How to design a survey to test dark energy/modified gravity

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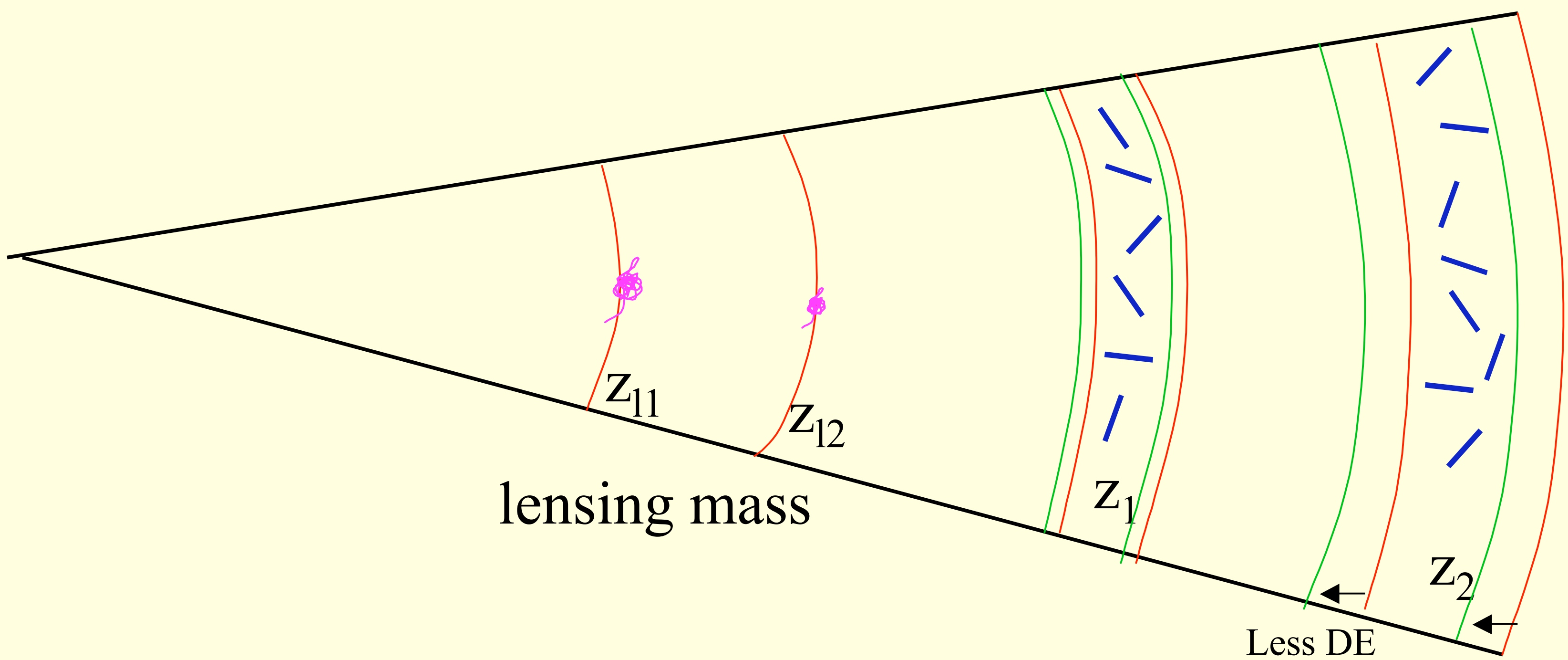
Outline

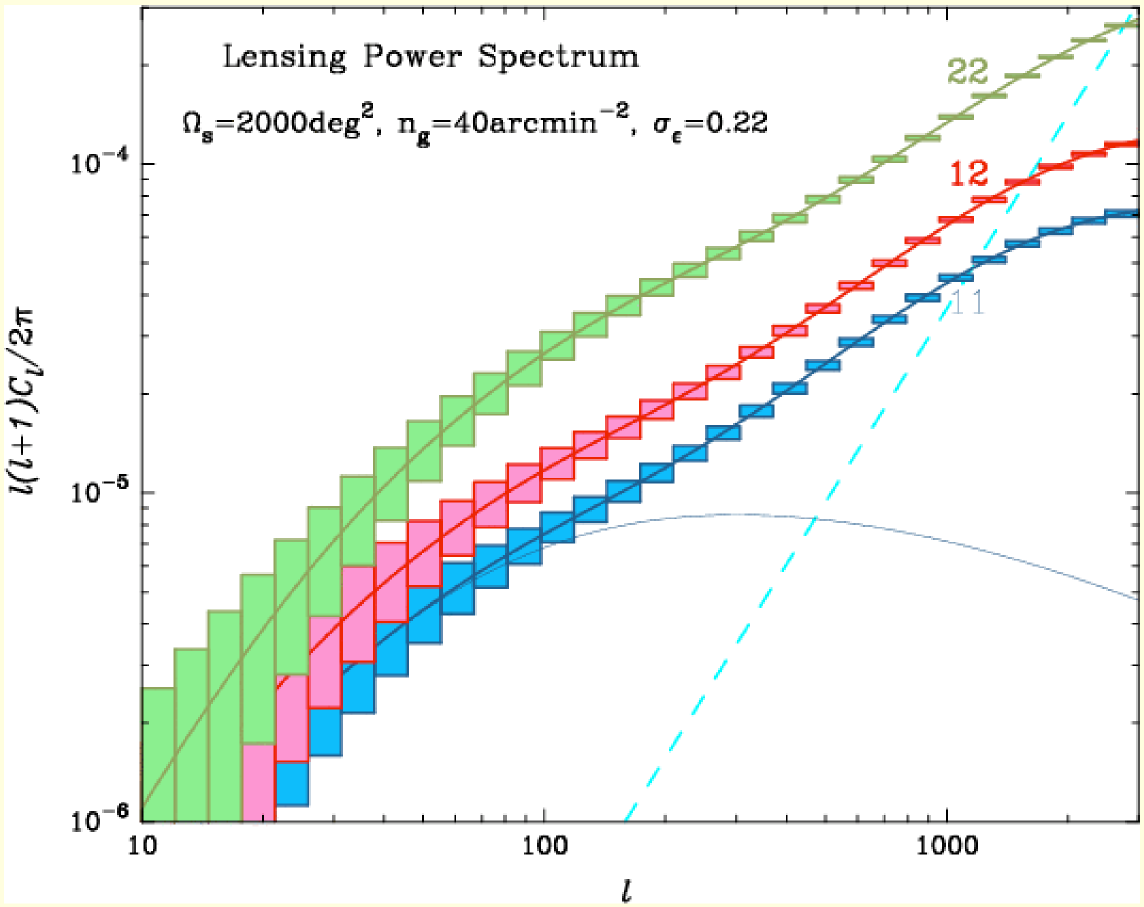
- Prospects for dark energy and modified gravity
- Surveys, future surveys, and futuristic surveys
- Systematic errors and analysis techniques
- Photometric redshifts: why all the fuss?

Lensing tomography



Shear at z_1 and z_2 given by integral of growth function & distances over lensing mass distribution ➡ Lensing tomography probes expansion kinematics and growth of structure

Lensing power spectra



Three auto and cross spectra. Note level of intrinsic ellipticity error.

Modified gravity theories

Cosmic acceleration may be due to modified Friedman equation

Goal: Weaken gravity at late cosmic times and large scales

Alternate gravity theories are not easy to construct!

And they must pass early universe and solar system tests

Types of theories:

- Higher dimensional theories, e.g. DGP $H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho$
- Additional terms in the action, e.g. powers of R or 1/R or log R
- Additional fields that couple to Ricci scalar, e.g. Brans-Dicke
- MOND-like explanation of dark matter in galaxies and clusters: using scalar+vector+tensor fields, e.g. TeVeS

Testing modified gravity

Homogeneous solution of modified gravity model must give correct distance-redshift relation.

Relation of metric perturbations to growth of density/velocity perturbations can distinguish the model from dark energy.

Growth of density perturbations is slowed by ~5% compared to equivalent dark energy model. This *may* be a generic feature of a class of modified gravity models (Lue et al 03).

The relation of every observable to *H(z)* must be altered. Distances, density and potential perturbations will in general have different relations to *H(z)* than in GR plus dark energy.

Warning!

What follows involves no real theory of gravity

(this may be the case for a while)

Simulating Alternate Gravity Models

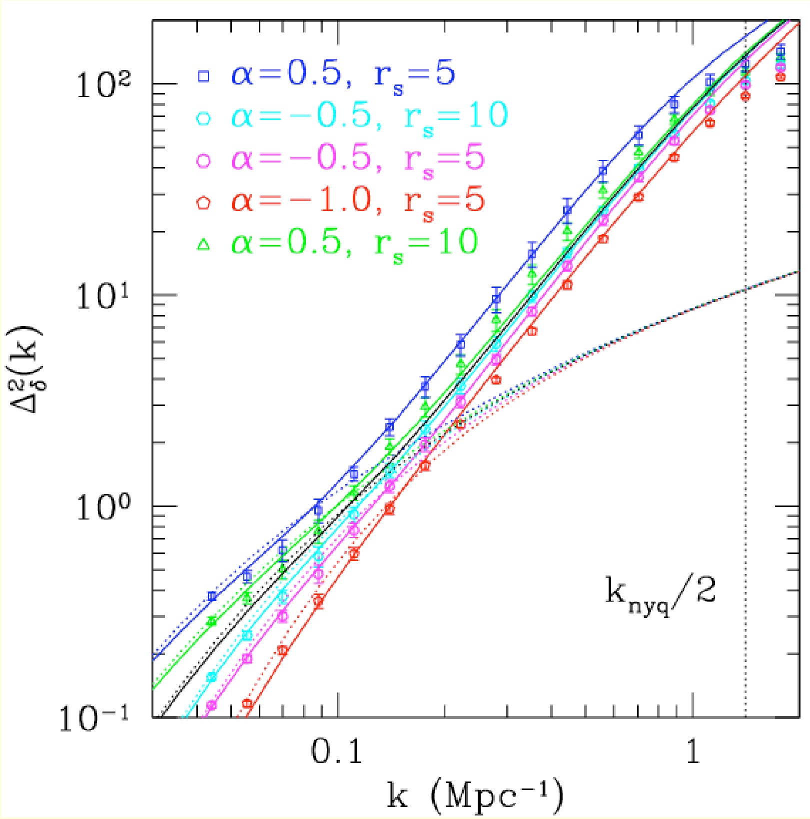
- Models weaken gravity on ~1000 Mpc scales: what about 1-100 Mpc, where observations exist? Need quasilinear/nonlinear predictions.
- Modify Poisson's eqn with Yukawa term ➡ gravity weaker/stronger on large scales at late times

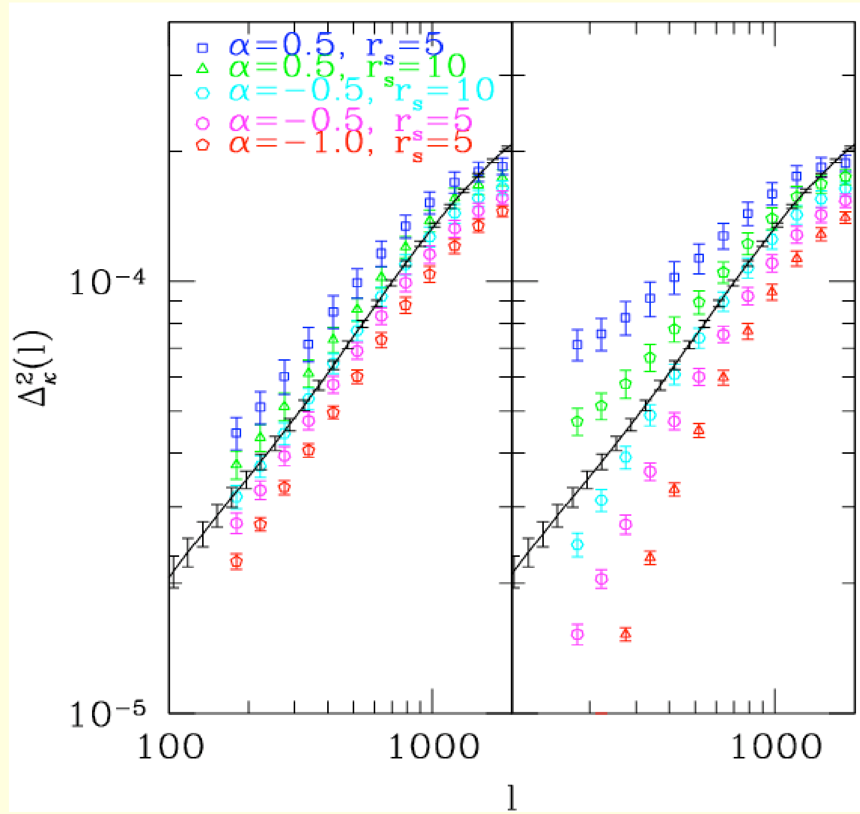
$$\tilde{\phi}(k) = \tilde{\phi}_N(k)\left(1 + \frac{\alpha}{1 + (kr_s/a)^2}\right)$$

- Expansion rate as in ΛCDM to match SN data
- N-body simulations of 5 models with different sign/scale of modification
- At initial redshift, all power spectra are identical to ΛCDM
- At late times/low-z, power spectra still match at small scales, but differ at large scales. Consider *2/Mpc < r < 200/Mpc*
- Compute 3D power spectra at low-z, and the lensing power spectra

Shirata et al 05, Sealfon et al 05, Stabenau & Jain 06

Nonlinear power spectra





3D power spectra

Lensing power spectra

Two different light deflection potentials

- Prospects for dark energy and alternate gravity
- **Surveys, future surveys, and futuristic surveys**
- **Systematic errors and analysis techniques**
- Photometric redshifts: why all the fuss?

Lensing measurements: statistical errors

Statistical errors: intrinsic ellipticity variance and sample variance

Assume: Intrinsic galaxy shapes are uncorrelated: $< \varepsilon_{intrinsic} > = 0$

– RMS ellipticity: $\sigma_\varepsilon = 0.3$: uncertainty in shear estimate $\sim \sigma_\varepsilon /(N^{1/2})$

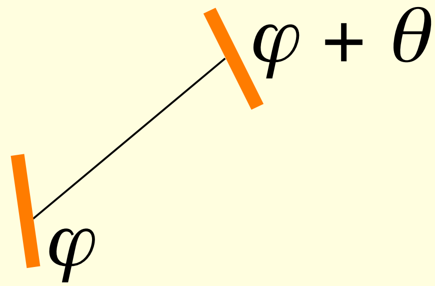
– Additional uncertainty in shear statistics due to sample variance.

Both errors scale with f_{sky}

Rough numbers for signal and detection:

Shear	Galaxies Needed	Example
10%	10^2	Rich Clusters
3%	10^3	Typical Clusters
1%	10^4	Galaxy Group
0.3%	10^5	Field Lensing

2-Point Correlations



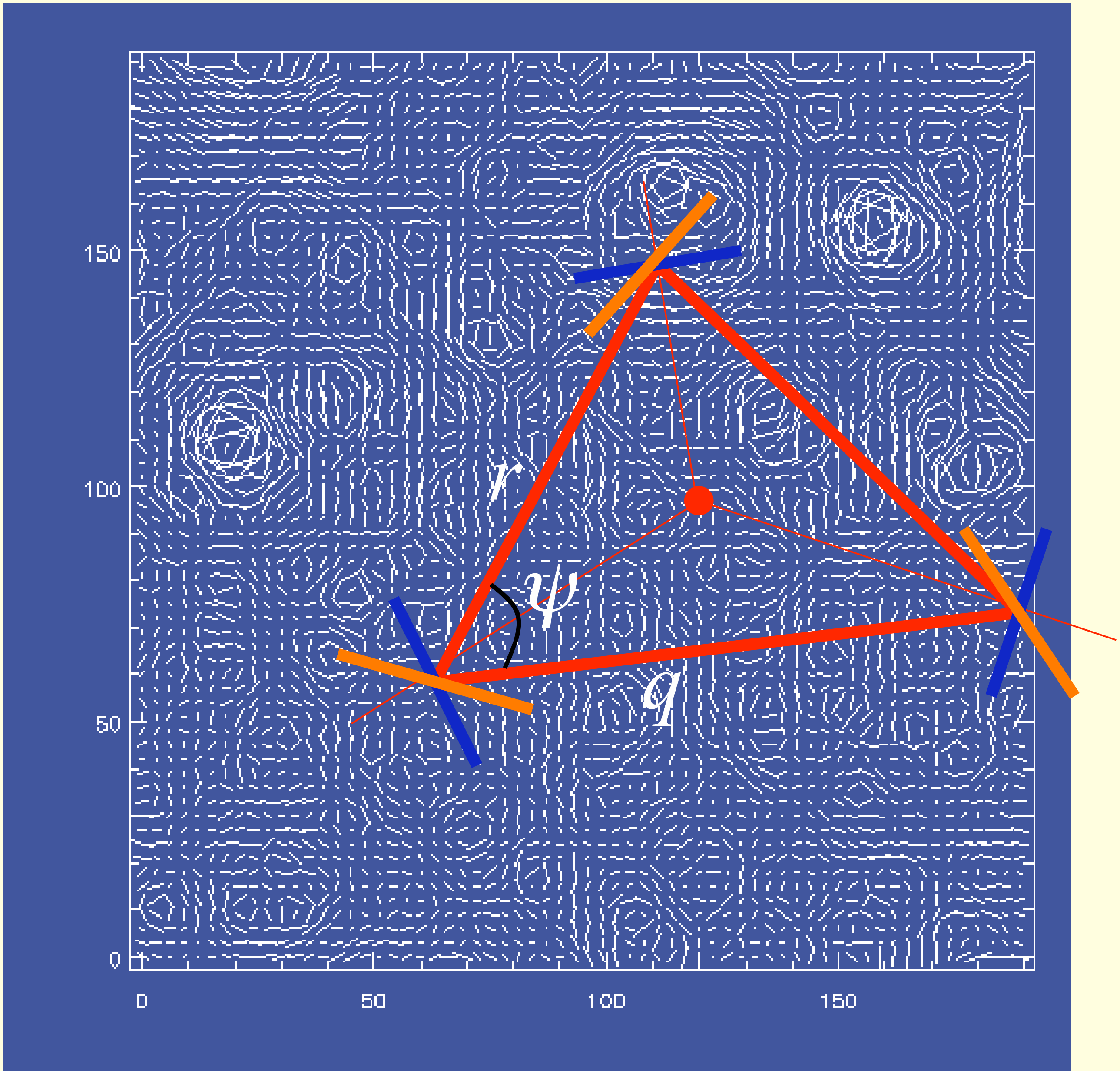
$$\xi_\gamma(\theta) = \left\langle \gamma(\varphi)\gamma^*(\varphi+\theta) \right\rangle \overset{F.T.}{\Leftrightarrow} C_\gamma(l)$$

Cosmological information is contained in statistical correlations.

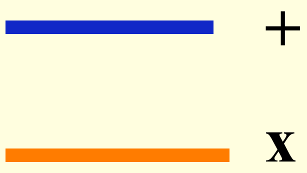
Lensing correlations given by projection of the mass power spectrum:

$$\left\langle \gamma\,\gamma^* \right\rangle(\theta, z_s) = \int dz\, W^2(z, z_s) \int dk\; P_\delta(k,z)\; F(k,\theta,z)$$

Shear 3-point correlations: $\zeta_{ijk} \equiv \left\langle \gamma_i(\mathbf{x}_1)\gamma_j(\mathbf{x}_2)\gamma_k(\mathbf{x}_3)\right\rangle$



8 components!



The last 5 years and the next 15

- I: Weak lensing in “blank fields” detected in 2000
- IIa: WL measurements and cosmology in 2006:
  - Shear correlations measured over 1 arcmin-1 deg using 10-100 sq deg data
  - E/B mode tests, and other checks of systematics
  - Cosmology at 10% level using information on redshift distributions
- IIb: Methods for systematic error analysis
  - ~ 5 systematics identified as leading contributors
  - Methods developed to advance shape measurements and test for others
  - Fit for systematics from multiple redshifts and different statistics
- III: Prospects for the next ~ 5-8 years
  - Effective survey size could increase by x10
  - Photo-z’s for individual galaxies; calibration accuracy?
  - Need systematic errors to be below few percent level of signal
- IV: Prospects for futuristic surveys
  - Goal: Better than 1% accuracy in lensing measurements
  - Systematic correction over all currently known errors and several new ones!

Wide field lensing surveys

- CFHT Legacy Survey
  Ω_s=200 deg^2, r ~ 25, 5 filters

Future surveys: begin in 2008-2010

- KIDS
  - 2.5m telescope, 1 deg^2 FOV , 4(+5) filters
  - Ω_s =1,500, r ~ 24.5
- DES
  - 4m telescope, 3 deg^2 FOV, 5 filters
  - Ω_s =5,000, r ~ 24
- PS1

Futuristic [billion(s) of dollars later] surveys: 2014+

- LSST (Large Synoptic Survey Telescope)
  - 8m telescope, 10 deg^2 FOV
  - Ω_s =20,000, r ~ 26, n_g=40 arcmin^{-2}
- SNAP (Supernova/Acceleration Probe)
  - 2m telescope, 0.7 FOV, 9 filters
  - Ω_s =1,000-4,000 deg^2, r ~ 26.5, n_g=100 arcmin^{-2}

Planning a lensing survey?

1. Instrumental effects: How good is the image quality?

2. Correct from the data: How well can it be corrected from measured stars?

3. Self-calibration regime?: How much do residual errors degrade cosmological measurements?

Any planned survey needs to answer these questions.

With increasing survey size statistical errors go down.

Will systematic errors keep pace?

The Lensing Pipeline

1. Object detection, star-galaxy classification
2. PSF (point spread function) measurement from stars
3. PSF interpolation onto galaxy positions
4. Galaxy shape measurement and PSF deconvolution
5. Shear correlation measurement + Redshift binning ➡ cosmological parameters

Systematic errors enter at all stages.

From the first detection in 2000, there have been major advances in correction and testing for systematics.

There's still a long way to go for next generation surveys. Lensing and photo-z requirements are likely to set the primary calibration requirements for imaging surveys.

Systematic Errors in Weak Lensing: PSF Anisotropy

• Point spread function (PSF): the image of a point source (star) due to atmosphere and telescope optics

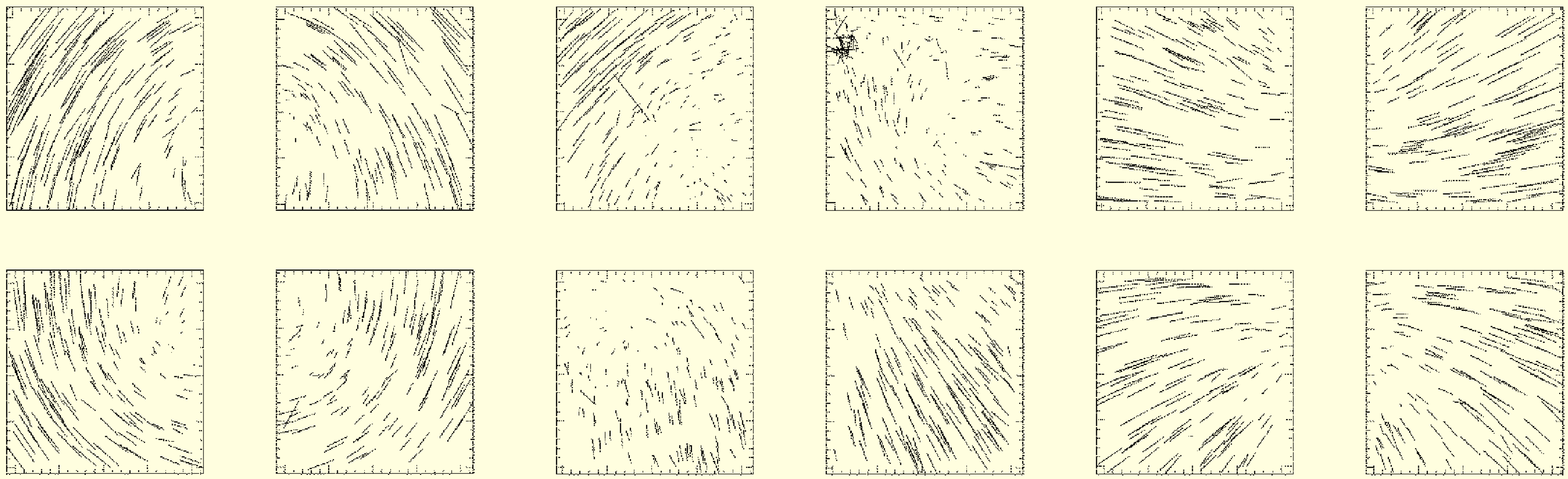
• PSF anisotropy is the primary systematic errors in current lensing data: before correction, its at 1-5% level (statistical errors: ~0.1%)

• Galaxy shapes are convolved by the PSF, so PSF anisotropy must be removed to get accurate galaxy shapes

• There are good methods for de-convolving the PSF

• So what's the problem? *Interpolating the PSF* from where it is measured (stars) to where we need it (galaxies)

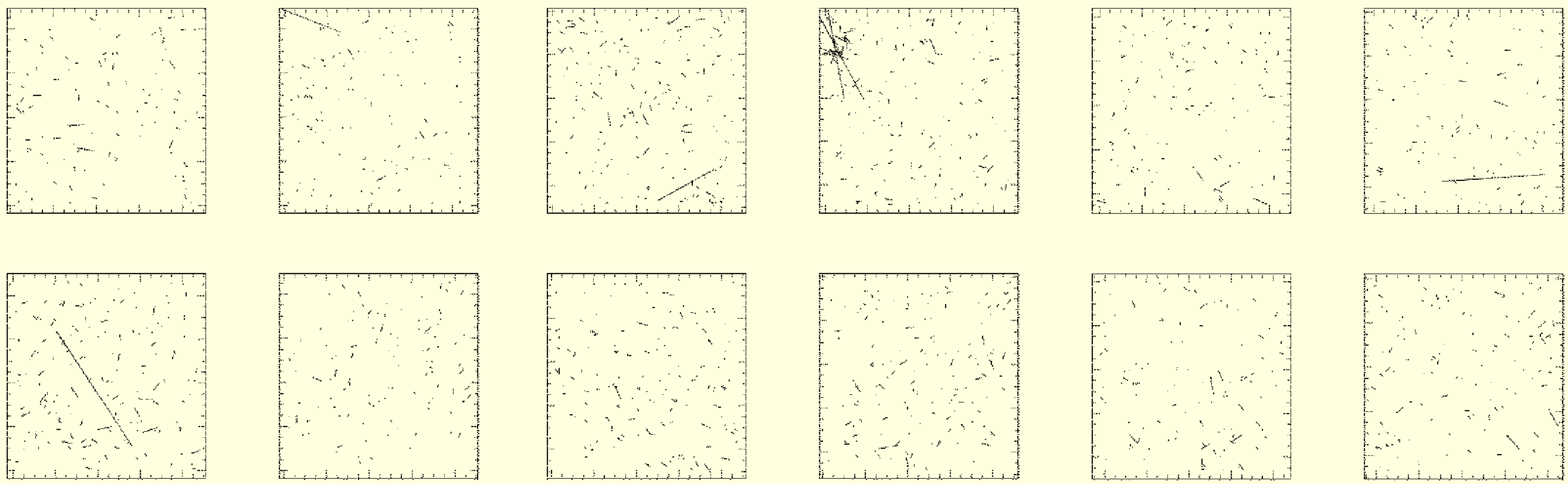
Anisotropic PSF



Focus too low   Focus (roughly) correct   Focus too high

- Whisker plots for three BTC camera exposures; ~10% ellipticity
- Left and right are most extreme variations, middle is more typical.
- Is there a correlated variation in the different exposures? Yes!

After Processing



Focus too low | Focus (roughly) correct | Focus too high

- Remaining ellipticities are essentially uncorrelated.
- Measurement error is the cause of the residual shapes.
- 1st improvement: higher order polynomial means PSF accurate to below 1 arcmin.
- 2nd improvement: Much lower correlated residuals on all scales

Techniques for PSF correction

• PCA (principal component analysis) uses stars from different exposures and different pointings to improve PSF interpolation. It deals with PSF patterns that are correlated in different exposures.

• Uncorrelated PSF patterns (e.g. atmosphere) are circumvented by measuring shear correlations from cross-correlation of galaxy shapes measured in different exposures.

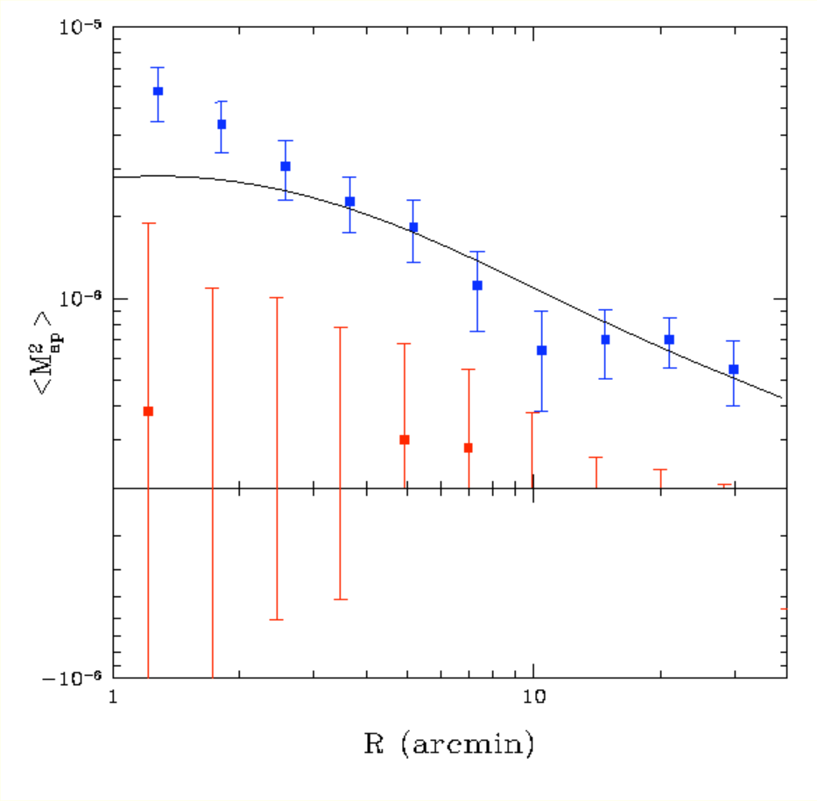
These two techniques can tackle generic PSF anisotropy patterns.

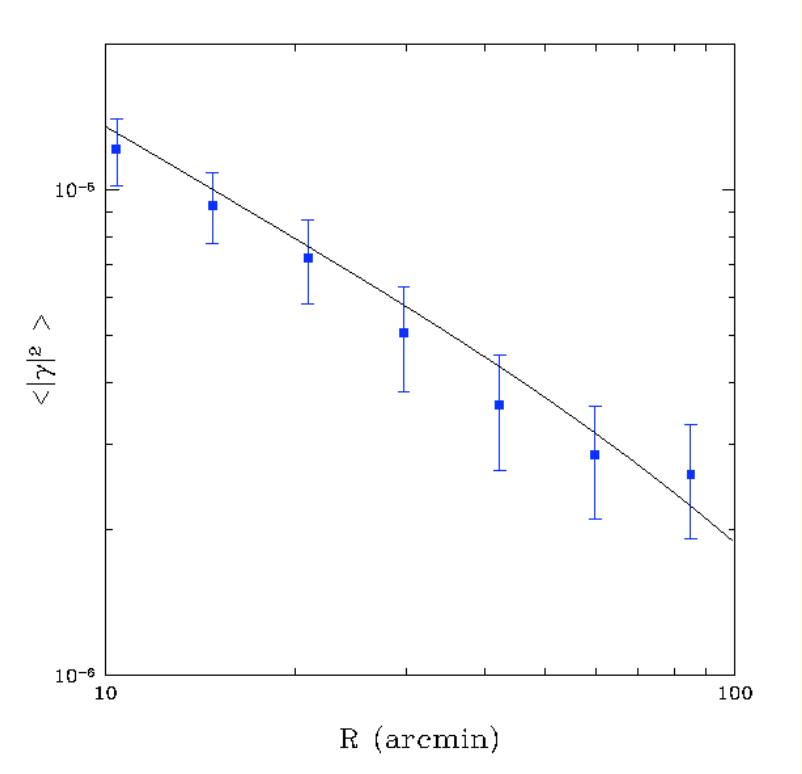
Requirements: sufficient well measured stars per exposure; few principal components; PSF patterns are smooth and depend linearly on telescope variables; ~5 or more exposures per pointing

Jarvis & Jain 2004, astro-ph/0412234

Jain, Jarvis, Bernstein 2006, astro-ph/0510231

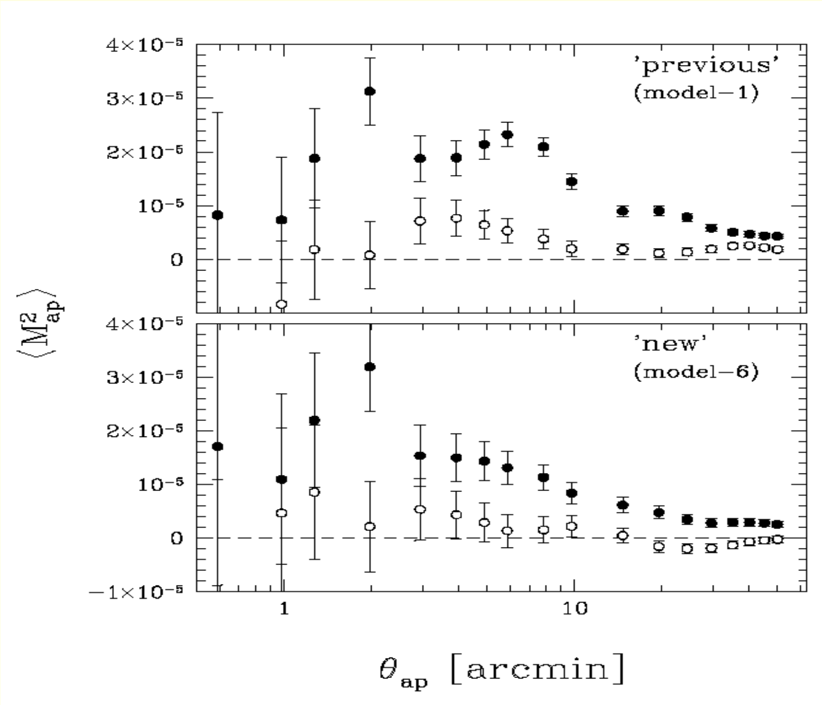
Results: 2-point correlations

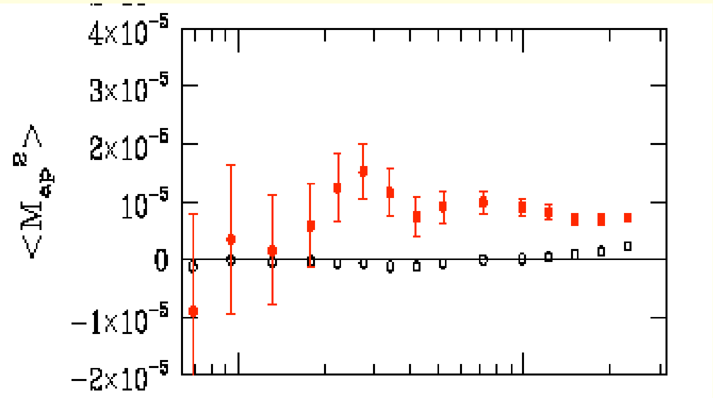


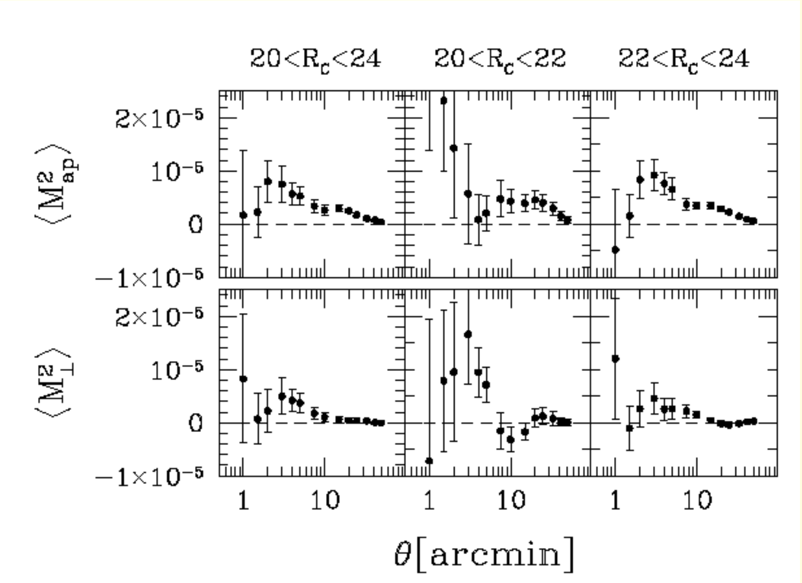


Shear 2-point statistics from CTIO survey (Jarvis et al 05)

Current Lensing Results







Virmos, CFHLS, RCS surveys

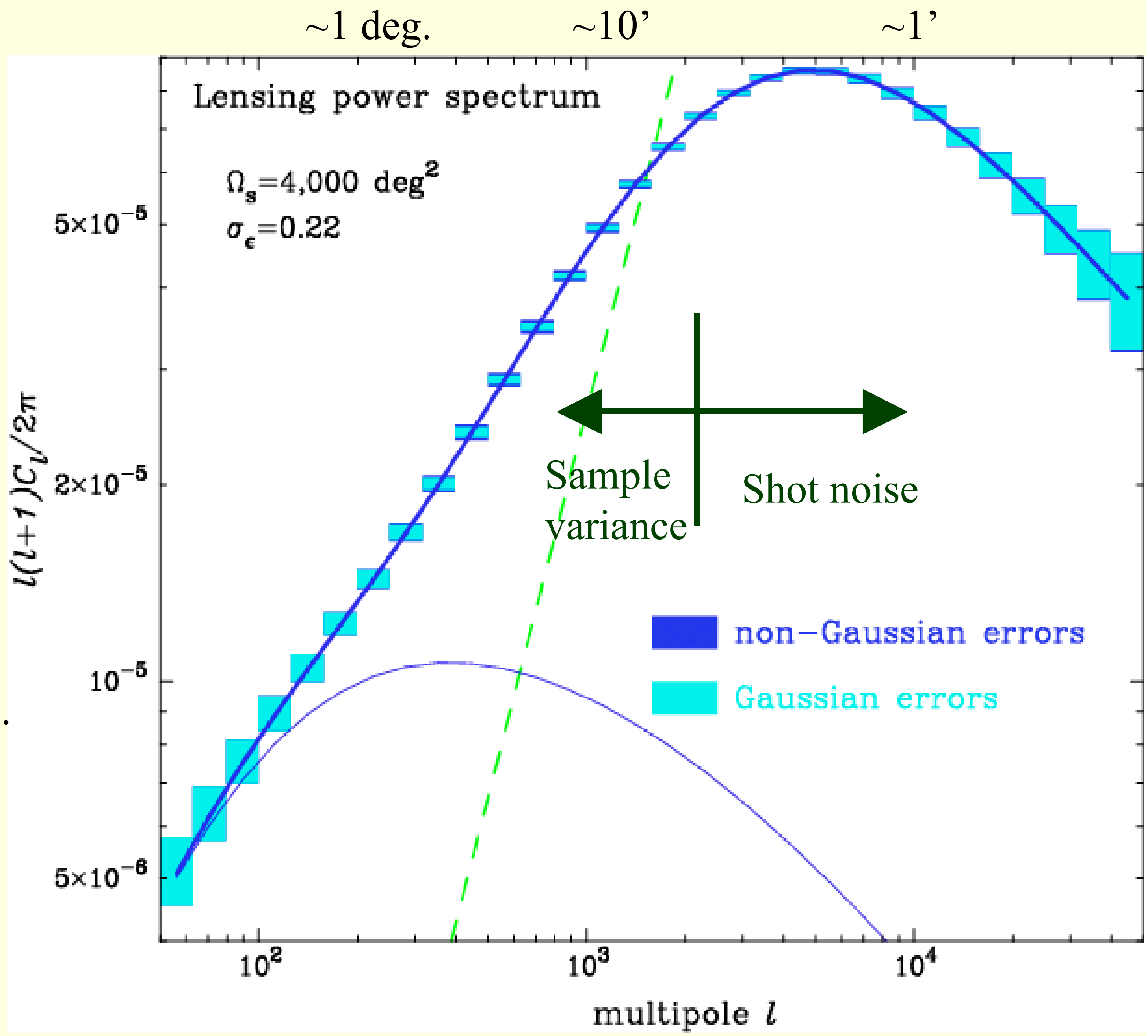
Non-Gaussian Effects

- The lensing bispectrum arises due to nonlinear evolution and carries additional information
- Non-Gaussian contributions add to the errors on the power spectrum and the bispectrum.
- They also cause the bispectrum and power spectrum to be correlated
- All these contributions to the diagonal and off-diagonal parts of the covariance matrices must be included for forecasts and measurements.

Lensing Power Spectrum (PS)

- Lensing PS has a featureless shape
- Most of WL signal is from small angular scales
- Non-linear clustering boosts the lensing signal at l>100

Takada & Jain, 2007, in prep.



Non-Gaussian Covariances

- Lensing signals are from non-linear scales: the errors are non-Gaussian
- PS covariance describes correlation between the two spectra of multipoles l_1 and l_2.
- The non-Gaussian errors for PS arise from the 4-pt function of mass clustering in LSS (Cooray & Hu 01 and White & Hu 2001)

$$\mathrm{Cov}[P(l_1),P(l_2)] = \langle \kappa(l_1)\kappa(-l_1)\kappa(l_2)\kappa(-l_2)\rangle - P(l_1)P(l_2)$$

Gaussian errors →

$$= \frac{\delta_{l_1 l_2}}{f_{\mathrm{sky}}\, l\Delta l}\left[P(l_1) + \frac{\sigma_\varepsilon^2}{n_g}\right]^2$$

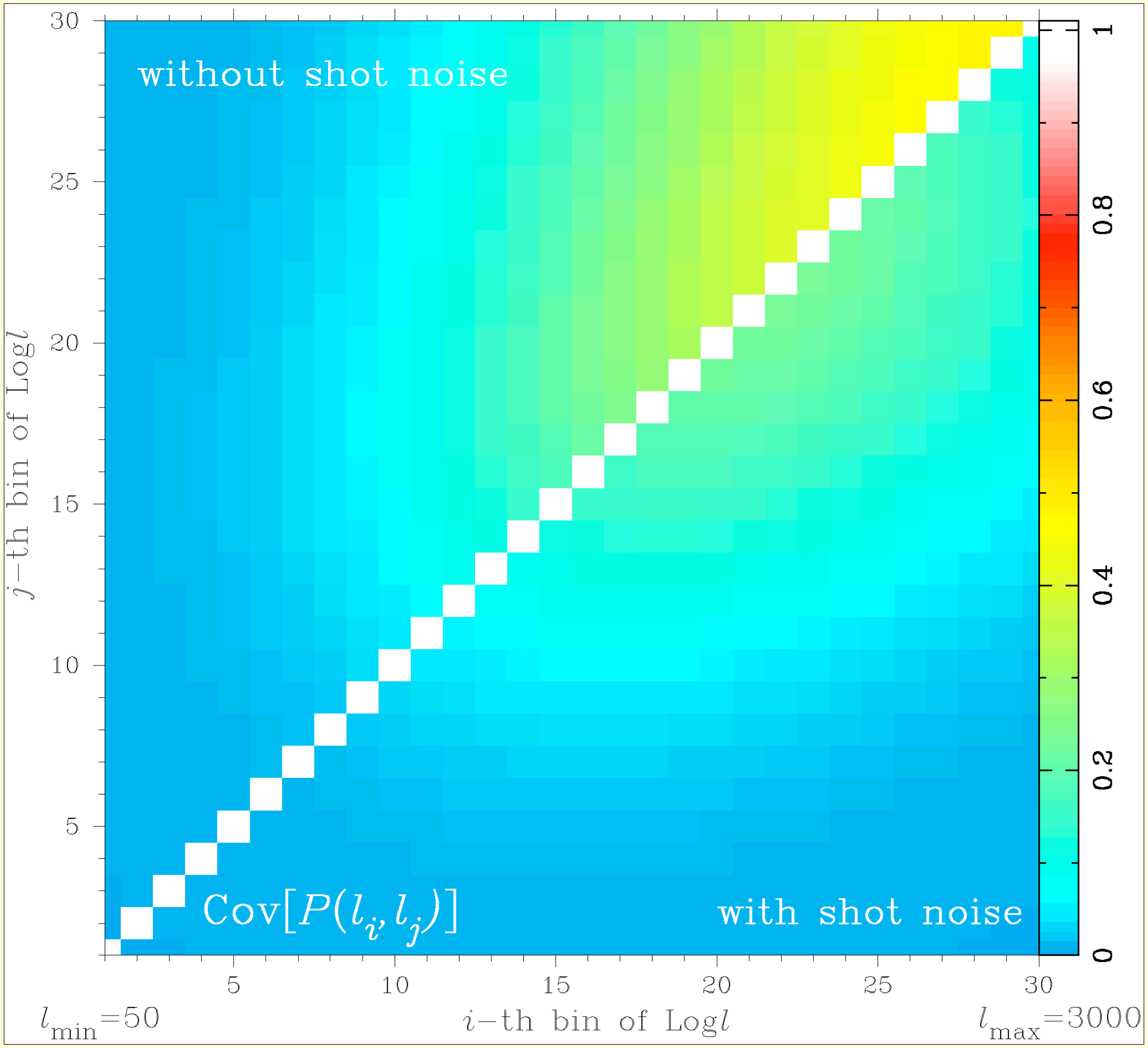
Non-Gaussian errors →

$$+ \frac{1}{4\pi f_{sky}}\int_{l_1}\frac{d^2\mathbf{l}_1'}{2\pi l_1\Delta l_1}\int_{l_2}\frac{d^2\mathbf{l}_2'}{2\pi l_2\Delta l_2}T(\mathbf{l}_1',-\mathbf{l}_1',\mathbf{l}_2',-\mathbf{l}_2')$$

Covariance matrix for the power spectrum

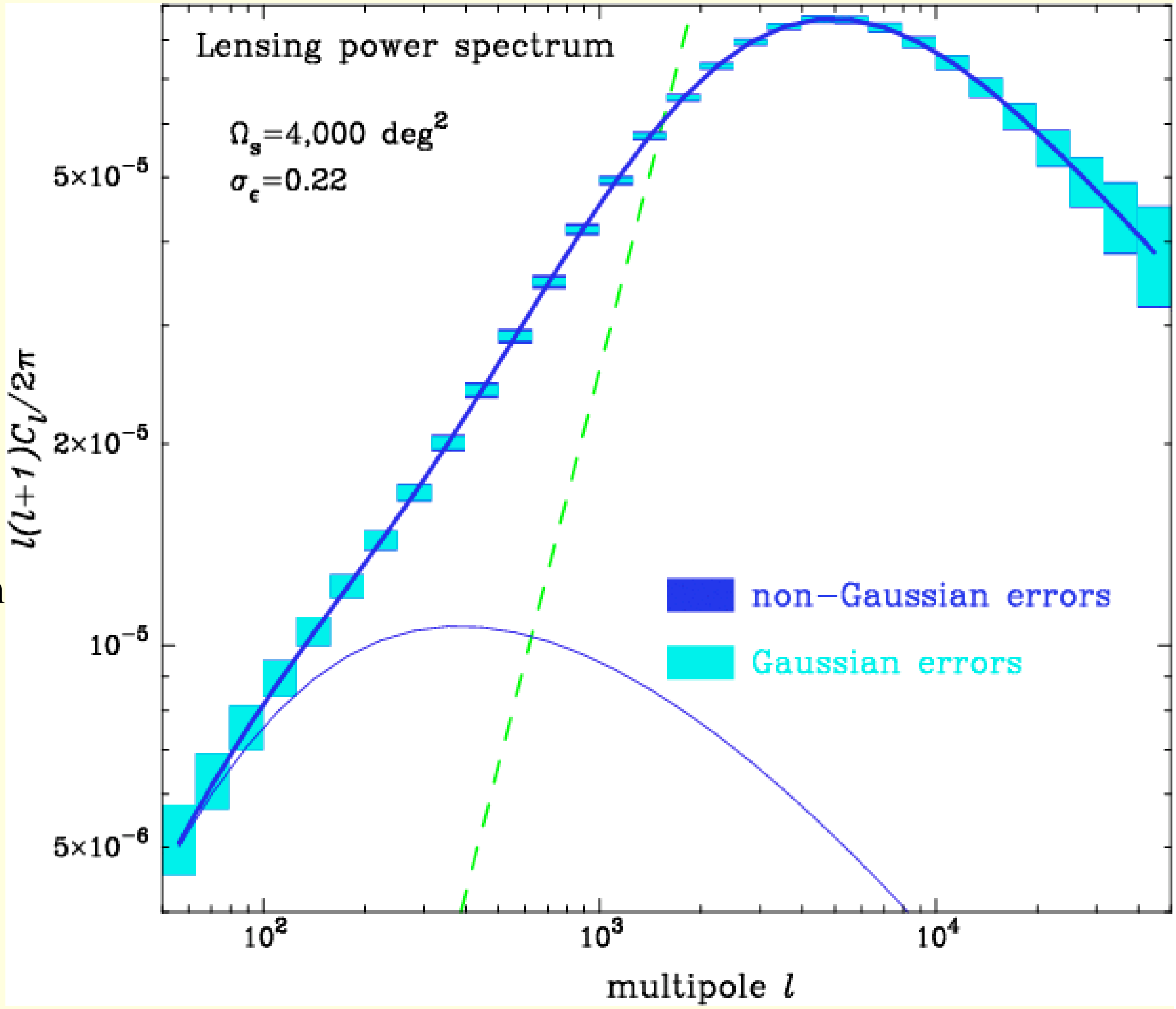
$$r_{ij} = \frac{\mathrm{Cov}[P_i, P_j]}{\sqrt{\mathrm{Cov}[P_i, P_i]\mathrm{Cov}[P_j, P_j]}}$$

- If maximally correlated
  $r\_ij \rightarrow 1$
- Diagonal: Gaussian
- Off-diagonal: non-Gaussian, 4-pt function
- 30 bins: 50<l<3000
- Shot noise only contributes to the diagonal terms



Power Spectrum with NG errors

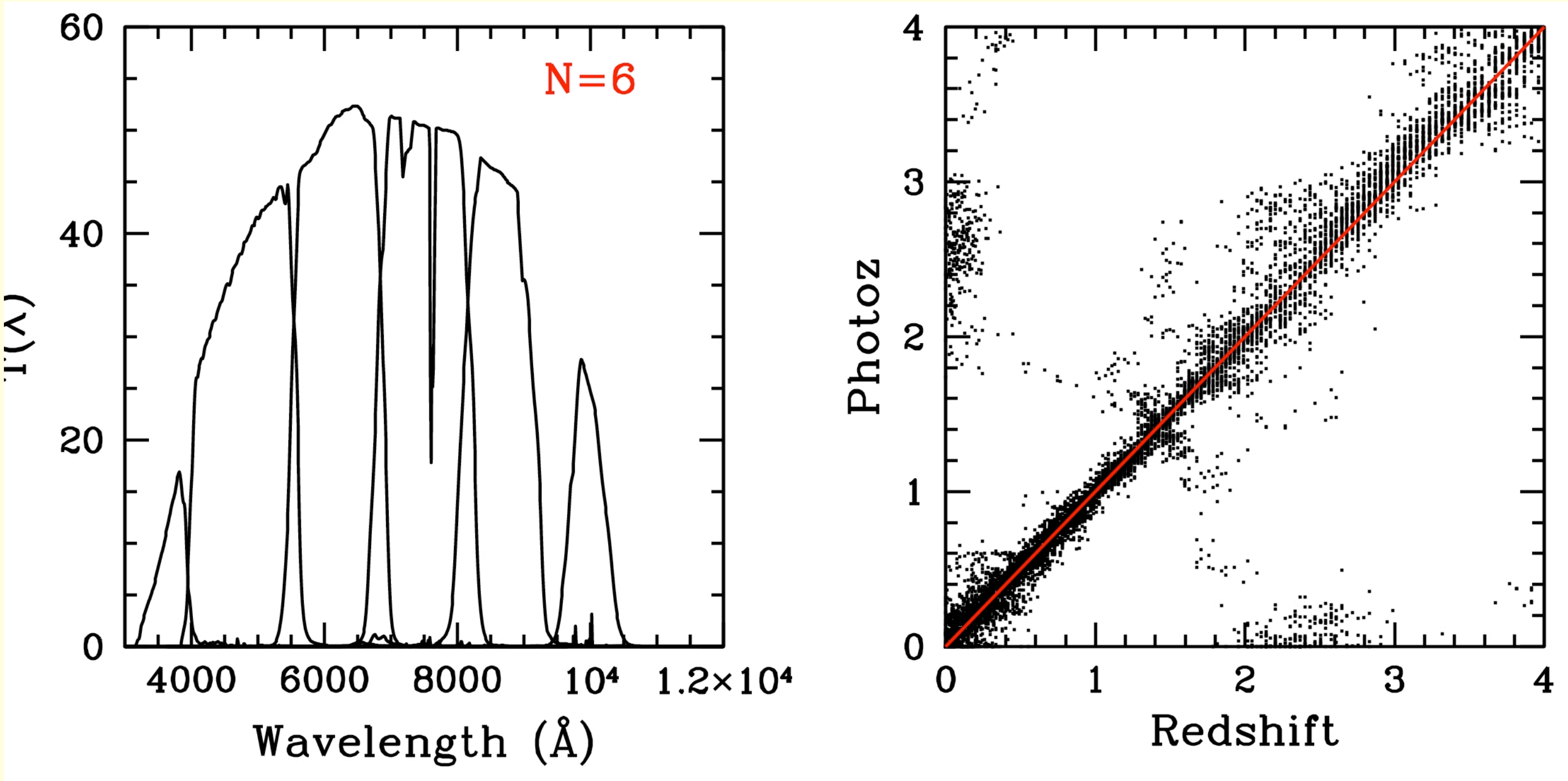
- For l<100, and l>1000, the errors are close to the Gaussian+shot-noise case
- The non-Gaussian contribution is less important for surveys with lower galaxy number density
- At worst ~50% degradation of power spectrum errors at l~1000; below 10% for parameter errors



- Surveys, future surveys, and futuristic surveys
- Prospects for dark energy and alternate gravity
- Systematic errors and analysis techniques
- **Photometric redshifts: why all the fuss?**

with A. Connolly, M. Jarvis, H. Stabenau, M. Takada

Filter Shape and Scatter



From Andrew Connolly

Metric for Photoz's

- Getting photo-z's is a many dimensional problem: require metrics for errors. With models for scatter (percentiles) and mean redshift, can estimate:
  - Error on mean and width of redshift bins
  - Number of catastrophic values

- Questions relevant for lensing:
  - What's the required accuracy in mean z and width of z-bin?
  - What is needed to calibrate photoz's from given set of filters?
  - What's the damage for given level of error in the mean?

Redshift Calibration Sample

- Photo-z's require a spectroscopic verification sample:
  - Need ~ 10^4- 10^5 spectra
  - Limiting magnitude of imaging survey: r ~ 24-26 for planned surveys
  - Even sampling of color/type
  - Calibration across the sky

  - Cross-correlation trick may help with some galaxy types and magnitudes

  - Use galaxy angular correlations as check/constraint on photo-z's

  - Two step calibration? Spectra and mega-band imaging as calibrating datasets for photo-z's.

Bernstein, Jain 04, Huterer et al 05, Ma et al 05, Newman 07, Knox et al 06

Removing Catastrophic Redshifts

- Systematic (catastrophic) redshift errors
  - Multimodal likelihood function
  - Confusion of breaks (Lyman vs Balmer)
  - Could dominate lensing errors
- Priors and auxiliary information
  - Luminosity function (high redshift errors)
  - Size distribution (high redshift errors)
  - Surface brightness
  - Require characteristics from existing surveys and planned surveys
- Likelihood filtering
  - Remove multimodal sources
  - Trade off of numbers vs accuracy
  - Require goal from lensing

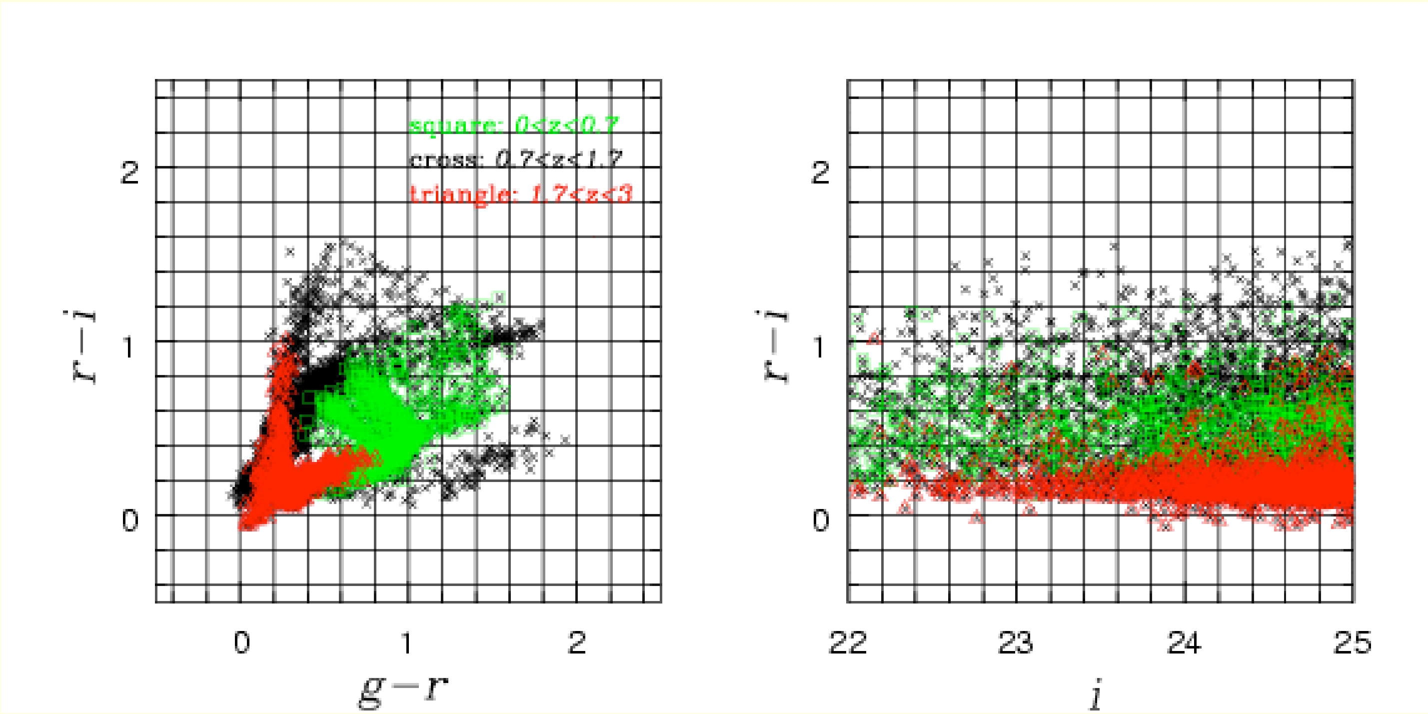
Color Tomography

- Lensing kernel is broad in redshift
- 4-6 broad z-bins get nearly all the cosmological information
- For a large survey, 50% or more of the galaxies are dispensable

- Imaging in 6 or more bands is what it takes to get good photo-z's
- Imaging in 6 bands over 1000s of sq deg takes a lot of nights

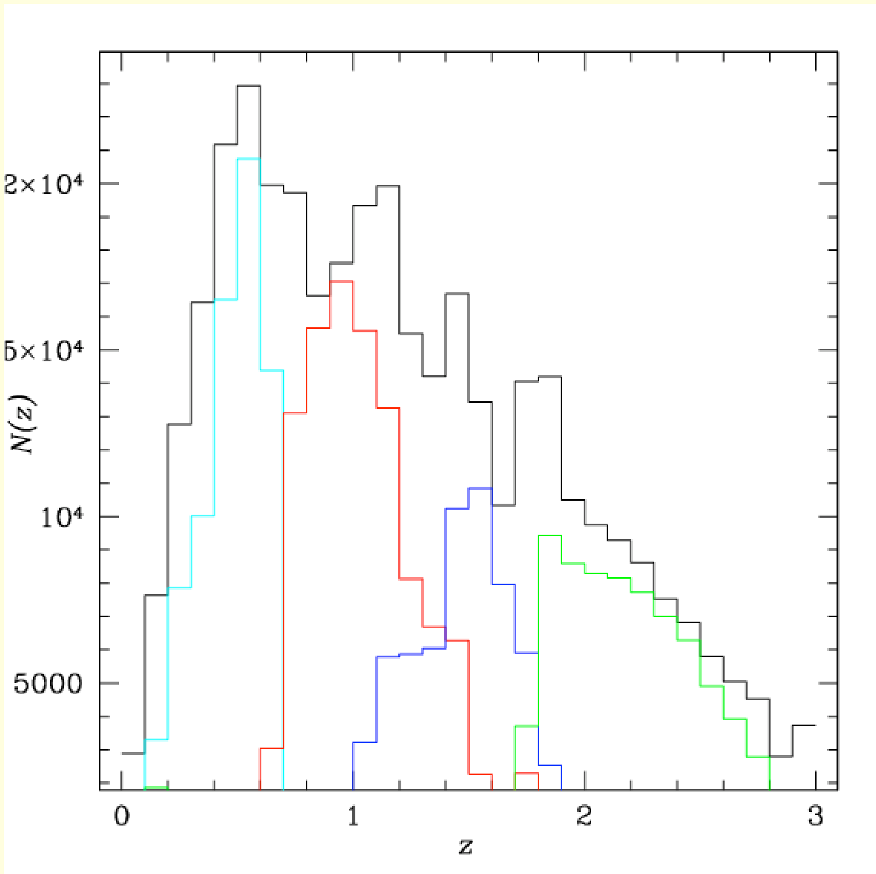
Agreed?

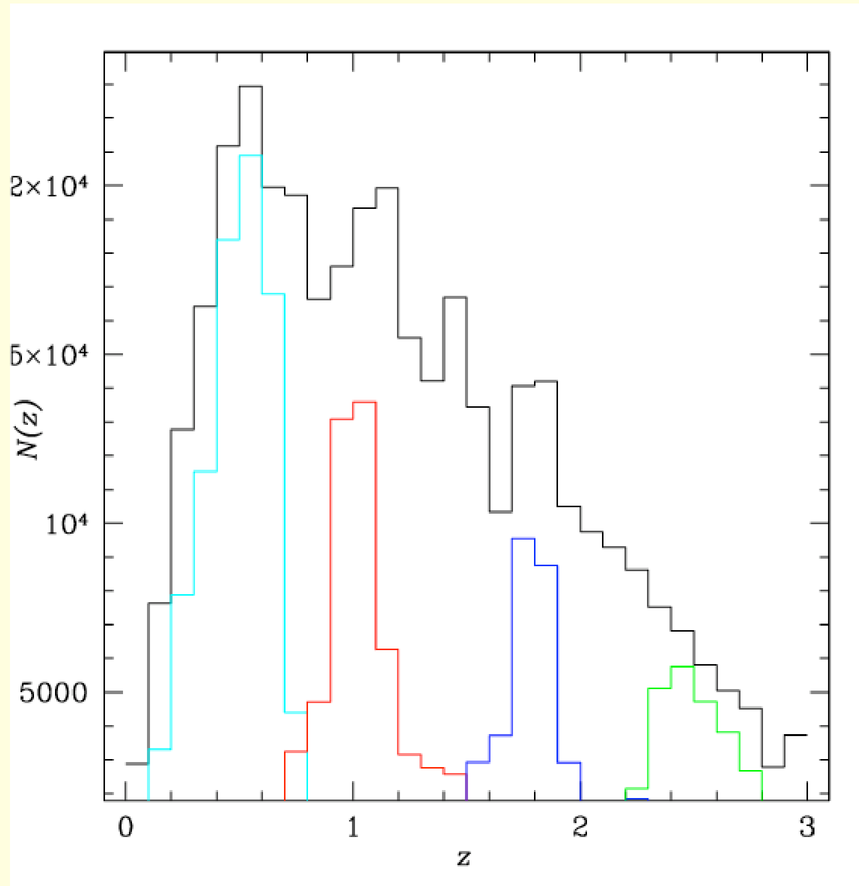
Galaxies in color space



Galaxies in 3 different redshift ranges in color space.

Redshift distributions

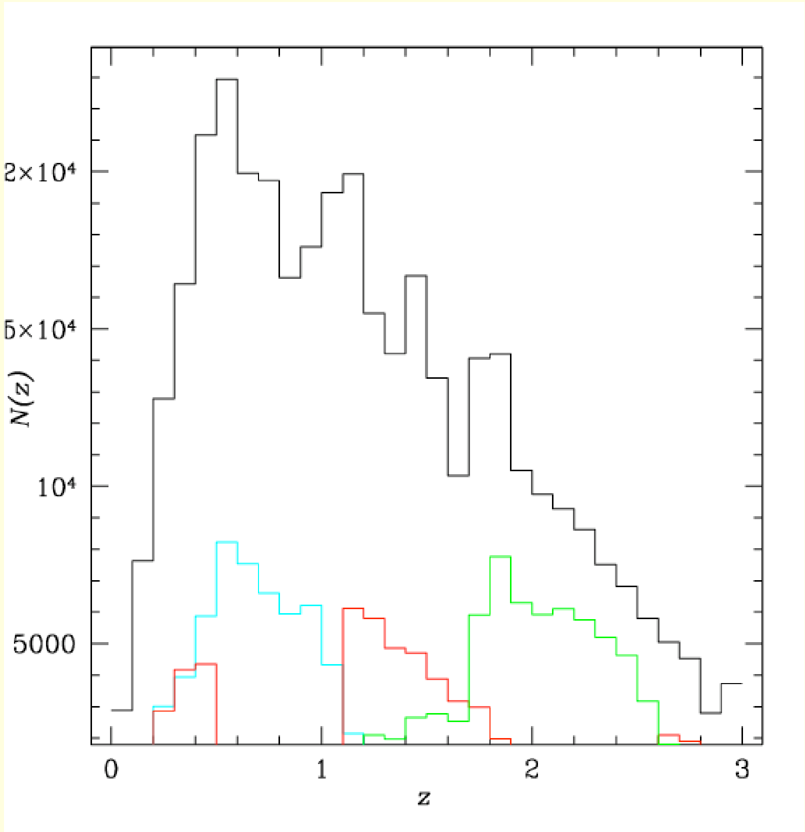


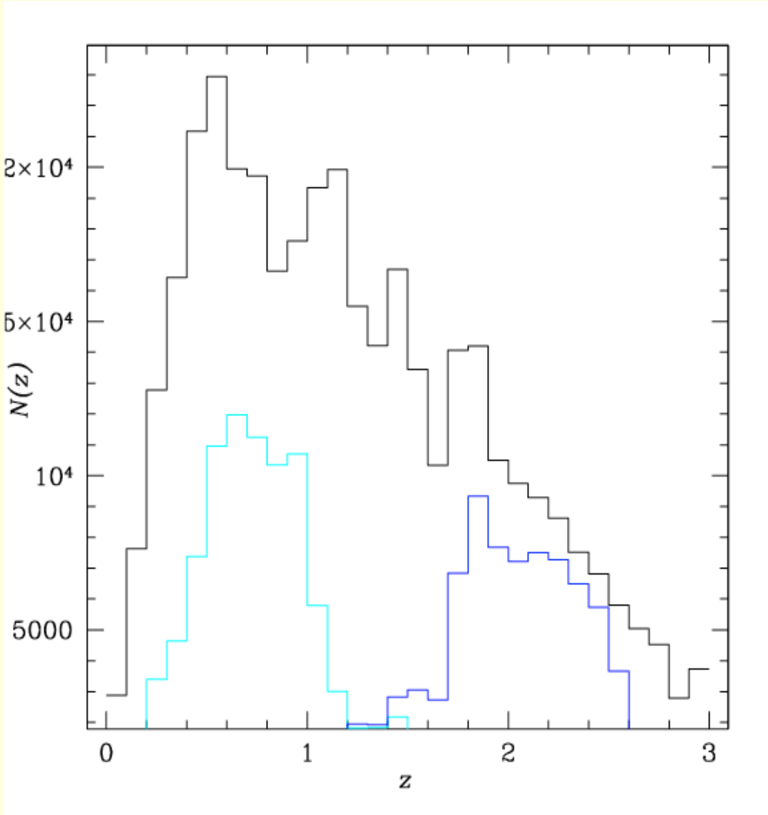


Cuts in *g-r* and *r-i* create 4 samples with distinct redshift distributions

Jain, Connolly, Takada, 2006

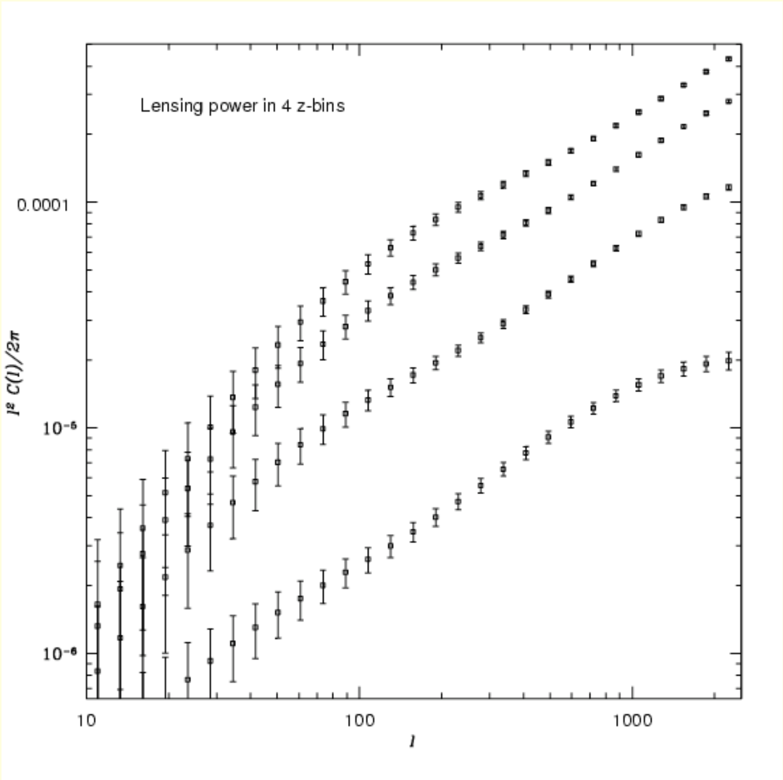
Redshift Distributions



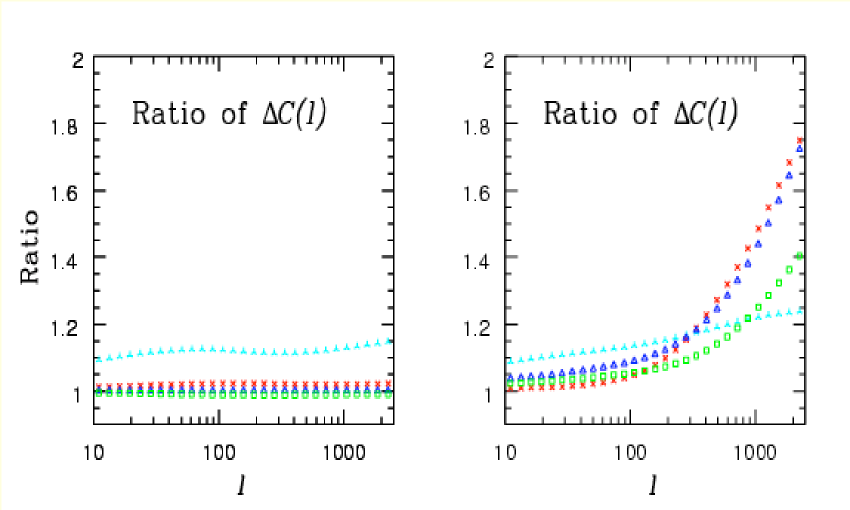


Cuts in *i* and *r-i* create 3 samples with three overlapping redshift distributions or two distinct ones.

Errors in power spectra

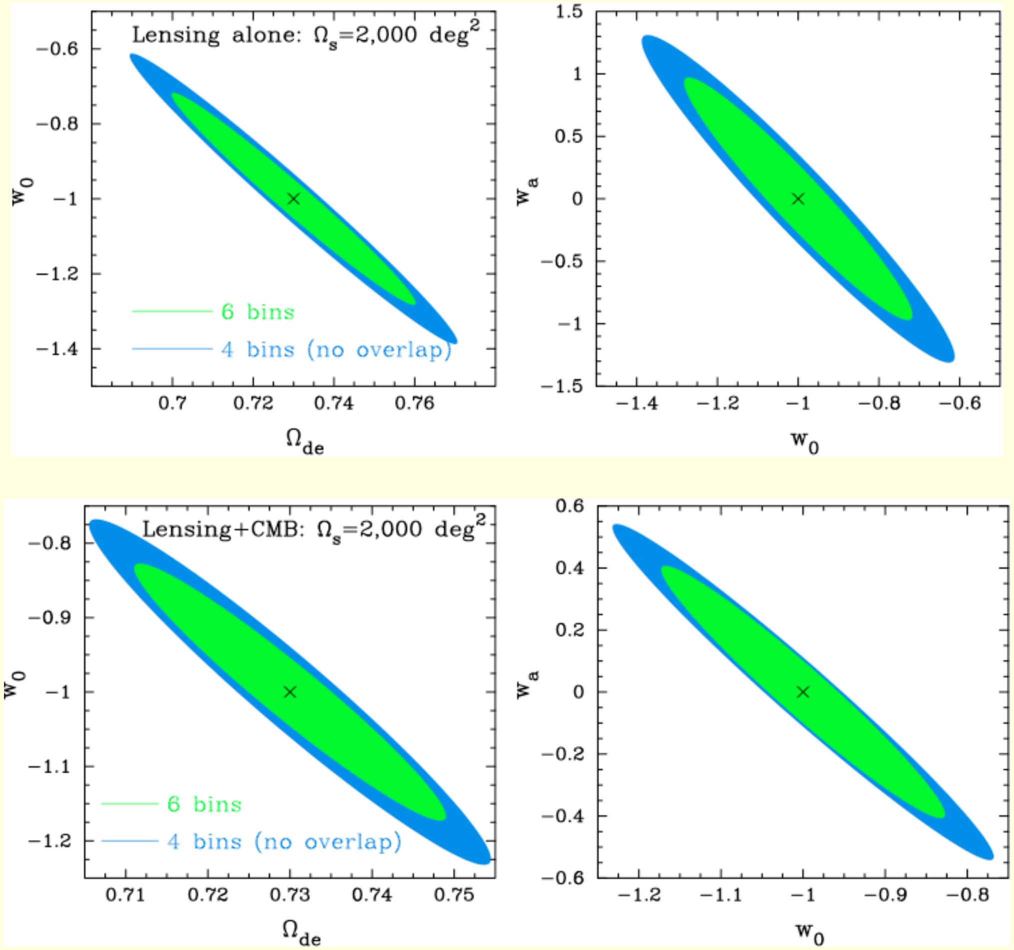


Lensing power spectra with errors



Ratio of errors: two sets of color cuts vs. using all galaxies (perfect photo-z's).

Color Tomography: Dark Energy Errors



Fisher error degradation: compare idealized photo-z's with 2 color tomography.
Use *r-i* and *g-r* colors for 2000 sq deg survey to *r=25*. *Planck priors*.

Color Tomography: Conclusions

- Bottom line: given calibration sample, a full survey with ~3 filters can get lensing cosmology
- **Caveat: INTRINSIC ALIGNMENTS**
- Calibration in two steps:
  - Spectra (~1 sq deg) + 6 or more band imaging (~10s sq deg).
- Detailed study needed: photometric errors, template mismatch…and calibration requirements.
- Color tomography *may* be useful for next-generation surveys (somewhere between CFHLS and LSST/SNAP level of precision).
- But more generally, it lets us re-examine assumptions about filters, especially uniform depth in all filters.
- Likely to apply to weak lensing cluster masses and strong lensing as well (for statistical studies).
- Other science goals that require narrow z-bins are not possible, e.g. baryon oscillations.