Cosmology with large-scale structure

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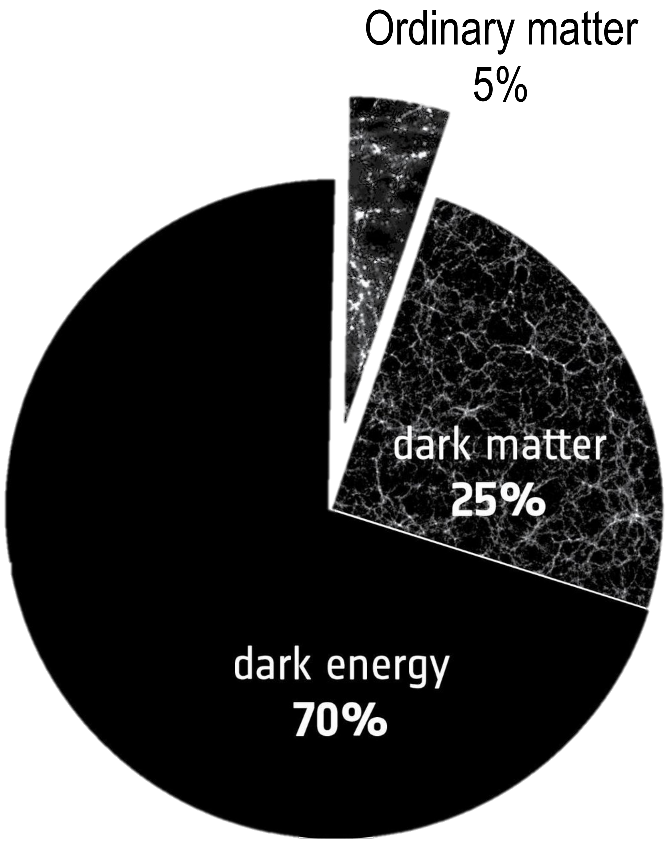
We know we must be “wrong”



We now have a good inventory of the constituents of the Universe, but 96% of the “ingredients” are not described by the standard model of particle physics.

New physics to be discovered!

True ignorance is not the absence of knowledge, but the refusal to acquire it.

Karl Popper

The hardest thing of all is to find a black cat in a dark room.

Confucius

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

Confucius

What should we study?

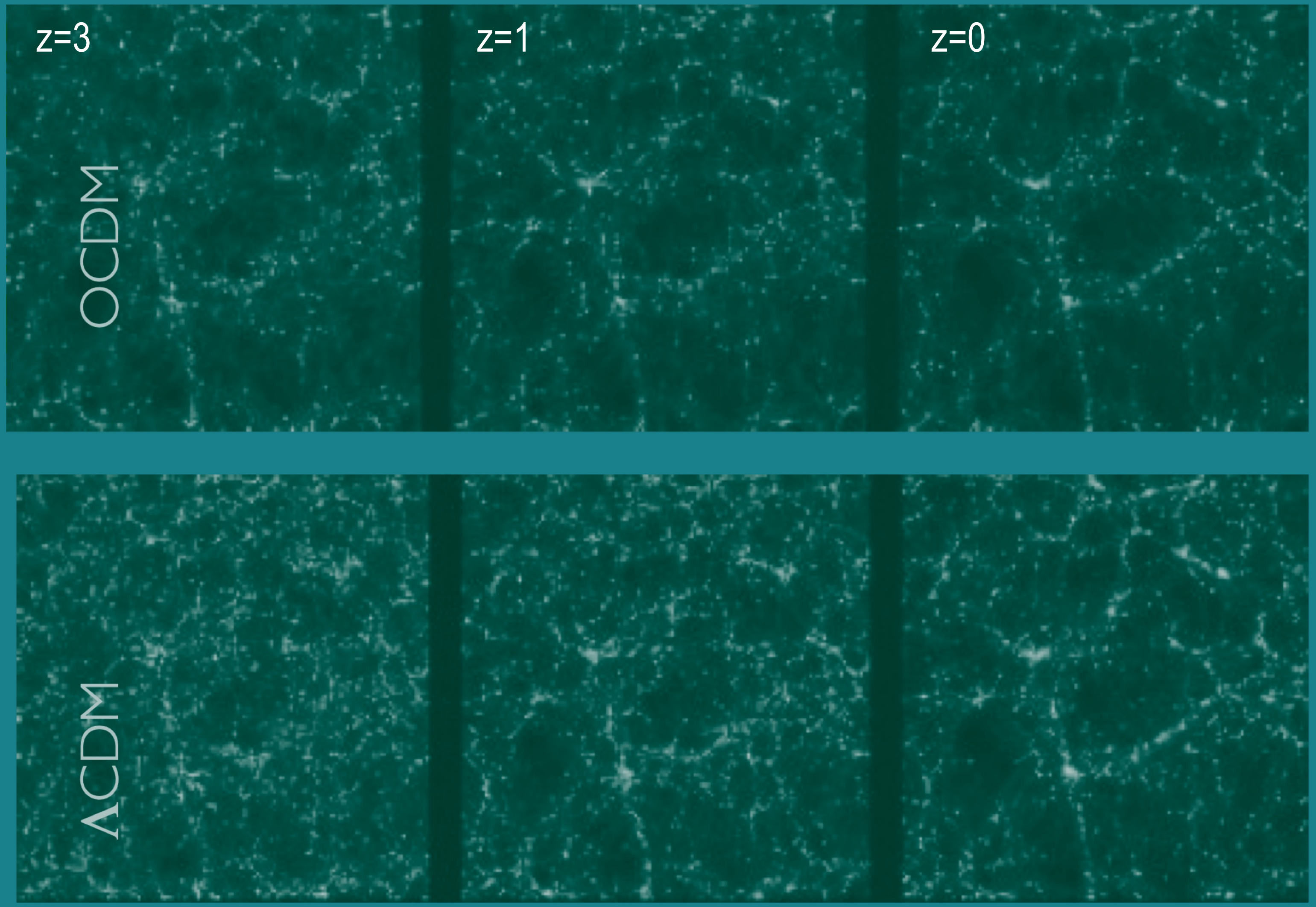
Investigate which physical effects and observables are sensitive to dark energy and/or modified gravity *and can be measured reliably.*

Cosmic expansion history

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

Cosmic history of structure formation

growth rate of structure $f(z)$



Credit: Virgo collaboration

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?

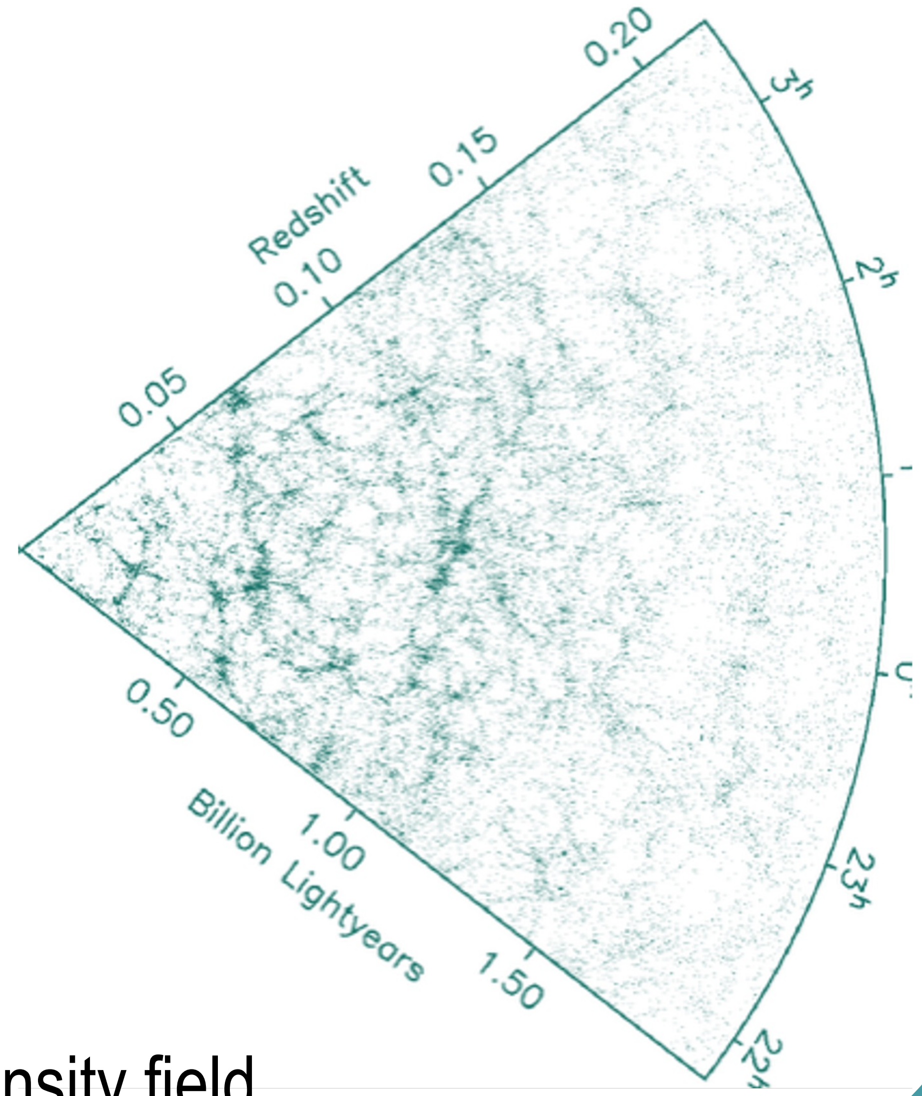
Clustering of galaxies

- 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

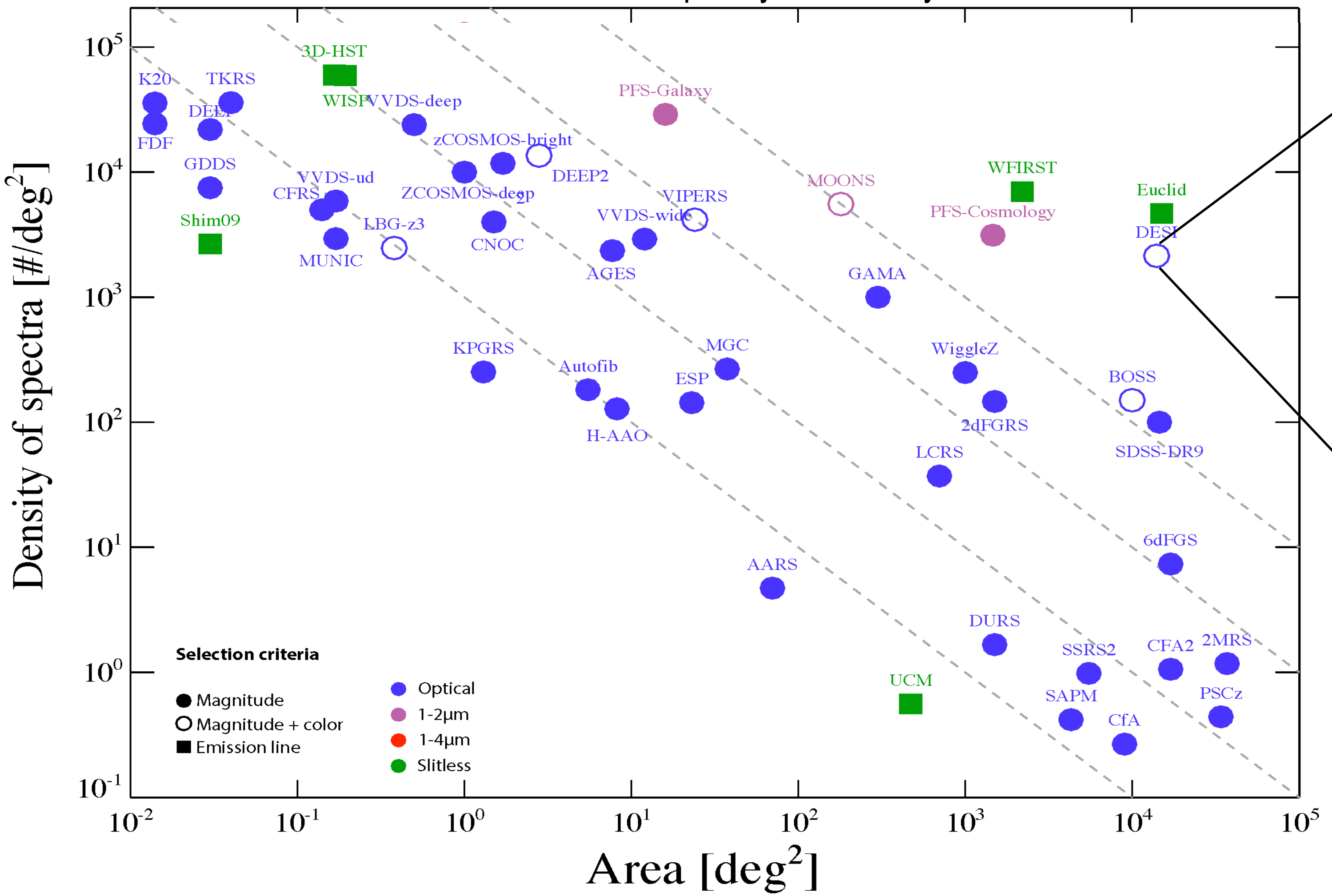
This is the hard part

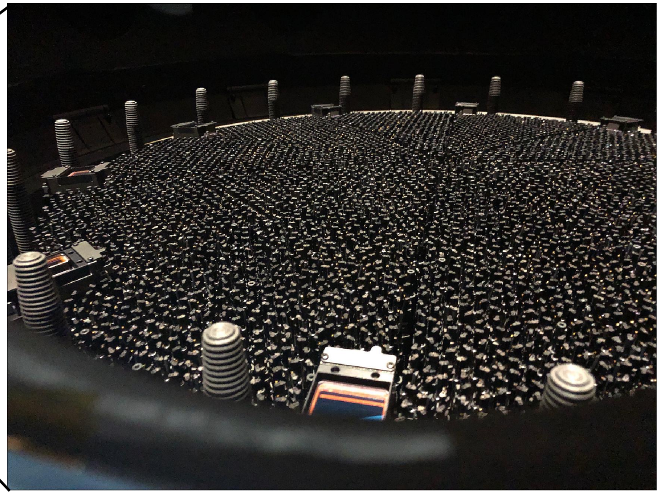


Then we can go from a density field to an over-density field, and measure statistics as a function of scale and redshift.

Redshift surveys are getting larger

Based on plot by Ivan Baldry



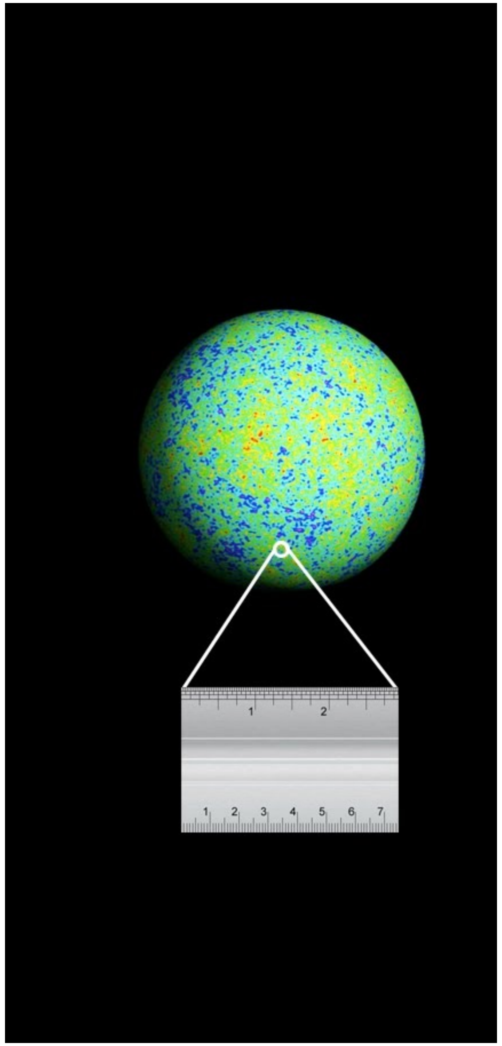


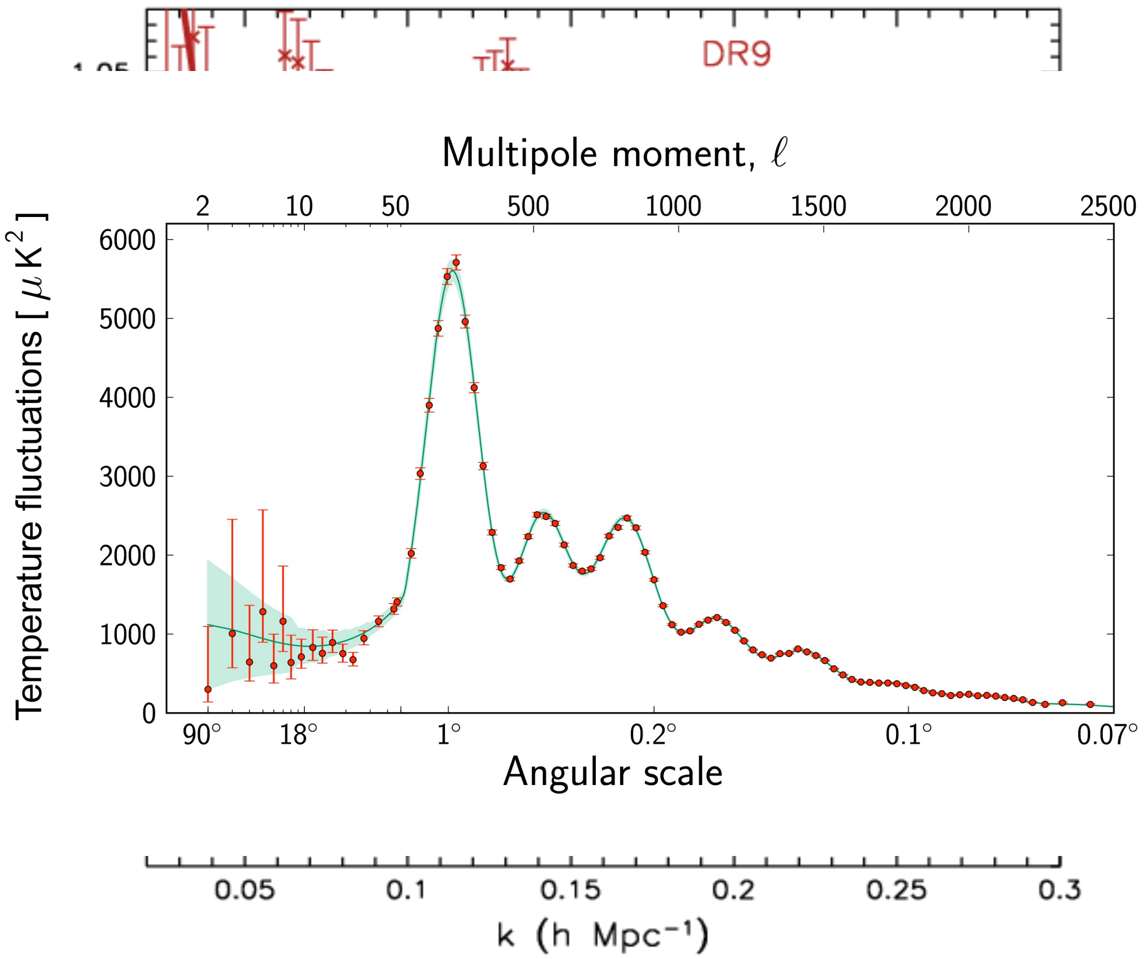
Credit: DESI team

Light ≠ density

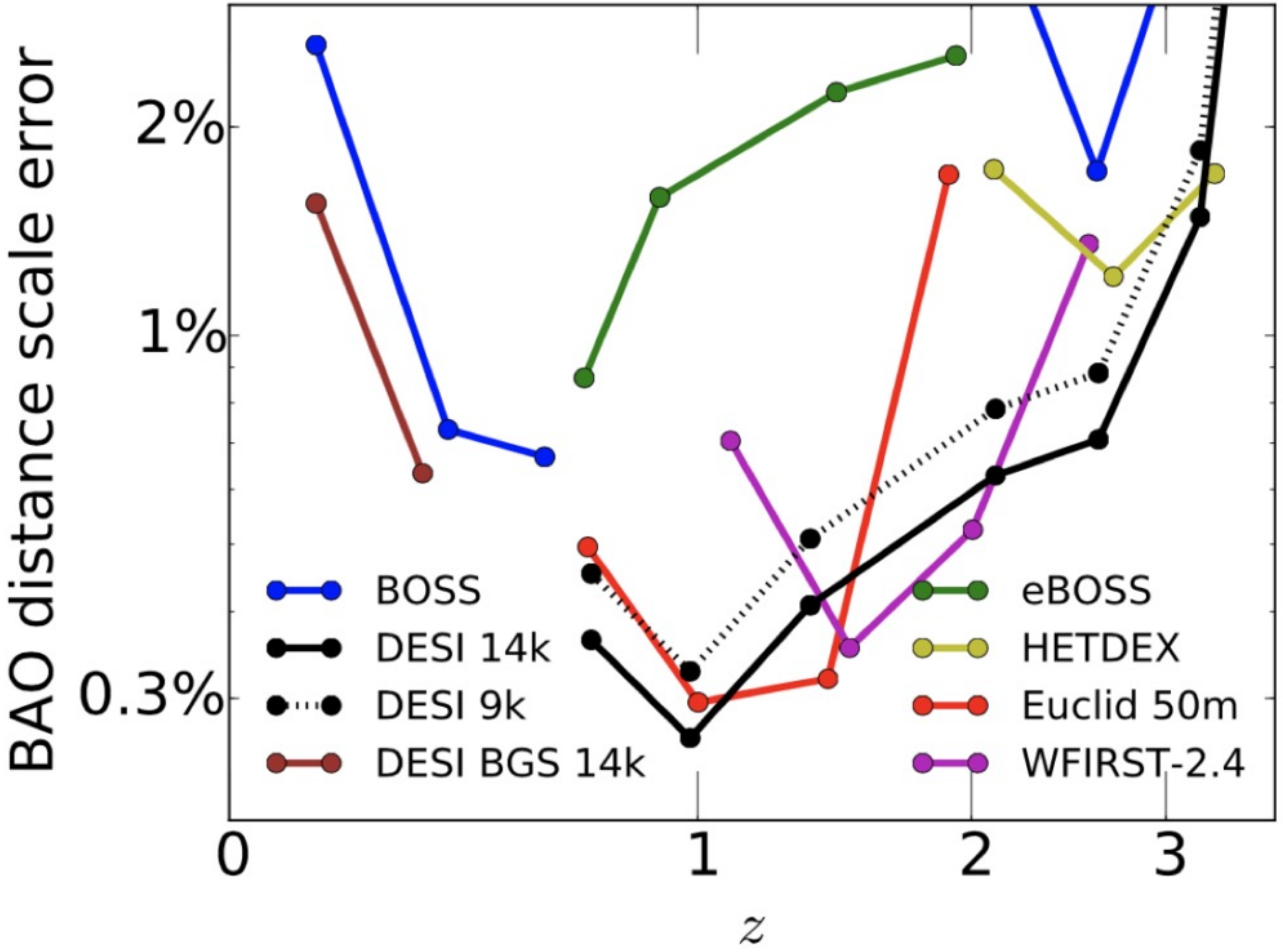
The distribution of galaxies can be used as a proxy for the large-scale mass distribution, but this can yield "biased" results! Large-scale features may be fine…

Baryon Acoustic Oscillations





BAO: excellent probe of expansion history



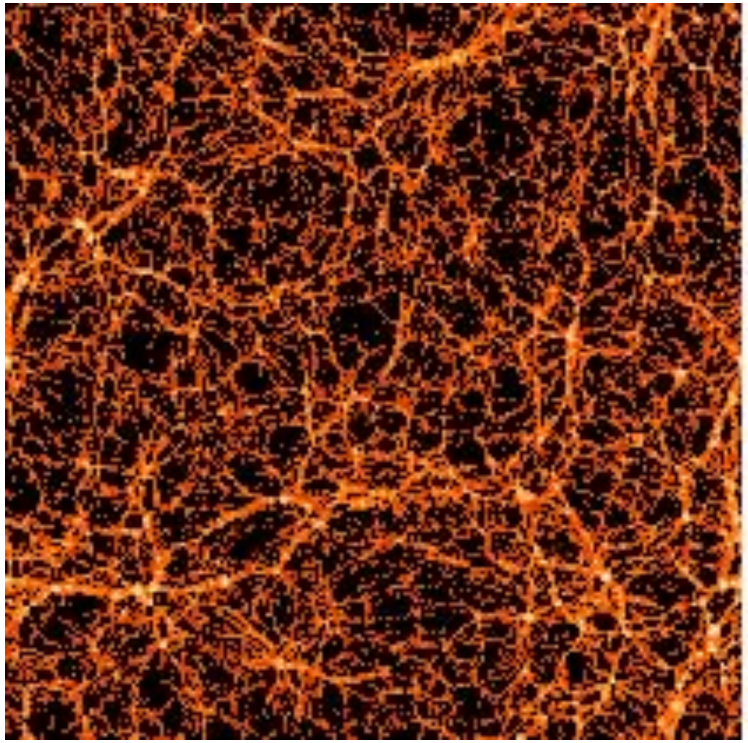
Credit: DESI collaboration

The phases matter

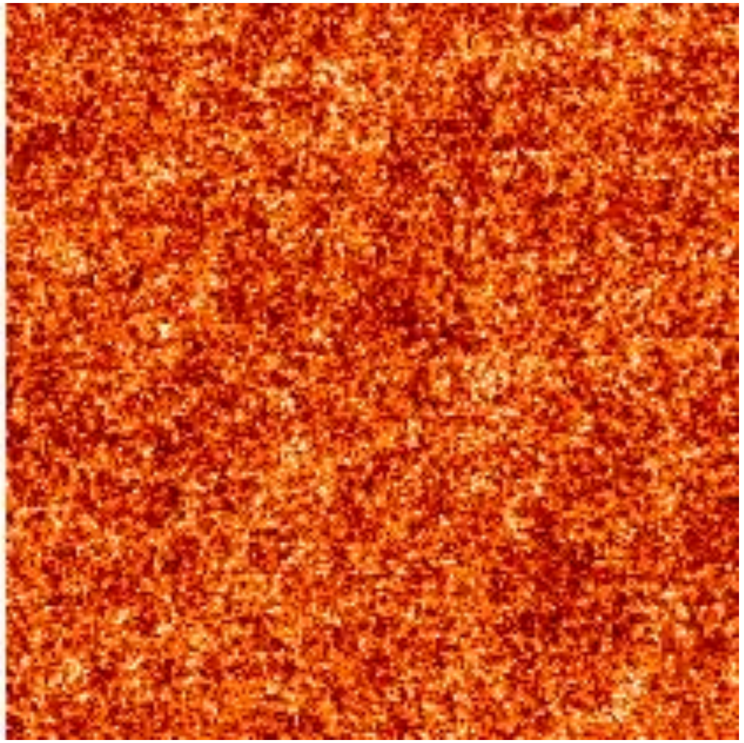
Non-linear growth of structure: information leaks beyond 2-point statistics → need N-body simulations for predictions; interpretation more complicated.

Can be captured by:

- Peaks
- Higher-order correlations
- Betti numbers
- Minkowski functional
- …



“cosmological” phases

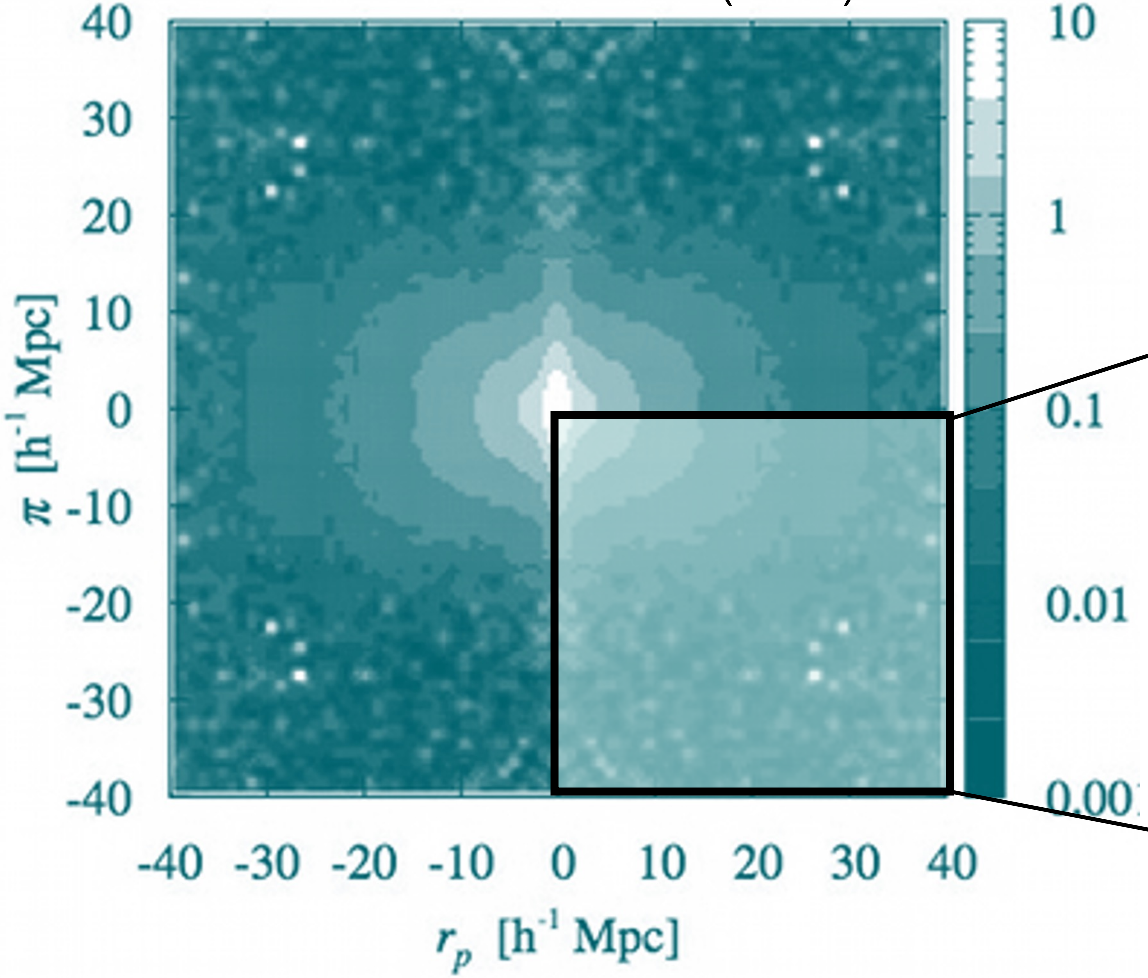


Random phases

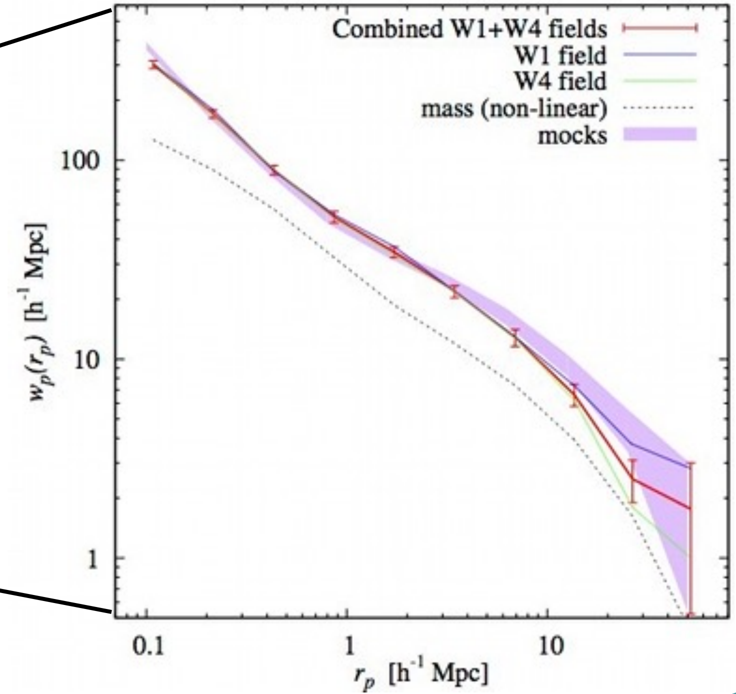
Coles (2001)

Redshift space distortions - clustering

de la Torre et al. (2013)

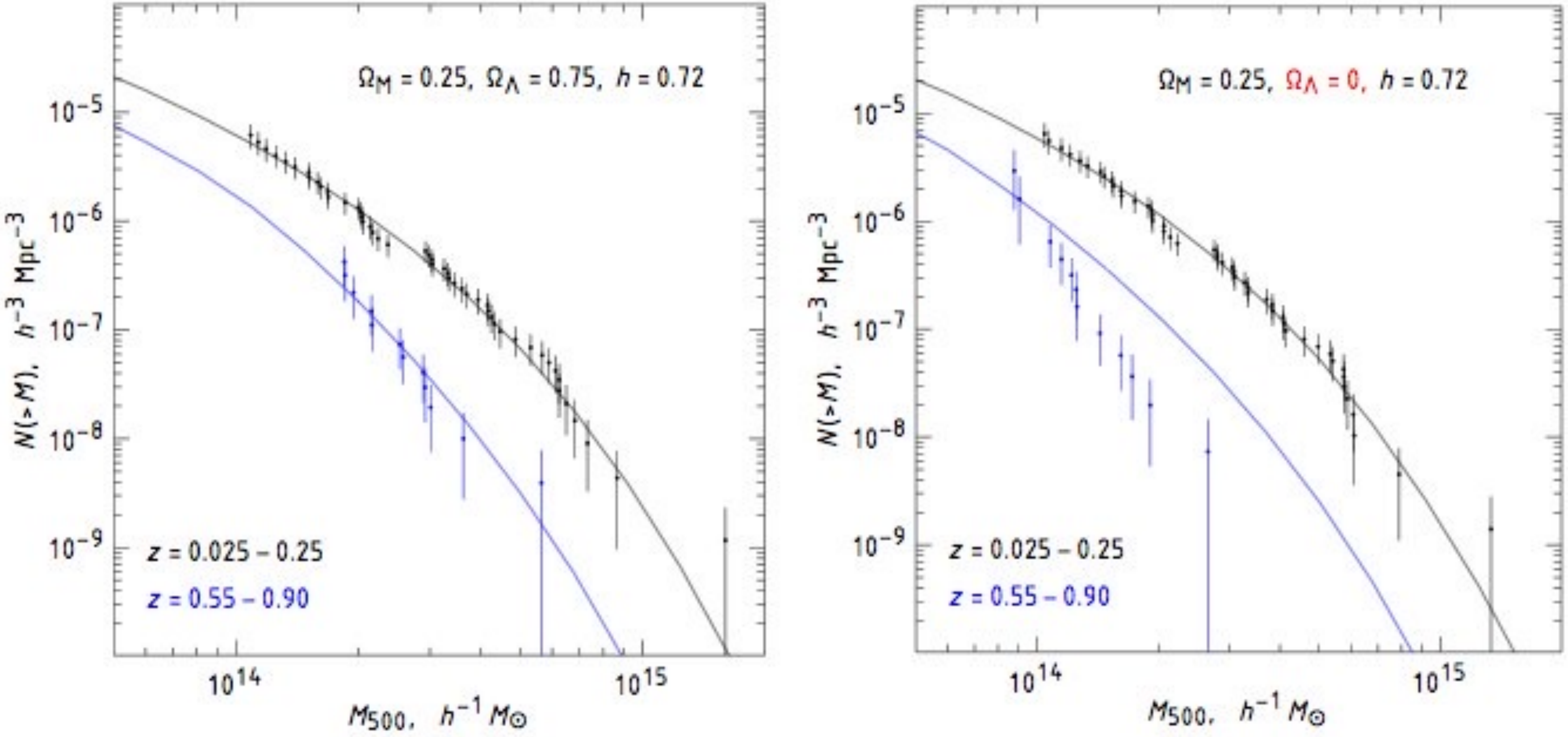


Lots of information, but we need to model how (biased) galaxies populate dark matter haloes.



Counting clusters of galaxies

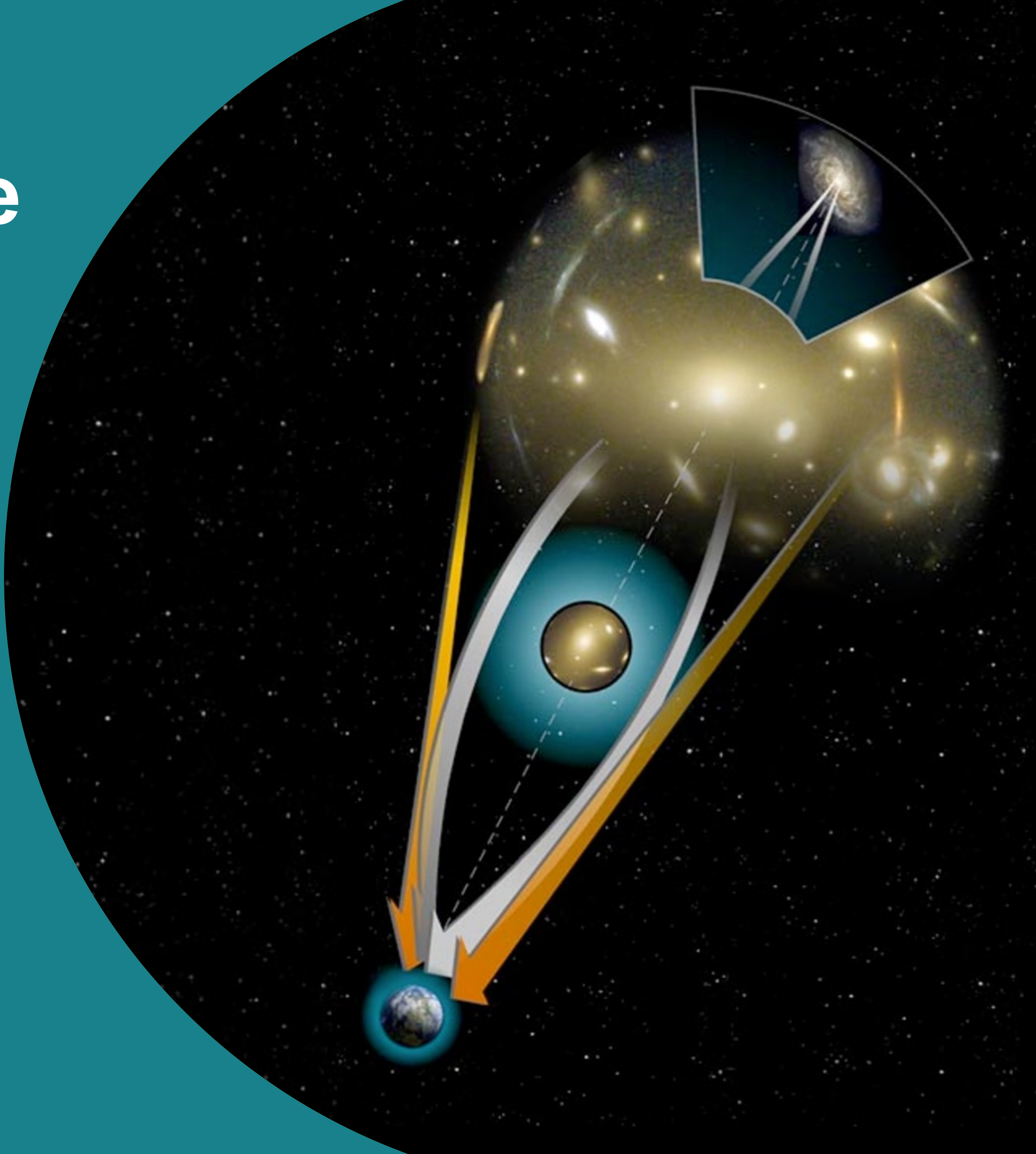
Vikhlinin et al. (2009)



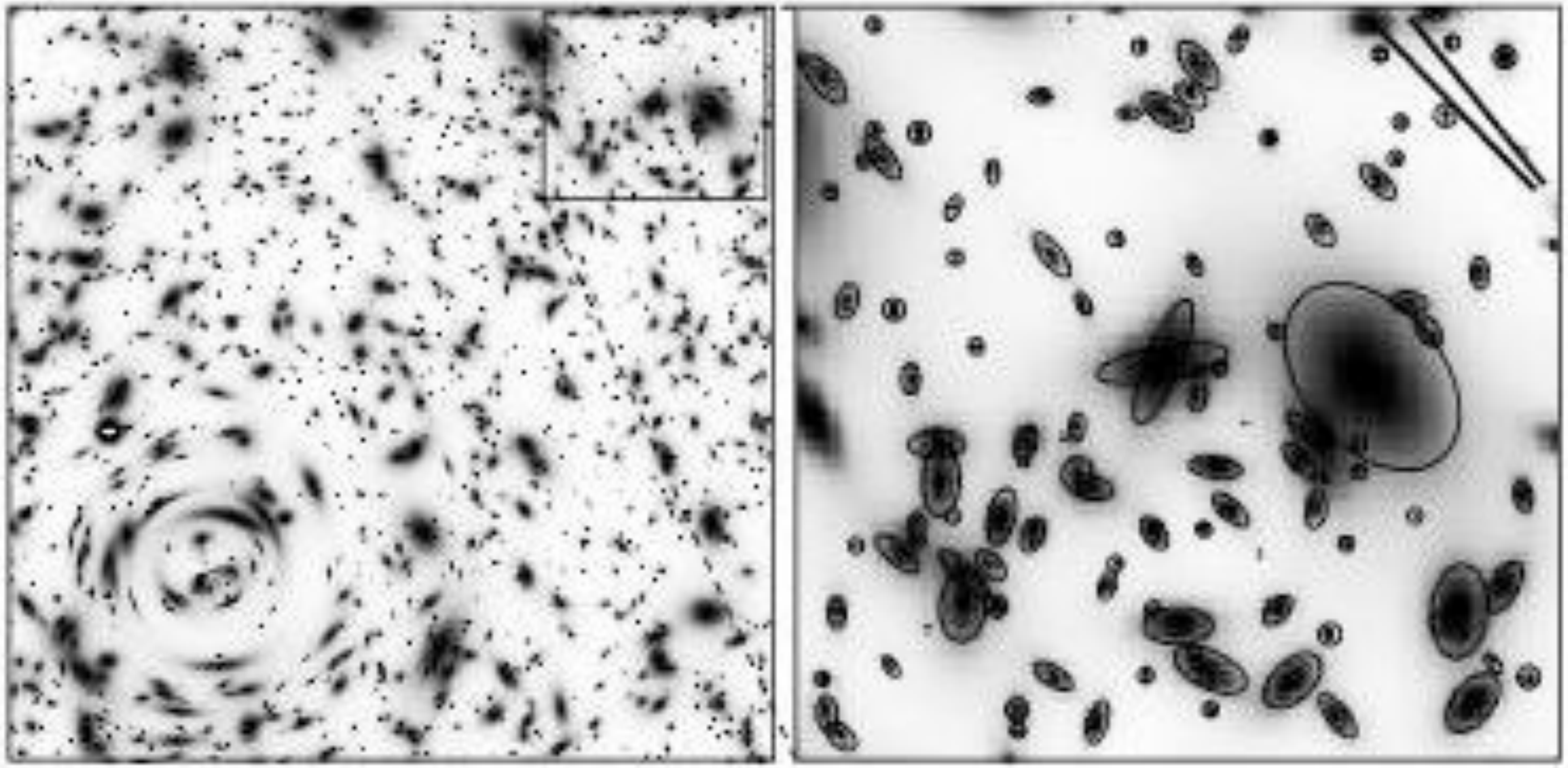
- We need to understand the selection of the clusters
- We need reliable estimates of their masses

“seeing” the invisible

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



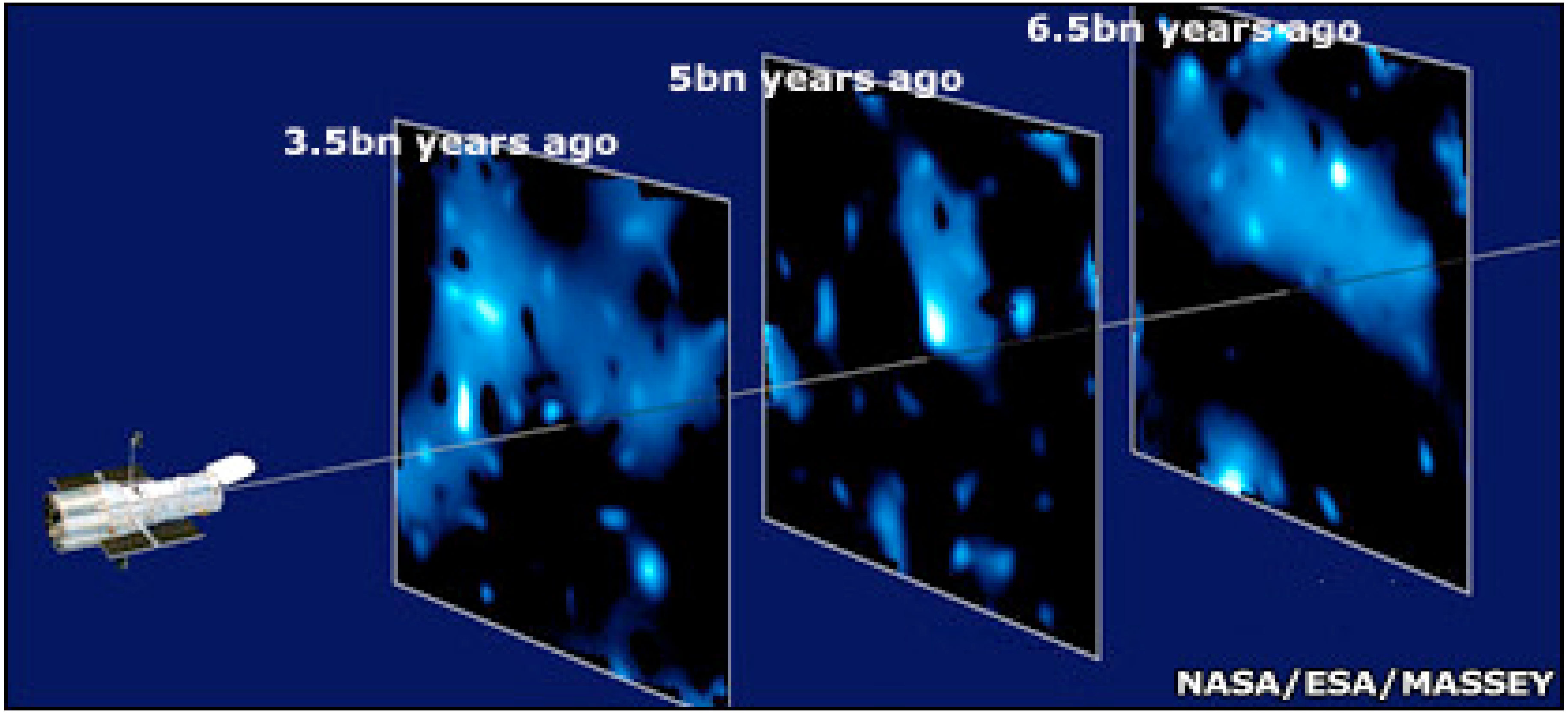
Weak gravitational lensing



Mellier (1999)

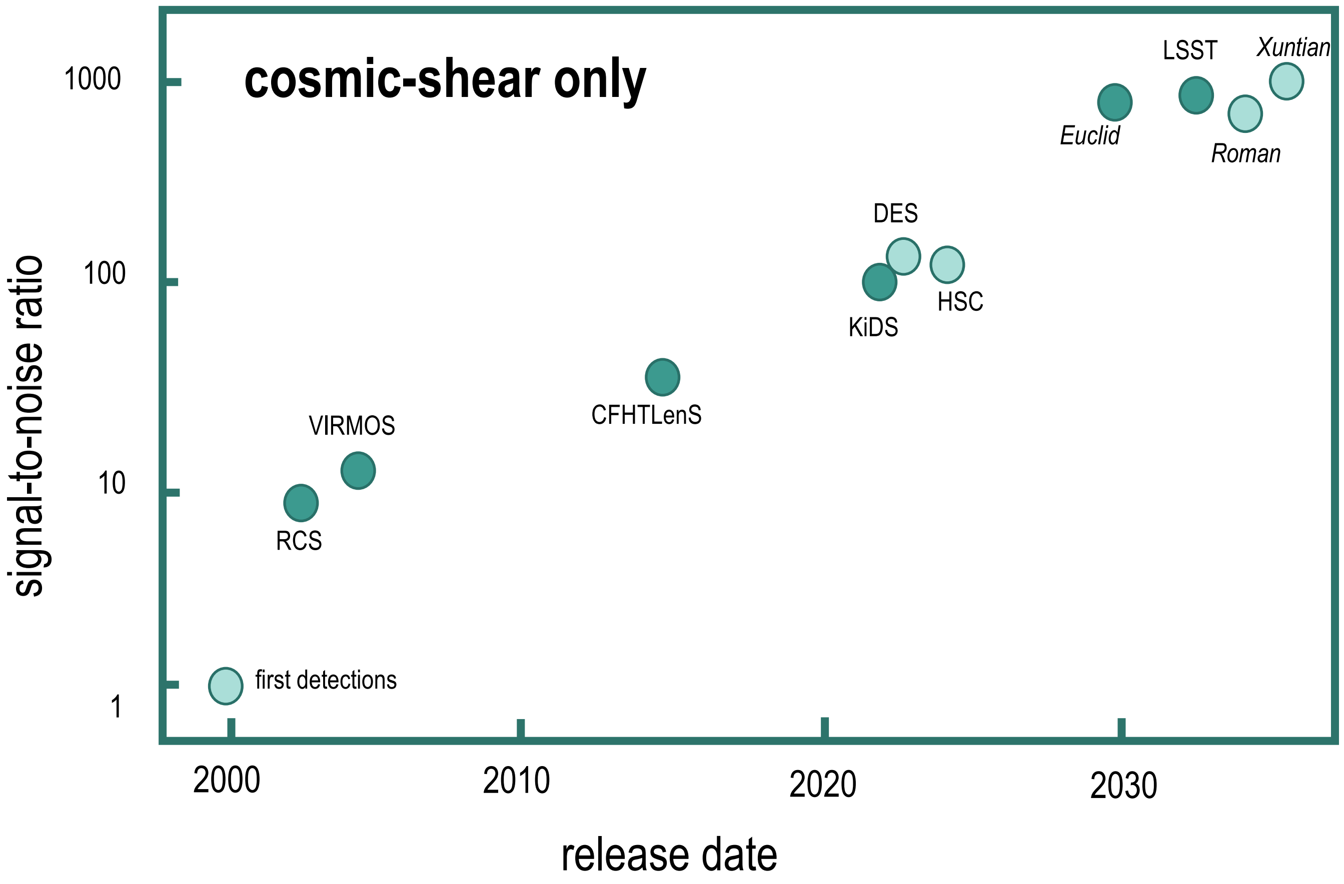
A measurement of the ellipticity of a single galaxy provides an unbiased but very noisy estimate of the shear.

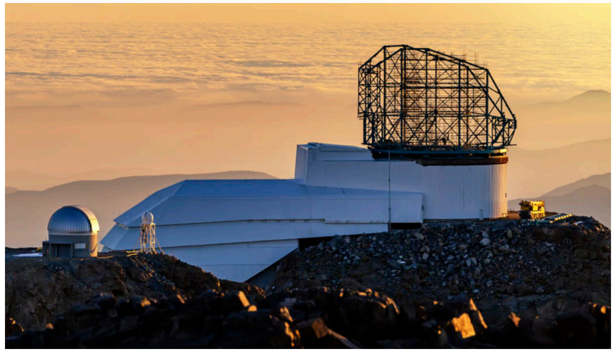
3d-mapping of the Universe



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 sources.

More data → more precision



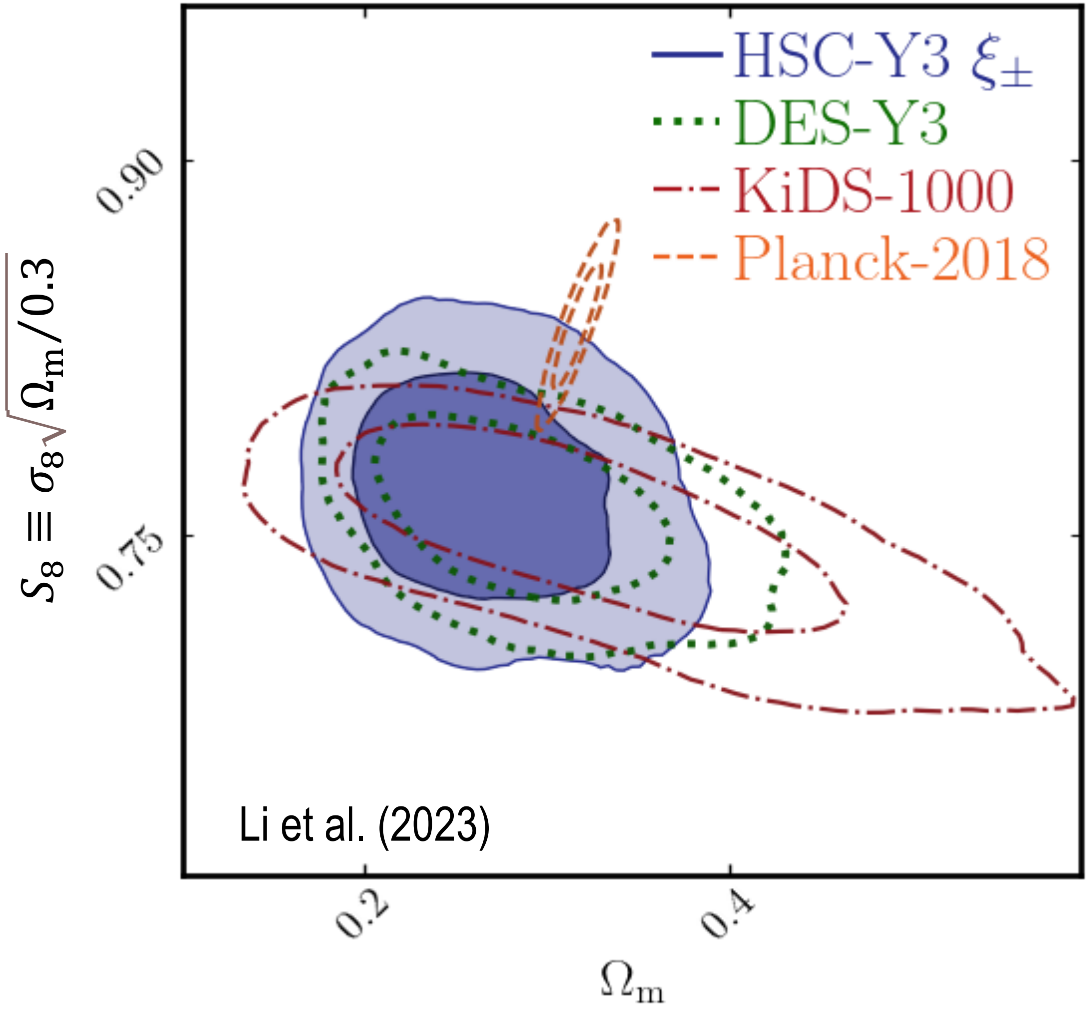


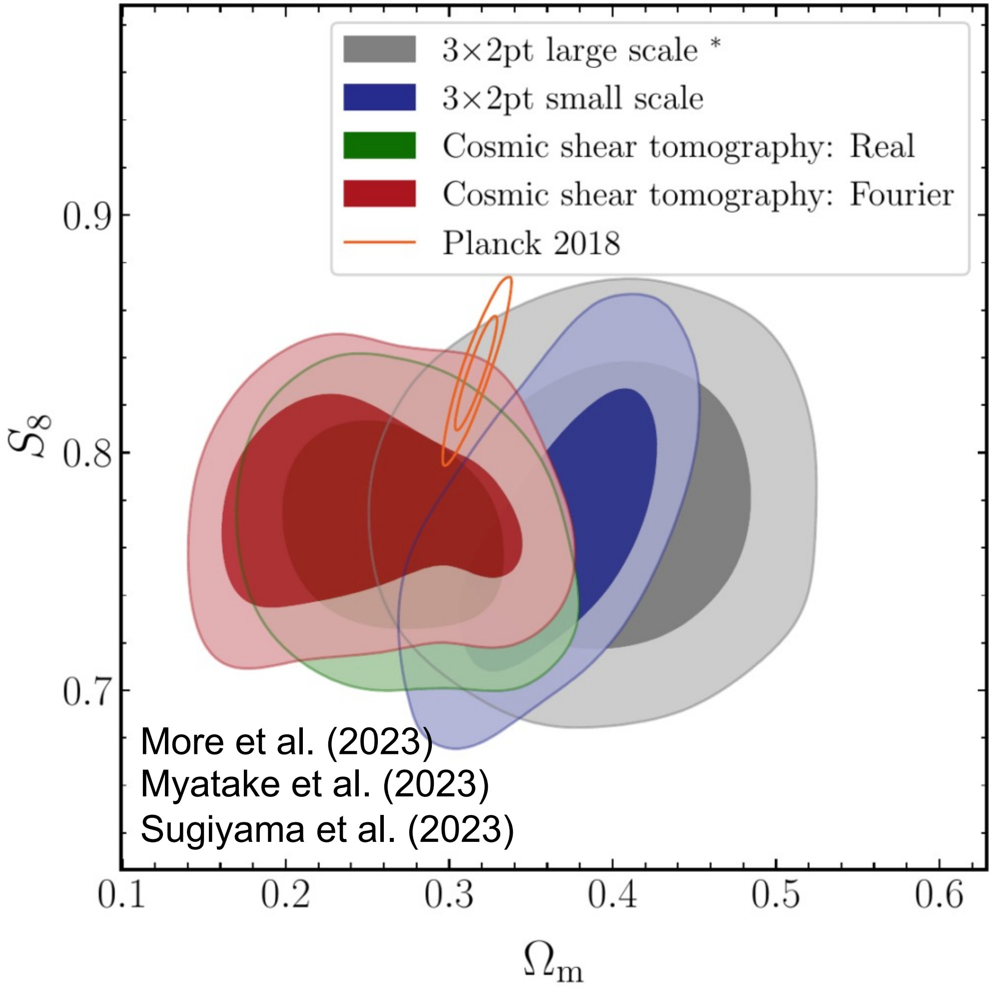
LSST: start 2025

Xuntian (CSST):
launch 2025?

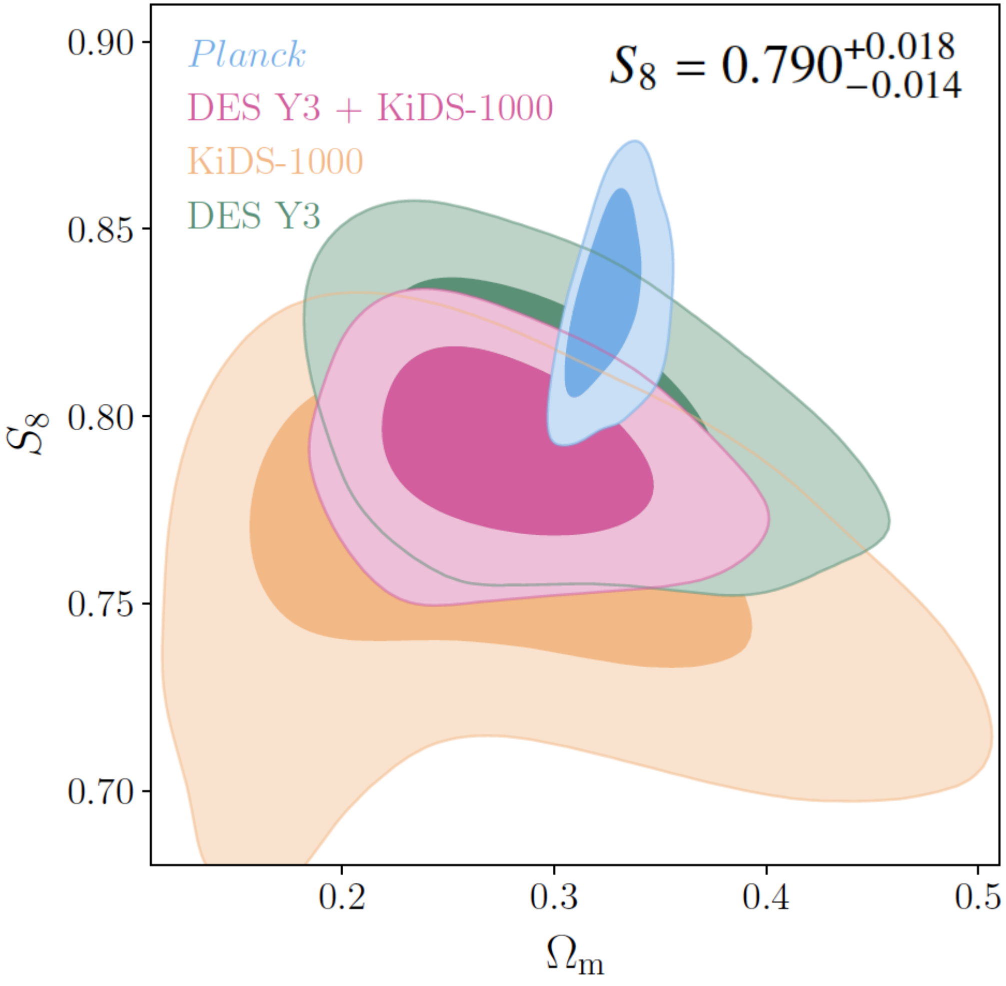
Roman
launch 2027?

Some recent results

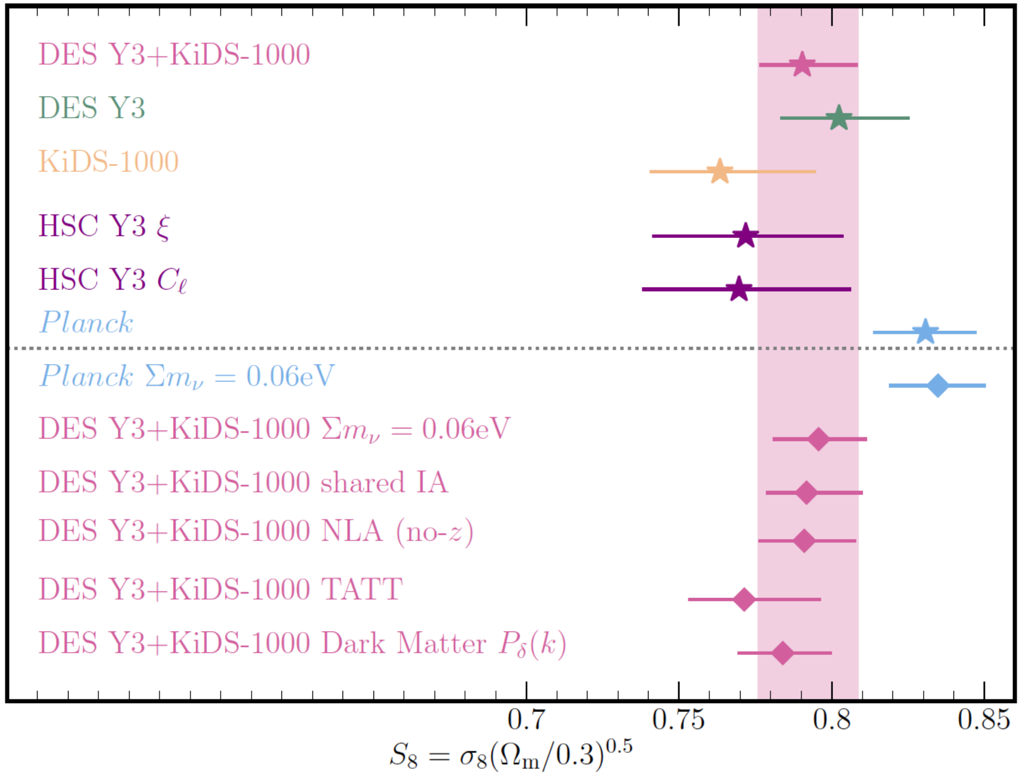




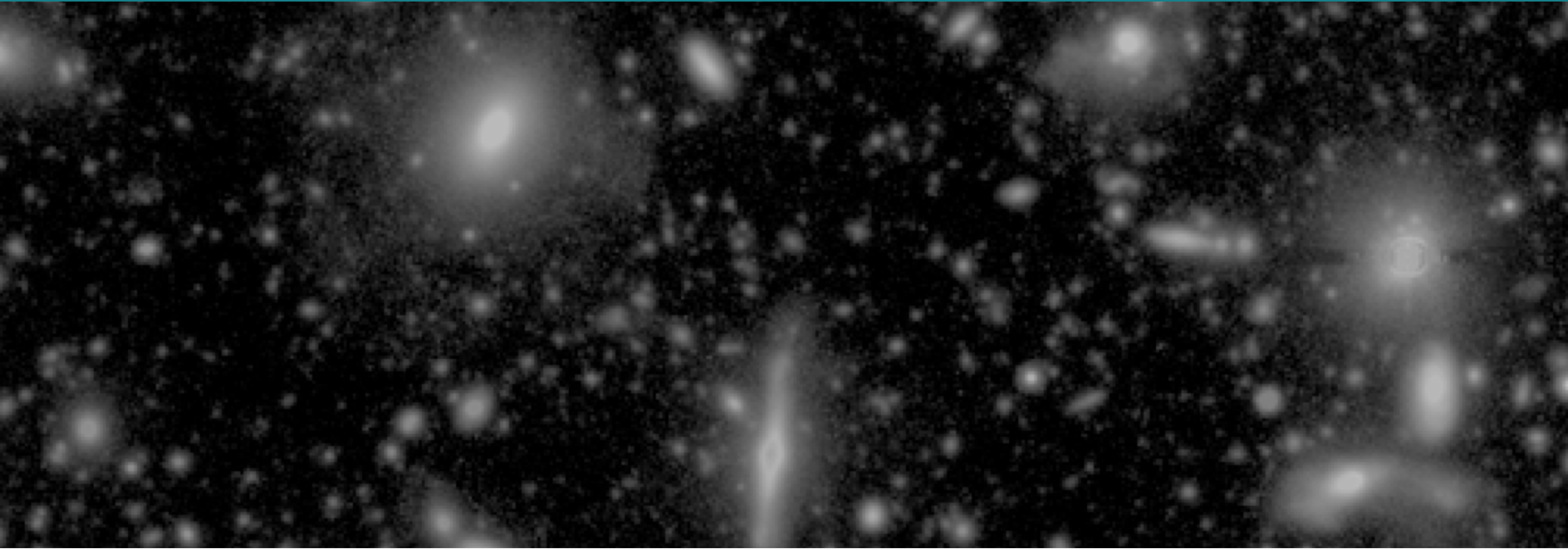
Results from DES-Y3 + KIDS-1000



DES + KiDS collaboration: Abbott et al. (2023)



Better data should help a lot



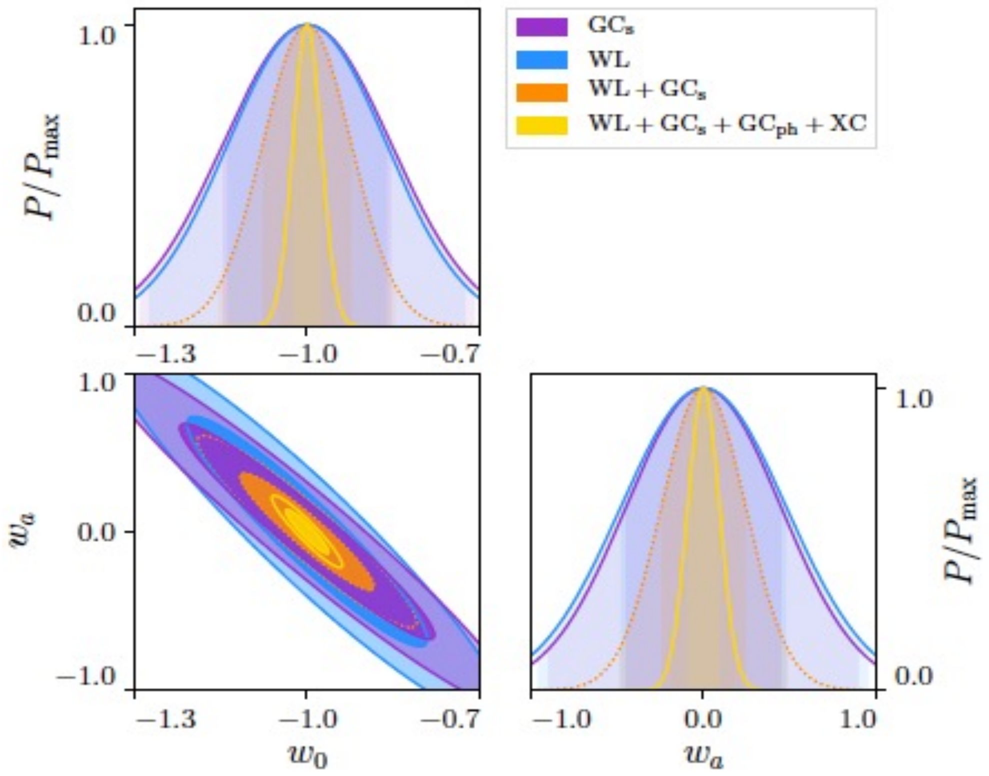
0.0005 deg^2 with Subaru in the COSMOS field

Better data should help a lot

0.0005 deg^2 with HST in the COSMOS field

We also need to combine probes

Euclid Collaboration: Blanchard et al. (2020)



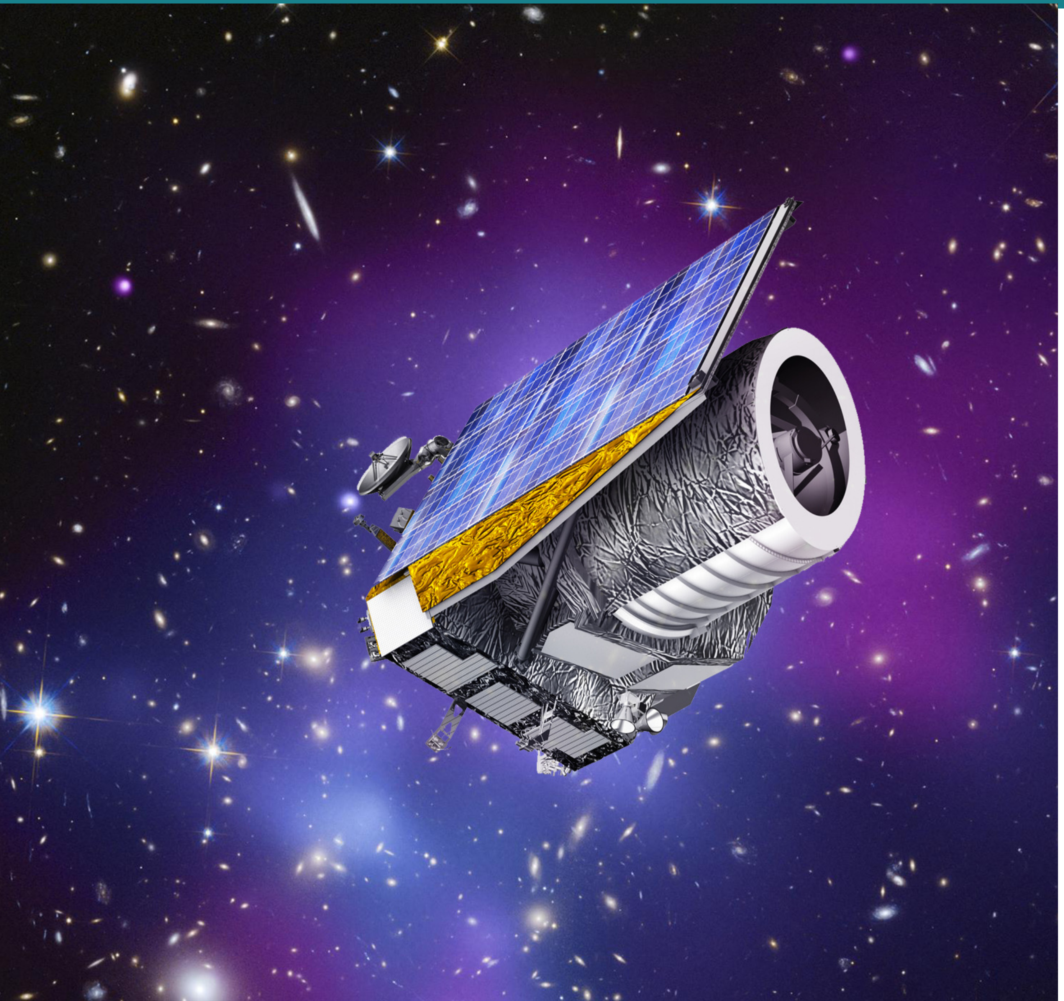
Constraints on the dark enegy equation-of-state

$$w_{\rm DE}(z) = w_0 + w_a \frac{z}{1+z},$$

Weak lensing measurements alone are not enough: percent precision on the dark energy equation-of-state requires the combination of probes.

How do galaxies populate dark matter halos and how do they interact with their environment?

Euclid: exploring the dark Universe



- Weak lensing by large scale structure
- Clustering of galaxies

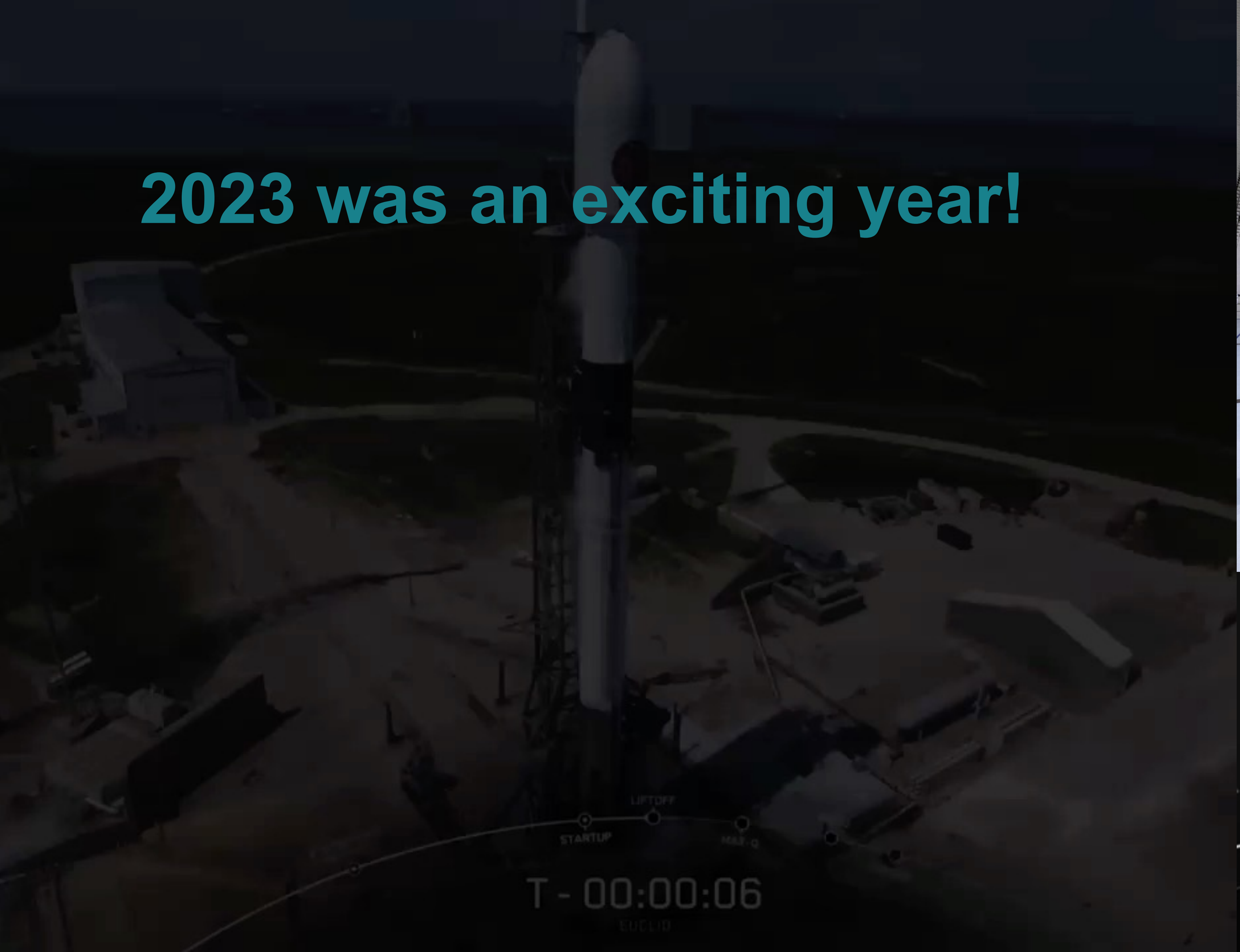
Imaging:

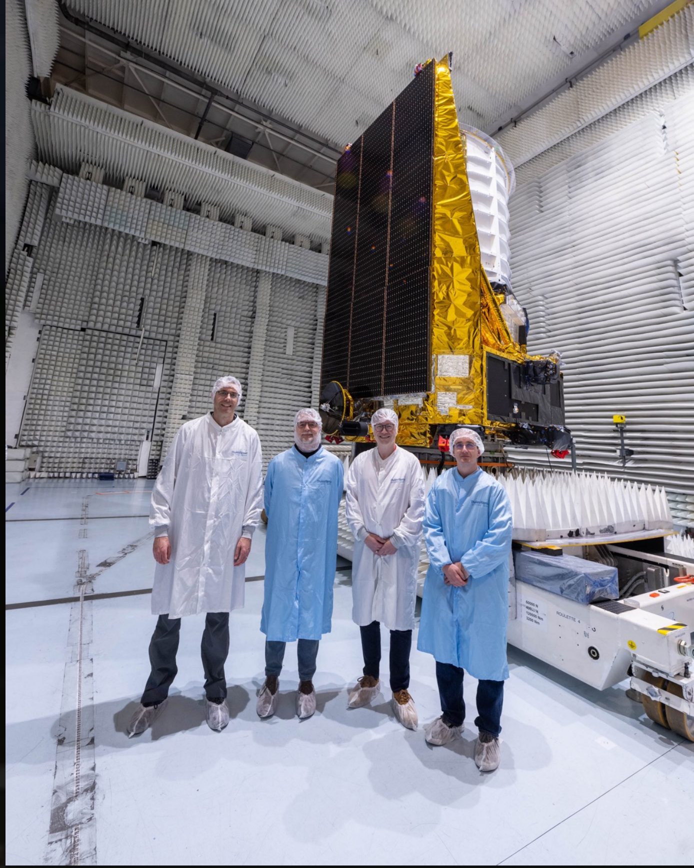
- best 1/3 of the sky (15000 deg^2)
- similar resolution at HST in optical
- NIR imaging in 3 filters (YJH)
- Images for $1.5x10^9$ galaxies

Slitless redshift survey over the same area:

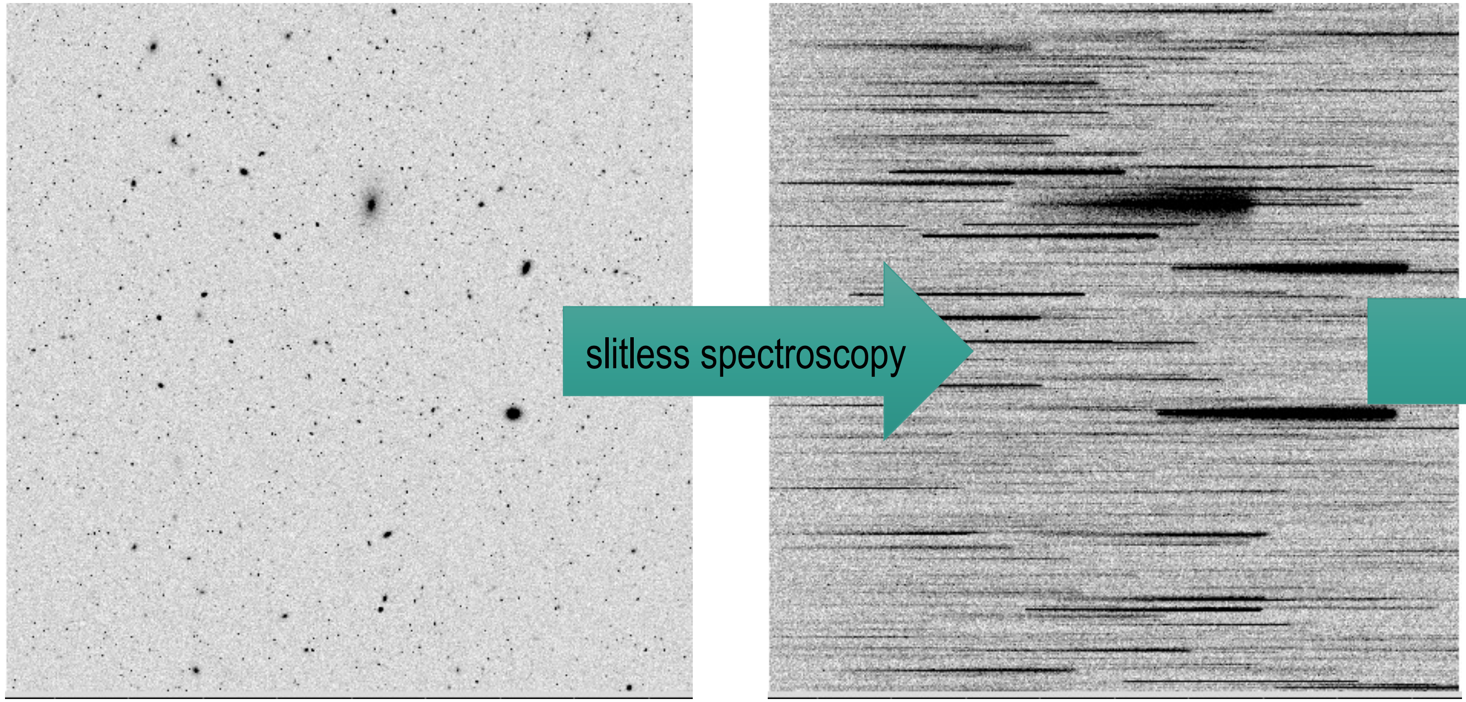
- NIR spectra for ~$3.5x10^7$ galaxies ($0.9<z<1.8$)
- Spectral resolution R~350 (for 0.5” source)

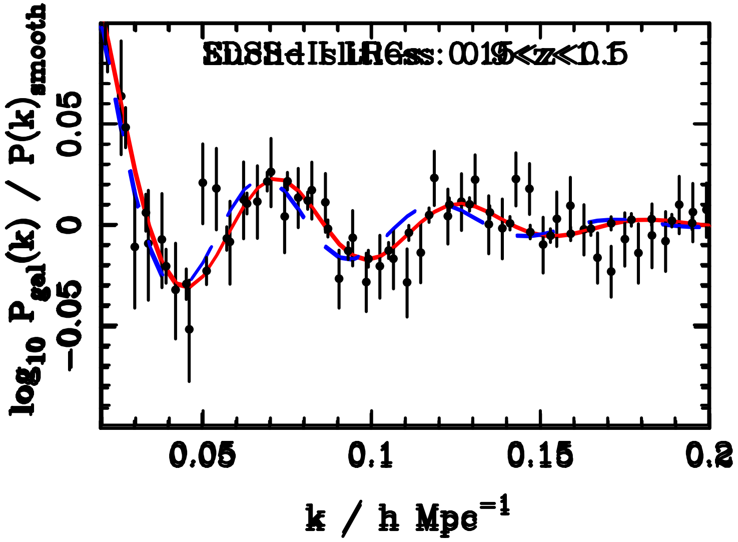
2023 was an exciting year!





Euclid: a phenomenal redshift survey

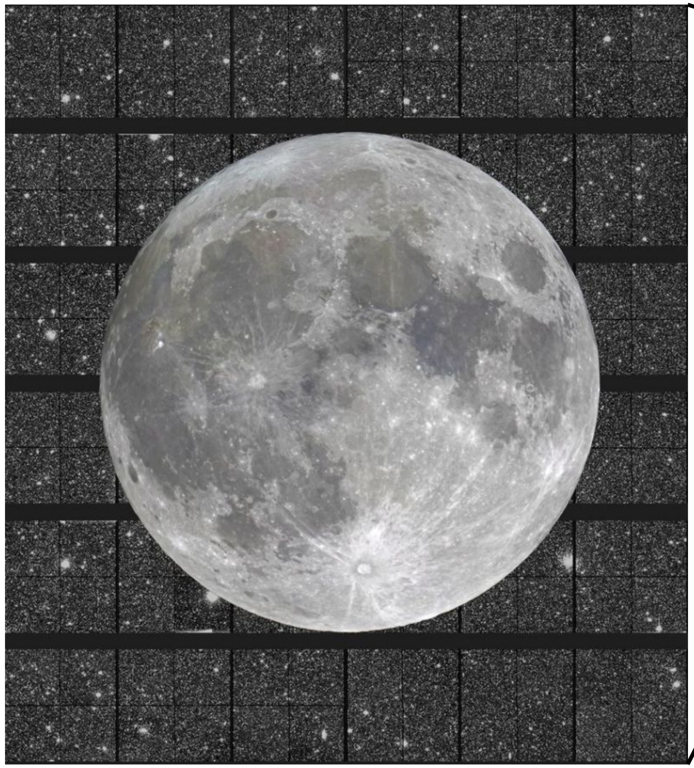


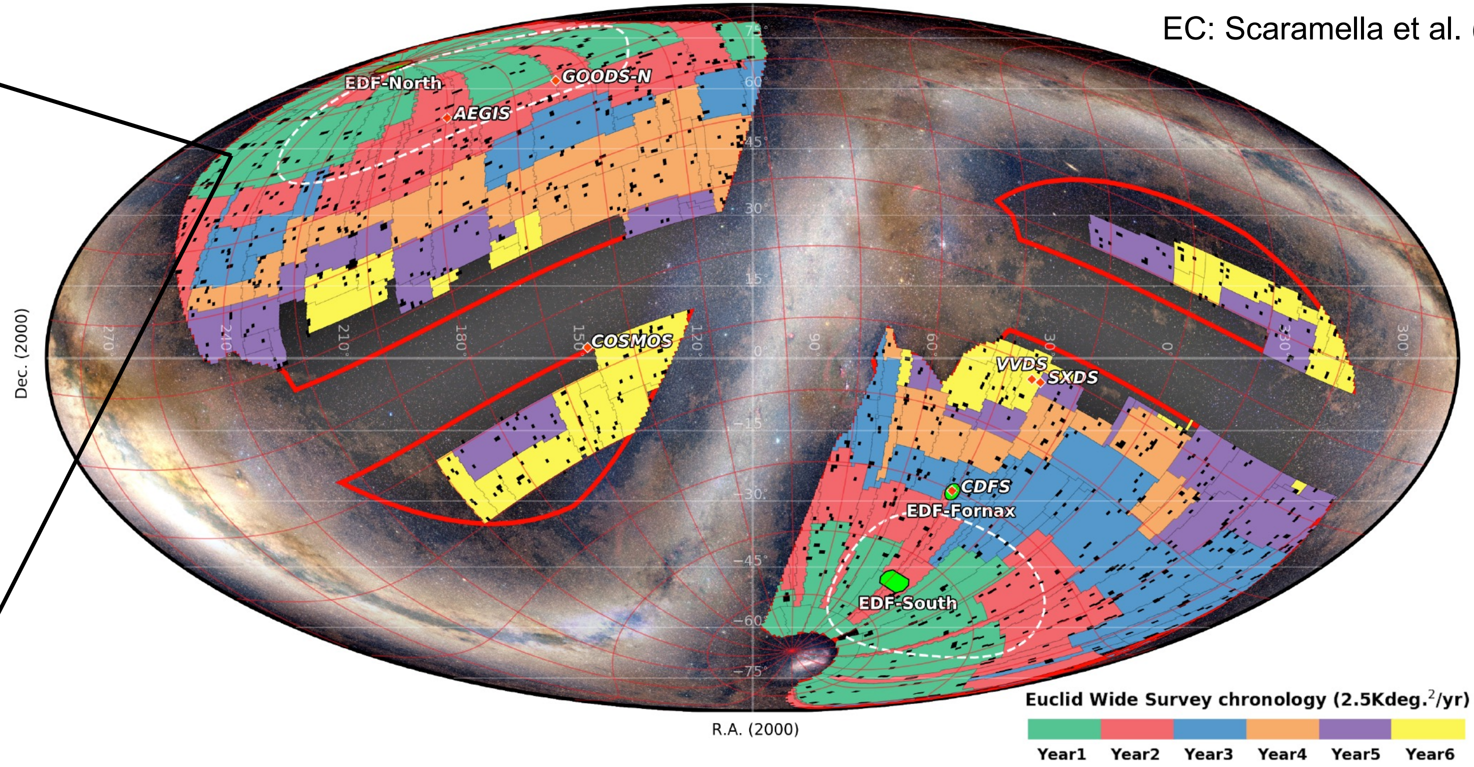


By dispersing the light in the field-of-view we obtain (overlapping) spectra for all objects. This enables *Euclid* to measure redshifts for about 35 million galaxies

Euclid: a high-definition view of the Universe

EC: Scaramella et al. (2022)

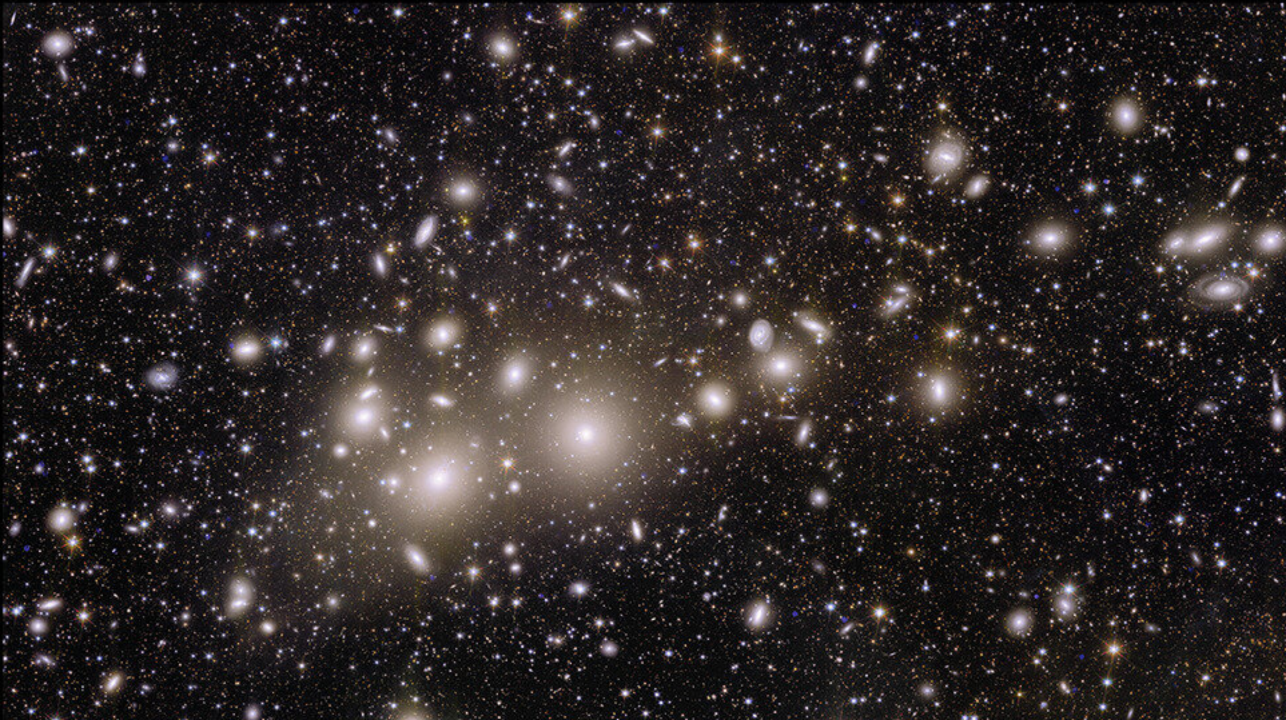




Euclid will provide a high-definition view of 1/3 of the sky allowing us to measure shapes for about 1.5 billion galaxies. This enormous data set has the potential to lead to many other discoveries.







→ THE EUROPEAN SPACE AGENCY

A lot of potential information

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:
positions
shapes
redshifts
PSF errors
…

Covariance
cosmology
survey properties
…

Theory vector:
cosmology
new physics!
baryon physics
intrinsic alignments
…

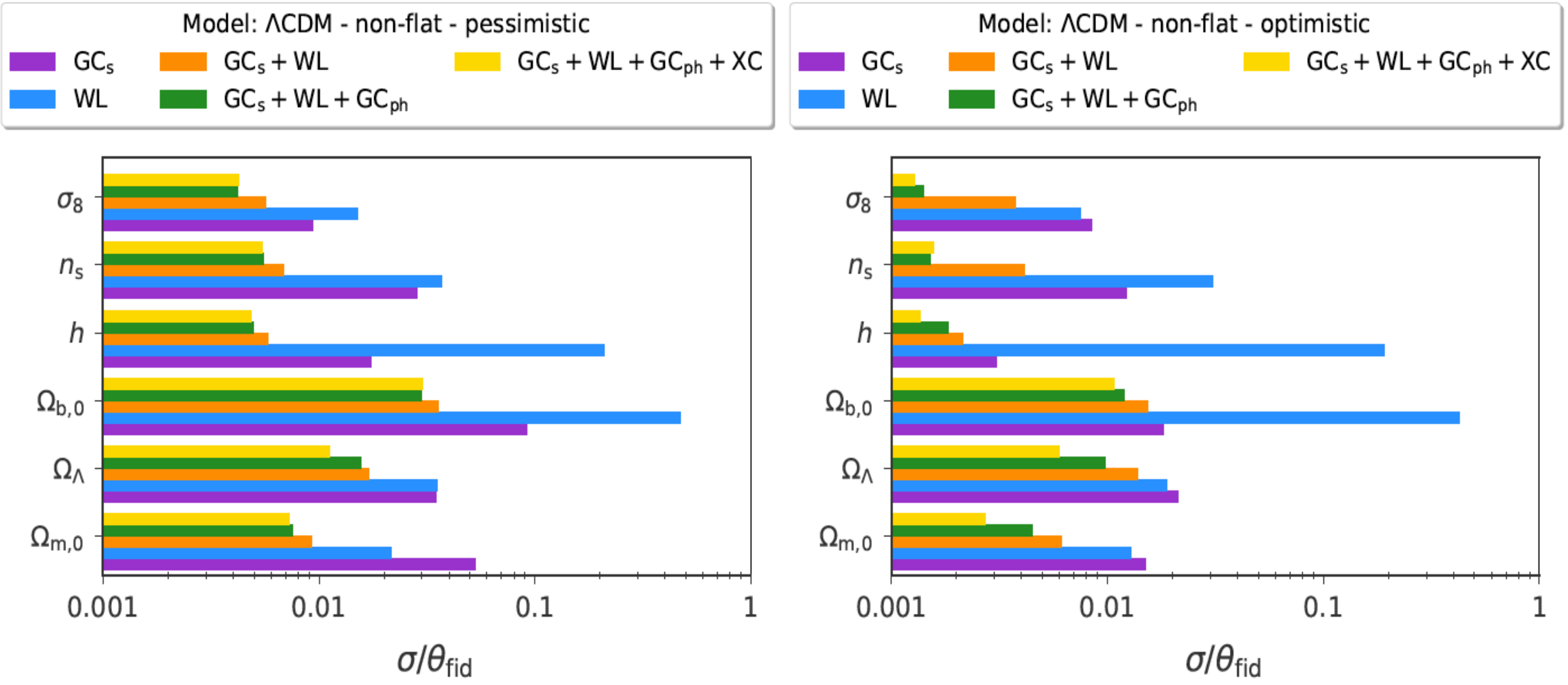
Including small scales helps a lot

Pessimistic settings:

$$k_{\rm max}(\mathrm{GC_s}) = 0.25\, h\,\mathrm{Mpc}^{-1},$$
$$\ell_{\rm max}(\mathrm{WL}) = 1500,$$
$$\ell_{\rm max}(\mathrm{GC_{ph}}) = \ell_{\rm max}(\mathrm{XC}^{(\mathrm{GC_{ph}},\mathrm{WL})}) = 750,$$

Optimistic settings:

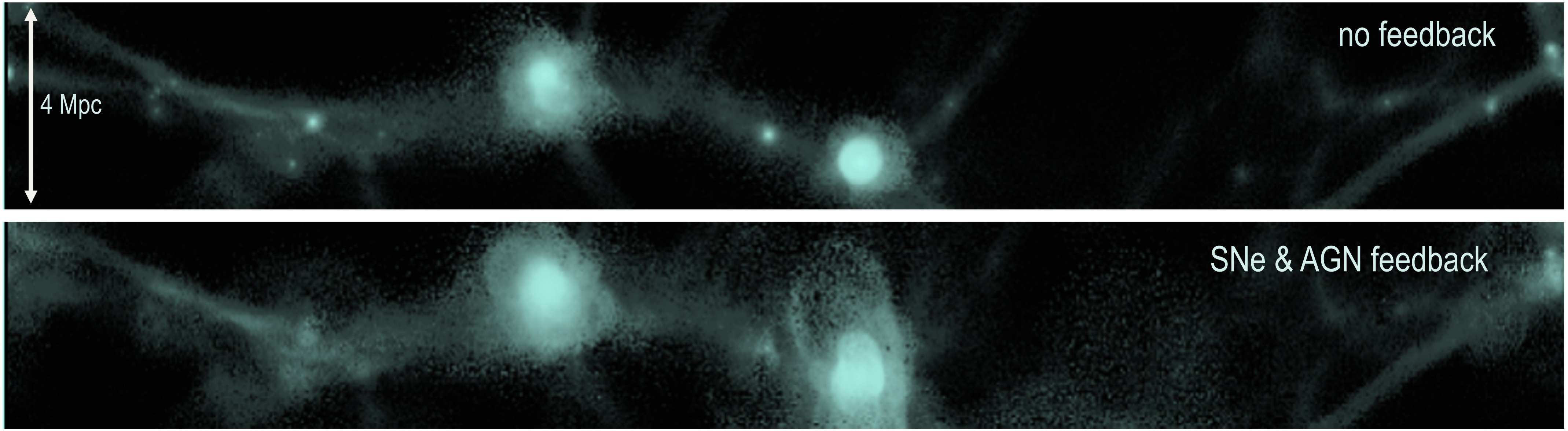
$$k_{\rm max}(\mathrm{GC_s}) = 0.3\, h\,\mathrm{Mpc}^{-1}, \text{with fixed } \sigma_{\rm p} \text{ and } \sigma_{\rm v},$$
$$\ell_{\rm max}(\mathrm{WL}) = 5000,$$
$$\ell_{\rm max}(\mathrm{GC_{ph}}) = \ell_{\rm max}(\mathrm{XC}^{(\mathrm{GC_{ph}},\mathrm{WL})}) = 3000.$$



Euclid Collaboration: Blanchard et al. (2020)

Different physics on different scales

Distribution of gas particles in EAGLE hydrodynamic simulations (Paillas et al. 2017)



Small scales (<1 Mpc): astrophysics dominates irrespective of cosmological model
Large scales (> 5-10 Mpc): astrophysics can be captured statistically → **cosmology**

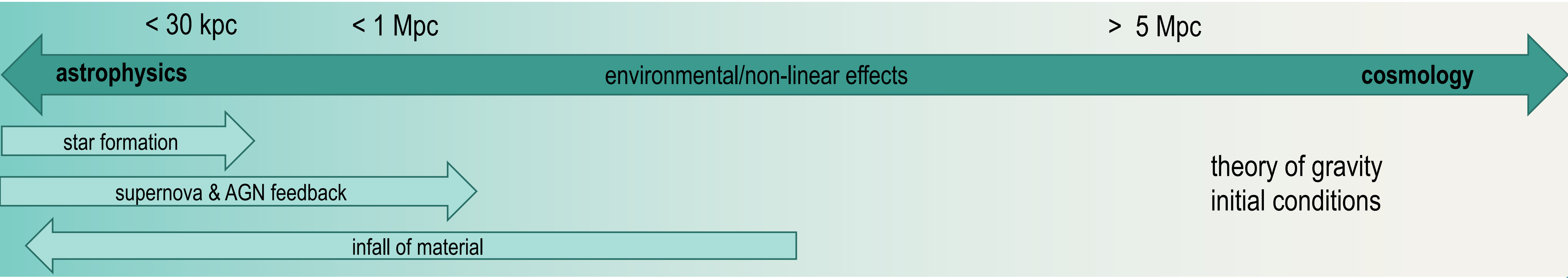
Small scales = opportunity

"True ignorance is not the absence of knowledge, but the refusal to acquire it."
– Karl Popper

nothing can go wrong here

but this is more interesting!

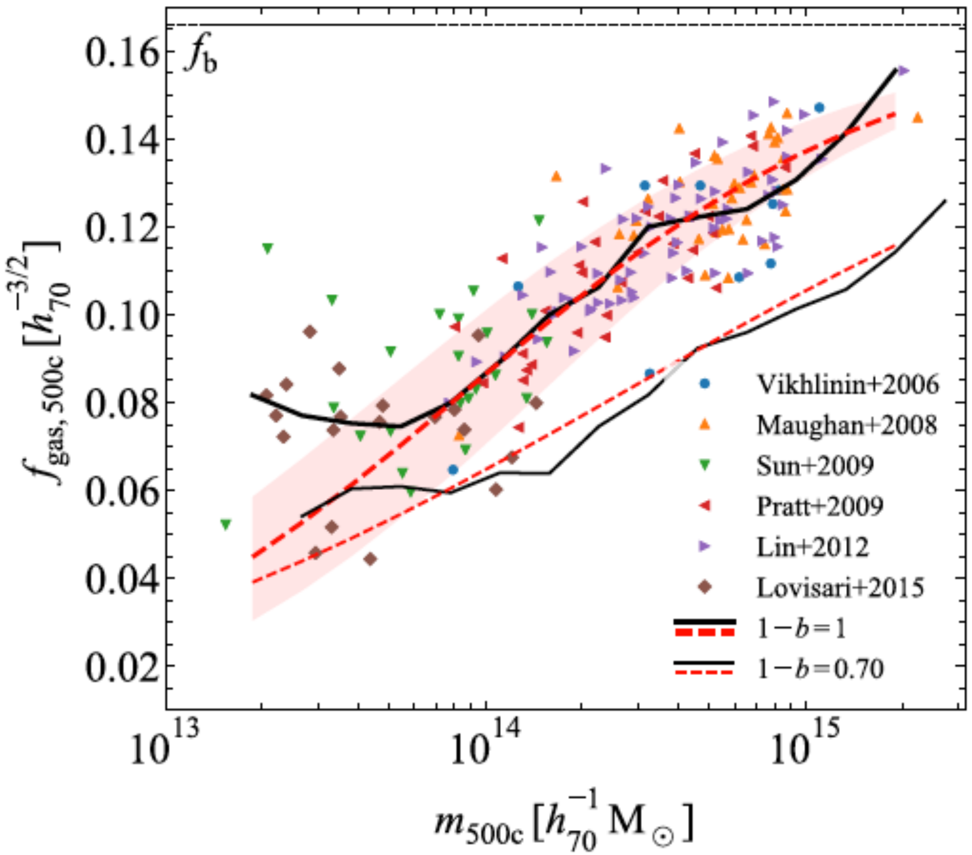
The scales are linked by physics



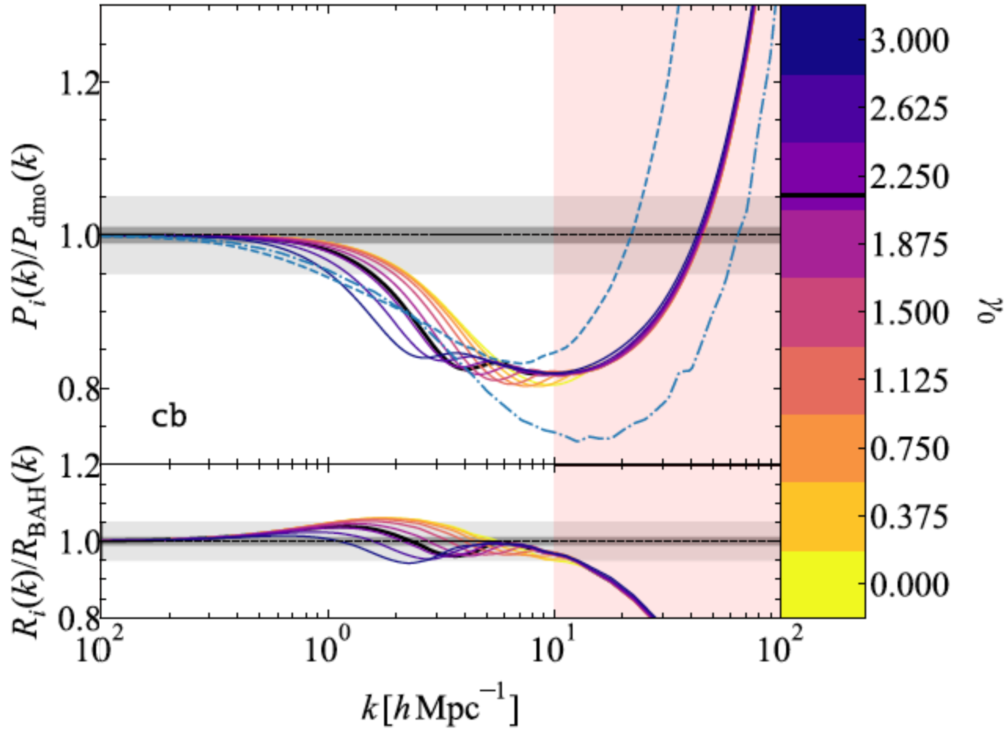
- Small scale measurements: direct measurement efficiency of conversion gas→stars
- Scaling relations with baryonic tracers: constraints on distribution/energetics of ejected hot gas
- Measurements of intrinsic alignments: unique constraints on galaxy assembly

Relies on accurate shape measurements by Euclid

We can observe the effects of feedback

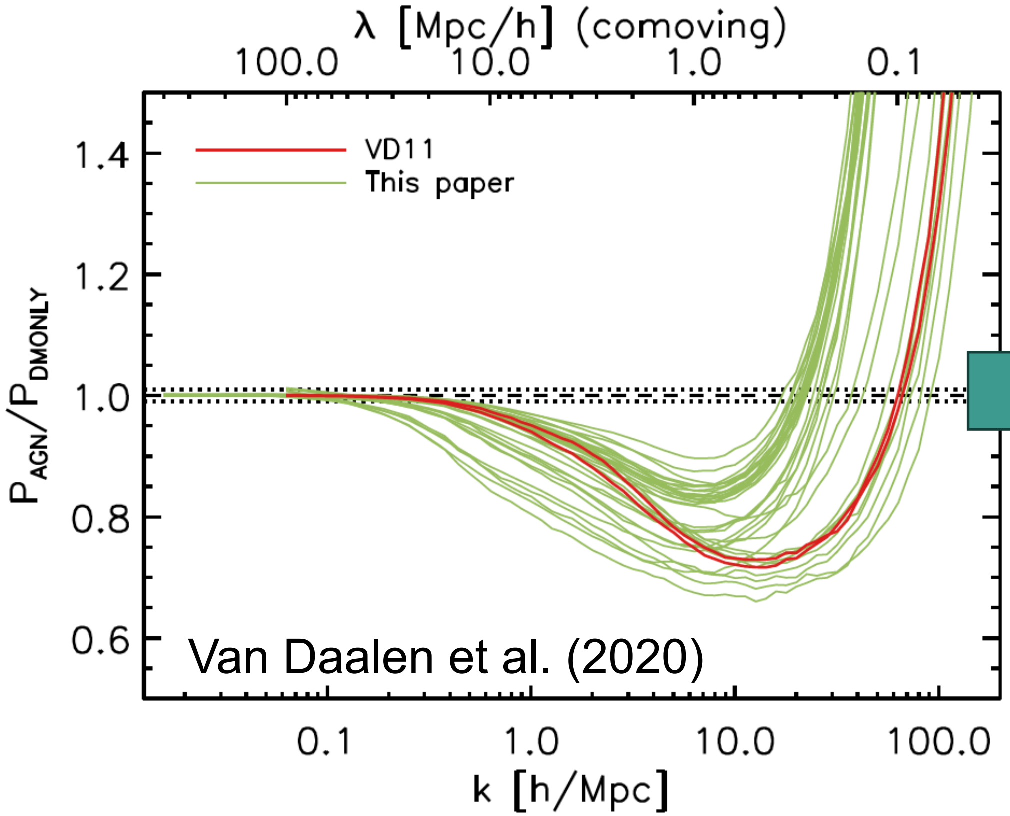


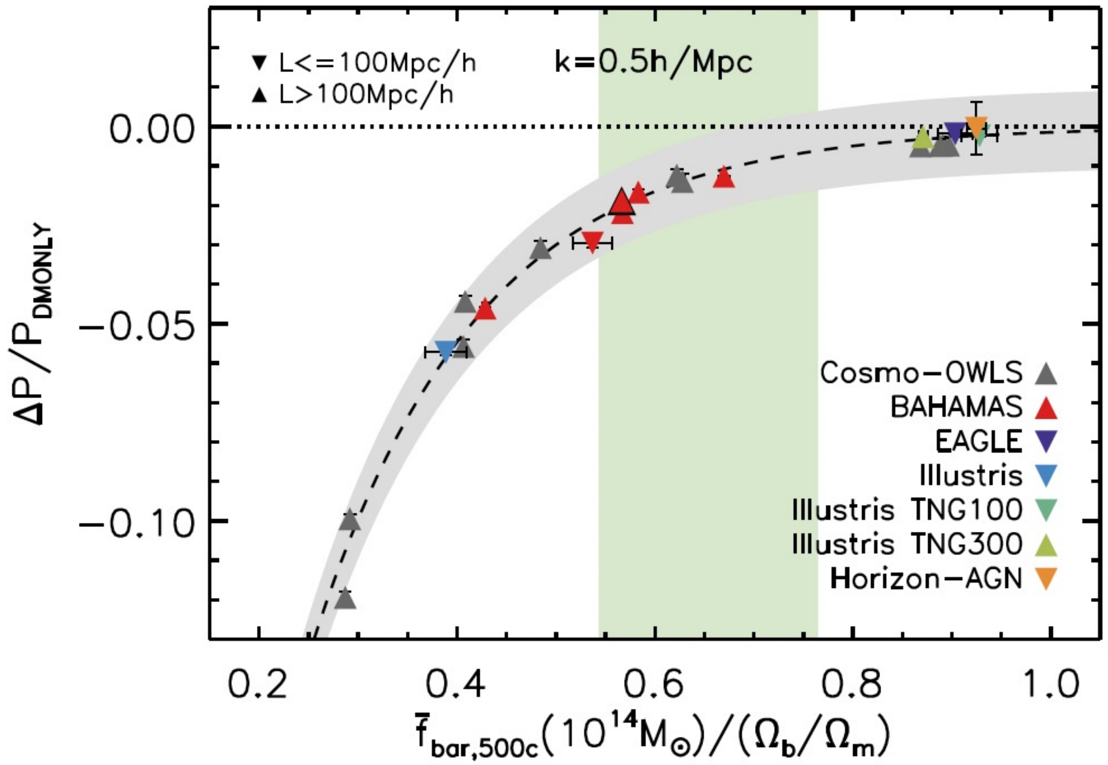
Debackere et al. (2020)



Constraints on the gas distribution in the outskirts of clusters and groups
→ test of hydro simulations + useful priors

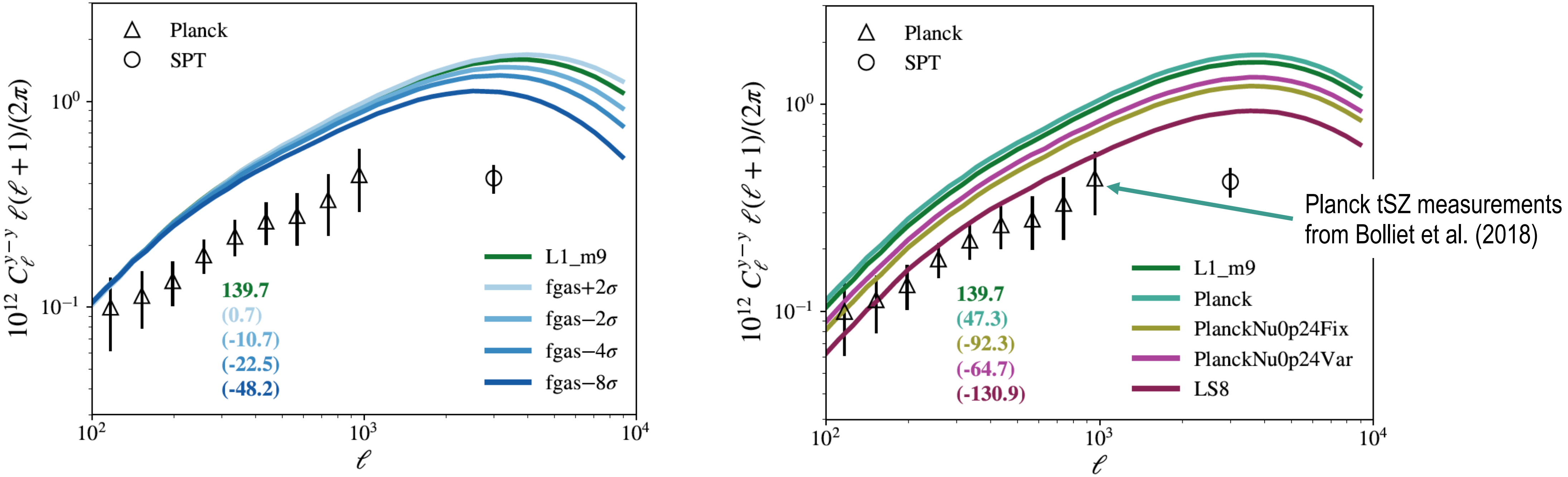
How complicated is the feedback really?





The mean baryon fraction in 10^{14} $M_{\odot}$ halos at k=0.5h/Mpc is a good indicator of feedback: mostly gravity on relevant scales?

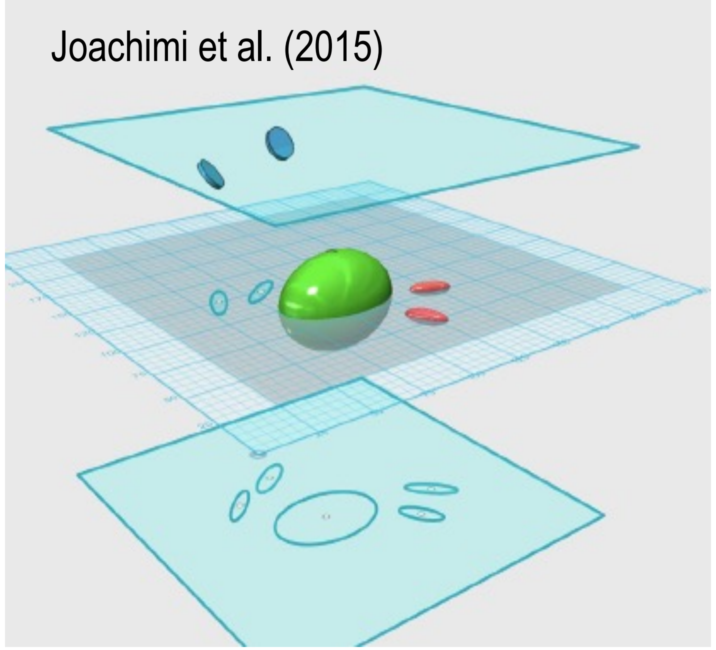
Could this explain the S_8 tension?

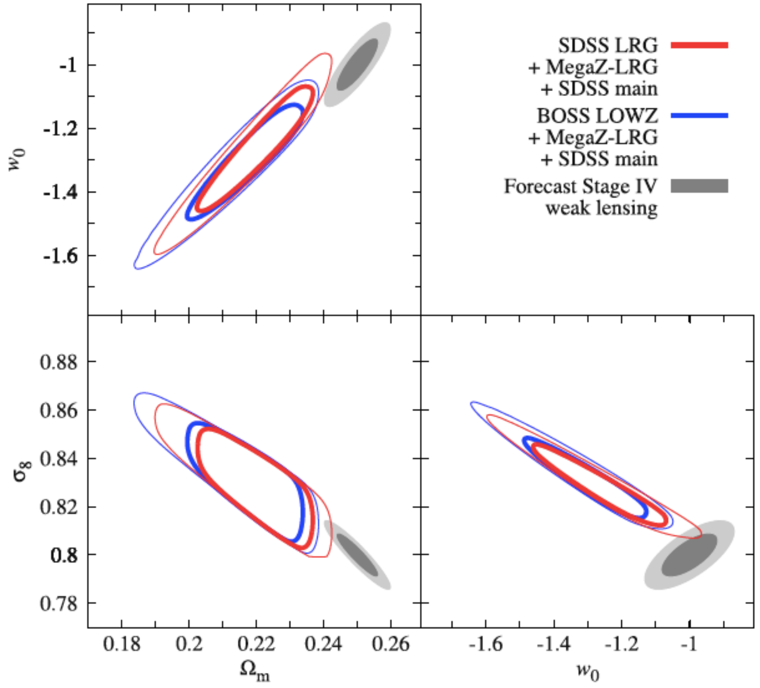


McCarthy et al. (2023): "Despite the wide range of astrophysical behaviours simulated, we find that baryonic effects are not sufficiently large to remove the *S*8 tension … some mechanism is required to slow the growth of fluctuations at late times and/or on non-linear scales, but that it is unlikely that baryon physics is driving this modification.

Intrinsic alignments

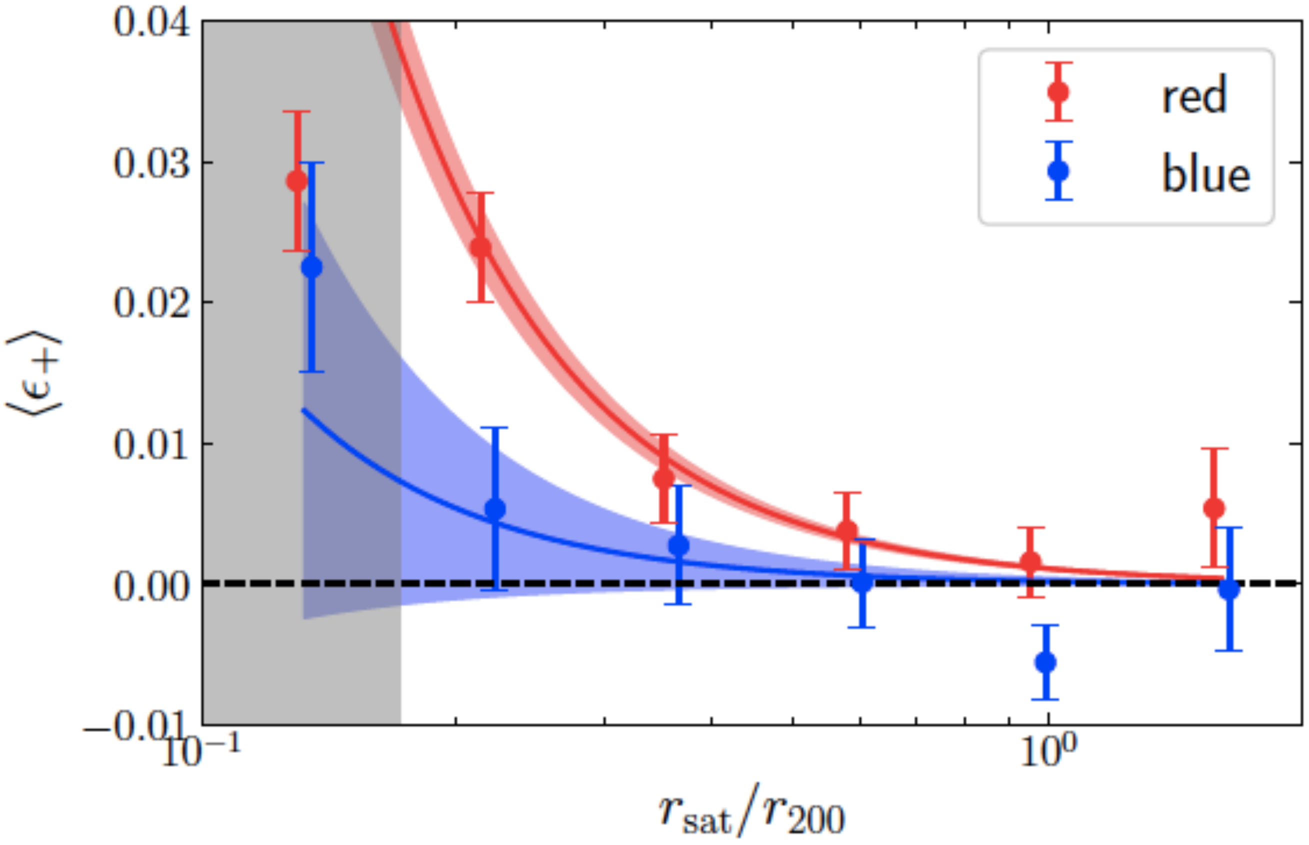
Gravitational lensing introduces *apparent* alignments in the shapes of galaxies, but local tidal effects may align galaxies *intrinsically*.





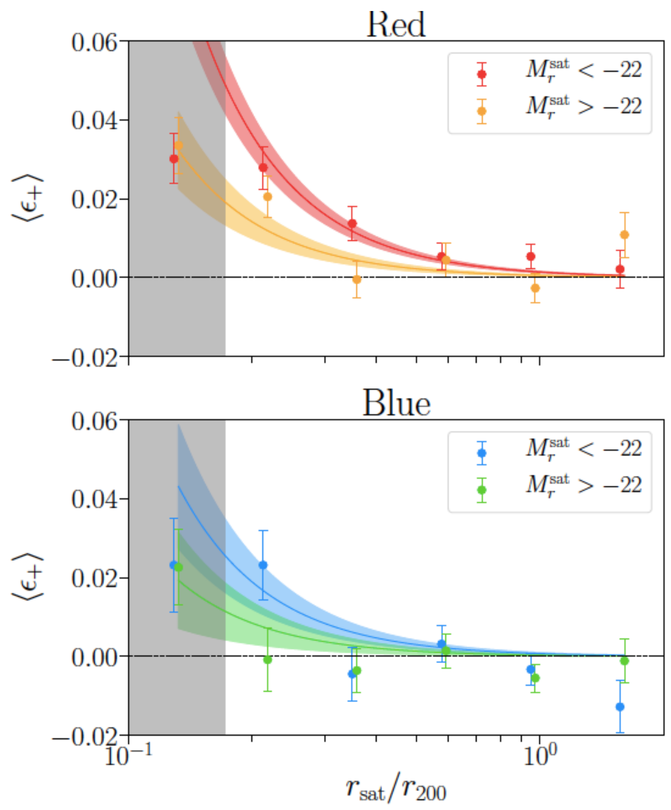
The amplitude of these *intrinsic alignments* depends on the complex physics of galaxy formation. They are small, but cannot be ignored!

Intrinsic alignments of satellites



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

A consistent model of intrinsic alignments



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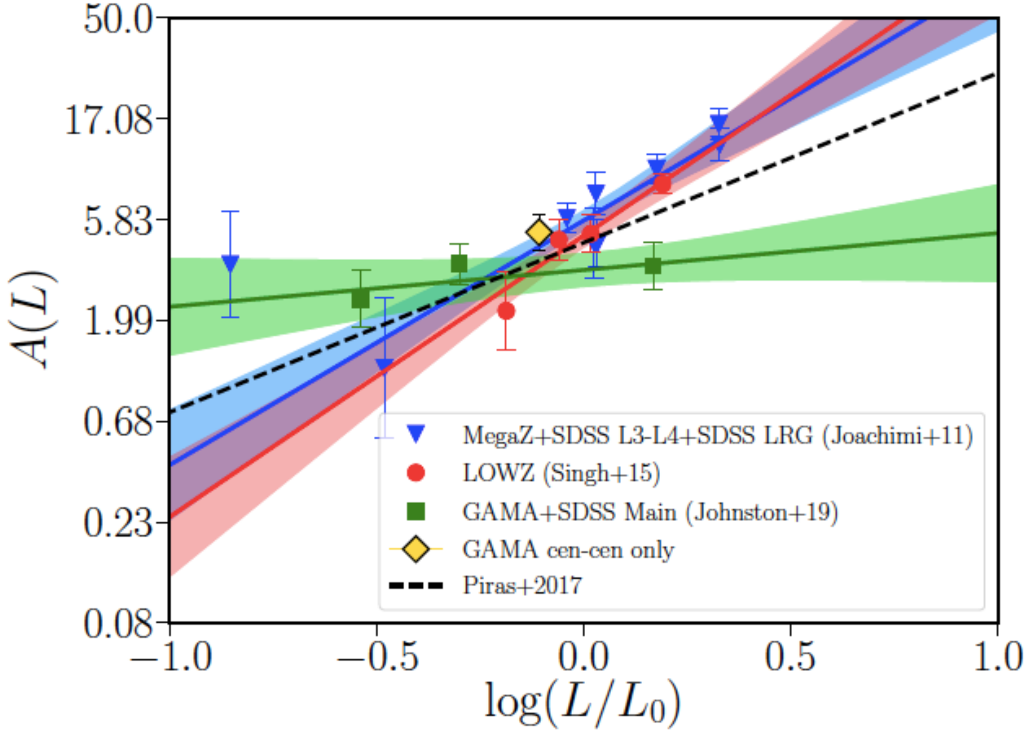
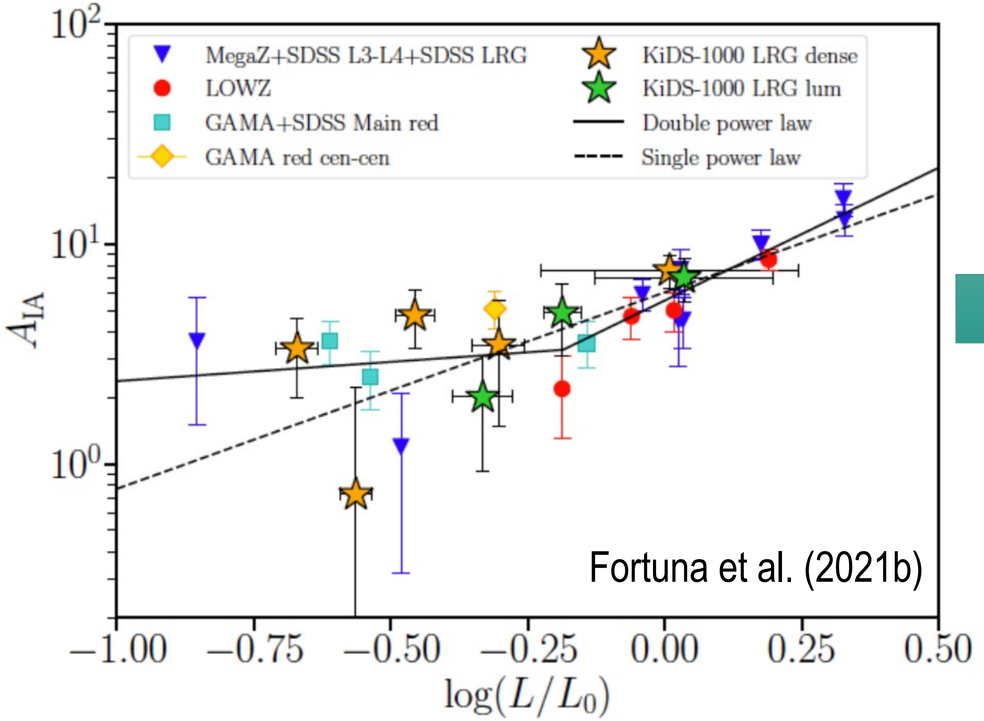
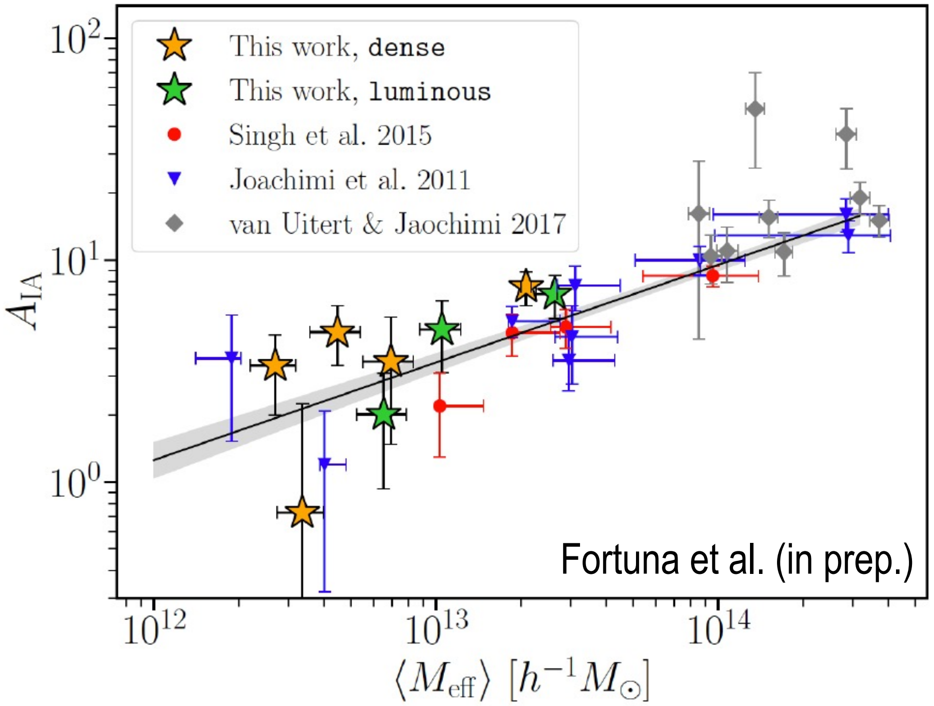


Fortuna et al. (2021): halo model approach that uses observational constraints on blue/red galaxies to predict the alignment signal.

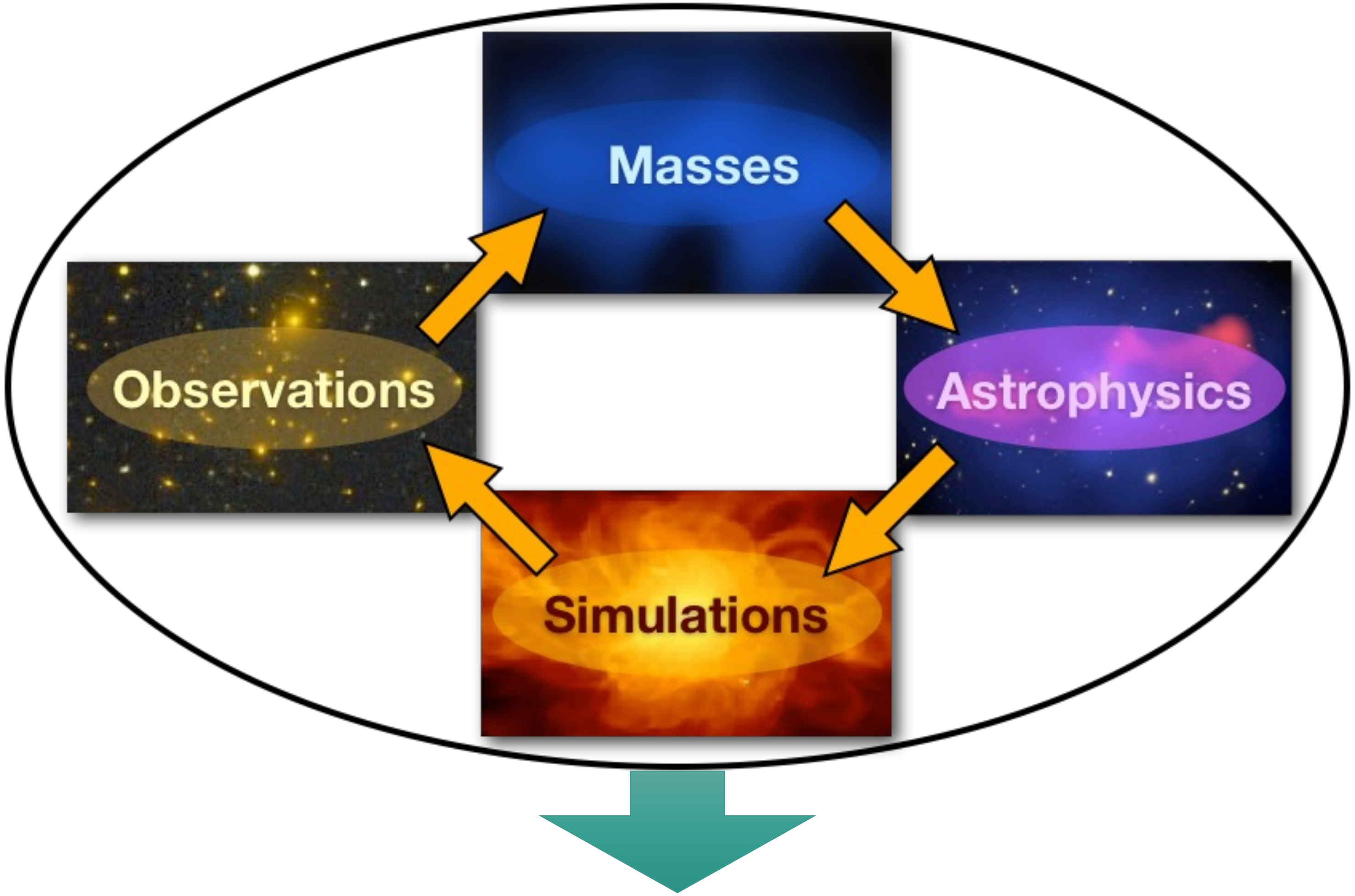
A consistent model of intrinsic alignments





We probed lower luminosity LRGs using KiDS and found a more complex dependence with luminosity. However, the relation with halo mass may be simpler (after all alignments are a function of mass to first order).

Unlocking the potential of large-scale structure



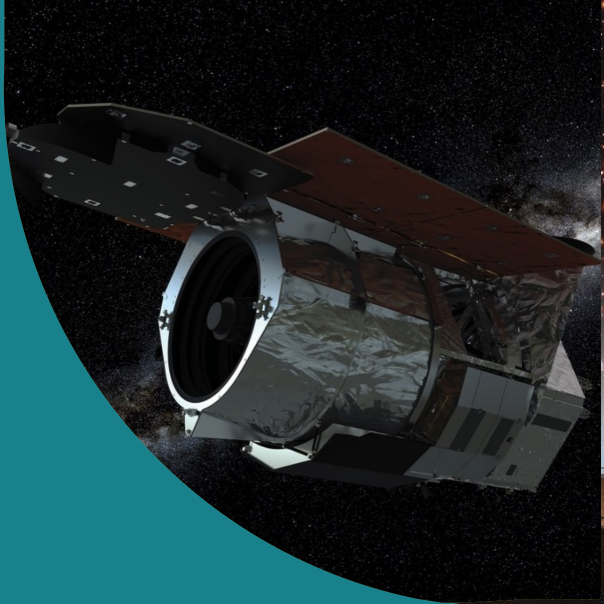
cosmology **and** galaxy formation

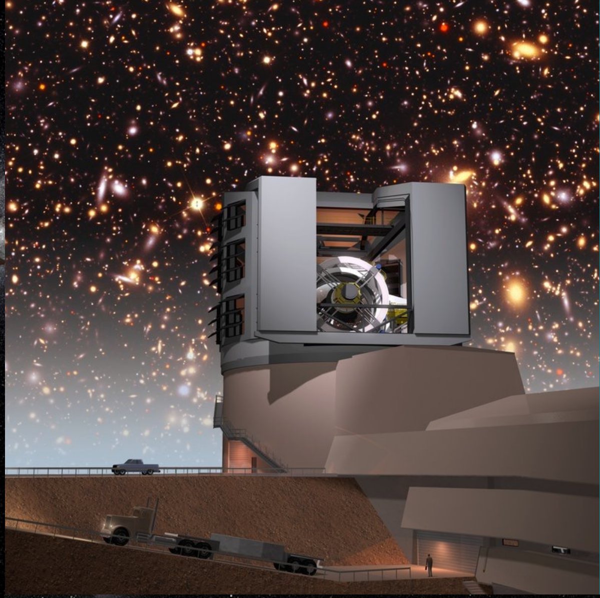
Conclusions

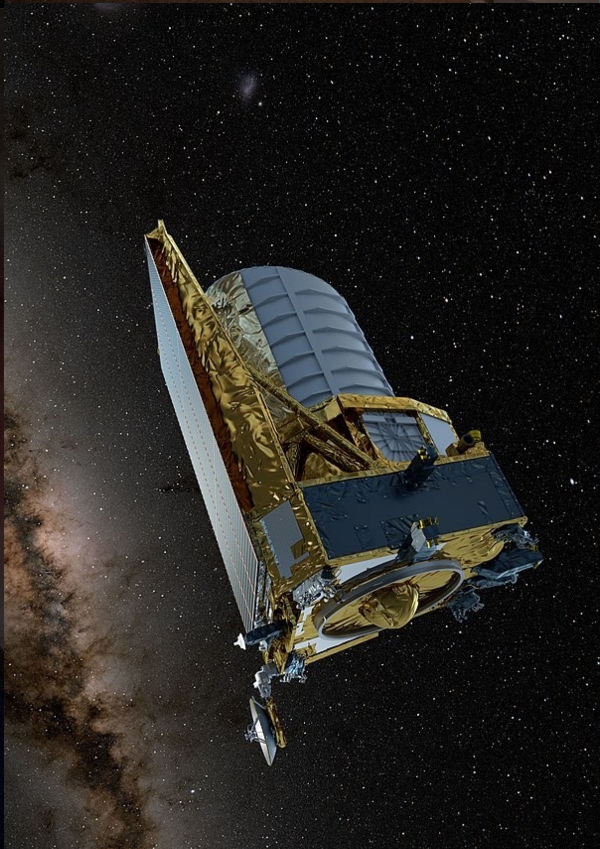
Progress in cosmology in the coming decade will come from mapping the large-scale structure.

- (sub)percent constraints on dark energy parameters
- detection of the sum of neutrino masses
- unique tests of general relativity

… and much more!







Thank You