Weak Gravitational Lensing

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Cosmo-
RENATA
Valencia
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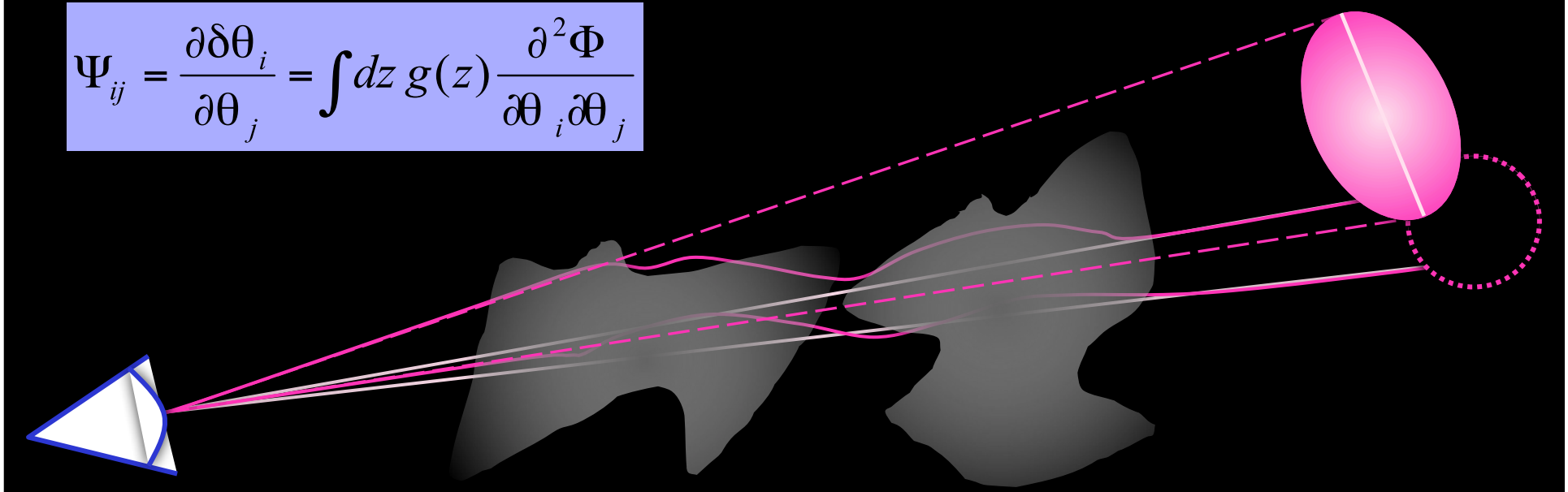
Weak Gravitational Lensing

Massey et al.
review: Refregier 2003

Distortion matrix:

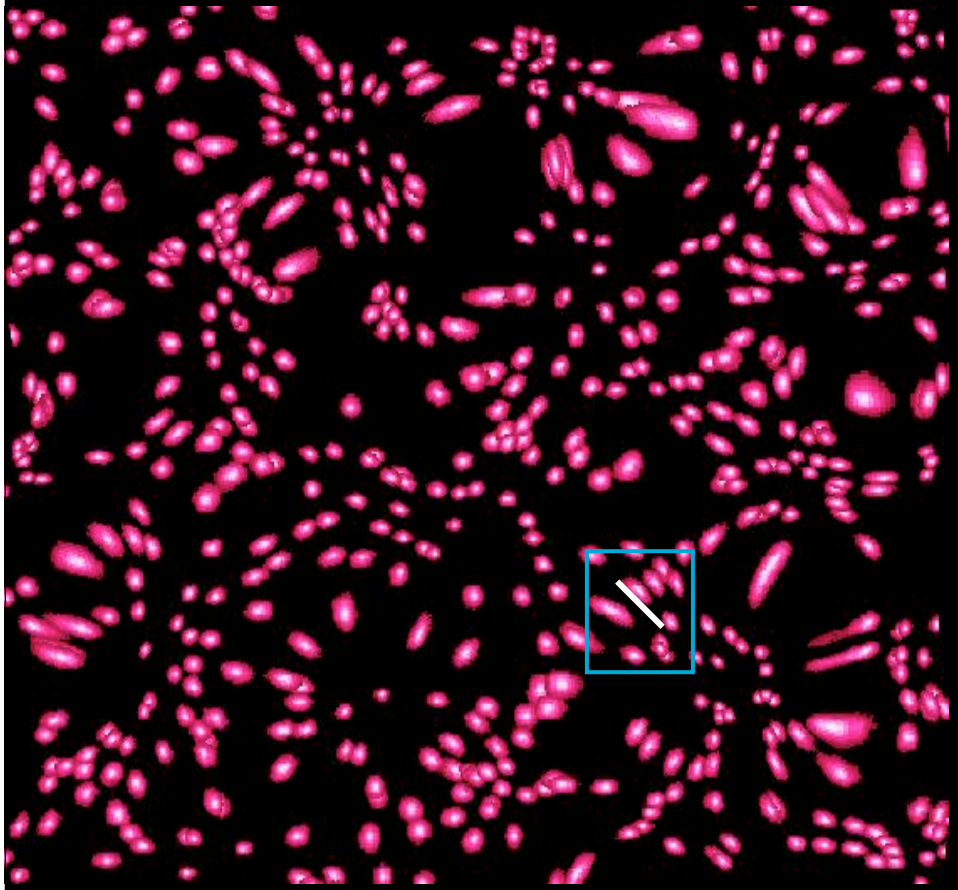
$$\Psi_{ij} = \frac{\partial \delta\theta_i}{\partial \theta_j} = \int dz\, g(z) \frac{\partial^2 \Phi}{\partial \theta_i \partial \theta_j}$$



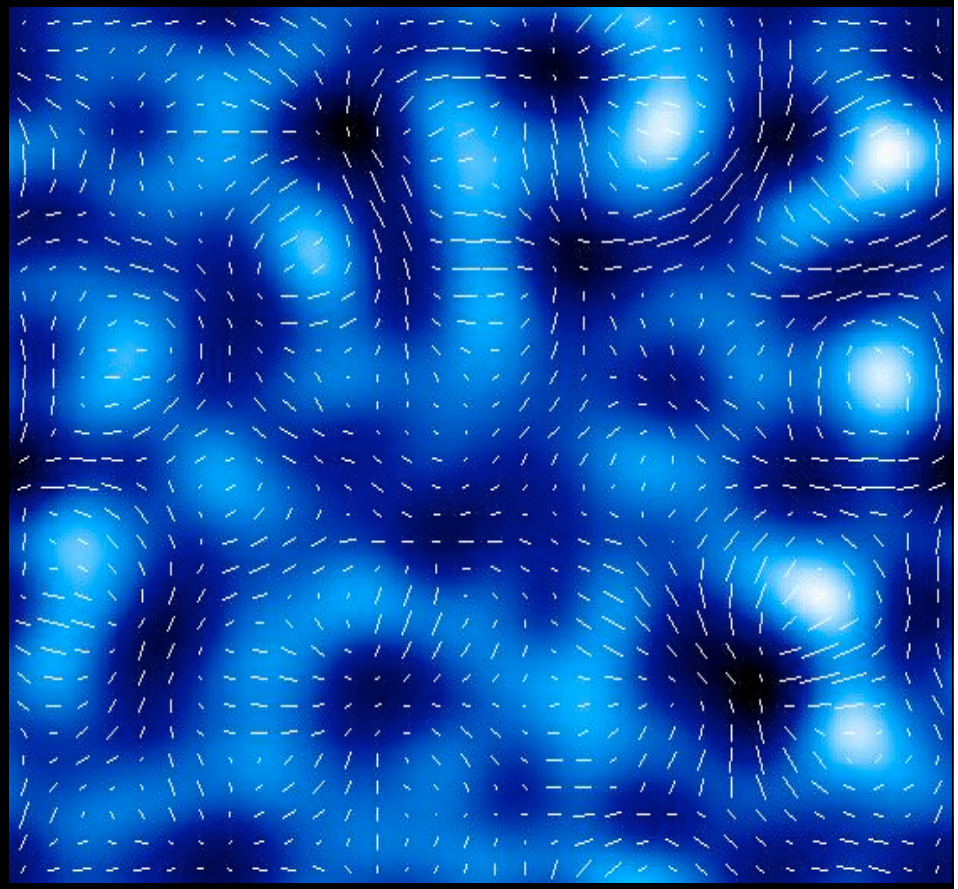
Theory

Direct measure of the distribution of mass in the universe, as opposed to the distribution of light

Weak Lensing Shear Measurement



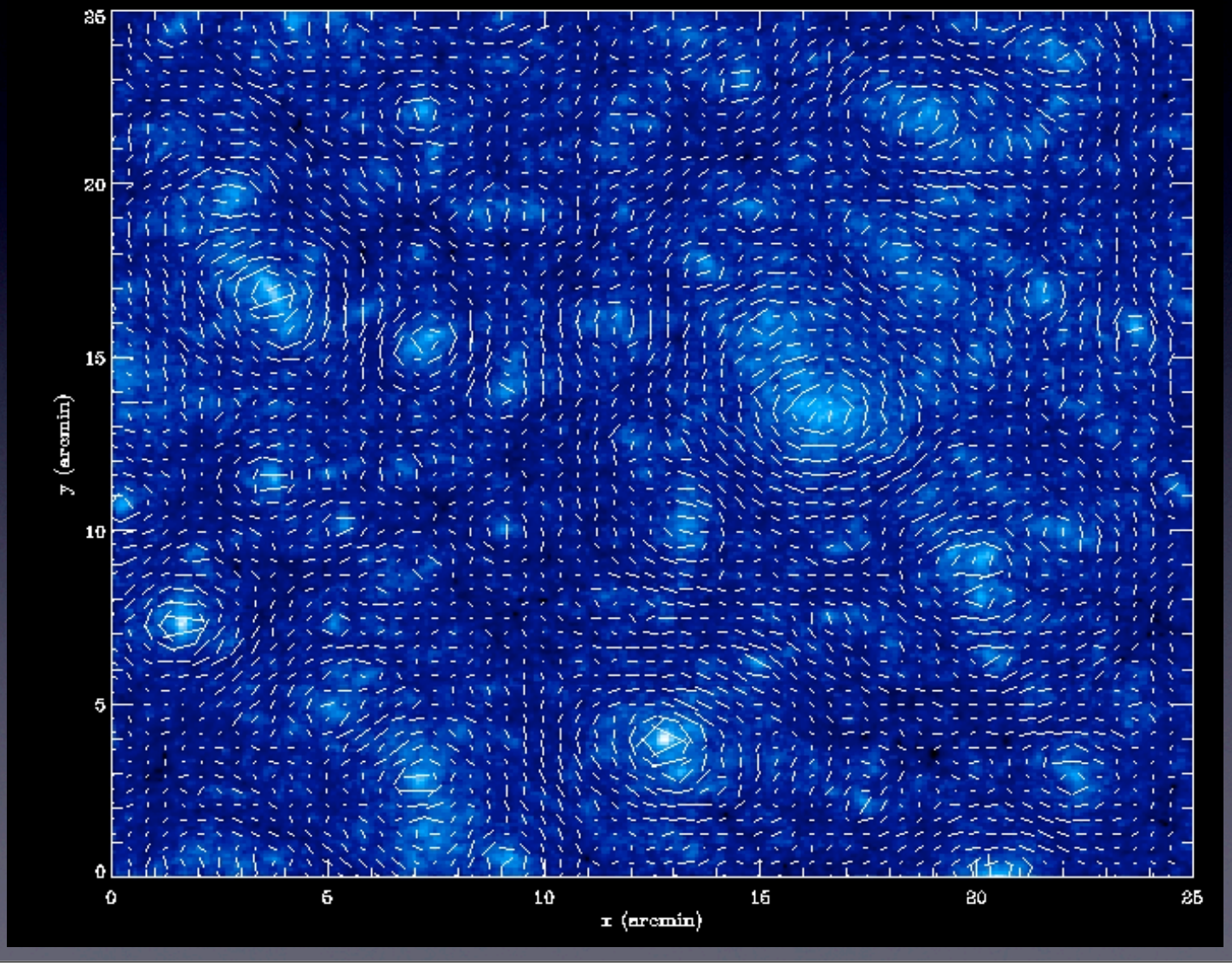
lensed background galaxies



mass and shear distribution

Simulated Shear Map

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



2-Point Statistics

Shear Power Spectrum:

$$\sum_{i=1}^{2} \langle \tilde{\gamma}_i(\ell) \tilde{\gamma}_i(\ell') \rangle = (2\pi)^2 \delta(\ell - \ell') C_\ell$$

$$C_\ell = \frac{9}{16}\left(\frac{H_0}{c}\right)^4 \Omega_m^2 \int_0^{\chi_h} d\chi \left[\frac{g(\chi)}{ar(\chi)}\right]^2 P\left(\frac{\ell}{r}, \chi\right)$$

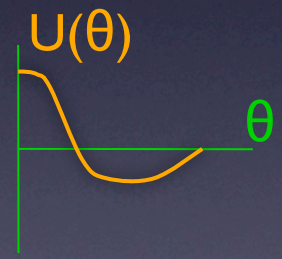
Shear Variance in circular cells:

$$\sigma_\gamma^2(\theta) = \langle \bar{\gamma}^2 \rangle = \frac{1}{2\pi} \int_0^\infty d\ell\, \ell C_\ell \left|\tilde{W}_\ell\right|^2$$

Mass Aperture Statistic:

$$\langle M_{ap}^2(\theta) \rangle = \frac{1}{2\pi} \int_0^\infty d\ell\, \ell C_\ell \left|\tilde{V}_\ell\right|^2$$

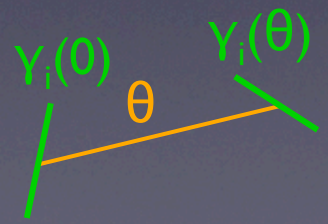
$$M_{ap}(\theta) = \int d^2\vartheta\, \gamma_t(\vartheta) U(\vartheta/\theta) = \int d^2\vartheta\, \kappa(\vartheta) Q(\vartheta/\theta)$$



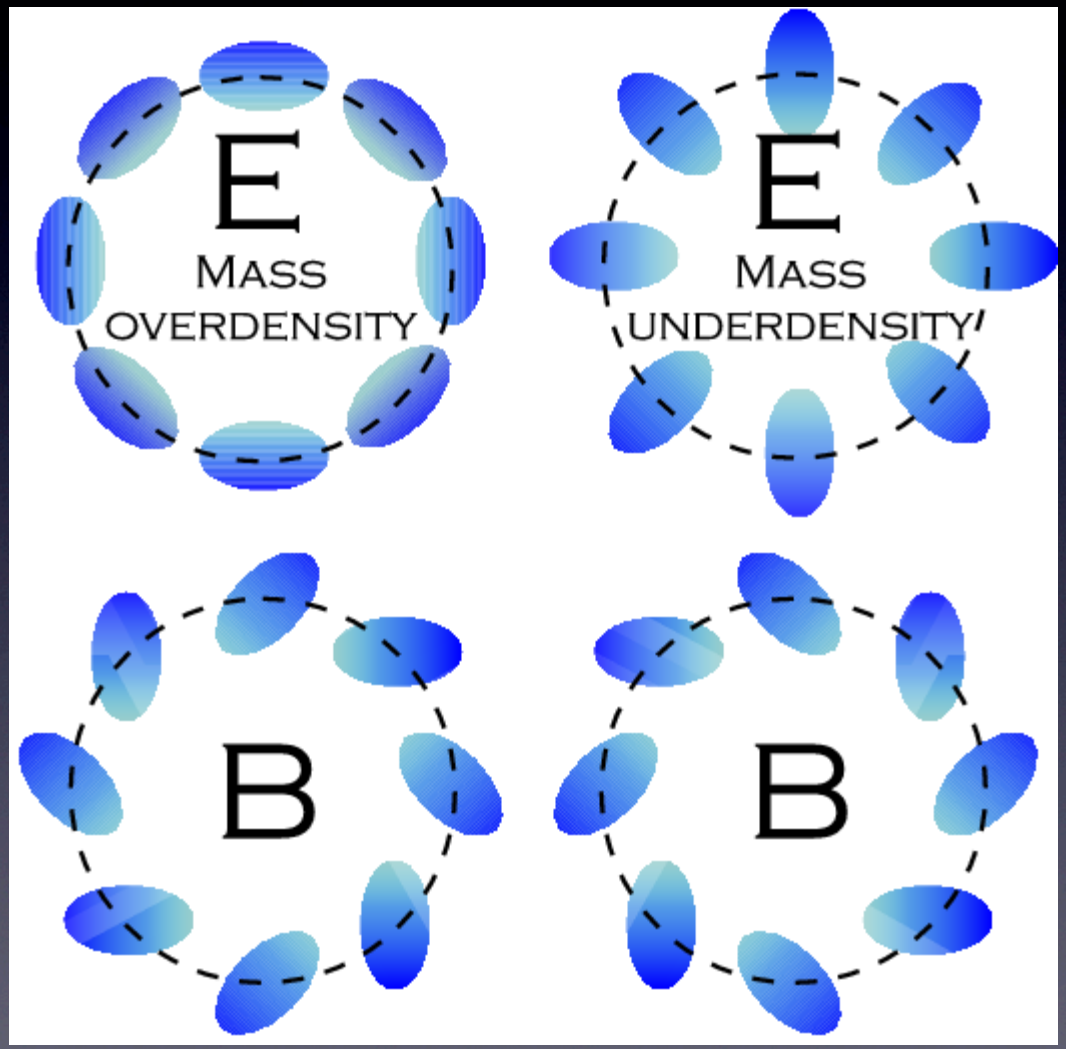
Correlation functions:

$$C_1 = \langle \gamma_1(0) \gamma_1(\theta) \rangle, \; C_2 = \langle \gamma_2(0) \gamma_2(\theta) \rangle$$

$$C_3 = \langle \gamma_1(0) \gamma_2(\theta) \rangle + \langle \gamma_2(0) \gamma_1(\theta) \rangle$$



E/B Decomposition

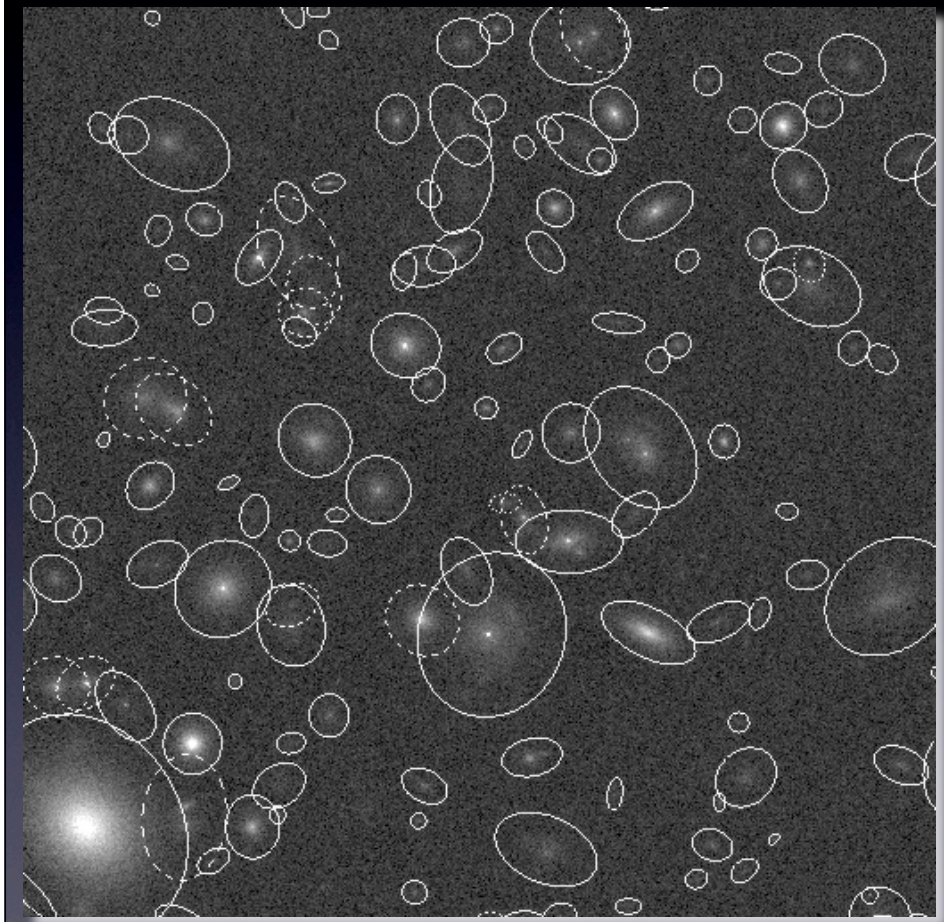


Weak Lensing arises from a scalar potential (Newton potential) and therefore only produces E-Modes

B-Modes: diagnostic for systematics

Switch from one to the other by rotating shear by 45°

Shear Measurement



Quadrupole Moments

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

Ellipticity

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

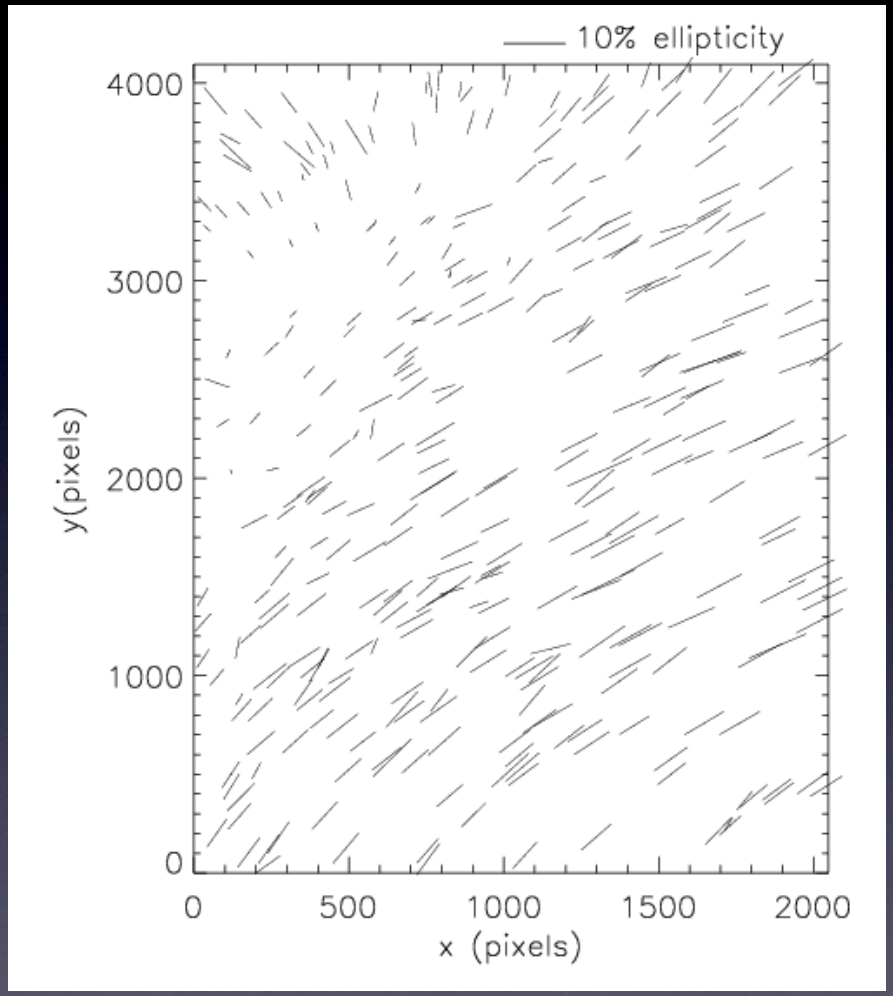
Shear

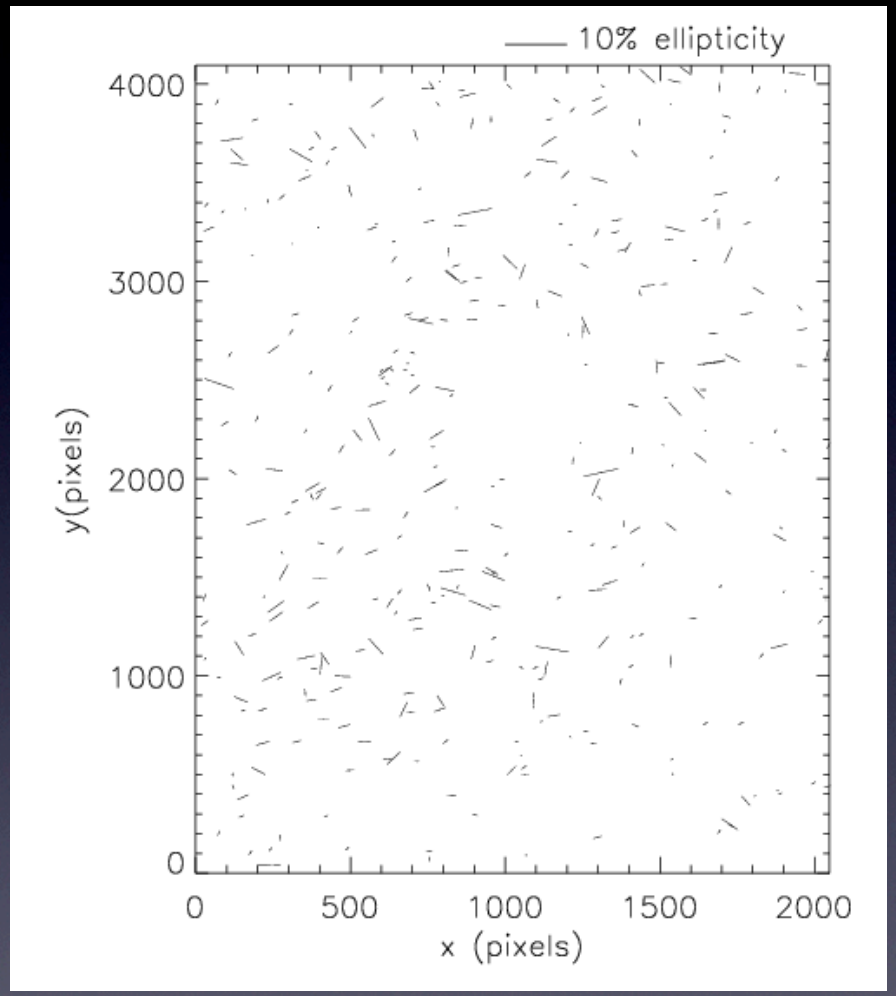
$$\Psi_{ij} = \begin{pmatrix} 1 - \kappa - \gamma_1 & \gamma_2 \\ \gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix}$$

Relation

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

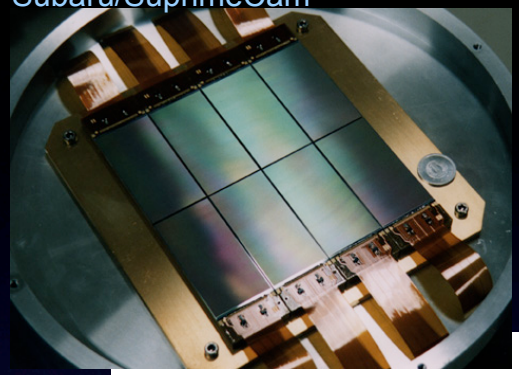
Systematics: PSF

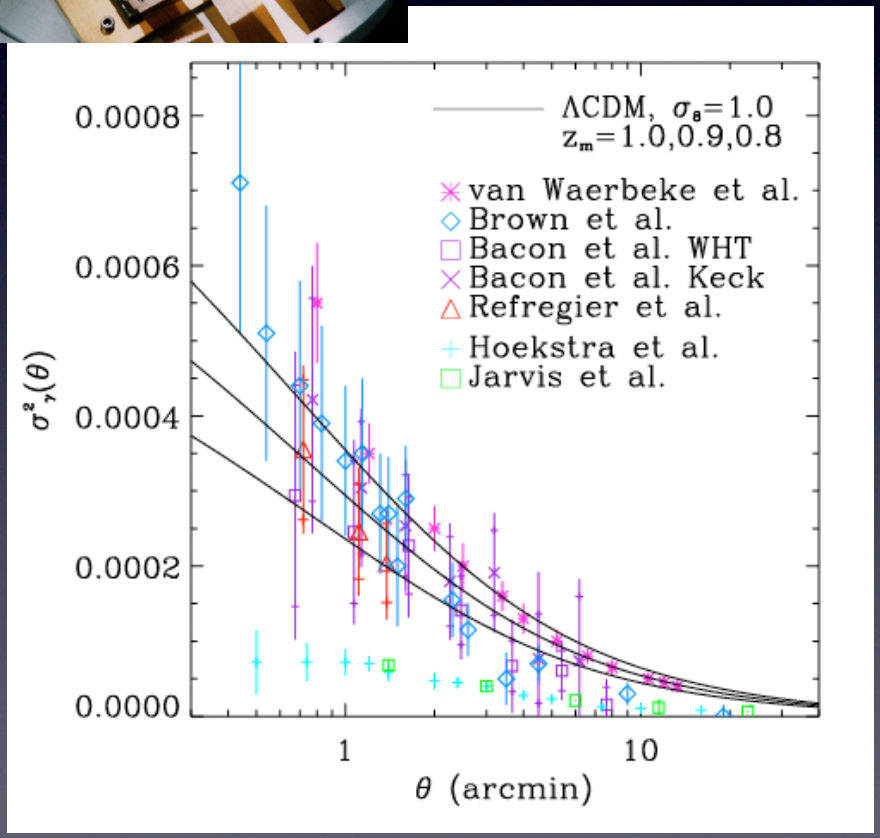




Cosmic Shear Measurements

Subaru/SuprimeCam





First detections

Wittman et al. 2000
Bacon, Refregier & Ellis 2000
Kaiser et al. 2000
Maoli et al. 2000
van Waerbeke et al. 2000*

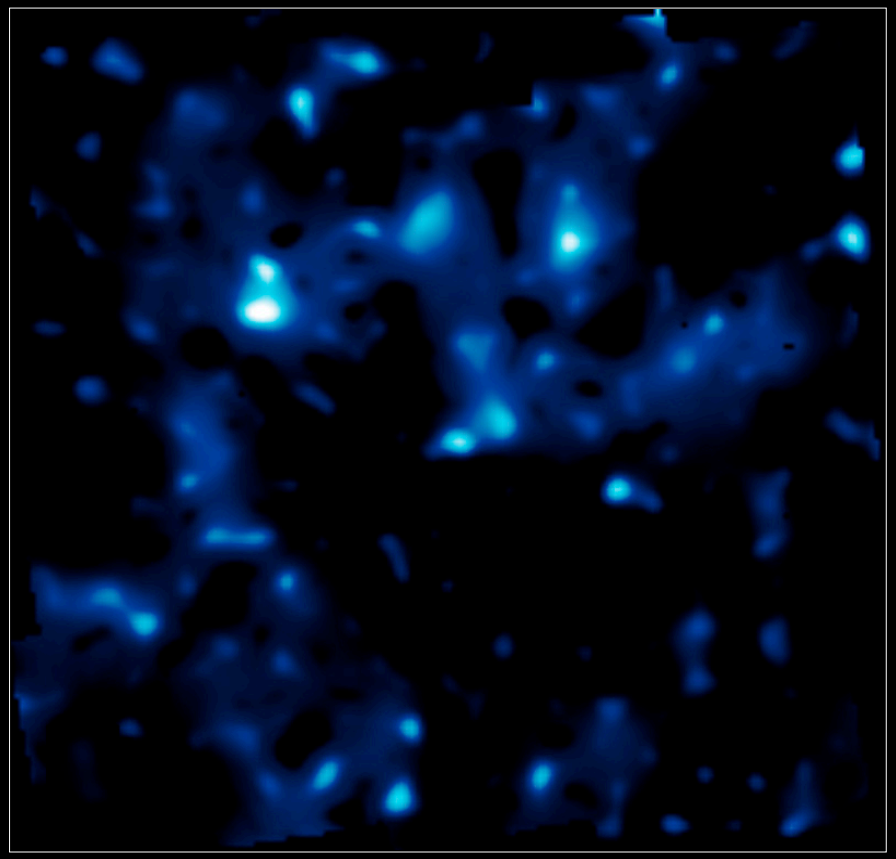
space

Bacon, Massey, Refregier, Ellis 2001
Rhodes, Refregier & Groth 2001
van Waerbeke et al. 2001
Hammerle et al. 2001
Refregier, Rhodes & Groth 2002
Hoekstra et al. 2002
Brown et al. 2003
Hamana et al. 2003
Jarvis et al. 2003
Casertano et al 2003
Rhodes et al 2004

radio

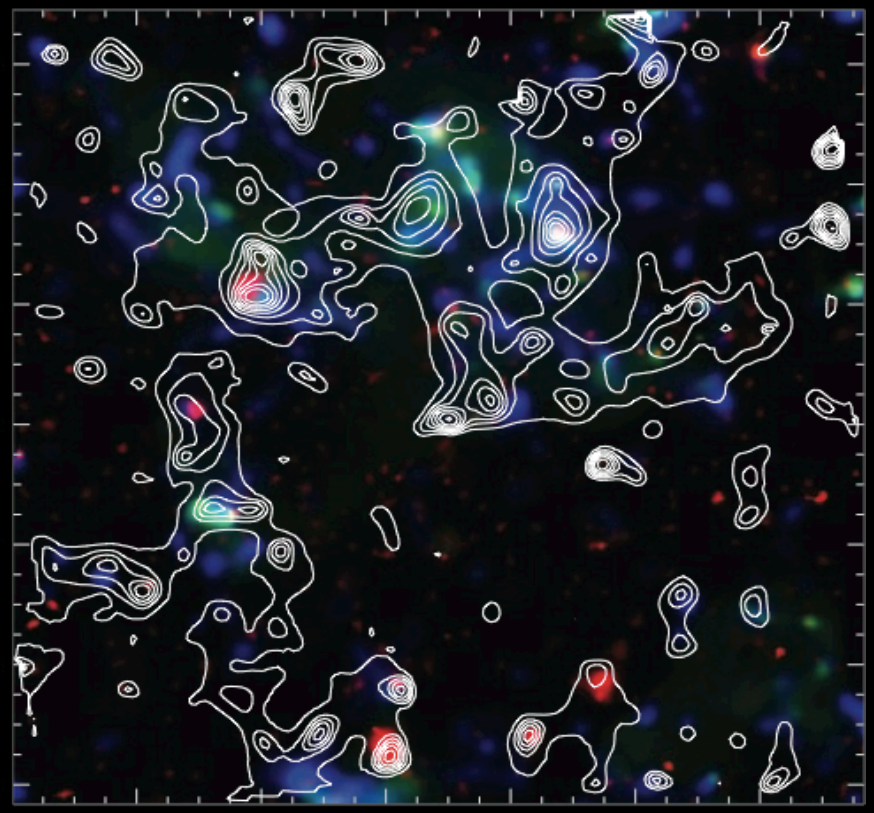
Chang, Refregier & Helfand 2004
Massey et al. 2004
Sembolini et al 2005
Hoekstra et al 2005
Benjamin et al. 2006
Fu et al. 2008
Schrabback et al. 2009
Lin et al. 2011
Heymans et al. 2013+
Jee et al. 2013

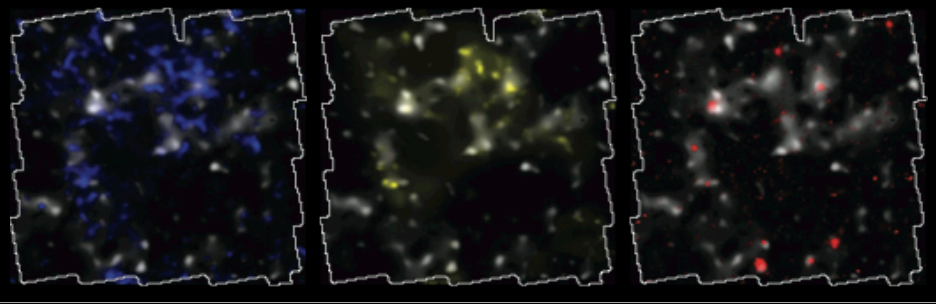
COSMOS Dark Matter Map



COSMOS HST
ACS survey
2 deg^2
Massey et al.
2006, Nature

COSMOS Dark Matter Map

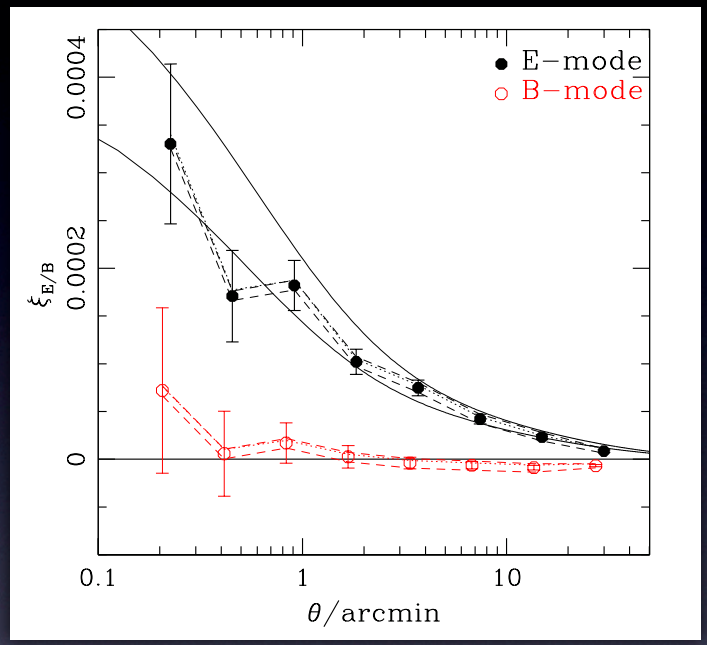




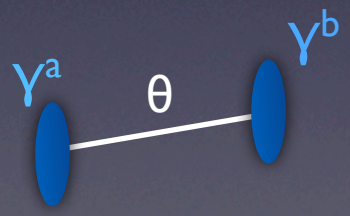
COSMOS HST
ACS survey
2 deg^2
Massey et al.
2006, Nature

Cosmological Constraints

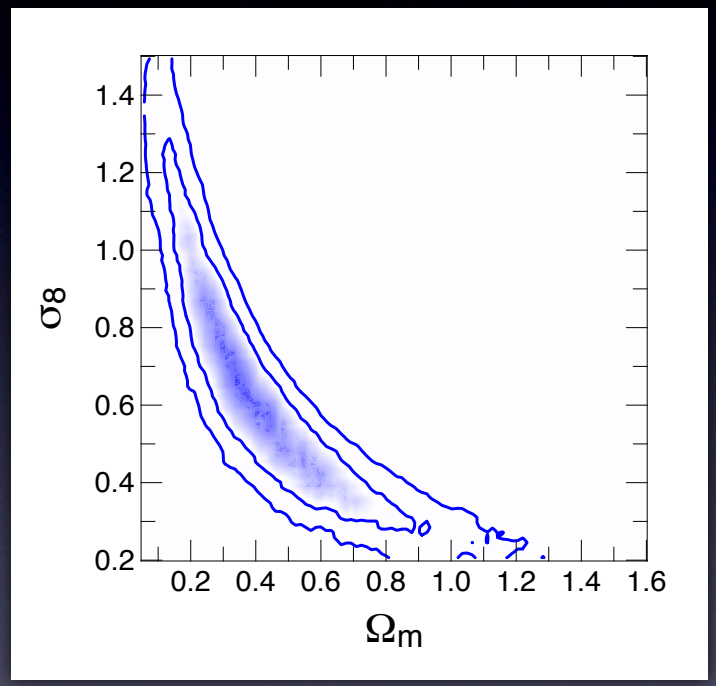
Schrabback et al. 2010



Shear correlation functions



$C_{ij}(\theta^{ab})=\langle\gamma_i^a\gamma_j^b\rangle$



$$\sigma_8(\Omega_m/0.3)^{0.51} = 0.79 \pm 0.09$$

Dark Energy Constraints

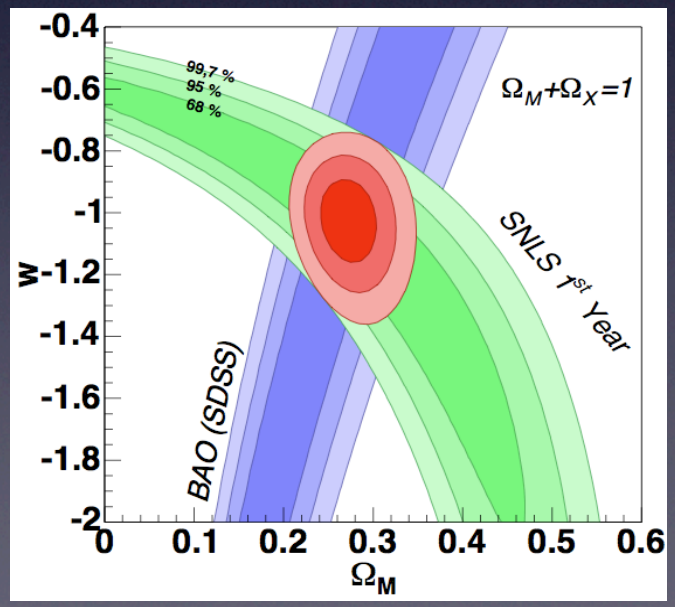
Dark Energy parameters:

- Energy density: Ω_Λ in unit of critical density
- Equation of state $w=p/\rho$: $w=-1$ for all z for a cosmological constant Λ

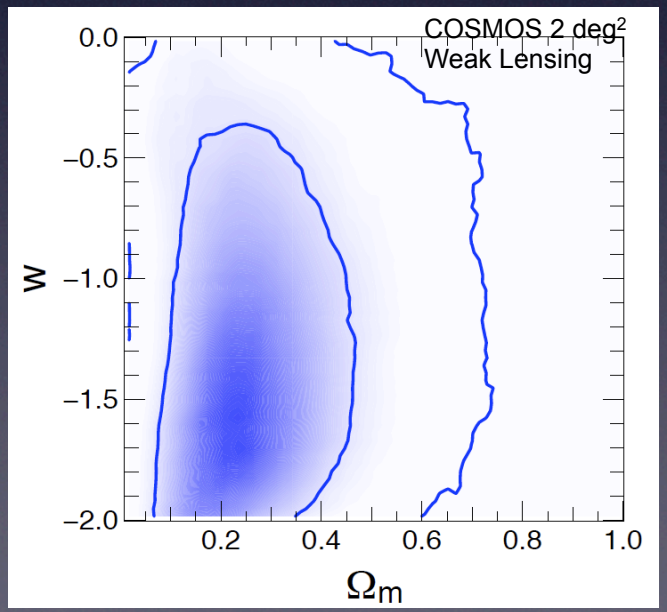
Constraints:

- Current constraints: 10% on constant w
- For definite answers on DE: need to reach a precision of 1% on (varying) w and 10% on $w_a=dw/da$

Astier et al. 2005

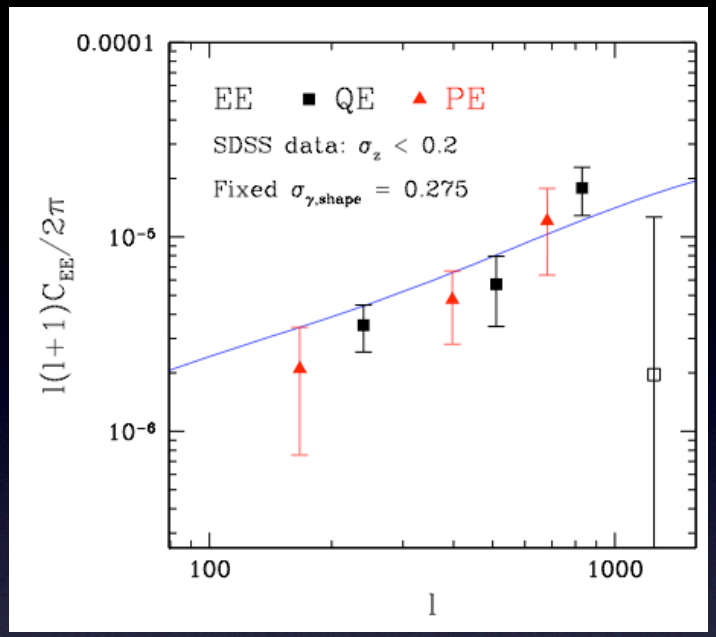


Schrabback et al. 2009

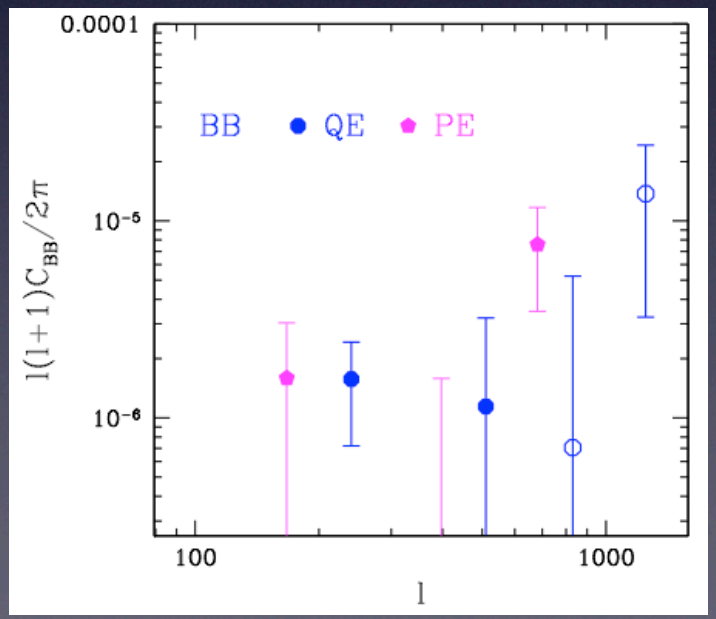


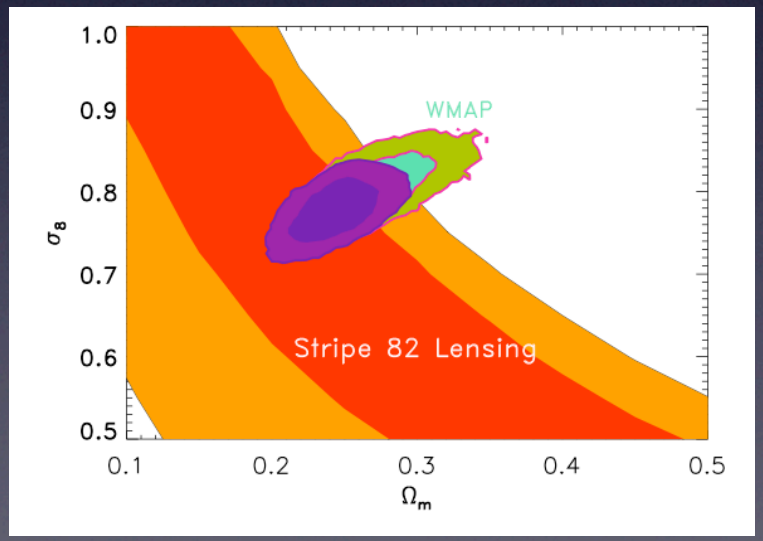
SDSS Stripe 82

Lin et al. 2011



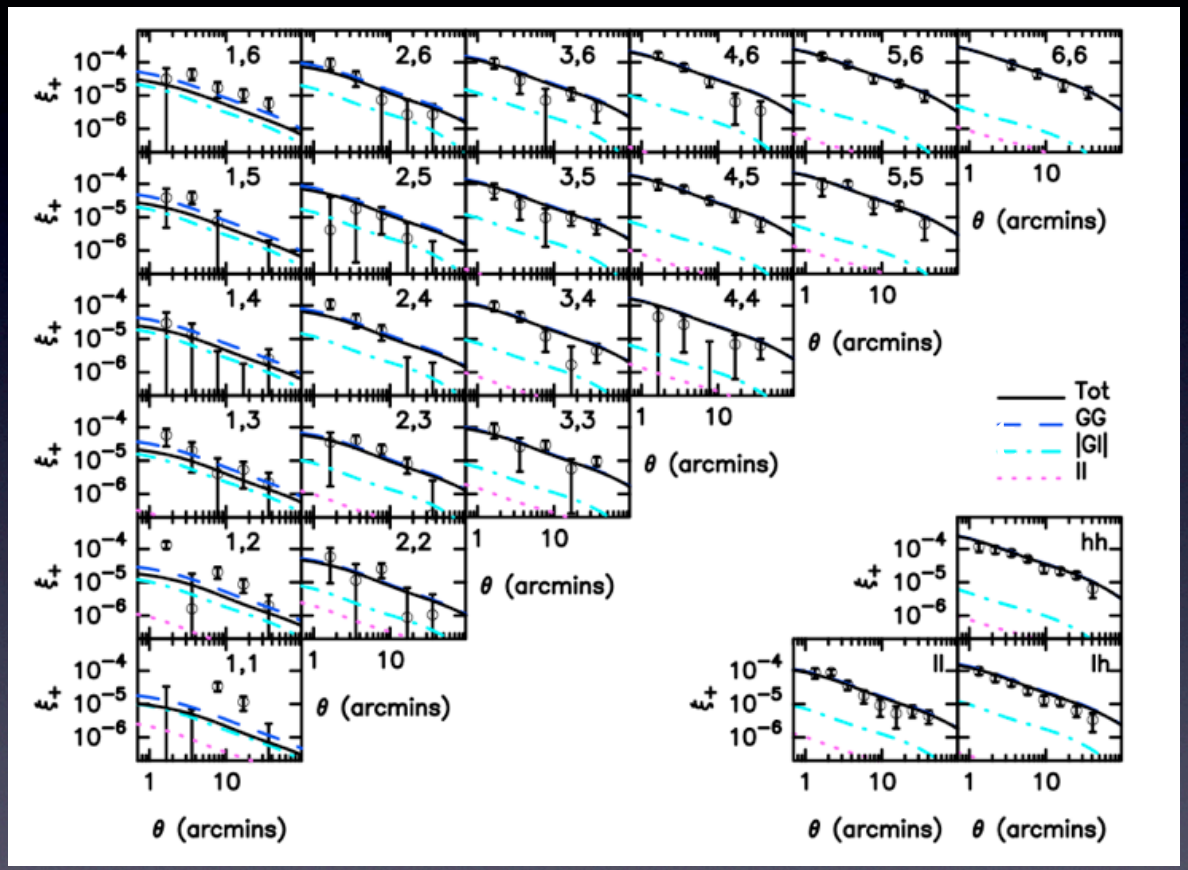
275 sq. deg.
20-30 coadded exposures
<2" seeing
18<i<24, median z~0.6

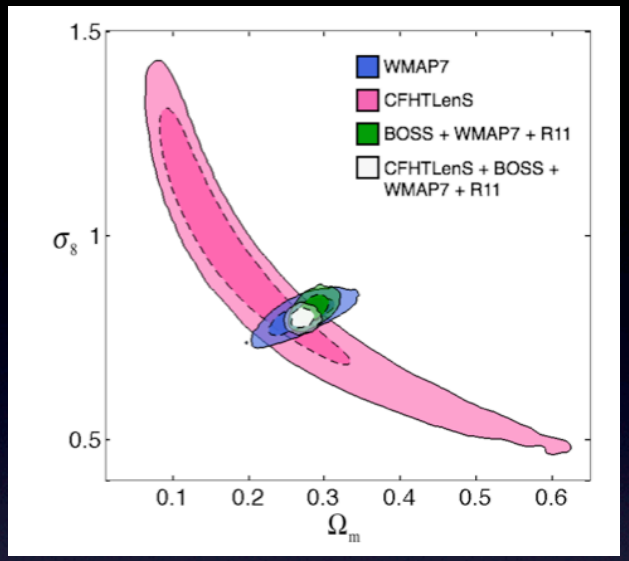


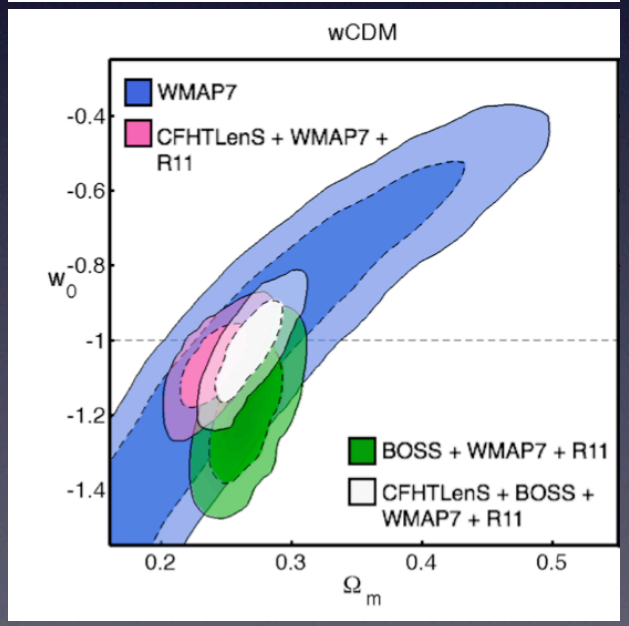


CFHTLenS

Heymans et al. 2013





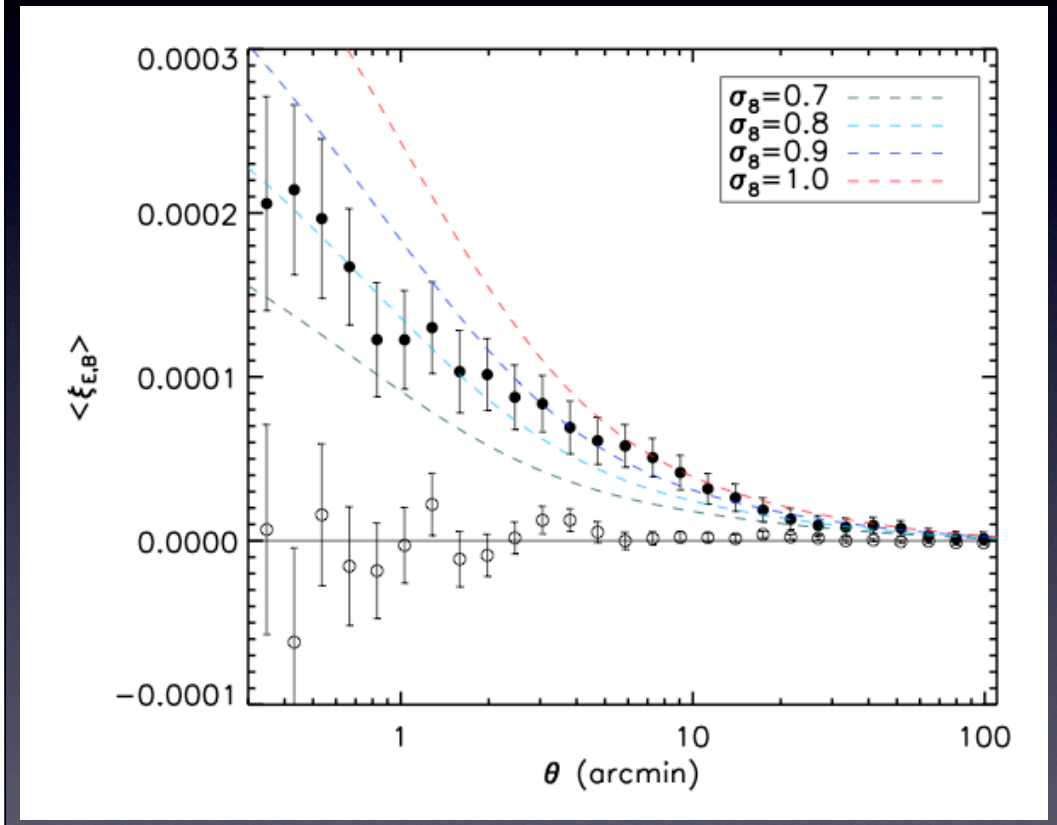


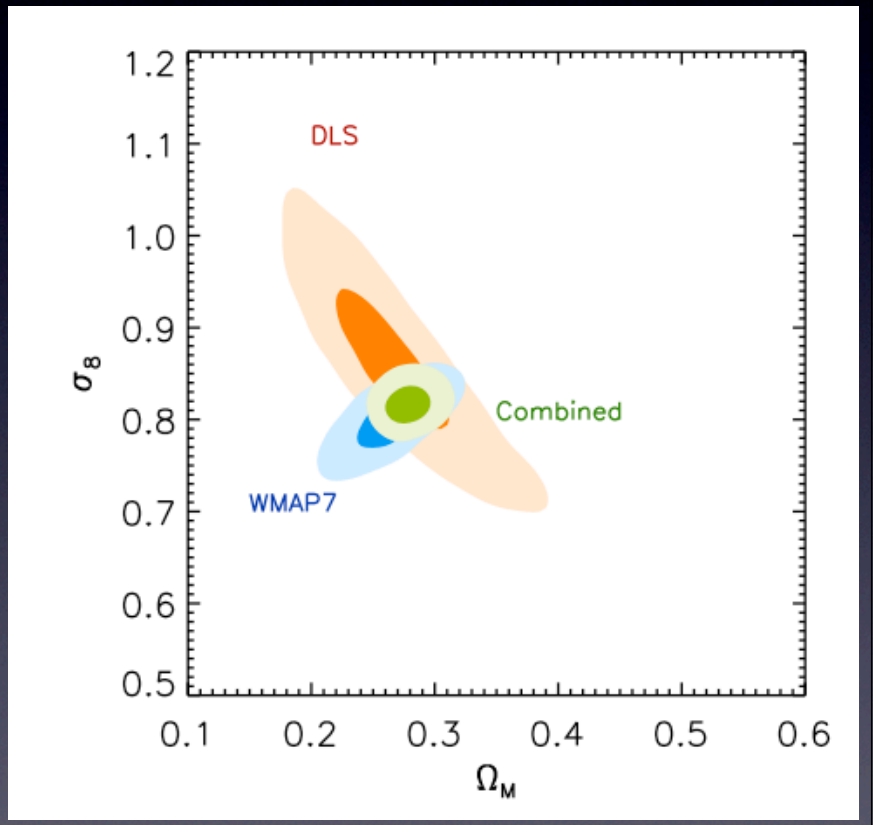
154 sq. deg., median z~0.7

Deep Lens Survey

Jee et al. 2013

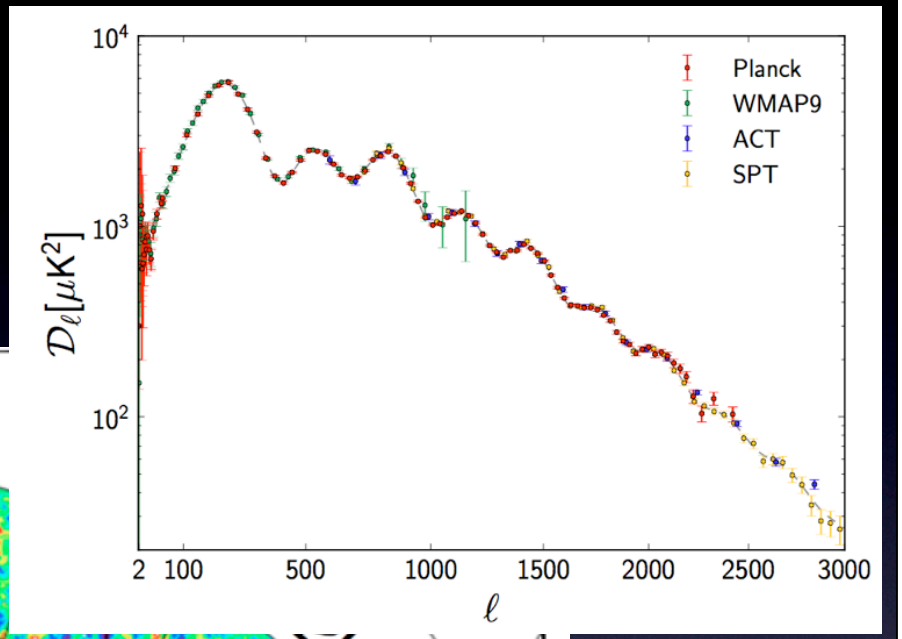
NOAO Blanco and Mayall 4m
20 sq. deg, mag<26.5, median z~1





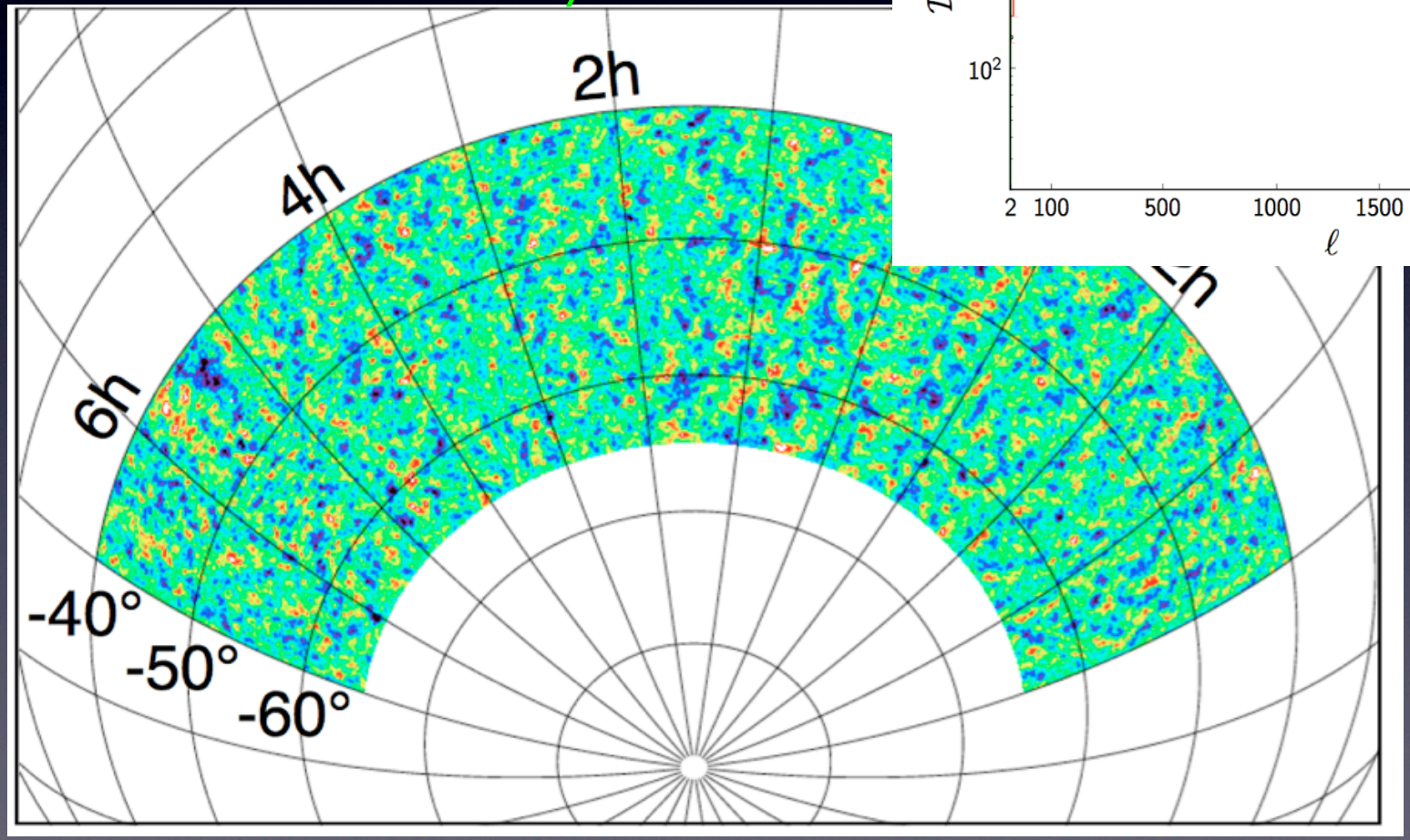
CMB Anisotropies

Planck XVII, 2013



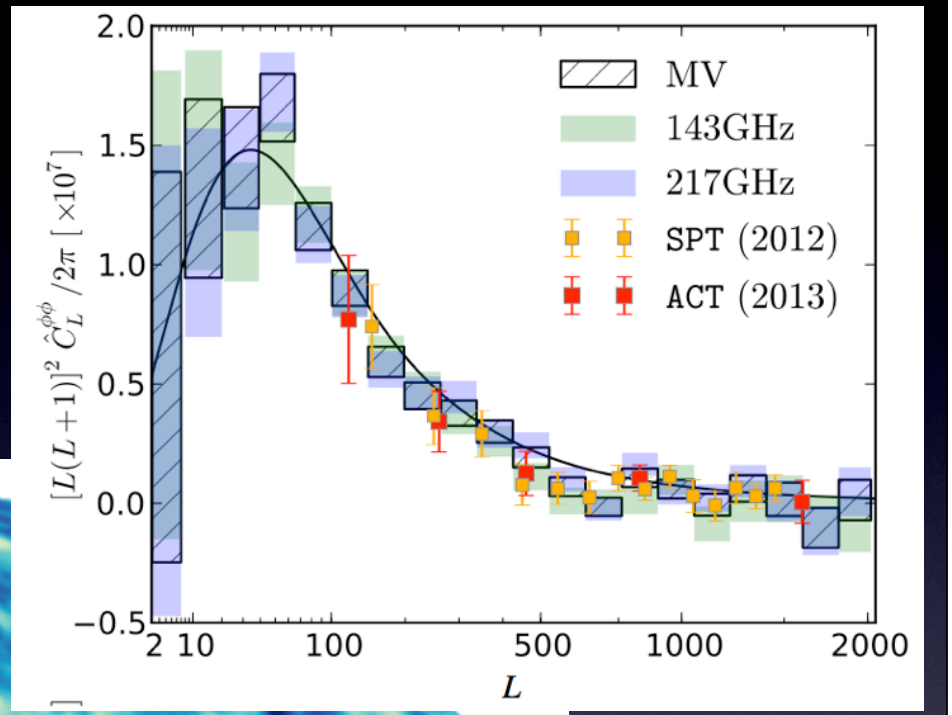
SPT 2540 deg^2

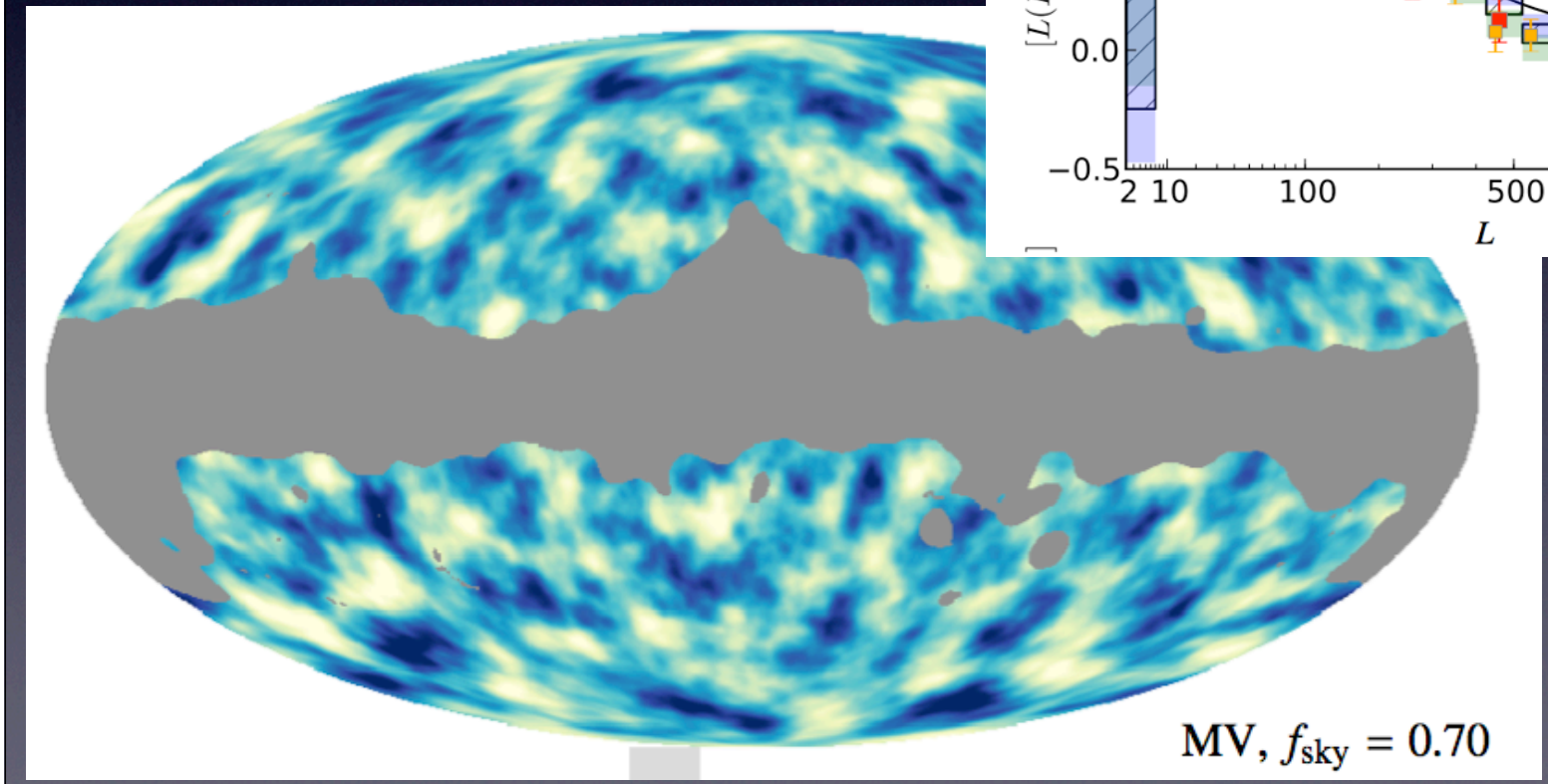
Story et al. 2011



CMB Lensing

Planck XVII, 2013





Wide-Field Imaging

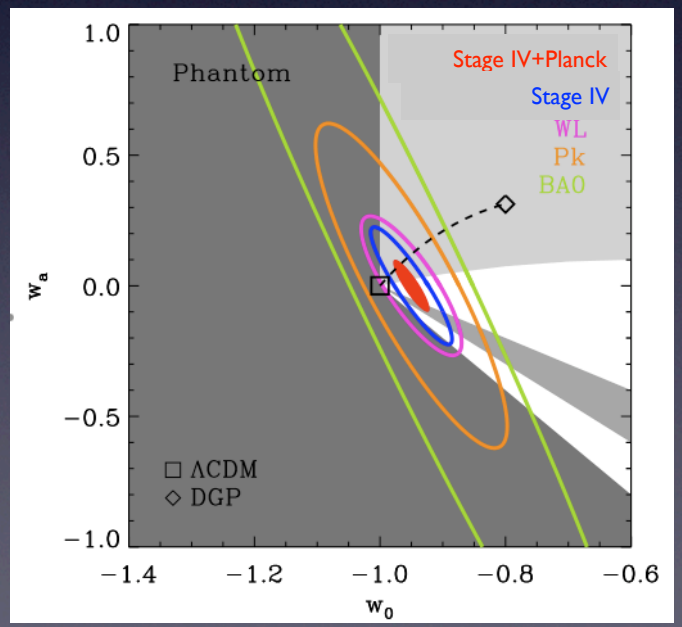
Survey	diameter (m)	FOV (deg2)	Area (deg2)	start
CFHTLS	3.6	1	172	2003
KIDS (VST)	2.6	1	1700	2012
DES (NOAO)	4	2.2	5000	2012
HSC (Subaru)	8	2	2000(?)	2012
Pan-STARRS	1.8(x4)	4(x4)	30000	2009(2014)
LSST	8	7	30000	2020
Euclid	1.2 space	2x0.5	15000	2019
WFIRST	2.0 space	3x0.5?	10000?	2021?

+PAU

Impact on Cosmology

Amara et al. 2008

	Δw_p	ΔW_a	$\Delta\Omega_m$	$\Delta\Omega_\Lambda$	$\Delta\Omega_b$	$\Delta\sigma_8$	Δn_s	Δh	DE FoM
Current+WMAP	0.13	-	0.01	0.015	0.0015	0.026	0.013	0.013	~10
Planck	-	-	0.008	-	0.0007	0.05	0.005	0.007	-
Weak Lensing	0.03	0.17	0.006	0.04	0.012	0.013	0.02	0.1	180
Imaging Probes	0.018	0.15	0.004	0.02	0.007	0.0009	0.014	0.07	400
Stage IV	0.016	0.13	0.003	0.012	0.005	0.003	0.006	0.020	500
Stage IV+Planck	0.01	0.066	0.0008	0.003	0.0004	0.0015	0.003	0.002	1500
Factor Gain	13	>15	13	5	4	17	4	7	150



Stage IV Surveys will challenge all sectors of the cosmological model:

- Dark Energy: w_p and w_a with an error of 2% and 13% respectively (no prior)
- Dark Matter: test of CDM paradigm, precision of 0.04eV on sum of neutrino masses (with Planck)
- Initial Conditions: constrain shape of primordial power spectrum, primordial non-gaussianity
- Gravity: test GR by reaching a precision of 2% on the growth exponent ($d\ln_m/d\ln a_m$)

→ Uncover new physics and map LSS at 0<z<2: Low redshift counterpart to CMB surveys

Requirements

Statistics

$$\mathrm{cov}[\hat{p}_i, \hat{p}_j] = (F^{-1})_{ij}$$

$$F_{ij} = \sum_\ell \Delta C_l^{-2} \frac{\mathrm{d}C_\ell^{\mathrm{lens}}}{\mathrm{d}p_i} \frac{\mathrm{d}C_\ell^{\mathrm{lens}}}{\mathrm{d}p_j}.$$

shape noise per galaxy: $\delta\gamma \sim 10^{-1}$
shear signal: $\delta\gamma \sim 10^{-2}$
requirement : $\delta\gamma \sim 3\times10^{-4}$ for $\sigma_{sys}^2 = 10^{-7}$

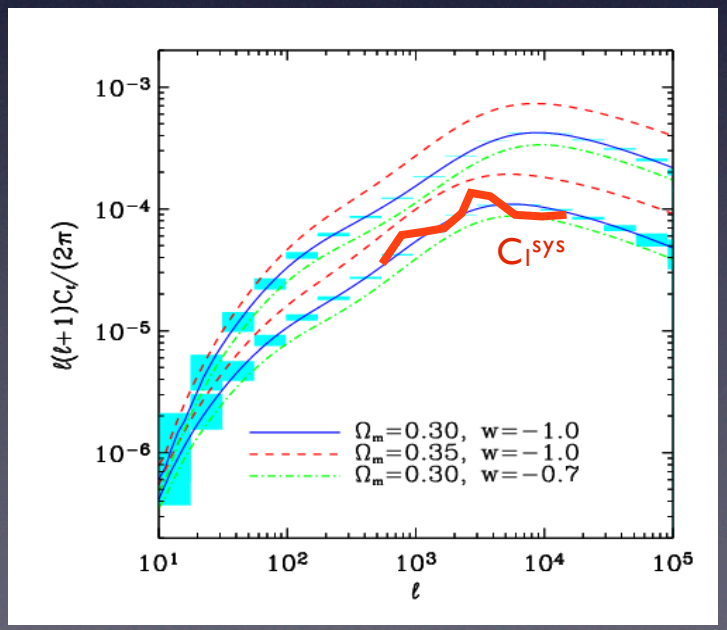
Systematics

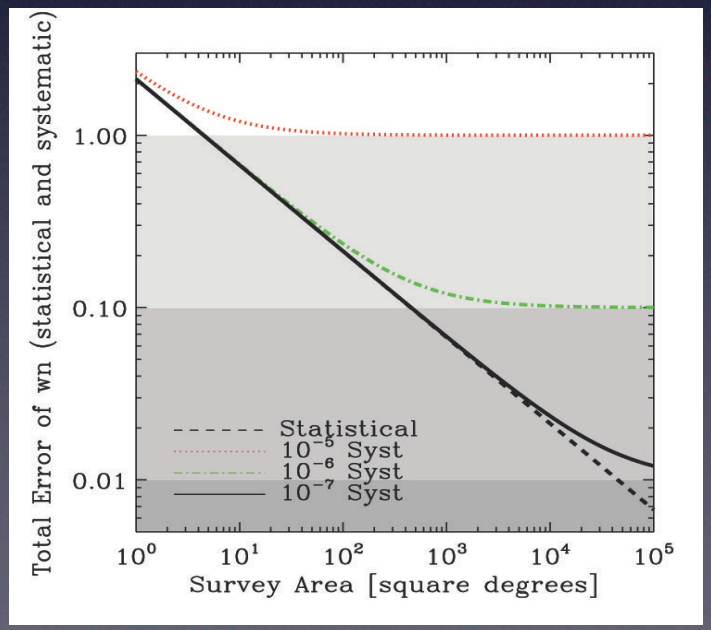
$$b[\hat{p}_i] = \langle \hat{p}_i \rangle - \langle p_i^{\mathrm{true}} \rangle = (F^{-1})_{ij} B_j$$

$$B_j = \sum_\ell \Delta C_l^{-2} C_\ell^{\mathrm{sys}} \frac{\mathrm{d}C_\ell^{\mathrm{lens}}}{\mathrm{d}p_j}$$

$$\sigma_{\mathrm{sys}}^2 = \frac{1}{2\pi} \int |C_\ell^{\mathrm{sys}}| \ell(\ell+1)\, \mathrm{d}\ln \ell$$

Amara & Refregier 2006,2007
Paulin-Henriksson et al. 2008





Open Problems

- Measurement
  - Shape measurement
  - Photometric redshifts
- Interpretation
  - Astrophysical systematics (IA, baryonic corrections)
  - Non-gaussian field statistics
- Implementation
  - Large Data Volume
  - Quality Control

Conclusions

- Weak Lensing is a special probe of the dark universe: purely gravitational, direct probe of mass (DM), strong statistical power

- Several wide field lensing surveys coming online or being planned; progress with CMB Lensing

- For lensing to reach its full potential, many open problems in theory, observations, data analysis, instrumentation