# P5: February 22, 2008
# Weak Gravitational Lensing

Bhuvnesh Jain
University of Pennsylvania

# Outline

- Lensing measurements as probes of distance and growth
- Systematic Errors
  - Recent advances
  - What we don't know (and will need to within 5 years)
- Ground based surveys: Stage III and IV
- Lensing from space
- Discovery potential beyond the dark energy equation of state

# Lensing Basics

Consider the lensing convergence $\kappa$

$$\kappa = \Omega_m \int dz\, W(z, z_s)\delta(z)$$

- Distances affect W
- Linear growth rate affects $\delta(z)$
- The observable shear $\gamma$ is similar to $\kappa$ (but due to tidal fields)

Lensing Statistics

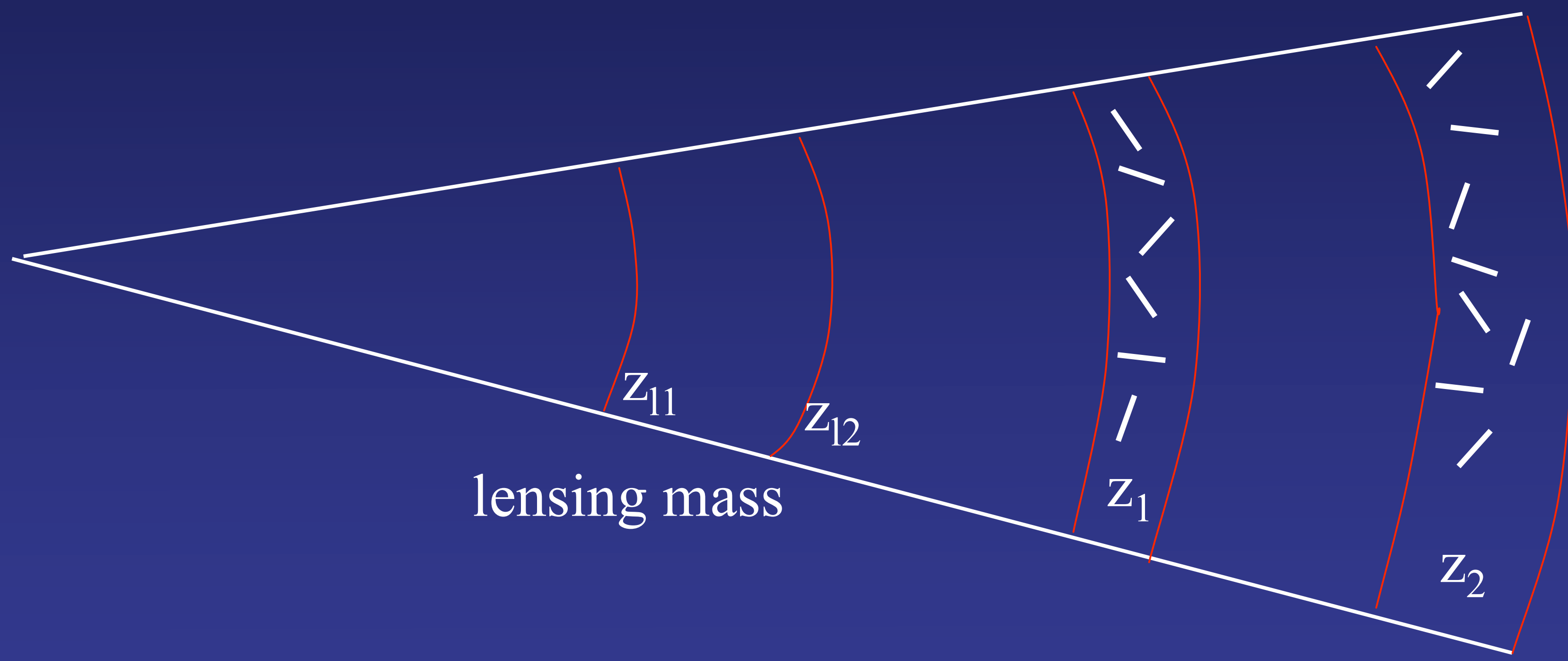
- Shear-shear correlations: $C_{\gamma\gamma}$
- Galaxy-shear correlations: $C_{g\gamma}$
- Cluster statistics
- Higher order shear correlations

These multiple statistics make weak lensing more complex than other probes. But they also provide better statistical power and robustness to systematics.

# Beyond the DETF Figure of Merit

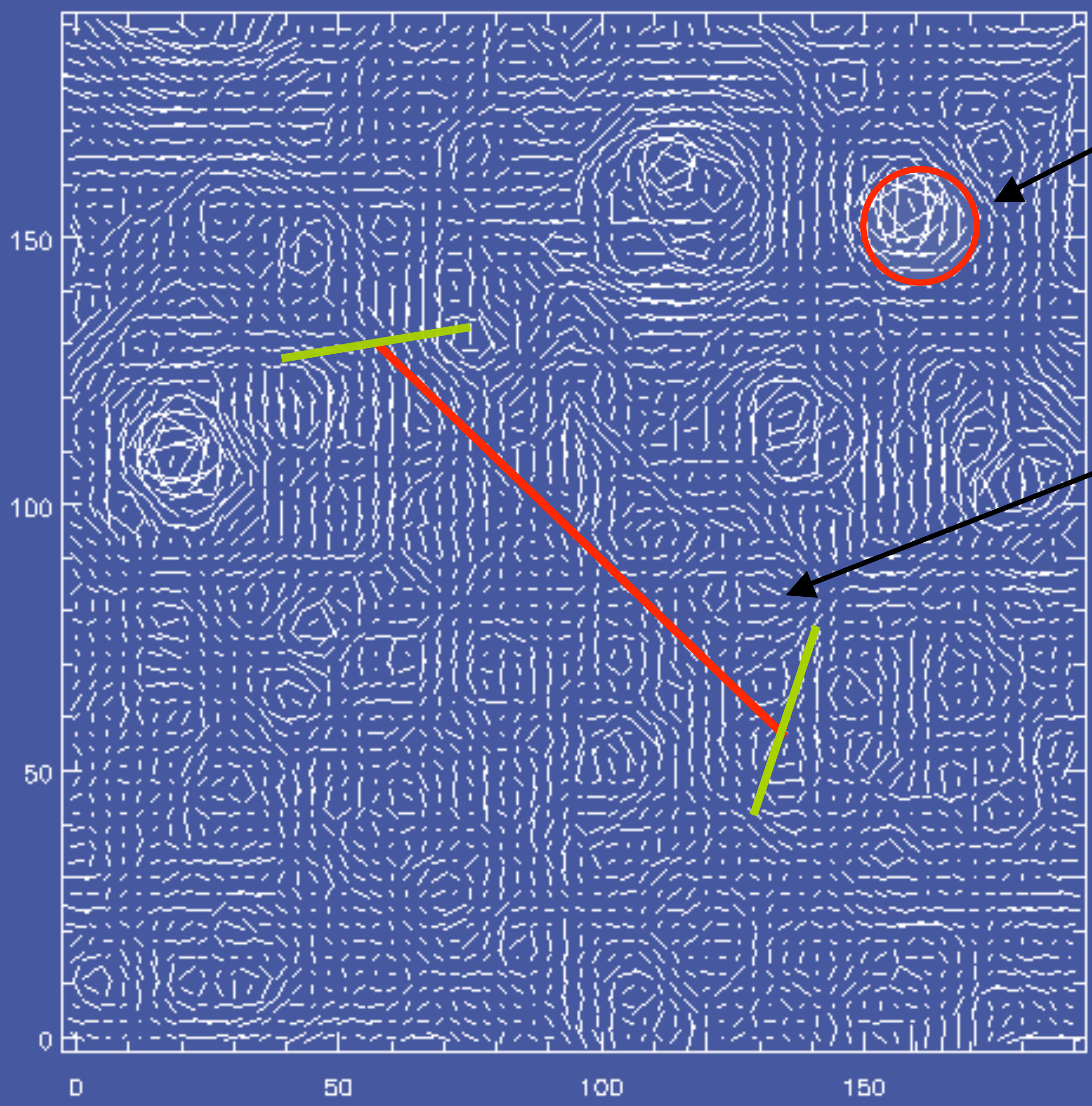
- Stage III surveys aim for x3 improvement on w0-wa Figure of Merit; Stage IV surveys aim for x10 or more.
- DE parameter space has more than two parameters that can be well measured ➡ Stage IV surveys in fact do much better.
- Modified Gravity: Lensing sensitivity to growth makes it a valuable probe. Gravity can be tested in different ways and on different scales (see discussion at end).
- This changes the metric of survey capability. E.g. nonlinear regime and individual clusters may provide new tests. (Current work is targeting linear growth to get an extended Figure of Merit.)

# Lensing tomography




- Shear of galaxies at $z_1$ and $z_2$ given by integral of growth function & distances over lensing mass distribution.

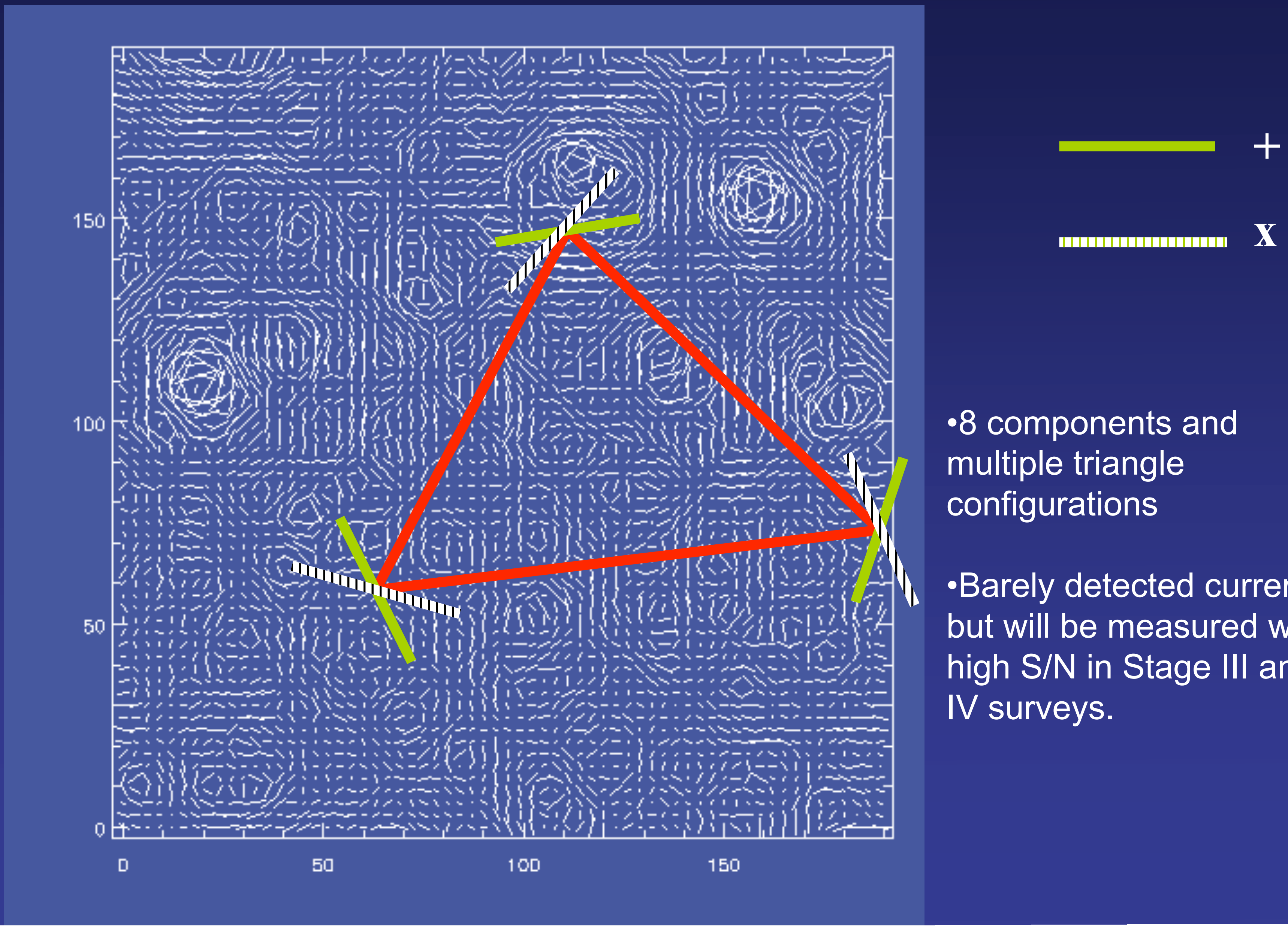
# Shear-shear and galaxy-shear correlations




$C_{g\gamma}$ Mean tangential shear inside apertures. Can be used in the nonlinear regime.

$C_{\gamma\gamma}$ compared at different z. Angle must be large to stay in quasi-linear or linear regime.

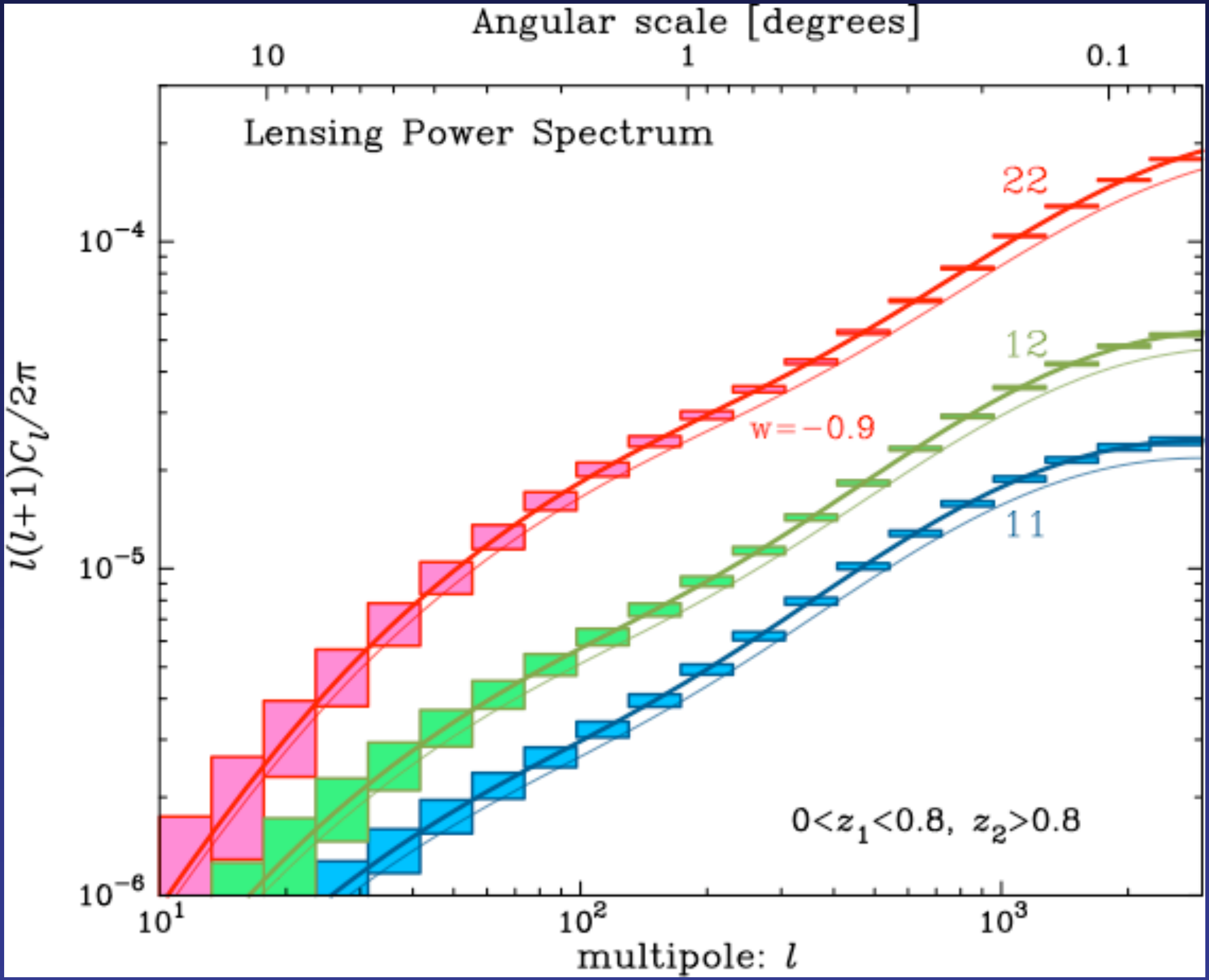
# Shear 3-point correlations: $\zeta_{ijk} \equiv \langle \gamma_i(\mathbf{x}_1)\gamma_j(\mathbf{x}_2)\gamma_k(\mathbf{x}_3)\rangle$




- 8 components and multiple triangle configurations

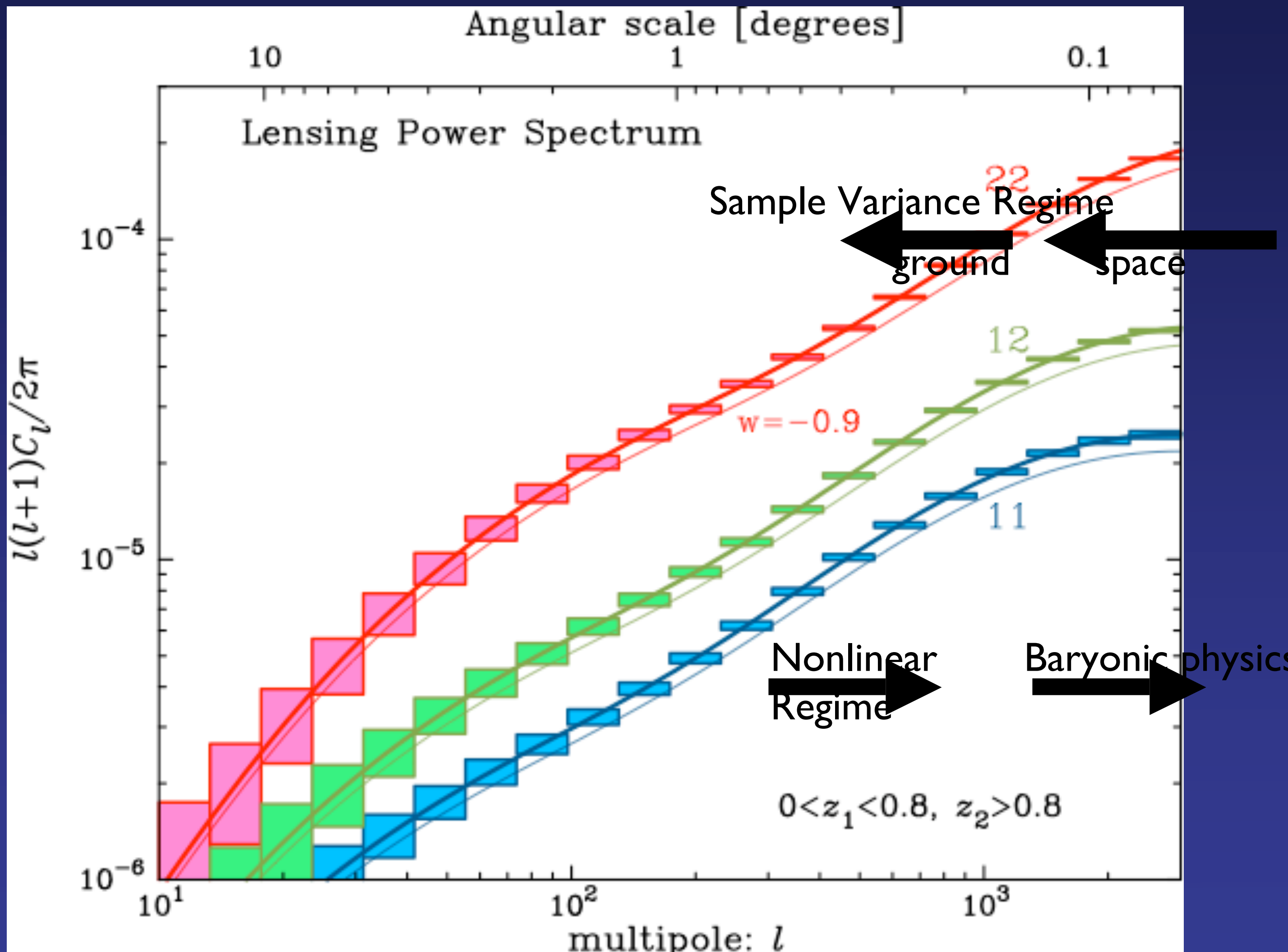
- Barely detected currently but will be measured with high S/N in Stage III and IV surveys.

# Lensing Cl's




Dark energy signature: relative amplitudes of the different spectra.
Full power spectra contain other cosmological information.
5000 sq. deg. survey with 40 galaxies/sq. arcmin. Takada & Jain 2004

# Lensing Cl's: Sources of uncertainty




Additive and multiplicative systematic errors enter at different $l$ and z.

# Statistical errors

$$\Delta C(l)^2 = \frac{1}{f_{\rm sky}\, l \Delta l}\left[C(l) + \frac{\sigma_\varepsilon^2}{n_g}\right]^2$$

- Requiring a systematic error to be, say, half the statistical error leads to a quantitative estimate of tolerable level of systematics for a given survey.
- Stage IV surveys will achieve sub-percent level statistical accuracy on lensing power over a decade in $l$.
- For $l < 1000$, even deep ground based surveys are in the sample variance regime.

# 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 can enter at all stages of the lensing pipeline. Progress so far:
- 2000: First detection of cosmological lensing signal.
- 2002-2008: significant advances in correction and testing for systematics.
- Currently measure ~0.1% rms shear to ~5% accuracy
- Using galaxy-shear cross-correlation, shear values below $10^{-4}$ have been measured!

# Galaxy and star images

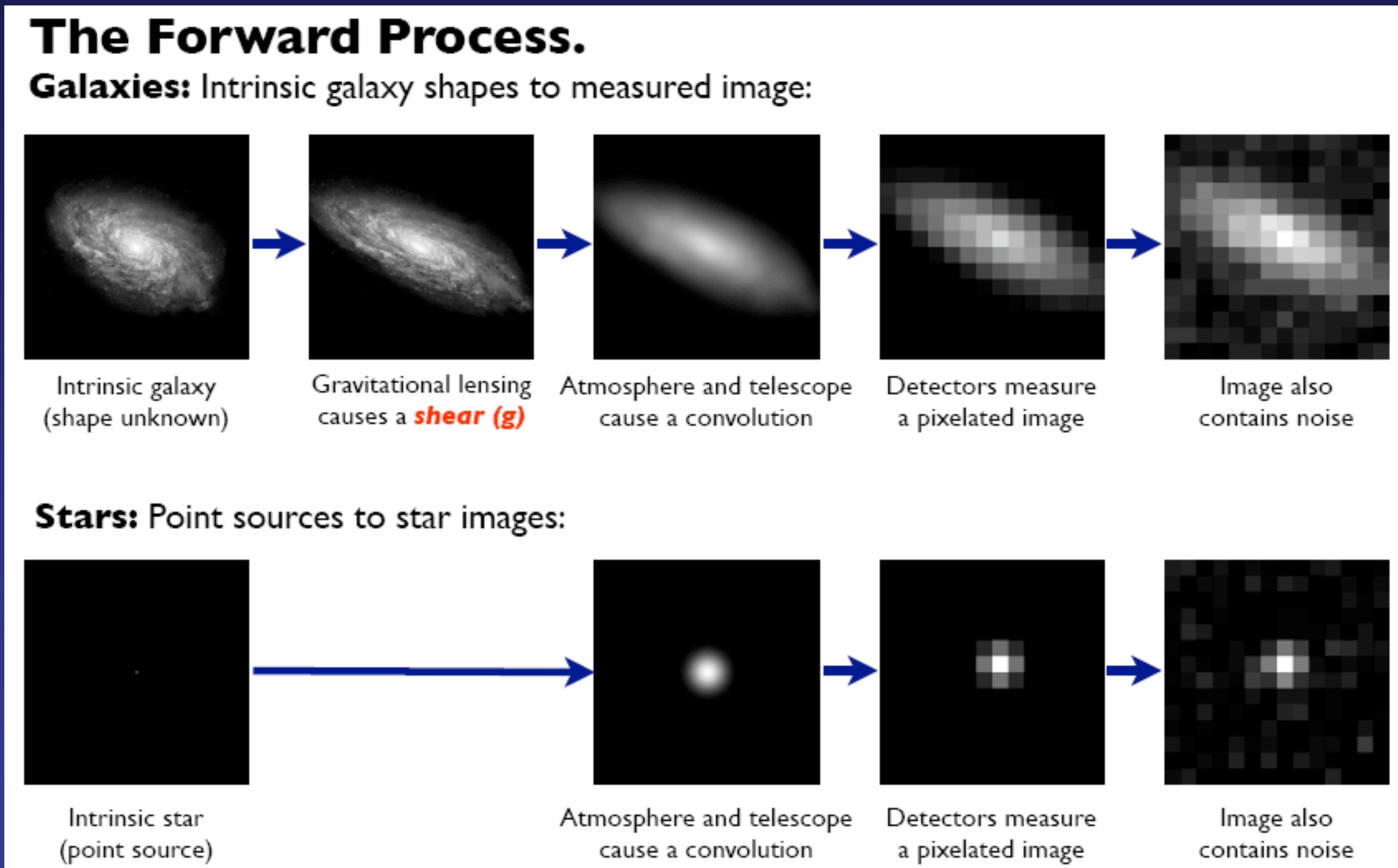



Figure from S. Bridle

# Primary Systematic Errors

- PSF correction
- Shear calibration
- Intrinsic alignments
- Theory uncertainty/high $l$ information
- Photo-z calibration

- Level of each of these systematics in current data would exceed statistical errors in Stage III and IV surveys.

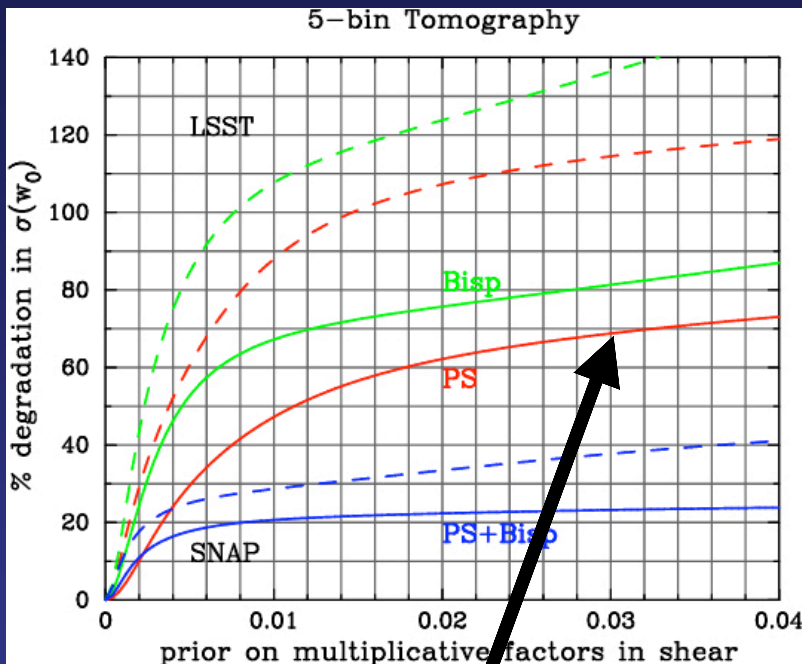
# Systematic errors: what we have learned

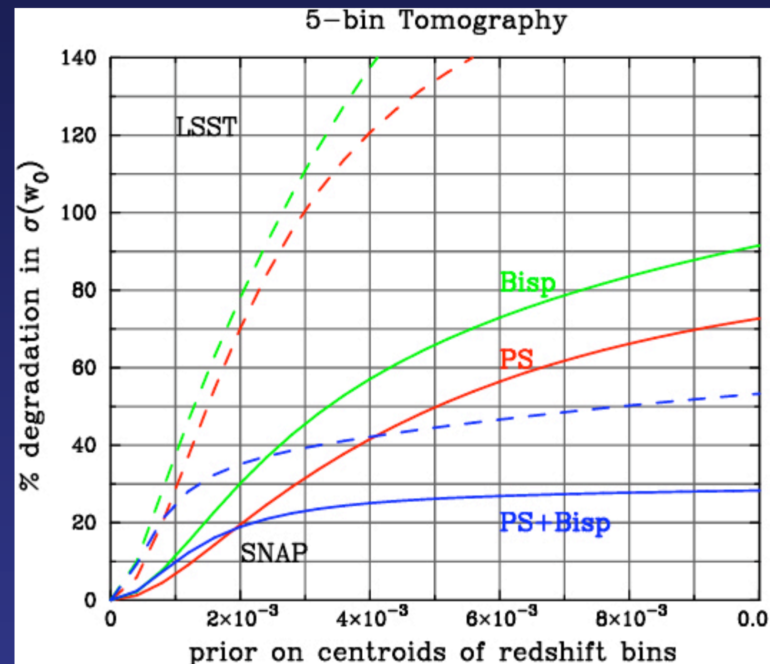
- Formulation of lensing systematic errors:
  1. Additive, 2. Multiplicative, 3. Redshift errors

$$\gamma(z_s) = \gamma(z_s + \delta z)\left[1 + \zeta(z_s)\right] + \gamma_{sys}(z_s)$$

- PSF correction (1)
  - PCA interpolation; fit for telescope aberrations
  - Multiple exposures help PSF correction
  - Cross-correlating shapes from different exposures get rid of atmosphere
- Shear calibration (2): STeP sims now get sub-percent performance.
- Spectroscopic calibration of photo-z's (3):
  - Estimation of needed sample. Shortcuts based on cross-correlations will help.
- Intrinsic alignment errors (1): there are two kinds! Measured from SDSS.

# Degradation in w: shear and redshift calibration errors




Self-calibration regime.

Note:

1. Degradation higher for survey with lower statistical error.
2. PS+Bispectrum curves too optimistic (Gaussian covariances).
3. Such analysis needed for all key lensing statistics and sources of systematics.

Huterer et al 2006

# Systematic errors: understanding galaxies

- Three reasons we need to learn about galaxies
  - How best to calibrate photo-z's? Which are the (impossibly) difficult populations?
  - Intrinsic alignment errors: how does the signal grow with redshift? Which galaxies are immune?
  - How best to use cross-correlations, including tests of general relativity?
- We will need to understand the relevant properties of galaxies as a function of type up to z~1 and beyond.
- Important simplification: lensing does not require fair sampling of galaxies. We have the liberty to discard 10s of percent of galaxies of certain type or redshift.

# Systematic Errors: Outlook for Stage IV (ground)

| Sources of systematic errors | Improvement Factor | Comments |
|---|---|---|
| Observed PSF anisotropy | - | Depends on telescope |
| Interpolation of PSF | >10 | Analytical scaling OK. Tests needed. |
| Dilution/Shear calibration | ~10* | In progress w/ simulations. Algorithm driven. Self-calibrates. |
| Source redshift distribution | >10 | Extra Data. Need ~ $10^5$ spectra. Cross-correlation shortcuts? |
| Power spectrum prediction | 4 | In progress. Gas physics? |
| Intrinsic shape correlations | ? | Measured from SDSS. Need more data and modeling. Self-calibrates. |

- Note: For systematics like PSF correction, current datasize (~2 million galaxies) is what limits tests of systematic correction schemes.

# Systematic errors: a 5 year wish-list

- What is the accuracy of photo-z's as a function of redshift and galaxy type? (Depends on photo-z calibration and PSF. )
- What is the correct model for intrinsic alignments? Are most galaxy types immune? What is the overall degradation if fit from data?
- How well does self-calibration work from real data (e.g. with photo-z outliers)? Especially relevant for shear calibration, intrinsic alignments.
- Theory uncertainty at high $l$: how well can we model/measure gas physics? Are current forecasts too optimistic/pessimistic?
- What is the highest redshift bin with useful lensing information from the ground? What subset of galaxies are useful beyond the limit inferred from median seeing and median galaxy size?
- How much will cross-correlation and other shortcuts reduce the needed redshift calibration sample?
- Galaxy bias: how well is it measurable, and what is the level of nonlinear and stochastic bias at large scales?

Hope / Worry

# Systematic errors: show stoppers?

- Lensing power spectra and cross-spectra have a large amount of partially redundant information.
- Multiple statistics, gravitational origin of the signal, and redshift tomography ➡ data provides many cross-checks. There isn't a single exceptional property, as in SNIa or even galaxy clusters, that could let us down!
- Lensing shape measurements are very challenging. But given (i) PSF correction from stars, which scales with survey size, and, (ii) the recent progress in algorithm/software development, there do not seem to be show stoppers for Stage III or IV surveys.
- The accuracy of redshift calibration is critical in suppressing a direct bias in dark energy parameters and in controlling intrinsic alignment. If inadequate, it would make certain galaxy types and redshift ranges inaccessible from the ground ➡ loss of depth and effective number density.

# Ground surveys: Stage III ➡ Stage IV

- Stage III suveys: DES, Subaru (also PS1 and KiDS). More than an order of magnitude increase over current datasize.
- Stage IV (LSST) survey size increase: factor of 4-10 in area; up to 3 in number density due to depth; and additional filter(s).
- Telescope capability: Stage III surveys have different strengths and strategies. Stage IV must learn lessons from all of them.
- Currently vigorous activity in algorithm development and code testing. The progress in software developed and in systematic error analysis will be invaluable to Stage IV survey.
- The importance of this staged progress in ground based lensing cannot be over-emphasized. Stage III experiences could lead to changes in Stage IV survey strategy and many other elements.
- **Analysis methods and software testing need continued support all the way to Stage IV !**

# Space: advantages in shape measurement

- For shape measurements the most important factor in favor of space is PSF size:
  - Residual systematics scale with PSF size for all galaxies
  - Galaxies smaller than PSF provide very little information. E.g. effective number density for SNAP lensing survey is ~3x bigger.
- PSF anisotropy and stability: a space mission that performs to specs will require only modest PSF correction on galaxy shapes.
- We can be confident that lensing measurements from a well designed space telescope will meet Stage IV targets.

# Space: systematics beyond shapes

- Photo-z calibration errors
  - NIR imaging and better photometric calibration will produce improved photo-z's to begin with. But how high in redshift is calibration feasible?
- Intrinsic alignments
- Theory uncertainty at high $l$

- The high-z and high $l$ regime requires significant progress in the next ~5 years.

# New Discovery Modes

- Consider Tests of Modified Gravity and Dark Matter
- High resolution (space) and sky coverage (ground) are complementary. And multi-wavelength imaging and spectroscopy play a role.
- Individual Clusters come in two useful varieties:
  - Golden lenses (strong and weak lensing): isolated, relaxed, spherical systems
  - Merging systems with displaced baryons and DM: constrain DM interaction cross-section.
- Bigger sky coverage helps find rare objects; good resolution and redshift info. helps study them in detail.
- Other tests of gravity: robust tests combine lensing or ISW cross-correlations with dynamical measurements.
  Target $0.3<z<1$ and scales $1$ Mpc$<\lambda<$200 Mpc.
  - Well designed complementary probes, especially imaging+spectroscopy, are more important than in a dark energy scenario. E.g. adjust design of BAO surveys?

# Complementarity

- Deep imaging from space of part of a ground survey would facilitate shear calibration and other tests of PSF correction
- Imaging and spectra in NIR would be an enormous asset in calibrating photo-z's from ground survey
- Tests of gravity benefit from a combination of the depth/resolution of space and sky coverage of ground
- There is ongoing work on the best tests of gravity using dynamics from spectroscopic data plus lensing from imaging surveys.