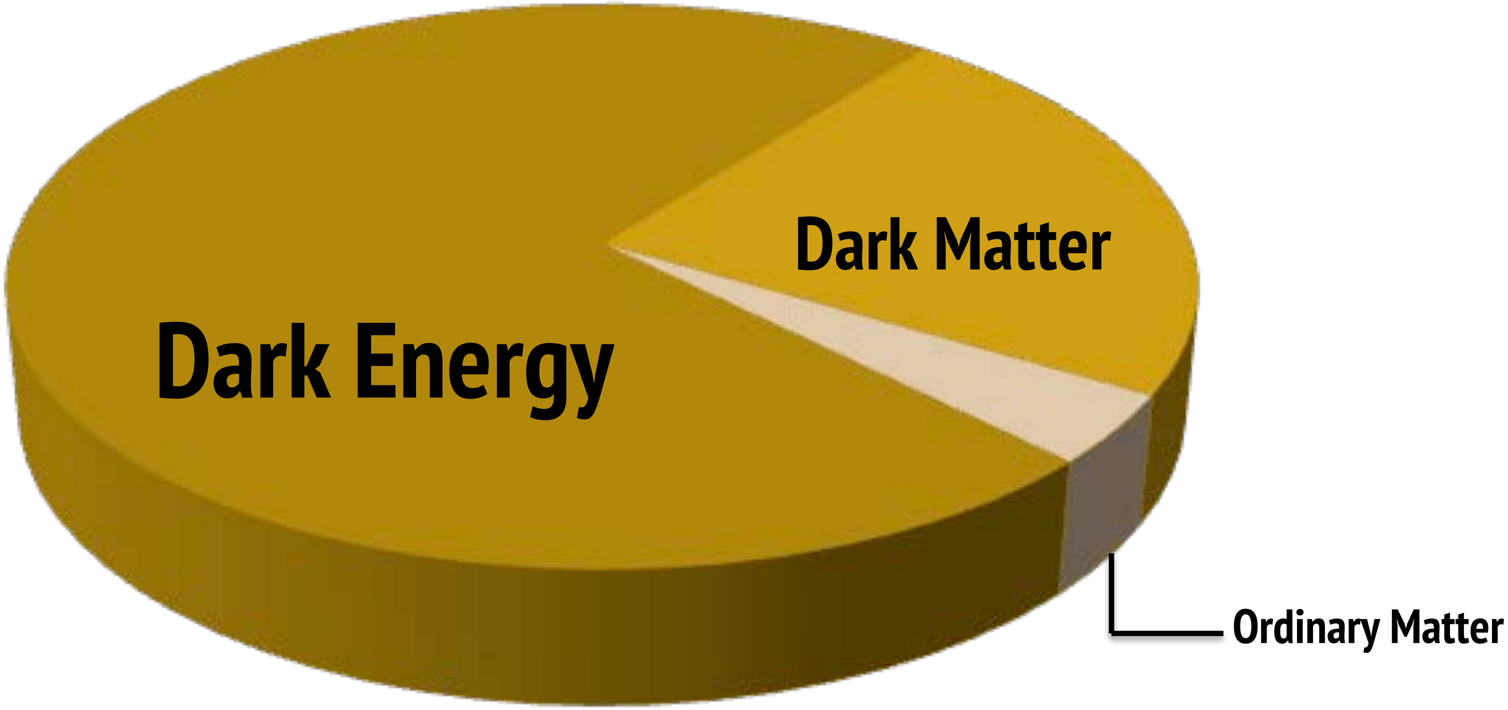
Weak lensing by large-scale structure as an accurate probe of cosmology and much more!

Henk Hoekstra
Leiden University

What is the Universe made of?



The biggest problem in physics: who ordered this?

What is dark matter?

We do not know, but we do know a few things:

- it is non-baryonic (a new particle)
- it is a “heavy” particle (cold or non-relativistic)

This cannot be a standard model particle

↓

We need new physics!

What is dark energy?

We do not know… and it is a serious problem!

- **Is it a cosmological constant or a dynamic field?**
- **Is there a problem with General Relativity?**

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

What should we study?

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

Investigate which physical effects and observables are sensitive to dark energy and/or modified gravity *and can be measured reliably.*

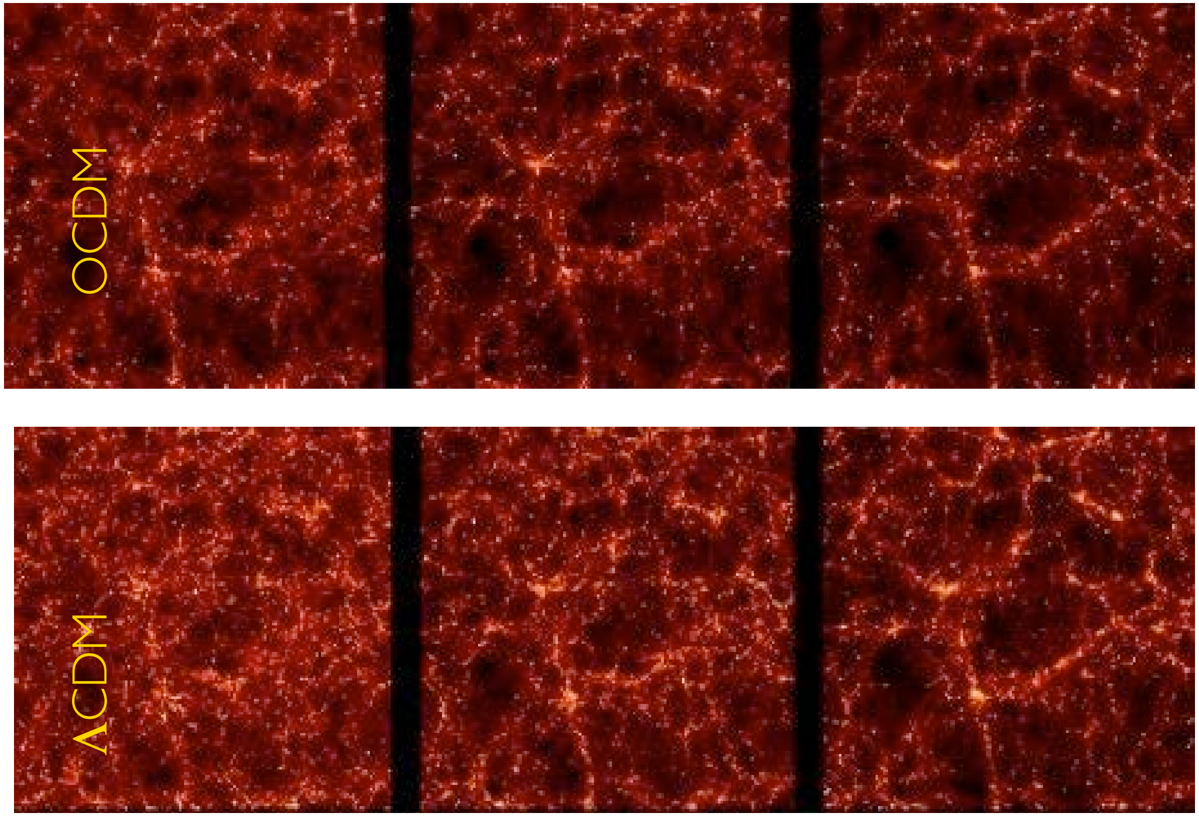
- **Cosmic expansion history**

  dark energy equation-of-state *w(t)*

- **Cosmic history of structure formation**

  growth rate of structure *f(z)*

Clustering of matter



The clustering of matter as a function of scale and redshift can be used to determine the underlying cosmology

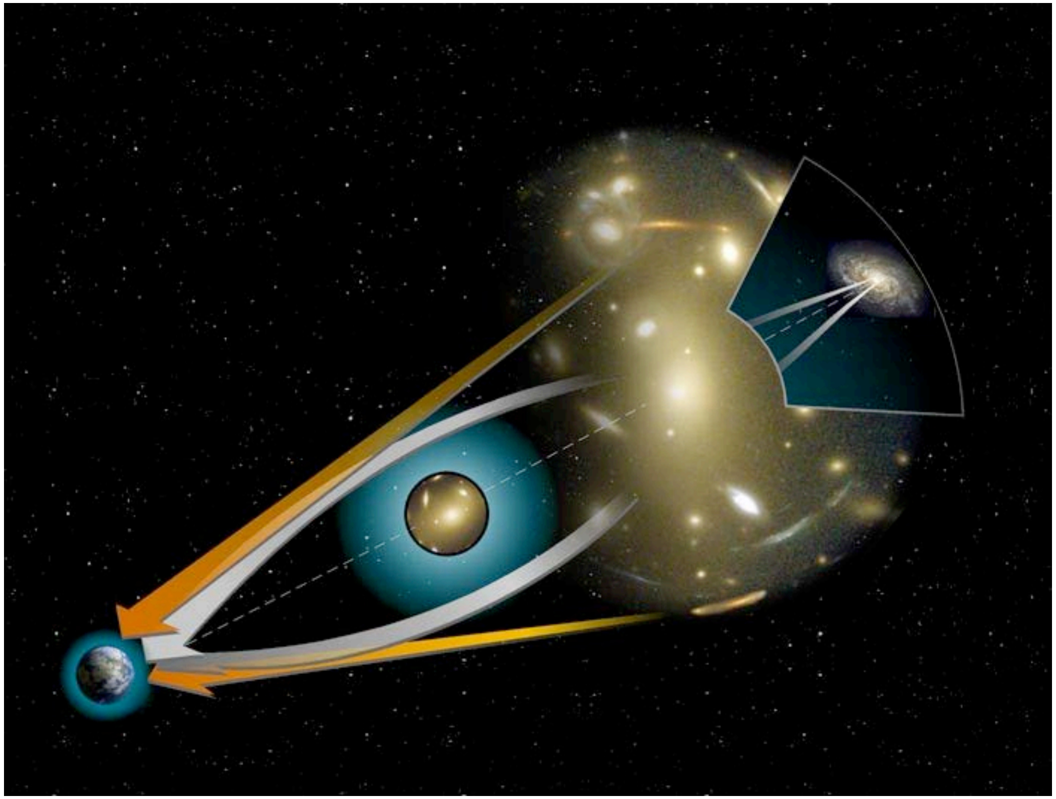
Many probes

The statistical properties of the matter distribution can be probed using a variety of techniques, such as:

- Clustering of galaxies
- Number density of galaxy clusters

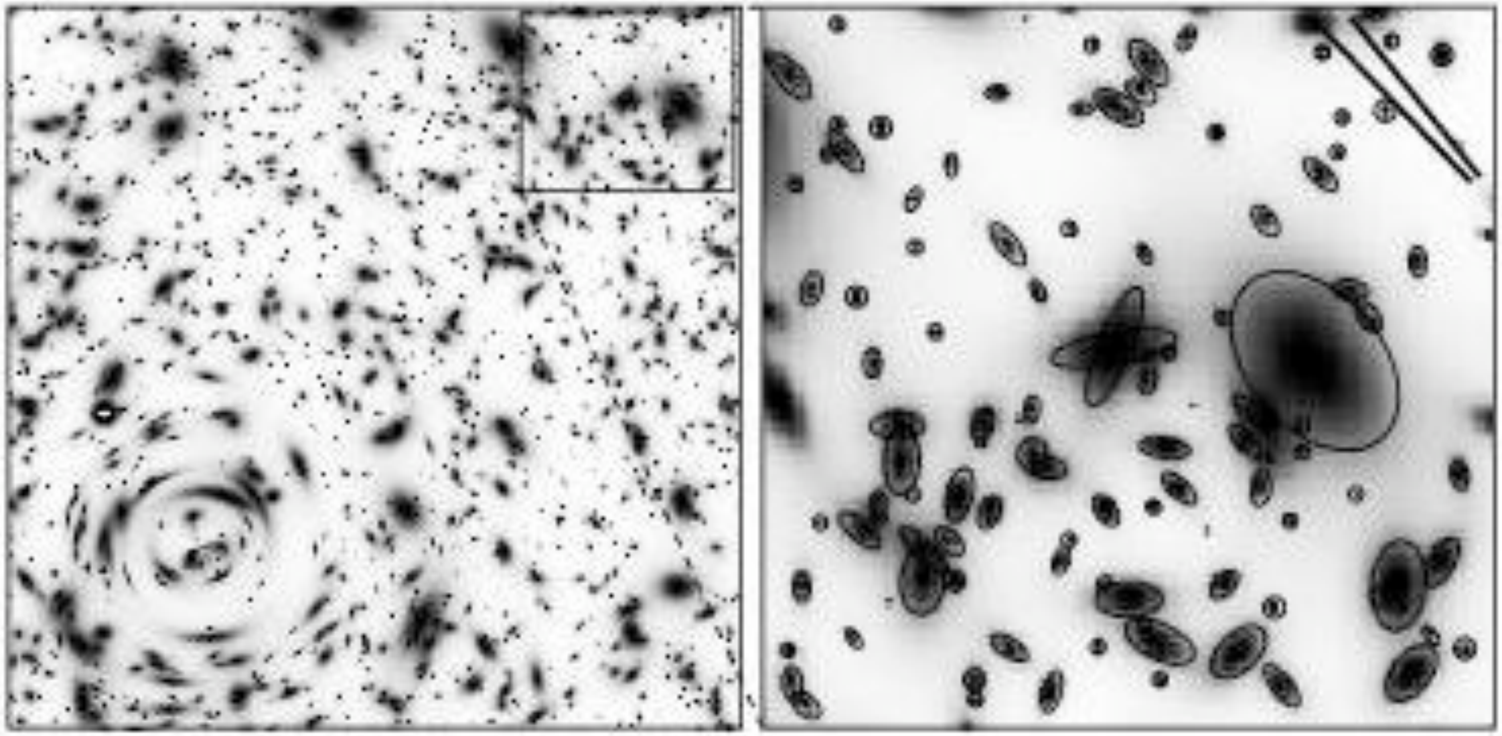
and …

Weak gravitational lensing



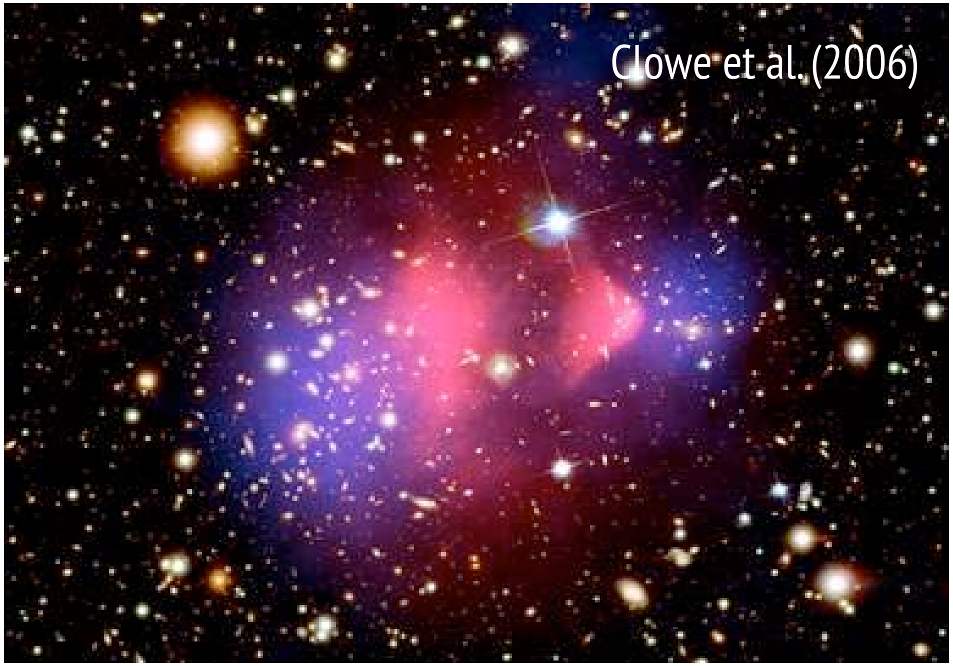
Density fluctuations in the universe affect the propagation of light rays, leading to correlations in the the *observable* shapes of galaxies.

Weak gravitational lensing

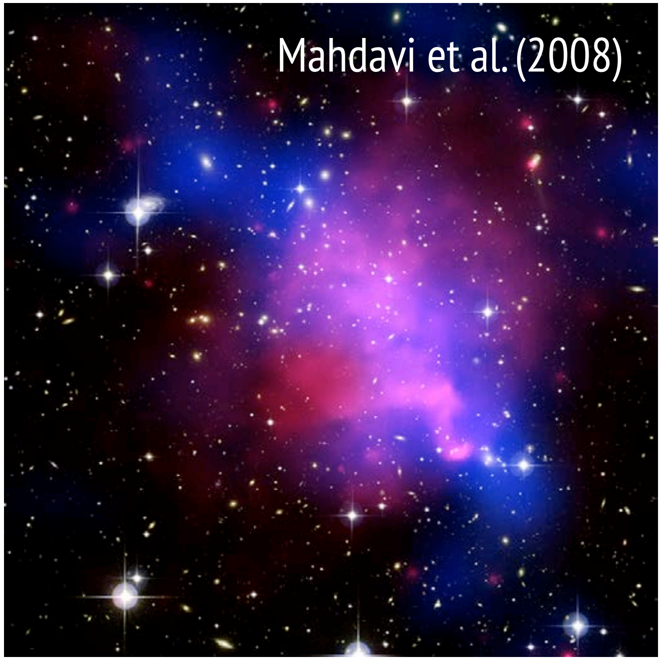


A measurement of the ellipticity of a galaxy provides an unbiased but very noisy estimate of the shear.

We can see dark matter!



Clowe et al. (2006)

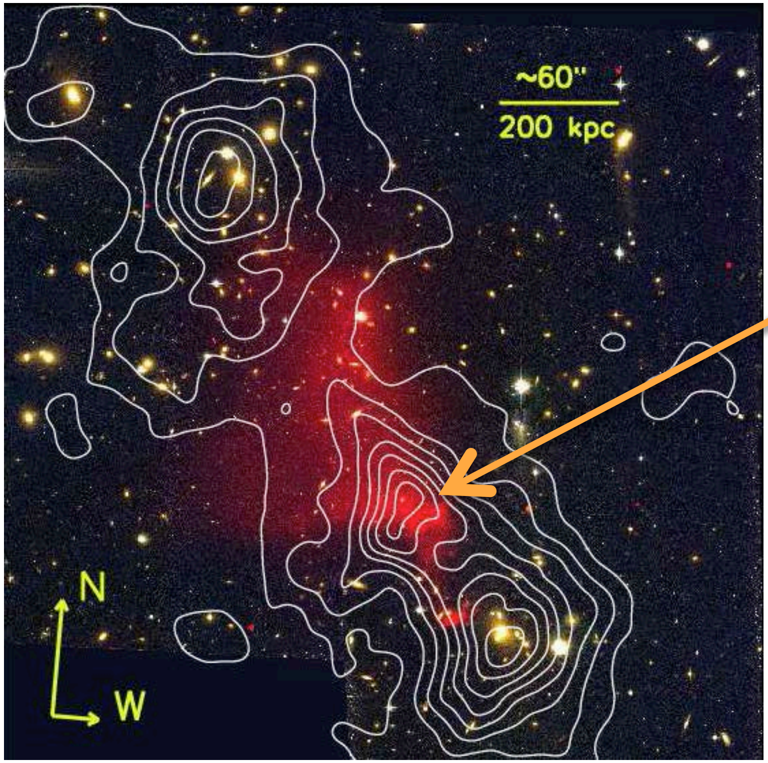


Mahdavi et al. (2008)

By averaging the shapes of many galaxies it is possible to reconstruct the (projected) matter distribution, independent of the dynamical state of the object of interest (e.g. a cluster of galaxies)

Abell 520: a puzzling target

Abell 520 (z=0.21) is a major collision of multiple clusters. We found a very dark region in the cluster, which was confirmed in our most recent analysis of ACS data (Jee et al., 2014).

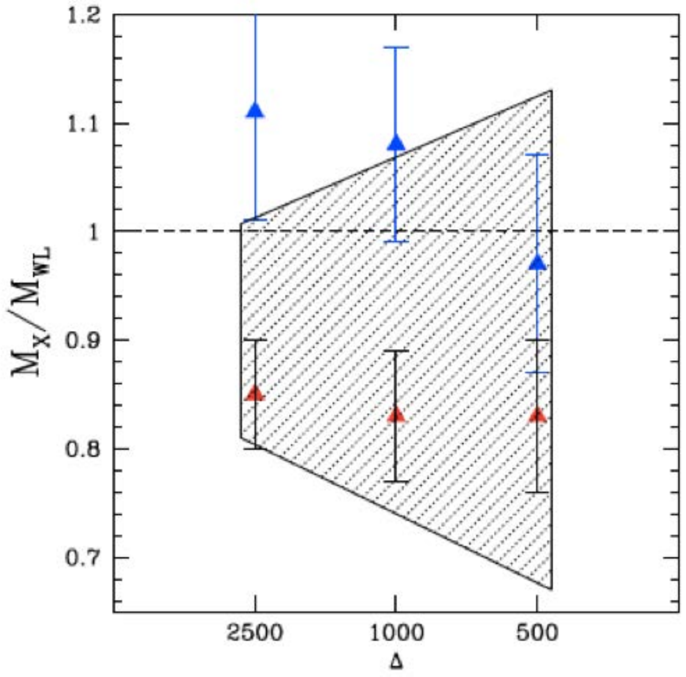


?

(13 σ)

Reliable cluster masses

In Mahdavi et al. (2013) we studied how the weak lensing masses compare to estimates based on X-ray observations, assuming hydrostatic equilibrium.



We found that the gas mass showed the lowest overall scatter; the product of gas mass and temperature (Y_X) is the most robust.

How accurate are cluster lensing masses?

In these comparisons we implicitly assumed that the lensing masses are accurate. Is this a reasonable assumption?

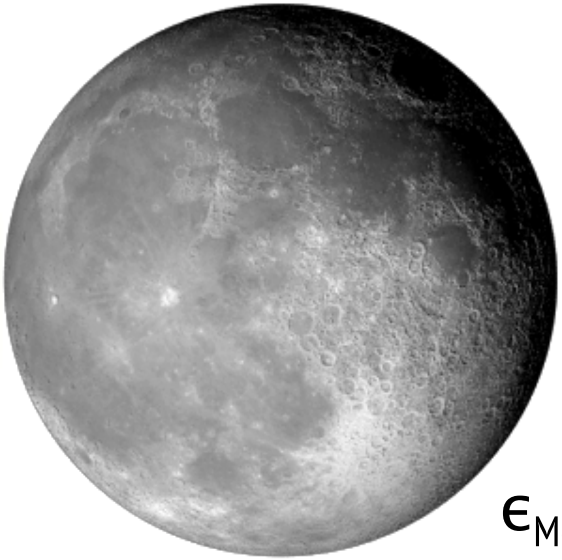
Key ingredients:

- Accurate shapes (corrected for instrumental effects)
- Accurate knowledge of the source redshift distribution
- Accurate removal/accounting of cluster members
- Need to account for cluster geometry

The distorted Universe

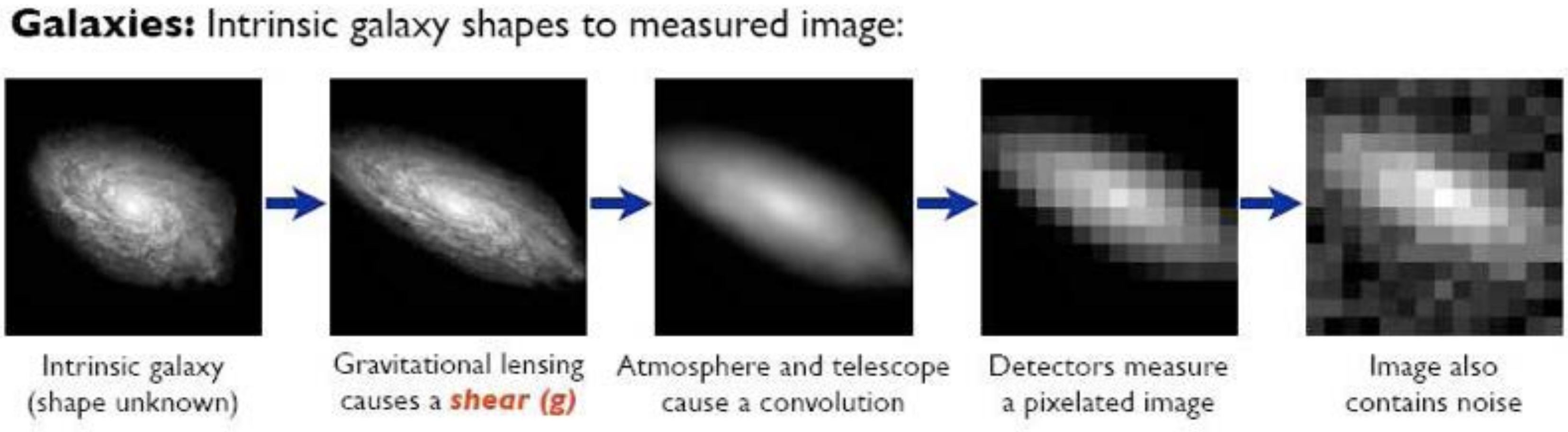
To infer unbiased cluster masses, we need to ensure that the measurement of the galaxy ellipticities is sufficiently accurate. In the case of future projects, such as *Euclid*, this means that the bias in the ellipticity is <0.2%.

$\epsilon_{\mathrm{Earth}}=0.00335$



$\epsilon_{\mathrm{Moon}}=0.00125$

Measuring shapes of objects like this?

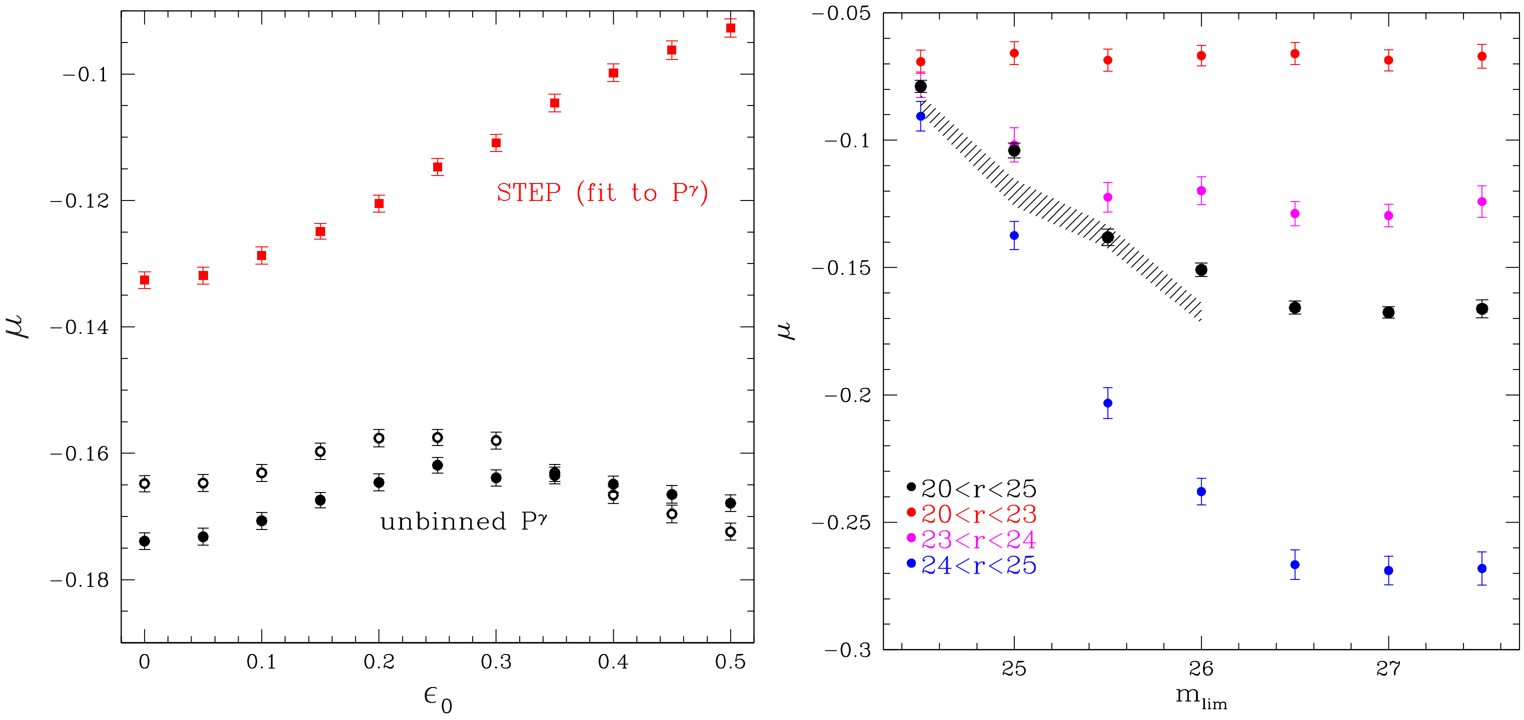


GREAT'08 challenge

The observed images are "corrupted" by the PSF which needs to be corrected for with high accuracy, but also by detector effects.

The importance of image simulations

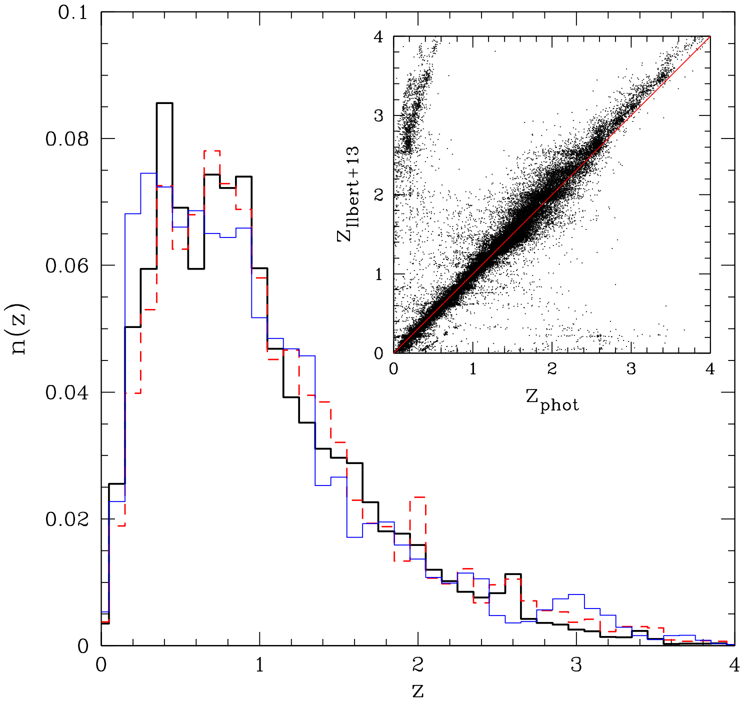
The accuracy of weak lensing measurements can be determined using image simulations. However, the results are only meaningful if the simulations match the data!



Hoekstra et al. (2015)

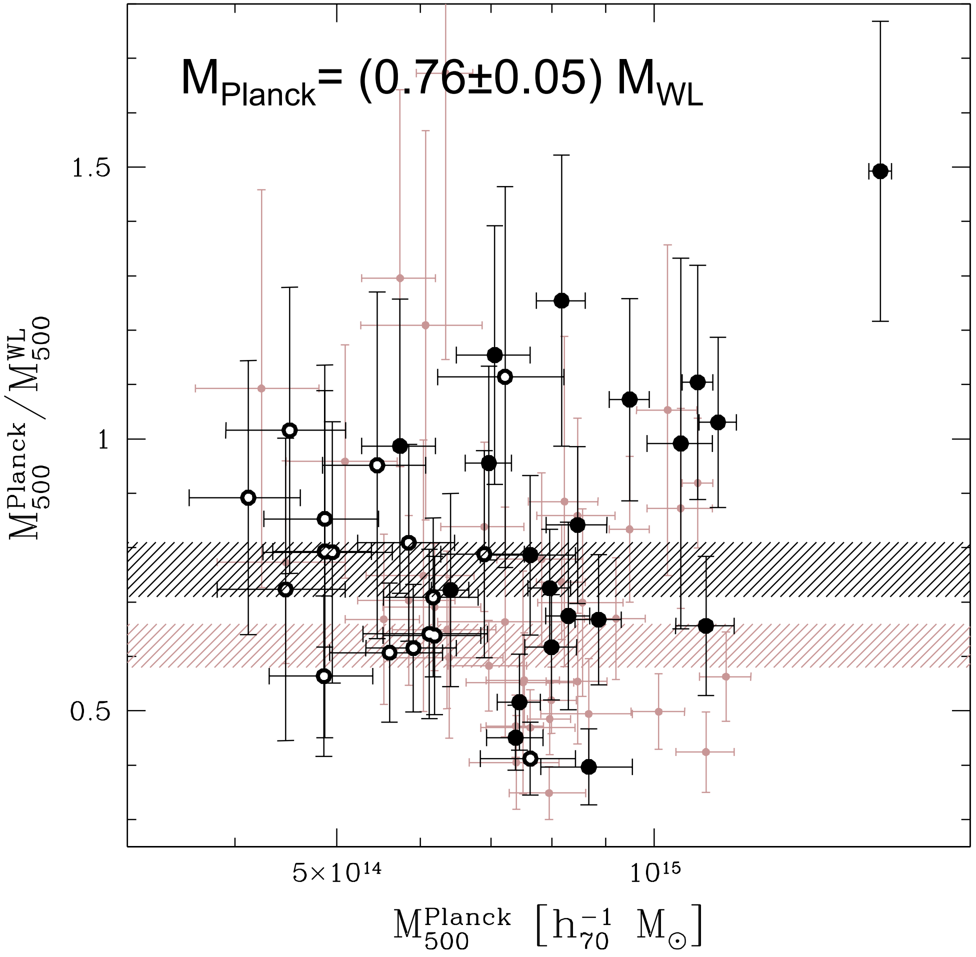
The importance of source redshifts

Thanks to deep NIR data from UltraVISTA the COSMOS-30 photometric redshift are now more reliable. However, the uncertainty in the n(z) of the sources is now the dominant source of systematic uncertainty.



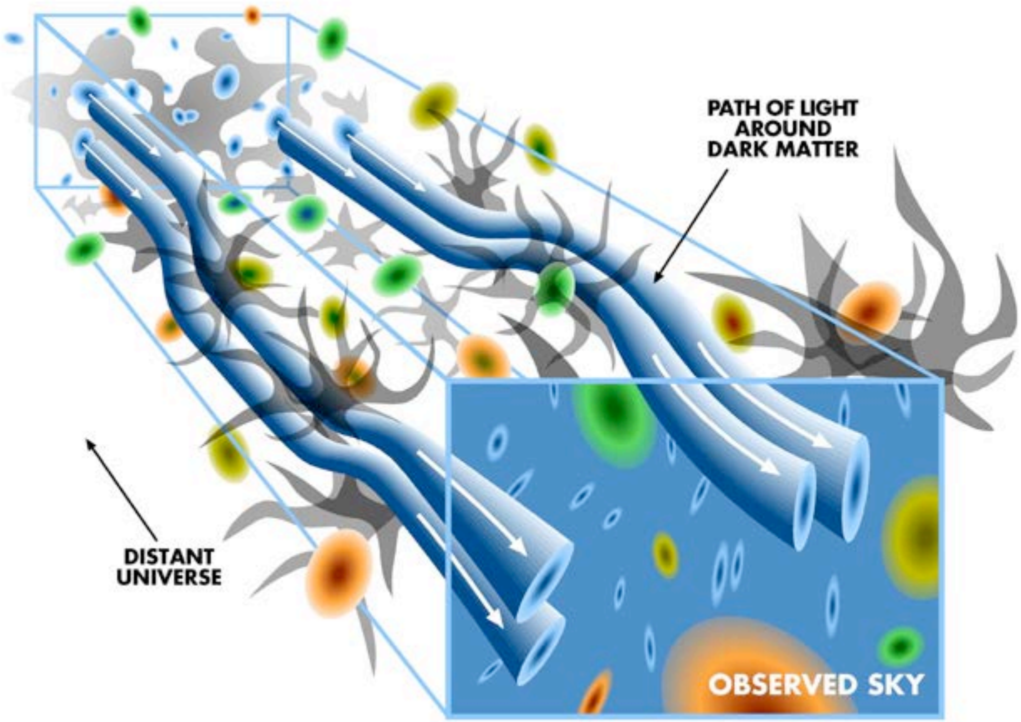
Hoekstra et al. (2015)

Comparison to Planck masses



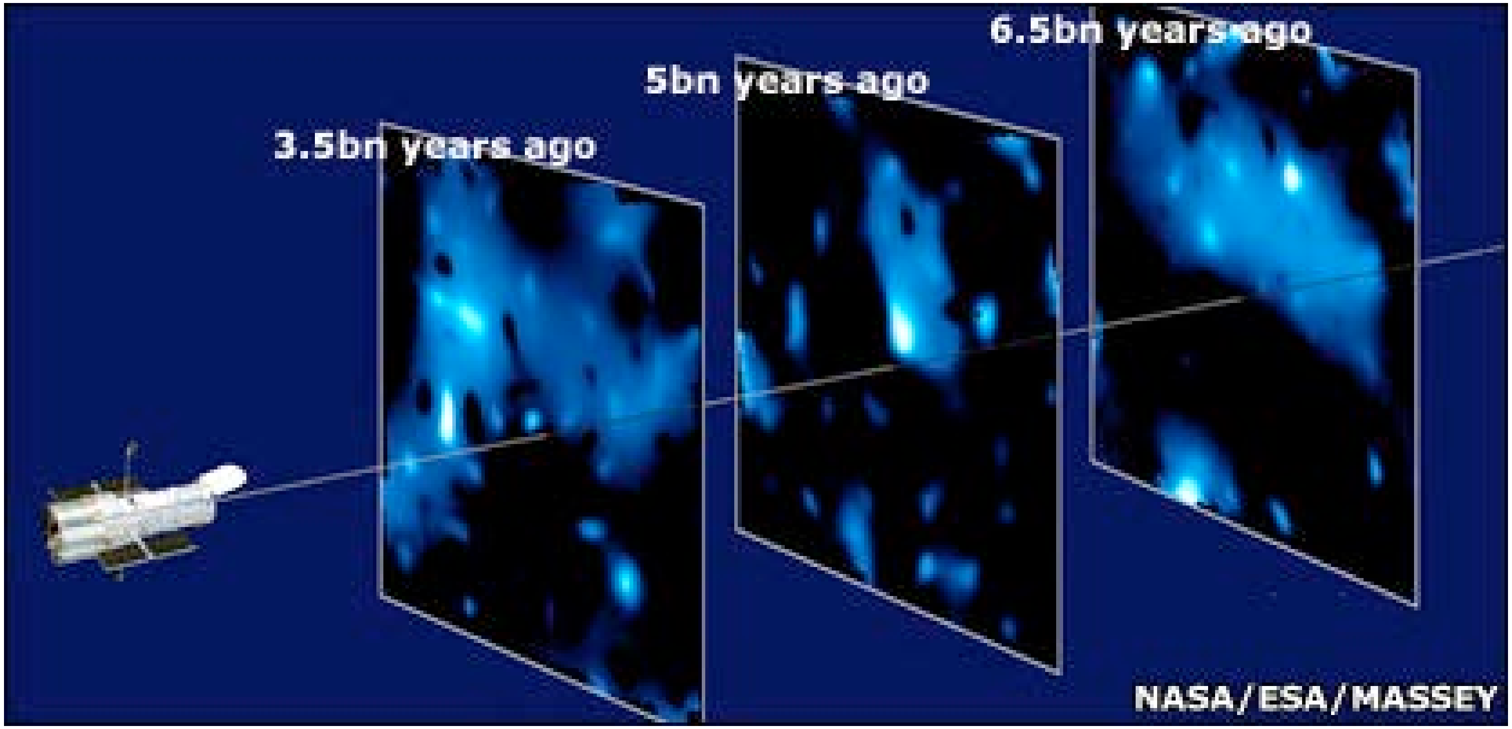
Hoekstra et al. (2015)

Cosmic shear



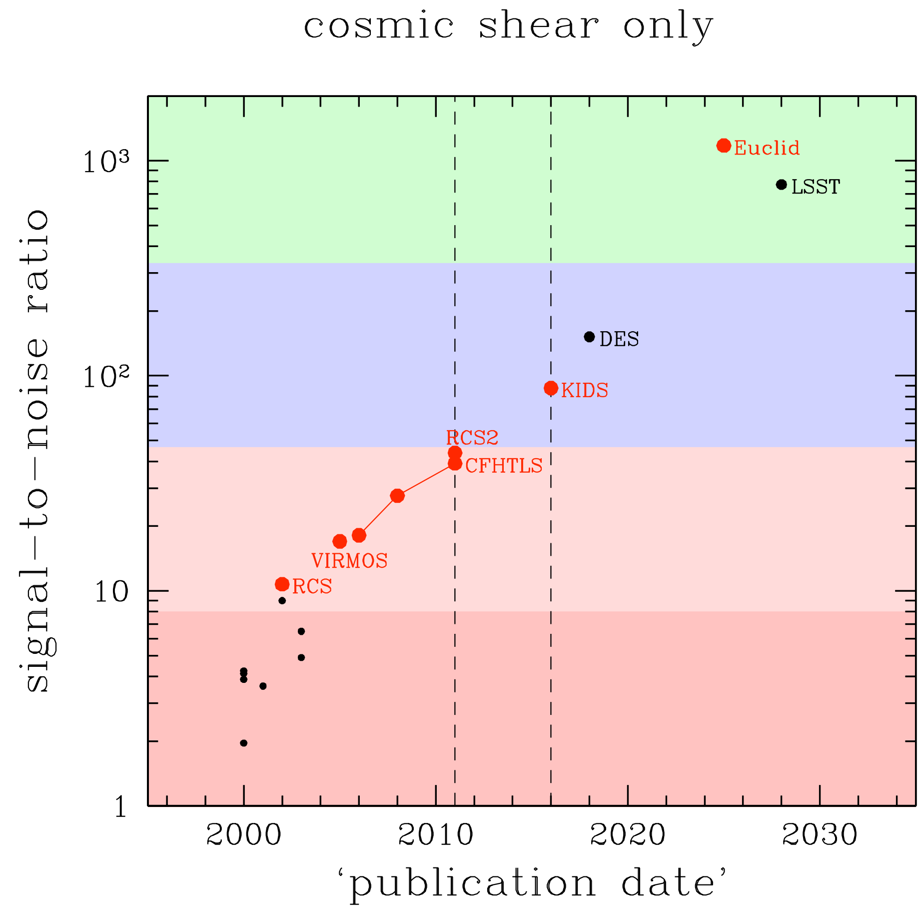
The statistics of shape correlations as a function of angular scale and redshift can be used to *directly* infer the statistics of the density fluctuations and consequently cosmology.

3d mapping of the Universe



We need to measure the matter distribution as a function of redshift: in addition to the shapes, weak lensing tomography requires photometric redshifts for the individual sources.

We are getting the numbers!



Dark energy physics

↑

Dark energy constraints

↑

Measurements

↑

Detection

Precision ≠ Accuracy

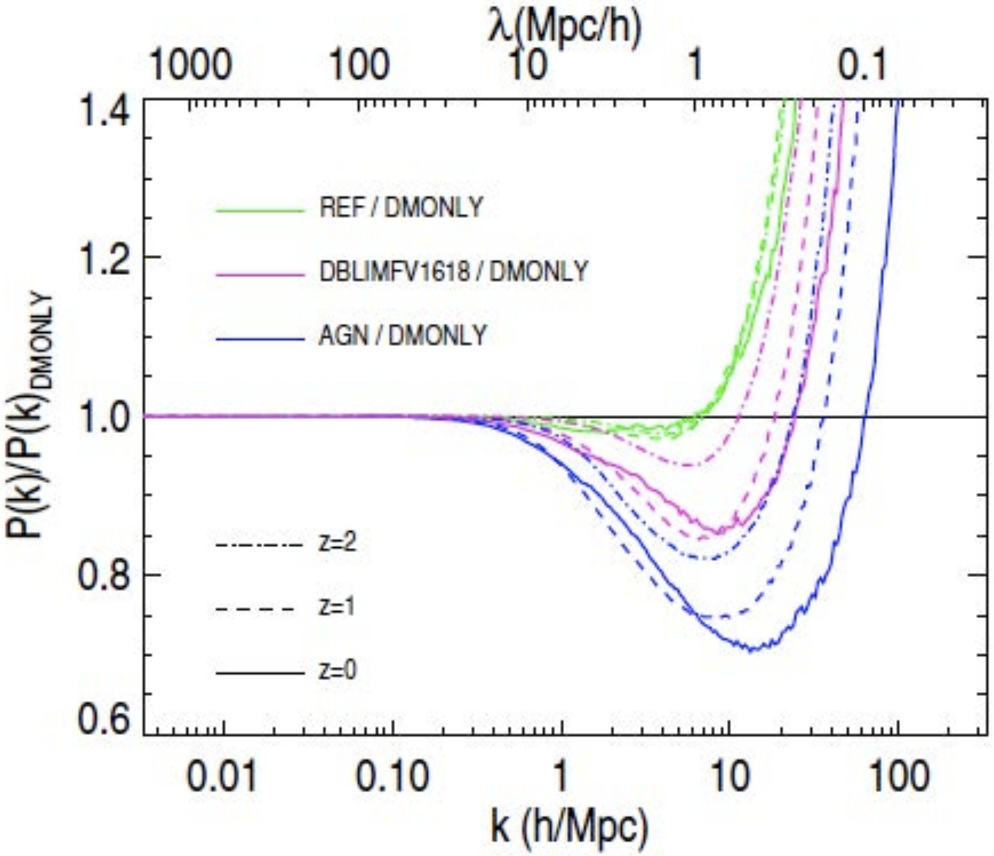
For accurate cosmology we need:

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

The complications we have to deal with:

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

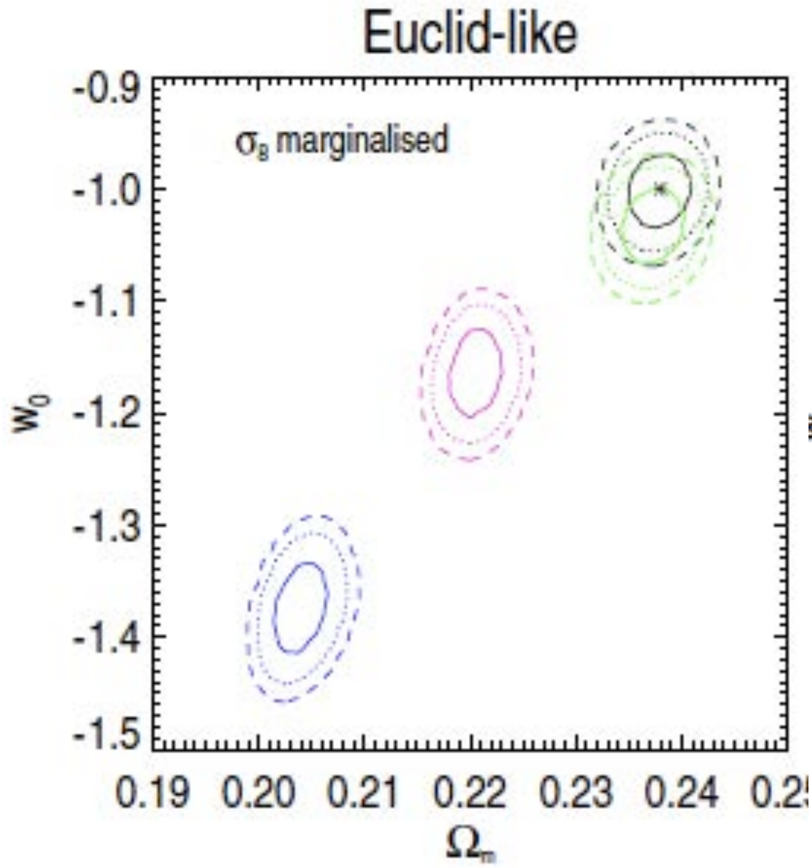
Baryonic physics



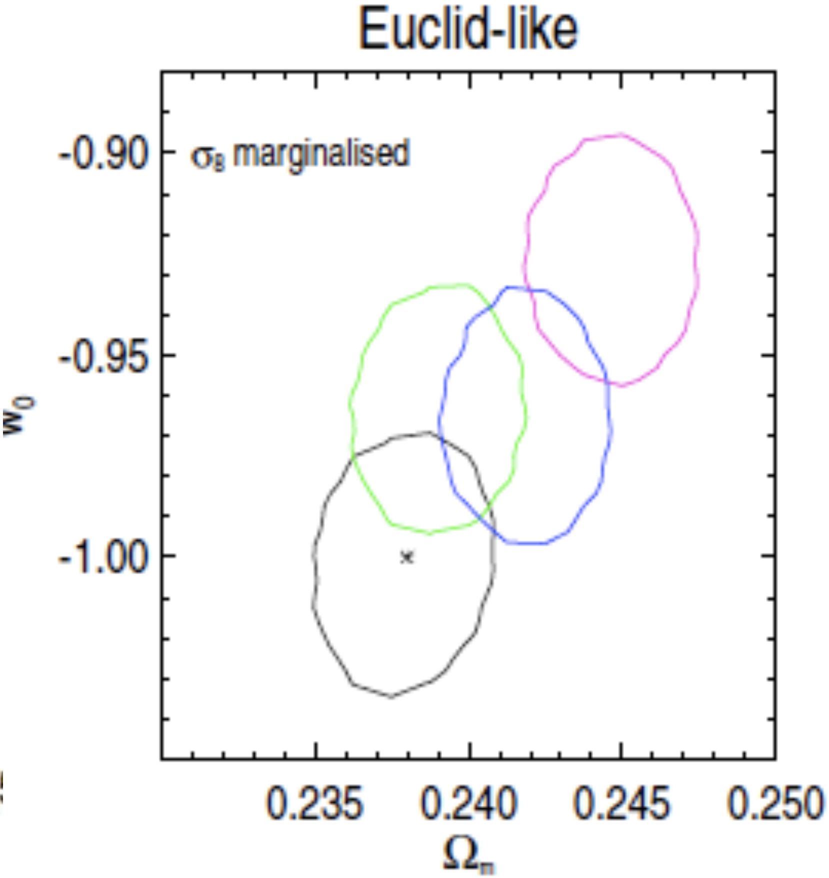
van Daalen et al. (2011)

Feedback can modify the matter power spectrum significantly!

We cannot ignore the (g)astrophysics



Feedback ignored



Accounted for feedback

Semboloni et al. (2011)

CFHTLenS

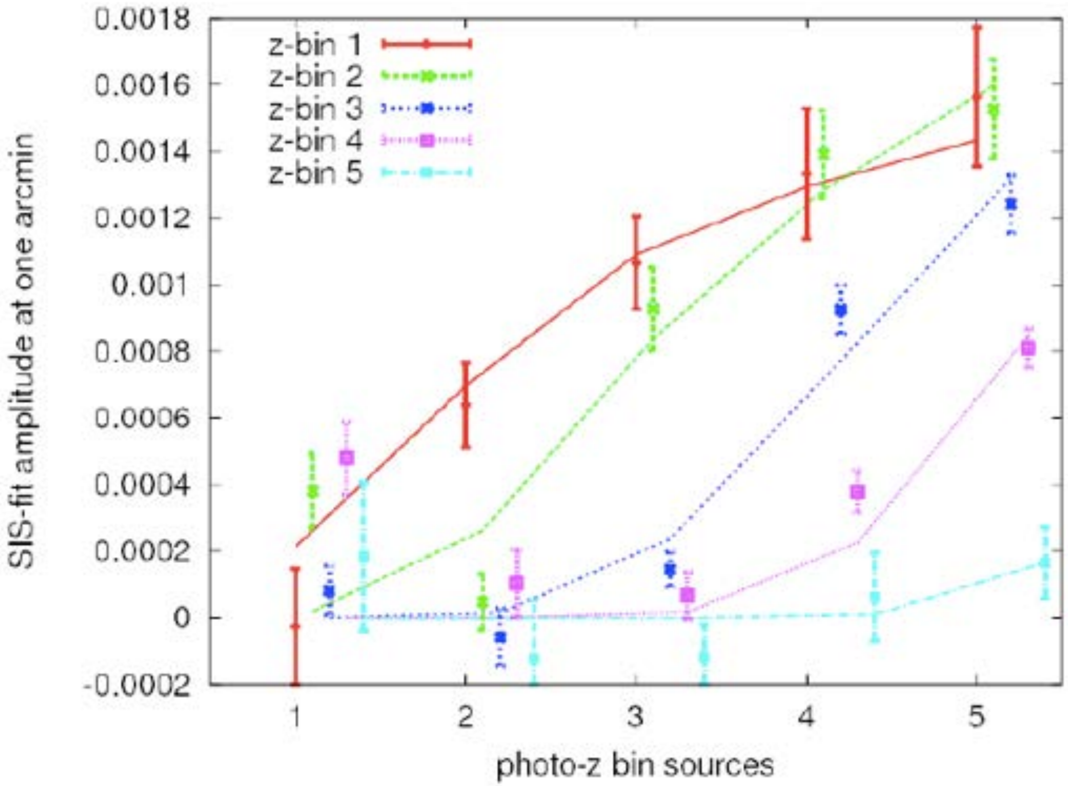
Uses 5 yrs of data from the Deep, Wide and Pre-survey components of the CFHT Legacy Survey, which covers a total of 154 deg^2 of the sky spread over 4 fields.

- Lensing analysis: 7 i-band images (seeing <0.85")
- Photometric redshifts: ugriz to i<24.7 (7 σ extended source)

Public release: www.cfhtlens.org

CFHTLenS: the team

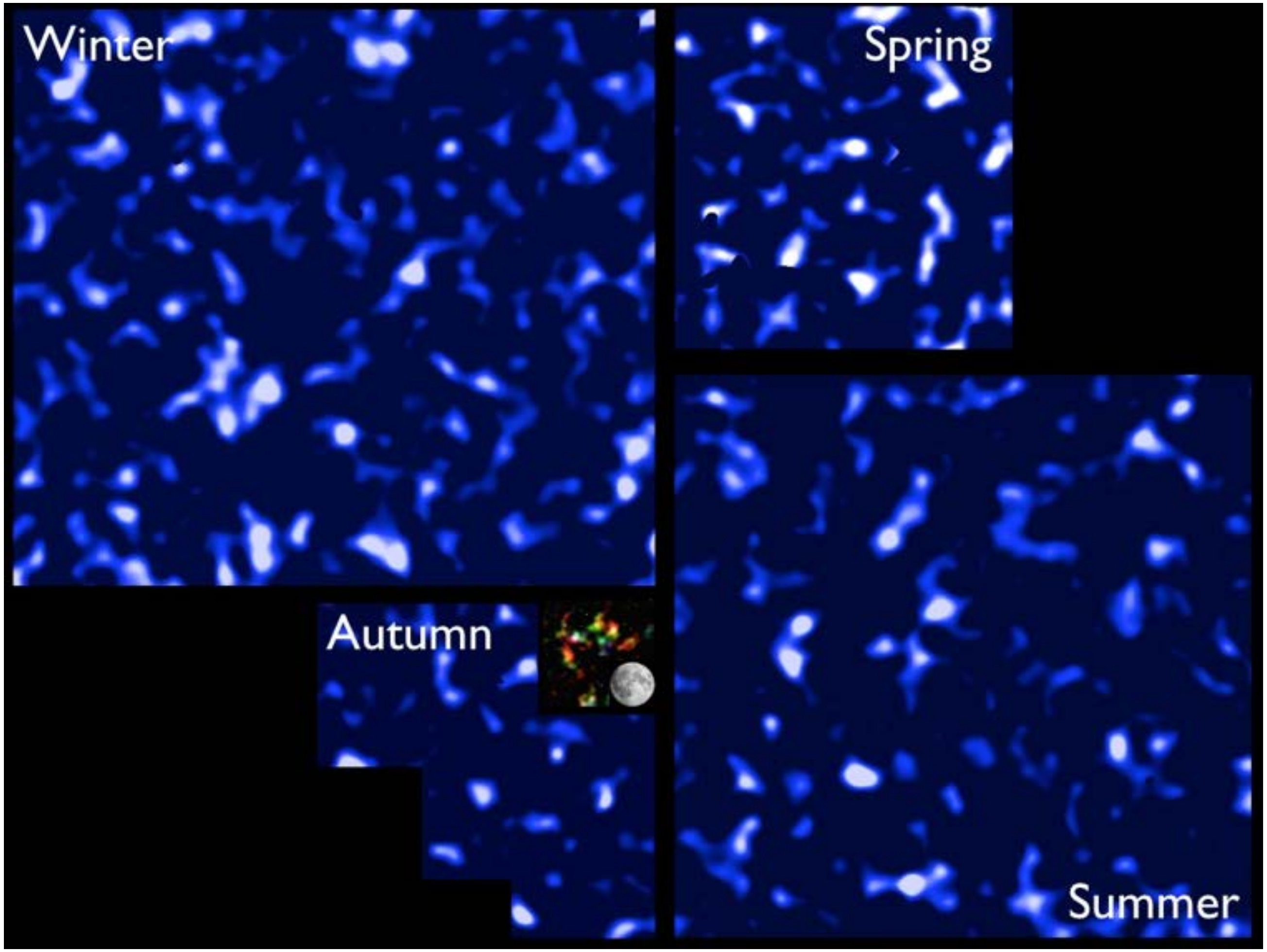
CFHTLenS: lots of testing



To test the redshift dependence we examine the galaxy-galaxy lensing signal

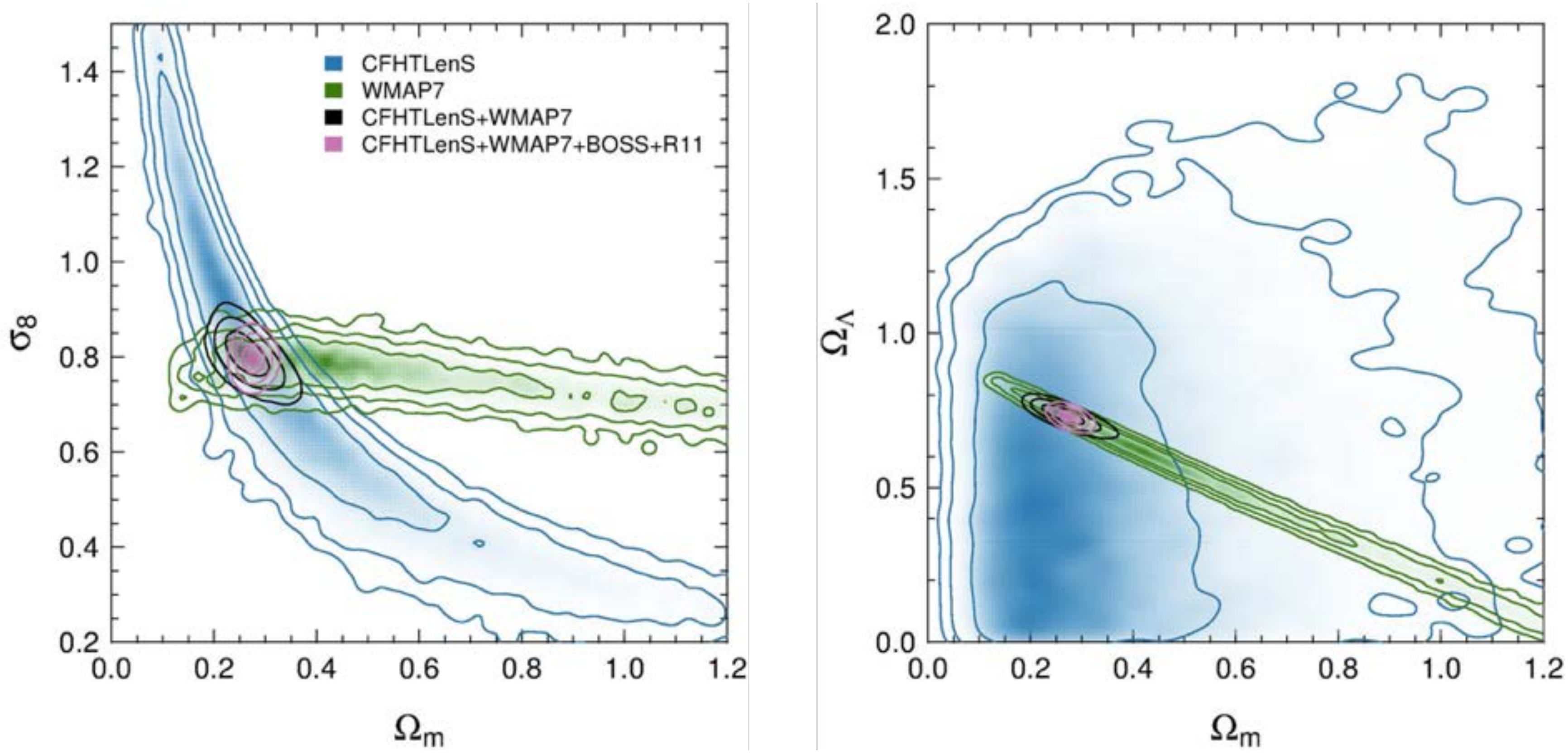
(very weak cosmology dependence)

CFHTLenS: looking at the dark side



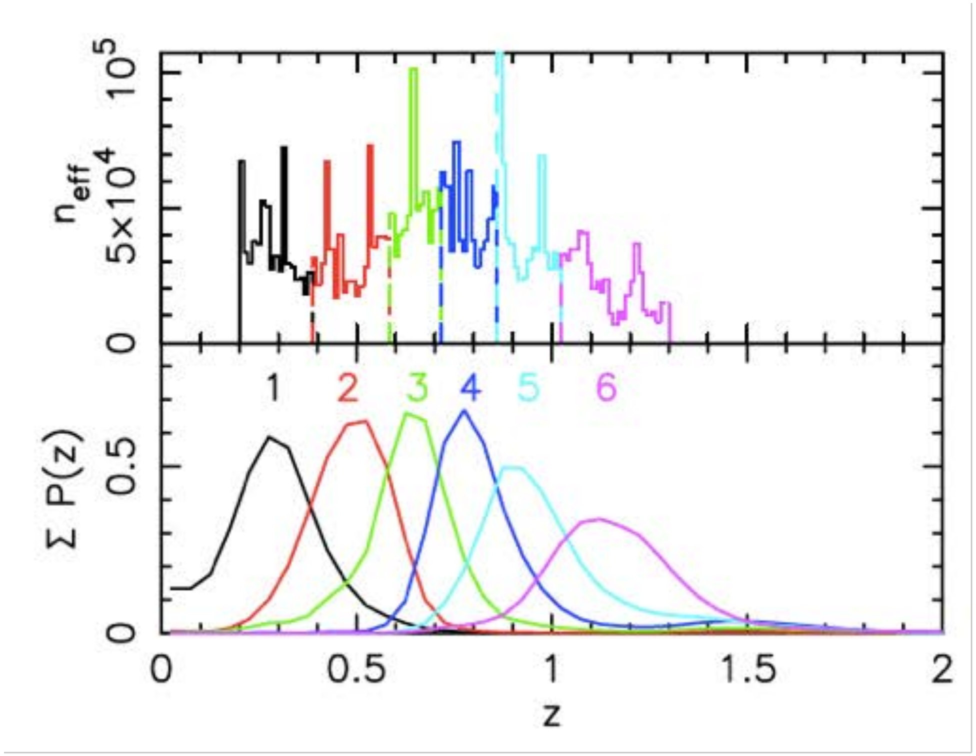
Van Waerbeke et al. (2013)

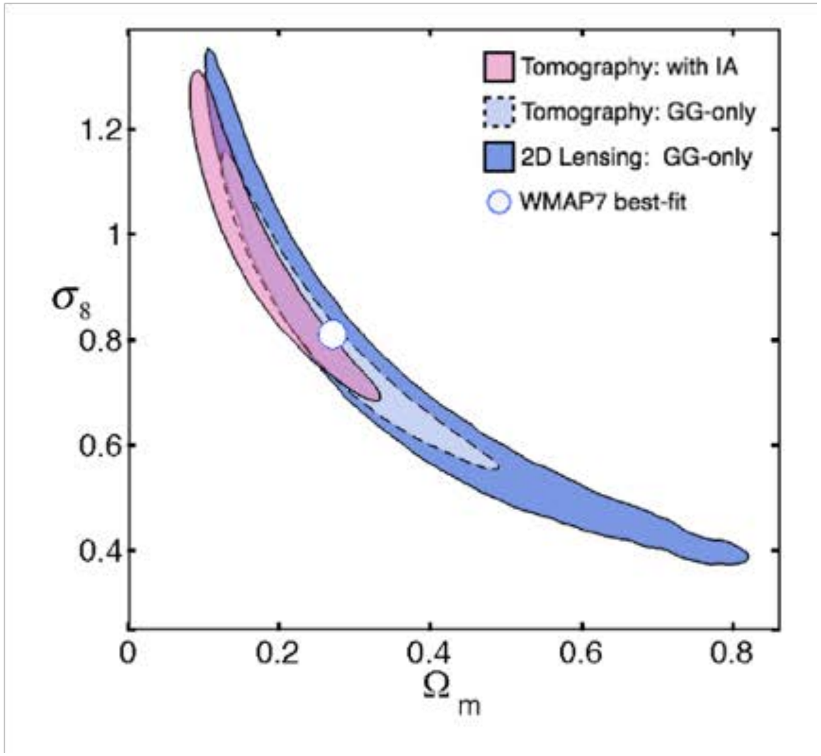
CFHTLenS: 2-bin tomography



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

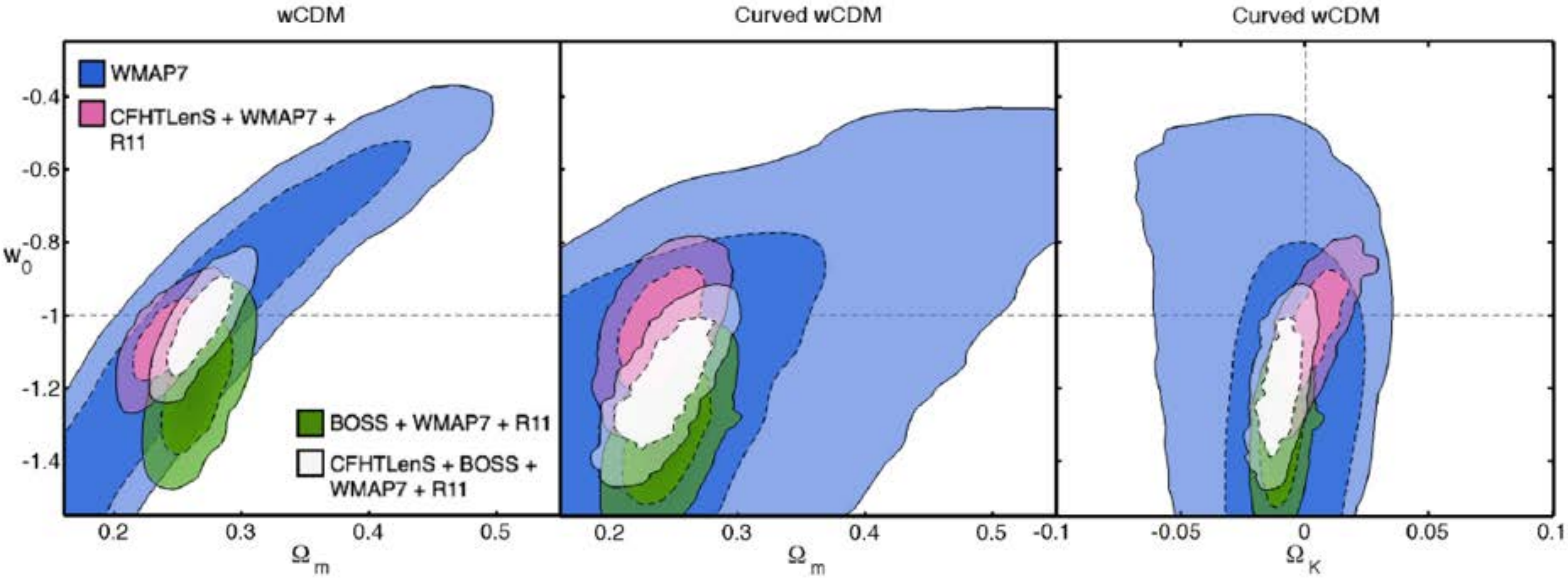
CFHTLenS: tomography





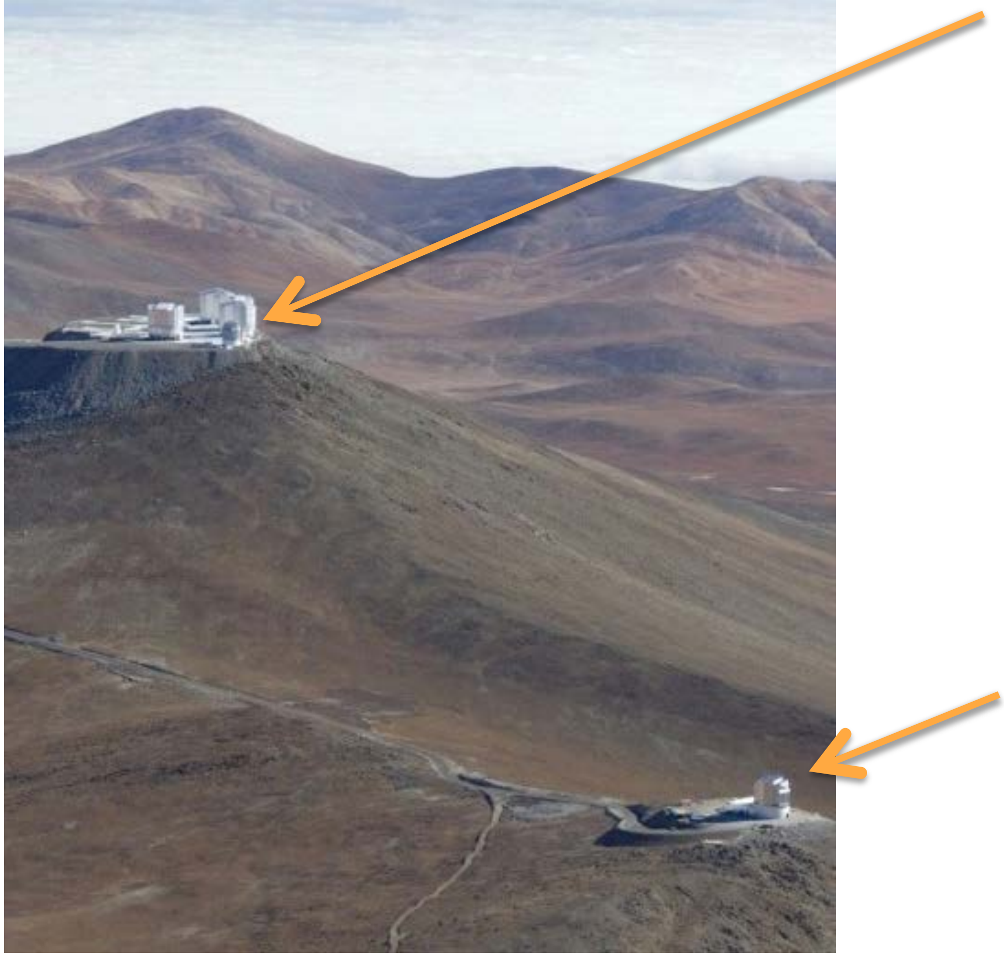
Heymans et al. (2013): narrower bins means that we need to account for intrinsic alignments (which we did).

CFHTLenS: constraints on dark energy



Heymans et al. (2013): w=-1.02±0.10

KiloDegree Survey: the next step



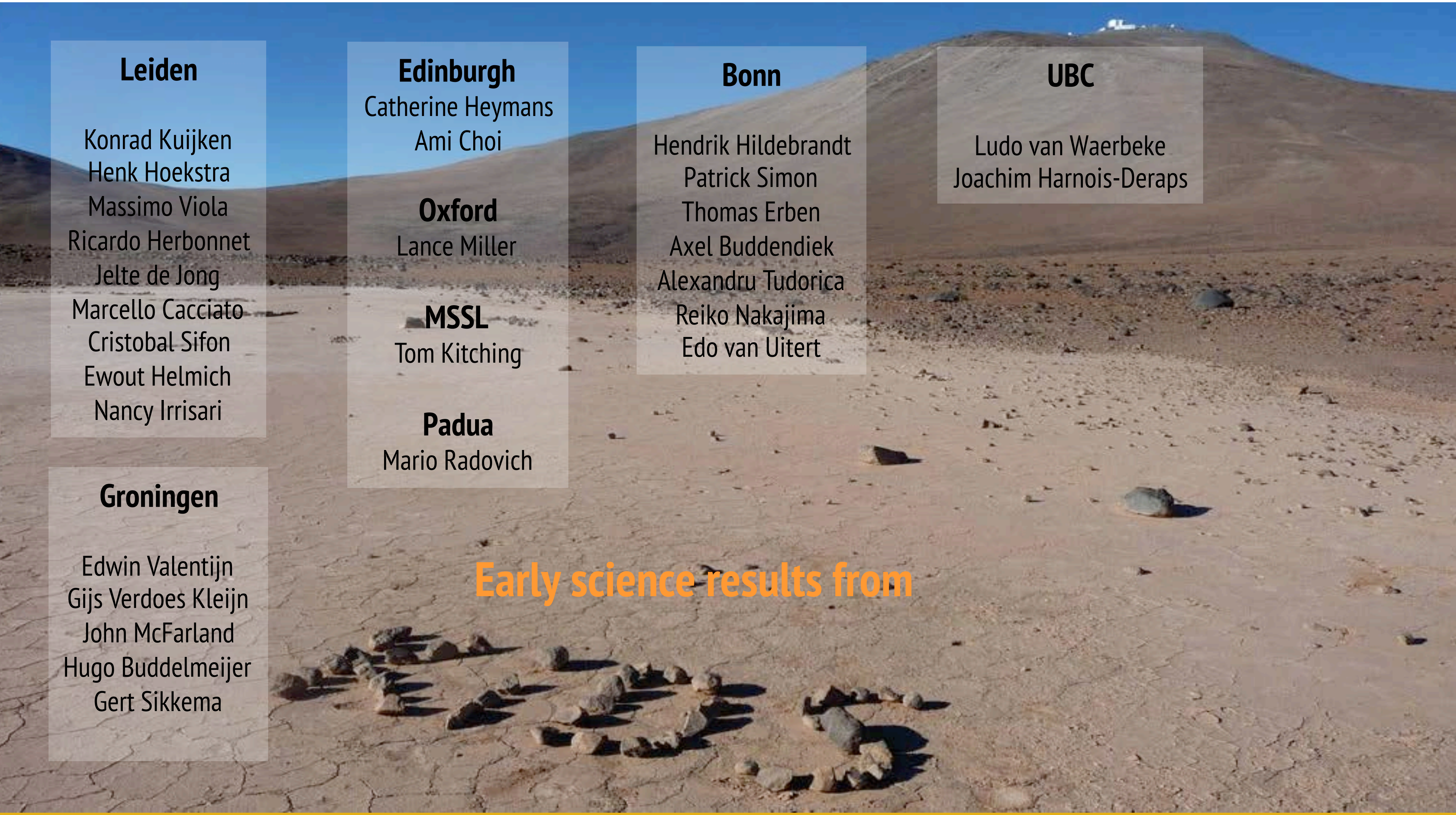
KIDS (@VST): 440 nights

- PI: Konrad Kuijken
- 1500 deg^2 (currently 200+)
- optical photometry (ugri)
- r-band median seeing 0.7
- stable and "circular" PSF
- 2 magnitudes deeper than SDSS

VIKING (@VISTA): 250 nights

- PI: Alistair Edge
- 1500 deg^2 (currently 200+)
- NIR photometry (zYJHK)

KiDS: The Team



Leiden

Konrad Kuijken
Henk Hoekstra
Massimo Viola
Ricardo Herbonnet
Jelte de Jong
Marcello Cacciato
Cristobal Sifon
Ewout Helmich
Nancy Irrisari

Groningen

Edwin Valentijn
Gijs Verdoes Kleijn
John McFarland
Hugo Buddelmeijer
Gert Sikkema

Edinburgh
Catherine Heymans
Ami Choi

Oxford
Lance Miller

MSSL
Tom Kitching

Padua
Mario Radovich

Bonn

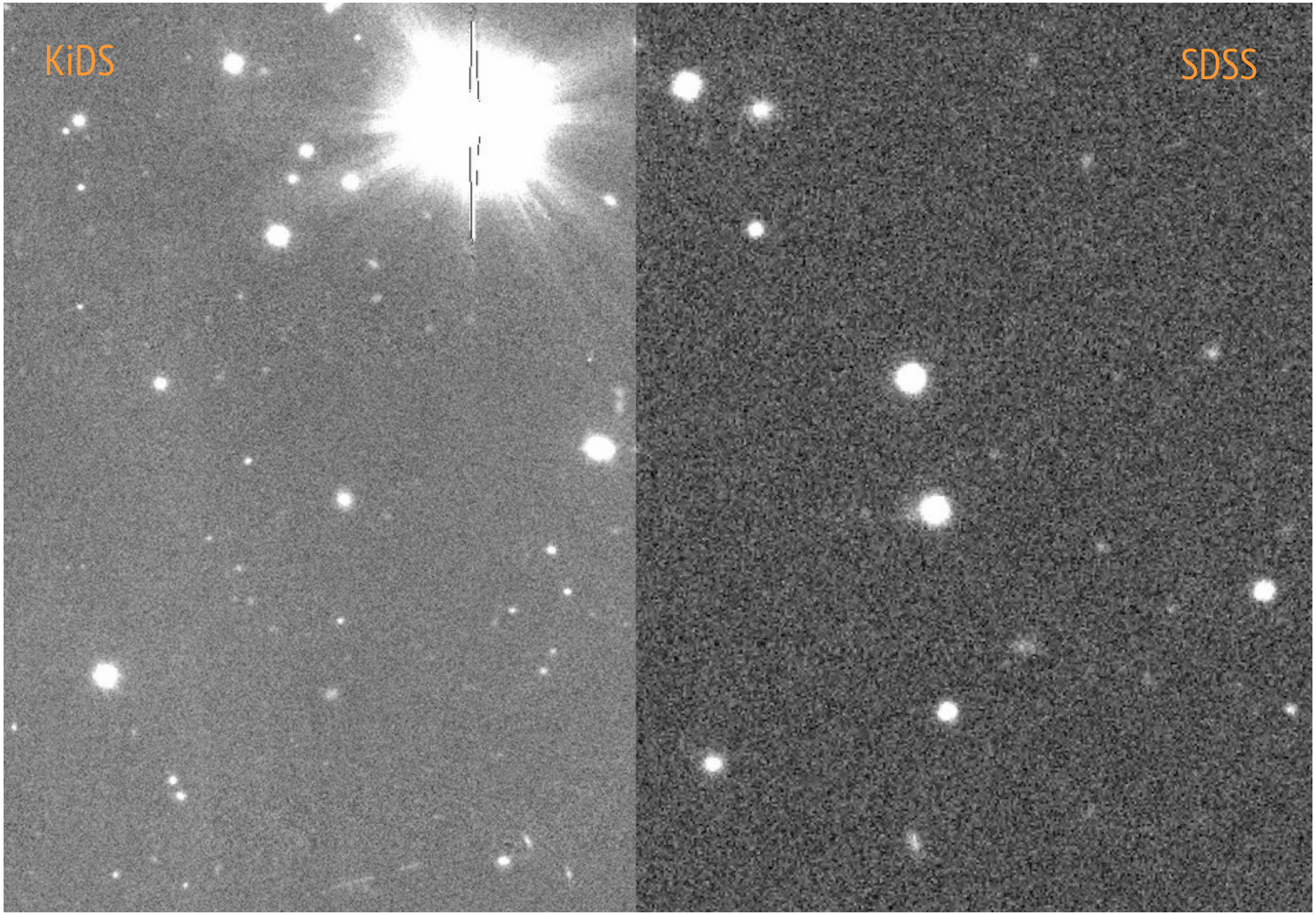
Hendrik Hildebrandt
Patrick Simon
Thomas Erben
Axel Buddendiek
Alexandru Tudorica
Reiko Nakajima
Edo van Uitert

UBC

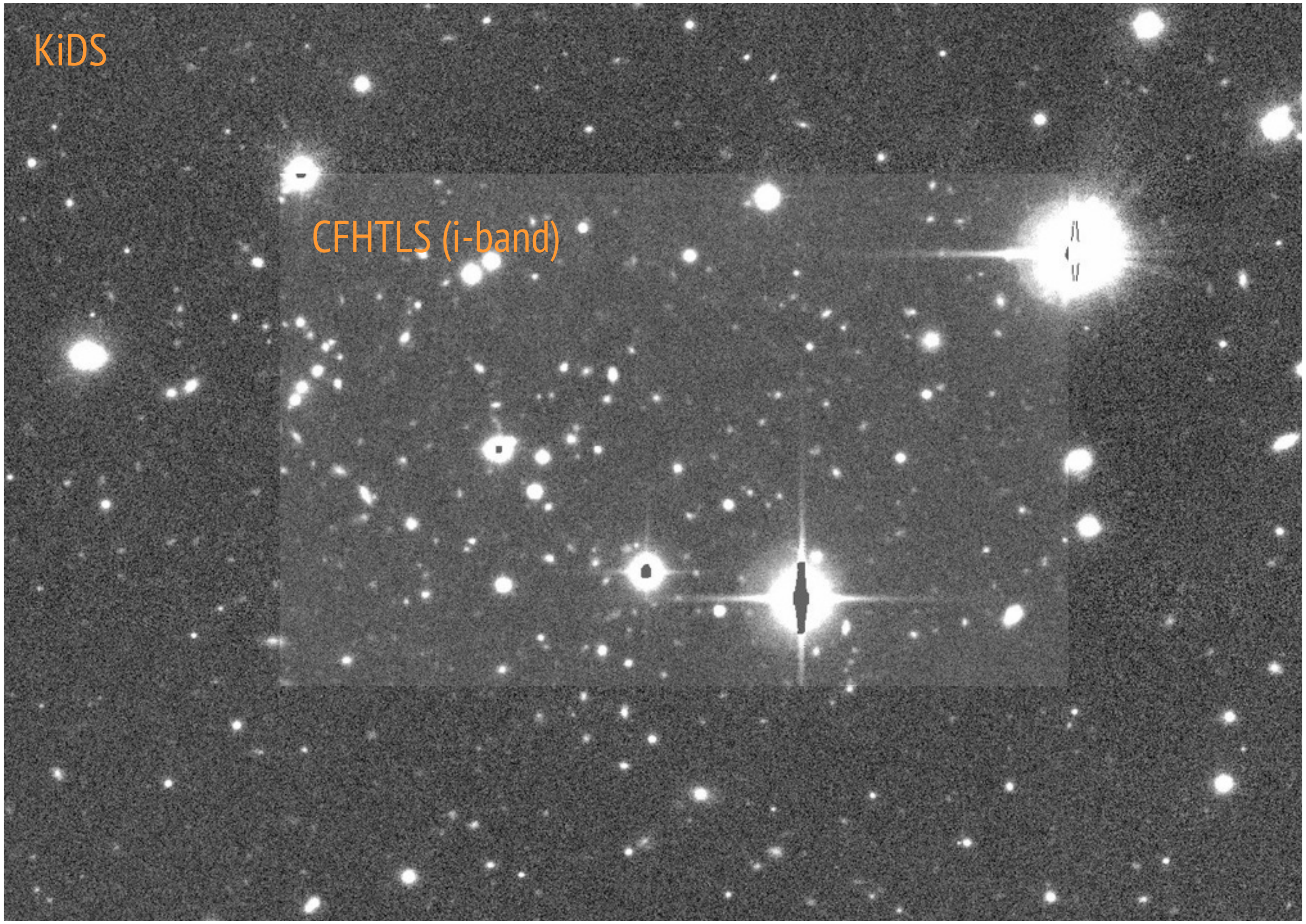
Ludo van Waerbeke
Joachim Harnois-Deraps

Early science results from

KIDS: comparison with SDSS



KIDS: comparison with CFHTLS



KIDS: early science results

These projects use the unique overlap of KiDS with the GAMA spectroscopic survey, which is highly complete down to m_r~19.8

Galaxy groups (Viola et al.)

properties of the groups, M/L ratio, BCG offset from center of DM halo

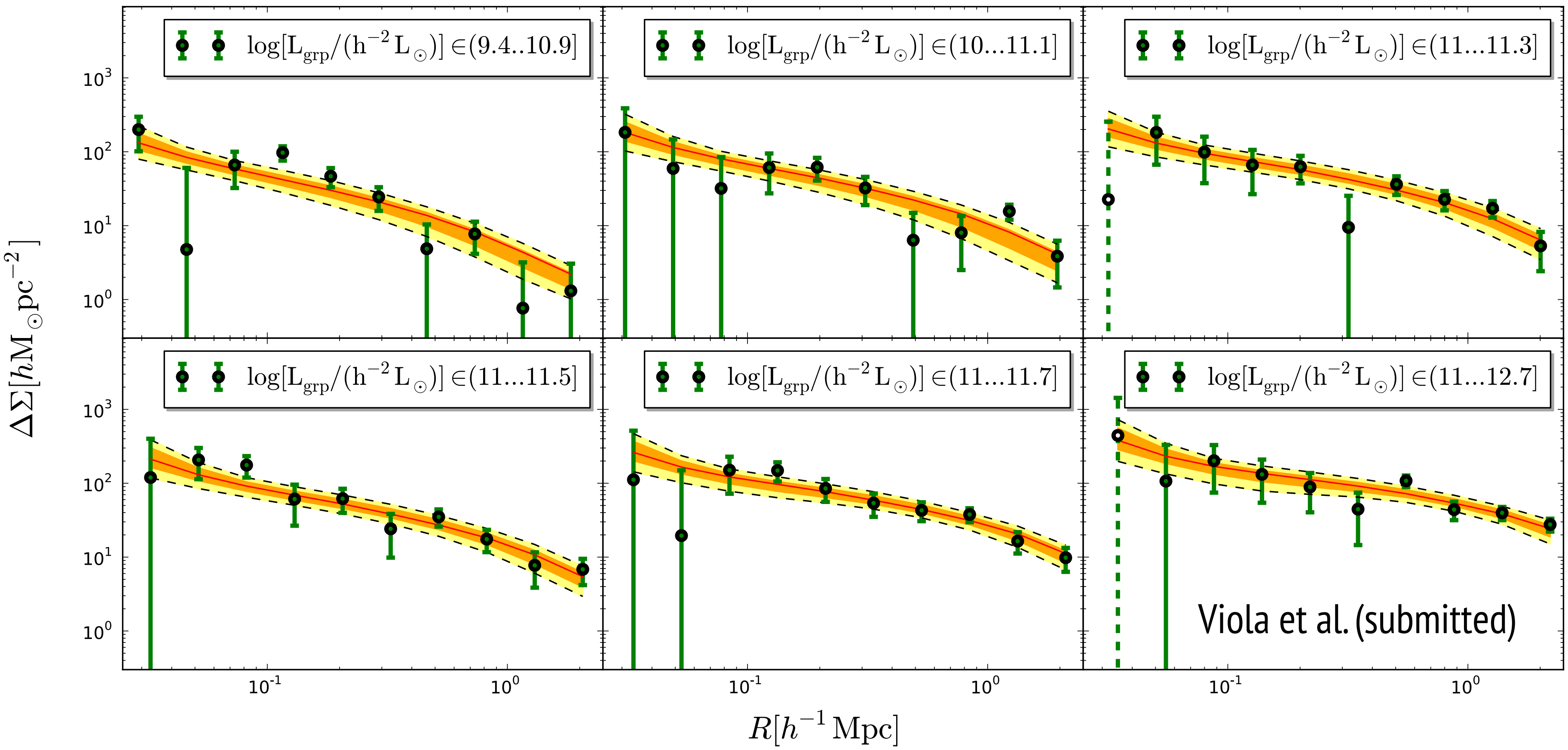
Central galaxies (van Uitert et al.)

halo mass as a function of stellar mass, color, redshift, environment, etc.

Satellite galaxies (Sifon et al.)

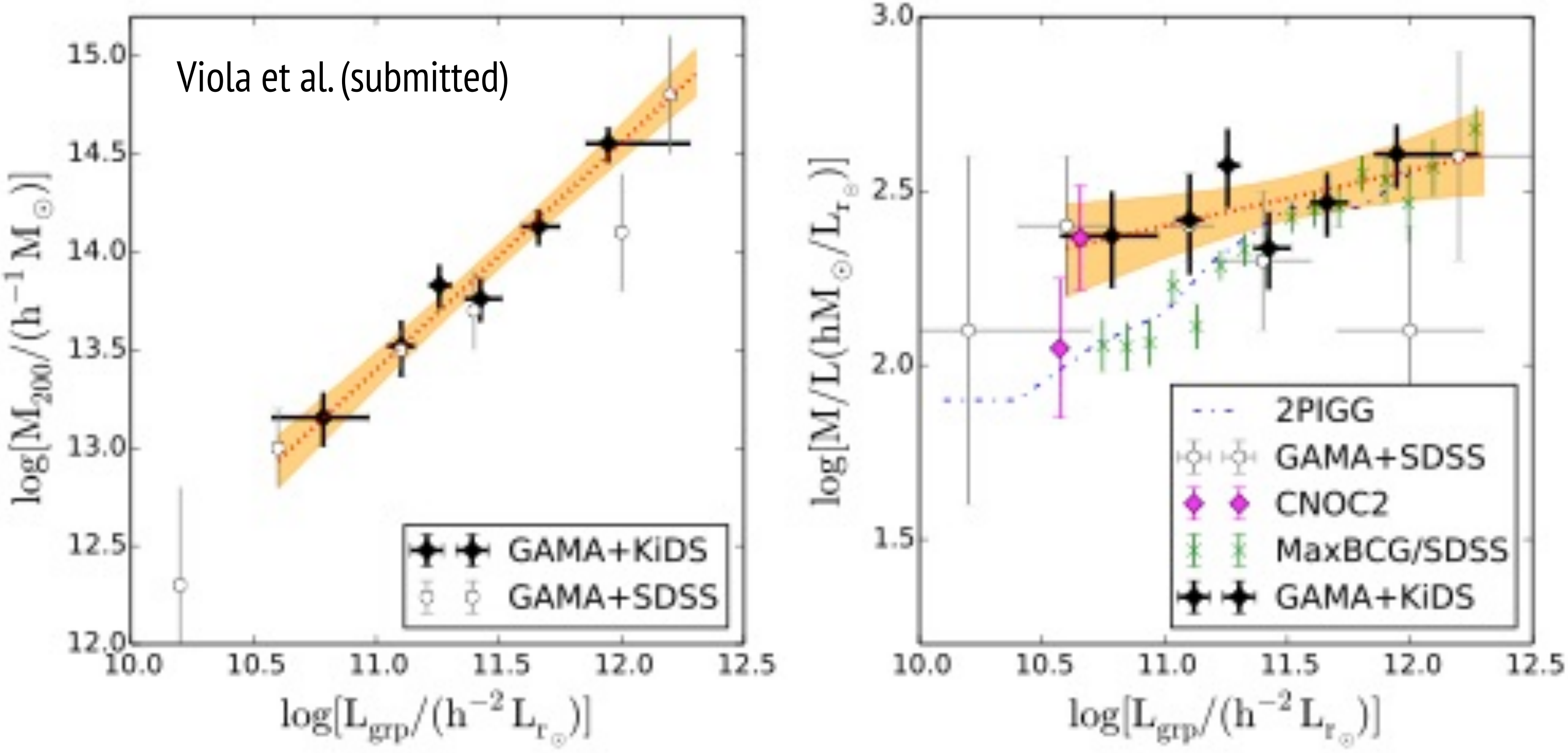
mass as a function of their distance from the BCG to quantify stripping

Group signal as a function of luminosity



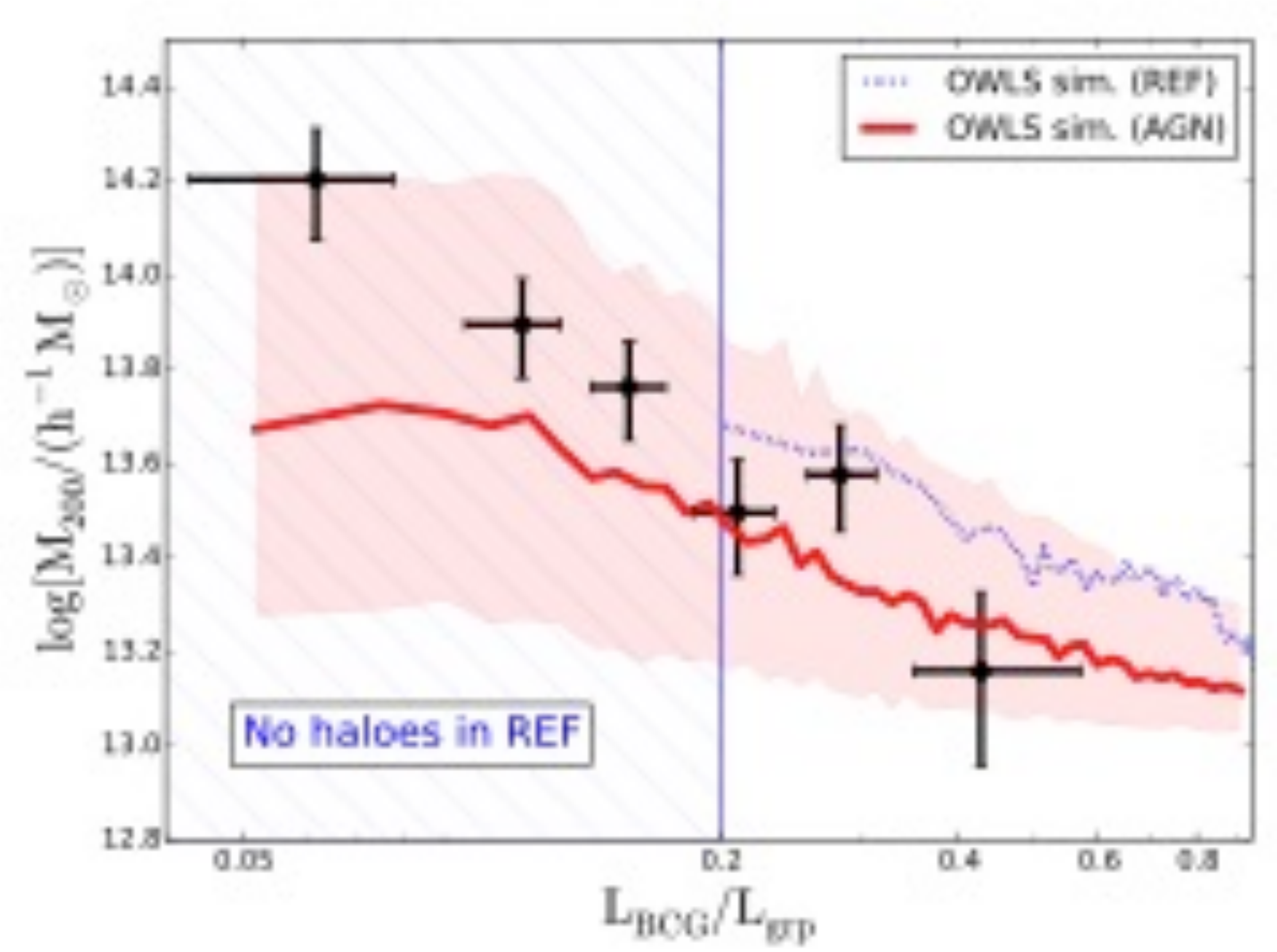
Viola et al. (submitted)

Mass-to-light ratio



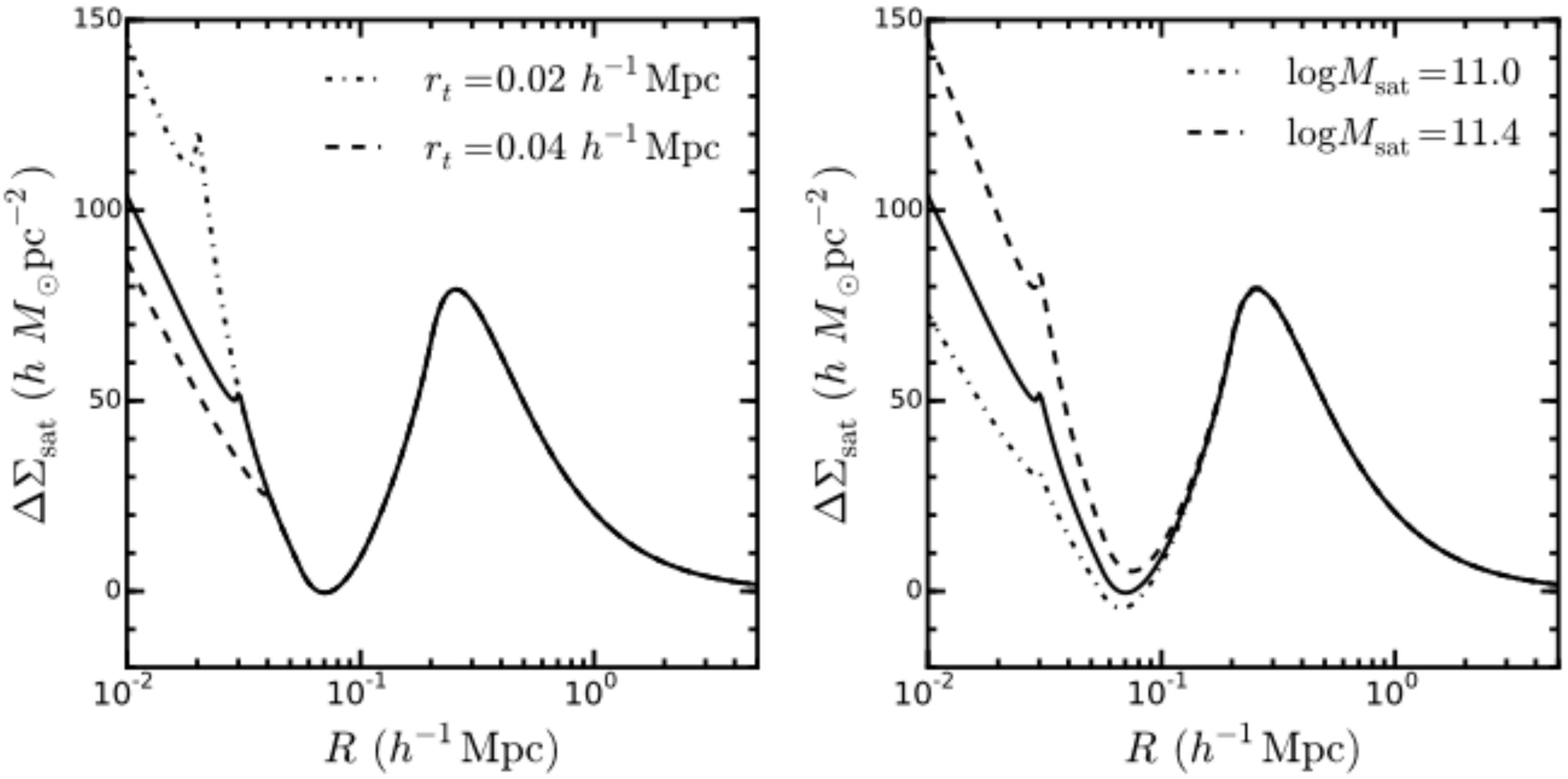
Viola et al. (submitted)

Testing feedback models



Viola et al. (submitted)

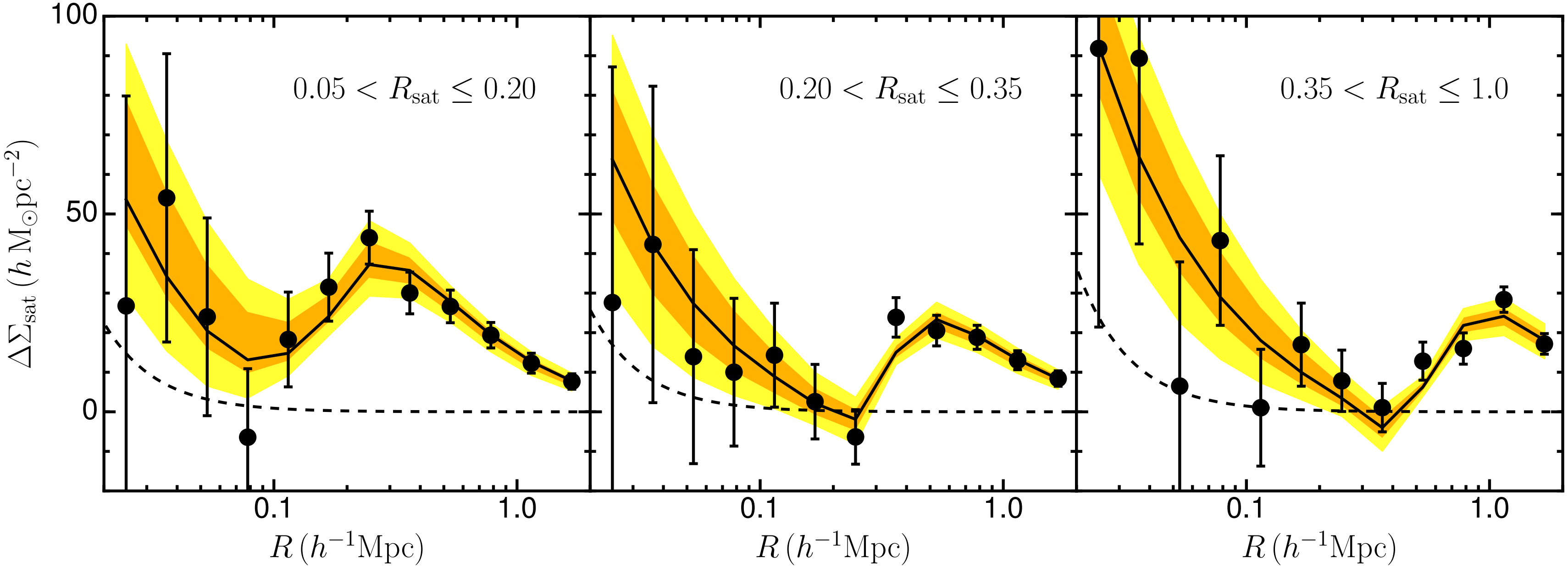
Satellites in groups: a complex signal



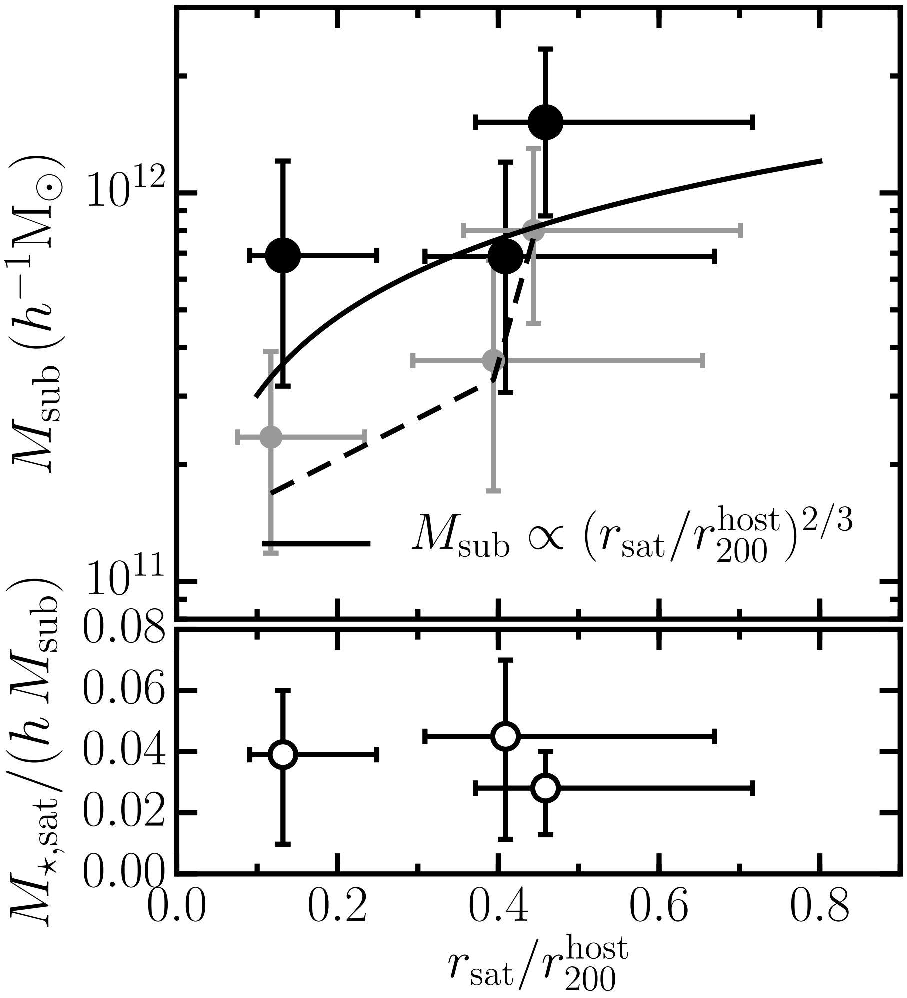
Sifon et al. (in prep.)

Satellites in groups: halo modeling

Sifon et al. (in prep.)



Satellites in groups: evidence for stripping



Sifon et al. (in prep.)

As KiDS grows up...

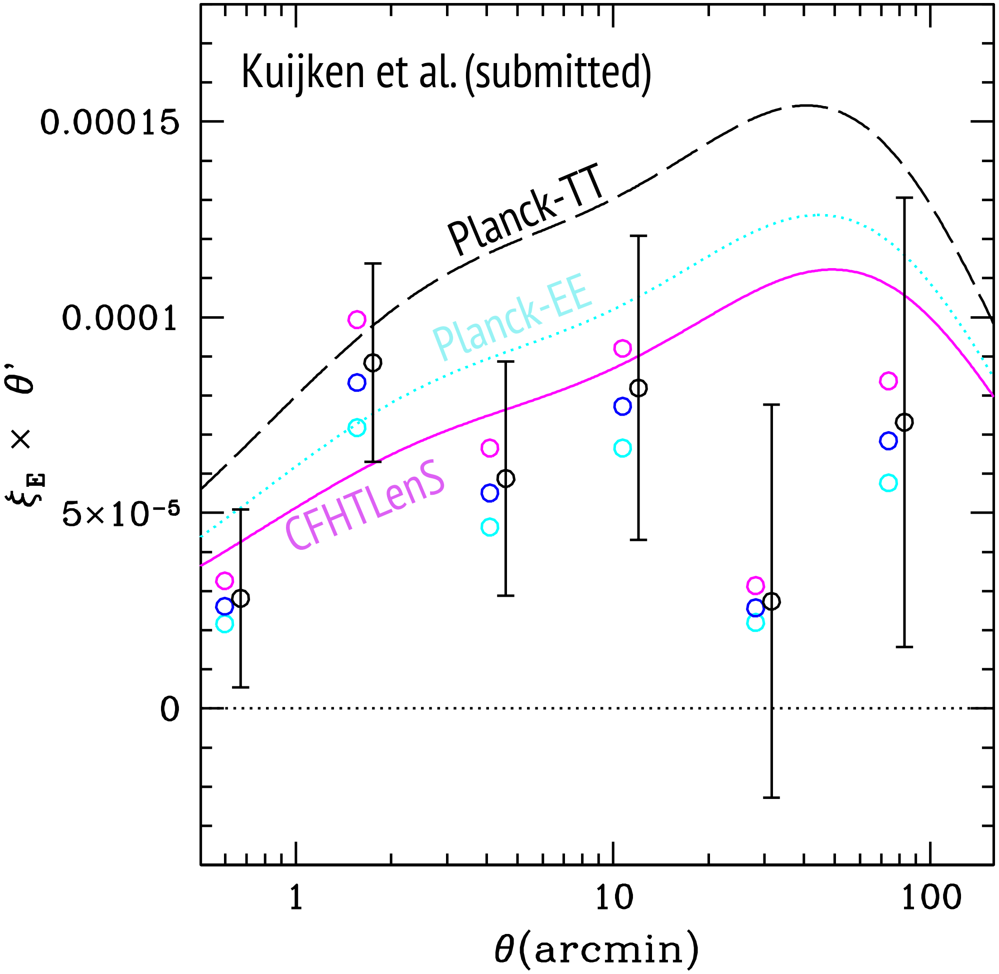
The early science papers use only half of the overlap with GAMA. The full analysis will not only reduce uncertainties, but by combining lensing and clustering measurements we can break some parameter degeneracies.

Cosmic shear results will also be competitive:

- Thanks to GAMA redshifts we can constrain models of intrinsic alignments.
- Thanks to the NIR data photometric redshifts should be more reliable compared to CFHTLenS: better constraints on cosmological parameters.

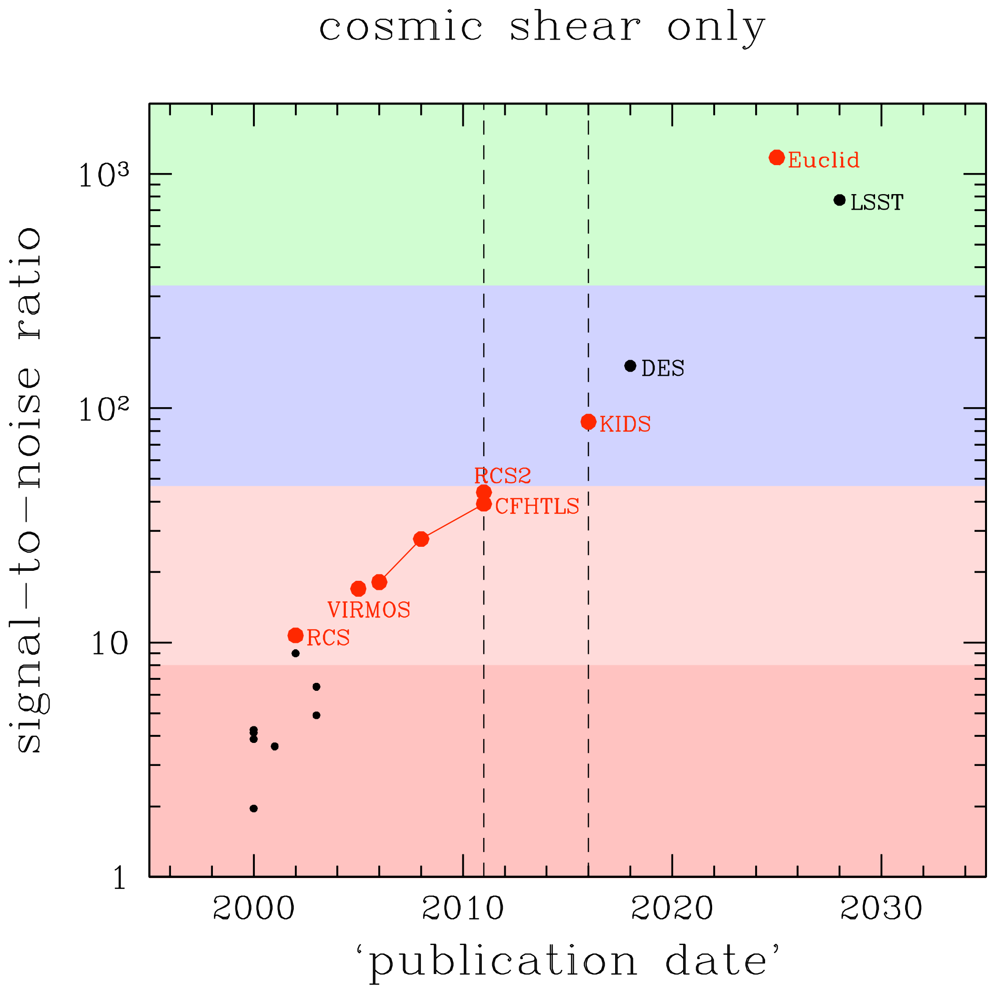
Much more to come in the next few years!

As KiDS grows up... (1/15th of the data)



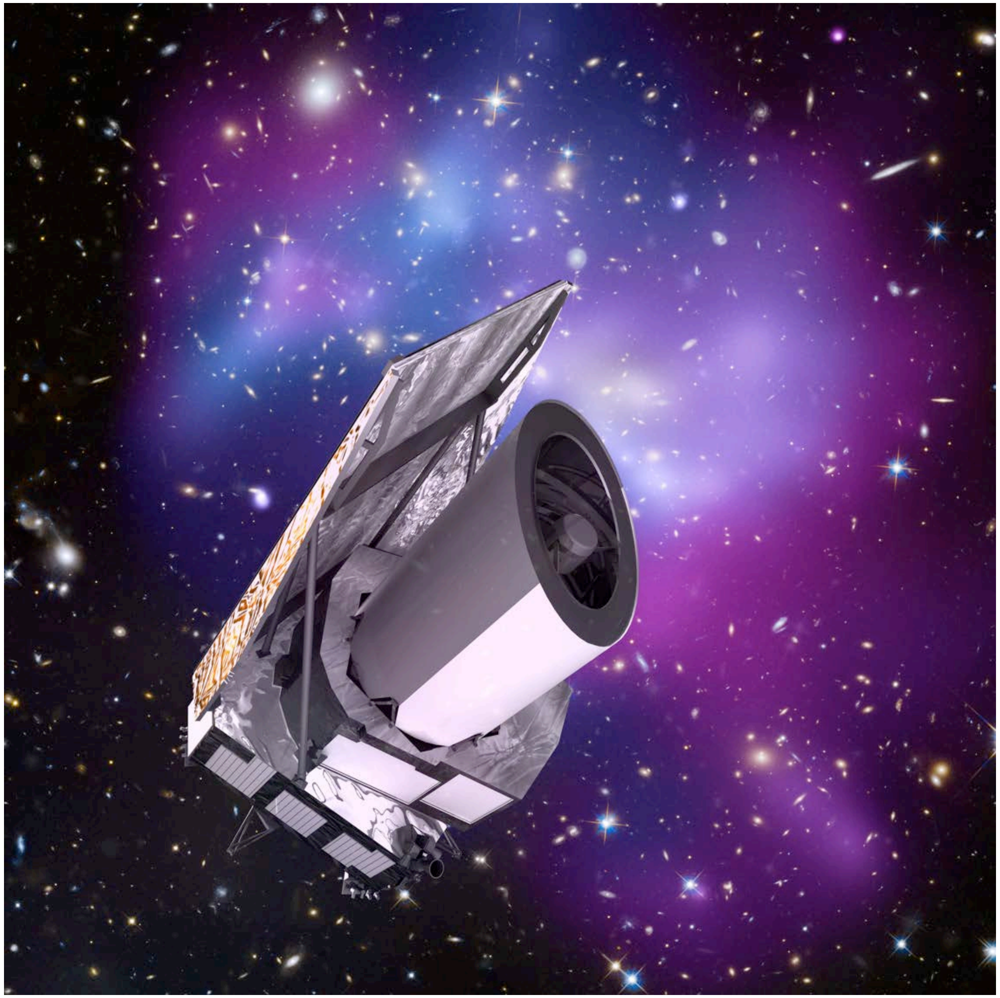
What is next?

We need to do 10x better



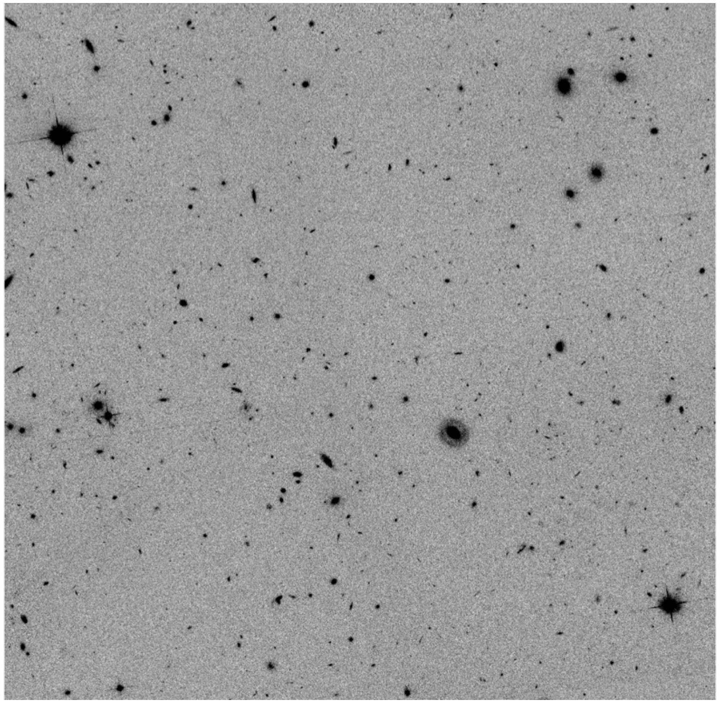
This leads to big research teams!

Euclid: a satellite designed to do weak lensing



Euclid: a High Definition view of the sky

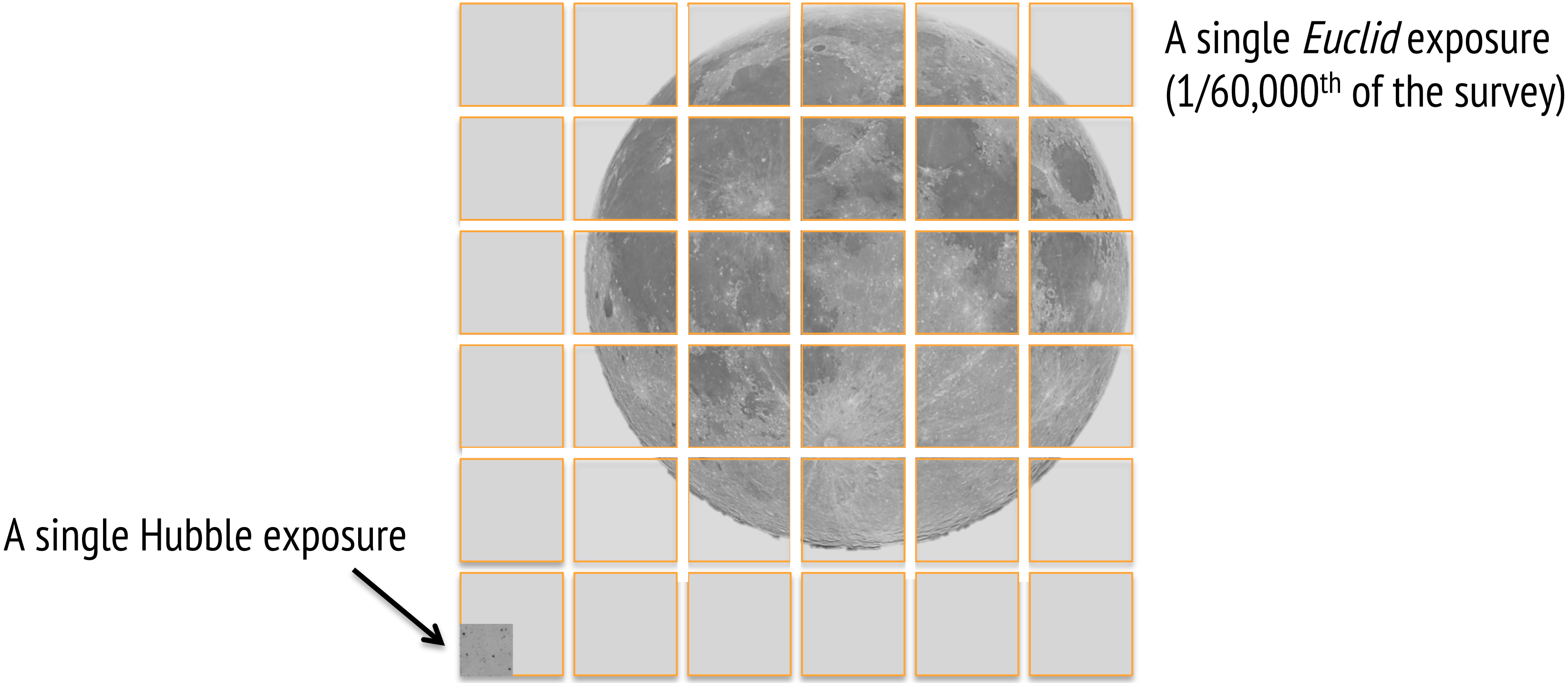
To measure the amount of stretching we need to take sharp pictures. The Hubble Space Telescope has been taking sharp pictures of the Universe for the past 25 years, but the camera is too small …



A single Hubble exposure

Euclid: a High Definition view of the sky

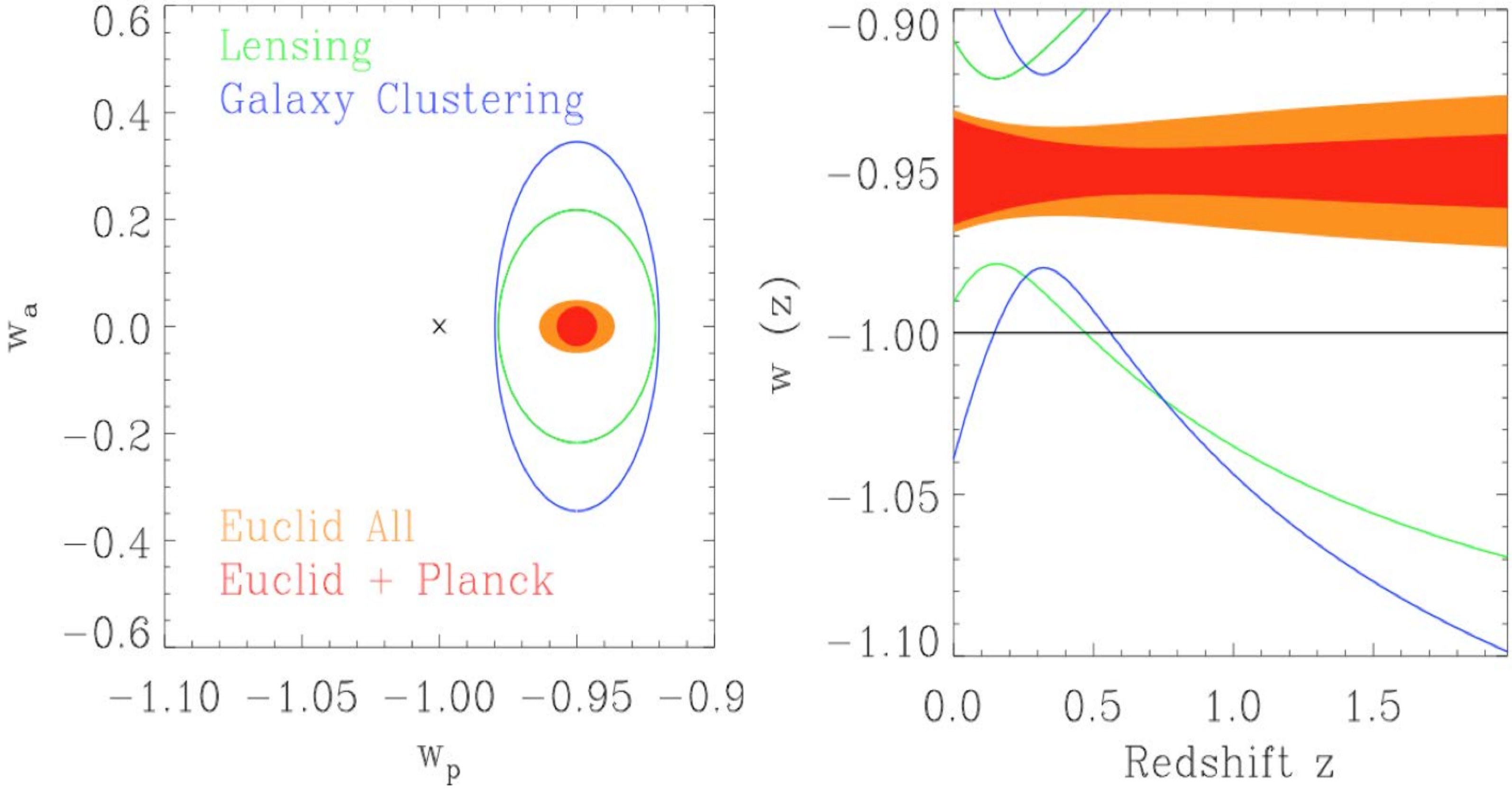
Euclid will provide a high-definition view of 1/3 of the sky allowing us to measure shapes for more than two billion galaxies. This enormous data set has the potential to lead to many other discoveries.



A single *Euclid* exposure (1/60,000th of the survey)

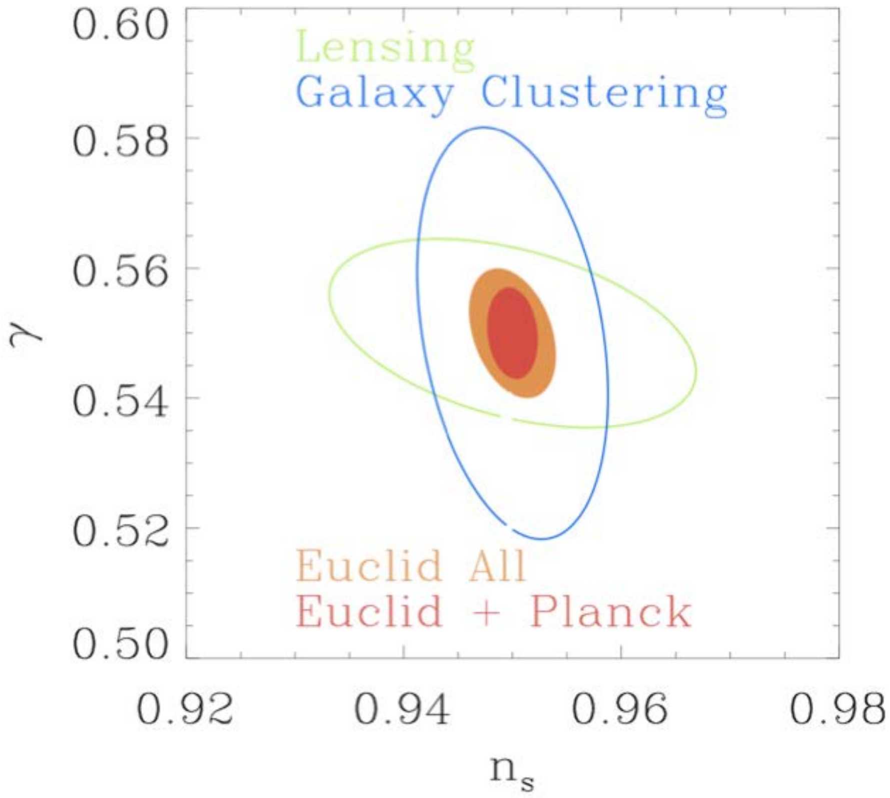
A single Hubble exposure

Euclid: dark energy constraints



FoM > 4000 when combined with *Planck*

Euclid: modified gravity constraints



ΛCDM+GR predict γ=0.55; Euclid will achieve an error of $\Delta\gamma$~0.007, sufficient to decisively prefer GR over some modified gravity theories.

But Euclid can do much more!

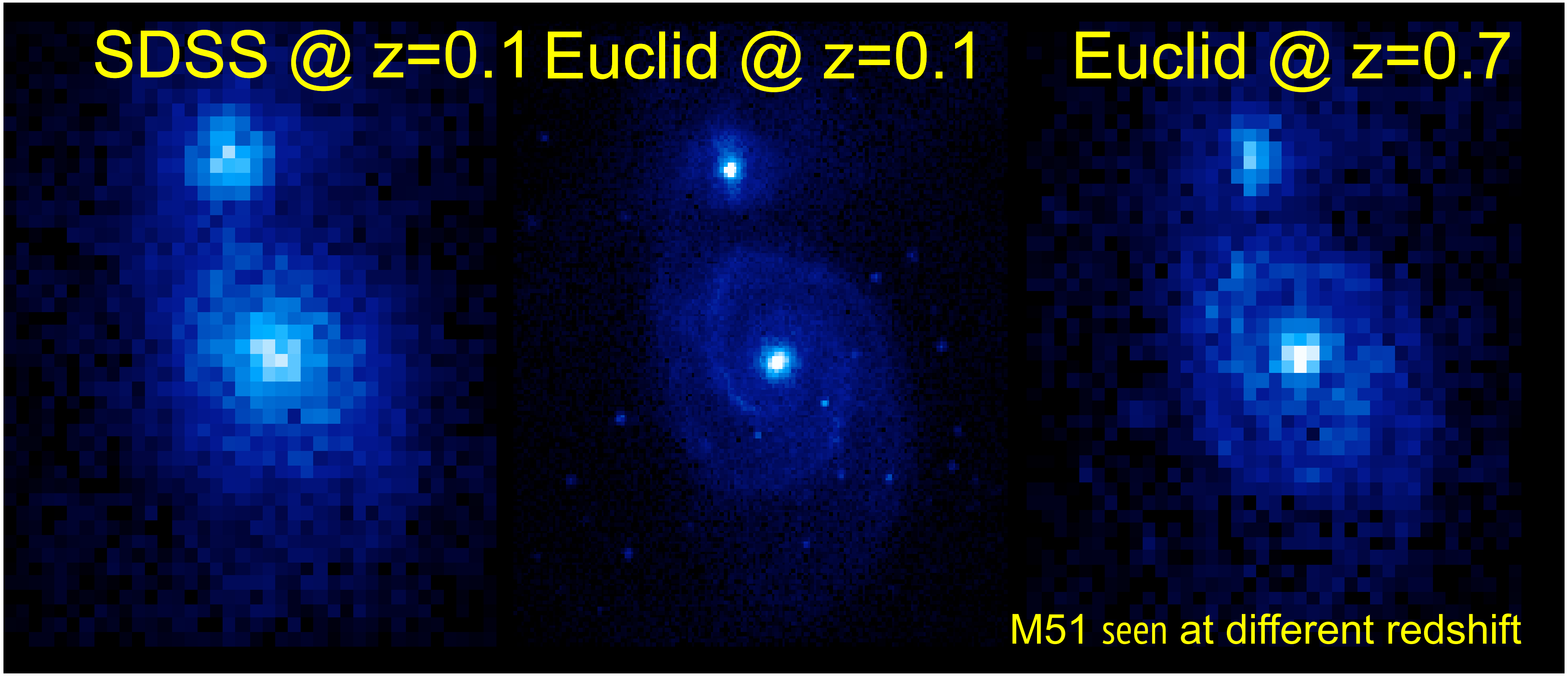
The primary cosmology probes drive the design of the survey, but the resulting data set enables an enormous amount of legacy science, which cannot be done otherwise:

Euclid will image 15000 deg^2 in YJH$_{AB}$=24, which would take 680 years to complete with VISTA. The deep survey of 40 deg^2 down to YJH$_{AB}$=26 would take 72 years with VISTA.

The Euclid NIR imaging is a 100 times more ambitious than anything currently underway!

Euclid probes a much larger volume than the SDSS: 20 Gpc^3 at $z\sim2\pm0.05$ compared to ~0.3 Gpc^3 probed by SDSS at $z\sim0.2$

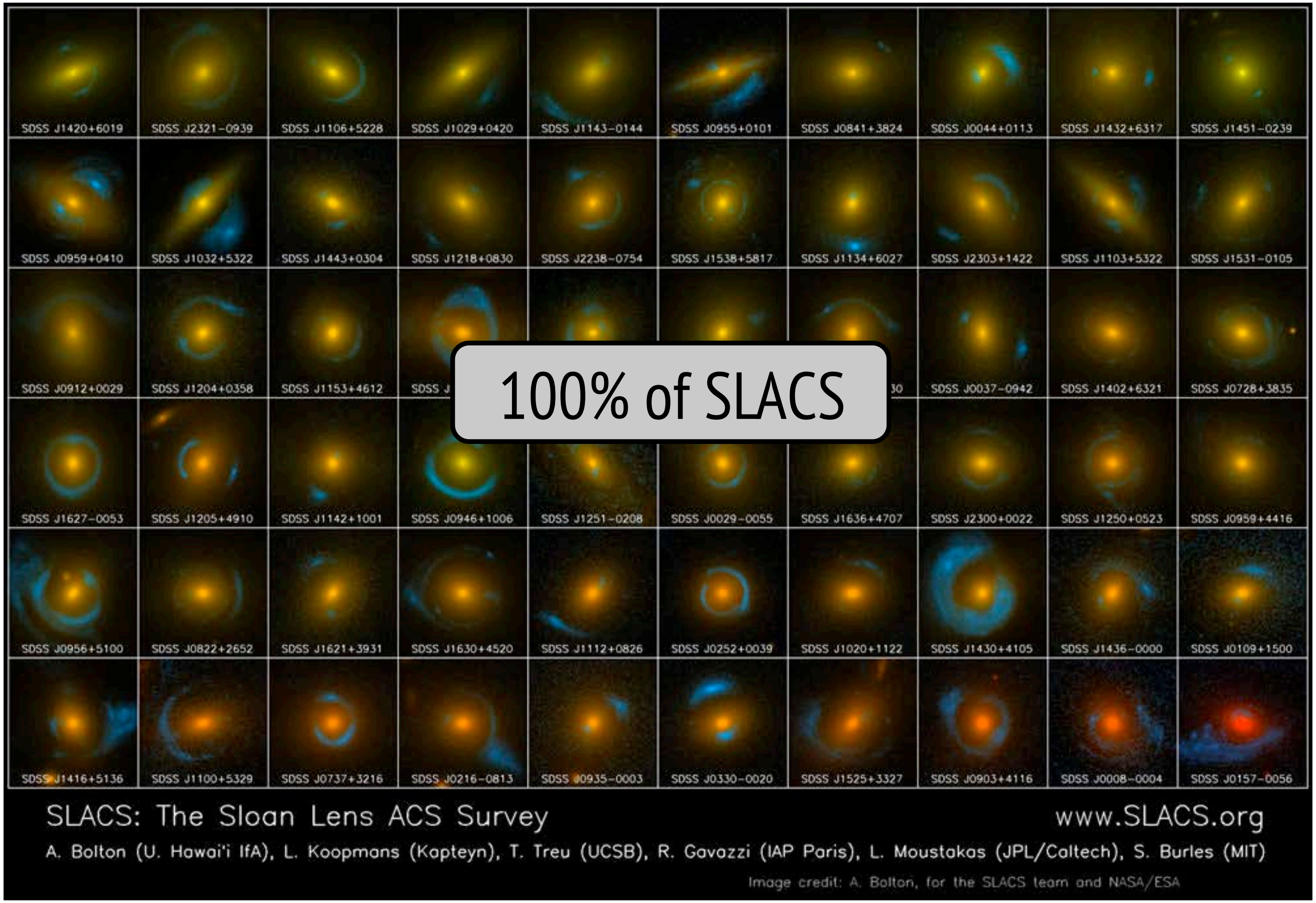
Euclid is “SDSS” at z~1



M51 seen at different redshift

Euclid images of *z*~1 galaxies will have the *same* resolution as SDSS images at *z*~0.05 and will be at least 3 magnitudes *deeper.*

Large samples of strong lenses



SLACS: The Sloan Lens ACS Survey

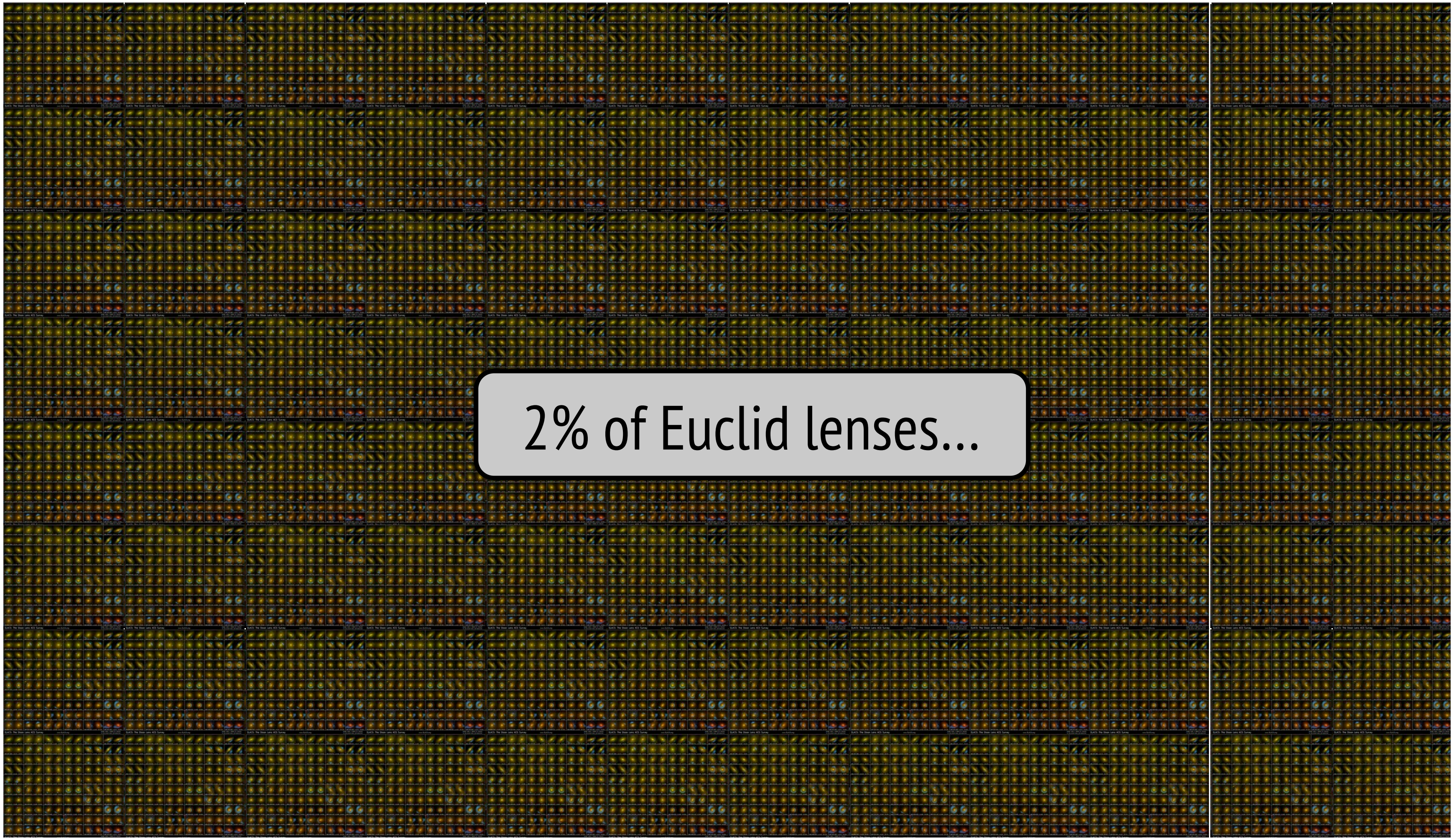
www.SLACS.org

A. Bolton (U. Hawai'i IfA), L. Koopmans (Kapteyn), T. Treu (UCSB), R. Gavazzi (IAP Paris), L. Moustakas (JPL/Caltech), S. Burles (MIT)

Image credit: A. Bolton, for the SLACS team and NASA/ESA

100% of SLACS

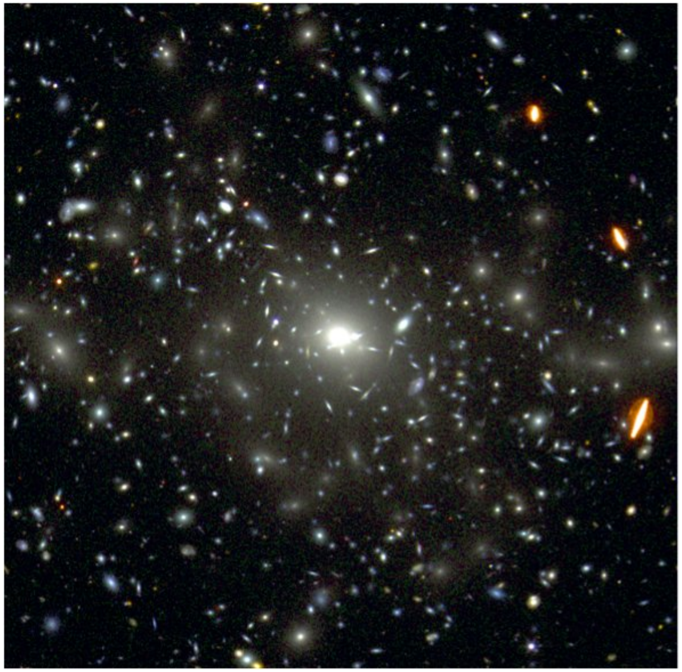
Large samples of strong lenses



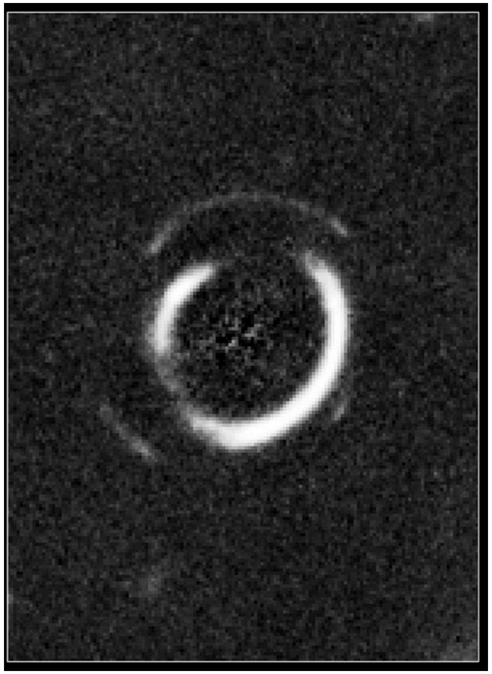
2% of Euclid lenses...

Strong lensing

- **Increase the number of strong lensing galaxy systems to ~300,000**. This allows for *population* studies, but also provides interesting numbers of rare events (double rings, high magnification, substructure statistics).
- **Increase the number cluster strong lenses to ~5000**.



Simulated Euclid image (VIS+NIR)



Rare lensing event

Conclusions

Weak gravitational lensing studies are yielding excellent results.

Still very much a work in progress as better measurements lead to new insights. To achieve the full potential of the next surveys a number of issues remain...

The data analysis and interpretation is complex: success relies on improving our understanding of observational and astrophysical biases.

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