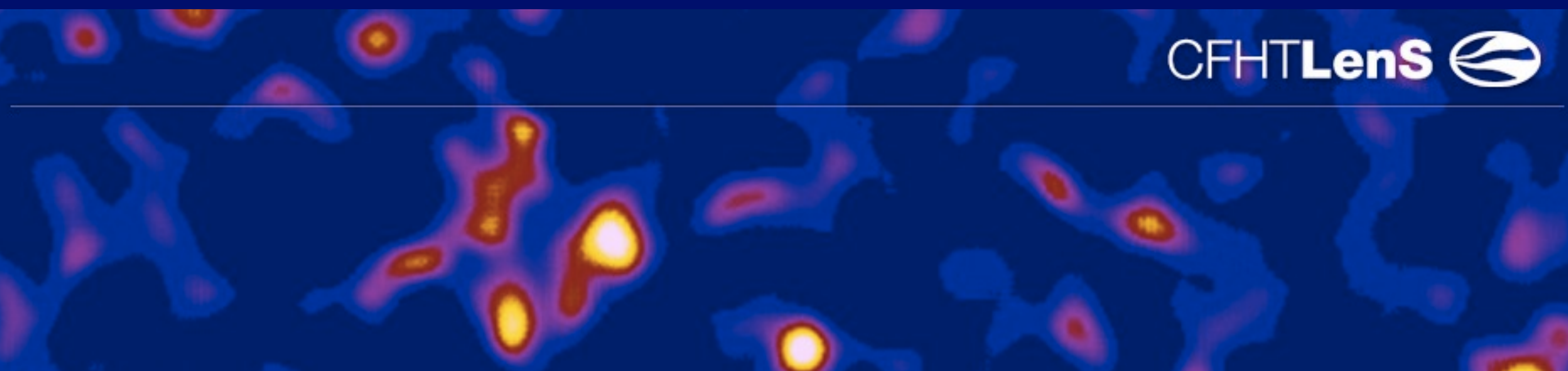
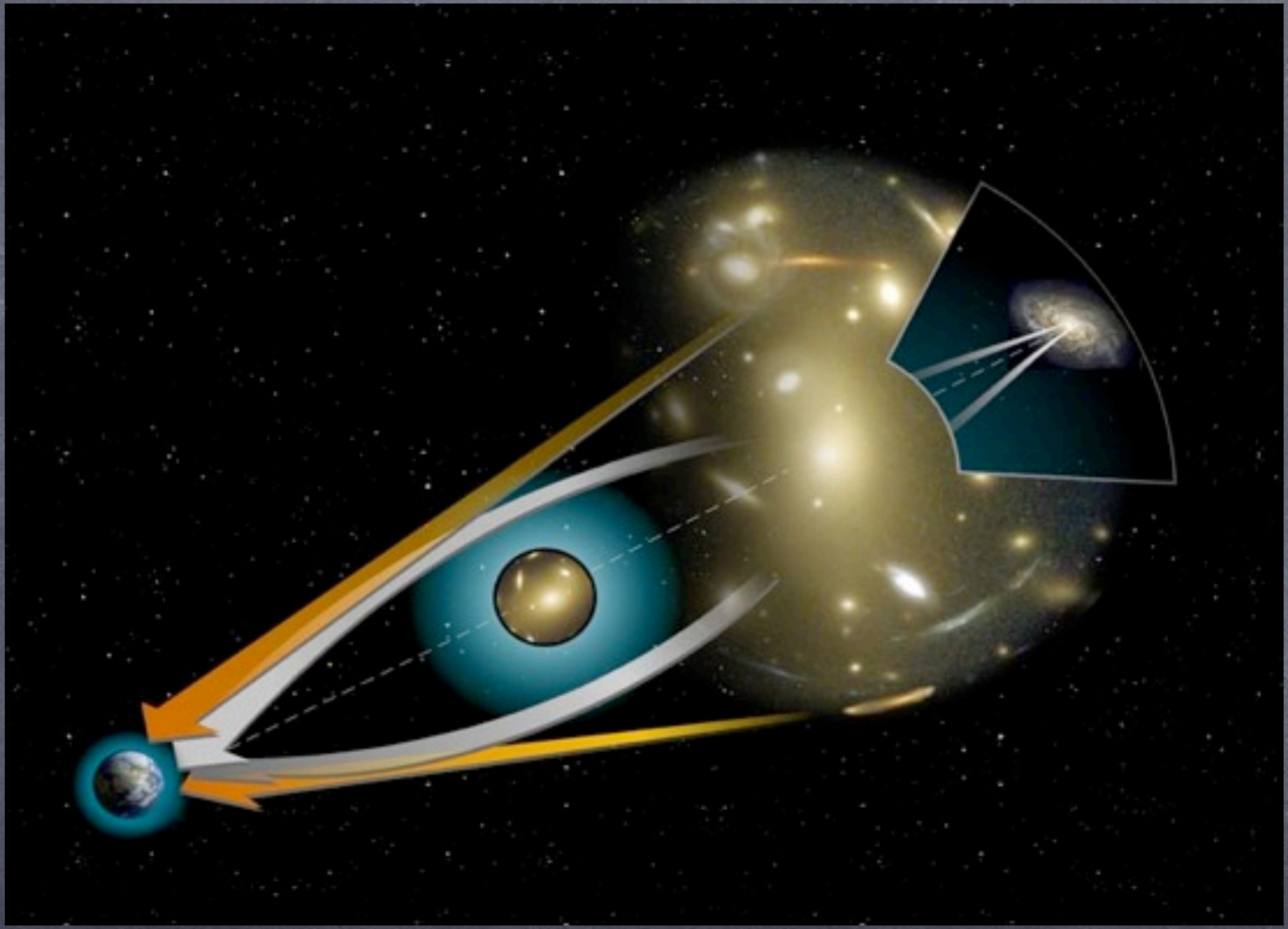
Weak Lensing by Large-scale Structure

A look at the dark side of the Universe



Henk Hoekstra
Leiden Observatory

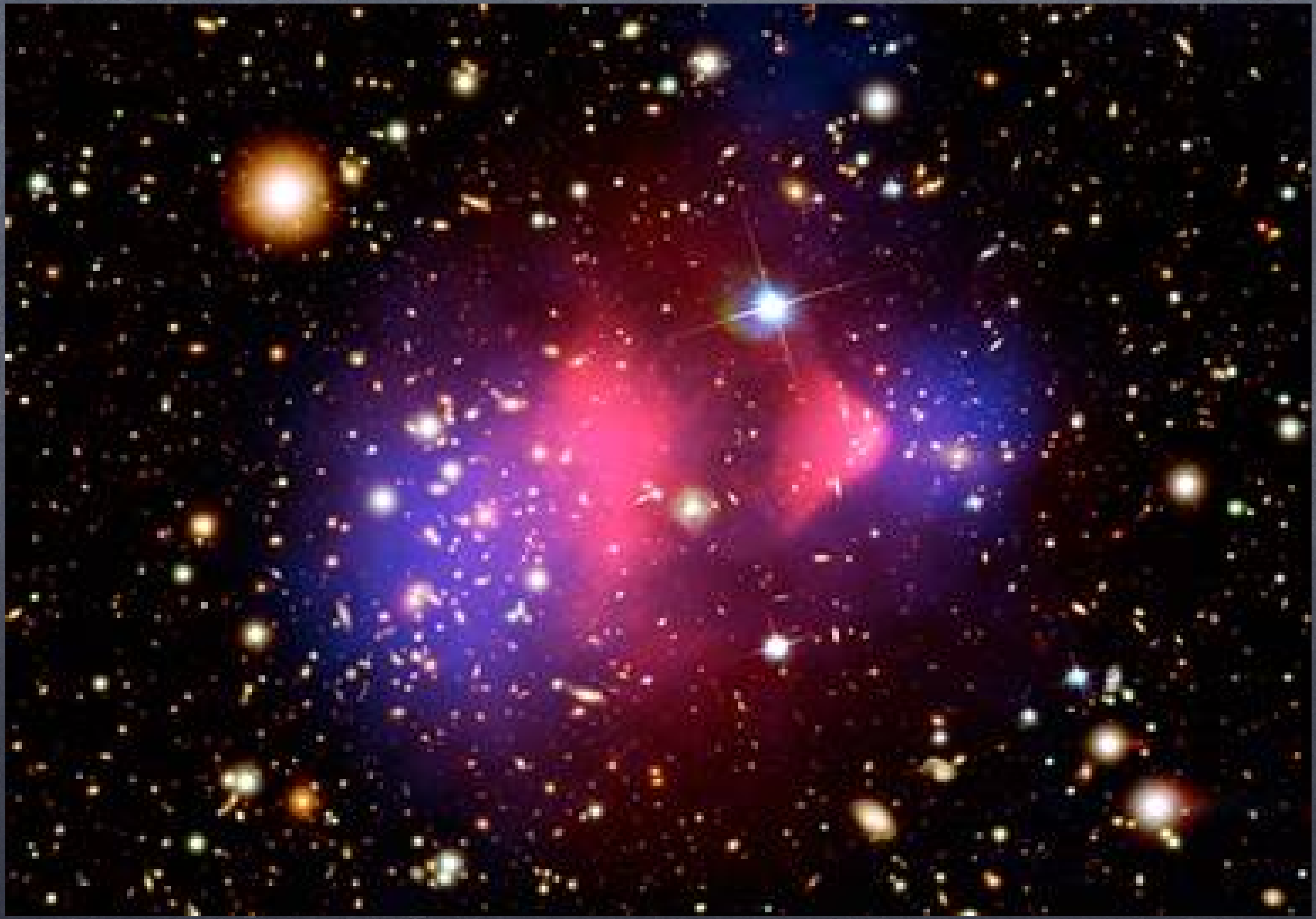
Gravitational lensing



Inhomogeneities in the mass distribution distort the paths of light rays: differential deflection leads to coherent distortions in the shapes of distant galaxies.

We can see dark matter!

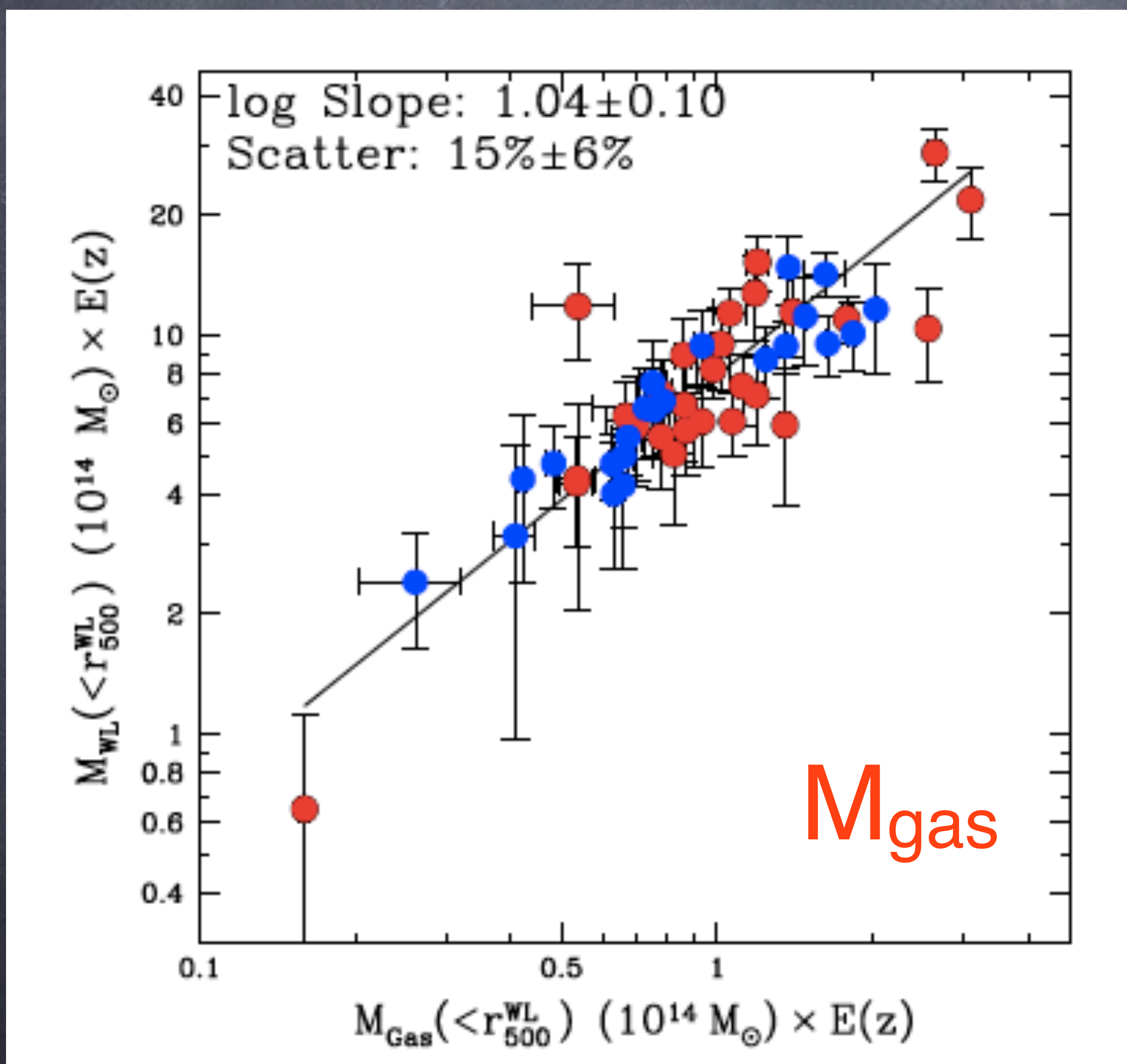
These coherent distortions can be *directly* related to the (projected) matter density!

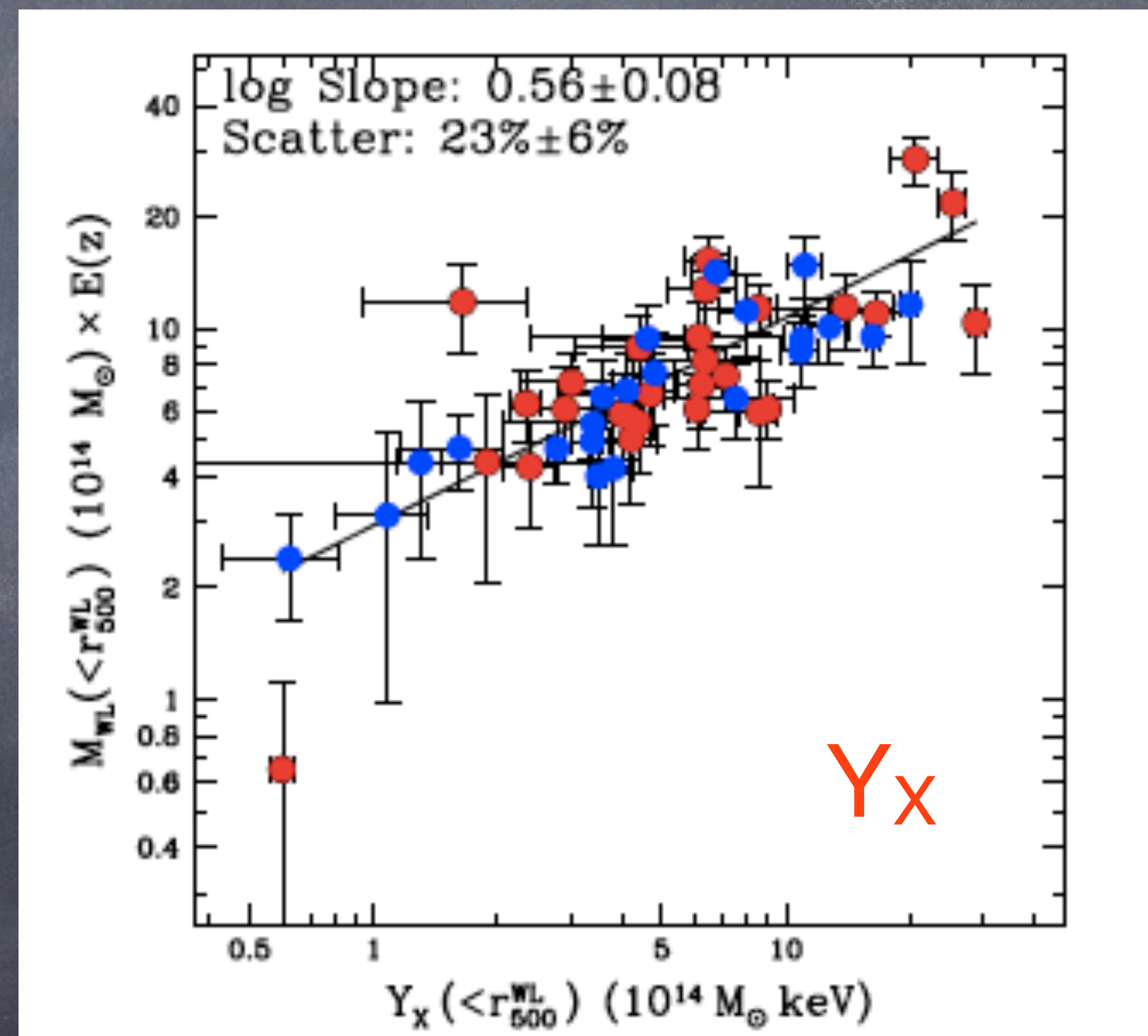


Clowe et al. (2006)

Nature's weighing scales

Mahdavi et al. (2013)

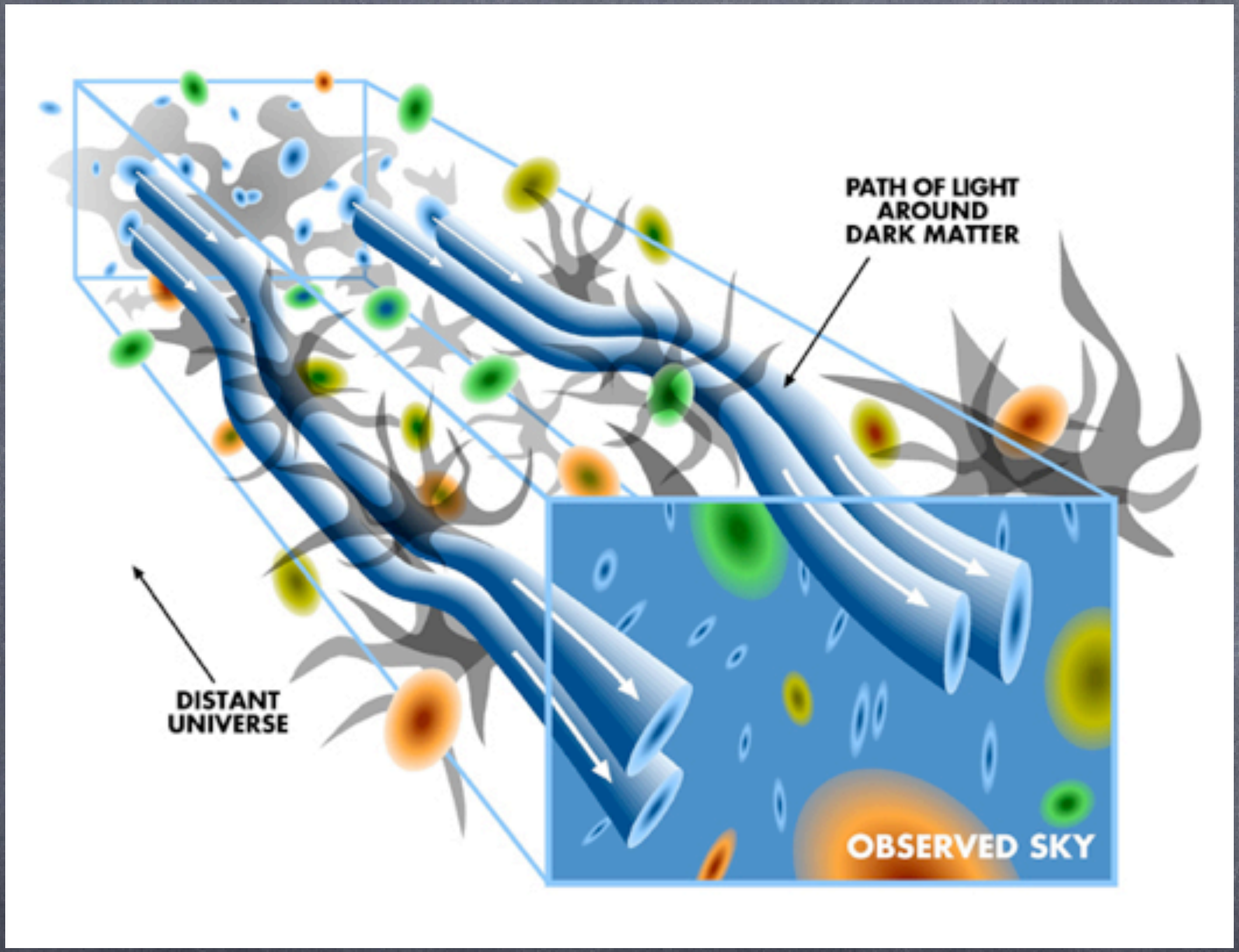




Low S_0: no intrinsic scatter?

No difference between low/high S_0

Weak lensing by LSS

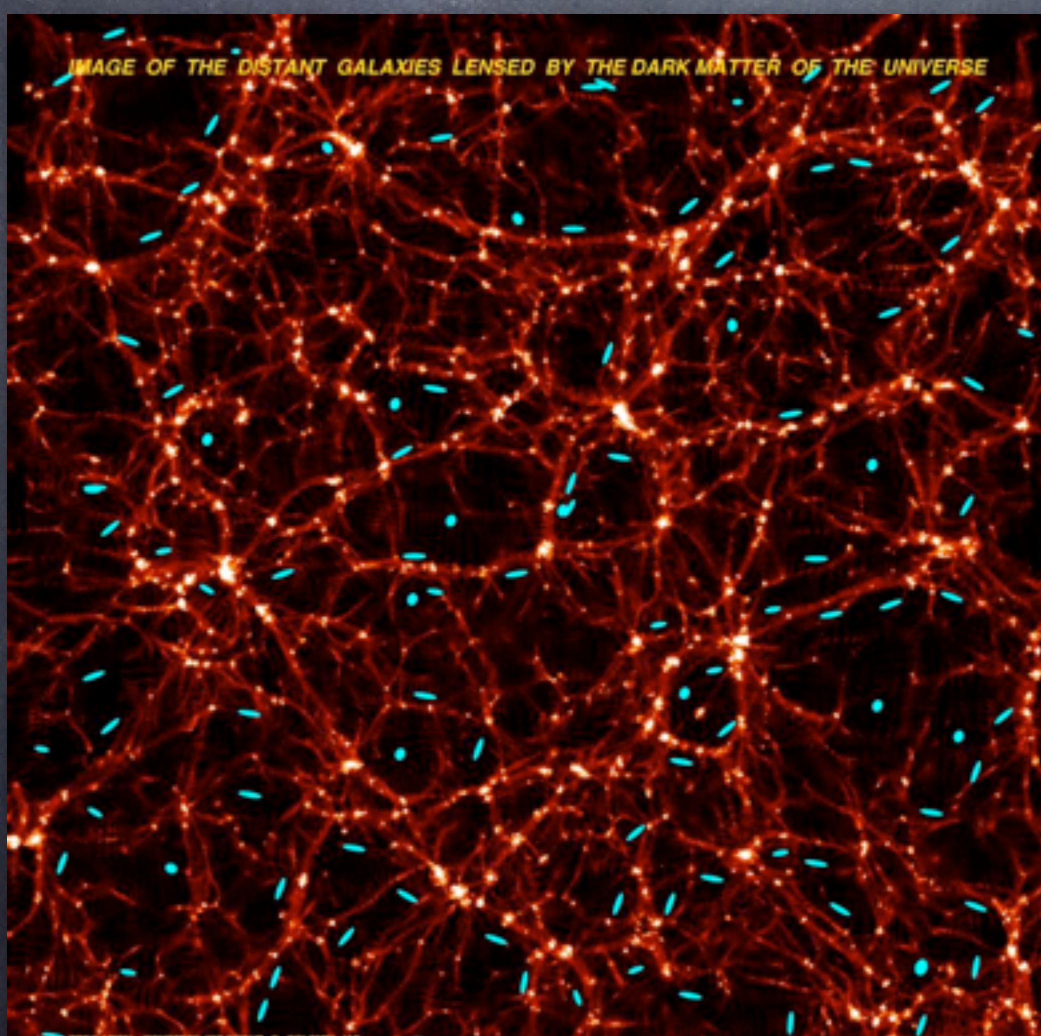


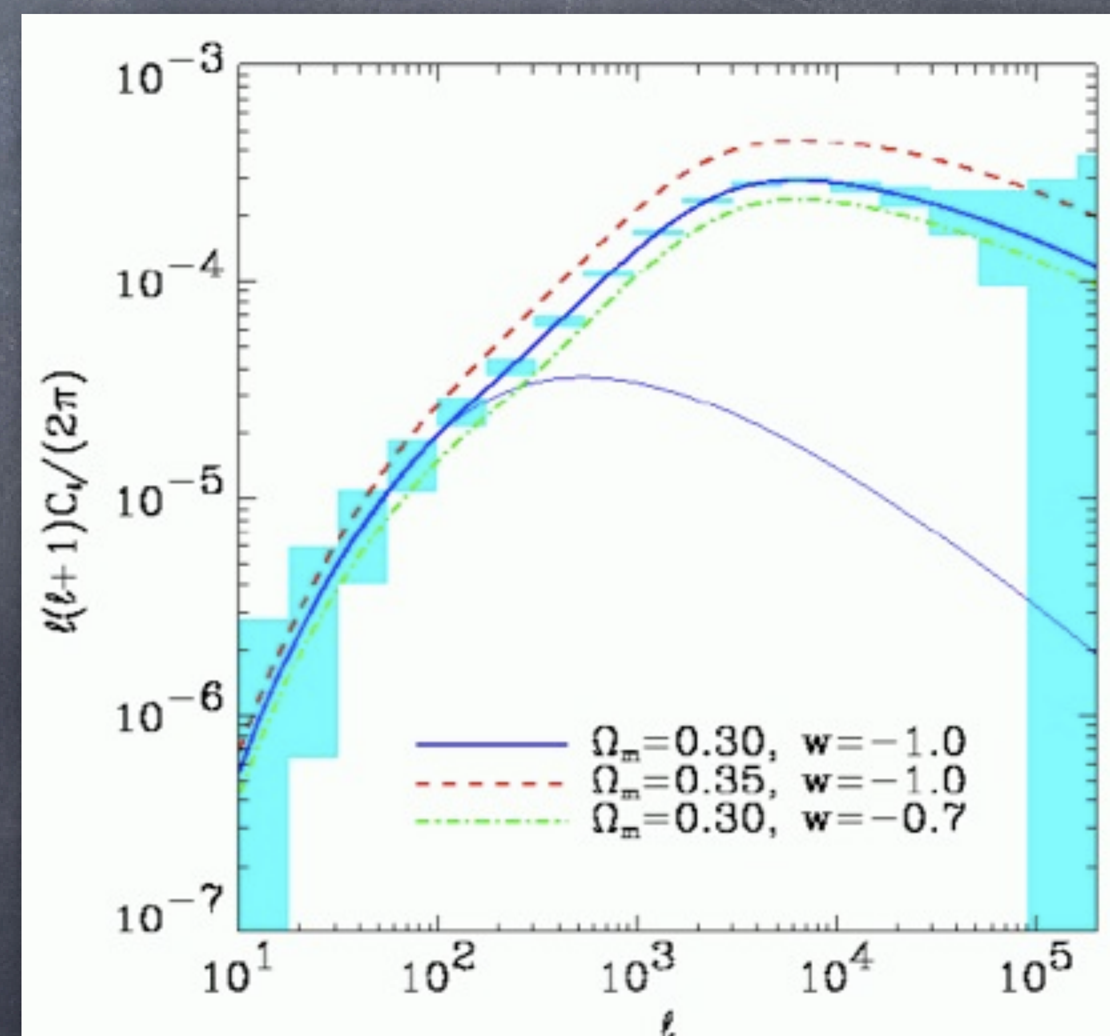
Credit: Tyson et al. (2000)

Cosmic shear is the lensing of distant galaxies by the overall large-scale distribution of matter in the universe: it is the most "common" lensing phenomenon.

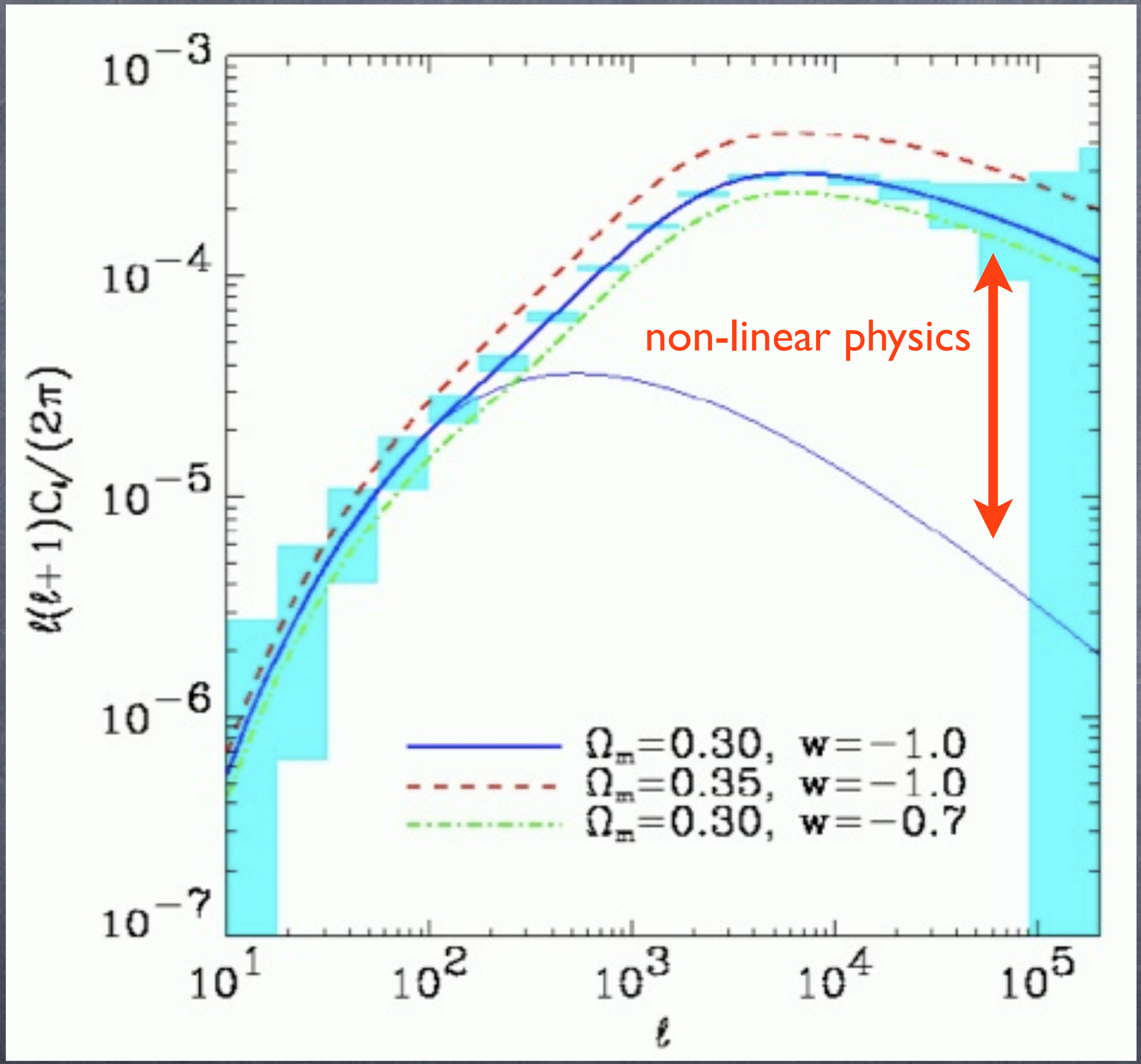
Cosmic shear: *mapping the invisible*

Weak lensing by large-scale structure is the most direct way to measure the clustering of matter.





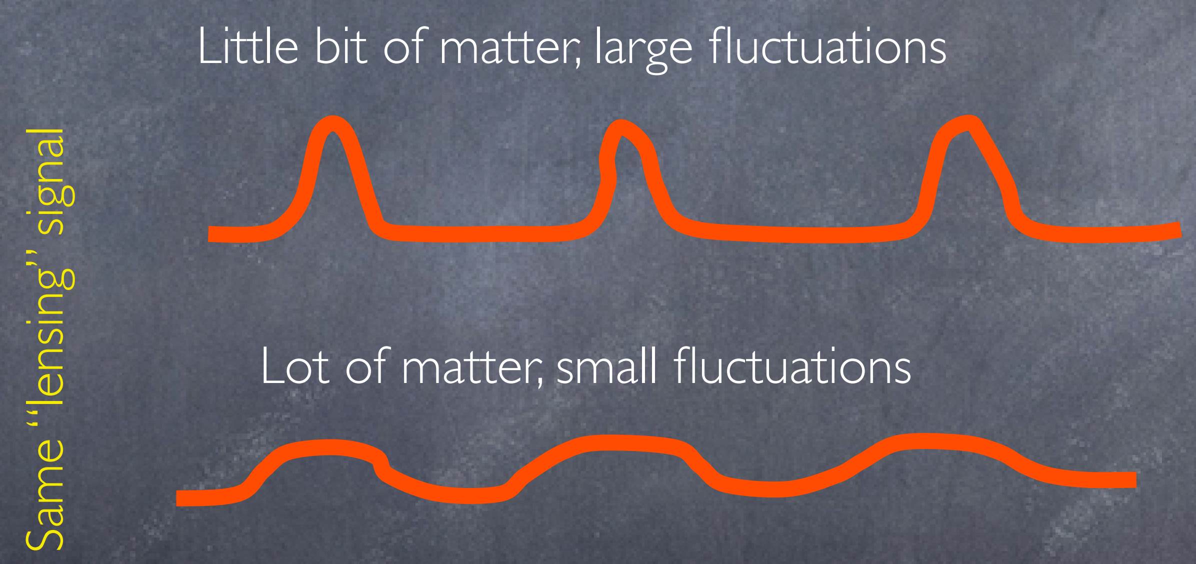
What does the signal mean?



The matter power spectrum (analogous to the that of the CMB) is one way to represent the measurements.

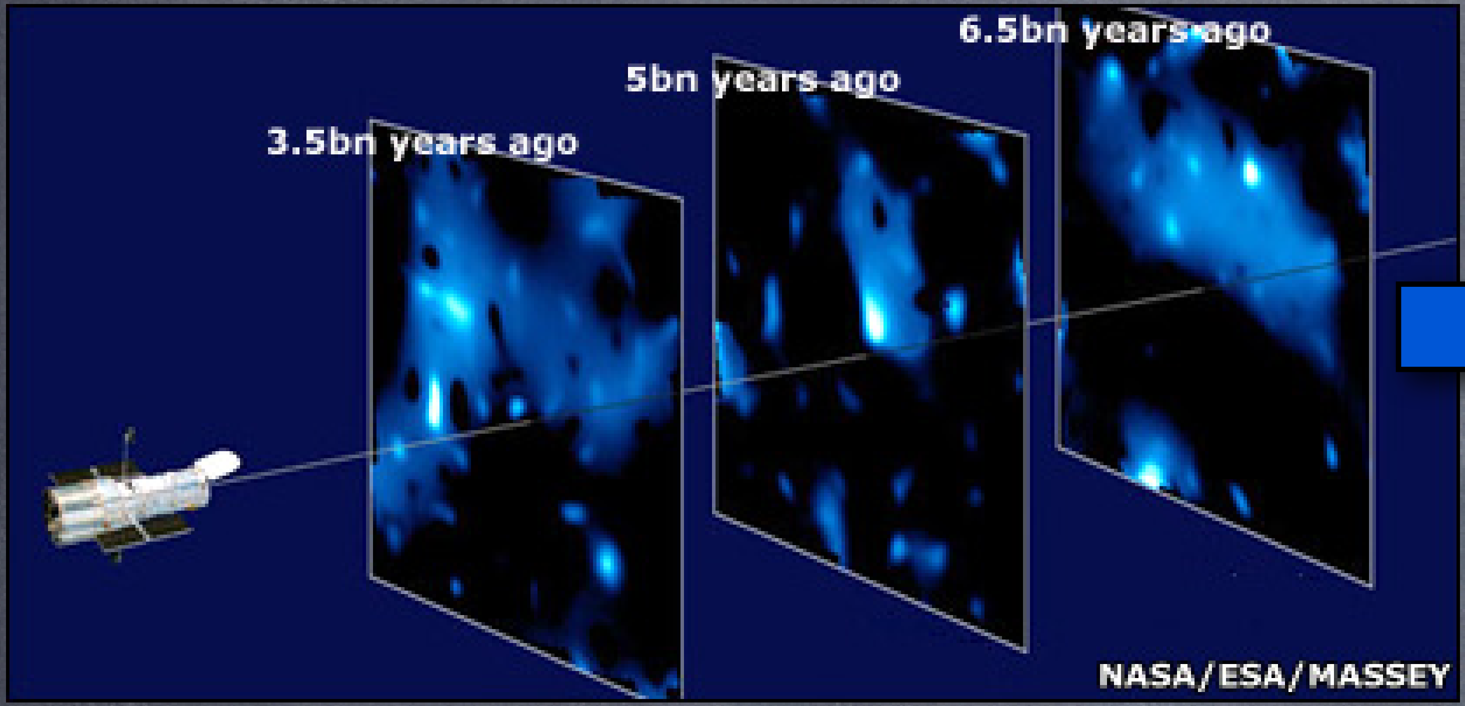
What does the signal mean?

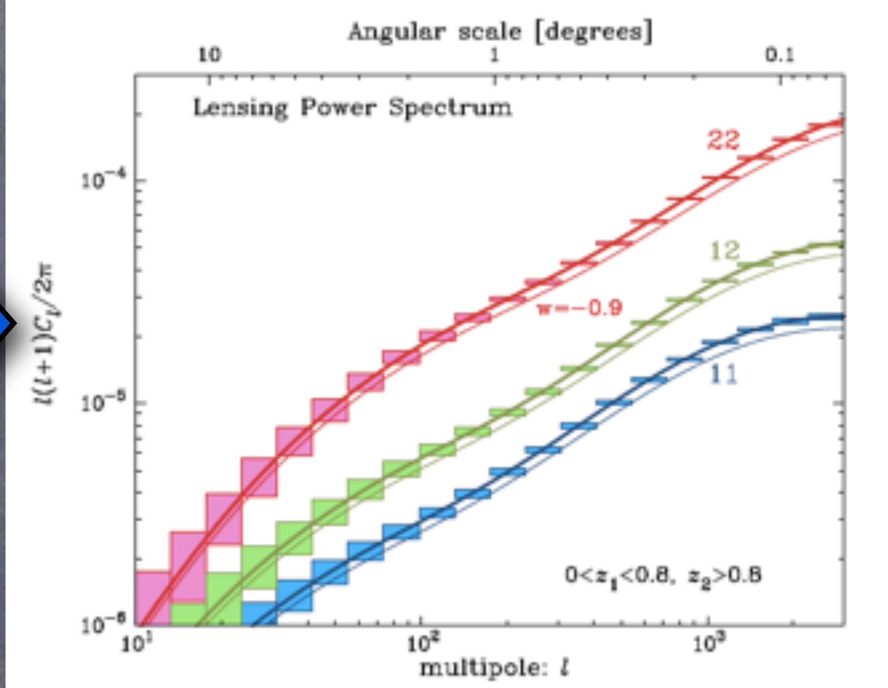
The cosmic shear signal is mainly a measurement of the variance in the density fluctuations.



To first order lensing measures a combination of the amount of matter Ω_m and the normalisation of the power spectrum σ_8.

Weak lensing tomography

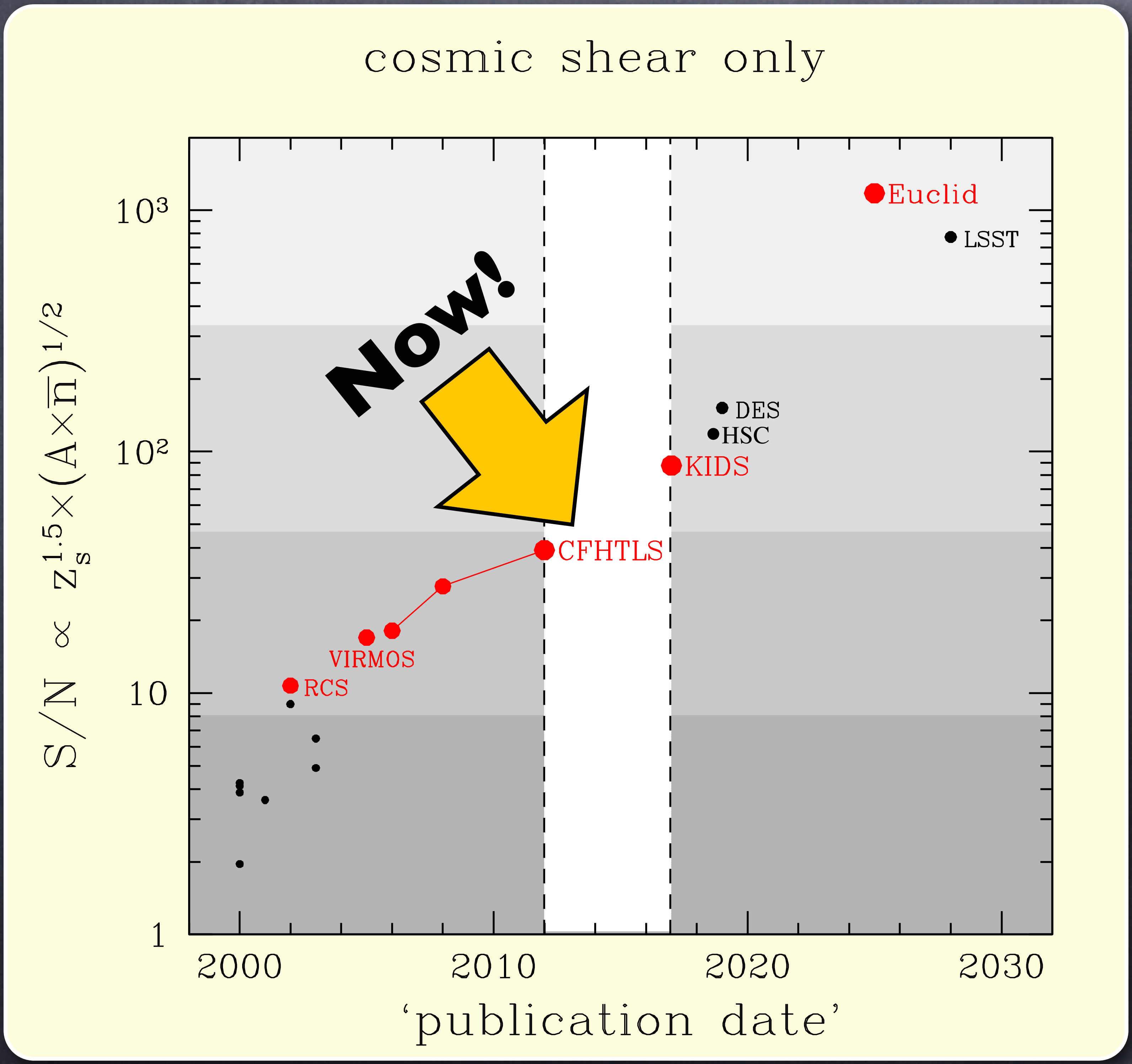




Source redshifts allow us to study the growth of structure

- Constraints on dark energy properties
- Test of gravity on cosmological scales

We are getting the numbers



Dark energy physics

↑

Dark energy constraints

↑

Measurement

↑

Detection

So far so good...

Precision ≠ Accuracy

For accurate cosmology we need:

- accurate shapes for the sources
- accurate photometric redshifts
- accurate interpretation of the signal

- Observational distortions are larger than the signal
- Galaxies are too faint for large spectroscopic surveys
- Sensitive to non-linear structure formation

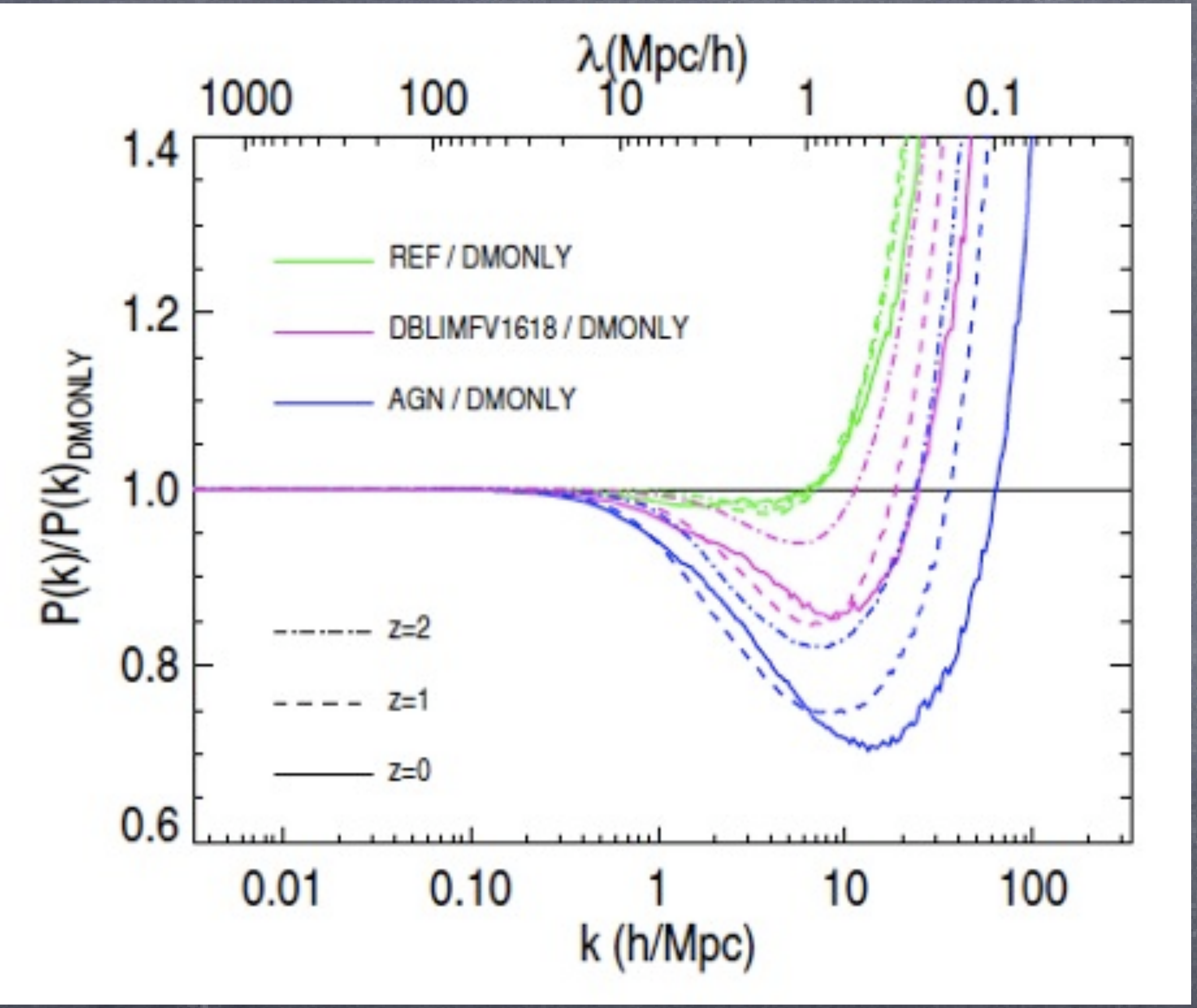
Power spectrum prediction

To interpret the observed lensing signal we need to compare to the predicted matter power spectrum, including non-linear scales.

↓

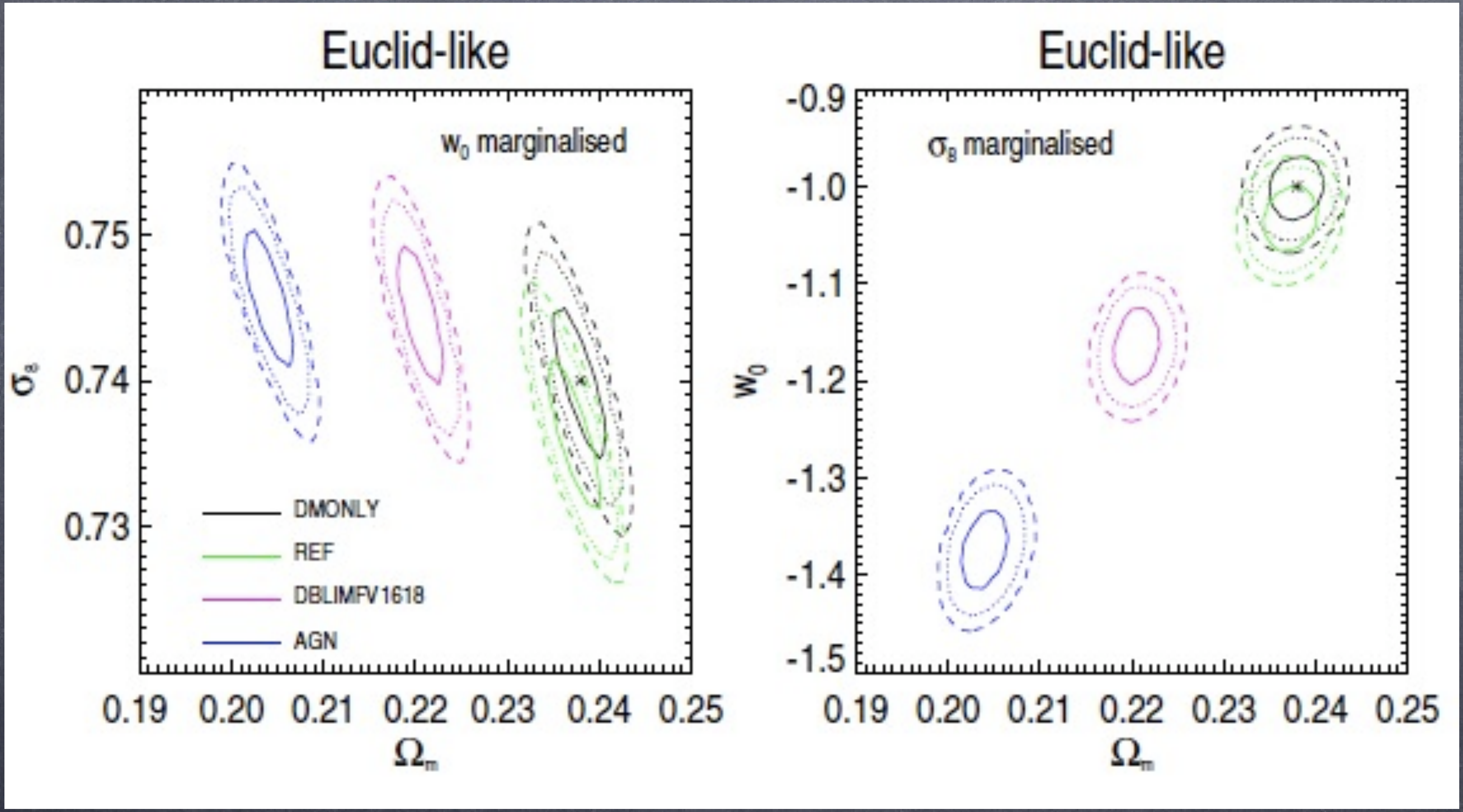
Solution: XXXXXXXXL simulations?

Baryon physics is important



van Daalen et al. (2011): feedback processes can modify the matter power spectrum significantly on scales that are important for cosmic shear.

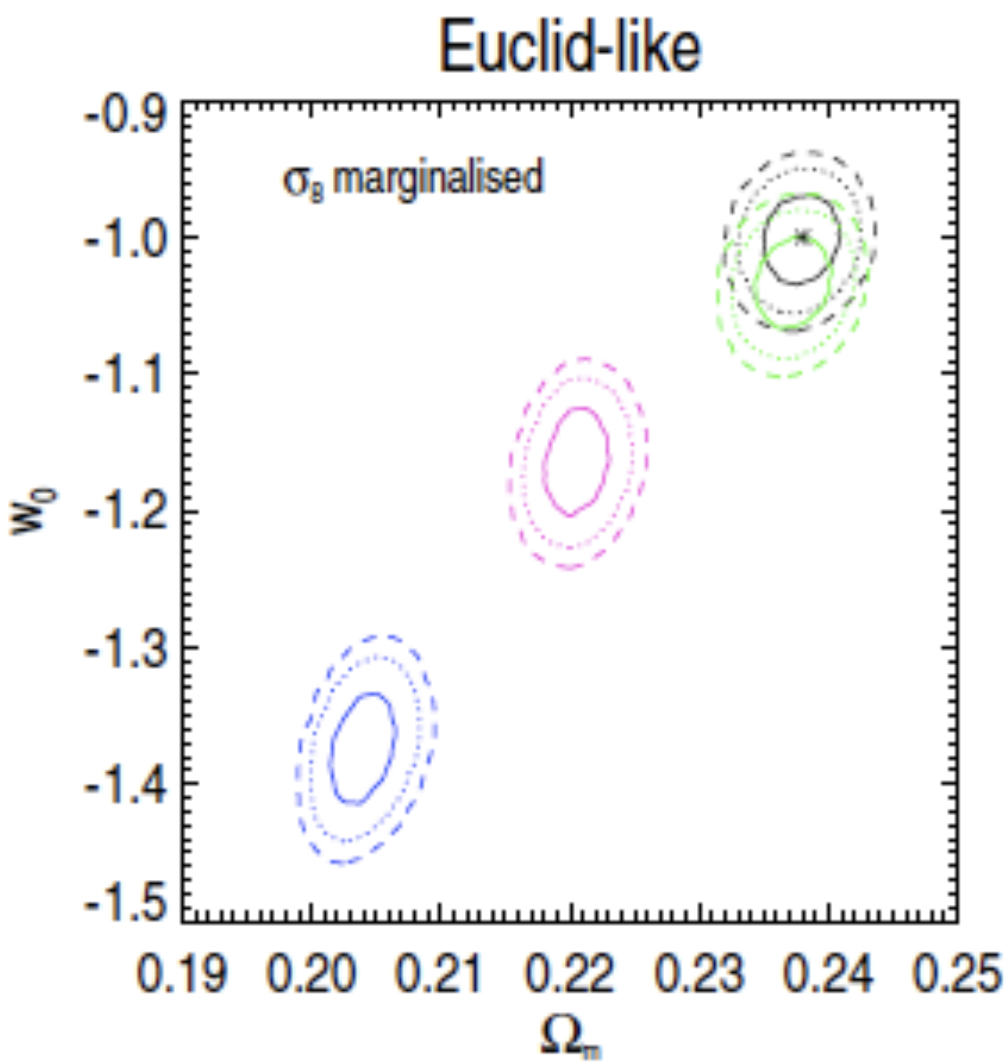
Baryon physics is important



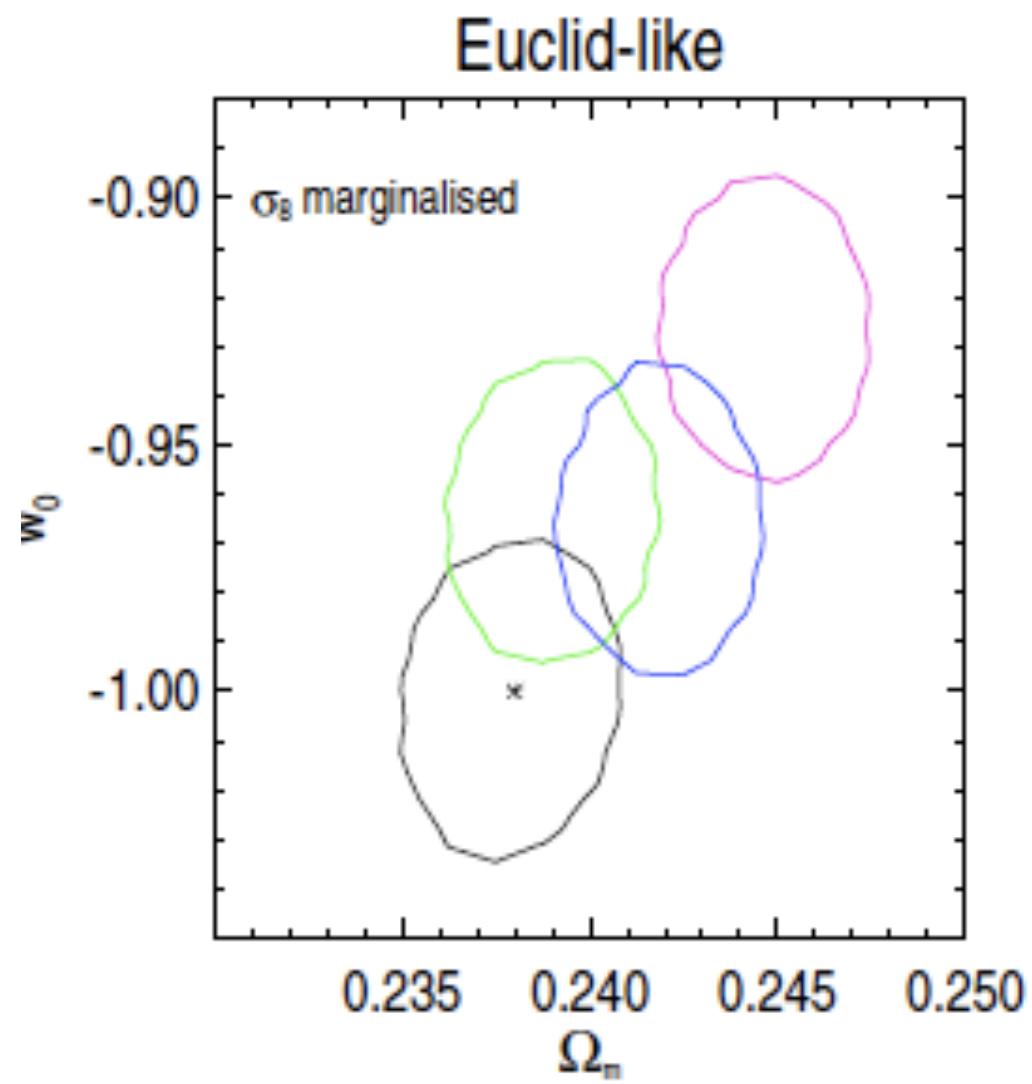
Semboloni et al. (2011; 2013): ignoring feedback may lead to large biases. We cannot just use bigger dark matter-only simulations.

Biases can be reduced

Semboloni et al. (2011; 2013)



Ignoring feedback

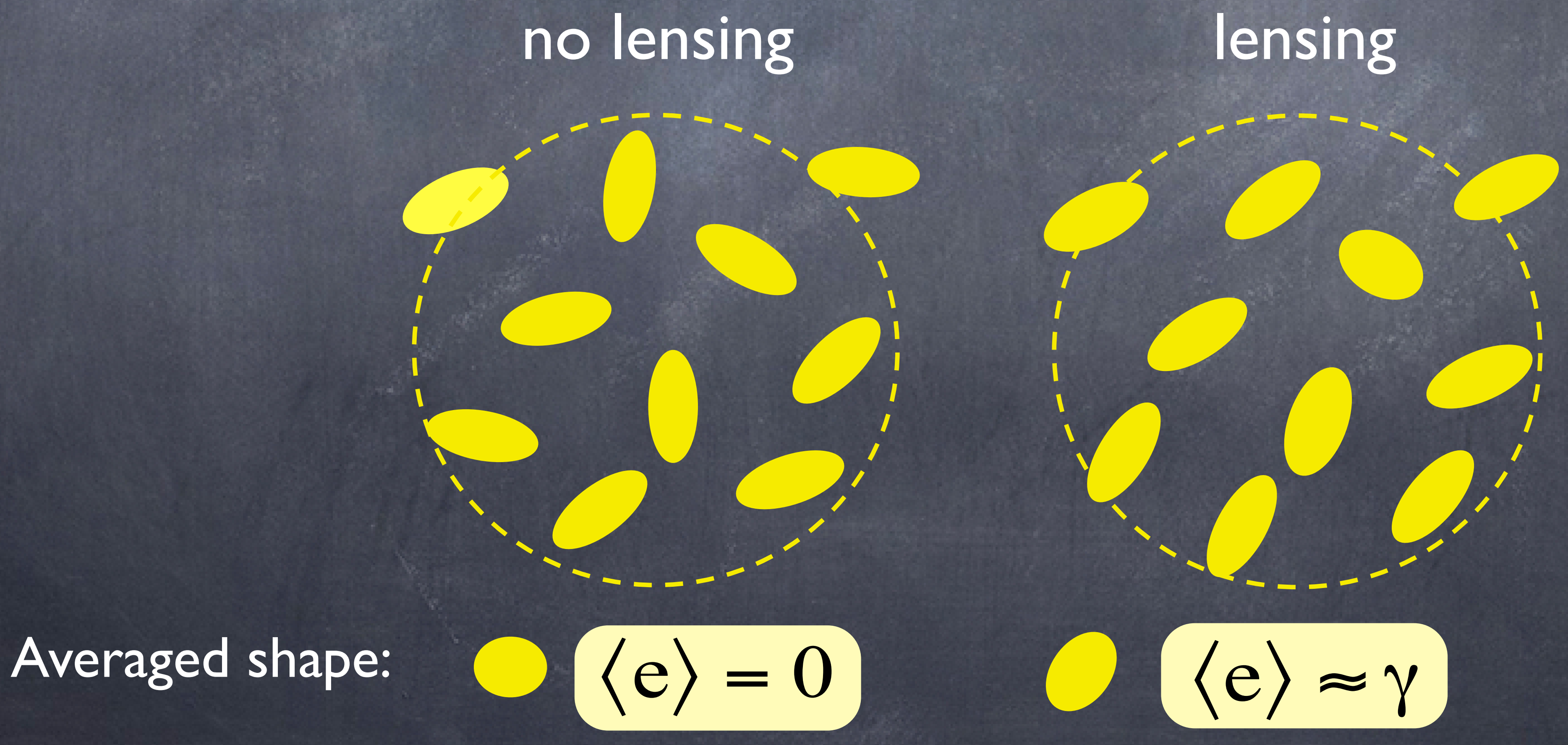


Accounting for feedback

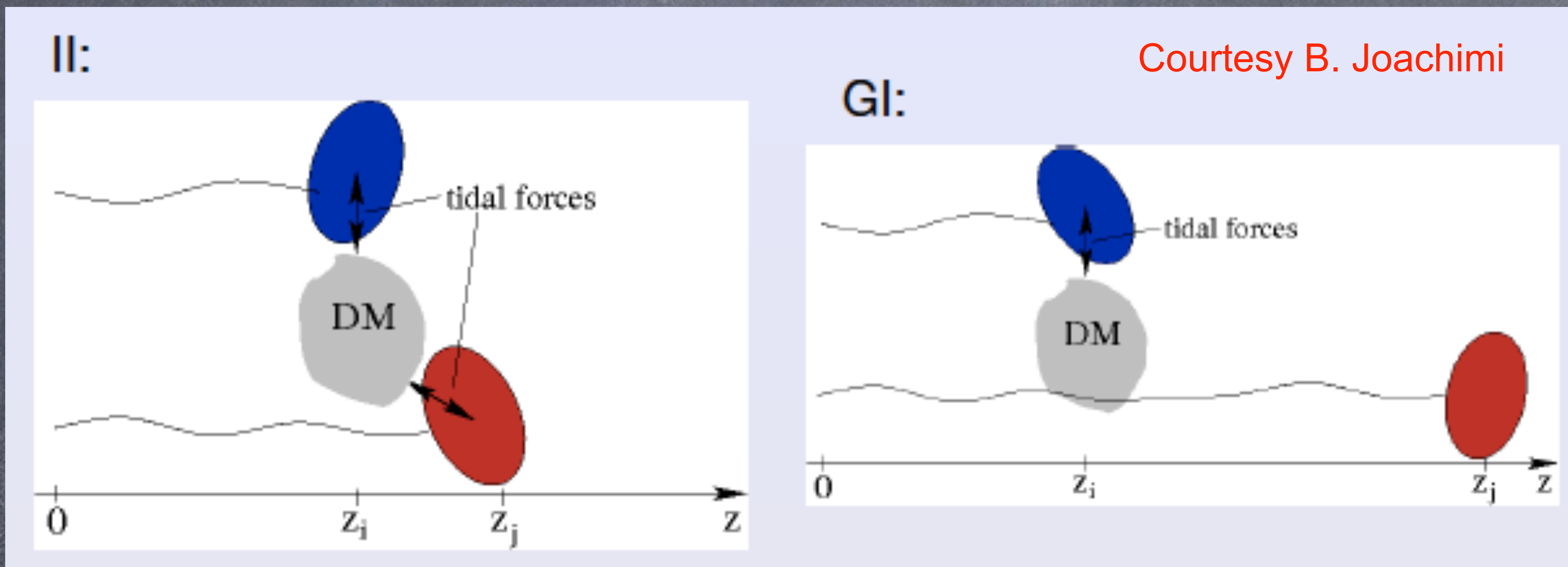
It is a noisy business

The lensing signal is small: we need measure the shapes of many galaxies with high accuracy

The underlying assumption is that the position angles are random in the absence of lensing. Intrinsic alignments will complicate things for the next generation of surveys.



Intrinsic Alignments

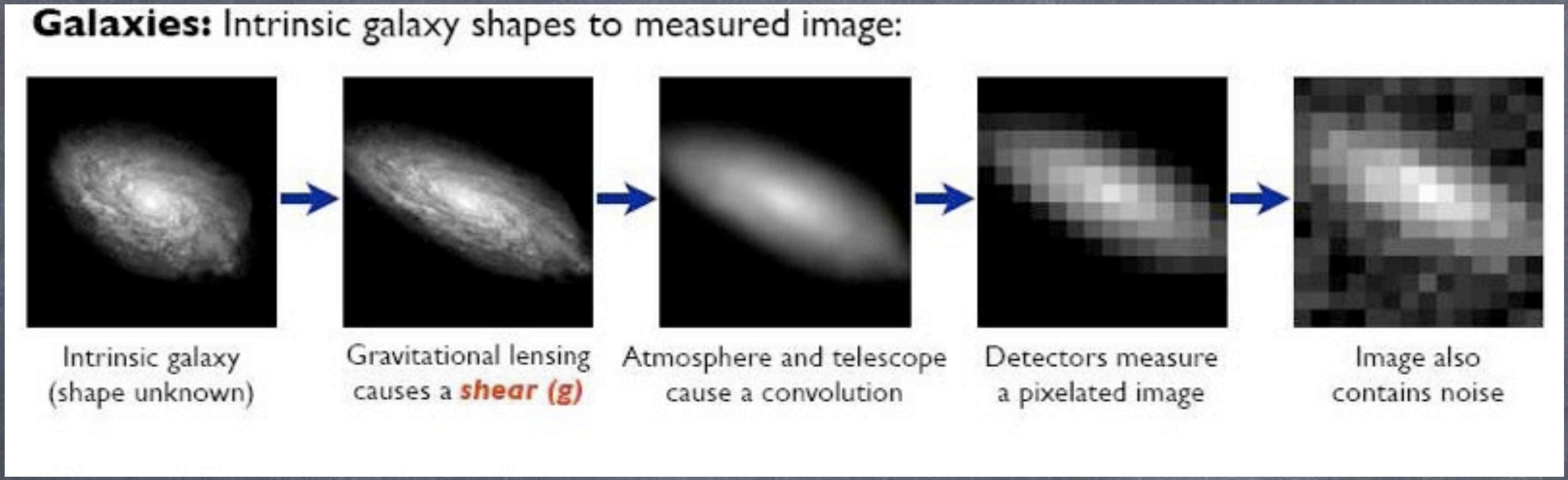


2pt correlation:

$$\langle\epsilon_i\epsilon_j\rangle = \underbrace{\langle\gamma_i\gamma_j\rangle}_{\text{GG}} + \underbrace{\langle\epsilon^s_i\epsilon^s_j\rangle}_{\text{II}} + \underbrace{\langle\gamma_i\epsilon^s_j\rangle + \langle\epsilon^s_i\gamma_j\rangle}_{\text{GI}}$$

This drives required photometric redshift precision

Measuring shapes...

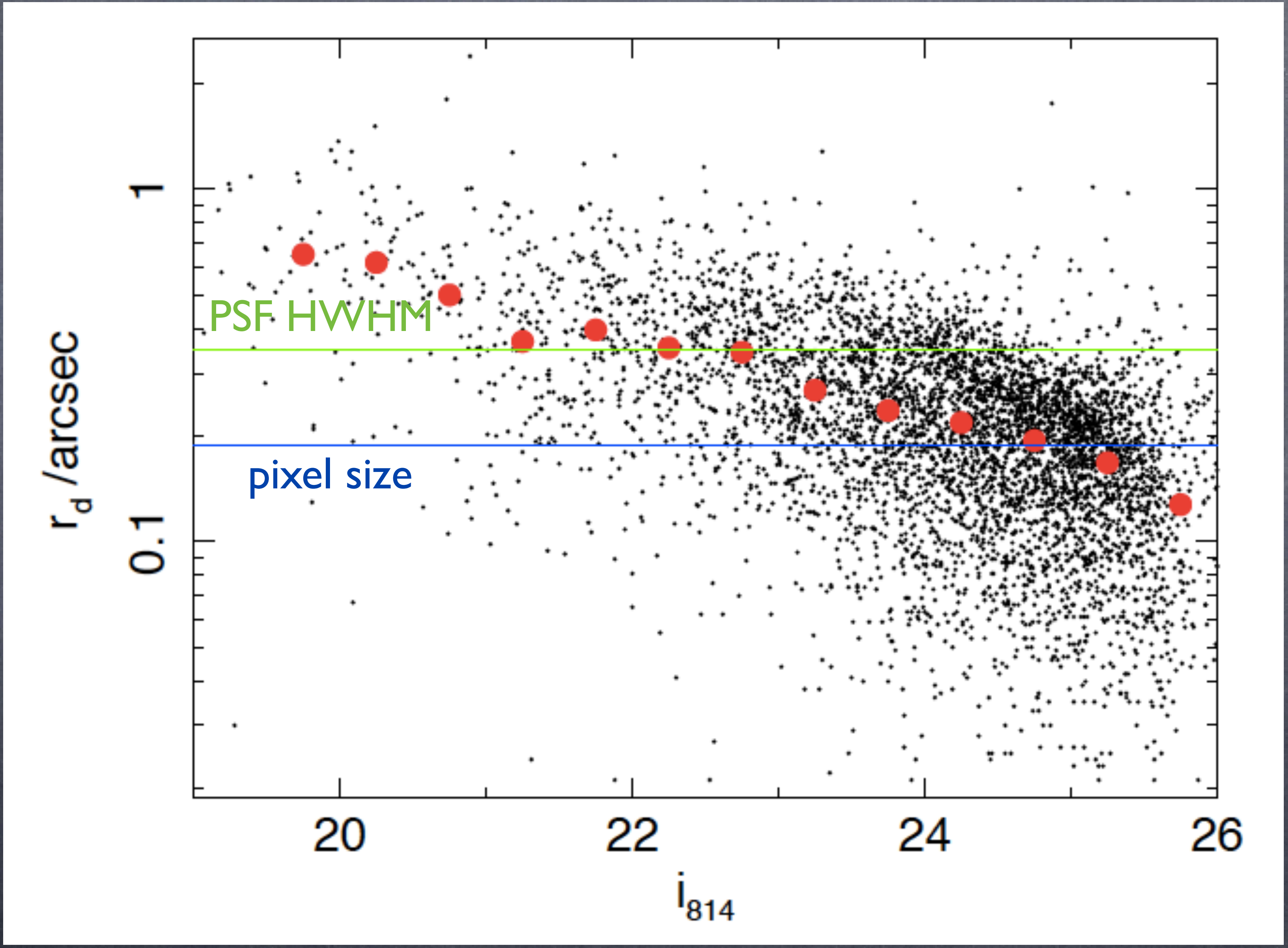


GREAT'08 challenge

Measure the shapes of objects like this?

The observed images are "corrupted" by the PSF which needs to be corrected for with high accuracy.

... of small galaxies



Miller et al. (2013)

PSF matters

Massey et al. (2013): flow of systematics
Cropper et al. (2013): experiment design

$$\varepsilon_{\rm gal} = \frac{\varepsilon_{\rm obs} R^2_{\rm obs} - \varepsilon_{\rm PSF} R^2_{\rm PSF}}{R^2_{\rm obs} - R^2_{\rm PSF}}$$

what we want — what we observe

$$\widehat{\gamma} = (1+m)\gamma + c$$

multiplicative — additive

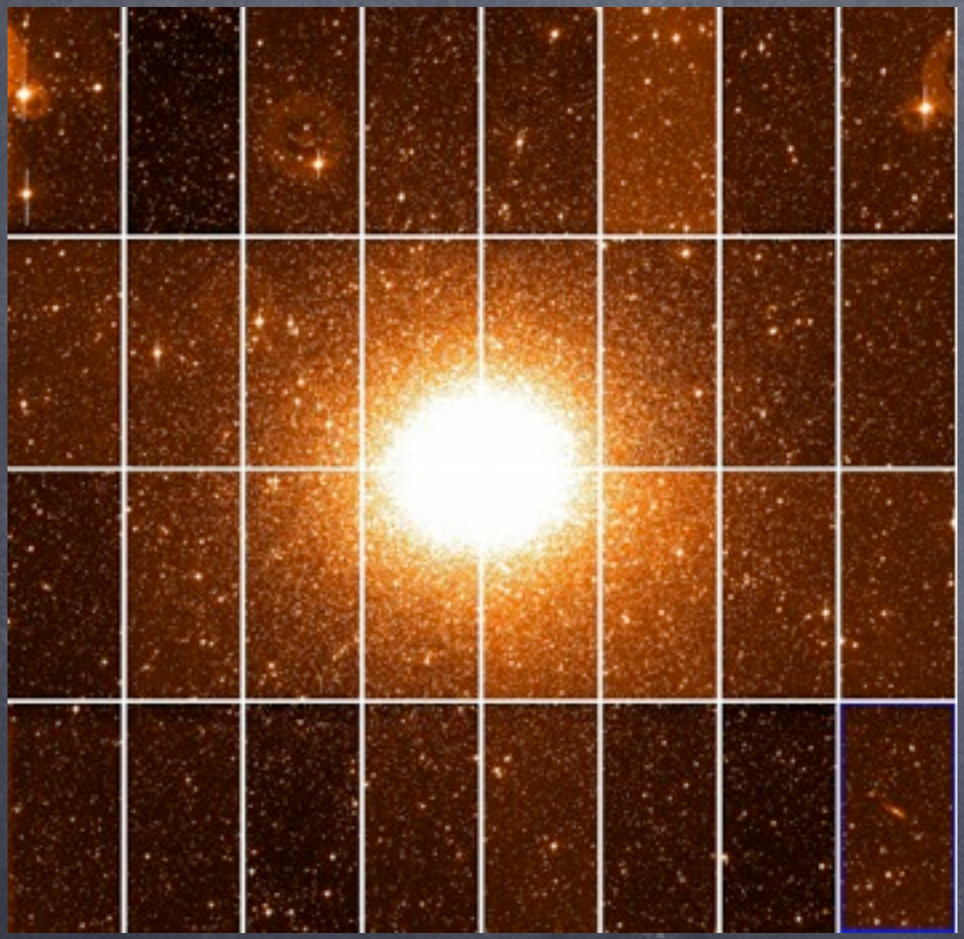
PSF matters

Many things contribute...

$$\mathcal{M} = \frac{2}{P_R}\left\langle \frac{R^2_{\rm PSF}}{R^2_{\rm gal}} \right\rangle \left(\frac{\langle \delta(R^2_{\rm PSF})\rangle}{\langle R^2_{\rm PSF}\rangle} + 2\frac{\langle \delta(R_{\rm NC})\rangle}{\langle R_{\rm obs}\rangle} + \langle \mu \rangle \right)$$
$$+ \frac{1}{P_R^2}\left\langle \frac{R^4_{\rm PSF}}{R^4_{\rm gal}} \right\rangle \left(\frac{\sigma^2[R^2_{\rm PSF}]}{\langle R^4_{\rm PSF}\rangle} + 4\frac{\sigma^2[R_{\rm NC}]}{\langle R^2_{\rm obs}\rangle} \right).$$

- PSF size
- PSF model
- correction method

More complications



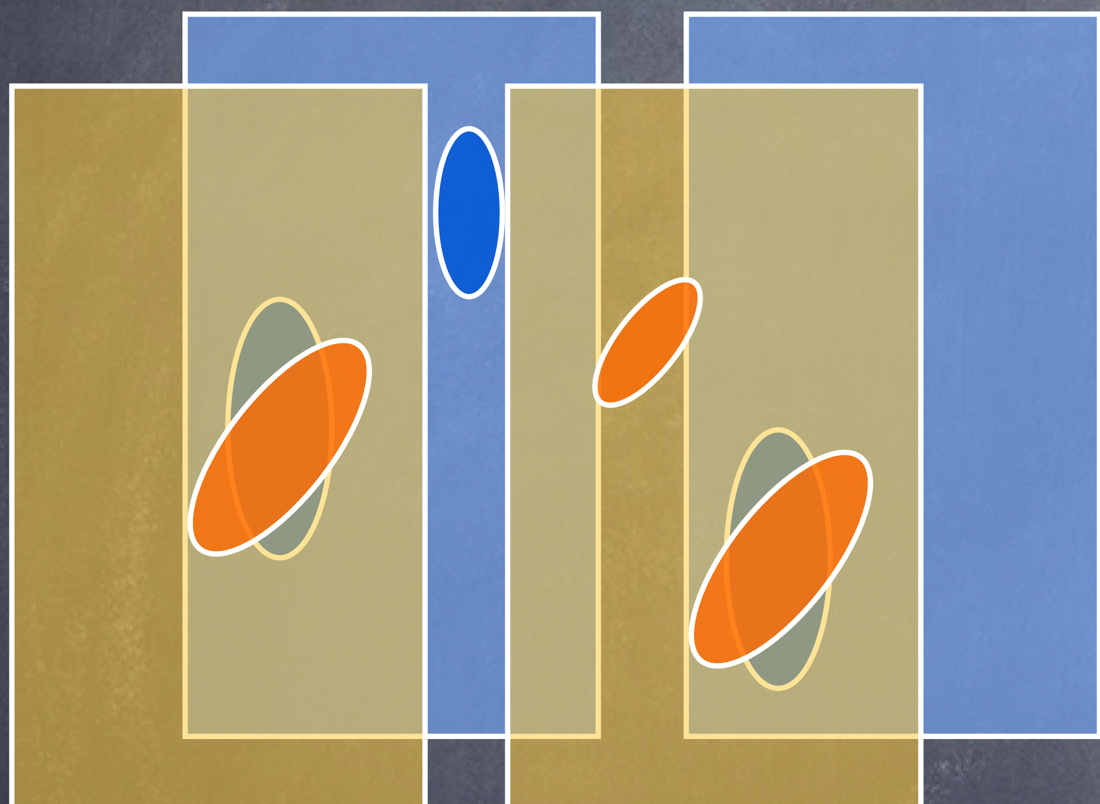
VST image of ωCen

The mapping between pixel and sky coordinates is not linear: the camera induces a shear.
Remapping smooths the image

To cover the large field of view need a mosaic of CCDs.

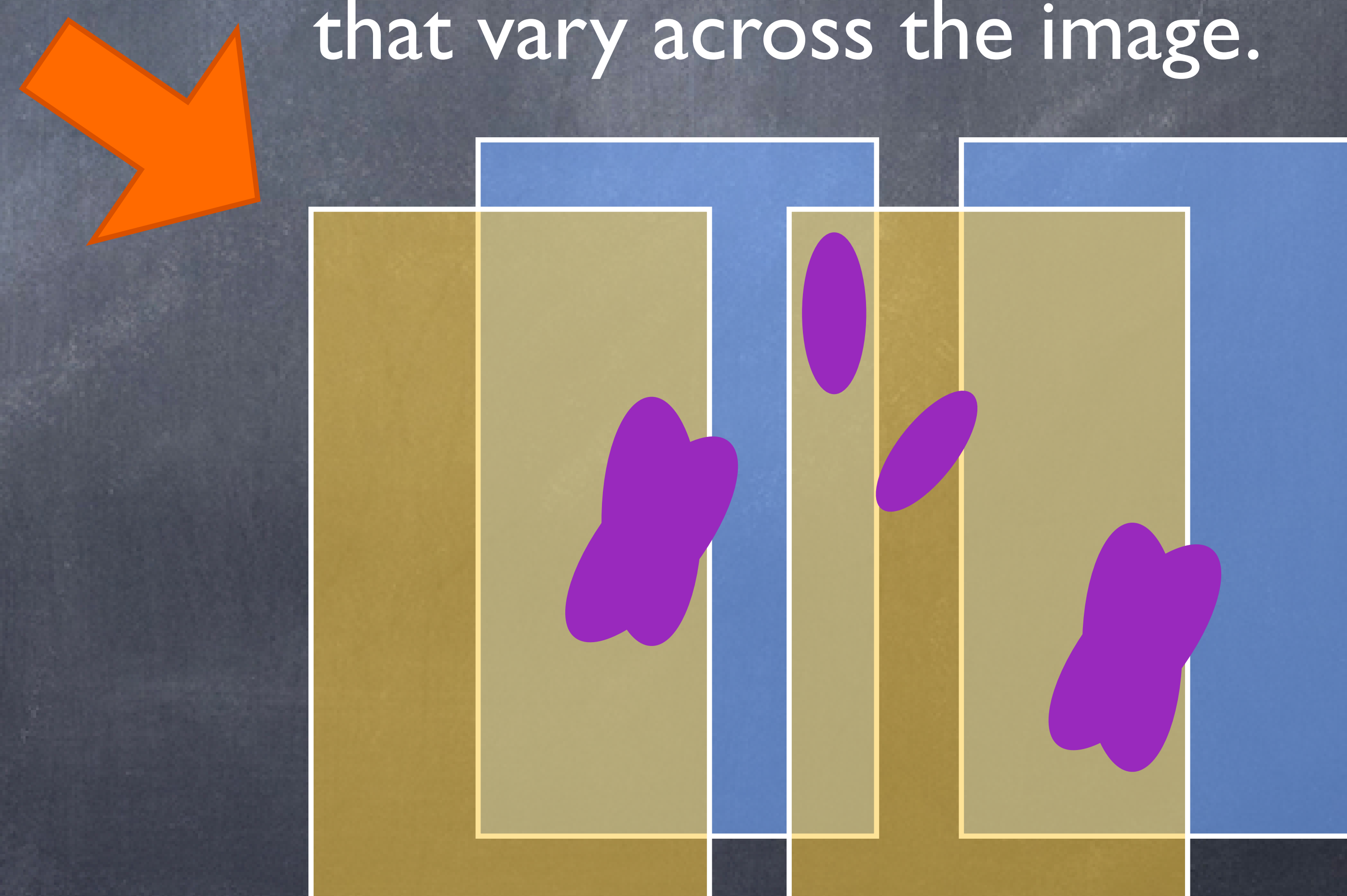
We combine multiple exposures that have been offset.

More complications



Observing conditions change between exposures

This leads to complicated PSF that vary across the image.



New methods

We need methods that can operate on individual exposures instead of stacked images.

This was developed for CFHTLenS: ***lensfit***
(Miller et al. 2013)

Bayesian forward-fitting of galaxy model to the individual exposures (each has its own PSF model)

- bulge+disk components (B/T variable but ratio of scale lengths fixed)
- priors based on SDSS and HST data

Dealing with systematics

Weak lensing is rather unique in the sense that we can study (PSF-related) systematics very well.

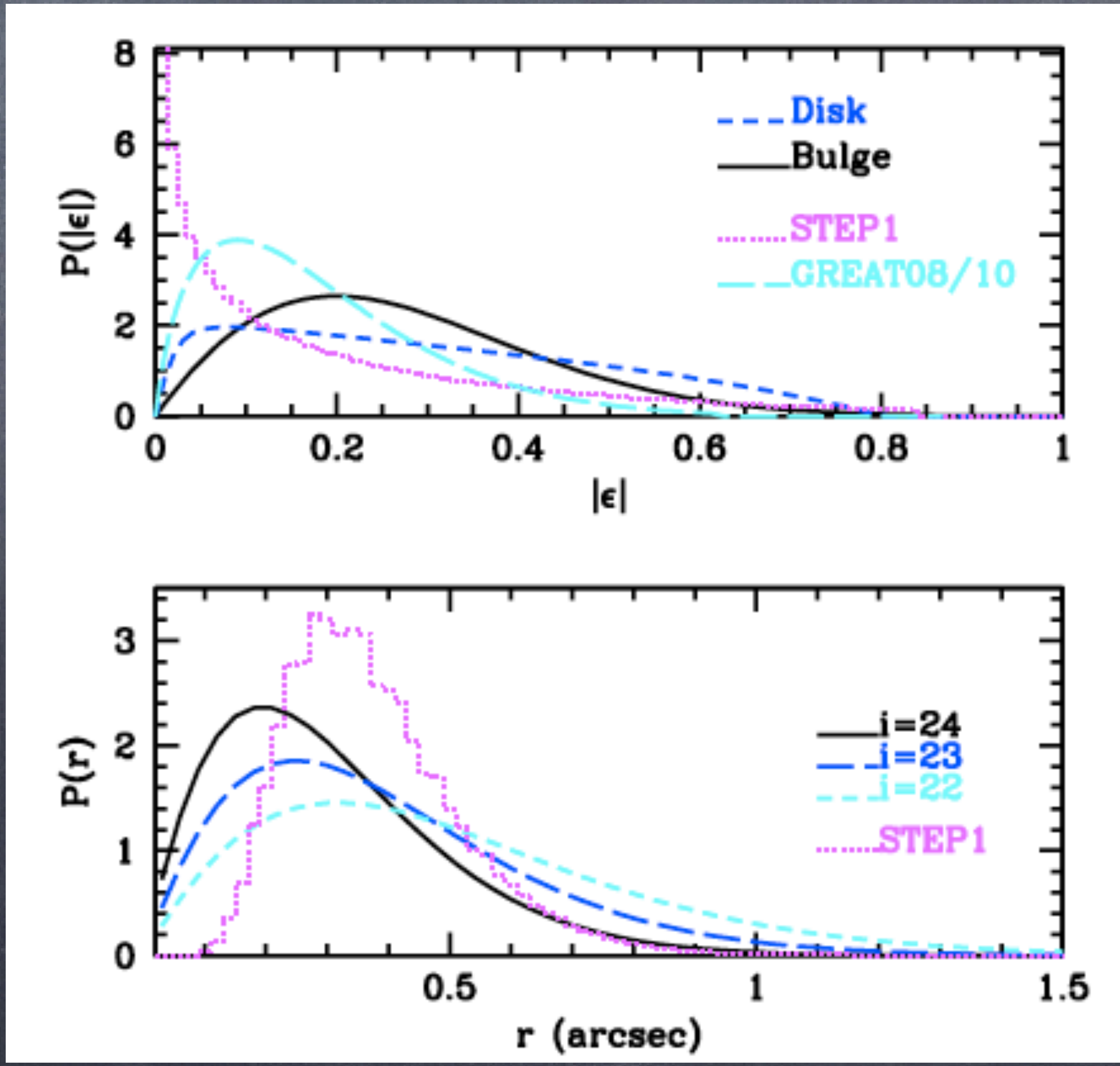
-we can create simulated data to test the measurement techniques (e.g. STEP, GREAT)

-we can perform cosmology-independent tests (star-galaxy correlations)

-we can search for systematics-induced patterns in the final results (E/B modes)

Tests on simulations

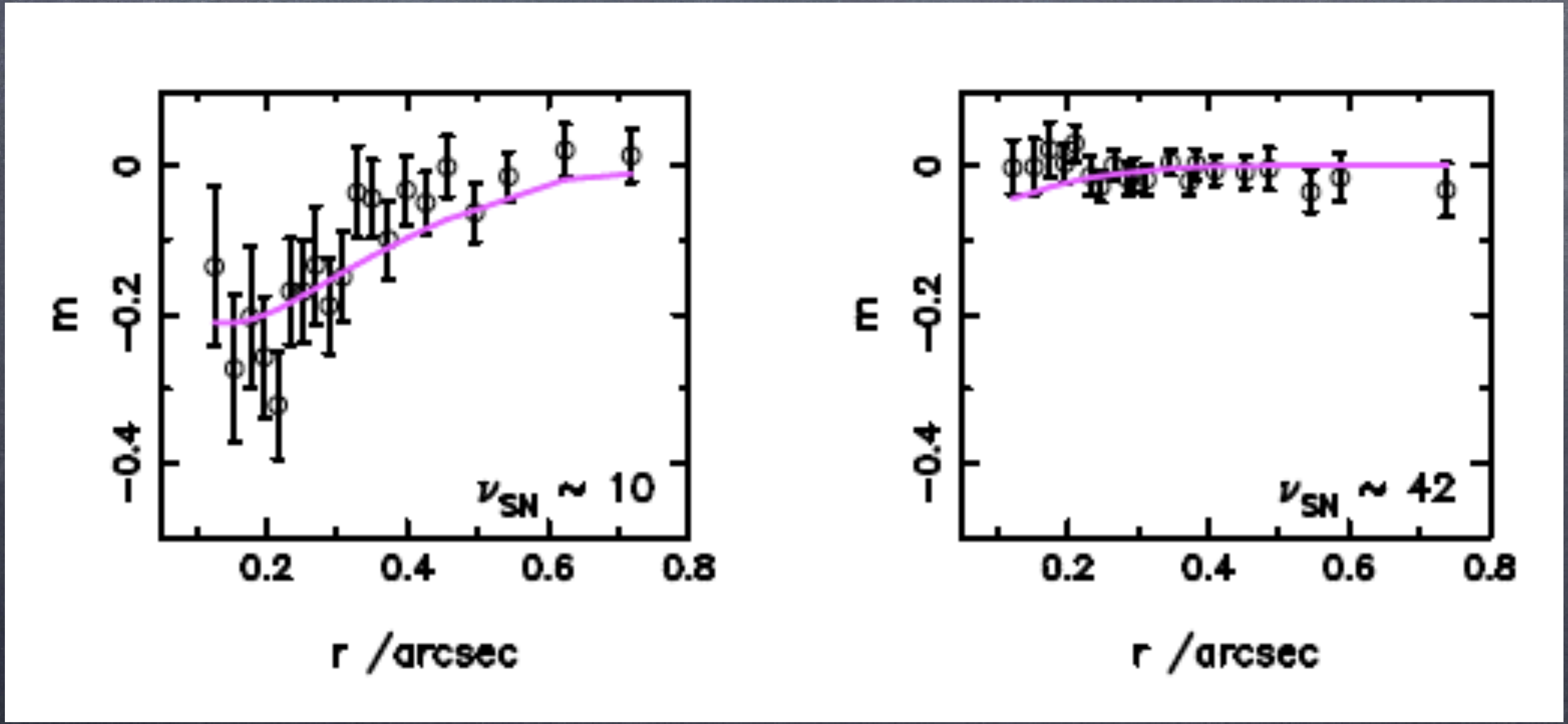
CFHTLenS image simulations are created to match the observed properties of galaxies and the PSF.



Miller et al. (2013)

Tests on simulations

Simulations show a S/N dependent multiplicative bias.
This is expected (also see Melchior & Viola, 2012)



Miller et al. (2013)

CFHT Legacy Survey

Uses 5 yrs of data from the Deep, Wide and Pre-survey components of the CFHT Legacy Survey

State-of-the-art cosmological survey with 154 deg^2 uniquely covered

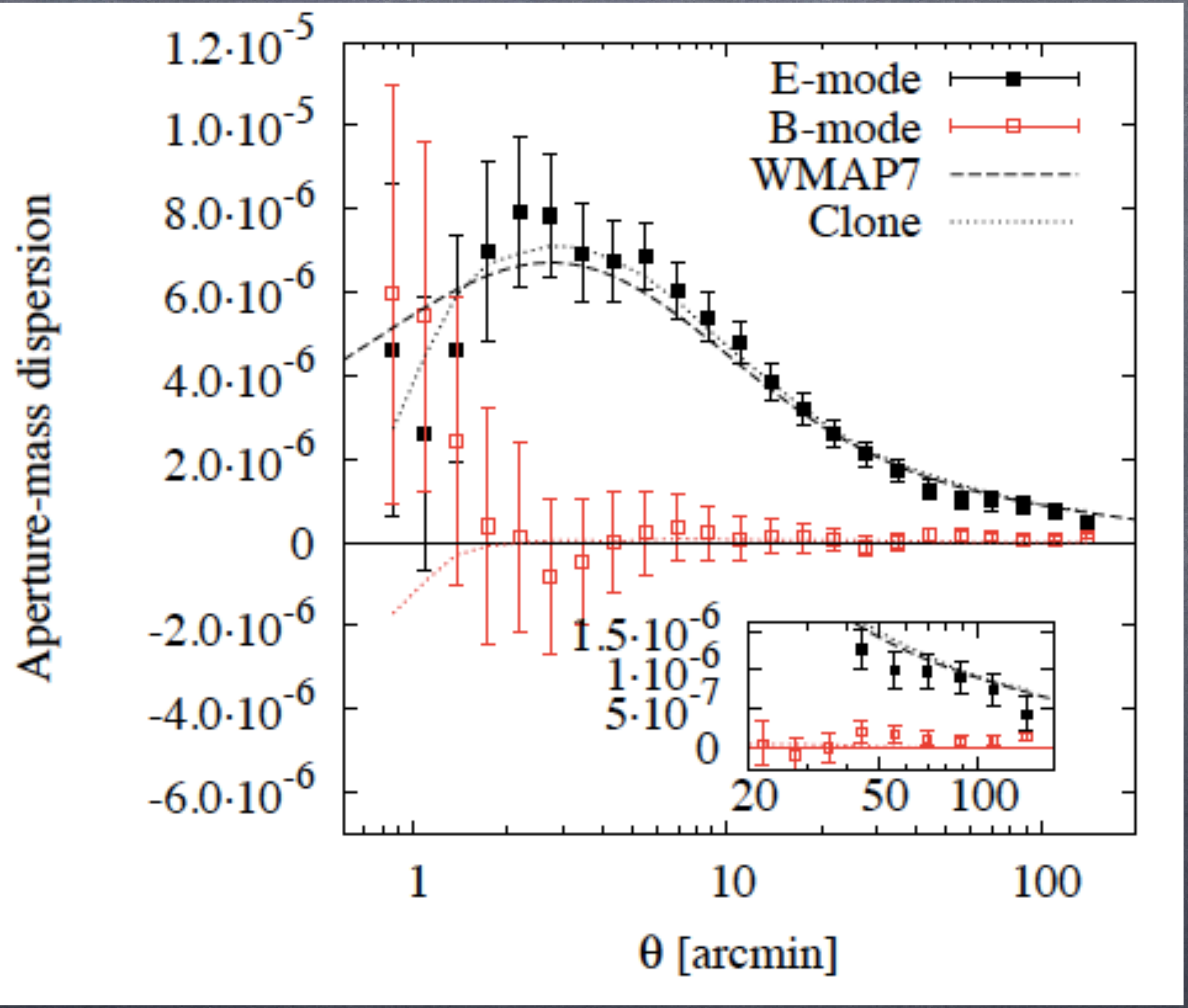
- lensing analysis used the 7 i-band images (seeing <0.85")
- ugriz to i<24.7 (7σ extended source)
- 4 fields

Public release:
www.cfhtlens.org

CFHTLenS: the team

Tomography is difficult: we need a large team!

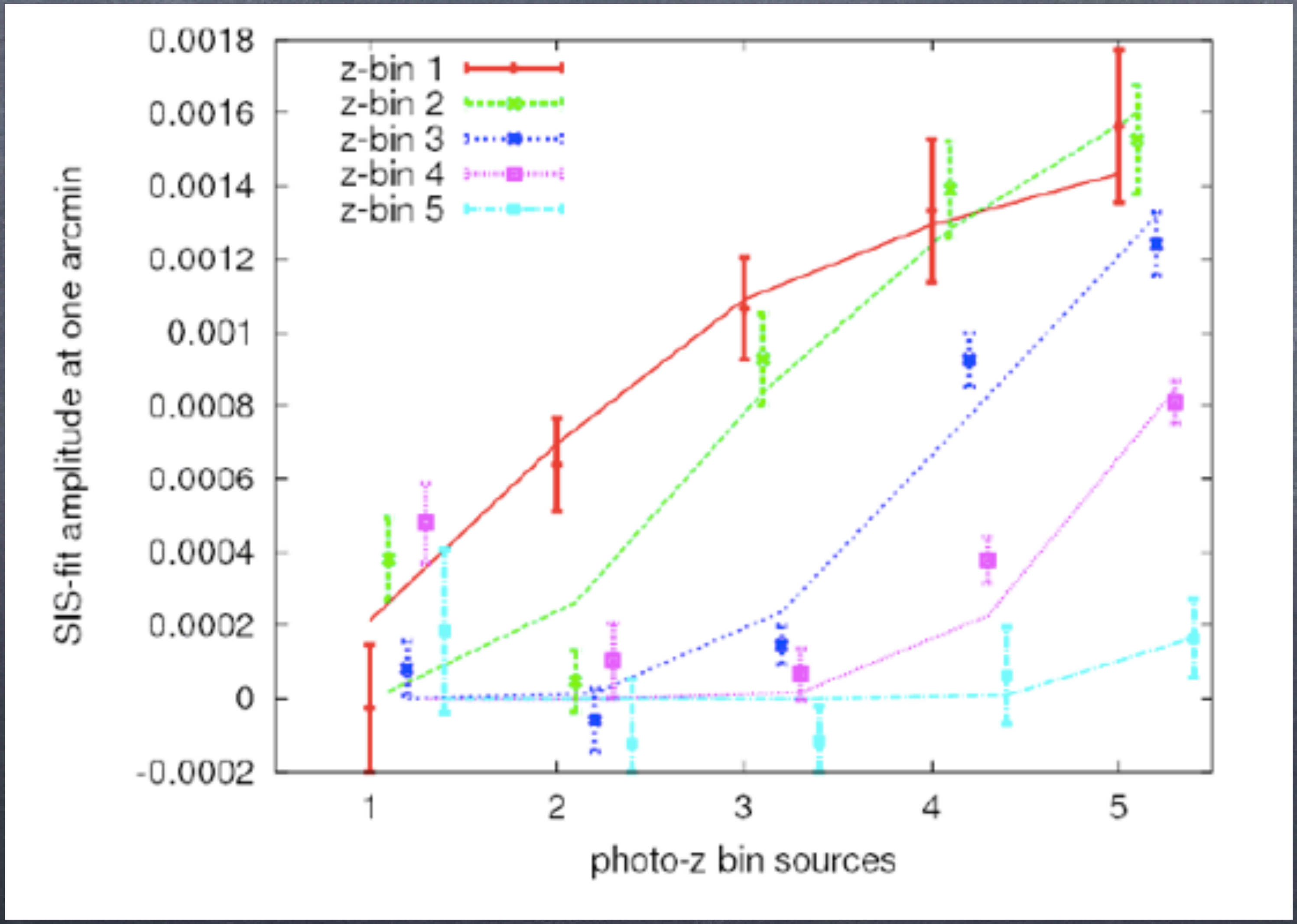
Signal looks good!



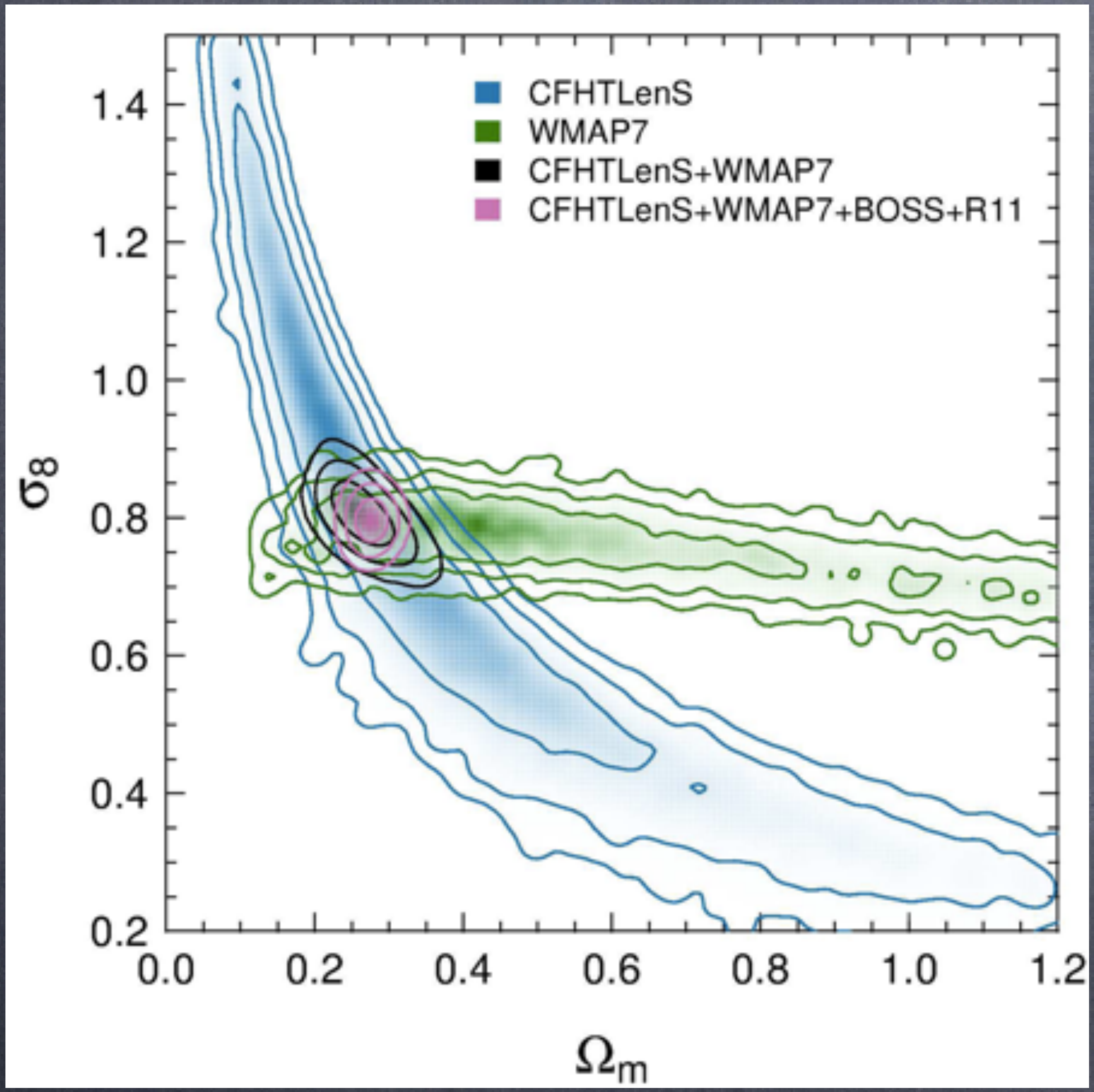
Kilbinger et al. (2013)

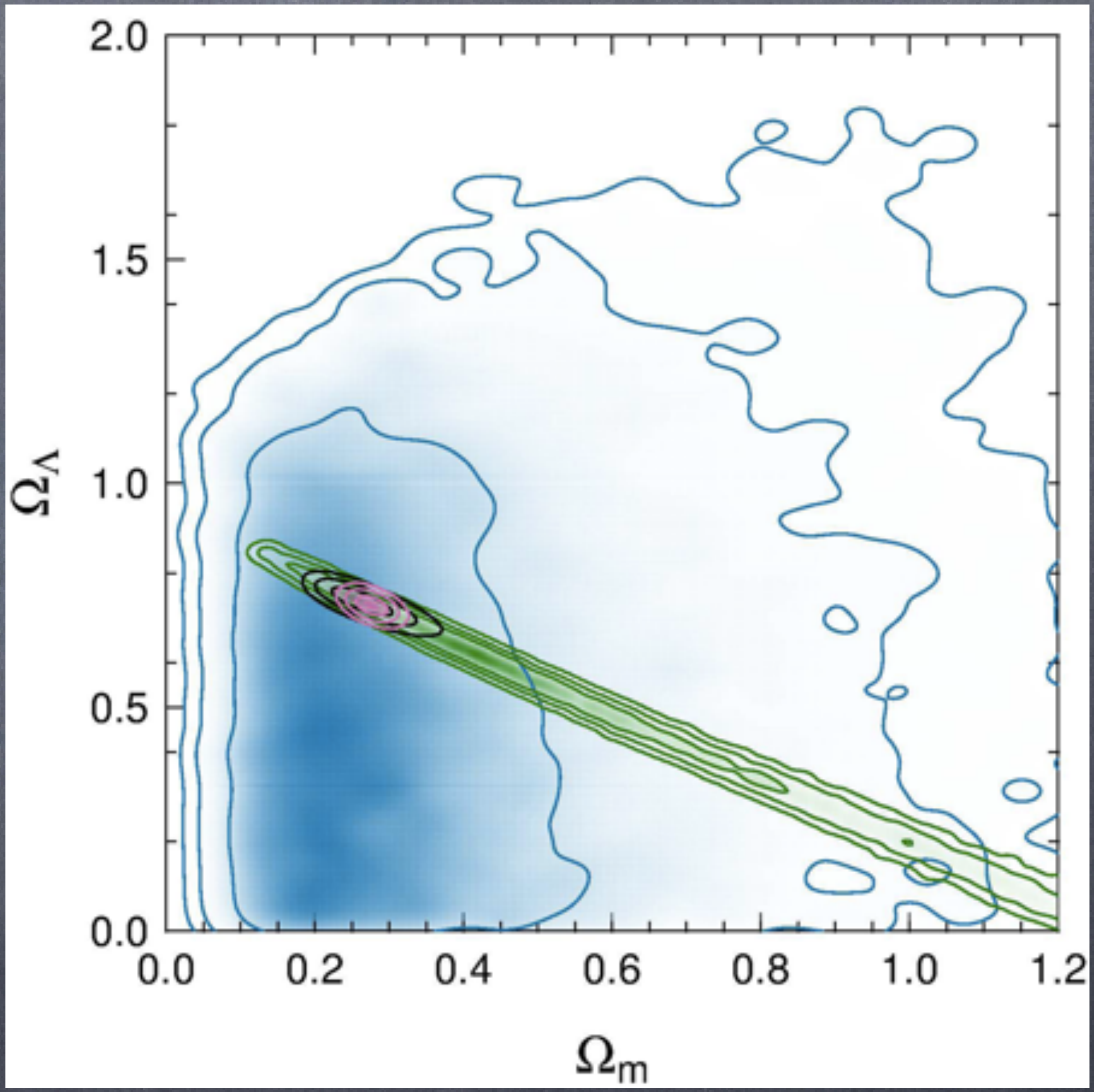
Lensing signal vs redshift

To test the redshift dependence we examine the galaxy-galaxy lensing signal (very weak cosmology dependence)



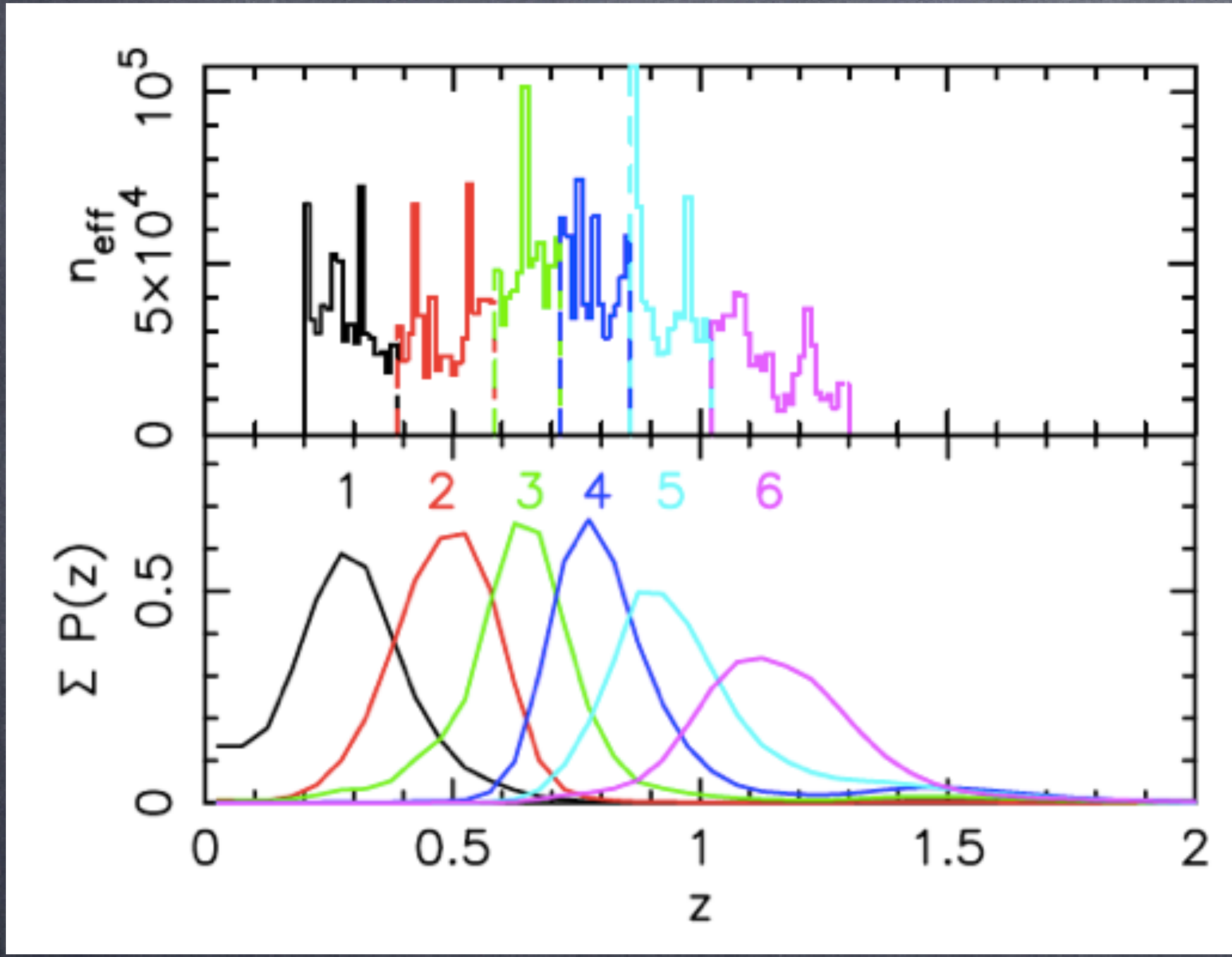
2-bin tomography

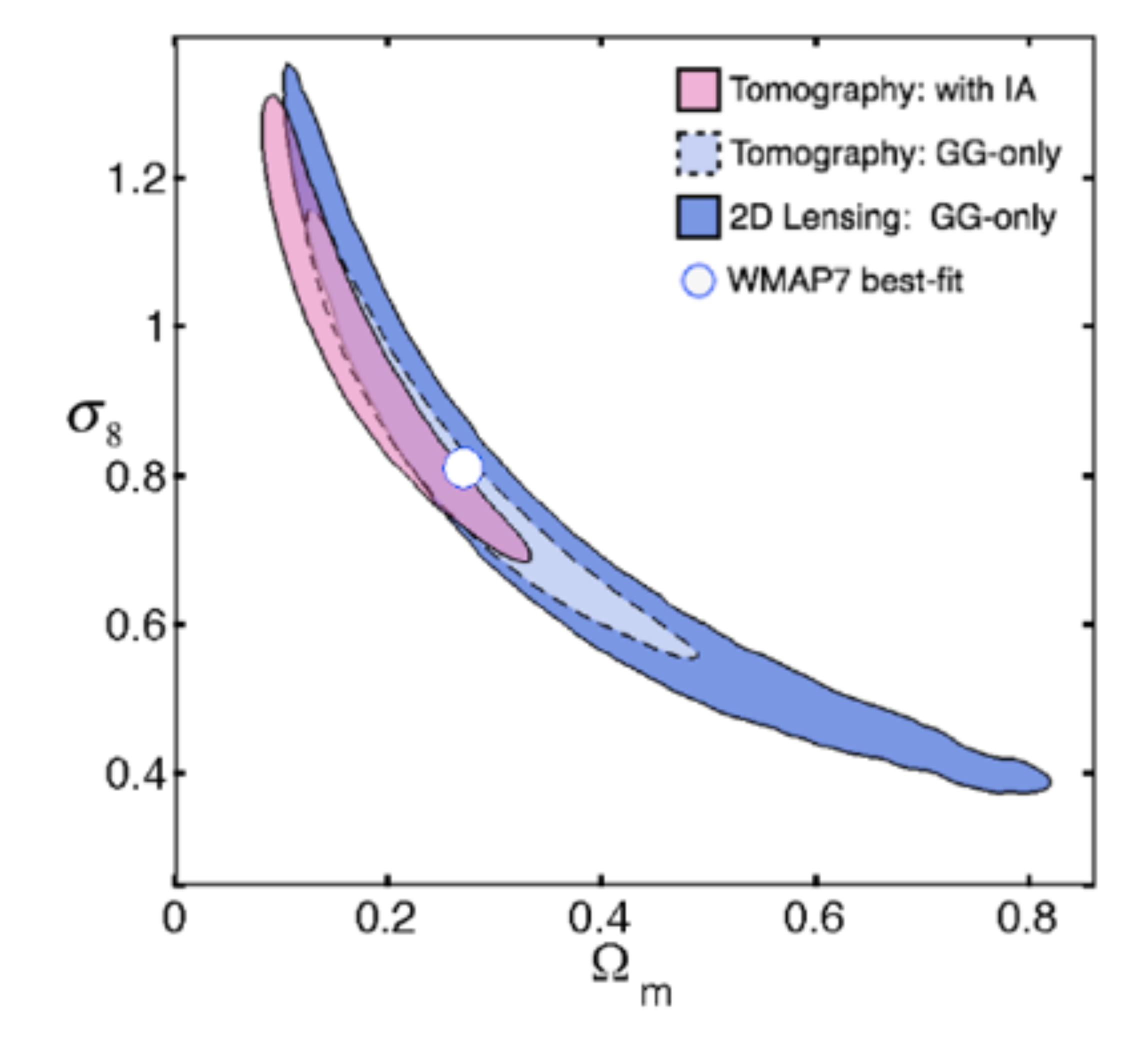




Benjamin et al. (2013): a detailed study of the fidelity of photometric redshift shows we can do tomography

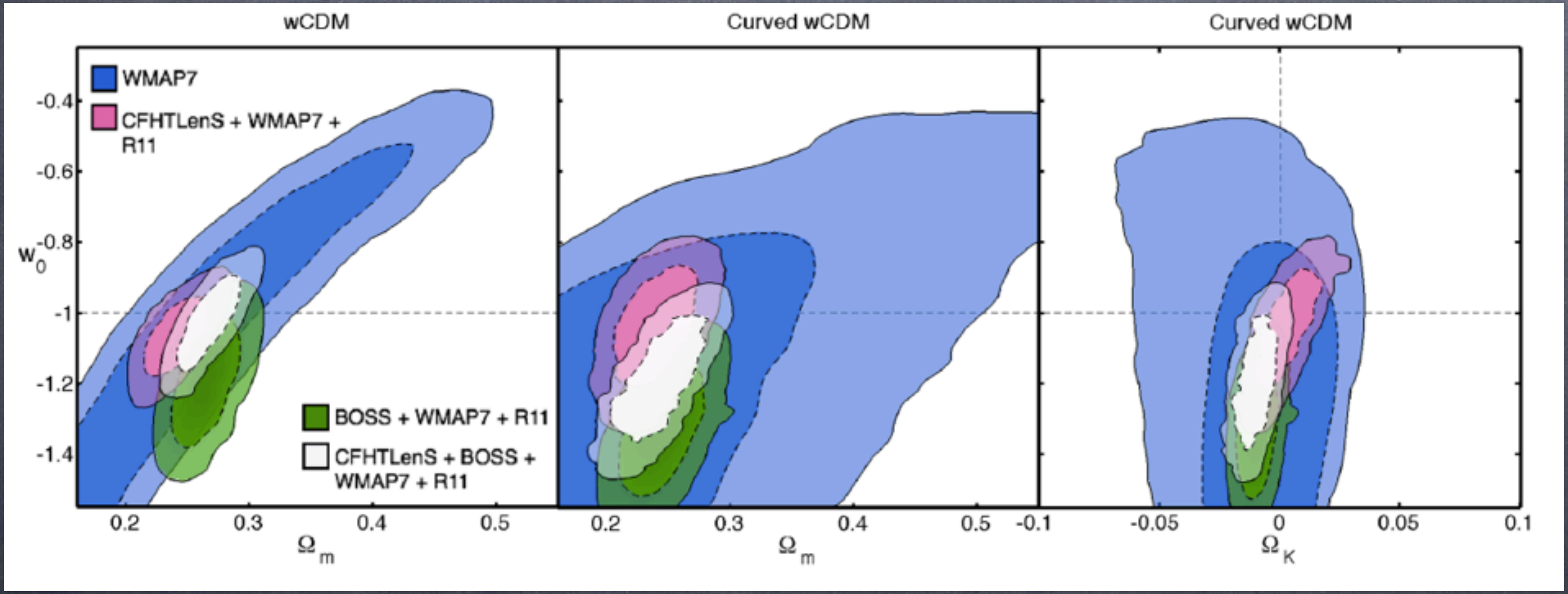
6-bin tomography





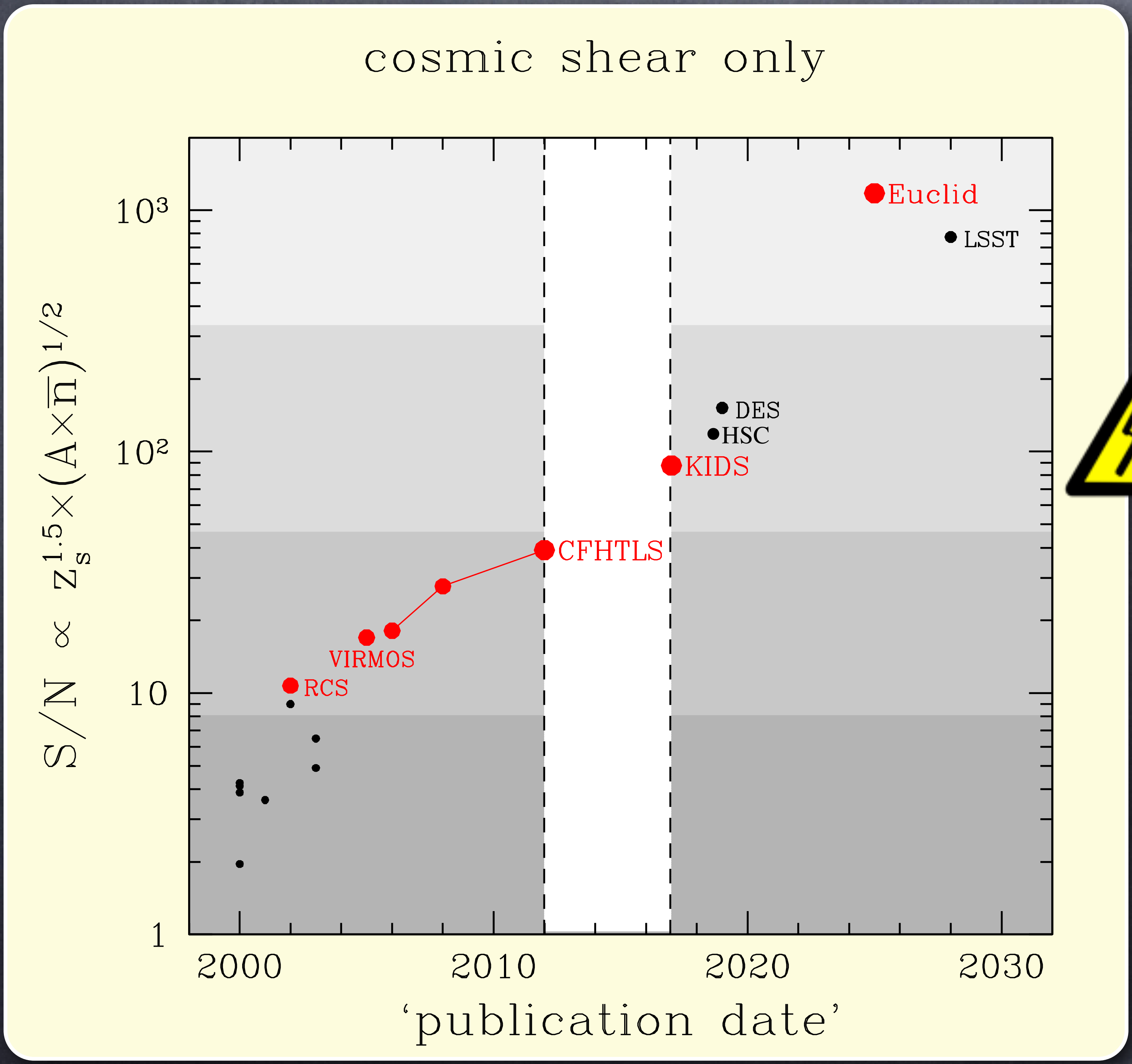
Heymans et al. (2013): narrower bins which means we cannot ignore the intrinsic alignment signal

6-bin tomography



Heymans et al. (2013): w=-1.02±0.10

Great future ahead!

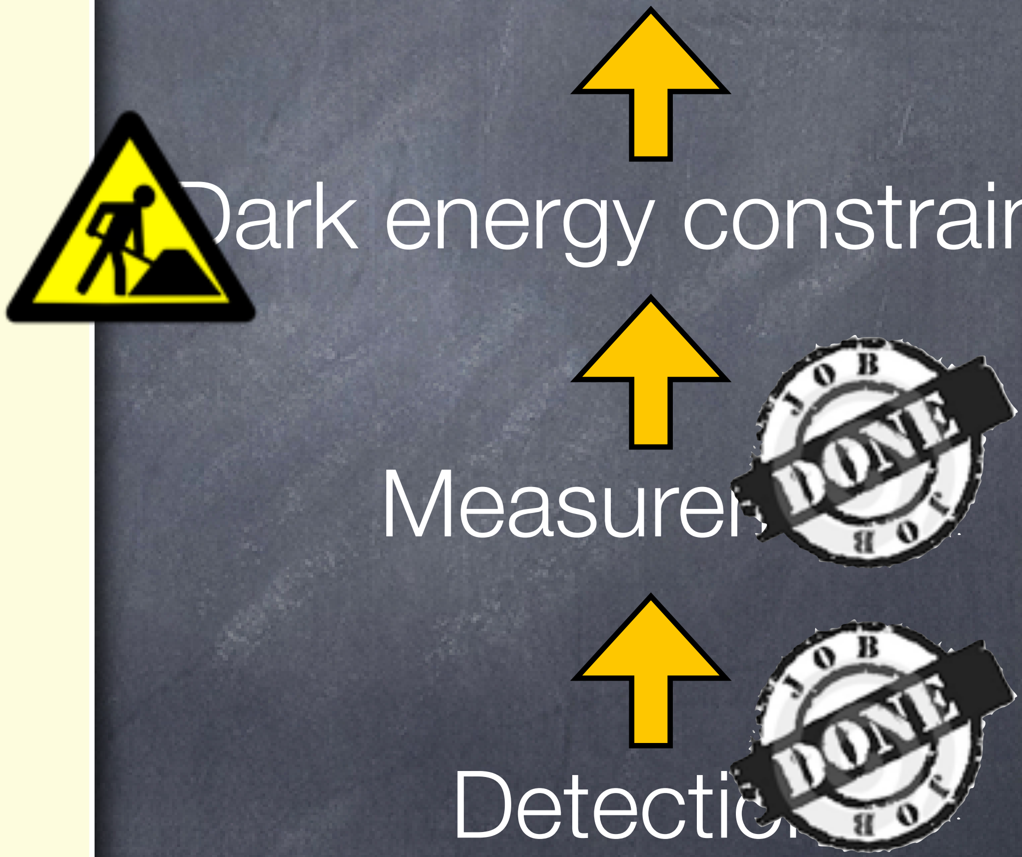


Dark energy physics

Dark energy constraints

Measurem

Detectio




The Future
NEXT EXIT