Weak lensing simulations

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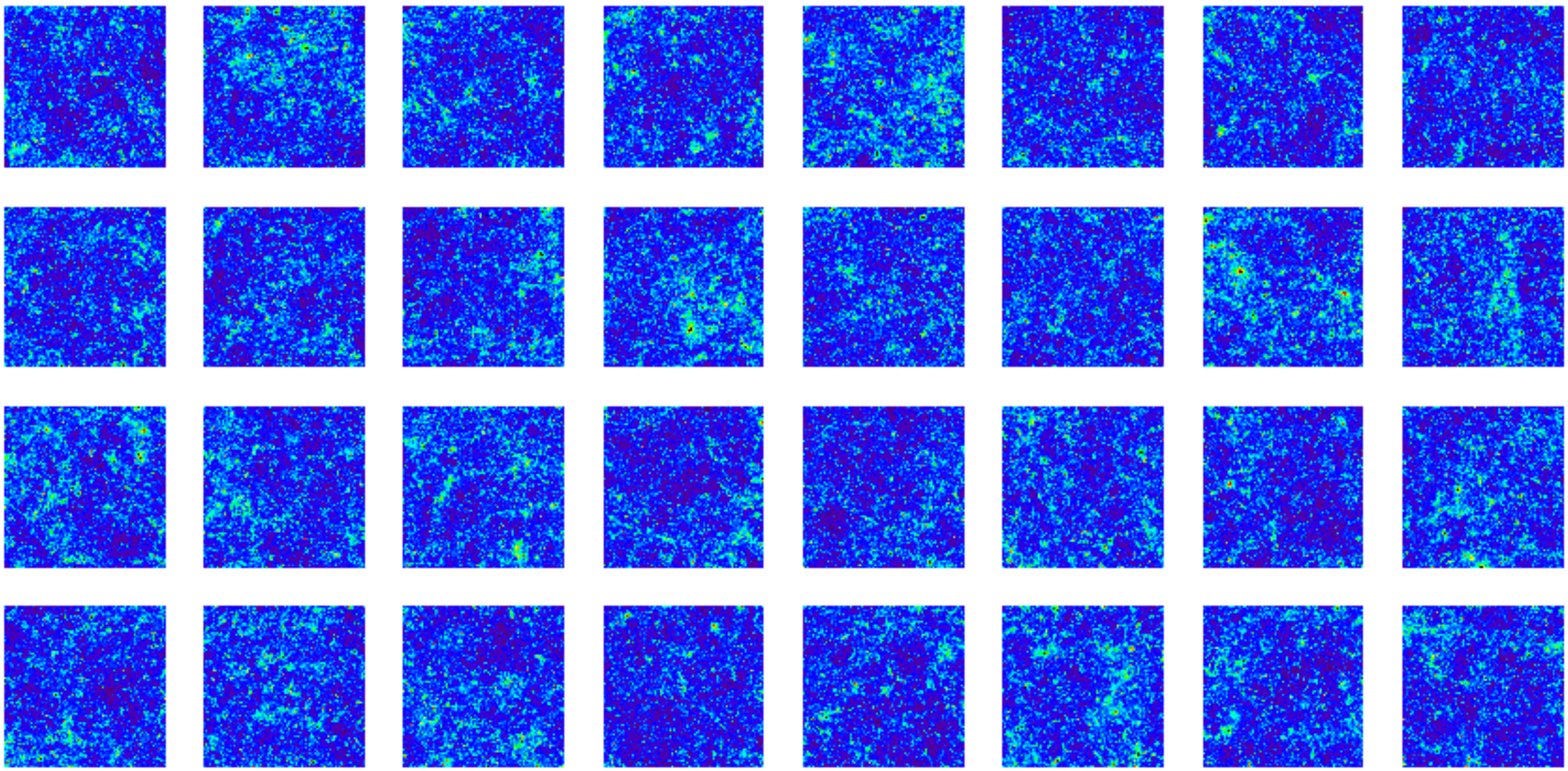
Theory & Analysis

- Using the code described in Vale & White (2003) we have produced simulated weak lensing maps for a number of cosmological models.
  - These maps are very useful for investigating higher order functions and higher order effects.
  - The maps make good tests of algorithms.
  - The maps can be used to model systematic errors and their removal or estimate error bars from sample variance.
- Available
  - Convergence and shear maps [different $p(z_s)$]
  - Halo catalogs
  - Sheared “galaxy” catalogs
  - Power spectra, …
- Recent run: maps of one cosmology covering 1000 sq. deg.

http://mwhite.berkeley.edu/Lensing/

$\Omega_m = \mathbf{0.357}$ $w = -0.8$ $h = \mathbf{0.64}$ $n = \mathbf{1.00}$ $\sigma_8 = 0.88$ $\tau = 0.15$

Tracing light rays through a simulation of structure formation…



32 convergence maps, 3^o on a side

http://mwhite.berkeley.edu/Lensing/

Next steps

- For the 2-pt function we need to know the non-linear power spectrum in the range 0.1<k<10Mpc^{-1} to 1-2% accuracy, with the requirement at k~1 being the most stringent.
- Current state of the art is ~3%.
- For gravity only, there is no known obstacle to reaching the above requirement.

Beyond gravity

- Non-gravitational physics becomes important on small scales, becoming dominant beyond *l*~3000.
  - White (2005), Zhan & Knox (2005)
- Dramatic progress in modeling extra physics!
  - Expect small # of simulations including relevant physics will be available within 5-10 years.
  - Can mock up some of the physics in gravity-only simulations
    - Put gas in hydrostatic equilibrium with known DM potential.
    - Apply adiabatic contraction to halos where gas would have cooled.
- Use photo-*z* to apply “nulling tomography”.
  - Huterer & White (2005)

Lessons from what we have now

- We already have a large number of high-fidelity simulations in hand.
- What can we do with these?
  - These maps are very useful for investigating higher order functions and higher order effects.
  - The maps make good tests of algorithms.
  - The maps can be used to model systematic errors and their removal or estimate error bars from sample variance.

Reduced shear

- Unless we have a measurement of the intrinsic size or magnification of a galaxy we cannot measure γ but only $g=\gamma/(1-\kappa)$

$$\frac{\partial \theta^{\rm src}}{\partial \theta^{\rm img}} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$
$$= (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}$$

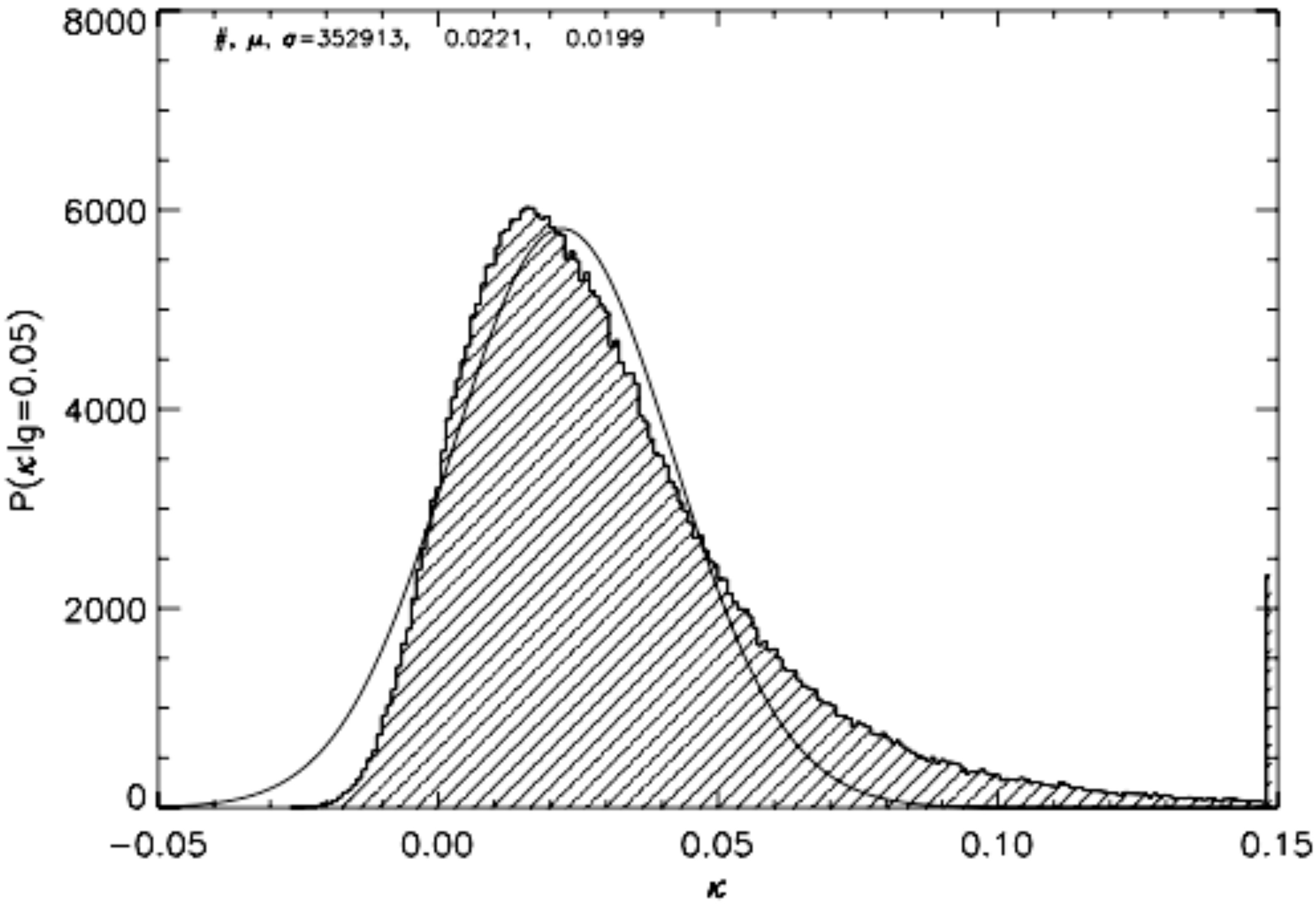
- Since γ and κ are usually small this difference is often neglected (except around clusters).
- Can be a few percent effect on arcminute scales!

Reducing shear enhances shear

- On small scales κ can be quite large, and spatial smoothing does not commute with the "reducing" operation.

- Generally g has larger fluctuations than γ because κ is skew positive.
  - —Excess small-scale power compared to naïve predictions.
- The effect is different for different estimators
  - —A signal of "reduced shear" vs. e.g. intrinsic alignments or systematics.
- The effect is non-linear
  - —Provides cross-check on shear calibration

Conditional probability



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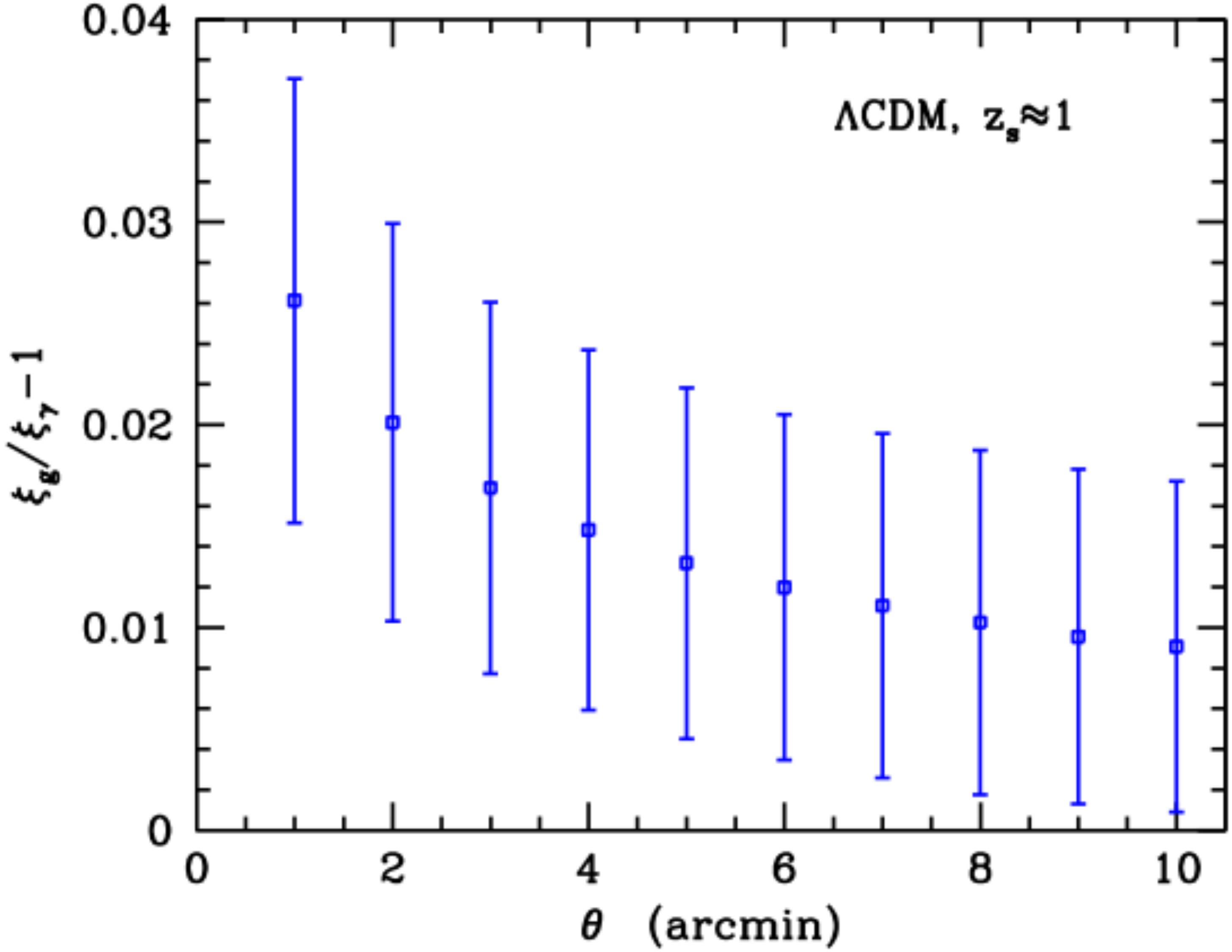
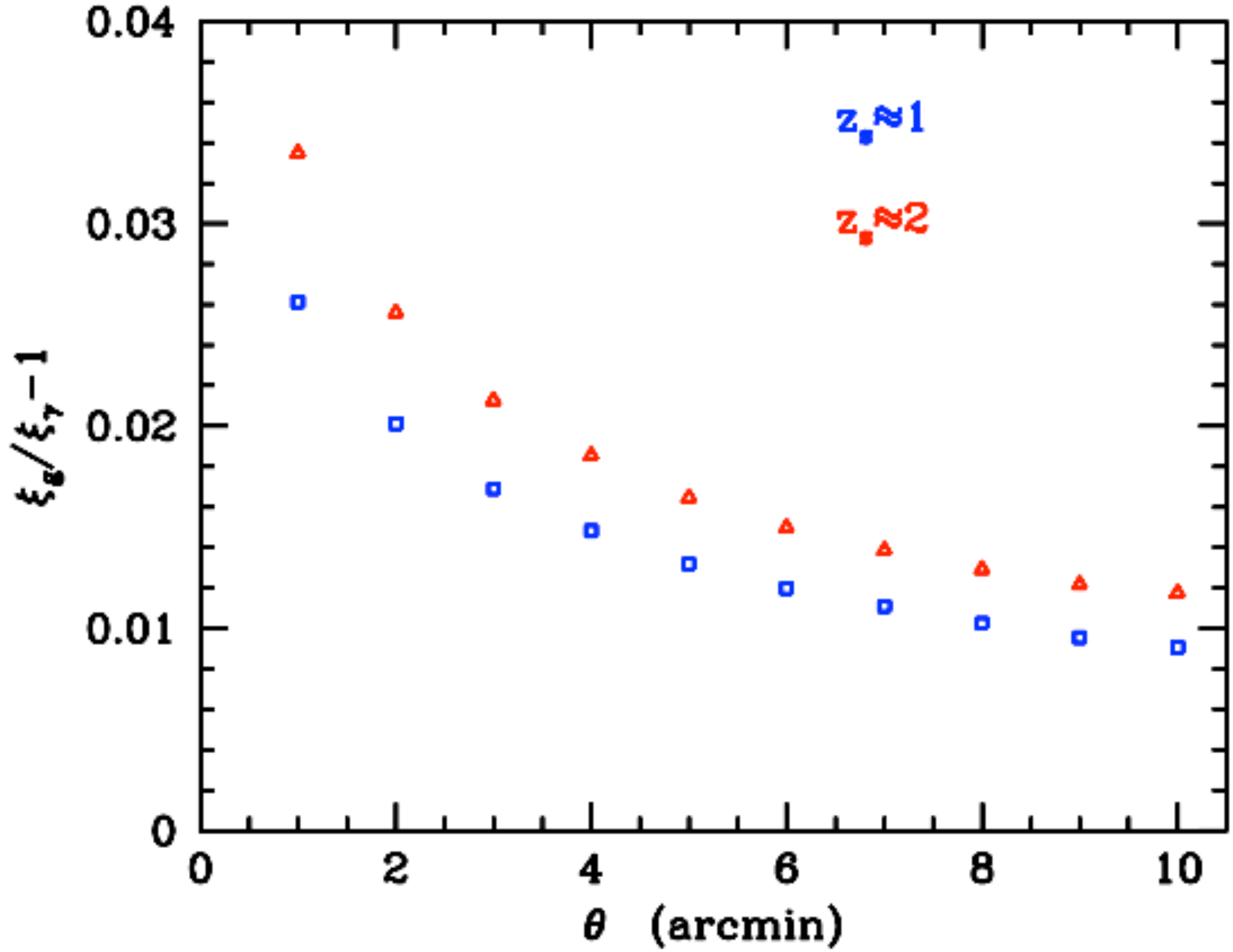
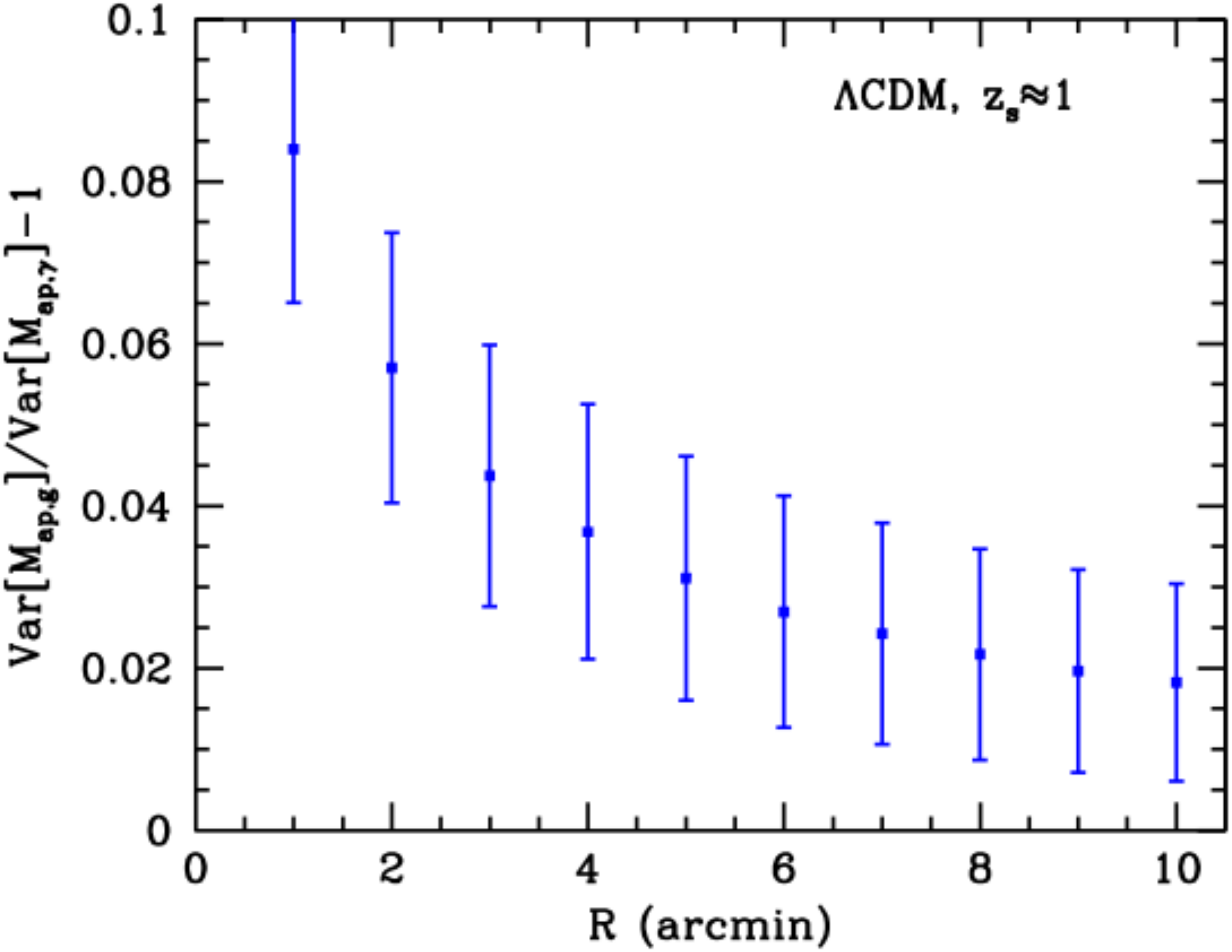
Effect on correlation function



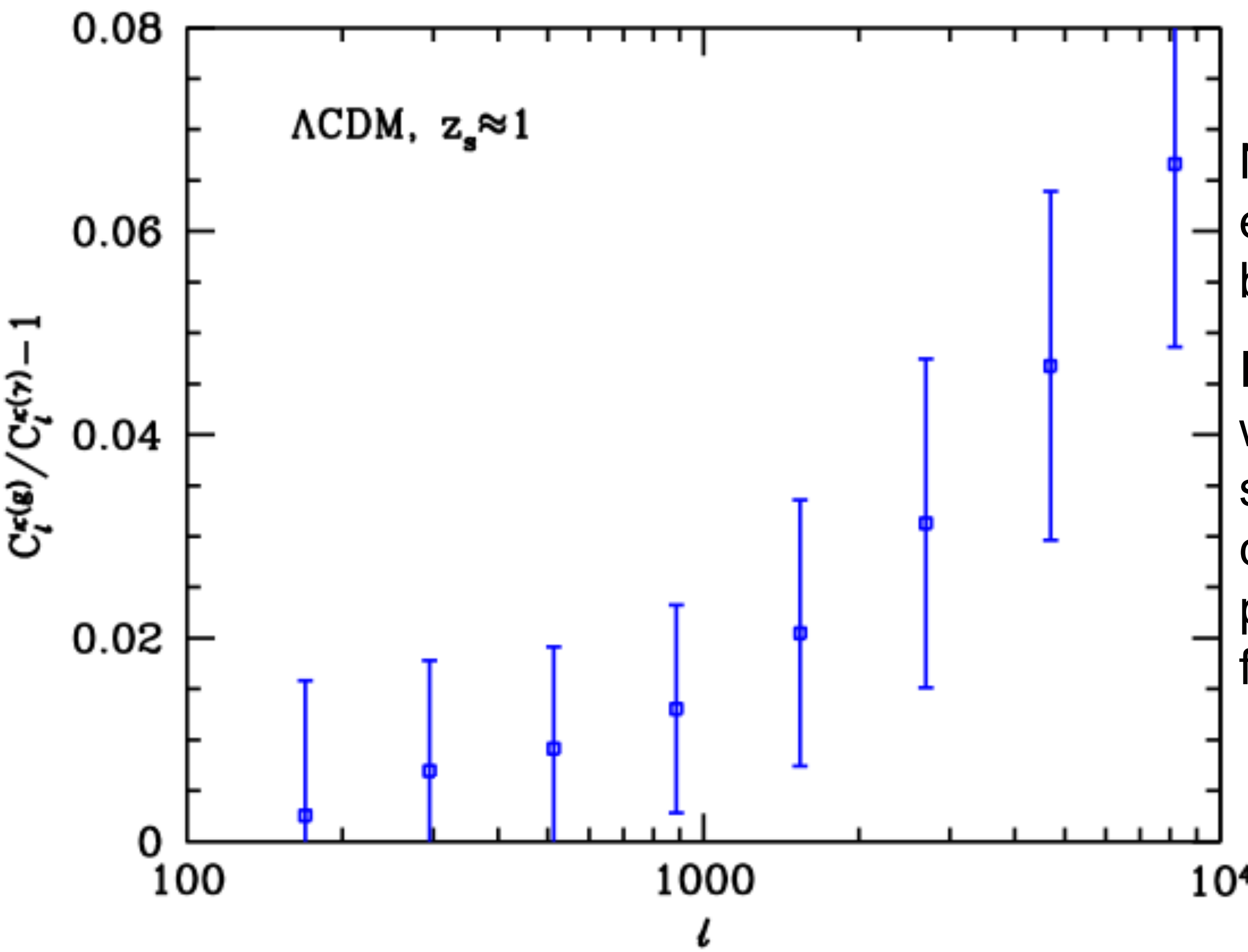
… increases to higher redshift



Effect on aperture mass variance



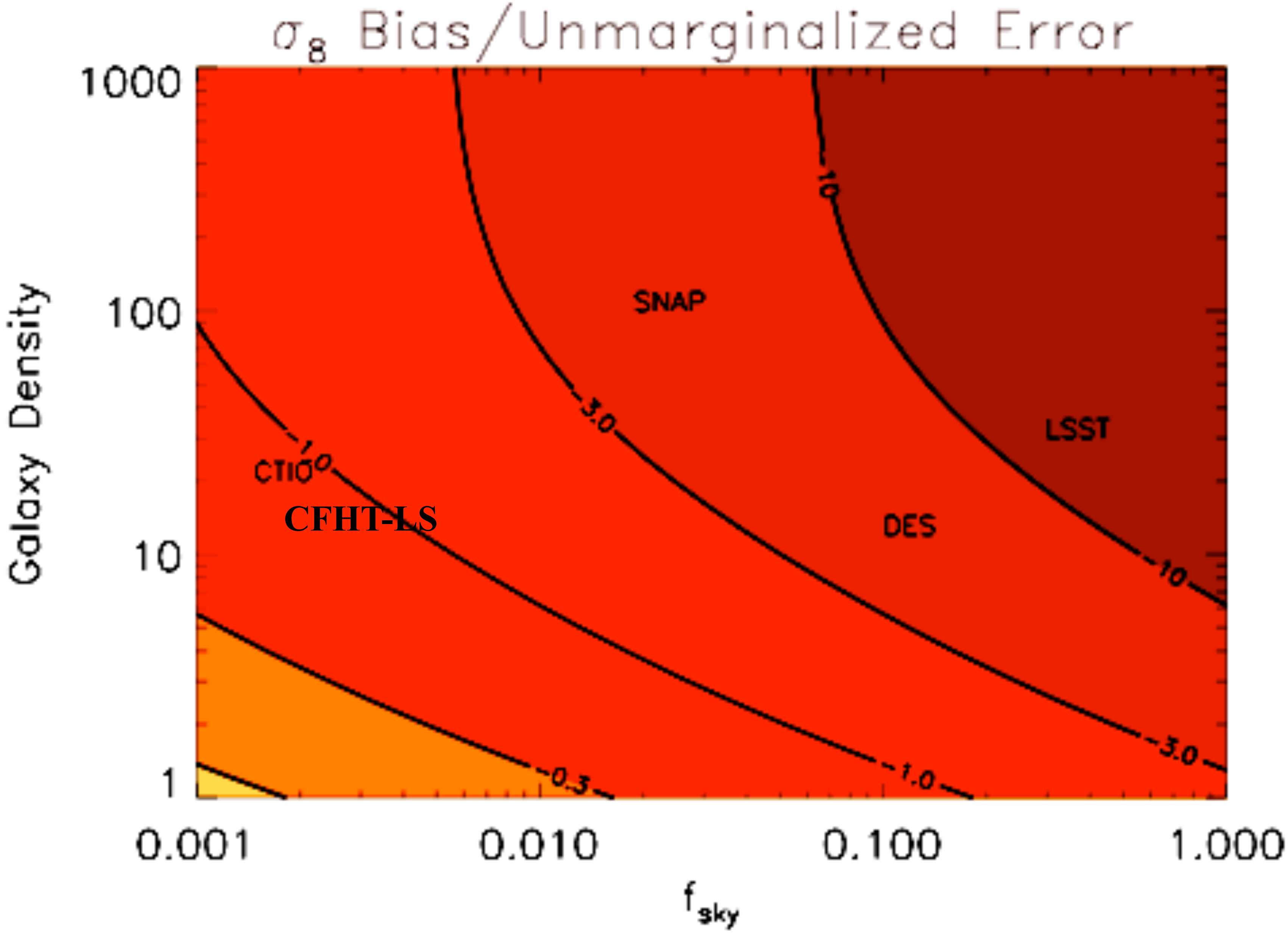
Effect on the power spectrum



Not a problem for existing surveys, but …

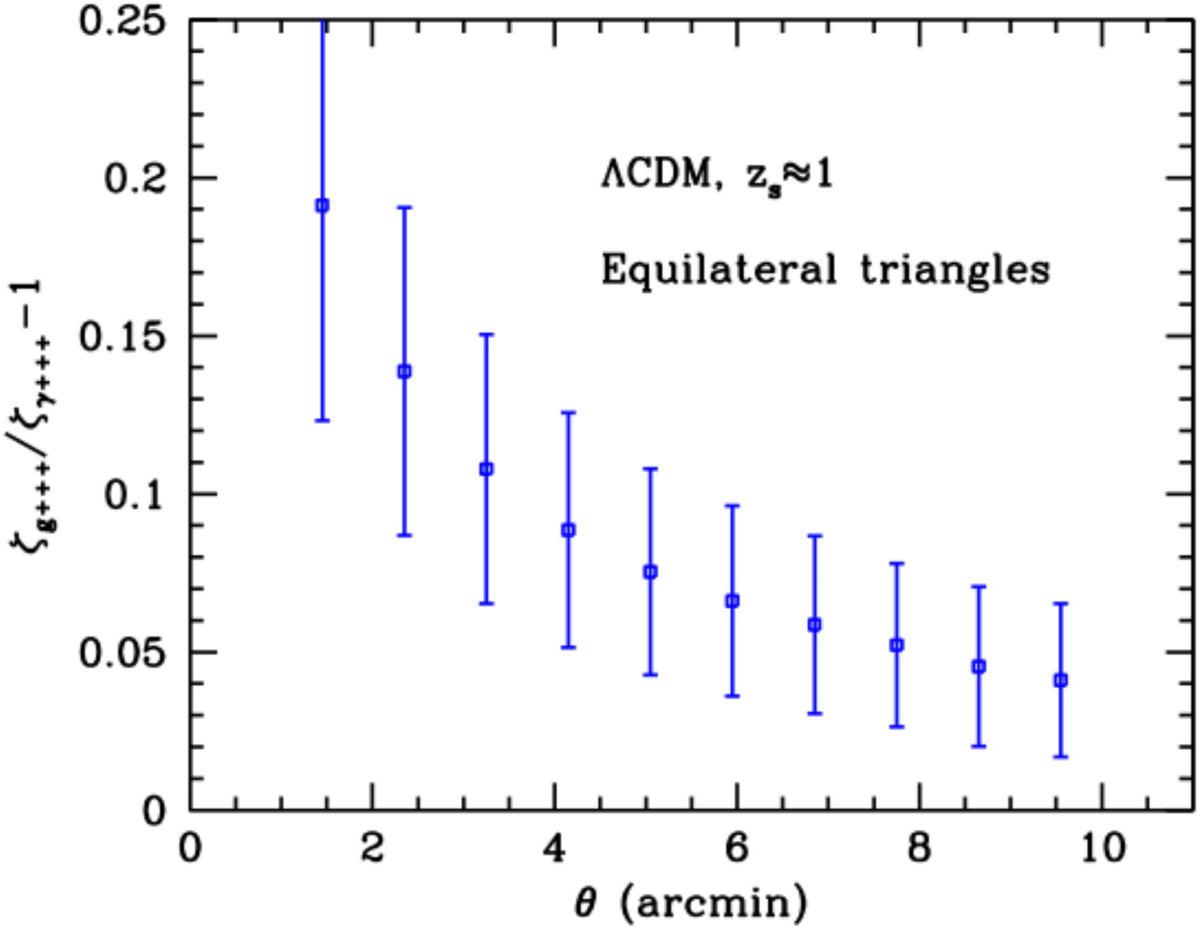
Ignoring this effect would lead to a significant bias in cosmological parameters for future surveys.

Bias in parameters



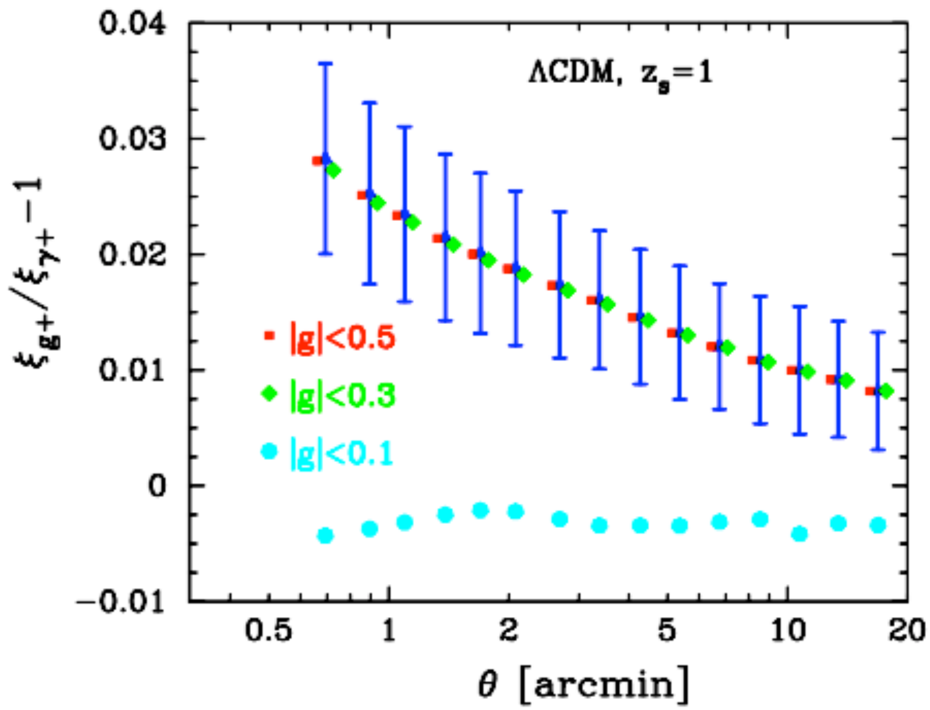
Effect on higher-order functions

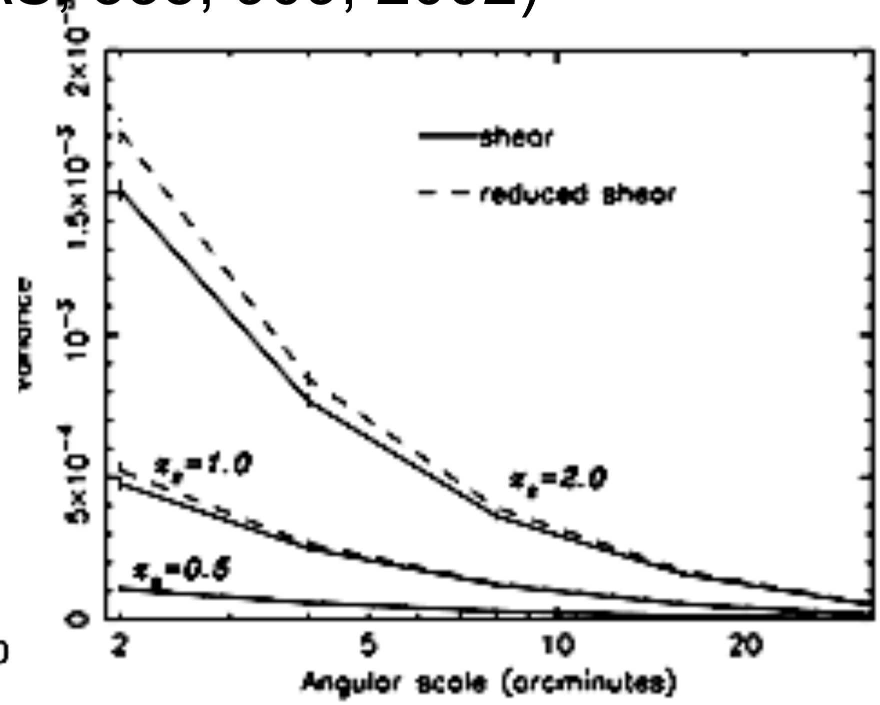
Might think that difference would be much larger for higher order functions - but it is not. It *does* however change the configuration dependence of the 3-pt function slightly.



Robust across simulations

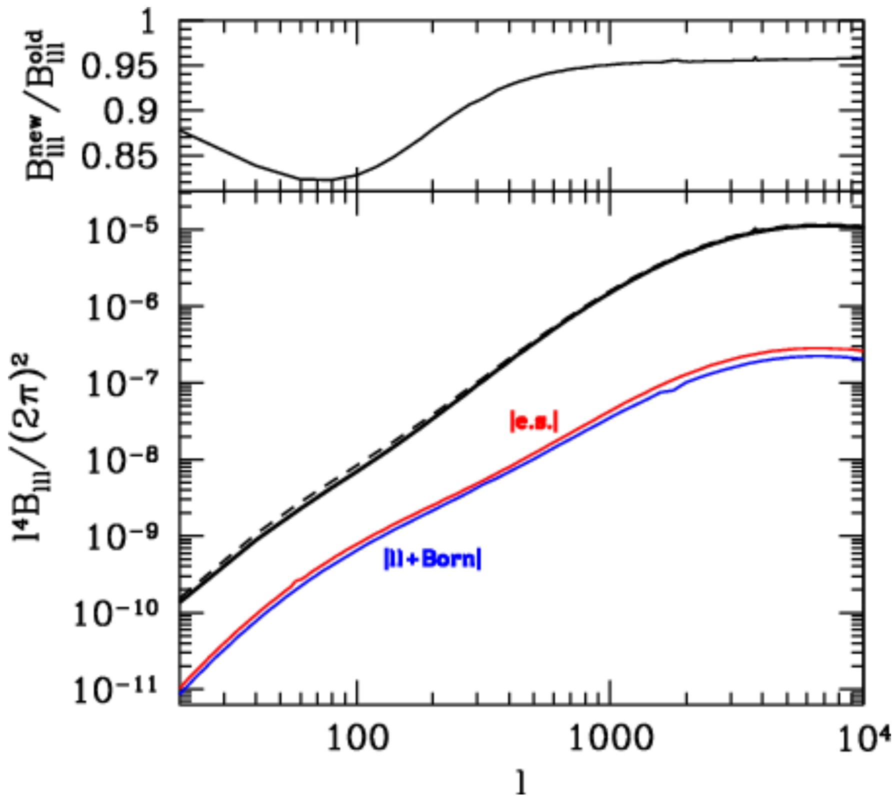
- Comparison of these results with other ray-tracing simulations (where available) shows good agreement.
  —M. Takada (ξ(r), private communication)
  —A. Barber (Var[γ], MNRAS, 335, 909, 2002)





Analytic work

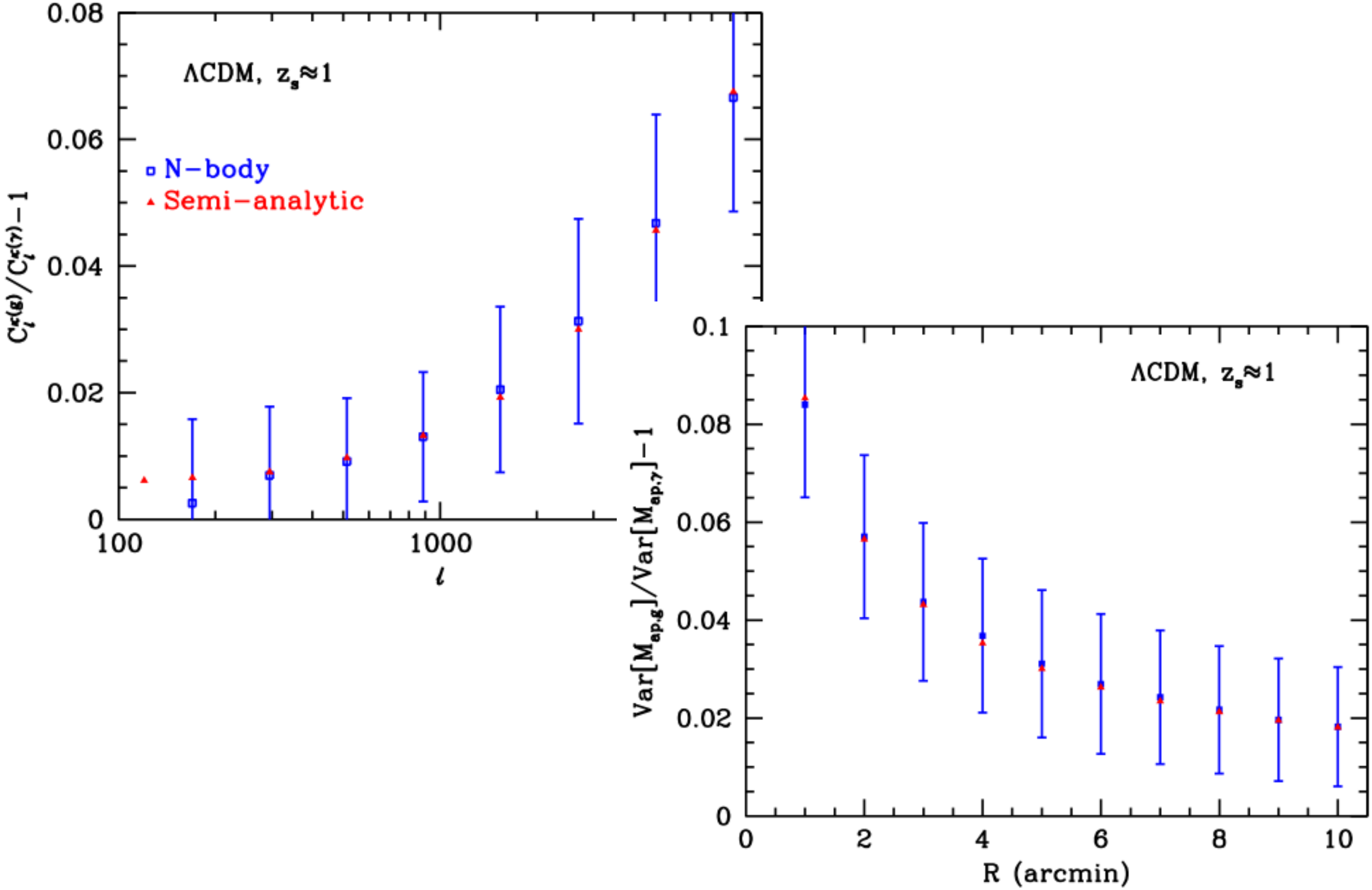
Dodelson, Zhang et al. have computed corrections to the 2- and 3-point functions using an analytic approach. They find roughly comparable results, though some quantitative disagreements with simulations and previous analytic estimates remain.



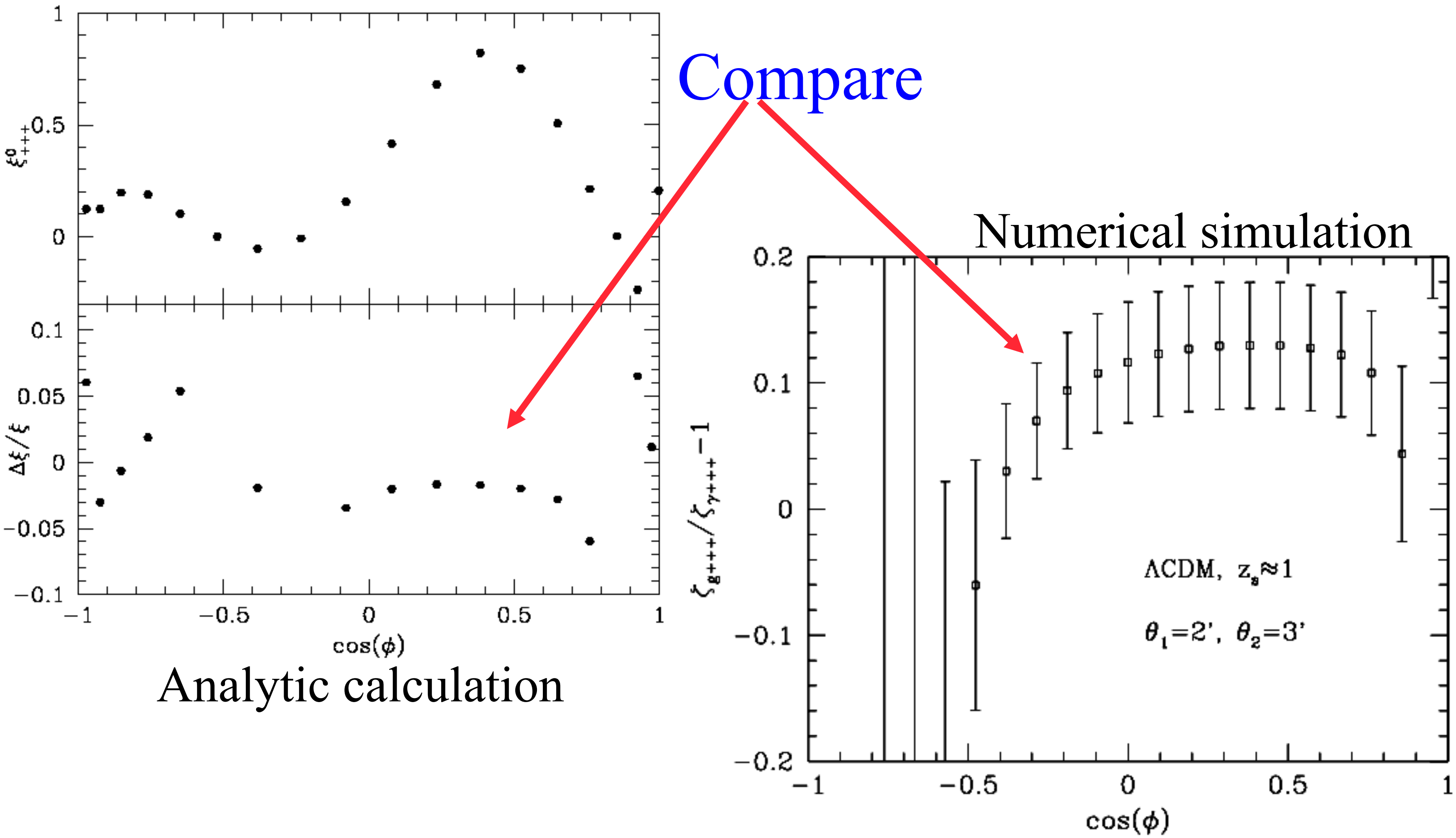
Work currently in progress to assess agreement: <u>Charles Shapiro</u>, Scott Dodelson, MW.

An analytic model would allow us to incorporate the results into Fisher matrix calculations.

2-point functions: agreement



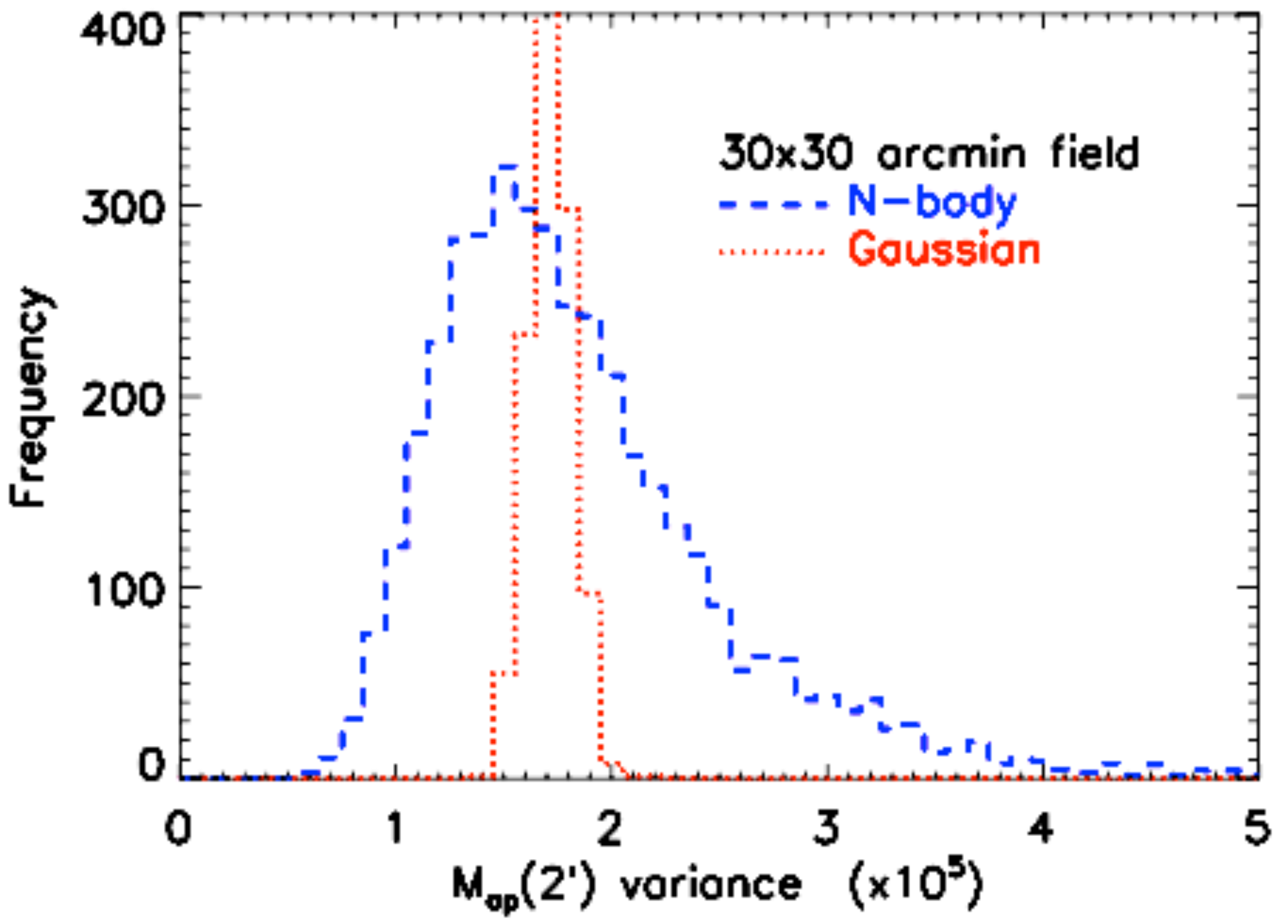
Real Space 3-point function



Clustering statistics

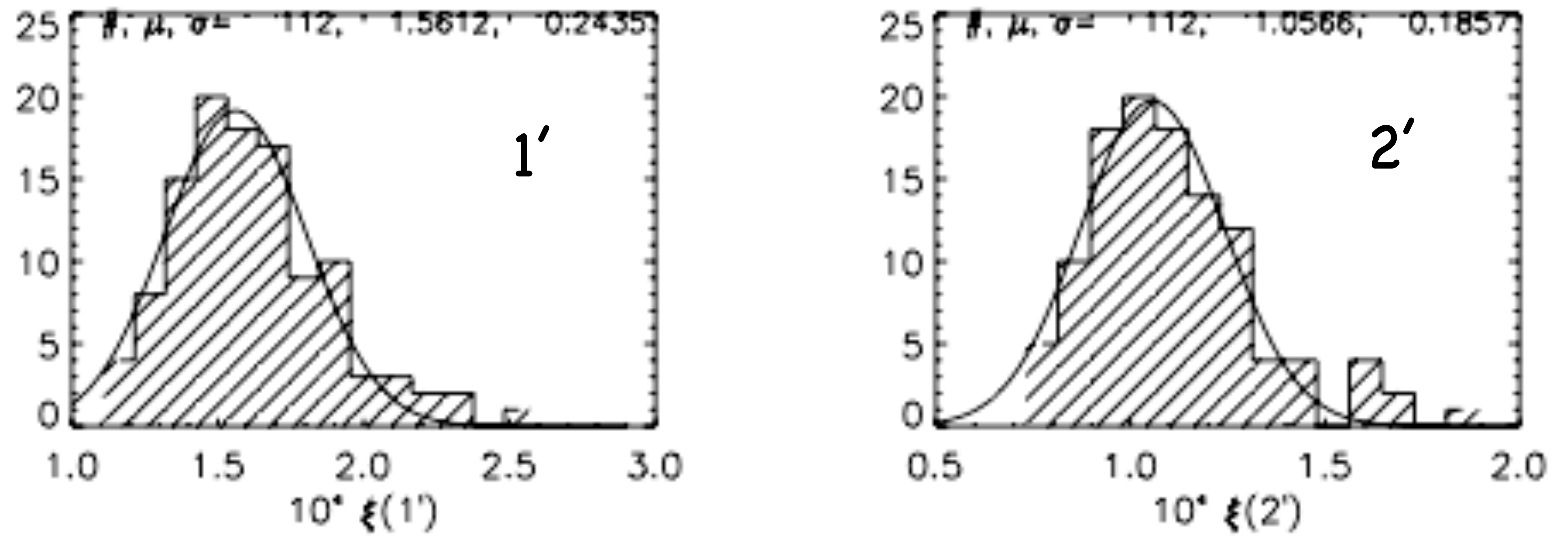
- With the 1000 sq. deg run we are now in a position to look at the distribution of these statistics.
- Moving from central values to error bars!
  - —See also Kilbinger & Schneider (2005)

Non-Gaussianity & sample variance

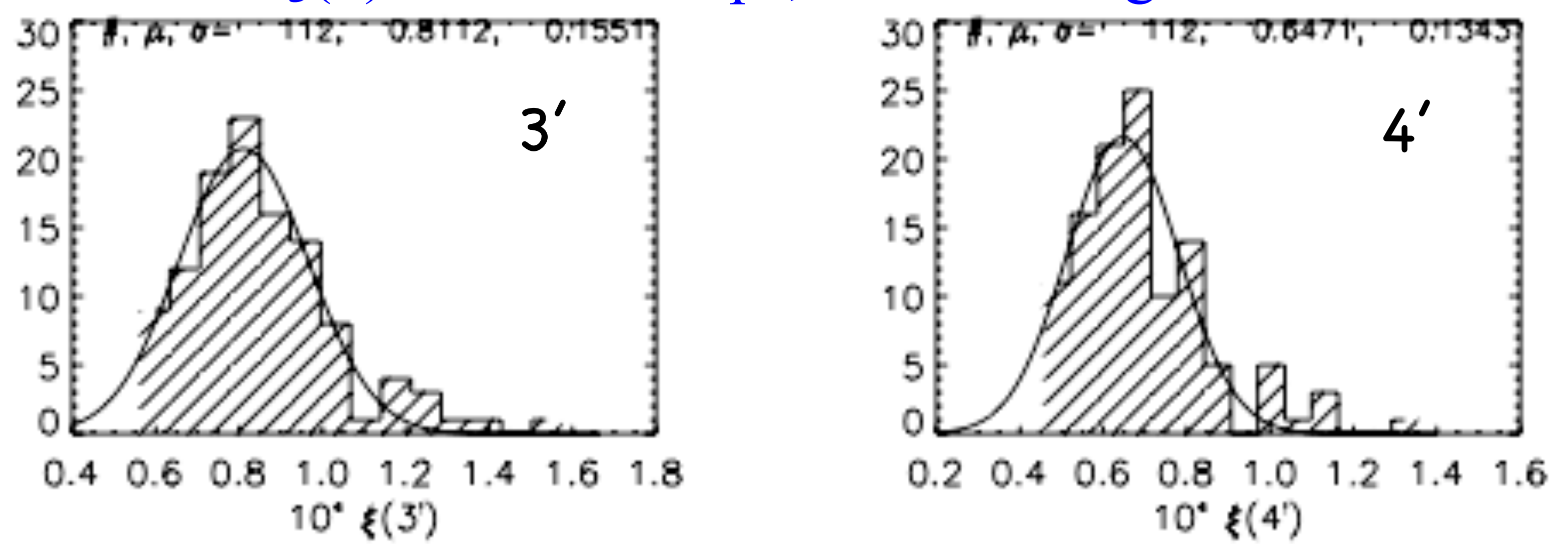


The distribution of variances is not well approximated by a Gaussian on small scales. Sample variance is a larger effect than a naïve calculation would indicate.

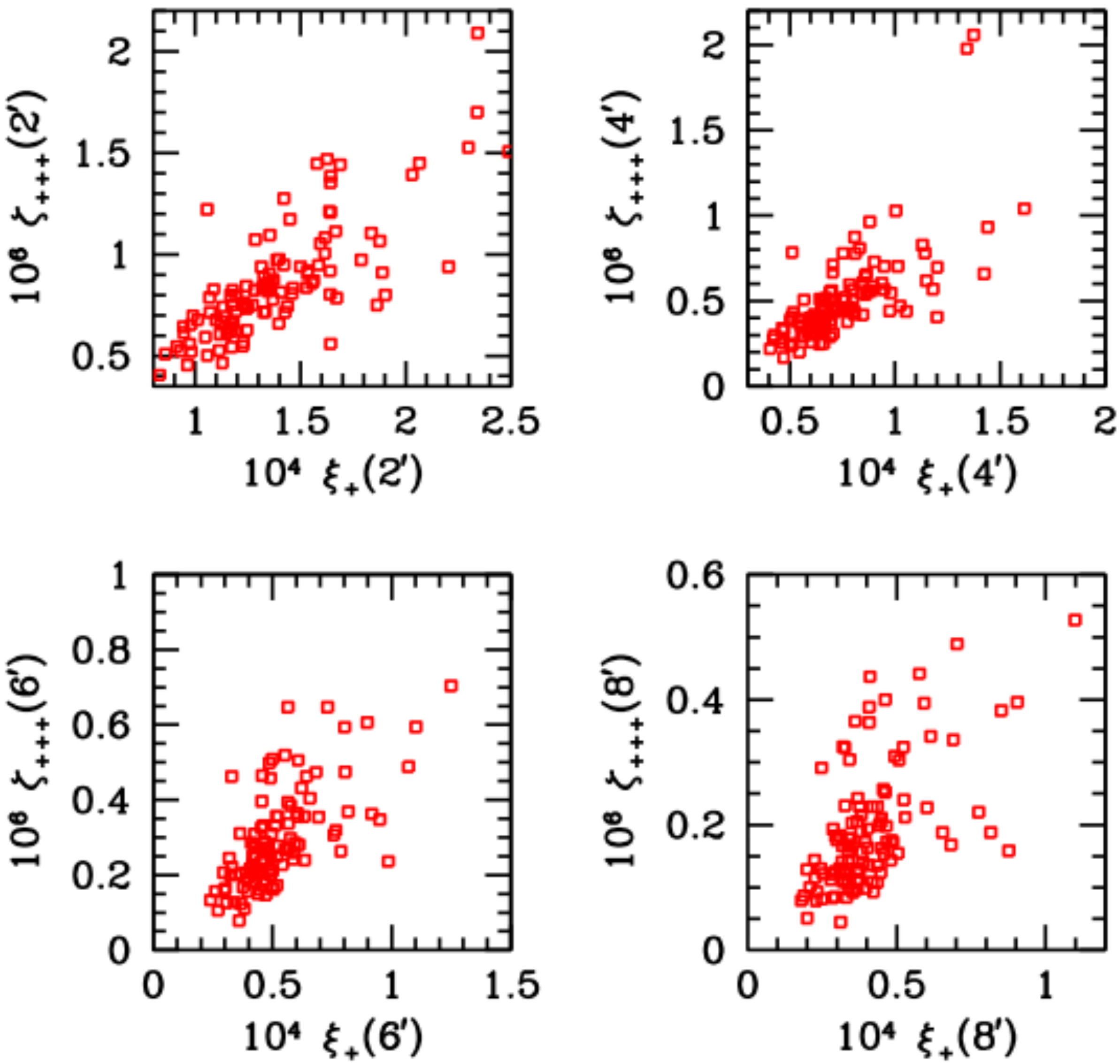
Correlation function errors



ξ(θ) from 112 maps, each 3x3 degrees



Correlations in clustering

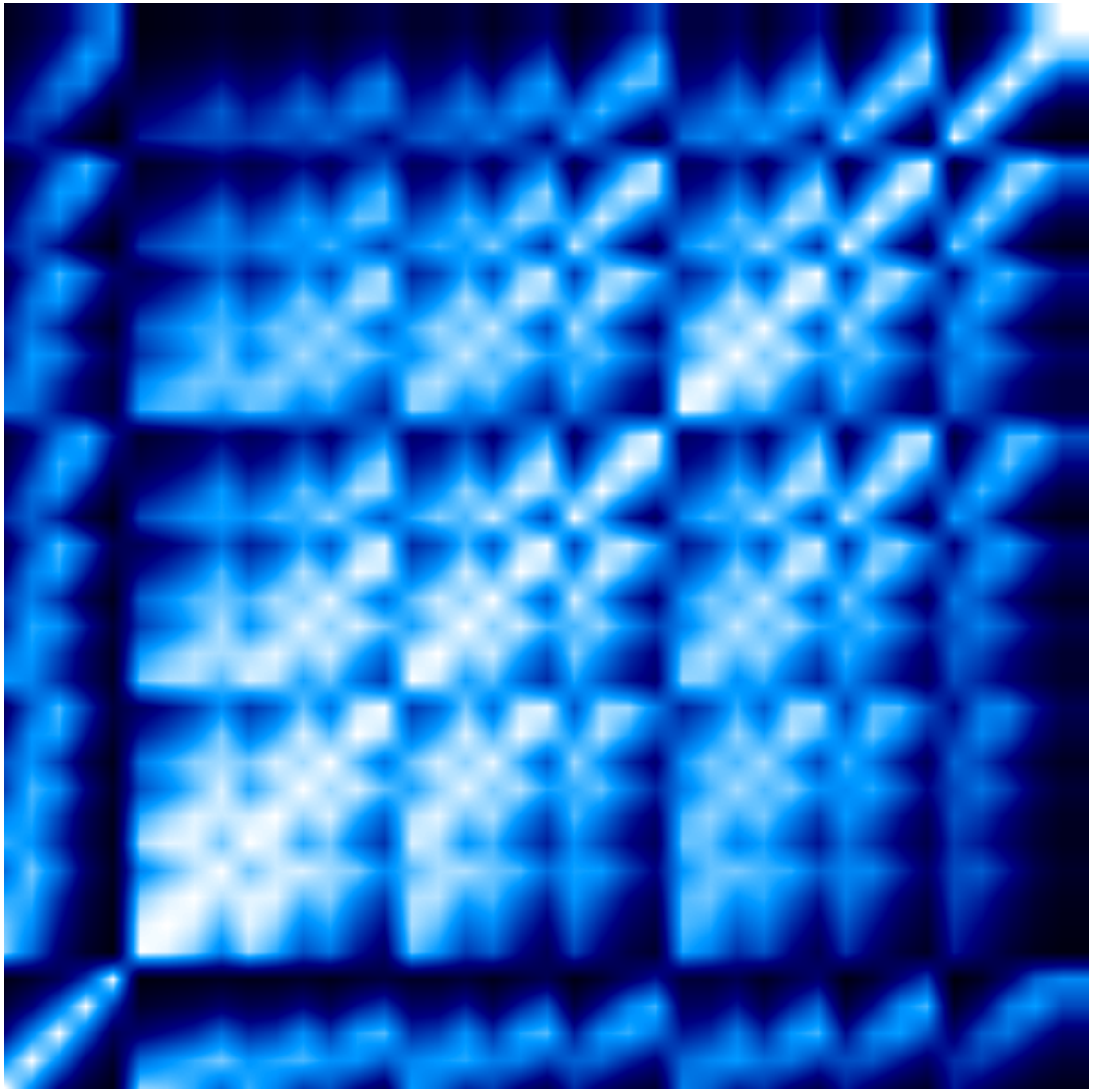


Find that the 2-point and 3-point functions are highly correlated on small scales.

This is not too surprising when thought of from an “object” perspective but is not often assumed.

Correlations contd.

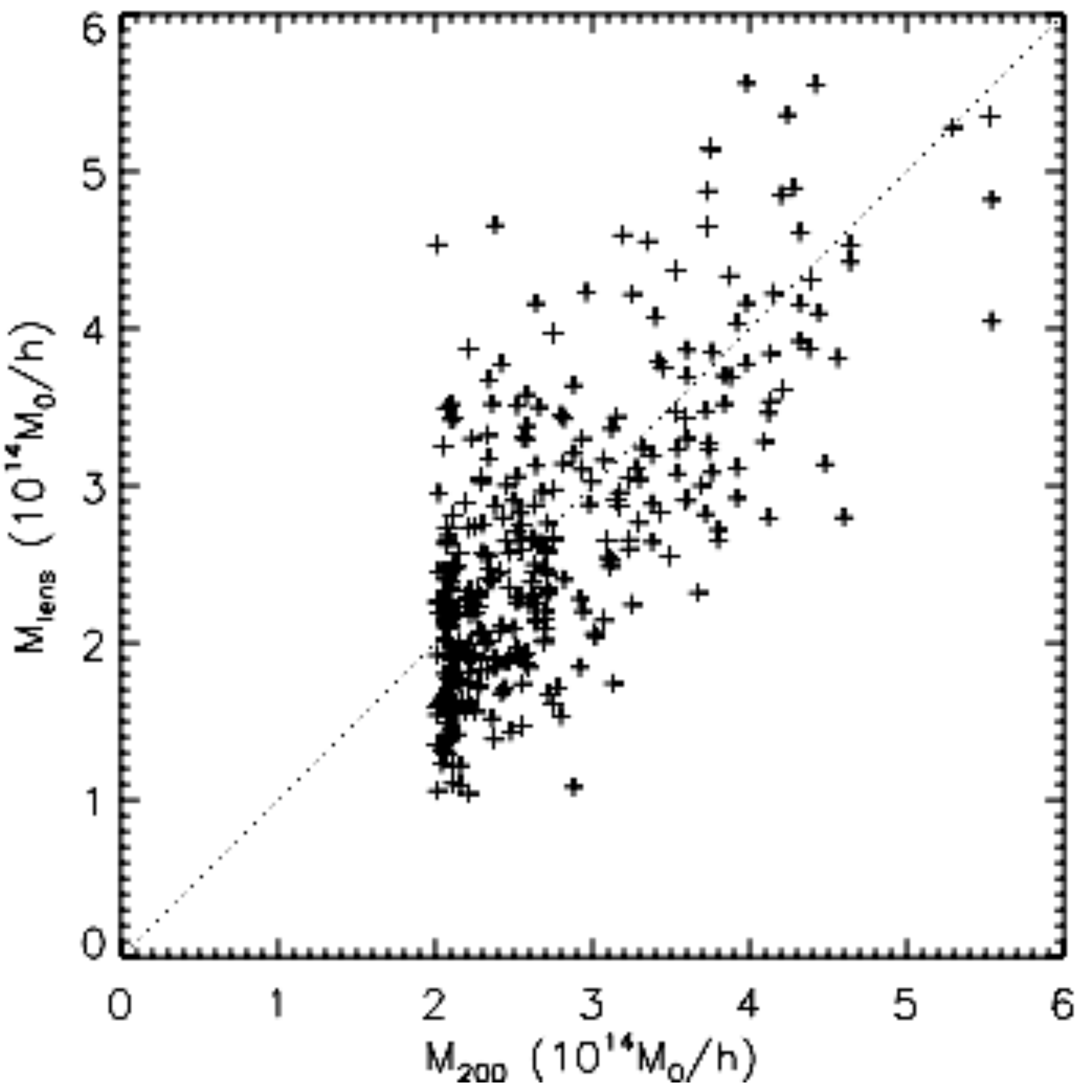
- Correlation matrix for 2nd and 3rd order M_{ap} statistics (computed from κ maps).
- Uses Mexican hat filter with scales 1, 2, 4, 8 & 16 arcmin (40 measures: 5x 2-pt and 35x 3-pt).



Scatter in lensing “masses”

- Lots of confusion about lensing mass, bias and scatter.
- Just measuring projected mass will lead to generally overestimated 3D masses since clusters live in overdense regions.
- One can correct for this statistically by assuming a model for the contamination
  - —This can be thought of as an extension of the halo profile beyond the virial radius
- The resulting scatter can bias mass function estimates unless it is included in the analysis.

Scatter in mass estimator

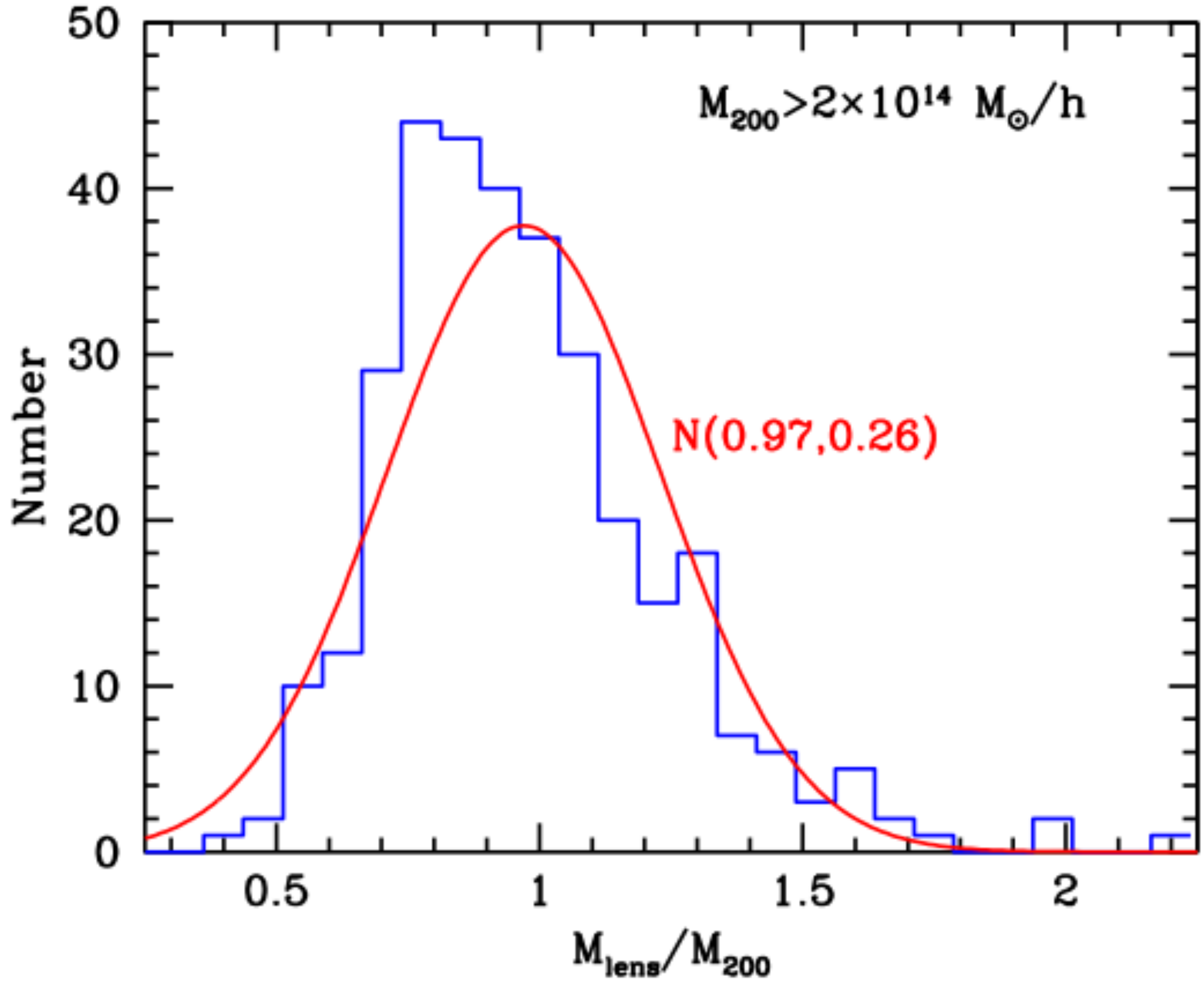


Correction for line-of-sight contamination by fitting a projected NFW profile to the shear and computing M_{200} from the fit.

Bias is a few percent.

Scatter is ~25%.

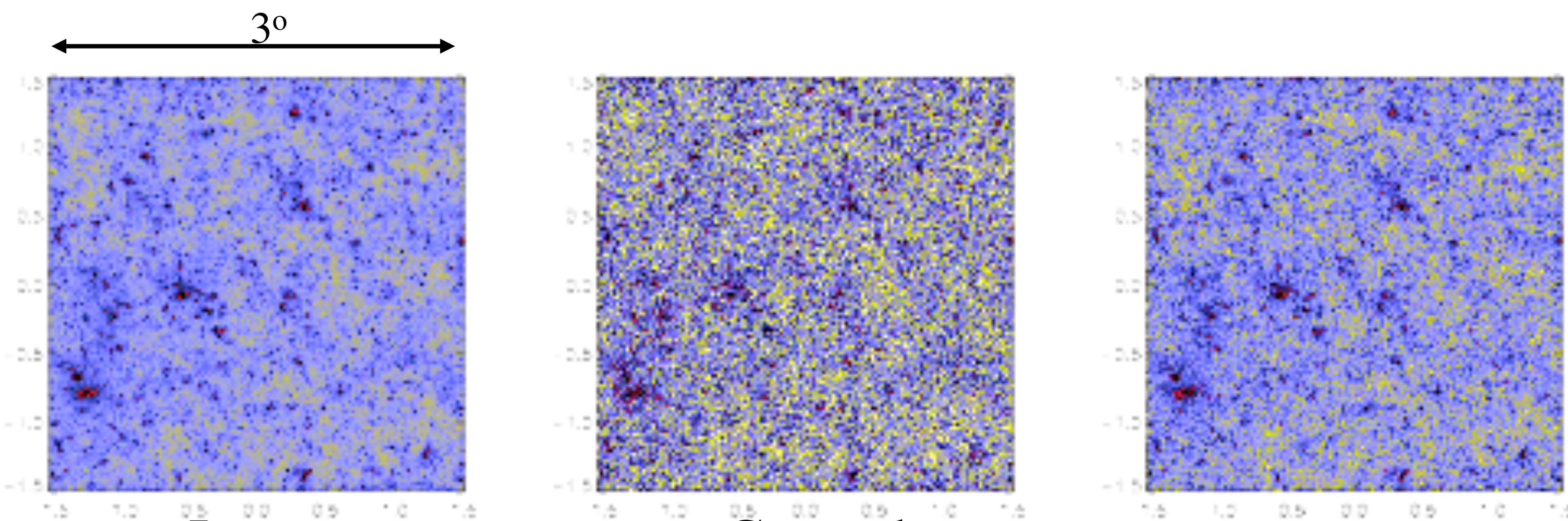
Distribution of errors



The End

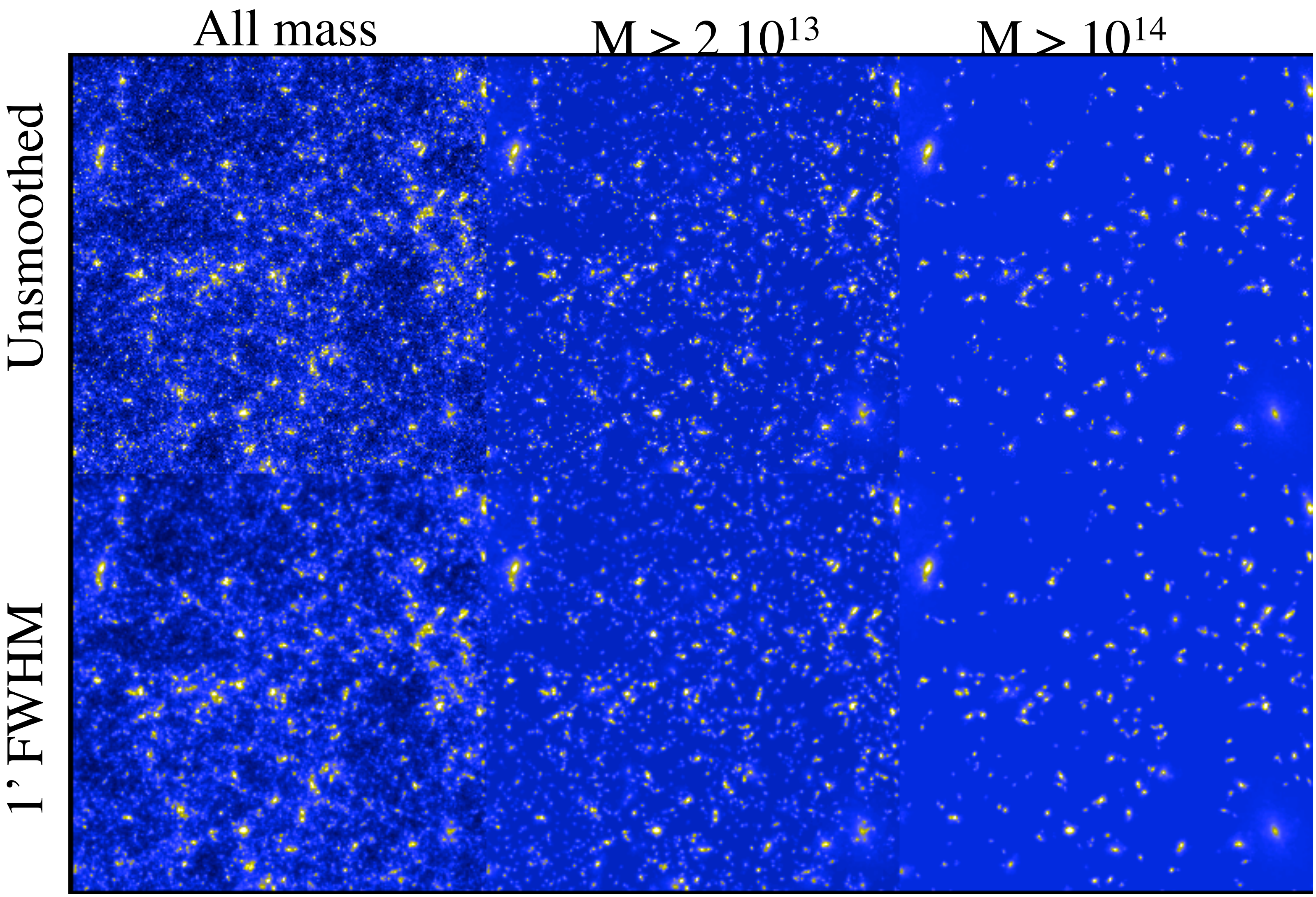
Information content

We are used to considering power spectra for cosmological constraints, but lensing maps are clearly non-Gaussian and SNAP is best positioned to measure this non-Gaussianity.



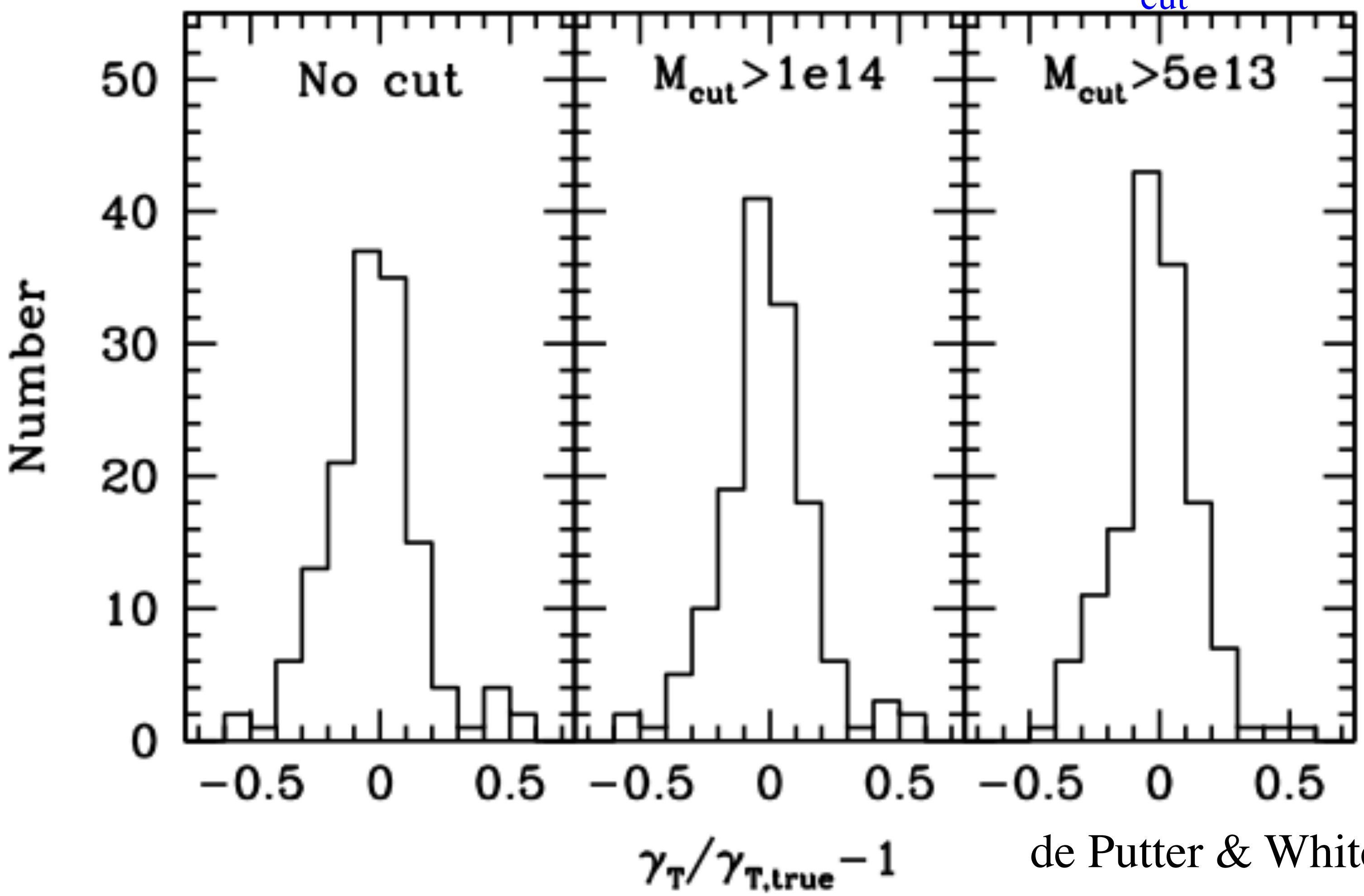
Input Ground Space

Halos and lensing



Modeling the line-of-sight

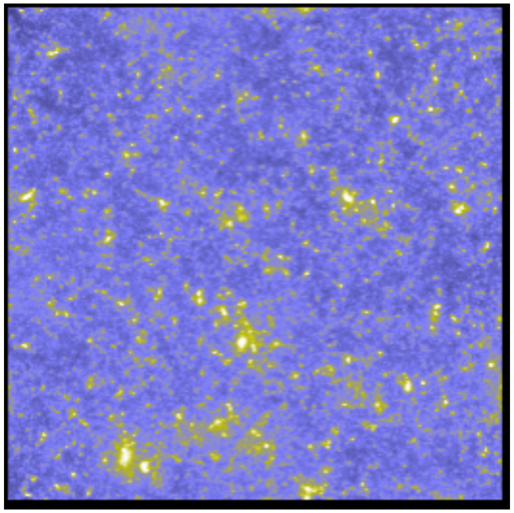
Around efficient lensing halos with $M > 3x10^{14}\ h^{-1}M_{sun}$
subtract the effect of halos with $M > M_{cut}$

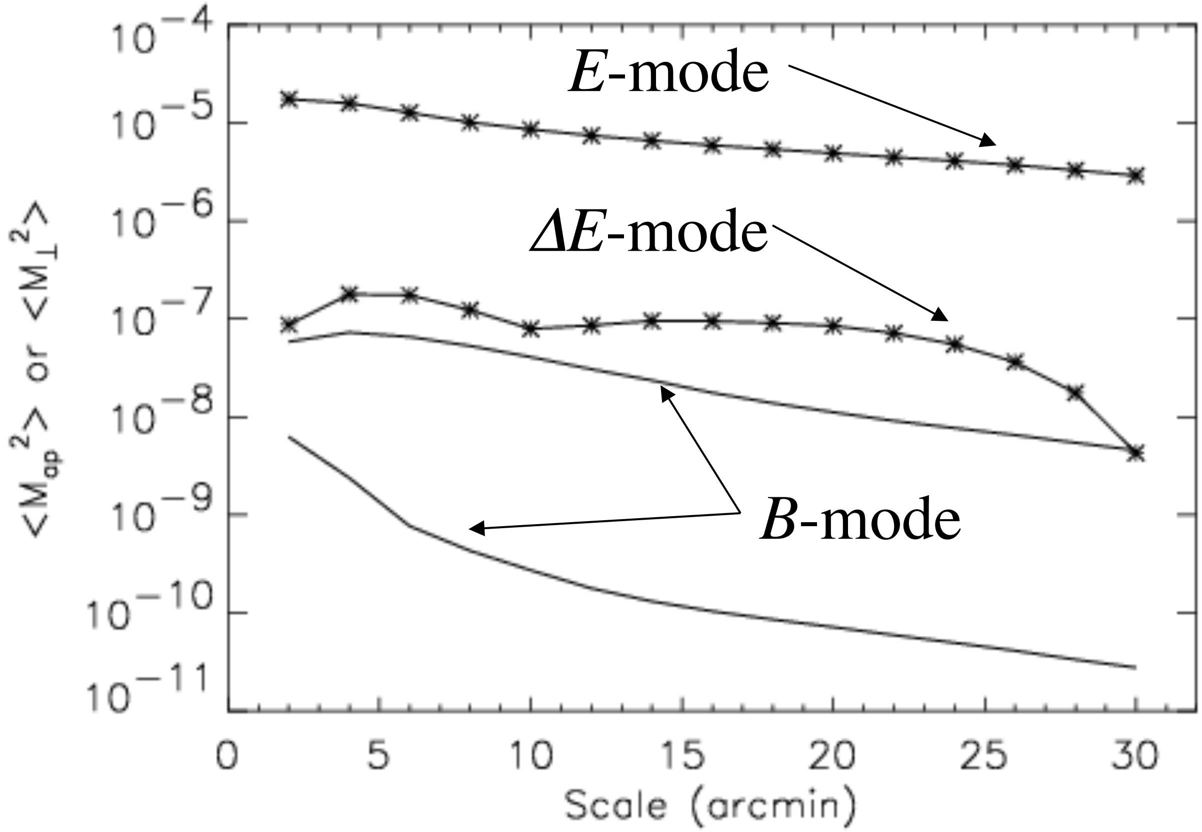


de Putter & White (2005)

Example: systematics

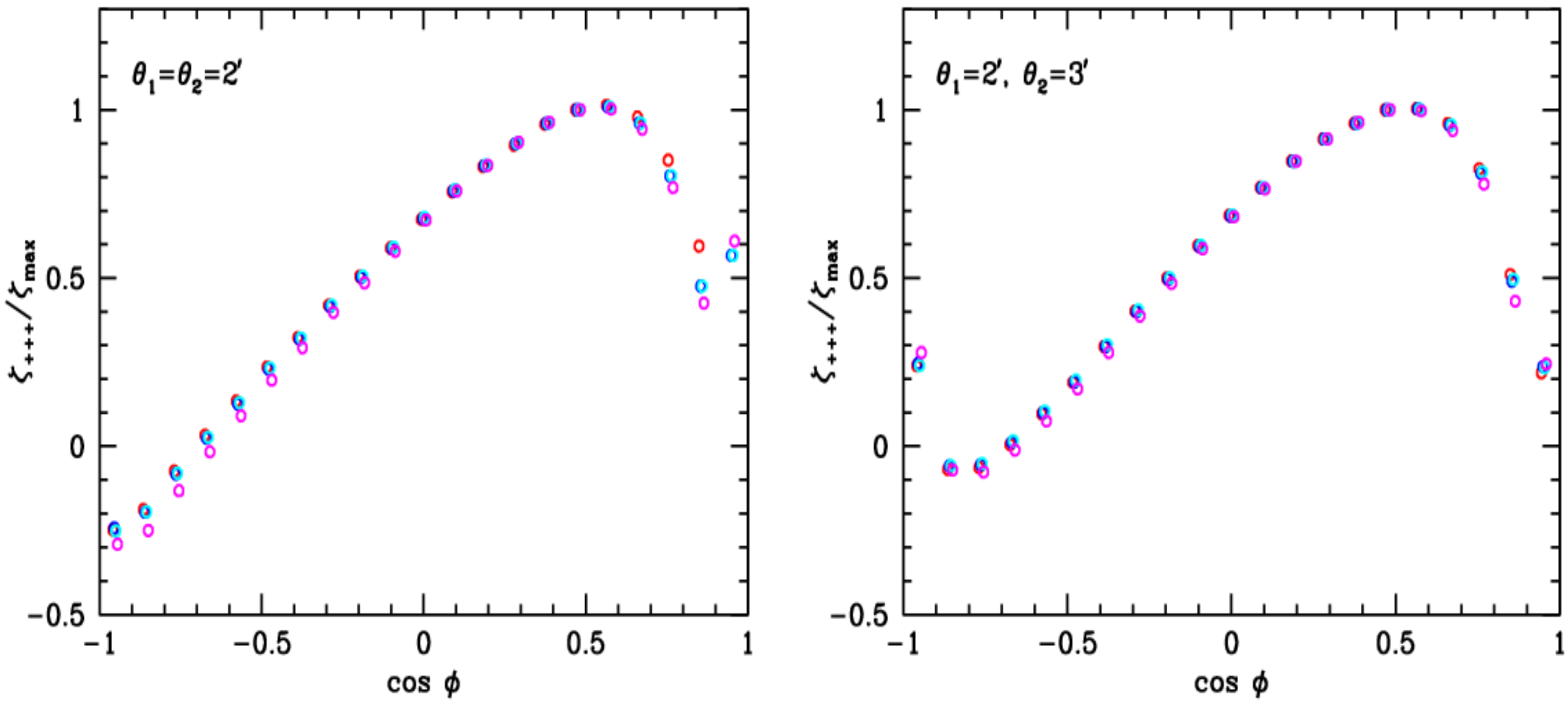
(Vale, Hoekstra, van Waerbeke & White 2004)





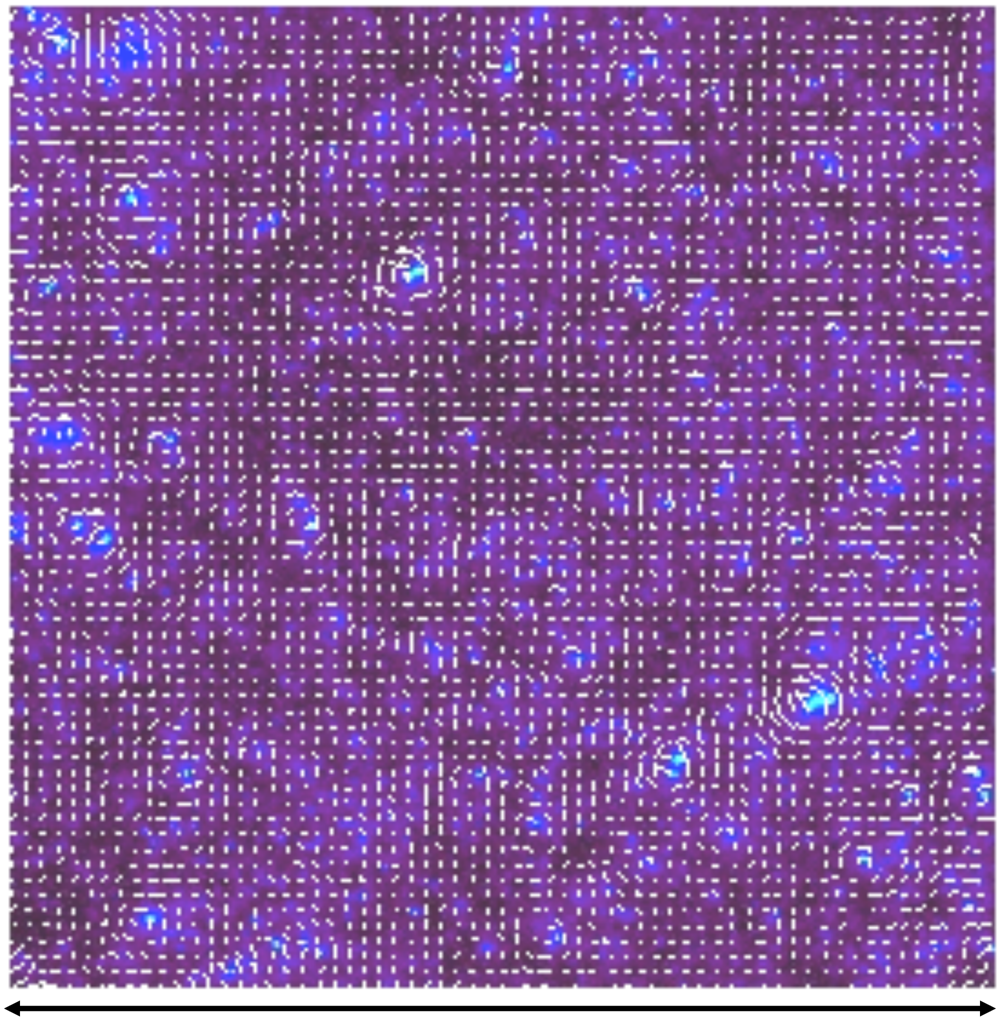
The 3 Point Correlation Function

Future observations will measure the 3PCF. Many functions, many configurations.



Is it just a normalization measurement?

A simulated shear field


2 degrees

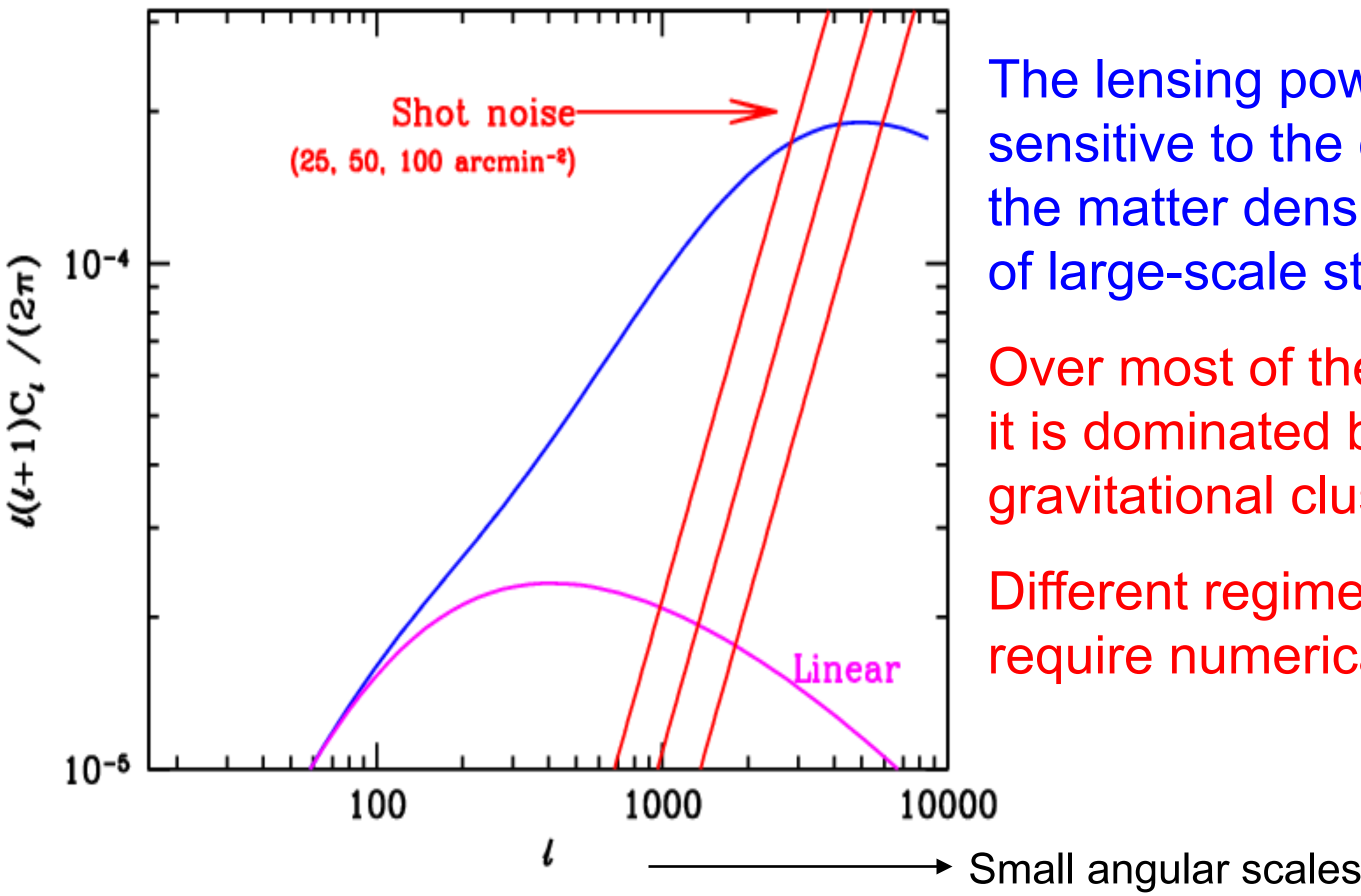
Obvious non-linear structure, with shear tangential about κ peaks of typical size ~1 arcmin.

Filamentary structure erased by projection.

Shear field sampled (regularly) at about the level achievable observationally from deep space based data.

Lensing power spectrum

Can measure the statistics of such lensing fields, for example the power spectrum of the shearing.



The lensing power spectrum is sensitive to the distance factors, the matter density and the growth of large-scale structure.

Over most of the measurable range it is dominated by non-linear gravitational clustering.

Different regime than CMB - require numerical simulations!

Types and uses of simulations

Lensing lends itself to numerical simulation …

We need numerical simulations to refine and calibrate algorithms and analytic approximations, and potentially serve as templates when the data become available.

Simulations can be used to extract:

- **Halo abundances and shapes**
- **Mass power spectra (and covariance matrices)**
- **Projected mass maps**
- **Ray tracing maps**
- **Mock galaxy catalogues**

We have implemented all of these approaches…

Weak gravitational lensing

- *Cosmic shear* is the distortion of the shapes of background galaxies due to the bending of light by the potentials associated with large-scale structure.
- For sources at z_s~1 it is a percent level effect which can only be detected statistically.
- Contains “interesting” information.
  - —Measures not just distances but also growth of large-scale structure
  - —Test of dark energy vs modified gravity.

Refregier et al. (2004)