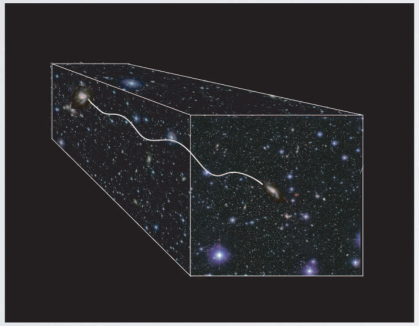
COSMIC SHEAR

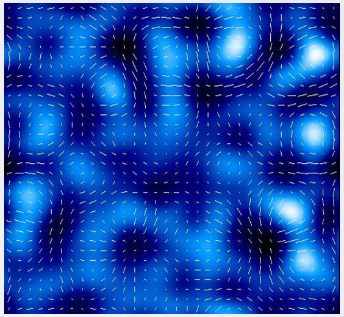
Alan Heavens
Institute for Astronomy
University of Edinburgh
afh@roe.ac.uk
Benasque
18 February 2011

GRAVITATIONAL LENSING

- Coherent distortion of background images by gravity

- Shear, magnification, amplification





Jain & Seljak

- Independent of the dynamical state of matter and the nature of matter

- Don't need to understand galaxies...

- ...or maybe we do

COSMOLOGICAL LENSING

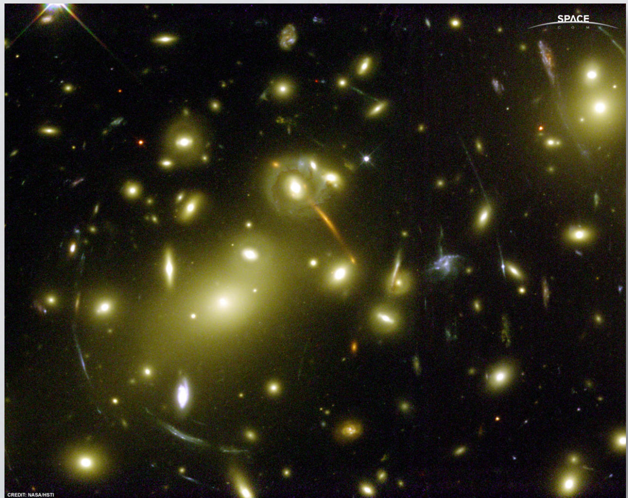
- For small scalar perturbations

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

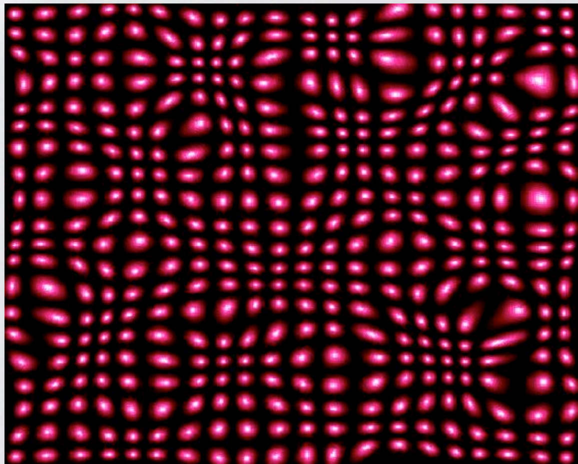
- In terms of conformal time [dη=dt/R(t)] (flat)

$$\frac{d^2\mathbf{x}}{d\eta^2} = -\frac{1}{c^2}\nabla(\Phi + \Psi) \quad [\mathbf{x} = r(\theta_x, \theta_y)]$$

If no anisotropic stress, and GR, $\Phi=\Psi$

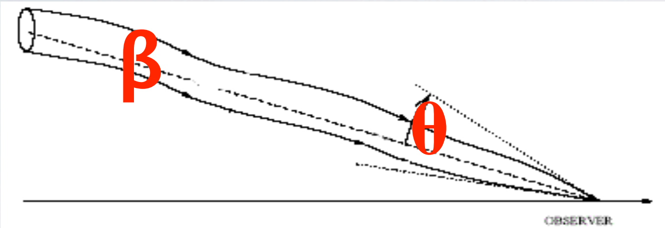


A2218 HST


Refregier

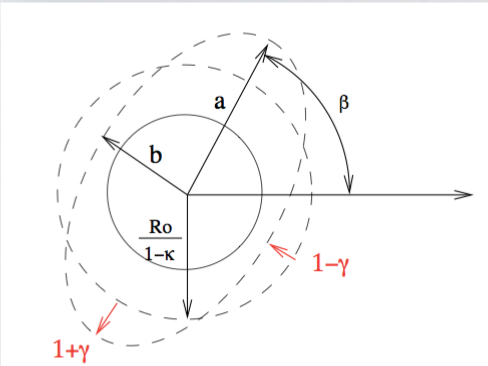
AMPLIFICATION, MAGNIFICATION & SHEAR

Cosmological lensing potential (Born approximation):



$$\phi(\mathbf{r}) = \frac{1}{c^2} \int_0^r dr' \, \frac{S_k(r-r')}{S_k(r)S_k(r')} \, [\Phi(\mathbf{r}) + \Psi(\mathbf{r})]$$

Mapping is described by an amplification matrix:



$$A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \phi_{ij}$$

Decompose into convergence and shear

$$A_{ij} = \begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix} + \begin{pmatrix} -\gamma_1 & -\gamma_2 \\ -\gamma_2 & \gamma_1 \end{pmatrix}$$

$\gamma = \gamma_1 + i\gamma_2$ is a spin-weight 2 field (cf polarisation)

Reduced shear $\quad g = \dfrac{\gamma}{1-\kappa}$


10 times larger distortion than we want to measure (to 1% accuracy)

3D MATTER DENSITY RECONSTRUCTION

- Taylor 2001

Can invert lensing potential:

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

to

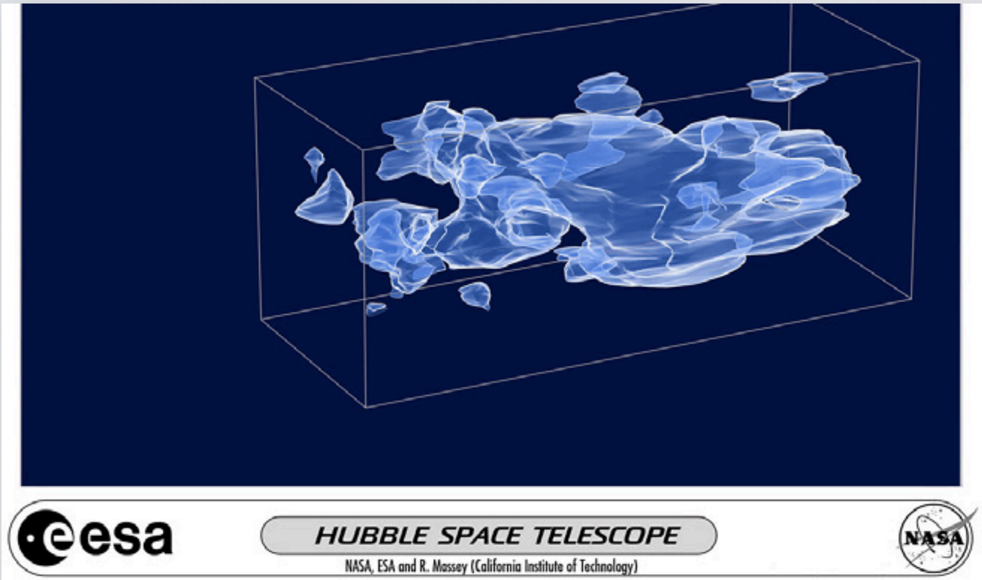
$$\Phi(\vec{r}) = \frac{c^2}{2} \frac{\partial}{\partial r} \left[r^2 \frac{\partial}{\partial r} \phi(\vec{r}) \right]$$

and hence to the mass overdensity:

$$\delta(\vec{r}) = \frac{a(t)c^2}{3H_0^2\Omega_m} \nabla_{3D}^2 \left\{ \frac{\partial}{\partial r} \left[r^2 \frac{\partial}{\partial r} \phi(\vec{r}) \right] \right\}$$

3D RECONSTRUCTION: COSMOS FIELD

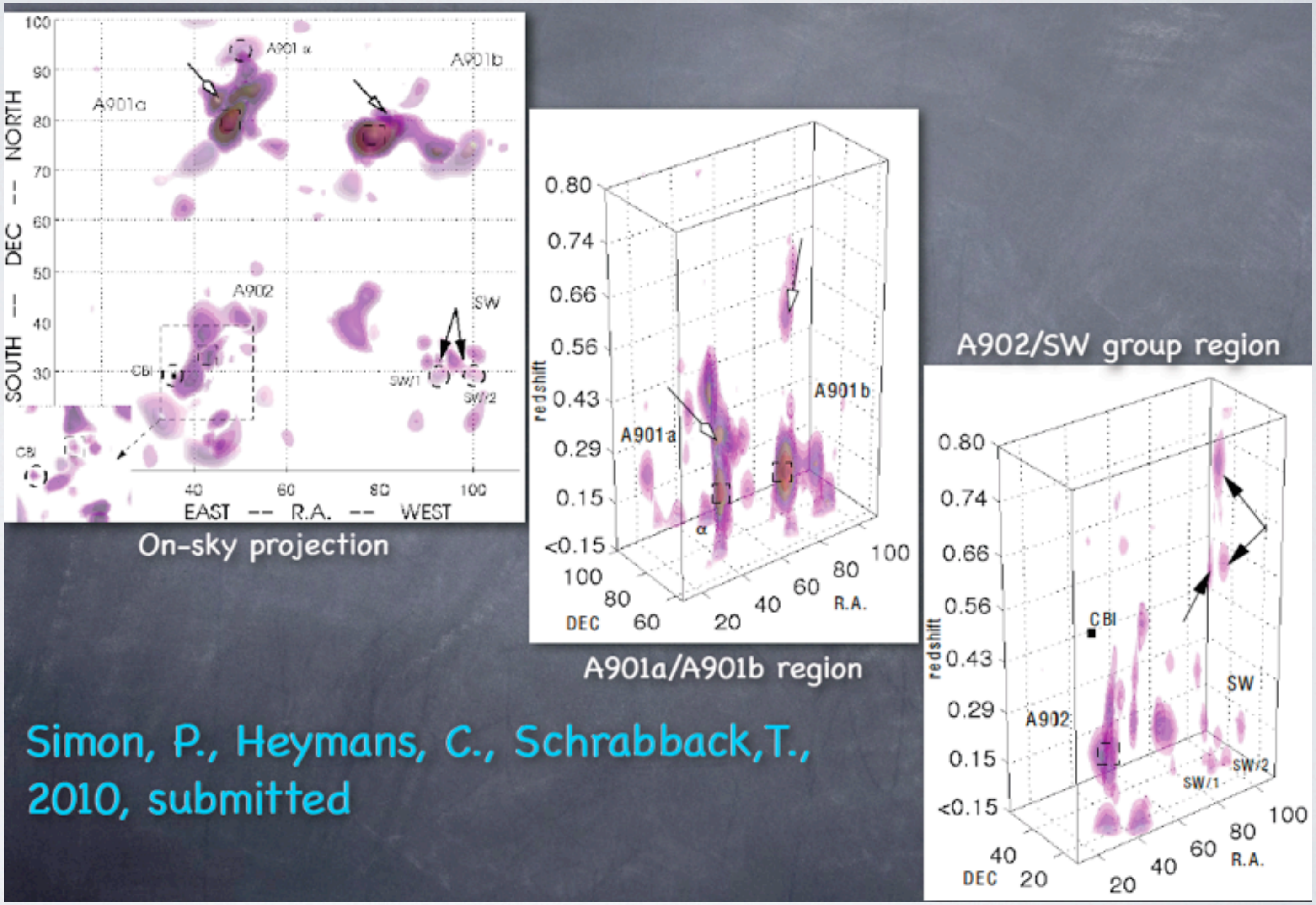
- COSMOS data (Massey et al 2007)



Beware! poor resolution in *z* (200 Mpc)

Latest from HST STAGES programme

- Very noisy
- Wiener filtered maps in 3D (Simon et al 2010)



SENSITIVITY TO COSMOLOGY

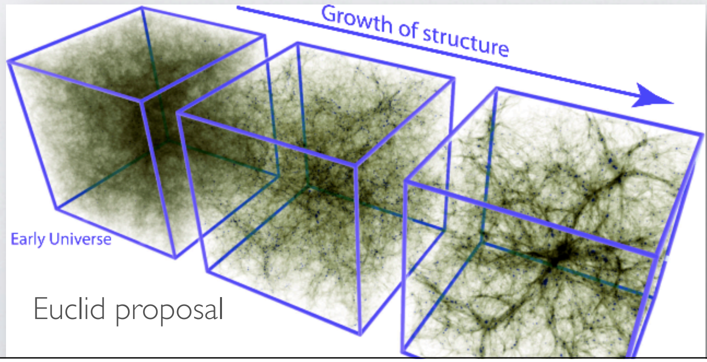
$$\phi(\mathbf{r}) = \frac{1}{c^2} \int_0^r dr' \, \frac{S_k(r - r')}{S_k(r) S_k(r')} \, [\Phi(\mathbf{r}) + \Psi(\mathbf{r})]$$

- Observables: shear, magnification, redshift
- Cosmic Shear statistical properties depend on

a) how clumpy the Universe is, and its *growth rate*, i.e. $P_\Phi(k,t)$ (GR) or $P_{\Phi+\Psi}(k,t)$.

b) the source distances, hence the *distance-redshift relation*, r(z)

c) The *gravity law* (e.g. modified Poisson equations)



DARK ENERGY

- Measurable Effects of Dark Energy:
  - Distance-redshift relation

$p_q = w(a)\ \rho_q c^2$

$$r = \int_0^z dz' \, \frac{c}{H(z')}$$

where the Hubble parameter is given by

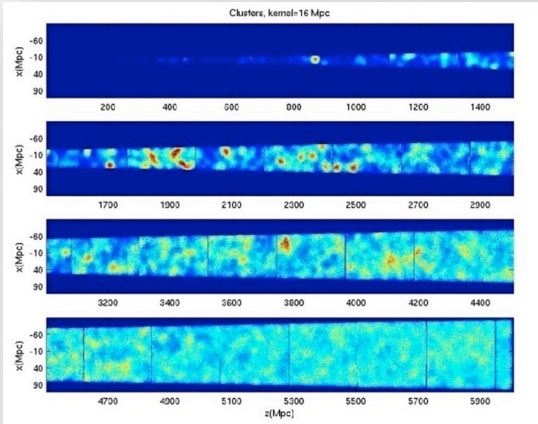
$$H^2(a) = H_0^2 \left[\Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_q \exp\left(3 \int_1^a \frac{da'}{a'} \left[1 + w(a') \right] \right) \right]$$

  - Growth rate of perturbations (via H(a))

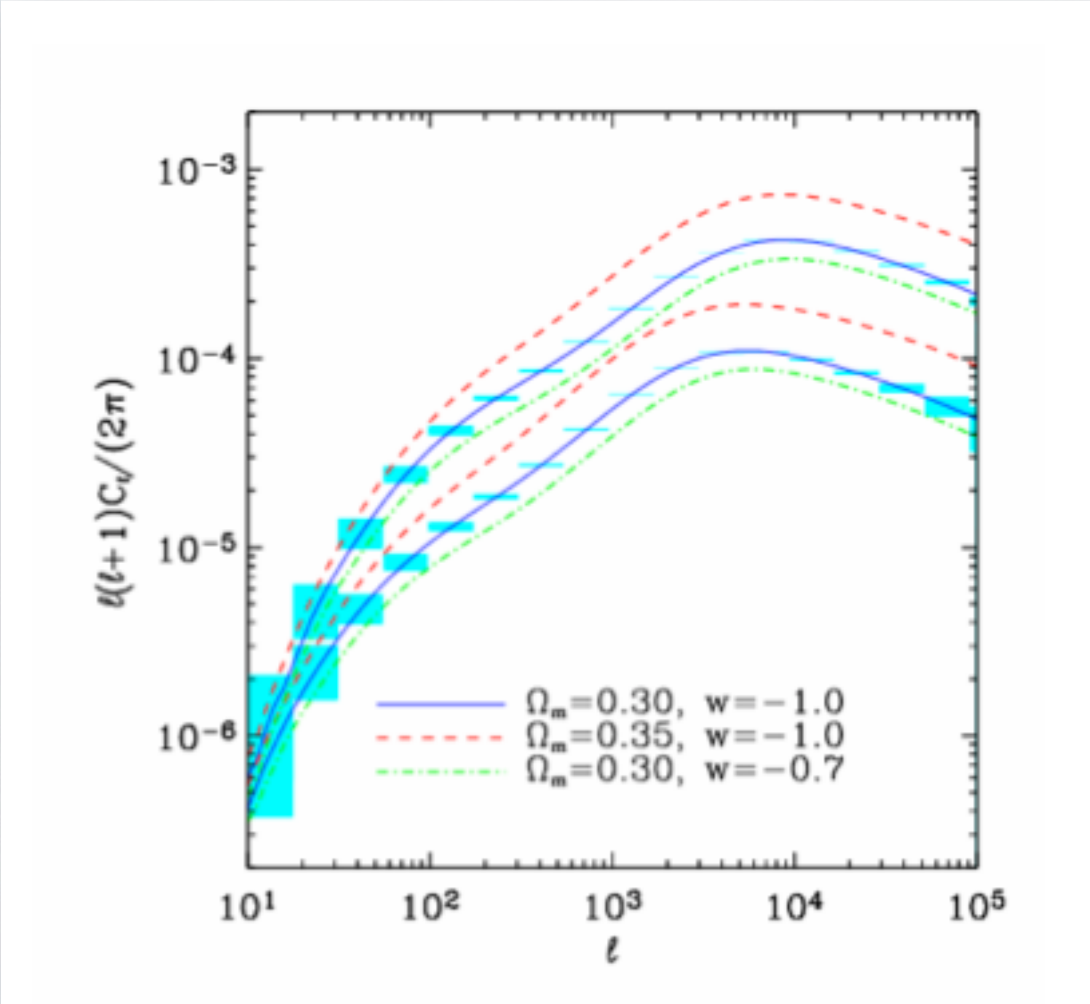
Assuming DE is smooth,

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G \rho_m \delta = 0$$

Assumes GR. δ = fractional mass overdensity



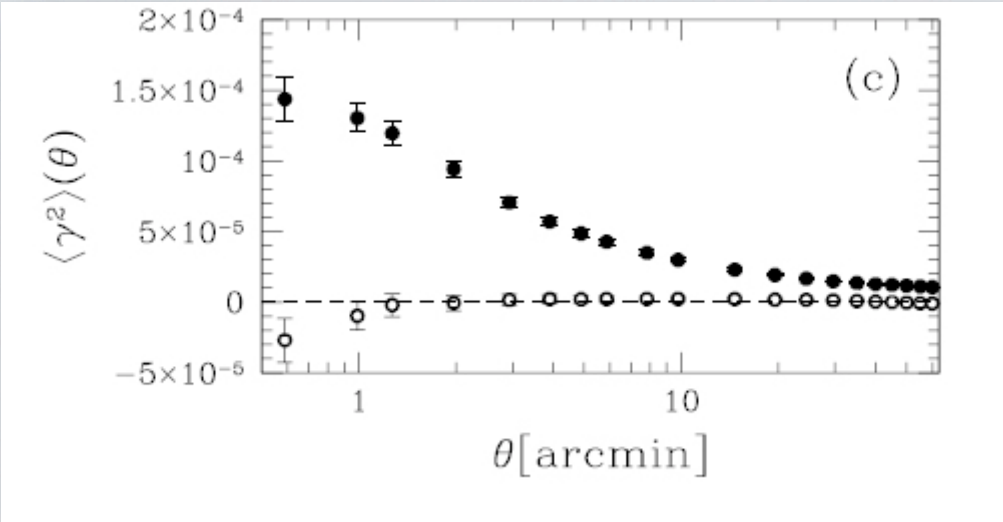
CONVERGENCE POWER SPECTRUM

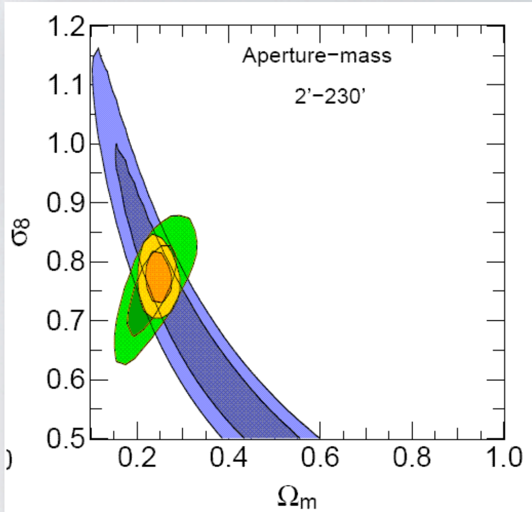


- From Euclid Yellow Book

RECENT RESULTS: CFHTLENS AND COSMOS

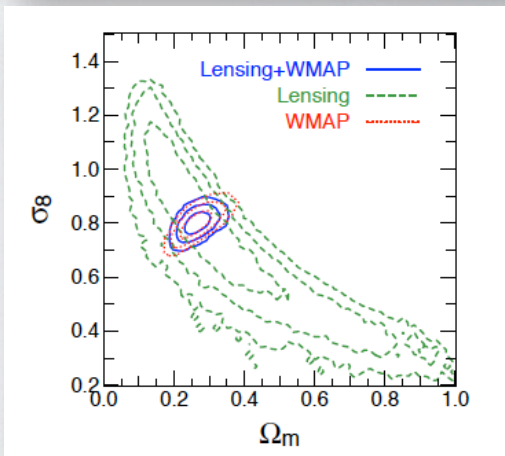
New CFHTLenS results soon





100 sq deg; median z=0.8

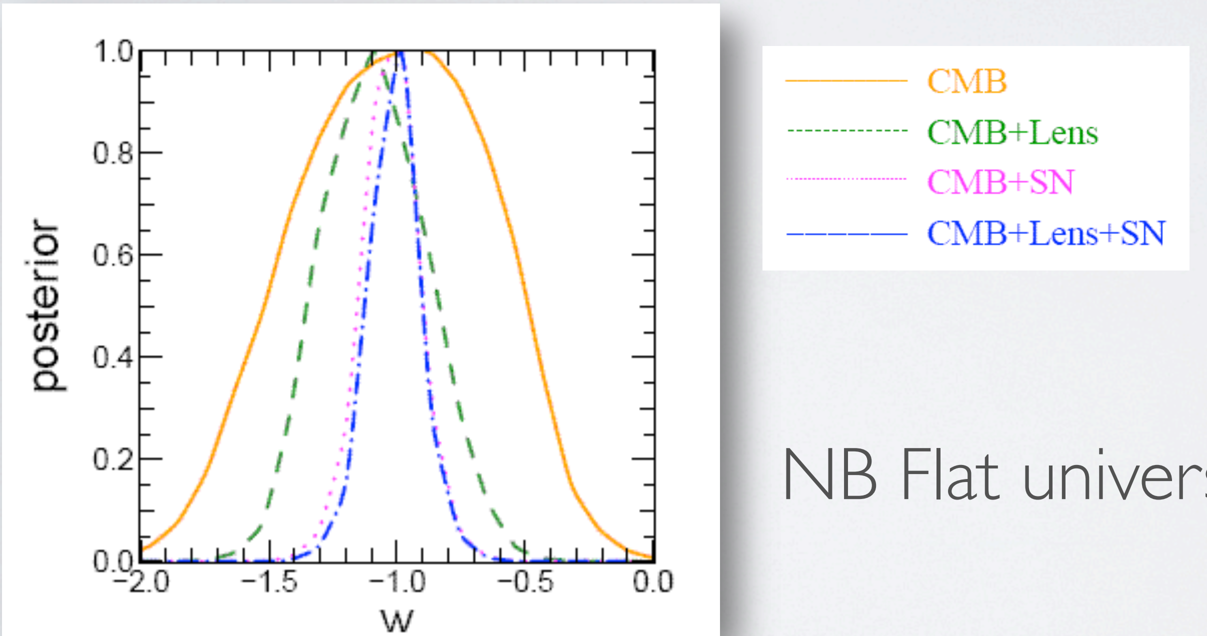
Hoekstra et al 2005; Benjamin et al. 2007; see also Semboloni et al 2005



COSMOS: Schrabback et al 2010

DARK ENERGY PROPERTIES

- CFHTLenS: -1.18 < w < -0.88 (95%) [$p=w\rho c^2$]



Kilbinger et al (2009)

NB Flat universe assumed

MODIFIED GRAVITY

- Alters H(z)
- Alters growth rate of matter perturbations (Poisson equation)
- Alters light-matter relationship $\Phi + \Psi \leftrightarrow \delta$

- Different H(z) can *always* be mimicked by GR+DE

MODIFIED GRAVITY OR DARK ENERGY?

- Modified Gravity theory will give a certain *H(a)*.
- We can *always* find 'Dark Energy' to mimic this in GR:

Friedmann:

$$H^2 + \frac{k}{a^2} = \frac{8\pi G\rho}{3}$$

and

$$\frac{d}{da}\left(\rho_q a^3\right) = -p_q a^2 = -w(a)\rho_q a^2$$

- Solve for any given *H(a)*:

$$w(a) = -\frac{1}{3}\frac{d}{d\ln a}\ln\left[\frac{1}{\Omega_m(a)} - 1\right]$$

- which depends on *H(a)* via the critical density

$$\rho_{crit}(a) = \frac{3H^2(a)}{8\pi G}$$

Probes of H(z) alone (e.g. supernovae) cannot unambiguously distinguish GR from modified gravity

- *Can the growth rate and light-matter relation also be mimicked by GR and DE?*

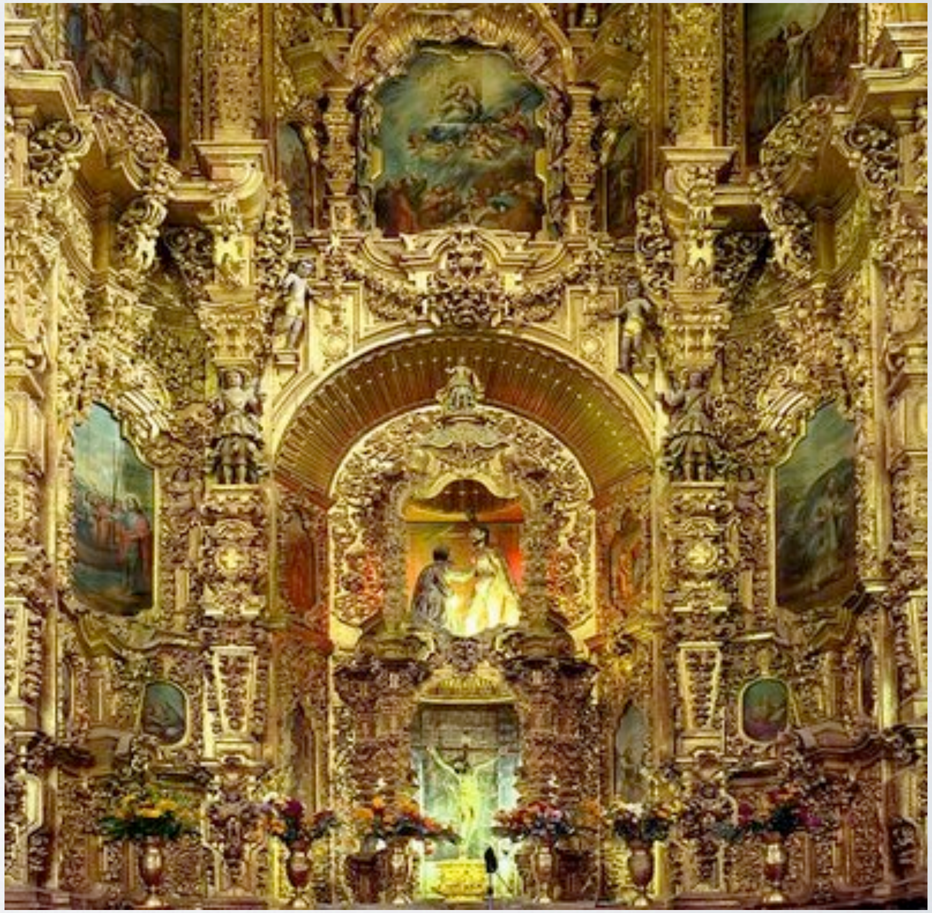
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}(T_{\mu\nu} + U_{\mu\nu})$$

Yes? (C. Skordis, W. Hu)

Then how do we decide between DE and MG?

Aesthetic judgement?

Just too baroque...



MODIFIED G/POISSON EQUATIONS

- Generically Φ and Ψ are different. Formally we can define the *gravitational slip*, by (Maybe not the full story - see Wayne Hu's talk)

$$\Psi(k,a) = [1 + \varpi(k,a)]\,\Phi(k,a)$$

Daniel et al 2009

- and the change to the effective G by

$$-k^2\Phi_{\mathbf{k}} = 4\pi G Q(k,a)\, a^2 \rho_m \delta_{\mathbf{k}}$$

- The sum Ψ+Φ obeys

$$-k^2(\Psi + \Phi)_{\mathbf{k}} = (2Q + \varpi)\frac{3H_0^2\Omega_m}{2a}\delta_{\mathbf{k}}$$

GR: Q=1; $\varpi = 0$

- e.g. Flat DGP:

$$\begin{aligned} k^2\Phi_{\mathbf{k}} &= -4\pi G a^2\left(1 + \frac{1}{3\beta}\right)\rho_m\delta_{\mathbf{k}} \\ k^2\Psi_{\mathbf{k}} &= -4\pi G a^2\left(1 - \frac{1}{3\beta}\right)\rho_m\delta_{\mathbf{k}} \end{aligned}$$

$$r_c^{-1} = H_0(1 - \Omega_m)$$

$$\beta = 1 - 2r_c H\left(1 + \frac{\dot{H}}{3H^2}\right)$$

CURRENT MEASUREMENTS

- Reyes et al 2010 (astroph 1003.2185)
- Galaxy-galaxy lensing by 70,000 LRGs from the SDSS ($\Psi+\Phi$):
- LRG clustering: Galaxy-galaxy clustering
- Measurement of the growth rate/bias from LRGs (Φ)
- Form bias-independent combination

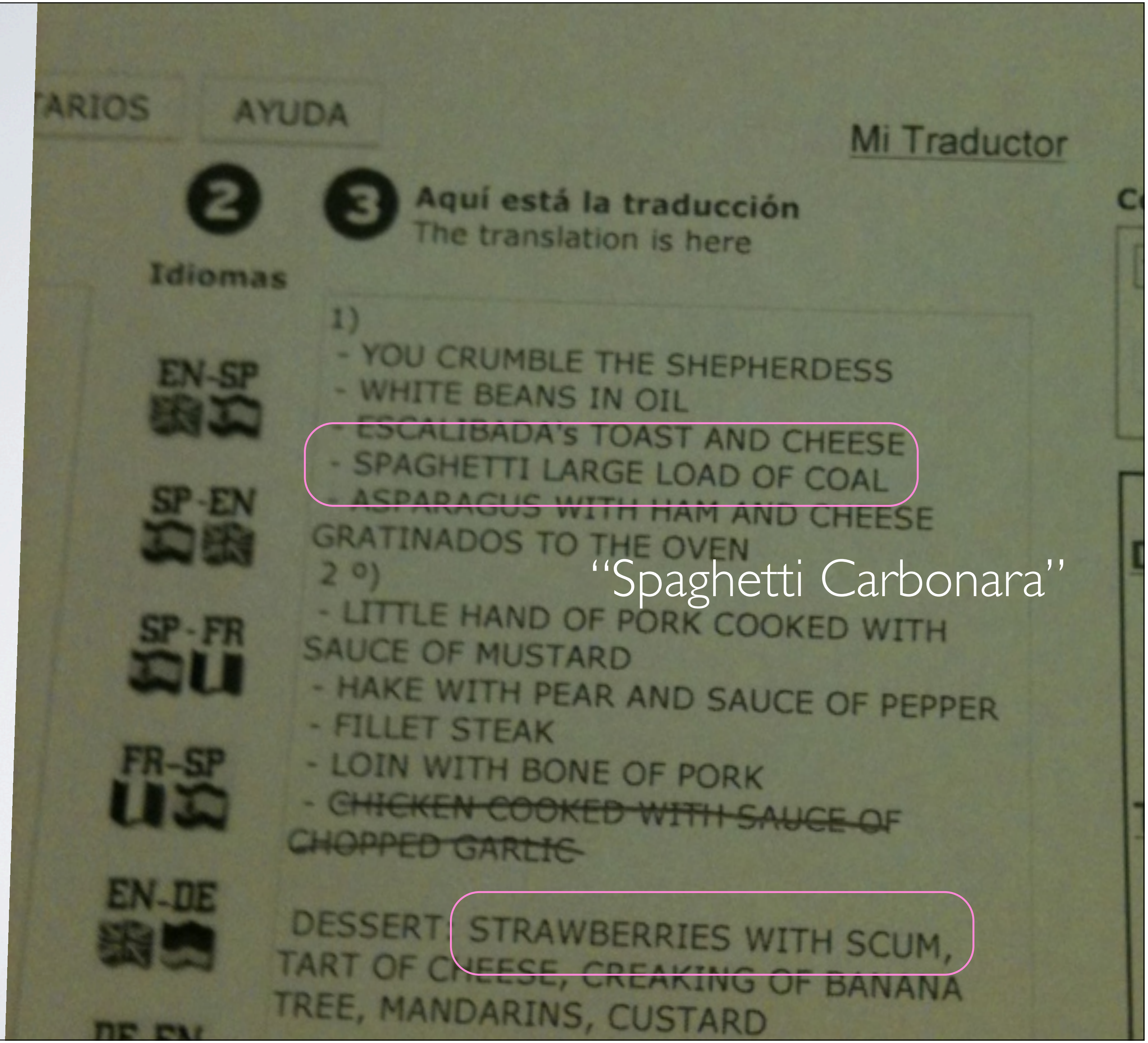
$$E_G(R) = \frac{1}{\beta} \frac{\Upsilon_{\rm gm}(R)}{\Upsilon_{\rm gg}(R)}.$$

- GR: E_G=0.41±0.03; f(R): 0.33, TeVeS: 0.22: Observed 0.39±0.07

UNSOLVED PROBLEMS

- Classify them:
    - Problems we can solve, perhaps with a Turing Observatory, or massive computers
    - Problems we may never be able to solve
- Strategy:
    - Model
    - Avoid

Things we don't under-stand



UNSOLVED PROBLEMS

- Classify them:
  - Problems we can solve, perhaps with a Turing Observatory, or massive computers
  - Problems we may never be able to solve
- Strategy:
  - Model
  - Avoid

SHAPE MEASUREMENT

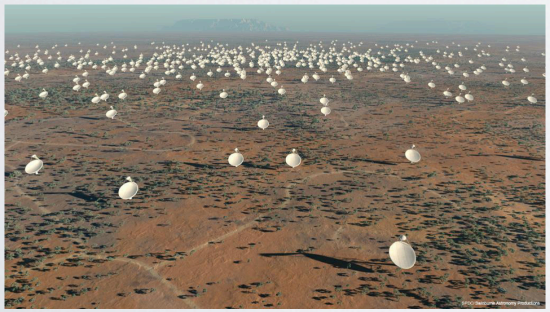
Galaxy | Sheared (here g=0.2) | Blurred | Pixellised | Noise

- Shear is only ~0.03
- Blurring kernel ~ size of typical galaxies
- Many galaxies have only a handful of pixels

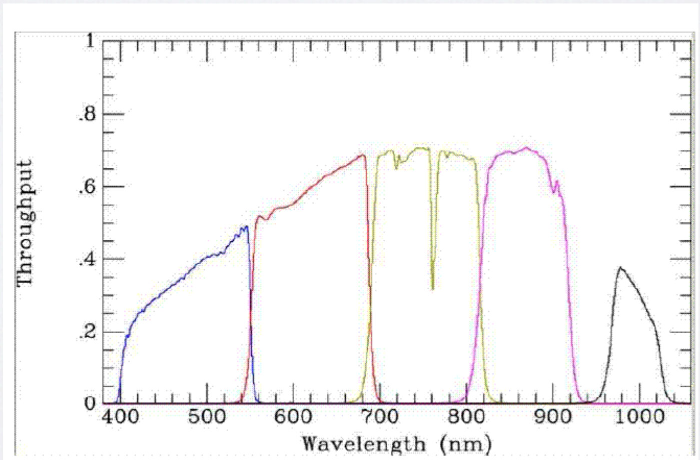
- Lensfit (Miller et al 2007): systematic uncertainties of ~0.0001 in g
- *Kernel estimated from stars, which have different colour*
- *PSF may be undersampled*

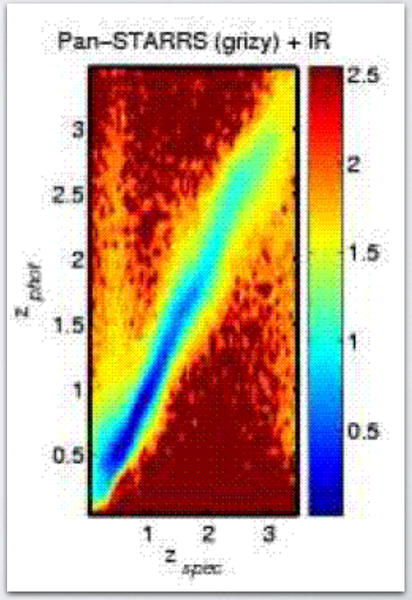
DISTANCE ESTIMATION

- Lensing surveys need large depth (so lensing signal is measureable), and large volume (each galaxy has very low S/N)
- Spectroscopic survey impractical for now (Turing)
- Use photometry, and estimate redshift from colours
- Imperfect: errors~0.05(1+z); outliers. *Can we improve?*



SKA





Abdalla et al 2007

INTRINSIC ALIGNMENTS

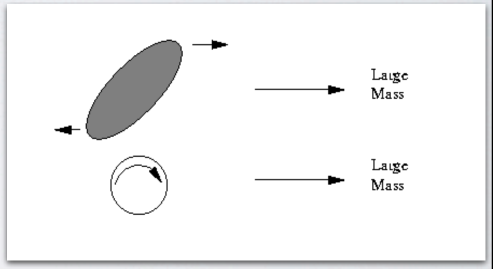
- Lensing measures the *ellipticity* of the image, which is the source ellipticity modified by the effect of shear: $e = \gamma + e_s$

- Dispersion in e_s is ~0.3; shear is ~0.02

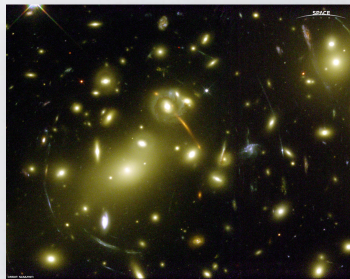
- Two-point statistics:

$$\langle e_1 e_2^* \rangle = \langle \gamma_1 \gamma_2^* \rangle + \langle \gamma_1 e_{s2}^* \rangle + \langle e_{s1} \gamma_2^* \rangle + \langle e_{s1} e_{s2}^* \rangle$$

- IG GI II



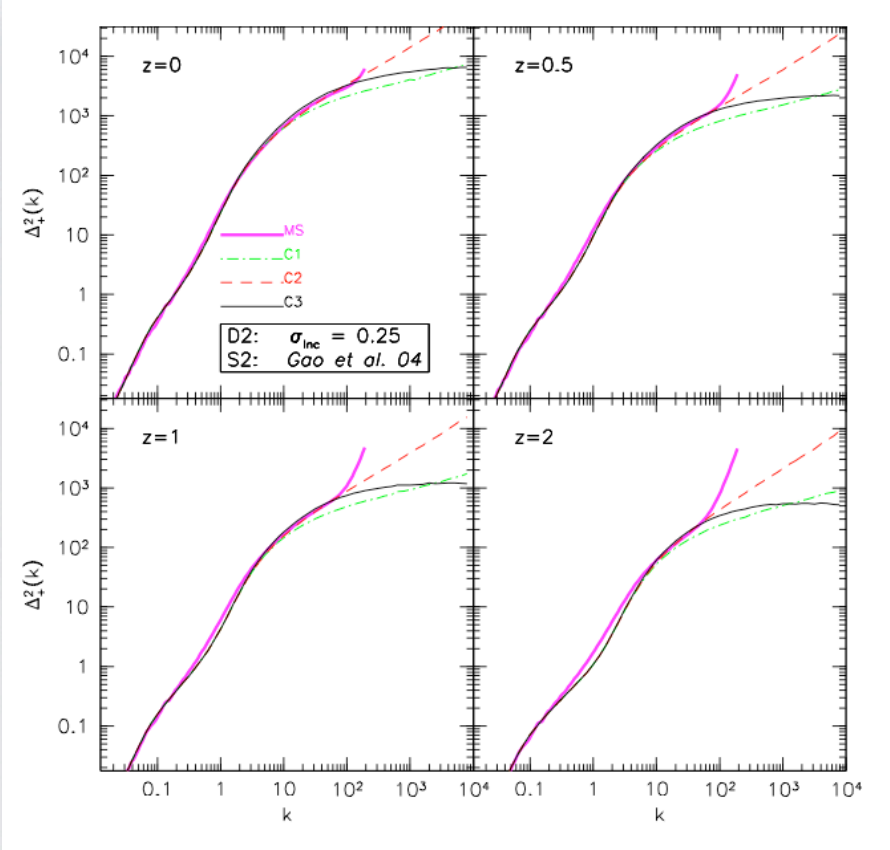
- Tidal torques (e.g. Heavens et al 2000, Croft & Metzler 2000,...) give an II term, easily removed by downweighting close pairs



- GI (Hirata & Seljak 2004) term is more problematic. *Modelling possible, but little known*. Alternative is to project out the signal (nulling; Joachimi & Schneider 2008, 2009)

NONLINEAR POWER SPECTRUM

- Lensing needs to probe the nonlinear regime in order to have high sensitivity to cosmology
- Beyond some wavenumber, theoretical uncertainties become large (e.g. baryon physics)
- *What is this wavenumber?*
- *What happens in nonlinear regime in clustering DE models and modified gravity models?* (e.g. Heitmann et al 2009, Schmidt 2009, Schmidt et al 2009, Chan and Scoccimarro 2009)

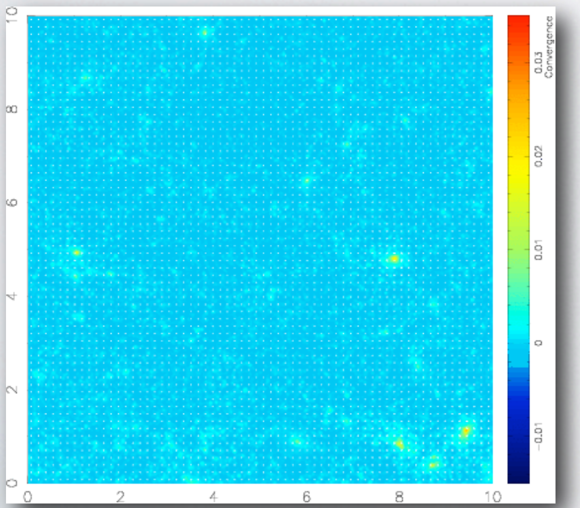


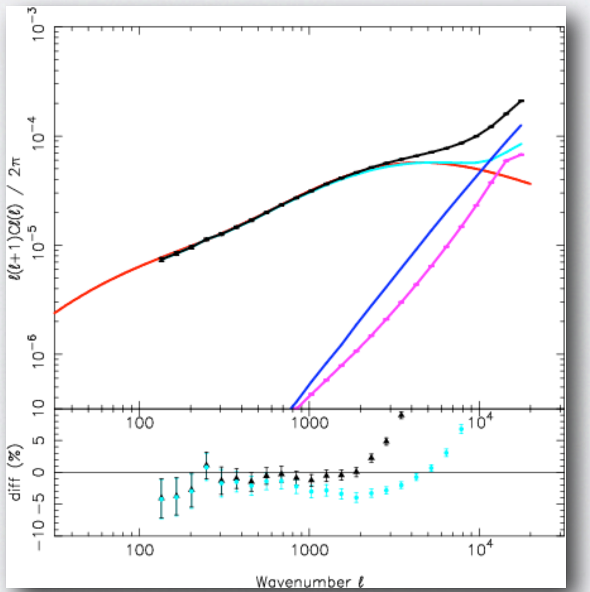
Giocoli et al 2010

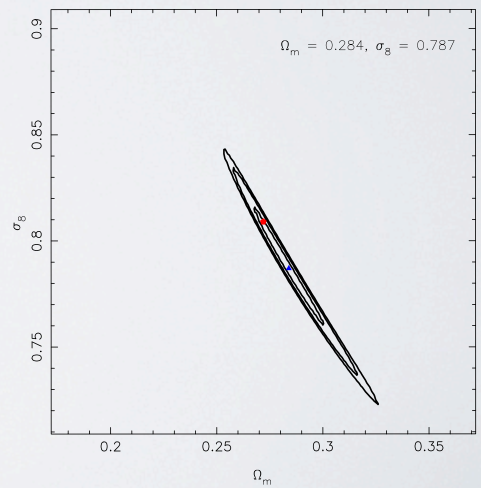
COVARIANCE PROPERTIES

- Much of the signal comes from the nonlinear regime, where modes are coupled

- Data analysis requires (at least) the covariance of the modes - needs simulations







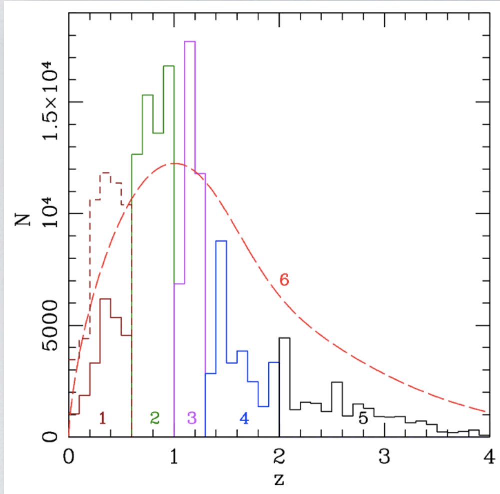
Kiessling, Heavens, Taylor, Joachimi (2011)

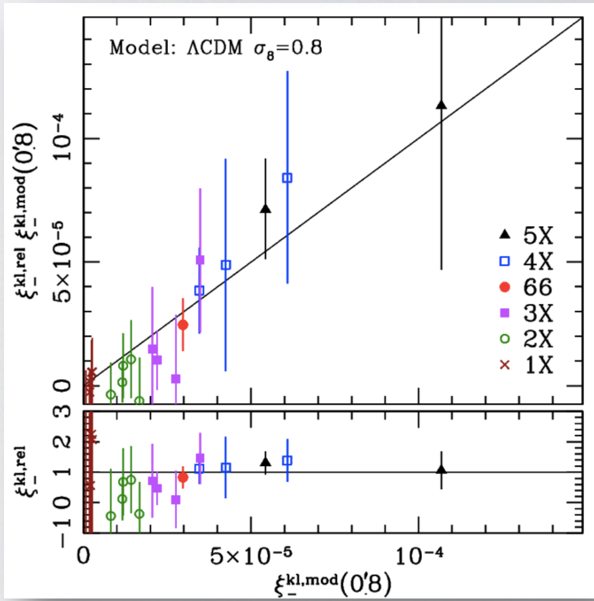
MITIGATION STRATEGIES

- **Shape measurement:** good optical design. Bayesian analysis.
  - Turing solution: observe for a long time from space, with small pixel size, and narrow band
- **Photo-zs:** ???
  - Turing solution: spectroscopic survey (optical/IR or SKA)
- **Intrinsic alignments:** avoid the problem
- **Uncertainties in P(k):** avoid the problem
- Systematics may degrade errors by a factor ~ 2 (Amara & Refregier 2008, Kitching et al 2008)

TOMOGRAPHY Hu (1999)

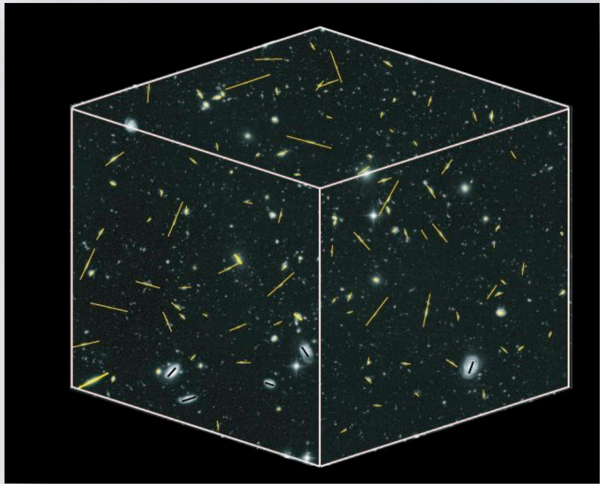
- With photo-zs: bin galaxies according to their estimated redshift ('tomography')
- Cross-correlate different bins
- COSMOS (Schrabback et al 2010) shows expected scaling of lensing signal with redshift
- Better control of systematic errors (e.g. II, GI)
(e.g. Bridle and King 2007)
- Remove II by avoiding auto-correlations





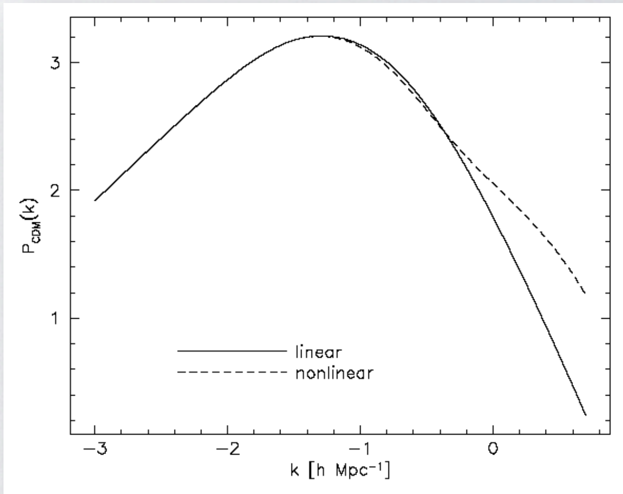
ALTERNATIVE: 3D LENSING (Heavens 2003)

- Galaxy 'shape' field is a very noisy, 3D point process sample of the underlying radially-smoothed shear field



- 3D analysis has better statistics

- 3D shear power spectrum in radial (k) and angular wavenumber (l): can avoid the highly nonlinear regime where baryon physics is uncertain (Kitching, Heavens, Miller 2010)



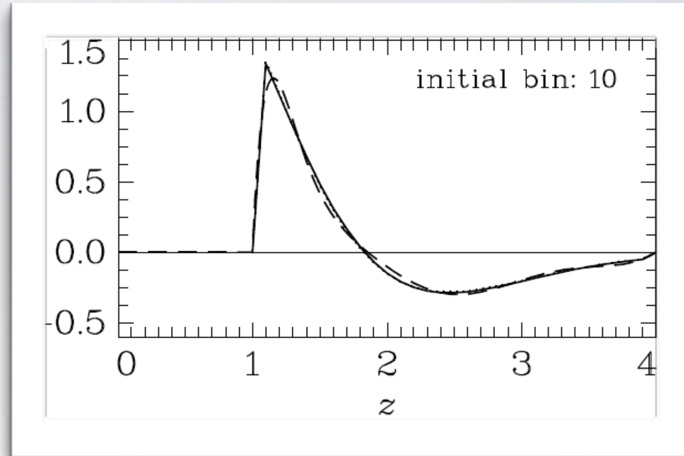
BACK TO CLEAN PHYSICS: NULLING

- Remove contaminating GI cross-term by cross-correlating with weighted sums of the shear in different tomography bins
  (Joachimi & Schneider 2008, 2009, Heavens & Joachimi 2010)

- We know the z-dependence of the lensing signal, so can choose weights to span the null space which project the GI to zero

- Reduce contamination to ~ zero

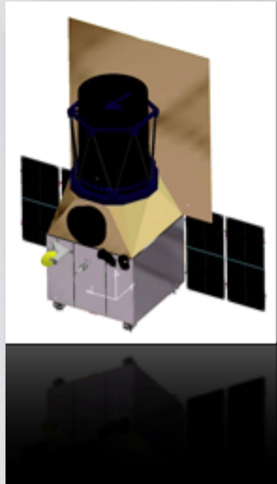
- ~factor 2 hit on S/N

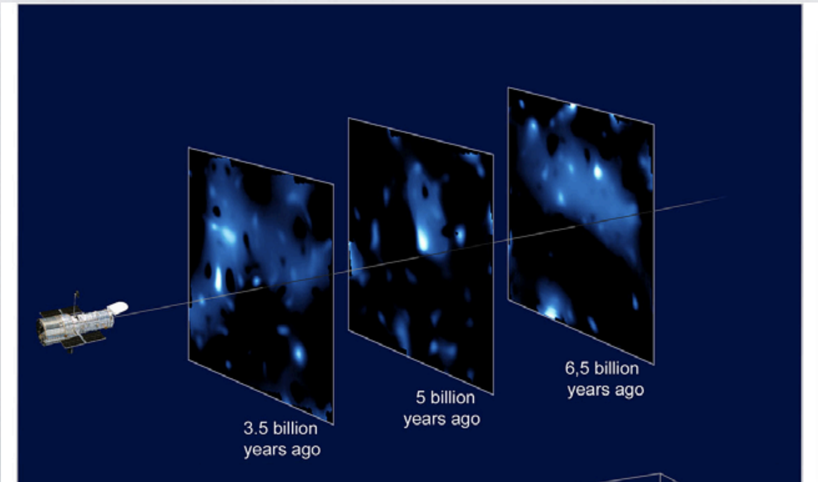


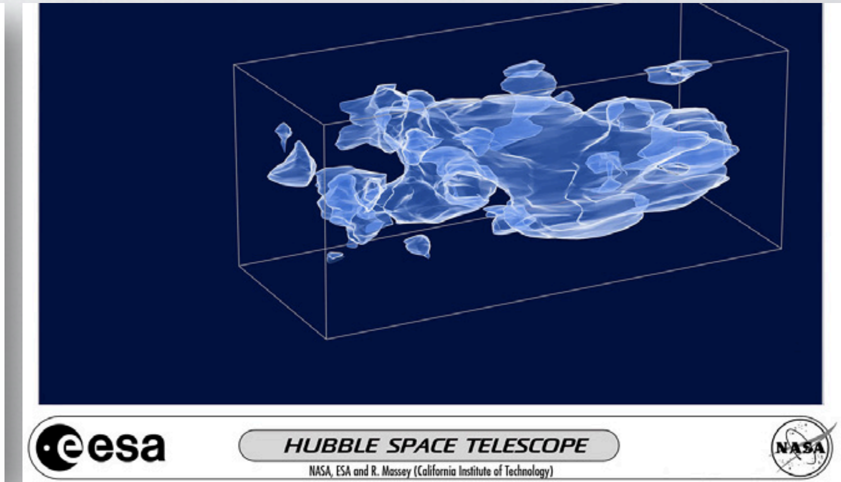
Joachimi & Schneider 2008

FUTURE EXPERIMENTS

- Euclid (ESA)
  - Cosmic Vision 2017
  - Imaging + spectroscopy
  - 20,000 sq deg, median z=0.9, optical+IR
  - Ideal for Cosmic Shear, also BAOs
  - First space-based experiment designed for lensing
- WFIRST (NASA)



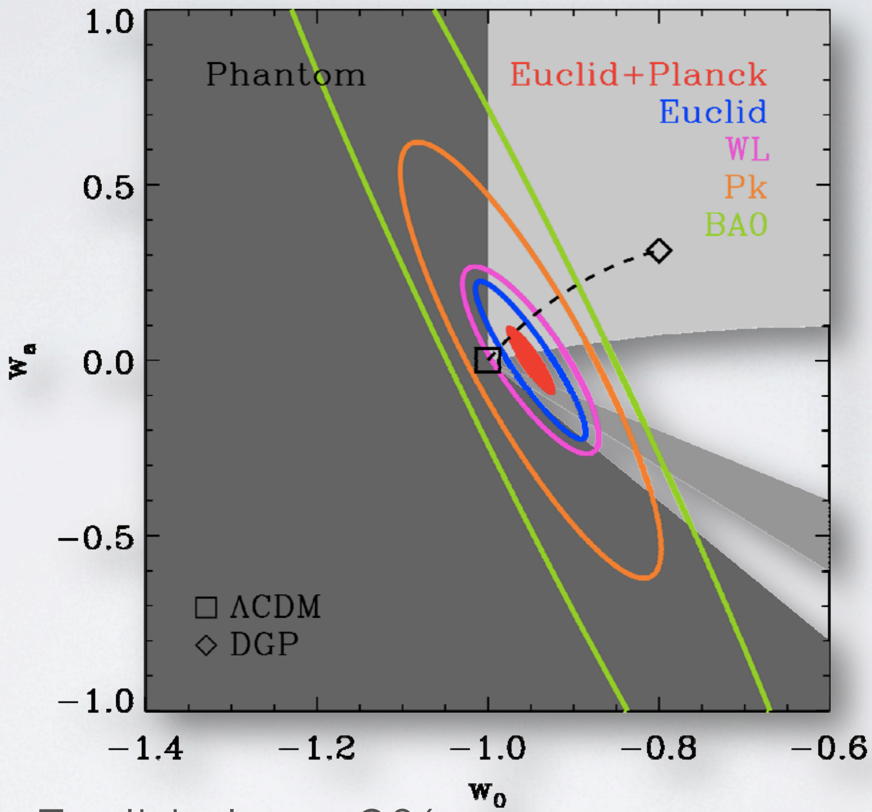




PROSPECTS FOR DARK ENERGY

- Forecasts

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

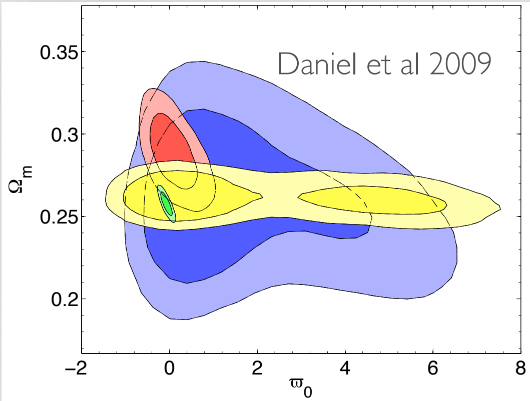


Euclid alone: 2% accuracy on w at z=0, 0.2 on w_a

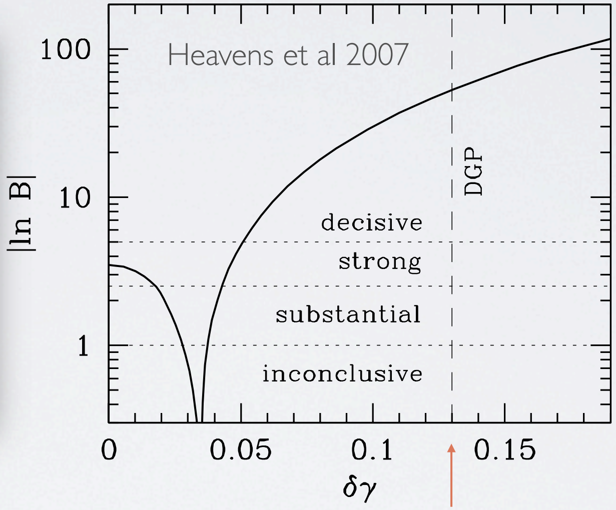
Caveats: nonlinear clustering; DE clustering

PROSPECTS FOR DARK GRAVITY

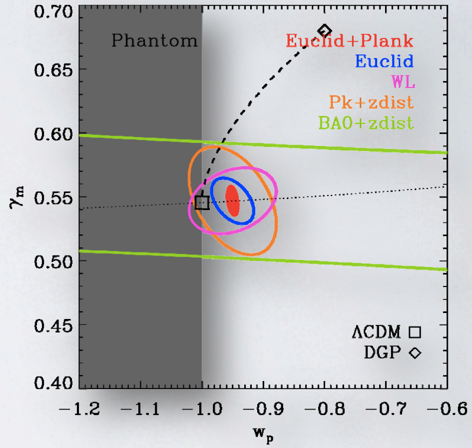
Compare GR with Dark Energy with a modified gravity model *with the same expansion history.* Growth rate 0.55 (GR) 0.68 (Flat DGP)



WMAP +WL (now)
Planck
Planck+Euclid



DGP



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

Prospects very good.

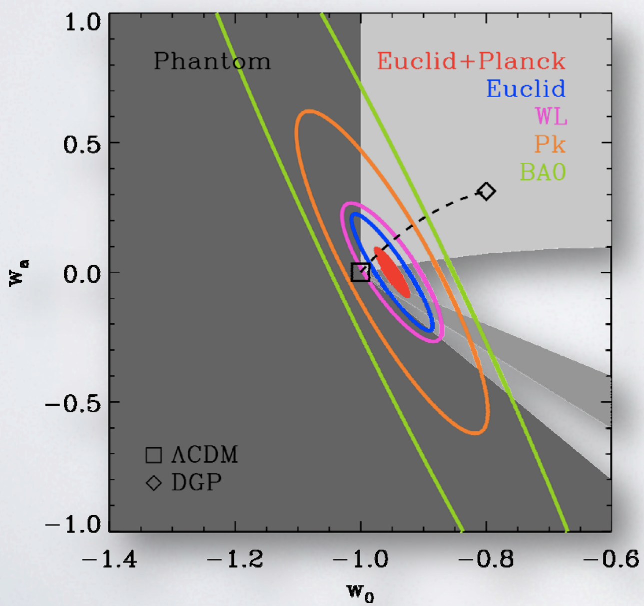
Caveat - coupled DE-matter models can alter growth rate (Simpson et al 2010)

CHALLENGE: HOW TO GO BEYOND LCDM

- *How do we explore Dark Energy and Dark Gravity?*
- Full w(z) is too challenging to obtain
- Full $\Phi(k,t), \Psi(k,t)$ is far too challenging
- Regularising the problem may exclude theory space.

OBSERVATION TO THEORY

- *What should observations report to theoreticians?*
- Ideally (?) H(z), (statistical properties of) $\Phi(k,t), \Psi(k,t)$
- Observations often constrain some different things much better



Here, w at a pivot redshift ~0.5 is much better constrained than w_0 and w_a individually.

So far, nothing to disturb LCDM

Radiator in Raul and Licia's flat

CONCLUSIONS

Lensing can probe a variety of phenomena of fundamental interest, such as

- The properties of Dark Matter, neutrinos
- The Dark Energy equation-of-state
- Evidence for modifications to Einstein gravity

CMB and 3D lensing are particularly promising probes, as the physics is well-understood, and they have high sensitivity

Almost all complex astrophysics can be avoided in lensing, at cost of S/N

Challenges:

- Shape measurement (GREAT10 challenge)
- Photo-z estimation (PHAT challenge)
- Intrinsic alignments
- Baryon, Dark Energy and Modified Gravity clustering on small scales
- How do we go beyond LCDM?
- What should observers report to theorists?