Weak Lensing & Systematics

Slides from Alexandra Amon's Cargese course and Martin Kilbinger

Fabian Hervas Peters

Weak Lensing resources

Very detailed theoretical reviews, mathematical formalism of lensing:

Bartelman & Schneider 2001, very detailed review

Schneider Sans-Fee proceedings 2004, similar to 2001 but more pedagogical

Kilbinger 2015, a bit more updated and friendlier

Baryonic Feedback:

https://arxiv.org/pdf/1910.11357.pdf Schneider 2019

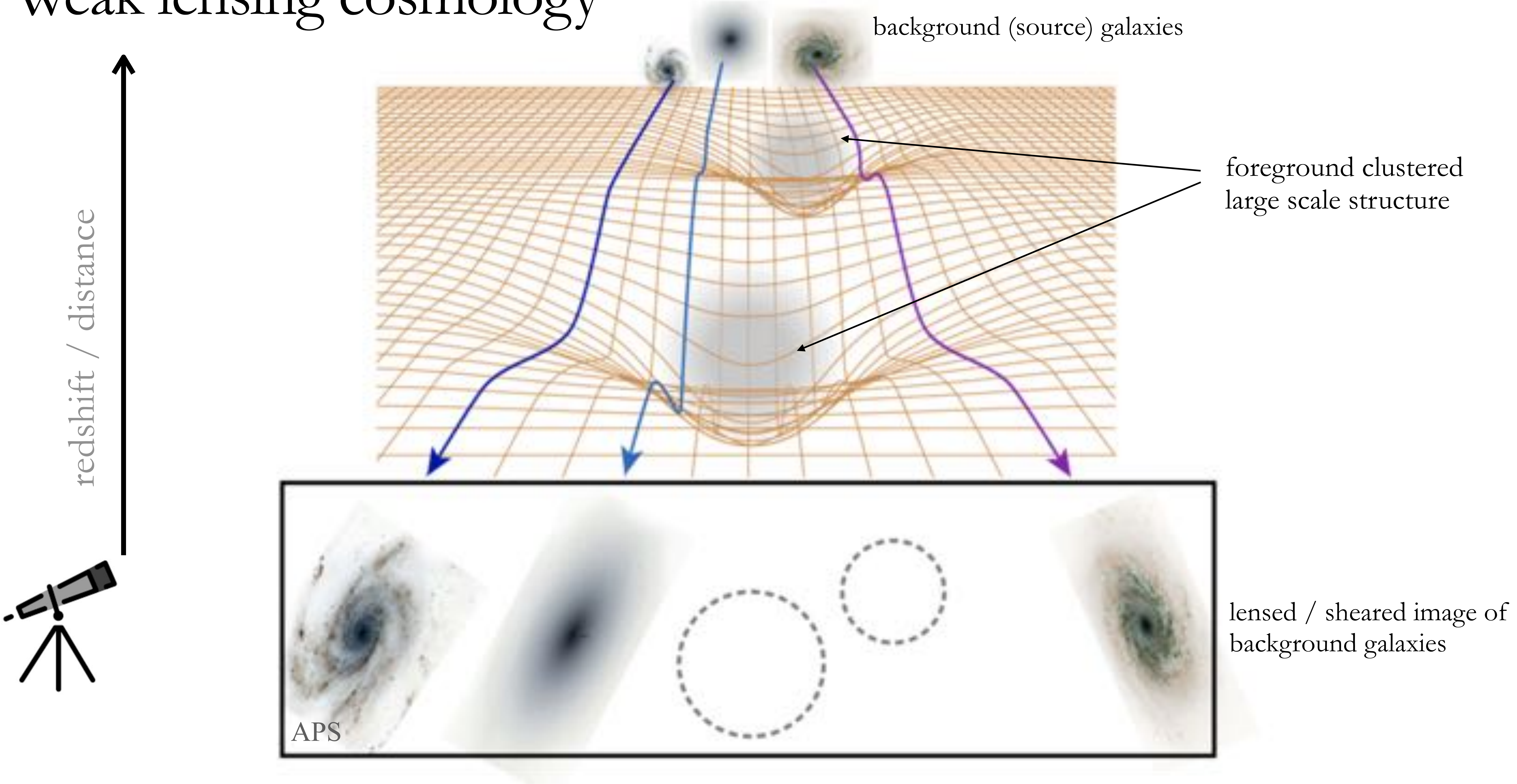
Intrinsic Alignment:

Joachimi 2015, Galaxy alignments an overview

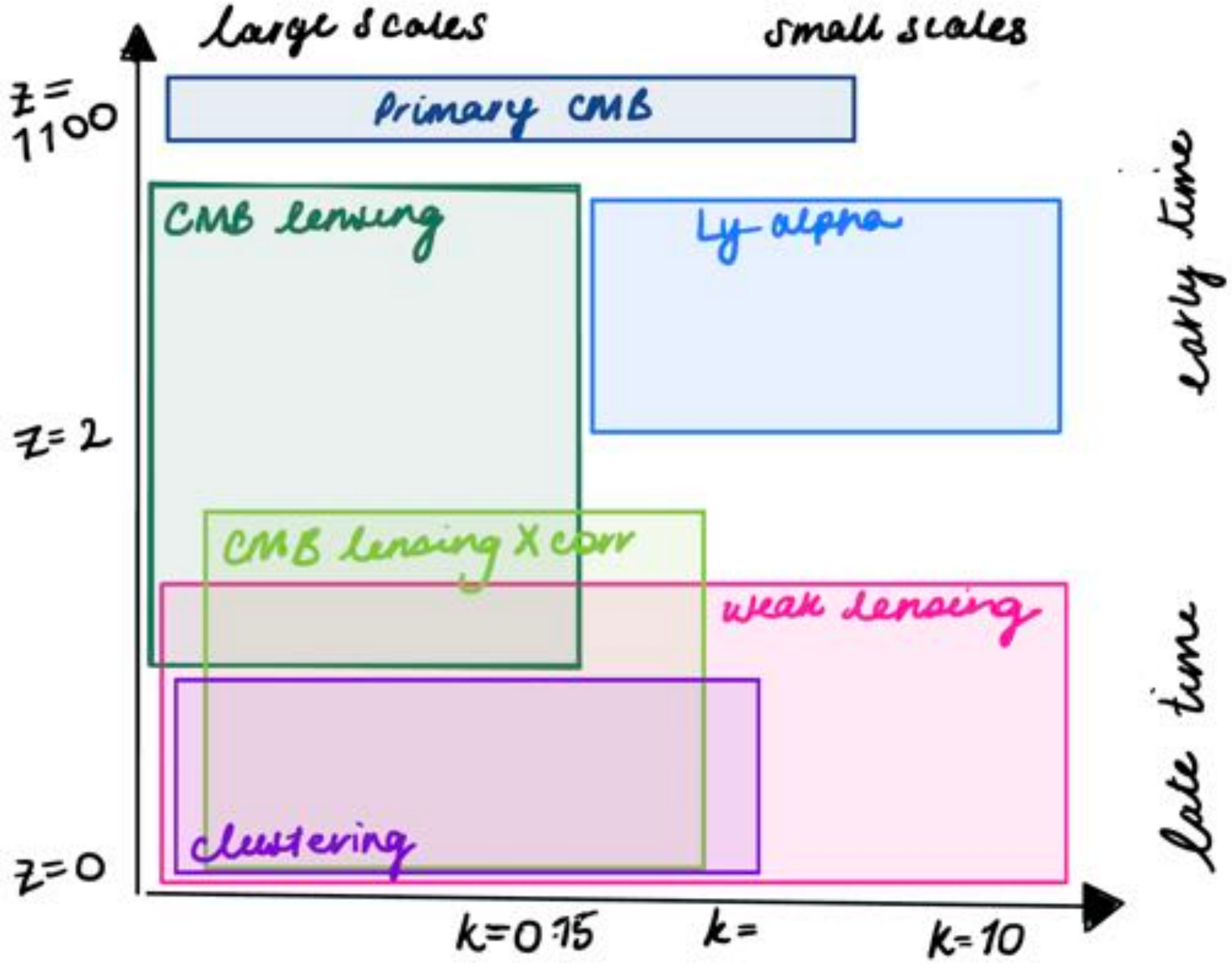
Photo-z, Shape measurement & all systematics:

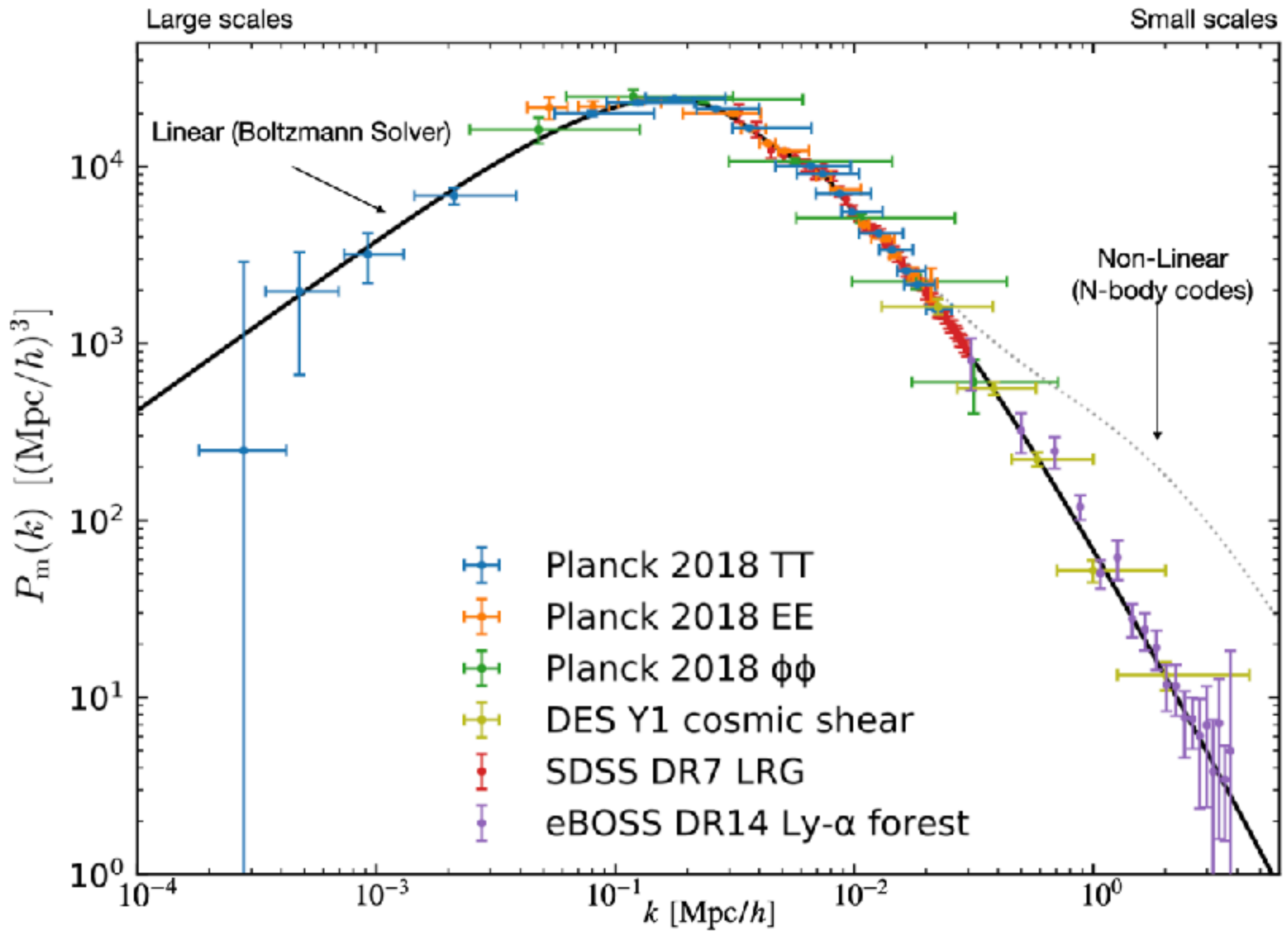
Mandelbaum 2018 https://arxiv.org/pdf/1710.03235.pdf, very comprehensive review of technical challenges

Weak lensing cosmology



Measuring the distribution of matter





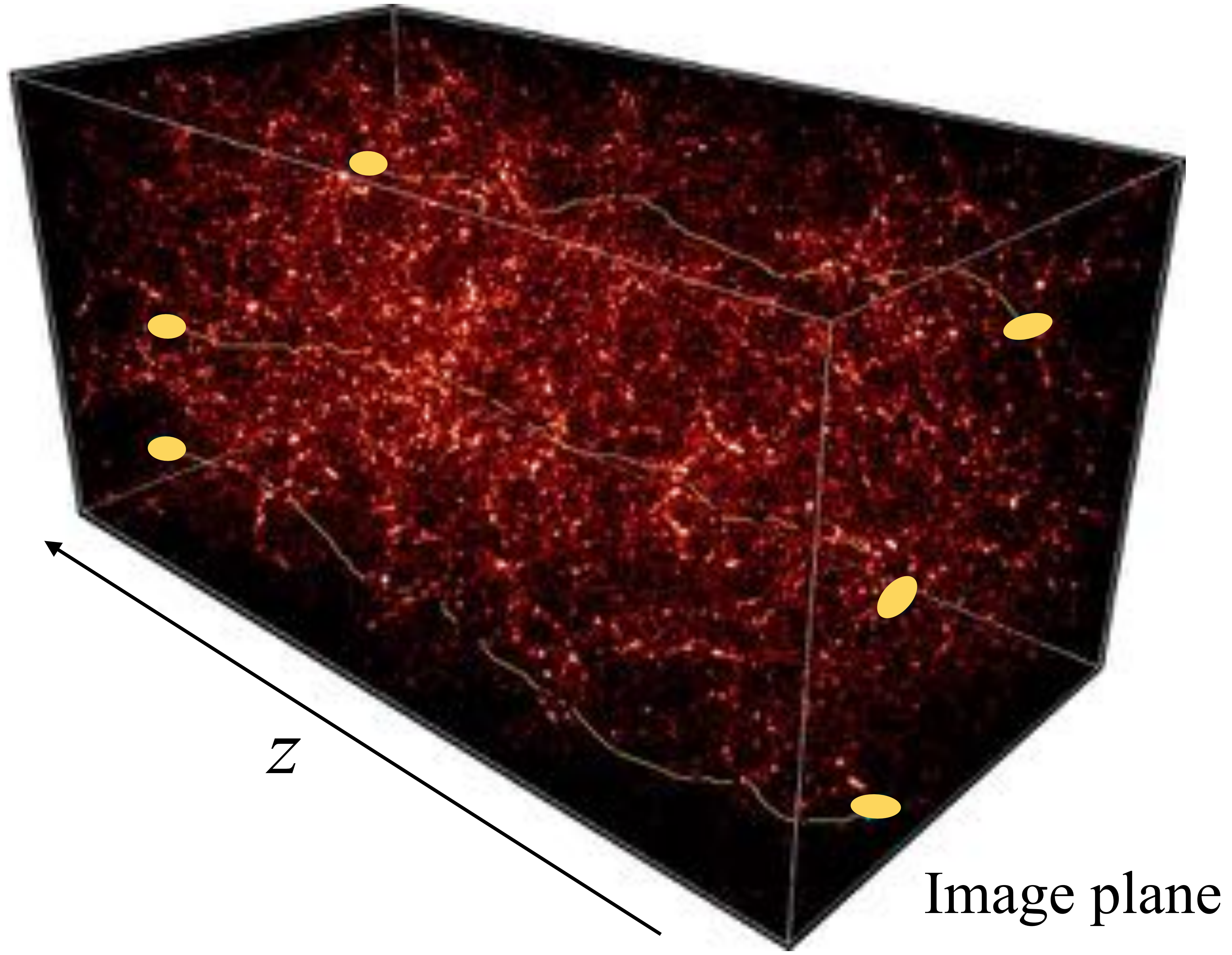
Matter power spectrum

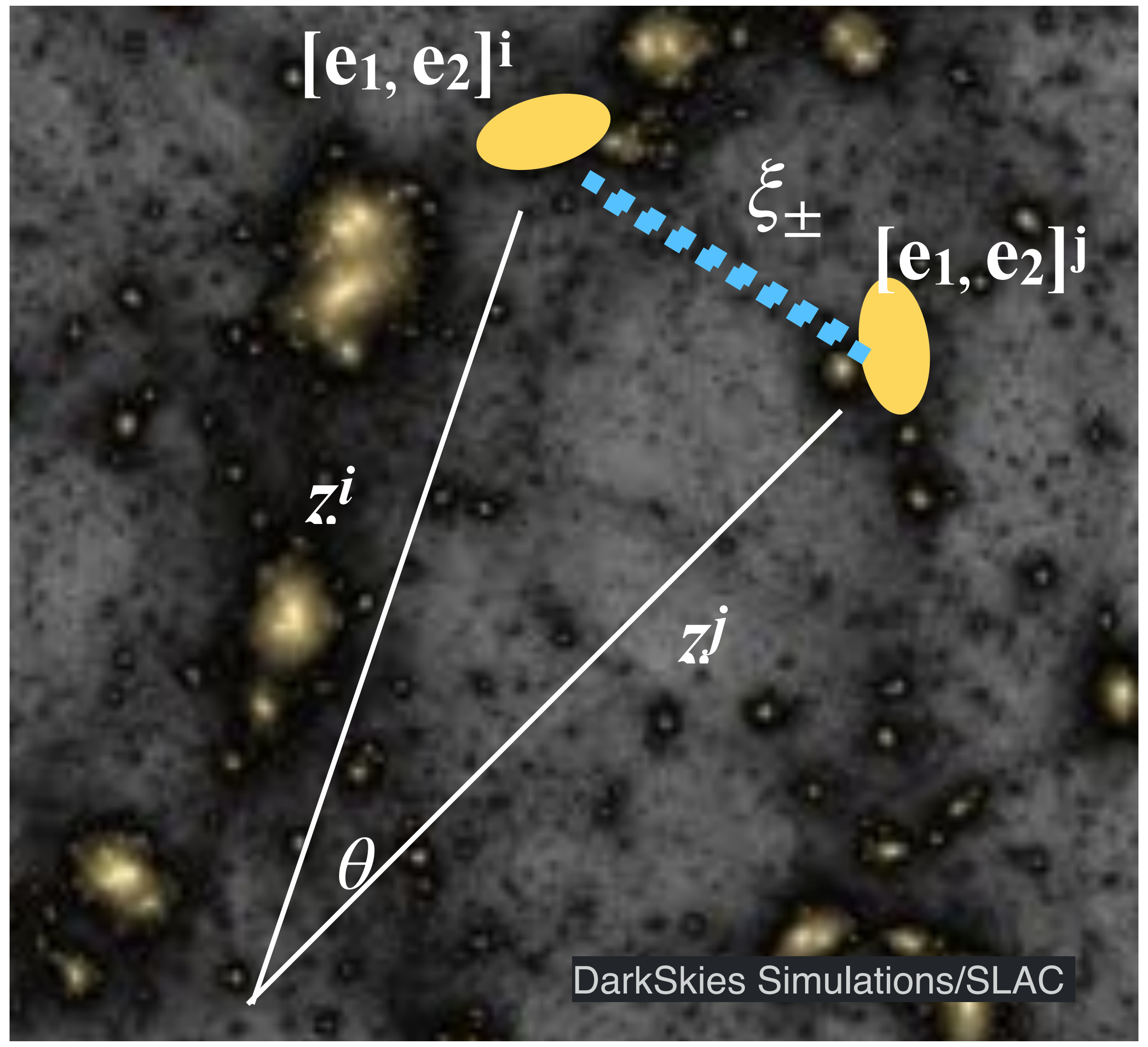
$$P(k) = \langle |\delta_k|^2 \rangle$$

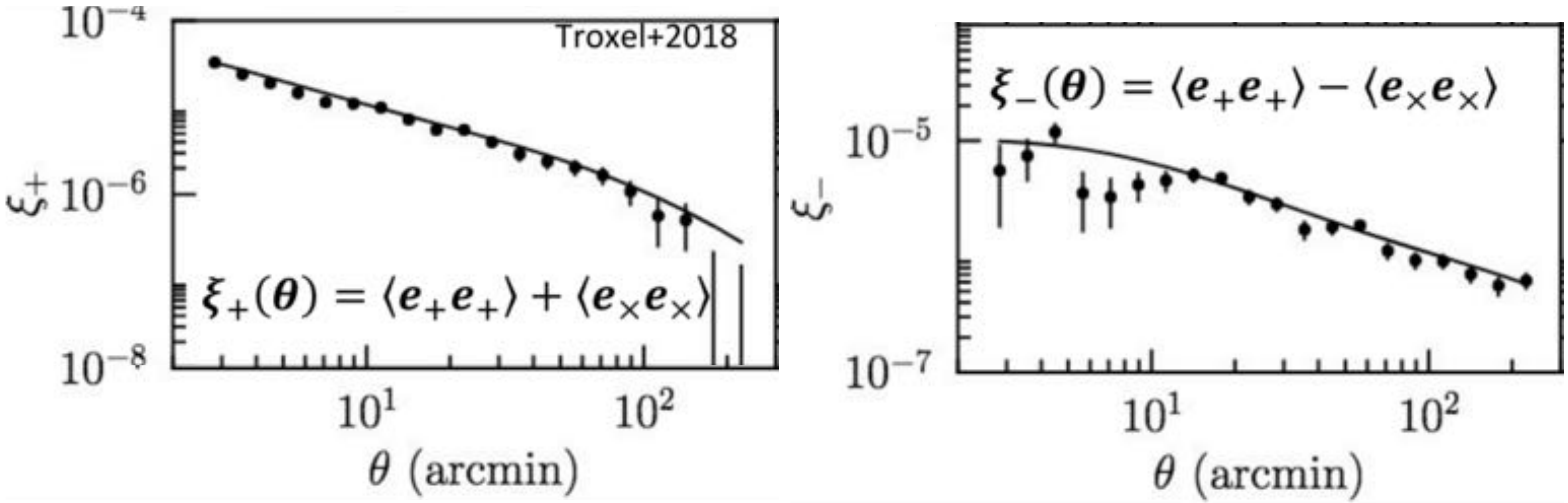
Weak lensing cosmology

Light from distant galaxies passes the same foreground structure.

We measure the correlation of the **shapes** of source galaxy pairs [i,j] as a function of angular radius and to model the signal, we estimate the distribution of redshifts of the galaxy sample.







Weak lensing cosmology

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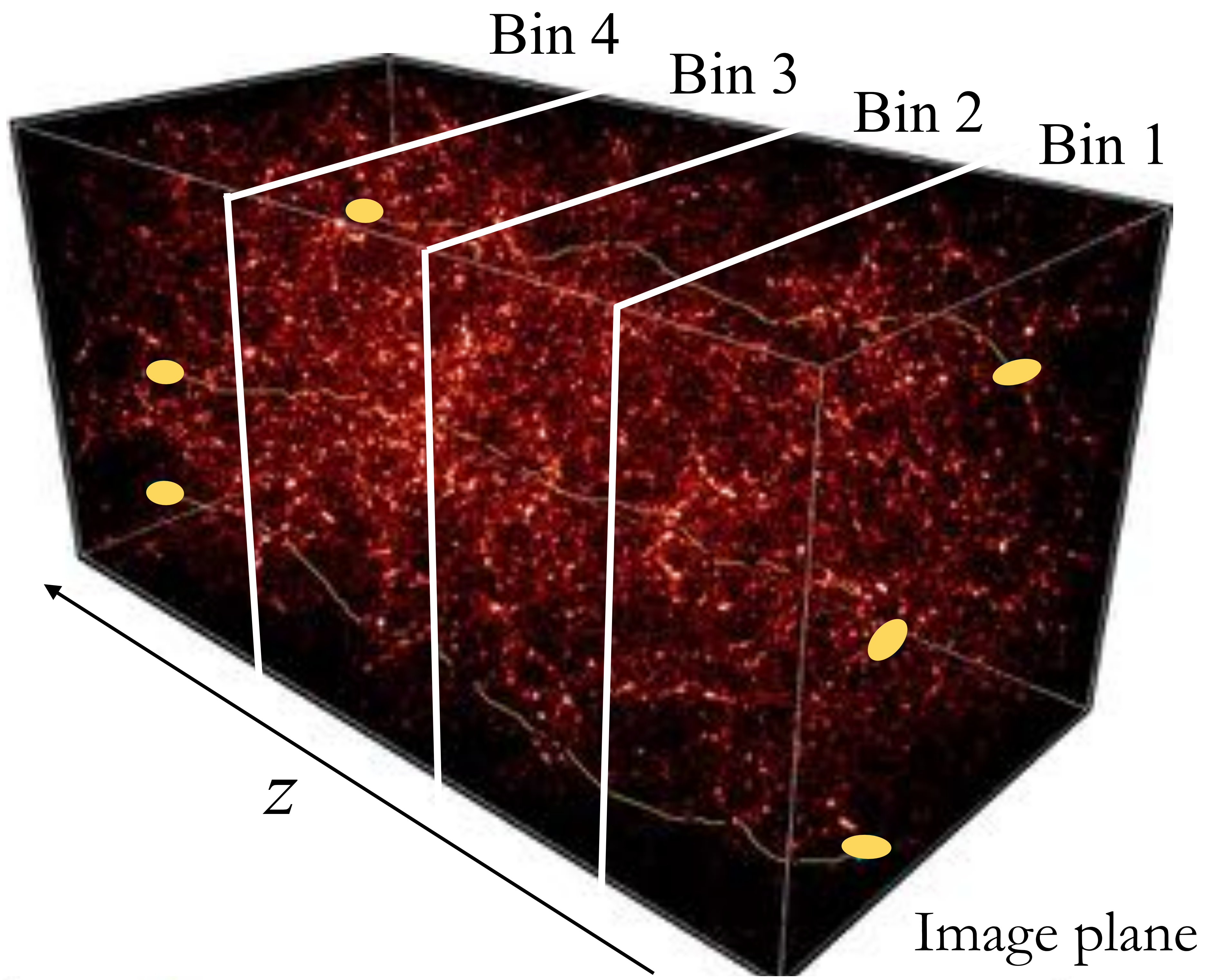
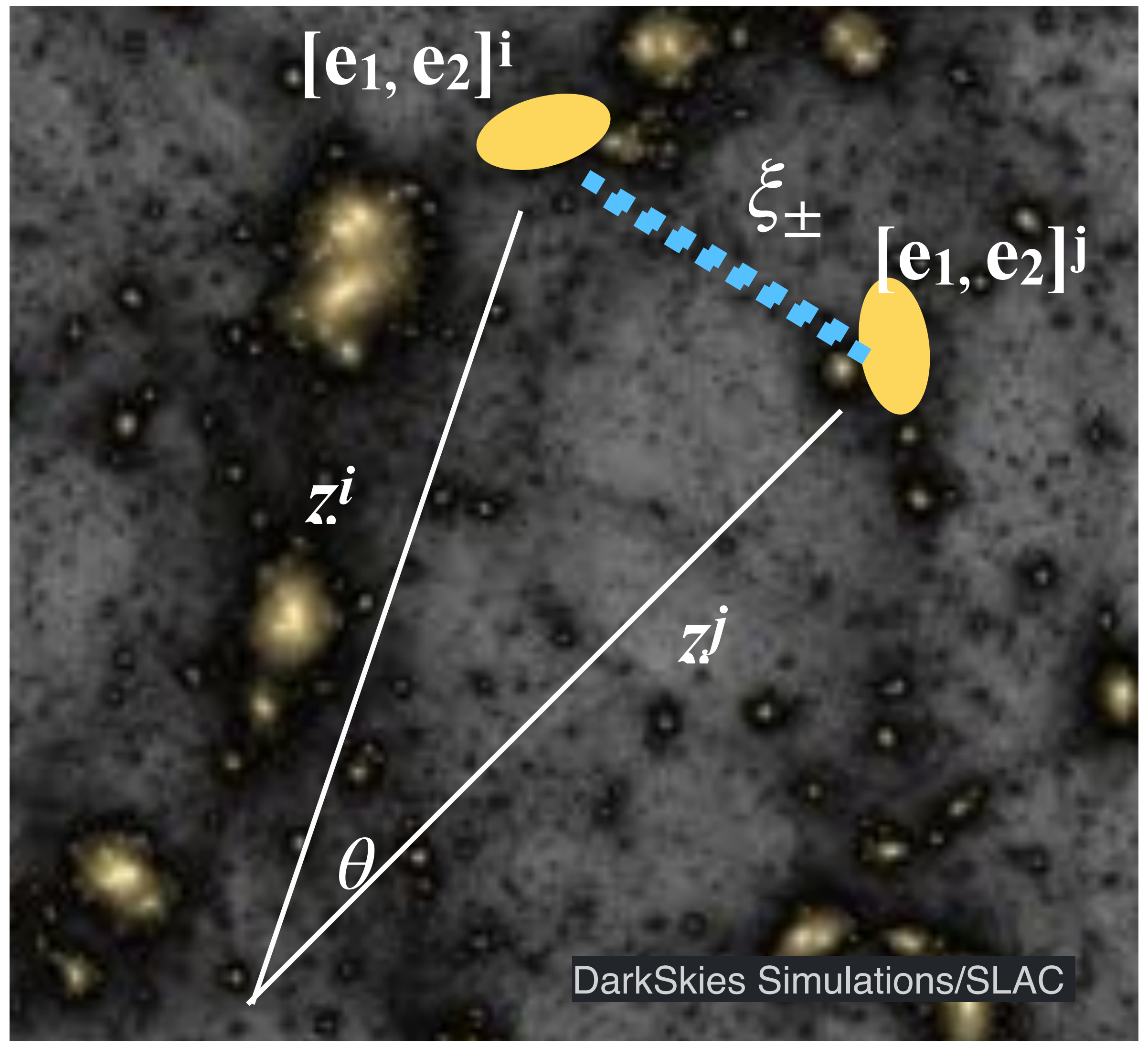
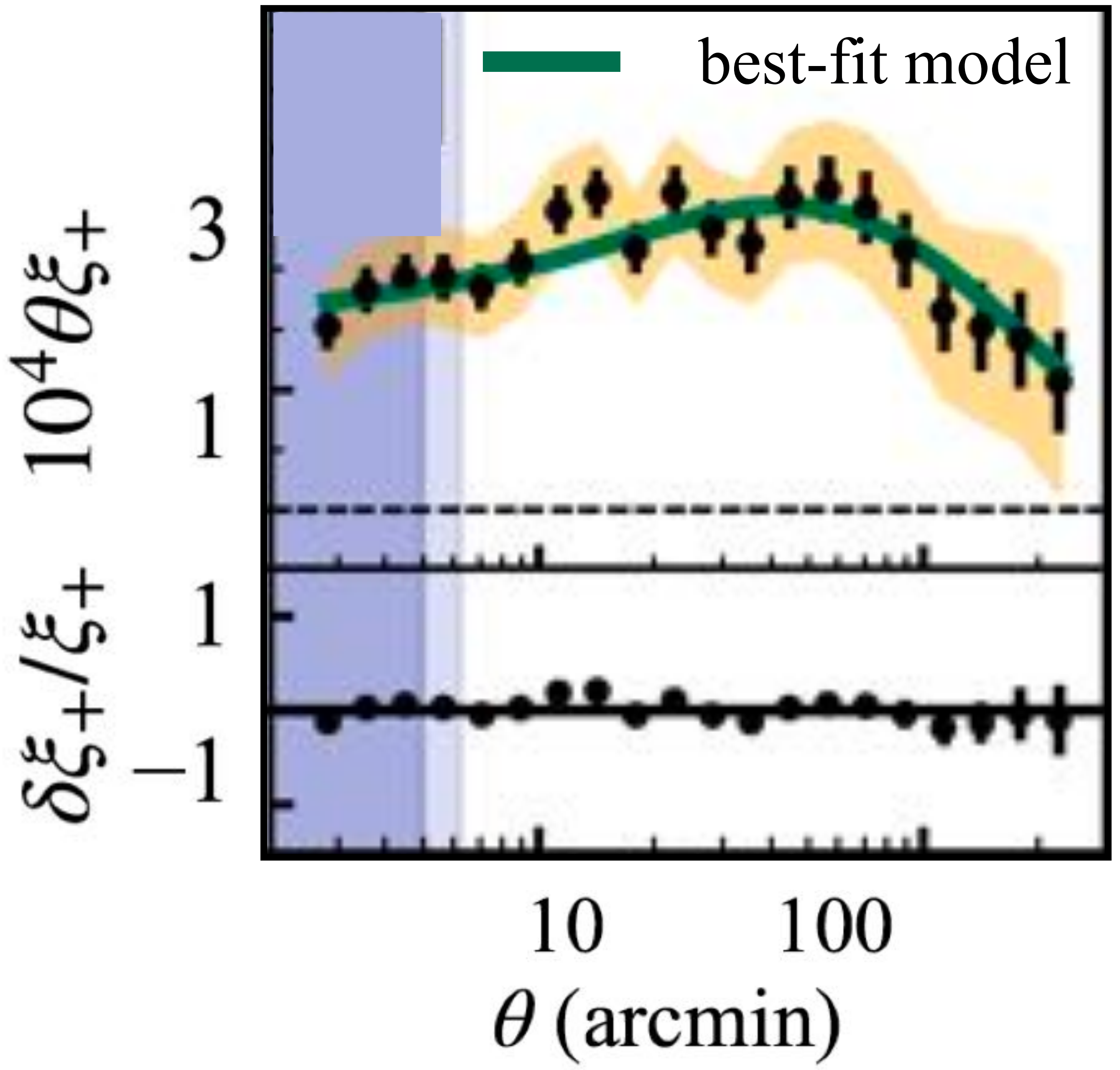
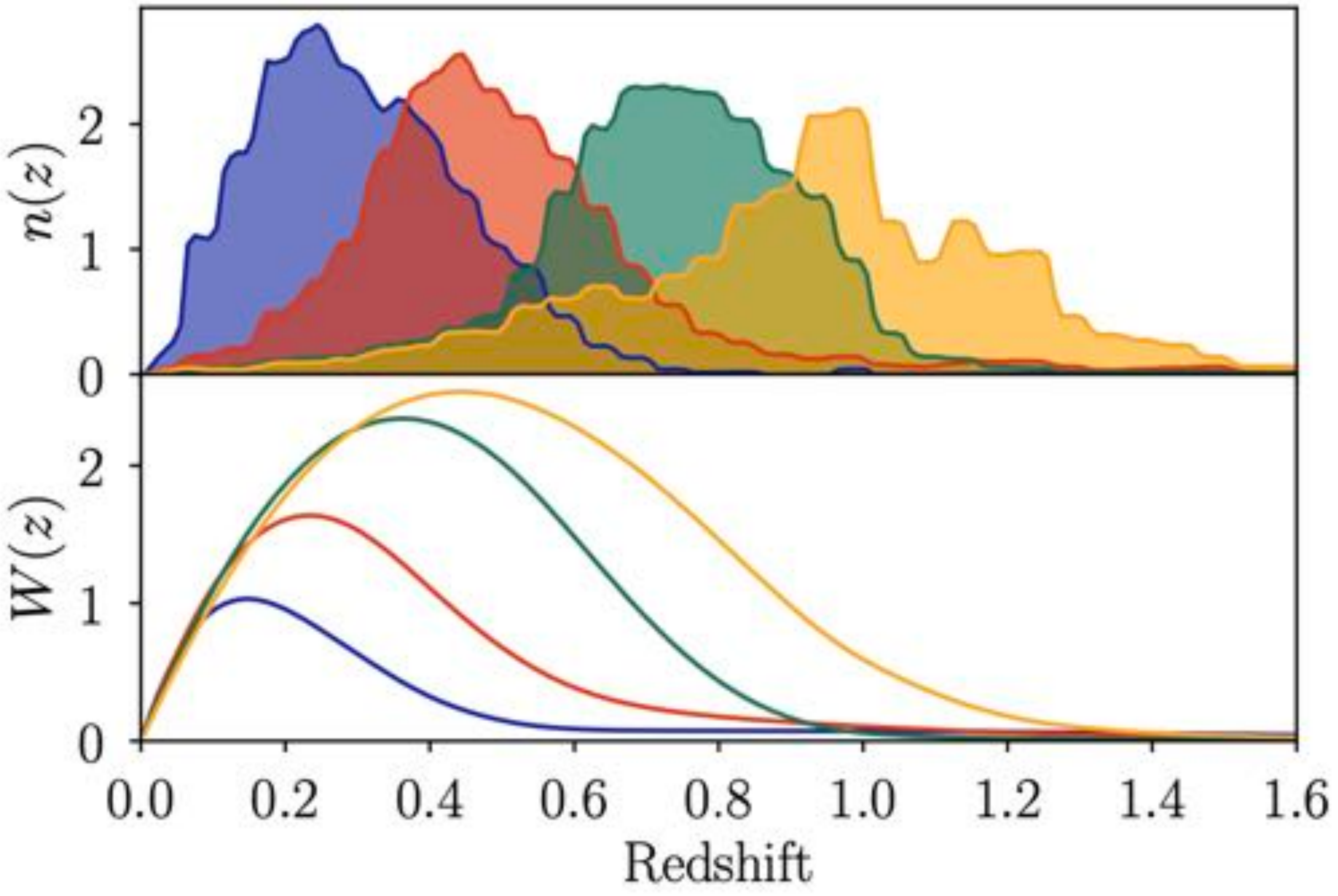
We measure the correlation of the **shapes** of source galaxy pairs [i,j] as a function of angular radius and to model the signal, we estimate the distribution of redshifts of the galaxy sample.

Do analysis tomographically, *i.e.* in **redshift** bins.

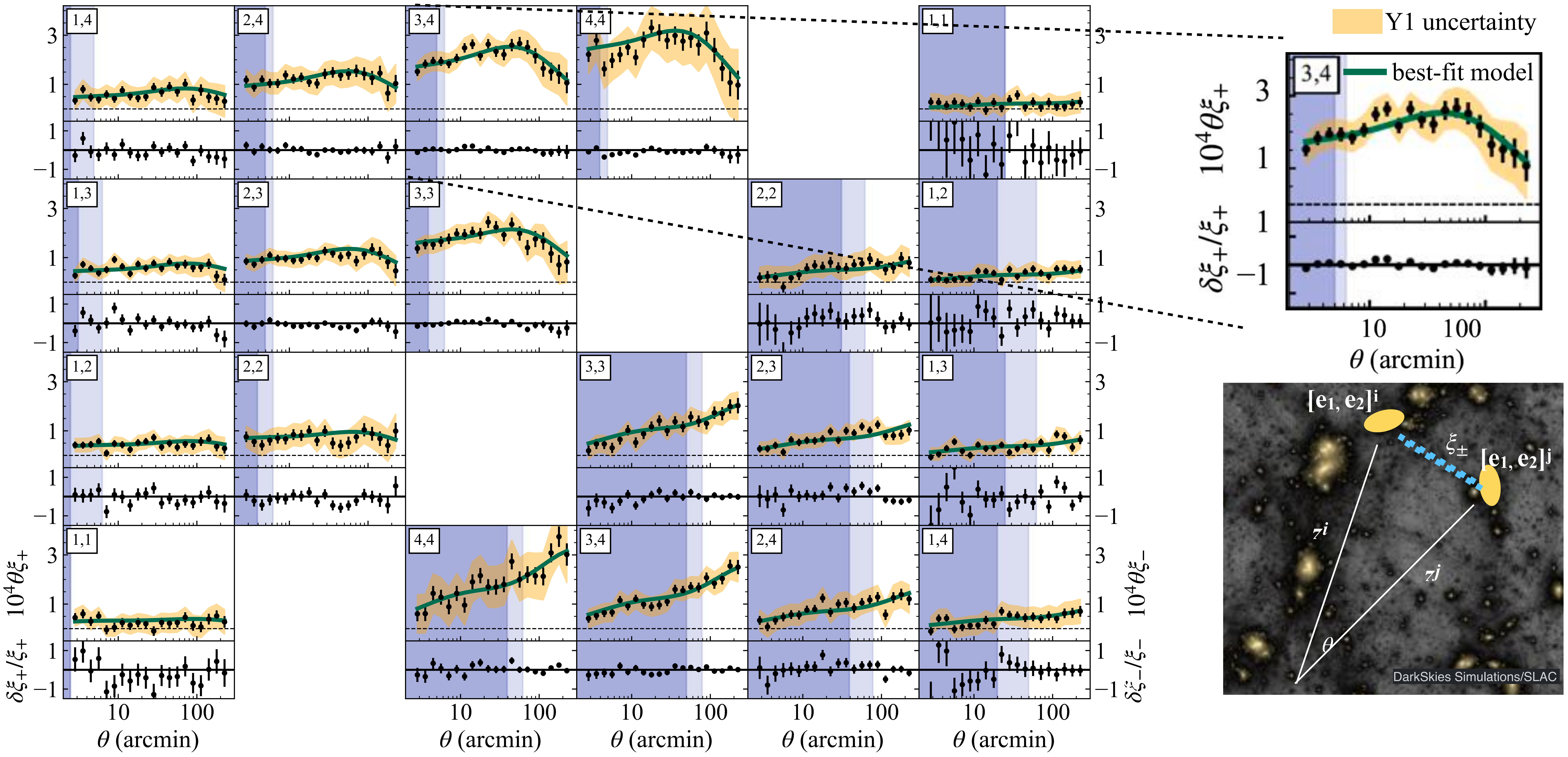






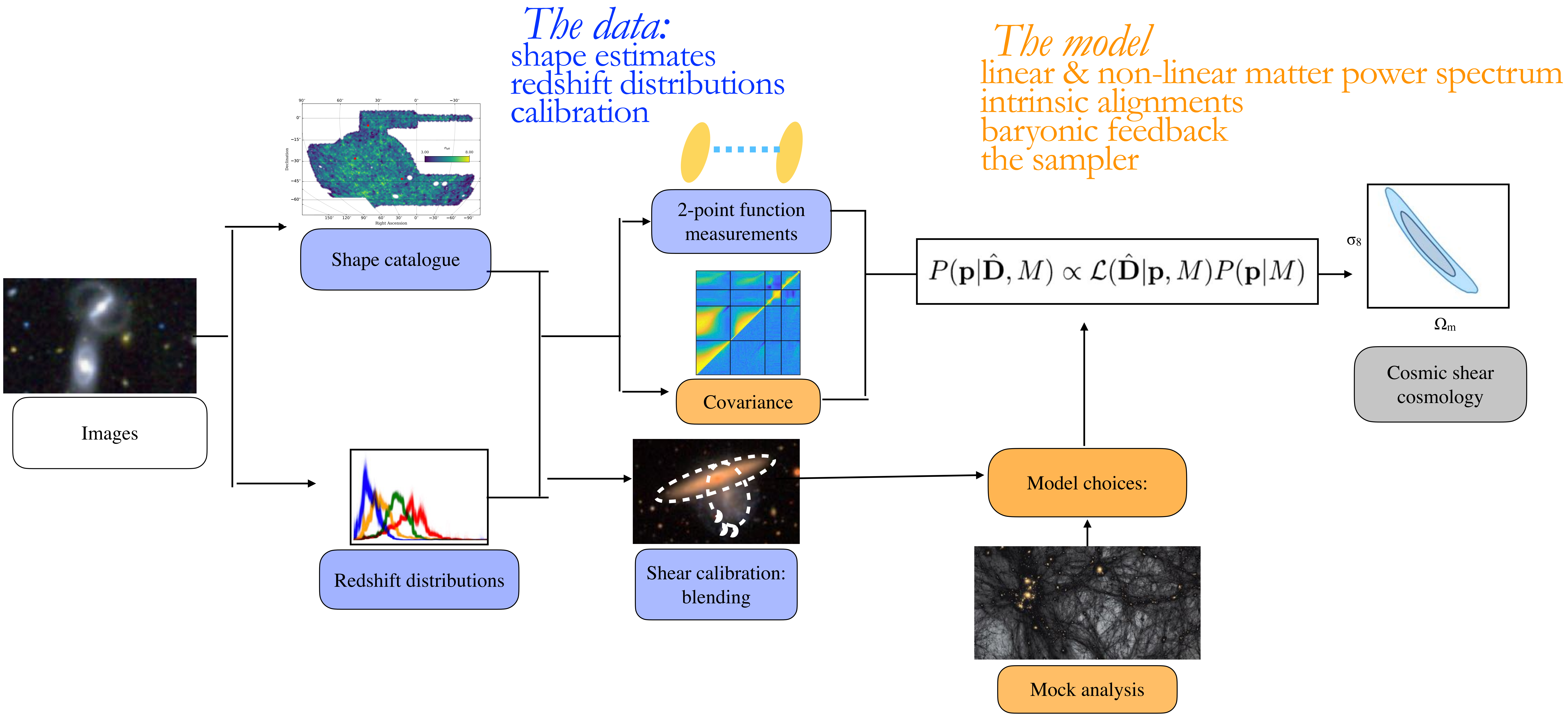


Weak lensing measurements today: >100 million DES galaxies

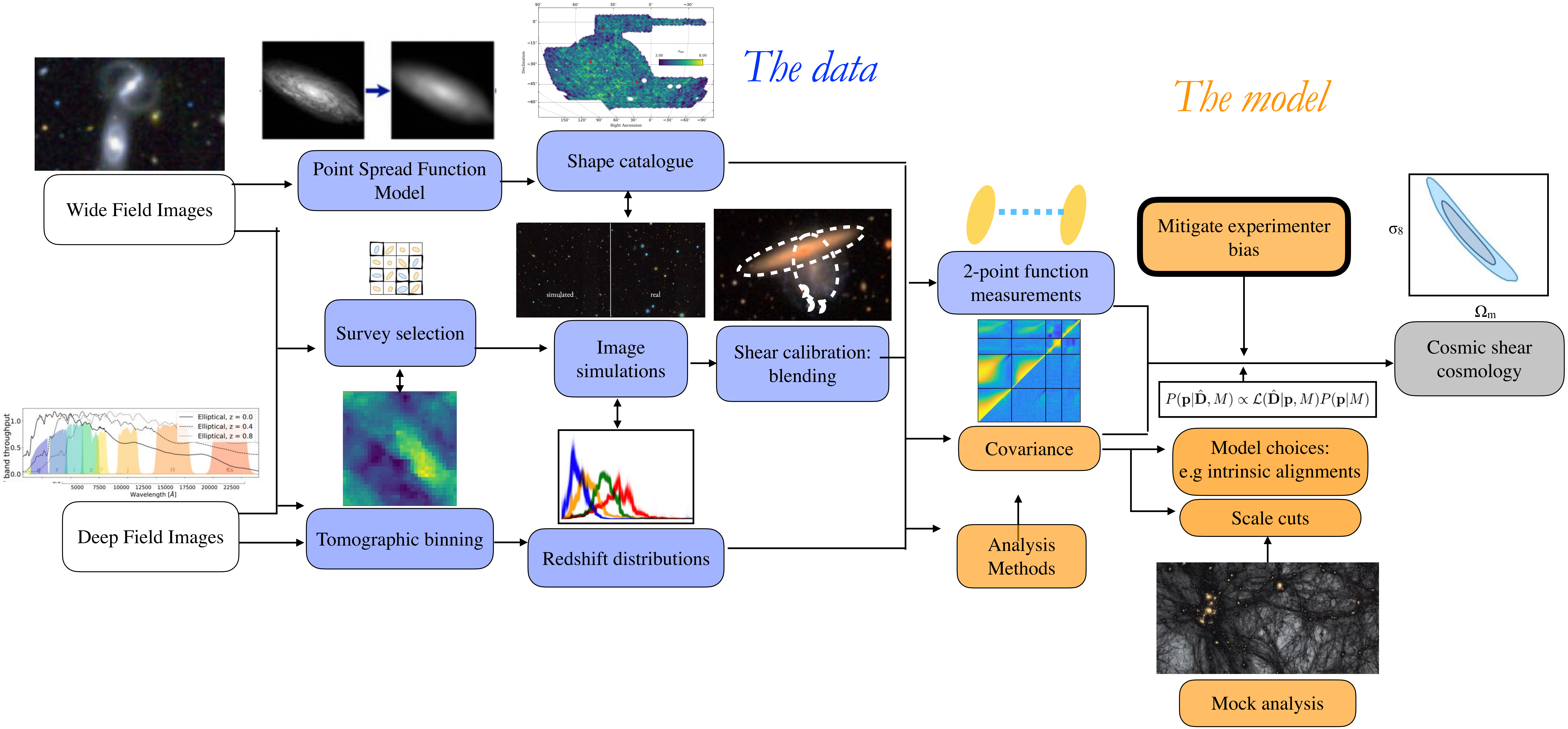


[Amon+2021]

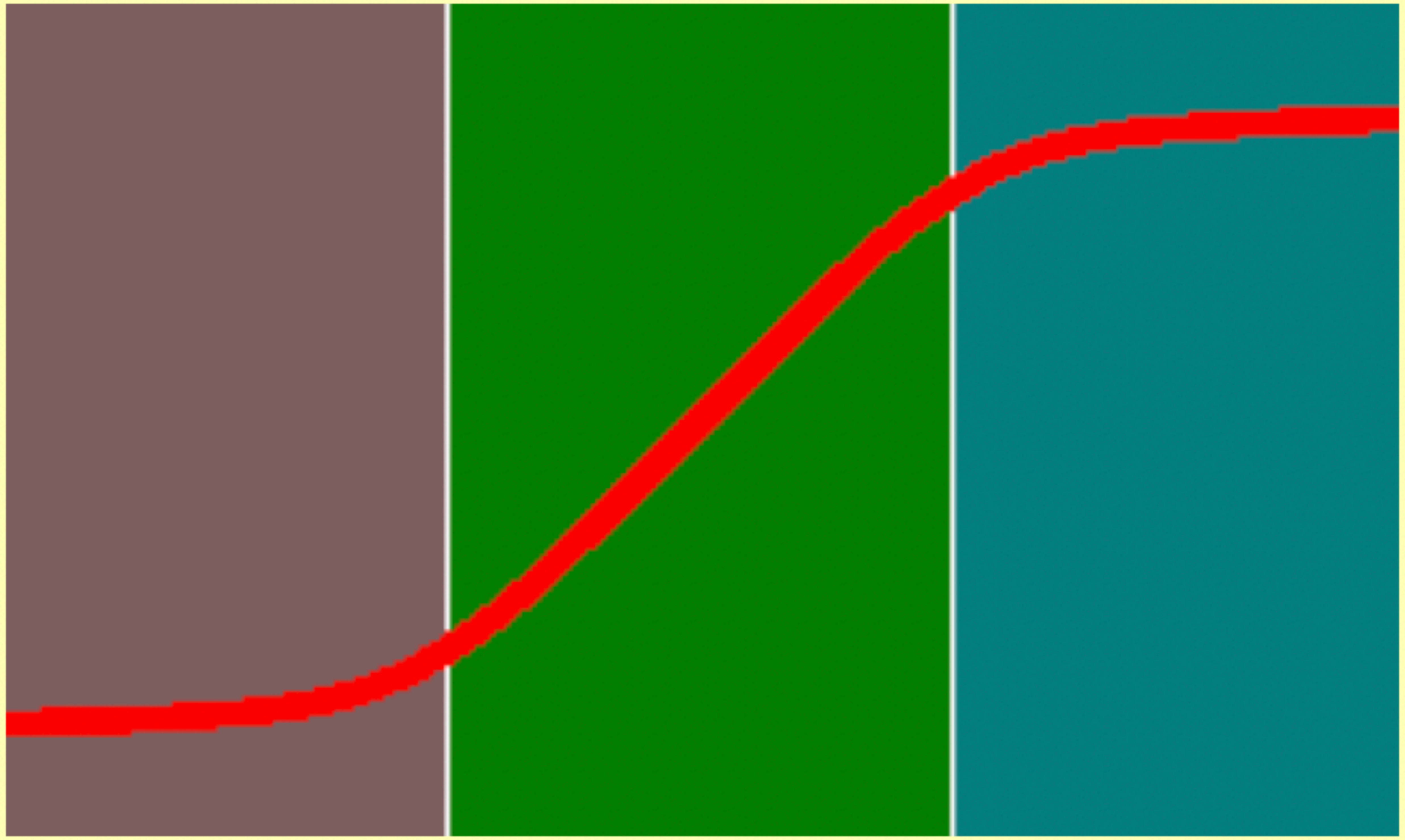
Cosmic shear: pixels to cosmology **Simple picture**



Cosmic shear: pixels to cosmology **Complex picture**



The statistical demographic transition



Data hopeless

Careful statistics can give results

Systematics dominated

4 riders of the apocalypse, Viktor Vatsnetov

Cosmic shear *usual suspects*

Redshift calibration

Shear calibration: blending

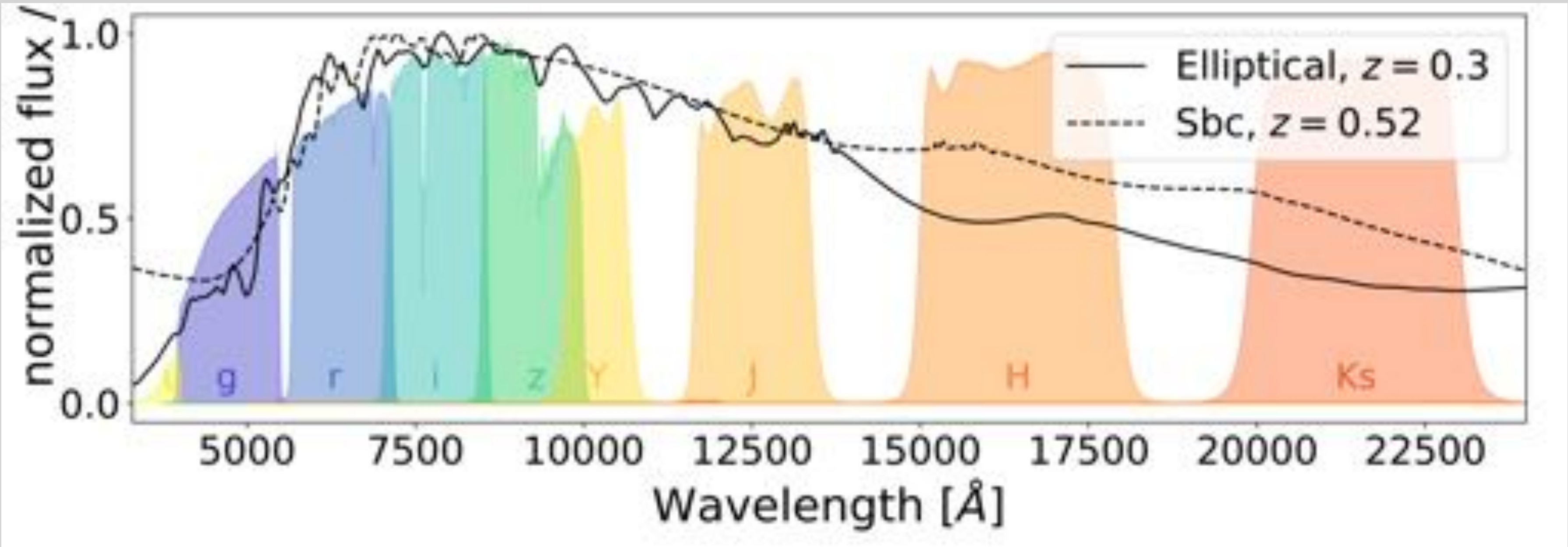
Model choices: intrinsic alignments

Scale cuts & baryonic effects

Cosmic shear *usual suspects*

Redshift calibration

Challenge: Estimating the distances to galaxies using only a few colours



Shear calibration: blending

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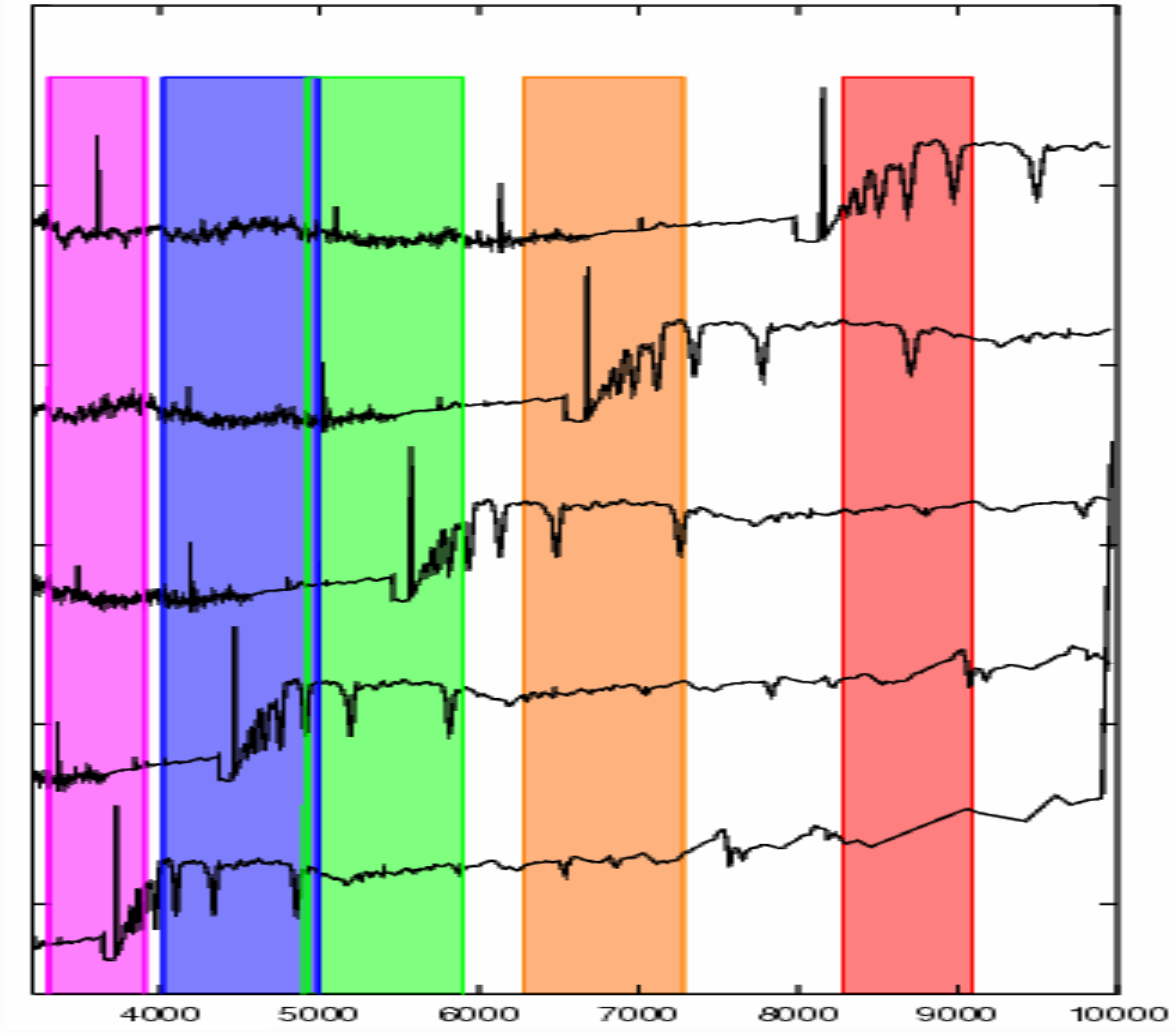
Redshift estimation I

Redshifted galaxy spectra have different colors.
Photometric redshifts = very low resolution spectra.
#bands between 3 (RCS) and 30 (COSMOS). Typical are 4-5 optical filters (g, r, i, y, z), maybe with UV (u) and IR (I, J, K).



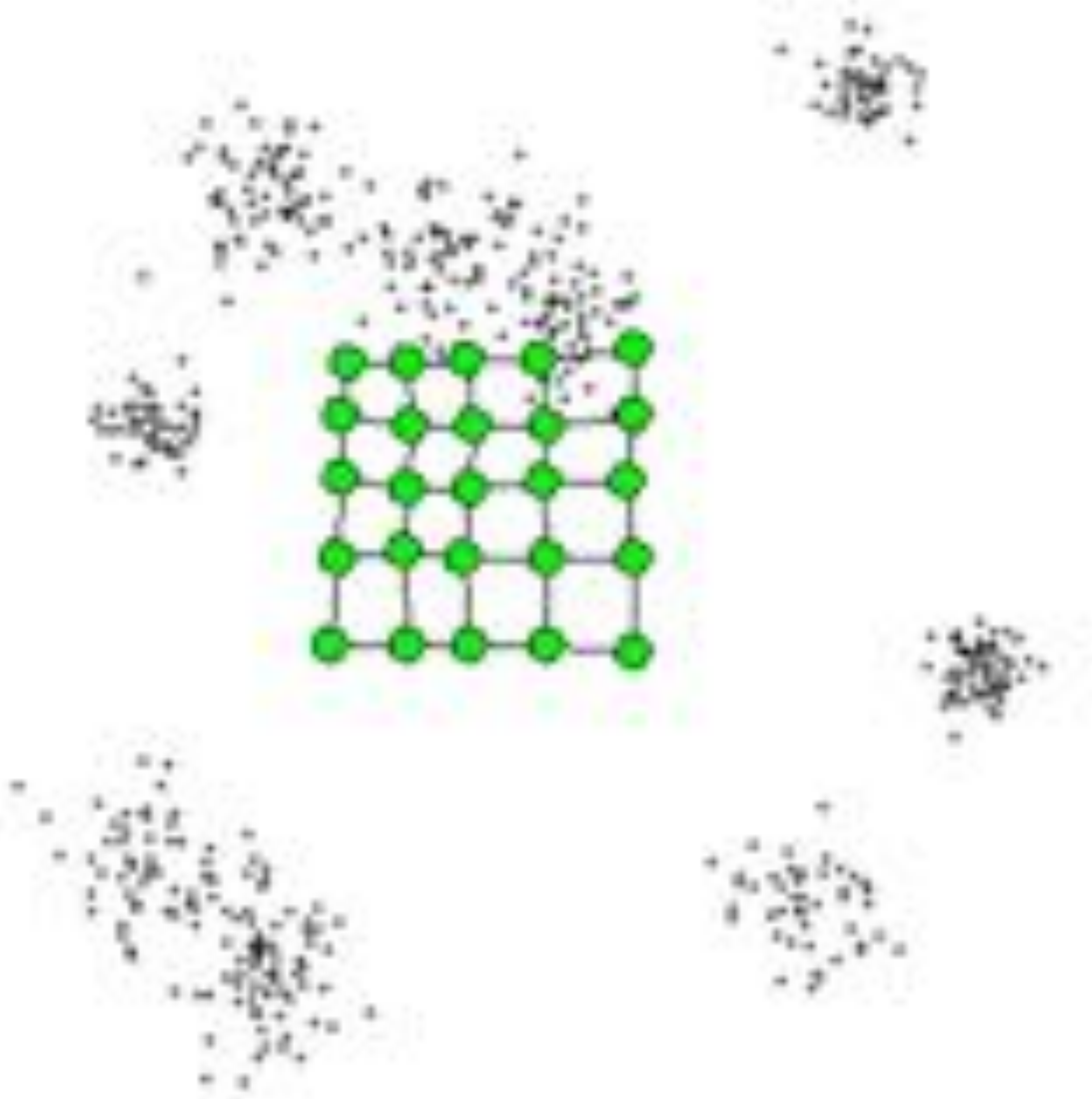
[from Y. Mellier]

4000 Å-break strongest feature due to metal absorption and absence of blue stars. If not pronounced: metal-poor, young stars.
→ ellipticals (old, metal-rich stellar population) best,
→ spirals ok,
→ irregular/star-burst (emission lines) less reliable.

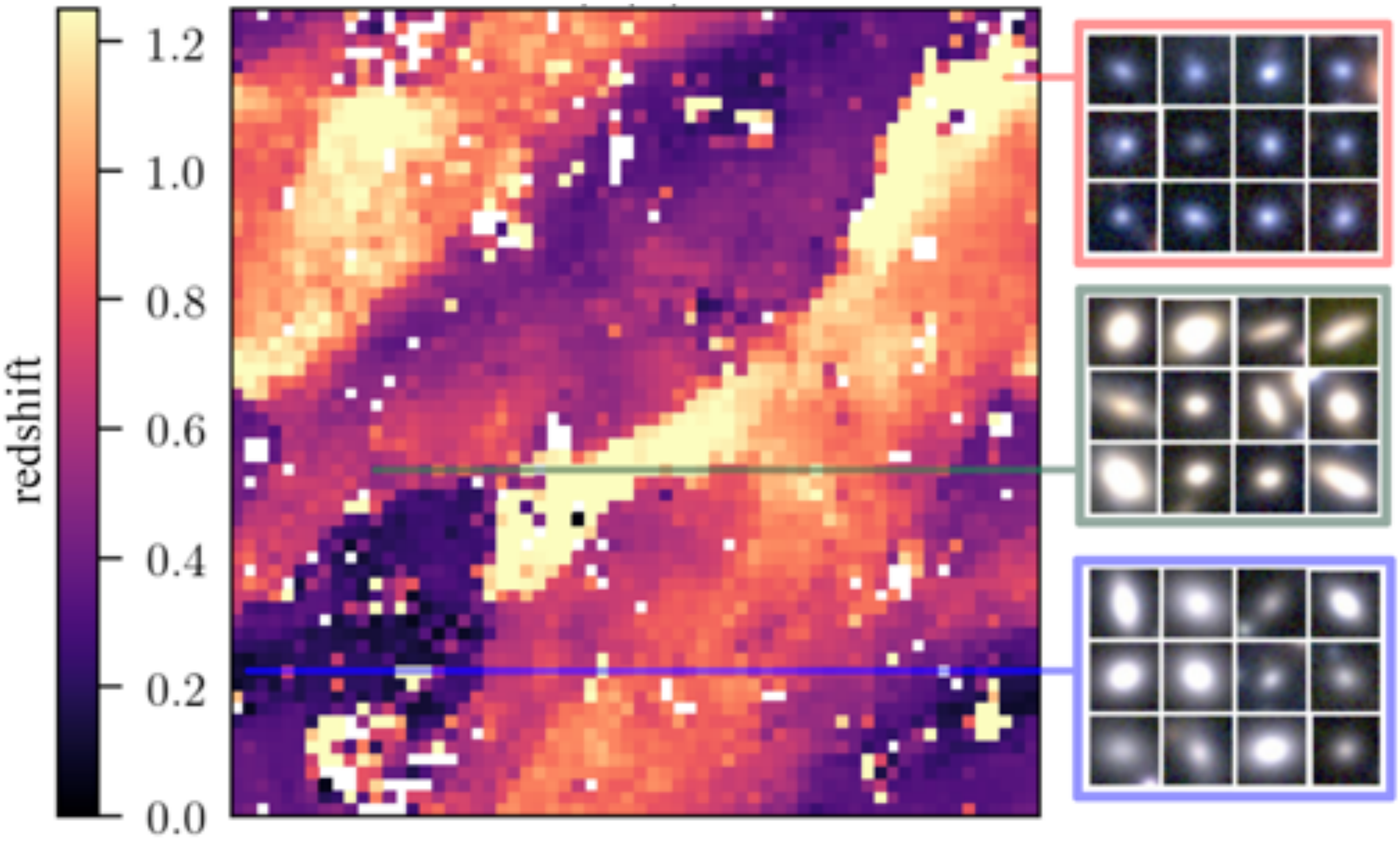
SED: Spectral Energy Distribution,
Depends on stars and gas in the galaxy

Measuring a spectra is slow so we get a few flux values (1 per color band (5-9))
Try fitting these values with SED templates

Self-organising map



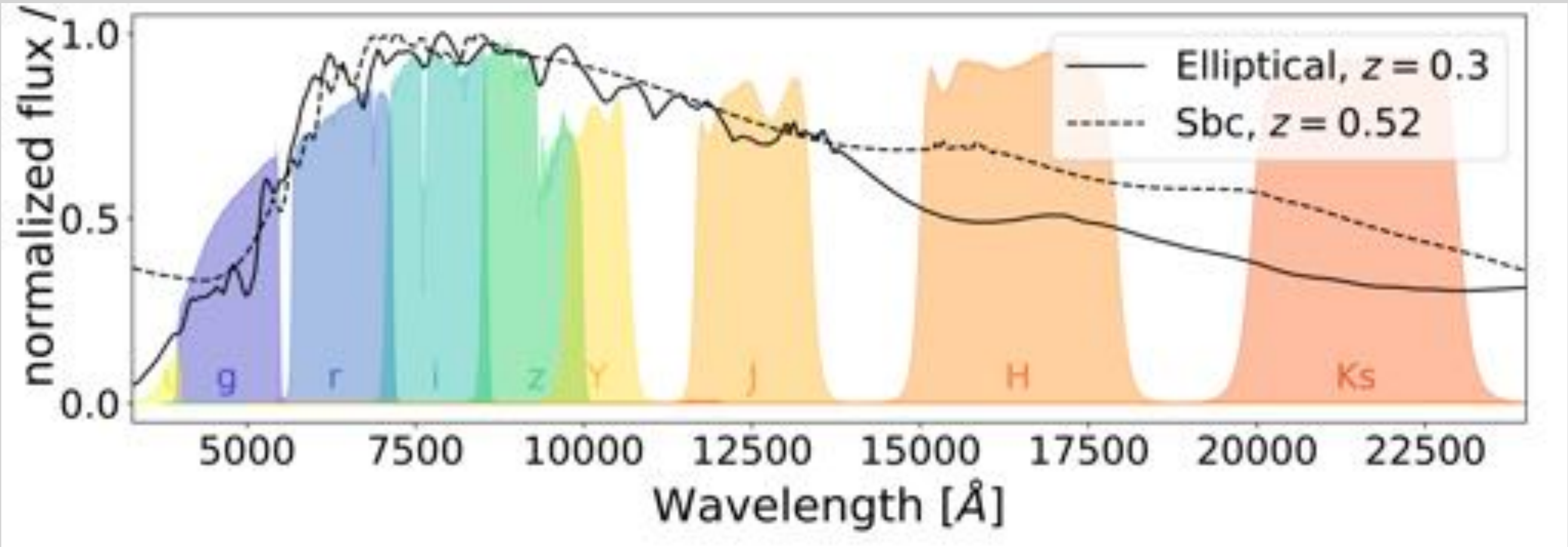
Myles, Alarcon, Amon+2021



Cosmic shear *usual suspects*

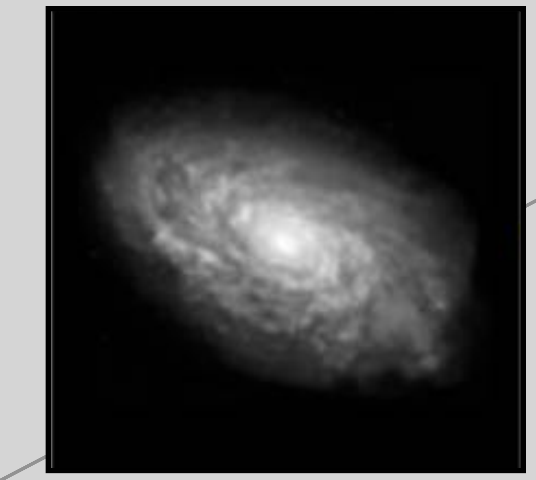
Redshift calibration

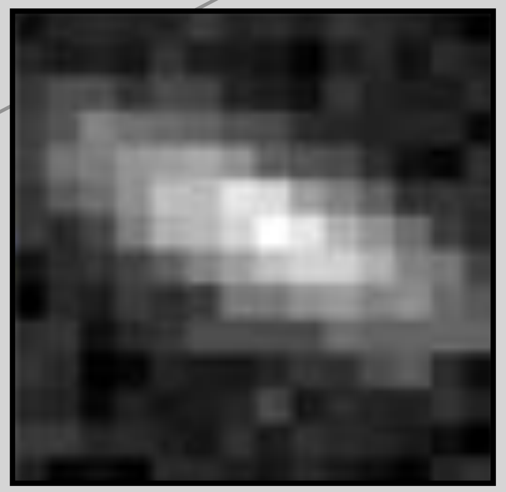
Challenge: Estimating the distances to galaxies using only a few colours

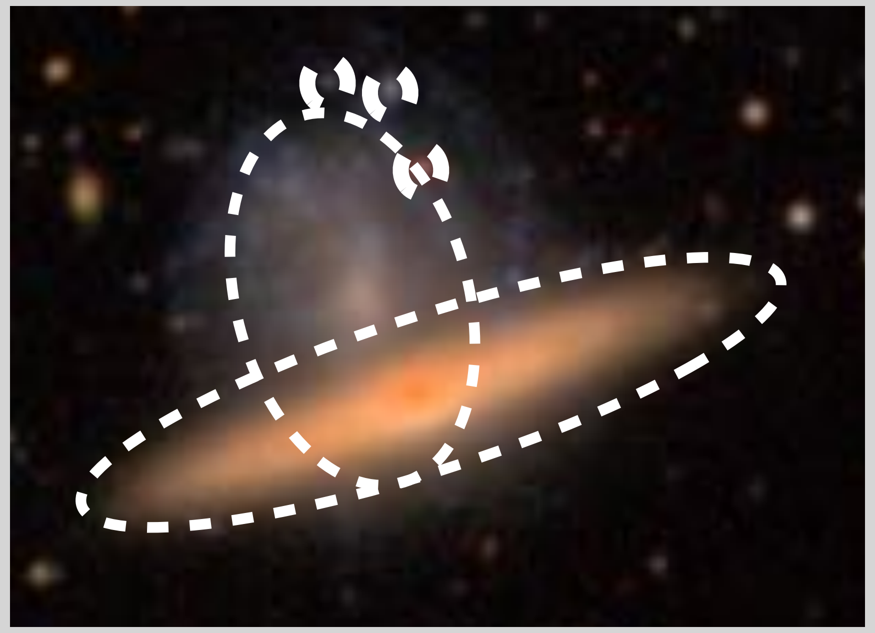


Shear calibration: blending

Challenge: Galaxies are not only sheared, but smeared, blurred, pixellated, noisy & blended



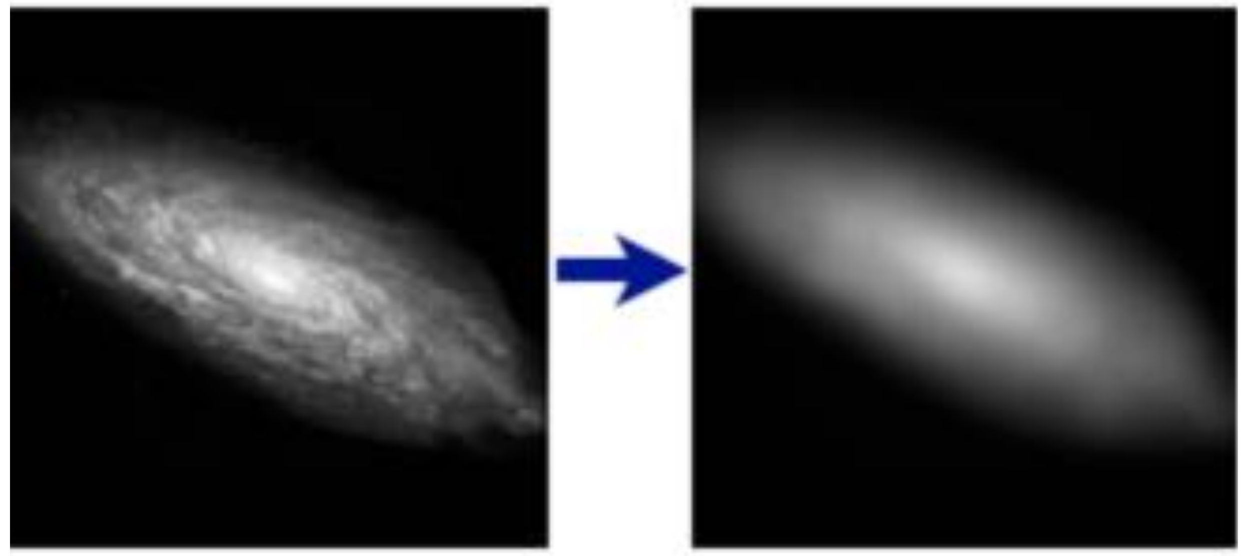


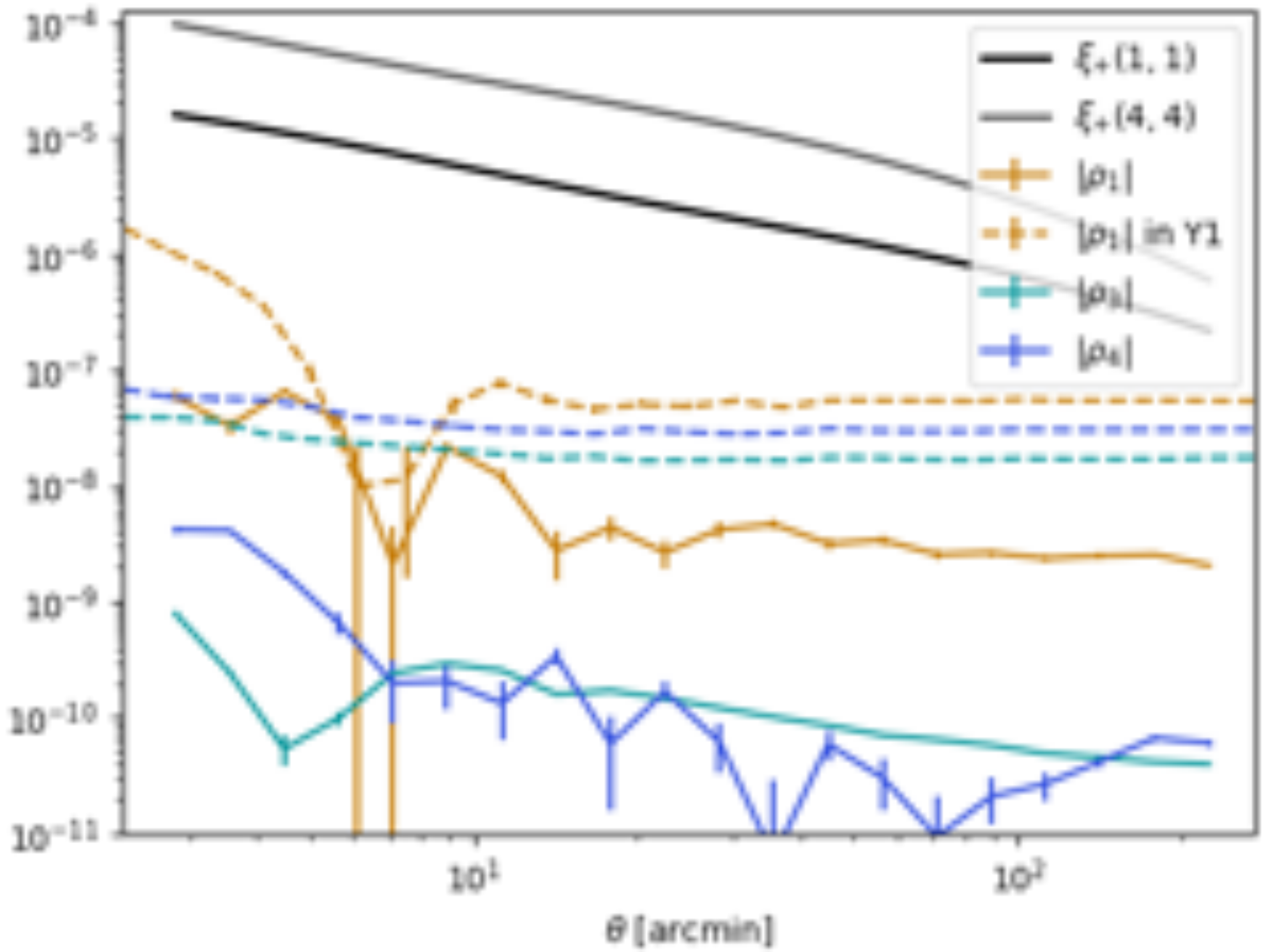


Model choices: intrinsic alignments

Scale cuts & baryonic effects

Point spread function





The PSF residuals tell you how well you're modelling this

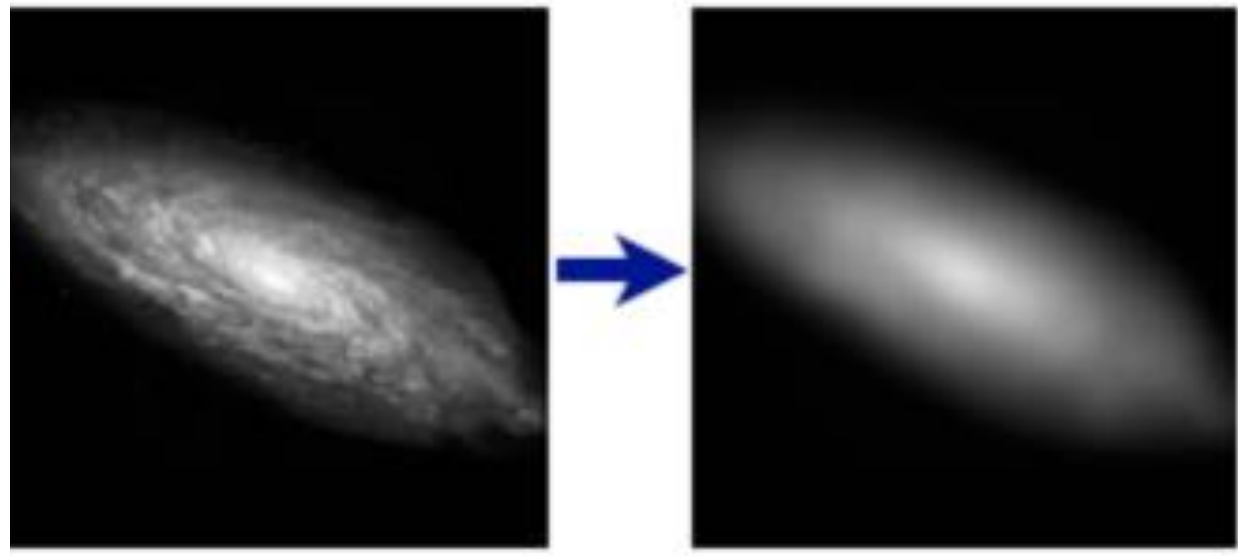
$$\boldsymbol{\delta e^* = e_{PSF} - e_{model}} \quad ; \qquad \boldsymbol{\delta T^* = T_{PSF} - T_{model}}$$

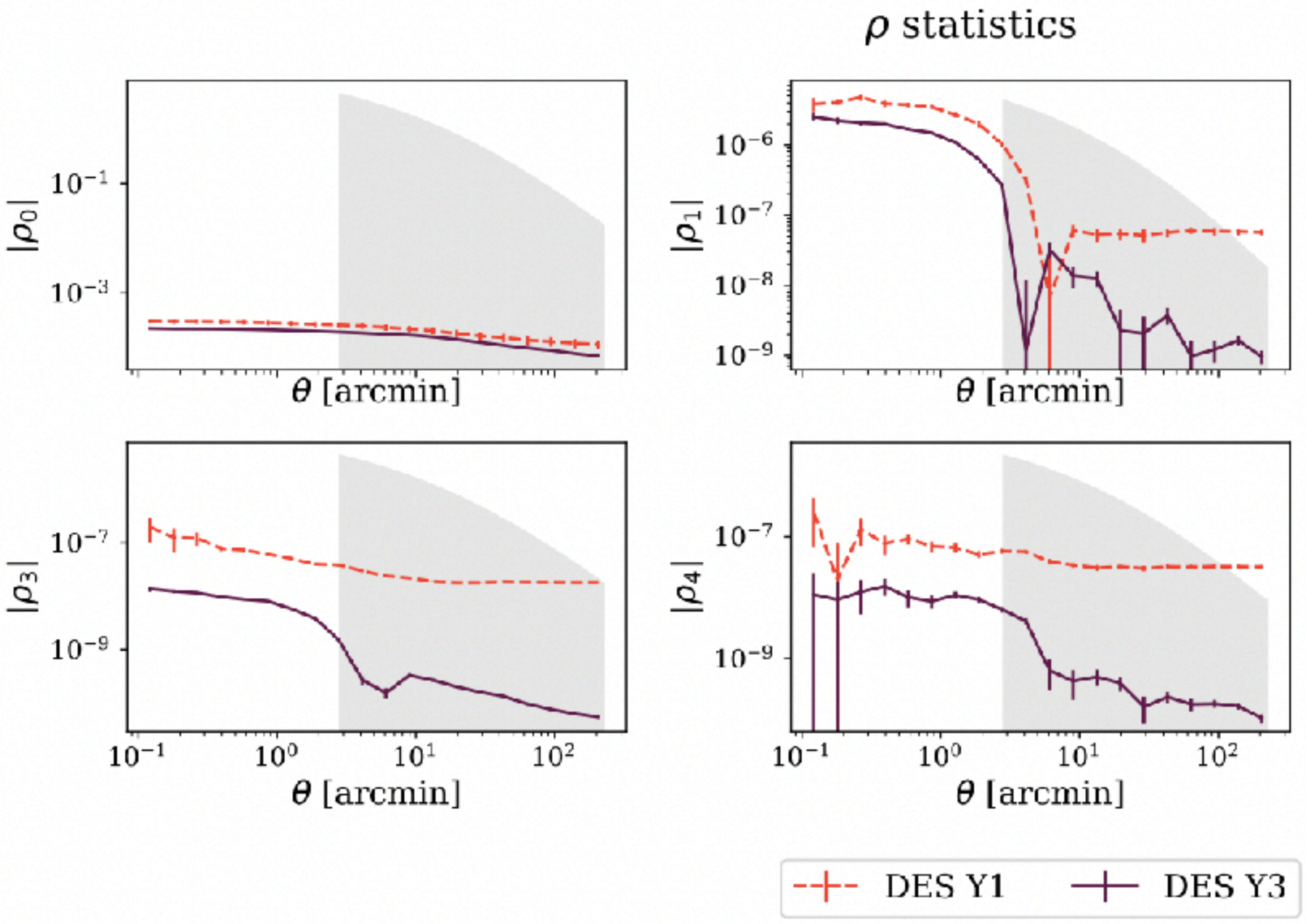
Rowe et al. statistics allow us to quantify how the systematic errors due to PSF mis-estimation propagate into our measurements.

$$\rho_1 = \langle \delta e^* \delta e^* \rangle$$

additively biases cosmic shear.

Point spread function





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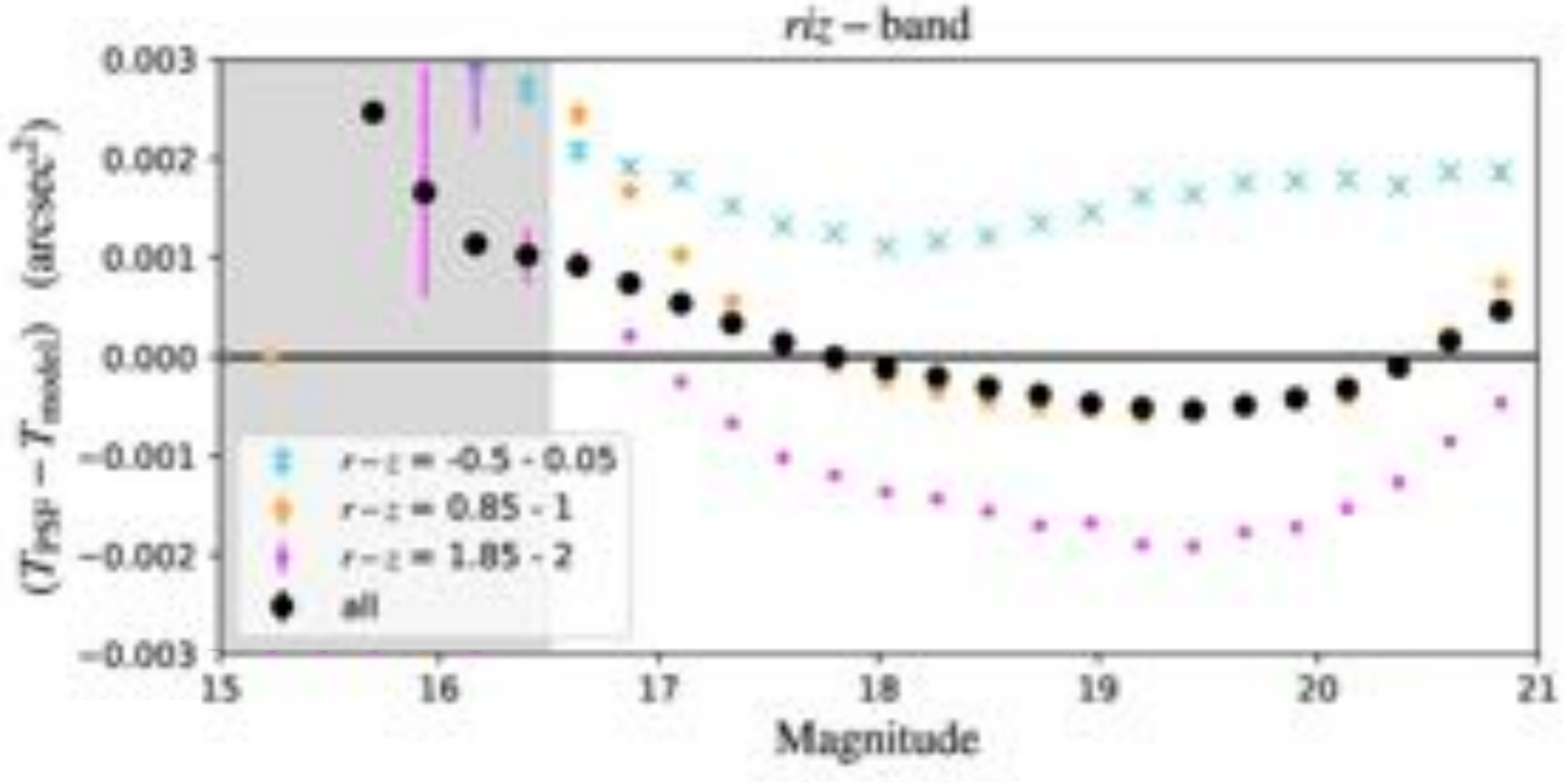
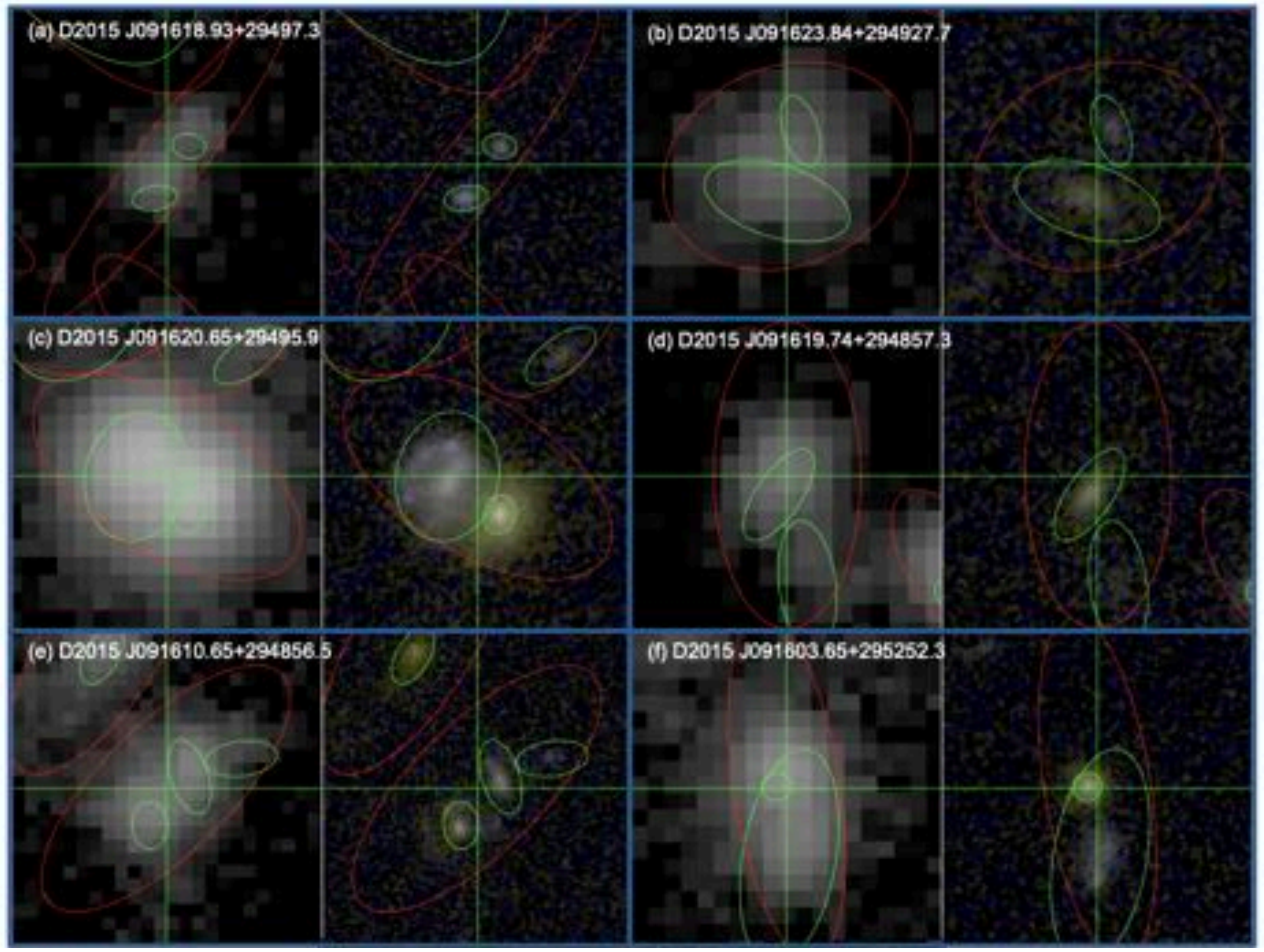
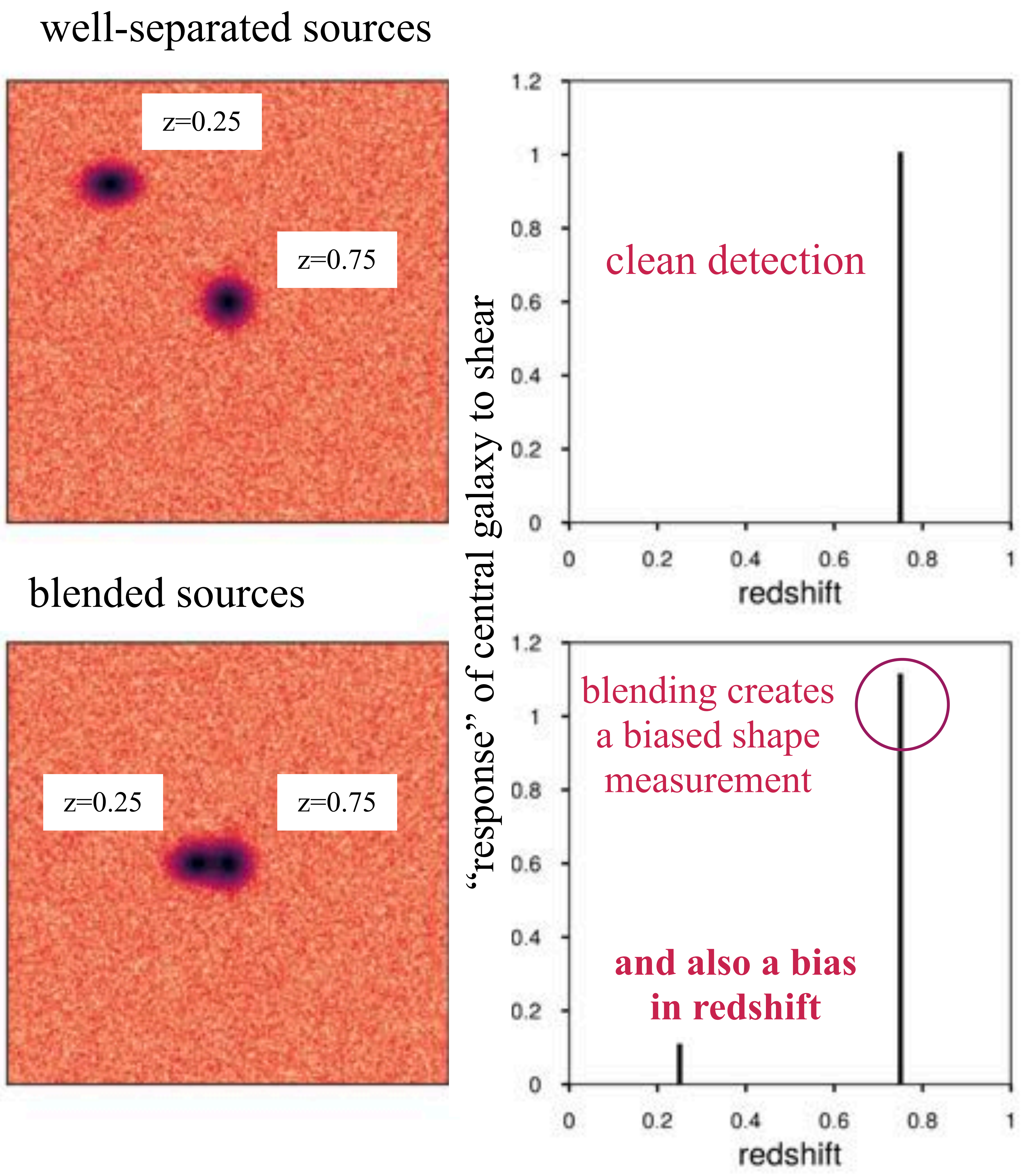


Identified chromatic effects: Bluest stars are larger e_2 and T than the average model & the red stars are smaller.

DES Year 6 work (with Theo Schutt+) includes a colour term and finds g-band calibration improved enough for Y6 use!

Shape measurement & calibration: blending





HSC Y1 estimated ~60% recognised blends.
Rubin Y1 estimates >10% unrecognised blends.
Cannot remove blends or de-blend.
Leaves reliance on image simulations! Euclid + Rubin ?

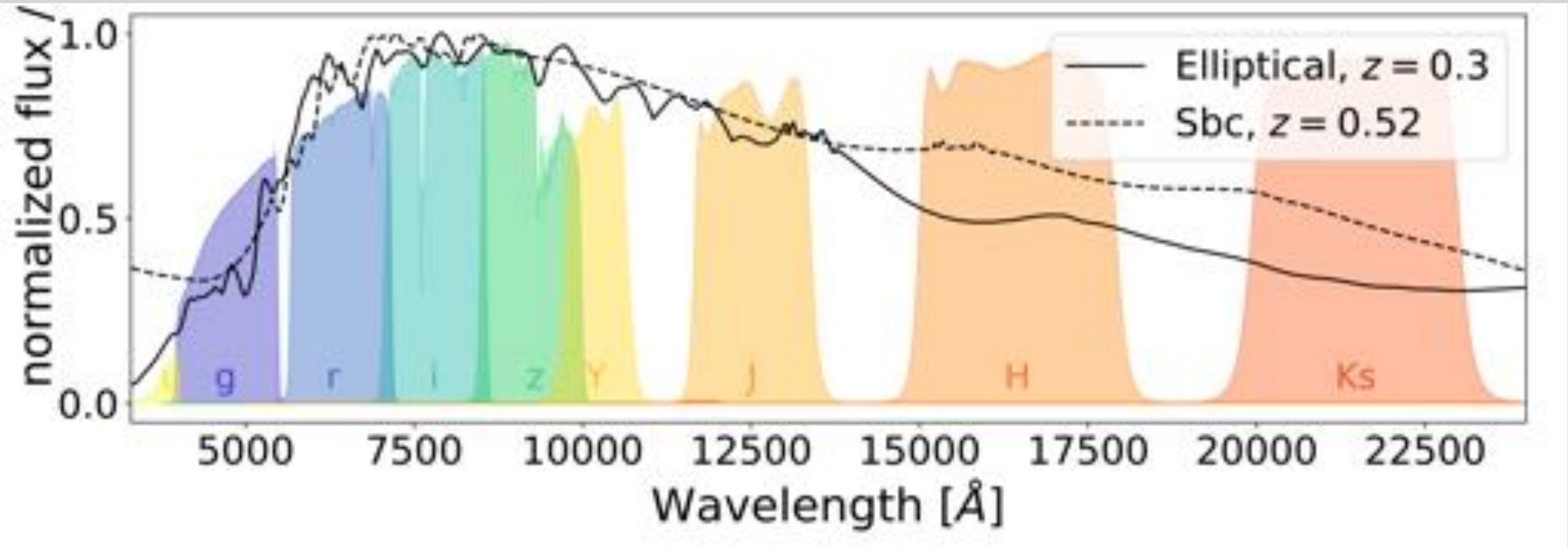
Blending demands an additional correction and uncertainty on redshift distribution (as well as the shear) that increases with redshift.

*[MacCrann, Becker, **McCullough**+2020]*

Cosmic shear *usual suspects*

Redshift calibration

Challenge: Estimating the distances to galaxies using only a few colours



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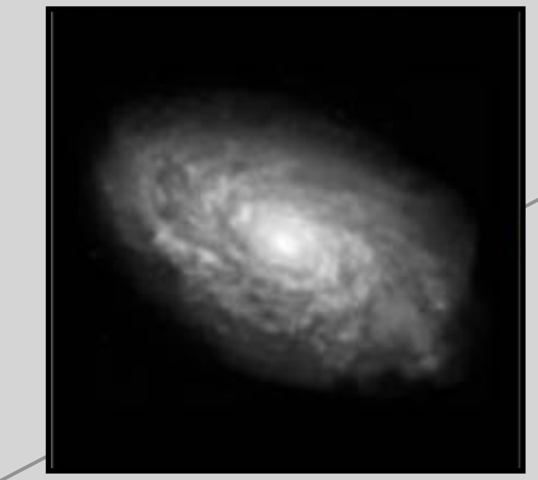
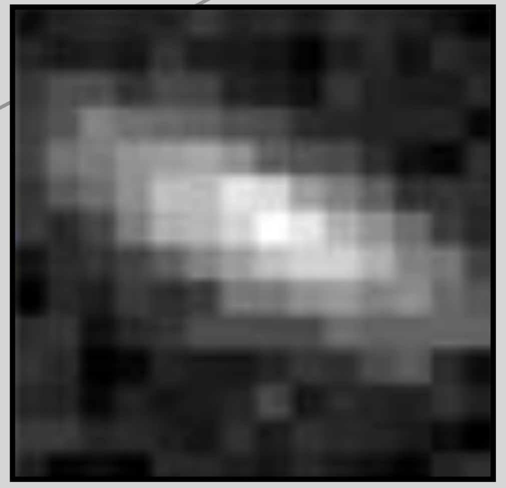
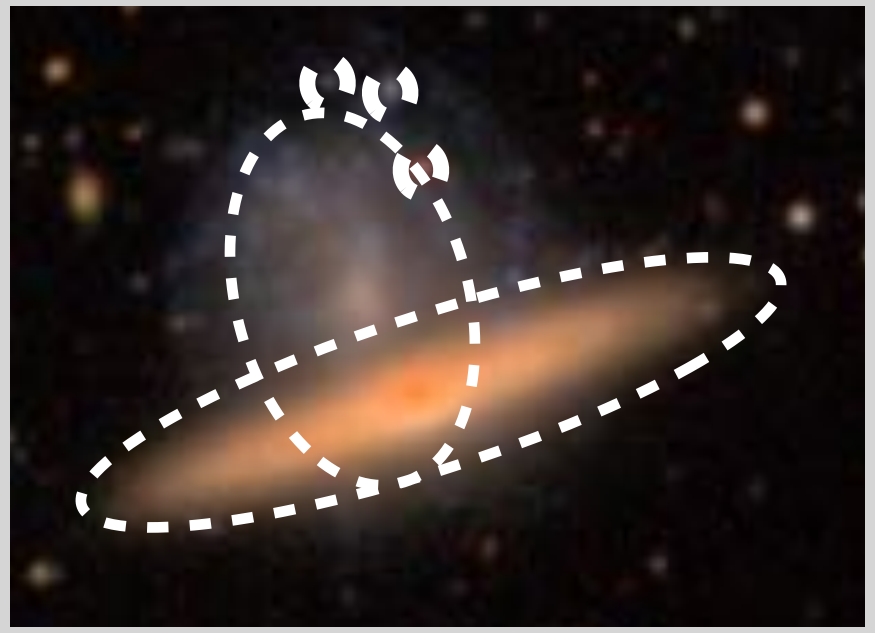
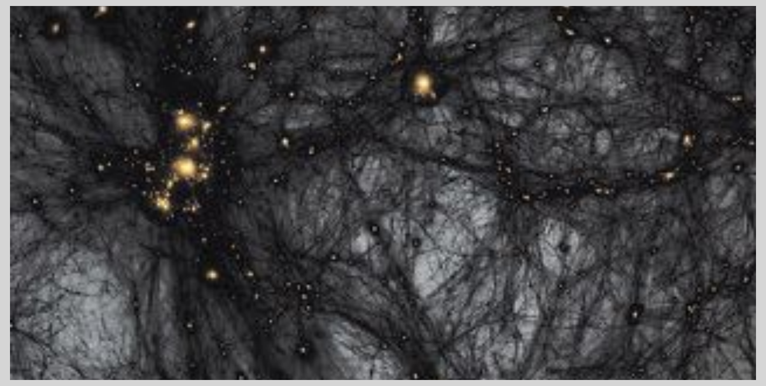






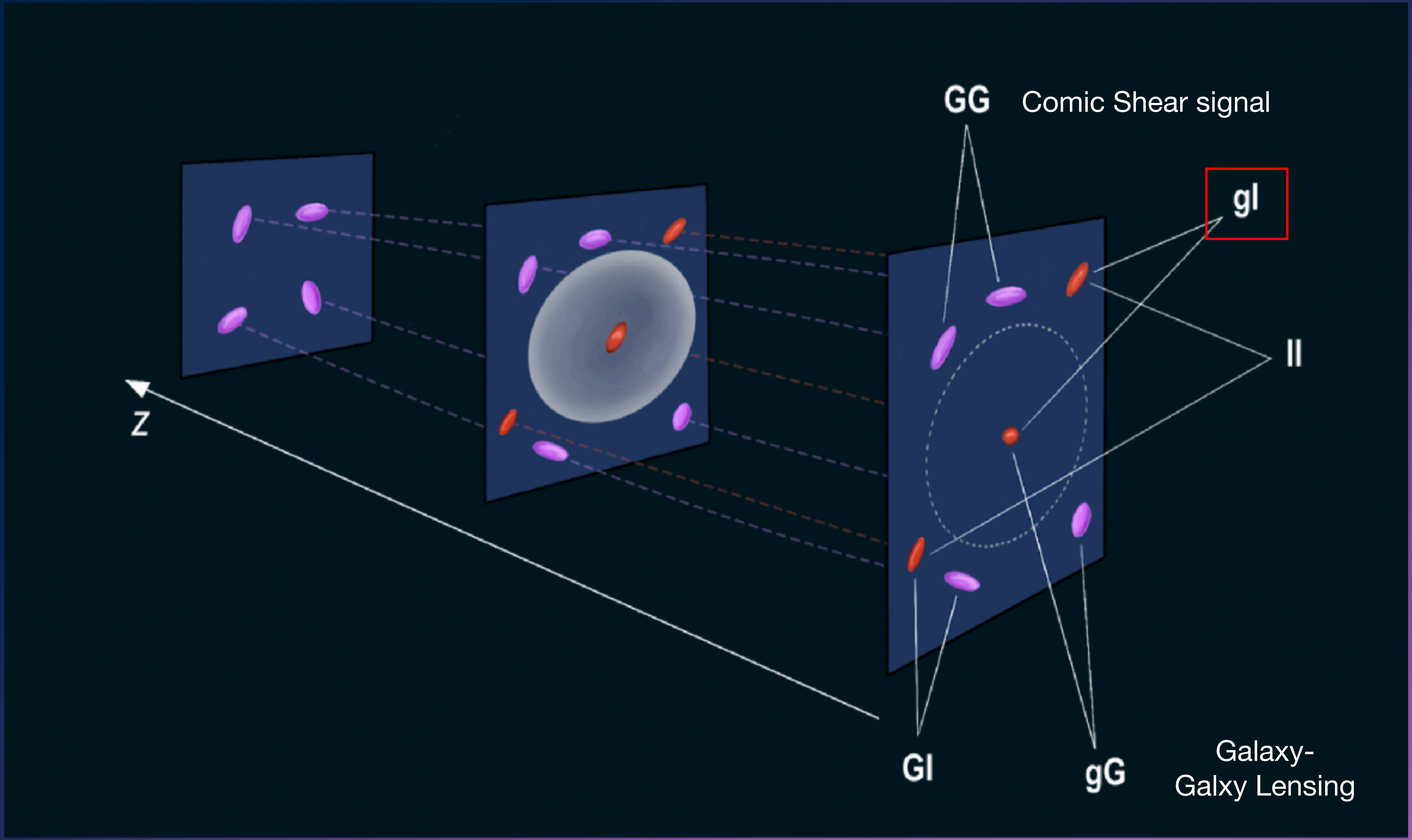
Model choices: intrinsic alignments



Challenge: Galaxies intrinsically aligned (IA). Is the IA model well-suited to late-type galaxies, which dominate lensing samples? Is it flexible enough to encompass our lack of understanding of this effect?

Scale cuts & baryonic effects

Intrinsic Alignment



Credit: *Fortuna and Chisari 2022*

Total ellipticity described as:

$$\gamma = \gamma_I + \gamma_G$$

Cosmic Shear 2PCF:

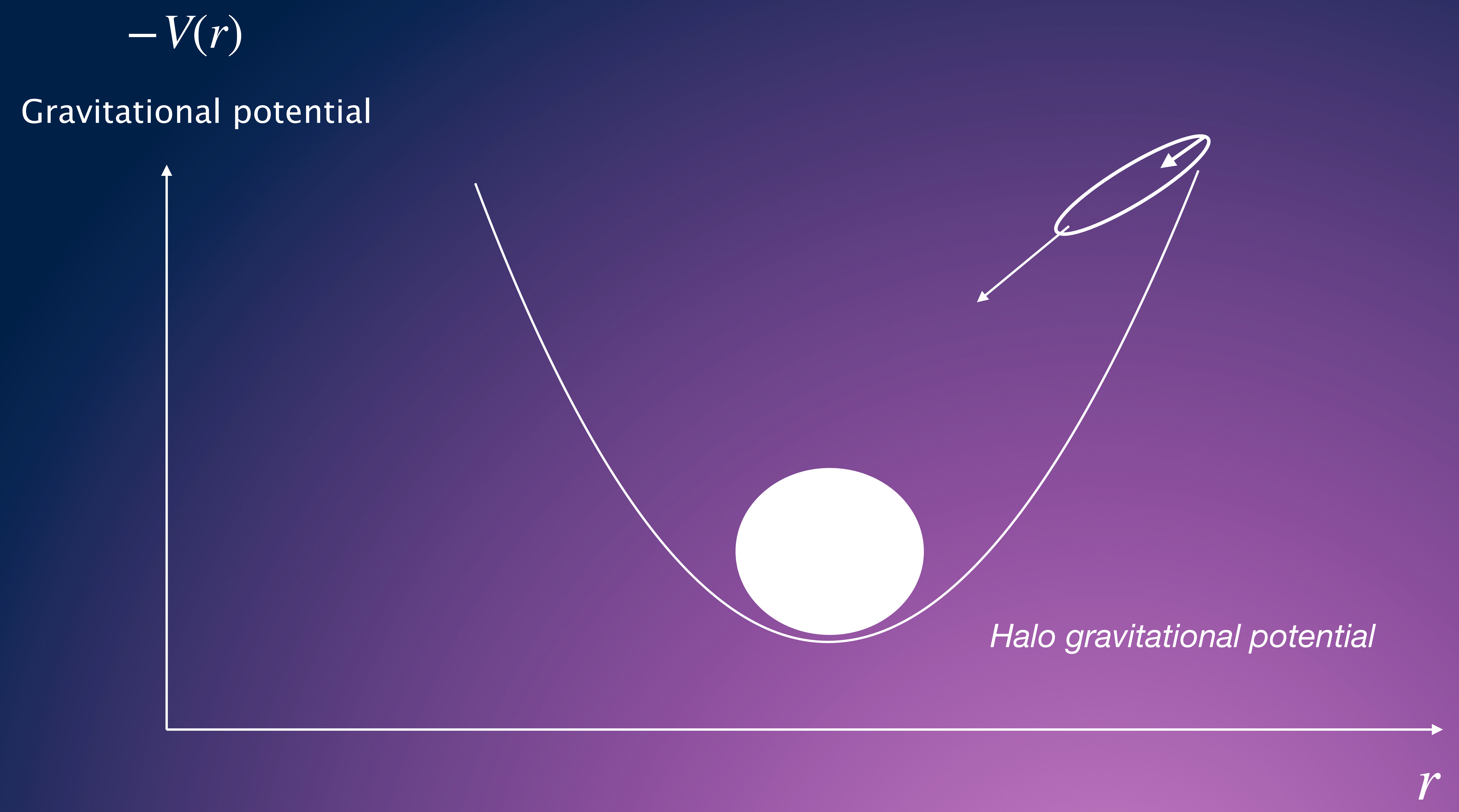
$$\langle \gamma\gamma \rangle = \underbrace{\gamma_G\gamma_G}_{\text{Lensing-Lensing}} + \overbrace{\gamma_I\gamma_I}^{\text{Intrinsic-Intrinsic}} + 2\underbrace{\gamma_I\gamma_G}_{\text{Lensing-Intrinsic}}$$

Want to measure for Cosmic shear

What we measure

→ Need to model both effects jointly

The Non Linear Alignment model (NLA)



Overdensities:

$$\delta(r) = \frac{\rho(r) - \bar{\rho}}{\bar{\rho}}$$

NLA parametrisation:

$$\gamma_I \propto A_1 \; k^2 \; \delta(r) \; \frac{\Omega_m}{D_+(z)}$$

-$D_+(z)$ linear growth factor
-A_1 (or A_{IA}) free parameter

Accounting for intrinsic alignments

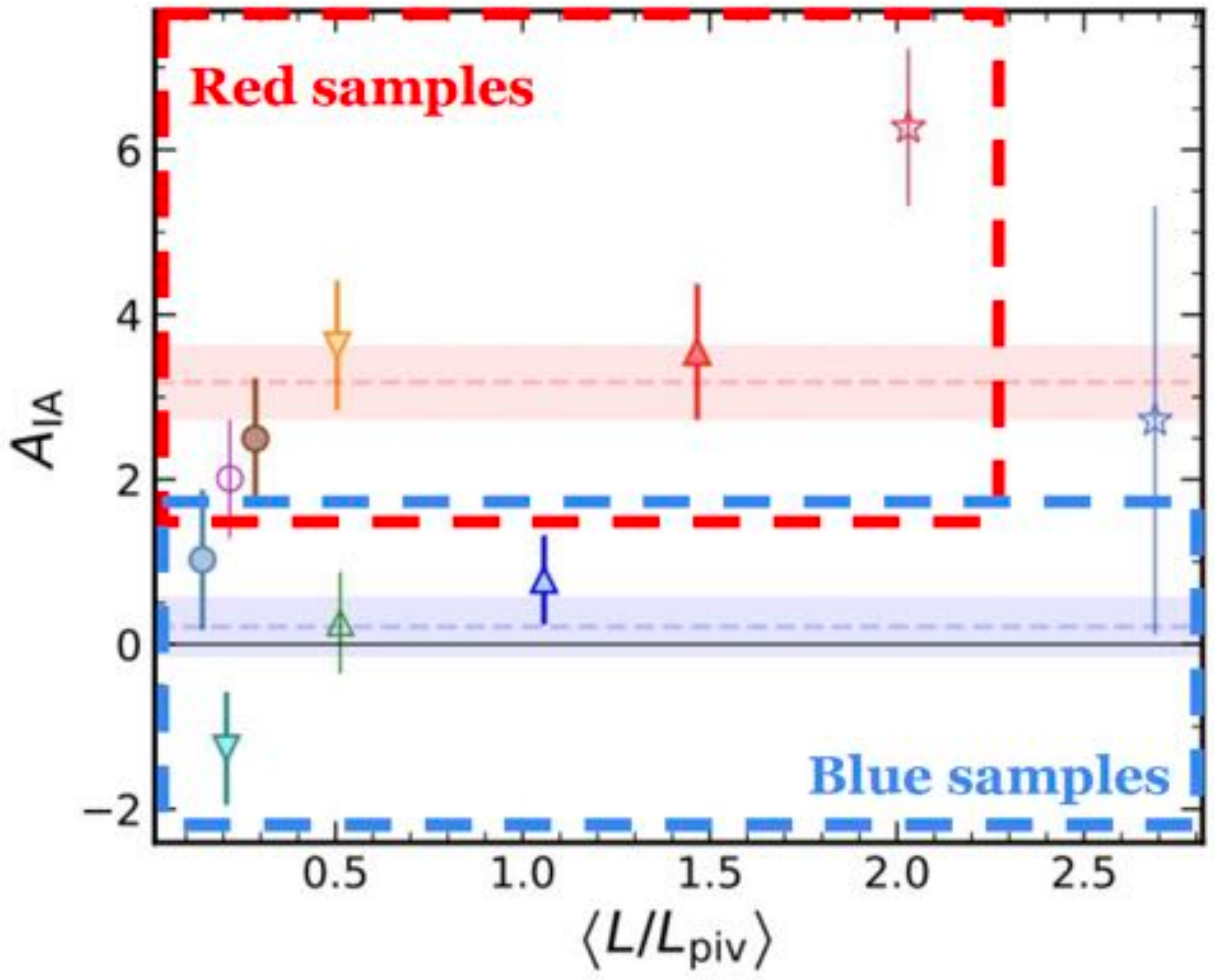
- **Tidal Alignment & Tidal Torquing (TATT)**
  - 5 nuisance parameters -
  - more flexible to account for late-types
  - super-space of NLA model: up to quadratic order in the tidal field

- Non-linear alignment (NLA)
  - 2 nuisance parameters
  - Linear order in the tidal field & non-linear power spectrum

- NLA without a redshift-dependence
  - 1 nuisance parameter

Direct detections show dichotomy in colour.

In WL, about 80% of the sample is blue, and we have never detected IA for blue galaxies.

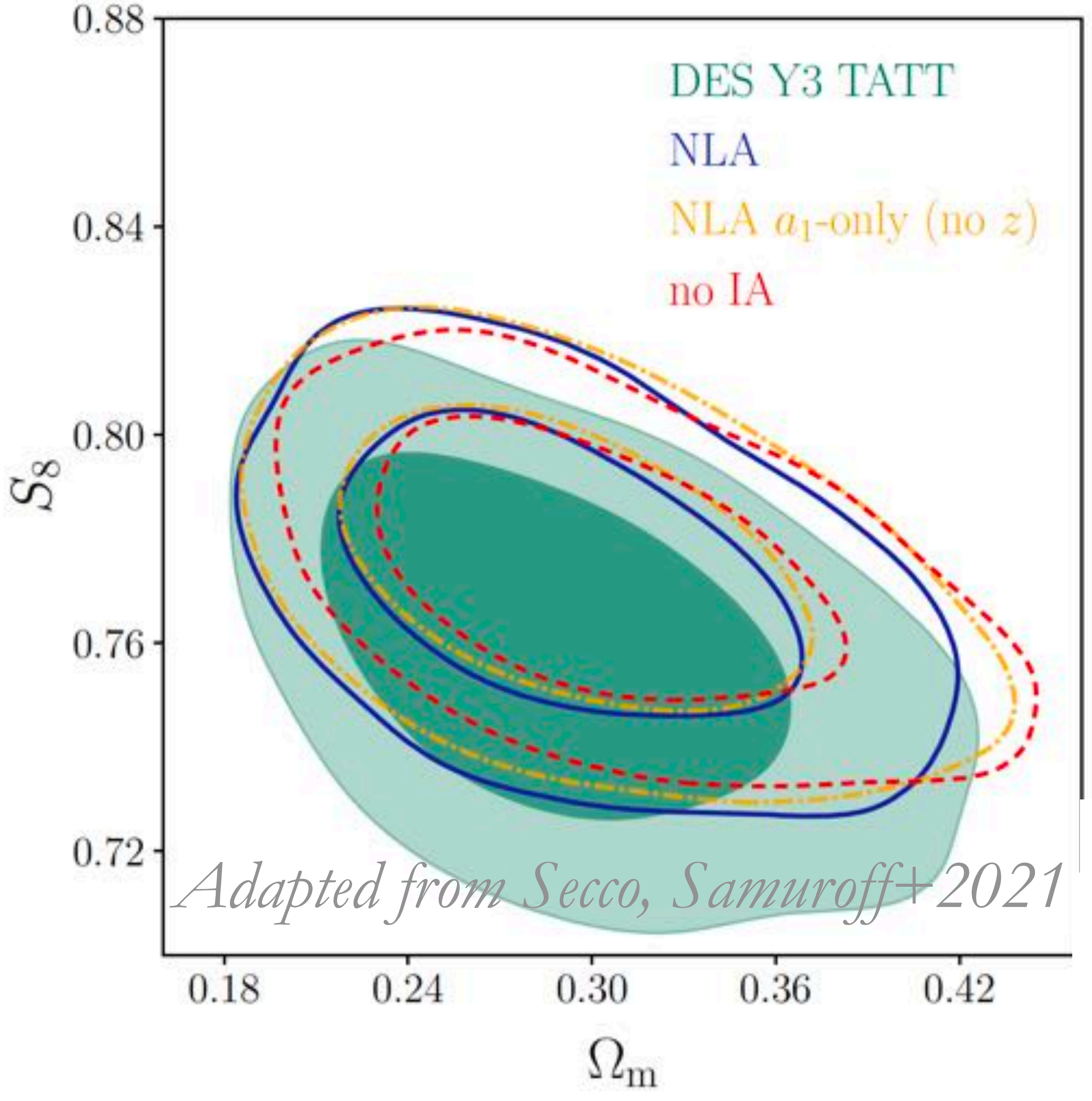


IA modelling in KiDS, DES, HSC

Changes in S_8 with different model choices are small at current precision,

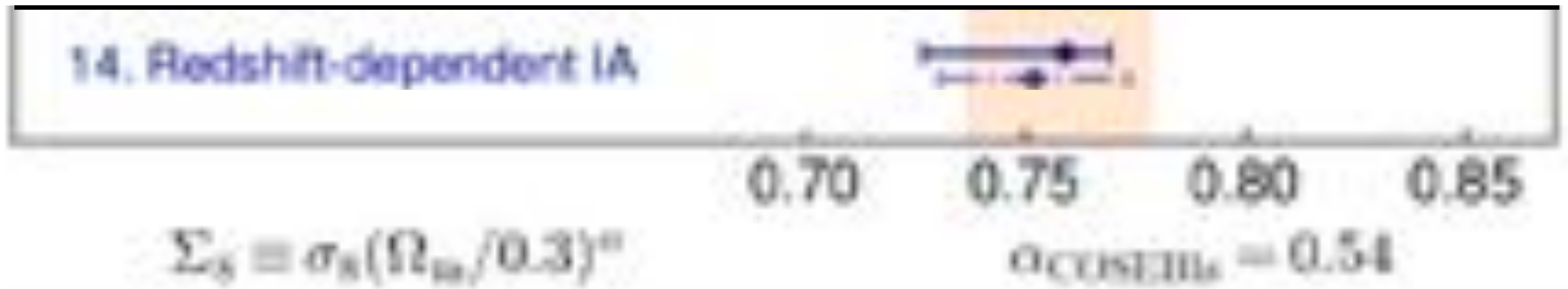
but this is the leading source of uncertainty in the analysis.

DES Y3

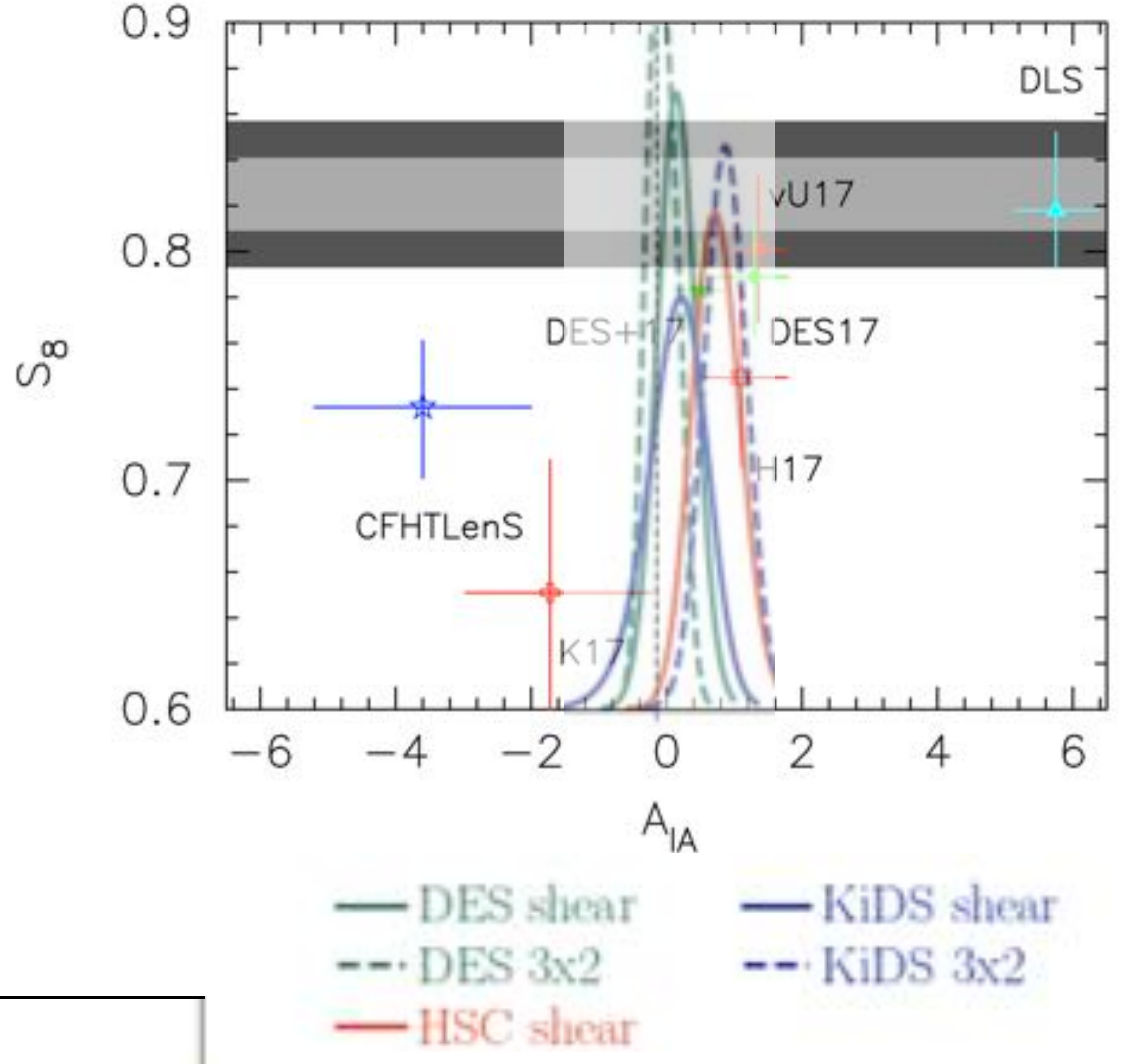


Adapted from Secco, Samuroff+2021

KiDS-1000 *[Asgari+2020]*



IA amplitude parameter much smaller across surveys — **better photo-z control?**



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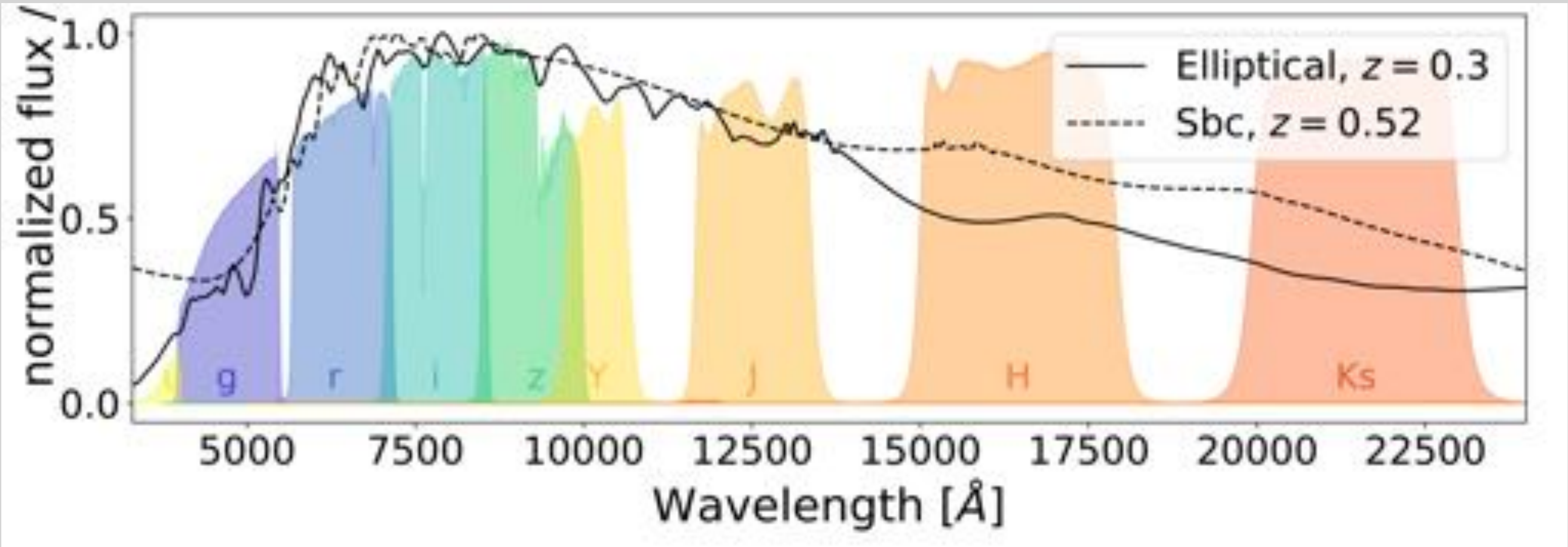

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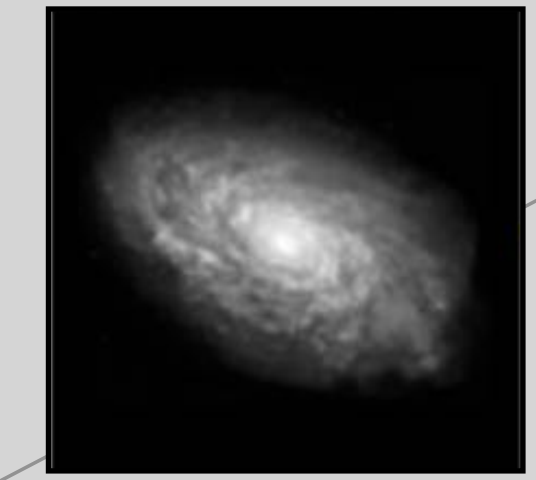

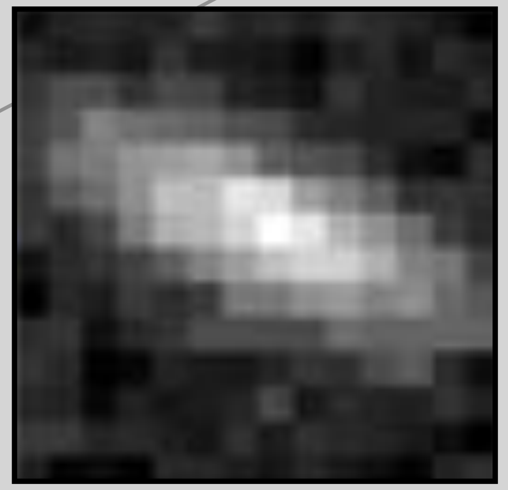

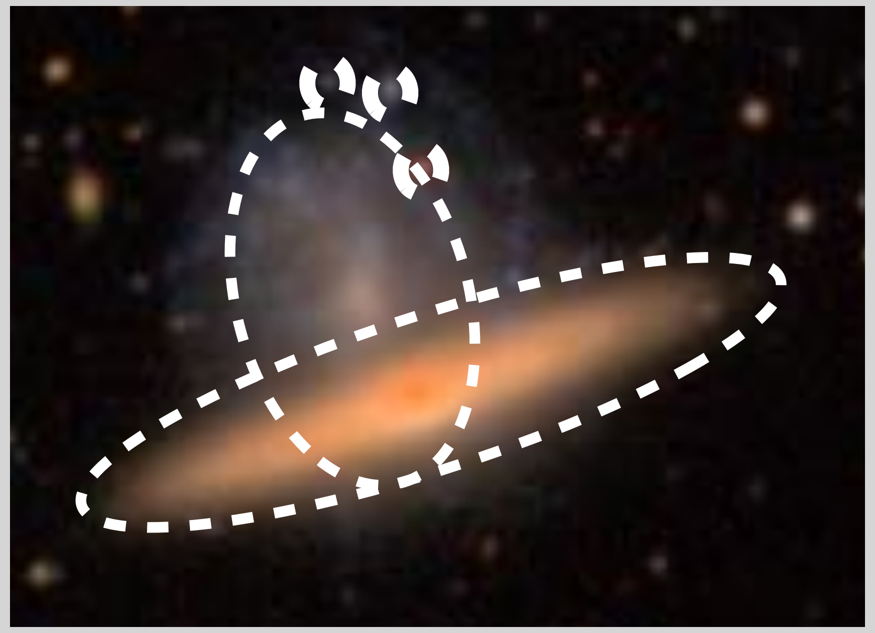

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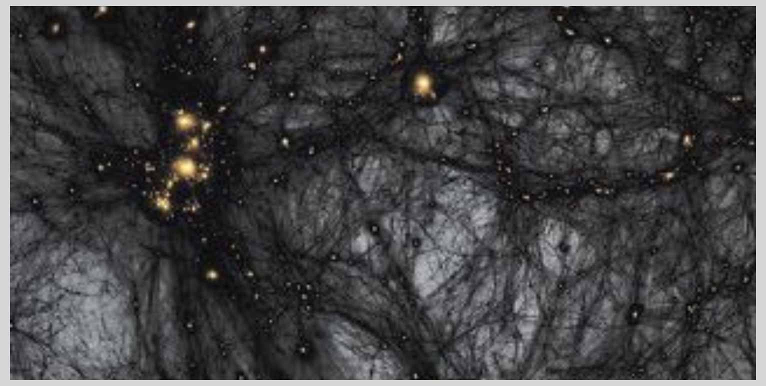

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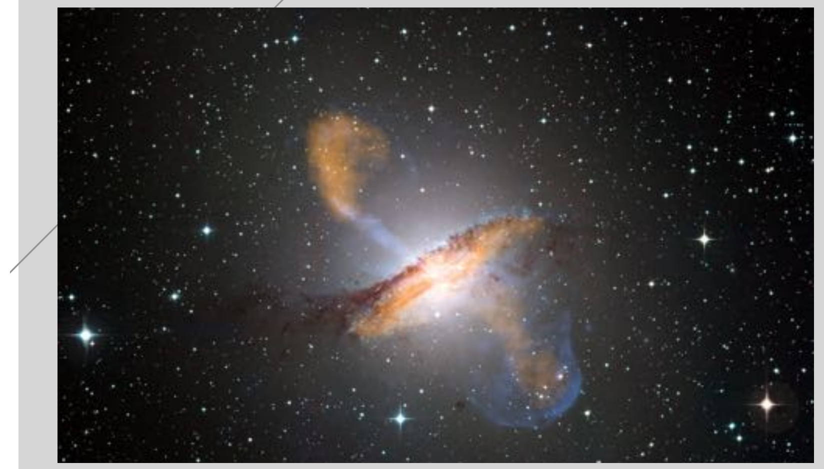
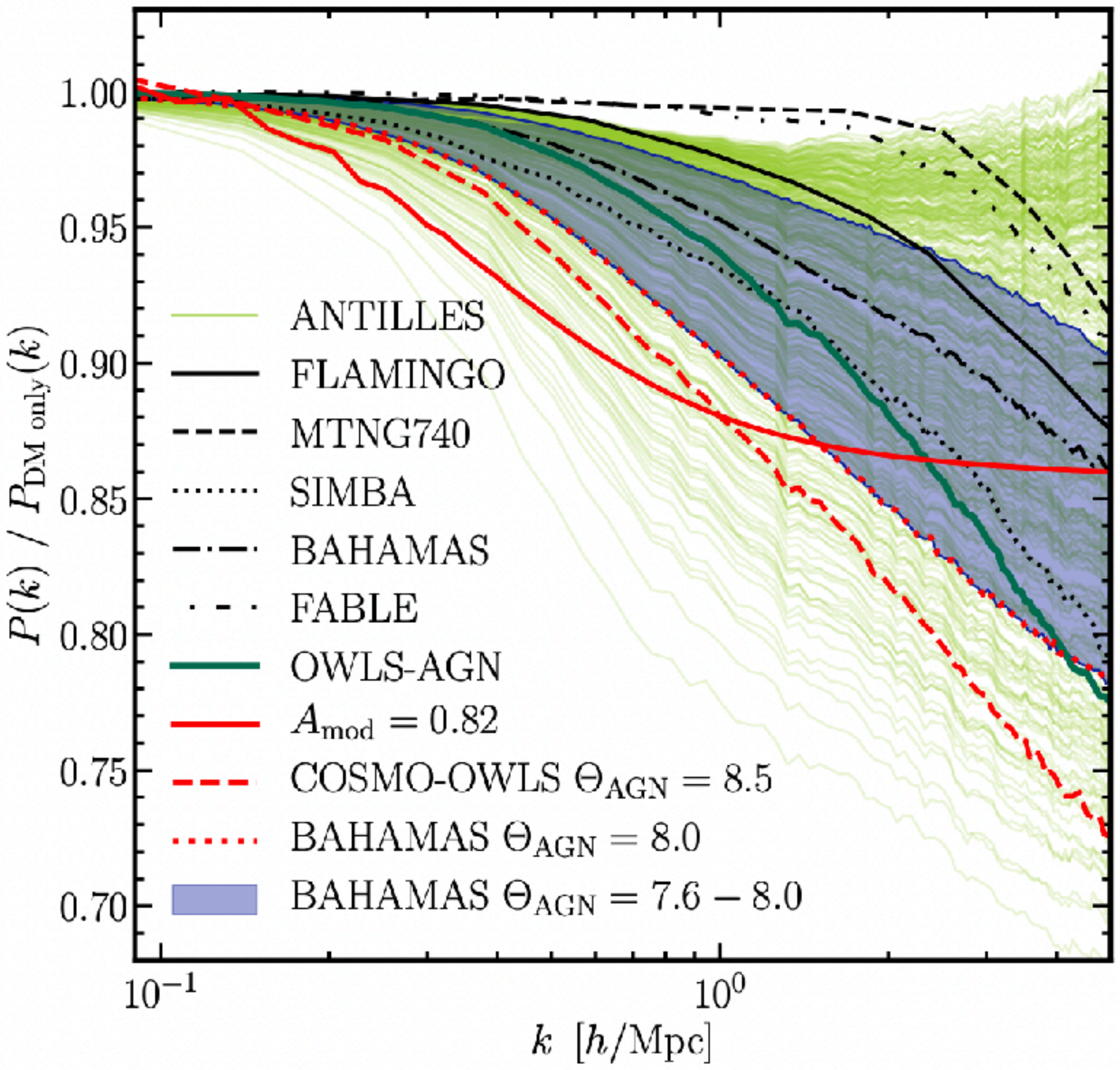
Scale cuts & baryonic effects

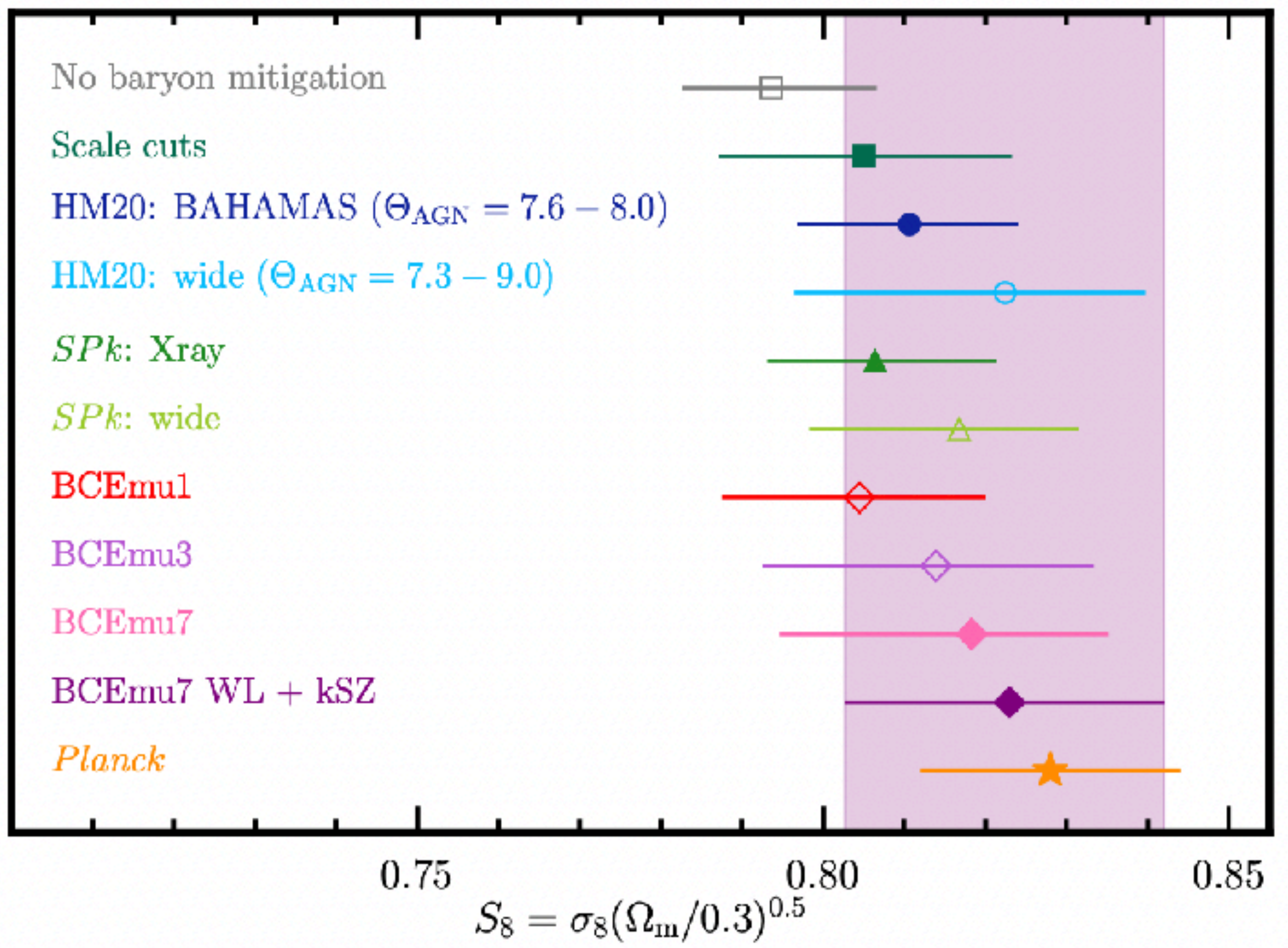


Challenge: Baryon feedback in galaxies alters the matter power spectrum on small scales. There is a large uncertainty on the amplitude and the extent of this effect.

Mitigating baryonic effects

Impact of baryons on the small-scale matter power spectrum is poorly understood





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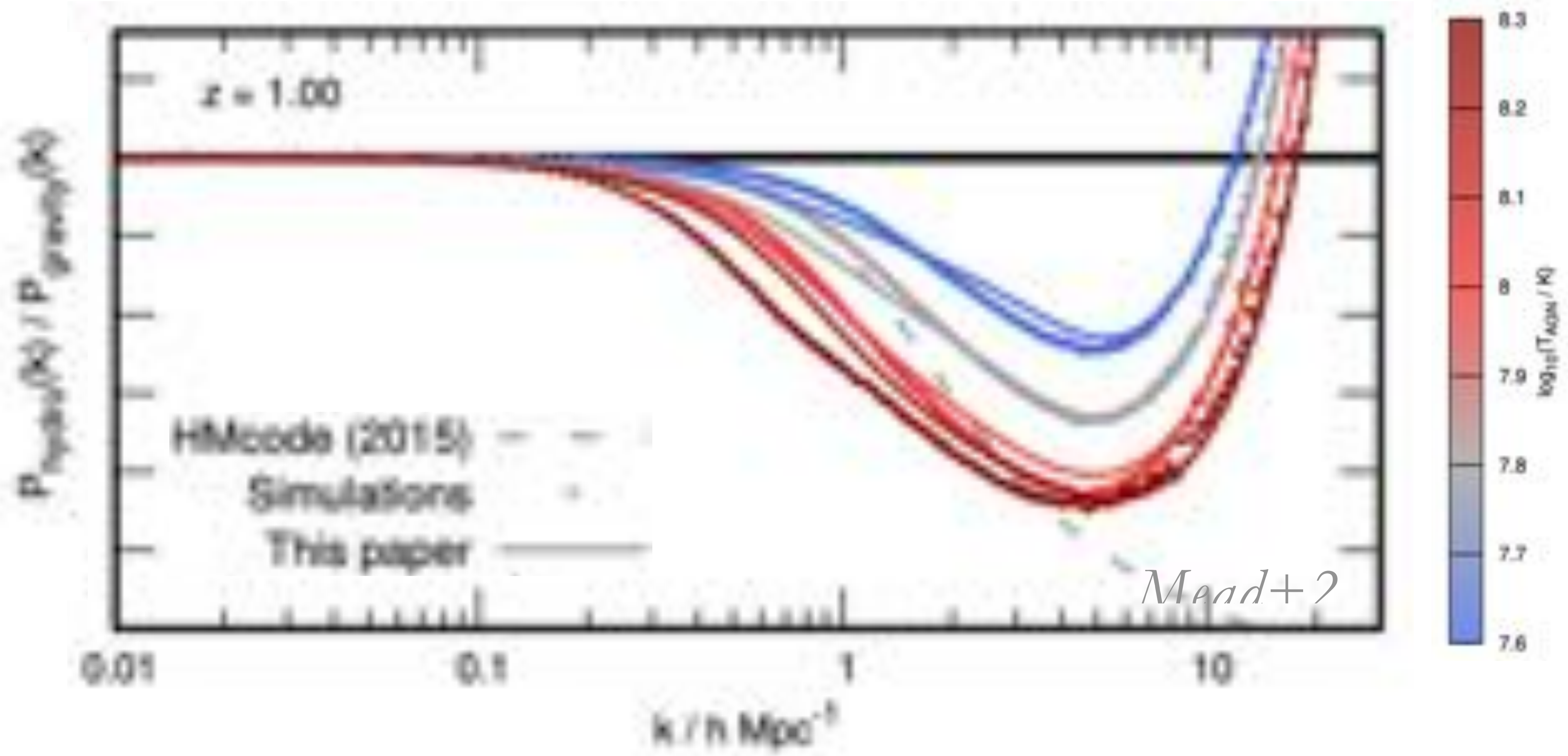
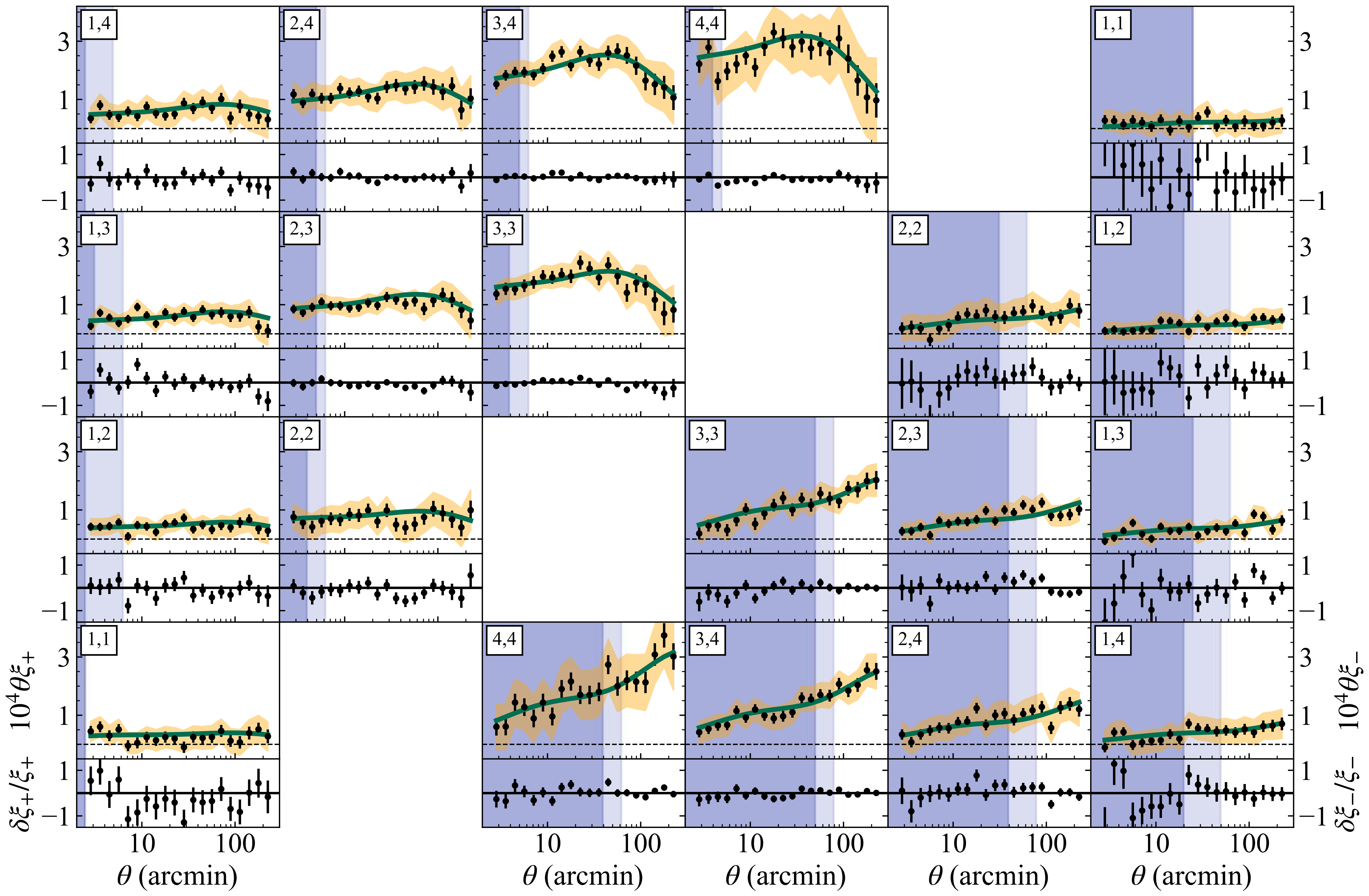


1. Model with flexibility & uncertainty

   Derived from a halo model approach
   Calibrated on BAHAMAS simulations



2. Toss small-scales

Cut data until bias <0.1sigma

Parameter	Type	Value
Cosmological		
Ω_{m}, Total matter density	Flat	[0.1, 0.9]
Ω_{b}, Baryon density	Flat	[0.03, 0.07]
$10^{-9}A_{\mathrm{s}}$, Scalar spectrum amplitude	Flat	[0.5, 5.0]
h, Hubble parameter	Flat	[0.55, 0.91]
n_{s}, Spectral index	Flat	[0.87,1.07]
$\Omega_\nu h^2$, Neutrino mass density	Flat	[0.00060,0.00644]
w, Dark energy parameter	Fixed	[-2,-1/3]
Observational		
Δz^1, Source redshift 1	Gaussian	(0.0, 0.018)
Δz^2, Source redshift 2	Gaussian	(0.0, 0.015)
Δz^3, Source redshift 3	Gaussian	(0.0, 0.011)
Δz^4, Source redshift 4	Gaussian	(0.0, 0.017)
m^1, Shear calibration 1	Gaussian	(-0.006, 0.009)
m^2, Shear calibration 2	Gaussian	(-0.020, 0.008)
m^3, Shear calibration 3	Gaussian	(-0.024, 0.008)
m^4, Shear calibration 4	Gaussian	(-0.037, 0.008)
Intrinsic alignment		
a_1, Tidal alignment amplitude	Flat	$[-5, 5]$
a_2, Tidal torque amplitude	Flat	$[-5, 5]$
η_1, Tidal alignment redshift index	Flat	$[-5, 5]$
η_2, Tidal torque redshift index	Flat	$[-5, 5]$
b_{ta}, Tidal alignment bias	Flat	$[0, 2]$

- What we want
- Known things we account for
- Known things we don't account for, but we can estimate how bad it is
  - e.g. ??
- Known things we don't account for, but it's hard to estimate how bad it is
  - e.g. ??
- Unknown things we don't account for