Weak Lensing: a Probe of Dark Matter and Dark Energy

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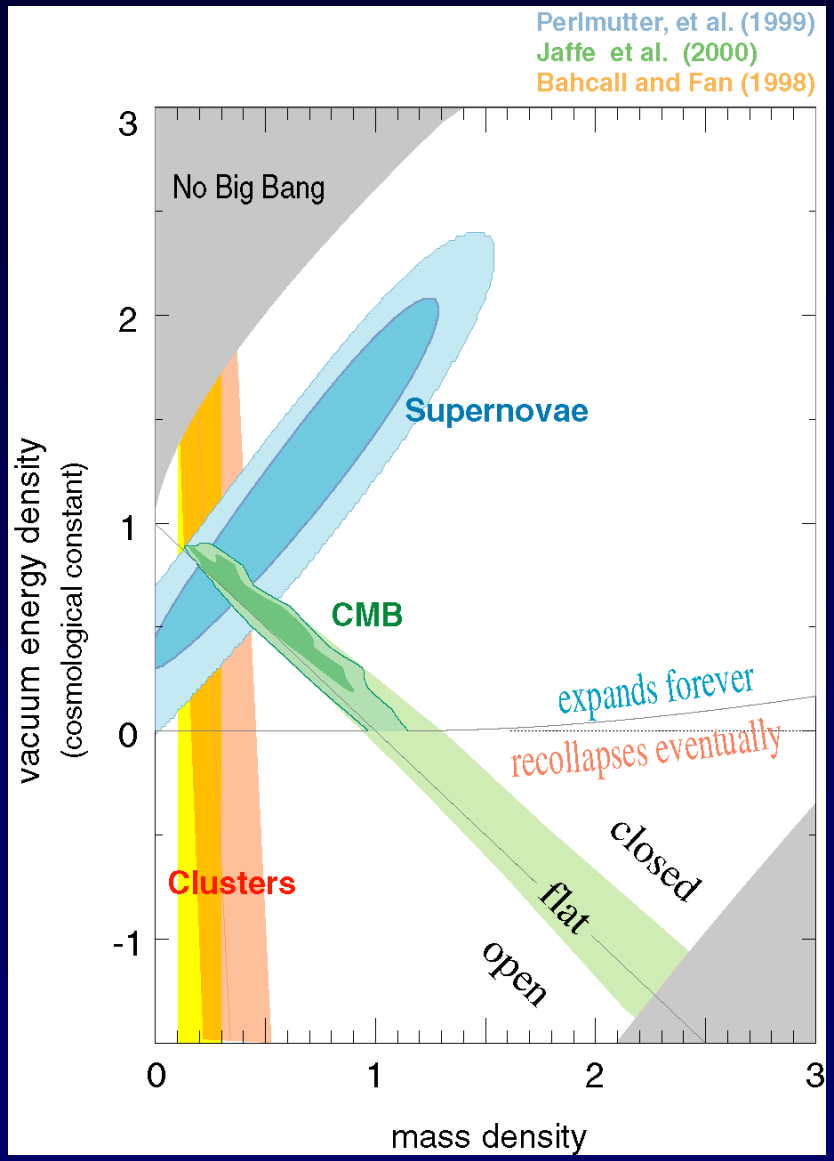
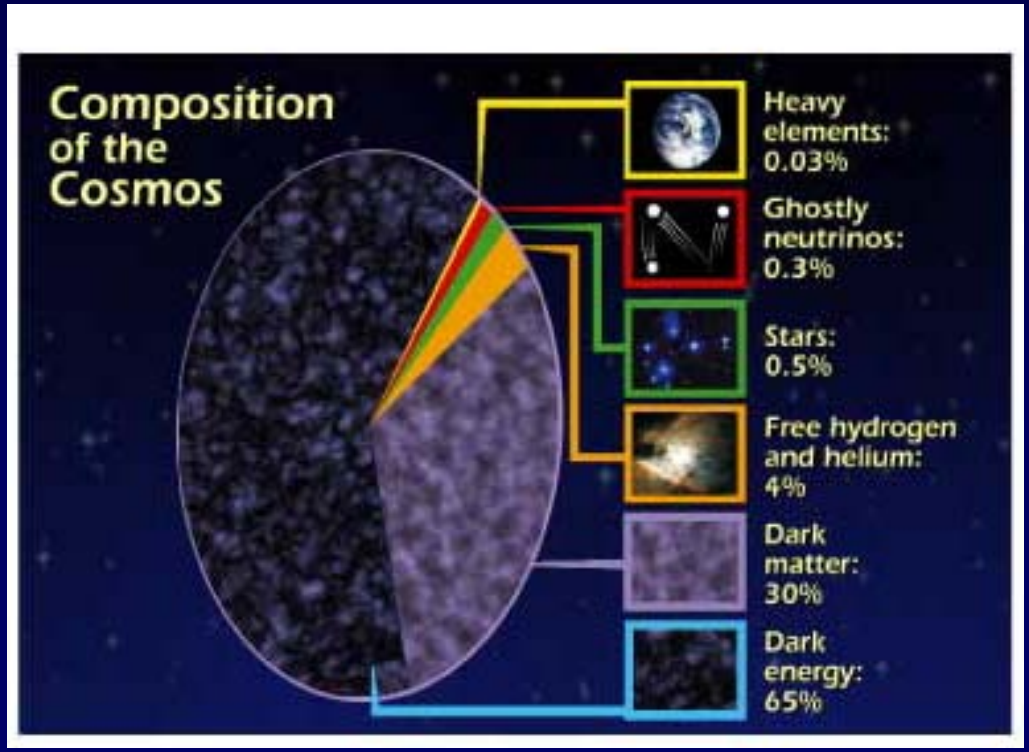
SLAC – August 2004

Concordance ΛCDM Model

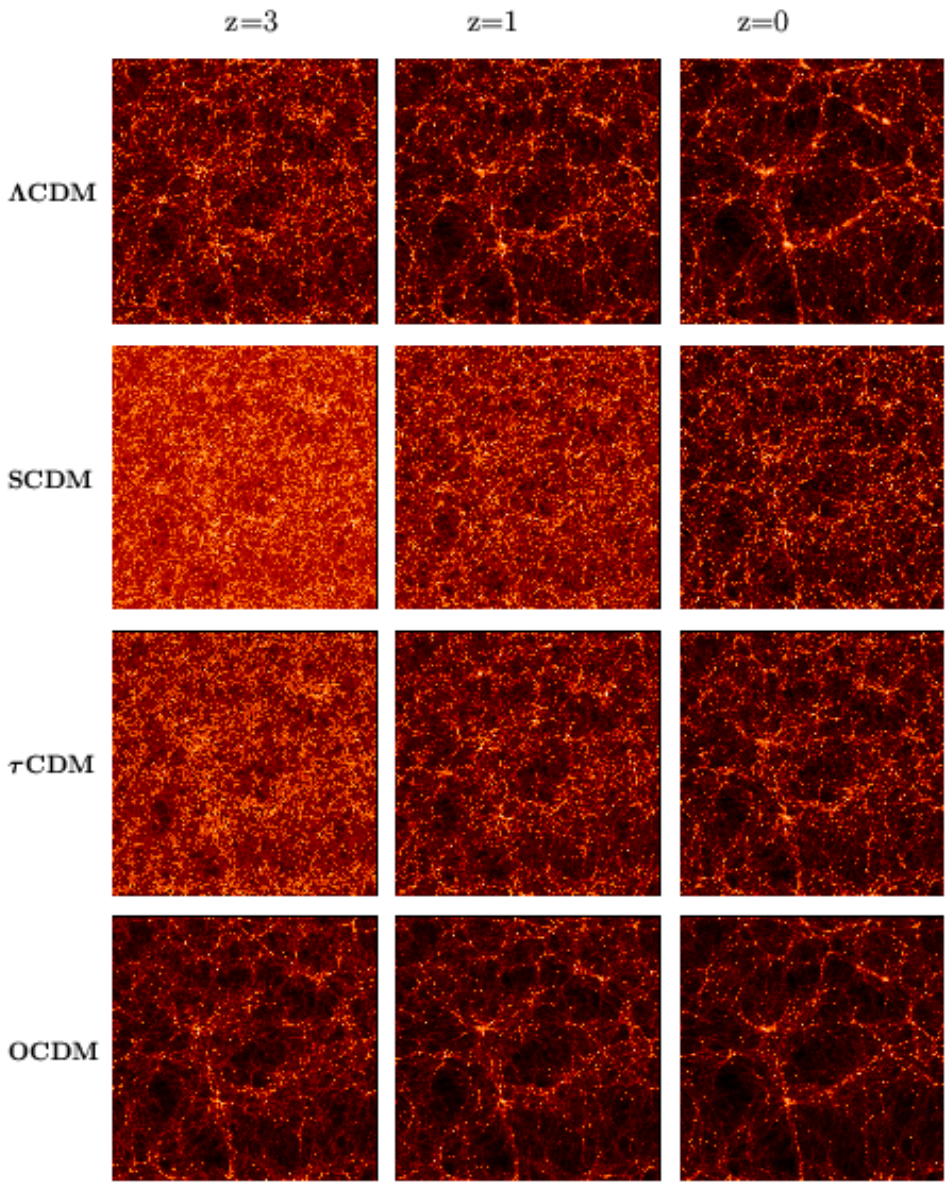


Outstanding questions:

- initial conditions (inflation?)
- nature of the dark matter
- nature of the dark energy



Cosmic Structure Formation



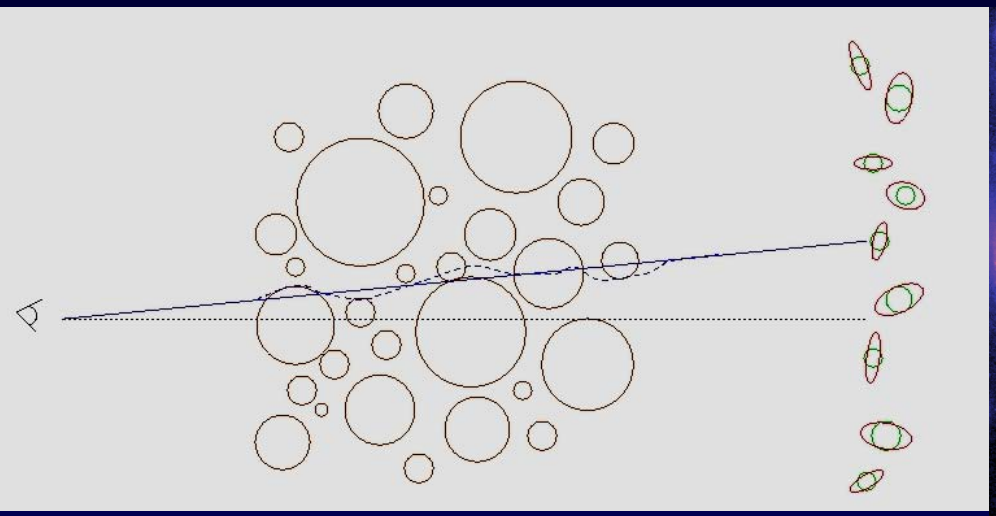
Virgo consortium

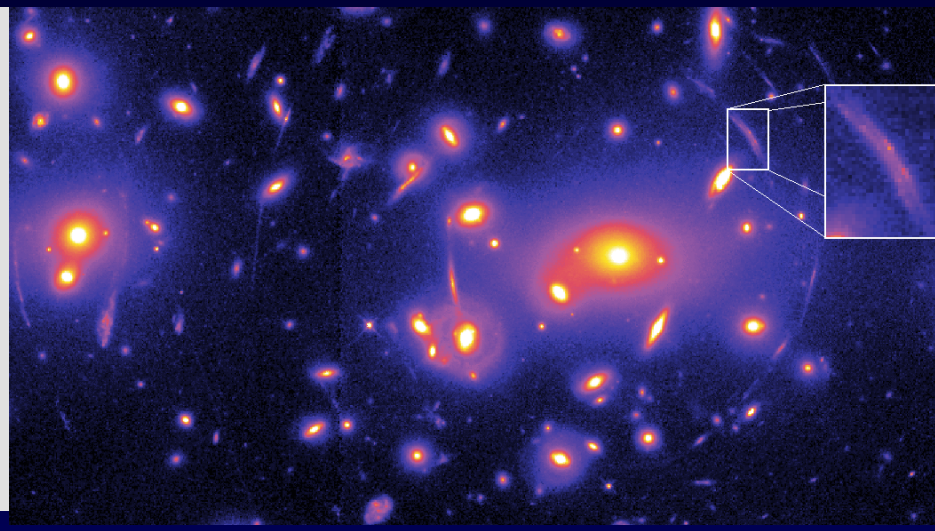
Ingredients:

- initial conditions
- CDM particles
- gravity

→ The statistics and evolution of the density fluctuations depend on cosmology

Weak Gravitational Lensing





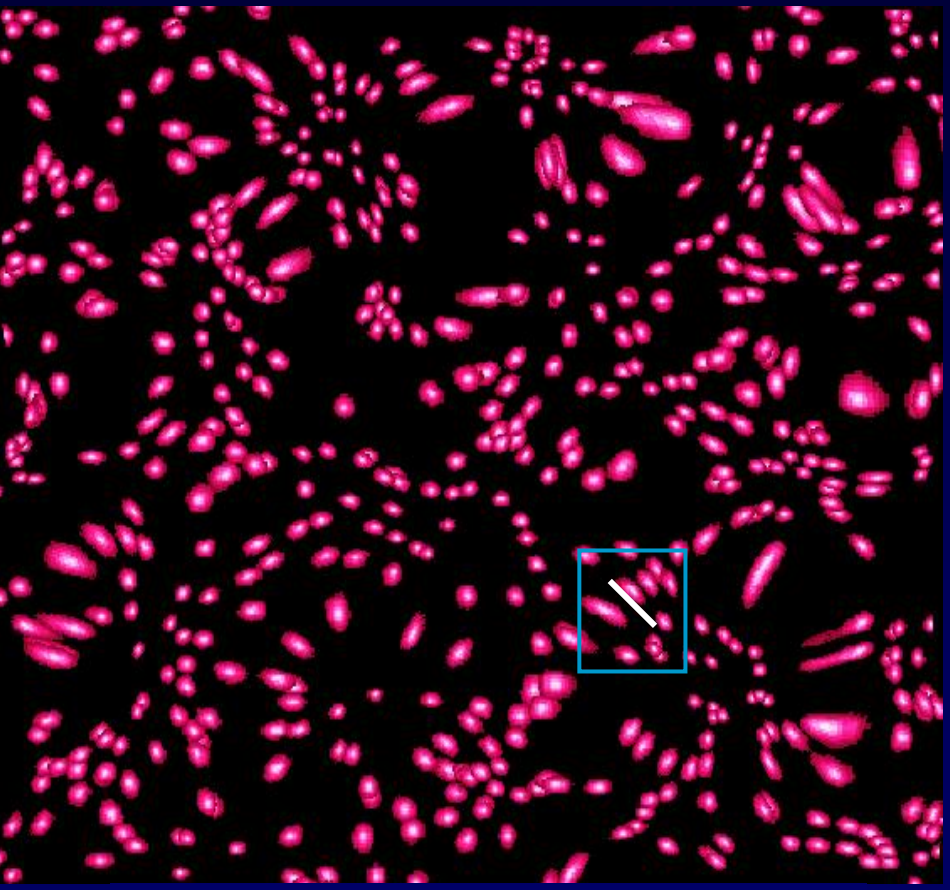
Distortion Matrix:

$$\Psi_{ij} = \frac{\partial \delta\theta_i}{\partial \theta_j} = \int dz\, g(z) \frac{\partial^2 \Phi}{\partial \theta_i \partial \theta_j}$$

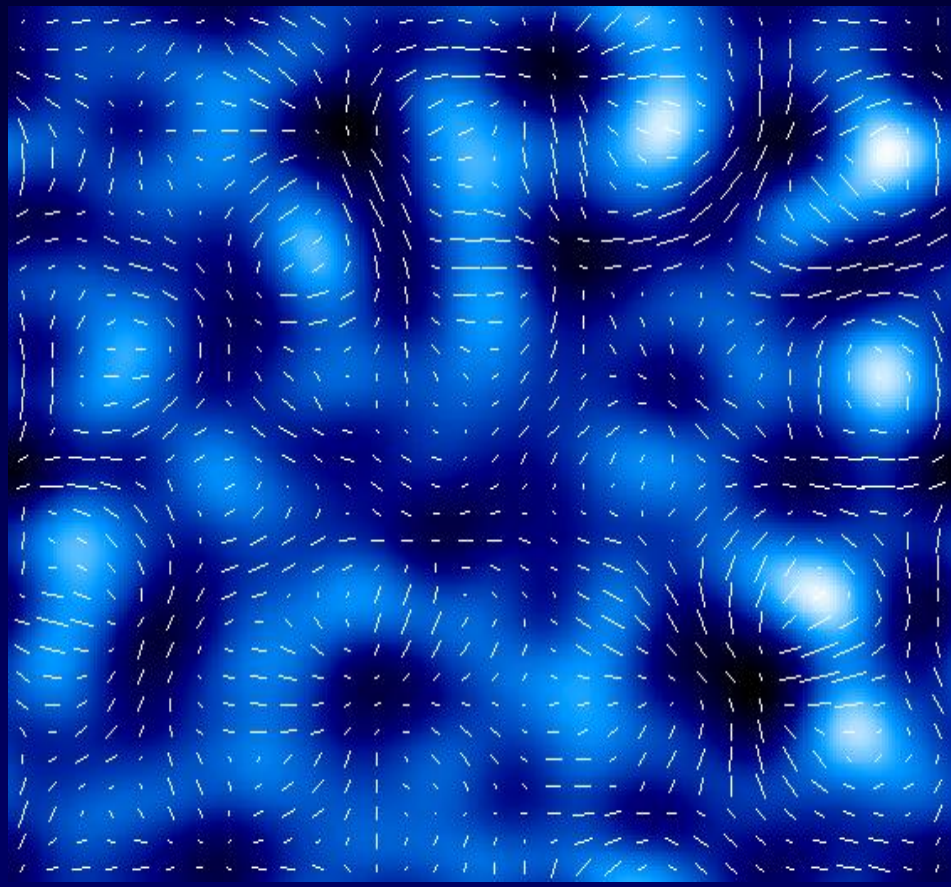
Theory

→ Direct measure of the distribution of mass in the universe, as opposed to the distribution of light, as in other methods (eg. Galaxy surveys)

Weak Lensing Shear Measurement



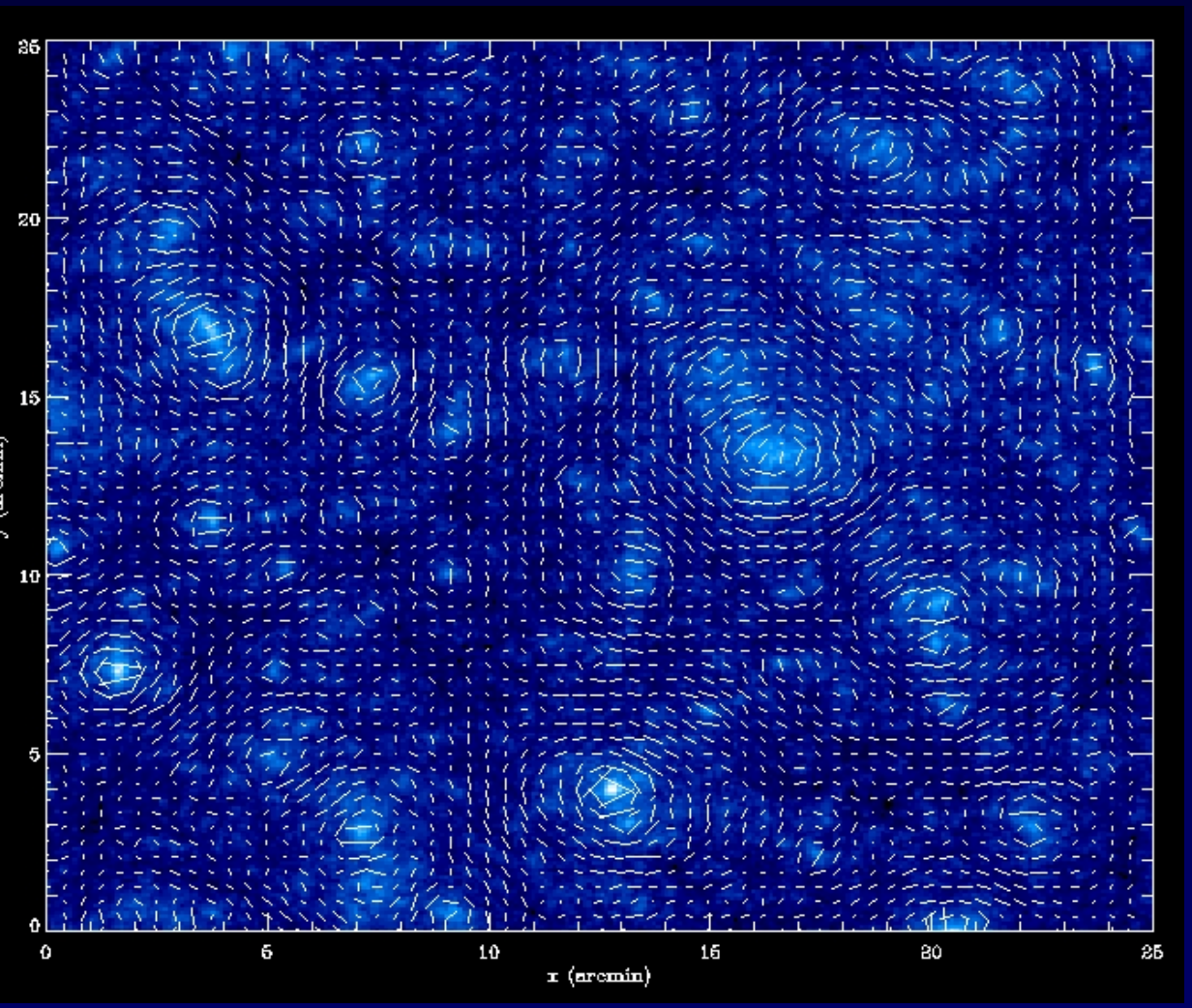
lensed background galaxies



mass and shear distribution

Scientific Promise of Weak Lensing

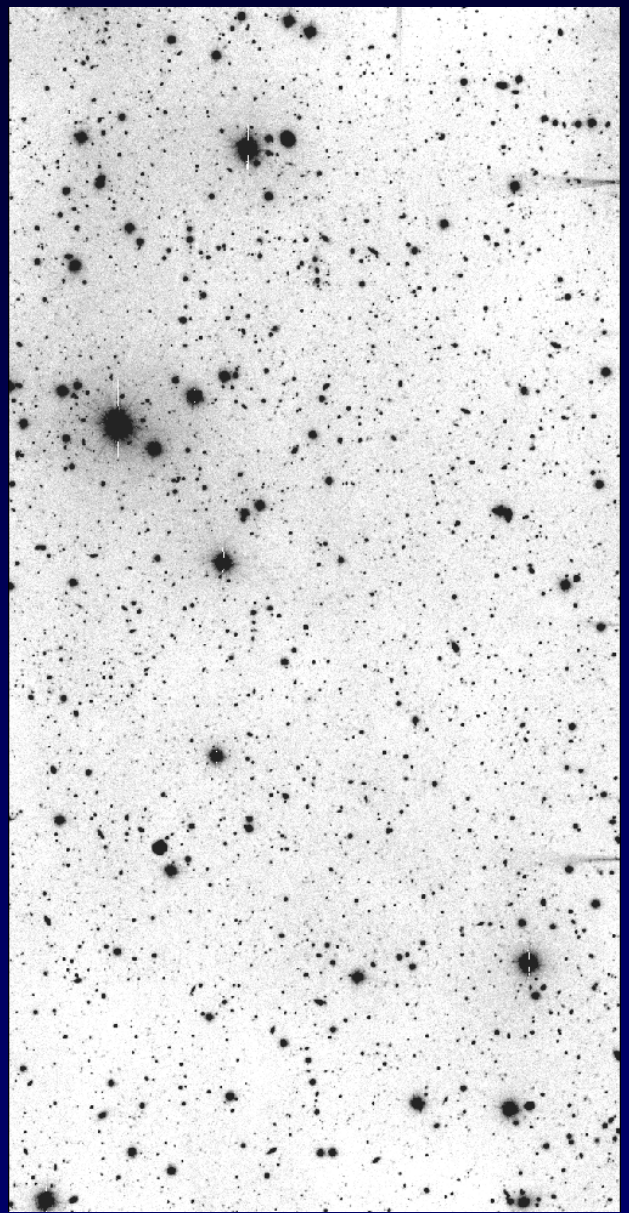
From the statistics of the shear field, weak lensing provides:



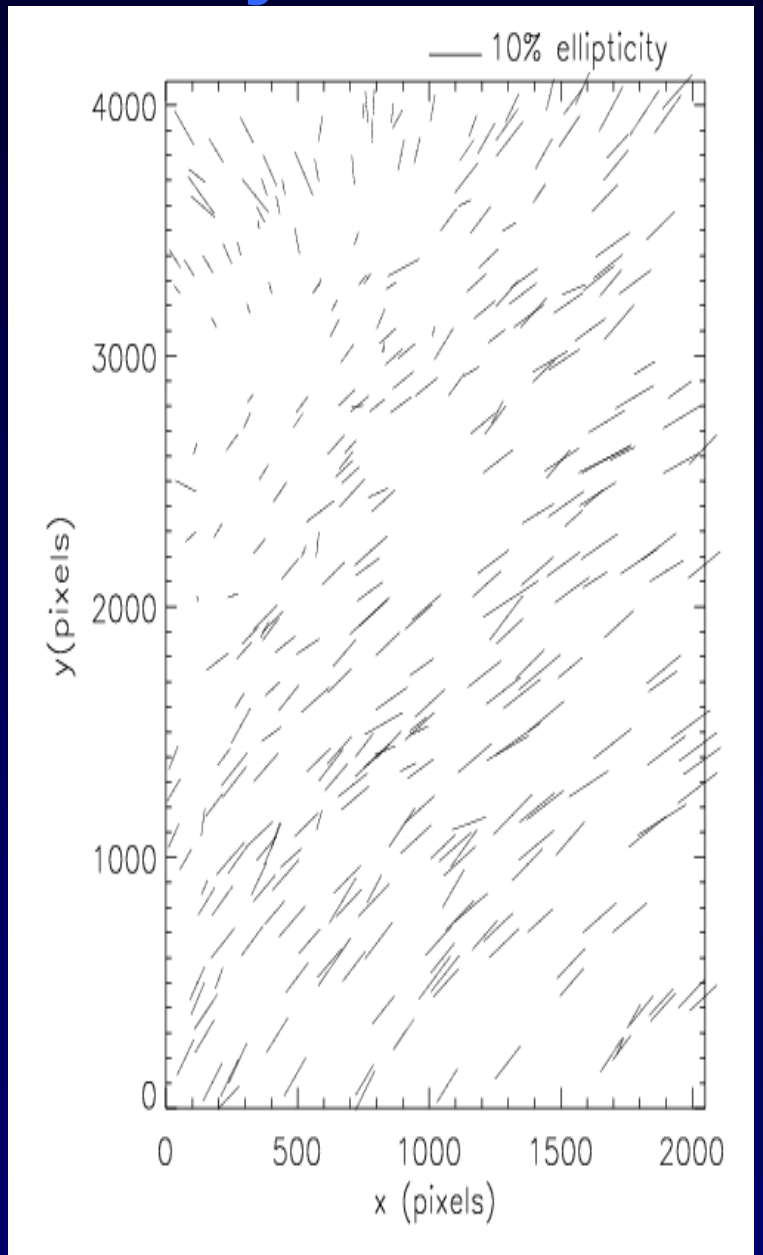
- Mapping of the distribution of Dark Matter on various scales
- Measurement of the evolution of structures
- Measurement of cosmological parameters, breaking degeneracies present in other methods (SNe, CMB)
- Explore models beyond the standard osmological model (ΛCDM)

Jain, Seljak & White 1997, 25'x25', SCDM

Cosmic Shear Surveys

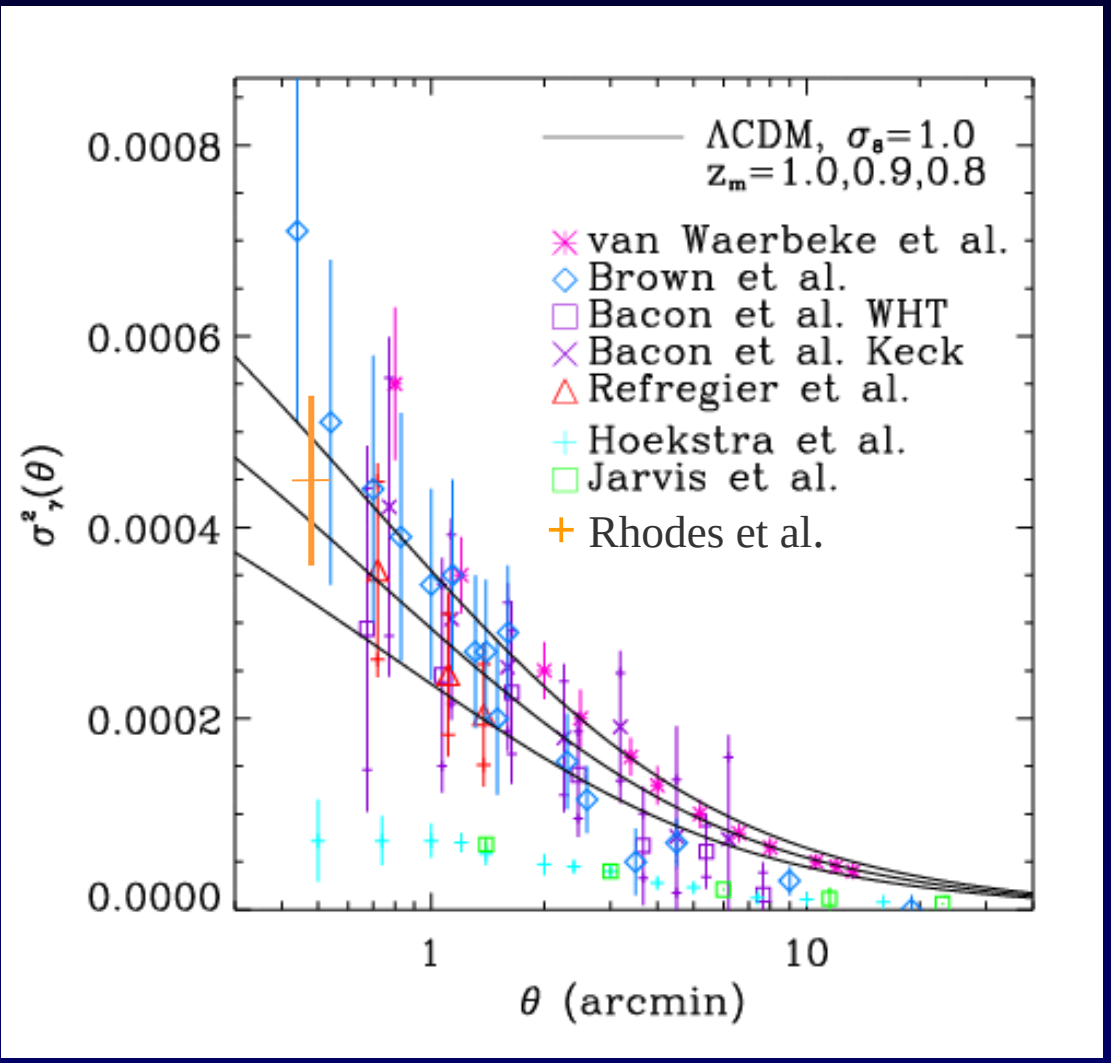


WHT survey:
16'x8'
R<25.5
20 gals/amin^2

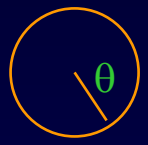


Systematics:
Anisotropic
PSF

Cosmic Shear Measurements



Shear variance in circular cells:



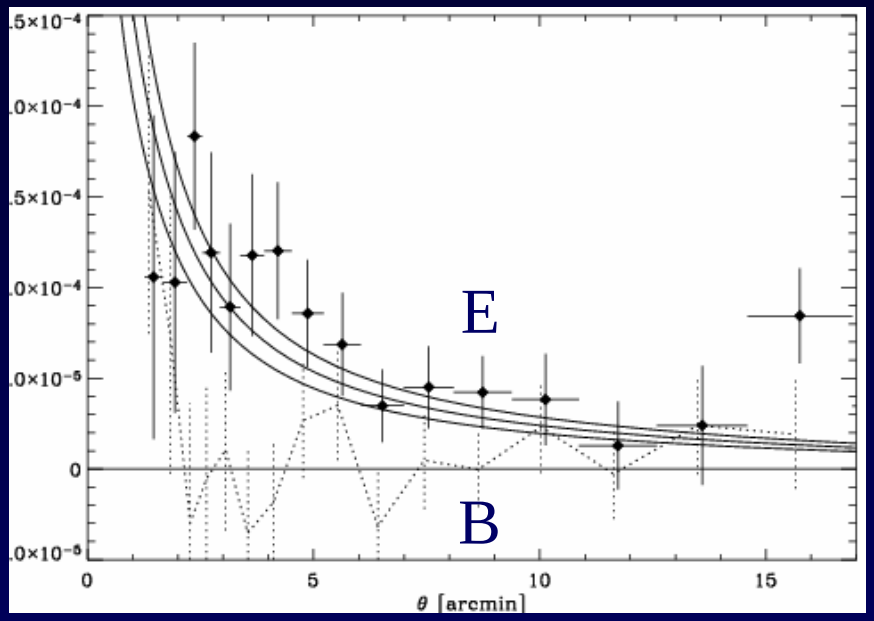
$\sigma^2_\gamma(\theta)=\langle\gamma^2\rangle$

Bacon, Refregier & Ellis 2000*
Bacon, Massey, Refregier, Ellis 2001
Kaiser et al. 2000*
Maoli et al. 2000*
Rhodes, Refregier & Groth 2001*
Refregier, Rhodes & Groth 2002
van Waerbeke et al. 2000*
van Waerbeke et al. 2001
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

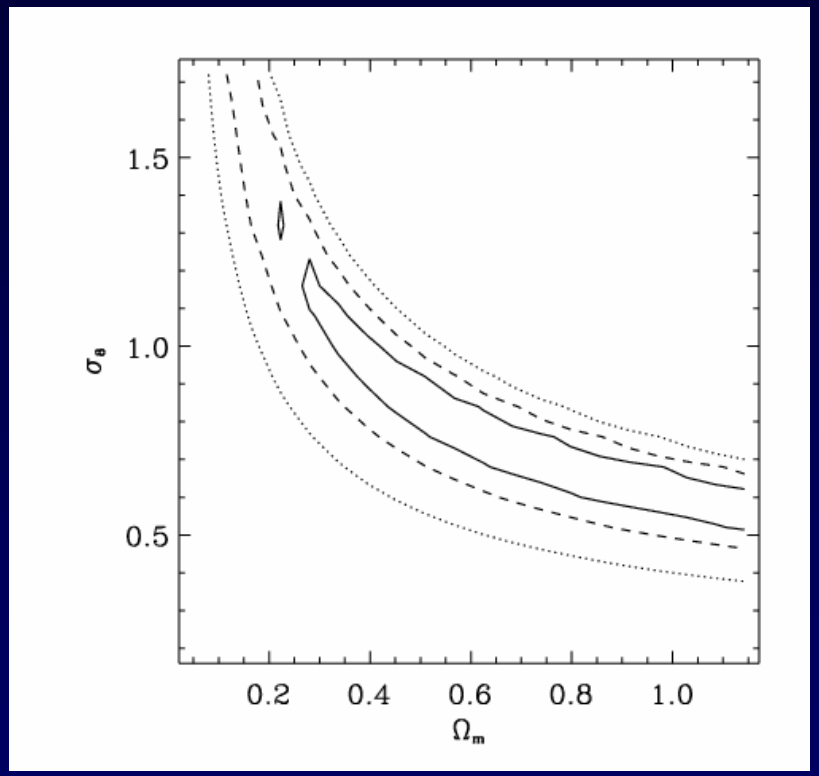
* not shown

Cosmological Constraints

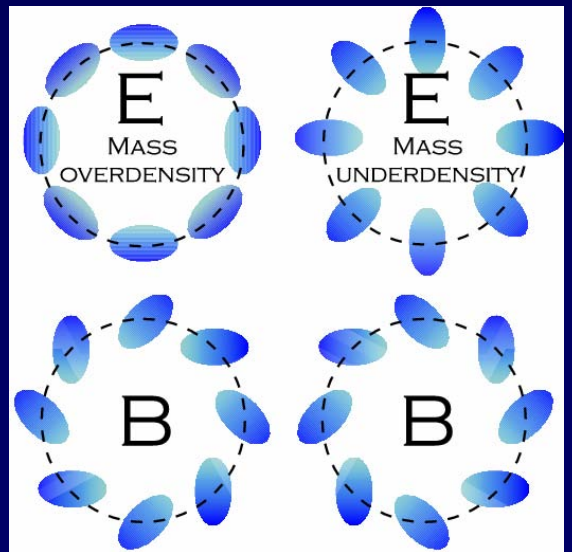
Shear correlation functions



Massey, Refregier, Bacon & Ellis 2004

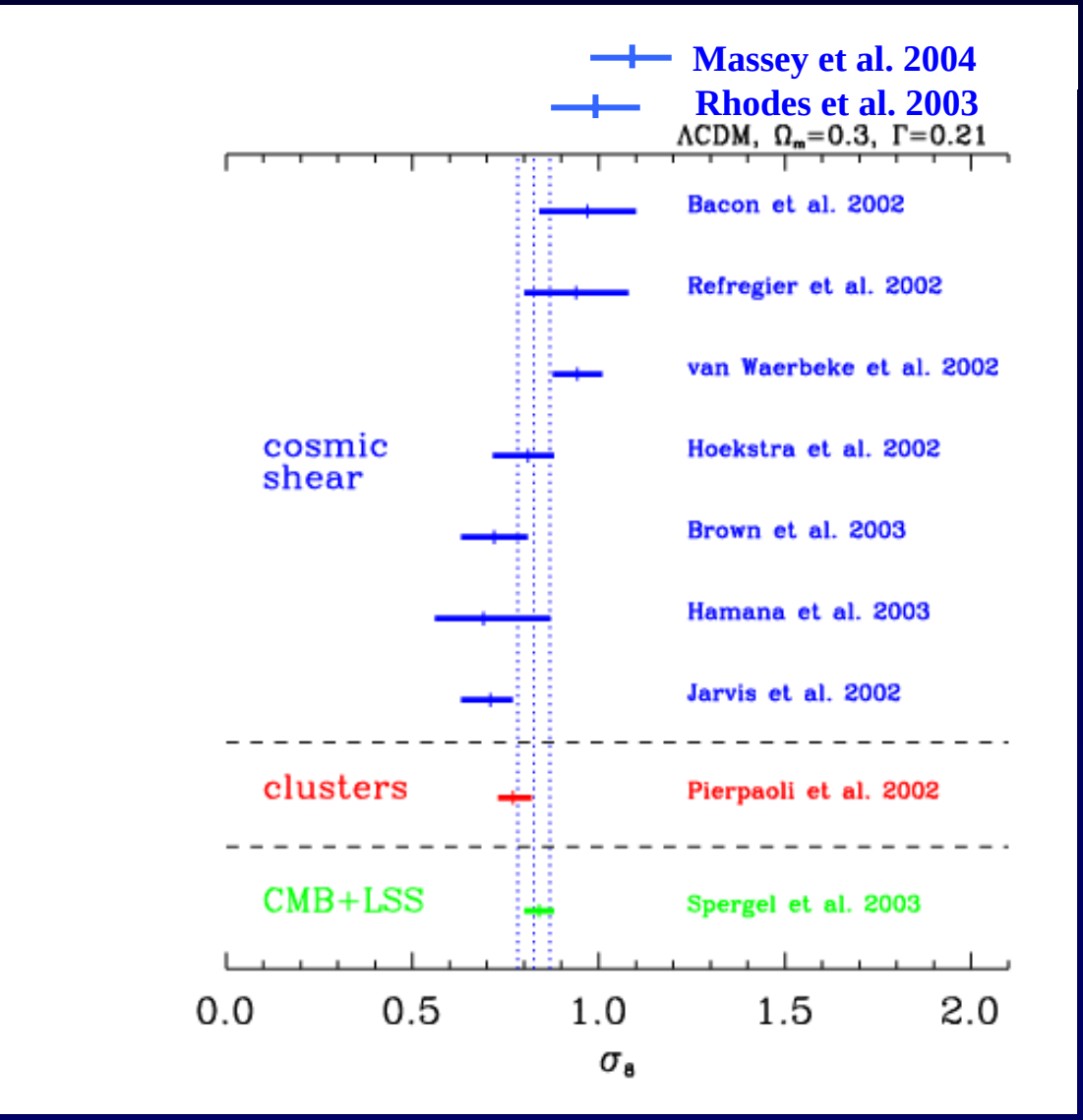


E/B decom-position



$$\sigma_8 \left(\frac{\Omega_m}{0.3} \right)^{0.51} = 1.09 \pm 0.12$$

Normalisation of the Power Spectrum



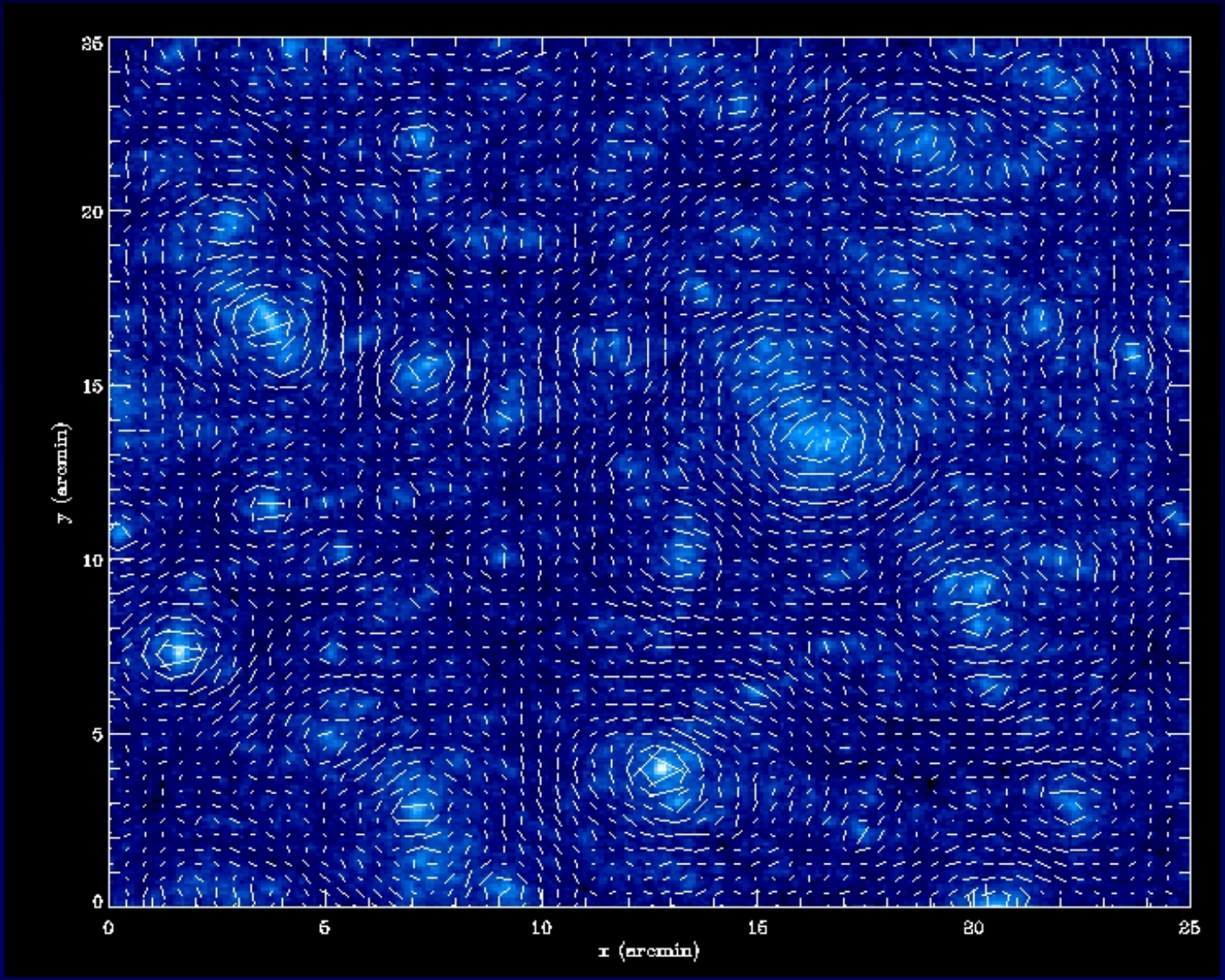
→ Moderate disagreement among cosmic shear measurements (careful with marginalisation)

→This could be due to residual systematics (shear calibration?)

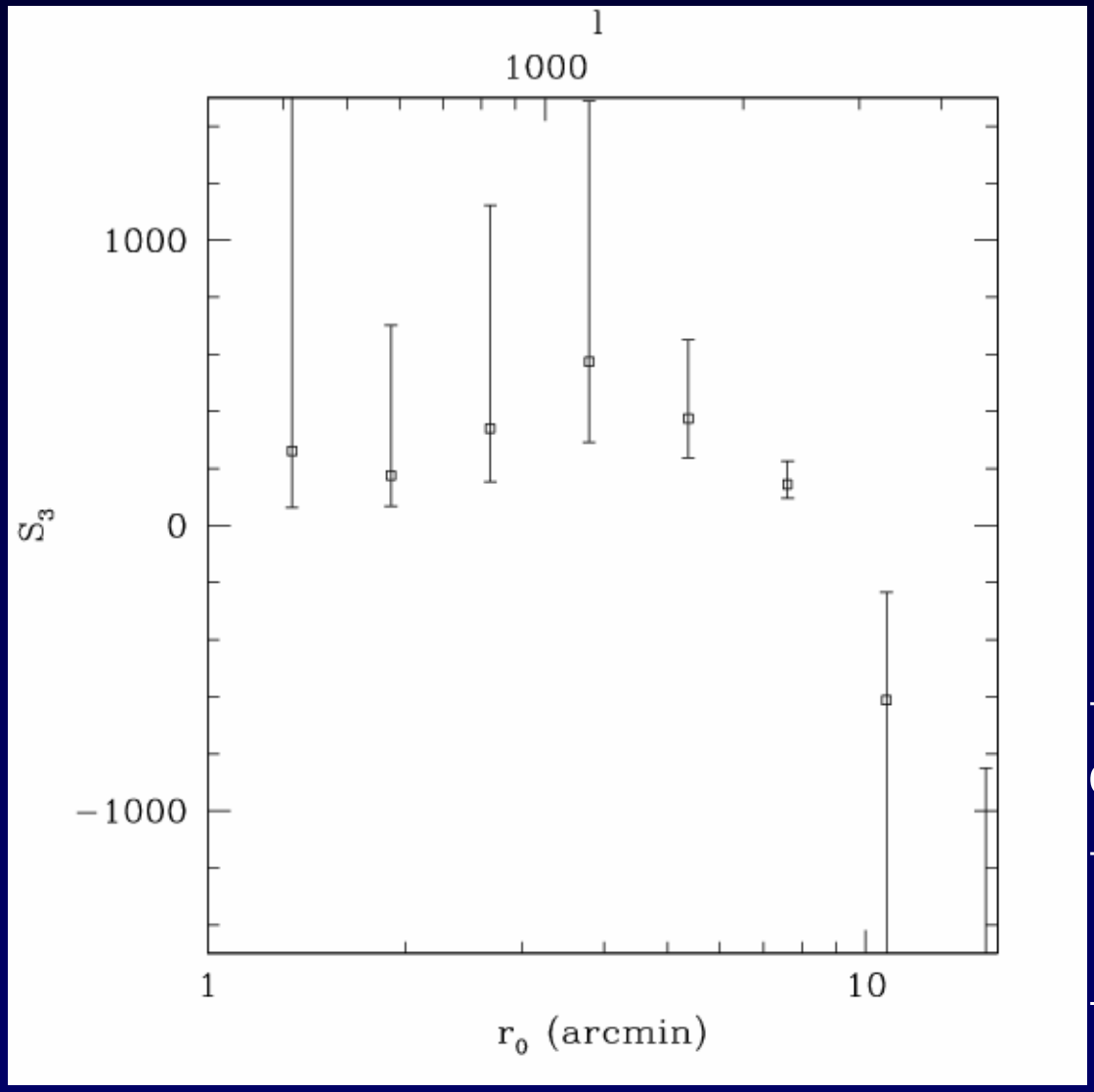
→Agreement on average with CMB constraints

→ moderate inconsistency with cluster abundance (systematics or new physics?)

Cosmic Shear Field is Non-Gaussian



Skewness



Pen et al. 2003

Cf. Bernardeau et al. 1997,
Bernardeau et al. 2002

Variance: $\langle \kappa^2 \rangle$

Skewness:

$$S_3 = \langle \kappa^3 \rangle / \langle \kappa^2 \rangle^2$$

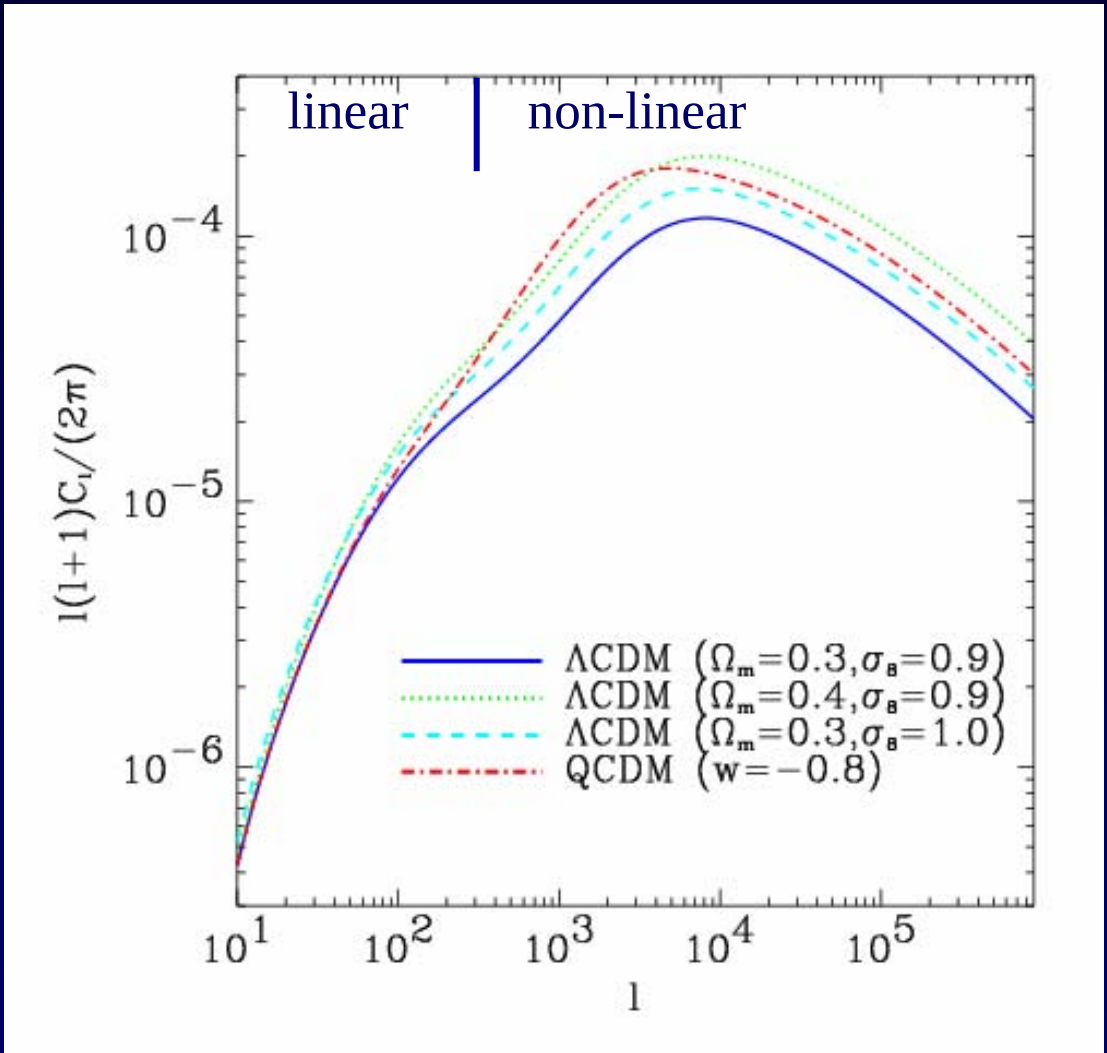
→ Skewness depends only weakly on σ_8 and h
→ break degeneracies

→ Pen et al. find $\Omega_m < 0.5$ (90%CL)

Future Surveys

Survey	Diameter (m)	FOV (deg^2)	Area (deg^2)	start
DLS	2×4	2×0.3	28	1999
CFHTLS	3.6	1	172	2003
VST	2.6	1	x100	2004
VISTA	4	2	10000	2007
Pan-STARRS	4×1.8	4×4	31000	2008
LSST	8.4	7	30000	2012
SNAP/JDEM	2 (space)	0.7	1000	2014

Dark Energy and Weak Lensing



Dark Energy equation of state:

$w=p/\rho$ (w=-1 for Λ)

modifies:

- angular-diameter distance
- growth rate of structure
- power spectrum on large scales

a(t)

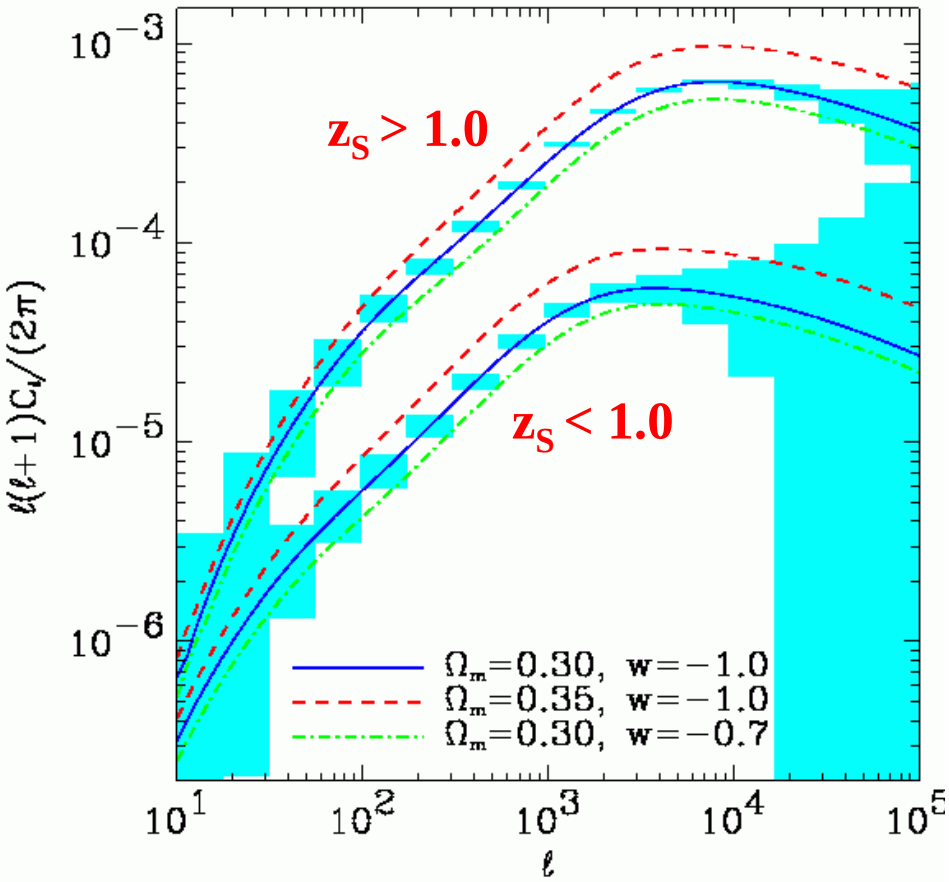
(Ma, Caldwell, Bode & Wang 1999)

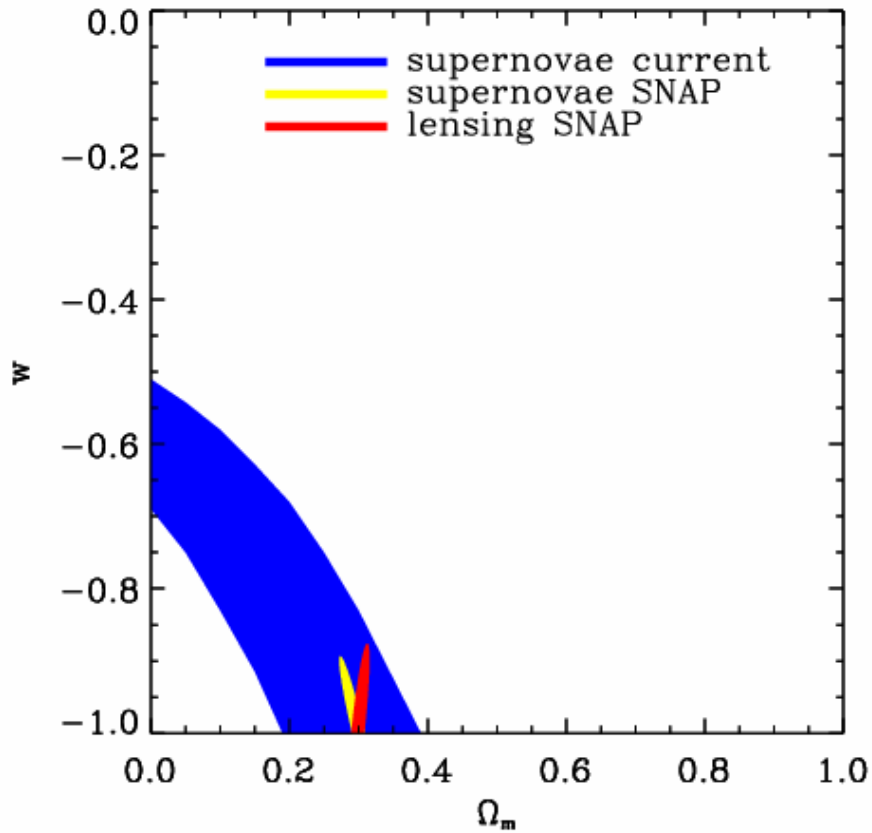
→ w can be measured from the lensing power spectrum

→ But, there are degeneracies between w, Ω_M ,σ_8 and Γ

Cf. Hui 1999, Benabed & Bernardeau 2001, Huterer 2001, Hu 2000, Munshi & Wang 2002

Prospects for SNAP

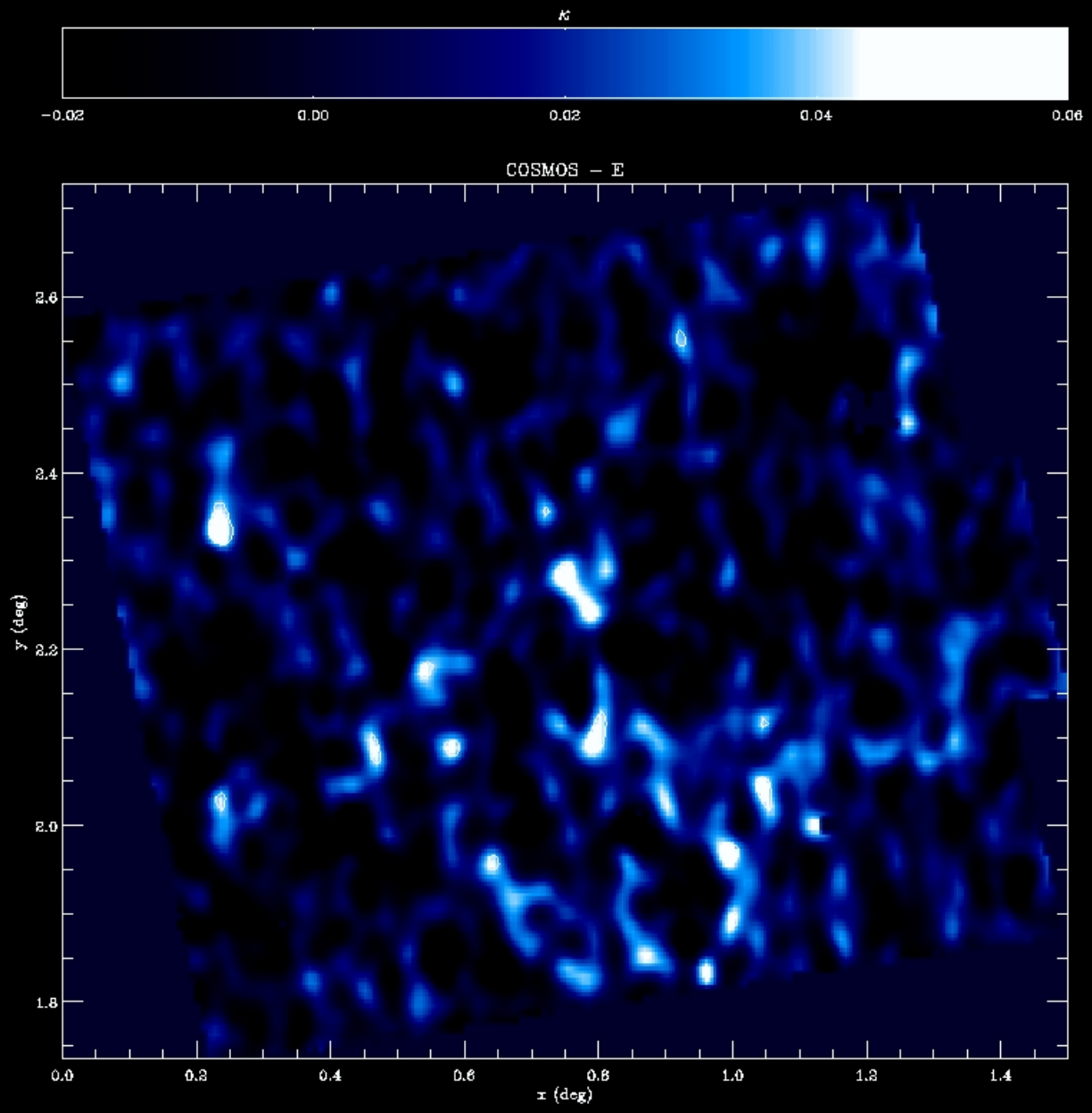




SNAP wide survey Rhodes et al. 2003, Massey et al. 2003, Refregier et al. 2003

→ SNAP will measure the evolution of the lensing power spectrum and set tight constraints on dark energy

Dark Matter Map



COSMOS
HST Survey
(preliminary)

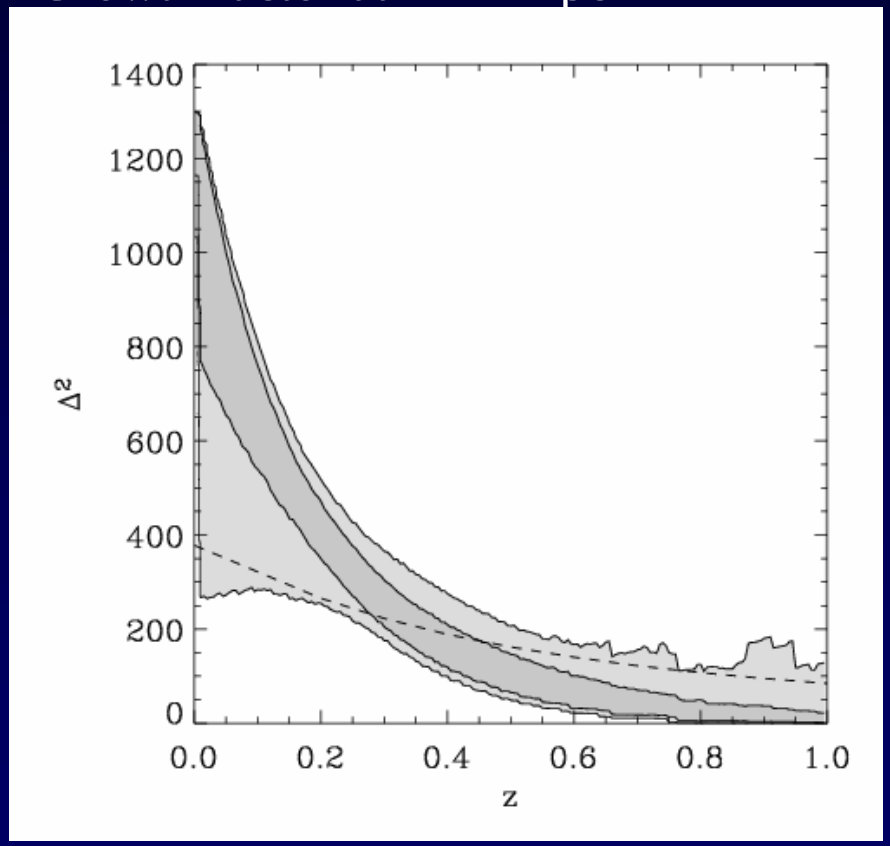
Conclusions

- Weak Lensing has emerged as a unique method to map the large scale structure of the Universe
- Weak Lensing is sensitive to both dark matter and dark energy
- Future surveys and instruments will afford excellent sensitivity and tight constraints on cosmological parameters
- Challenge of systematics requires precise understanding of the instrument $\rightarrow$ similar to a physics experiment

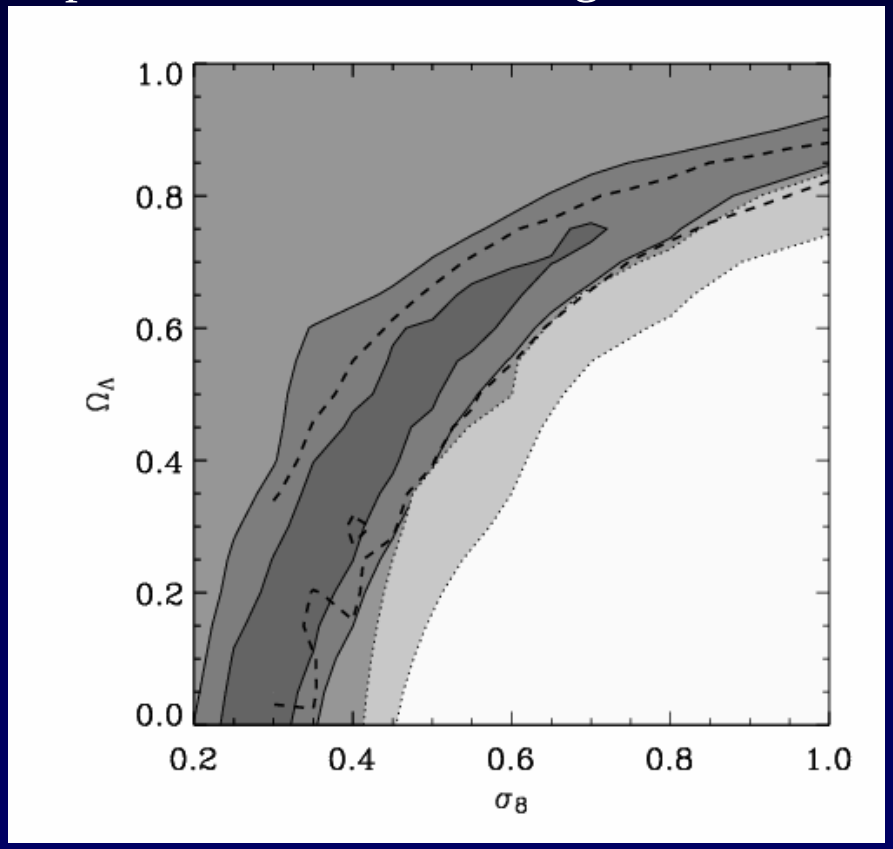
3D Lensing: Statistical

COMBO17: Bacon, Taylor et al. 2004

Growth factor at k=14Mpc^{-1}



Improvements on cosmological constraints

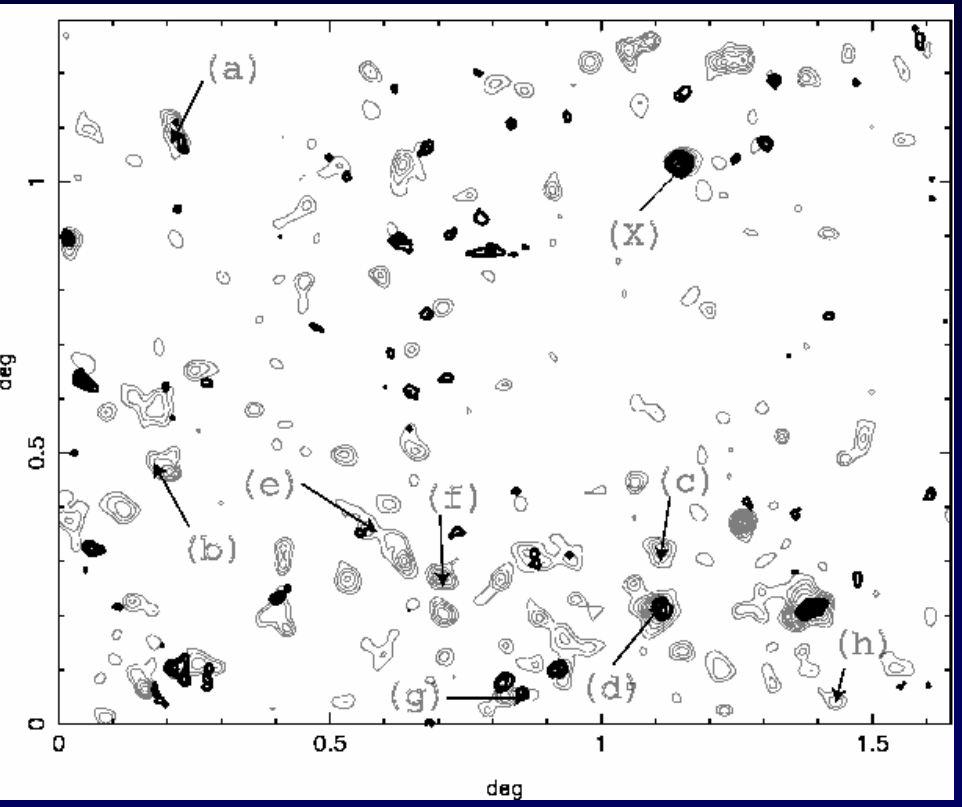


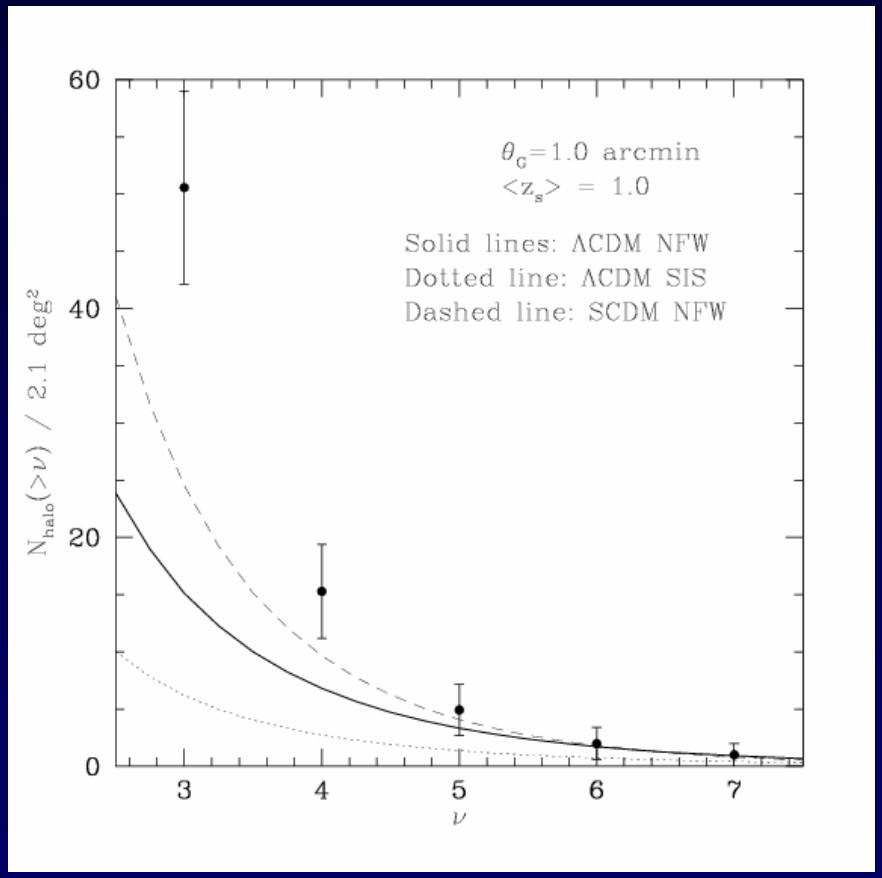
Tomography & cross-correlation cosmography:

Hu 2002, Jain & Taylor 2003, Bernstein & Jain 2003, Hu & Jain 2003

Mass-Selected Clusters

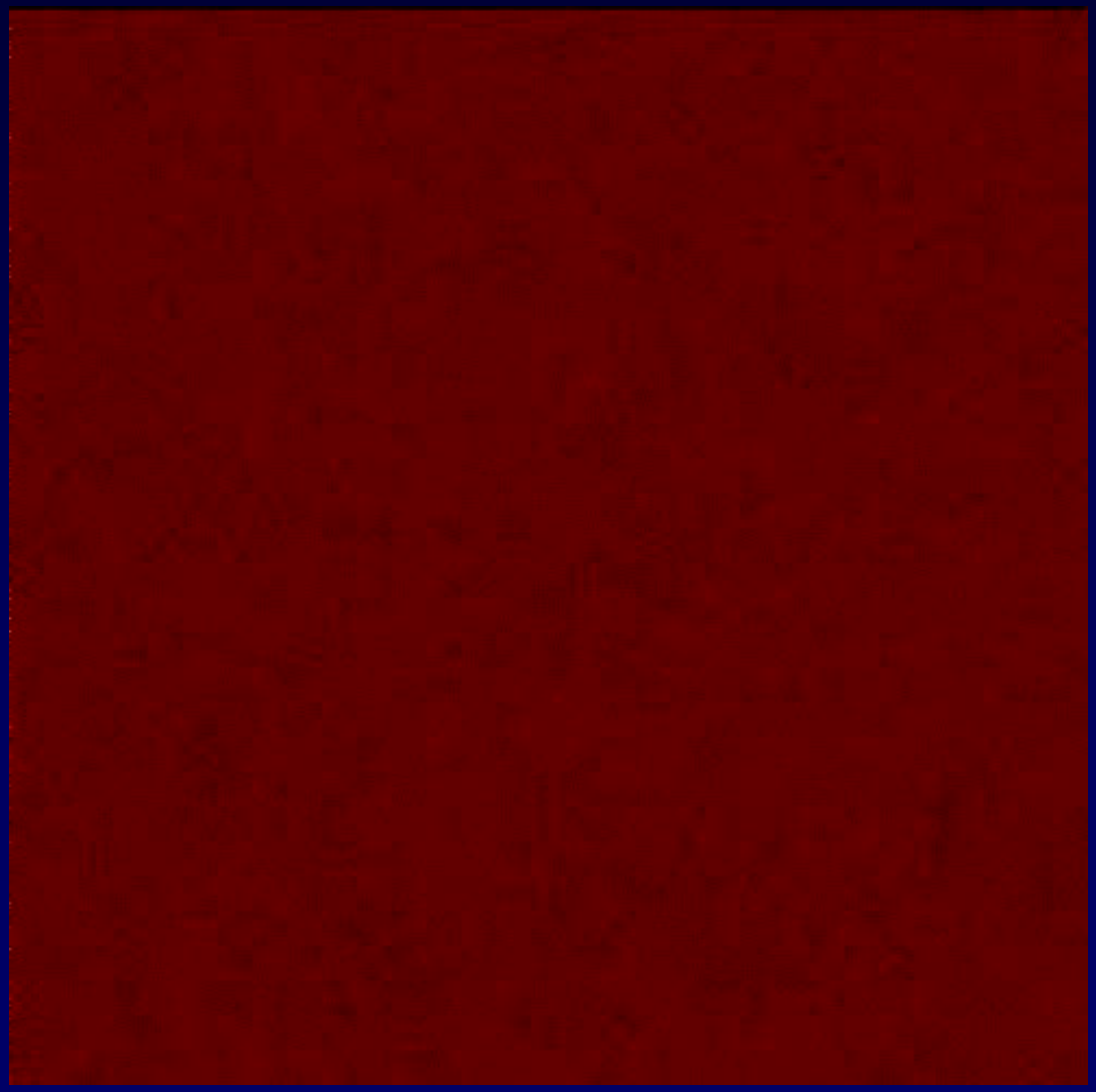
Miyazaki et al. 2002 2.1 deg^2 survey with Subaru





- complex relation between mass and light
- bright cluster counts in agreement with CDM models
- discovery of new clusters

Cosmic Structure Formation



Ingredients:
Initial conditions
CDM particles
Gravity

CDM Simulation
Virgo Consortium
Z=50 to 0

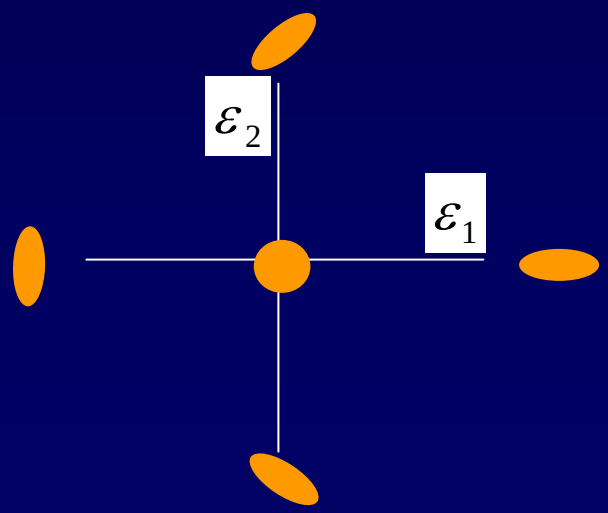
Measuring the Shear

Quadrupole moments:

$$Q_{ij} = \int d^2x \; x_i x_j w(\vec{x}) I(\vec{x})$$

Ellipticity:

$$\varepsilon_1 = \frac{Q_{11} - Q_{22}}{Q_{11} + Q_{22}}, \; \varepsilon_2 = \frac{2Q_{12}}{Q_{11} + Q_{22}}$$



Shear:

$$\Psi_{ij} = \begin{pmatrix} 1-\kappa-\gamma_1 & \gamma_2 \\ \gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

Relation:

$$\langle \varepsilon_i \rangle = P^{\gamma} \gamma_i$$

Correction Method

KSB Method: (Kaiser, Squires & Broadhurst 1995)

PSF Anisotropy:

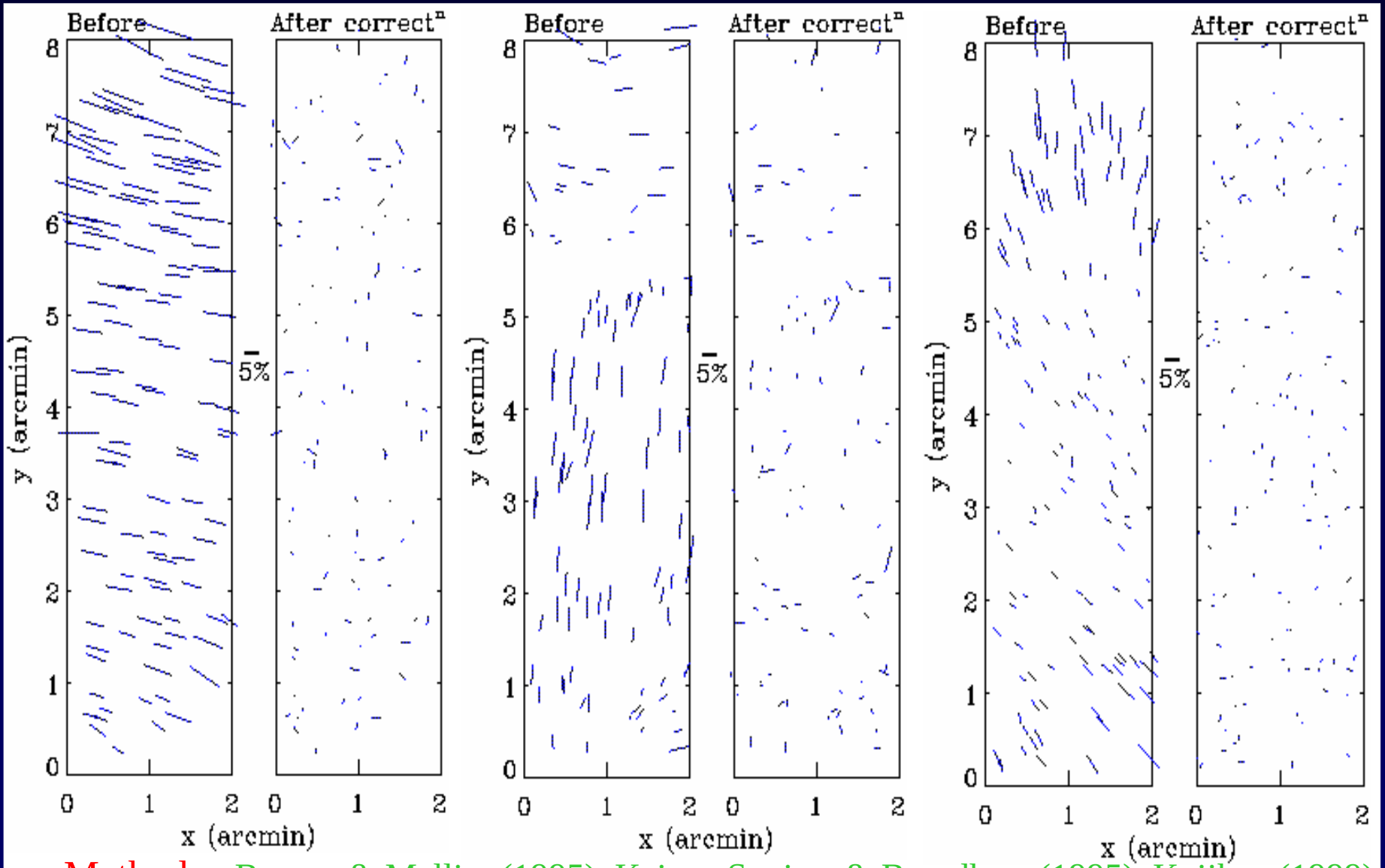
$$\varepsilon_g = \varepsilon'_g - \frac{P_g^{sm}}{P_*^{sm}} \varepsilon_*$$

PSF Smear & Shear Calibration:

$$\gamma = (P^\gamma)^{-1} \varepsilon_g$$

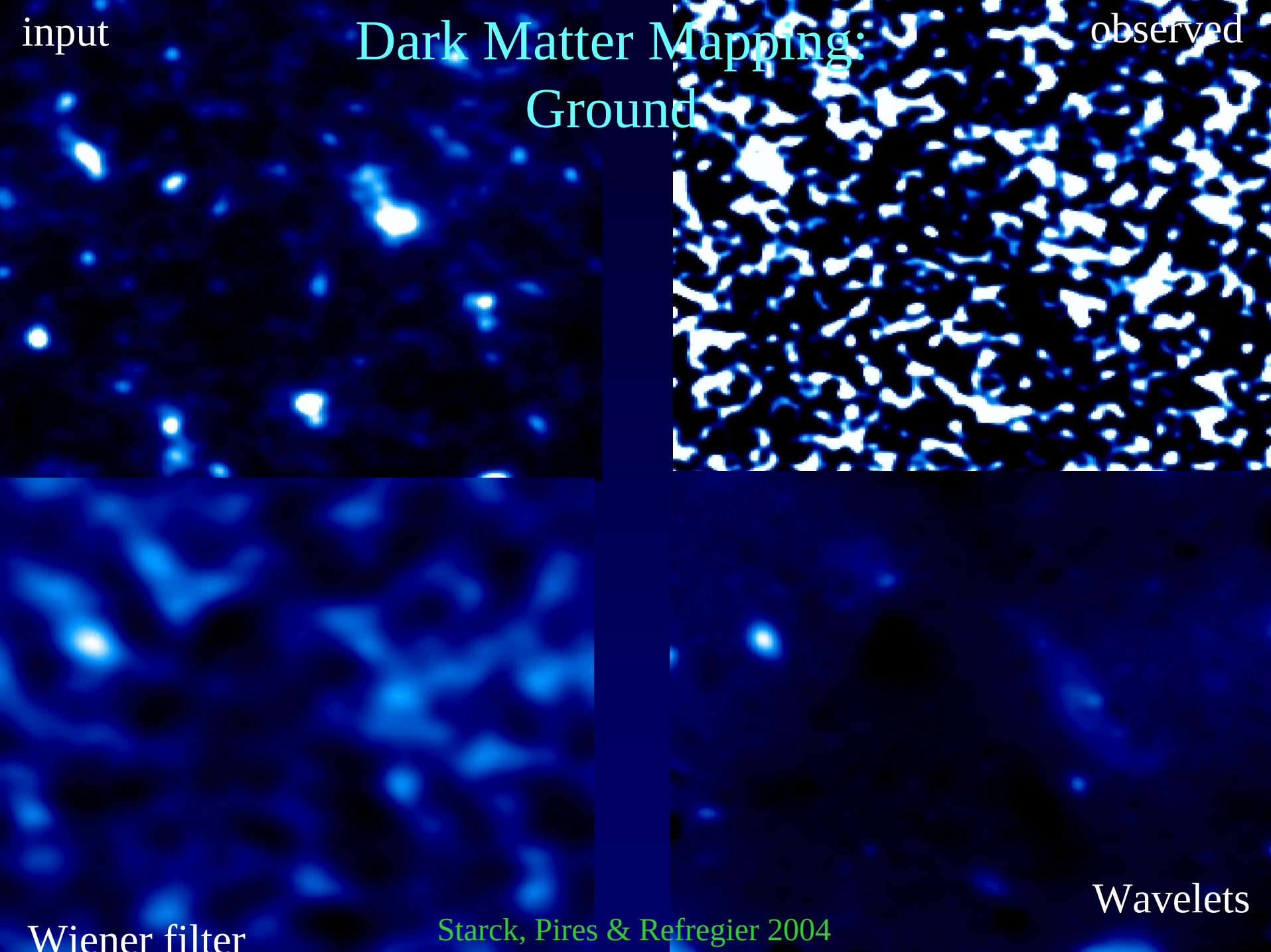
Other Methods: Kuijken (1999), Kaiser (1999), Rhodes, Refregier & Groth (2000), Refregier & Bacon (2001), Bernstein & Jarvis (2001)

Systematic Effects: PSF Anisotropy



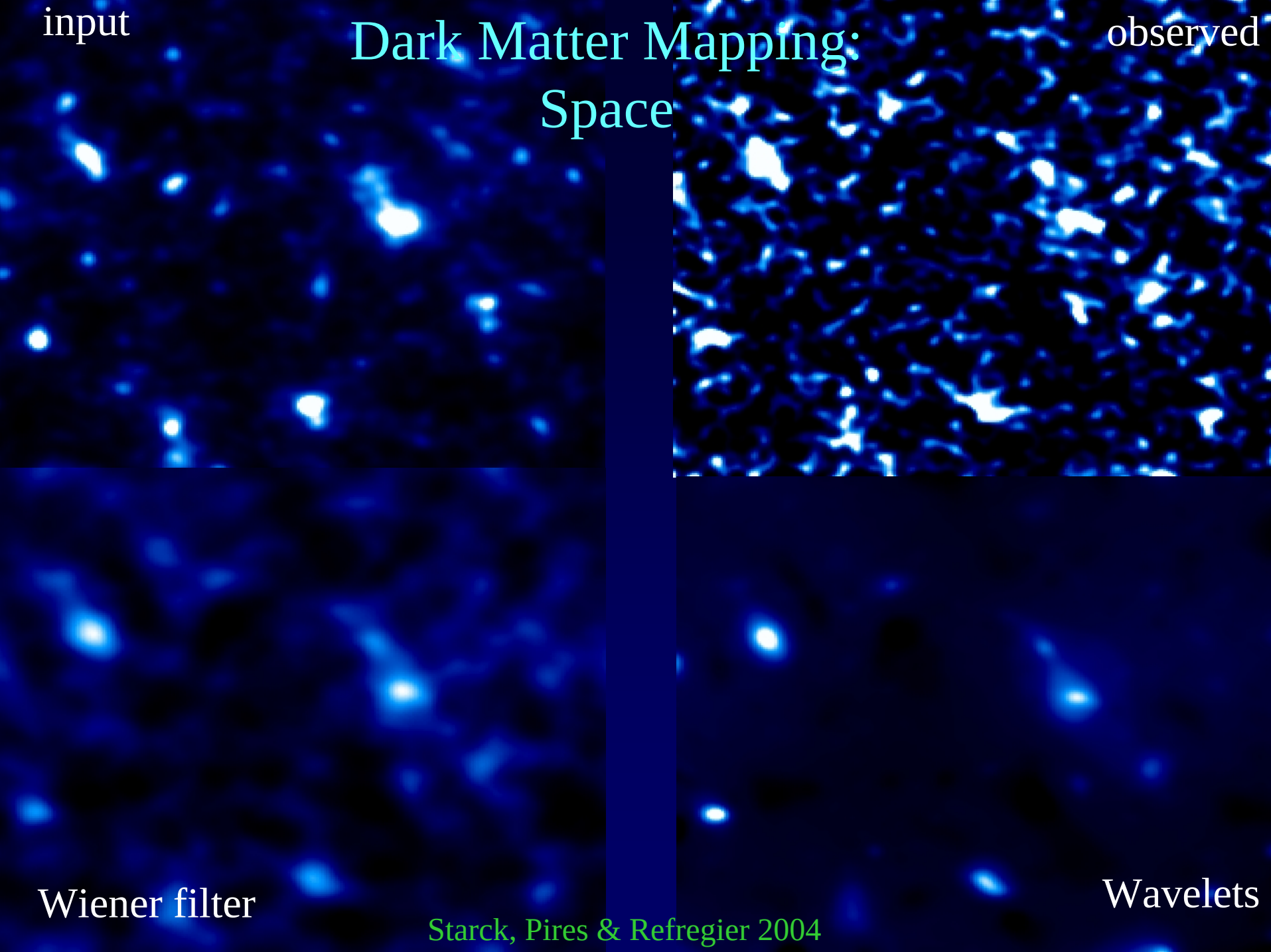
Methods: Bonnet & Mellier (1995), Kaiser, Squires & Broadhust (1995), Kuijken (1999), Kaiser (1999), Rhodes, Refregier & Groth (2000), Refregier & Bacon (2001), Bernstein & Jarvis (2001), Hirata & Seljak (2002)

Dark Matter Mapping: Ground



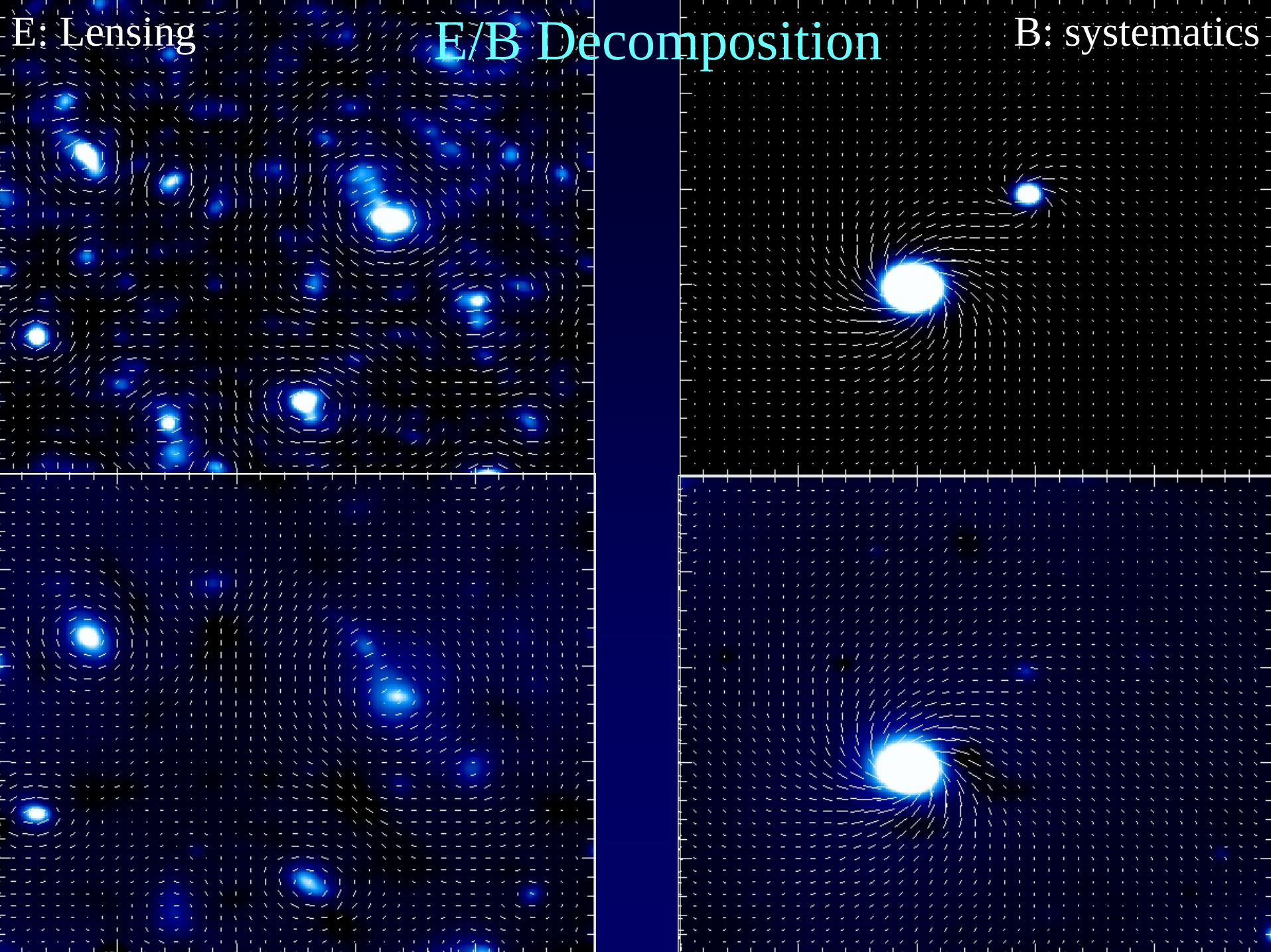
Starck, Pires & Refregier 2004

Dark Matter Mapping: Space

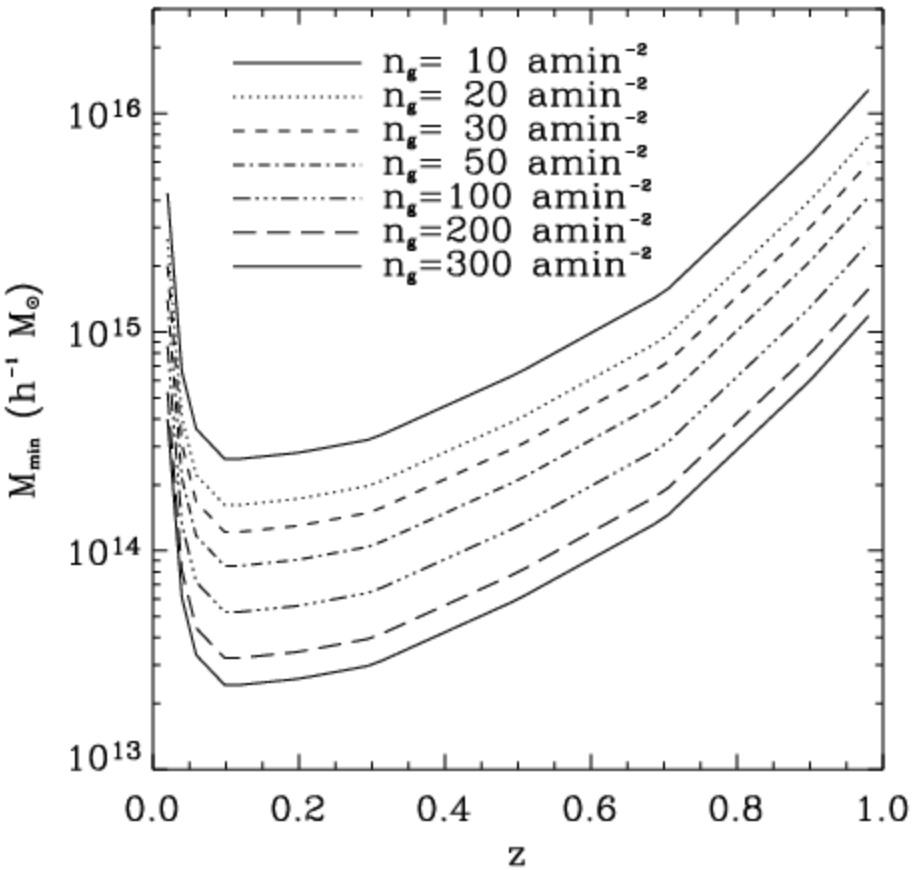


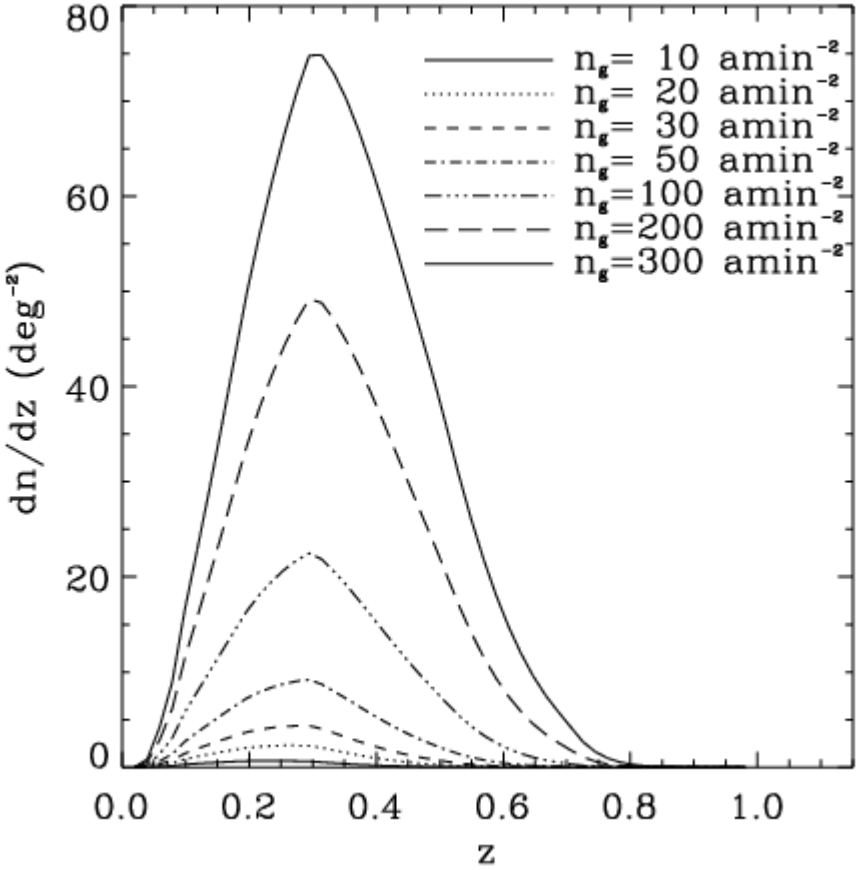
Starck, Pires & Refregier 2004

E/B Decomposition



Cluster Search with Weak Lensing

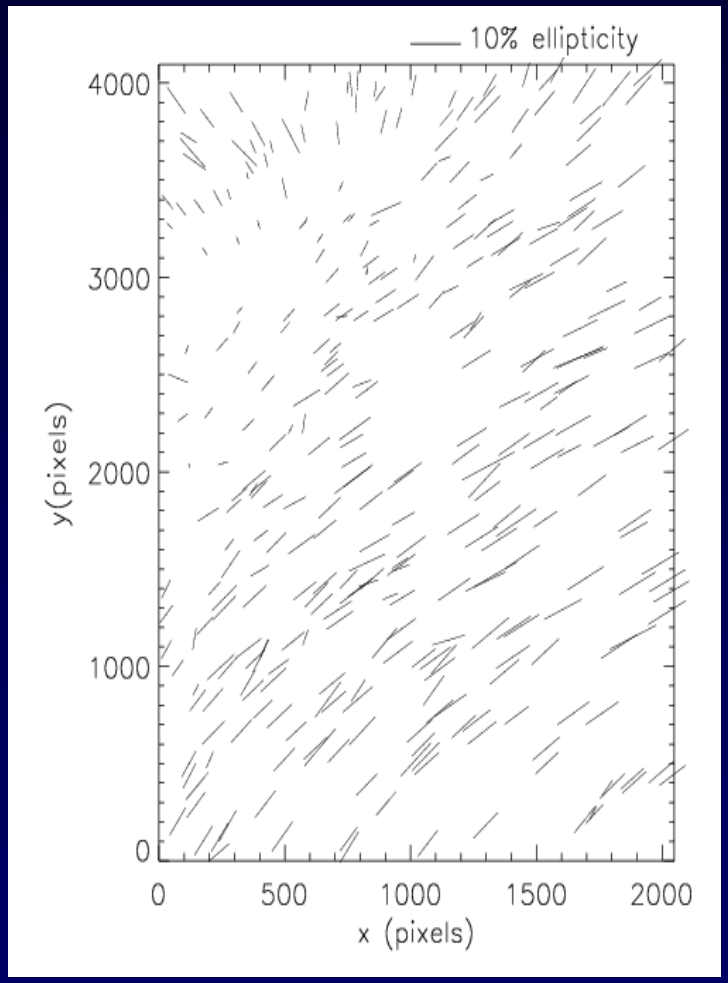




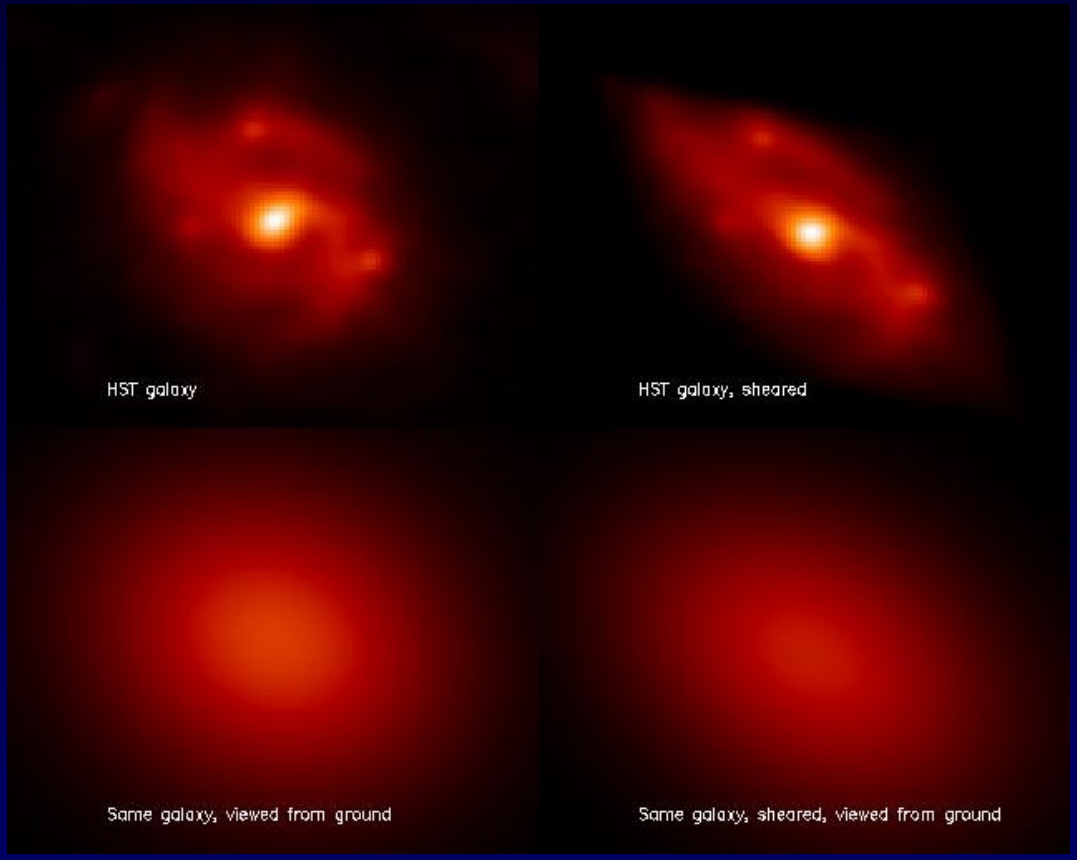
Cf. Hamana et al. 2003

Space-based surveys: more sensitive for cluster search, easier to compare to other probes (X-rays, SZ, optical)

Advantages of Space

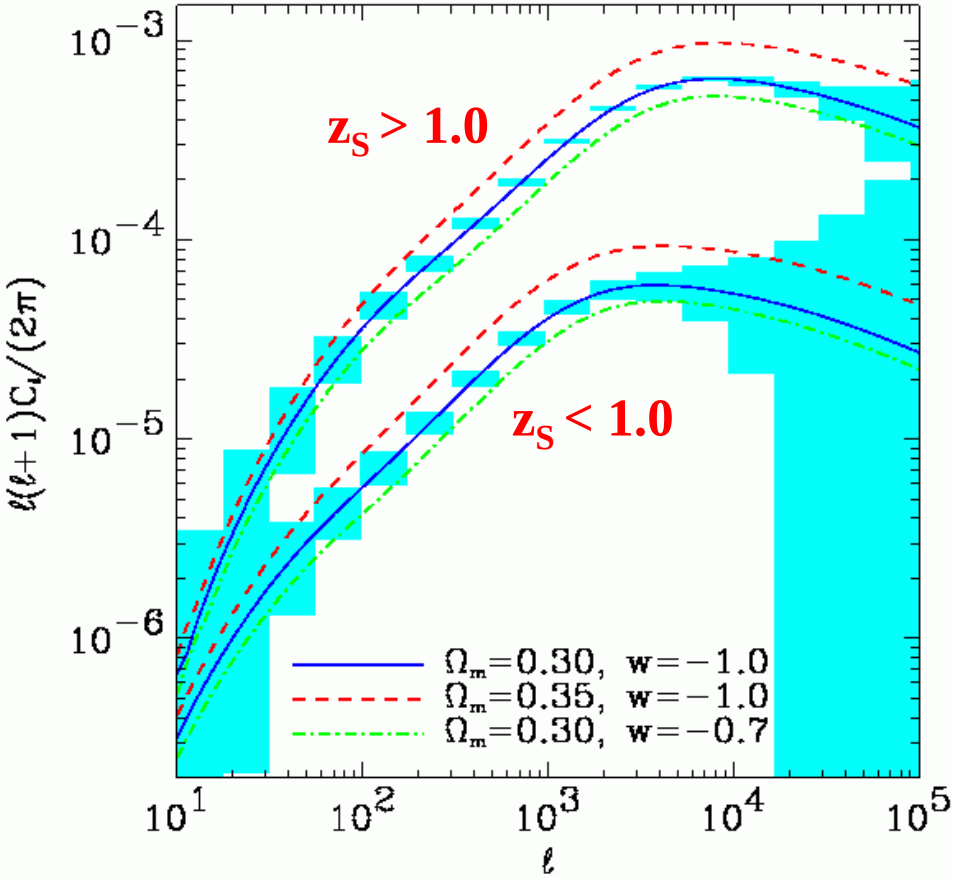


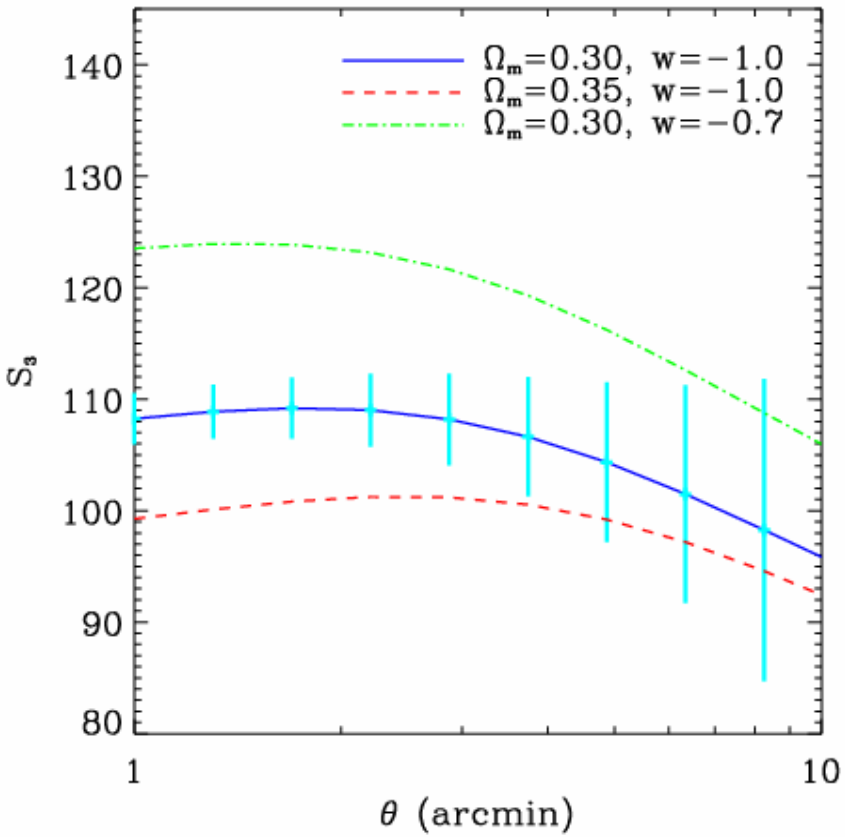
Ground based PSF



Space: small and stable PSF
→larger number of resolved galaxies
→ reduced systematics

Prospect for SNAP

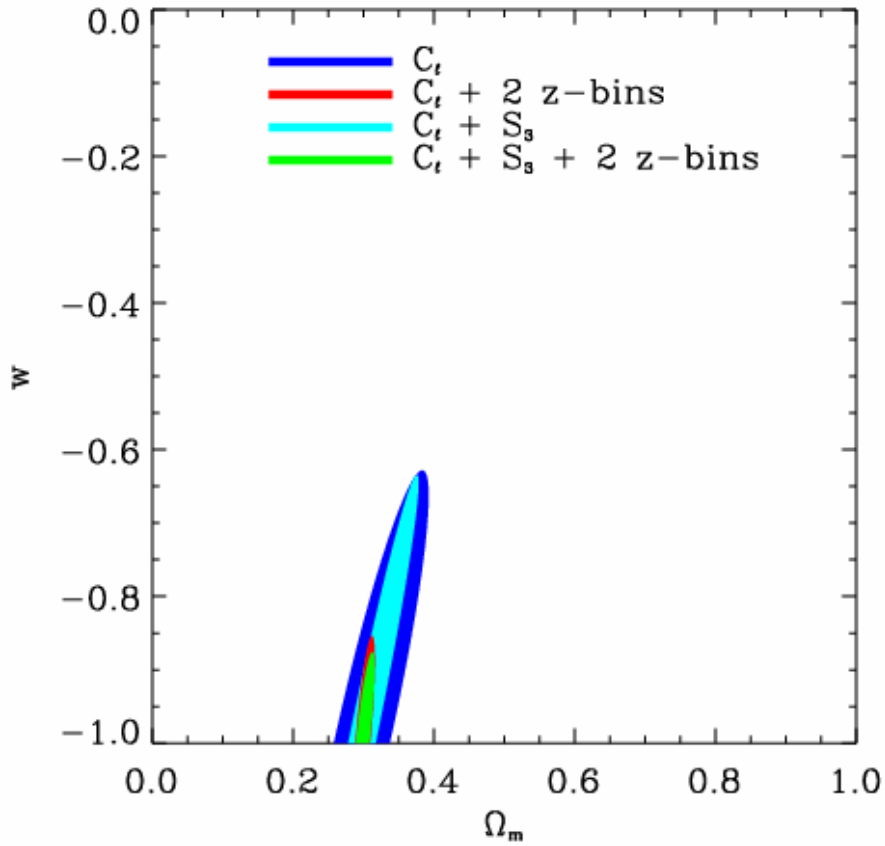


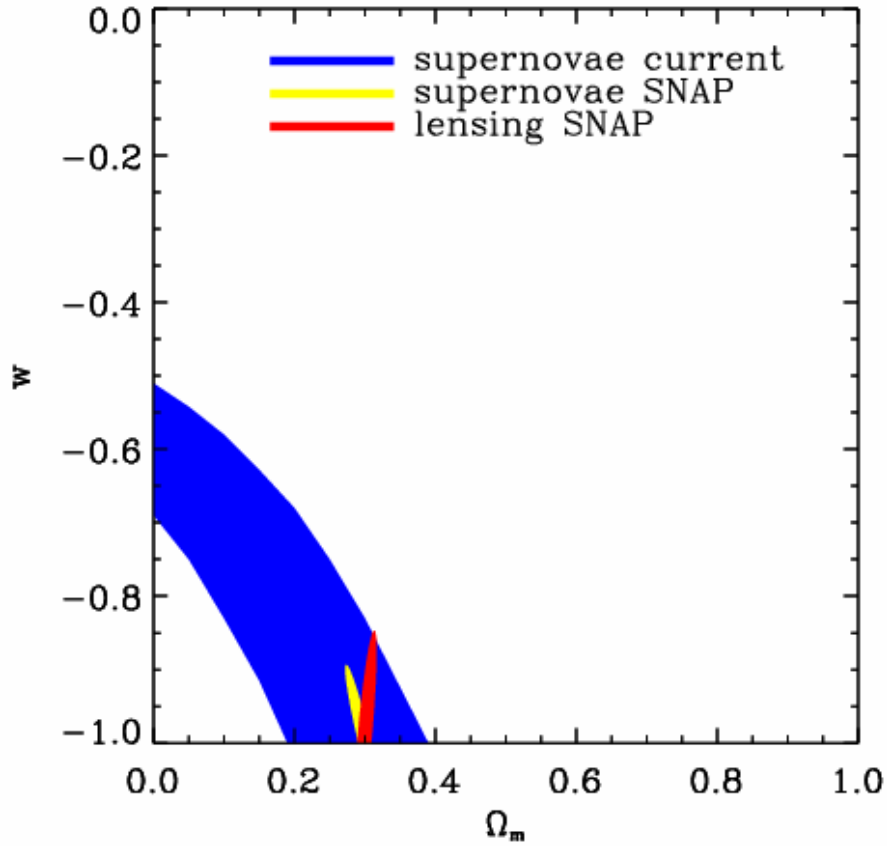


SNAP wide (300 deg^2) Rhodes et al. 2003, Massey et al. 2003, Refregier et al. 2003

→ SNAP will measure the evolution of the lensing power spectrum and skewness and is sensitive to the non-linear evolution of structures

Constraints on Dark Energy





SNAP wide (300 deg^2)

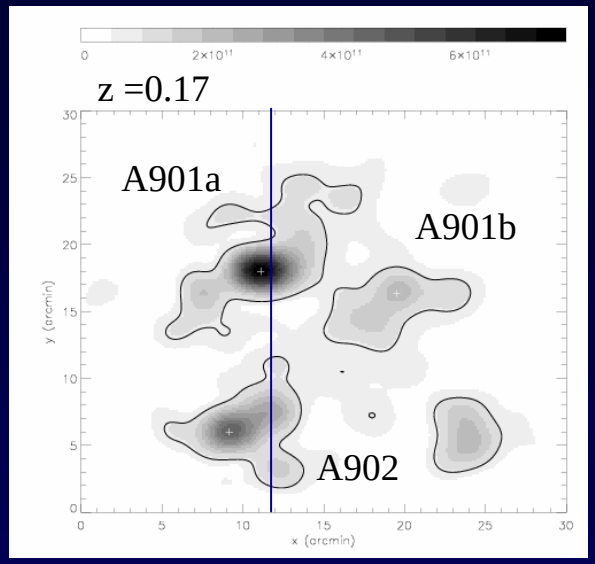
→ Tomography improves constraints on *w* by a factor of 2

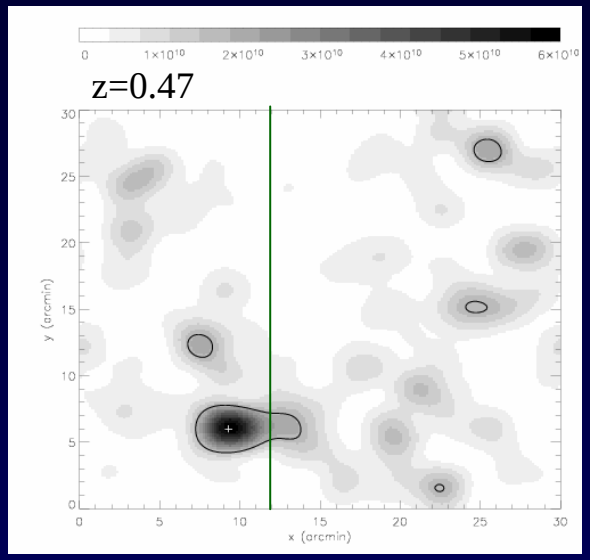
→ Cosmic shear constraints complementary to those from SNe

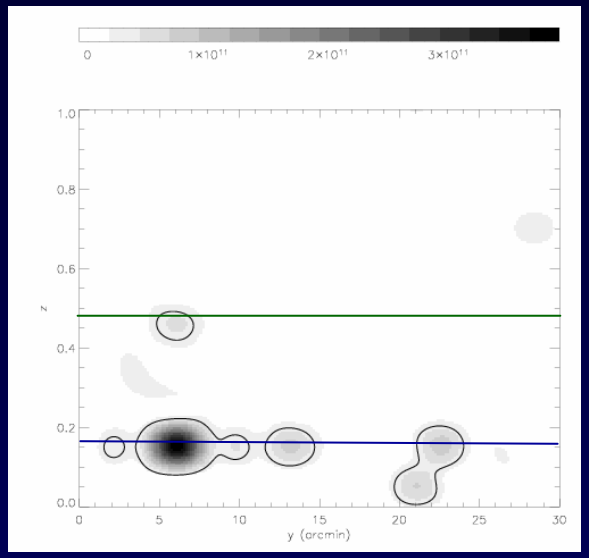
3D Lensing: Mapping

COMBO17: Taylor, Bacon et al. 2004

Luminosity







Gravitational potential