Studying dark matter halo structure with galaxy-galaxy lensing

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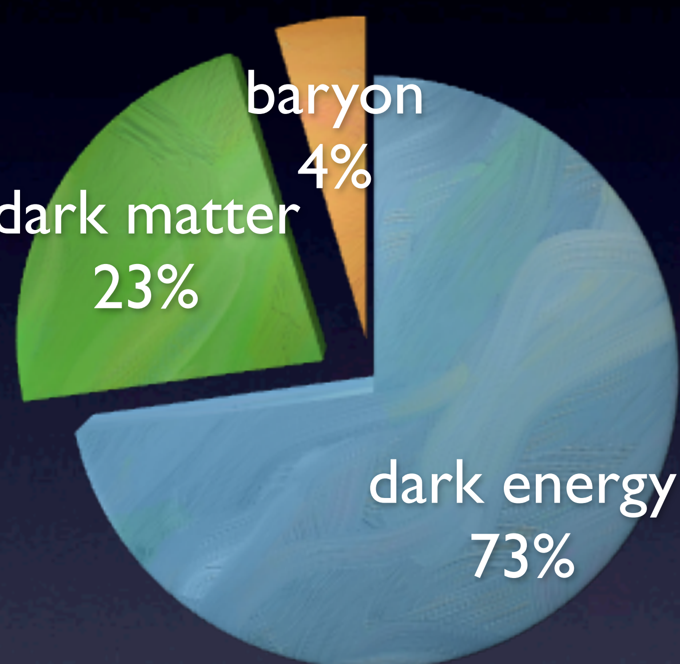
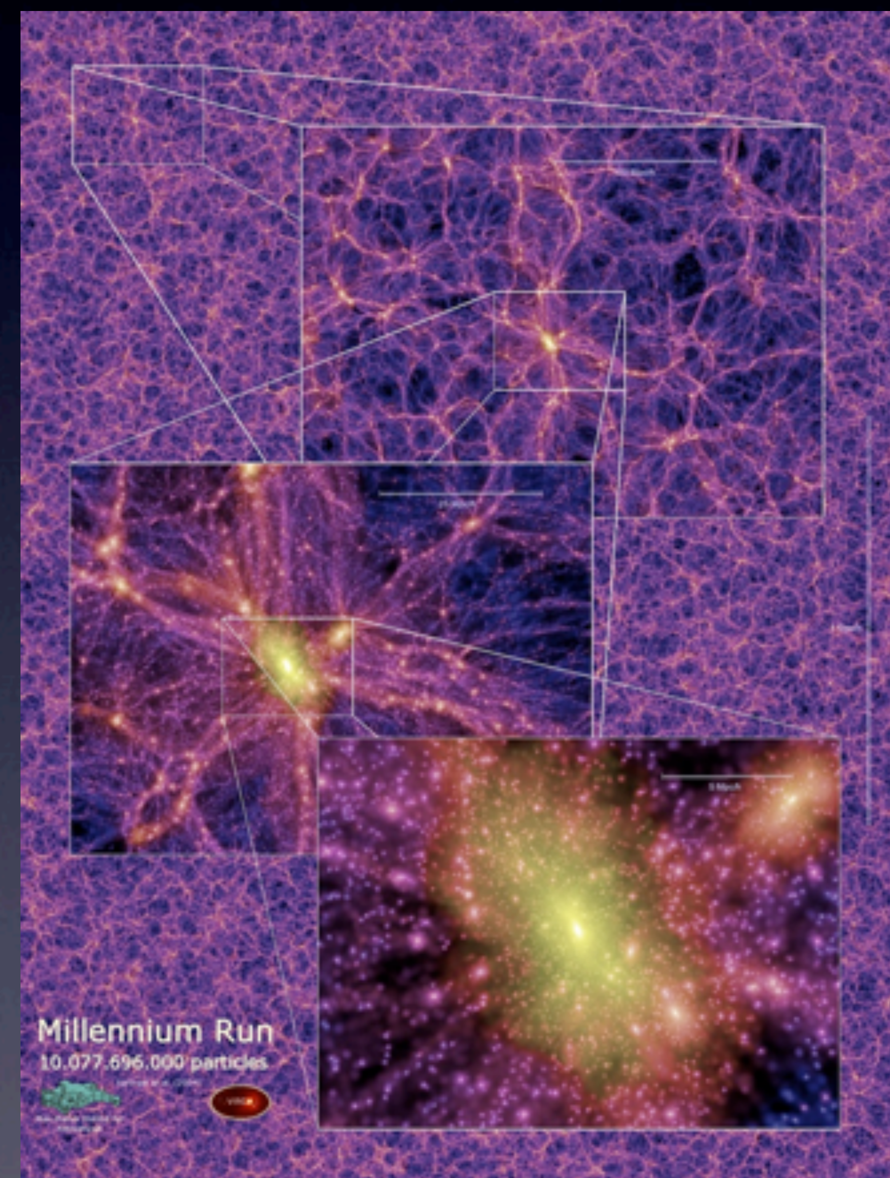
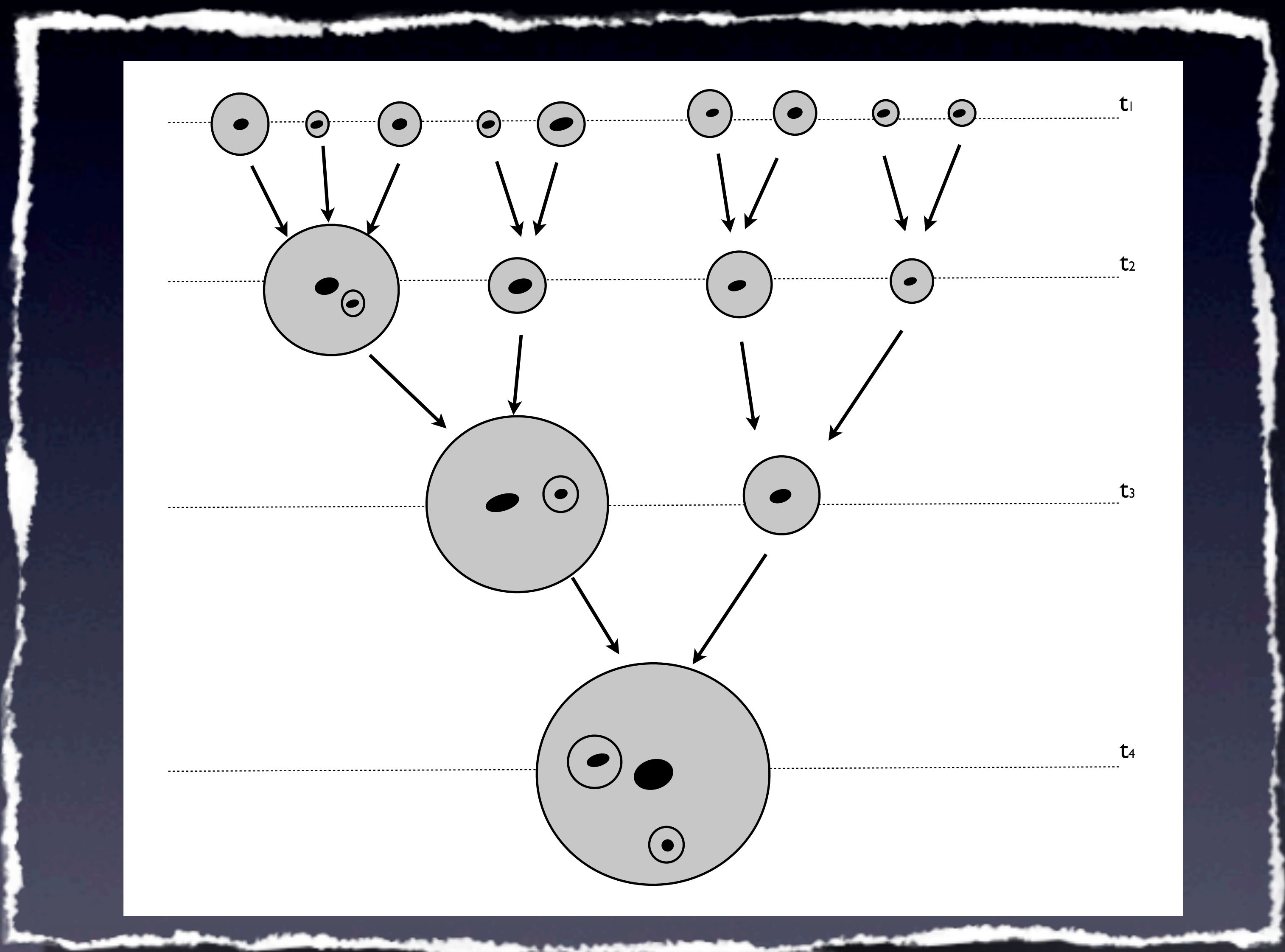
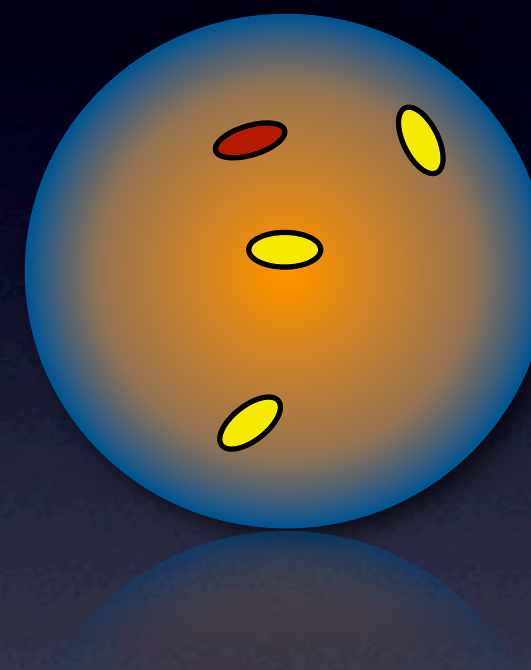
LCDM Universe





Hierarchical Structure Formation





How do galaxies co-evolve with halos ?

Gravitational Lensing Basics

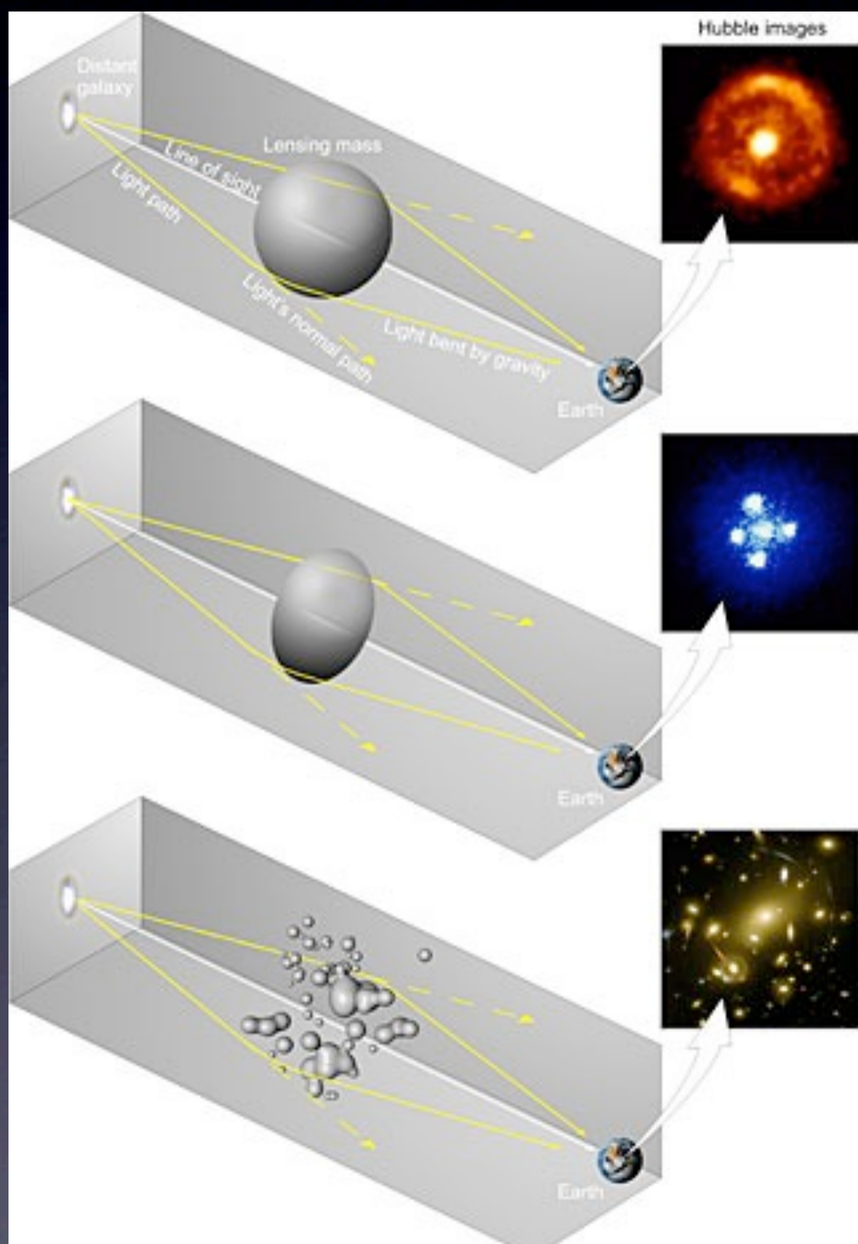
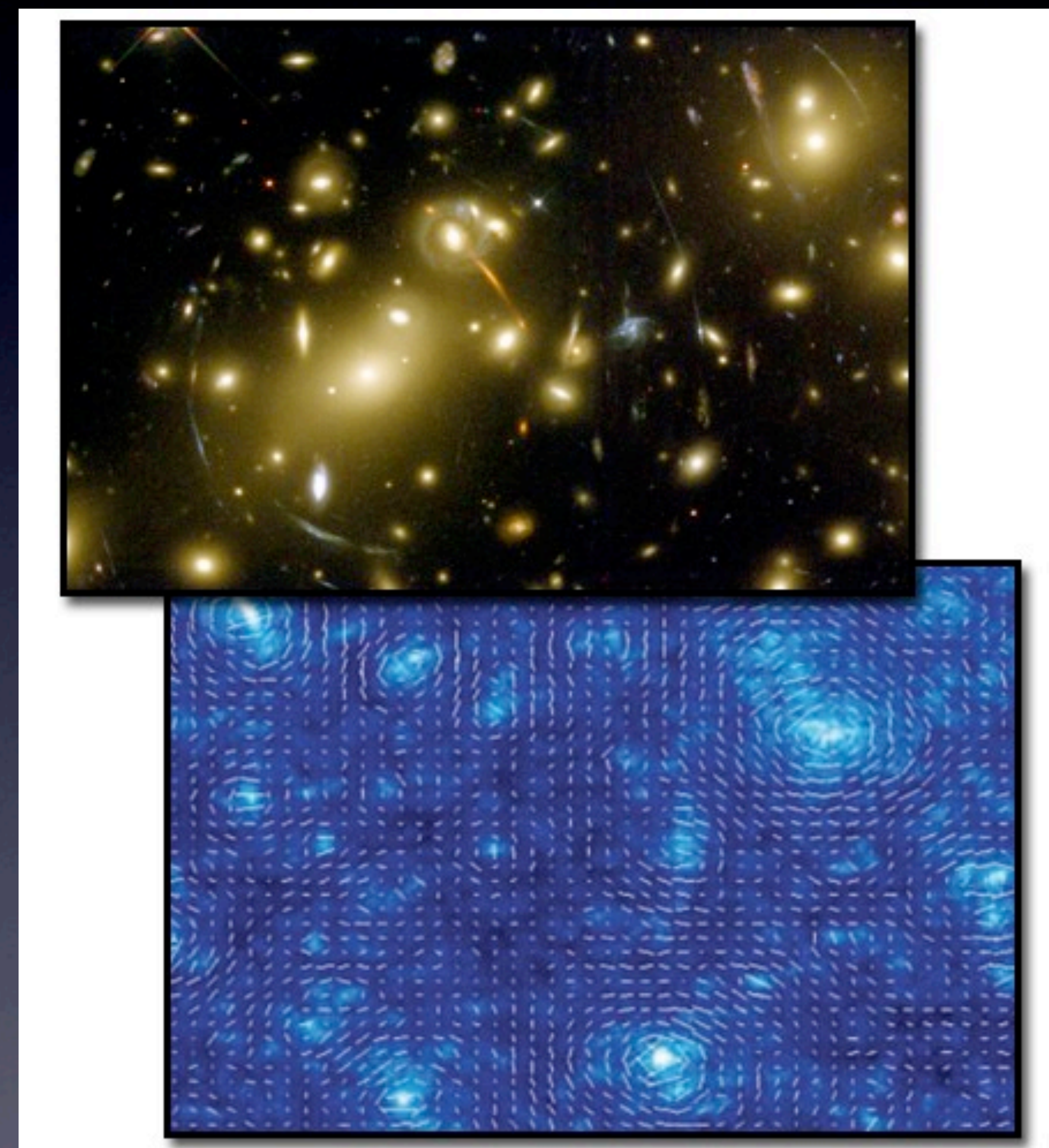


image credit: ESA



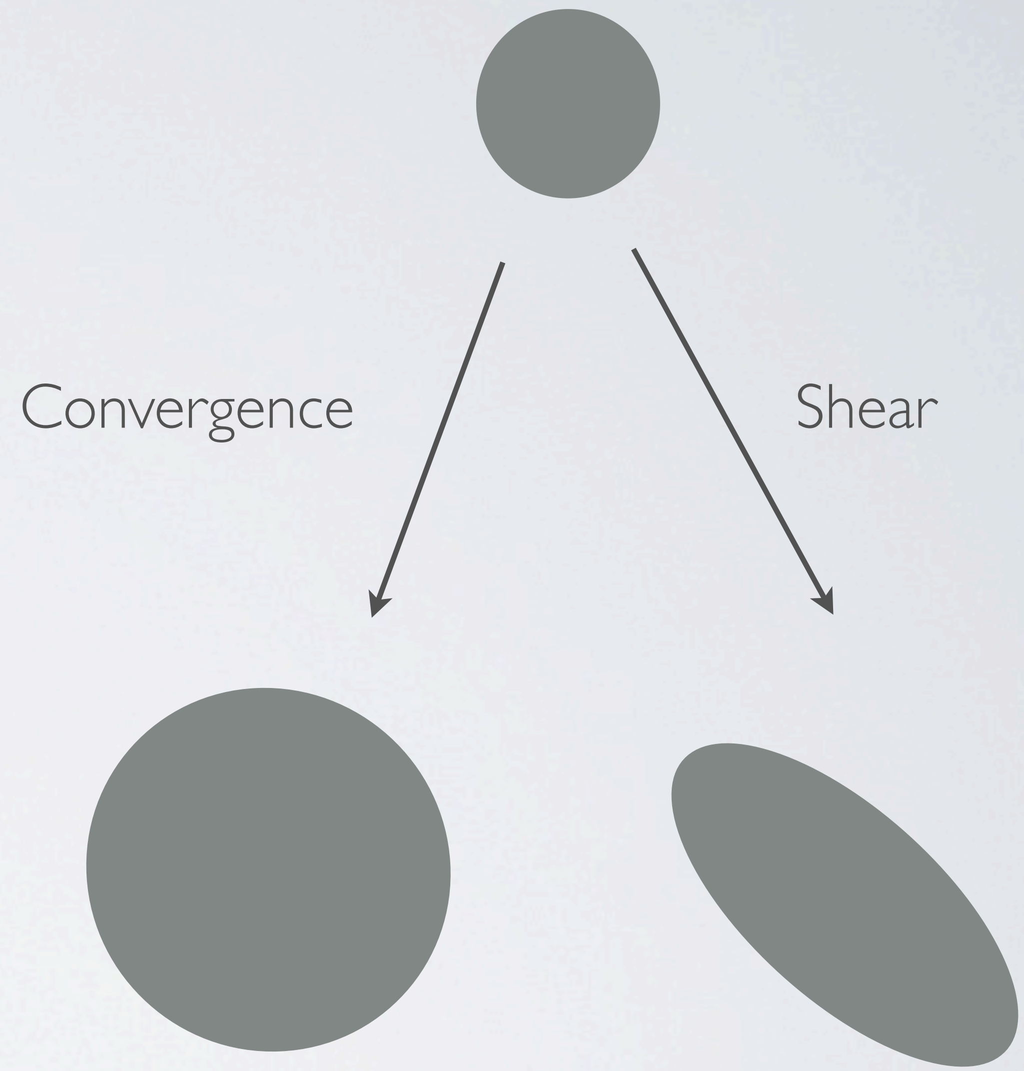
Strong and Weak

WEAK LENSING BASICS

$$\mathcal{A} \equiv \frac{\partial \vec{\beta}}{\partial \vec{\theta}} = \left(\delta_{ij} - \frac{\partial \alpha_i(\vec{\theta})}{\partial \theta_j} \right) = \left(\delta_{ij} - \frac{\partial^2 \psi(\vec{\theta})}{\partial \theta_i \partial \theta_j} \right) = \mathcal{M}^{-1} \ .$$

$$\begin{aligned} \mathcal{A} &= \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} \\ &= (1-\kappa)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \gamma \begin{pmatrix} \cos 2\phi & \sin 2\phi \\ \sin 2\phi & -\cos 2\phi \end{pmatrix} \ . \end{aligned}$$

$$\begin{aligned} \gamma_1(\vec{\theta}) &= \frac{1}{2}(\psi_{11} - \psi_{22}) \equiv \gamma(\vec{\theta}) \cos\left[2\phi(\vec{\theta})\right] \ , \\ \gamma_2(\vec{\theta}) &= \psi_{12} = \psi_{21} \equiv \gamma(\vec{\theta}) \sin\left[2\phi(\vec{\theta})\right] \ . \end{aligned}$$

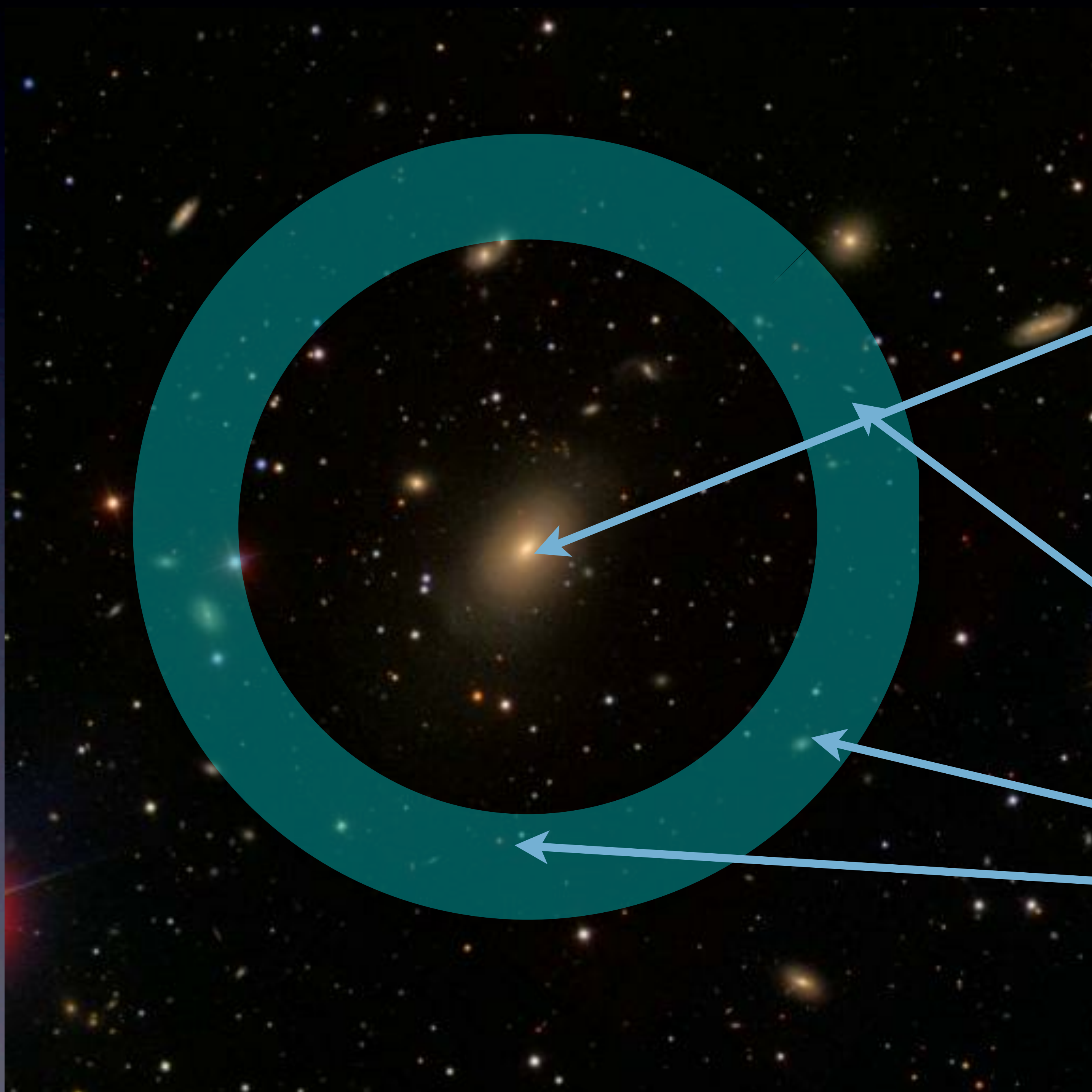


In the absence of shear, the resulting image is a circle with modified radius, depending on κ.

Shear causes an axis ratio different from unity, and the orientation of the resulting ellipse depends on the phase of the shear

Usually the effect is small. One need to study shape of galaxies statistically.

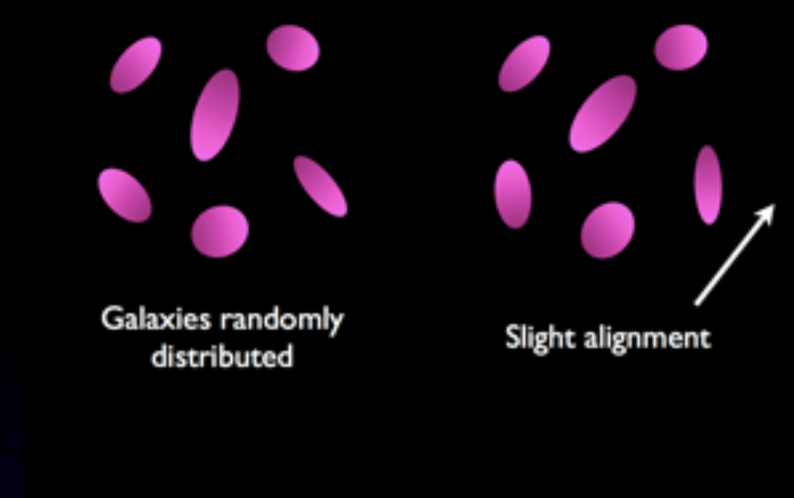
Galaxy-galaxy lensing

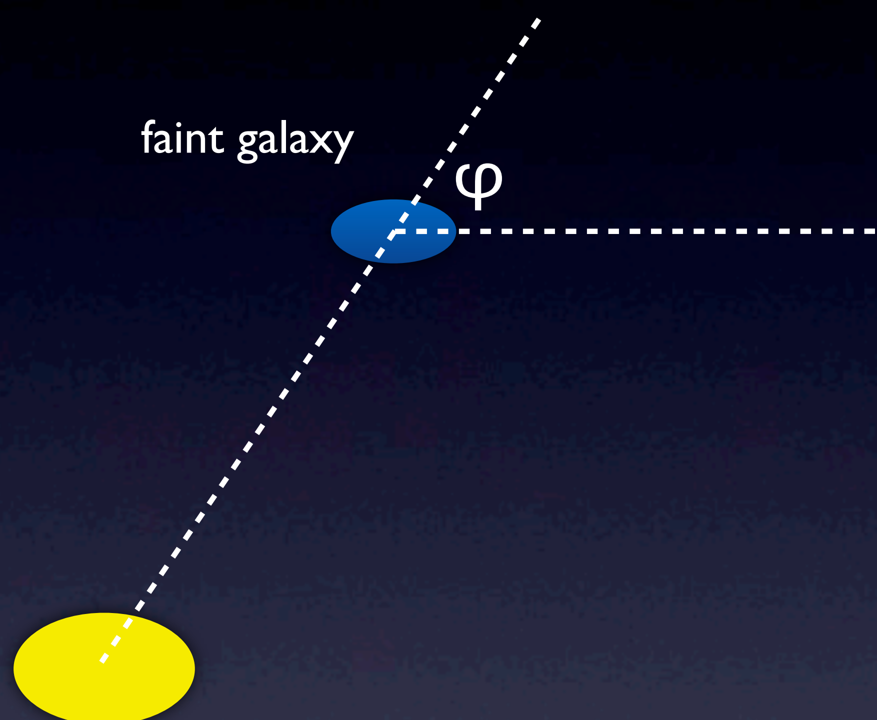


foreground galaxy position

Background galaxy shape

Early work





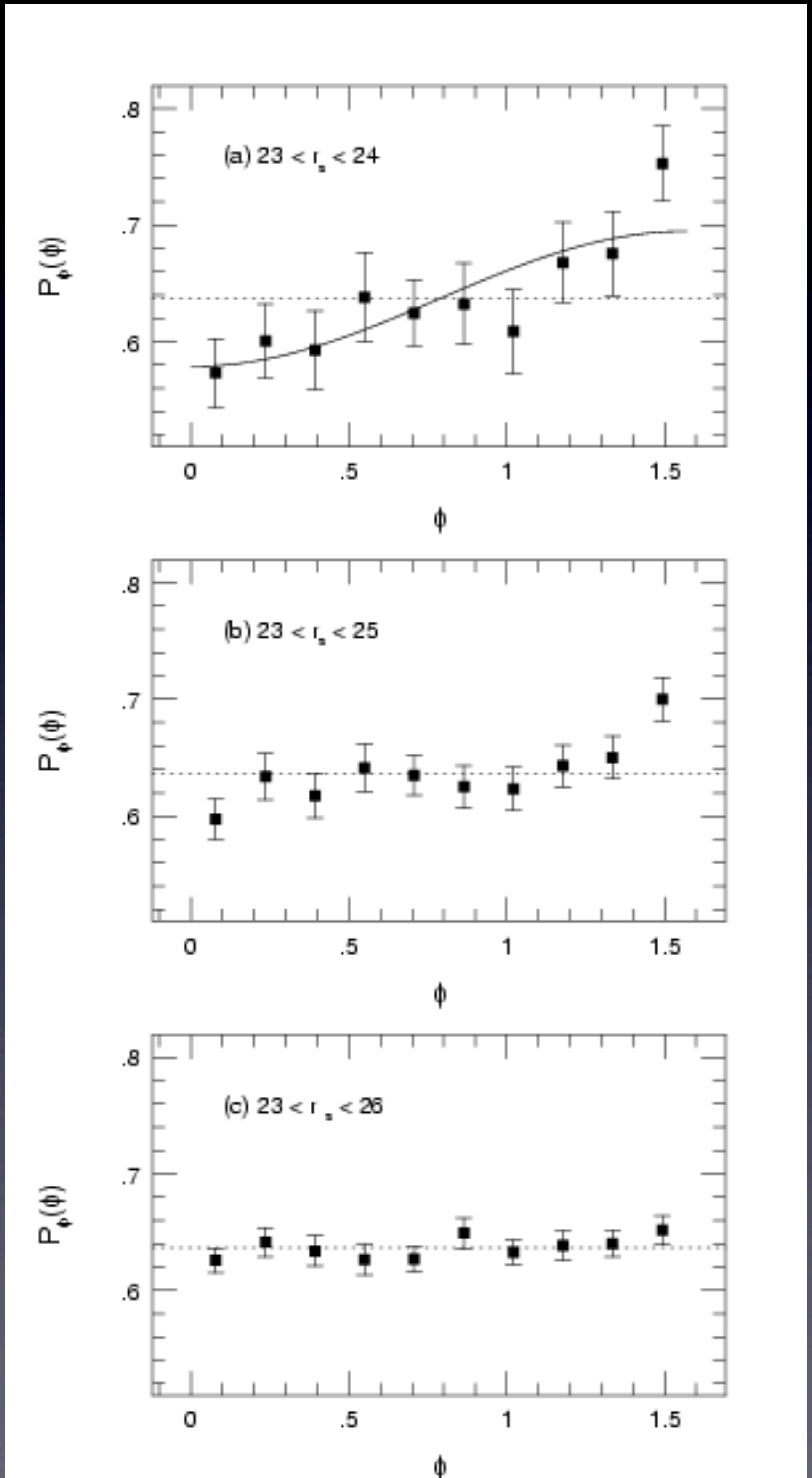
Bright galaxy

$$P(\phi) = \frac{2}{\pi}\left[1 - 2\langle\gamma\rangle\langle\epsilon^{-1}\rangle\cos 2\phi\right]$$

- Brainerd, Blandford & Smail 1996, ApJ, 466, 623 ("BBS")
- Compute the position angles of faint galaxies with respect to the line that connects faint and bright galaxies.

If the faint galaxies are systematically lensed by the bright galaxies, there will be an excess of pairs in which the faint galaxy is tangentially aligned and a deficit of pairs in which the faint galaxy is radially aligned.

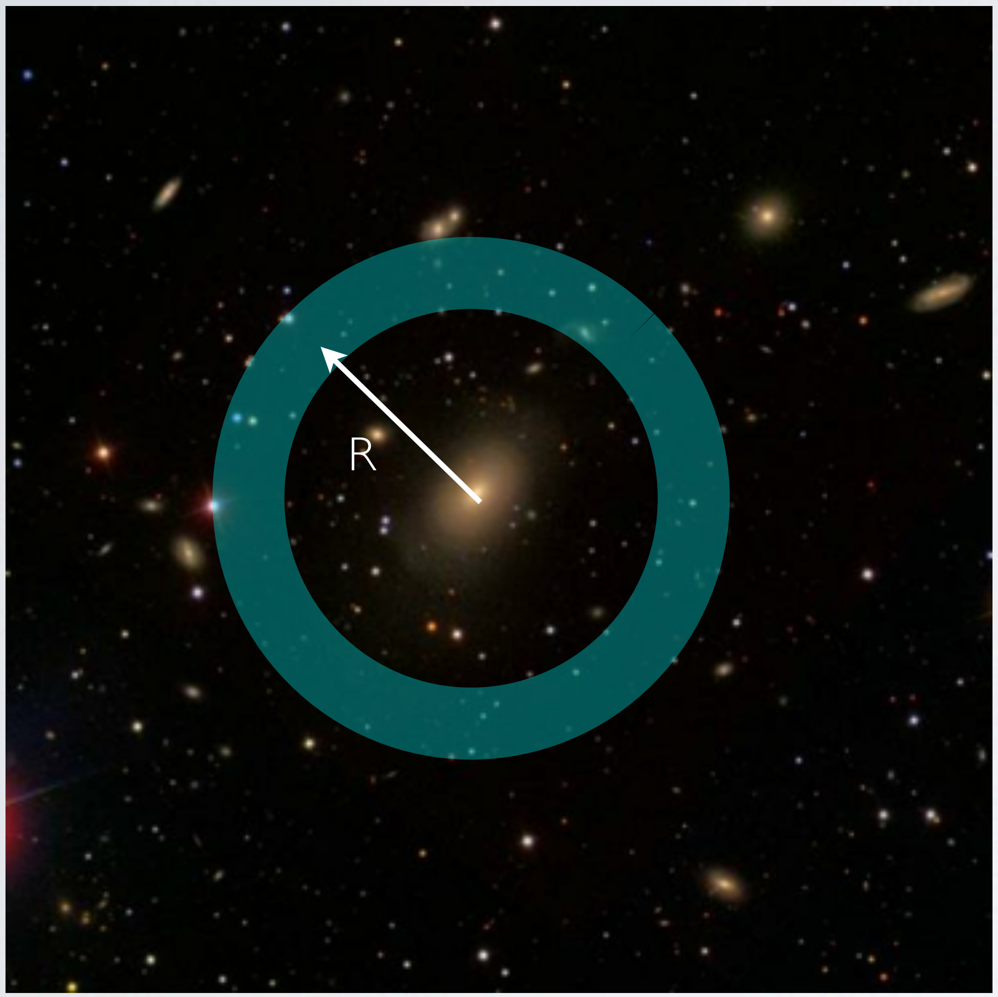
Early work



BBS 1996, Deep CCD image from Palomar 5m; complete to r=26

- 439 bright galaxies (20 < r < 23), 511 faint galaxies (23 < r < 24)
- KS test rules out a uniform distribution for a) at the 99.9% confidence level
- Signal "goes away" for fainter sources because of circularization.

TANGENTIAL SHEAR



$$\langle\gamma_{\rm t}\rangle = \bar{\kappa} - \langle\kappa\rangle$$

$$\Delta\Sigma(R) = \gamma_t(R)\Sigma_c = \overline{\Sigma}(< R) - \Sigma(R)$$

$$e_+ = 2\gamma_T\mathcal{R} + e_+^{\rm int},$$

Galaxies are intrinsically elliptical with

< e >   - 0.2-0.3

Sensitivity: **0.3 / (N)$^{1/2}$**

γ ~ 0.007

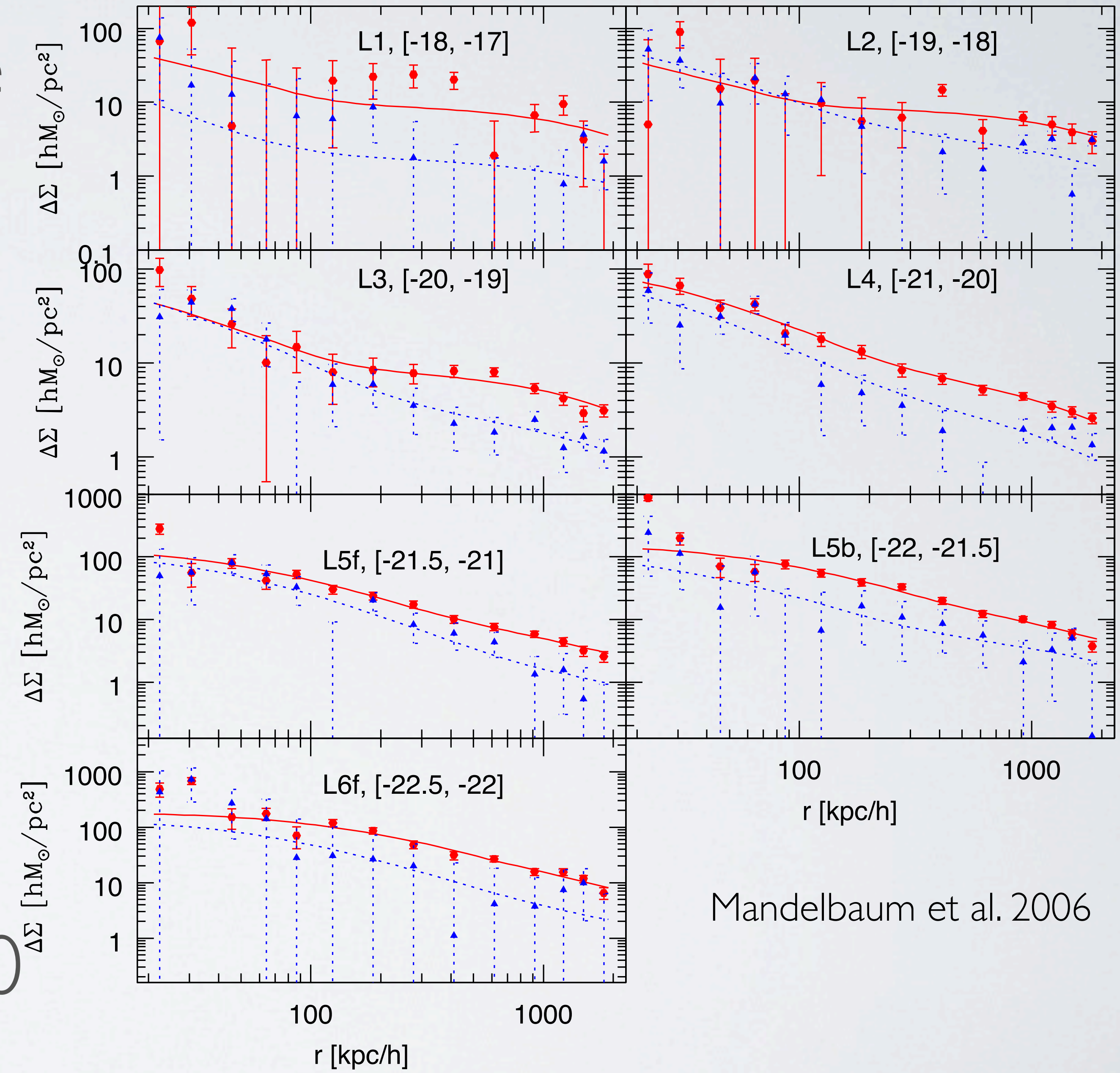
Lensing induces shape correlations that can be measured by averaging over many lenses(~ 10000)

$$\gamma_{\rm t} = -\mathcal{R}{\rm e}\left[\gamma\,{\rm e}^{-2{\rm i}\phi}\right] \quad , \quad \gamma_\times = -\mathcal{I}{\rm m}\left[\gamma\,{\rm e}^{-2{\rm i}\phi}\right]$$

GALAXIES OF DIFFERENT LUMINOSITY

- Lens: SDSS DR4 spectroscopic sample, r<17.77, 4783 square degree

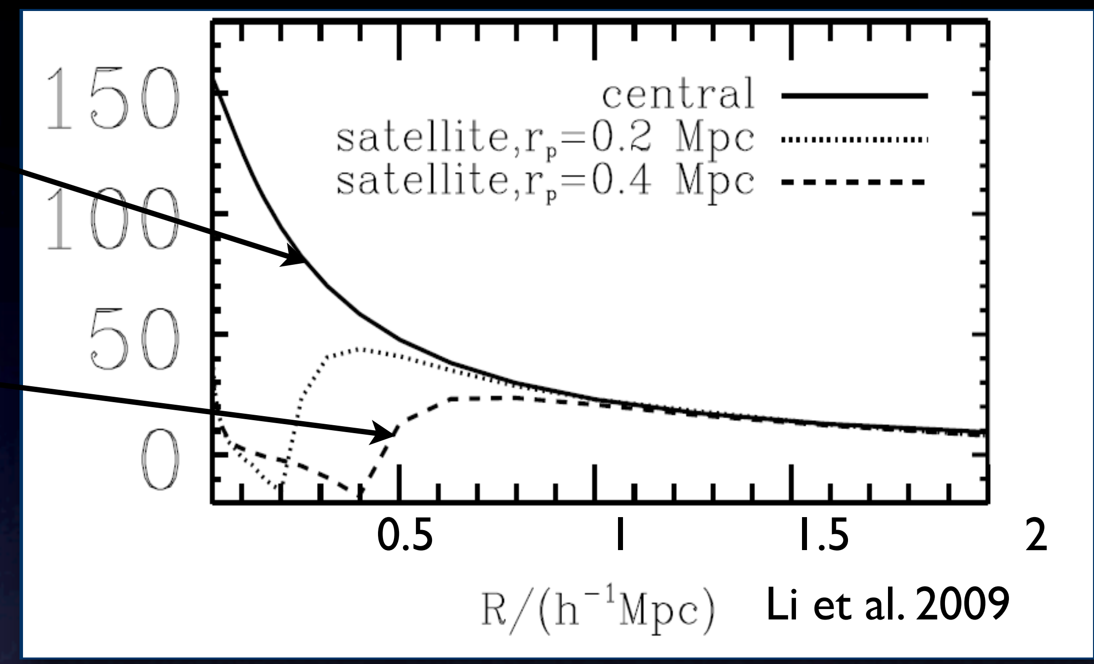
Sample	M_r	N_{gal}	$\langle z \rangle$	$\langle L/L_* \rangle$	f_{spiral}
L1	$-17 \geq M_r > -18$	10 047	0.032	0.075	0.80
L2	$-18 \geq M_r > -19$	29 730	0.047	0.19	0.69
L3	$-19 \geq M_r > -20$	85 766	0.071	0.46	0.53
L4	$-20 \geq M_r > -21$	141 976	0.10	1.1	0.35
L5f	$-21 \geq M_r > -21.5$	60 994	0.14	2.1	0.23
L5b	$-21.5 \geq M_r > -22$	34 920	0.17	3.2	0.16
L6f	$-22 \geq M_r > -22.5$	13 067	0.20	4.9	0.08
L6b	$-22.5 \geq M_r > -23$	2 933	0.22	7.7	0.05



Mandelbaum et al. 2006

- Source: SDSS imaging data, 30 million galaxies down to magnitude r=21.8

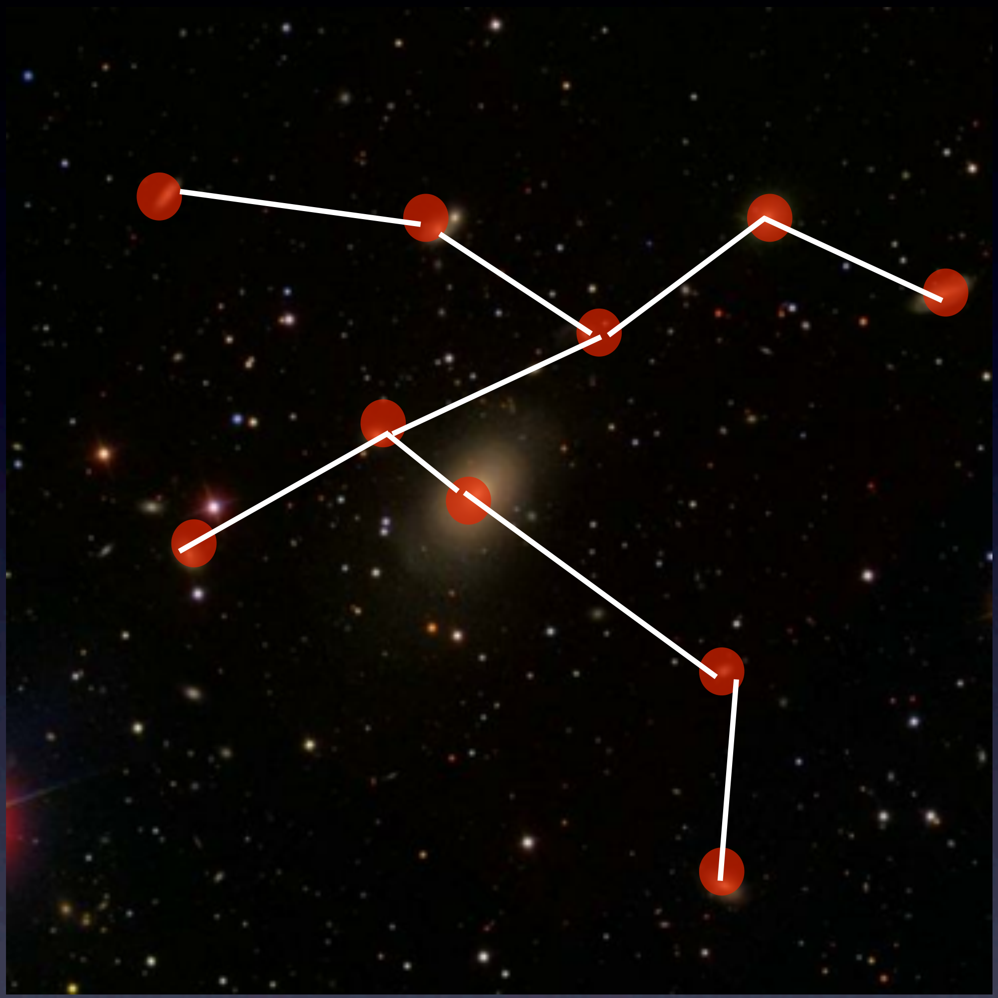
Modeling the data



- One should model centrals and satellites differently

Method 1 : group catalog

- Using galaxy groups to represent the halos
- Estimate group mass(Abundance matching)
- Model dark matter distribution in each group(NFW)
- Predict lensing signal for certain galaxy sample



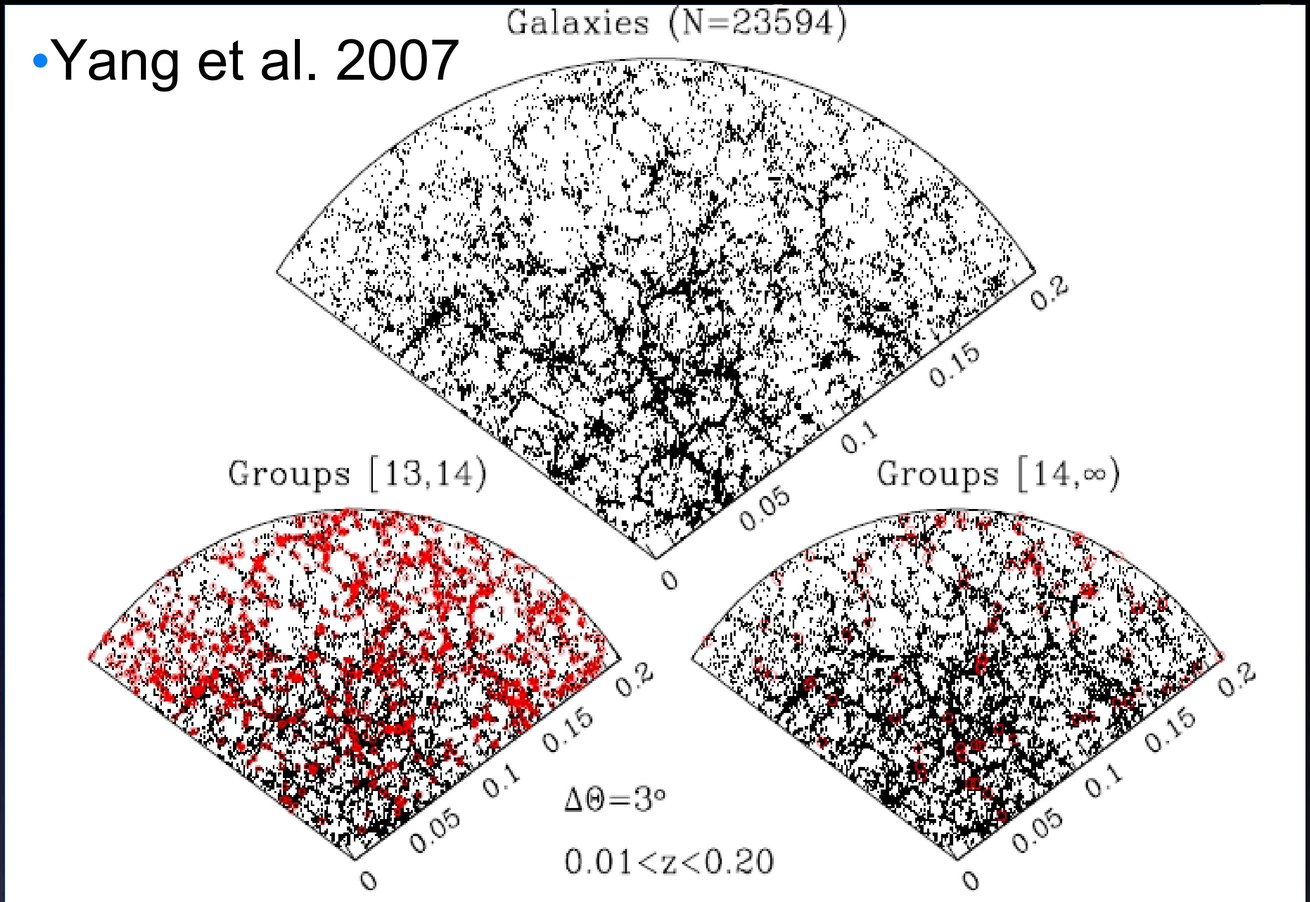
Group finder

Yang, Mo, vdBosch. 2007, using SDSS spectroscopic sample

1. A self-calibrated FOF method.

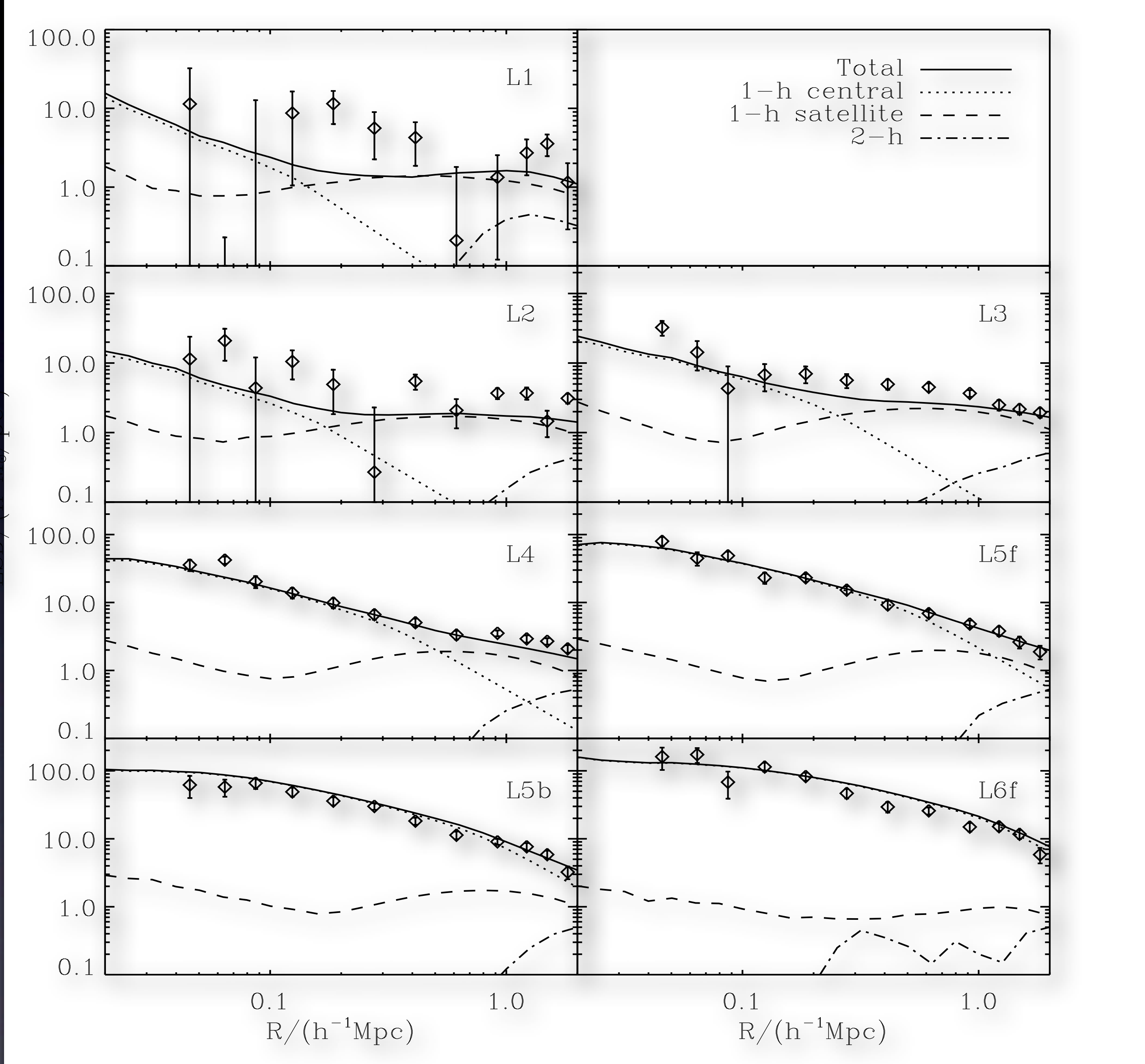
2. Assign all galaxies to groups.

2. Estimate group mass by ranking method.

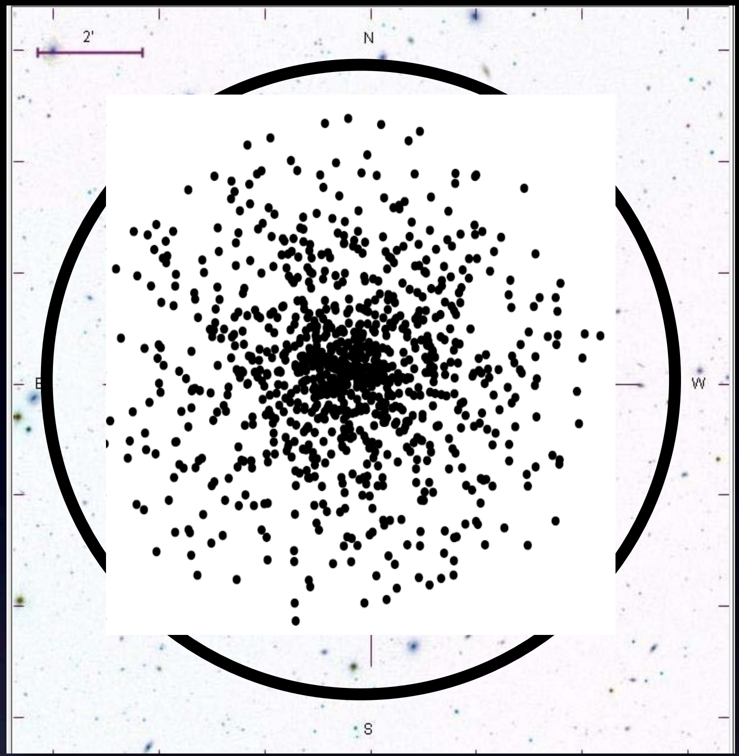


Catalogue	sky cov	redshift	galaxies	groups	groups(N=1)	groups(N=2)	groups(N=3)	groups(N>3)
Sample I	4514	0.01-0.20	362356	295992	266763	19522	4511	5196
Sample II	4514	0.01-0.20	369447	301237	271420	19868	4619	5330
Sample III	4514	0.01-0.20	408119	300049	250492	33537	7848	8172

Modeling g-g lensing signal



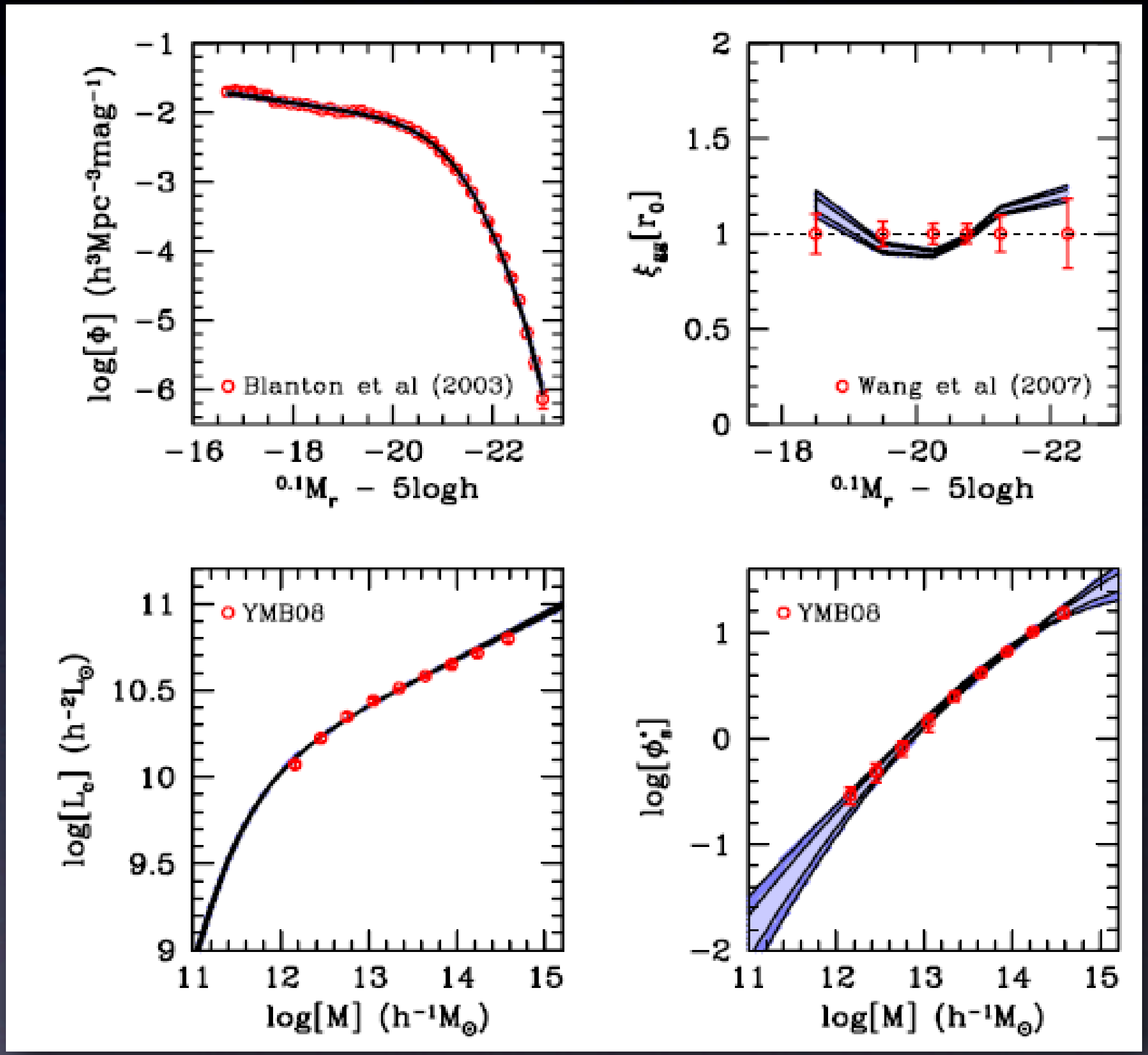
Li et al. 2009



- Assuming central galaxies are the most massive ones in each group
- Each satellite is assigned a subhalo mass
- NFW profile for host halo
- Truncated NFW profile for subhalo

The model reproduce observed g-g lensing signal with good agreement.

Method 2 : Conditional luminosity function



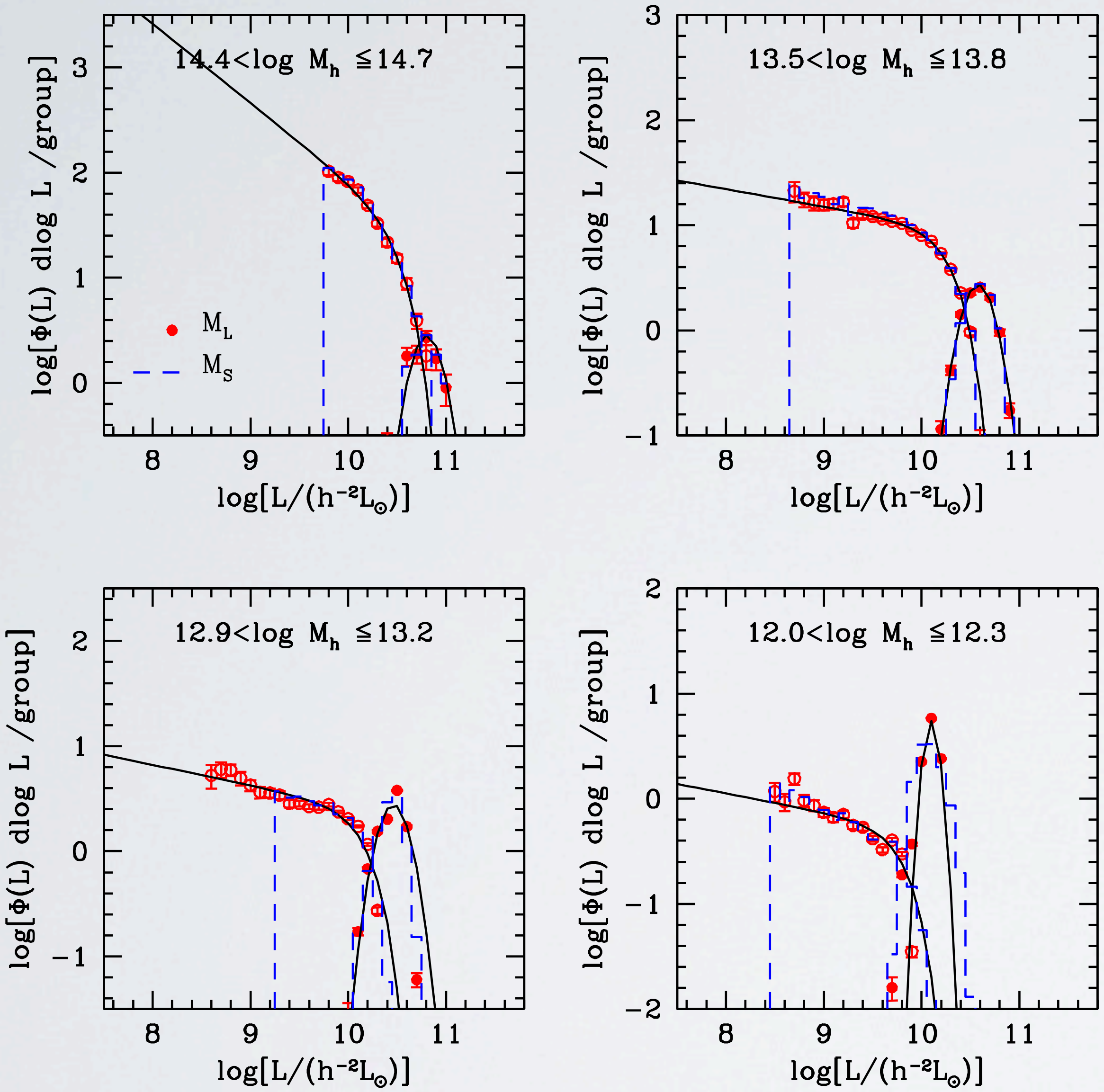
Cacciato et al 2009

- $\Phi(L|M)$ tells the luminosity function inside a halo with mass M.

- Can be constrained using $\Phi(L)$, $\xi_{gg}(r)$, group catalog. (Cacciato et al. 2009)

$$\Phi(L|M) = \Phi_c(L|M) + \Phi_s(L|M)$$

METHOD 2: CONDITION LUMINOSITY FUNCTION

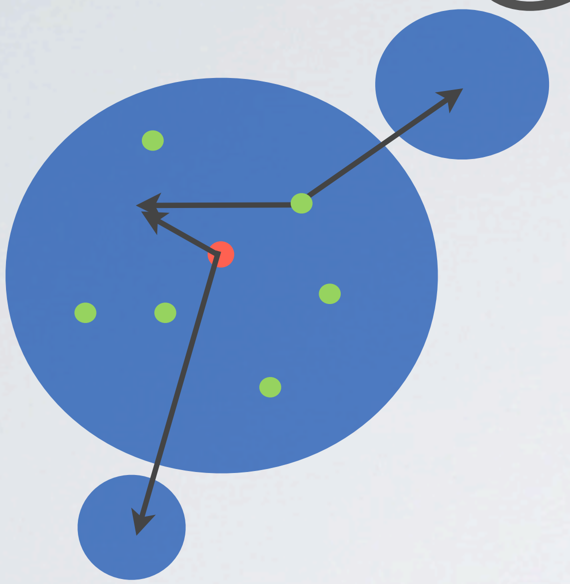


$$P^c(M|L)dM = \frac{\Phi^c(L|M)n(M)}{\Phi^c(L)}dM$$

$$P^s(M|L)dM = \frac{\Phi^s(L|M)n(M)}{\Phi^s(L)}dM$$

Yang, Mo, van den Bosch 2008

GALAXY-MATTER CORRELATION



$$P_{\rm g,dm}(k) = 4\pi \int_0^\infty \xi_{\rm g,dm}(r) \frac{\sin(kr)}{kr} r^2 \, {\rm d}r \, .$$

$$P^{1h,{\rm c}}_{\rm g,dm}(k|L) = \frac{1}{\bar{\rho}} \int_0^\infty \mathcal{P}_{\rm c}(M|L) \tilde{u}_{\rm dm}(k|M) \, {\rm d}M \, .$$

$$P^{1h,{\rm s}}_{\rm g,dm}(k|L) = \frac{1}{\bar{\rho}\Phi_{\rm s}(L)} \int_0^\infty \Phi_{\rm s}(L|M) \tilde{u}_{\rm s}(k|M) \tilde{u}_{\rm dm}(k|M) \, n(M) \, {\rm d}M$$

- 1. CENTRAL GALAXY–HALO
- 2 . SATELLITE GALAXY–HALO
- 3.CENTRAL GALAXY–NEIGHBORING HALO
- 4.SATELLITE GALAXY–NEIGHBORING HALO

$$P^{2h,{\rm x}}_{\rm g,dm}(k|L) = P_{\rm lin}(k) \mathcal{I}_{\rm x}(L) \mathcal{I}_M \, ,$$

$$\mathcal{I}_{\rm c}(L) = \int_0^\infty \frac{\Phi_{\rm c}(L|M)}{\Phi_{\rm c}(L)} b(M) \, n(M) \, {\rm d}M \, , \qquad (2.57)$$

$$\mathcal{I}_{\rm s}(L) = \int_0^\infty \frac{\Phi_{\rm s}(L|M)}{\Phi_{\rm s}(L)} \tilde{u}_{\rm s}(k|M) \, b(M) \, n(M) \, {\rm d}M \, , \qquad (2.58)$$

$$\mathcal{I}_M = \frac{1}{\rho} \int_0^\infty \tilde{u}_{\rm dm}(k|M) b(M) n(M) {\rm d}M \, . \qquad (2.59)$$

Halo mass function

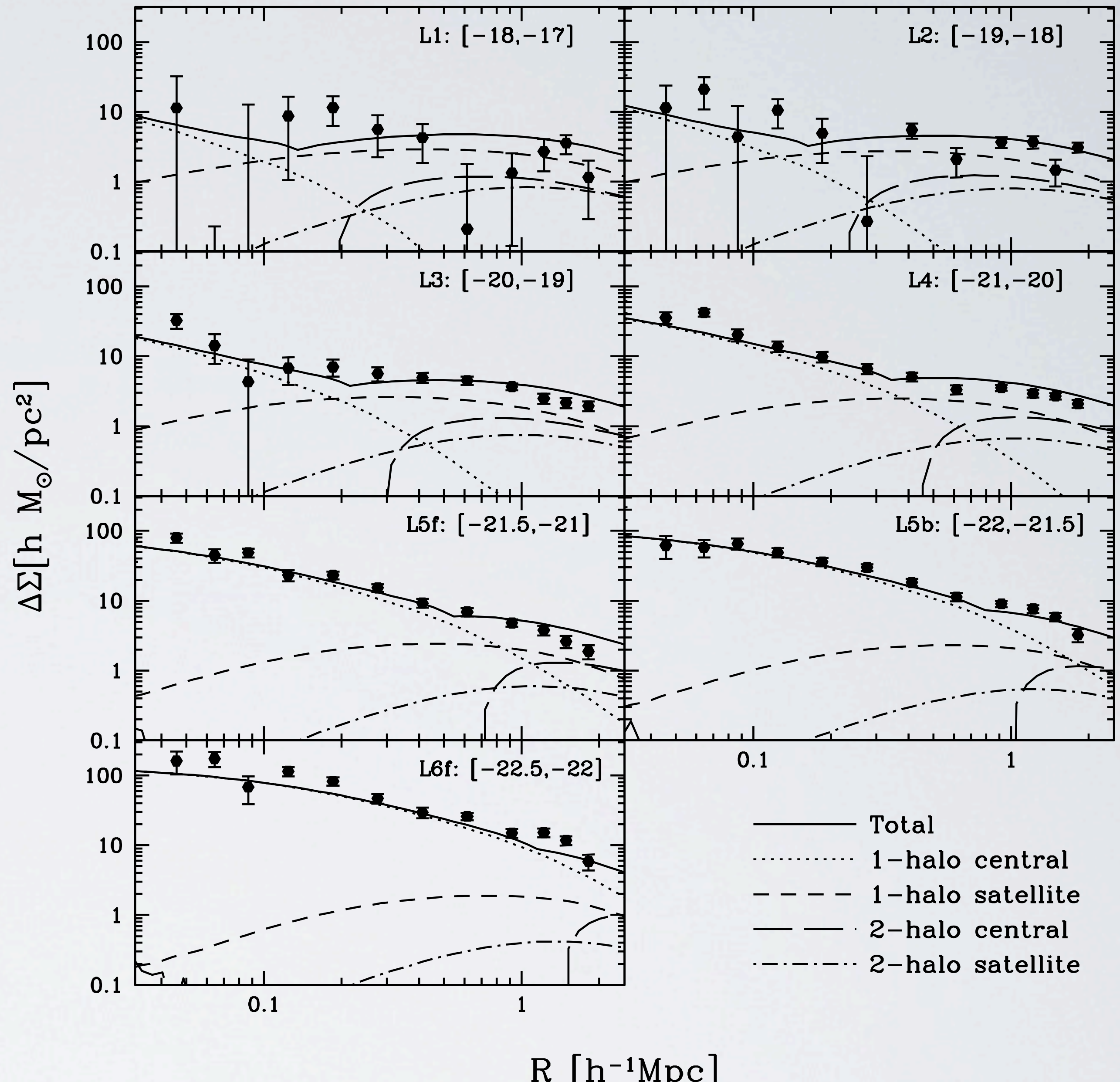
Condition luminosity function

Satellite density profile

Halo bias

Halo density profile

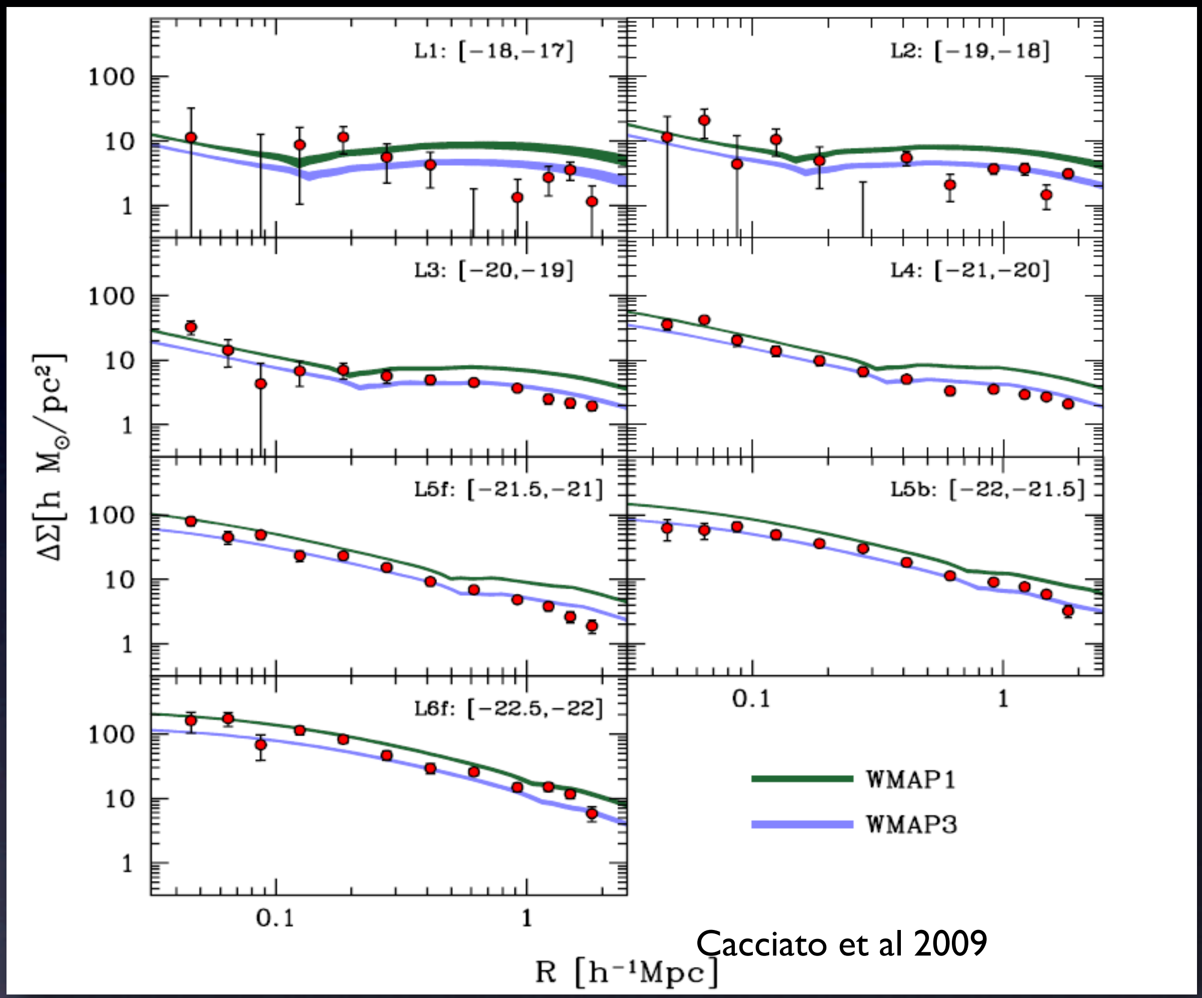
$$\Delta\Sigma(R|L) = f_c \int P^c(M|L)\Delta\Sigma^c(R|M)dM + f_s \int P^s(M|L)\Delta\Sigma^s(R|M)dM$$



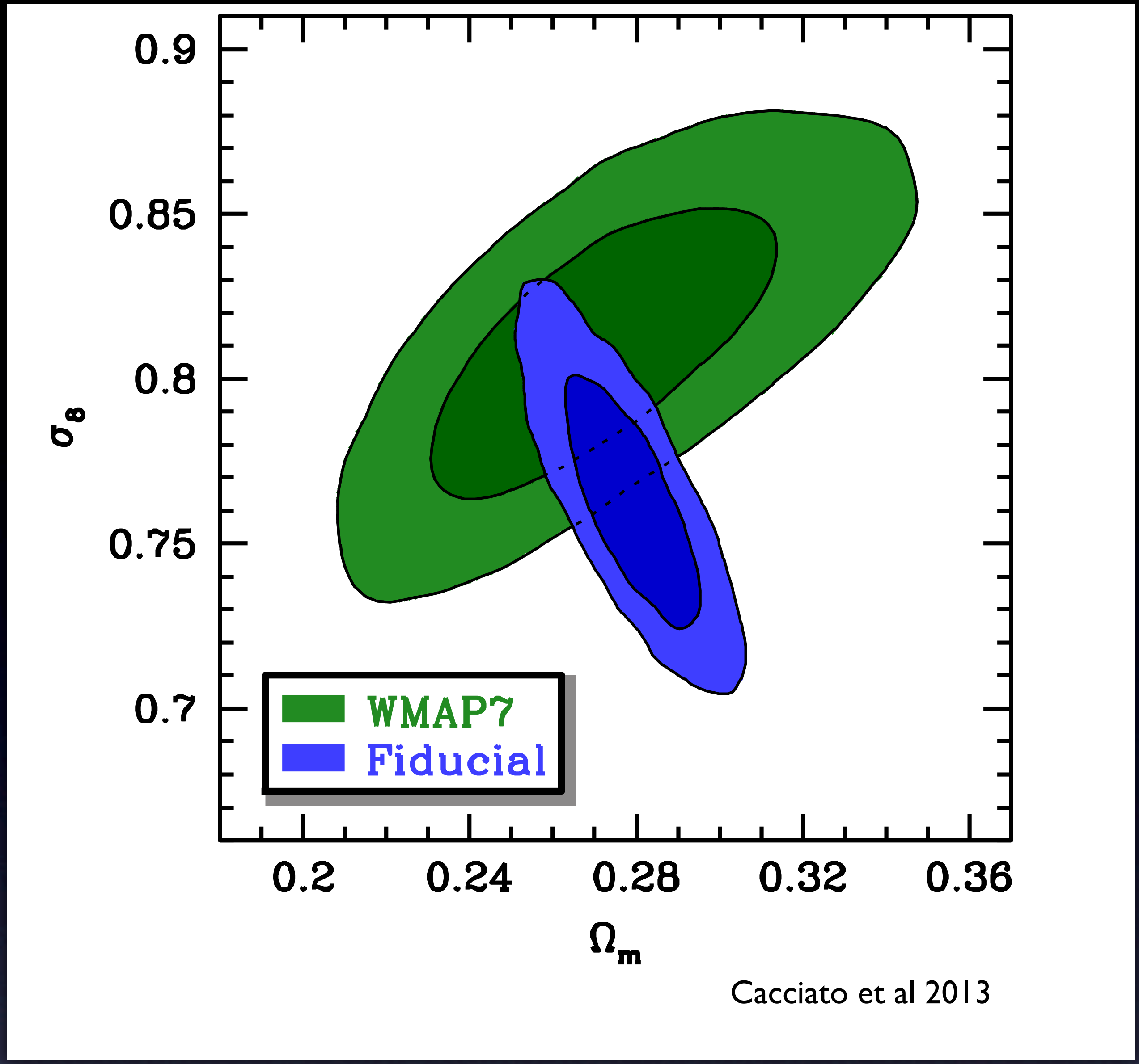
Cacciato et al 2009

Produced observed g-g lensing signal again.

Constrain Cosmology Parameters



Cacciato et al 2009



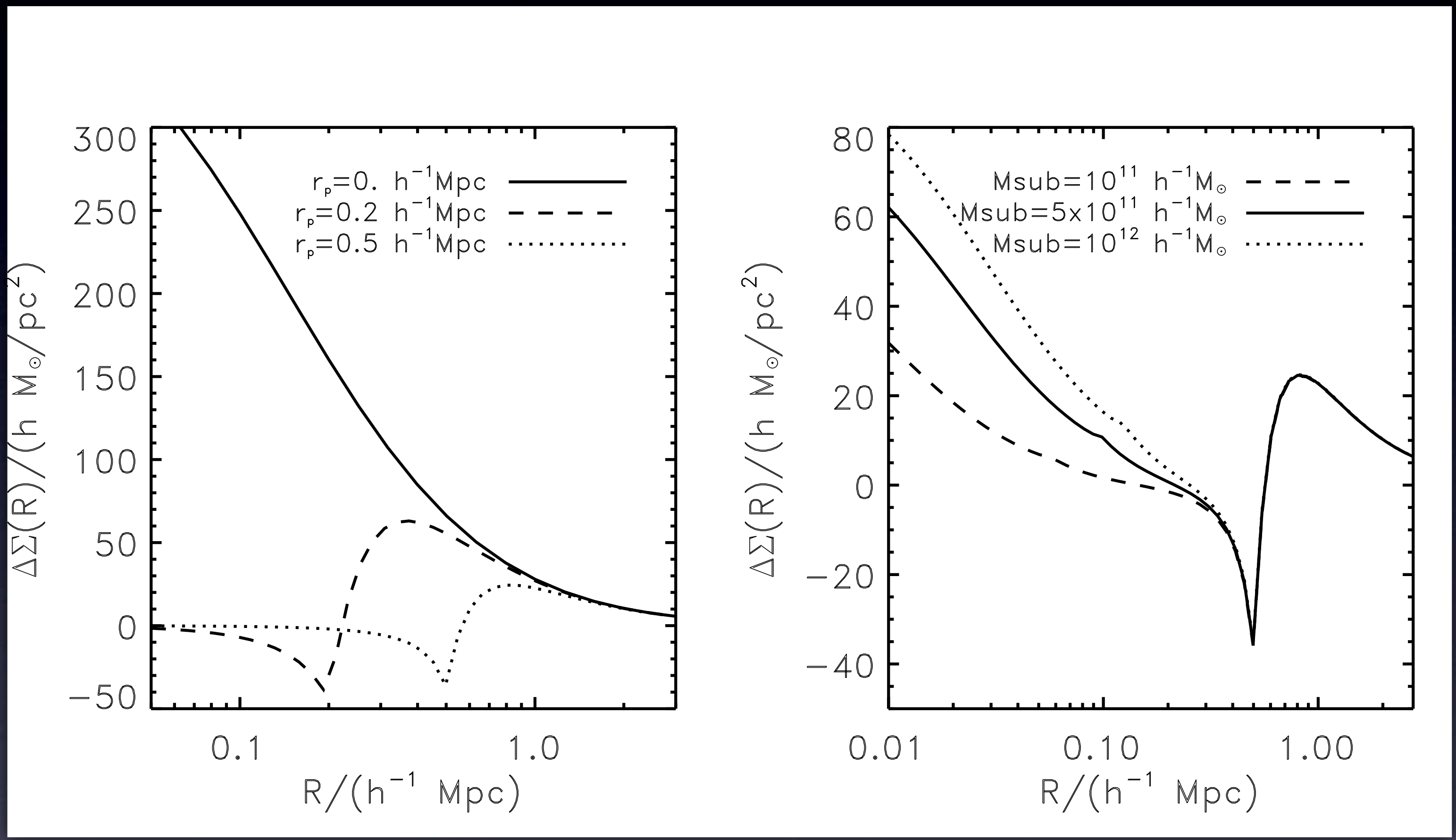
Cacciato et al 2013

Constrain Cosmology

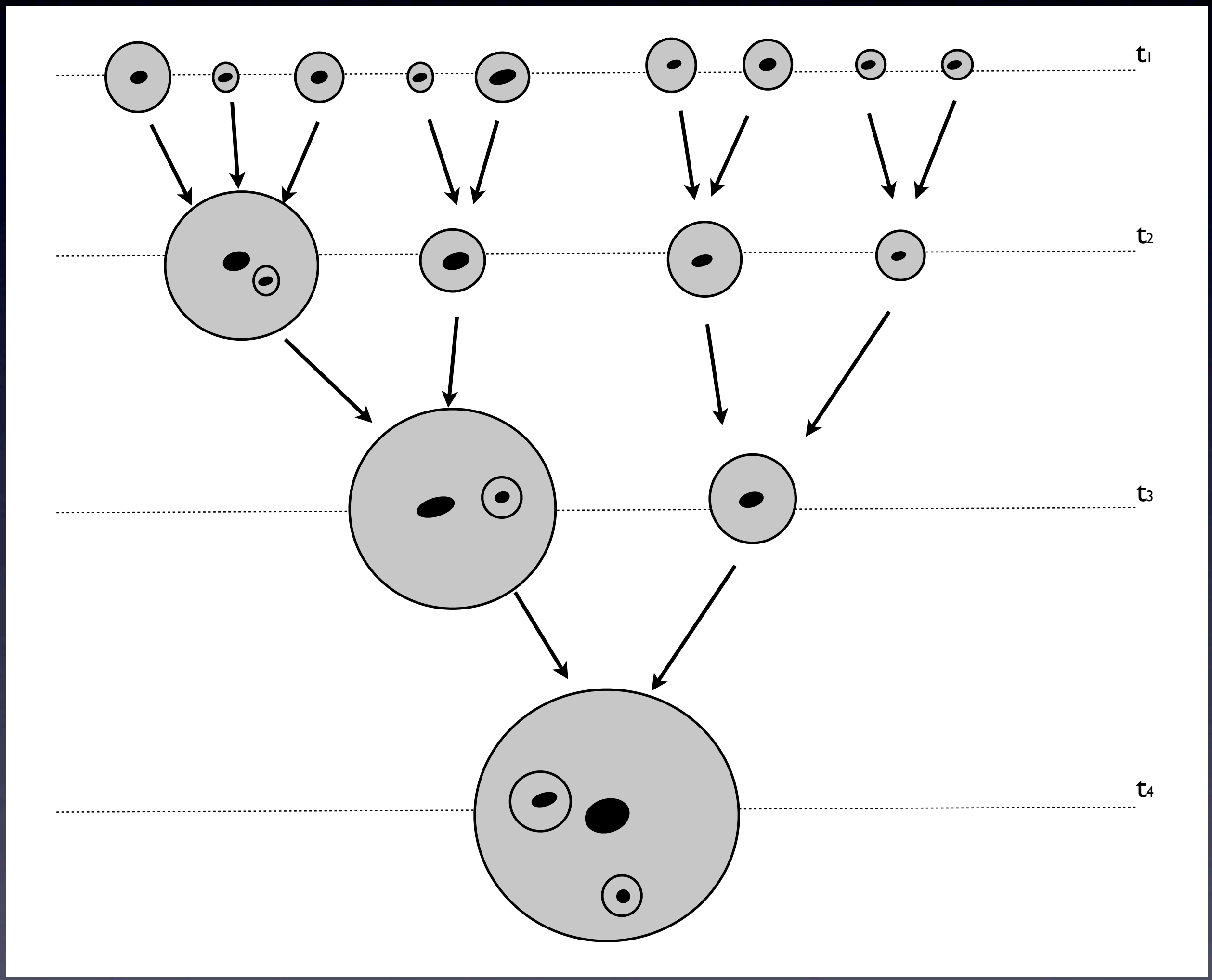
Can we constrain subhalo properties?

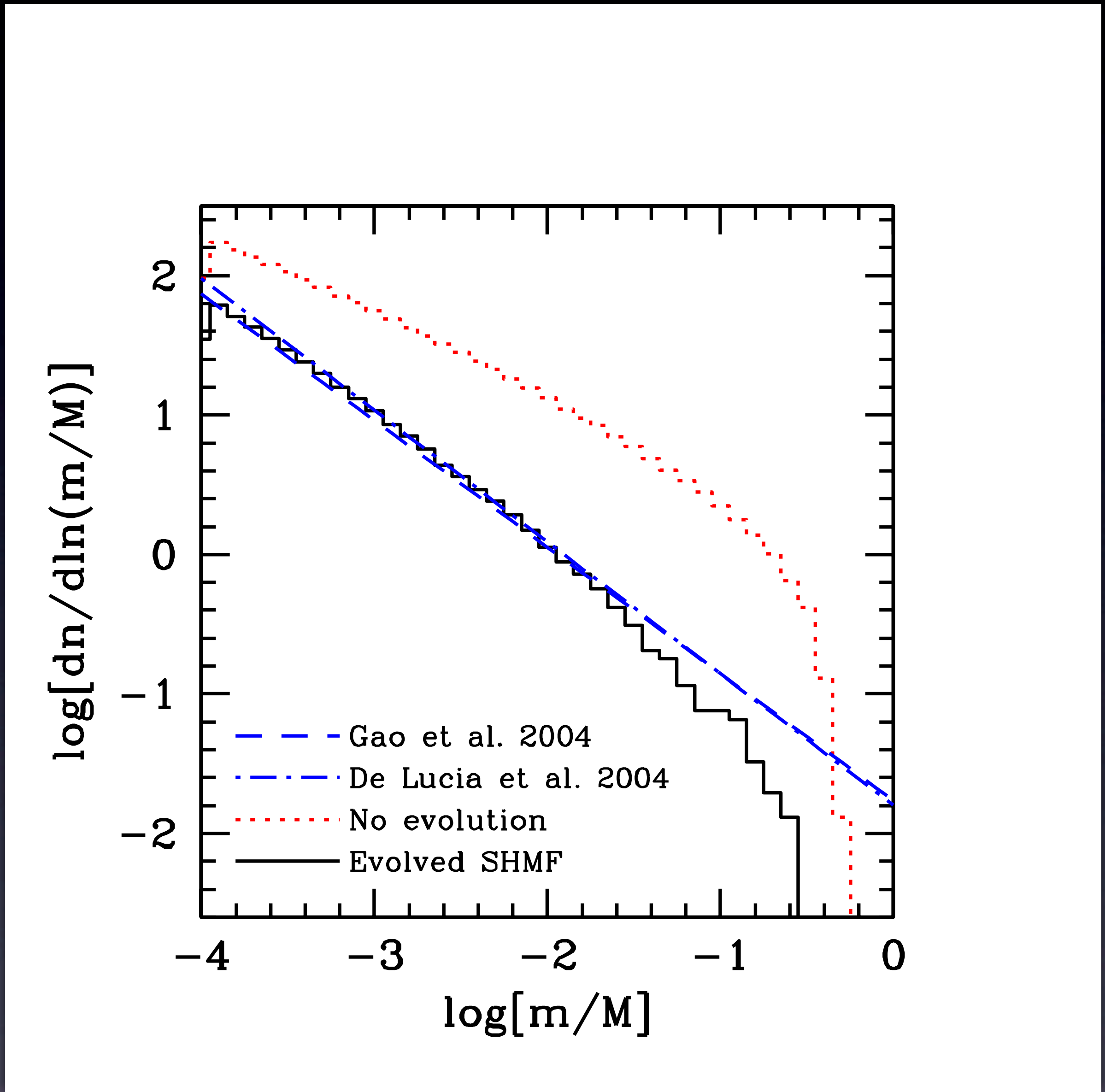
Using group catalog

Stack satellites with host halo of similar mass, and at similar halo-centric distance.



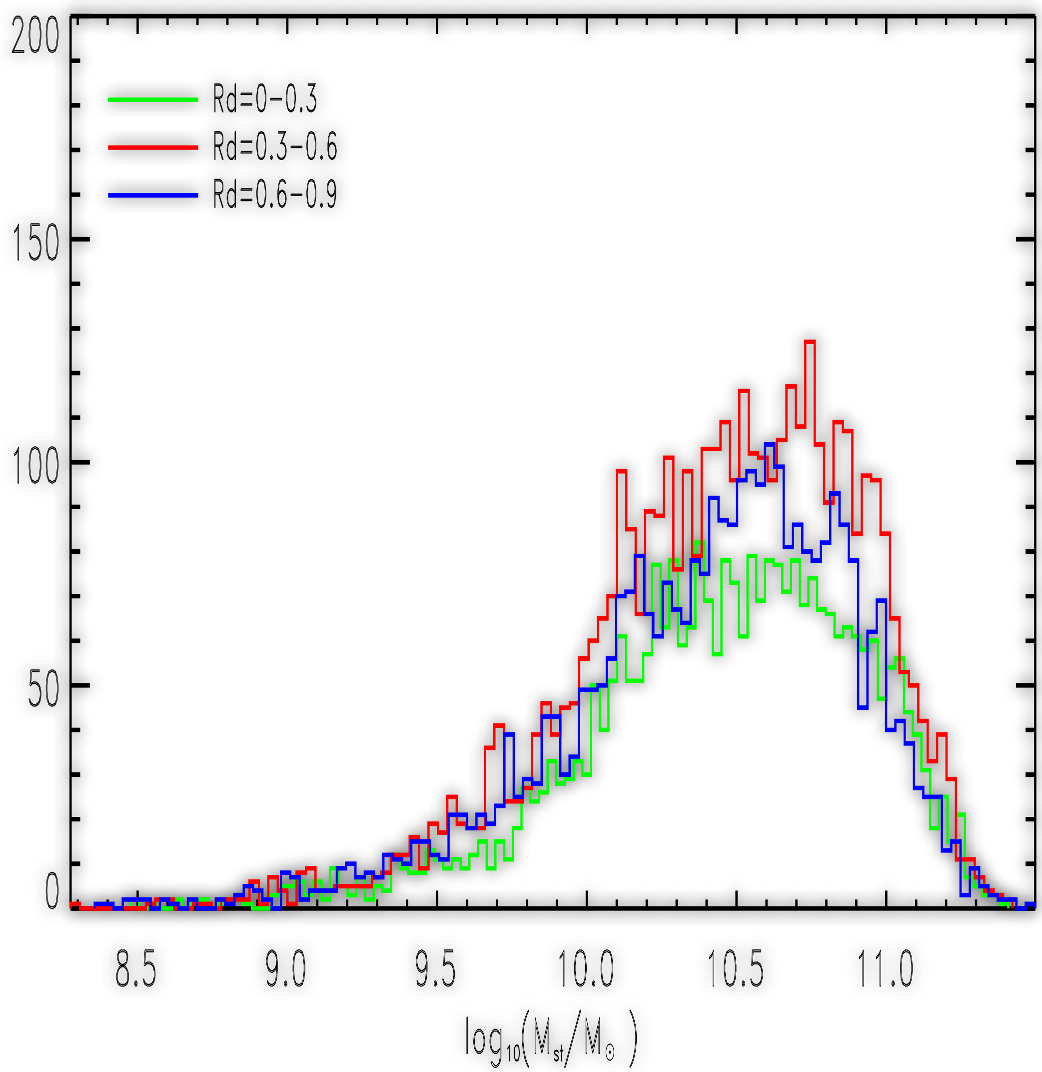
Subhalo mass function



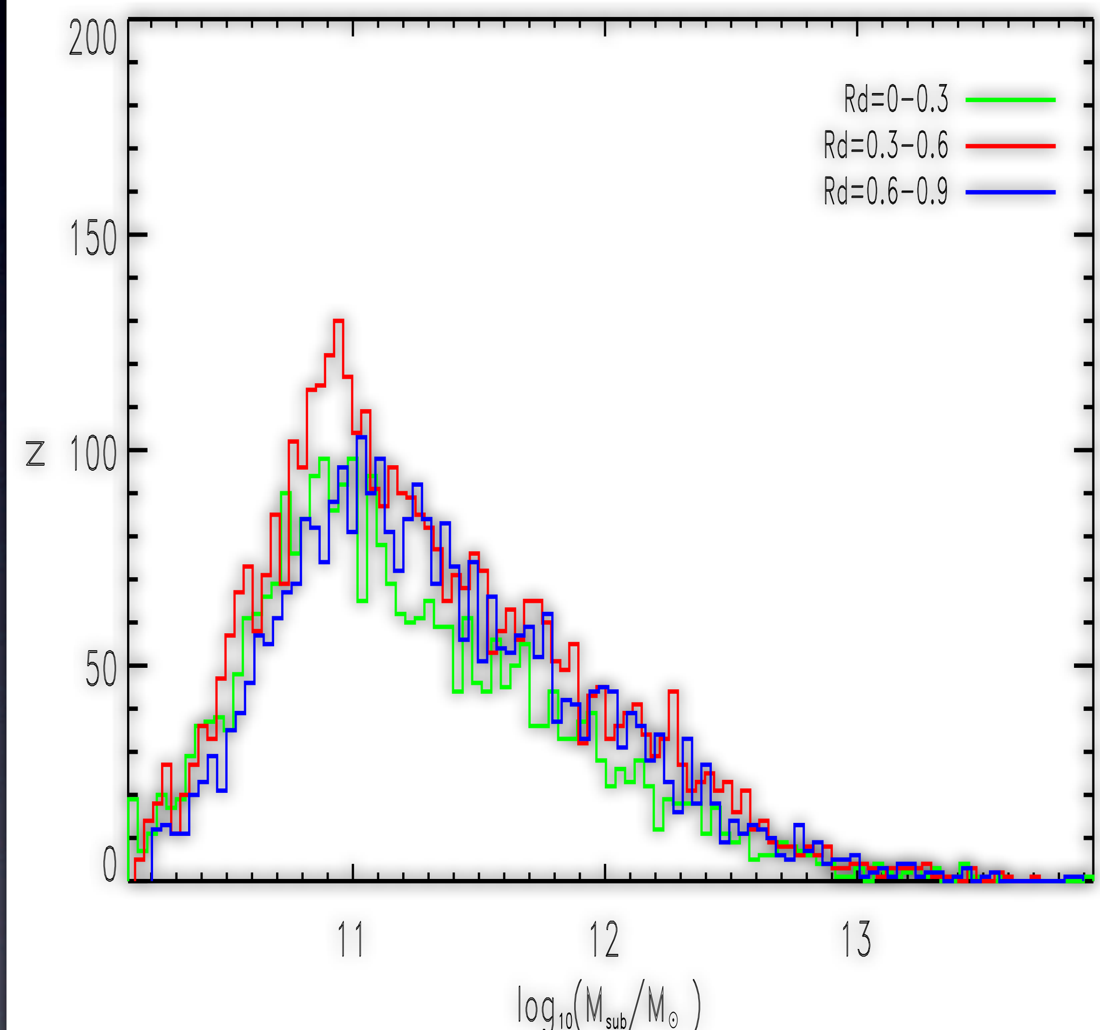


van den Bosch et al. 2005

Satellite mass estimation



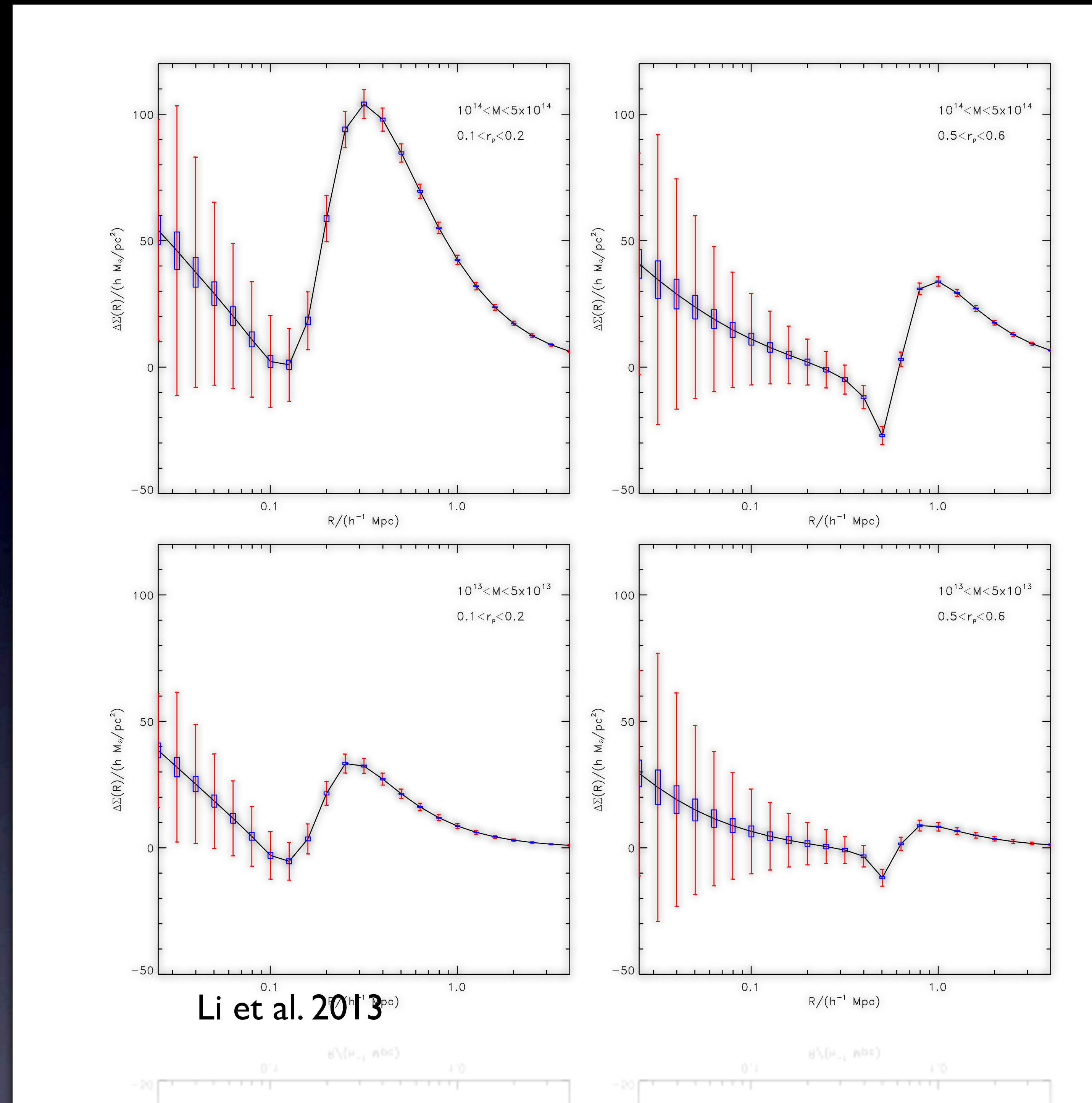
Stellar mass of all satellites in halo with mass larger than $10^{14}h^{-1}M_{\odot}$



Subhalo mass distribution according to subhalo mass function from simulation.
(van den Bosch, Tormen, Giocoli 2005)

Prediction for subhalo lensing signal

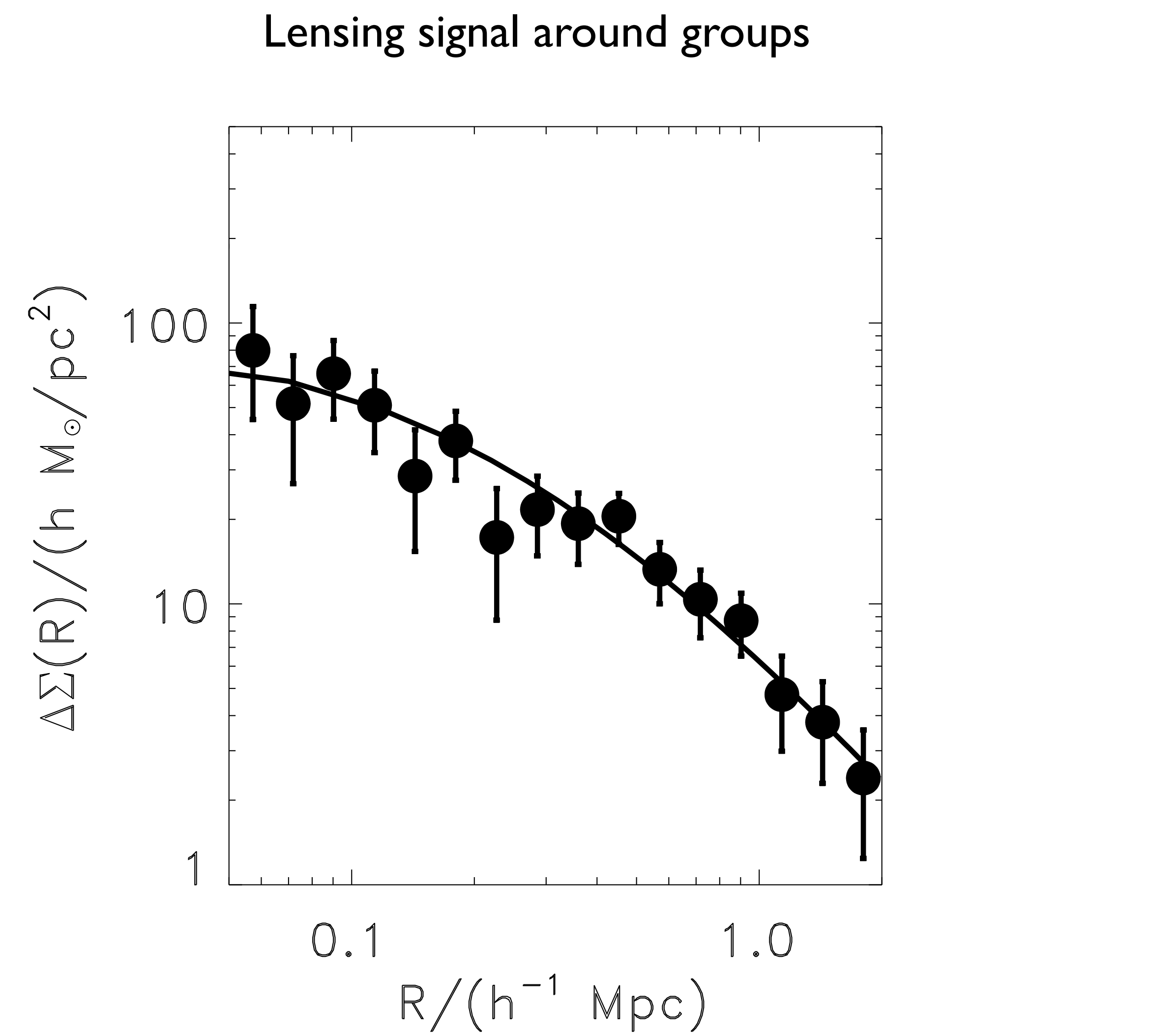
Errorbar: expected uncertainties
of SDSS(Red) and LSST(Blue) survey



Li et al. 2013

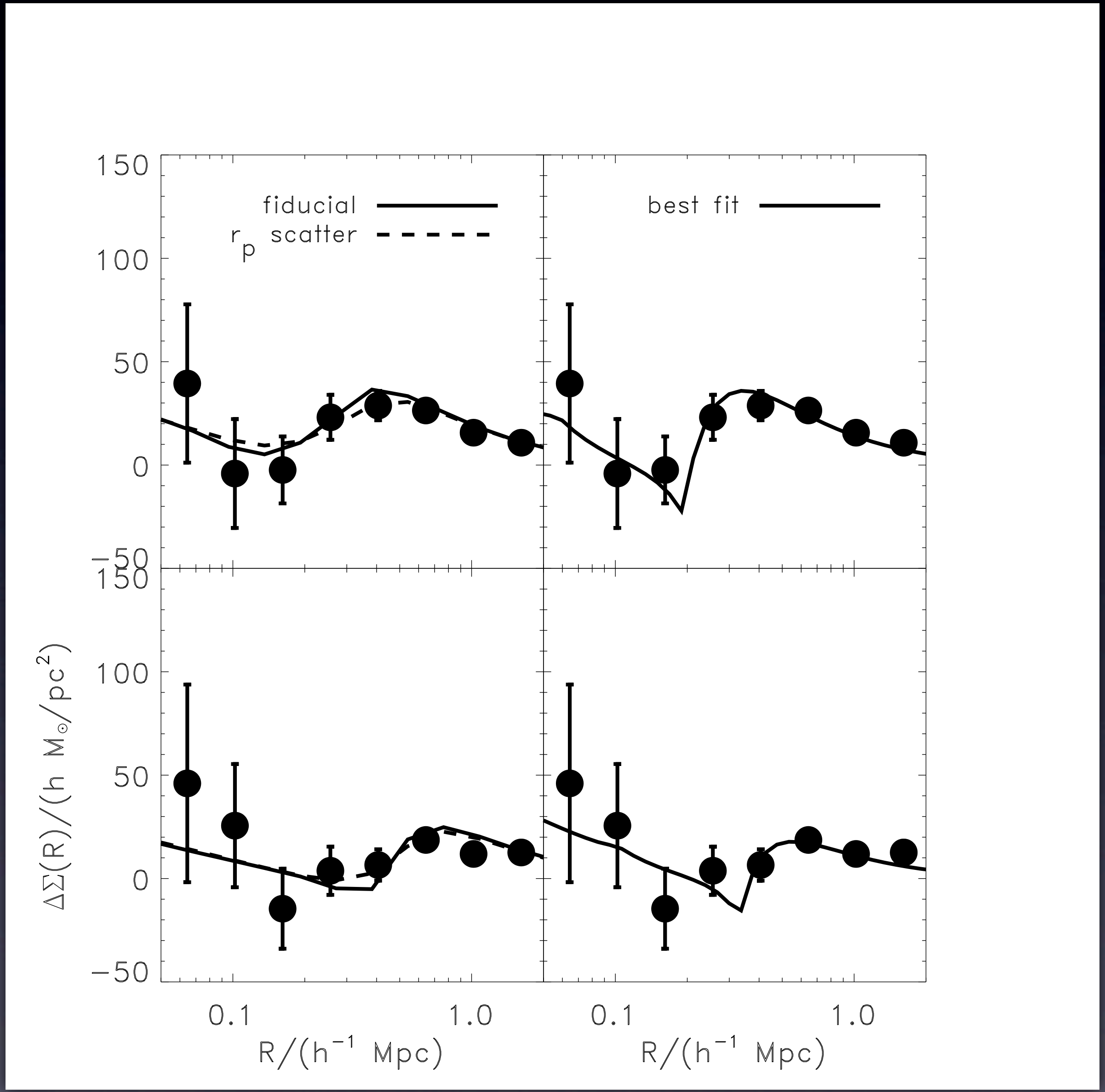
Test with Data: CFHT/ Stripe82

- CFHT/Stripe 82
- 170 deg^2
- 10 source/arcmin
- seeing 0.6"
- Shear catalog by KSB90 method

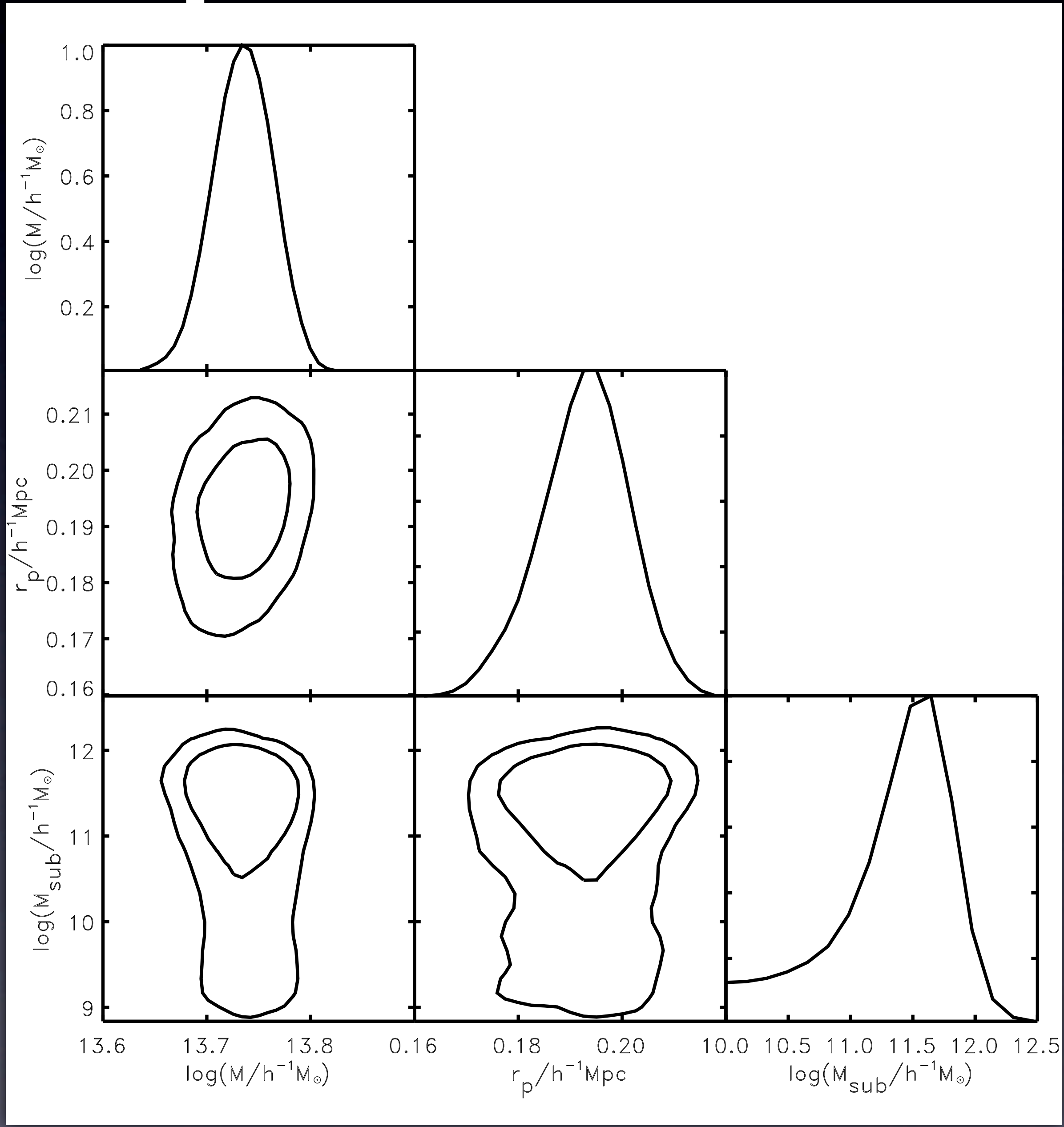


Li et al. 2013(in preparation)

Satellite lensing: CFHT/Stripe82



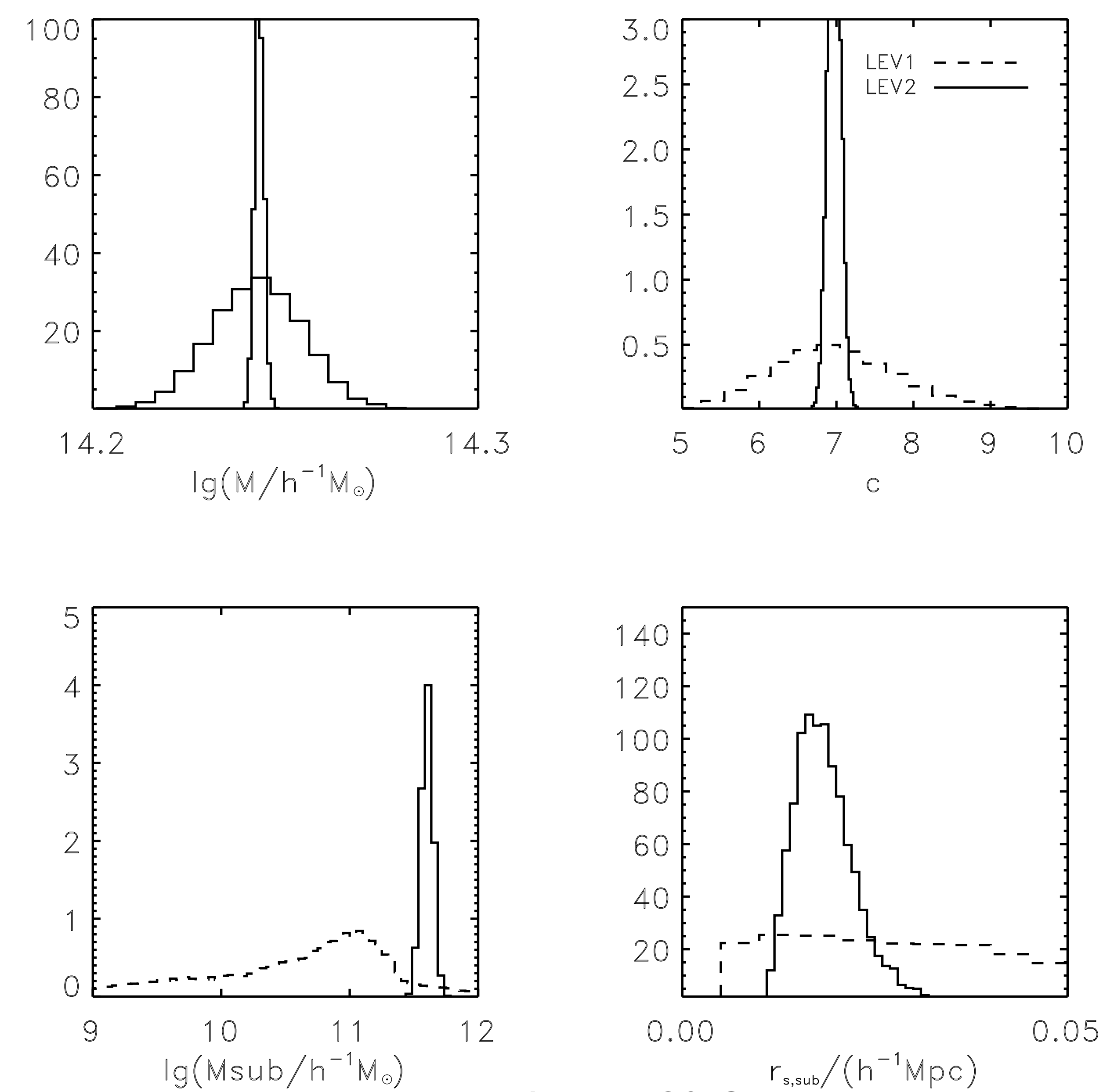
Lensing around satellites in groups with mass>10^13 solar mass



Li et al. 2013(in preparation)

Forecast LSST vs SDSS

- Both survey can constrain host halo mass and concentration in narrow range
- LSST can put tight constraints on subhalo mass



Li et al. 2013

HIGHER ORDER: FLEXION

$$\mathcal{F} = |\mathcal{F}|e^{i\phi} = \frac{1}{2}\partial\partial^*\partial\psi = \partial\kappa = \partial^*\gamma,$$
$$\mathcal{G} = |\mathcal{G}|e^{3i\phi} = \frac{1}{2}\partial\partial\partial\psi = \partial\gamma,$$

Bacon et al.

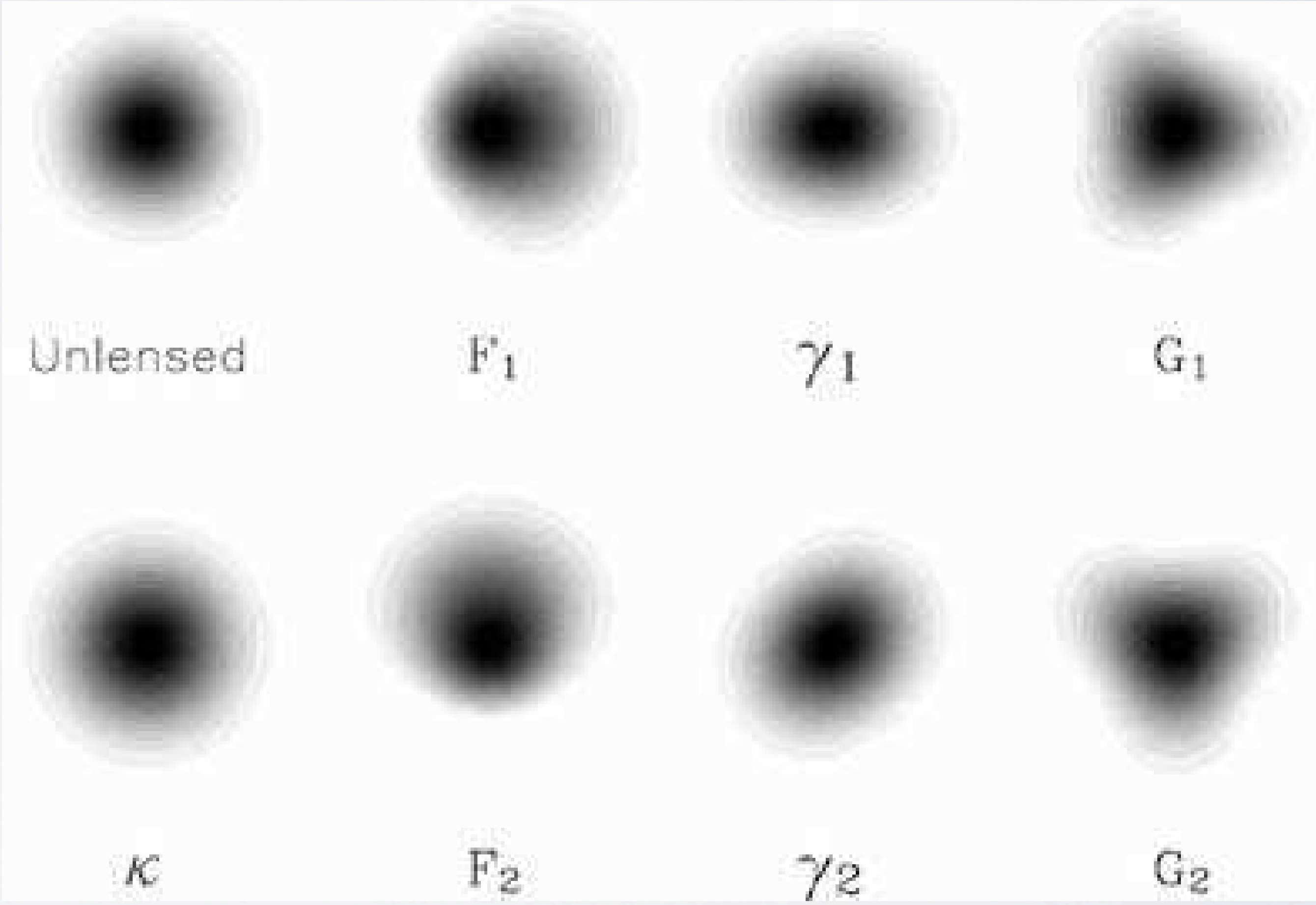
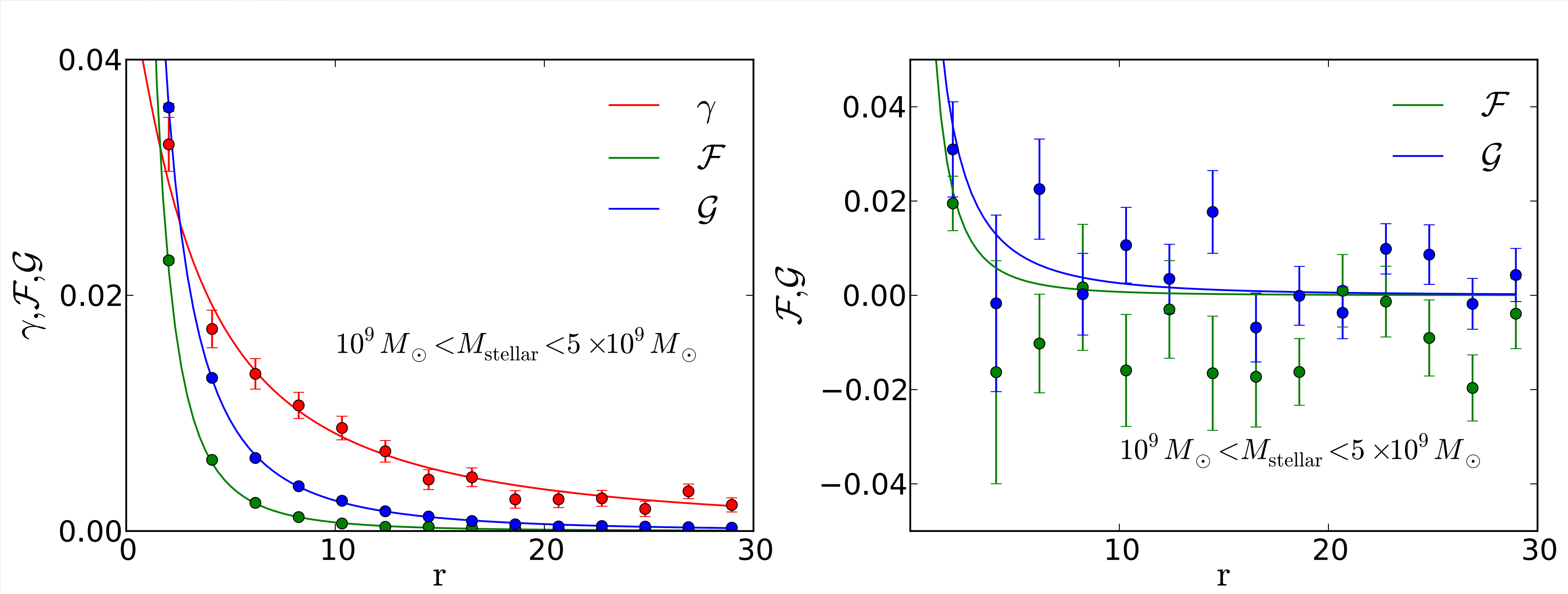
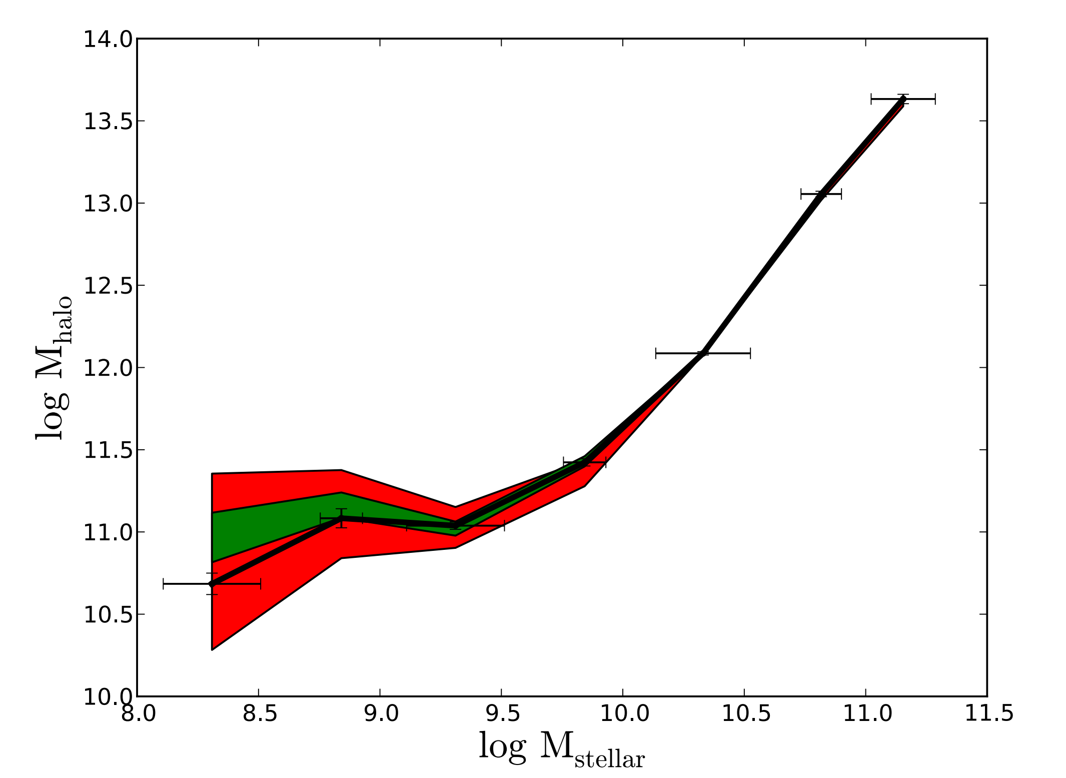


Figure 1. Weak lensing distortions with increasing spin values. Here an unlensed Gaussian galaxy with radius 1 arcsec has been distorted with 10 per cent convergence/shear, and 0.28 arcsec^{-1} flexion. Convergence is a spin-0 quantity, first flexion is spin-1, shear is spin-2 and second flexion is spin-3.

CONSTRAIN M/L WITH SHEAR +FLEXION





Constrains on M/L for field galaxies, assuming LSST like survey.

Nan Li, Ran Li and Xingzhong Er 2013

Conclusion

- Galaxy-galaxy is a promising tool to study dark matter halo structure.
- One can link theory and observation using group catalog and CLF.
- Next generation lensing survey will be able to constrain substructure
- Higher order: galaxy-galaxy Flexion
- Apply the methods to future observation data.

Thank You