Weak Gravitational Lensing

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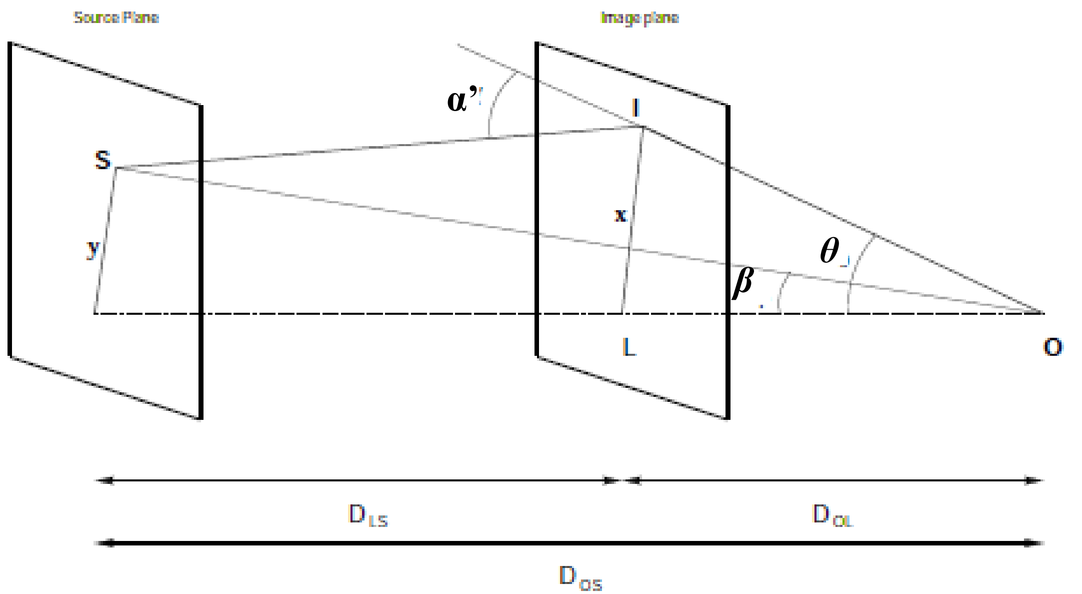
IAP

Paris, Sept. 15, 2009

Gravitational lensing

weak field limit, small deflection angle, stationary lens



Lens equation

$$\beta = \theta - \alpha'(\theta)$$

Deflection angle and projected mass density

$$\alpha'(\theta) = \frac{4G}{c^2}\frac{D_{OL}D_{LS}}{D_{OS}}\int \Sigma(D_{OL}\theta')\frac{\theta-\theta'}{|\theta-\theta'|^2}\mathrm{d}^2\theta' = \frac{1}{\pi}\int\frac{\theta-\theta'}{|\theta-\theta'|^2}\kappa(\theta')\ \mathrm{d}^2\theta'\ ,$$

Image position shifted, image multiplication, achromatic effect

Gravitational lensing

Projected Newtonian gravitational potential

$$\psi(\boldsymbol{\theta}) = \frac{1}{\pi}\int \kappa(\boldsymbol{\theta}') \ln|\boldsymbol{\theta}-\boldsymbol{\theta}'| \, \mathrm{d}^2\theta' \quad \text{and} \quad \boldsymbol{\alpha}'(\boldsymbol{\theta}) = \frac{1}{\pi}\int \kappa(\boldsymbol{\theta}') \frac{\boldsymbol{\theta}-\boldsymbol{\theta}'}{|\boldsymbol{\theta}-\boldsymbol{\theta}'|^2} \, \mathrm{d}^2\theta' .$$

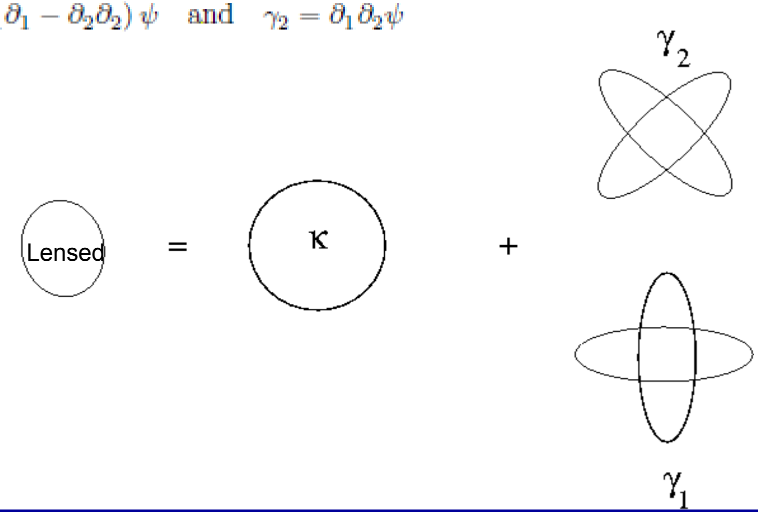
$$\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}'(\boldsymbol{\theta}) \longrightarrow \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} = \delta_{ij} - \frac{\partial^2 \psi(\boldsymbol{\theta})}{\partial\theta_i \partial\theta_j} = \delta_{ij} - \partial_i \partial_j \psi$$

Magnification, gravitational convergence κ and gravitational shear γ

$$M^{-1}(\boldsymbol{\theta}) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} = (1-\kappa)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} -\gamma_1 & -\gamma_2 \\ -\gamma_2 & +\gamma_1 \end{pmatrix}$$

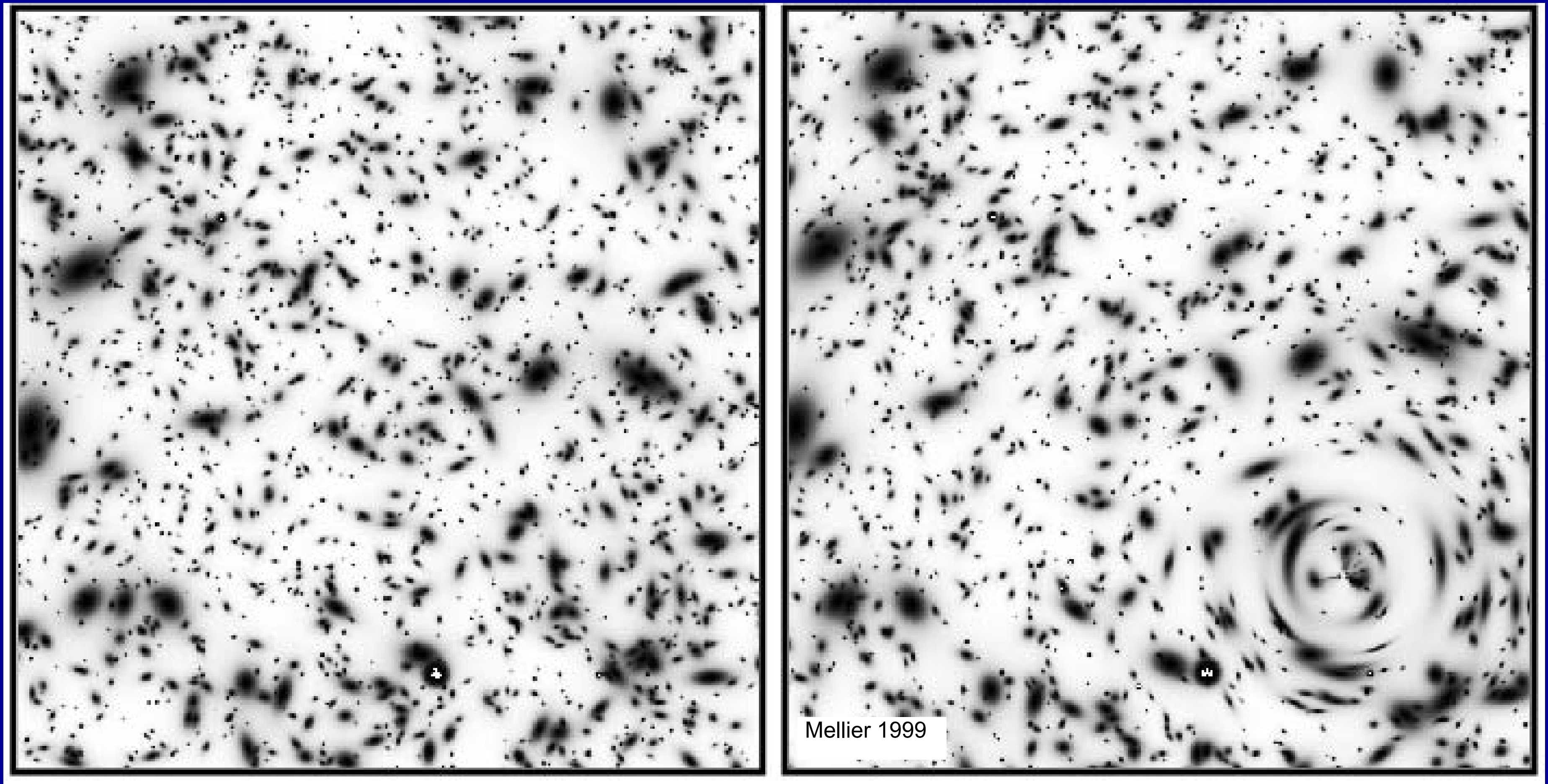
$$\kappa = \frac{1}{2}(\partial_1\partial_1 + \partial_2\partial_2)\psi$$

$$\gamma_1 = \frac{1}{2}(\partial_1\partial_1 - \partial_2\partial_2)\psi \quad \text{and} \quad \gamma_2 = \partial_1\partial_2\psi$$



Sampling the gravitational shear field on the sky:

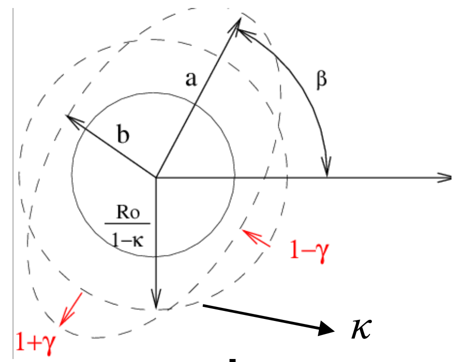
gravitational distortion of background sources

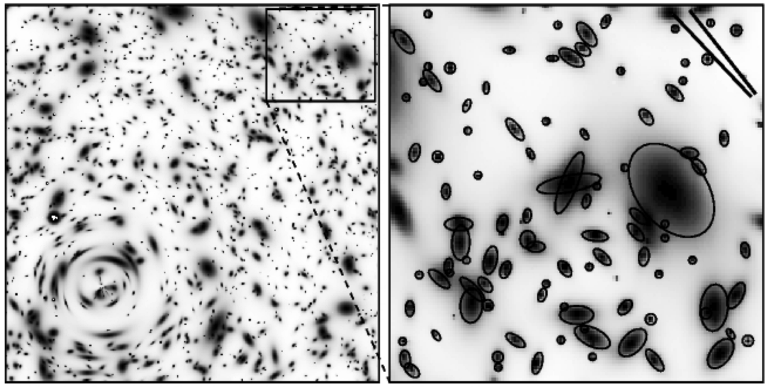


Simulated unlensed field

Same field lensed by an isothermal sphere lens mass model:
800 km/sec, z=0.3

Weak gravitational shear = ellipticity of galaxies





Mellier 1999

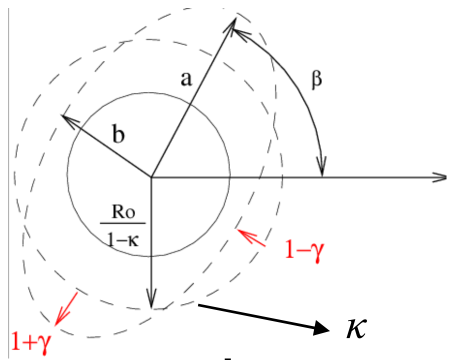
$$M_{ij} = \frac{\int I(\boldsymbol{\theta})\, \theta_i\, \theta_j\, \mathrm{d}^2\theta}{\int I(\boldsymbol{\theta})\, \mathrm{d}^2\theta}$$

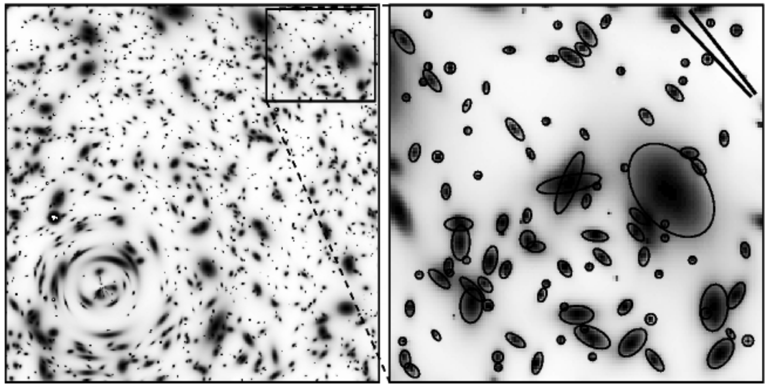
Weak Lensing: $2\gamma = \frac{a^2 - b^2}{a^2 + b^2}$

$$= \frac{a^2 - b^2}{a^2 + b^2}$$ → PSF correction

$$2\,\gamma = \varepsilon^I - \varepsilon^S$$

Weak gravitational shear = ellipticity of galaxies





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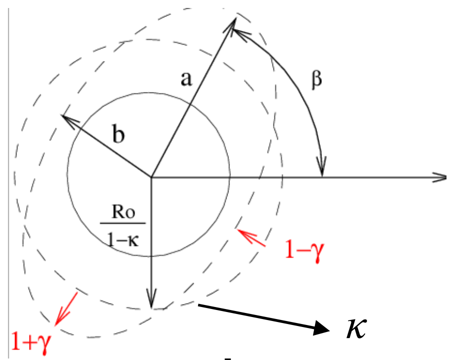
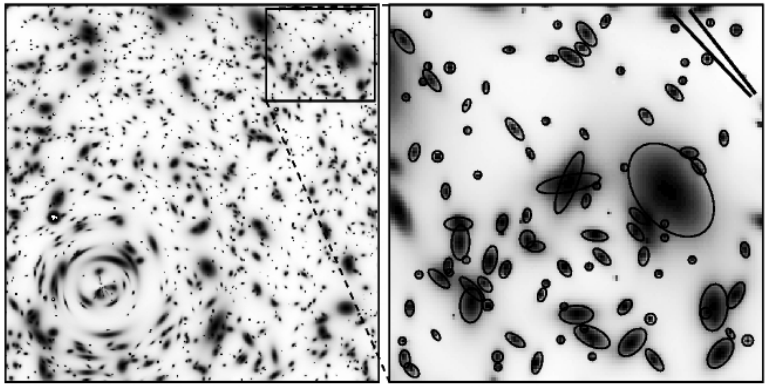
Assume sources orientation is isotropic:

$$2\,\gamma = \langle \varepsilon^{I} \rangle \rightarrow \kappa = \textbf{projected mass density}$$

Weak gravitational shear = ellipticity of galaxies





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↓

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… + noise + systematics

Probing the universe with strong/weak lensing

- **Galaxy-galaxy lensing** Hoekstra et al 2006, Mandelbaum et al 2006, Parker et al 2007, Kubo et al 2008
- **Galaxies/Groups : arcs/rings** Cabanac et al 2007, Bolton et al 2006, 2008, Gavazzi et al 2007
- **Clusters of galaxies** Kneib et al 1996, Johnston et al 2007, Hoekstra et al 2007, Oguri et al 2009, Ebeling et al 2009
- **Superclusters** Kaiser et al 1998, Gavazzi et al 2004, Heymans et al 2008
- **Dark matter vs. baryon distribution** Clowe et al 2004, 2006, Hoekstra et al 2007, Bergé et al 2008, Leauthaud et al 2009
- **Testing CDM haloes with gravitational lensing** Bartelmann 1996, Dahle et al 2003, Kochanel & Dalal 2004, Mandelbaum et al 2006, 2008, Leauthaud et al 2009
- **Is dark matter collisionless ?** Meneghetti 2001, Miralda-Escudé 2002, Randall et al 2008, Bradac et al 2008
- **Mass of DM particles/neutrinos** Li et al 2008, Gong et al 2008, Tereno et al 2009, Ichiki et al 2008
- **Large Scale structure, the dark matter power spectrum and cosmology**
- **Dark matter or modified gravity ?**

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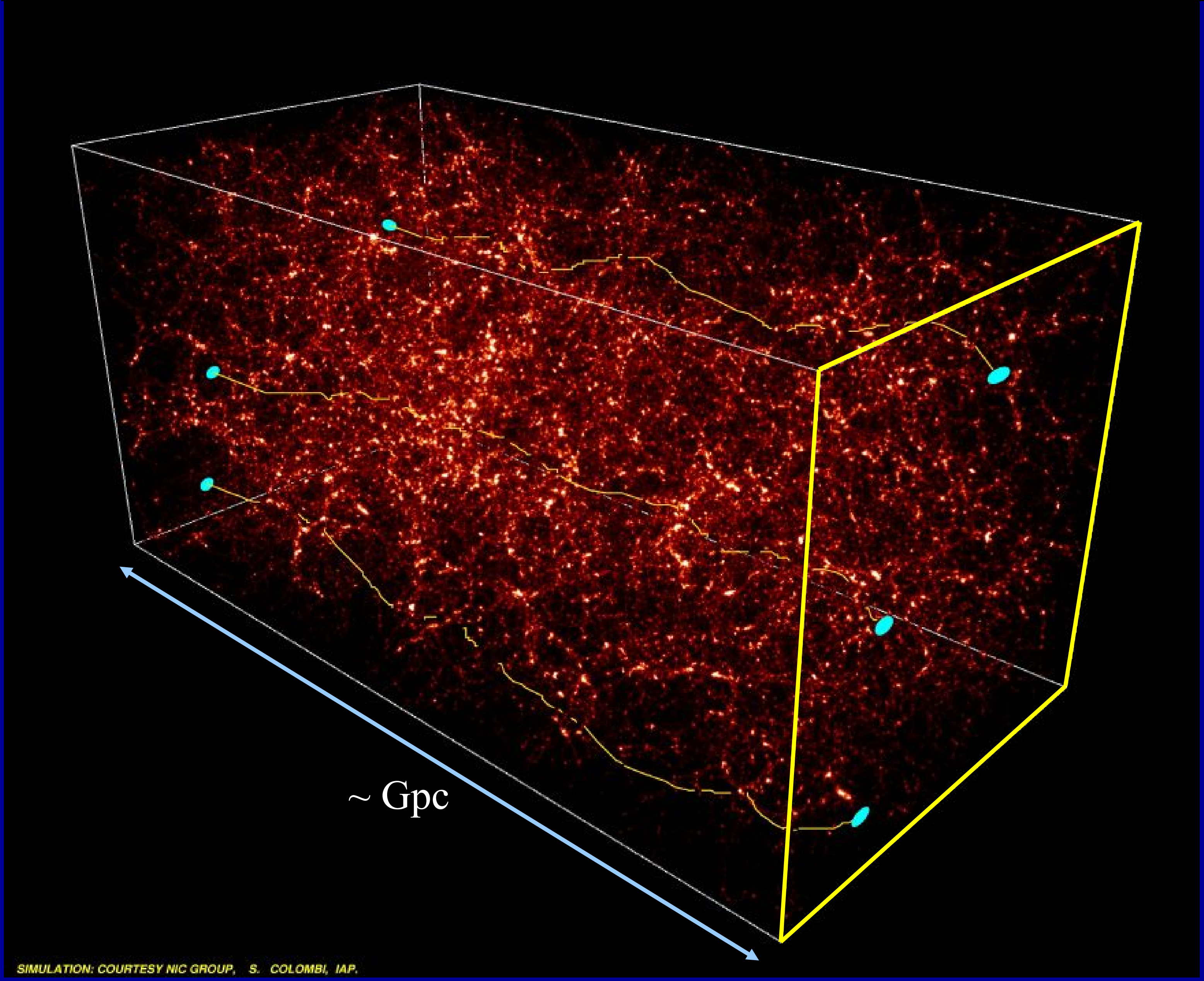
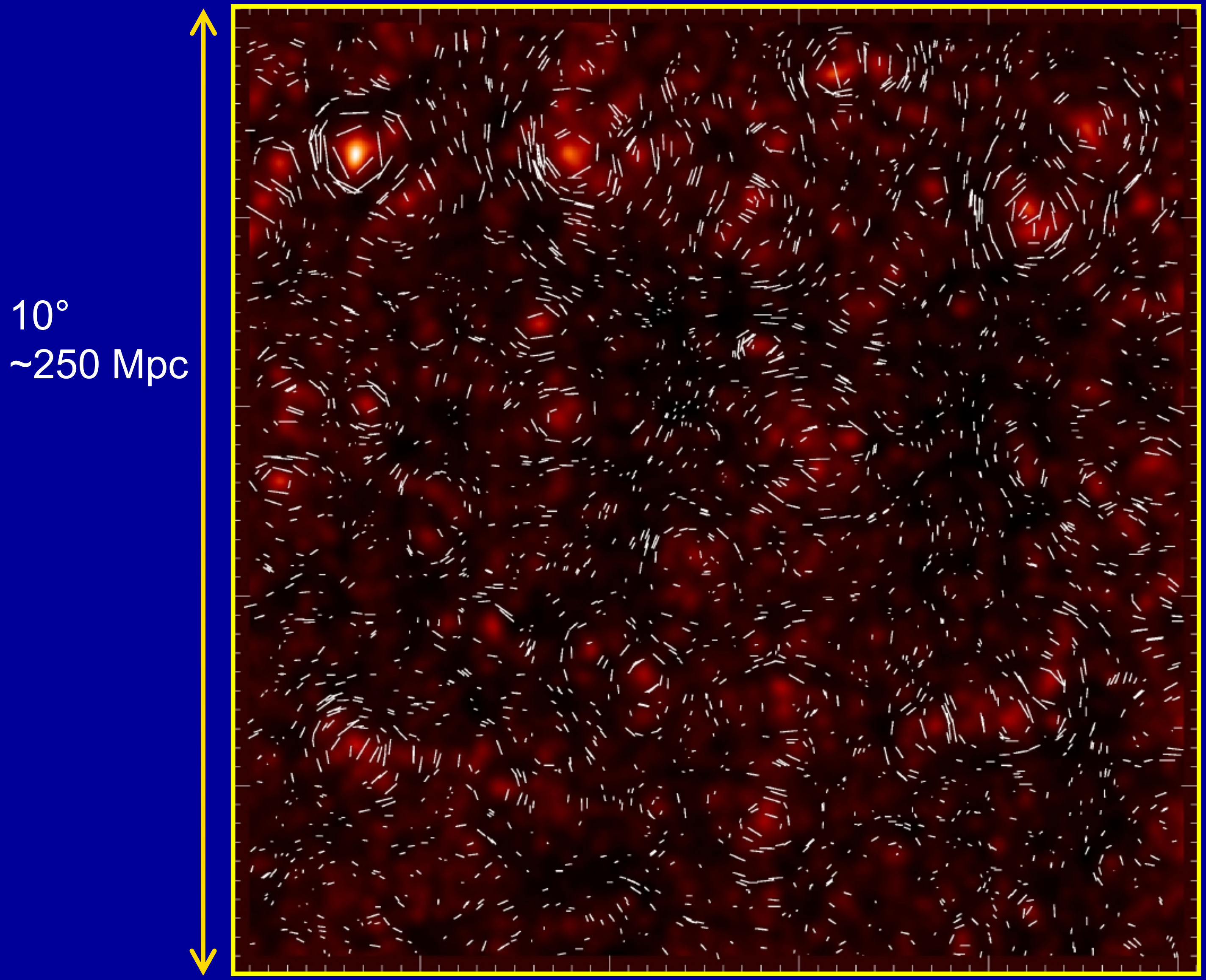
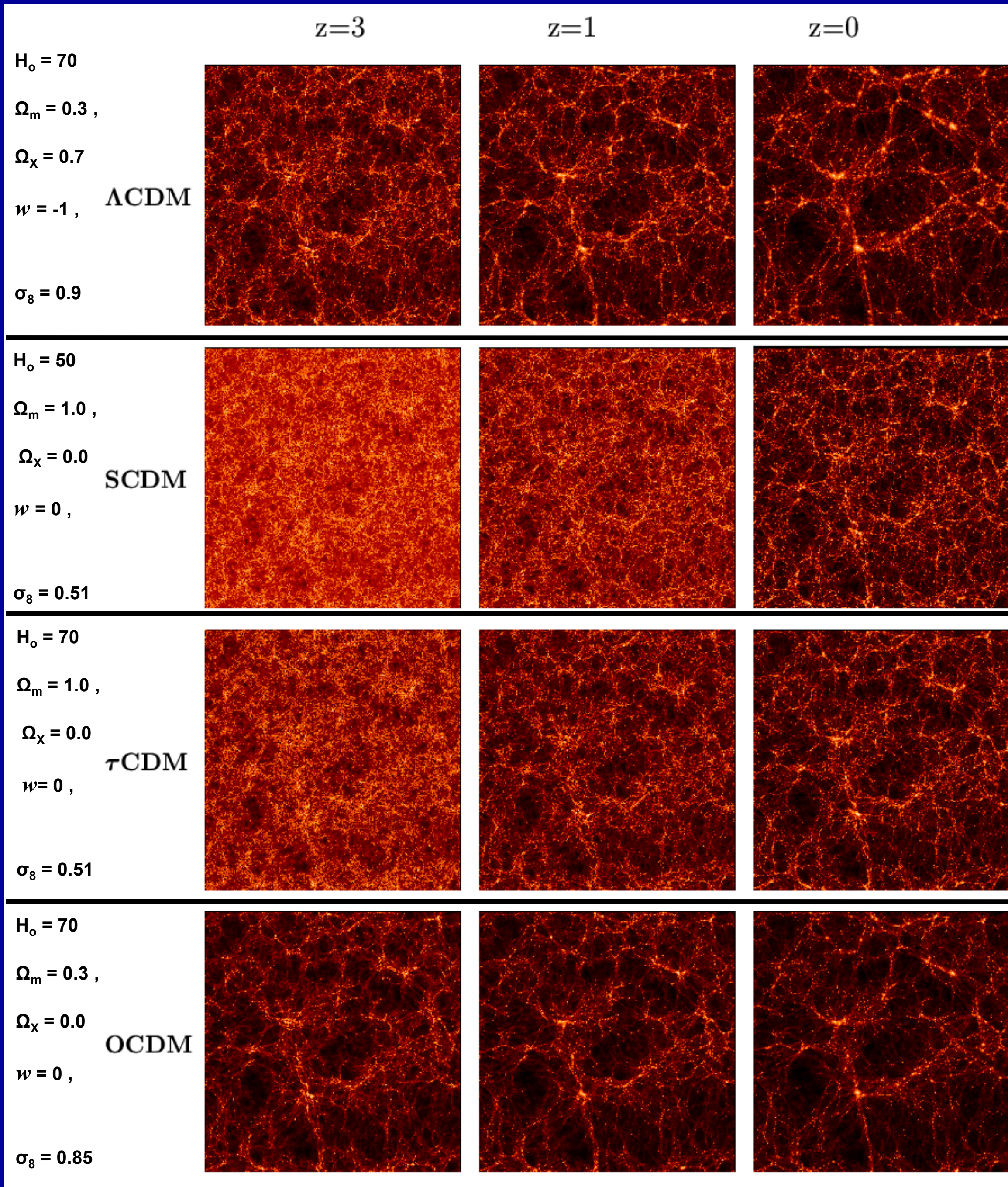
Cosmic shear : propagation of light through the cosmic web



Cosmological convergence, κ , and shear, γ ,fields

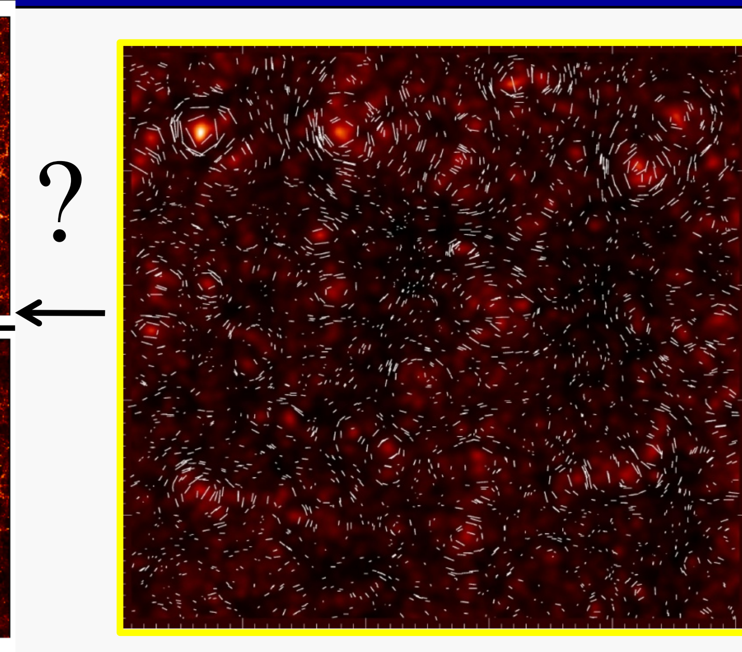




Understanding

- gravity and the dark universe,
- the gravitational instability scenario…

from the lensed universe



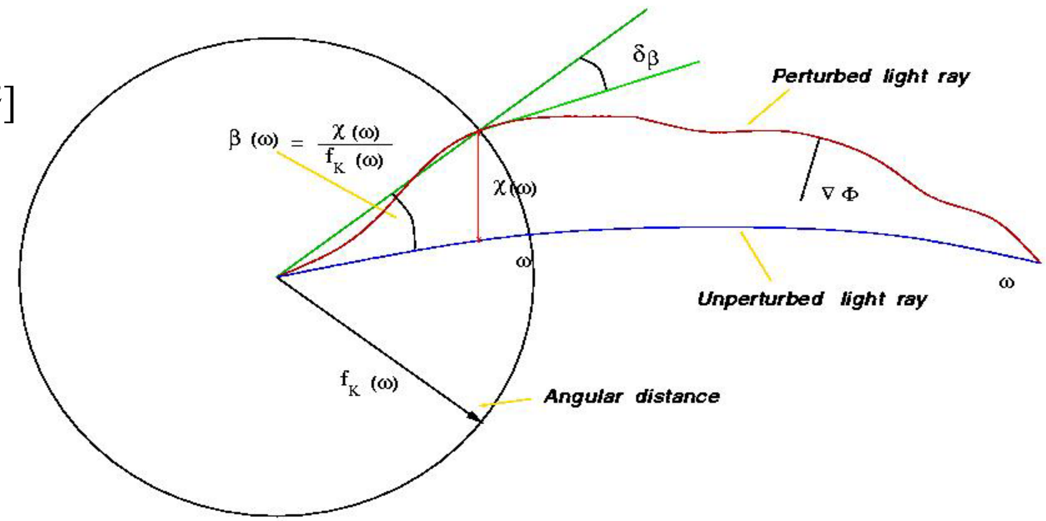
The VIRGO consortium

Cosmological Weak Lensing

Light propagation in the inhomogeneous universe

Bartelmann & Schneider 2001

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



Deflection angle:

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

Gravity

Distances/Geometry

Power spectrum,

growth rate of structure

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

Cosmic shear can « see » $P_\delta(k,z)$ of dark matter

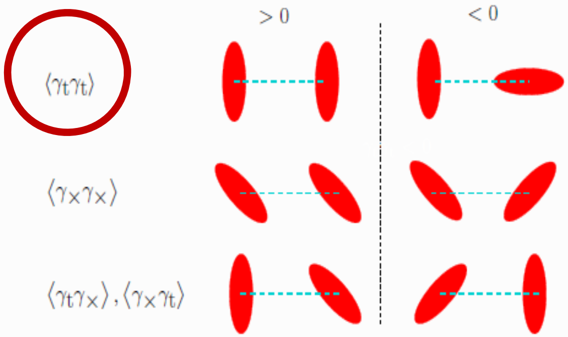
The projected dark matter power spectrum:

2-D cosmic shear

What we measure:

What we want:

- Correlation of the shear at two points yields four quantities



$$\xi_+(\vartheta) = \langle\gamma_t\gamma_t\rangle(\vartheta) + \langle\gamma_\times\gamma_\times\rangle(\vartheta)$$
$$\xi_-(\vartheta) = \langle\gamma_t\gamma_t\rangle(\vartheta) - \langle\gamma_\times\gamma_\times\rangle(\vartheta)$$

ellipticity 2 pt correlation function
= shear 2 pt correlation function

- Two-point correlation function

$$\xi_+(\theta) = \frac{1}{2\pi}\int d\ell\,\ell J_0(\ell\theta)P_\kappa(\ell)$$
$$\xi_-(\theta) = \frac{1}{2\pi}\int d\ell\,\ell J_4(\ell\theta)P_\kappa(\ell),$$

- Aperture-mass variance/dispersion

$$\langle M_{ap}^2\rangle(\theta) = \frac{1}{2\pi}\int d\ell\,\ell\,P_\kappa(\ell)\hat{U}^2(\theta\ell)$$

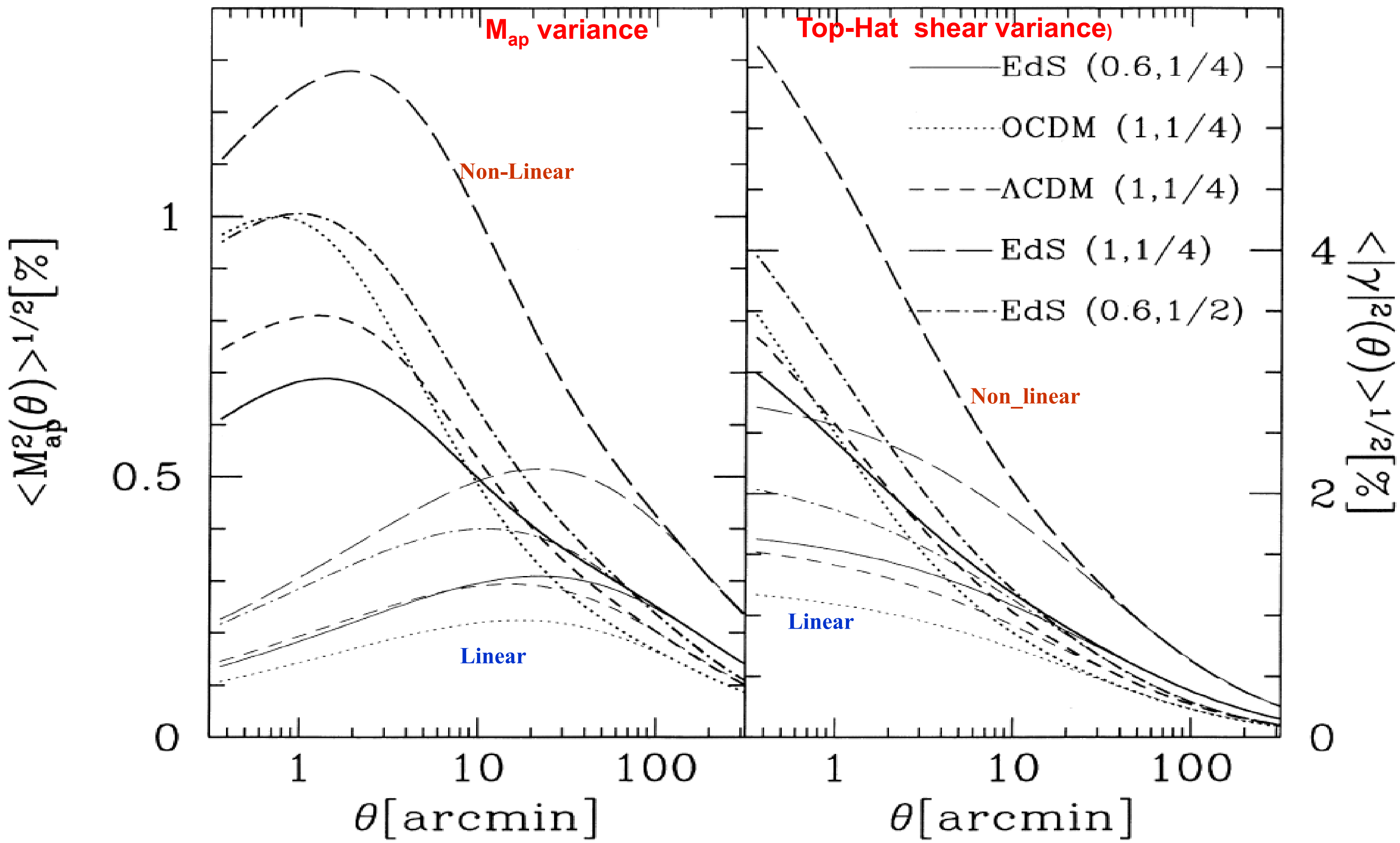
- Top-hat-variance

$$\langle|\bar{\gamma}|^2\rangle(\theta) = \frac{1}{\pi\theta^2}\int d^2\vartheta\,\gamma(\boldsymbol{\vartheta})\gamma^*(\boldsymbol{\vartheta})$$
$$= \frac{1}{2\pi}\int d\ell\,\ell\,P_\kappa(\ell)\left[\frac{2J_1(\ell\theta)}{\ell\theta}\right]^2$$

reconstruct the 2D and 3D dark matter power spectra

Statistics : theoretical predictions

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



Theoretical predictions from the gravitational instability scenario

Properties of cosmic shear signal

A simple toy model: single lens plane at redshift z_0, $P_\delta(k) \propto \sigma_8^2 k^n$, CDM, no Λ, linear growth:

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

Bernardeau et al 1997

- Amplitude cosmic shear (shear-induced ellipticity): ~1%
- Intrinsic ellipticity distribution of galaxies ~30%

Cosmic shear signal, dark matter power spectrum and cosmological parameters

A simple toy model: single lens plane at redshift z_0, $P_\delta(k) \propto \sigma_8^2 k^n$, CDM, no Λ, linear growth:

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Bernardeau et al 1997

Observing the real world : cosmic shear surveys

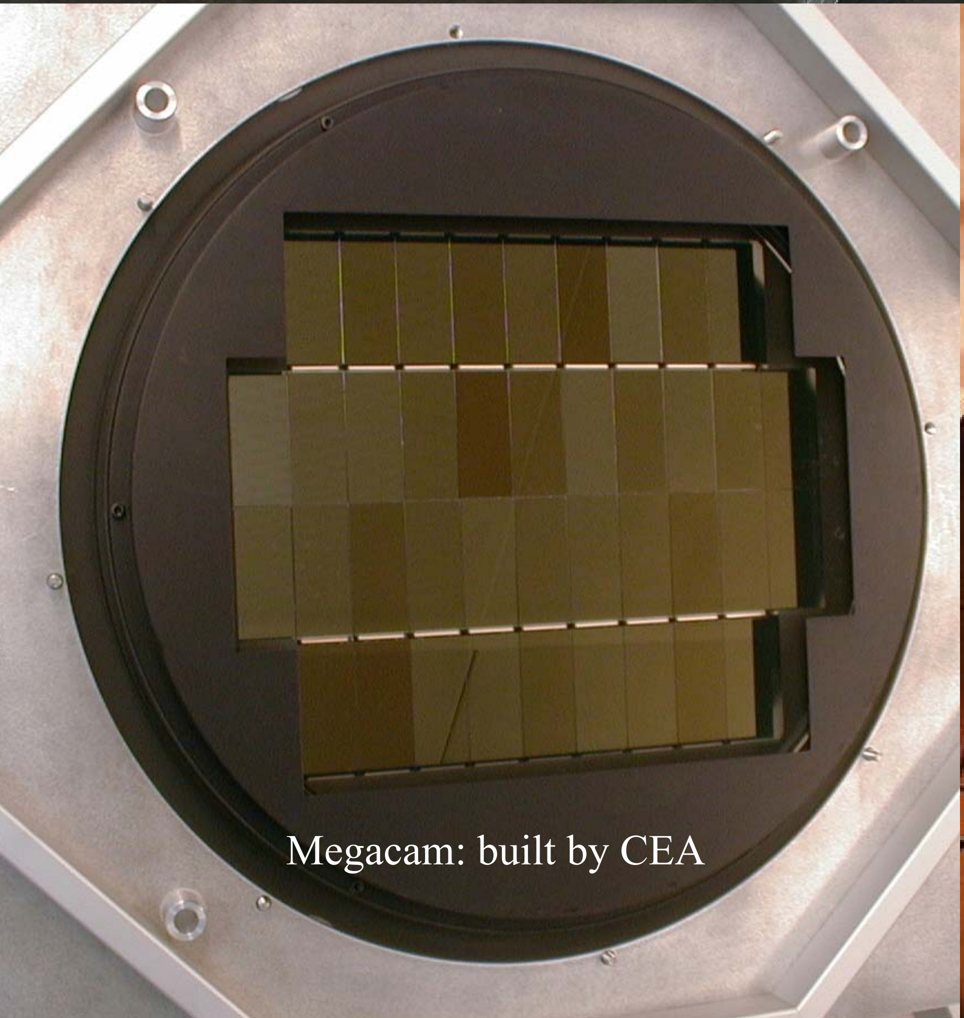
Munshi et al 2008

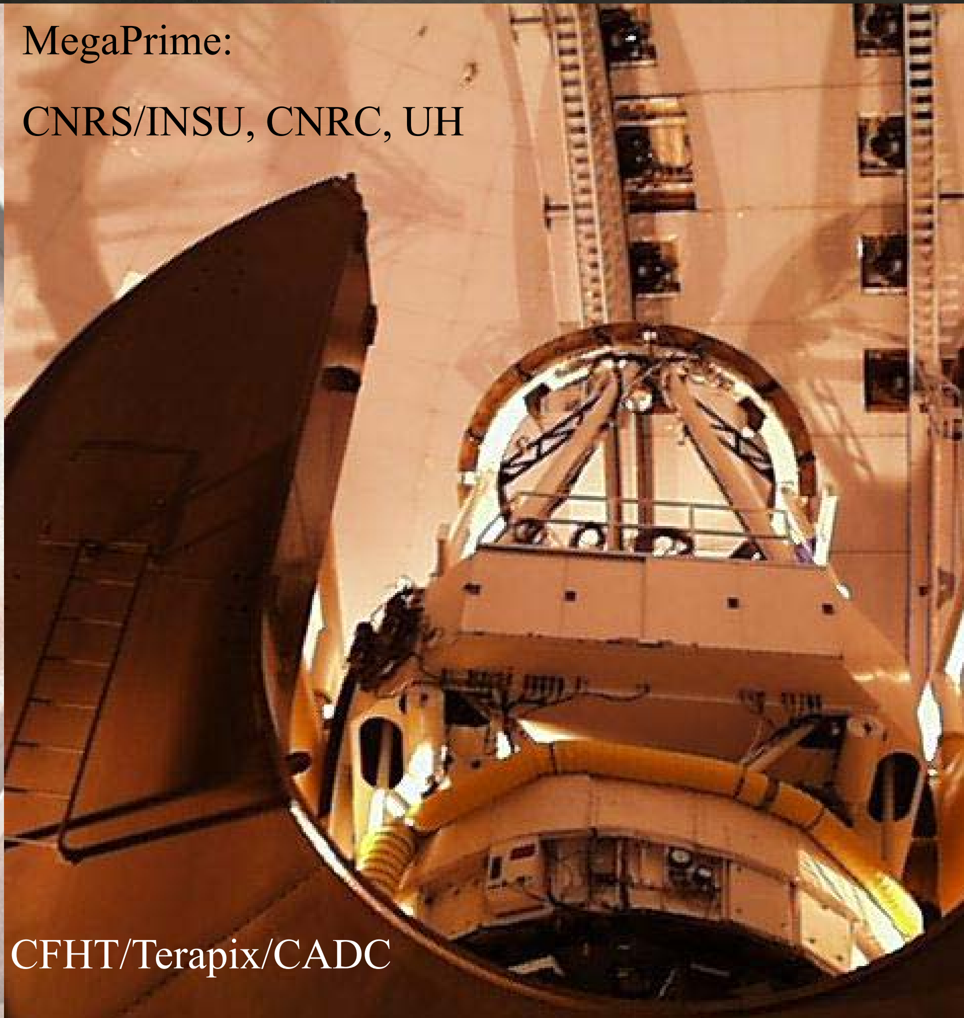
ID	Statistic	Field	$m_{\rm lim}$	z_s
Maoli et al. 01	$\langle\gamma^2\rangle$	VLT+CTIO+WHT+CFHT	-	-
Van Waerbeke et al. 01	$\langle\gamma^2\rangle$, $\xi(r)$, $\langle M^2_{\rm ap}\rangle$	CFHT 8 sq.deg.	I=24.5	1.1
Rhodes et al. 01	$\xi(r)$	HST 0.05 sq.deg.	I=26	0.9-1.1
Hoekstra et al. 02	$\langle\gamma^2\rangle$	CFHT+CTIO 24 sq.deg.	R=24	0.55
Bacon et al. 03	$\xi(r)$	Keck+WHT 1.6 sq.deg.	R=25	0.7-0.9
Réfrégier et al. 02	$\langle\gamma^2\rangle$	HST 0.36 sq.deg.	I=23.5	0.8-1.0
Van Waerbeke et al. 02	$\langle M^2_{\rm ap}\rangle$	CFHT 12 sq.deg.	I=24.5	0.78-1.08
Hoekstra et al. 02	$\langle\gamma^2\rangle$, $\xi(r)$, $\langle M^2_{\rm ap}\rangle$	CFHT+CTIO 53 sq.deg.	R=24	0.54-0.66
Brown et al. 03	$\langle\gamma^2\rangle$, $\xi(r)$	COMBO17 1.25 sq.deg.	R=25.5	0.8-0.9
Hamana et al. 03	$\langle M^2_{\rm ap}\rangle$, $\xi(r)$	Subaru 2.1 sq.deg.	R=26	0.8-1.4
Jarvis et al. 03	$\langle\gamma^2\rangle$, $\xi(r)$, $\langle M^2_{\rm ap}\rangle$	CTIO 75 sq.deg.	R=23	0.66
Rhodes et al. 04	$\langle\gamma^2\rangle$, $\xi(r)$	STIS 0.25 sq.deg.	$\langle I\rangle = 24.8$	1.0 ± 0.1
Heymans et al. 05	$\langle\gamma^2\rangle$, $\xi(r)$	GEMS 0.3 sq.deg.	$\langle m_{606}\rangle = 25.6$	~ 1
Massey et al. 05	$\langle\gamma^2\rangle$, $\xi(r)$	WHT 4 sq.deg.	R=25.8	~ 0.8
Van Waerbeke et al. 05	$\langle\gamma^2\rangle$, $\xi(r)$	CFHT 12 sq.deg.	I=24.5	0.9 ± 0.1
Heitterscheidt et al. 06	$\langle\gamma^2\rangle$, $\xi(r)$	GaBoDS 13 sq.deg.	R=[21.5,24.5]	~ 0.78
Semboloni et al. 06	$\langle M^2_{\rm ap}\rangle$, $\xi(r)$	CFHTLS-DEEP 2.3 sq.deg.	i=25.5	~ 1
Hoekstra et al. 06	$\langle\gamma^2\rangle$, $\xi(r)$, $\langle M^2_{\rm ap}\rangle$	CFHTLS-WIDE 22 sq.deg.	i=24.5	0.8 ± 0.1

+ **Massey et al 2007 (COSMOS)** + Schrabback et al 2007 (ACS) +

Benjamin et al 2007 (CFHTLS-T01+Virmos-Descart+RCS+GaBoDS) **+ Fu et al 2008 (CFHTLS-T03)**

The Canada-France-Hawaii Telescope Legacy Survey





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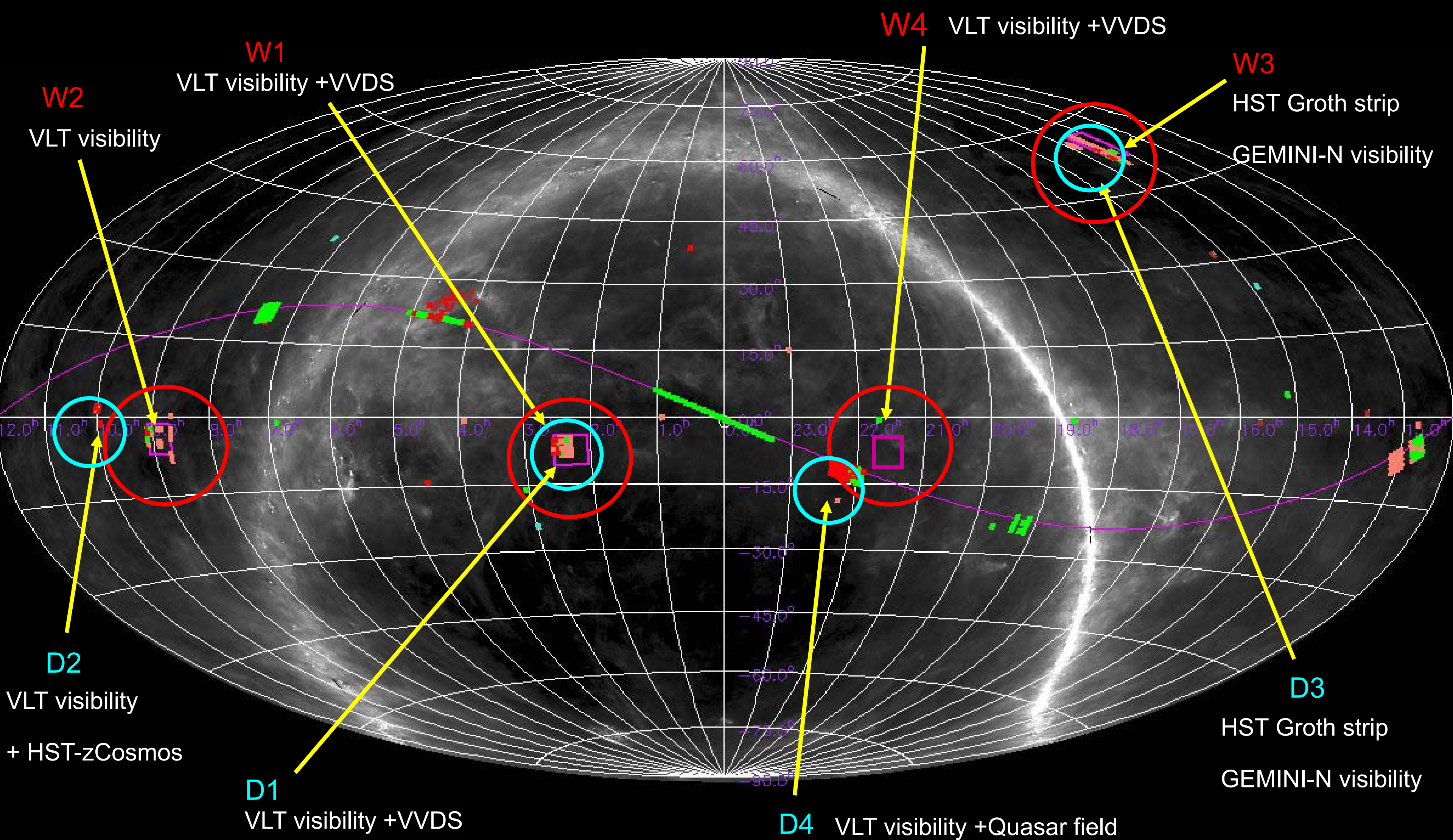
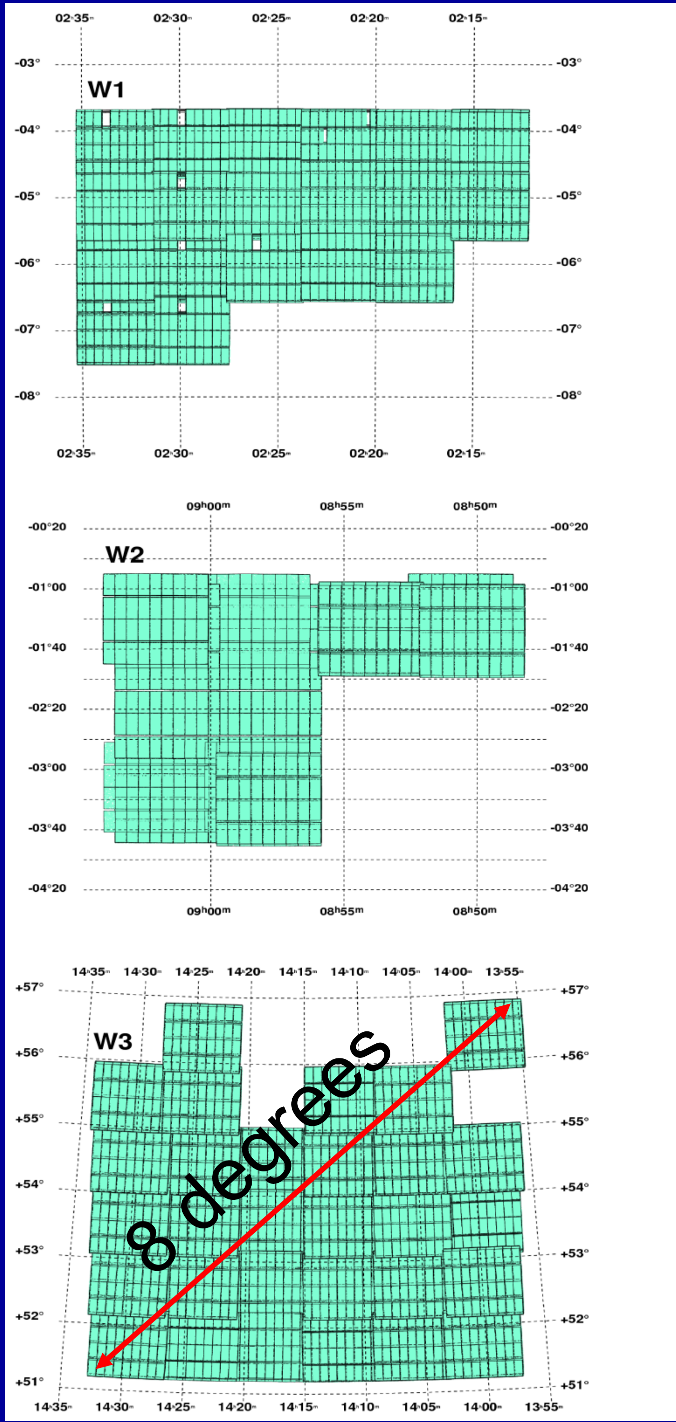


4 Wide W: 170 deg^2 (ugriz, 1h/filter) + 4 Deep D: 4x1 deg^2 (ugriz, 50hrs/filter)

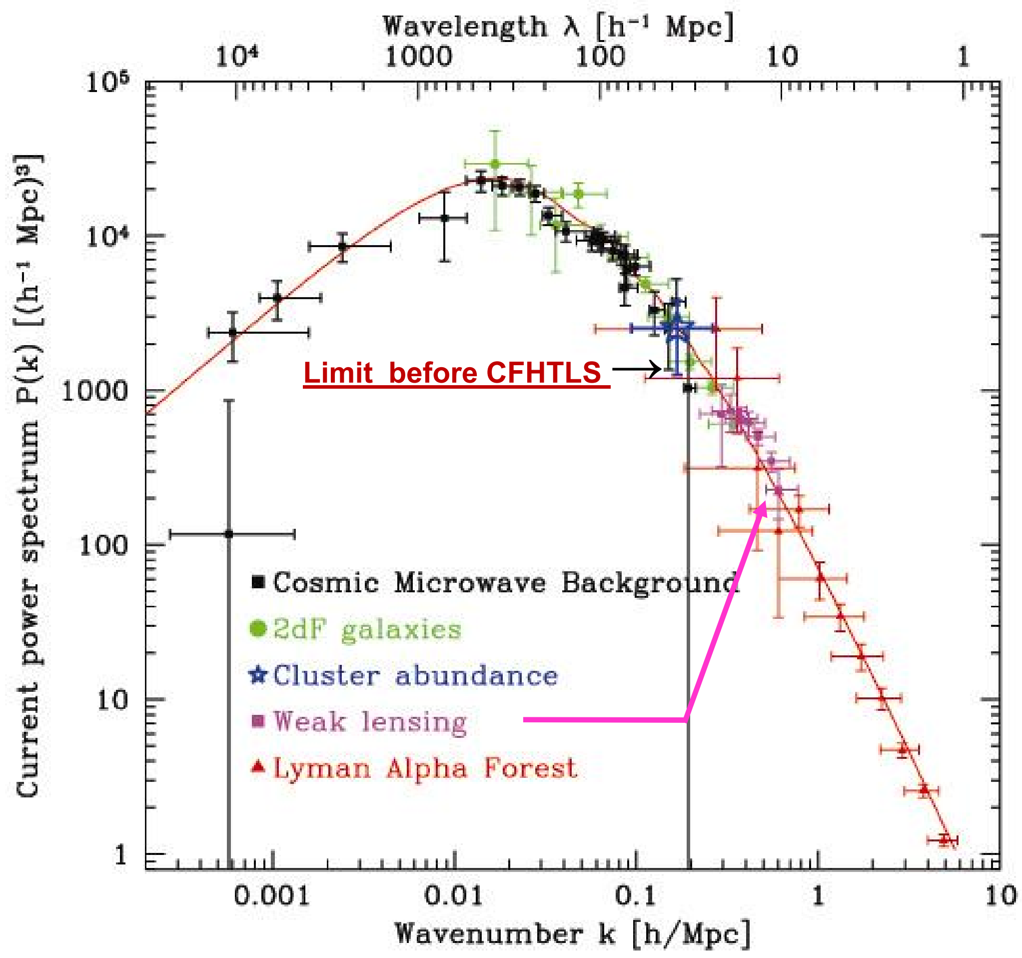
CFHTLS Weak Lensing T03



- Data: Wide + Deep
- Sky coverage : 55 deg^2
- 3 independent fields: W1, W2, W3
- Homogeneous data set:
- Spectro-z inside CFHTLS fields (VVDS)
- Photo-z inside CFHTLS Deep
- Scales :
- 1' – 8°
- ~400 kpc - ~100 Mpc at z=0.5

Fu et al 2008

Exploration of the dark matter power spectrum with the CFHTLS-Wide: angular scales explored



Tegmark & Zaldarriaga 2002

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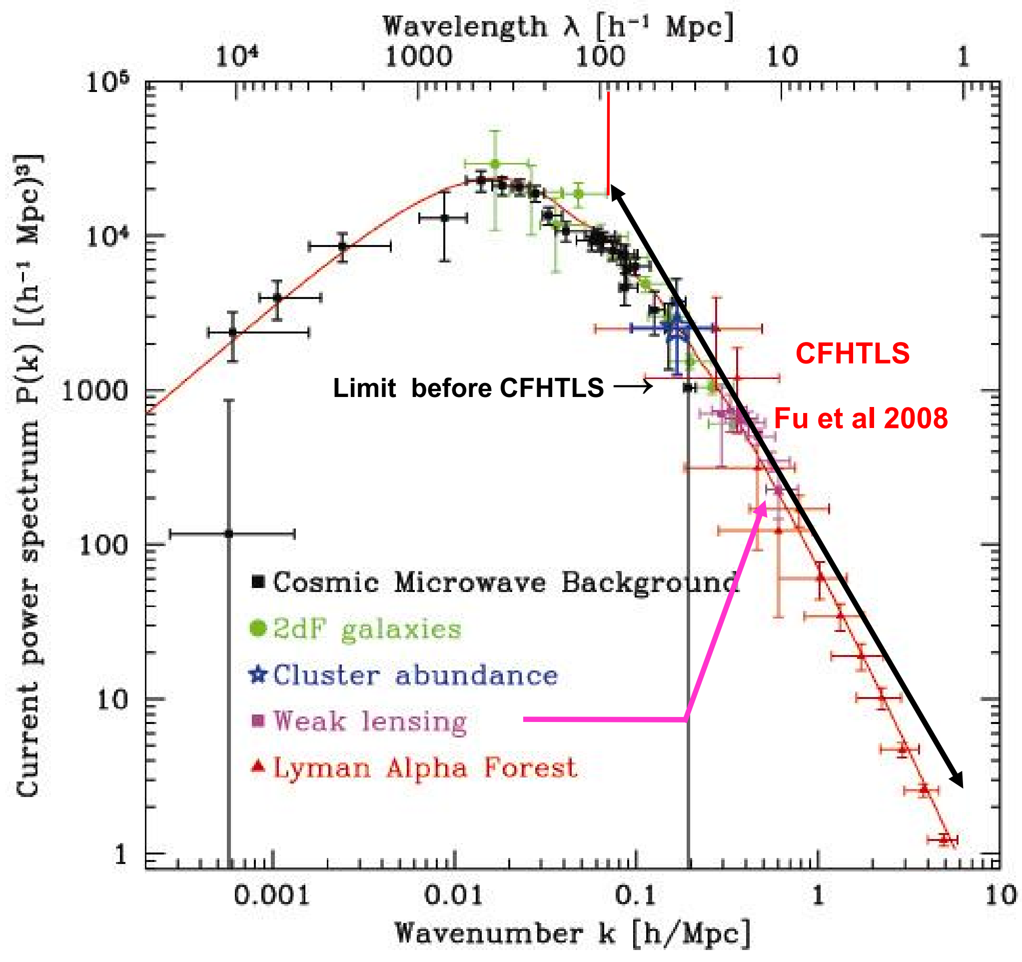
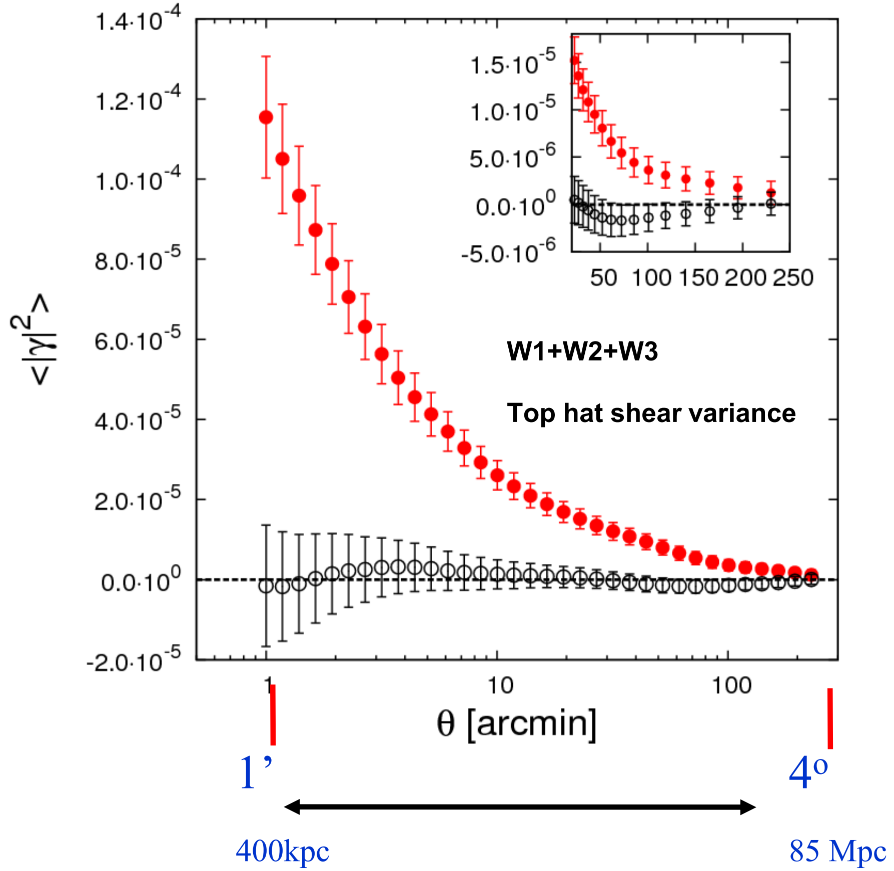
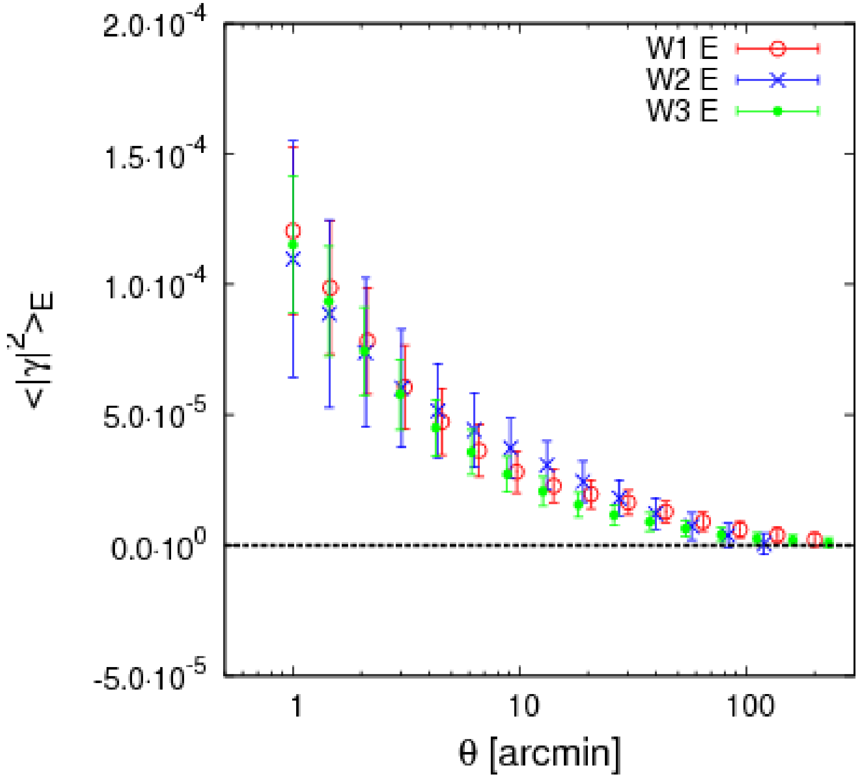


Tegmark & Zaldarriaga 2002

CFHTLS weak lensing: 3 fields W1, W2, W3

very large scales covered





Fu et al 2008

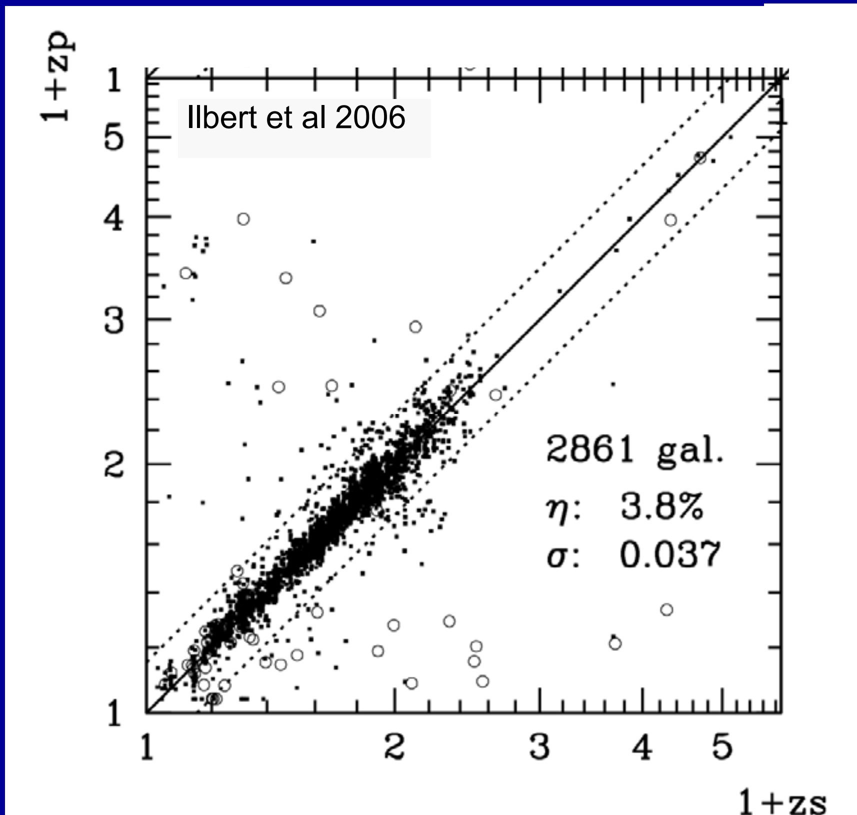
Amplitude and cosmological interpretation of the cosmic shear signal

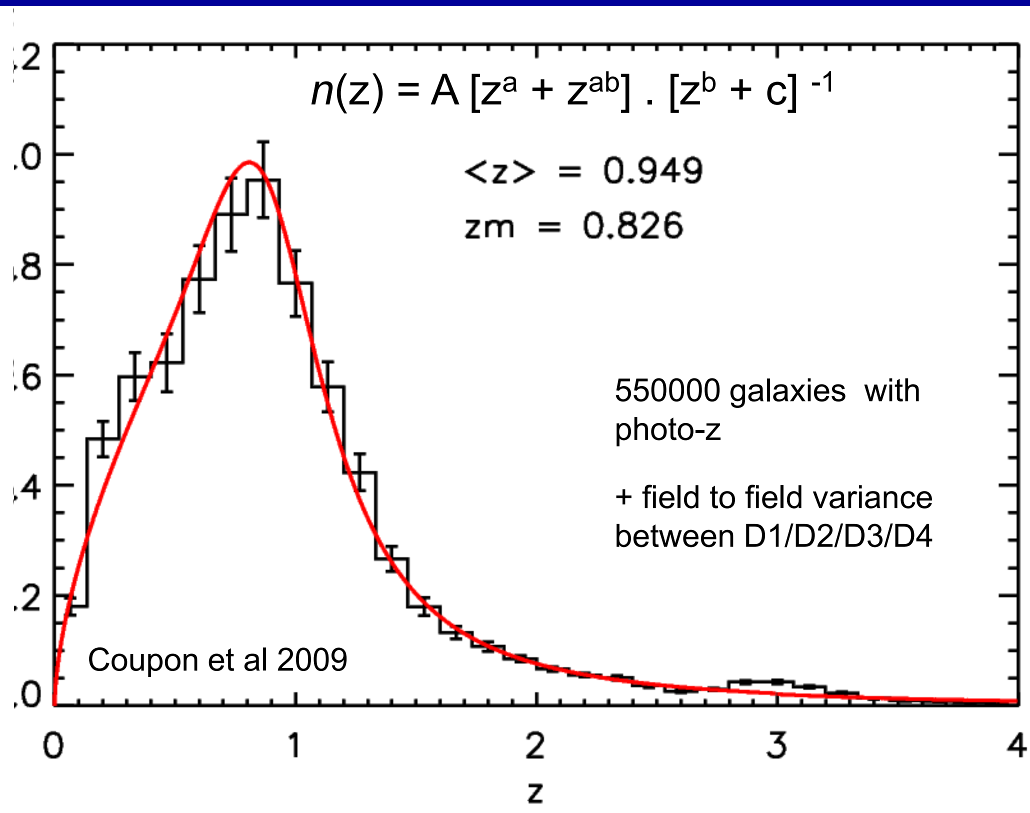
A simple toy model: single lens plane at redshift z_0, $P_\delta(k) \propto \sigma_8^2 k^n$, CDM, no Λ, linear growth:

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

redshifts information:
as important as good shape measurements

Redshift distribution of sources

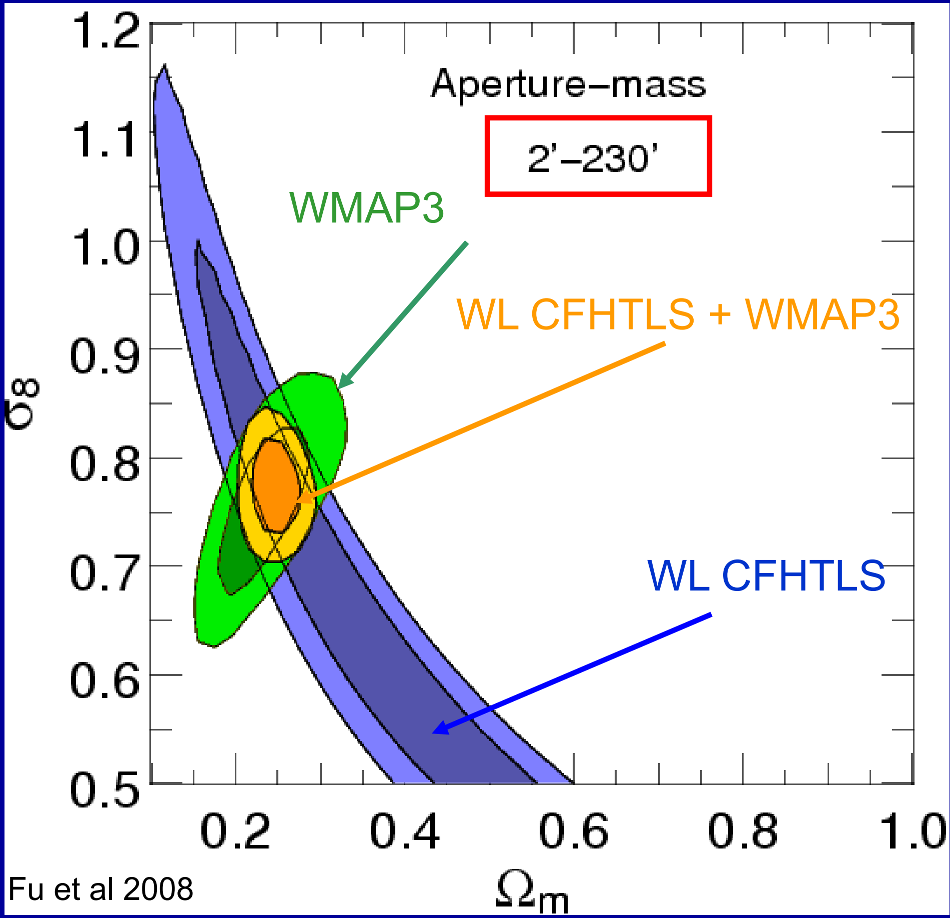




Photometric redshift calibrated with the VVDS spectroscopic sample

- CFHTLS Deep data + ESO-VLT / VVDS spectra INSIDE the CFHTLS Deep and Wide fields
- CFHTLS+VVDS: Ilbert et al 2006, Coupon et al 2009:
    - Accurate $n(z)$
    - Field to field scatter from the data

Constraints on Ω_m-σ_8 :all scales



Fu et al 2008

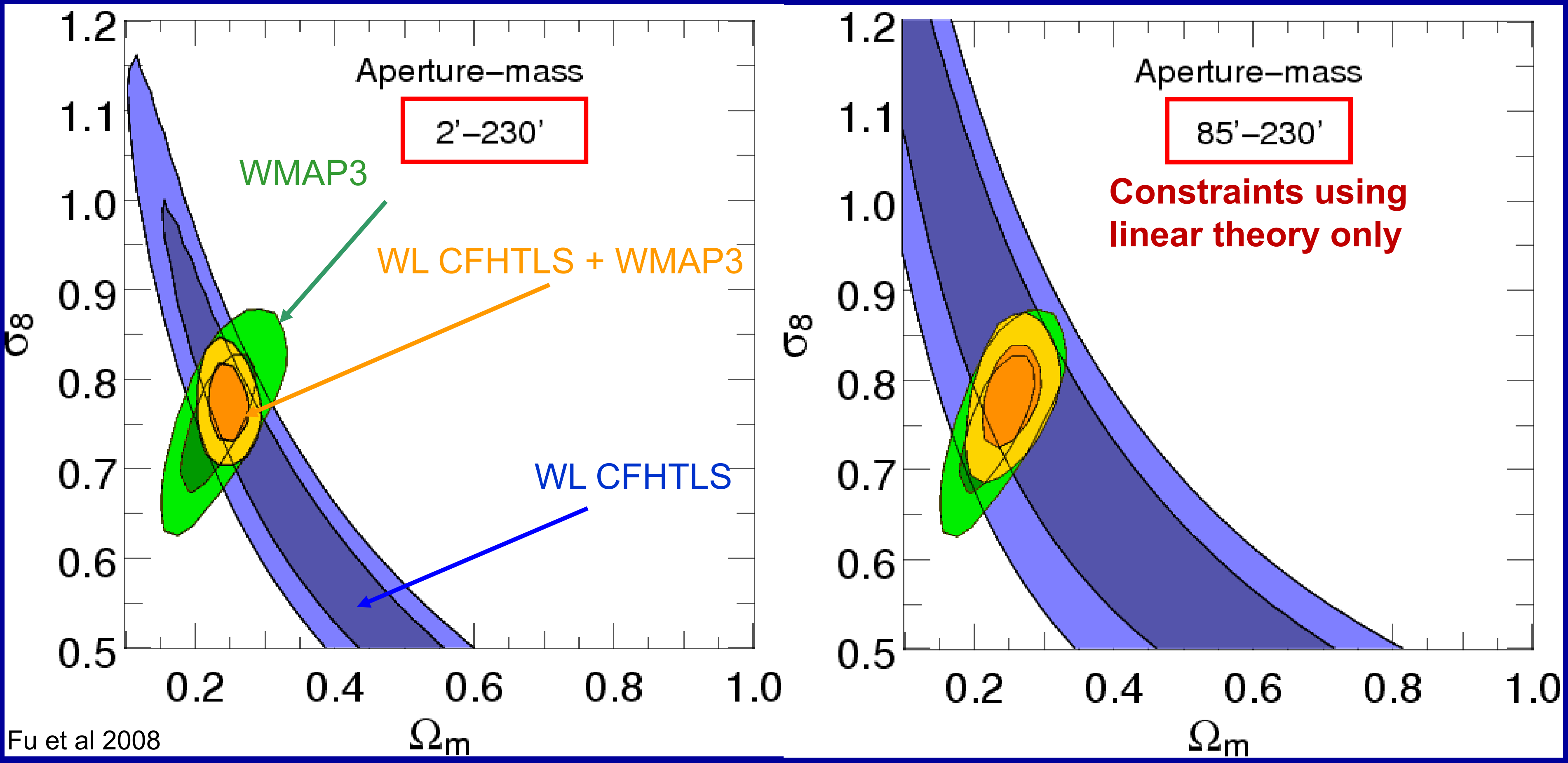
$$\langle \kappa^2(\theta) \rangle^{1/2} = \langle \gamma^2(\theta) \rangle^{1/2} \approx 0.01\, \sigma_8\, \Omega_m^{0.8} \left(\frac{\theta}{1 \text{deg}} \right)^{-(n+2)/2} z_0^{0.75}$$

All scales

σ_8 for $\Omega_m = 0.25$:

0.784 ± 0.049	for	ξ_E
0.795 ± 0.042	for	$\langle \lvert\gamma\rvert^2 \rangle_E$
0.785 ± 0.043	for	$\langle M_{ap}^2 \rangle$

Constraints on Ω_m-σ_8 : linear scales



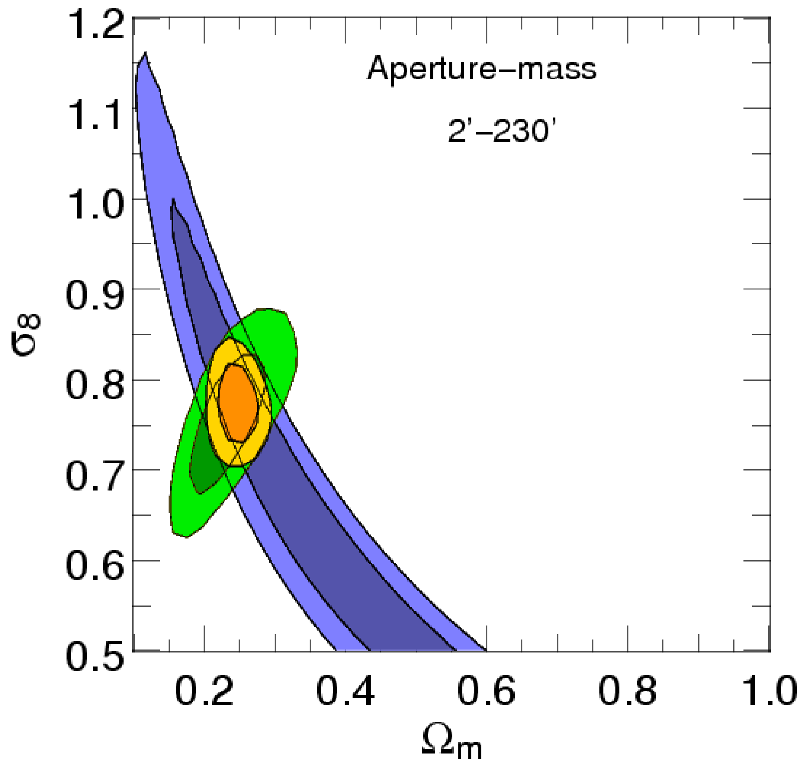
σ_8 for $\Omega_m = 0.25$:

All scales				
0.784 ± 0.049	for	ξ_E	0.780 ± 0.044	$(2' < \theta < 35')$
0.795 ± 0.042	for	$\langle|\gamma|^2\rangle_E$	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 Ω_m-σ_8

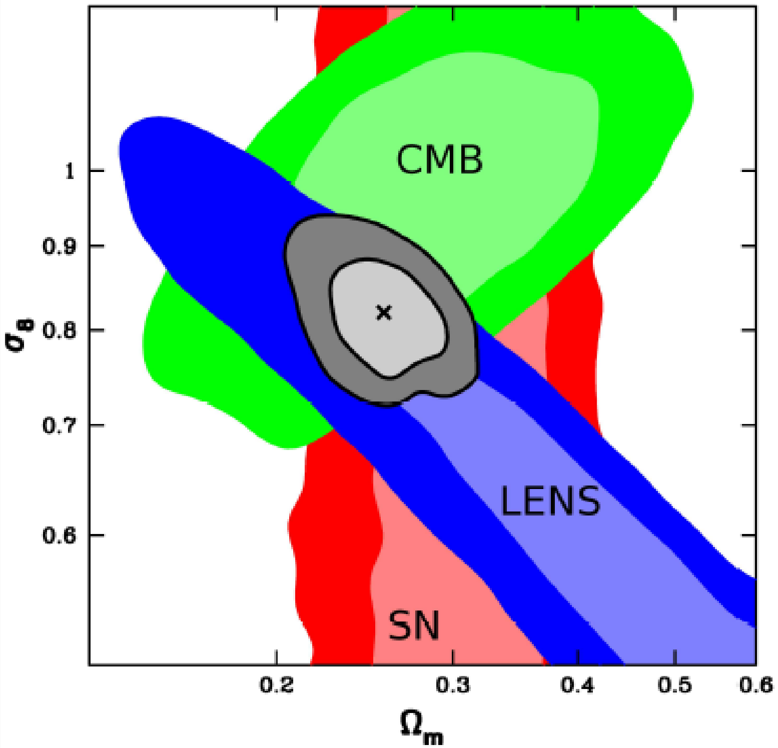
CFHTLS Weak lensing

Fu el al 2008



CTIO lensing survey

Jarvis et al 2006



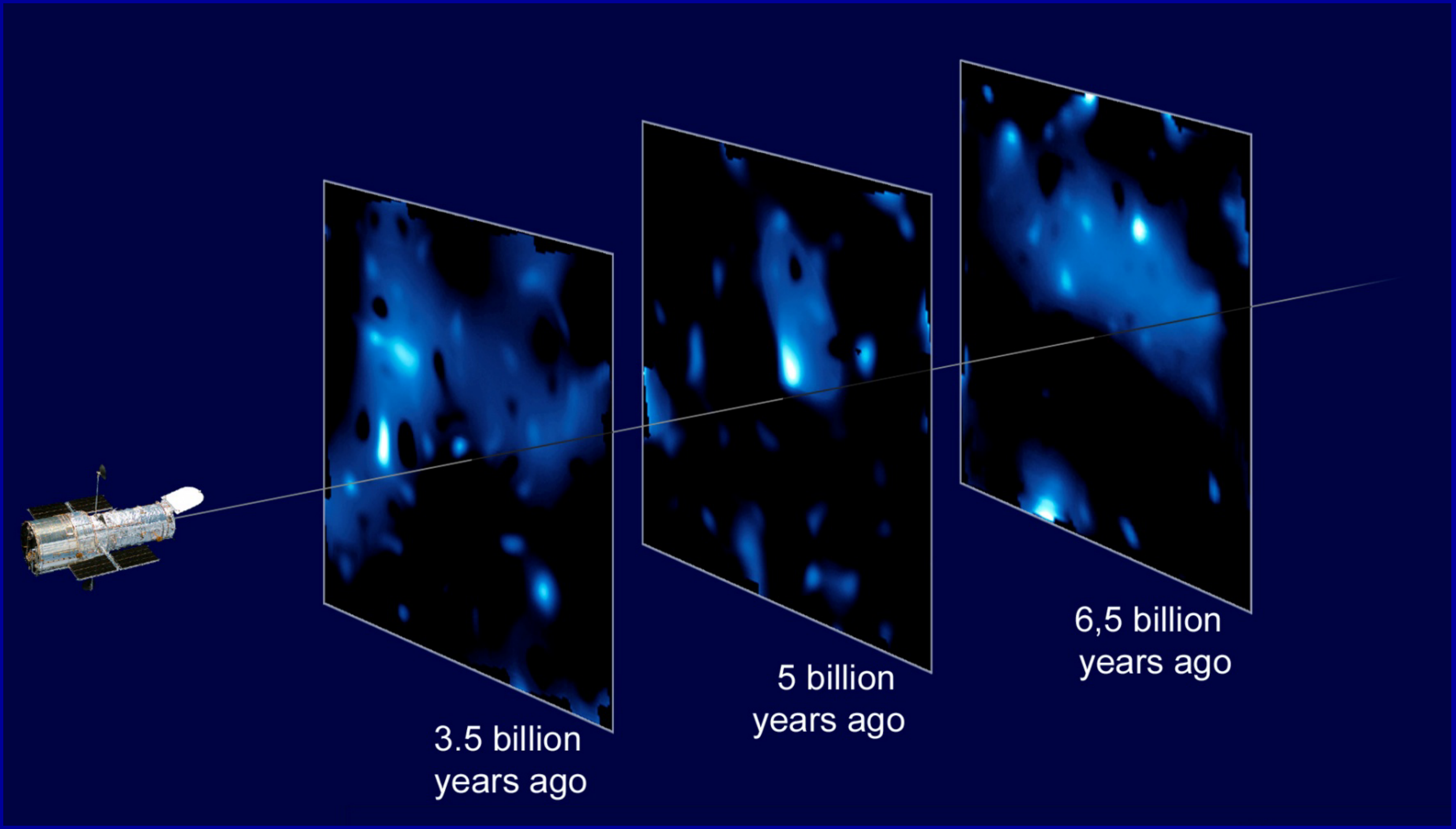
Dunkley et al 2008
WMAP5

Data	Parameter	Lensing limits	5-year *WMAP* limits
CFHTLS Wide	$\sigma_8(\Omega_m/0.25)^{0.64}$	0.785 ± 0.043	0.814 ± 0.090
100 Sq Deg	$\sigma_8(\Omega_m/0.24)^{0.59}$	0.84 ± 0.07	0.832 ± 0.088
COSMOS 2D	$\sigma_8(\Omega_m/0.3)^{0.48}$	0.81 ± 0.17	0.741 ± 0.069
COSMOS 3D	$\sigma_8(\Omega_m/0.3)^{0.44}$	$0.866^{+0.085}_{-0.068}$	0.745 ± 0.067

Beyond the projected dark matter power spectrum:

tomography

Tomography: the lensed universe in slices



Massey et al 2007

Lensing tomography is challenging

- Need very deep exposures to get enough background (lensed) galaxies even for the highest redshift slices …

- Deep exposures → most galaxies very small, need excellent image quality and sampling: space much better

- Need accurate redshifts to split galaxies into slices

- Need large field of view to probe the dark matter power spectrum over enough scales and limit cosmic variance

The COSMOS/*z*COSMOS survey

COSMOS imaging (PI . N. Scoville)

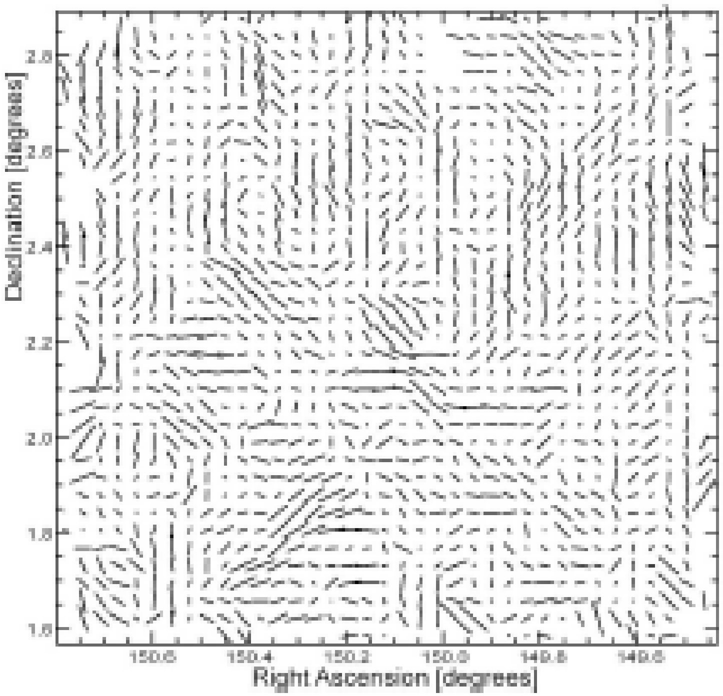
- 2 deg^2 HST/ACS , 640 orbits
- 2 10^6 galaxies up to I_{AB}=27 mag.
- Huge follow up: radio, Spitzer, Galex, XMM, Chandra, Subaru+ CFHT visible+ NIR complementary data,

*z*COSMOS (PI: S. Lilly)

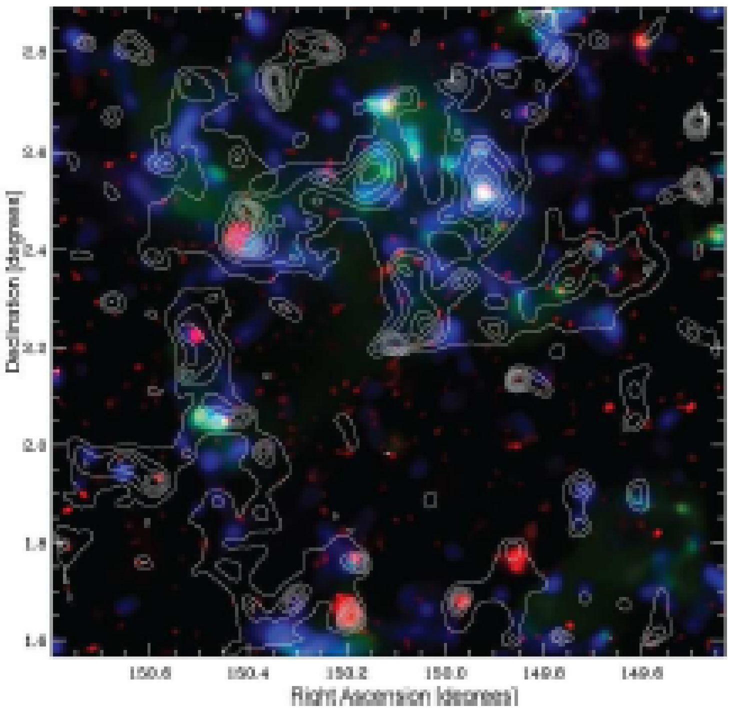
- 540 hrs of VLT/VIMOS spectroscopic follow up
- 25000 redshifts with I_{AB}=22.5 ($z<1.0$)
- 12000 redshifts $1.4<z<2.5$

Weak lensing with COSMOS

Shear map



Convergence map

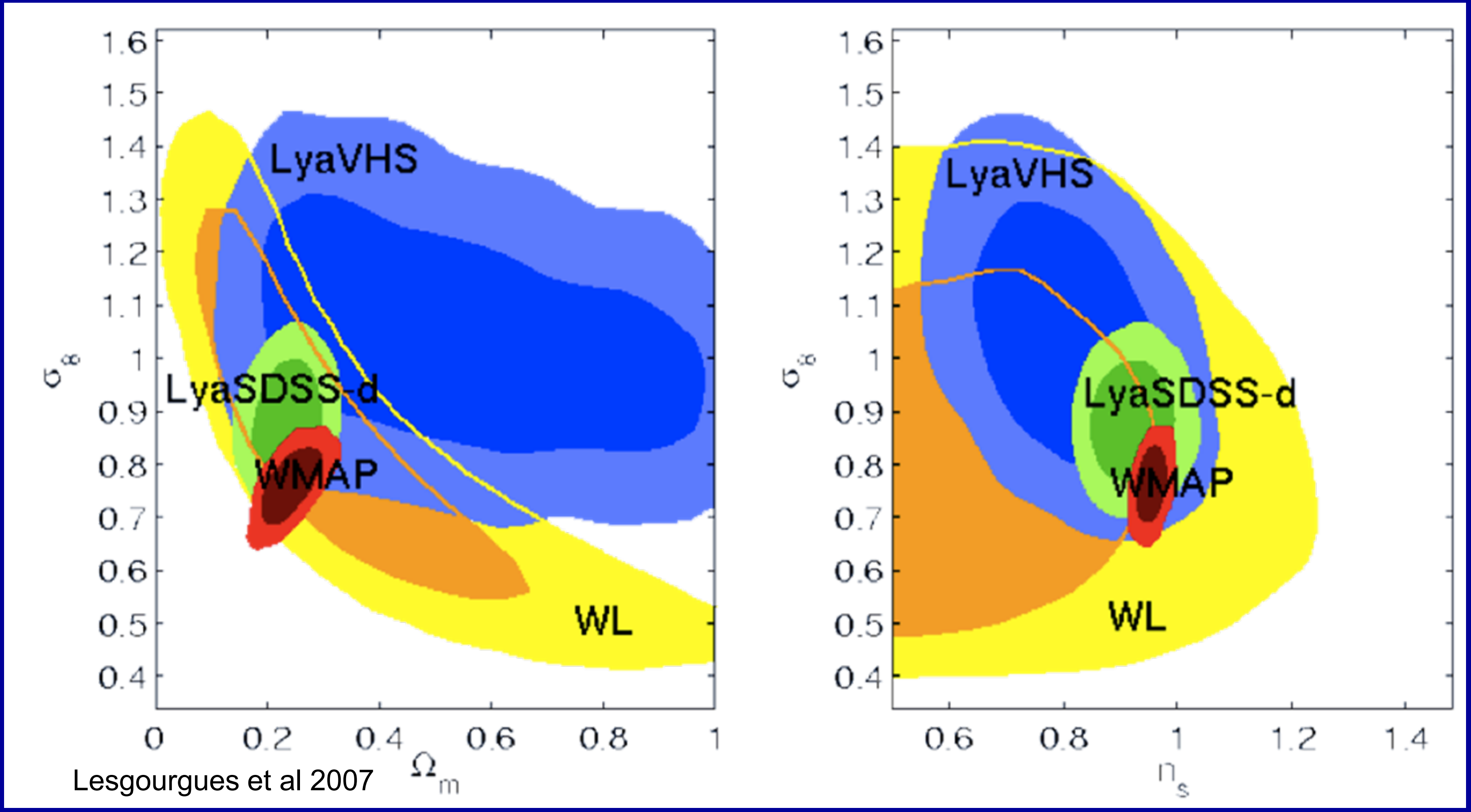


Massey et al 2009

Cosmic shear with COSMOS

Joint contraints on the dark matter power spectrum

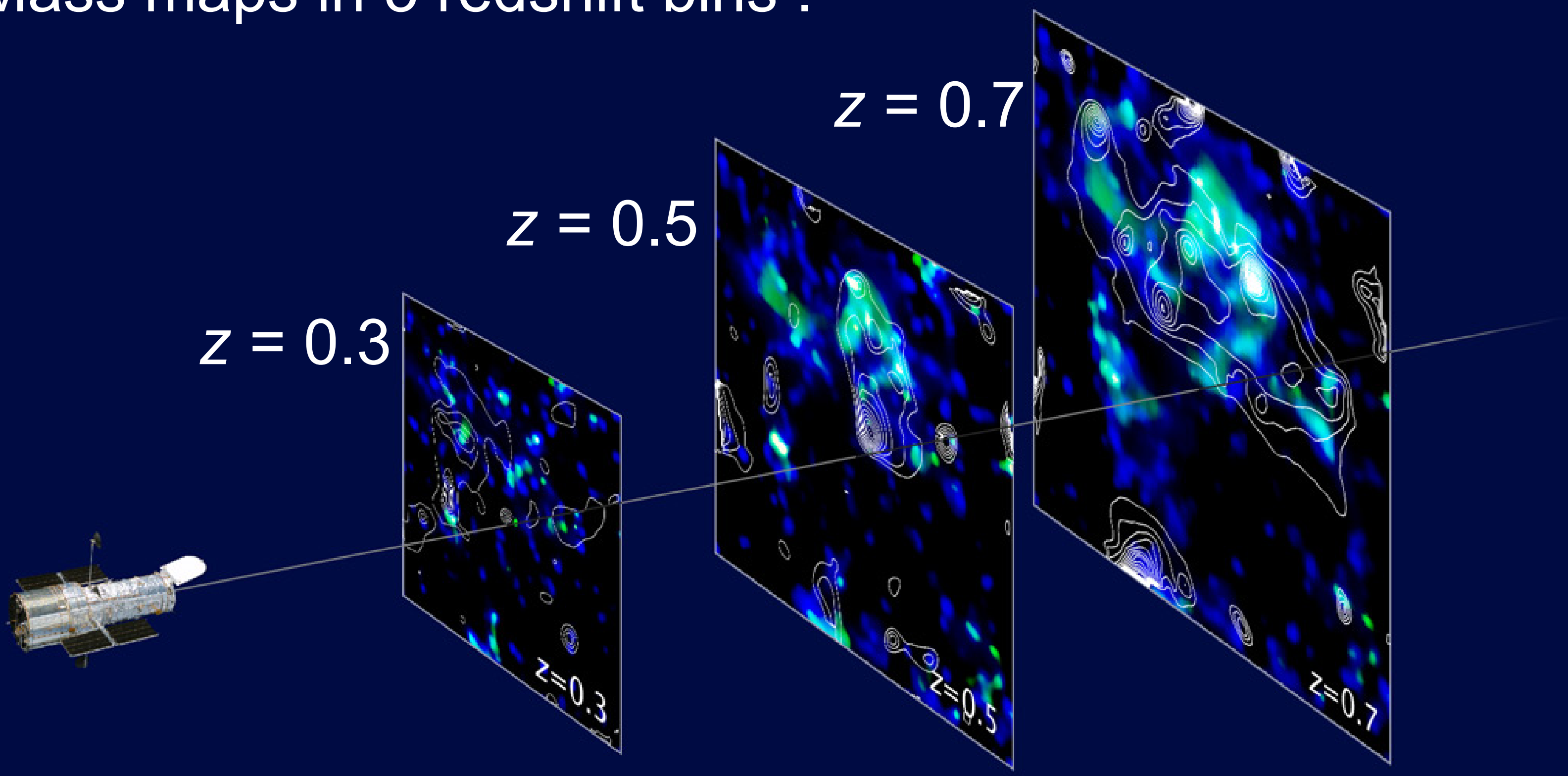
$\Omega_m = 0.247 +/- 0.016$; $\sigma_8 = 0.800 +/- 0.023$; $n_s = 0.971 +/- 0.011$



Lesgourgues et al 2007

Lensing tomography with COSMOS

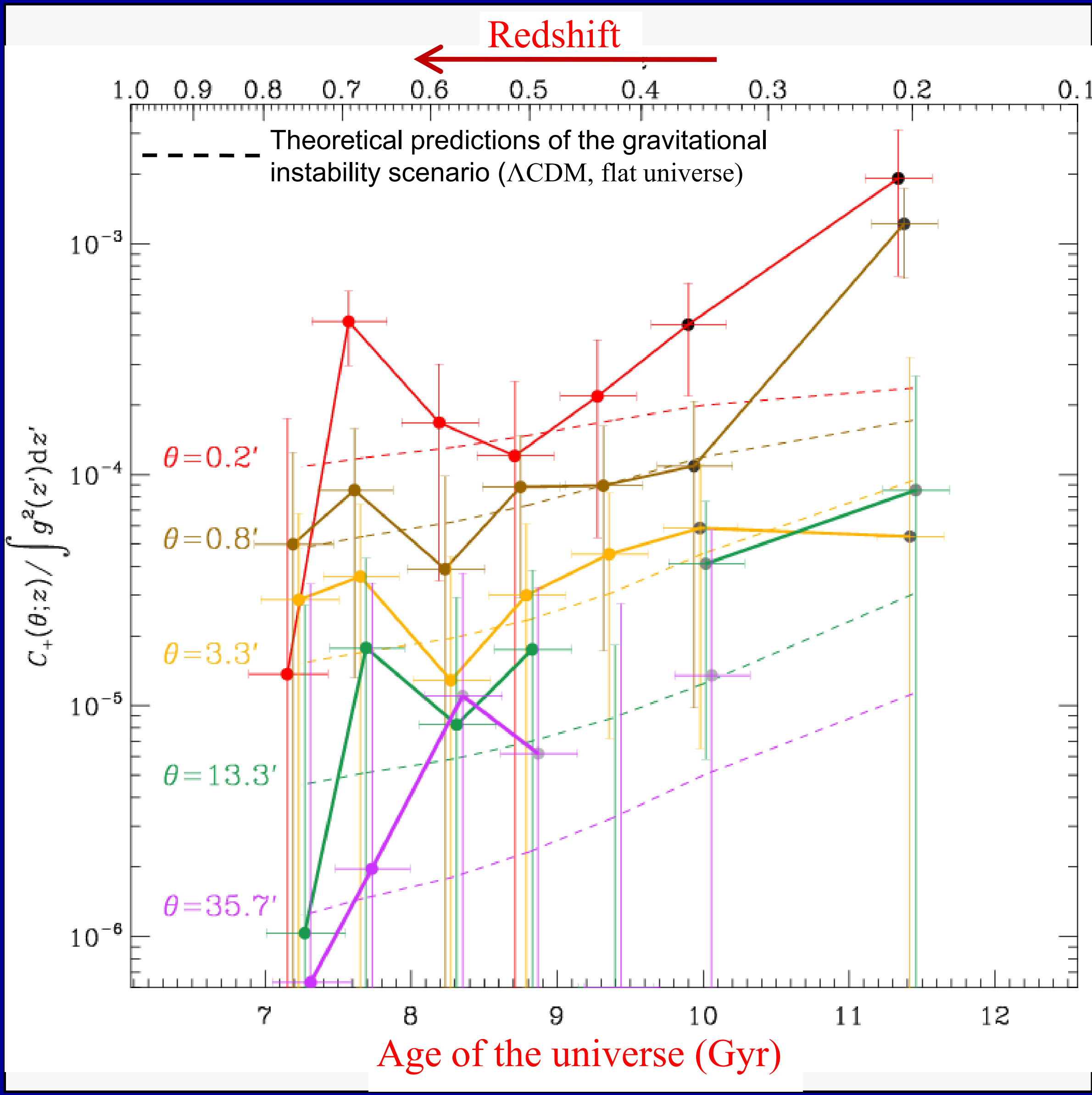
Mass maps in 3 redshift bins :



Massey et al 2007

Observing the growth of structure at work:

weak lensing tomography in COSMOS



Shear correlation function at fixed angular scale as function of redshift

Massey et al 2007

Dark energy

The gravitational convergence power spectrum:

weak dependence on *w*

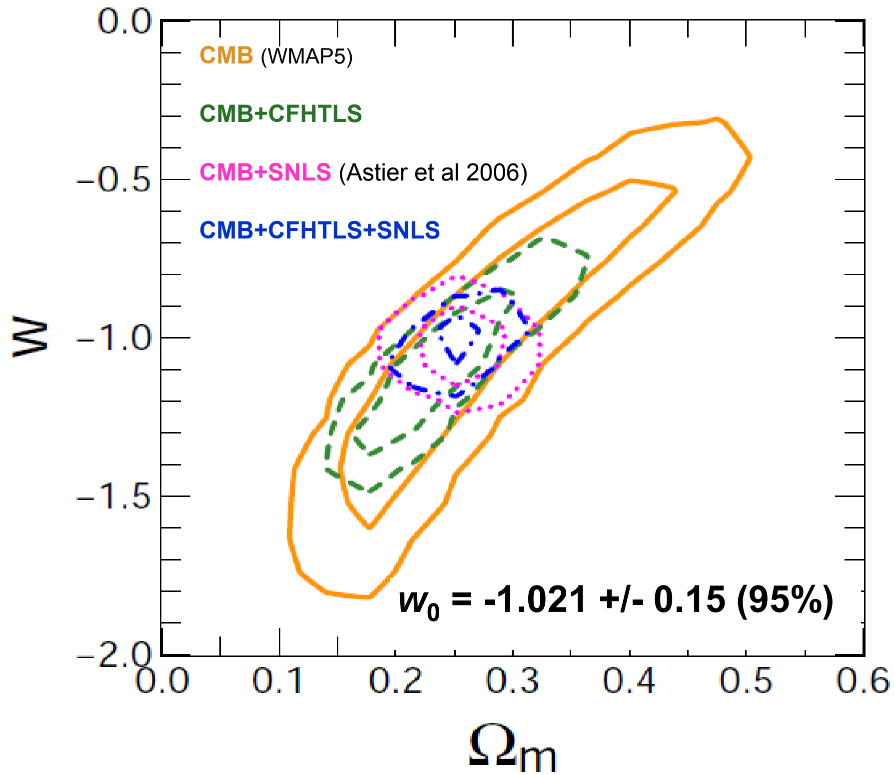
$$P_{\kappa} \propto \sigma_8^{2.9}\ \Omega_{DE}^{3}\ |w|^{0.31}\ \ z^{1.6}$$

Huterer et al 2006

Equation of state of dark energy : P = $w\,\rho$

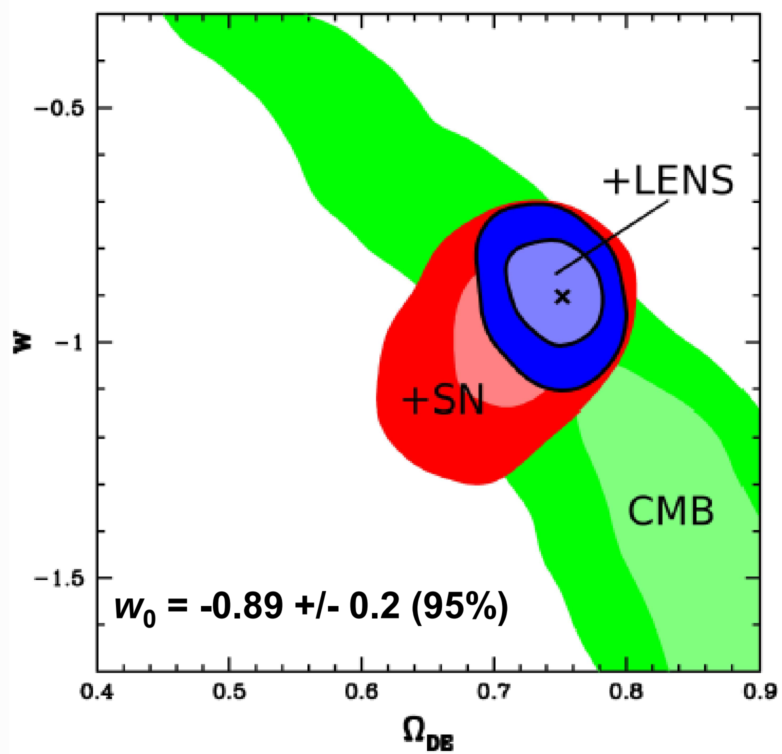
Constraints on $\Omega_m - w$
($P = w\,\rho$, with w = constant)

CFHTLS Weak lensing



Kilbinger et al 2009

CTIO lensing survey



Jarvis et al 2006

Dark energy from CFHTLS weak lensing + SNLS + WMAP

Parameter	CMB	CMB+Lens	CMB+SN	CMB+Lens+SN	CMB+Lens+SN+sys
Ω_b	$0.045^{+0.020}_{-0.016}$	$0.041^{+0.016}_{-0.008}$	$0.0433^{+0.0028}_{-0.0026}$	$0.0432^{+0.0026}_{-0.0023}$	0.0428 ± 0.0029
Ω_m	$0.262^{+0.099}_{-0.093}$	$0.242^{+0.092}_{-0.048}$	$0.257^{+0.025}_{-0.023}$	$0.253^{+0.018}_{-0.016}$	$0.251^{+0.023}_{-0.018}$
τ	0.087 ± 0.016	$0.086^{+0.016}_{-0.017}$	$0.088^{+0.019}_{-0.016}$	$0.088^{+0.019}_{-0.015}$	0.088 ± 0.017
w	$-1.08^{+0.39}_{-0.53}$	$-1.09^{+0.24}_{-0.22}$	$-1.025^{+0.071}_{-0.072}$	$-1.010^{+0.059}_{-0.060}$	$-1.021^{+0.079}_{-0.081}$
n_s	$0.963^{+0.019}_{-0.014}$	$0.961^{+0.014}_{-0.016}$	0.962 ± 0.015	$0.963^{+0.015}_{-0.014}$	$0.963^{+0.014}_{-0.015}$
$10^9\Delta^2_R$	$2.43^{+0.13}_{-0.14}$	$2.418^{+0.083}_{-0.110}$	$2.43^{+0.12}_{-0.11}$	$2.414^{+0.098}_{-0.092}$	2.41 ± 0.11
h	$0.74^{+0.18}_{-0.12}$	$0.754^{+0.096}_{-0.089}$	$0.719^{+0.025}_{-0.022}$	$0.720^{+0.023}_{-0.021}$	$0.723^{+0.027}_{-0.025}$
σ_8	$0.82^{+0.14}_{-0.15}$	$0.819^{+0.061}_{-0.069}$	$0.807^{+0.044}_{-0.046}$	$0.795^{+0.030}_{-0.027}$	$0.798^{+0.037}_{-0.044}$

Kilbinger et al 2009

Without tomography w , WL performs less than SNIa… Need

- More data
- More accurate weak lensing signal
- Tomography « a la COSMOS » to explore the growth of structure

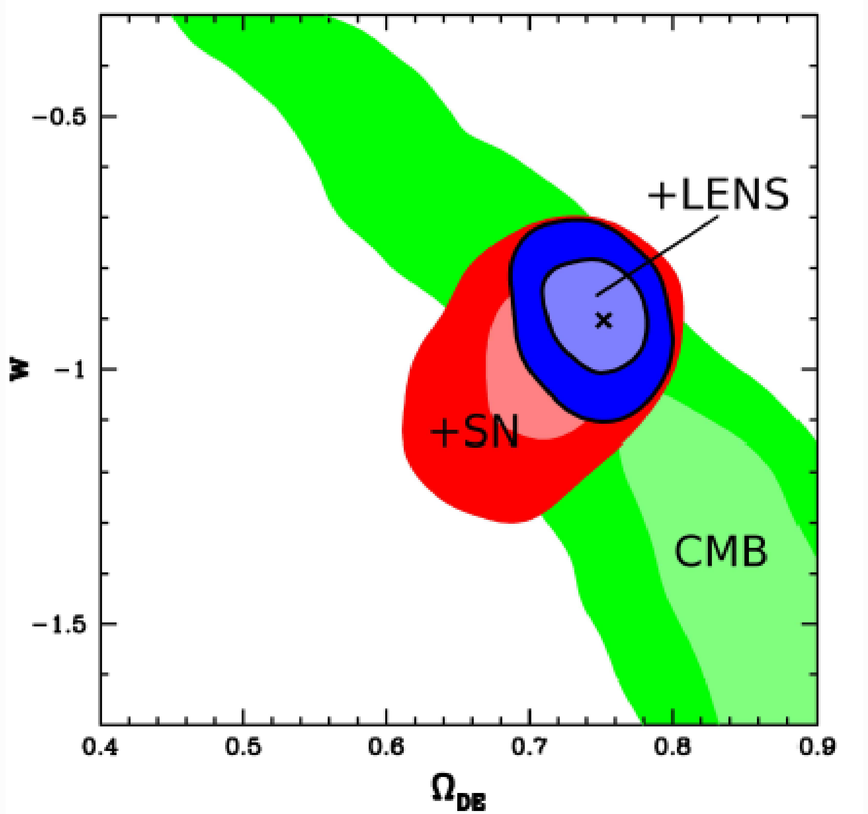
Dark energy

- Constraining the equation of state of dark energy is promising, but not yet achieved by weak lensing surveys

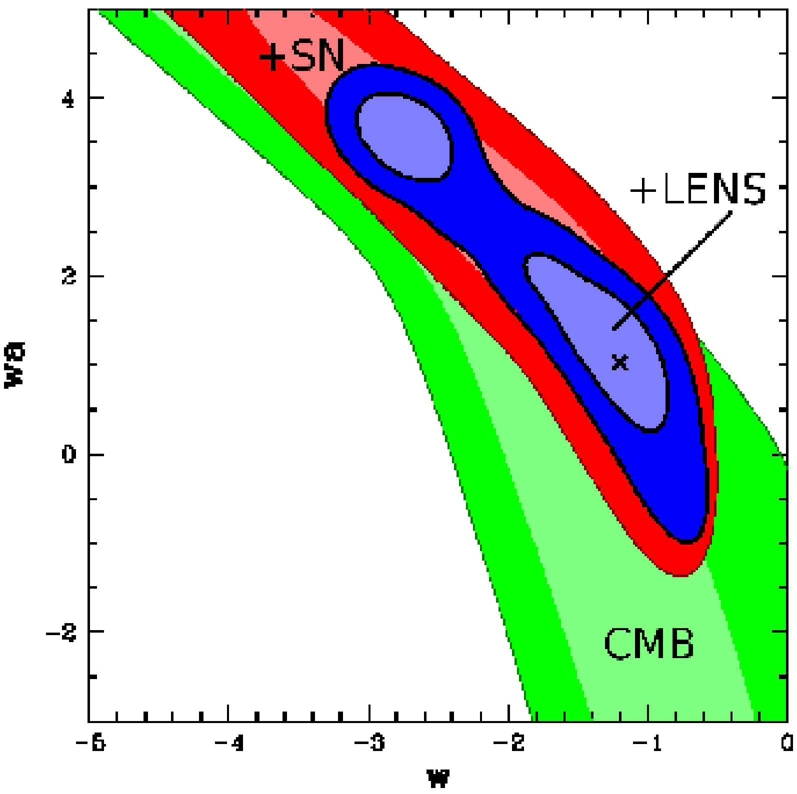
- Getting w(z) will be hard with CFHTLS only

Large freedom if *w* not constant

CTIO, *w*=constant



CTIO $w(a) = w_o + (1\text{-}a)w_a$



Jarvis et al 2006

Dark energy

- Constraining the equation of state of dark energy is promising, but not yet a achieved by weak lensing surveys

- Getting w(z) will be hard with CFHTLS only… Need

  - photo-*z* for all CFHTLS galaxies (Coupon et al 2009),
  - more accurate shear measurement,
  - more galaxies,
  - more sky coverage,
  - tomography, … in progress for ground surveys, …

…the HST/COSMOS shows the route!

Testing gravity

Gravitational lensing in non-GR models

Metric, scalar perturbations

$$ds^2 = -(1+2\psi)\ dt^2 + (1-2\phi)\ a(t)^2\ dx^2$$

Deflection angle

$$\alpha = -2\nabla_\perp \phi_{2D} \qquad \longrightarrow \qquad \alpha = -\nabla_\perp (\phi + \psi)_{2D}$$

Gravitational convergence

$$\kappa = \frac{1}{2}\left(\partial_1^2 + \partial_2^2\right)(\phi + \psi) = \bar{\rho} \int G\ W(z, z_s)\, \delta(z)\ dz$$

$$\downarrow$$

$$\nabla^2 (\psi + \phi) = 8\pi G_{eff}\ a^2 \bar{\rho}\ \delta$$

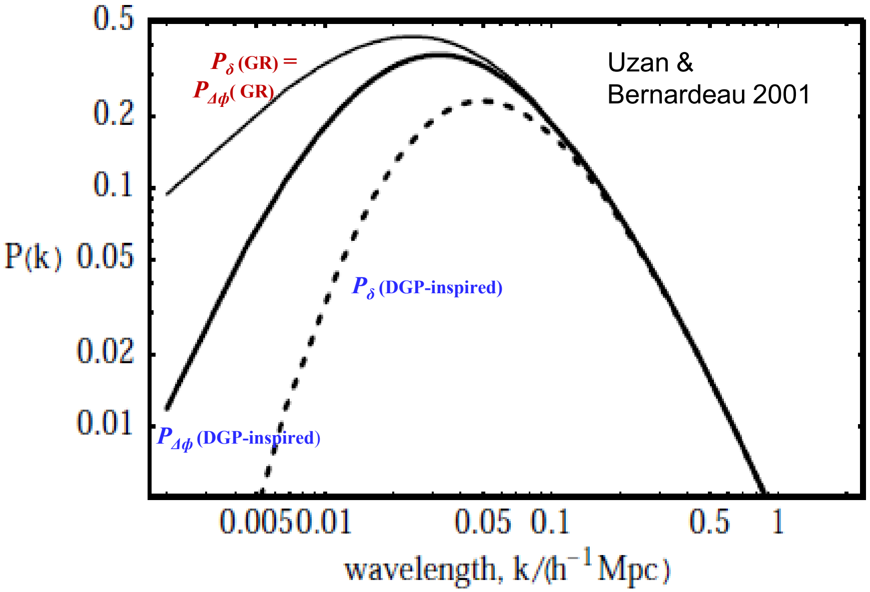
(Uzan 2007, Jain & Zhang 2007)

$$\downarrow$$

$$\kappa = \frac{1}{2}\left(\partial_1^2 + \partial_2^2\right)(\phi + \psi) = \bar{\rho} \int G_{eff}\ W(z, z_s)\, \delta(z)\ dz$$

Uzan & Bernardeau 2001, Jain & Zhang 2007

Growth of structure, power spectra in non-GR models: testing GR by exploring the different power spectra



$$ds^2 = -(1+2\psi)\ dt^2 + (1-2\phi)\ a(t)^2\ d\mathbf{x}^2$$

$$\nabla^2(\psi+\phi) = 8\pi G_{eff}\ a^2\bar{\rho}\ \delta$$

$$\gamma = \frac{\psi}{\phi}$$

$\longrightarrow$ $M_{\text{lensing}} = [(1+\gamma)/\ 2\ \gamma]\ M_{\text{dynamics}}$

$\longrightarrow$ G_{eff} and γ are both scale and time dependent

Growth factors for density and metric potentials:

- Density growth factor : $D_\delta(z,k)$
- Lensing growth factor : $D_{\psi+\phi} \sim G_{eff}\ .\ D_\delta$
- Dynamical growth factor : $D_\gamma = \gamma\ .\ D_\phi$

Uzan & Bernardeau 2001, White & Kochanek 2001, Song, 2006, Jain & Zhang 2007, Hu & Sawicki 2007, Doré et al 2007, Uzan 2007, Amendola et al 2007, Song & Doré 2009, Guzik et al 2009

Testing gravity with weak lensing:

recents results

	Author	Survey /Data	G-G WL $r_E \propto M_*^\alpha$	G-G WL $\varepsilon_h \neq 0$	Cosmic Shear WL	X-ray Cluster SL+WL	Galaxy SL+ dyn.	Conclusion
Galaxy	Hoekstra et al 2004	RCS		X				$\varepsilon > 0$: MOND disfavored
	Parker et al 2004	CFHTLS		X				$\varepsilon > 0$: MOND disfavored
	Tian et al 2009	RCS+SDSS	X					$r_E \propto M_*^{0.75}$: MOND disfavored
	Sanders & Land 2008	SLACS					X (FP)	Ok with MOND
	Ferreras et al 2008	CASTLES					X (FP)	MOND disfavored
	Zhao et al 2006	CASTLES					X (SL)	$\sim$ ok with MOND
	Ferreras et al 2009	CASTLES					X (Rot)	TeVeS disfavored
Cluster	Clowe et al 2004 Bradac et al 2006	1E 0657-56				X X		DM favored (WL only) DM favored (WL+SL)
	Angus et al 2006	1E 0657-56				X		ok with MOND: need $m_\nu \sim$ 2eV SL unexplained
	Takahashi & Chiba 2007	45 clusters				X		MOND disfavored. Need $m_\nu > 2$ eV
	Natarajan & Zhao 2008	6 HST clusters				X		MOND + low mass ν disfavored.
	Bradac et al 2008	MACS J0025.4+1222				X		DM favored
Large scale structure	White & Kochanek 2001	VIRMOS/ DESCART			X			GR ok Yukawa-type
	Dore et al 2007	CFHTLS +SDSS			X			GR ok Yukawa-type or Uzan & Bernardeau (2001)
	Wang et al 2008	CTIO			X			DGP disfavored
	Thomas et al 2008	CFHTLS			X			GR ($\alpha = 0$) ok, DGP ($\alpha = 1$) rejected $H^2 - \frac{H^\alpha}{r_c^{2-\alpha}} = \frac{8\pi G}{3}$ $r_c = (1-\Omega_m)^{\frac{1}{2-\alpha}} H_o^{-1}$

SL = Strong Lensing
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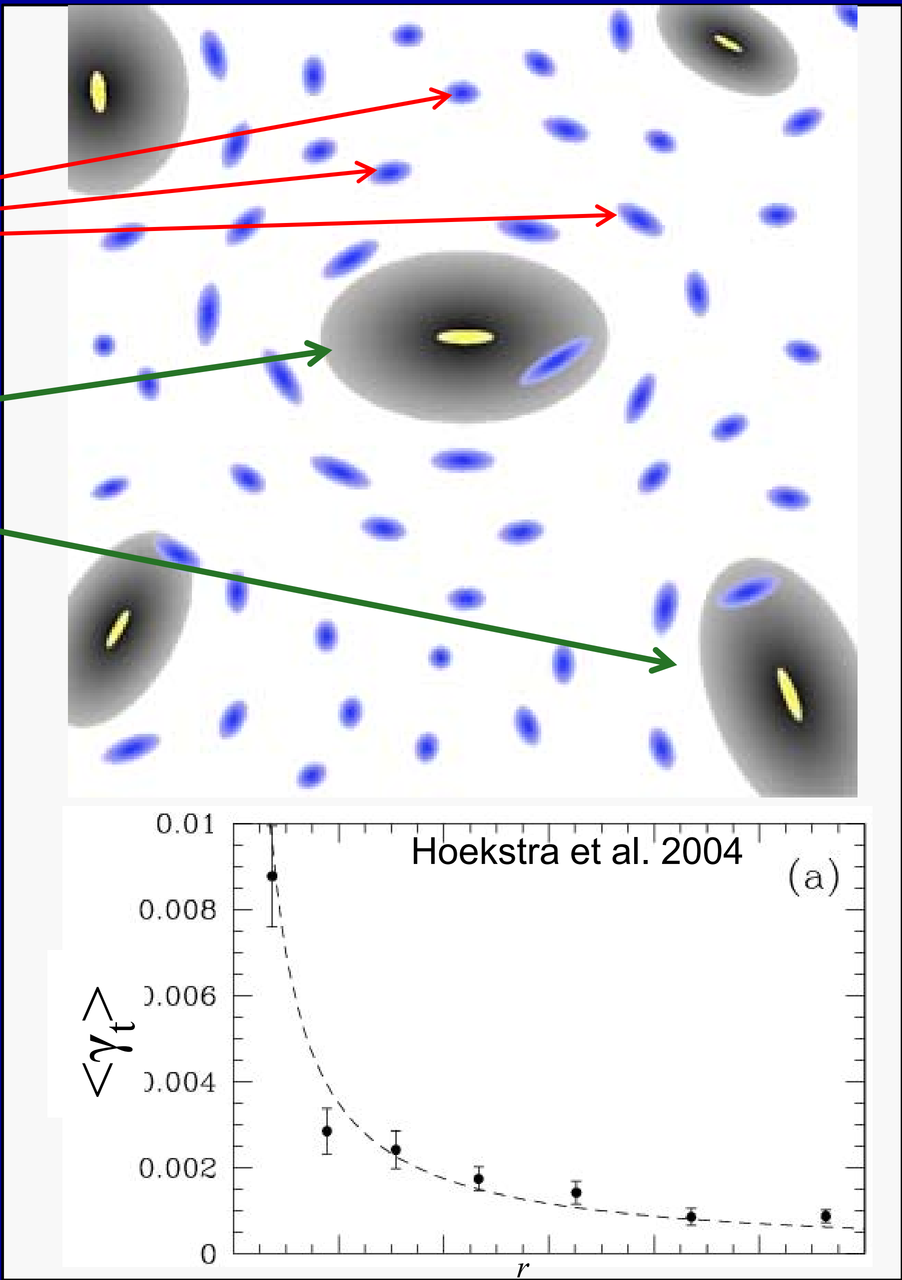
Galaxy-galaxy lensing

- Weak *tangential shear* $\langle\gamma_t\rangle$ of background galaxies

  around an

  ensemble of lenses

- Measure $\langle\gamma_t\rangle$ as function of radial distance galaxy-mass correlation, out to Mpc

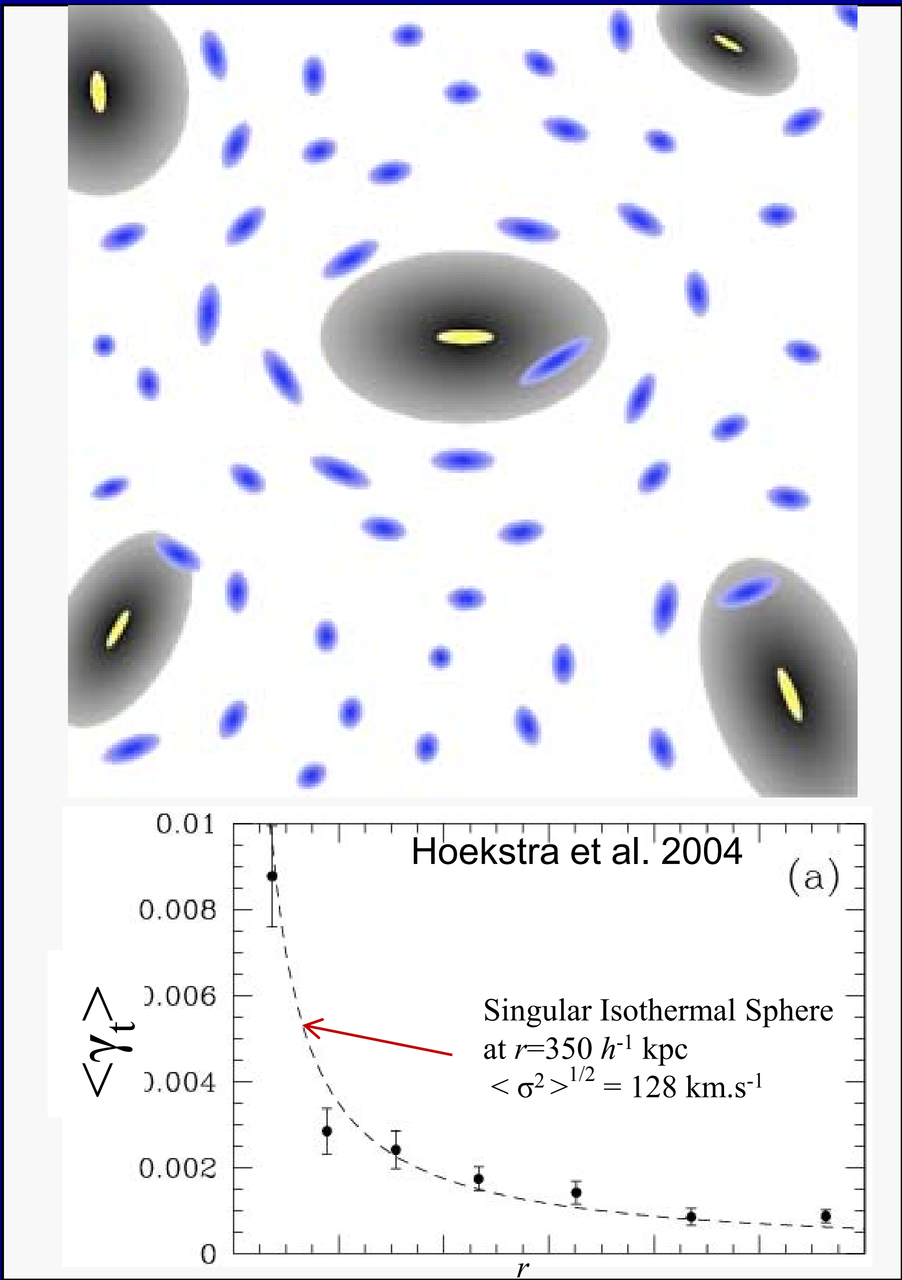


Galaxy-galaxy lensing

$<\gamma_t>$ as function of radial distance

$\longrightarrow$

- Mass-to-light ratio
- Typical size of dark haloes
- Shape of haloes
- Halo properties as function of galaxy type and redshift
- Test halo properties in
    - standard cosmological (CDM) scenarios
    - MOND/TeVeS



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Contraints on neutrino mass from current cosmological probes

No WL Data	Authors	$\sum m_{\nu_i}$
2dF (P01)	Elgaroy et al 2002	< 1.8 eV
WMAP5+BAO+SN	Komatsu et al 2005	< 0.67 eV
2dF(C05)+CMB	Sanchez et al 2005	< 1.2 eV
BAO+CMB+LSS + SN	Goobar et al 2006	< 0.62 eV
Ly-α + SDSS + WMAP	Seljak et al 2004	< 0.17 eV
WMAP3 alone	Fukugita et al 2006	< 2.0 eV
WMAP5+LSS + SN+BAO	Komatsu et al 2008	< 0.61 eV
WMAP5+SDSS(R7)+WMAP5+U-SN	Beth et al 2009	< 0.61 eV

Cosmic shear data (+joint data)	Authors	
Benjamin et al 2008 WL: CFHTLS T0001+ RCS+ VIRMOS-Descart+GaBoDS	Li et al 2008	< 0.47 eV (95% C.L.)
Benjamin et al 2008	Gong et al 2008	< 0.80 eV (2σ)
Fu et al 2008 WL: CFHTLS T0003	Tereno et al 2009	$0.03 < \sum m_{\nu_i} < 0.54$ eV (95% C.L.)
Fu et al 2008	Ichiki et al 2008	< 0.54 eV (95% C.L.)

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SL = Strong Lensing
WL = Weak Lensing
G-G WL = Galaxy-Galaxy Lensing
FP = Test predictions for Fundamental Plane
Rot = Comparison between Strong Lensing and Rotation curve predictions.

Testing gravity with gravitational lensing

Author	Survey /Data	G-G WL $r_E \propto M_*^\alpha$	G-G WL $\varepsilon_h \neq 0$	Cosmic Shear WL	X-ray Cluster SL+WL	Galaxy SL+ dyn.	Conclusion
Hoekstra et al 2004	RCS		X				$\varepsilon > 0$: MOND disfavored
Parker et al 2004	CFHTLS		X				$\varepsilon > 0$: MOND disfavored
Tian et al 2009	RCS+SDSS	X					$r_E \propto M_*^{0.75}$: MOND disfavored
Sanders & Land 2008	SLACS					X (FP)	Ok with MOND
Ferreras et al 2008	CASTLES					X (FP)	MOND disfavored
Zhao et al 2006	CASTLES					X (SL)	$\sim$ ok with MOND
Ferreras et al 2009	CASTLES					X (Rot)	TeVeS disfavored
Clowe et al 2004 Bradac et al 2006	1E 0657-56				X X		DM favored (WL only) DM favored (WL+SL)
Angus et al 2006	1E 0657-56				X		ok with MOND: need $m_\nu \sim 2$eV SL unexplained
Takahashi & Chiba 2007	45 clusters				X		MOND disfavored. Need $m_\nu > 2$ eV
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Simple test of GR with CFHTLS lensing data

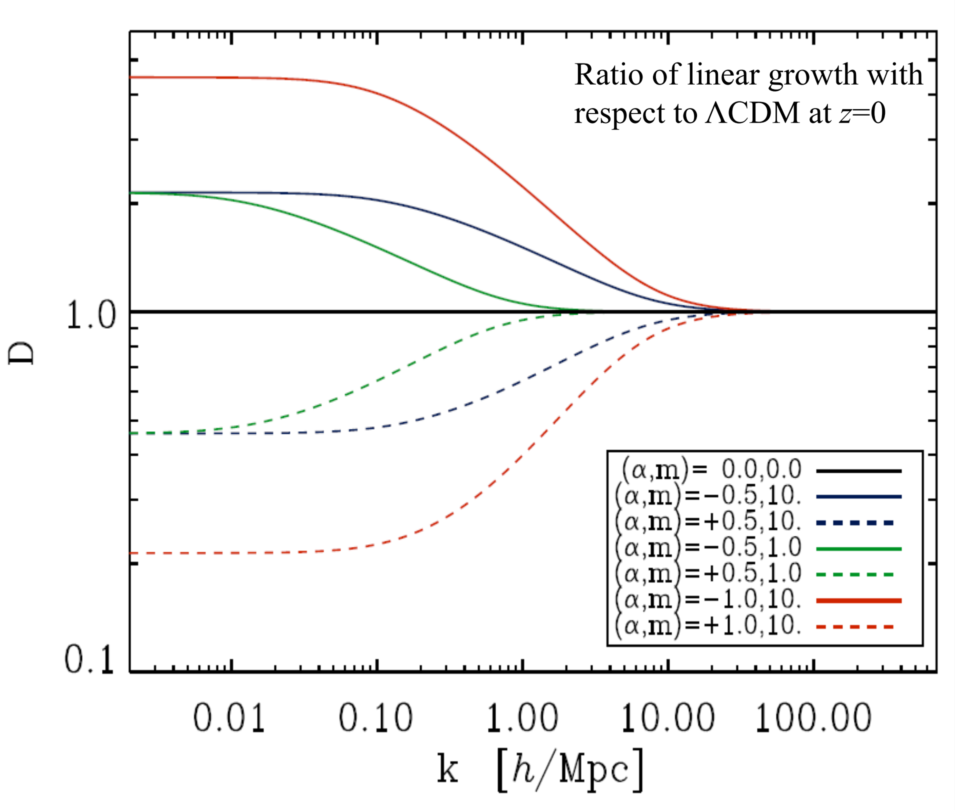
Background cosmology: flat ΛCDM Friedmann-Lemaître

Yukawa potential; alteration of gravity above scales ~ 1/m , increase/decrease of gravity: sign of α

$$\Phi(\mathbf{r}) = (1-\alpha)\Phi(\mathbf{r},0) + \alpha\Phi(\mathbf{r},m)$$
$$\Phi(\mathbf{r},m) = G\int \frac{\rho(\mathbf{r}')d^3\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|}e^{-m|\mathbf{r}-\mathbf{r}'|}.$$

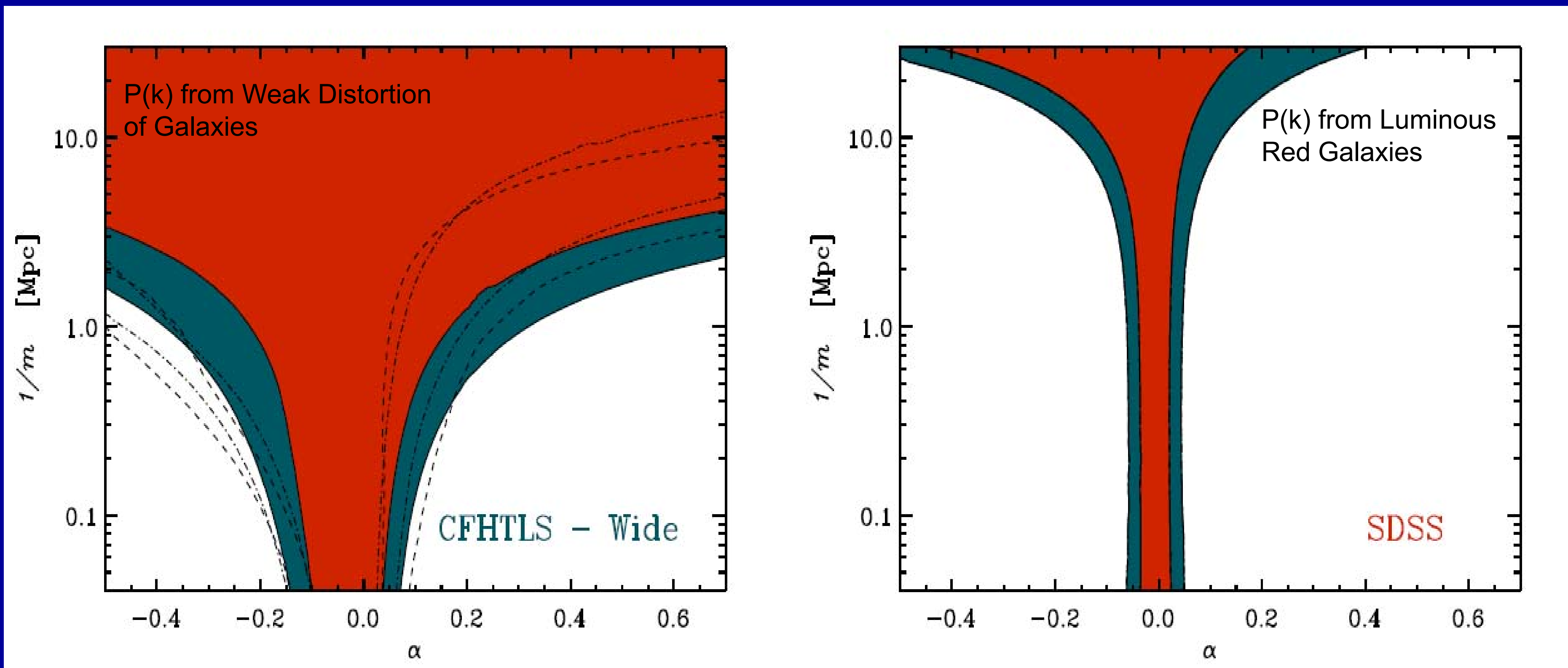
$$\ddot{D} + 2H\dot{D} = \frac{3}{2}\frac{H_0^2\Omega_{m0}}{a^3}f(k)D$$

$$f^{Yuk}(\mathbf{k}) \equiv f(\mathbf{k}) = 1 - \alpha\frac{1}{1+\left(\frac{k}{a\ m}\right)^2}$$



Doré, Martig, Mellier, Kilbinger et al. 2007

Constraints from CFHTLS and SDSS data



(WMAP3-priors, marginalised over lensing redshift distribution & linear galaxy bias)

$\alpha = 0$:= GR

Doré et al. 2007

Testing gravity with gravitational lensing

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Testing gravity with gravitational lensing

- All data agree with GR predictions (with DM,DE)
- Overall : standard MOND/TeVeS models not favored in most cases

- However, not really conclusive, so far:
  - analyses not always based on a fully internal consistency ground,
  - analyses depend on the choice of the parameterisation of gravity models,
  - analyses of same data do not always lead to same conclusions,
  - all may agree with data within a factor of 2… need to improve accuracy,
  - astrophysical systematics (like environment), technical systematics or contaminations in data not always taken into account,

What next?

Problems

Weak lensing (serious) issues:

- shape measurement: hard,still unstable results:
  on going CFHTLS surveys focus on that problem

- intrinsic alignement and other astrophysical systematics: serious but no show stoppers,
  need redshifts

- … outstanding collaborative works done over the past 3 years …

Task forces set up since 2007

Weak lensing (serious) issues:

– … outstanding collaborative works done over the past 3 years:

– STEP(s) team (C. Heymans, R. Massey, L. van Waerbeke, et al),
– GREAT08 team (S. Bridle et al),
– DUEL team (FP6 EC RTN) (Bonn, Edinburgh, Paris, Heidelberg, Munchen, Naples, Vancouver+UVic),
– CFHTLS Systematic collaboration team (L. van Waerbeke, C. Heymans, Hoekstra, Erben, Mellier et al),
– EUCLID WL Team (A. Réfrégier, A. Amara, et al)

Cosmic shear = shape + redshift of sources

- Different way of processing the native images
  - Better stacks, no more stacks?
  - CCD by CCD instead of full detector at once?
- New tools to analyse the PSF, deconvolve and measure shapes of sources (model fitting?)
- Cosmic shear surveys are big and demand collaborations and huge resources:
  - Imaging surveys
  - Visible + NIR Photometric surveys
  - Spectroscopic survey
  - Very wide fields needed
  - Medium deep surveys needed…

Cosmic shear = shape + redshift of sources

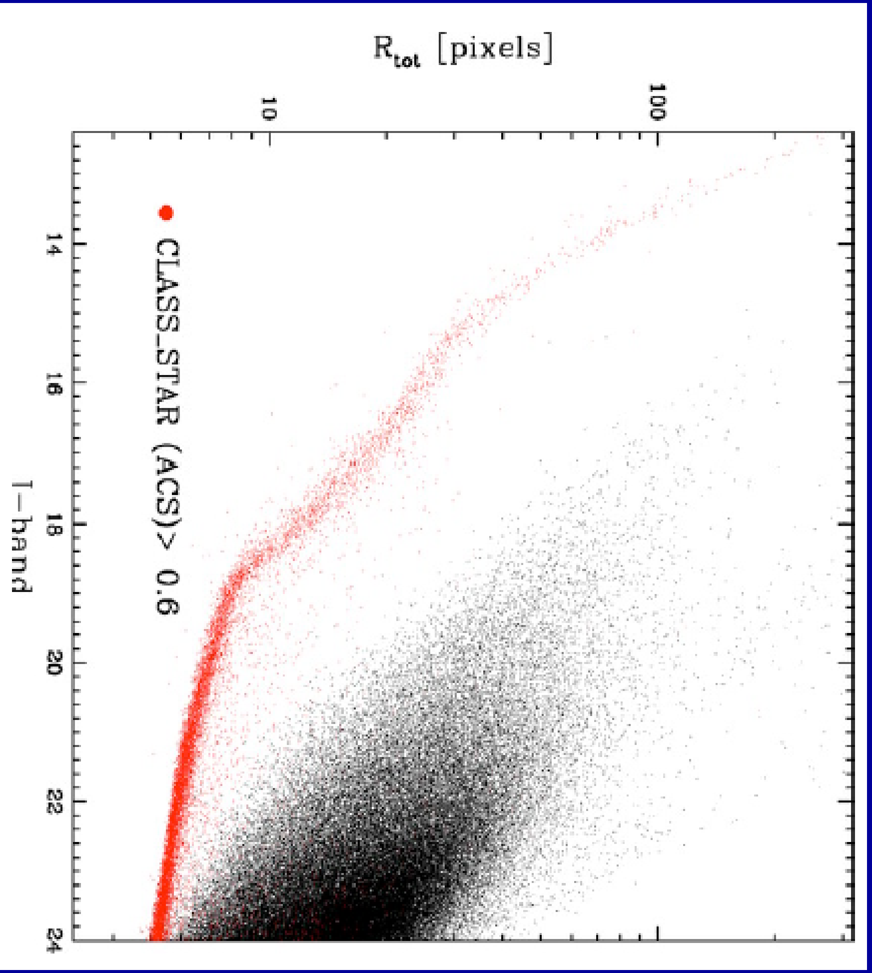
Medium deep surveys needed…

– Need large number density of lensed galaxies

– Need “spectroscopable” samples
– Need photo-z-able galaxies (high S/N NIR signal)

– Need galaxies with well sampled size: pixel and PSF issues

– Very distant has complex morphology, increases the intrinsic ellipticity noise contribution



Goals of next generation surveys

Weak lensing is primarily a probe of gravity, and a unique probe of the dark universe

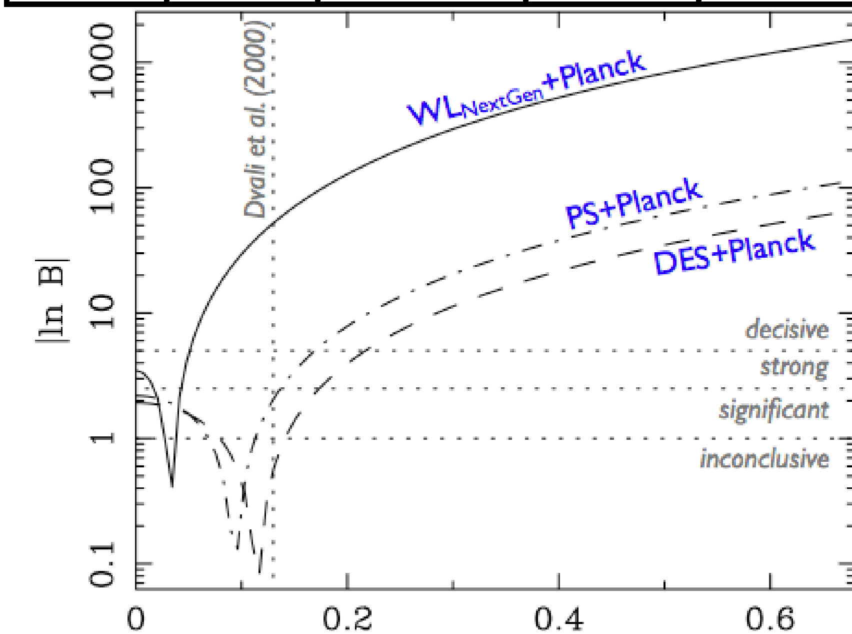
- Exploration of Dark Matter distribution:
  - Amplitude and shape of $P(k)$,
  - Properties of haloes, tests against numerical simulations,
  - mass reconstruction with strong and weak lensing;

- Exploration of the growth, and the growth rate of structure $P(k,z)$;
  - History of structure formation
  - Test of General Relativity;
  - Dark energy w(z) : properties or tests of models (schimd et et 2007);
  - Mass of neutrinos
  - Non-gaussianity;

To test gravity, next generation surveys must be BIG

SURVEY	SIGNIFICANCE OF TEST (#σ)	BAYES FACTOR |ln B|	ASSESSMENT
DES+Planck+BAO +SN	3.5	1.28	significant
DES+Planck	2.2	0.56	inconclusive
DES	0.7	0.54	inconclusive
PS1+Planck+BAO+ SN	2.9	3.78	Strong
PS1+Planck	2.6	2.04	significant
PS1	1.0	0.62	inconclusive
$WL_{NextGen}$+Planck+ BAO+SN	10.6	63.0	decisive
$WL_{NextGen}$+Planck	10.2	52.2	decisive
$WL_{NextGen}$	5.4	11.8	decisive

SURVEY	AREA (deg^2)	MEDIAN REDSHIFT	SOURCE DENSITY (#/$arcmin^2$)	PHOTO-Z ERROR $\sigma_z(z)$
DES	5000	0.80	10	0.050(1+*z*)
PS1	30,000	0.75	5	0.060(1+*z*)
$WL_{NextGen}$	20,000	0.90	35	0.025(1+*z*)



GR : γ =0.55; DGP : γ = 0.68   δγ

Heavens et al 2007

On going and future weak lensing surveys

Survey	Telescope	Sky coverage	Filters	depth
Deep Lens Survey	CTIO	7x4 deg^2	BVRz'	R=25
CFHTLS-Wide	CFHT	170 deg^2	ugriz	i_{AB}=24.5
RCS2	CFHT	1000 deg^2	grz	i_{AB}=22.5
KIDS	VST	1500 deg^2	ugriz	i_{AB}=22.9
Pan-STARRS	PS1	30000 deg^2	grizy	i_{AB}=24
VIKING	VISTA	1500 deg^2	zYJHK	i_{AB}=22.9
Dark Energy Survey	CTIO	5000 deg^2	griz	i_{AB}=24.5
HyperCam	SUBARU	~2000 deg2?	TBD	TBD
JDEM	Space	~20000 deg2 ?	Vis. + NIR ?	TBD
LSST	6m ground	20000 deg^2	Narrow band (0.35-1.2)	i_{AB}=27
EUCLID	Space	20000 deg^2	(R+I+Y)+J,H,(K)	i_{AB}=25.5

Munshi et al 2008

Unveiling the dark lensed universe will still demand some work…

Summary

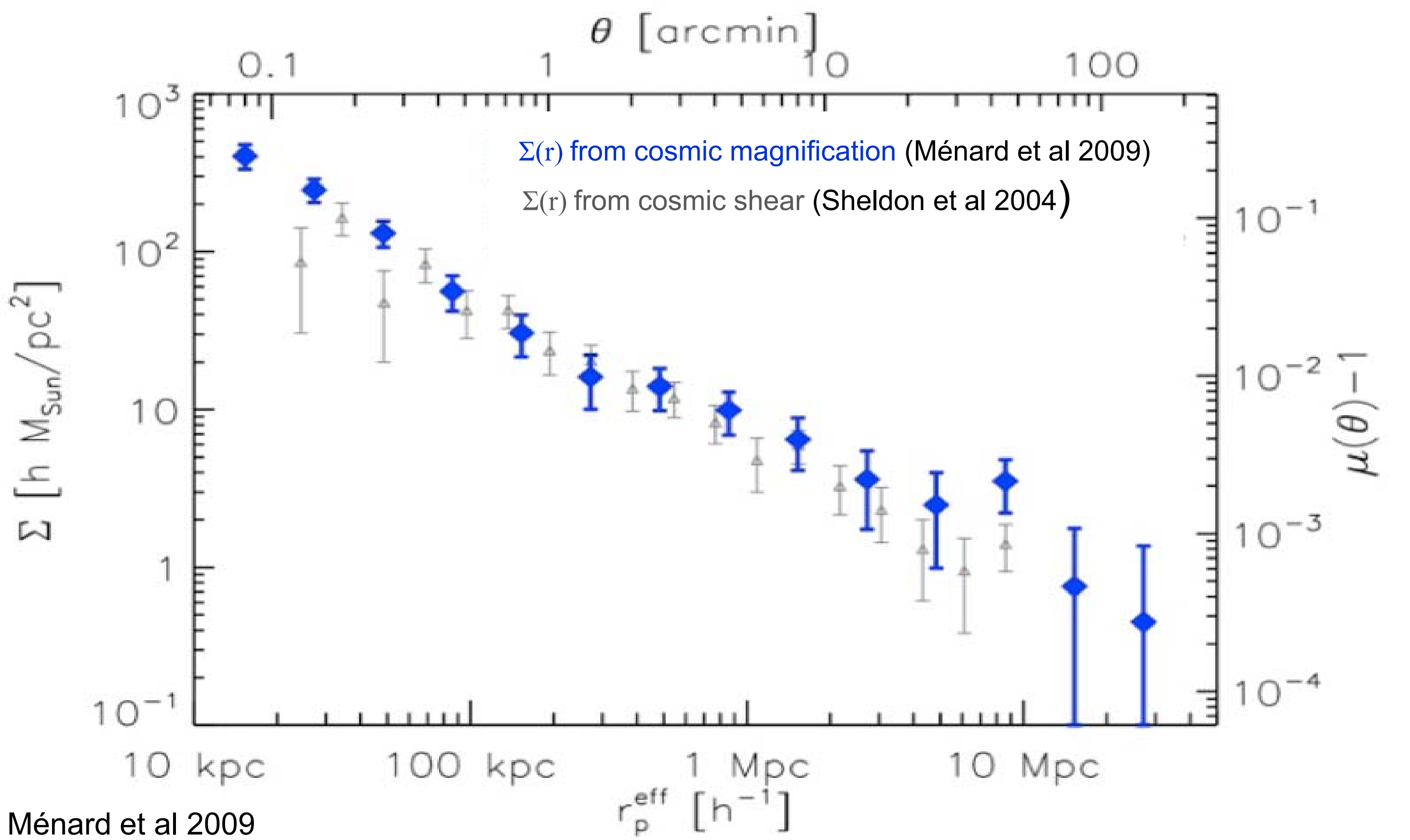
- Weak lensing demonstrated
  - it works up to ~100 Mpc scales: can be used where linear theory applies,
  - it provides competitive constraints on the dark matter power spectrum:

  Cosmic shear 2005: σ_8 = 0.80 +/- 0.15 ; Cosmic shear 2009: σ_8 = 0.80 +/- 0.05

  - it provides promising results on tests of gravity and tomograph
- Much more to come (KIDS, DES, HSC, JWST, EUCLID, JDEM, LSST) … but…
  - weak lensing is a very difficult, not fully matured, technique,
  - measuring extremely weak lensing is still a challenge,
  - still issues on astrophysical systematics,
  - photometric redshifts are needed for all galaxies
  - higher order statistics even weaker, but most promising: non-gaussinaity, breaking degeneracies
  - growing interest for cosmic magnification (Ménard et al 2008, Hildebrandt et al 2009) … complement cosmic shear… should be explored in details

Cosmic magnification in SDSS

- Correlation between bright QSOs and foreground galaxies (lenses) in Large Scale Structure: QSOs get brighter
- 85000 QSOs at z>1 ; 20 10^6 galaxies at z~0.3



Ménard et al 2009

Thank you

Testing systematics and reliability of cosmic shear signal:

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