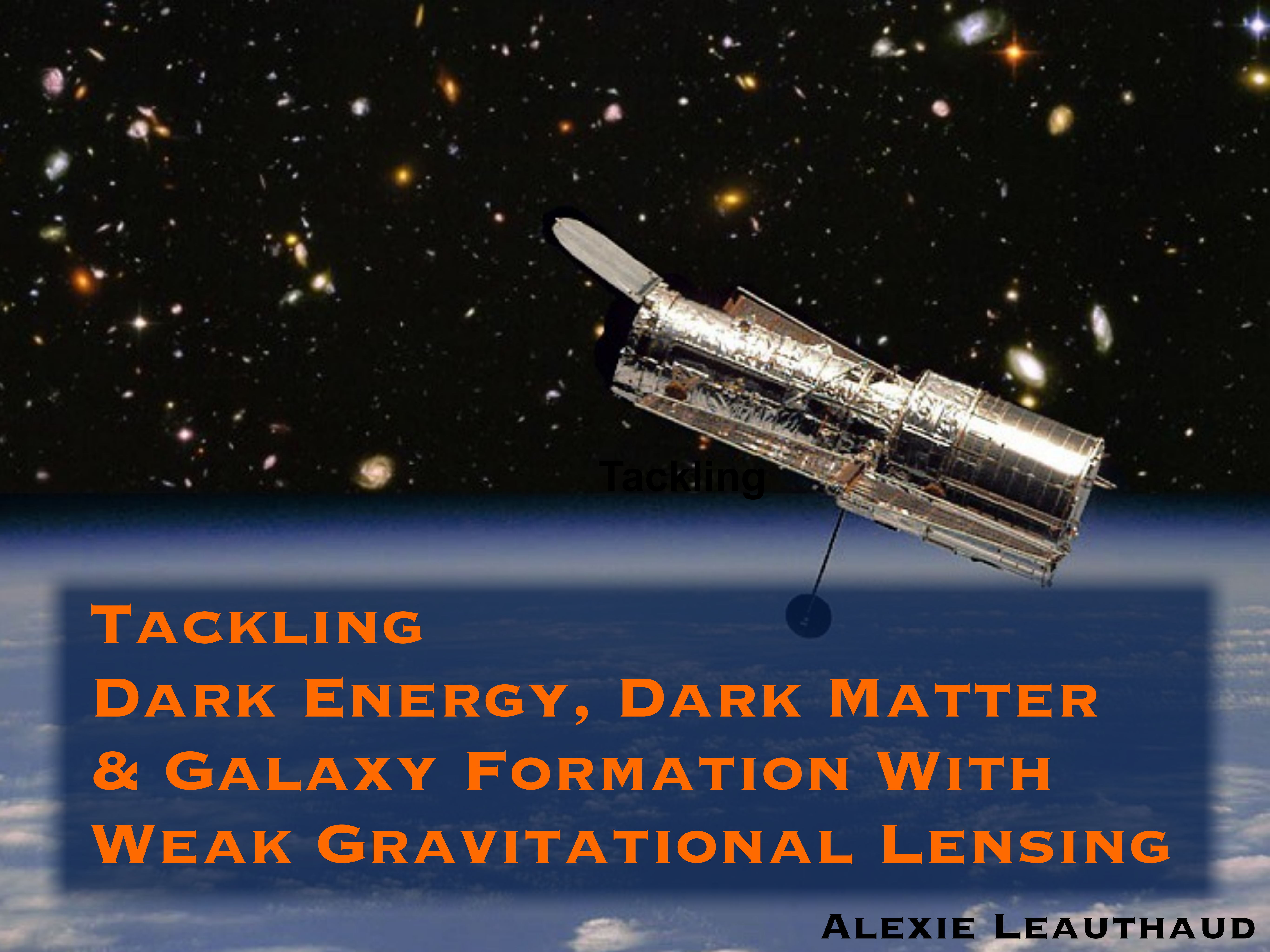


Tackling Dark Energy, Dark Matter & Galaxy Formation With Weak Gravitational Lensing

Alexie Leauthaud

Gravitational Lensing

Lensing Modifies Galaxy Shapes

Illustration of the lensing effect caused by a massive (invisible) object passing in front of galaxies in the Hubble Deep Field.

L. L. Christensen (ESA)

The Scientific Promise of Gravitational Lensing

I. Weak lensing by large-scale structure ('**Cosmic shear'**) → evolution of the non-linear power spectrum & constraints on cosmological parameters Ω_M, σ_8, w, w'…complementing and breaking degeneracies present in other methods (Super Novae, Cosmic Microwave Background).

II. Direct mapping of the dark matter distribution

III. Weak shear around galaxy clusters → estimate of total cluster mass study of dark matter profiles

IV. The average weak lensing shear of distant galaxies and groups (**'galaxy-galaxy lensing'**) → ensemble average properties of dark matter halos → connecting mass and light.

V. Measurements of the Hubble constant, H0.

Cosmic Acceleration Lensing Experiments

STAGE 2

CFHTLS : Canada / France / Hawaii, 170 deg^2

KIDS : Europe, 1000 deg^2, VLT.

STAGE 3 (now)

Pan Starrs : USA, Haleakala, 15000 deg^2

DES : USA, 5000 deg^2

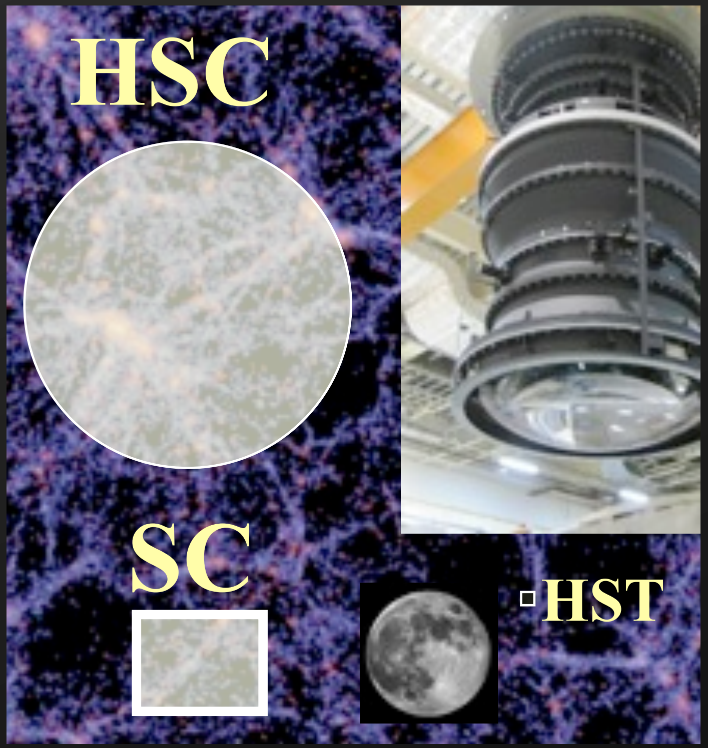
HSC : Japan, 1500 deg^2, Subaru on Mauna Kea

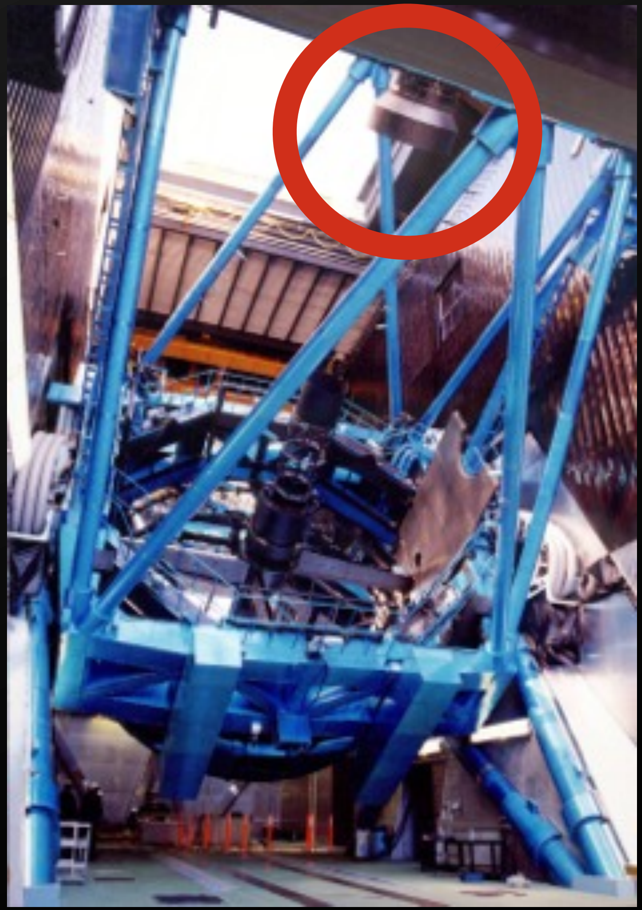
STAGE 4 (~2020)

EUCLID : space mission, Europe, 15000 deg^2

WFIRST : space mission, USA

LSST : USA, 20000 deg^2

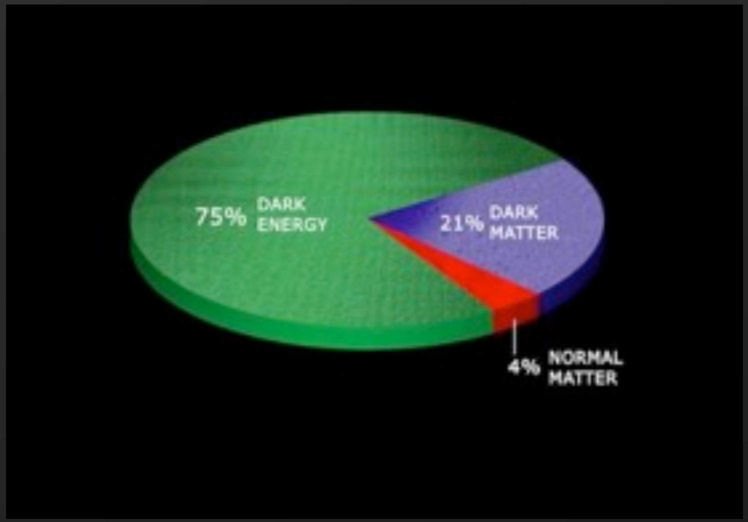




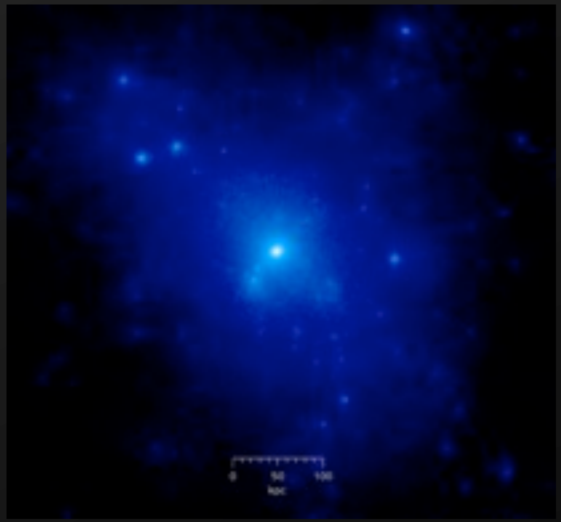
Outline

What do we learn from gravitational lensing about :

1. Dark Energy



2. Dark Matter



3. Galaxy Formation

Dark Energy

The acceleration of the Universe is, along with dark matter, the observed phenomenon that most directly demonstrates that our theories of fundamental particles and gravity are either incorrect or incomplete.

Peacock et al. 2006, ESA-ESO Working Group on "Fundamental Cosmology"

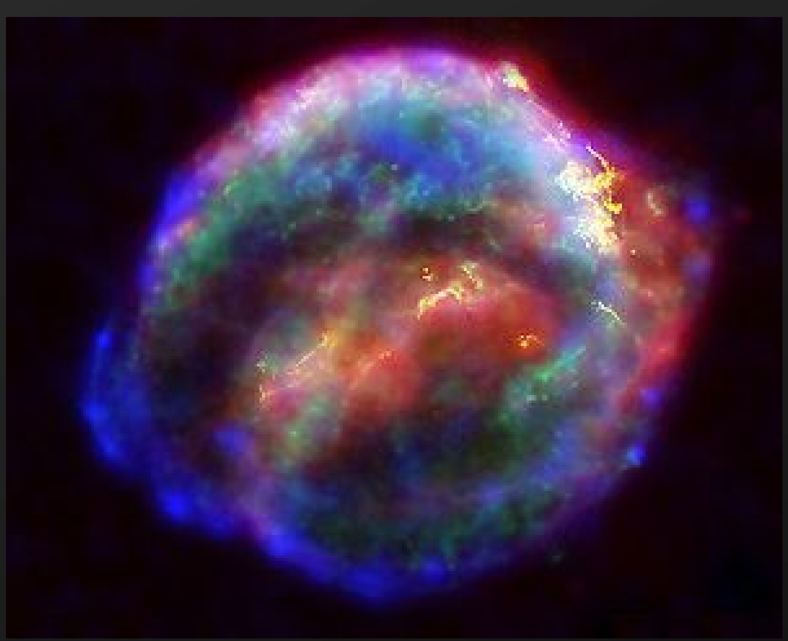
Dark Energy

1. Does acceleration arise from a breakdown of GR on cosmological scales or from a new energy component that exerts repulsive gravity within GR?

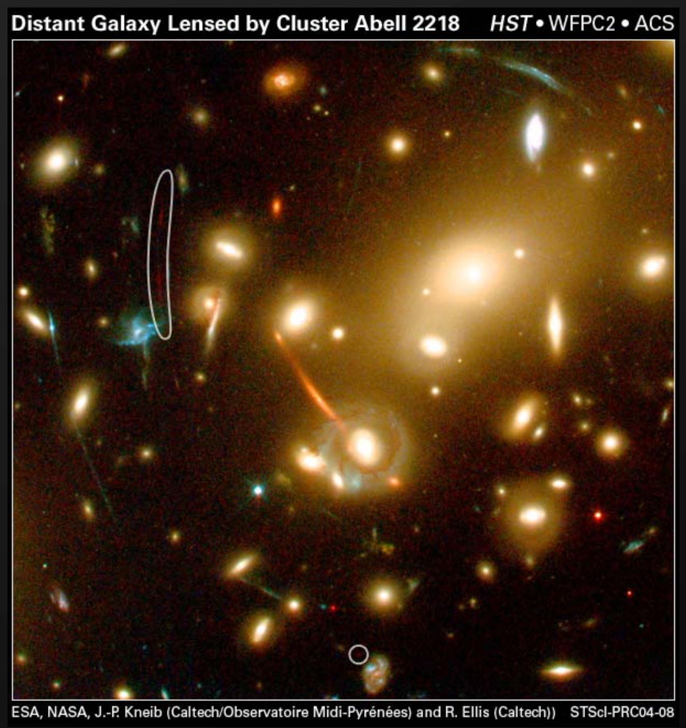
2. If acceleration is caused by a new energy component, is its energy density constant in space and time?

Four Probes of Dark Energy

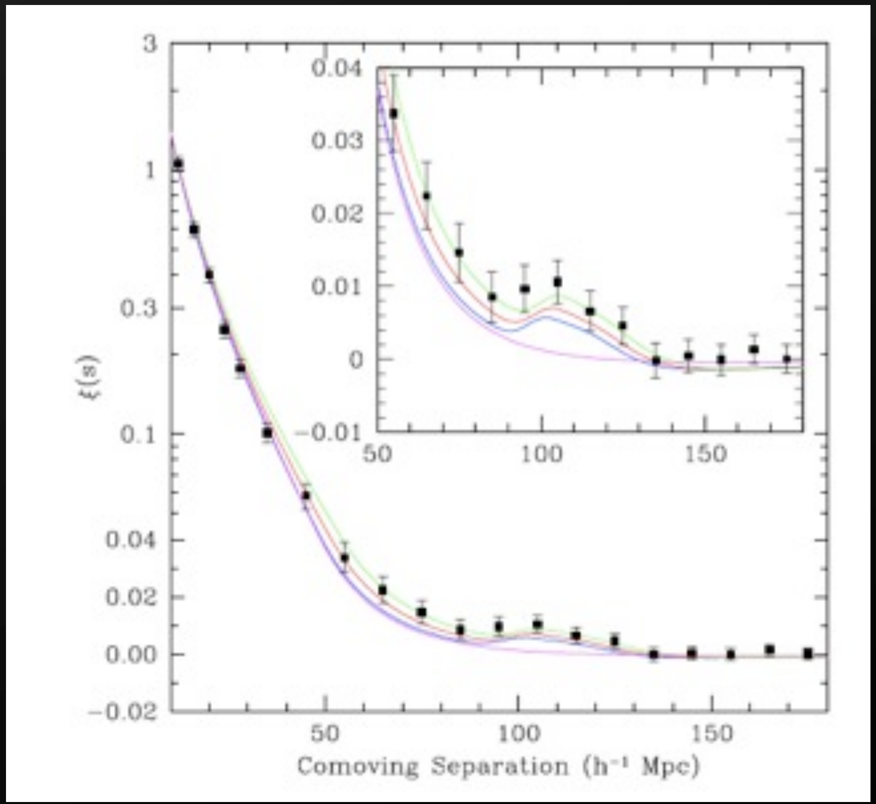
1. SNe Ia distance measurements
2. Baryon Acoustic Oscillation (BAO)
3. Abundance of galaxy clusters
4. Weak gravitational lensing of large-scale structure



SN 1604, Chandra & Spitzer



Amas Abell 2218
J.P Kneib & E.Ellis



BAO, Eisenstein et al. 2004

My Efforts in this Field

Traditional Methods

➡ **Shear tomography** - *(Leauthaud et al. 2007, Massey et al. 2007)*

➡ **Shear ratio** - constraints on Ω_λ *(Taylor et al. 2012)*

➡ **Clusters** - calibration of mass-observable relations *(Leauthaud et al. 2010)*

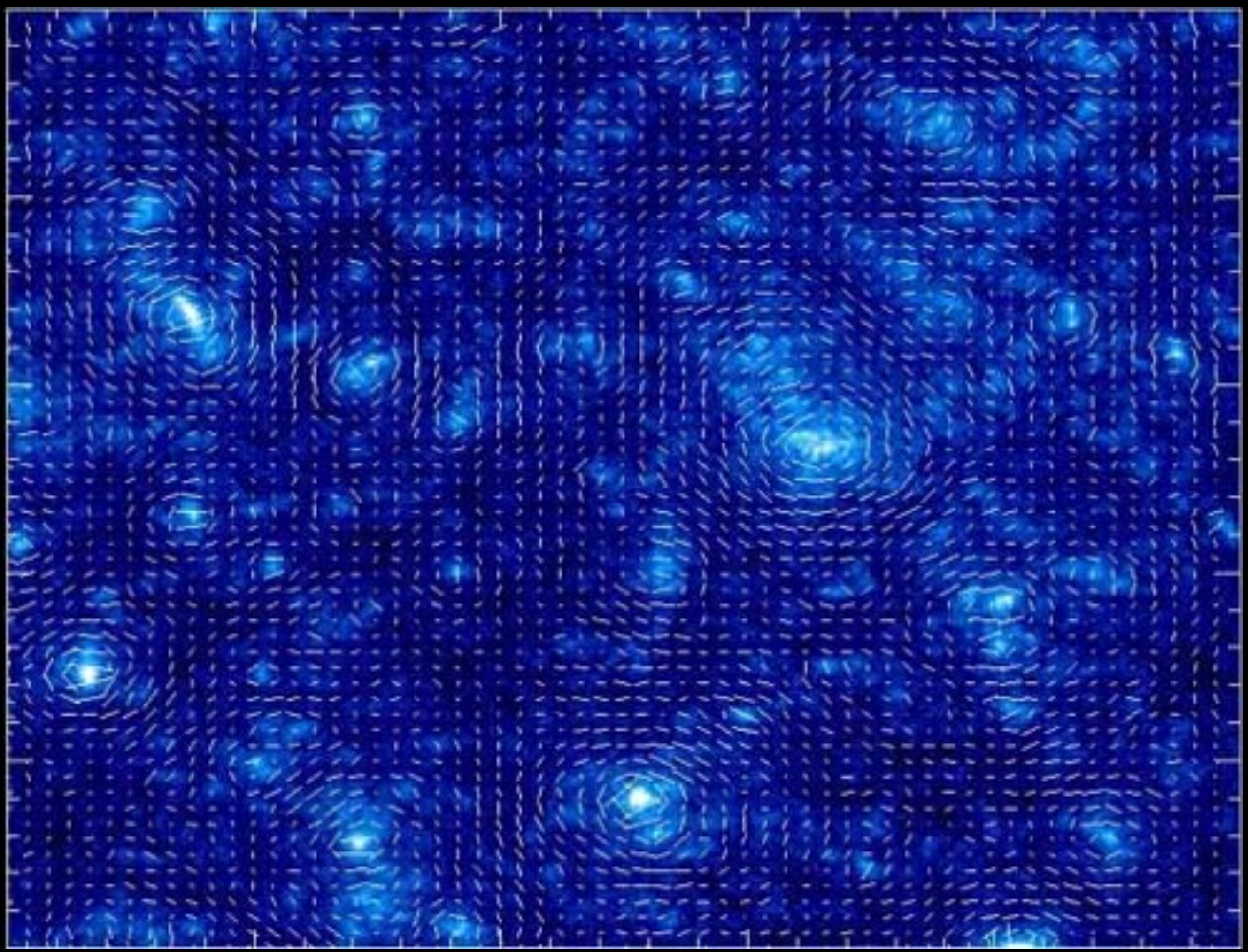
➡ **Clusters** - mis-centering effects *(George et al. 2011, George et al. 2012)*

Less Traditional methods

➡ **Probe combinations** - galaxy-galaxy lensing, clustering, redshift-space distortions *(Leauthaud et al. 2011, Leauthaud et al. in prep)*

➡ **Cross-correlations** - CMB lensing + shear *(Das et al. in prep)*

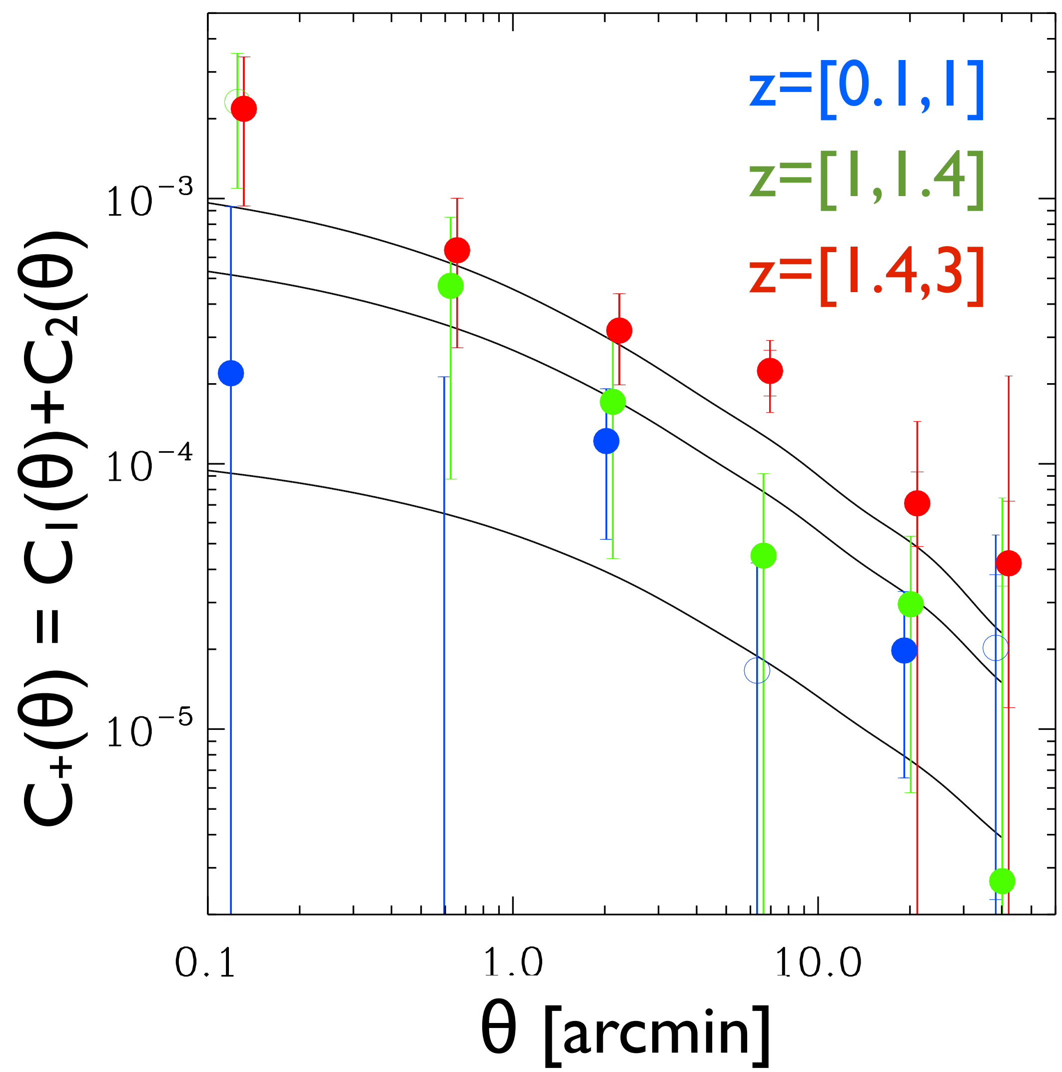
Lensing by a Diffuse Matter Distribution
'Cosmic shear' or 'Shear Tomography'



Shear field from dark matter simulation

Early Proof of Concept of Shear Tomography

Massey et al. 2007 Leauthaud et al. 2007, Rhodes et al. 2007



2d power spectrum of projected shear field :

$$C_\ell^\gamma = \frac{9}{16}\left(\frac{H_0}{c}\right)^4 \Omega_m^2 \int_0^{\chi_h} \left[\frac{g(\chi)}{D_A(\chi)}\right]^2 P(k,\chi)\, \mathrm{d}\chi,$$

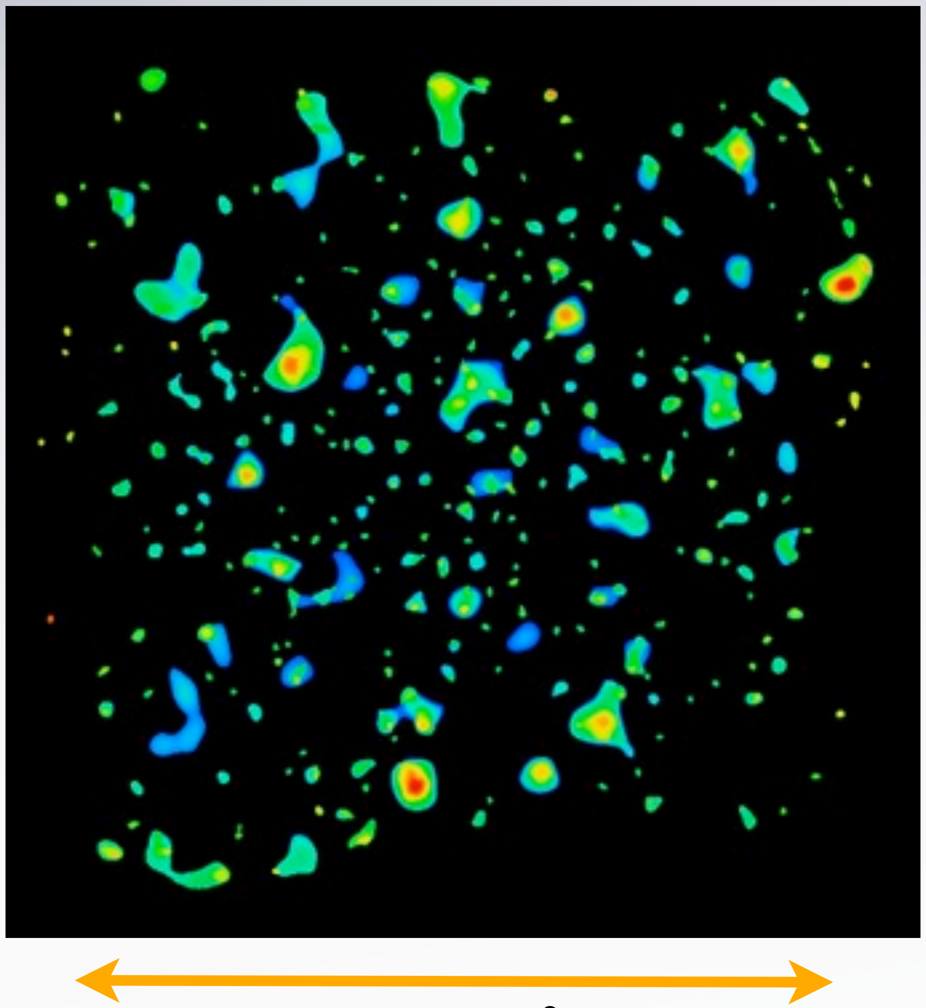
2pt shear correlation function :

$$\begin{aligned} C_1(\theta) &= \langle\, \gamma_1^r(\mathbf{r})\ \gamma_1^r(\mathbf{r}+\theta)\, \rangle \\ C_2(\theta) &= \langle\, \gamma_2^r(\mathbf{r})\ \gamma_2^r(\mathbf{r}+\theta)\, \rangle\ , \end{aligned}$$

$\sigma_8(\Omega_m/0.3)^{0.44} = 0.866$ +/- 0.075

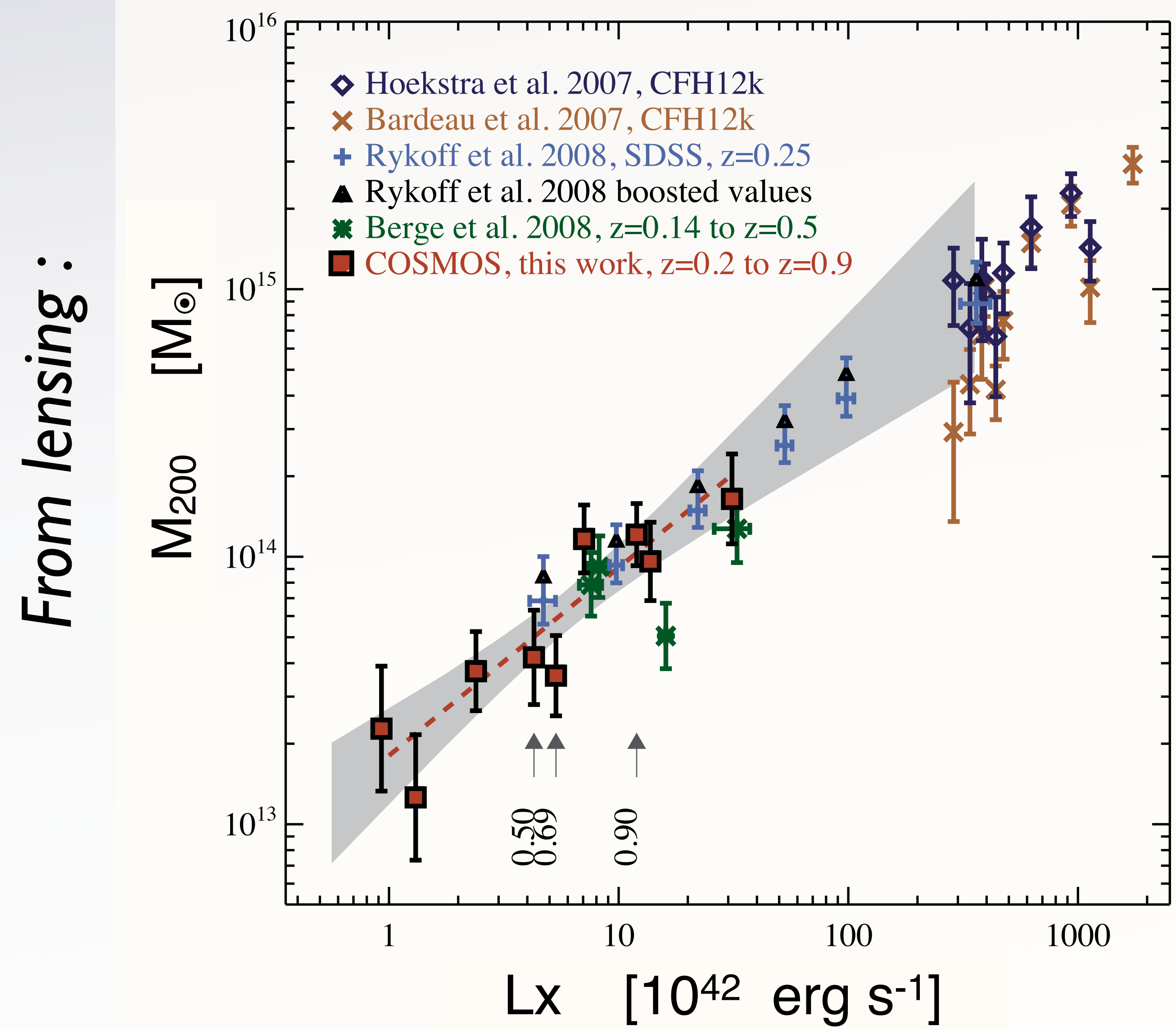
also see Schrabback et al. 2010

Improving Cluster Mass Estimates



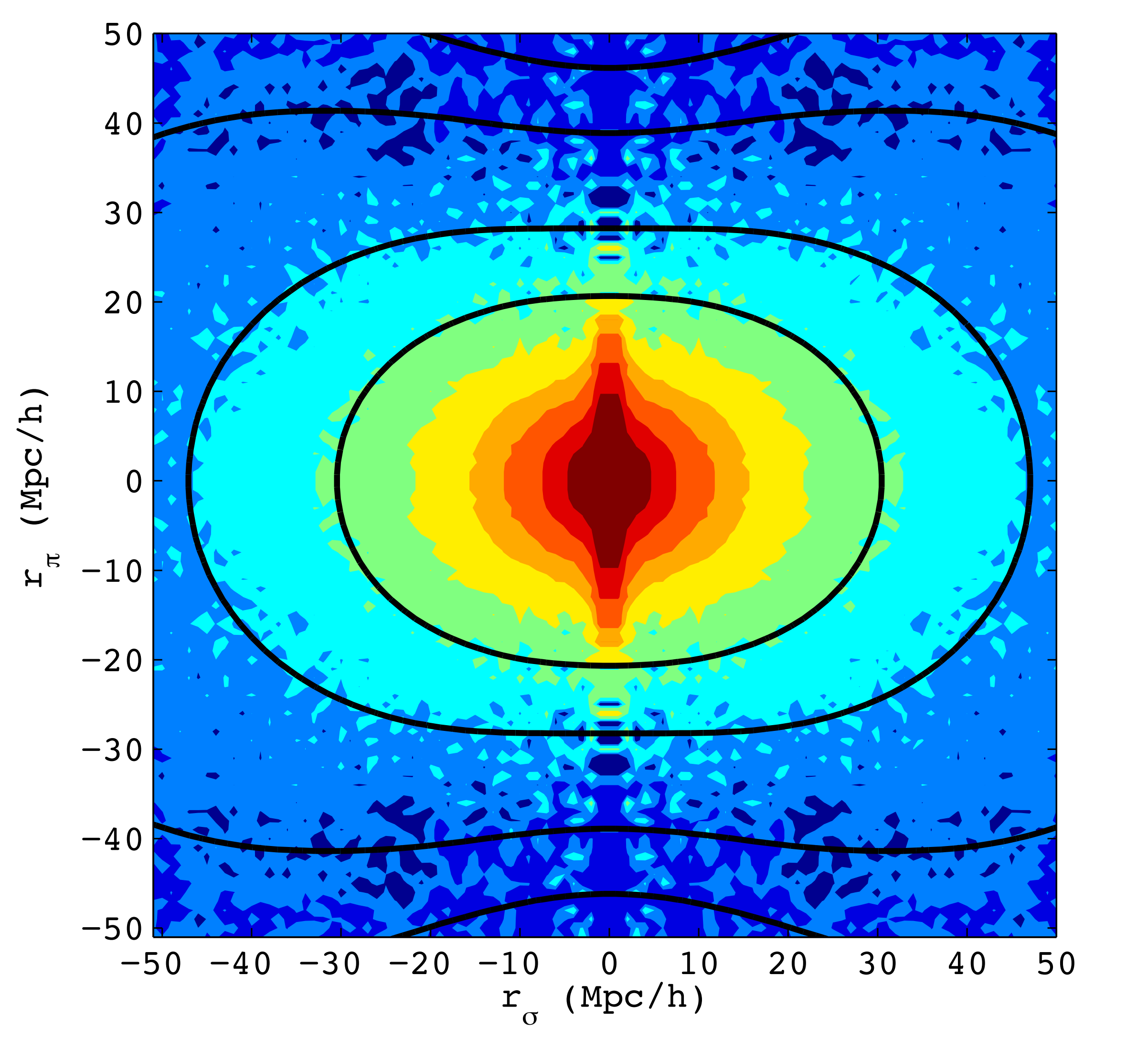
1.3 deg^2

~150 groups/clusters detected via extended XMM emission in the COSMOS survey.
One of the largest samples of it's kind. $M_{200} \sim 5.10^{13}$ M_{sun}.
(Finoguenov et al. 2007)



L_x-M_h relation down to $M_h=10^{13}$ $M_\odot$.
Improved constraints on slope of this relation.
(Leauthaud et al. 2010).

Redshift-Space Distortions



Two dimensional correlation function of BOSS galaxies, z=0.57
D_A, H(z), growth rate of structure
Reid et al. 2012

cosmological constraints from RSD & AP demands precise modeling of :

- *nonlinear evolution of matter density*
- *velocity field*
- *how galaxies trace these fields*

BOSS: strongest statistical constraints from smaller scales where there are a large number of independent samples.
$f.\sigma_8$ 6% at 60 Mpc and 1% at 10 Mpc

Statistical precision ≲ theoretical errors

Satellites : Fingers of God, affect ξ_2 at 10% level at 25 Mpc

Lensing, Clustering, & Redshift-Space Distortions

AL, Beth Reid, Martin White, Jeremy Tinker

- ➡ Lensing & clustering = cosmological probe *(e.g, Cacciato et al. 2012)*
- ➡ & redshift-space distortions = modified gravity (e.g, *Reyes et al. 2012*)
- ➡ Tremendous S/N gain at small scales. Modeling is more complicated.
- ➡ WFIRST SDT report : lensing FOM **200** ⇒ **580** when using smaller scales

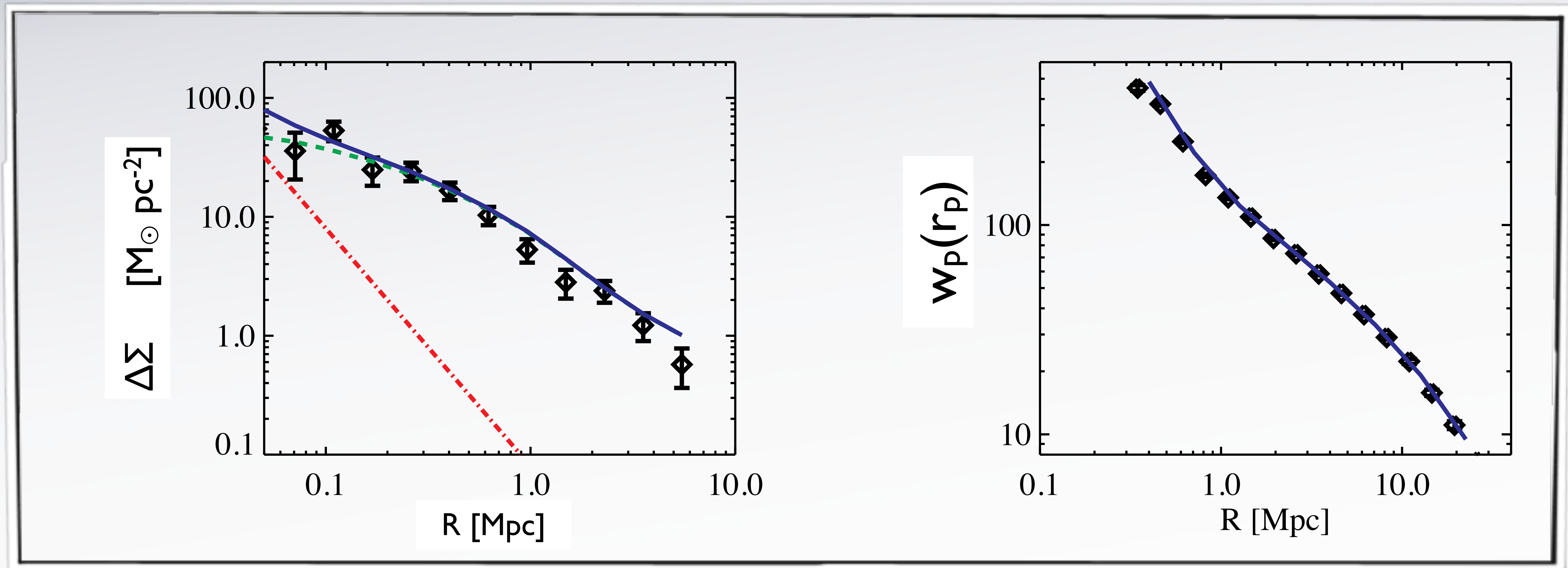
IN PREP:

➡ Lensing + Clustering + RSD at R<40 Mpc.
Use N-body simulations directly for the theoretical model (by-pass analytical modeling).

Galaxy-galaxy lensing of BOSS galaxies. From the CS82 survey of Stripe 82 .
1/10th HSC area
(Leauthaud et al. in prep)

Lensing & Clustering of Boss Galaxies

AL, Beth Reid, Martin White, Jeremy Tinker



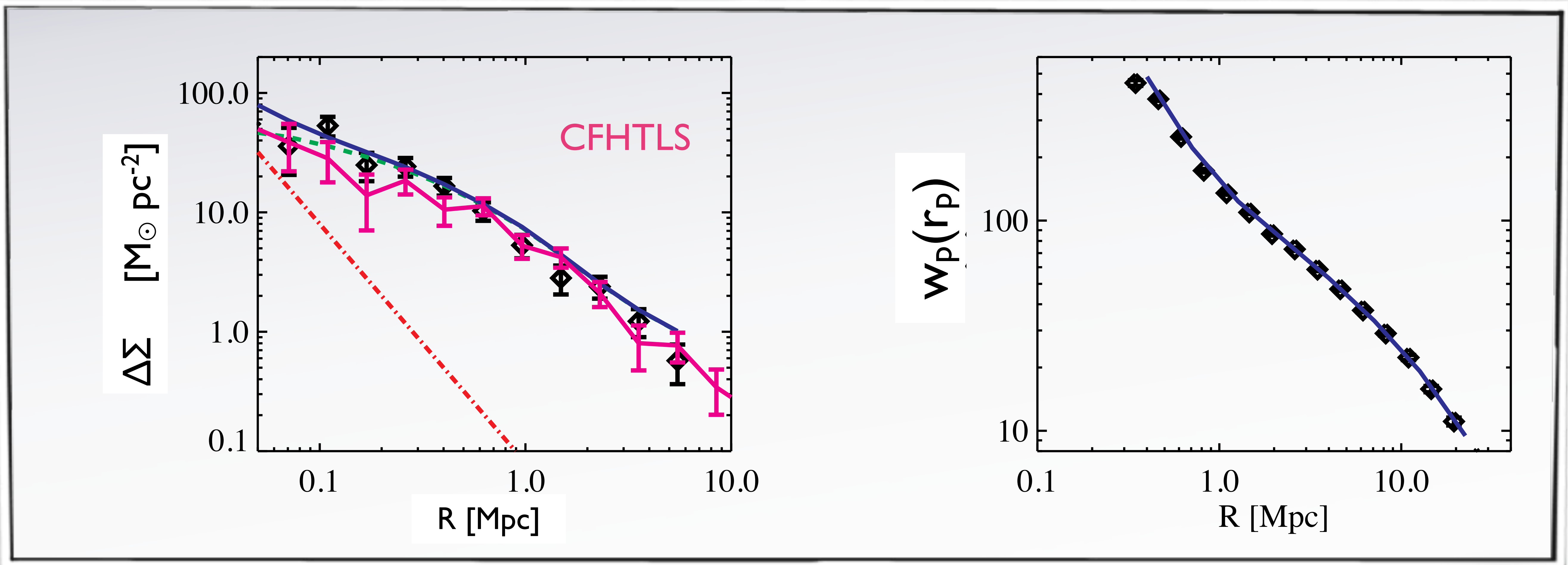
- Note: this is just a 'by eye' HOD fit
- Also plan to fit monopole ξ_0 and quadrupole ξ_2
- Divide by stellar mass

Preliminary

- ***Reid et al 2013: small-scale redshift space clustering of CMASS***
- ***Leauthaud et al. 2013: lensing + redshift space clustering***

Lensing & Clustering of Boss Galaxies

AL, Beth Reid, Martin White, Jeremy Tinker



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Preliminary

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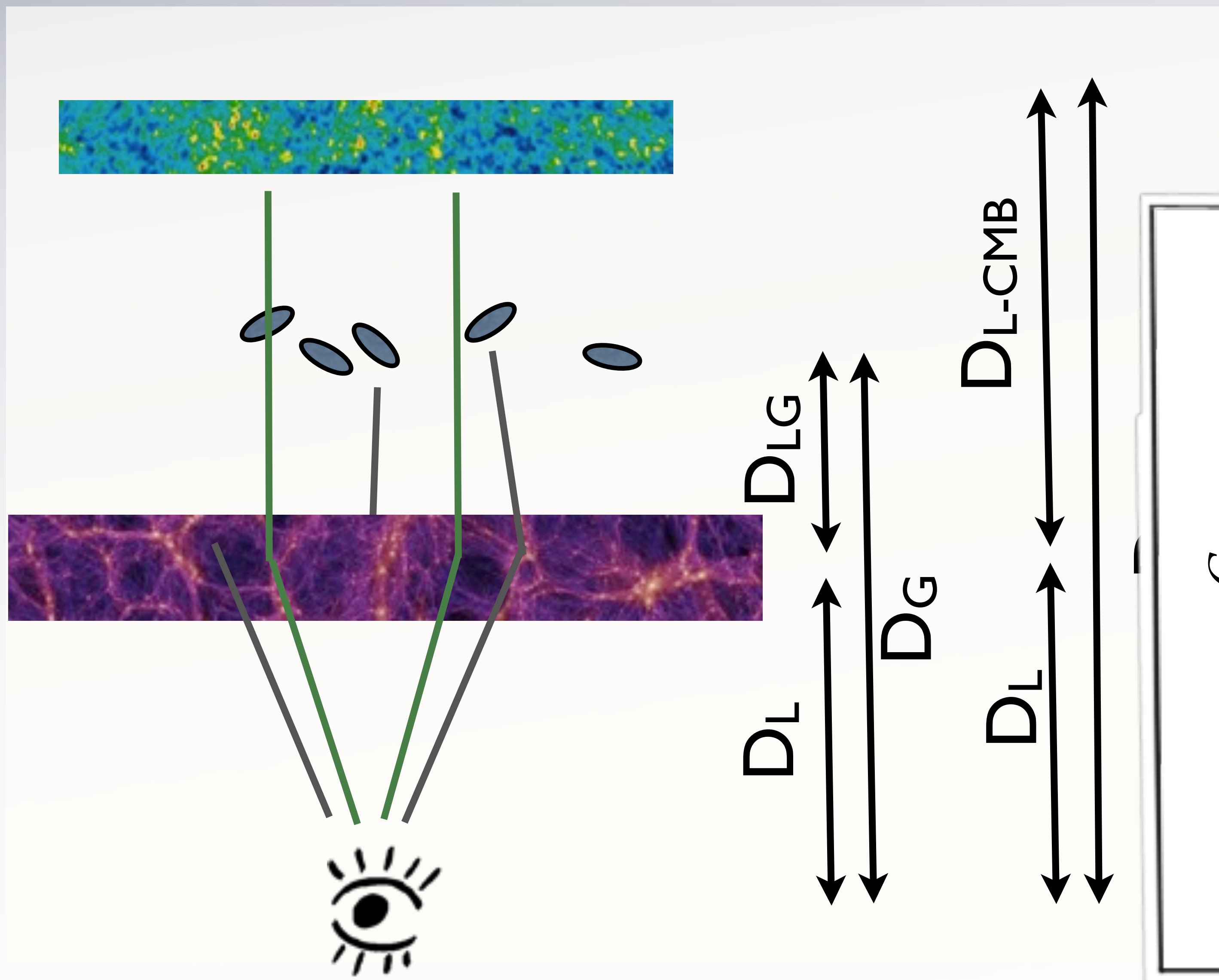
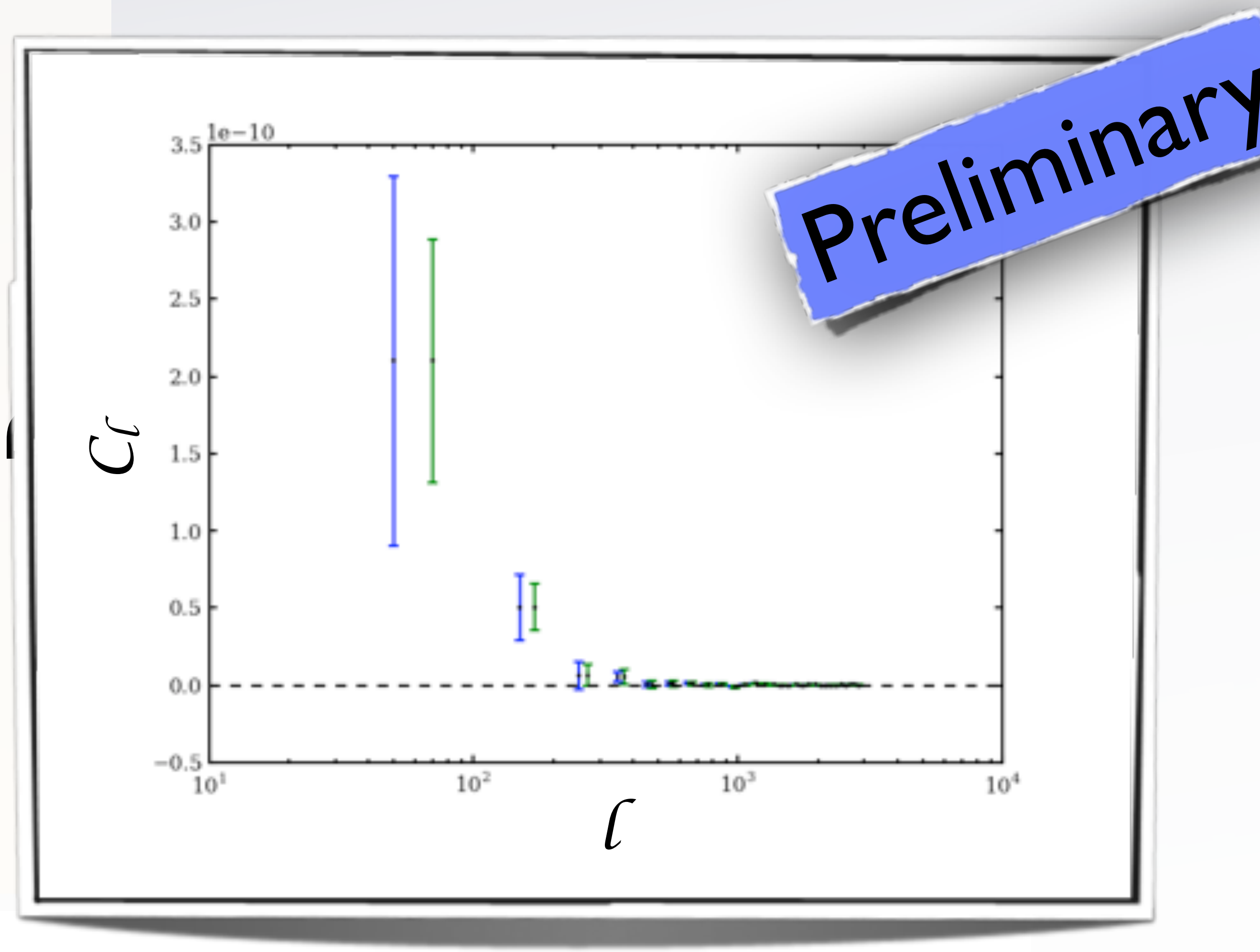
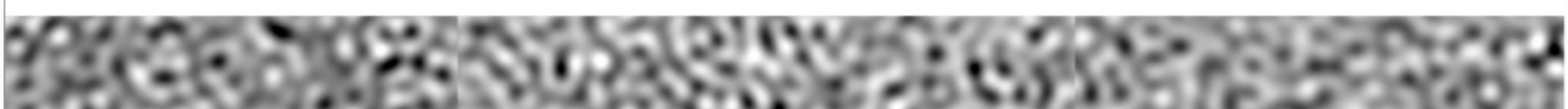
CMB-Lensing Galaxy Cross Correlations

Das, Leauthaud, Hand et al. in prep







ACT Kappa map

Galaxy Kappa map

Dark Matter

λCDM Predictions for Dark Matter Halos

➡ Universal profile for DM halos *(Navarro et al. 1997, 2012)*

➡ Correlation between halo mass & concentration $C \sim Mh^{\alpha}$

(Bullock et al. 2001, Wechsler et al. 2002, Maccio et al. 2007)

➡ Triaxial shapes with b/a~0.7 *(Jing & Suto 2002)*

All three predictions can be tested using weak lensing.

Clusters at $M_h > 10^{14}$ & $z < 0.8$

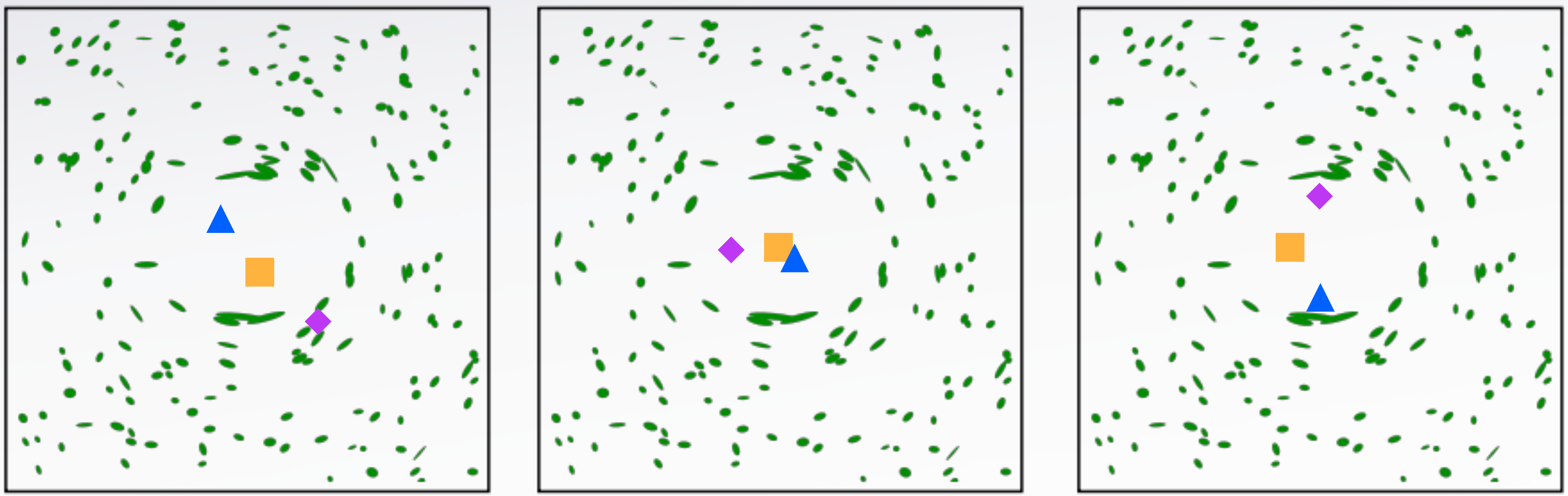
- **HSC = 7000**
- **DES = 24,000**
- **EUCLID = 70,000**

➡ **TREMENDOUS STATISTICS USING STACKED LENSING.**

Finding the Centers of Dark Matter Halos

George, AL, et al. 2012

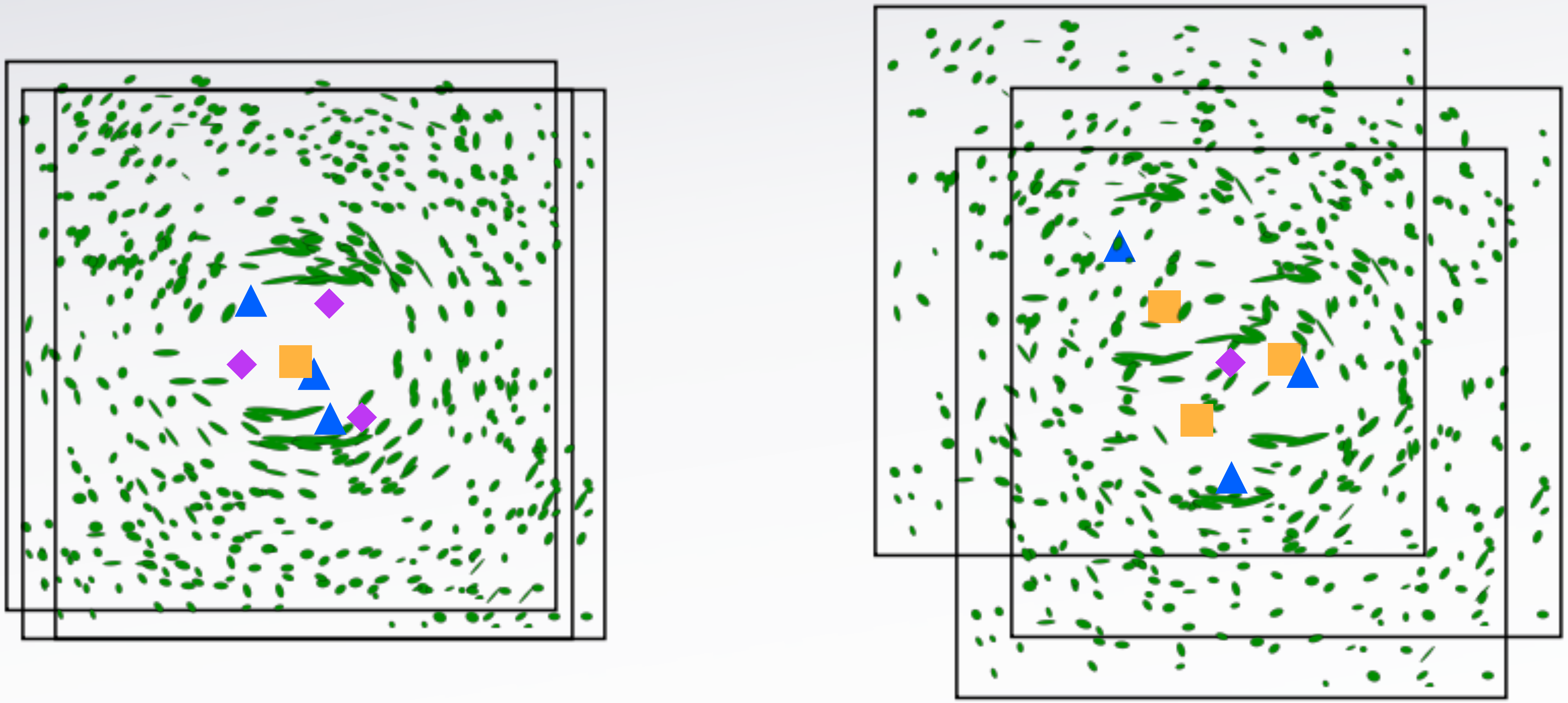
Cluster 1 | Cluster 2 | Cluster 3



1. Determine centers
2. Measure shapes of background sources
3. Stack on centers

Finding the Centers of Dark Matter Halos

George, AL, et al. 2012



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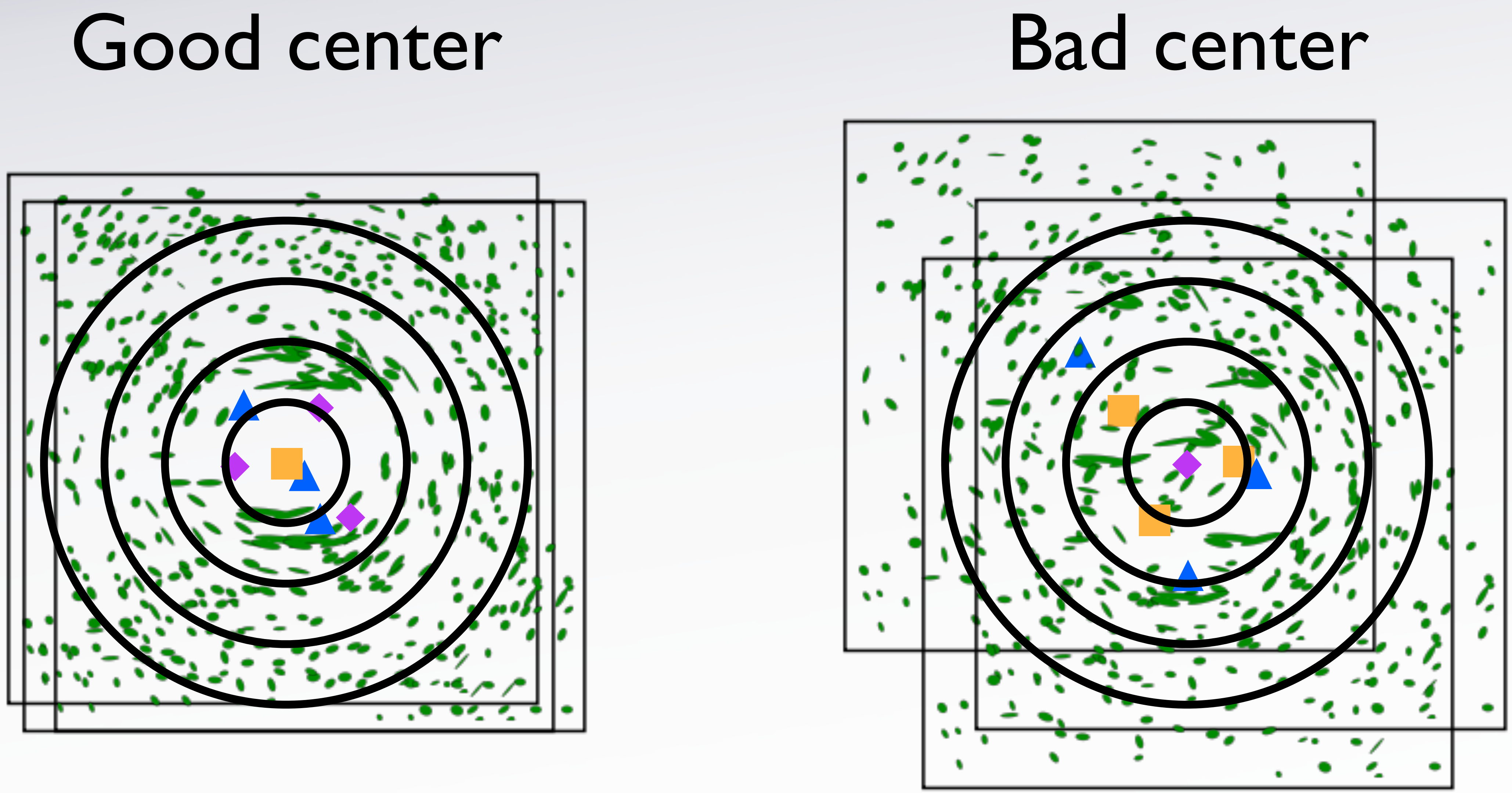
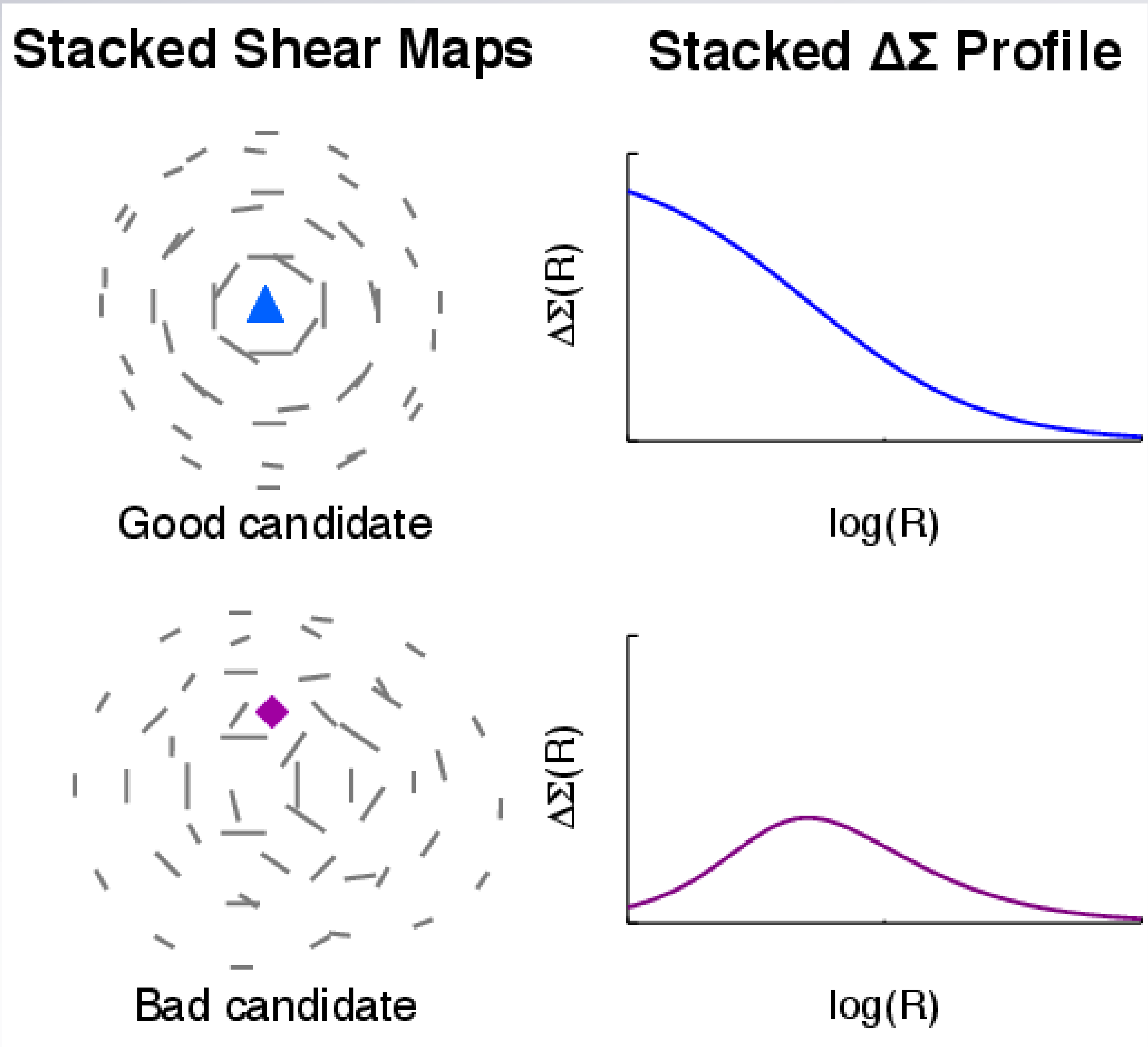
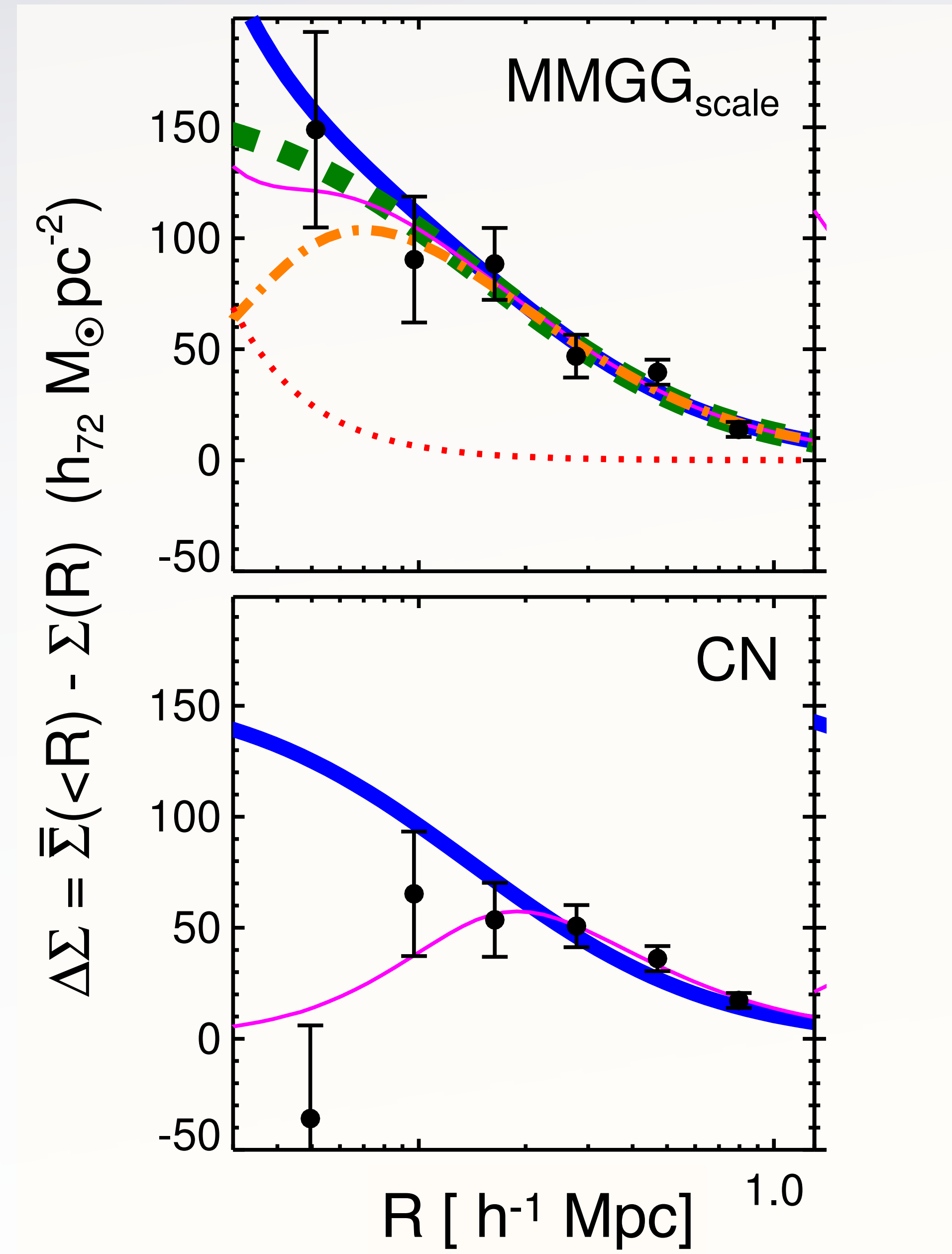
George, AL, et al. 2012



1. Determine centers ▲ ■ ◆
2. Measure shapes of background sources
3. Stack on centers ■

Finding the Centers of Dark Matter Halos



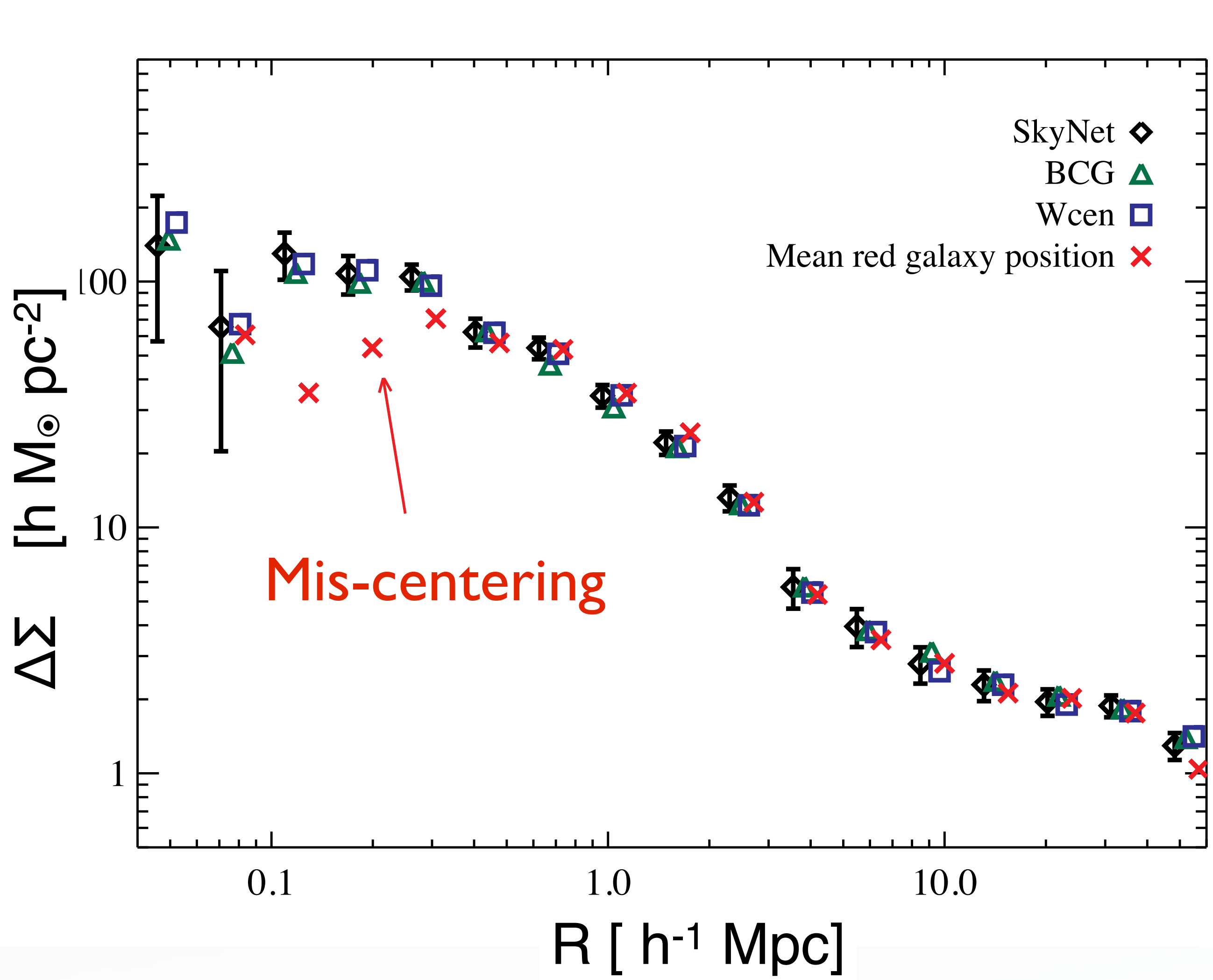


Demonstrating the power of stacked weak lensing to improve centroid algorithms for galaxy clusters (George, AL, et al. 2012).

➠ *Will lead to improved constraints on halo profiles & concentrations*

A Sample of 800 Clusters in Stripe 82

Large sample to z=0.7. Test-bed for HSC/DES/Euclid.



Effects of mis-centering on weak lensing measurements of halo profiles.

Currently :

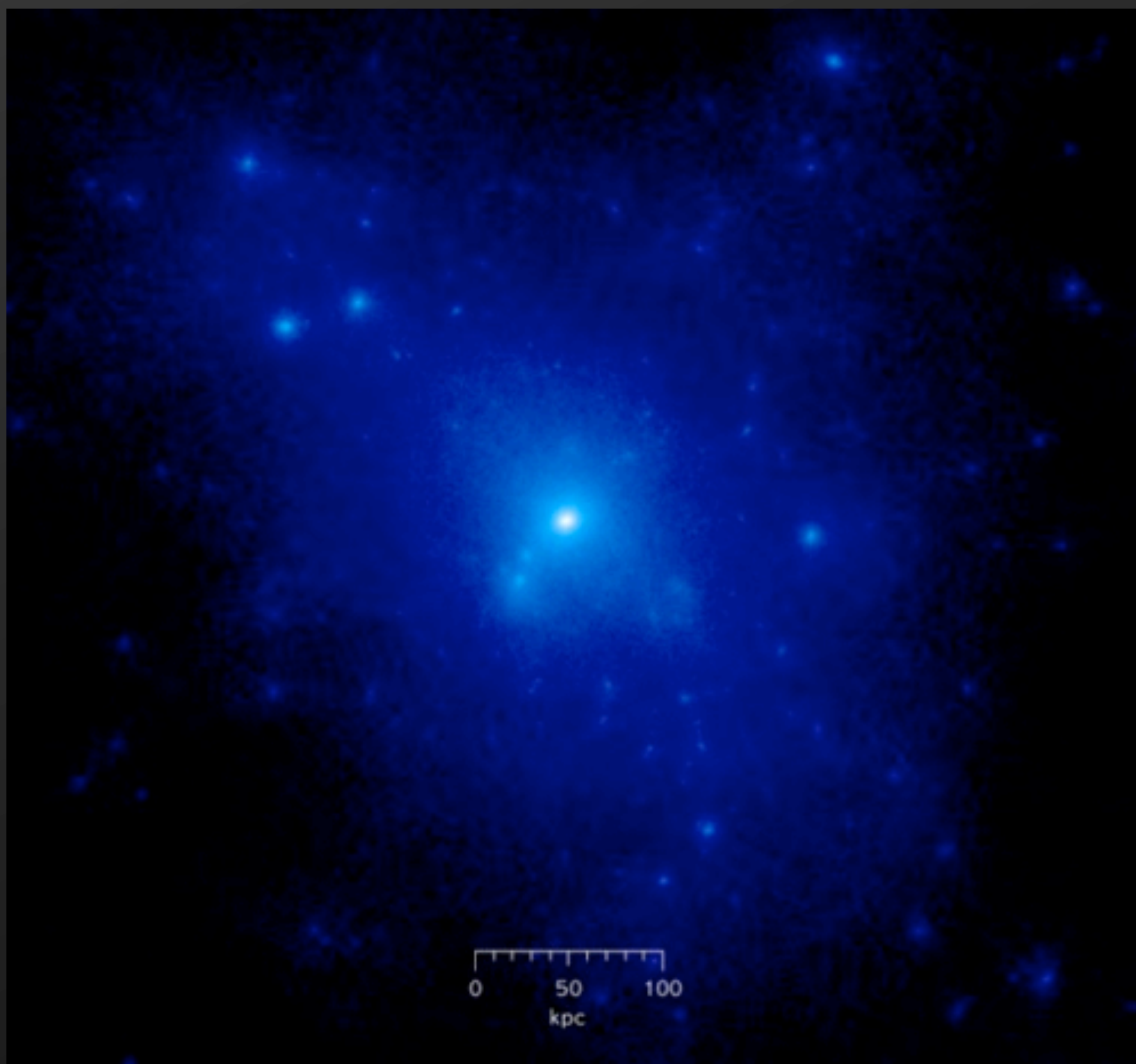
- Improve centroid schemes via lensing
- Visual inspection of central galaxies
- Color bias in central galaxy selection?
- Richness-Mh relation to z=0.7

Future :

- Add clustering information for centering
- Use stacked weak lensing to improve the identification of mergers and fragmented systems (tests using N-body simulations)
- Constraints on halo concentration

Detecting Cluster Tri-axiality?

AL, Takada M, Oguri M, Mineo S, Katayama N, Okabe N



Traditional method: azimuthal variation in tangential shear *(Natarayan & Refregier 2000)*

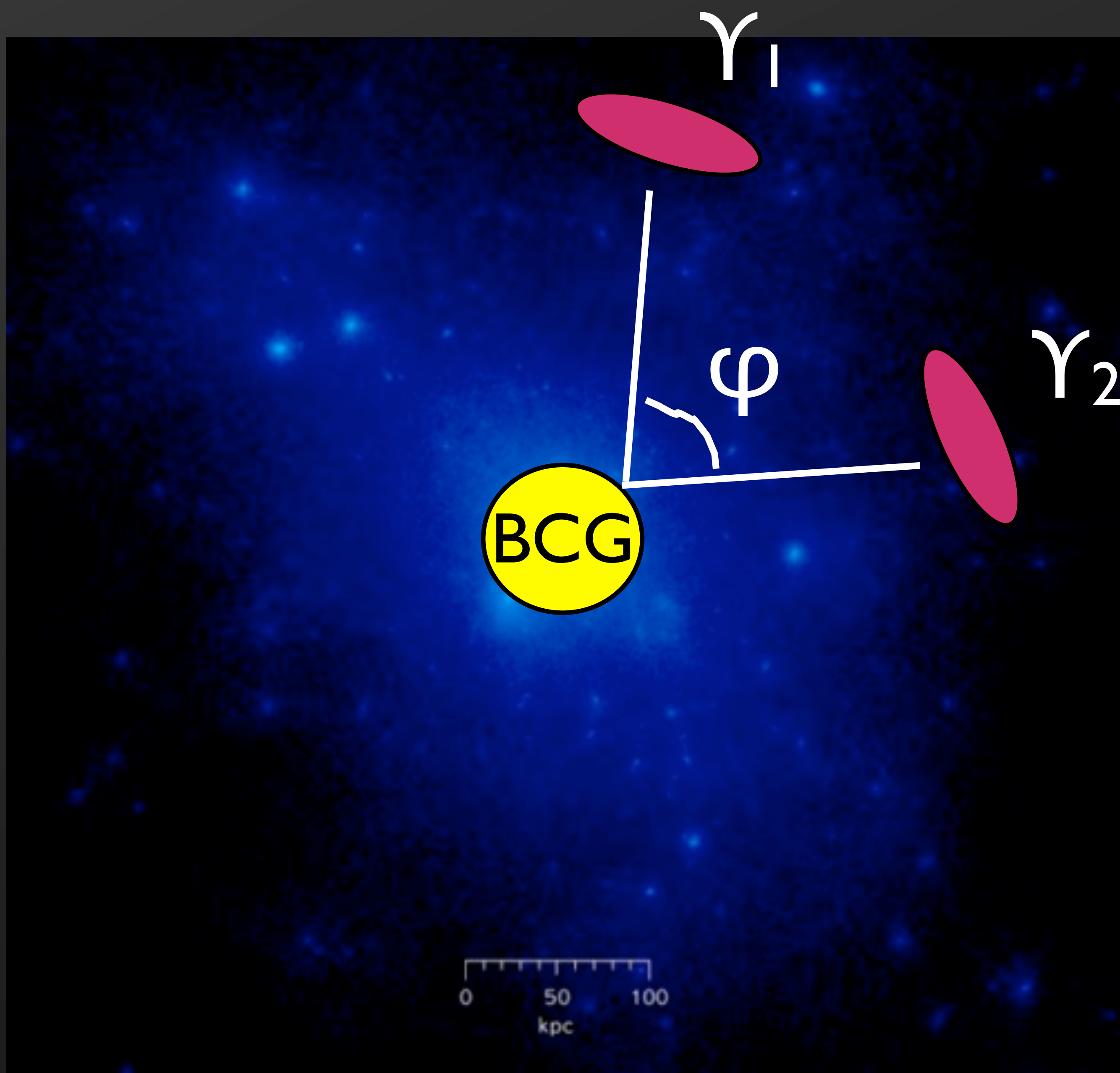
Relies on optical axis for stacking. Signal washed out with galaxy-halo mis-alignements.

Investigating new methods to probe halo ellipticity based on 3-pt correlation functions. No assumption about alignments between baryons and dark matter.

Leauthaud et al. in prep, Mineo et al. in prep

Detecting Cluster Tri-axiality?

AL, Takada M, Oguri M, Mineo S, Katayama N, Okabe N



Can we use the 3pt correction function $< \gamma_1 \times \gamma_2 >$ to detect :

- ➡ Halo triaxiality?
- ➡ Sub-structure?
- ➡ Filamentary structure?

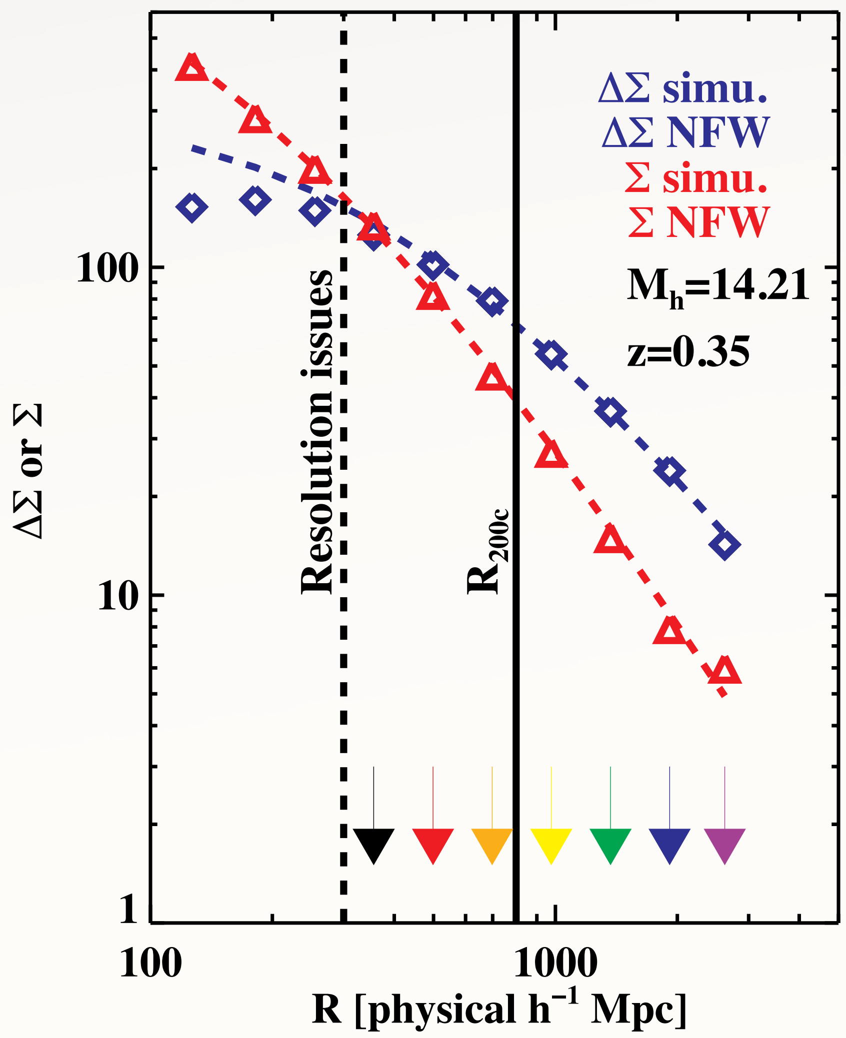
A direct probe of λCDM predictions for dark matter halos!

Leauthaud et al. in prep, Mineo et al. in prep

Detecting Cluster Tri-axiality?

Preliminary

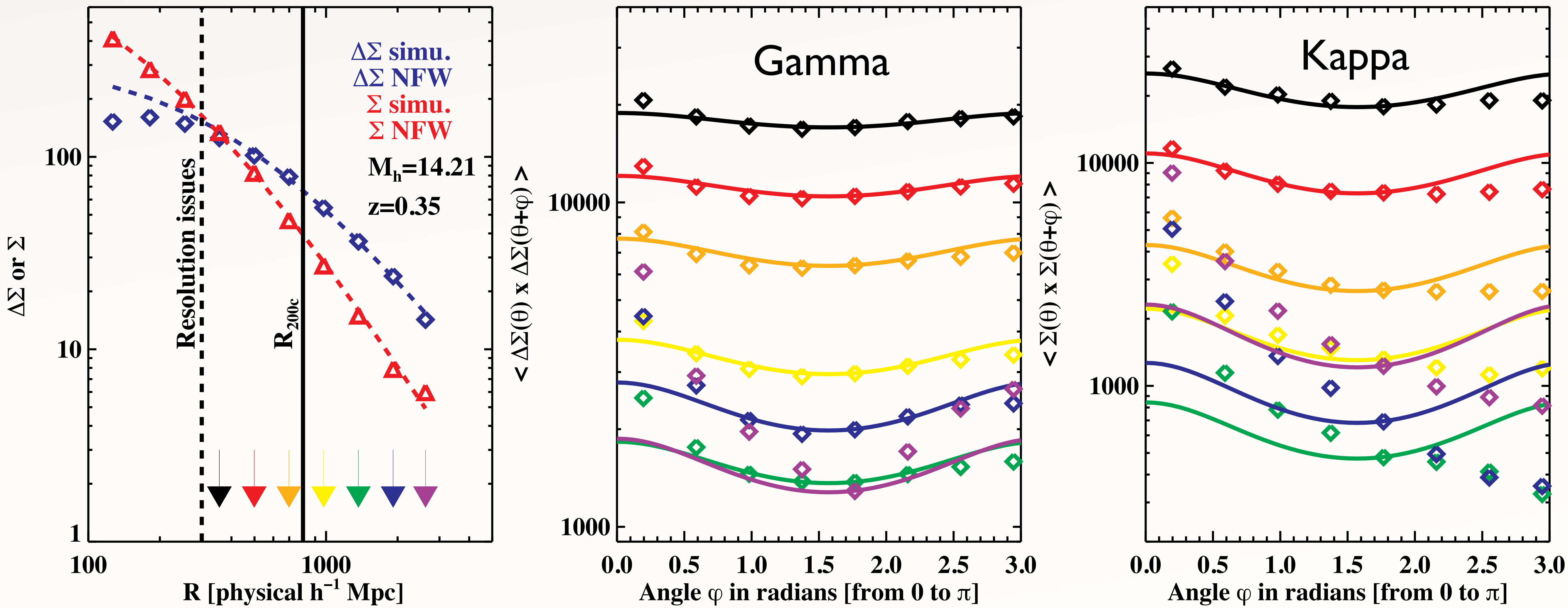
From N-body simulations :



Detecting Cluster Tri-axiality?

Preliminary

From N-body simulations :



Detecting Cluster Tri-axiality?

Preliminary

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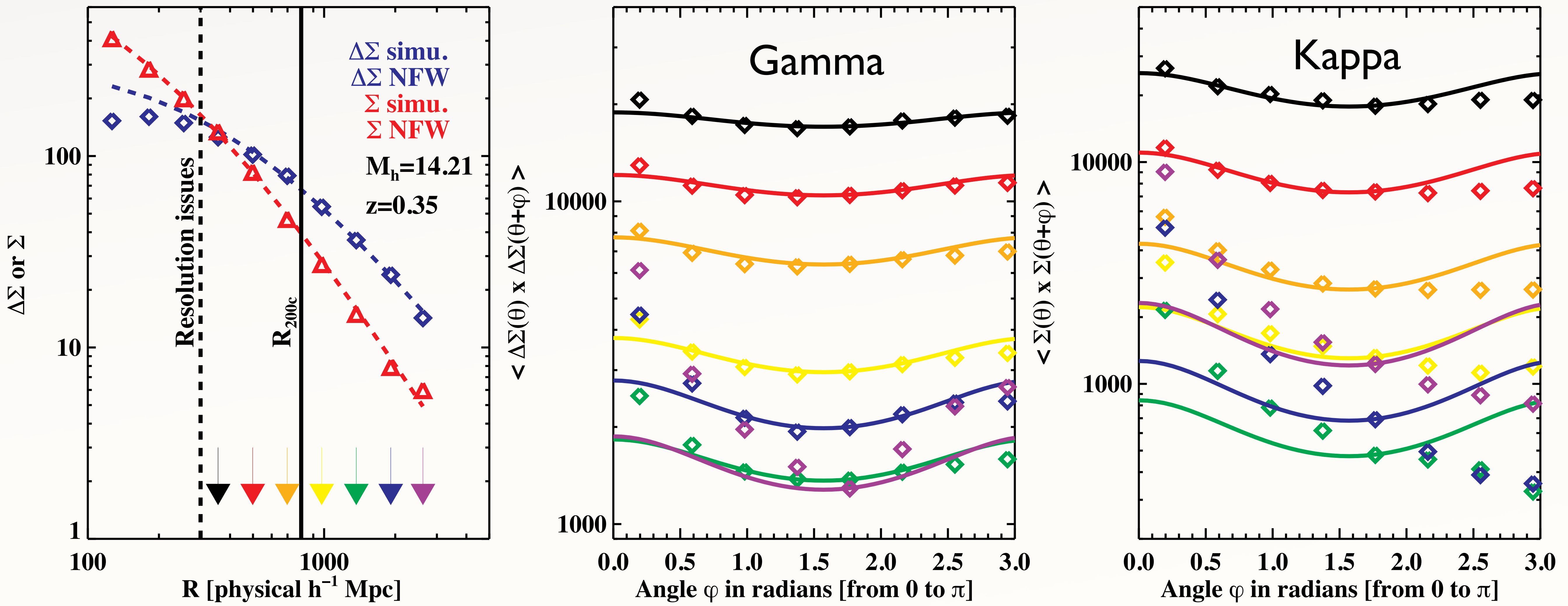
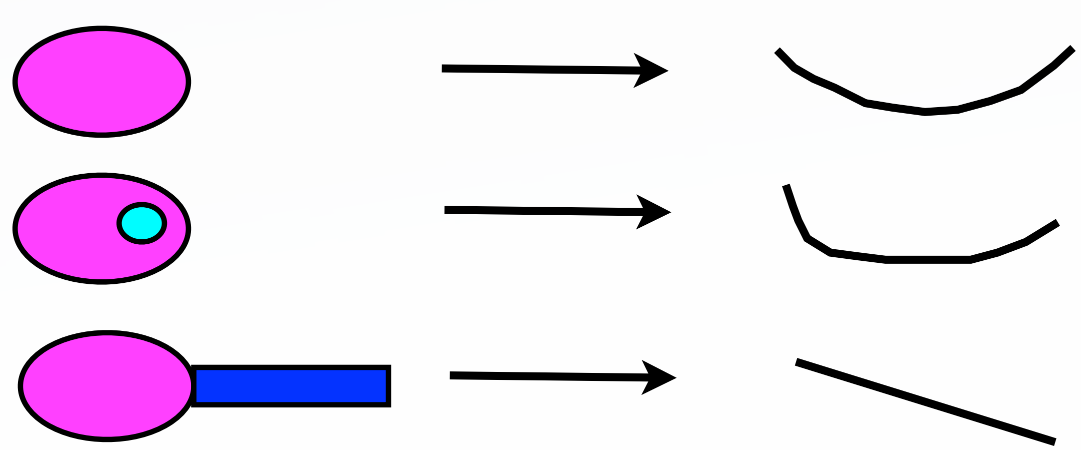
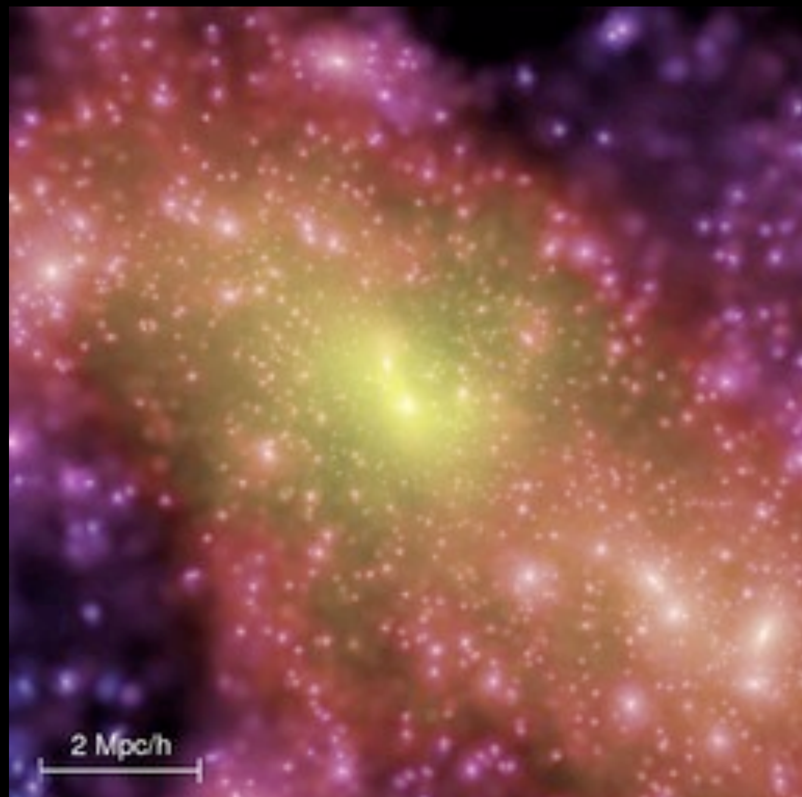
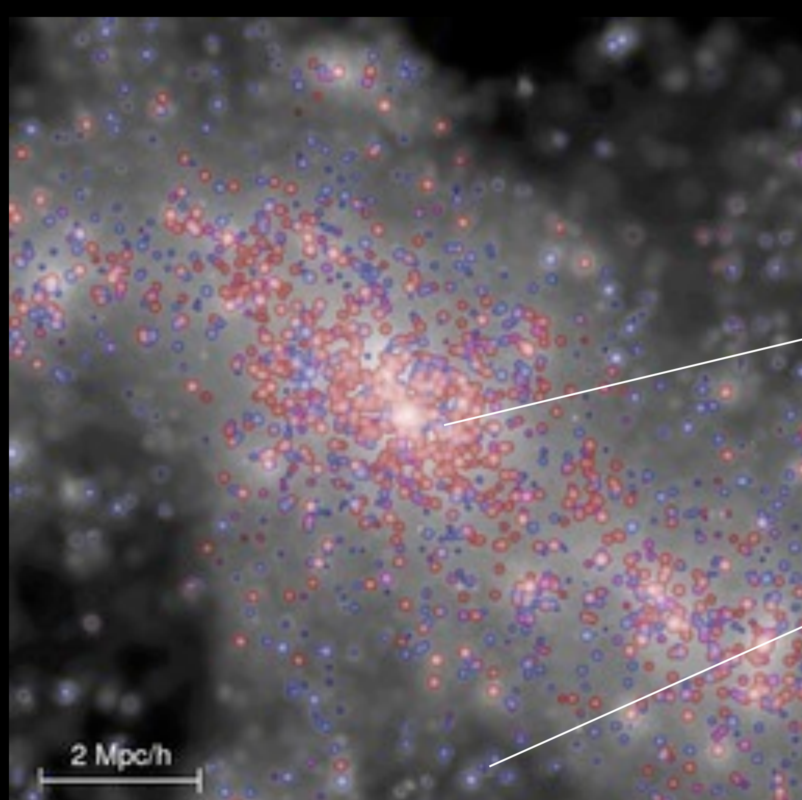




Galaxy Formation

Connecting Galaxies to Dark Matter





30kpc

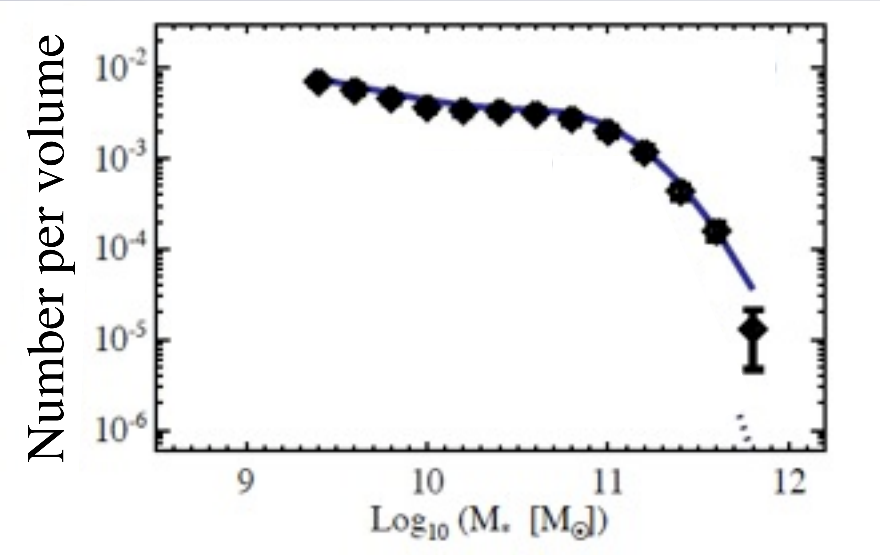
ELLIPTICAL

SPIRAL

IRREGULAR

Combining Lensing + Clustering

Leauthaud et al. 2011



The galaxy stellar mass function :

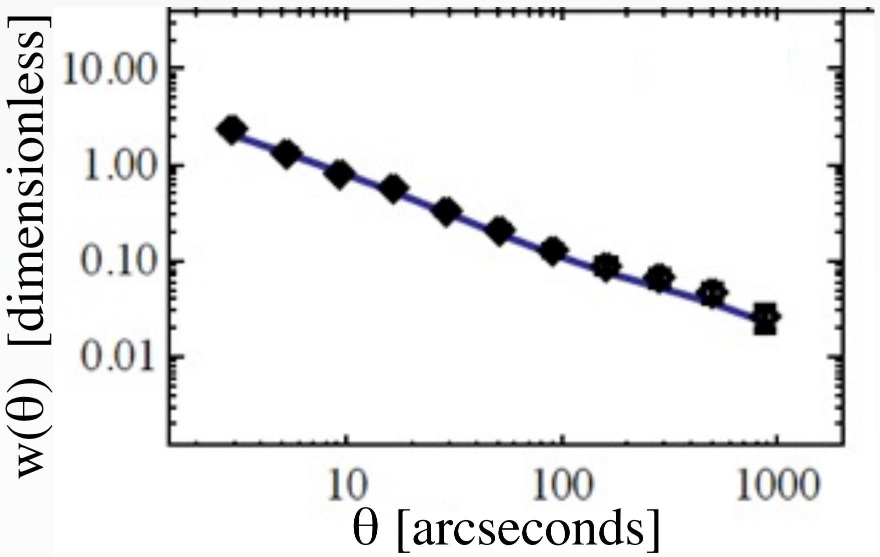
1

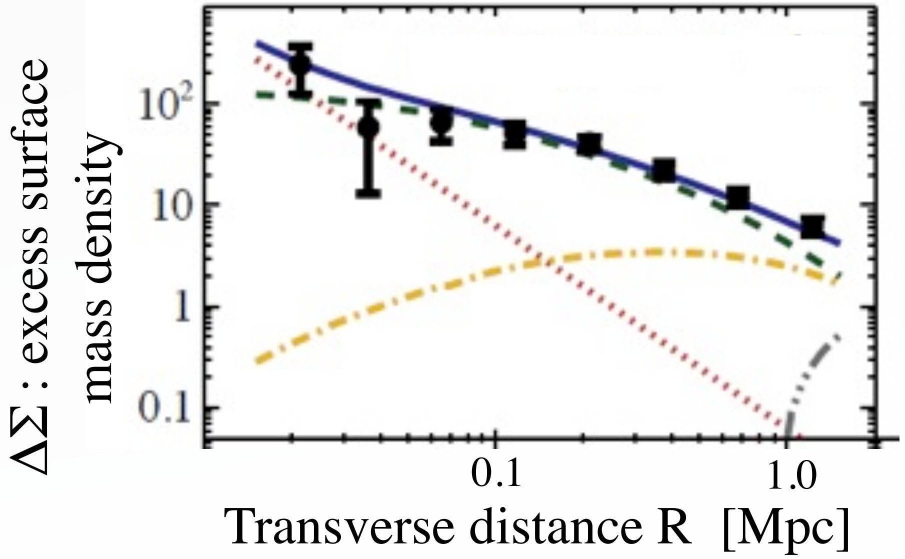
- Number of galaxies per unit volume
- "easy" to calculate
- Typically modeled through "abundance matching"

Galaxy auto correlation function :

2

- Excess probability above random of finding two galaxies with a given separation
- Typically modeled through HOD models





Galaxy-galaxy lensing :

- Measures the galaxy-matter correlation function
- Weak signal that is difficult to measure
- Tells us directly about the galaxy-dark matter connection

3

The Galaxy-Galaxy Lensing Signal

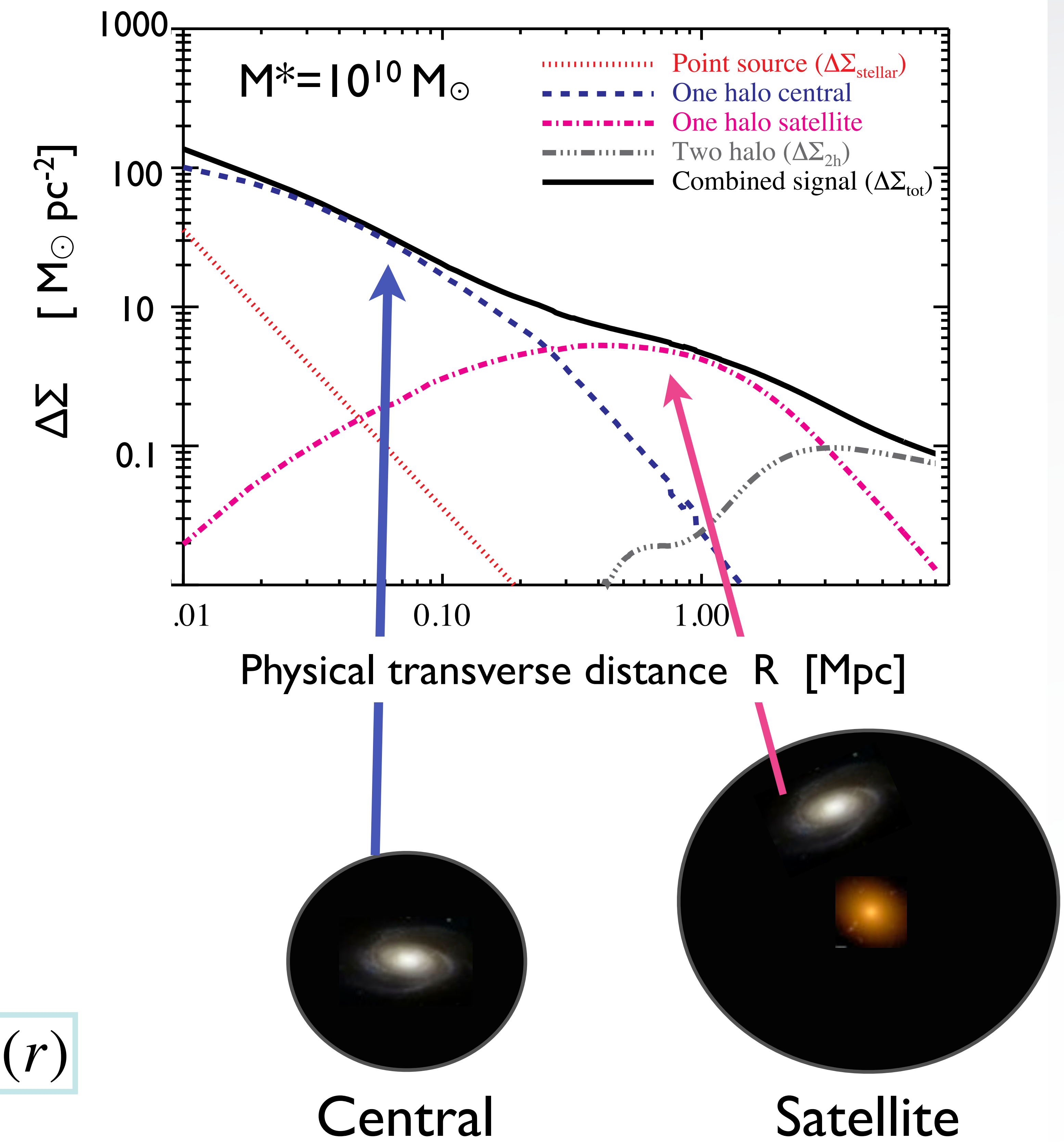
galaxy-galaxy lensing: stacked weak lensing around a large number of foreground galaxies.

The quantity that we seek to measure is *Delta Sigma*

Sigma: surface mass density of the central lens.

Delta Sigma: surface mass density contrast.

$$\Delta\Sigma(r) \equiv \overline{\Sigma}(<r) - \overline{\Sigma}(r) = \Sigma_{crit} \times \gamma_t(r)$$



Ten Parameter Model

- Parametric form for the stellar-to-halo mass relation $(M_1, M_{*0}, \beta, \delta, \gamma)$

$$\log_{10}(\mathbf{f}^{-1}_{\mathrm{SHMR}}(\mathbf{M}_*)) = \log_{10}(\mathbf{M_h}) =$$

$$\log_{10}(\mathbf{M_1}) + \beta \log_{10}\left(\frac{\mathbf{M}_*}{\mathbf{M}_{*,0}}\right) + \frac{\left(\frac{\mathbf{M}_*}{\mathbf{M}_{*,0}}\right)^{\delta}}{\mathbf{1} + \left(\frac{\mathbf{M}_*}{\mathbf{M}_{*,0}}\right)^{-\gamma}} - \frac{\mathbf{1}}{\mathbf{2}}$$

- Central occupation function $(\sigma_{\log(M^*)})$

$$\langle \mathbf{N}_{\mathrm{cen}}(\mathbf{M_h}|\mathbf{M}_*^{\mathbf{t_1}})\rangle =$$

$$\frac{\mathbf{1}}{\mathbf{2}}\left[\mathbf{1} - \mathrm{erf}\left(\frac{\log_{10}(\mathbf{M}_*^{\mathbf{t_1}}) - \log_{10}(\mathbf{f}_{\mathrm{SHMR}}(\mathbf{M_h}))}{\sqrt{\mathbf{2}}\sigma_{\mathrm{logM}_*}}\right)\right]$$

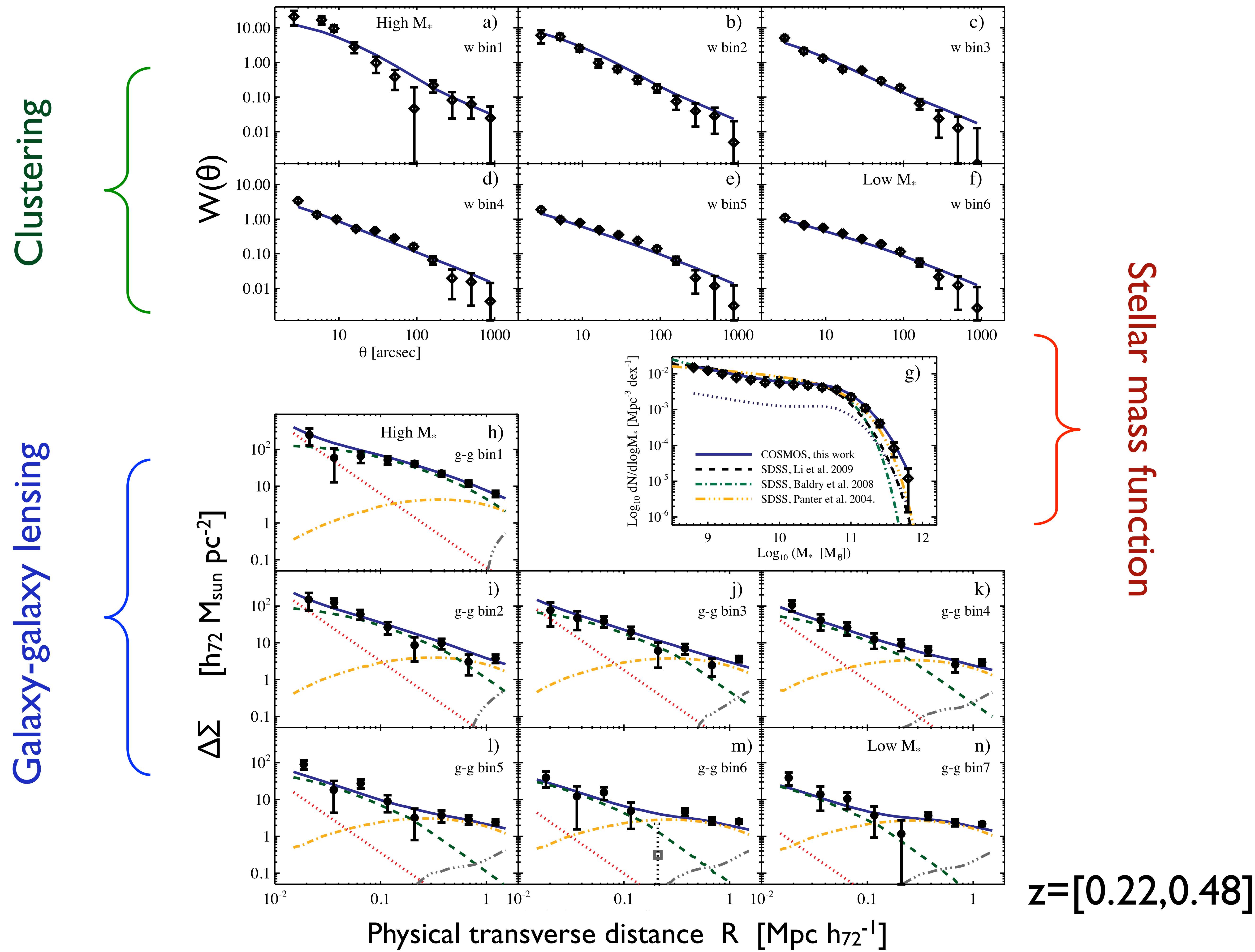
- Satellite occupation function $(B_{cut}, B_{sat}, \beta_{cut}, \beta_{sat})$

$$\langle \mathbf{N}_{\mathrm{sat}}(\mathbf{M_h}|\mathbf{M}_*^{\mathbf{t_1}})\rangle = \langle \mathbf{N}_{\mathrm{cen}}(\mathbf{M_h}|\mathbf{M}_*^{\mathbf{t_1}})\rangle \left(\frac{\mathbf{M_h}}{\mathbf{M}_{\mathrm{sat}}}\right)^{\alpha_{\mathrm{sat}}} \exp\left(\frac{-\mathbf{M}_{\mathrm{cut}}}{\mathbf{M_h}}\right)$$

$$\frac{\mathrm{M_{sat}}}{10^{12}\mathrm{M}_\odot} = \mathrm{B_{sat}}\left(\frac{\mathrm{f}^{-1}_{\mathrm{SHMR}}(\mathrm{M}_*^{\mathrm{t_1}})}{10^{12}\mathrm{M}_\odot}\right)^{\beta_{\mathrm{sat}}}$$

$$\frac{\mathrm{M_{cut}}}{10^{12}\mathrm{M}_\odot} = \mathrm{B_{cut}}\left(\frac{\mathrm{f}^{-1}_{\mathrm{SHMR}}(\mathrm{M}_*^{\mathrm{t_1}})}{10^{12}\mathrm{M}_\odot}\right)^{\beta_{\mathrm{cut}}}$$

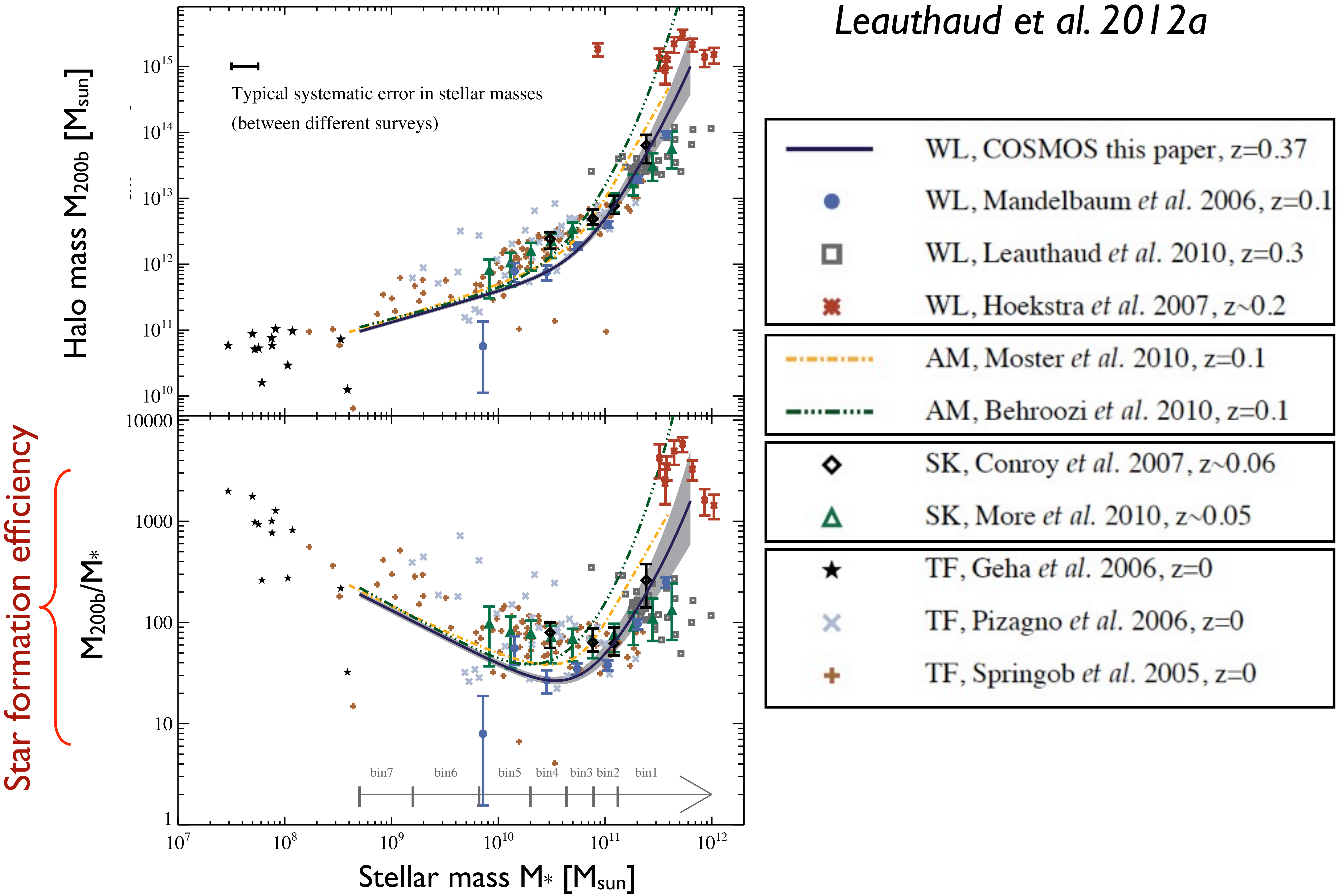
+ Tinker et al. 2008 halo mass function
+ Tinker et al. 2010 bias function
+ Halo exclusion



Clustering
W(θ)
High M*
a)
w bin1
b)
w bin2
c)
w bin3
d)
w bin4
e)
w bin5
Low M*
f)
w bin6
θ [arcsec]
g)
Log10 dN/dlogM* [Mpc^-3 dex^-1]
COSMOS, this work
SDSS, Li et al. 2009
SDSS, Baldry et al. 2008
SDSS, Panter et al. 2004.
Log10 (M* [M⊙])
Stellar mass function
Galaxy-galaxy lensing
ΔΣ [h72 Msun pc^-2]
High M*
h)
g-g bin1
i)
g-g bin2
j)
g-g bin3
k)
g-g bin4
l)
g-g bin5
m)
g-g bin6
Low M*
n)
g-g bin7
Physical transverse distance R [Mpc h72^-1]
z=[0.22,0.48]

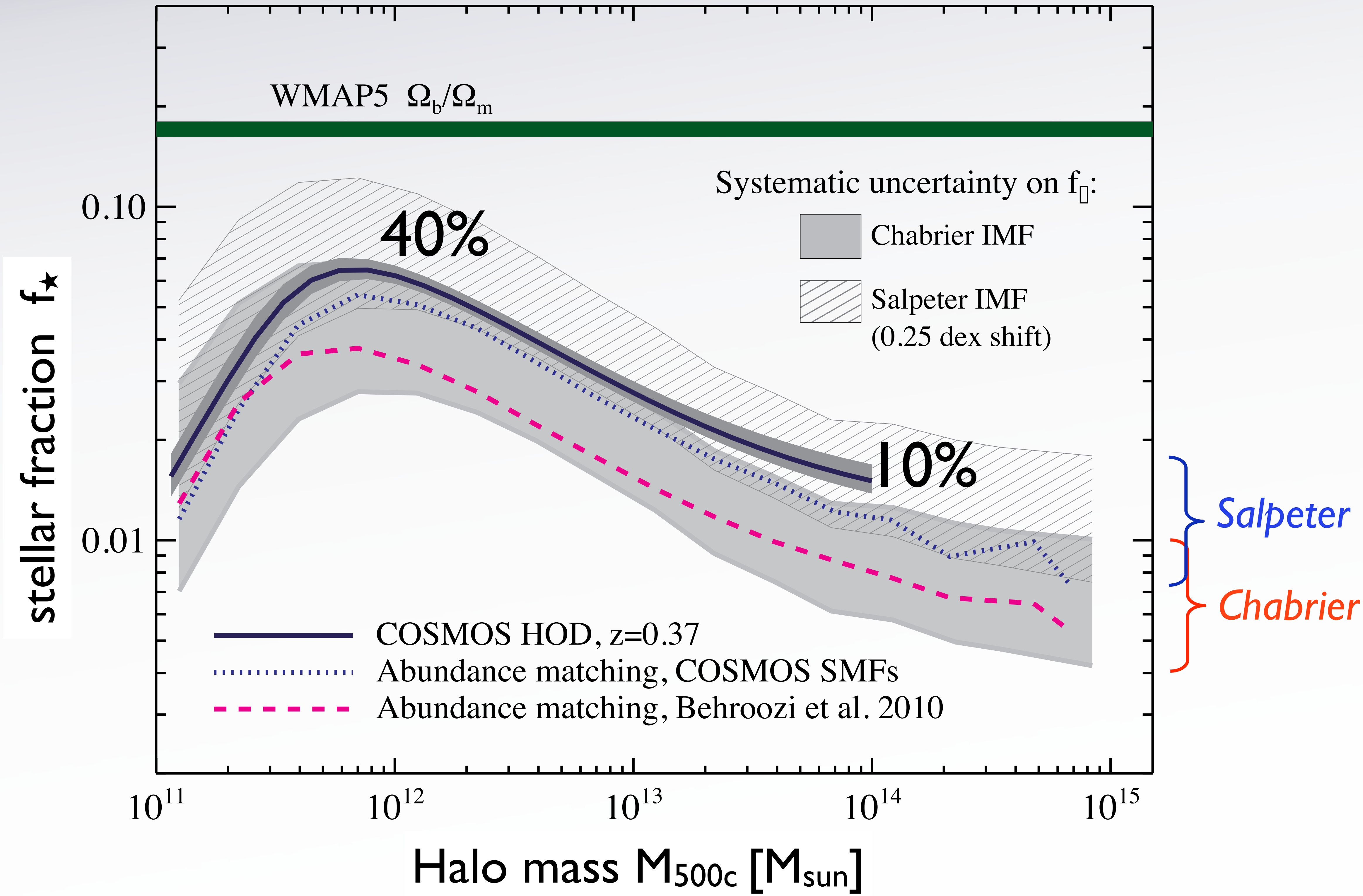
Stellar mass vs Halo mass

Leauthaud et al. 2012a



The Global Stellar Content of DM Halos

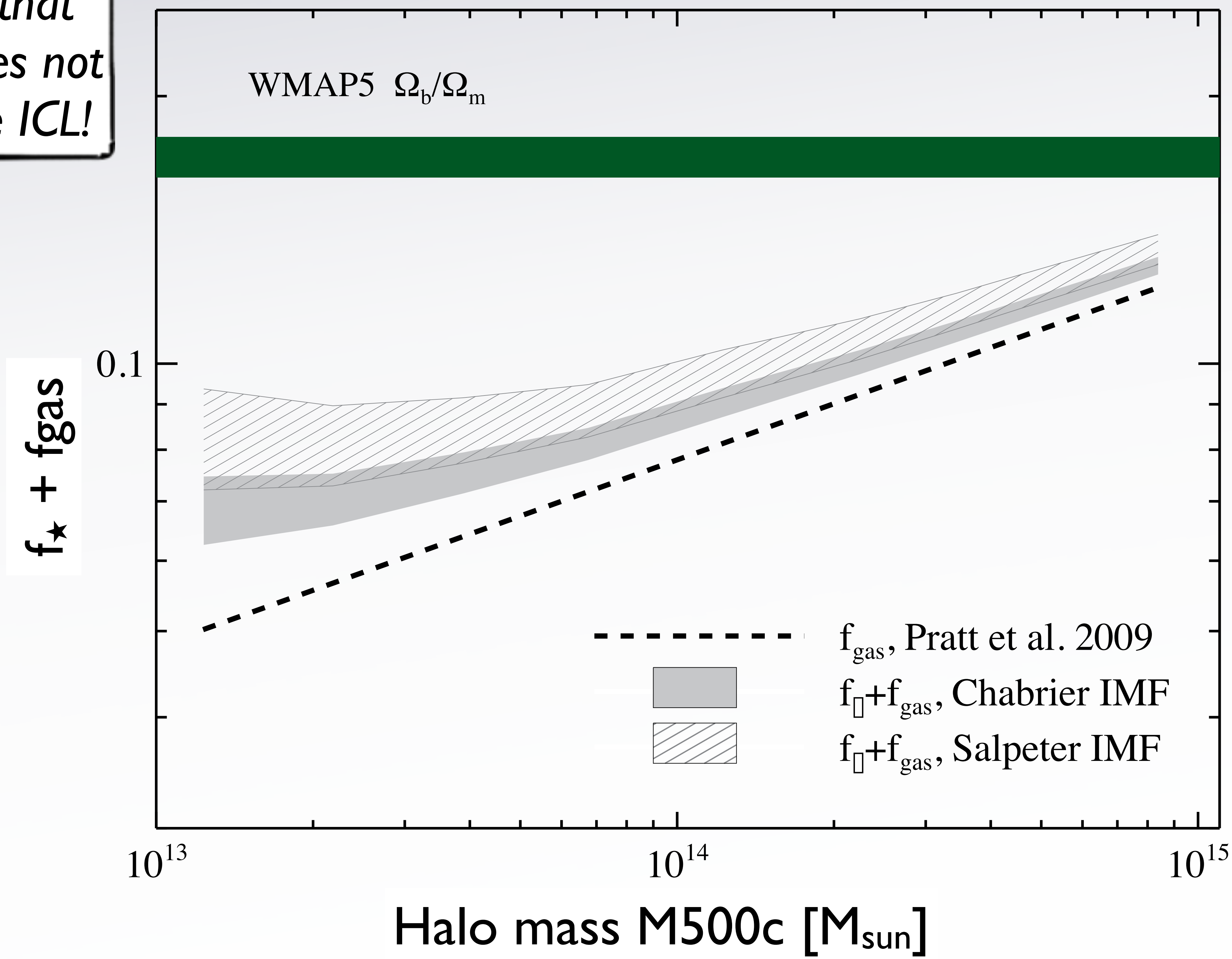
Leauthaud et al. 2012b



The Global Stellar Content of DM Halos

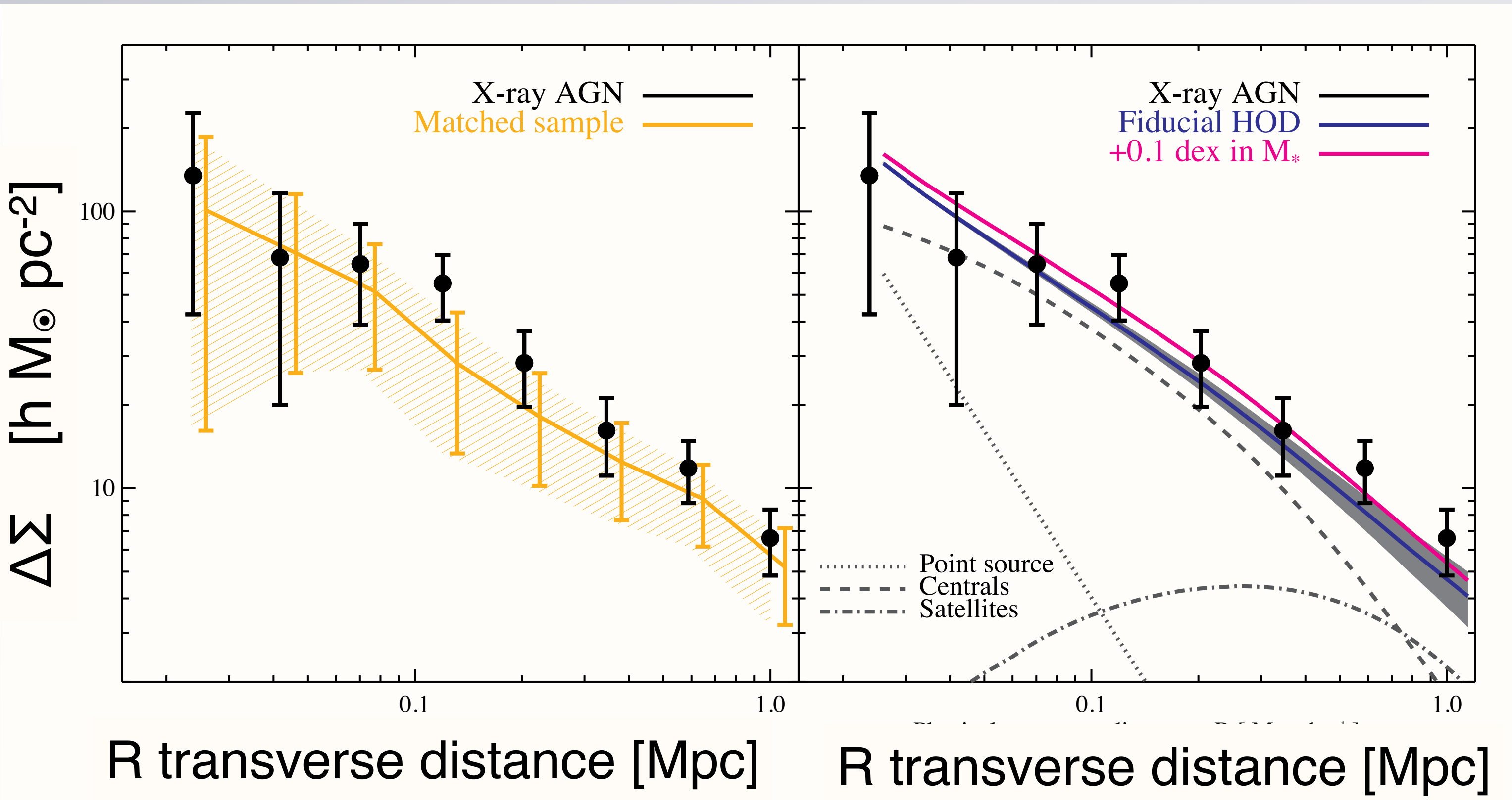
Leauthaud et al. 2012b

Note that this does not include ICL!



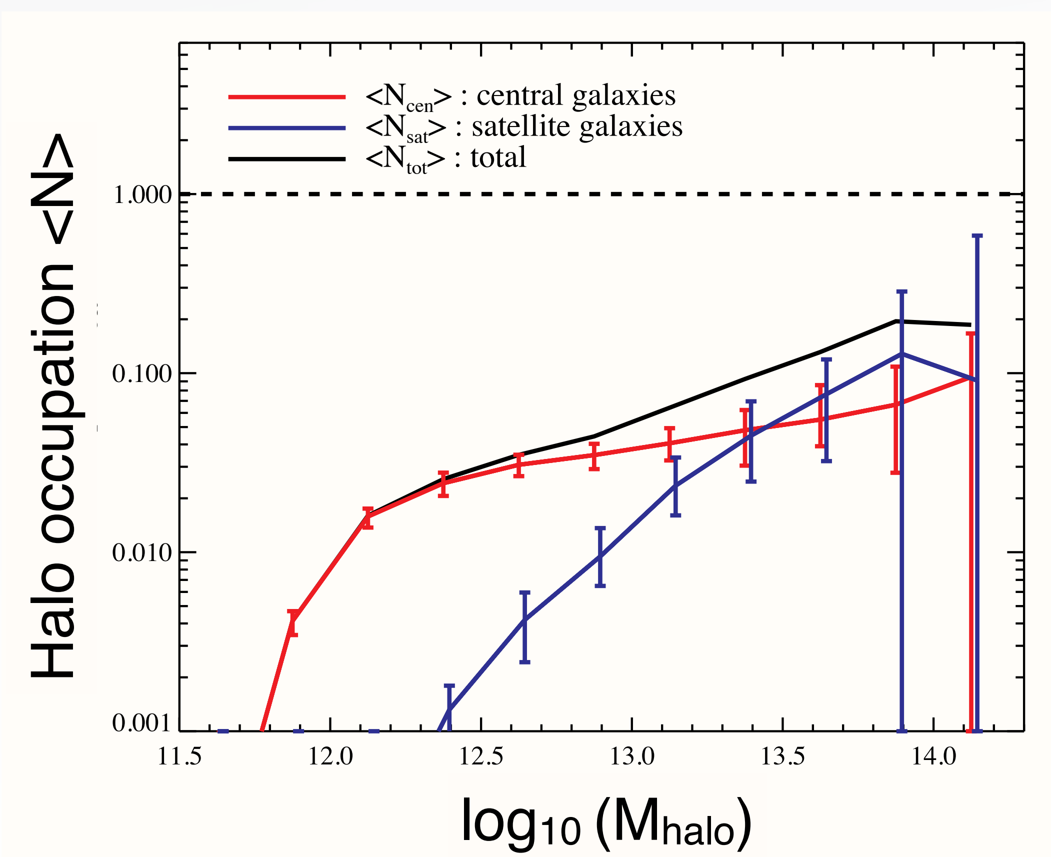
Halo Occupation of X-ray AGN

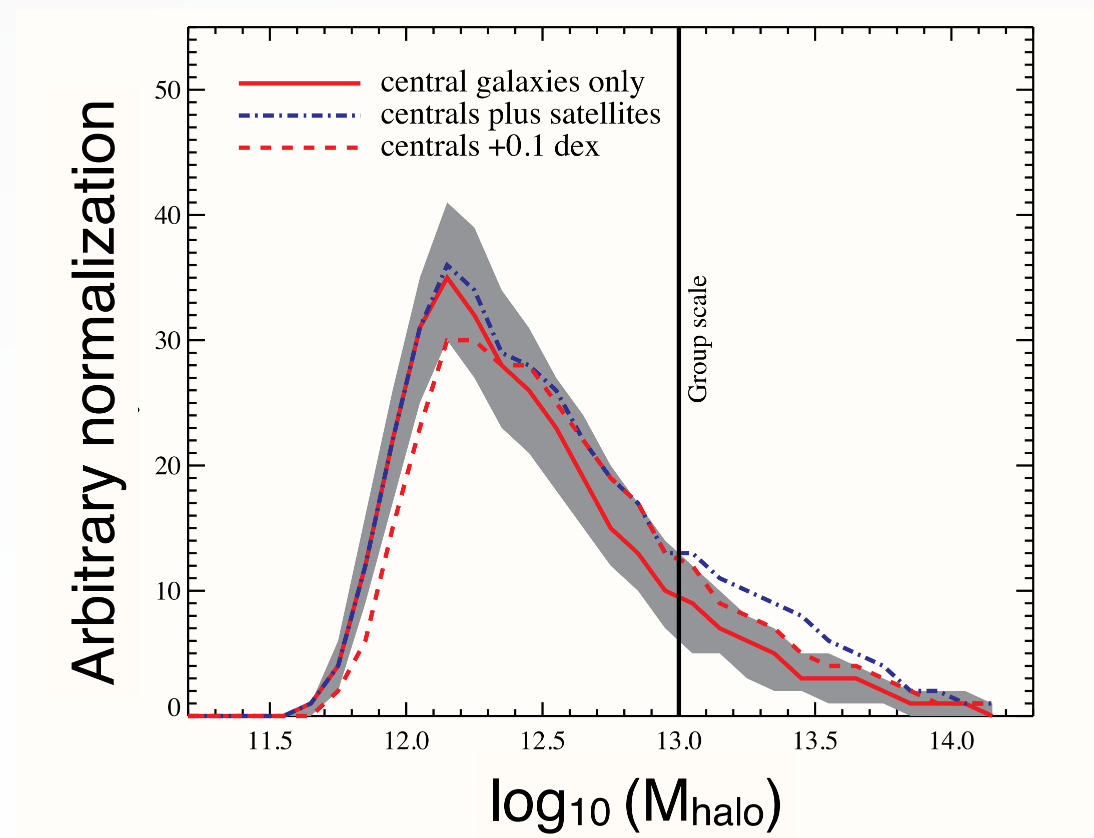
Leauthaud, Benson et al. in prep



Galaxy-galaxy lensing can be used to study specific galaxy types.

Occupation function of x-ray AGN.
Halo mass distributions.
Satellite fraction ~ 15%.





Conclusions

Conclusions & Future Directions

Harness the power of BOSS, HSC, & Euclid

Gravitational lensing is a powerful tool to probe cosmic acceleration, dark matter, & galaxy formation.

BUT: measurement precision ≃ theoretical understanding

- ➡ Improve 2d clustering & lensing as a cosmological tool
- ➡ Theory: use N-body simulations directly? Reduce systematic uncertainties due to analytical models.
- ➡ Combine BOSS RSD with HSC lensing. GR tests?
- ➡ 3pt statistics
- ➡ Clusters to z=1 from HSC. Calibrate mass-observable relations, study dark matter profiles, properties of central galaxies, etc ...
- ➡ Connection between galaxies and dark matter with HSC to z=1. Probe mechanisms responsible for the quenching of star formation.