The Present and Future of Weak Lensing

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Outline

1. Introduction to large scale structure
2. Weak lensing
3. Some SDSS results
4. The future

Two Ways to Probe the Universe

- Measure the "mean" Universe
  - Classic tests – standard candles (e.g. SN Ia), direct H_0, etc.
  - Measure the distance scale of the Universe:

$$D = \sin_K \left[H_0^{-1} \int_0^z \frac{dz}{\sqrt{\Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_K (1+z)^2 + \Omega_{de} e^{3\int_0^z [1+w(z)]dz/(1+z)}}} \right]$$

  - and in turn to the density of each component, the equation of state of dark energy (w=p/ρ; note w=−1 for a cosmological constant), …
- Measure the perturbations

Two Ways to Probe the Universe

- Measure the "mean" Universe
  - Classic tests – standard candles (e.g. SN Ia), direct H_0, T_{CMB}, etc.
- Measure the perturbations
  - Inform us about the background, sometimes easier to measure
  - One of the few ways of accessing early epochs (e.g. inflation)

  Examples:
  - CMB anisotropies/polarization (radiation)
  - Galaxy surveys, 2D or 3D (galaxies)
  - Lyman-α, 21 cm (gas)
  - Weak lensing (mass, or really curvature)

Matter Perturbations

- Want the matter power spectrum – contribution to density variance from each Fourier mode:

$$\left\langle \delta_m(\mathbf{k})\delta_m^*(\mathbf{k}')\right\rangle = (2\pi)^3 P(k)\delta(\mathbf{k}-\mathbf{k}')$$

- Depends on 3 factors:

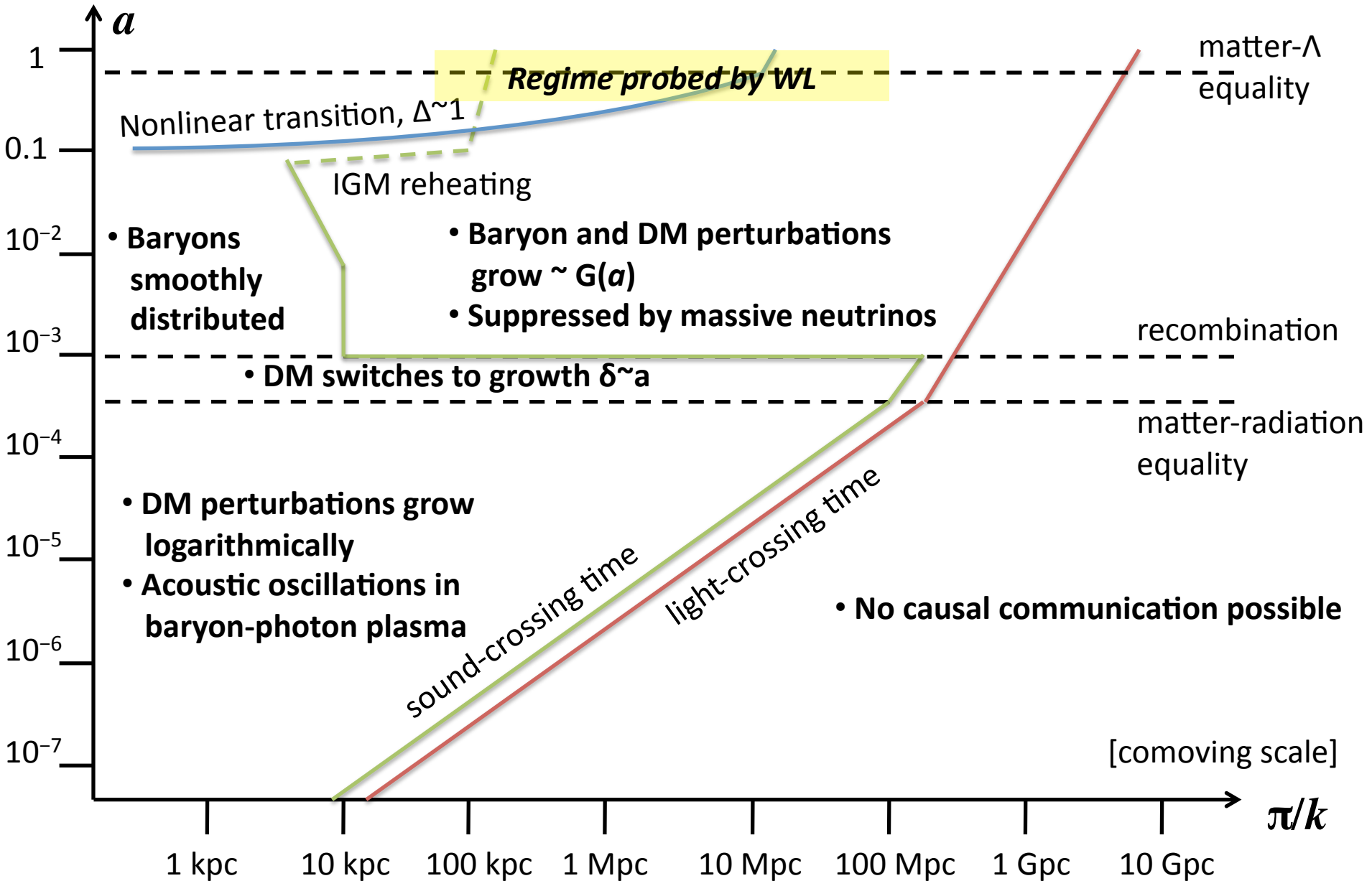
$$P(k,a) = \left(\frac{2c^2}{5\Omega_m H_0^2}\right)^2 k^4 P_\zeta(k)[T(k)]^2[G(a)]^2$$

Primordial perturbations
(from inflation or alternative)

Transfer function – processing through
early Universe (radiation era, recombination)

Growth function – gravitational instability in
ΛCDM background (or alternative)

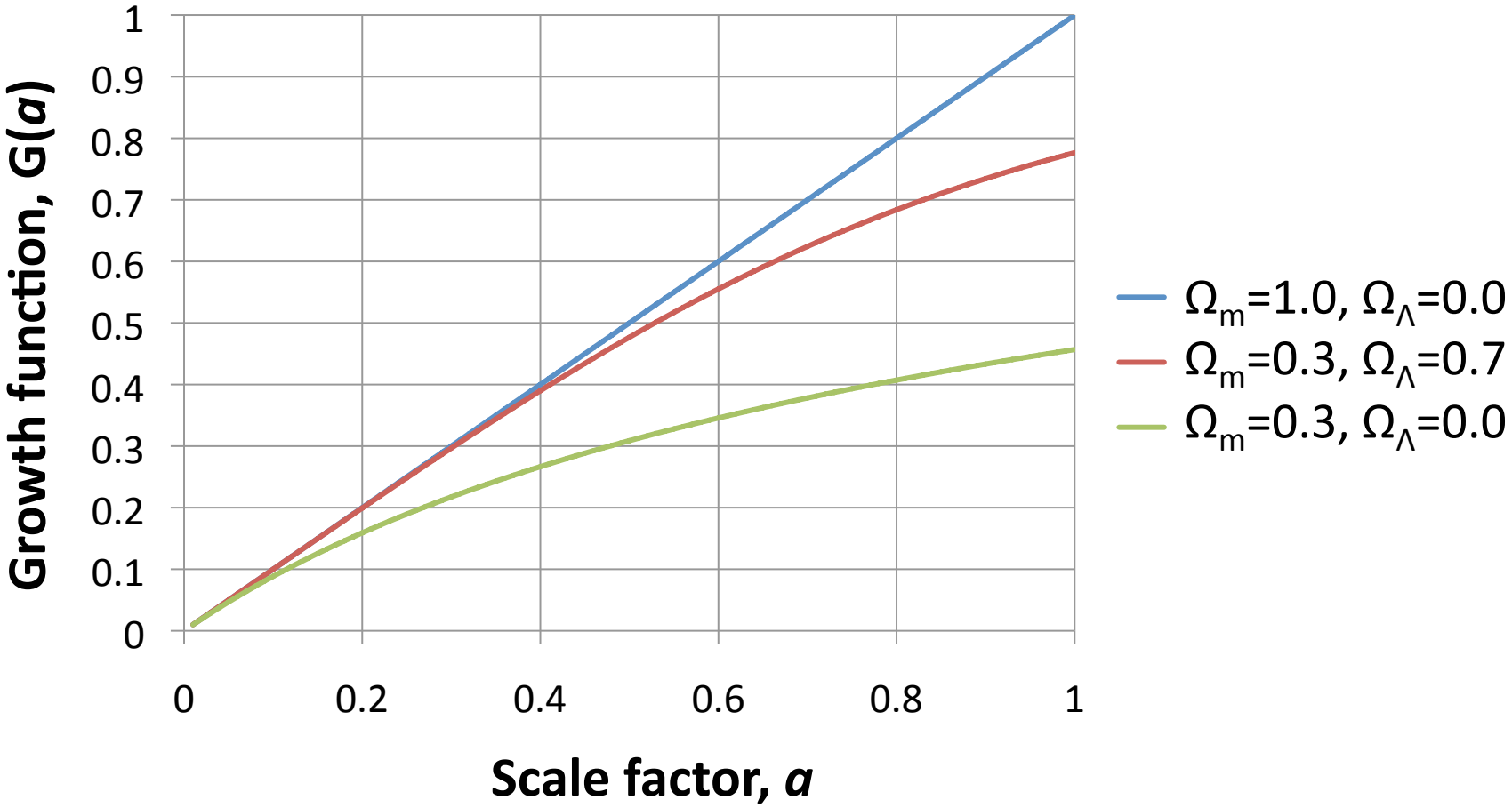
Evolution of Perturbations



Growth of perturbations

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G\bar{\rho}_m\delta_m = 0$$

The growing mode G(a) is the *growth function*.
The decaying mode is only useful as a mathematical tool.

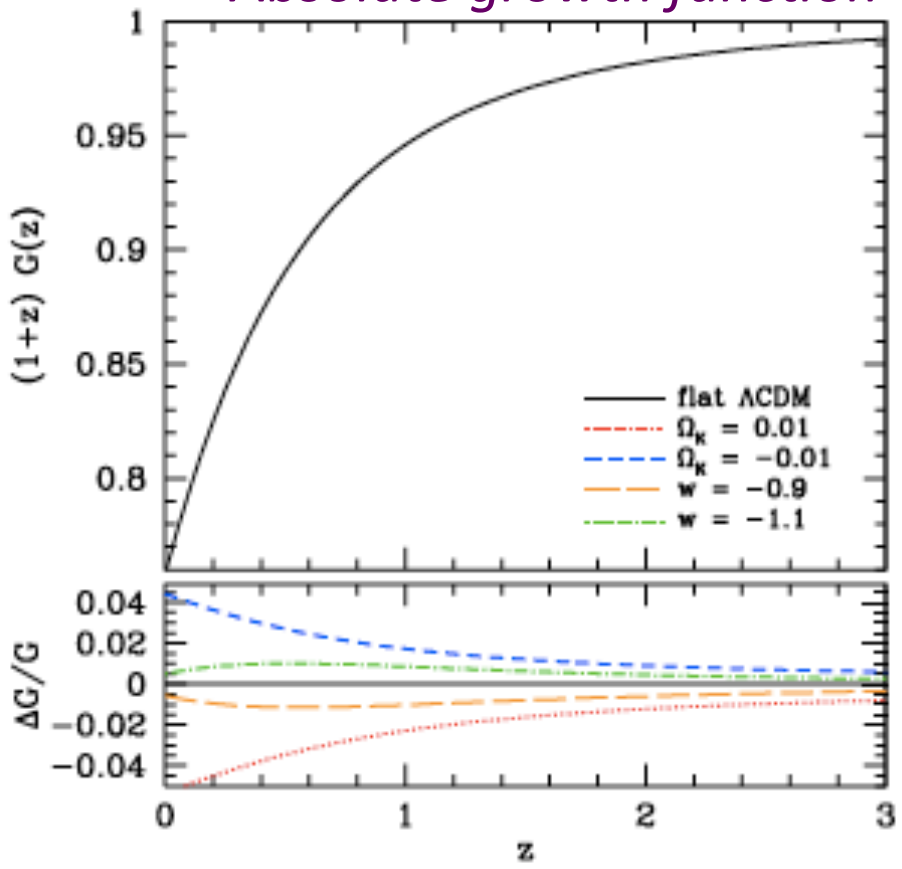


Perturbations and Dark Energy

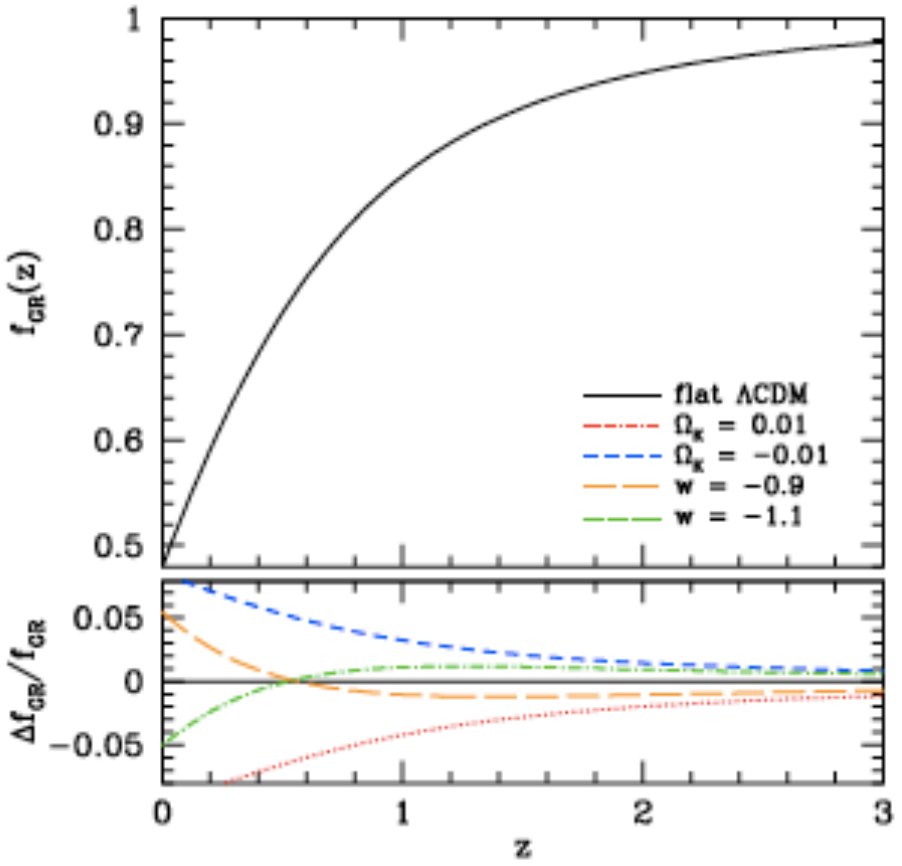
- Use features in the perturbation spectrum as a standard ruler (e.g. baryon acoustic oscillations)
- Measure the growth function by redshift dependence of P(k)
  - The entire difference between $\Lambda=0$ and the $\Omega_m=0.3$ cosmology is 22% from $z=\infty$ to $z=0$.
  - Need to be doing <1% measurements to get a decisive result.
- Also a test of gravity – is the growth of perturbations as predicted by GR for CDM + unclustered dark energy?

Effect of Dark Energy on Growth

Absolute growth function



Growth rate



Weak Lensing

- Slight (~1%) distortion of the image of a galaxy due to matter along the line of sight.
  - **Shear** = l.o.s. integral of tidal field
    - Manifest in the ellipticity of a galaxy.
    - Since shear << intrinsic ellipticity, must do statistics.

  - **Magnification** = l.o.s. integral of density
    - Less mature – not this talk.

Thanks to B. Jain for the cartoon.

Major Uses

WL serves both cosmology and galaxy evolution

1. The growth of large scale structure via the statistics of weak lensing.
2. The connection between galaxies and their host dark matter haloes.
3. Galaxy biasing – the relation between galaxies and their large-scale environment.

Cosmic Shear

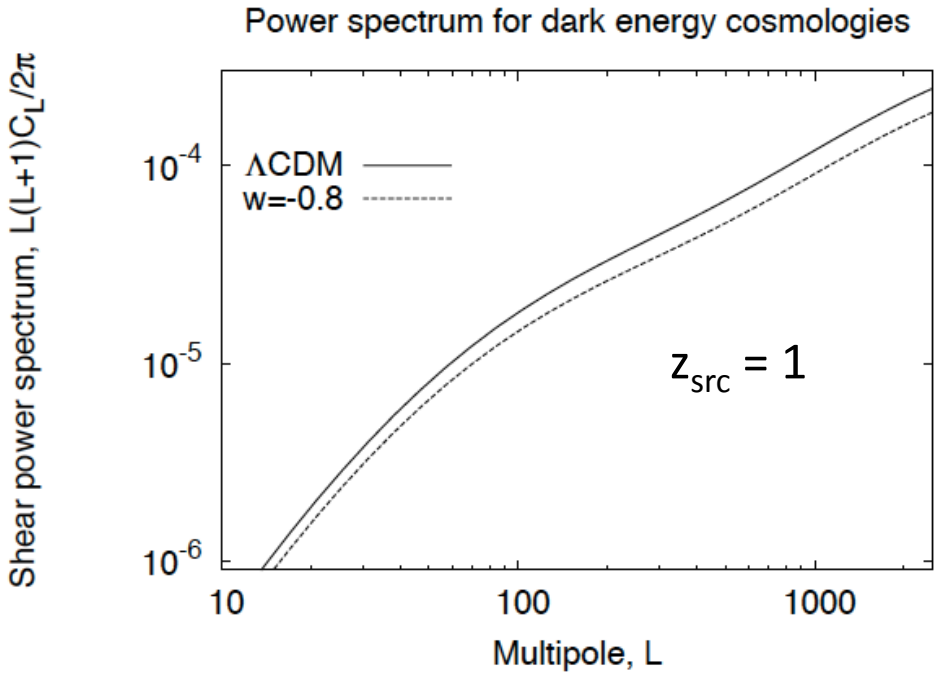
- Use the power spectrum or correlation function of galaxy ellipticities.
- This depends directly on the matter (and background cosmology) – no more messy galaxy biasing uncertainties!

$$W_{\rm flat}(D_{C1}, D_C) = \frac{3}{2}\Omega_m H_0^2 (1+z_1)\frac{D_{C1}(D_C - D_{C1})}{D_C}\Theta(D_C - D_{C1})$$

$$C_{EE}(l) = \int_0^{D_C} [W(D_{C1}, D_C)]^2 \frac{P_\delta(k = l/D_{A1})}{D_{A1}^2} dD_{C1}$$

… but to date, has not fulfilled its promise.

- Needs lots of time to resolve shapes of distant (small/faint) galaxies!
- Systematic errors in measuring a <1% signal.



Optical Cosmic Shear Results, 2000—present

Reference	Telescope/instrument	Area (deg^2)	Number of galaxies	Result
Bacon et al. (2000)	WHT/EEV-CCD	0.5	27k	$\sigma_8 = 1.5 \pm 0.5$ (@ $\Omega_m = 0.3$)
van Waerbeke et al. (2000)	CFHT/UH8K+CFH12K	1.75	150k	Detection[a]
Wittman et al. (2000)	Blanco/BTC	1.5	145k	Detection[b]
Rhodes et al. (2001)	HST/WFPC2	0.05	4k	$\sigma_8(\Omega_m/0.3)^{0.48} = 0.91^{+0.25}_{-0.30}$
Van Waerbeke et al. (2001)	CFHT/CFH12K	6.5	400k	$\sigma_8(\Omega_m/0.3)^{0.6} = 0.99^{+0.08}_{-0.10}$ (95%CL)[c]
Hoekstra et al. (2002)	CFHT/CFH12K + Blanco/Mosaic II	53	1.78M	$\sigma_8(\Omega_m/0.3)^{0.55} = 0.87^{+0.17}_{-0.23}$ (95%CL)
Refregier et al. (2002)	HST/WFPC2	0.36	31k	$\sigma_8 = 0.94 \pm 0.14$ (@ $\Omega_m = 0.3$, $\Gamma = 0.21$)
Bacon et al. (2003)	Keck II/ESI + WHT	1.6		$\sigma_8(\Omega_m/0.3)^{0.68} = 0.97 \pm 0.13$
Brown et al. (2003)	MPG ESO 2.2m/WFI	1.25		$\sigma_8(\Omega_m/0.3)^{0.49} = 0.72 \pm 0.09$[d,e]
Jarvis et al. (2003)	Blanco/BTC+Mosaic II	75	2M	$\sigma_8(\Omega_m/0.3)^{0.57} = 0.71^{+0.12}_{-0.16}$ (2σ)
Hamana et al. (2003)	Subaru/SuprimeCam	2.1	250k	$\sigma_8(\Omega_m/0.3)^{0.37} = 0.78^{+0.55}_{-0.29}$ (95%CL)
Rhodes et al. (2004)	HST/STIS	0.25	26k	$\sigma_8(\Omega_m/0.3)^{0.46}(\Gamma/0.21)^{0.18} = 1.02 \pm 0.16$
Heymans et al. (2005)	HST/ACS	0.22	50k	$\sigma_8(\Omega_m/0.3)^{0.65} = 0.68 \pm 0.13$
Massey et al. (2005)	WHT/PFIC	4	200k	$\sigma_8(\Omega_m/0.3)^{0.5} = 1.02 \pm 0.15$
Hoekstra et al. (2006)	CFHT/MegaCam	22	1.6M	$\sigma_8 = 0.85 \pm 0.06$ @ $\Omega_m = 0.3$
Semboloni et al. (2006)	CFHT/MegaCam	3	150k	$\sigma_8 = 0.89 \pm 0.06$ @ $\Omega_m = 0.3$
Benjamin et al. (2007)	Various[5]	100	4.5M	$\sigma_8(\Omega_m/0.3)^{0.59} = 0.74 \pm 0.04$
Hetterscheidt et al. (2007)	MPG ESO 2.2m/WFI	15	700k	$\sigma_8 = 0.80 \pm 0.10$ @ $\Omega_m = 0.3$
Massey et al. (2007a)	HST/ACS	1.64	200k	$\sigma_8(\Omega_m/0.3)^{0.44} = 0.866^{+0.085}_{-0.068}$
Schrabback et al. (2007)	HST/ACS	0.4	100k	$\sigma_8 = 0.52^{+0.11}_{-0.15}$(stat)$\pm$0.07(sys) @ $\Omega_m = 0.3$[f]
Fu et al. (2008)	CFHT/MegaCam	57	1.7M	$\sigma_8(\Omega_m/0.3)^{0.64} = 0.70 \pm 0.04$
Schrabback et al. (2010)	HST/ACS	1.64	195k	$\sigma_8(\Omega_m/0.3)^{0.51} = 0.75 \pm 0.08$
Huff et al. (2011)	SDSS	168	1.3M	$\sigma_8 = 0.636^{+0.109}_{-0.154}$ @ $\Omega_m = 0.265$[h]
Lin et al. (2011)	SDSS	275	4.5M	$\sigma_8(\Omega_m/0.3)^{0.7} = 0.64^{+0.08}_{-0.12}$[h]
Jee et al. (2012)	Mayall+CTIO/Mosaic	20	1M	$\sigma_8 = 0.833 \pm 0.034$[i]
Kilbinger et al. (2012)	CFHT/MegaCam	154	4.2M	$\sigma_8(\Omega_m/0.27)^{0.6} = 0.79 \pm 0.03$

Review article by Weinberg et al 2013

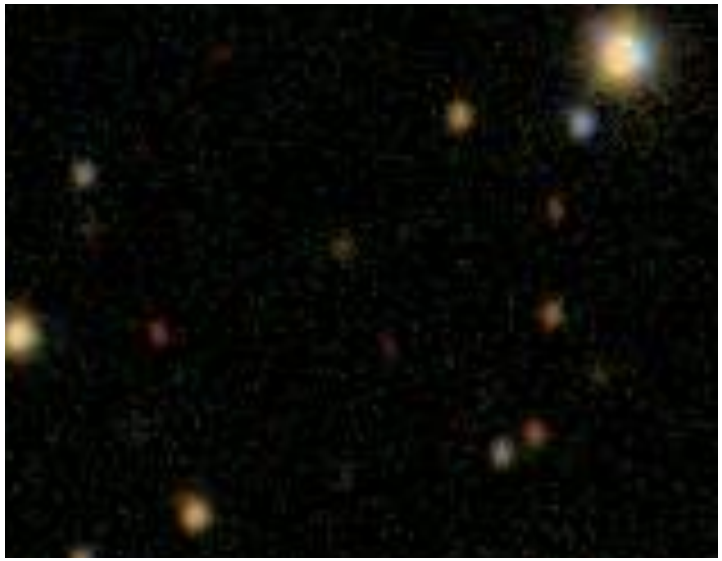
What Makes This Hard?

1. The Point Spread Function

Everything we see on the sky is convolved with the PSF.

$$I_{\rm obs}(\mathbf{x}) = \int I_{\rm true}(\mathbf{x}')G(\mathbf{x}-\mathbf{x}')d^2\mathbf{x}'$$

SDSS Run 756



Must know "G" – which includes:

- The atmosphere
- Diffraction effects
- The optical aberrations
- Charge diffusion & pixelization

… may be color or flux-dependent

… and the above terms are **not** independent!

Try measuring a few × 10^{-3} ellipticity when your data looks like that.

What Makes This Hard?

2. Estimating "shear" is messy.

We don't a priori know what the unlensed galaxies look like.

$$I_{\rm obs}(\mathbf{x}) = \int I_{\rm unlensed}(\mathbf{S}\mathbf{x}')G(\mathbf{x}-\mathbf{x}')d^2\mathbf{x}' \qquad \mathbf{S} = \begin{pmatrix} 1-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1+\gamma_1 \end{pmatrix}$$

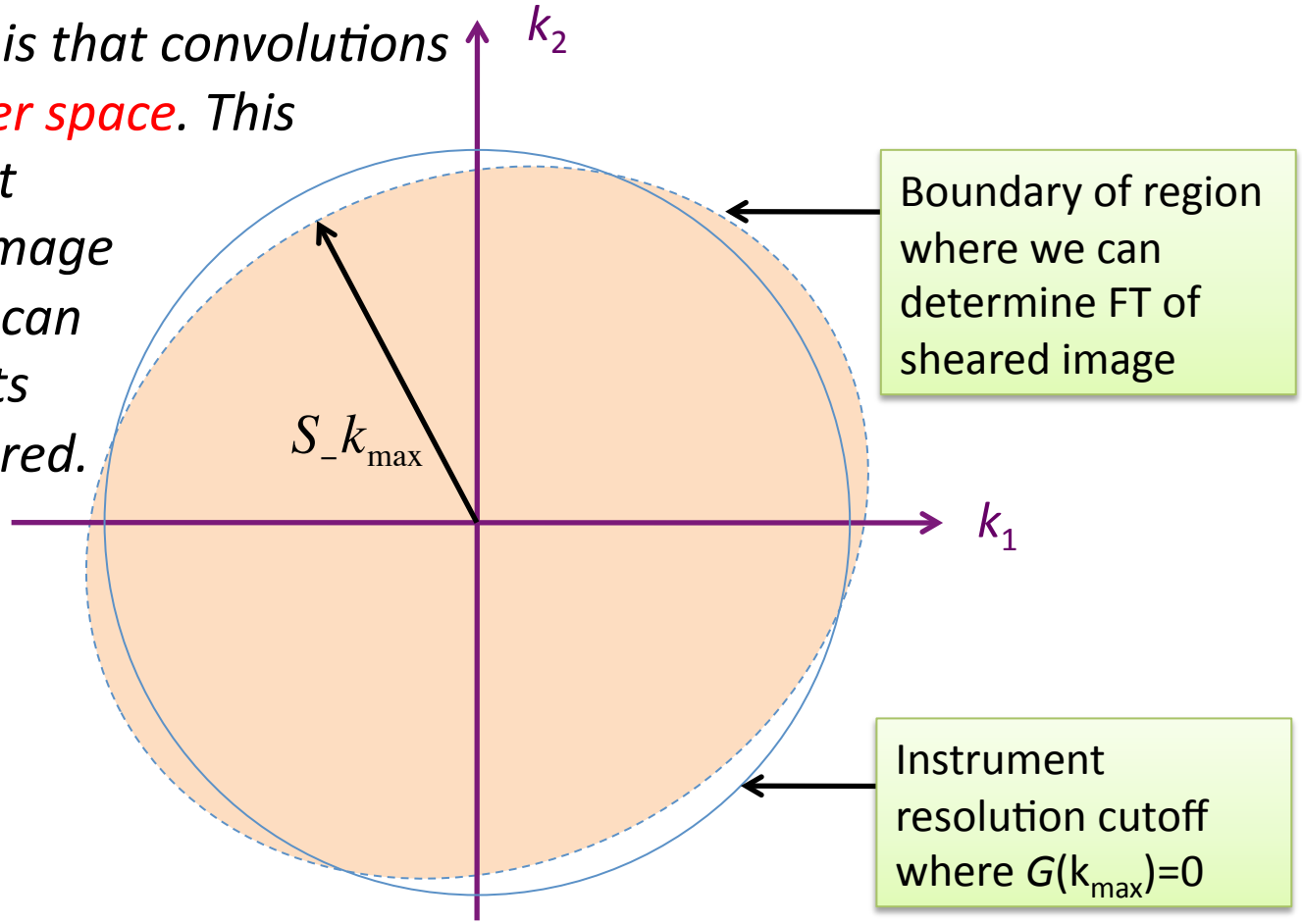
- "Shear measurement algorithm" = an algorithm that returns an unbiased estimate of γ from an ensemble of observed images (or really a sky map!) – without being told the true distribution of unlensed galaxies.
- Many approaches, lots of ideas!
- Mathematical foundations of the problem now understood for isolated, S/N=∞ galaxies. Work needed by the community to solve the "real" problem.

What Makes This Hard?

2. Estimating "shear" is messy.

$$\tilde{I}_{\rm obs}(\mathbf{k}) = \tilde{I}_{\rm unlensed}(\mathbf{S}^{-1\rm T}\mathbf{k})\tilde{G}(\mathbf{k})$$

The key realization is that convolutions are simple in Fourier space. This makes explicit what information each image contains and what can be inferred about its appearance if sheared.

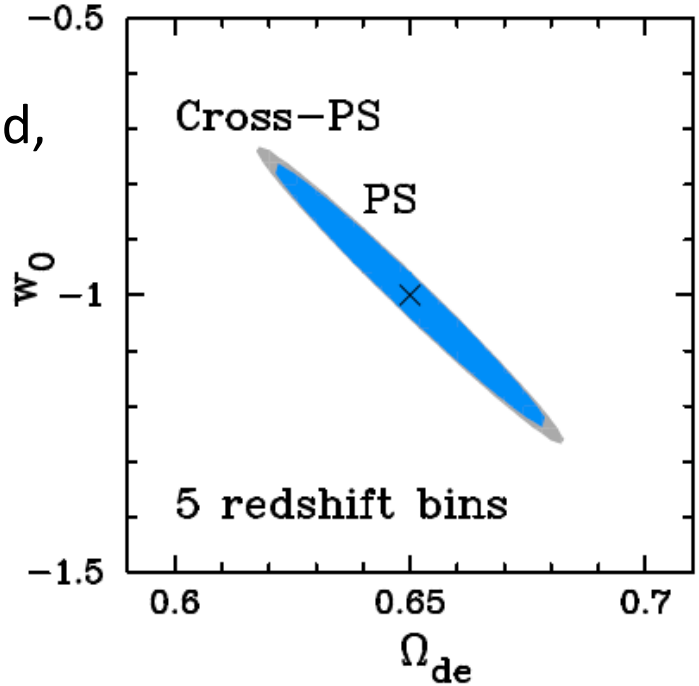


What Makes This Hard?

3. Intrinsic galaxy alignments.

If galaxies were randomly oriented, then their intrinsic shapes would average out in correlation functions. But:

- If galaxies near each other are correlated, this can mimic cosmic shear.
- Reports going back at least to the 1980s (Binggeli et al)
- This can be solved **if** you can identify galaxies at the same redshift (nearby in 3D space) and remove these pairs – actually little information loss!



Forecast by Takada & White 2003

What Makes This Hard?

4. Intrinsic galaxy alignments, worse this time.

The intrinsic alignment and cosmic shear are correlated.

$$C_\ell^{\text{obs}} = C_\ell^{\text{lensing}} + C_\ell^{\text{intrinsic alignment}} + C_\ell^{\text{correlation}}$$

- Theory says galaxies are aligned by large-scale tidal quadrupoles.
- The same tidal field that aligns a nearby galaxy can gravitationally lens a more distant one.

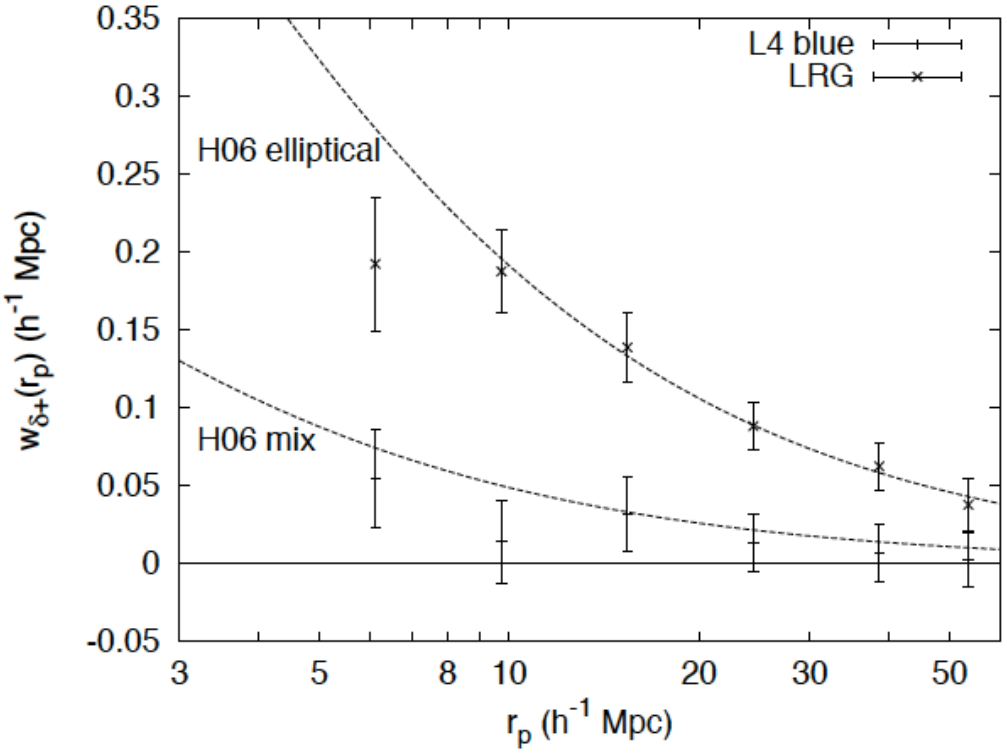
Hirata & Seljak 2004

What Makes This Hard?

4. Intrinsic galaxy alignments, worse this time.

The intrinsic alignment and cosmic shear are correlated.

- SDSS provides ~13σ detection of correlation of galaxy orientations with tidal field (as predicted from nearby structures).
- Worst for luminous red galaxies.



Hirata et al 2007

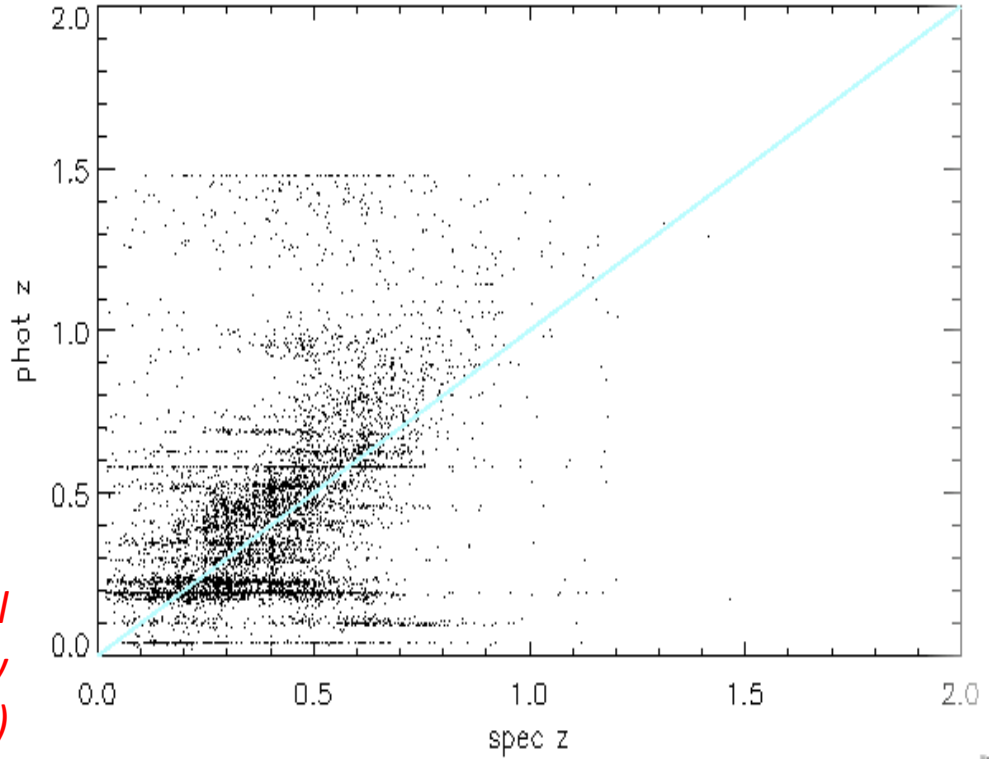
What Makes This Hard?

5. But where are the galaxies?

The lensing signal depends strongly on source redshift.

- Can't afford spectra for every galaxy.
- Use photometric redshifts (from broadband photometry, using continuum shape)

- … + calibration samples.

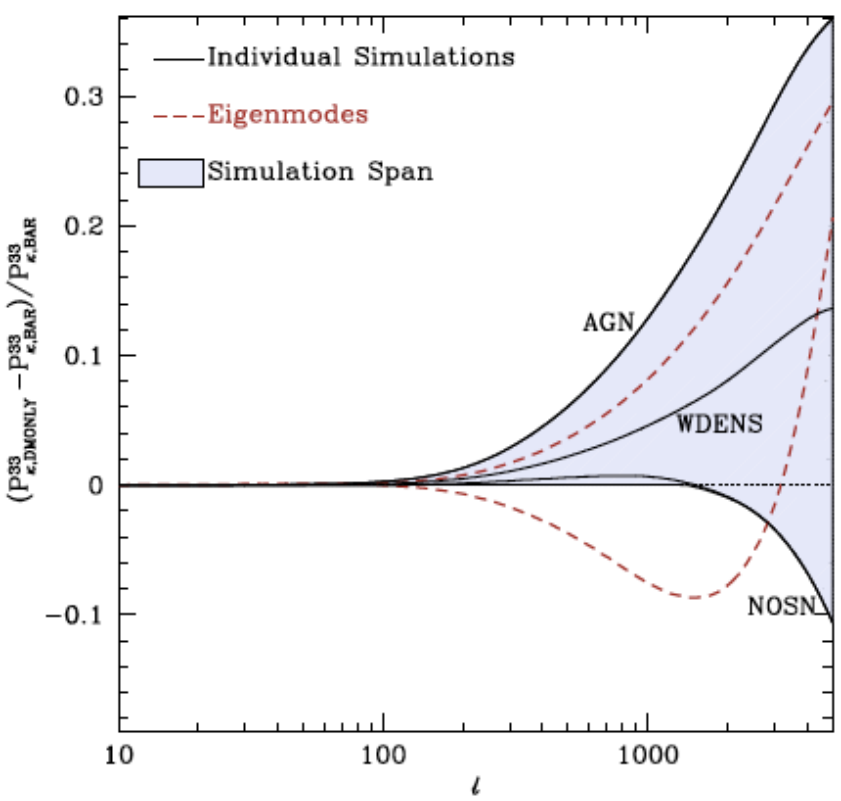


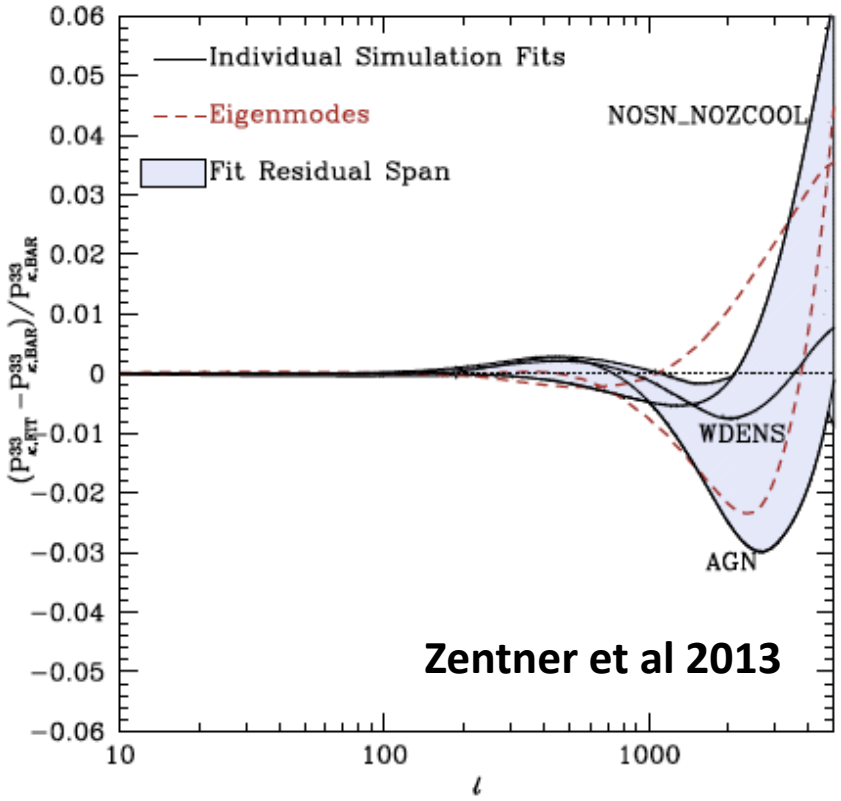
Eric Huff et al
SDSS ugriz photometry
(plot descoped from 12/2011 paper)

What Makes This Hard?

6. Remember the 17%:

Even theorists are made of baryons.





Zentner et al 2013

SDSS Results

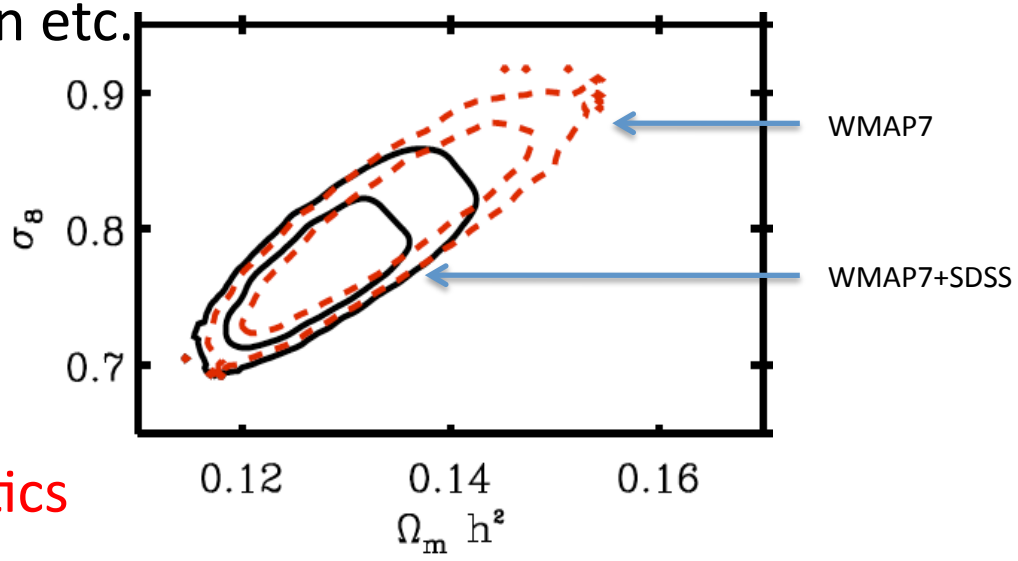
- Amplitude of fluctuations (Huff et al):
  - Fixed other parameters to WMAP values

$$\sigma_8 = 0.64^{+0.10}_{-0.15}(1\sigma)$$

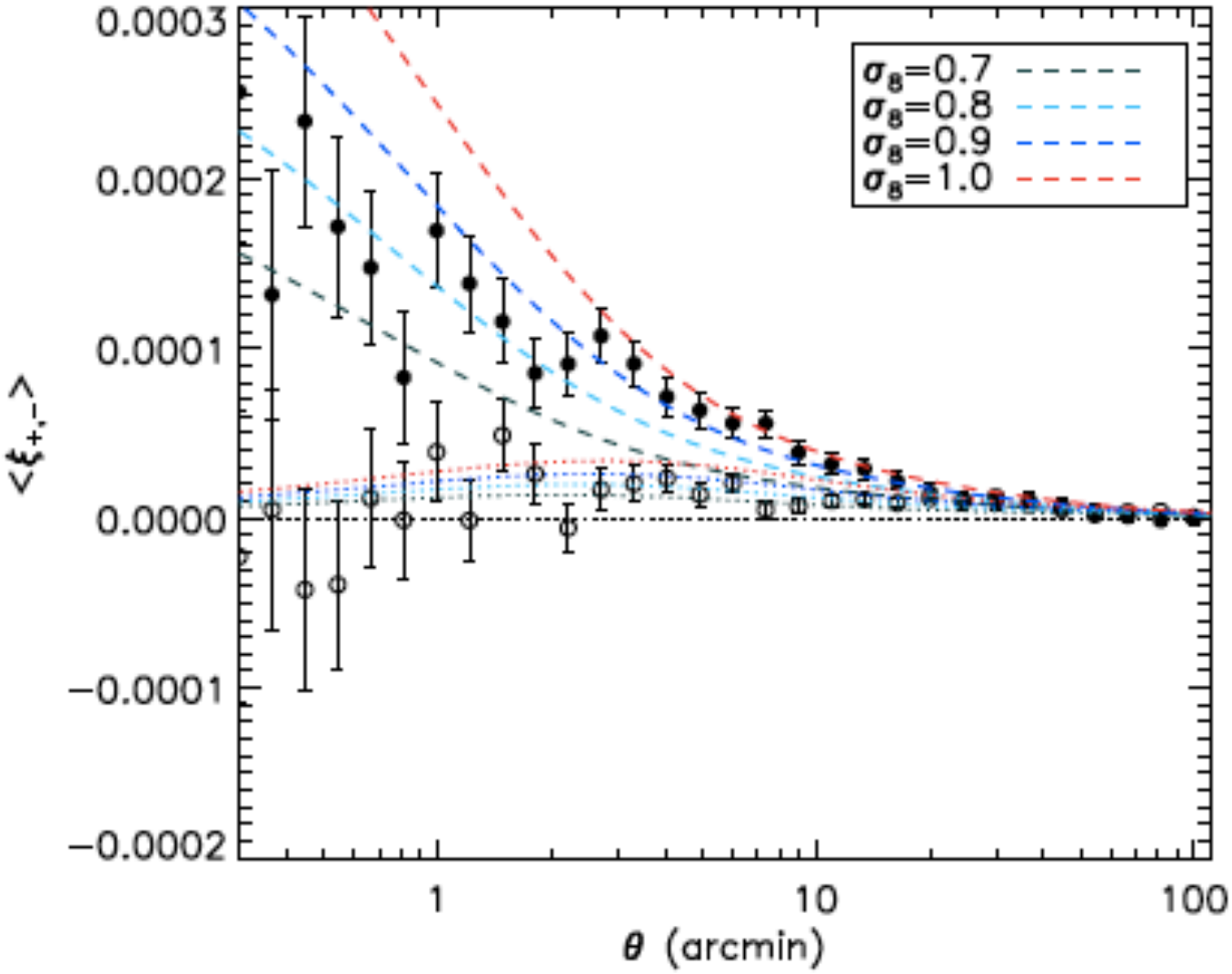
- Independent* analysis of the same dataset by Fermilab group (Lin et al):
  - Includes e.g. different image stacking algorithm, sky subtraction, object selection etc.

$$\sigma_8 = 0.64^{+0.08}_{-0.13}(1\sigma)$$

- This worked but:
  - Statistical errors are large
  - Limited redshift baseline
  - There are residual systematics

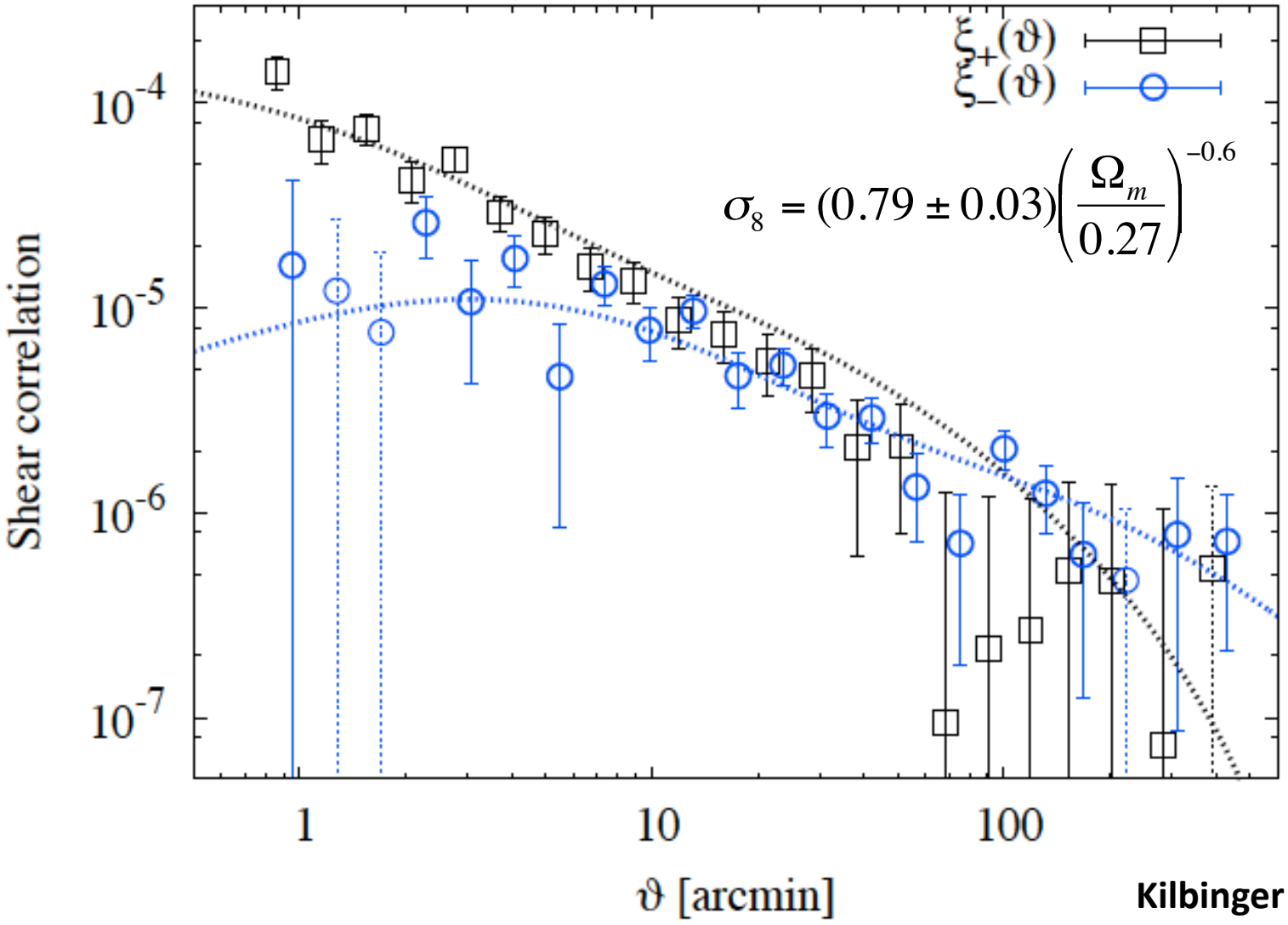


DLS



Jee et al 2012

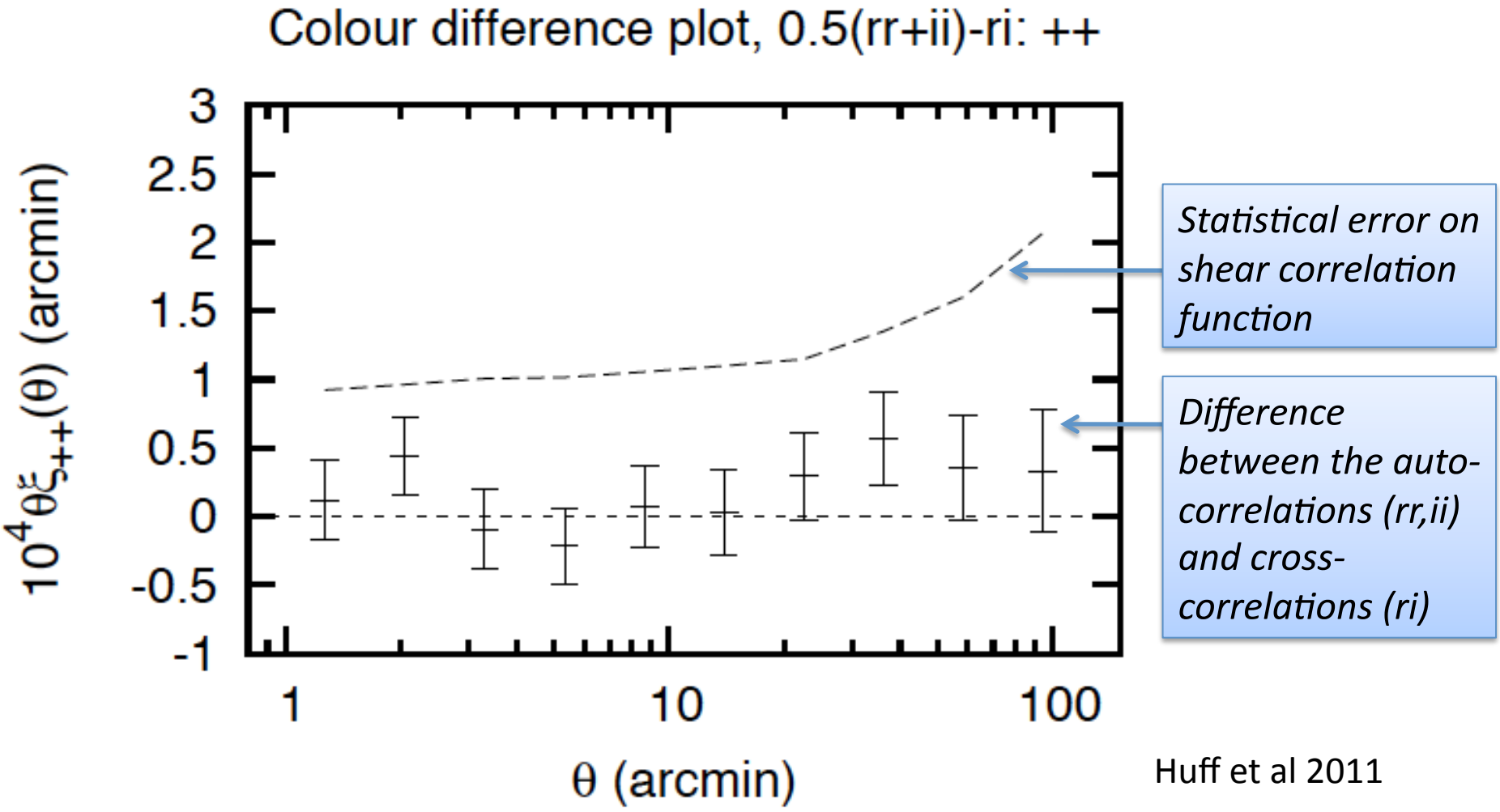
CFHT Lensing Results!



Kilbinger et al 2013

Tests for Residual Systematics

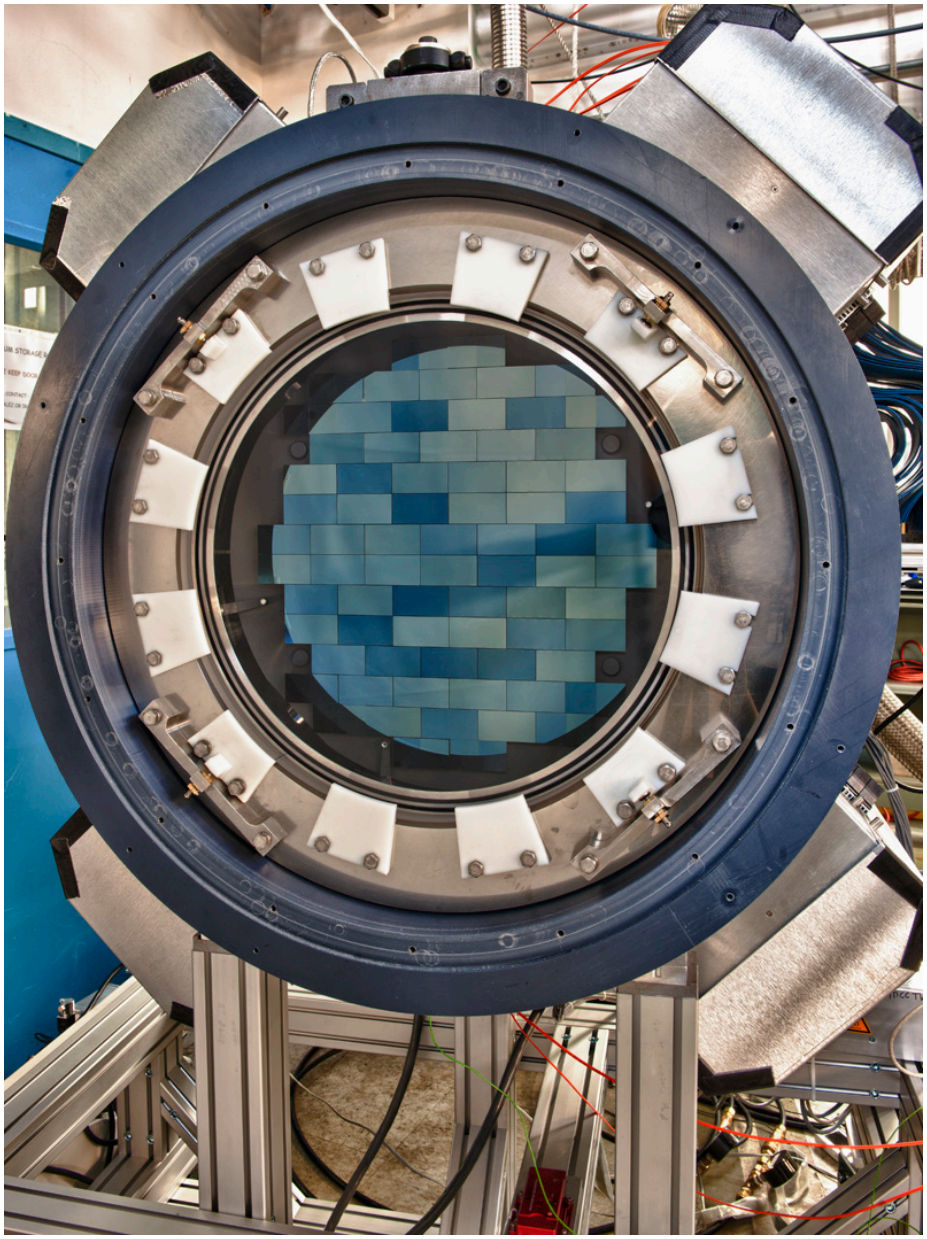
… or, what tests convince you that you are doing something right …



Huff et al 2011

What's Needed for a Great WL Program

- More area & depth
- Much better "seeing"
  - Only way to resolve more galaxies, especially at high z, is at an excellent ground based site, or (better) in space
- More filters for photo-z (including NIR at z>1.2)
- Plenty of redundancy
  - Needed for the aforementioned tests – should include multiple filters to check color corrections.
  - The foundation of science is the reproducibility of results, especially where small effects are concerned.
- More stable, better characterized PSF
  - On the ground, the PSF often varies by tens of percents within an exposure.
  - Includes detector response, in addition to optics.
- Spectroscopic survey for photo-z calibration
  - Today a mix-and-match strategy
  - In the future: Subaru-PFS, MS-DESI, JWST, Euclid, WFIRST



Dark Energy Survey

Hyper Suprime Cam

“Stage IV” – 2020+

	LSST	Euclid	WFIRST
Area [deg^2]	~12,000 (S Hemisphere)	~15,000	2,000 (in 440 days)
Source density n_{eff} [gal am^{-2}]	~30? [15 at Res>0.4]	33 [Res>0.4, S/N>18, σ_e<0.2]	75 [Res>0.4, S/N>18, σ_e<0.2]
Median z	0.8	0.8	1.3
Shape measurement filter	r + i	VIS (550—920 nm)	J + H + F184
Detectors	CCD	CCD (e2v)	HgCdTe (H4RG-10)
Photo-z filters	6 (ugrizy)	4 (VIS + YJH)	4 (YJH+F184)
Location	Ground	Space (L2)	Space (GEO)
PSF half light radius	~0.39” (median)	0.13”	0.12”
Exposures in filled shape survey	~700× 15 s (r+i)	3× 600 s	16× 184 s (6+5+5)

Number densities based on the COSMOS Mock Catalog – S. Jouvel et al (2009)

Conclusions

- There's lots to do in both fundamental physics and galactic astronomy with weak lensing.

- We are still learning how to make weak lensing work, especially for "autocorrelation" measurements. Not mature but recent progress has been rapid.

- The past lessons are being incorporated into new surveys, both DES+HSC and more ambitious surveys in the future.