

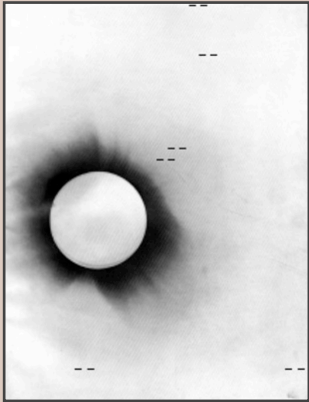
ON THE ROAD TOWARDS STAGE-IV COSMOLOGY

Andrina Nicola, AlfA Bonn

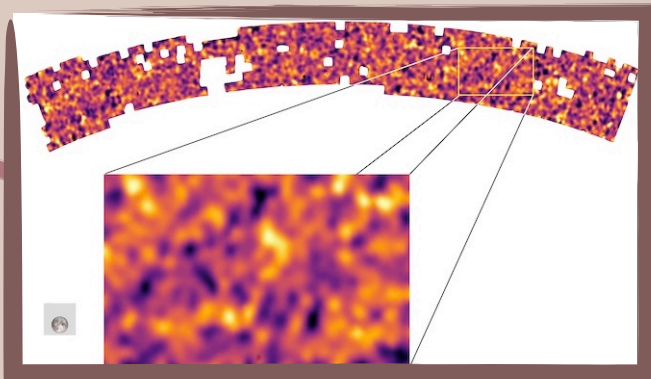
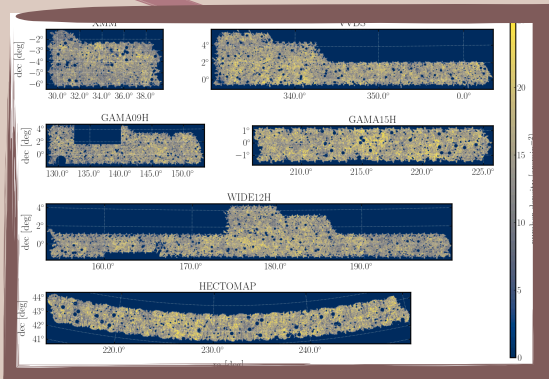
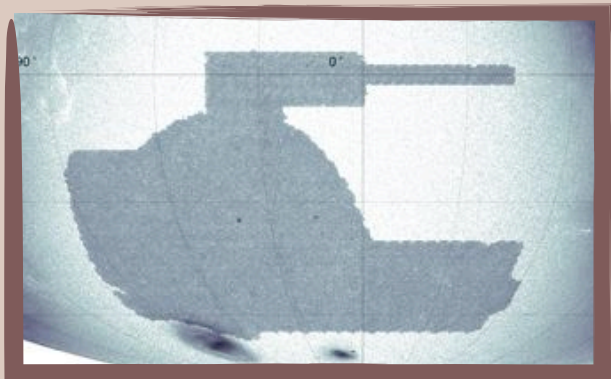
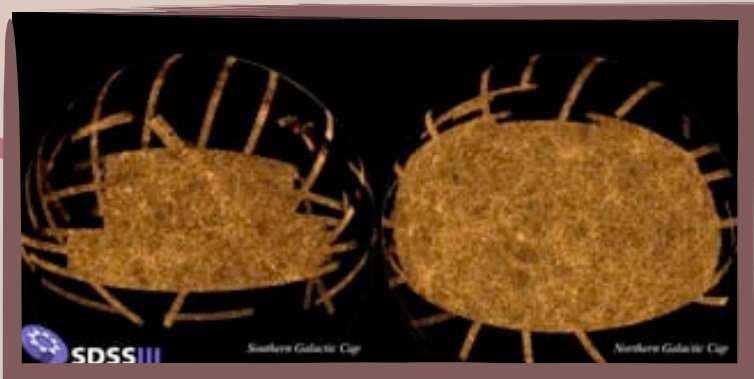
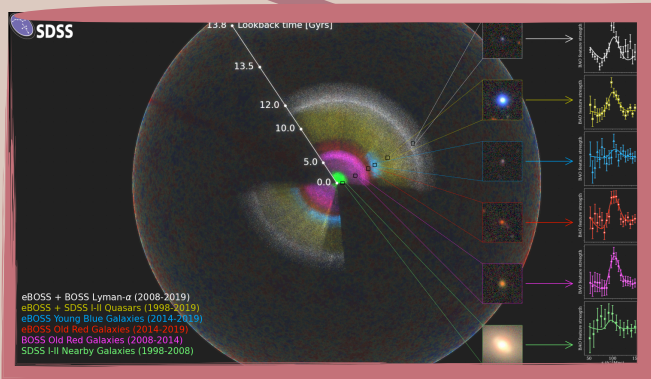
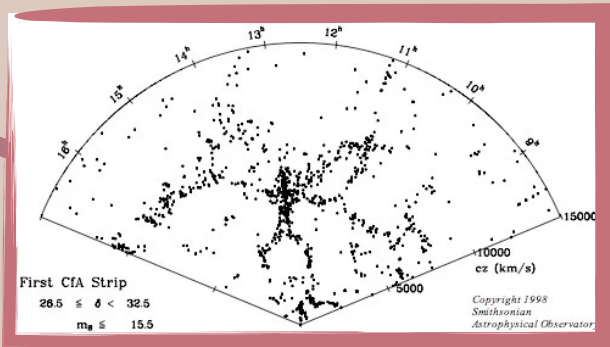
LSS@Prague, June 28th 2023

LSS Cosmology Has Come A LONG Way...

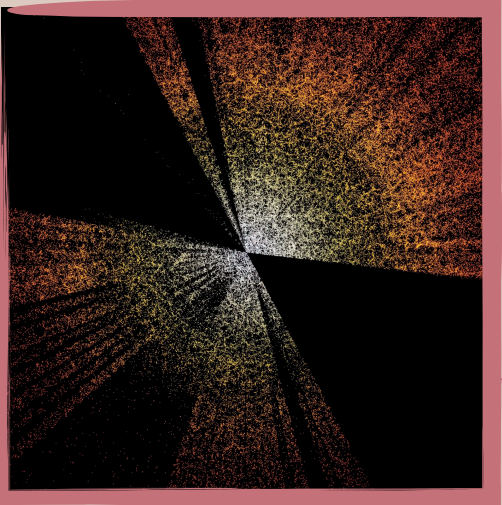
1919



1923

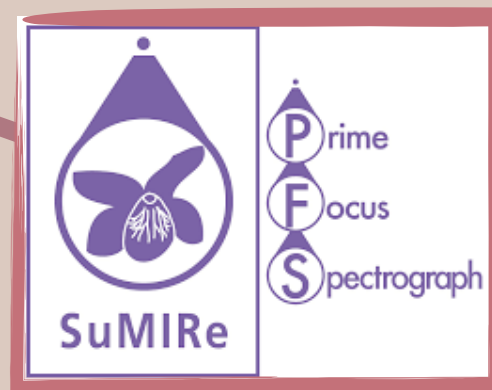
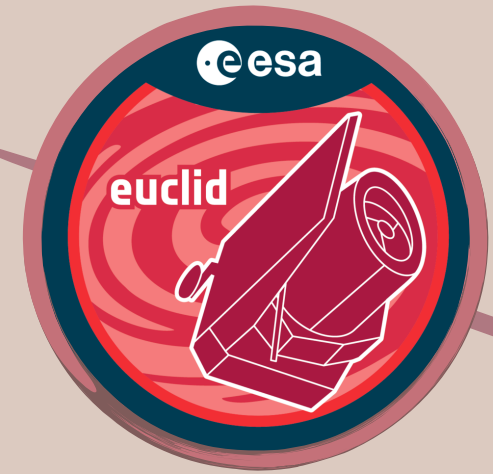


2019

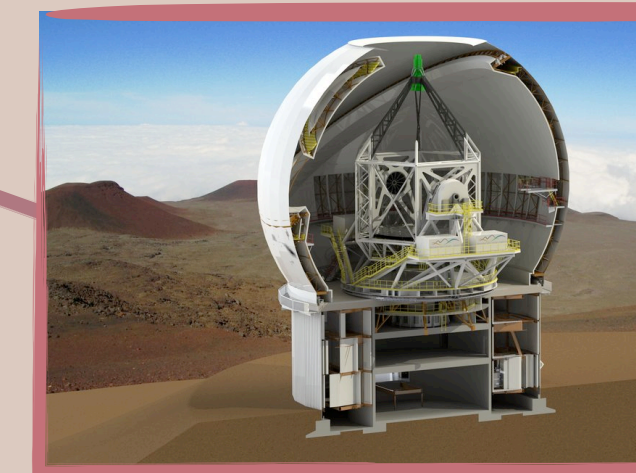


... AND THERE'S MUCH MORE TO COME...

~ now (Saturday)

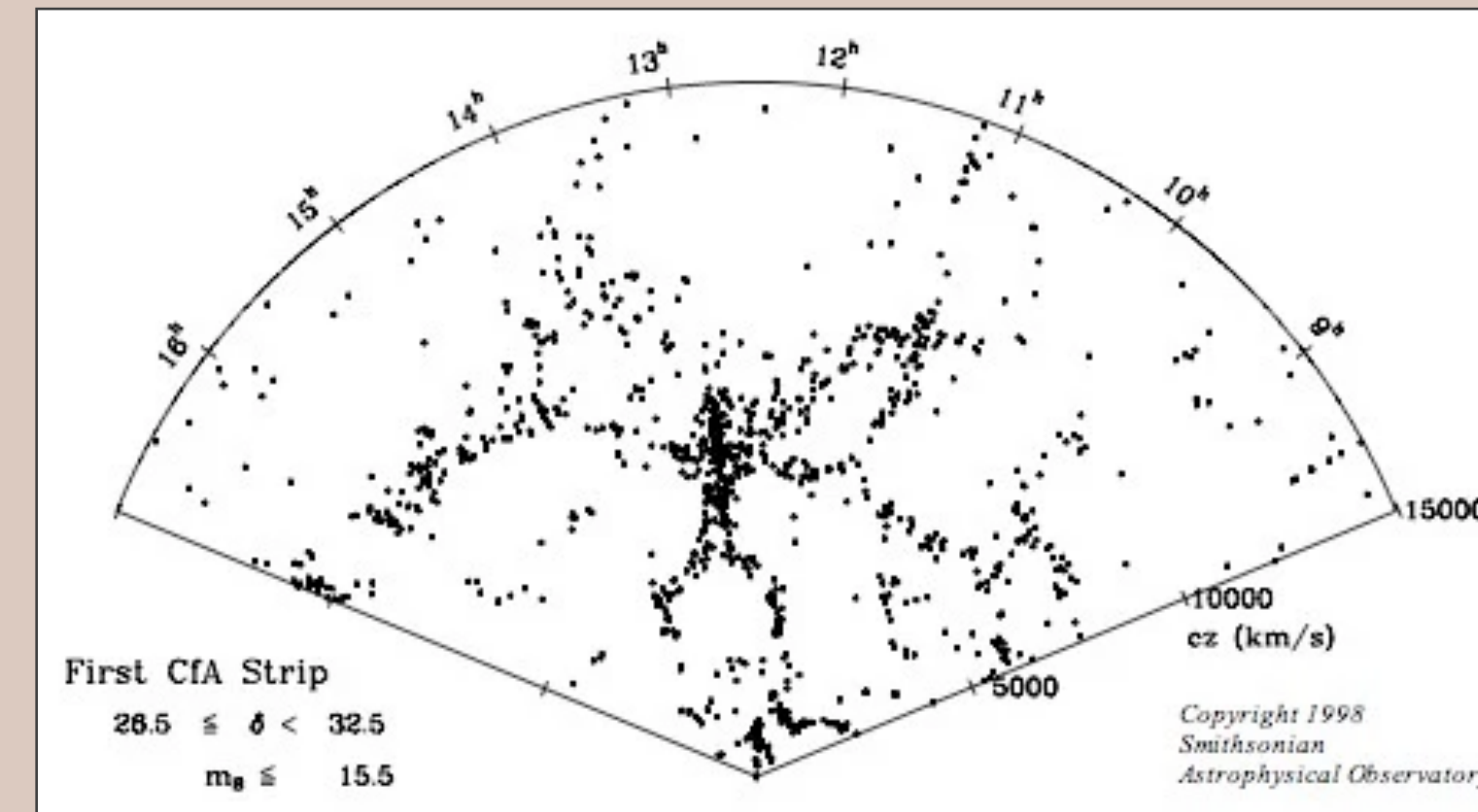


2030

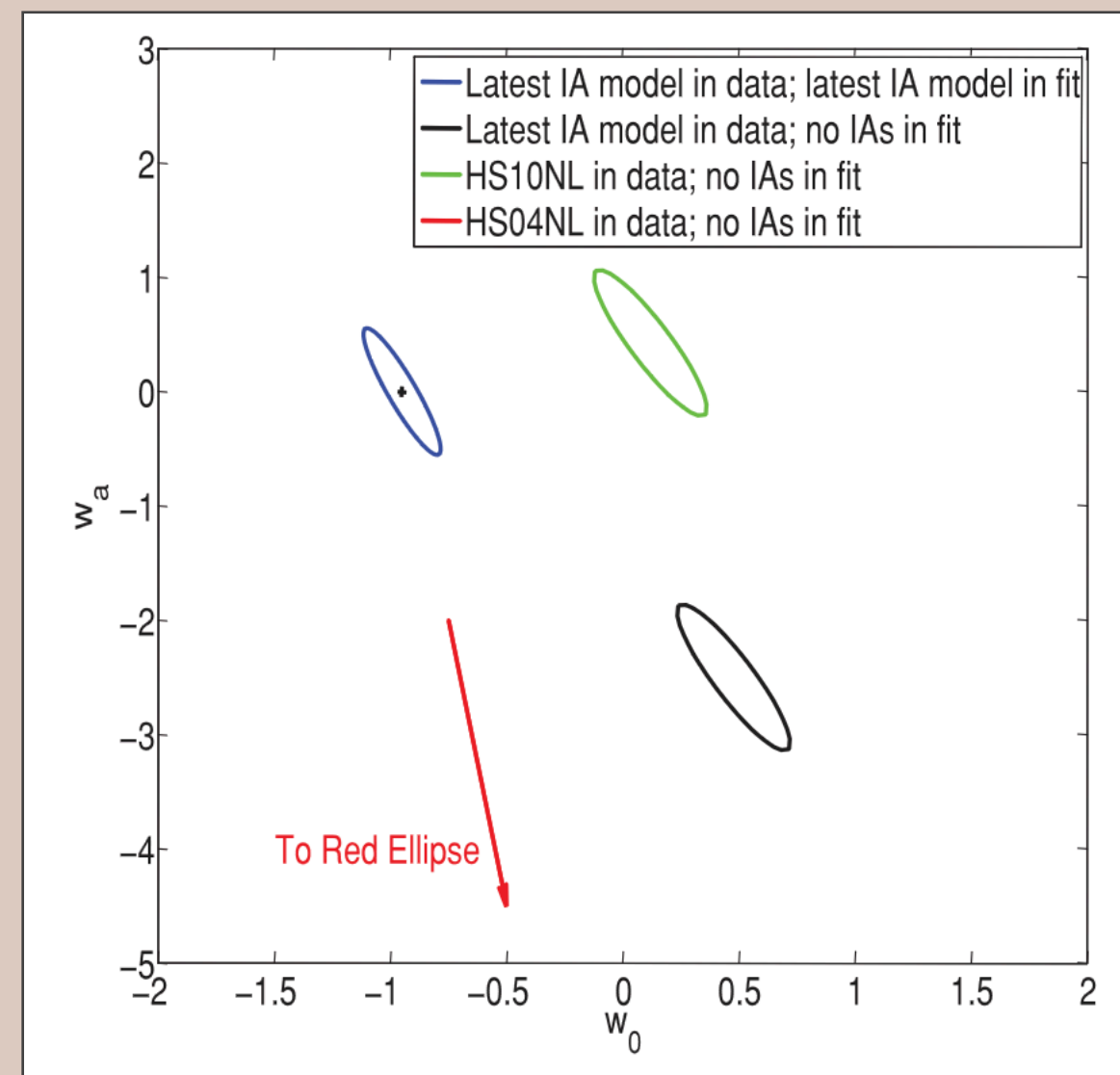


THE JOURNEY OF OBSERVATIONAL COSMOLOGY (SO FAR...)

statistics-limited



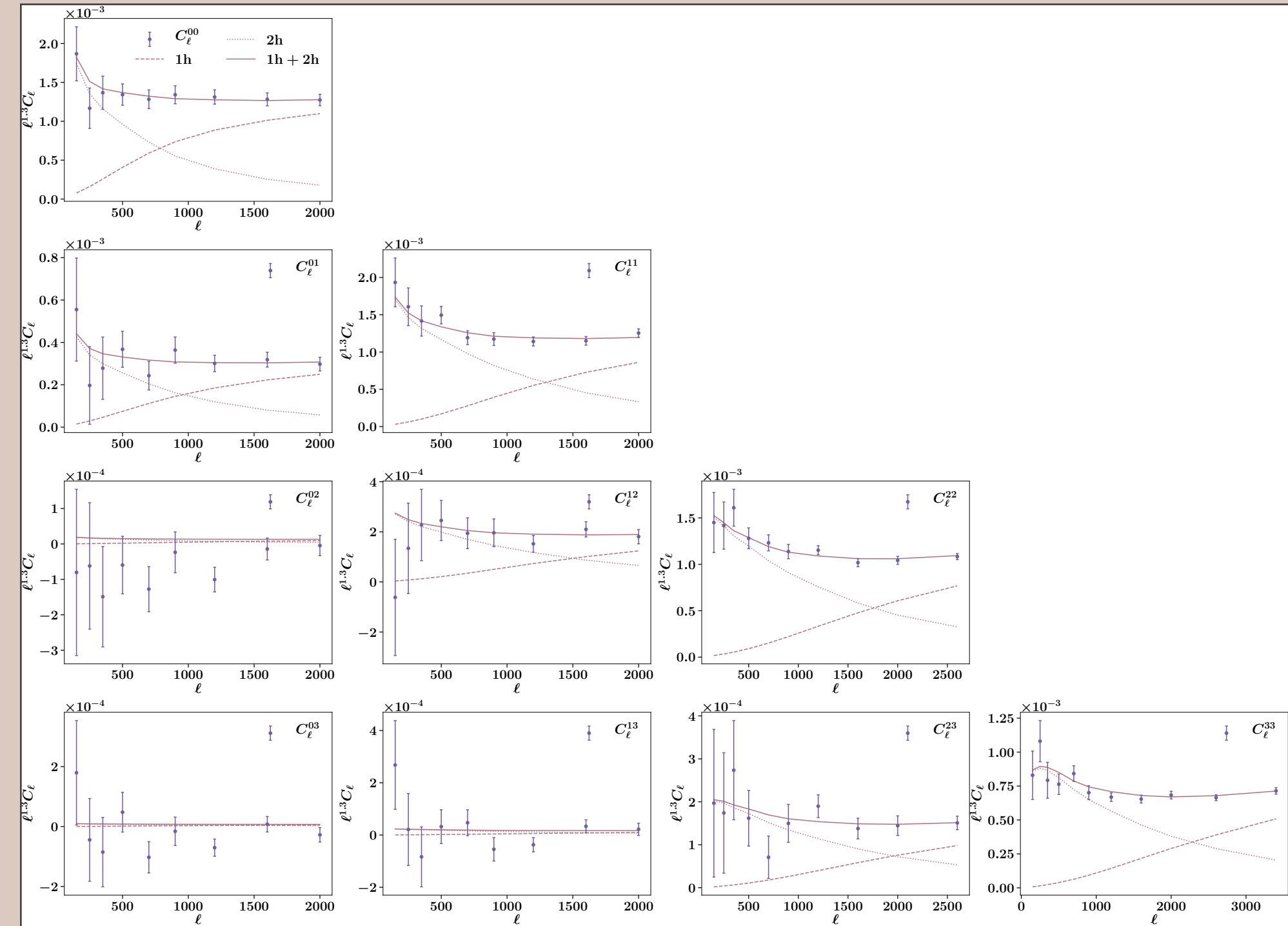
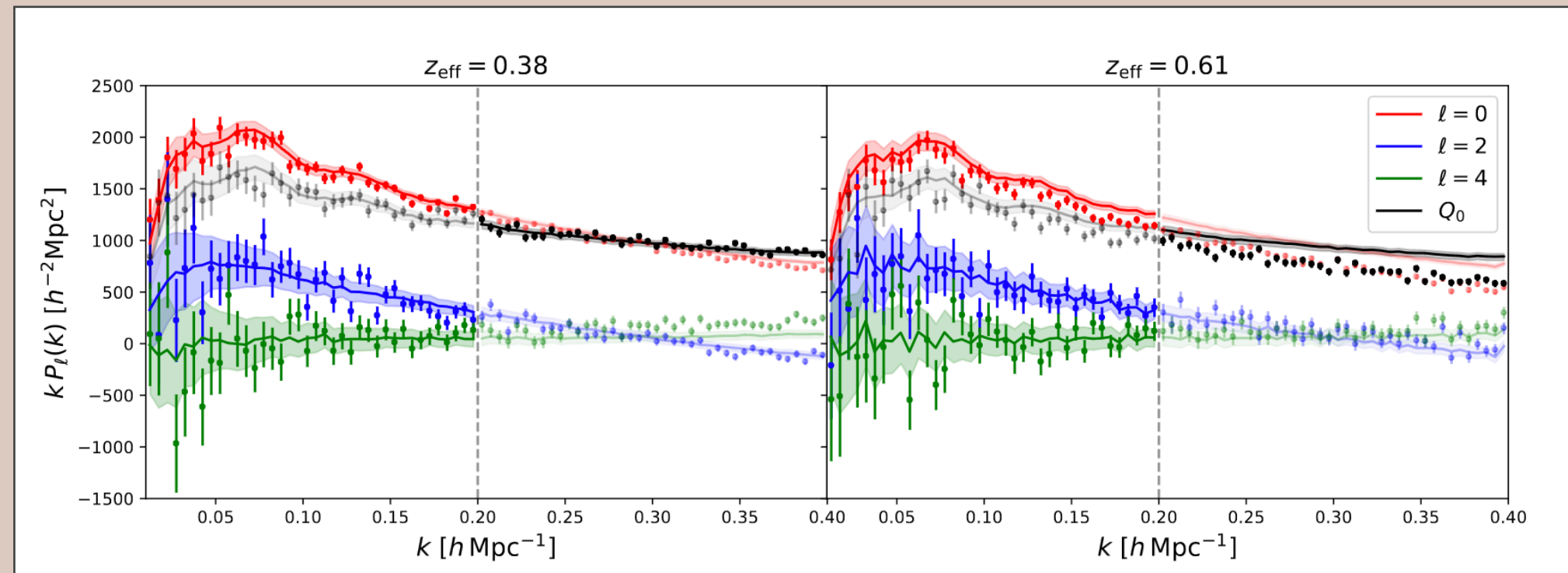
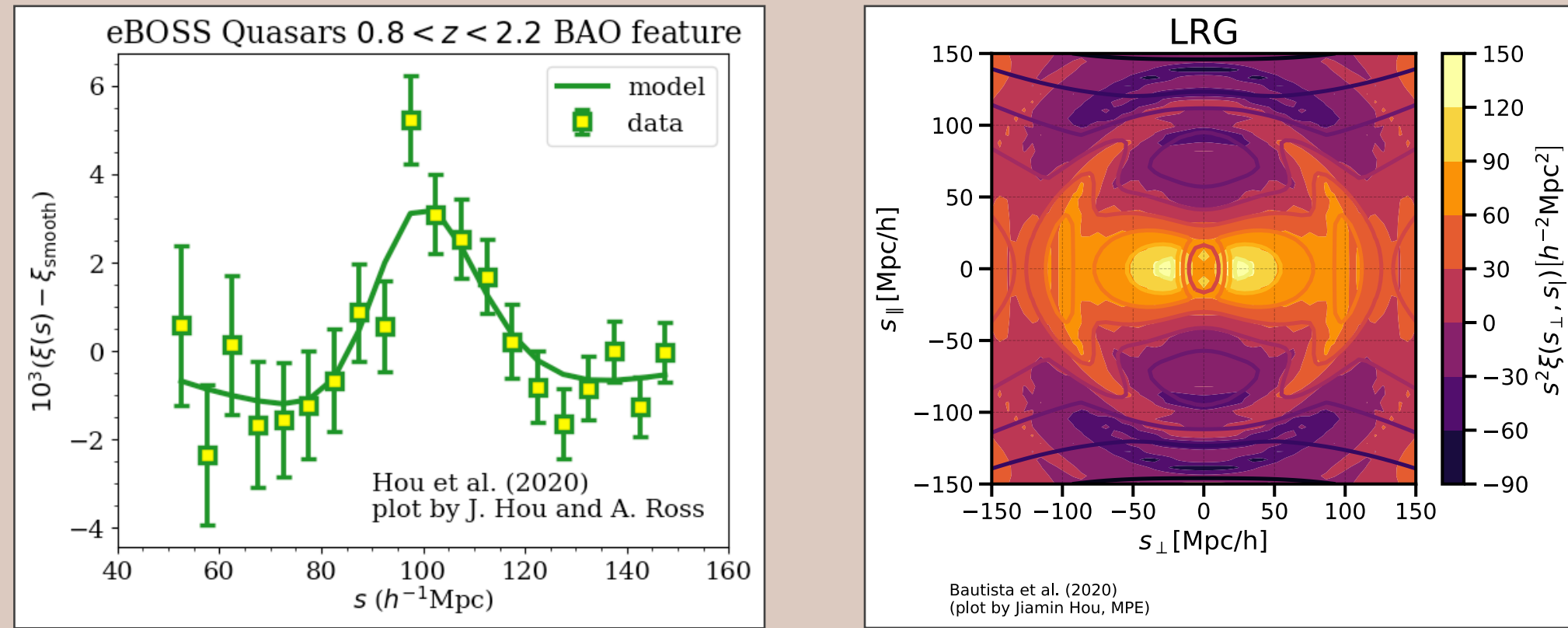
Huchra et al., 1988



Kirk et al., 2012

systematics-limited

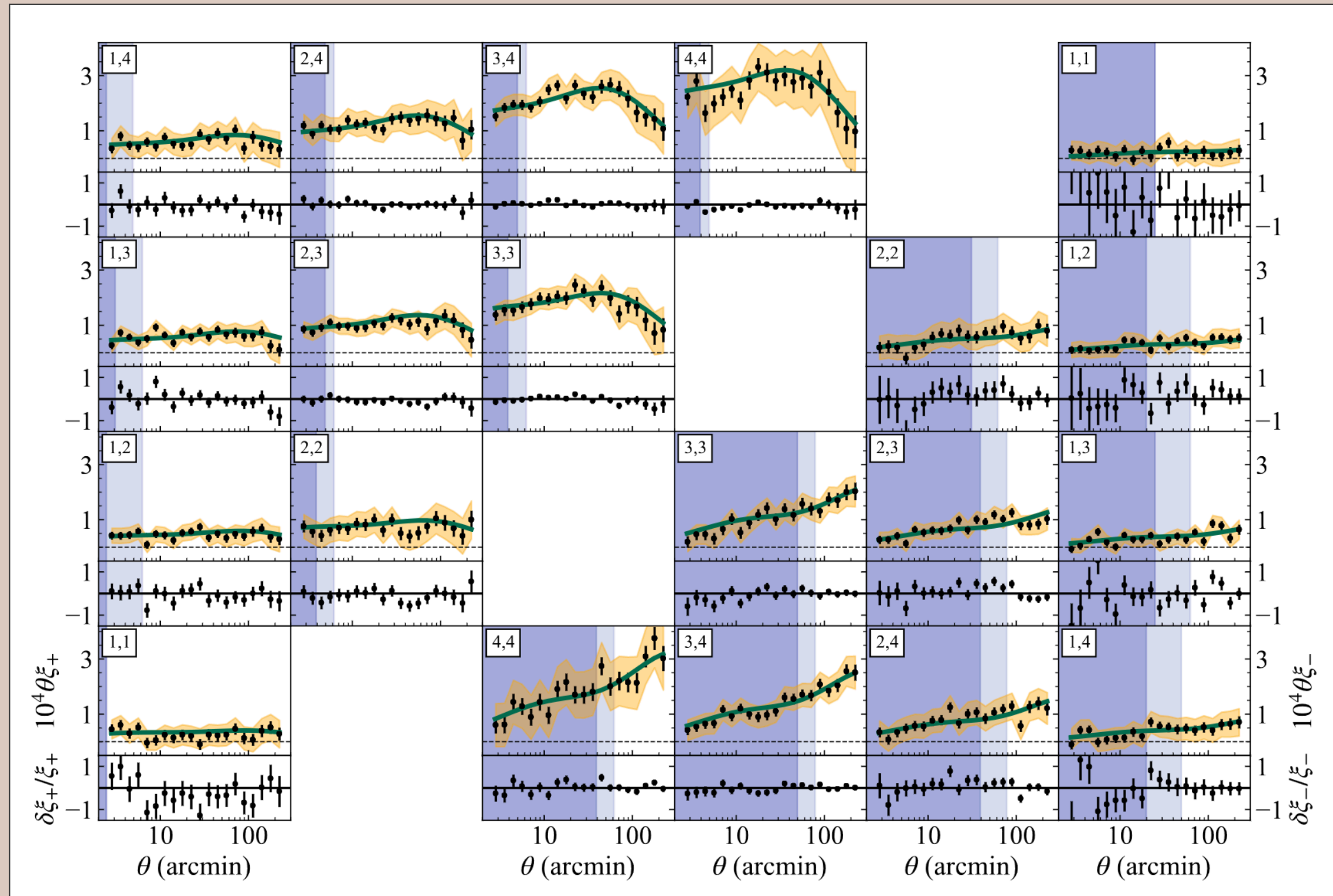
GALAXY CLUSTERING OBSERVABLES



Bautista et al., 2020, Hou et al., 2020, Philcox et al., 2022

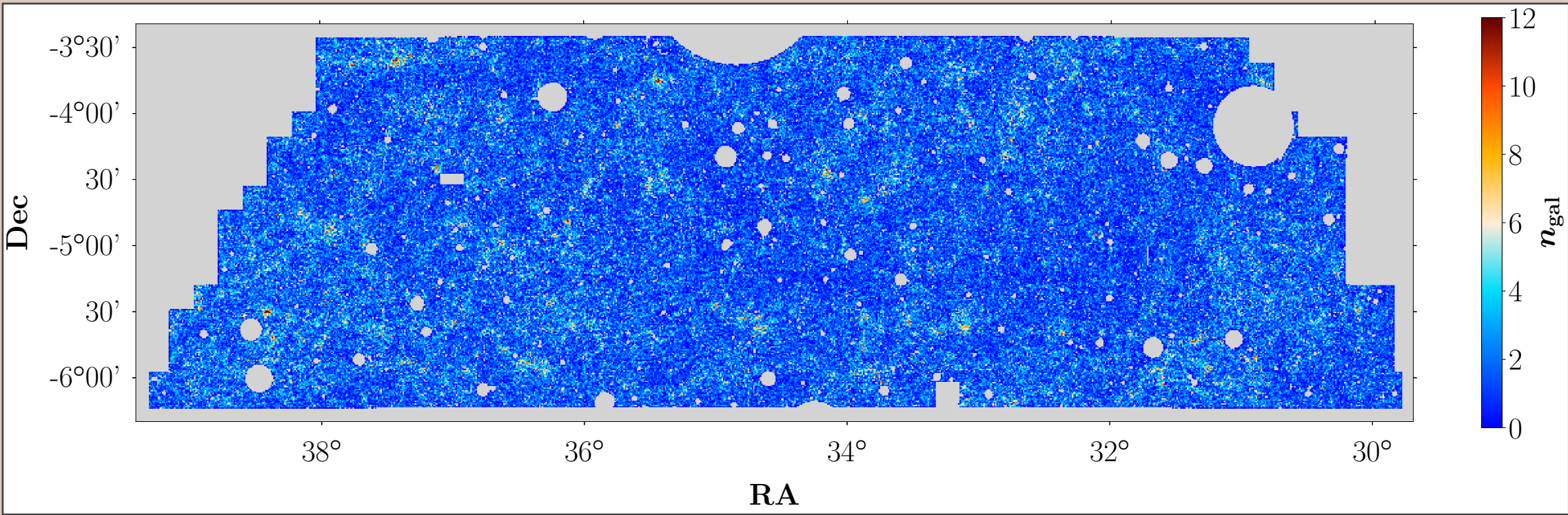
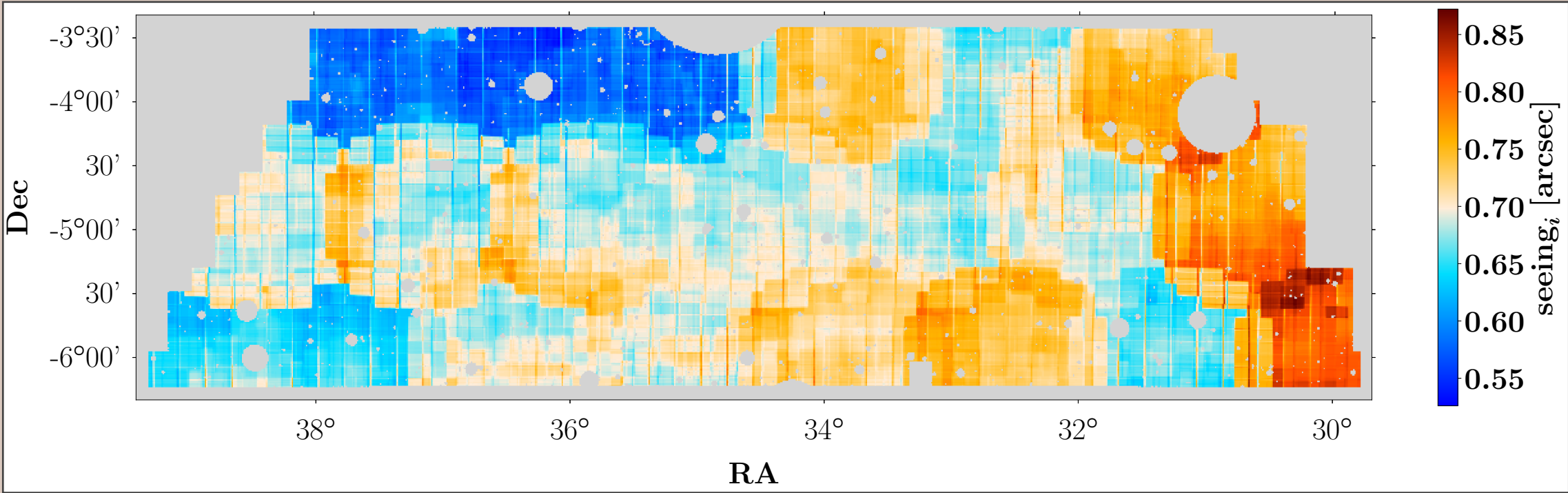
Nicola et al., 2020

WEAK LENSING OBSERVABLES

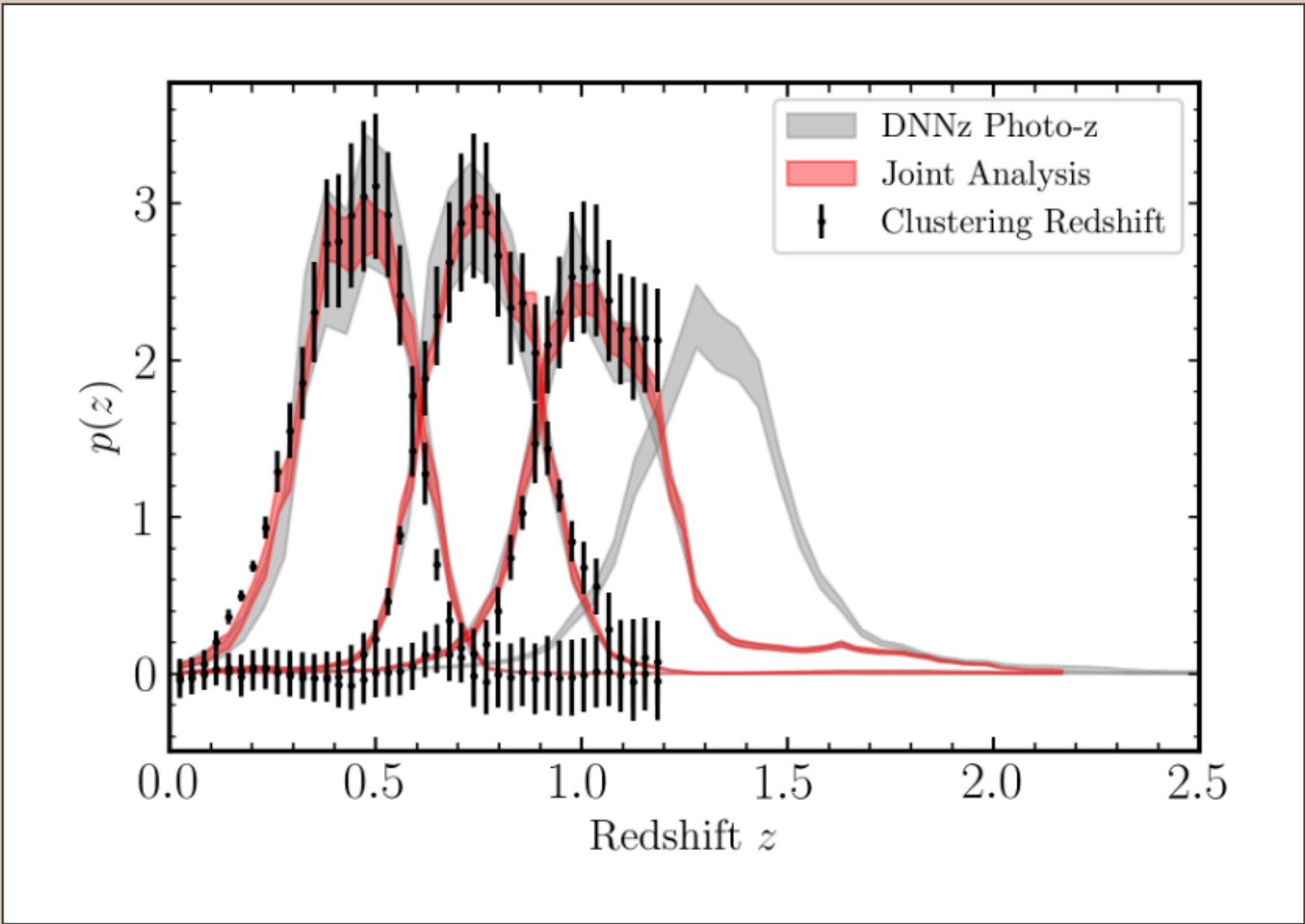


Amon, Secco et al., 2022

EXPERIMENTAL SYSTEMATICS (CLUSTERING-BIASED)

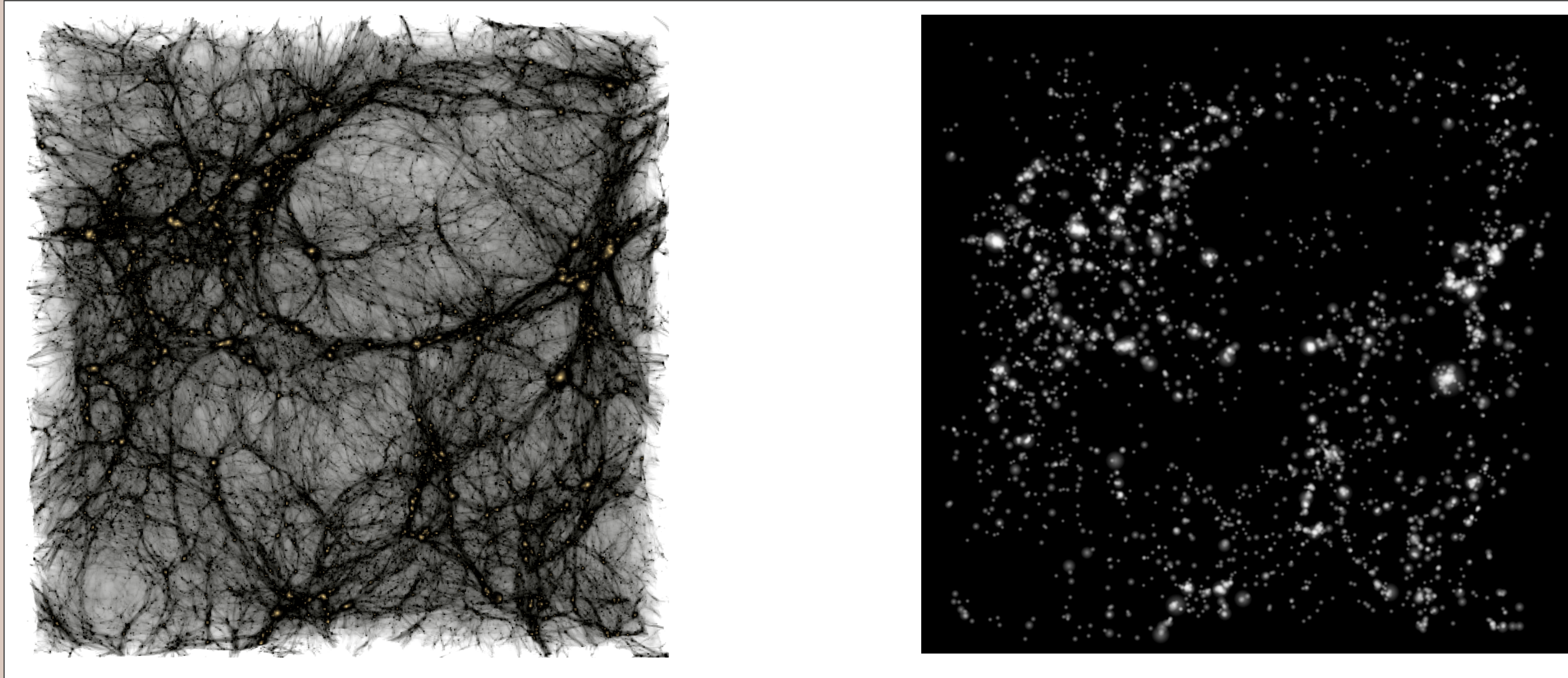


Nicola et al., 2020



Dalal et al., 2023

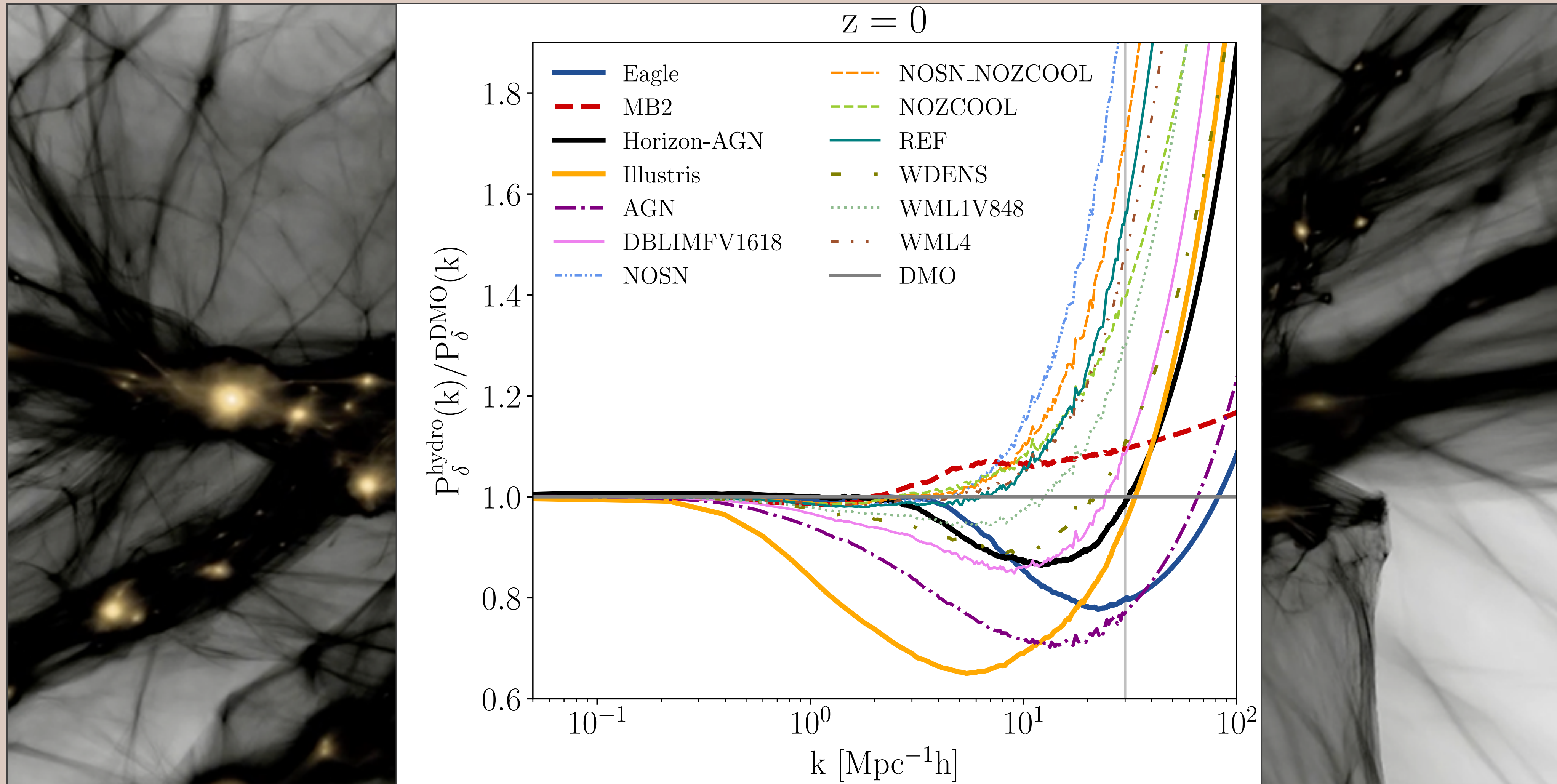
THEORETICAL SYSTEMATICS: GALAXY BIAS



$$1 + \delta_g = F[\partial_i \partial_j \Phi]$$

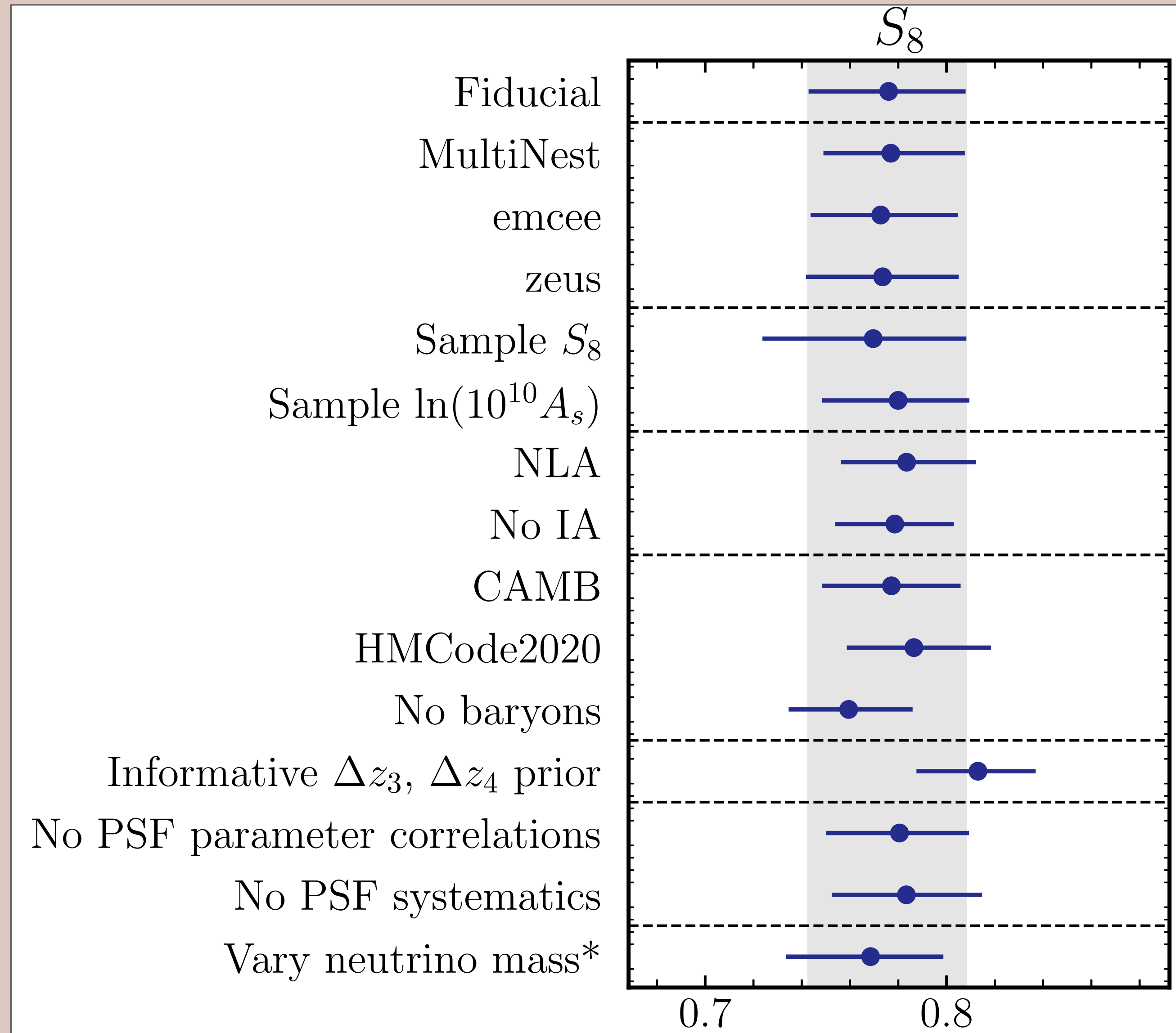
Image: Wechsler et al., 2018

THEORETICAL SYSTEMATICS: BARYONIC EFFECTS



Images: S. Skillman, Y-Y. Mao, KIPAC/SLAC National Accelerator Laboratory, Huang et al., 2019

SYSTEMATICS TODAY



Dalal et al., 2023



Cannes, February 2023

Science driver: WL, clustering, BAO

Final data products: images of 10 billion sources,
>1 billion WL galaxies, spectra of 35 million
galaxies, 15,000 deg²

Timeline: launch via Space X Falcon 9 rocket July
1st 2023

Data release: Quick release (single-pass 50 deg²
deep field) - end of 2024, Year 1 - end of 2025



Cerro Pachón, November 2022

Science drivers: WL, clustering, SNe, solar system, transients, Milky Way

Final data products: images of 37 billion sources, >2 billion WL galaxies, 10 million alerts per night, 18,000 sq. deg.

Timeline: system first light - Summer 2024, survey start Winter 2024

Data release: first 6 months - end of 2025, Year 1 - end of 2026

ROMAN TELESCOPE

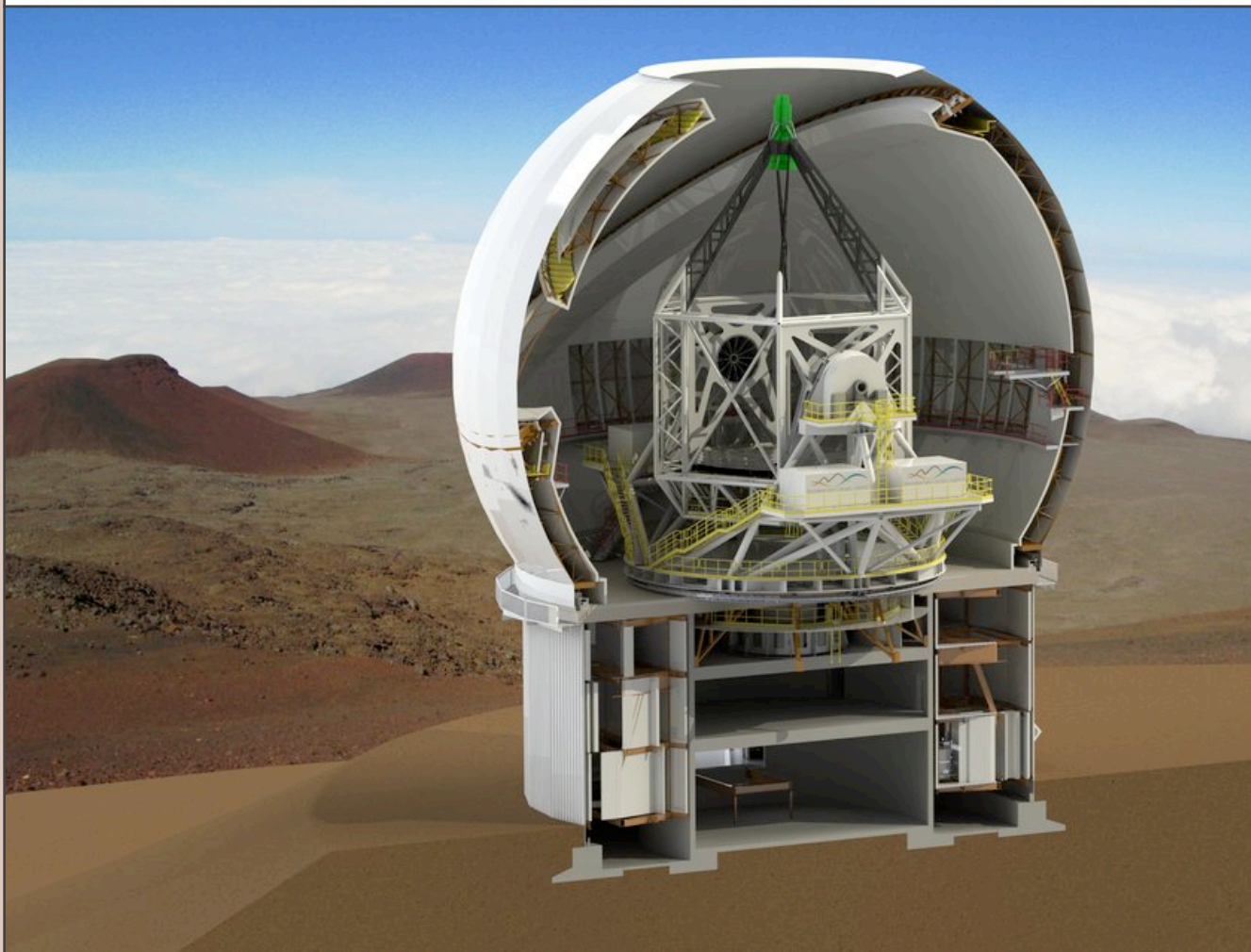
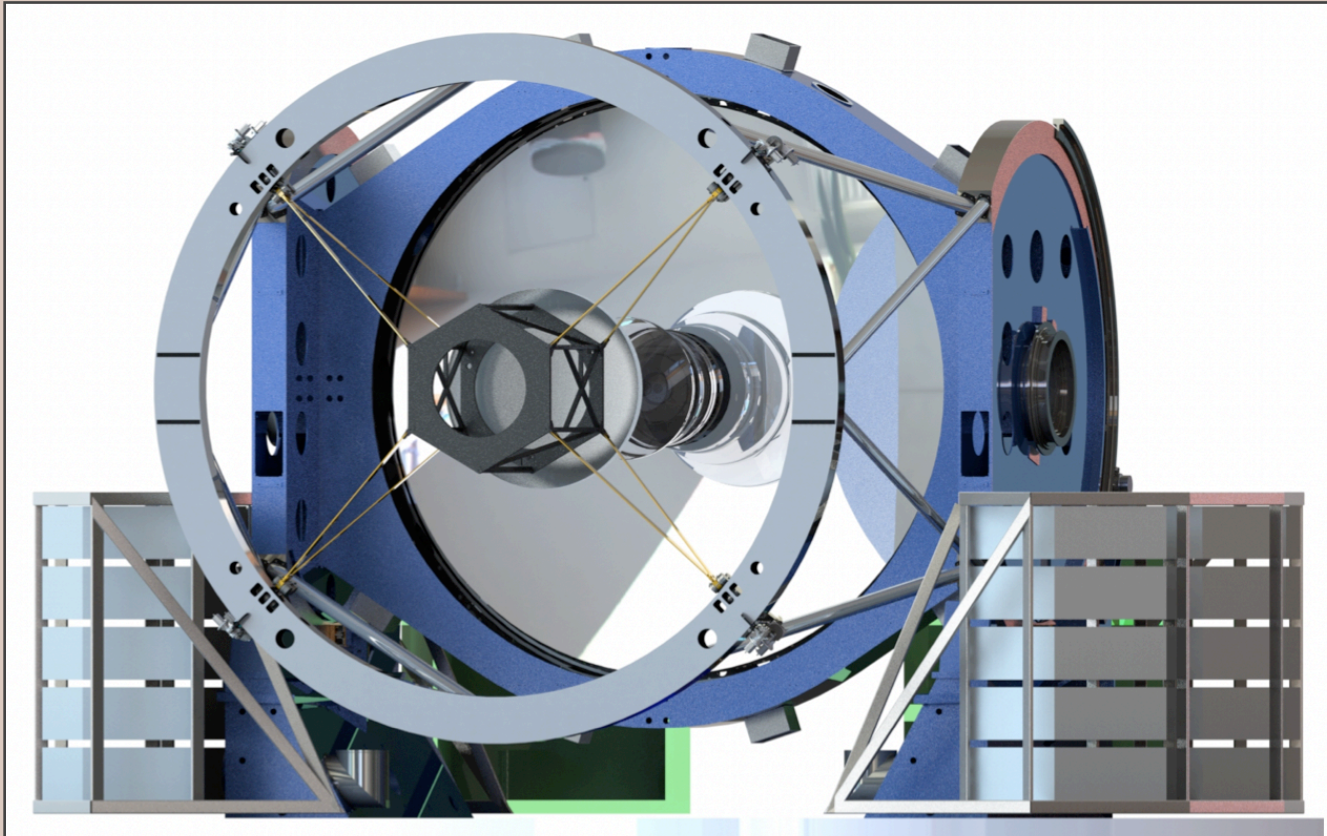


February 2023

Science drivers: WL, clustering, SNe, exoplanets
Final data products (High Latitude Survey): images of 380 million WL galaxies, 2700 SNe, 22 million ELG spectra at $1 < z < 3$, 2,000 deg²; exact area, location, pointing strategy still under discussion through community process
Timeline: launch by May 2027

credit: Chihway Chang

STAGE V SPECTROSCOPIC SURVEY



Concept: target high- z sources from Euclid/LSST/Roman
Science drivers:

Dark energy at higher redshift ($2 < z < 5$)

Inflation (primordial non-Gaussianity)

Modifications to General Relativity

Neutrinos and other Light Relics

Fundamental Nature of Dark Matter

Current mission concepts:

MegaMapper

Maunakea Spectroscopic Explorer

Wide-Field Spectroscopic Telescope

credit: Chihway Chang

A NEW LOOK AT COSMIC FIELDS

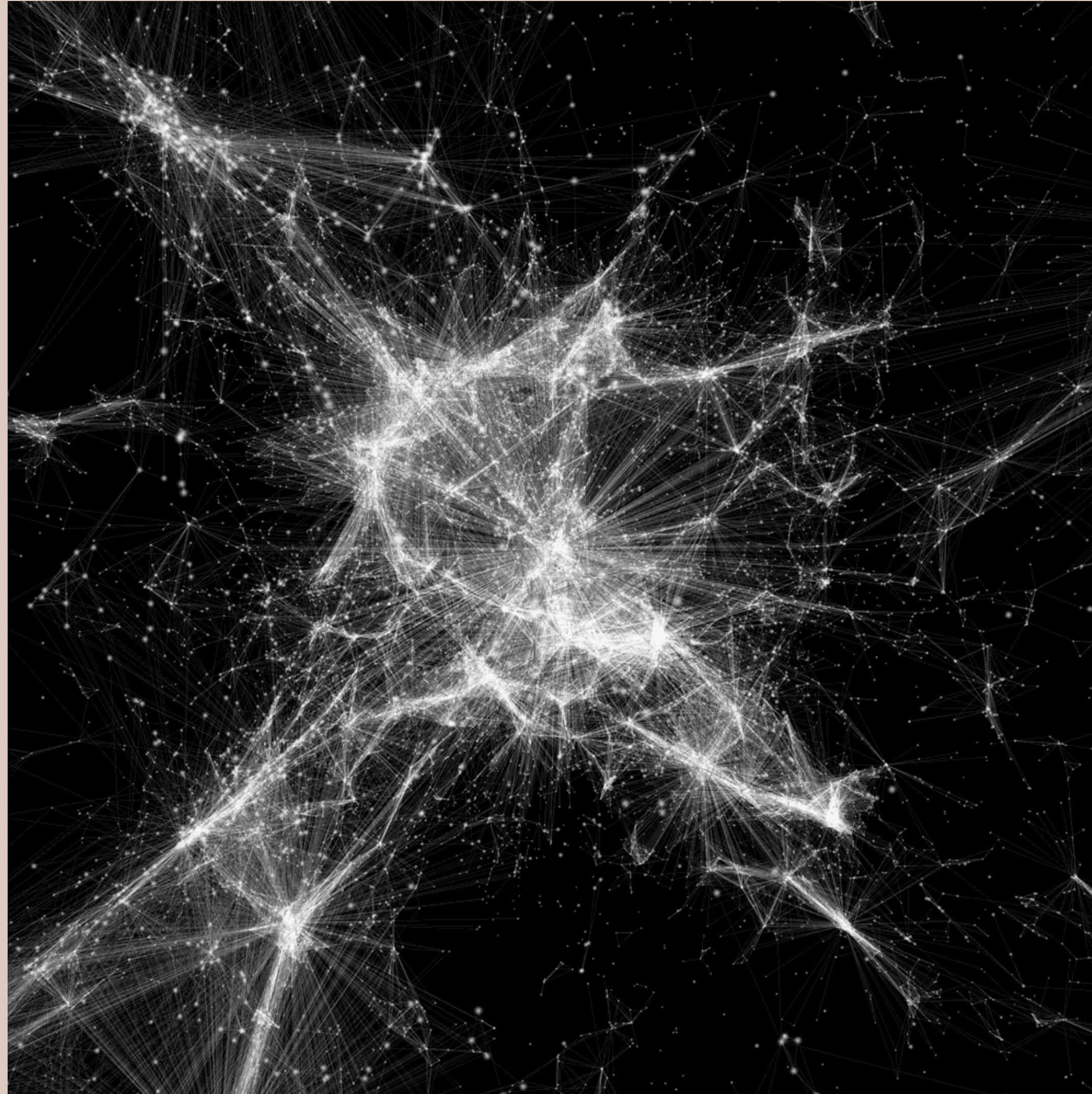


Image: Illustris Collaboration / Illustris Simulation

CHALLENGES & OPPORTUNITIES

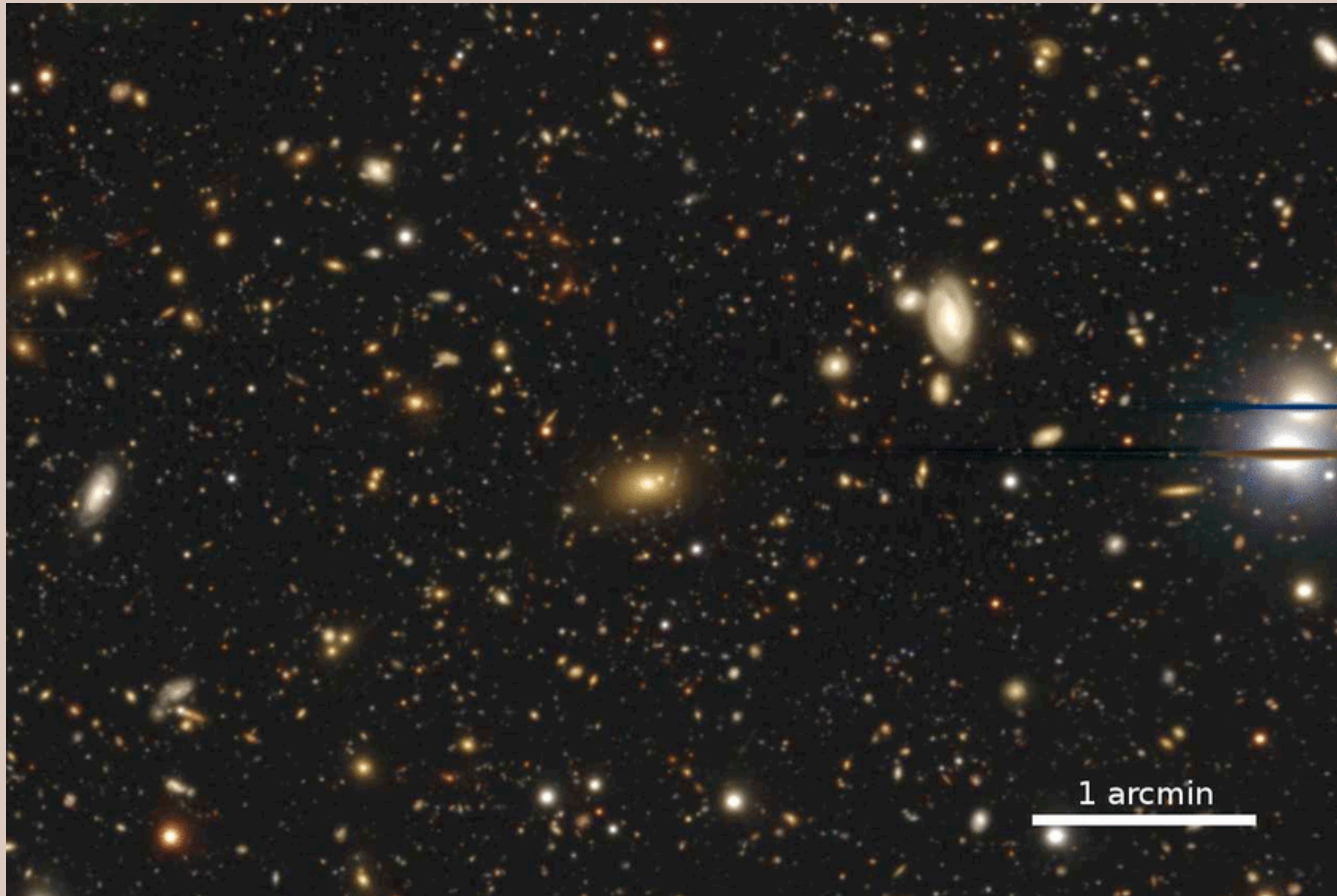
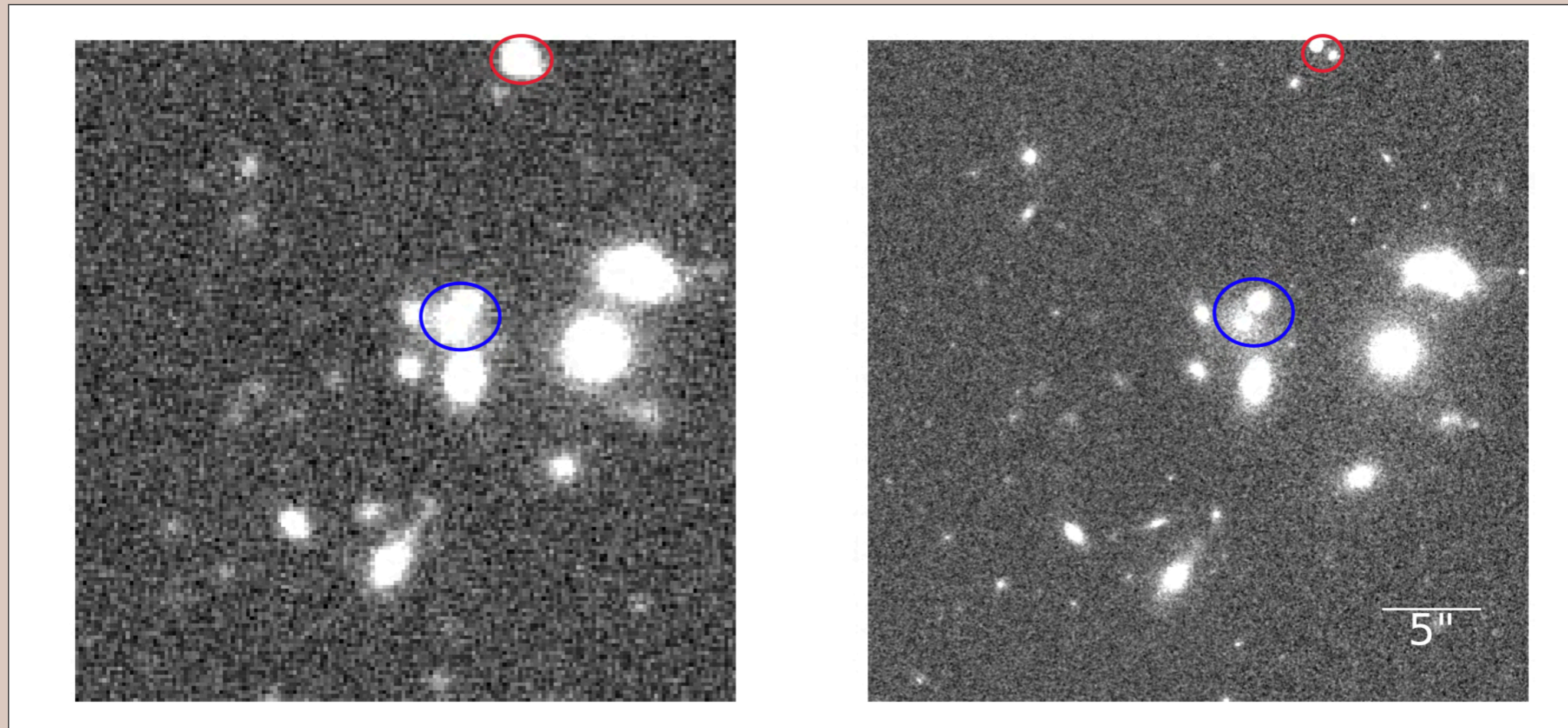


image: H. Aihara, et al., "First Data Release of the Hyper Suprime-Cam Subaru Strategic Program."

SYNERGIES – OBJECT DETECTION & SHAPE MEASUREMENT



Troxel et al., 2022

SYNERGIES - PHOTO-Z

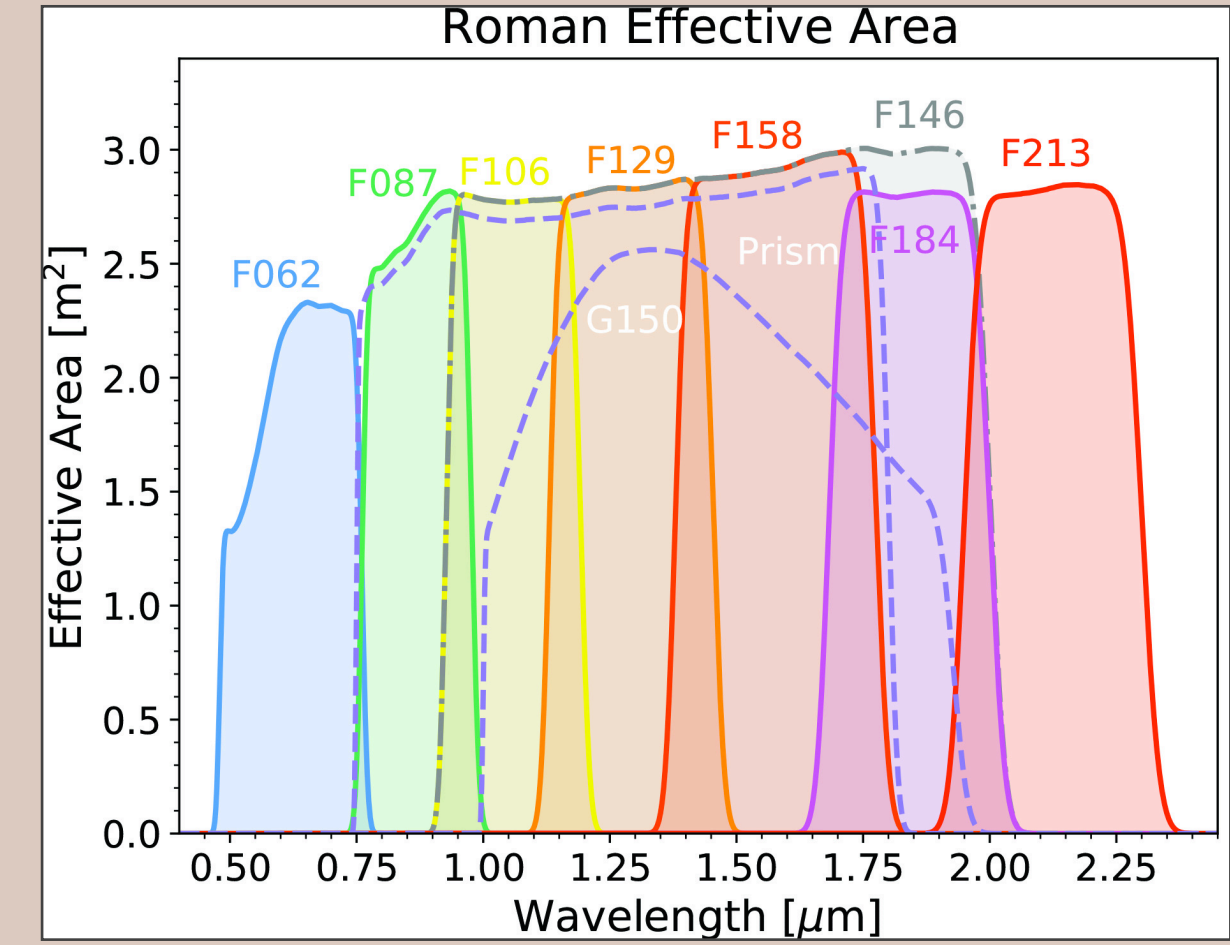
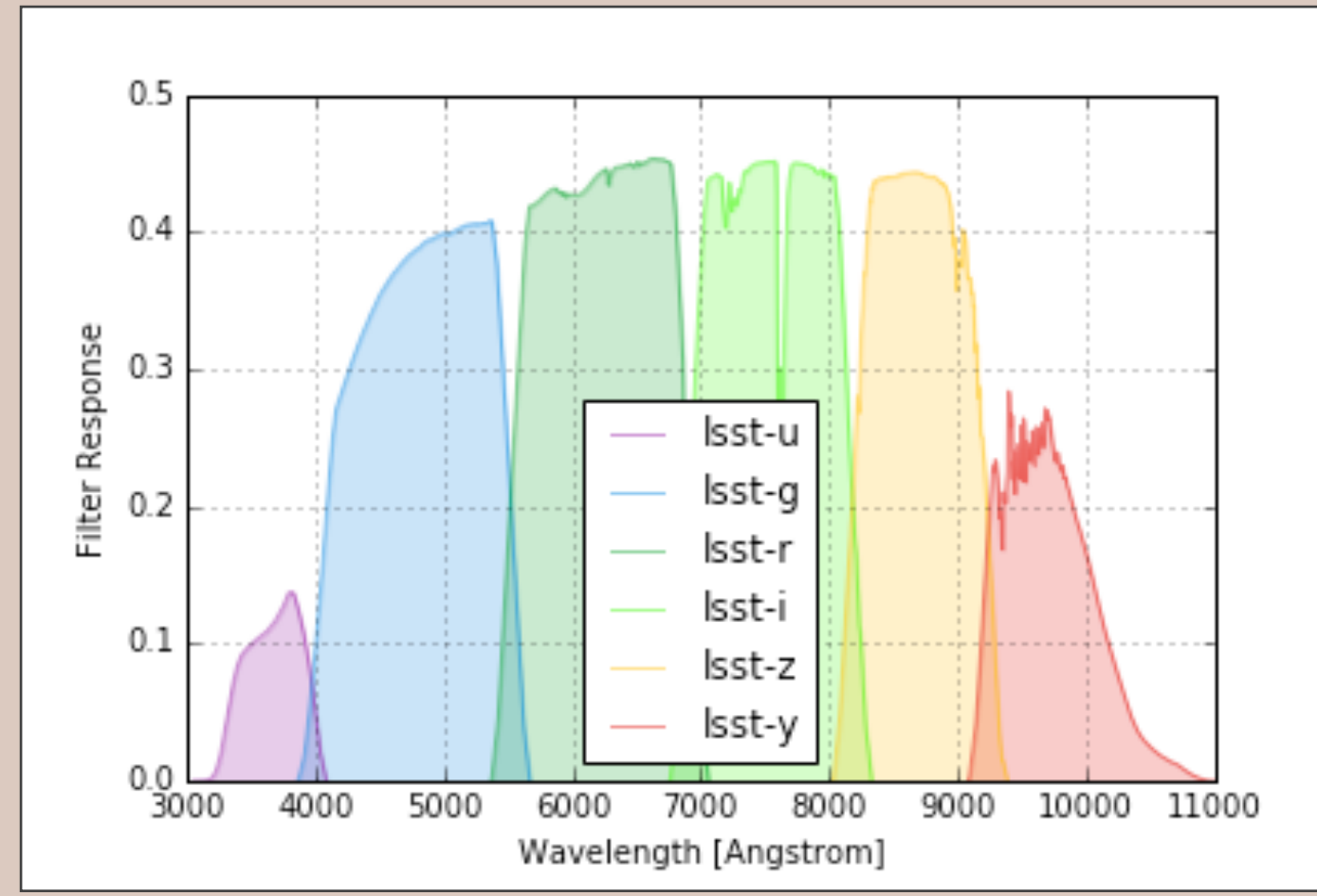
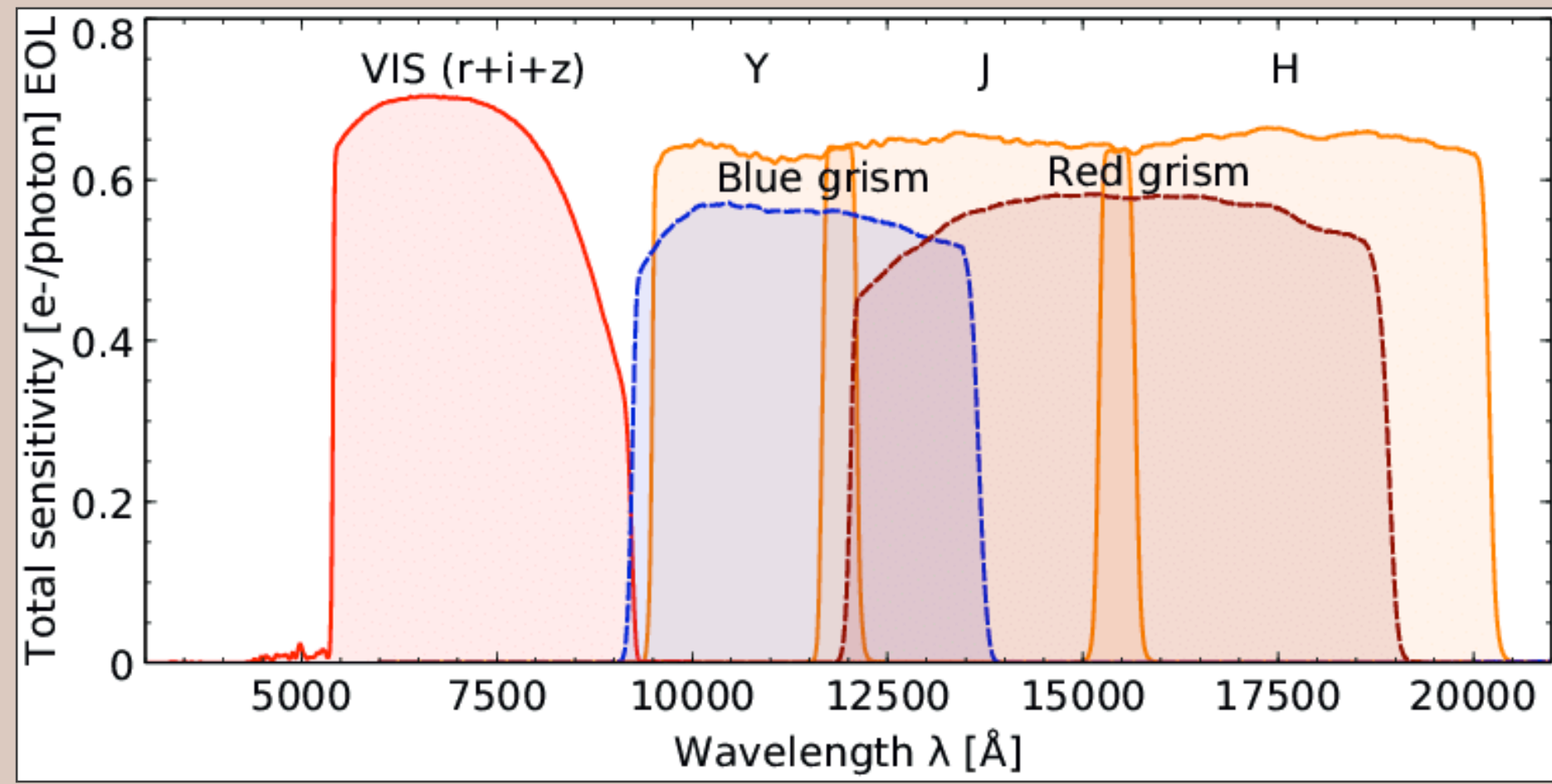


image credit: Euclid, LSST, Roman

PROPOSED PATH TOWARDS STAGE IV

Joint/coordinated analyses

- Deblending/shape measurement

- Photometric redshifts

- Joint pixel-level analyses

Cross-correlations with other surveys/probes

- Consistency tests

- Self-calibration

Complementary methods and observables



icon made by smashicon

SUMMARY

We are entering the era of Stage IV experiments

- Large amount of high-precision data

- Significant information in small-scales, non-Gaussian features

- Limited by systematics

Complementarity of surveys, probes & methods

- Systematics calibration, mitigation & identification

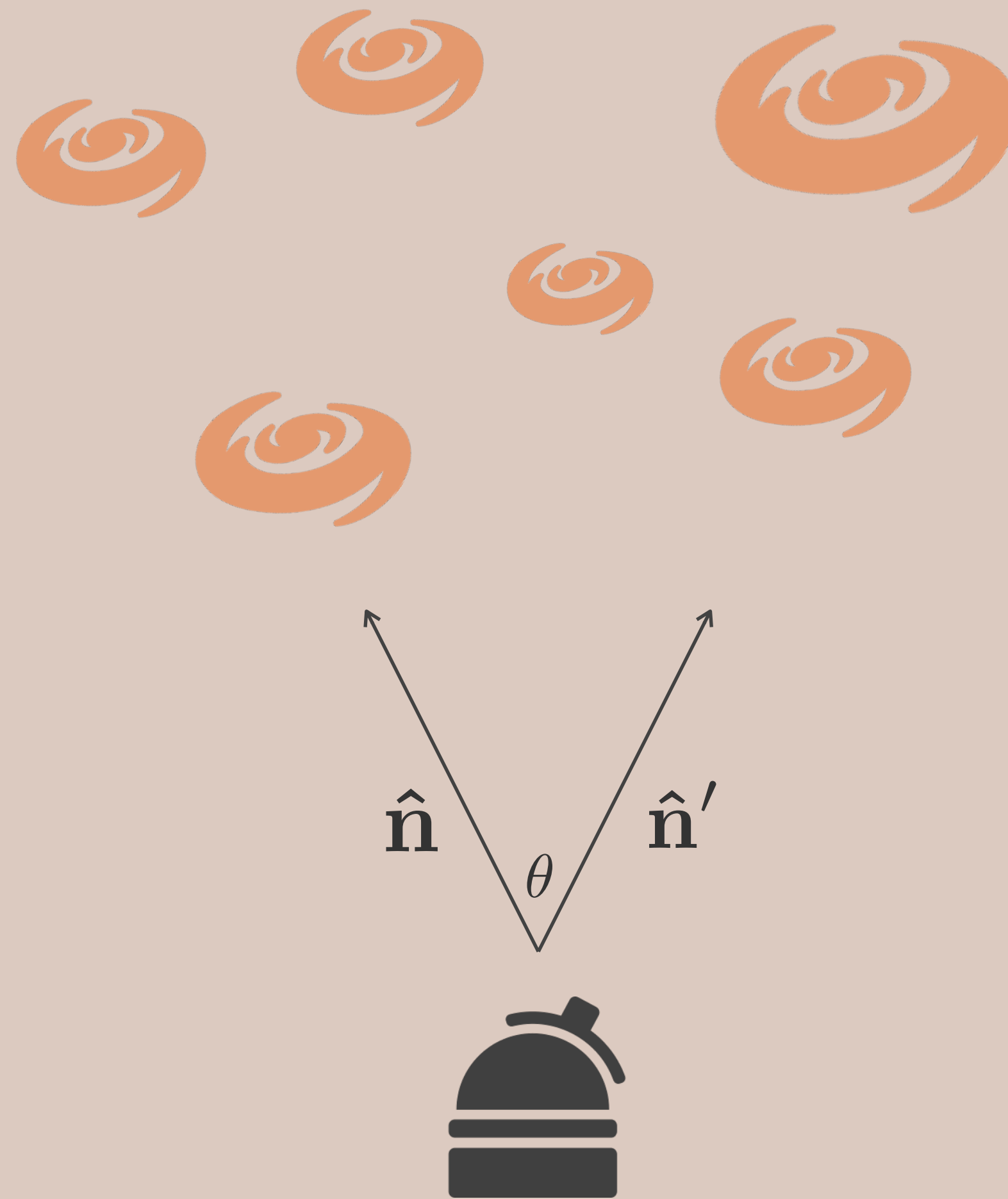
Early coordination and collaboration between surveys

Be prepared for surprises!

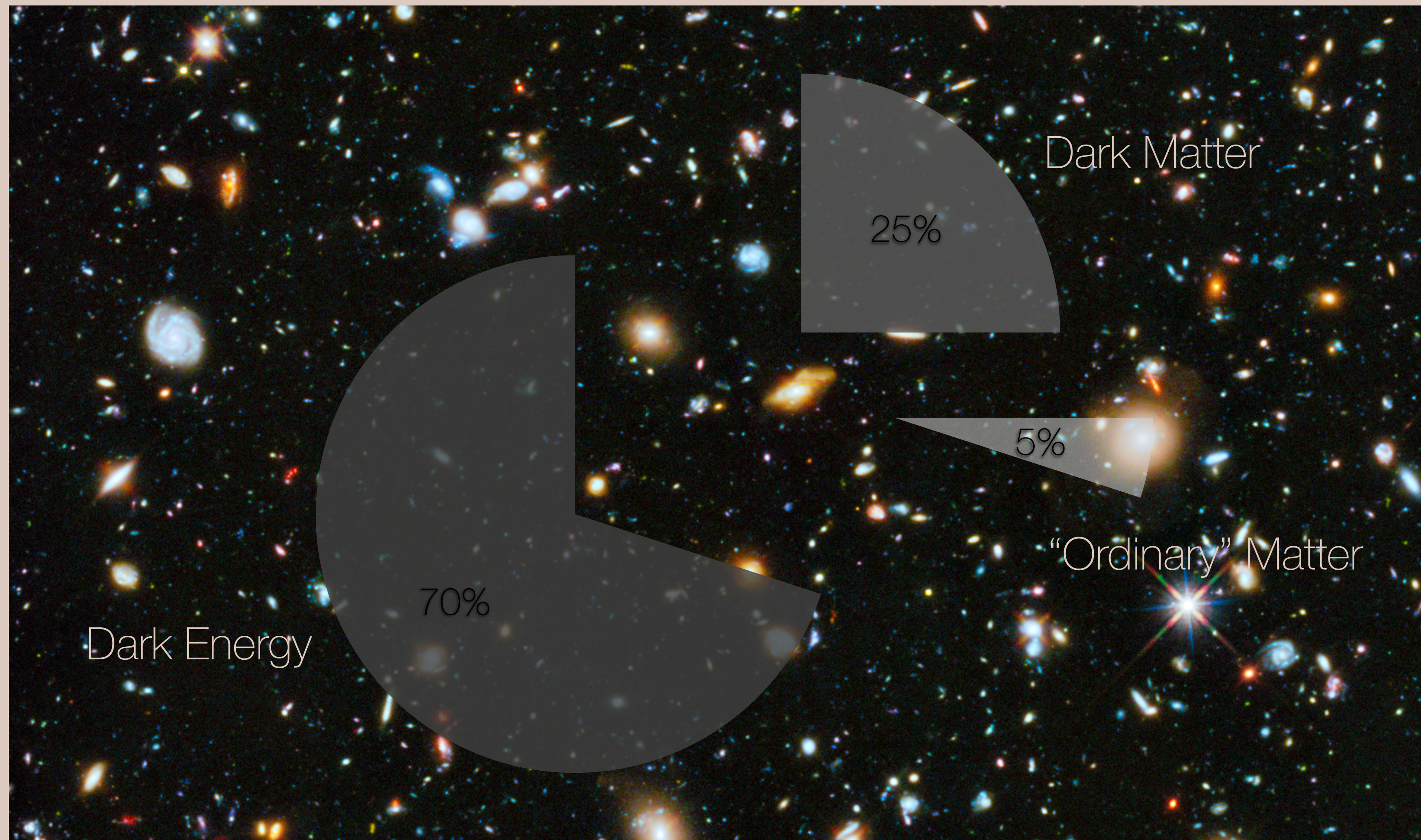


Dekuj!

GALAXY CLUSTERING



OUR DARK UNIVERSE



*“I say, there is no darkness but ignorance.”
— William Shakespeare, Twelfth night (IV.II)*

COSMOLOGICAL PROBES

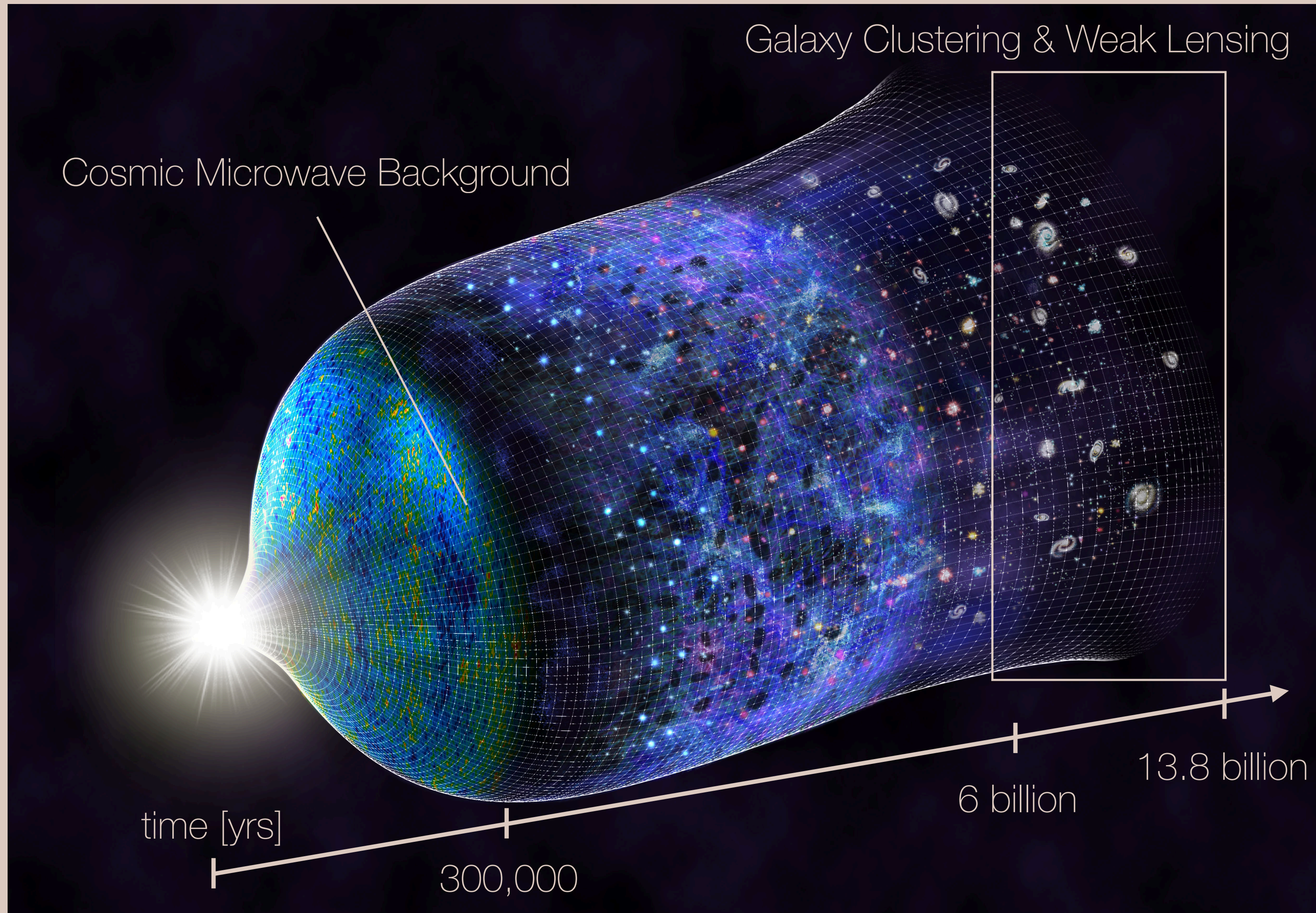


Image: Nicolle R. Fuller, National Science Foundation

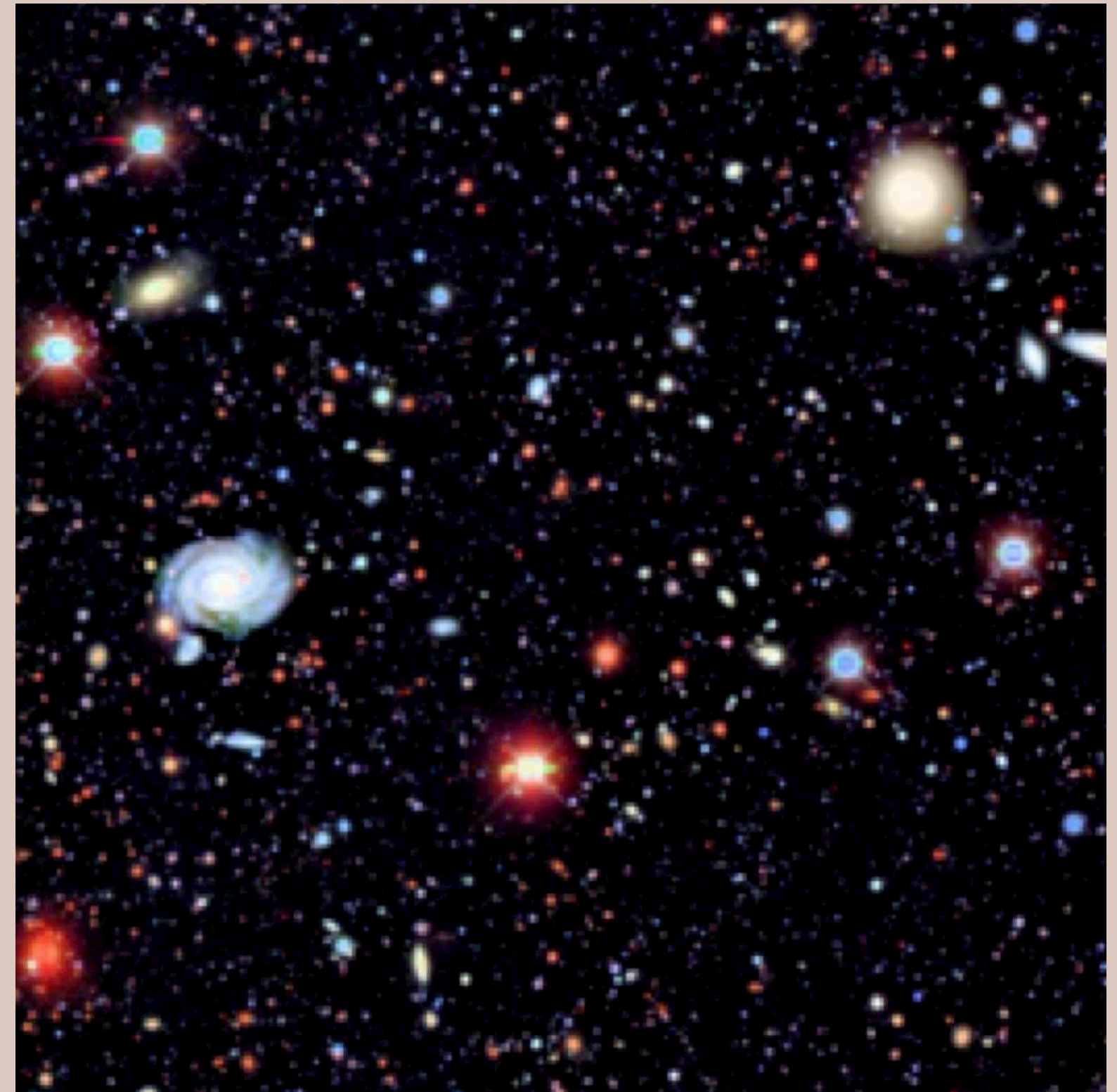
A NEW ERA FOR LARGE-SCALE STRUCTURE COSMOLOGY

P_{PAST}



e.g. SDSS

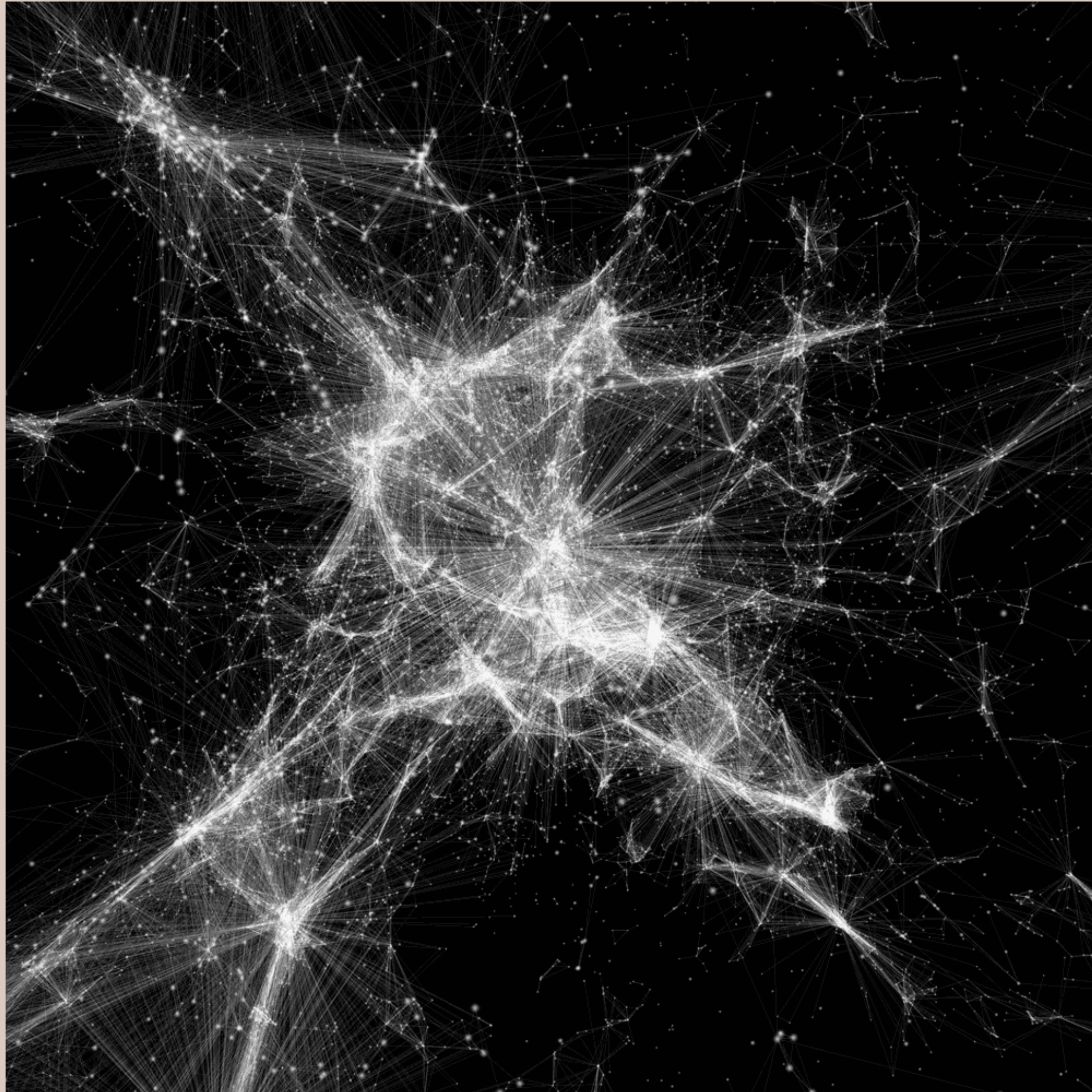
P_{PRESENT & FUTURE}



e.g. HSC, Rubin/LSST

Image: Ivezić et al., 2008

OUR NON-LINEAR UNIVERSE



Additional information contained in:
Cosmological fields at small spacial scales
Non-Gaussian features

Image: Illustris Collaboration / Illustris Simulation

HSC PHOTOMETRIC CLUSTERING WITHIN LSST DESC



Test viability of tomographic Fourier space analyses for high S/N data

Try to maximize sample size, i.e. go beyond e.g. LRGs, redMaGiC

Go to small-scales

Apply/test LSST pipeline on LSST-like data set

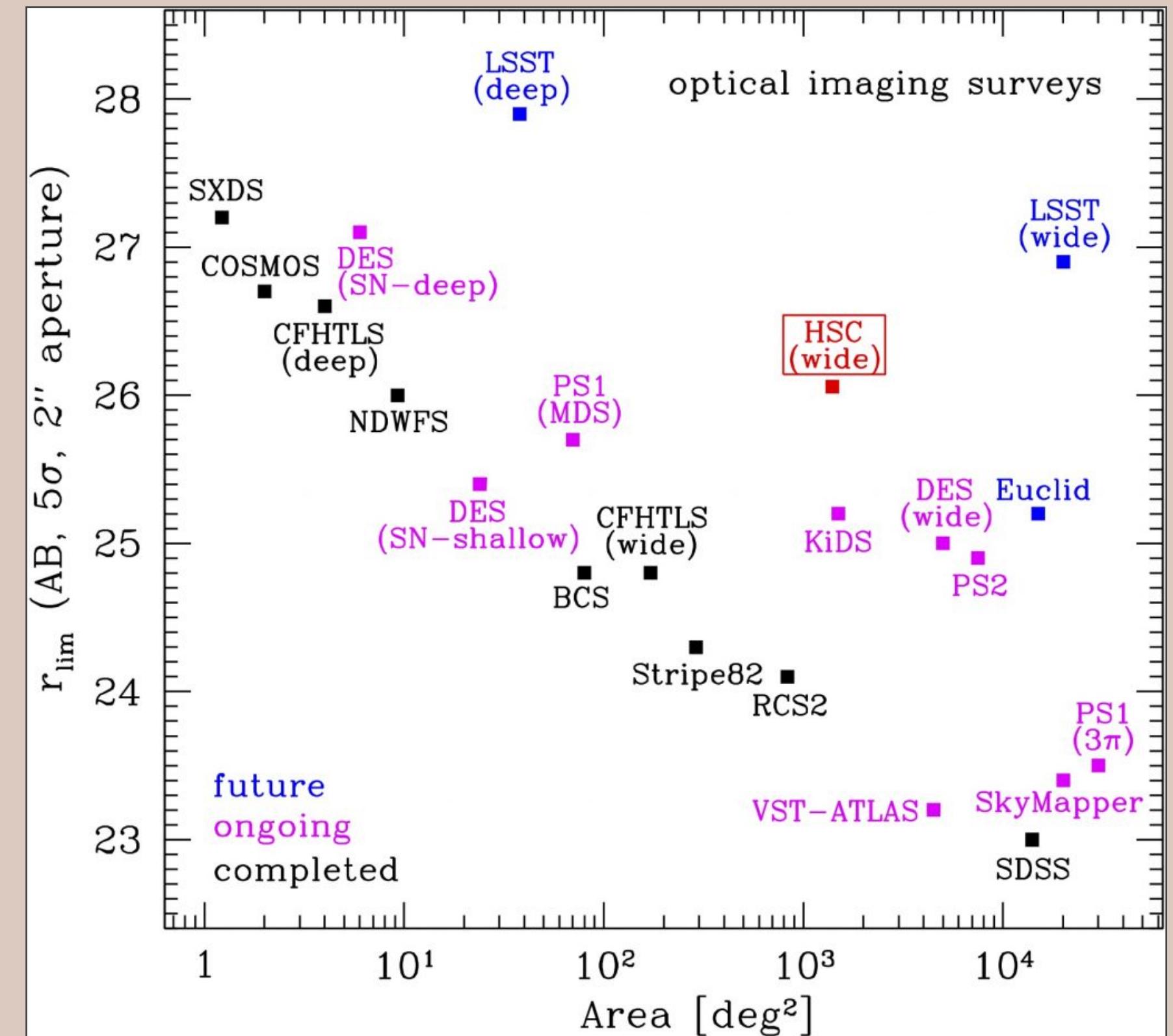
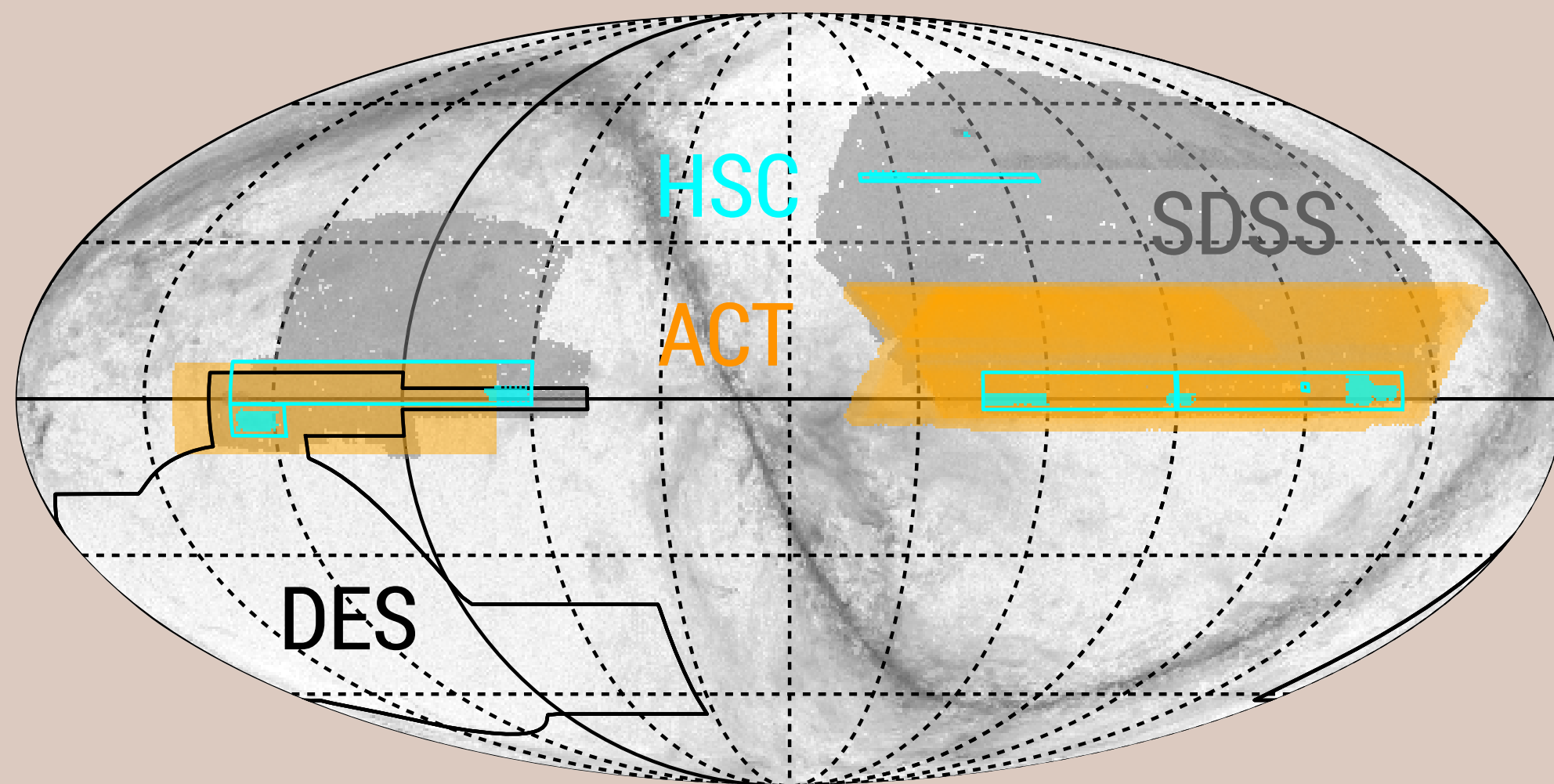
THE HYPER SUPRIME CAM SURVEY (HSC) AS A PRECURSOR FOR LSST

HSC: 5-year survey, covering 1000 sq. deg.

Deep ($r_{\text{lim}} \sim 26$), good seeing

Precursor to LSST

First data: DR1 covering 150 sq. deg.



Survey table: HSC SSP, footprint: E. Medezinski

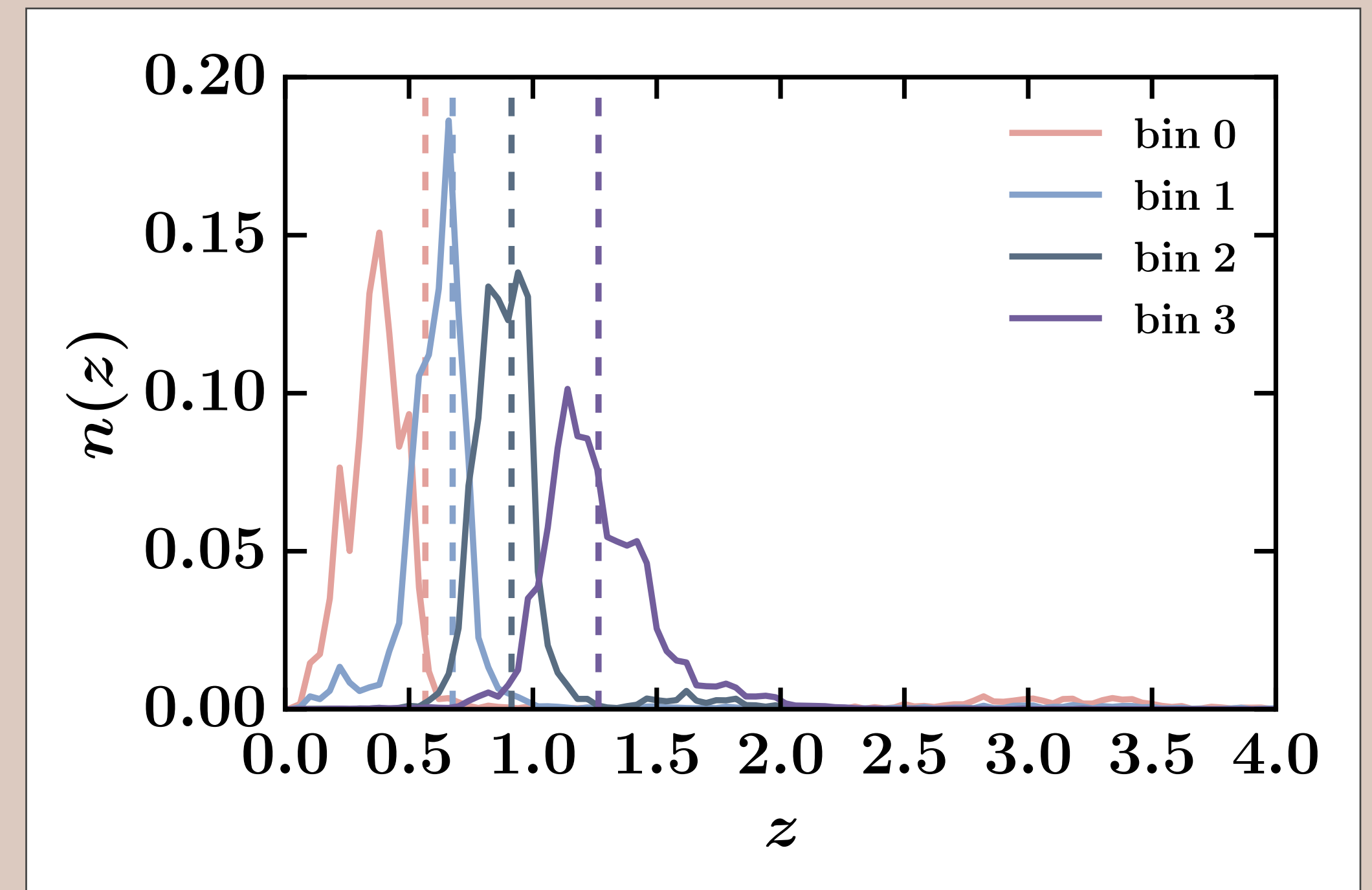
SAMPLE SELECTION

HSC DR1 data

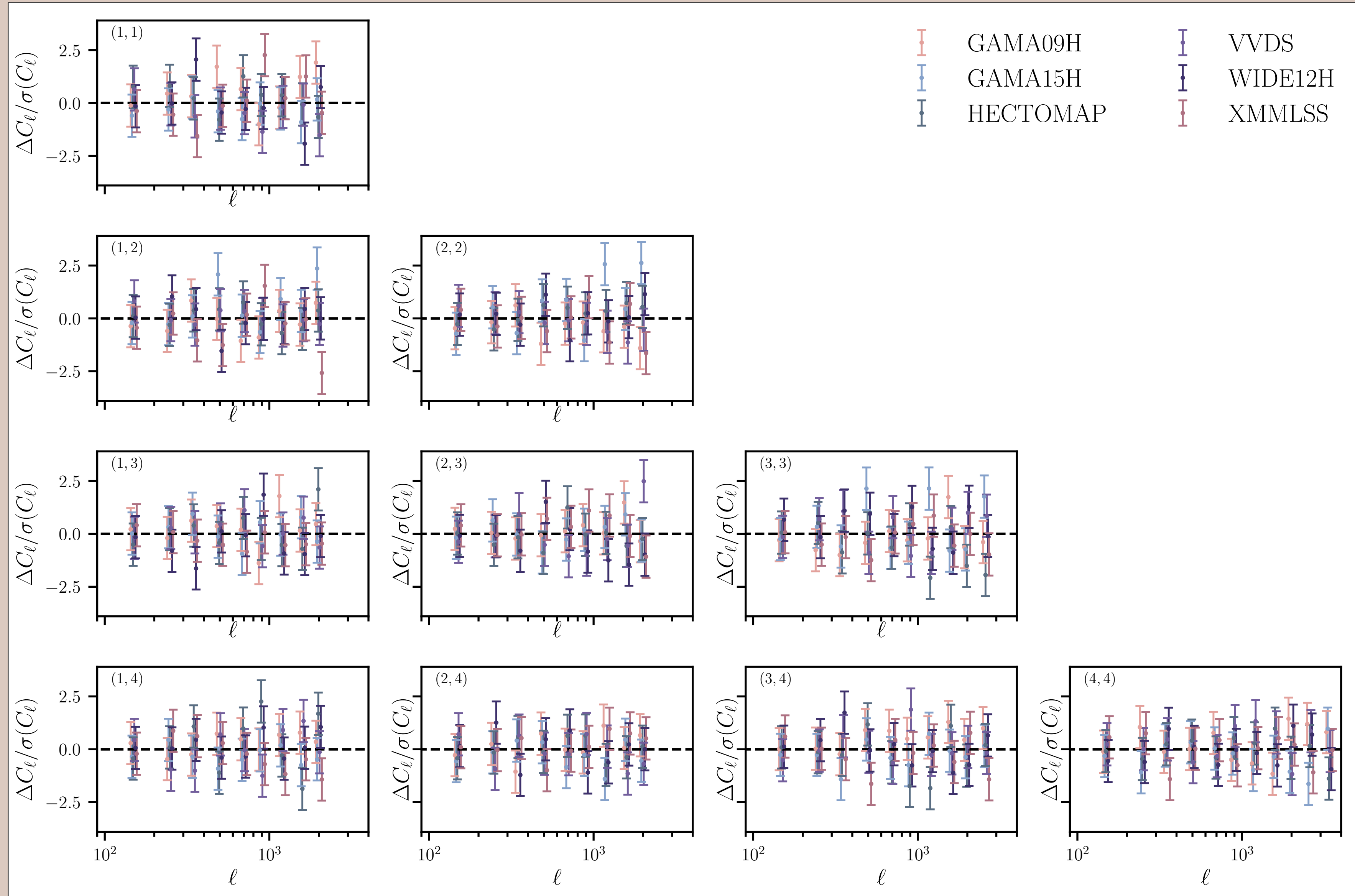
Galaxies with $\text{mag}_i < 24.5$

4 redshift bins: 0.15-0.50, 0.50-0.75,
0.75-1.00, 1.00-1.50

Photo-z: COSMOS reweighting



POWER SPECTRUM CONSISTENCY TESTS

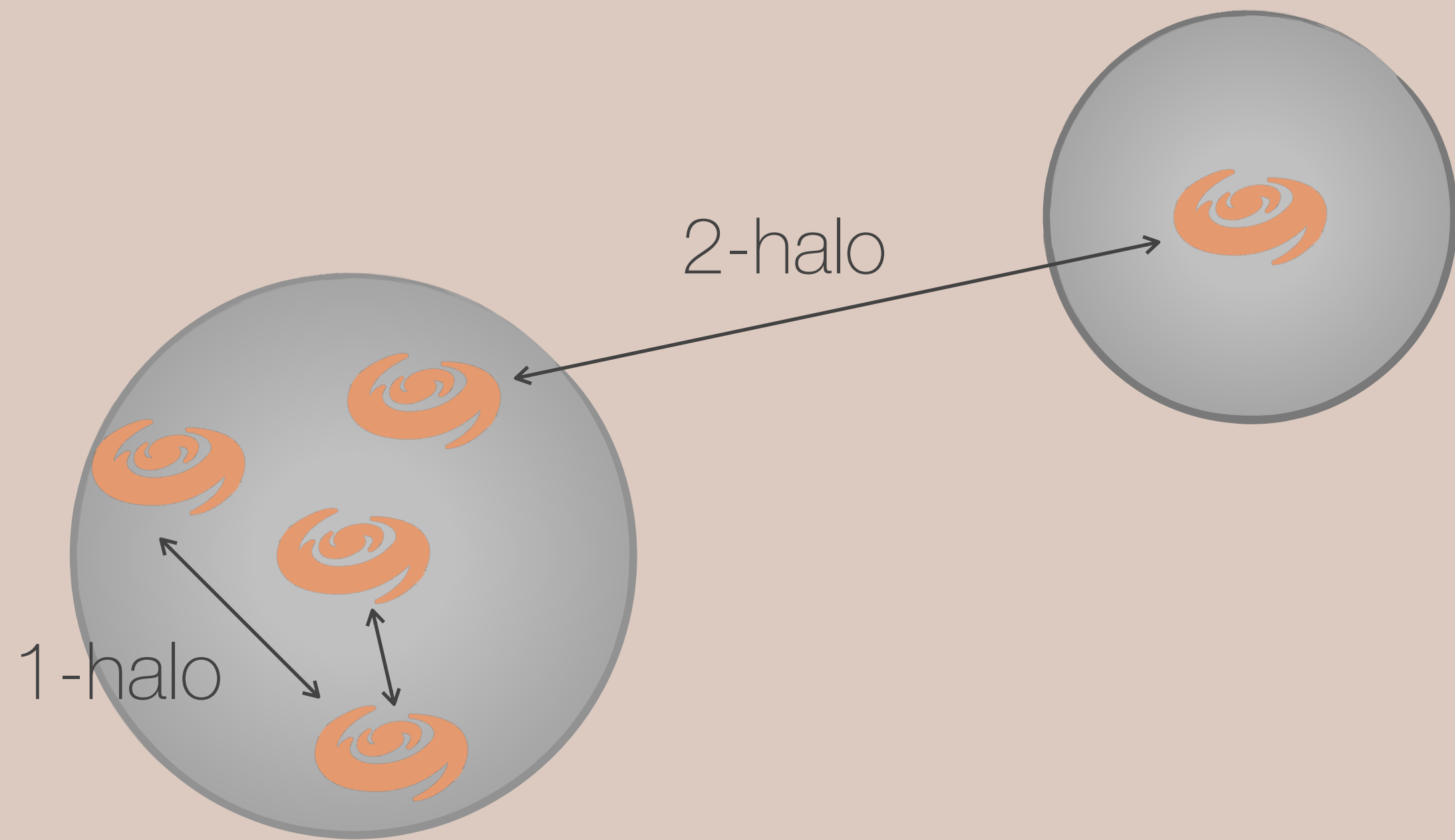


THEORETICAL MODELING

Small-scale clustering ($k_{\text{max}} \sim 1 \text{ Mpc}^{-1}$)

Halo model (e.g. *Seljak 2000, Peacock et al., 2000, Ma et al., 2000*)

Halo occupation distribution (e.g. *Berlind & Weinberg, 2002, Zheng et al., 2005*)



$$P_{gg}(z, k) = P_{gg,1h}(z, k) + P_{gg,2h}(z, k)$$

$$P_{gg,1h}(k) = \frac{1}{\bar{n}_g^2} \int dM \frac{dn}{dM} \bar{N}_c [\bar{N}_s^2 u_s^2(k) + 2\bar{N}_s u_s^2(k)]$$

$$P_{gg,2h}(k) = \left(\frac{1}{\bar{n}_g} \int dM \frac{dn}{dM} b_h(M) \bar{N}_c [1 + \bar{N}_s u_s(k)] \right)^2 P_{\text{lin}}(k)$$

HOD MODELING DETAILS

Redshift-dependent 6-parameter HOD model

$$\bar{N}_g(M) = \bar{N}_c(M)(f_c + \bar{N}_s(M))$$

centrals:
$$\bar{N}_c(M) = \frac{1}{2} \left[1 + \text{erf} \left(\frac{\log M - \log M_{\text{min}}(z)}{\sigma_{\ln M}} \right) \right]$$

satellites:
$$\bar{N}_s(M) = \Theta(M - M_0(z)) \left(\frac{M - M_0(z)}{M_1(z)} \right)^\alpha$$

where

$$\log M_i(z) = \mu_i + \mu_{i,p} \left(\frac{1}{1+z} - \frac{1}{1+z_p} \right), \quad i \in [\text{min}, 0, 1]$$

Fiducial model

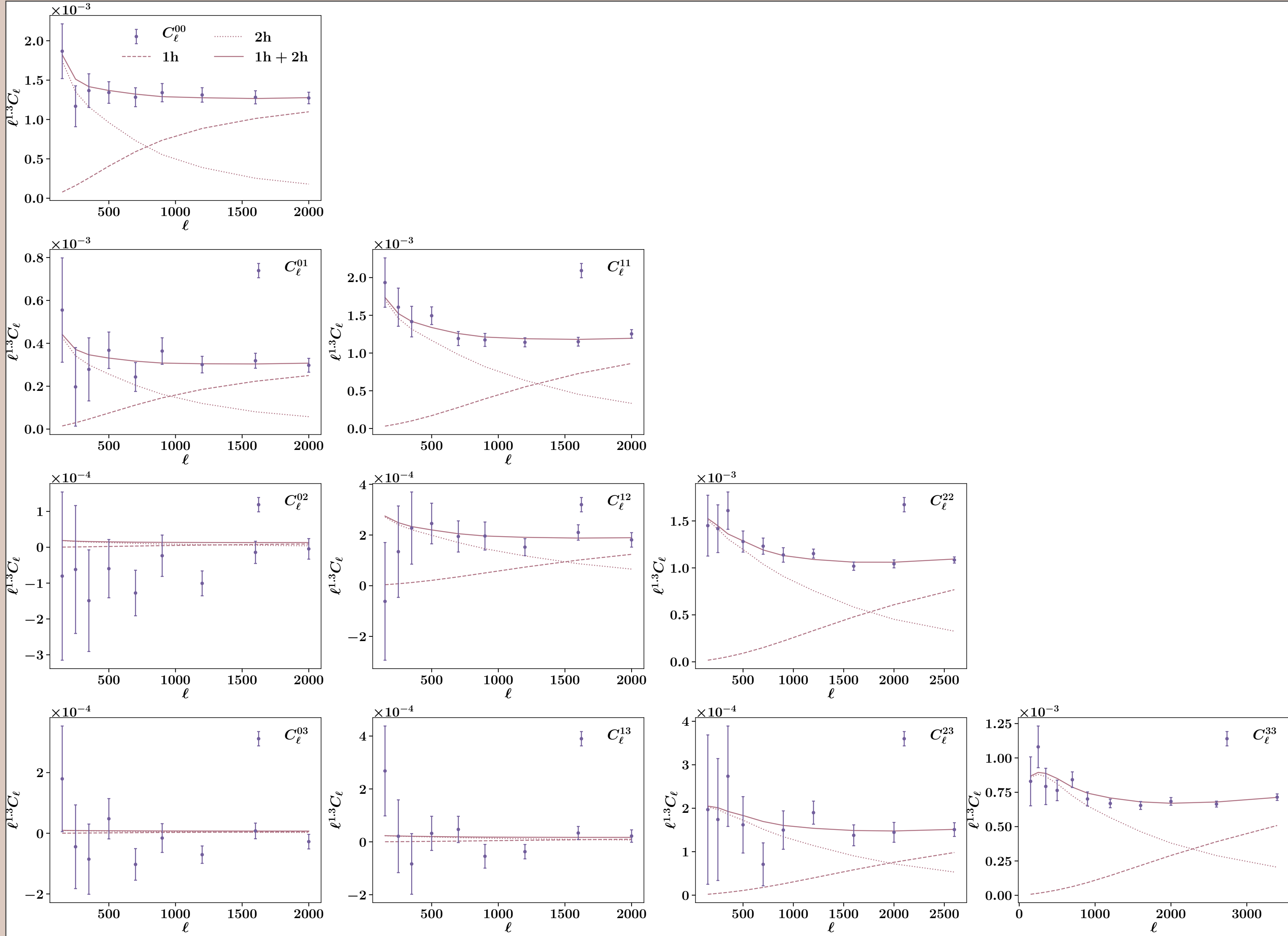
Redshift-dependent 3(+3)-parameter HOD: $M_{\text{min}}(z)$ $M_0(z)$ $M_1(z)$

Remaining HOD parameters fixed to $f_c = 1$ $\alpha = 1$ $\sigma_{\ln M} = 0.4$

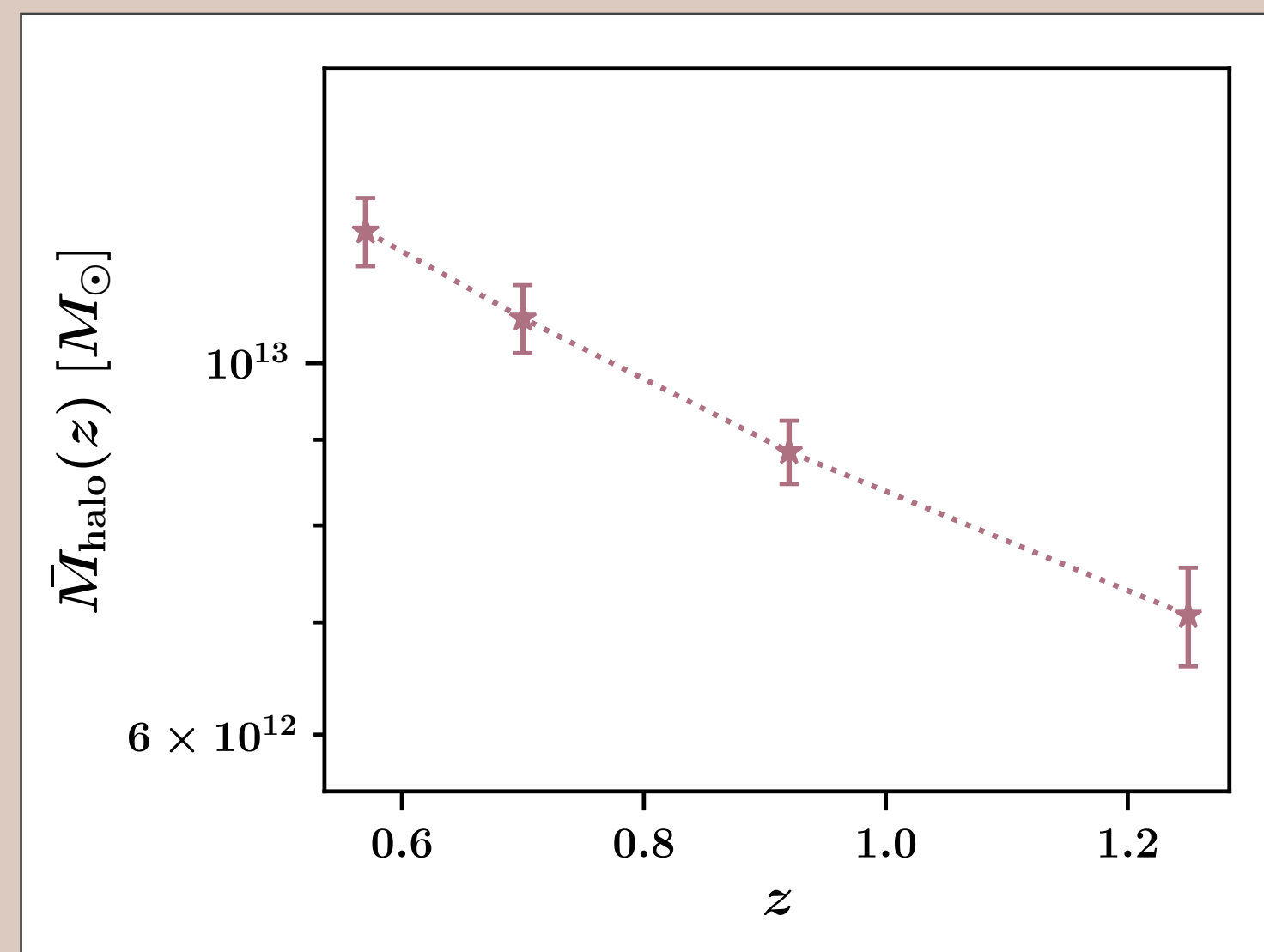
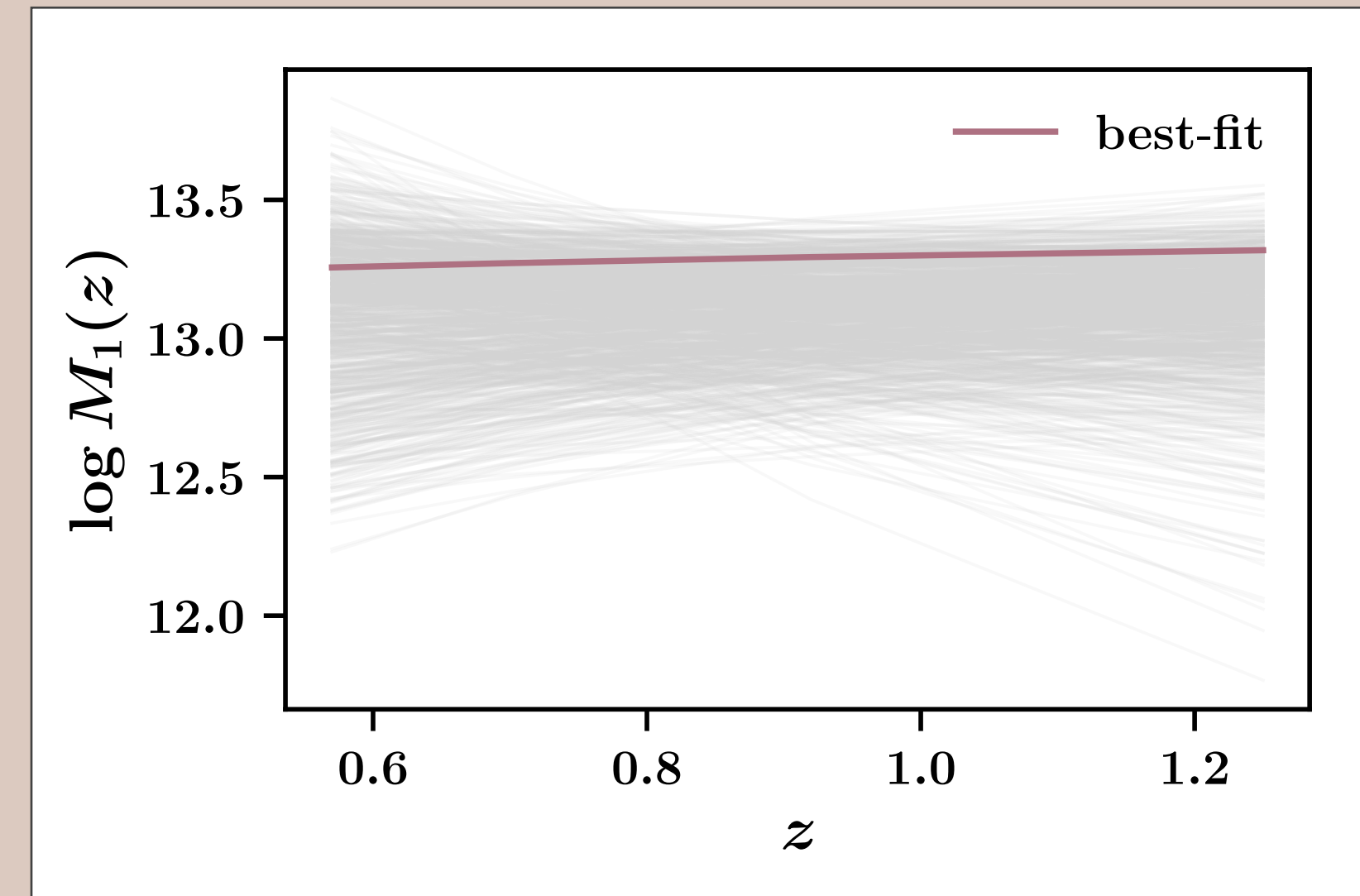
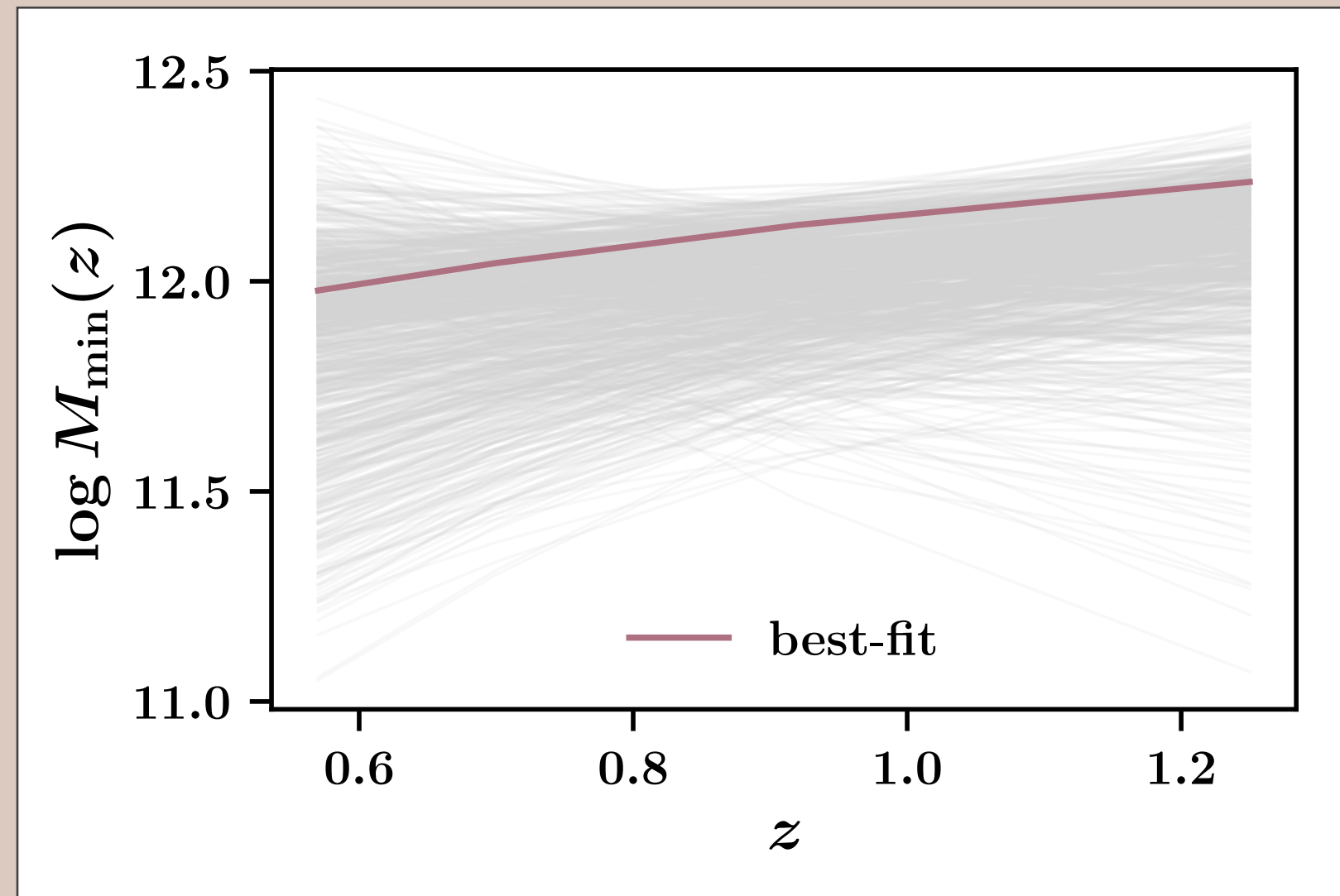
Cosmological parameters fixed to Planck 2018

Photo-z uncertainties: $p(z)$ shift Δz_i & width $z_{w,i}$

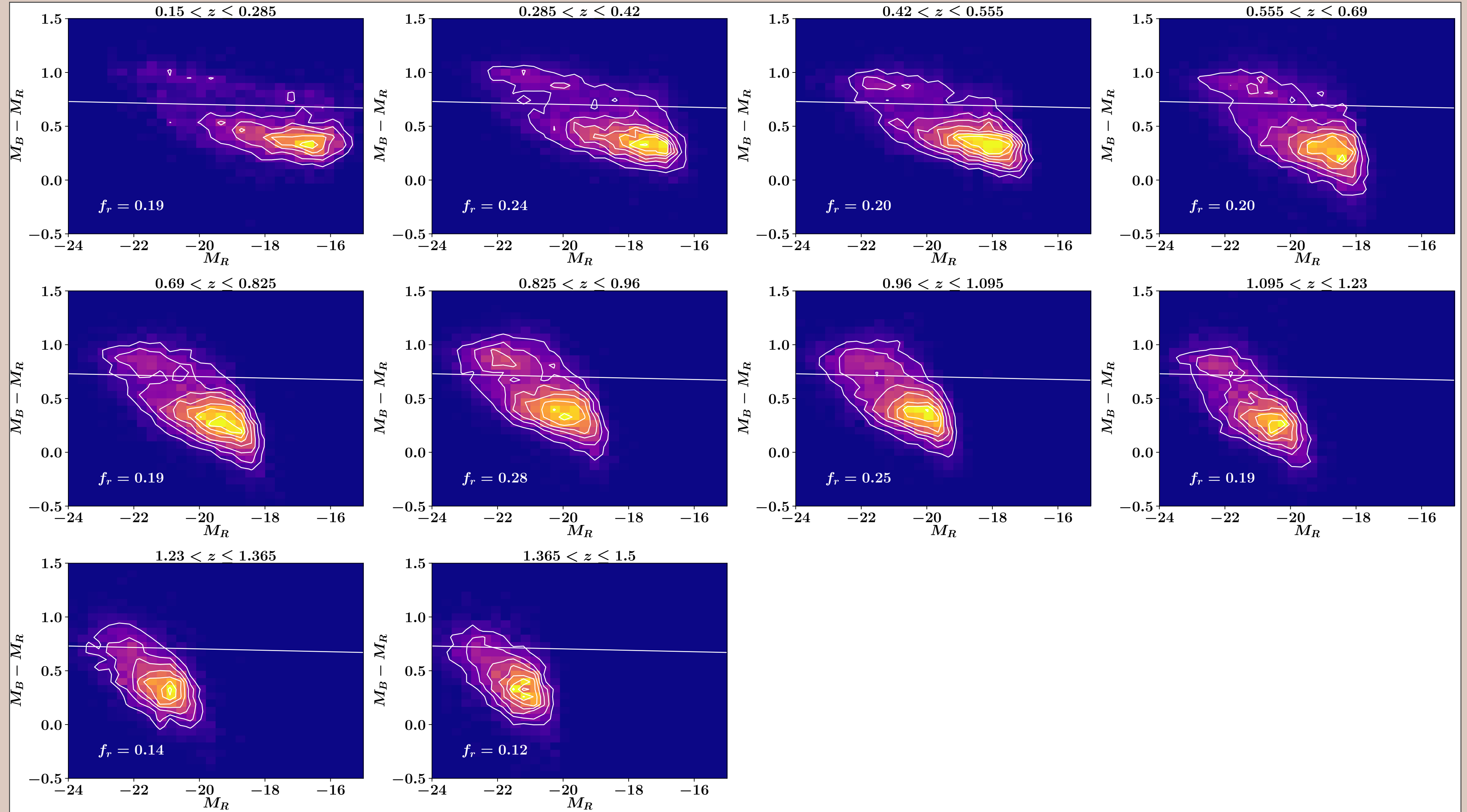
POWER SPECTRA



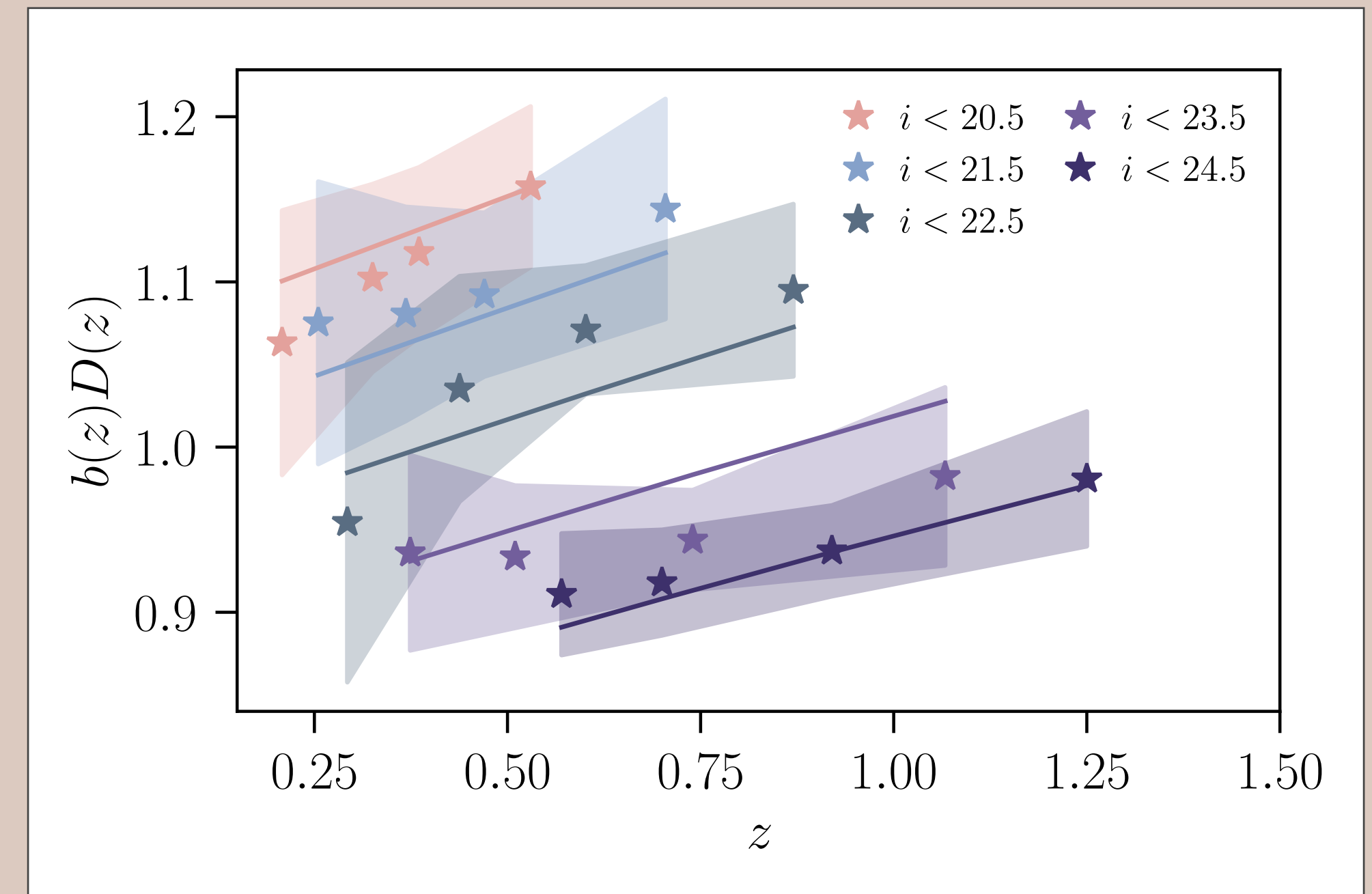
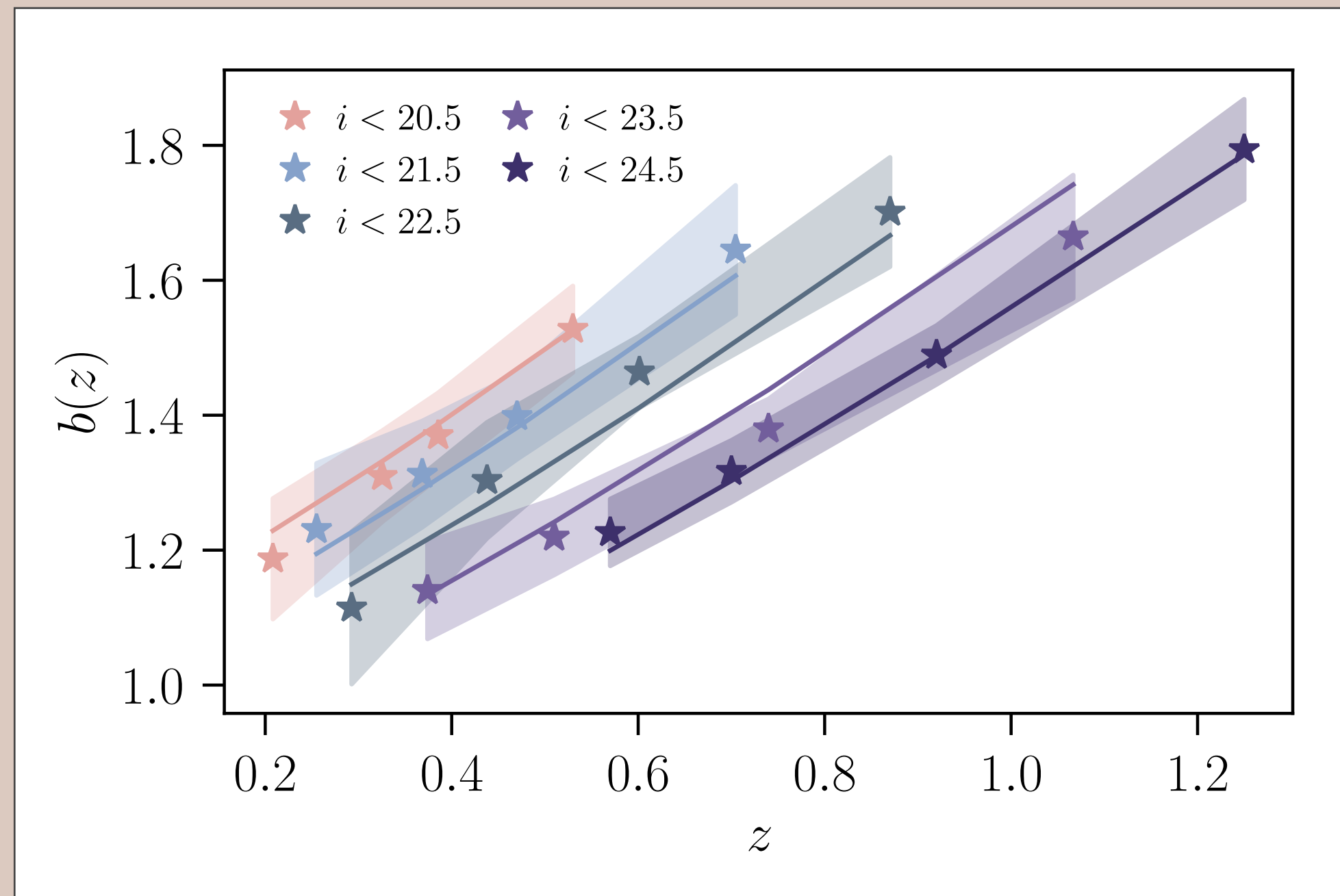
HOD REDSHIFT EVOLUTION



PROPERTIES OF GALAXY SAMPLE



GALAXY BIAS FOR MAGNITUDE-LIMITED SAMPLES



$$b(z, m_{\text{lim}}) = \bar{b}(m_{\text{lim}})D(z)^\alpha$$

THE LSST DESC BIAS CHALLENGE



PERTURBATIVE BIAS MODELING

Perturbative models:

$$1 + \delta_g = F[\partial_i \partial_j \Phi]$$

$$1 + \delta_g = 1 + b_1 \delta_m + \frac{b_2}{2!} (\delta_m^2 - \langle \delta_m^2 \rangle) + \frac{b_{s^2}}{2!} (s^2 - \langle s^2 \rangle) + b_{\nabla^2} \nabla^2 \delta_m + \varepsilon$$

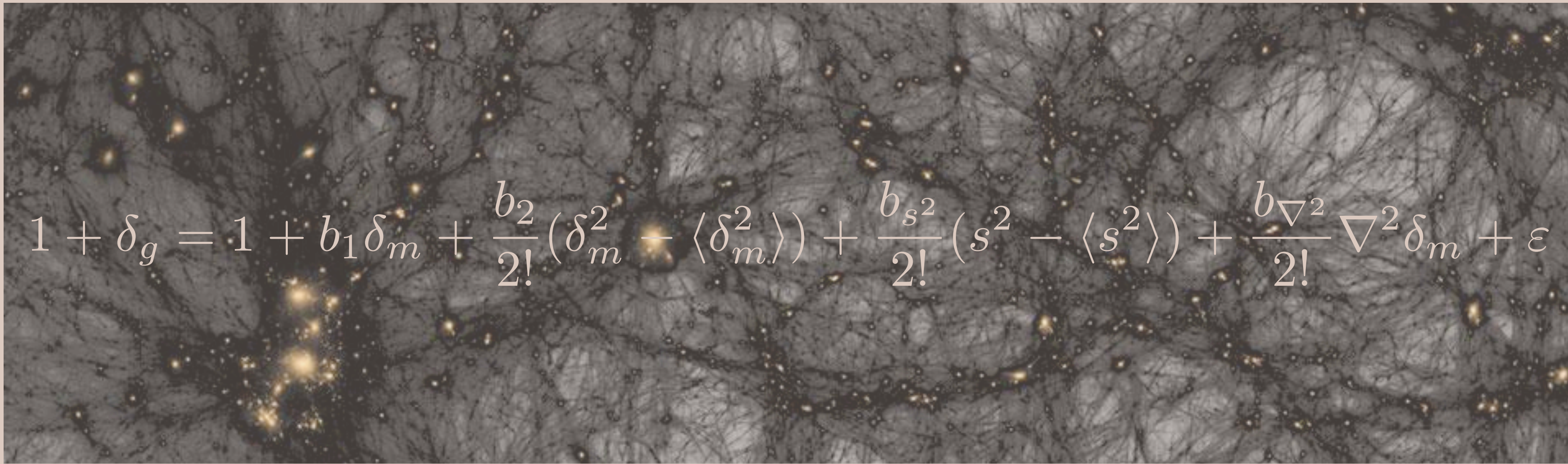
Model ingredients:

Perturbative expansion to second order

Non-local bias contribution

Stochastic component

MODELS CONSIDERED


$$1 + \delta_g = 1 + b_1 \delta_m + \frac{b_2}{2!} (\delta_m^2 - \langle \delta_m^2 \rangle) + \frac{b_{s^2}}{2!} (s^2 - \langle s^2 \rangle) + \frac{b_{\nabla^2}}{2!} \nabla^2 \delta_m + \varepsilon$$

Eulerian bias (*Bernardeau et al., 2002*)

Bias expansion at current time

Lagrangian bias (*Matsubara, 2008*)

Bias expansion at initial time then evolved using LPT

Hybrid Effective Field Theory (HEFT): anzu, BACCO (*Modi et al., 2020, Kokron et al., 2021, Zennaro et al., 2021*)

Bias expansion at initial time then evolved using N-body simulations

SYNTHETIC DATA



3D power spectra from AbacusSummit

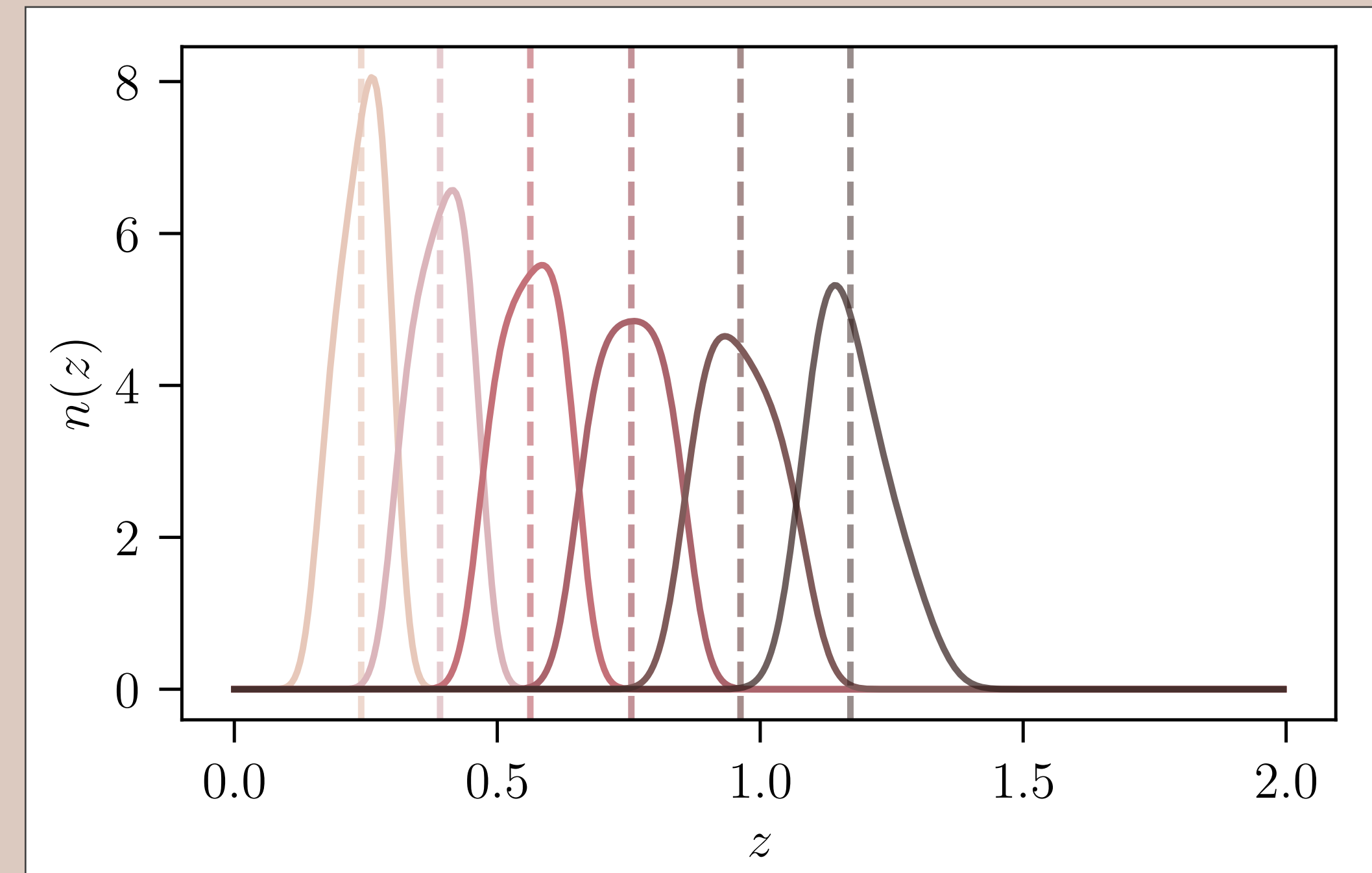
Limber-projection to obtain C_ℓ s

Observables:

3x2pt from LSST Y10

CMB lensing from CMB S4

Galaxy clustering sample: red (DESI-like LRGs)



Maksimova et al., 2021

ASSESSING MODEL PERFORMANCE

Determine best-fit through χ^2 minimization

Uncertainties from Fisher matrix

Goodness of fit: $\chi^2 = \chi^2_{\min} + N_{\text{dof}}$

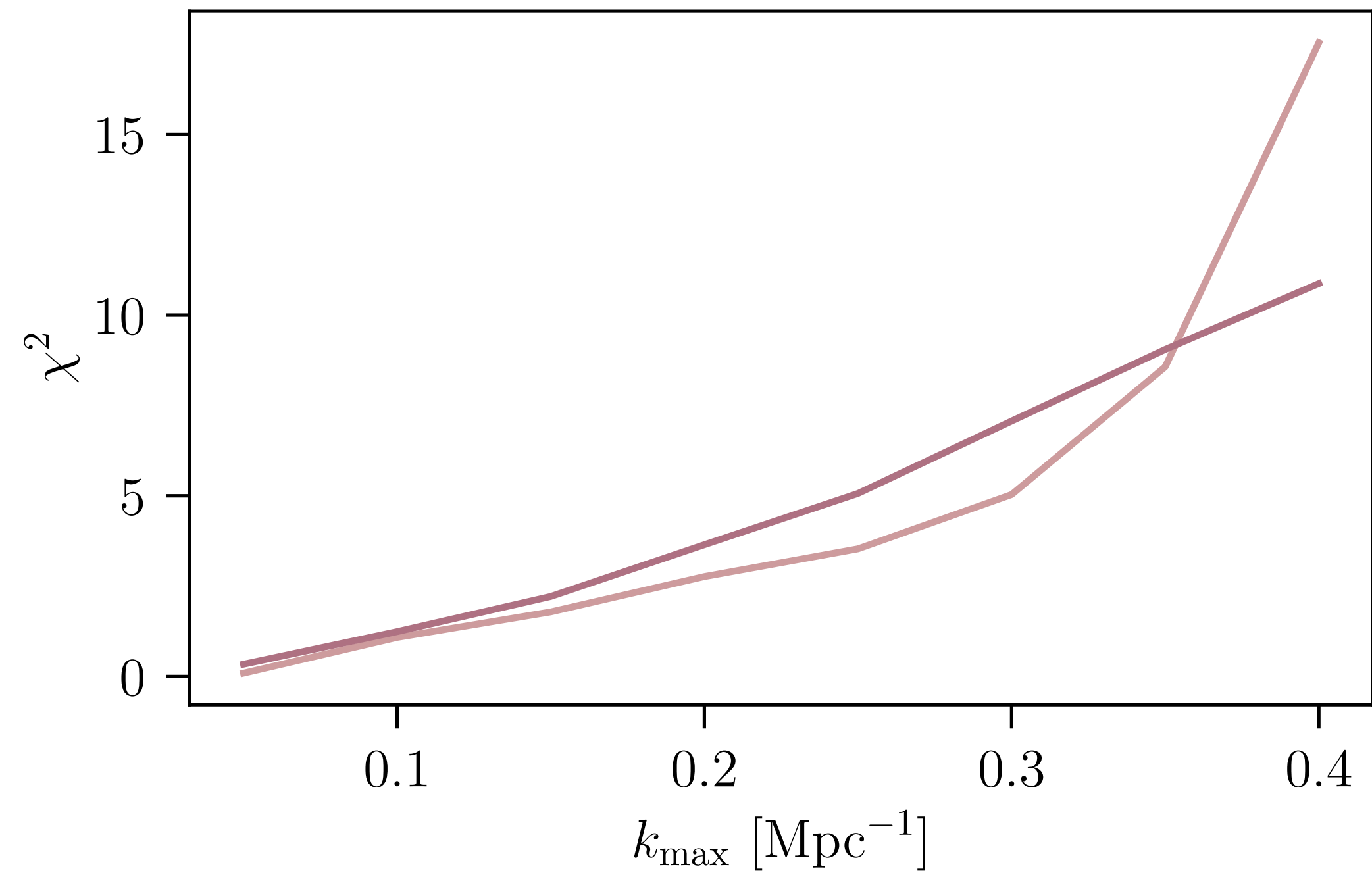
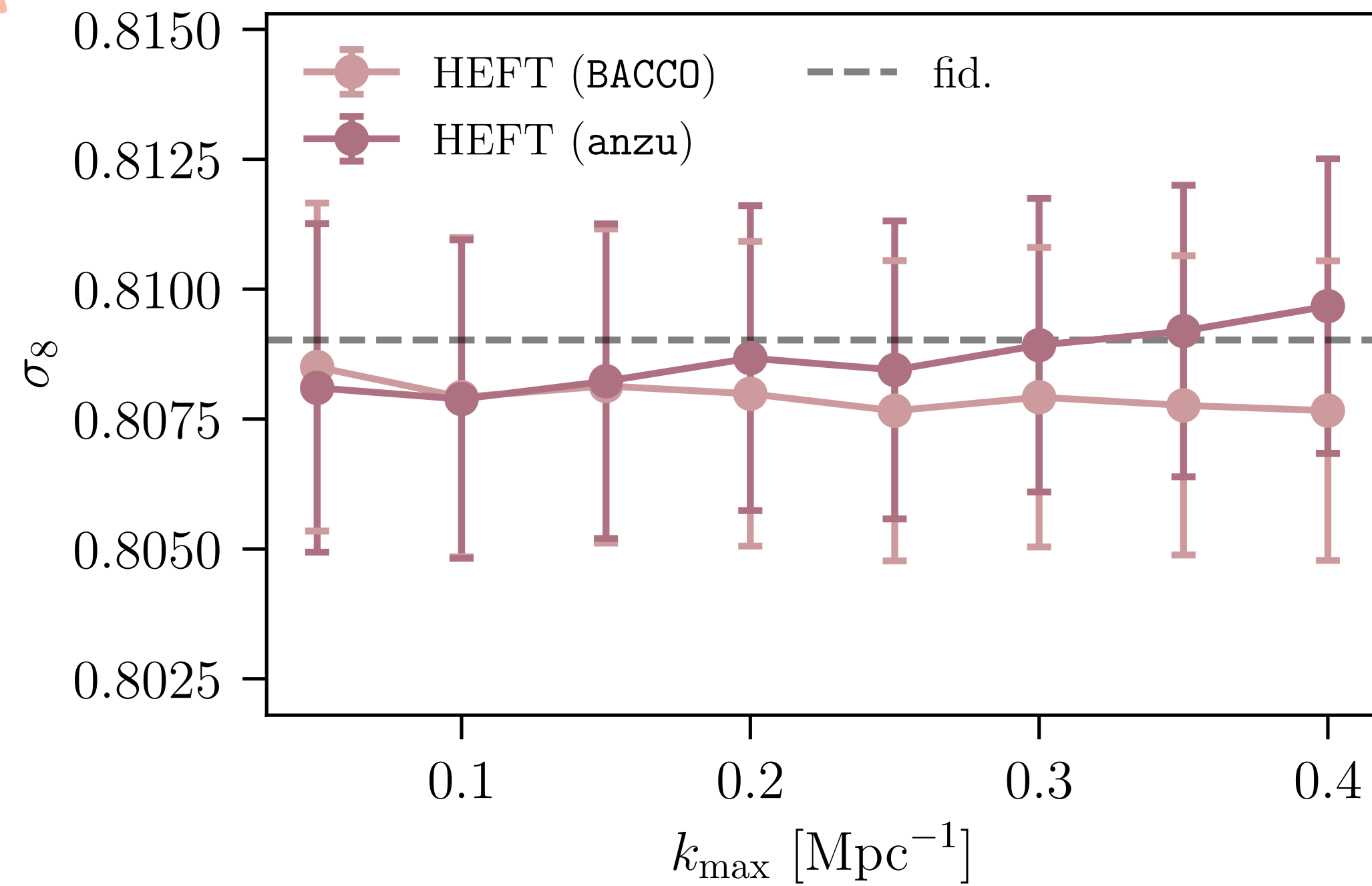
PTE > 0.05

Check against Gaussian realizations



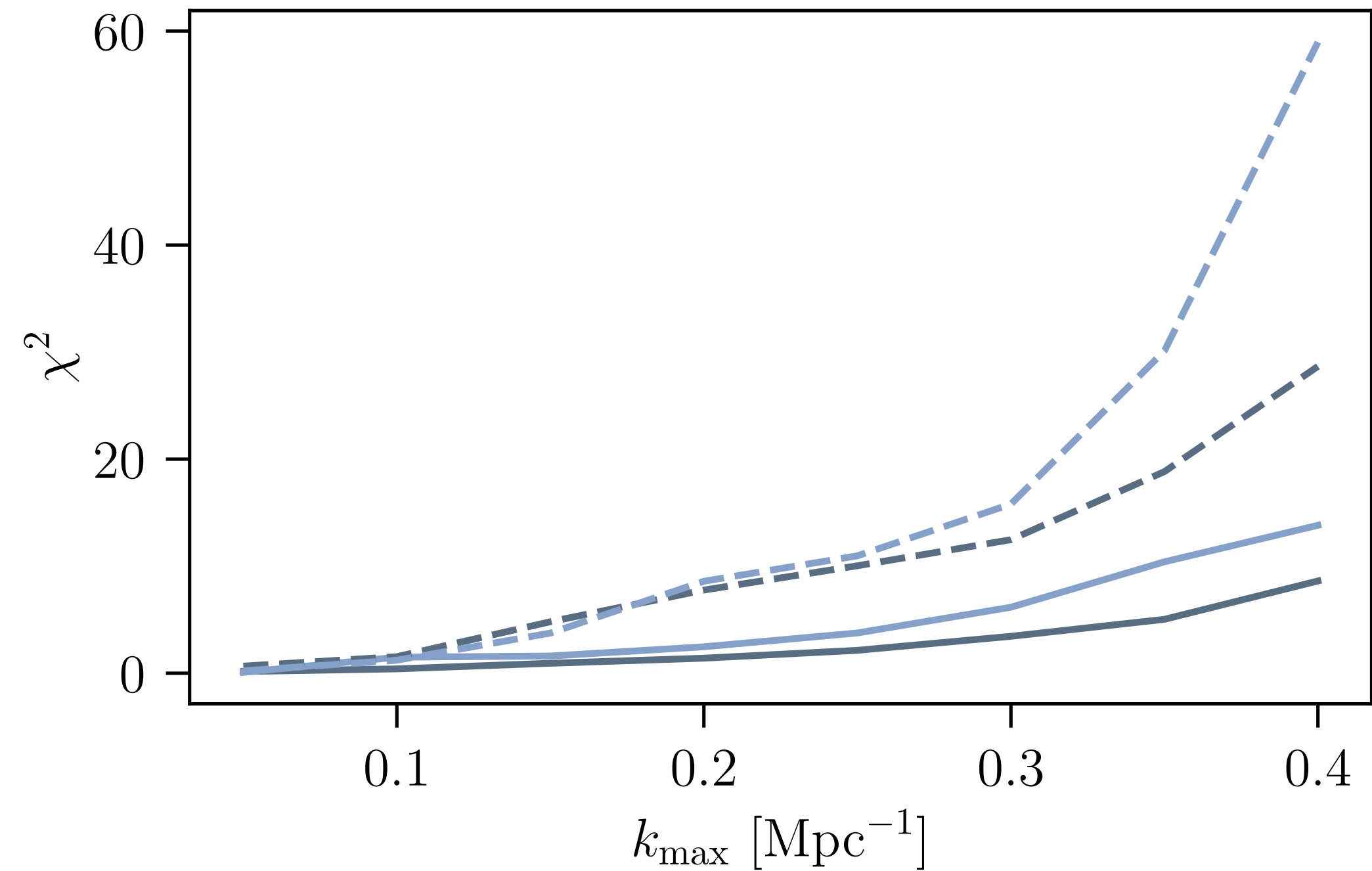
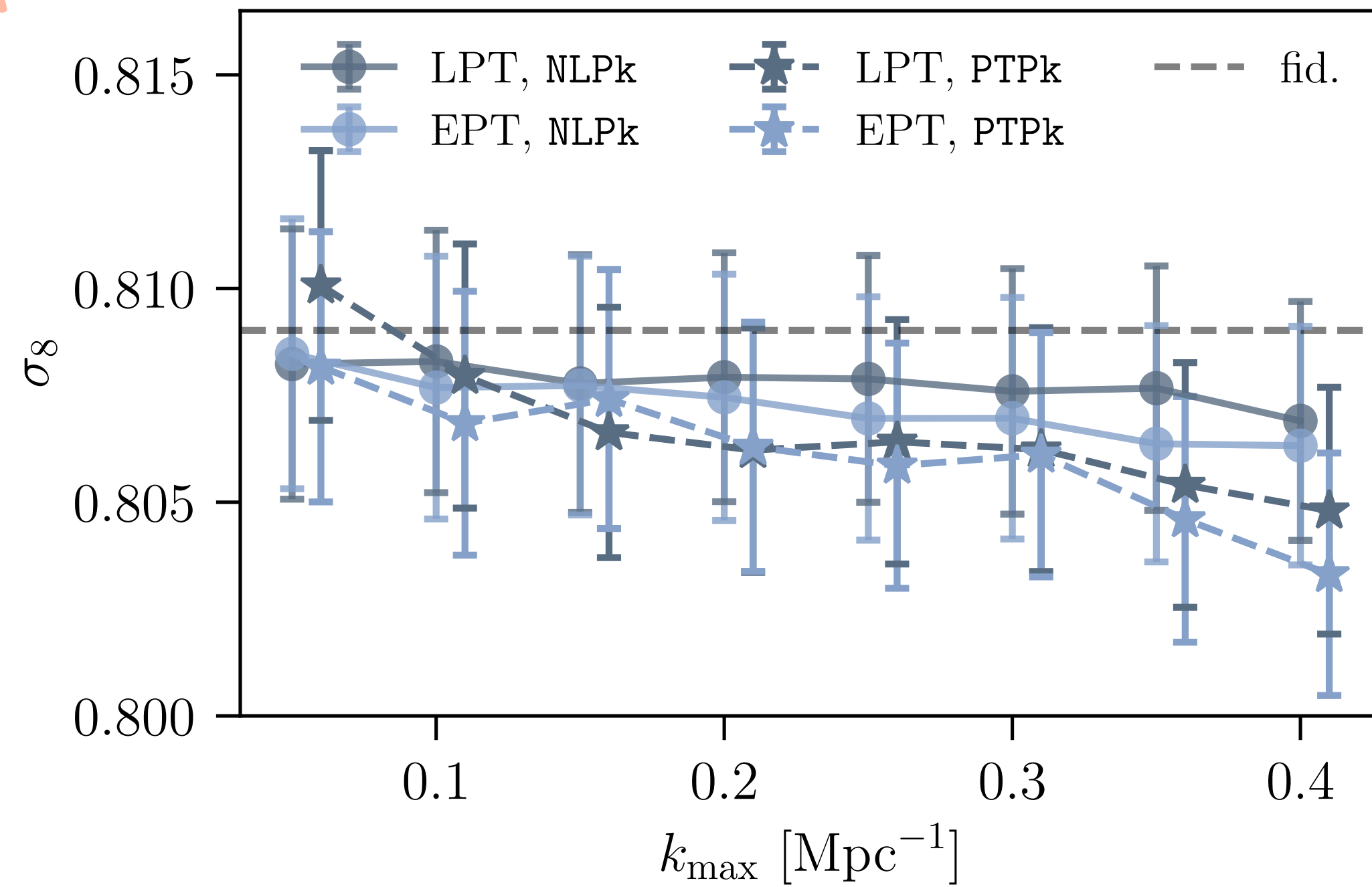
RED SAMPLE WITH HEFT

Preliminary



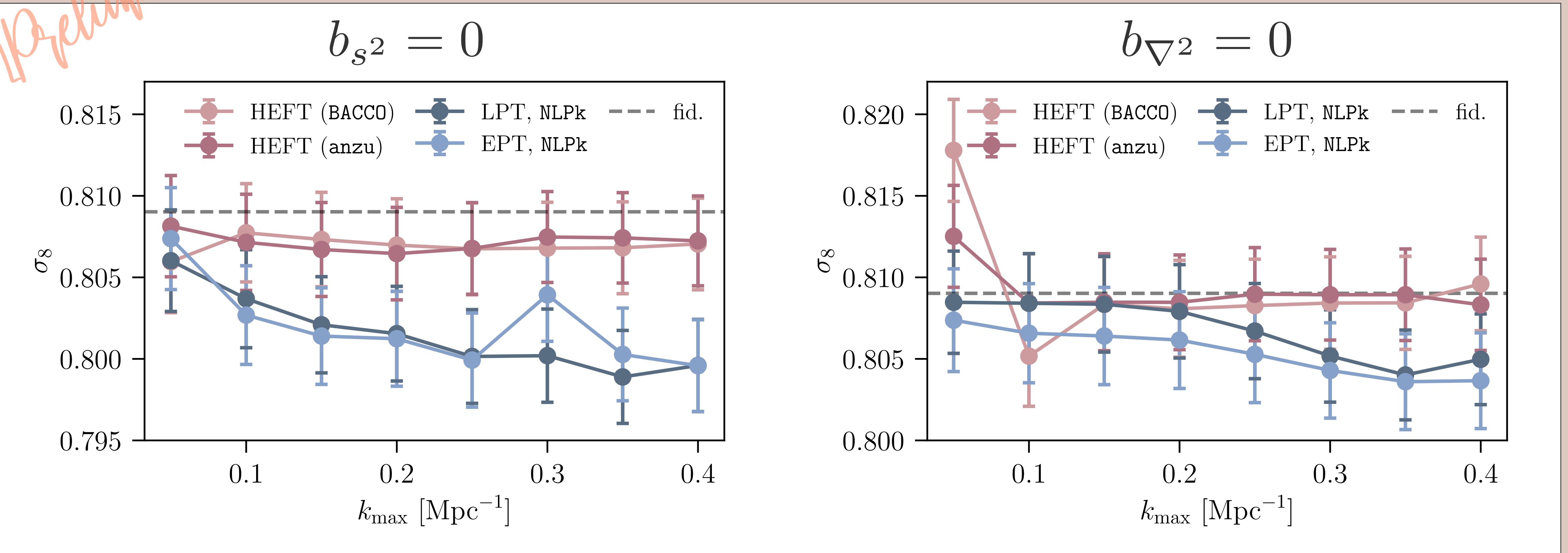
RED SAMPLE WITH EPT/LPT

Preliminary



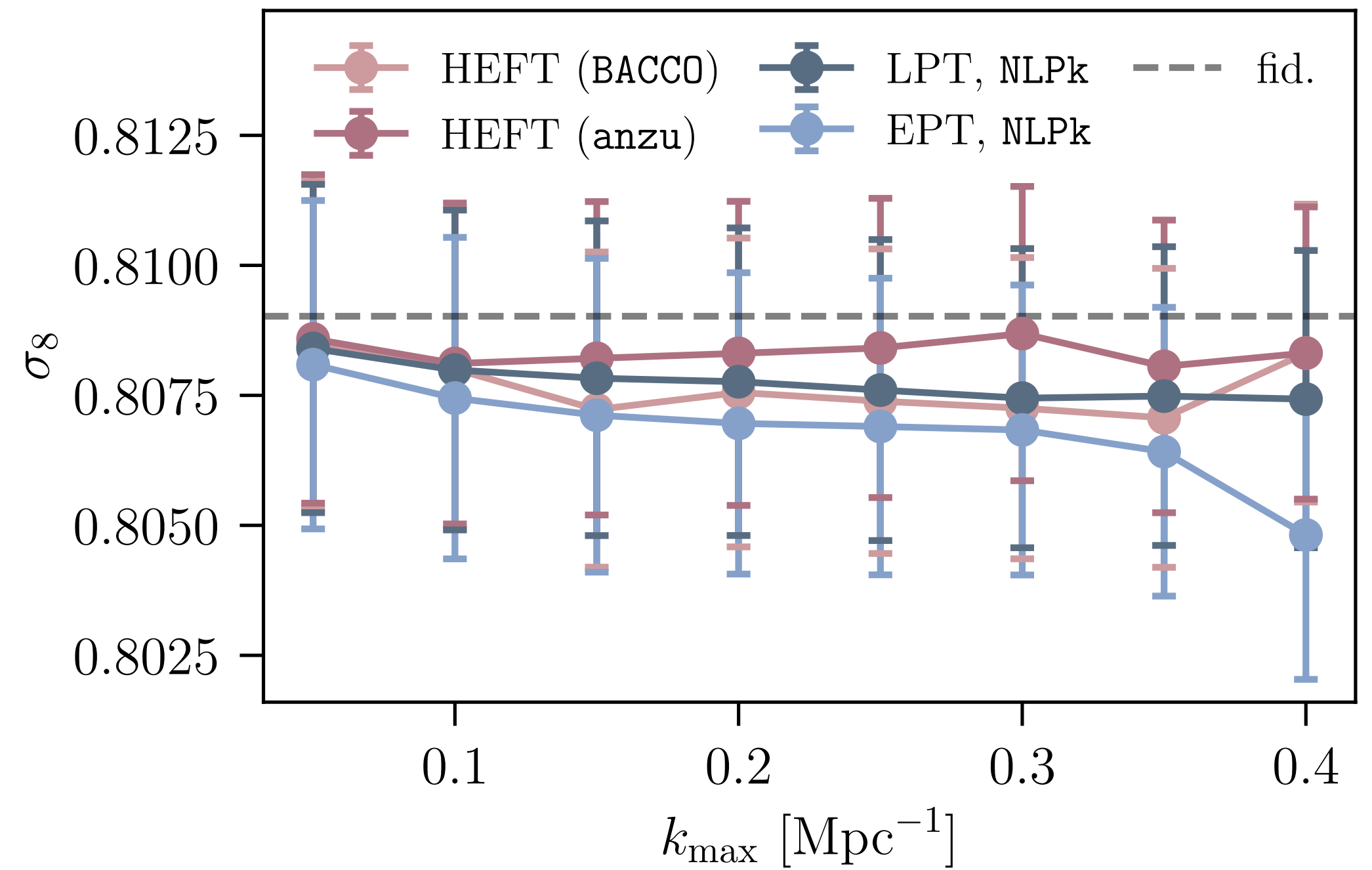
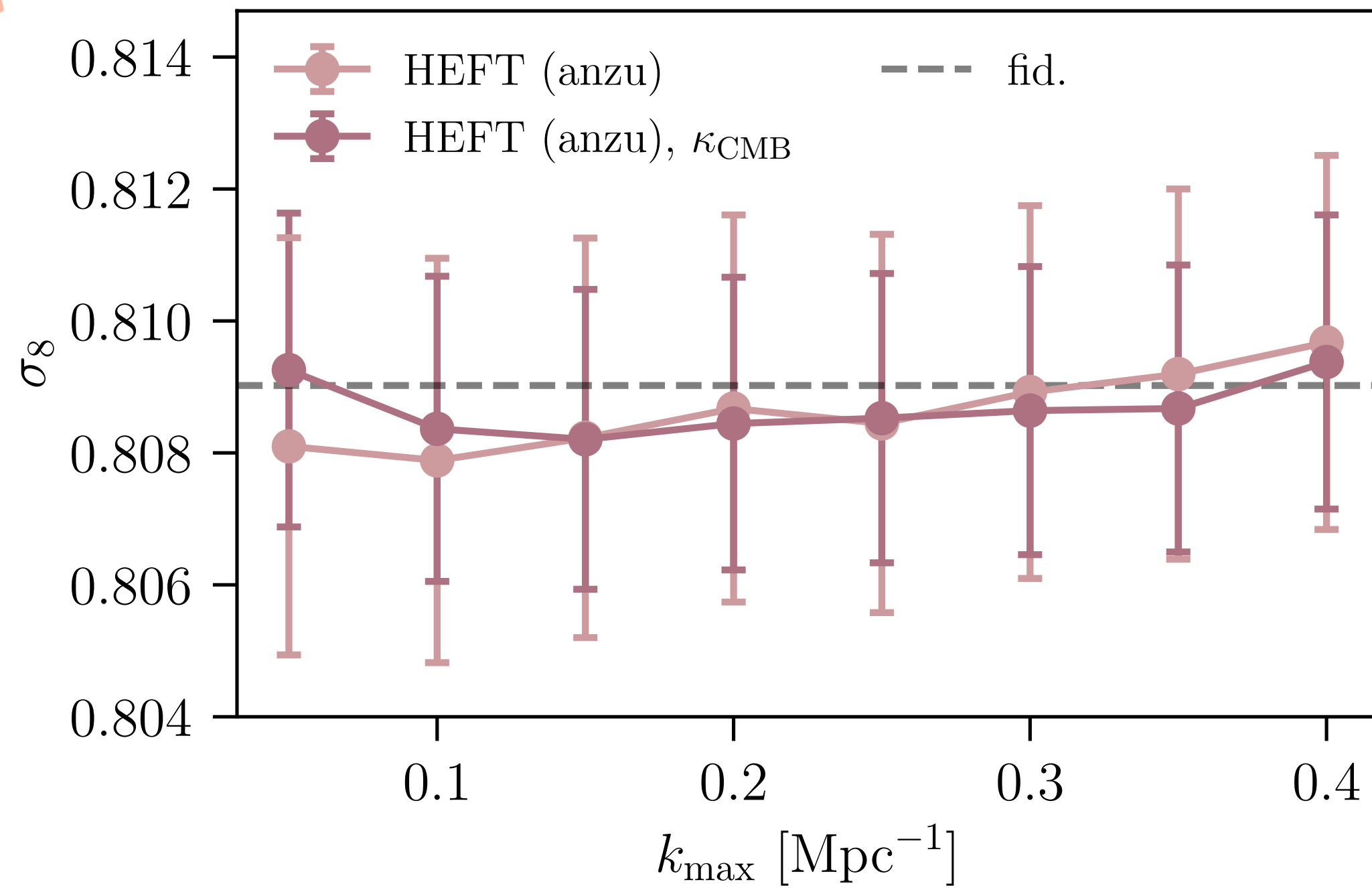
RED SAMPLE WITH REDUCED BIAS MODEL

Preliminary



ALTERNATIVE RED SAMPLES

Preliminary



Nicola et al., in prep.

MOVING BEYOND TRADITIONAL METHODS

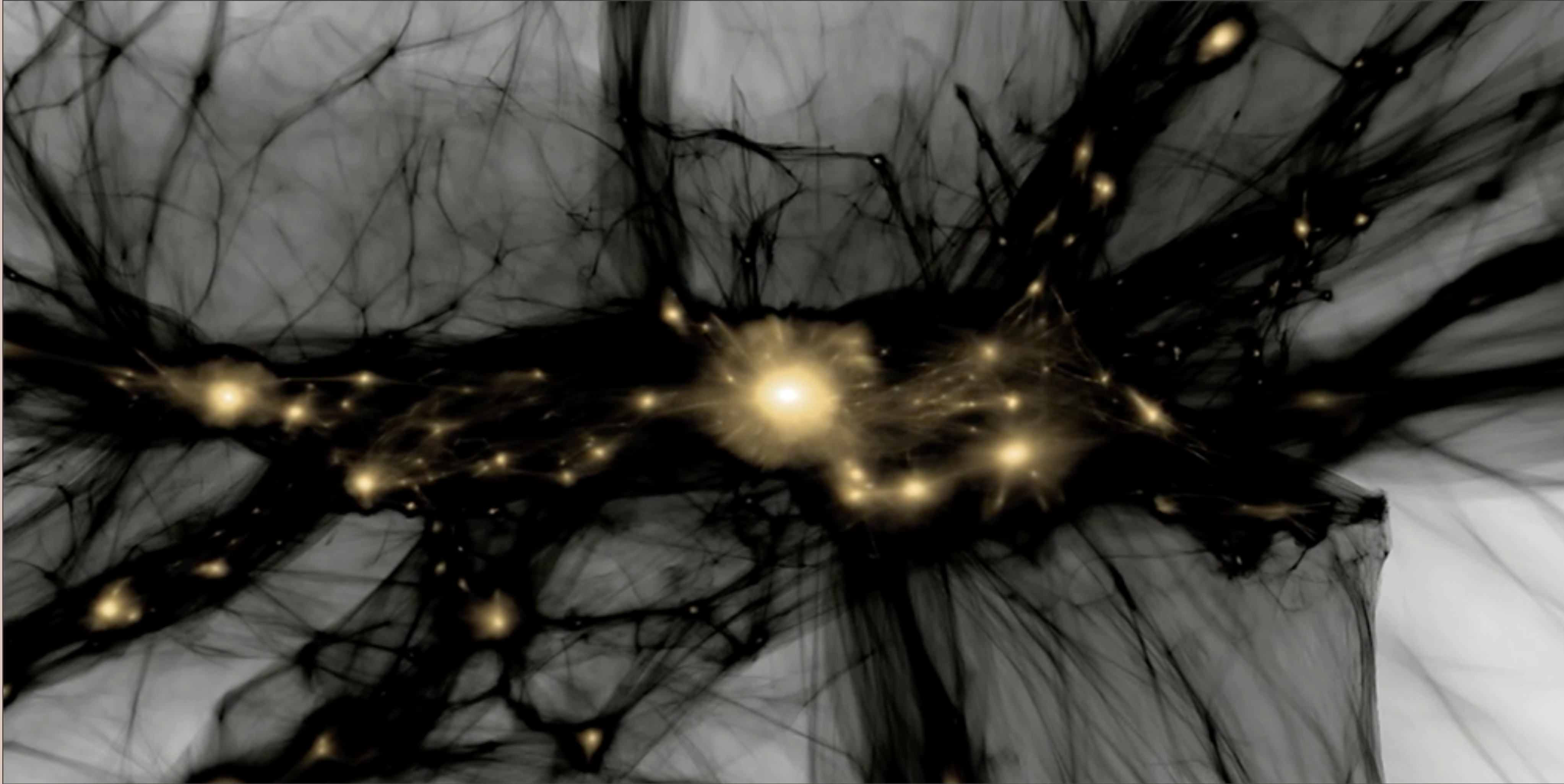


Image: S. Skillman, Y-Y. Mao, KIPAC/SLAC National Accelerator Laboratory

THE COSMOLOGICAL DATA REVOLUTION



Images: DESI, Euclid, SO, Rubin/LSST, Roman, CMB S4, Freepik

UNCOVERING THE MYSTERIES OF Λ CDM WITH FUTURE SURVEYS



SUMMARY

Future surveys will deliver high-precision data

- Significant information in small-scales, non-Gaussian features

- Limited by experimental & theoretical systematics

Galaxy clustering: preparation for LSST

- Analysis of precursor data

- Nonlinear galaxy bias

Future

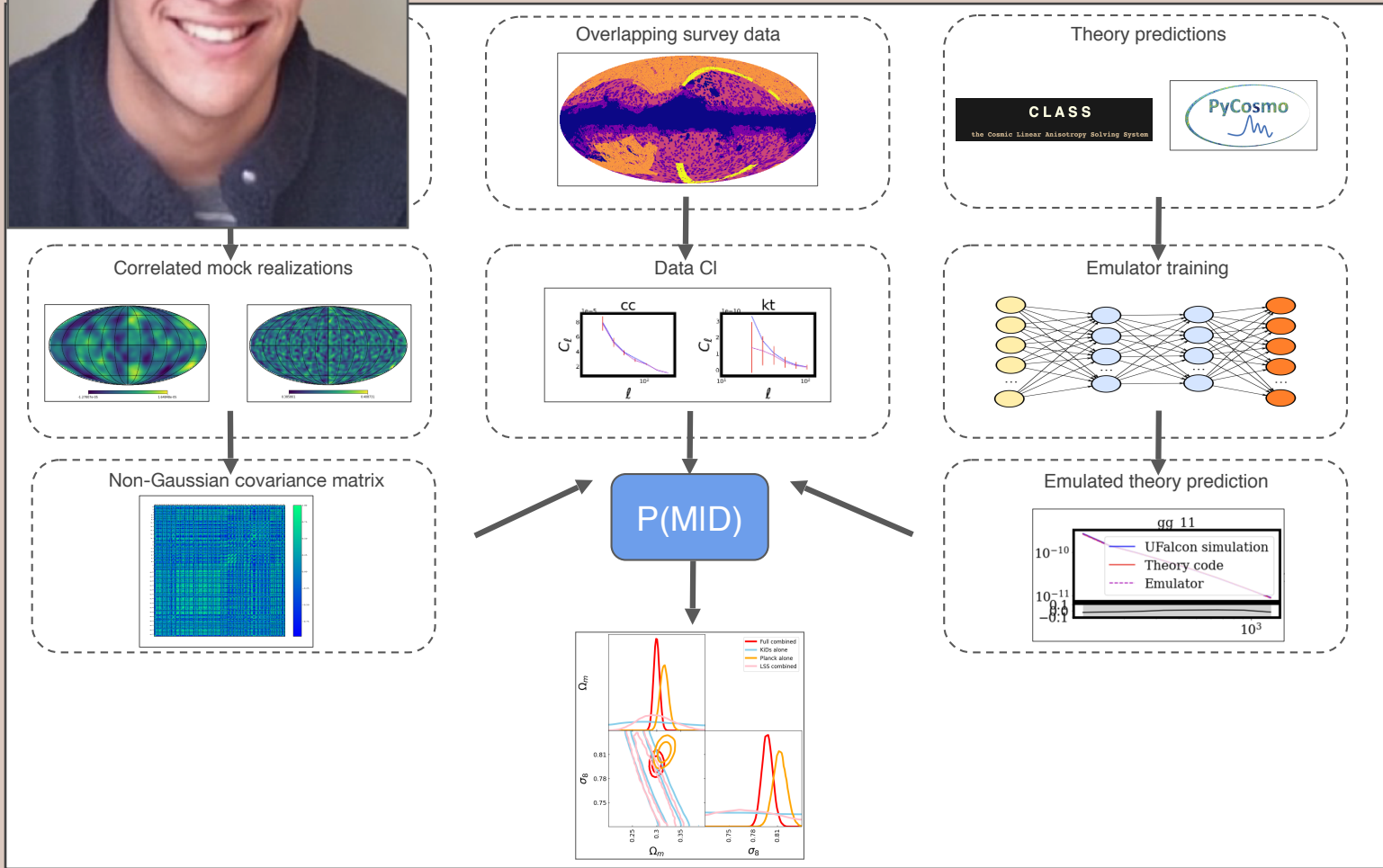
- Higher-order statistics

- Simulation-based inference

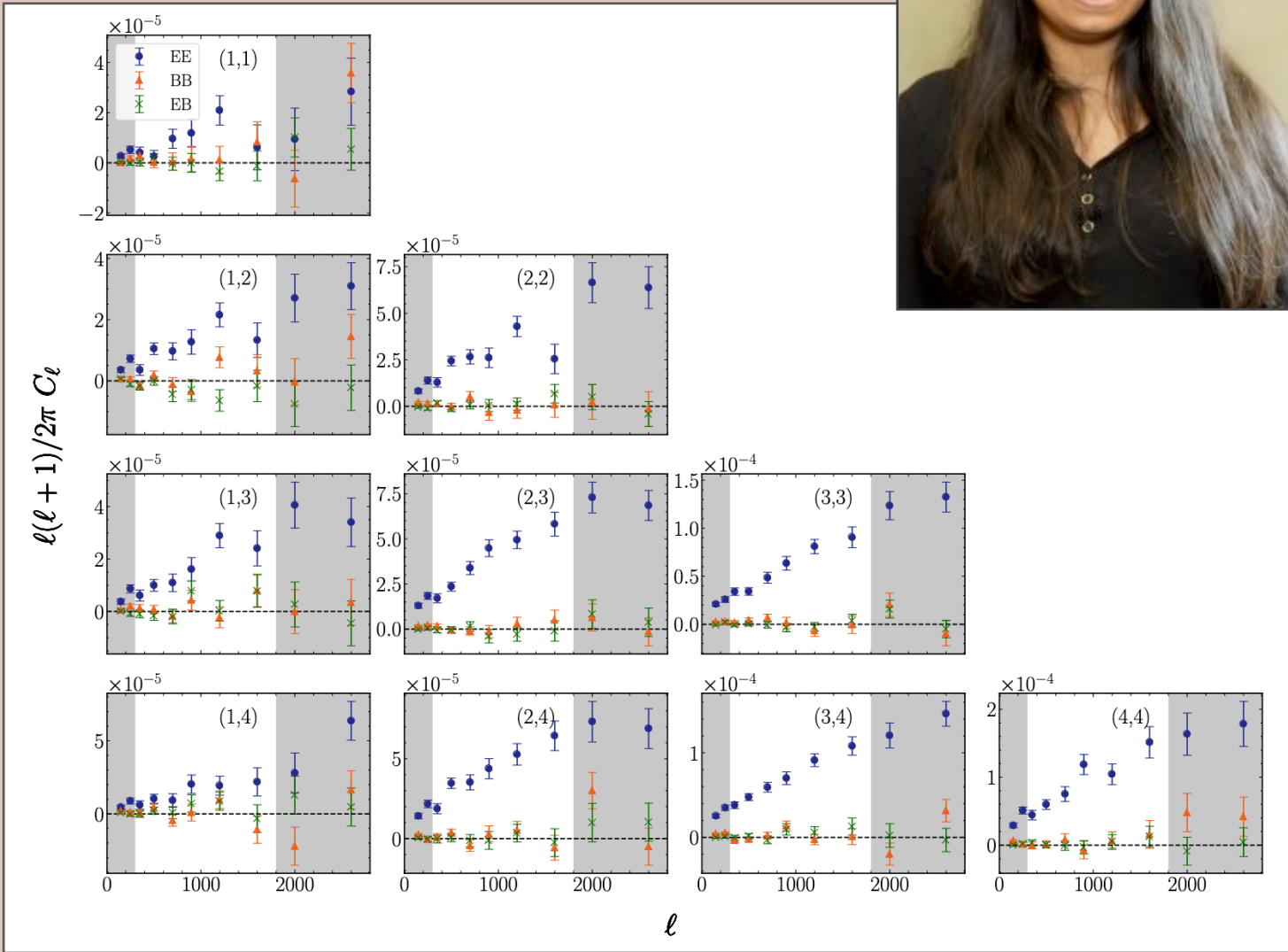
SOME OF THE THINGS I DIDN'T TALK ABOUT...



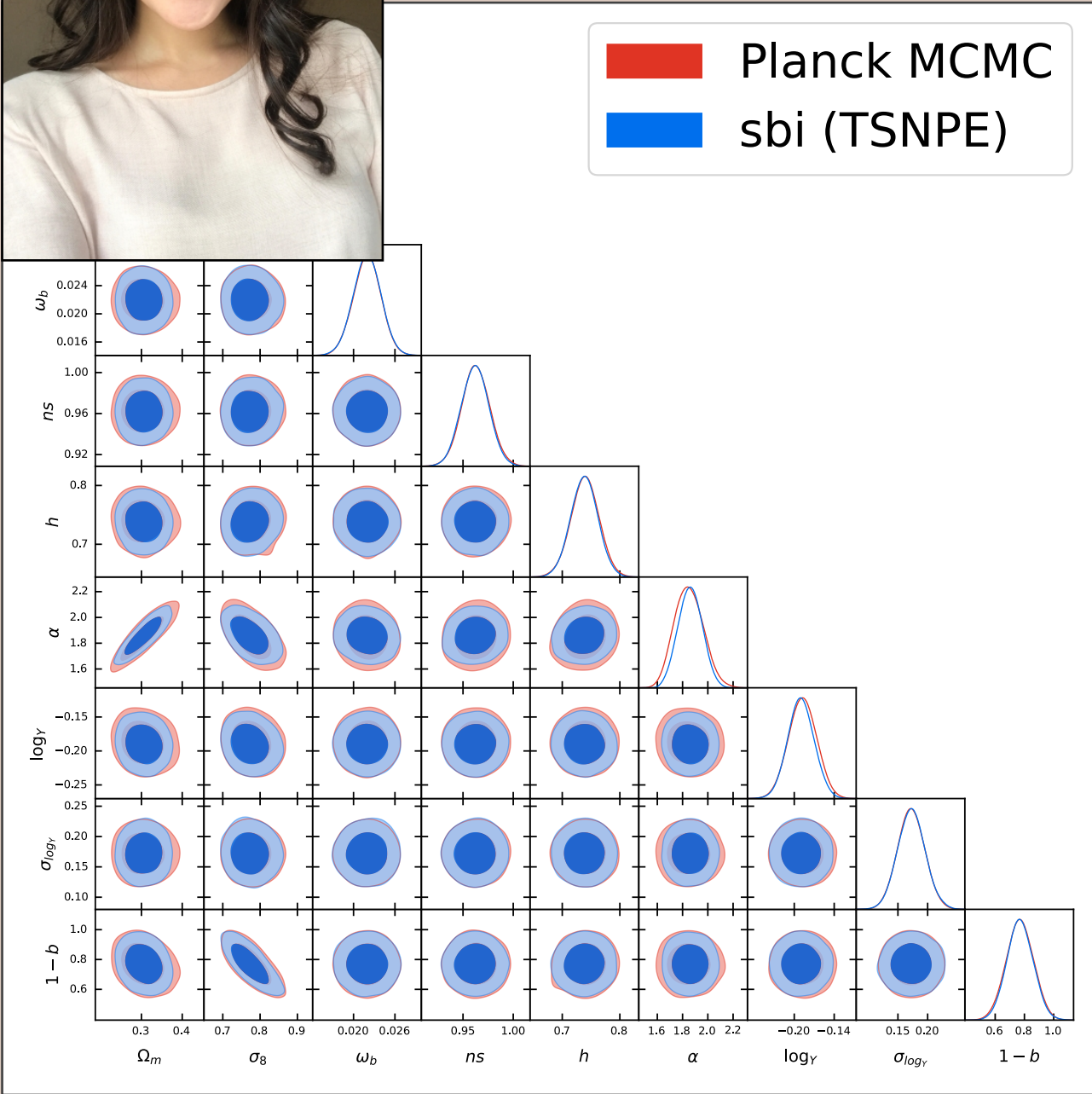
Alex Reeves - ETH Zürich



Roohi Dalal - Princeton

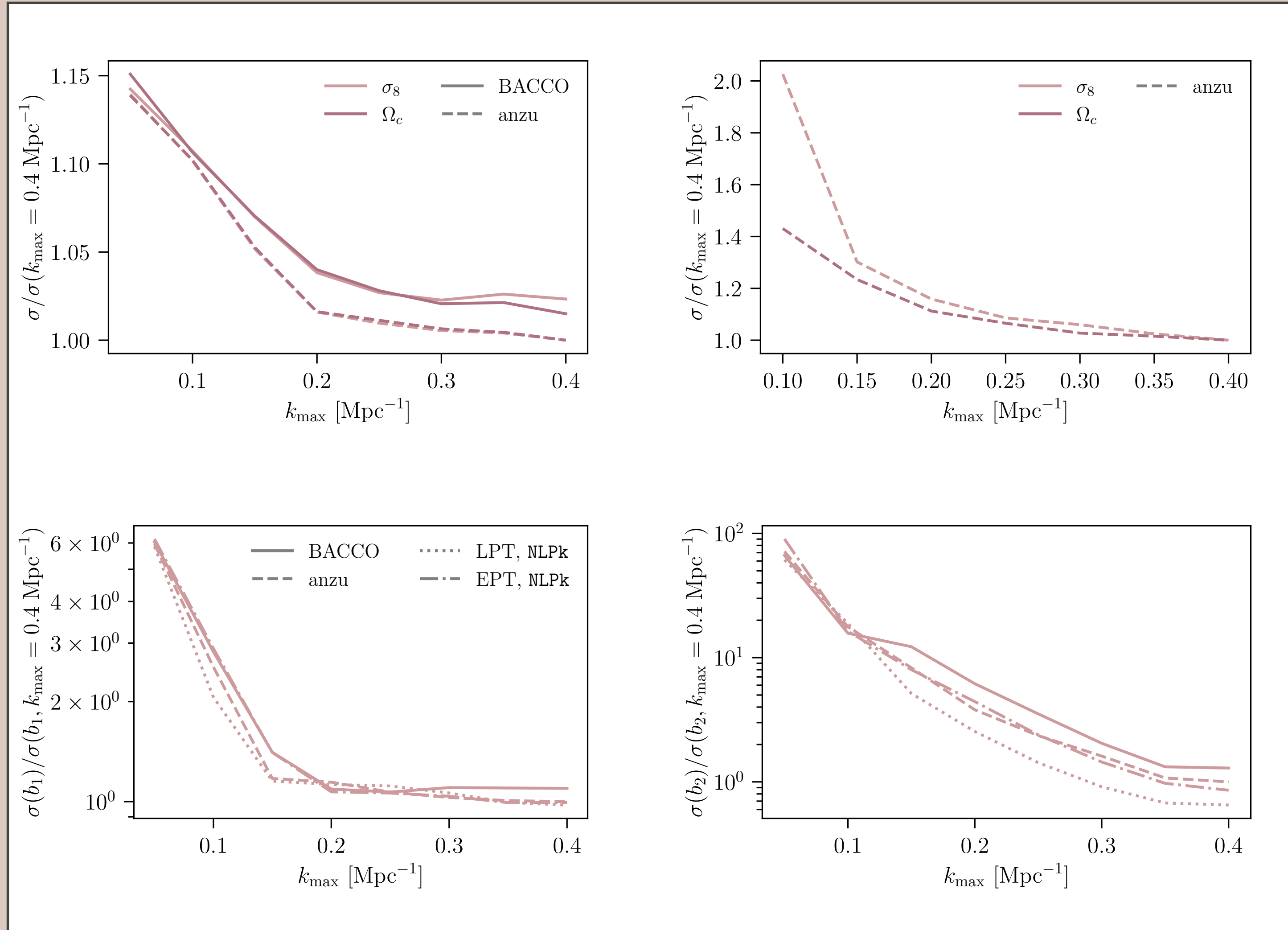


Aizhan Akhmetzanova - Harvard



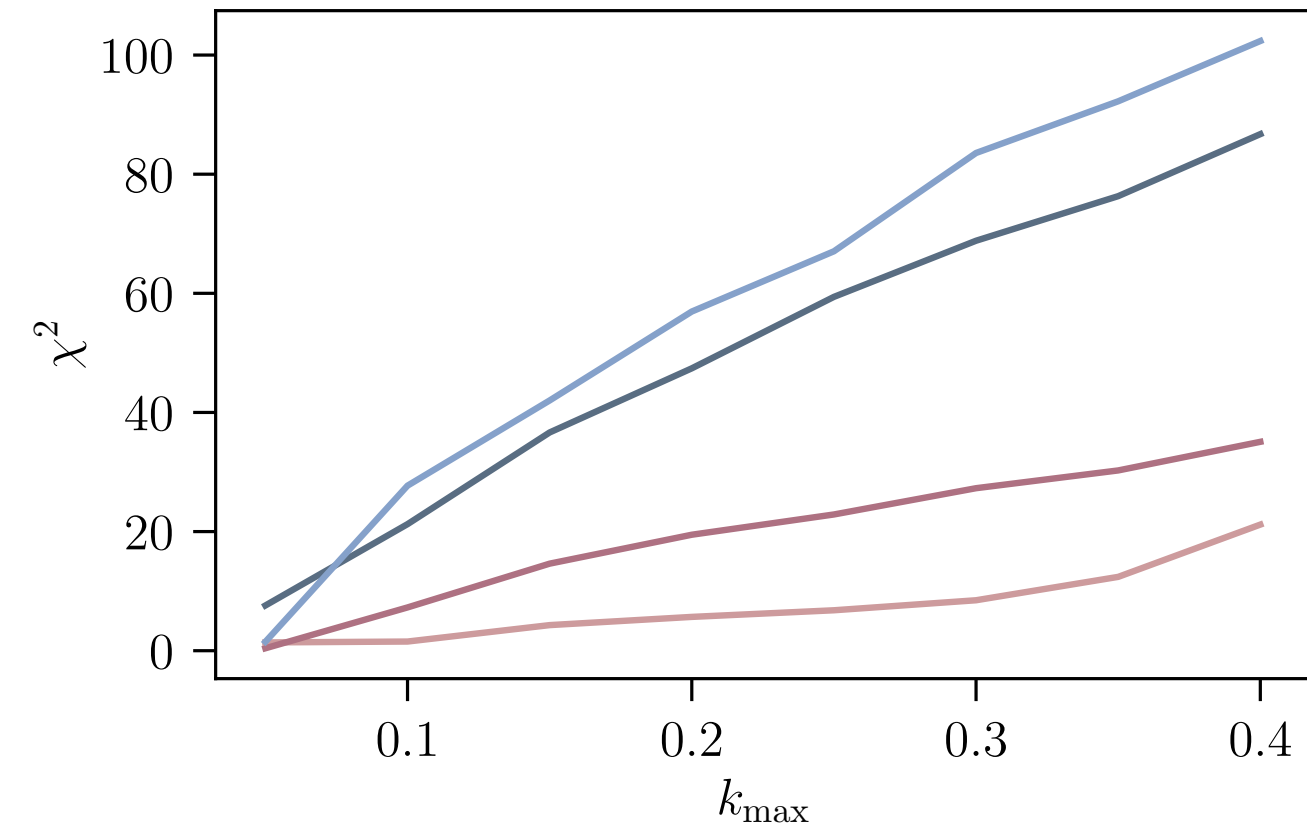
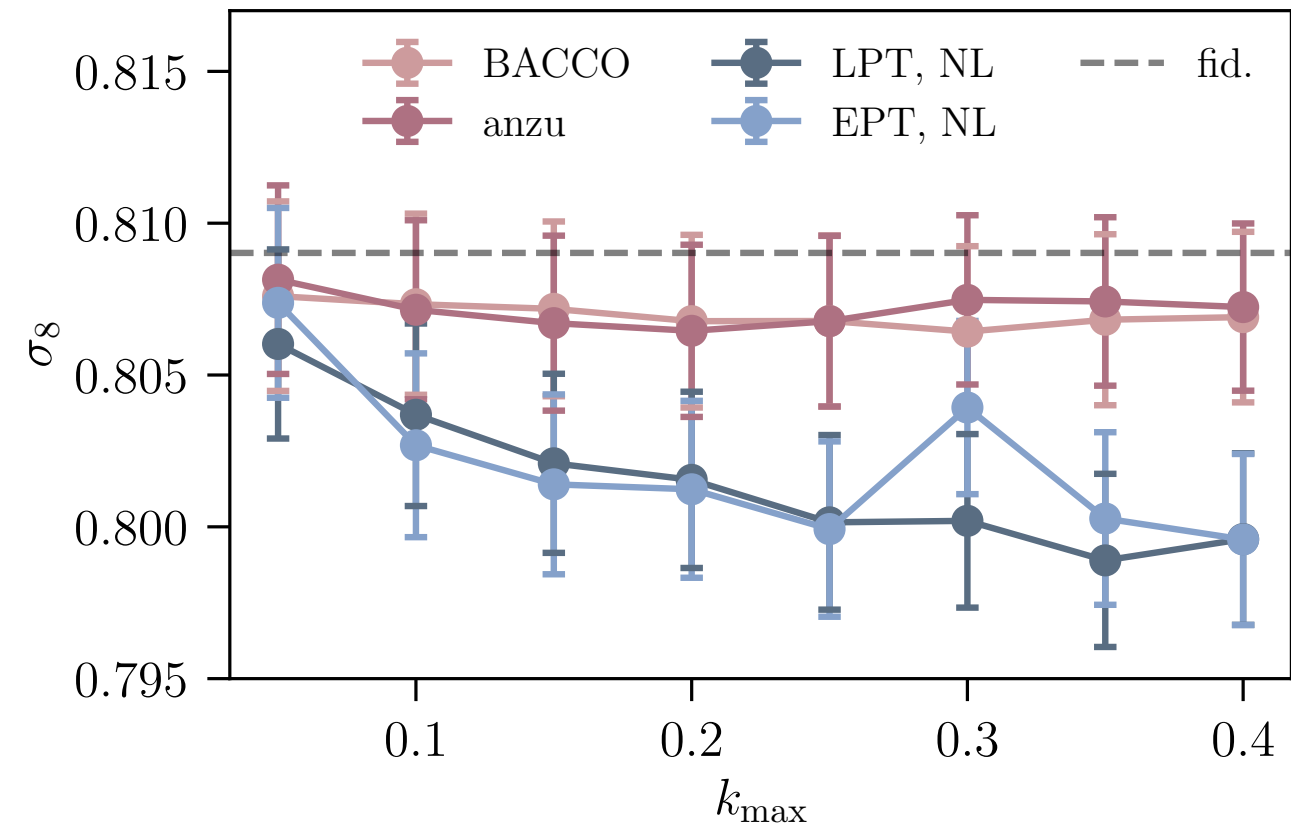
BACKUP SLIDES

ERROR AS A FUNCTION OF MINIMAL SCALE

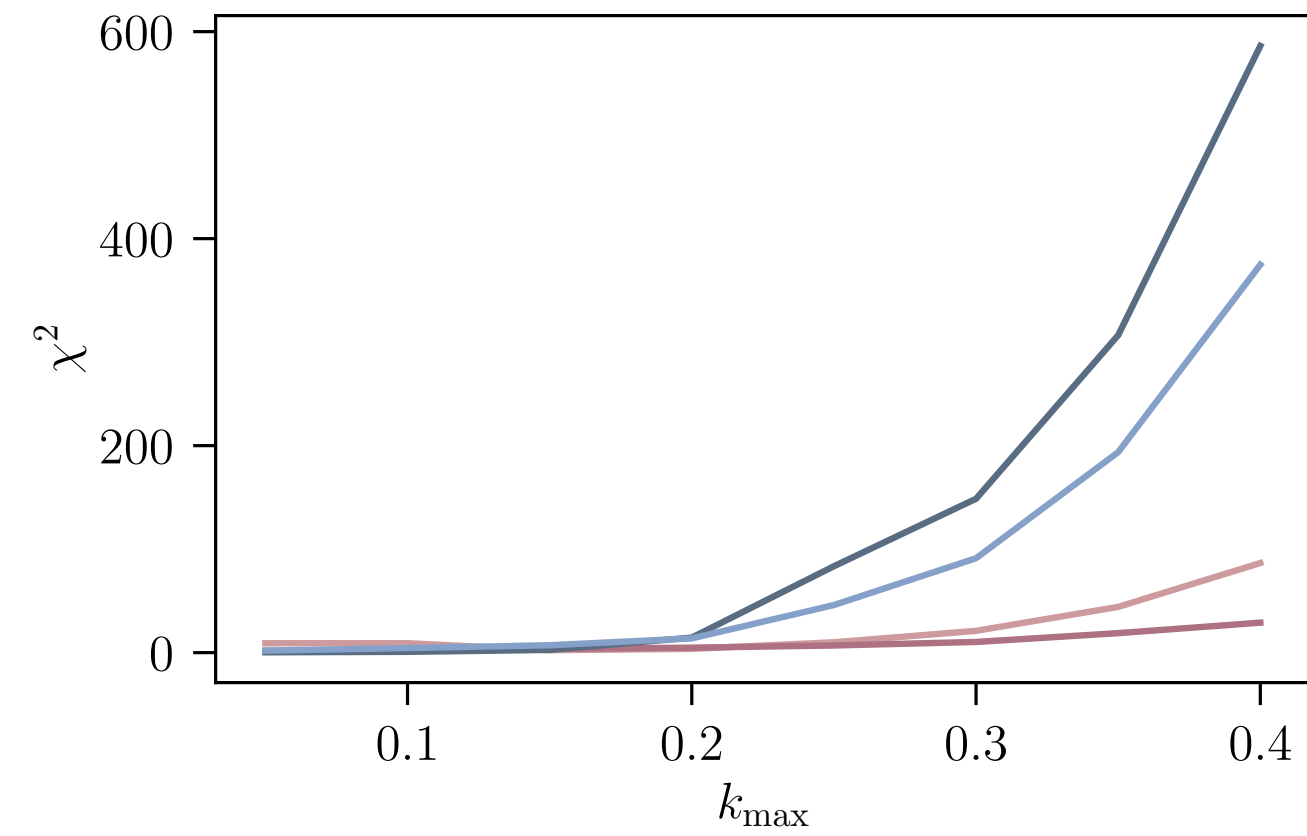
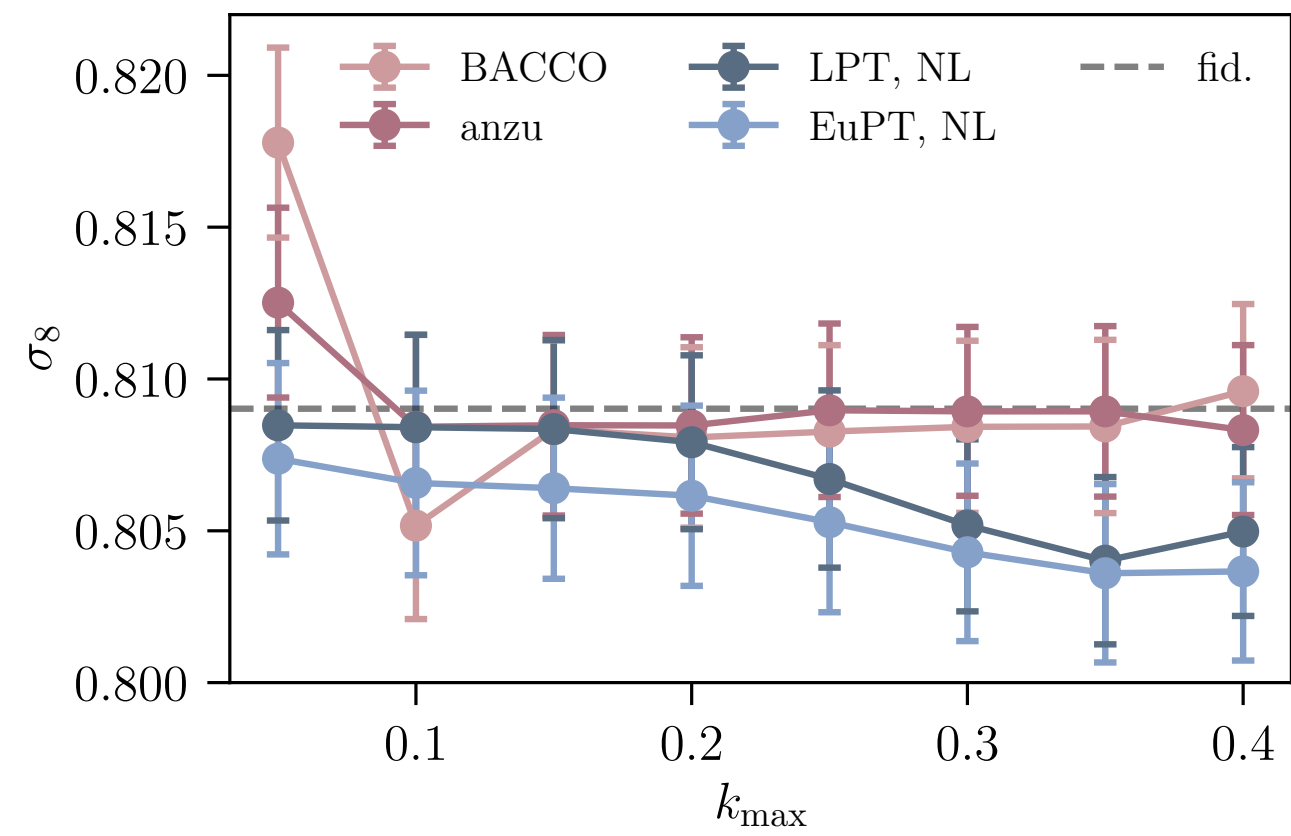


MINIMAL BIAS MODEL

$$b_{s^2} = 0$$

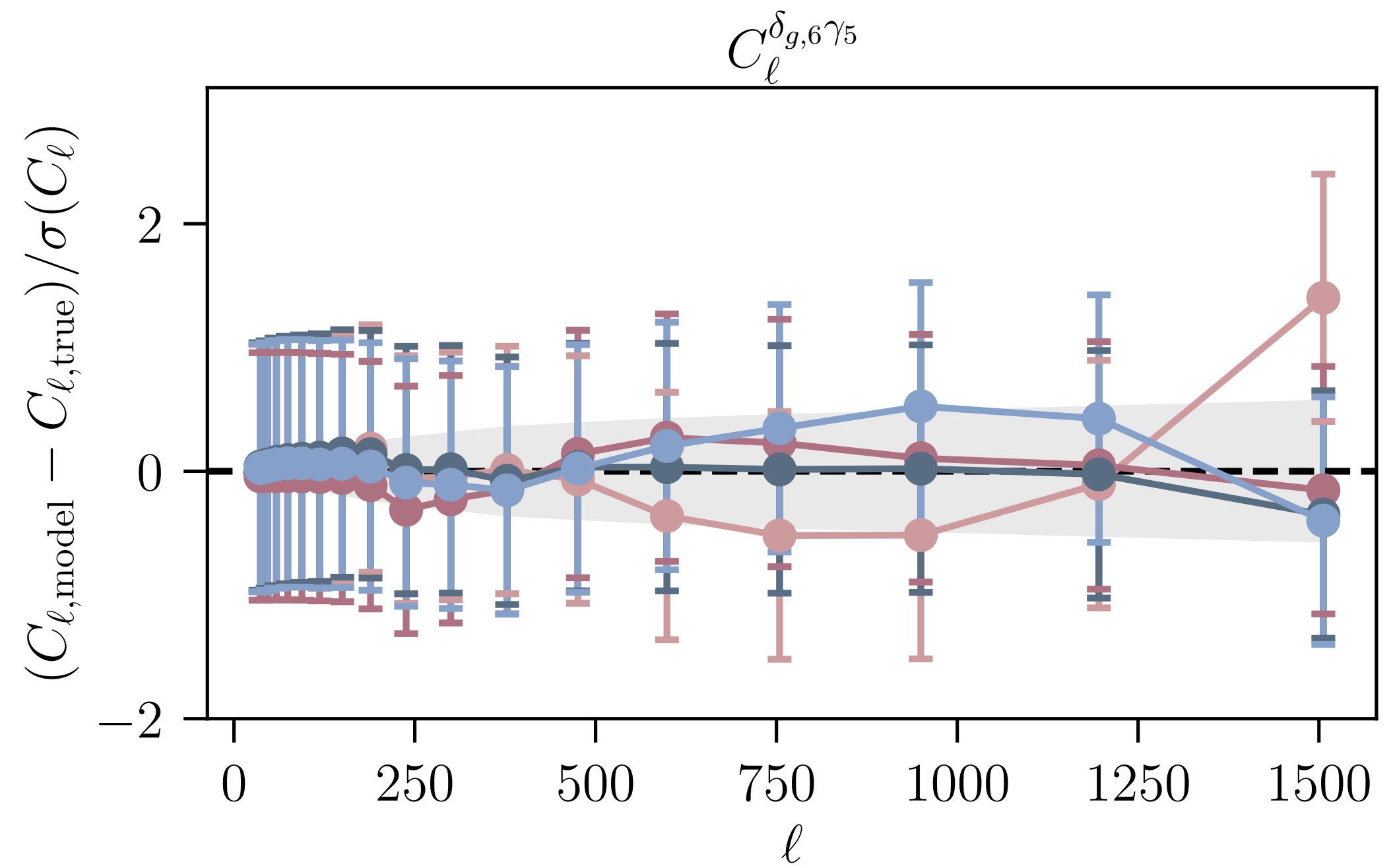
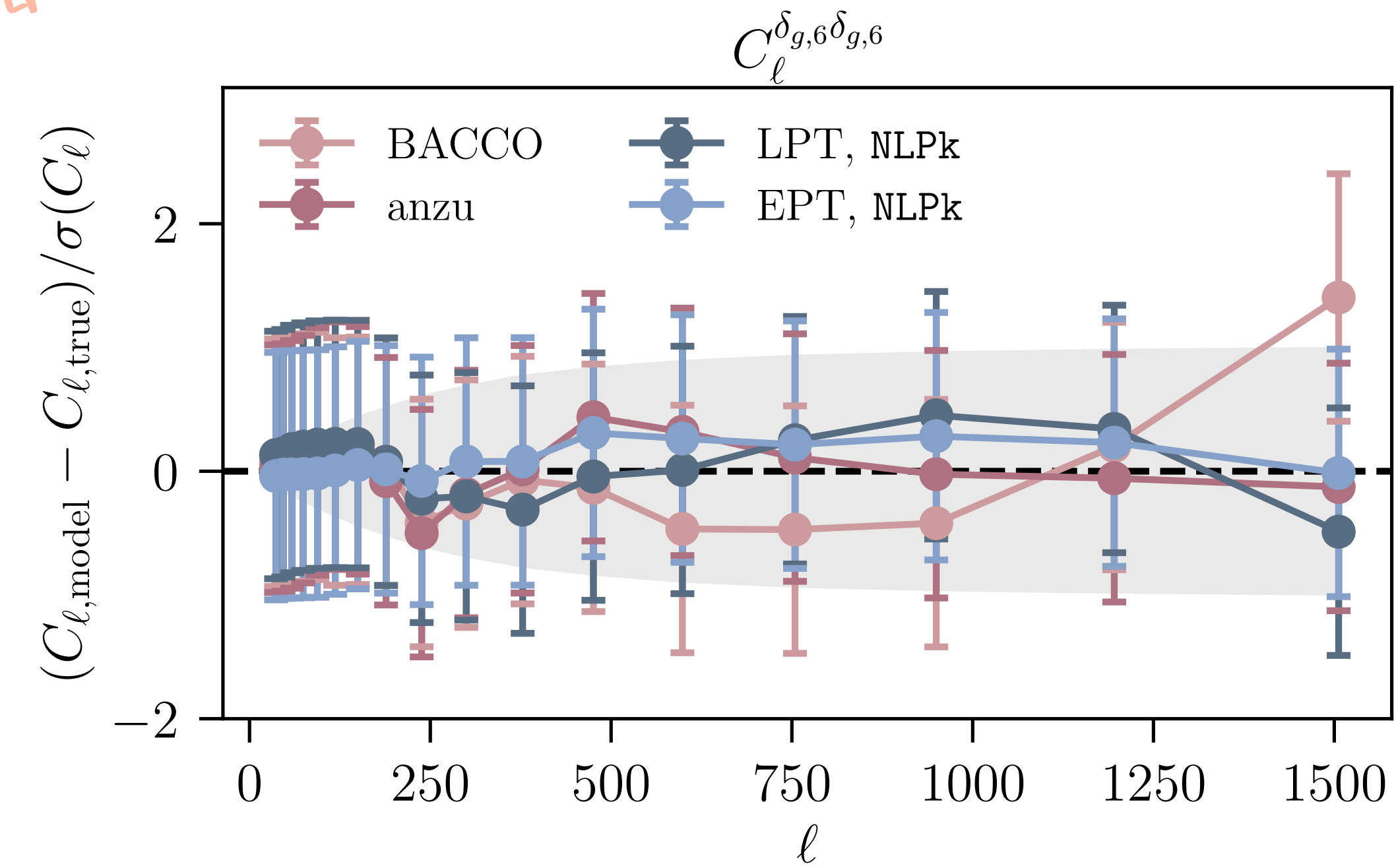


$$b_{\nabla^2} = 0$$



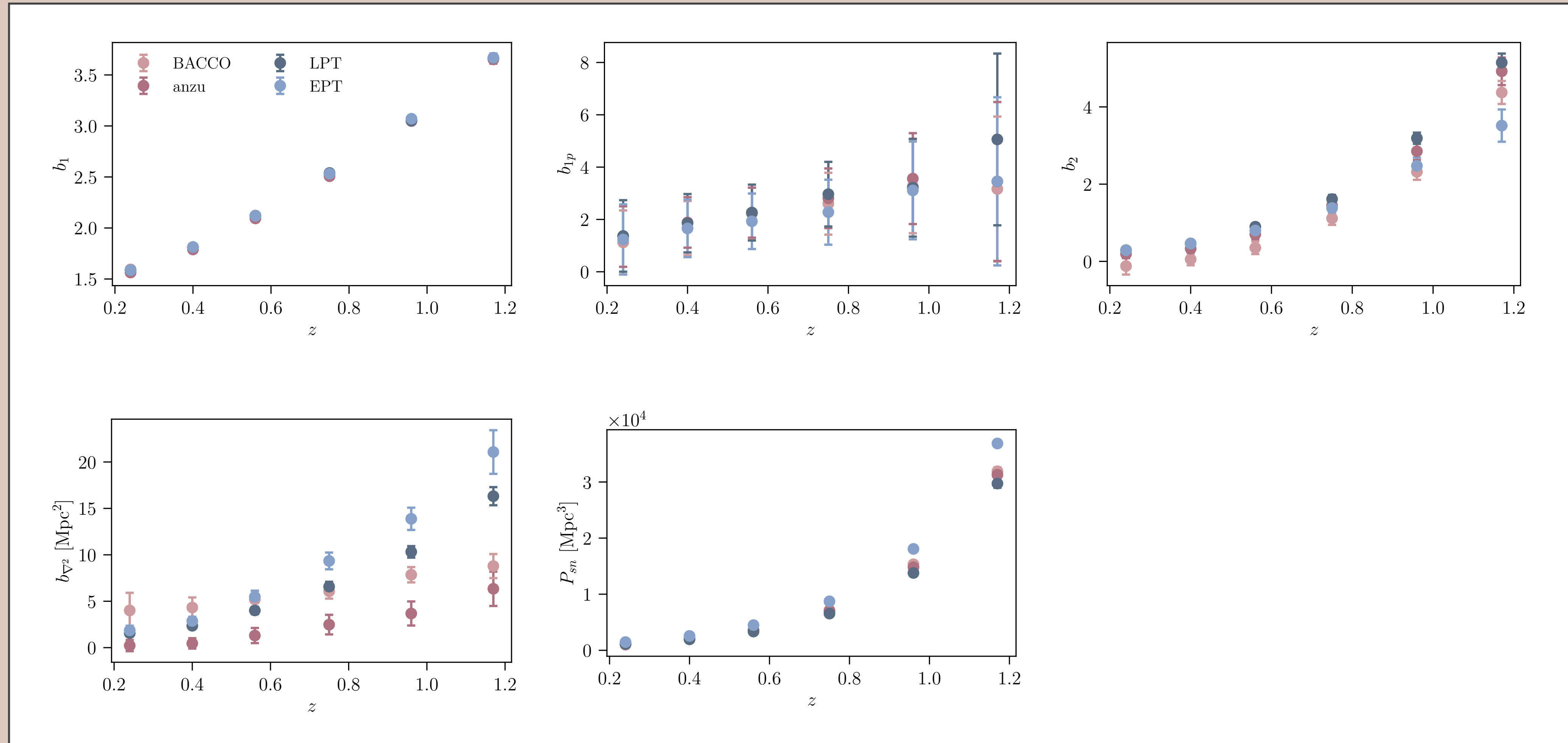
FIT RESIDUALS

Preliminary

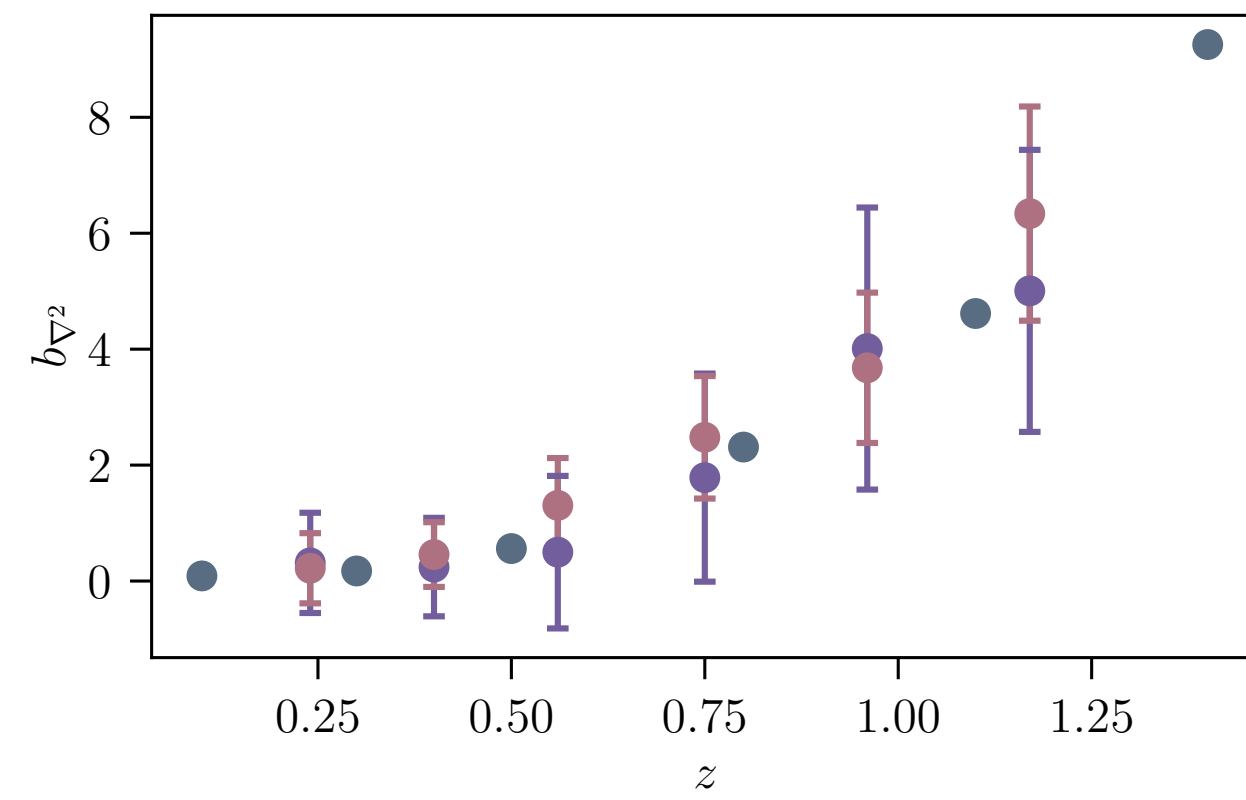
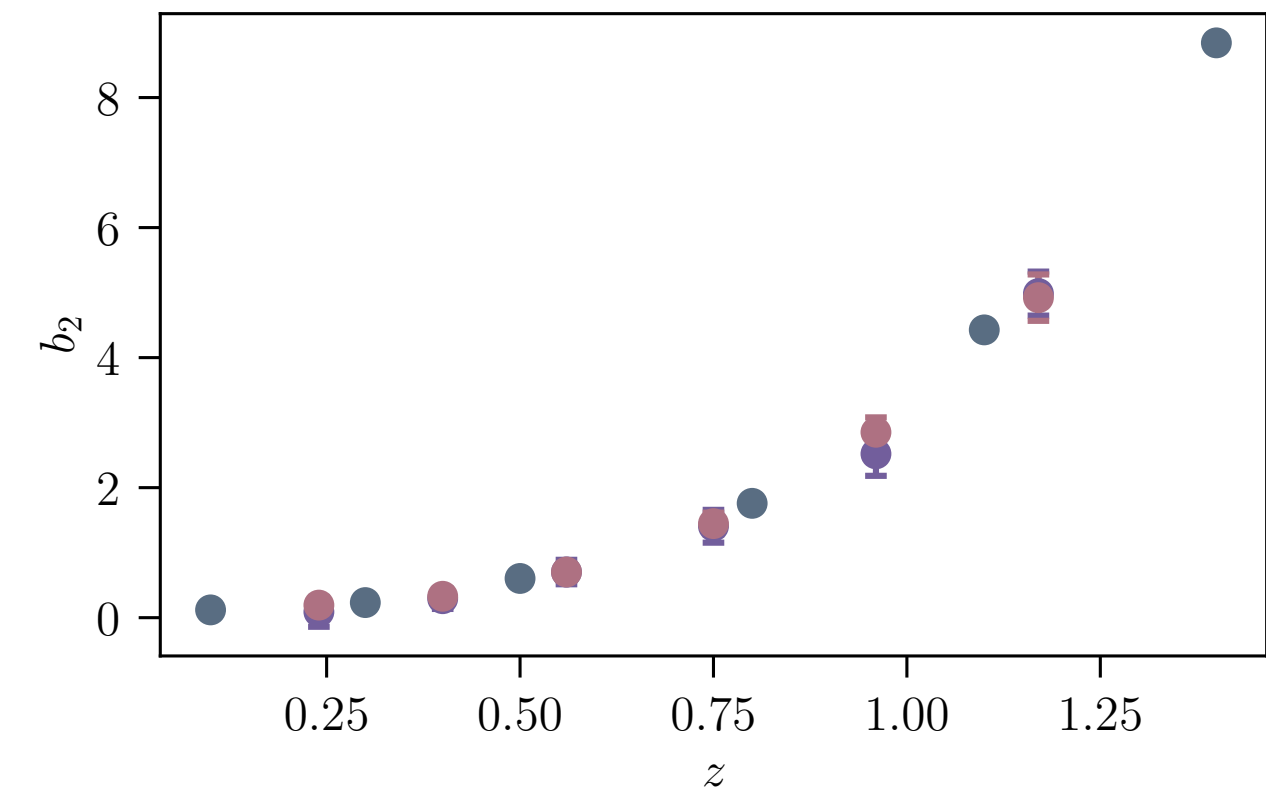
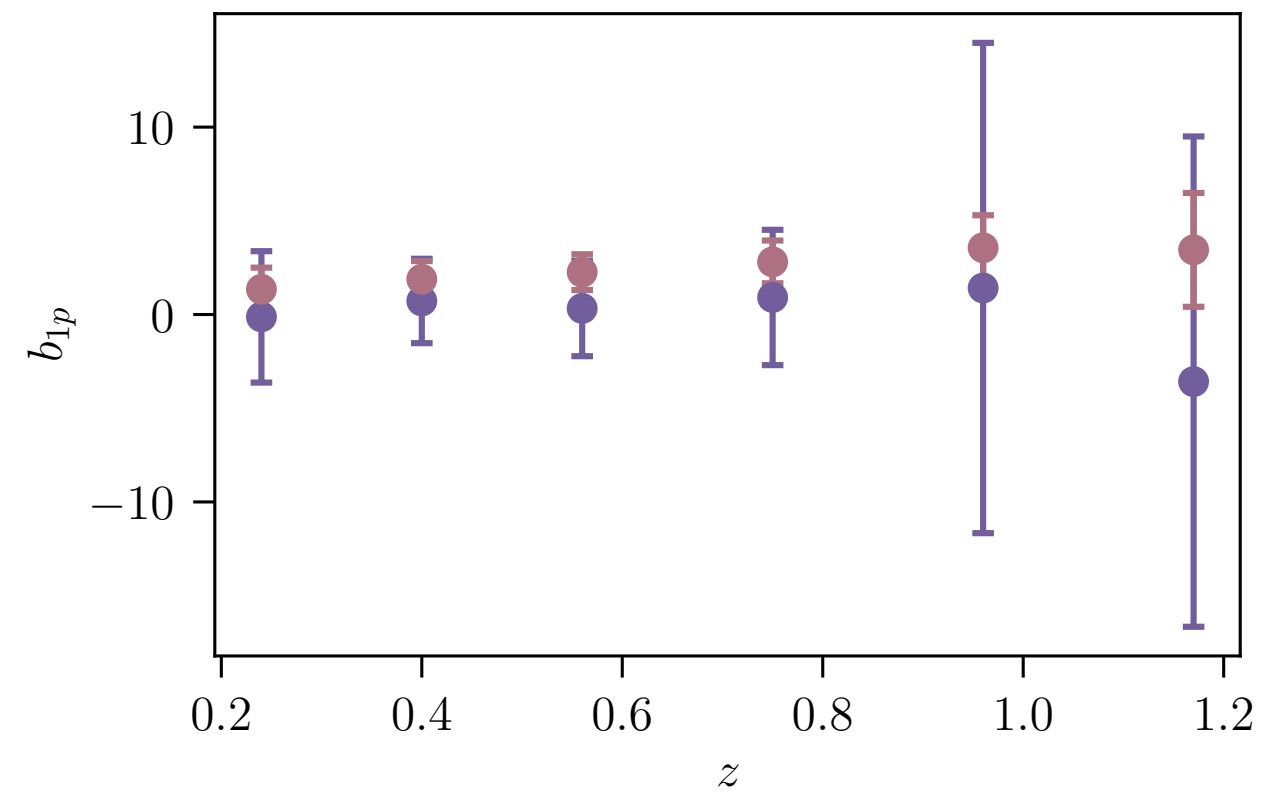
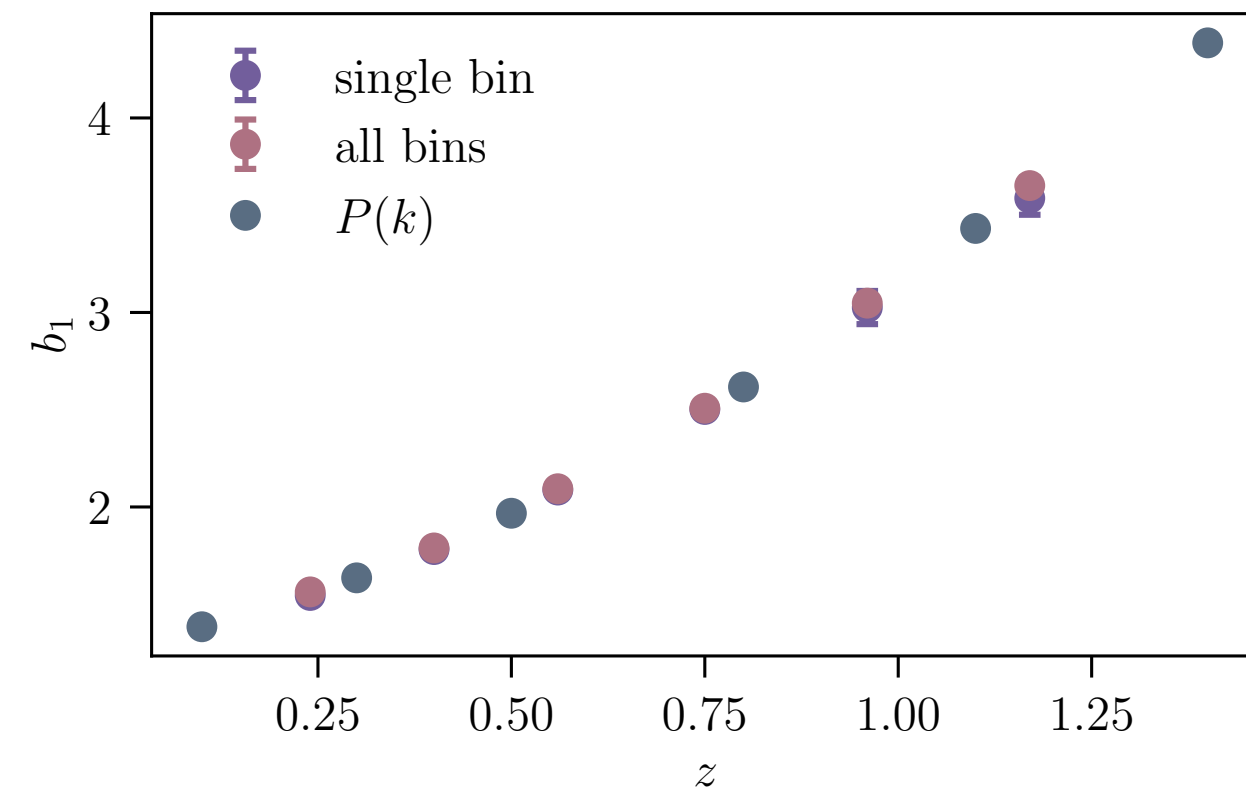


Nicola et al., in prep.

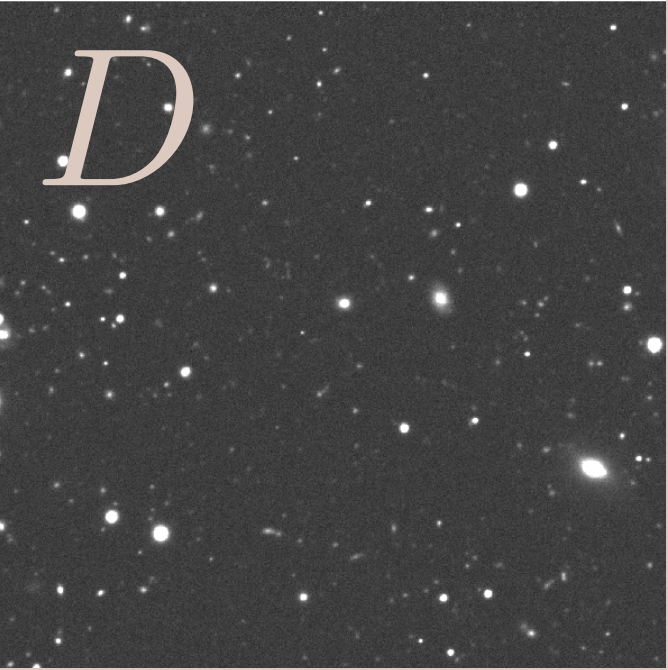
COMPARISON OF BIAS PARAMETERS



COMPARISON OF BIAS PARAMETERS



SIMULATION-BASED INFERENCE



Akhmetzhanova et al., in prep.

$$p(D_*|\theta)$$

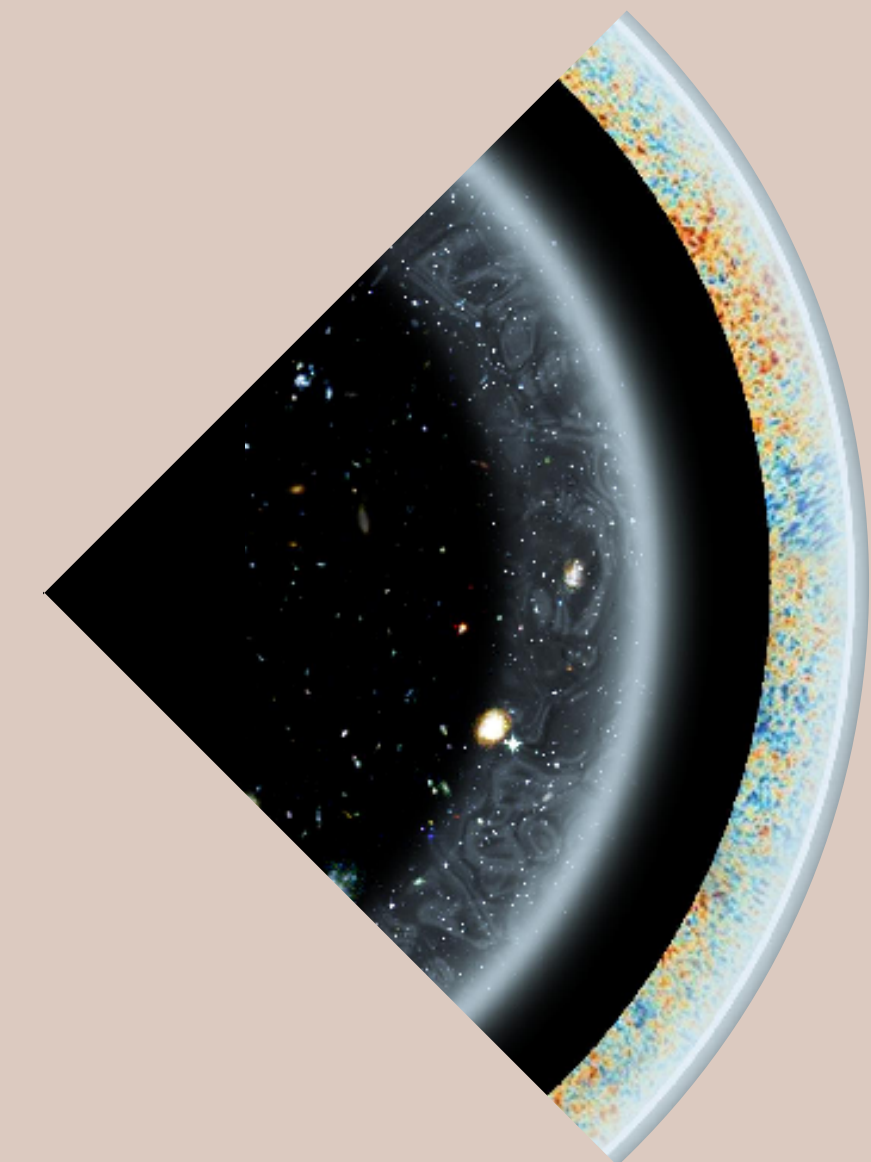
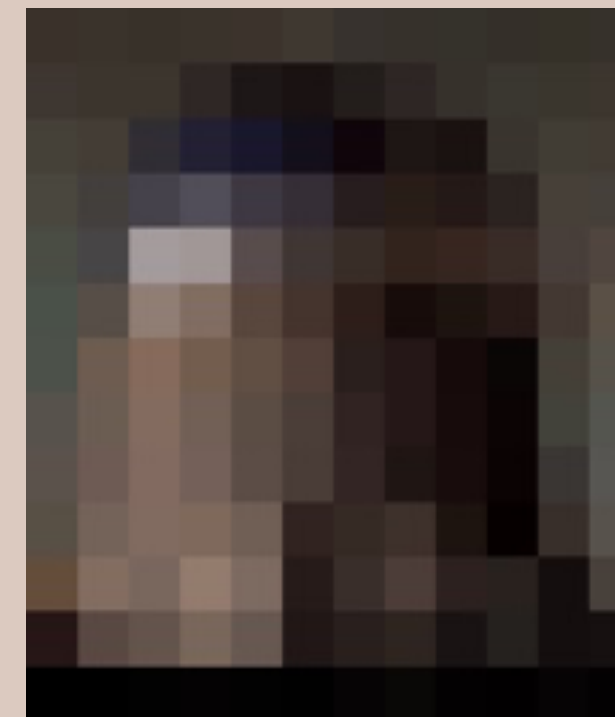
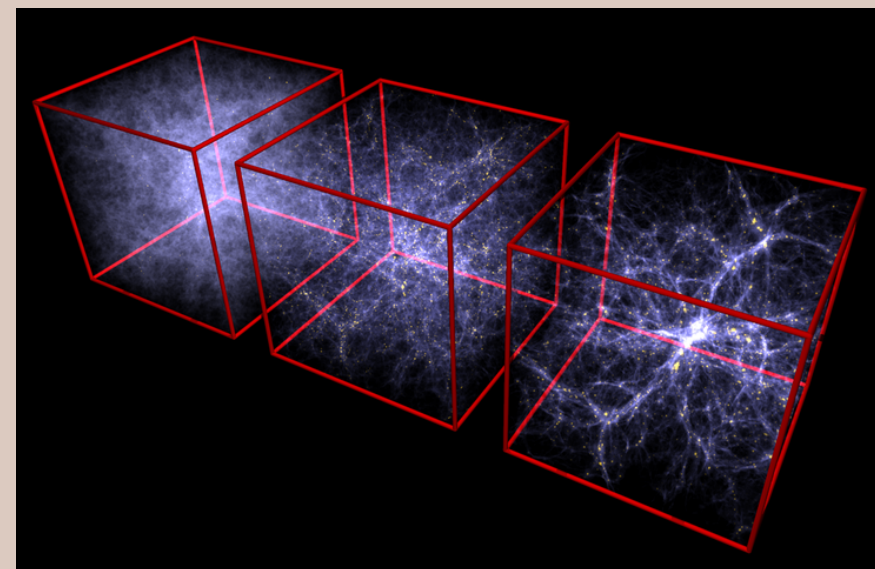


Alsing et al., 2019, Tejero-Cantero et al., 2020

FORWARD MODELING

INPUT

OUTPUT



*e.g. Bruderer, Nicola et al., 2018,
Kacprzak, ..., Nicola et al., 2020,
Images: Millenium simulation, DES, PICO*

HSC CLUSTERING

HSC CLUSTERING

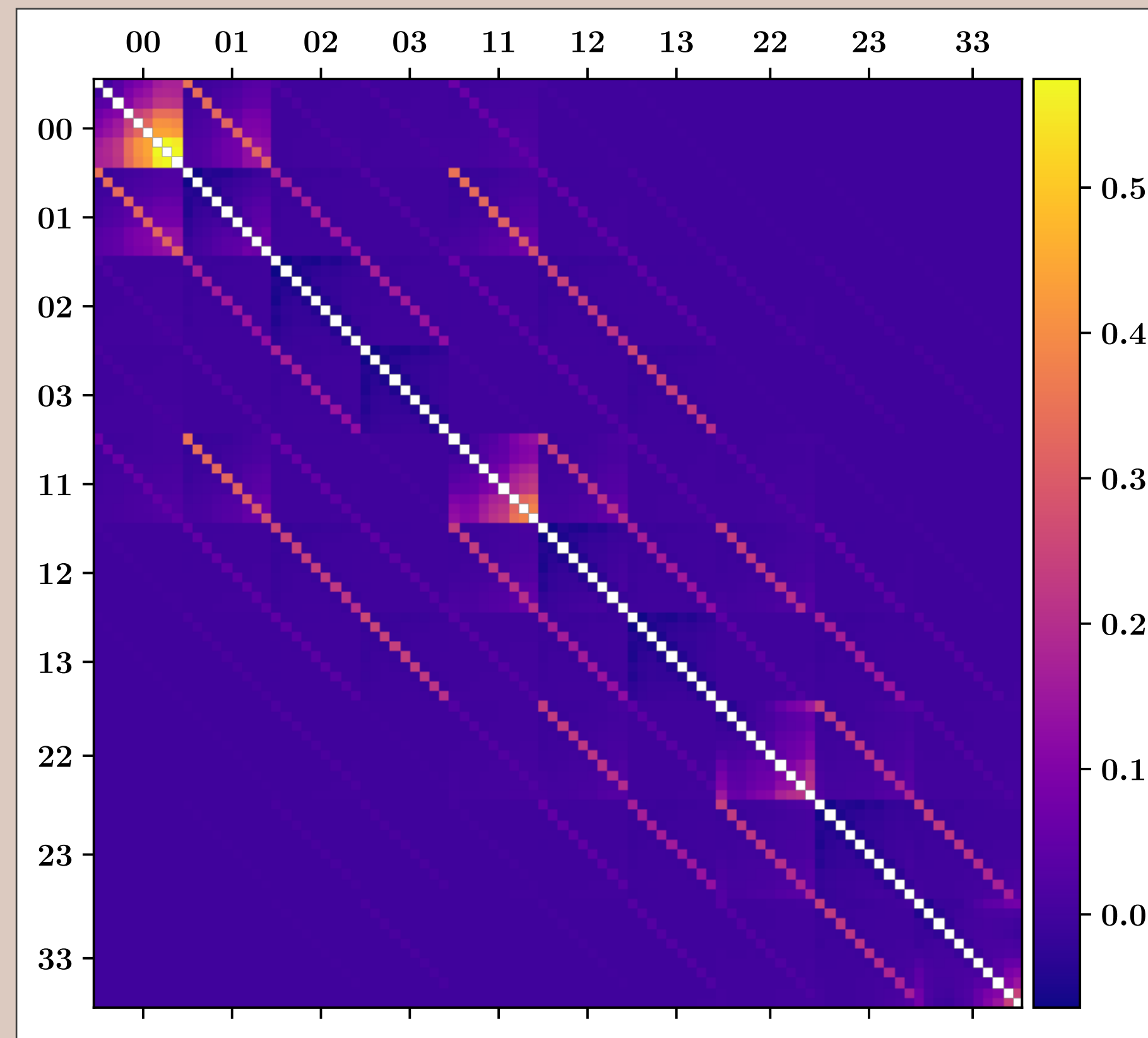
COVARIANCE MATRIX

$$\text{Cov}(C_\ell, C_{\ell'}) = \text{Cov}_G(C_\ell, C_{\ell'}) + \text{Cov}_{\text{NG}}(C_\ell, C_{\ell'}) + \text{Cov}_{\text{SSC}}(C_\ell, C_{\ell'})$$

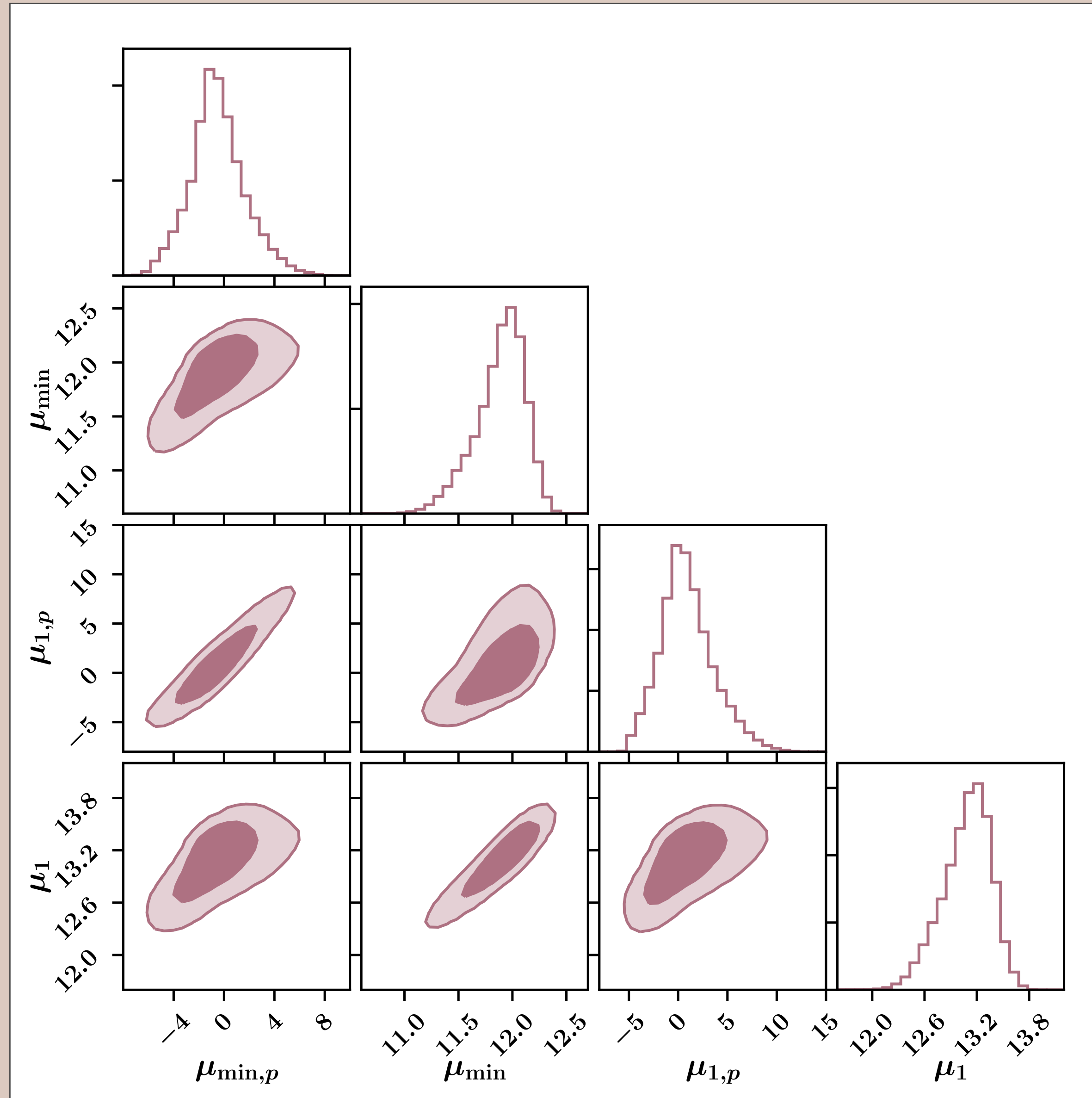
$\text{Cov}_G(C_\ell, C_{\ell'})$: computed analytically, accounting for survey geometry (NaMaster)

$\text{Cov}_{\text{NG}}(C_\ell, C_{\ell'})$: computed analytically using Halo Model/HOD (e.g. *Krause et al., 2017*)

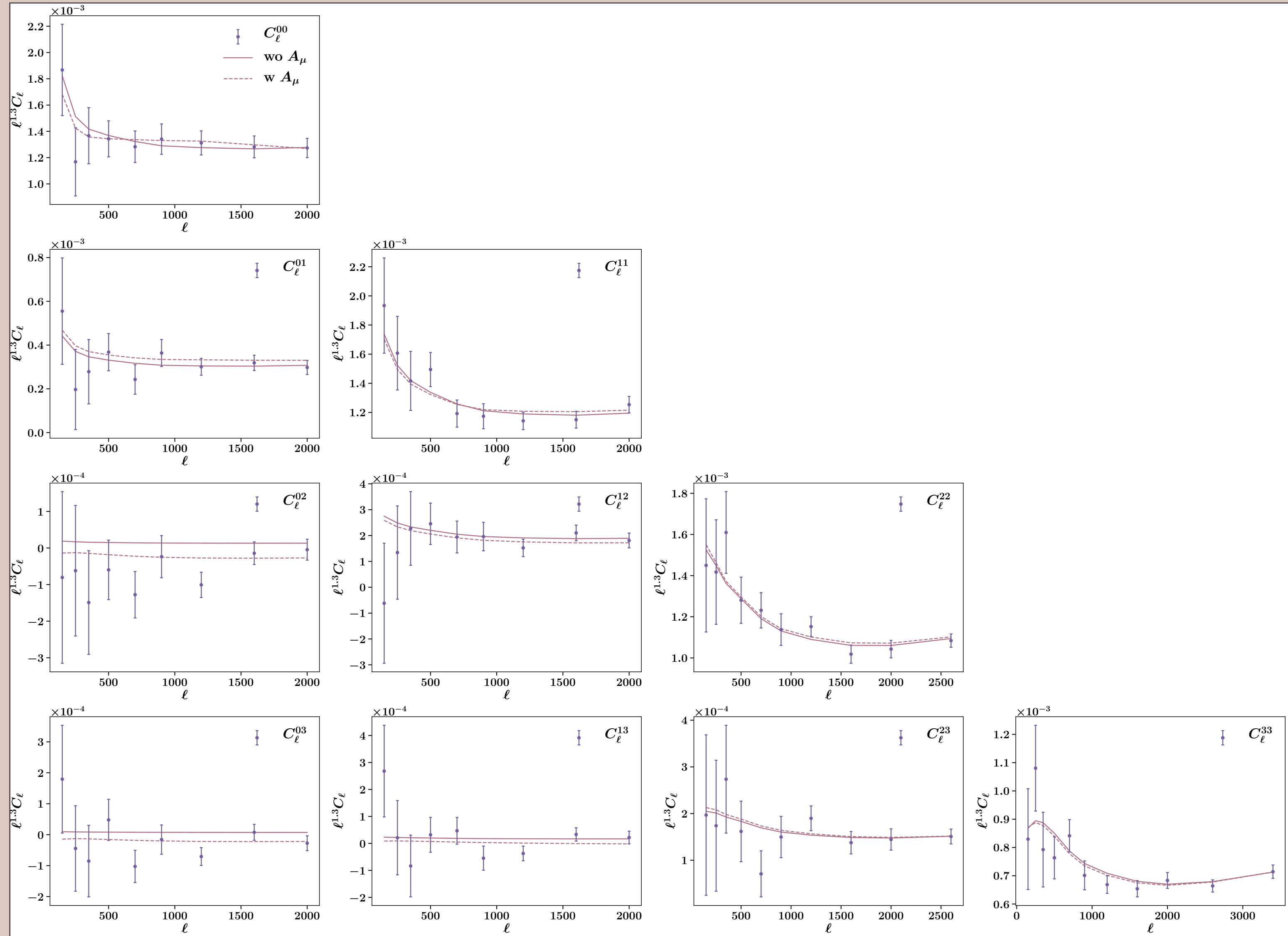
$\text{Cov}_{\text{SSC}}(C_\ell, C_{\ell'})$



HOD CONSTRAINTS



MAGNIFICATION



MAGNIFICATION

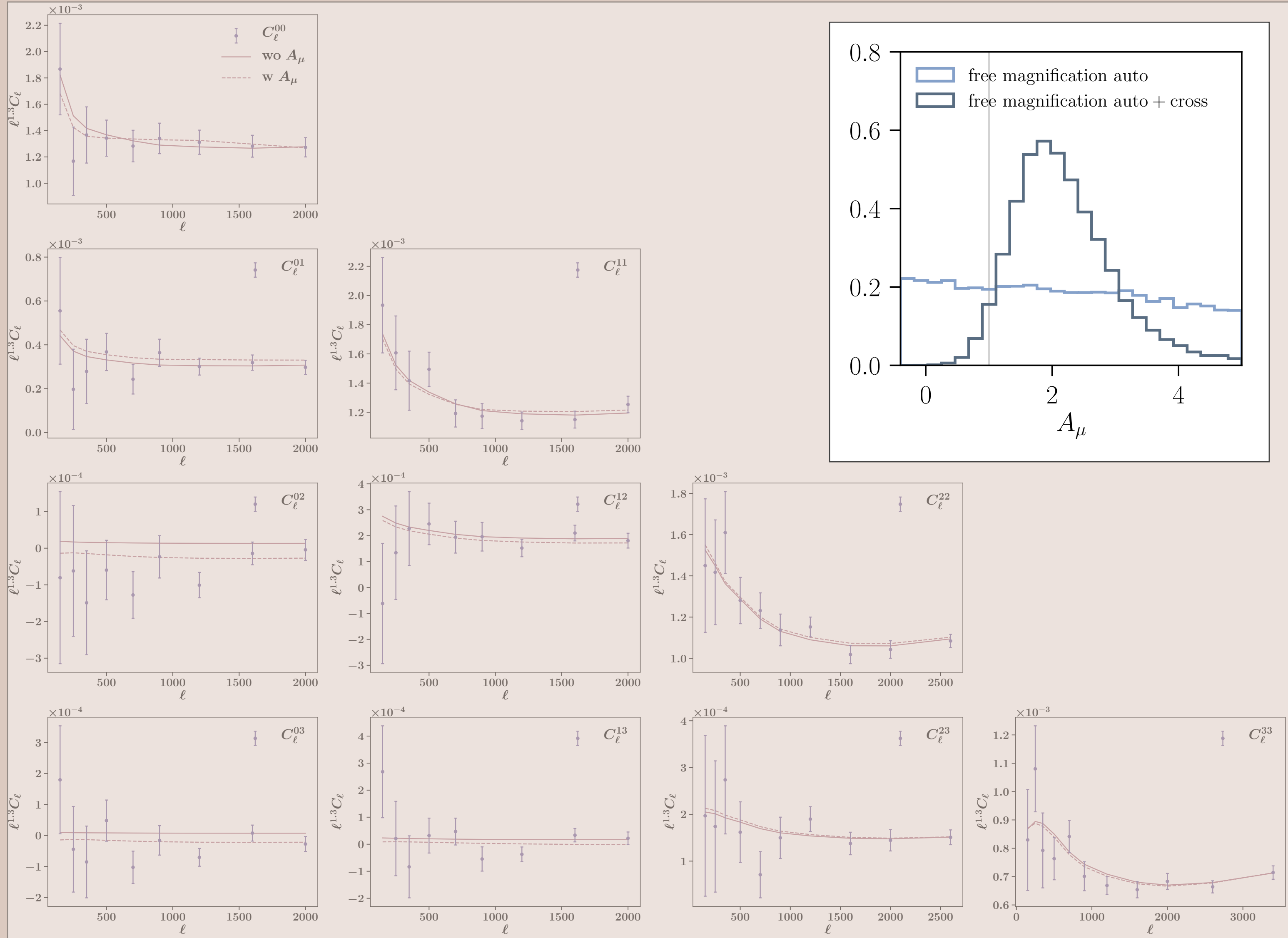
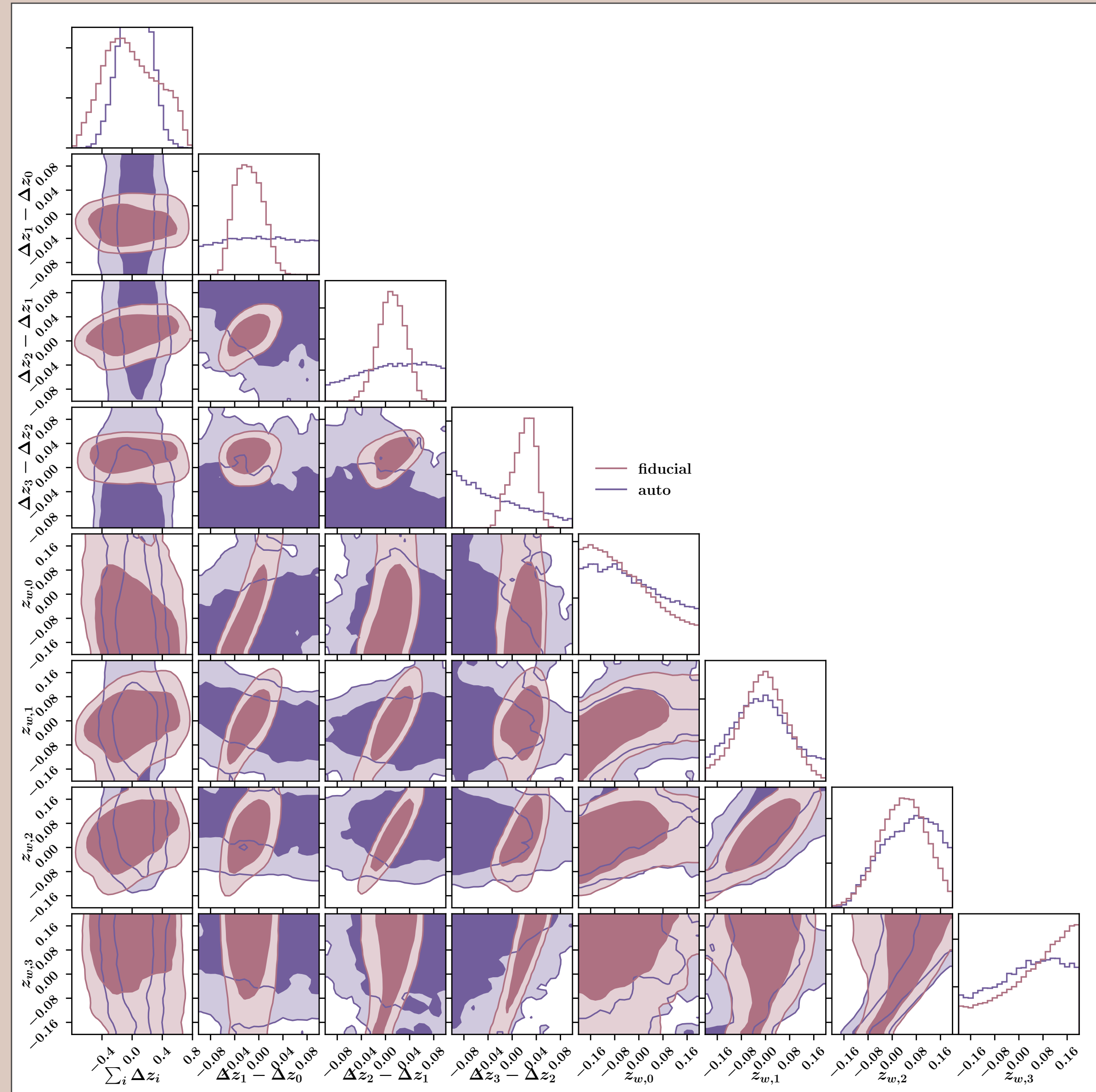
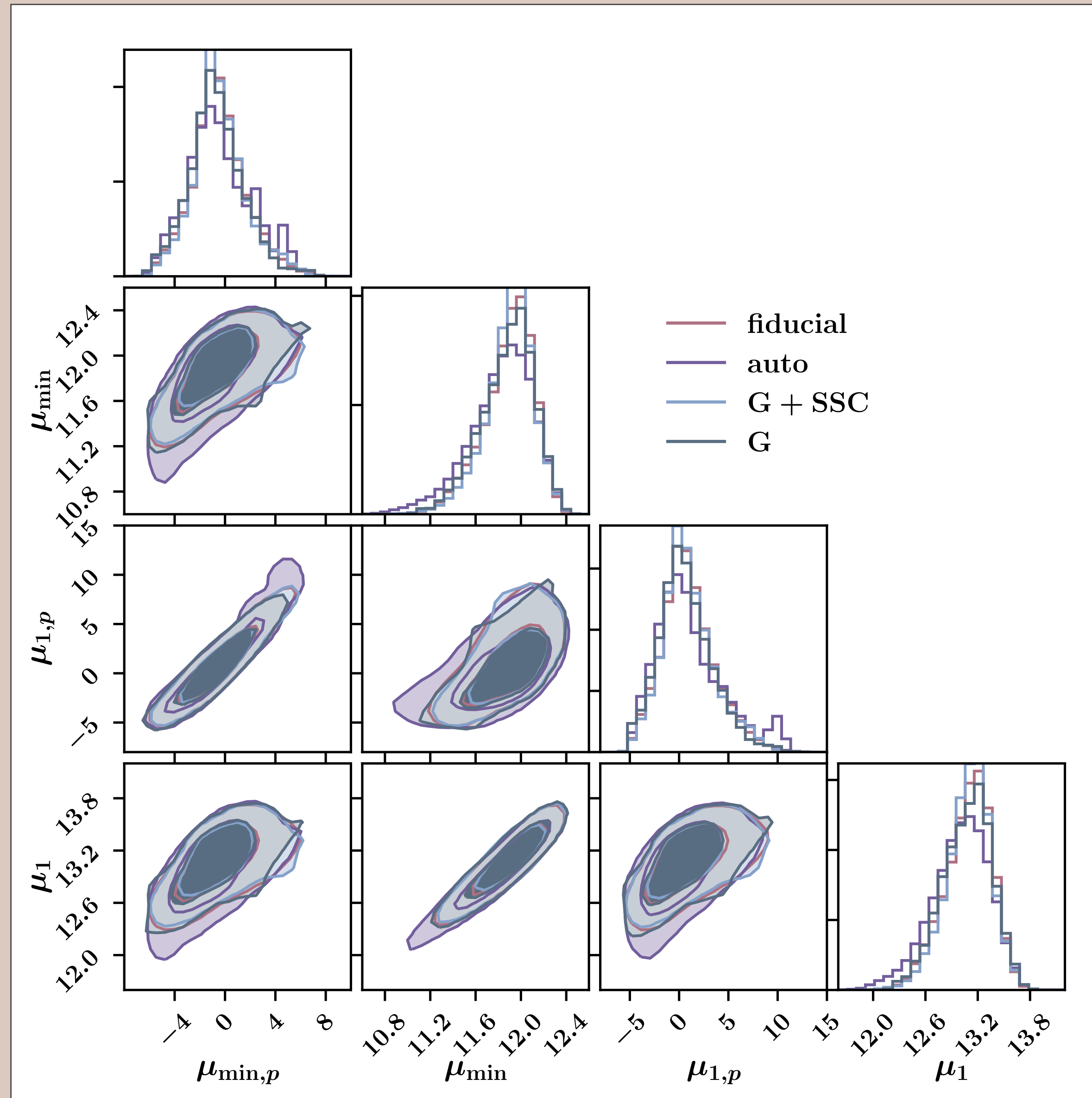


PHOTO-Z SYSTEMATICS

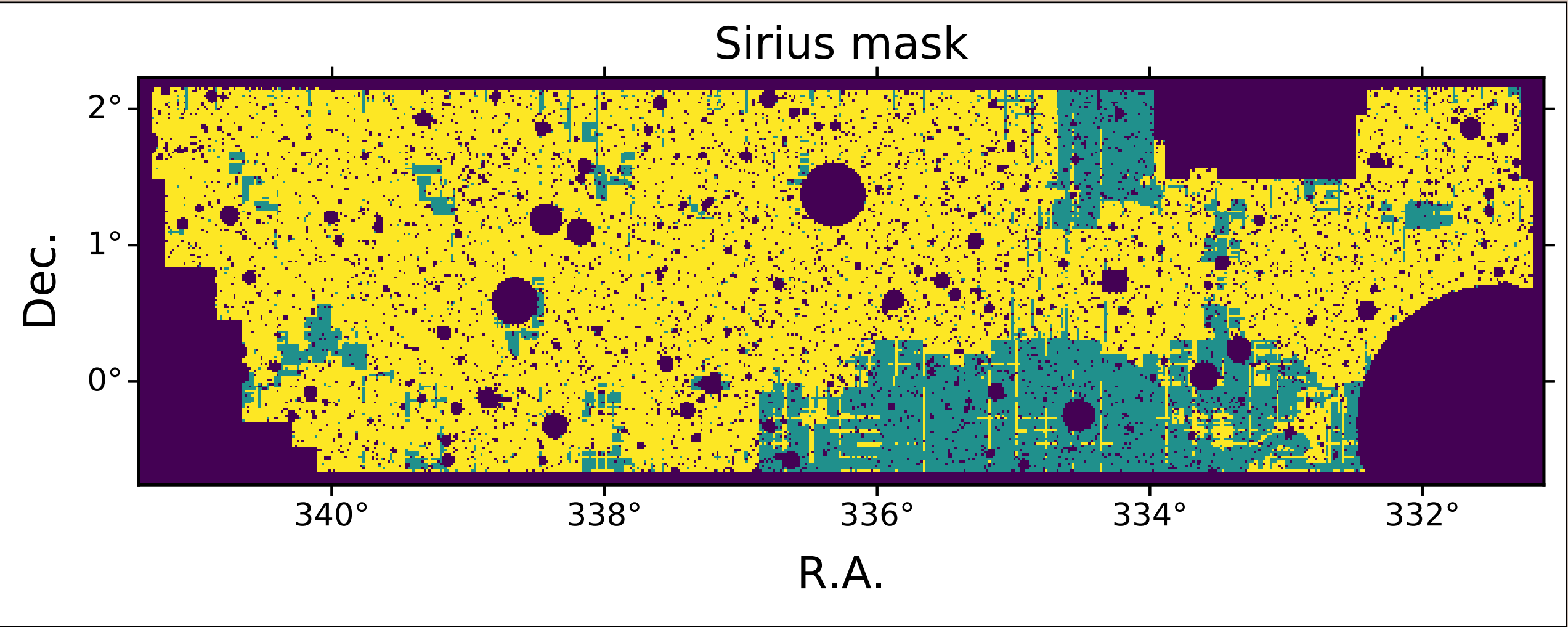
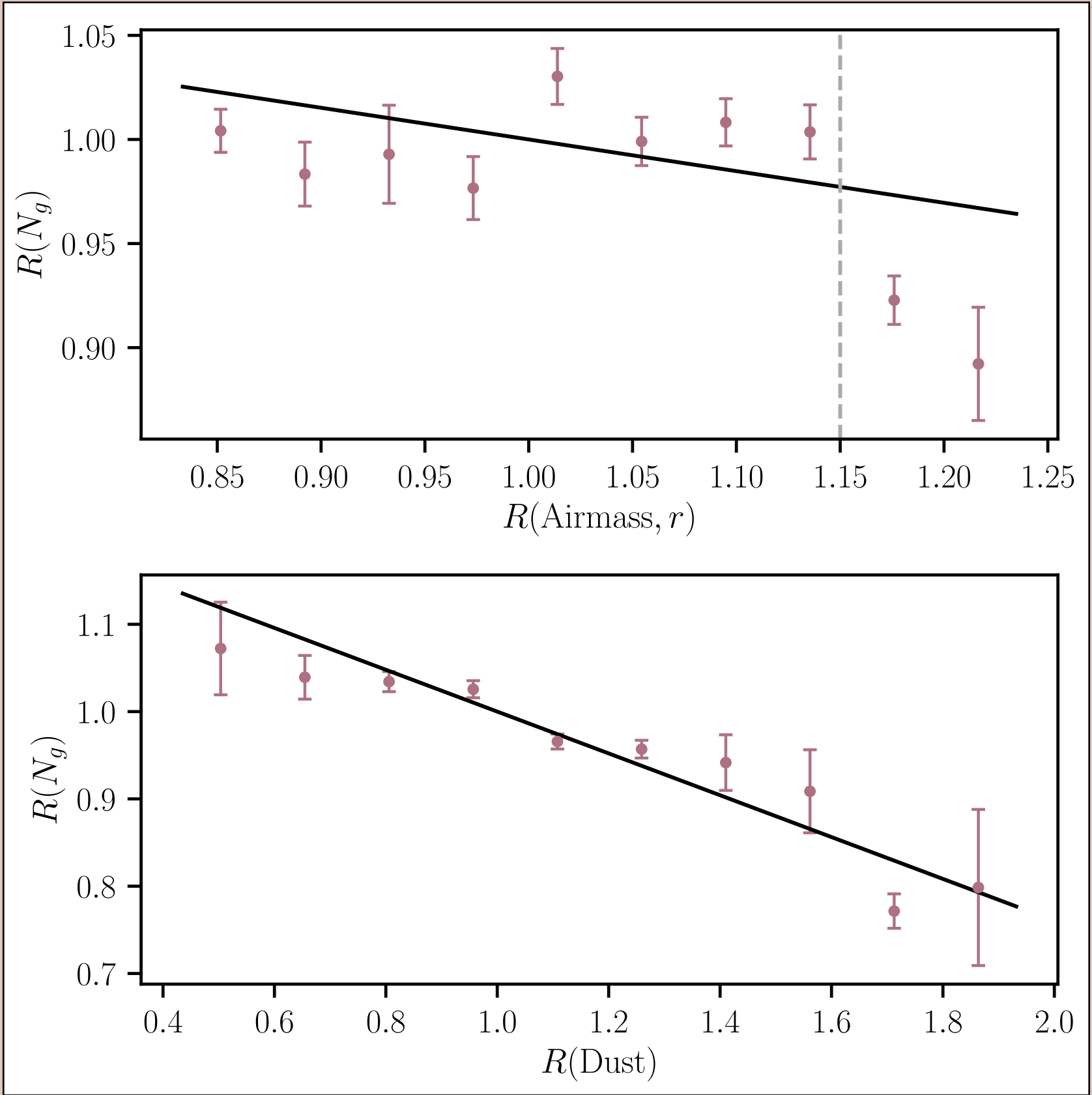


Nicola et al., 2020

STABILITY OF RESULTS



SYSTEMATICS MODELING



$$(F^{-1})_{ij} = \int d\boldsymbol{\theta} f^{i\dagger}(\boldsymbol{\theta}) f^j(\boldsymbol{\theta})$$

ANALYSIS VARIANTS

Analysis variant	χ^2/ν	$\mu_{\text{min},p}$	μ_{min}	$\mu_{1,p}$	μ_1	A_μ	Ω_c	σ_8
fiducial	86.2/80 (0.30)	$-0.491^{+2.09}_{-2.02}$	$11.88^{+0.22}_{-0.23}$	$0.933^{+2.67}_{-2.56}$	$13.08^{+0.27}_{-0.28}$	-	-	-
auto	19.2/25 (0.79)	$-0.886^{+2.19}_{-2.17}$	11.82 ± 0.28	$0.368^{+2.67}_{-2.64}$	12.99 ± 0.33	-	-	-
G cov	87.2/80 (0.27)	$-0.675^{+2.11}_{-2.08}$	$11.88^{+0.23}_{-0.24}$	$0.70^{+2.67}_{-2.61}$	$13.08^{+0.28}_{-0.29}$	-	-	-
G+SSC cov	86.2/80 (0.30)	$-0.433^{+1.96}_{-1.90}$	11.89 ± 0.20	$0.982^{+2.55}_{-2.44}$	$13.09^{+0.24}_{-0.25}$	-	-	-
no $z_{w,i}$	88.0/84 (0.36)	$-0.855^{+0.648}_{-0.653}$	11.87 ± 0.11	$0.327^{+0.889}_{-0.900}$	13.07 ± 0.15	-	-	-
no $z_{w,i}, \Delta z_i$	95.2/88 (0.28)	$-1.09^{+0.624}_{-0.771}$	11.78 ± 0.13	$-0.108^{+0.727}_{-0.940}$	12.93 ± 0.16	-	-	-
bins = 0, 1, 2	44.4/43 (0.41)	$-0.354^{+2.34}_{-2.25}$	$11.88^{+0.22}_{-0.23}$	$0.624^{+2.87}_{-2.75}$	$13.09^{+0.27}_{-0.28}$	-	-	-
bins = 1, 2, 3	44.4/46 (0.54)	$1.20^{+2.88}_{-2.94}$	$11.97^{+0.31}_{-0.36}$	$3.46^{+3.66}_{-3.63}$	$13.23^{+0.39}_{-0.43}$	-	-	-
pz = Ephor_AB	93.6/80 (0.14)	$0.270^{+2.05}_{-1.88}$	$12.14^{+0.19}_{-0.17}$	$1.82^{+2.87}_{-2.59}$	$13.39^{+0.24}_{-0.23}$	-	-	-
pz = Ephor	107.2/80 (0.023)	$0.895^{+1.97}_{-2.03}$	12.15 ± 0.17	$2.64^{+2.71}_{-2.80}$	$13.40^{+0.23}_{-0.22}$	-	-	-
pz = DEmP	105.4/80 (0.031)	$0.616^{+1.90}_{-1.88}$	$12.07^{+0.17}_{-0.16}$	$2.29^{+2.59}_{-2.55}$	$13.30^{+0.22}_{-0.21}$	-	-	-
pz = FRANKEN-Z	90.8/80 (0.19)	$0.0421^{+1.97}_{-1.76}$	$12.12^{+0.18}_{-0.16}$	$1.41^{+2.75}_{-2.44}$	$13.38^{+0.23}_{-0.22}$	-	-	-
fiducial magn.	72.8/80 (0.70)	$-0.358^{+2.56}_{-2.32}$	$11.94^{+0.21}_{-0.22}$	$1.04^{+3.32}_{-2.97}$	$13.16^{+0.26}_{-0.27}$	-	-	-
fit magn., auto+cross	69.0/79 (0.78)	$-1.78^{+2.13}_{-2.35}$	$11.79^{+0.26}_{-0.27}$	$-0.724^{+2.60}_{-2.74}$	$12.98^{+0.30}_{-0.31}$	2.18 ± 0.74	-	-
fit magn., auto	19.4/24 (0.73)	$-0.844^{+2.29}_{-2.17}$	11.81 ± 0.26	$0.409^{+2.80}_{-2.65}$	12.98 ± 0.31	$0.627^{+2.71}_{-2.61}$	-	-
fit cosmo	84.4/78 (0.29)	$0.0143^{+2.72}_{-2.53}$	$11.79^{+0.27}_{-0.24}$	$1.63^{+3.44}_{-3.20}$	$12.96^{+0.36}_{-0.35}$	-	0.237 ± 0.025	$0.807^{+0.149}_{-0.143}$

PHOTO-Z SYSTEMATICS I

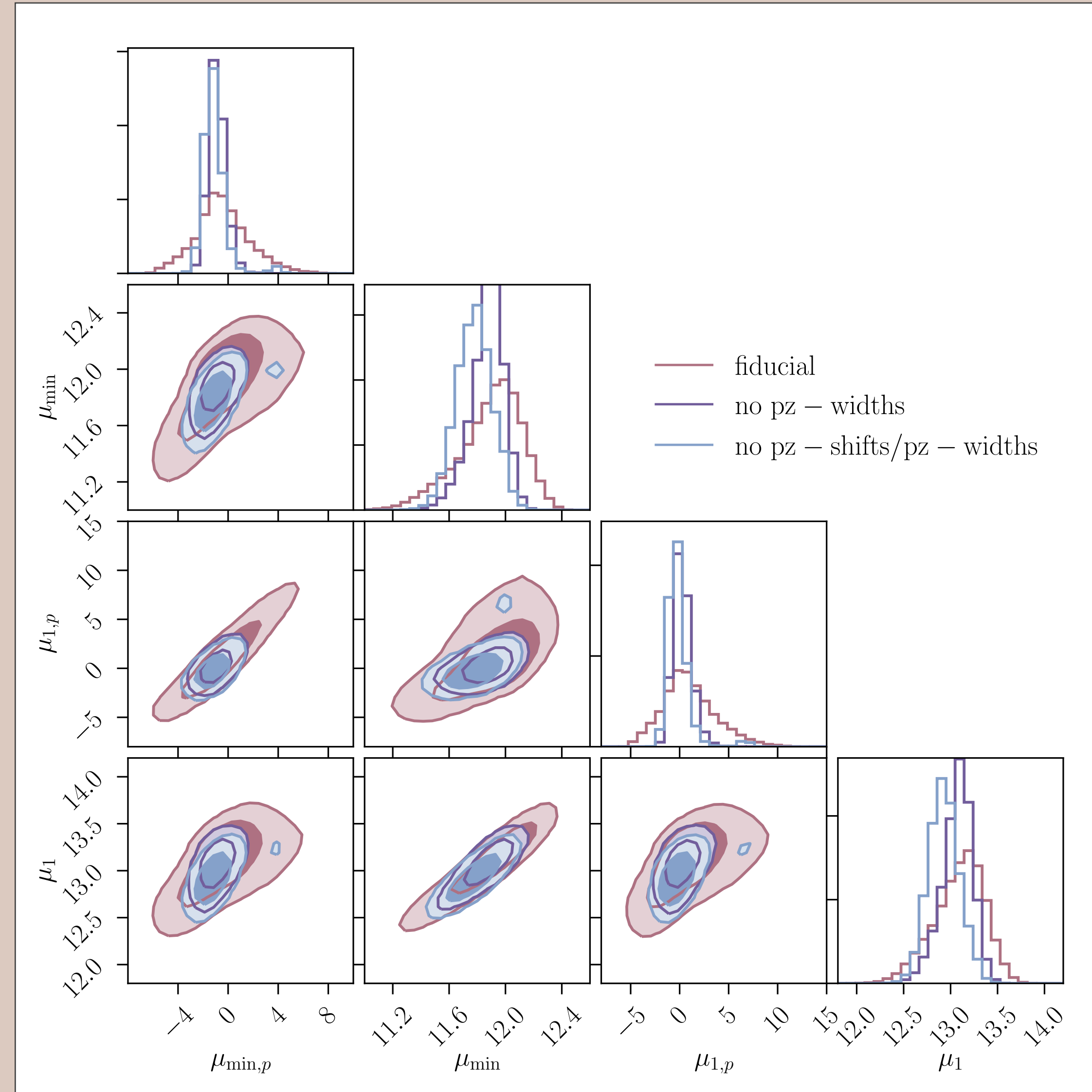


PHOTO-Z SYSTEMATICS II

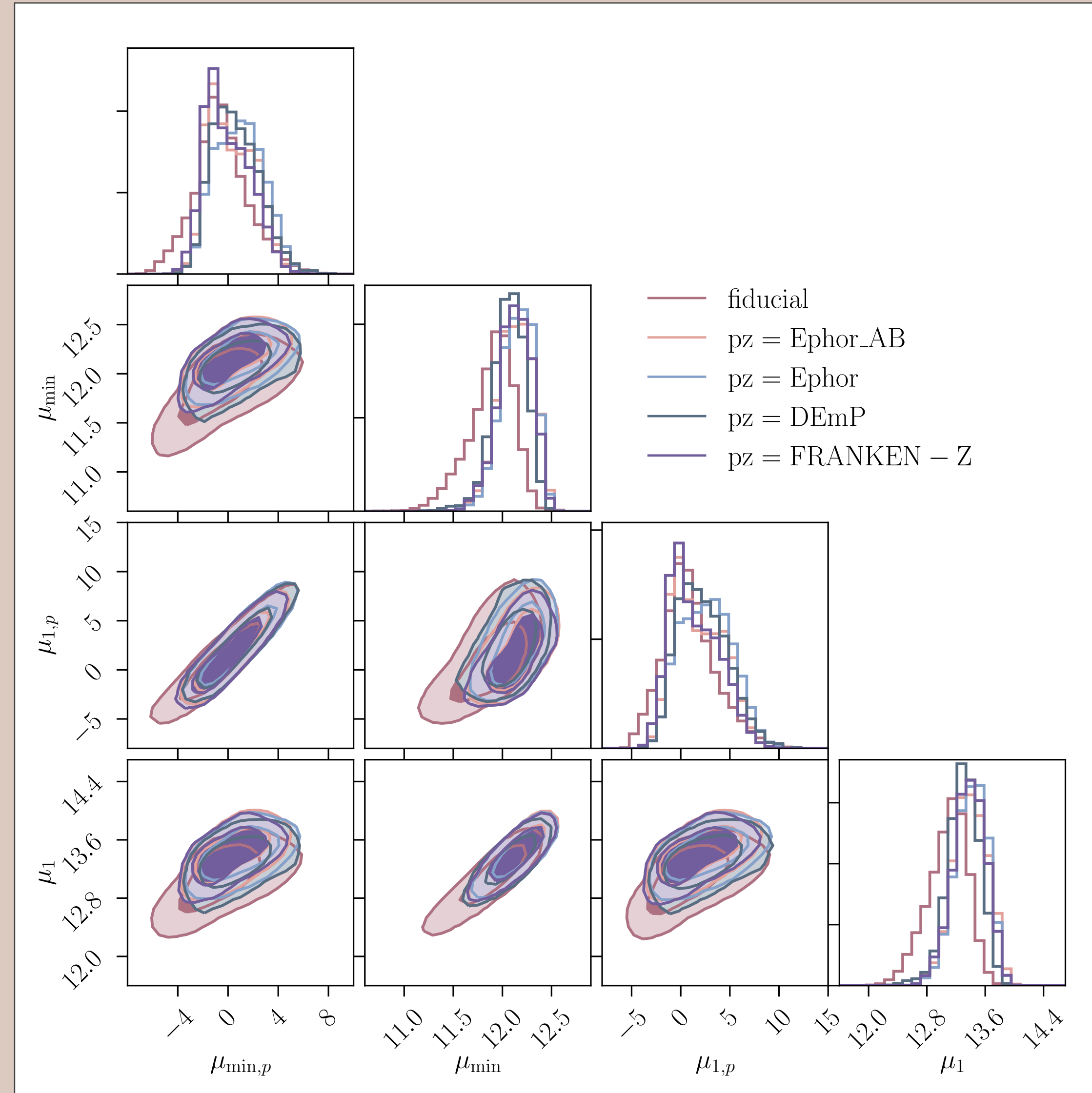
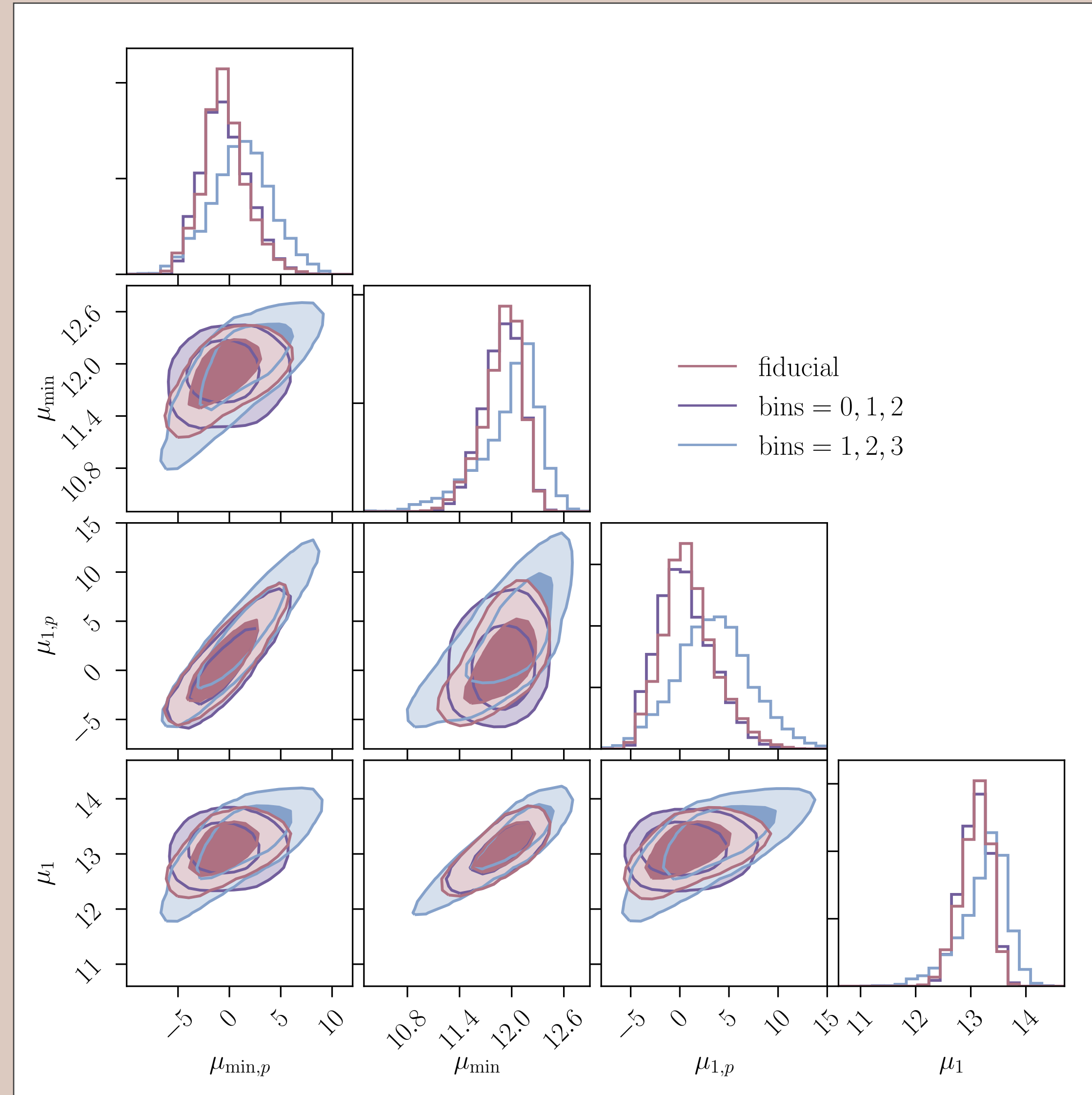


PHOTO-Z SYSTEMATICS III



IMPORTANCE OF CROSS-CORRELATIONS

