Cosmic shear as a probe of precision cosmology

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Overview

Introduction

Very weak lensing in the CFHTLS-Wide

Effects of galaxy clustering on the shear signal

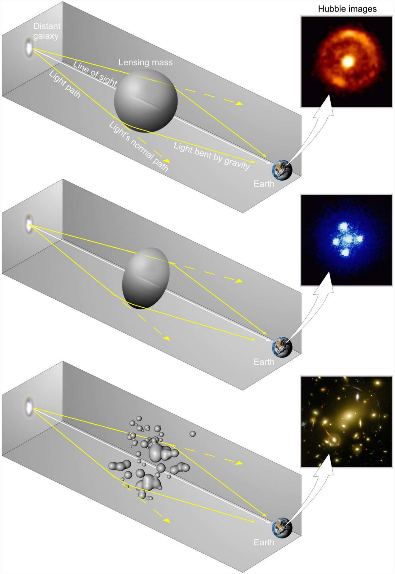
Combining Weak lensing, SNIa and CMB

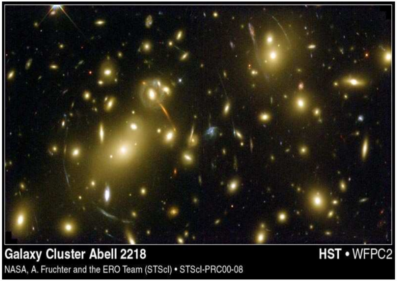
Questions to the Universe . . .

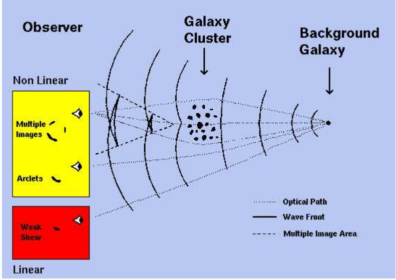
. . . that cosmic shear can help to answer:

- Composition and geometry of the Universe: $H(z)$, $d_{\mathrm{A}}(z)$
- Growth of structure: $G(z)$
- Nature of dark energy: $w = p/(\rho c^2) = -1$? const?, Quintessence
- Initial conditions: n_{s}, inflation
- Amplitude of density fluctuations: σ_8, A_s

Gravitational lensing: strong & weak

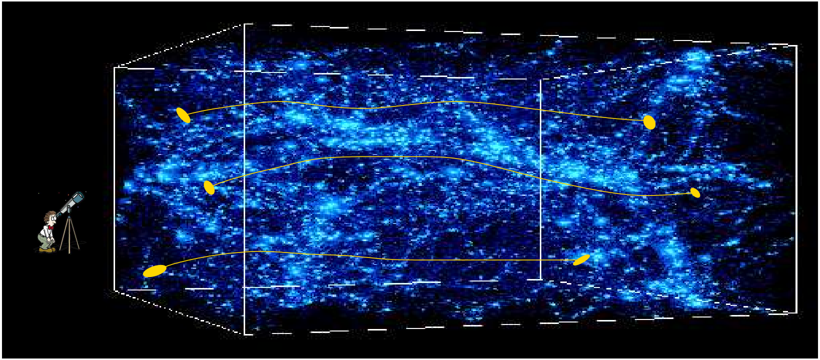




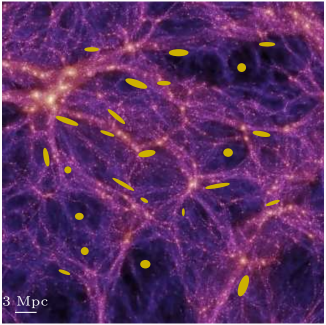


Principle of cosmic shear

- Light from distant galaxies is continuously deflected on its way through an inhomogeneous Universe
- Light bundles are differentially distorted due to gravitational lensing by tidal field of large-scale structure



- Images of galaxies are coherently distorted leading to shape correlations which depend on statistical properties of LSS
- Probes total (dark+luminous) matter, no tracer for dark matter needed
- Distortions are very small (weak lensing regime), can be detected only statistically using large number of galaxies

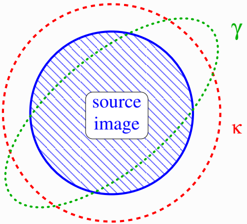


“Cosmic shear”

Convergence and shear

Effect of lensing

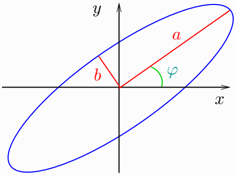
- isotropic magnification (convergence κ)
- anisotropic stretching (shear γ)



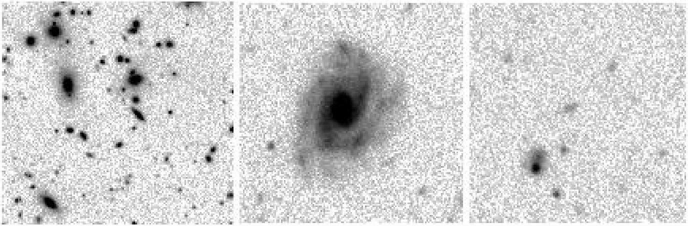
Shear transforms a circle into an ellipse.
Define complex ellipticity

$$\gamma = \gamma_1 + \mathrm{i}\gamma_2 = |\gamma| \mathrm{e}^{2\mathrm{i}\varphi};$$

$$|\gamma| = |1 - \kappa| \frac{1 - b/a}{1 + b/a}$$



Typical faint, high-redshift galaxies [Y. Mellier]



Galaxies are not circles! Not even ellipses... However, "ellipticity" ε for any galaxy can be defined and measured.

Weak lensing regime

$\kappa \ll 1, |\gamma| \ll 1$

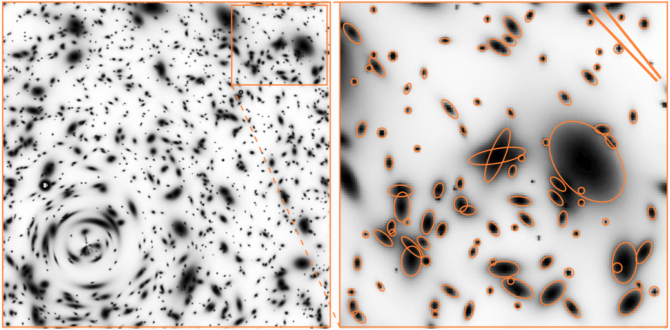
The observed ellipticity of a galaxy is the sum of the intrinsic ellipticity and the shear:

$$\boxed{\varepsilon \approx \varepsilon^{\mathrm{s}} + \gamma} \qquad \text{(complex sum)}$$

Random intrinsic orientation of galaxies

$$\langle \varepsilon^{\mathrm{s}} \rangle = 0 \quad \longrightarrow \quad \boxed{\langle \varepsilon \rangle = \gamma}$$

The observed ellipticity is an unbiased estimator of the shear. Very noisy though! $\sigma_\varepsilon = \langle |\varepsilon^{\mathrm{s}}|^2 \rangle^{1/2} \approx 0.3 - 0.4 \gg \gamma$. Beat down noise by averaging over large number of galaxies.



Distortion of background galaxy images due to foreground mass

Typical numbers

Regime	γ	$\gamma/\sigma_\varepsilon$	$N_{\rm gal}$ for S/N~ 1
weak lensing by clusters	0.03	0.1	10^2
galaxy-galaxy lensing	0.003	0.01	10^4
cosmic shear	0.001	0.003	10^5

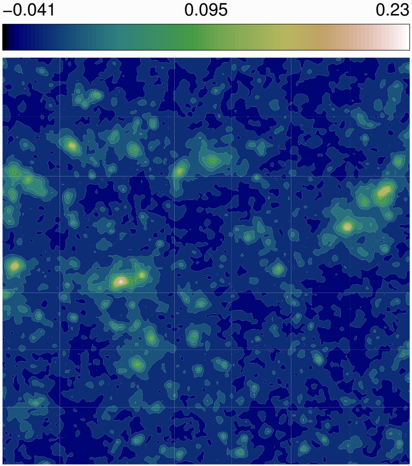
Much more galaxies for precision measurements needed.

Cosmic shear galaxy surveys

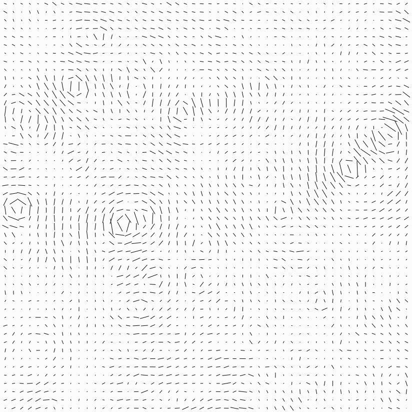
$n_{\rm gal}$ [arcmin^{-2}]	10 – 30	(from ground)
	60 – 100	(from space)

Area:	past:	from < 1 deg^2 to ≈ 100 deg^2.
	ongoing:	Subaru (33 deg^2), DLS (36 deg^2), CFHTLS-Wide (170 deg^2)
	future:	DES, KIDS, SNAP (1000–5000 deg^2), Pan-STARRS-4, LSST, DUNE (20 000 deg^2)

convergence κ



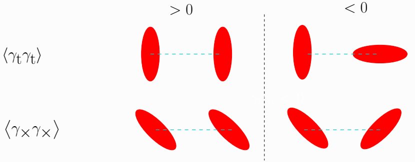
shear γ



Source galaxies at $z = 1$, ray-tracing simulations by T. Hamana

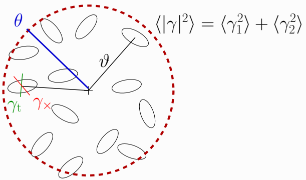
Second-order shear observables

Two-point correlation function $\xi_\pm$



$$\xi_+(\vartheta) = \langle \gamma_\mathrm{t} \gamma_\mathrm{t} \rangle (\vartheta) + \langle \gamma_\times \gamma_\times \rangle (\vartheta)$$
$$\xi_-(\vartheta) = \langle \gamma_\mathrm{t} \gamma_\mathrm{t} \rangle (\vartheta) - \langle \gamma_\times \gamma_\times \rangle (\vartheta)$$

Top-hat shear variance

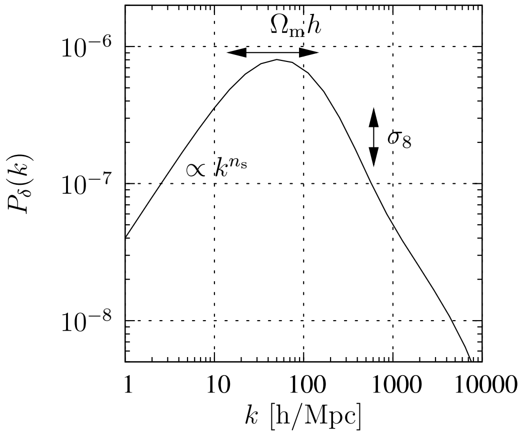


$$\left\langle |\gamma|^2 \right\rangle (\theta) = \int \mathrm{d}^2\vartheta \, |\gamma|^2(\vartheta)$$

Aperture-mass dispersion

Dispersion of weighted tangent. shear $M_\mathrm{ap}(\theta) = \int \mathrm{d}^2\vartheta \, Q_\theta(\vartheta) \gamma_\mathrm{t}(\boldsymbol{\vartheta})$

Cosmic shear and cosmology



All second-order statistics probe the power spectrum P_κ (P_δ).

$$\langle \kappa^2(\theta) \rangle^{1/2} = \langle \gamma^2(\theta) \rangle^{1/2} \approx 0.01\, \sigma_8\, \Omega_{\rm m}^{0.8} \left(\frac{\theta}{1\rm deg} \right)^{\frac{-(n+2)}{2}} z_0^{0.75}$$

Very weak lensing in the CFHTLS-Wide

L. Fu et al. 2008, A&A in press (astro-ph/0712.0884)

Collaboration:

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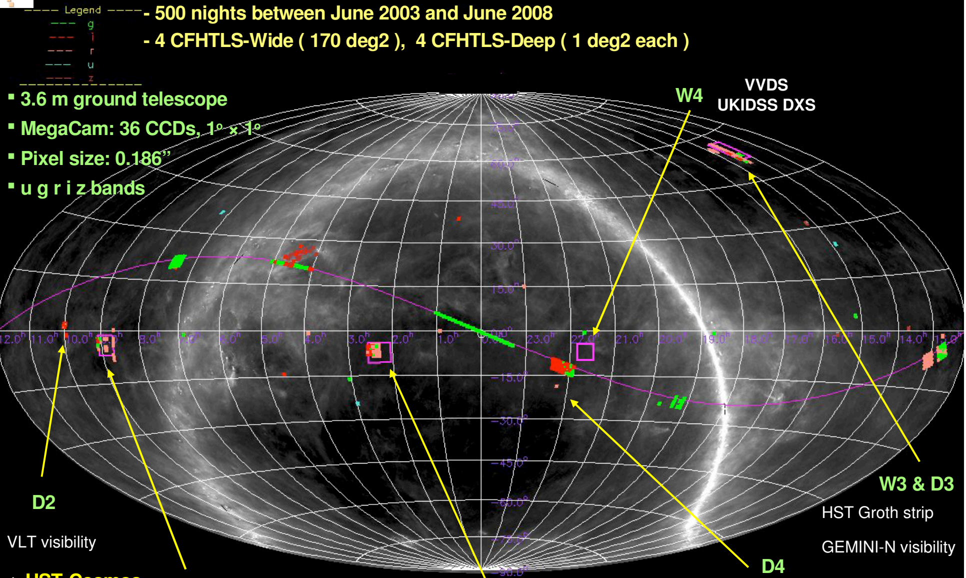
	H.J. McCracken		
		U Waterloo	M. Hudson
AIfA Bonn	E. Semboloni		
	I. Tereno		

Canada-France-Hawaii Telescope Legacy Survey: Canada-France collaboration

- 500 nights between June 2003 and June 2008
- 4 CFHTLS-Wide (170 deg2), 4 CFHTLS-Deep (1 deg2 each)

- 3.6 m ground telescope
- MegaCam: 36 CCDs, 1° x 1°
- Pixel size: 0.186"
- u g r i z bands



W4
VVDS
UKIDSS DXS

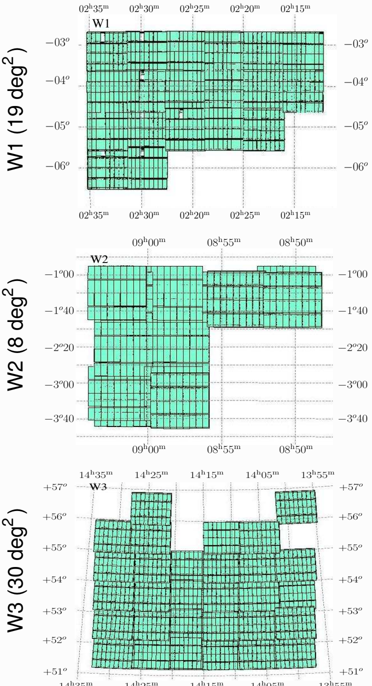
D2
VLT visibility
+ HST-Cosmos

W2
VLT visibility

W1 & D1
VLT visibility + XMM fields

D4
VLT visibility +
Quasar field

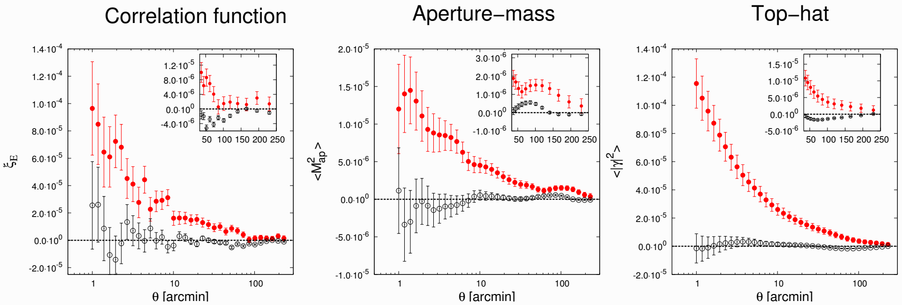
W3 & D3
HST Groth strip
GEMINI-N visibility



CFHTLS Wide, 3rd data release (T0003)

- 57 deg^2 (effective area 35 deg^2)
- $21.5 \leq i_{AB} \leq 24.5$
- $n_{\rm eff} = 12$ galaxies/arcmin^2
- 2.5×10^6 galaxies for lensing
- largest separation $\sim 470'$, nearly 8 degrees

Very weak lensing measurements



- Shear measurement between 1 and 230 arcmin
- B-modes consistent with zero on most scales
- B-mode “bump” at 100 arcmin, origin?

PSF effects

We need to measure galaxy shapes to percent-level accuracy.

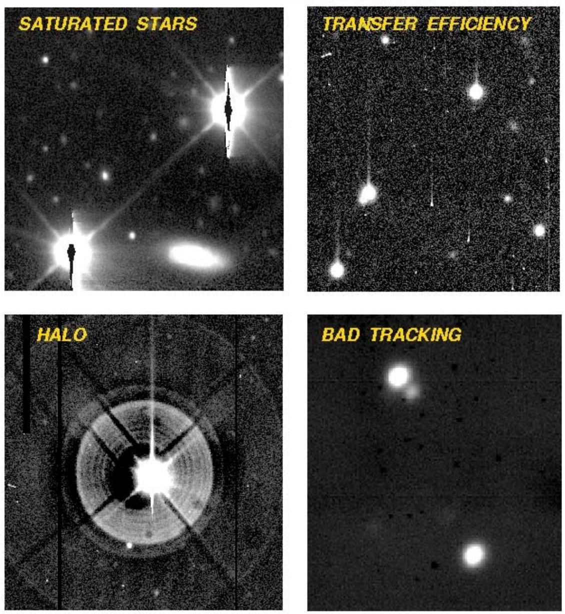
Galaxies are faint ($I > 21$), small ($\gtrsim$ arcsec = few pixel) and are

1. smeared by seeing
2. distorted by instrumental imperfections: defocusing, abberation, coma etc., tracking errors, chip not planar, image coaddition

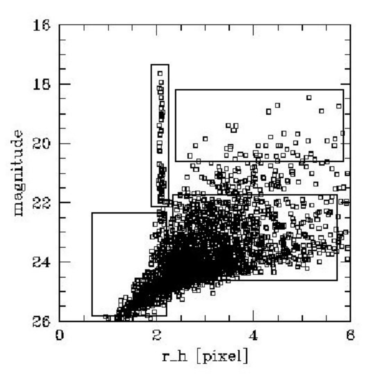
These distortions are much larger than the cosmic shear signal!

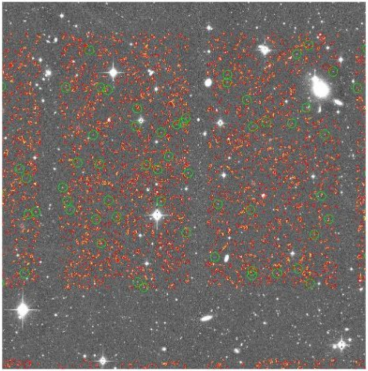
We have to correct for PSF effects.

Example of star images



Object selection

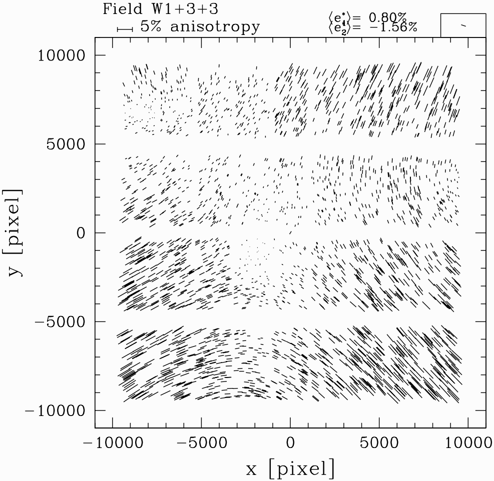




CFHTLS Wide [I. Tereno]

From size-magnitude diagram select galaxies and stars.

PSF pattern



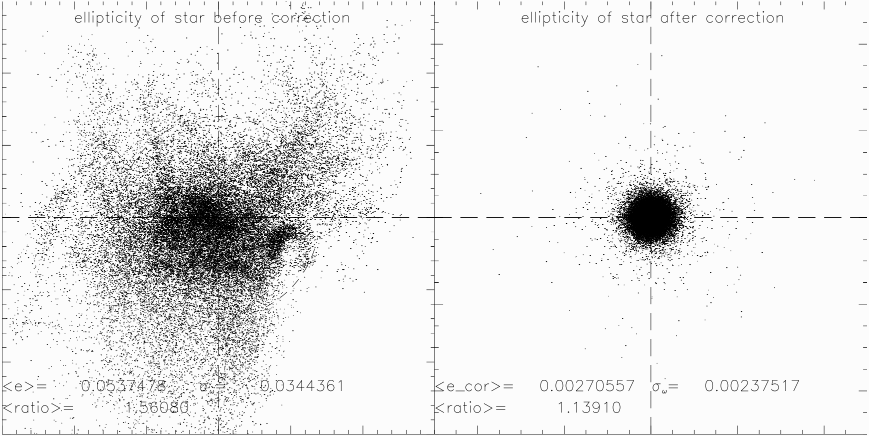
PSF correction works if

- PSF pattern is smooth (can be fitted by simple function)
- star density is high enough ($\sim$ 10-20 stars per chip)

[Hoekstra et al. 2006]

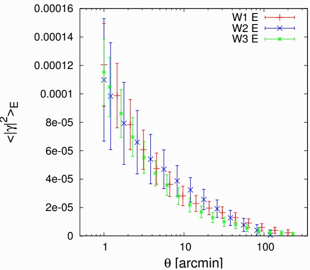
Star ellipticity

All CFHTLS-Wide pointings

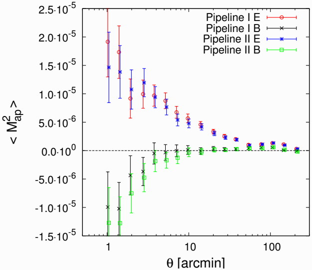


Cross-checking

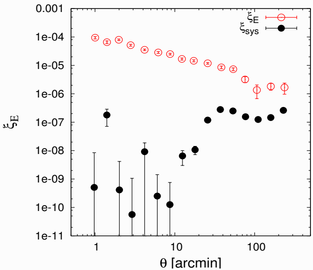
W1, W2, W3



Two pipelines

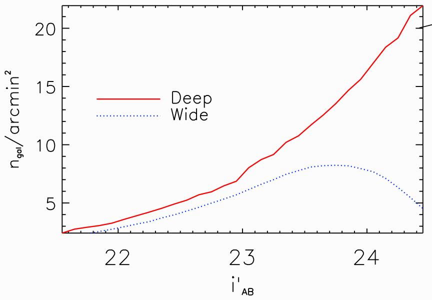


PSF residuals



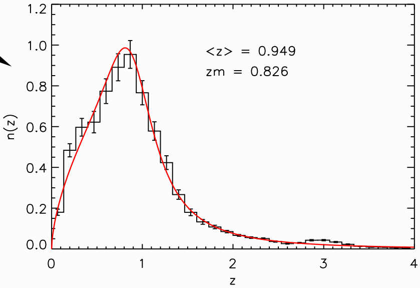
The lensing signal is robust, reliable; systematics are well under control

Redshift distribution



CFHTLS−Deep:

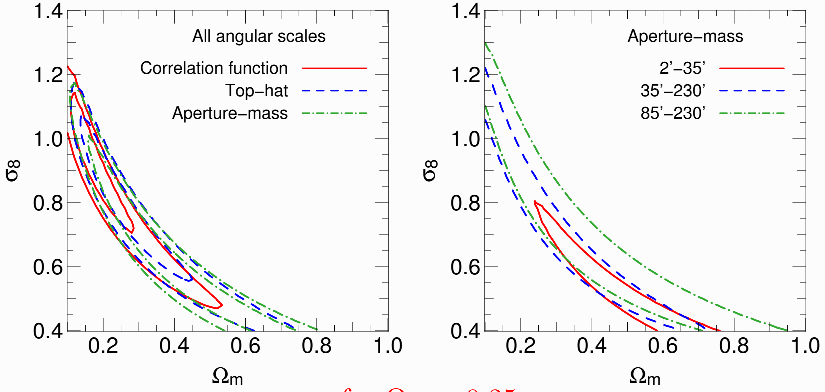
318,776 galaxies with photo−zs from u*g'r'i'
calibrated with 3241 VVDS spectra
[Ilbert et al. 2006]



CFHTLS−Wide redshift distribution

error bars: – photo−z uncertainty
– Poisson noise
– cosmic variance

Constraints on Ω_m and σ_8



σ_8 for $\Omega_m = 0.25$:

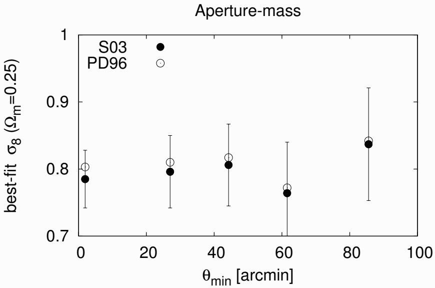
0.784 ± 0.049	for	ξ_E	0.780 ± 0.044	$(2' < \theta < 35')$
0.795 ± 0.042	for	$\langle \lvert\gamma\rvert^2 \rangle_E$	0.780 ± 0.060	$(35' < \theta < 230')$
0.785 ± 0.043	for	$\langle M_{ap}^2 \rangle$	0.837 ± 0.084	$(85' < \theta < 230')$

Constraints on large scales

Measurement $\sigma_8 = 0.837 \pm 0.084$ ($\Omega_m = 0.25$) on scales $85' < \theta < 230'$ obtained in the linear regime.

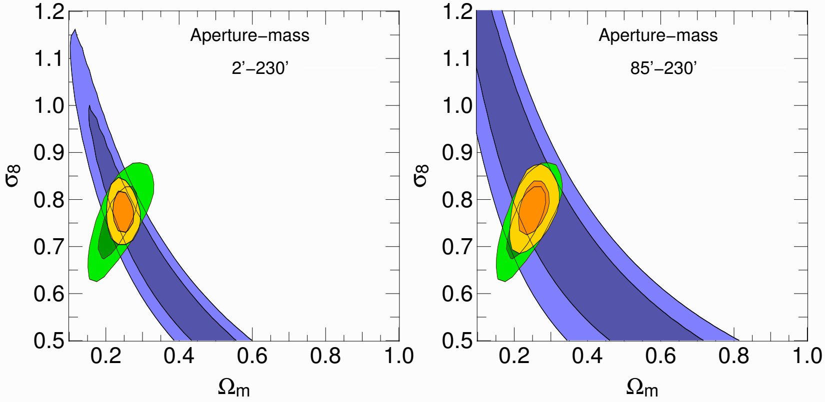
Insensitive against

- non-linear physics
- baryonic physics
- intrinsic galaxy alignment



However, more sensitive to PSF residuals because signal is small, correlations across pointings

Combination with WMAP3



all scales

$$\Omega_\mathrm{m} = 0.248 \pm 0.019$$
$$\sigma_8 = 0.771 \pm 0.029$$

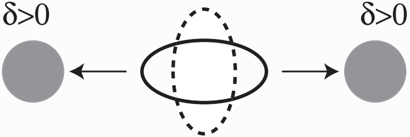
large scales, linear regime

$$\Omega_\mathrm{m} = 0.255 \pm 0.027$$
$$\sigma_8 = 0.782 \pm 0.038$$

Intrinsic alignment (shape-shape correlation, II)

Correlation of intrinsic galaxy orientation mimics a shear signal

Shape-shear correlation (GI)



Shape of foreground galaxy anti-correlated with shear of background galaxy → decreases cosmic shear signal

[Hirata et al. 2004, 2007]

Intrinsic alignment (II)

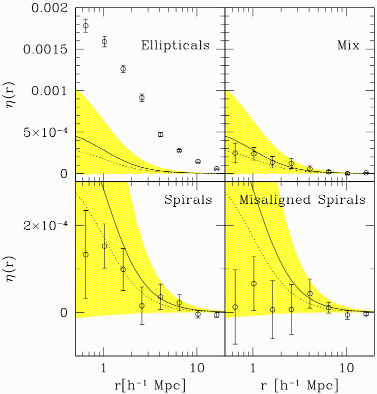
- Detection in COMBO-17 [Heymans et al. 2004]
- Non-detection in SDSS, $II \lesssim 0.15\, GG$ at $\theta < 3'$ [Hirata et al. 2004]
- Can be separated from lensing signal by excluding close physical pairs (need photo-zs!)

Shape-shear correlation (GI)

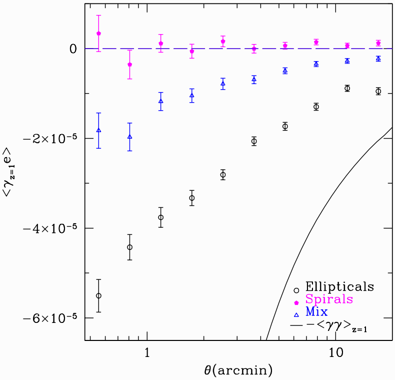
- Measured in SDSS [Hirata et al. 2004, 2007]
- $\lesssim$ 10% of GG at all scales?
- Difficult to separate from GG. Need many z-bins [Joachimi et al. in prep.]

Measurements and simulations

Intrinsic alignment II



Shape-shear correlation GI



[Heymans et al. 2006, Mandelbaum et al. 2006]

Shape-shear correlation in CFHTLS-Wide

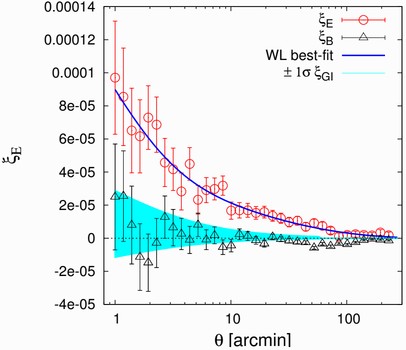
Simple model

$$\xi_{\mathrm{GI}}(\theta) = \mathcal{E}\frac{A}{\theta + \theta_0}; \quad \theta > 60'$$

Lensing efficiency $\mathcal{E}$ is integral over galaxy redshift distribution weighted by geometrical factors

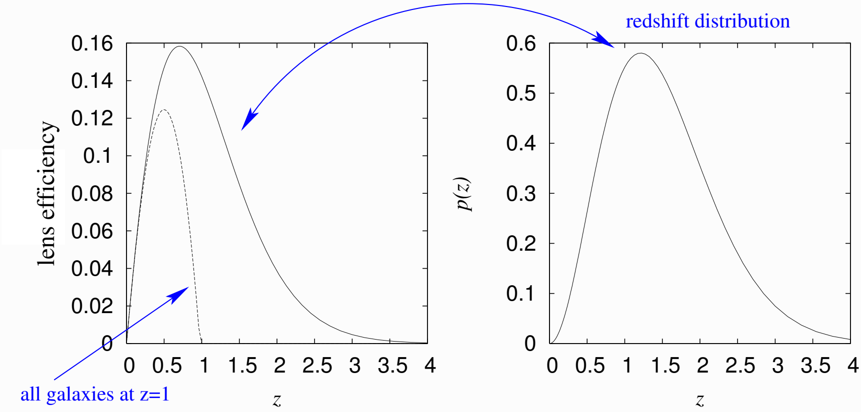
We fix $\theta_0 = 1'$ and determine GI amplitude A by fitting WL + GI models to data:

$$A = 2.2^{+3.8}_{-4.6}$$



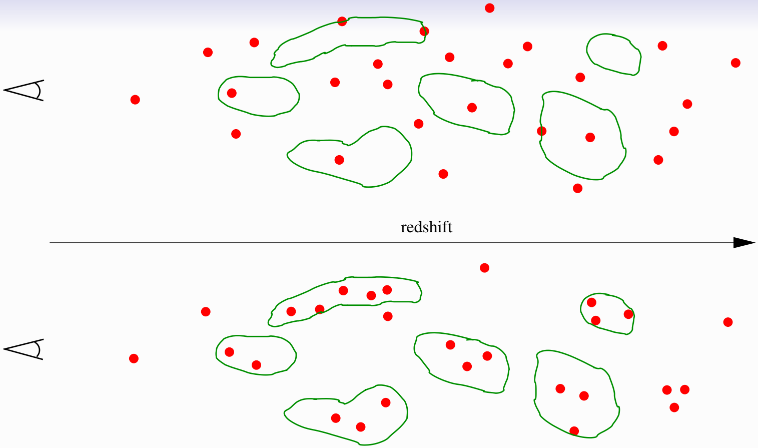
Effects of galaxy clustering on the shear signal

Galaxy distribution



$$\text{lensing signal} = \int_0^{z_{\mathrm{lim}}} \text{lens efficiency(z)}\ \delta(z)$$

lens efficiency = geometrical factors weighted by source galaxy redshift distribution



Galaxies not distributed homogeneously but cluster:
$p(z) = p(\boldsymbol{\theta}, z)$

- Different lines of sight probe LSS at different depths
- Additional dispersion which contaminates lensing signal
- Amplitude depends on the galaxy bias

Source-source clustering (SSC)

- SSC $\propto$ galaxy-galaxy correlation, observable

Source-lens clustering (SLC)

- Foreground (“lens”) and background (“source”) structures overlap
- SLC $\propto$ galaxy-dark matter correlation, not observable!
- SLC contamination very high for cosmic shear skewness

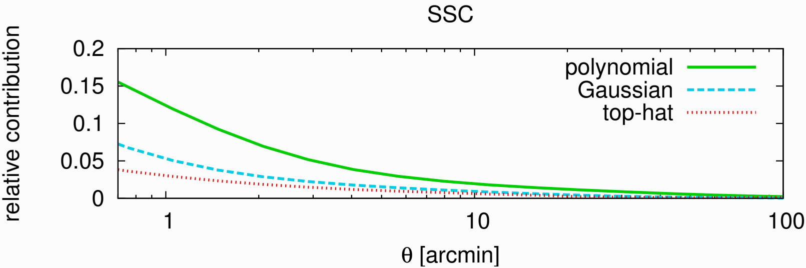
Bias model

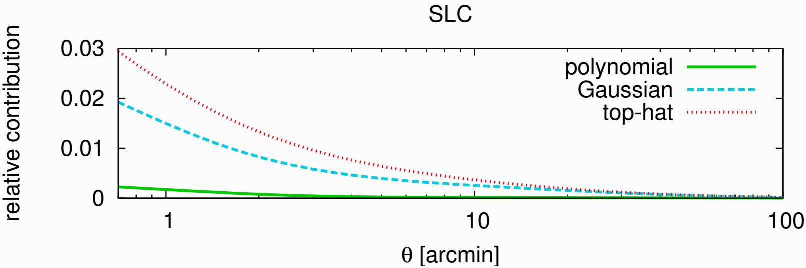
Linear deterministic bias $b = b_0(1+z)^\gamma$

(Later: measure bias from semi-analytical simulations)

Theoretical expectations I

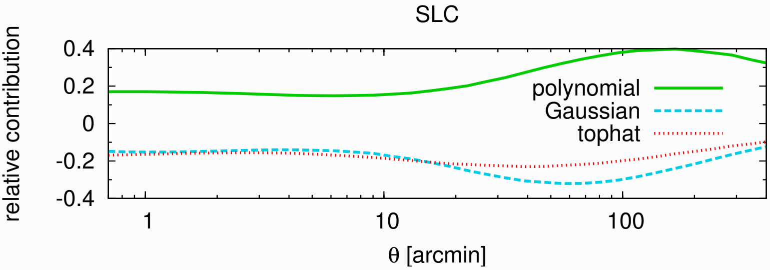
Second-order statistics (variance)



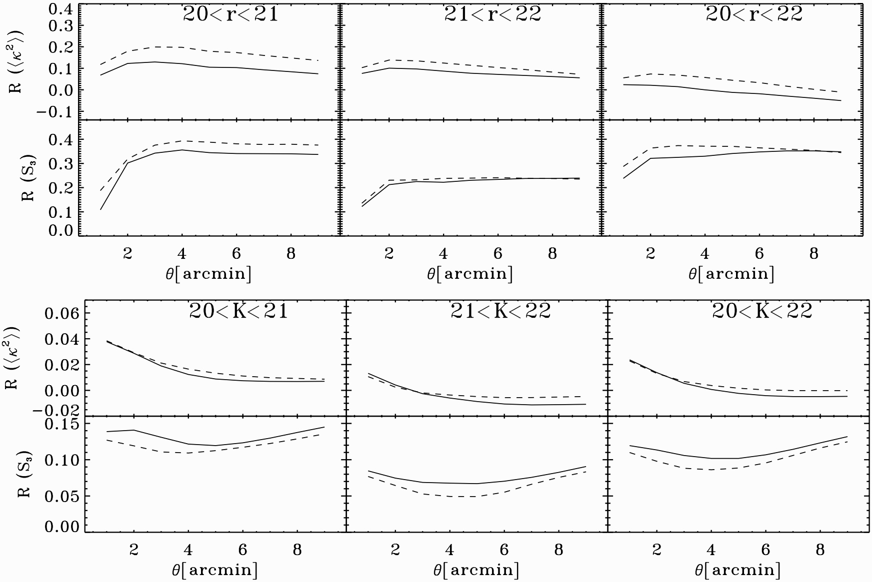


Theoretical expectations II

Third-order statistics (skewness)

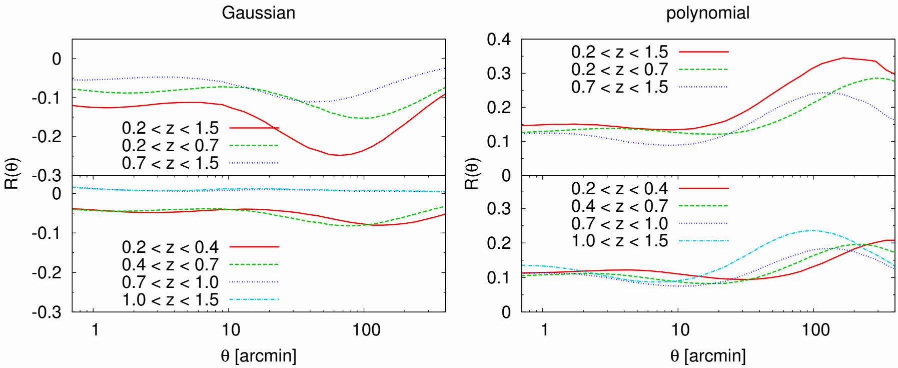


SLC compared to simulations



[Forero-Romero et al. 2007]

Reducing SLC skewness: redshift binning



Reducing the overlap between sources and lenses.

Combining weak lensing with other cosmological experiments

Improving cosmological parameters constraints

… together with I. Tereno, K. Benabed, P. Astier, J. Guy

Combining…

- Cosmic shear (CFHTLS-Wide)
- CMB (WMAP3)
- Supernovae Ia (SNLS)

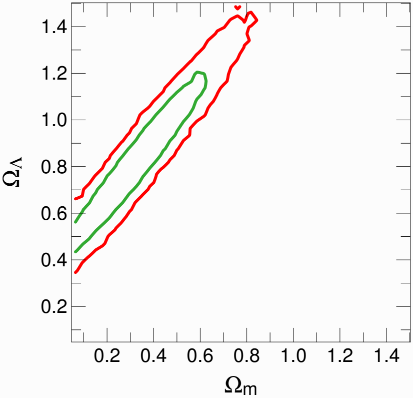
SNLS [Astier et al. 2006]

- CFHTLS-Deep 1$^{\text{st}}$ year data, spectroscopic follow-up (VLT, Gemini, Keck), 118 SN up to $z = 1$
- Full treatment of nuisance parameters (photometric calibration, filter curve uncertainties)
- Correlation of nuisance and cosmological parameters

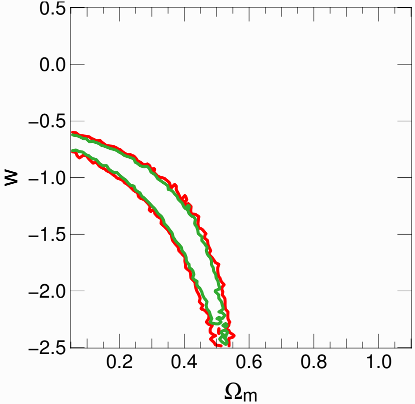
First results

SNIa alone

ΛCDM model ($w = -1$)

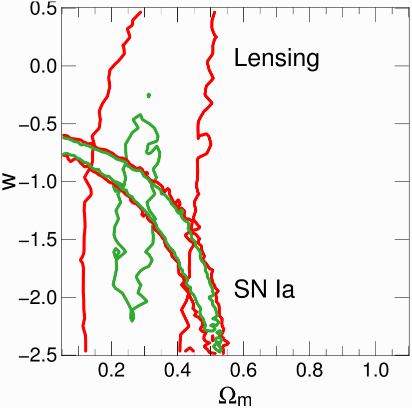


flat ΛCDM model



First results

flat ΛCDM model



+ WMAP3 prior on σ_8

Outlook

- CFHTLS-Wide T0004: 30 square degree in 5 optical bands, photo-zs for all galaxies: shear tomography
- Combining weak lensing with other probes will provide tight constraints on dark energy (quintessence, early dark energy), primordial spectral index $n_{\rm s}$, massive neutrinos
- CFHTLS best data set for cosmic shear

Merci et Joyeuses Fêtes!