# SubHalo Abundance Matching for eBOSS Galaxies

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# Contents:

- Principles
  - Galaxy Bias Models
  - SubHalo Abundance Matching Description
  - Two-point Correlation Function
- SHAM implementation
- Results
- Conclusions and Outlooks

# SHAM Principles: Galaxy Bias

✓ self-consistent
framework

Theories: DM

validate

Simulations

# SHAM Principles: Galaxy Bias

✓ self-consistent framework

? meaninful parameters

Theories: DM | Galaxy

validate | constrain

Simulations | Observations

# SHAM Principles: Galaxy Bias

✓ self-consistent framework

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Theories: DM + Galaxy Bias =Galaxy

validate

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# SHAM Principles: Galaxy Bias

✓ self-consistent framework

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✓ meaningful parameters

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constrain

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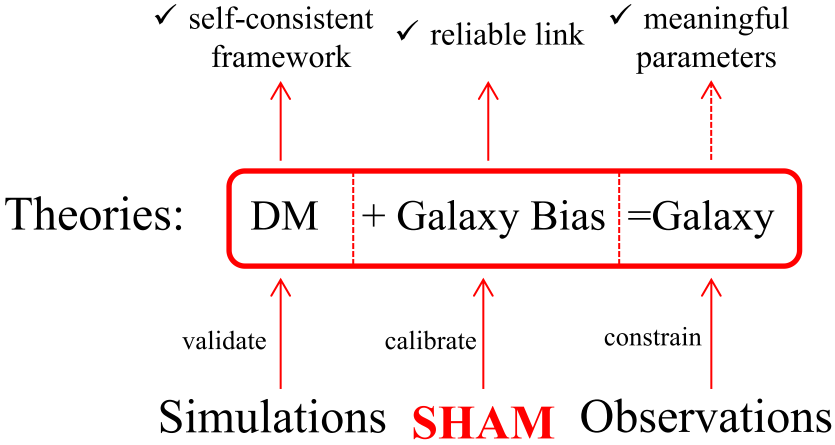
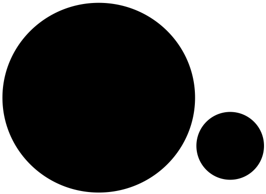
# SHAM Principles: Galaxy Bias



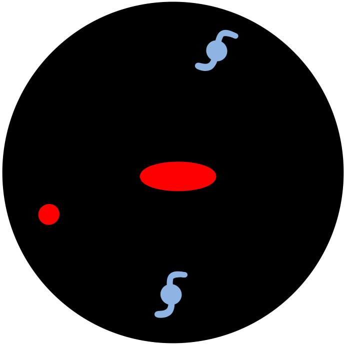
# SHAM Principles: Galaxy Bias Models

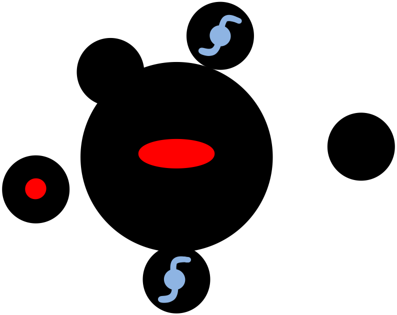


**Halo/Subhalo Simulations**

**ELG/LRG Observations**

# SHAM Principles: Galaxy Bias Models





**HOD**

**$P(N|M_{halo})$**

**SHAM**

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

# SHAM Principles: SHAM Descriptions

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

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- Match the **galaxy probability distribution function** (P.D.F)

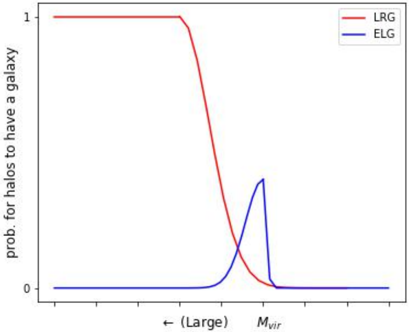



Fig 1. The ideal probability distribution function for halos with a certain mass to have a galaxy inside

# SHAM Principles: SHAM Descriptions

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

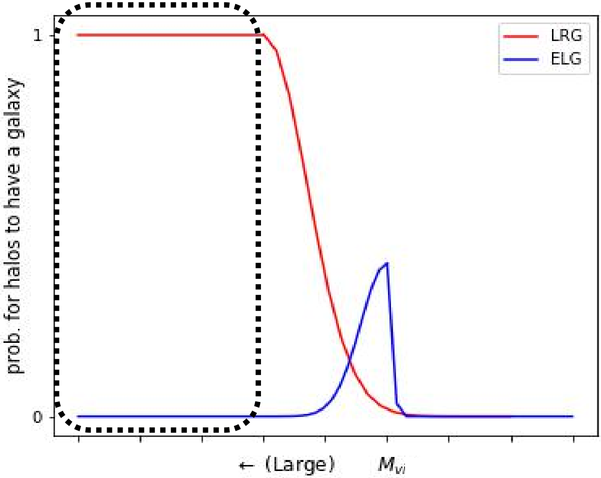
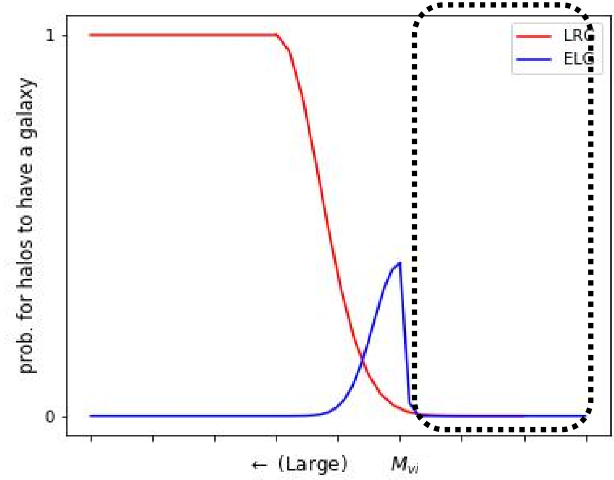



Fig 1. The ideal probability distribution function for halos with a certain mass to have a galaxy inside

# SHAM Principles: SHAM Descriptions

**The lightest halos: no galaxy**




*** mention the linear bias here**

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

# SHAM Principles: SHAM Descriptions

**Intermediate halos: physical processes lead to Stochasticity**

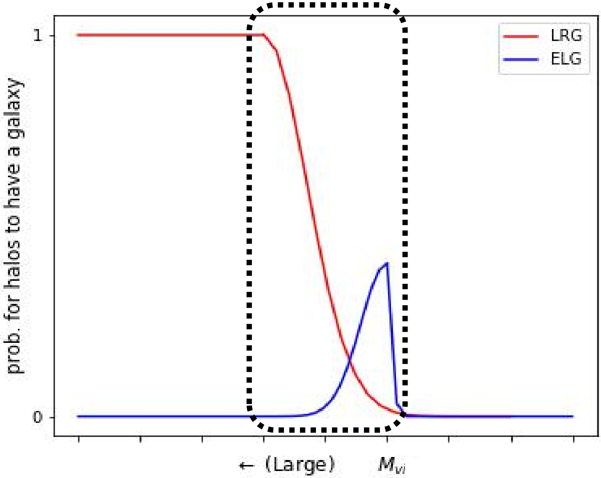



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Fig 1. The ideal probability distribution function for halos with a certain mass to have a galaxy inside

# SHAM Principles: SHAM Descriptions

**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 **5-25 Mpc/h**

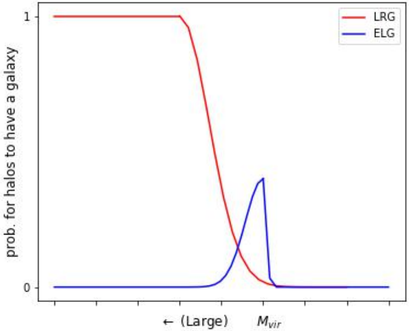
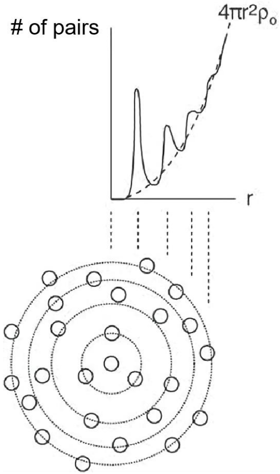



Fig 1. The ideal probability distribution function for halos with a certain mass to have a galaxy inside

# SHAM Principles: 2PCF




**For SHAM galaxies:**

$$\xi_{PH}(s,\mu) = \frac{DD(s,\mu)}{RR(s,\mu)} - 1$$

**(Peebles & Hauser 1974)**

**For eBOSS galaxies:**

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

**(Landy & Alexander 1993)**


Ref 1. Peebles, P. J. E., & Hauser, M. G. 1974, The Astrophysical Journal Supplement Series, 28, 19

Ref 2. Landy, S., & Alexander, S. 1993, the astropysical journal, 412, 64


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

# SHAM Principles: 2PCF(*b*) with RSD

**density contrast in the real space:**

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

**the linear galaxy bias in the real space:**

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

**density contrast in the redshift space:**

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

**(Kaiser 1987)**

**correlation function in the redshift space:**

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

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

$$\xi_2(\boldsymbol{s}) \propto f(b)$$

**(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

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**peculiar velocity's effects**

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

**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
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- SHAM implementation
  - 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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**eBOSS observations:**

PIP+ANG weighted galaxy pair counts

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

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

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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**

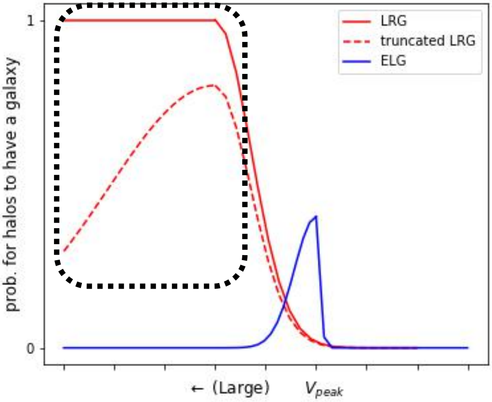



Fig 2. The eBOSS galaxy P.D.F compared with the ideal one

**mention the target selection effect**

# SHAM Implementation: SHAM using $V_{peak}$

**eBOSS LRGs and ELGs have the same SHAM model**

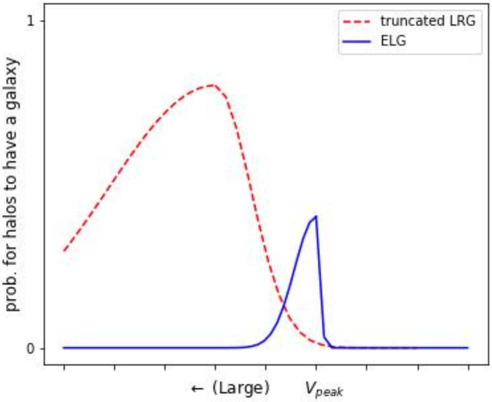
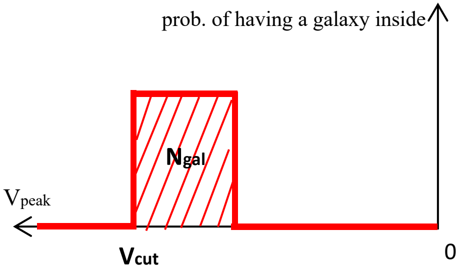


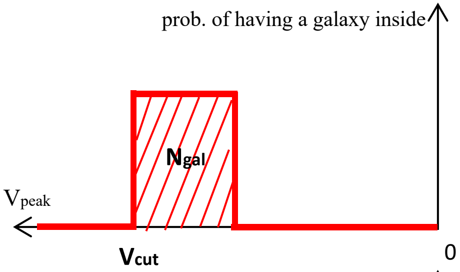

Fig 3. The eBOSS galaxy P.D.Fs

# SHAM Implementation: SHAM using $V_{peak}$

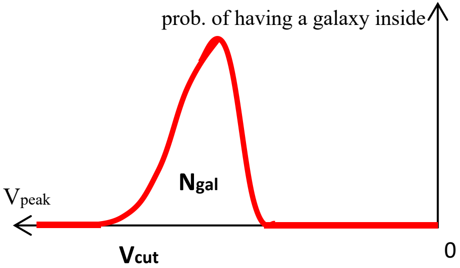



**Simply Cut at $V_{cut}$**

# 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:

- Scattering $V_{peak}$ of (sub)halos with $N(0,\sigma^2)$
- Truncate the massive end of $V_{peak}^{scat}$ at $V_{cut}$
- Select the $N_{gal}$-th largest $V_{peak}^{scat,cut}$ as galaxies

  ($N_{gal}= n_{eff}$*(1Gpc/h)$^3$)

# SHAM Implementation: SHAM using $V_{peak}$

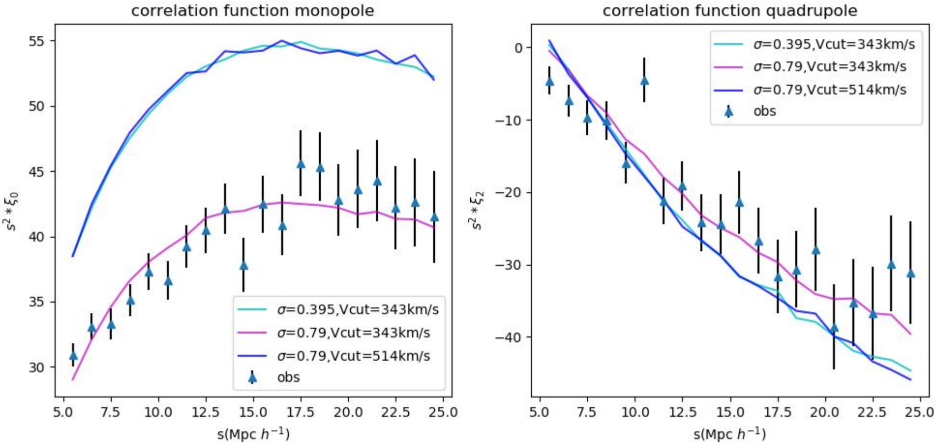



Fig 4. The impacts of σ and Vcut on the 2PCF monopole (left), quadrupole (right) and the Vpeak PDF (the next page)

# SHAM Implementation: SHAM using $V_{peak}$

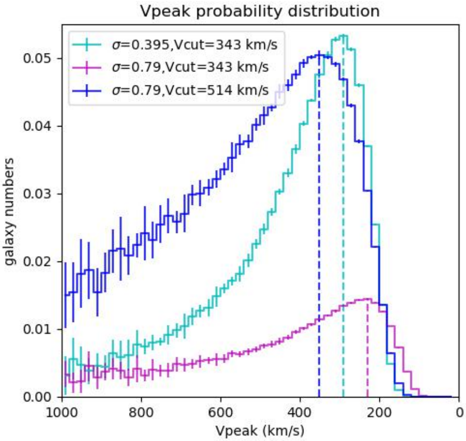



Fig 4. The impacts of σ and Vcut on the Vpeak PDF

**mention the possible degeneracy here**

# SHAM Implementation: Calibration

**(Sub)Halos**

↓ SHAM selection ($\sigma$, $V_{cut}$)

**SHAM galaxy catalogue & 2PCF**

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

**Average over the 2PCFs of 20 catalogues for a single ($\sigma$, $V_{peak}$)**

# SHAM Implementation: Calibration

**(Sub)Halos**

↓ SHAM selection ($\sigma$, $V_{cut}$)

**SHAM galaxy catalogue & 2PCF**

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

**Average over the 2PCFs of 20 catalogues for a single ($\sigma$, $V_{peak}$)**

↓ calculate $\chi^2$ with the observations

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

(iminuit as a reference)

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

# Results: ELG NGC 2PCF

| $\sigma$ | $V_{peak}$ (km/s) | $\chi^2$ | Reduced $\chi^2$ |
|---|---|---|---|
| $0.513^{+0.433}_{-0.081}$ | $268^{+124}_{-30}$ | 52.296 | 1.376 |

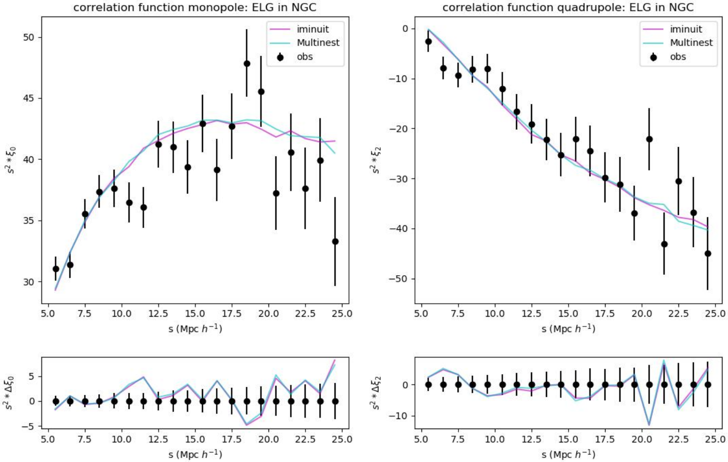


Fig 5. The correlation functions of eBOSS SHAM ELGs in NGC

# Results: ELG NGC P.D.F

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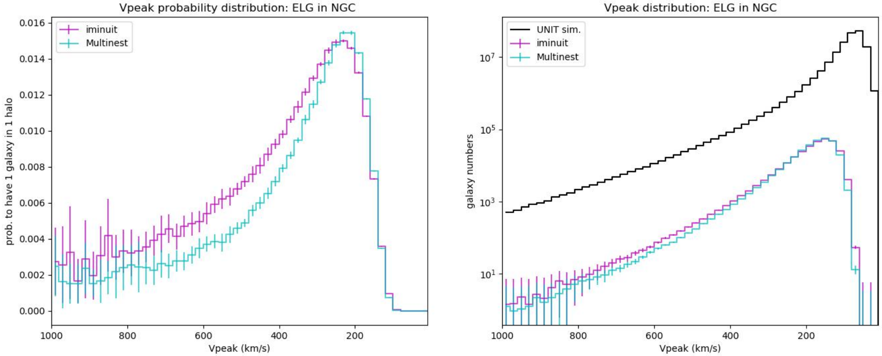


Fig 6. The probability distribution function of eBOSS SHAM ELGs in NGC

# Results: ELG NGC Posterior

| $\sigma$ | $V_{peak}$ (km/s) | $\chi^2$ | Reduced $\chi^2$ |
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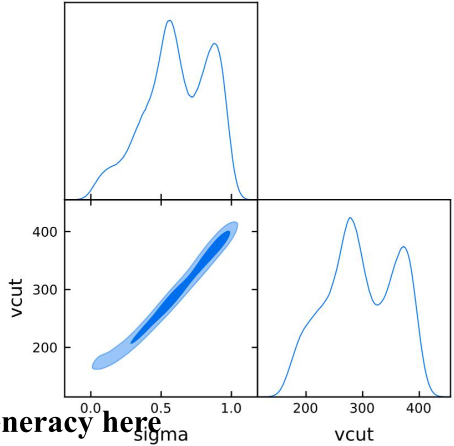


**mention the degeneracy here**

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

# Results: ELG SGC 2PCF

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

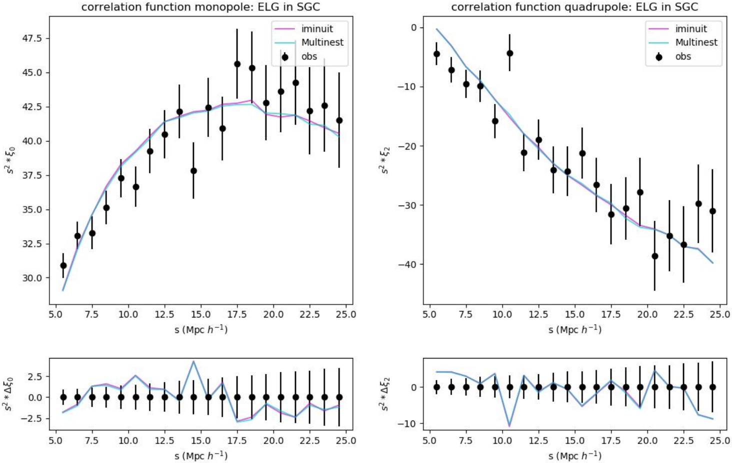


Fig 8. The correlation functions of eBOSS SHAM ELGs in SGC

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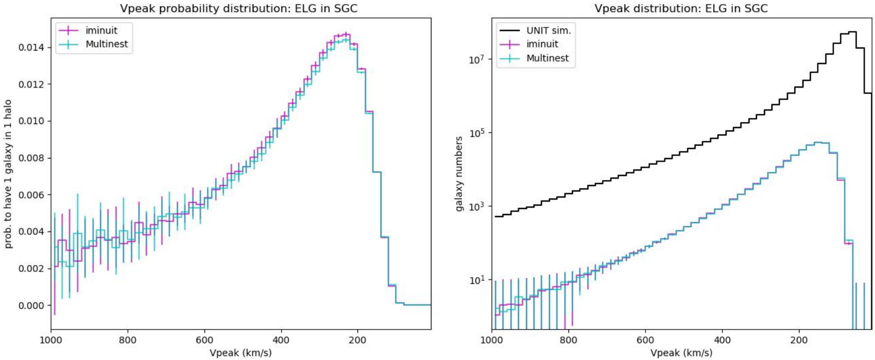


Fig 9. The probability distribution function of eBOSS SHAM ELGs in SGC

# Results: ELG SGC Posterior

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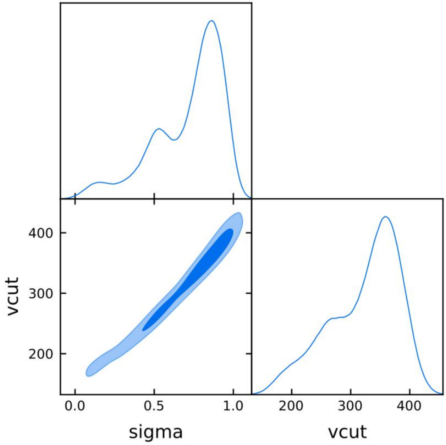


Fig 10. The posterior distributions of eBOSS SHAM ELGs in SGC

# Results: LRG NGC 2PCF

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

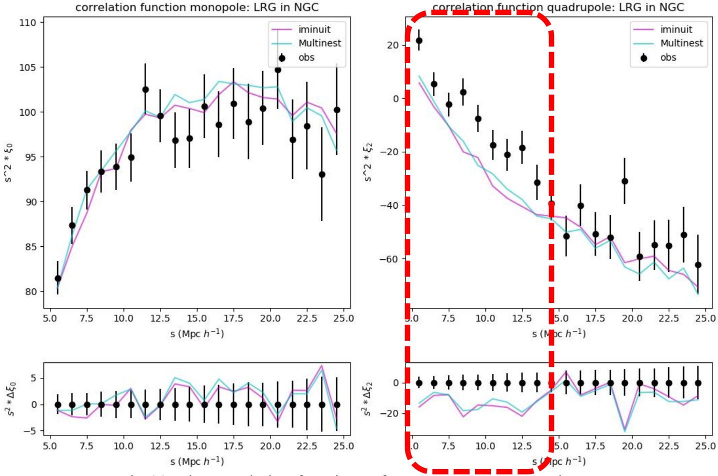


Fig 11. The correlation functions of eBOSS SHAM LRGs in NGC

# Results: LRG NGC P.D.F

| σ | $V_{peak}$ (km/s) | $\chi^2$ | Reduced $\chi^2$ |
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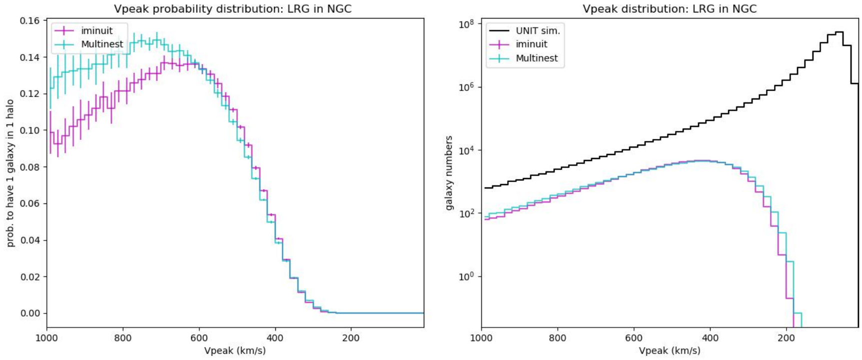


Fig 12. The probability distribution function of eBOSS SHAM LRGs in NGC

# Results: LRG NGC Posterior

| σ | $V_{peak}$ (km/s) | $\chi^2$ | Reduced $\chi^2$ |
|---|---|---|---|
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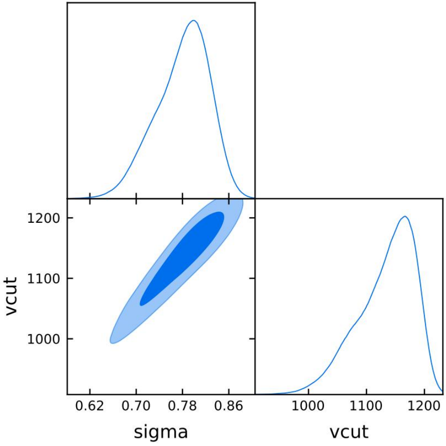


Fig 13. The posterior distributions of eBOSS SHAM LRGs in NGC

# Results: LRG SGC 2PCF

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

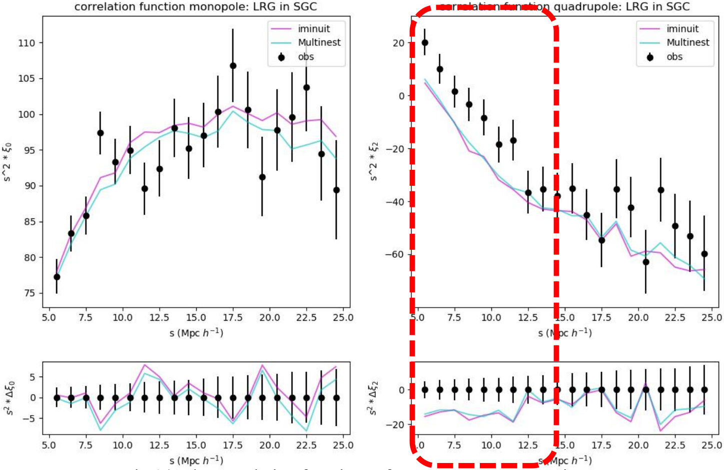


Fig 14. The correlation functions of eBOSS SHAM LRGs in SGC

# Results: LRG SGC P.D.F

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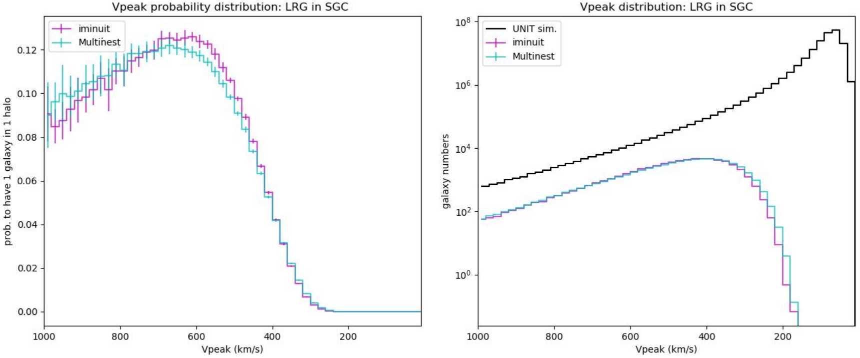


Fig 15. The probability distribution function of eBOSS SHAM LRGs in SGC

# Results: LRG SGC Posterior

| σ | $V_{peak}$ (km/s) | $\chi^2$ | **Reduced $\chi^2$** |
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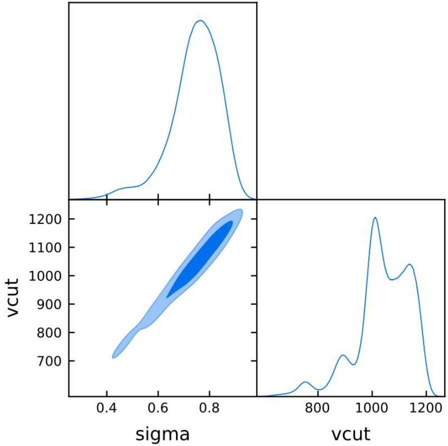



Fig 16. The posterior distributions of eBOSS SHAM LRGs in SGC

# Results: LRG SHAM Improvement

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

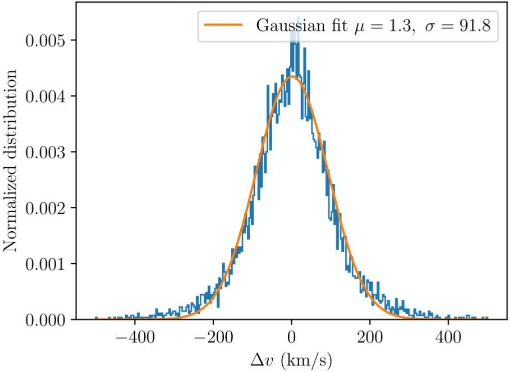


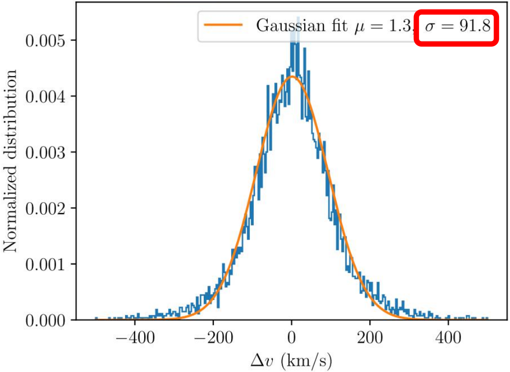

Fig 17. The redshift uncertinty of eBOSS LRG observation pairs, Figure 2 of Ross et al. (2020)

# Results: LRG SHAM Improvement

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

* the Peculiar velocity not sensitive to the galaxy bias

⇨the **Quadrupole shifts larger** than the monopole shift (?)

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|---|---|---|---|
| $0.800^{+0.035}_{-0.056}$ | $1167^{+29}_{-63}$ | 72.785 | 1.915 |
| 0.806 | 1170 | 33.910 | 0.916 |

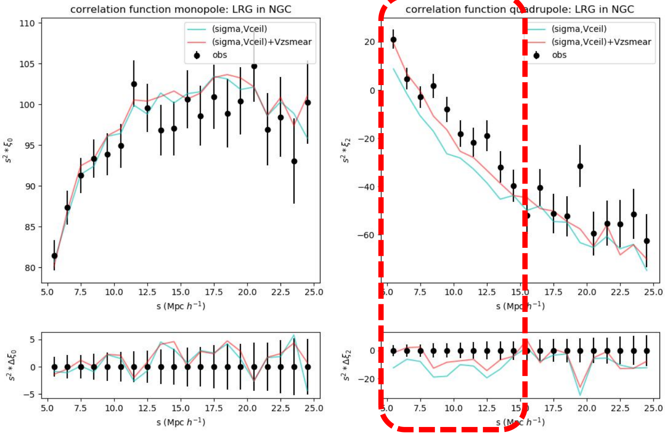


Fig 18. The peculiar-velocity-smeared SHAM LRG in NGC

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# Conclusions:

- ✓ Applyed SHAM on UNIT (sub)halo catalogue
- ✓ Reproduced the 2PCF of eBOSS LRG and ELG respectively

| | σ | $V_{peak}$ (km/s) | $\chi^2$ | Reduced $\chi^2$ |
|---|---|---|---|---|
| **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 |
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| **LRG SGC** | $0.710^{+0.144}_{-0.029}$ | $994^{+167}_{-12}$ | 54.593 | 1.437 |

- ✓ Improved the LRG SHAM by adding the redshift uncertainty effect

# Outlooks:

- ✓ Reliable eBOSS LRG & ELG SHAM models
- ☐ Robust SHAM models
  - ☐ Implement ($\sigma$, $\sigma_{pec}$, $V_{cut}$) SHAM models
  - ☐ Test the three-parameter model in different redshift bins
- ☐ Multi-tracer SHAM
  - ☐ 'generate' multiple tracers simultaneously
  - ☐ difficulty: overlapped distribution function
- ☐ Cross-Correlation between tracers

**Thanks!**