Cosmic Shear: Past and Future – the Good and Ugly

Peter Schneider, Argelander-Institut für Astronomie
Universität Bonn

Outline:

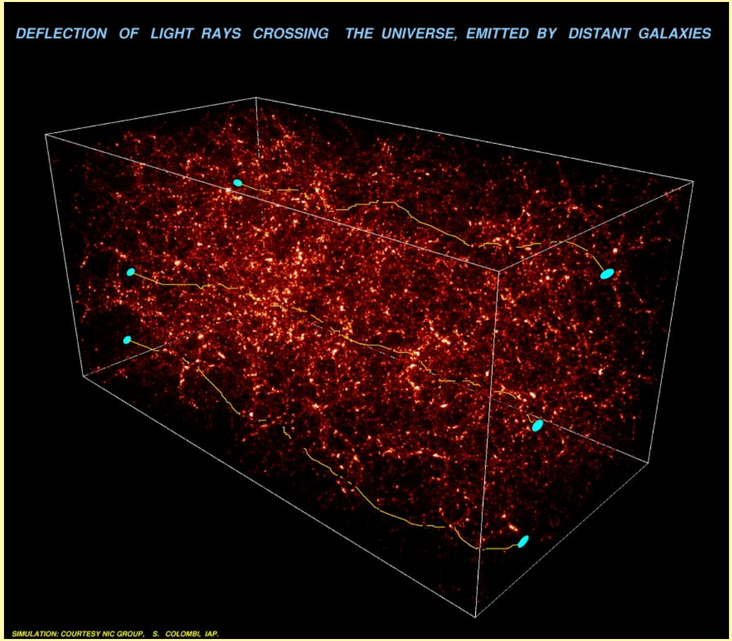
Introduction & History
Basic principles
Observables & estimates
Successes
Problems & Systematics
Theoretical uncertainties
Third dimension

Selected reviews:

Mellier 1999
Bartelmann & Schneider 2001
van Waerbeke & Mellier 2003
Refregier 2003
Schneider 2006
Munshi et al. 2006

Introduction & Developments

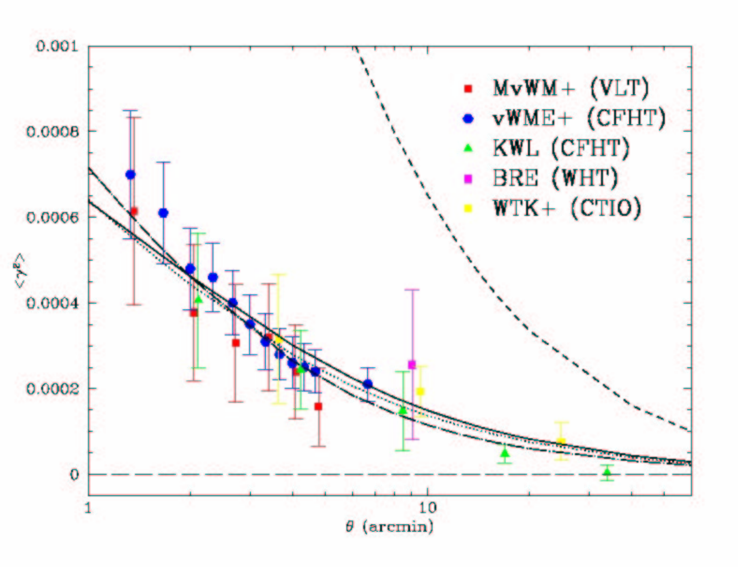
- Light bundles are distorted as they propagate through the Universe
- their distortion carries information about the LSS
- Cosmic Shear exploits this information by measuring image shapes of many distant objects



Cosmic Shear deals with the investigation of the connection between matter distribution and image shapes, from the measurement of the correlated image distortion to the inference of cosmological information from this distortion field.

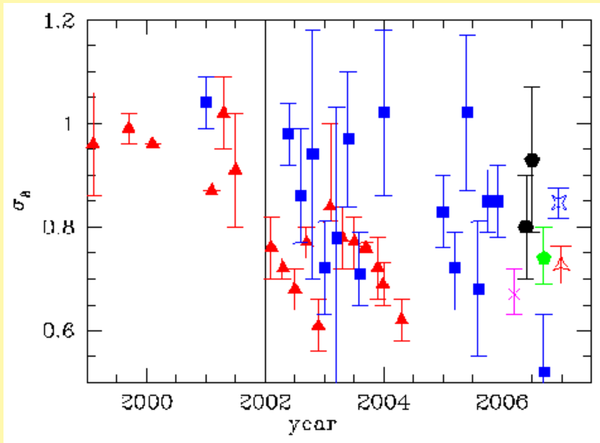
Towards cosmic shear detection

- Zel'dovich (1964); Gunn (1967): light propagation in inhomogeneous Universe
- Blandford et al. (1991); Miralda-Escudé (1991); Kaiser (1992): basic theory of cosmic shear; relation to power spectrum
- Mould et al. (1994); Fort et al. (1996); Schneider et al. (1998): attempts to detect a cosmic shear signal
- Bernardeau et al. (1997); Jain & Seljak (1997): higher-order shear effects; accounting for non-linear power spectrum of the LSS
- Kaiser (1998); Schneider et al. (1998): new shear measures
- Bacon et al. (2000); Kaiser et al. (2000); van Waerbeke et al. (2000); Wittman et al. (2000): first detection of cosmic shear with $\sim 10^5$ galaxies



- First results from 4 different groups, 3 cameras/telescopes agreed within their (fairly large) error bars
- soon larger surveys became available, from the ground (e.g., Virmos-Descart, RCS, COMBO-17, GaBoDS, CFHTLS) and also from space (WFPC2, STIS, ACS, COSMOS)

- E.g., all groups agree that they can measure σ_8 within $\sim 10\%$ accuracy
- though they don't agree 10% of what
- Current state-of-the-art: well, follow this week's program!



Lensing measures projected mass distribution

Lensing effect of the 3-D matter distribution (the LSS) on source at distance χ is described by effective surface mass density $\kappa(\boldsymbol{\theta}, \chi)$,

$$\kappa(\boldsymbol{\theta}, \chi) = \frac{3H_0^2\Omega_{\rm m}}{2c^2} \int_0^\chi {\rm d}\chi' \, \frac{(\chi - \chi')\,\chi'}{\chi} \frac{\delta\,(\chi'\boldsymbol{\theta}, \chi')}{a(\chi')} \; ; \tag{1}$$

a spatially flat Universe was assumed; $a(\chi) = (1+z)^{-1}$: scale factor;
χ: comoving distance; $\delta(\boldsymbol{x}, \chi) = \Delta\rho/\bar{\rho}$: density contrast.

The cosmological model enters in two different ways:

- Properties of the mass distribution $\delta(\boldsymbol{x}, z)$; depend on growth factor, transfer function, and non-linear evolution;
- Geometrical factors, $(\chi - \chi')/\chi$ (= "$D_{\rm ds}/D_{\rm s}$" in standard lensing notation), depend on distance-redshift relation, hence on expansion history.

Both effects can be probed, jointly or separately.

Select a set of galaxies with redshift distribution $p_z(z)\,\mathrm{d}z = p_\chi(\chi)\,\mathrm{d}\chi$ in the survey, and define geometric weight factor

$$g(\chi) = \int_\chi^{\chi_\mathrm{h}} \mathrm{d}\chi'\, p_\chi(\chi') \frac{(\chi' - \chi)}{\chi'} = \left\langle \frac{D_\mathrm{ds}}{D_\mathrm{s}} \right\rangle \ .$$

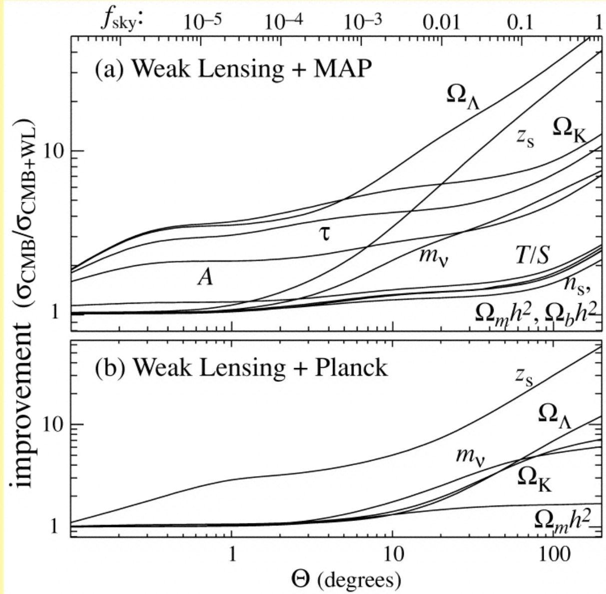
Effective κ for this redshift distribution:

$$\kappa(\boldsymbol{\theta}) = \frac{3H_0^2\Omega_\mathrm{m}}{2c^2} \int_0^{\chi_\mathrm{h}} \mathrm{d}\chi\, g(\chi)\, \chi \frac{\delta\left(\chi\boldsymbol{\theta}, \chi\right)}{a(\chi)} \ ,$$

Then use Limber's equation to get power spectrum

$$P_\kappa(\ell) = \frac{9H_0^4\Omega_\mathrm{m}^2}{4c^4} \int_0^{\chi_\mathrm{h}} \mathrm{d}\chi \frac{g^2(\chi)}{a^2(\chi)}\, P_\delta\left(\frac{\ell}{\chi}, \chi\right) \ .$$

This assumes that δ does not change much on the timescale which a photon needs to traverse the largest-scale structures in the Universe – simulations support this assumption.



Cosmic shear in combination with other cosmic probes is very powerful to constain cosmological parameter (Hu & Tegmark 1999)

Use color information to select different redshift distributions of sources, i.e.,

$$g^{(i)}(\chi) = \int_{\chi}^{\chi_{\rm h}} \mathrm{d}\chi' \, p_{\chi}^{(i)}(\chi') \frac{(\chi' - \chi)}{\chi'} \; . \tag{2}$$

Then, cross-power is

$$P_{\kappa}^{ij}(\ell) = \frac{9 H_0^4 \Omega_{\rm m}^2}{4 c^4} \int_0^{\chi_{\rm h}} \mathrm{d}\chi \, \frac{g^{(i)}(\chi) g^{(j)}(\chi)}{a^2(\chi)} \, P_{\delta}\left(\frac{\ell}{\chi}, \chi\right) \; . \tag{3}$$

Different redshift distributions not only useful for increasing cosmological power of cosmic shear, but also **absolutely necessary** to control systematics.

Observables and estimates

Observables

Image ellipticities ϵ_i, defined in terms of second brightness moments; related to intrinsic ellipticity $\epsilon_i^{\rm s}$ by

$$\epsilon_i = \frac{\epsilon_i^{\rm s} + g}{1 + \epsilon_i^{\rm s} g^*} \approx \epsilon_i^{\rm s} + \gamma(\boldsymbol{\theta}_i) \; ; \tag{4}$$

γ: shear = projected tidal gravitational field,

$$\hat{\gamma}(\boldsymbol{\ell}) = \hat{\kappa}(\boldsymbol{\ell}) \, \exp\left[2{\rm i} \, {\rm phase}(\boldsymbol{\ell})\right] \; . \tag{5}$$

As galaxies have random orientation intrinsically, one finds for the expectation value of image ellipticity

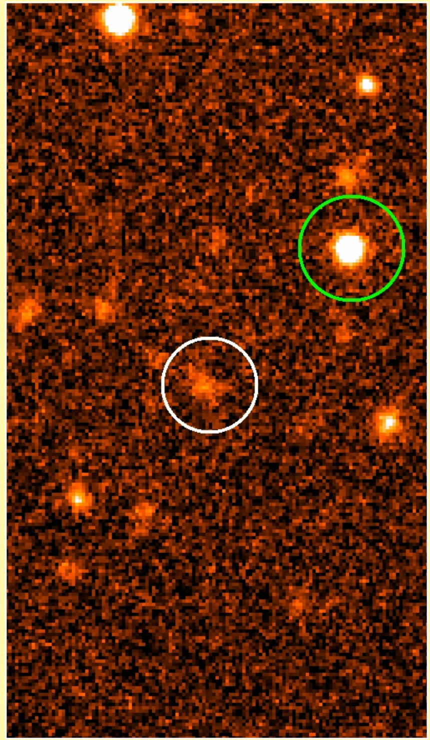
$$\langle \epsilon_i \rangle = g(\boldsymbol{\theta}_i) \equiv \frac{\gamma(\boldsymbol{\theta}_i)}{1 - \kappa(\boldsymbol{\theta}_i)} \approx \gamma(\boldsymbol{\theta}_i) \;\; : \tag{6}$$

$\Rightarrow$ every image ellipticity is unbiased (though noisy) estimate of (reduced) shear along a line-of-sight.

In the real world ...

the observed ellipticities are affected by various effects:

- seeing, PSF anisotropy, caused by atmospheric turbulence, tracking errors, field distortions (coaddition);
- pixelization, noise, blending, bad pixels, cosmics;
- diffraction spikes, ghosts, fringing, ...



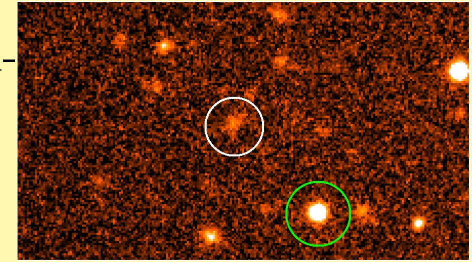
These effects need to be controlled (the PSF is observable through the images of stars) and corrected; effective methods for this are available.

The community has made major **STEP**s to study these issues,

we believe we can measure shears with $\sim 2\%$ accuracy by now, with further improvements to come.

In the real world ...

the observed ellipticities are affected by various effects:



- seeing, PSF anisotropy, caused by atmospheric turbulence, tracking errors, field distortions (coaddition);
- pixelization, noise, blending, bad pixels, cosmics;
- diffraction spikes, ghosts, fringing, ...

These effects need to be controlled (the PSF is observable through the images of stars) and corrected; effective methods for this are available.

The community has made major **STEP**s to study these issues,

we believe we can measure shears with $\sim 2\%$ accuracy by now, with further improvements to come; THUS:

Estimates

All second-order statistical information is contained in shear 2-point correlation functions (2PCF) $\xi_\pm(\theta)$,

$$\xi_\pm(\theta) = \langle\gamma_{\rm t}\gamma_{\rm t}\rangle(\theta) \pm \langle\gamma_\times\gamma_\times\rangle(\theta) \; , \quad \xi_\times(\theta) = \langle\gamma_{\rm t}\gamma_\times\rangle(\theta) \; . \tag{7}$$

$\xi_\times(\theta)$ should vanish due to parity symmetry!

Unbiased (in absence of intrinsic effects) estimator of 2PCF in a θ-bin

$$\hat{\xi}_\pm(\vartheta) = \frac{\sum_{ij} w_i\, w_j\, (\epsilon_{i{\rm t}}\epsilon_{j{\rm t}} \pm \epsilon_{i\times}\epsilon_{j\times})\, \Delta_\vartheta(|\boldsymbol{\theta}_i - \boldsymbol{\theta}_j|)}{N_{\rm p}(\vartheta)} \; , \tag{8}$$

$$N_{\rm p}(\vartheta) = \sum_{ij} w_i\, w_j\, \Delta_\vartheta(|\boldsymbol{\theta}_i - \boldsymbol{\theta}_j|) \; ; \tag{9}$$

The w_i are weight factors of the i-th galaxy ellipticity, Δ_ϑ defines an angular bin.

$N_{\rm p}(\vartheta)$: effective number of pairs in the bin.

All other 2-point statistical shear statistics can be derived from $\xi_\pm$.

$\xi_\pm$ is the prime observable, insensitive to gaps in data

Relation of shear 2PCF to power spectrum

$$\xi_\pm(\theta) = \int_0^\infty \frac{\mathrm{d}\ell\,\ell}{2\pi}\,\mathrm{J}_{0,4}(\ell\theta)\,P_\kappa(\ell)\;.$$

Parameter estimate

Shear 2PCF can be directly compared with cosmological predictions:

$$\chi^2(\boldsymbol{p}) = \sum_{ij}\left[\xi_\pm^{\mathrm{obs}}(\theta_i) - \xi_\pm(\theta_i;\boldsymbol{p})\right] C_\pm^{-1}(\theta_i,\theta_j)\left[\xi_\pm^{\mathrm{obs}}(\theta_j) - \xi_\pm(\theta_j;\boldsymbol{p})\right]$$

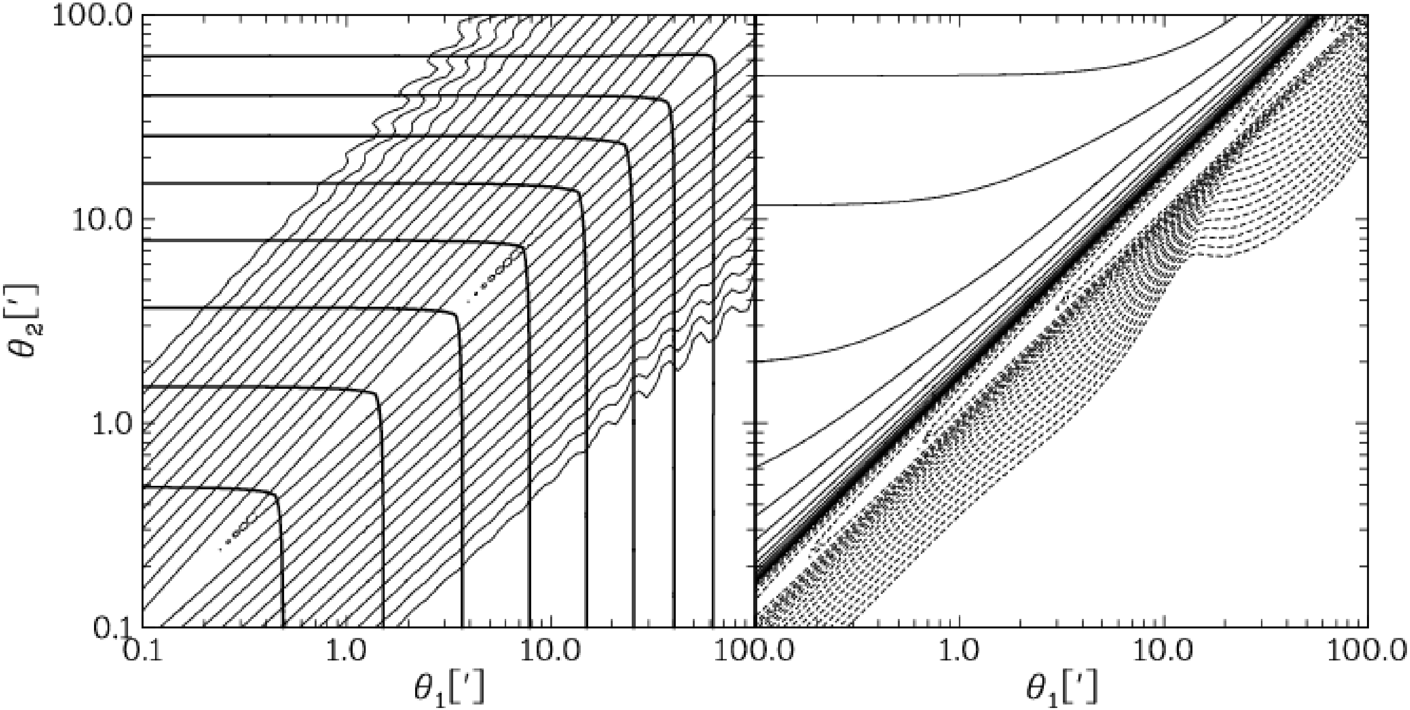
$C_\pm(\theta_i,\theta_j)$ is the covariance matrix of the shear 2PCF, given as

$$C_\pm(\theta_i,\theta_j) = \frac{1}{\pi\omega}\int_0^\infty \mathrm{d}\ell\,\ell\,\mathrm{J}_{0,4}(\ell\theta_1)\mathrm{J}_{0,4}(\ell\theta_2)\left[\left(P_\delta(\ell) + \frac{\sigma_\epsilon^2}{2n}\right)^2 \pm \left(\frac{\sigma_\epsilon^2}{2n}\right)^2\right]$$

(Joachimi & Schneider, in prep.), where ω is solid angle of the survey, n is number density of galaxies, and the J's are Bessel functions.

Equivalent to covariance of Schneider et al. (2002), but much simpler.

Then minimize χ^2 w.r.t. cosmological parameters: done!



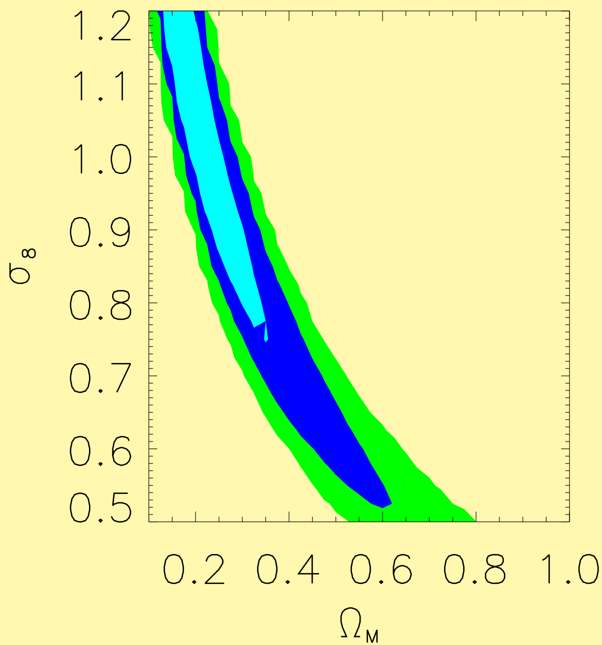
Left: Covariance C_{++} (thick curves) and C_{--} (thin curves).
Right: Mixed covariance C_{+-} (Joachimi & Schneider, in prep.)

Successes

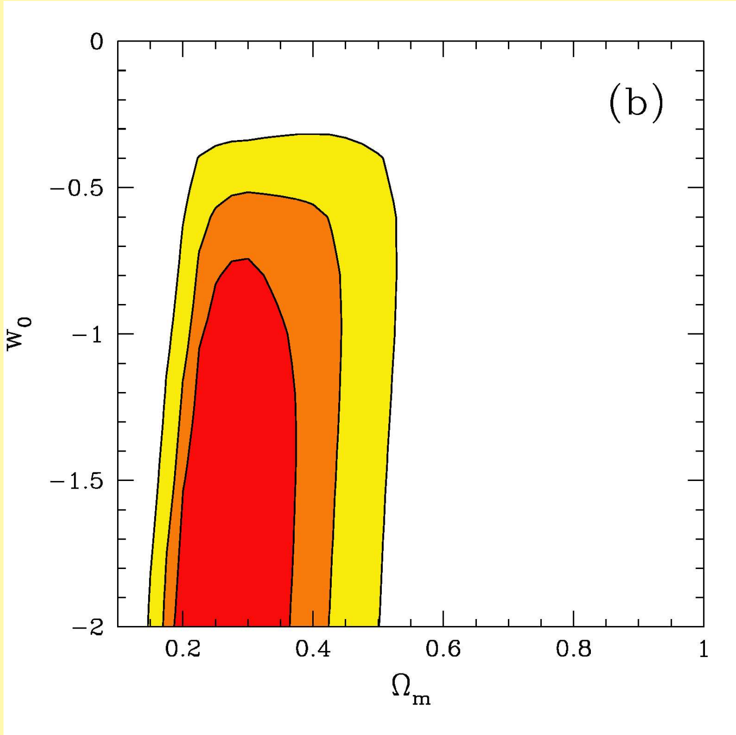
Since 2000, great progress has been made:

- Lensing surveys have extended greatly in size.
- Shear measurements have been much better understood (KSB, Jarvis & Bernstein, shapelets, ... $\Leftarrow$ STEP).
- New diagnostics for data integrity have been developed and applied (E/B-modes; parity invariance; star-galaxy shape correlations, etc.).
- Currently, systematic uncertainties believed to be smaller than statistical ones (will change soon).
- Cosmic shear turned into a cosmological tool.

Example; CFHTLS

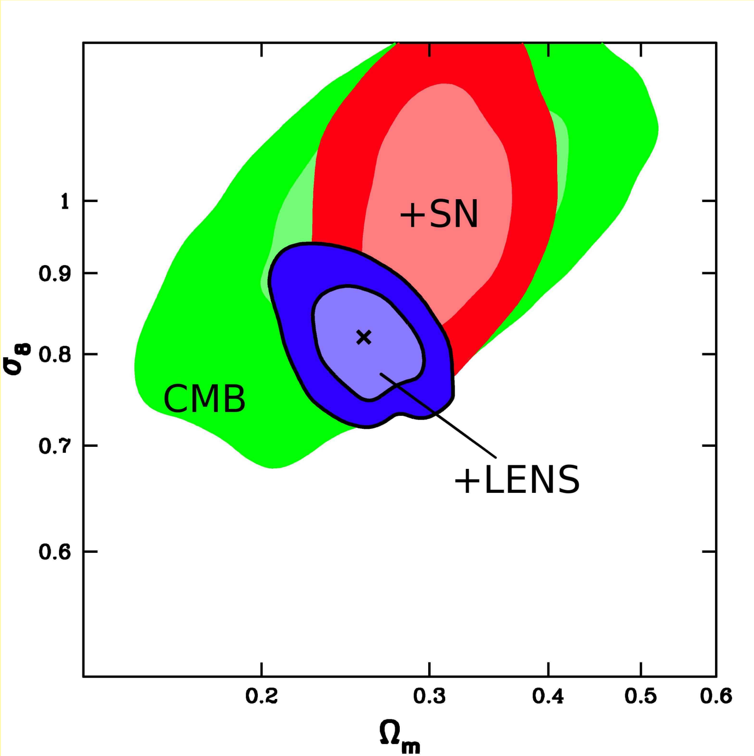


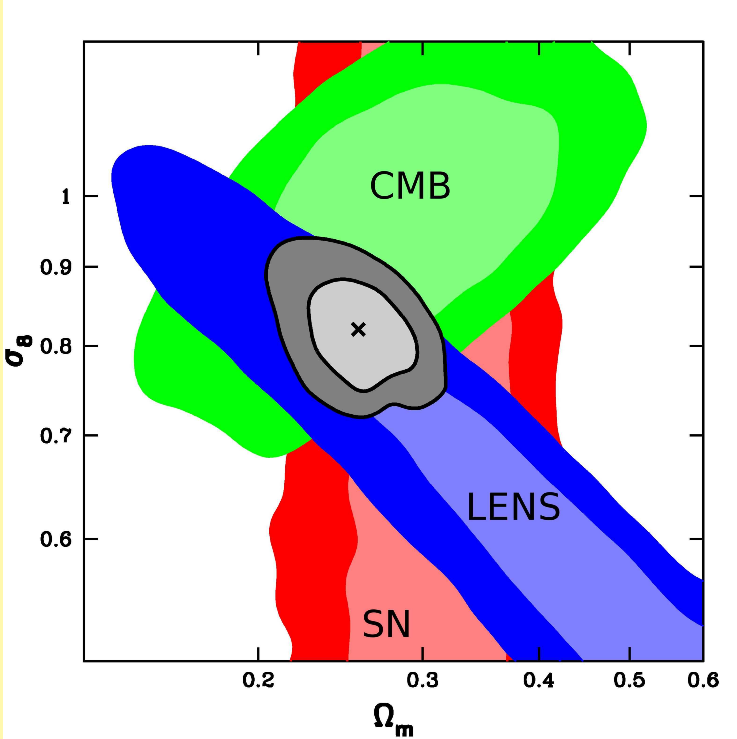
Semboloni et al. 2005



Hoekstra et al. 2005

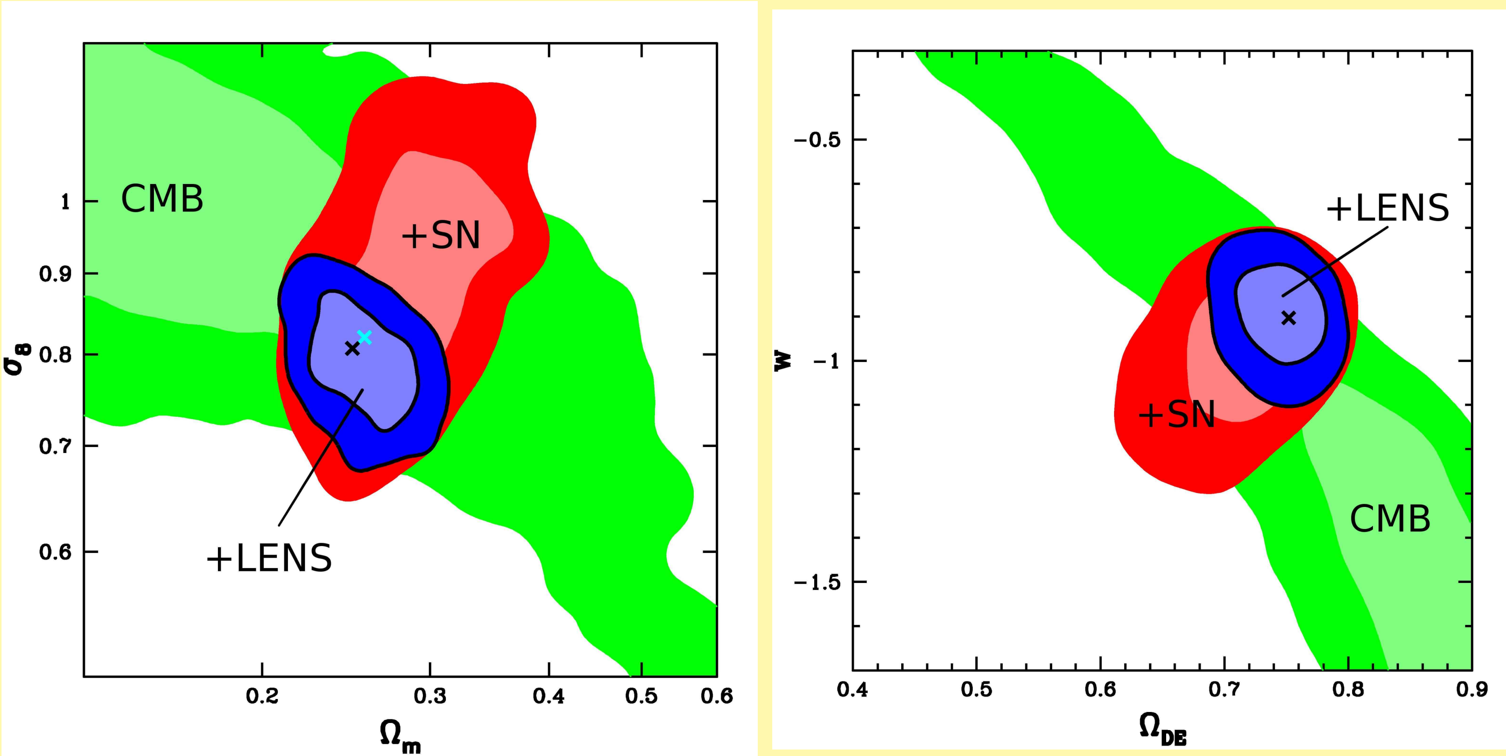
Example: CTIO survey (Jarvis et al. 2005)



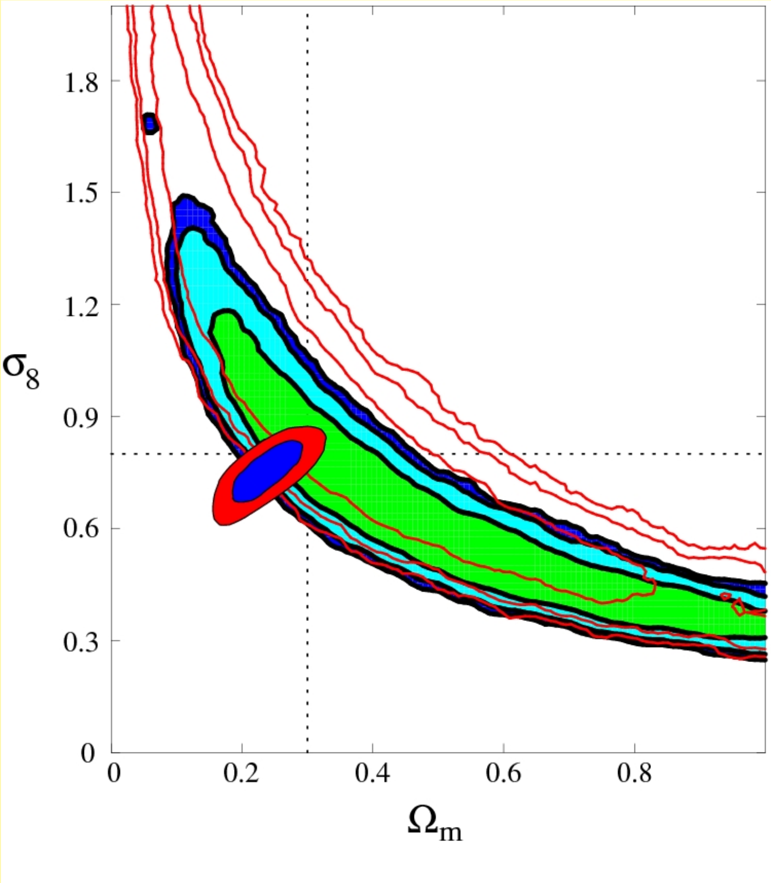


here, $w \equiv -1$

w left as free parameter:



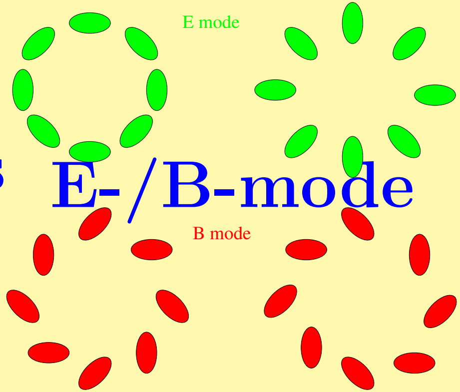
Example: GaBoDS (Hetterscheidt et al. 2007)



Constraints obtained with two different cosmic shear statistics

small contours:
result from WMAP

The notorious E-/B-mode Problem



E-mode shear is believed to come from lensing;

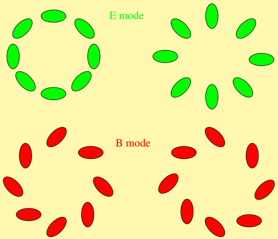
B-mode shear is not expected from lensing (except for some higher-order corrections, such as lens-lens coupling, Born-approximation, source clustering, etc.)

$$\hat{\gamma}^{\mathrm{E,B}}(\boldsymbol{\ell}) = \frac{1}{2}\left[\hat{\gamma}(\boldsymbol{\ell}) \pm \hat{\gamma}^*(-\boldsymbol{\ell})\,\mathrm{e}^{4\mathrm{i}\,\mathrm{phase}(\boldsymbol{\ell})}\right]\;, \quad \boldsymbol{\ell} = \mathbf{0}\ \text{mode undetermined}$$

Strategy: separate both modes; check whether (and be happy if) the B-modes vanish.

Three such separation methods are used at the second-order level: E/B-mode power spectra, E/B-mode correlation functions, and aperture statistics.

E/B-mode power spectra



$$P_{\mathrm{E/B}}(\ell) = \pi \int_0^{\infty \Leftarrow} \mathrm{d}\theta\, \theta\, \left[\xi_+(\theta) \mathrm{J}_0(\ell\theta) \pm \xi_-(\theta) \mathrm{J}_4(\ell\theta)\right]$$

in this form, requires ξ's to infinite separation

There are better ways of determining the power spectrum (e.g., Kaiser 1998; Hu & White 2001) or band powers.

E/B-mode correlation functions

$$\xi_{\mathrm{E/B}}(\theta) = \frac{1}{2}\left[\xi_+(\theta) \pm \xi_-(\theta) \pm 4\int_\theta^{\infty \Leftarrow} \frac{\mathrm{d}\vartheta}{\vartheta}\xi_-(\vartheta) \mp 12\theta^2 \int_\theta^{\infty \Leftarrow} \frac{\mathrm{d}\vartheta}{\vartheta^3}\xi_-(\vartheta)\right] .$$

Same problem; can be fixed by fitting two constants $C_{1,3} = \int_{\theta_{\mathrm{max}}}^{\infty} \mathrm{d}\vartheta\ \vartheta^{-1,3}\, \xi_-(\vartheta)$ such that B-mode shear vanishes on largest scale (Crittenden et al. 2002).

But then throws away information on large scales.

E/B-mode separation in aperture statistics

Consider circular aperture of radius θ; for a point inside the aperture, define tangential and cross-components of the shear relative to center of aperture; define

$$M_{\rm ap}(\theta) = \int \mathrm{d}^2\vartheta \; Q(|\boldsymbol{\vartheta}|) \, \gamma_{\rm t}(\boldsymbol{\vartheta}) \; ,$$

with Q: a weight function with support $\vartheta \in [0, \theta]$; e.g.,

$$Q(\vartheta) = \frac{6}{\pi\theta^2} \frac{\vartheta^2}{\theta^2} \left(1 - \frac{\vartheta^2}{\theta^2}\right) \mathrm{H}(\theta - \vartheta) \; .$$

First advantage: $\left\langle M_{\rm ap}^n(\theta)\right\rangle$ is sensitive *only* to E-mode shear, for all n.

Dispersion of $M_{\rm ap}(\theta)$ is related to power spetrum as

$$\left\langle M_{\rm ap}^2\right\rangle(\theta) = \frac{1}{2\pi} \int_0^\infty \mathrm{d}\ell \; \ell \, P_\kappa(\ell) \, W(\theta\ell) \; , \quad \text{with} \quad W(\eta) := \frac{576 \mathrm{J}_4^2(\eta)}{\eta^4} \; .$$

Second advantage: $\left\langle M_{\rm ap}^2(\theta)\right\rangle$ is local measure of power spectrum

Similarly, one defines cross-aperture

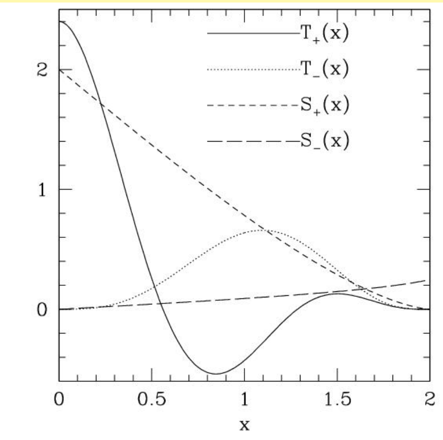
$$M_\perp(\theta) = \int \mathrm{d}^2\vartheta \, Q(|\boldsymbol{\vartheta}|) \, \gamma_\times(\boldsymbol{\vartheta}) \ ,$$

$\langle M_\perp^n(\theta) \rangle$ is sensitive *only* to B-mode shear, for all n.

Aperture mass dispersion in terms of 2PCF

$$\left\langle M_{\rm ap}^2 \right\rangle(\theta) = \frac{1}{2} \int_{0 \Leftarrow}^{2\theta \Leftarrow} \frac{\mathrm{d}\vartheta \, \vartheta}{\theta^2} \left[\xi_+(\vartheta) \, T_+(\vartheta/\theta) + \xi_-(\vartheta) \, T_-(\vartheta/\theta) \right] \ ,$$

$$\left\langle M_\perp^2 \right\rangle(\theta) = \frac{1}{2} \int_{0 \Leftarrow}^{2\theta \Leftarrow} \frac{\mathrm{d}\vartheta \, \vartheta}{\theta^2} \left[\xi_+(\vartheta) \, T_+(\vartheta/\theta) - \xi_-(\vartheta) \, T_-(\vartheta/\theta) \right] \ ,$$

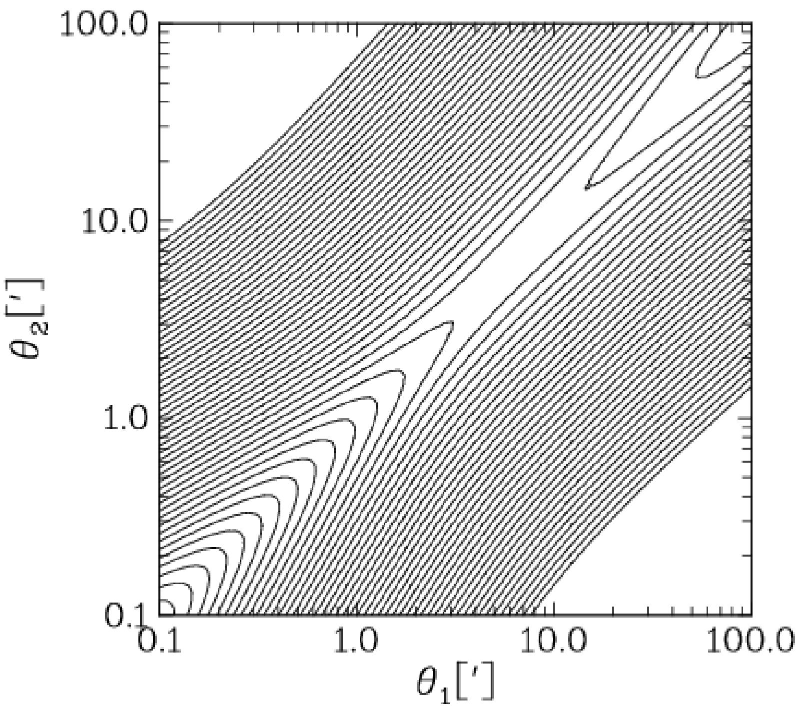


with $T_\pm$ being know functions.

No need to place apertures on the field.

Third advantage: aperture dispersion can be derived in terms of the measured shear correlation functions over a finite separation interval.

Joachimi & Schneider, in prep.



Fourth advantage: The covariance of $\langle M_{\rm ap}^2(\theta)\rangle$ is simple, at least under Gaussian assumptions

in particular, it decorrelates quickly away from the diagonal

see Kilbinger & Schneider (2005) and Semboloni et al. (2007) for modification due to non-Gaussianity, important for angular scales $\lesssim 20'$.

$$\mathrm{Cov}_{M_{\rm ap}^2}(\theta_1,\theta_2) = \frac{576^2}{\pi\omega}\int_0^\infty \frac{\mathrm{d}\ell}{\ell^7}\,\frac{\mathrm{J}_4^2(\ell\theta_1)}{\theta_1^4}\frac{\mathrm{J}_4^2(\ell\theta_2)}{\theta_2^4}\left(P_\delta(\ell)+\frac{\sigma_\epsilon^2}{2n}\right)^2$$

Fifth advantage:Aperture statistics can be easily generalized to higher order

e.g., $\left\langle M_{\rm ap}^n(\theta) M_\perp^{3-n}(\theta)\right\rangle$ can be calculated in terms of the shear 3PCFs Γ.

Then:

- $\left\langle M_{\rm ap}^3(\theta)\right\rangle$ is linearly related to bispectrum of LSS
- $\left\langle M_{\rm ap}(\theta) M_\perp^2(\theta)\right\rangle$ contains a B-mode signal
- $\left\langle M_{\rm ap}^2(\theta) M_\perp(\theta)\right\rangle$ and $\left\langle M_\perp^3(\theta)\right\rangle$ must be **strictly** zero, in order not to violate parity invariance!

These aperture measures can also be generalized to three different filter radii; in this way they probe all triangle configurations of the bispectrum.

$$\langle M_{\rm ap}(\theta_1)\, M_{\rm ap}(\theta_2)\, M_{\rm ap}(\theta_3)\rangle \equiv \left\langle M_{\rm ap}^3\right\rangle(\theta_1,\theta_2,\theta_3) = \int \text{Kernel } \times \ \Gamma \,,$$

where the Kernel is a known function (Jarvis et al. 2004; Schneider et al. 2005)

$\left\langle M_{\rm ap}^3\right\rangle(\theta_1,\theta_2,\theta_3)$ simply related to bispectrum.

2nd-order cosmic shear: the problems

Problems can be broadly catagorized as follows:

- Observational effects: unbiased shape estimates
- Redshift information
- Intrinsic alignments and shape-shear correlations
- Theoretical predictions
  - uncertainties in the lensing predictions
  - uncertainties in cosmological predictions

All of them have to be solved very accurately to render future cosmic shear surveys a precision tool for cosmology.

Intrinsic alignment; shape–shear correlations

Let $\epsilon_i = \epsilon_i^{\rm s} + \gamma(\boldsymbol{\theta}_i)$, $z_1 \le z_2$:

$$\begin{aligned}
\langle \epsilon_1 \epsilon_2^* \rangle &= \langle \epsilon_{\mathbf{1}}^{\rm s} \epsilon_{\mathbf{2}}^{\rm s*} \rangle && : \text{intrinsic}, \ = 0 \text{ unless } z_1 \approx z_2 \\
&+ \langle \epsilon_{\mathbf{1}}^{\rm s} \gamma_{\mathbf{2}}^{*} \rangle && : \text{unfortunately}, \ \neq 0 \text{ (Mandelbaum et al. 2006)} \\
&+ \langle \gamma_1 \epsilon_2^{\rm s*} \rangle && : \equiv 0 \\
&+ \langle \gamma_1 \gamma_2^{*} \rangle && : \text{WANTED!}
\end{aligned}$$

$$= \xi_+(|\boldsymbol{\theta}_1 - \boldsymbol{\theta}_2|)$$

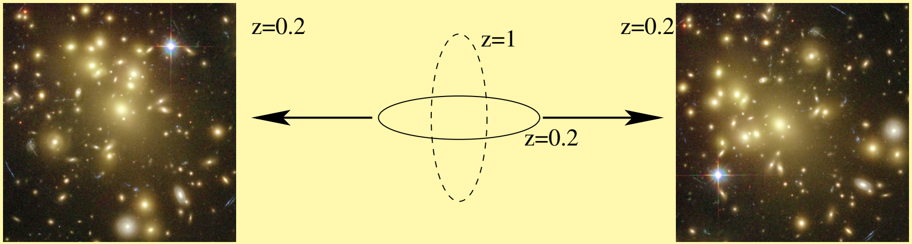
Intrinsic correlations can be eliminated with phot-z, by avoiding pairs of similar redshift or used their localization in Δz explicitly (King & Schneider 2002, 2003; Heymans & Heavens 2003);

however, requires accurate photometric redshift estimates;

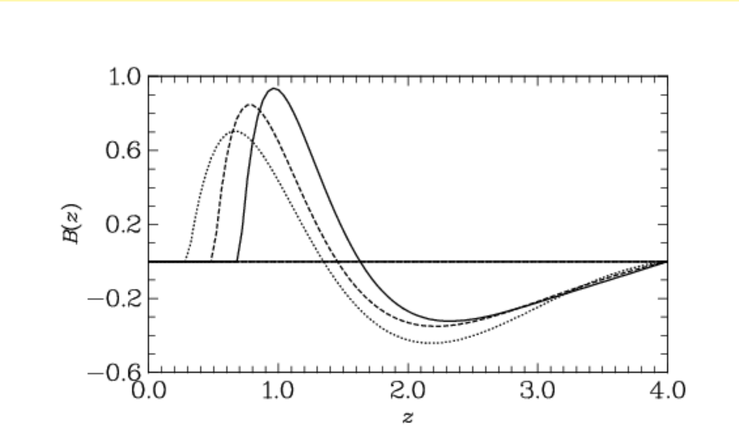
relative effect stronger for shallower cosmic shear surveys.

Shape-shear correlations (Hirata & Seljak 2004)

Ellipticity of light is affected by tidal field of environment; can be identified through their characteristic redshift dependence $\propto (\chi_2 - \chi_1)/\chi_2$ and filtered out.



If redshift information is available, shape-shear correlation can be eliminated:



if $\xi_\pm(\theta; z_1, z_2)$ is z-dependent shear 2PCF, then

$$\Xi_\pm(\theta; z_1) = \int_{z_1}^{\infty} \mathrm{d}z\, \xi_\pm(\theta; z_1, z)\, B(z; z_1)$$

no longer contains shape-shear correlations if $\int_{z_1}^{\infty} \mathrm{d}z\, B(z; z_1)\, (D_{\mathrm{ds}}/D_{\mathrm{s}}) = 0$.

Both of these effects discovered – need to be controlled $\Rightarrow$ z info!

Relative strength of both effects larger for shallow surveys.

Theoretical uncertainties I

Usual lens treatment makes number of approximations:

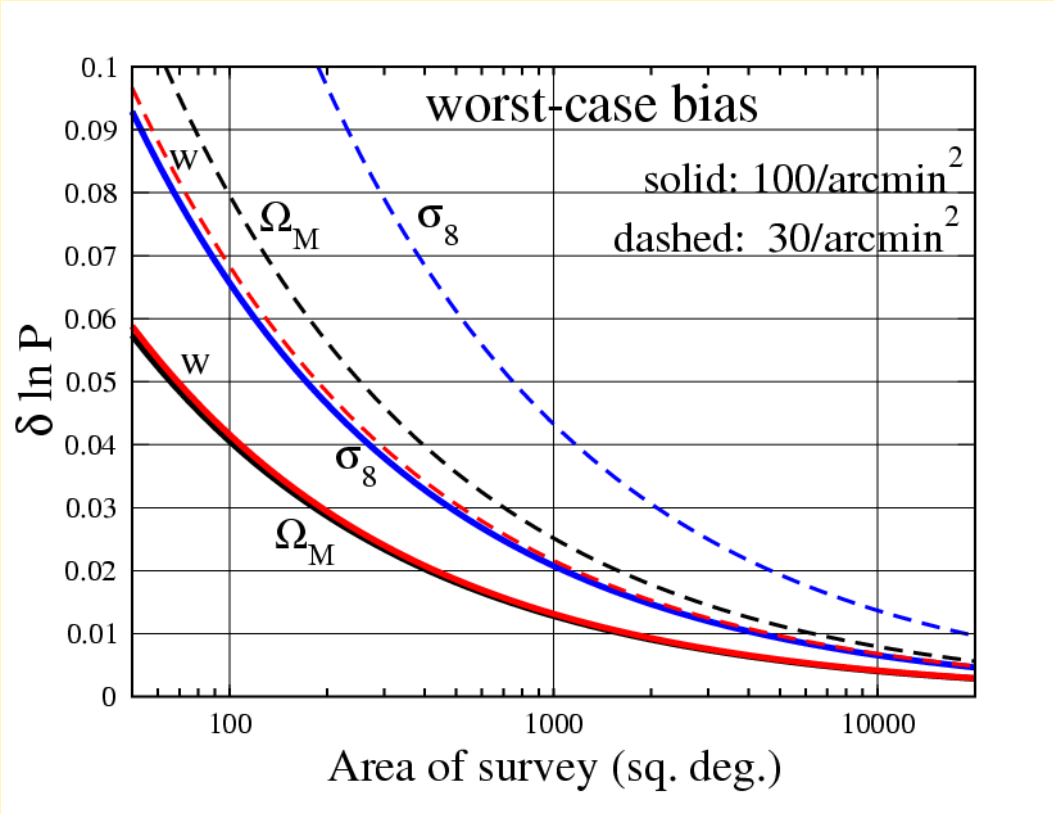
- Born approximation: light lays propagate along straight lines
- Neglect of lens-lens coupling: lens effect linear in gravitational potential
- flat-sky approximation: $\cos\theta = 1$
- Limber's equation: slow evolution of all quantities, and neglect of very large-scale modes
- Lens-source coupling: dense regions (where high shear is created) are populated with overdensity of galaxies – those are unaffected by the shear.
  Consequence: $\langle M_{\rm ap} \rangle < 0$, and dispersion affected as well
  (Hamana et al. 2004; Kilbinger et al. in prep.)
  can be avoided by using redshift information.

Theoretical uncertainties II

- The power spectrum $P_\delta(k)$ not sufficiently well known; fit formulae (e.g., Peacock & Dodds 1996; Smith et al. 2003) not accurate enough for precision cosmology;
  NOTE: Almost all current cosmic shear measurements extend into the non-linear regime.
- Higher-order spectra (bispectrum, trispectrum) analytically unknown – strongly affects the use of higher-order shear statistics.
- Trispectrum needs to be determined in order to get reliable covariance matrix for 2-nd-order shear – Gaussian approximation grossly underestimates covariance on scales below $\sim 15'$.
- Masking bias: Noone will measure cosmic shear in the inner $\sim 1'$ of A1689, though it is contained in the power spectrum.
- Baryon cooling will affect the power spectrum on small scales.

Accuracy with which the power spectrum needs to be known (in the worst case) in order for systematics to be smaller than statistical (sampling variance) errors

from Huterer & Takada (2004)



Theoretical uncertainties III: Implications

- Ray-tracing though large LSS simulations must be an essential part of any future cosmic shear effort – both for the lensing part (Born appr.; lens-lens coupling; flat-sky; Limber) as well as for power-, bi-, and trispectra, covariances.
- They must be supplemented by hydro-simulations to study effects of baryons on small scales.
- Observational biases (masking of central parts of clusters; lens-source coupling) can be simulated by adding (semi-analytic) galaxy evolution models.

The third dimension

- z-dependent cosmic shear signal, i.e., $\xi_\pm(\theta; z_1, z_2)$;
- yields much better accuracy for cosmological parameters;
- 2 or 3 or 5 redshift bins? **Many more!** For control of systematics!
- 3-D lensing occurs in many different forms: shear tomography, shear ratio test, 3-D mass reconstruction, etc.
- z-dependent cosmic shear already observed in several surveys; e.g., shows growth of the power spectrum (Bacon et al. 2006).
- Essential feature for self-calibration.

One version of tomography

Constraints from shear measurements can be obtained independent on knowledge of mass distribution:

Let $P_{12}(\ell)$ be cross-power spectrum between two populations of galaxies 1, 2, without redshift overlap;

P can be either shear-shear or galaxy-shear power spectrum;

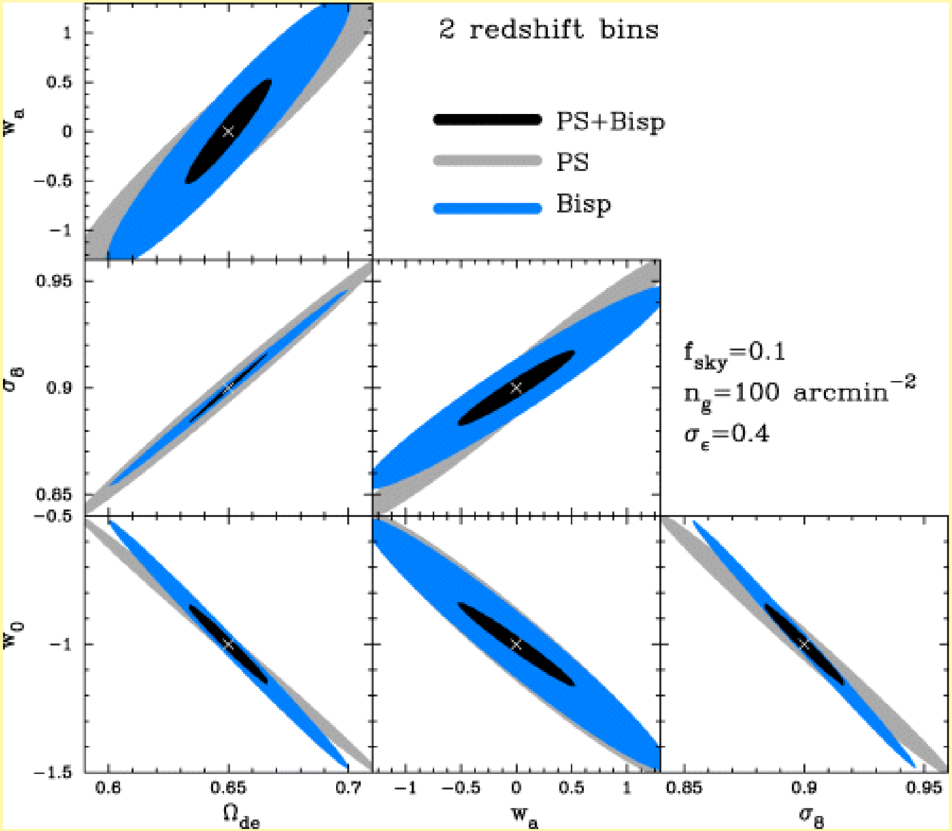
using 3 background populations $2, 2', 2''$, the ratio

$$\frac{P_{12} - P_{12'}}{P_{12} - P_{12''}} = \frac{\langle 1/\chi_2 \rangle - \langle 1/\chi_{2'} \rangle}{\langle 1/\chi_2 \rangle - \langle 1/\chi_{2''} \rangle}$$

is independent of matter power spectrum – a purely geometrical test (Zhang et al. 2006);

best used in combination with ‘traditional’ method, particularly at small scales.

Higher-order shear IS useful



Higher-order shear statistics yield very valuable information;

here (Takada & Jain 2004) in combination with redshift slicing (just two z-bins)

simplified expressions for covariance matrices – 'Gaussian';

most current Figure-of-merit estimates use only 2nd-order shear statistics

$\Rightarrow$ thus underestimate the power of cosmic shear.

Beyond 3rd order?

- Since cosmic shear field is non-Gaussian, we don't know how to best characterize it.

- 2PCF + 3PCF do not contain full information. Going to 4PCF? Shear peak statistics (counting peaks of $M_{\rm ap}(\boldsymbol{\vartheta};\theta)$)?

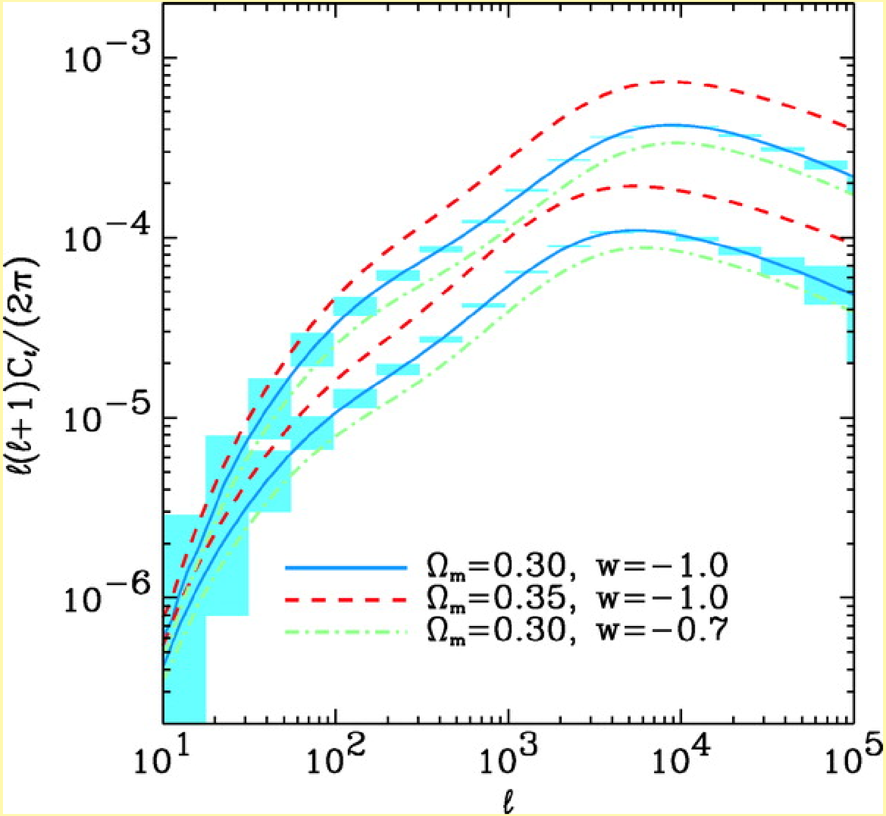
- Higher-order shear for self-calibration, e.g.,

$$4\mathrm{PCF} = \mathcal{F}(2\mathrm{PCF}, 3\mathrm{PCF})\ ?$$

- Higher-order test for data integrity, such as parity invariance of the observed shear field, $\left\langle M_{\rm ap}^m M_\perp^n \right\rangle \equiv 0$ for n odd.

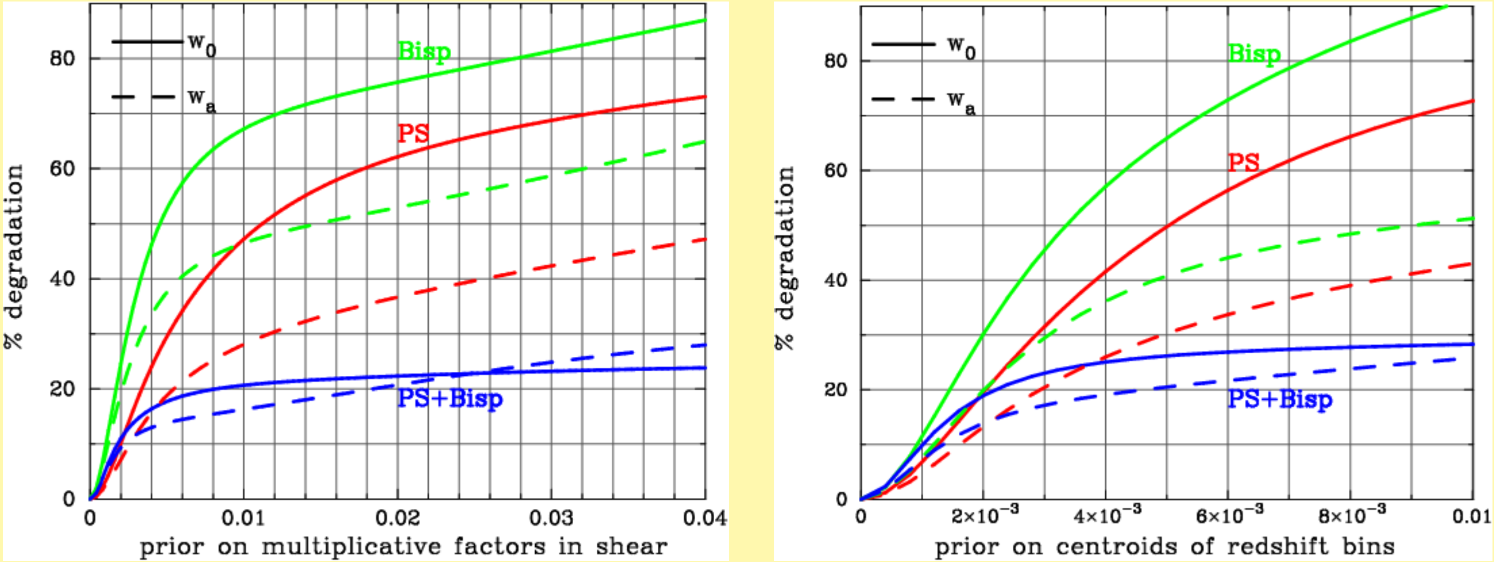
Towards Dark Energy

Cosmic shear is seen as most promising method to constrain the e.o.s. of DE (Dark Energy Task Force; ESA-ESO WG on Fundamental Cosmology)



Power spectra for different cosmological models and different redshift distributions of sources; error boxes correspond to anticipated SNAP wide survey (from Refregier et al. 2004)

However, we need to get systematics under control – and this requires reliable photometric redshifts and shear calibration.



Degradation of accuracy in determination of w and w_a from SNAP, depending on knowledge of shear calibration (left) and mean redshift in phot-z redshift slices (right) – combining 2nd- and 3rd-order statistics **very** useful: self-calibration

from Huterer et al. (2005)

There's more than shearing galaxies

- Shearing the CMB
- Shearing the (pre-)reionization 21 cm radiation (e.g., SKA)
- Flexion galaxies (arclets)

Implications

In order to turn cosmic shear into a tool for precision cosmology, we need

- an imaging survey across a major fraction of the sky,
  $\Rightarrow$ telescope/camera(s) with large throughput
- with well behaved imaging properties (stable PSF),
  $\Rightarrow$ excellent site, or better: space
- with reliable and well-calibrated photo-z's,
  $\Rightarrow$ multi-color data needed,
  $\Rightarrow$ major spectroscopic effort required
- with an appreciable depth, both for large n and for independent redshift bins,
  $\Rightarrow$ implications for exposure time,
  $\Rightarrow$ NIR-photometry needed, which can **only** be done from space.
- Reliable theoretical predictions
  $\Rightarrow$ major ray-tracing-through-simulated-density-field efforts required.