Gravitational Lensing and Cosmology

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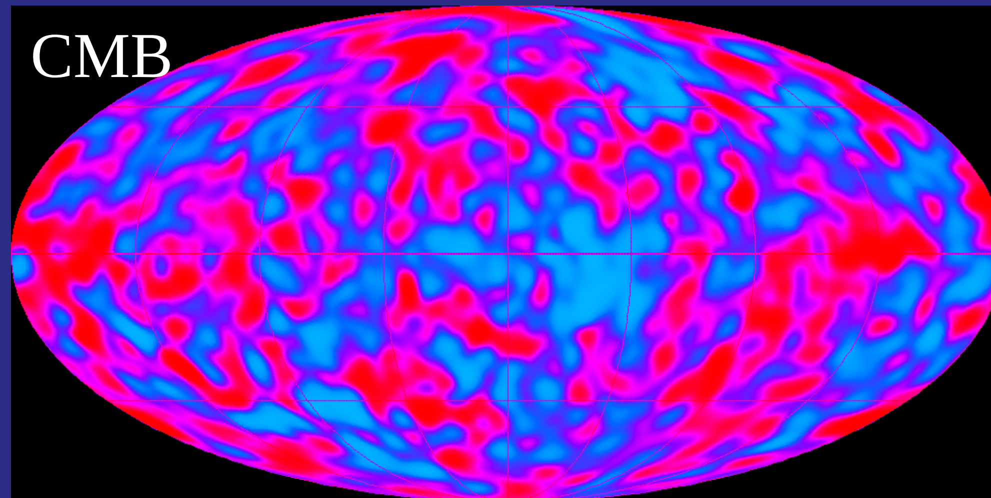
Outline

- Introduction to cosmology and gravitational lensing
- Shear correlations: dark matter and dark energy
- Analysis techniques and current results
- Testing dark energy and alternate gravity theories

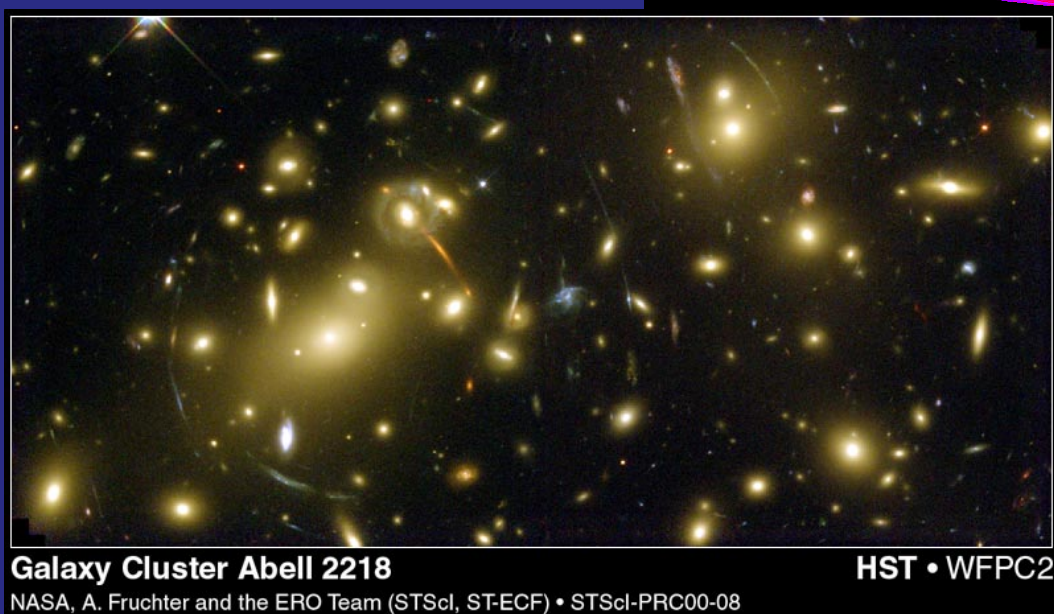
Cosmological Surveys

CMB

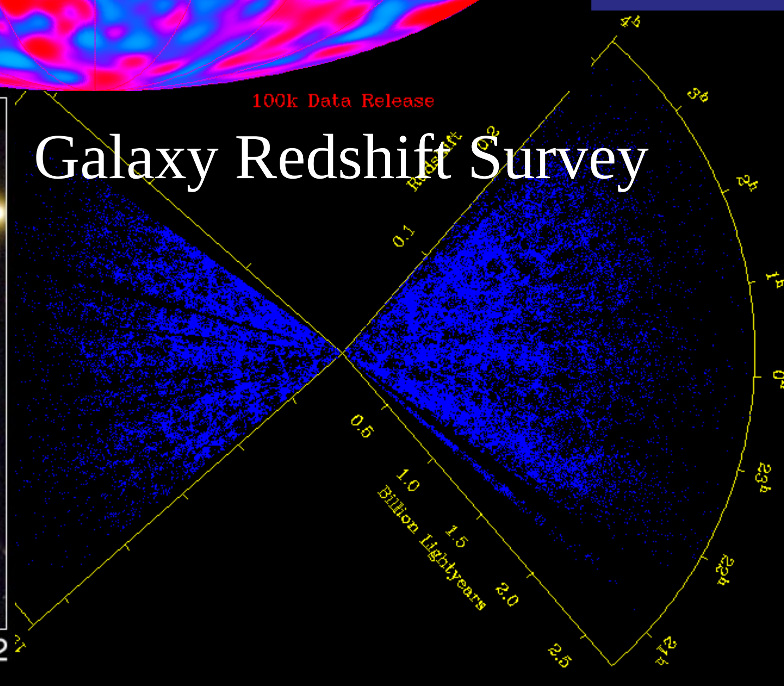


Supernovae

Gravitational Lensing



Galaxy Redshift Survey



Measure correlation statistics ⇔ Constraints on cosmological models

Cosmology: knowns & unknowns

What we have learnt in the last decade:

- Spatially flat universe consistent with Inflation
- Age: 13.7 billion years old
- 26% dark matter, 4% baryons, 70% dark energy
- Nearly scale invariant fluctuation spectrum

CMB (cosmic microwave background) and other data validates the basic cosmological model. Questions, questions...

- » What is the dark matter?
- » Is the dark energy a cosmological constant?
- » Primordial gravity waves? non-Gaussian fluctuations, non-scale invariant spectrum?
- » How did stars & galaxies form and evolve?

The Mystery of Dark Energy

What is responsible for the accelerated expansion of the universe at late times?

Ordinary matter and radiation slow down the expansion.

➔***The energy density of the universe must be dominated by an exotic form of energy, such as vacuum energy, which has a repulsive gravitational force on cosmological scales.***

Further this dark energy has begun to dominate only recently (last few billion years).

Dark energy is a great mystery for cosmology and fundamental physics. Astronomical observations are our best bet for learning more about it.

Learning about Dark Energy

Source of acceleration?

Vacuum energy: $p = -\rho$

Dynamical dark energy: scalar field gives $p = w\rho$

Alternate gravity: modfiy Friedman eqn. $H^2 = \frac{8\pi G}{3}\rho$

Observational tests:

Kinematic: distance measures, e.g. Type Ia Supernovae

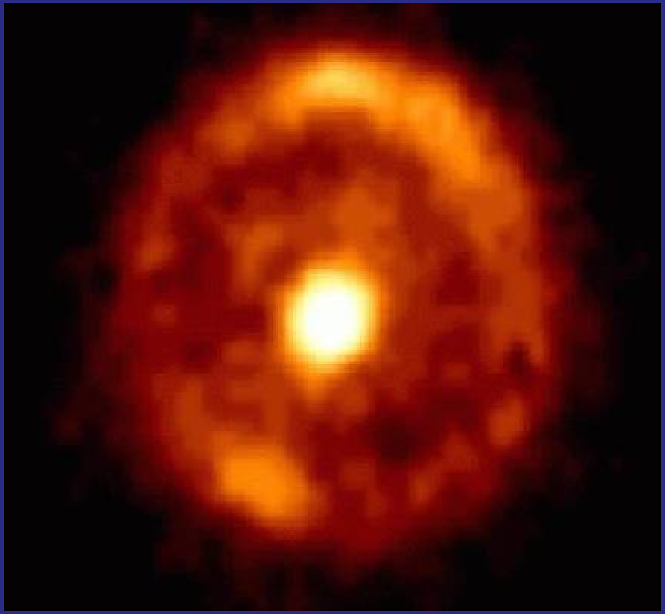
Dynamical: growth of structure between $0 < z < 1$

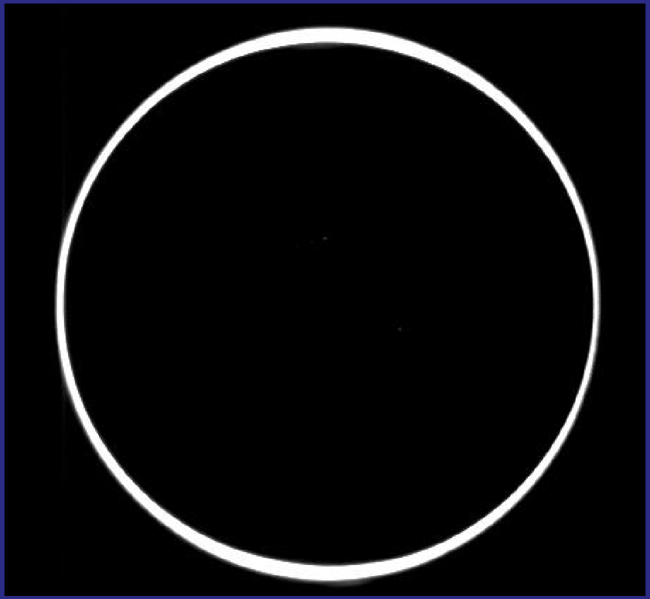
Both tests are needed to distinguish DE from alt gravity

What is gravitational lensing?

- In Einstein's general relativity, massive bodies curve space-time.
- So light rays are deflected, just as if they were refracted by a lens with index of refraction given by $n_{eff} = 1 - 2\phi / c^2$
- Images of distant galaxies are distorted and magnified
- Strong lensing: on rare occasions, multiple images are formed
- Weak lensing: the small (few percent) distortions in the images of essentially every distant galaxy

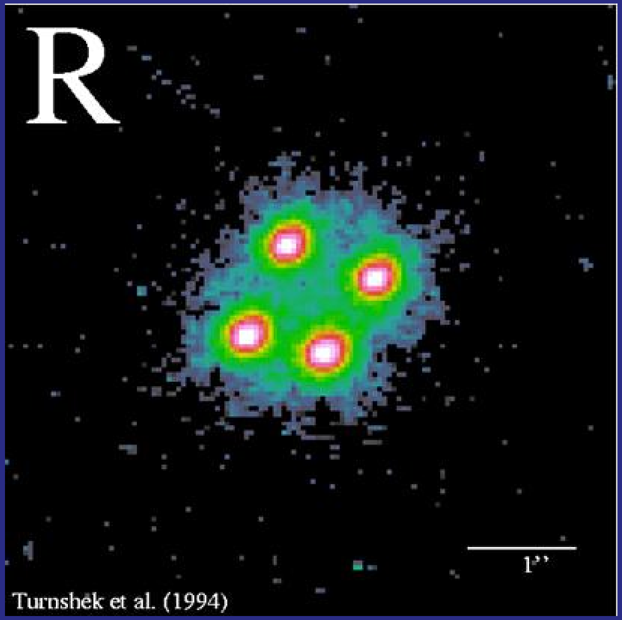
Lensing by galaxies: Einstein Rings

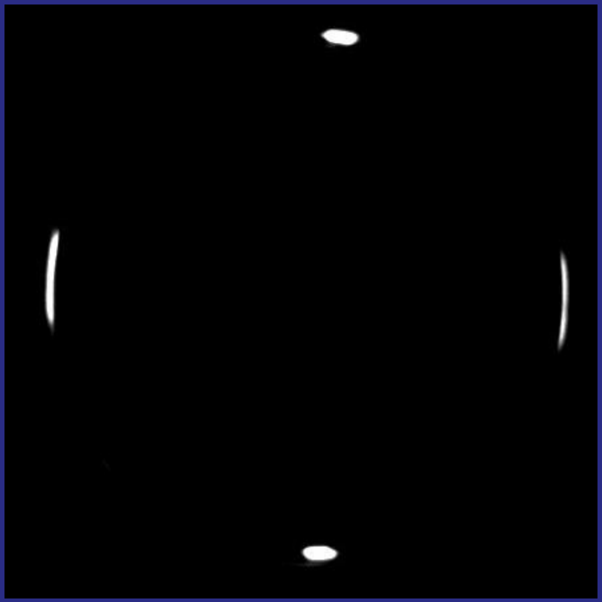




- Left: Einstein Ring observed with HST
- Right: Lab reproduction using plexi-glass lens
- Size of the Einstein ring gives total mass enclosed: direct evidence for dark matter.

Strong lensing by galaxies: quads





- Left: 4 images of the same quasar formed by a foreground galaxy lens.
- Right: Lab reproduction using plexiglass lens
- Currently weak lensing by galaxies measured out to 100x visible radii!

Dark Matter Census

Galaxy clusters: dark matter “observed” using lensed arcs.

Using strong and weak lensing data on galaxies and clusters accounts for the majority of dark matter in the universe.

Consistent with mean mass density needed for CMB and Nucleosynthesis!

See Takada talk for Galaxy Clusters

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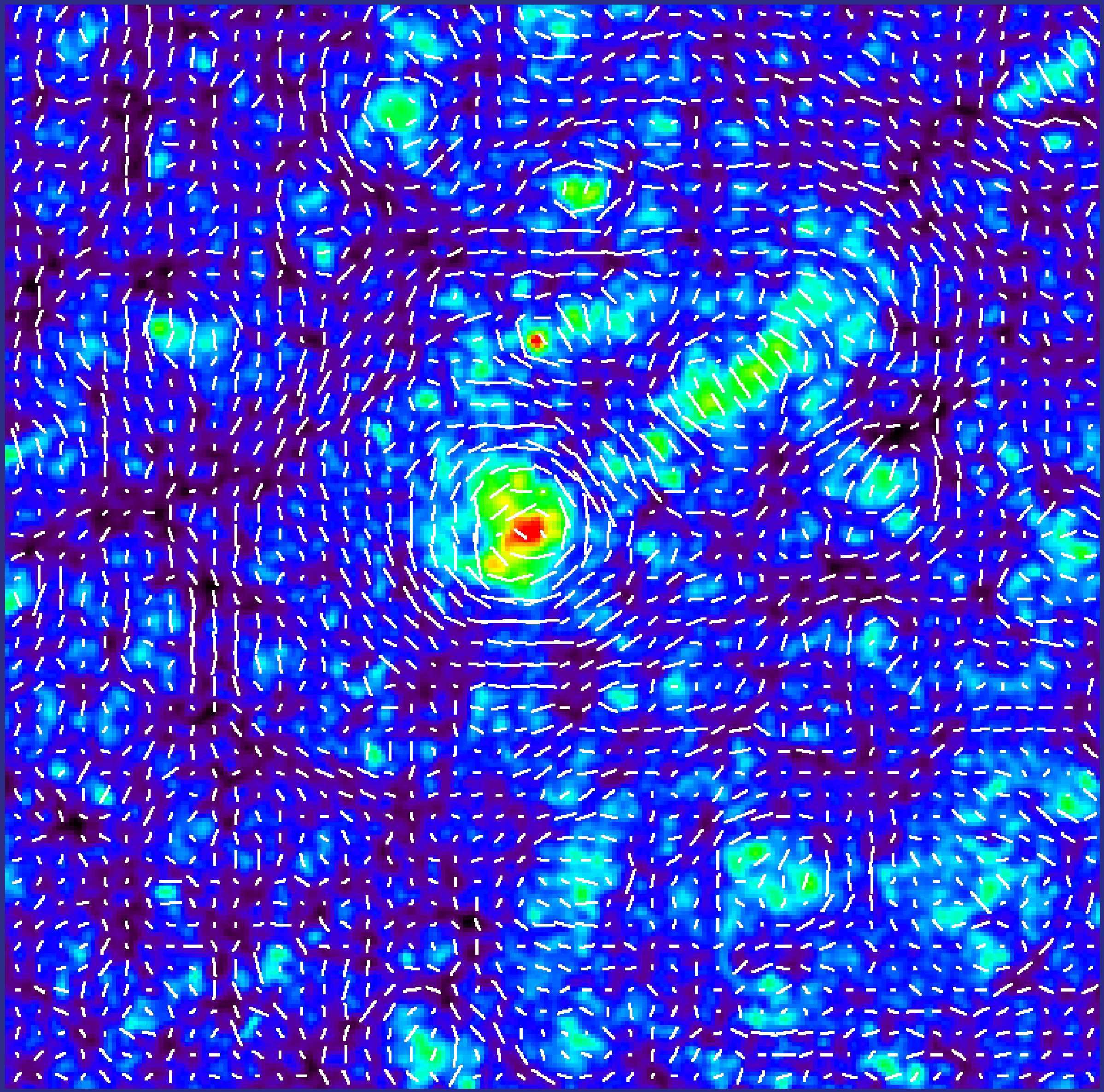
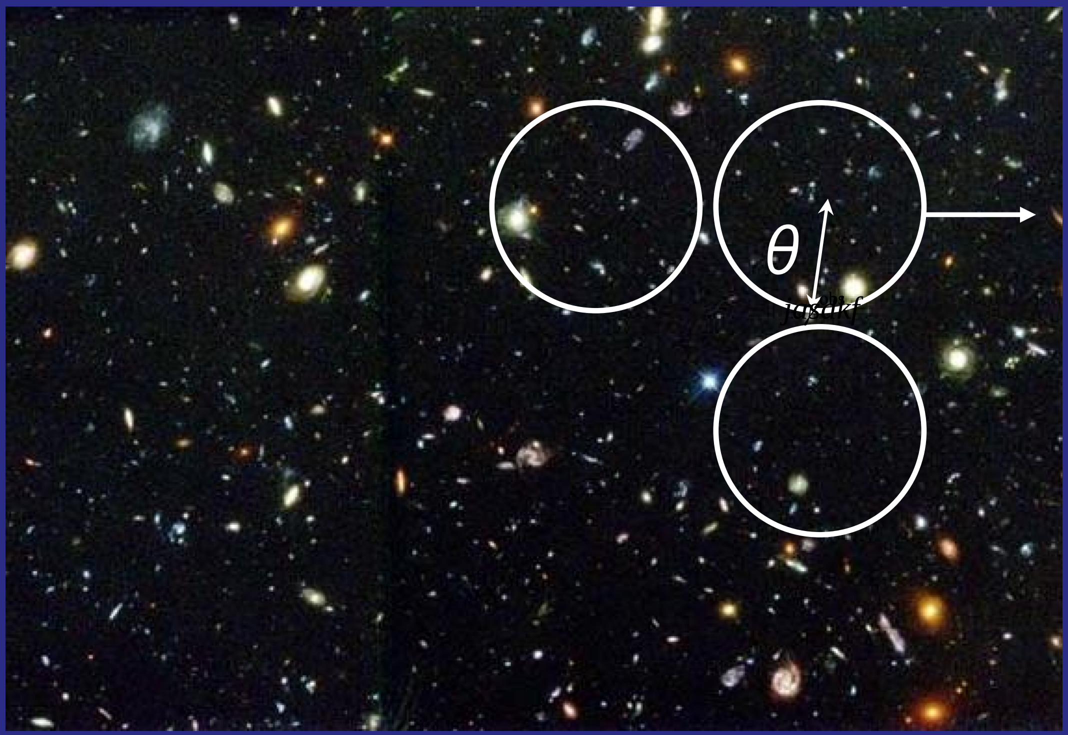
Weak lensing: shear and mass



Simulated 3x3 degree field, Hamana 2002

Measurement of shear correlations

➔ Smooth over patches of sky to measure coherent gravitational shear.

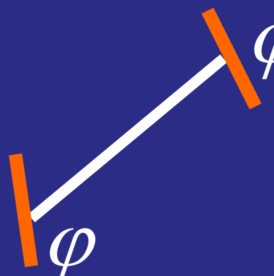


$$\gamma^{\text{obs}} = \varepsilon + \gamma$$

$$\bar{\gamma}^{\text{obs}}(\theta) \approx \frac{\varepsilon}{\sqrt{\text{N}}} + \gamma(\theta)$$

Average its square over patches ➔ shear variance

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:

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

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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. But there's a long way to go for LSST level surveys.

For details see: Jain, Jarvis, Bernstein 2005

Systematic Errors in Weak Lensing: PSF Anisotropy

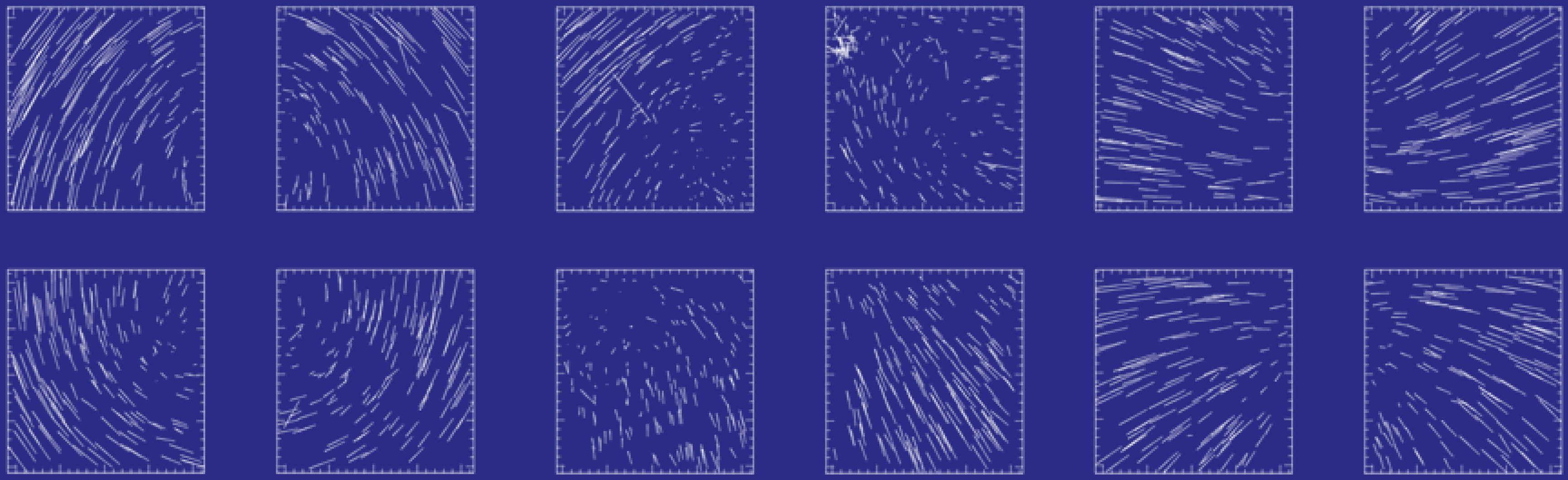
- Point spread function (PSF): the image of a point source (star) due to atmosphere and telescope optics
- PSF anisotropy is currently the primary systematic errors in weak lensing data: it is 1-5% level (shear signal 0.1-1%, statistical errors: ~0.1%).
- Galaxy shapes are convolved by the PSF, so PSF anisotropy must be removed to get accurate galaxy shapes.
- There are good methods for deconvolving the PSF
- So what’s the problem? *Interpolating the PSF* from where it is measured (stars) to where we need it (galaxies).
- A fundamental limitations in scaling lensing accuracy to ambitious future surveys?

A Completed Lensing Survey

- 4m telescope at CTIO, Chile
- 12 widely separated 2.5º x 2.5º fields
- Total area ~ 75 square degrees
- Total usable galaxies ~ 1.8 million
- Galaxy redshift distribution peak at z ~ 0.6
- Similar surveys with results: Subaru, RCS, CFHLS

Jarvis, Bernstein et al 03

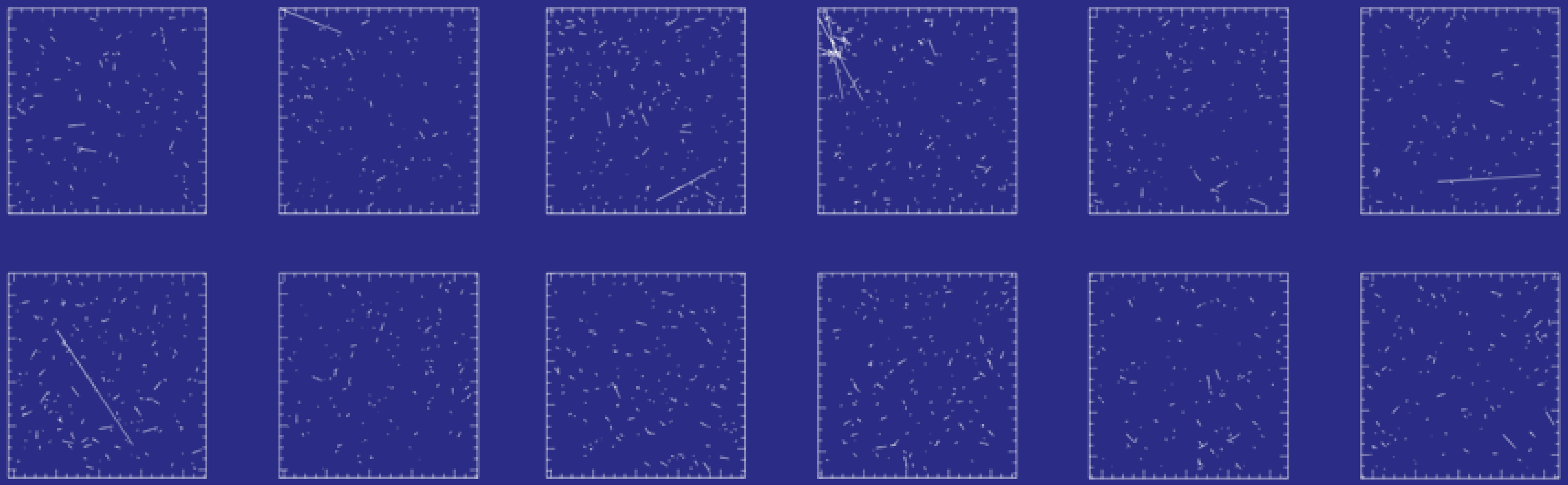
Anisotropic PSF



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



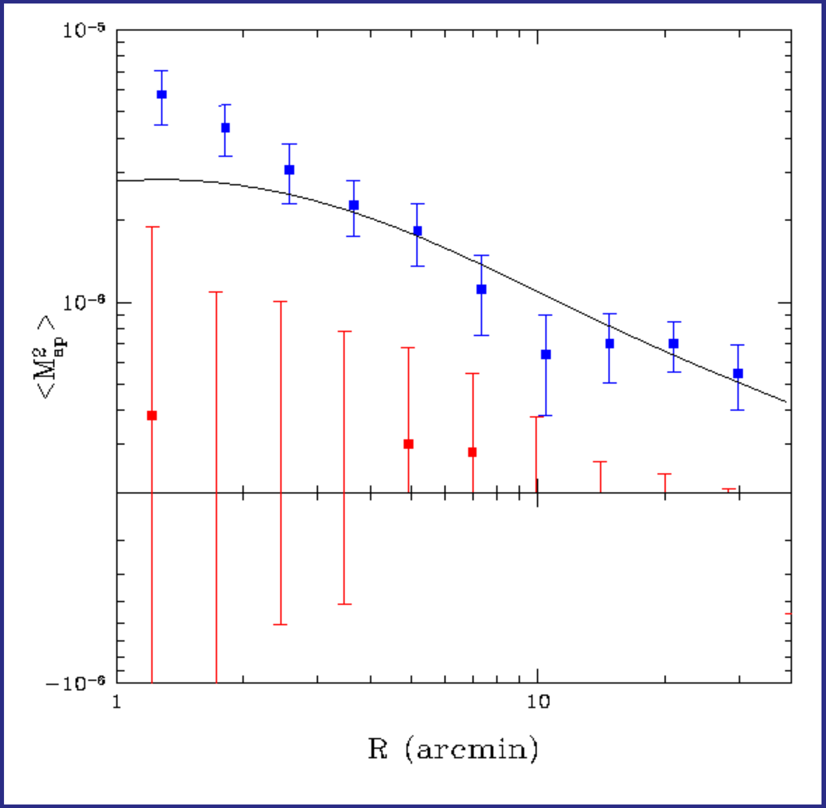
Focus too low   Focus (roughly) correct   Focus too high

- 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: Much lower correlated residuals on all scales!

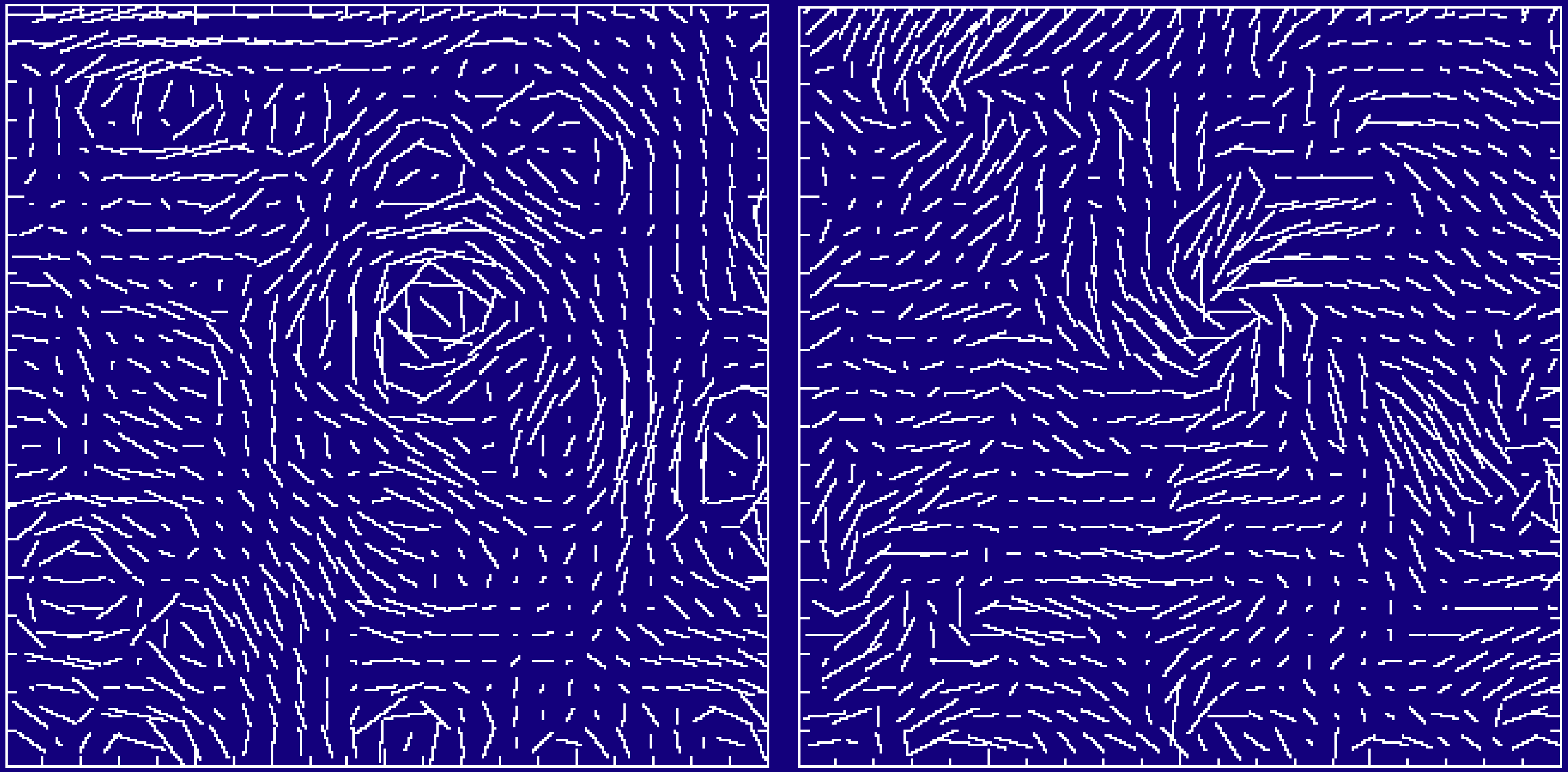
Systematic Errors Summary

Sources of systematic errors:	Improvement Factor:	
▪PSF anisotropy	2-4	Expected
▪Interpolation of PSF	5-10	Expected
▪PSF dilution	5-10	Not Fatal
▪Shear calibration	5-10	Not Fatal
▪Source redshift distribution	5-10	Extra Data
▪Power spectrum prediction	2-4	Expected
▪Intrinsic shape correlations	?	Work in progress

Results: 2-point correlations



E/B mode decomposition

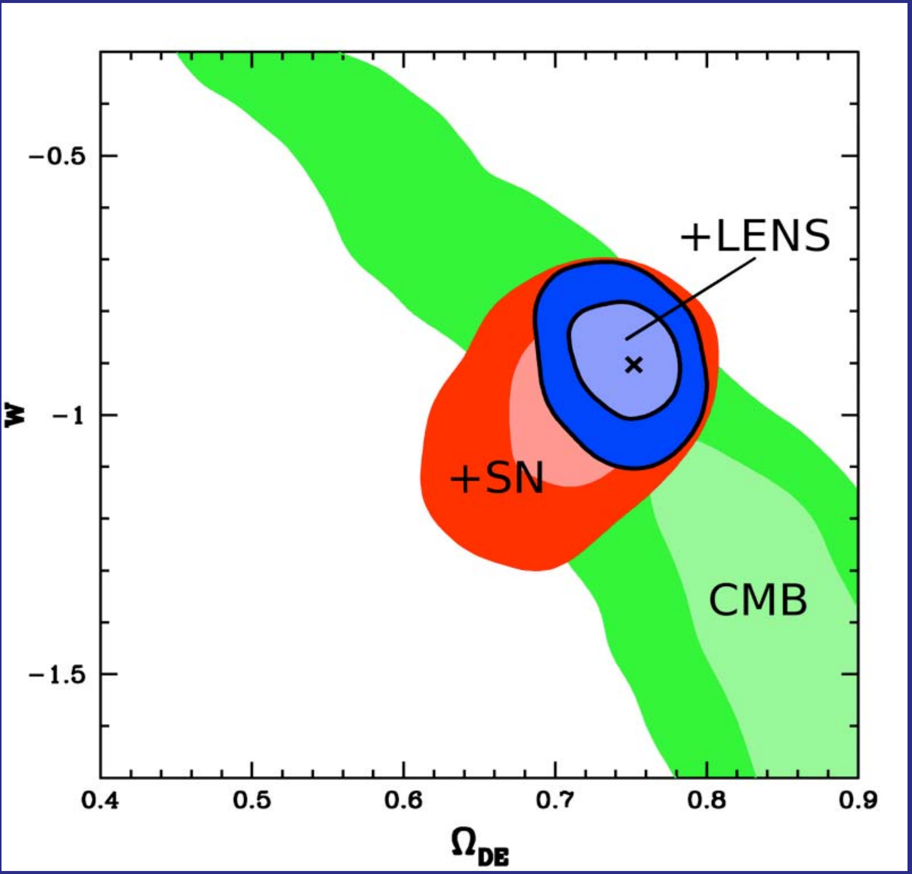


E mode

B mode

Gravitational lensing due to scalar potential field: no B-mode

Cosmology Constraints

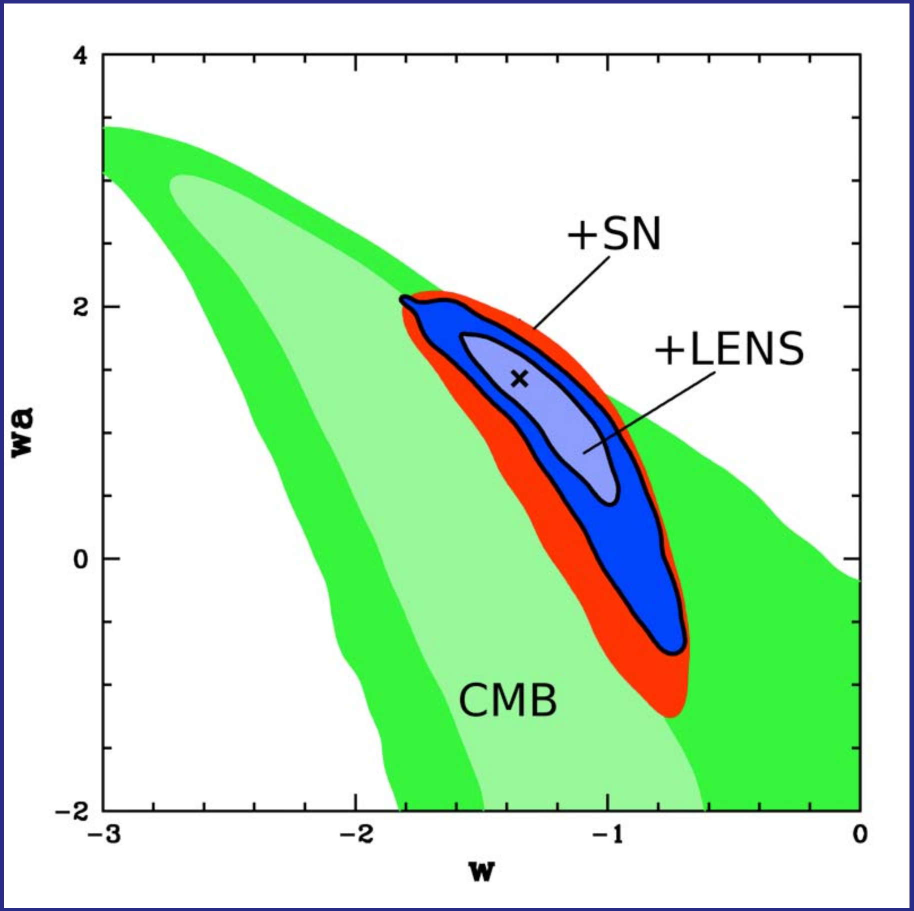


2D marginalized best fit with $-3 < w < 0$ and $w_a = 0$

$$\Omega_{DE} = 0.75$$
$$w = -0.90$$

Cosmology Constraints

$-8 < w < 8\ ,\quad -8 < w_a < 8$



We do not know anything about the possible evolution of dark energy!

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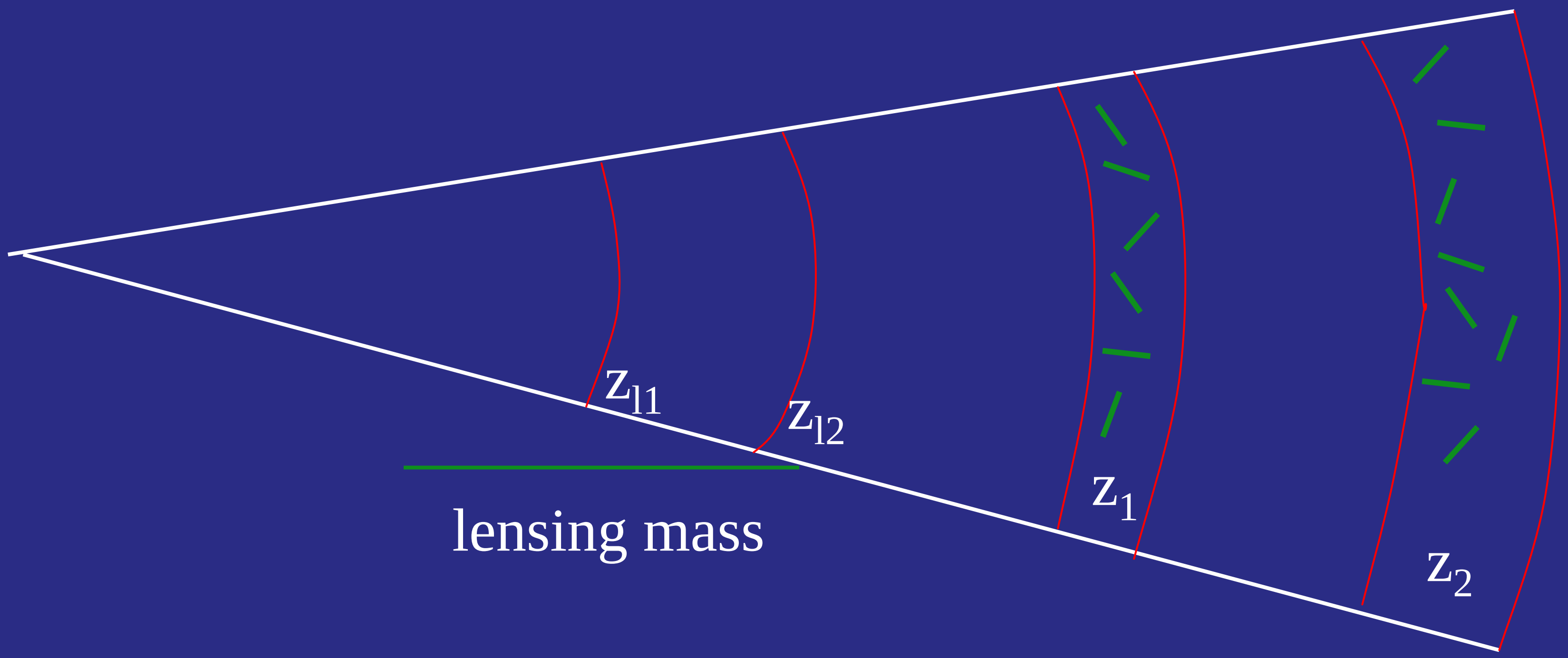
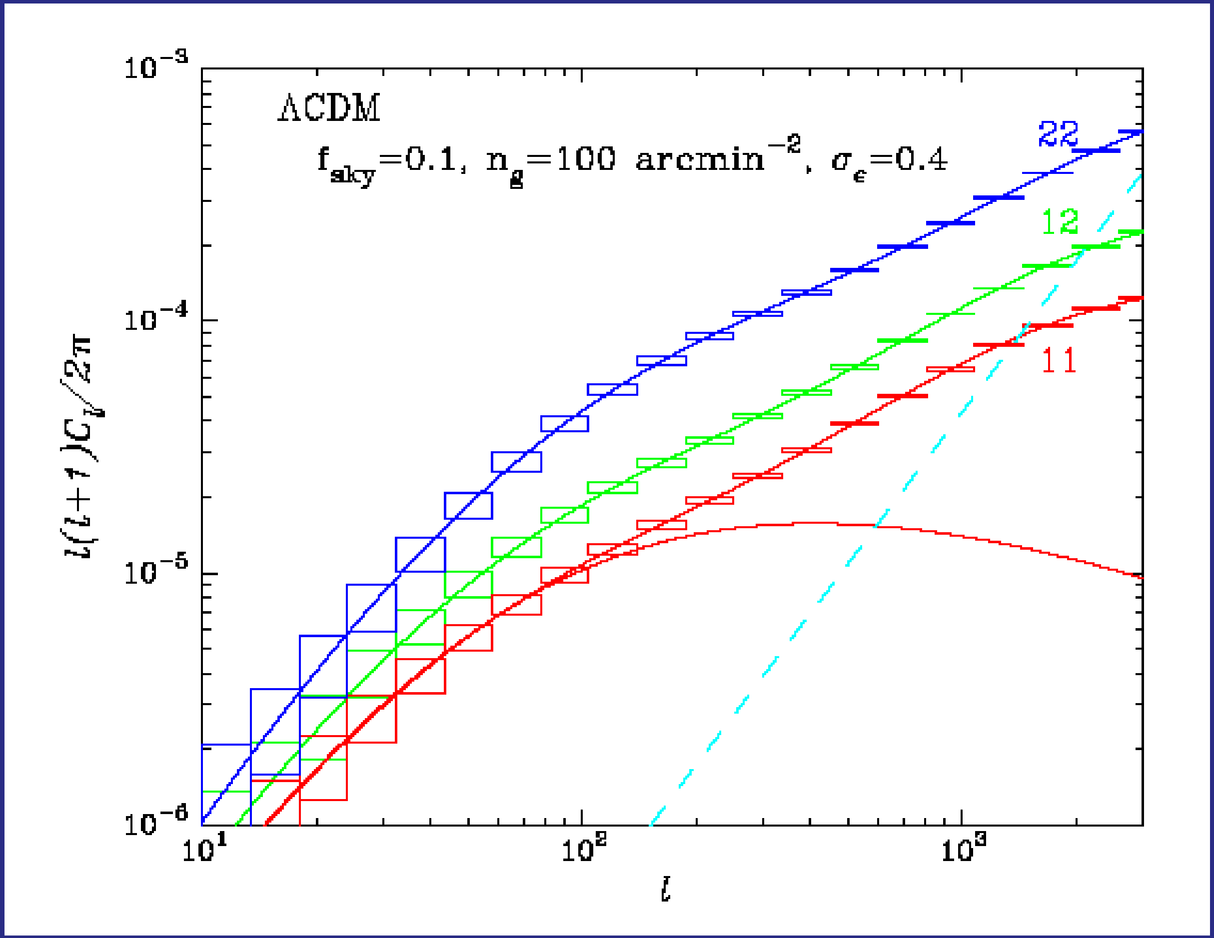
Lensing tomography



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

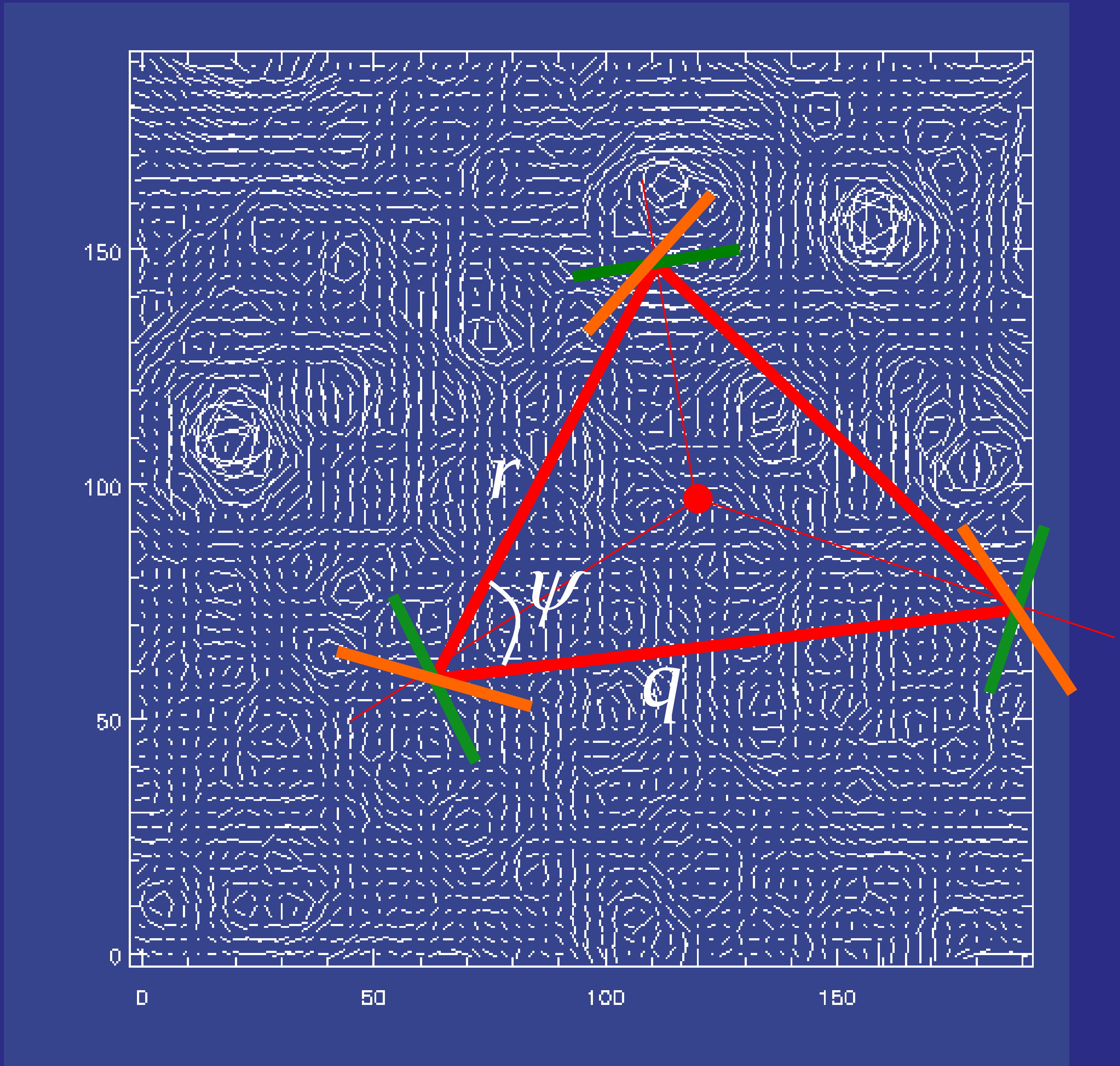
Lensing power spectrum



The theorists version of a future lensing measurement

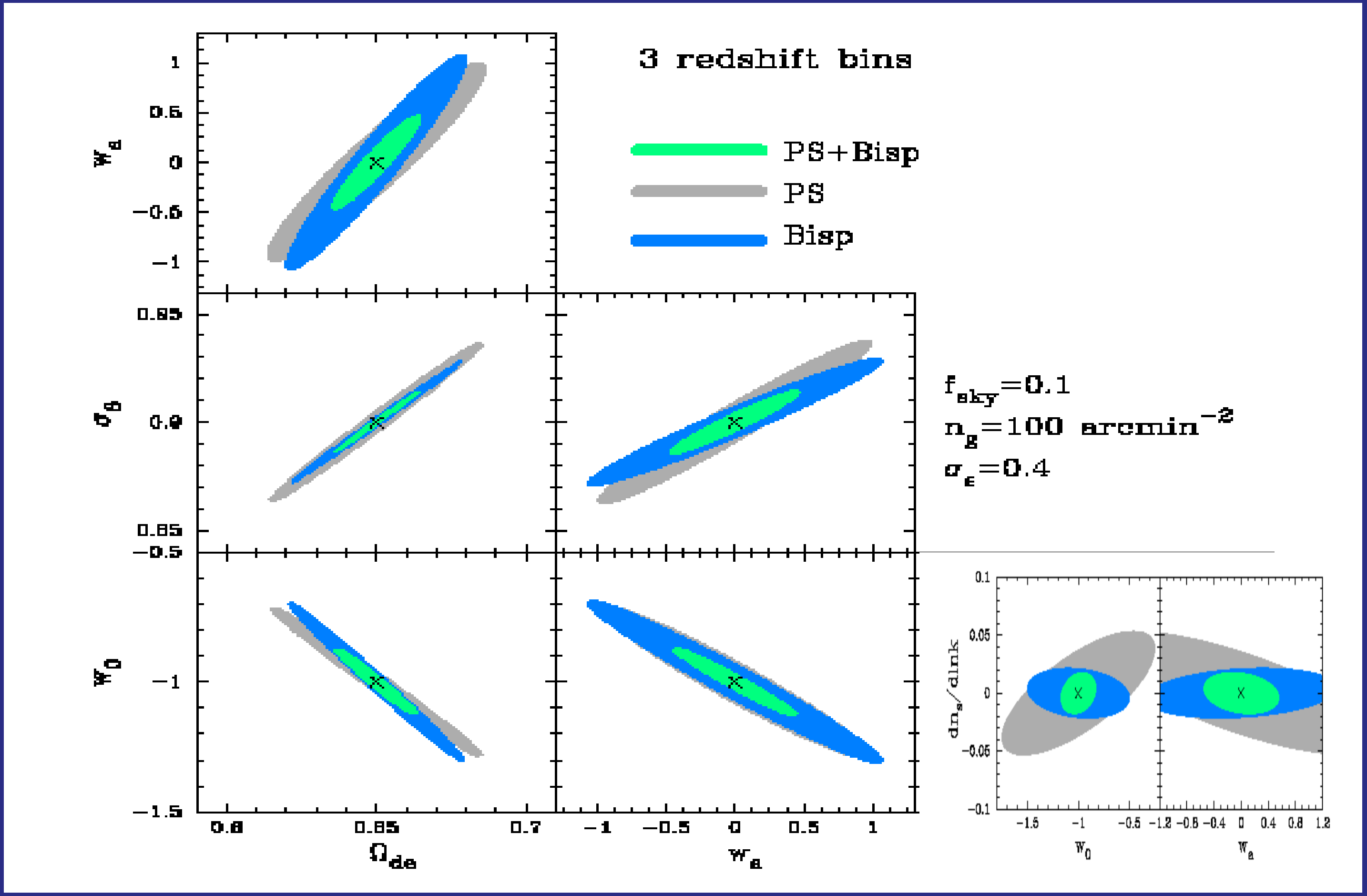
Takada & Jain 2004

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!

Parameter forecasts with tomography



Gravitational growth: 3-point and 2-point information is complementary.

Caveat: nonlinear model, non-Gaussian covariance. (Takada & Jain 03)

(2-point studies: Hu 99,02; Huterer 02; Heavens 03; Linder&Jenkins 03)

Summary

- Shear correlations are induced by massive structures
- Lensing tomography probes dark energy and gravity by measuring the evolution of clustering and distances factors
- Measurements require exquisite control of systematic errors
- Where the action is: next generation imaging surveys. Lensing, along with SN, Clusters, Baryon oscillations, will test models with different fundamental physics.