Weak Lensing by Large-scale Structure

A look at the dark side of the Universe

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CIFAR

What is dark energy?

The hardest thing of all is to find a black cat in a dark room, especially if there is no cat - Confucius

Is it a cosmological constant or a dynamic field? Or is there a problem with General Relativity?

We lack a theoretical framework that can explain the observations. Observational constraints are needed to make progress.

How to proceed?

We have a number of probes at our disposal, each with their own advantages and disadvantages.

Distances:

- standard candles (type Ia SNe)
- standard rulers (CMB, BAO)

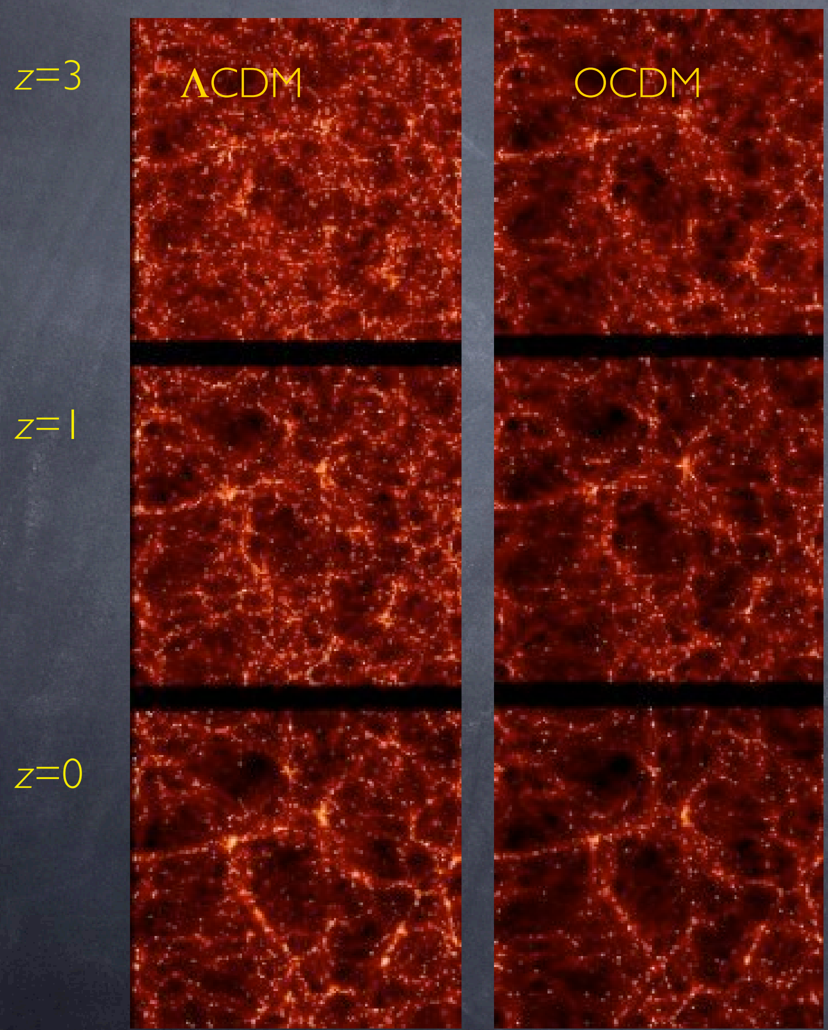
expansion history only

Growth of structure:

- counting galaxy clusters
- clustering of matter

expansion history
+
modified gravity

Spot the difference...



Different values for cosmological parameters lead to a different distribution of (dark) matter and a different evolution.

The clustering properties of matter as a function of scale and redshift can be used as a tool to measure the cosmology!

Kauffmann et al.

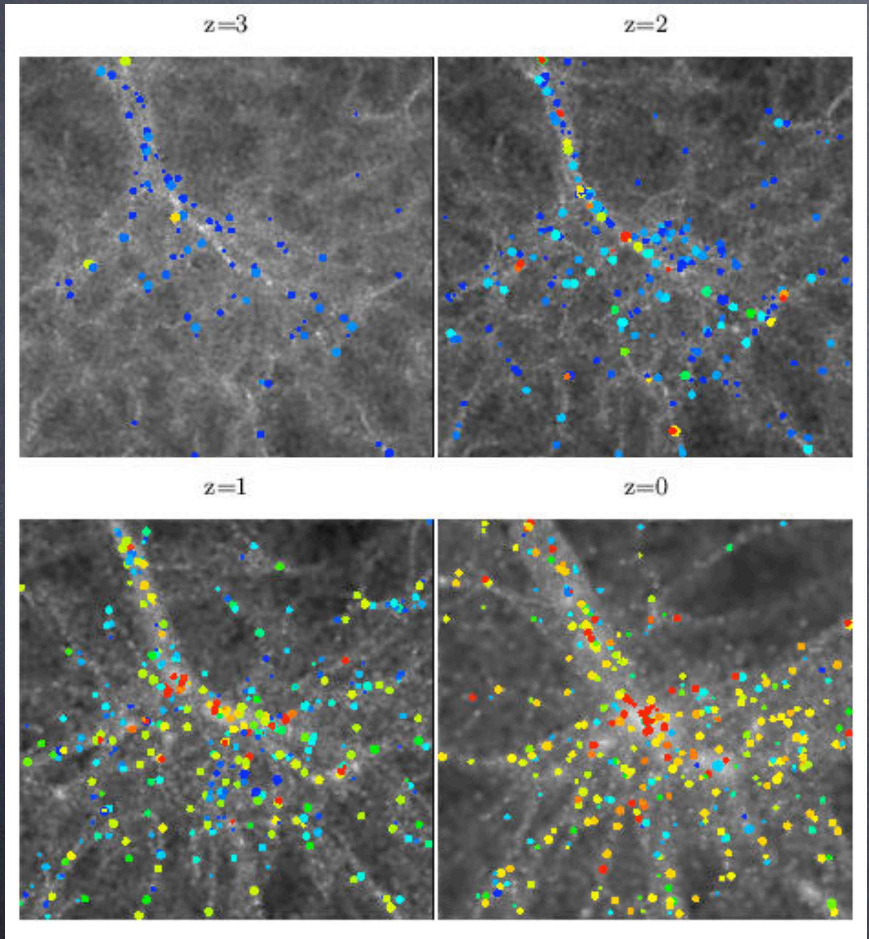
Look at the bright side?

We can simulate the dark matter distribution quite well, but unfortunately that is not what we can observe...

Can we use the observed distribution of galaxies instead? Or predict the distribution of galaxies for a given set of cosmological parameters?

Light $\neq$ Density!

Simulating the Universe



GIF simulations, Colberg et al.

Example of the galaxy distribution based on semi-analytic models.

Need to include:

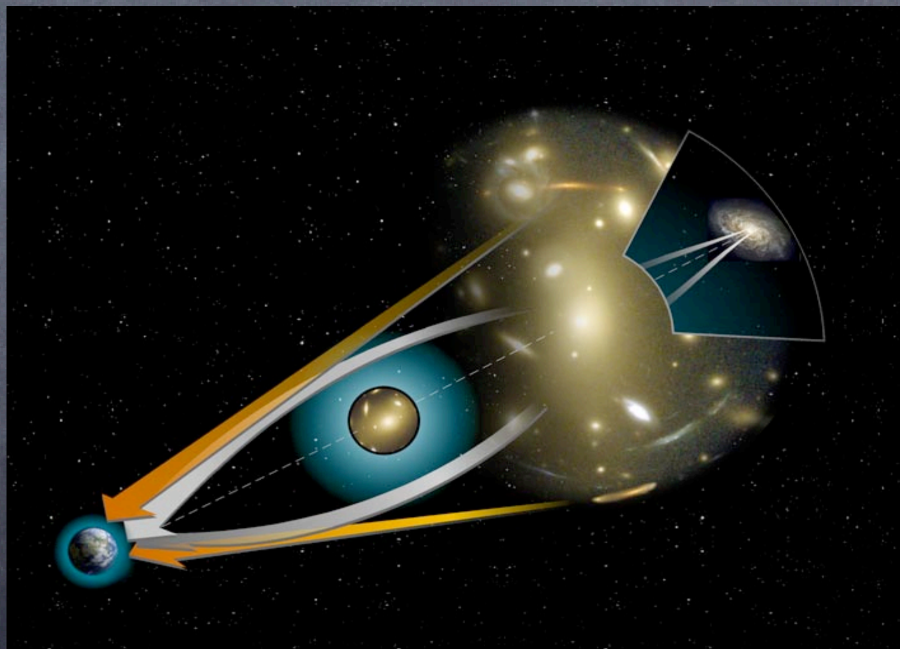
- Star formation
- SNe feedback
- Chemical enrichment
- Gas infall
- Merger history

Use the force...

"For my ally is the force, and a powerful ally it is" - Yoda

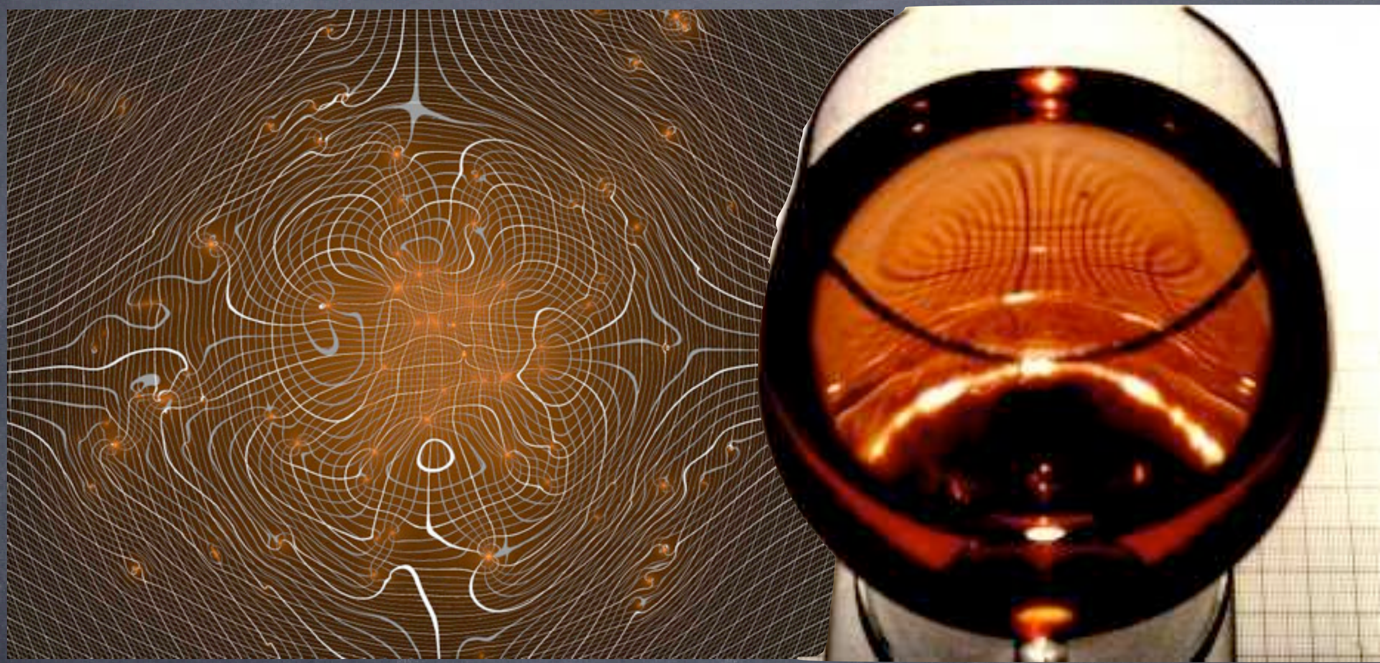
Gravitational lensing

As predicted in the early 20th century, rays of light are deflected by massive objects in the universe.



The angle of deflection is a direct measure of mass!

Gravitational lensing

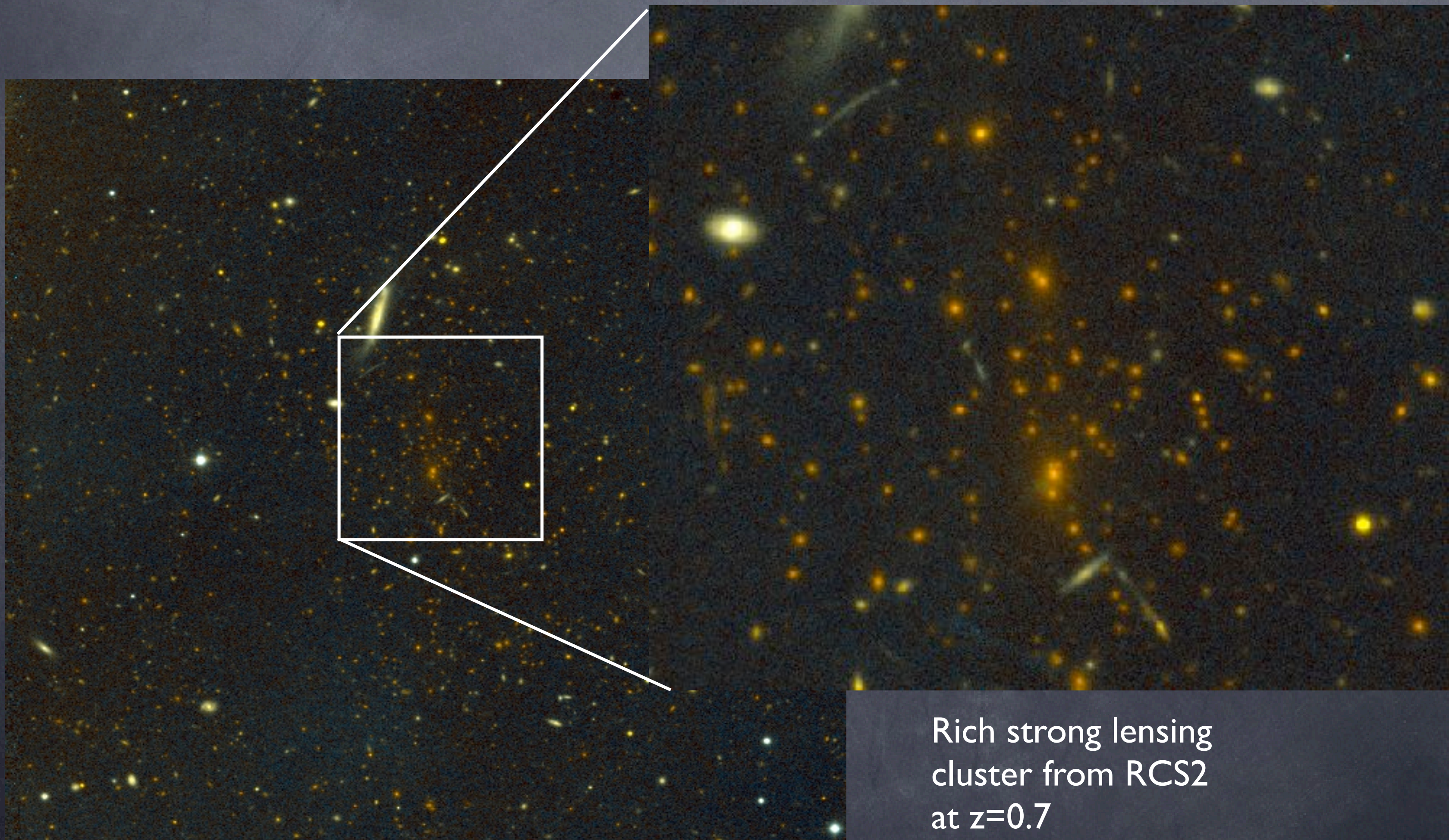


Inhomogeneities in the mass distribution distort the paths of light rays, resulting in a remapping of the sky. This can lead to spectacular lensing examples…

Gravitational lensing

Galaxy Cluster Abell 2218 **HST** • WFPC2
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

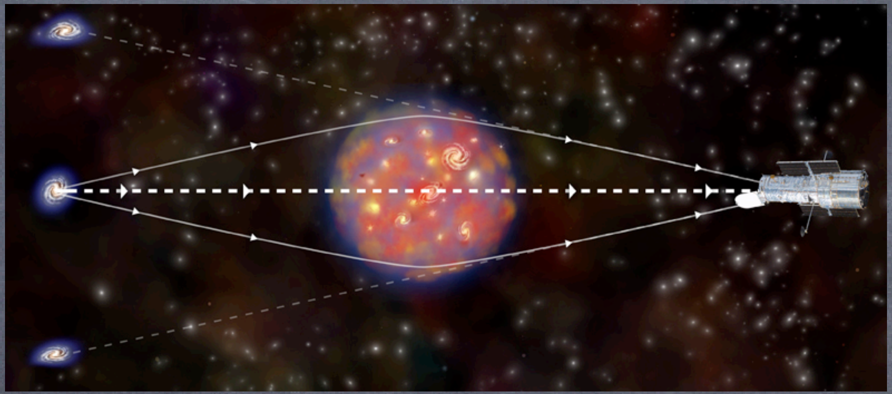
Gravitational lensing



Rich strong lensing
cluster from RCS2
at z=0.7

Gravitational lensing

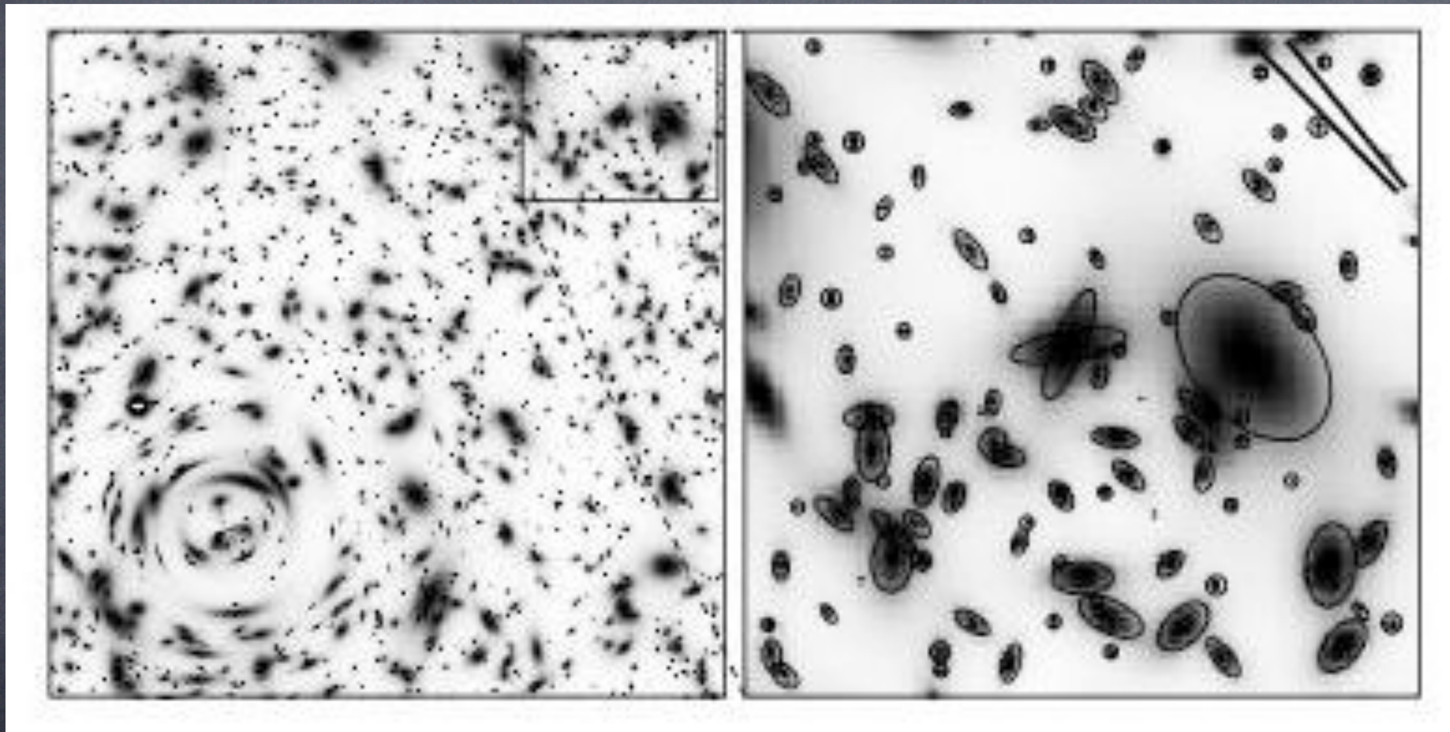
Strong gravitational lensing requires a good alignment of the source and the lens. This doesn't happen often...



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

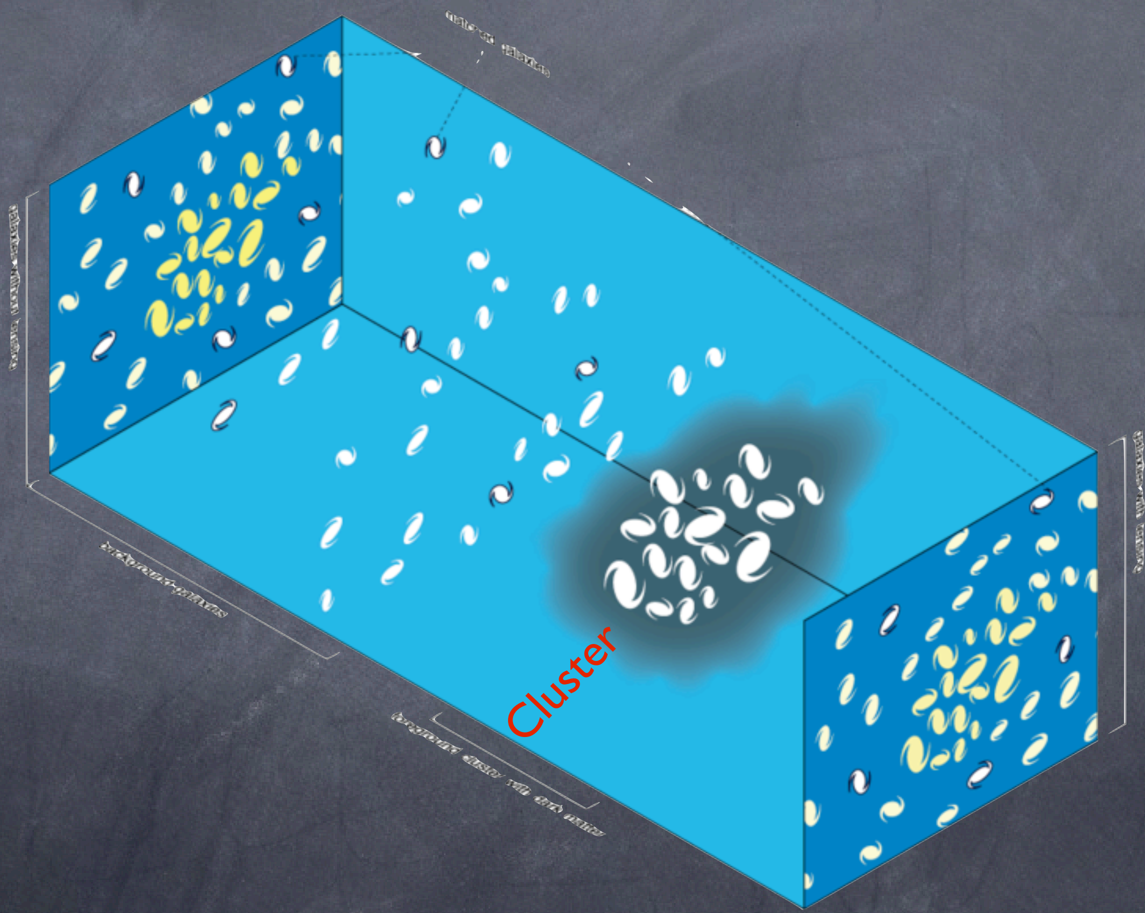
- an (unknown) shift in position
- a small distortion of the shapes of the galaxies

Weak gravitational lensing



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

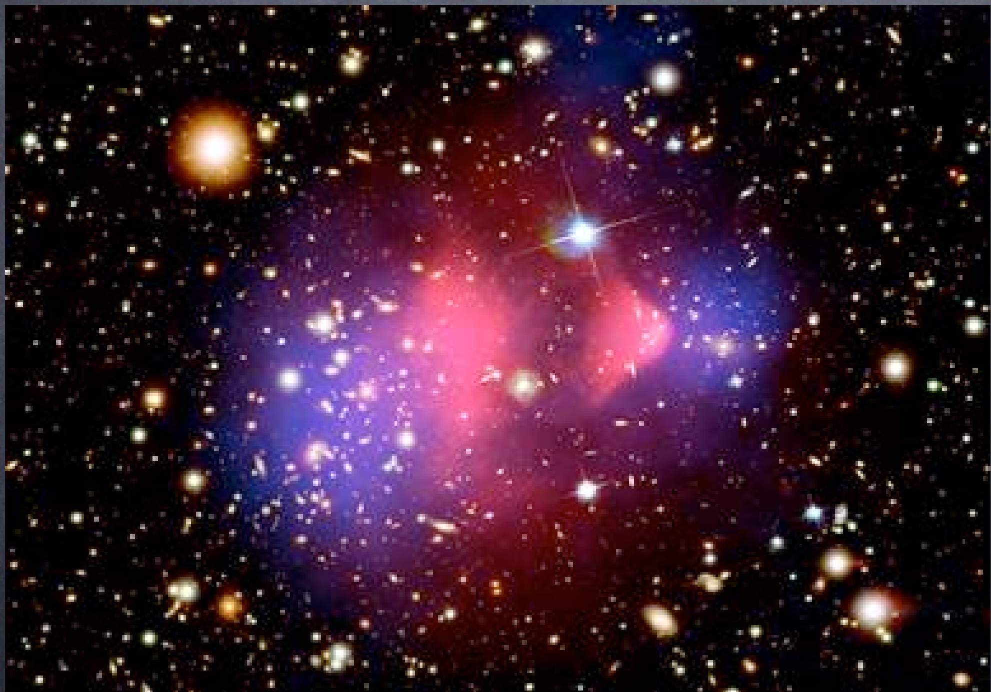
Weak gravitational lensing



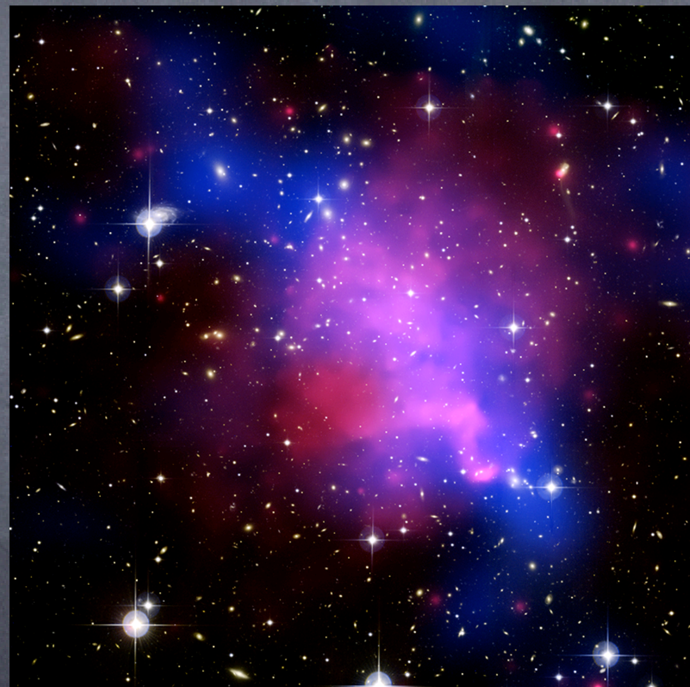
In the absence of noise we would be able to map the matter distribution in the universe (even “dark” clusters).

We can see dark matter!

... and it's blue!

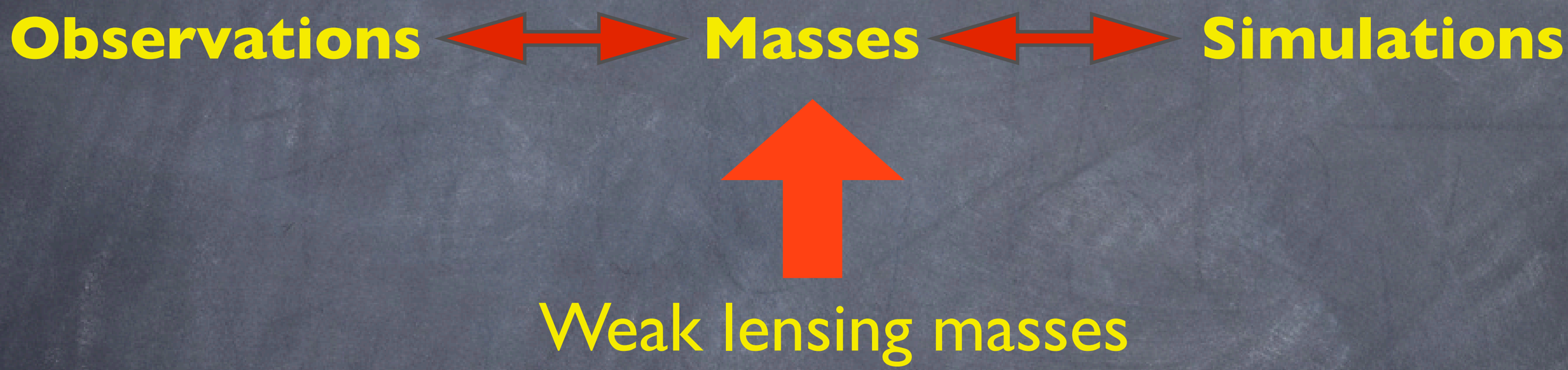


Clowe et al. (2006)



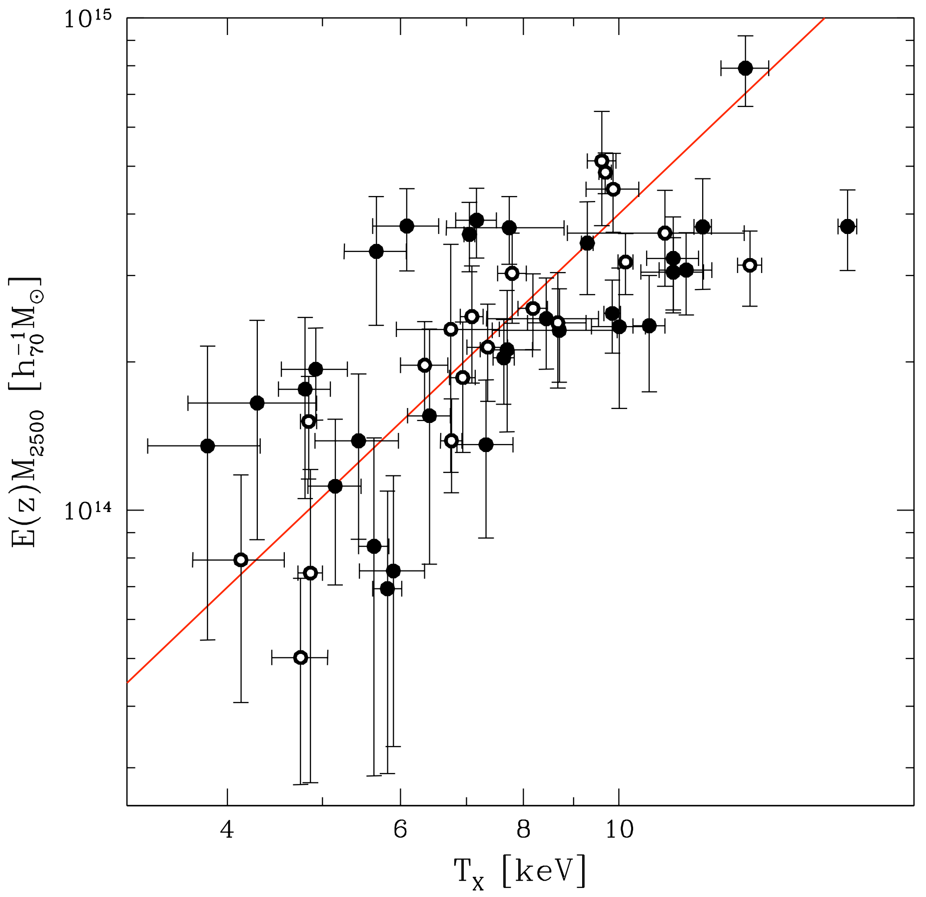
Mahdavi et al. (2008)

Weak lensing mass calibration

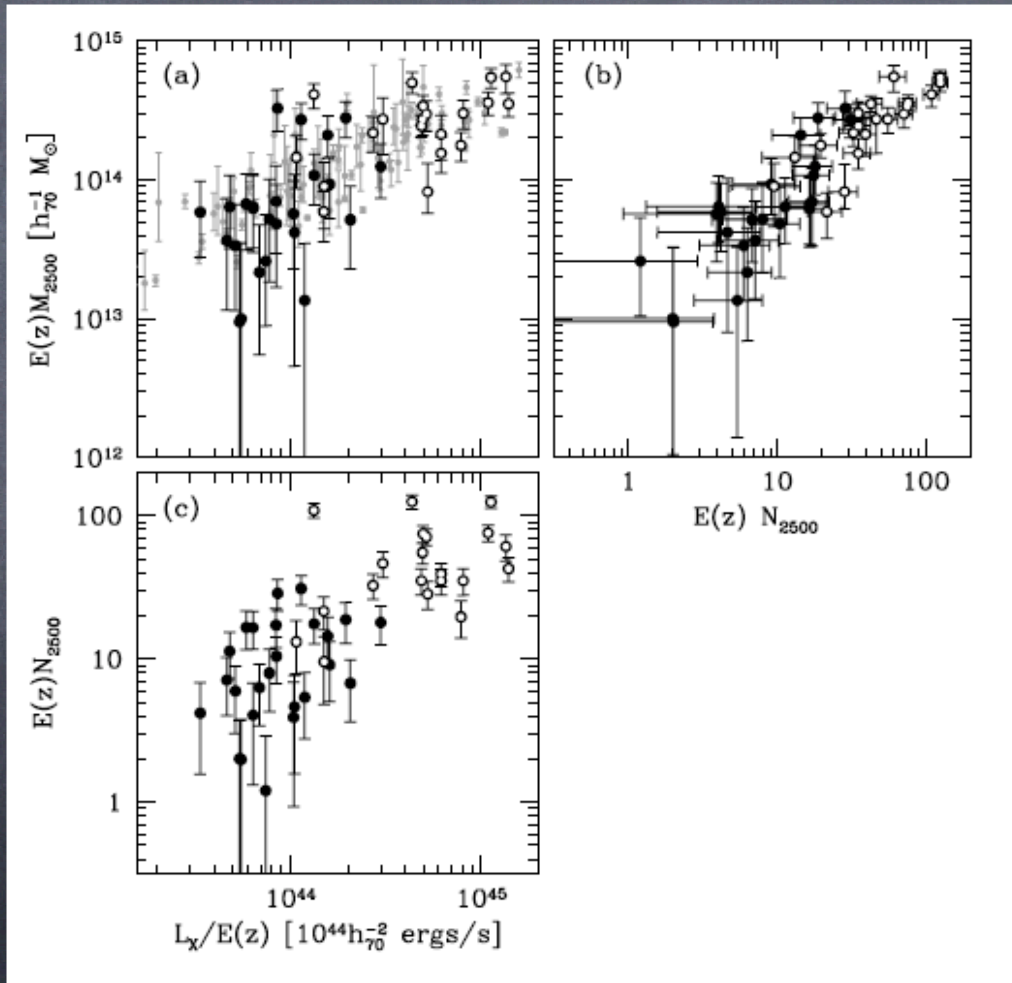


A large sample of clusters with accurate weak lensing masses is important for the success of cluster abundance studies.

Weak lensing mass calibration



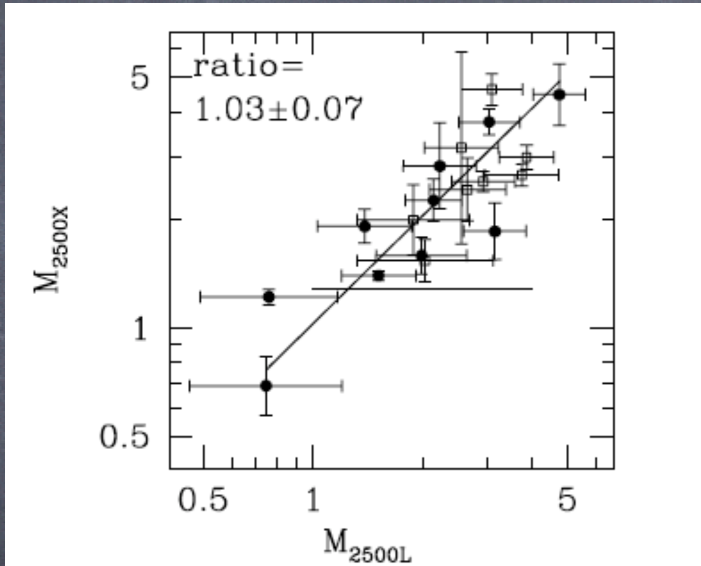
Quantifying scatter



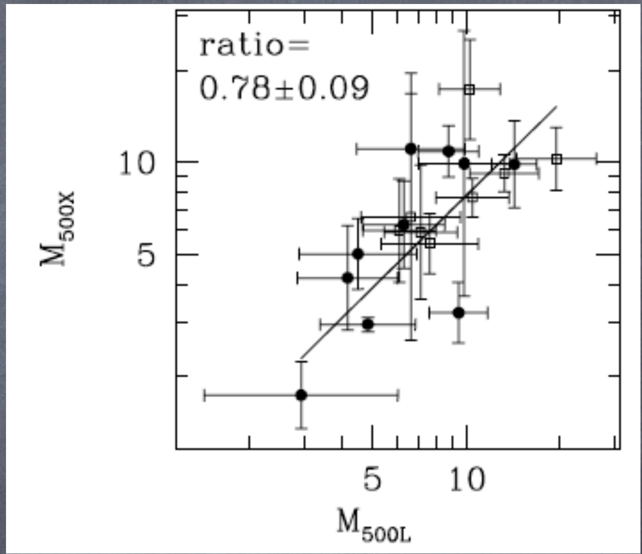
Hoekstra et al. (submitted)

Lensing vs X-ray masses

Δ= 2500



Δ= 500

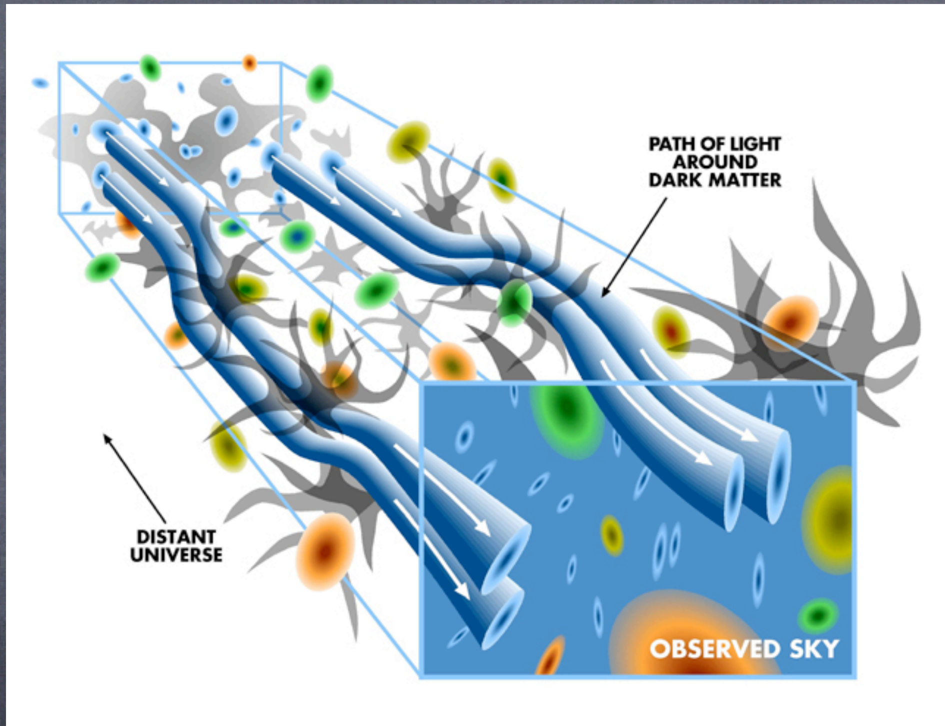


X-ray mass

lensing mass

Mahdavi et al. (2008): at large radii the gas is not in hydrostatic equilibrium.

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.

An ideal probe of cosmology?

- Weak lensing provides a *direct* measurement of what we want: the (projected) matter distribution

- The physics is *well understood*: General Relativity

- The applications are numerous.
    - ❑ statistical properties of the matter (cosmological parameters).
    - ❑ relation between galaxies and dark matter (galaxy biasing).
    - ❑ properties of dark matter halos (test of CDM and law of gravity).

Why cosmic shear?

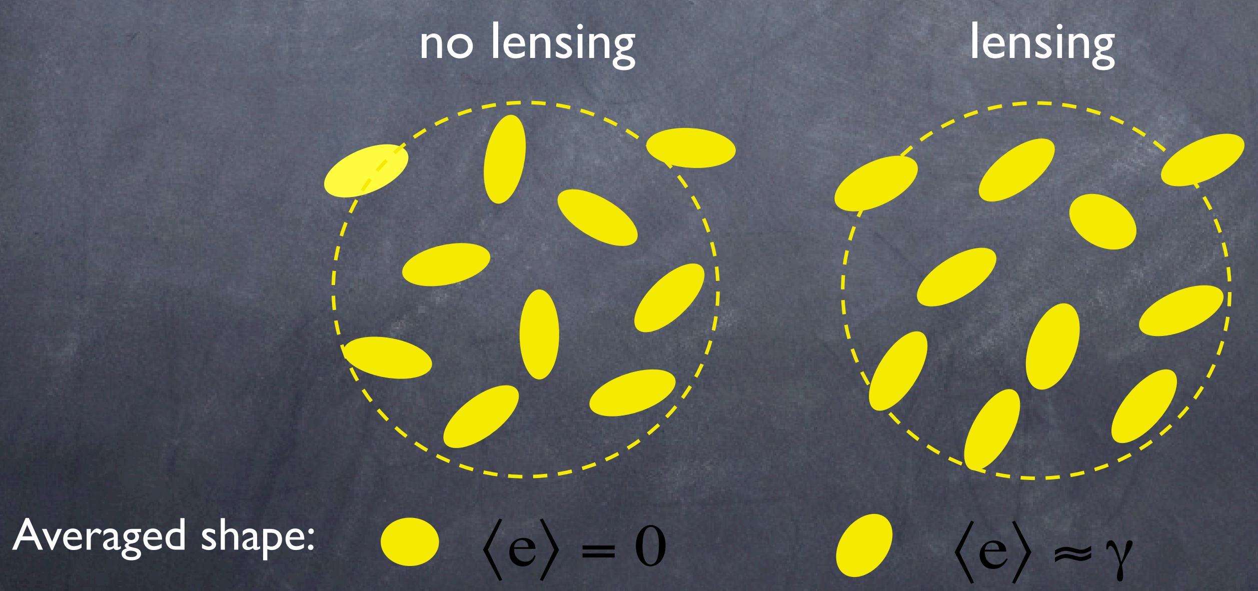
Current observational constraints on the properties of dark energy are crude at best. Progress depends critically on how well various cosmological probes can be understood:

Do we understand what we are doing?

DETF comments: "The **WL** technique is also an emerging technique. Its eventual accuracy will also be limited by systematic errors that are difficult to predict. *If* the systematic errors are at or below the level asserted by the proponents, it is likely to be the most powerful individual Stage-IV technique and also the most powerful component in a multi-technique program."

Do we understand?

The underlying assumption is that the position angles are random in the absence of lensing. At some level intrinsic alignments will complicate things (can be dealt with using photometric redshifts).



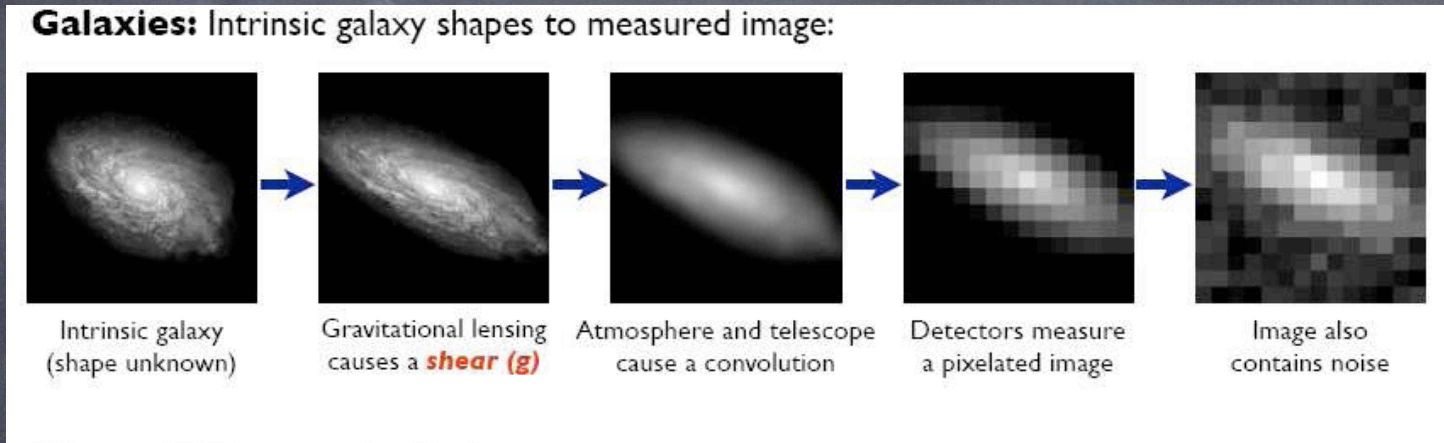
What do we need to do?

We *only* need to measure :

- shapes
- redshifts

The background (or source) galaxies are typically very faint and spectroscopic redshifts cannot be obtained. Even determining photometric redshifts can be difficult.

What do we need to do?



GREAT'08 challenge

Measure the shapes of objects like this?

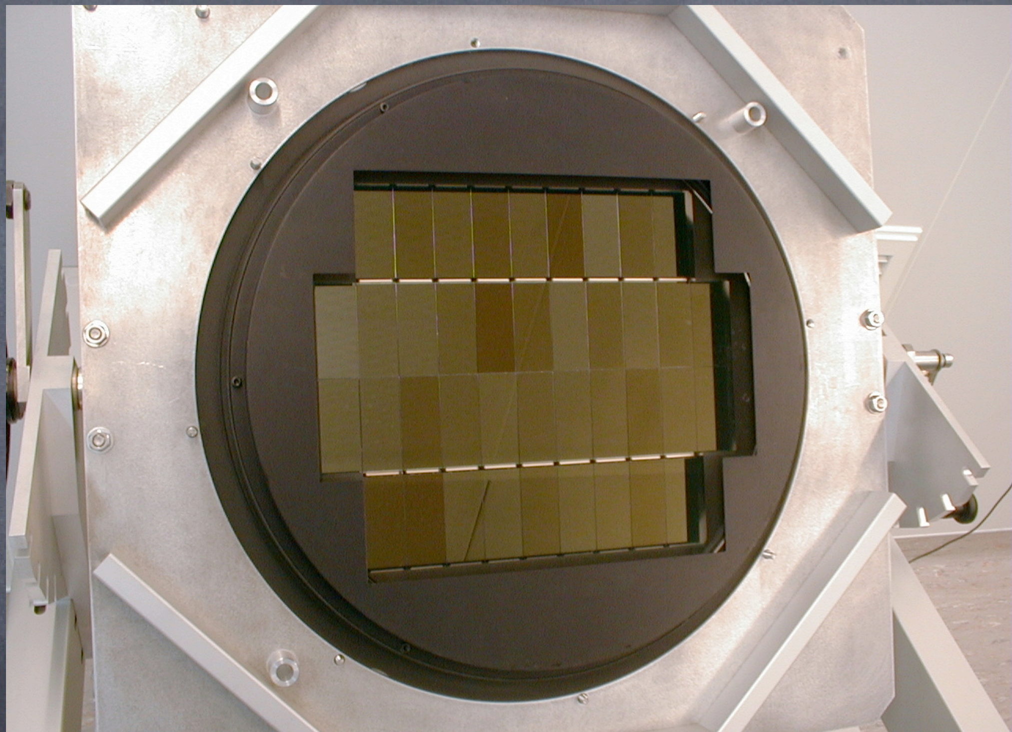
What do we need to do?

The weak lensing signal is small:

- We need to measure the shapes of many galaxies.
- We need to remove systematic signals at a high level of accuracy.

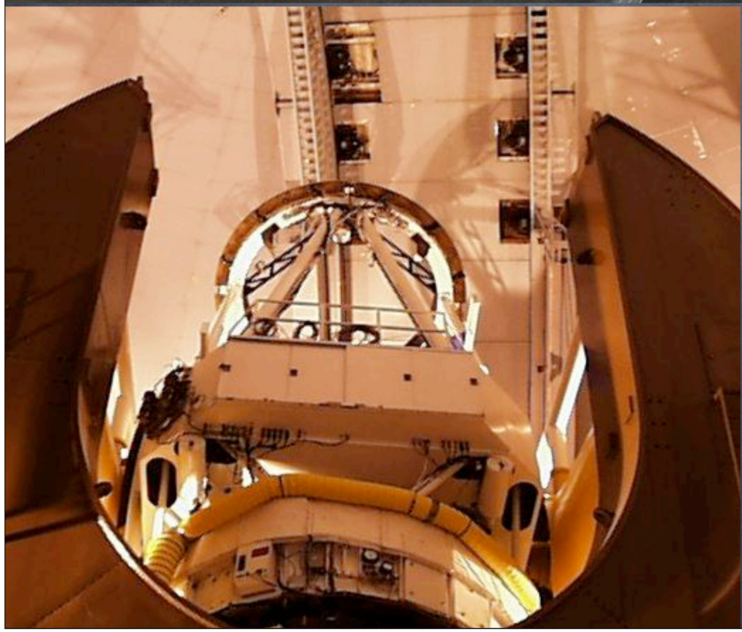
Only recently we have been able to overcome both obstacles, although we still need various improvements to deal with the next generation of surveys.

Build a big camera ...



Megacam:
- ❑ 1 square degree field of view
- ❑ ~350 megapixels

... put it on a good telescope ...



Such as the CFHT

or VST, Subaru SNAP, etc

... and take a lot of data

CFHT:

CFHTLS
RCS2
CCCP
MENeaCS

VST:

KIDS

Systematics

The observational distortions are typically larger than the lensing signal.

The observed shapes of galaxies need to be corrected for

- PSF anisotropy
- Circularisation by seeing
- Camera shear

Various correction techniques have been developed and tested extensively. In particular the Kaiser et al. (1995) approach is widely used. This method works fine for current data sets, but we need improved methods for upcoming large surveys.

Dealing with systematics

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

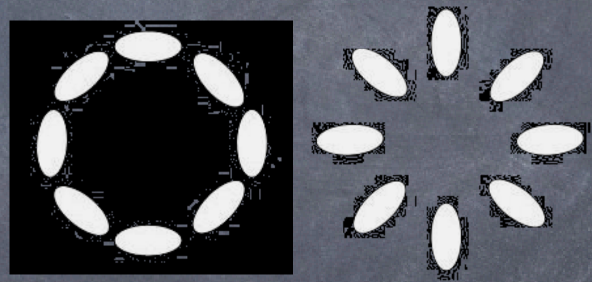
Several diagnostic tools can be used. However, knowing systematics are present doesn't mean we know how to deal with them…

But we can readily simulate weak lensing surveys. The Shear TEsting Programme (STEP) and the GREAT'08 challenge are aiming to improve our techniques this way.

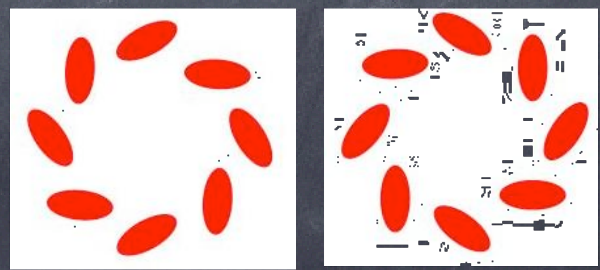
Diagnostics

The lensing signal should be curl-free. We can project the correlation functions into one that measures the divergence and one that measures the curl: *E-B mode decomposition*. We can also look for correlations between the corrected galaxy shapes and the PSF anisotropy.

E-mode (curl-free)



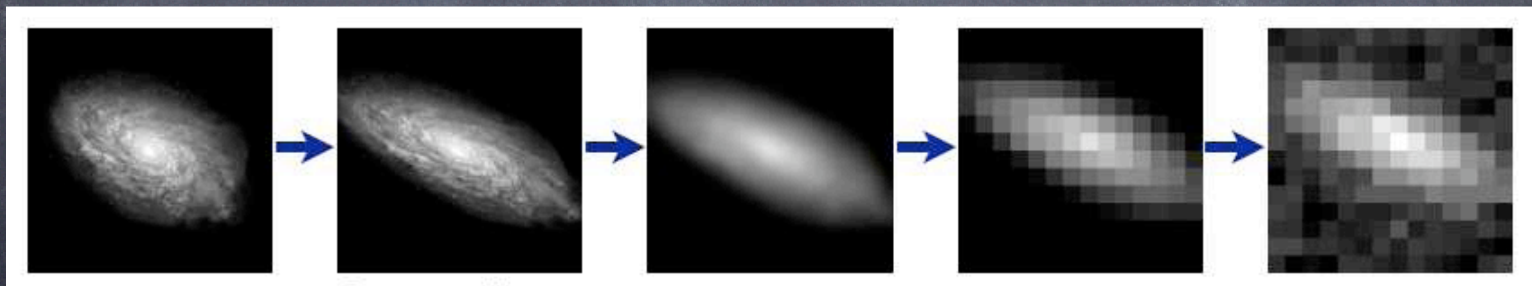
B-mode (curl)



Simulations

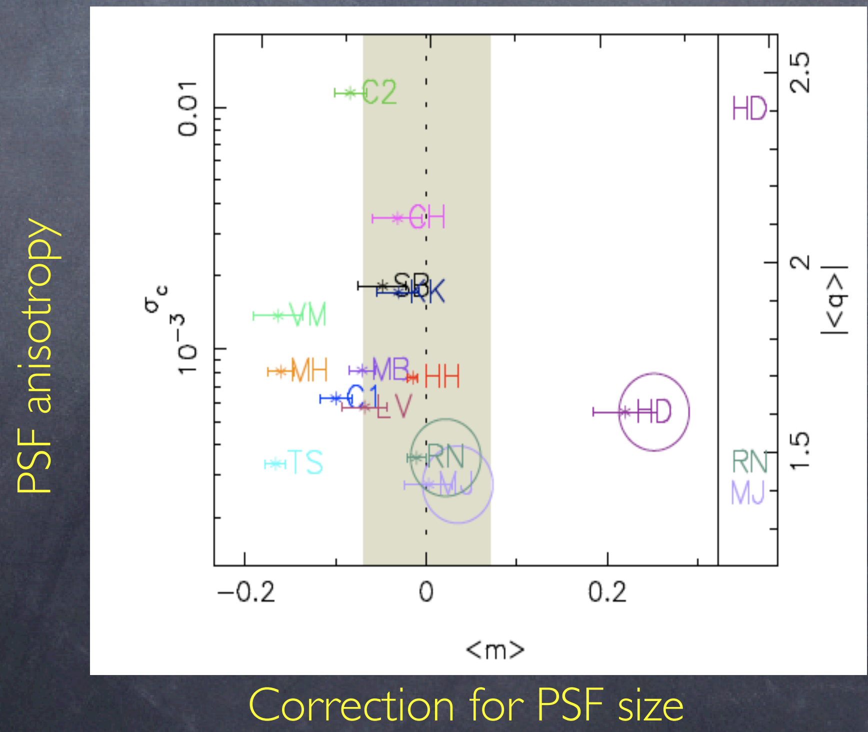
It is relatively easy to create simulated data to test the measurement techniques.

The Shear TEsting Programme is an international collaboration to provide a means to benchmark the various methods. This has evolved into a challenge to involve computer scientists: GREAT'08

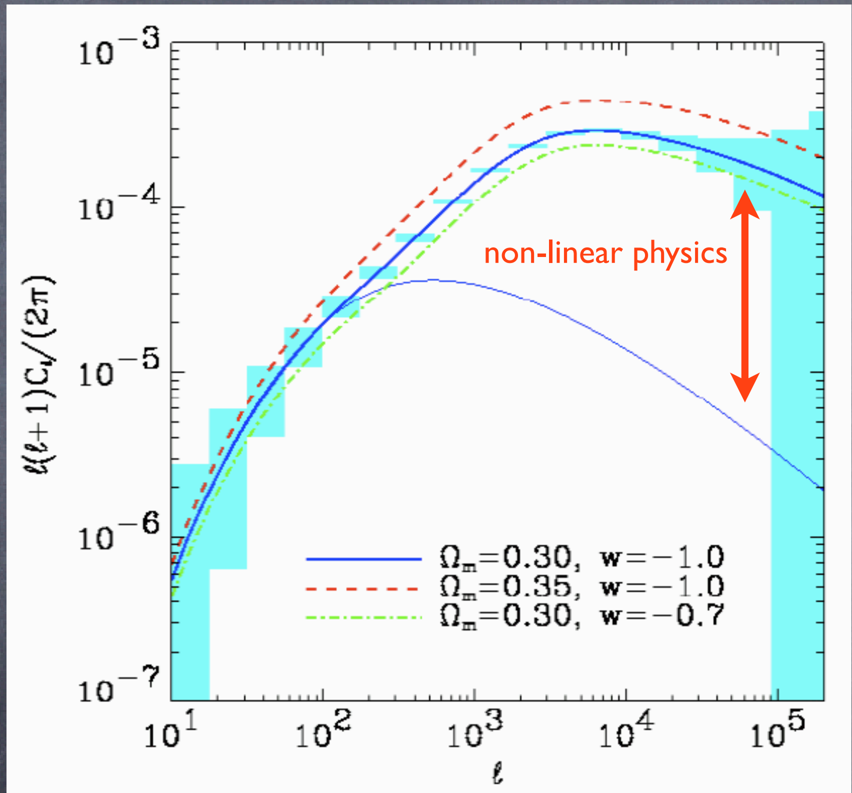


Simulations

So far two papers have been published (Heymans et al., 2006 and Massey et al., 2007). These results provide a snapshot of the current accuracy that can be reached (~1-2%).



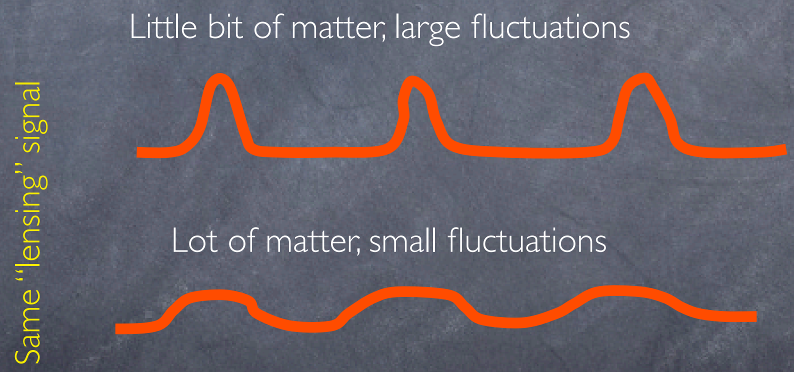
What does the signal mean?



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

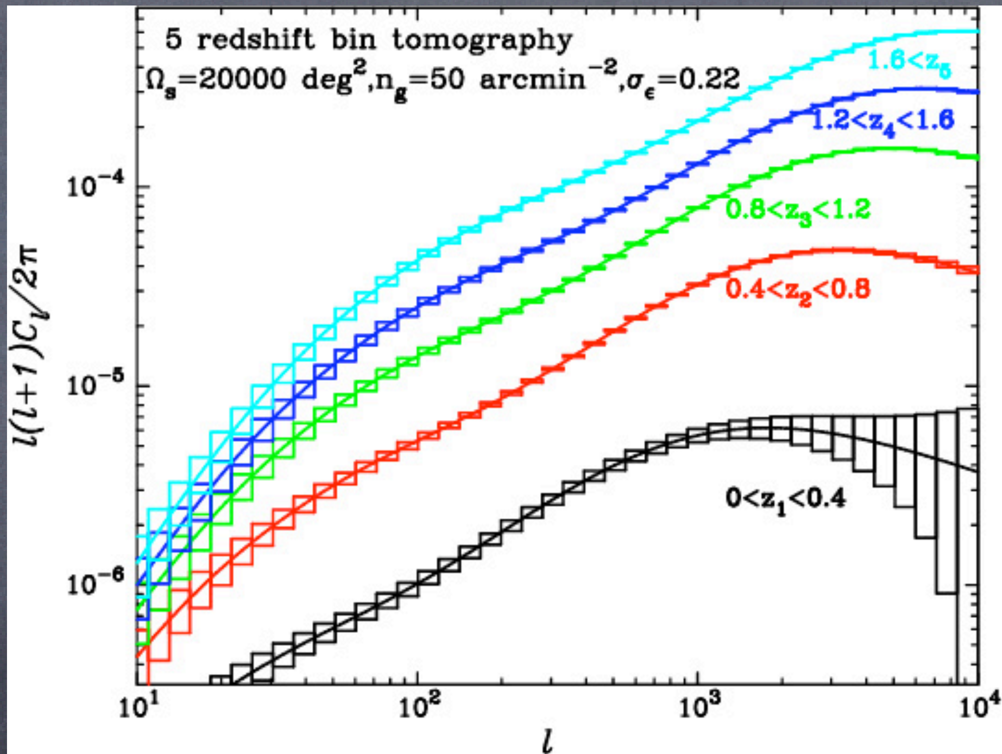
What does the signal mean?

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.

What does the signal mean?



We can break this degeneracy by measuring the lensing signal as a function of source redshift.

Results: a decade ago...

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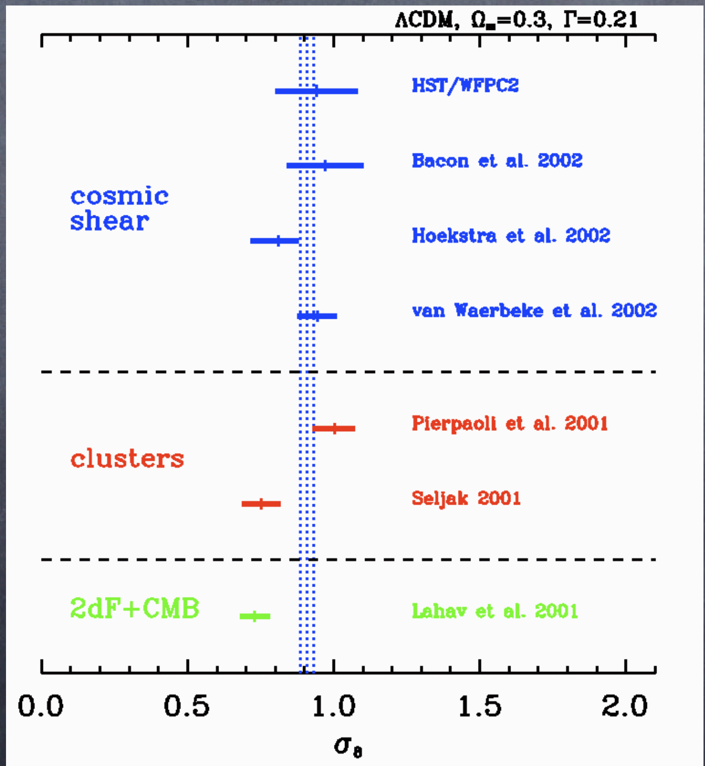
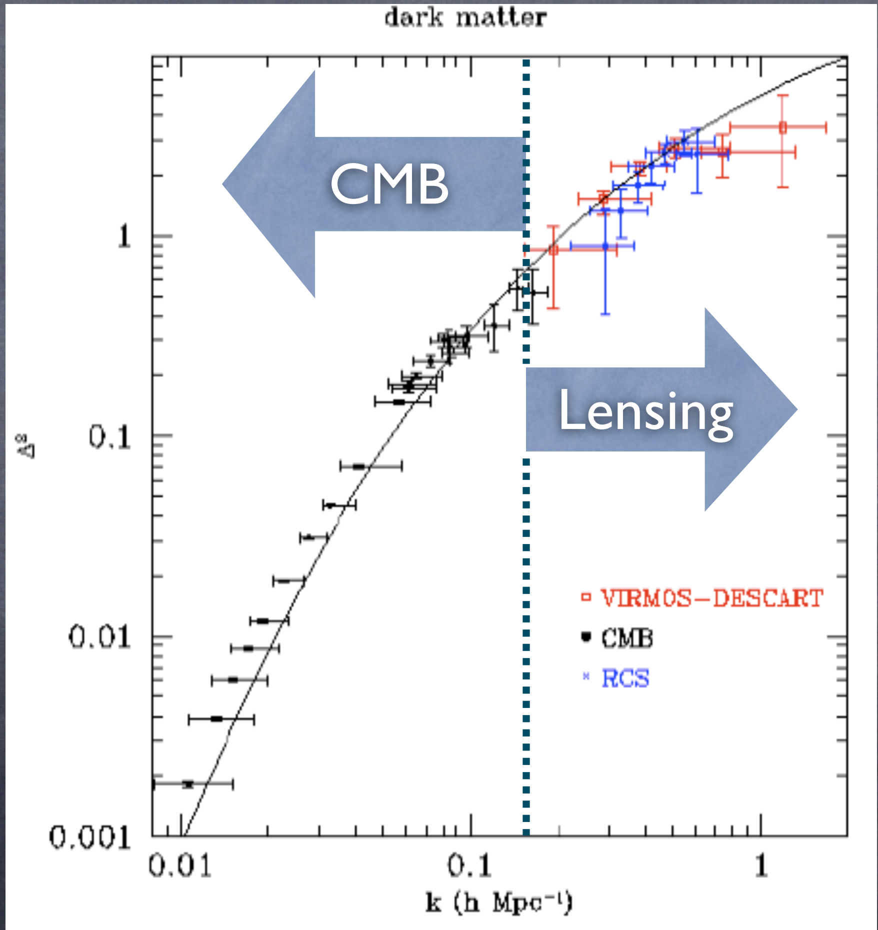
Results: status in 2002

Since the first detections reported in spring 2000, several cosmic shear measurements have been published.



Refregier (2003)

Results: status in 2003



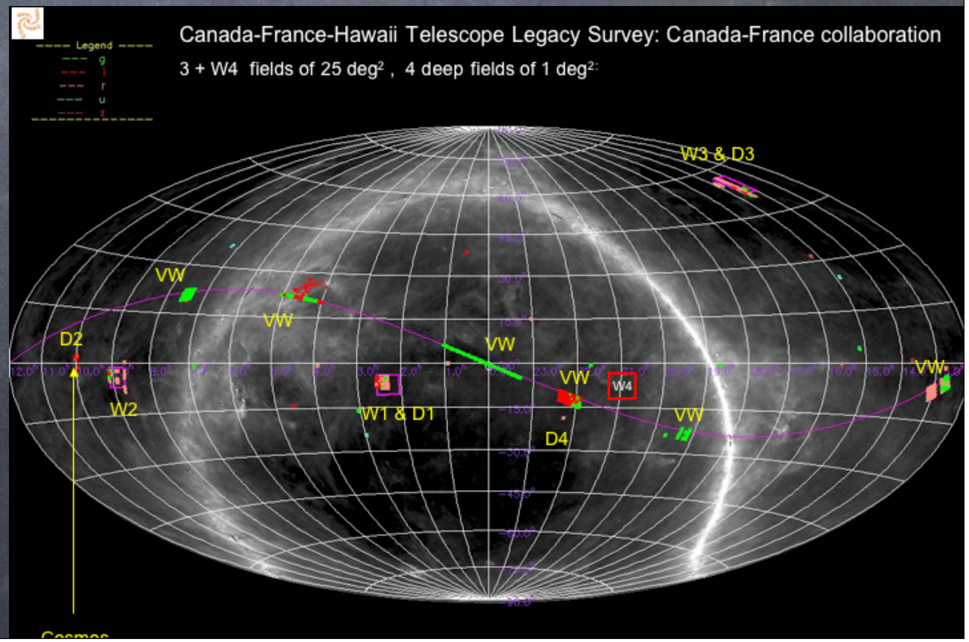
Van Waerbeke & Mellier (2003)

CFHT Legacy Survey

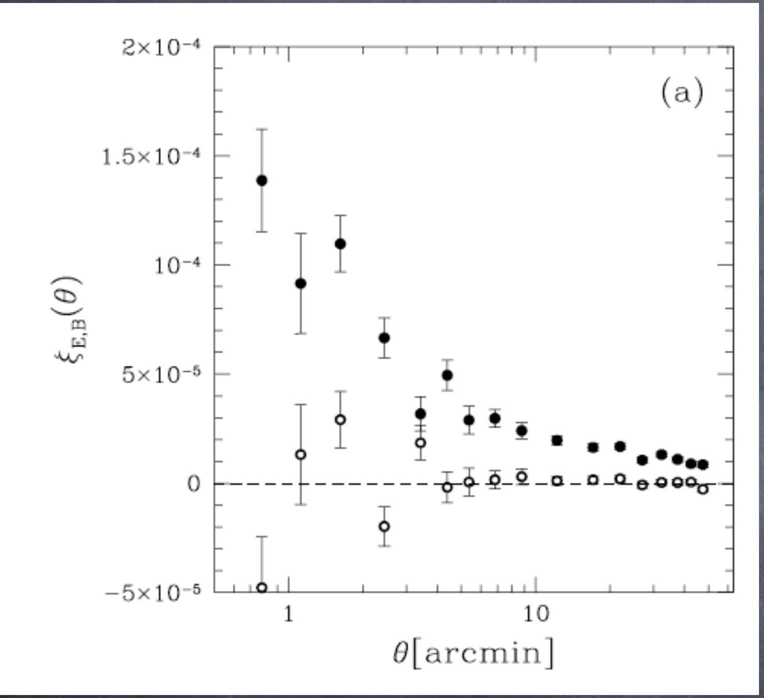
The Canada-France-Hawaii Telescope Legacy Survey is a five year project, with three major components. Observations were completed in the 2008B semester.

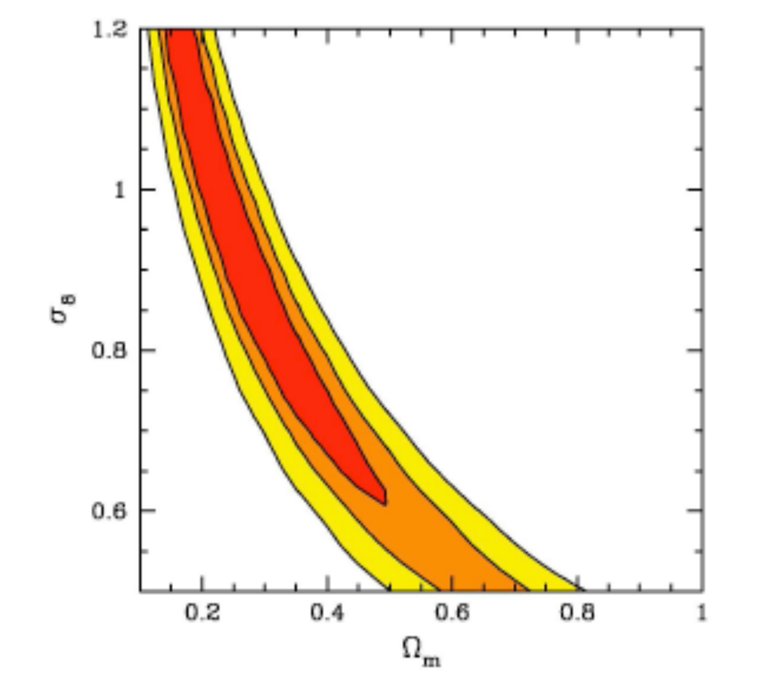
The Wide Survey focuses on weak lensing.

- ~140 square degrees
- 4 fields
- 5 filters (u,g,r,i,z')
- i<24.5



CFHTLS: first results





~20 square degree used in Hoekstra et al. (2006)

CFHTLS: first results

We think the observed lensing signal is fairly accurate.
But how about the interpretation. **Do we know?**

Were getting there!

The early results were based on the HDF photometric redshift distribution. The redshift distribution obtained by Ilbert et al. (2006) based on CFHTLS Deep data suggests a higher mean redshift!

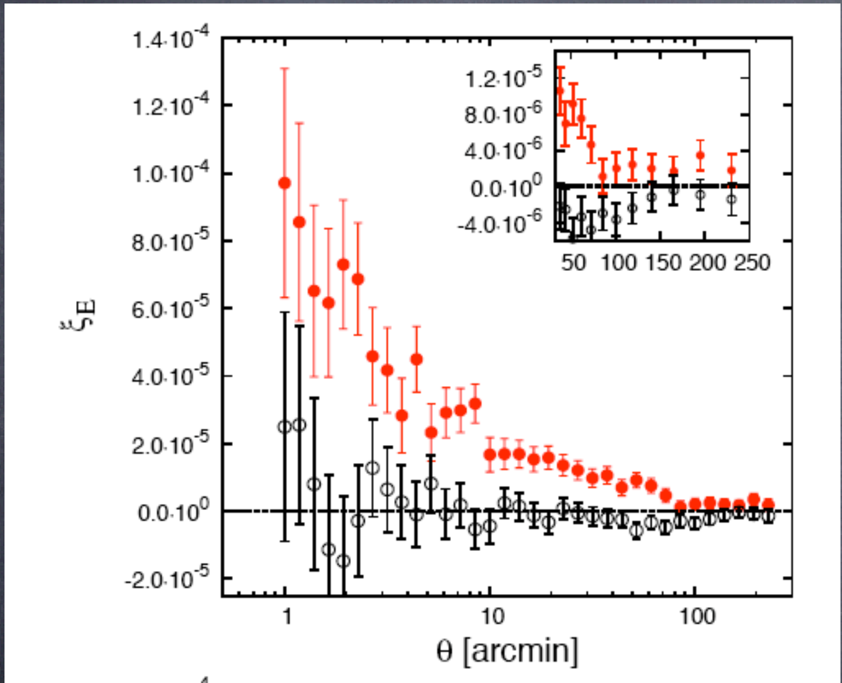
CFHTLS: first results

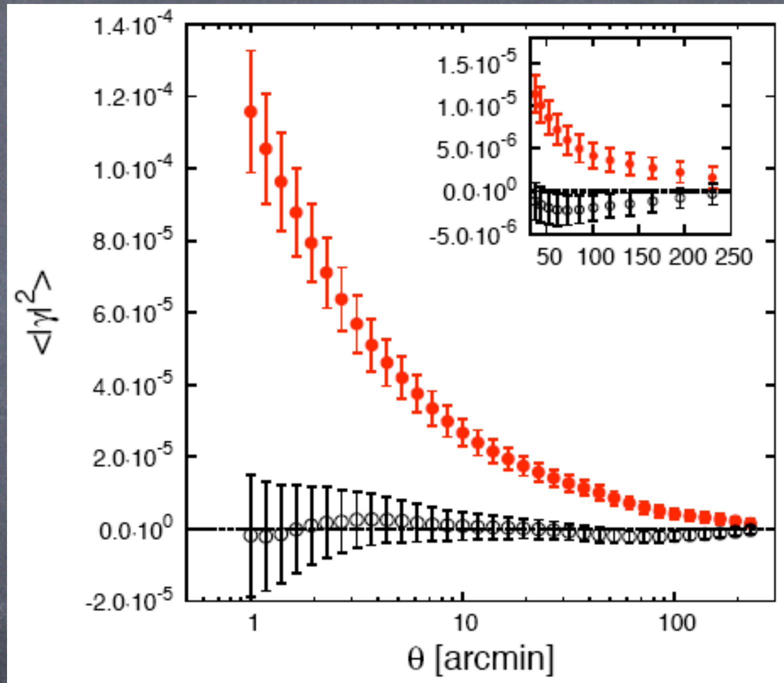
Since the publication of the first results a number of things have improved:

✓ Reduced systematics
✓ Larger area observed (we can probe larger scales)
✓ Improve estimates of cosmological parameters using photo-z's

The latest results, based on the analysis of 57 sq. deg. spread over 3 fields have recently been published in Fu et al. (2008)

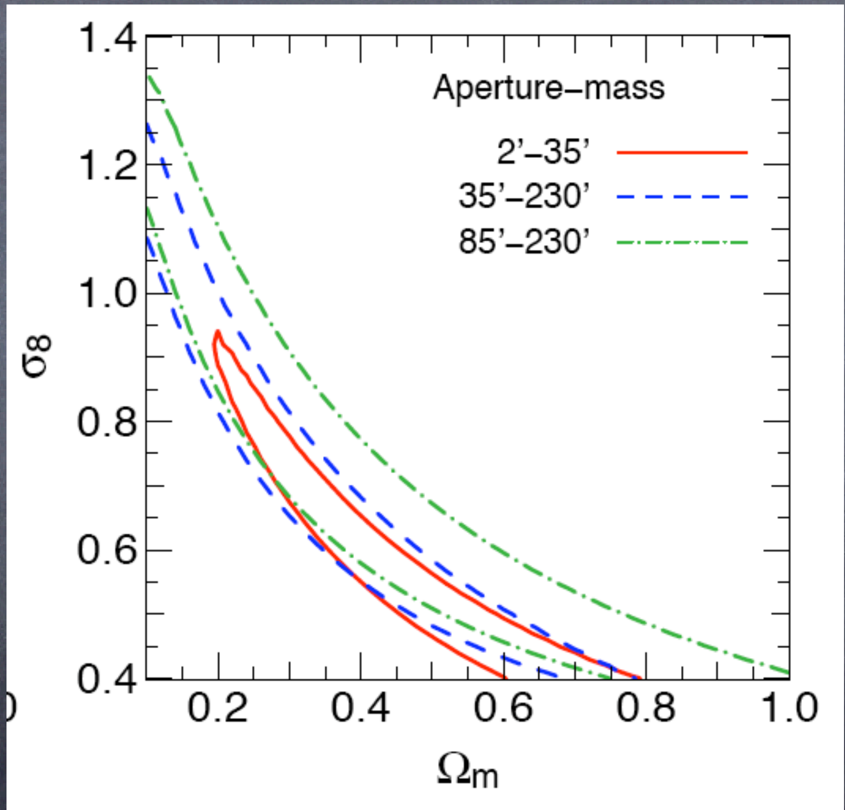
CFHTLS: recent results





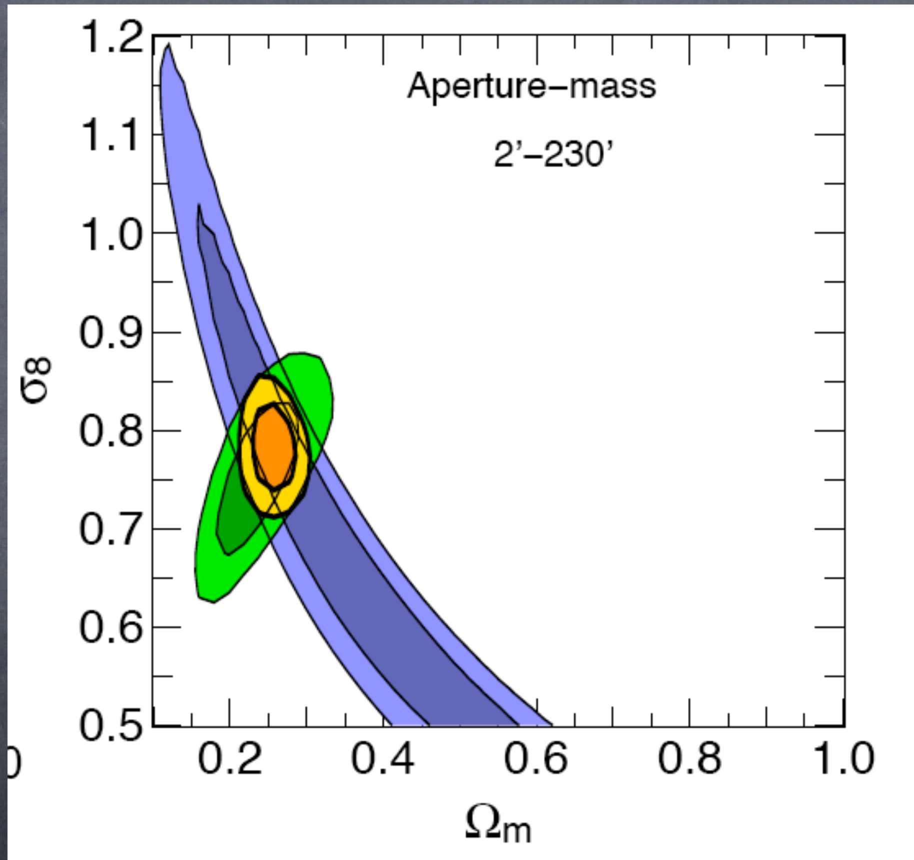
Measurements out to 4 degree scales!

CFHTLS: recent results



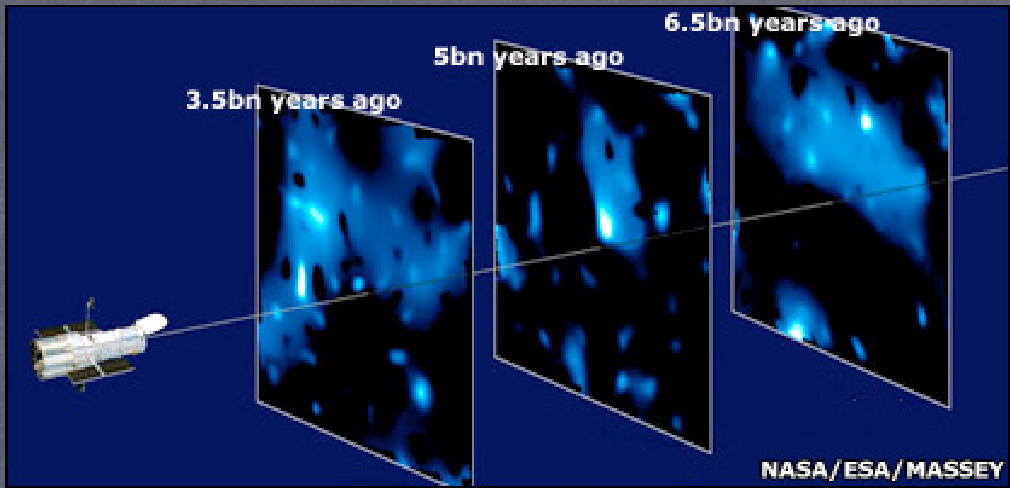
Cosmology is "scale independent": non-linear corrections sufficient so far.

CFHTLS: recent results



Results agree well with WMAP3 (and WMAP5…)

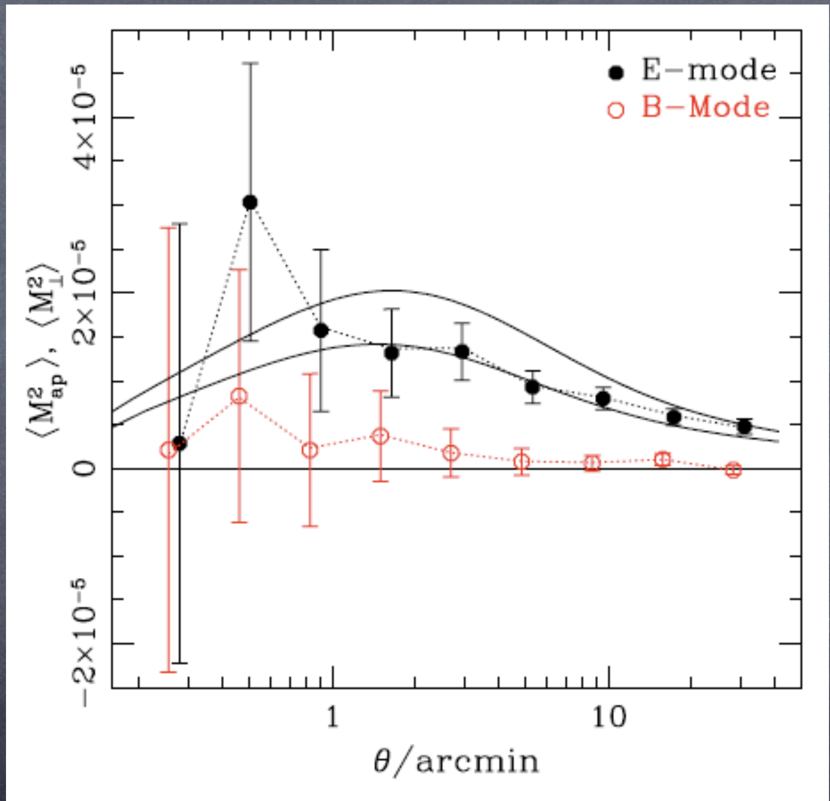
CFHTLS: what is next?



Currently ~140 sq. deg. of data have the full *ugriz* coverage and photometric redshift have been determined.

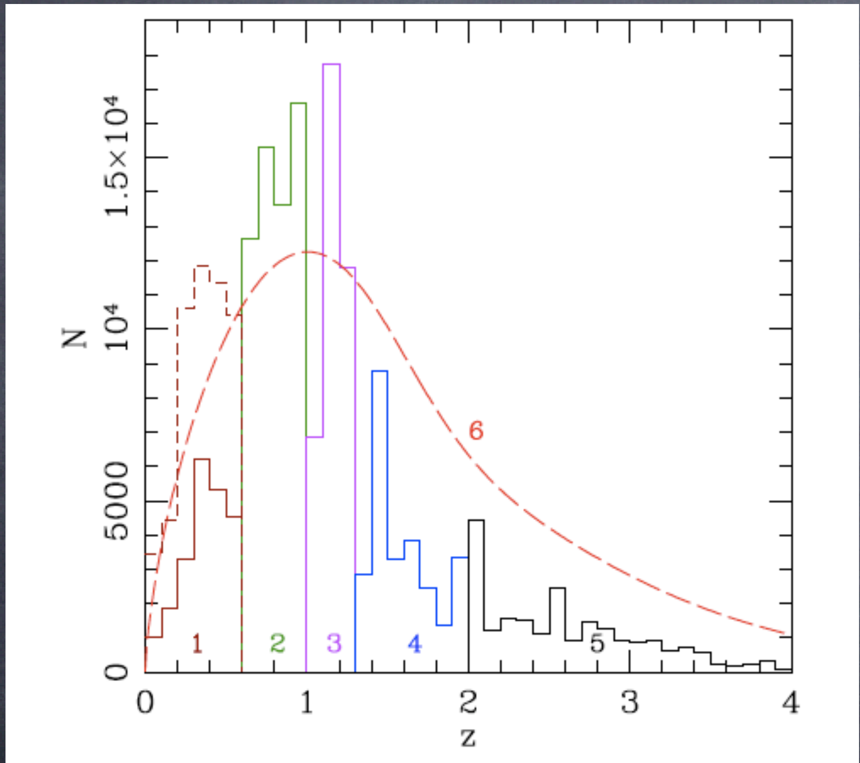
With photometric redshift information for the sources we can study the growth of structure, which significantly improves the sensitivity to cosmological parameters.

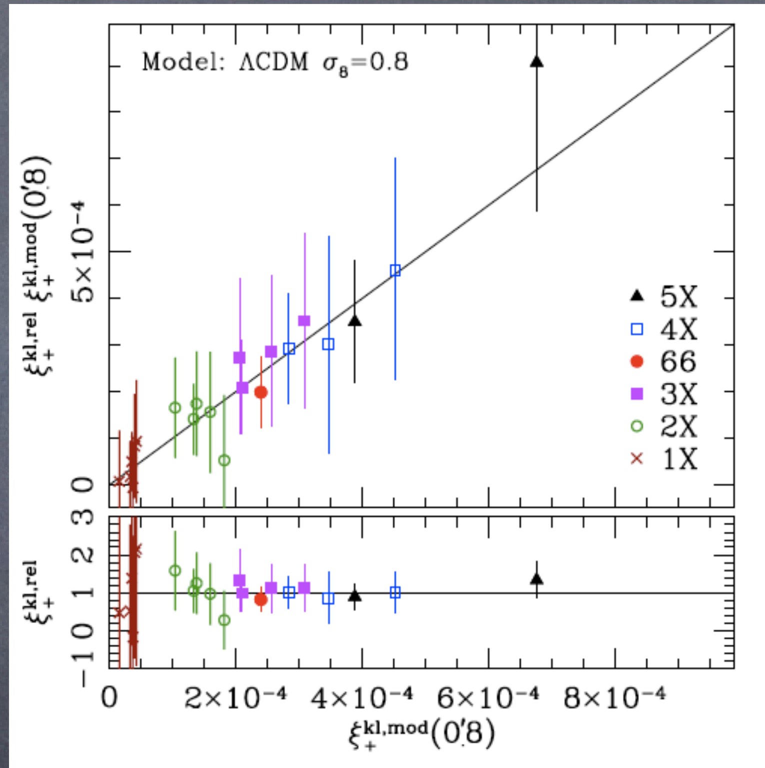
Hot of the press!



Schrabback et al. (submitted): analysis of COSMOS

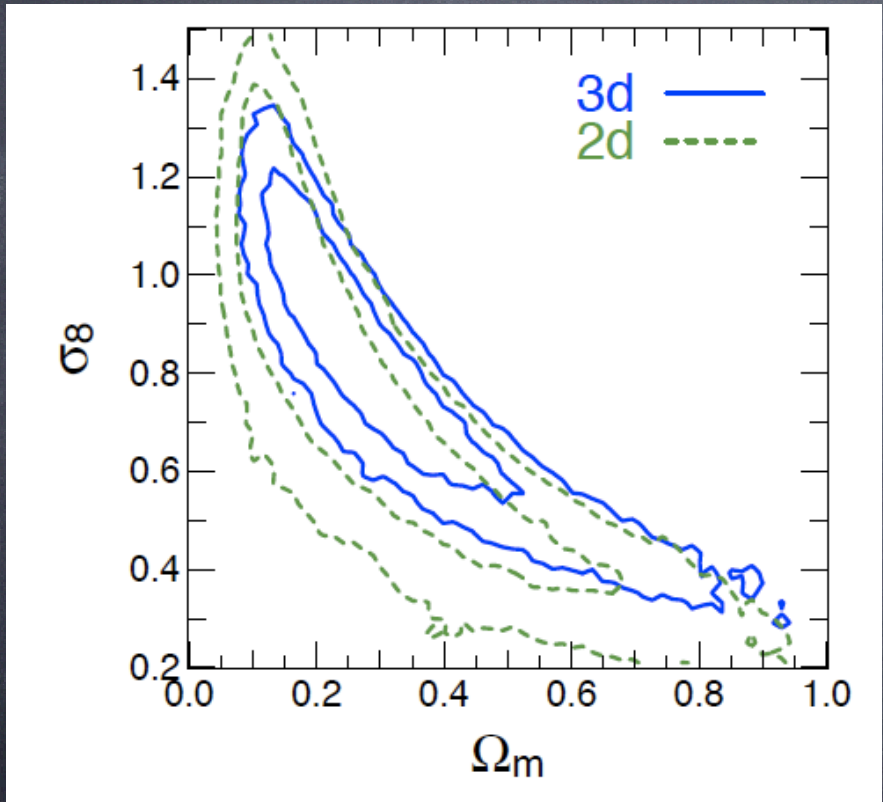
Tomography works!

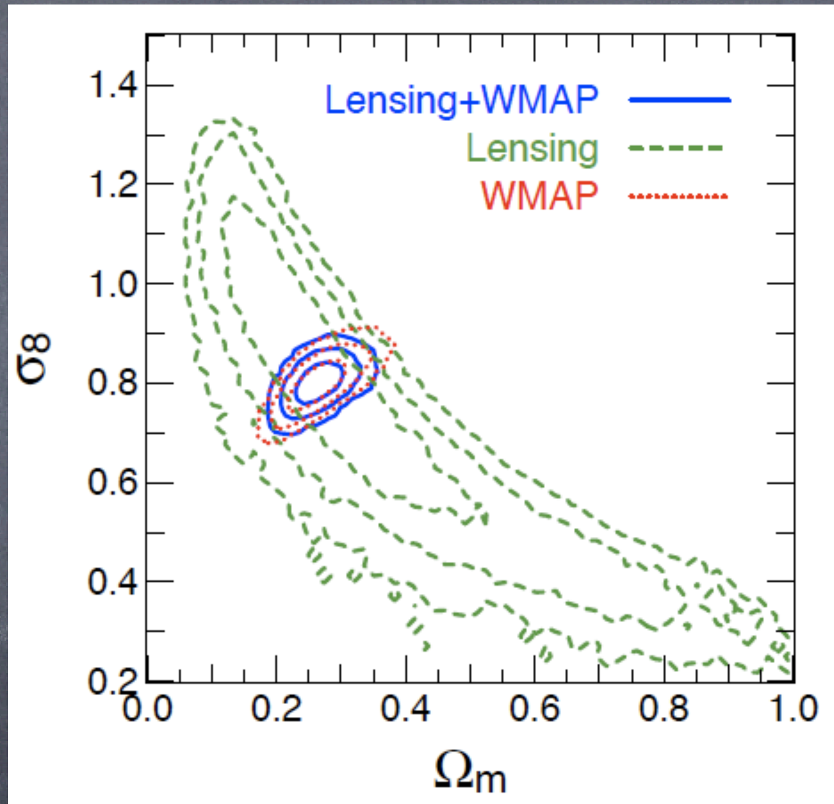




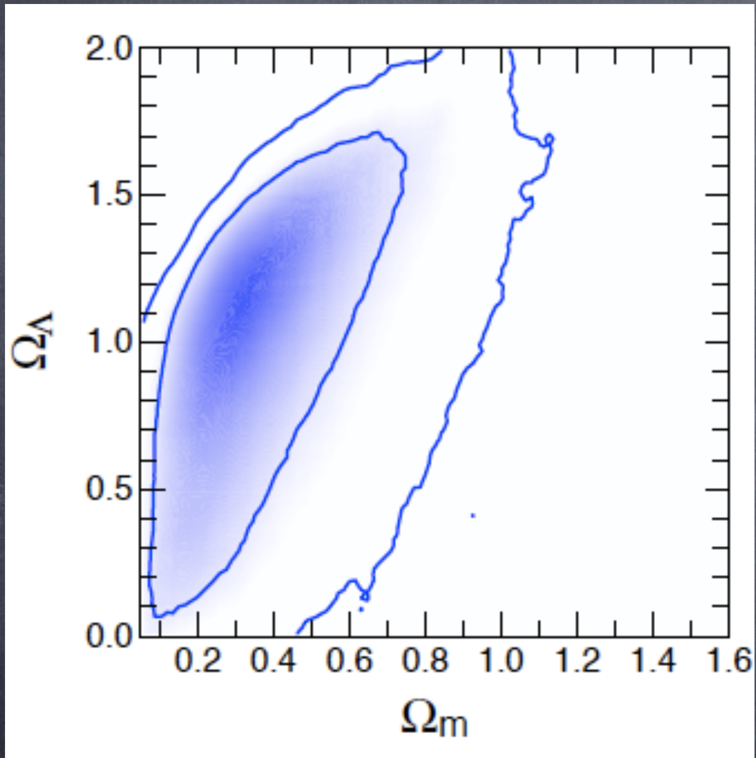
Redshift dependence is as expected in ΛCDM...

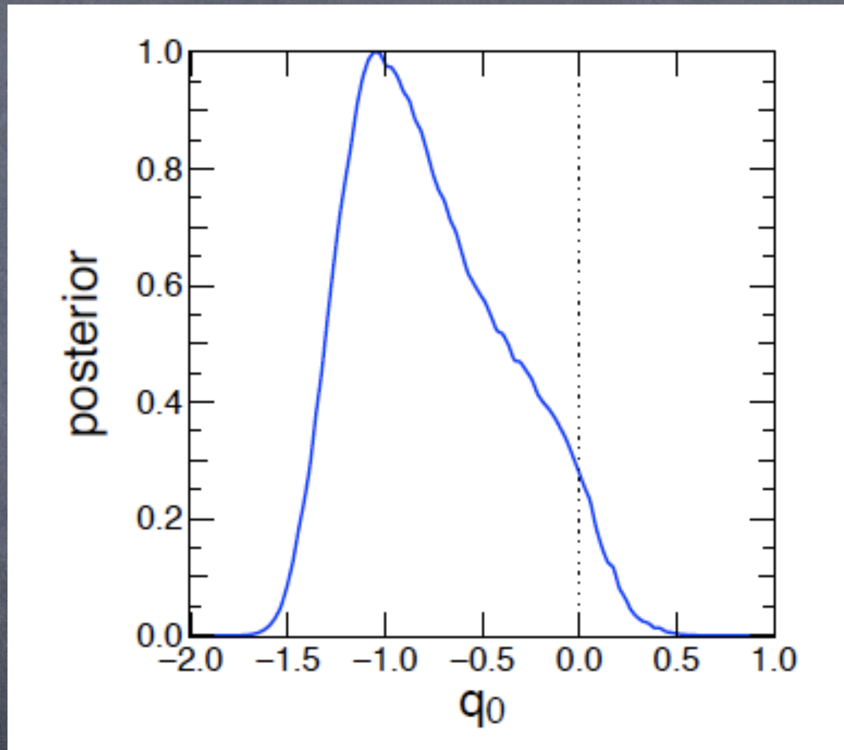
Tomography works!





Evidence for dark energy





From COSMOS weak lensing analysis *only*

The devil is in the details...

The accuracy of the first cosmic shear surveys is mostly limited by statistical noise (small areas).

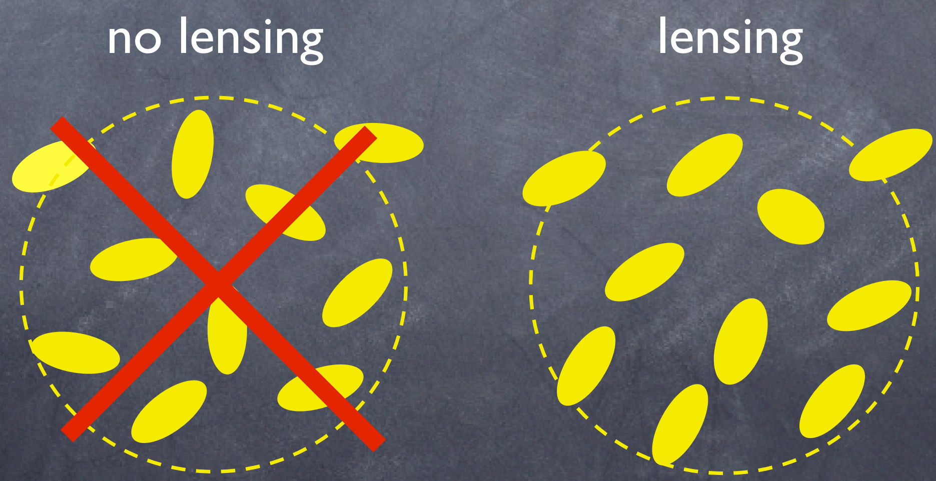
For the next generation many subtle effects need to be taken into account. This is already evident from our new COSMOS analysis.

We are discovering these (and correcting these) as we go along…

Do we understand?

Are position angles random in the absence of lensing?

No! There are intrinsic alignments



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

Complications

Intrinsic alignments complicate the cosmological interpretation of the lensing signal. CFHTLS and other surveys will allow us to measure the amplitude of the intrinsic alignments.

Dealing with intrinsic alignments will benefit greatly from these photometric redshift data. Recent work suggests that the effect of intrinsic alignements can be corrected for to a sufficiently low level.

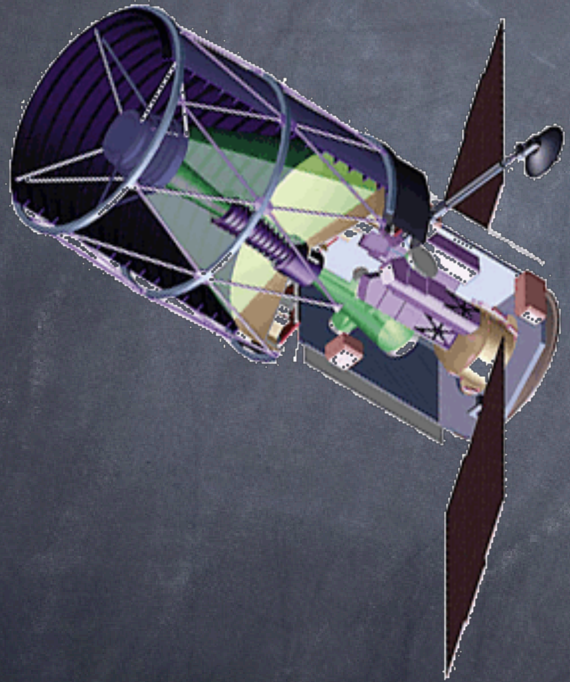
Further ahead...

The study of dark energy is an important application of cosmic shear. The CFHTLS will provide the first constraints from a ground based survey. But a useful measurement of the dark energy parameters requires much better precision.

The several hundred million dollar questions is:

Can we reach percent precision from the ground of do we have to go to space?

Advantages of space



- much smaller PSF
- optical + NIR bands

- higher source density
- higher source redshift
- better photo-z's
- large reduction in systematics

SuperNova Acceleration Probe or JDEM?

Conclusions

The CFHTLS weak lensing project is progressing well and is producing competitive cosmological results, but it is still work in progress.

To achieve the full potential of the survey a number of issues remain...

...but no show-stopper has been found!