Using Galaxy-Galaxy Lensing as a Tool to Correct Finger-of-God

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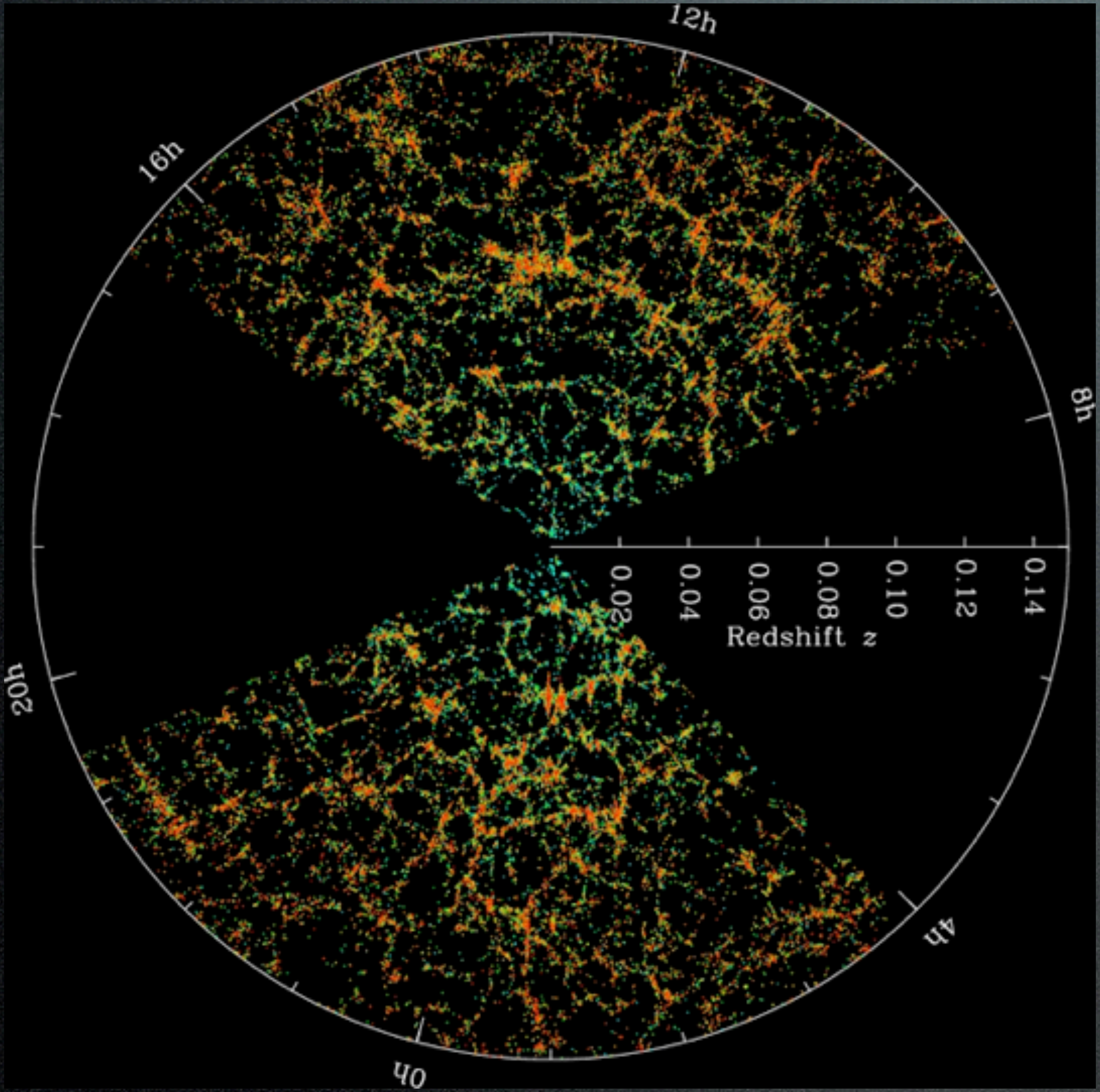
Large-Scale Structure traced by galaxies



SDSS Collaboration

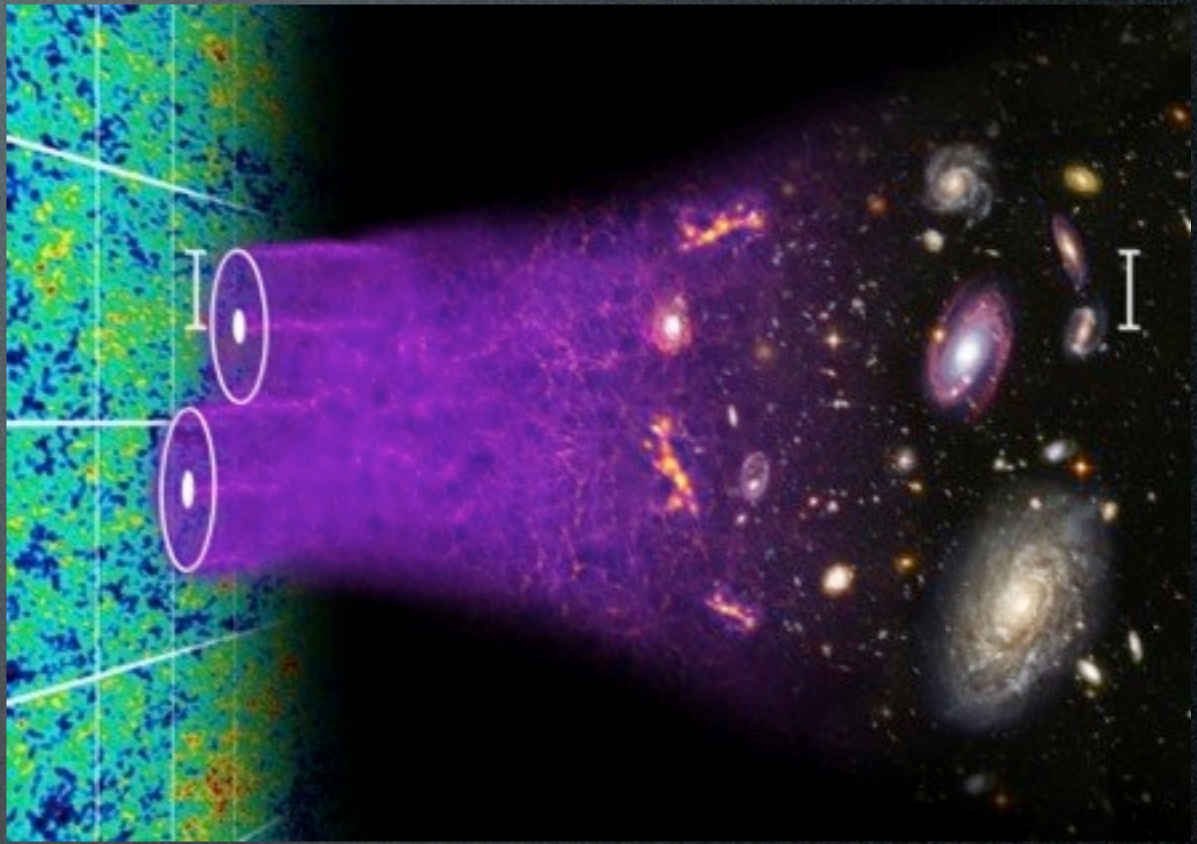
Scientific Goals

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

Galaxy redshift surveys

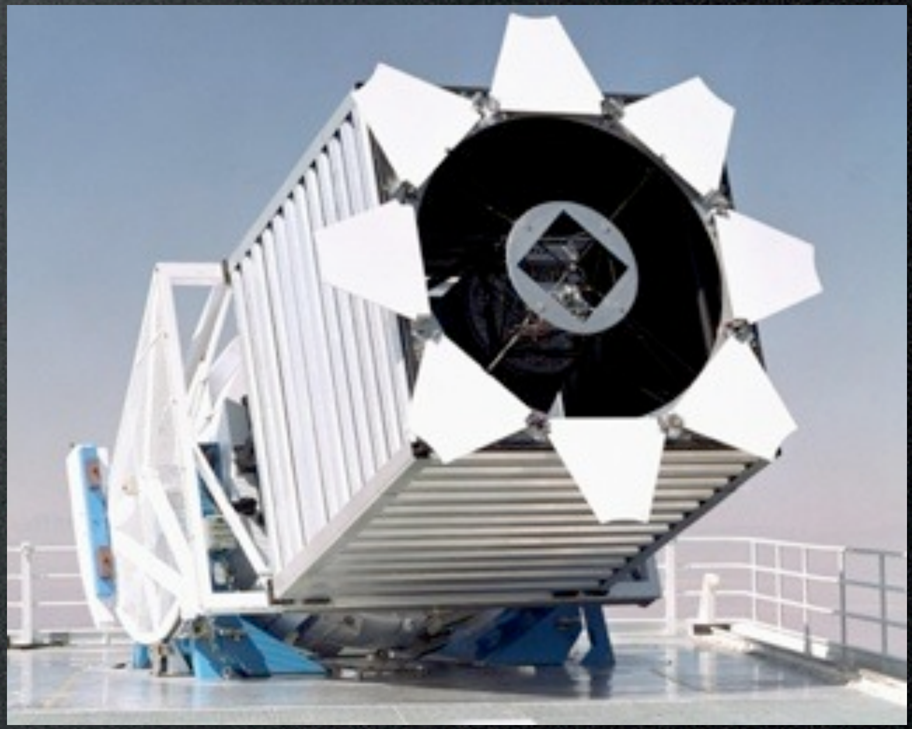
- 2dF, SDSS
- BOSS, WiggleZ, VVDS, Vipers, FMOS
- Subaru, HETDEX, BigBOSS, Euclid, WFIRST

SDSS III BOSS survey(2009-2014)



Goal
distance measurements using BAO with 1% ($z=0.35$ and 0.6) and 1.5% ($z=2.5$) precisions

Target
1,500,000 LRGs ($0.2<z<0.8$)
160,000 QSOs ($2.2<z<3$)
over 10,000 deg^2 of sky

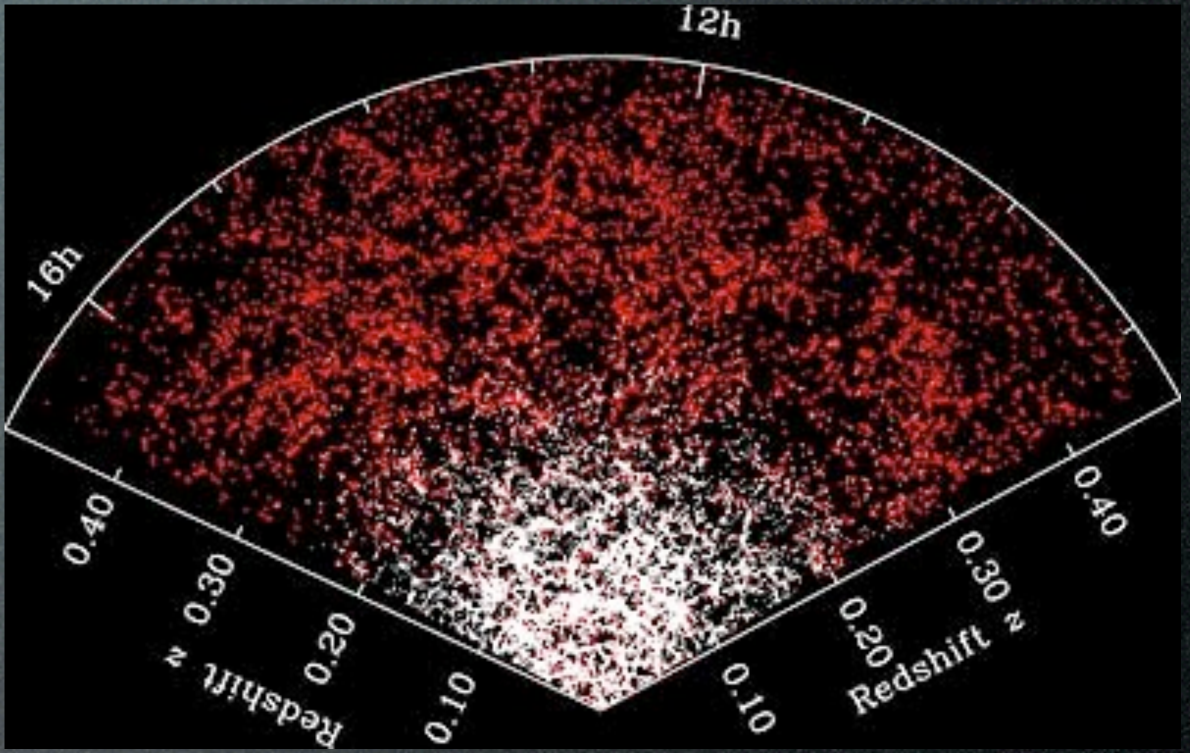


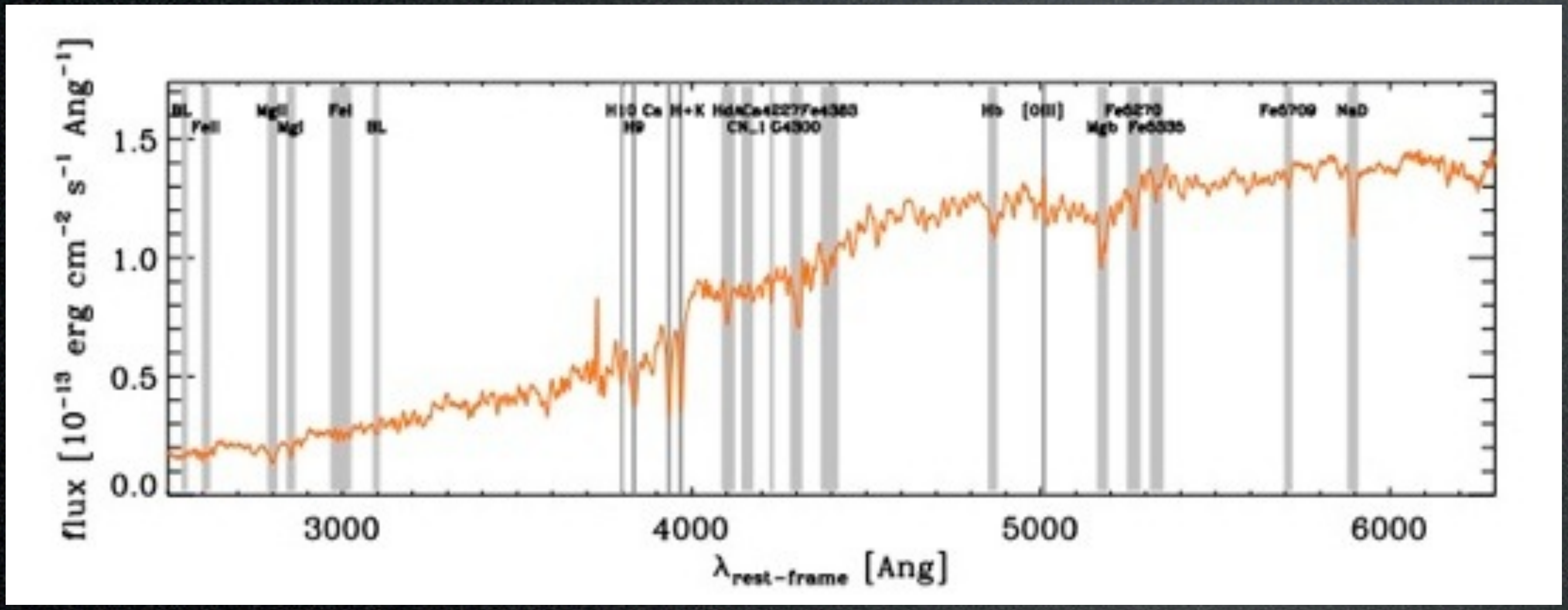
Instruments
SDSS 2.5m telescope at Apache Point observatory (2788m, 1.2”seeing)
Camera: 30 2kx2k CCDs with 5 filters (*r,i,u,z,g*), 6deg^2 FOV
Spectrographs: 1000 fibers (2” diameter), R~2000, 360-1000nm

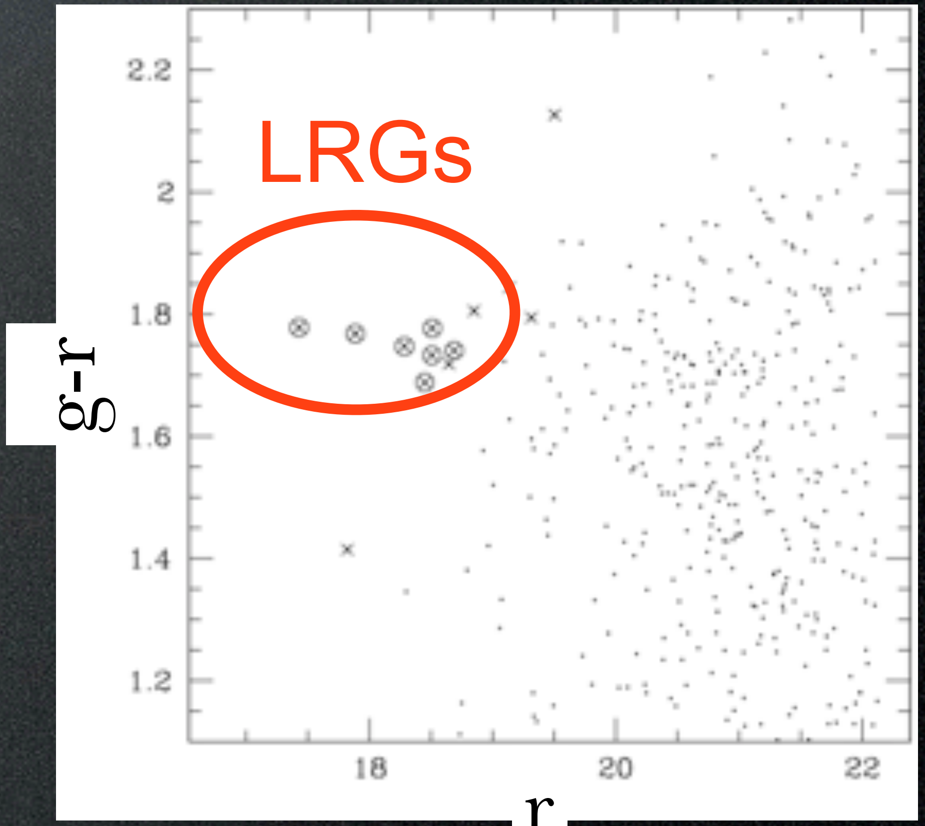
Luminous Red Galaxies (LRGs)

Main target of SDSS, BOSS

- Luminous: wide coverage of redshift range
- Red: old stellar populations host subhalos are massive

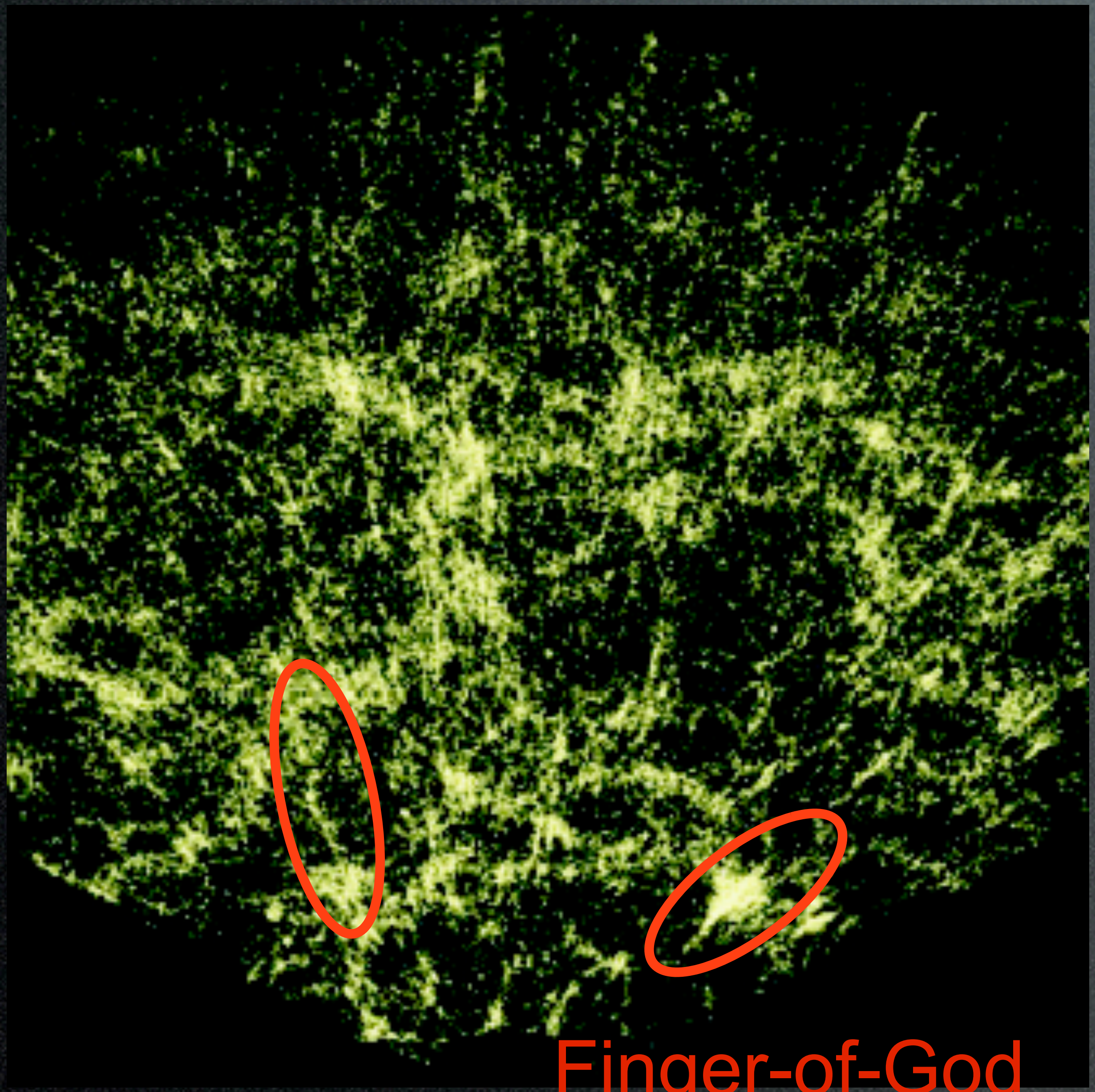




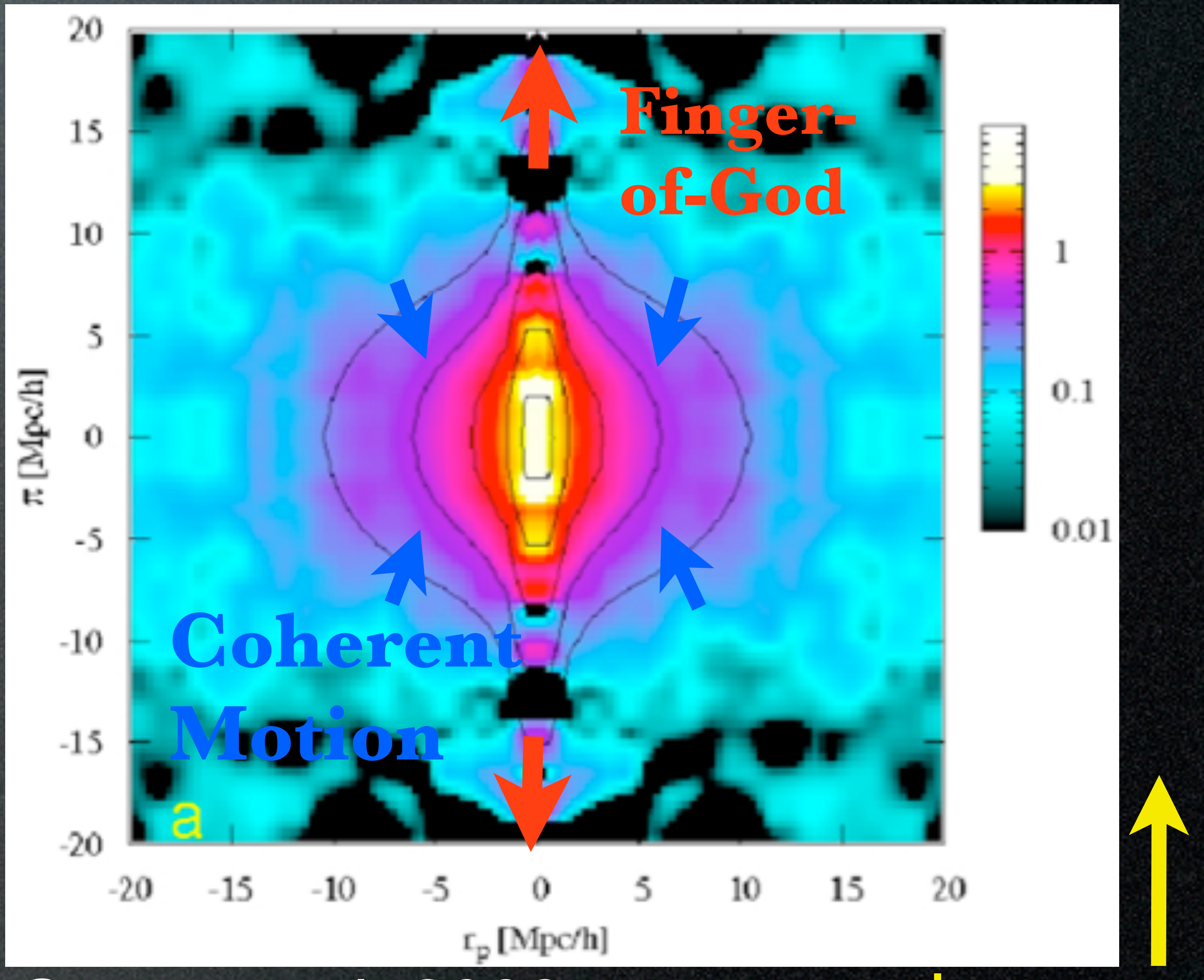


Finger-of-God: Nonlinear Redshift-Space Distortion

Peculiar motions of galaxies distort observed galaxy distribution. FoG effect is a major systematic uncertainty in knowing matter distribution from observed galaxy distribution



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

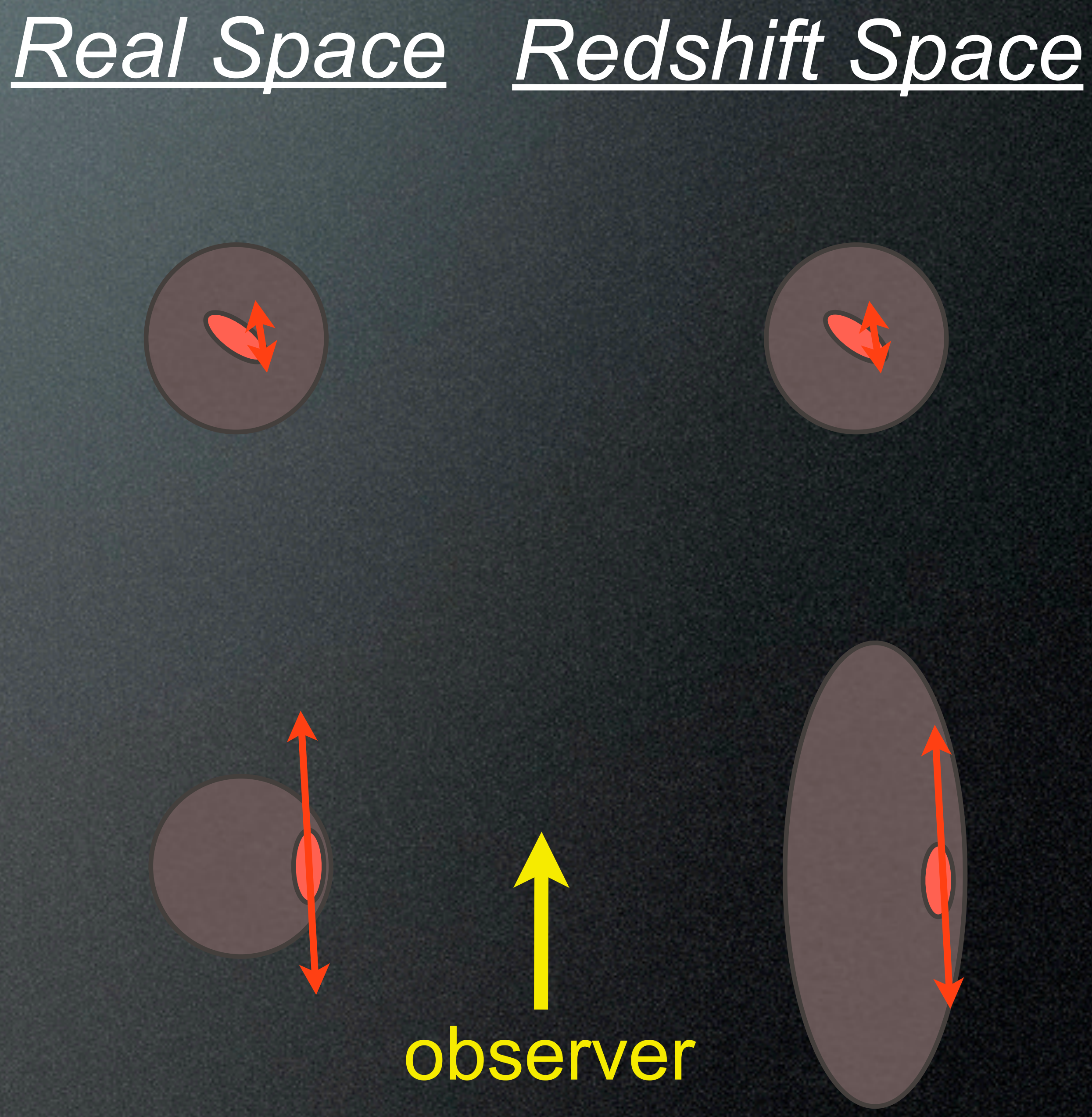


Guzzo et al. 2008

What produces FoG effect ?

<u>Central LRGs</u> locate on the potential minimum and then their internal motion within halos should be small

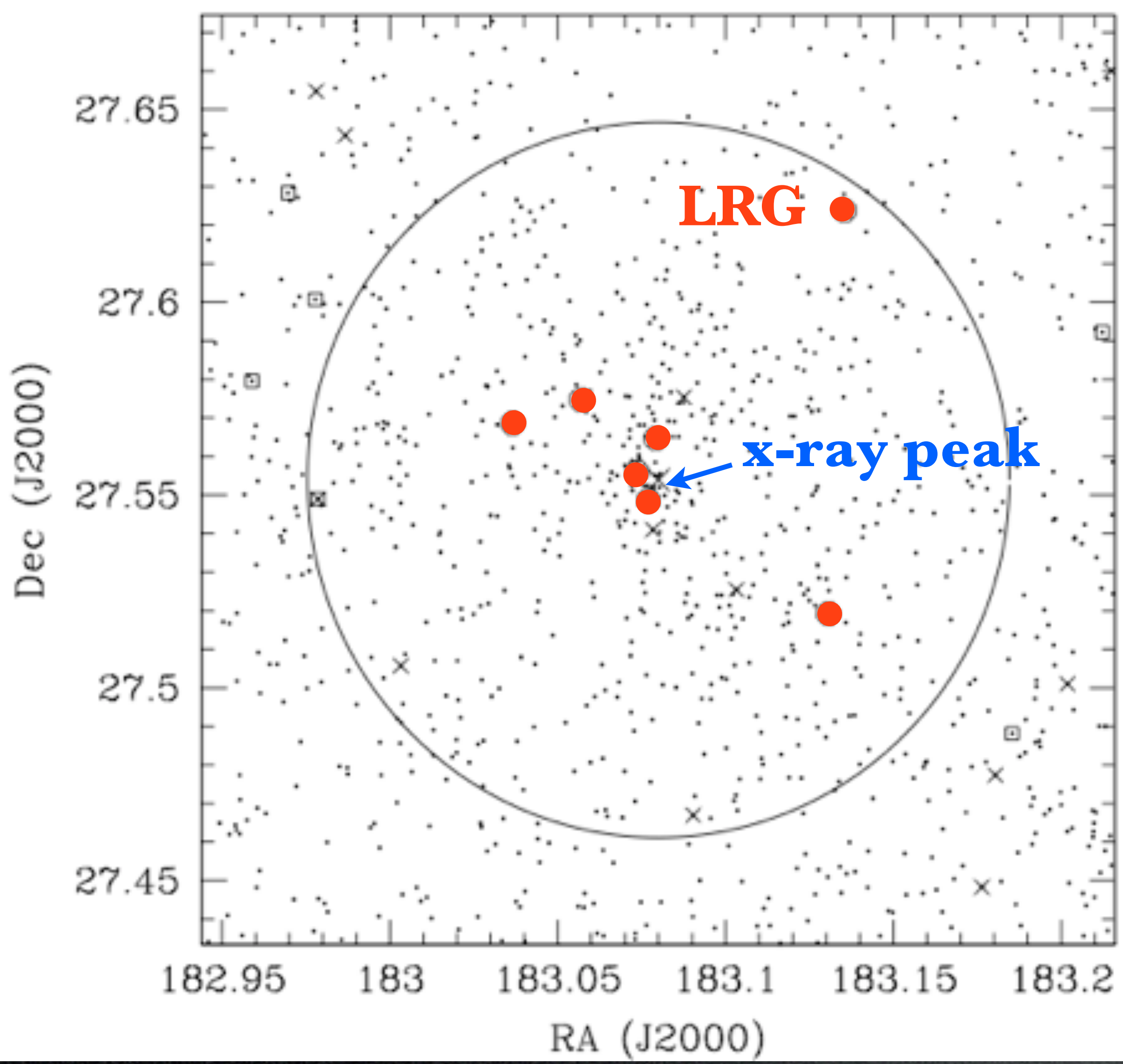
<u>Satellite (off-centered) LRGs</u> can have large internal motion (e.g., recent merger)

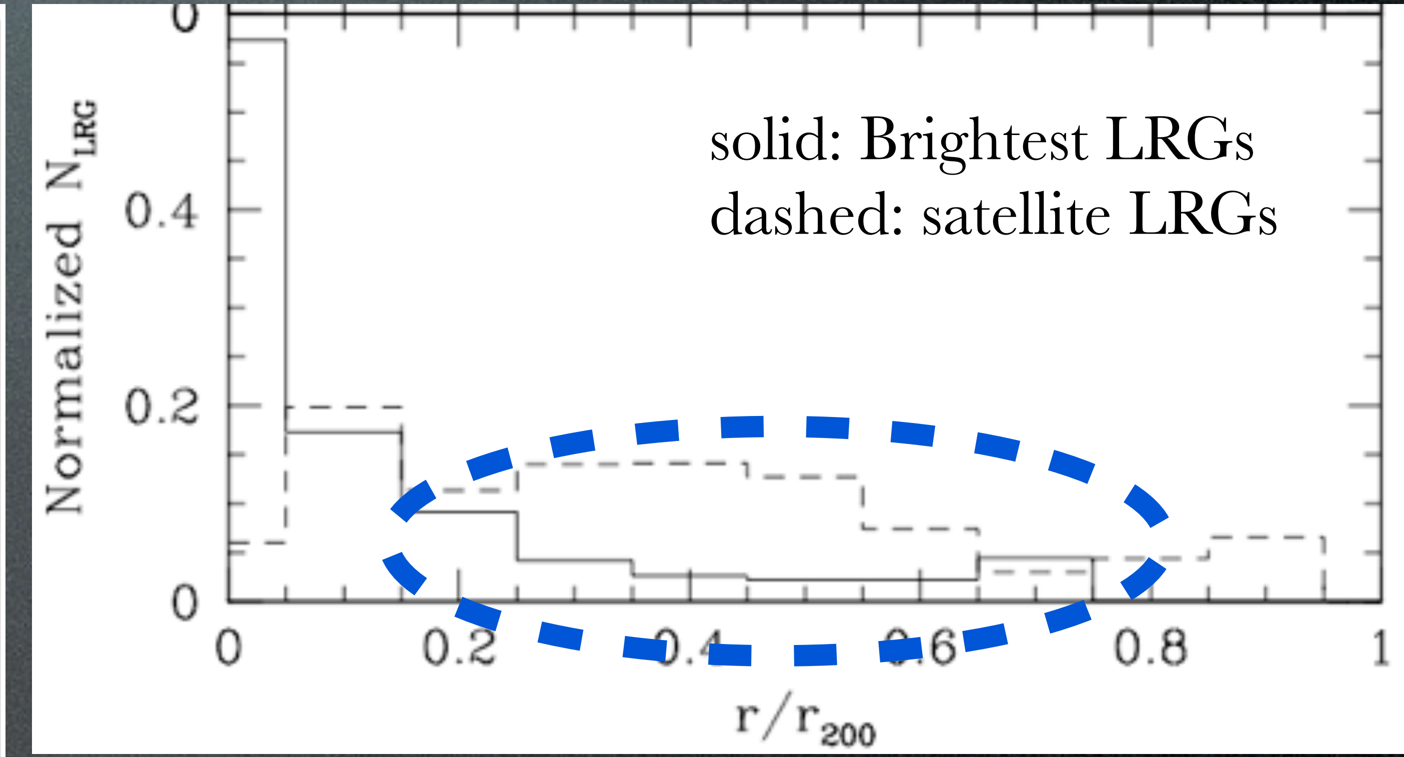


FoG effect is sensitive to satellite fraction of LRGs

LRGs locate at halo mass center ?
Offset from X-ray peak

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





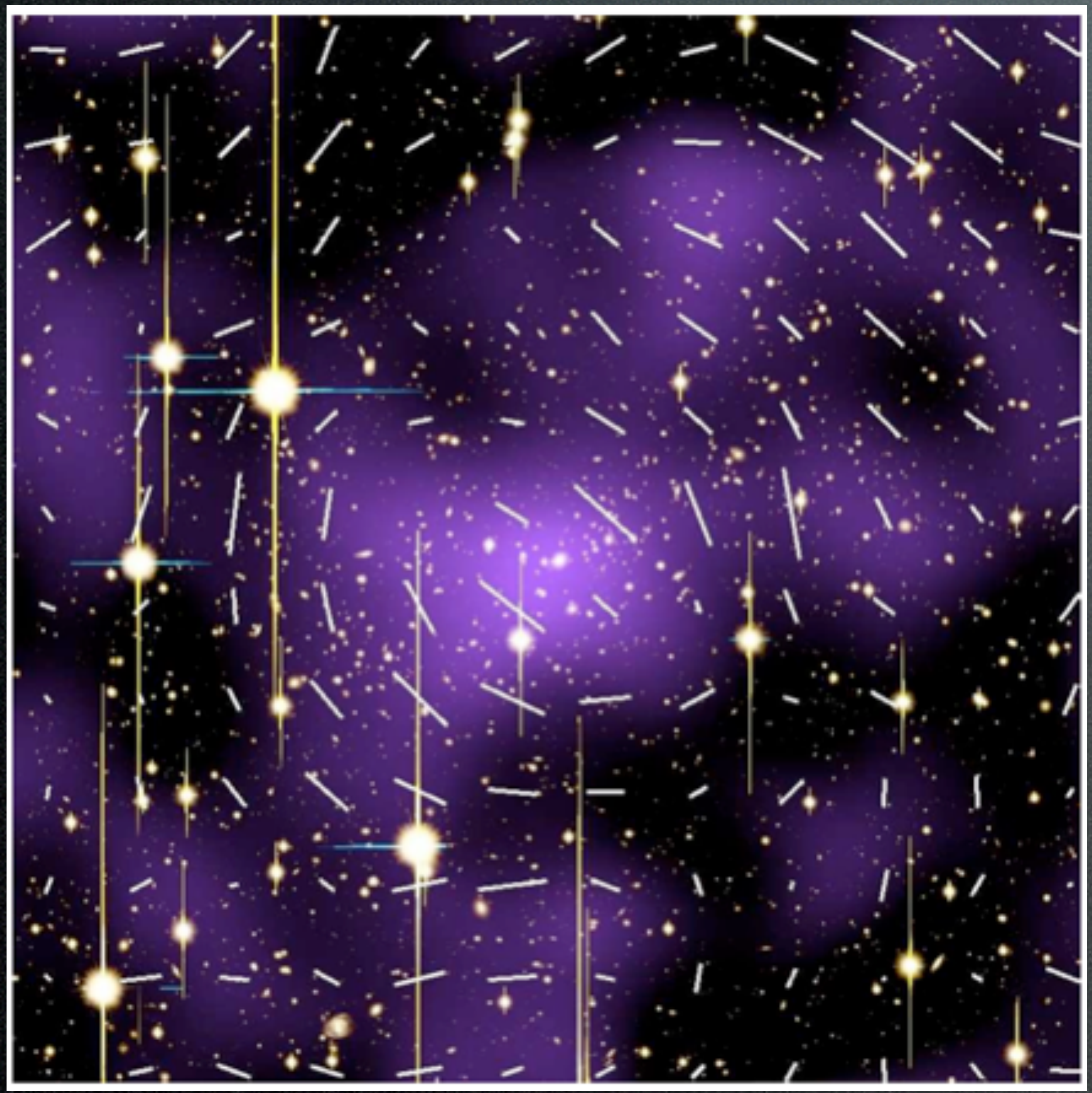
20% of Brightest LRGs have offset from X-ray peak

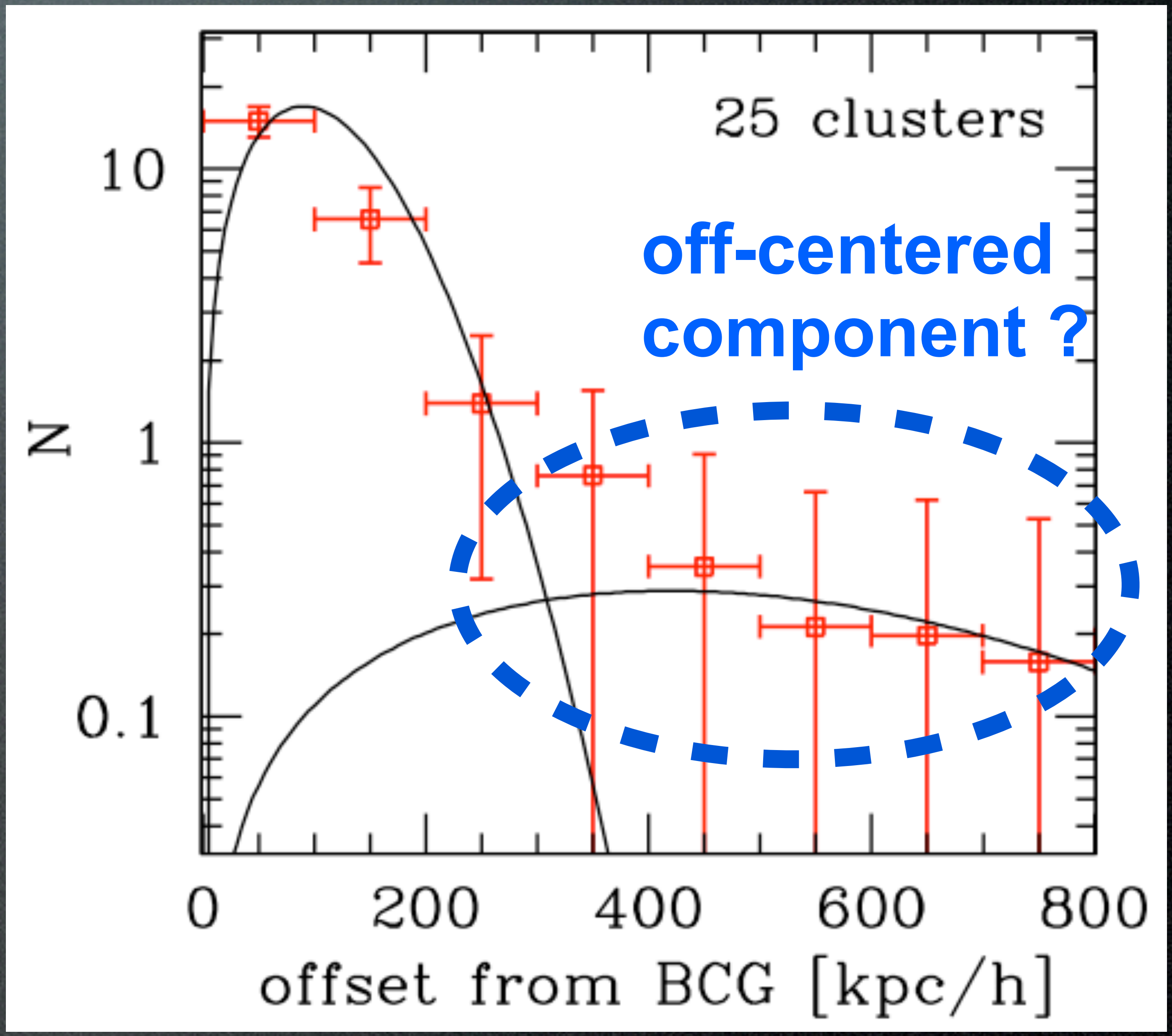
Most massive clusters

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

Offset from lensing mass center

Weak lensing analysis of 25 X-ray luminous clusters (Oguri et al. 2010)

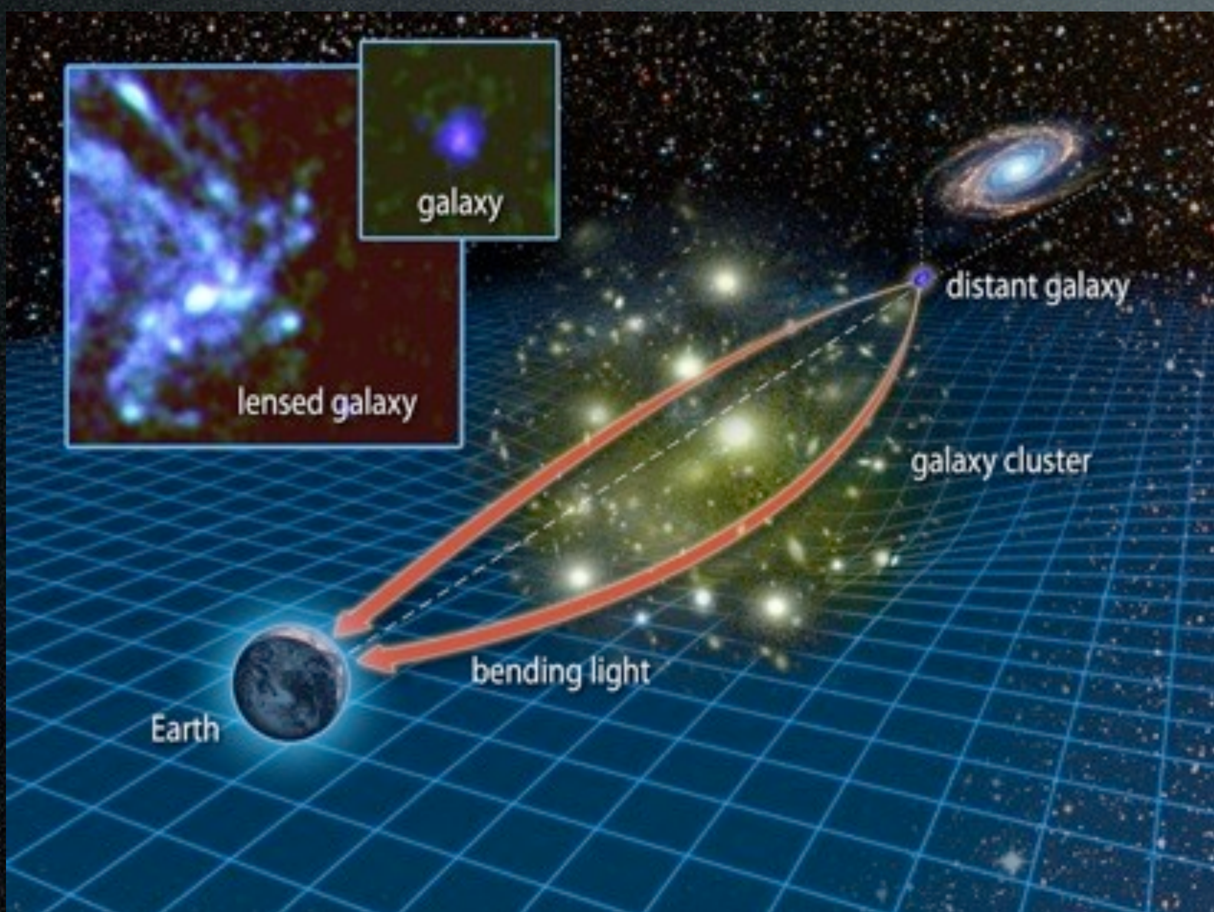




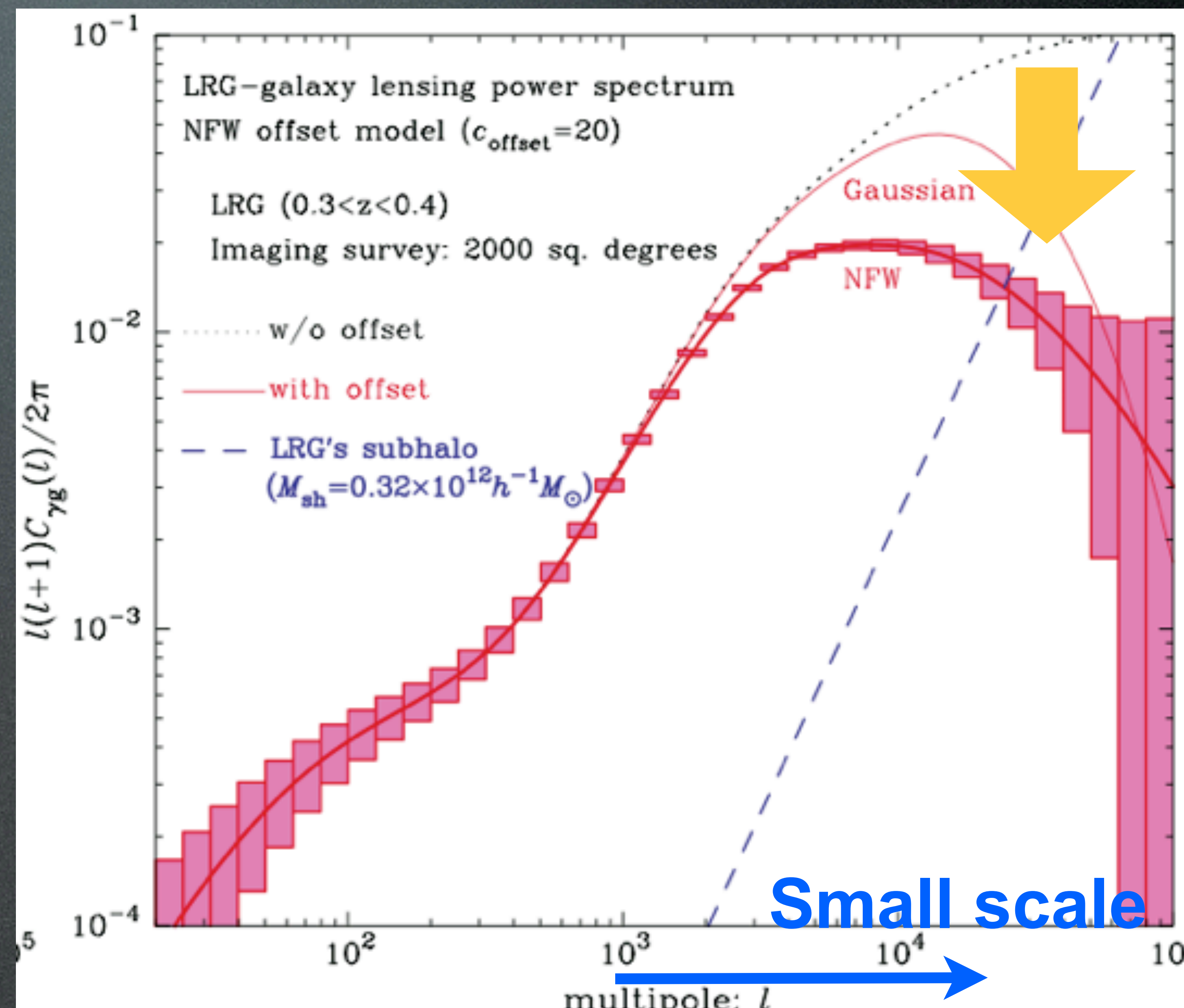
Lensing also suggests a off-centered component from mass center

Off-centering effect on LRG-galaxy lensing

Smearing due to off-centered LRGs



Credit: Karen Teramura, U Hawai IfA



LRG-galaxy lensing provides the off-centering profile information

Modeling of LRG-galaxy lensing

Projected mass profile around LRGs as a function of projected radius R[Mpc/h]

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

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

Single halo mass approximation

$$C_{\Sigma g}^{1h}(k) \simeq \left[\bar{M}\tilde{u}_{\rm NFW}(k;\bar{M},z_{\rm LRG})\,\tilde{p}_{\rm off}(k;\bar{M}) + m_{\rm sh,LRG}\right]$$

$$C_{\Sigma g}^{2h}(k) \simeq b(\bar{M})\bar{\rho}_{m0} P_m^L(k;z)\,.$$

sub-halo term

bias

LRG distribution within halos (Center + Gaussian Offset)

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

Fraction of central LRGs

Gaussian offset scale

Fitting result of LRG-Galaxy Lensing

SDSS DR7 LRG catalog
(Kazin et al. 2010)
92046 LRGs ($-23.2<M_g<-21.2$)
$0.16<z<0.47$, $1.58(\mathrm{Gpc}/h)^3$

Projected mass density

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

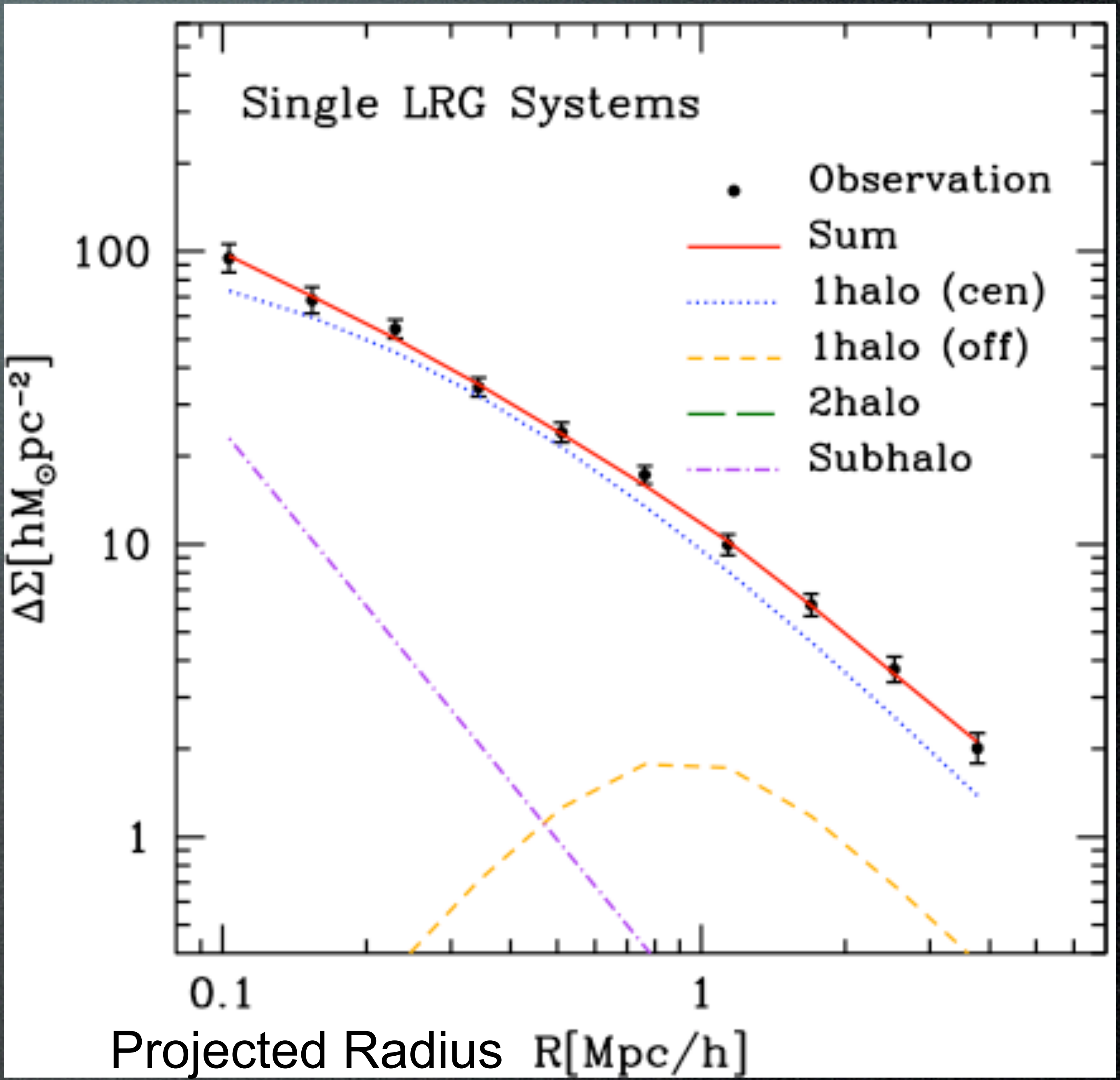
Inverse variance weight

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

(Mandelbaum et al. 2012)

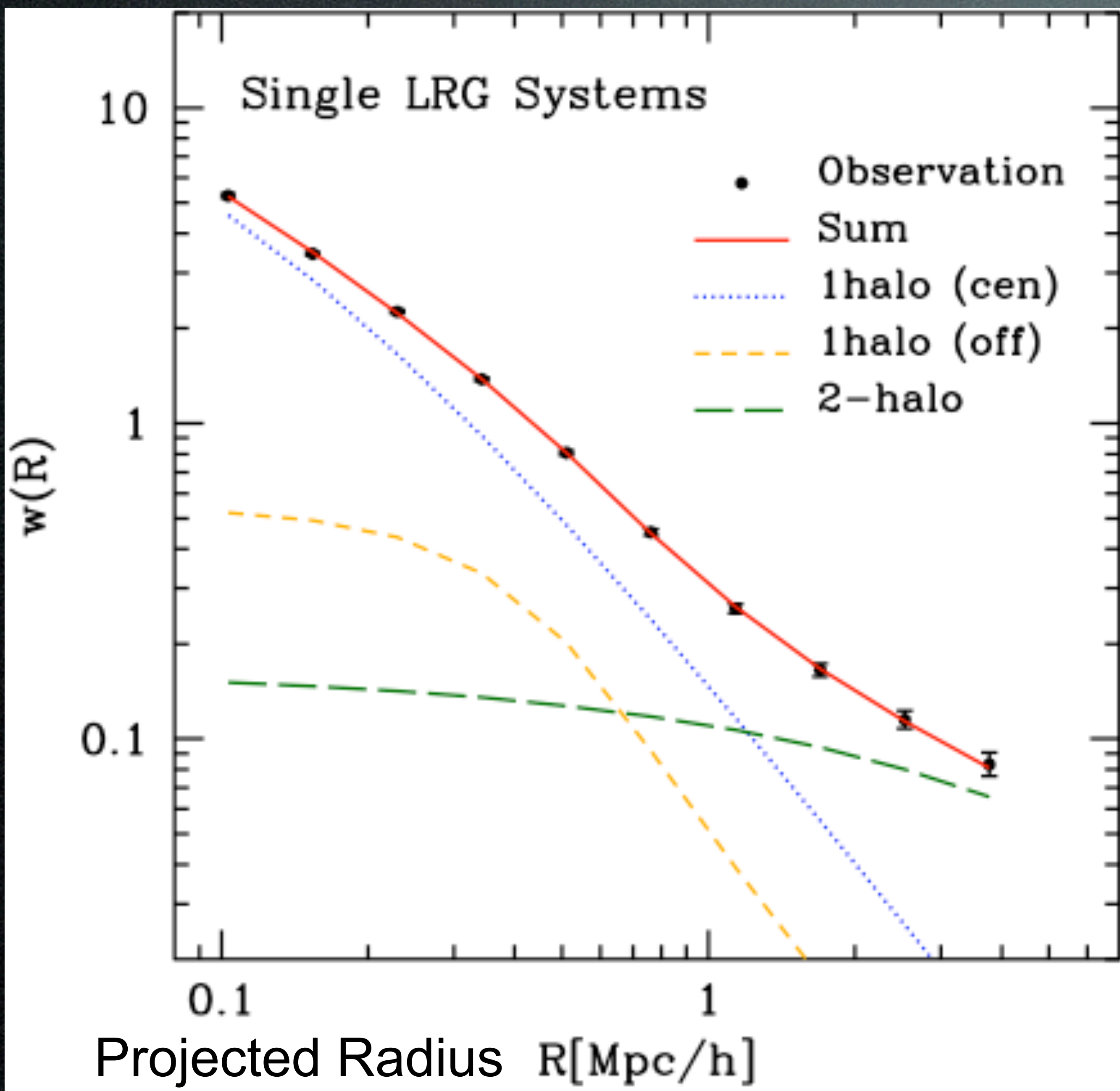
1.2 galaxies per arcmin^2

$z_{\rm photo} > z_{\rm LRG}$



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

2. Cross Correlation of LRGs with photo-z red galaxies



Halo infered from LRGs

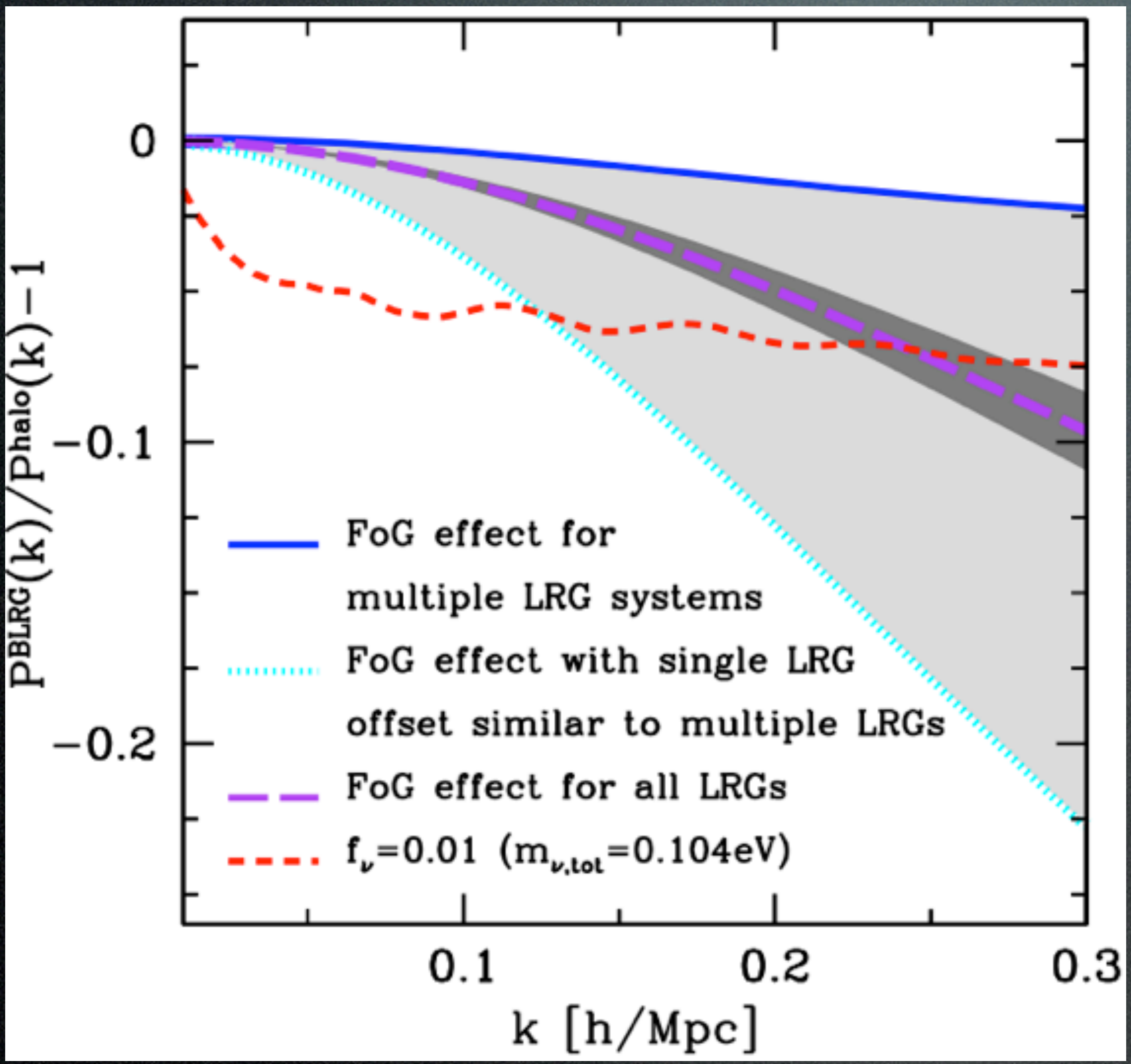
$$w^{\rm cross}(R) = \frac{\sum HG(z_{\rm ll} \leqslant z_H \leqslant z_{\rm ul})}{\sum RG(z_{\rm ll} \leqslant z_R \leqslant z_{\rm ul})} - 1$$

Random   photo-z galaxies

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

Measurement	$q_{\rm cen}^{\rm BLRG}$ [%]	$R_{\rm off}^{\rm BLRG}$ [Mpc/h]
$w(R)$	77 ± 6	0.26 ± 0.03

Finger-of-God for SDSS LRGs



$$P^{\rm LRG}(k,\mu) = P^{\rm halo}(k,\mu) \left[q_{\rm cen} + (1-q_{\rm cen})\sqrt{F(k,\mu)}\right]^2$$

FoG function

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

Velocity dispersion of satellite (off-centered) LRGs

$$\sigma^2_{{\rm off},v} = \frac{GM(<R_{\rm off})}{2R_{\rm off}}$$

FoG suppression reaches 5% (k=0.2h/Mpc) and 10% (k=0.3h/Mpc)

FoG suppression of all LRGs is comparable to the free-streaming damping due to neutrinos with $m_{\nu,tot}$=0.104eV

SUbaru Measurement of Images and REdshift (SUMIRE)

Joint Mission of Imaging and Redshift surveys using 8.2m Subaru Telescope

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

Hyper-Suprime Cam (HSC)

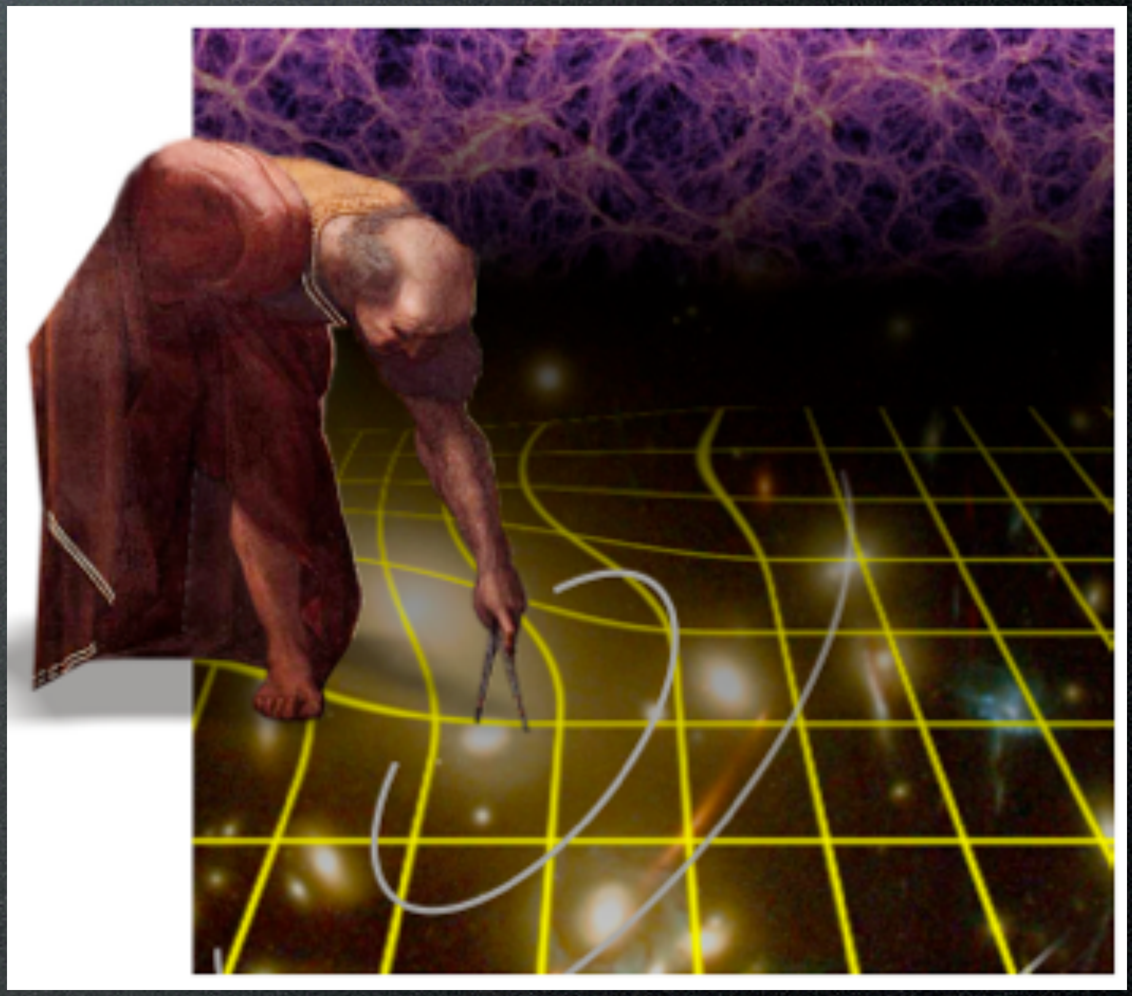
- 1400 deg^2 sky (overlap w ACT, BOSS)
- 30gals/$arcmin^2$, z_{mean}=1, i~26(5σ)
- 1.5 deg FoV, grizy band, 0.16"pix,
- 2013-2017

Prime Focus Spectrograph (PFS)

- 1400 deg^2 of sky (overlap with HSC)
- Redshift of LRGs + OII emitters at 0.8<z<2.4 (9.3 Gpc/h^3 comoving vol)
- 2400 fibers, 380--1300nm
- 2018-2023 (planed)

Euclid

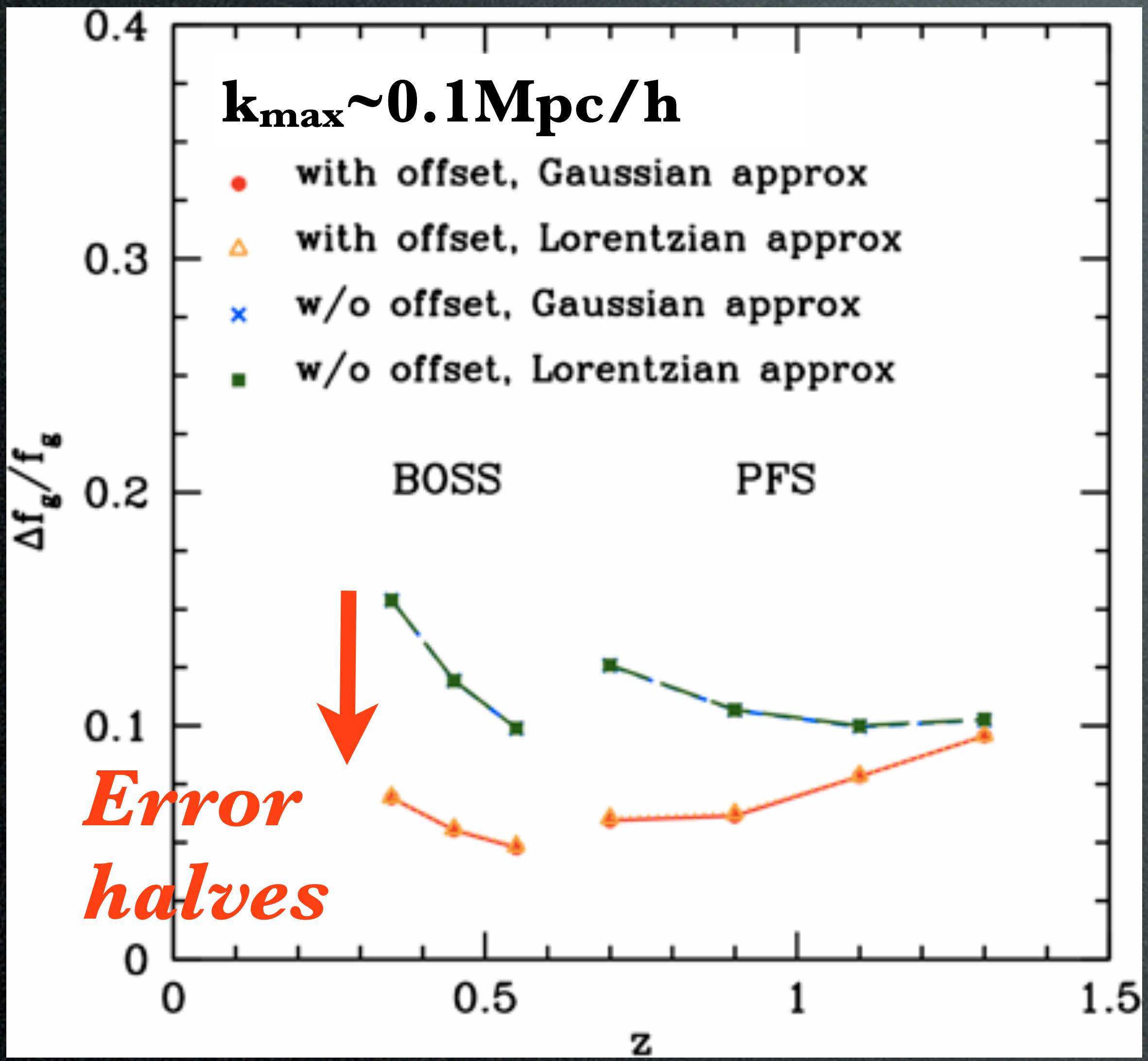
- ESA M-class mission
- Dark energy probe via weak lensing & BAO
- Imaging 20,000 deg^2 sky, 40gals/arcmin^2
- Spectrum of 70M Hα emitters at $0.5<z<2$
- 1.2m telescope
- FOV 0.5deg^2, rizYJH band (550--1800nm), 0.2-0.3" pixel size
- Spectrograph: 1-2μm, R=500
- 2020-2025 (planed)

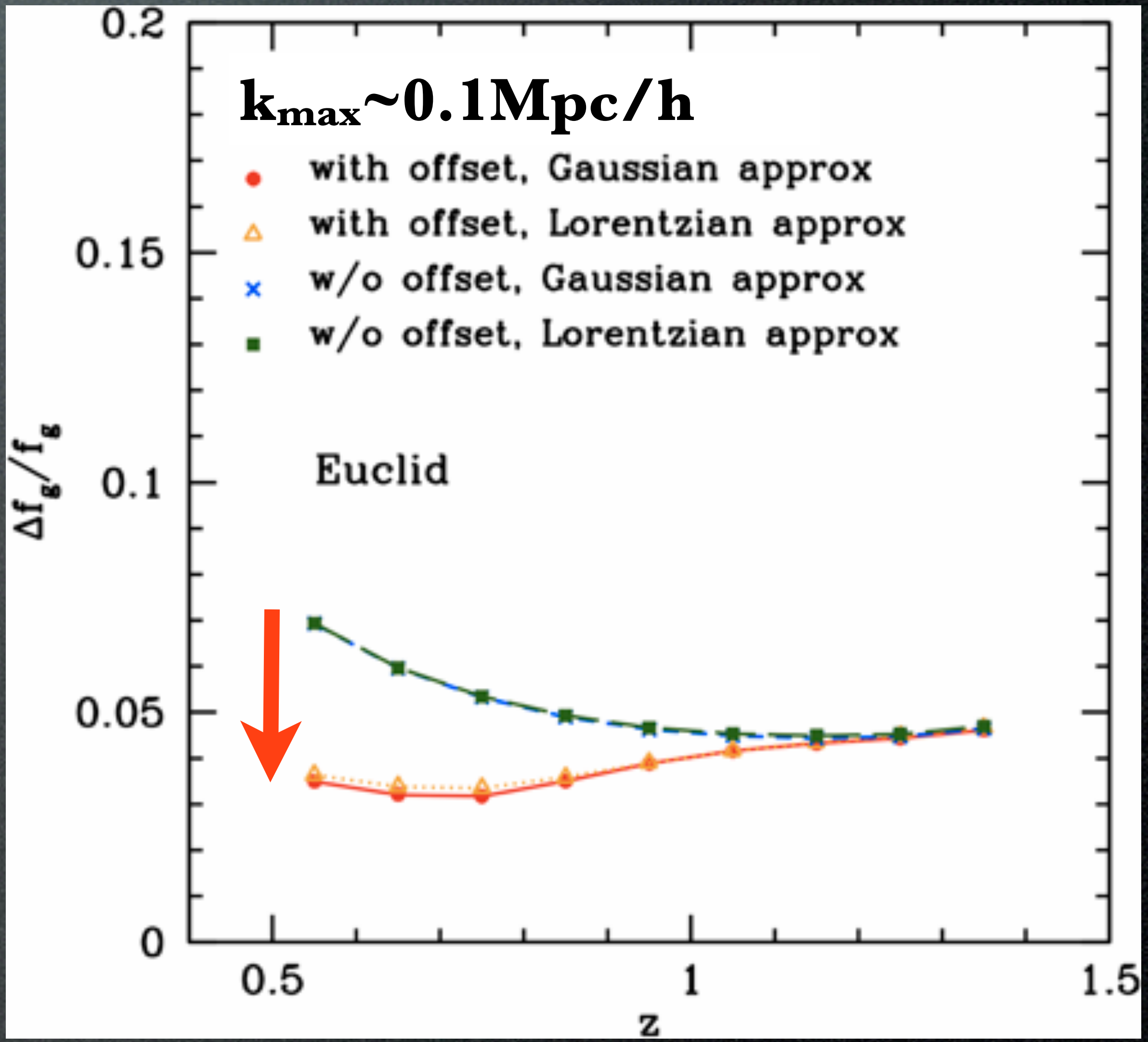


Impact on Growth Rate Measurement

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

Relative error of growth rate





Neutrino mass fraction f_ν and dark energy parameter w_0

LRG lensing also improve measurements of f_ν and w_0 upto 25%

Marginalized Error and Bias of Neutrino Mass (f_ν)

Survey	k_{max}	w/o offset			with offset		
		$\sigma(f_\nu)$	δf_ν(Gauss)	δf_ν(Lorentz)	$\sigma(f_\nu)$	δf_ν(Gauss)	δf_ν(Lorentz)
BOSS	0.1h/Mpc	0.0075	0.0001	−0.0002	0.0056 (25%)	−0.0010	0.0016
	0.2h/Mpc	0.0048	0.0025	−0.0034	0.0044 (9%)	−0.0014	0.0021
PFS	0.1h/Mpc	0.0057	0.0006	−0.0011	0.0051 (11%)	−0.0003	0.0005
	0.2h/Mpc	0.0043	0.0028	−0.0048	0.0042 (2%)	−0.0015	0.0027

f_ν=0.01 corresponds to $m_{\nu\,tot}$=0.104eV

Marginalized Error and Bias of w_0

Survey	k_{max}	w/o offset			with offset		
		$\sigma(w_0)$	δw_0(Gauss)	δw_0(Lorentz)	$\sigma(w_0)$	δw_0(Gauss)	δw_0(Lorentz)
BOSS	0.1h/Mpc	0.035	0	0	0.028 (22%)	−0.005	0.008
	0.2h/Mpc	0.025	0.009	−0.012	0.021 (14%)	−0.014	0.021
PFS	0.1h/Mpc	0.033	0.001	−0.003	0.030 (9%)	−0.003	0.005
	0.2h/Mpc	0.027	0.009	−0.016	0.026 (4%)	0	0

error improvement

Summary

- FoG effect of satellite LRGs challenges precise measurements of halo (matter) power spectrum especially at small scale
- Galaxy lensing and cross-correlation with photo-z galaxies around LRGs are also sensitive to their off-centering properties.
- We give limits on the satellite fraction of SDSS LRGs and their typical offset scale : q_{cen}=80% with R_{off}=0.2Mpc/h (Single LRGs); q_{cen}=60% with R_{off}=0.4Mpc/h (Multiple LRGs)
- Estimated FoG effect of all LRGs reach 5% at k<0.2h/Mpc and 10% at 0.3h/Mpc, which are comparable to the neutrino damping with m=0.1eV
- Our method reduces the uncertainty of growth rate measurement and neutrino mass for current/upcoming imaging and spectroscopic joint surveys