Weak Lensing, Dark Matter and Dark Energy

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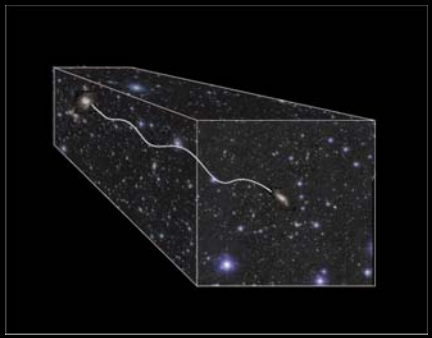
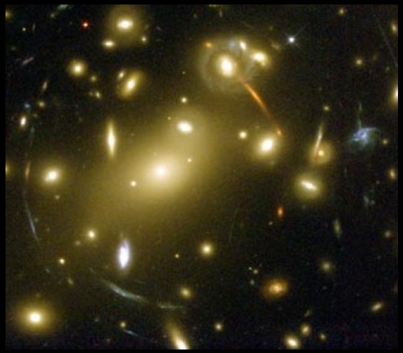
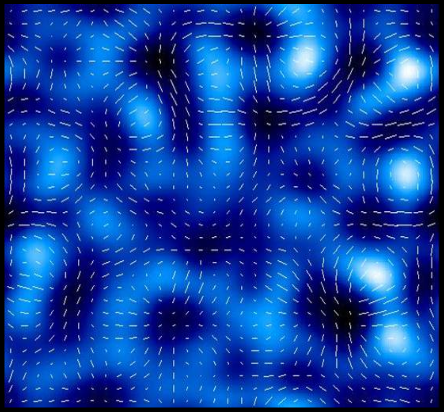
Weak Gravitational Lensing

- Coherent distortion of background images by gravity
- Shear, Magnification, Amplification

Jain & Seljak

- Independent of dynamical state of matter
- Independent of nature of matter

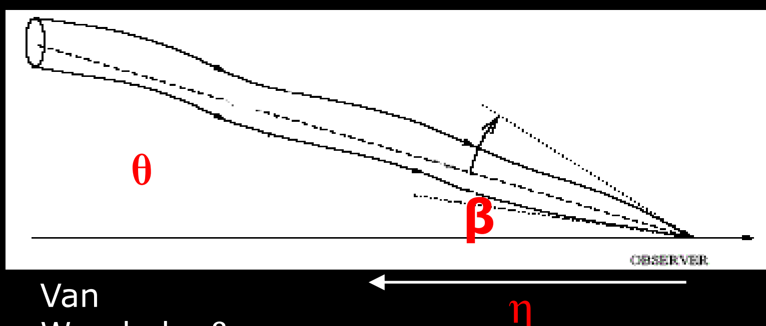
Weak lensing: the Bush years

- 2000 First detections (Bacon et al, Kaiser et al, Wittman et al, van Waerbeke et al)
- 2002+ Weak-lensing selected cluster catalogues (e.g. Miyazake et al, Wittman et al)
- 2003+ Non-parametric mass distributions in clusters (e.g. Kneib et al, Clowe et al, Jee et al, Gray et al)
- 2003+ Dark matter power spectrum (Brown et al, Heymans et al, Hoekstra et al, Semboloni et al)
- 2004 Bullet cluster challenge to MOND (Clowe et al)
- 2004+ 3D potential reconstruction (Taylor et al, Massey et al)
- 2005+ Evolution of structure (Bacon et al)
- 2006+ 3D analyses (Heavens et al, Kitching et al, Taylor et al)
- 2007 100 sq deg surveys, with small error bars (Benjamin et al, Fu et al)

Physics

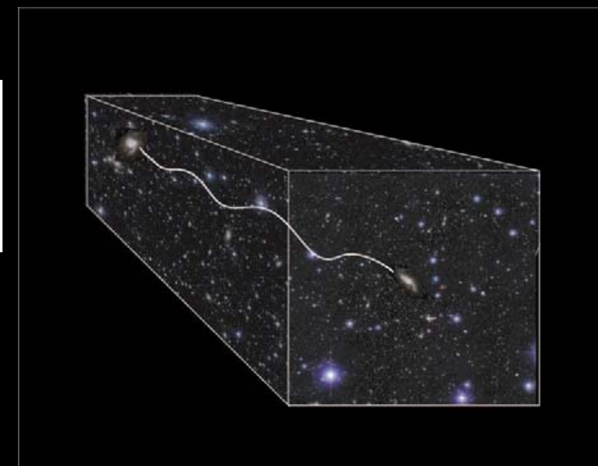
- Einstein gravity

$$ds^2 = \left(1+\frac{2\Phi}{c^2}\right)c^2dt^2 - \left(1-\frac{2\Phi}{c^2}\right)R^2(t)\left[dr^2 + S_k^2(r)d\psi^2\right]$$

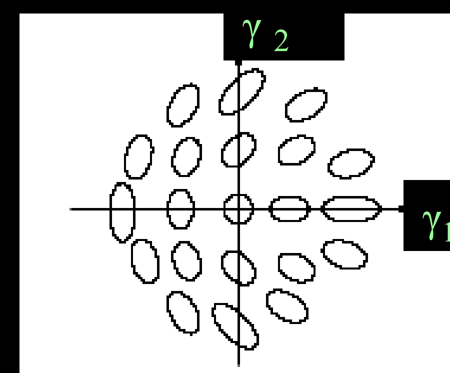


Van Waerbeke & Mellier 2004

$$\frac{d^2\beta}{d\eta^2} = -\frac{2}{c^2}\nabla\Phi$$



$$A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \underbrace{\begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix}}_{\text{Magnification}} + \underbrace{\begin{pmatrix} -\gamma_1 & \gamma_2 \\ \gamma_2 & \gamma_1 \end{pmatrix}}_{\text{Shear}}$$



Complex shear $\gamma = \gamma_1 + i\,\gamma_2$

e.g. Gunn 1967 (Feynman 1964); Kristian & Sachs 1966

Lensing potential

- Integrate: Lensing *potential*

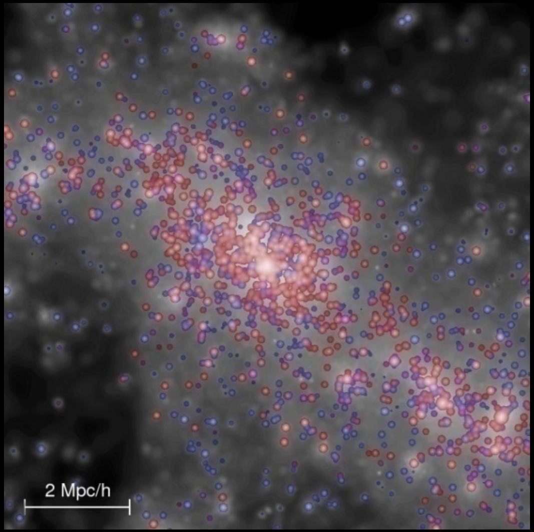
$$\phi(\mathbf{r}) = \frac{2}{c^2}\int_0^r dr'\,\Phi(\mathbf{r}')\left(\frac{1}{r}-\frac{1}{r'}\right)$$

(Flat Universe)

And convergence κ and shear are given by transverse derivatives of φ:

$$\begin{aligned}\kappa &= \frac{1}{2}\left(\phi_{,11}+\phi_{,22}\right)\\ \gamma_1 &= \frac{1}{2}\left(\phi_{,11}-\phi_{,22}\right)\\ \gamma_2 &= \phi_{,12}\end{aligned}$$

$$\phi_{,ij} = \frac{\partial^2\phi}{\partial\theta_i\partial\theta_j}$$

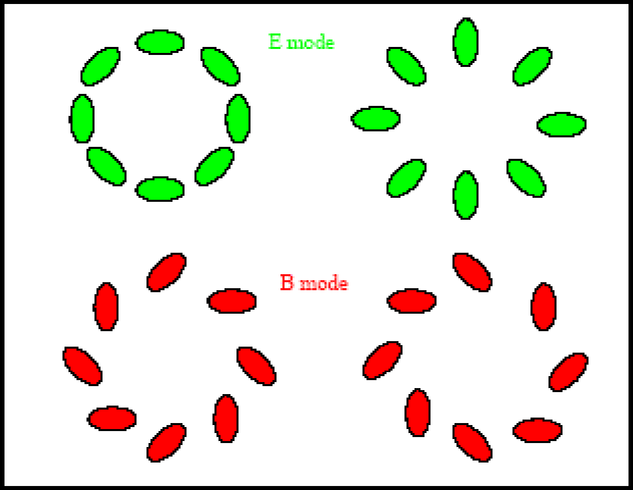


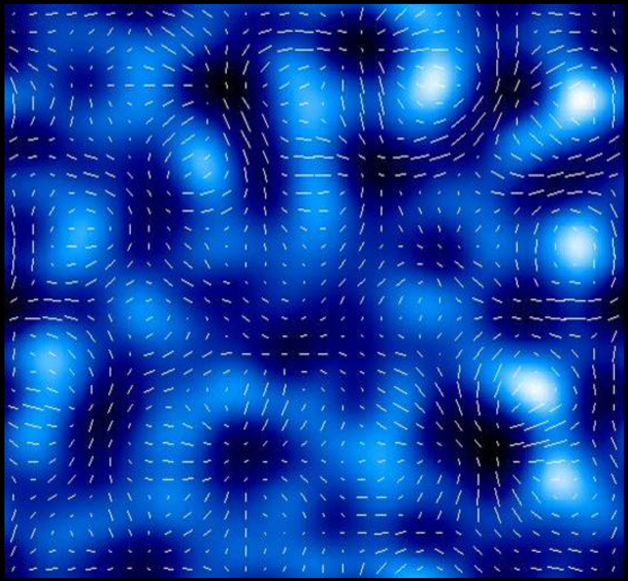
Springel et al 2005

Note: dependence is on gravitational potential: lensing probes the *mass* distribution directly. Bias is not an issue.

Expected Shear is ~ 1%

E and B modes





Lensing essentially produces only E modes

Jain & Seljak

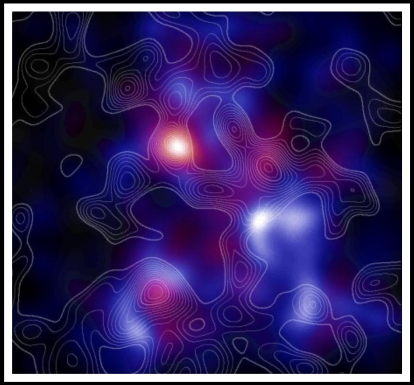
B modes from galaxy clustering, 2nd-order effects (both small), imperfect PSF modelling, optics systematics, intrinsic alignments of galaxies

Lensing in clusters

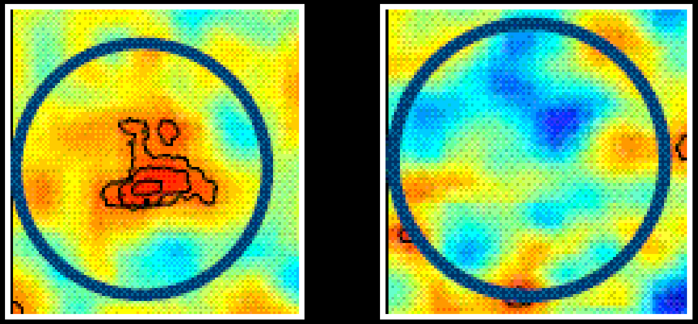
- A1689 (HST)

Reconstruction of density/potential

- 2D cluster potential/density

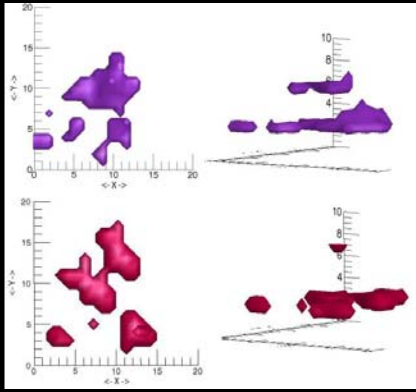


A901: Gray et al 2004

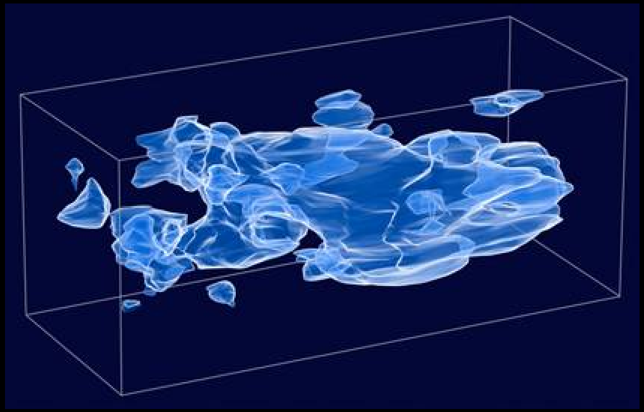


E McInnes et al 2009 **B**

- 3D



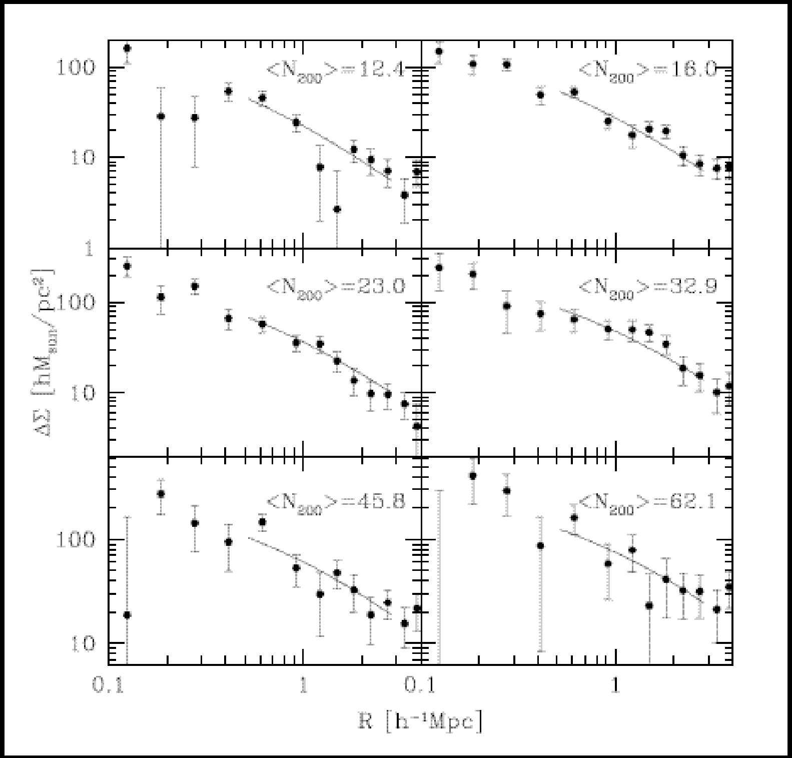
COMBO-17: Taylor et al 2004

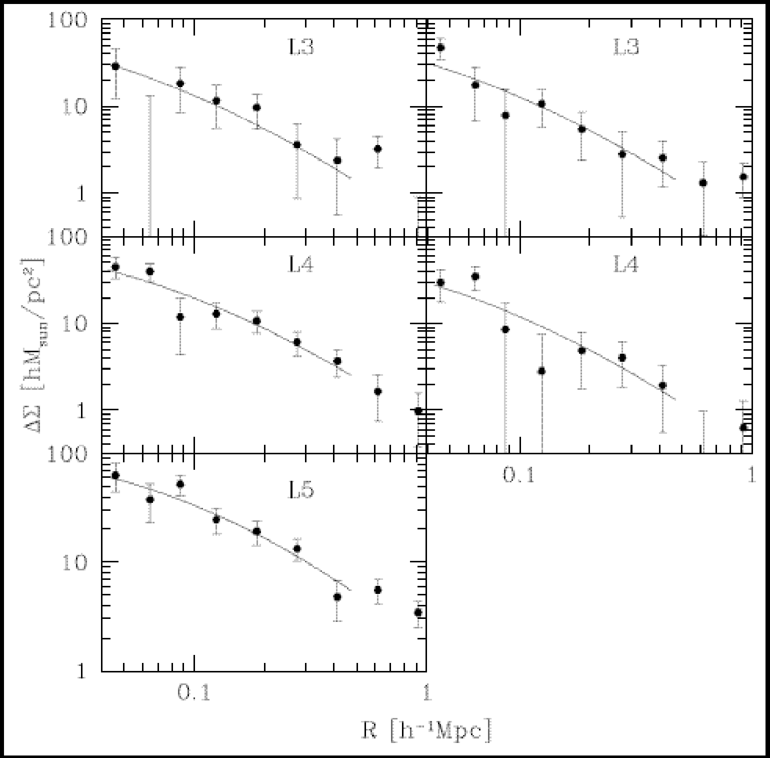


COSMOS: Massey et al 2007

Testing (Dark) Matter profiles

- Cluster profiles fit NFW

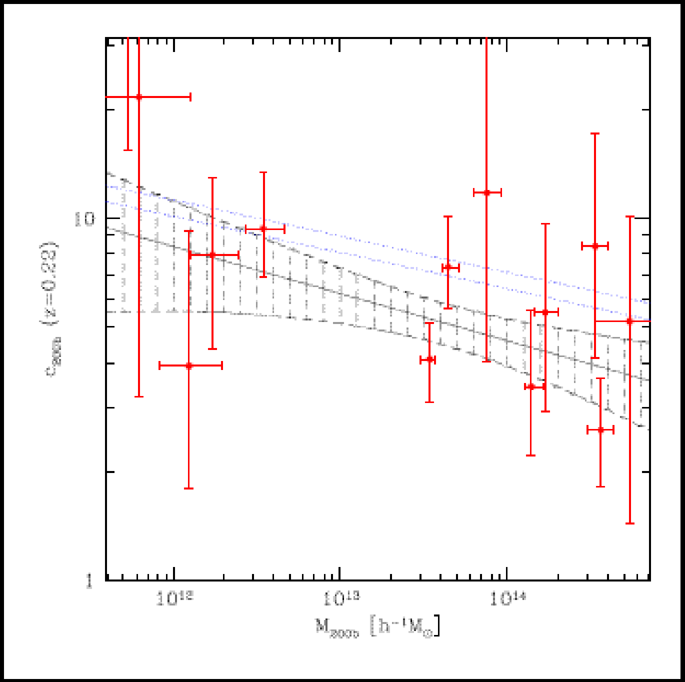




Clusters SDSS: Mandelbaum et al 2008 Galaxies (E & S)

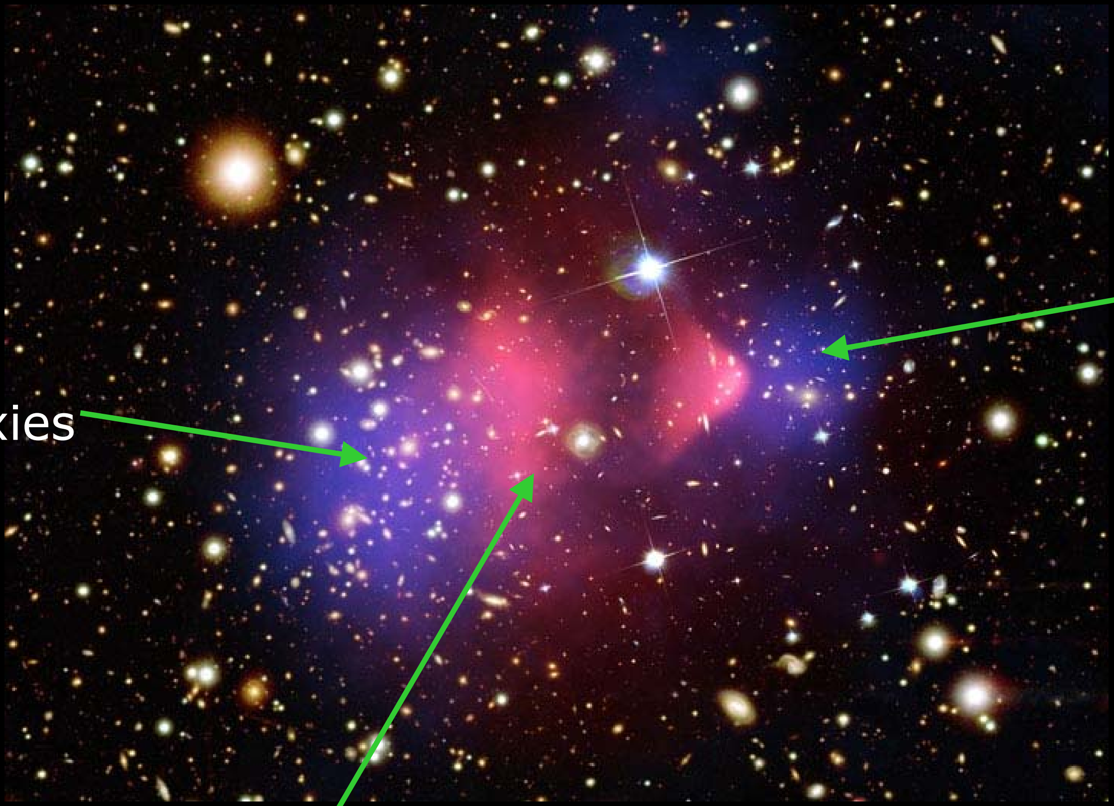
Concentration indices

- Close to simulations (some tension claimed – e.g. Oguri et al 2009)



Bullet cluster

- Challenges MOND, TeVeS



Galaxies

Dark Matter

(Lensing)

Hot Gas (X-ray)

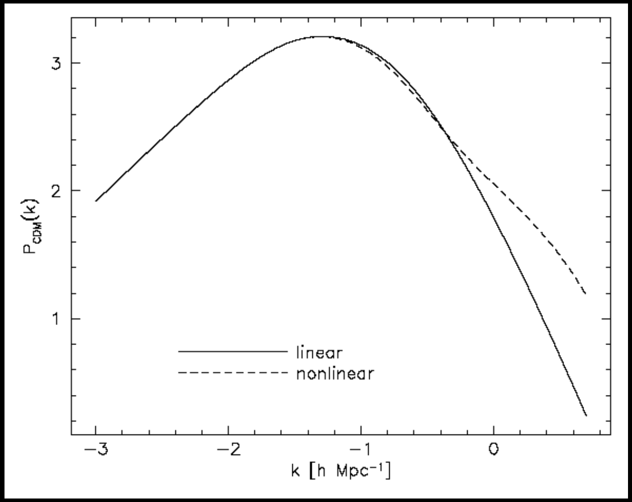
$\sigma/m < 0.12\ m^2/kg$
(Randall et al 2007)

Markevitch et al 2002

Clowe et al 2004

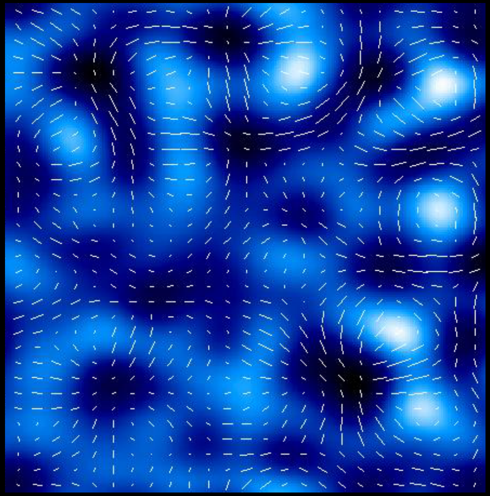
Statistical analysis: 2D

- E.g. Shear-shear correlations *on the sky*
- Depends on
  - how clumpy the Universe is: P(k,t)



Peacock & Dodds 96;

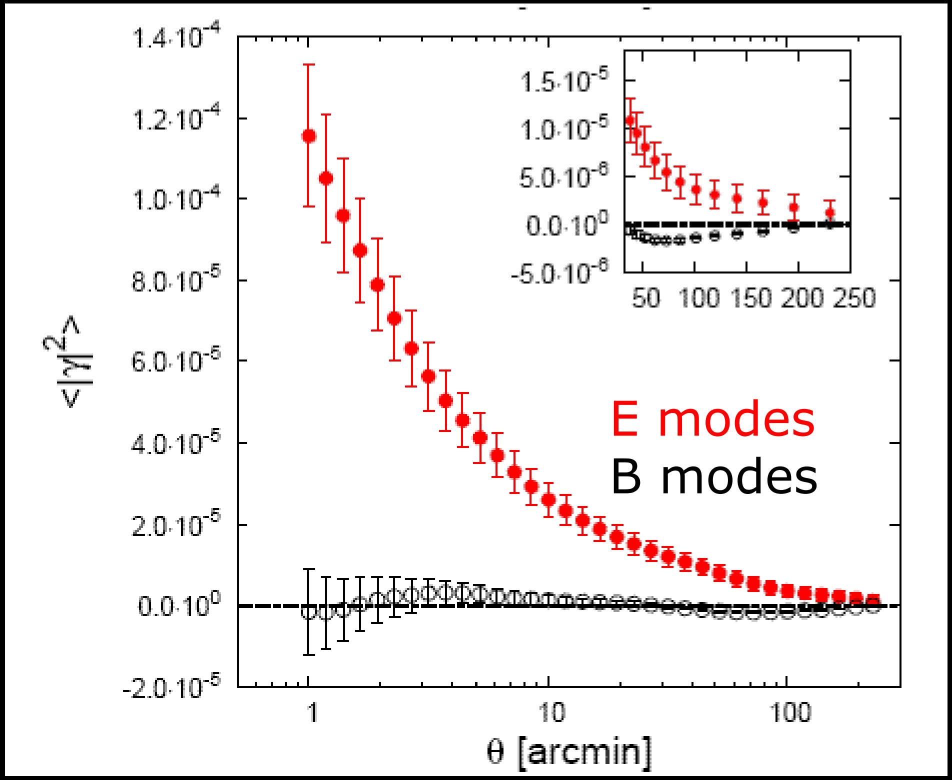
Smith et al 2003

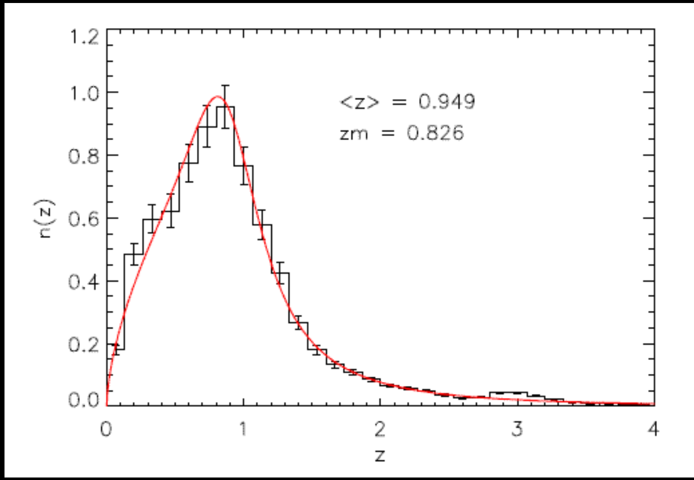


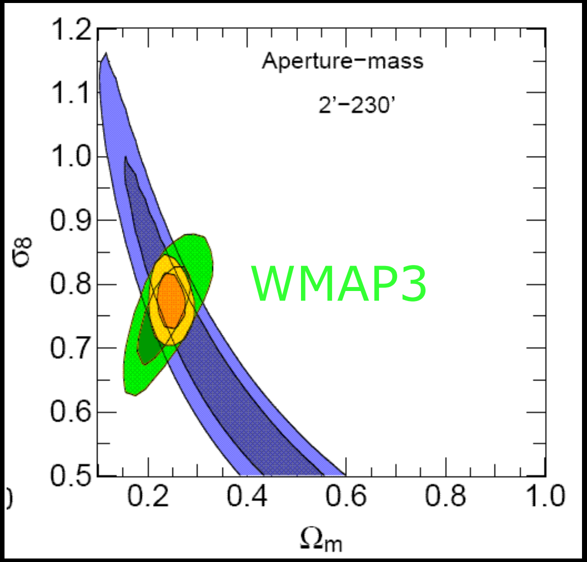
Simulated: Jain et al 2000

  - How far away the galaxies are: n(z)
- To get n(z), best practical way is via photo-zs

1→100→10000 square degrees:
CFHTLS







57 sq deg; median z=0.95

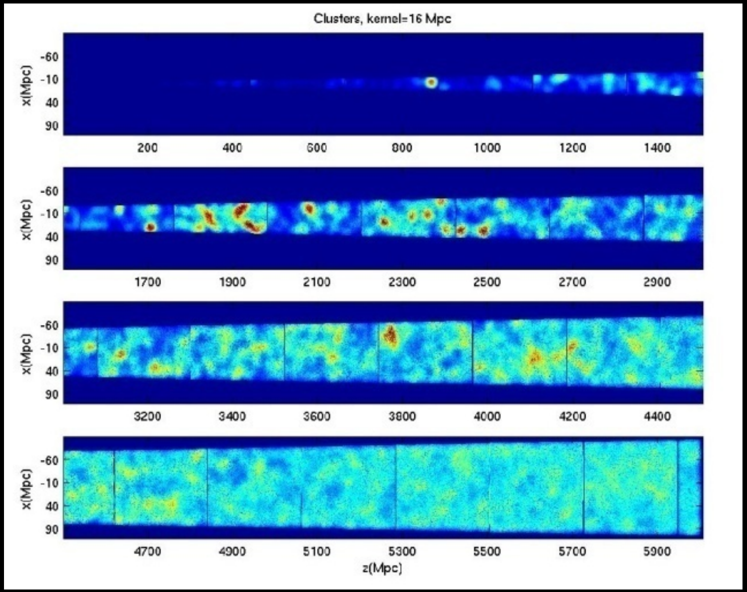
Fu et al 2008; (Benjamin et al 2007)

$$\sigma_8 = 0.84 \pm 0.07 \left(\frac{\Omega_m}{0.24}\right)^{0.59}$$

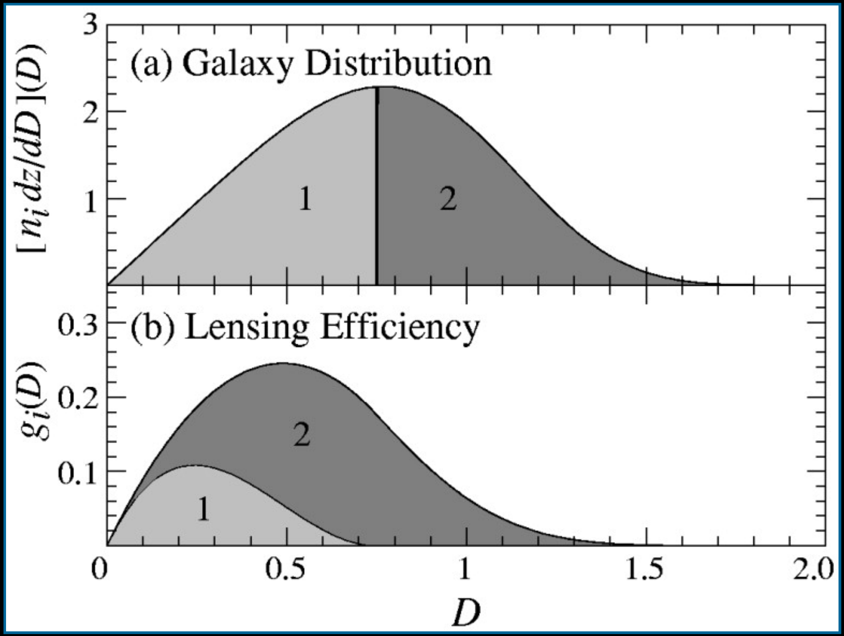
Dark Energy: effects

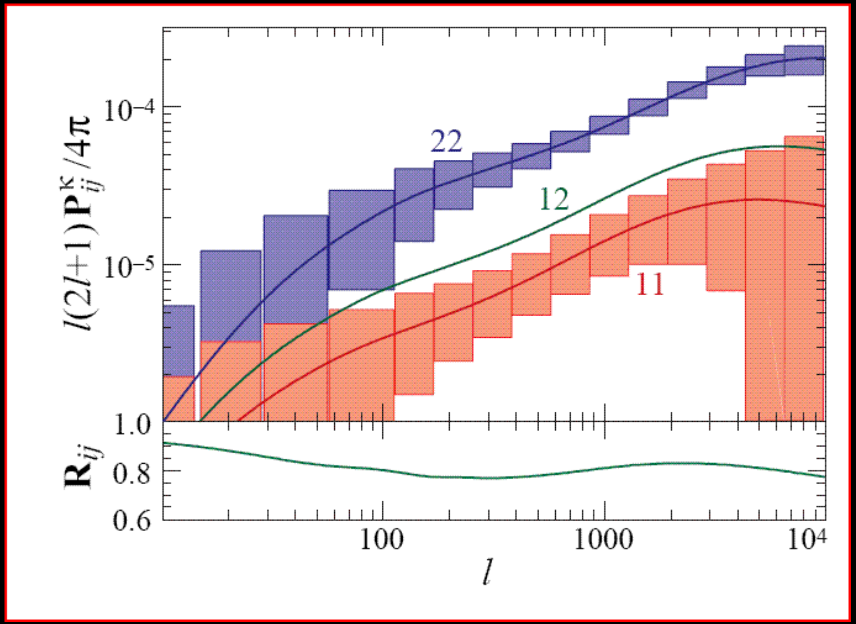
$$\phi(\mathbf{r}) = \frac{2}{c^2}\int_0^r dr'\,\Phi(\mathbf{r}')\left(\frac{1}{r} - \frac{1}{r'}\right)$$

- Distance-redshift relations
  $r(z)$, D_A, D_L
- Growth rate of perturbations
  $g(z)$
- z information is crucial
- Equation of state parameter
  $w \equiv p/\rho c^2$ ($w=-1 \Leftrightarrow \Lambda$)
  $w(a)=w_0+w_a(1-a)$



Steps to 3D: lensing in slices





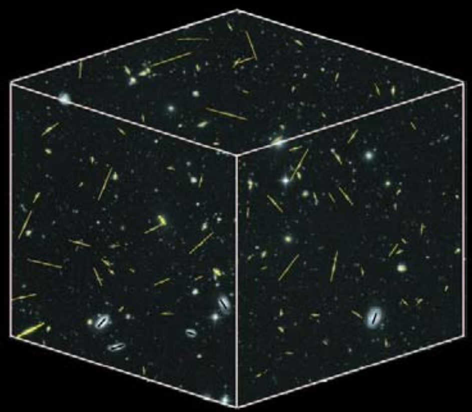
Hu (1999)

Dividing the source distribution improves parameter estimation

Full 3D weak lensing

Heavens 2003

- Use individual photo-zs:

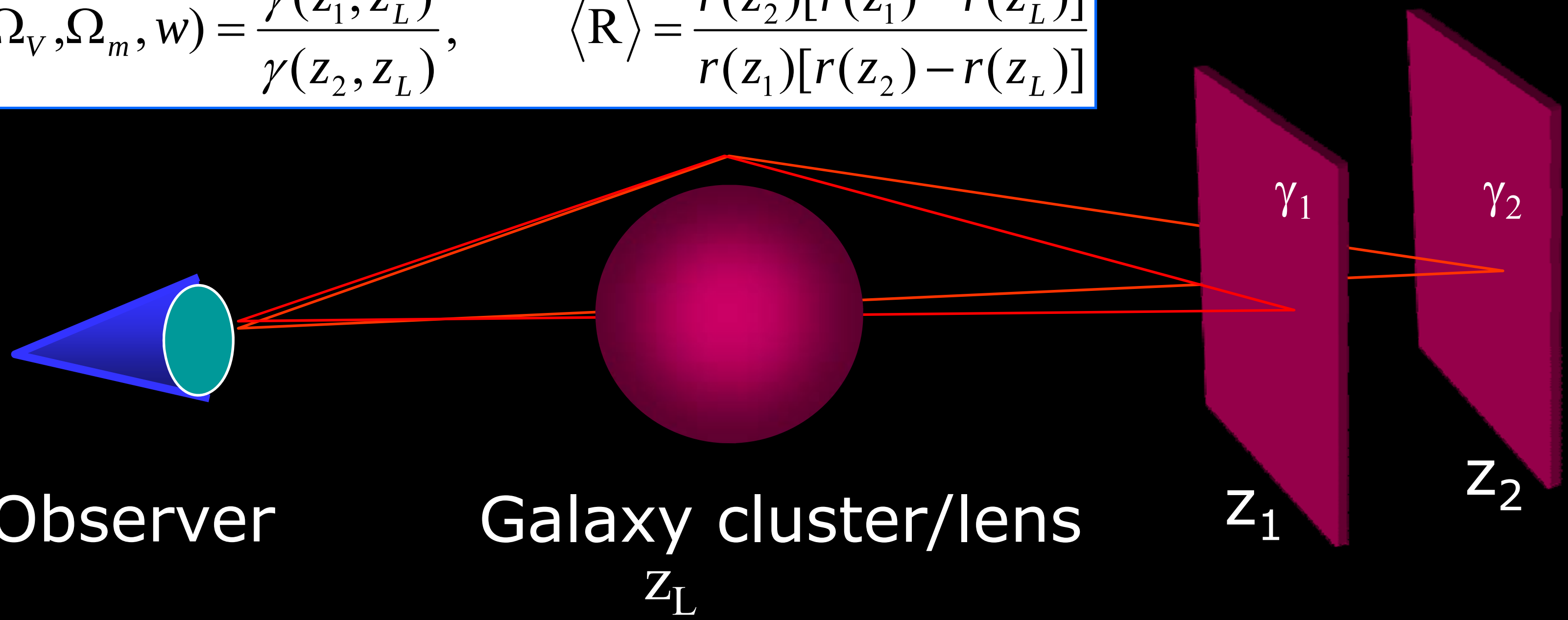


- Very noisy, point-process sampling of 3D shear field
- 3D shear power spectrum probes r(z) and g(z)
- Reduces statistical errors

Shear Ratio Test

The ratio of shears has a purely geometric dependence

$$R(\Omega_V, \Omega_m, w) = \frac{\gamma(z_1, z_L)}{\gamma(z_2, z_L)}, \qquad \langle \mathrm{R} \rangle = \frac{r(z_2)[r(z_1) - r(z_L)]}{r(z_1)[r(z_2) - r(z_L)]}$$

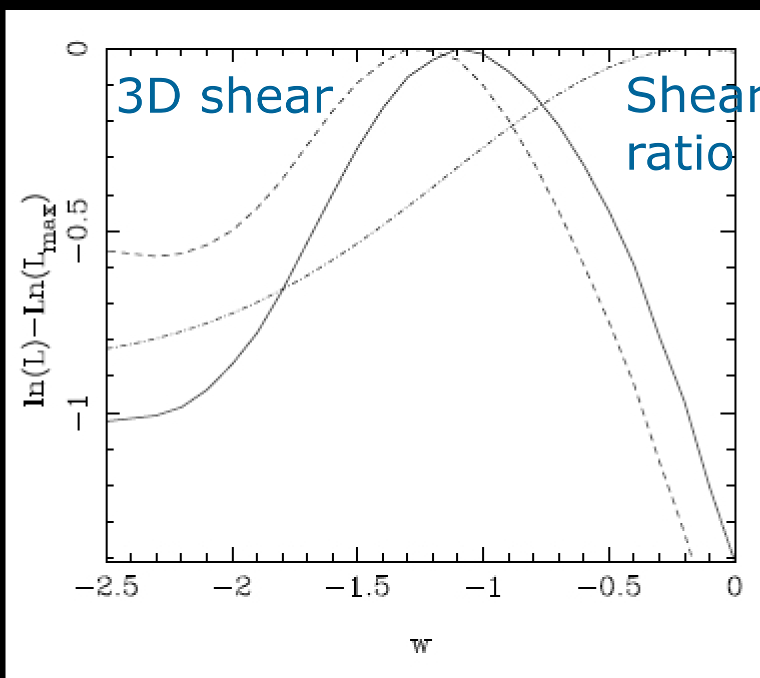


- Depends only on global geometry: Ω_{DE}, Ω_m and *w*.
- Apply to large signal from galaxy clusters
- Similar accuracy to 3D shear power spectrum

(Jain & Taylor, 2003, Taylor et al 2007)

1 sq deg: w from 3D lensing

- Proof of concept: COMBO-17 (0.75 square degrees)



Predicted a priori

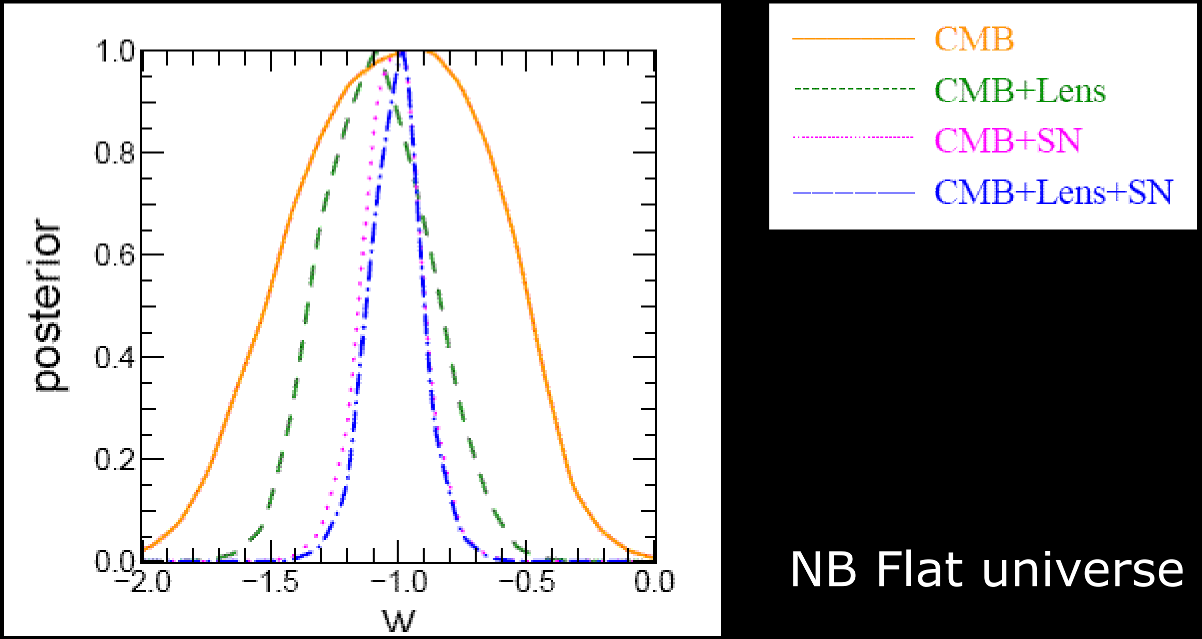
w = -1.1 ± 0.6

Not a competitive error, but proof of concept for future large 3D surveys

Kitching et al 2007

w from CFHTLS, CMB and SNe

- w=-1.02 ± 0.08 ± ~0.07 (Kilbinger et al 2009)

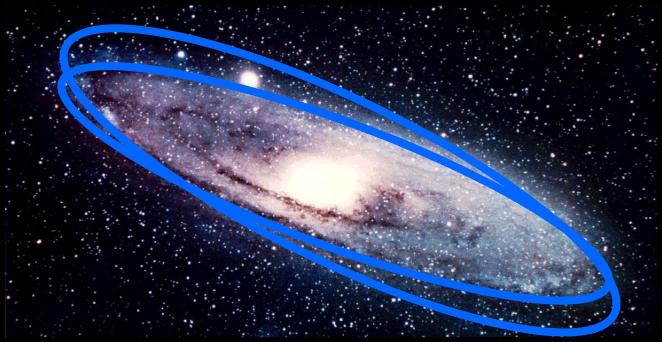


NB Flat universe assumed

Estimating shear

- Measure ellipticity of galaxy

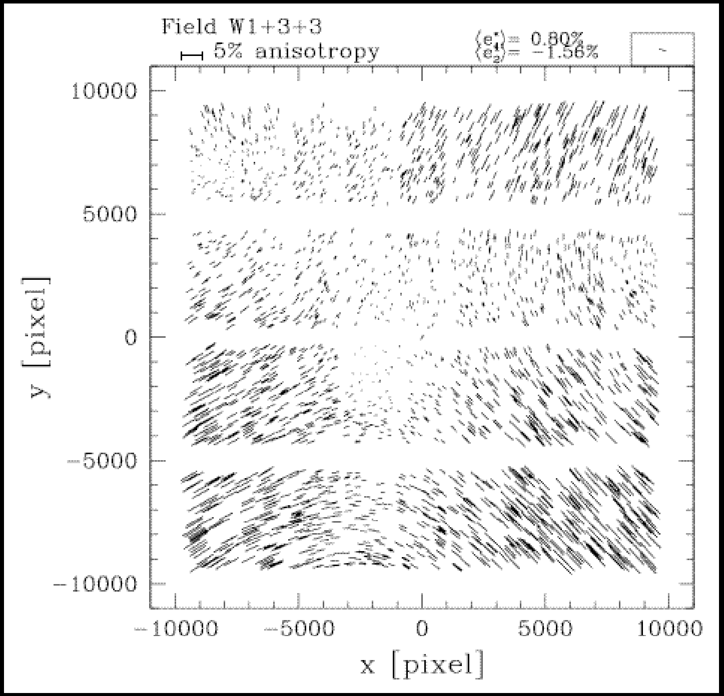
$$e = \frac{e_I + \gamma}{1 + \gamma^* e_I}$$



- Estimate shear γ by averaging over many galaxies (since $\langle e_I \rangle = 0$)
- Dispersion in e_I is ~0.3
- Shear is ~0.01

Image quality

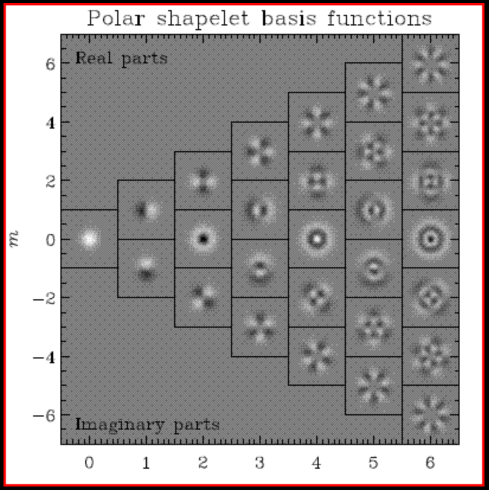
- Telescope optics & atmosphere may distort images up to ~10%
- Use stars to correct for the Point Spread Function (PSF) distortions



Shape measurement

- Needs to be done without significant bias
- Examples:
  - moments (KSB)
  - orthogonal function decomposition (shapelets)
  - shape fitting (im2shape, Bayesian lensfit)

  (Miller et al 2007; Kitching et al 2008)



Requirements are stringent:

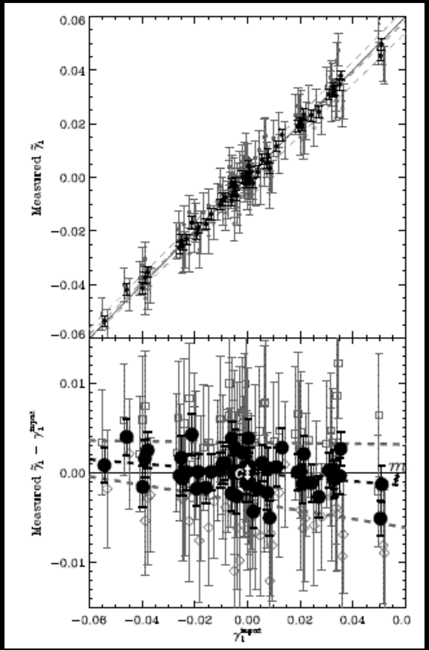
- Fit $\gamma = (1+m)\,\gamma_{true} + c$

- Need $|m| < 5\text{-}8 \times 10^{-3}$ for shape measurement not to dominate errors on w in Euclid/JDEM

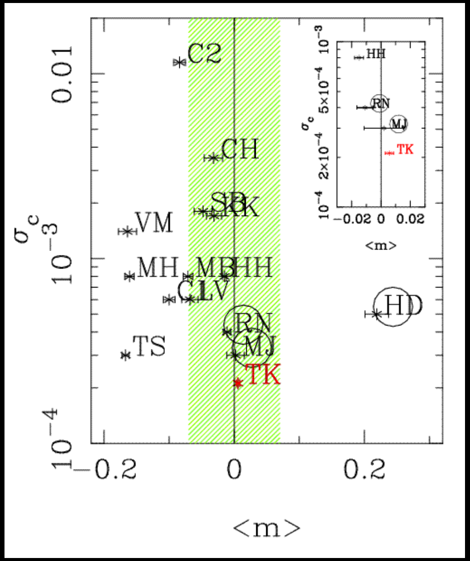
- *Lensfit* (Miller et al 2007; Kitching et al 2008):

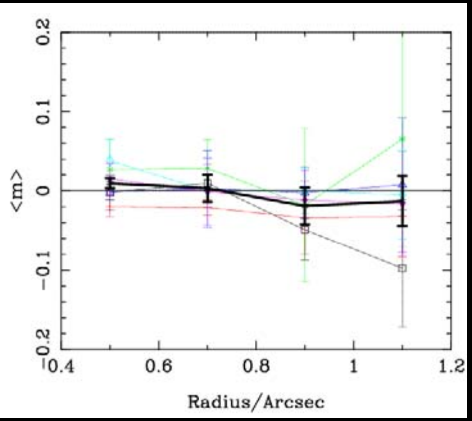
  $m = (6 \pm 5) \times 10^{-3}$

  from simulated STEP (Heymans et al 2006) data



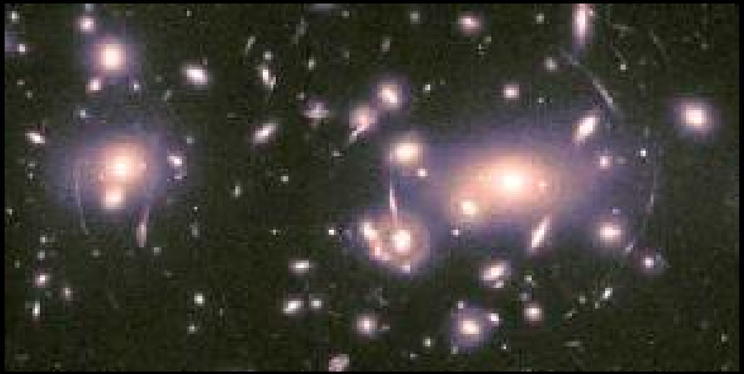
Massey et al 2007





Astrophysical complications

- Intrinsic alignments



• Lensing analysis assumed orientations of source galaxies are uncorrelated

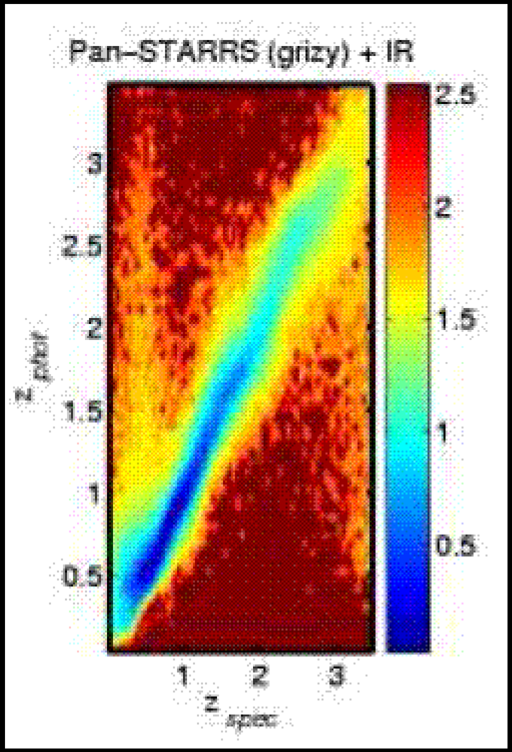
• Intrinsic correlations (e.g. from tidal torques) could mimic lensing (Heavens, Refregier & Heymans 2000 Croft & Metzler 2000 Crittenden et al 2001 Catelan et al 2001 etc)

• Shear-intrinsic ellipticity alignments are most problematic (Hirata & Seljak 2004) (intrinsic-intrinsic alignments can be removed with photo-zs) (Heymans & Heavens 2002; King & Schneider 2002a,b)

• Shear-intrinsic can be modelled (Heymans et al 2006; King 2006) or projected out (Joachimi & Schneider 2008)

Photometric redshifts

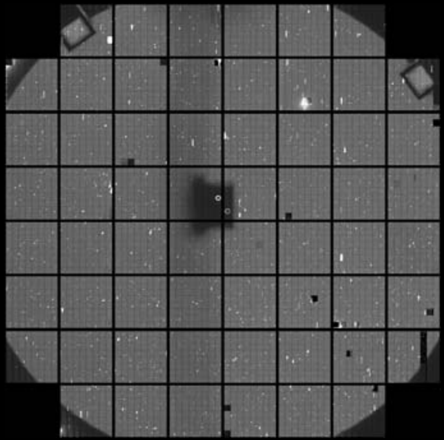
- If $|\langle z_{true} - z_{photometric} | z_{photometric} \rangle| > 0.002$, it is an important systematic for w for Euclid/JDEM
- Need to calibrate with many (~3 x 10^5) spectra (Abdalla et al 2007)
- Need good photo-zs to model and remove shear-intrinsic alignments (Bridle & King 2007)
- Reasonable priors suggest a degradation by a factor of ~2 in Euclid/JDEM Figure of Merit ($1/\Delta w_0 \Delta w_a$) from systematics (Kitching et al 2008b)



Abdalla et al 2007

Prospects: Pan-STARRS

- 7 square degree camera (1.4 Gpixels)



- First >10000 deg survey, designed for lensing
- Starting ~June 2009

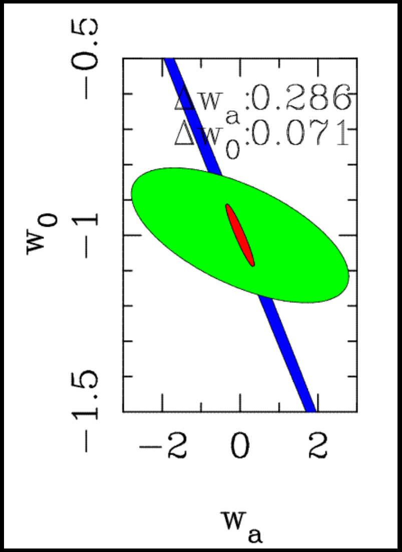
Prospects

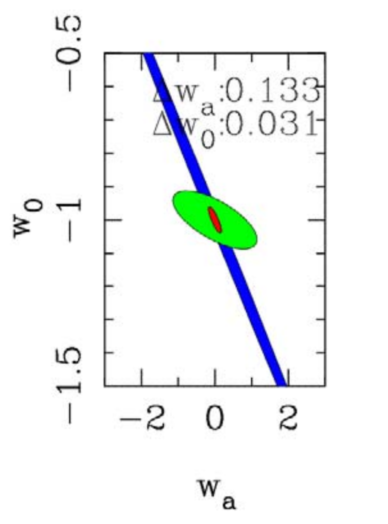
$w(a)=w_0+w_a(1-a)$

Chevallier & Polarski

- Ground: KIDS, Pan-STARRS 1, DES, HSC, LSST

- Space: Euclid/JDEM





	Area / sq deg	Median z	Gals / sq min	Start Date
KIDS	1700	~0.65	~5	2009
PS1	20000	~0.6	~4	2009
DES	5000	~0.7	7	2011
HSC	2000	>1		2013
Euclid/JDEM	20000	~0.9	40	~2016

Beyond-Einstein gravity

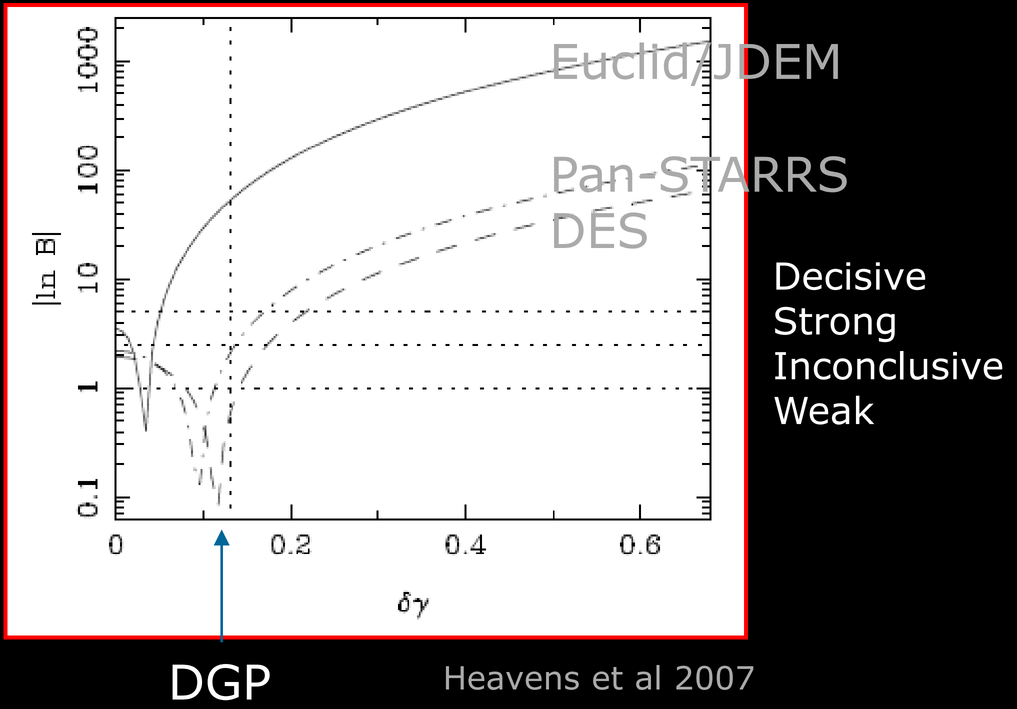
- Dynamic Dark Energy can mimic H(z), r(z) of any gravity law
- Probing both r(z) and g(z) allows lifting of this degeneracy, at least for some classes of model
- Parametrise gravity by Minimal Modified Gravity law (Linder 2005)

$$\frac{\delta}{a} \equiv g(a) = \exp\left\{\int_0^a \frac{da'}{a'}\left[\Omega_m(a')^{\gamma} - 1\right]\right\}$$

- $\gamma \cong 0.55$ (GR); $\gamma \cong 0.68$ (Flat DGP model)
- Currently no evidence against GR (CFHTLS+SDSS) Dore et al 2008
- Prospects: Bayesian Evidence ratio 3.8 (2.8σ) for Pan-STARRS 1, 63 (11σ) for Euclid/JDEM (Heavens et al 2007; Amendola et al 2007)

Bayesian evidence for branes

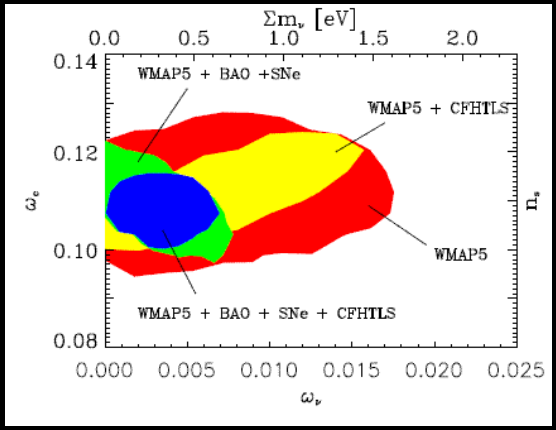
- Clear evidence of failure of GR possible



Heavens et al 2007

Neutrino masses

- Shape of power spectrum sensitive to sum of neutrino masses
- Current CFHTLS+WMAP+BAO+SN (95%) 0.03eV - 0.54eV
  - (Tereno et al 2008)



- Expect errors of 0.03eV (if mass ~ 0.5eV), to 0.07eV (if mass ~0). (factor 4 better than Planck alone) Kitching et al 2008; see also Hannestad et al 2006

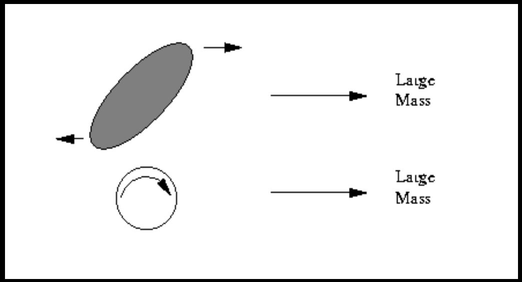
Conclusions

- Much progress since 2000: 1 → 10^2 → 10^4 sq deg
- Lensing in 3D is potentially very powerful:
  - ~1% on Dark Energy equation of state parameter
  - Sum of neutrino masses to ~0.05 eV
  - Test of braneworld gravity models etc.
- Needs:
  - Large area (tens of thousands of square degrees)
  - Depth z~1
  - Very small telescope distortions
  - Good photometric redshifts
  - Good understanding of shear-intrinsic alignments

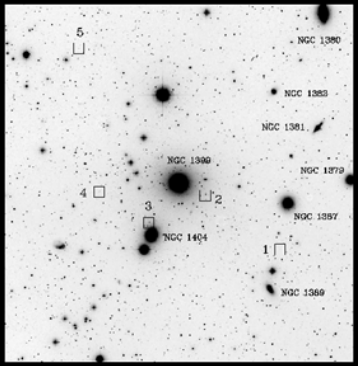
Appendix: Intrinsic alignments

$$\langle e\, e^* \rangle = \langle \gamma\, \gamma^* \rangle + \langle e_I e_I^* \rangle + \langle \gamma\, e_I^* \rangle + \langle e_I\, \gamma^* \rangle$$

- $\langle e_I e_I^* \rangle$ Theory: Tidal torques



Heavens, Refregier & Heymans 2000, Croft & Metzler 2000, Crittenden et al 2001, Catelan et al 2001 etc



Brown et al 2000

Downweight/discard pairs at similar photometric redshifts

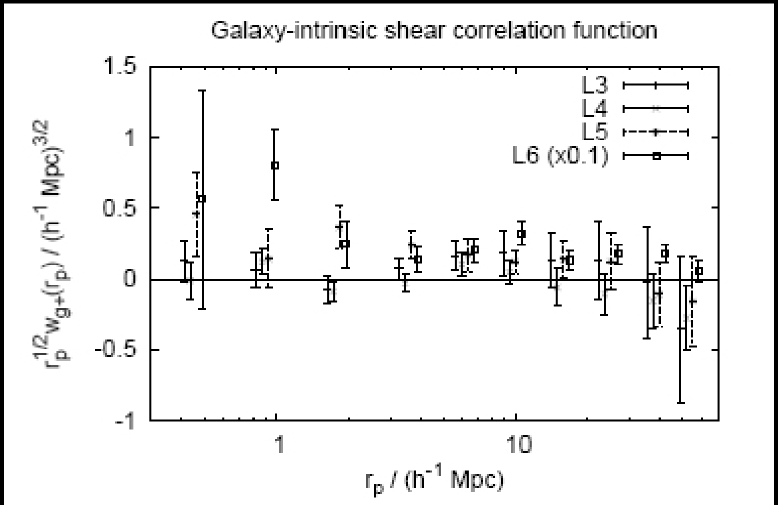
(Heymans & Heavens 2002; King & Schneider 2002a,b)

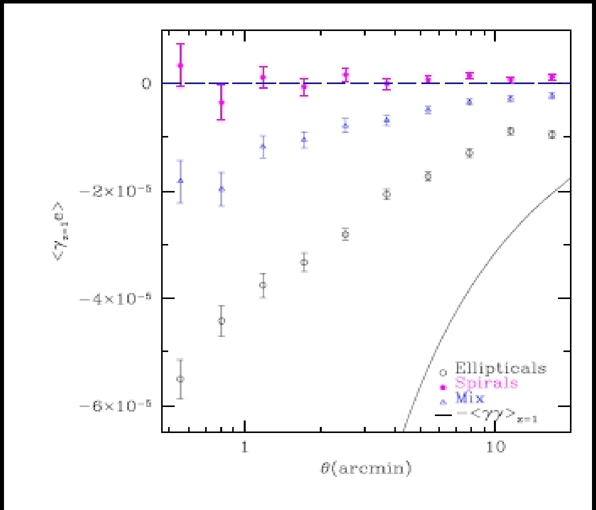
REMOVES EFFECT ~COMPLETELY

Shear-intrinsic alignments $\langle \gamma\, e_I^* \rangle$

Hirata & Seljak 2004

- Tidal field contributes to weak shear (of background)
- Tidal field could also orient galaxies (locally) (Hirata and Seljak 2004; Mandelbaum et al 2005, Trujillo et al 2006, Yang et al 2006, Hirata et al 2007)



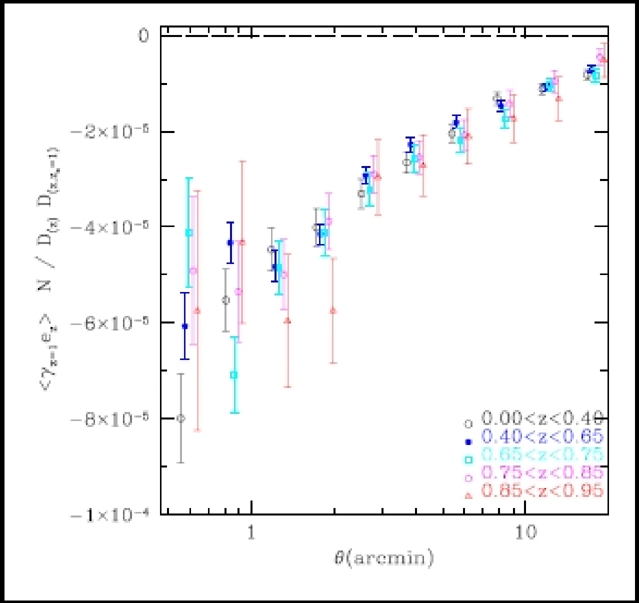


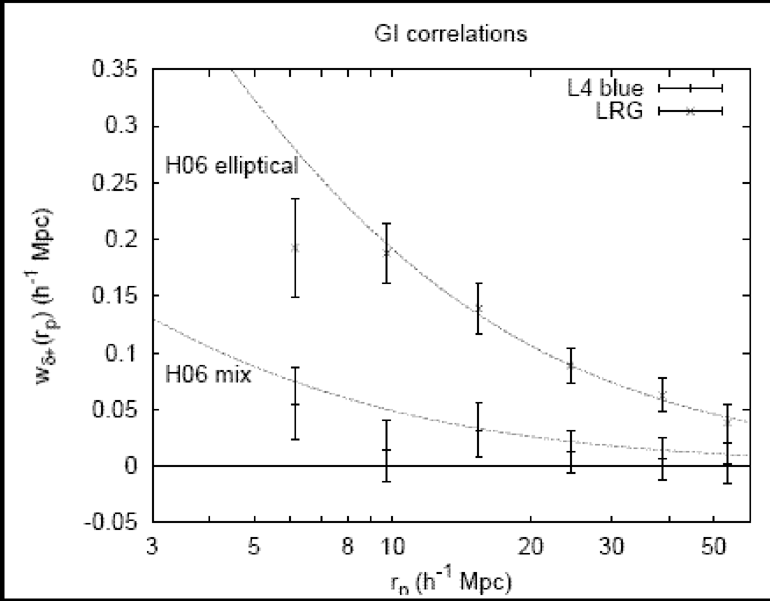
SDSS: Mandelbaum et al 2005 Simulations: Heymans et al 2006

Expect 5-10% contamination

Removing shear-intrinsic ellipticity contamination

- Expect signal to have different redshift dependence from weak lensing ⇒ model it





Heymans et al 2006; King 2006; Hirata & Seljak 2004

Hirata et al 2007

- Or project it out (with loss of S/N) Joachimi & Schneider 2008