Unveiling ΛCDM: beyond the power spectrum

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PERU
BOLIVIA
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Atacama
Copiapó
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La Serena
Coquimbo
CHILE
Valparaíso
Valparaíso
SANTIAGO
Libertador General Bernardo O'Higgins
Rancagua
ARGENTINA
Maule
Talca
Concepción
Bío Bío
La Araucanía
Temuco
OCEAN
Valdivia
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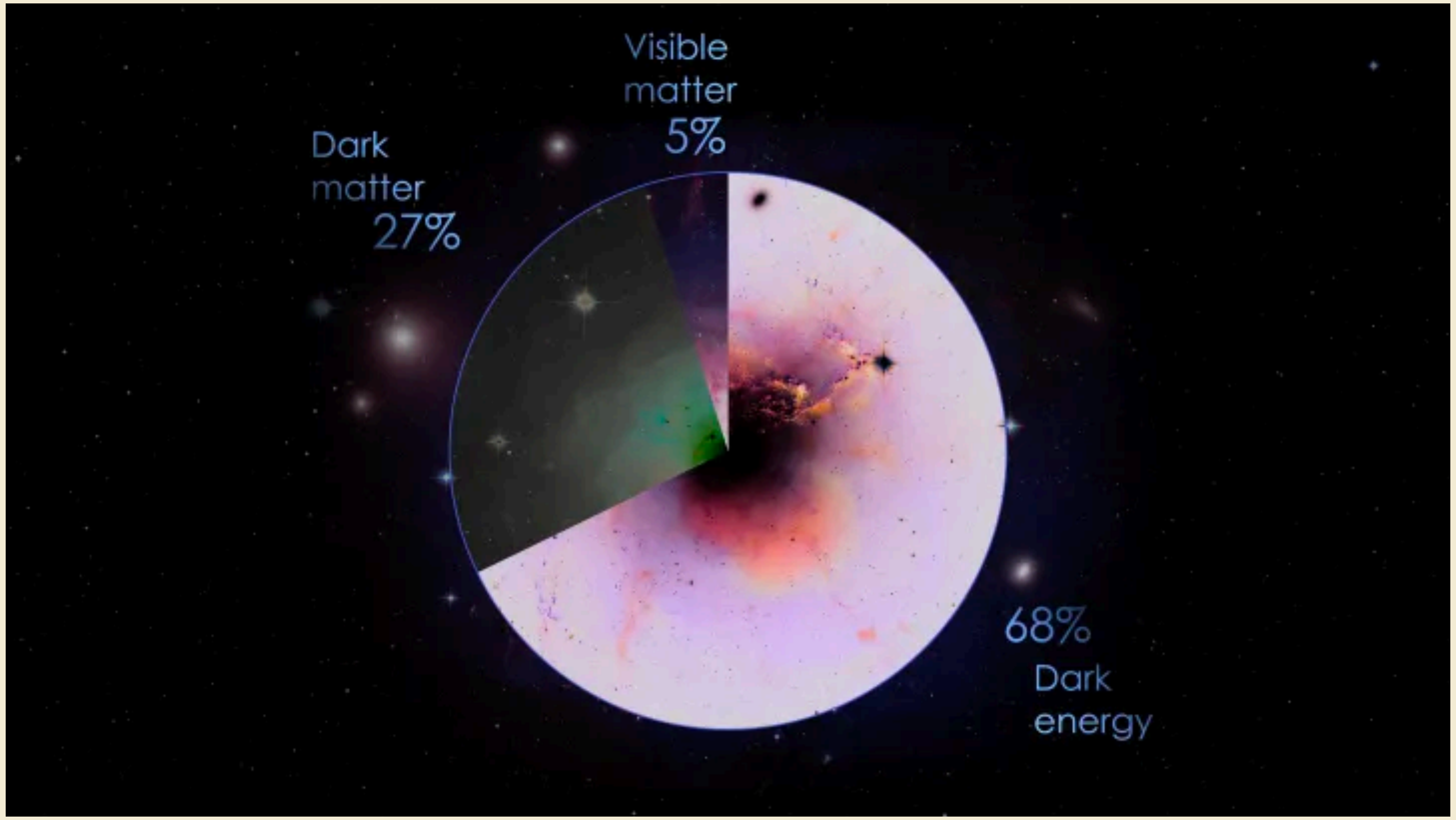
Puerto Montt
Isla Grande de Chiloé
Los Lagos
Coyhaique
Aysén
ATLANTIC
OCEAN
Magallanes y la Antártica Chilena
Punta Arenas
Isla Grande de Tierra del Fuego
Cabo de Hornos

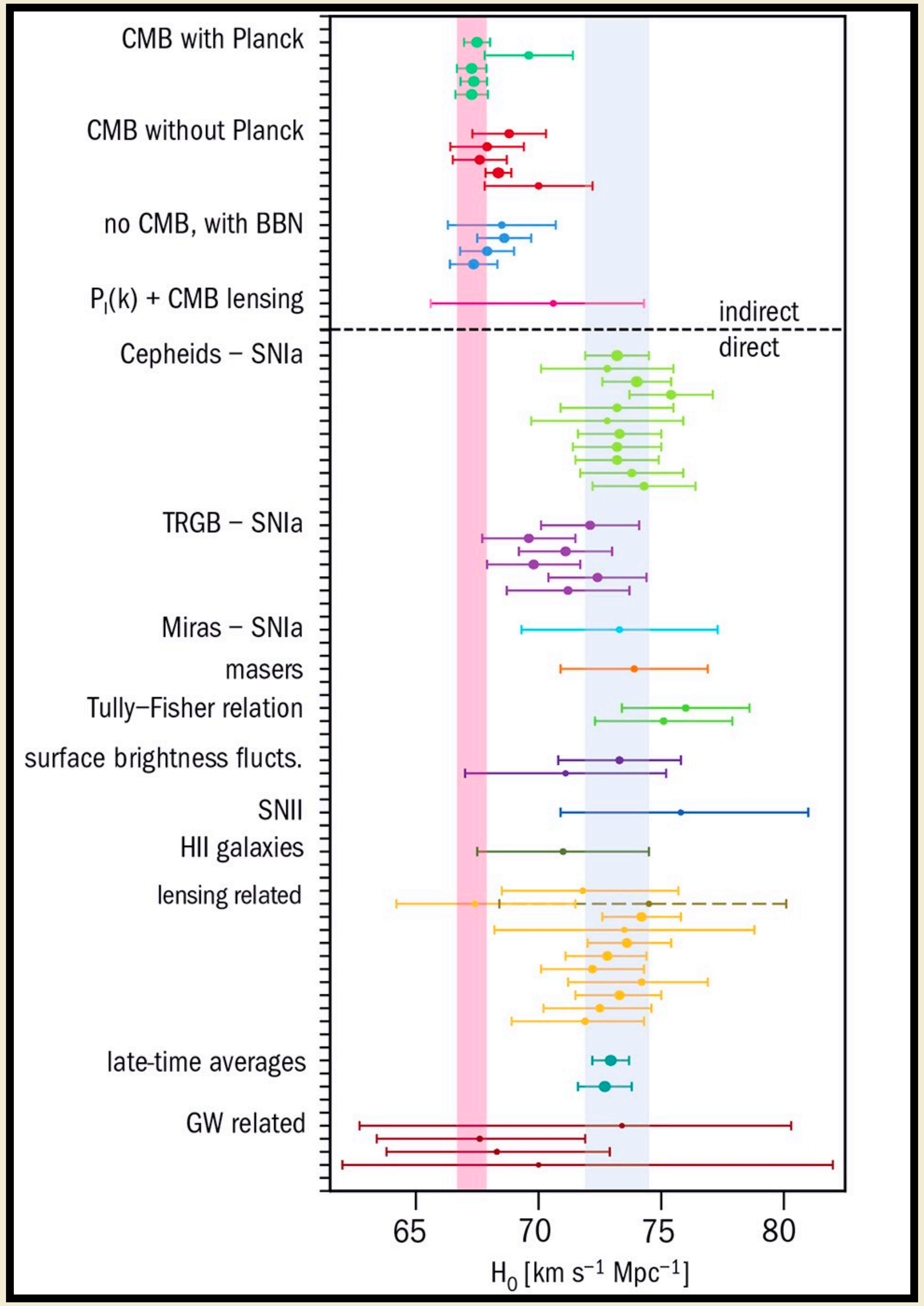


ΛCDM: our cosmological paradigm

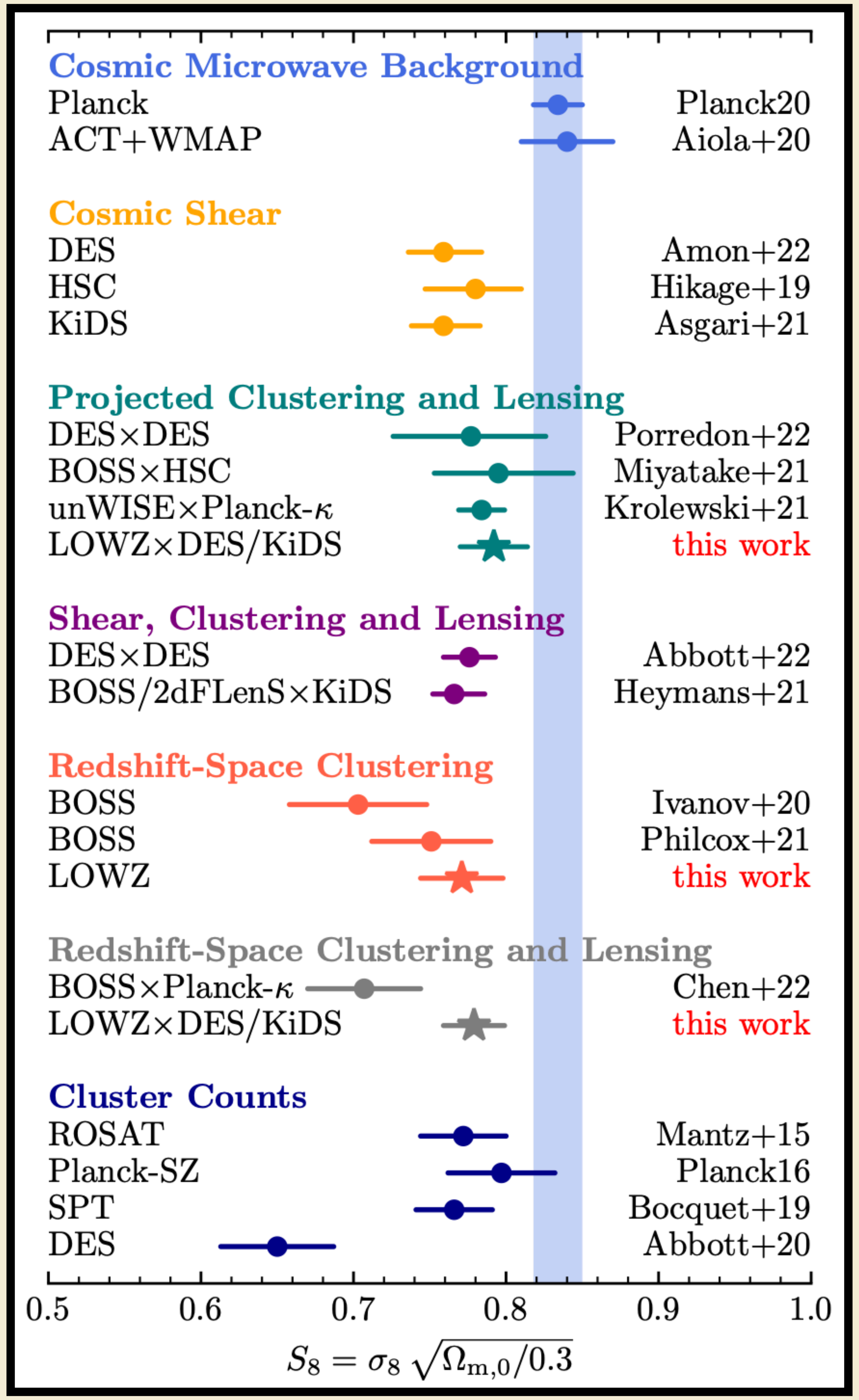


Credit: Simons Observatory

"There is nothing wrong with ΛCDM, maybe just the Λ and the CDM part".



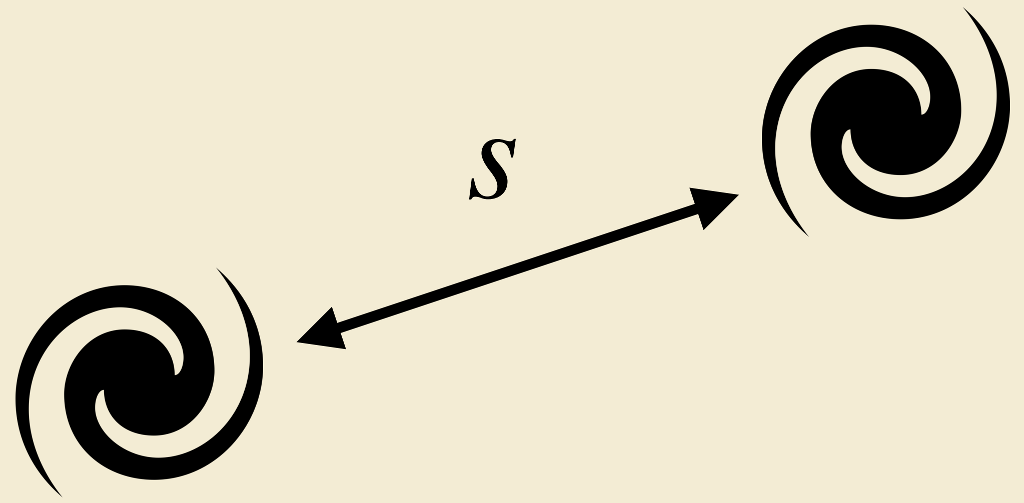
Di Valentino et al. 2021

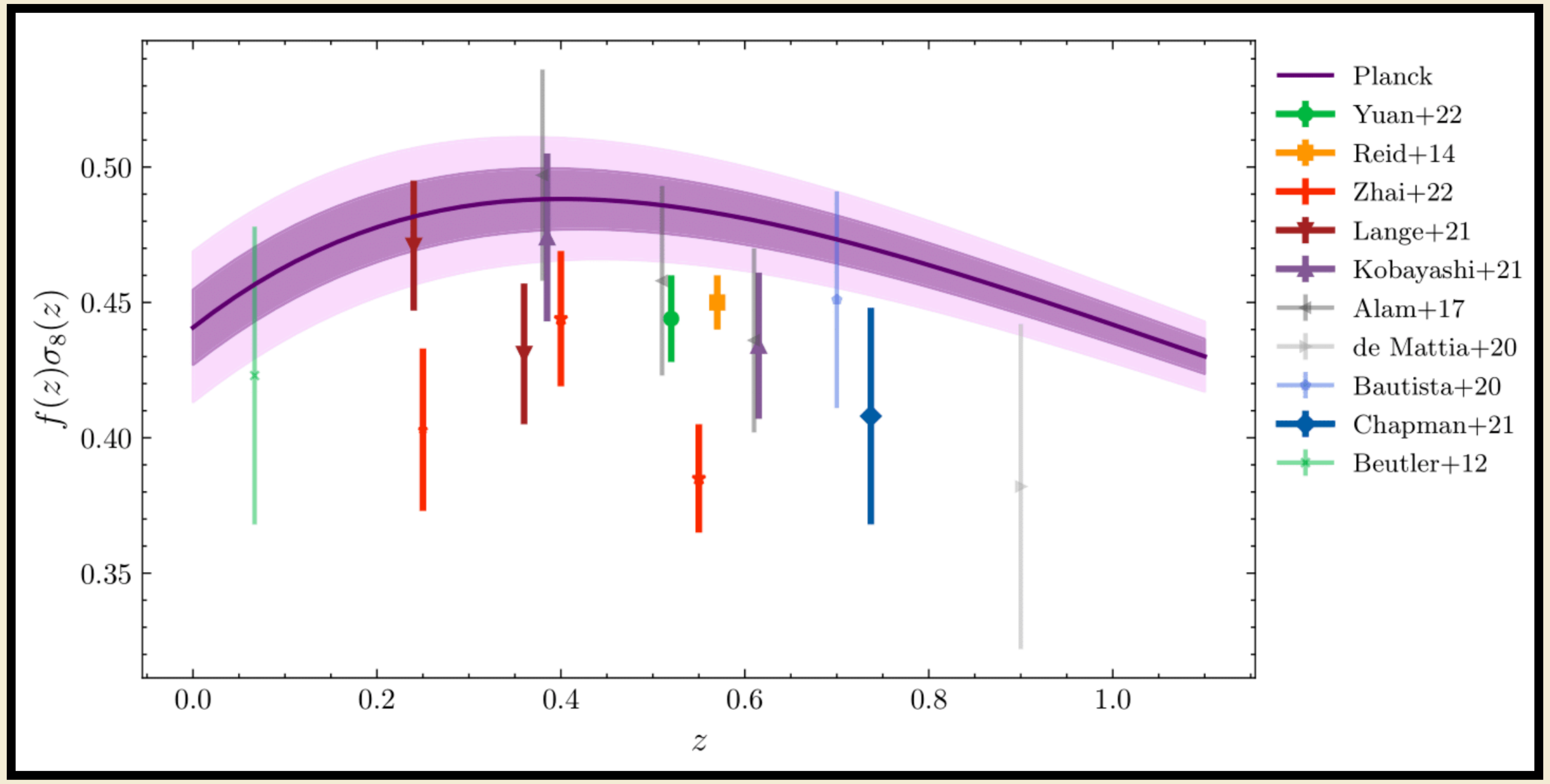


Lange et al. 2023

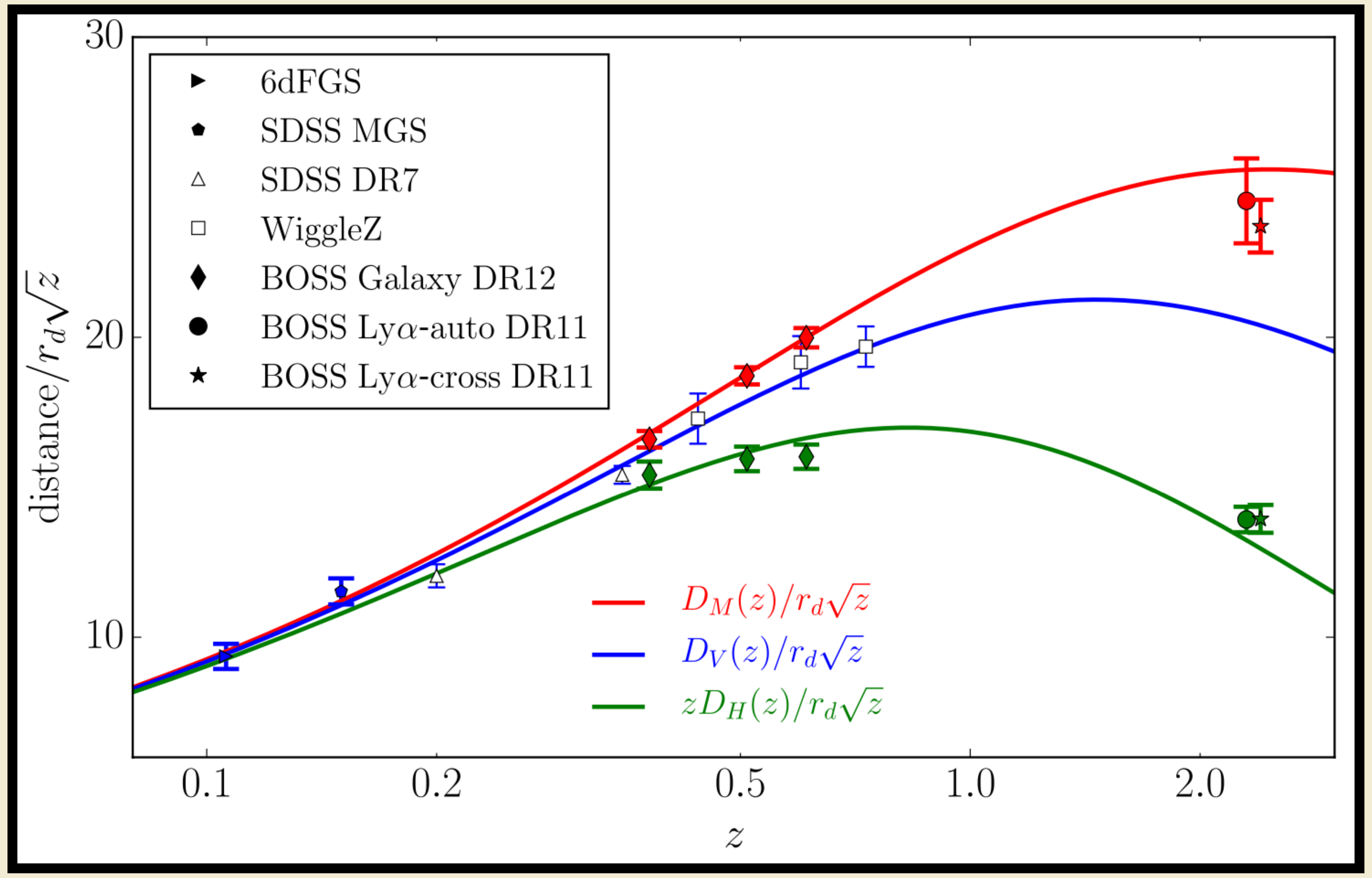

2020
2022
2024
KiDS
UNIONS
Euclid
Roman
SDSS
DESI
Rubin LSST
DES
Subaru HSC
SPHEREx

Measurements of the galaxy power spectrum or the two-point correlation function have allowed precise measurements of the geometry and growth.



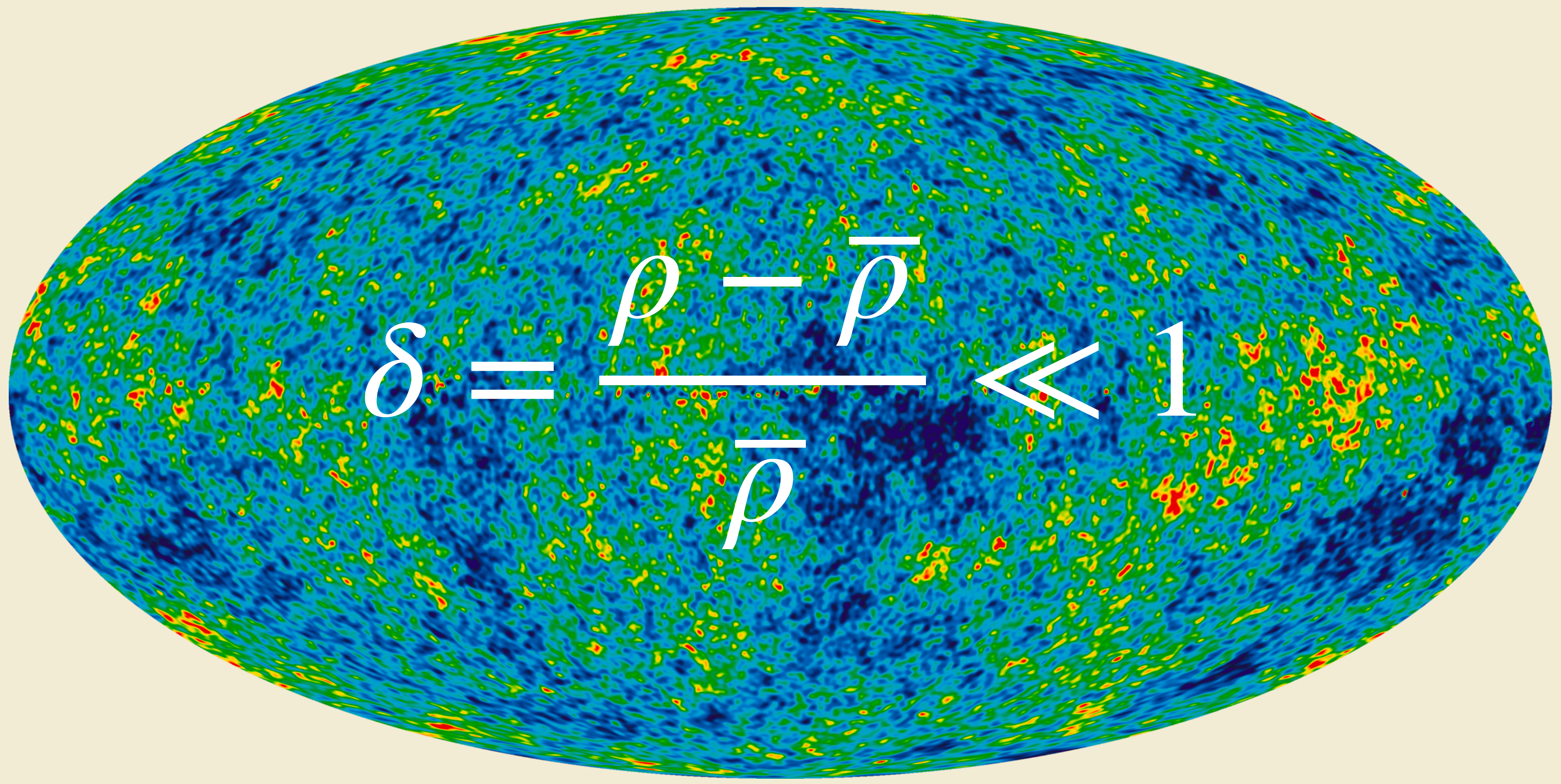


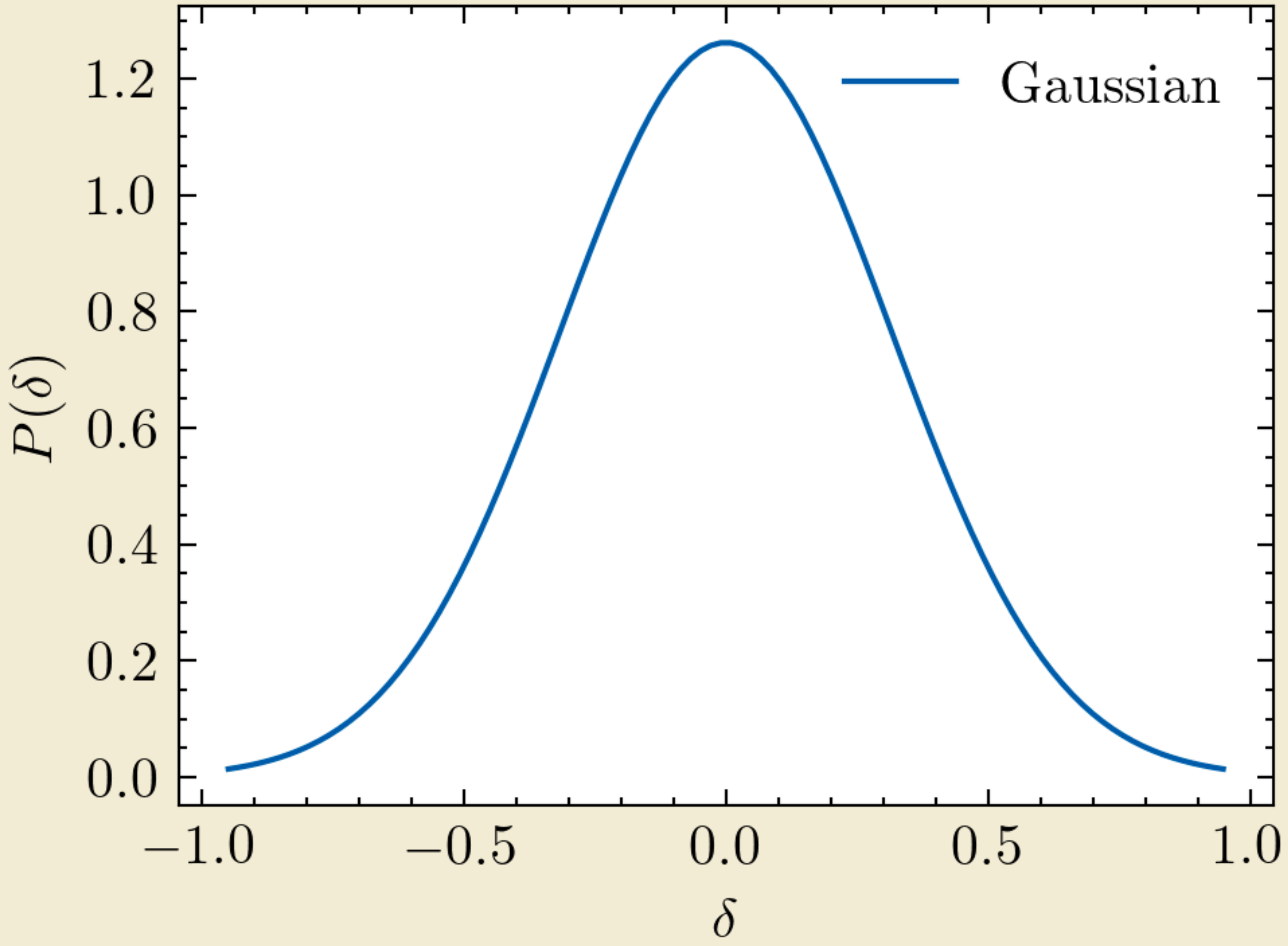
Credits: Carolina Cuesta-Lazaro



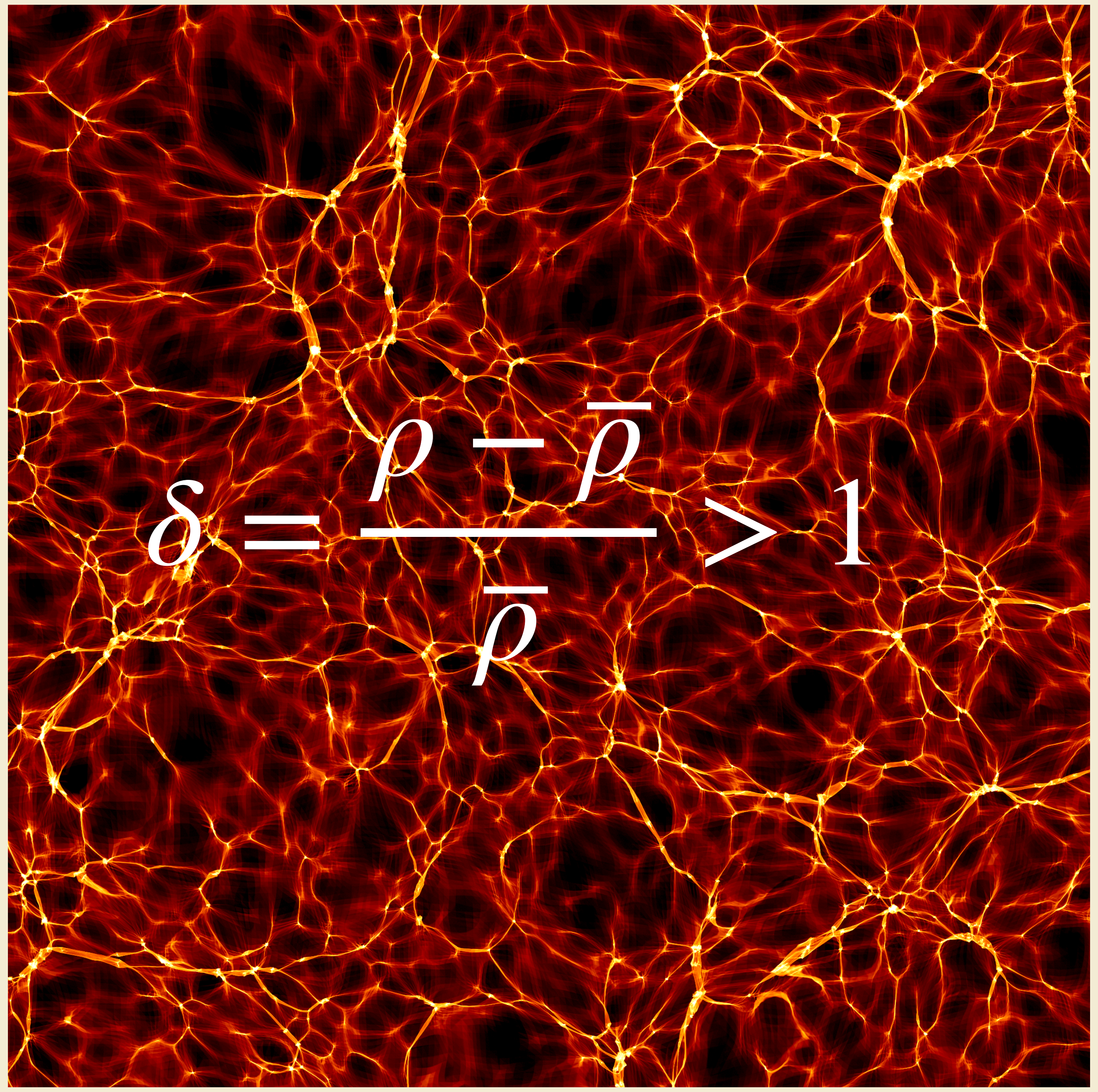
Alam et al. (2017)

Early Universe: Close to Gaussian PDF of density fluctuations. Governed by linear dynamics.

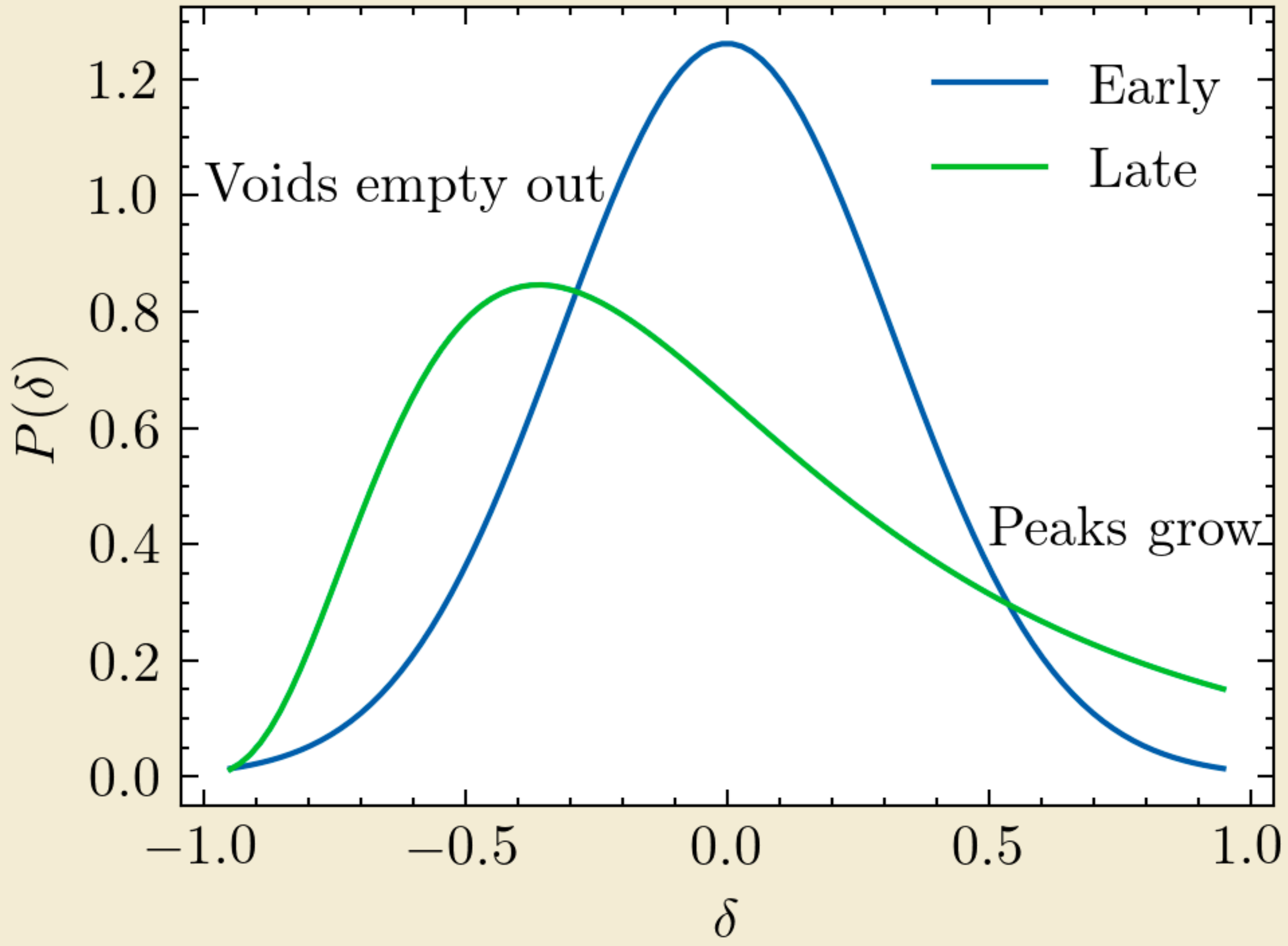




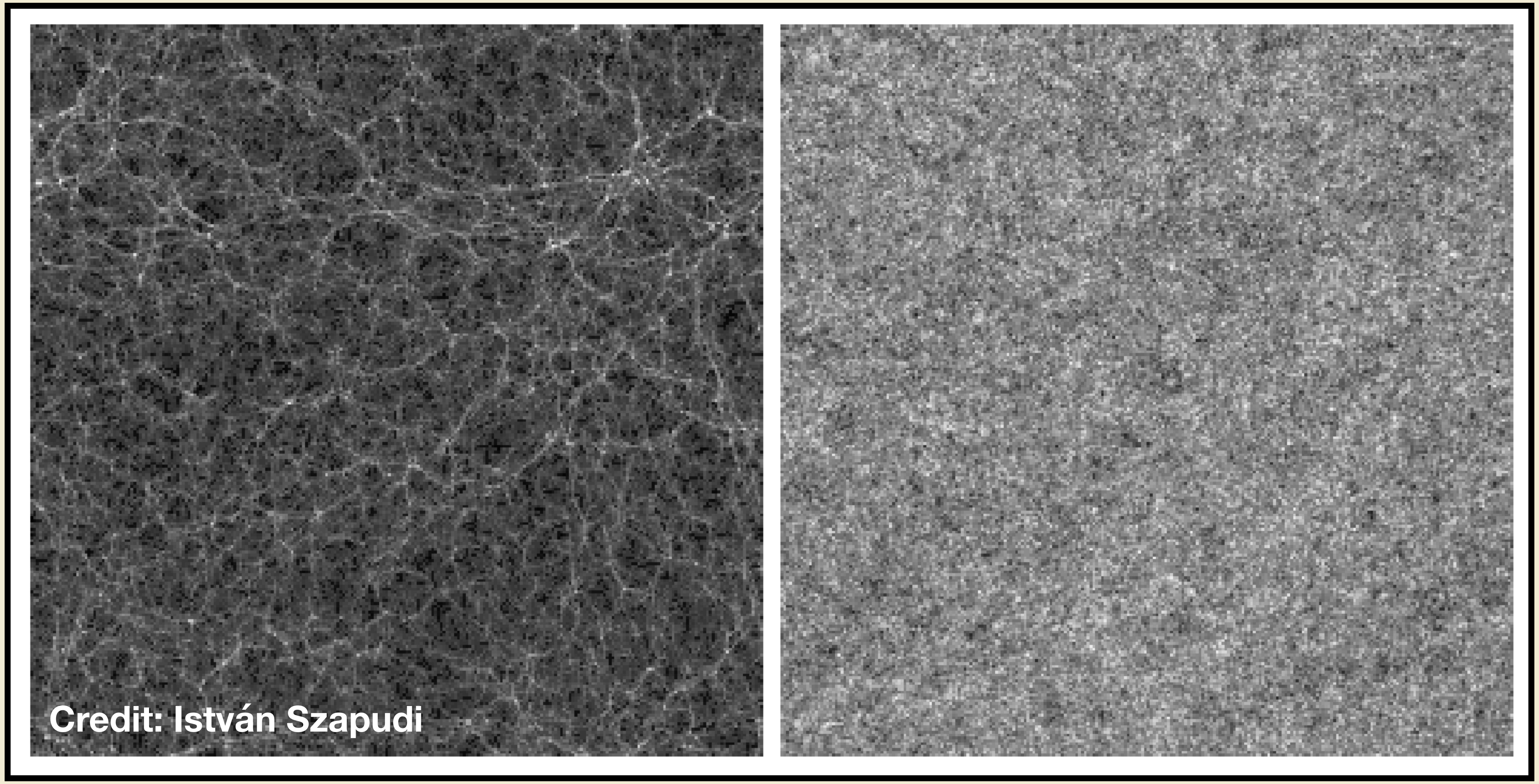
Late-time Universe: Non-Gaussian density field. Non-linear evolution governing small scales.



A slice through the AbacusSummit cosmological simulation at redshift 1.0.
Credits: Lehman Garrison



Two fields with the same two-point correlation function or P(k). **Higher-order correlations** become essential to capture non-Gaussian information.

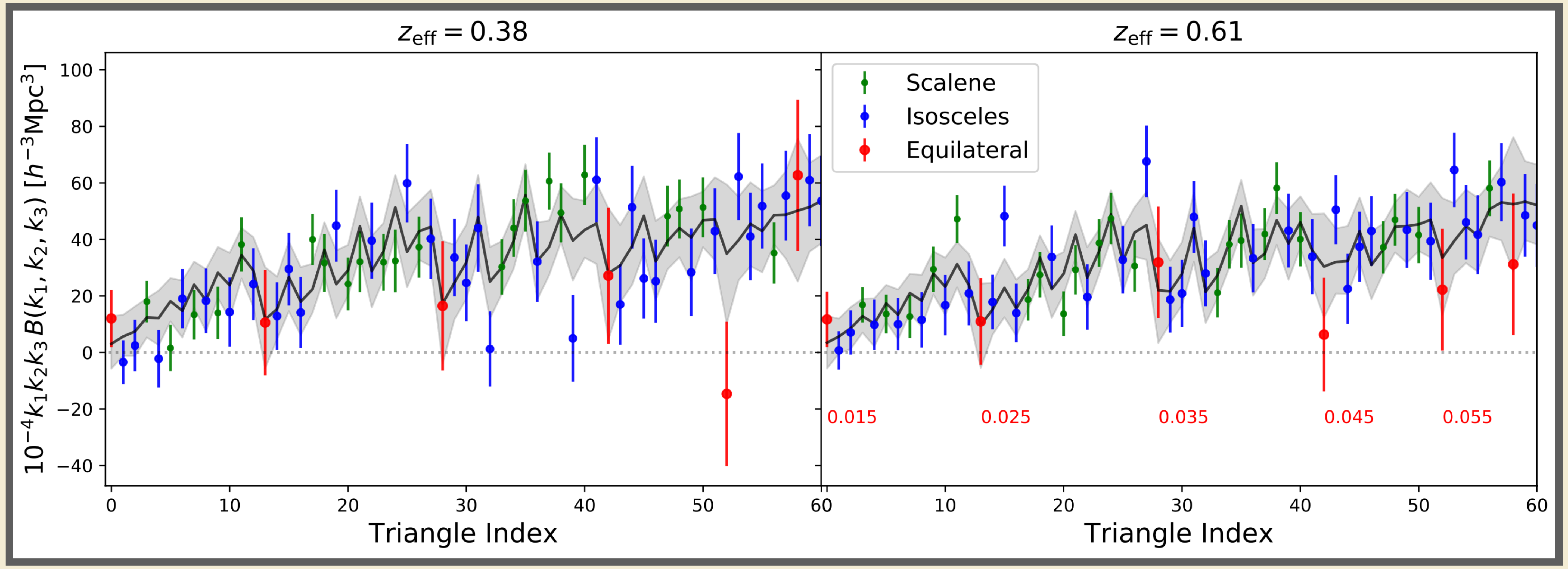


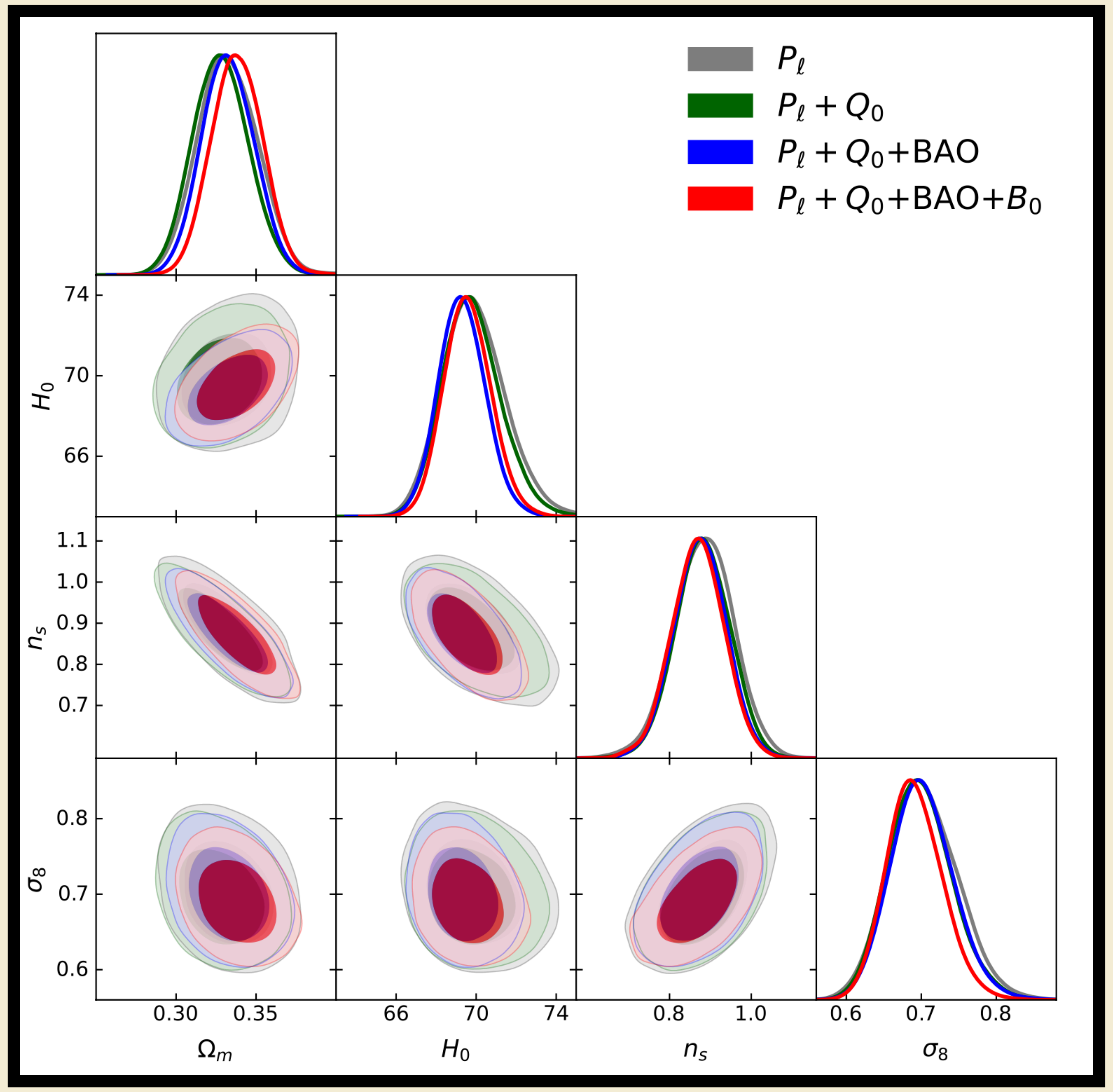
Finding alternative clustering methods that can be complemented with the P(k) is now an active field in cosmology.

- N-point correlation functions, polyspectra
- Non-linear transformations of the density field
- Counts-in-cells statistics
- Separate Universes
- Density-dependent clustering
- Density field reconstruction
- Cosmic voids
- Marked correlation functions
- Wavelet-based methods

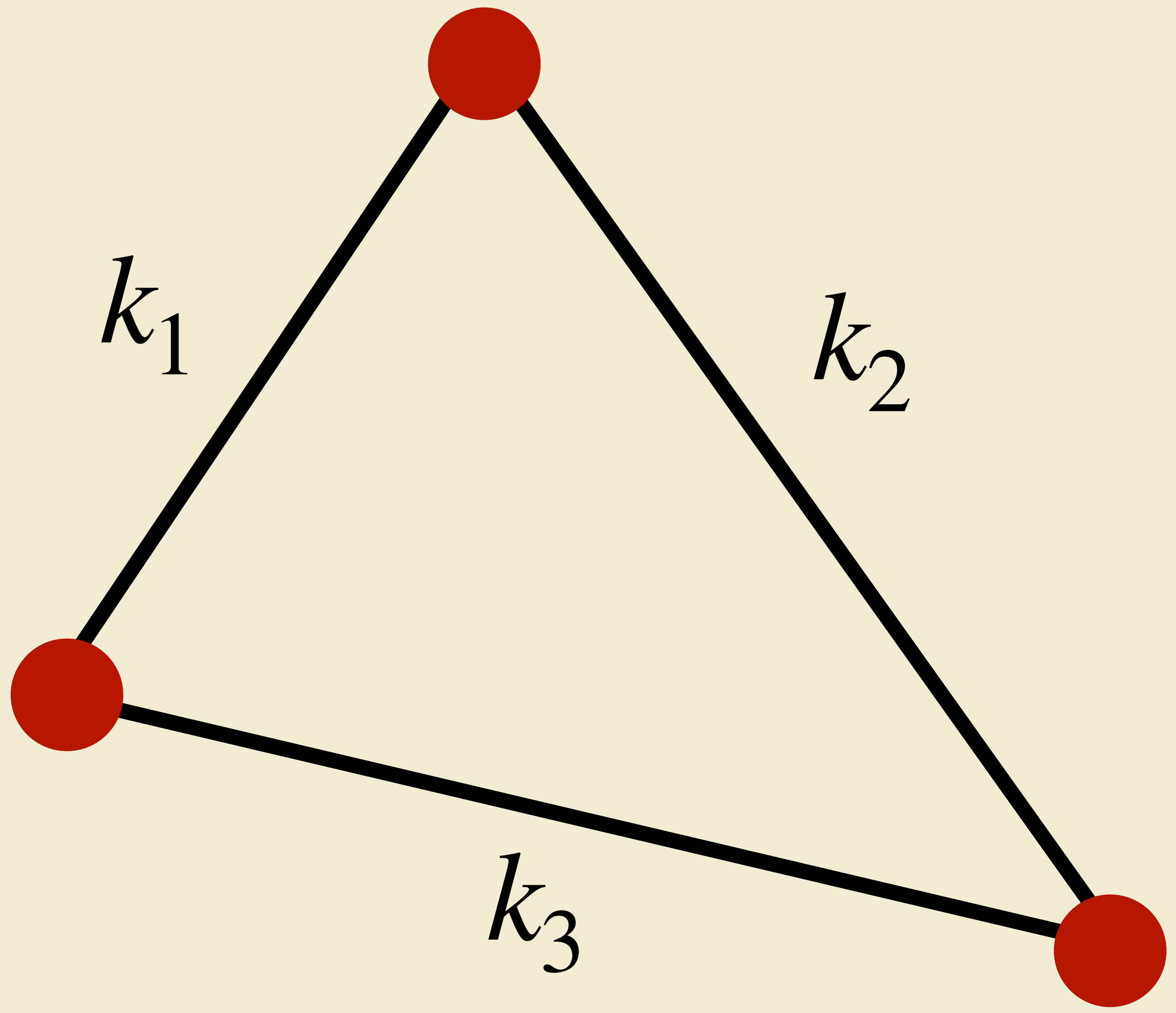
Galaxy Bispectrum

Measured bispectrum in BOSS (Philcox & Ivanov 2021)



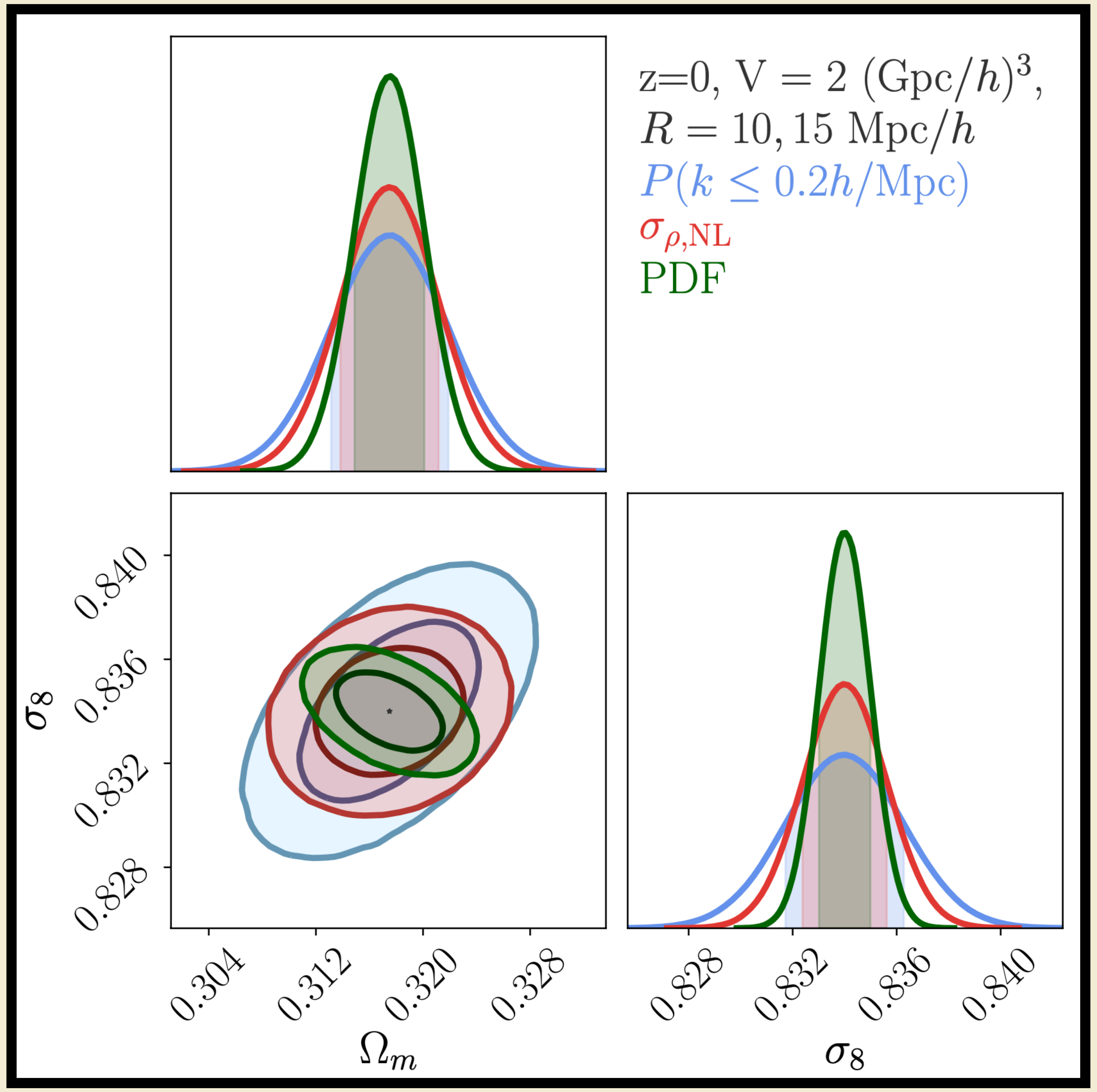


Constraints from a full-shape analysis of the bispectrum in BOSS (Philcox & Ivanov 2021)

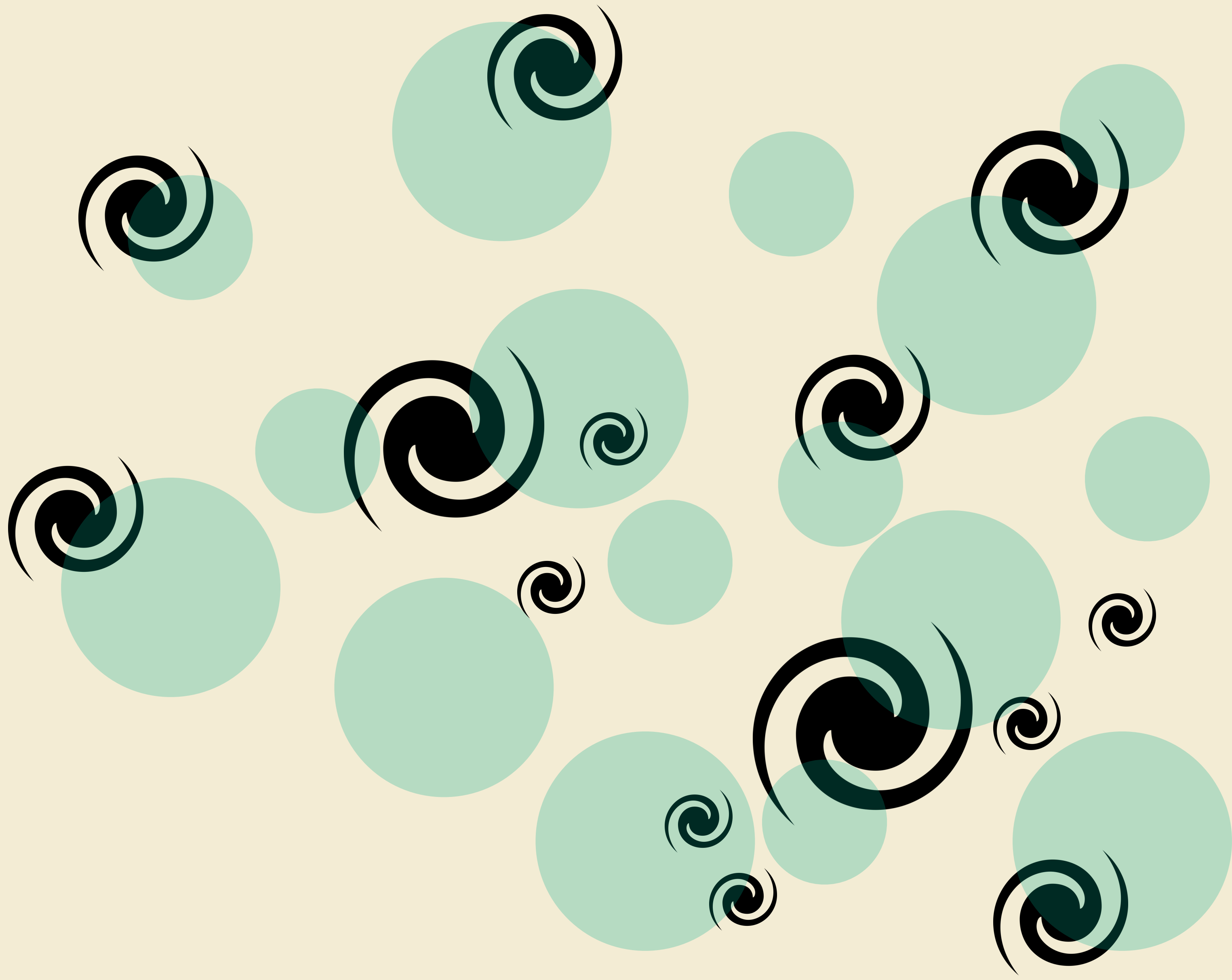


Measures the excess probability of finding galaxy triplets over a random distribution

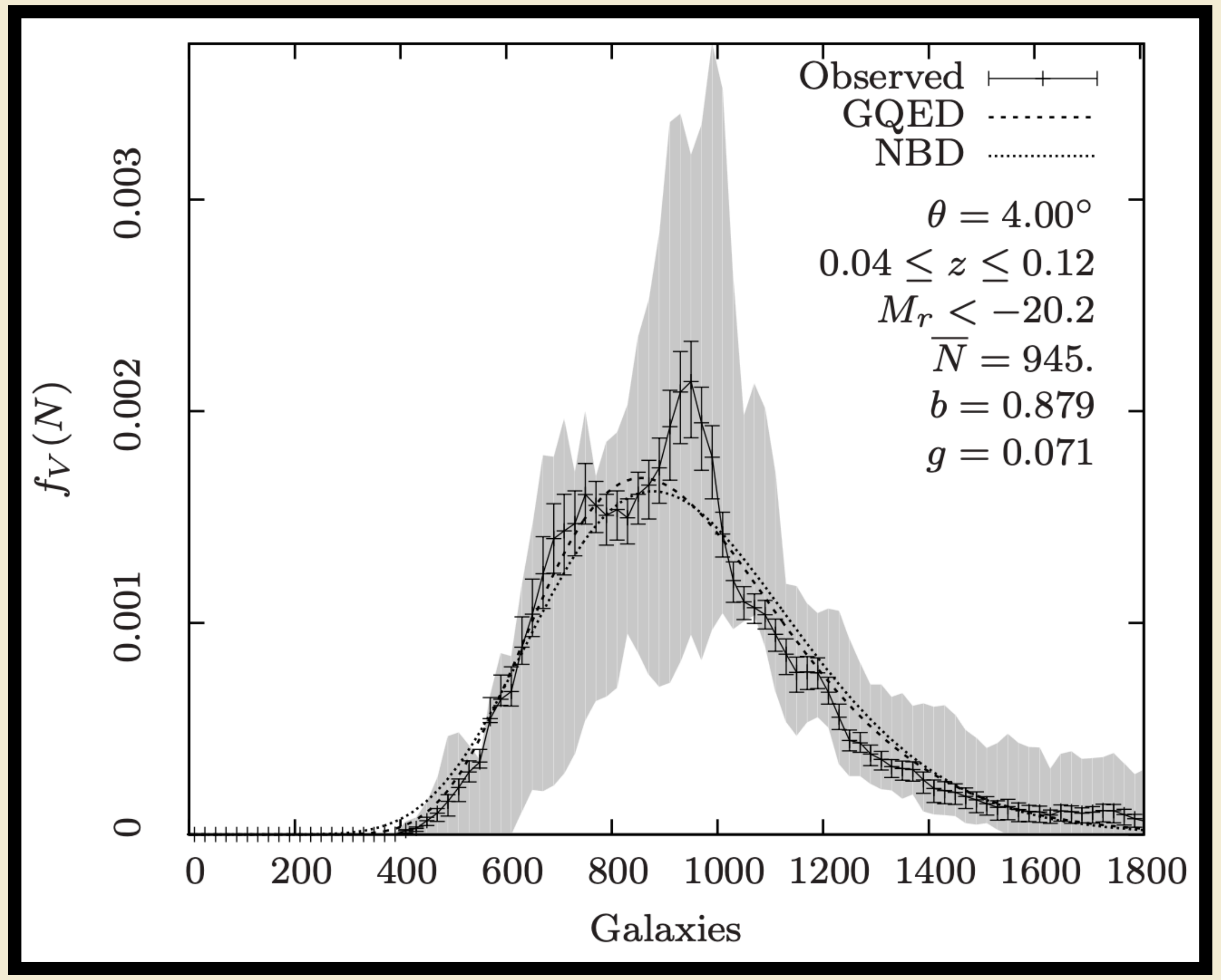
Counts-in-cells statistics



Constraints from the matter PDF (green) and the standard P(k) from simulations (Uhlemann et al. 2019)

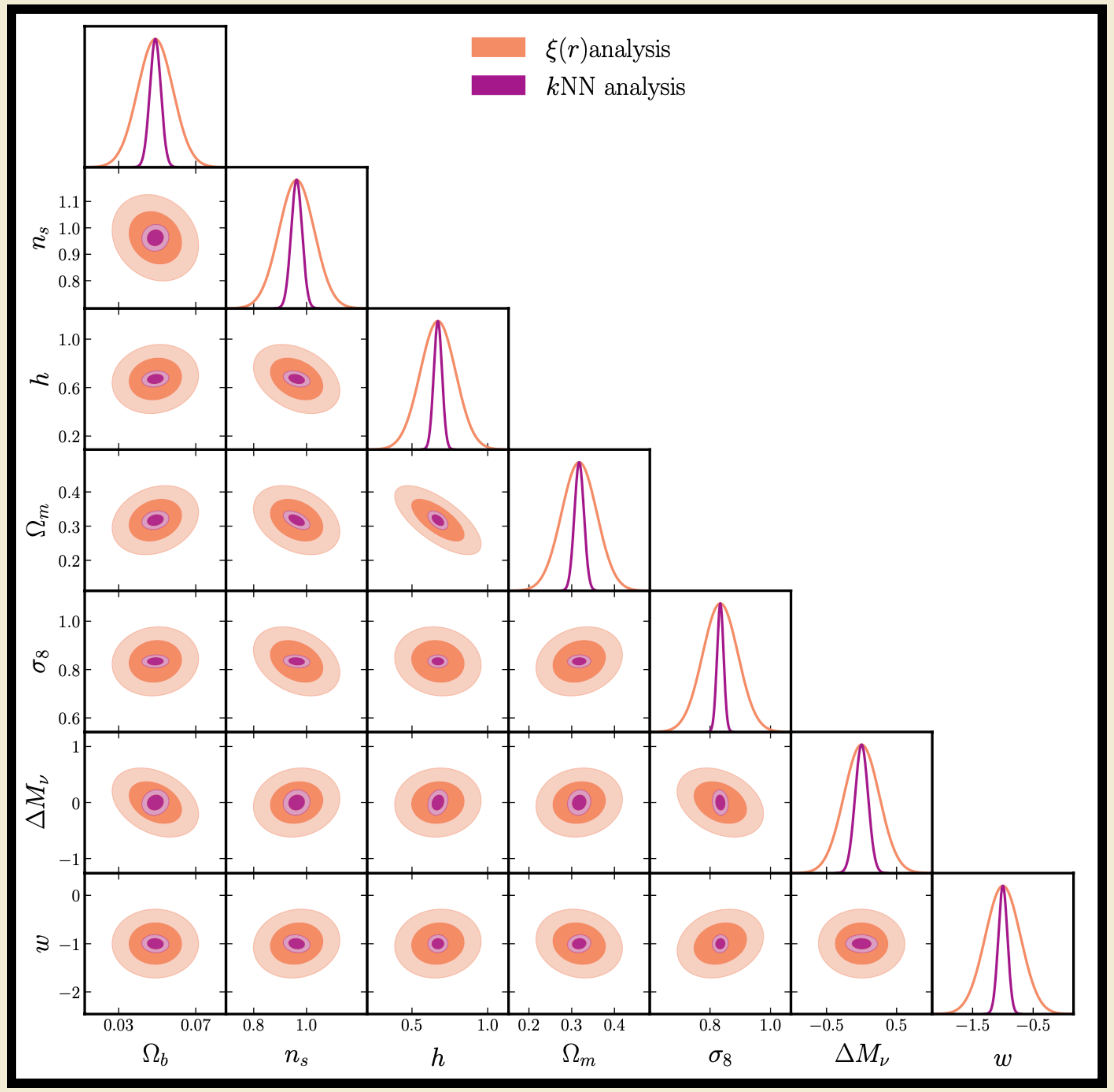


Measures galaxy counts in "cells" or spheres of a certain size

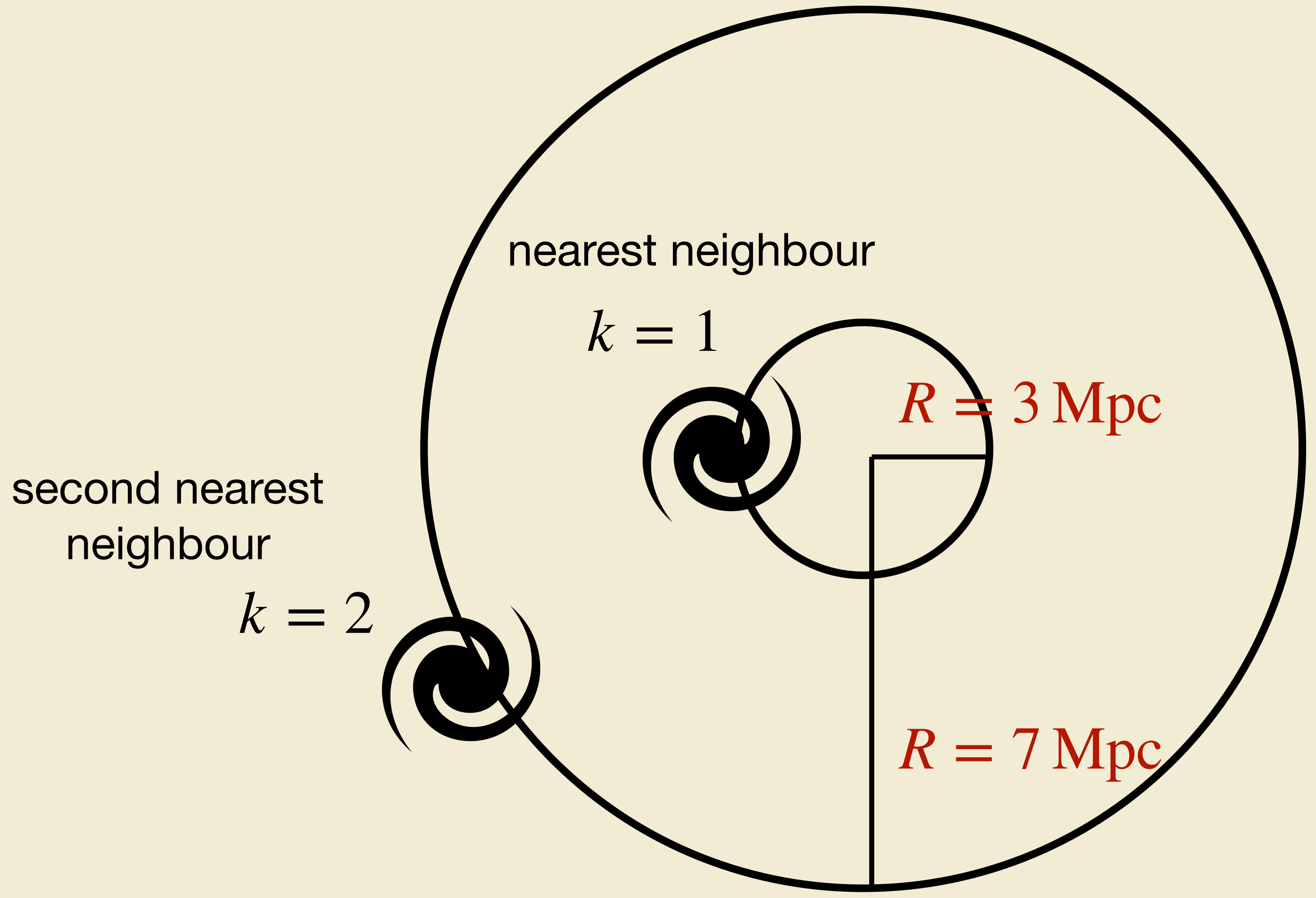


A measurement of the galaxy counts-in-cells in SDSS (Yang & Saslaw 2011)

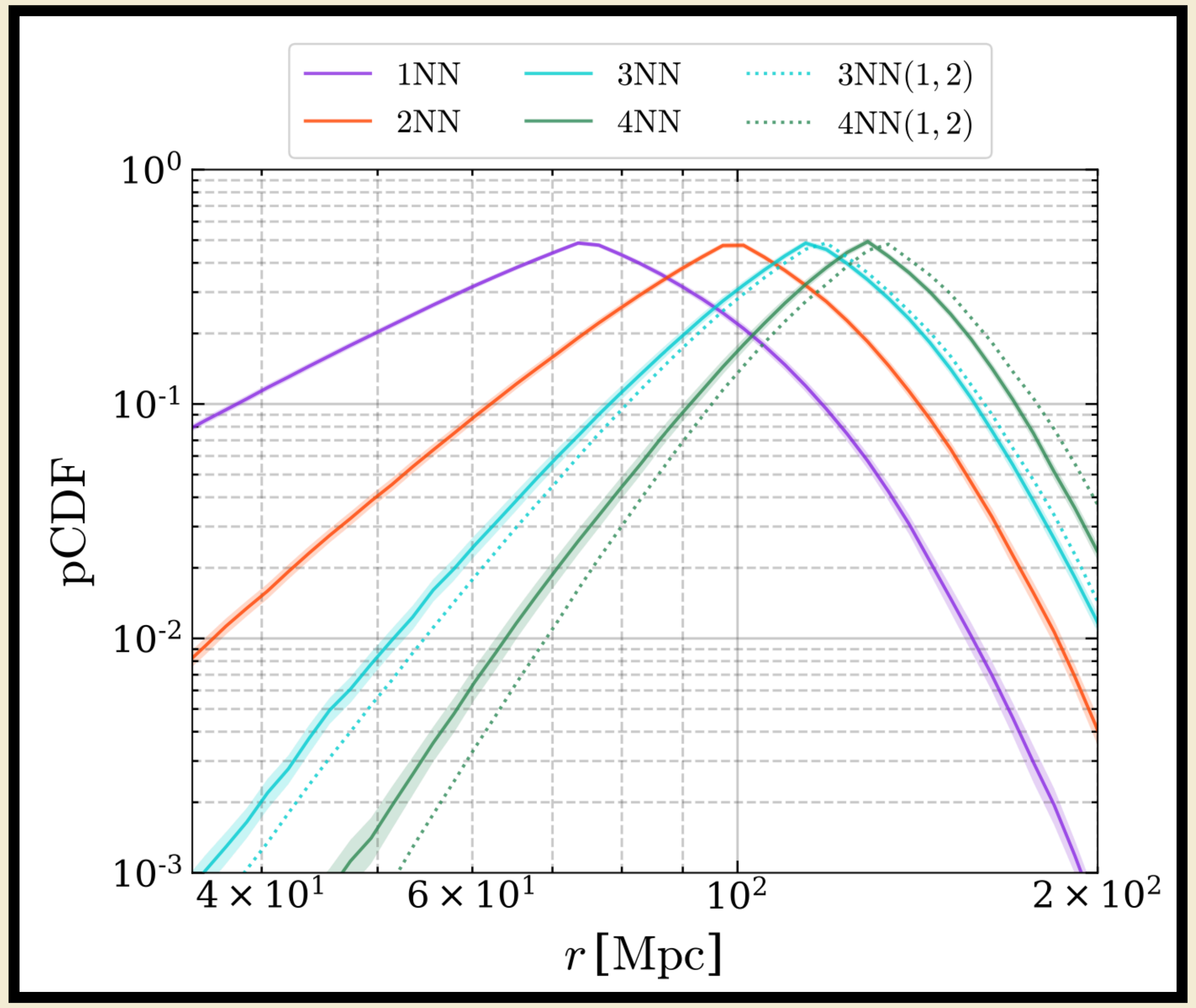
Nearest-neighbour distributions



Constraints from kNN analysis against the standard 2PCF from simulations (**Banerjee & Abel 2020**)



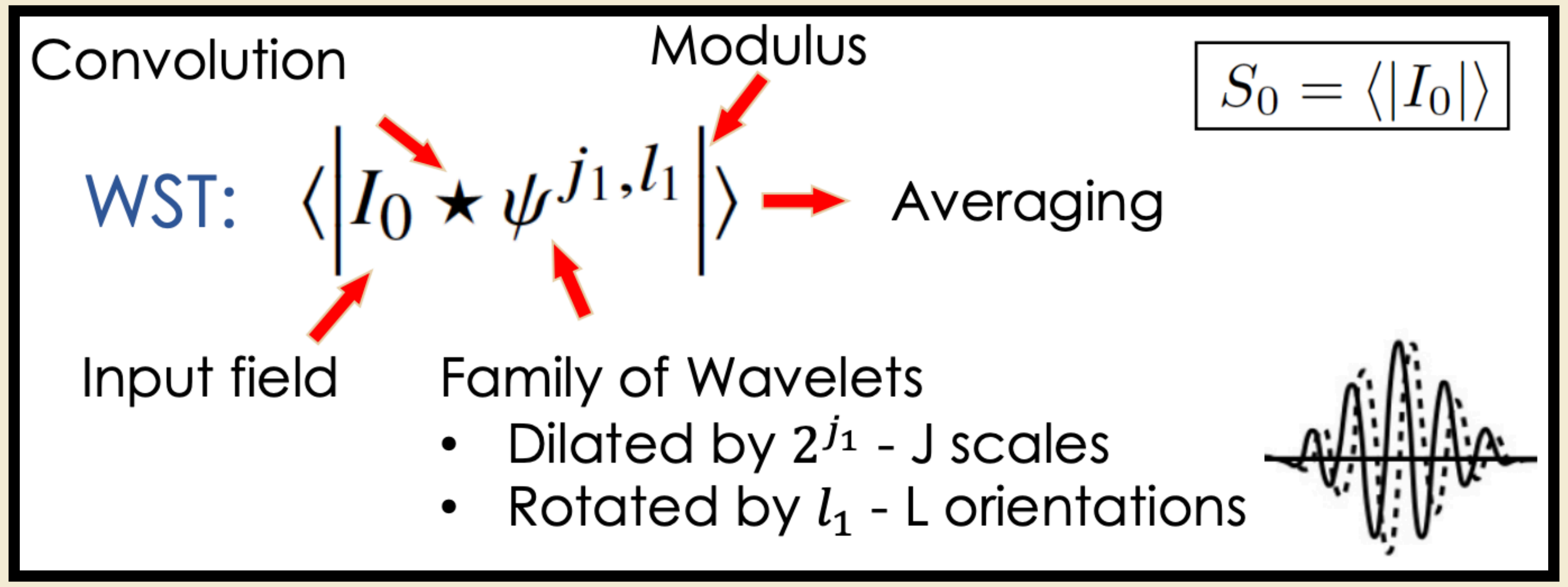
Measures the probability distribution of the distances to the nearest neighbouring points

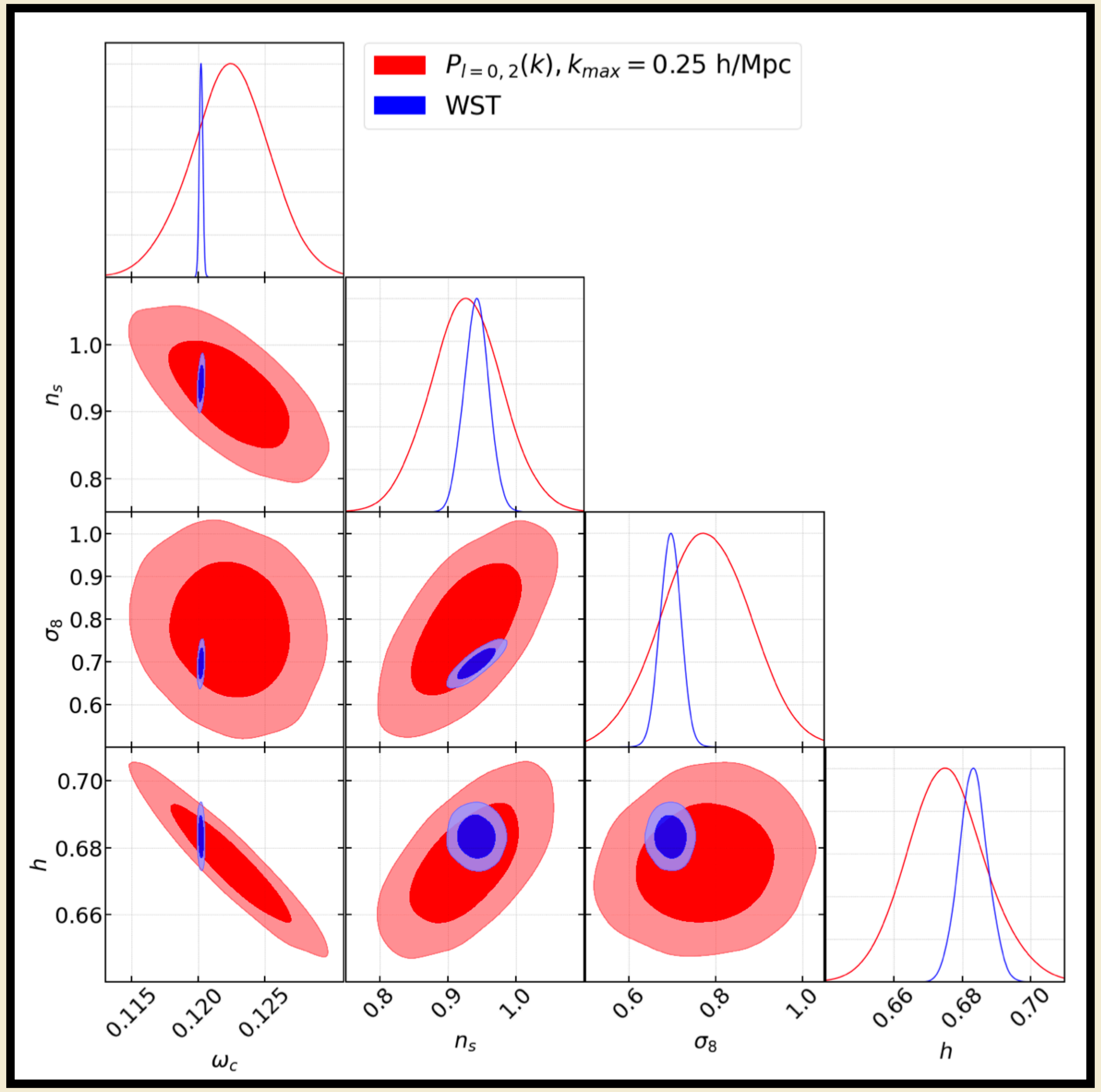


kNN analysis in redMaPPer clusters (Wang et al. 2021)

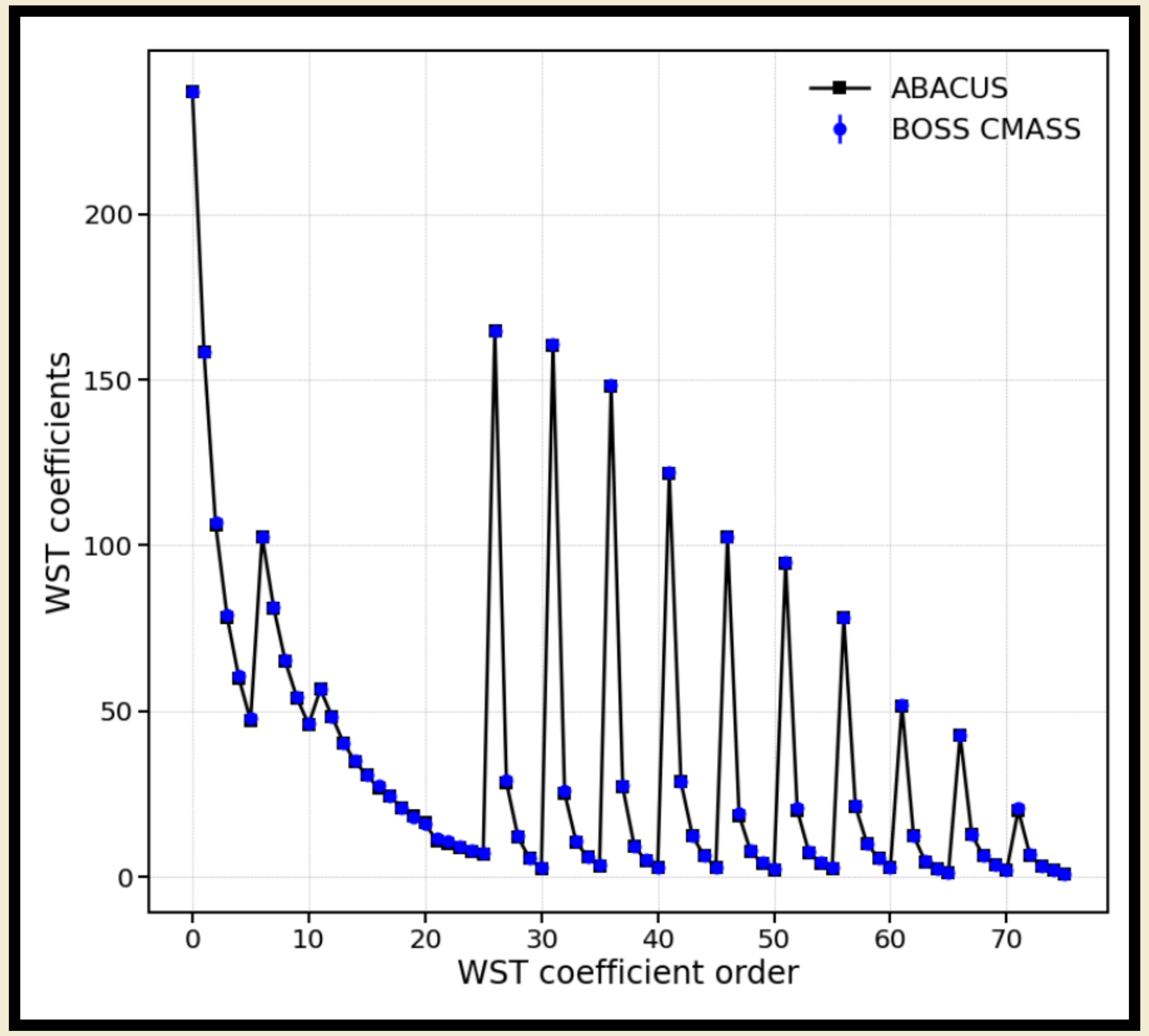
Wavelet scattering transform

Credits: Georgios Valogiannis



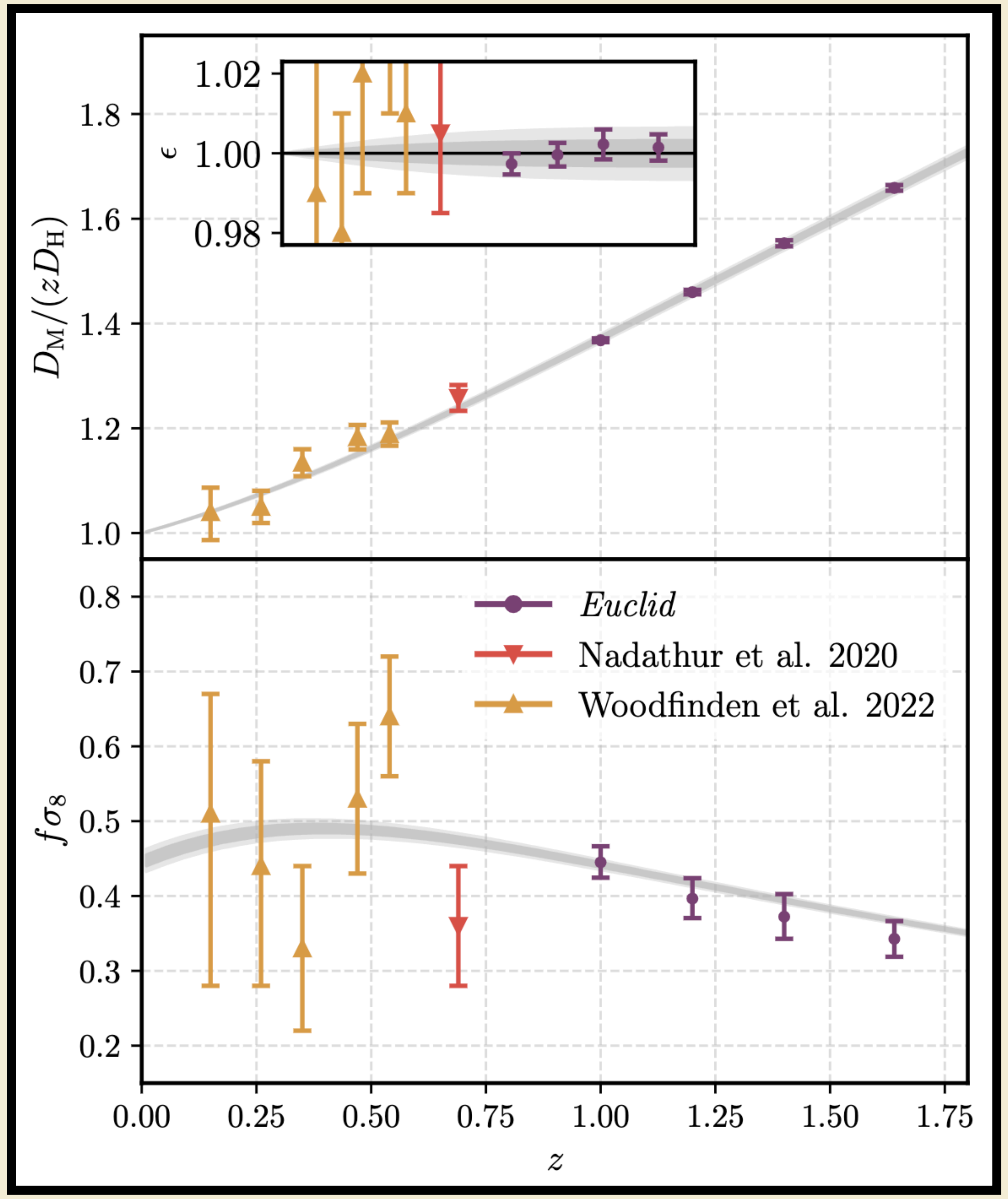


Constraints from a WST analysis in BOSS (Valogiannis & Dvorkin, 2022)



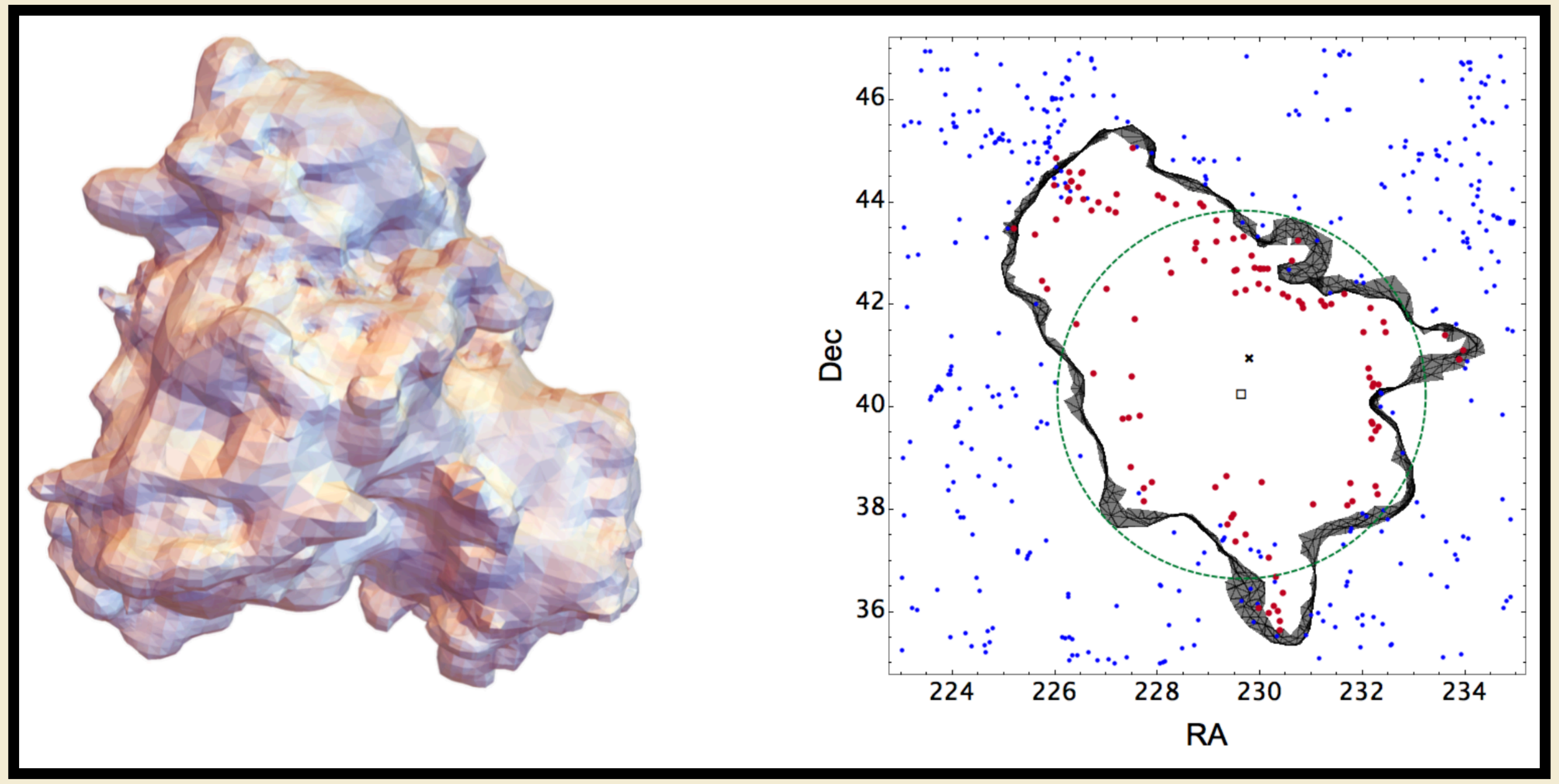
Measured WST coefficients from BOSS (Valogiannis & Dvorkin, 2022)

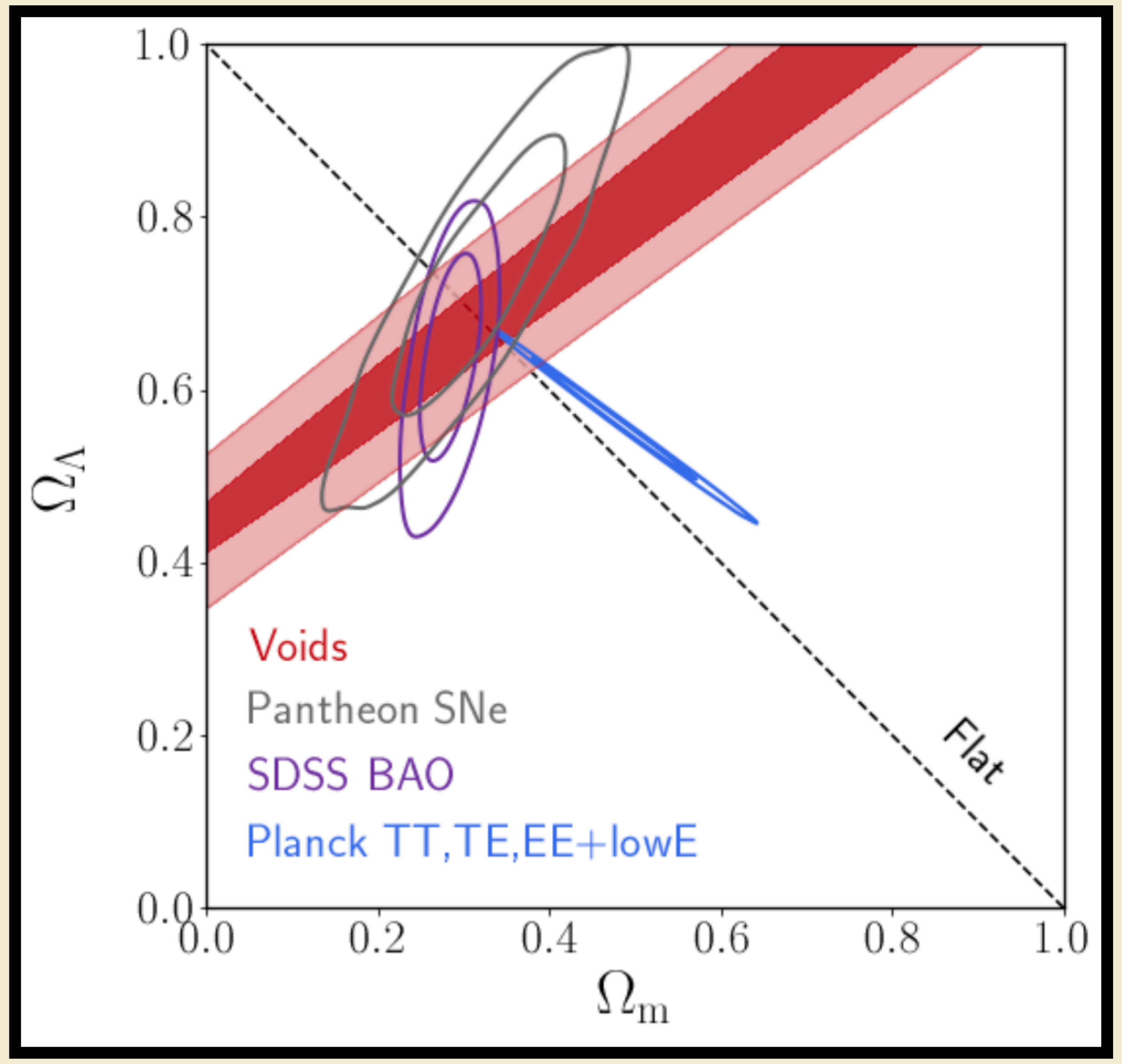
Cosmic void statistics



Constraints on geometry and growth from the void-galaxy CCF (Radinovic et al., including Paillas, in prep.)

A void measured in SDSS CMASS (Nadathur 2016)



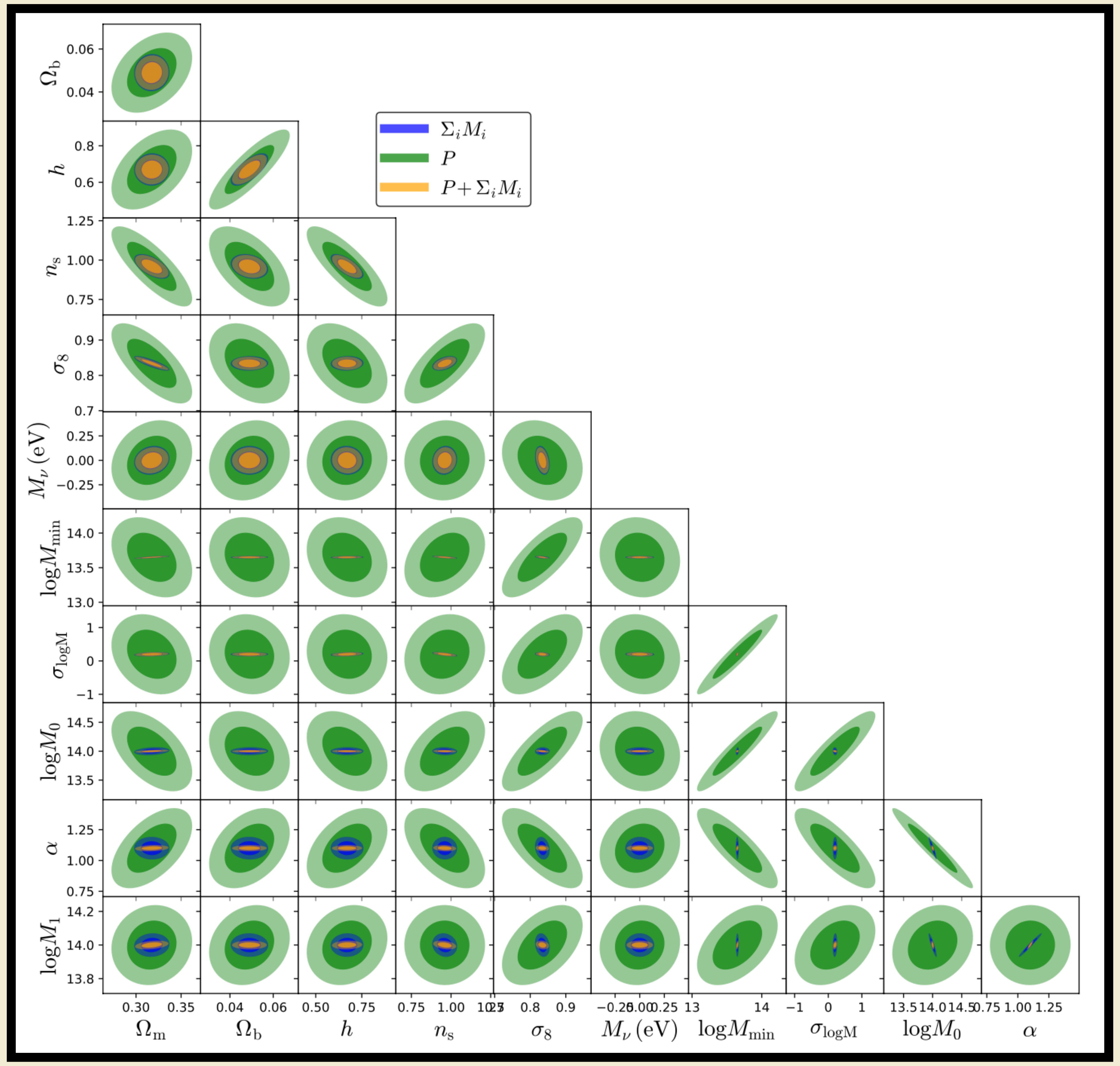


Voids provide independent evidence for dark energy and accelerated expansion (Woodfinden et al., 2022)

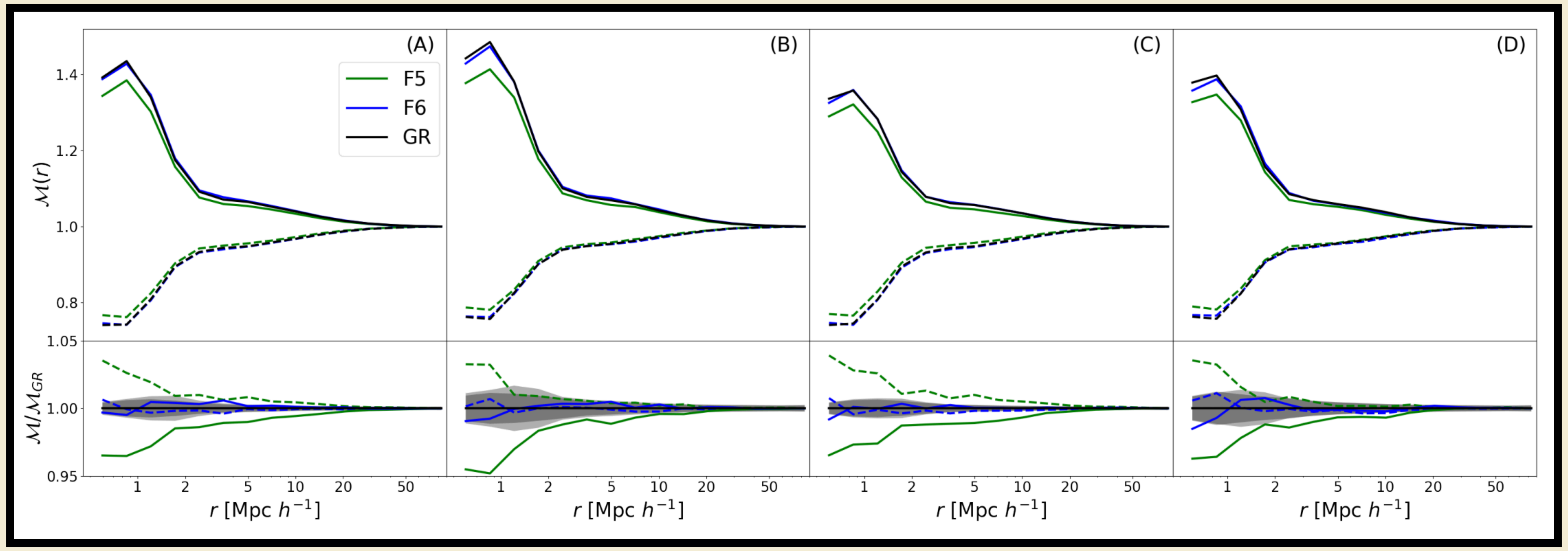
Marked power spectra or correlation functions

Similar to the power spectrum, but weights each galaxy according to a mark that depends on the local density (White 2016)

$$m(\vec{x}; R, p, \delta_s) = \left[\frac{1+\delta_s}{1+\delta_s+\delta_R(\vec{x})}\right]^p \equiv \left[1+\frac{\delta_R(\vec{x})}{1+\delta_s}\right]^{-p}$$



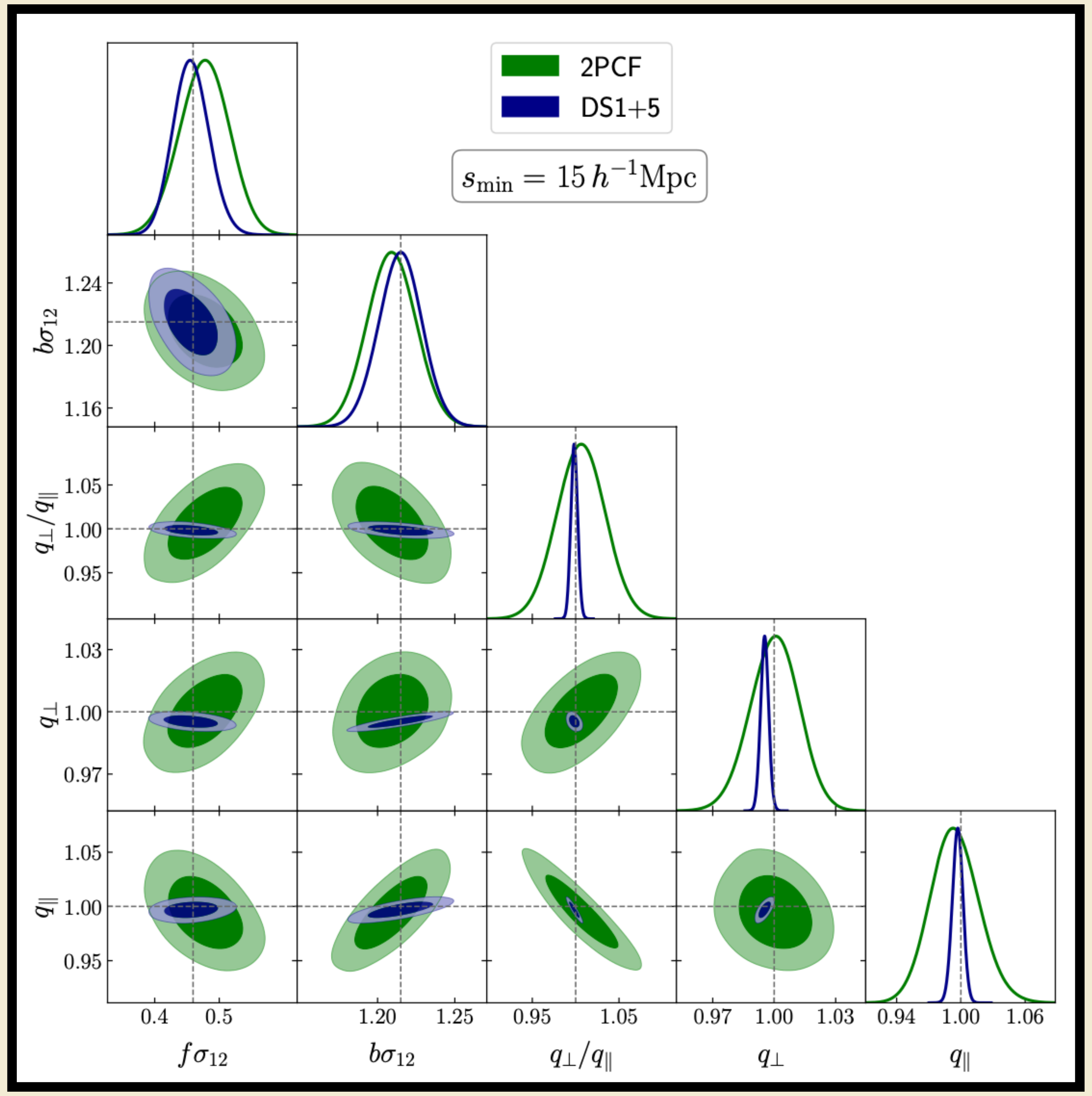
Marked power spectrum constraints from the galaxy field in simulations (Massara et al. 2022)



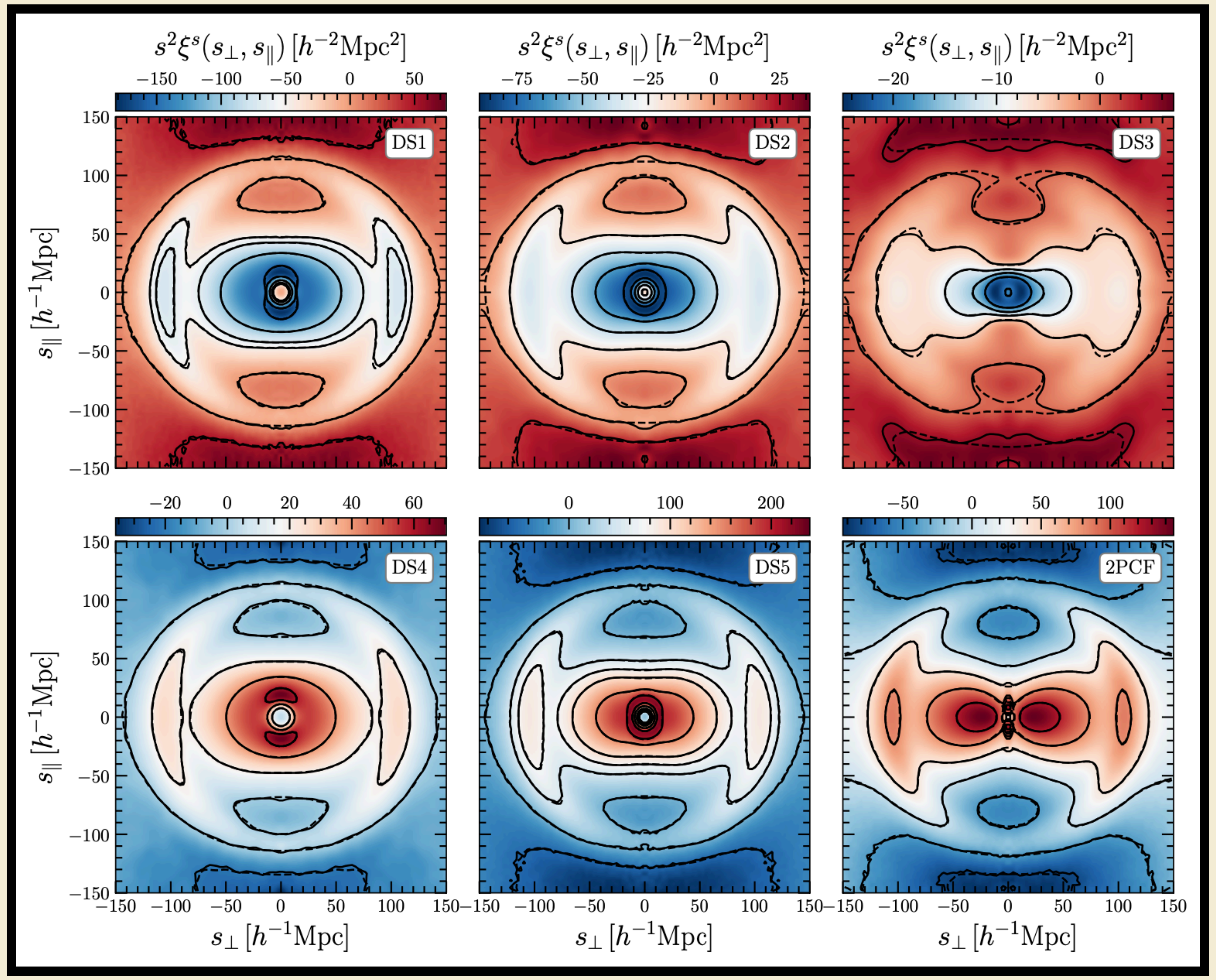
Marked correlation functions show sensitivity to modifications to gravity (Armijo et al. 2018)

Density-split clustering

Measures clustering statistics associated with regions of different environmental density, and performs a joint cosmological analysis.

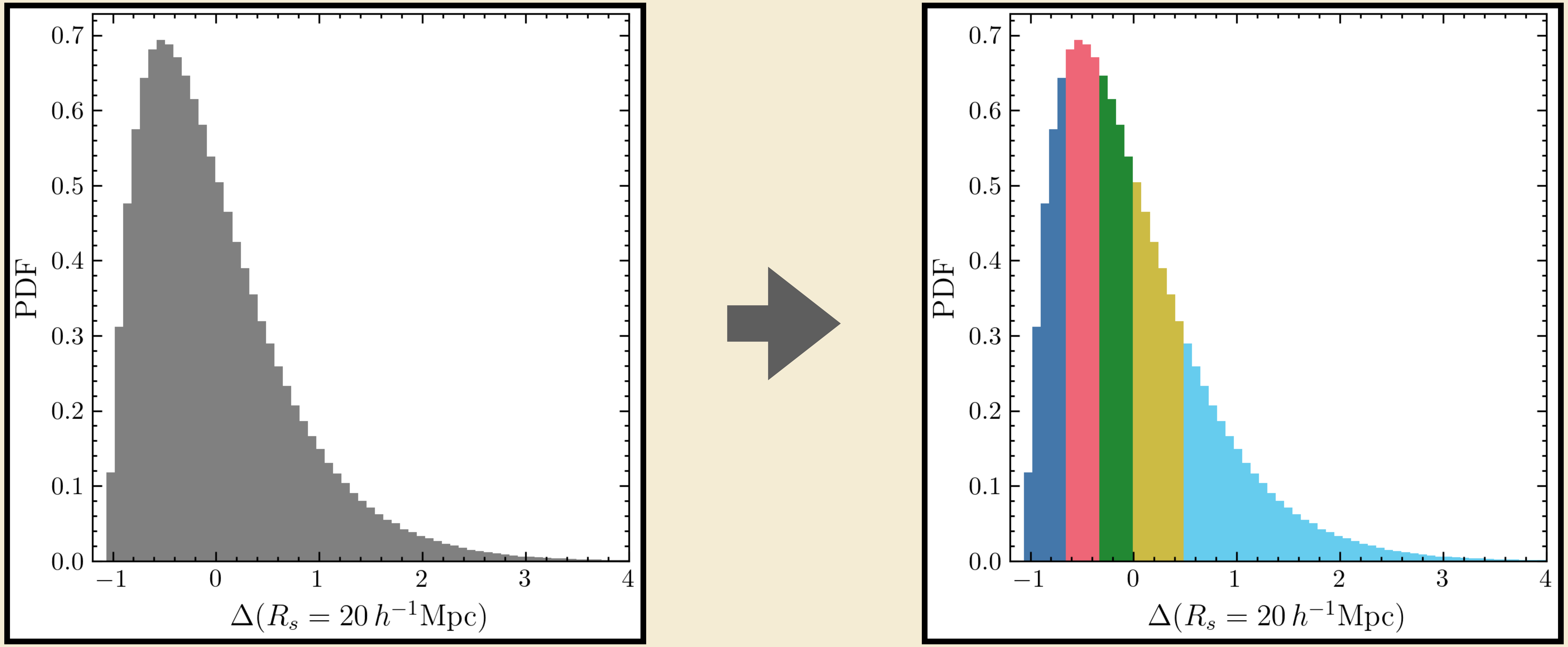


Constraints from a density-split RSD analysis in simulations (Paillas et al. 2021)



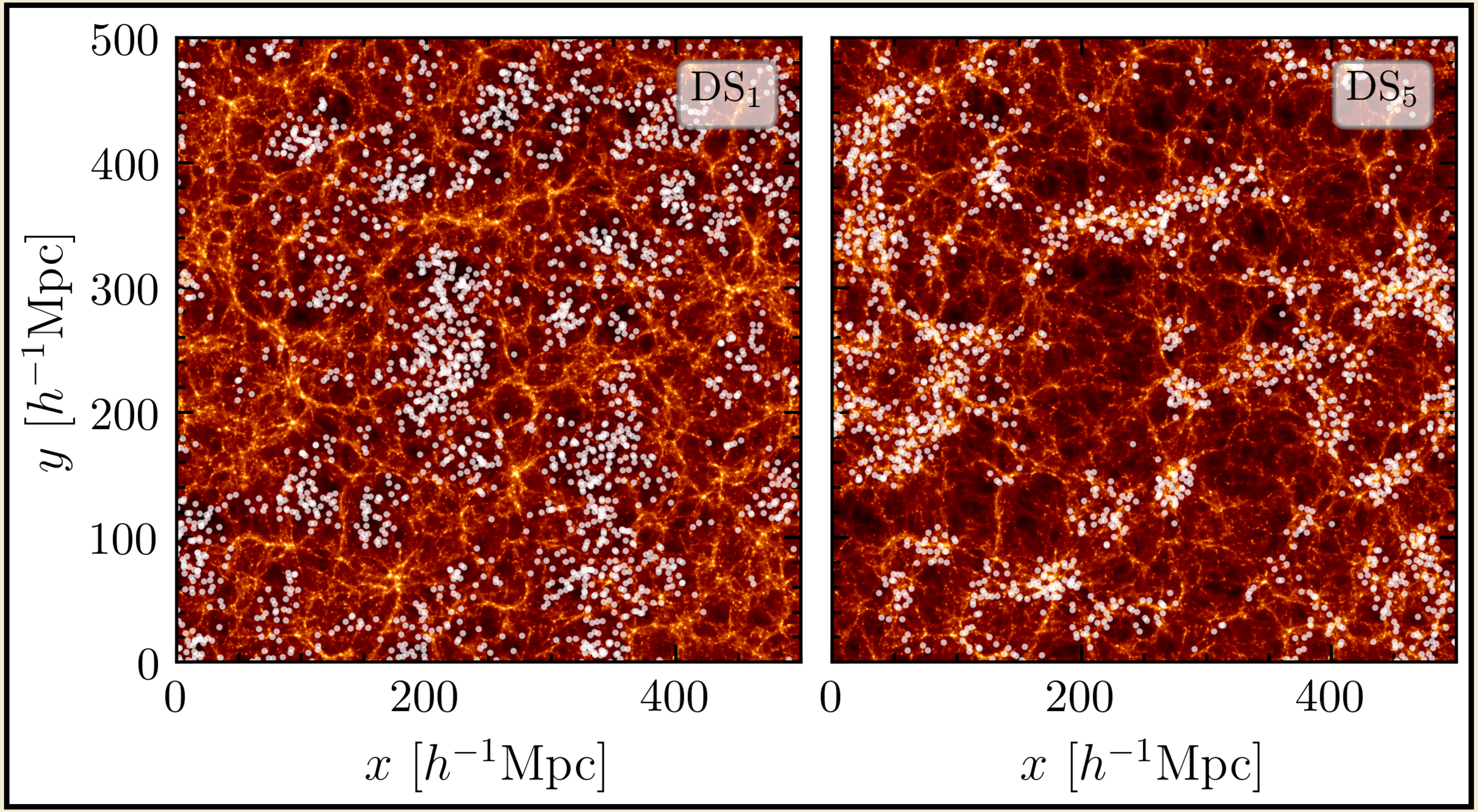
Correlation functions for different density environments in the Minerva simulations (Paillas et al. 2021)

❶ Splitting the density field



Low-density

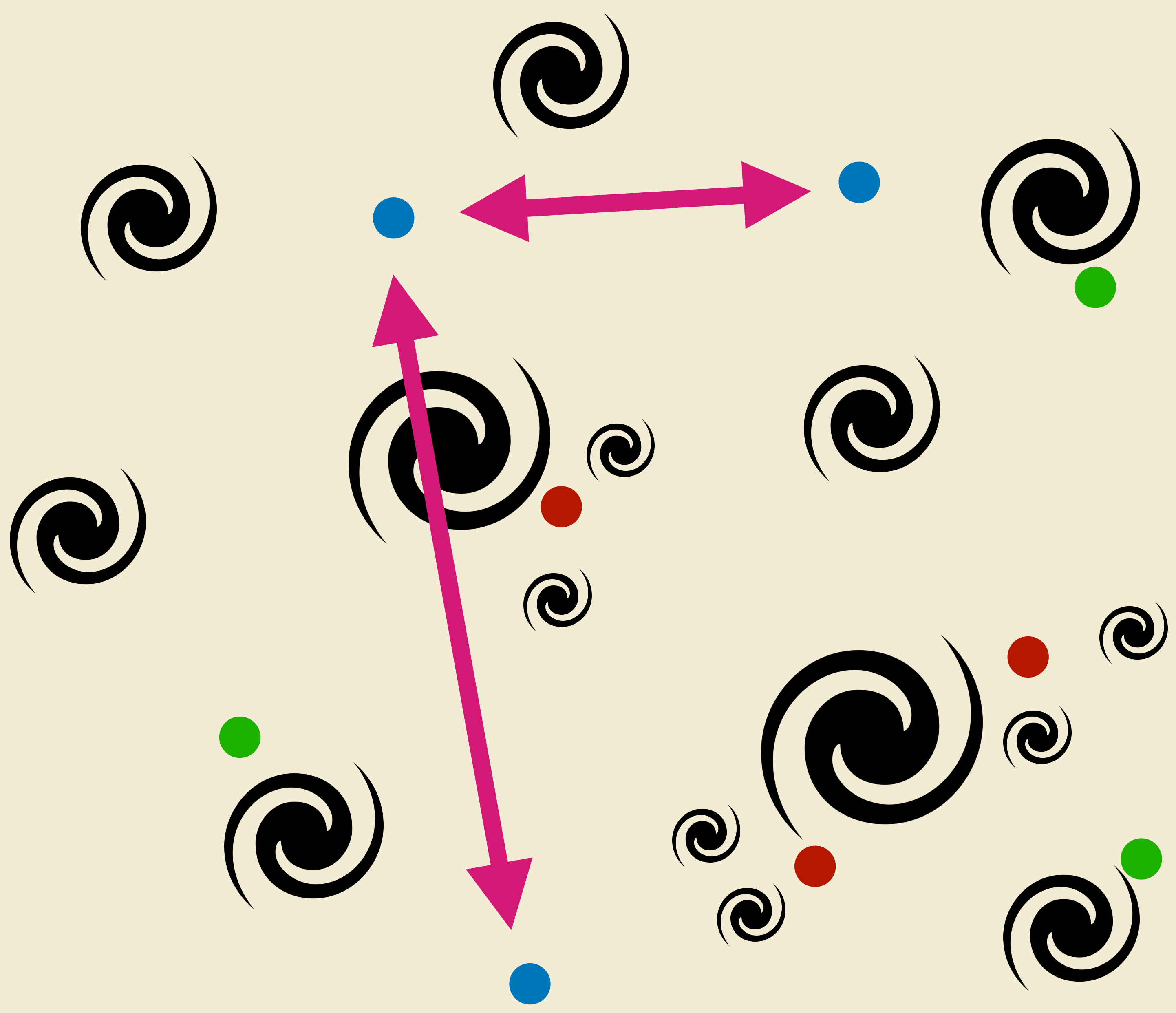
High-density



② Clustering statistics

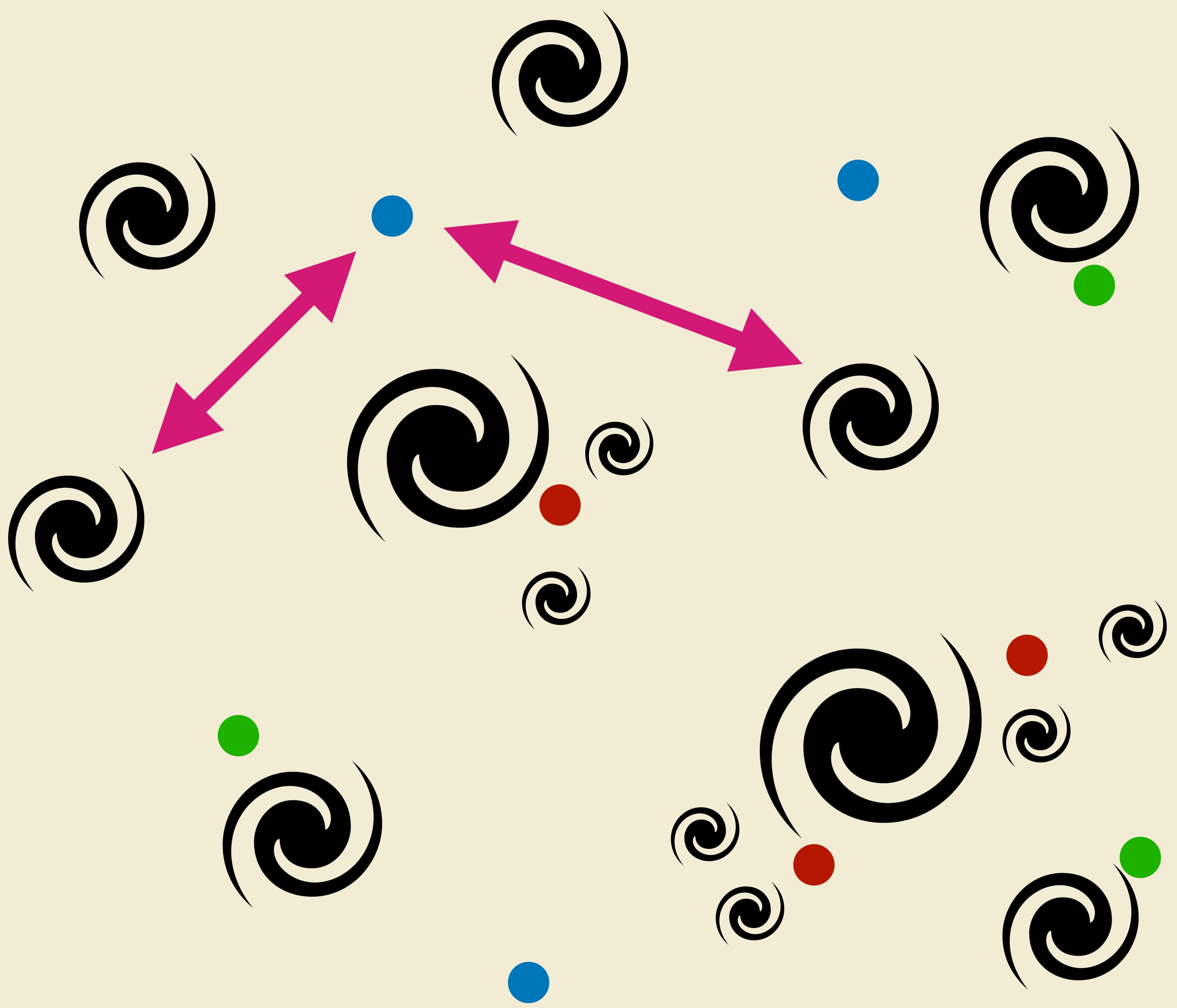
$\xi^{qq}(s)$

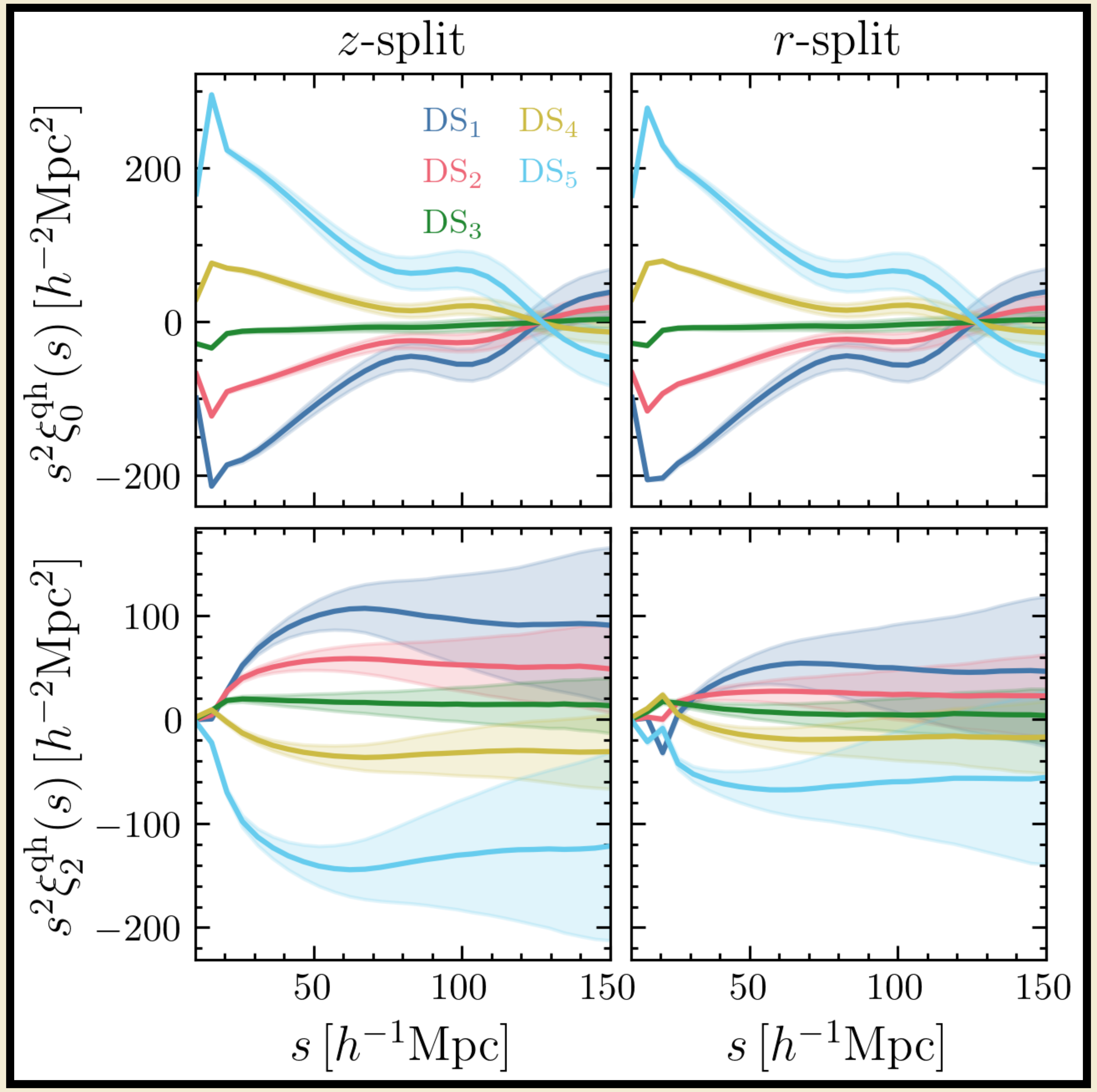
Quintile autocorrelation function



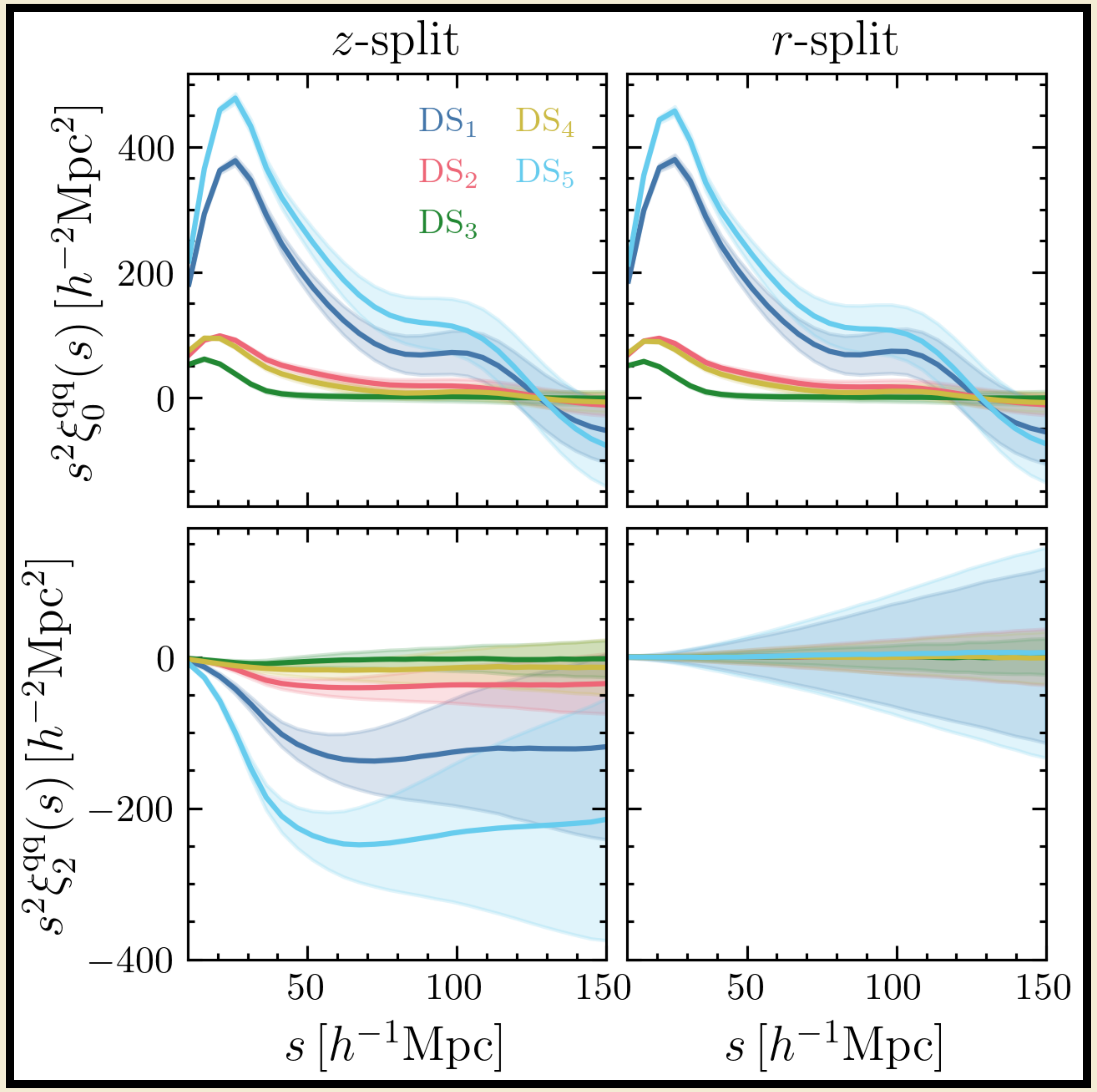
$\xi^{qg}(s)$

Quintile-galaxy cross-correlation function



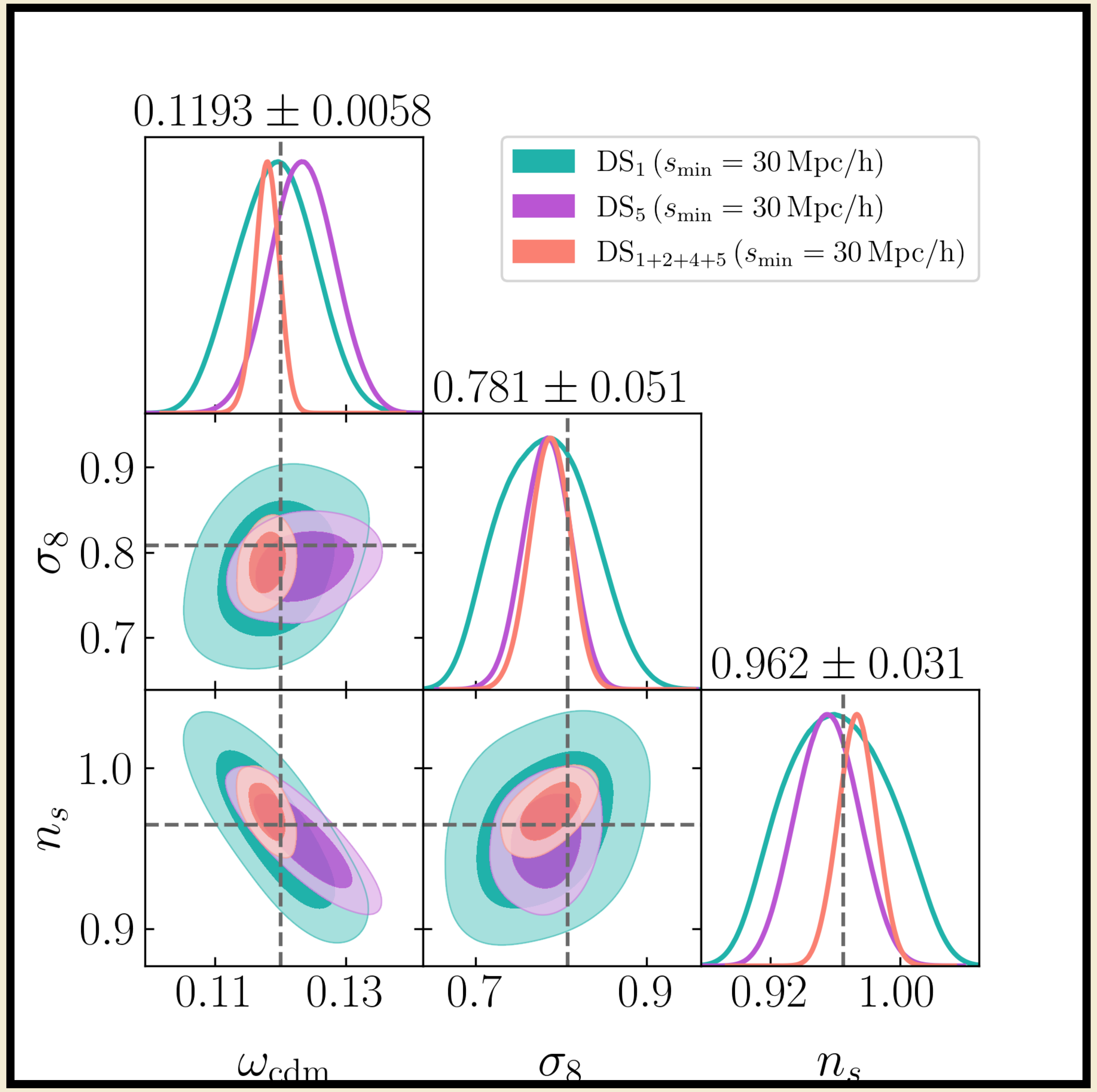


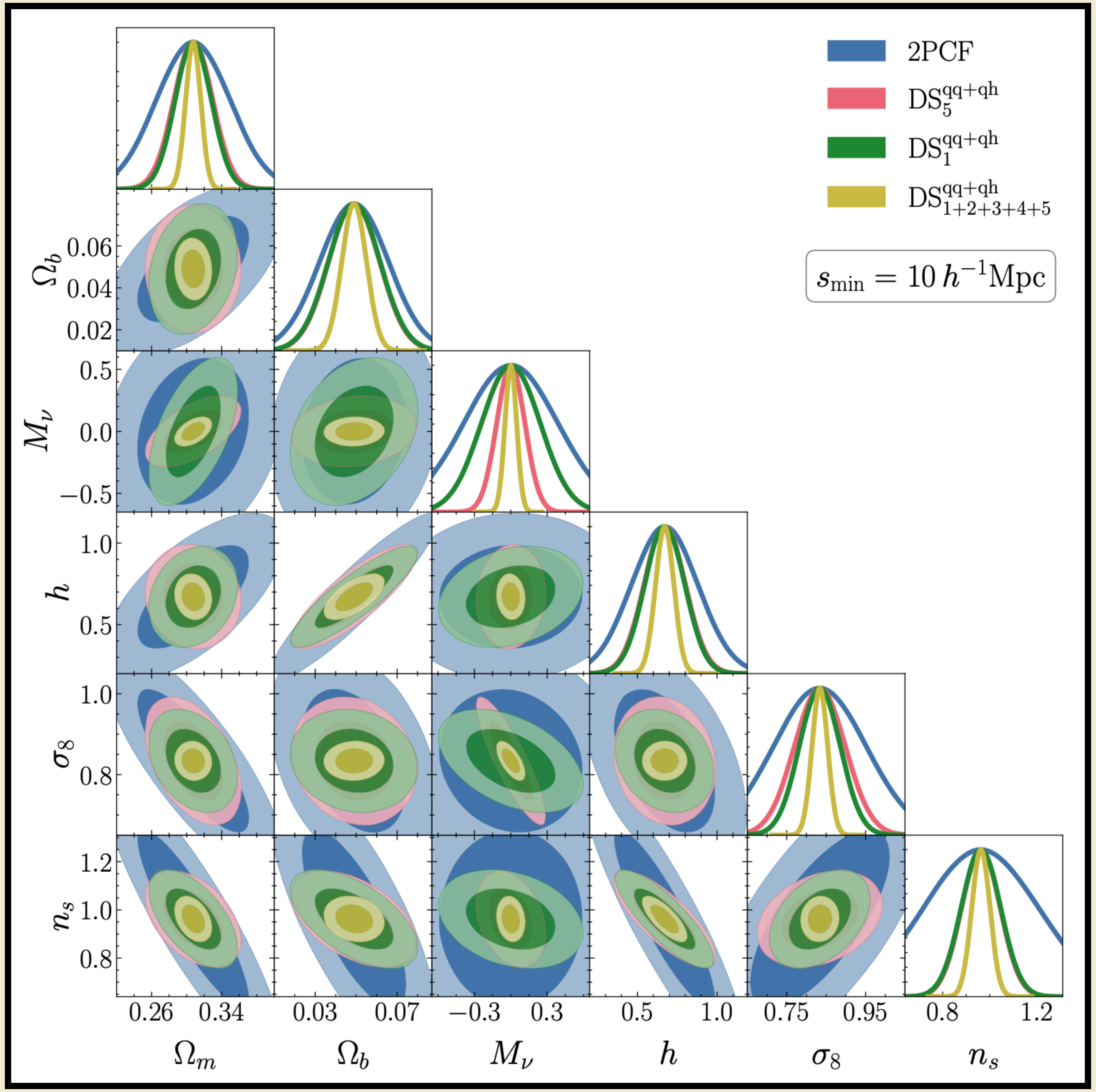
z-split
r-split
DS1
DS2
DS3
DS4
DS5
$s^2\xi_0^{\rm qh}(s)\ [h^{-2}{\rm Mpc}^2]$
$s^2\xi_2^{\rm qh}(s)\ [h^{-2}{\rm Mpc}^2]$
200
0
−200
100
0
−100
−200
50
100
150
$s\ [h^{-1}{\rm Mpc}]$



z-split
r-split
DS1
DS2
DS3
DS4
DS5
$s^2\xi_0^{\rm qq}(s)\ [h^{-2}{\rm Mpc}^2]$
$s^2\xi_2^{\rm qq}(s)\ [h^{-2}{\rm Mpc}^2]$
400
200
0
0
−200
−400
50
100
150
$s\ [h^{-1}{\rm Mpc}]$

③ Joint likelihood analysis





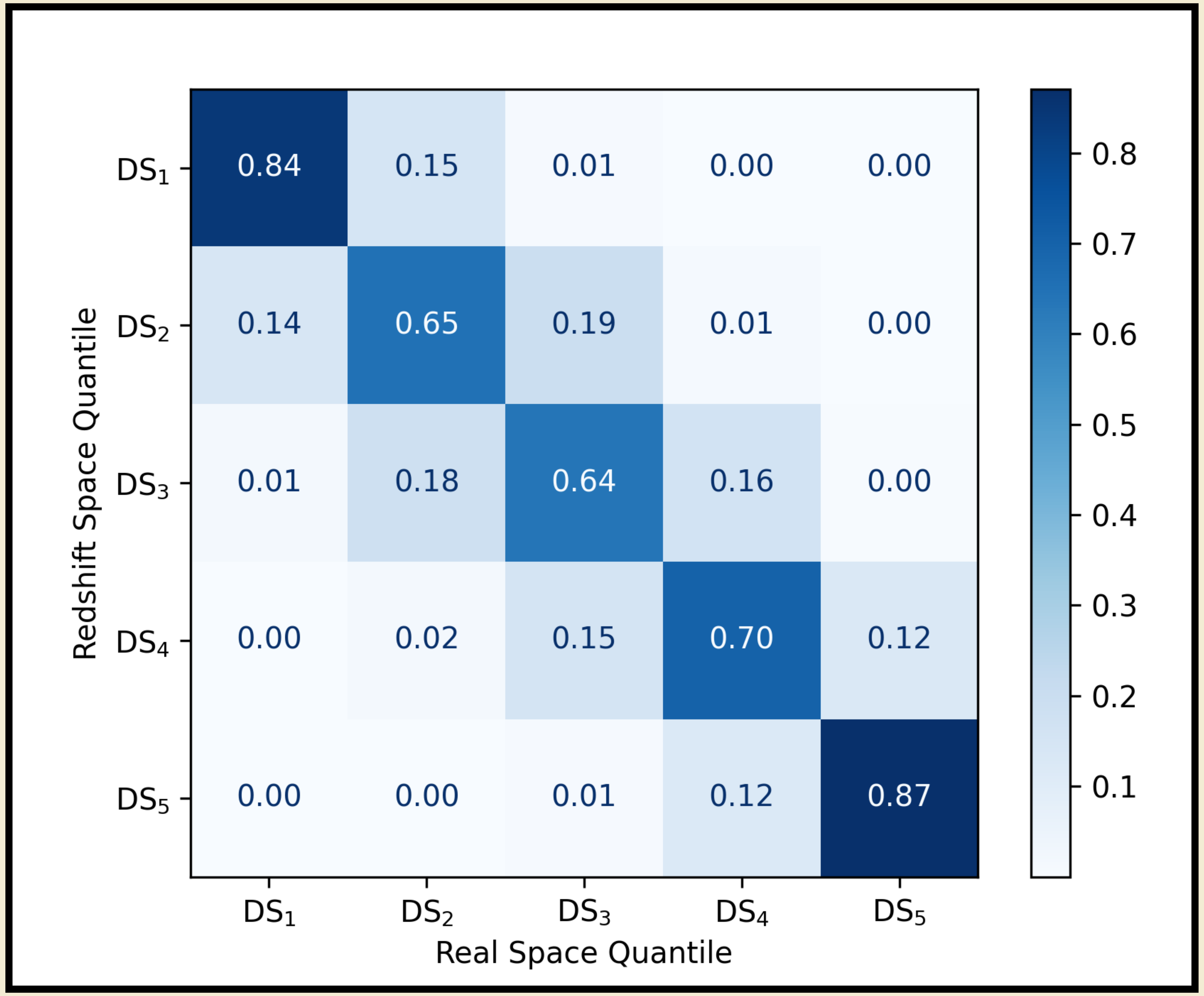
- DS provides **more precise constraints** on the parameters of the ΛCDM model compared to the 2PCF.

- DS improves the **constraints on the sum of neutrino masses** by a factor of 8 and by factors of 5, 3, 4, 6, and 6 for Ω_m, Ω_b, h, n_s, and σ_8, respectively.

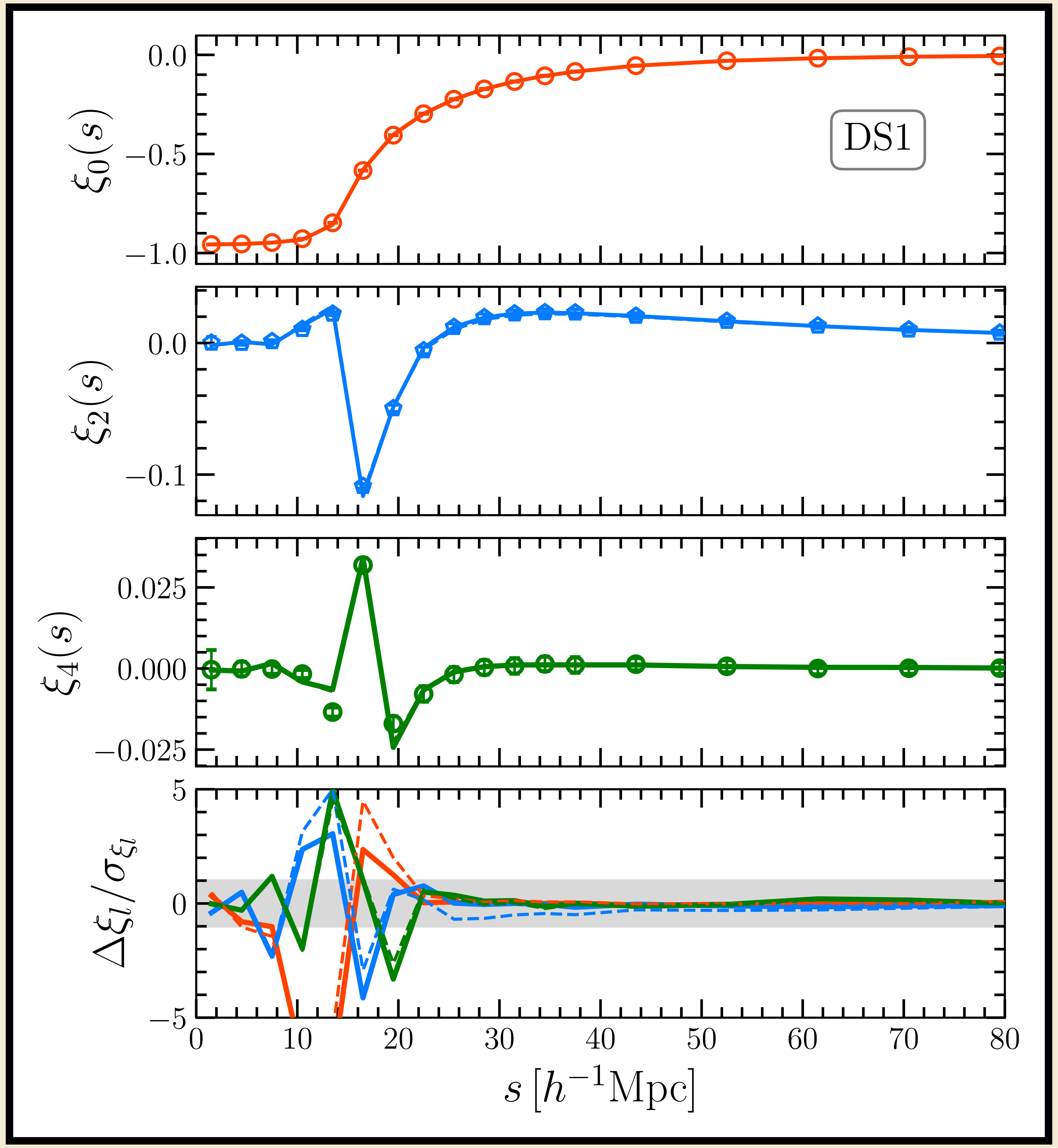
- It makes a difference if you split the densities in **real v/s redshift space**; there's a non-negligible fraction of points that swap to neighbouring quintiles.

- Similar effect as running a void finder in real v/s redshift space.

- Usually difficult to account for this in the RSD model (but see Correa et al. 2021)



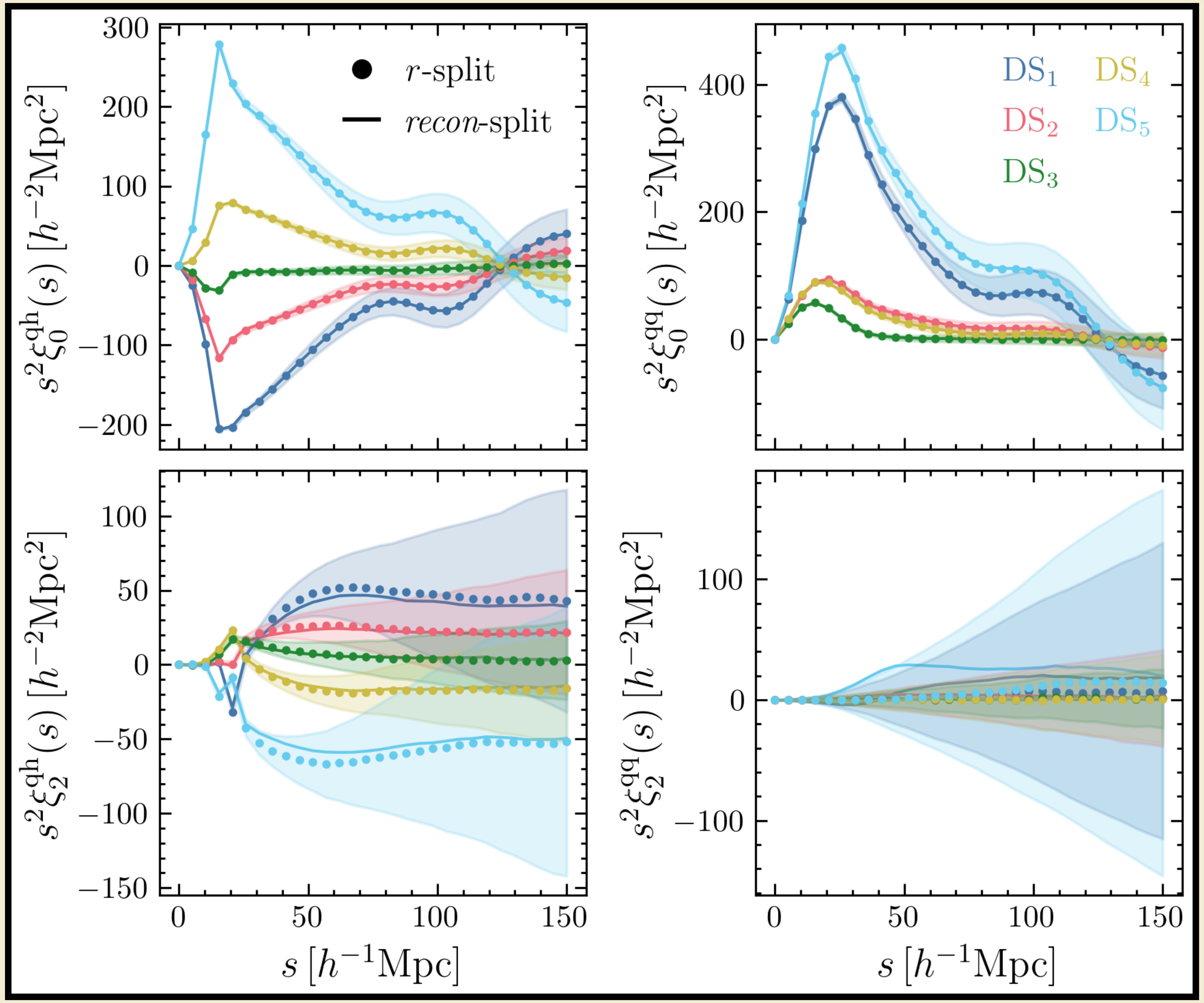
Paillas et al. (2022)



The **Gaussian Streaming Model** provides an accurate description of the density-split multipoles when we define the densities in real space.

$$1 + \xi^s(s_\perp, s_\parallel) = \int \left[1 + \xi(r)\right] \frac{1}{\sqrt{2\pi\sigma_\parallel^2(r,\mu)}} \exp\left\{ -\frac{\left[v_\parallel - v_r(r)\mu\right]^2}{2\sigma_\parallel^2(r,\mu)} \right\} \mathrm{d}v_\parallel$$

However, the real-space density field **is not immediately available** from observations.



A potential way around this is to use **reconstruction** to remove RSD from the galaxy field, and estimate the split densities in the post-reconstructed catalogue.

This method has been successful for void statistics (e.g. **Nadathur et al. 2019c**)

Using neural networks to emulate clustering statistics

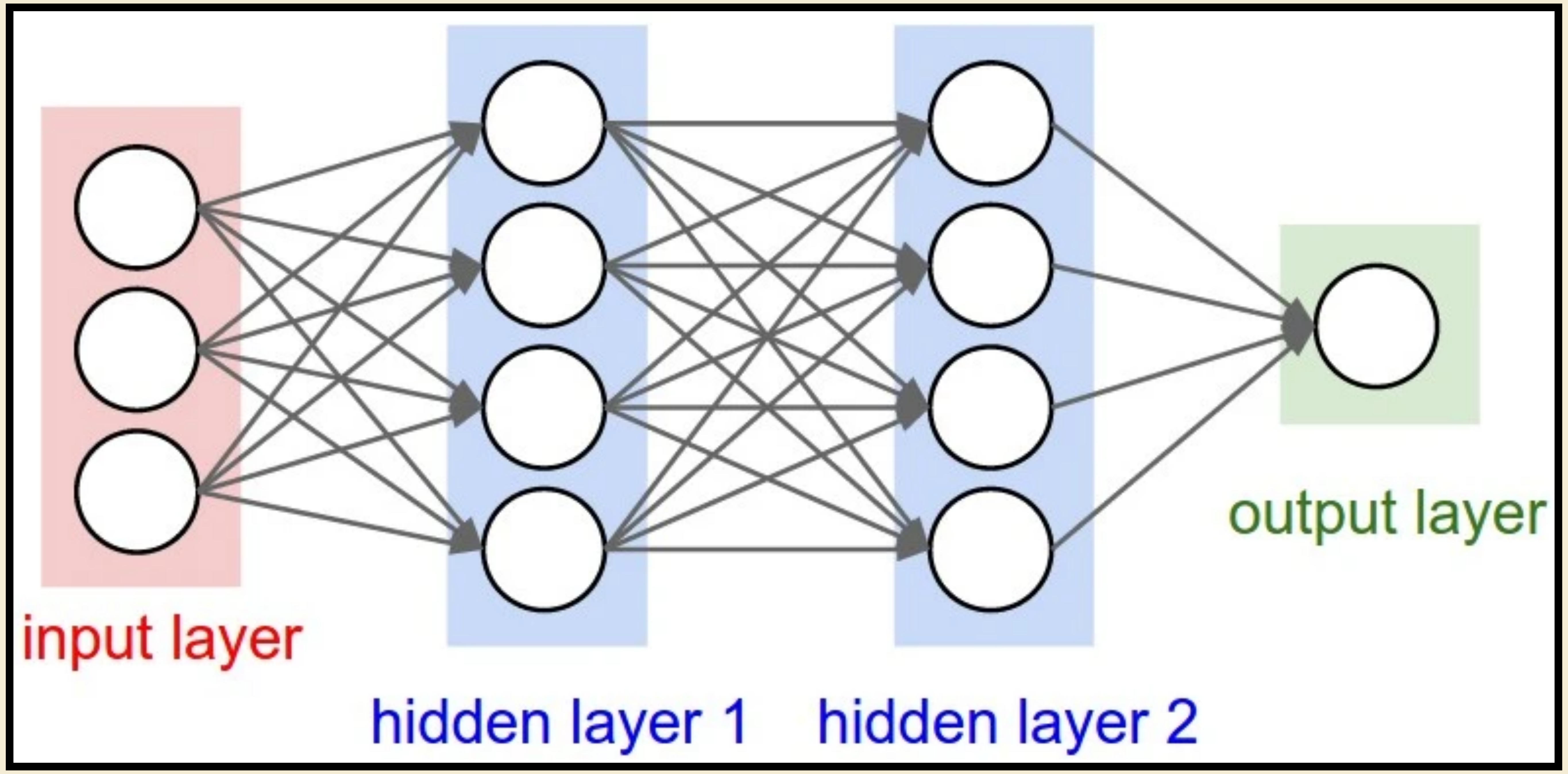
ω_b

$\omega_{\rm cdm}$

n_s

σ_8

…



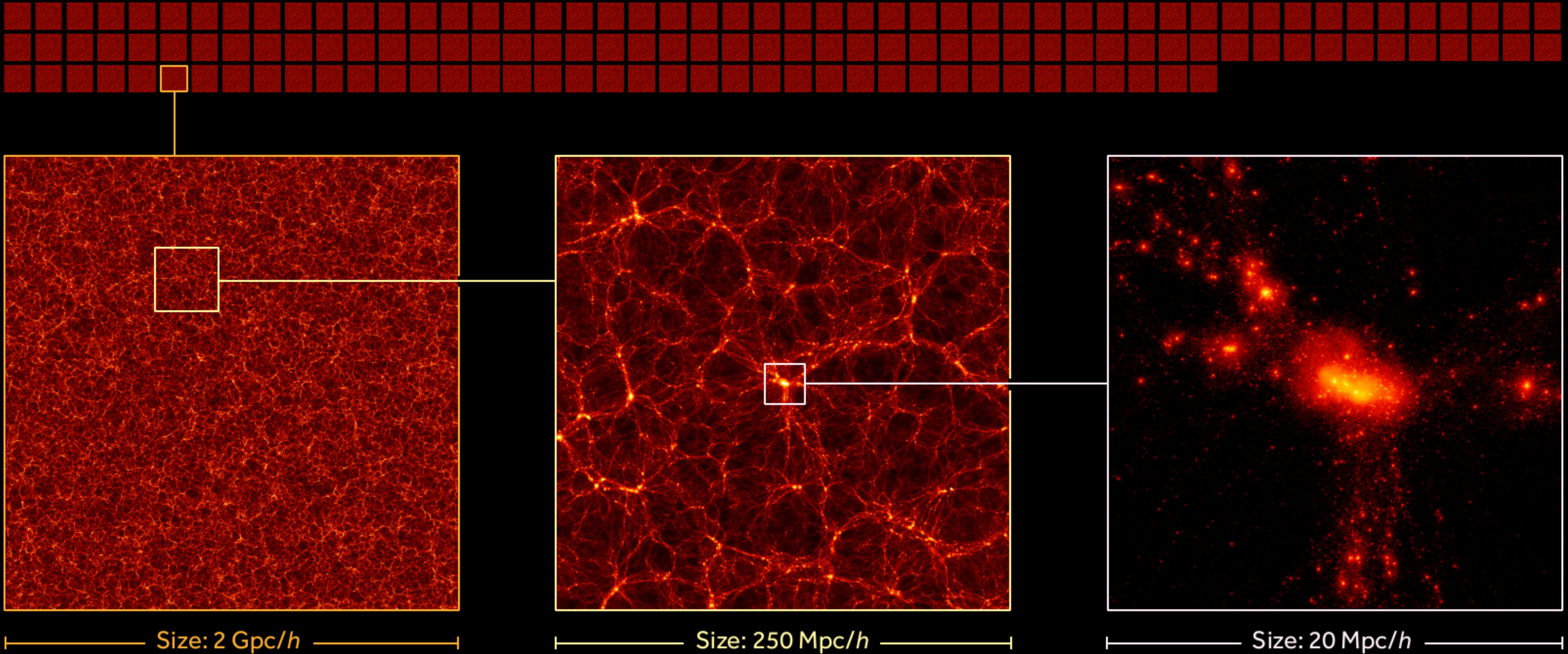
$\xi_0(s)$

$\xi_2(s)$

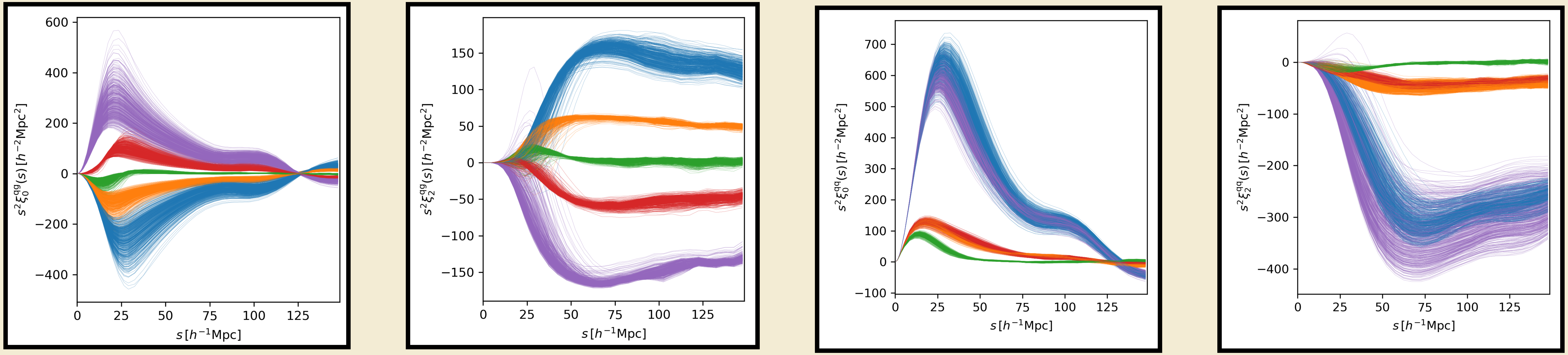
AbacusSummit: A Massive Set of High-Accuracy, High-Resolution *N*-Body Simulations

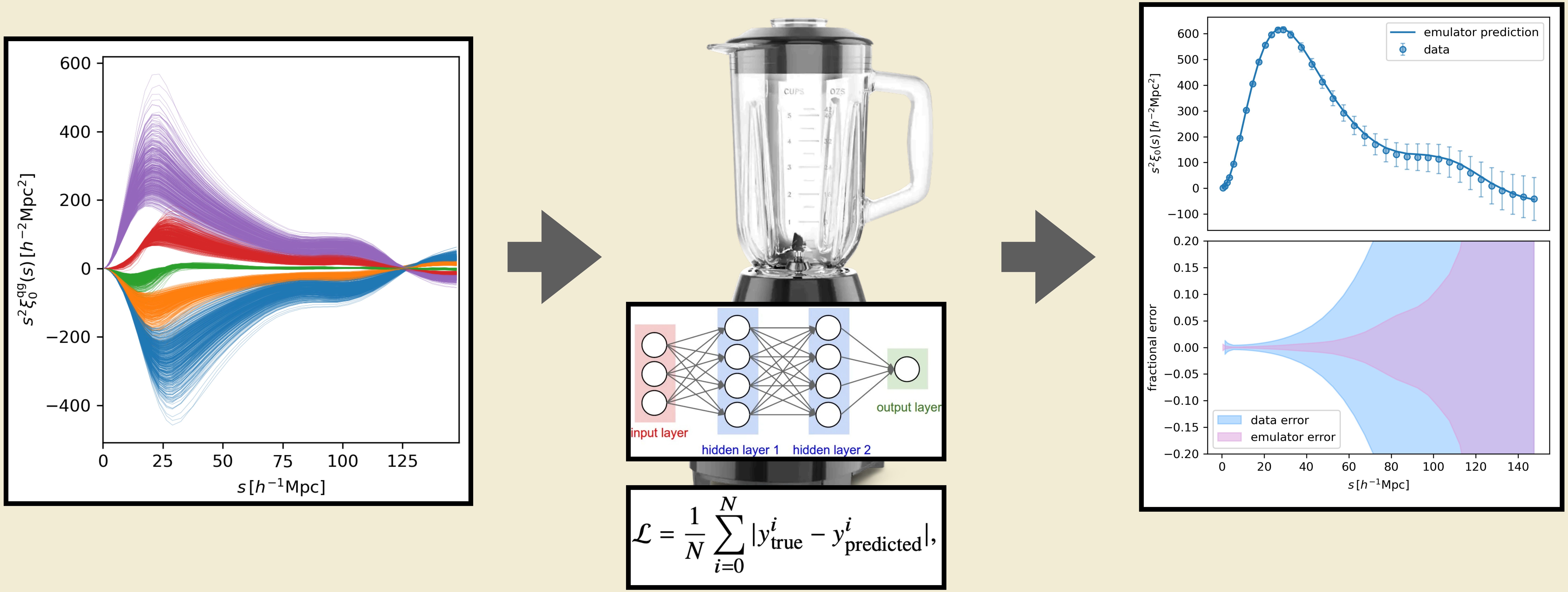
Nina Maksimova, Lehman Garrison, Daniel Eisenstein, Boryana Hadzhiyska, Sownak Bose, and Thomas Satterthwaite

139 base simulations | 60 trillion particles | 97 cosmologies | 67 billion halos | Particle mass $2 \times 10^9 h^{-1} M_\odot$ | AbacusSummit.readthedocs.io

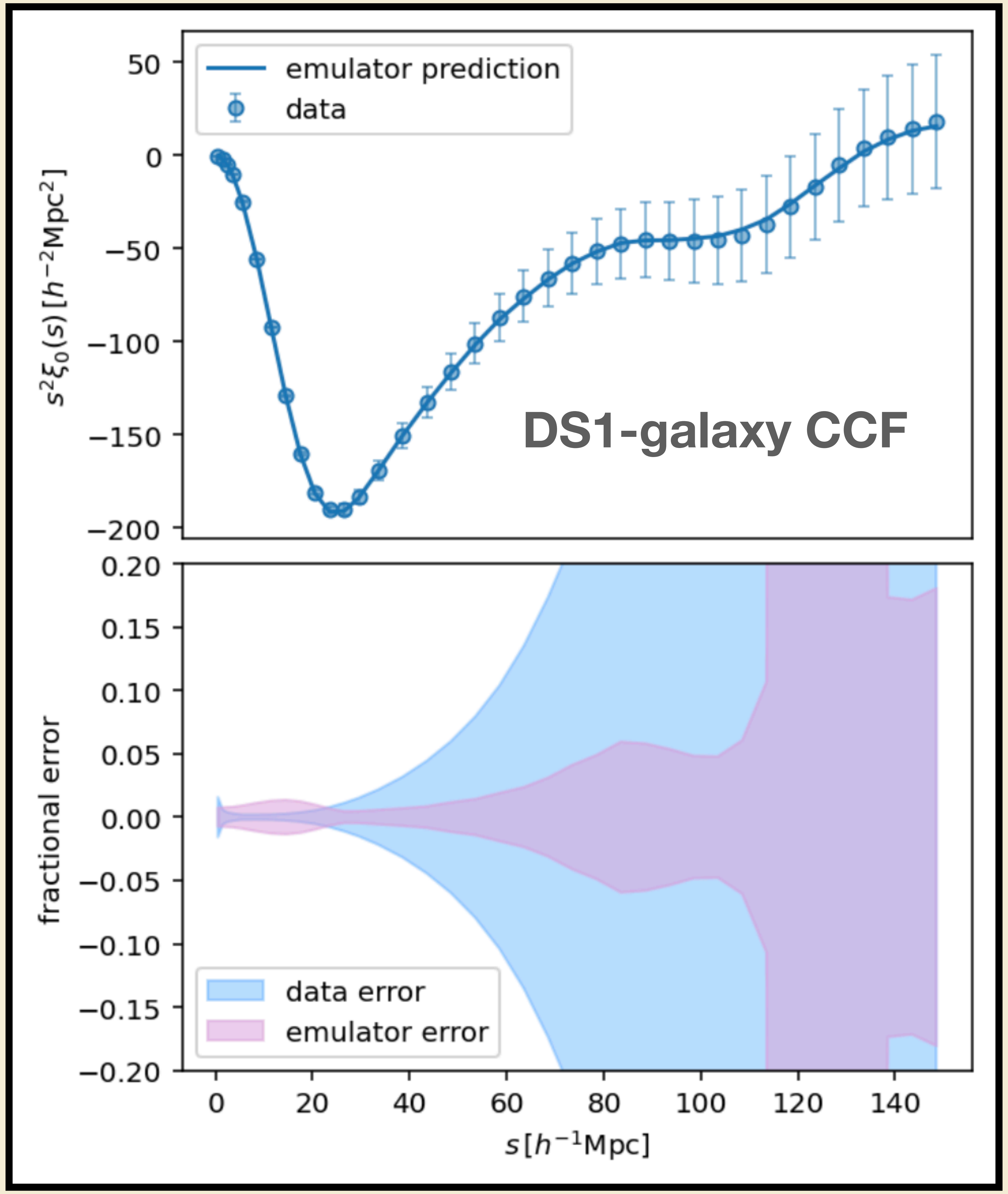


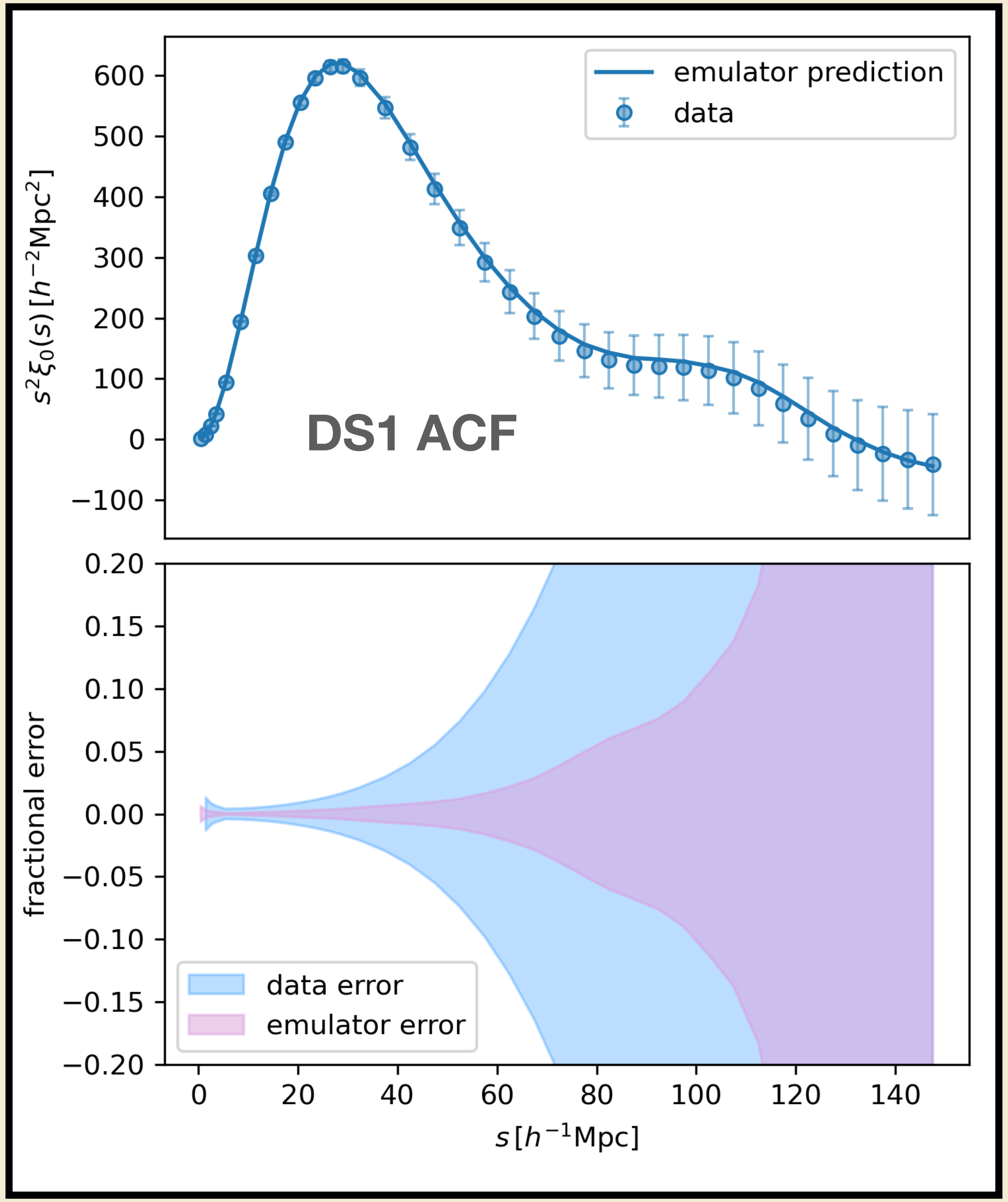
The training data for the neural network: monopole and quadrupole moments of the density-split auto/cross correlation functions (80,000 samples each)



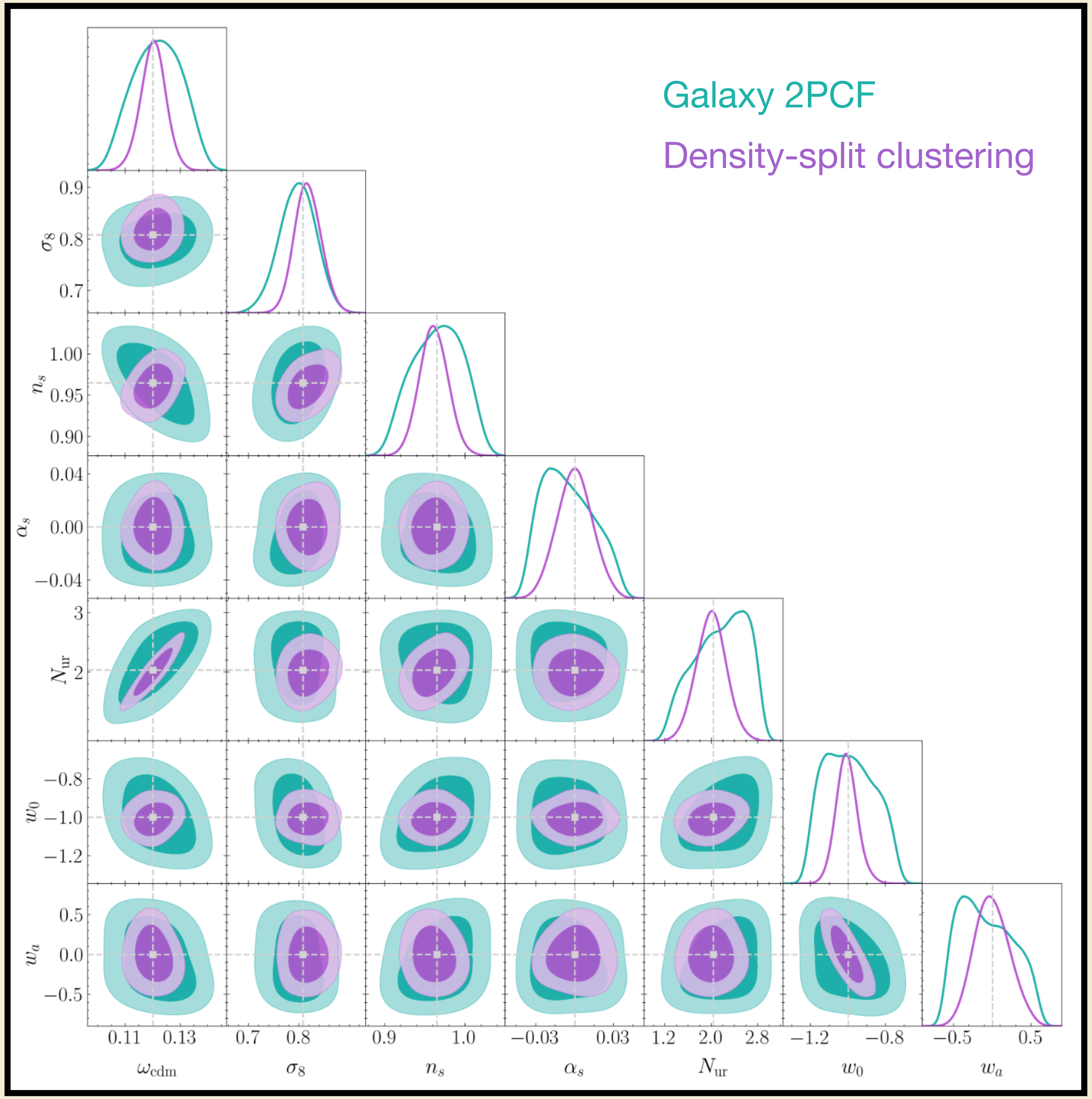


$s^2\xi_0^{qg}(s)\,[h^{-2}\mathrm{Mpc}^2]$
600
400
200
0
−200
−400
0
25
50
75
100
125
$s\,[h^{-1}\mathrm{Mpc}]$
CUPS
OZS
input layer
hidden layer 1
hidden layer 2
output layer
$\mathcal{L} = \frac{1}{N}\sum_{i=0}^{N} |y^i_{\mathrm{true}} - y^i_{\mathrm{predicted}}|,$
emulator prediction
data
$s^2\xi_0(s)\,[h^{-2}\mathrm{Mpc}^2]$
600
500
400
300
200
100
0
−100
fractional error
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
data error
emulator error
0
20
40
60
80
100
120
140
$s\,[h^{-1}\mathrm{Mpc}]$

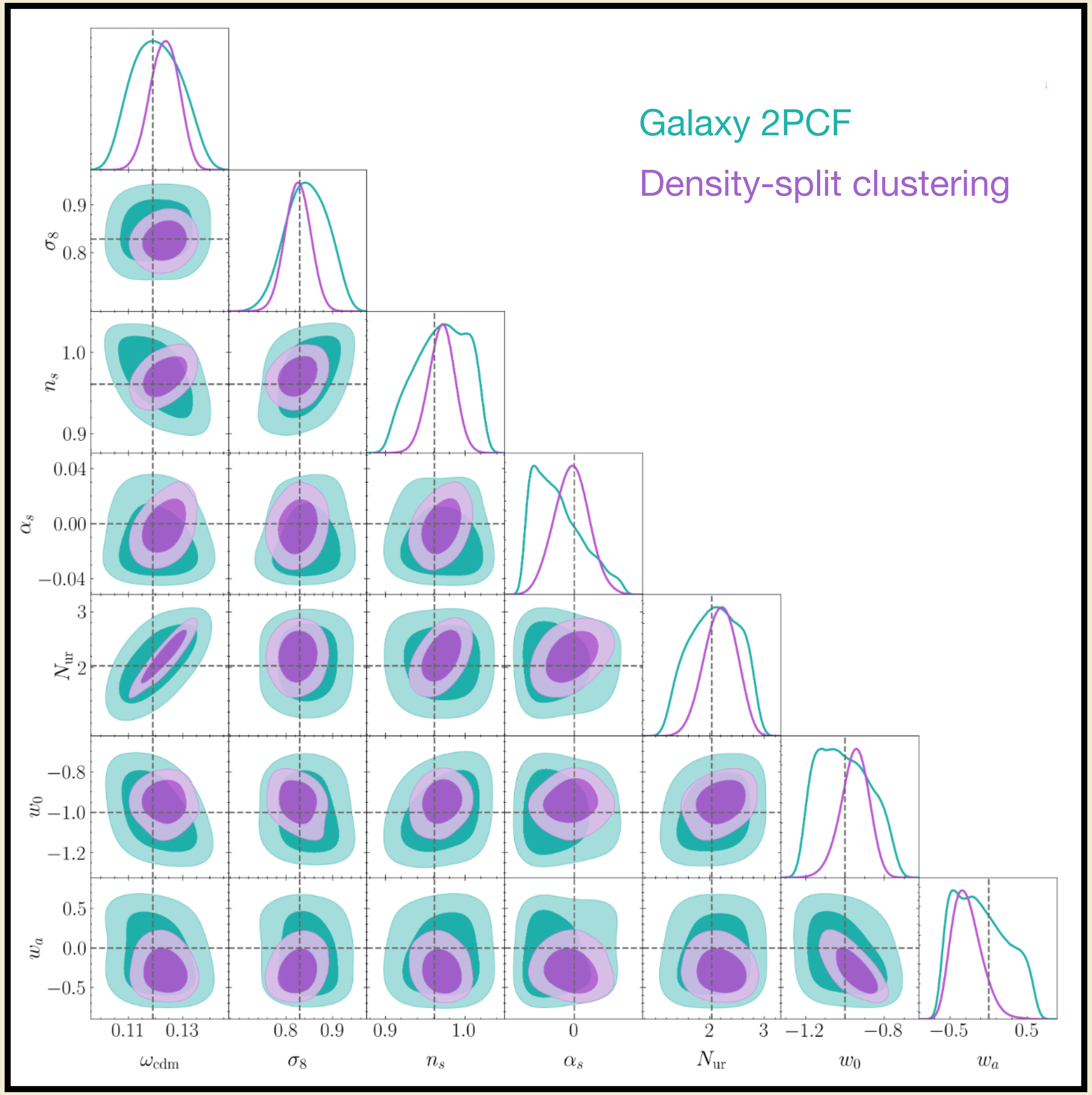

emulator prediction
data
DS1-galaxy CCF
$s^2\xi_0(s)\,[h^{-2}\mathrm{Mpc}^2]$
fractional error
data error
emulator error
$s\,[h^{-1}\mathrm{Mpc}]$


emulator prediction
data
DS1 ACF
$s^2\xi_0(s)\,[h^{-2}\mathrm{Mpc}^2]$
fractional error
data error
emulator error
$s\,[h^{-1}\mathrm{Mpc}]$

Recovery tests on AbacusSummit



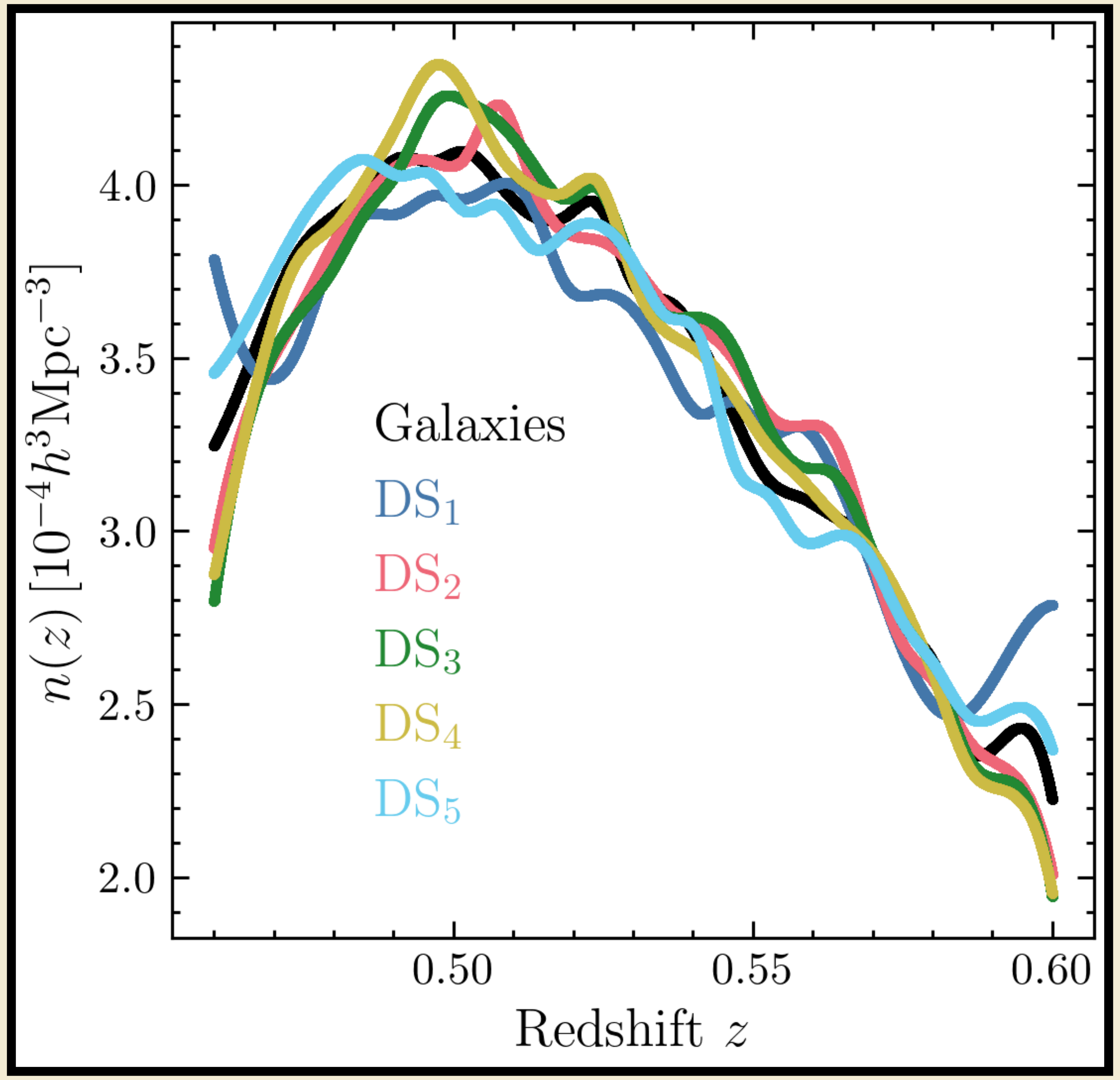
Constraints on cosmological parameters, after marginalizing over galaxy-halo connection parameters, for CMASS-like error bars.

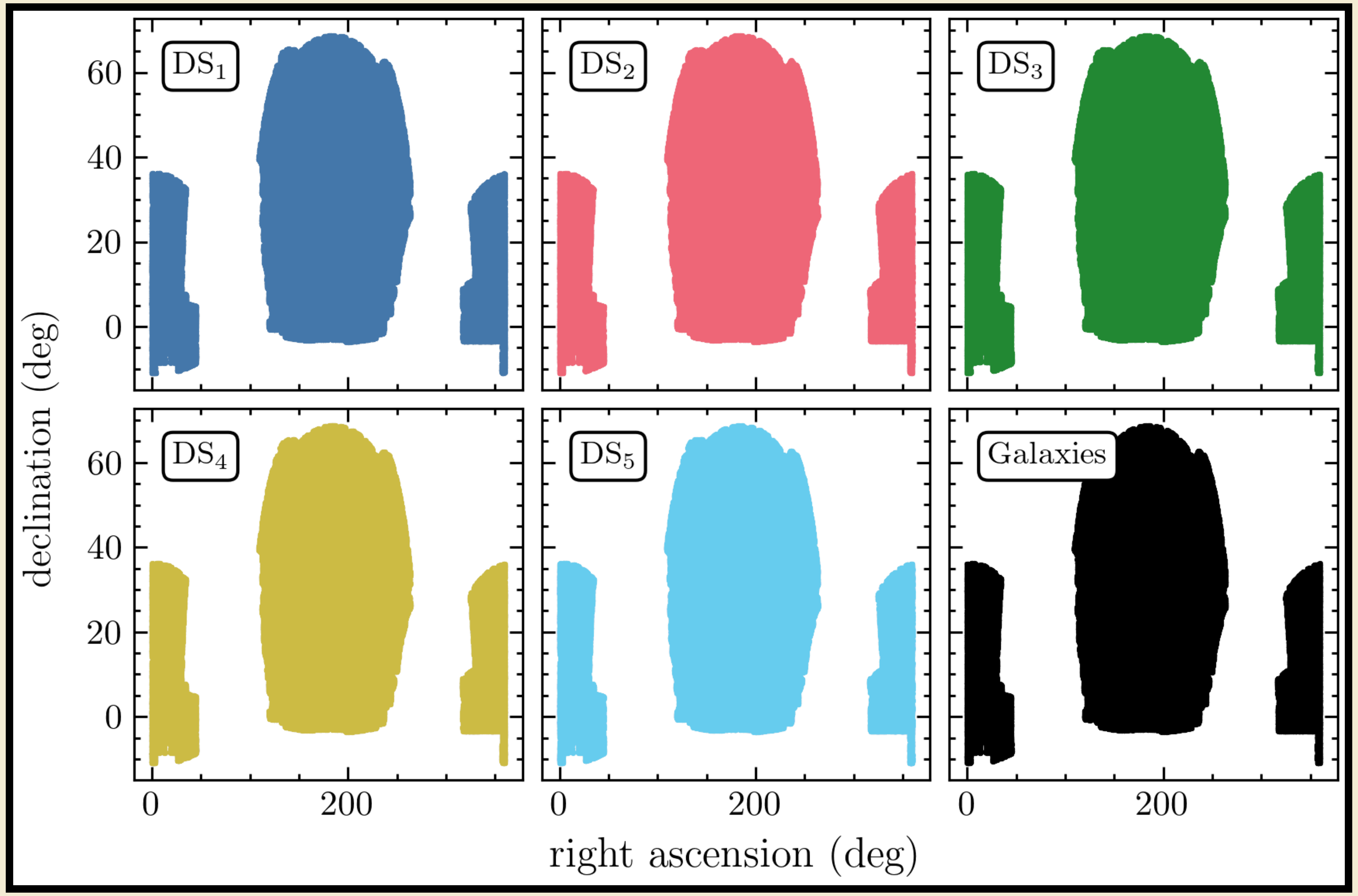


Recovery tests on Uchuu

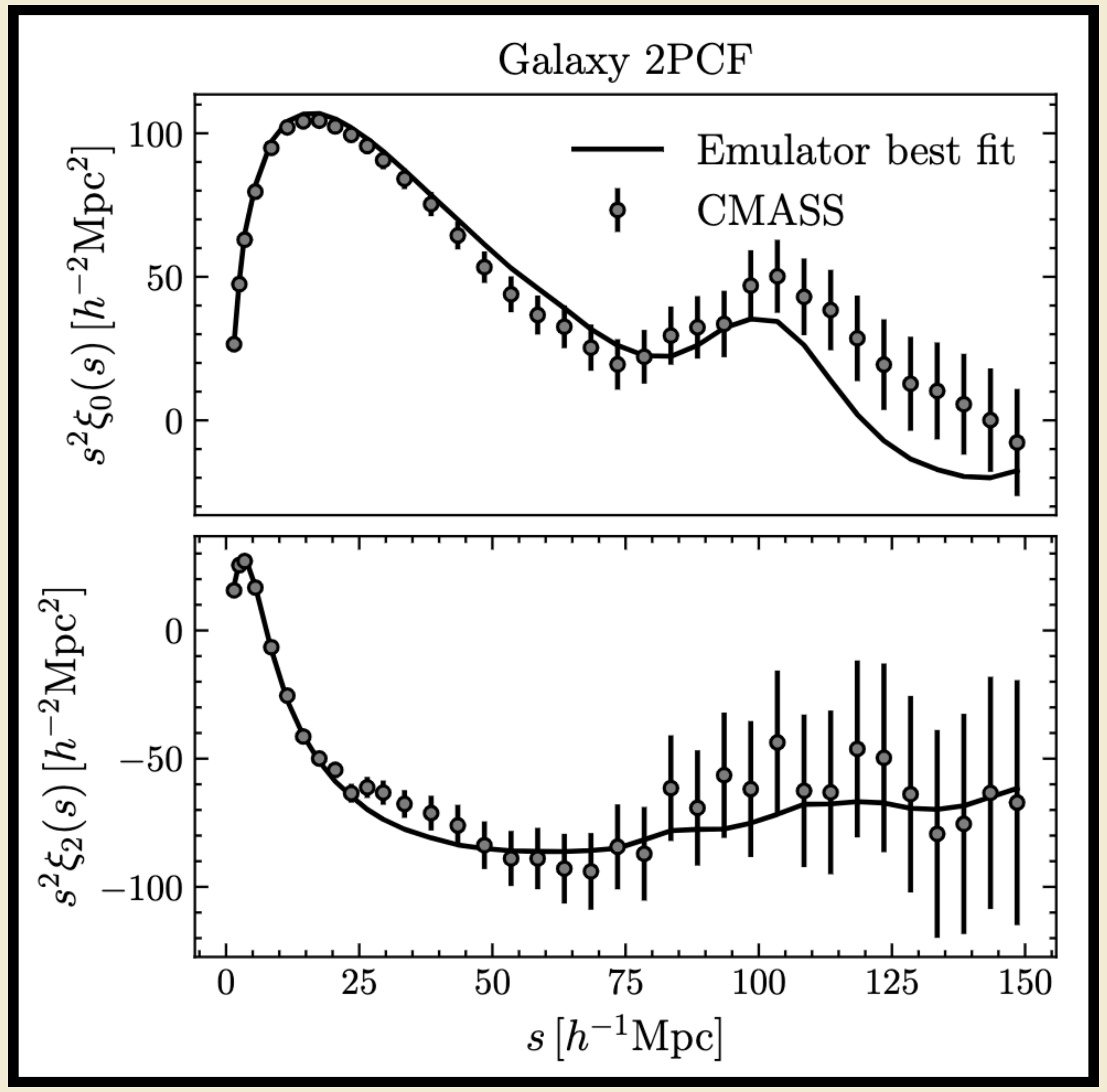
- Constraints on Uchuu simulations ran with Gadget and using a SHAM galaxy-halo connection model instead of HOD.
- Our emulator is able to recover unbiased constraints on a different set of simulations than its training data, using a different galaxy-halo connection model.

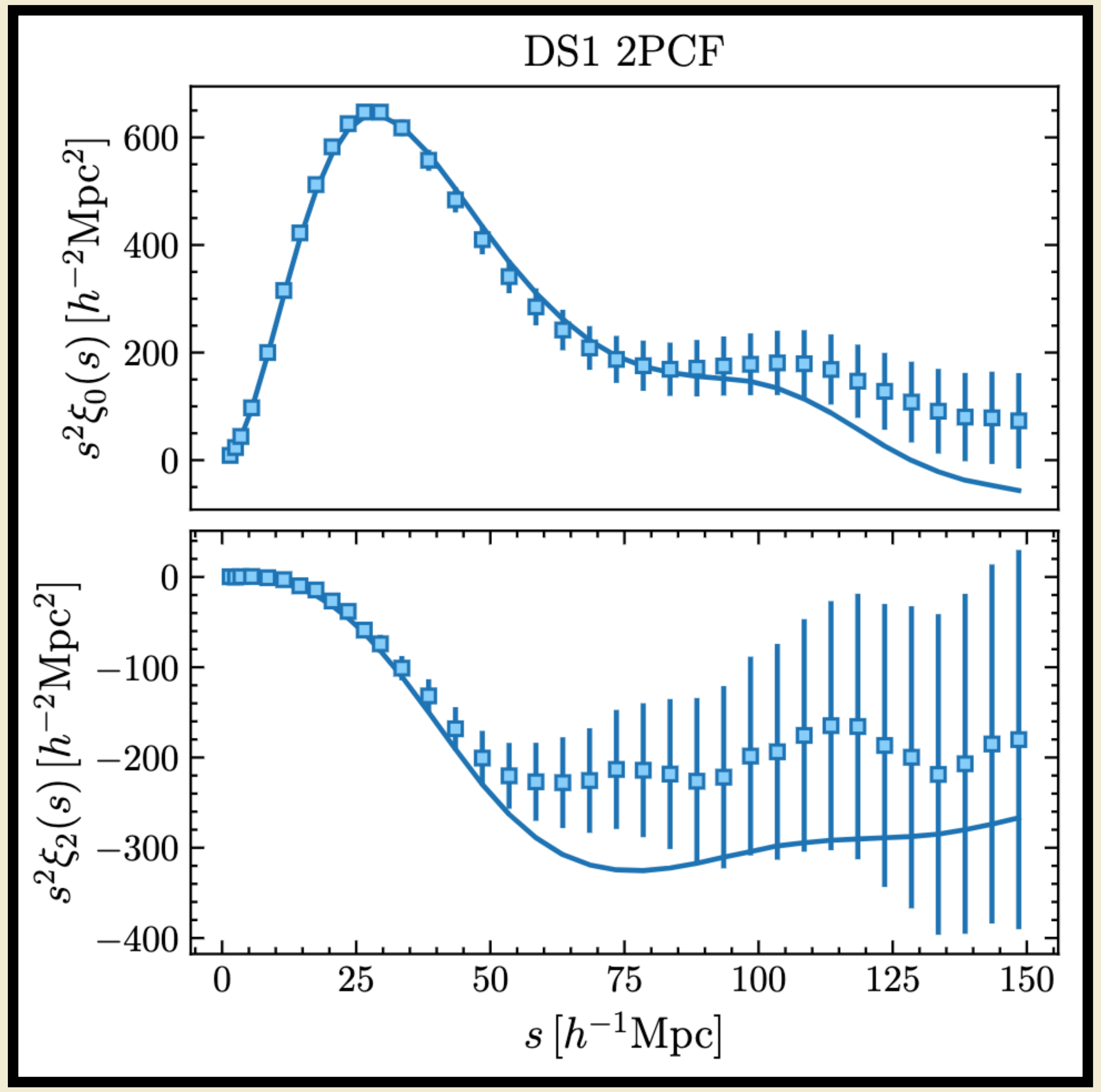
Application to BOSS CMASS

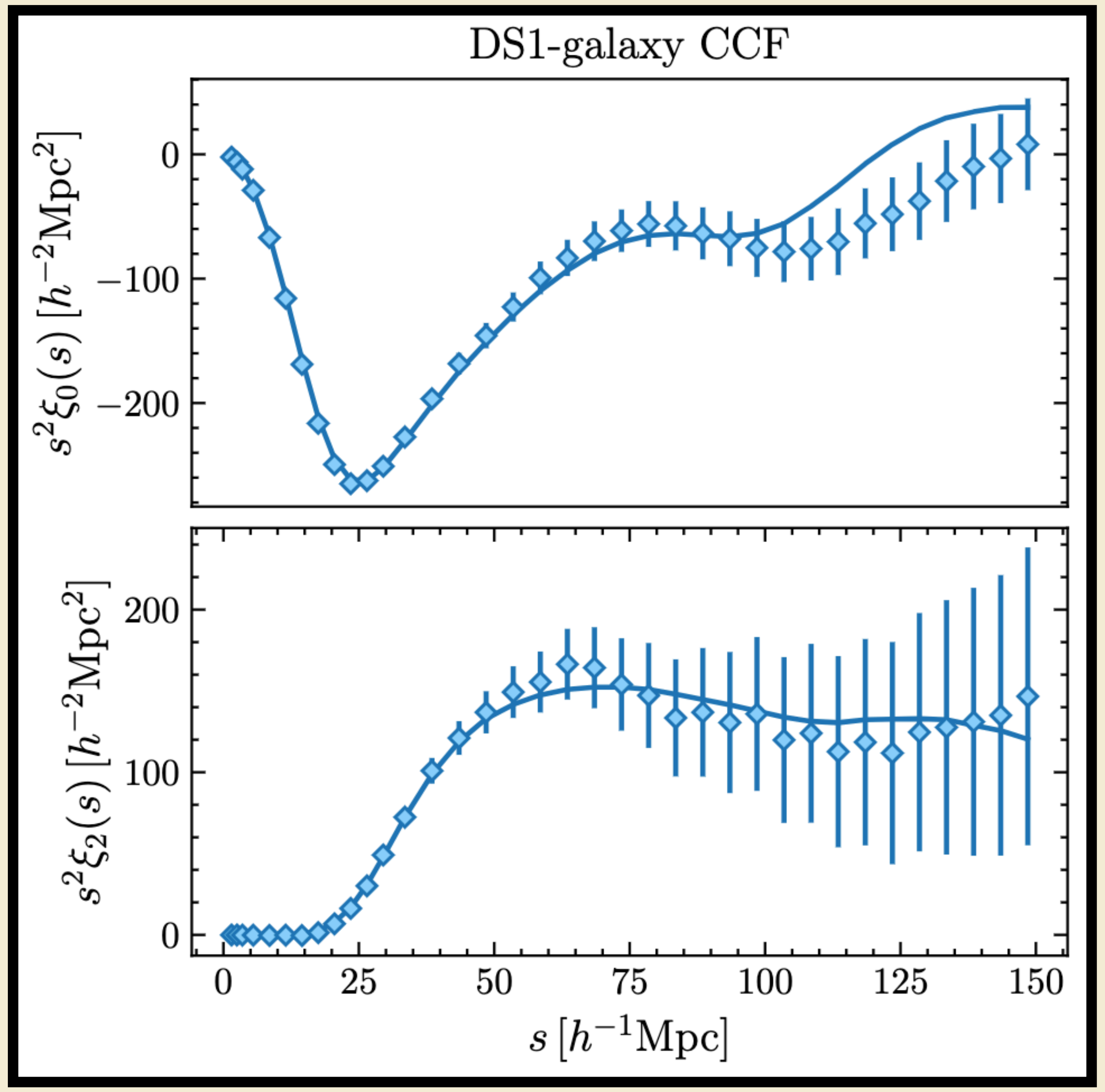




Application to BOSS CMASS







Interesting **excess clustering signal** at large scales from CMASS 2PCF, which has been previously reported in Kitaura et al. (2016), Ross et al. (2017). Also present in density-split multipoles.

Summary and conclusions

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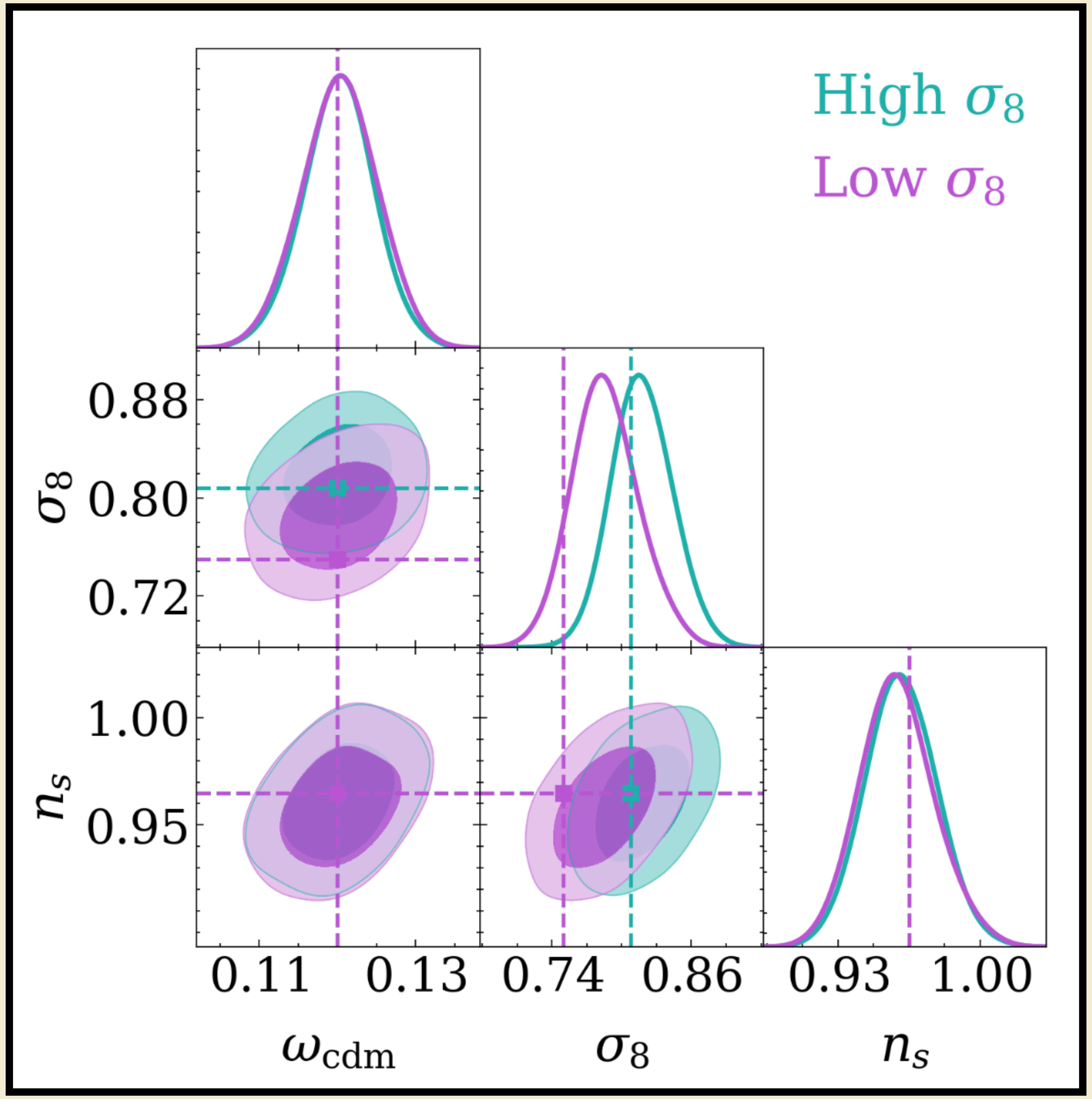
- Higher-order clustering statistics are crucial for extracting all cosmological information that is available from **non-Gaussian density fields**.
- Apart from polyspectra, several **novel clustering techniques** are now being applied in galaxy surveys, including the marked power spectrum, wavelet-based methods, nearest-neighbour distributions and counts-in-cells.
- **Density-split clustering** allows extraction of cosmological information from different density environments, including voids and clusters.
- We have constructed an **emulator for density-split statistics** that is currently being applied to BOSS, reaching percent-level accuracy down to very small scales.

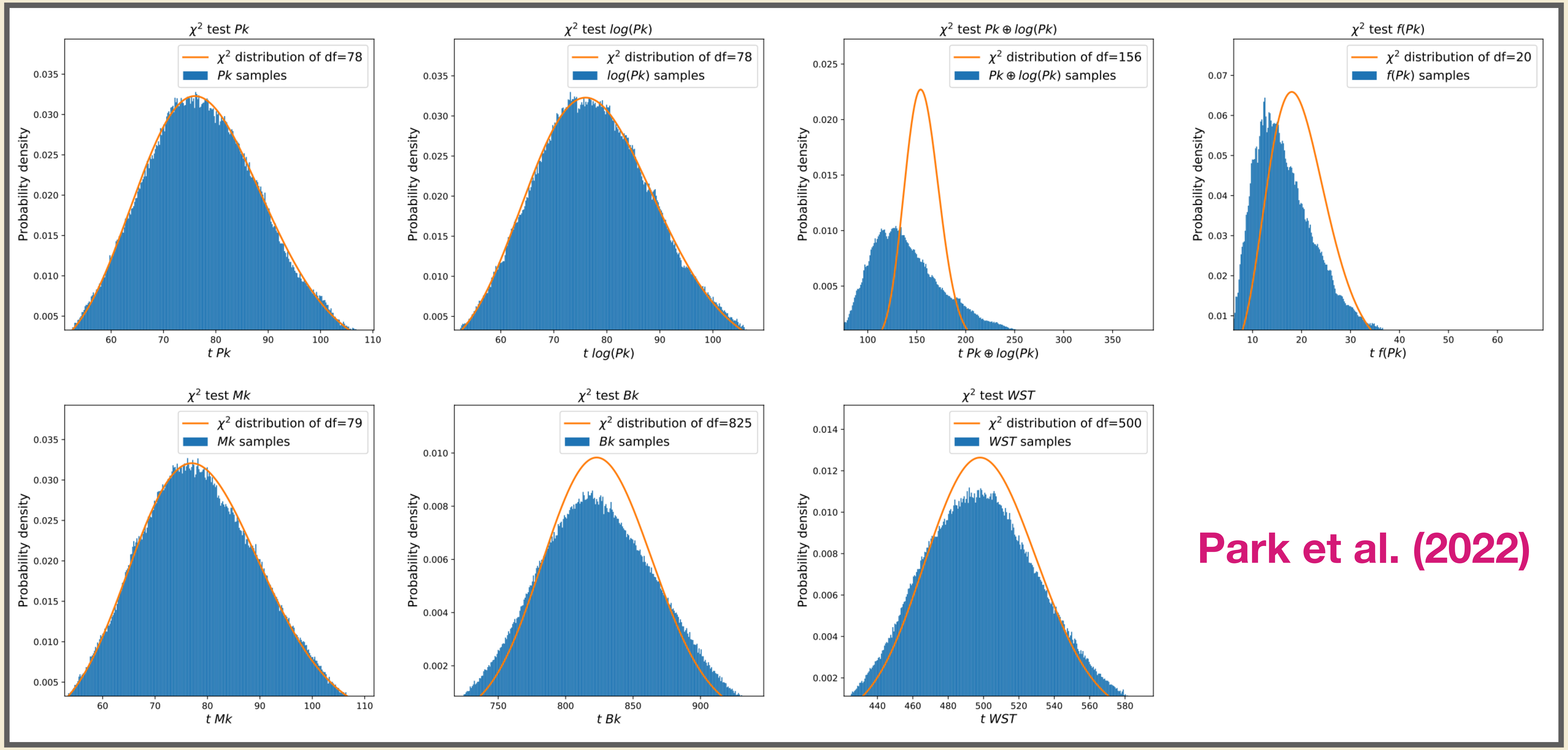
Backup slides

Recovery tests on AbacusSummit

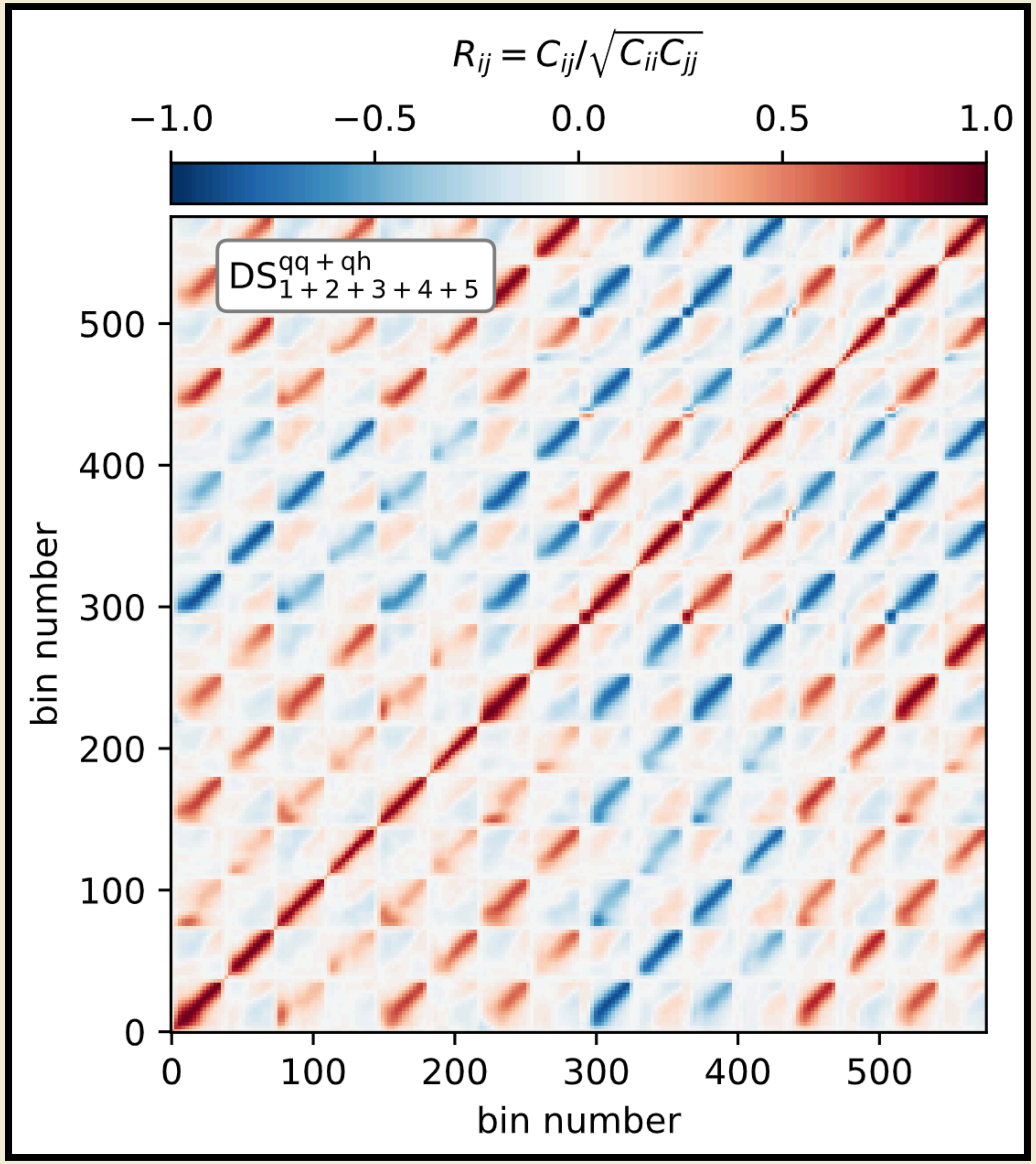
We can successfully recover cosmological parameters on simulations with **σ_8 values** that are lower and higher than Planck18.



Is the assumption of a **Gaussian likelihood** suitable for all statistics?



Park et al. (2022)



Covariance matrix

Covariance matrix of combined density-split multipoles, measured from 2048 realizations of the MD-Pachy mocks

PDF of peculiar velocities around density splits