Cosmological Probe Combination for Current & Future Surveys

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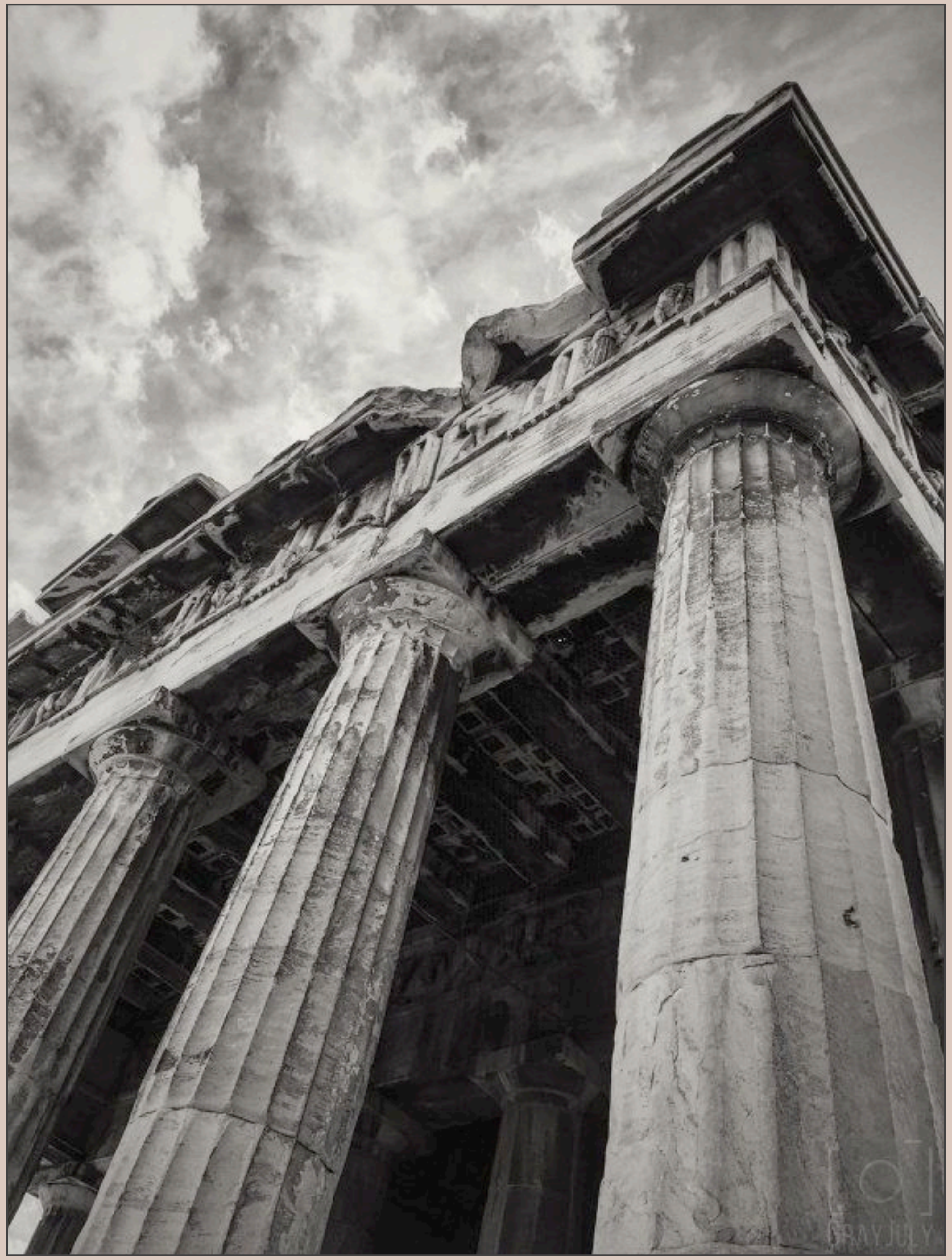
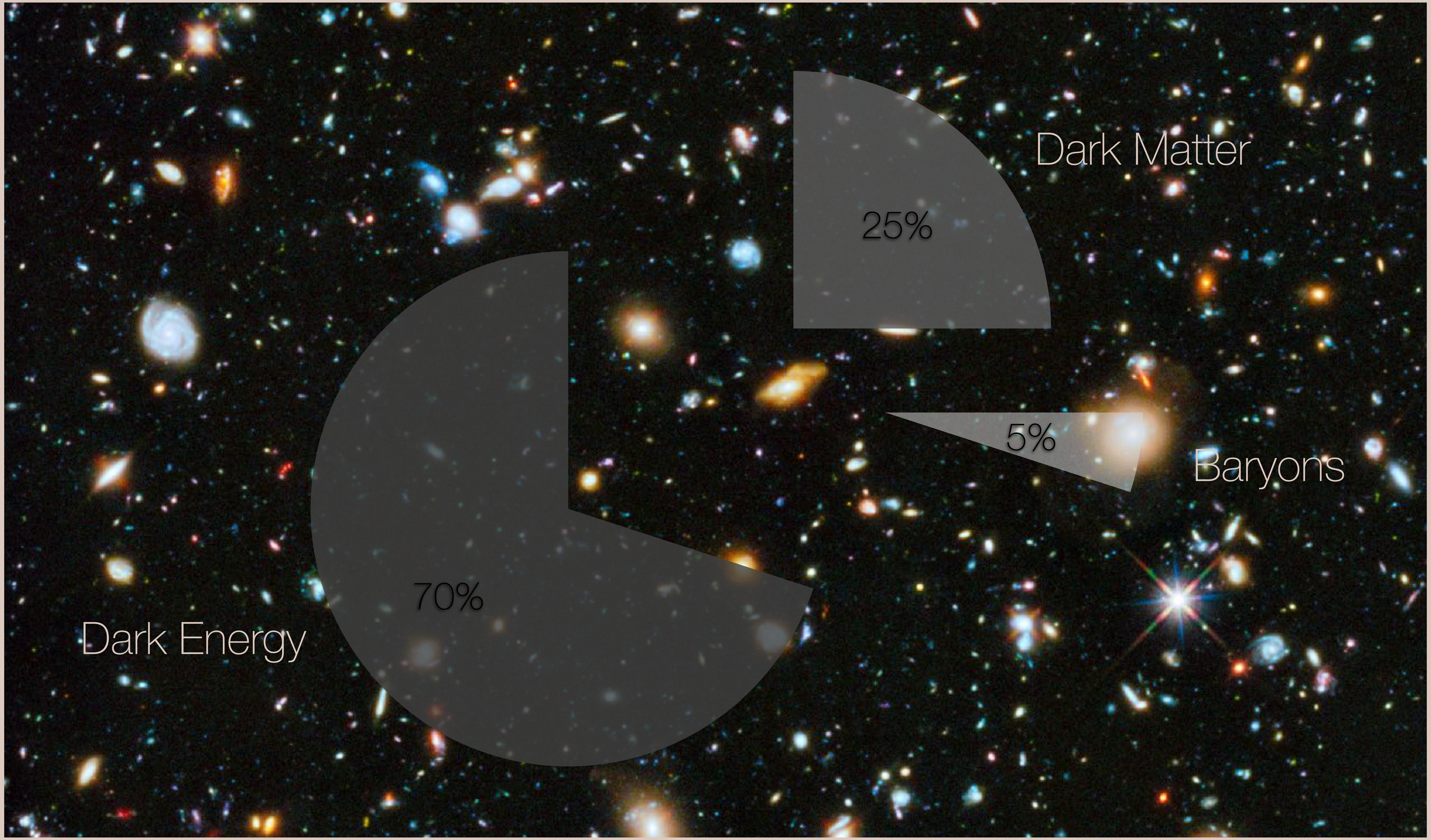
+ LSST-DESC LSS working group, Alexandre Refregier, Adam Amara

The Pillars of the ΛCDM Cosmological Model

Λ + DM + GR + Inflation



Our Dark Universe



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

Cosmological Probes

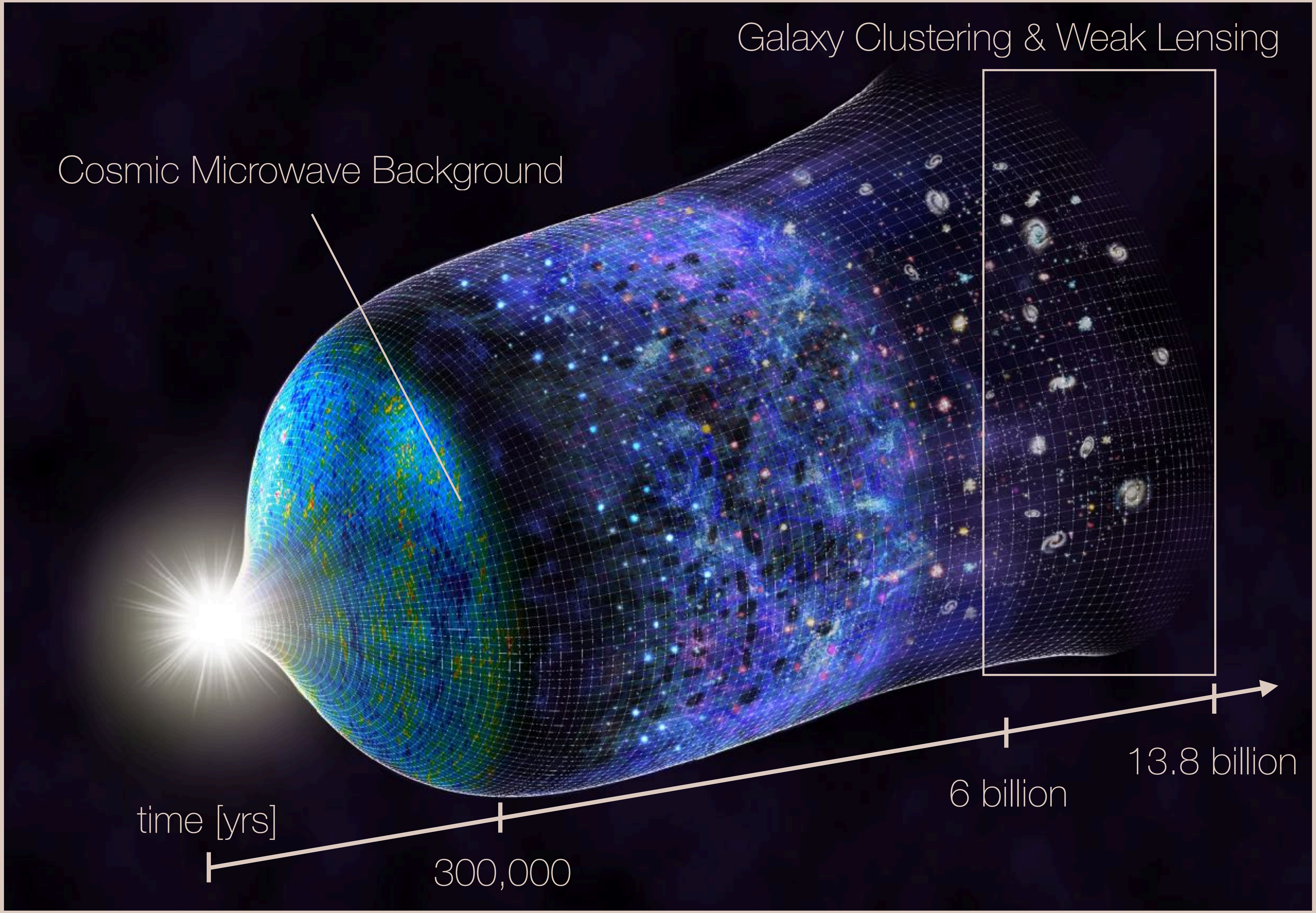
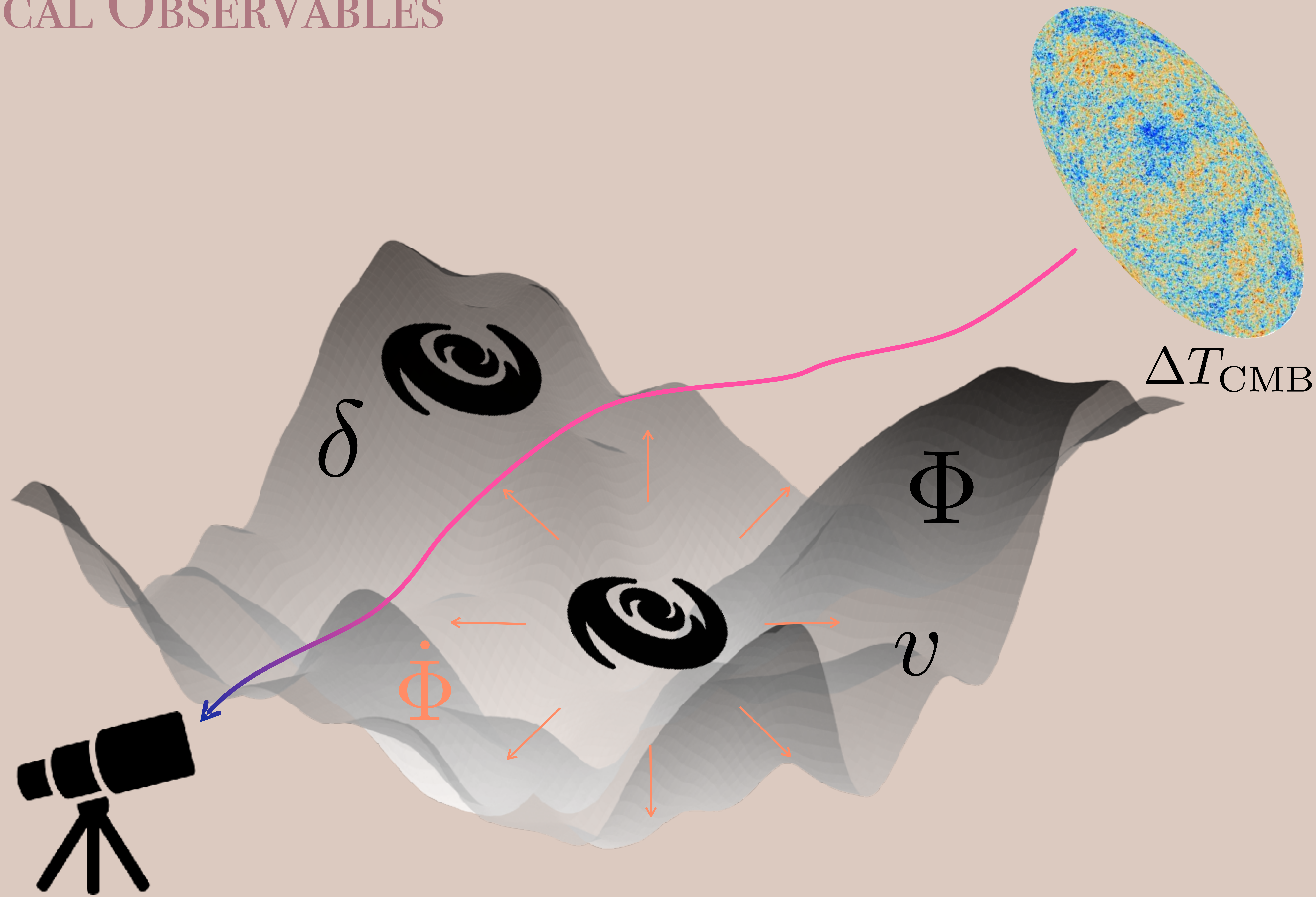


Image: Nicolle R. Fuller, National Science Foundation

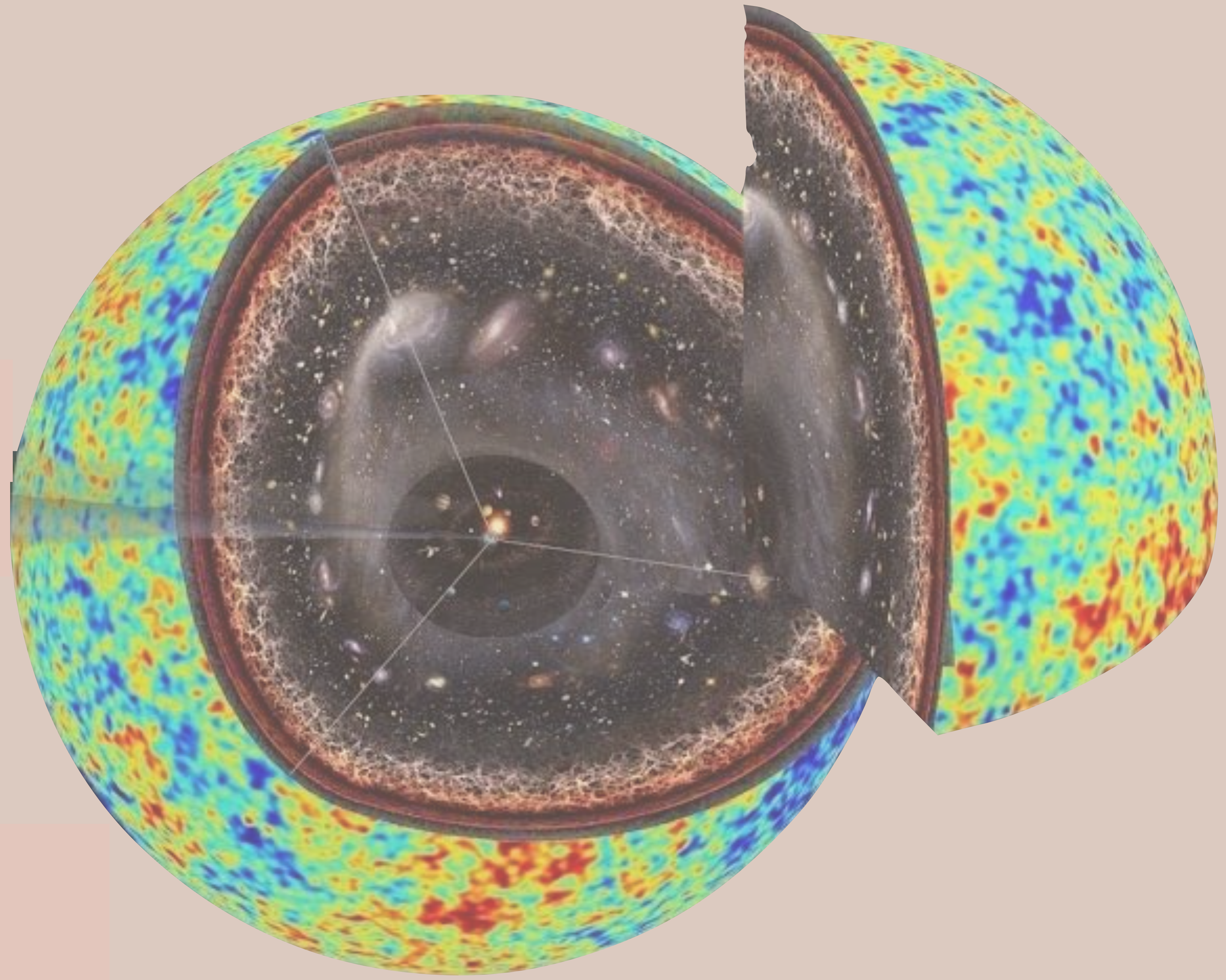
Cosmological Observables



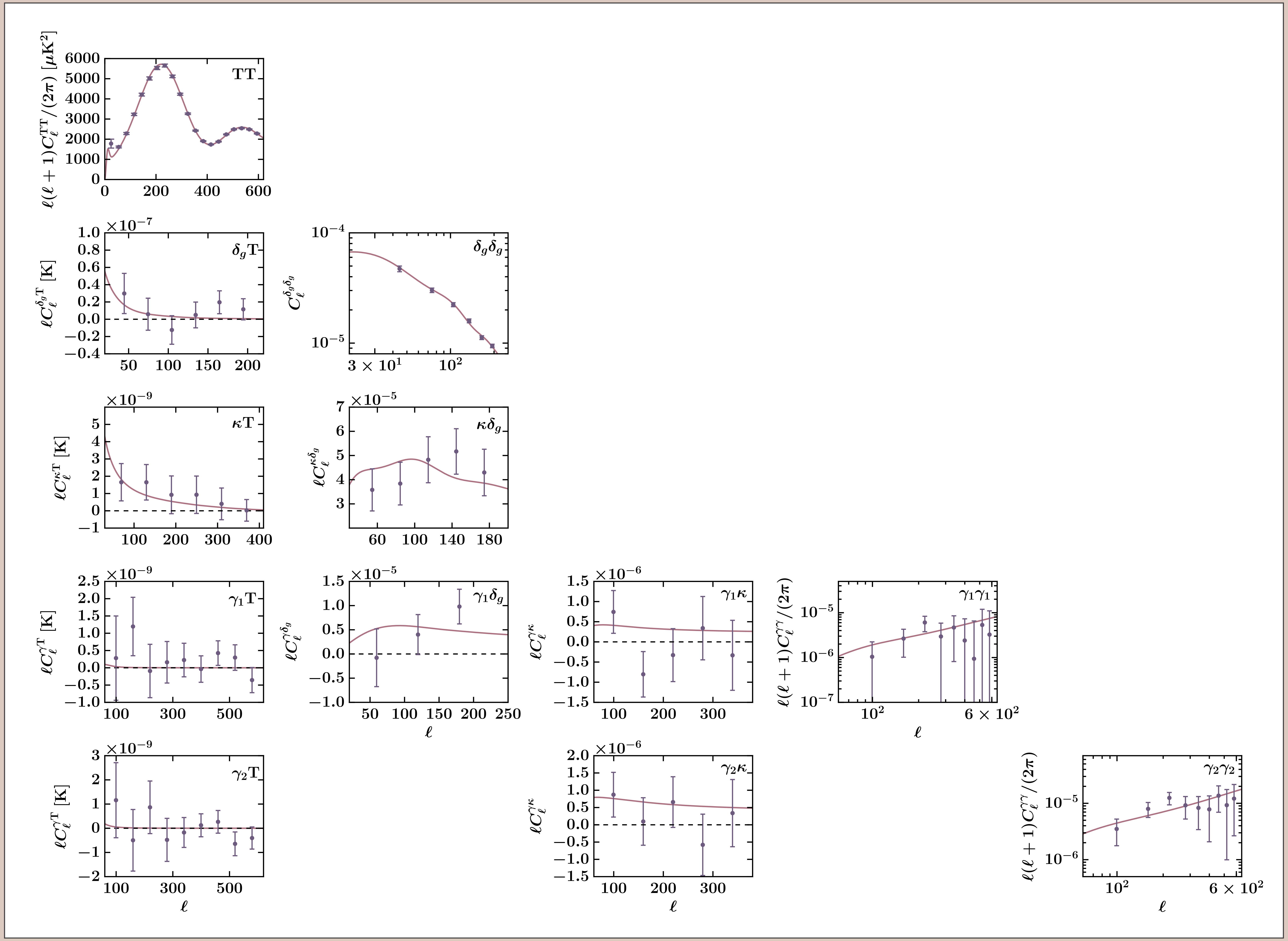
Images: Planck, Science, icons made by Freepik from www.flaticon.com

The Potential of Joint Analyses

- Robust constraints on ΛCDM & extensions due to complementarity
- Consistency tests of cosmological model
- Constraints on astrophysical systematics, e.g. baryon feedback
- Systematics calibration & identification



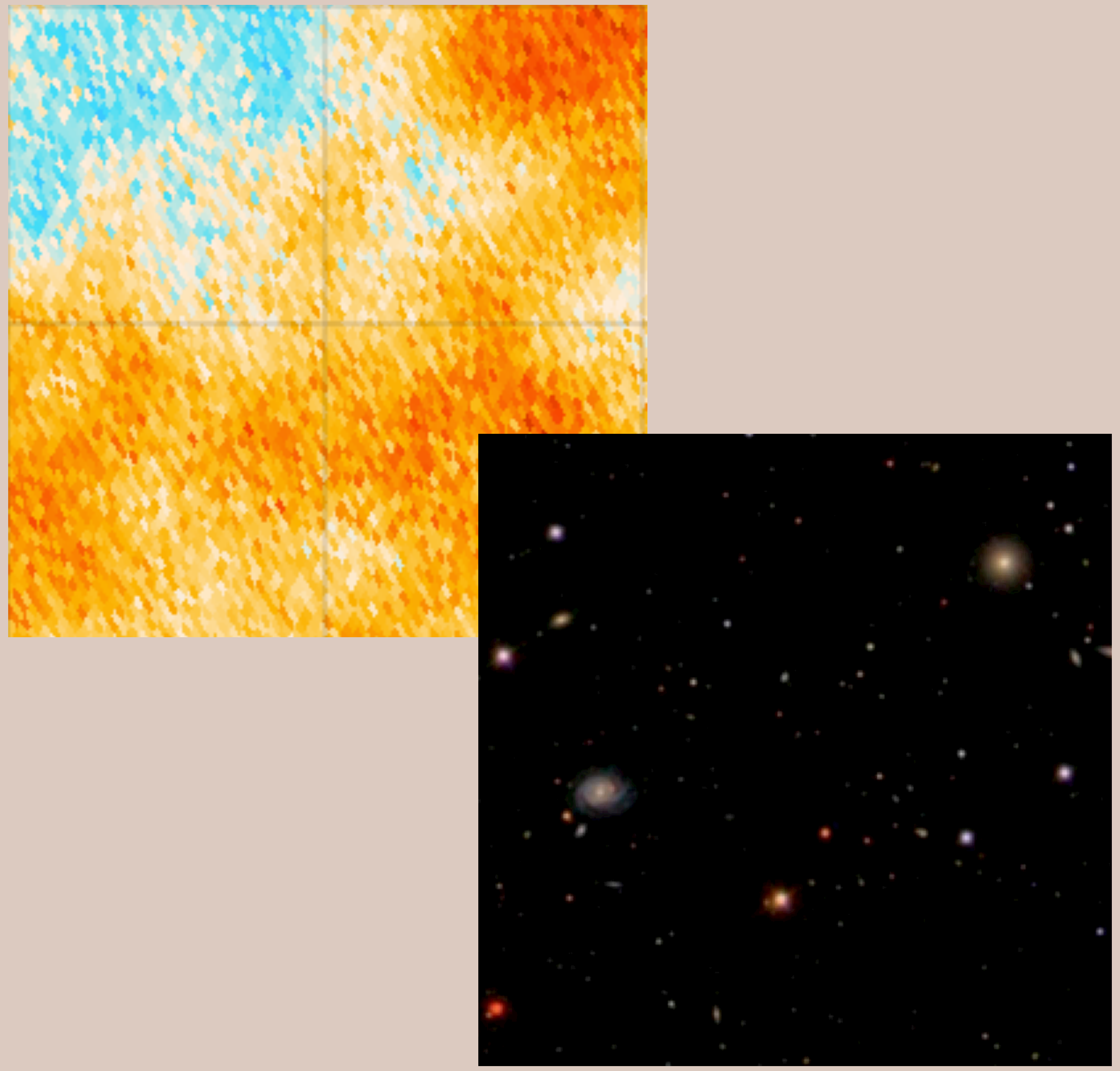
Power Spectra



Nicola et al., 2017

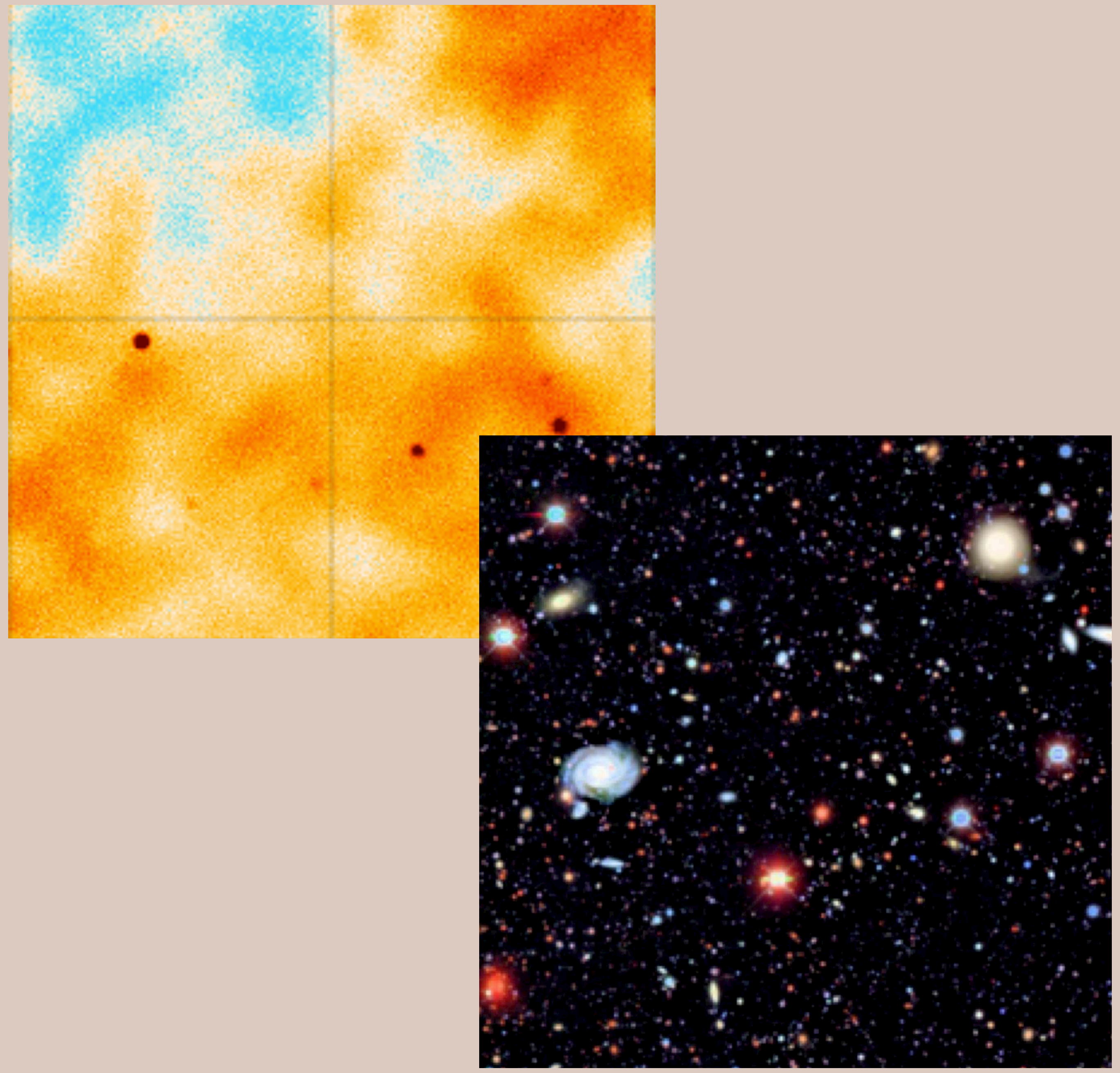
A New Era for Observational Cosmology

Past



e.g. SDSS, Planck

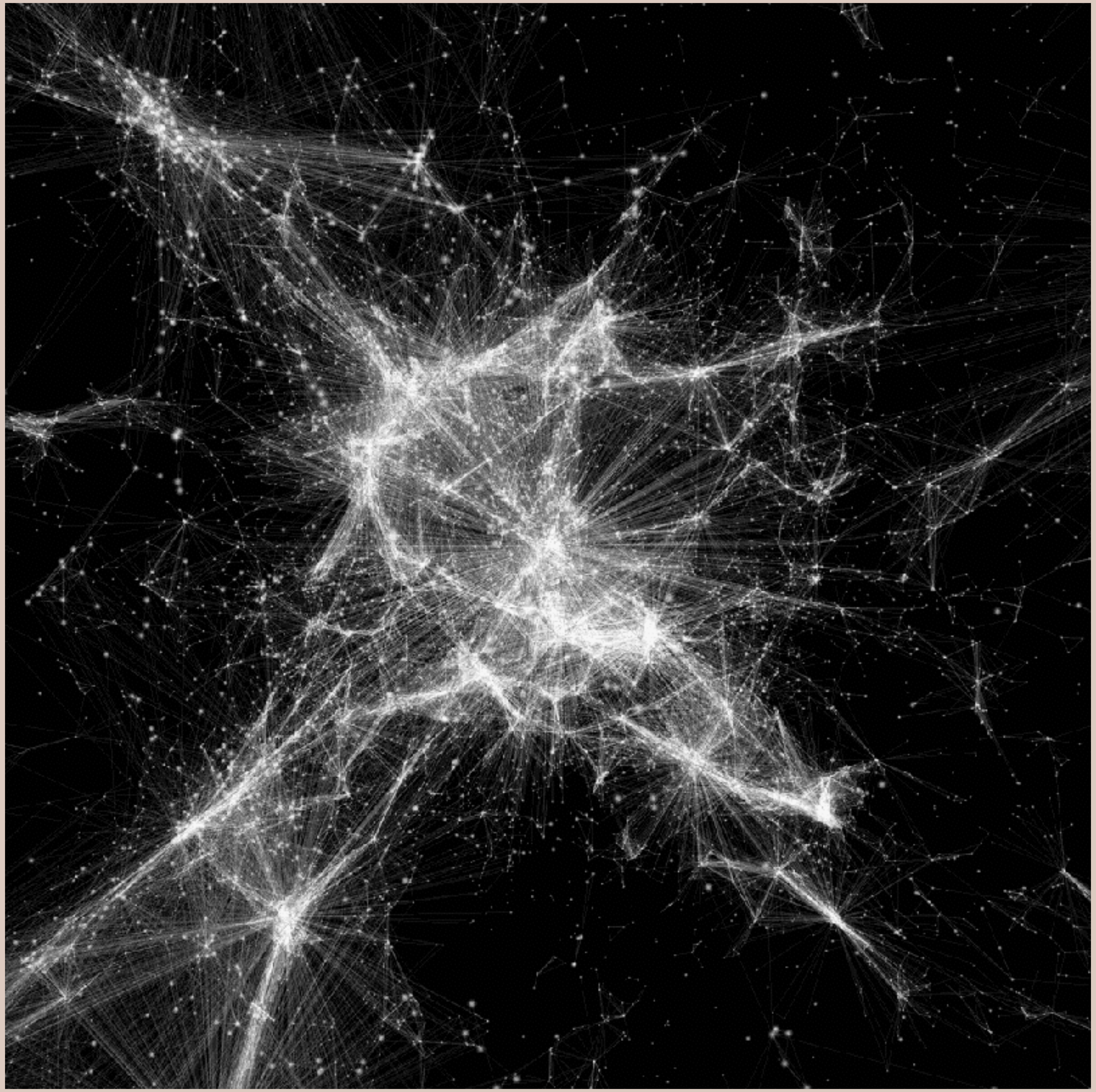
Present & Future



e.g. HSC, LSST/Rubin, ACT/SPT, CMB S4

Images: ACT, Ivezić et al., 2008

Our Non-Linear Universe



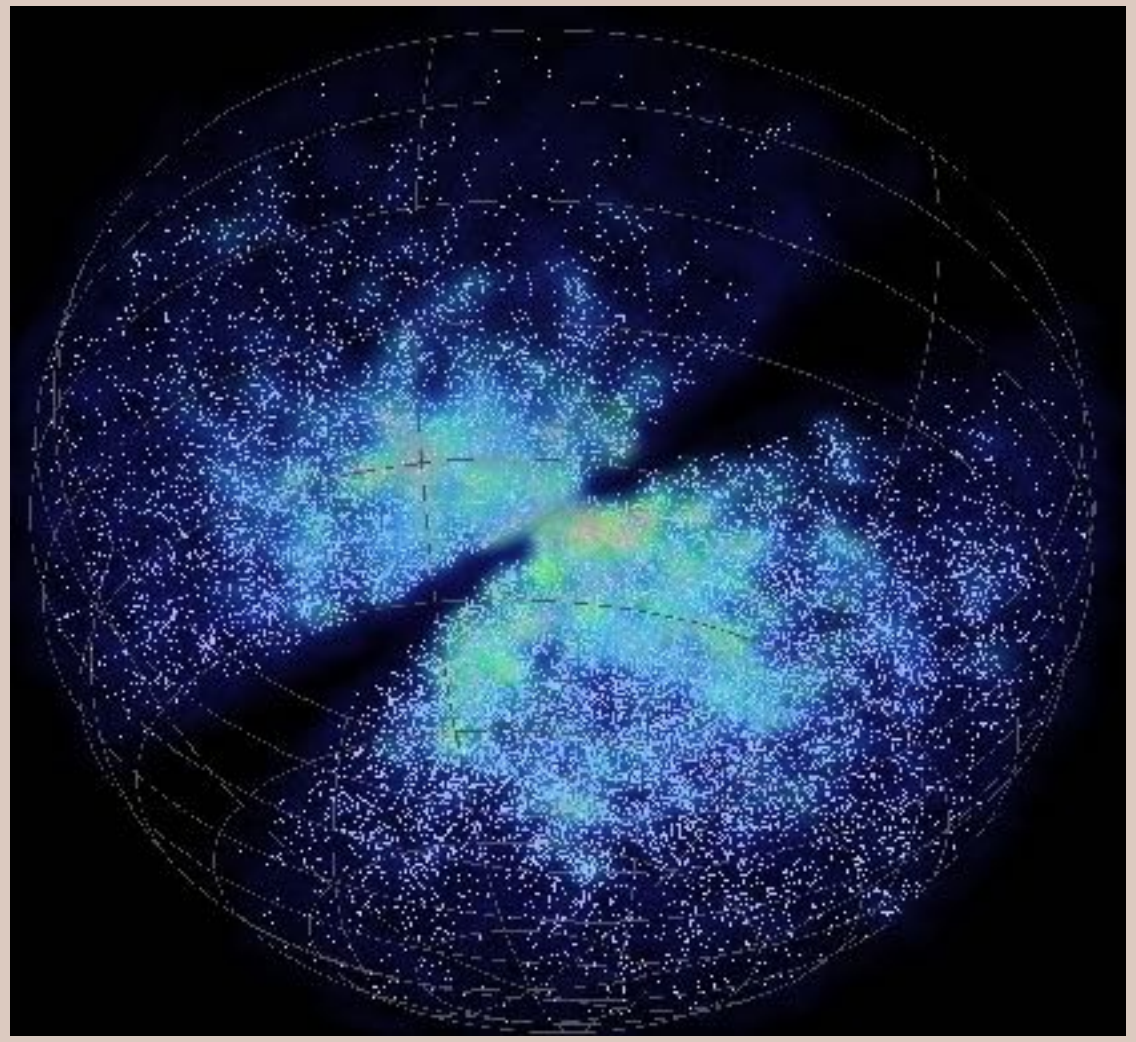
Additional information contained in:

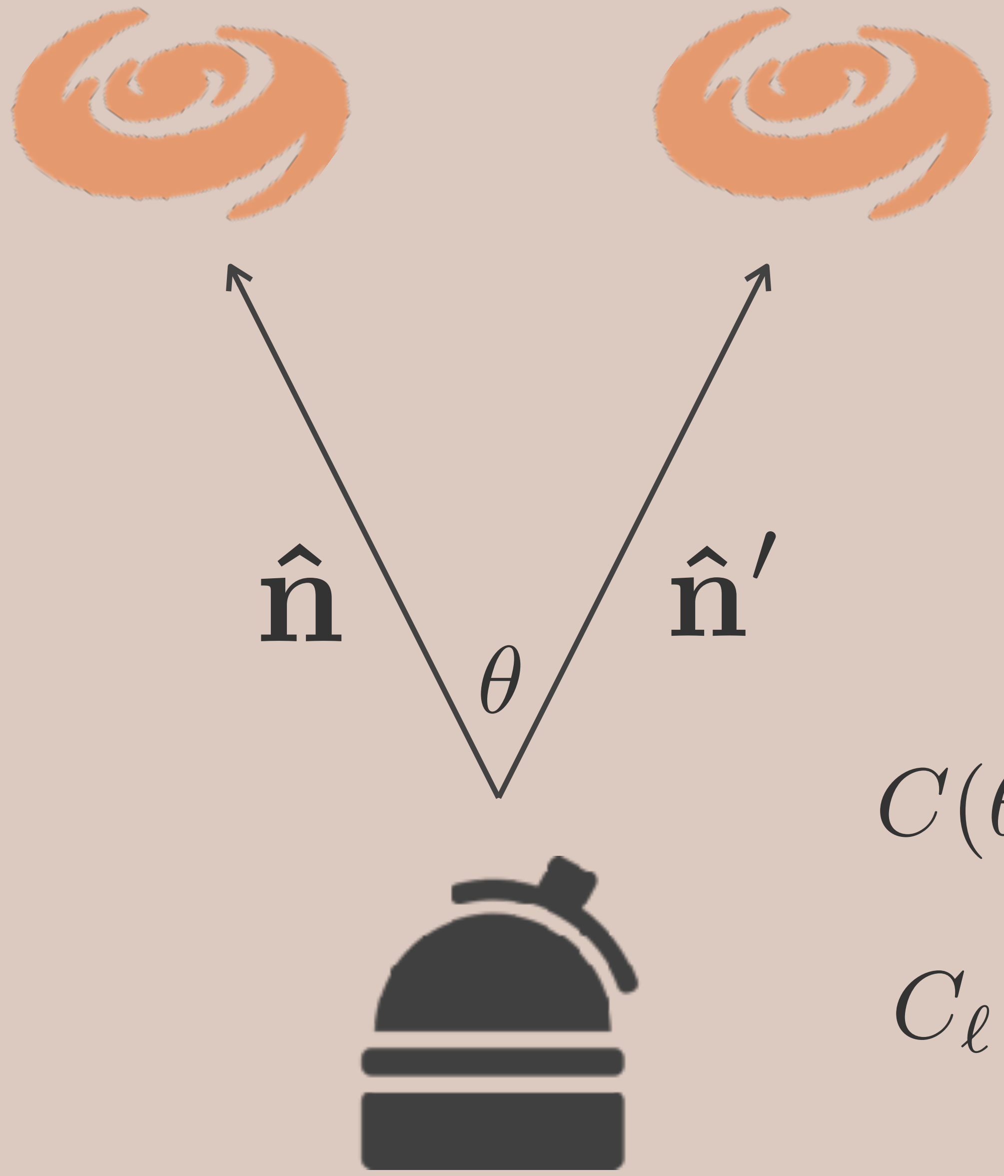
Cosmological fields at small spacial scales

Non-Gaussian features

Image: Ilustris Collaboration / Illustris Simulation

Galaxy Clustering





$$C(\theta) = \langle \delta(\hat{\boldsymbol{n}})\delta(\hat{\boldsymbol{n}}') \rangle$$

$$C_\ell = \langle \delta_{\ell m} \delta_{\ell m} \rangle$$

Images: 6dF, Science News

HSC Photometric Clustering within LSST DESC

Apply/test LSST pipeline on LSST-like data set

Test viability of tomographic Fourier space analysis for photometric clustering

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

Include small-scale information

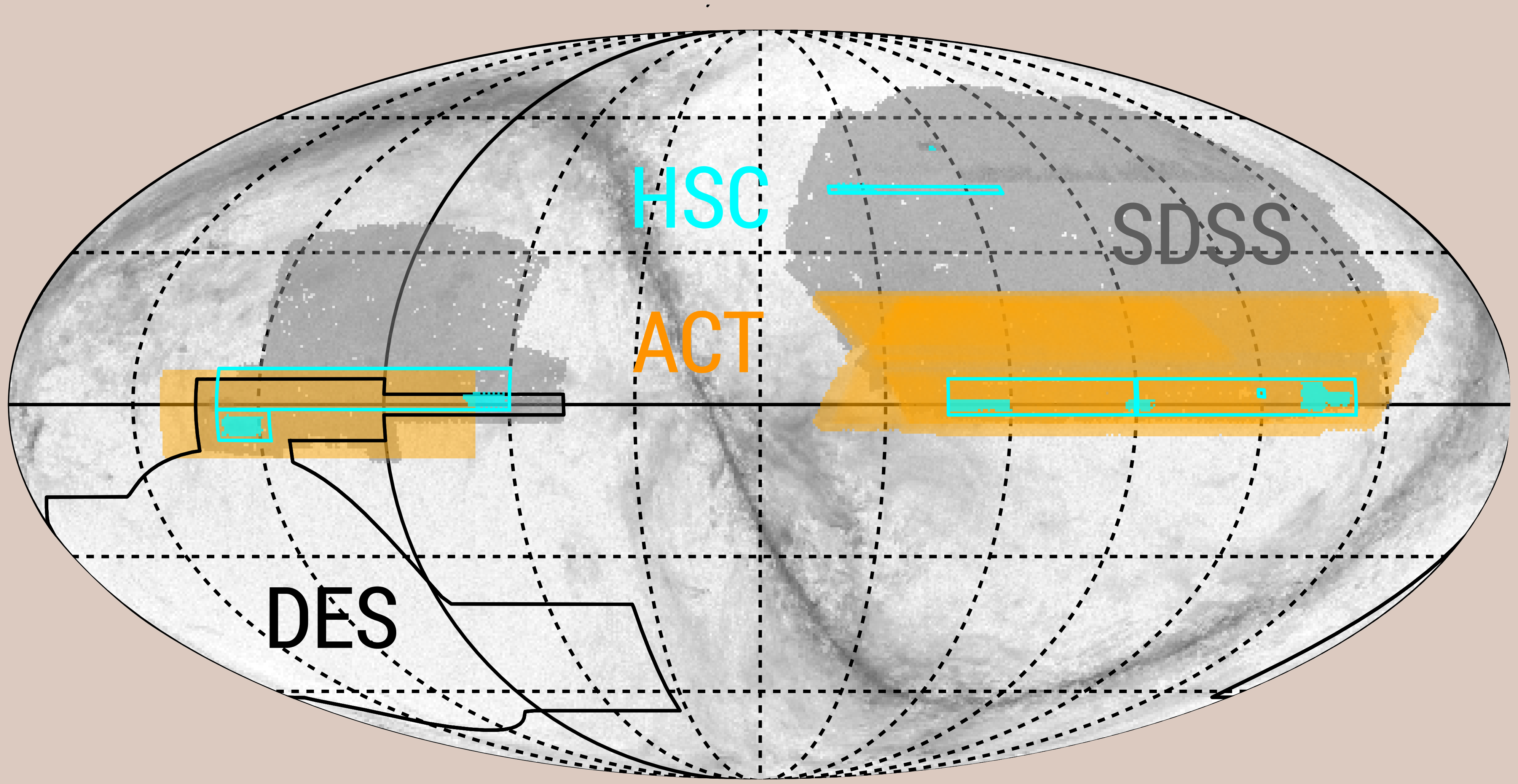
The Hyper Suprime Cam Survey (HSC) as a Precursor for LSST

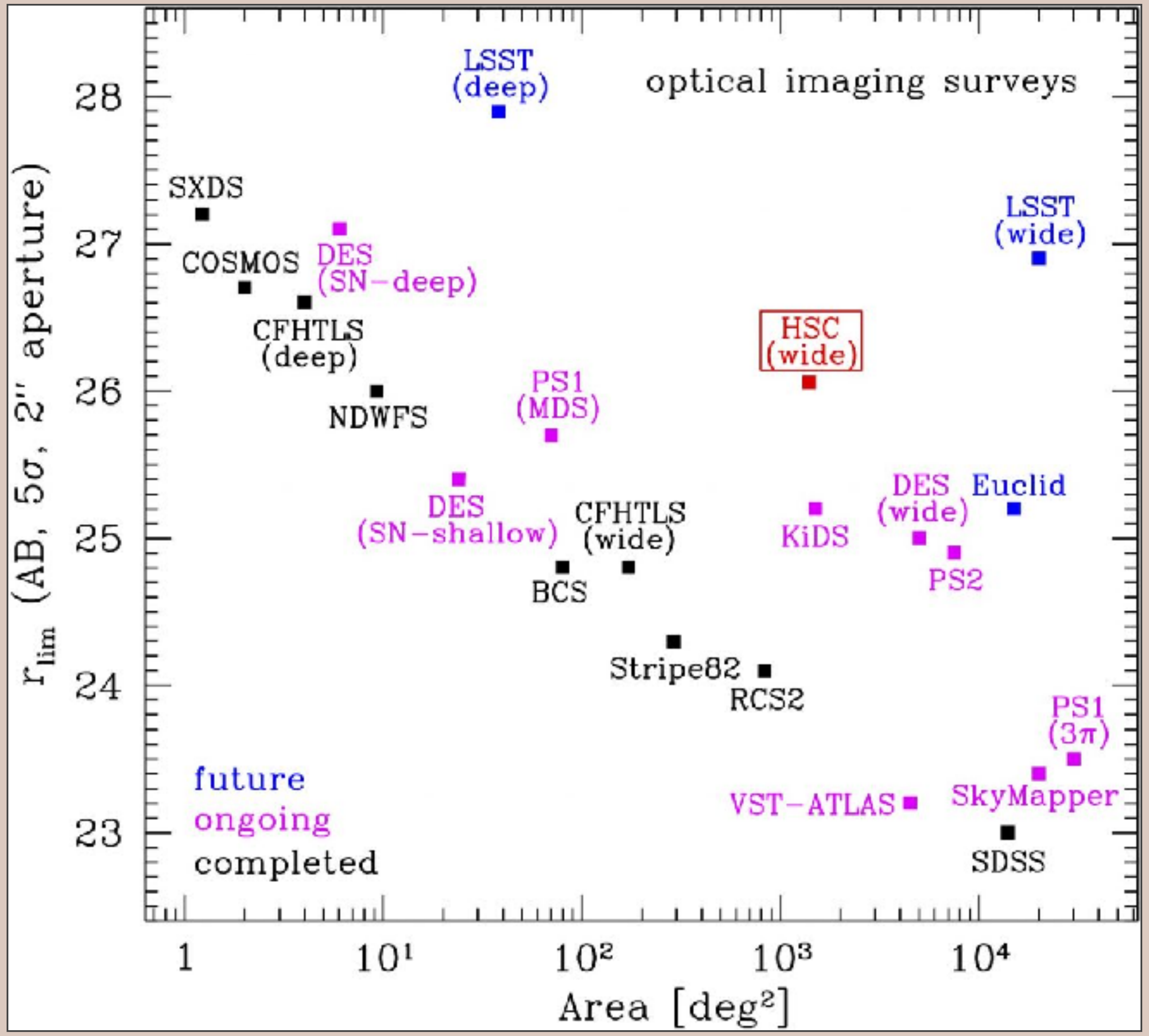
HSC area: 1000 sq. deg.

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

Precursor to LSST

Most analyses focused on 150 sq. deg. (DR1)





Survey table: HSC SSP, footprint: E. Medezinski

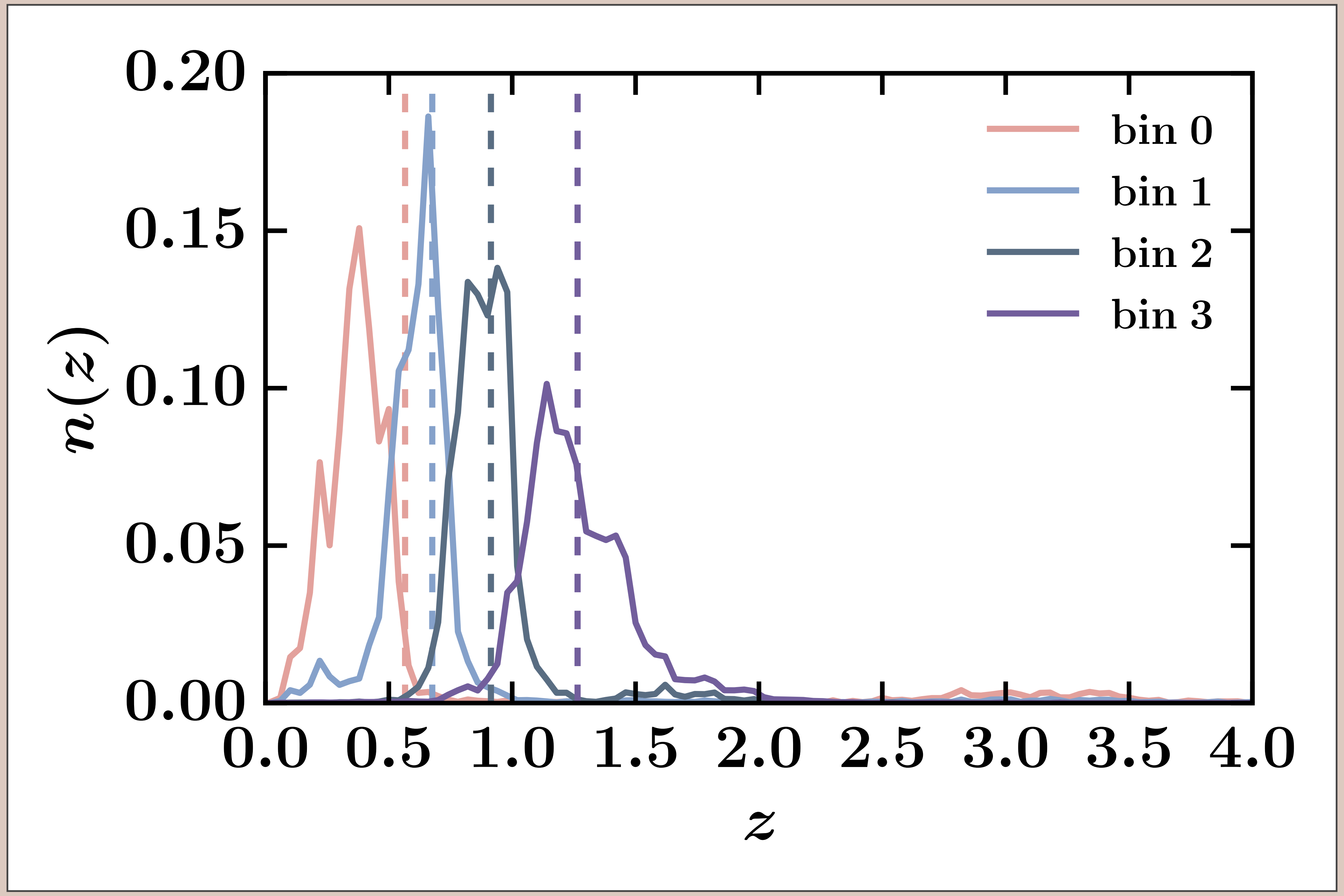
Sample Selection

HSC DR1 data

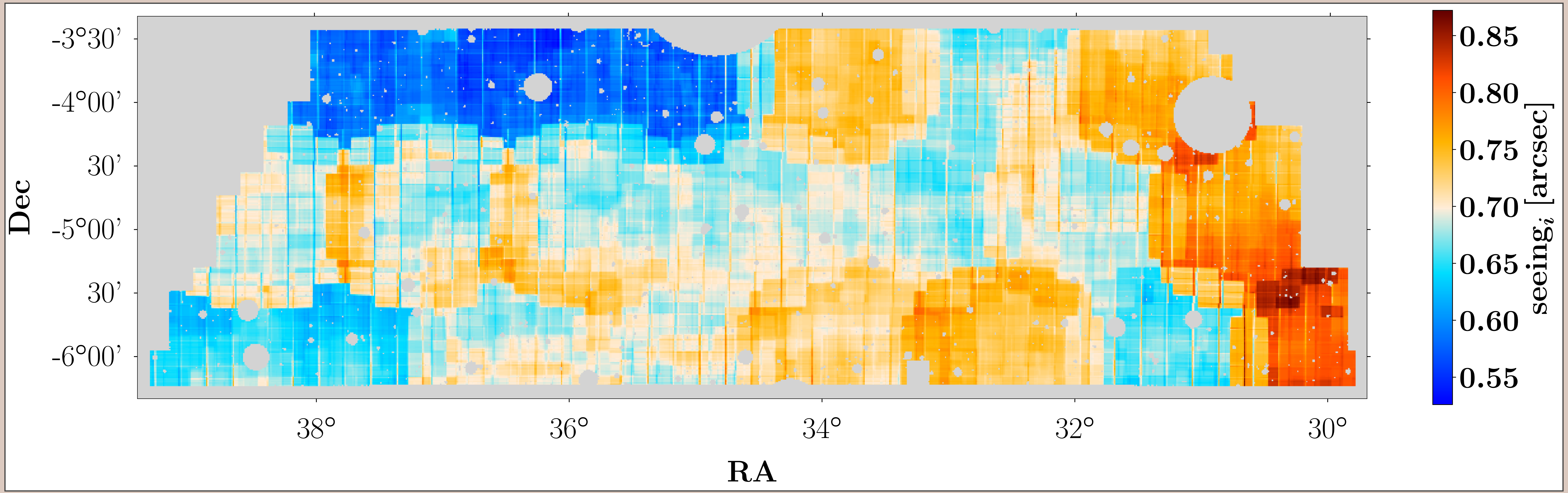
Galaxies with $mag_i < 24.5$

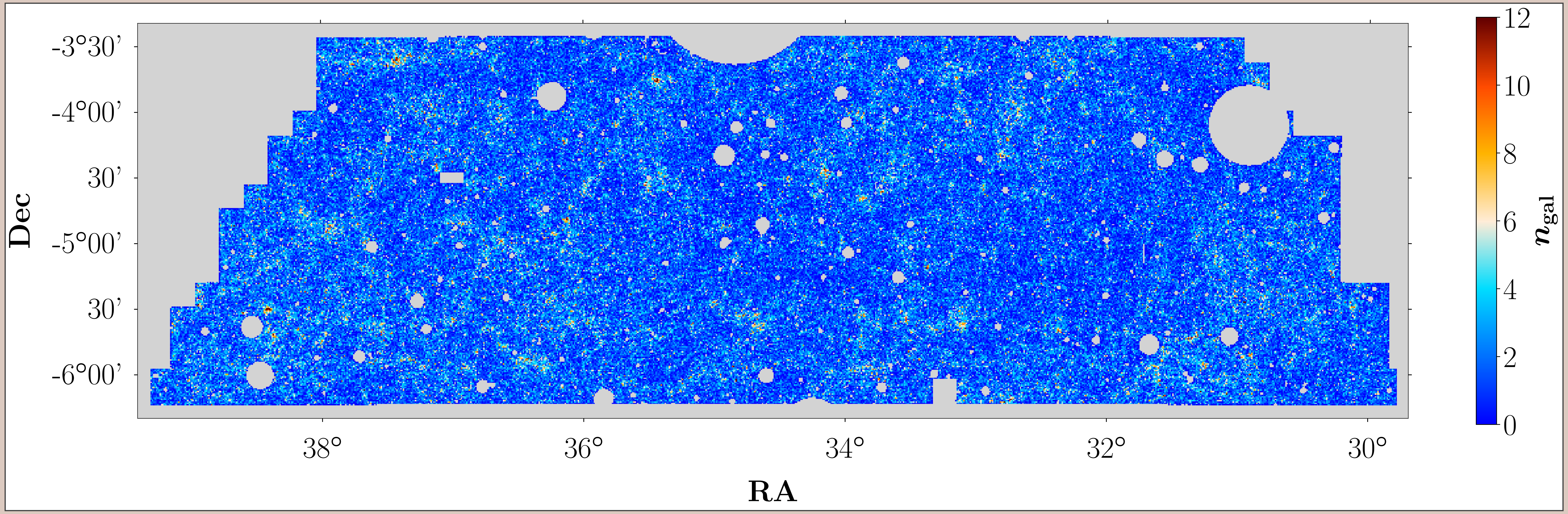
4 redshift bins: 0.15-0.50, 0.50-0.75,
0.75-1.00, 1.00-1.50

Photo-z: COSMOS reweighting

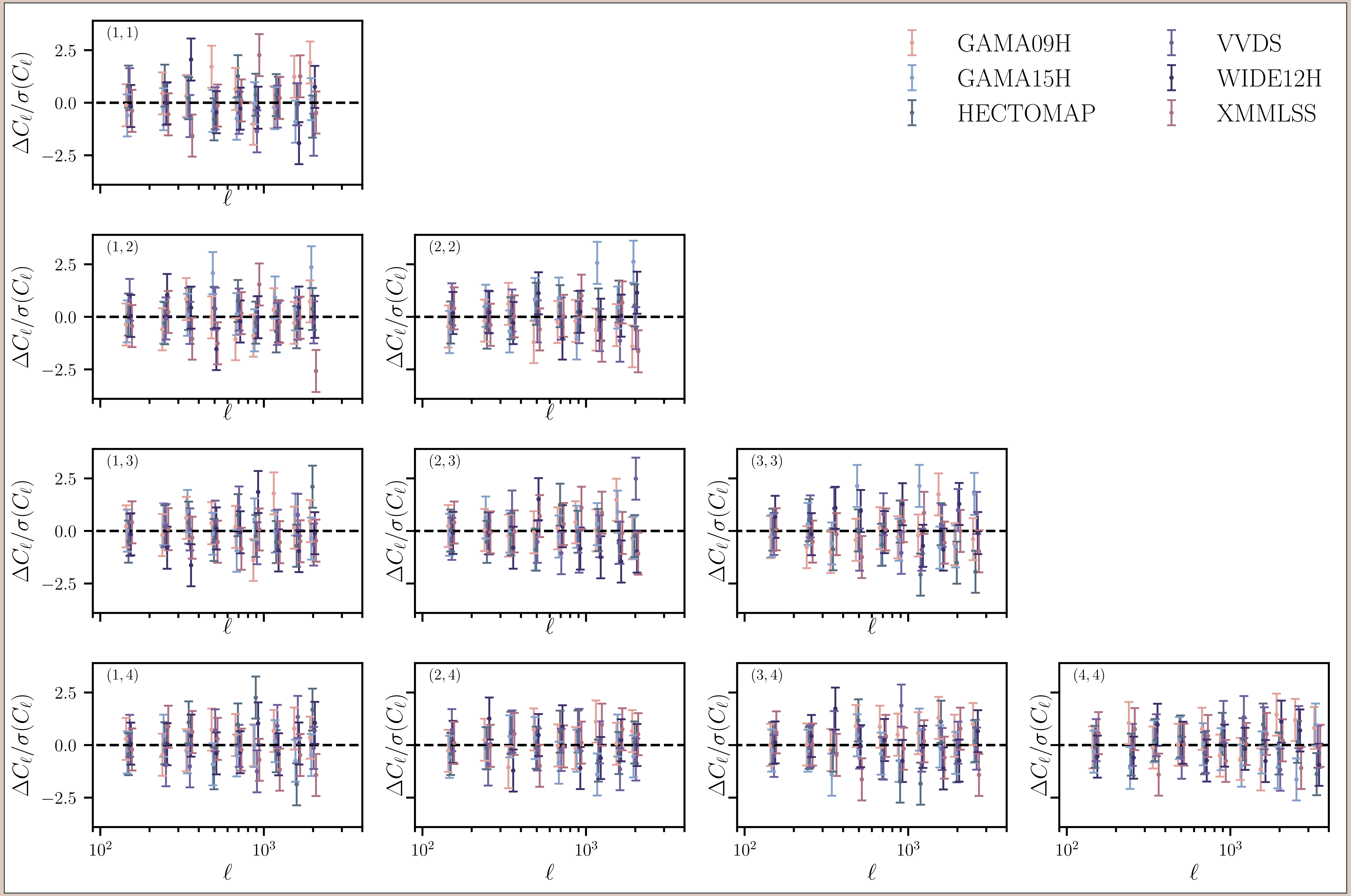


Systematics & Signal Maps





Power Spectrum Consistency Tests

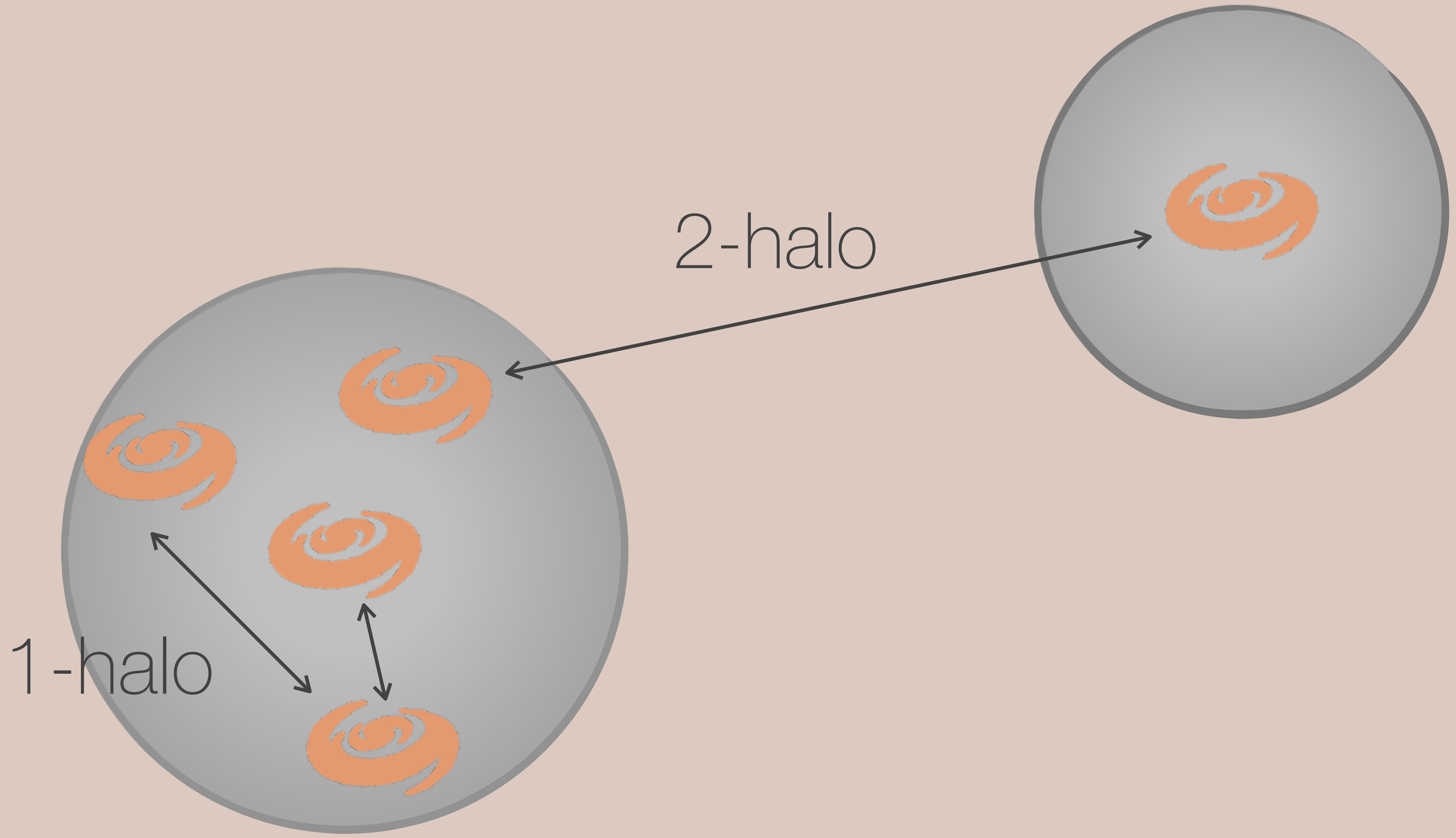


Theoretical Modeling

Small-scale clustering (k_{max} ~ 1 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*)



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

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

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

HOD Modeling Details

Redshift-dependent 6-parameter HOD model

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

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

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

where

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

Fiducial model

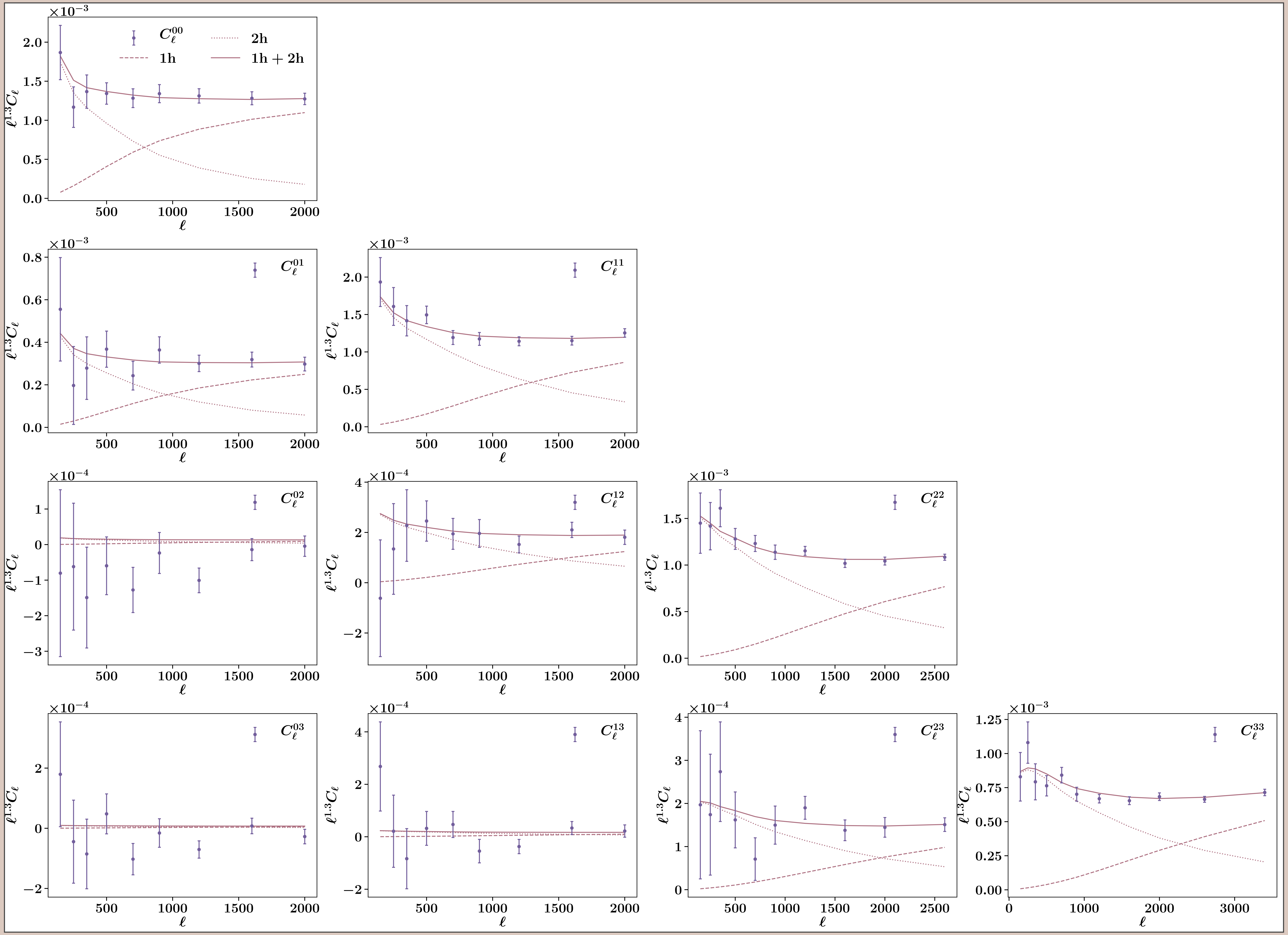
Redshift-dependent 3(+3)-parameter HOD: $M_{\min}(z)$ $M_0(z)$ $M_1(z)$

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

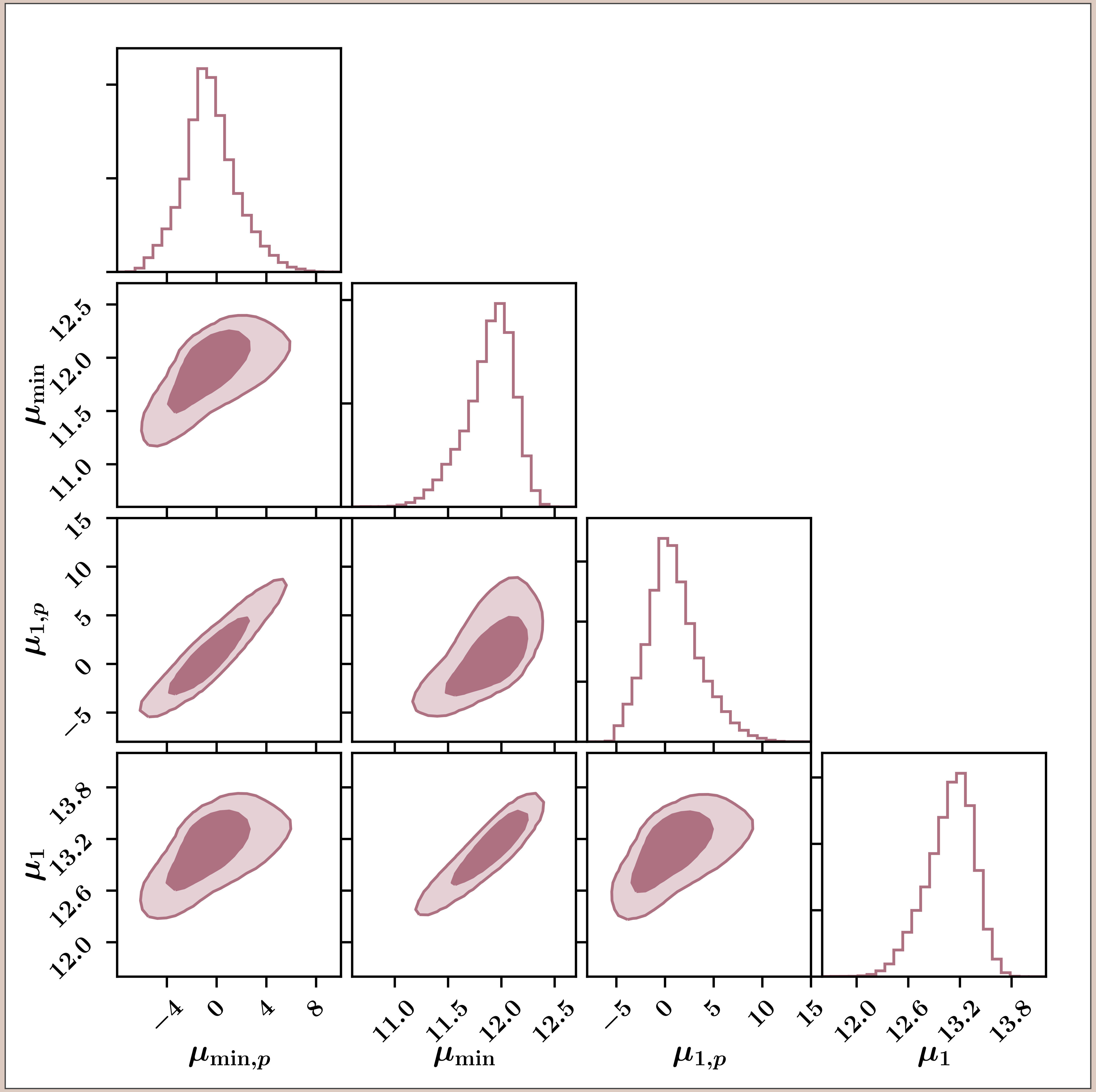
Cosmological parameters fixed to Planck 2018

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

Power Spectra

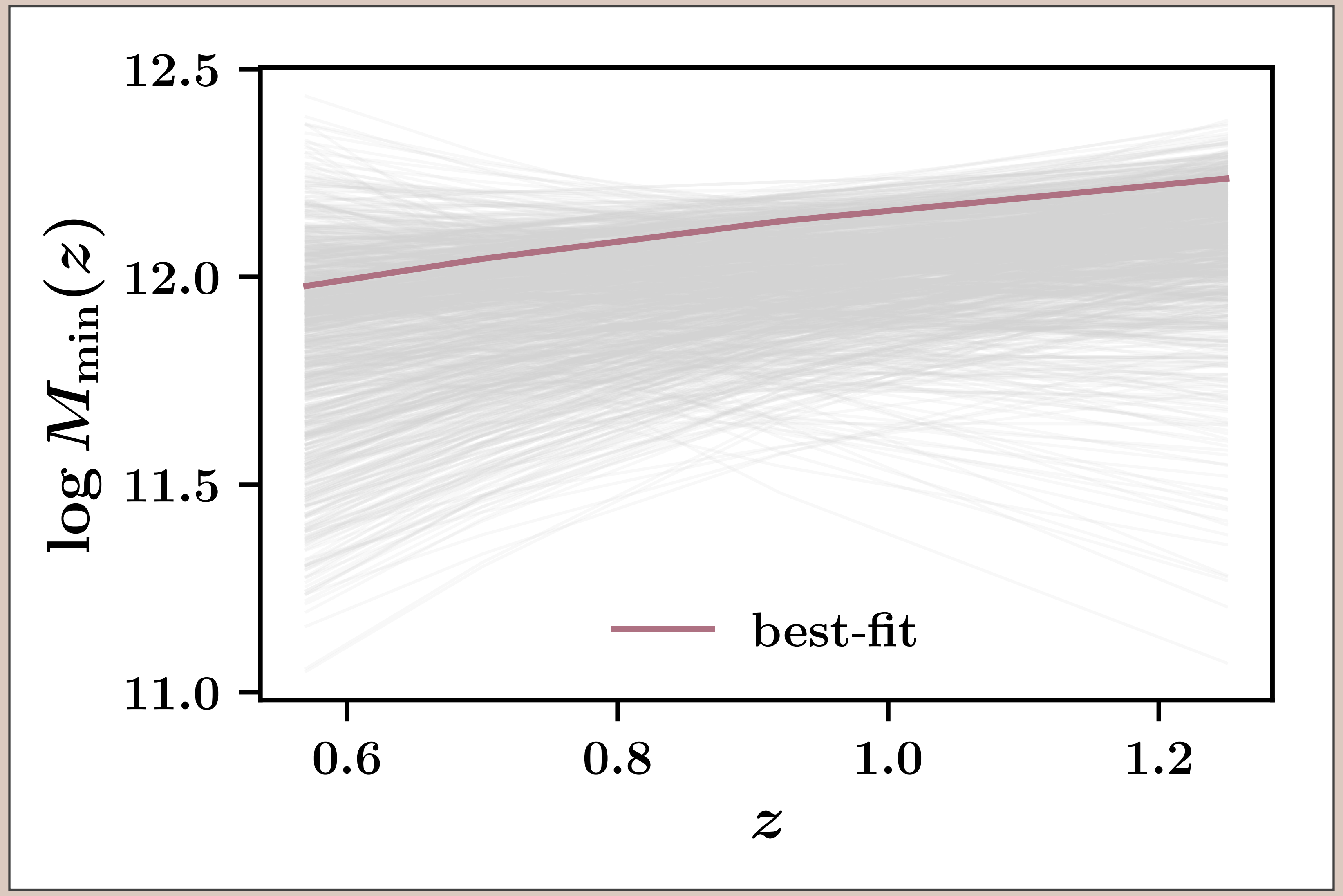


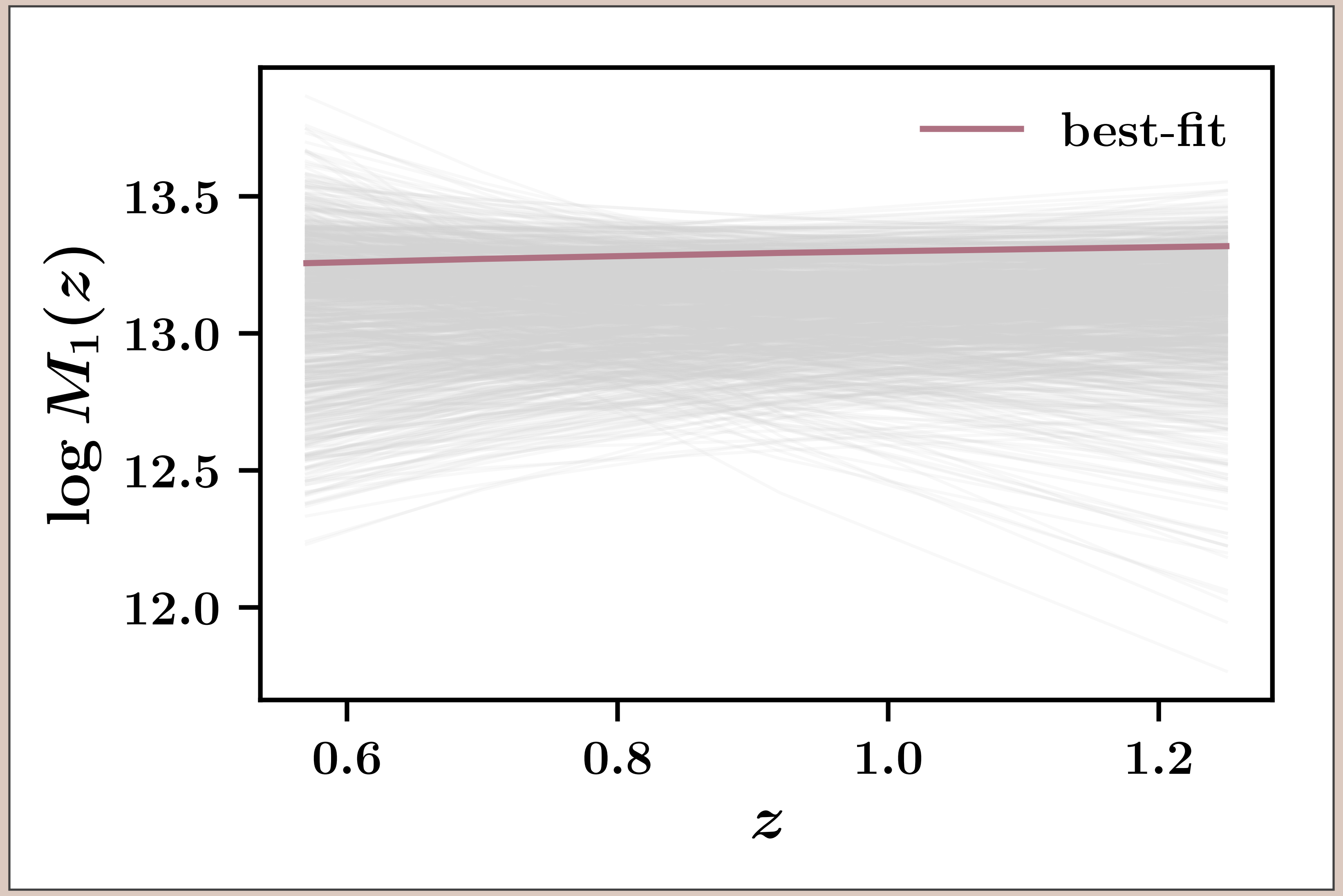
HOD Constraints

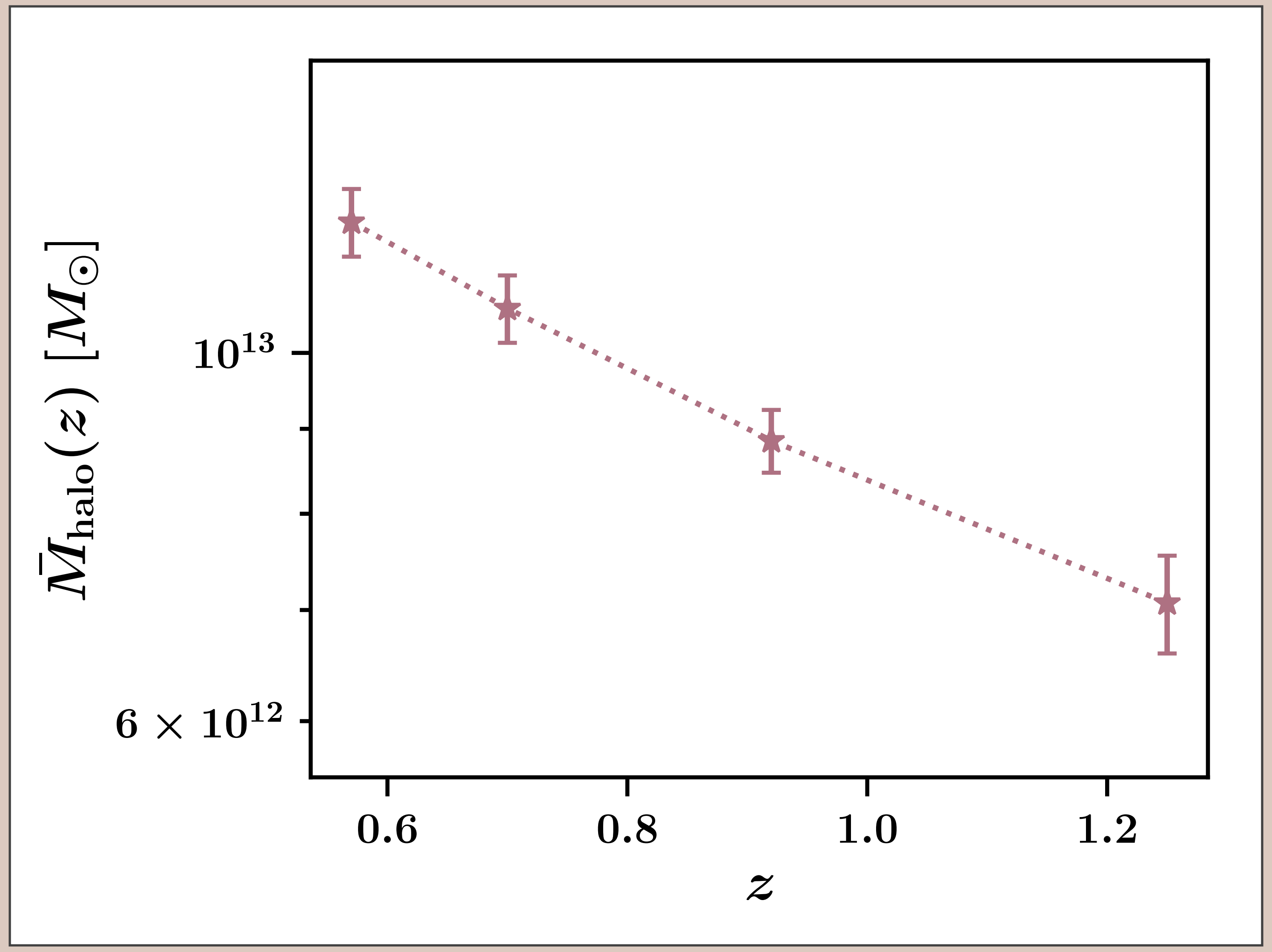


Nicola et al., 2020

HOD Redshift Evolution

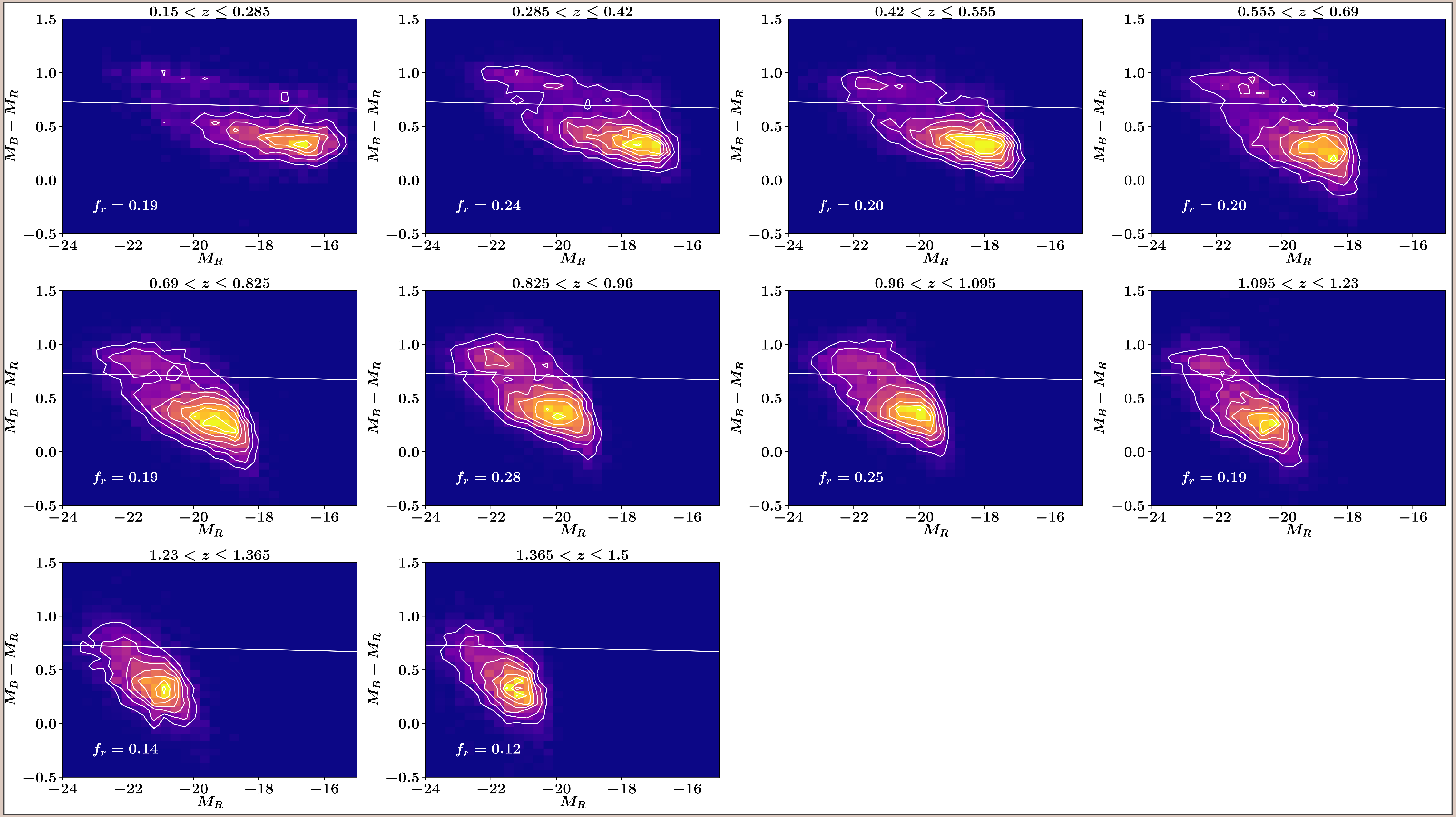




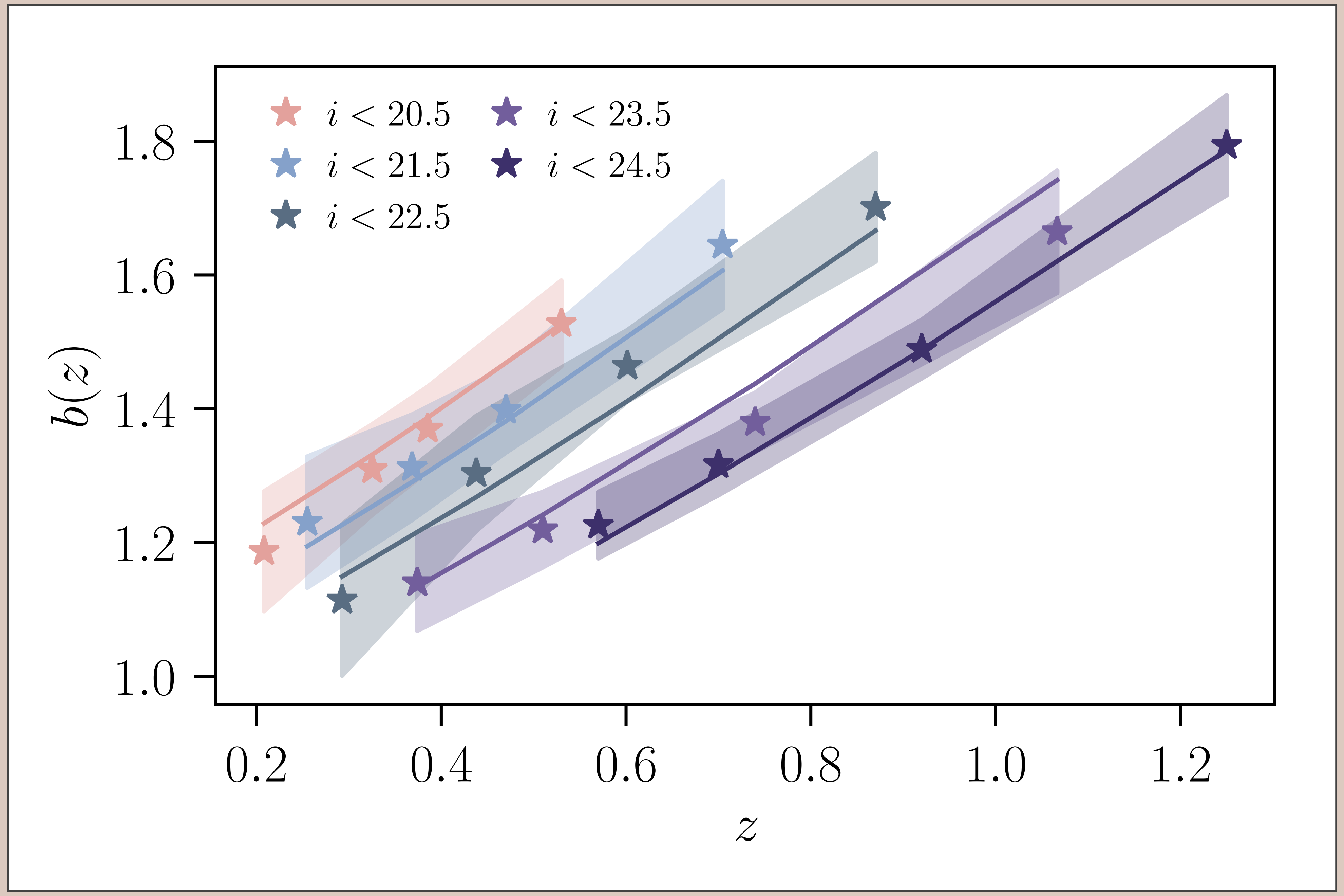


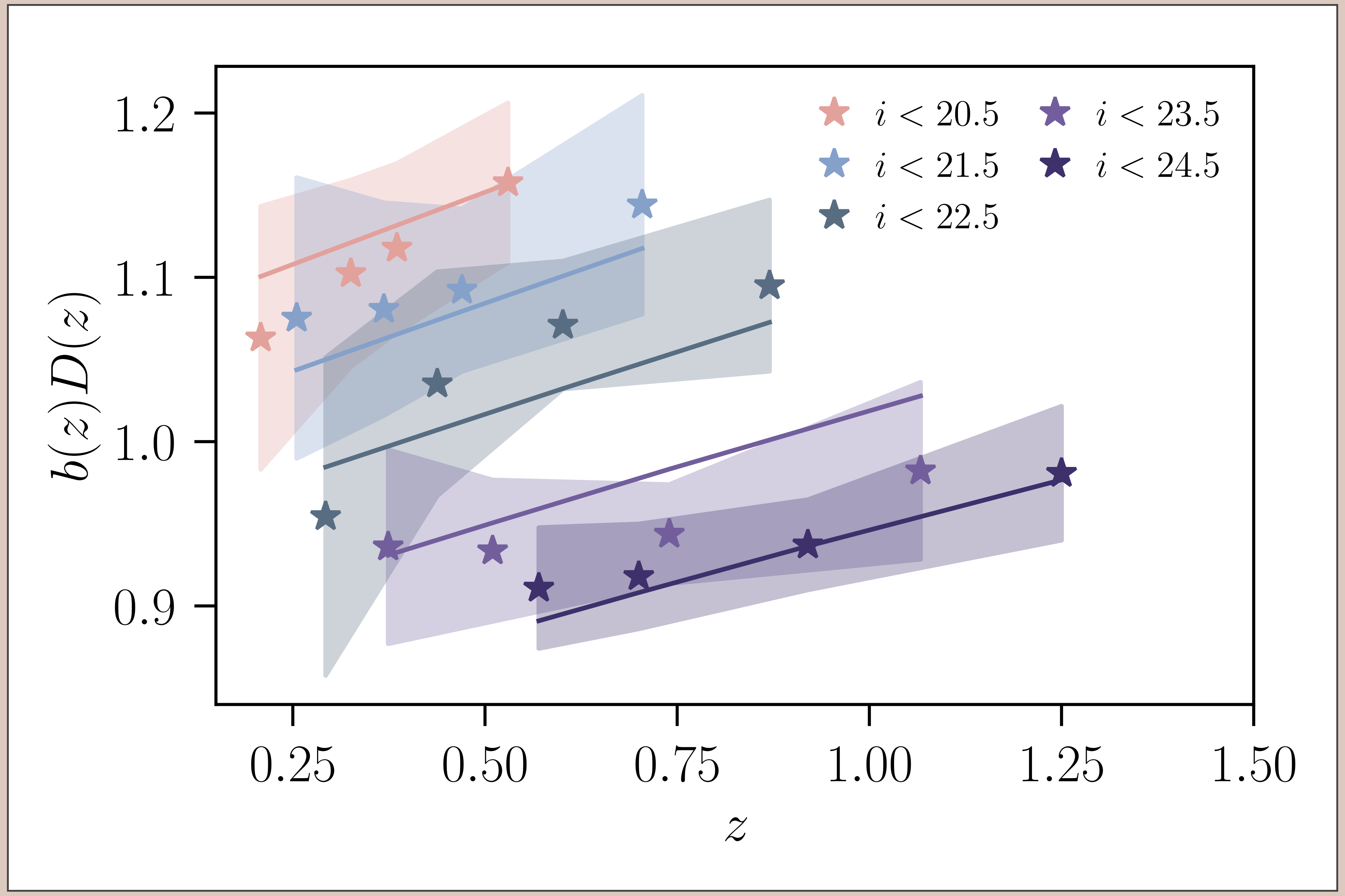
Nicola et al., 2020

Properties of Galaxy Sample



Galaxy Bias for Magnitude-Limited Samples

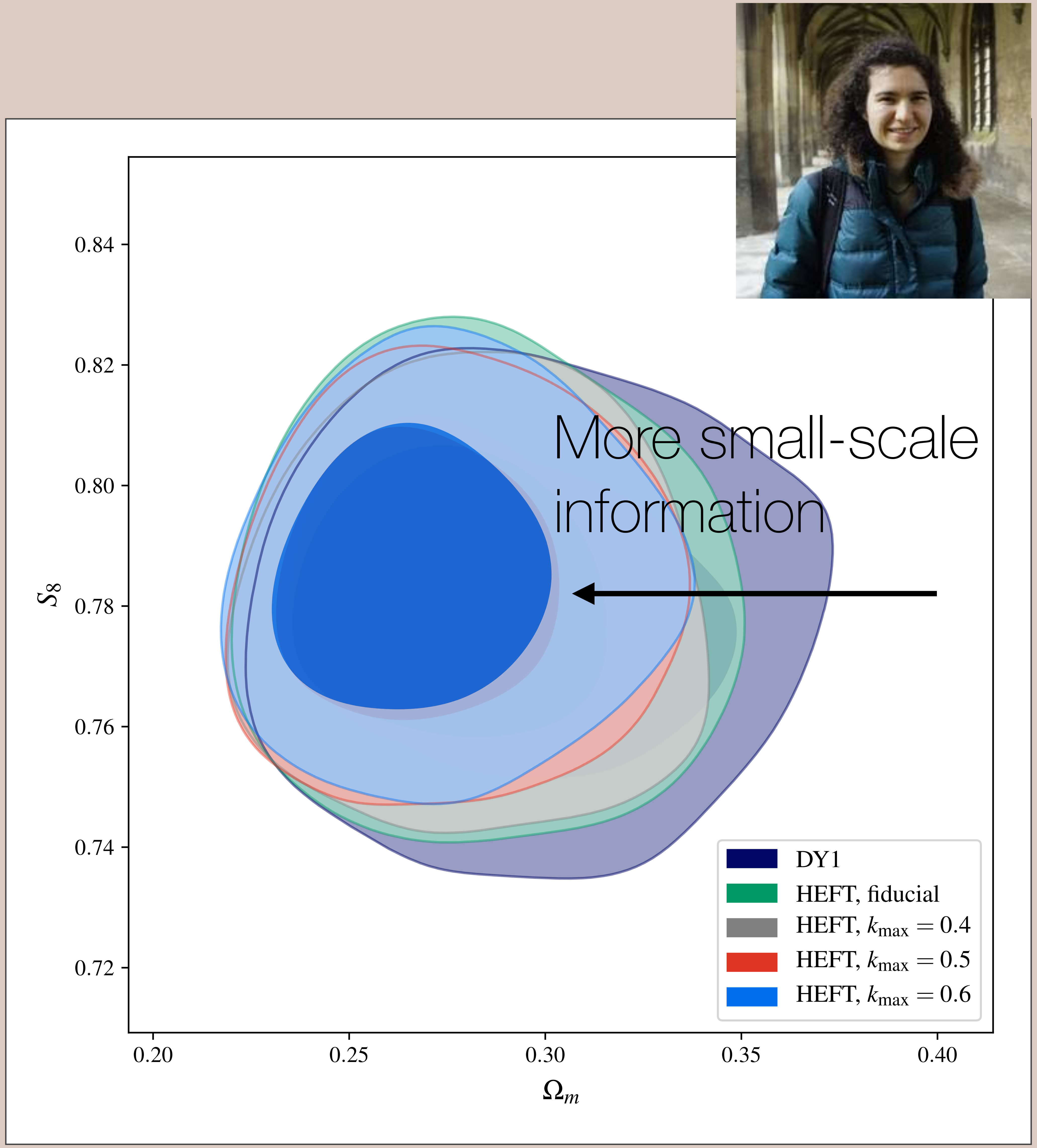




$$b(z, m_{\rm lim}) = \bar{b}(m_{\rm lim}) D(z)^{\alpha}$$

Nicola et al., 2020

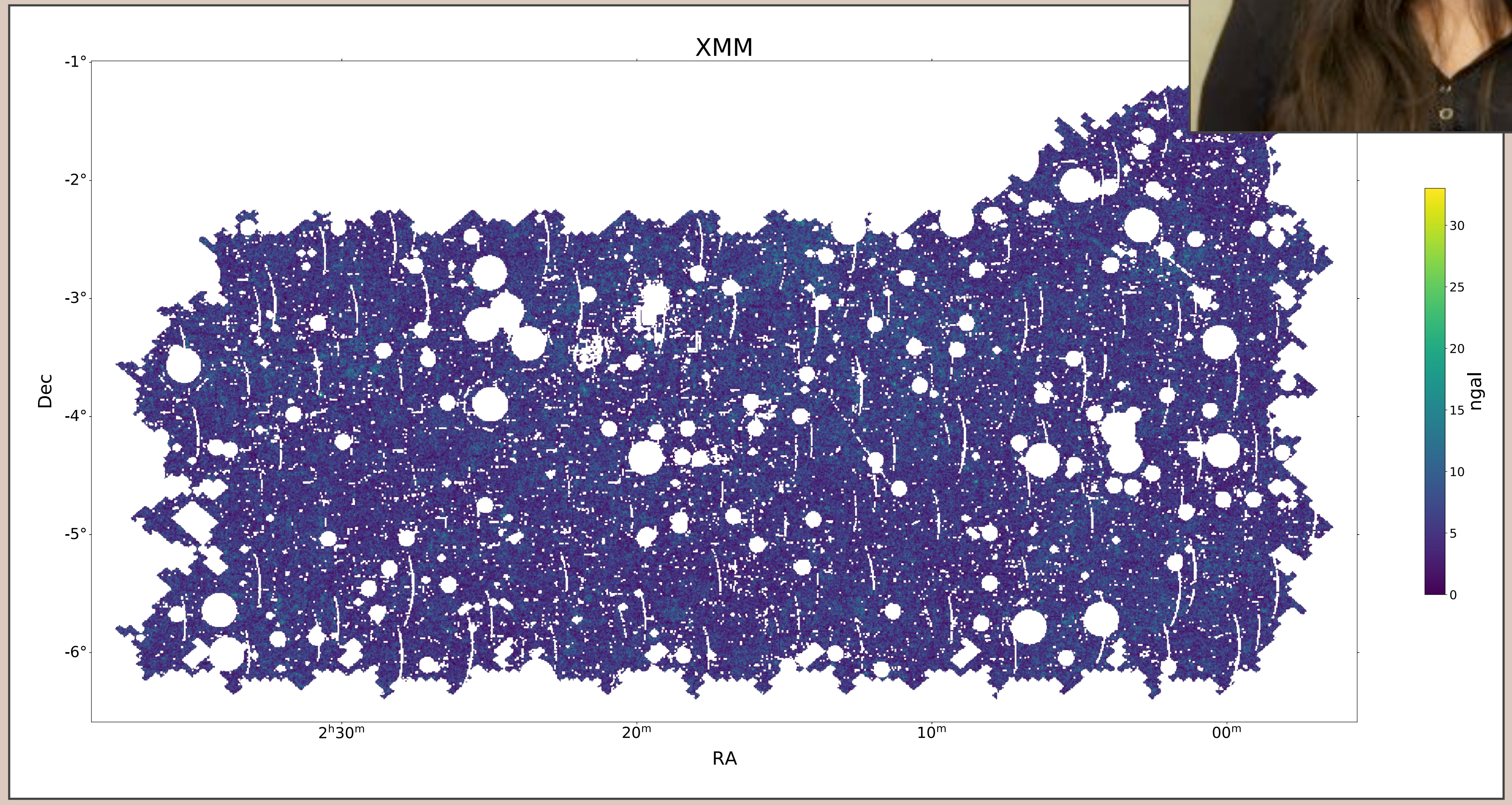
Small-Scale Power Spectrum



Hadzhiyska et al., 2021

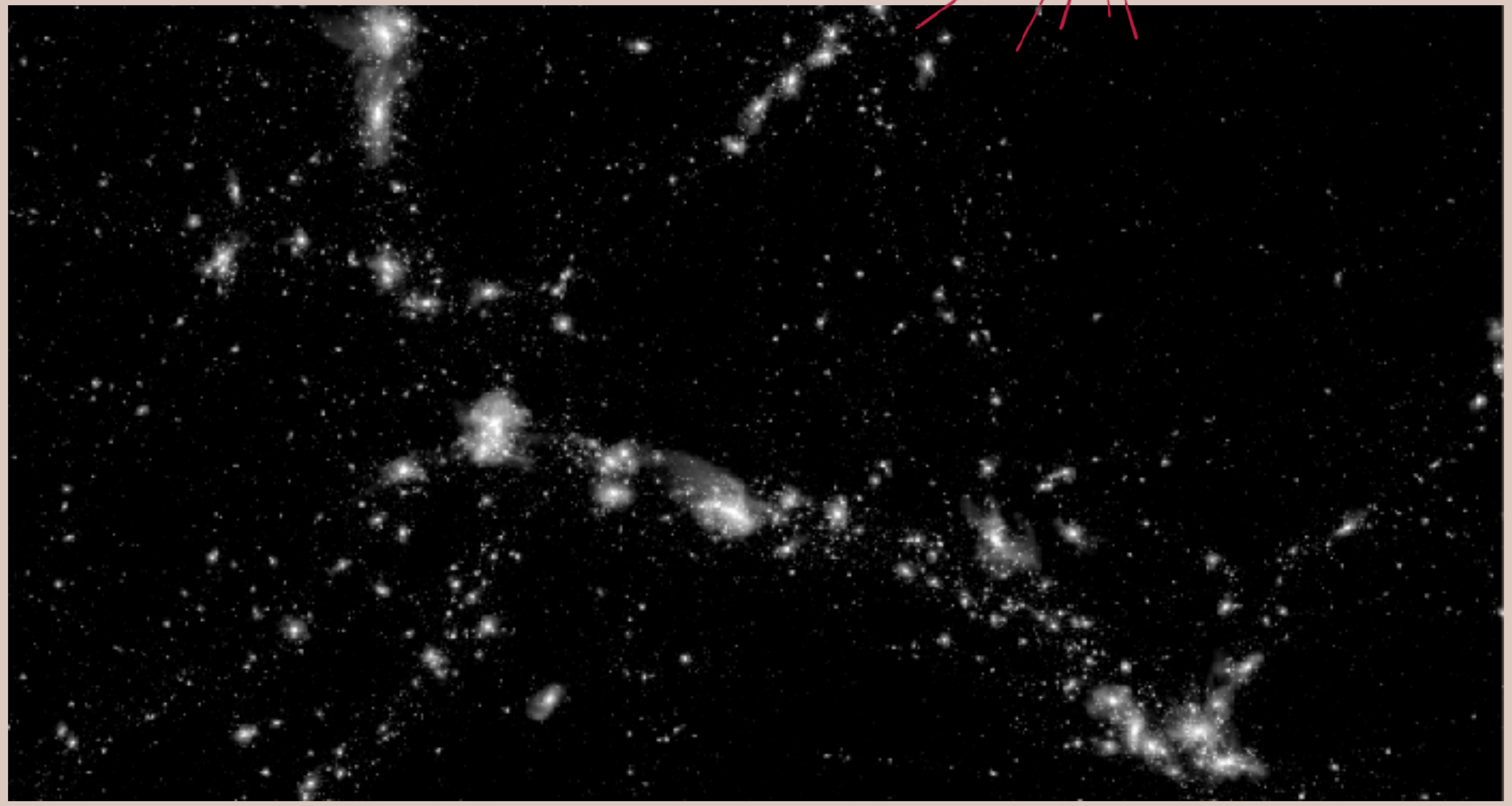
Small-Scale Power Spectrum - Ongoing Work

Galaxy Clustering with HSC DR3

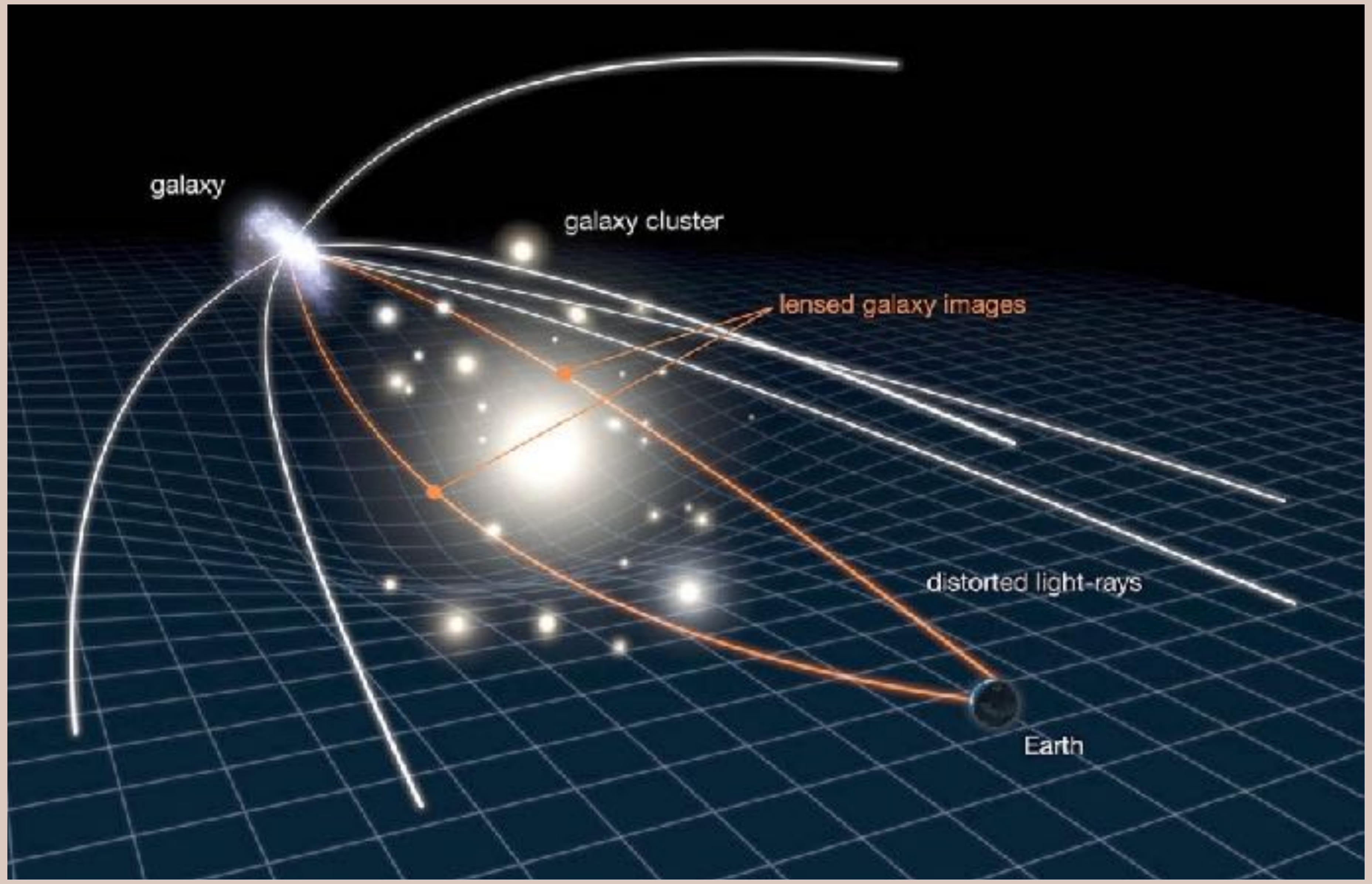


Dalal et al., in prep.

LSST DESC Bias Challenge

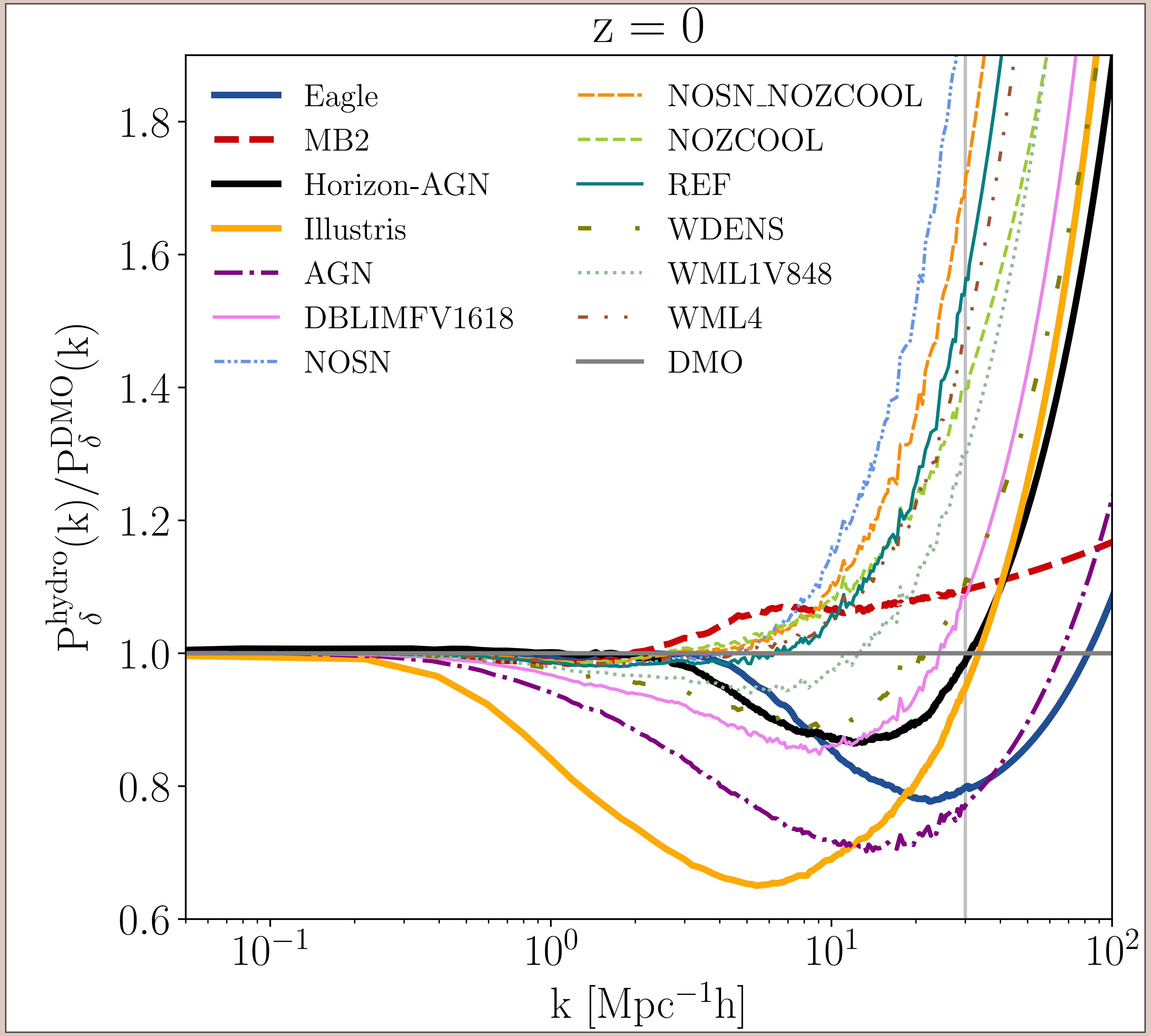


Weak Gravitational Lensing



Images: NASA/ESA, radioGREAT, NASA/STScI

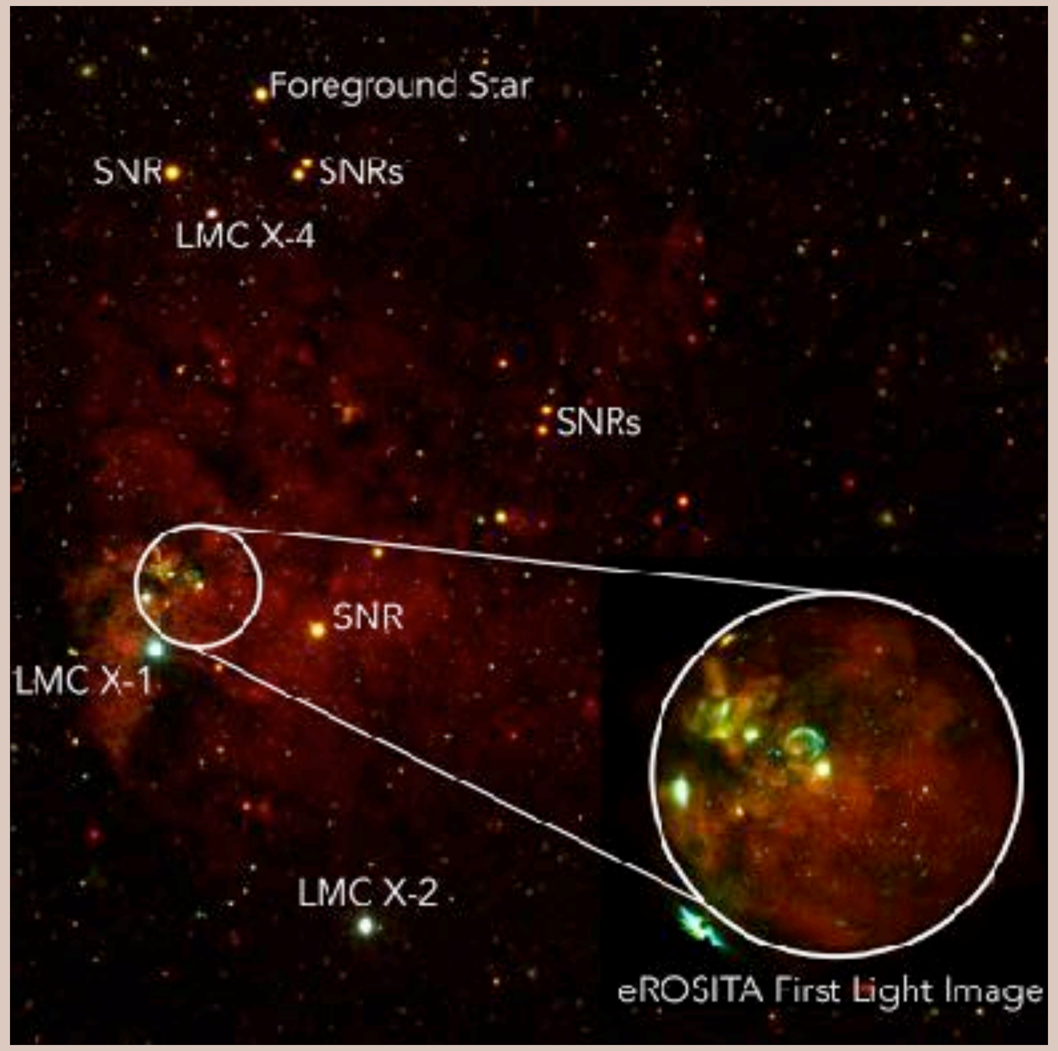
Accessing Small-Scale Information with Weak Lensing



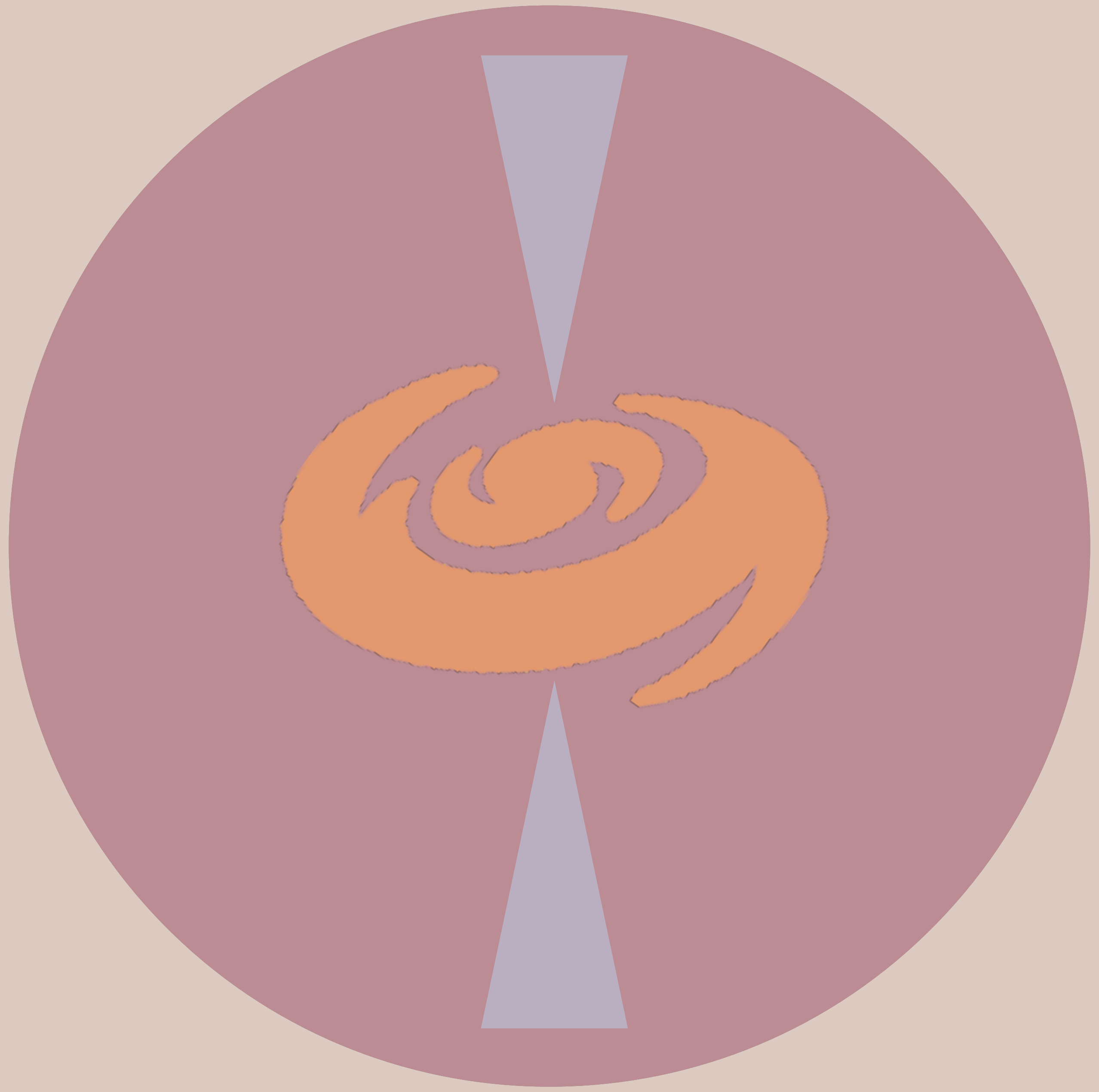
Images: S. Skillman, Y-Y. Mao, KIPAC/SLAC National Accelerator Laboratory, Huang et al., 2019

Constraining Cosmology & Baryon Physics from 2pt-Functions

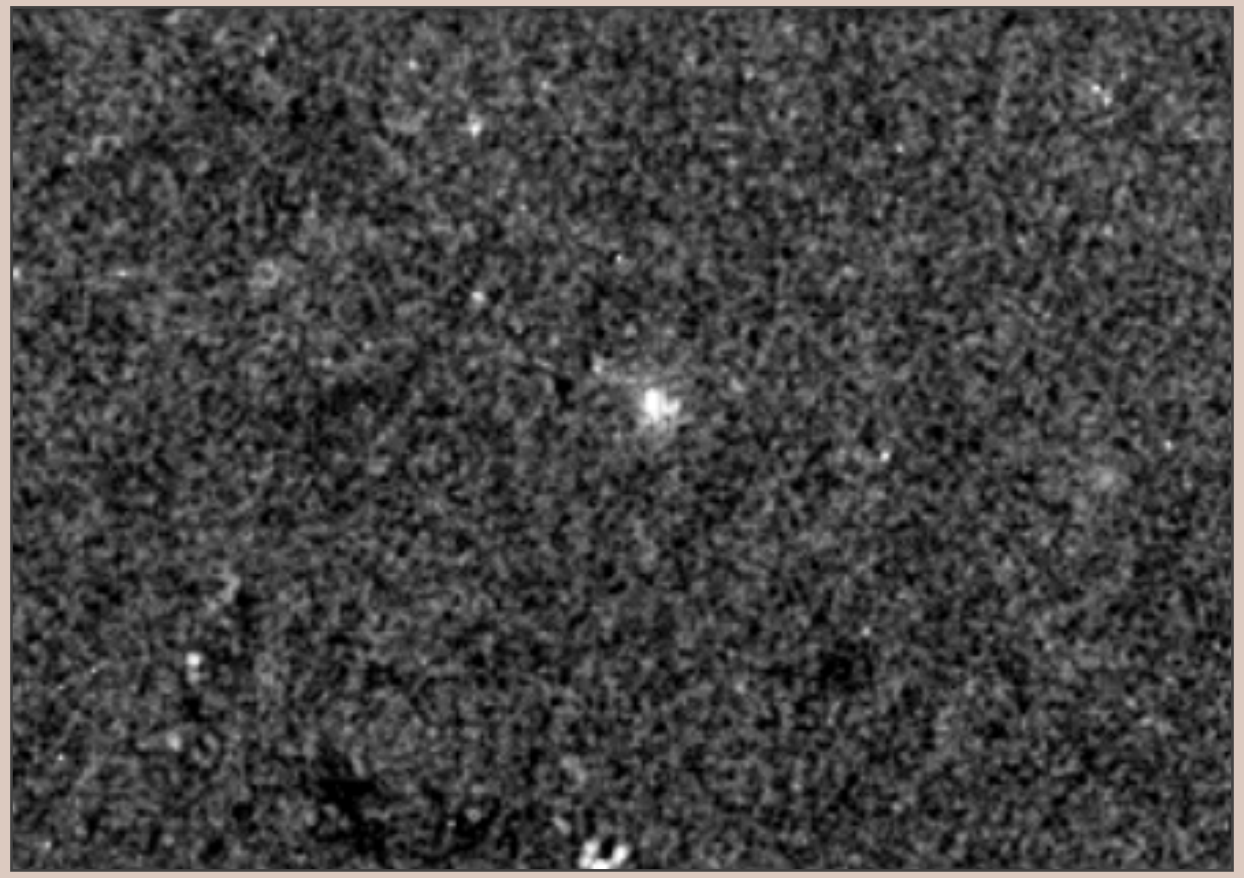
X-Ray



FRBs



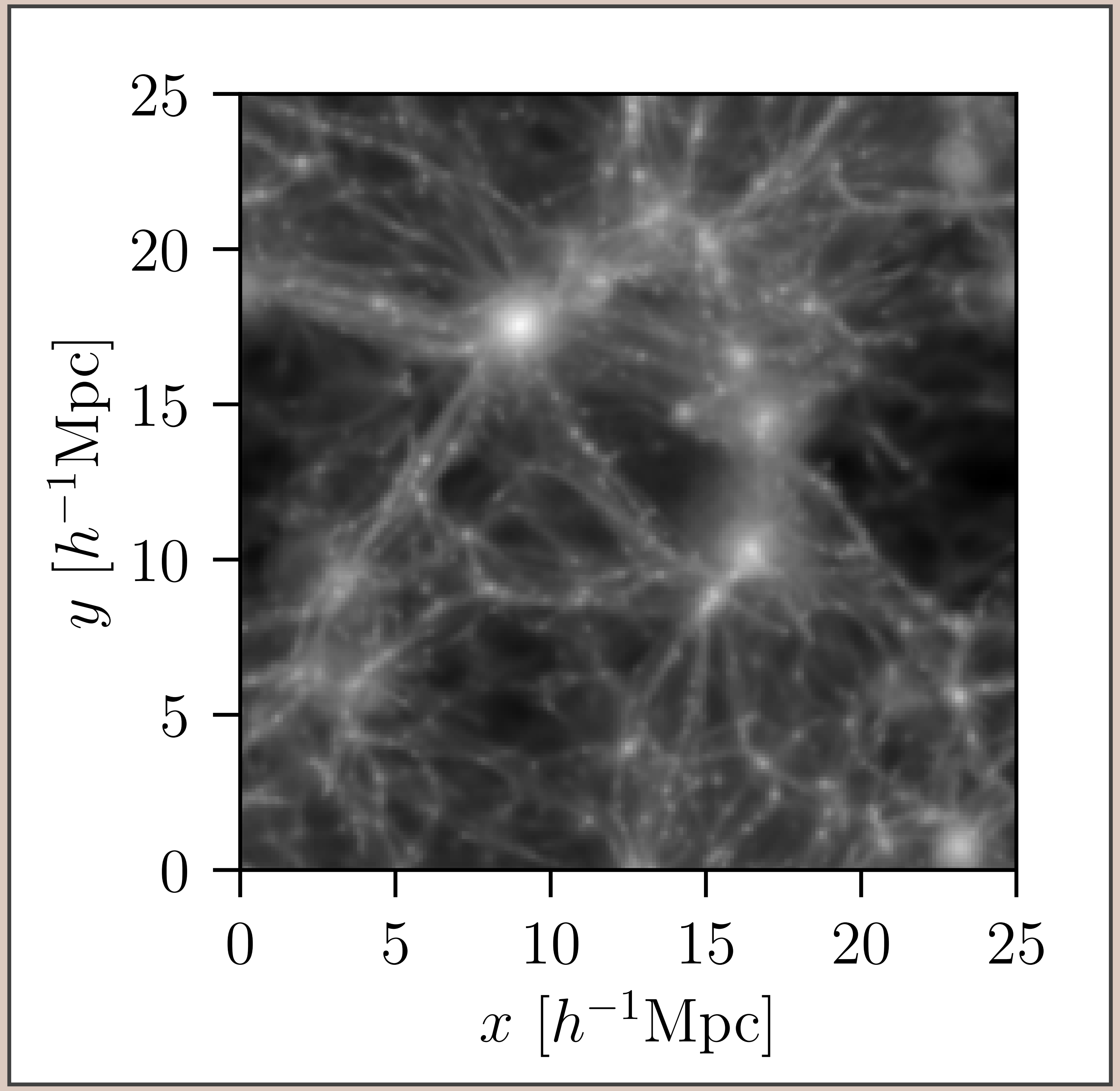
tSZ



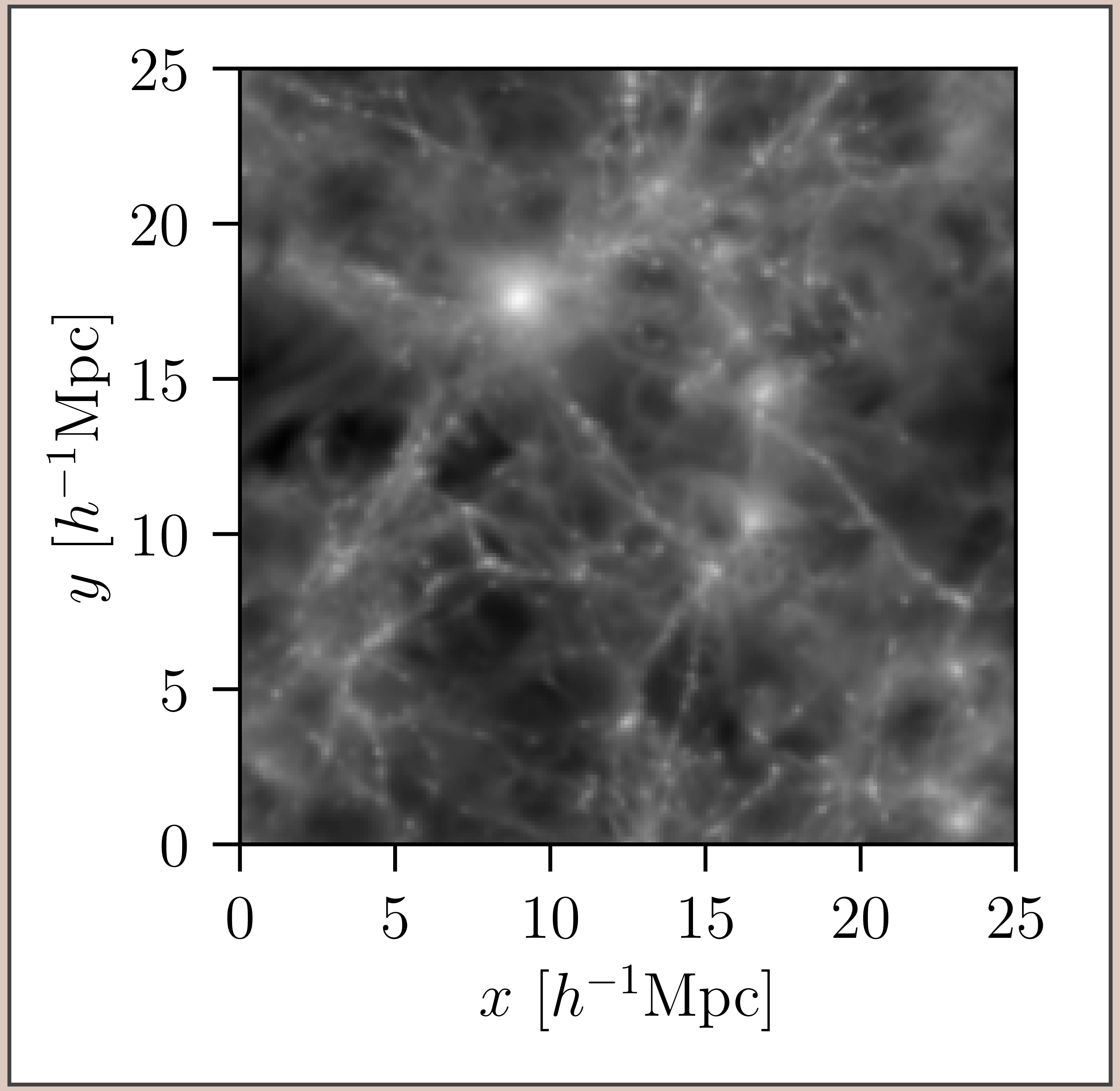
Images: eROSITA, Madhavacheril et al., 2020, Danielle Futselaar/artsource.nl

Simulations

IllustrisTNG



SIMBA



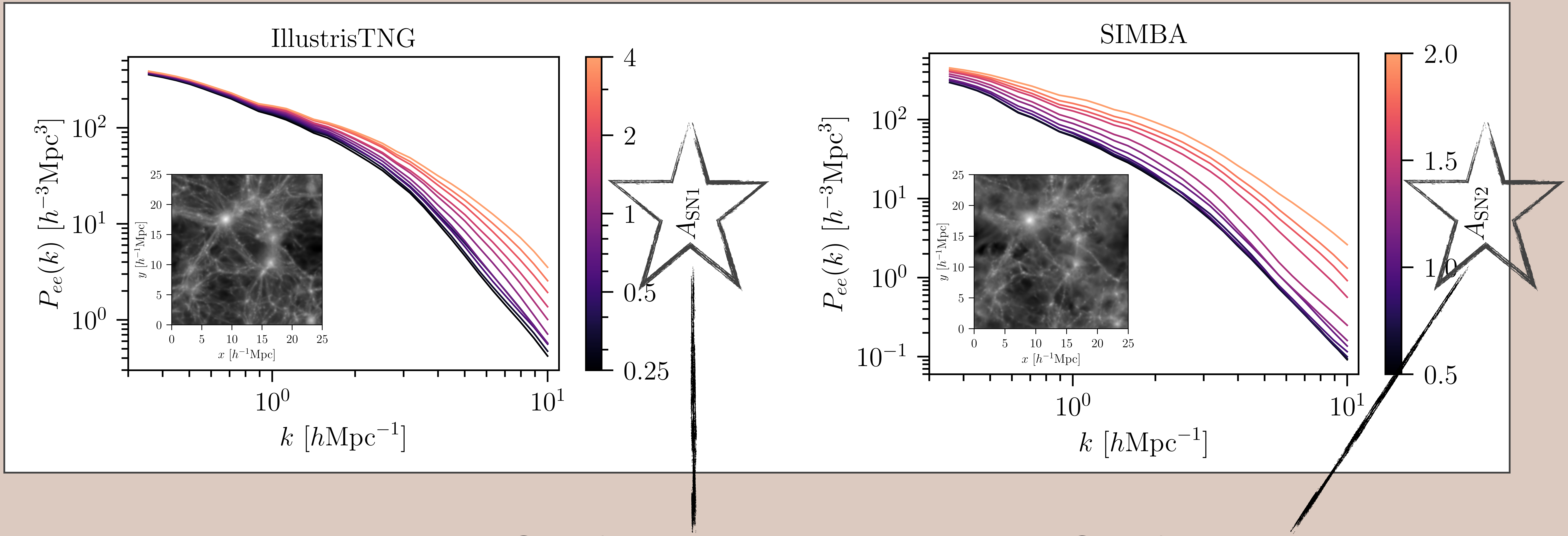
CAMELS: 2000+ simulations of $V = (25\ h^{-1}\ \mathrm{Mpc})^3$, run for IllustrisTNG/SIMBA

Nelson et al., 2019, Davé et al., 2019, Villaescusa-Navarro et al., 2021

Data

IllustrisTNG

SIMBA



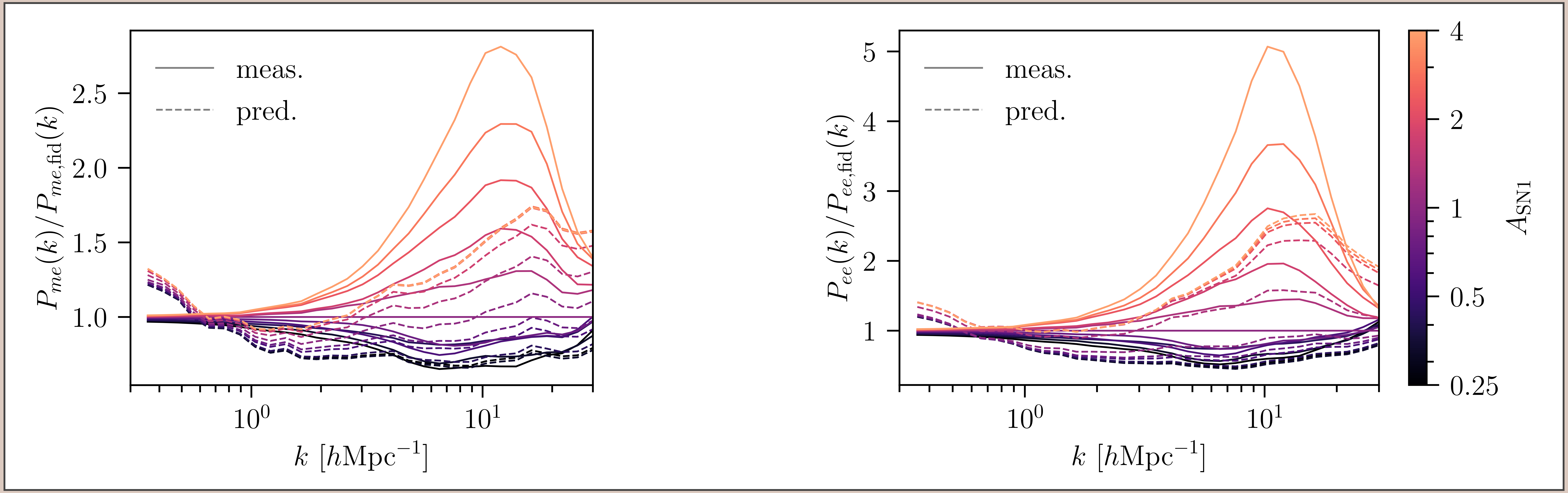
SNe feedback energy

SNe feedback wind speed

Weinberger et al., 2017, Pillepich et al., 2018, Davé et al., 2019

Baryon Fraction as Predictor of Feedback

$$\bar{f}_{\mathrm{bar}} = \frac{1}{N_h} \sum_{i}^{N_h} \frac{M_{\mathrm{bar},h,i}}{M_{\mathrm{tot},h,i}}, \;\; 10^{12} < M_{\mathrm{tot},h,i} < 10^{13}\ h^{-1}\ M_{\odot}$$

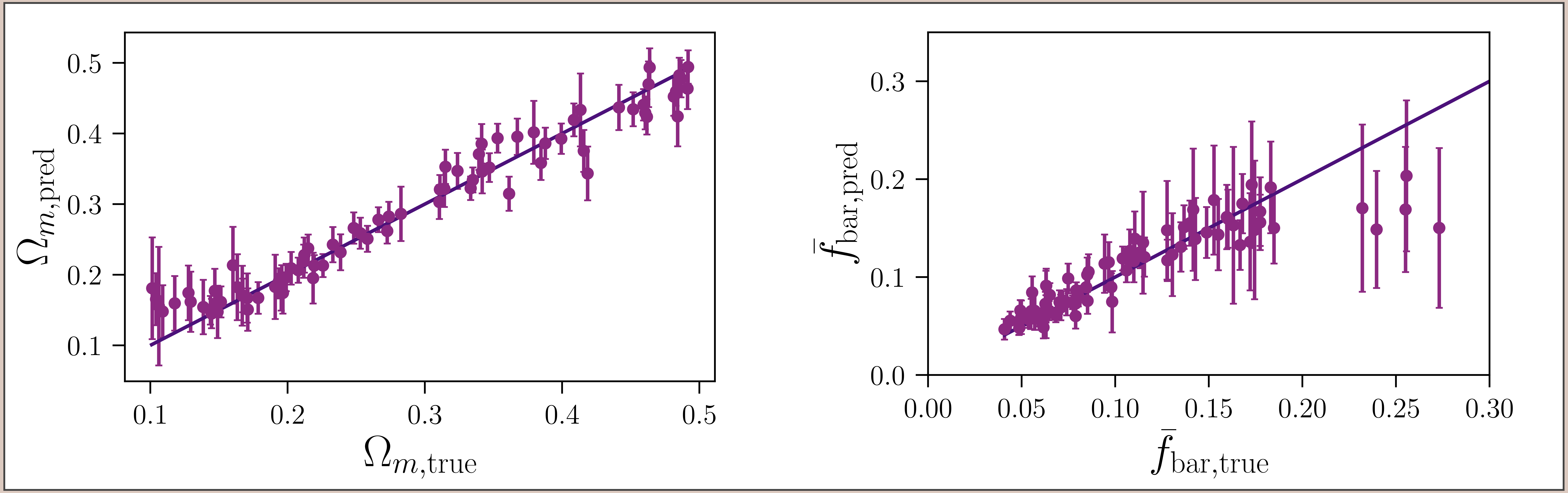


Averaged relative accuracy: $\langle \delta P/P \rangle \sim 25\%$

van Daalen et al., 2020

Forecasting Constraints

Forecasted Errors from IllustrisTNG

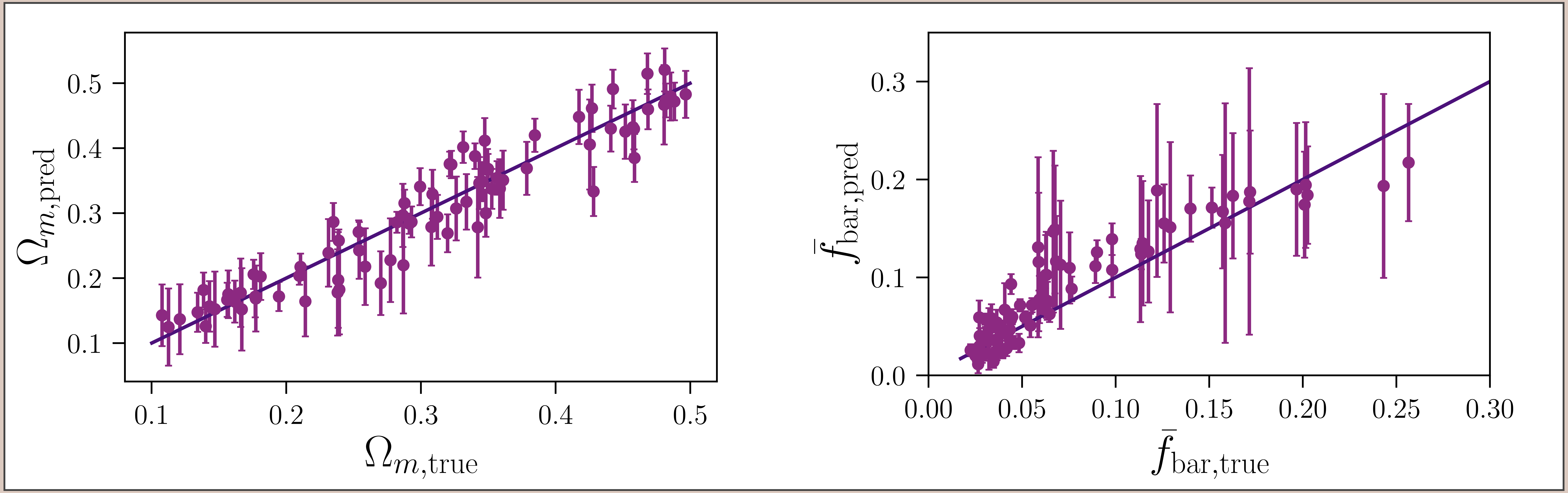


Forecasts for $P_{ee}(k), z = 0, k_{\mathrm{max}} = 10\ h\ \mathrm{Mpc}^{-1}$

Nicola et al., 2022

Robustness of Constraints to Subgrid Physics

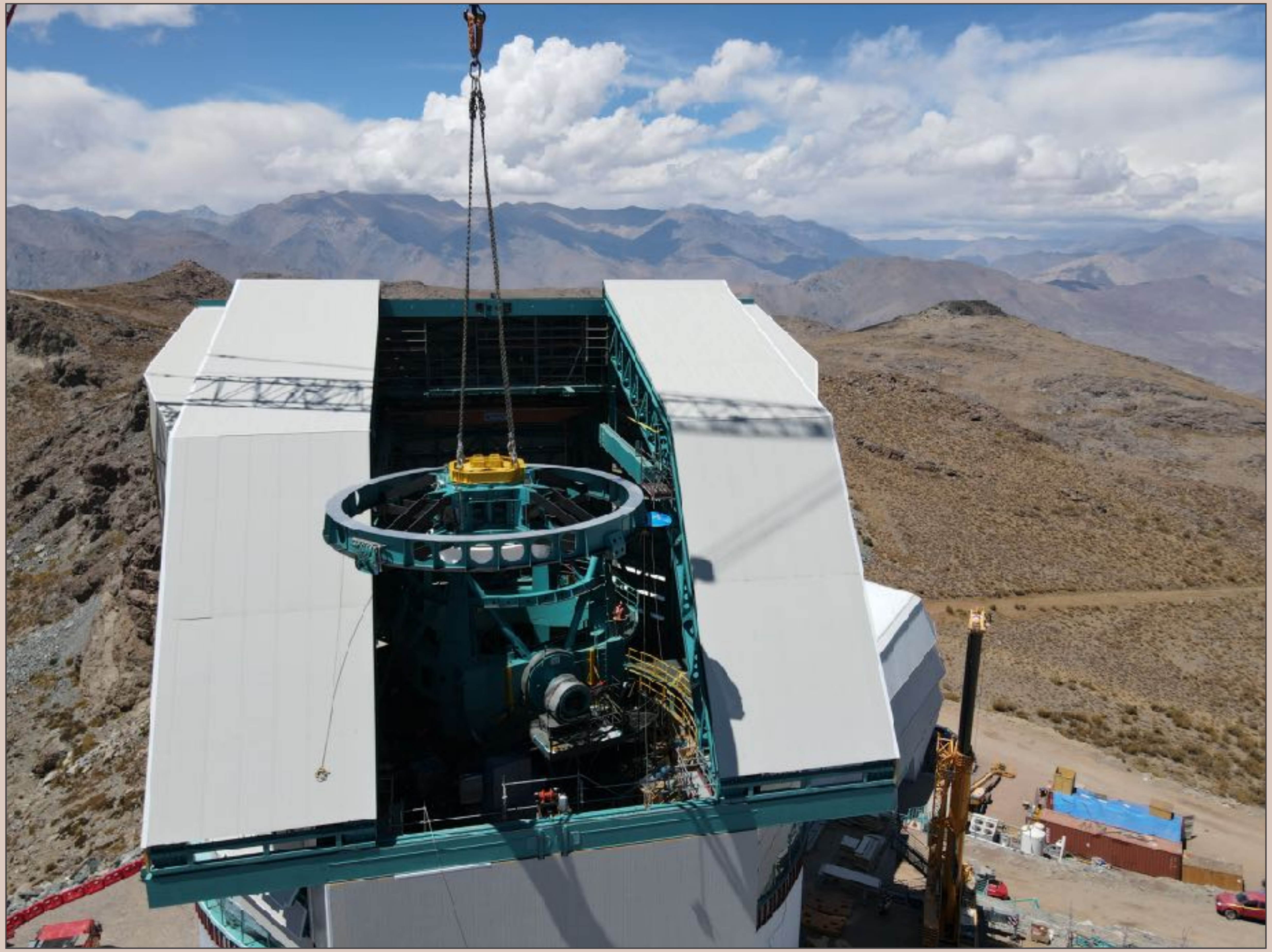
Systematic Uncertainties from Testing on SIMBA



Bias on recovered values not significant relative to error bars

Nicola et al., 2022

Rubin/LSST



Cerro Pachón, March 2nd 2021

10 year optical survey of 20'000 sq. deg.

First data expected in 2023

Deep, will image ~10^9s of galaxies

Main observables: weak lensing & clustering

Moving Beyond Traditional Methods

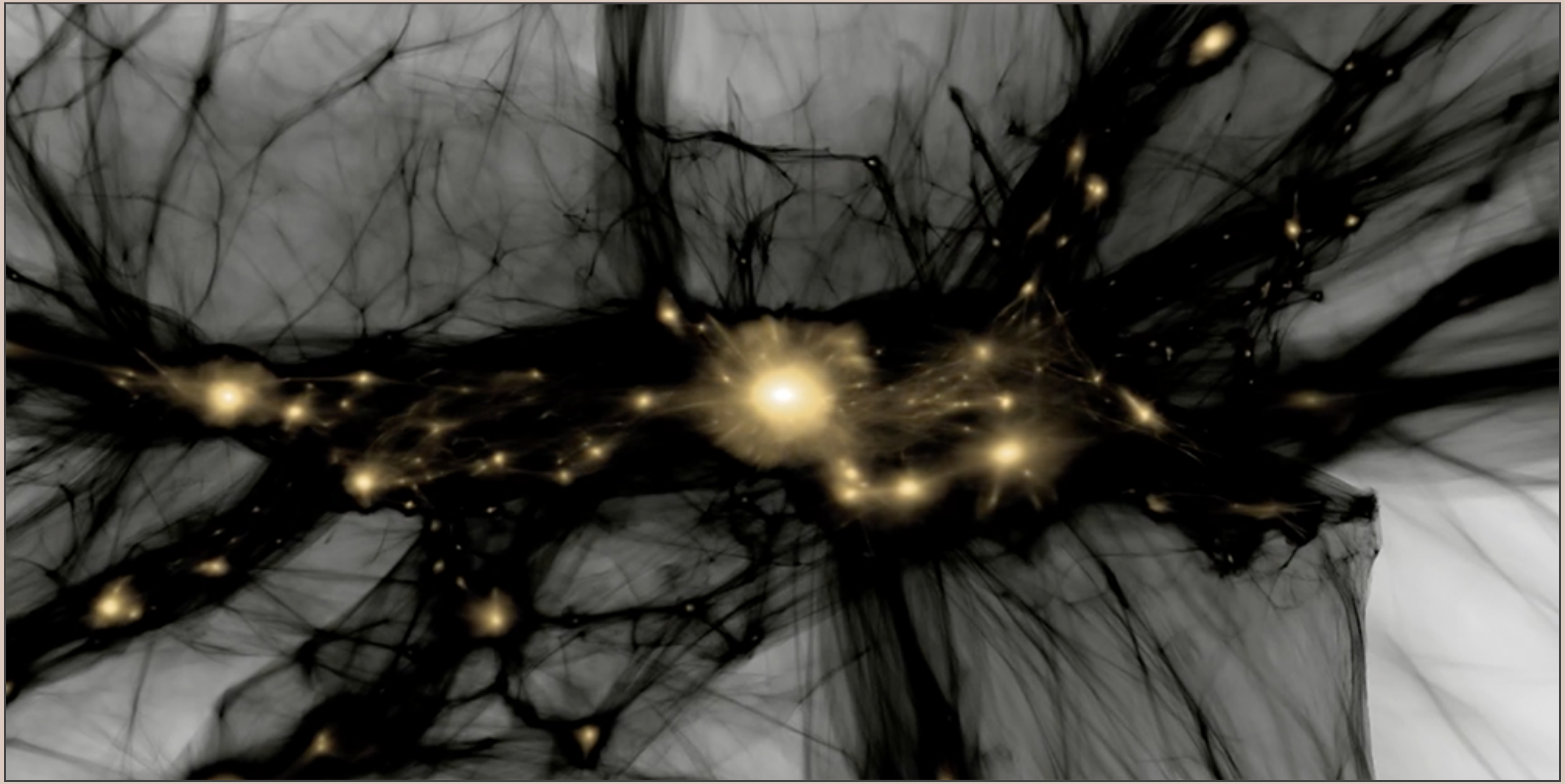
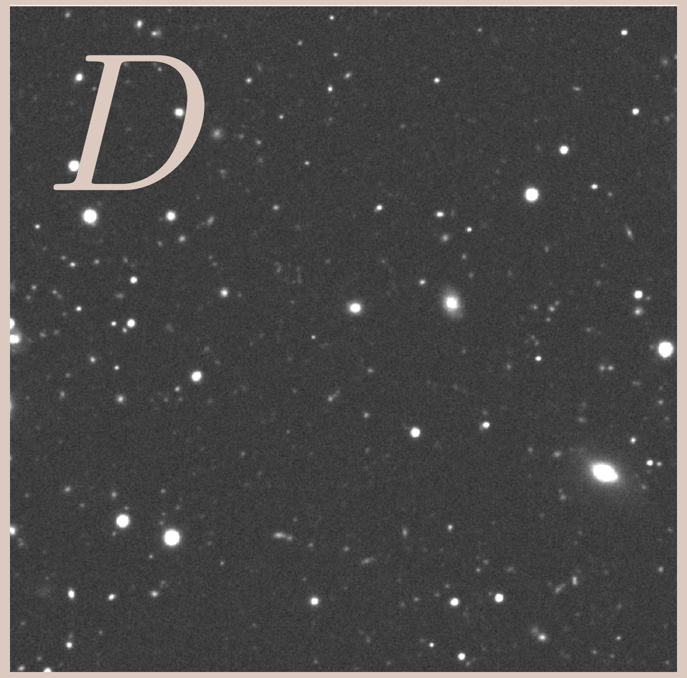


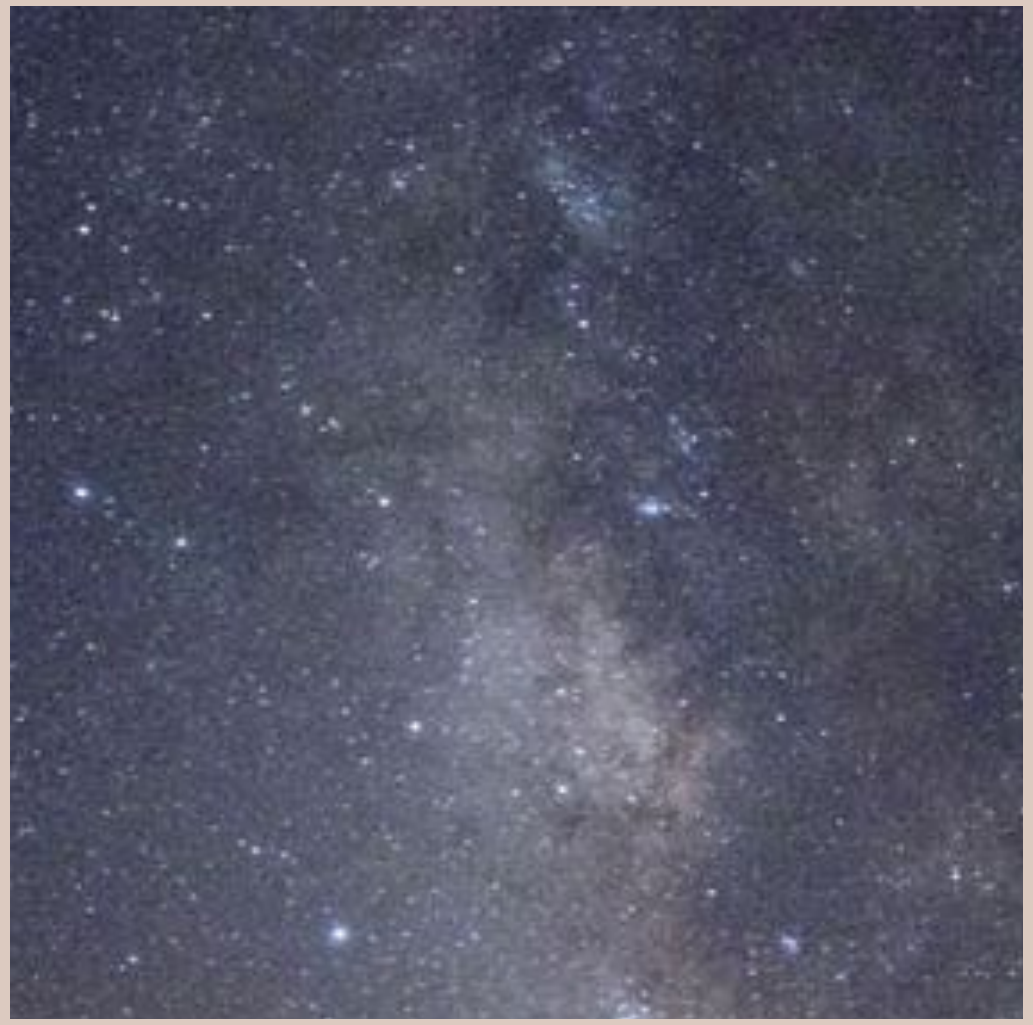
Image: S. Skillman, Y-Y. Mao, KIPAC/SLAC National Accelerator Laboratory

Simulation-Based Inference



Akhmetzhanova et al., in prep.

$$p(D_*|\boldsymbol{\theta})$$

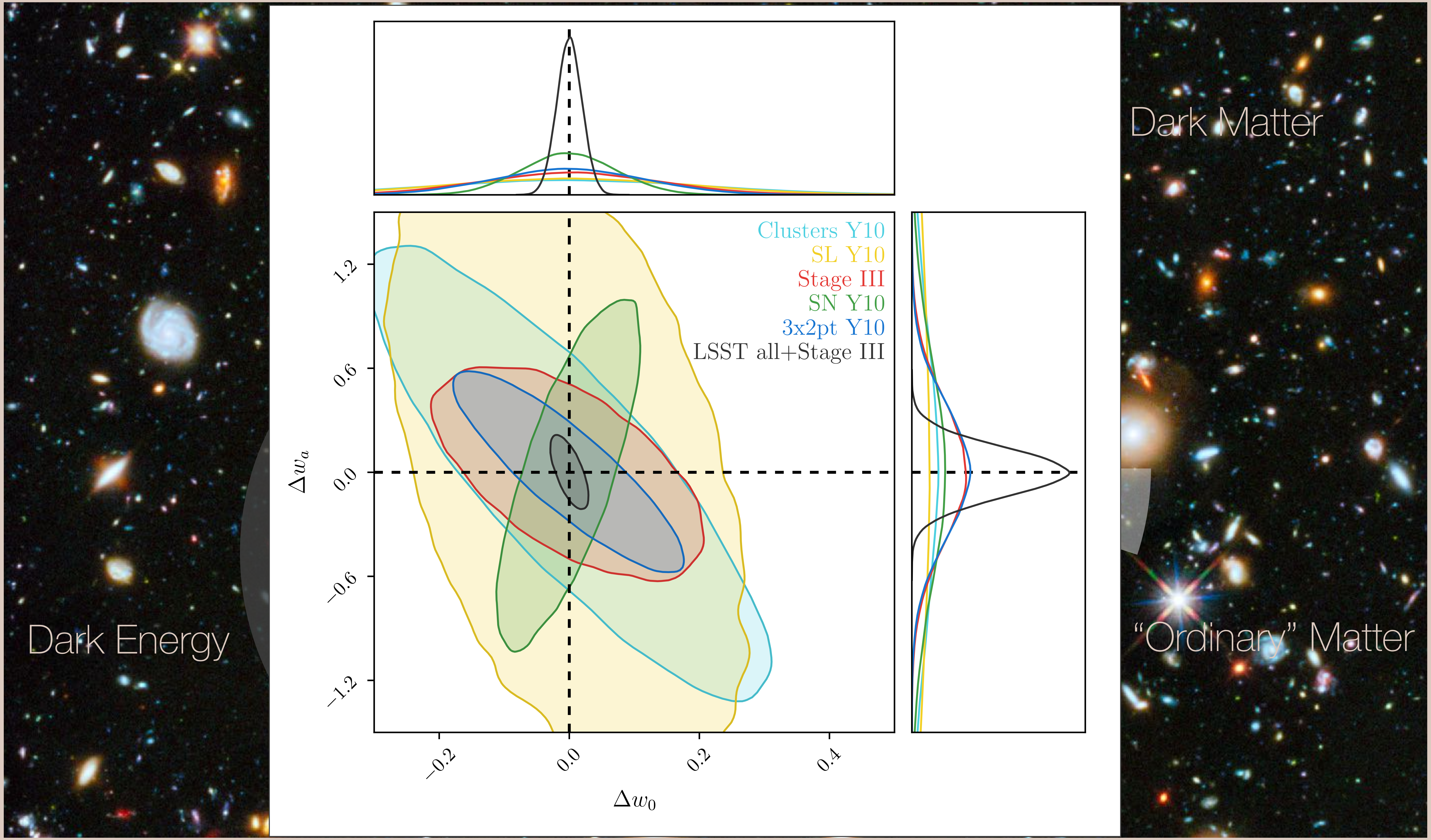


Alsing et al., 2019, Tejero-Cantero et al., 2020

The Cosmological Data Revolution

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

Testing Pillars of ΛCDM with Future Surveys



LSST DESC SRD, 2018

Summary

Combined probe analyses essential to constrain cosmology
- Break parameter degeneracies
- Robust test of cosmological model
- Identification, understanding and calibration of systematics

Future surveys will deliver high-precision data
- Significant information in small-scales, non-Gaussian features
- Limited by systematics

Two approaches
- Extend traditional analysis methods
- Develop novel analysis methods based on joint forward-modeling and simulation-based inference

Thank you!