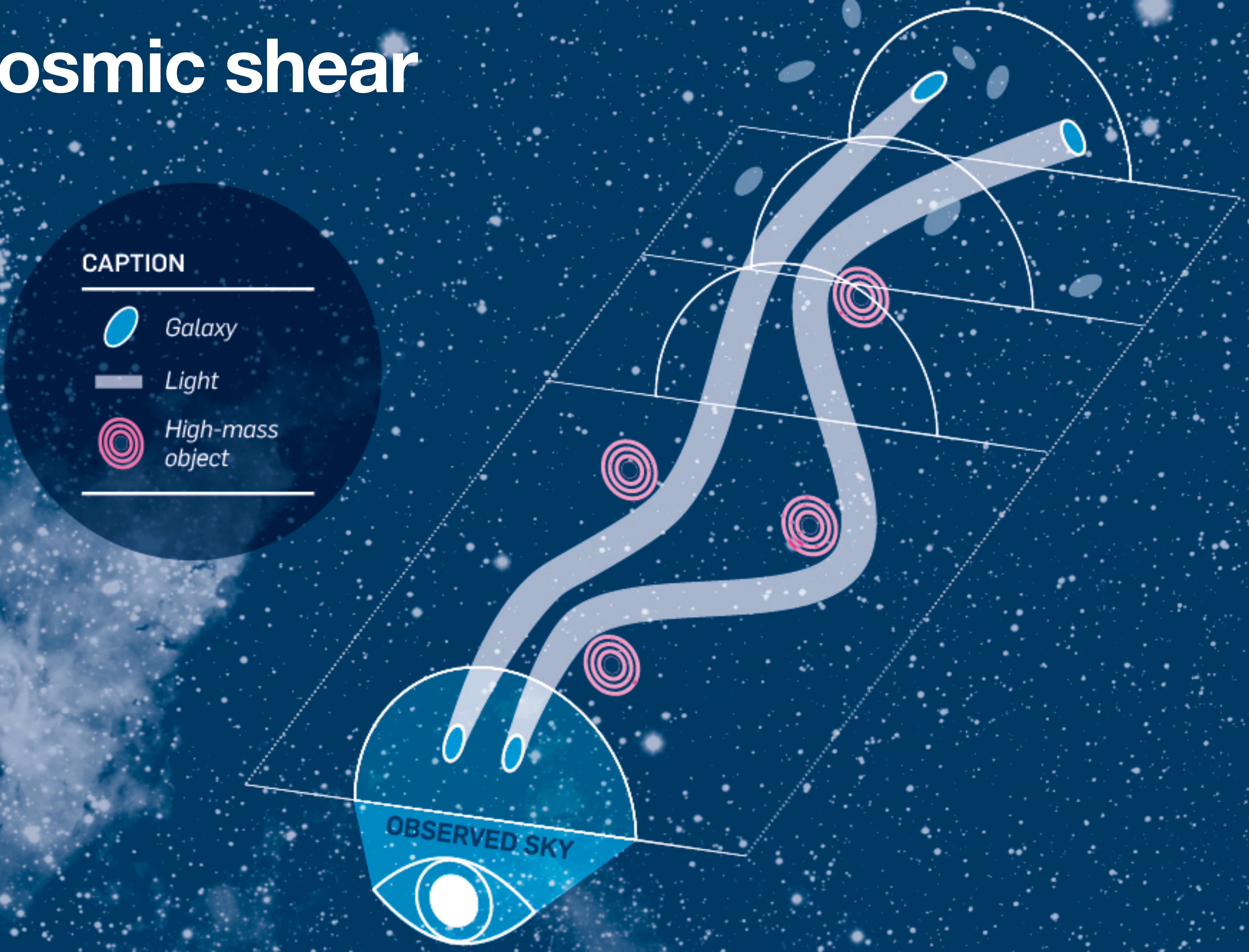
Cosmic shear

Going from stage-III to stage-IV

Hendrik Hildebrandt, Ruhr University Bochum, 2022-11-09

Cosmic shear



Sensitive to:

- Matter distribution
- Geometry

Observables:

- Ellipticities
- Photo-z

=>

Tomographic 2pt shear statistics

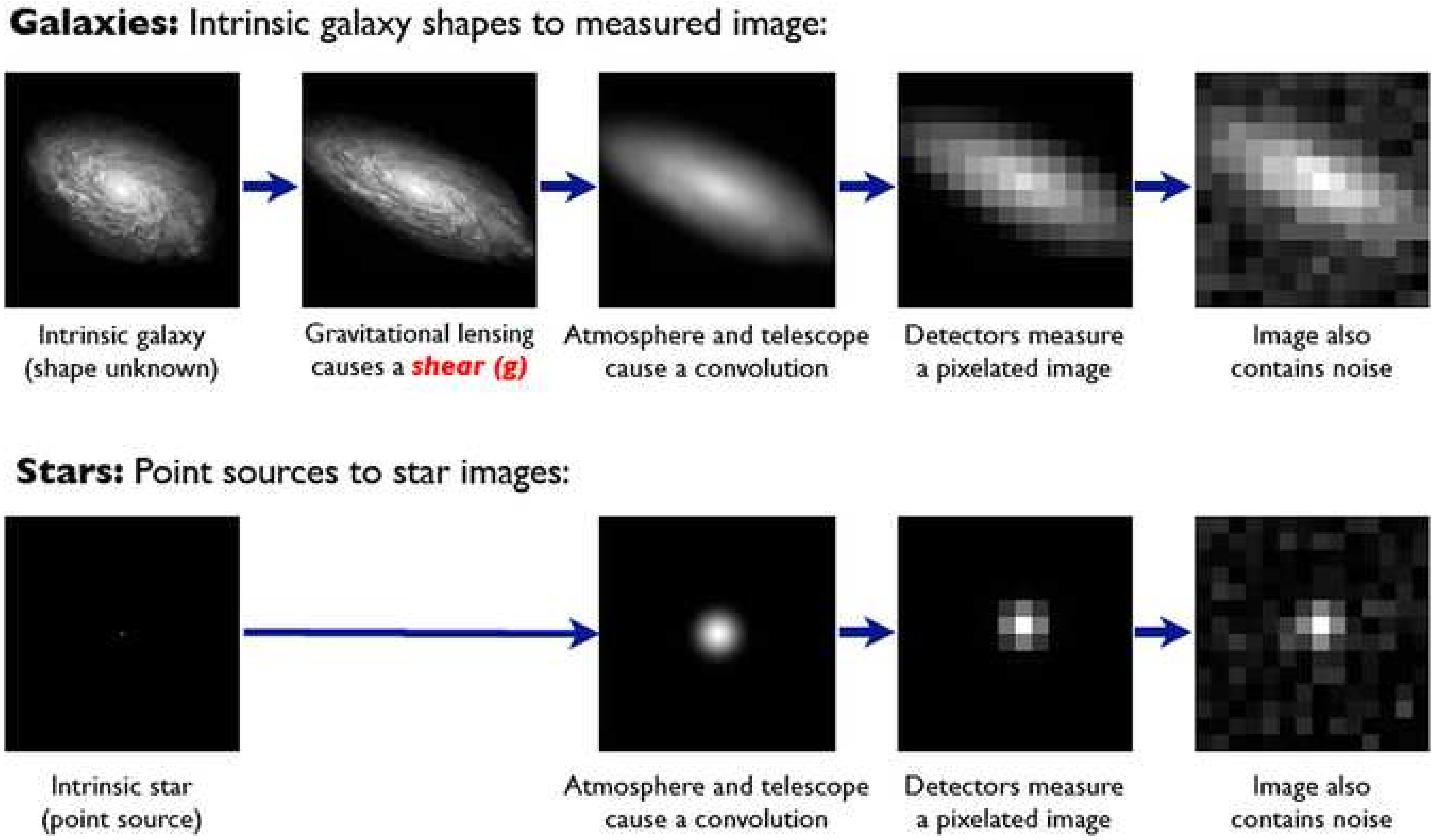
No galaxy bias!

KiDS-1000 re-analysis

Compared to DES-Y3 & HSC-Y1

van den Busch et al. (2022)

Shape measurements



Bridle et al. (2009)

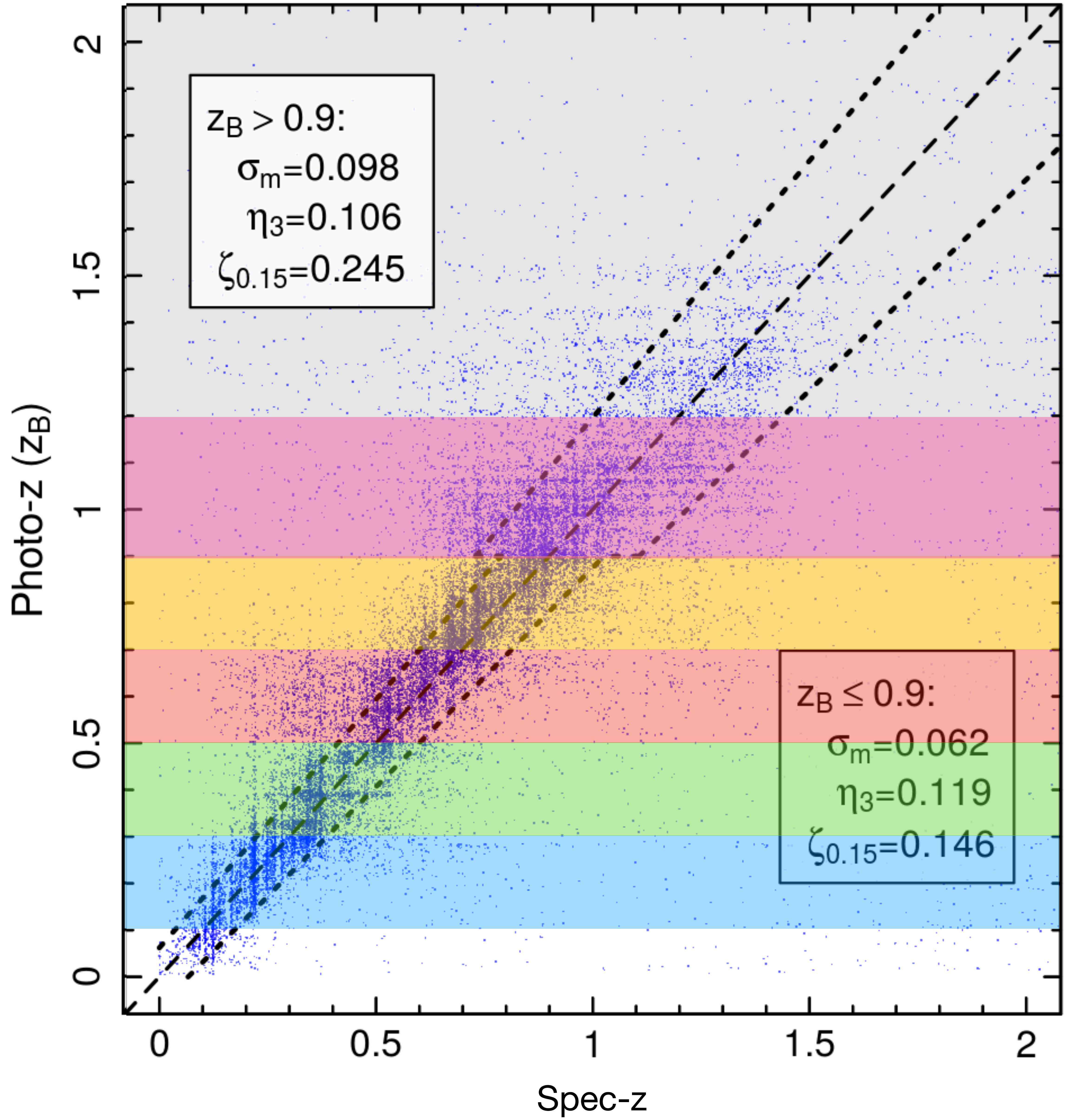
$$\gamma_{\rm obs} = (1 + m)\,\gamma_{\rm input} + c$$

Shape measurements

How it's done in practice

- PSF
  - Select stars as cleanly as possible, but also covering the whole image.
  - Measure PSF via moments or model-fitting.
- Galaxy shapes calibration
  - Simulate images of galaxies with as much realism as possible.
  - Run your shape measurement algorithm on sims (often assuming perfect PSF) => ***m*-bias for ensembles**. $\boldsymbol{\gamma}_{\text{obs}} = (1 + \boldsymbol{m})\,\boldsymbol{\gamma}_{\text{input}} + \boldsymbol{c}$
- Galaxy shapes on data
  - Measure shapes + weights individually.
  - Apply *m*-bias to the estimator (2pt function).
- Marginalise over σ_m in the inference.

Photometric redshifts



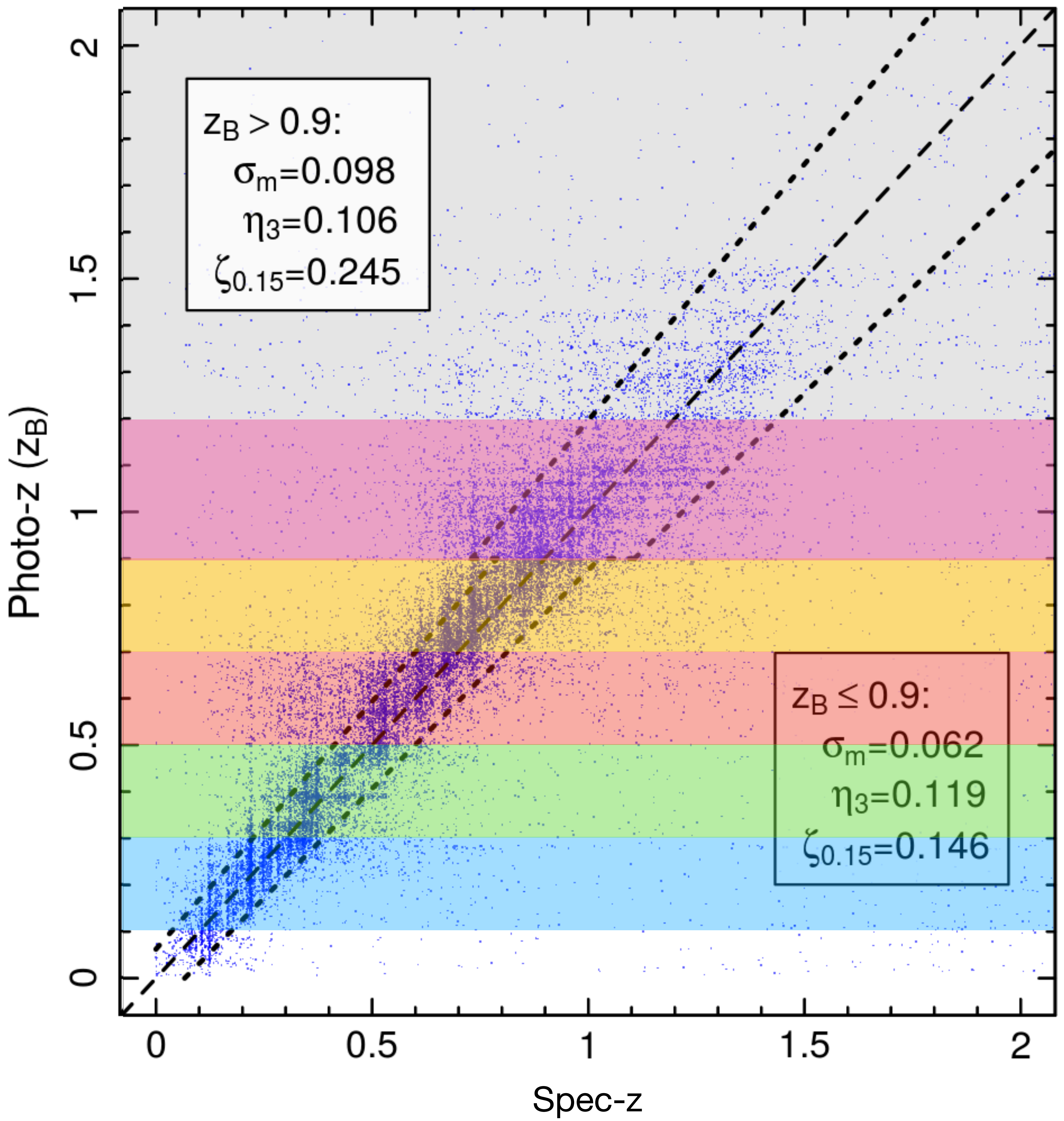
Wright et al. (2018)

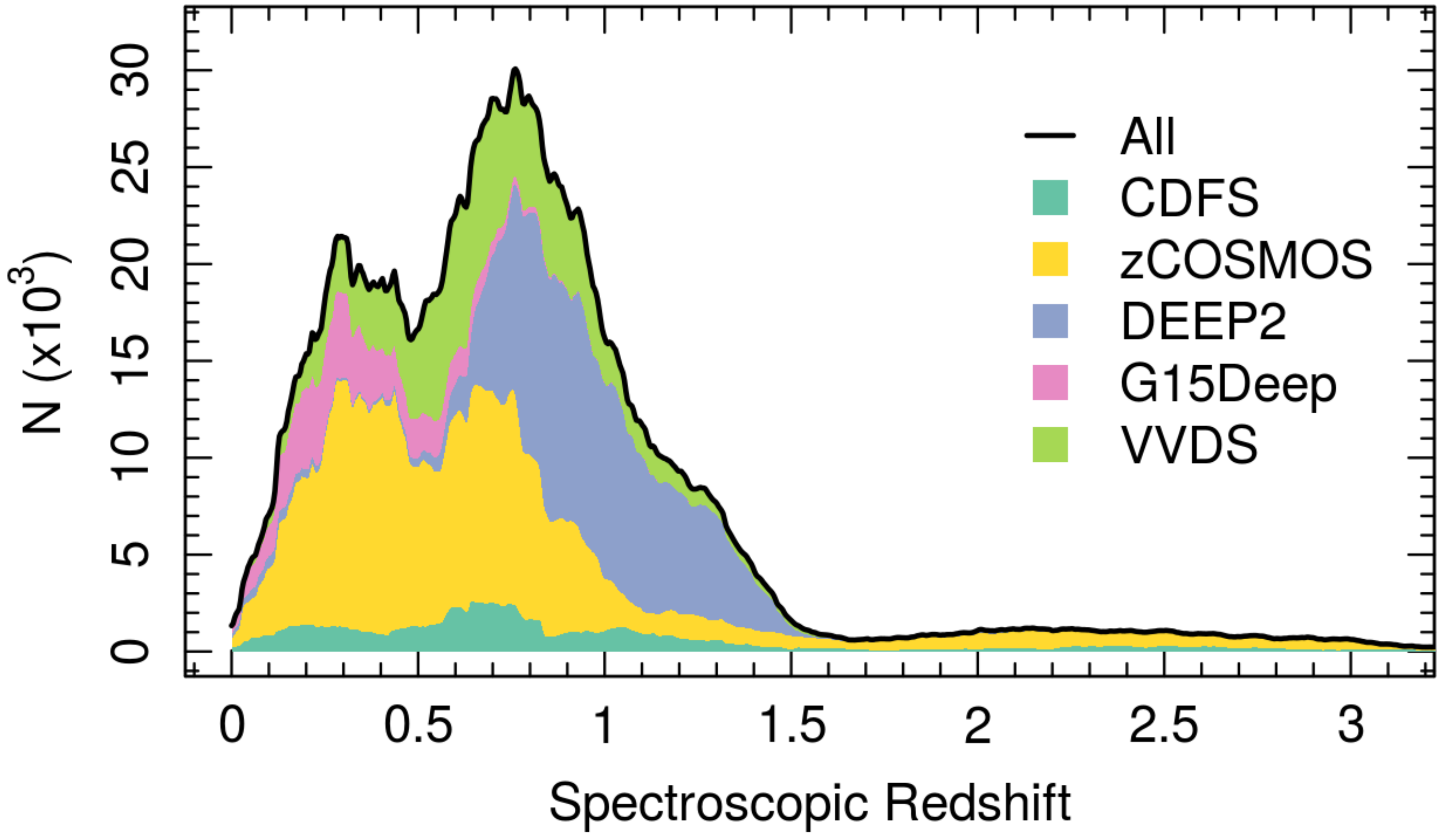
Photometric redshifts

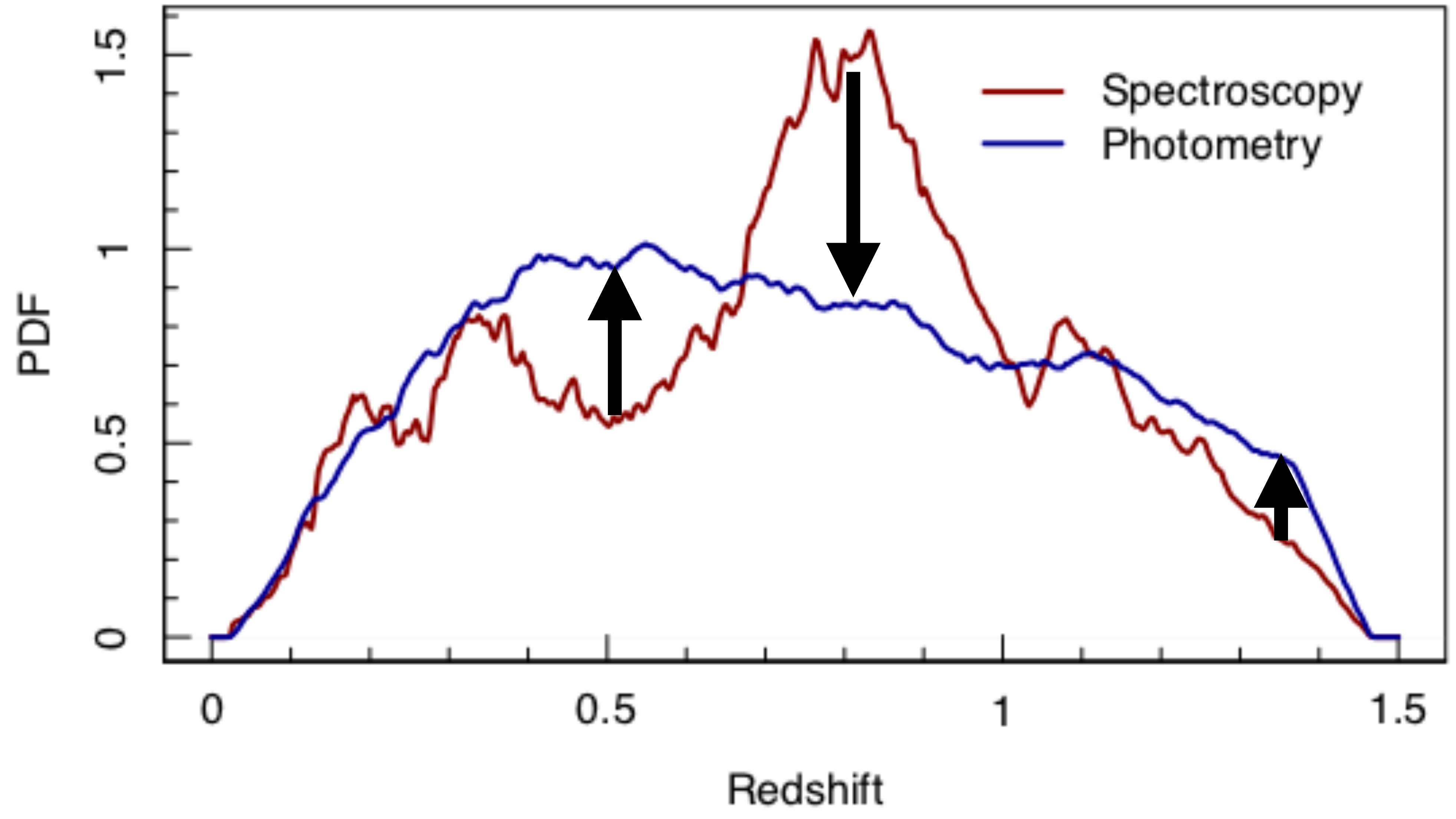
How it's done in practice

- Individual galaxy photo-*z*
    - Measure high-SNR, PSF-homo., matched-aperture, multi-band photometry.
    - Run a (typically template-based) photo-*z* algorithm.
    - Split galaxies into tomographic bins.
- Tomographic bins
    - Determine $n(z)$ empirically, i.e. with help of spec-*z* calibration sample.

Photo-z calibration



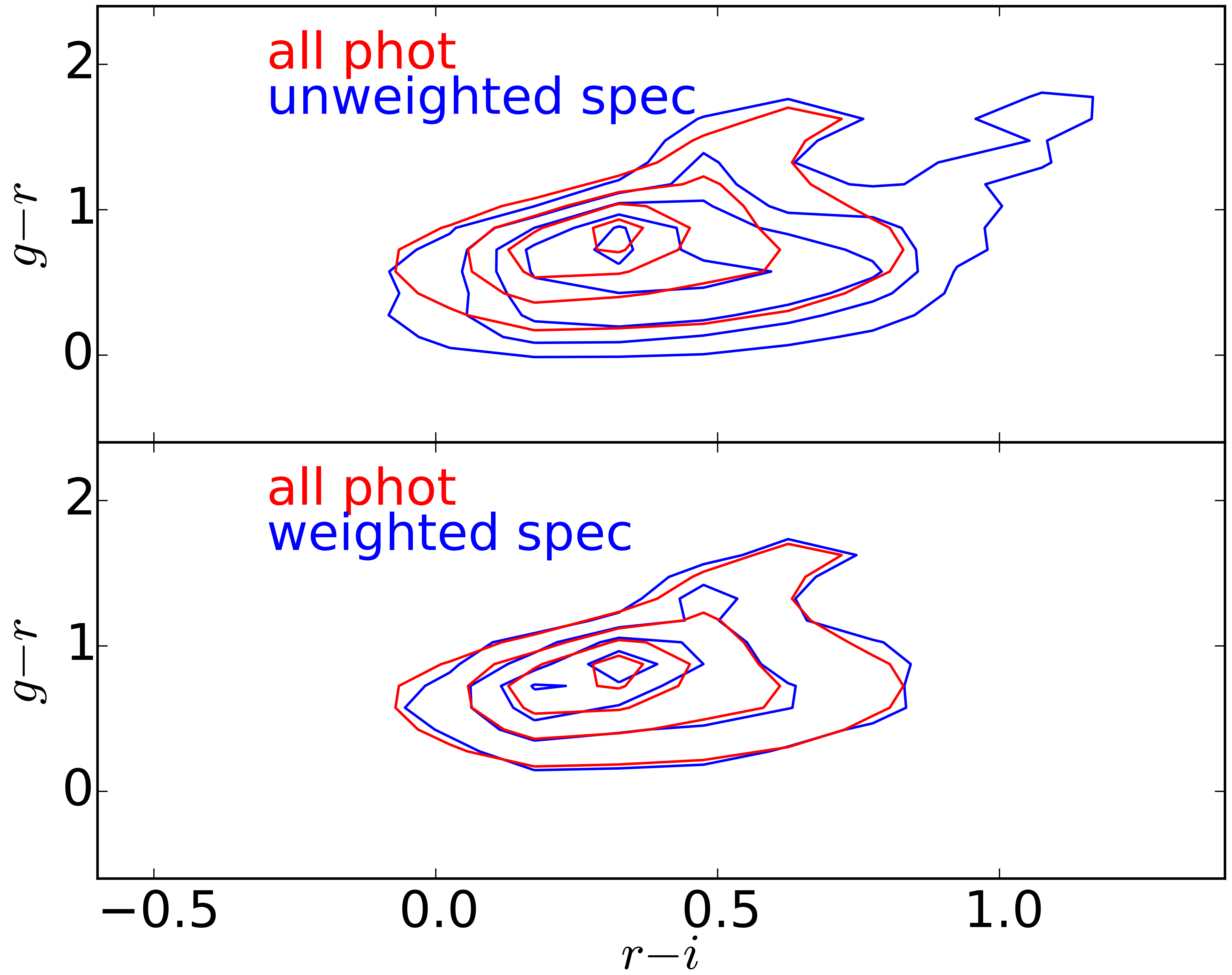




Wright et al. (2018)

Redshift calibration with *k*NN weighting

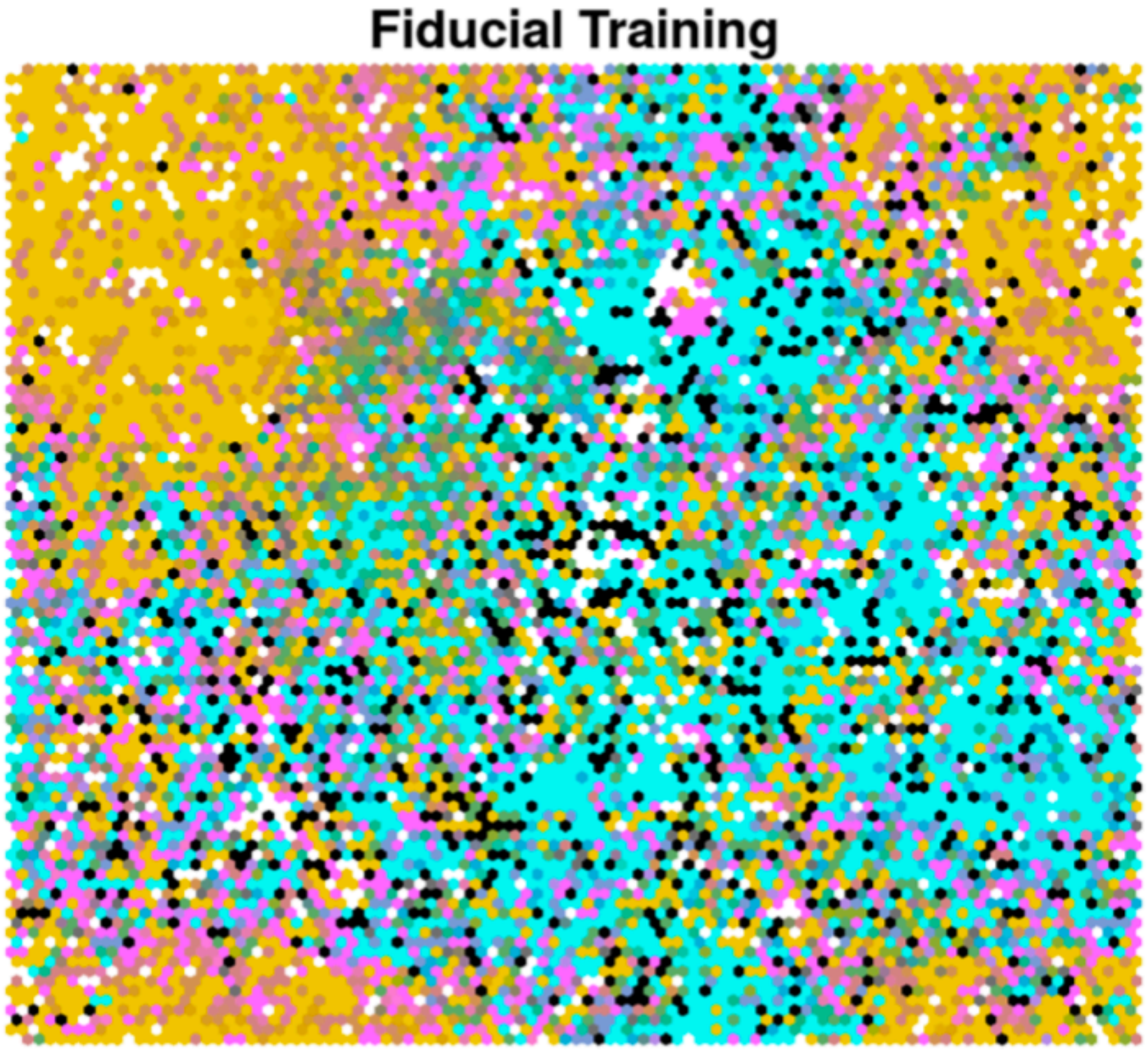
Re-weight spec-*z* surveys to be more representative.

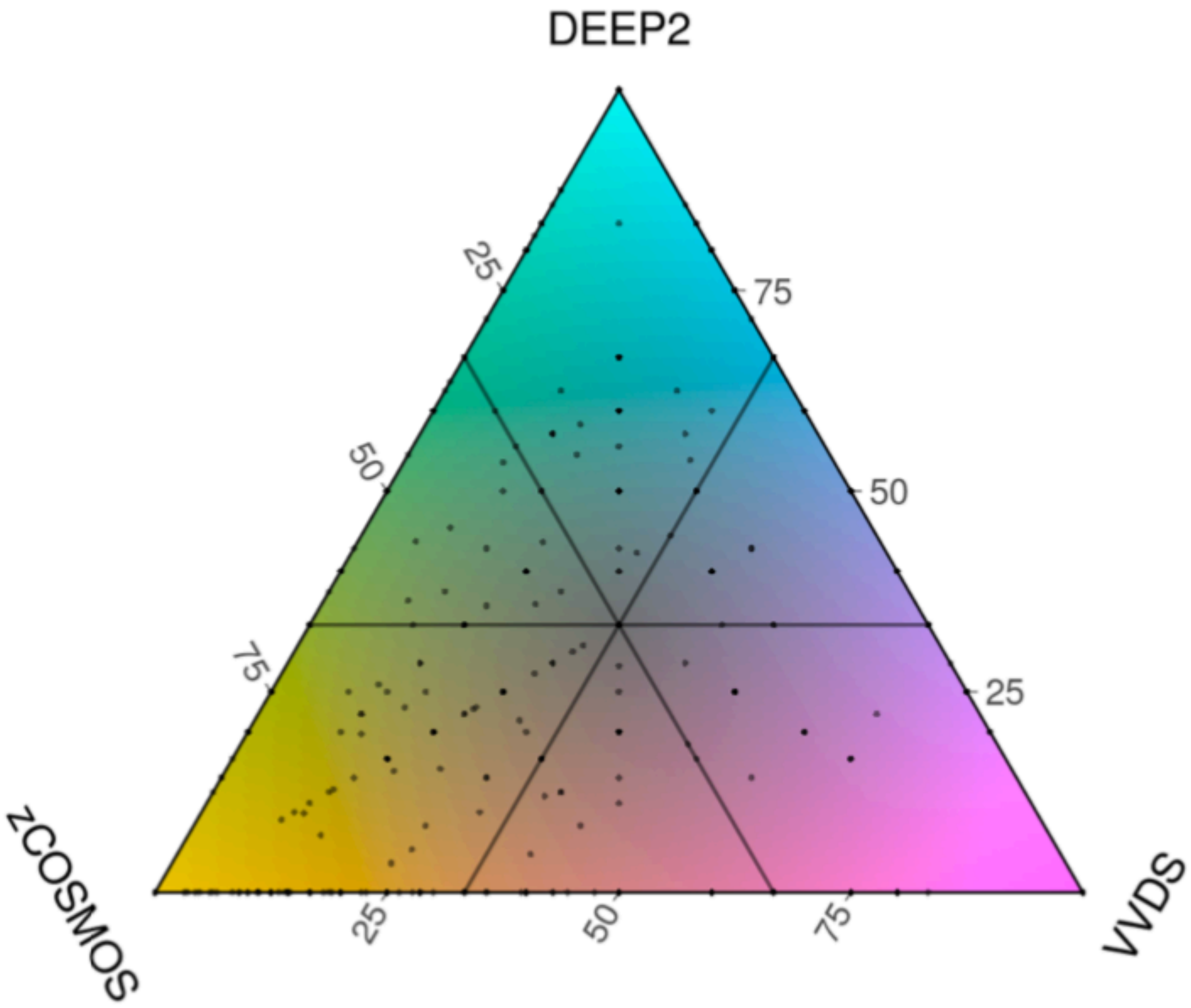


1. Magnitude space needs to be fully covered.
2. Requires unique relation colour-redshift relation.

Hildebrandt et al. (2017)

Self-organising map of mag space





~99% coverage of 9D mag space in KiDS.

Wright et al. (2019)

Photometric redshifts

How it's done in practice

- Individual galaxy photo-z
  - Measure high-SNR, PSF-homo., matched-aperture, multi-band photometry.
  - Run a (typically template-based) photo-z algorithm.
  - Split galaxies into tomographic bins.
- Tomographic bins
  - Determine $n(z)$ empirically, i.e. with help of spec-z calibration sample.
  - Estimate $n(z)$ uncertainties from data (bootstrap) or simulations.
  - Estimate residual biases from simulations.
- Use the $n(z)$ and their bias estimates (e.g. Δz) and marginalise over the uncertainties (e.g. $\sigma_{\Delta z}$) in the inference.

Weak lensing simulations

SKiLLS - SURFS-based KiDS-Legacy-Like Simulations

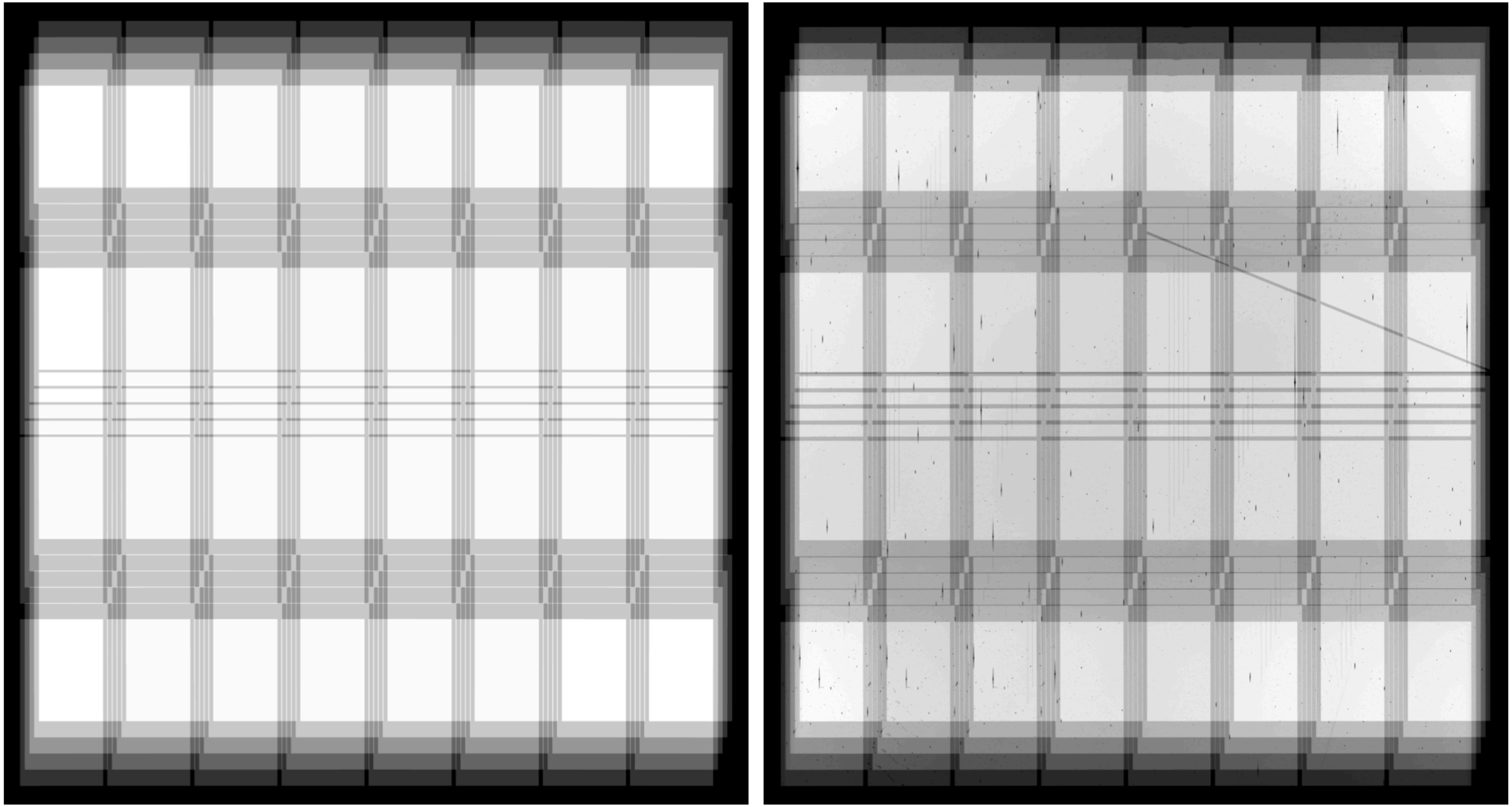
- Large box *N*-body simulation (SURFS).
- Populate with galaxies (Shark SAM).
- Light-cone catalogue with galaxy photometry and positions.
- Galaxy morphology learned from HST observations.
- Synthetic MW stellar catalogue from TRILEGAL model.
- Inject galaxies and stars into images, add noise.
- Run full KiDS pipeline on simulated multi-band images.

SKiLLS

Image layer

SKiLLS

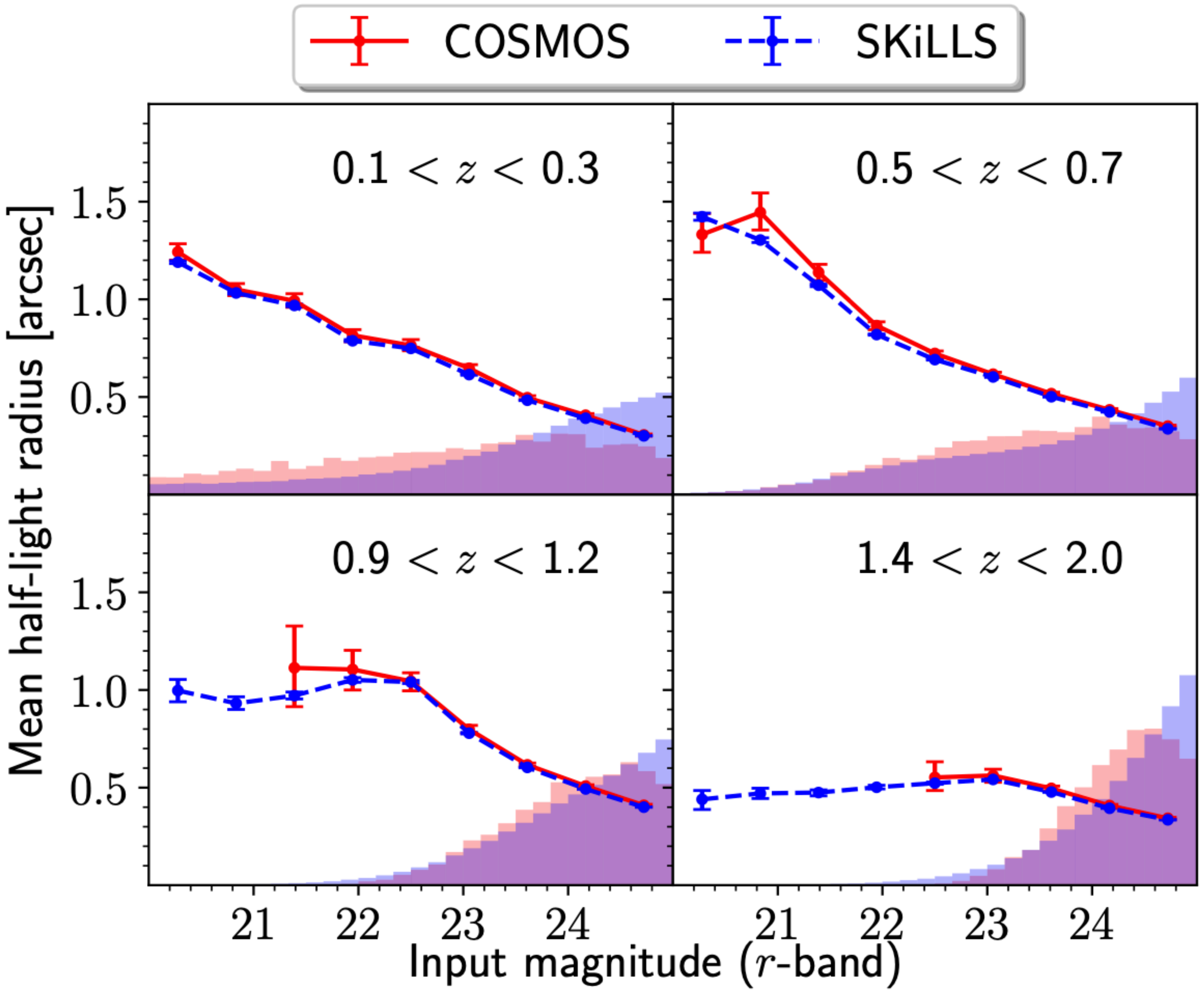
KiDS tile 133.0_0.5

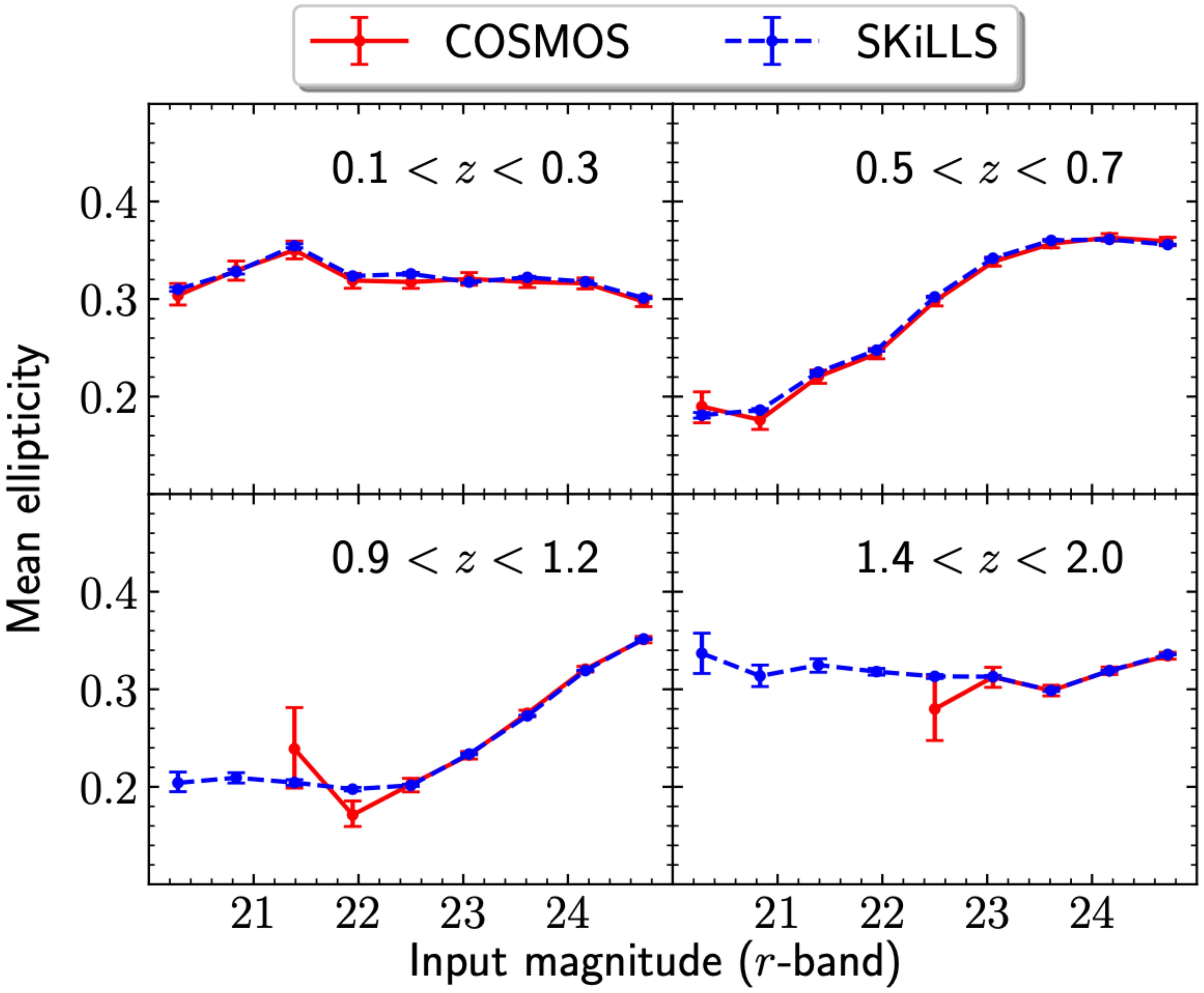


Shun-Sheng Li et al. (2022)

SKiLLS

Morphology

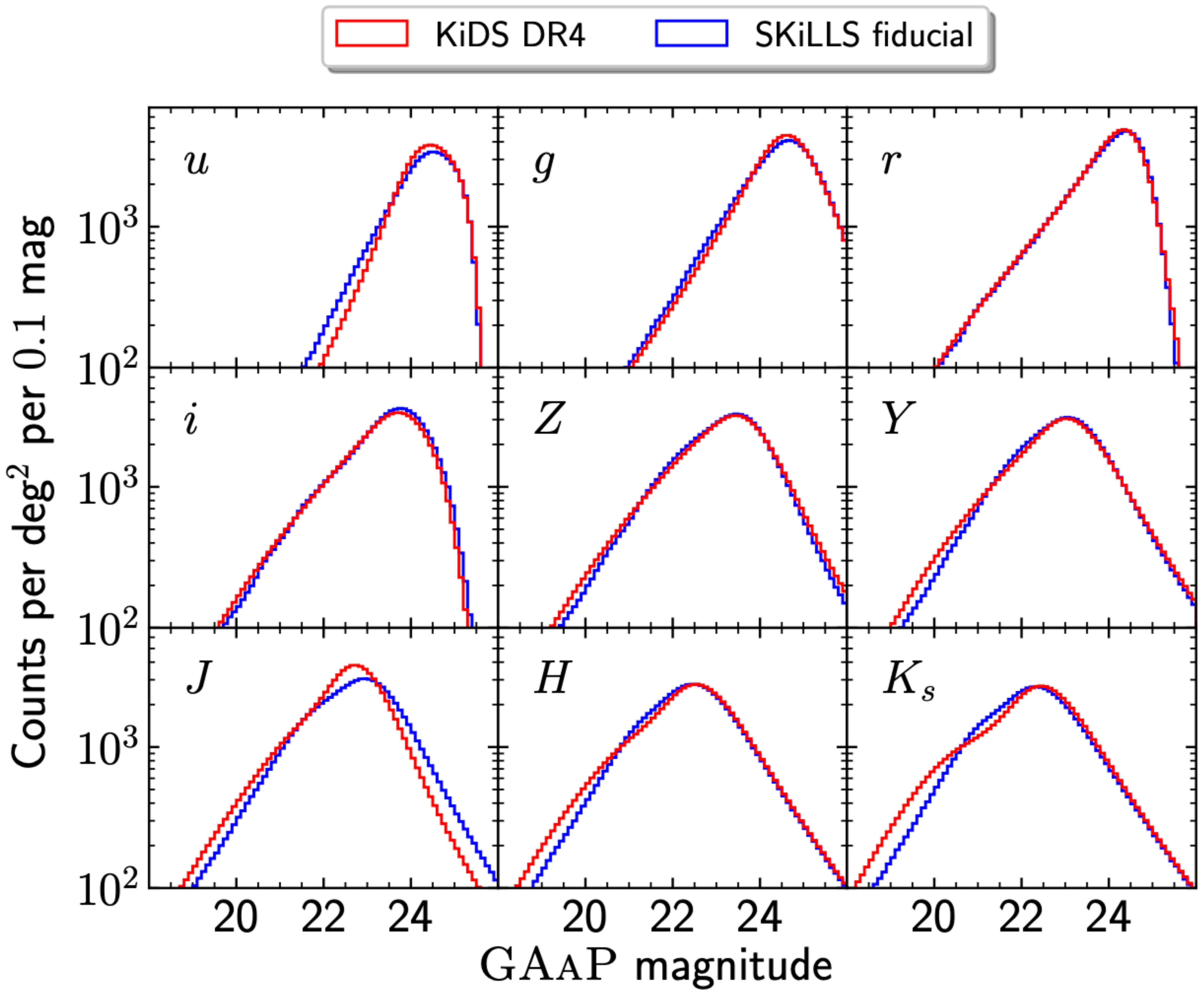


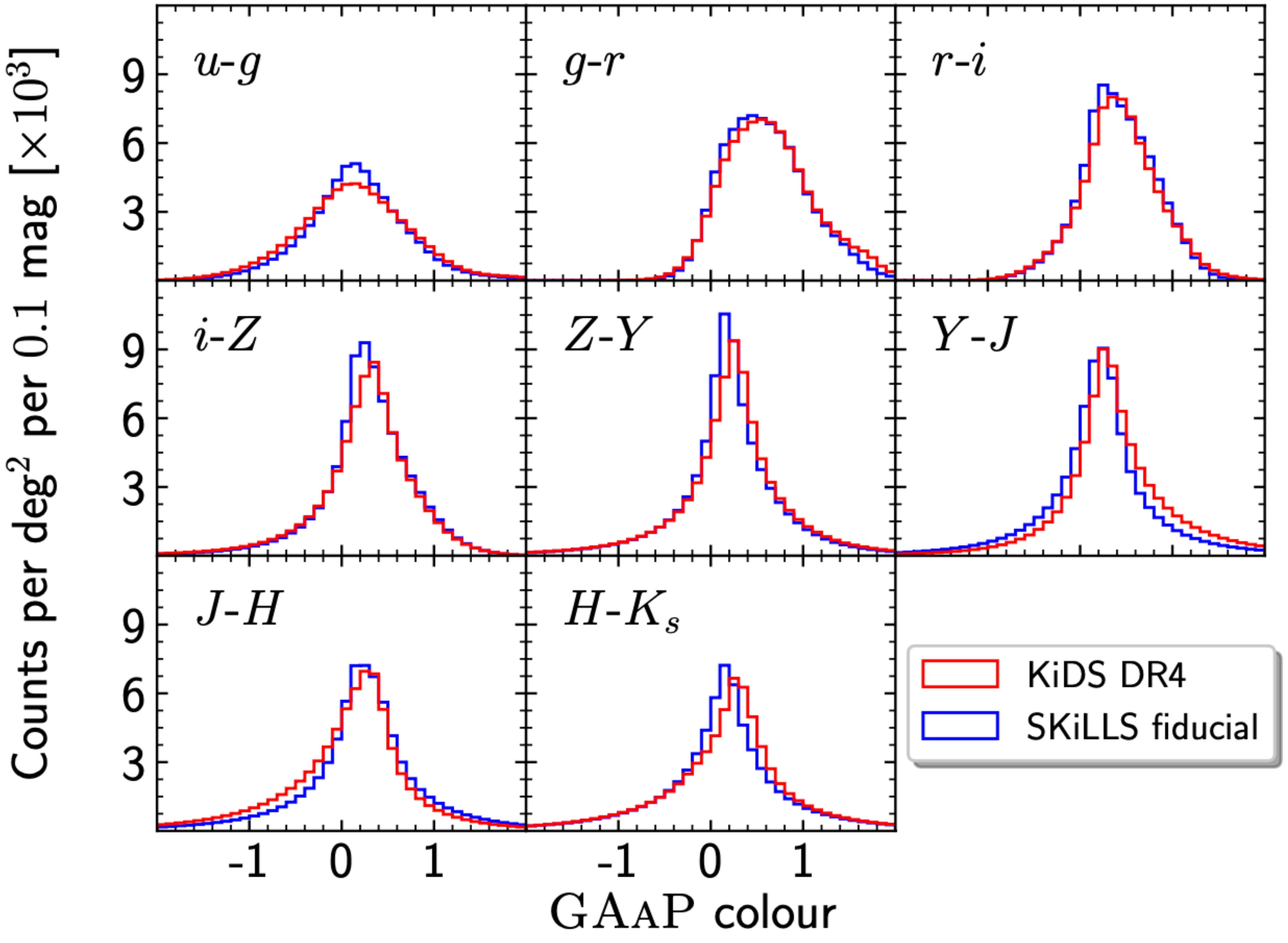


Shun-Sheng Li et al. (2022)

SKiLLS

Photometry

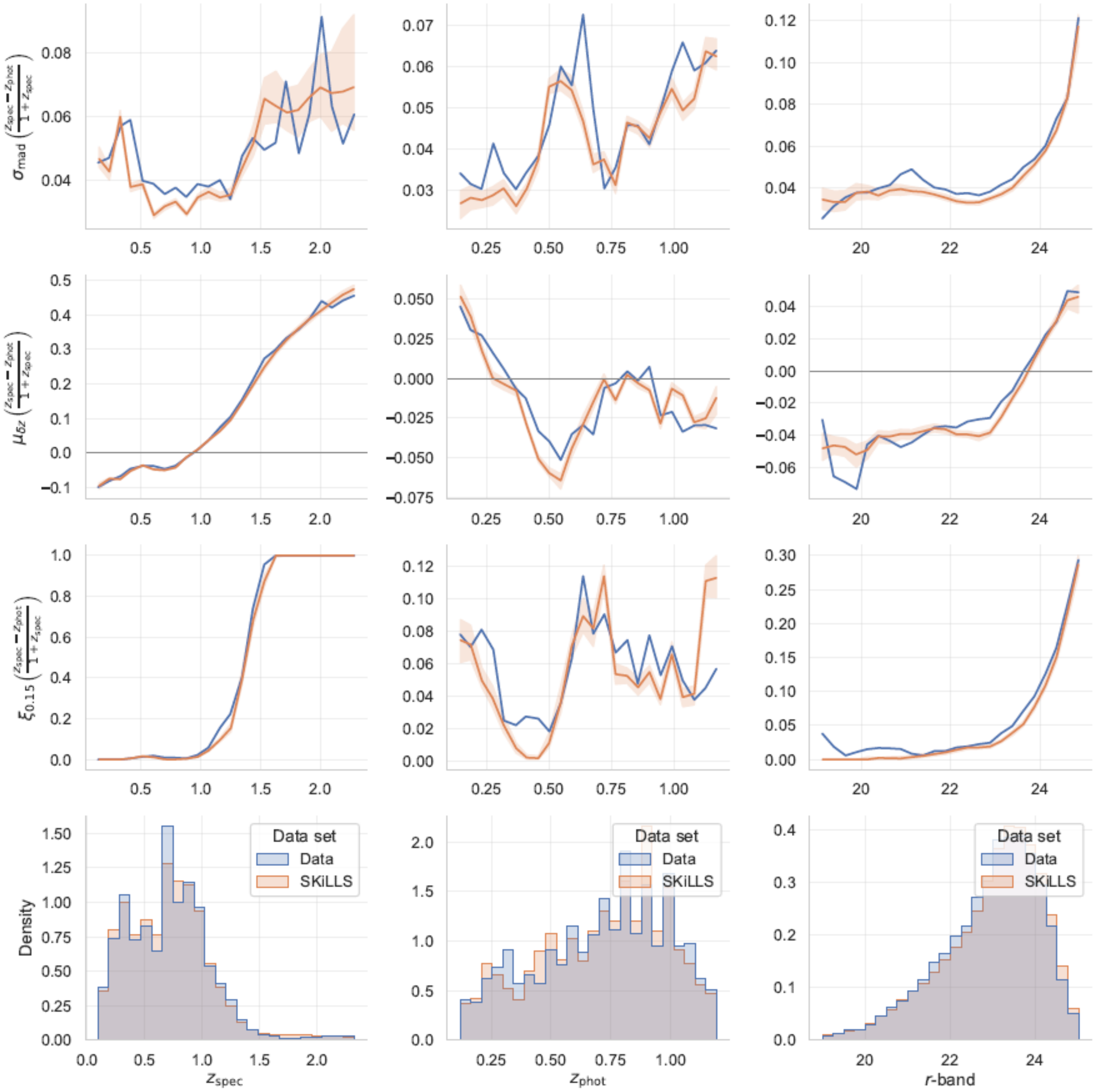




Shun-Sheng Li et al. (2022)

SKiLLS

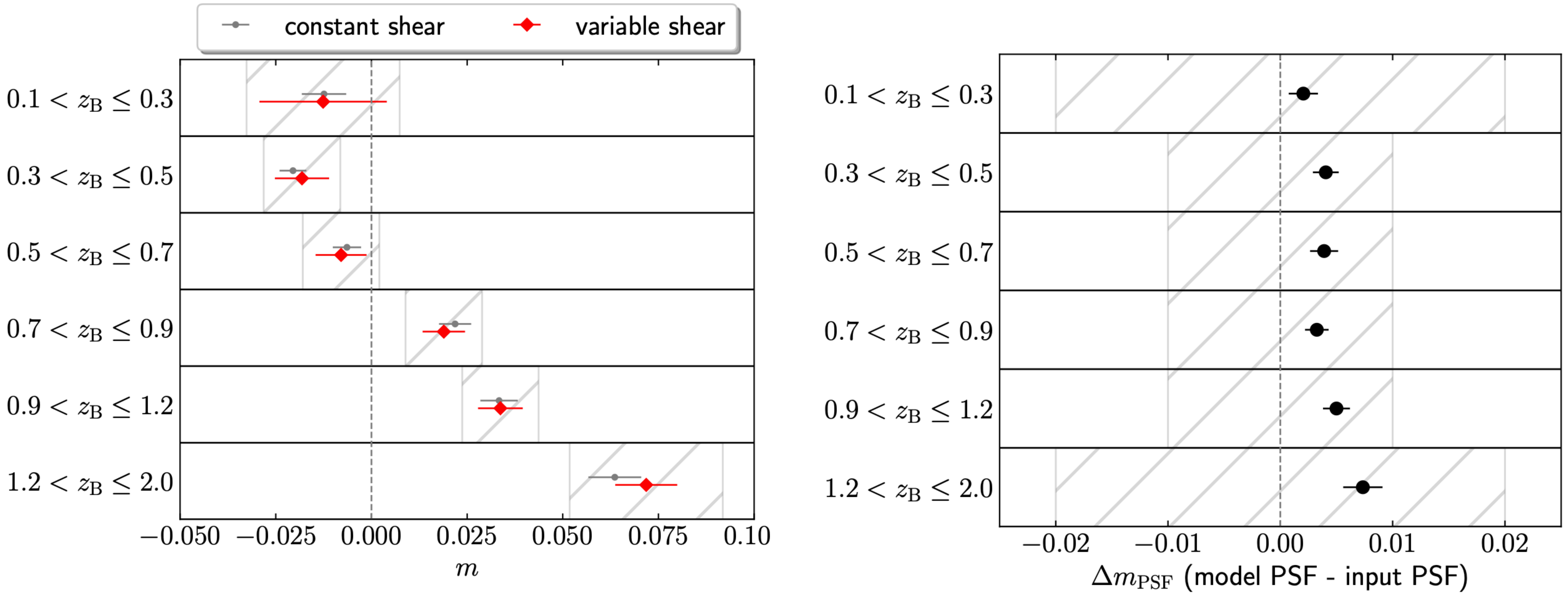
Photo-z



van den Busch et al. in prep.

SKiLLS

m-bias including the effect of blending of sources at different *z*

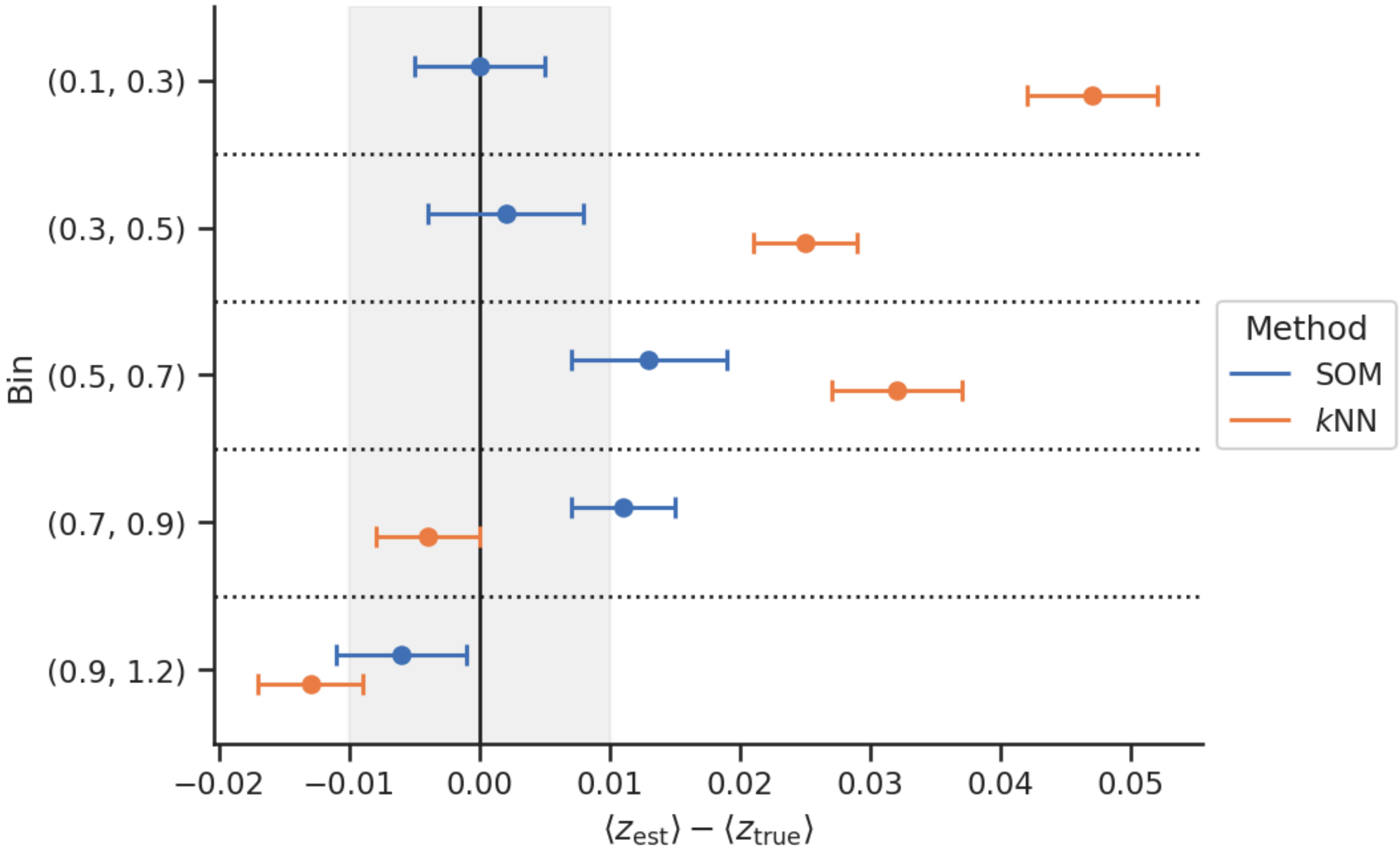


Stage-III requirement: σ_m <~ 0.01

Shun-Sheng Li et al. (2022)

MICE (SKiLLS still work in progress)

Redshift calibration

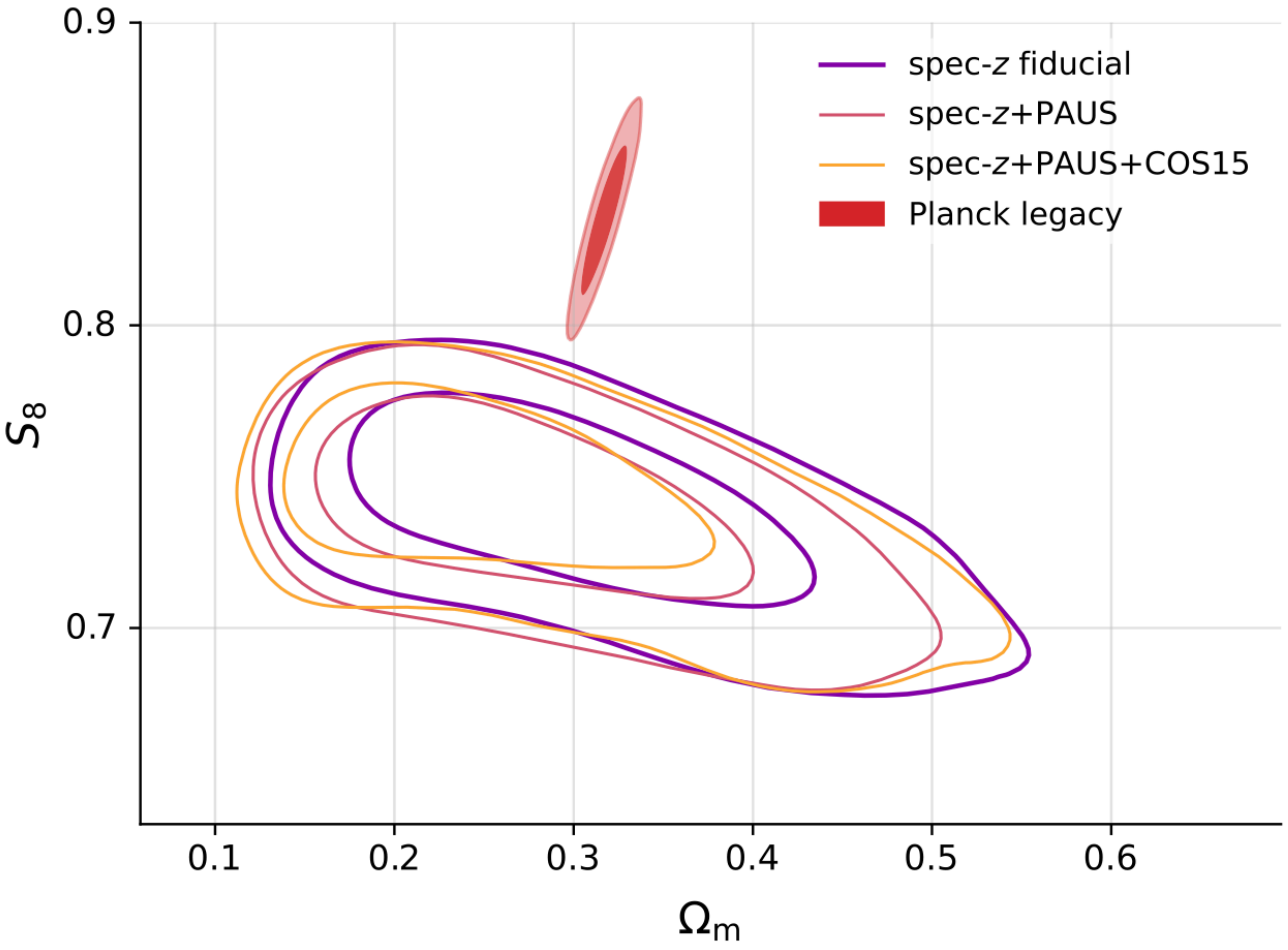


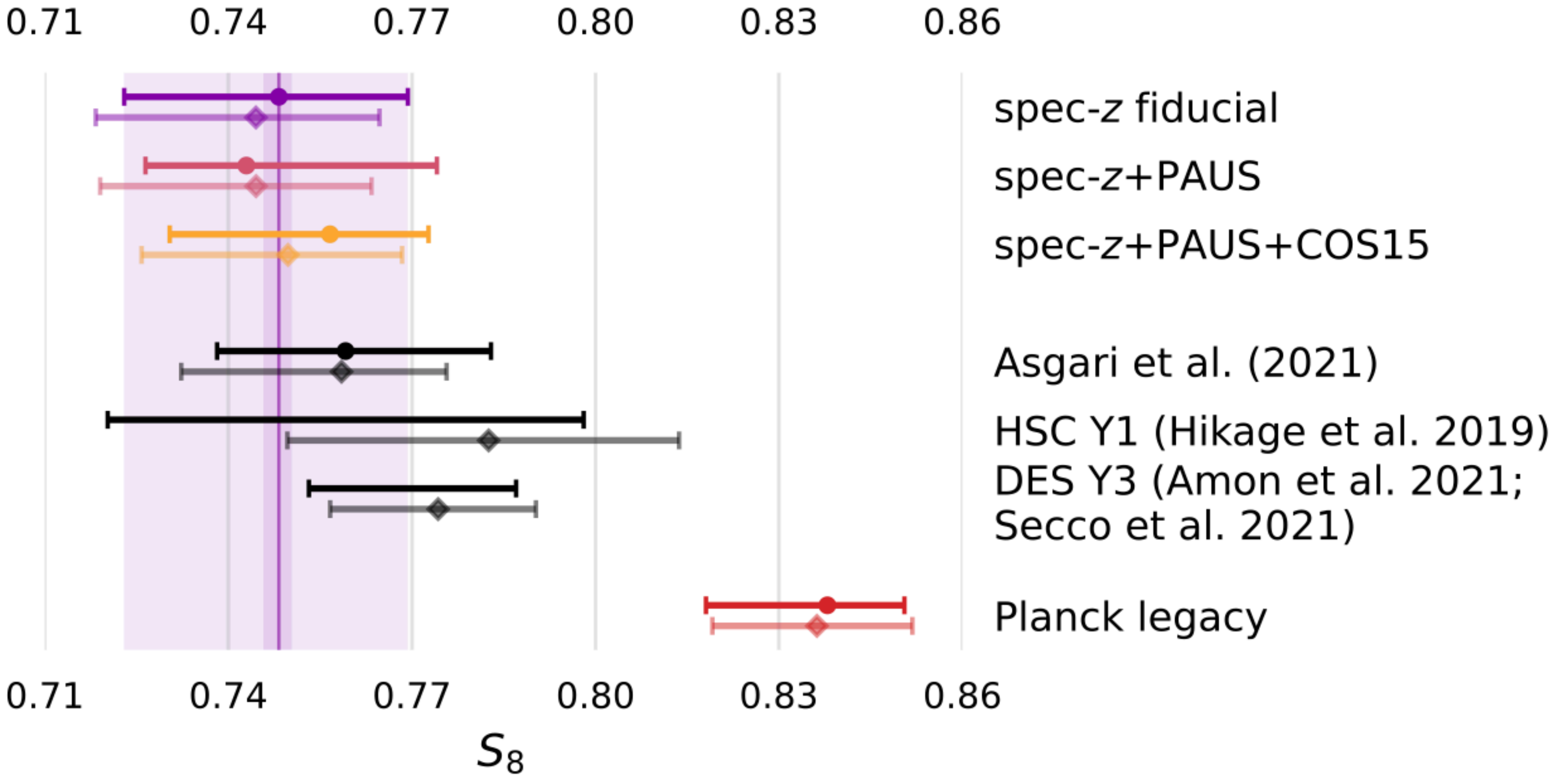
Stage-III requirement: $\sigma_{\Delta z}$ <~ 0.01*(1+z)

Credit: J. L. van den Busch

KiDS-1000 re-analysis

Complementing the redshift calibration sample; empirical test

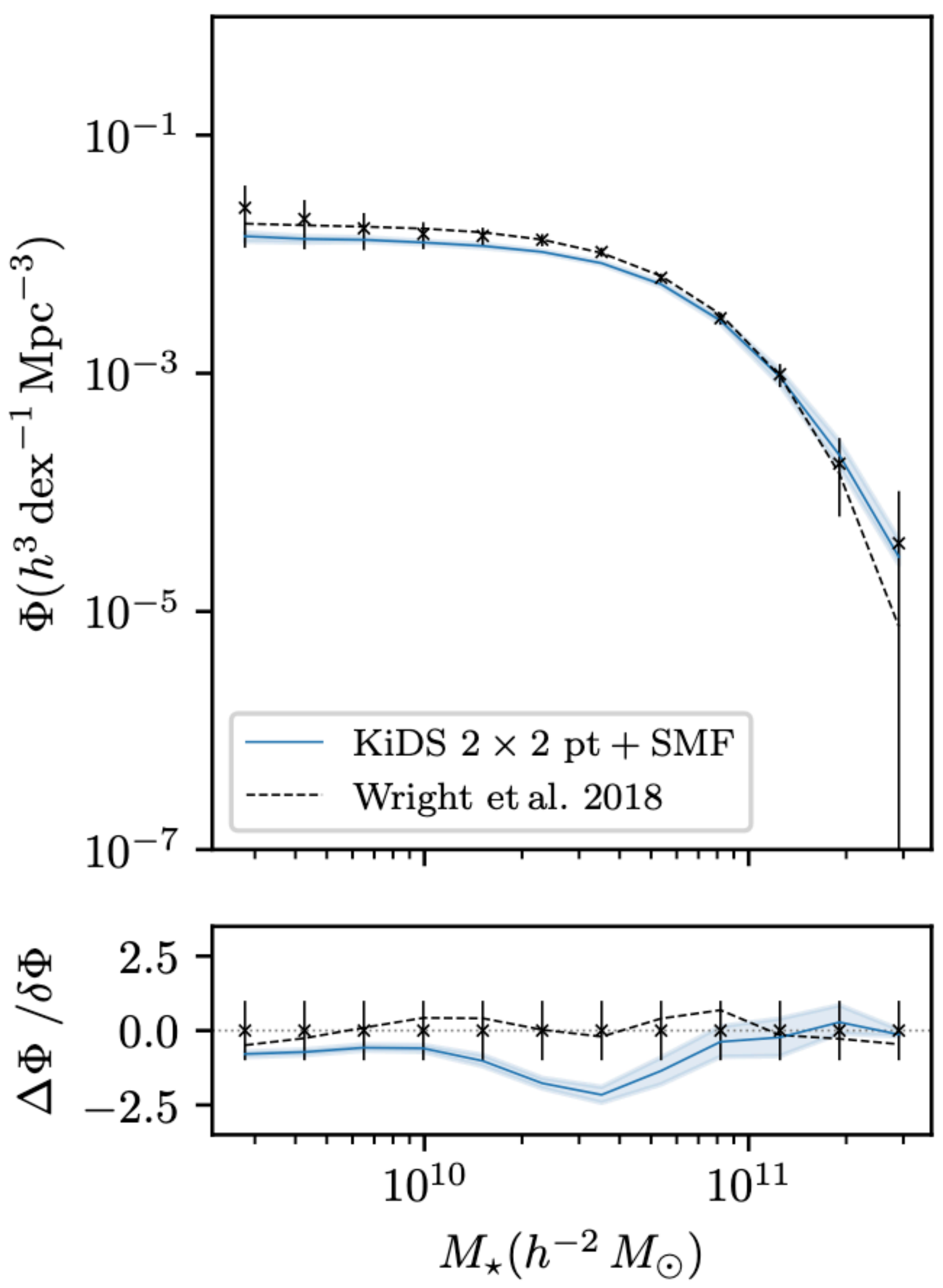




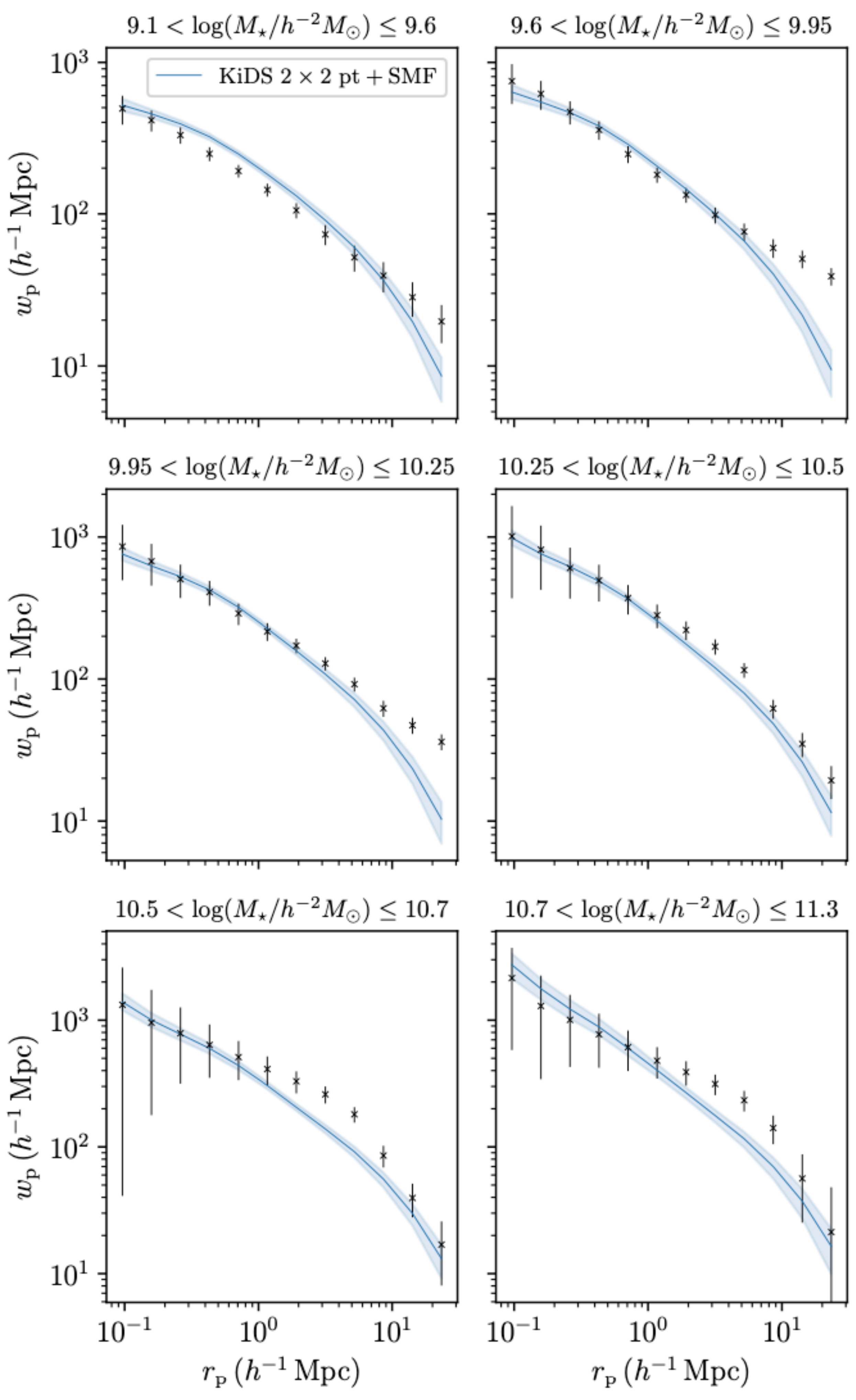
van den Busch et al. (2022)

KiDS-1000 non-cosmic-shear results

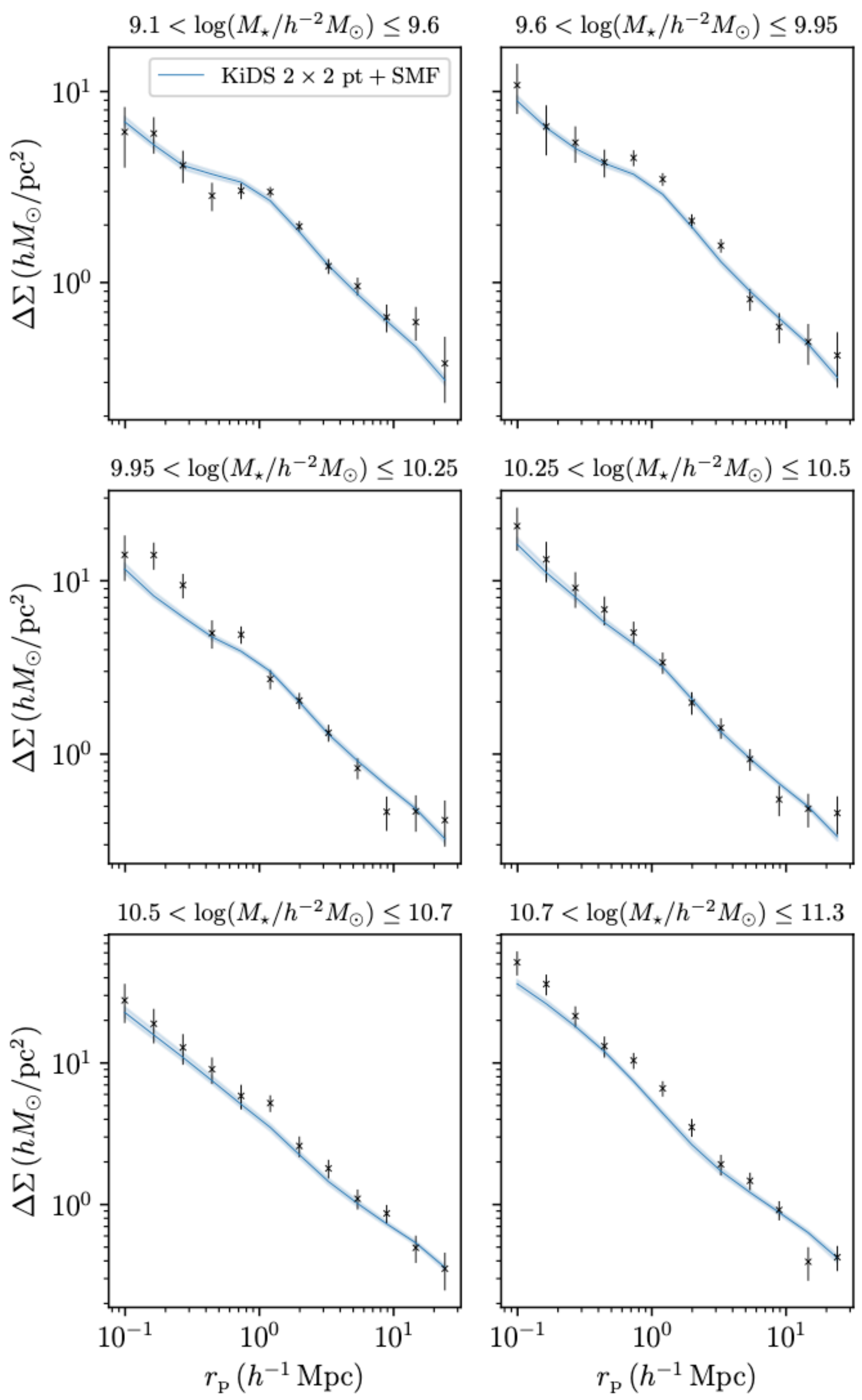
2x2pt + SMF



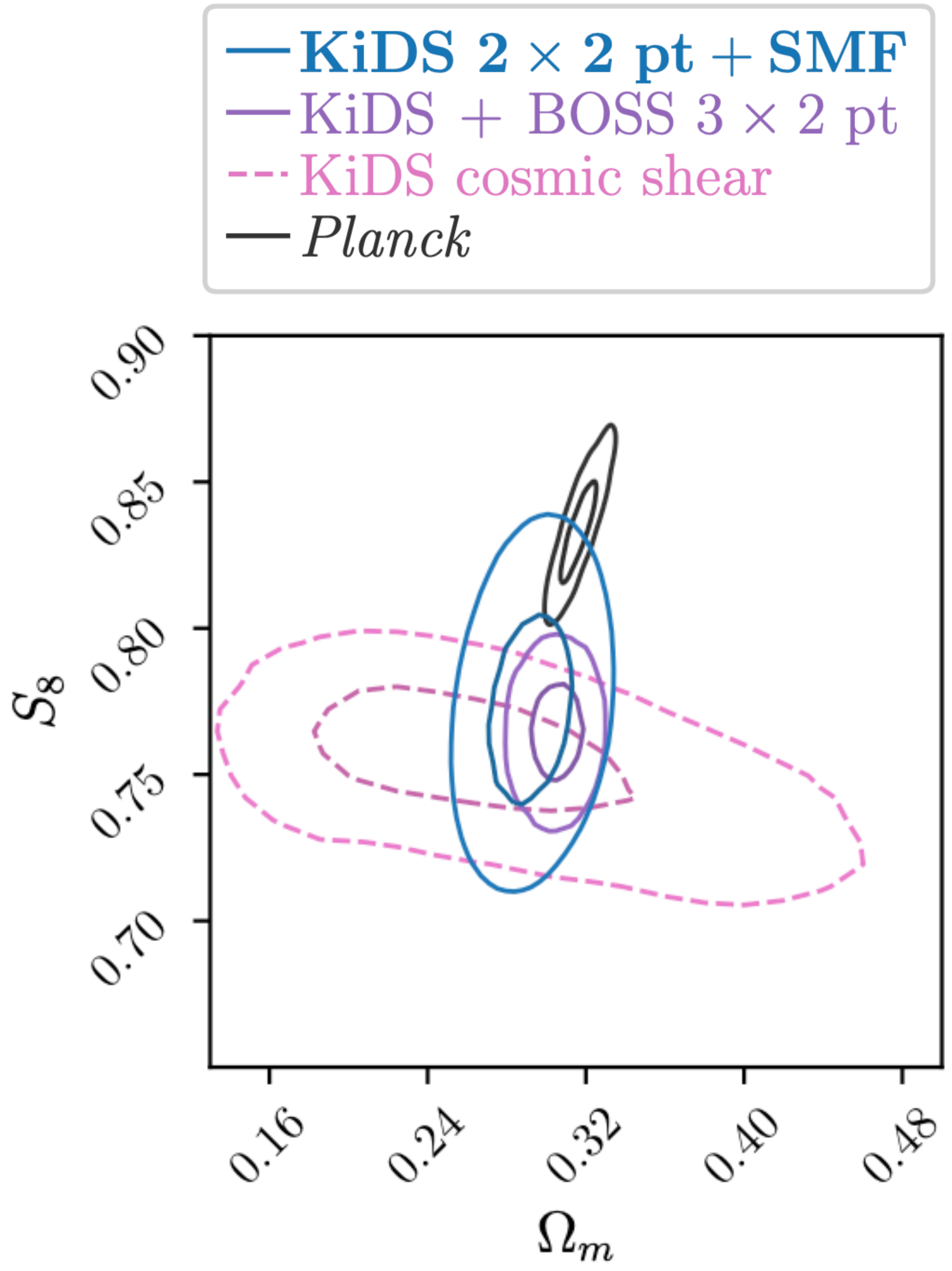
Stellar mass function



Clustering



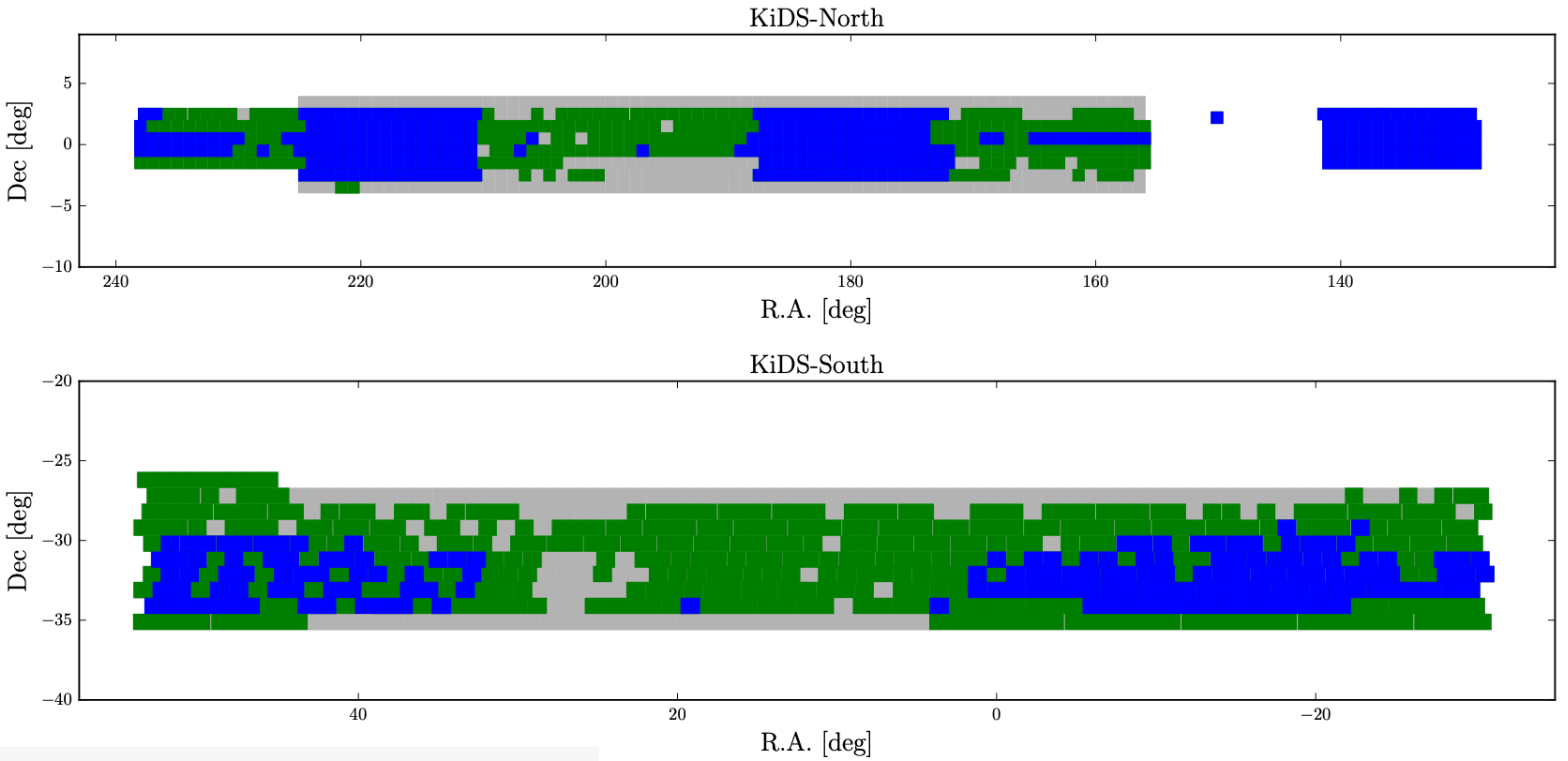
GGL



Dvornik et al. (2022)

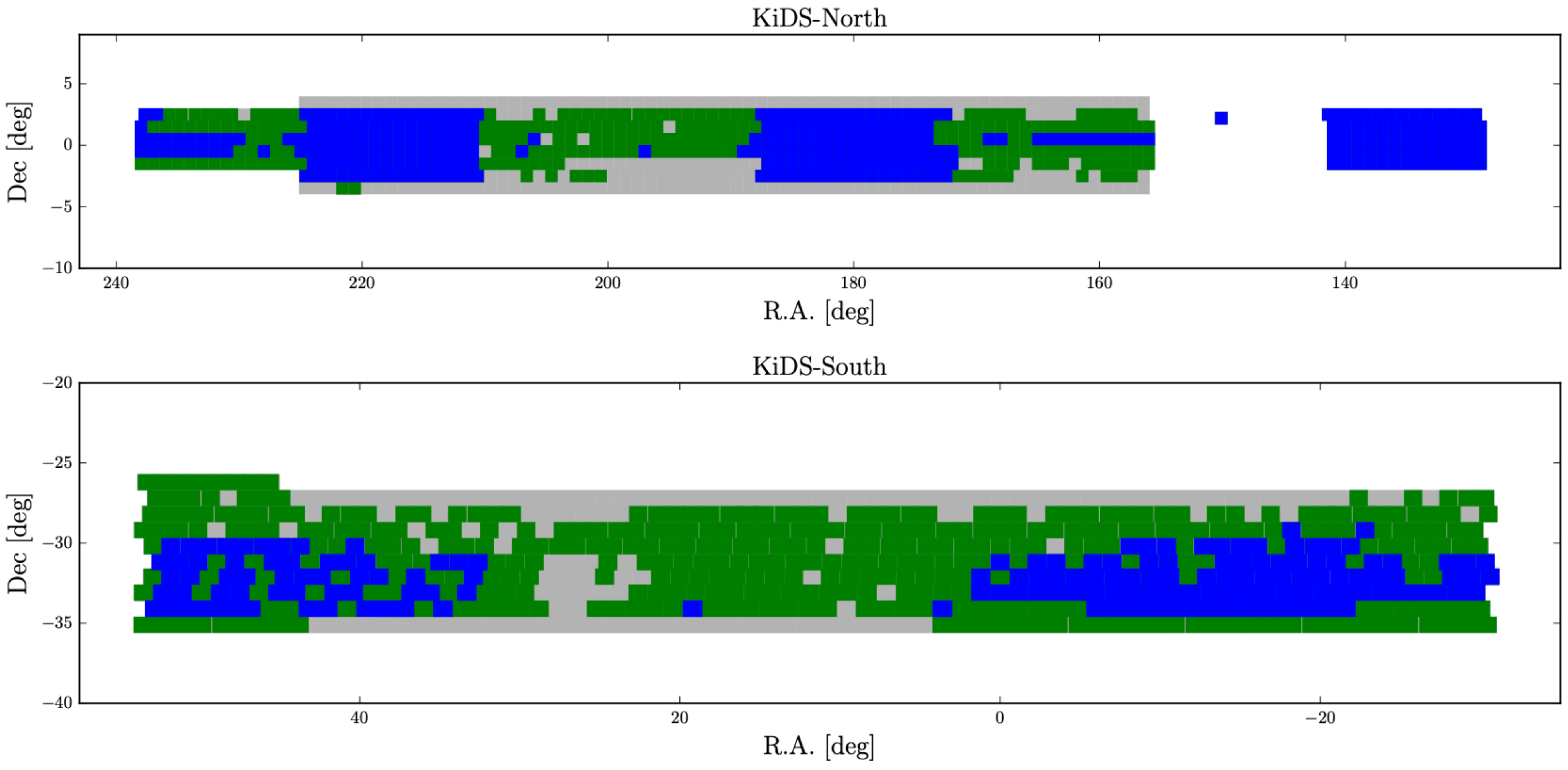
What comes next?
KiDS-Legacy (2023)

- Area: 1000 deg^2 -> 1350 deg^2



What comes next?

KiDS-Legacy (2023)



- Area: 1000 deg² -> 1350 deg²
- 6th tomographic bin, $z_{\mathrm{phot}} > 1.2$

$\Rightarrow 50\,\%$ increase in statistical power

S_8 error potentially smaller than Planck; on par with DES-Y6 cosmic shear.

- SKiLLS: high-z mock catalogues and multi-band image simulations
- KiDZ: greatly increased spec-z calibration sample
- MetaCal: 2nd shape measurement method besides *lensfit*

The Ultraviolet Near Infrared Optical Northern Survey

UNIONS

Footprint

The Ultraviolet Near Infrared Optical Northern Survey : sky areas

Galactic plane

BOSS

UNIONS ugriz : 4,861 deg.^{2} (CFIS / Pan−STARRS / WISHES)

Extended UNIONS u−band survey : 8,988 deg.^{2}

UNIONS

UNIONS

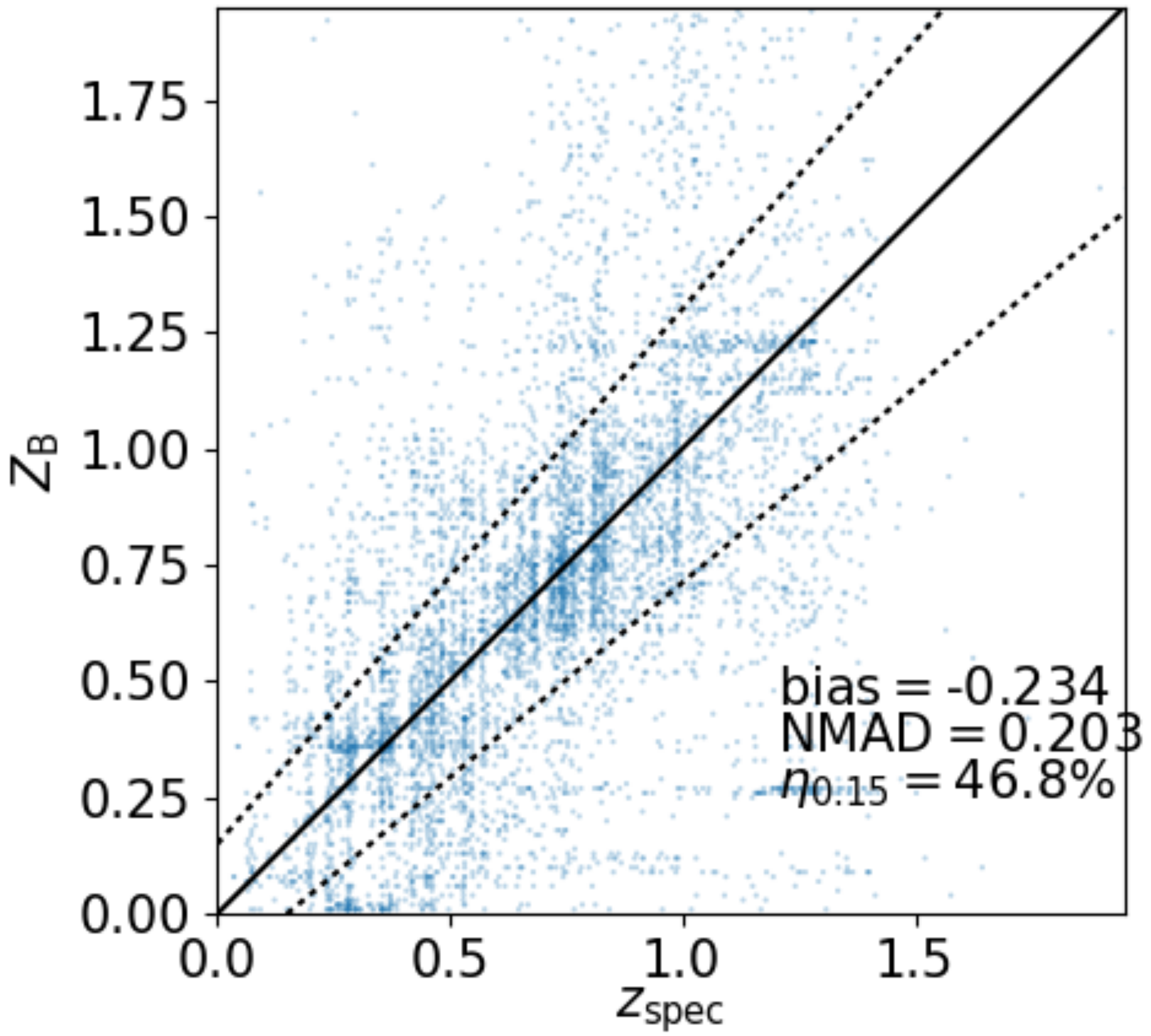
Survey characteristics

stage-III.V

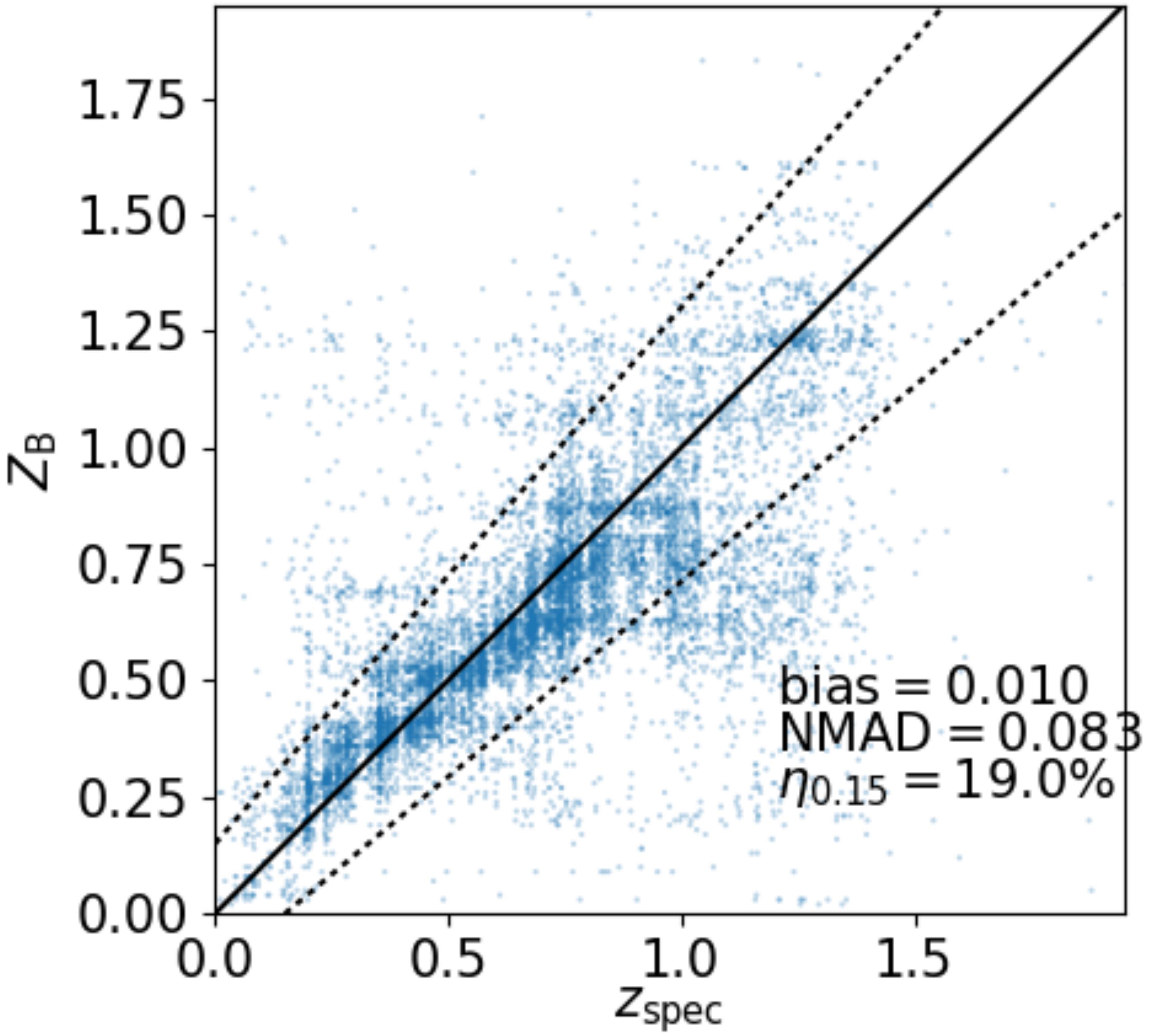
- ~5000 sq. deg.
- Five-band *ugriz* imaging data from three different telescopes.
- Excellent *r*-band image quality (median FWHM<0.7”).
- Similar depth as KiDS and DES in *ugri* and deeper in *z*.
- Huge overlap with spectroscopic surveys (SDSS/BOSS, DESI).
- Most powerful lensing survey before the first stage-IV analyses.
- Completely independent from KiDS, DES, and HSC.

UNIONS

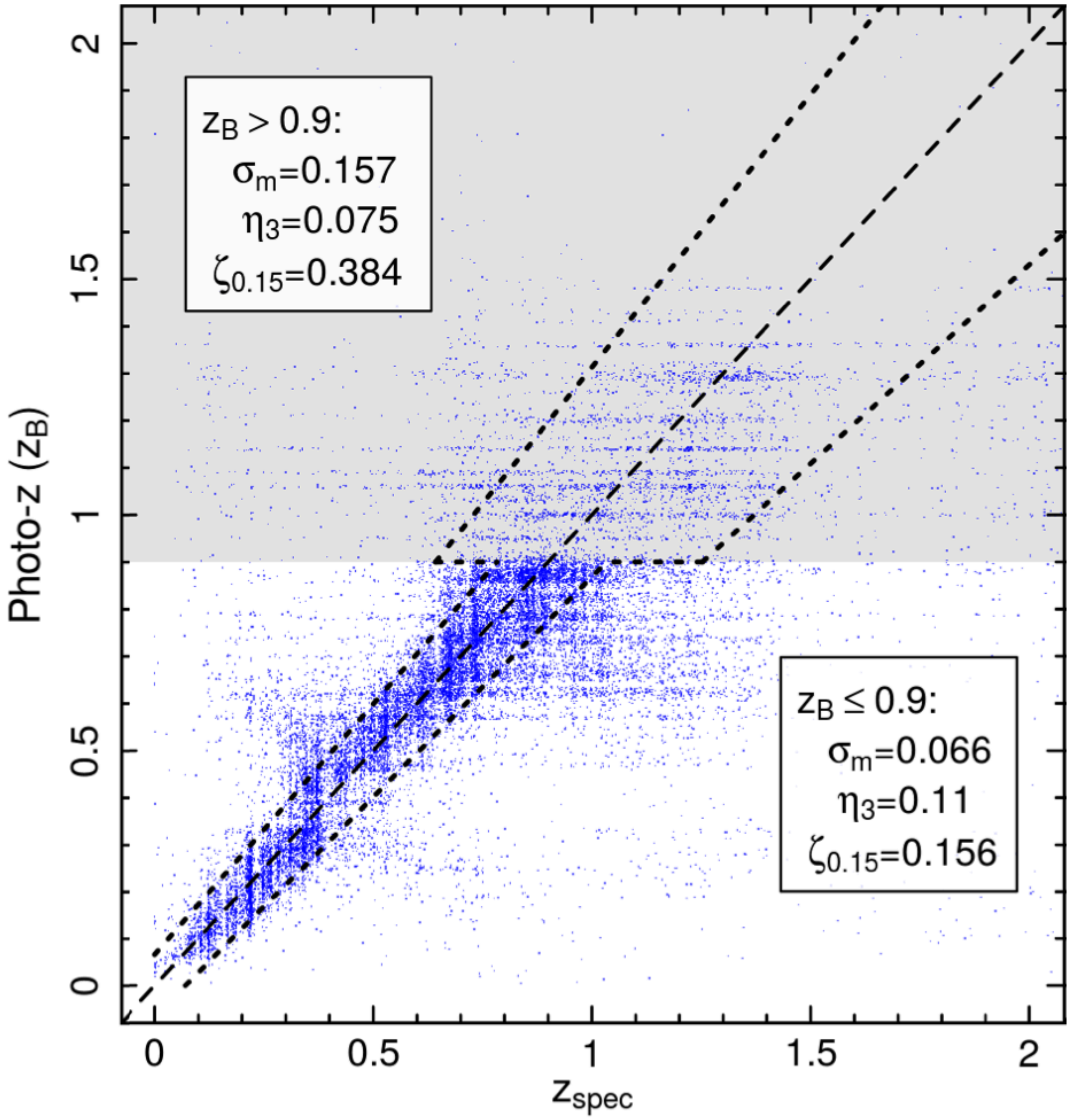
Photo-*z*



UNIONS *ugriz*
simple photometry

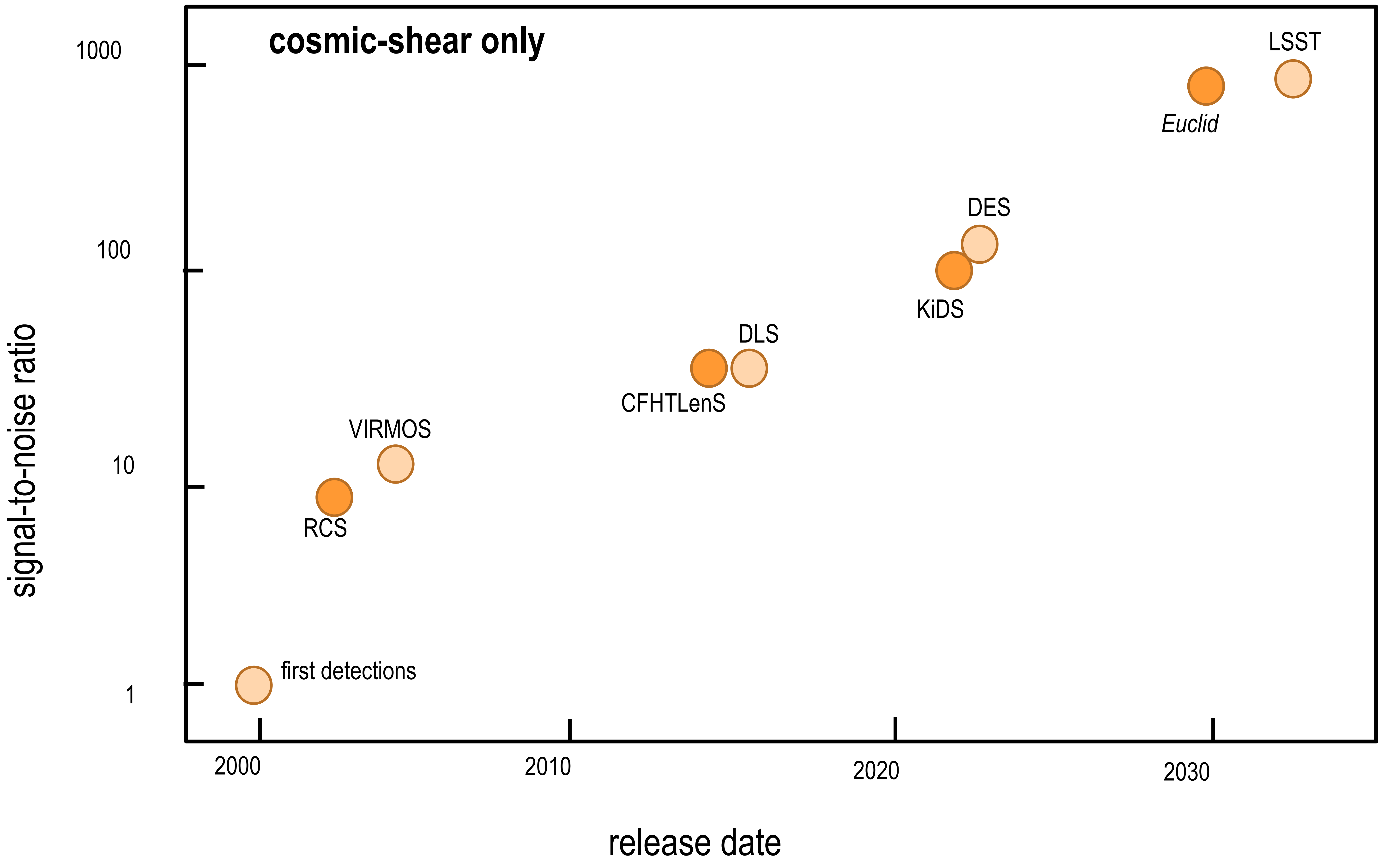


UNIONS *ugri*
GAaP photometry



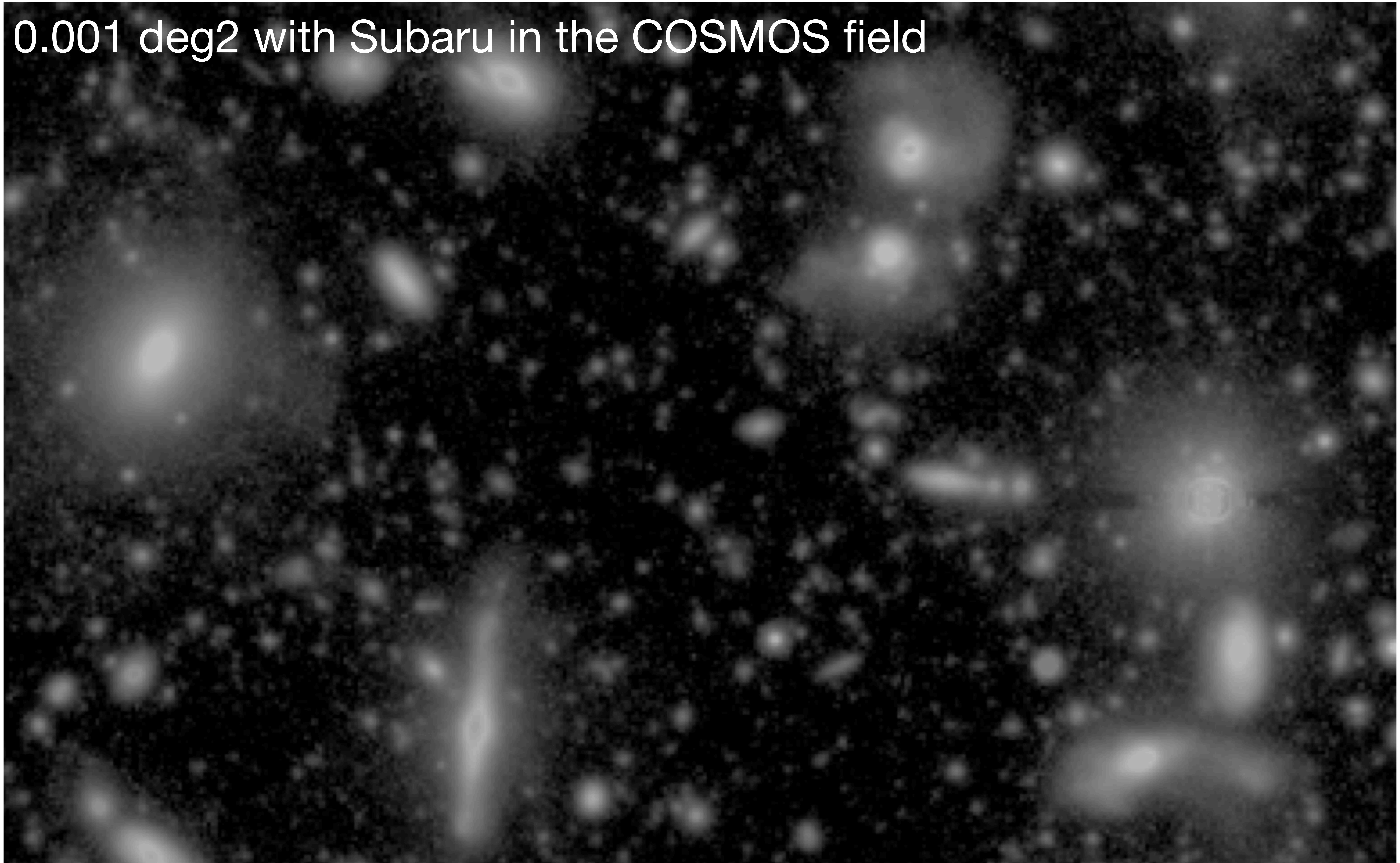
KiDS *ugri*
GAaP photometry

Cosmic shear surveys over time

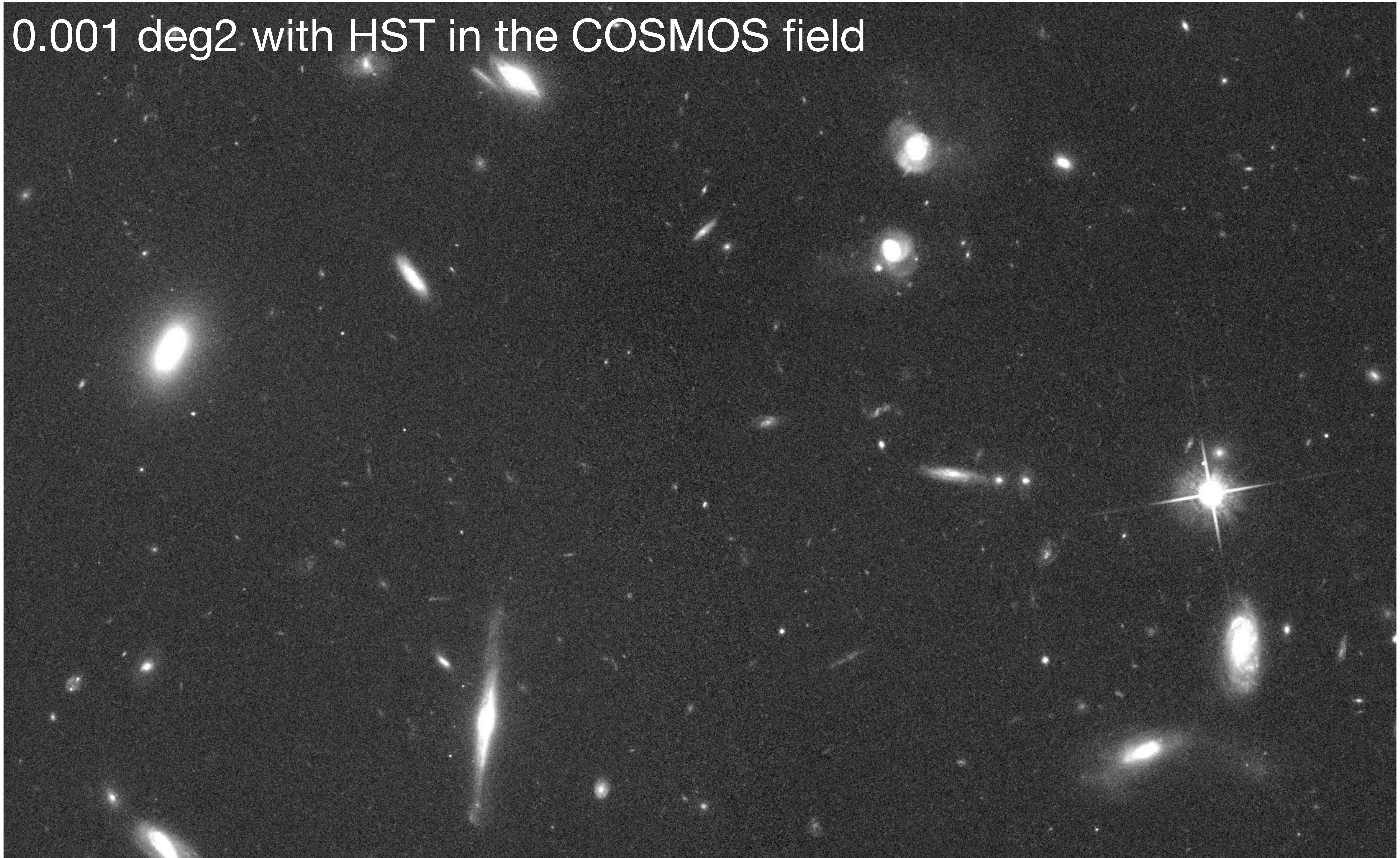


Credit: Henk Hoekstra

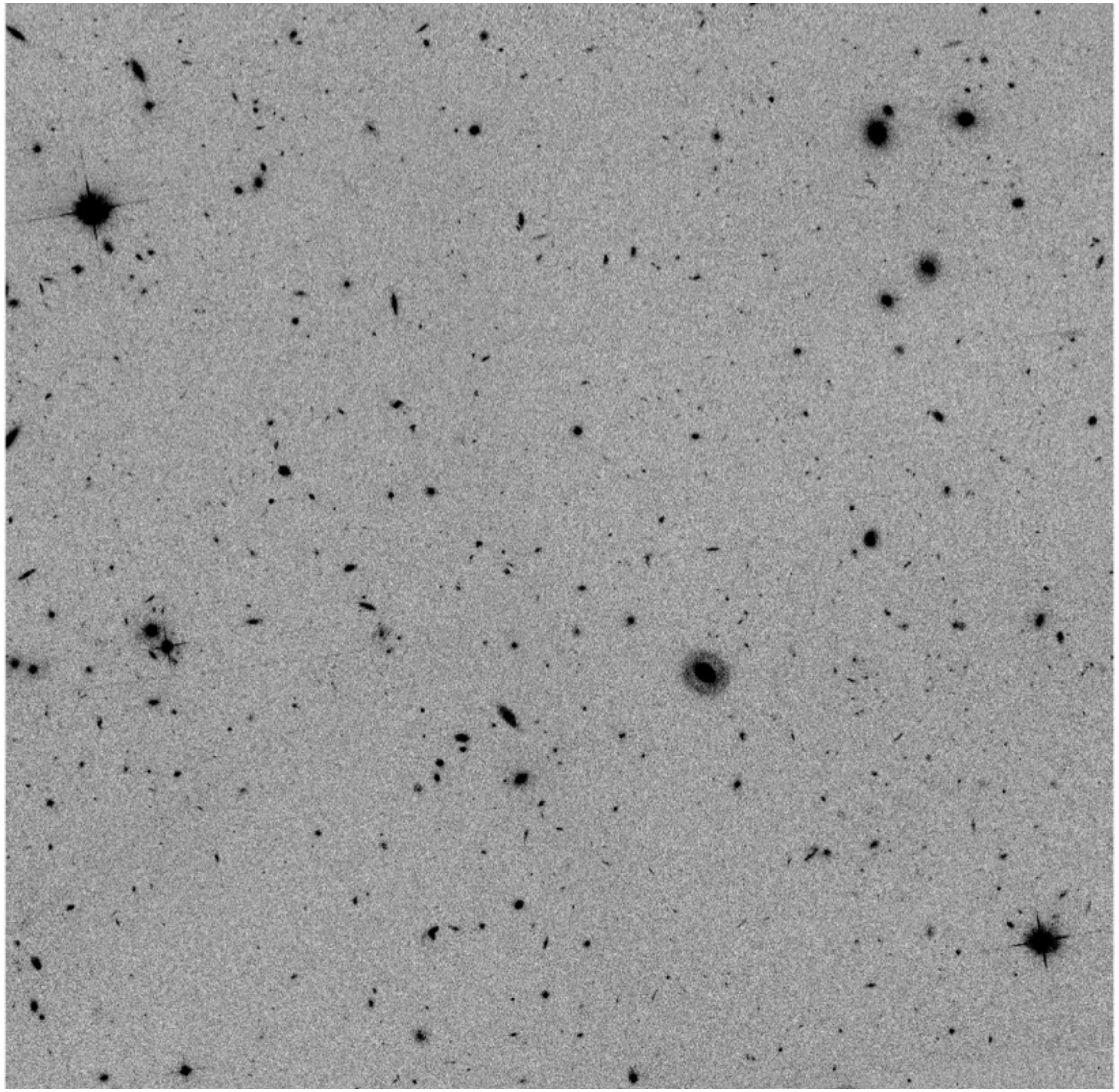
A taste of what is to come…



A taste of what is to come…

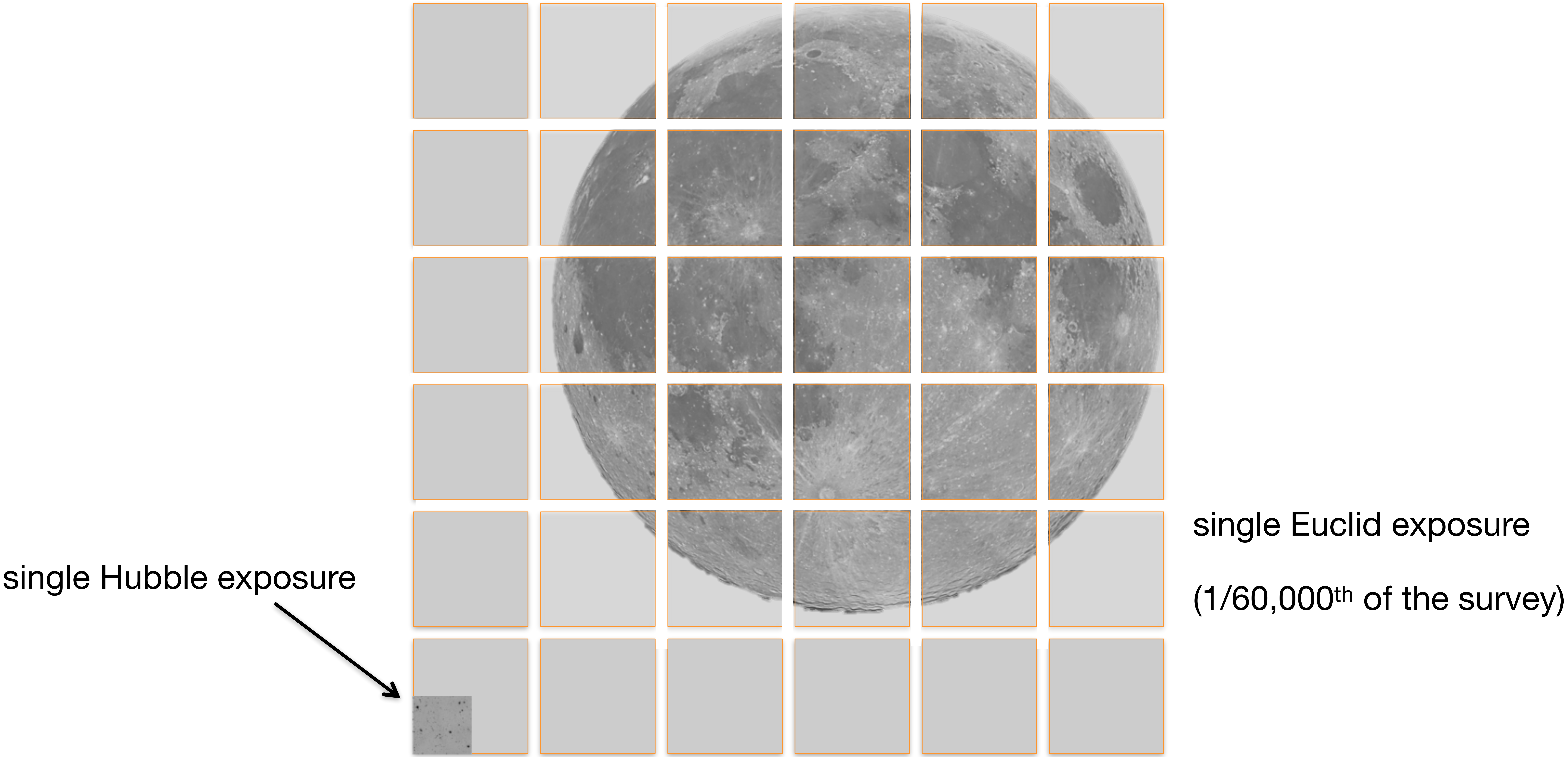


HST field of view



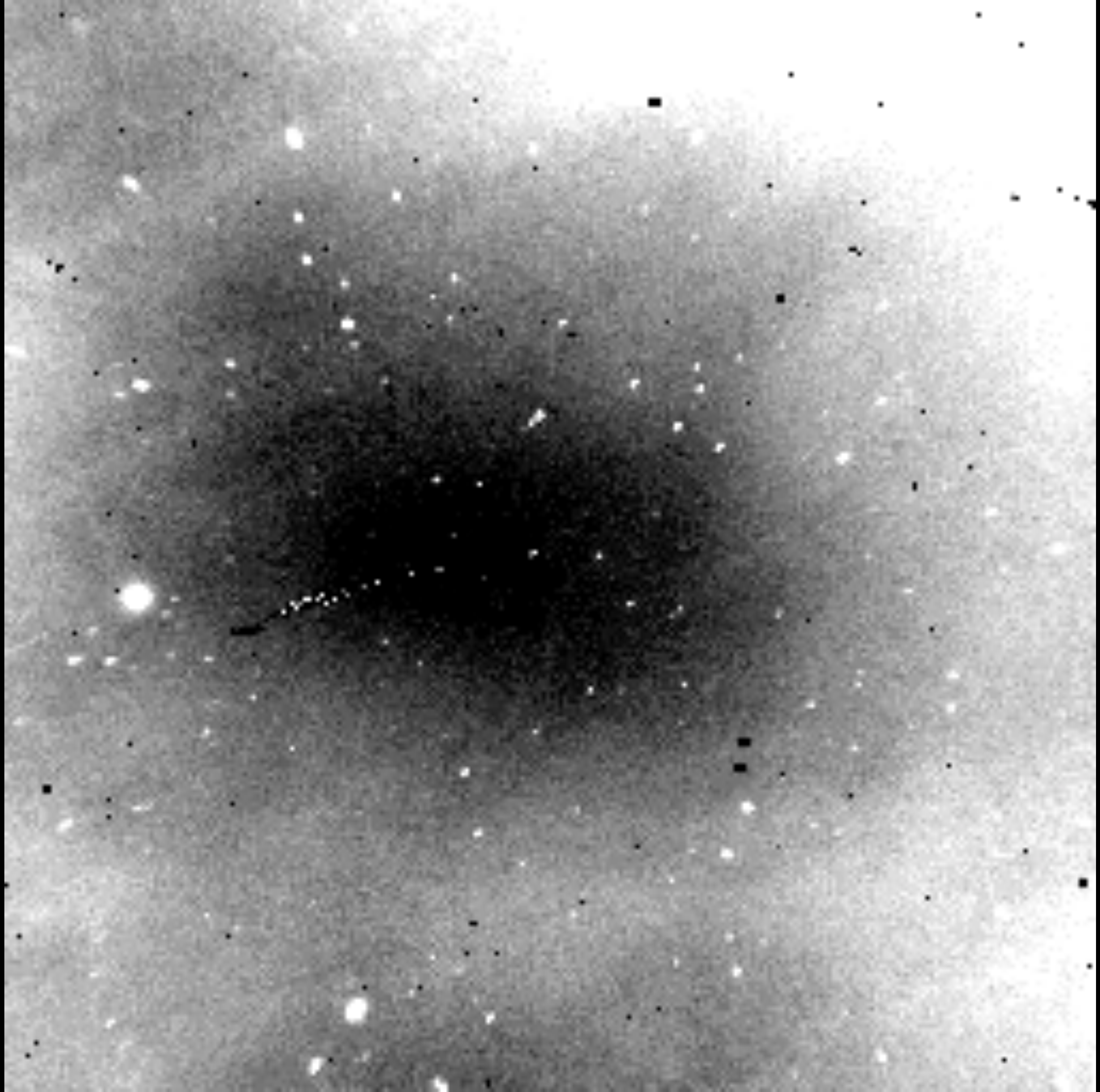
Single Hubble
exposure

Euclid field of view



Credit: Henk Hoekstra

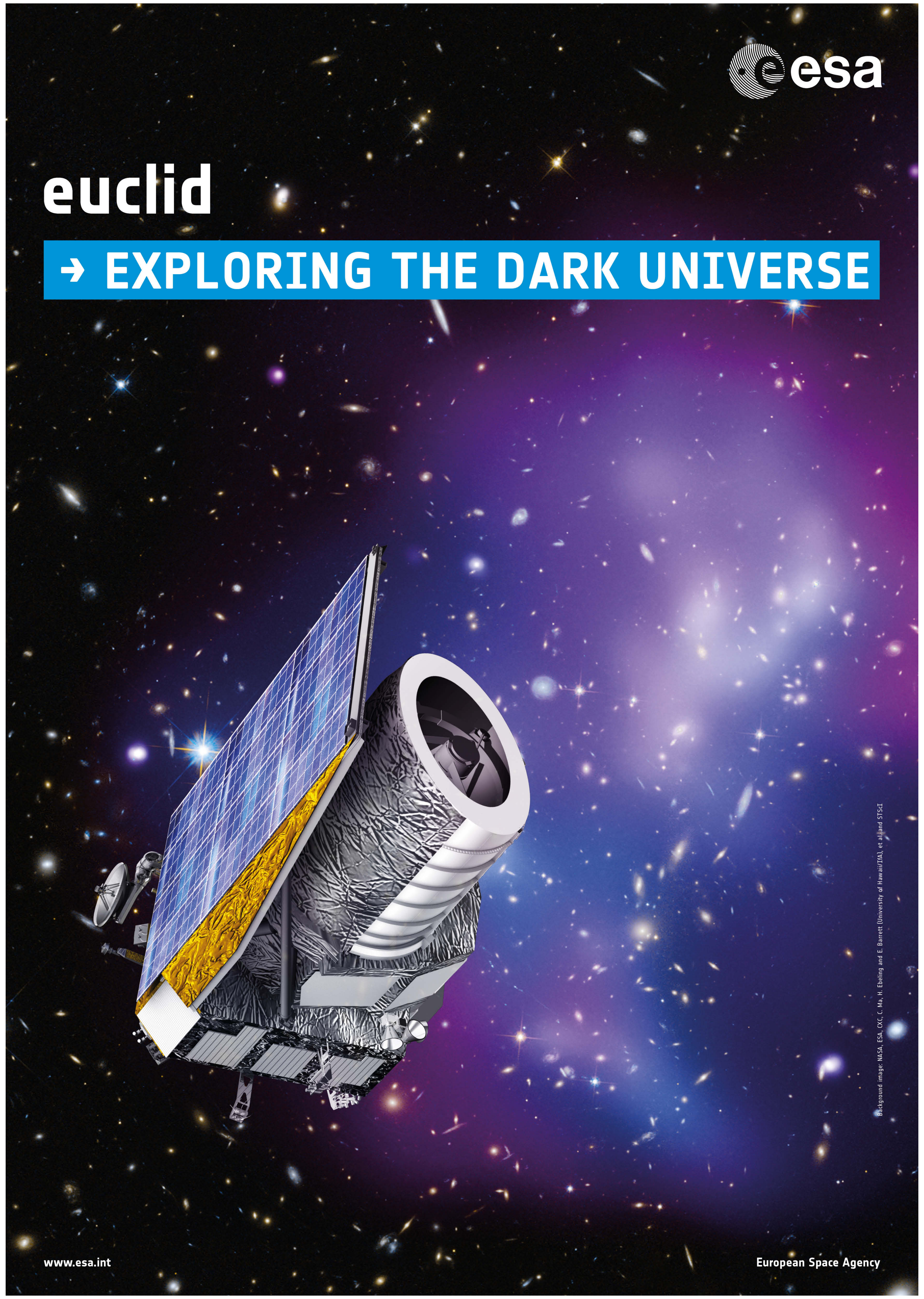
2MASS Wide-field Airglow Experiment



Adams & Skrutskie (1996)

https://skrutskie.uvacreate.virginia.edu/airglow/airglow.html

Euclid: a satellite designed to do weak lensing



- Launch in Q3/2023 on **SpaceX Falcon9** to L2
- Survey the sky for 6 years

- Primary cosmology probes:
  - Weak lensing by large scale structure
  - Clustering of galaxies

- Euclid will image the
  - best 1/3 of the sky (15000 deg^2)
  - with similar resolution as HST in optical; VIS(~*riz*) < 24.5 (10σ ext.)
  - NIR imaging in 3 filters; *YJH* < 24 (5σ point source)
  - Images for $2\text{x}10^9$ galaxies
  - Optical colours from the ground

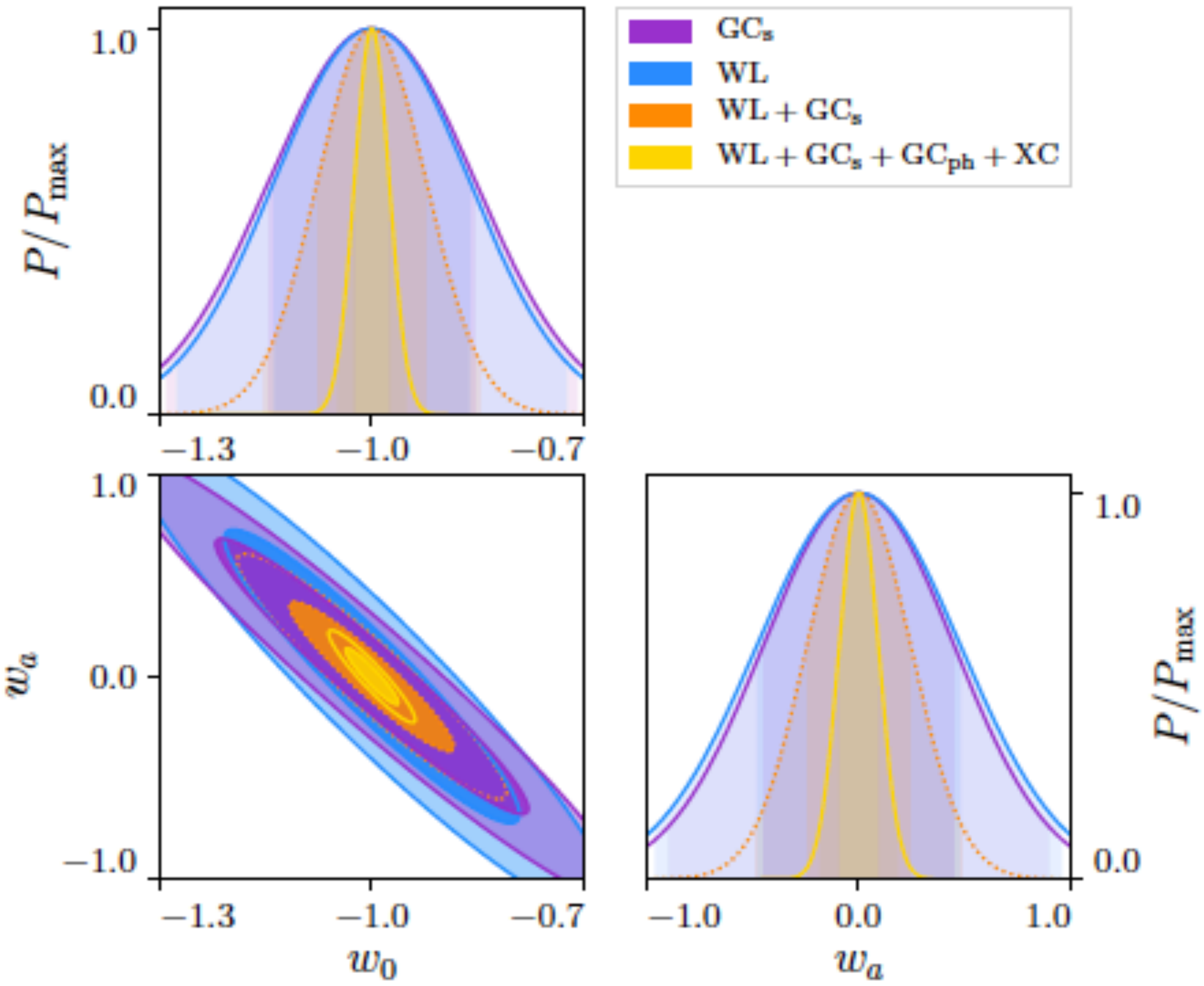
- Unprecedented (slitless) redshift survey over same area with
  - NIR spectra for ~$3.5\text{x}10^7$ galaxies ($0.9<z<1.8$)
  - Spectral resolution R~350 (for 0.5” source)

Scaramella et al. (2021)

Scaramella et al. (2021); adapted

Scaramella et al. (2021)

Euclid: combined probes

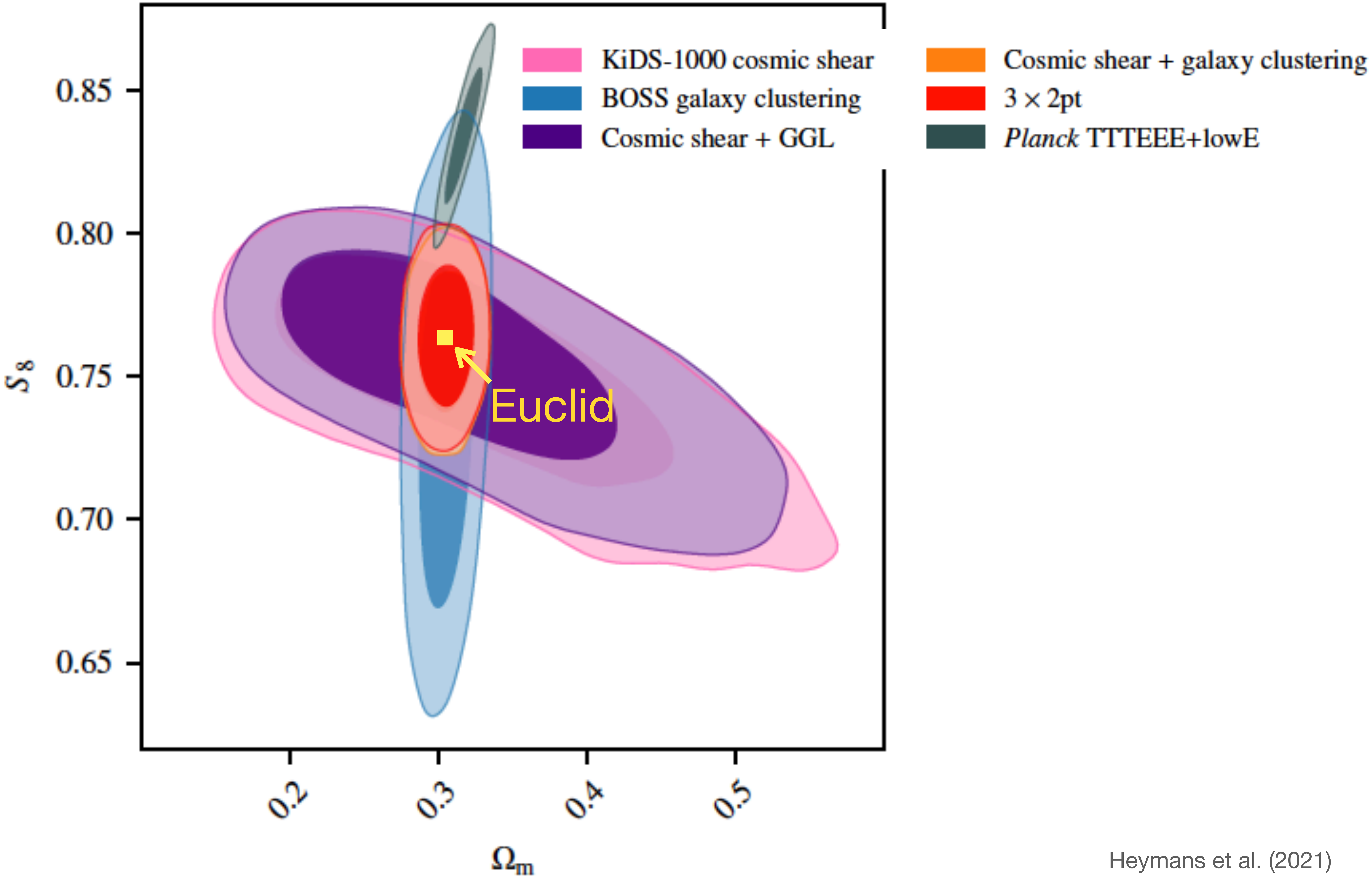


Constraints on the dark enegy equation-of-state

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

Euclid Collaboration: Blanchard et al. (2020)

Euclid will be a major step forward!



Heymans et al. (2021)

Cosmic shear
Systematic errors, general

- Shape measurements
- Photometric redshifts
- Intrinsic alignments
- Baryon feedback

Cosmic shear

Systematic errors, general, Euclid numbers

- Shape measurements; $\sigma_m < 2*10^{-3}$.
- Photometric redshifts; $\sigma_{\Delta z} < 2*10^{-3} * (1+z)$.
- Intrinsic alignments; amplitude known to <10% as fct. of *z* and *k*.
- Baryon feedback; needs to be well constrained to leverage small-scale power.

This can be measured. So let's do that!

=>

Realistic priors instead of uninformative priors on nuisance parameters!

Cosmic shear

Systematic errors, Euclid-specific

- Space-based PSF (requirement: ellipticity known to $<2\times10^{-4}$)
- Broad VIS band (PSF varies as fct. of SED)
- Broad VIS band (PSF varies as fct. of radius in case of colour gradients)
- Space environment => cosmic rays, detector degradation, CTI
- Complex ground-based follow-up in the optical:
  - Combination of data from at least three cameras
  - Variable data quality => photo-z calibration for each sub-survey
- Can’t completely avoid high extinction regions, etc.

SOM results from idealised Flagship2

Binning by SOM cell spec-*z*

W. Roster master thesis

SOM results from idealised Flagship2

Binning by photo-z

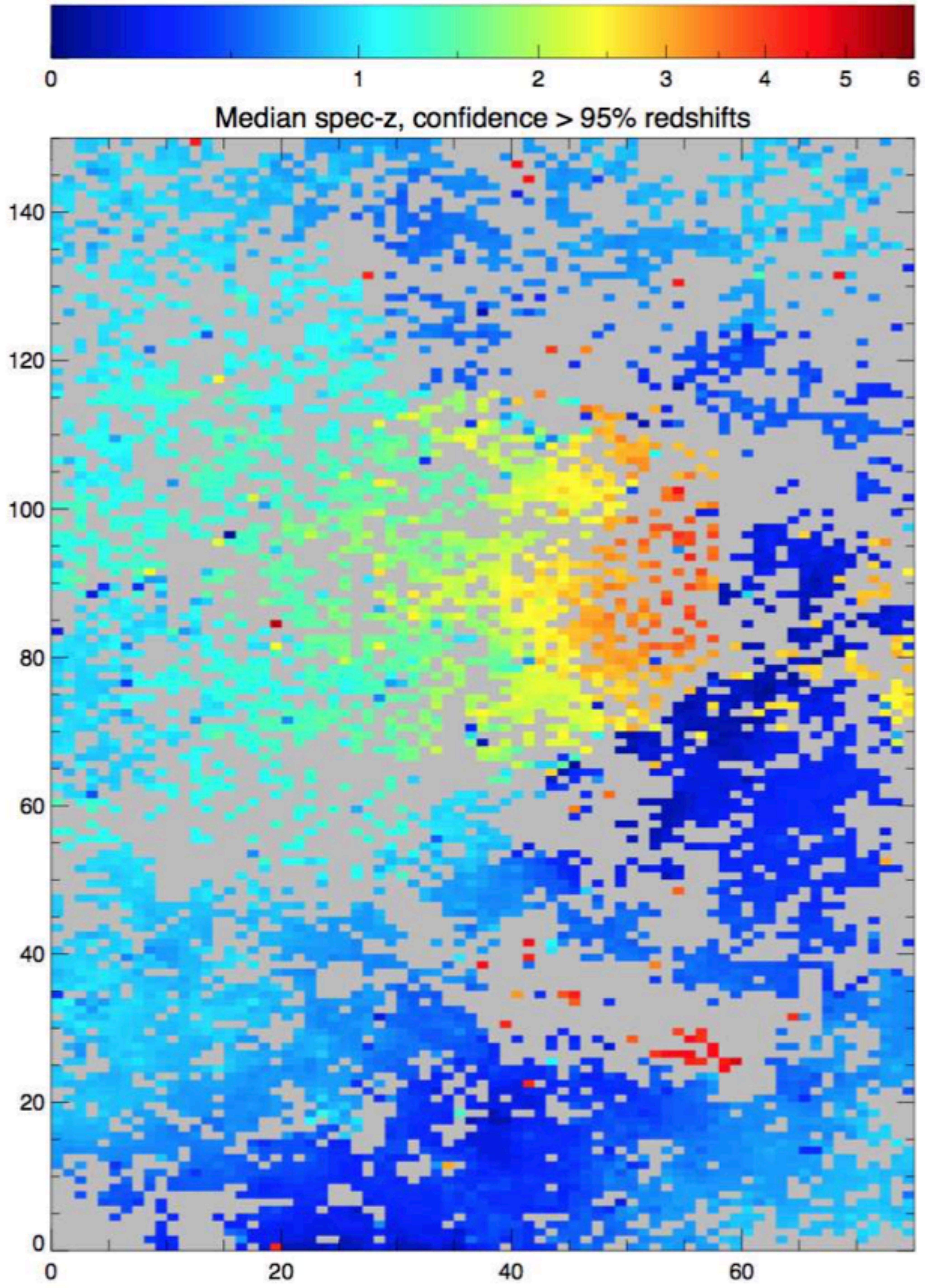
W. Roster master thesis

C3R2 =
Complete Calibration of the Colour-Redshift Relation

Before C3R2

SOM 50% filled

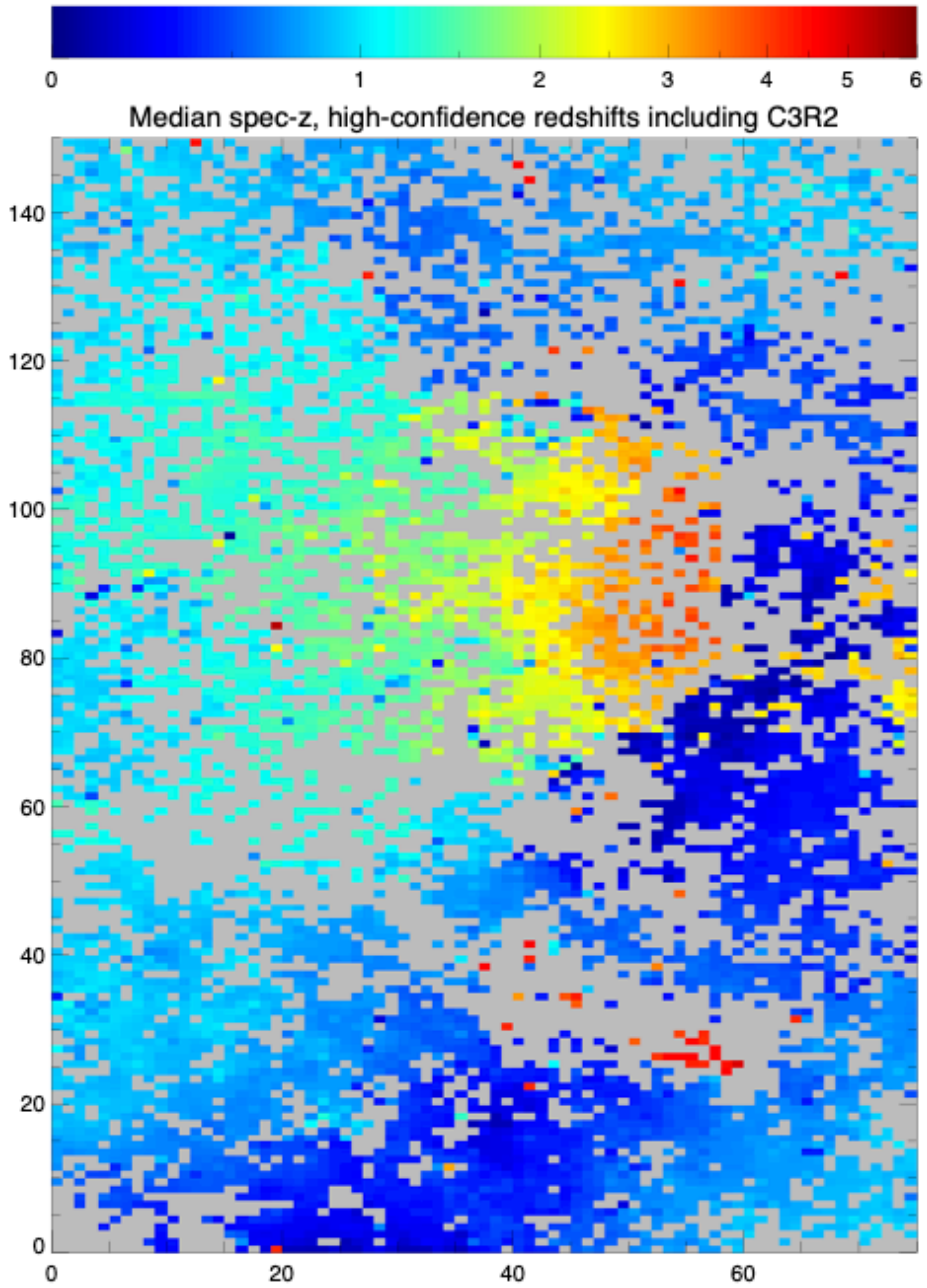
C3R2 =
Complete Calibration of the
Colour-Redshift Relation



Masters et al. (2015)

C3R2 DR1
SOM 56% filled

C3R2 =
Complete Calibration of the
Colour-Redshift Relation



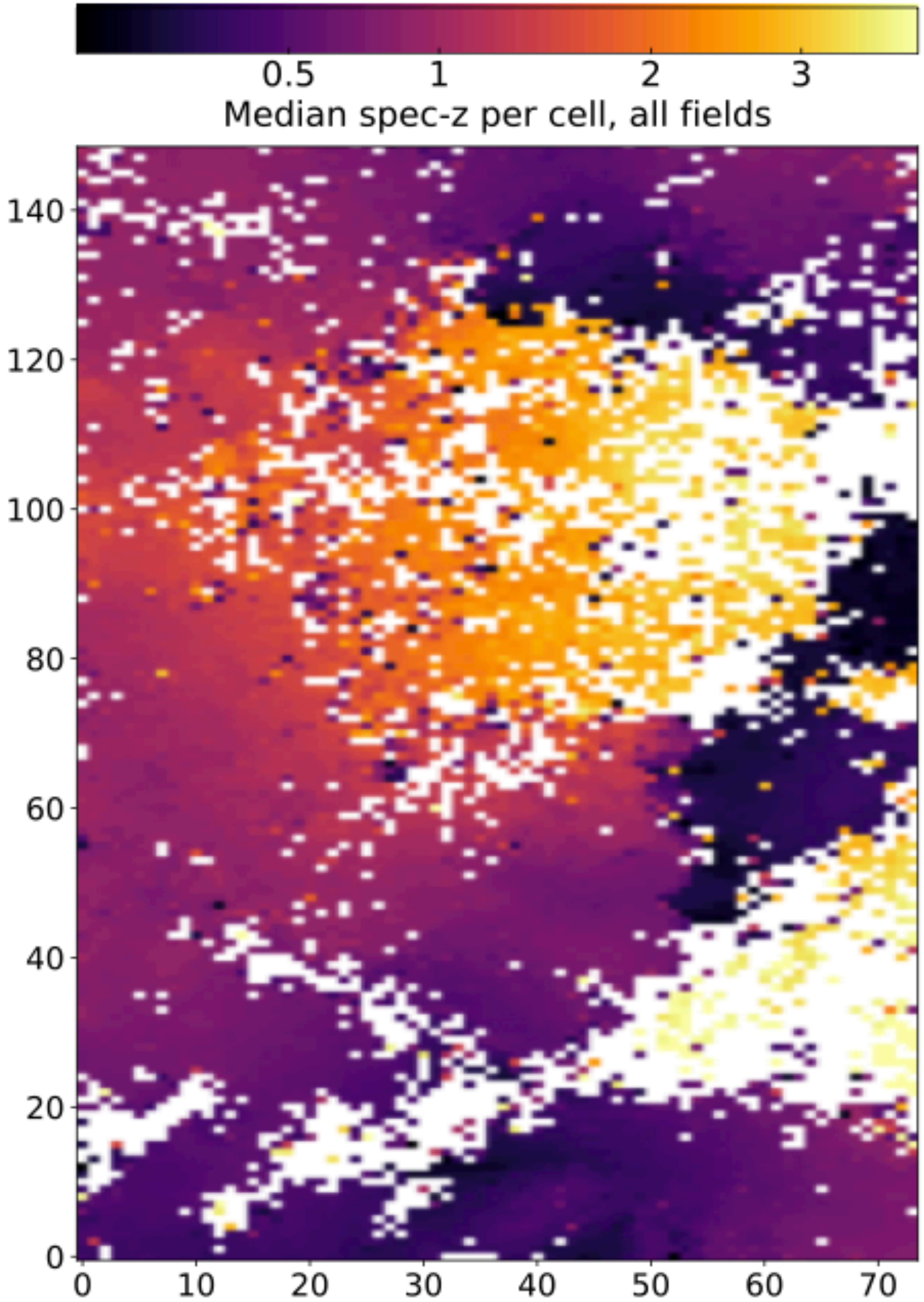
Only Keck observations.

Masters et al. (2017)

C3R2 DR2

SOM 76% filled

C3R2 =
Complete Calibration of the
Colour-Redshift Relation



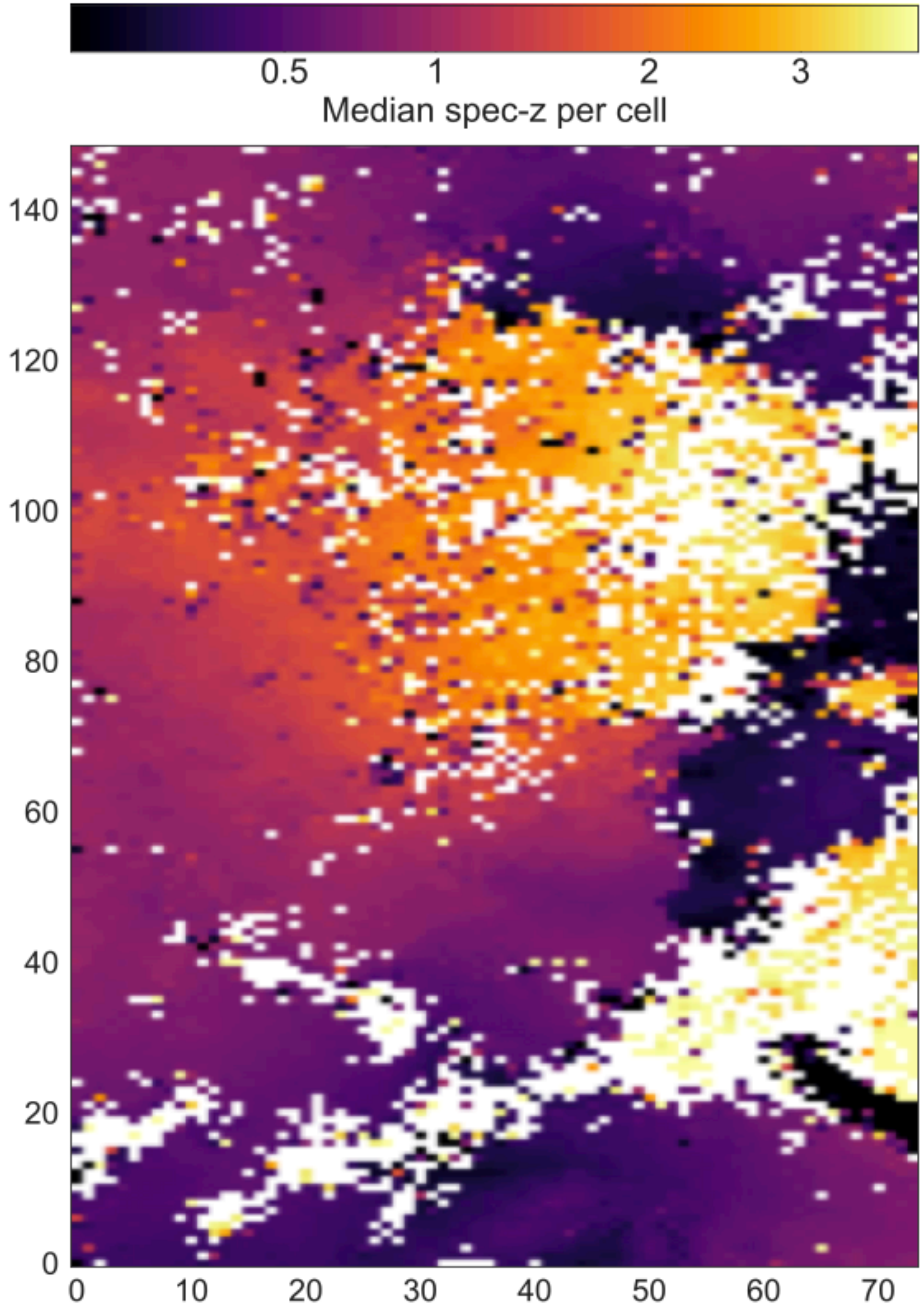
Only Keck observations.

Masters et al. (2019)

C3R2 DR3

SOM 84% filled

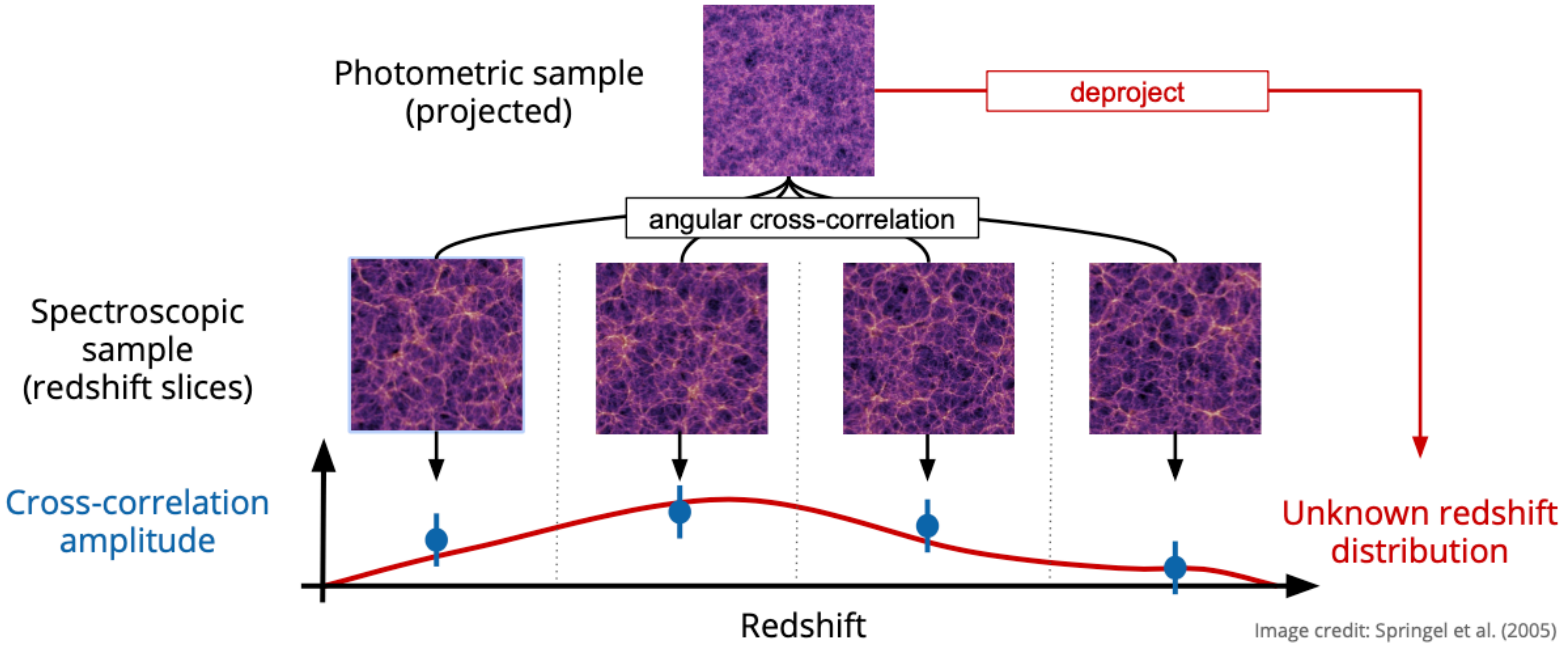
C3R2 =
Complete Calibration of the
Colour-Redshift Relation



Only Keck observations.

Stanford et al. (2021)

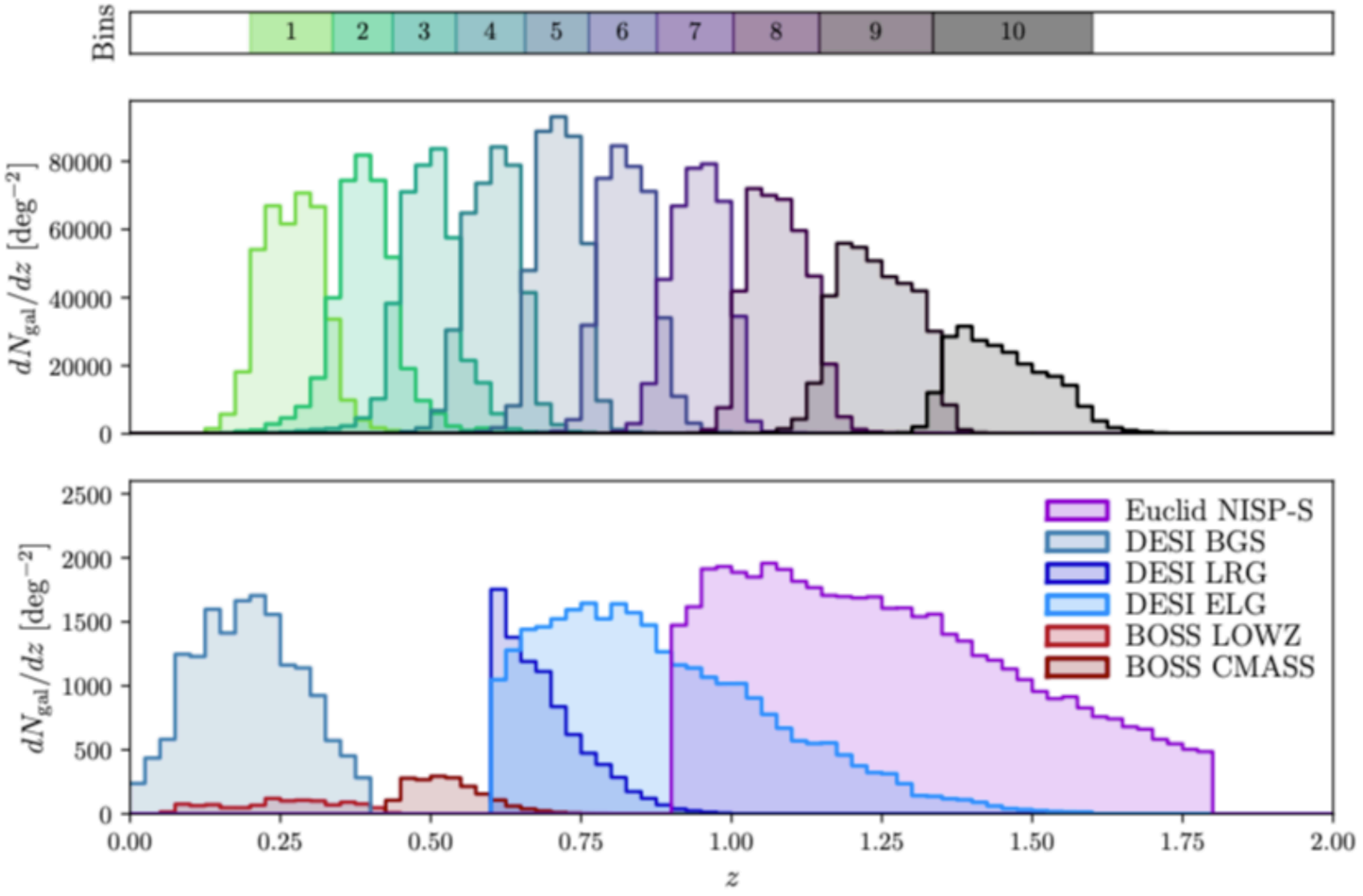
Clustering-z



- Spec-z sample does not have to be representative
- Correct for evolution of galaxy bias

Credit: Jan Luca van den Busch

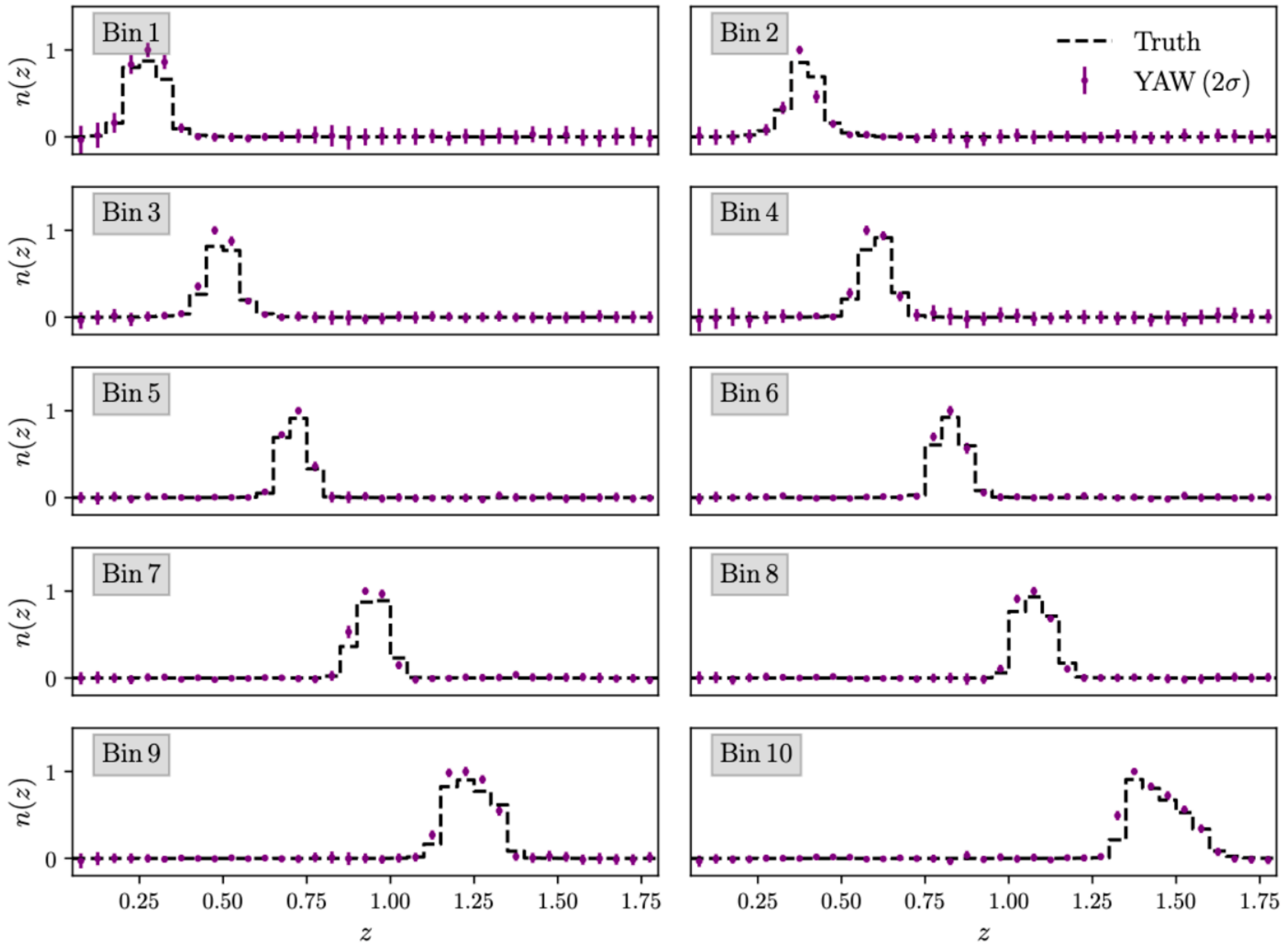
Galaxy Samples



Flagship 1

Naidoo et al. (2022a)

Clustering Redshifts Results



400 sq. deg.

Naidoo et al. (2022a)

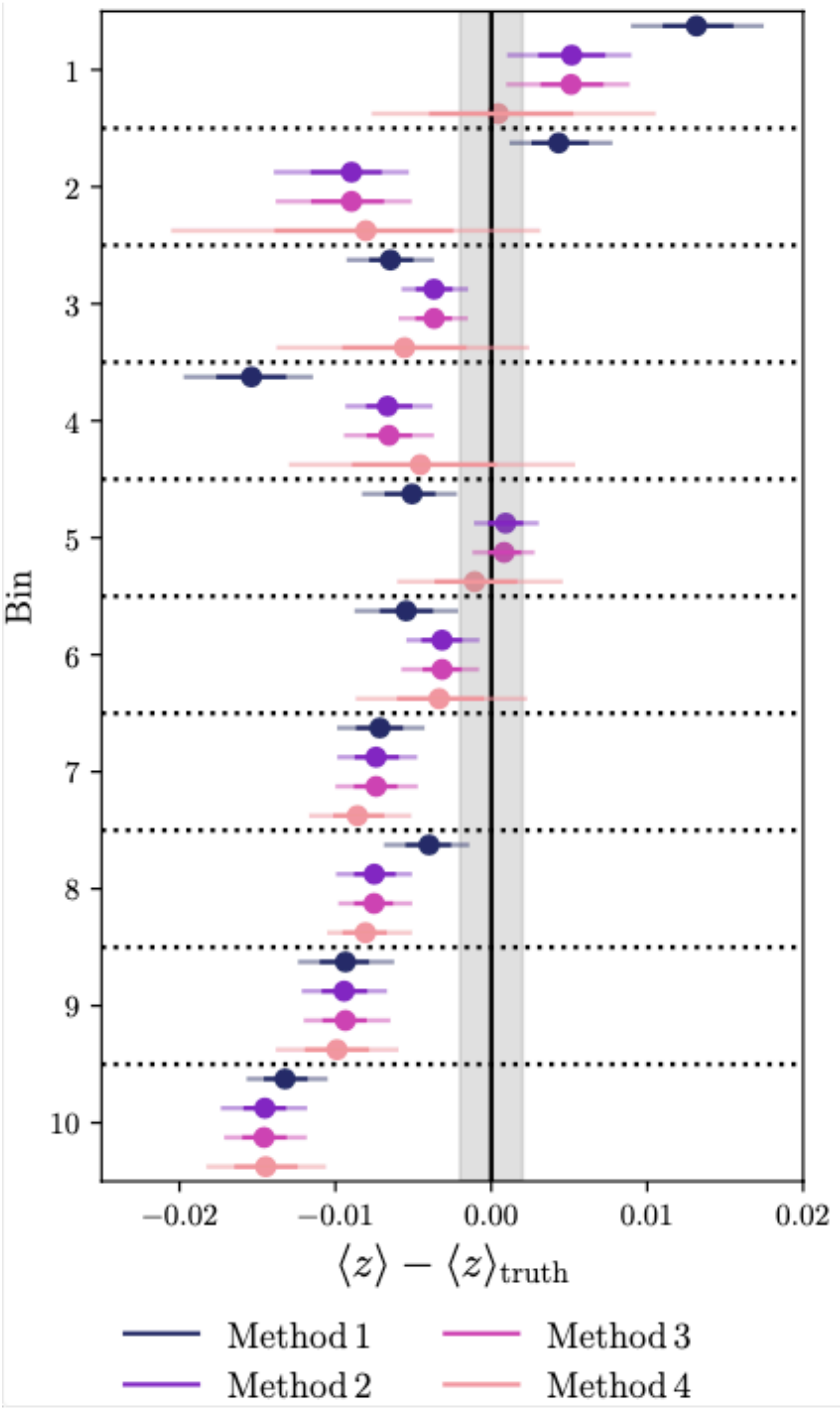
Residual biases

Method 1 : no correction

Method 2 : spectroscopic tracer sample bias approximated from auto-correlation function

Method 3 : redshift power law fitted to auto- and cross-correlations

Method 4 : bias for target photometric sample is also computed with the auto-correlation (only possible on simulations)



400 sq. deg.

Naidoo et al. (2022a)

Benefits of the Euclid survey strategy

Shallow+wide vs. deep

- Galaxies are relatively large, especially in relation to the space-based PSF.
- Galaxies are relatively bright => calibrate photo-z directly with 8m spec-z.
- Galaxies are relatively bright => calibrate IA without too much extrapolation.
- Less crowding (also helped by space-based PSF).
- Perfect synergy of a small space telescope and powerful ground-based telescopes.
- Highly complementary to LSST@Rubin and Roman.

Summary

- Current surveys require shear- and redshift-calibration at the ~1% level.
  Stage-IV surveys require a factor ~5 improvement.
- SKiLLS is one of the most advanced simulations to simultaneously calibrate shears and redshifts (and their cross-talk).
- KiDS-Legacy will present high-redshift cosmic shear tomography next year and potentially improve the S_8 constraint by 50%.
- UNIONS will be the most powerful cosmic shear survey before Euclid/LSST.
- Euclid will launch in less than a year and transform cosmic shear into “big science”.