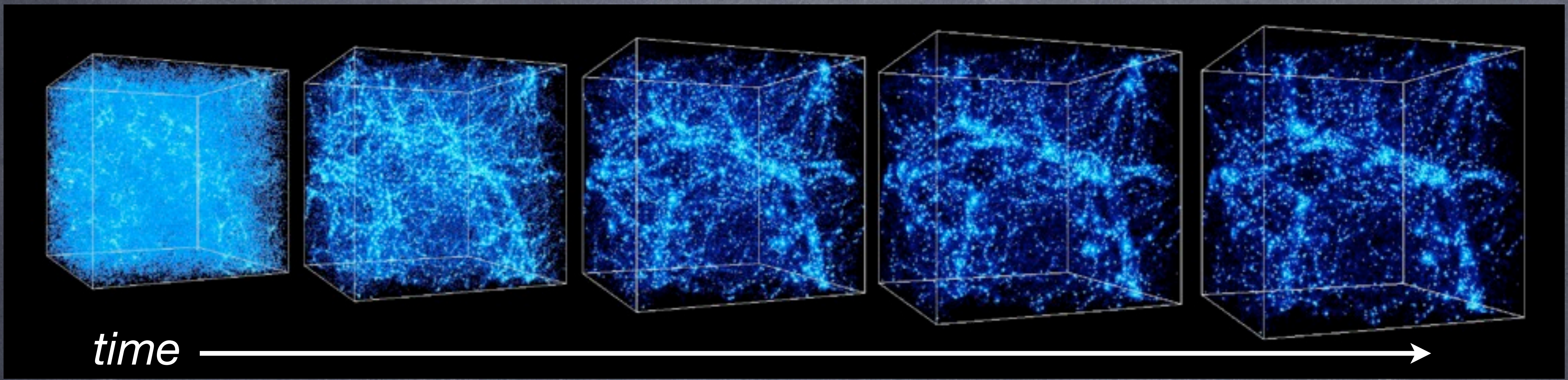
Weak Lensing by Large-scale Structure

A look at the dark side of the Universe

Henk Hoekstra
Leiden Observatory

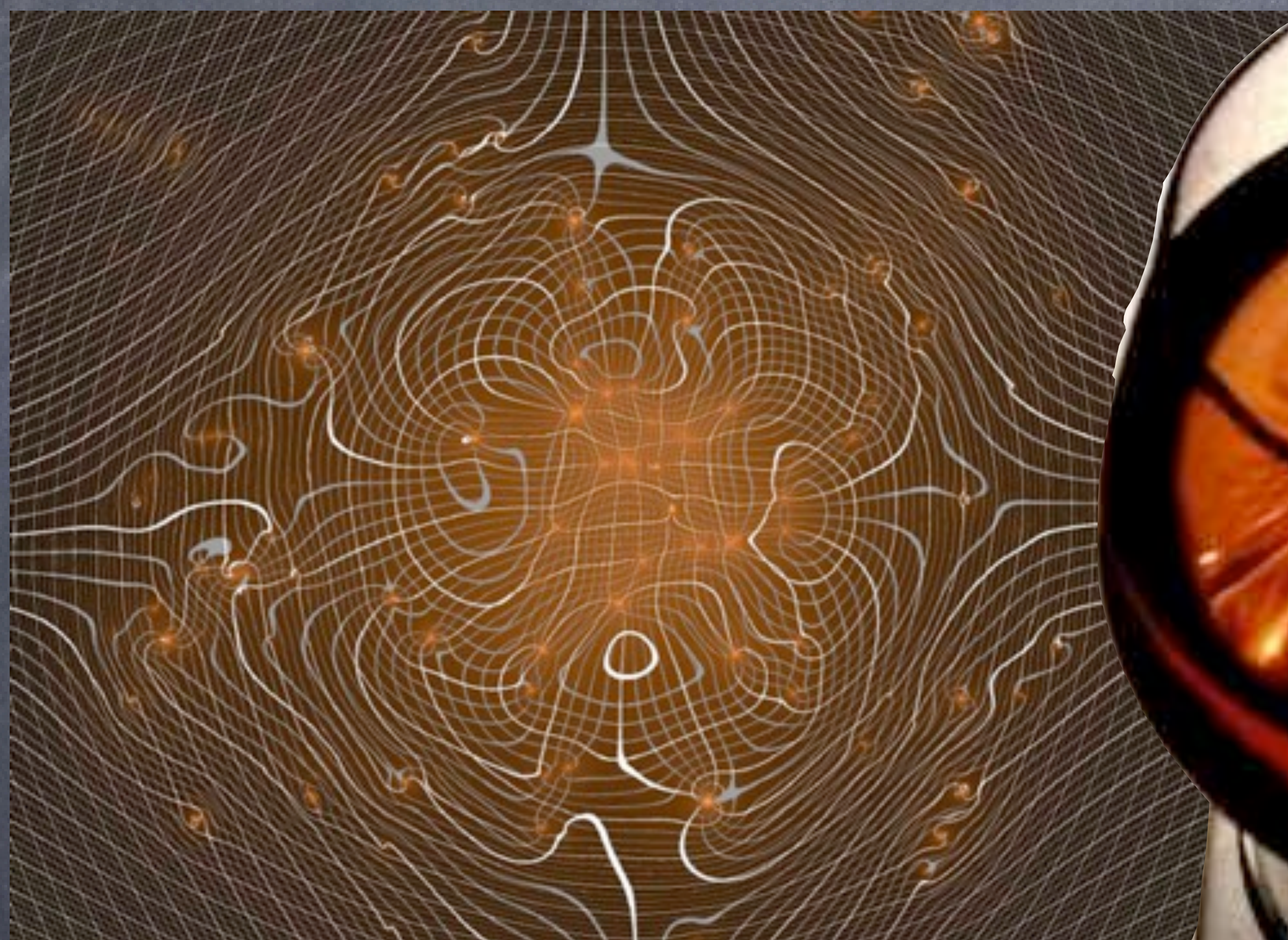
Growth of structure



Dark energy changes the expansion history of the Universe and thus modifies the growth of large-scale structures.

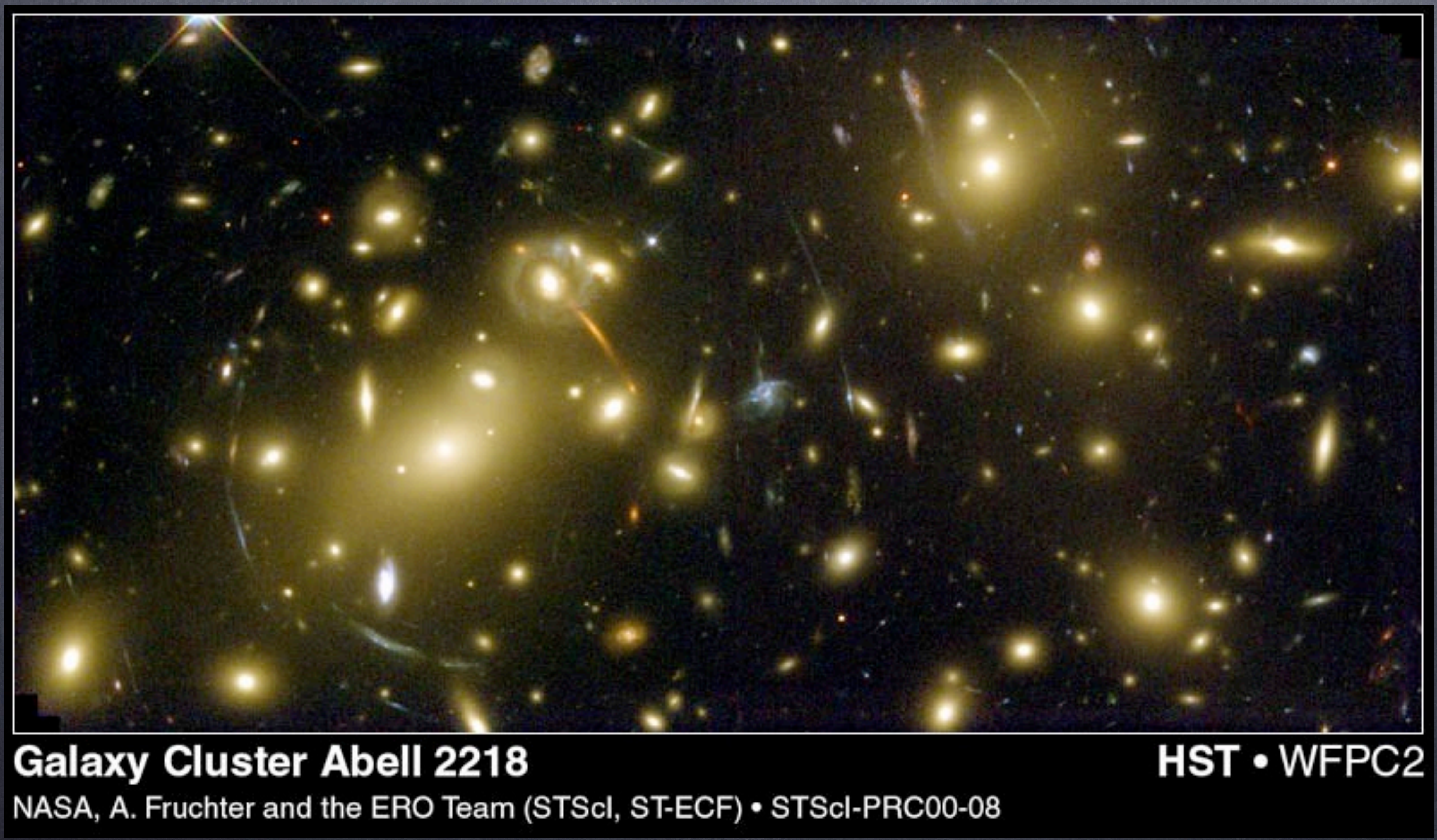
Measure the matter power spectrum

Gravitational lensing



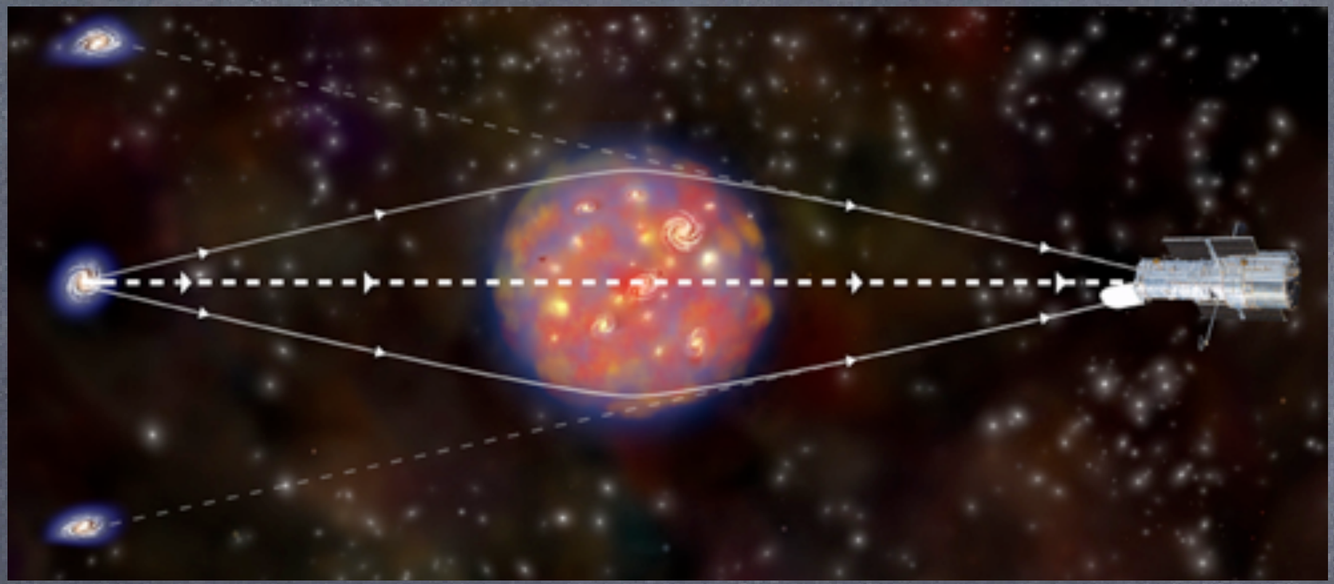
Inhomogeneities in the mass distribution distort the paths of light rays, resulting in a remapping of the sky. This can lead to spectacular lensing examples…

Gravitational lensing



Gravitational lensing

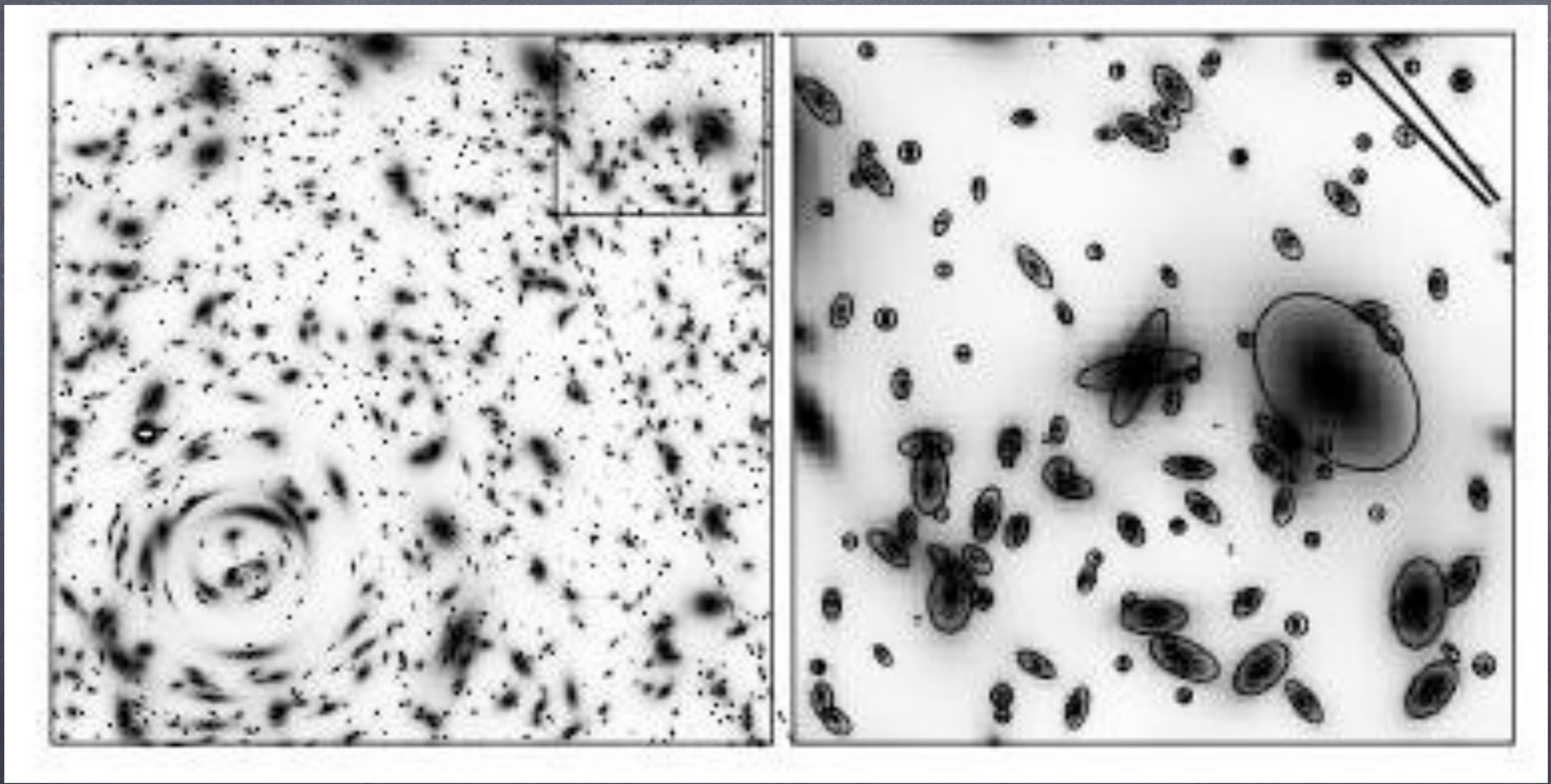
Strong gravitational lensing requires a good alignment of the source and the lens. This doesn't happen often...



The light rays of all objects are perturbed, but the effect is usually just too subtle to see:

- an (unknown) shift in position
- a small distortion of the shapes of the galaxies

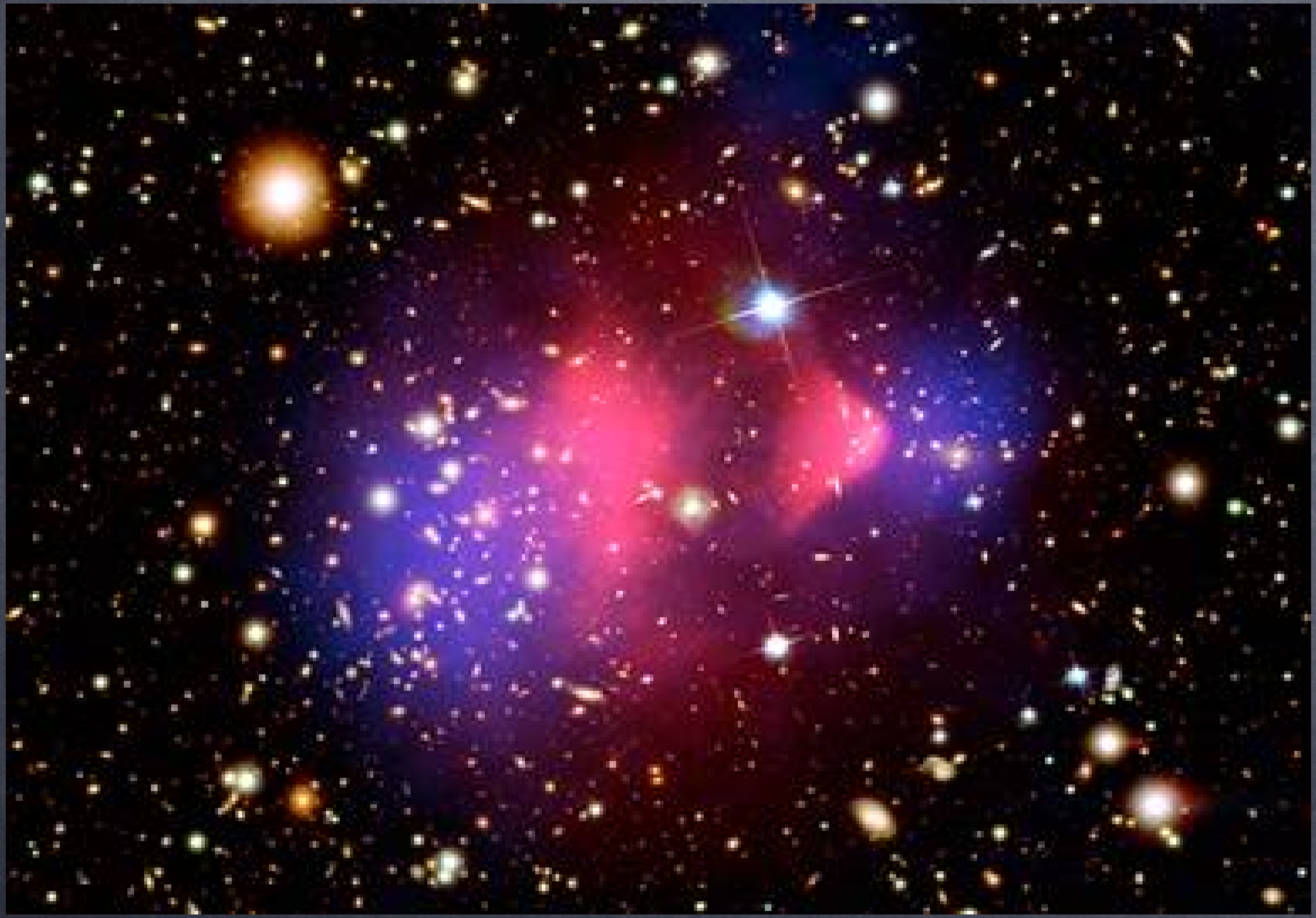
Weak gravitational lensing



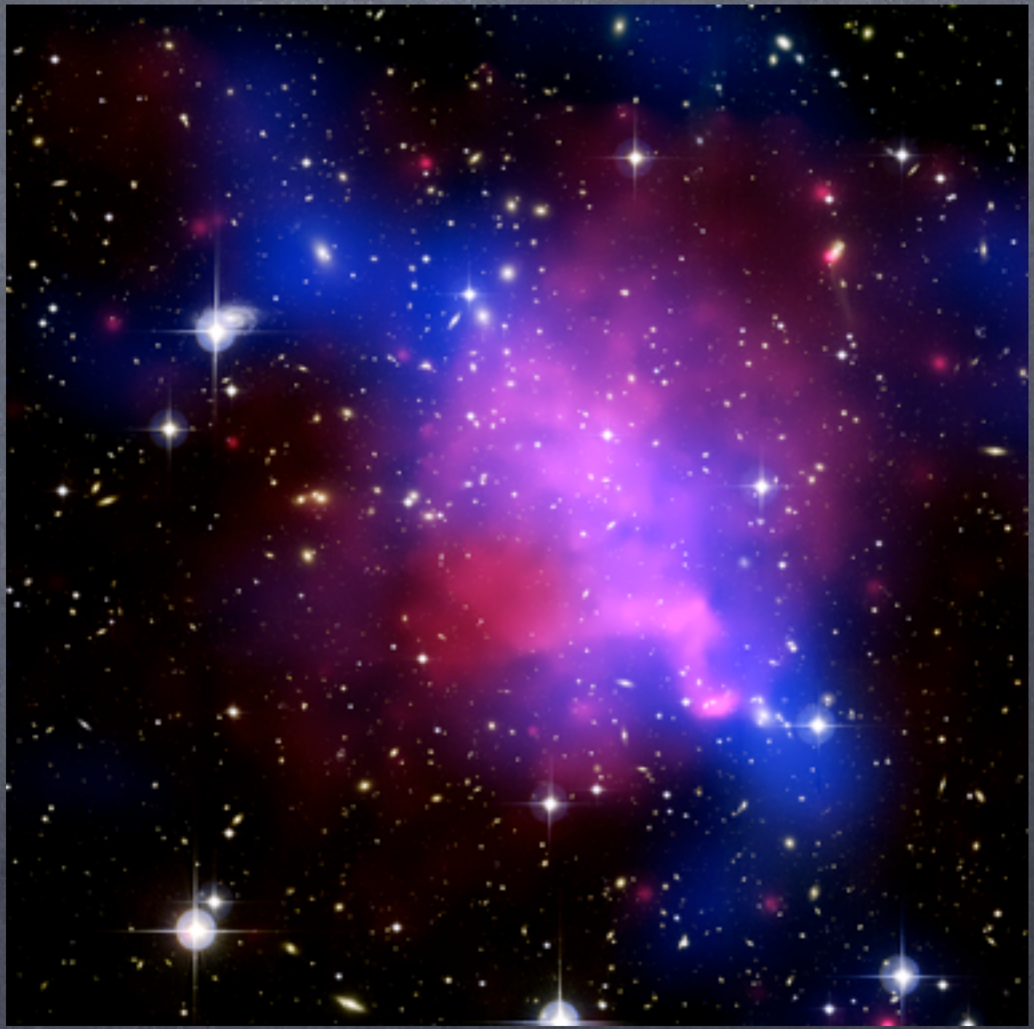
A measurement of the ellipticity of a galaxy provides an unbiased but noisy measurement of the shear

We can see dark matter!

... and it's blue!

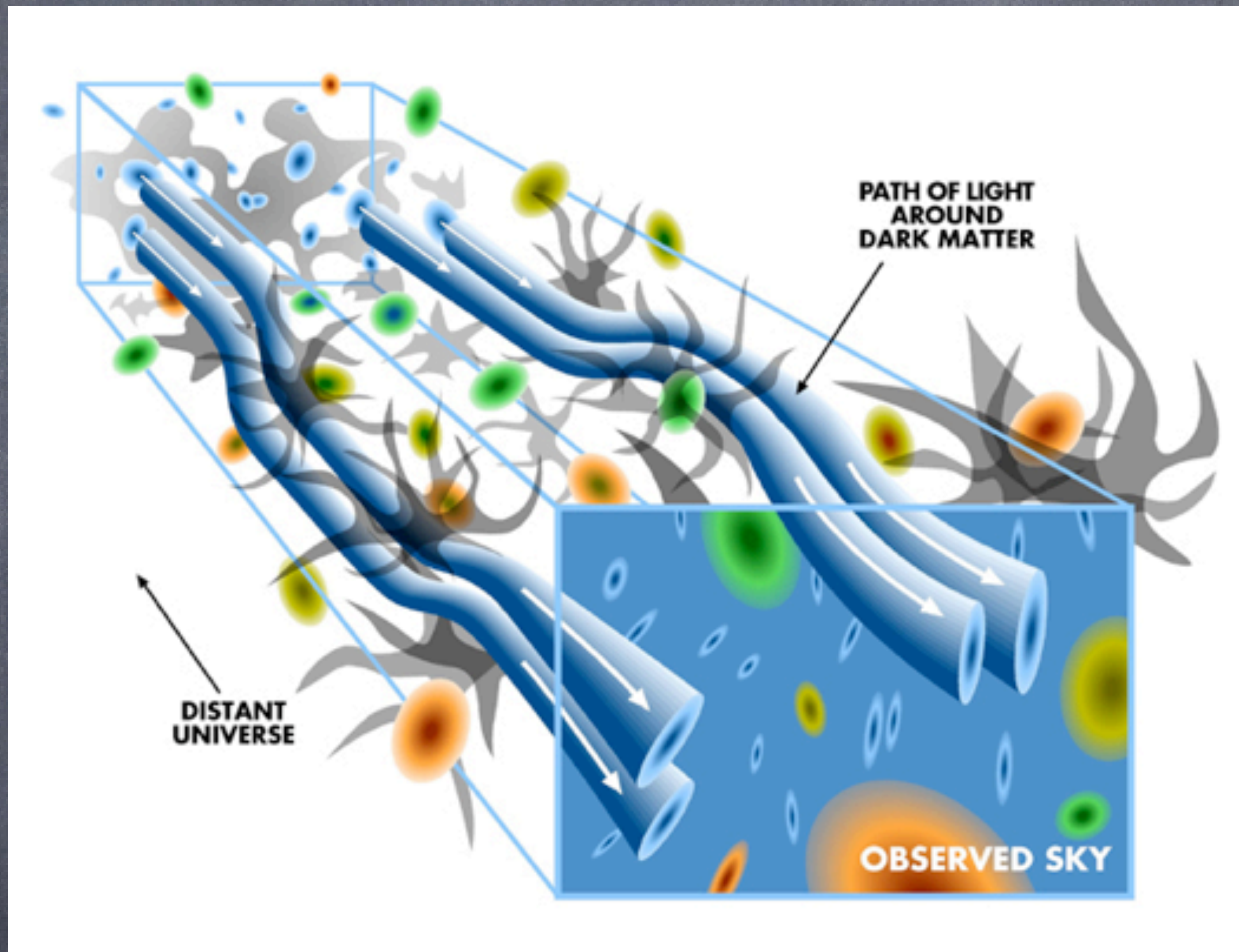


Clowe et al. (2006)



Mahdavi et al. (2008)

Cosmic shear is everywhere

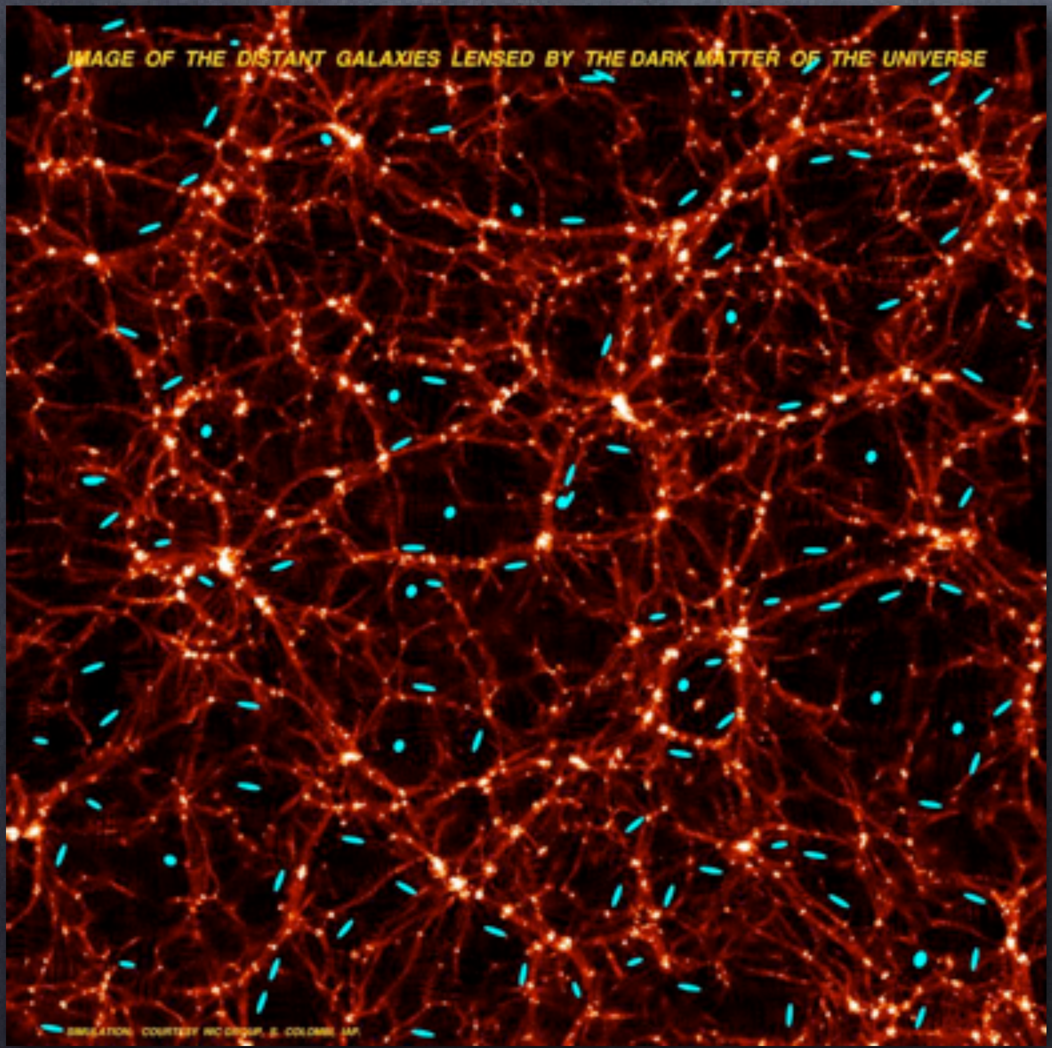


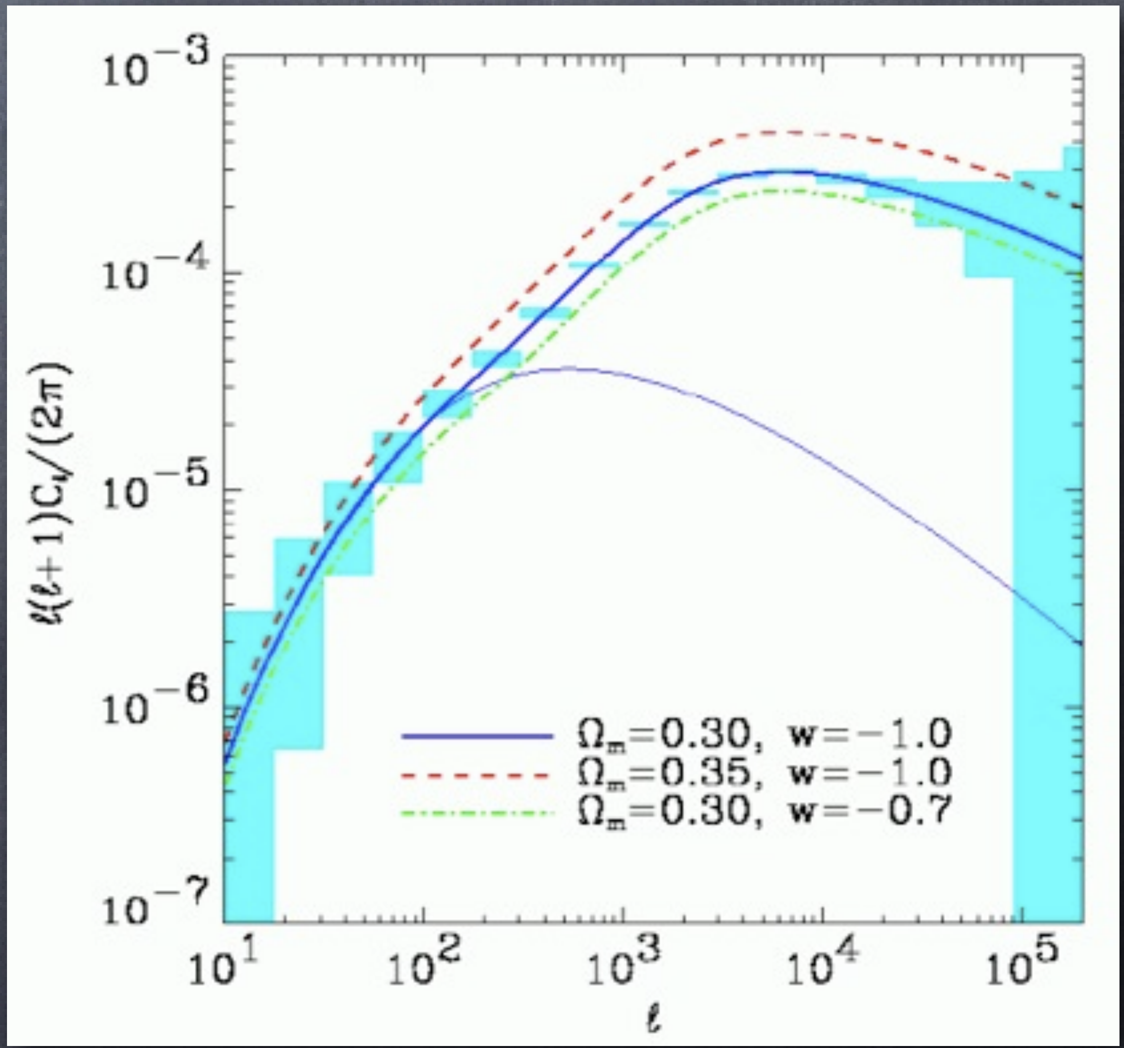
Credit: Tyson et al. (2000)

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

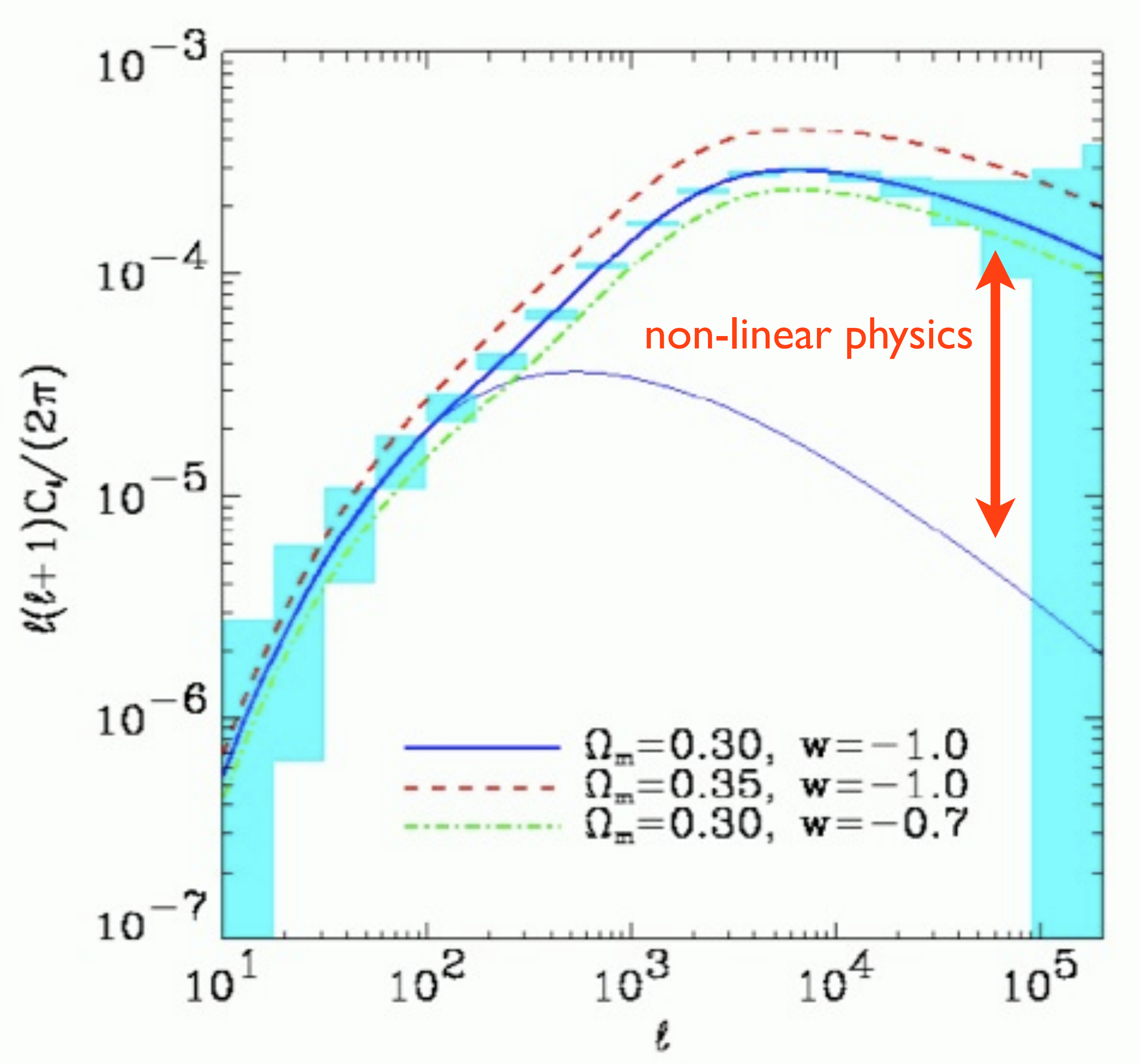
Cosmic shear: *mapping the invisible*

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





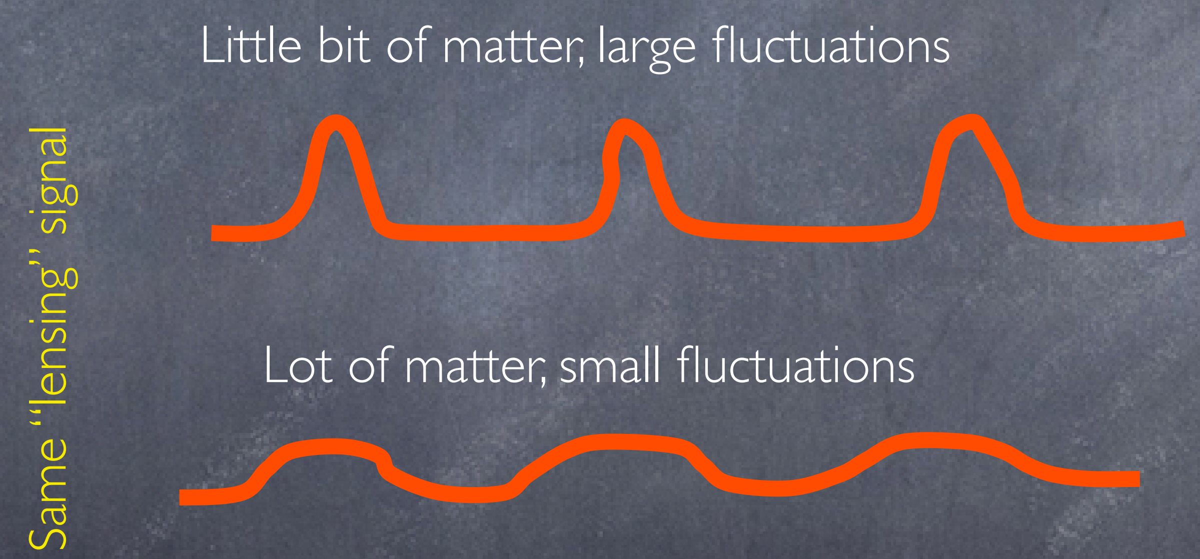
What does the signal mean?



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

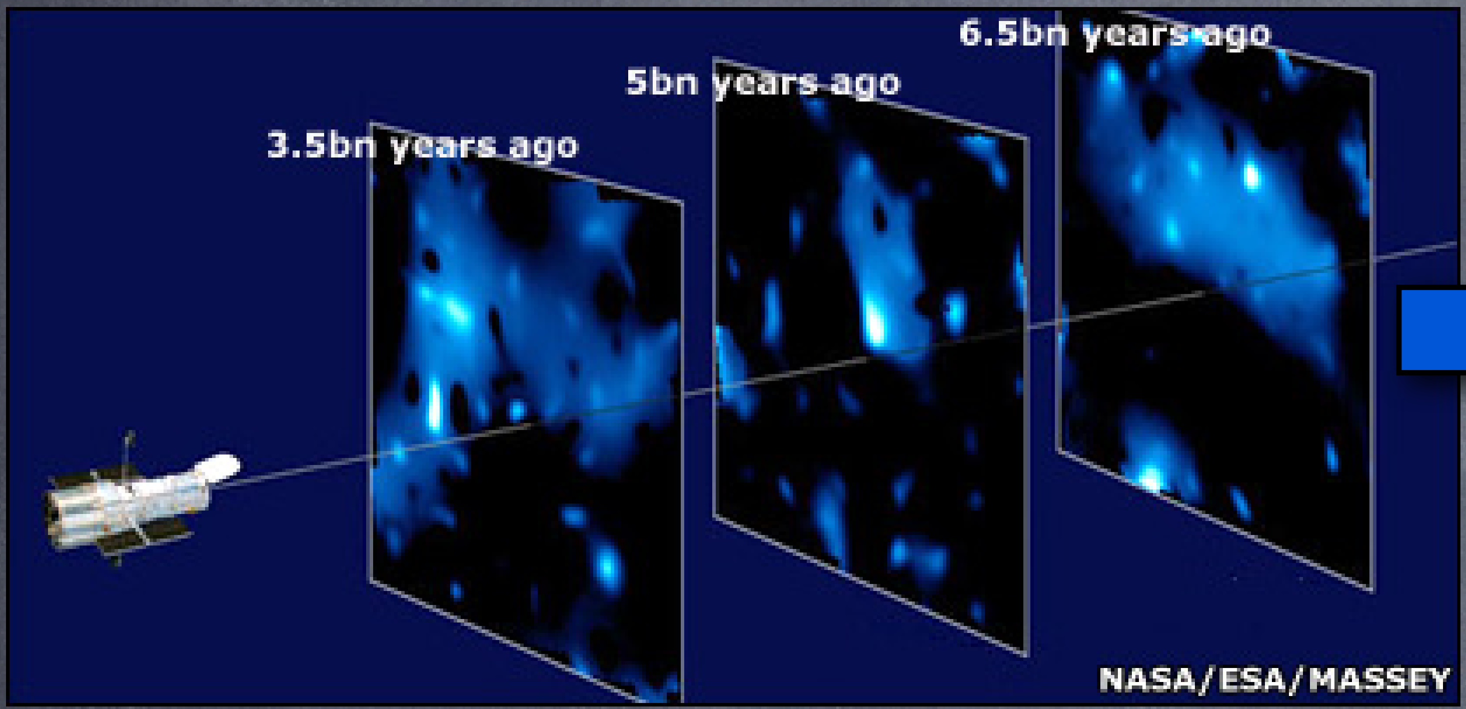
What does the signal mean?

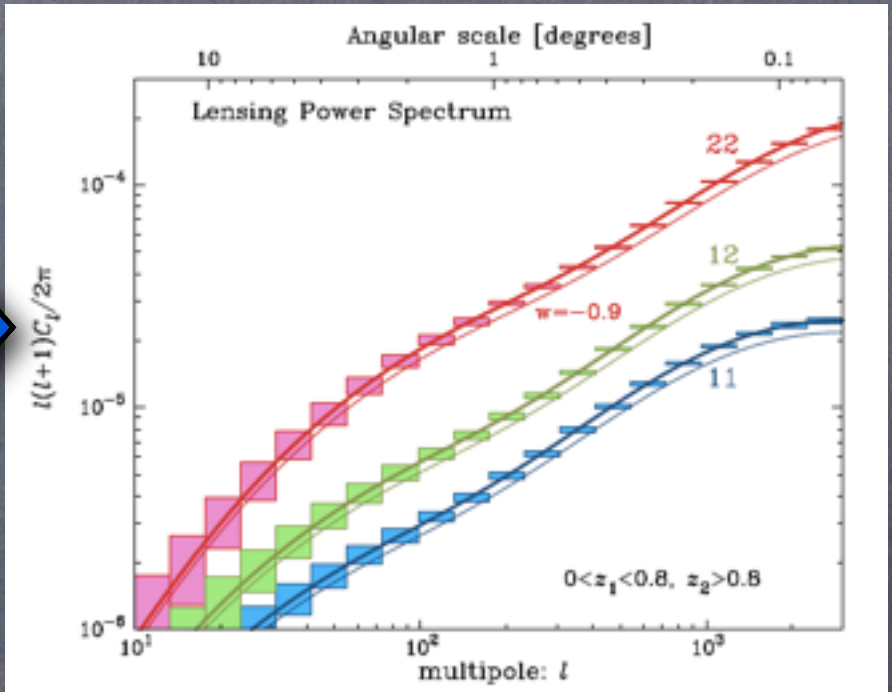
The cosmic shear signal is mainly a measurement of the variance in the density fluctuations.



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

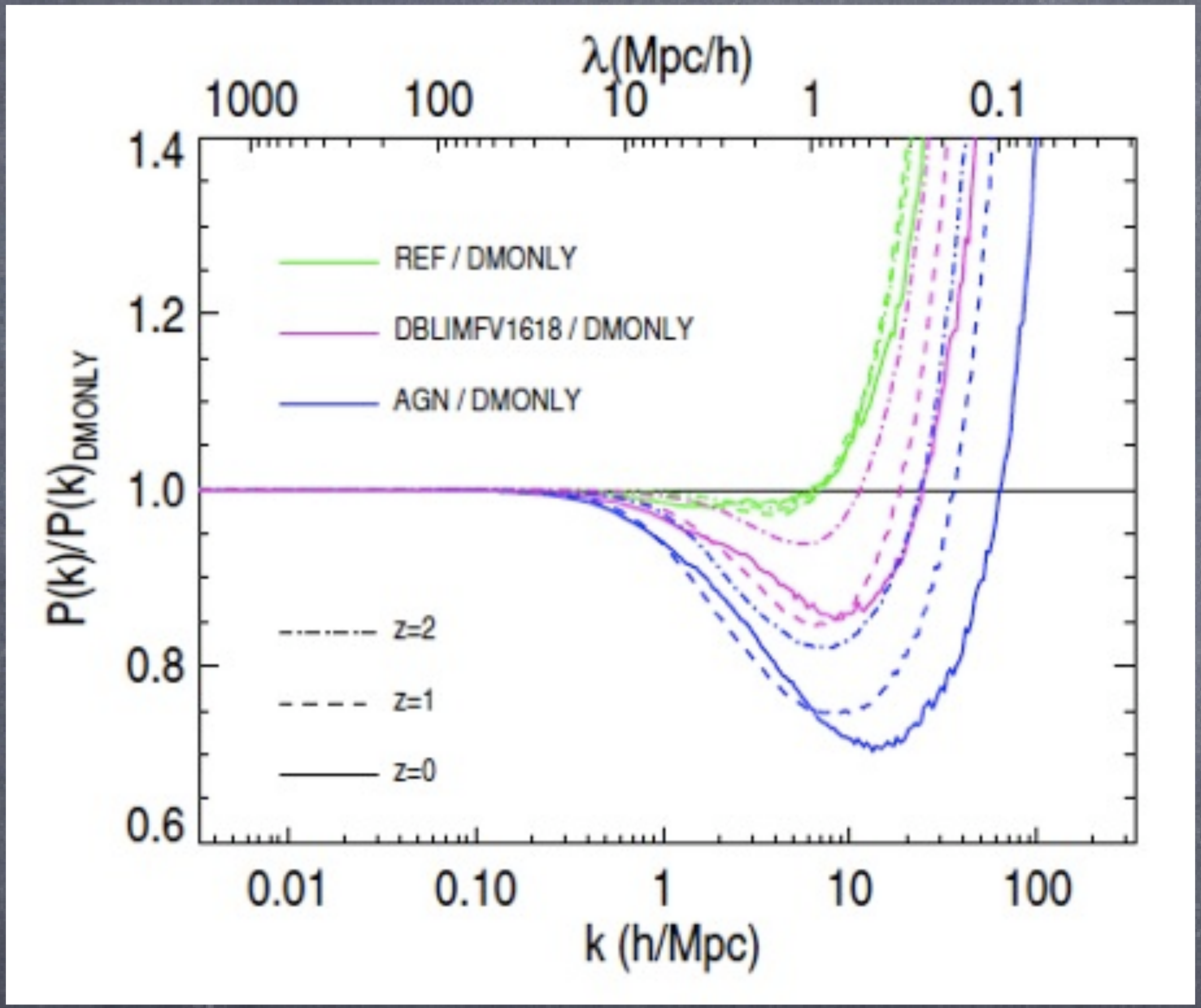
- Constraints on dark energy properties
- Test of gravity on cosmological scales

Power spectrum prediction

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

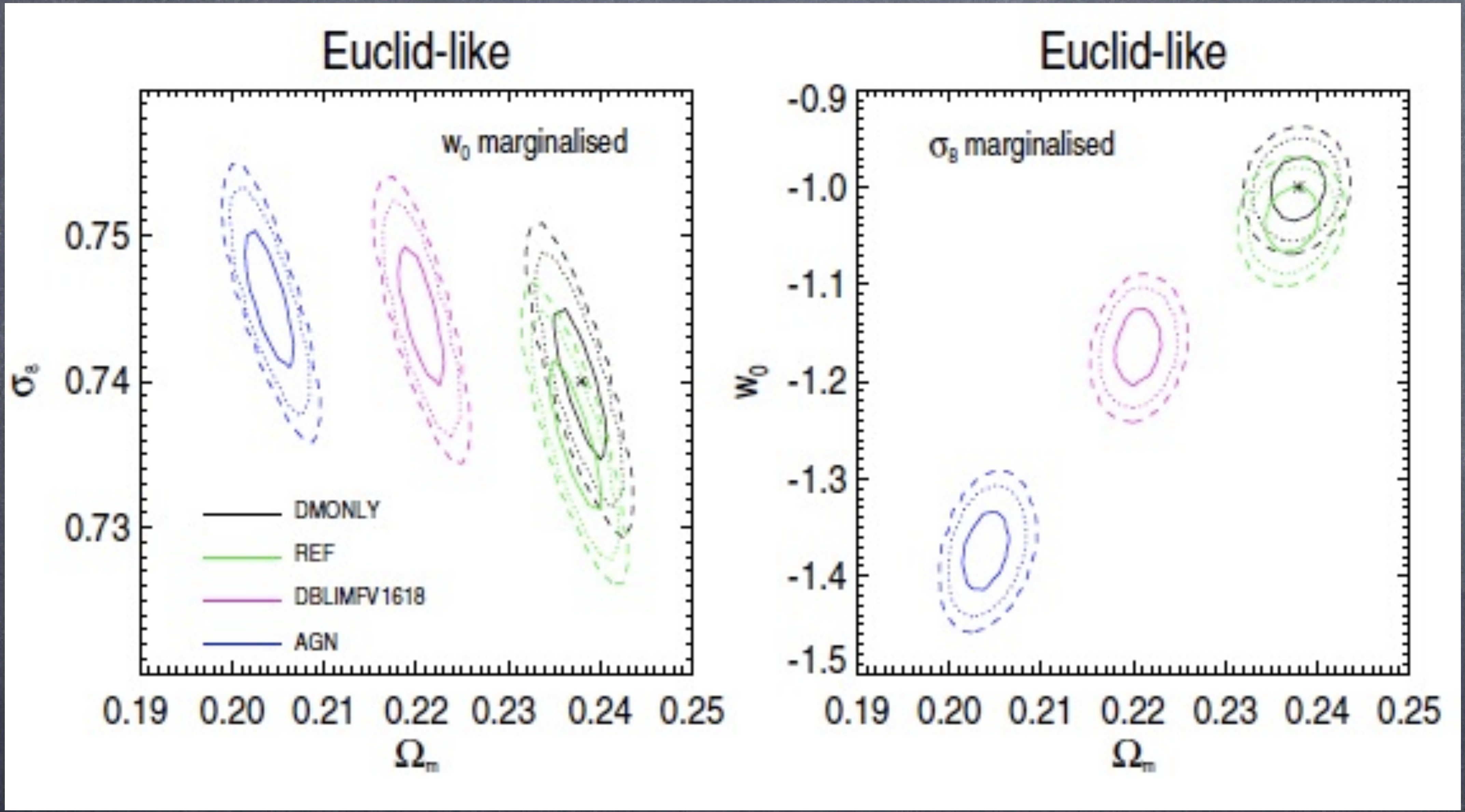
Solution: XXXXXXXXL simulations?

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.

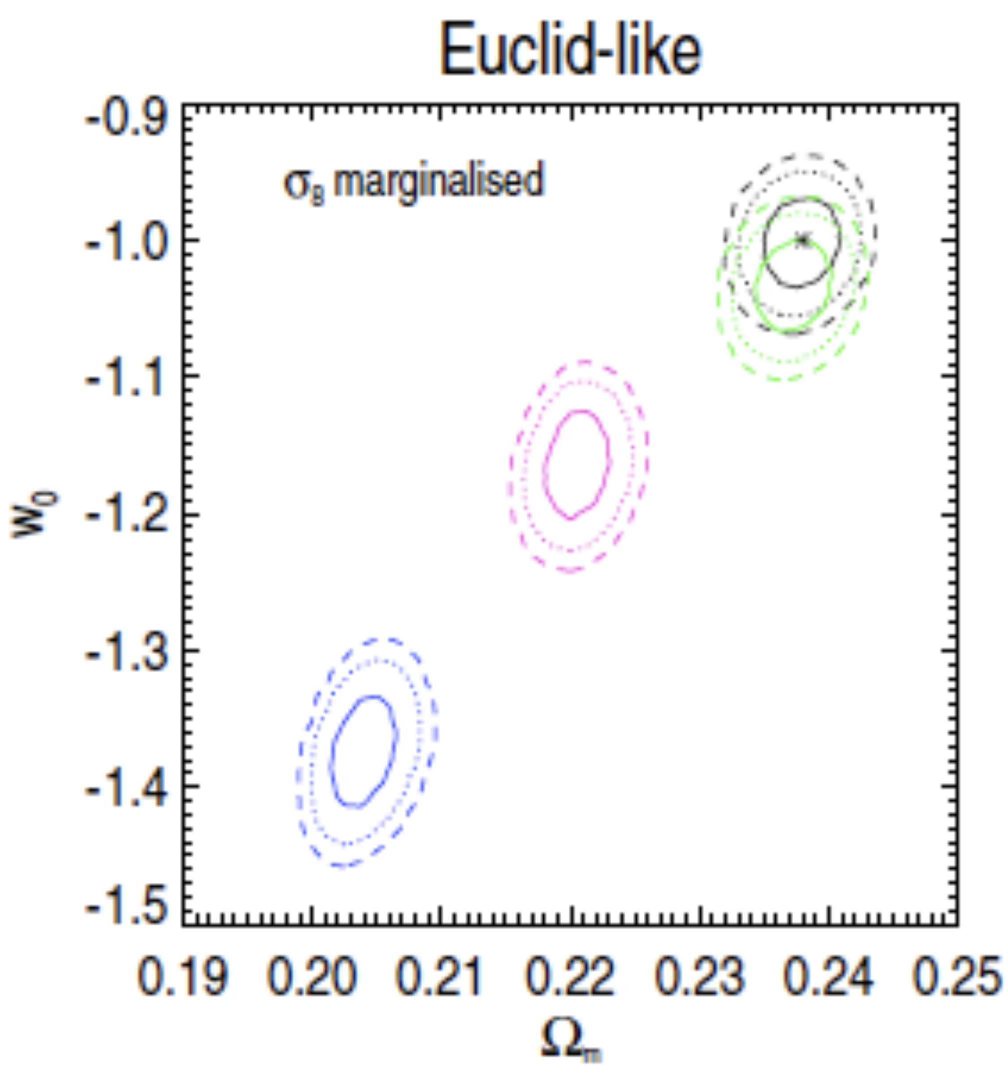
Baryon physics is important



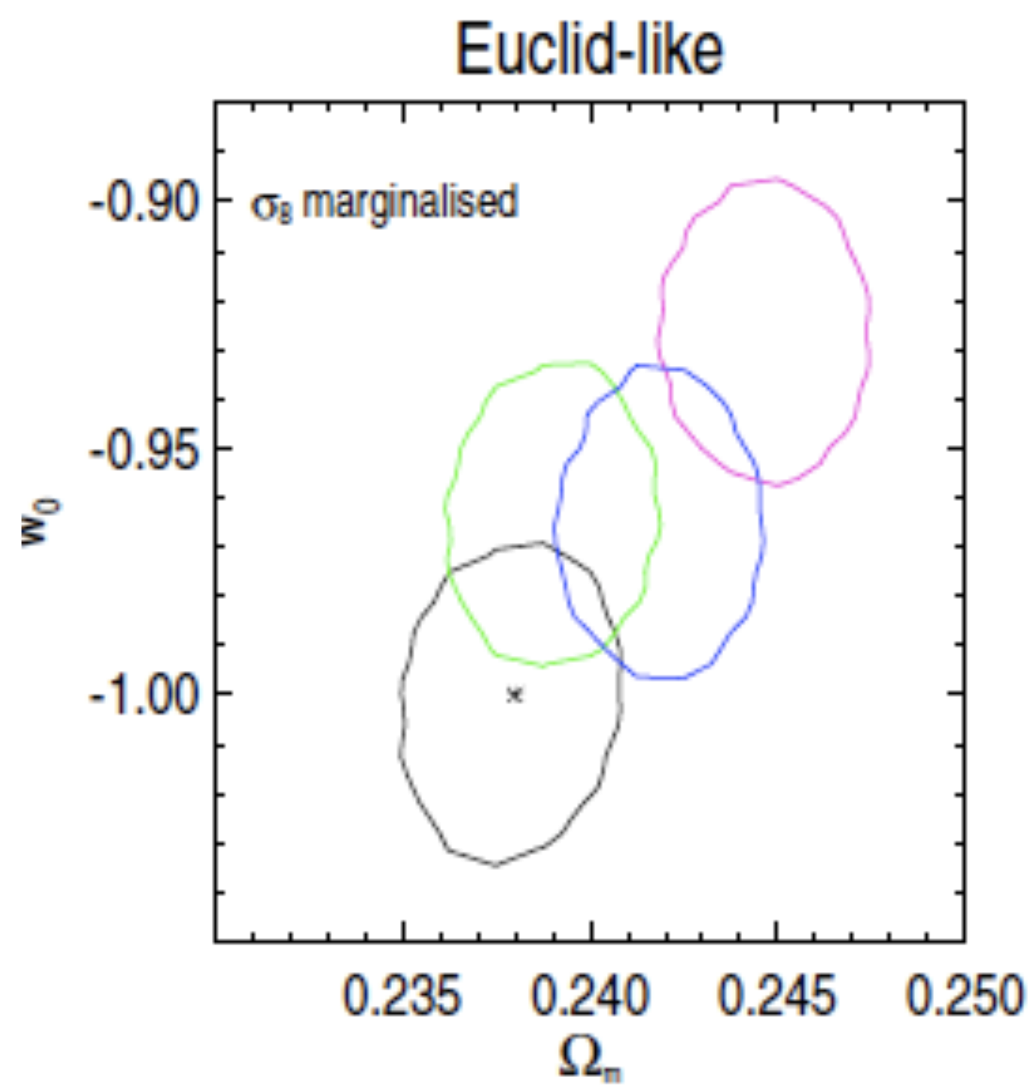
Semboloni et al. (2012; 2013): ignoring feedback may lead to large biases. We cannot just use bigger dark matter-only simulations.

Biases can be reduced

Semboloni et al. (2012; 2013)

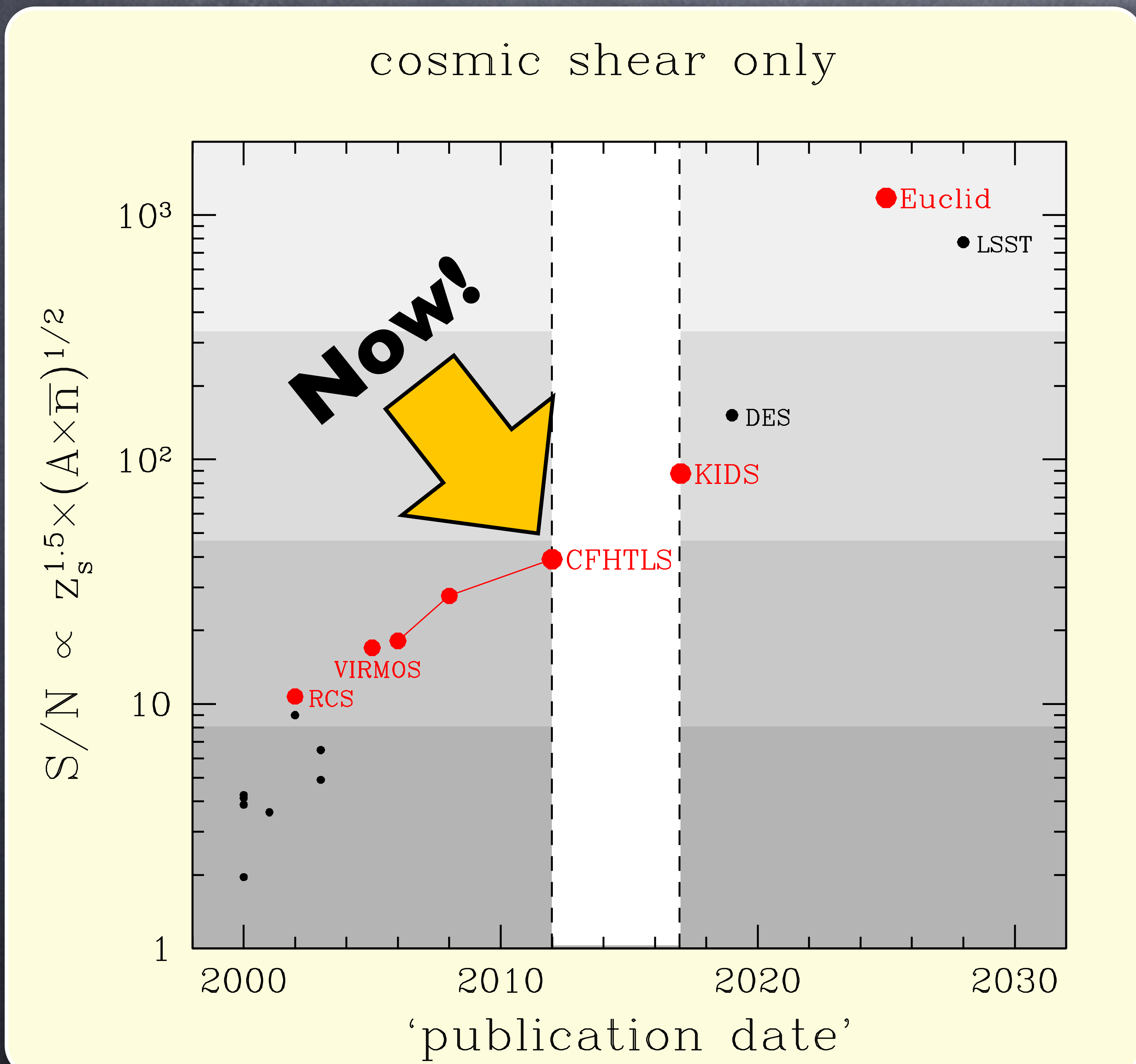


Ignoring feedback



Accounting for feedback

We are getting the numbers



Dark energy physics

Dark energy constraints

Measurement

Detection

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!

So far so good...

Precision ≠ Accuracy

For accurate cosmology we need:

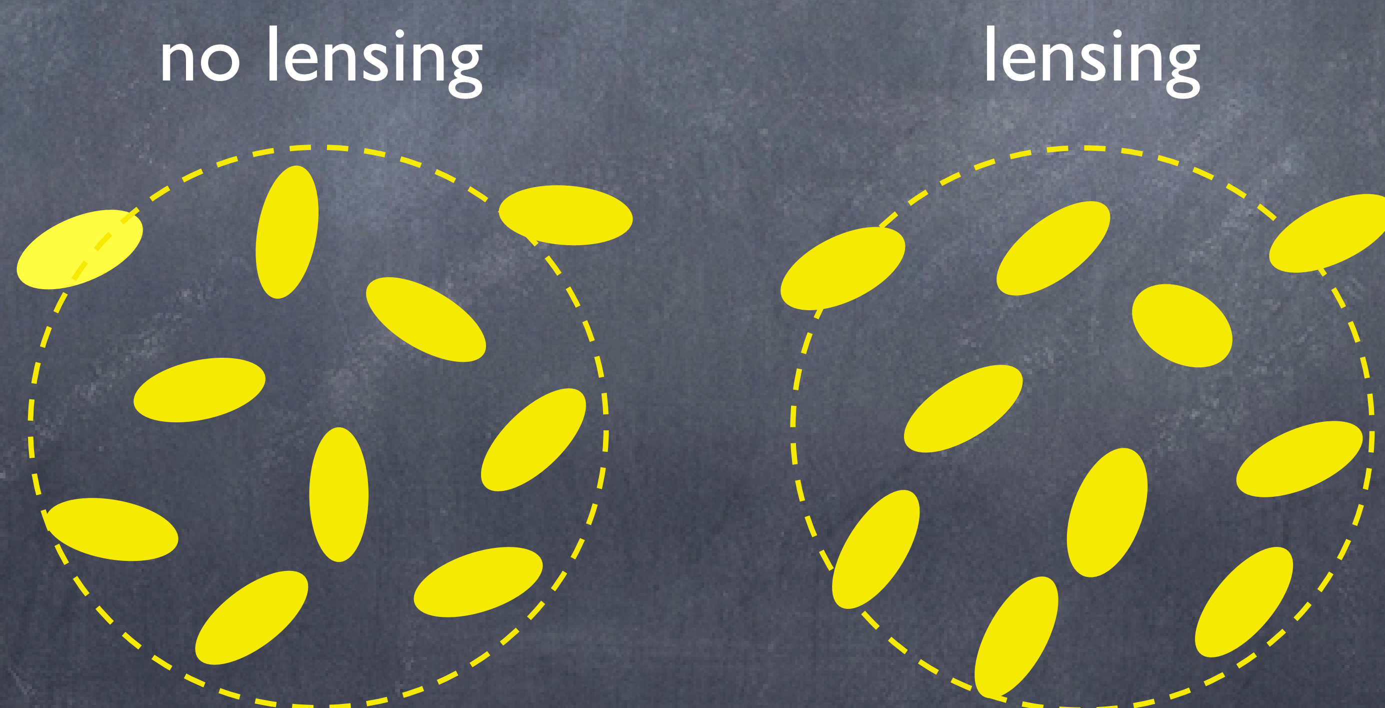
- accurate shapes for the sources
- accurate photometric redshifts
- accurate interpretation of the signal

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

It is a noisy business

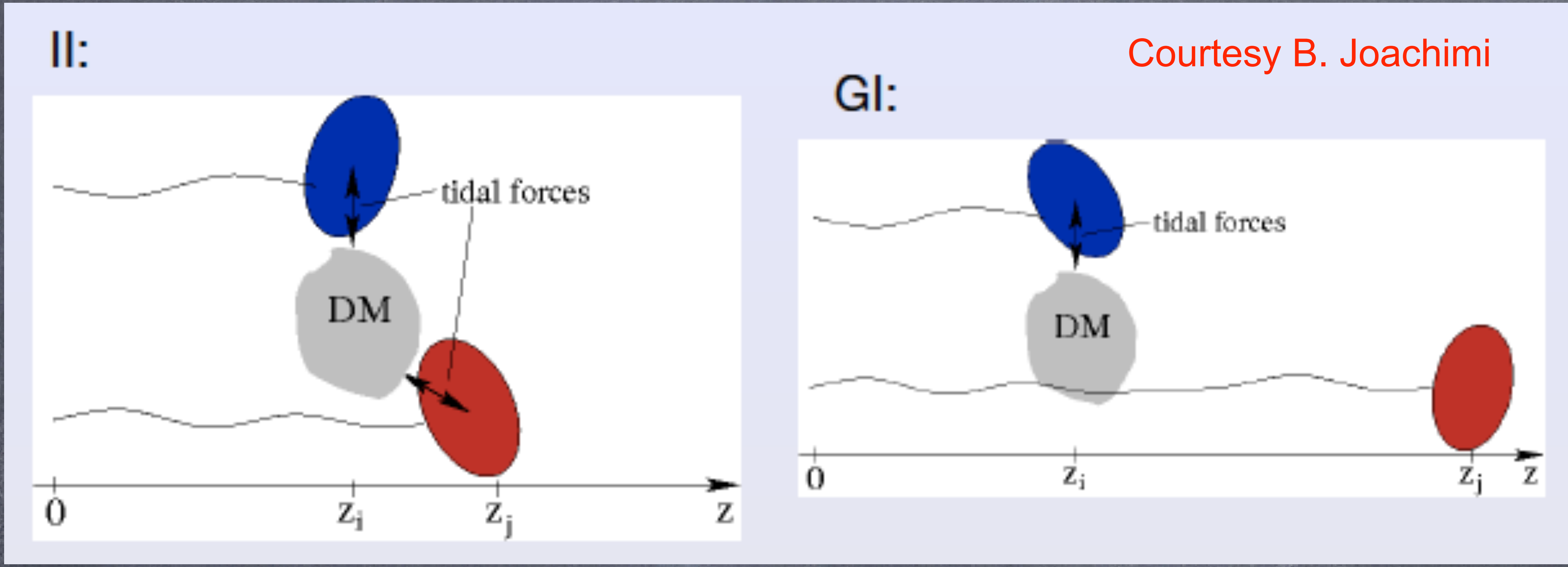
The lensing signal is small: we need measure the shapes of many galaxies with high accuracy

The underlying assumption is that the position angles are random in the absence of lensing. At some level intrinsic alignments will complicate things



Averaged shape: $\langle e \rangle = 0$ $\langle e \rangle \approx \gamma$

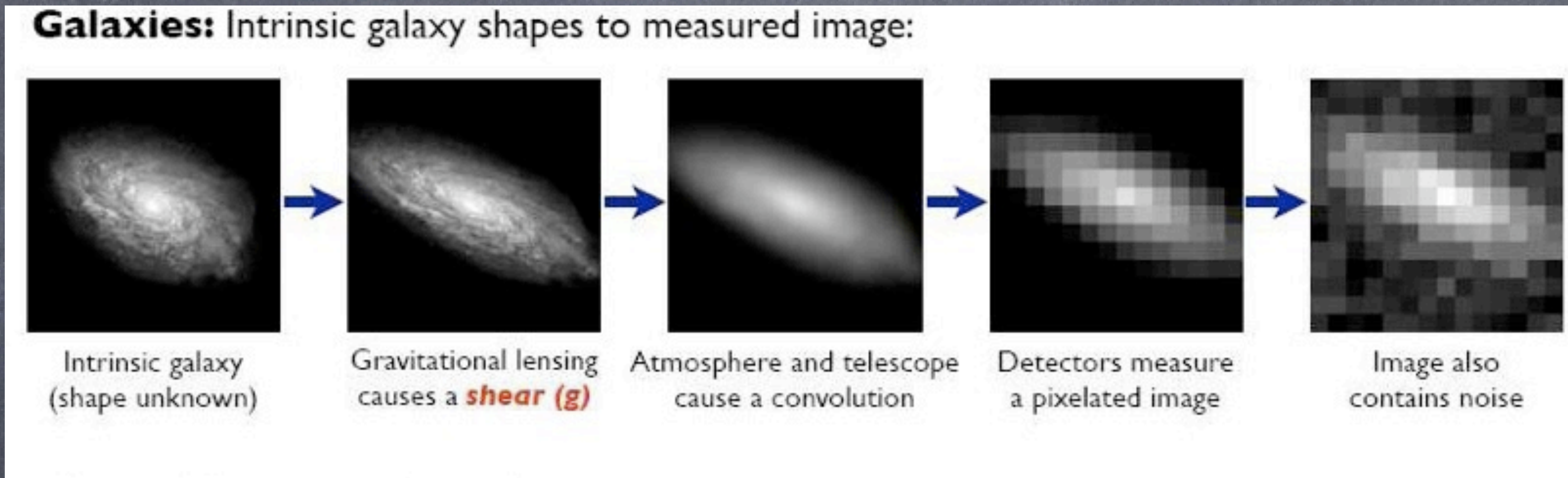
Intrinsic Alignments



2pt correlation: $$\langle\epsilon_i\epsilon_j\rangle = \underbrace{\langle\gamma_i\gamma_j\rangle}_{\text{GG}} + \underbrace{\langle\epsilon_i^s\epsilon_j^s\rangle}_{\text{II}} + \underbrace{\langle\gamma_i\epsilon_j^s\rangle + \langle\epsilon_i^s\gamma_j\rangle}_{\text{GI}}$$

This drives required photometric redshift precision

Measuring shapes...

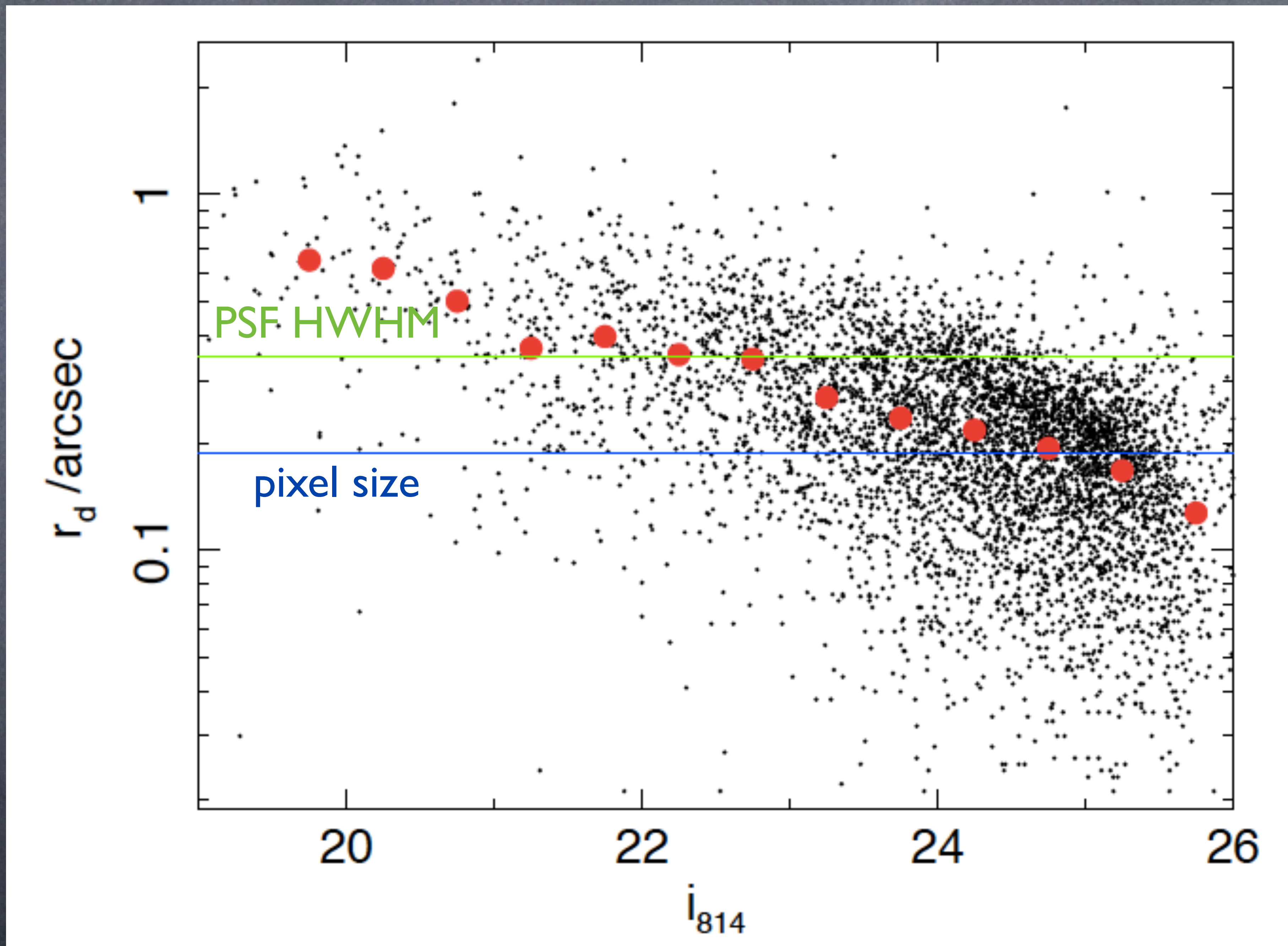


GREAT'08 challenge

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

$$R^2 \equiv \frac{\iint I(r,\theta)\ r^2\ r\mathrm{d}r\mathrm{d}\theta}{\iint I(r,\theta)\ r\mathrm{d}r\mathrm{d}\theta} \tag{1}$$

and complex ellipticity

$$\varepsilon = \varepsilon_1 + i\varepsilon_2 \equiv \frac{\iint I\ r^2 \mathrm{e}^{2i\theta}\ r\mathrm{d}r\mathrm{d}\theta}{\iint I\ r^2\ r\mathrm{d}r\mathrm{d}\theta}. \tag{2}$$

Gravitational lensing magnifies and shears a galaxy of intrinsic size R_{int} and ellipticity $\varepsilon_{\mathrm{int}}$ into one of size $R_{\mathrm{gal}} > 0$ and ellipticity

$$\varepsilon_{\mathrm{gal}} = \varepsilon_{\mathrm{int}} + P_\gamma \gamma, \tag{3}$$

PSF matters

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

what we want

what we observe

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

multiplicative

additive

PSF matters

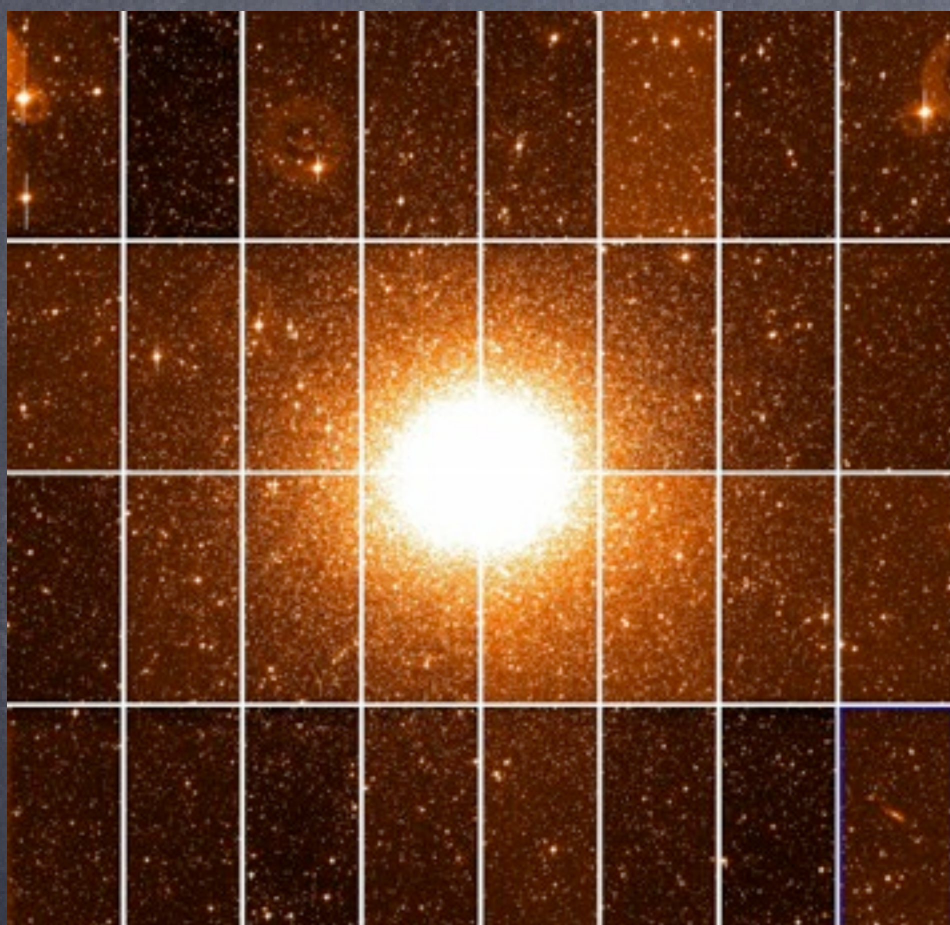
Many things contribute...

$$\mathcal{M} = \frac{2}{P_R}\left\langle \boxed{\frac{R^2_{\mathrm{PSF}}}{R^2_{\mathrm{gal}}}} \right\rangle \left(\boxed{\frac{\langle \delta(R^2_{\mathrm{PSF}})\rangle}{\langle R^2_{\mathrm{PSF}}\rangle}} + 2\boxed{\frac{\langle \delta(R_{\mathrm{NC}})\rangle}{\langle R_{\mathrm{obs}}\rangle} + \langle \mu \rangle} \right)$$

$$+ \frac{1}{{P_R}^2}\left\langle \boxed{\frac{R^4_{\mathrm{PSF}}}{R^4_{\mathrm{gal}}}} \right\rangle \left(\boxed{\frac{\sigma^2[R^2_{\mathrm{PSF}}]}{\langle R^4_{\mathrm{PSF}}\rangle}} + \boxed{4\frac{\sigma^2[R_{\mathrm{NC}}]}{\langle R^2_{\mathrm{obs}}\rangle}} \right).$$

- PSF size
- PSF model
- correction method

More complications



VST image of ωCen

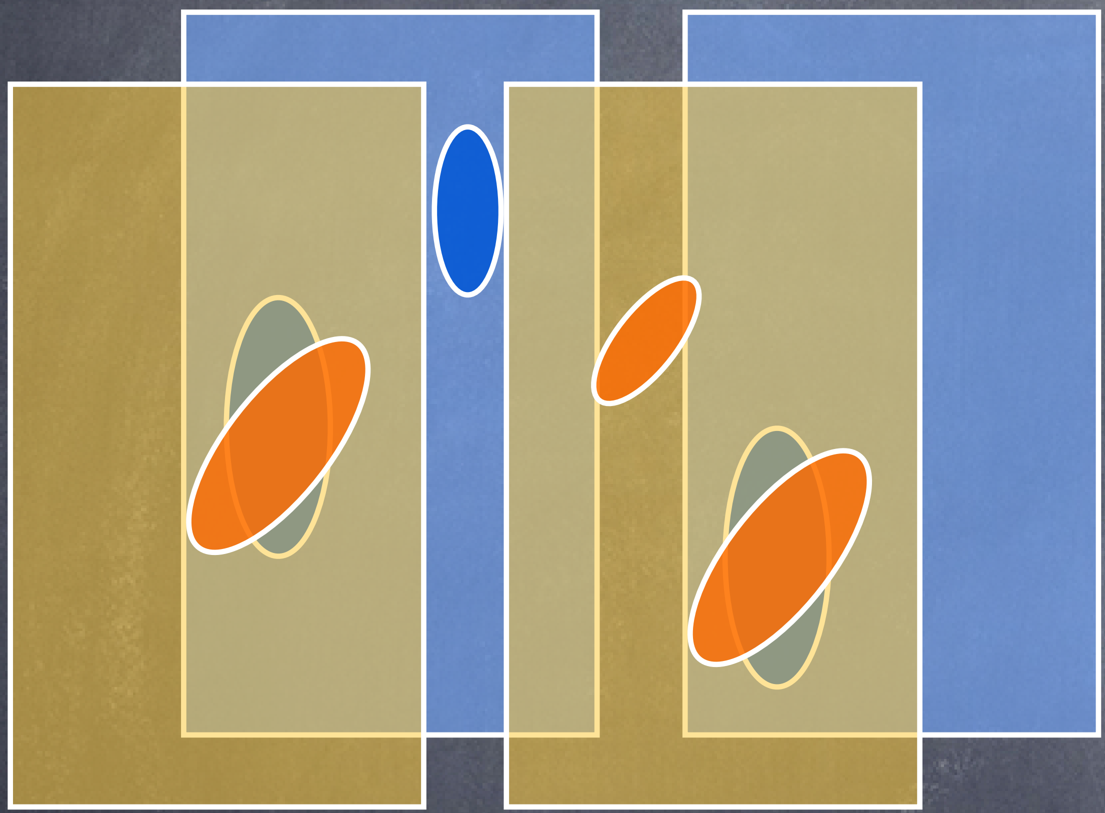
The mapping between pixel and sky coordinates is not linear: the camera induces a shear.

Remapping smooths the image

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

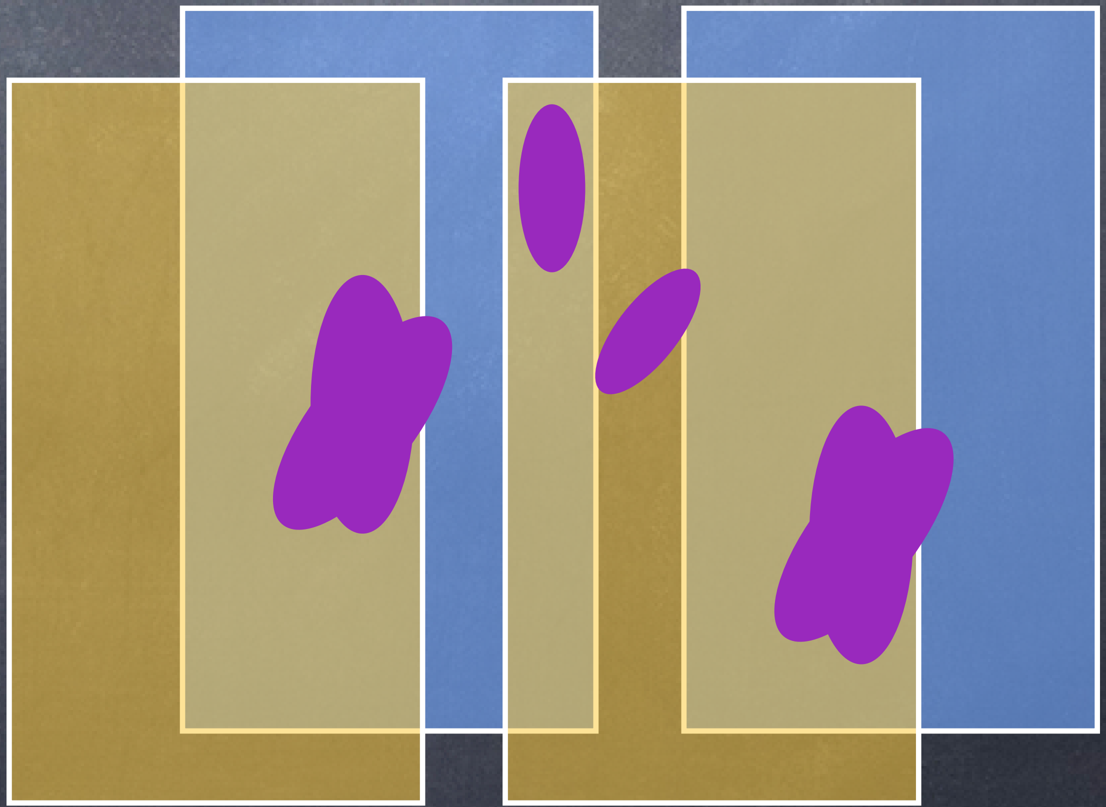
We combine multiple exposures that have been offset.

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.

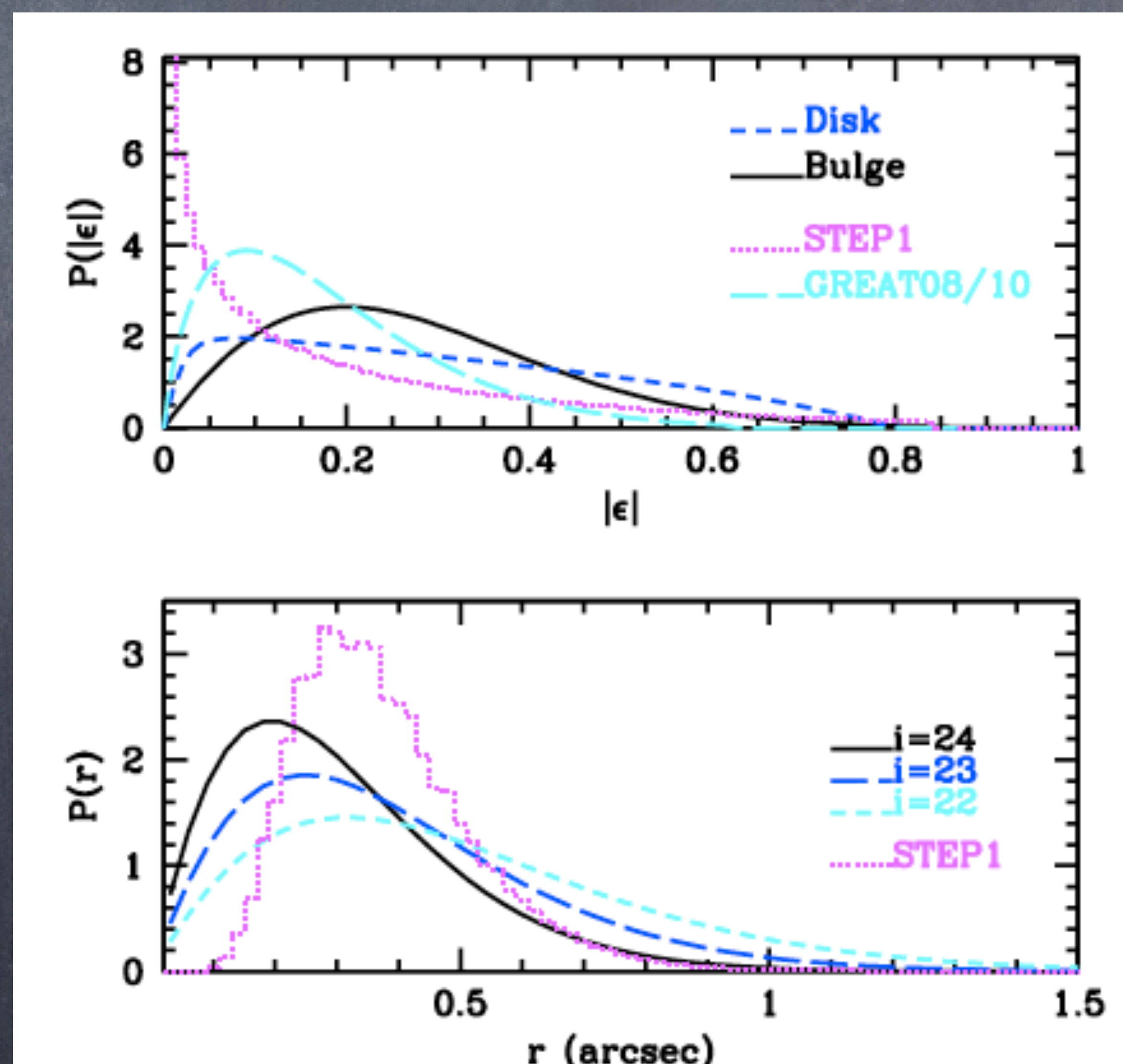
-we can create simulated data to test the measurement techniques (e.g. STEP, GREAT)

-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

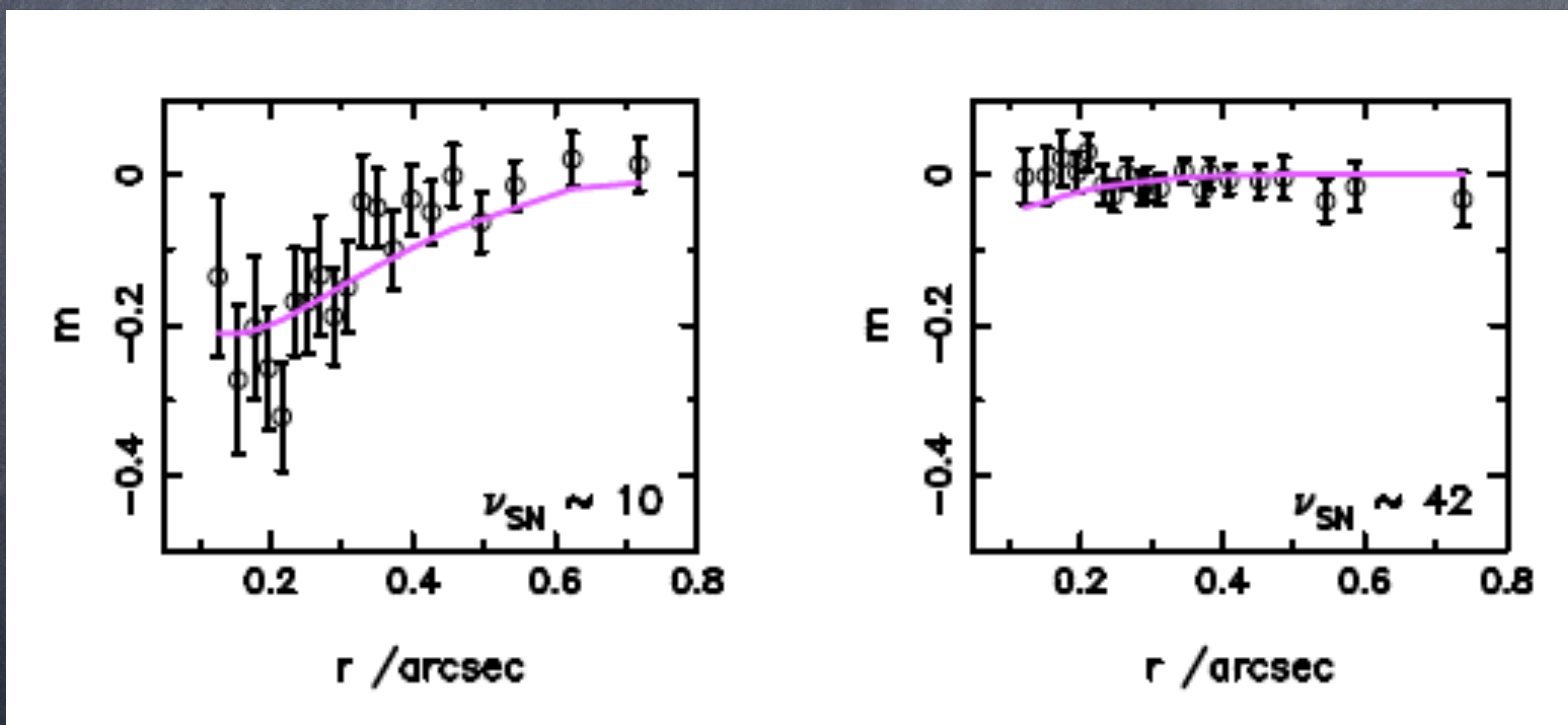
CFHTLenS image simulations are created to match the observed properties of galaxies and the PSF.



Miller et al. (2013)

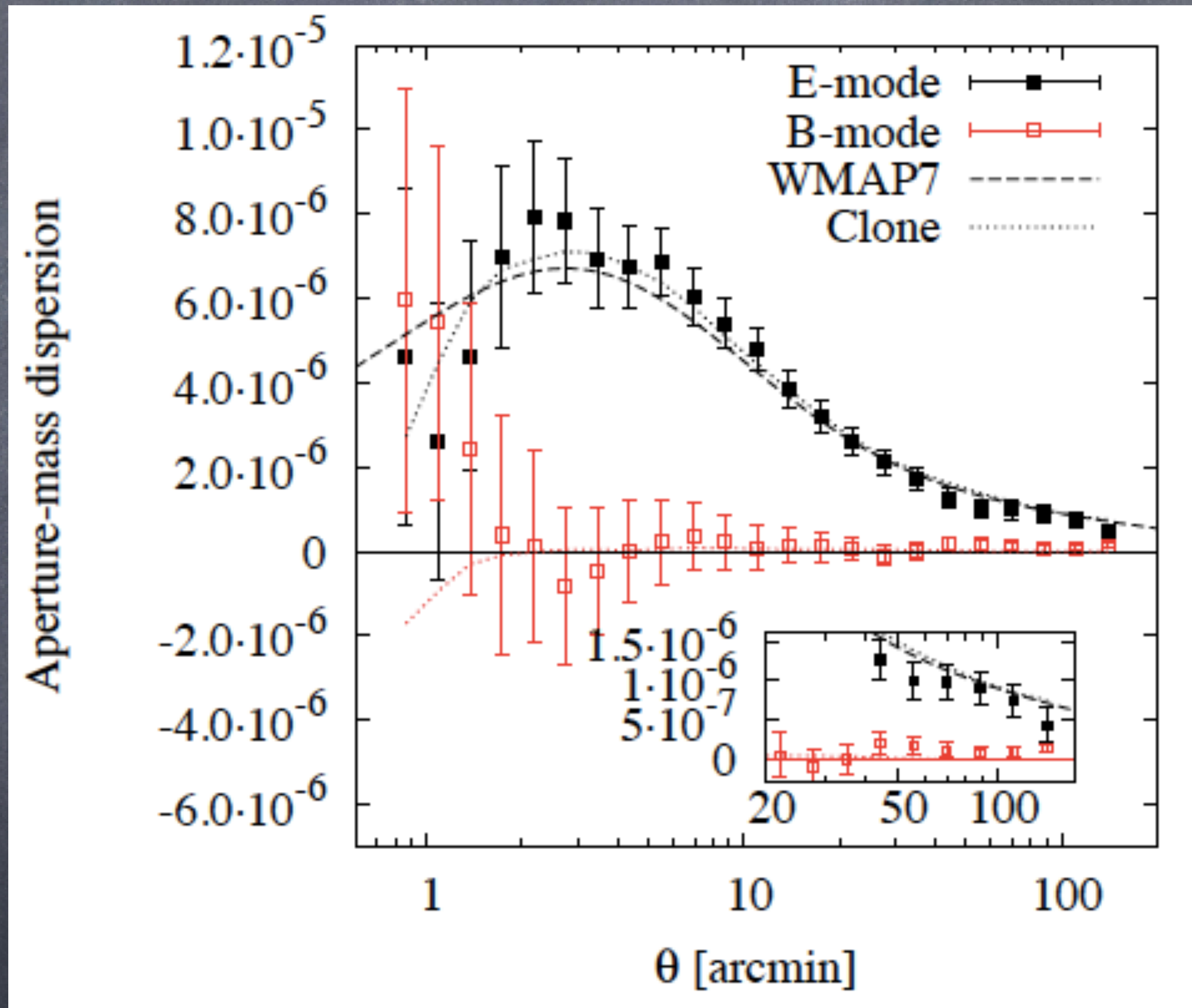
Tests on simulations

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



Miller et al. (2013)

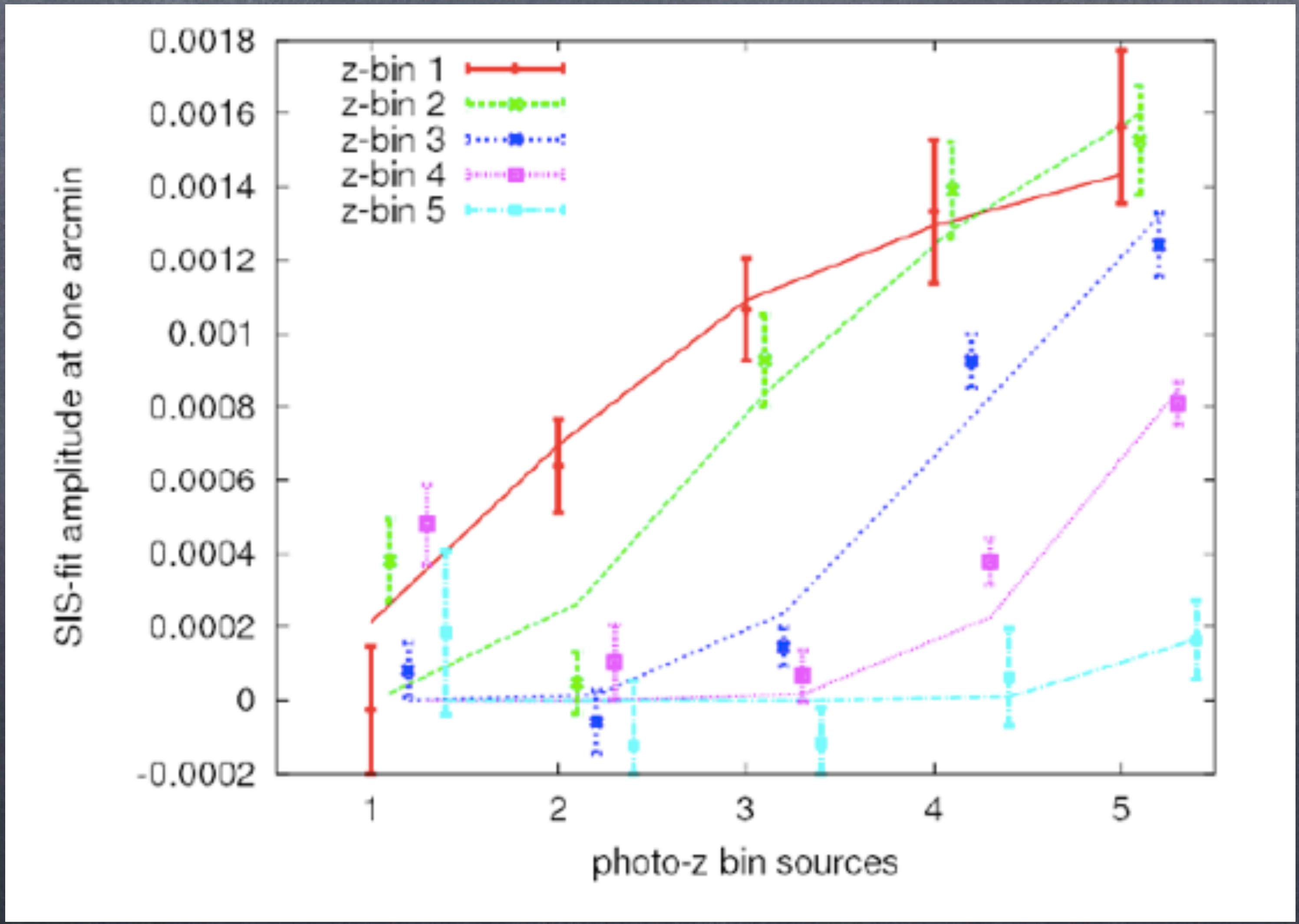
Signal looks good!



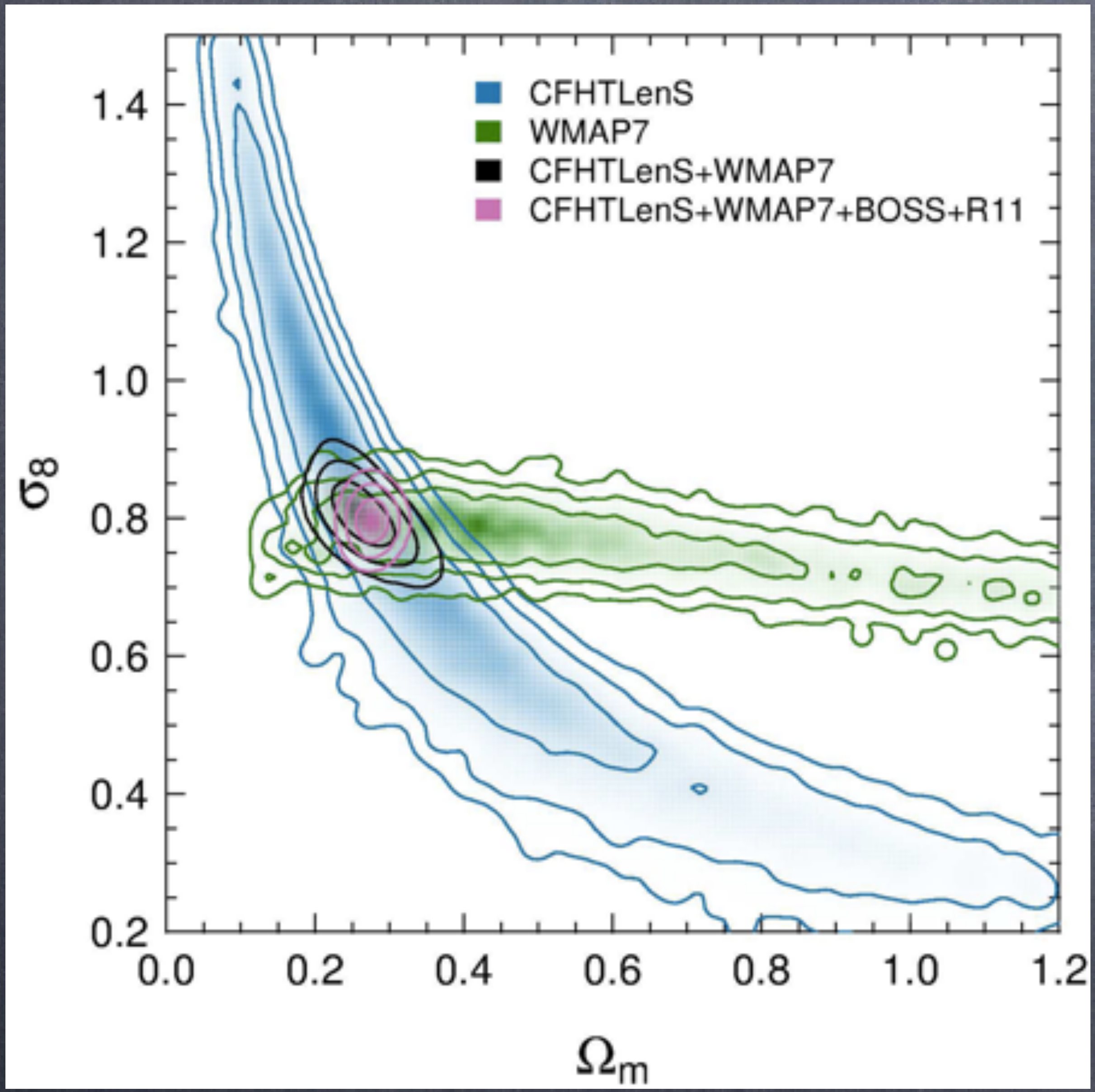
Kilbinger et al. (2013)

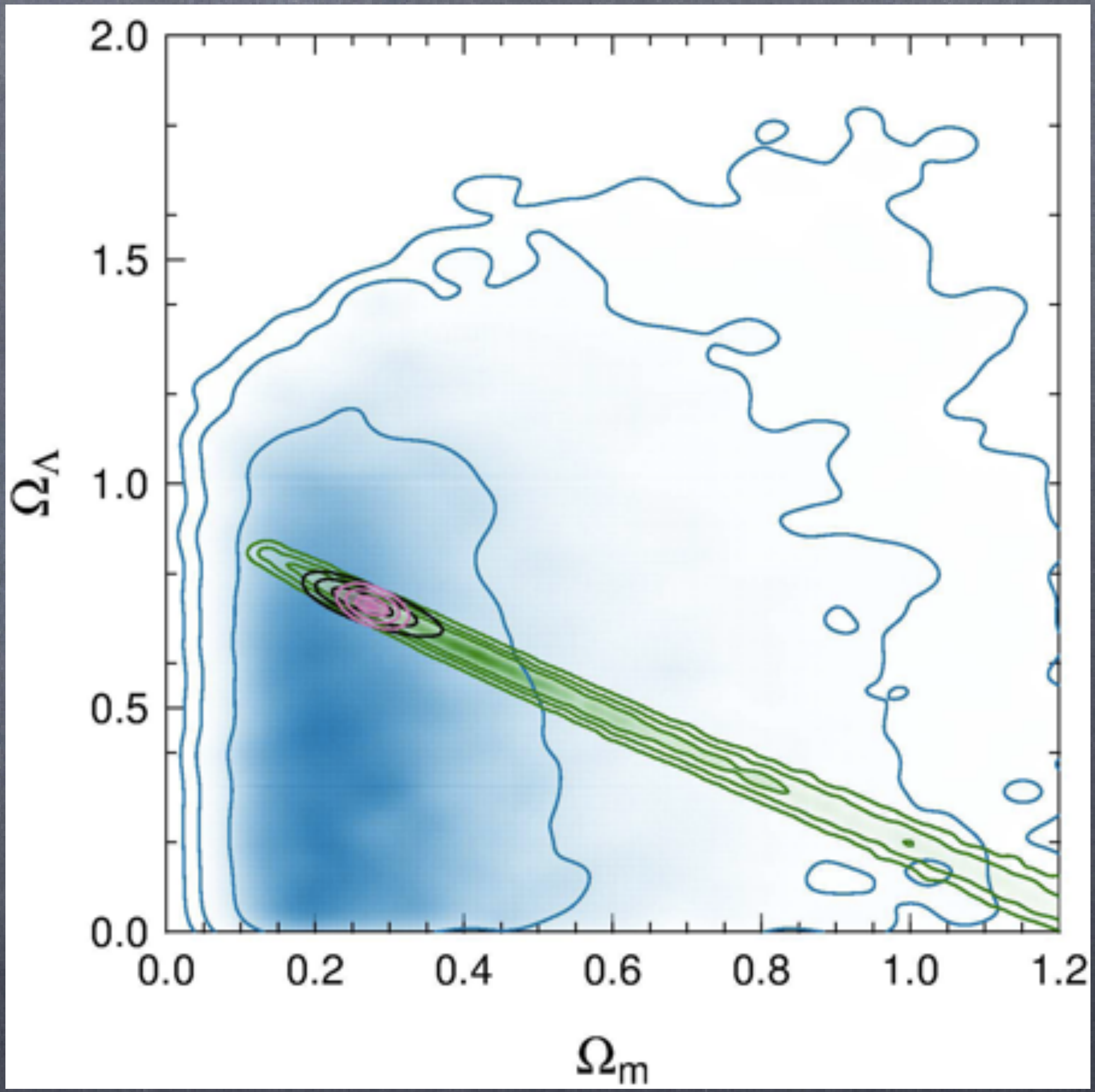
Lensing signal vs redshift

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

Testing General Relativity

For a linearly perturbed metric:

$$ds^2 = a^2[(1+2\phi)dt^2 - (1-2\psi)(dx^2 + dy^2 + dz^2)]$$

Ψ is potential experienced by non-relativistic particles, such as galaxies; measured from redshift space distortions.

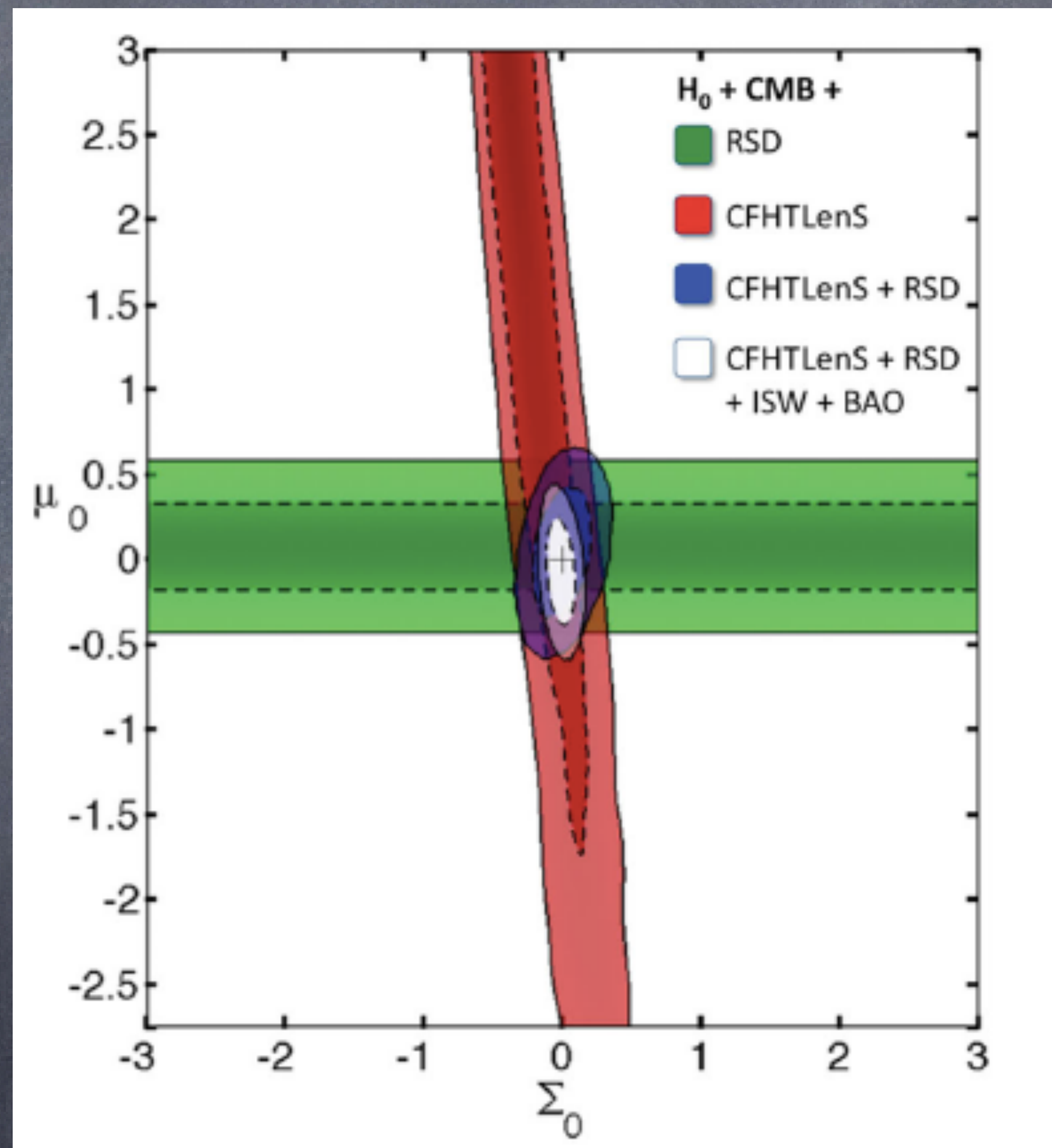
(Φ+ Ψ) is the potential experienced by relativistic particles, such as photons; measured using gravitational lensing

If we can decouple the potentials we can distinguish between dark energy and modified gravity.

Testing General Relativity

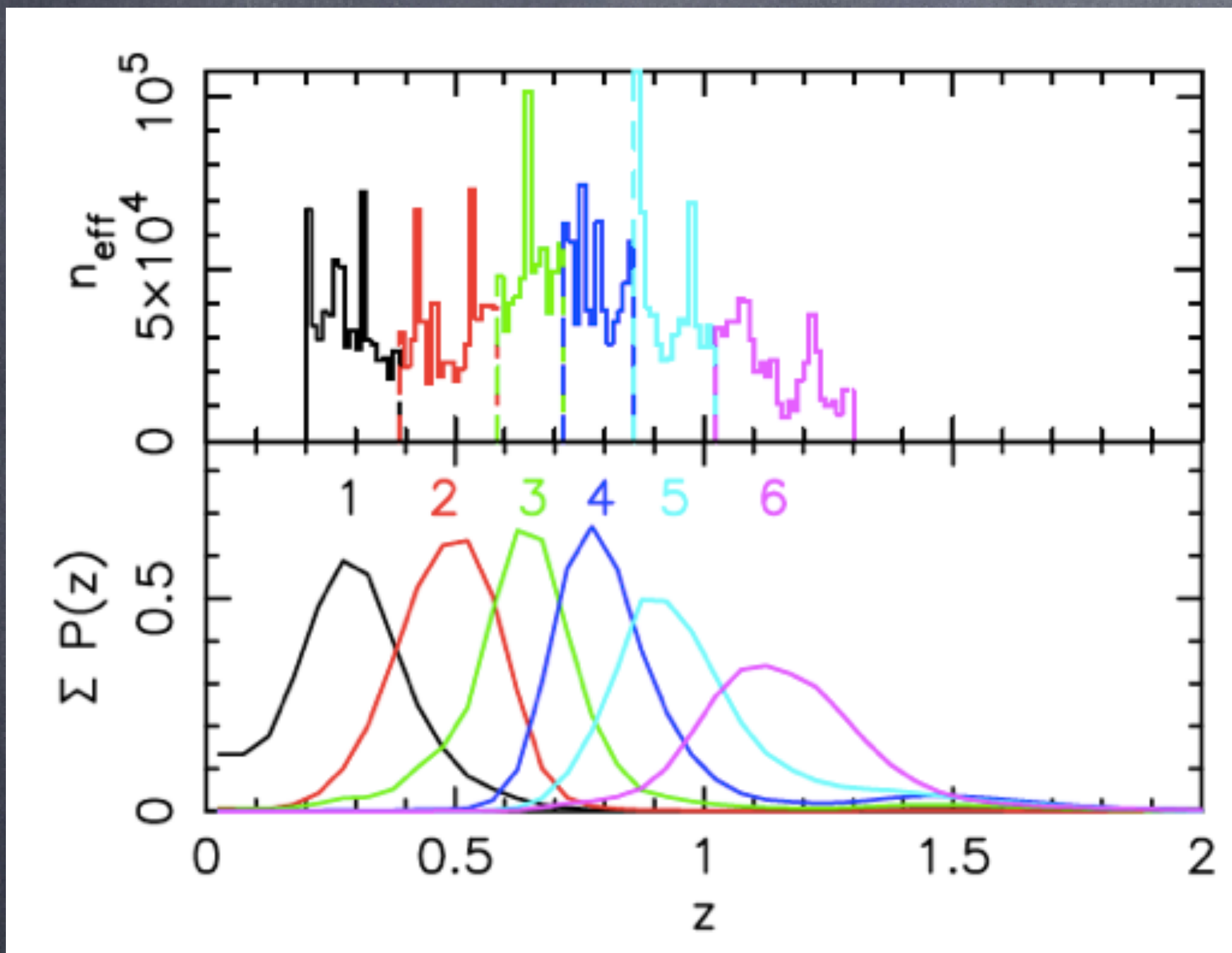
Simpson et al. (2013)

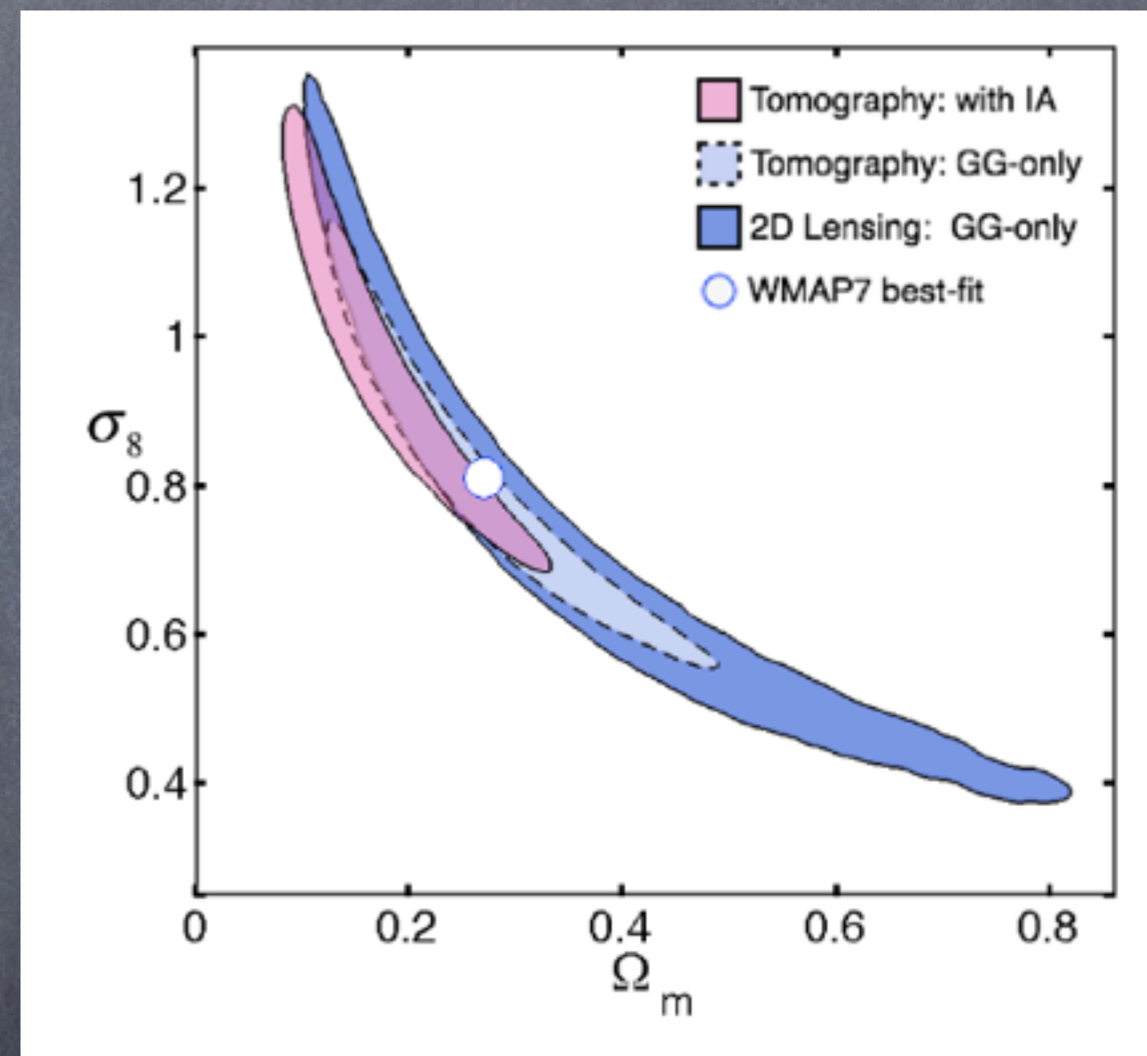
$$\Psi(k, a) = [1 + \mu(k, a)]\,\Psi_{\rm GR}(k, a)$$



$$[\Psi(k, a) + \Phi(k, a)] = [1 + \Sigma(k, a)]\,[\Psi_{\rm GR}(k, a) + \Phi_{\rm GR}(k, a)]$$

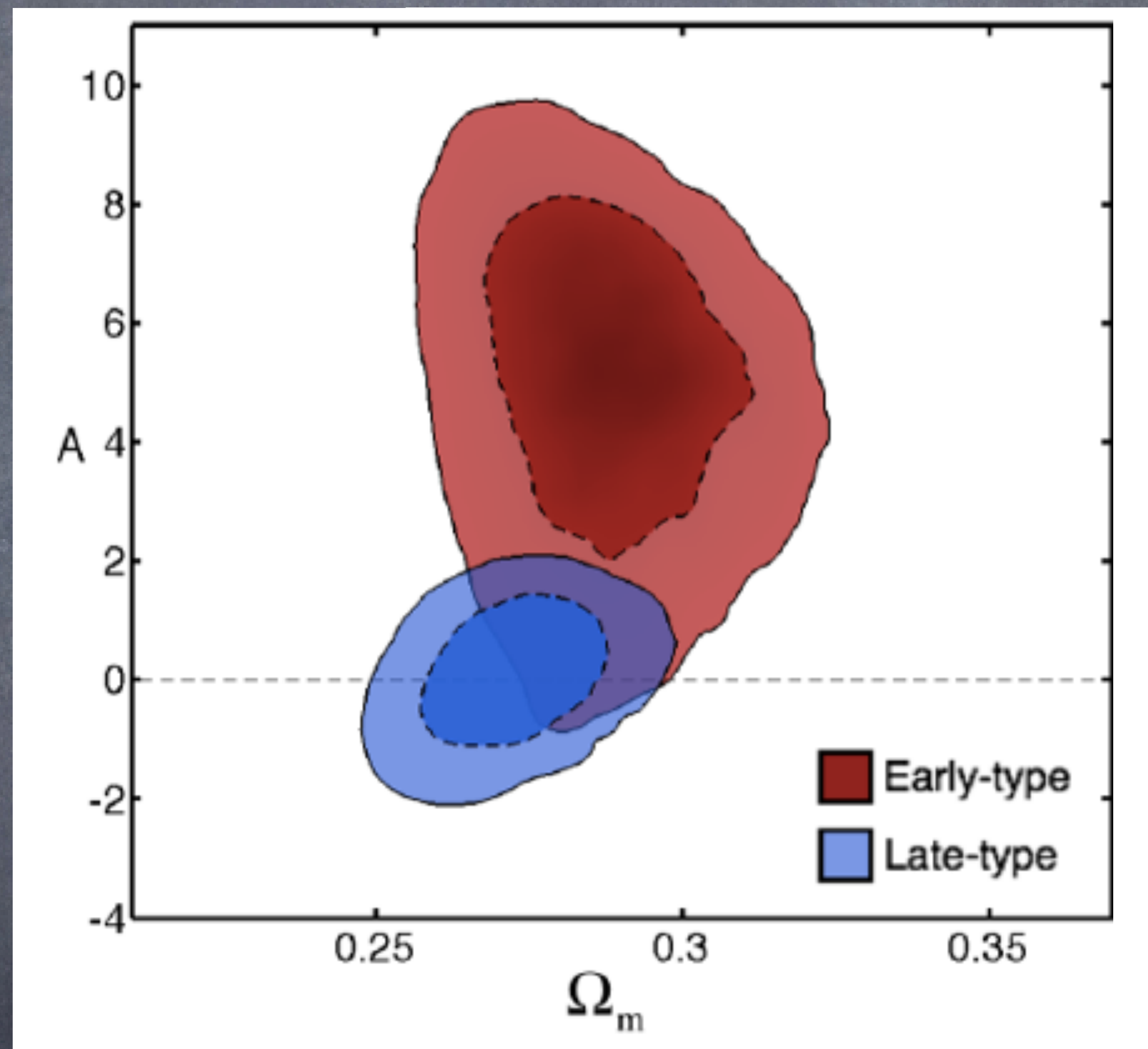
6-bin tomography





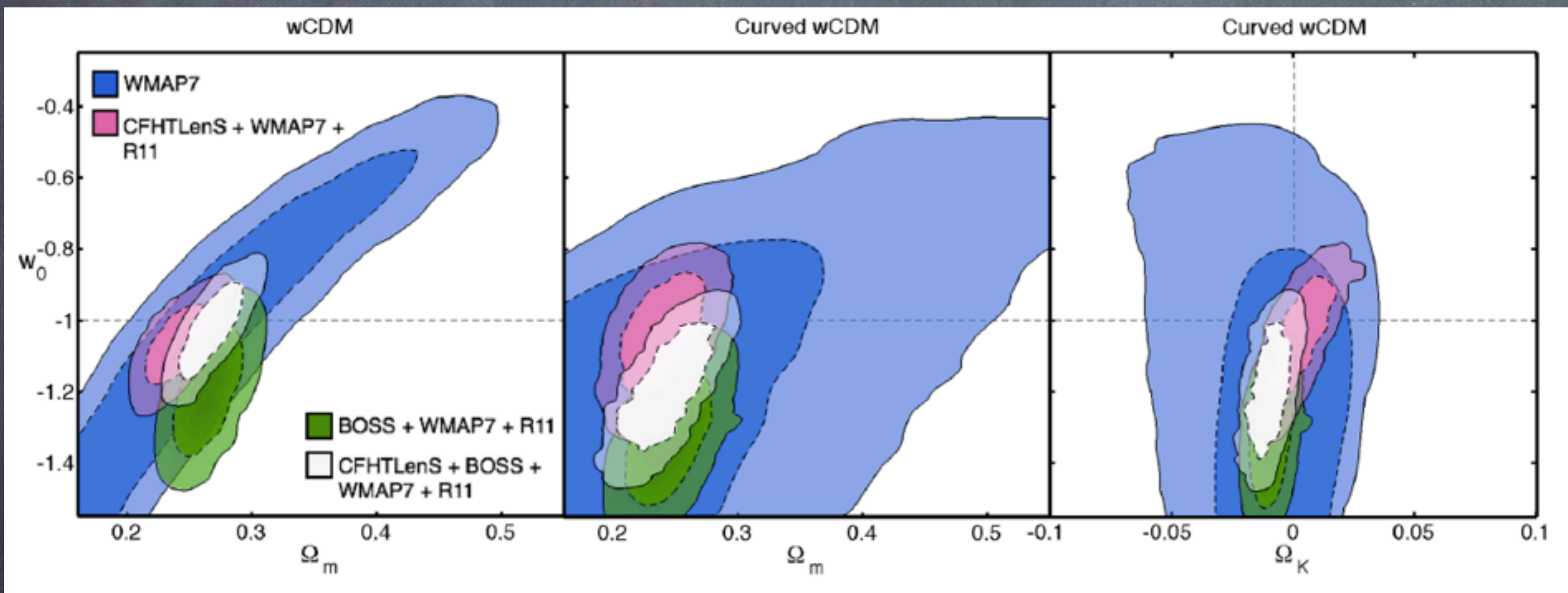
Heymans et al. (2013): narrower bins which means we cannot ignore the intrinsic alignment signal

Detection of IA



Heymans et al. (2013): The IA signal is expected to depend on galaxy type. We use the predictions from the non-linear IA model from Bridle & King (2007) which is based on the model proposed by Hirata & Seljak (2004) and fit the amplitude in the cosmology analysis.

6-bin tomography



Heymans et al. (2013): w=-1.02±0.10

Great future ahead!

The Kilo Degree Survey (KiDS) is the first cosmic shear survey that can provide dark energy constraints without the need of priors from other probes! Observations have started and the survey will be completed in ~3 years from now.

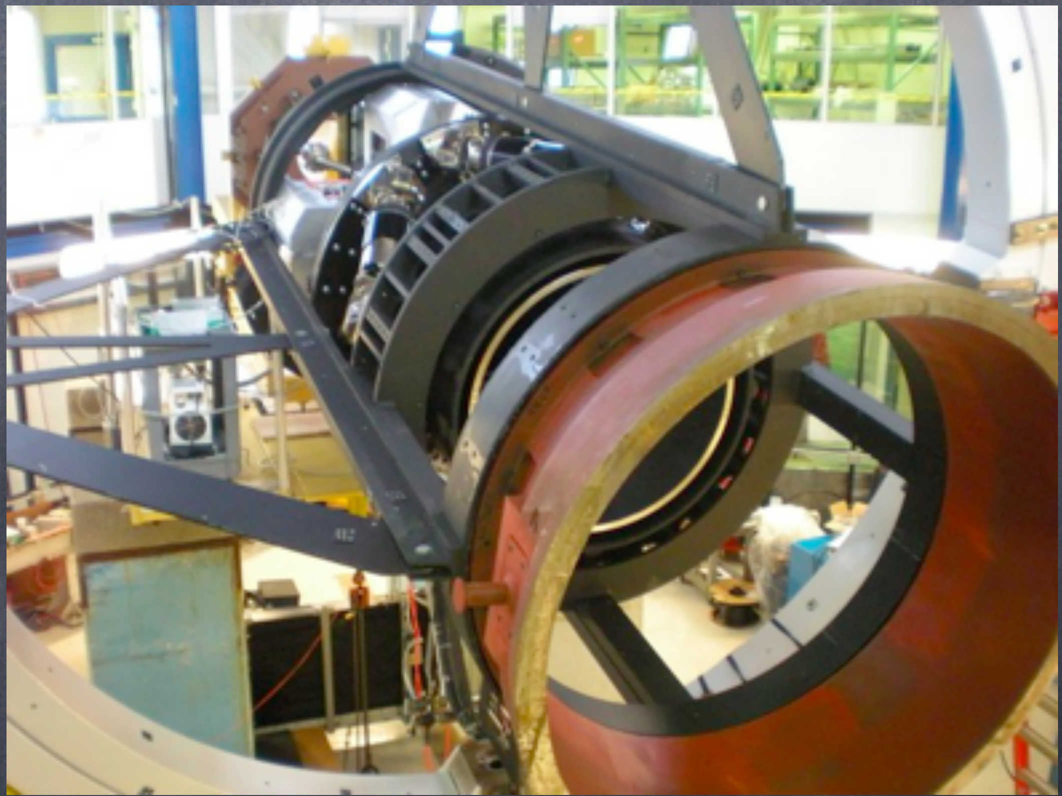
survey area: 1500 deg^2
filter coverage: ugri ZYJHK
depth (AB, 10σ point source):
u'=24.8; g'=25.4; r'=25.2; i'=24.2

~10% error in *w*

Dark Energy Survey

The Dark Energy Survey has started observations using the upgraded Blanco 4m telescope at CTIO (Chile). It will cover 5000 deg^2 in 525 nights. Current team ~120 scientists from 23 organizations.

survey area:5000 deg^2
filter coverage: grizy
depth (AB, 10σ galaxy; 0.8'' seeing):
g=25.2; r=24.8; i=24; z=23.4; y=21.7



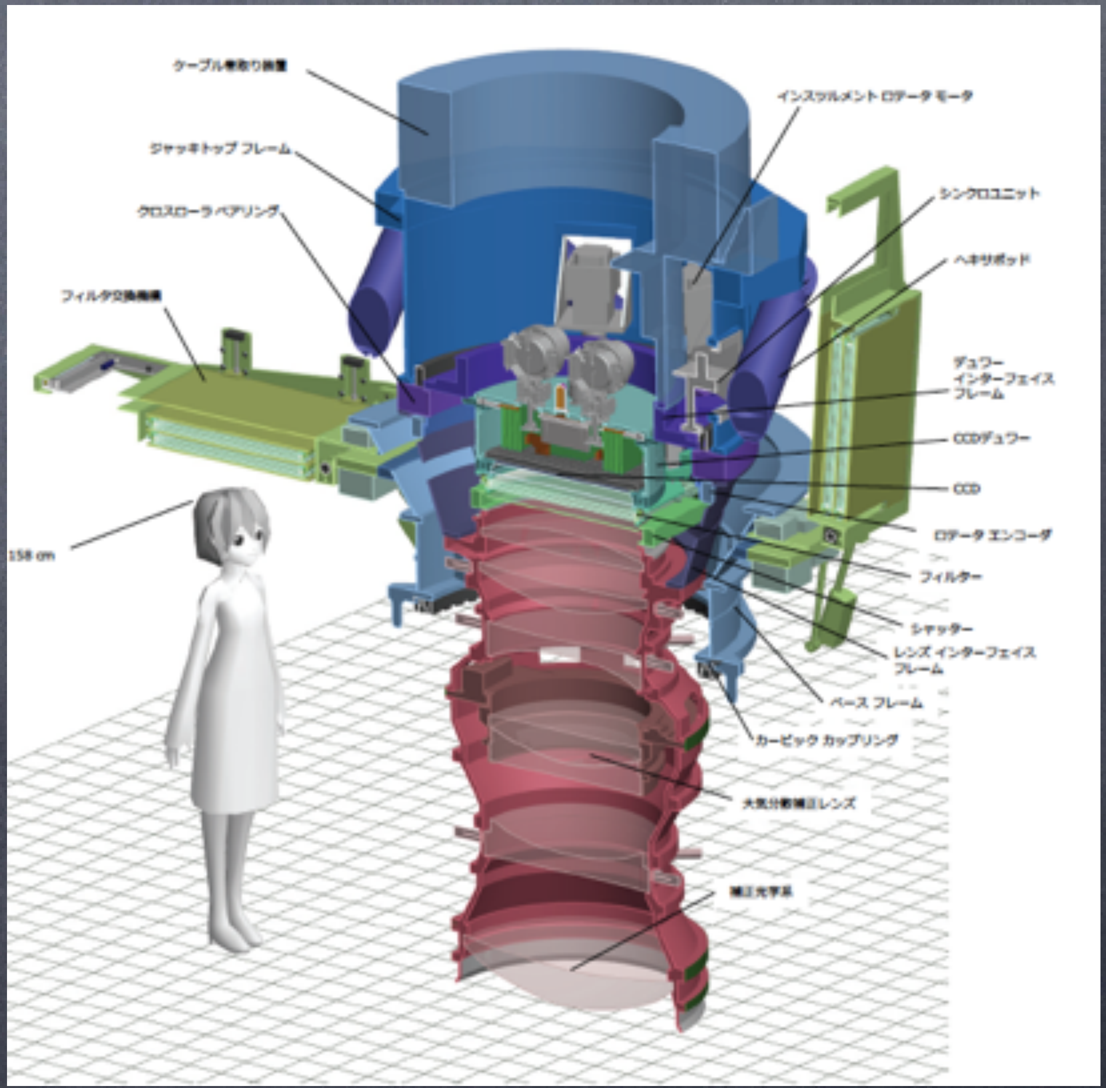
SuMIRe

Subaru Measurement of Images and Redshifts uses Hyper SuprimeCam (HSC) which has a FoV of 1.5 deg^2. It will cover 1500-2000 deg2 over a 5 year period starting soon.

survey area: 1500-2000 deg^2

filter coverage: grizy

depth: t_{exp}~15 min, i~26 (5σ)



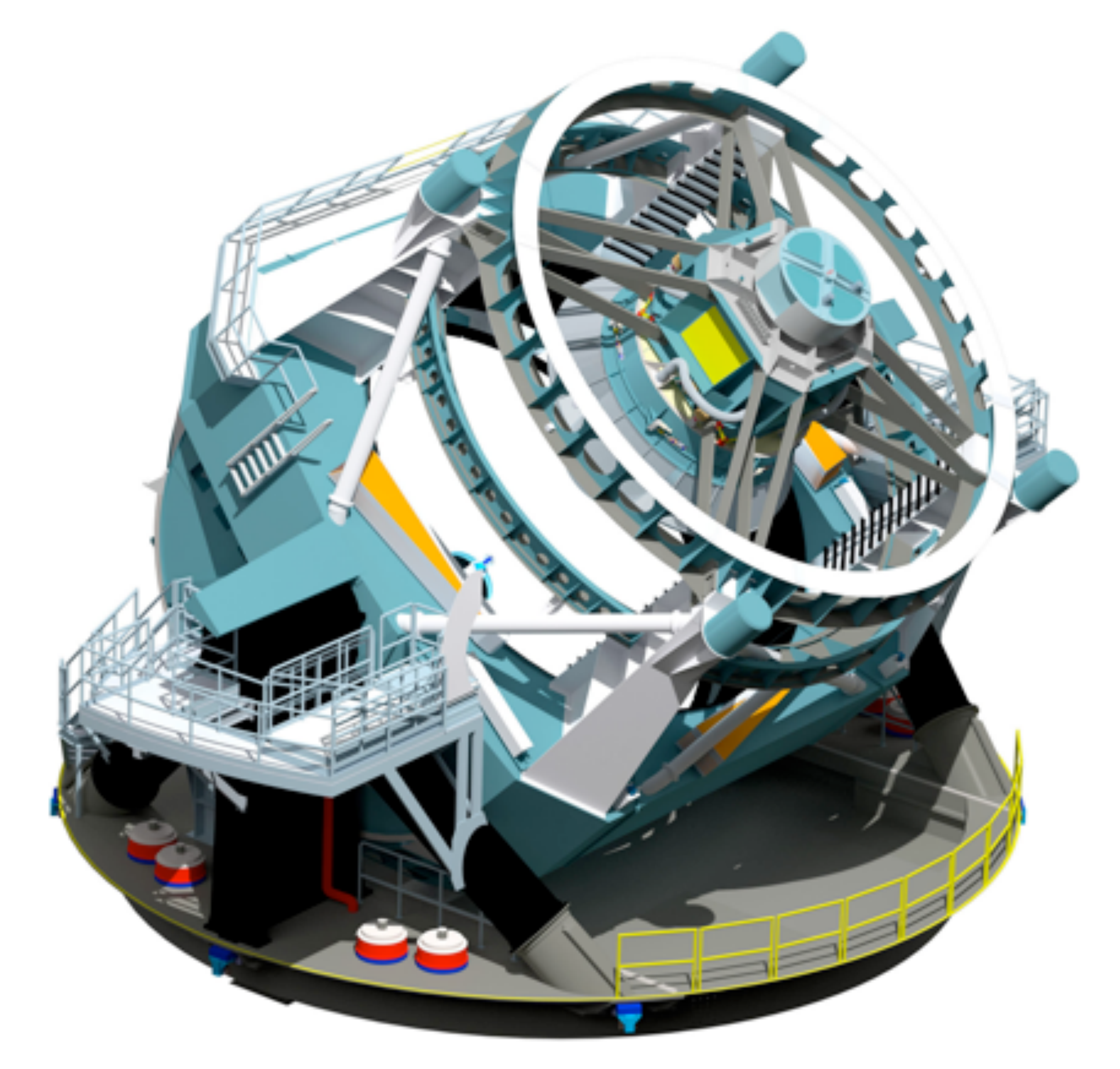
LSST

Unique synoptic survey

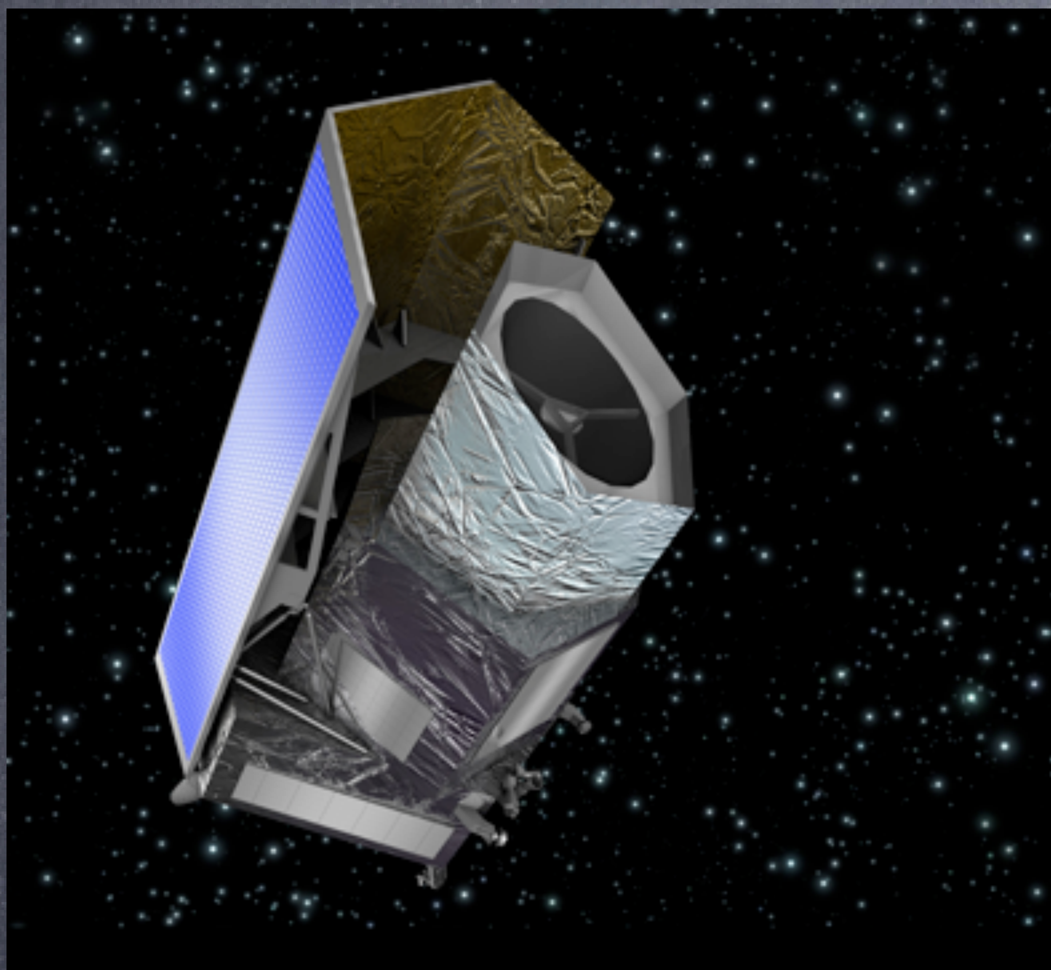
8.4m survey telescope
camera with FoV of 9.6 square degrees

scan the sky δ<10 deg
15s exposures reaching r~24.5
each patch ~1000+ ugrizy images: r~27.2

great for cosmology, although systematics at this level of precision still unclear.



Advantages of space



Euclid Consortium

1.2m + 0.5 sq.deg. FoV
"best" 15,000 deg^2 extragalactic sky

optical FWHM: 0.18"
NIR photometry & spectroscopy

many images: 2x10^9 galaxies
many spectra: 70x10^6 redshifts
many members: ~1100 people

- much smaller PSF
- optical + NIR bands

- better photo-z's
- large reduction in systematics

Euclid: ultimate cosmology machine

Euclid Definition Study Report, Laureijs et al. 2011, arXiv:1110.3193

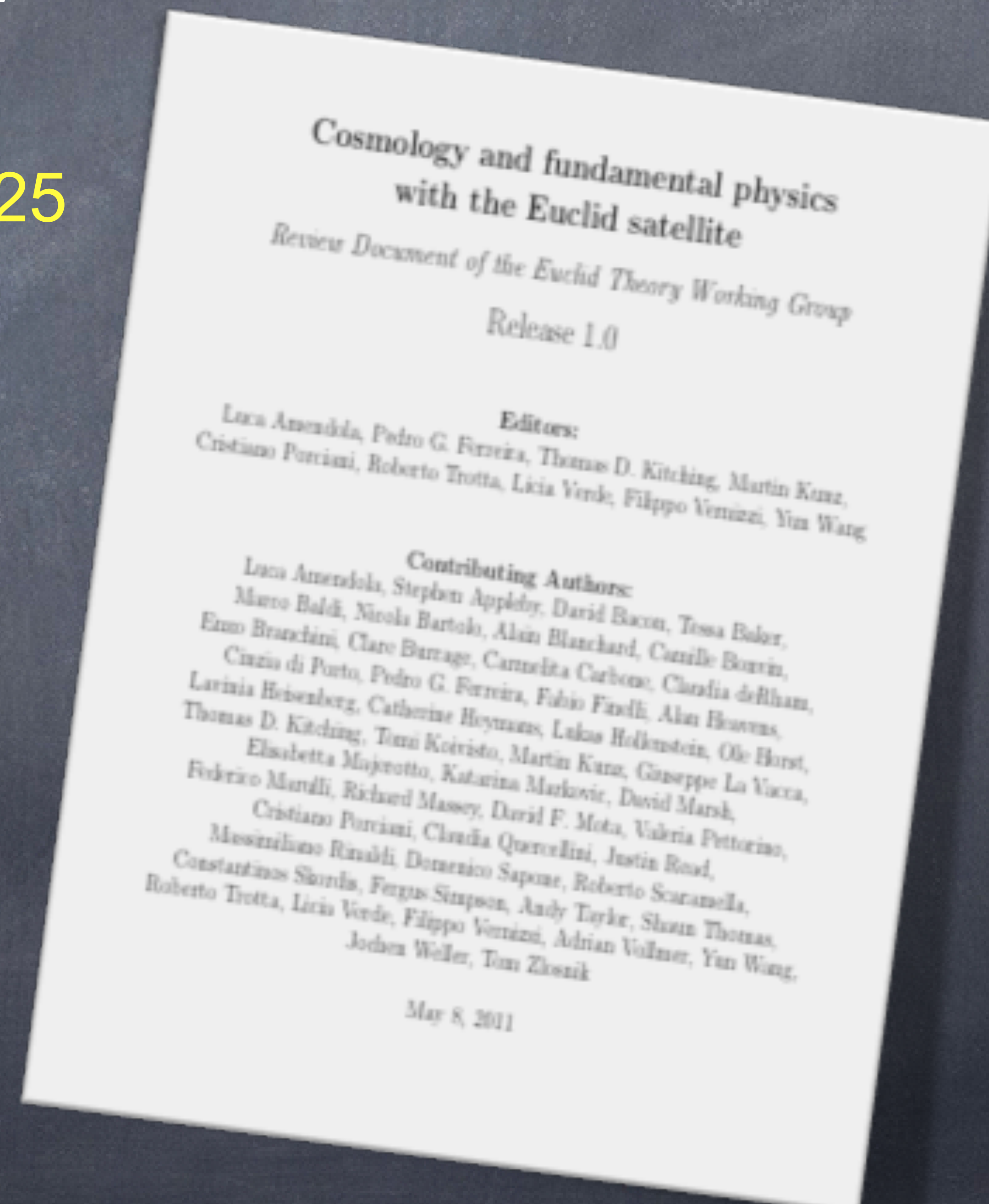
	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	*FoM*
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**

These numbers only have meaning if systematic biases are small.
Euclid is designed to achieve this!

Euclid: a lot of science

The Theory Group has prepared an extensive review of the cosmology and fundamental physics that can be studied using Euclid.

Amendola et al. (2012): arXiv:1206.1225



Cosmology and fundamental physics with the Euclid satellite

Review Document of the Euclid Theory Working Group

Release 1.0

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May 8, 2011

Great future ahead!