Using Lensing and Correlation measurements to Correct Finger-of-God

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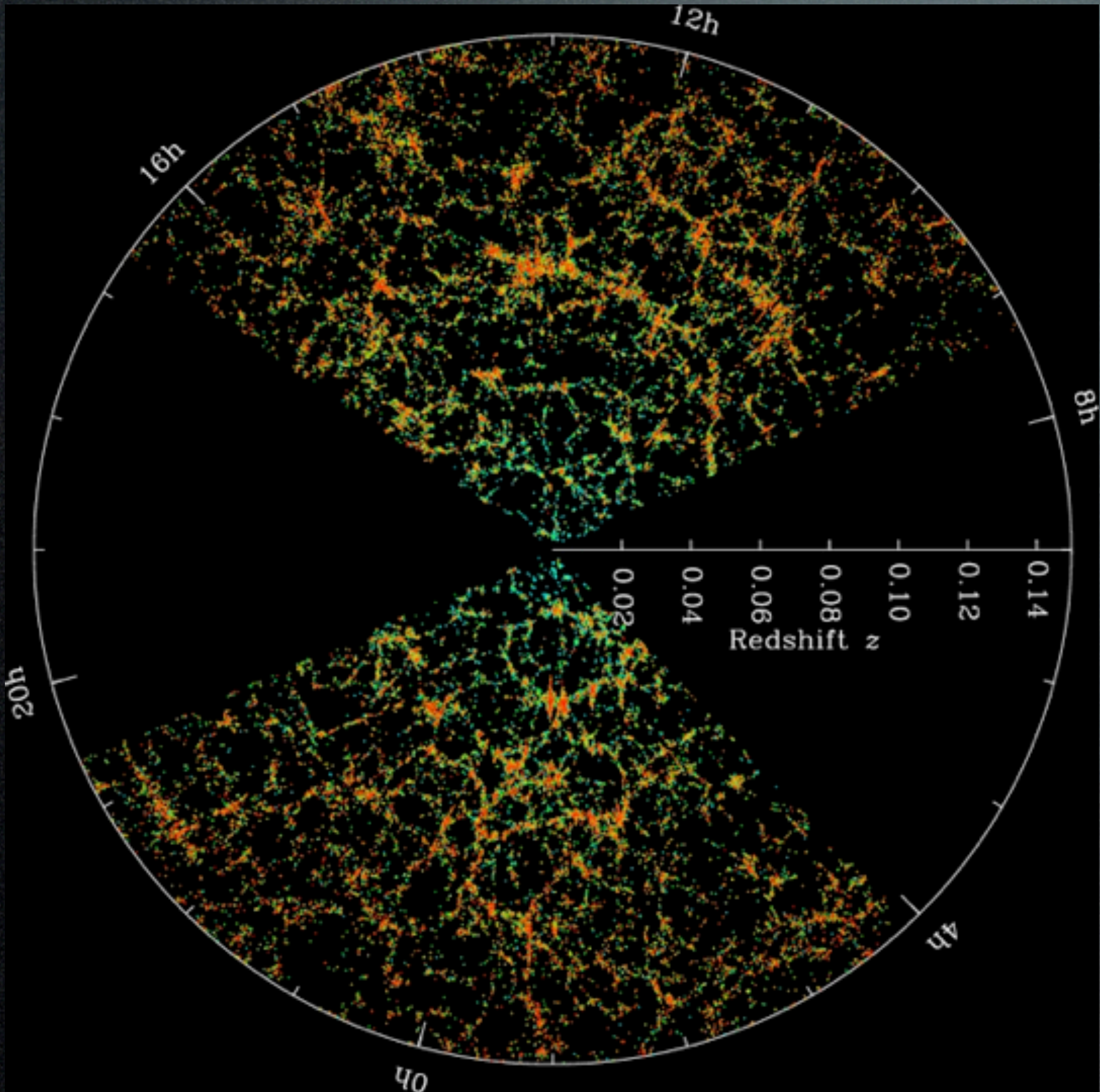
Large-Scale Structure traced by galaxies



SDSS Collaboration

What can we learn ?

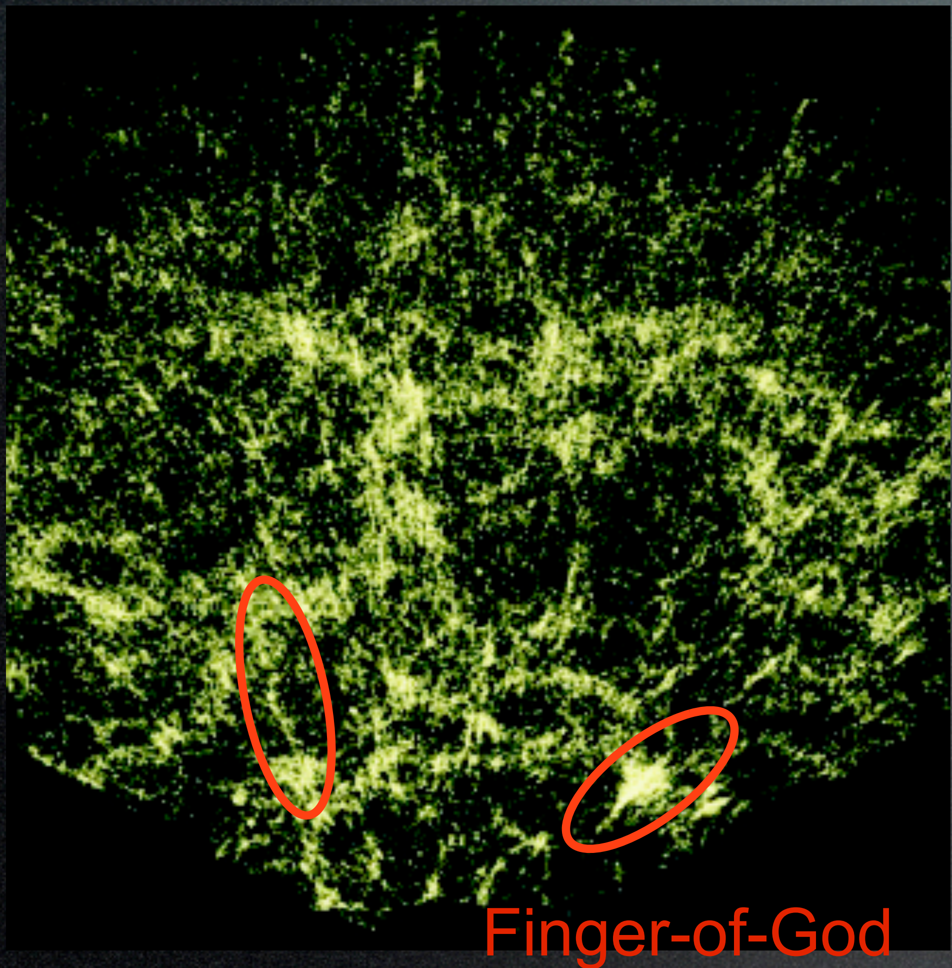
- Dark energy
- Modified Gravity
- Neutrino mass
- Primordial Non-Gaussianity

Galaxy redshift surveys

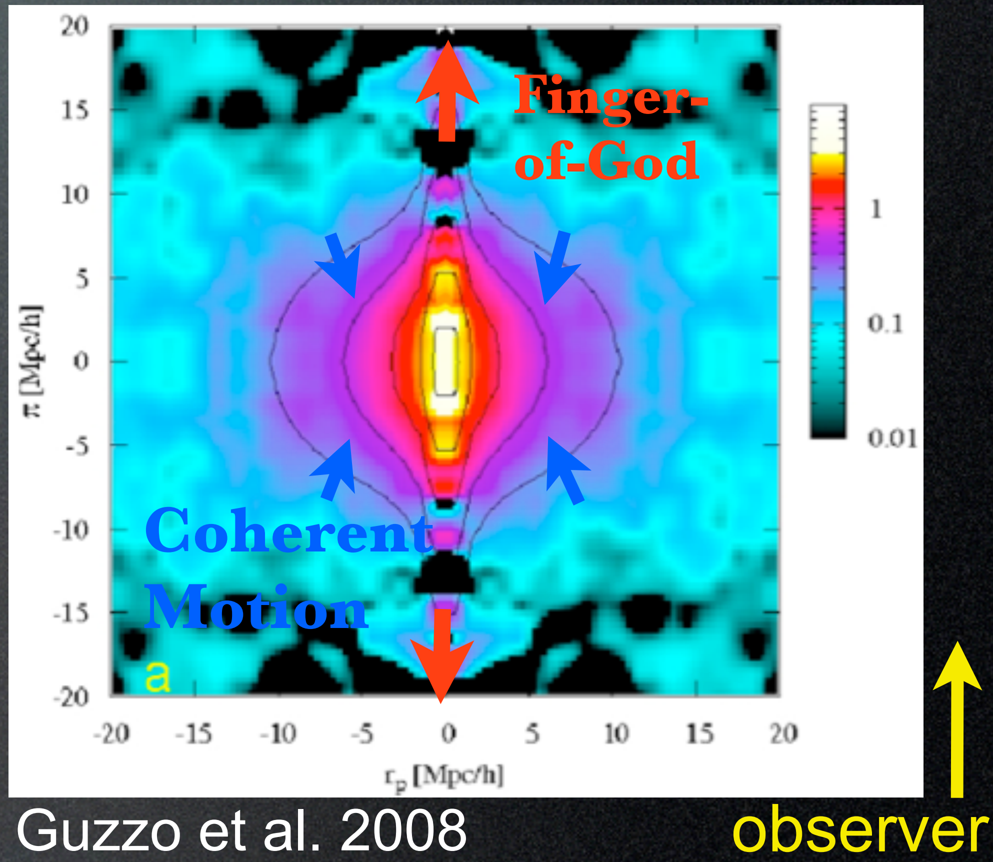
- CfA, LCRS, 2dF, SDSS
- BOSS, WiggleZ, VVDS, Vipers, FastSound
- PFS, HETDEX, BigBOSS, Euclid, WFIRST

Finger-of-God (FoG)

Finger-of-God: non-linear redshift distortion due to the internal motion of galaxies within the host halo



2-Point Correlation Function VVDS-Wide Survey (6000 gals, 0.6<z<1.2, 4deg^2)



Guzzo et al. 2008

Which galaxies generate FoG ?

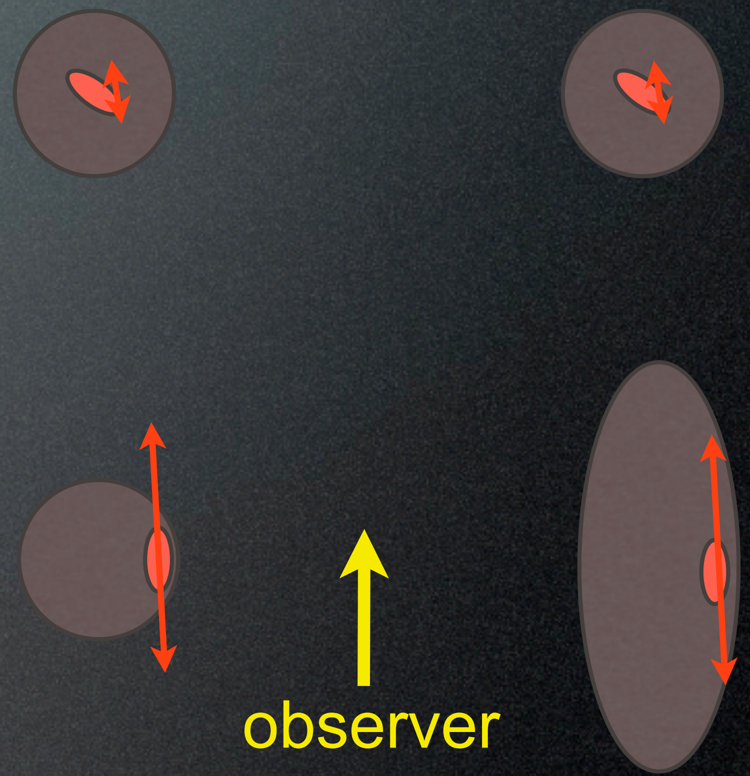
In this work, we focus on the luminous red galaxies (LRGs)

<u>Central LRGs</u> locating on the potential minimum has small internal motion within halos

<u>Off-centered (satellite) LRGs</u> have larger internal motion

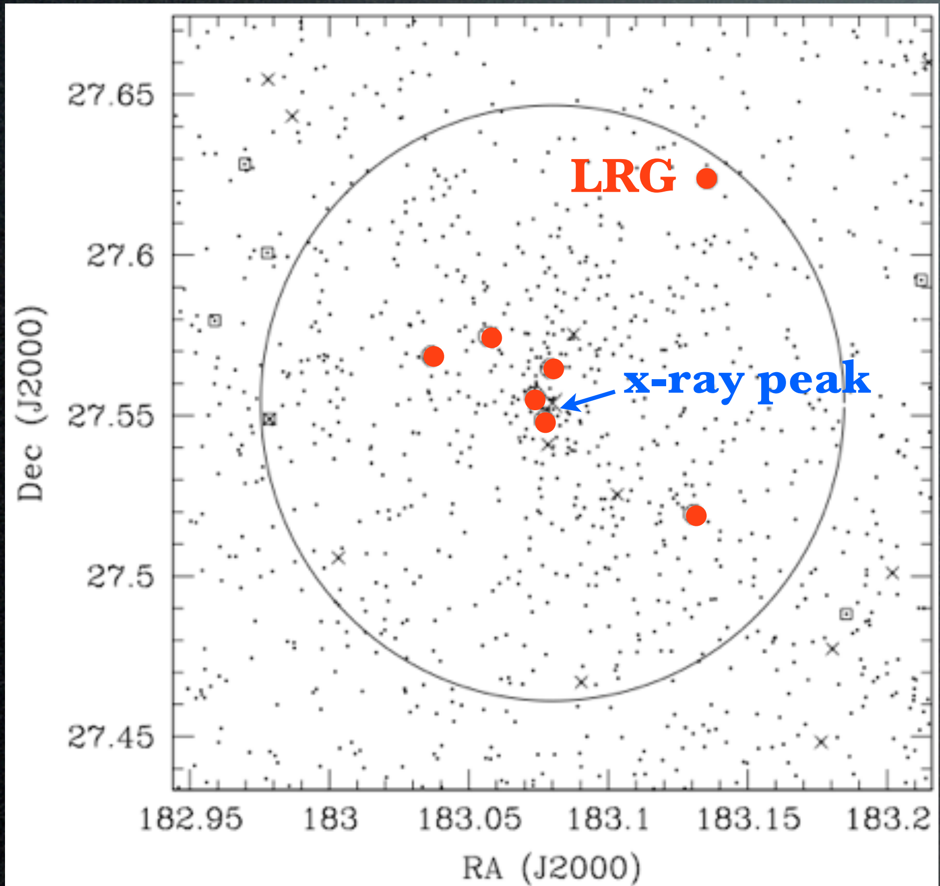
Main sources of FoG

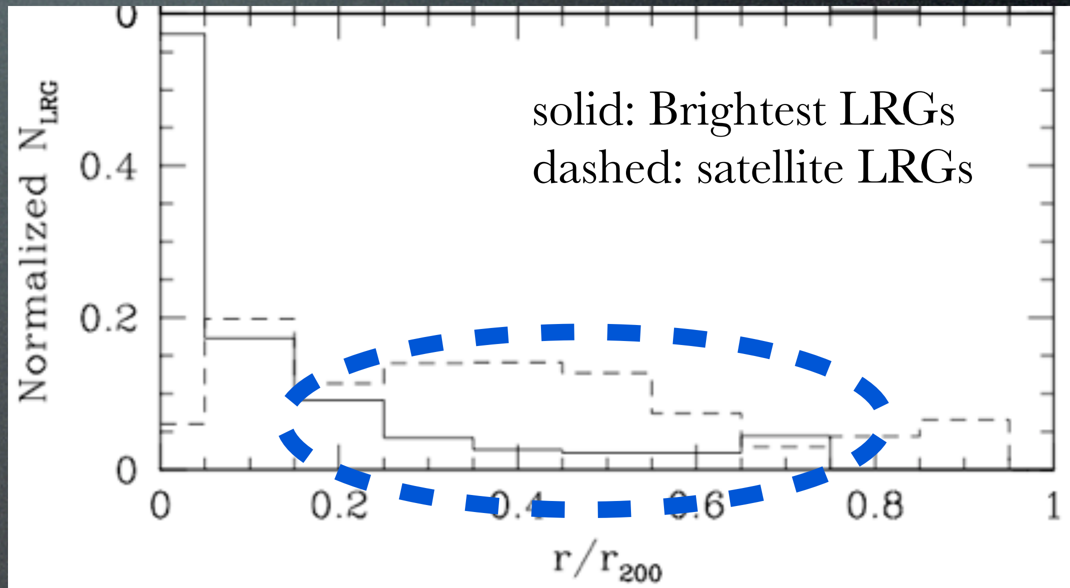
<u>Real Space</u> *<u>Redshift Space</u>*



LRGs locate at halo mass center ?

Comparison of LRG positions with X-ray peaks using 47 X-ray selected clusters at 0.2<z<0.6 (Ho et al. 2009)

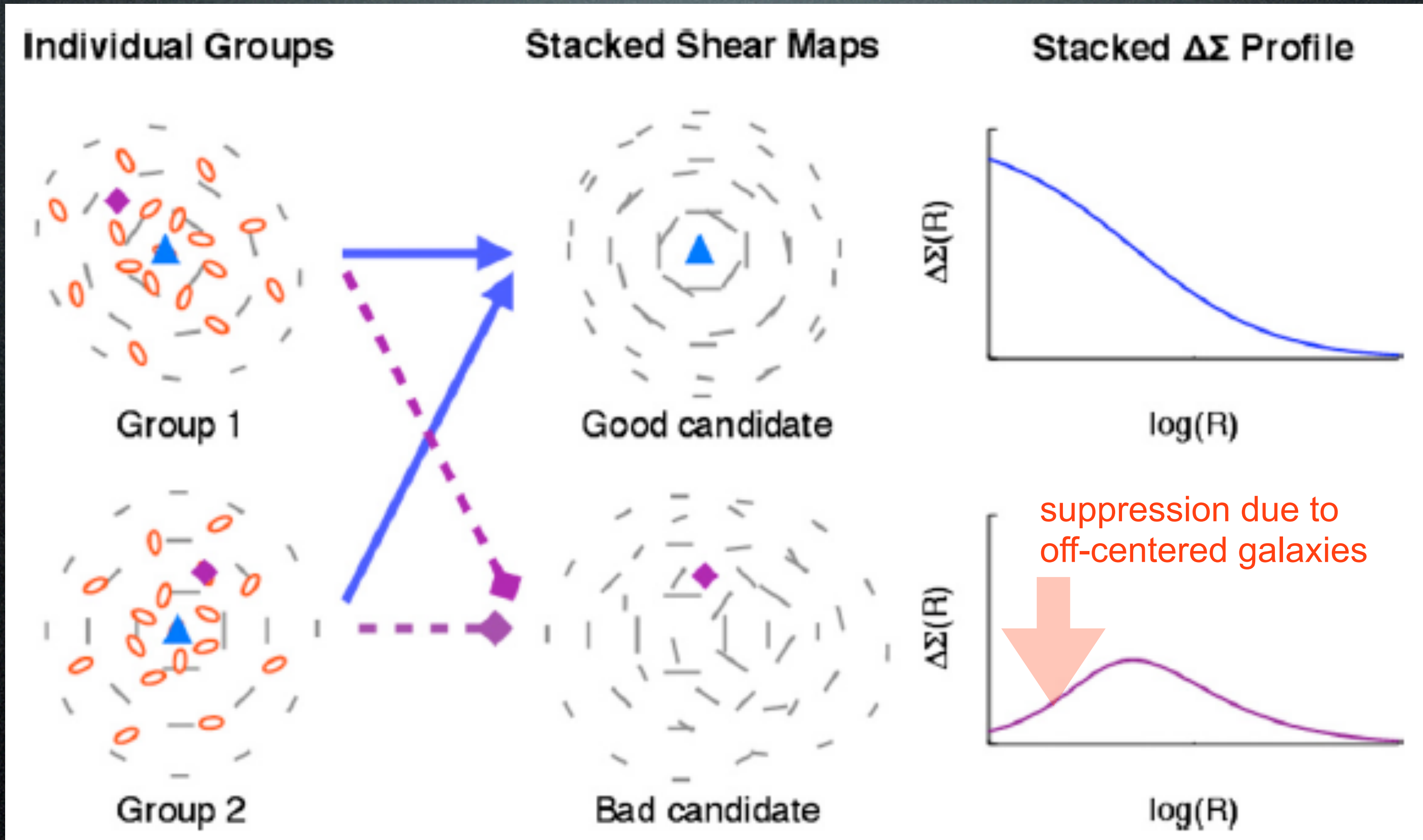




20% of Brightest LRGs have offset from X-ray peak

Most massive clusters
$M_{200}=7.7\times10^{14}h^{-1}M_{\odot}$, z=0.353

Off-centering effect on LRG-galaxy lensing



George et al. 2012

LRG-galaxy lensing/cross-correlation is sensitive to the off-centering properties, which can be used for calibrating FoG

Reconstruction of Halo Catalogs

SDSS DR7 LRG catalog (Kazin et al. 2010)
$-23.2<M_g<-21.2$, $0.16<z<0.47$

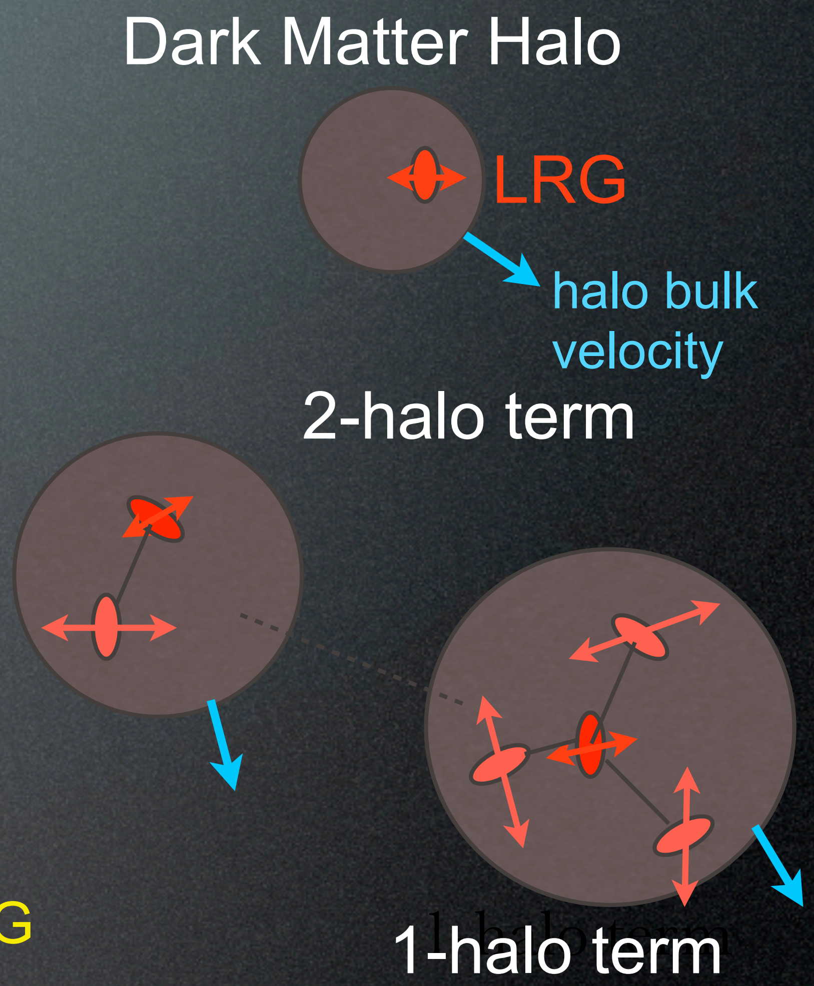
Reconstructing halo catalogs to reduce satellite contributions

Counts-in-Cylinder Grouping method (Reid & Spergel 2010):
$\Delta z/(1+z)<0.006$, $\Delta r_{\perp}<0.8h^{-1}$Mpc/h

$N_{\rm LRG}$	Number of LRG FoF groups
1	87889 (95.5 per cent)
2	3713
3	358
4	65
5	14
6	6
7	1
Total	92046 (100 per cent)

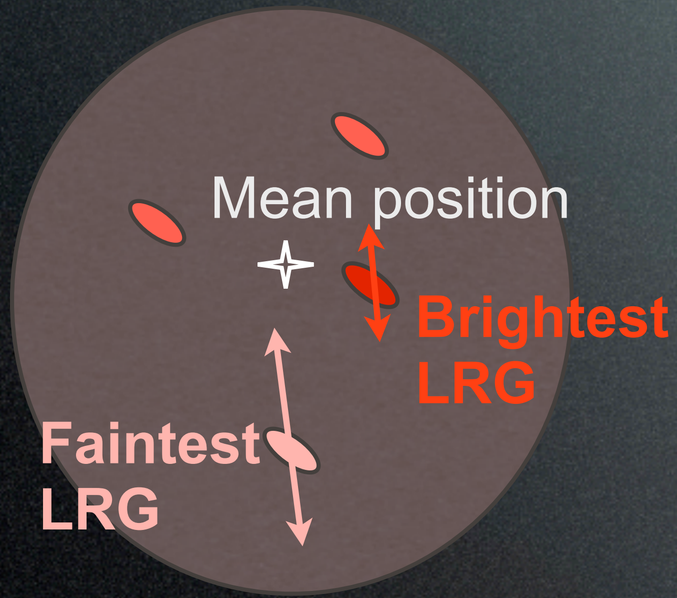
single LRG systems

multiple LRG systems



Off-centering in Multiple LRG Systems

Multiple LRG systems



Choices of halo positions
- Brightest LRG (BLRG)
- Faintest LRG (FLRG)
- Arithmetic mean position (Mean)

Let’s see the off-centering effect with the following three measurements:

1. Halo - galaxy lensing
2. Halo - galaxy cross-correlation
3. Halo power spectrum (Finger-of-God)

If all of BLRGs locate on the halo center,
BLRG offset < Mean offset < FLRG offset

1. Halo-Galaxy lensing with different centers

Excess surface mass density

tangential ellipticity

$$\Delta\Sigma(R) = \frac{\sum_{ls} w_{ls} e_t^{(ls)}(R) \Sigma_{\rm crit}(z_l, z_s)}{2\mathcal{R} \sum_{rs} w_{rs}}$$

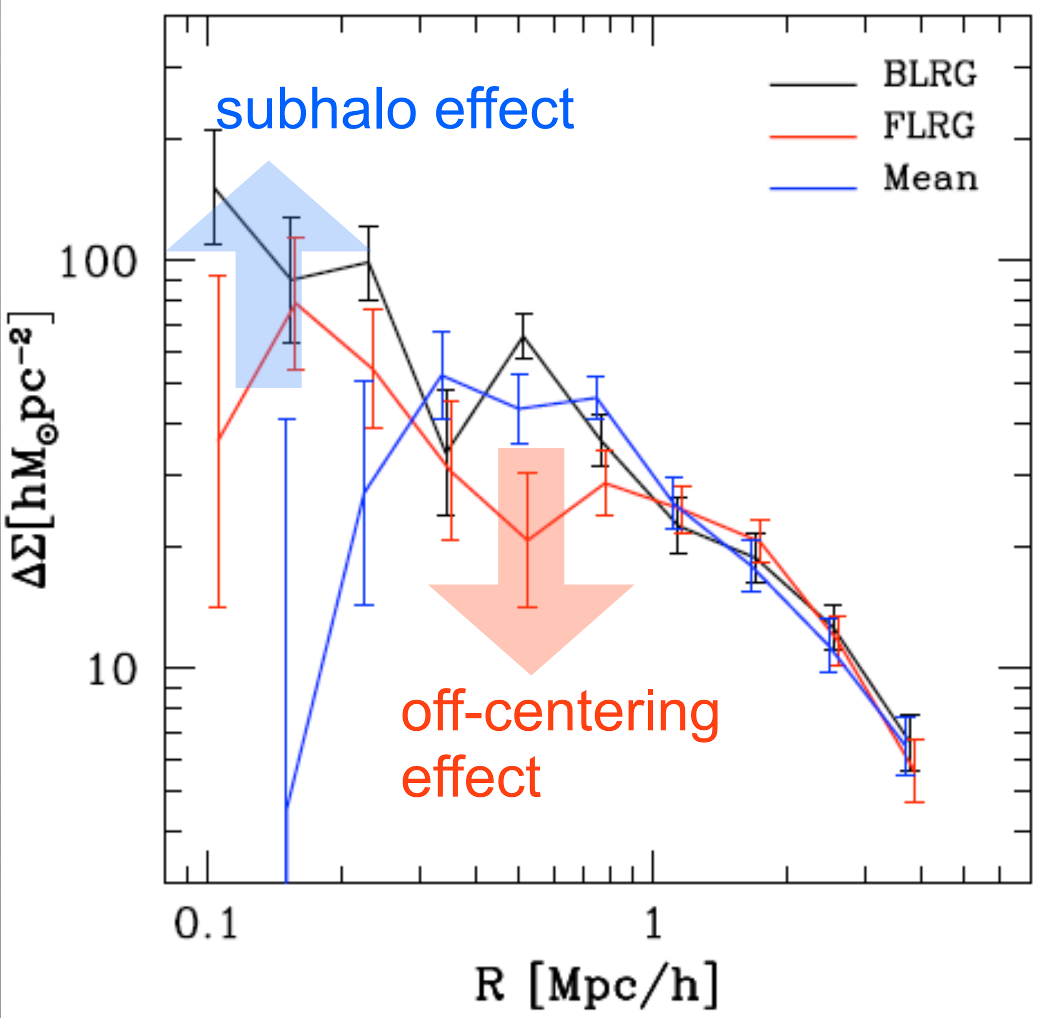
Inverse variance weight

$$w_{ls} = \frac{1}{\Sigma^2_{\rm crit}(\sigma_s^2 + \sigma_{SN}^2)}$$

shape measurement error

intrinsic ellipticitiy

(Mandelbaum et al. 2012)



Number density of SDSS photo-z galaxies with $z_{photo} > z_{LRG}$ are 1.2 galaxies per arcmin^2

Errors are estimated from Jackknife resampling method

Modeling Halo-galaxy lensing

Excess surface mass density around LRGs

$$\Delta\Sigma(R) \equiv \int \frac{k\mathrm{d}k}{2\pi} C_{\Sigma g}(k) J_2(kR),$$

$$C_{\Sigma g}(k) = C^{1h}_{\Sigma g}(k) + C^{2h}_{\Sigma g}(k).$$

Single halo mass approximation

$$\begin{aligned} C^{1h}_{\Sigma g}(k) &\simeq \left[\bar{M}\tilde{u}_{\mathrm{NFW}}\left(k;\bar{M}, z_{\mathrm{LRG}}\right)\underbrace{\tilde{p}_{\mathrm{off}}(k;\bar{M})}_{\text{offset profile}} + \underbrace{m_{\mathrm{sh,LRG}}}_{\text{sub-halo}}\right] \\ C^{2h}_{\Sigma g}(k) &\simeq \underbrace{b(\bar{M})}_{\text{bias}}\bar{\rho}_{\mathrm{m}0} P^L_m(k;z)\,. \end{aligned}$$

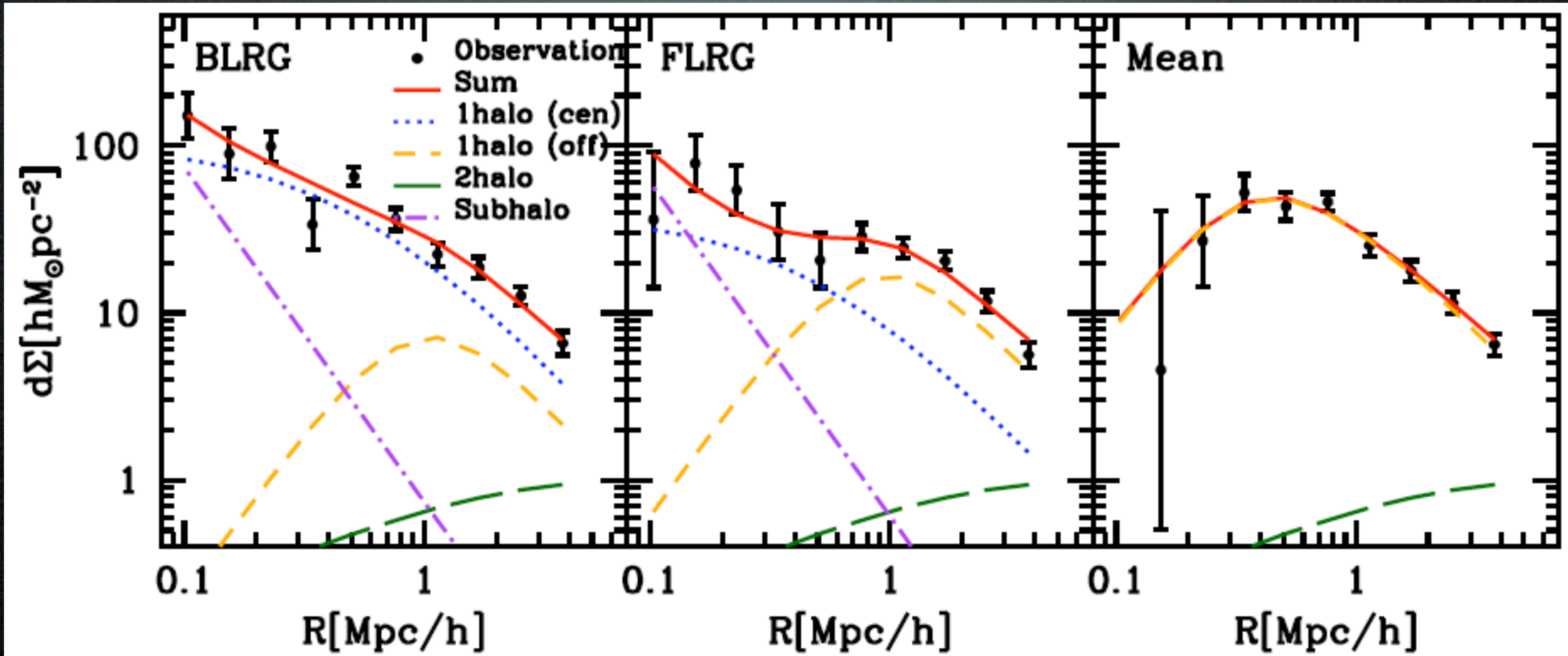
LRG distribution within halos (Center + Satellite with Gaussian Offset)

$$\tilde{p}_{\mathrm{off}}(k) \longrightarrow \underbrace{q_{\mathrm{cen}}}_{\text{Fraction of central LRGs}} + (1 - q_{\mathrm{cen}})\exp[-(k\underbrace{R_{\mathrm{off}}}_{\text{Gaussian offset scale}})^2]$$

Parameters used for fitting gal. lensing around BLRG/FLRG/Mean

$$p_\alpha = (\bar{M}_{180b}, \bar{c}_{180b}, q^{\mathrm{BLRG}}_{\mathrm{cen}}, R^{\mathrm{BLRG}}_{\mathrm{off}}, m^{\mathrm{BLRG}}_{\mathrm{sh}}, q^{\mathrm{FLRG}}_{\mathrm{cen}}, R^{\mathrm{FLRG}}_{\mathrm{off}}, m^{\mathrm{FLRG}}_{\mathrm{sh}}, R^{\mathrm{Mean}}_{\mathrm{off}}, \bar{b})$$

Offset properties from galaxy lensing



Measurement	$q_{\rm cen}^{\rm BLRG}$ [%]	$R_{\rm off}^{\rm BLRG}$ [Mpc/h]	$m_{\rm sh}^{\rm BLRG}$ [$10^{12}M_\odot/h$]	$q_{\rm cen}^{\rm FLRG}$ [%]	$R_{\rm off}^{\rm FLRG}$ [Mpc/h]	$m_{\rm sh}^{\rm FLRG}$ [$10^{12}M_\odot/h$]	$R_{\rm off}^{\rm Mean}$ [Mpc/h]	$\bar{M}_{180b}$ [$10^{14}M_\odot/h$]	$\bar{c}_{180b}$
$\Delta\Sigma(R)$	63 ± 21	0.44 ± 0.22	2.3 ± 1.4	24 ± 13	0.39 ± 0.06	1.9 ± 1.1	0.16 ± 0.03	1.63 ± 0.16	4.8 ± 1.4

Fraction of central galaxies are 63% for BLRGs and 24% for FLRGs.

2. Cross-correlation of Halos with photo-z red galaxies

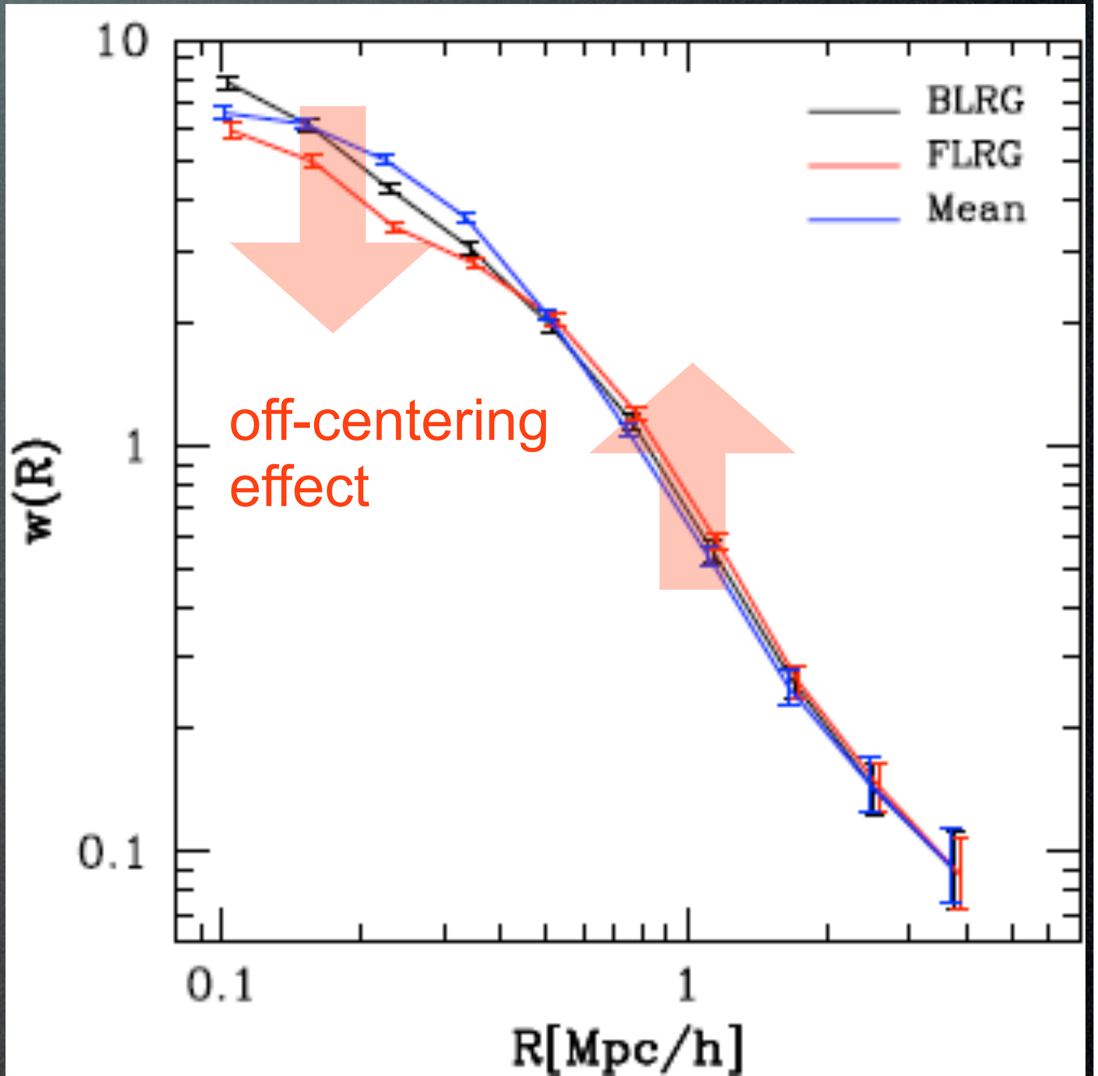
Halo(LRG) - galaxy pair counts

$$w^{\rm cross}(R) = \frac{\sum HG(z_{\rm ll} \leqslant z_H \leqslant z_{\rm ul})}{\sum RG(z_{\rm ll} \leqslant z_R \leqslant z_{\rm ul})} - 1$$

Random - galaxy pair counts

Differences from LRG lensing
- $z_{ph}-\Delta z_{ph} < z_{LRG} < z_{ph}+\Delta z_{ph}$
- small galaxies are available
- brighter flux limit (r<21) to reduce photo-z error

BLRG offset is larger than Mean.
→ all of BLRGs are not central



Modeling of LRG-galaxy cross correlations

$$w_{gg}^{\rm cross}(R) = \int \frac{k{\rm d}k}{2\pi} C_{gg}^{\rm cross}(k) J_0(kR)$$

$$\begin{aligned} C_{gg}^{1h}(k) &\simeq \underline{f_{\rm phg}(\chi)}\tilde{u}_{\rm NFW}\left(k;\bar{M}, z_{\rm LRG}\right)\tilde{p}_{\rm off}(k;\bar{M}) \\ C_{gg}^{2h}(k) &\simeq \underline{f_{\rm phg}(\chi)}\bar{b}_{\rm LRG}\bar{b}_{\rm phg}P_m^L(k;z_{\rm LRG}) \end{aligned}$$

photo-z distribution

LRG distribution within halos (Offset distribution)

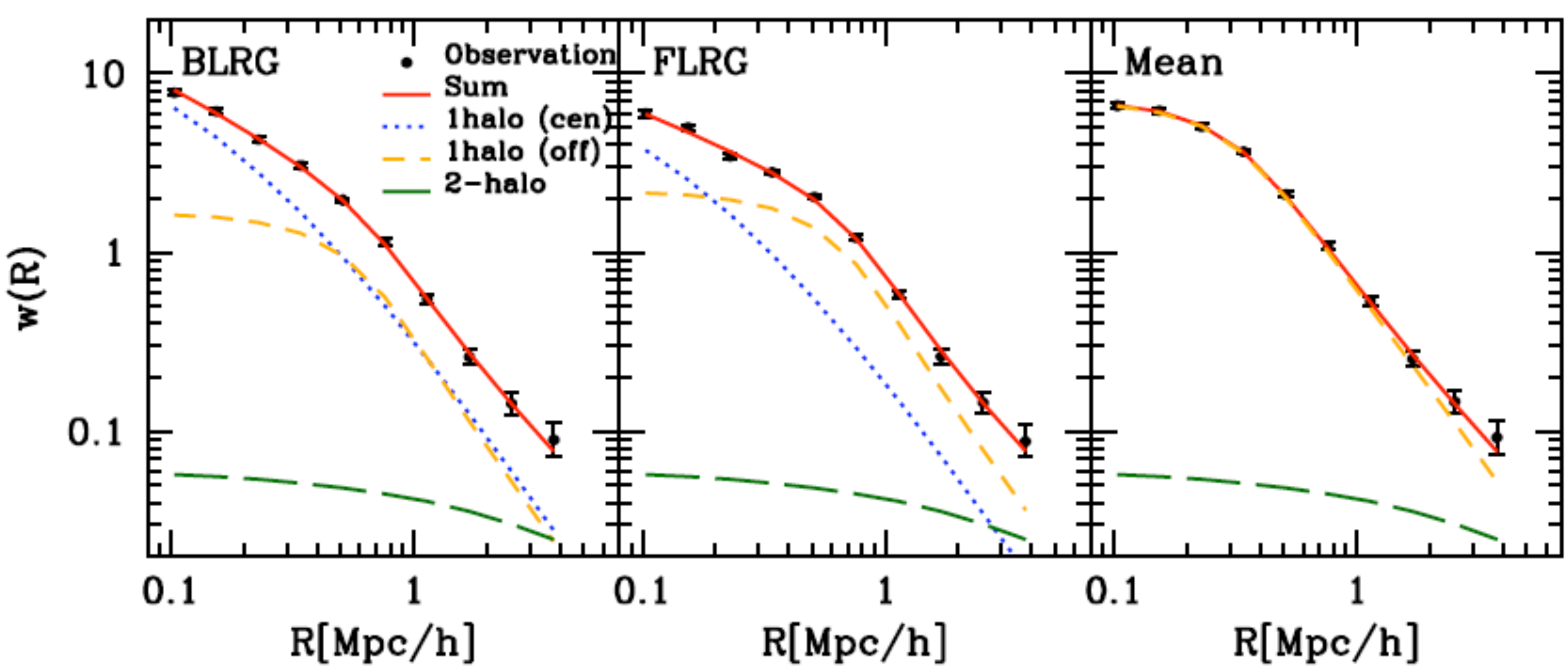
$$\tilde{p}_{\rm off}(k) \longrightarrow \underline{q_{\rm cen}} + (1-q_{\rm cen})\exp[-(\underline{kR_{\rm off}})^2]$$

Fraction of central LRGs

Gaussian offset scale

We do not use the amplitude which has large uncertainty of photo-z error distribution

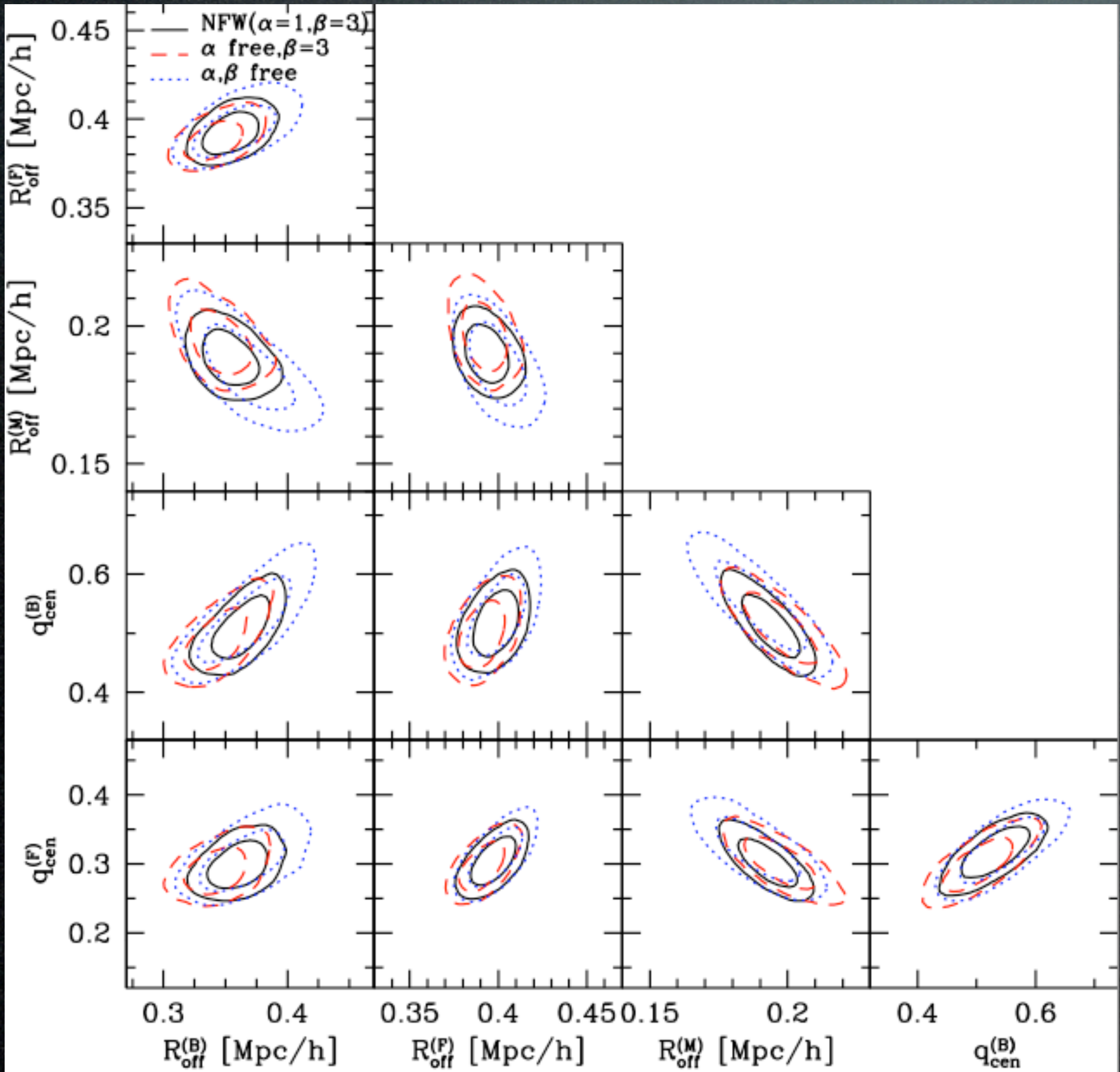
Limits on offset properties in multiple LRG systems from cross correlations



Measurement	$q_{\rm cen}^{\rm BLRG}$ [%]	$R_{\rm off}^{\rm BLRG}$ [Mpc/h]	$q_{\rm cen}^{\rm FLRG}$ [%]	$R_{\rm off}^{\rm FLRG}$ [Mpc/h]	$R_{\rm off}^{\rm Mean}$ [Mpc/h]
$w(R)$	54 ± 5	0.35 ± 0.02	32 ± 3	0.40 ± 0.01	0.19 ± 0.01

Constraints from cross-correlation measurements are consistent with those from lensing.

Does the result depend on the details of the profile ?



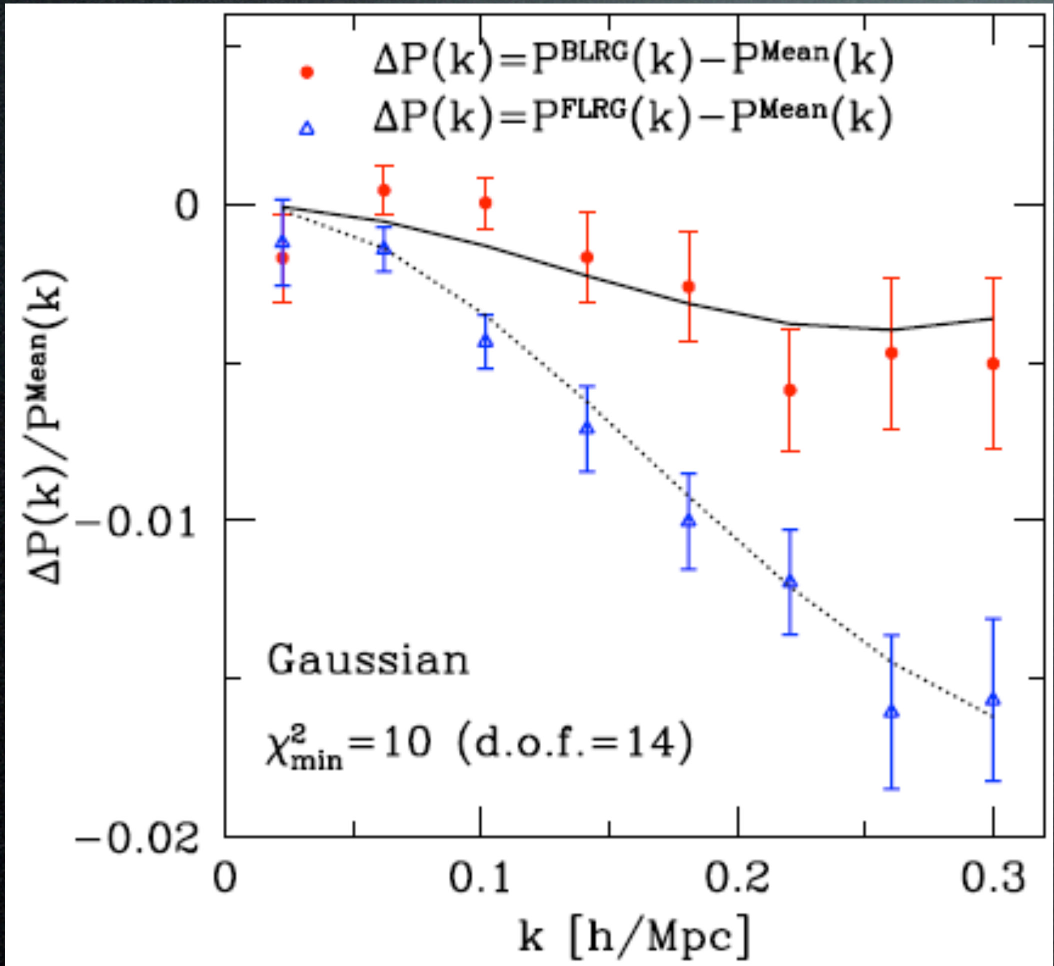
generalized NFW profile

$$n_{\rm LRG}(r) \propto \frac{1}{(r/r_s)^\alpha((r/r_s)+1)^{\beta-\alpha}}$$

The result does not change when the assumed profile is more general.

3. FoG and Velocity dispersion of Satellite Galaxies

FoG difference by different centers



LRG power spectrum

$$P^{\rm LRG}(k,\mu) = P^{\rm halo}(k,\mu)\left[q_{\rm cen} + \underbrace{(1-q_{\rm cen})]\sqrt{F(k,\mu)}}_{\text{FoG of satellite (off-centered) galaxies}}\right]^2$$

FoG function

$$F(k,\mu) = \exp[-(k\mu\sigma_{v,\rm off}/aH(z))^2]$$

Satellite velocity dispersions obtained by fitting the FoG differences are

$\sigma_{v,\rm off}^{\rm BLRG}$=498±41km/s at $q_{\rm cen}^{\rm BLRG}$=0.54
$\sigma_{v,\rm off}^{\rm FLRG}$=512±32km/s at $q_{\rm cen}^{\rm FLRG}$=0.32

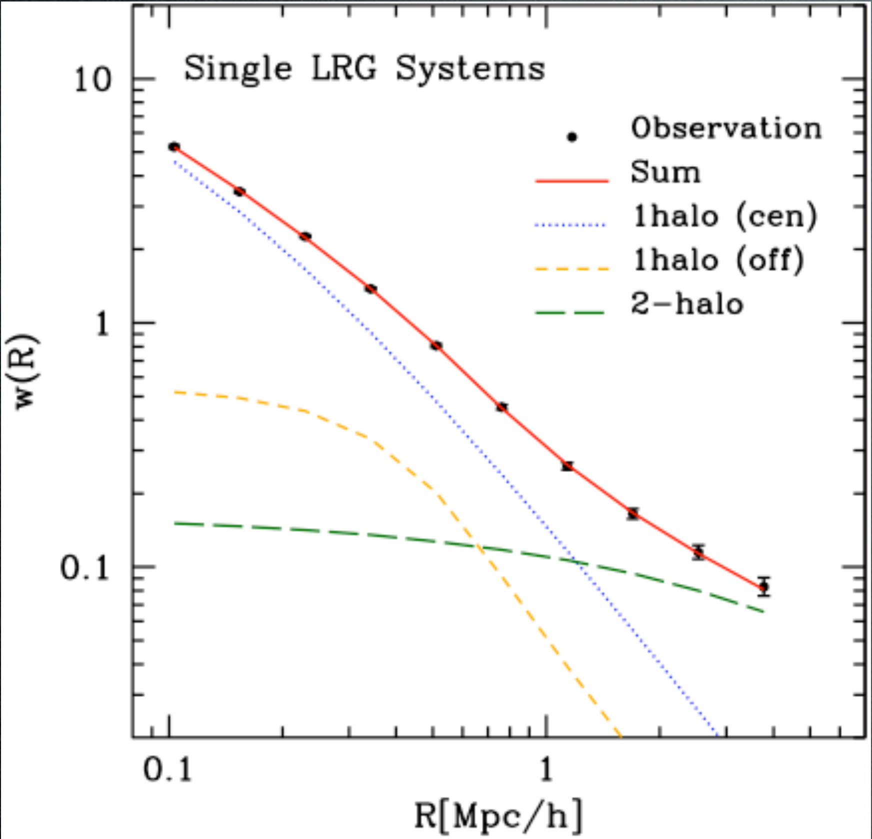
which agree with the Virial velocity:

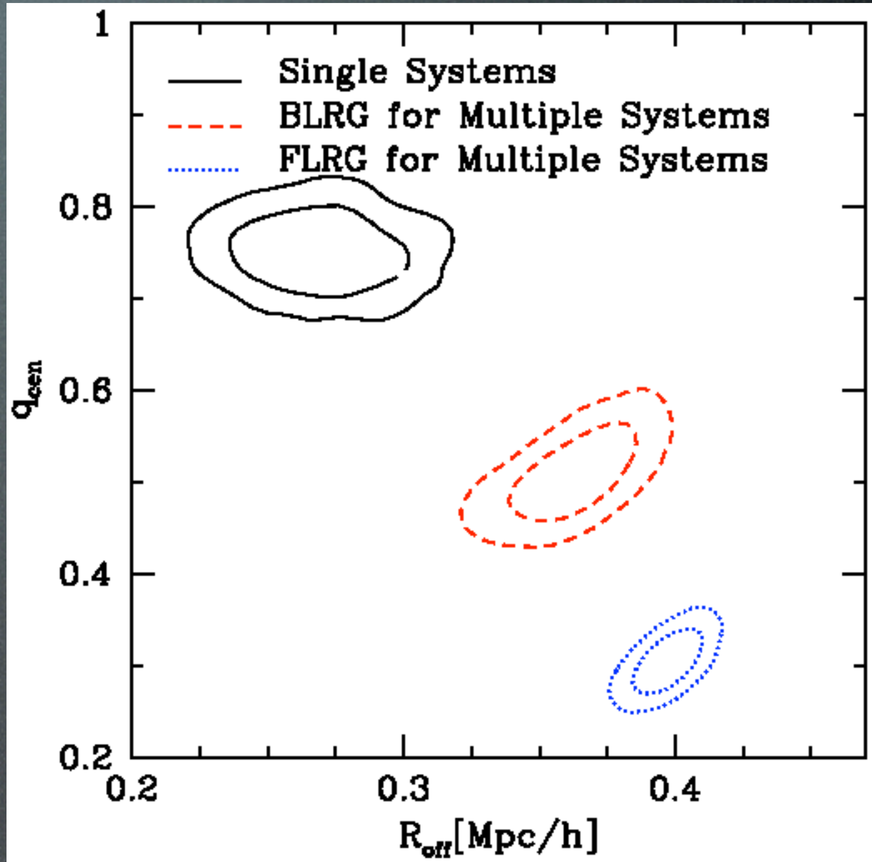
$\sigma_{\rm vir}$= $[GM_{\rm halo}/2R_{\rm off}]^{1/2}$= 510km/s
M_{180b}=1.6×10^{14}$M_{\rm sun}$/h, $R_{\rm off}$=0.4Mpc/h)

All of the three measurements have consistent results

Satellite fraction of Single LRG Systems

cross correlation with photo-z



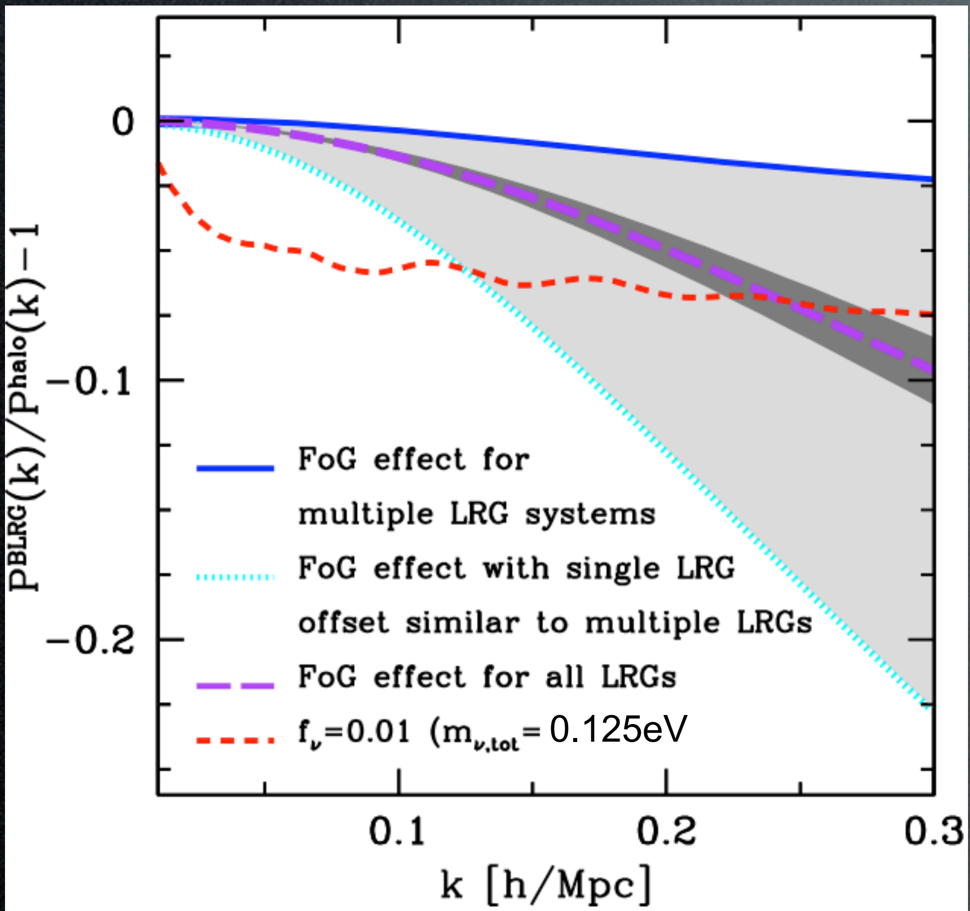


Measurement	$q_{\rm cen}^{\rm Single}$ [%]	$R_{\rm off}^{\rm Single}$ [Mpc/h]	$m_{\rm sh}^{\rm Single}$ [$10^{12}M_\odot/h$]	$\bar{M}_{\rm 180b}^{\rm Single}$ [$10^{14}M_\odot/h$]	$\bar{c}_{\rm 180b}^{\rm Single}$
$\Delta\Sigma(R)$	79 ± 13	0.39 ± 0.24	0.77 ± 0.47	0.42 ± 0.04	6.3 ± 1.6
$w^{\rm cross}(R)$	77 ± 6	0.26 ± 0.03	–	–	–

Single LRG system has higher central fraction (80%) than multiple LRGs (~60%)

Total FoG effect of SDSS LRGs

$$P_s(k,\mu) = \left[1+\beta\mu^2\right]^2 \Big[\underbrace{\bar{b}_{\mathrm{S-LRG}}(1-f_{\mathrm{M-LRG}})\left\{q_{\mathrm{cen}}^{\mathrm{S-LRG}} + (1-q_{\mathrm{cen}}^{\mathrm{S-LRG}})\sqrt{F_{\mathrm{S-LRG}}(k,\mu)}\right\}}_{\text{single}} + \underbrace{\bar{b}_{\mathrm{M-LRG}} f_{\mathrm{M-LRG}}\left\{q_{\mathrm{cen}}^{\mathrm{M-LRG}} + (1-q_{\mathrm{cen}}^{\mathrm{M-LRG}})\sqrt{F_{\mathrm{M-LRG}}(k,\mu)}\right\}}_{\text{multi}}\Big]^2 P_m^{\mathrm{NL}}(k)$$



Single LRG systems (95.5%)

b_{s_LRG}=2.12 (M_{180b}=0.42x$10^{14}M_{sun}$/h)

$q_{cen}^{s\_LRG}$=0.77, $\sigma_{v,off}=\sigma_{vir}$=344km/s

Multiple LRG systems (4.5%)

b_{M_LRG}=3.26 (M_{180b}=1.63x$10^{14}M_{sun}$/h)

$q_{cen}^{M\_LRG}$=0.54, $\sigma_{v,off}=\sigma_{vir}$=510km/s

FoG suppression reaches
5% at k=0.2h/Mpc
10% at k=0.3h/Mpc
which is comparable to the massive neutrino effect with $m_{\nu,tot}$~0.1eV

SUbaru Measurement of Images and REdshift (SUMIRE)

Joint Imaging and Redshift surveys

Hyper-Suprime Cam (HSC)

-Imaging survey over 1400 deg^2 sky (Wide) overlapped with BOSS, ACT, UKIDSS, VIKING, eROSITA
- 30gals/$arcmin^2$, z_{mean}~1, r~26(5σ)
- 1.5 deg FoV, grizy+4NB, 0.16"pix,
- 2013-2017

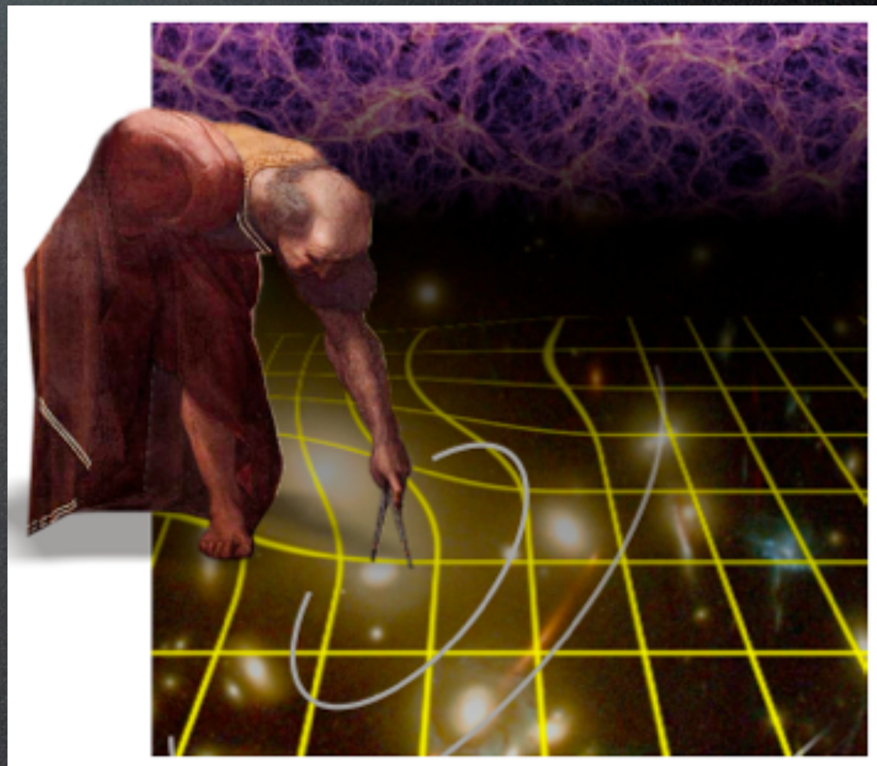
Prime Focus Spectrograph (PFS)

- Redshift survey of the same sky as HSC
- Main target: LRGs, OII emitters
- 0.8<z<2.4 (9.3 Gpc/h^3)
- 2400 fibers, 380nm~1300nm
- 2018-2023 (planed)

8.2m Subaru Telescope
Mauna Kea, Hawaii,
4139m alt., 0.6-0.7” seeing

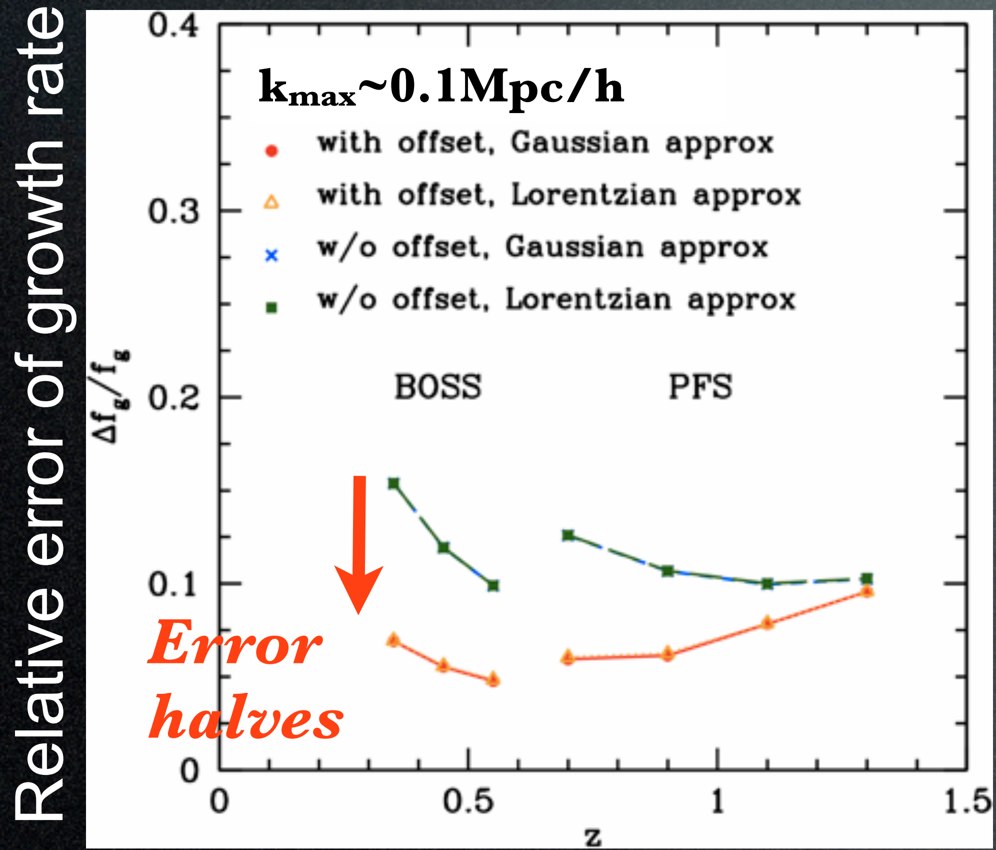
Euclid

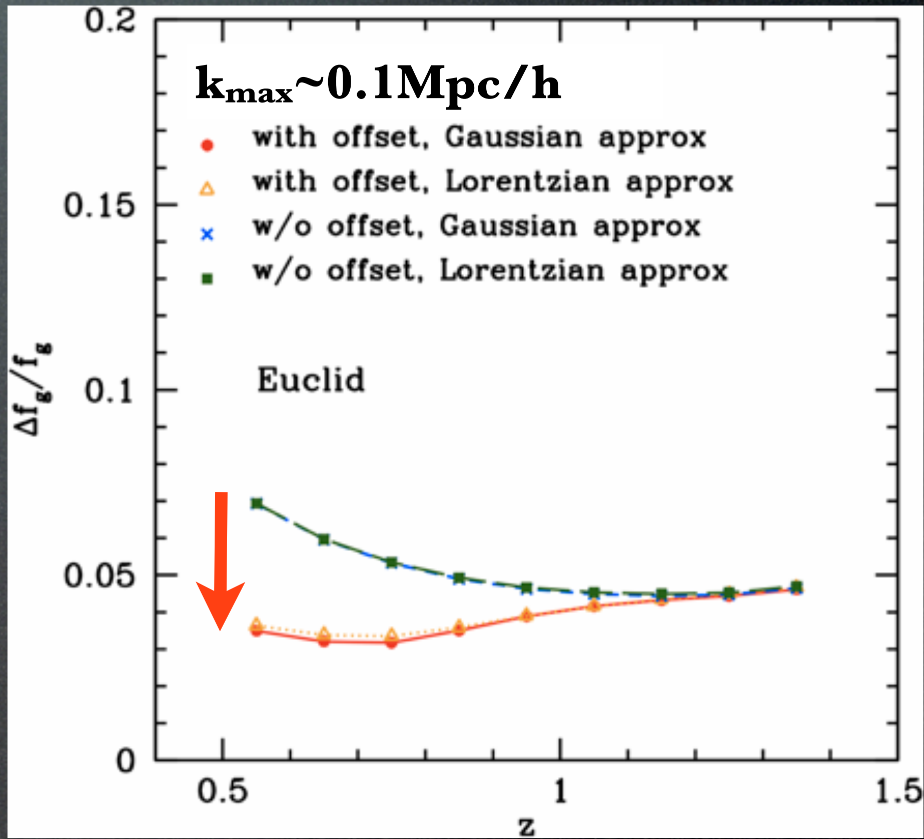
- ESA M-class mission
- Dark energy probe via weak lensing & BAO
- Imaging 20,000 deg^2 sky, 40gals/arcmin^2
- Spectrum of 70M Hα emitters at $0.5<z<2$
- 1.2m telescope
- FoV 0.5deg^2, rizYJH band (550nm~1800nm), 0.2-0.3" pixel size
- Spectrograph: 1~2μm, R=500
- 2020-2025 (planed)



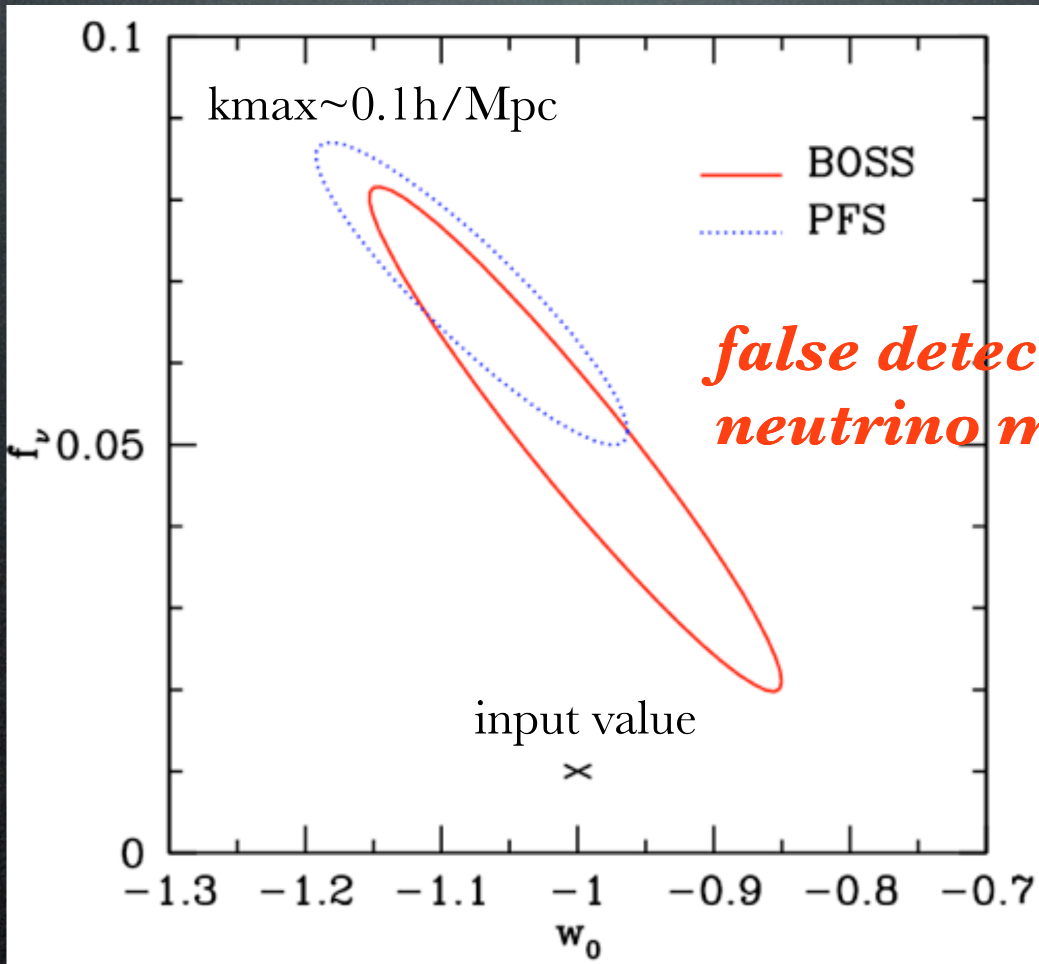
Impact on Growth Rate Measurement

HSC Lensing calibration of FoG effect improves the accuracy of growth rate measurement by nearly twice





If FoG effect is neglected ...



false detection of neutrino mass!

Understanding the nature of LRGs: Connecting LRGs to Subhalos

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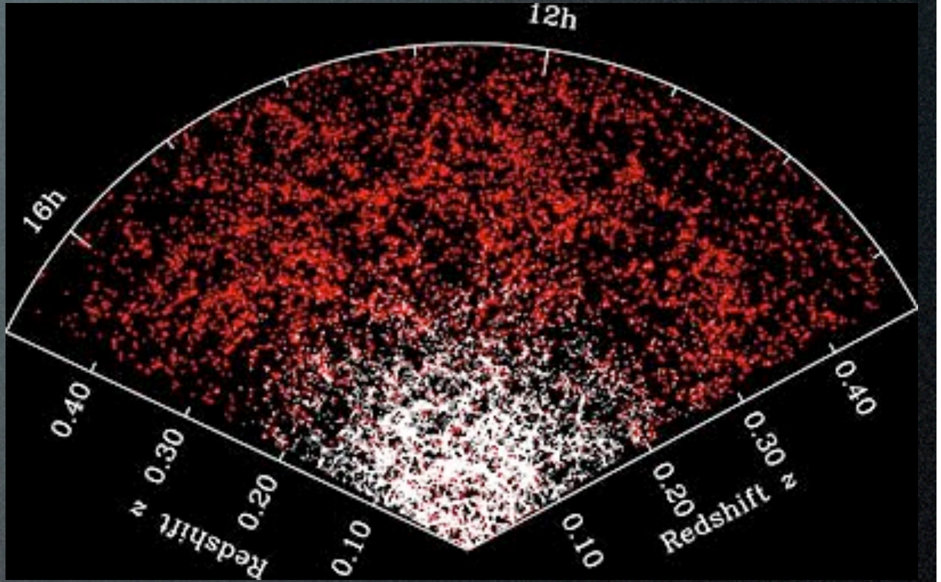
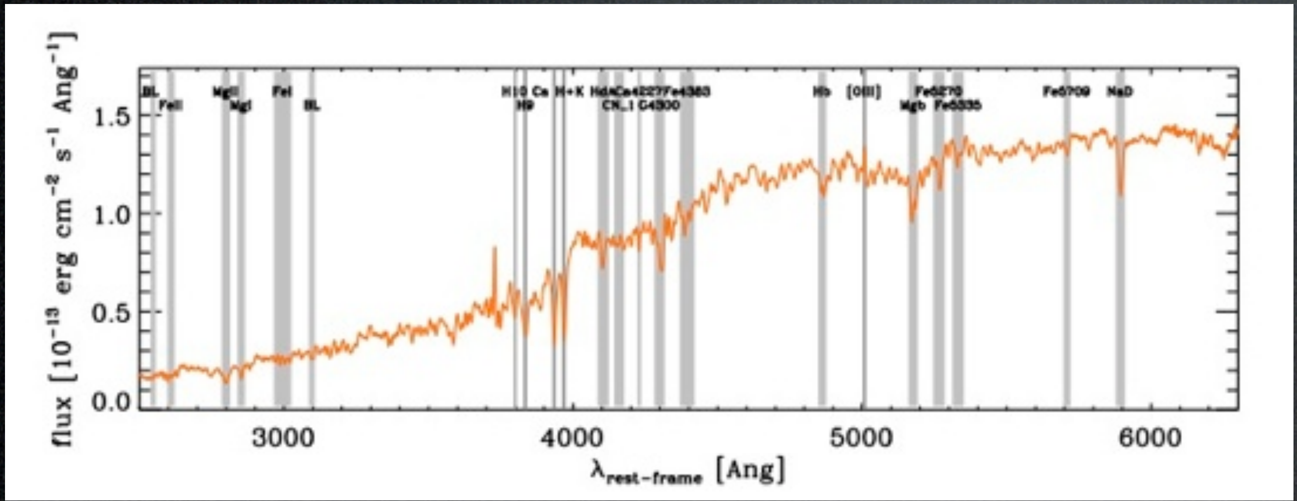
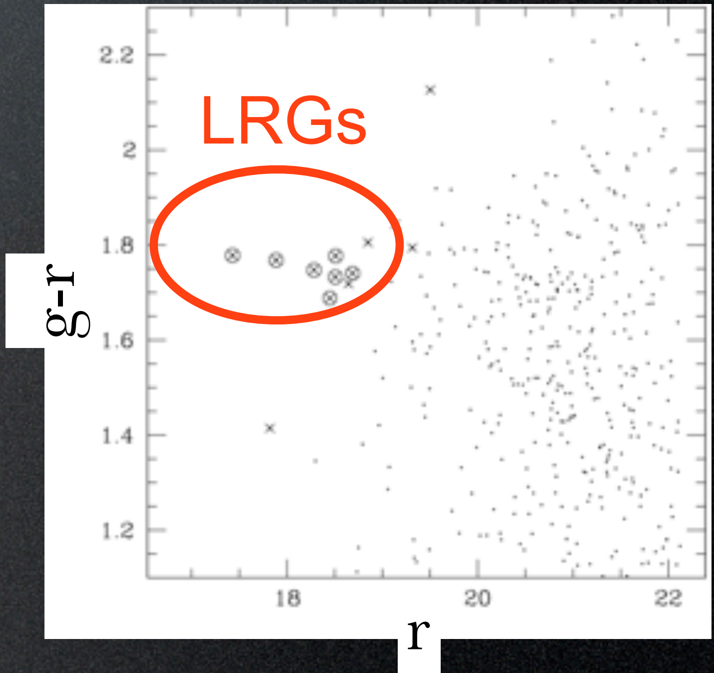
Luminous Red Galaxies (LRGs)

Main target of SDSS, BOSS
- Luminous: large stellar mass
- Red: old stellar (~5Gyr) populations

→ Progenitor halos of LRGs are massive and formed at early times

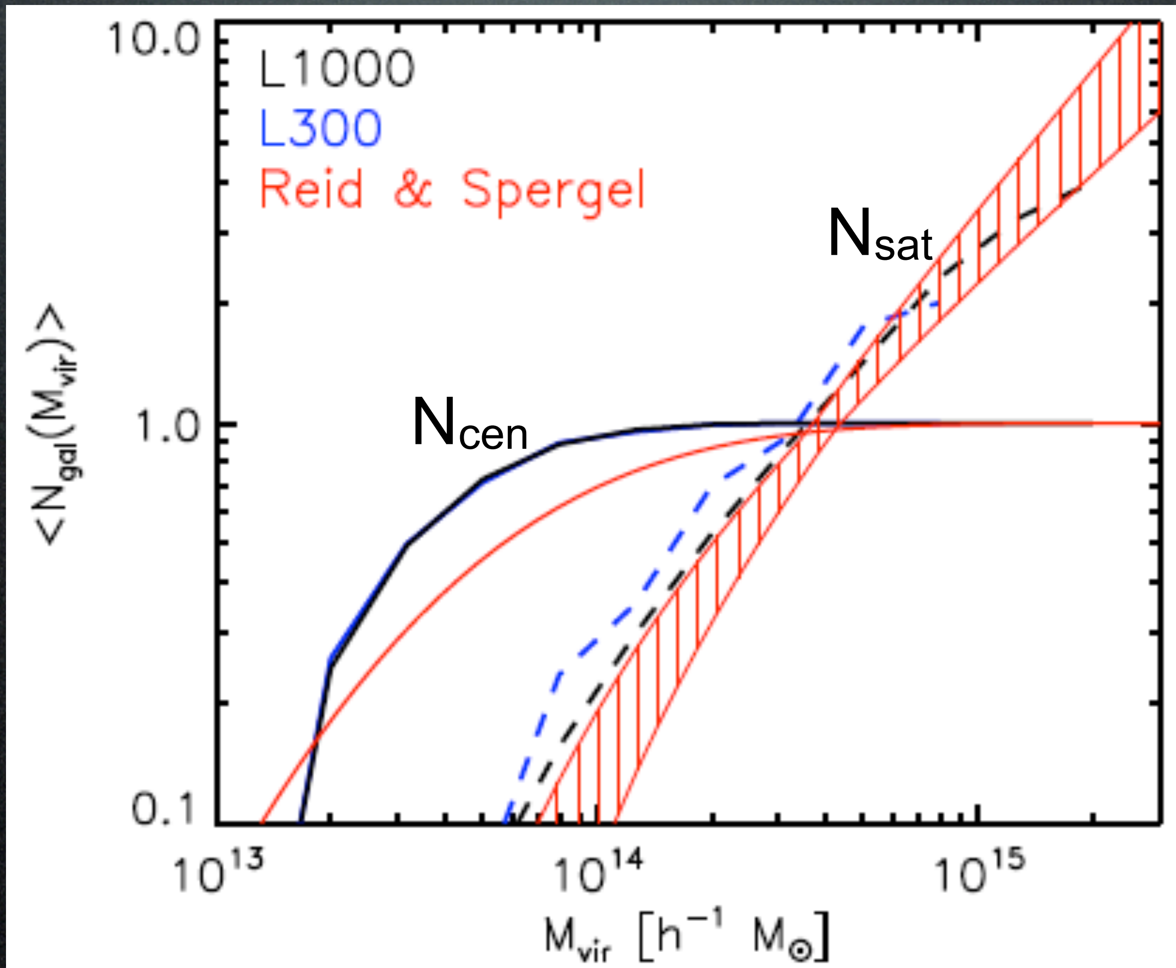






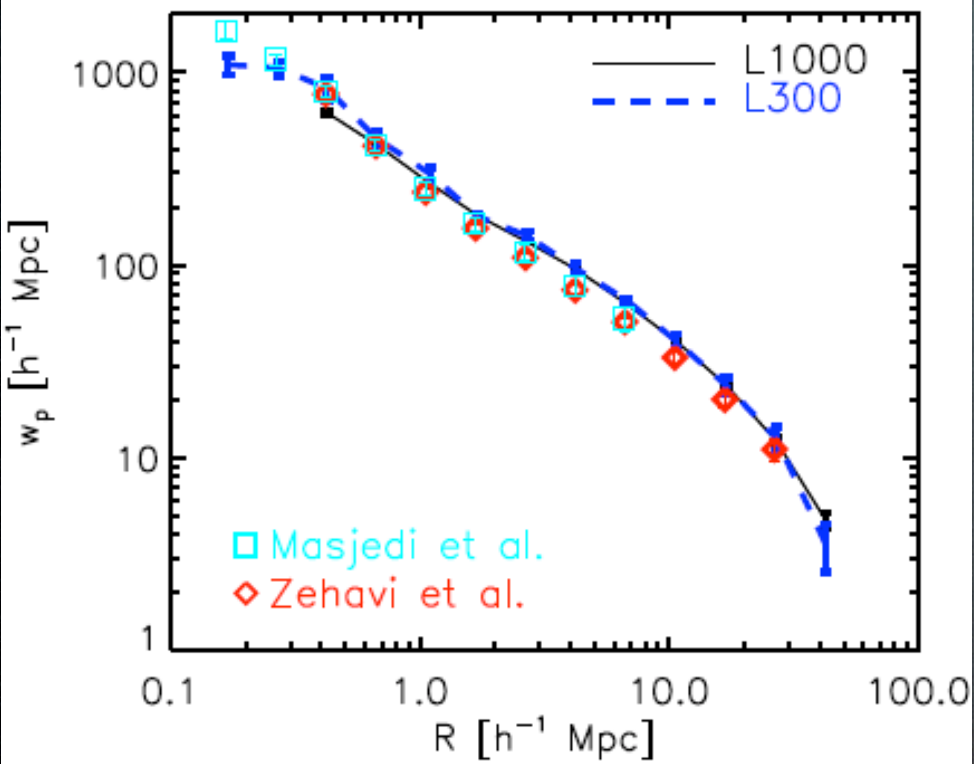
HOD of LRGs

Assumption: most massive halos at z=2 are the progenitors of LRG-host subhalos at z=0.3

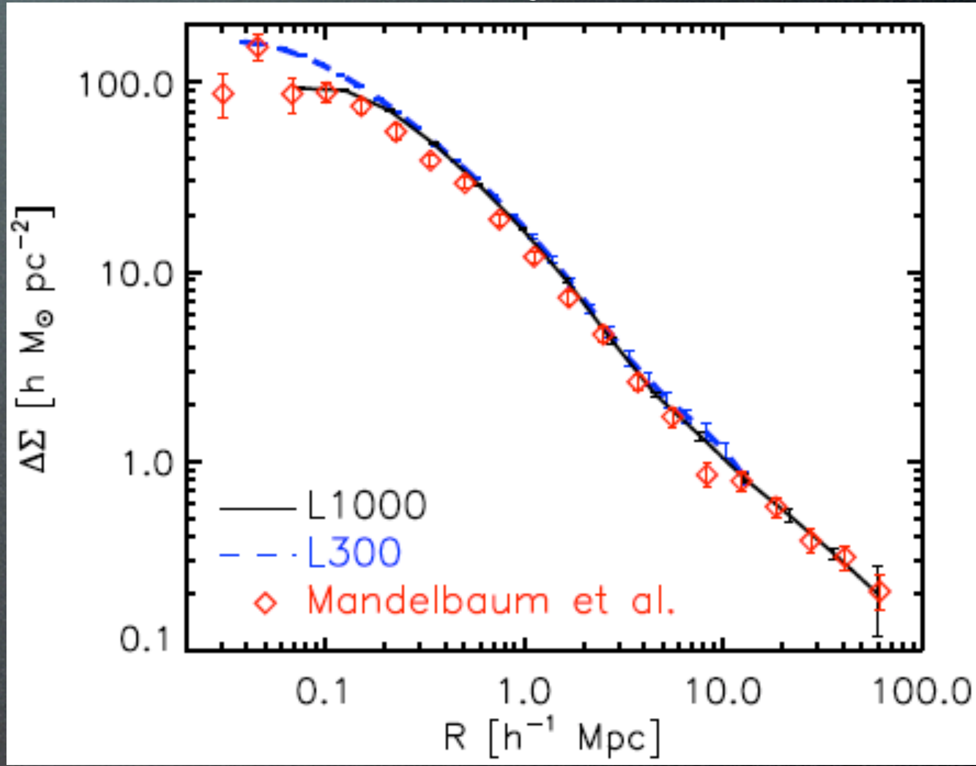


LRG clustering

Projected correlation function



Excess mass density

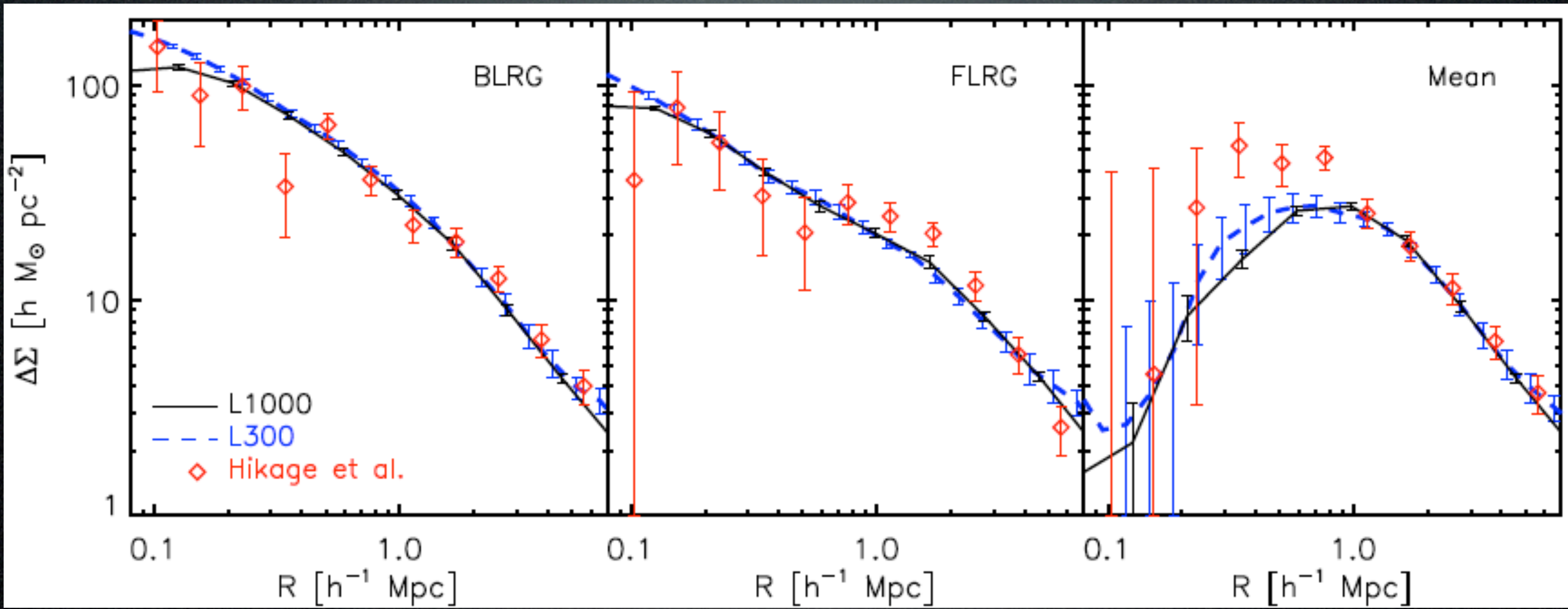


LRG-host subhalos well explain the real LRG clustering

there is no free parameter such as HOD or satellite fractions

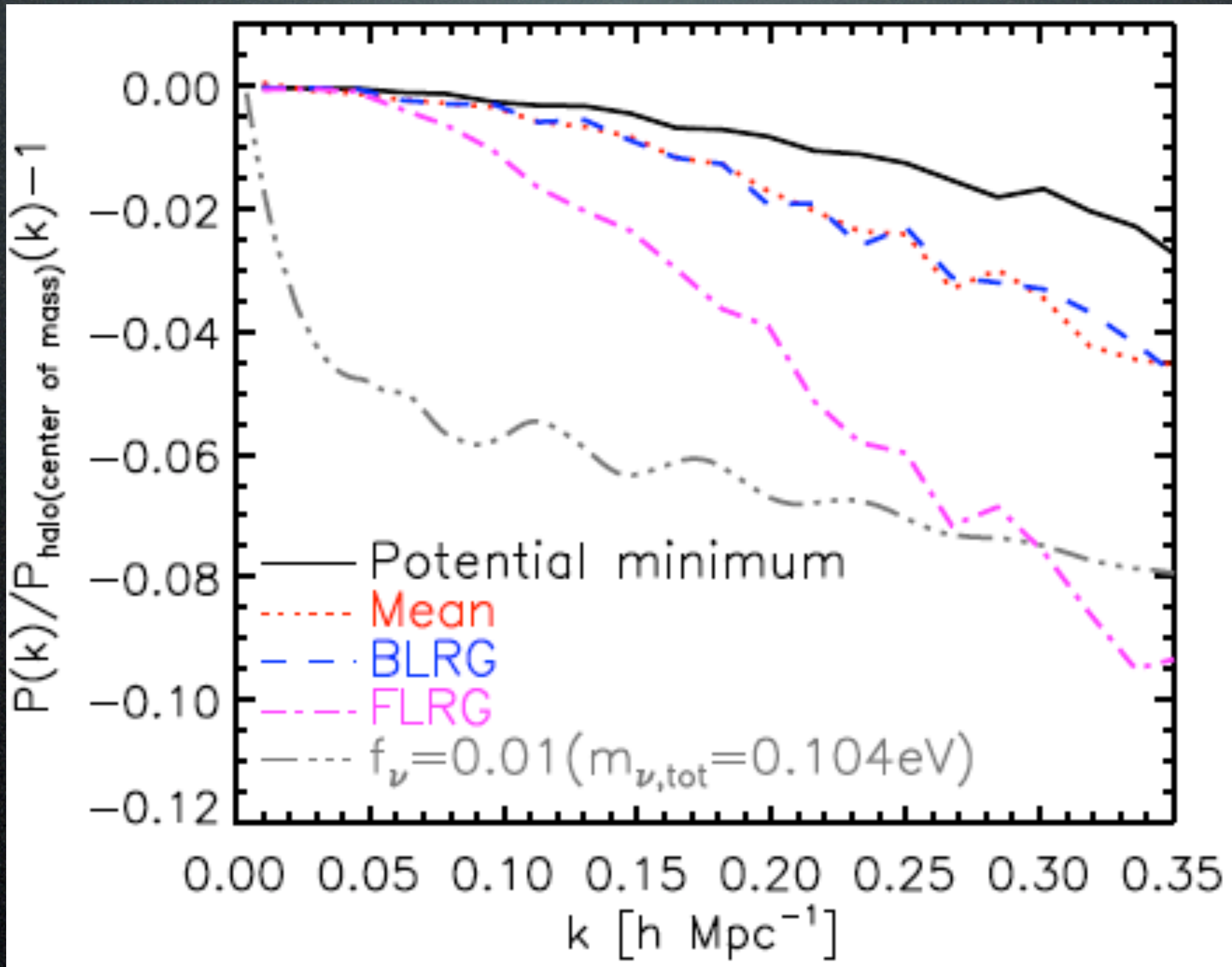
Projected mass profile for Multiple LRG systems

We determine LRG luminosity by the progenitor halo mass at z=2 (e.g., BLRG is the most massive halo at z=2)



LRG-host subhalos well explain the off-centering properties for multiple LRG systems too

Finger-of-God



Summary I

- FoG effect of off-centered LRGs challenges precise measurements of halo (matter) power spectrum
- Cross-correlation of LRGs with background galaxy image shapes or with photo-z galaxies around LRGs are sensitive to the satellite properties (satellite fraction, off-centering radius).
- We give limits on the central fraction and the typical offset scale of SDSS LRGs : q_{cen}=80% with R_{off}=0.2Mpc/h (Single LRGs); q_{cen}=60% with R_{off}=0.4Mpc/h (Multiple LRGs)
- Total FoG suppression reaches 5% at k=0.2h/Mpc and 10% at 0.3h/Mpc, which are comparable to the neutrino damping with the mass of 0.1eV
- Our method of FoG calibration significantly reduces the uncertainty of growth rate measurement and neutrino mass

Summary II

- We find that LRG clustering matches to that of subhalos whose progenitors are the most massive halos at z~2 (SFR peak).
- Successful abundance matching enables us study the merging history of LRG progenitor halos, the relation between LRGs and matter, assembly bias, FoG, etc.
- This is also useful for making more realistic mock LRG samples for SDSS/BOSS from N-body simulations