Gravitational Lensing

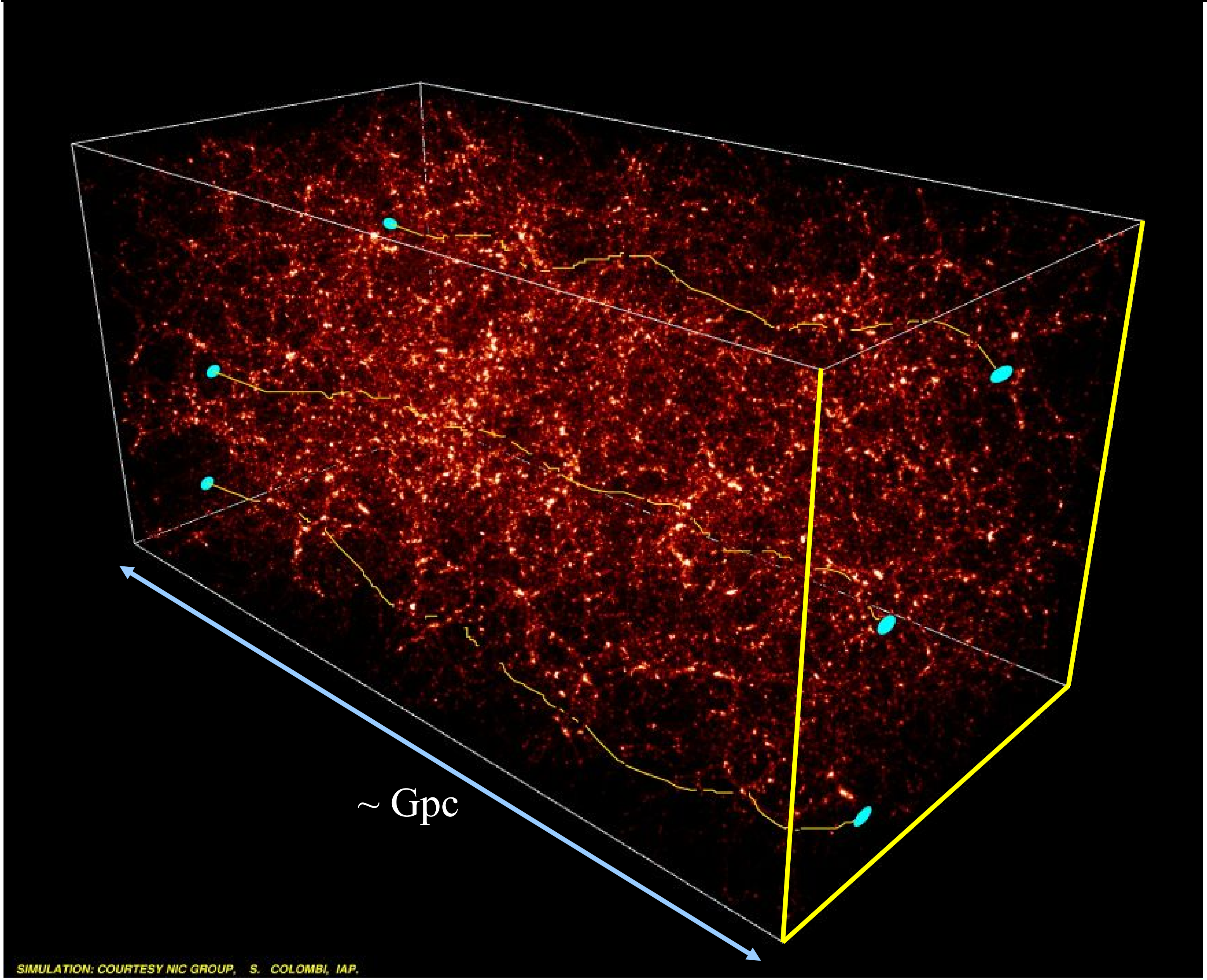
Yannick Mellier

IAP and Obs. de Paris / LERMA

V. Gravitational Lensing:

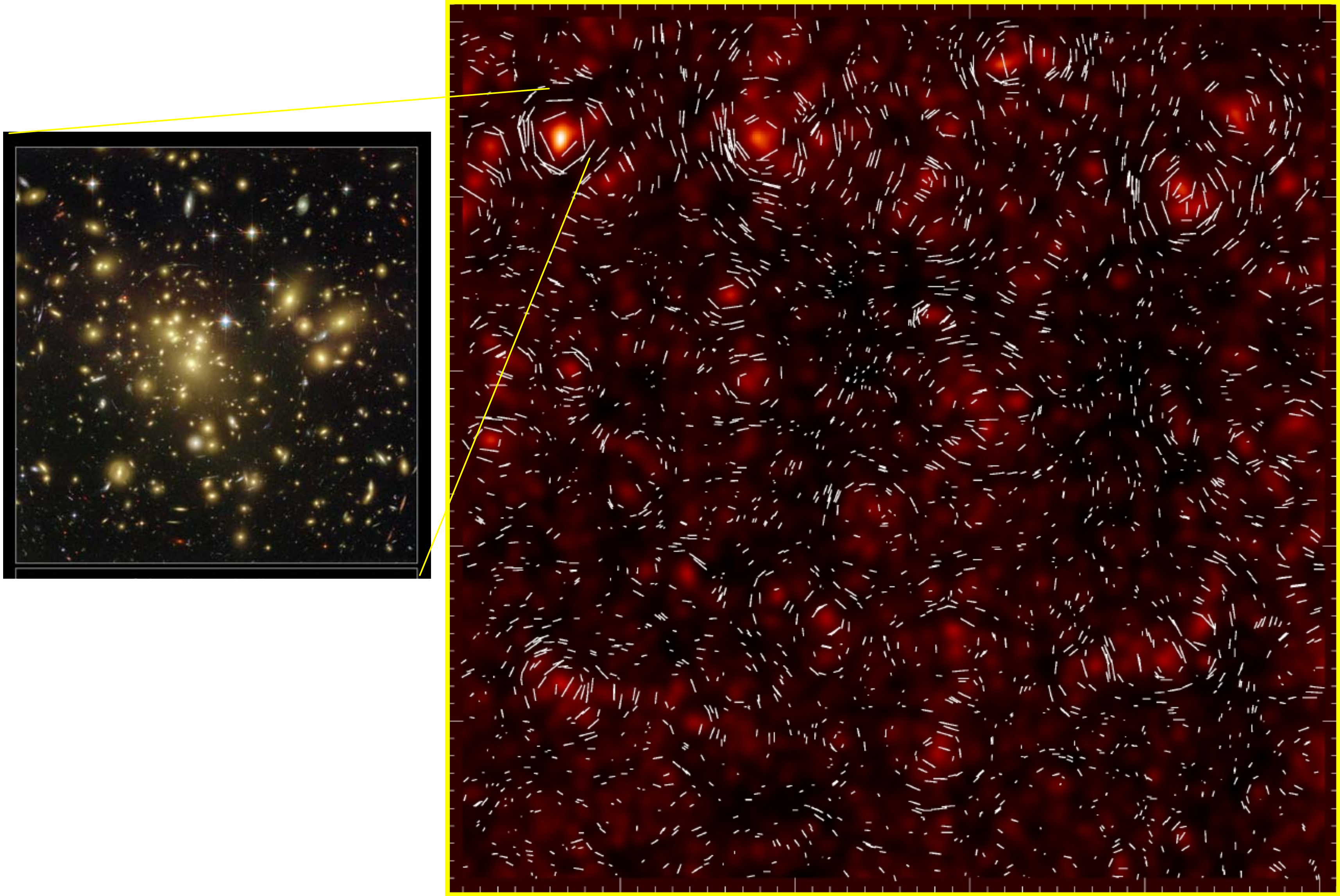
Cosmological weak lensing (cosmic shear)

Cosmic shear : propagation of light through the cosmic web

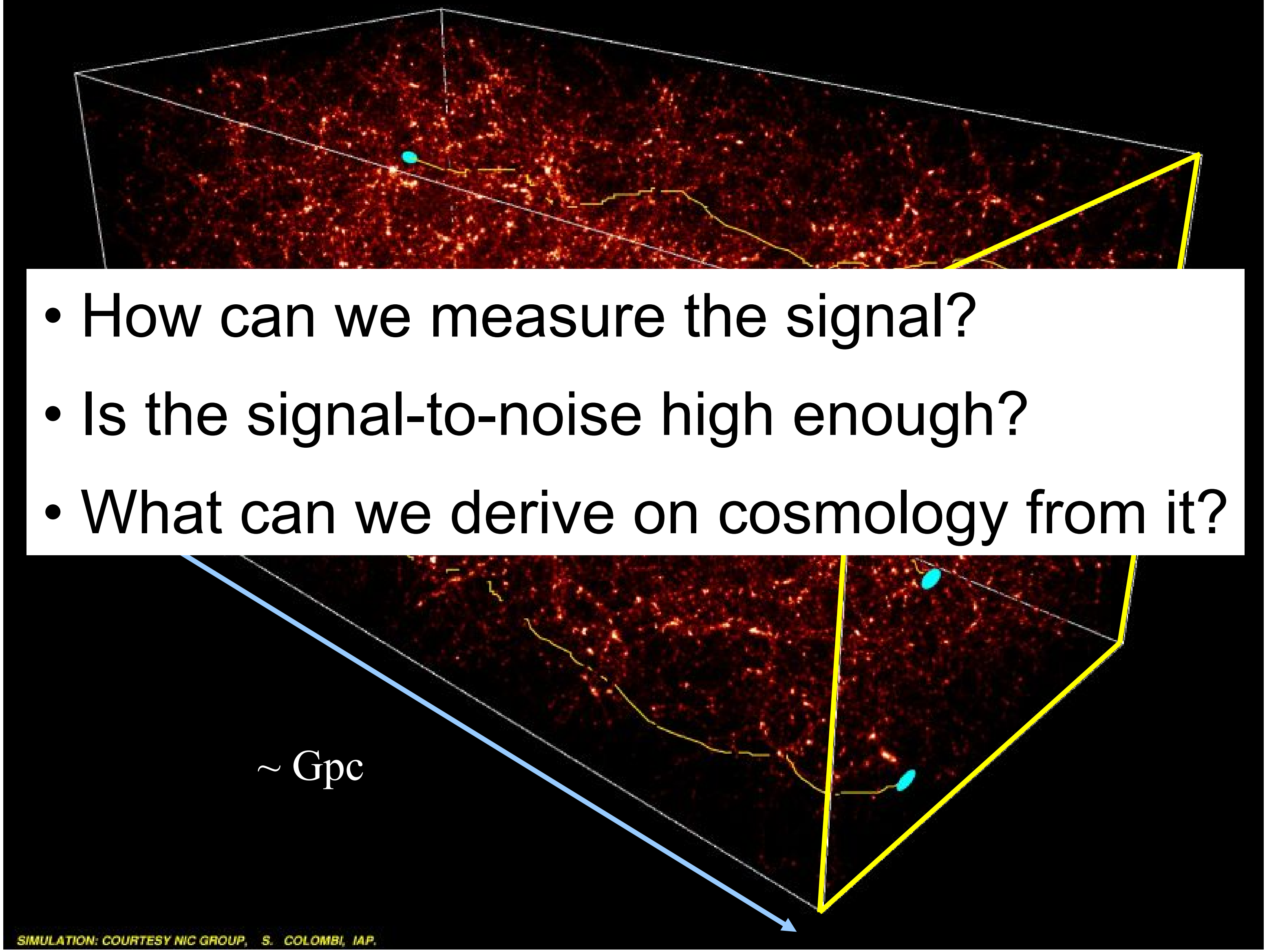


SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

Cosmological distortion field projected on the sky



Cosmic shear : propagation of light through the cosmic web



SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

- How can we measure the signal?
- Is the signal-to-noise high enough?
- What can we derive on cosmology from it?

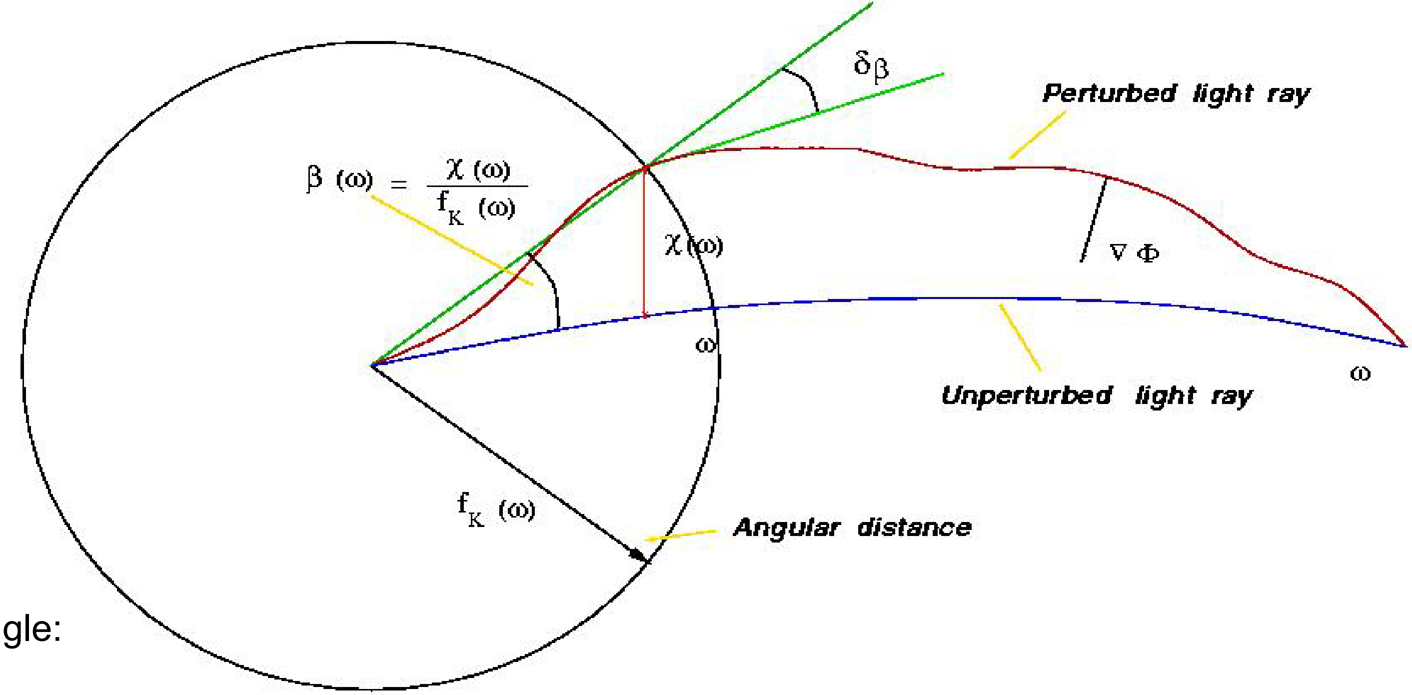
Cosmological Weak Lensing:

Theoretical expectations

Weak gravitational lensing and cosmology:

Light propagation in inhomogeneous universes

$$ds^2 = c^2 dt^2 - a^2(t)\,[dw^2 + f_K^2(w)\, d\omega^2]$$



Deflection angle:

$$\boldsymbol{\alpha} = -\frac{2}{c^2}\int_S^O \boldsymbol{\nabla}_\perp \Phi \, dl \, .$$

Blandford et al 1991, Miralda-Escudé 1990, Kaiser 1992, Bernardeau, van Waerbeke & Mellier, 1997, Jain & Seljak 1997

Weak gravitational lensing and cosmology: Light propagation in inhomogeneous universes

- Express the light propagation in a homogeneous and isotropic universe
- Include the effects of (small) perturbations
- Compute of the deflection angle, κ, γ as a function of $\delta = \frac{\delta\rho}{\rho}$, Ω, λ
- Then, infer $P_\kappa(k)$ and $P_\delta(k)$
- Analyse the sensitivity to cosmological quantities and propose an observational strategy

Weak gravitational lensing and cosmology:
Light propagation in inhomogeneous universes

Total deflection angle:

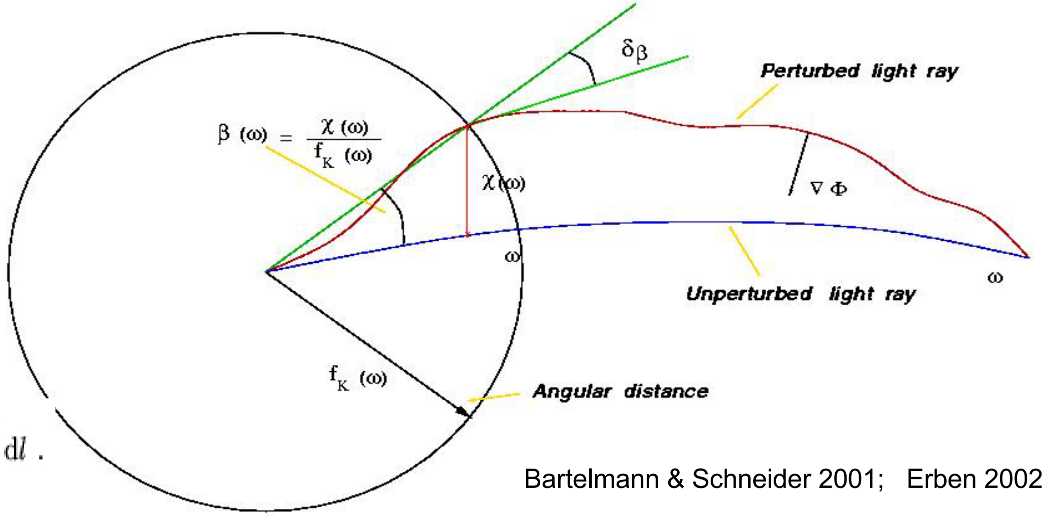
$$\vec{\alpha}\left(\vec{\theta};\omega\right)=\vec{\theta}-\vec{\beta}=\frac{2}{c^2}\int_0^{\omega}\frac{f_K\left(\omega-\omega'\right)}{f_K\left(\omega\right)}\vec{\nabla}_{\perp}\Phi\left(f_K\left(\omega'\right)\vec{\theta};\omega\right)\mathrm{d}\omega'$$

Total convergence:

$$\kappa_{eff}\left(\vec{\theta};\omega\right)=\frac{3\Omega_0 H_0^2}{2c^2}\int_0^{\omega}\frac{f_K\left(\omega-\omega'\right)f_K\left(\omega'\right)}{f_K\left(\omega\right)}\frac{\delta\left[f_K\left(\omega'\right)\vec{\theta};\omega'\right]}{a\left(\omega'\right)}\mathrm{d}\omega'$$

Weak gravitational lensing and cosmology:

$$ds^2=c^2dt^2 - a^2(t)\,[dw^2 + f_K^2(w)\,d\omega^2]$$



Bartelmann & Schneider 2001; Erben 2002

Deflection angle:

$$\alpha = -\frac{2}{c^2}\int_S^O \nabla_\perp \Phi \, dl \,.$$

$$\kappa_{eff} = \frac{3H_0^2\Omega_0}{2c^2}\int_0^\omega \overbrace{\frac{f_K(\omega-\omega')\,f_K(\omega')}{f_K(\omega)}}^{\text{Distances}}\;\overbrace{\frac{\delta\left[f_K(\omega')\,\boldsymbol{\theta};\omega'\right]}{a(\omega')}}^{\text{Power spectrum, growth rate of structure}}\,d\omega'$$

Both depend on the dark matter and dark energy content in the Universe

The convergence power spectrum

$$\boxed{P_\kappa(l) = \frac{9H_0^4\Omega_0^2}{4c^4}\int \frac{\bar{W}(\omega)^2}{a(\omega)} P_\delta\left(\frac{l}{f_K(\omega)};\omega\right)}$$

→ Power of the convergence at scale (1/*l*) :

Given by the 3-D power spectrum of the mass density fluctuation at scale $f_K(w)(1/l)$ integrated over *w* .

Relations between the convergence power spectrum and the shear power spectrum

We have

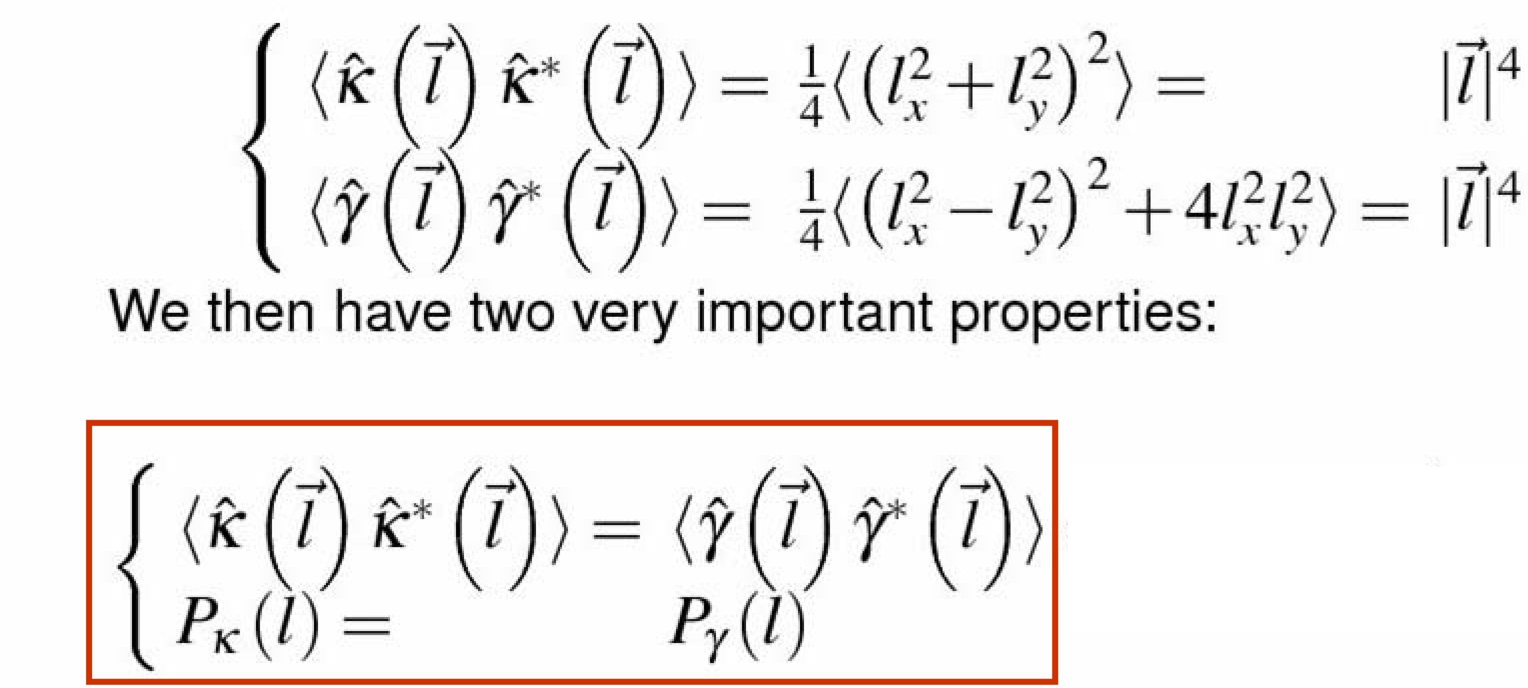
$$\begin{cases} \kappa = \frac{1}{2}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial yx^2}\right)\Psi \\ \gamma = \frac{1}{2}\left(\frac{\partial}{\partial x} + \mathrm{i}\frac{\partial}{\partial y}\right)^2\Psi \end{cases}$$

In Fourier space:

$$\begin{cases} \hat{\kappa} = \frac{1}{2}\left(l_x^2 + l_y^2\right)\hat{\Psi} \\ \hat{\gamma} = \frac{1}{2}\left(l_x^2 - l_y^2 + 2il_xl_y\right)\hat{\Psi} \end{cases}$$

Therefore

Relations between the convergence power spectrum and the shear power spectrum



$$\begin{cases} \langle \hat{\kappa}\left(\vec{l}\right) \hat{\kappa}^{*}\left(\vec{l}\right)\rangle = \frac{1}{4}\langle\left(l_x^2+l_y^2\right)^2\rangle = & |\vec{l}|^4 \\ \langle \hat{\gamma}\left(\vec{l}\right) \hat{\gamma}^{*}\left(\vec{l}\right)\rangle = \frac{1}{4}\langle\left(l_x^2-l_y^2\right)^2+4l_x^2l_y^2\rangle = & |\vec{l}|^4 \end{cases}$$

We then have two very important properties:

$$\boxed{\begin{cases} \langle \hat{\kappa}\left(\vec{l}\right) \hat{\kappa}^{*}\left(\vec{l}\right)\rangle = \langle \hat{\gamma}\left(\vec{l}\right) \hat{\gamma}^{*}\left(\vec{l}\right)\rangle \\ P_{\kappa}\left(l\right) = \qquad P_{\gamma}\left(l\right) \end{cases}}$$

Example of simple two-point statistics: the top-hat shear variance

Consider the mean shear inside a circular aperture of radius θ:

$$\bar{\gamma}_i(\theta) = \int_0^\theta \frac{\mathrm{d}^2\vec{\phi}^2}{\pi\theta^2}\gamma\left(\vec{\phi}\right)$$

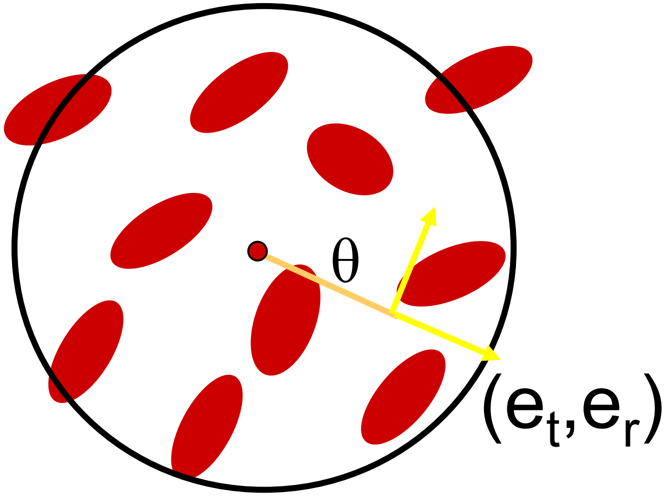
The shear variance inside the aperture is therefore:

$$\langle|\gamma|^2\rangle = \int_0^\theta \frac{\mathrm{d}^2\vec{\phi}^2}{\pi\theta^2}\int_0^\theta \frac{\mathrm{d}^2\vec{\phi}'^2}{\pi\theta^2}\langle\gamma\left(\vec{\phi}\right)\gamma^*\left(\vec{\phi}'\right)\rangle$$

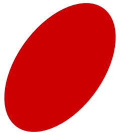
$$\langle|\gamma(\theta)|^2\rangle = 2\pi\int \boxed{P_\kappa(l)}\, l\,\mathrm{d}l\left(\frac{J_1(l\theta)}{\pi l\theta}\right)^2$$

Analysing the galaxy ellipticity: 2-points statistics

Map variance

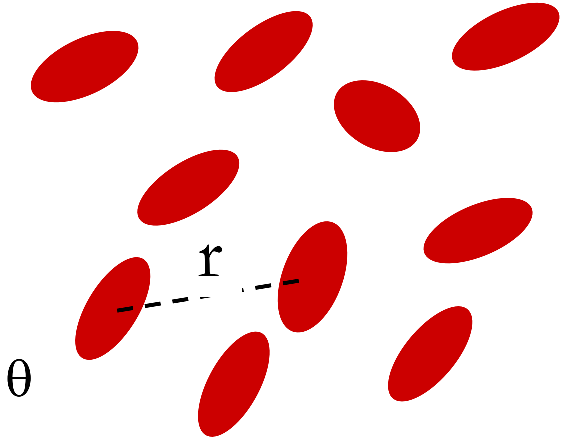


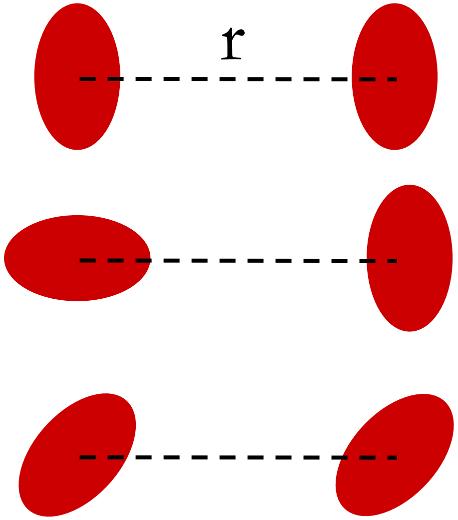
Top hat shear variance:



$\langle e^2 \rangle \sim \gamma^2$

Shear correlation functions:





$\langle \gamma_t \gamma_t \rangle > 0$

$\langle \gamma_t \gamma_t \rangle < 0$

$\langle \gamma_r \gamma_r \rangle > 0$

Cosmic Shear Statistics and Power Spectrum

(Blandford el al 1991, Miralda-Escudé 1991, Kaiser 1992, 1998, Bernardeau et al 1997, Jain & Seljak 1997, Schneider et al 1998)

- **Top-hat shear variance at scale θ_c:**

$$\langle\gamma^2\rangle = \frac{2}{\pi\theta_c^{\;2}}\int_0^\infty \frac{\mathrm{d}\,k}{k} P_\kappa(k)\,[\mathrm{J}_1(k\theta_c)]^2$$

- **Aperture mass (Map) variance at scale θ_c :**

$$\langle M_{ap}^{\;2}\rangle = \frac{288}{\pi\theta_c^{\;4}}\int_0^\infty \frac{\mathrm{d}\,k}{k^3} P_\kappa(k)\,[\mathrm{J}_4(k\theta_c)]^2$$

- **Shear correlation function at separation θ:**

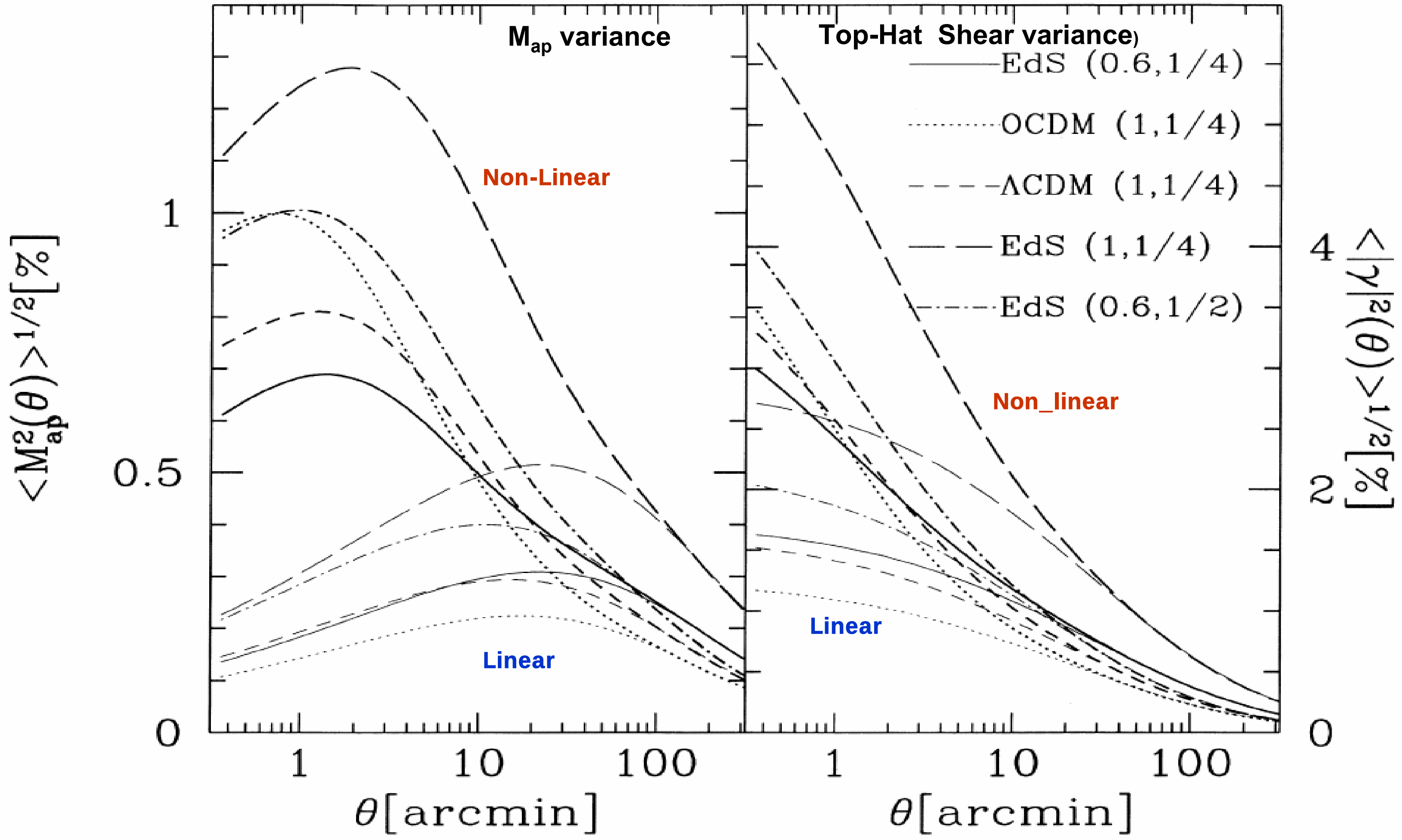
$$\langle\gamma(\mathrm{r})\gamma(\mathrm{r}+\theta)\rangle_\mathrm{r} = \frac{1}{2\pi}\int_0^\infty \mathrm{d}k\; k\; P_\kappa(k)\;\mathrm{J}_0(k\theta)$$

- **Convergence (projected mass) power spectrum:**

$$P_\kappa(k) = \frac{9}{4}\Omega_0^{\;2}\int_0^\infty \mathrm{d}\,z\;\;.\;\;\mathrm{P}_{3\mathrm{D}}\left(\frac{k}{D_L(z)};z\right)\;\;.\;\;\mathrm{F}\left[z,z_{\mathrm{source}}\right]^2$$

Shear Statistics : Theoretical Predictions

(Blandford el al 1991, Miralda-Escudé 1991, Kaiser 1992, 1998, Bernardeau et al 1997, Jain & Seljak 1997, Schneider et al 1998)



Bartelmann & Schneider 2001 : theoretical predictions from the gravitational instability scenario

Amplitude of the cosmic shear signal

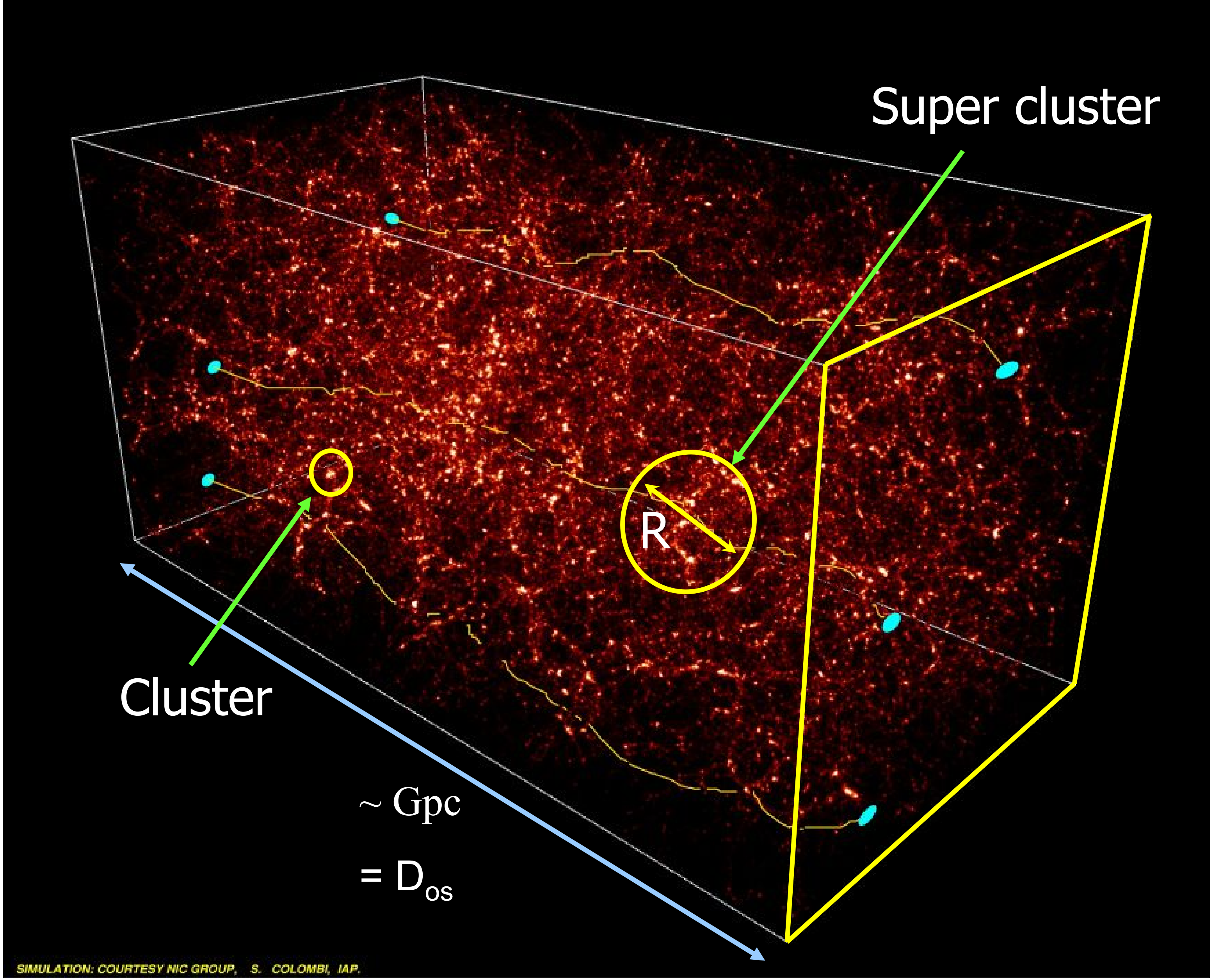
Properties of cosmic shear signal

Simple case, assuming a single lens plane and $P(k) \sim \sigma_8\, k^{n}$

$$\langle \kappa^2(\theta) \rangle^{1/2} \approx C \quad \sigma_8 \Omega_m^{0.8} \left(\frac{\theta}{1\mathrm{deg.}} \right)^{-\frac{n+2}{2}} \quad z_s^{0.75}$$

? …Amplitude of the lensing signal ?

Mean number of structures crossed by light beams?



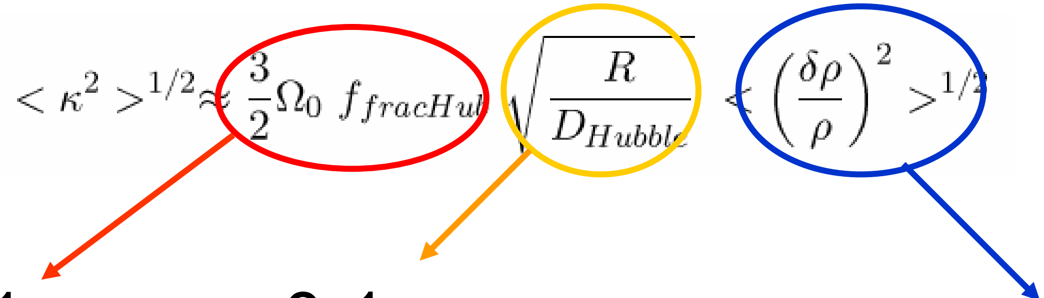
SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP.

Amplitude of cosmic shear signal

Amplitude for a single perturbation of size R………………. $\kappa \approx \frac{3}{2}\left(\frac{H_o}{c}\right)^2 \Omega_o \frac{D_{ol}\,D_{ls}}{D_{os}} \times R\frac{\delta\rho}{\rho}$

- Net magnification= random cumulative in all directions,
- After crossing N perturbations with typical size *R* ………………………… $N \approx \frac{D_{os}}{R},$

$$\kappa \approx \frac{3}{2}\left(\frac{H_o}{c}\right)^2 \Omega_o \frac{D_{ol}\,D_{ls}}{D_{os}} \times R\frac{\delta\rho}{\rho} \times \left(\frac{D_{os}}{R}\right)^{1/2}$$



$$< \kappa^2 >^{1/2} \approx \frac{3}{2}\Omega_0\ f_{fracHub}\sqrt{\frac{R}{D_{Hubble}}} < \left(\frac{\delta\rho}{\rho}\right)^2 >^{1/2}$$

~ 0.1 x ~ 0.1 for supercluster x ~ 1 : **1 %**

Properties of cosmic shear signal

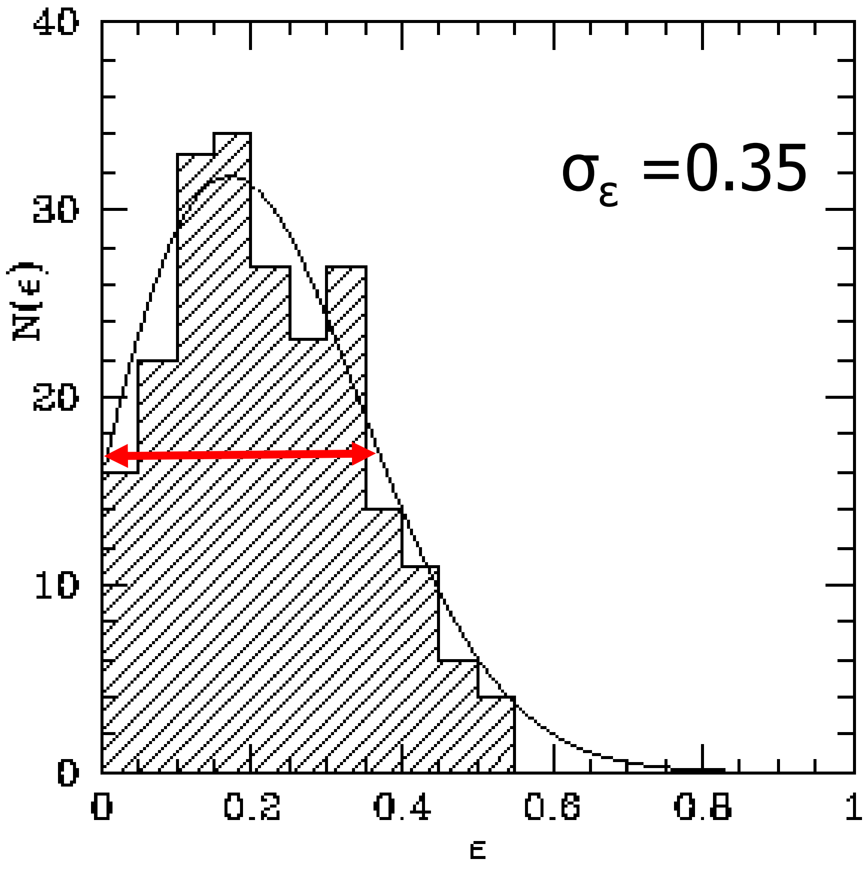
Simple case, assuming a single lens plane and P(*k*) ~ $\sigma_8 k^n$

$$\langle\kappa^2(\theta)\rangle^{1/2} \approx 0.01\ \sigma_8 \Omega_{\mathrm{m}}^{0.8} \left(\frac{\theta}{1\mathrm{deg.}}\right)^{-\frac{n+2}{2}} z_s^{0.75}$$

Amplitude of the lensing signal

If shear = ellipticity, then the S/N is basically a comparison with the intrinsic ellpiticity distribution of galaxies (projected on the sky)

Beating intrinsic ellipticity distribution



Assume a shear amplitude of 1%

- Minimum number of galaxies

$n_g = (0.35/0.01)^2$

- About 10000 galaxies just for 3-sigma detection

Summary

Simple case, assuming a single lens plane and P(*k*) ~ $\sigma_8\, k^n$

$$\langle \kappa^2(\theta)\rangle = \langle \gamma^2(\theta)\rangle$$

Gravitational convergence

From

ellipticities

Gravitational shear = ellipticity induced by gravitational lensing on galaxies

$$\langle \kappa^2(\theta)\rangle^{1/2} \approx 0.01\ \sigma_8 \Omega_{\mathrm{m}}^{0.8} \left(\frac{\theta}{1\mathrm{deg.}}\right)^{-\frac{n+2}{2}} z_s^{0.75}$$

Width of intrinsic ellipticity distribution of galaxies : ~ 30%

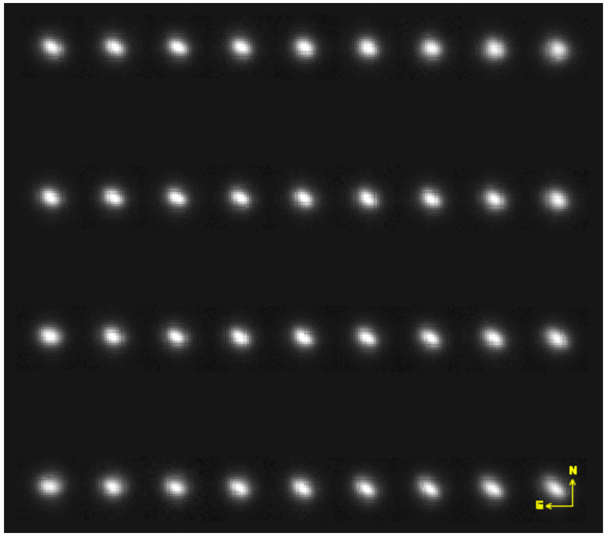
Contamination

Unfortunately…

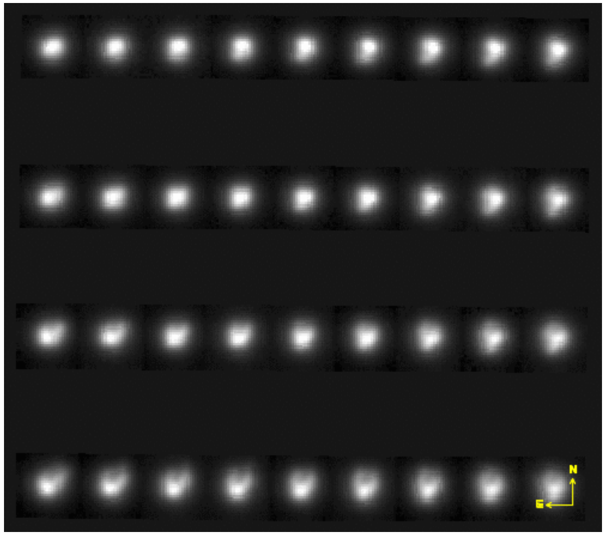
Gravitational ellipticity signal is contaminated by non-gravitational distortion

The MegaPrime Point Spread Function (PSF): anisotropic and isotropic contaminations

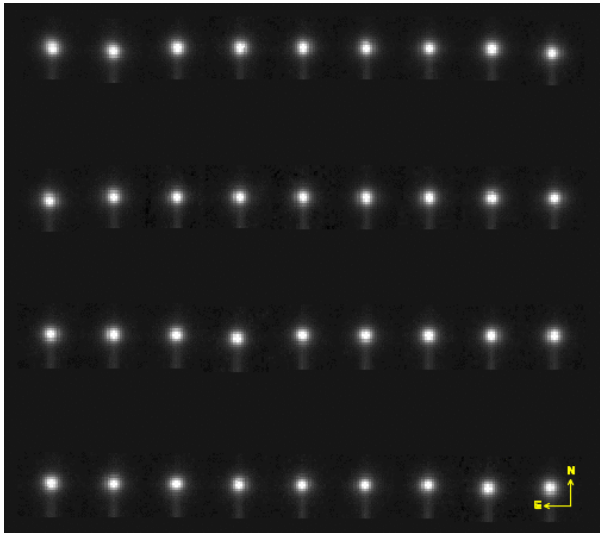
Telescope oscillating



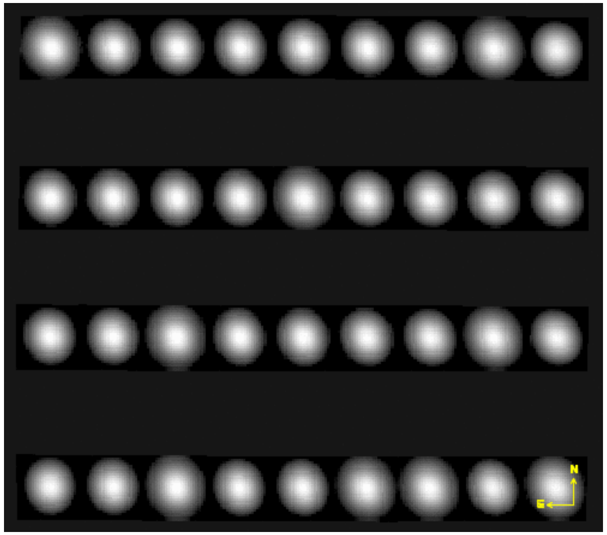
Telescope defocussed

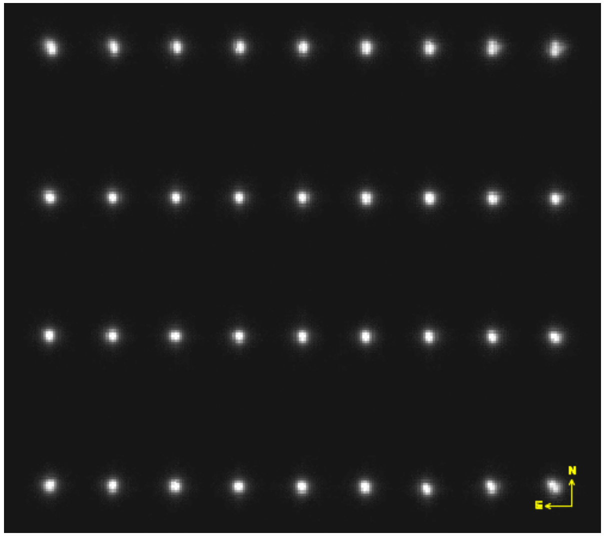


Telescope lost guiding



Seeing 2.5 ″





Seeing 0.55″

Correction : principle

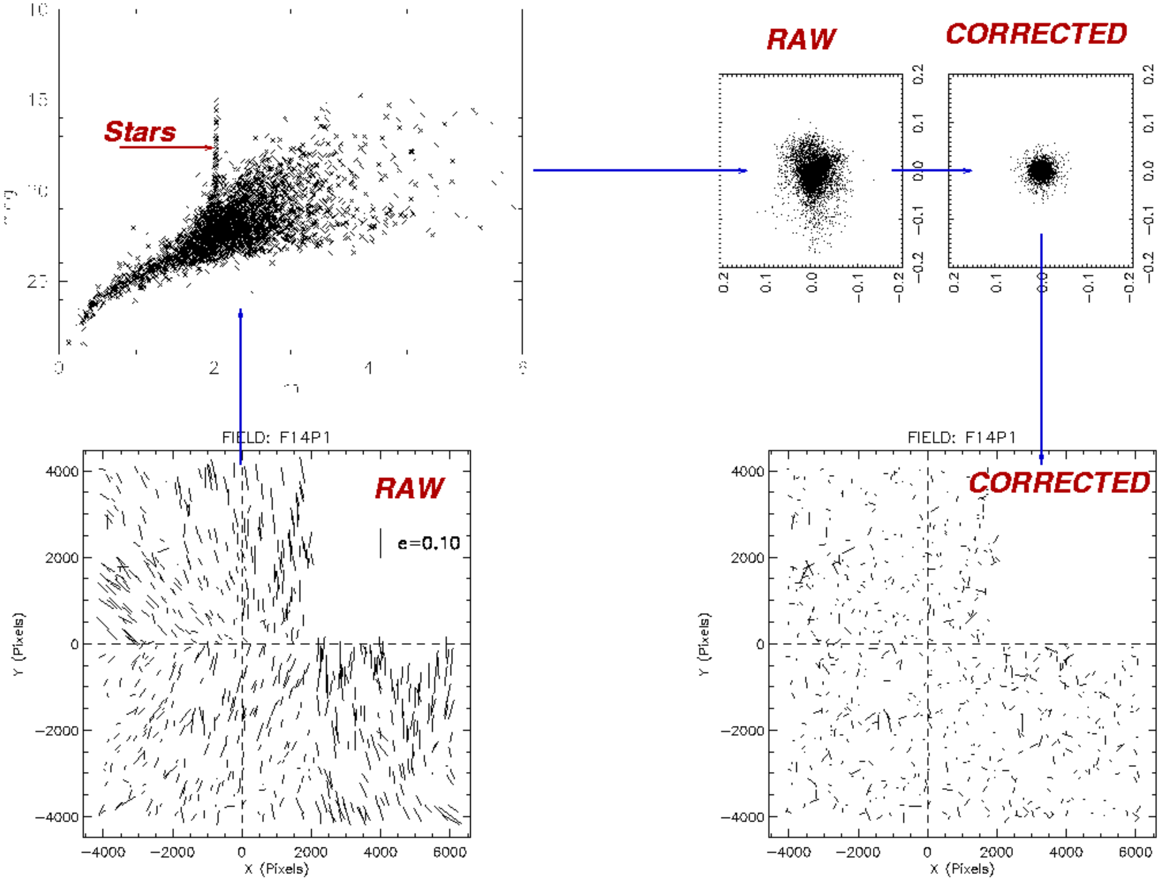
- Find objects that
  - are not lensed
  - are distorted by all other effects

  → **stars**
- Find the corrections to apply to each star at each star position
- **Interpolate** the correction for any field position
- Apply the correction to galaxies

- PSF corrections is the most difficult issue at very small distortion amplitude. Still considerable work going on.

Using stars for the PSF correction

Fahlman et al 1994, Bonnet & Mellier 1994, Mould et al 1994, KSB 1995, Kuijken 1999, 2006, Hoekstra et al 2000, Erben et al 2001, Bacon et al 2001, Refregier et al 2001, Bernstein et al 2001, etc…



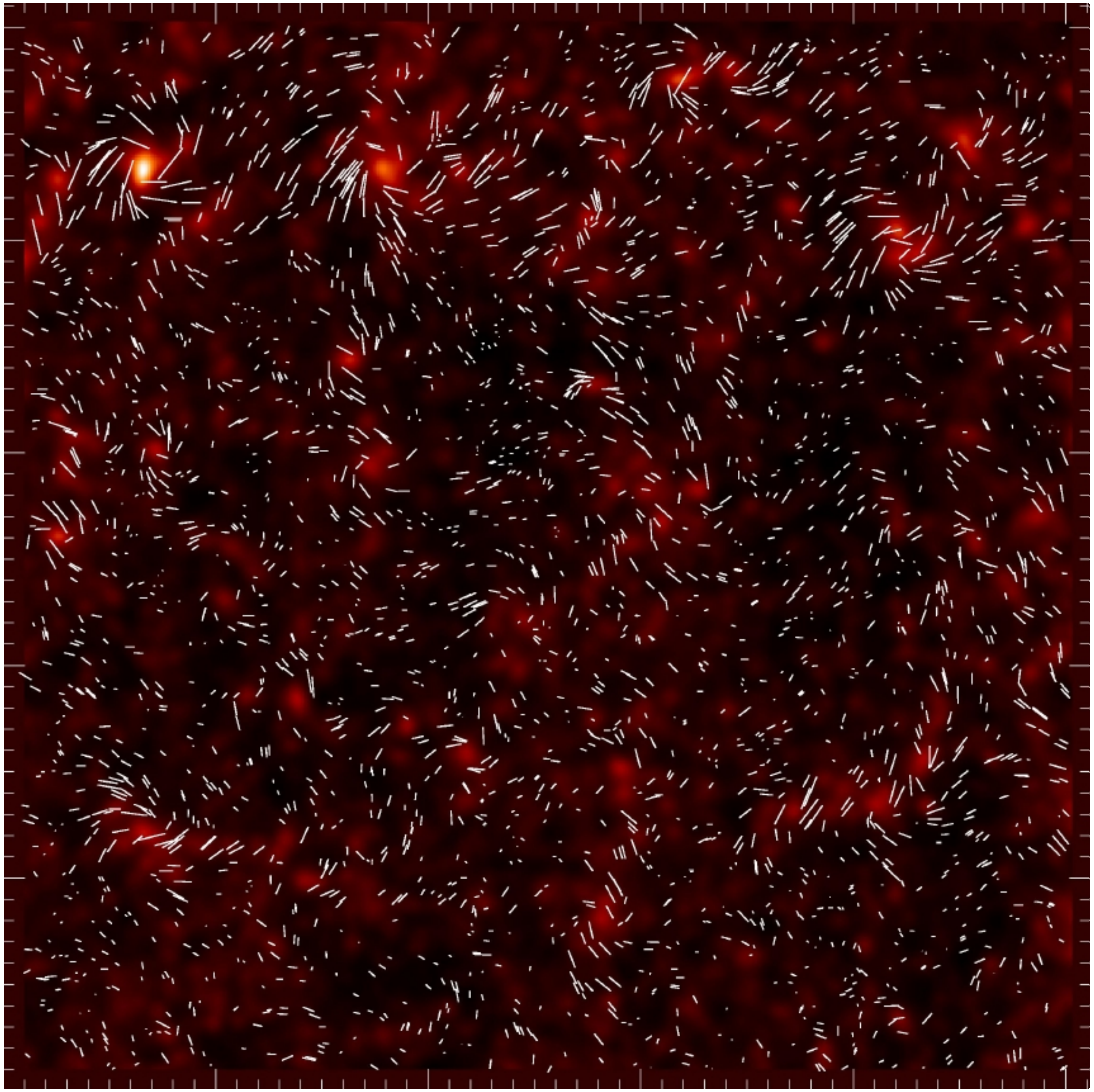
Need careful **check of systematic residual** after corrections

Testing systematics and reliability of cosmic shear signal:

Gravitational lensing does not produce B-modes (Curl=0)

E projection
Pure gravity signal

45 degrees rotated
galaxies, E -> B



Cosmic shear : results

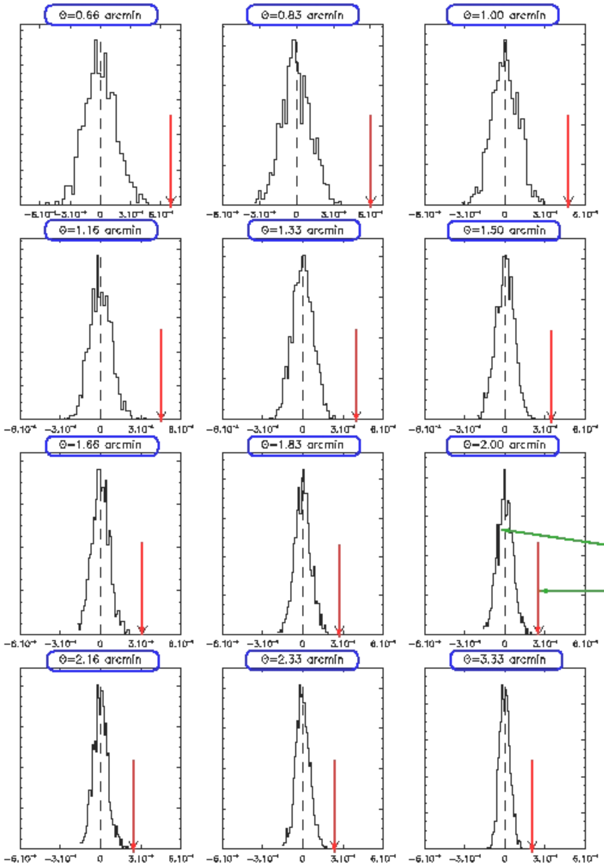
Measuring cosmic shear and first proof of detection

Measuring shear signal in practice

$$E[\gamma^2(\boldsymbol{\theta}_i)] = \frac{\sum_{\alpha=1}^{2}\sum_{k\neq l}^{N_i} w_k w_l \; e^{\rm gal}_\alpha(\boldsymbol{\theta}_k) e^{\rm gal}_\alpha(\boldsymbol{\theta}_l)}{\sum_{k\neq l}^{N} w_k w_l},$$

$$E[M^2_{\rm ap}(\boldsymbol{\theta}_i)] = \frac{\sum_{k\neq l}^{N_i} w_k w_l \; e^{\rm gal}_t(\boldsymbol{\theta}_k) e^{\rm gal}_t(\boldsymbol{\theta}_l) \; Q(\theta_k) Q(\theta_l)}{\sum_{k\neq l}^{N} w_k w_l},$$

$$E[\gamma\gamma;\theta] = \sum_{\alpha=1}^{2} \frac{\sum_{pairs} w_k w_l \; e^{\rm gal}_\alpha(\boldsymbol{\theta}_k) e^{\rm gal}_\alpha(\boldsymbol{\theta}_l)}{\sum_{pairs} w_k w_l}.$$



VAN WAERBEKE et al (2000)

Amplitude of the measured signal as function of the smoothing scale for the CFH12K data.

Histograms: randomised catalogs.

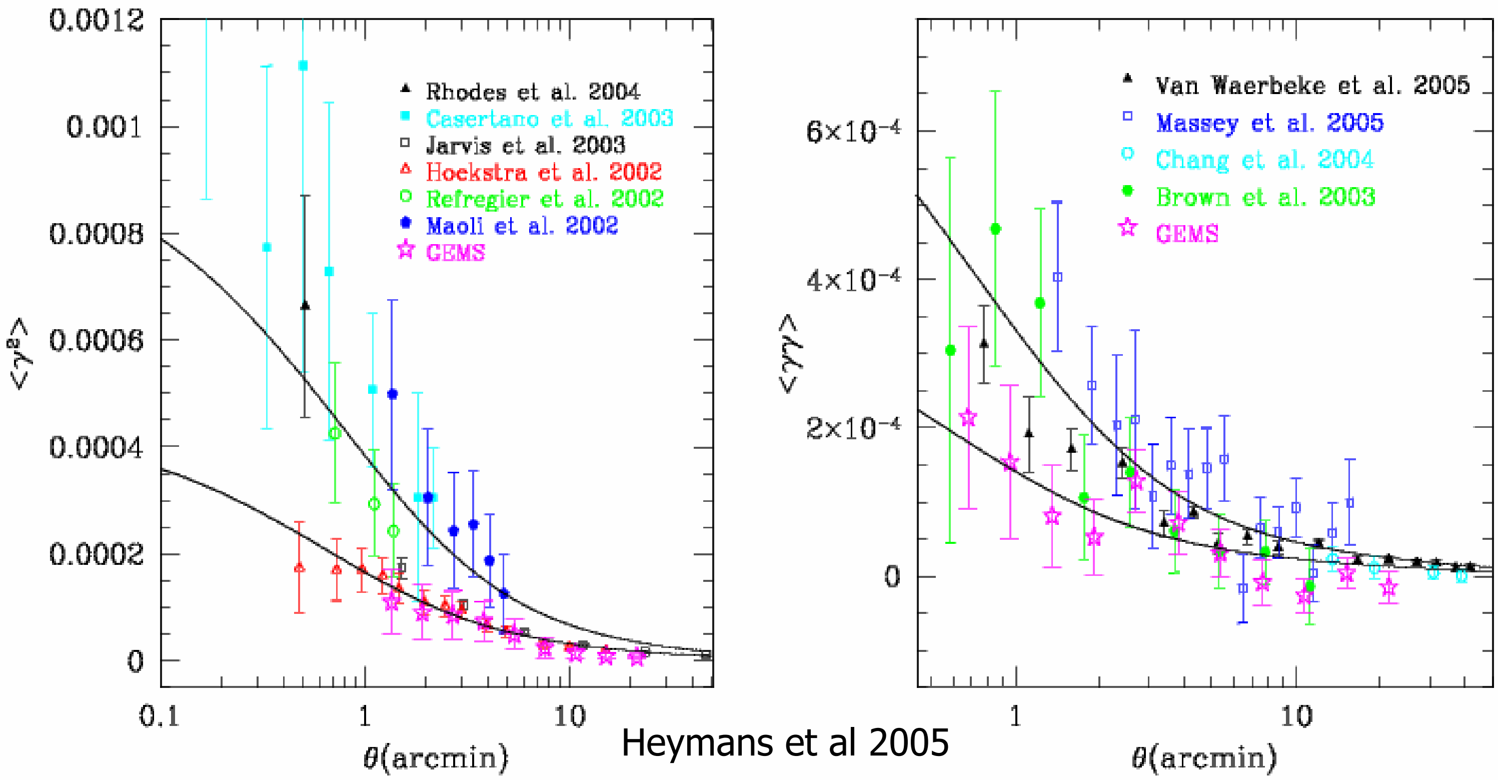
Red arrows: signal measured.

Van Waerbeke et al 2000

Detection level: 5.5-σ

Top-hat and shear correlation functions :

recent space ou ground-based weak lensing surveys



Heymans et al 2005

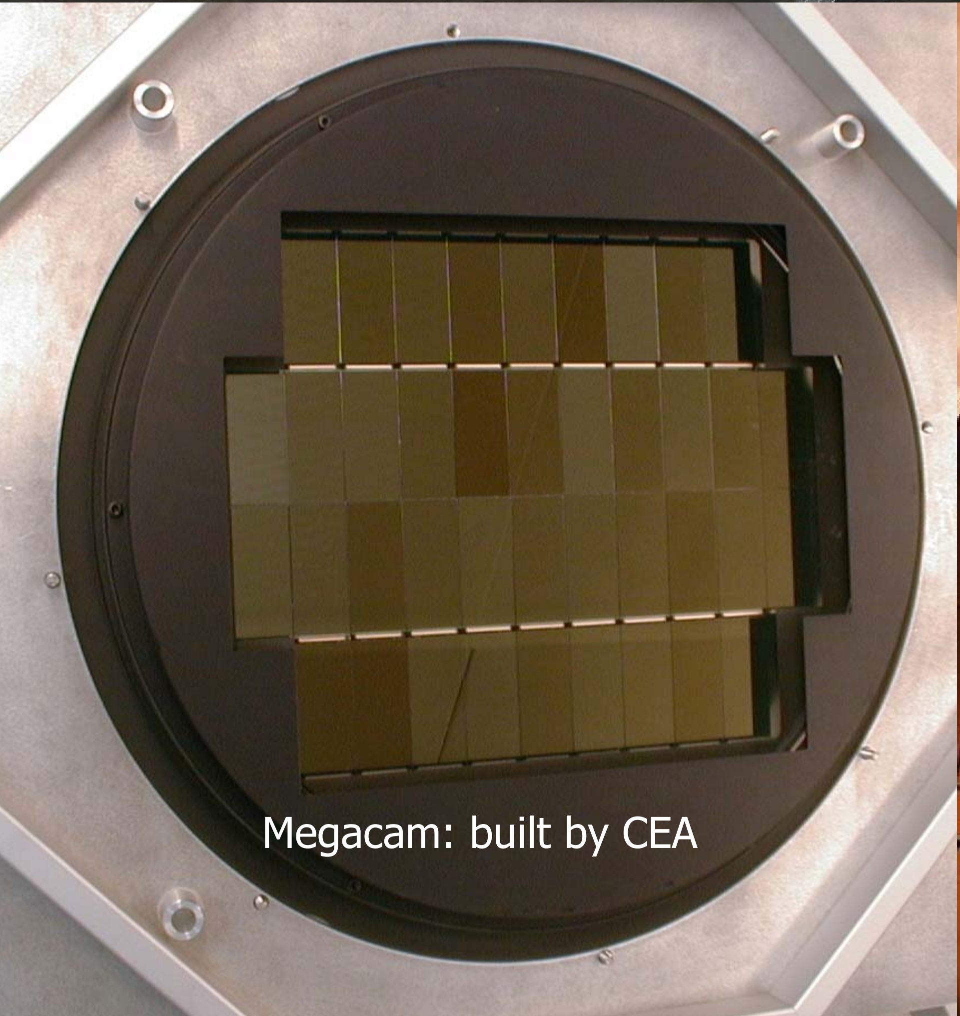
See: Bacon et al 2000* , 2001 ; Kaiser et al. 2000* ; Maoli et al. 2000* ; Rhodes et al 2001* ; Refregier et al 2002 ; van Waerbeke et al. 2000* ; van Waerbeke et al. 2001, 2005 ; Wittman et al. 2000* ; Hammerle et al. 2001* ; Hoekstra et al. 2002 * ; Brown et al. 2003 ; Hamana et al. 2003 * ; Jarvis et al. 2003 ; Casertano et al 2003* ; Rhodes et al 2004 ; Massey et al. 2004 ; Heymans et al 2004* ; Semboloni et al 2006 ; Hoekstra et al 2005, Hetterscheidt et al 2006, Schrabback et al 2006, Massey et al 2007, Benjamin et al 2007, Fu et al 2007

An example:

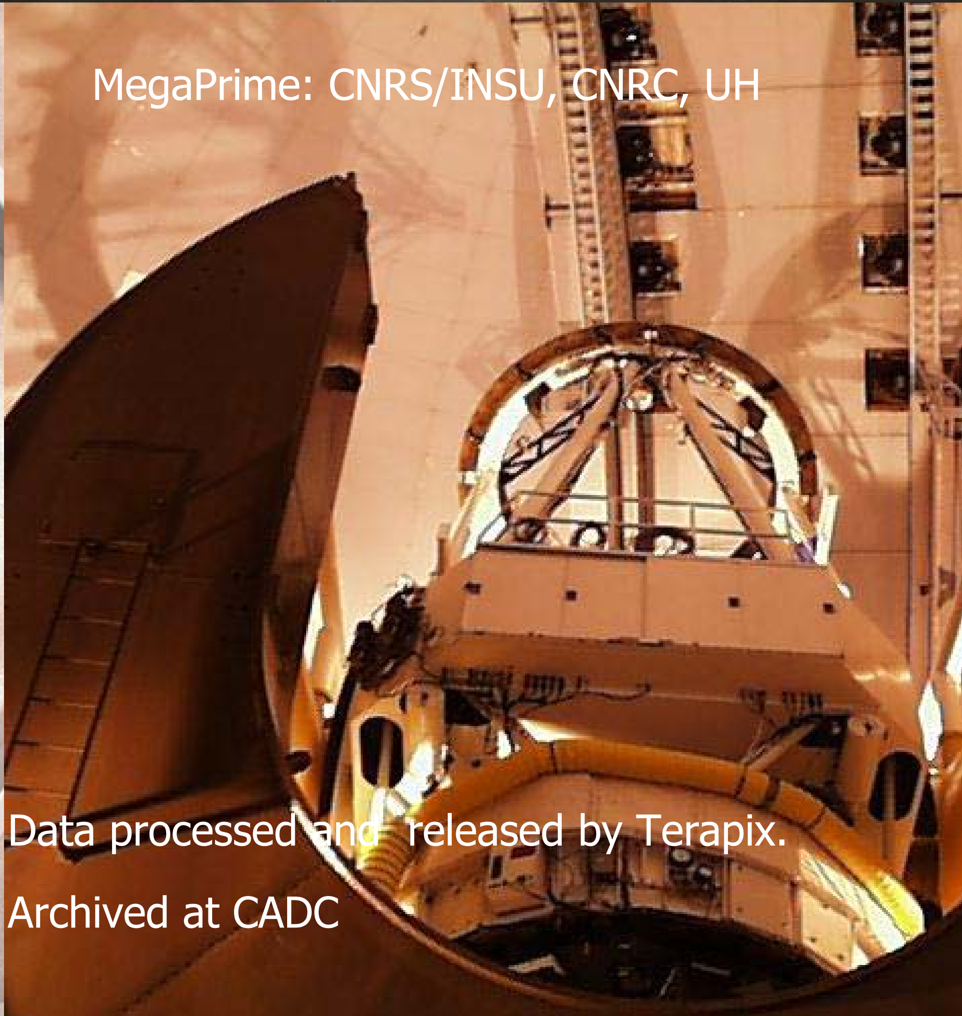
The Canada France Hawaii Telescope Cosmic Shear Legacy Survey (CSLS)

K. Benabed (IAP), F. Bernardeau (CEA/SPhT), A. Benjamin (UBC, Vancouver), J. Coupon (IAP), L. Fu (IAP), S. Gwyn (U. Victoria), C. Heymans (UBC Vancouver), H. Hoekstra (U. Victoria), M. Hudson (U. Waterloo), M. Kilbinger, R. Maoli (IAP), Y. Mellier (IAP), L. Parker (U. Waterloo), U.L. Pen (CITA), C. Schimd (CEA/SPP+IAP), E. Semboloni (IAP/Bonn), I. Tereno (IAP/Bonn), L. van Waerbeke (UBC, Vancouver), J.-P. Uzan (IAP)

CFHT telescope: built and operated by CNRS/INSU, CNRC et UH



Megacam: built by CEA



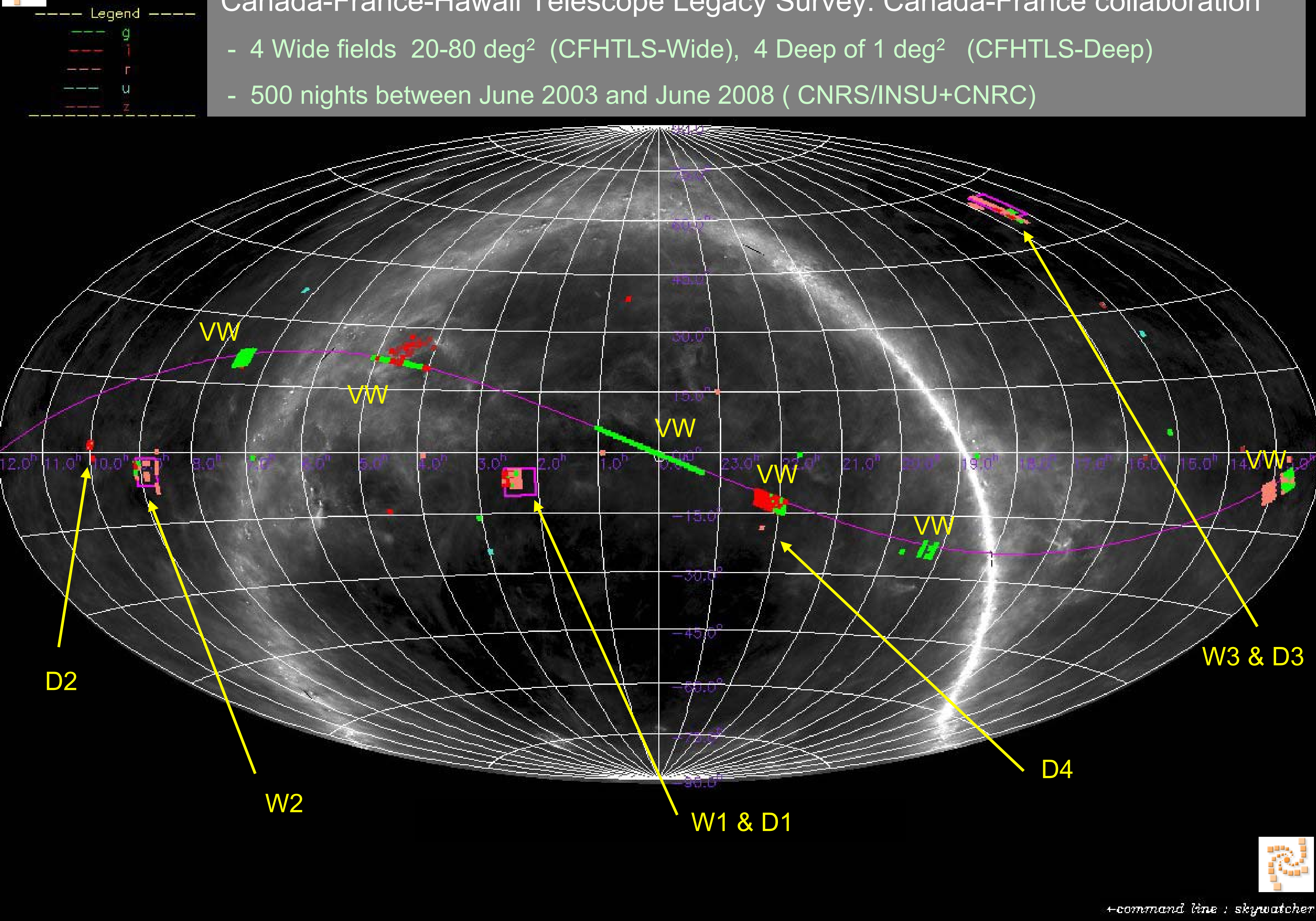
MegaPrime: CNRS/INSU, CNRC, UH

Data processed and released by Terapix.

Archived at CADC

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

- 4 Wide fields 20-80 deg^2 (CFHTLS-Wide), 4 Deep of 1 deg^2 (CFHTLS-Deep)
- 500 nights between June 2003 and June 2008 (CNRS/INSU+CNRC)

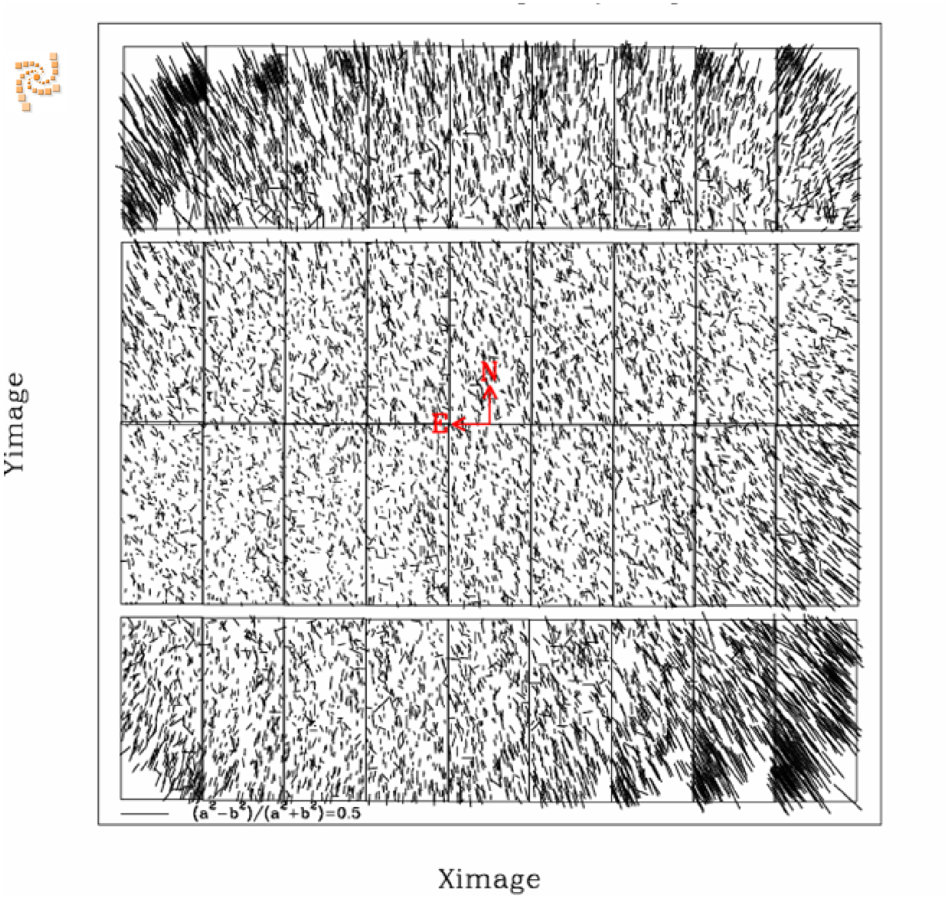


Terapix/Skywatcher : all data 03A-05A : 20000 Megacam images

Weak lensing needs good image quality instrument

MegaPrime among the best wide field instrument, but still…

MegaPrime image quality strong optical distortion : concerns about residuals after corrections



Reliability of Cosmic shear with CFHTLS data

- 2 independent pipelines:
  - One in Canada (UVic+UBC+Waterloo), one in France (IAP)
  - Each pipeline does astrometric calibration and image stacking differently
  - Two different IMCAT version used

- Both pipelines check B-modes .

- Both used 3 different cosmic shear statistics

- Cross-check: shapes and amplitudes are similar for the 2 pipelines.

- Deep: check achromaticity using *i* and *r* data independently

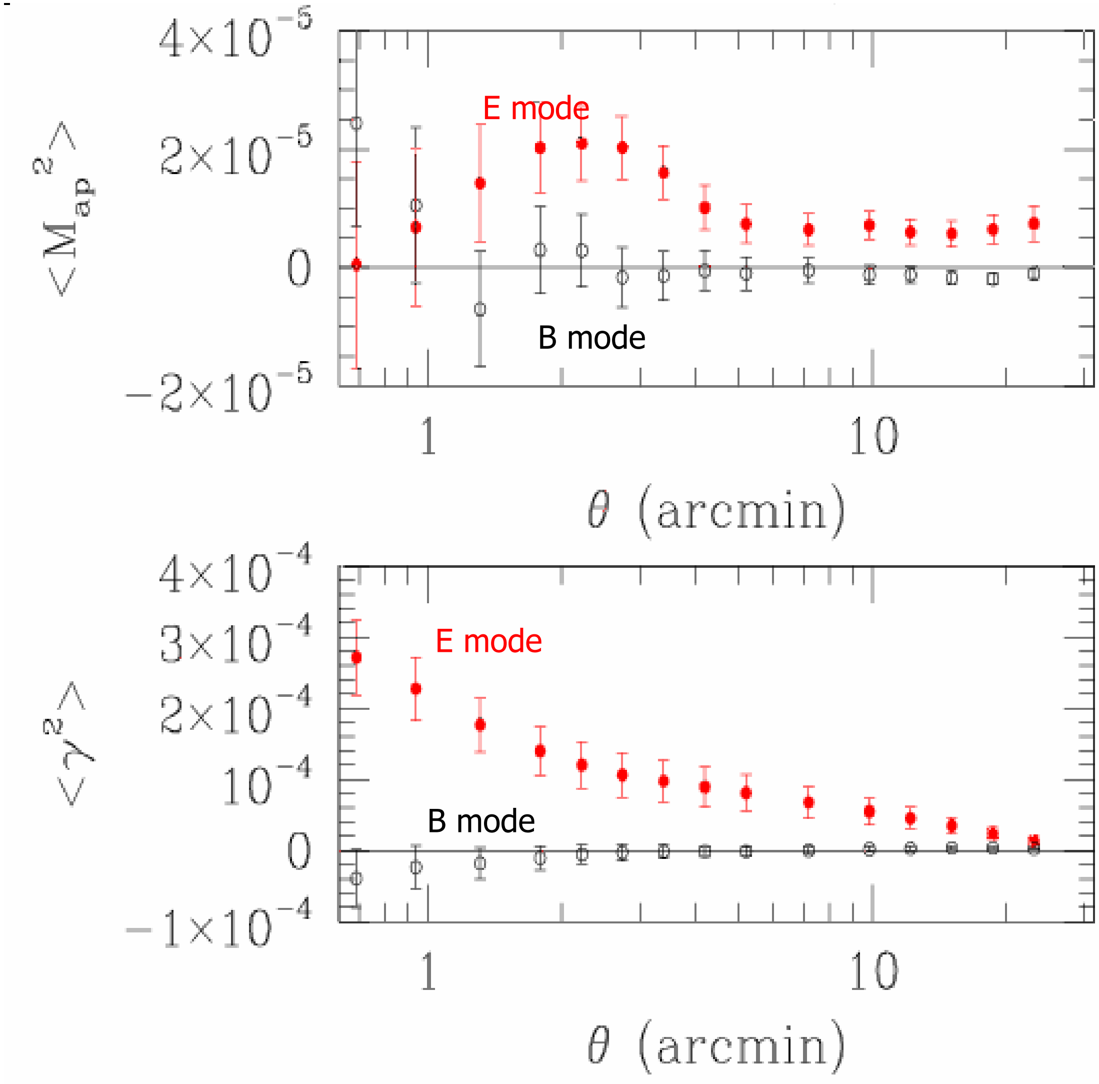
- Check with past results (VIRMOS-Descart)

CFHTLS Wide+Deep 1.5 year data:

early results

Cosmic shear in CFHTLS Deep fields

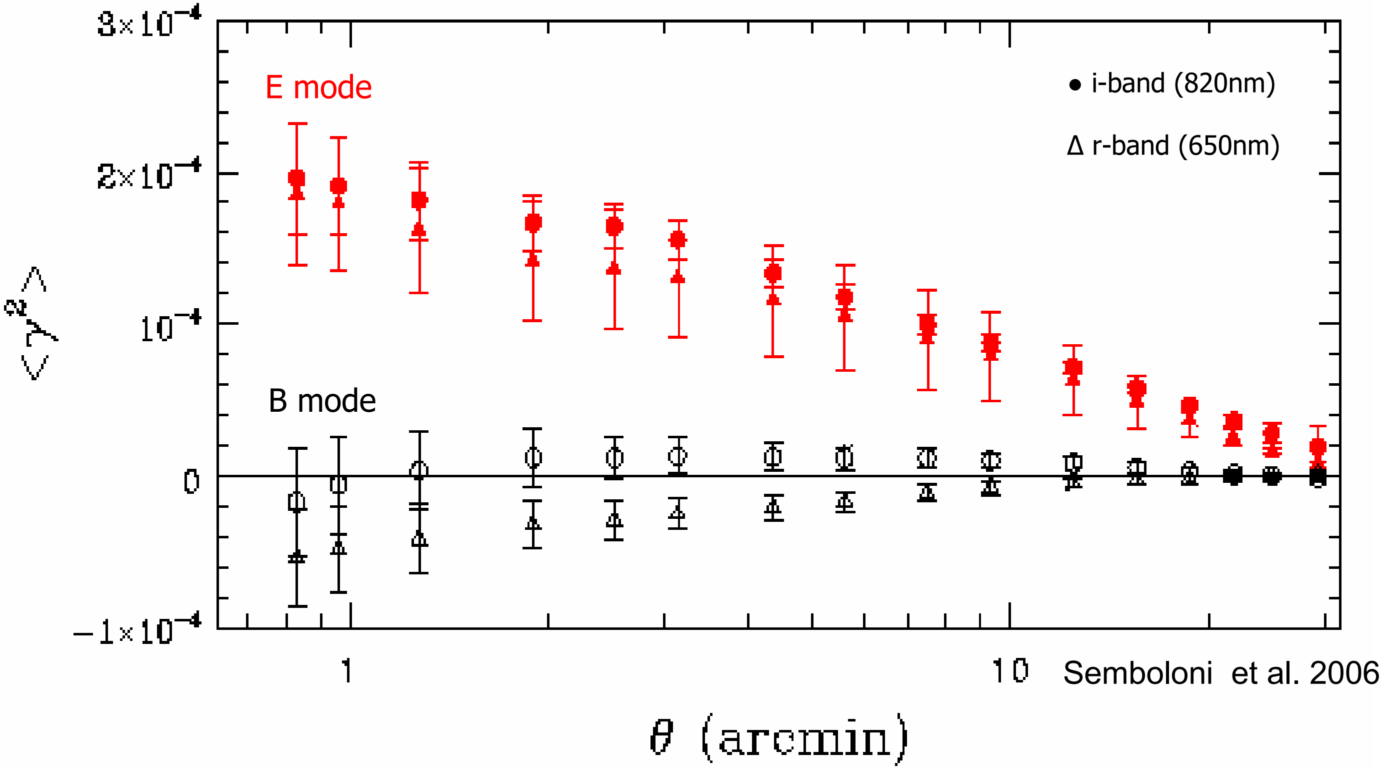
Terapix release T0001: E and B modes analysis



Semboloni et al 2006

Comparing signal in *r* and *i* bands:

achromatic effect confirmed

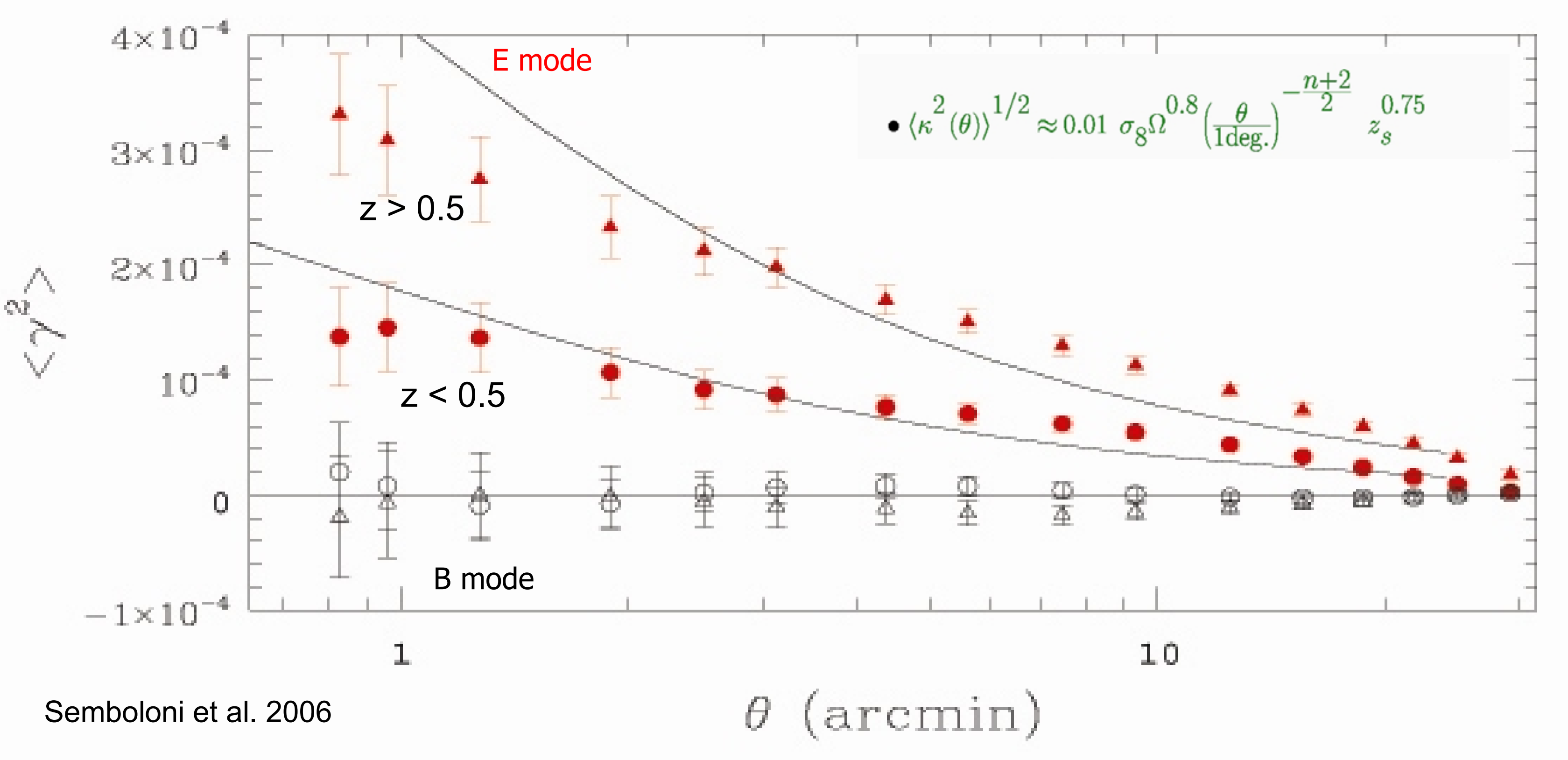


Semboloni et al. 2006

- *i* and *r* band processed independently
- Comparison catalogues contain the same galaxies

Signal evolution with redshift:

cosmological nature of the lensing signal

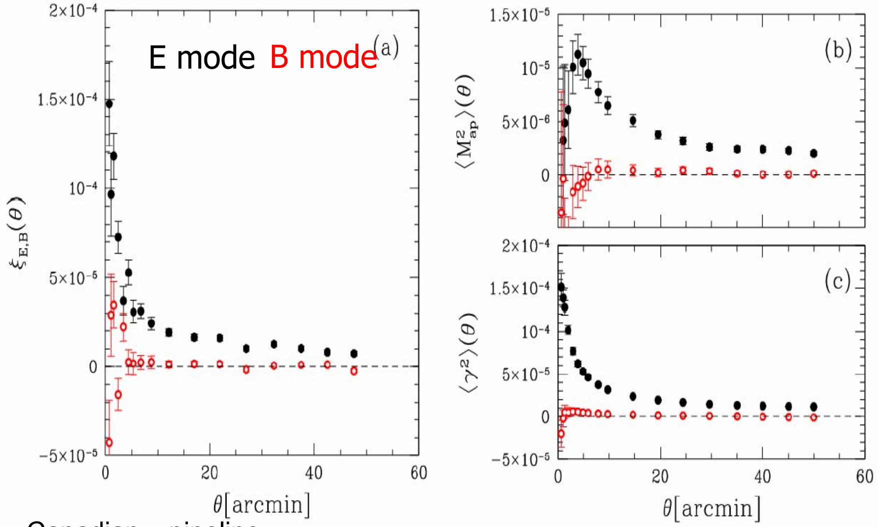


- $\langle\kappa^2(\theta)\rangle^{1/2} \approx 0.01\ \sigma_8\Omega^{0.8}\left(\frac{\theta}{1\mathrm{deg.}}\right)^{-\frac{n+2}{2}} z_s^{0.75}$

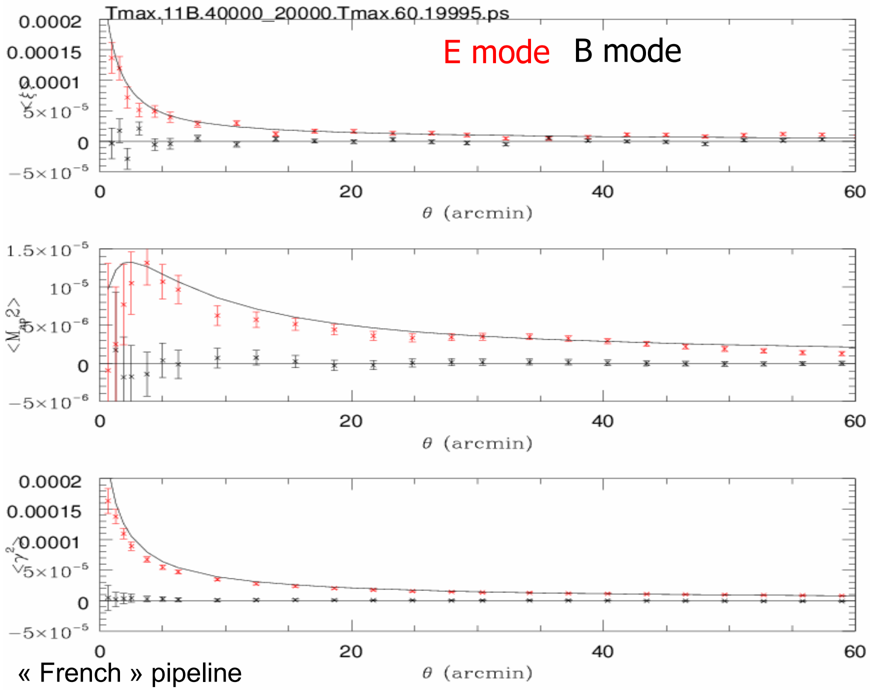
Semboloni et al. 2006

Cosmic shear in CFHTLS wide:

2 independent pipelines
same results

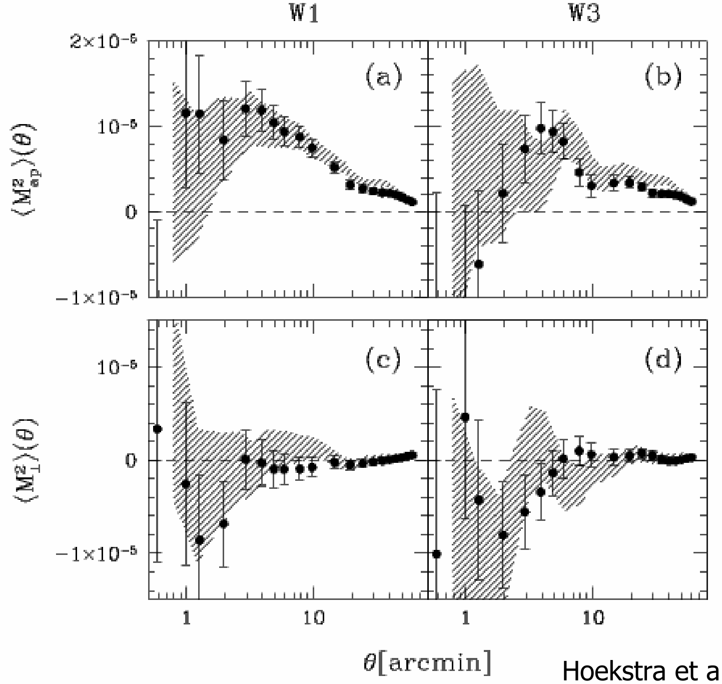


« Canadian » pipeline



« French » pipeline

Difference vs 1-σ error



Hoekstra et al 2006

Data processed and stacked in 3 different ways, cosmic shear analysed by 2 different pipelines

Summary

- 2 independent pipelines provide the same results ; same results as the previous survey Virmos-Descart: robust and reliable measurements
- No B-modes, no <e* γ_g> cross-correlation: no critical systematics residuals after PSF correction
- No B-mode at all scales (30'' ; 50'): likely signal from gravity (Curl-free)
- Achromatic: gravitational lensing
- Signal
  - has the amplitude and the shape predicted from theory of structure formation in a CDM-dominated scenario
  - increases with redshift as expected from cosmological structure formation and weak lensing theory

Cosmological weak lensing

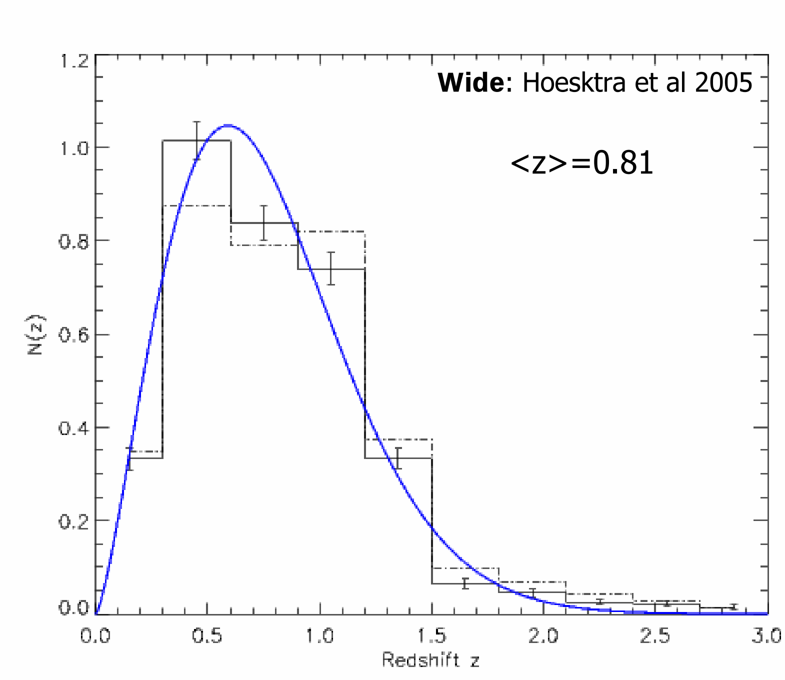
Weak lensing :

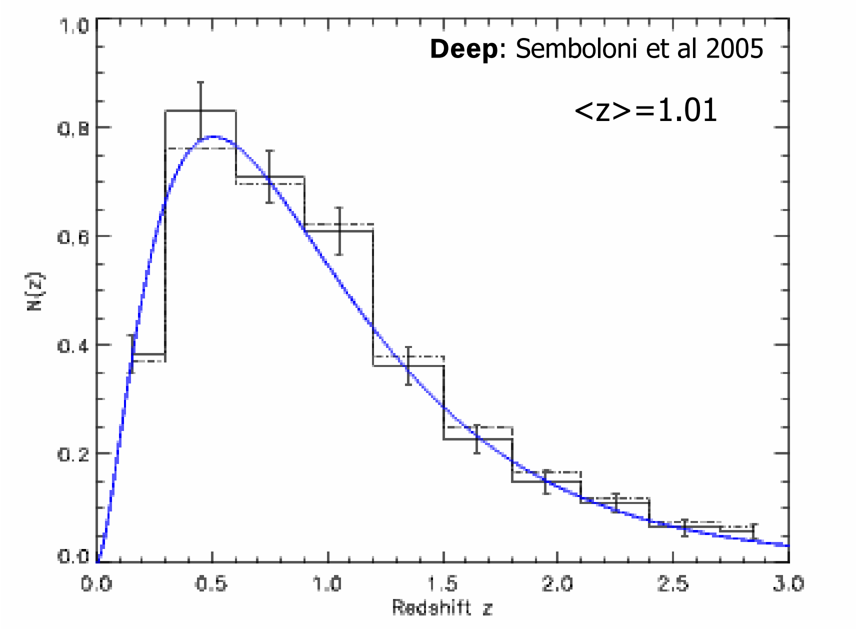
cosmological intepretation

Scaling the shear amplitude : Redshift distribution

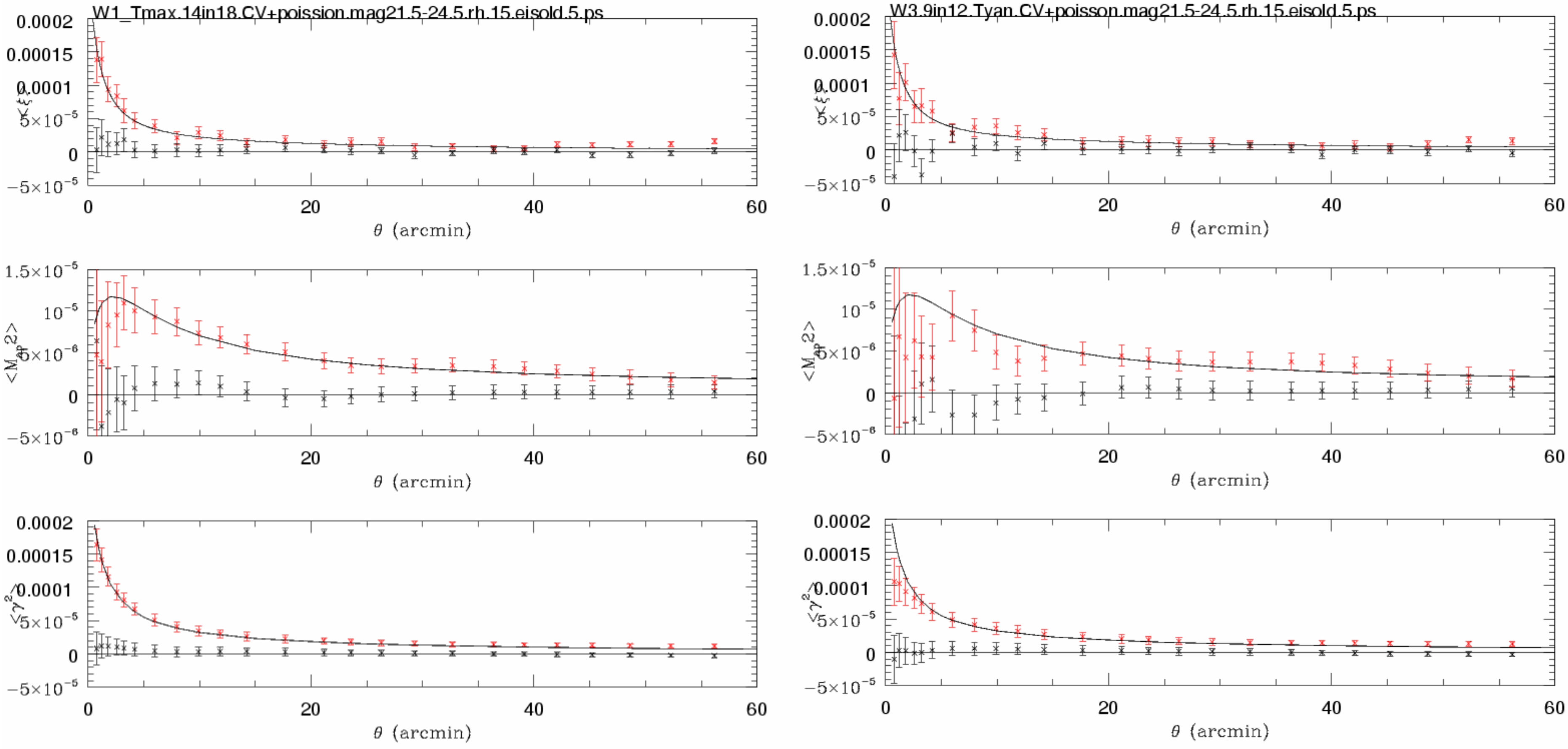
Photo-z from Hubble Deep Field optical+NIR data

- $\langle\kappa^2(\theta)\rangle^{1/2} \approx 0.01\ \sigma_8 \Omega^{0.8} \left(\frac{\theta}{1\mathrm{deg.}}\right)^{-\frac{n+2}{2}} \boxed{z_s^{0.75}}$





CFHTLS 1.5 yr in good agreement with the « concordance model »



- **Line: σ_8=0.85 ; Ω_m=0.27 ; Λ=0.73 ; h=0.71 ; $<z_s>$=0.85 ; σ_ε =0.36 ; n_{gal}=15 gal/arcmin^2**
- Errors: Poisson+cosmic variance included

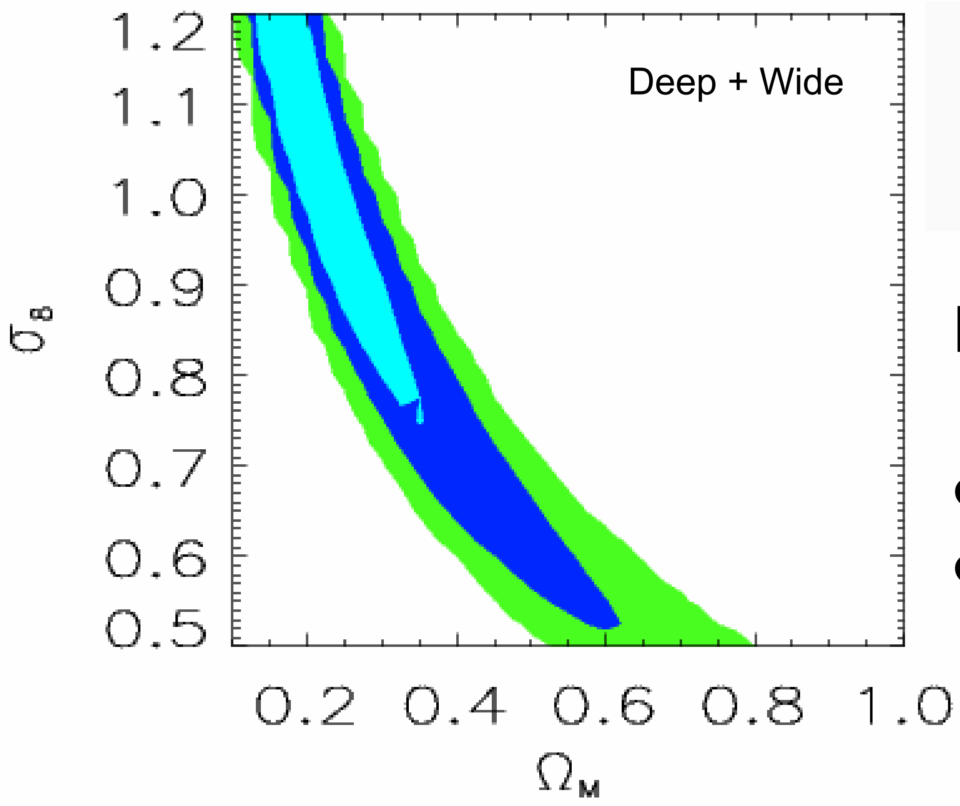
Concordance model overplot: no fit

Dark Matter:

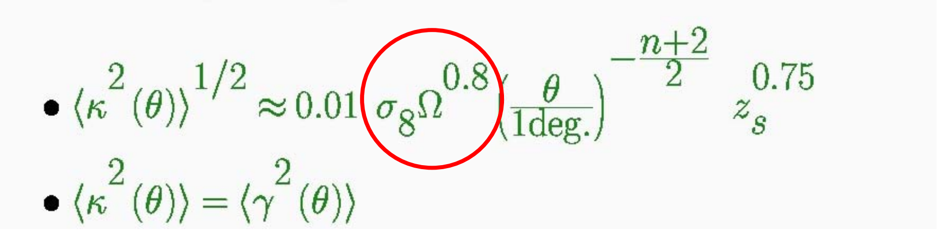
constraints on

$\Omega_m - \sigma_8$

CFHTLS T0001: constraints on Ω_m-σ_8



Semboloni et al 2006 & Hoekstra et al 2006



- $\langle \kappa^2(\theta) \rangle^{1/2} \approx 0.01 \, \sigma_8 \Omega^{0.8} \left(\frac{\theta}{1\text{deg.}} \right)^{-\frac{n+2}{2}} z_s^{0.75}$
- $\langle \kappa^2(\theta) \rangle = \langle \gamma^2(\theta) \rangle$

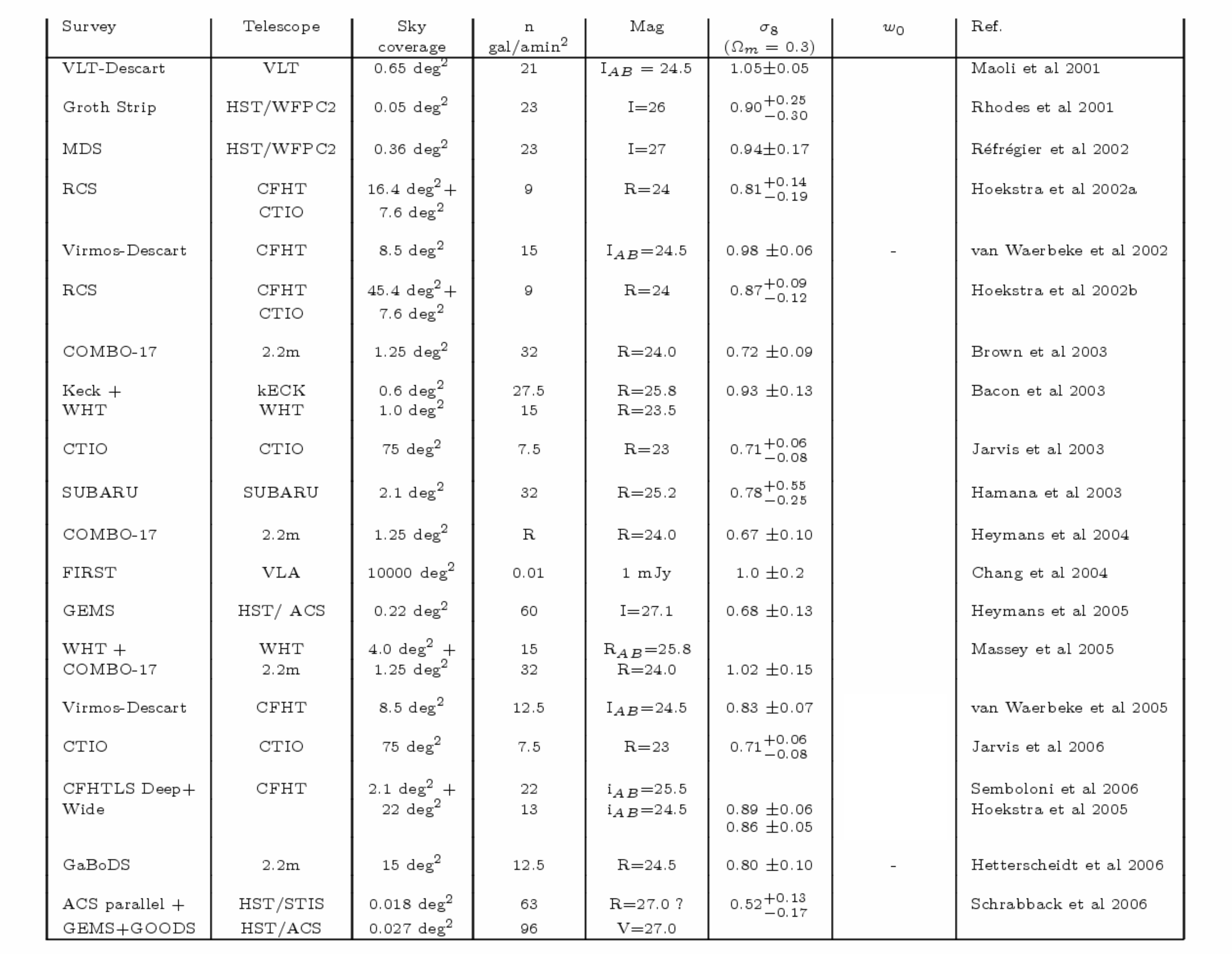
Deep+Wide assuming Ω_m=0.3 :

σ_8= 0.89 +/-0.06 (P&D)
σ_8= 0.86 +/-0.05 (Halo fit)

Deep effective area: 2.1 deg^2
Wide effective area : 22 deg^2

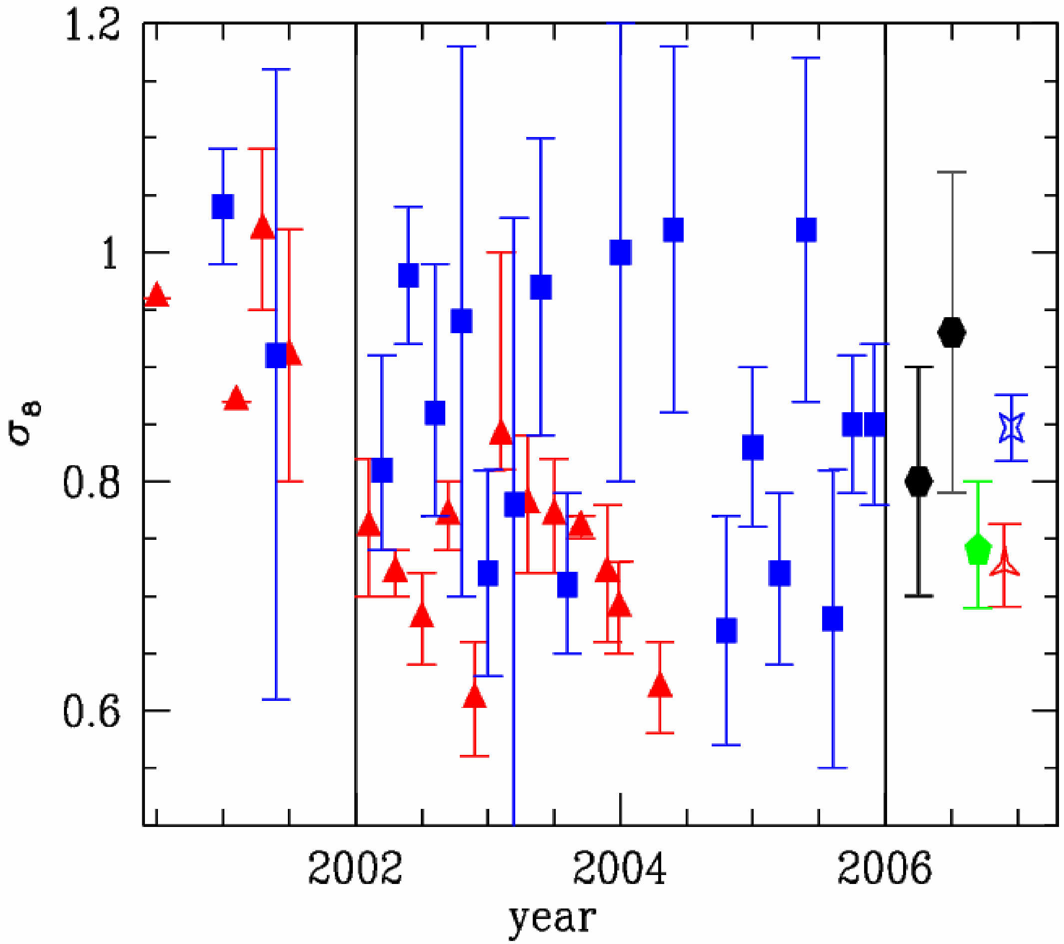
All WL surveys:

$$\langle\sigma_8\rangle \sim 0.90 \pm 0.15$$

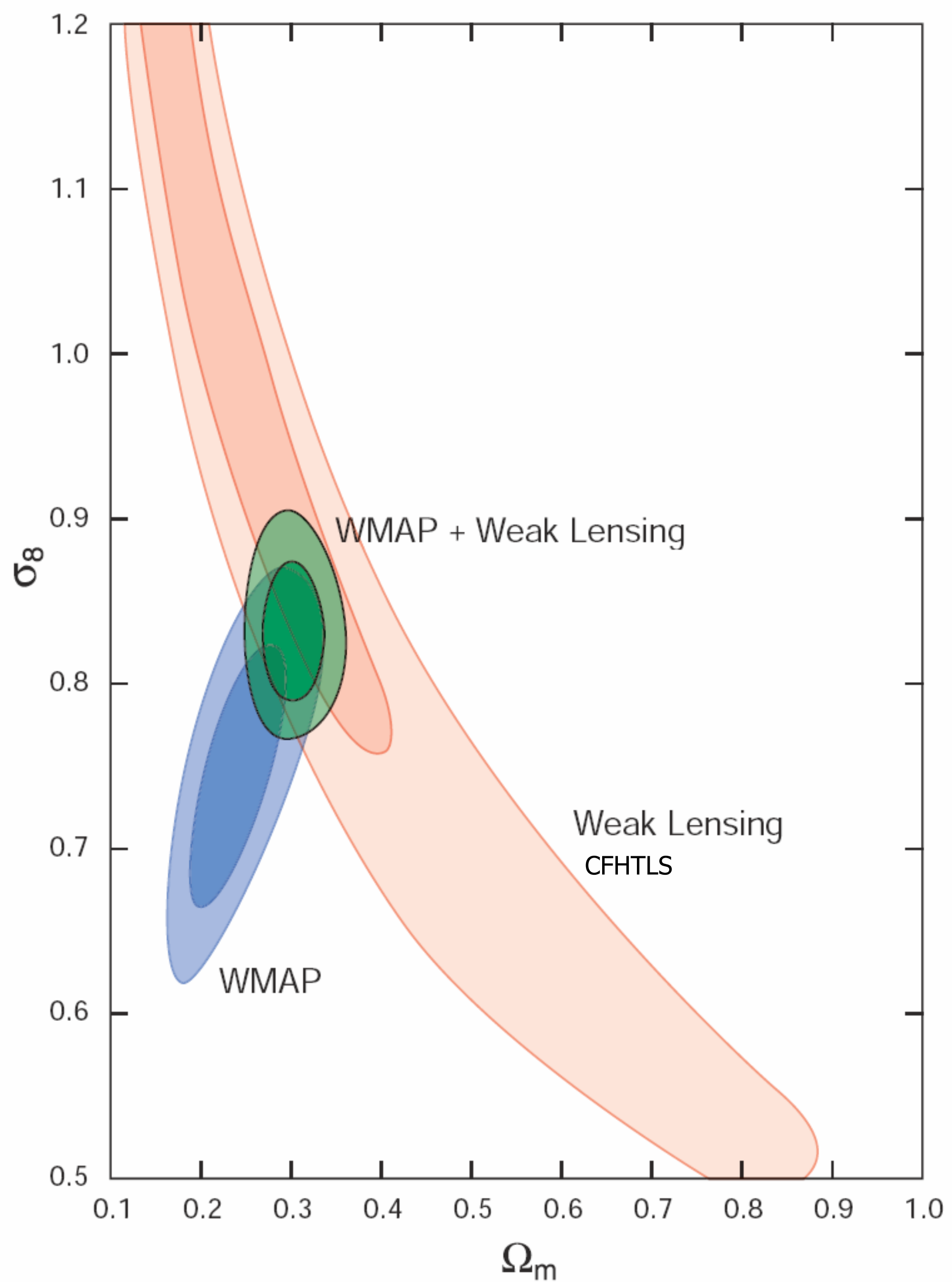


Survey	Telescope	Sky coverage	n gal/amin^2	Mag	σ_8 ($\Omega_m = 0.3$)	w_0	Ref.
VLT-Descart	VLT	0.65 deg^2	21	I_{AB} = 24.5	1.05±0.05		Maoli et al 2001
Groth Strip	HST/WFPC2	0.05 deg^2	23	I=26	$0.90^{+0.25}_{-0.30}$		Rhodes et al 2001
MDS	HST/WFPC2	0.36 deg^2	23	I=27	0.94±0.17		Réfrégier et al 2002
RCS	CFHT CTIO	16.4 deg^2+ 7.6 deg^2	9	R=24	$0.81^{+0.14}_{-0.19}$		Hoekstra et al 2002a
Virmos-Descart	CFHT	8.5 deg^2	15	I_{AB}=24.5	0.98 ±0.06	-	van Waerbeke et al 2002
RCS	CFHT CTIO	45.4 deg^2+ 7.6 deg^2	9	R=24	$0.87^{+0.09}_{-0.12}$		Hoekstra et al 2002b
COMBO-17	2.2m	1.25 deg^2	32	R=24.0	0.72 ±0.09		Brown et al 2003
Keck + WHT	kECK WHT	0.6 deg^2 1.0 deg^2	27.5 15	R=25.8 R=23.5	0.93 ±0.13		Bacon et al 2003
CTIO	CTIO	75 deg^2	7.5	R=23	$0.71^{+0.06}_{-0.08}$		Jarvis et al 2003
SUBARU	SUBARU	2.1 deg^2	32	R=25.2	$0.78^{+0.55}_{-0.25}$		Hamana et al 2003
COMBO-17	2.2m	1.25 deg^2	R	R=24.0	0.67 ±0.10		Heymans et al 2004
FIRST	VLA	10000 deg^2	0.01	1 mJy	1.0 ±0.2		Chang et al 2004
GEMS	HST/ ACS	0.22 deg^2	60	I=27.1	0.68 ±0.13		Heymans et al 2005
WHT + COMBO-17	WHT 2.2m	4.0 deg^2 + 1.25 deg^2	15 32	R_{AB}=25.8 R=24.0	1.02 ±0.15		Massey et al 2005
Virmos-Descart	CFHT	8.5 deg^2	12.5	I_{AB}=24.5	0.83 ±0.07		van Waerbeke et al 2005
CTIO	CTIO	75 deg^2	7.5	R=23	$0.71^{+0.06}_{-0.08}$		Jarvis et al 2006
CFHTLS Deep+ Wide	CFHT	2.1 deg^2 + 22 deg^2	22 13	i_{AB}=25.5 i_{AB}=24.5	0.89 ±0.06 0.86 ±0.05		Semboloni et al 2006 Hoekstra et al 2005
GaBoDS	2.2m	15 deg^2	12.5	R=24.5	0.80 ±0.10	-	Hetterscheidt et al 2006
ACS parallel + GEMS+GOODS	HST/STIS HST/ACS	0.018 deg^2 0.027 deg^2	63 96	R=27.0 ? V=27.0	$0.52^{+0.13}_{-0.17}$		Schrabback et al 2006

σ_8 derived from WL (blue) or clusters of galaxies (red)



Hetterscheidt et al 2006



WMAP3 and CFHTLS-T0001 :

1.5-σ tension

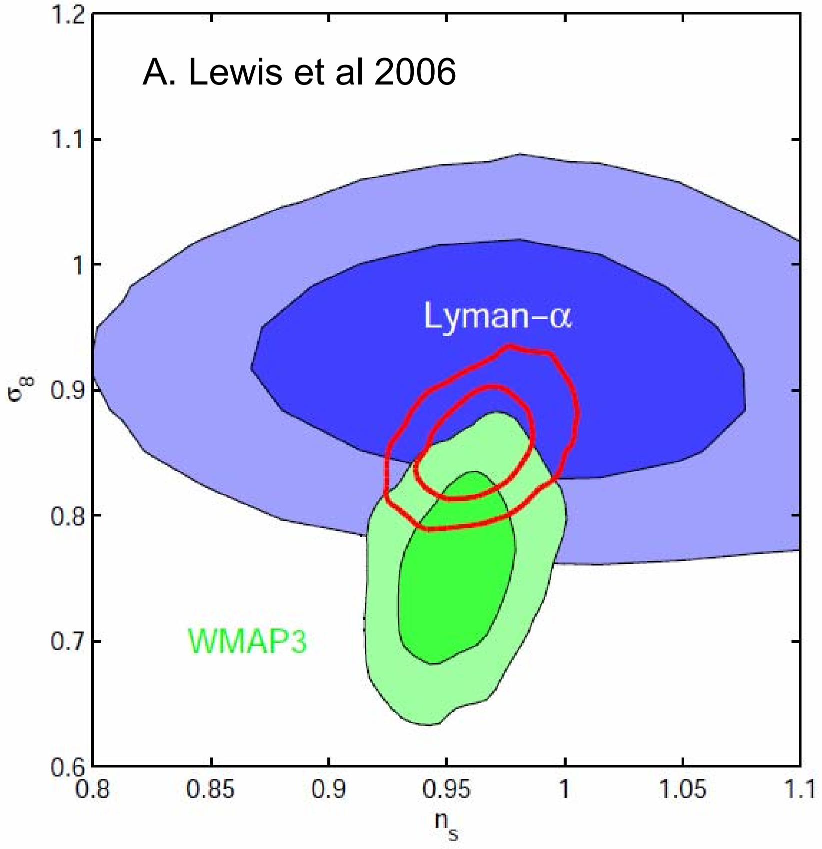
A « high σ_8 » ??

- In agreement the mean value of weak lensing data,

- with Lyα analysis,

- with some cluster results (not all, only few),

- with galaxy-galaxy lensing result of SDSS from Seljak et al



Tension: a WL or a WMAP3 issue?

- Why so much scatter?

- Why this « tension » with respect to WMAP data?

- Why WL seems to lead to a higher value than WMAP?

- WLs agree with other observations. But the agreements are only with other techniques that do have poorly controled astrophysical systematics

- Guess: the tension with WMAP3 comes from WL

From ellipticity to cosmology : not so obvious

Ellipticity badly measured (PSF anisotropy corrections, shape measurement)

Redshift of sources badly estimated (photo-z, too deep for spectroscopy)

$$\langle e^2\rangle_\theta^{1/2} = \langle\gamma^2\rangle_\theta^{1/2} \sim 0.01 \;\; \sigma_8 \, \Omega_m^{0.8} \;\; z_s^{0.75} \;\; \theta^{-(n+2)/2}$$

Shear is contaminated by non-lensing signal (instrinsic alignment of galaxies)

$\theta<15'$: Non-linear evolution of dark matter power spectrum unknown , extrapolation on small scales uncertain

Several issues may produce systematic errors

Errors and systematics uncertainties

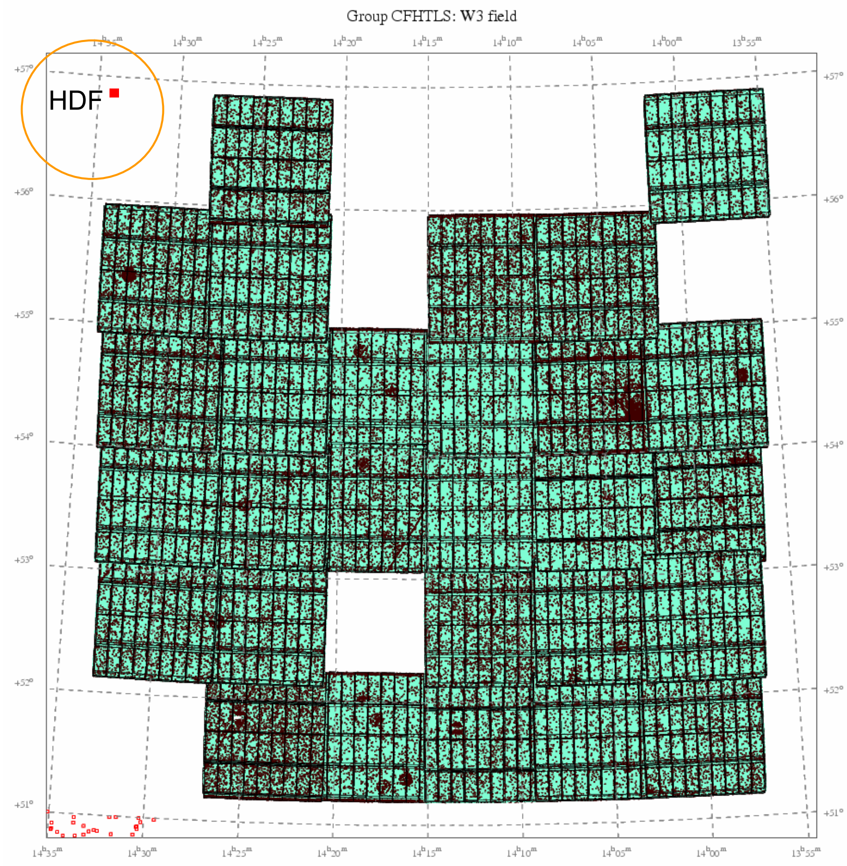
- PSF corrections
- Redshift distribution
- Galaxy source/lens clustering
- Contamination by overlapping galaxies
- Intrinsic alignement
- Intrinsic foreground/backgound correlations
- Sampling variance
- Non-linear variance
- Non-linear dark matter power spectrum
- \+ cosmic variance (survey size, survey topology, depth)

CFHTLS 1.5 yr weak lensing data :

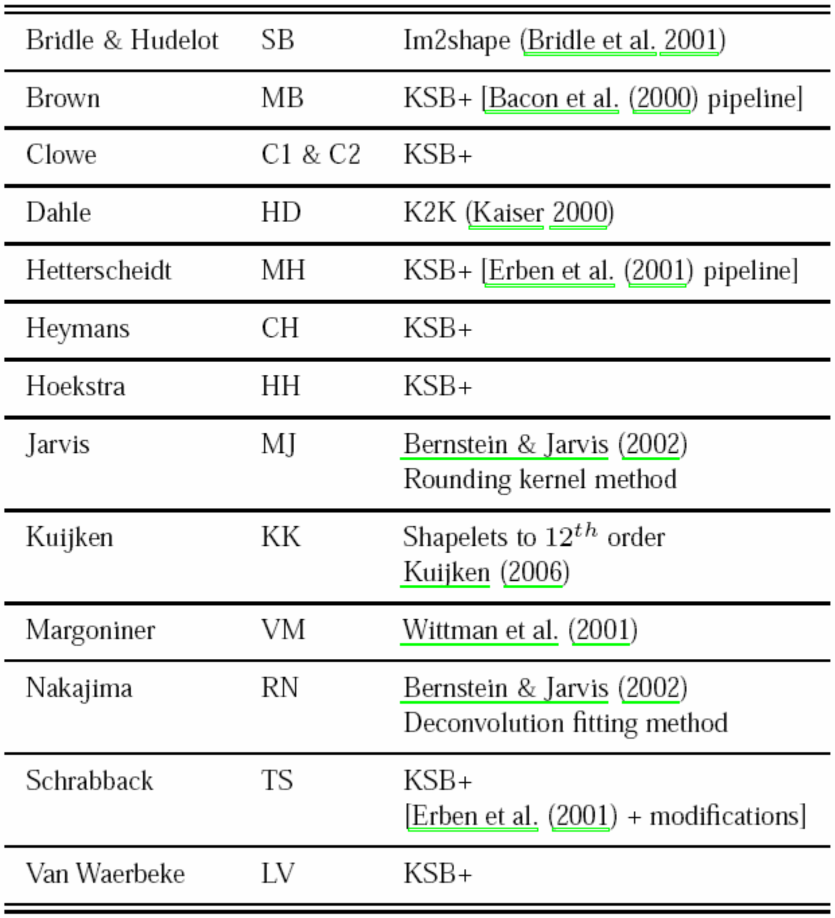
redshift calibrated with one HDF field

Only one field

HDF field size: 150000 smaller than total wide

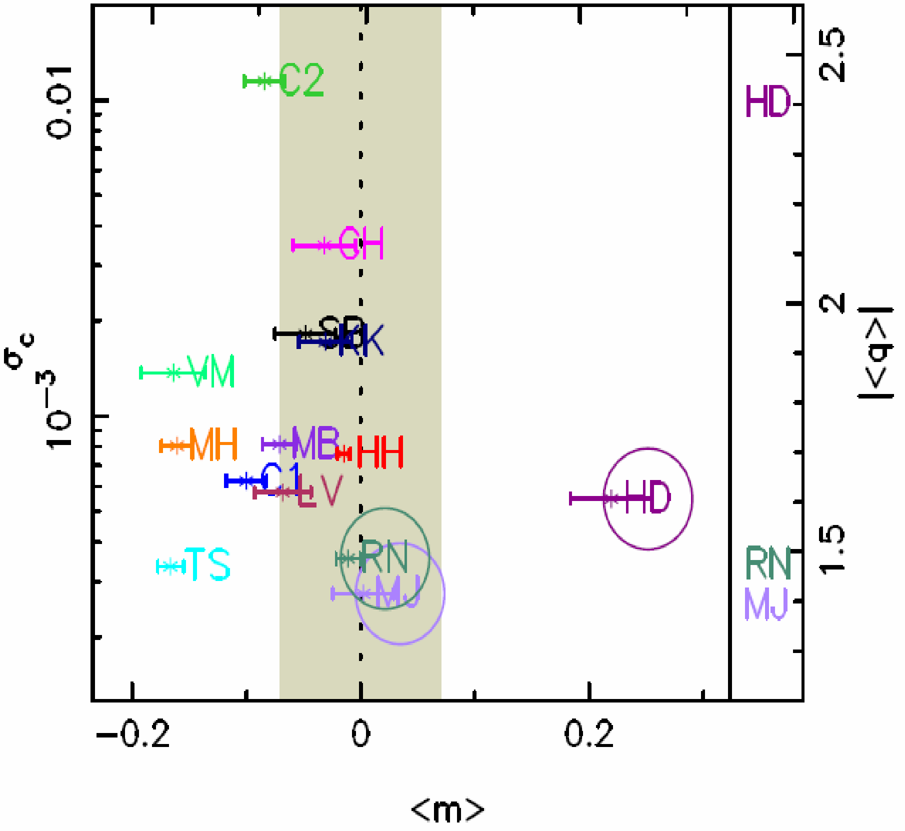


PSF : correction techniques tested with STEP1



Bridle & Hudelot	SB	Im2shape (Bridle et al. 2001)
Brown	MB	KSB+ [Bacon et al. (2000) pipeline]
Clowe	C1 & C2	KSB+
Dahle	HD	K2K (Kaiser 2000)
Hetterscheidt	MH	KSB+ [Erben et al. (2001) pipeline]
Heymans	CH	KSB+
Hoekstra	HH	KSB+
Jarvis	MJ	Bernstein & Jarvis (2002) Rounding kernel method
Kuijken	KK	Shapelets to 12^{th} order Kuijken (2006)
Margoniner	VM	Wittman et al. (2001)
Nakajima	RN	Bernstein & Jarvis (2002) Deconvolution fitting method
Schrabback	TS	KSB+ [Erben et al. (2001) + modifications]
Van Waerbeke	LV	KSB+

Heymans et al 2006



The Shear TEsting Program (STEP)

$$\gamma - \gamma^{true} = q(true)^2 + m(true) + c$$

q = linearity of the correction

m = calibration bias

c = PSF systematics and shot noise

Best method reach 1% accuracy

Largest error: calibration bias m

Second generation results

- PSF corrections improved: PSF + HST data (COSMOS)
- Astrophysical/instrument systematics: better controled and better taken into account in the error budget

- Better n(z)
- Sky coverage and number of uncorrelated fields continuously increasing

3 examples of new results

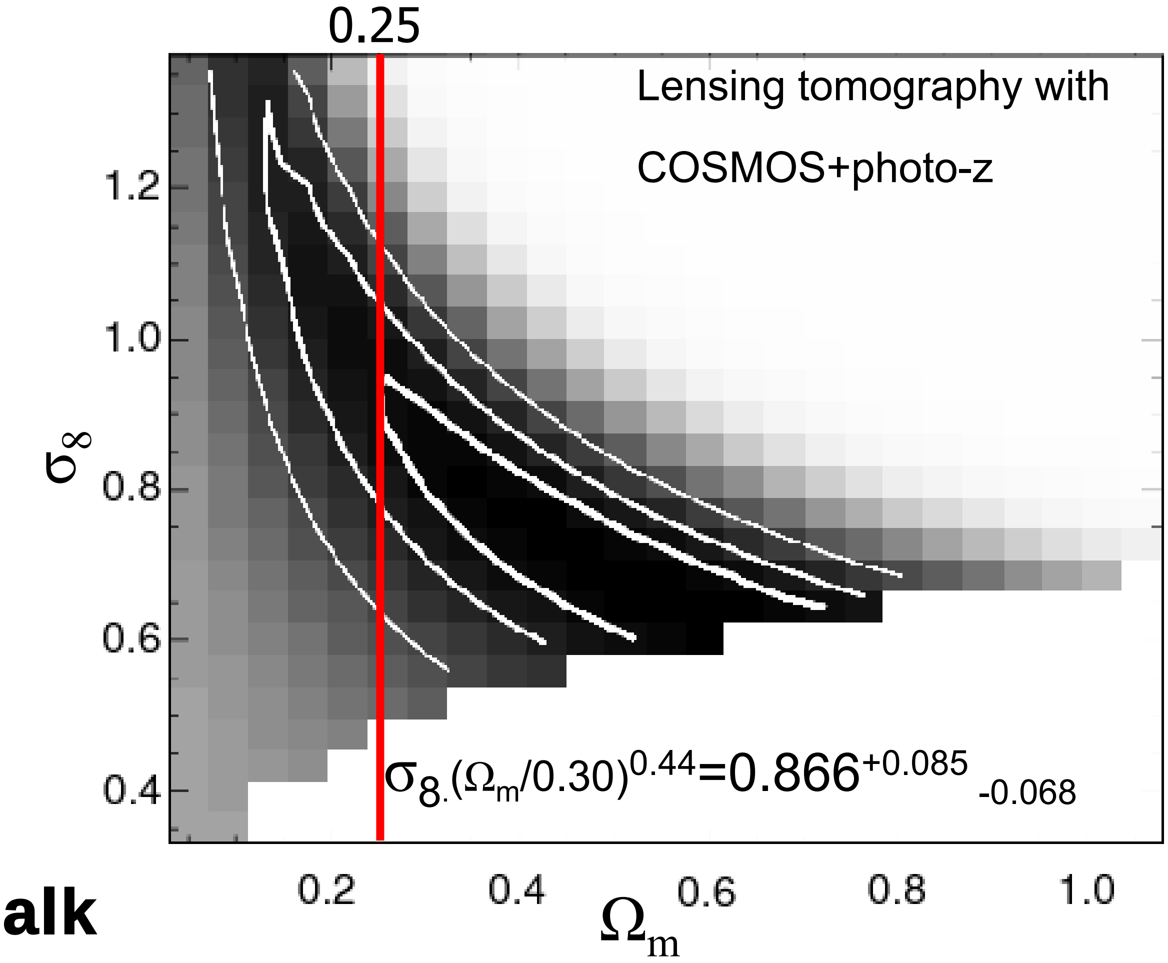
1. COSMOS + n(z): space ACS, 2 deg^2
2. Merging of 4 heterogenous surveys + n(z): 100 deg^2
3. A homogeneous large survey + n(z), 37deg^2 and VERY large angular scale: CFHTLS T0003, 1’, 4deg (85 Mpc!)

Cosmic Shear Tomography with COSMOS

Rhodes et al 2007, Leauthaud et al 2007, Massey et al 2007

Only 1 field 2deg^2

Cosmic variance important issue

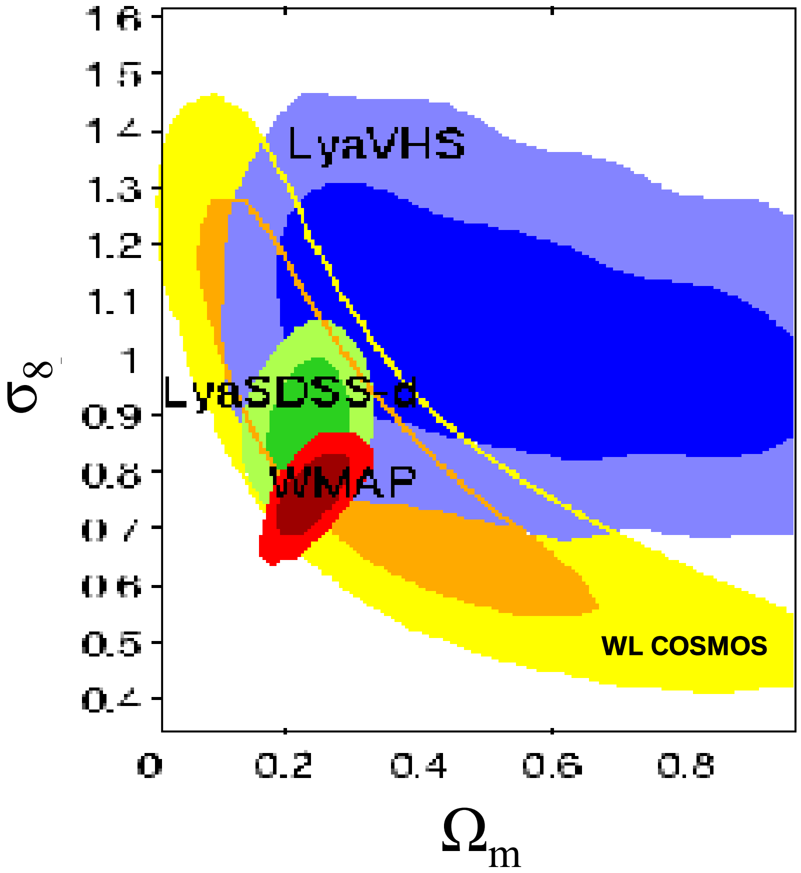


See R. Massey's talk

Join analysis:

Cosmic Shear COSMOS + Lya VHS+ SDSS + WMAP3

Lesgourdes et al 2007



$\sigma_{8.}(\Omega_m/0.3)^{0.44}=$

0.81+/-0.07

Improving the statistics and consistency between surveys:

join weak lensing survey analysis+ better n(z)

<u>1. CFHTLS-Wide (1.5 yr):</u>
MEGACAM Hoekstra et al 2006

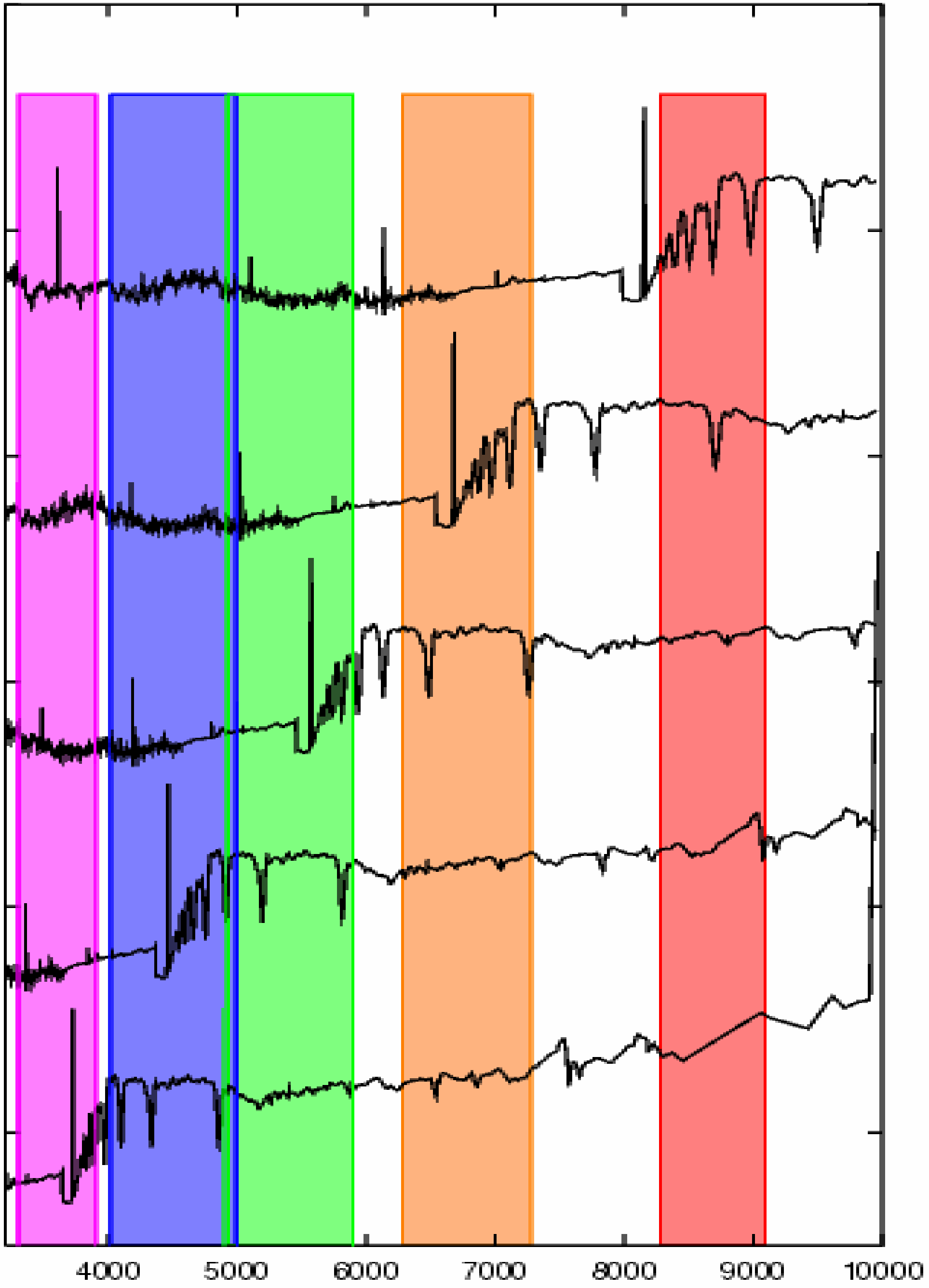
<u>2. CFHT-VIRMOS-Descart:</u>
CFHT12K, van Waerbeke, Mellier, Hoekstra 2005

<u>3. CFHT-RCS:</u>
CFH12K, Hoekstra et al 2002

<u>4. ESO-GaBoDS:</u>
WFI Hetterscheidt et al 2006

Merging the 4 surveys:

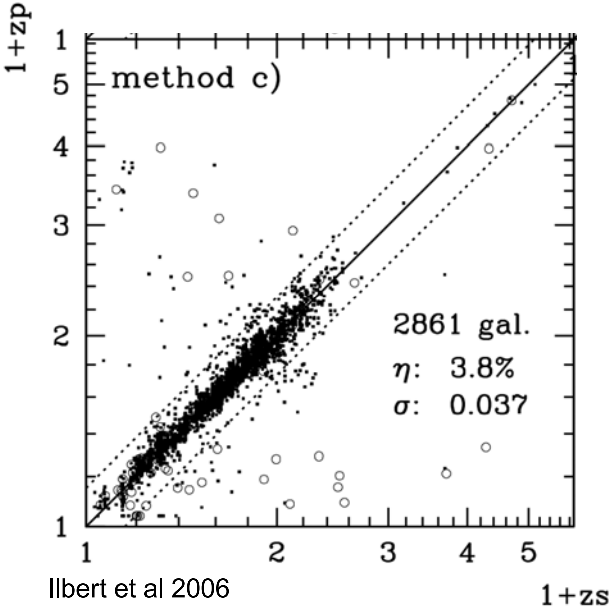
Benjamin et al 2007: 100 deg^2



Photometric redshift

Bernardeau & Mellier 2003

The uncertain n(z)



Ilbert et al 2006

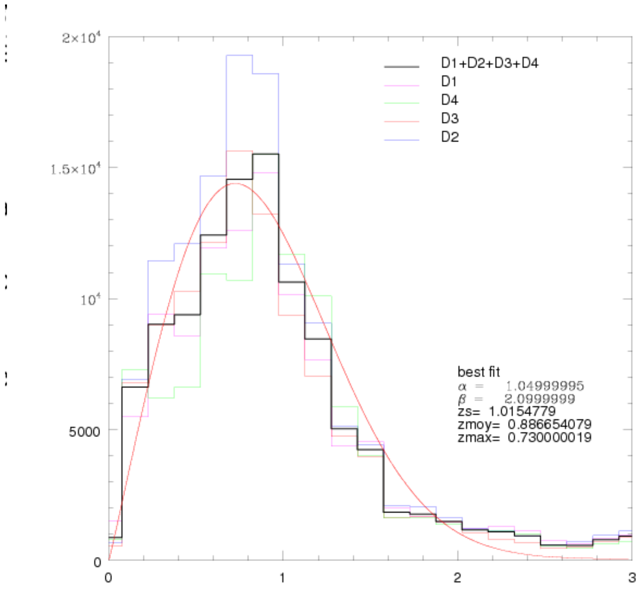


Photo-z in CFHTLS deep

550000 galaxies with photo-z

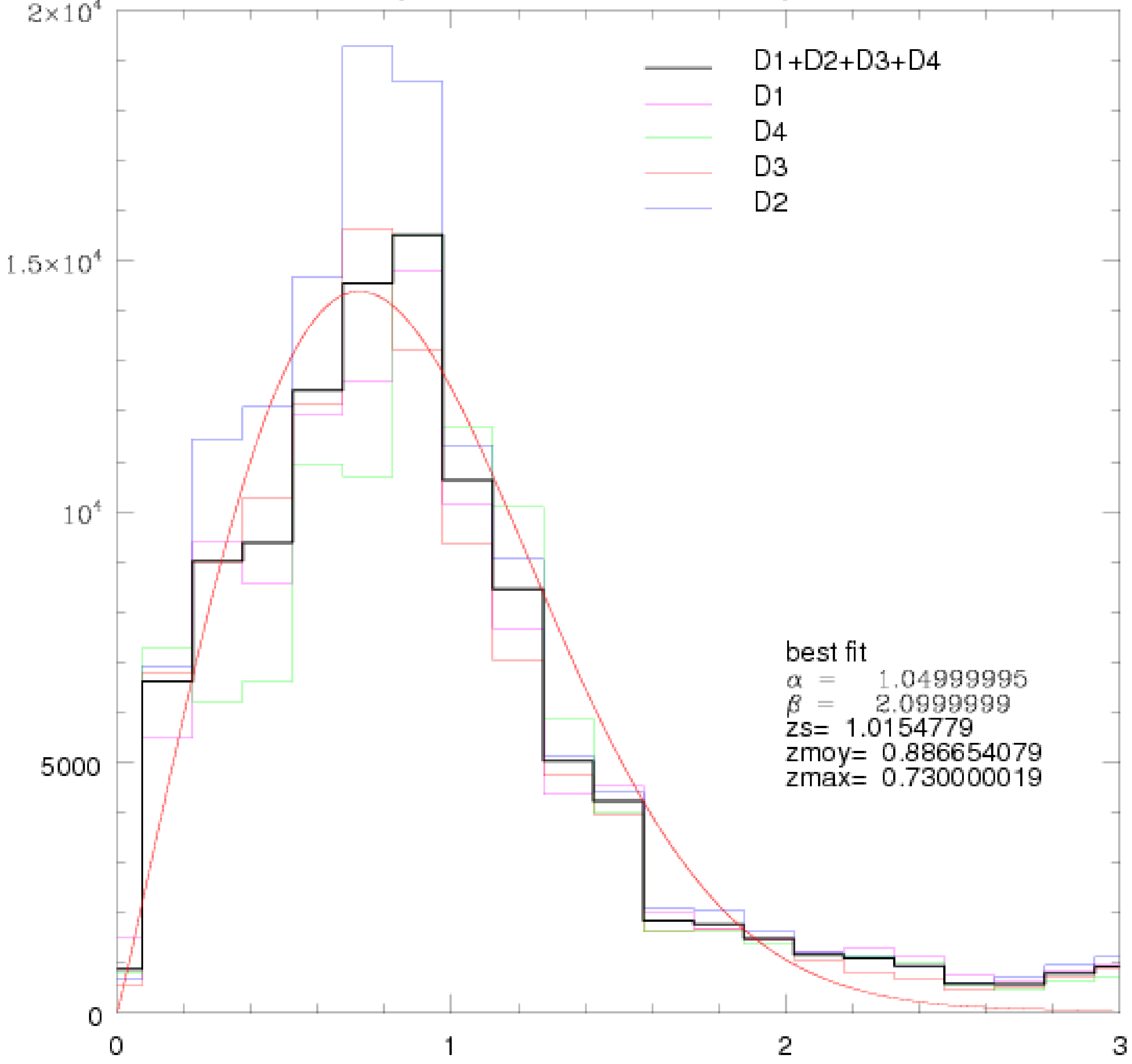
- HDF size too small as compared to CFHTLS: sampling variance increases error by 10% (van Waerbeke et al 2006)

- CFHLTS Deep photometry + ESO / VLT / VVDS spectroscopic survey of CFHTLS D1 field

- Photo-z from CFHTLS-Deep + VVDS: Seem to peak at higher *z* than our HDF *z*-calibration.

The uncertain n(z)

CFHLS Deep T0003+ VVDS specto calib.



HDF size too small as compared to CFHTLS: sampling variance increases error by 10% (van Waerbeke et al 2006)

Photo-*z* from CFHTLS-Deep + VVDS: Seem to peak at higher *z* than our HDF *z*-calibration? Would decrease σ_8

Cosmic Shear

VIRMOS-Descart +
CFHTLS-T0001 WIDE+Deep

WMAP3

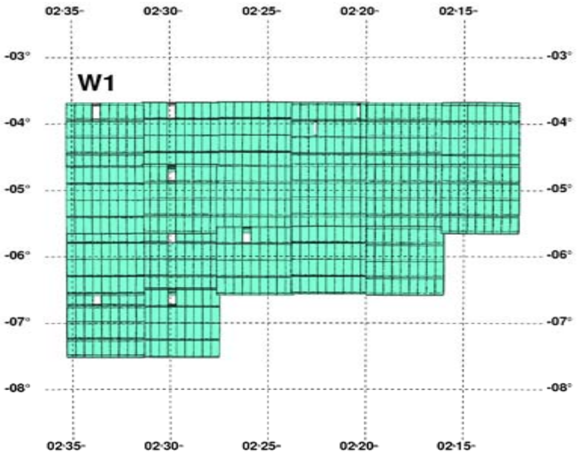
Benjamin et al 2006 In press

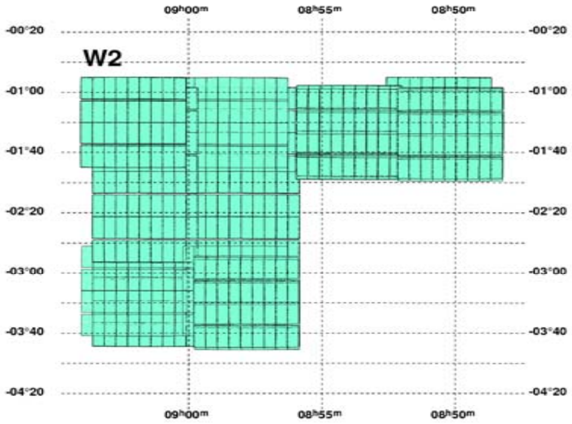
- Virmos-Descart +

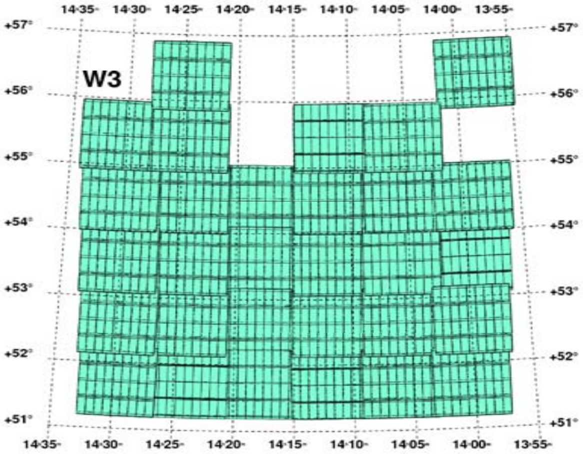
CFHTLS Deep+Wide

- Much better n(z)

CFHTLS T0003







-More sky coverage

-One more field

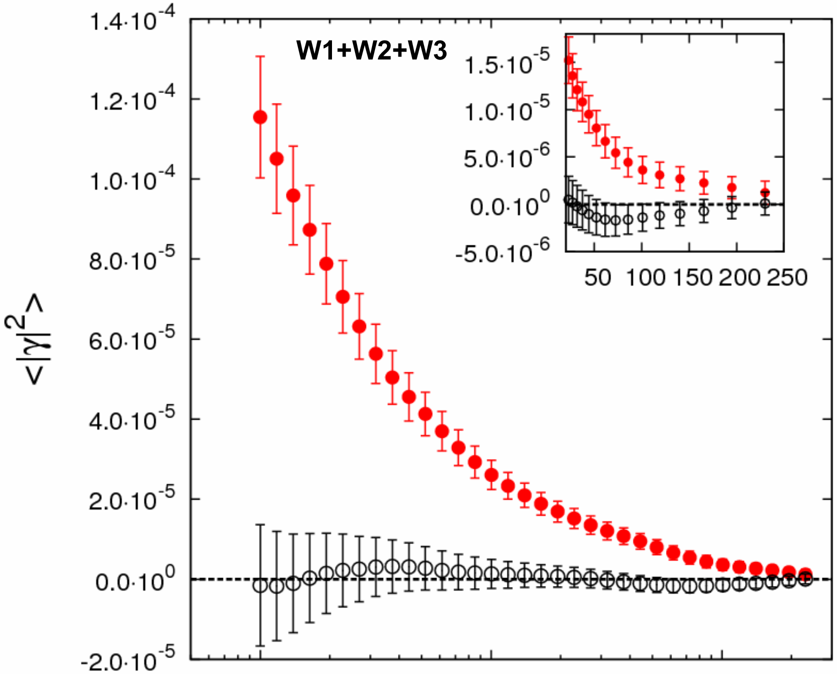
Much more angular scale

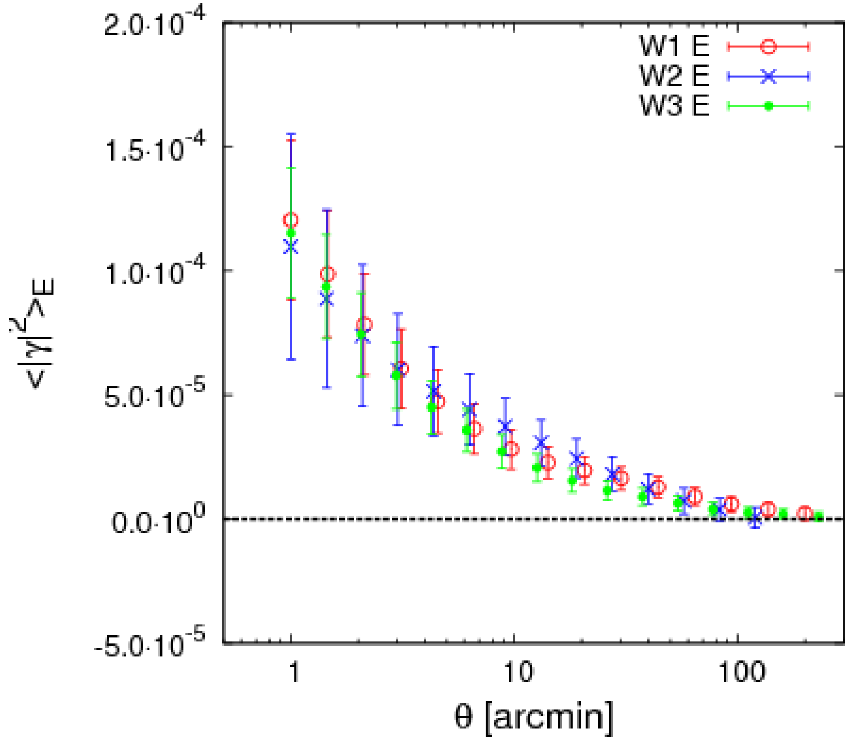
(1’ – 4 degrees: 85 Mpc@z=0.5)

- **Homogenous data** with photo-z from CFHTLS T0003 deep

Fu et al 2007

CFHTLS T0003:
comparing signal of each Wide





1′ ⟷ 4°

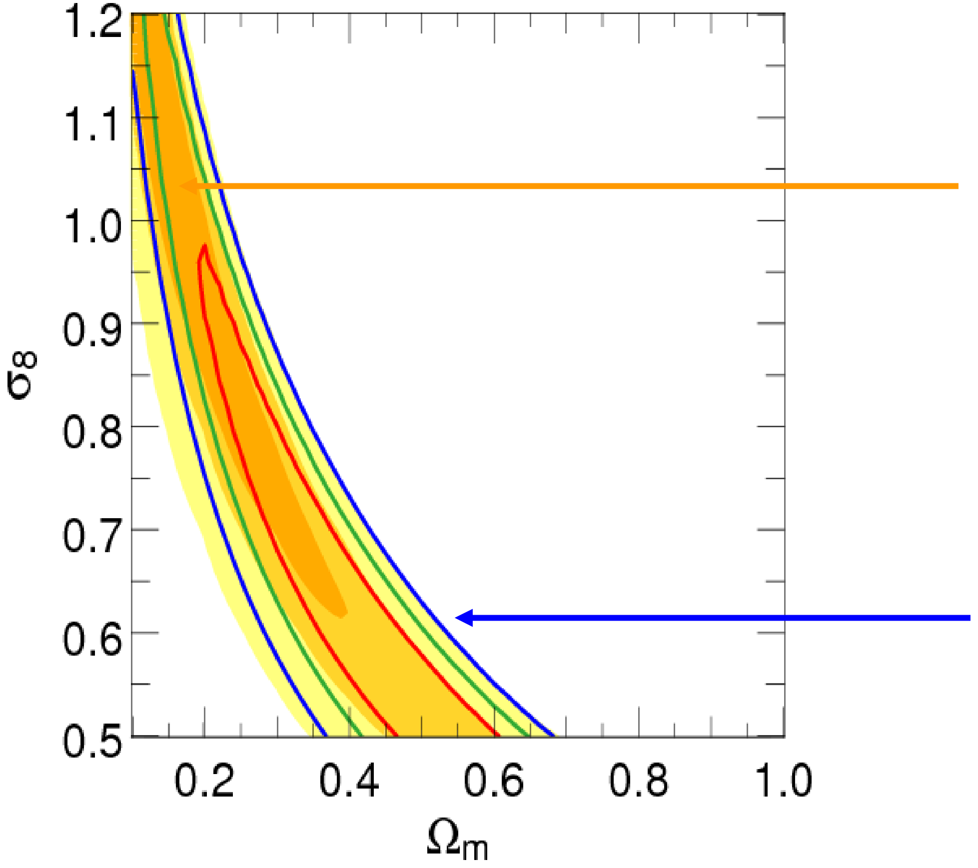
400kpc

85 Mpc

Fu et al 2007

CFHTLS T0003:

comparing cosmological contrains between Benjamin et al and Fu et al



Benjamin et al 100deg2 heterogenous

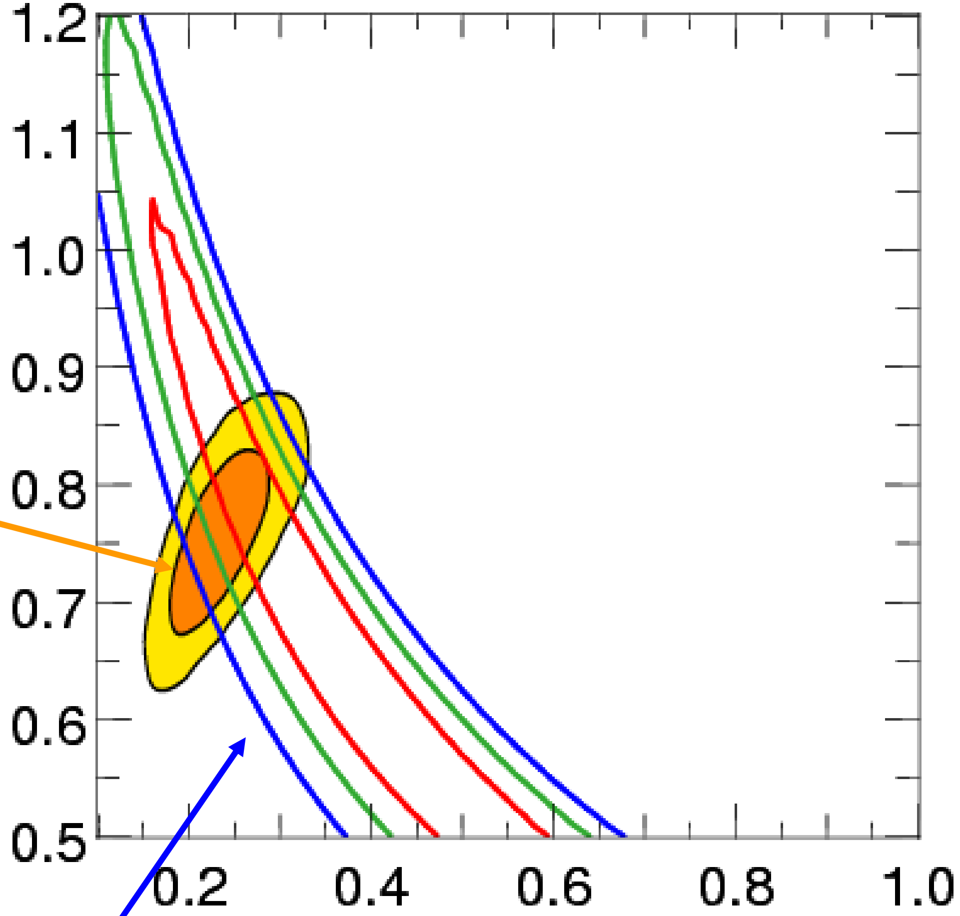
(scale 1’ – 40’)

Fu et al 2007: CFHTLS T0003 homogeneous

(scale 2’- 230’)

Fu et al 2007

CFHTLS T0003 and WMAP3



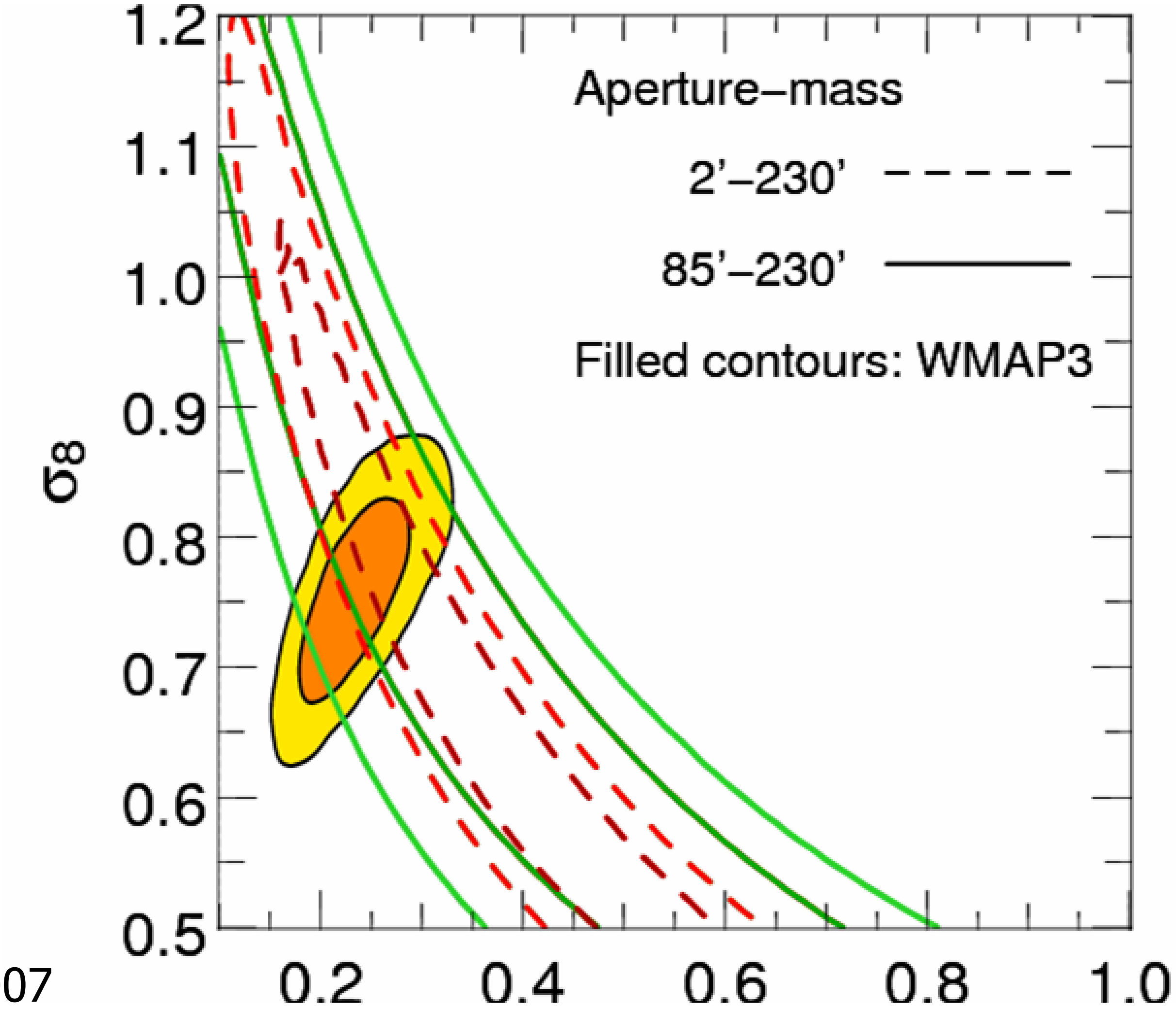
WMAP3

CFHTLS T0003

Fu et al 2007

CFHTLS T0003:

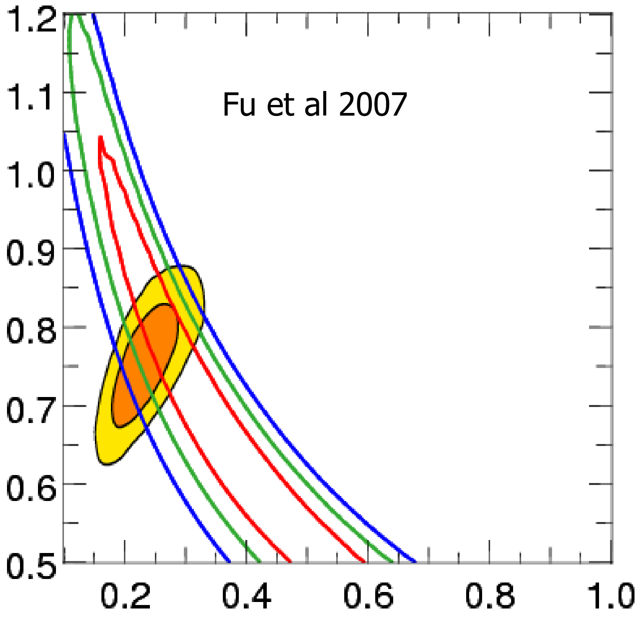
toward a linear analysis of weak lensing and CMB



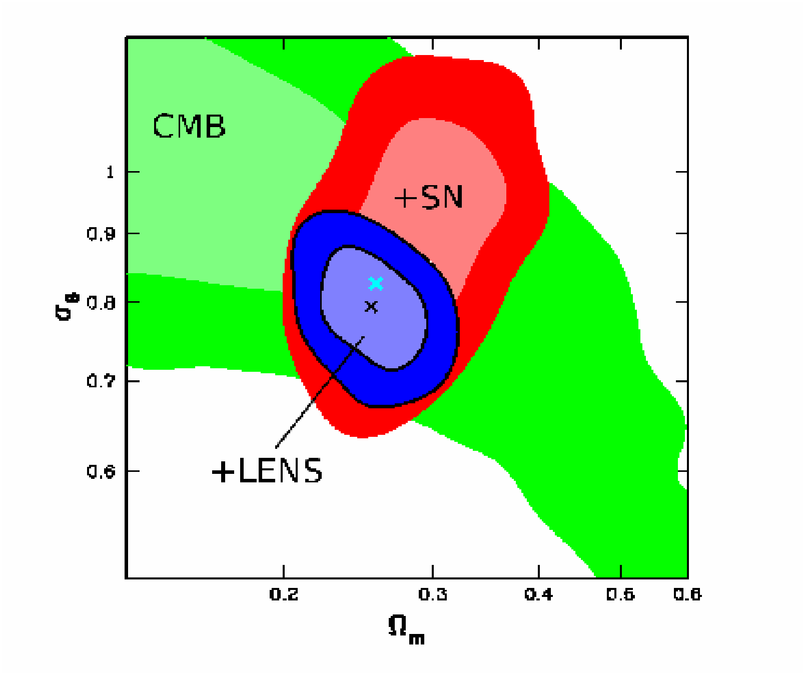
Fu et al 2007

Ω_m-σ_8 : no more tension

Deep CFHTLS T0003 / shallow CTIO 75 deg^2



With SNIa + CMB



Jarvis, Jain, Bernstein, Dolney 2005

CFHTLS cosmic shear summary

The main issues were n(z):

- faint high-redshift tail,
- sampling variance,
- non Gaussian corrections to cosmic variance

Non linear evolution of P(k) still produce a 2.5% systematics : need better numerical simulations

CFHTLS T0003 : scales up to 85 Mpc at $z=0.3$ with
57 deg^2 + Deep photo-z in the same fields.

Convergence $\sigma_8 = 0.80$? : $\Omega_m - \sigma_8$ to better than 5%

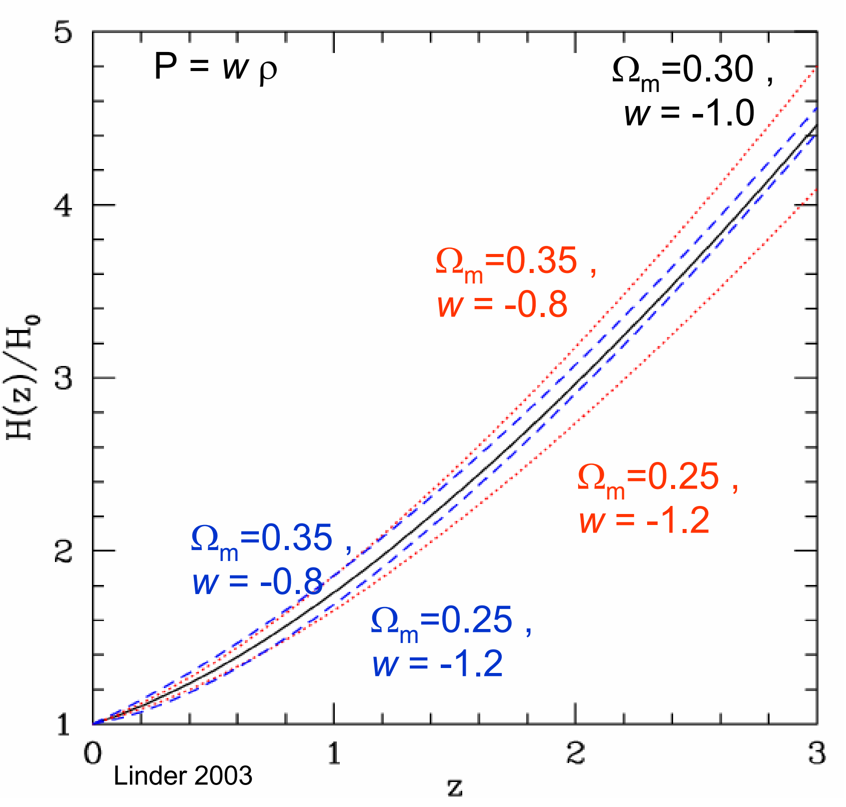
Dark Energy

exploring the role of dark energy on the growth rate of structures

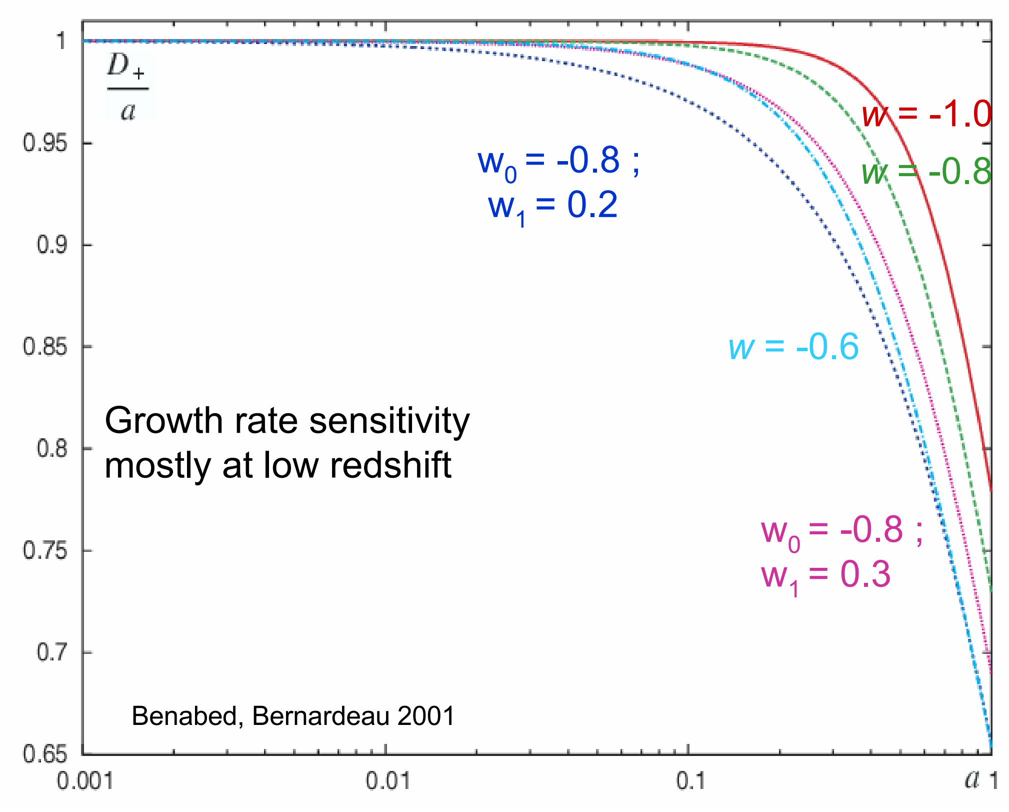
Projected matter distribution and dark energy

$$\kappa_{eff} = \frac{3H_0^2\Omega_0}{2c^2}\int_0^{\omega} \overbrace{\frac{f_K(\omega-\omega')\, f_K(\omega')}{f_K(\omega)}}^{\text{Geometry}}\, \overbrace{\frac{\delta\left[f_K(\omega')\,\boldsymbol{\theta};\omega'\right]}{a(\omega')}}^{\text{Power spectrum, growth rate of structure } D_+} d\omega'$$

The Universe with Dark Energy



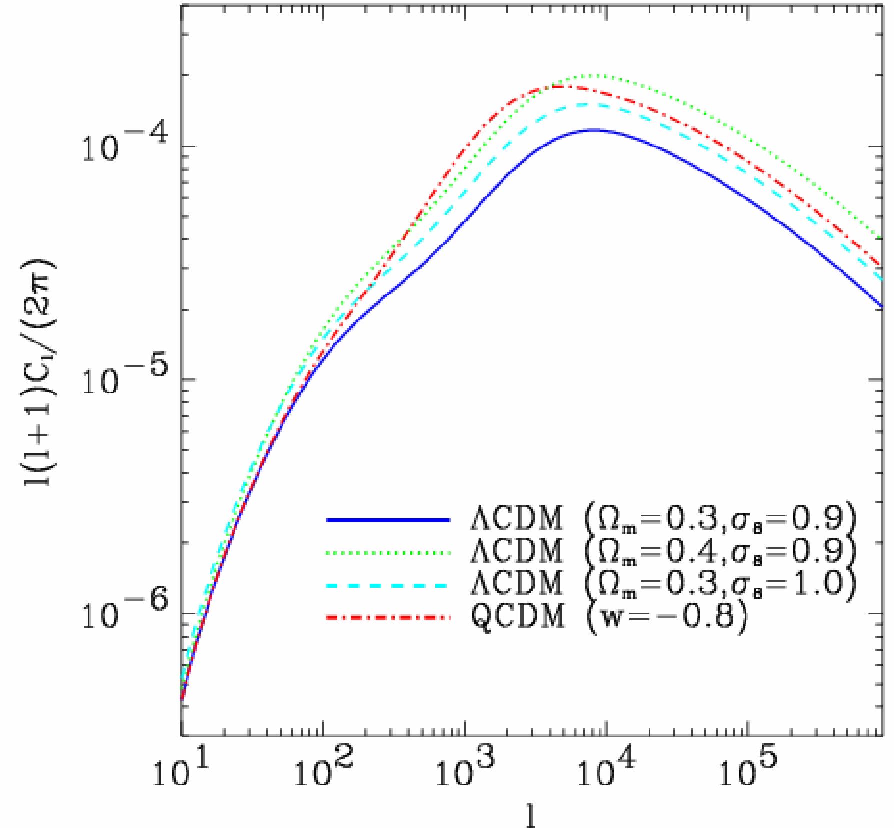
Linder 2003

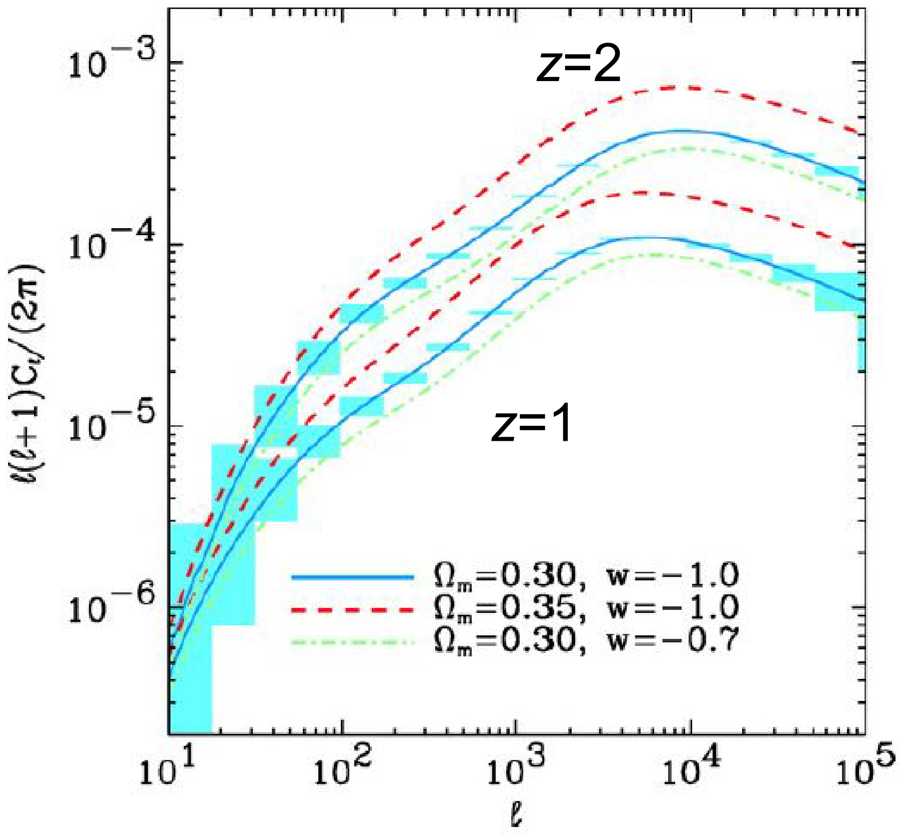


Growth rate sensitivity mostly at low redshift

Benabed, Bernardeau 2001

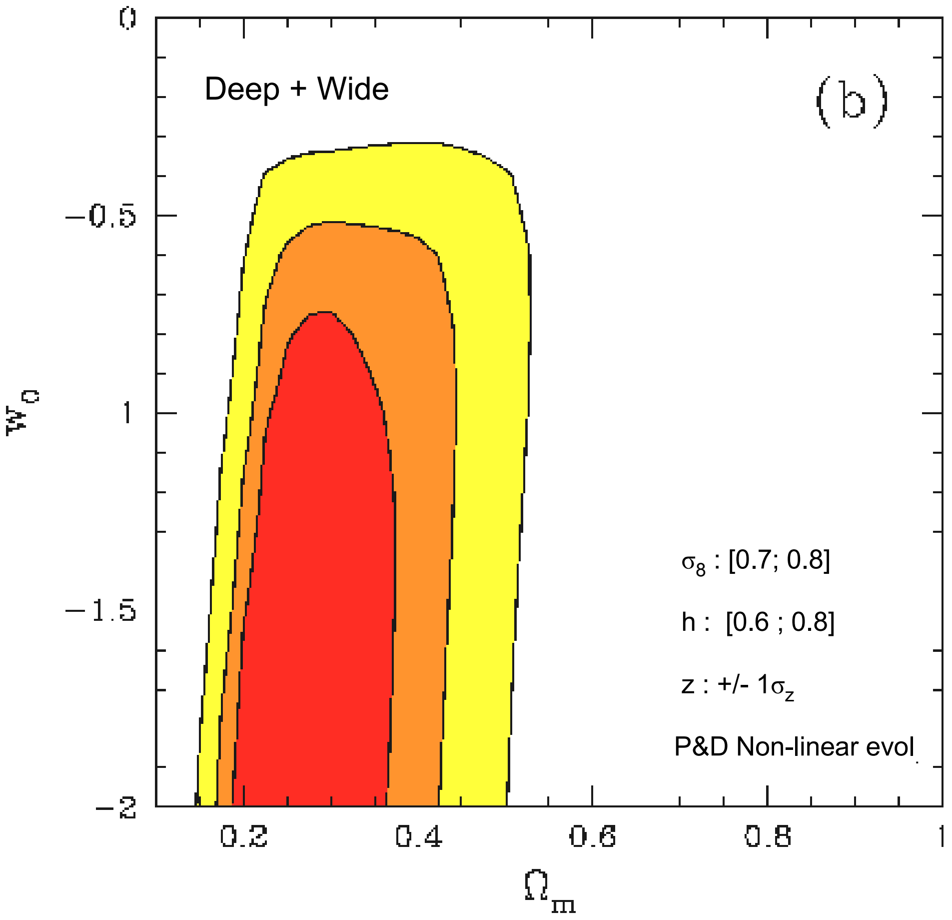
Cosmic shear surveys and dark cosmological models : exploring the power spectrum





CSLS: constraints on Dark Energy $P = w_0 \rho$

Deep + Wide : $w_0 < -0.8$ (68%) ; $w_0 < -0.4$ (99%)



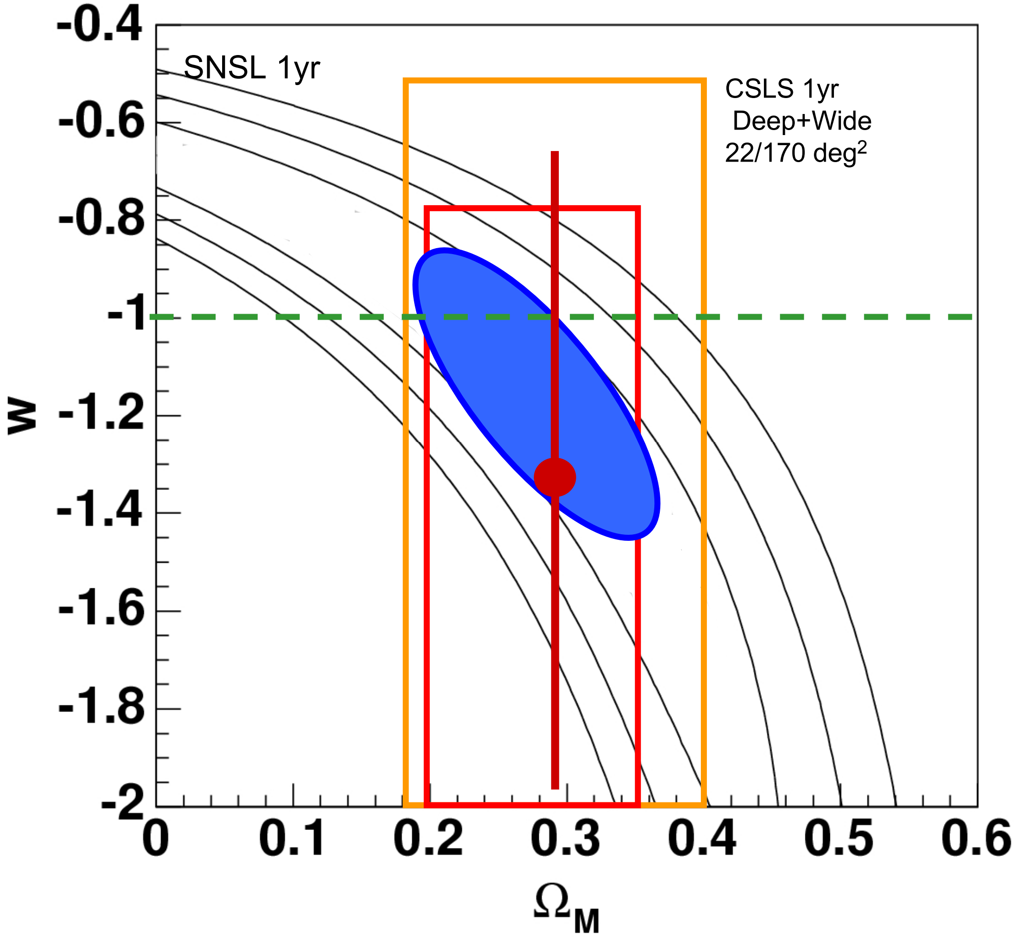
Hoekstra et al 2006 , Semboloni et al 2006

Flat universe

$n = 1$

w = -1 ?

CFHTLS T0001+SNLS +COMBO-17



Astier et al 2005+ Semboloni et al 2006+Hoesktra et al 2006

Exploring physical models of dark energy with CFHTLS cosmic shear data:

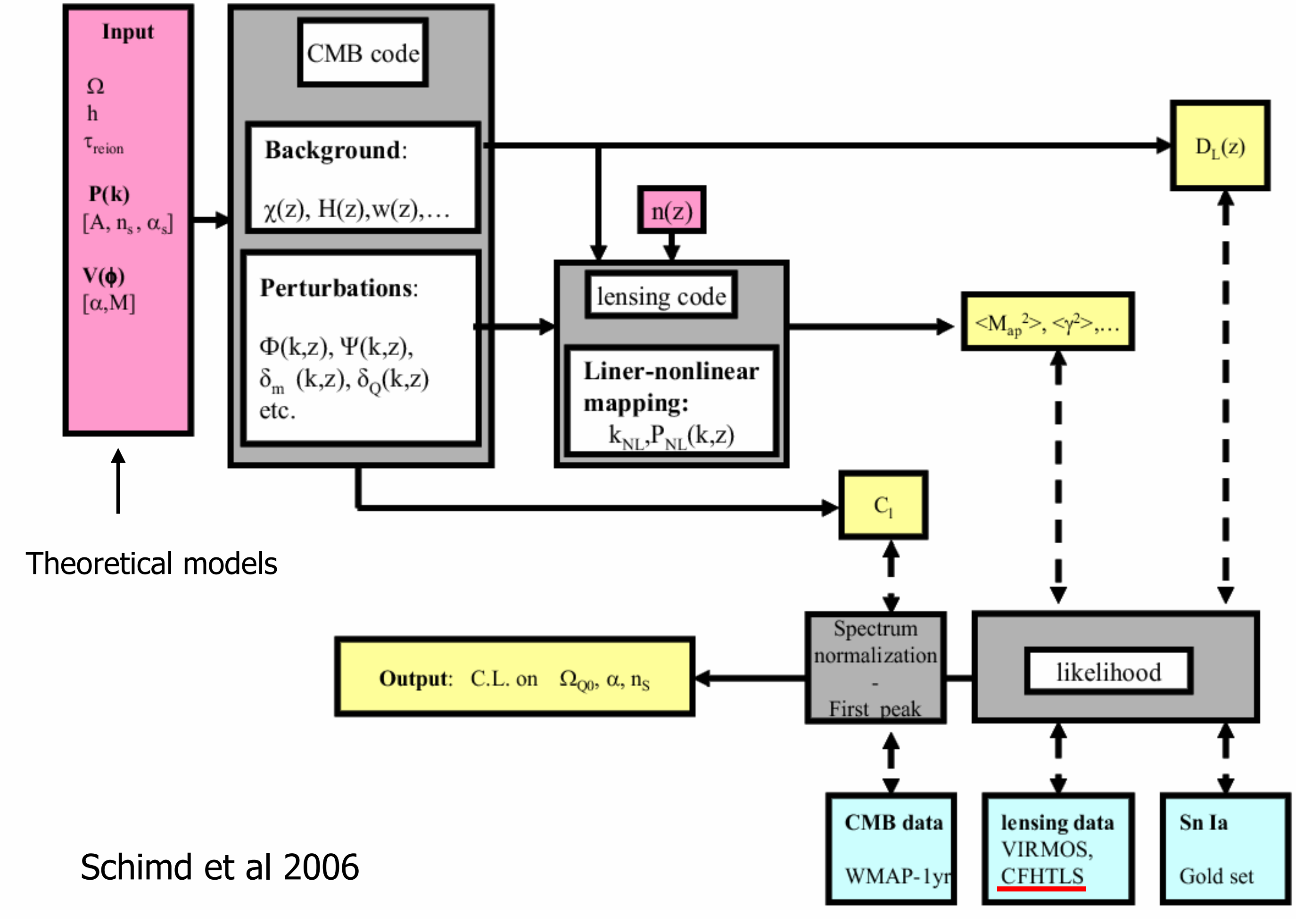
quintessence models

- Physical models:
  - Less general than the « empirical » and more conservative $P=w\rho$, but can challenge physical models to data
  - Can explore eolution with redshift. Avoid pivot redshift problems on joint data or in case $w(z)$ evolved at high z
  - Can be used in a coherent model with description of the evolution of perturbations and CMB data (normalisation , no use of σ_8)

PB: non linear evolution unknown for these models:

Peacock & Dodds and Halo models used

Cosmology with physical Dark Energy models

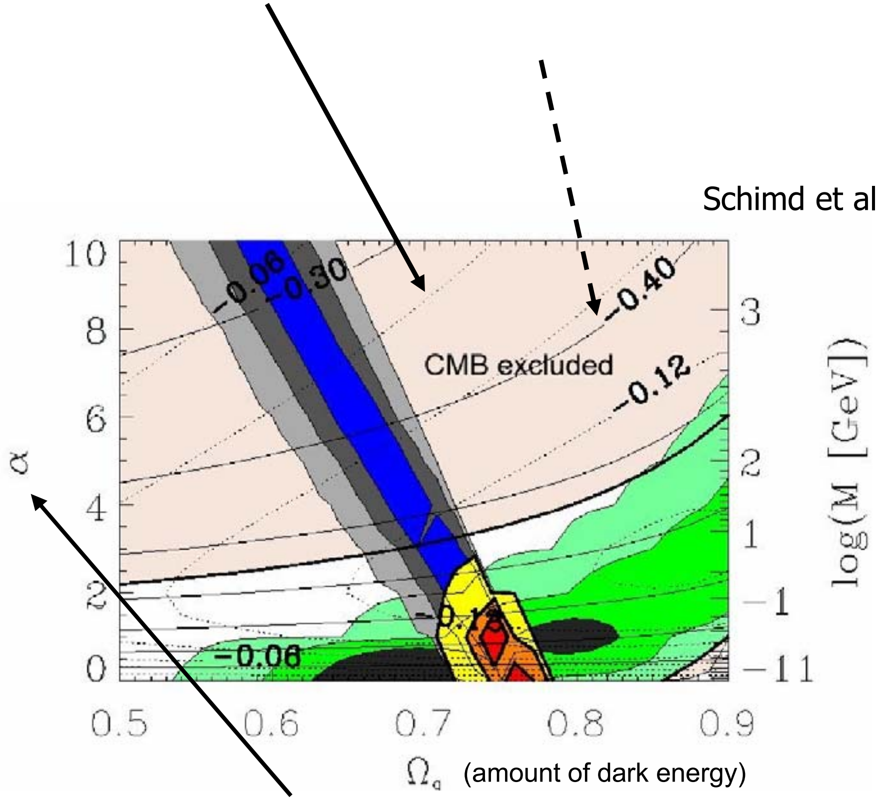


Theoretical models

Schimd et al 2006

Exploring quintessence models

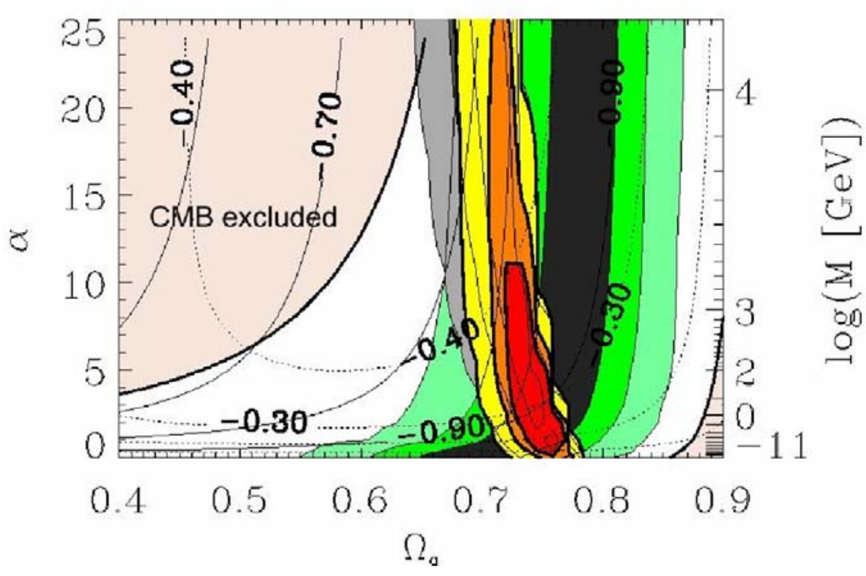
Schimd et al 2006



(amount of dark energy)

RP: $V(Q)=M^4(Q/M_p{}^{-\alpha}$

Ratra-Peebles



SUGRA: $V(Q)=M^4(Q/M_p)^{-\alpha}\ \exp(Q^2/2M_p{}^2)$

SUGRA

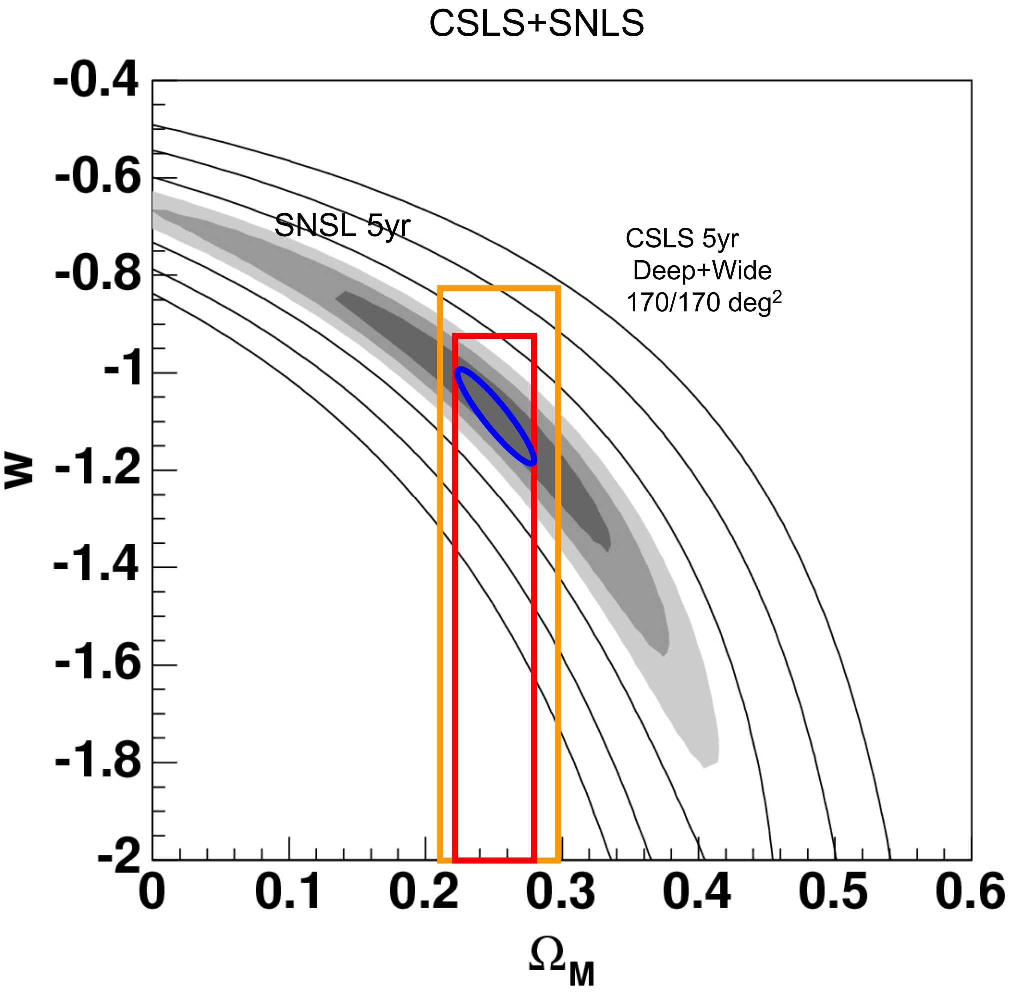
Cosmic shear Deep+Wide + SNIa gold set + WMAP-1

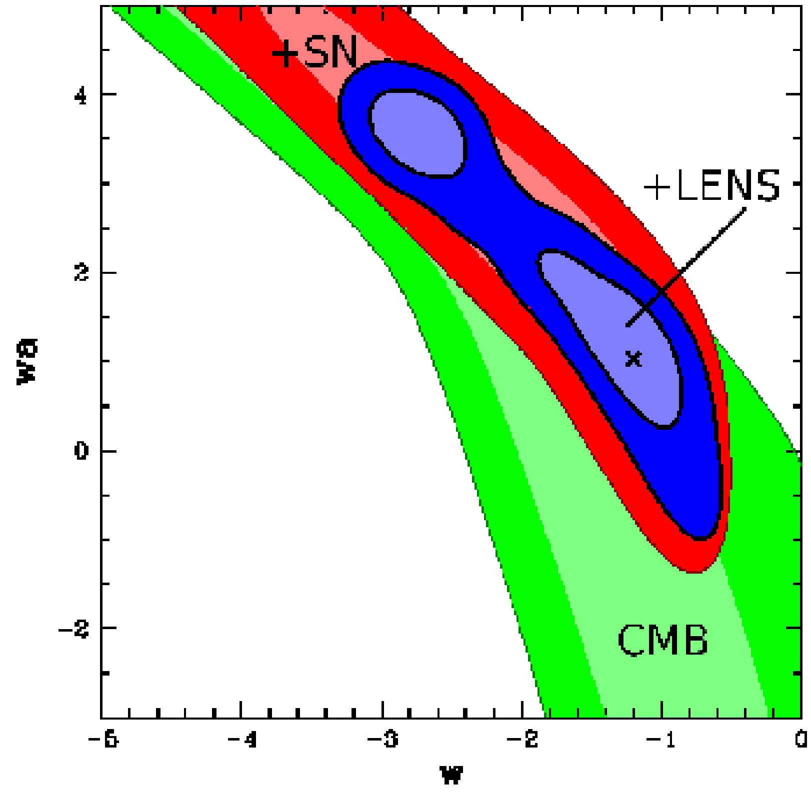
Next: explore $w(z)$

- Previous plots: assume w is constant
- Still missing precision to get a detailled description of dark energy properties
- Still concerns with systematics

Synergy CFHTLS: SNLS+CSLS

5 years (expectations): still far from getting w_a





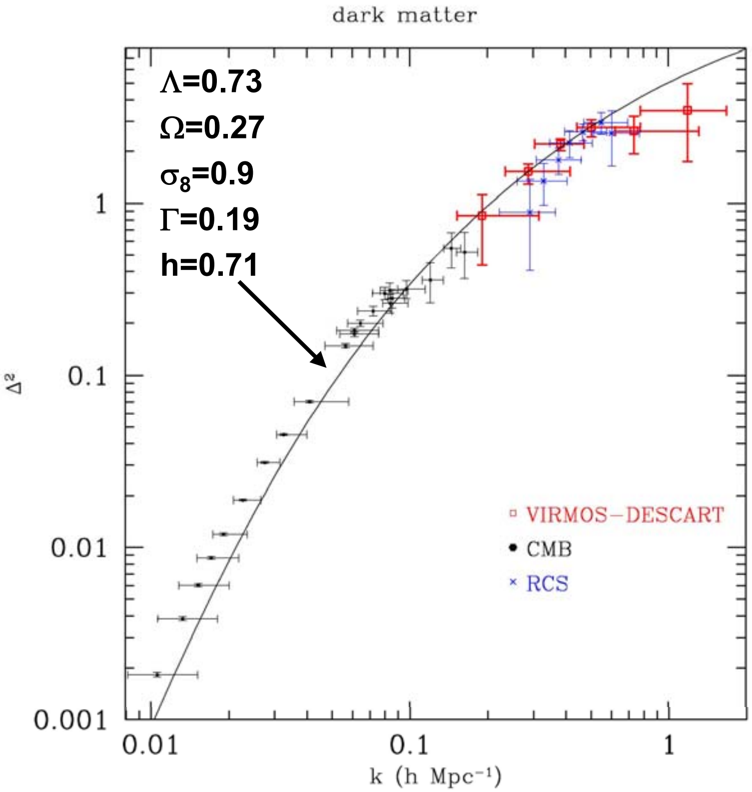
Jarvis, Jain, Bernstein, Dolney 2005

What next ?

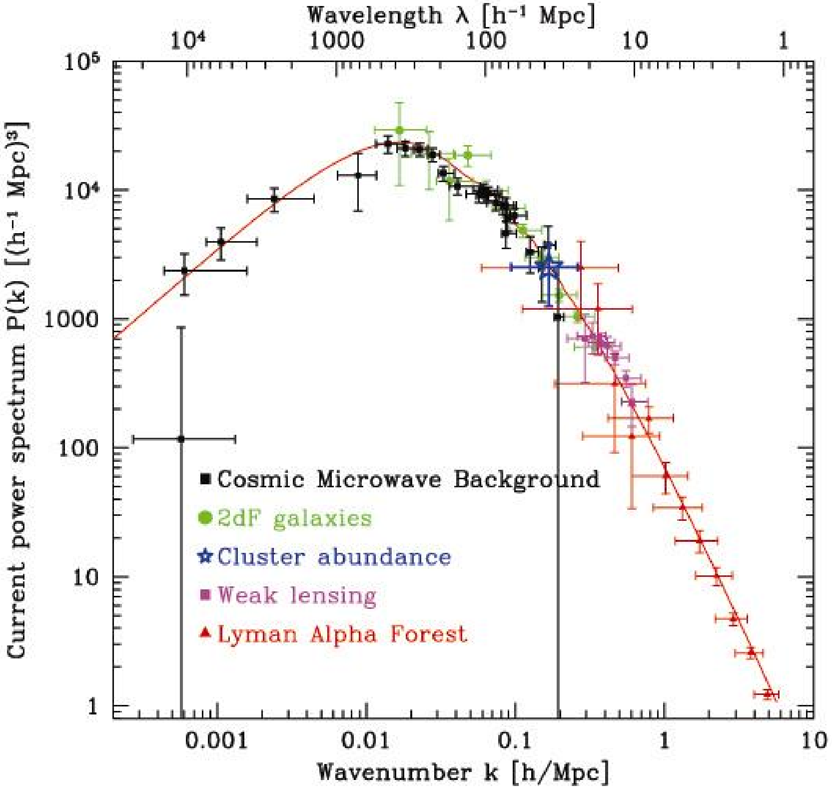
Not fully explored yet

- Photo-z for the full Wide survey
- 2-D/3-D power spectrum reconstruction
- Mass reconstruction and projected dark matter maps
- Real 3-D tomography
- Decoupling geometry and power spectrum
- Galaxy (light)-Mass-Map cross correlation: biasing
- Galaxy-galaxy lensing
- Exploring $w(z)$

3D dark matter reconstruction



Pen, Lu, van Waerbeke, Mellier 2003



Tegmark & Zaldarriaga (2002)

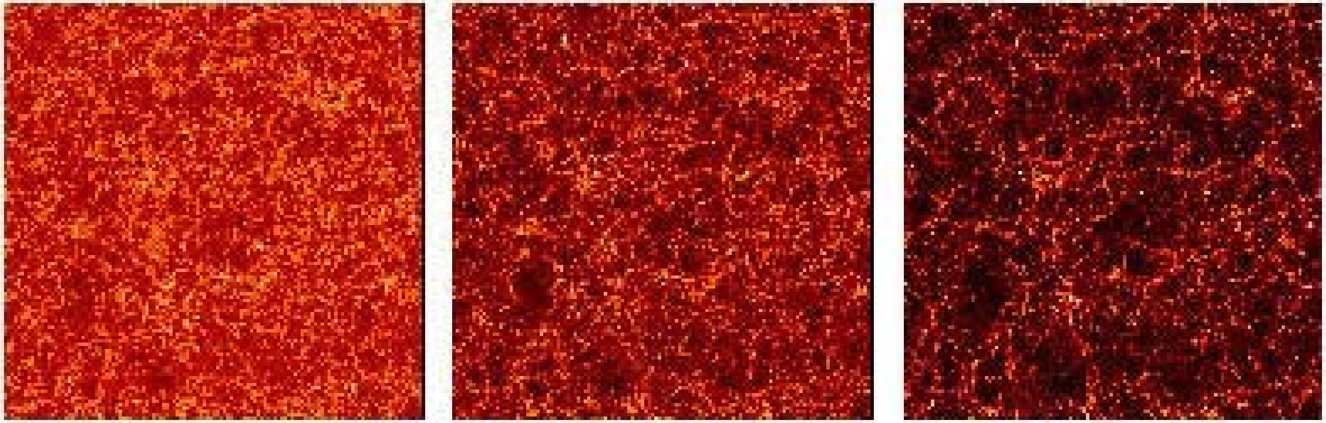
Still in a early phase, but

- Very promising for next generation surveys
- Evolution with photo-z +spectro-z likely feasible

(see also, Heavens 2003, Taylor et al 2003)

Breaking degeneracies with tomography

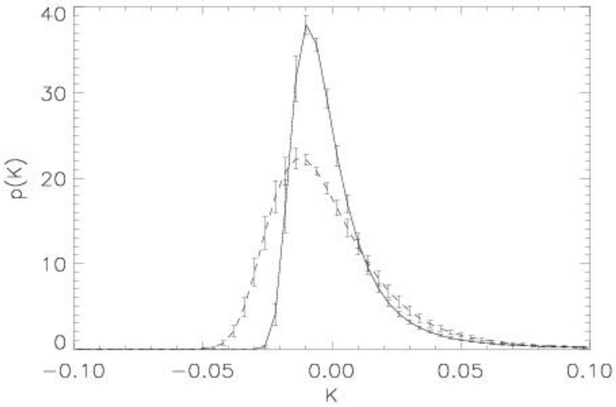
Ω_m-σ_8 degeneracy with higher order statistics: Skewness of the convergence



Assuming a single lens-plane and $P(k) \propto k^n$:

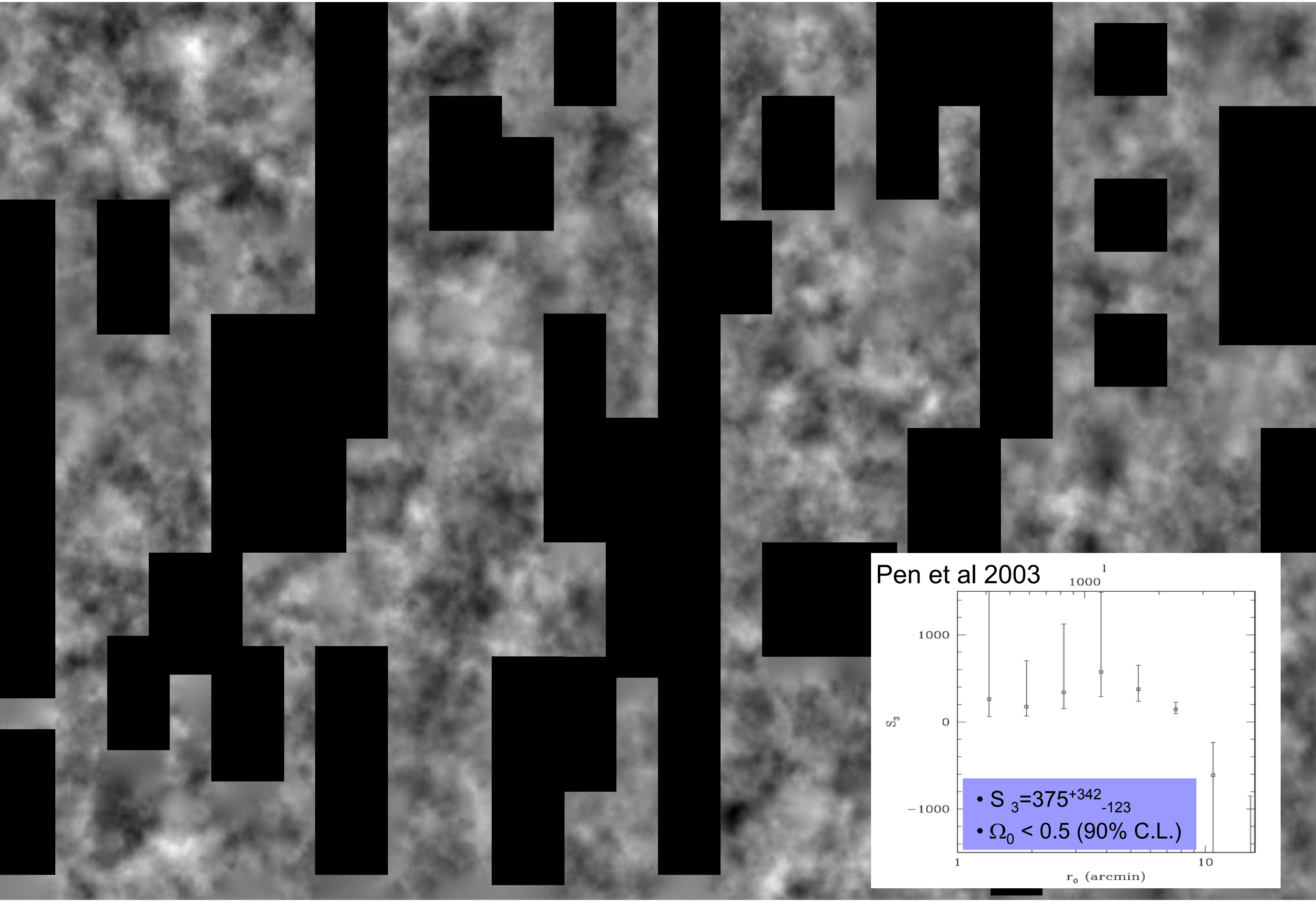
- $\langle\kappa^2(\theta)\rangle^{1/2} \approx 0.01\ \sigma_8 \Omega^{0.8} \left(\frac{\theta}{1\mathrm{deg.}}\right)^{-\frac{n+2}{2}} z_s^{0.75}$
- $\langle\kappa^2(\theta)\rangle = \langle\gamma^2(\theta)\rangle$
- $S_3(\kappa) \approx 40\ \Omega^{-0.8}\ z_s^{-1.35}$

Bernardeau, van Waerbeke, Mellier 1997,
Jain & Seljak 1997
Need mass maps for skewness



- Distribution increasingly skewed by gravity that will produce non-linear structures (clusters, groups, galaxies):
- $S_3(\kappa)$ will provide a statistical description of these non-linear systems

MASS MAP Skewness of the convergence measured in VIRMOS-Descart data



Pen et al 2003

- $S_3 = 375^{+342}_{-123}$
- $\Omega_0 < 0.5$ (90% C.L.)

Next Generation Cosmic Shear Surveys

Goal: dark energy properties know to 5%-1% (50%-20% today)

Larger field of view

Multiple lens planes (tomography)

Accurate 3D positions of lensed galaxies and lenses

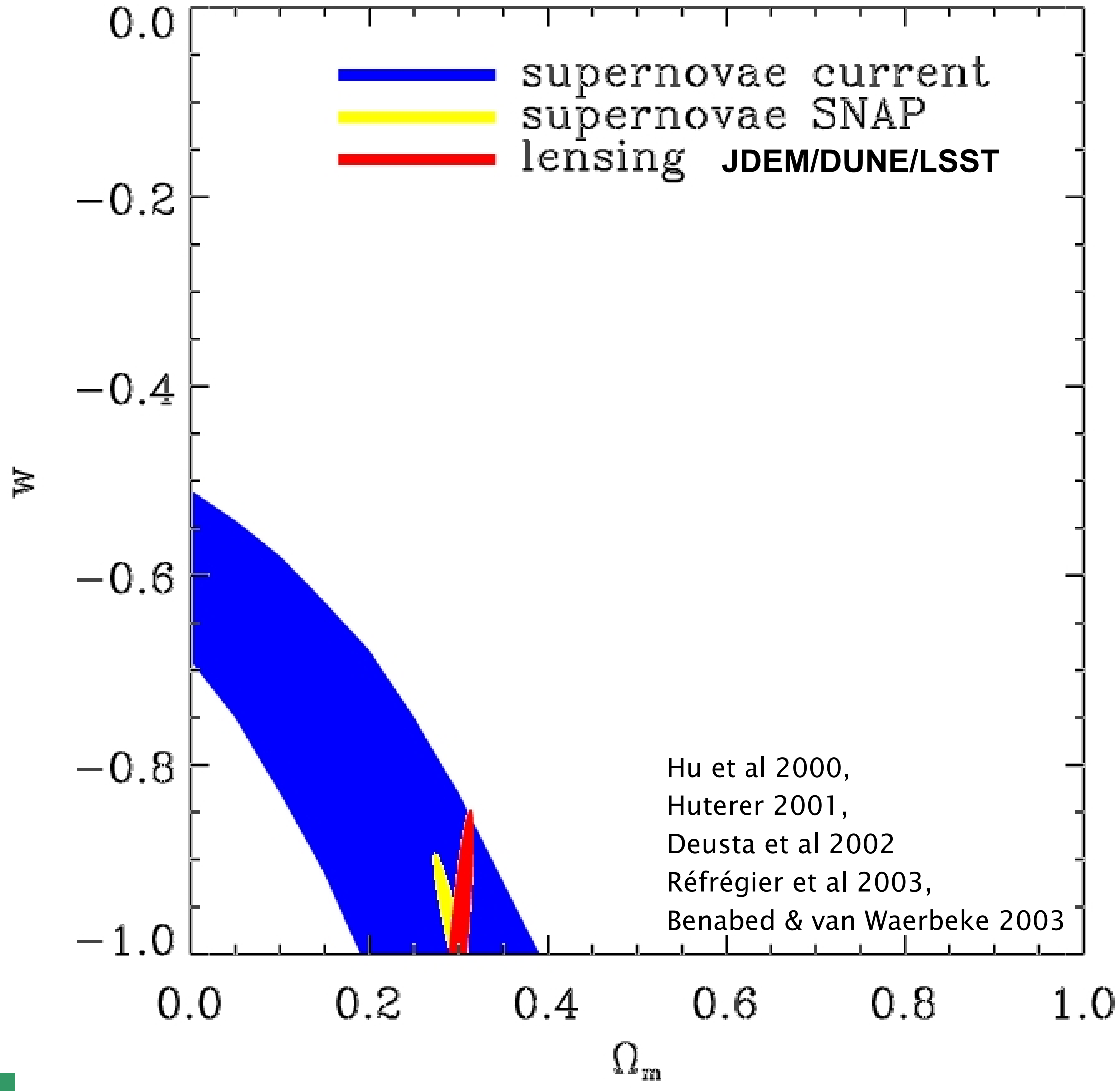
Better accuracy on galaxy shape measurements

Future Progress

Survey	Sq. Degrees	Filters	Depth	Dates	Status
CTIO	75	1	shallow		published
VIRMOS	9	1	moderate		published
COSMOS	2 (space)	1	moderate		complete
DLS (NOAO)	36	4	deep		complete
Subaru	30?	1?	deep	2005?	observing
CFH Legacy	170	5	moderate	2004-2008	observing
RCS2 (CFH)	830	3	shallow	2005-2007	approved
VST/KIDS/ VISTA/VIKING	1700	4+5	moderate	2007-2010?	50%approved
DES (NOAO)	5000	4	moderate	2008-2012?	proposed
Pan-STARRS	~10,000?	5?	moderate	2006-2012?	~funded
LSST	15,000?	5?	deep	2010-2020?	proposed
JDEM/SNAP	1000+ (space)	9	deep	2013-2018?	proposed
VST/VISTA	5000?	4+5	moderate	2010-2015?	proposed
DUNE	20000? (space)	2+1?	moderate	2012-2015?	proposed

KIDS + CFHTLS Wide + CFHTLS Deep: 3 lens planes

The ultimate step ?



Hu et al 2000,
Huterer 2001,
Deusta et al 2002
Réfrégier et al 2003,
Benabed & van Waerbeke 2003