euclid

→ EXPLORING THE DARK UNIVERSE

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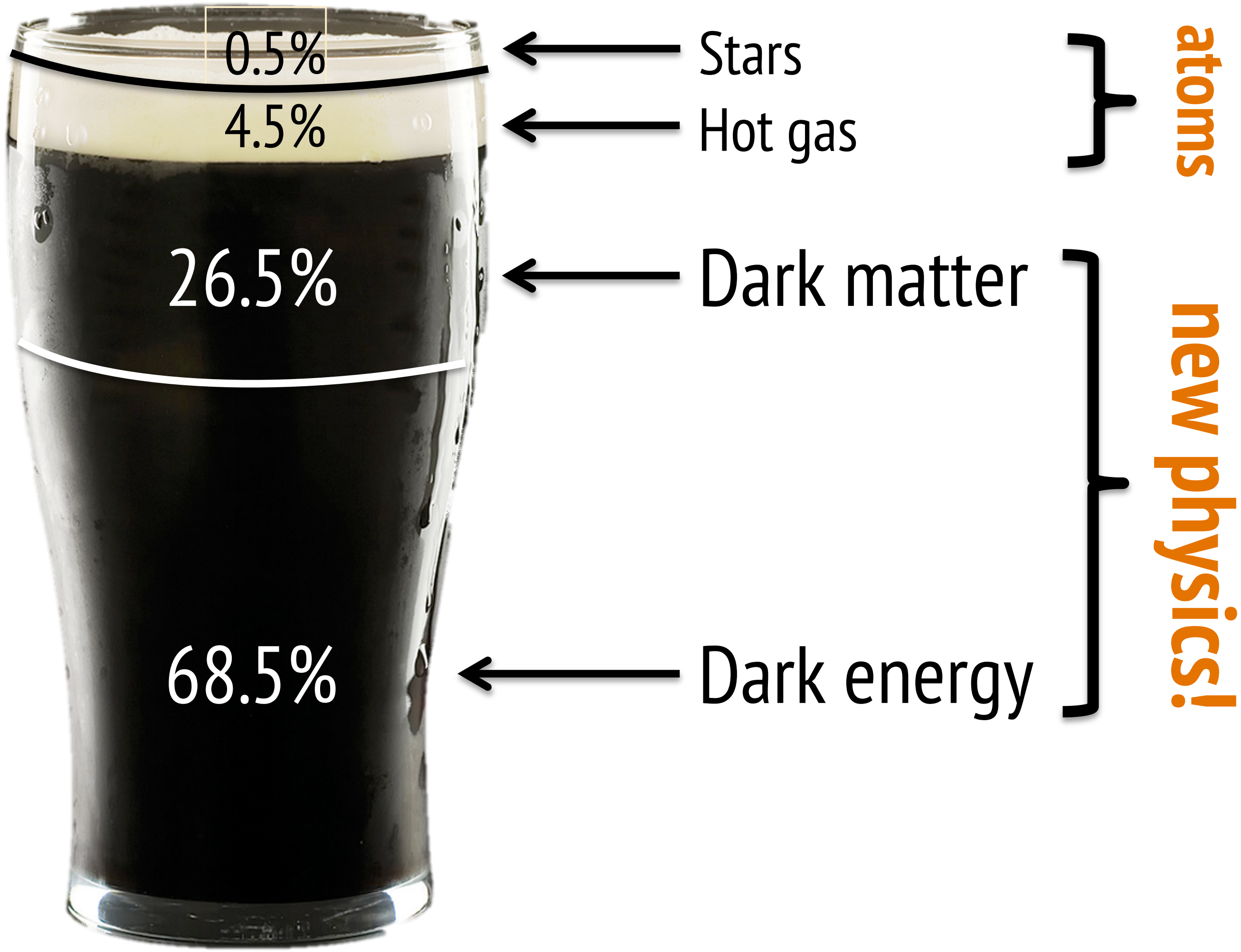
The biggest problem in physics: who ordered this?



What should we study?

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 $f(z)$

What should we study?

Designing a survey

The effects of dark energy are subtle:

- We need high precision (large survey)
- We need high accuracy (small biases)
- The probes should complement each other (consistency)

What if it the problem is with gravity?

- The project should test many aspects of the current paradigm.

What data do we need?

We want to study the *evolution* of the Universe

Accelerated expansion dominates at low redshift

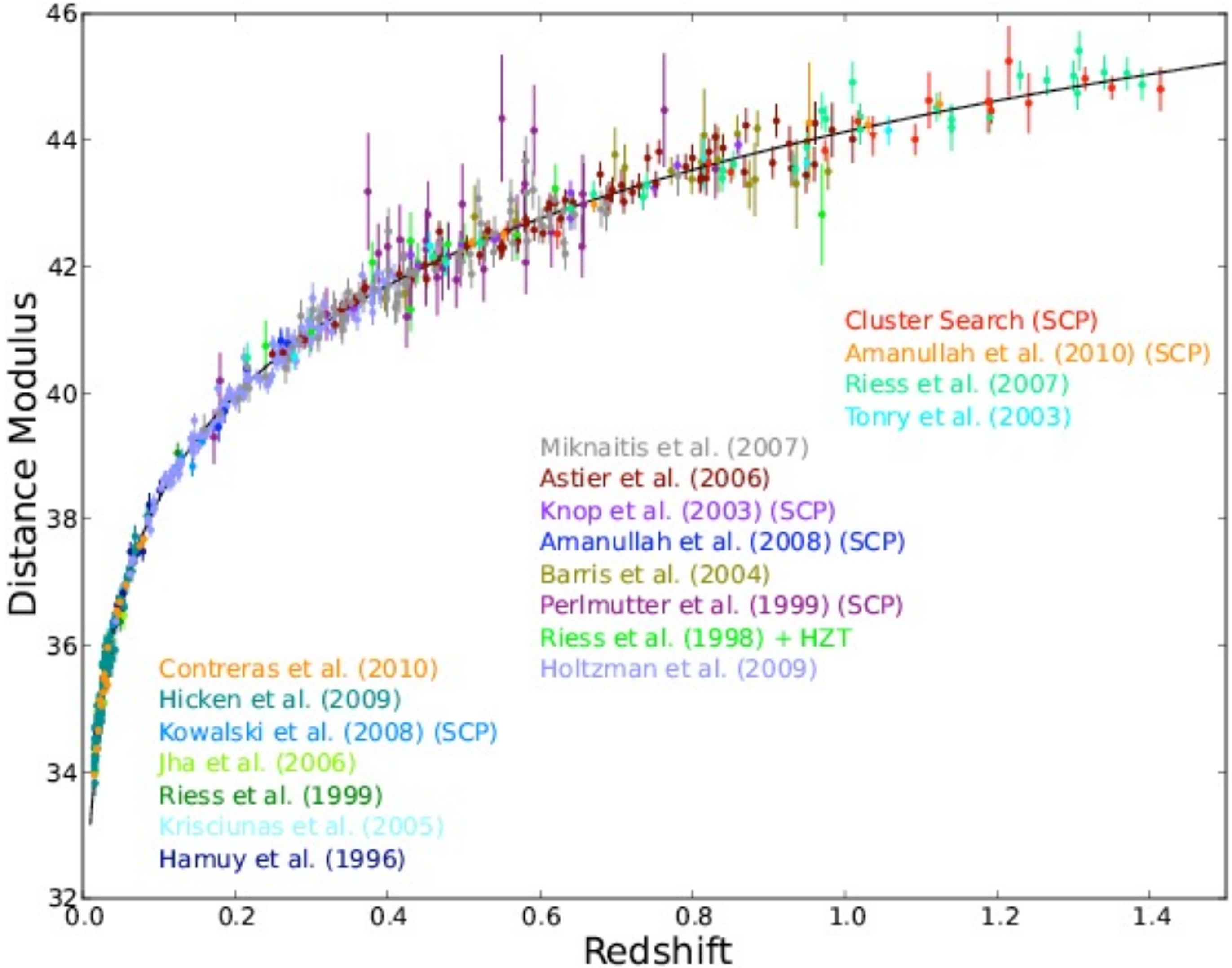
Decouple Ψ and Φ (deformation of time and space) to distinguish between dark energy and modified gravity

We need redshift information

Optimal redshift is $0<z<2$

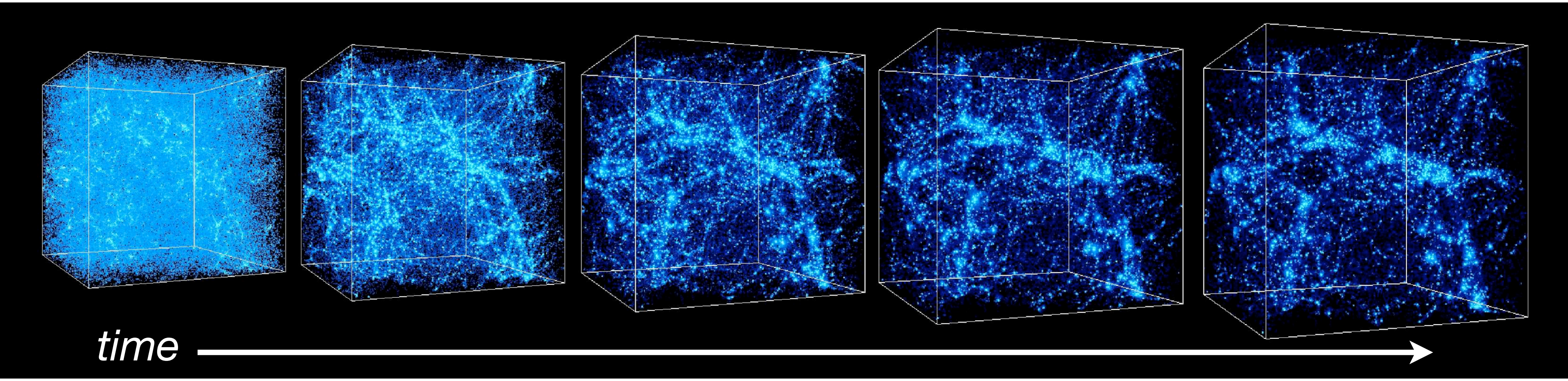
We need (at least) two probes, sensitive to expansion history and/or growth rate and one of them needs to be a relativistic effect

The distance-redshift relation depends on cosmology



Suzuki et al. (2011)

Clustering of matter

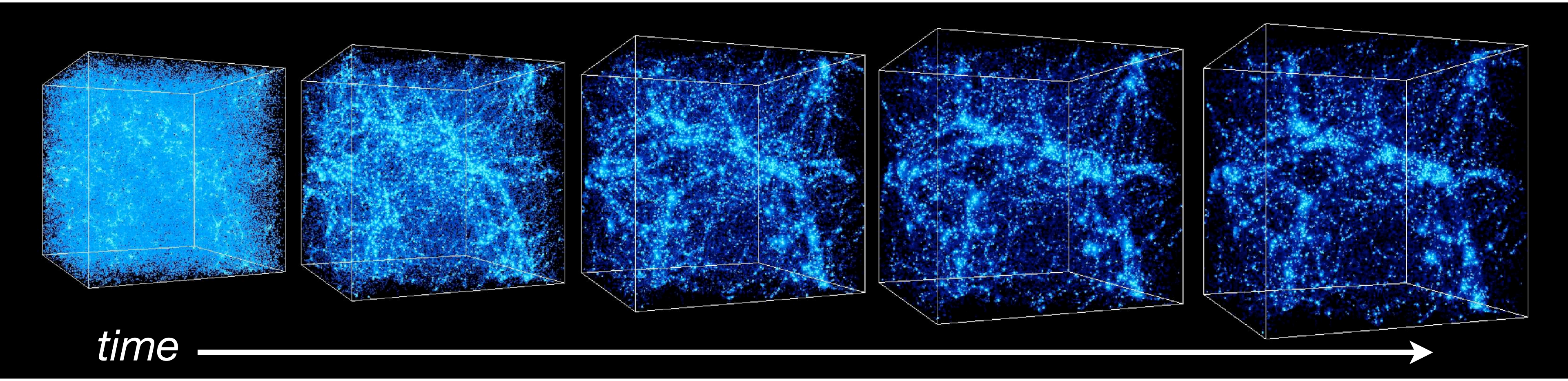


Dark energy changes the expansion history of the Universe and thus modifies the growth of large-scale structures. So does changing gravity on cosmological scales.

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R} = -\frac{8\pi G}{c^2} T_{\mu\nu} + \boxed{\Lambda} g_{\mu\nu}$$

problem here? or here?

Clustering of matter



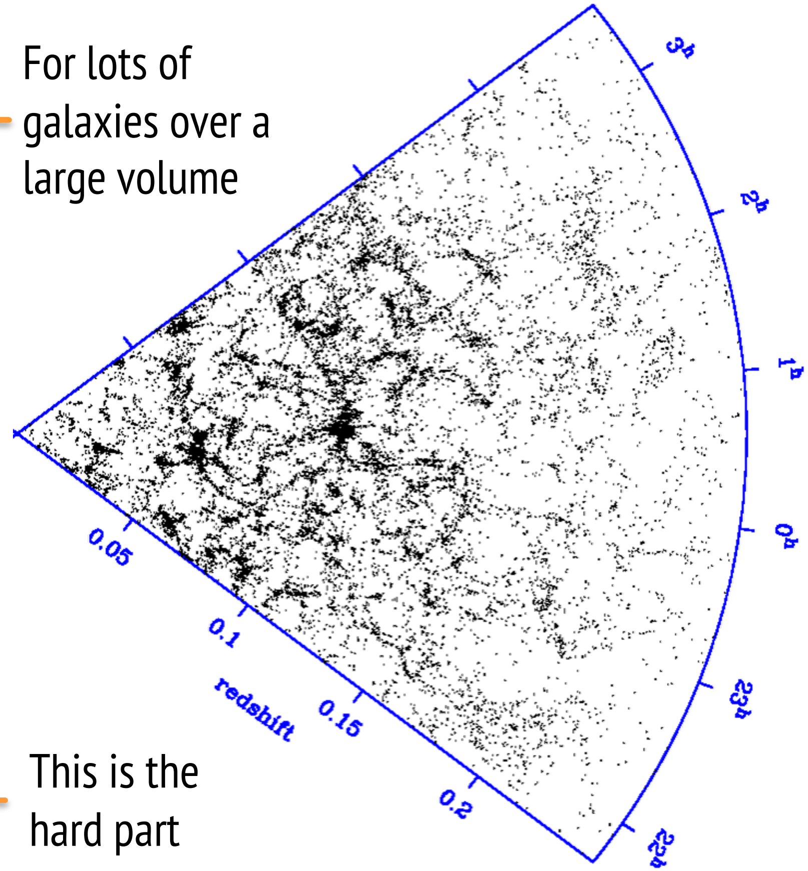
Dark energy changes the expansion history of the Universe and thus modifies the growth of large-scale structures. So does changing gravity on cosmological scales.

The clustering of matter as a function of scale and redshift can be used to determine the underlying cosmology. But how can we study this?

Clustering of galaxies

- Need angular galaxy positions
- Need galaxy redshifts

For lots of galaxies over a large volume



- Need to understand population
  - angular completeness
  - radial completeness
  - radial/angular fluctuations

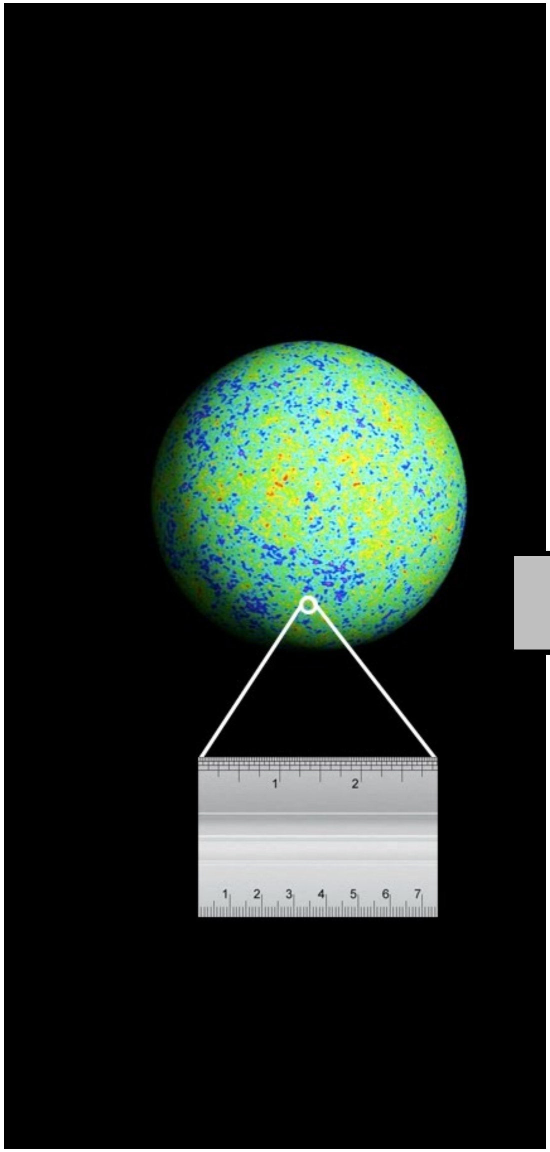
This is the hard part

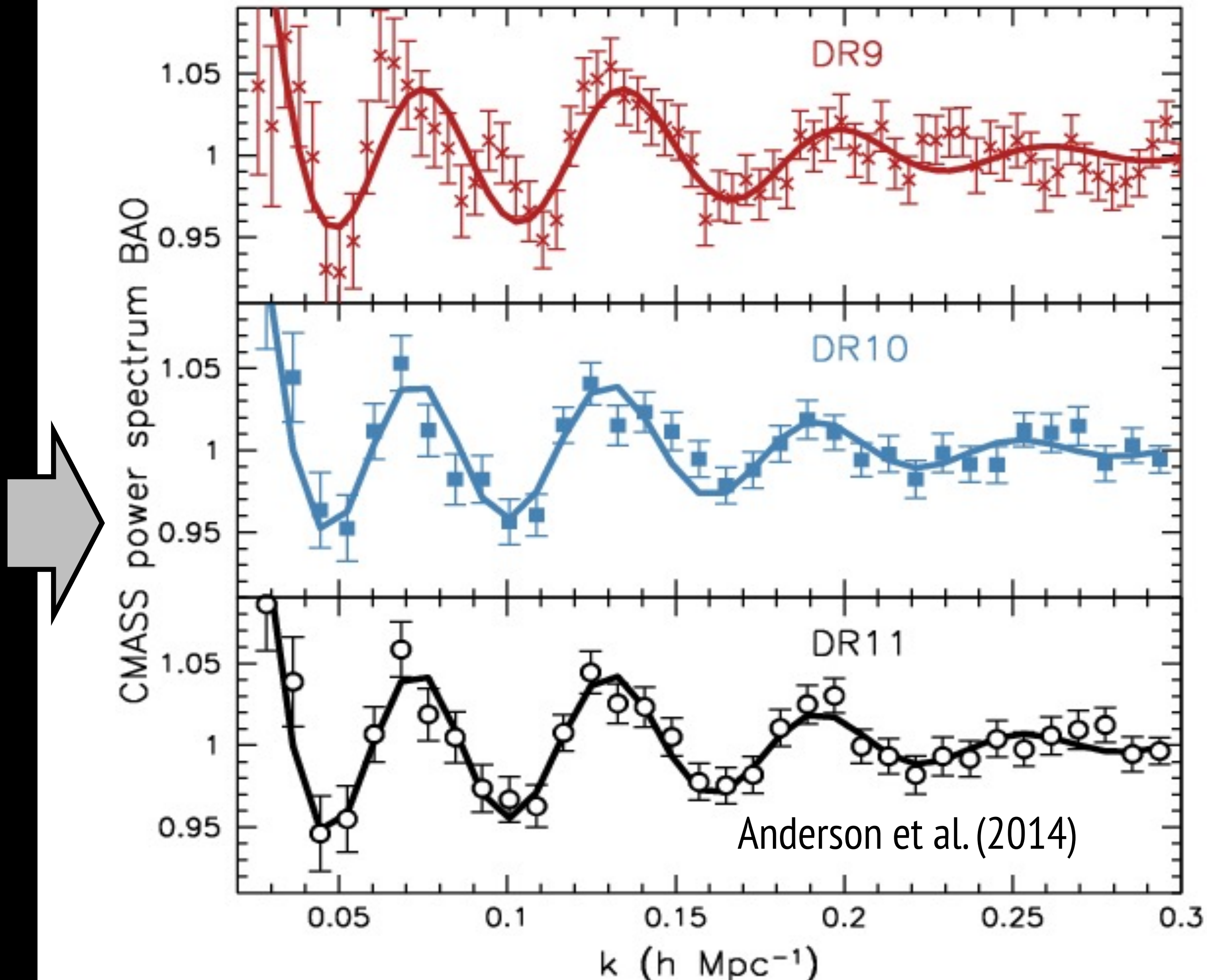
Then we can go from a density field to an over-density field, and measure statistics as a function of scale and redshift.

Light ≠ density

The distribution of galaxies can be used as a proxy for the large-scale mass distribution, but this can yield "biased" results! Large-scale features may be fine...

Baryon Acoustic Oscillations

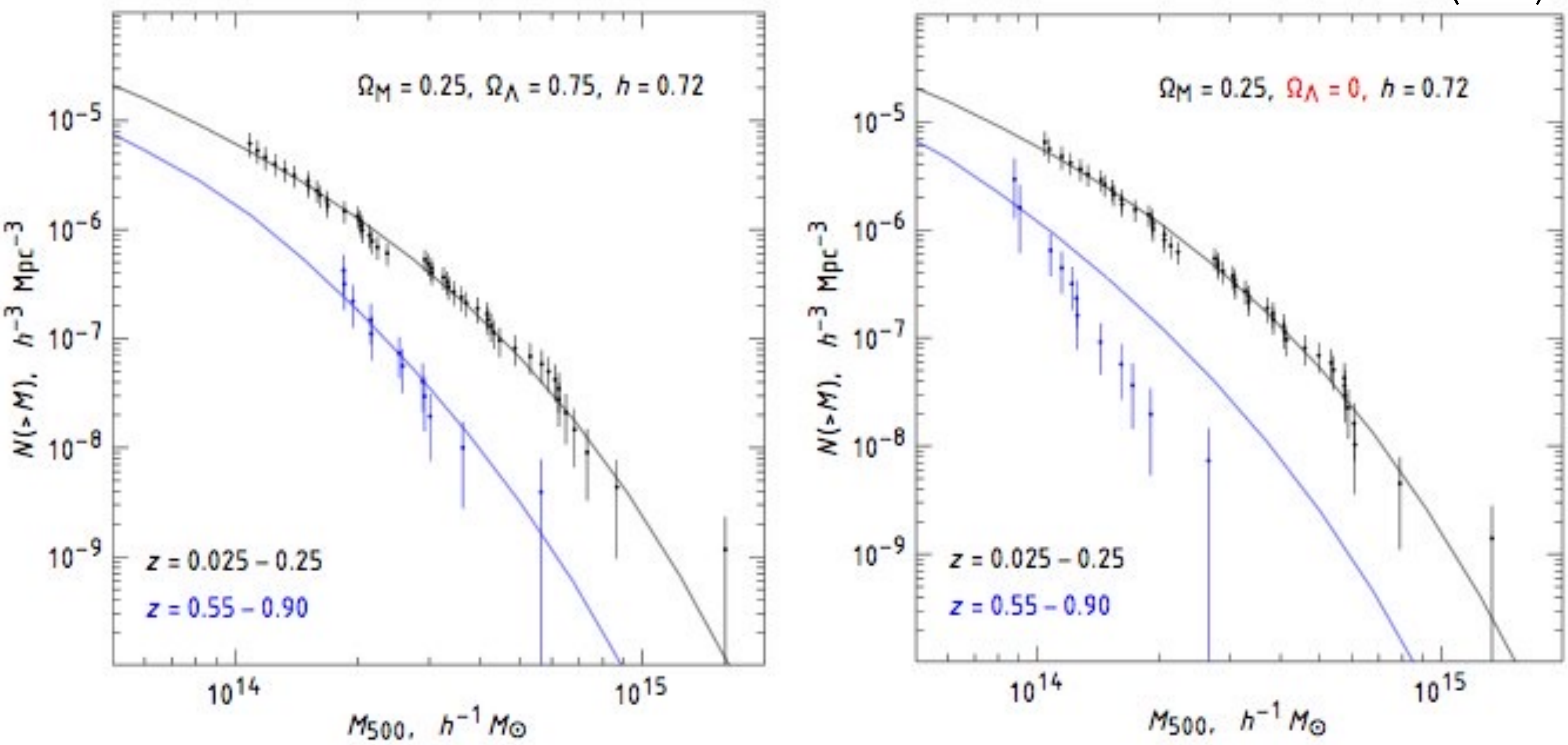




Anderson et al. (2014)

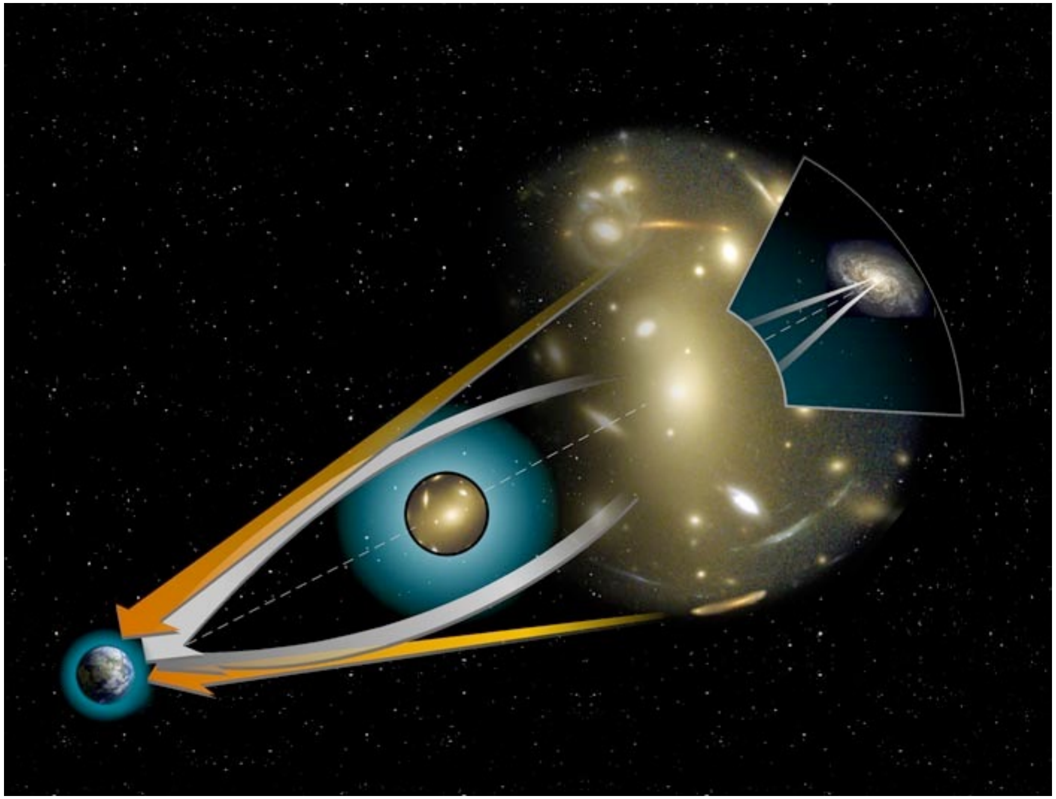
Counting clusters of galaxies

Vikhlinin et al. (2009)



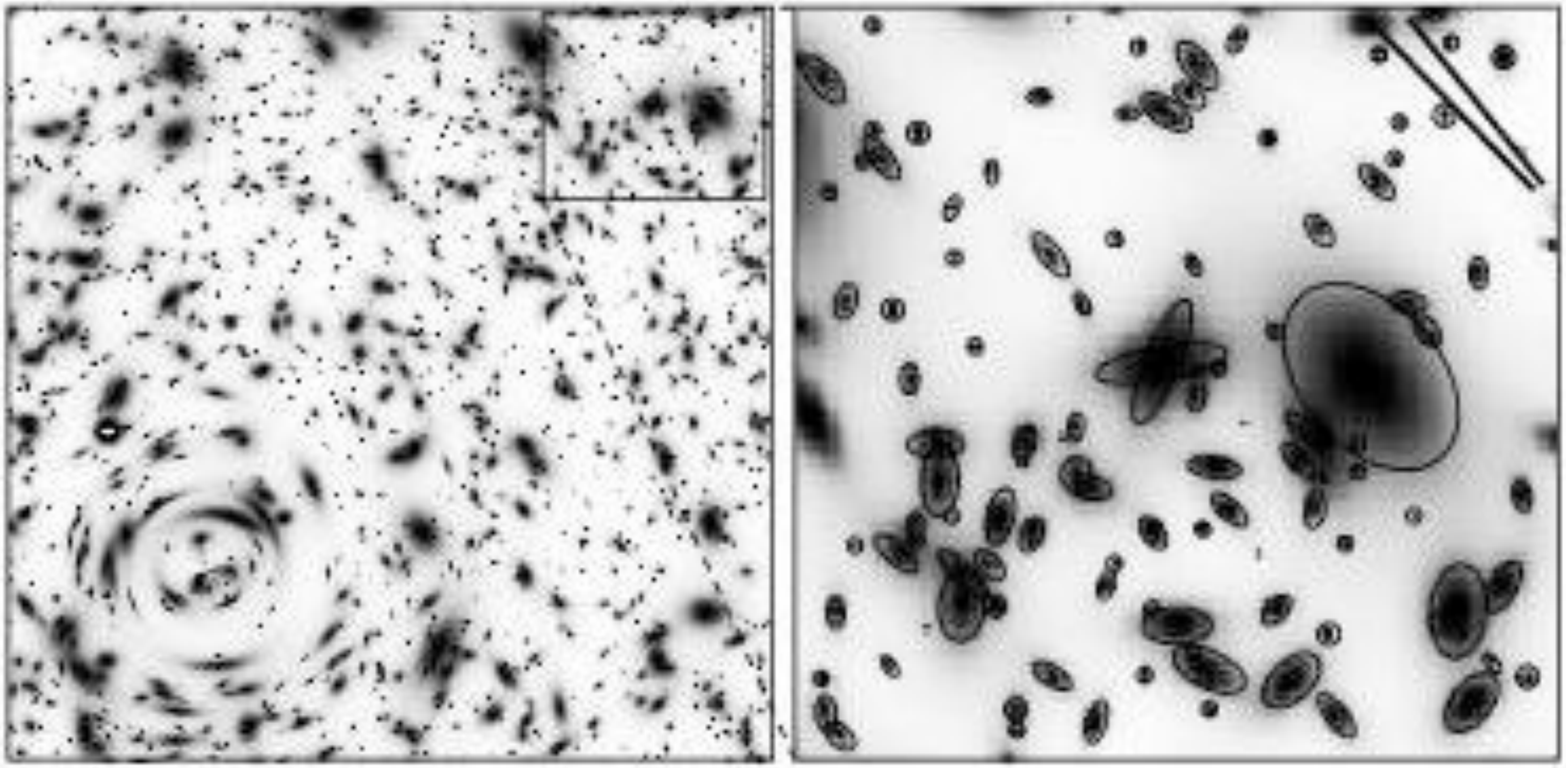
- We need to understand the selection of the clusters
- We need reliable estimates of their masses

Can we "see" the clustering of matter?



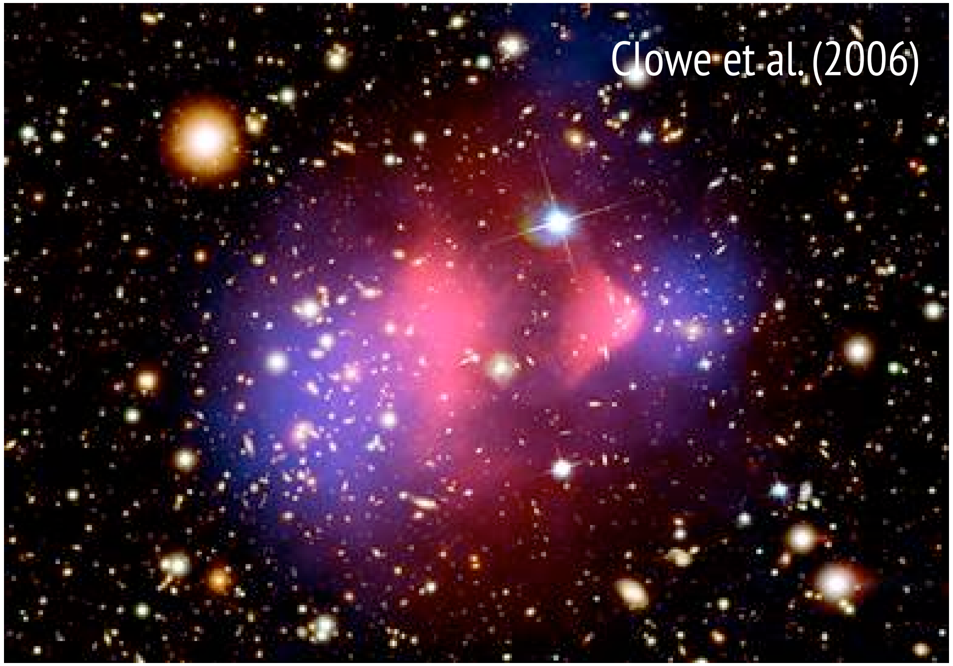
Density fluctuations in the universe affect the propagation of light rays, leading to correlations in the the *observable* shapes of galaxies.

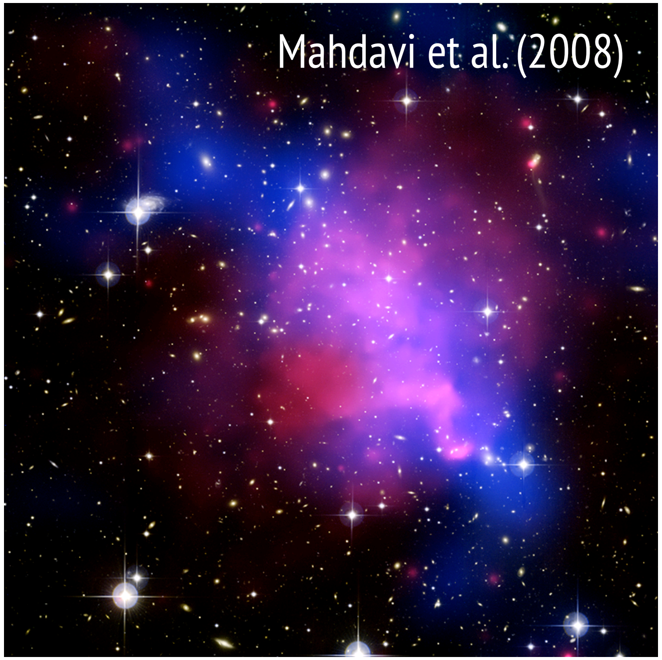
Weak gravitational lensing



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

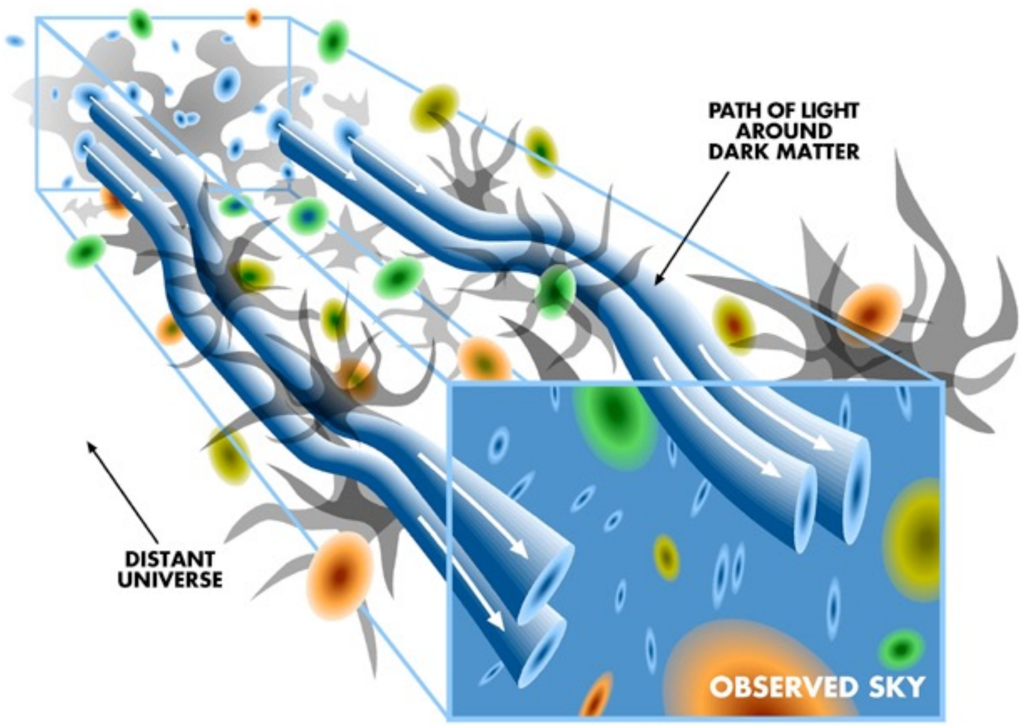
We can see dark matter!





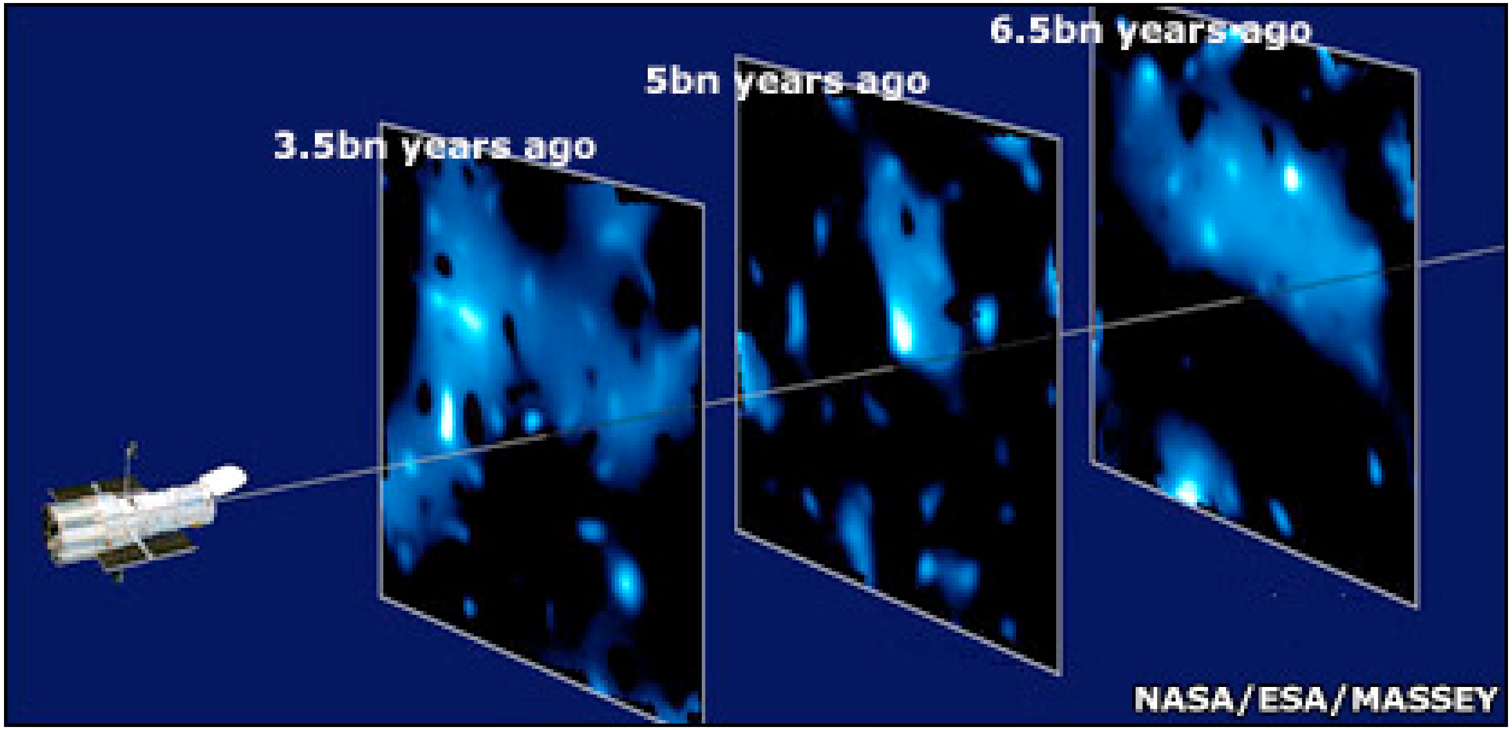
By averaging the shapes of many galaxies it is possible to reconstruct the (projected) matter distribution, independent of the dynamical state of the object of interest (e.g. a cluster of galaxies)

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.

How to proceed?

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

Distances:

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

expansion history only

Growth of structure:

- clustering of matter
- counting galaxy clusters

expansion history
+
modified gravity

Which probes should we use?

A "perfect" match

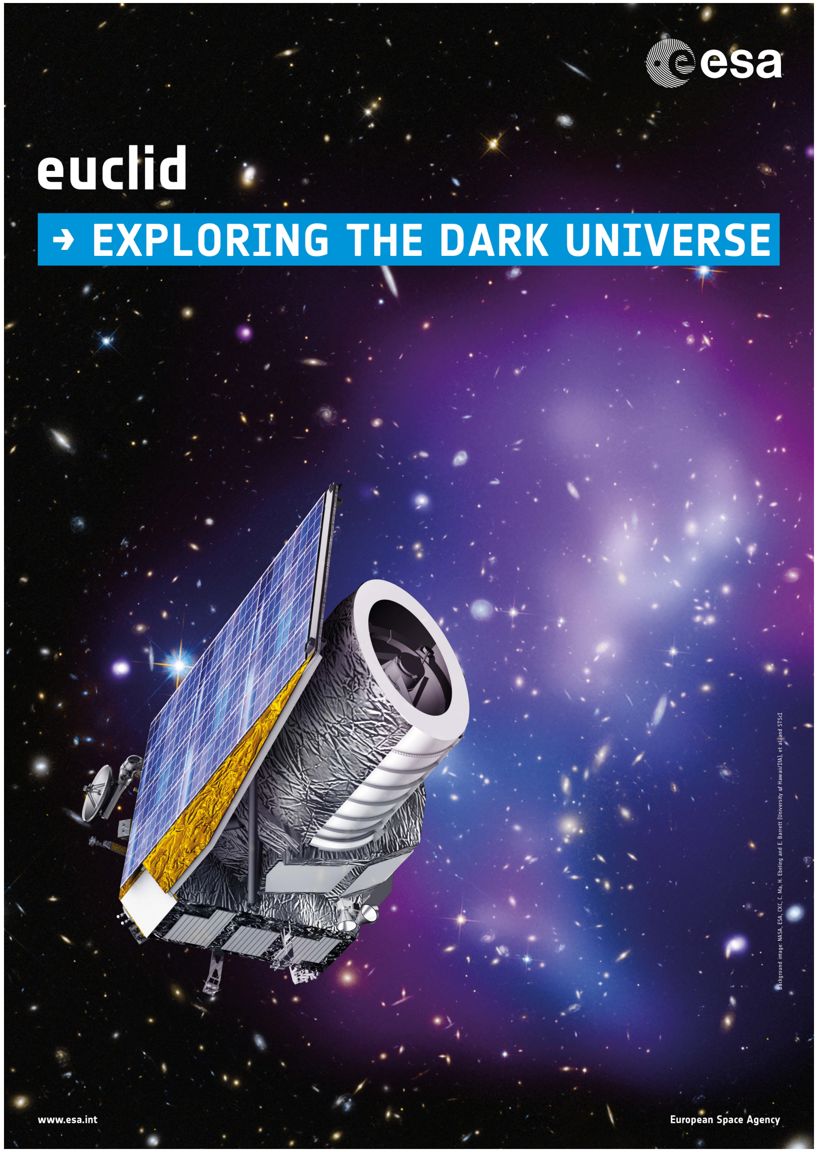
Weak lensing (WL): two-point 3-dimensional cosmic shear measurements over $0<z<2$ probes distribution of all matter, expansion history, growth factor, scalar potentials $\Phi+\Psi$.

Requires: accurate shapes of galaxies + multiband photometry to do tomography. To probe $0<z<2$ reliable photo-z's need both optical and NIR data. Accurate shapes require HST-like quality images.

Galaxy clustering (GC) : two-point 3-dimensional position measurements over the redshift range $0<z<2$ probes clustering history of galaxies induced by gravity, Ψ , exponent of the growth factor γ, $H(z)$).

Requires 3-dimensional distribution of galaxies from spectroscopic redshifts

Euclid: a satellite designed to do weak lensing



Euclid has been selected by ESA for a launch in 2022 to L2 from where it will survey the sky for 6 years. Its primary cosmology probes, which drive the design, are:

- Weak lensing by large scale structure
- Clustering of galaxies

Euclid will image the

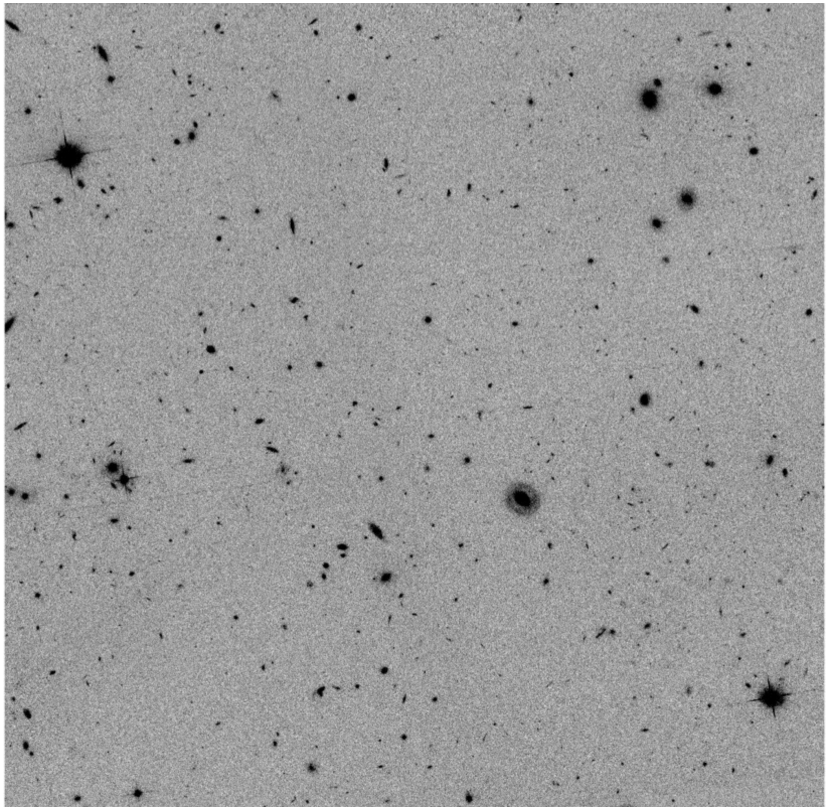
- best 1/3 of the sky (15000 deg^2)
- similar resolution at HST in optical
- NIR imaging in 3 filters (YJH)
- Images for $2x10^9$ galaxies

and carry out an unprecedented (slitless) redshift survey over the same area that is imaged with

- NIR spectra for ~$3.5x10^7$ galaxies (0.9<z<1.8)
- Spectral resolution R~350 (for 0.5" source)

Euclid: a HD view of the sky

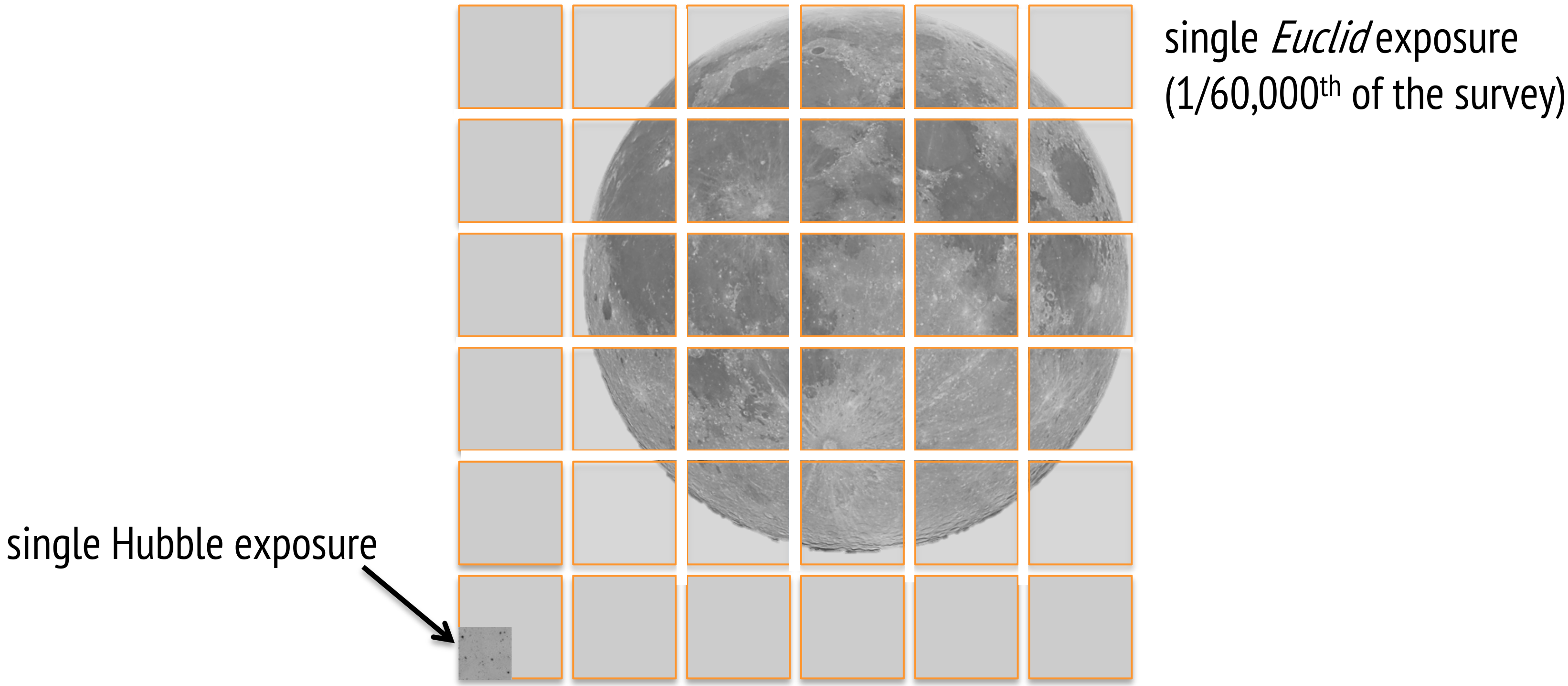
To measure the amount of stretching we need to take sharp pictures. The Hubble Space Telescope has been taking sharp pictures of the Universe for the past 25 years, but the camera is too small ...



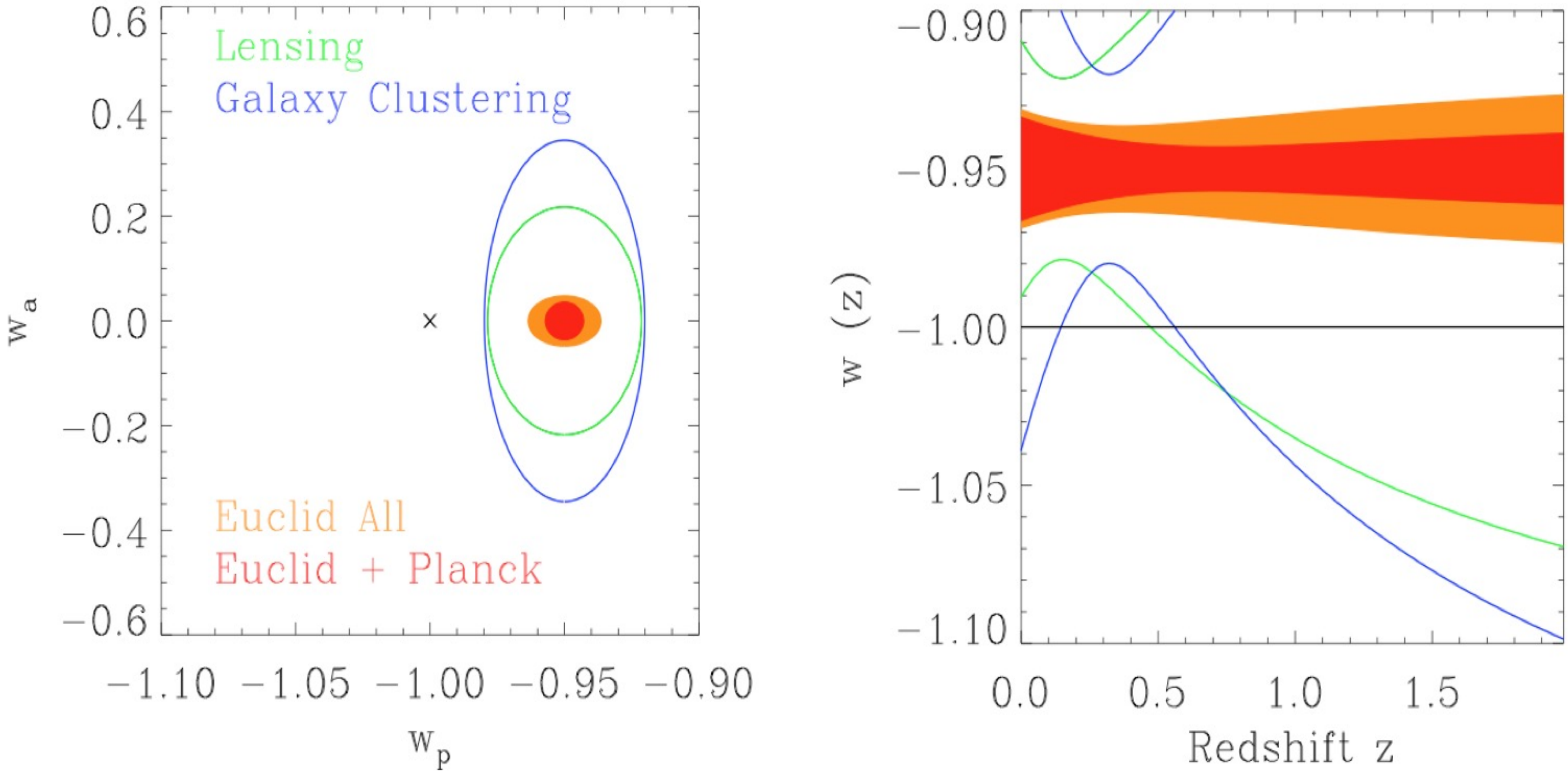
Single Hubble exposure

Euclid: a HD 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.



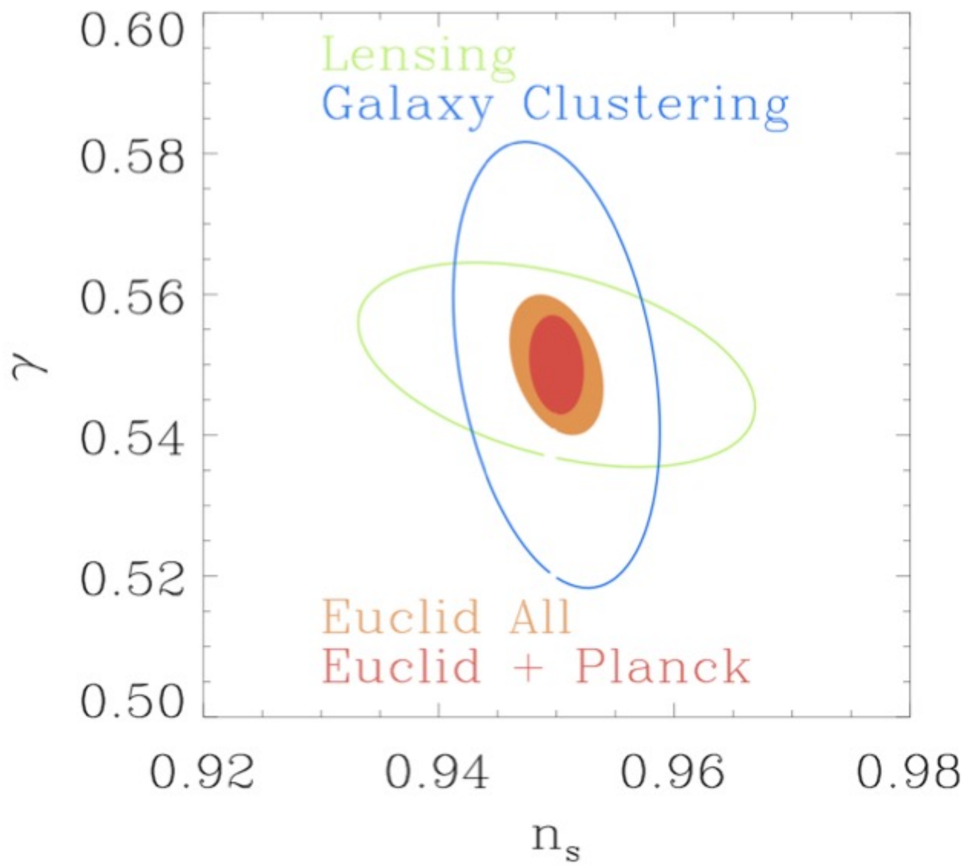
Euclid: a cosmology machine



When all probes are combined Euclid will constrain the dark energy equation of state and its evolution with unprecedented precision.

Euclid: a cosmology machine

ΛCDM+GR predict γ=0.55

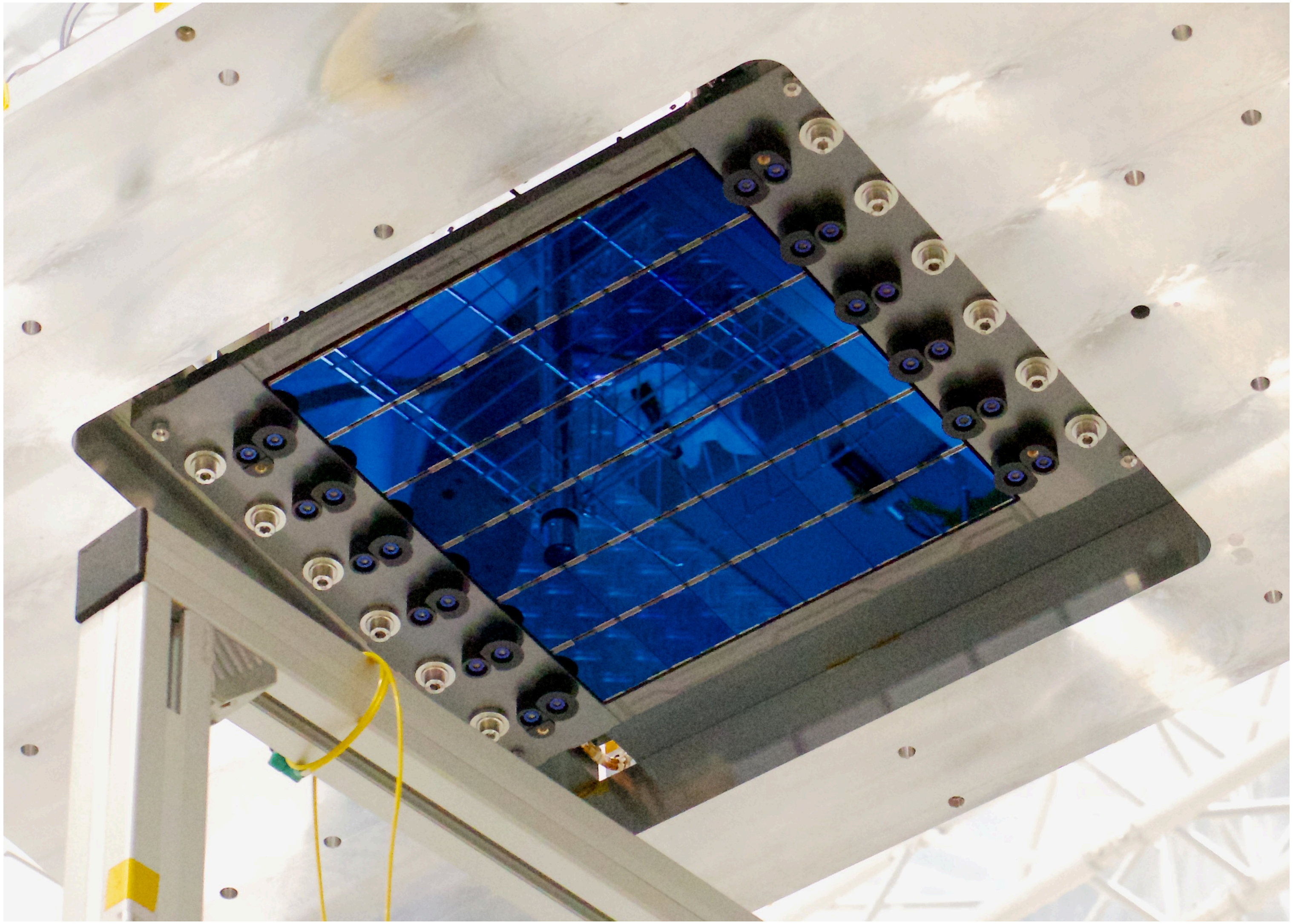


We can also use the small scale clustering to constrain modified gravity theories: Euclid will achieve an error of $\Delta\gamma$~0.02, testing GR on cosmological scales.

Hardware is being tested

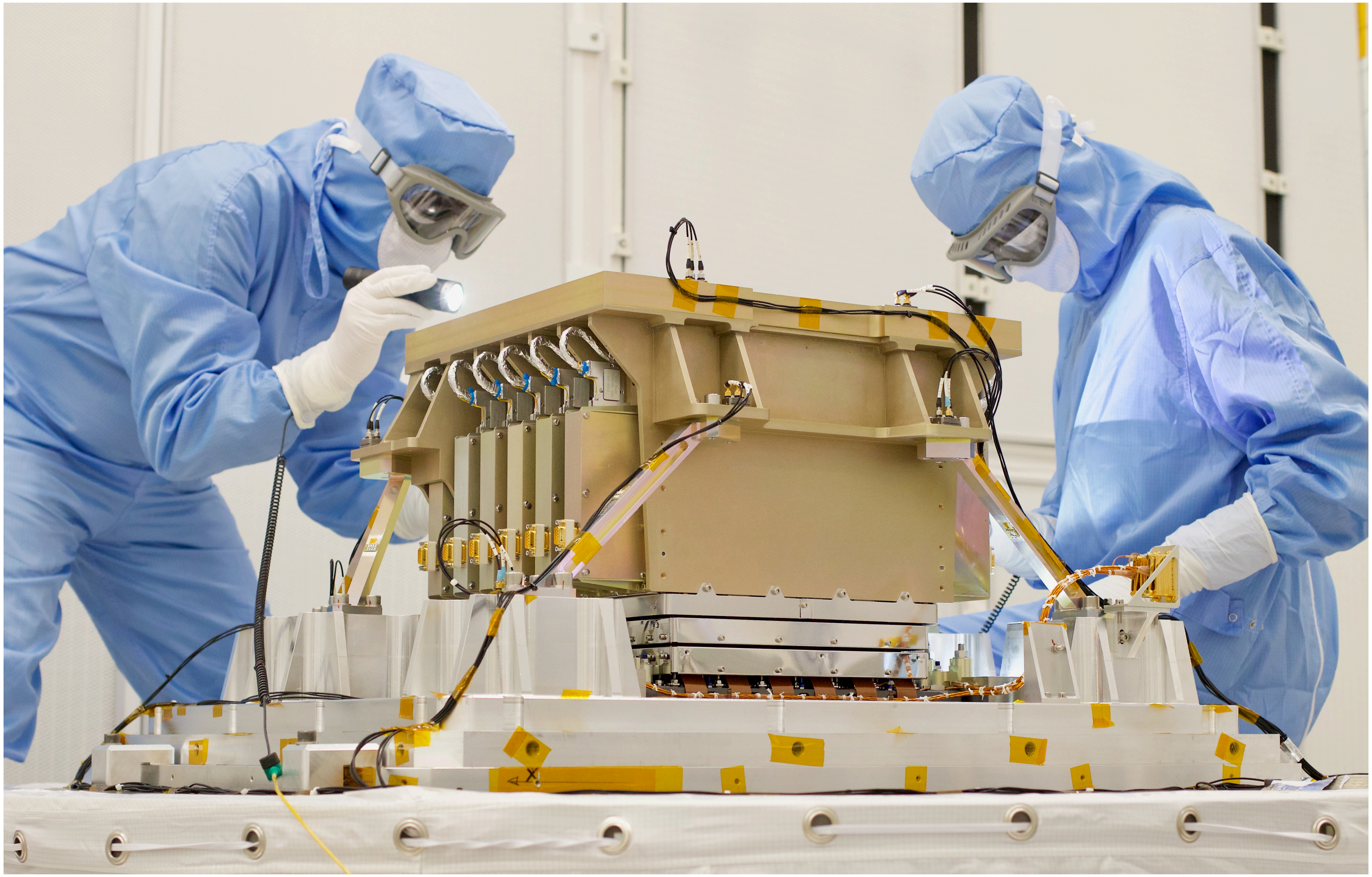
The detectors and electronics for the VIS camera have been built and were tested in the UK in a clean environment.

Hardware is being tested



Credit: VIS team and CEA

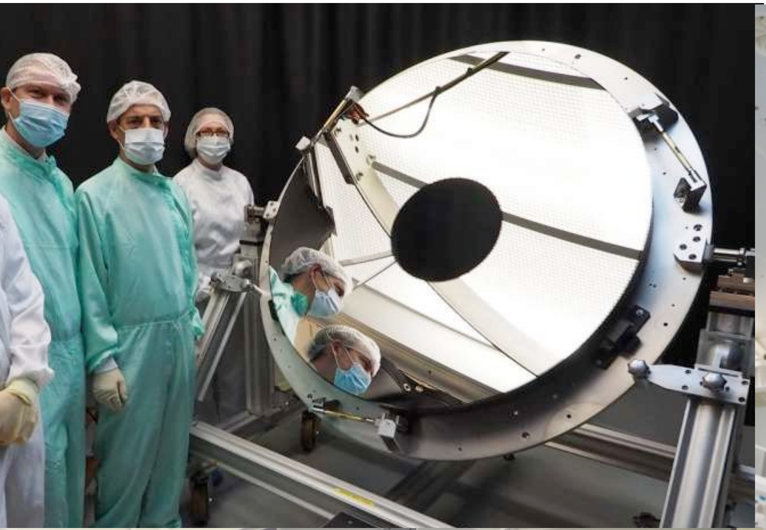
Hardware is being tested

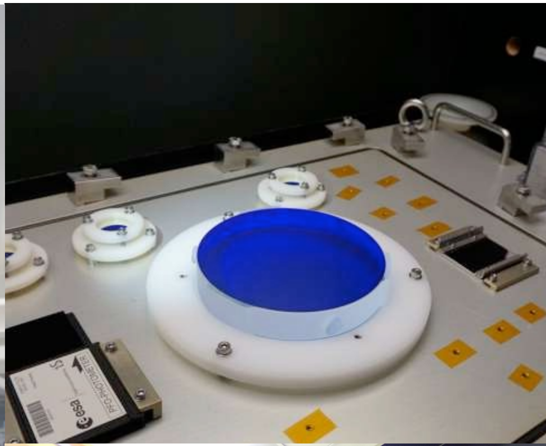


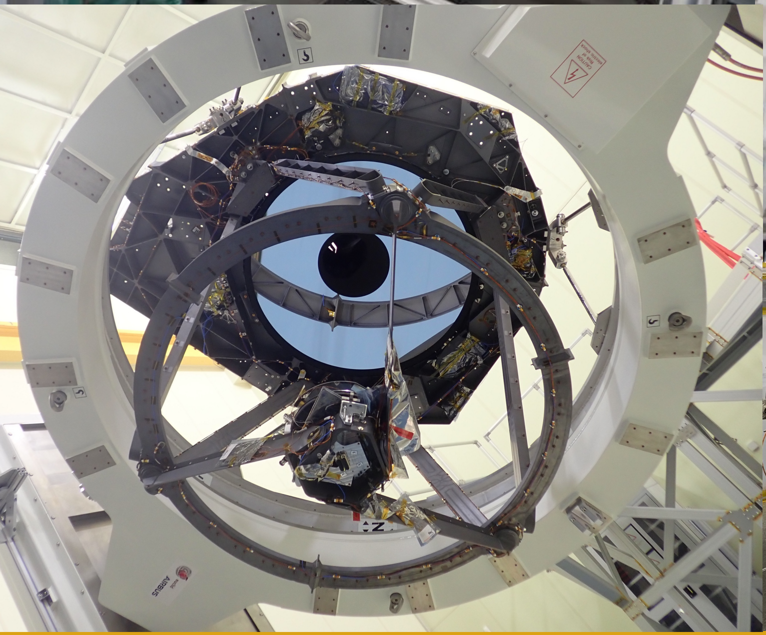
Credit: VIS team and CEA

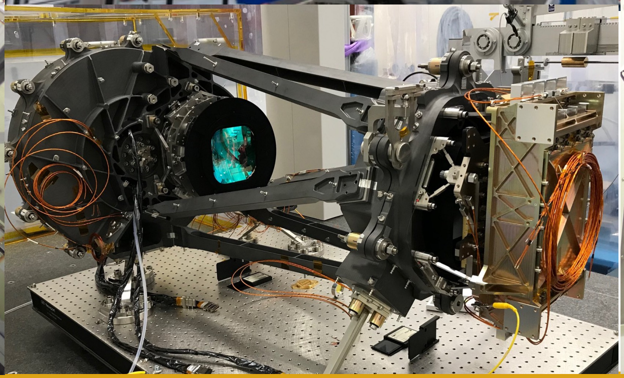
Euclid STM entering Thermal Vacuum chamber

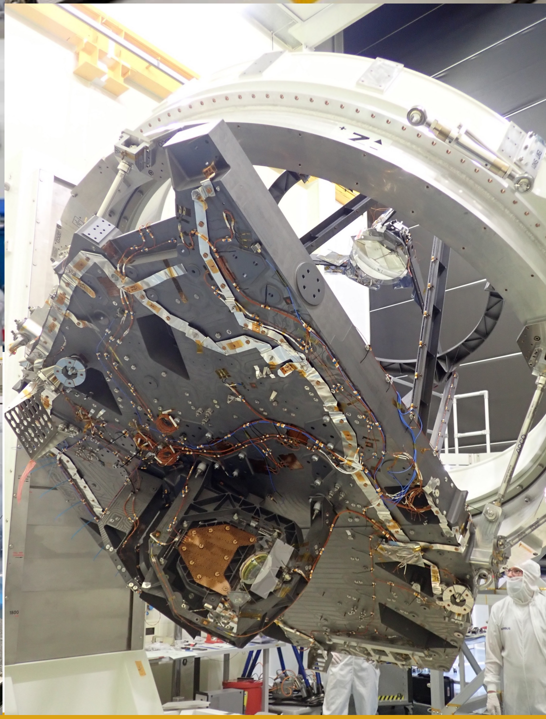
Euclid is (in parts) real!





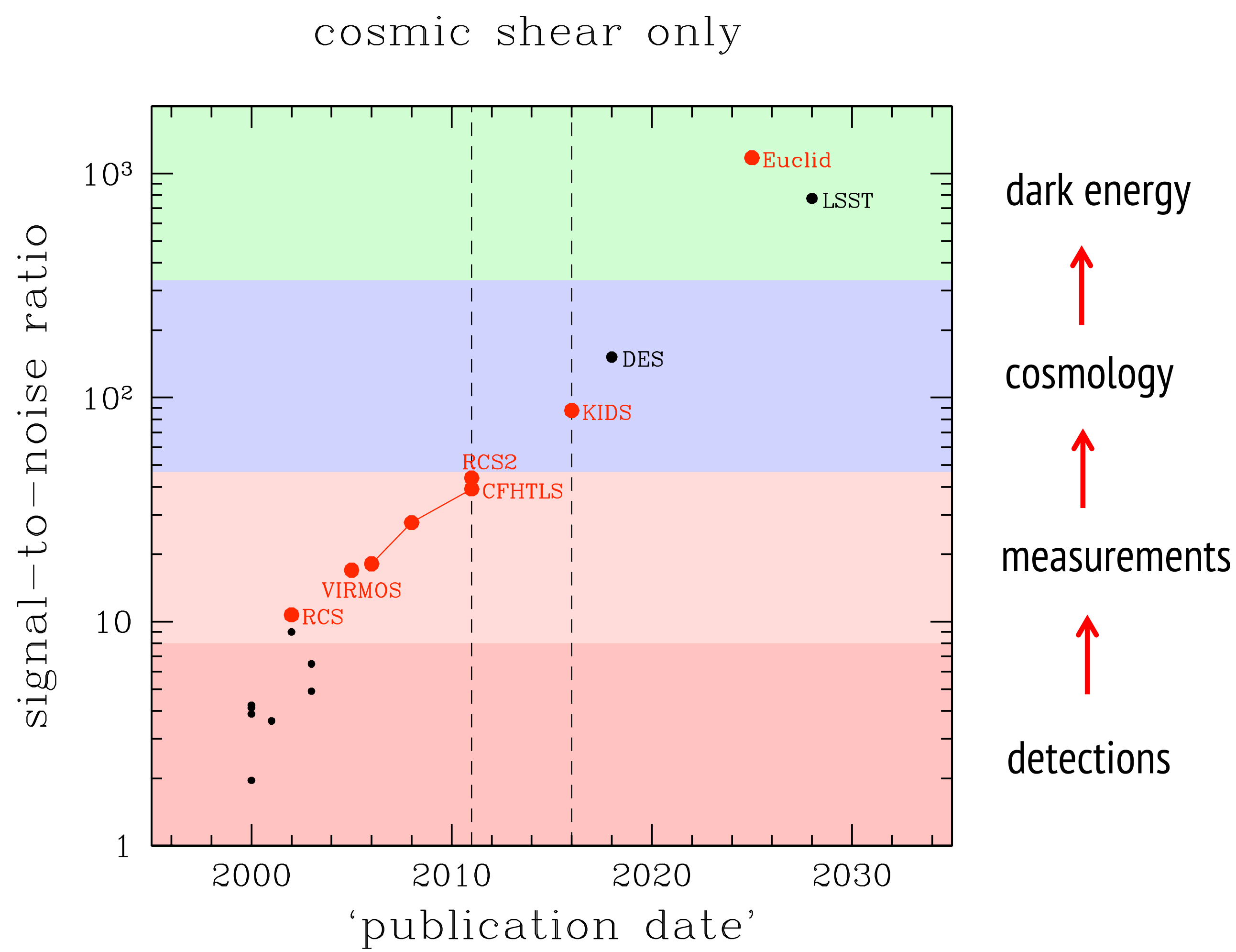






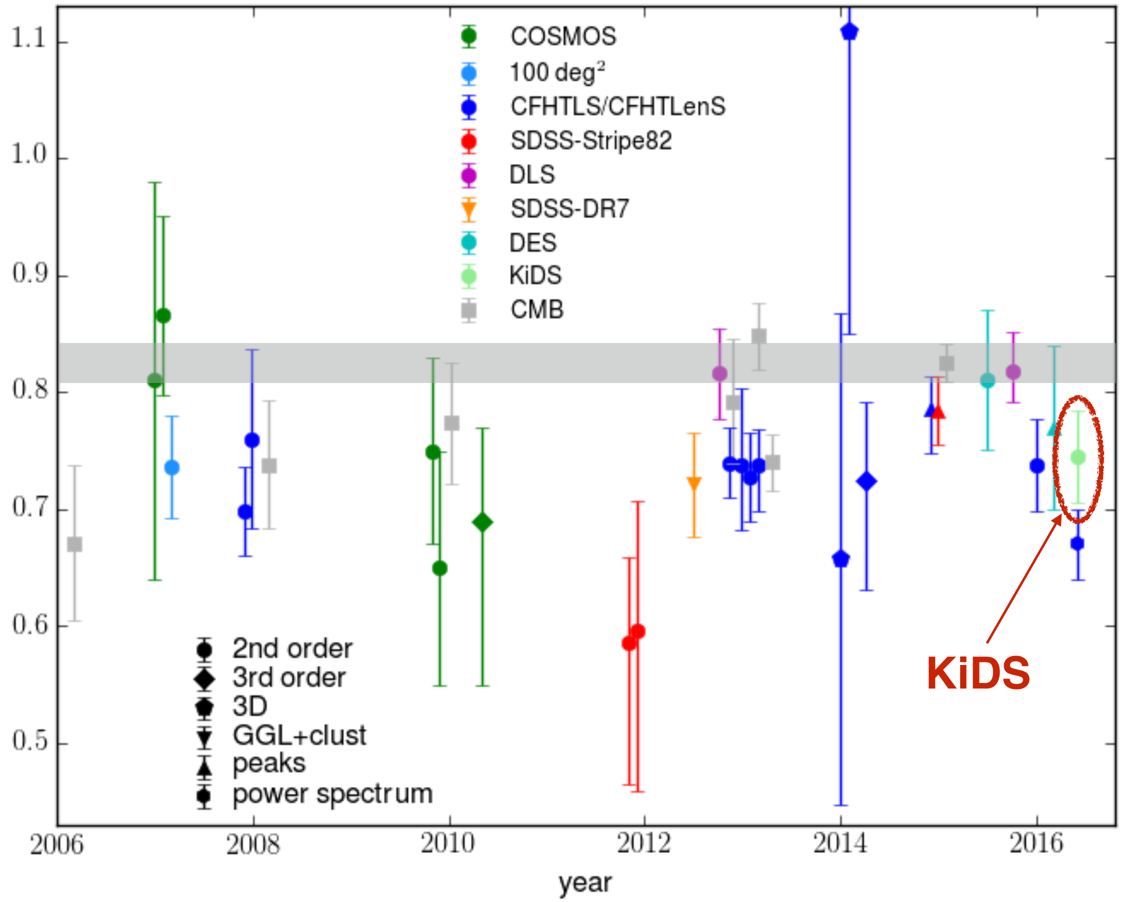
The challenge: Precision ≠ Accuracy

The precision is increasing...



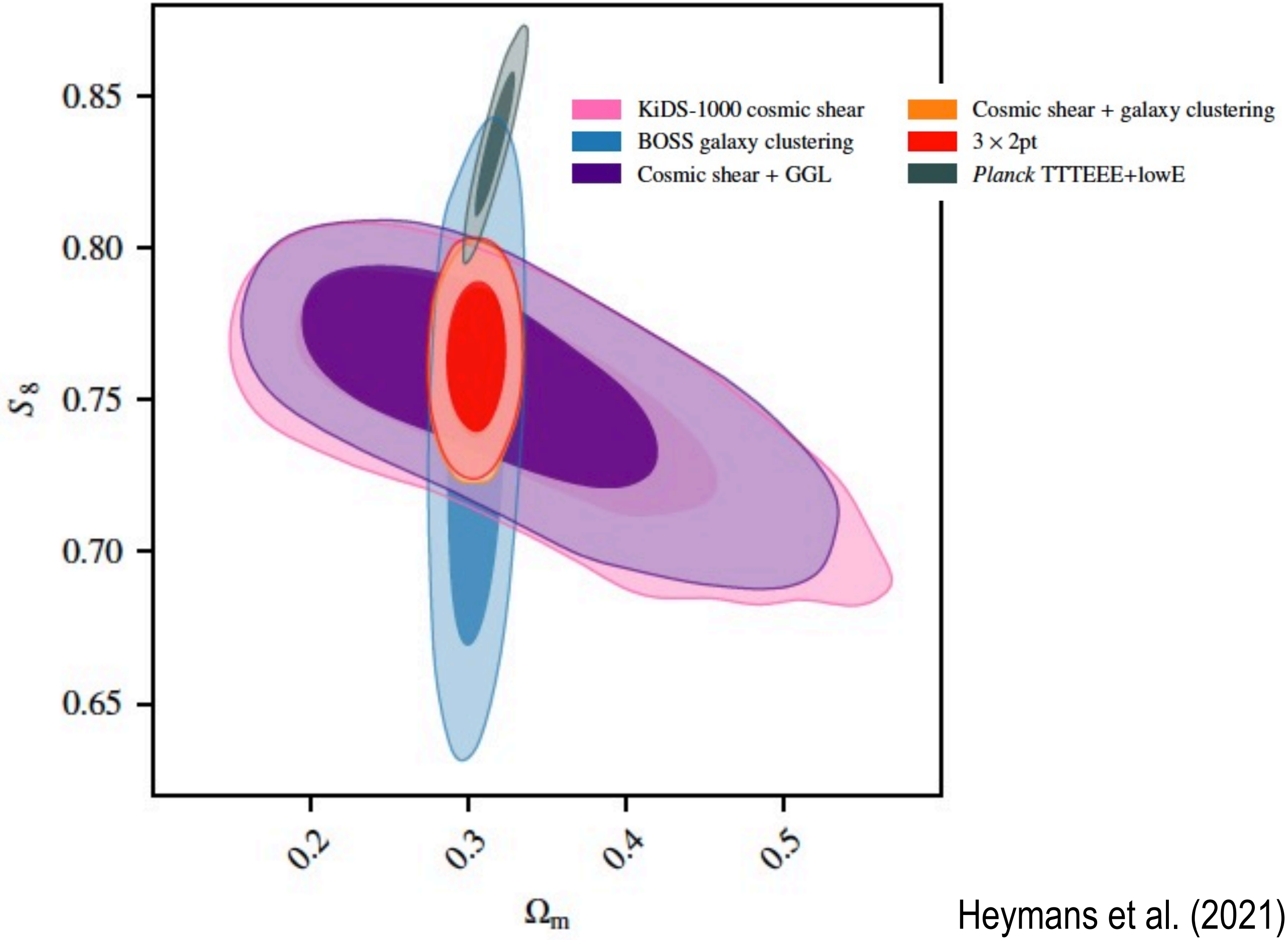
… but the uncertainties barely changed!

$$S_8 \equiv \sigma_8 \sqrt{\frac{\Omega_m}{0.3}}$$



Kilbinger et al. (2015; updated)

This is changing: results from KiDS-100



Heymans et al. (2021)

Everything matters

Is it Gaussian?

Do we need data compression?

$$\ln \mathcal{L}(\mathrm{p}) = -\frac{1}{2}\sum_{ij}[D_i - T_i(\mathrm{p})]\, C^{-1}{}_{ij}\, [D_j - T_j(\mathrm{p})]$$

Data vector:

shapes
redshifts
PSF errors
...

Covariance

cosmology
survey properties
...

Theory vector:

cosmology
new physics!
baryon physics
intrinsic alignments
...

Precision ≠ Accuracy

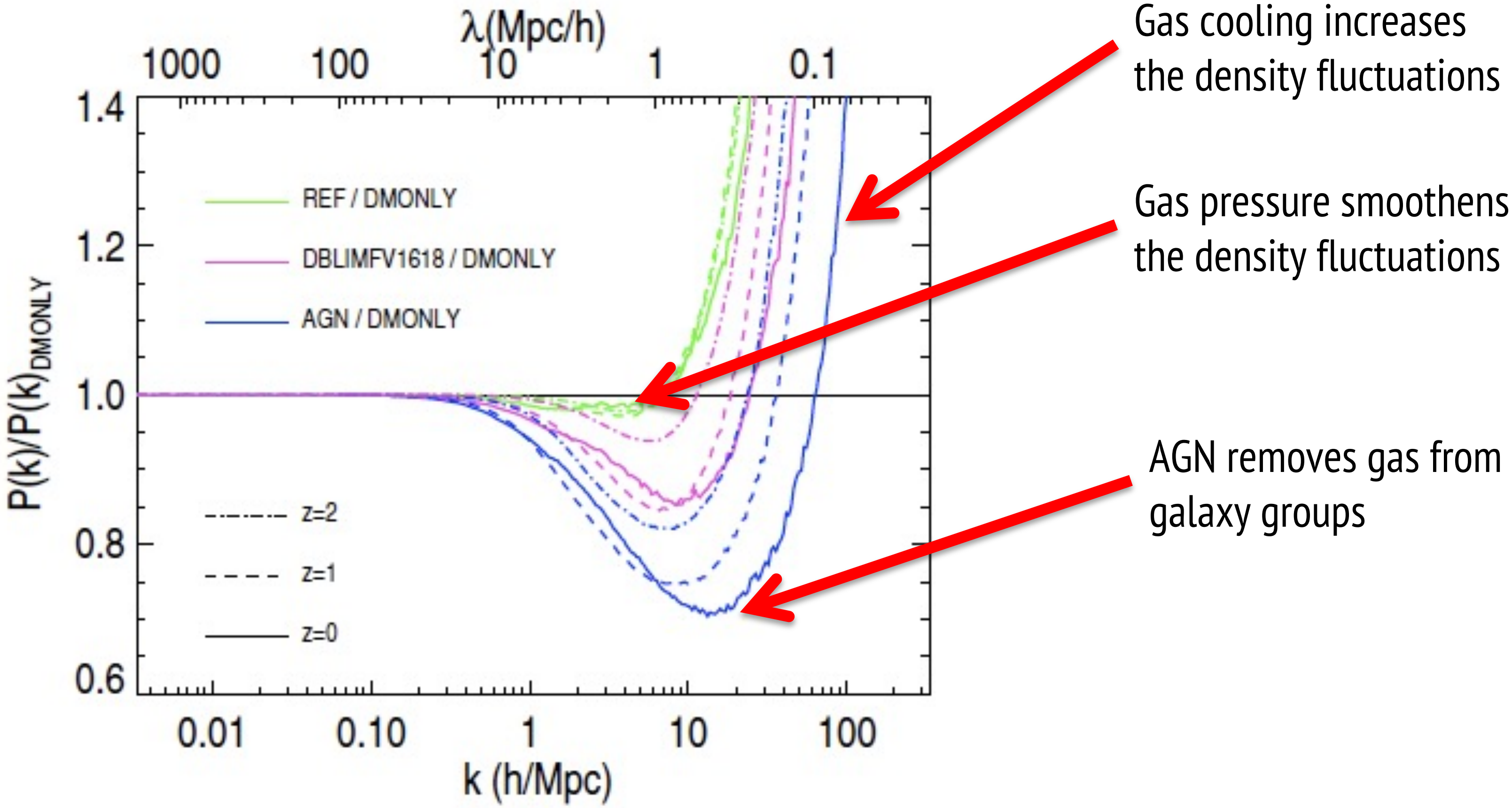
For accurate cosmology we need:

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

The complications we have to deal with:

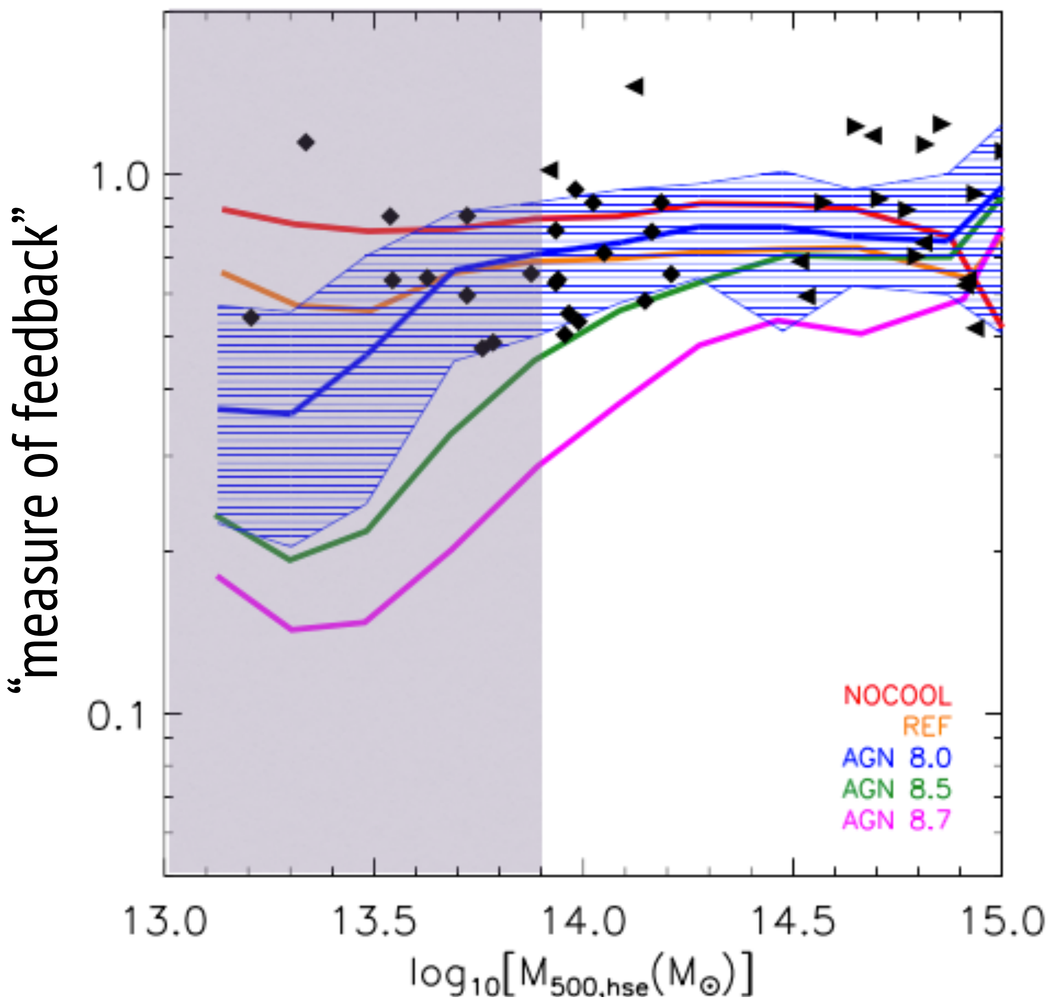
- Observational distortions are larger than the signal
- Galaxies are too faint for large spectroscopic surveys
- Sensitive to non-linear structure formation

Baryonic physics changes the power spectrum



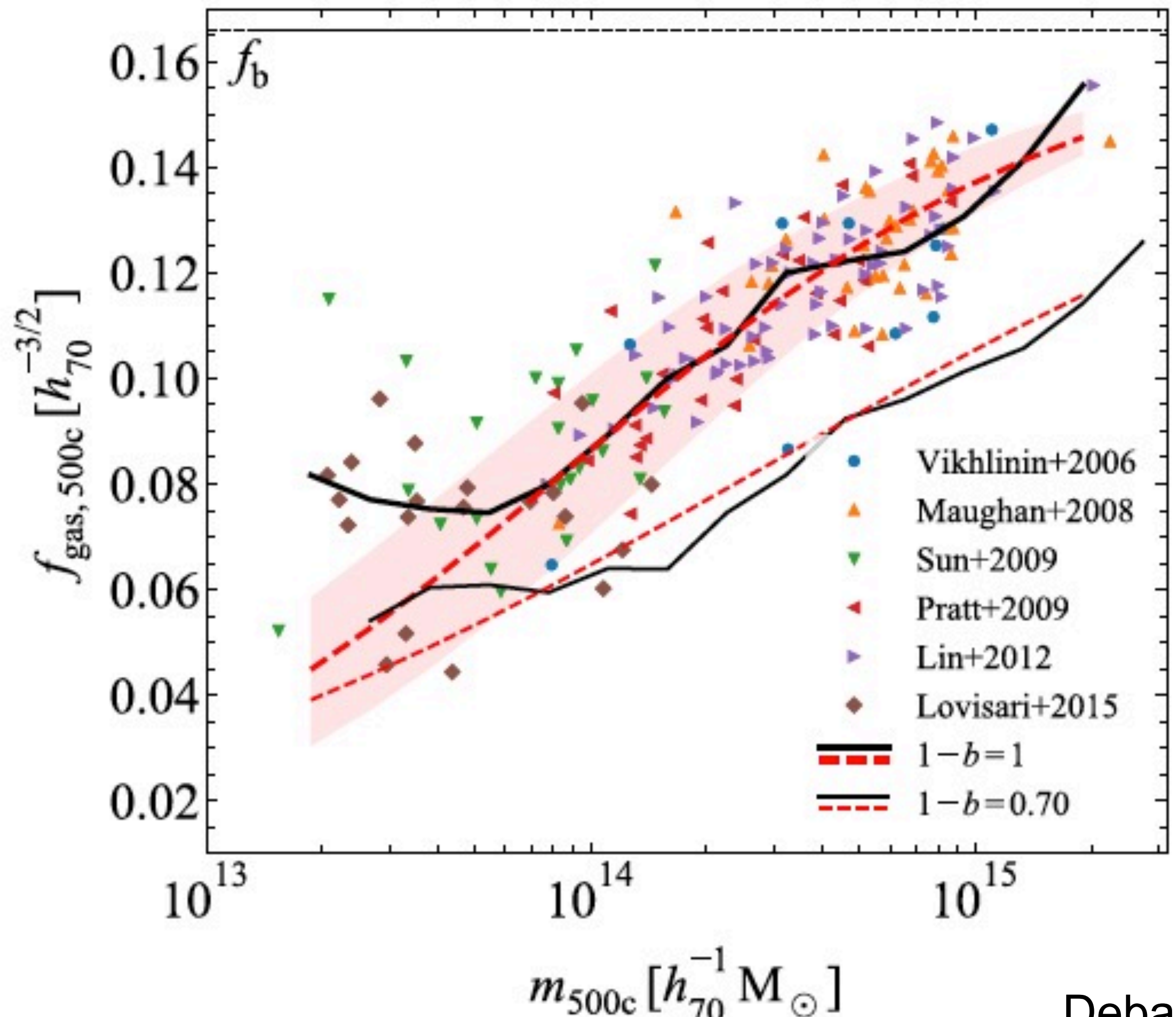
Semboloni et al. (2011)

We need to study galaxy groups



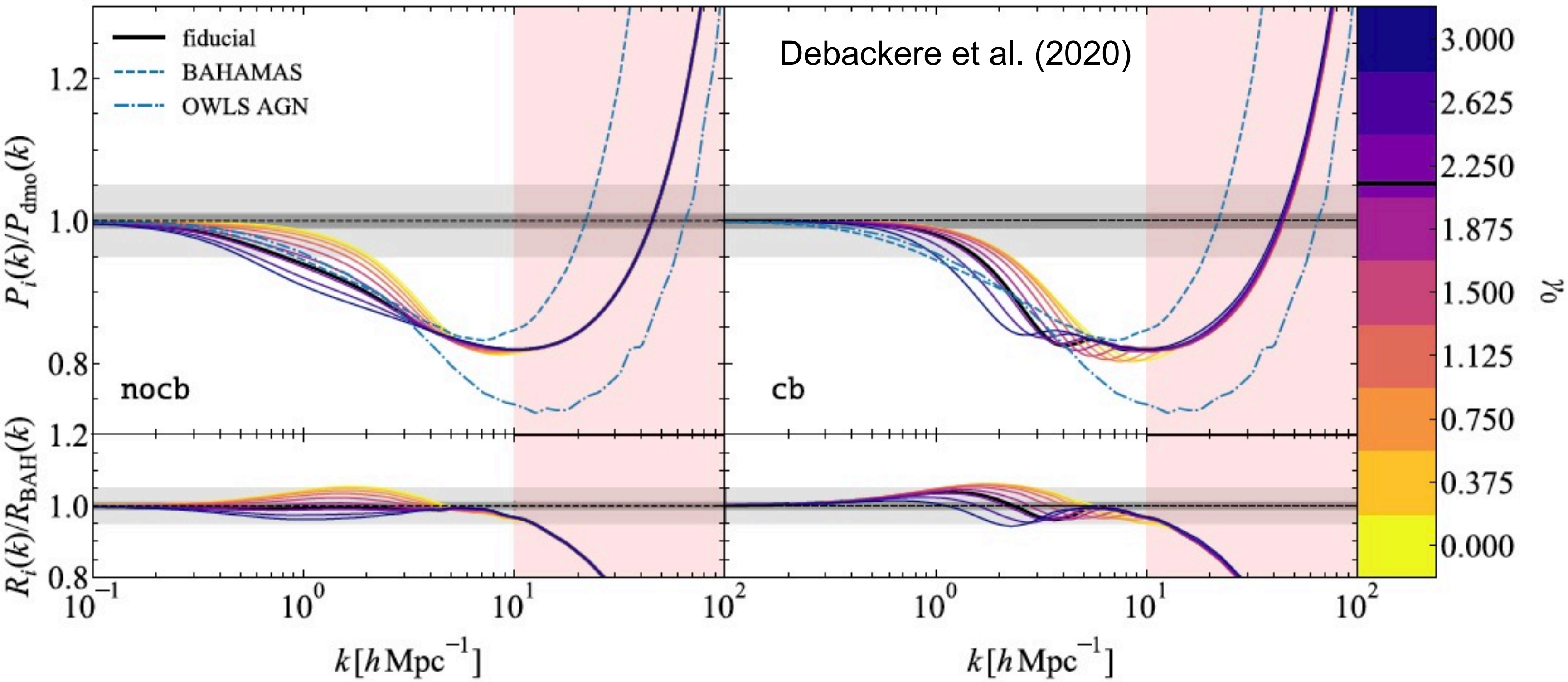
Le Brun et al. (2014)

We see the effects of feedback in groups



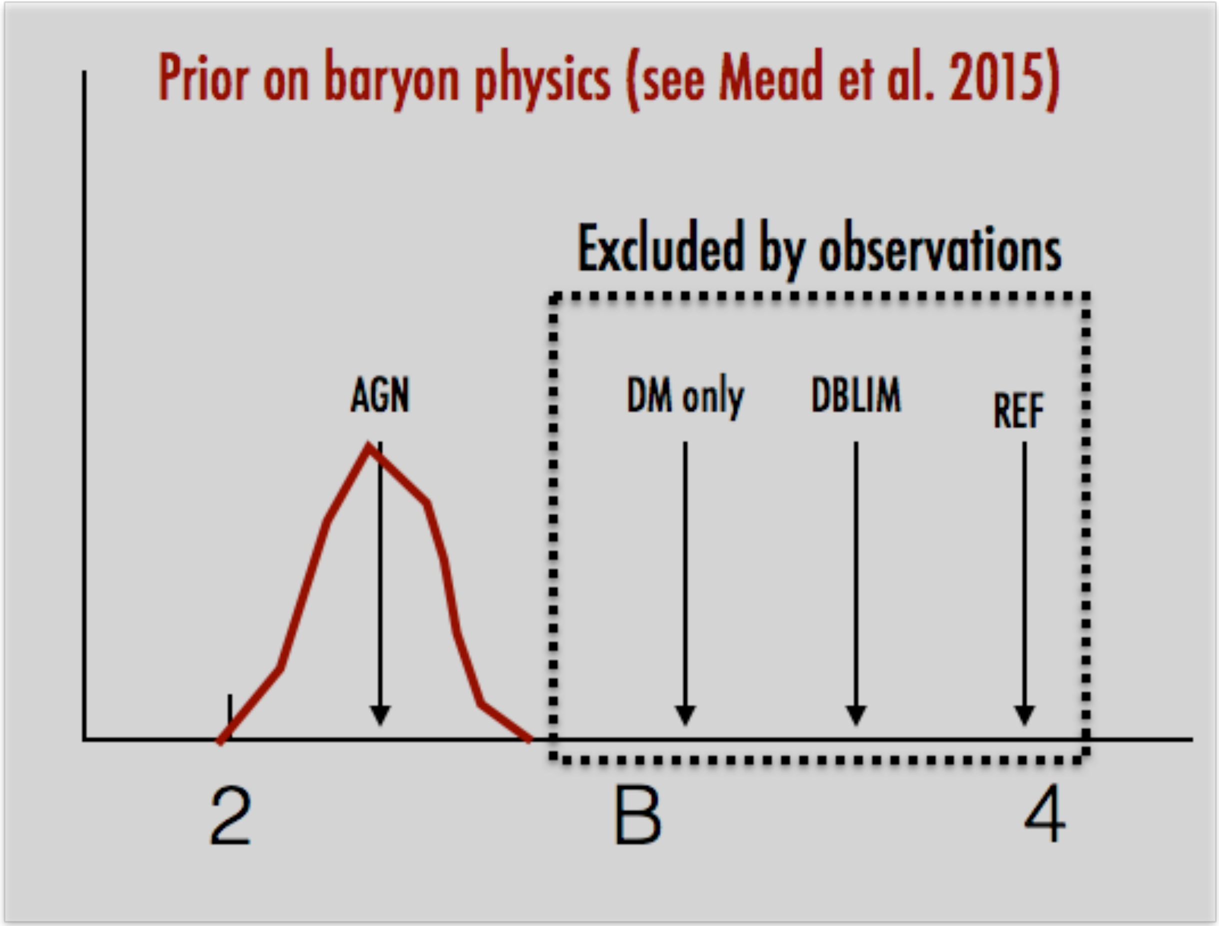
Debackere et al. (2020)

This has to change the matter power spectrum



We need to improve observational constraints on the gas distribution in the outskirts of clusters and groups ➞ test hydrosimulation constraints.

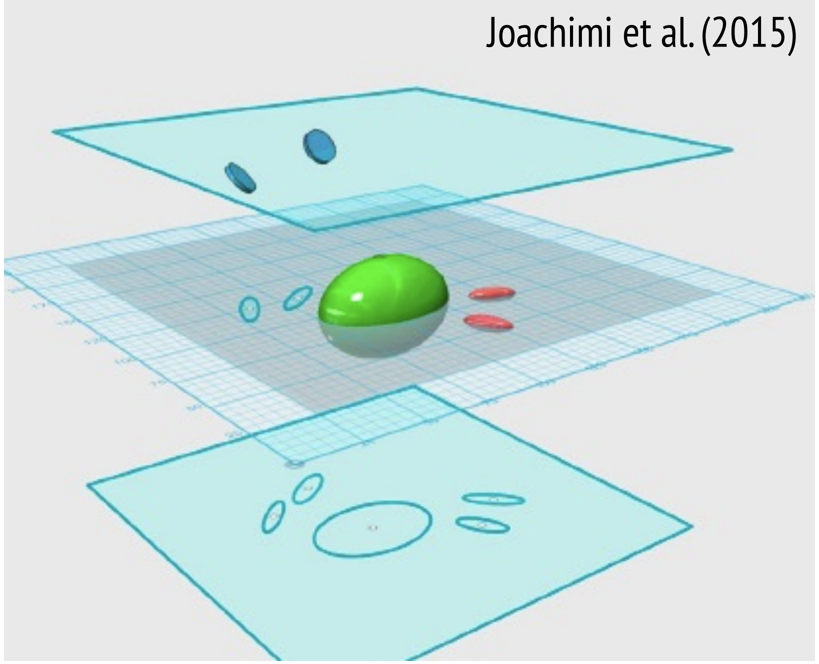
Improved feedback priors



Debackere et al. (2020): X-ray observations can help restrict the parameter space, but the next challenge is to understand the distribution of baryons in the outskirts of halos.

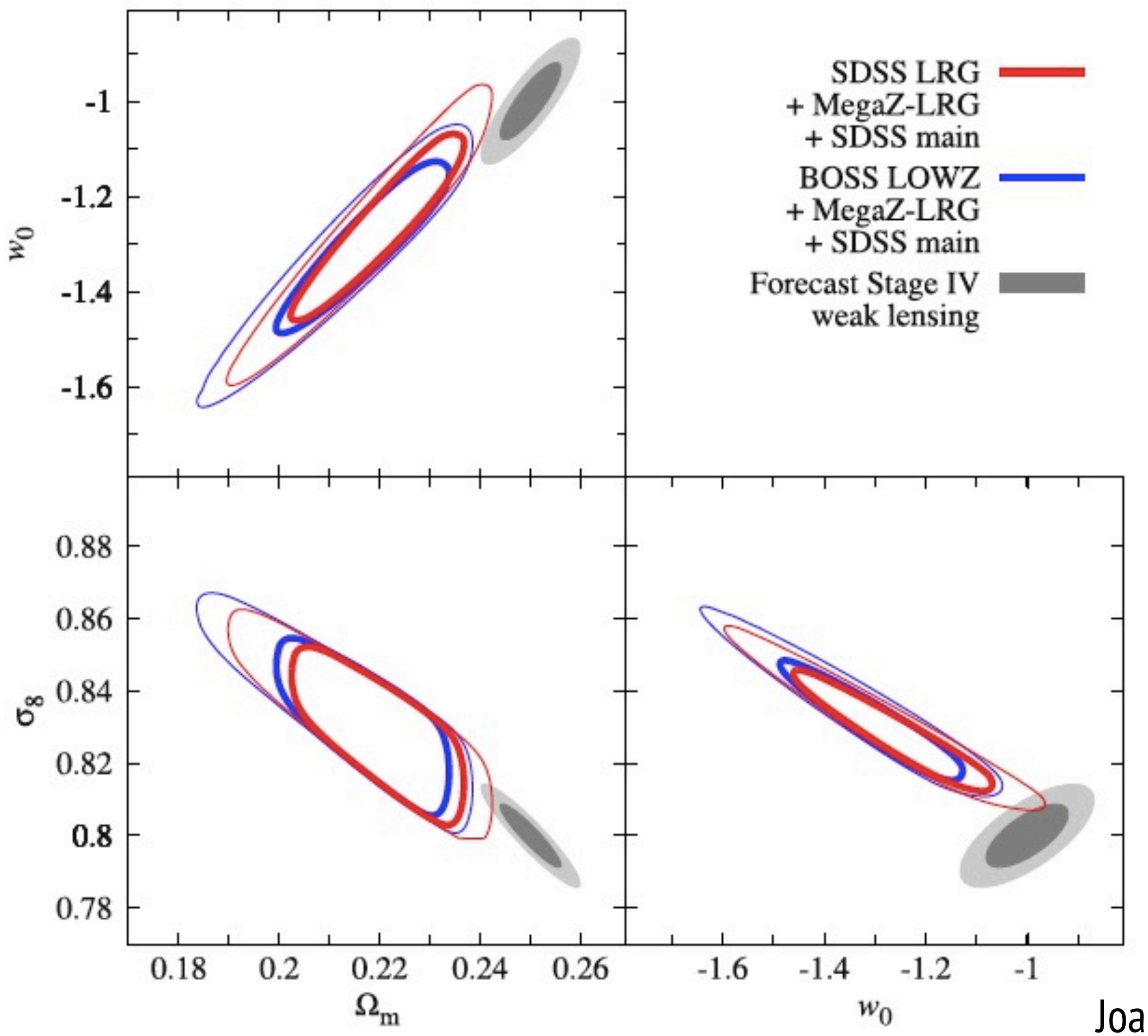
Intrinsic alignments

Gravitational lensing introduces *apparent* alignments in the shapes of galaxies, but local tidal effects may align galaxies *intrinsically*.



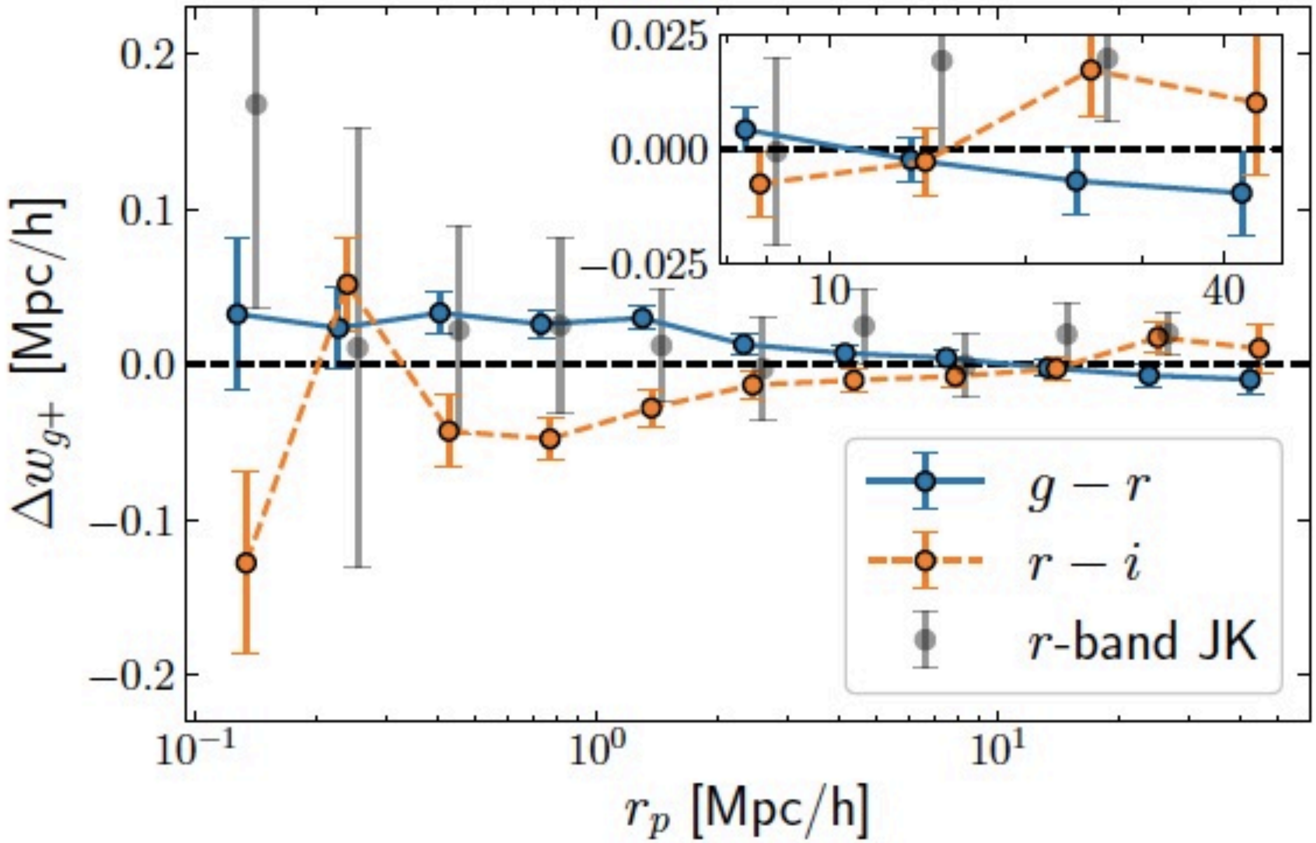
The amplitude of these *intrinsic alignments* depends on the complex physics of galaxy formation.

Intrinsic alignments → biased parameters



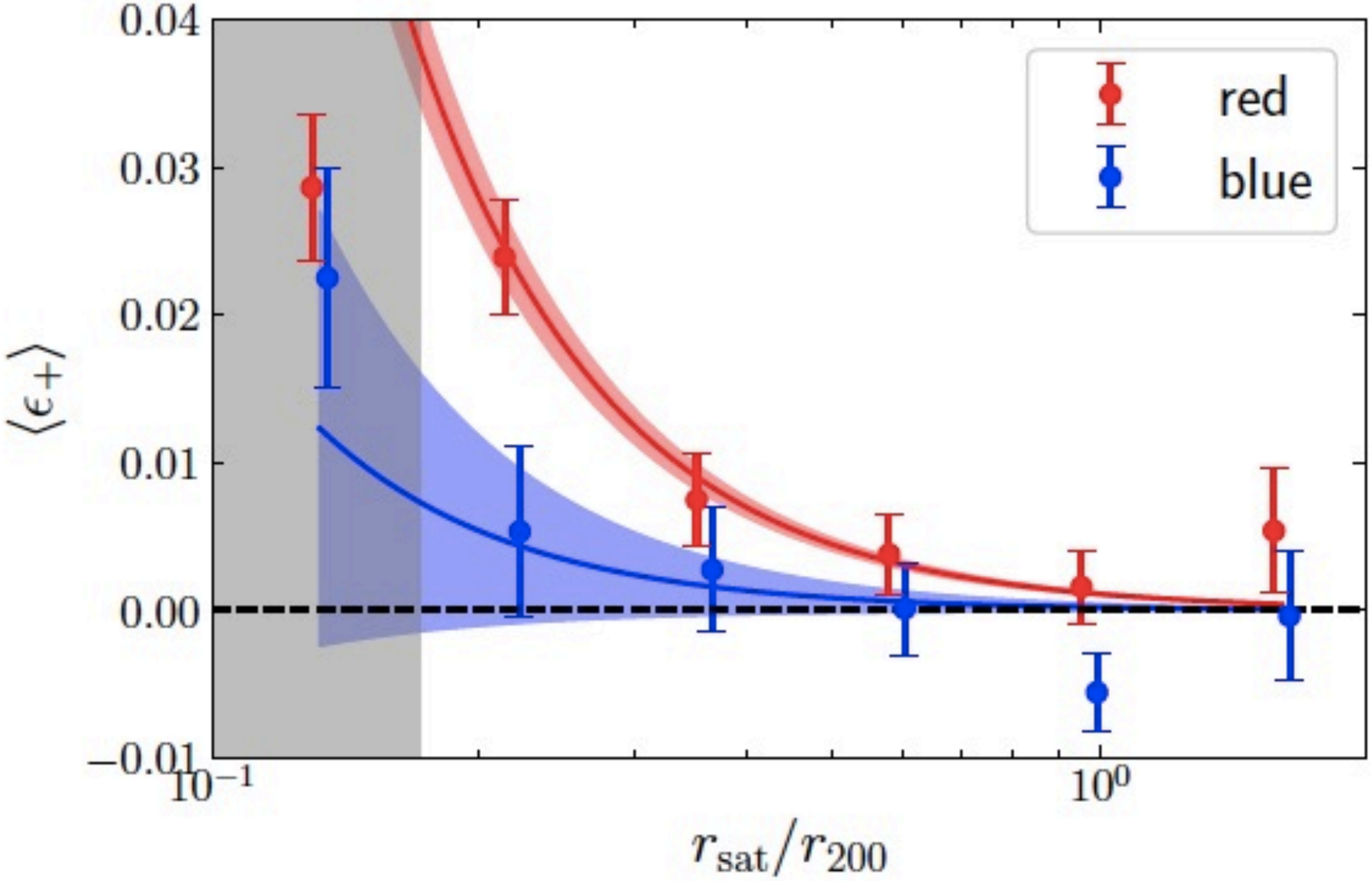
Joachimi et al. (2015)

Intrinsic alignments: dependence on passband



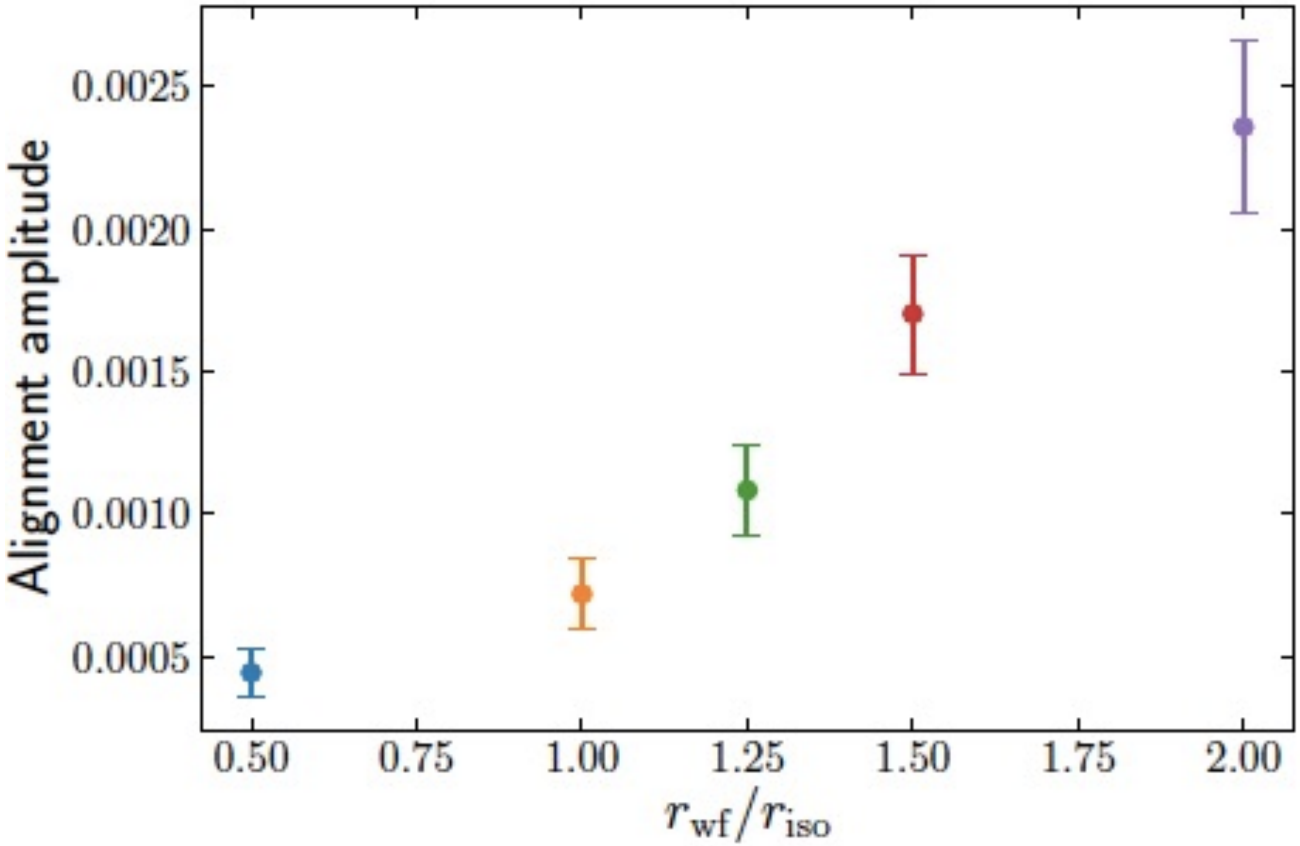
Georgiou et al. (2019a): the change in signal is caused by red satellite galaxies

Intrinsic alignments of satellites



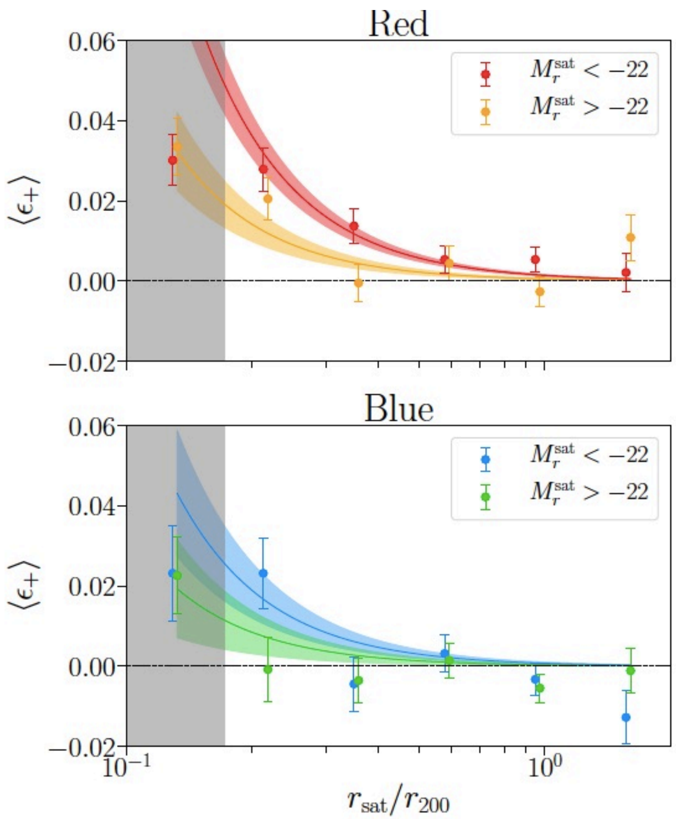
Georgiou et al. (2019b): measurement of the radial alignment of satellite galaxies in GAMA groups

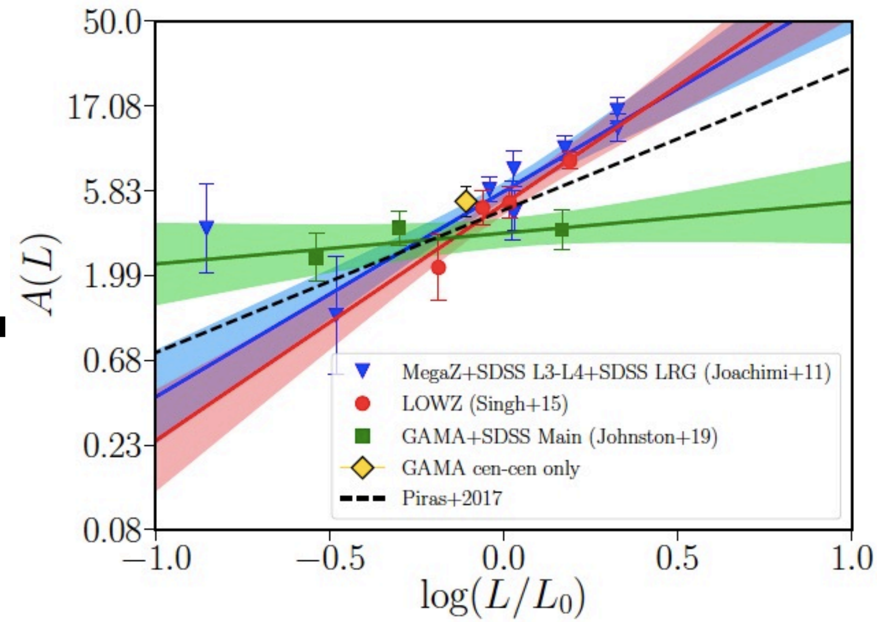
Intrinsic alignments of satellites



Georgiou et al. (2019b): the amplitude depends on the shape measurement ➞ outer regions show stronger signal.

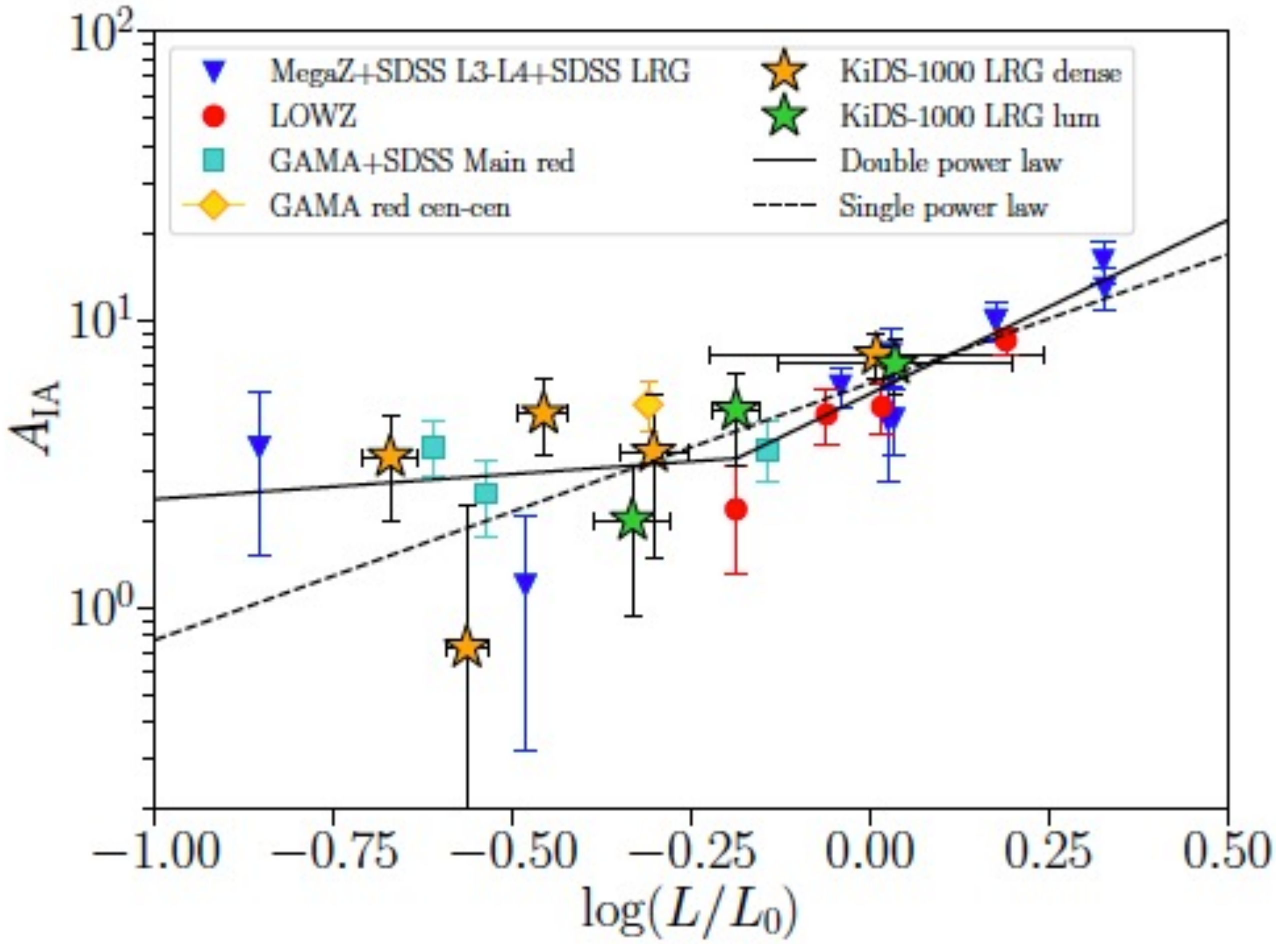
A consistent model of intrinsic alignments





Fortuna et al. (2021): halo model approach that uses observational constraints on blue/red galaxies to predict the alignment signal.

More complex dependence on luminosity?



Fortuna et al. (submitted): improved constraints from LRGs in KiDS

Lots of work ahead

Progress is made on many fronts and current ground-based surveys play a key role in improving the analyses.

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...

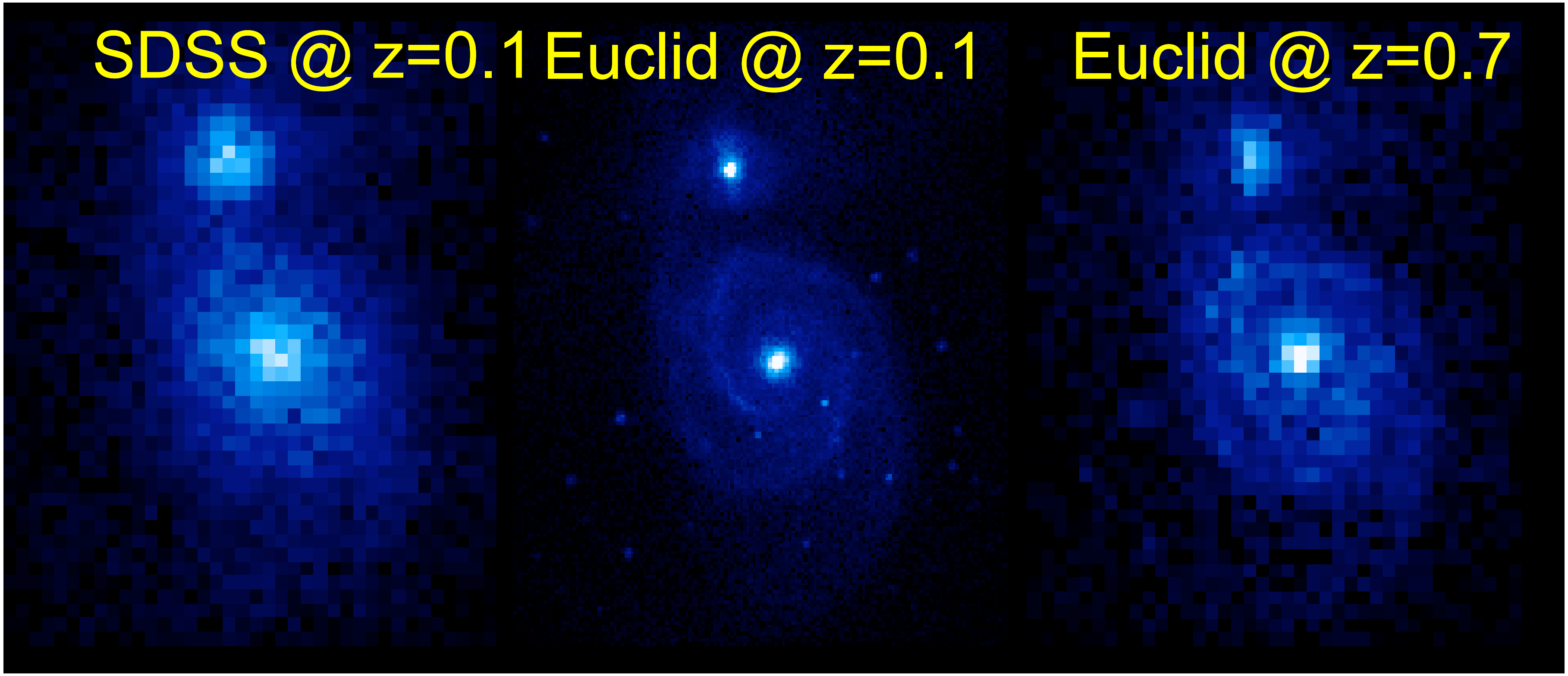
The data analysis and interpretation is complex: success relies on improving our understanding of observational and astrophysical biases.

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

euclid

→ CAN DO MORE THAN MEASURE PARAMETERS

Euclid: a rich data set

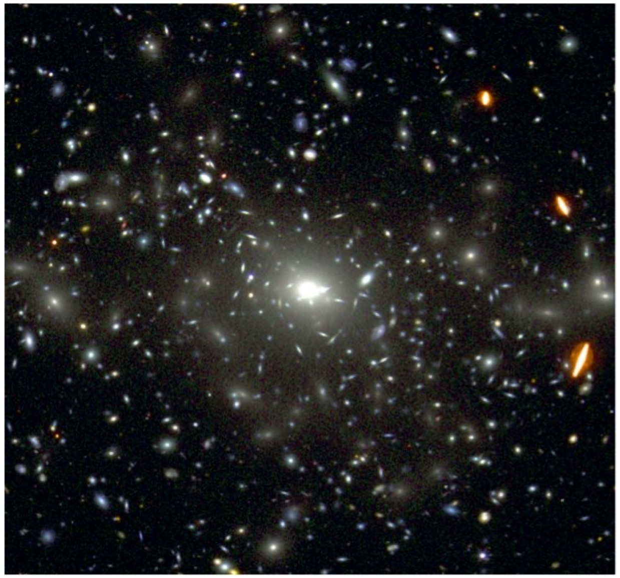


Euclid images of z~1 galaxies will have the *same* resolution as SDSS images at z~0.05 and will be at least 3 magnitudes *deeper*.

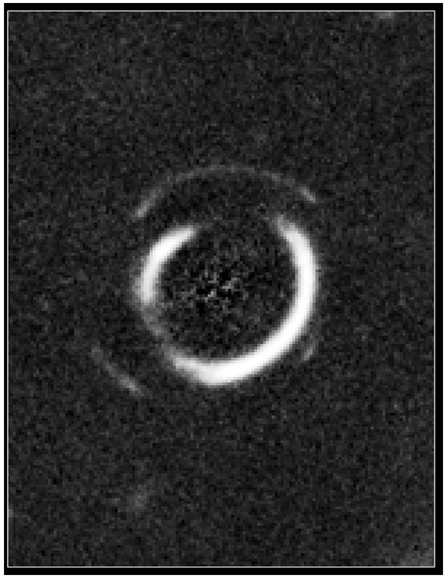
Euclid: a rich data set

The impact of Euclid is not limited to cosmological parameters

- Increase the number of strong lensing galaxy systems thousand fold to ~300,000
- Increase the number cluster strong lenses to ~5000.



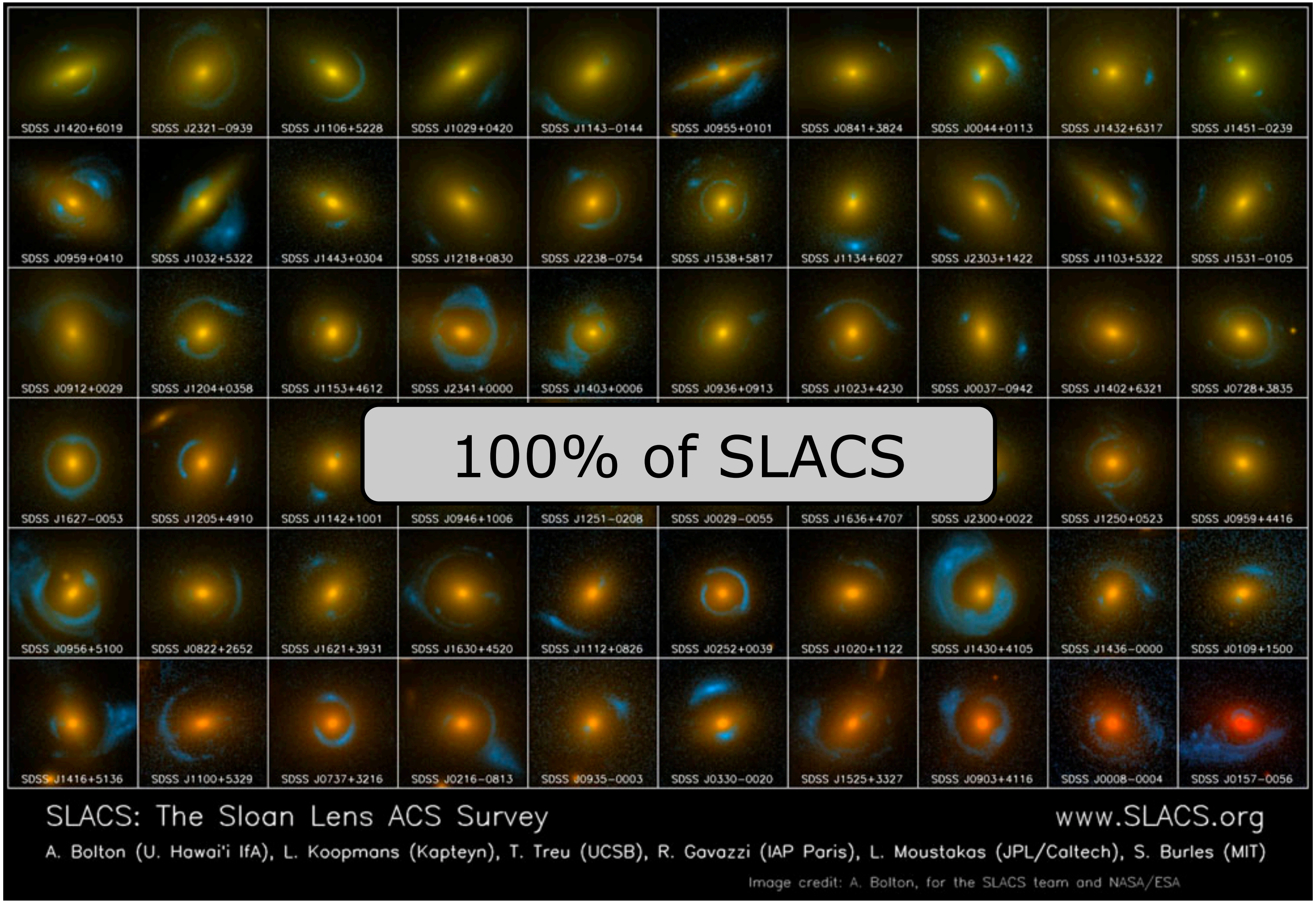
Simulated Euclid image (VIS+NIR)



Rare lensing event

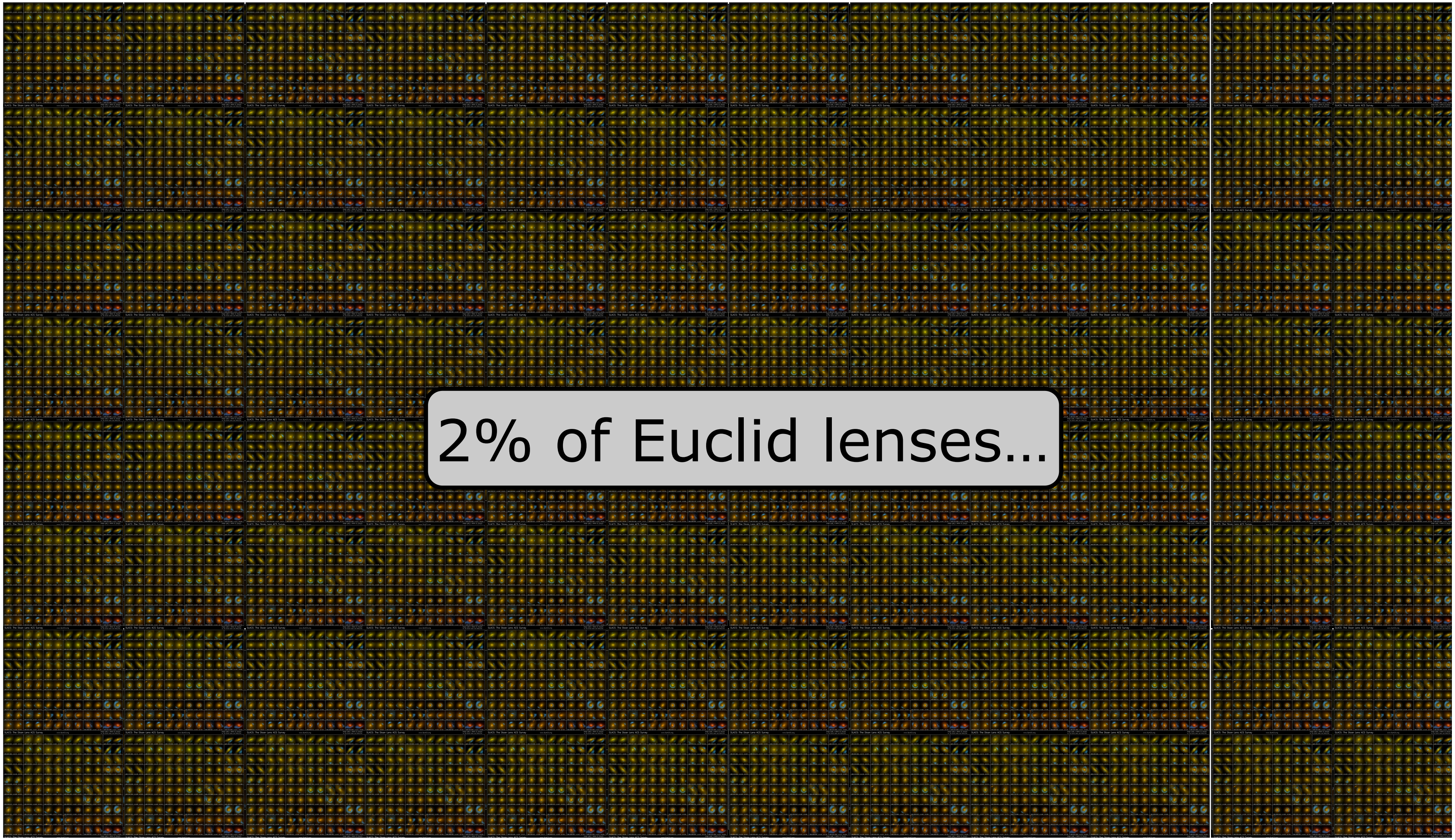
Courtesy M. Meneghetti

Euclid: transform strong lensing



100% of SLACS

Euclid: transform strong lensing

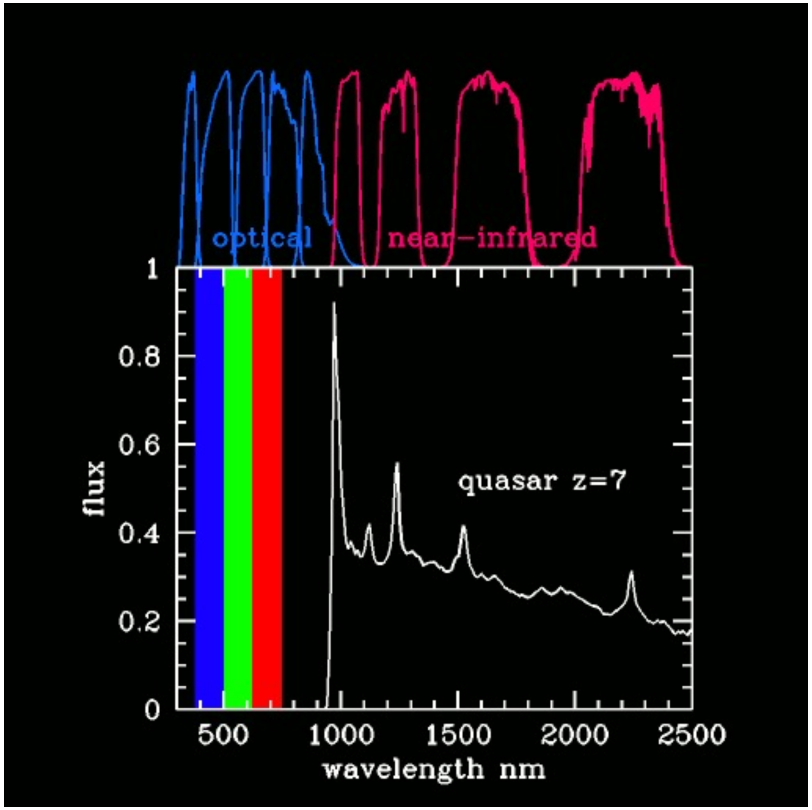


Credit: Leon Koopmans

Euclid: a unique NIR survey

The NIR survey that Euclid will carry out is good for:

- detecting obscured objects
- detecting cool objects
- detecting high redshift objects



Exciting times ahead!

Euclid is on track to be launched mid-2022.

Euclid will be a giant step forward in observational cosmology, testing all critical aspects of the current ΛCDM paradigm.

Euclid will also have a tremendous impact on many aspects of (extragalactic) astronomy, providing effectively a high redshift equivalent of the SDSS.