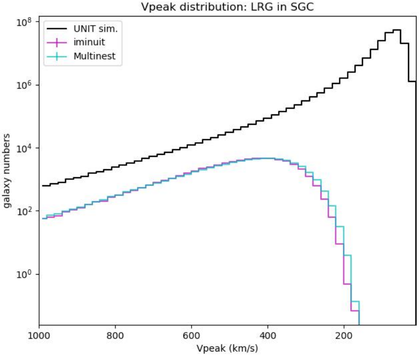


Fig 14. The correlation functions of eBOSS SHAM LRGs in SGC

Results: LRG SGC P.D.F

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.710^{+0.144}_{-0.029}$	994^{+167}_{-12}	54.593	1.437





660km/s

Fig 15. The probability distribution function of eBOSS SHAM LRGs in SGC

Results: LRG SGC Posterior

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.710^{+0.144}_{-0.029}$	994^{+167}_{-12}	54.593	1.437

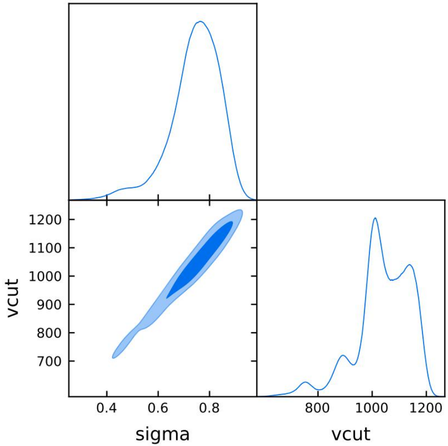


Fig 16. The posterior distributions of eBOSS SHAM LRGs in SGC

Results: LRG SHAM Improvement

the Ideal effect:

- ✓ Quadrupole on small scales increases
- ✓ Quadrupole on large scales and monopole have minor shifts

A Reminder:

- ➢ 2PCF = 2PCF(bias,v_{pec})

Results: LRG Improvement -- Bias

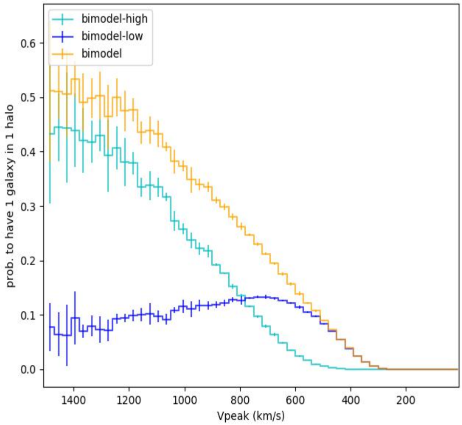


Fig 17. The PDF of a dual-population model

Results: LRG Improvement -- Bias

$$\xi_0(\boldsymbol{s}) \propto f(b^2, b) \qquad \xi_2(\boldsymbol{s}) \propto f(b)$$

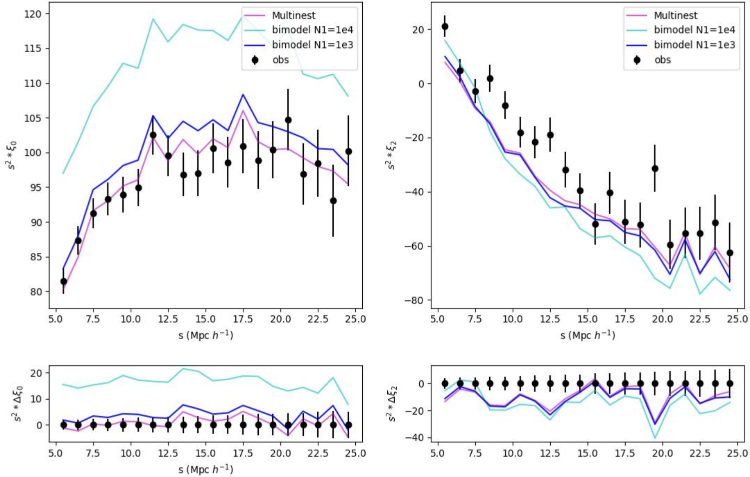


Fig 18. The dual-model's parameter impact on the monopole (left) and quadrupole (right)

Results: LRG Improvement -- v_{pec}

$$z_{obs} = z_{true} + z_{pec} + \boxed{\text{uncertainty}}$$

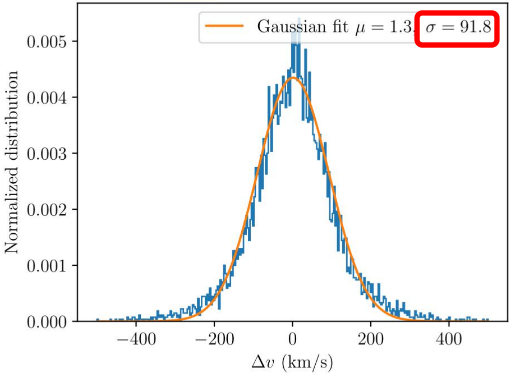


Fig 18. The redshift uncertinty of eBOSS LRG pairs, Figure 2 of Ross et al. (2020)

$$\Delta v = c\Delta z(1+z)$$

Results: LRG Improvement -- v_{pec}

Δv modelled by a **Gaussian smearing** $N(0, 91.8^2)$ on the **peculiar velocity**

⇨**Quadrupole shifts larger** than the monopole shift

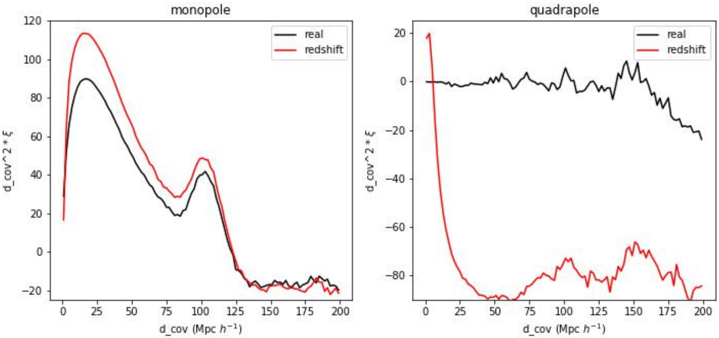


Fig 19. The peculiar velocity's effect on the correlation function monopole (left) and quadrupole (right)

Results: LRG Improvement -- v_{pec}

σ	V_{cut} (km/s)	χ^2	Reduced χ^2
$0.800^{+0.035}_{-0.056}$	1167^{+29}_{-63}	72.785	1.915
0.806	1170	33.910	0.916

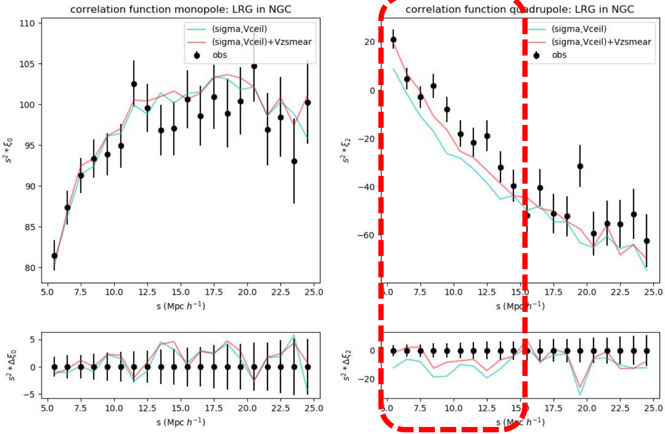


Fig 20. The peculiar-velocity-smeared SHAM LRG in NGC

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- SHAM Implementation
- Results
  - ELGs: good! degeneracy found
  - LRGs: quadrupole discrepancy on small scales
  - Improvement: the peculiar velocity smearing
- Conclusions and Outlooks

Contents:

- Introductions
- SHAM Implementation
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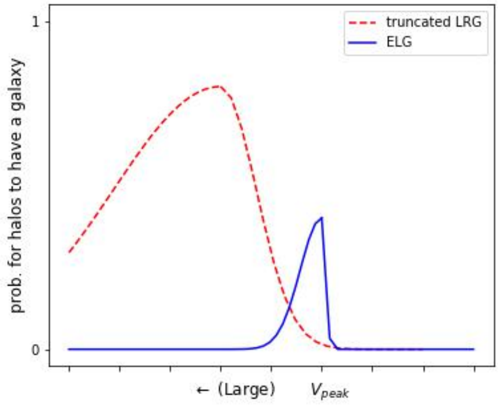
✓ Applied SHAM on UNIT (sub)halo catalogue



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ELG NGC	$0.513^{+0.433}_{-0.081}$	268^{+124}_{-30}	52.296	1.376
ELG SGC	$0.790^{+0.200}_{-0.285}$	342^{+58}_{-61}	51.526	1.356
LRG NGC	$0.800^{+0.035}_{-0.056}$	1167^{+29}_{-63}	72.785	1.915
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- ✓ Improved the LRG SHAM by adding the redshift uncertainty effect

Outlooks:

- ✓ Reliable eBOSS LRG & ELG SHAM models
- ☐ Robust SHAM models
    - ☐ More averaged realisations
    - ☐ Implement SHAM models with σ_{pec}
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- ☐ Multi-tracer SHAM
  - ☐ Generate multiple tracers simultaneously
  - ☐ Difficulty: overlapped P.D.F
  - ☐ Cross-Correlation Studies

Thanks!

SHAM Implementation: Data Description

the (Sub)Halo catalogue:

the UNIT simulation

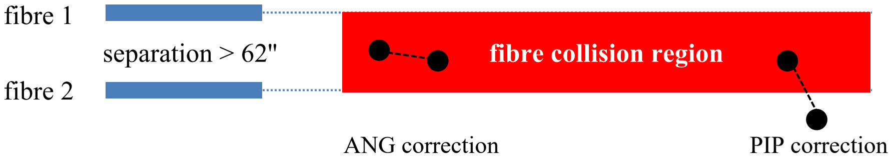
Box size: $1^3\ (\mathrm{Gpc}/h)^3$

Employed snapshots z=0.859 and z=0.702

V_{peak}: the peak maximum circular velocity over the mass accretion history

eBOSS observations:

PIP+ANG weighted galaxy pair counts (Mohammad et al. (2020))



Ref 1: Mohammad, F. G., Percival, W. J., Seo, H.-J., et al. submitted