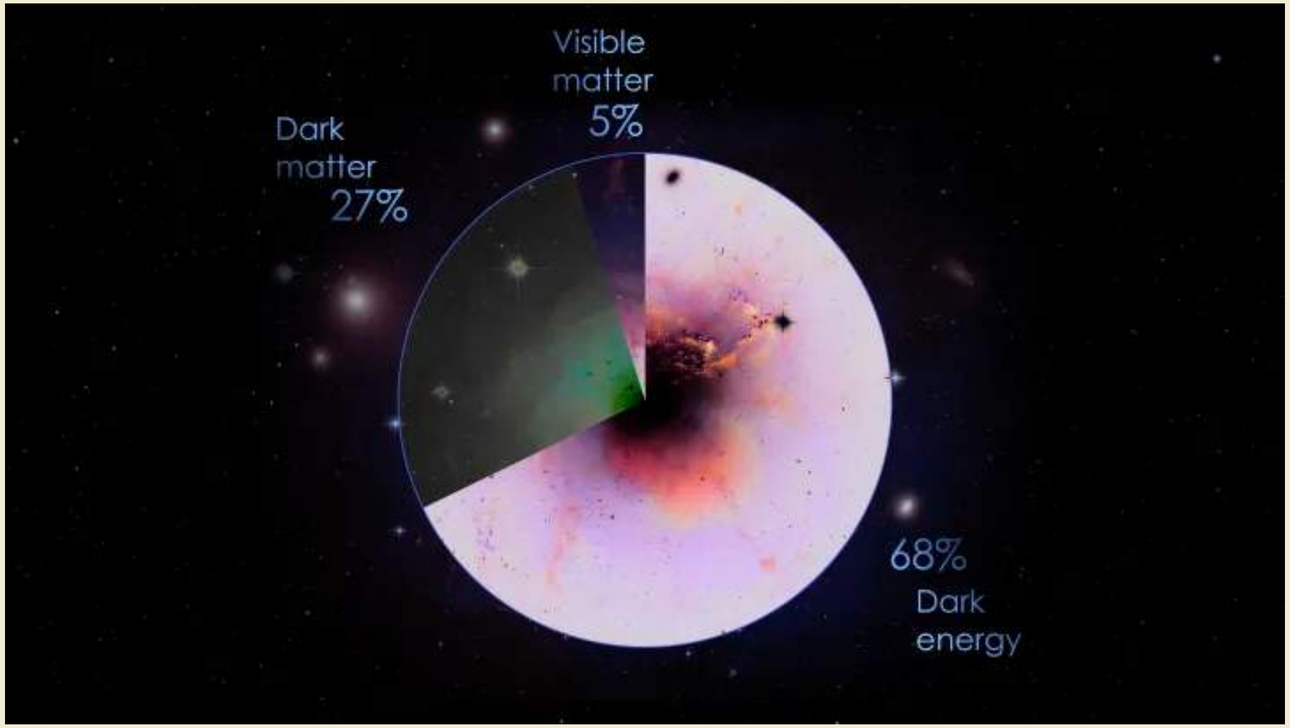
Constraining cosmology with density-split clustering

Enrique Paillas
Postdoctoral Fellow
Waterloo Centre for Astrophysics

In Collaboration with: Carolina Cuesta-Lazaro, Will Percival, Sandy Yuan, Yan-Chuan Cai, Sesh Nadathur, Mathilde Pinon, Arnaud de Mattia, Etienne Burtin, Ariel Sanchez, Nelson Padilla, Florian Beutler, Vanina Ruhlmann-Kleider, Daniel Forero-Sanchez, Georgios Valogiannis + DESI

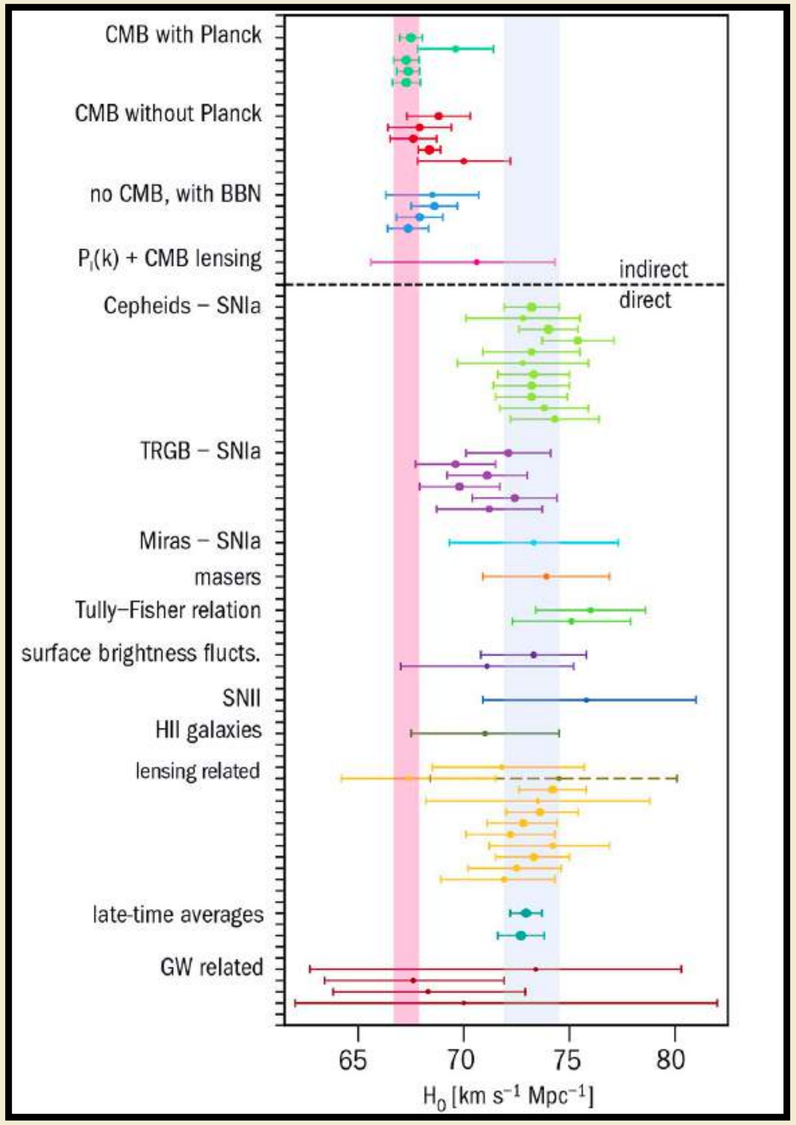
ΛCDM: our cosmological paradigm



Credit: Simons Observatory

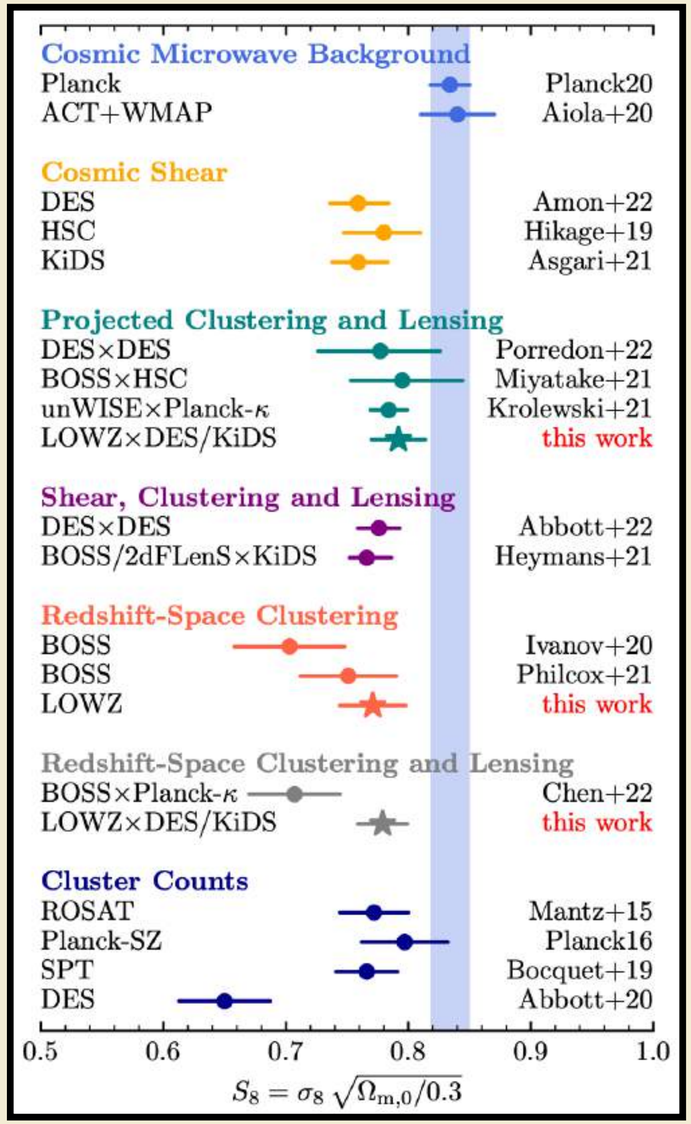
“There is nothing wrong with ΛCDM, maybe just the Λ and the CDM part”.

Hubble tension



Di Valentino et al. 2021

S8 tension

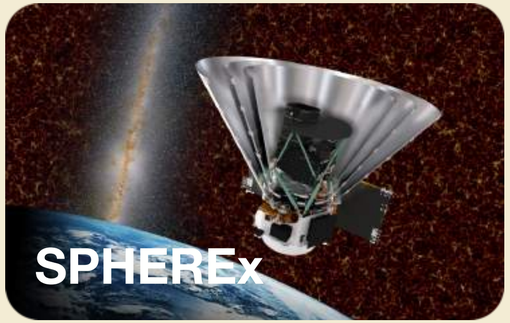


Lange et al. 2023

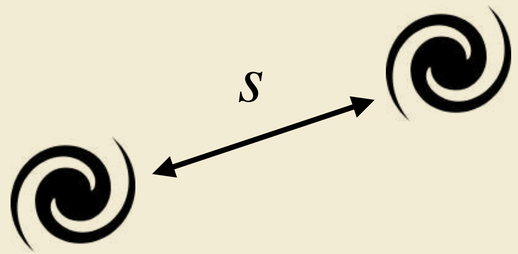
2020

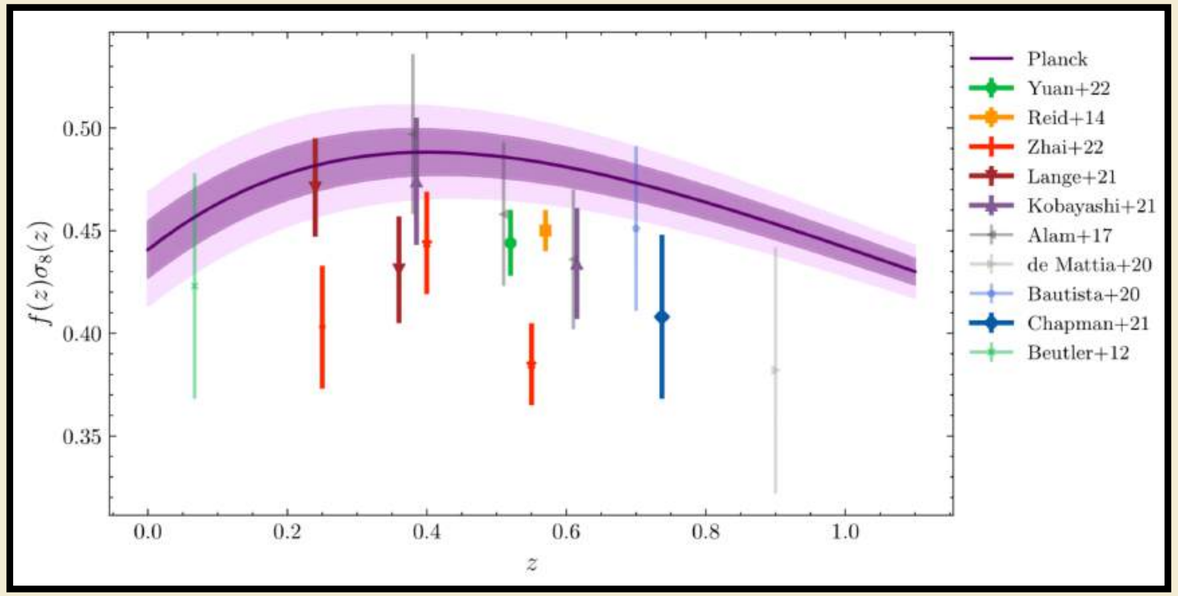
2022

2024

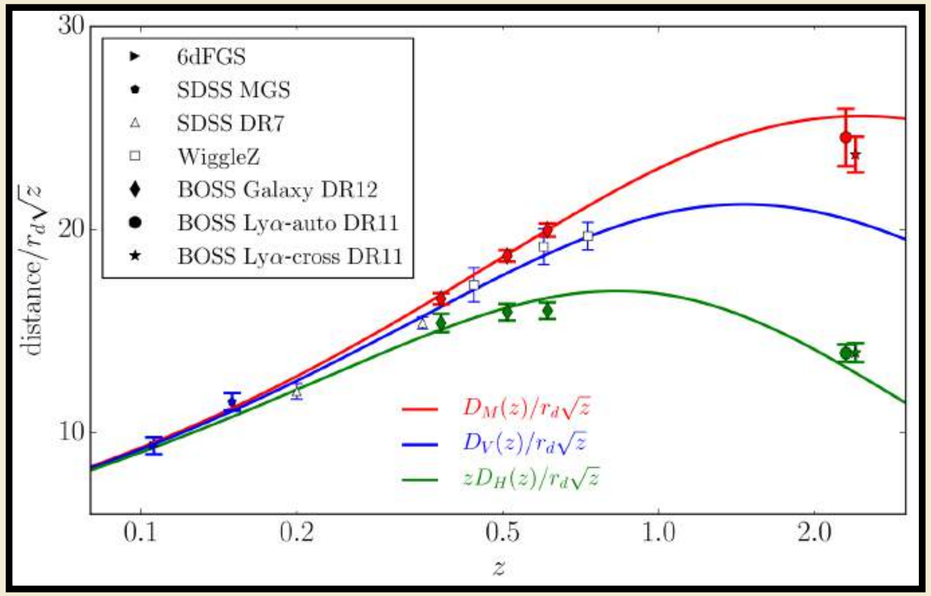


Measurements of the galaxy **power spectrum** or the **two-point correlation function** have allowed precise measurements of the **geometry and growth**.



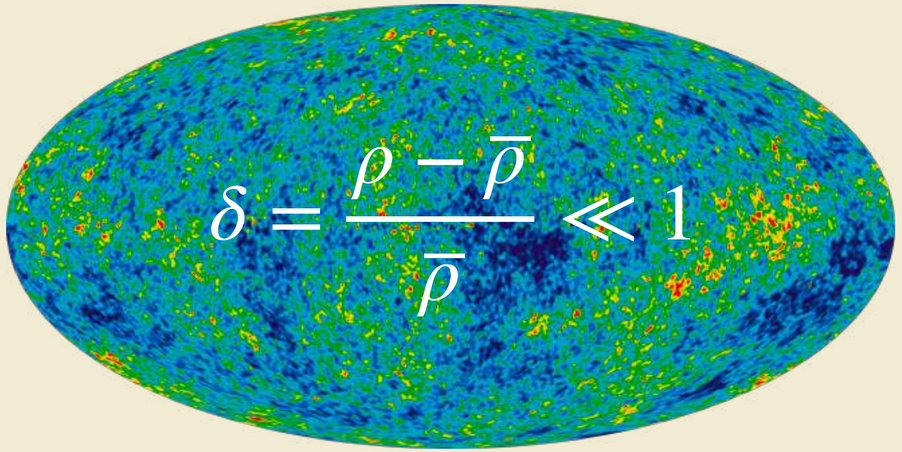


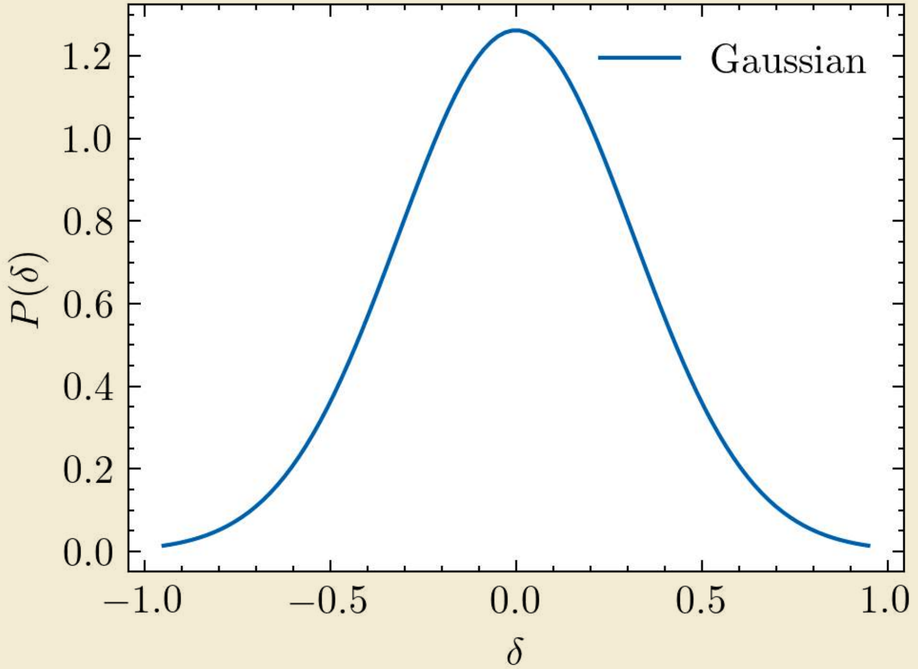
Credits: Carolina Cuesta-Lazaro



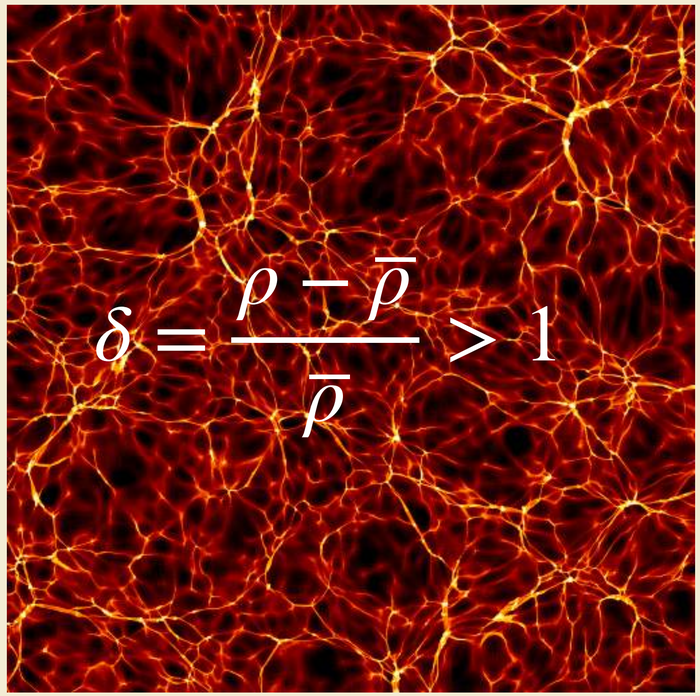
Alam et al. (2017)

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

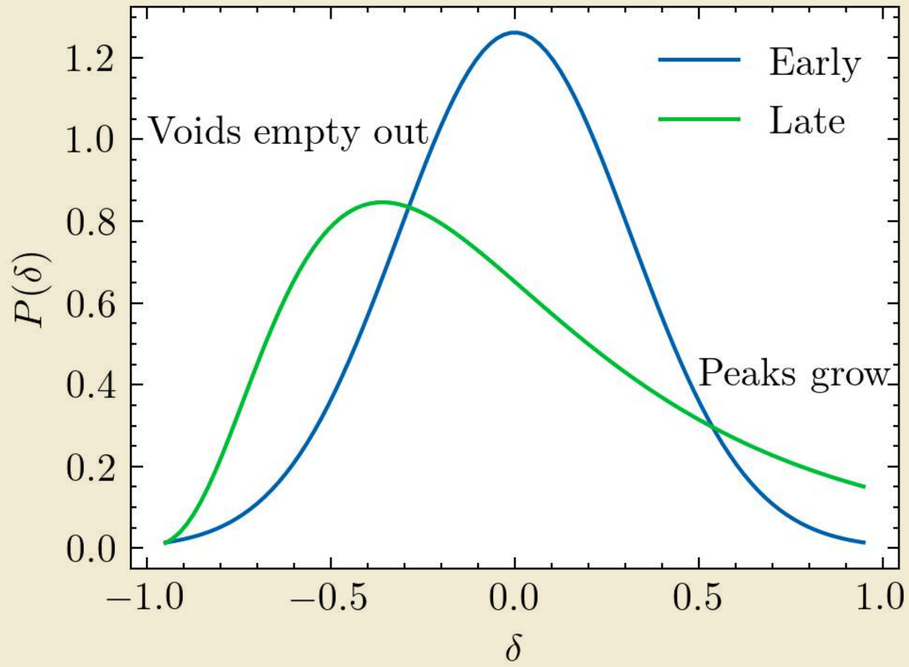




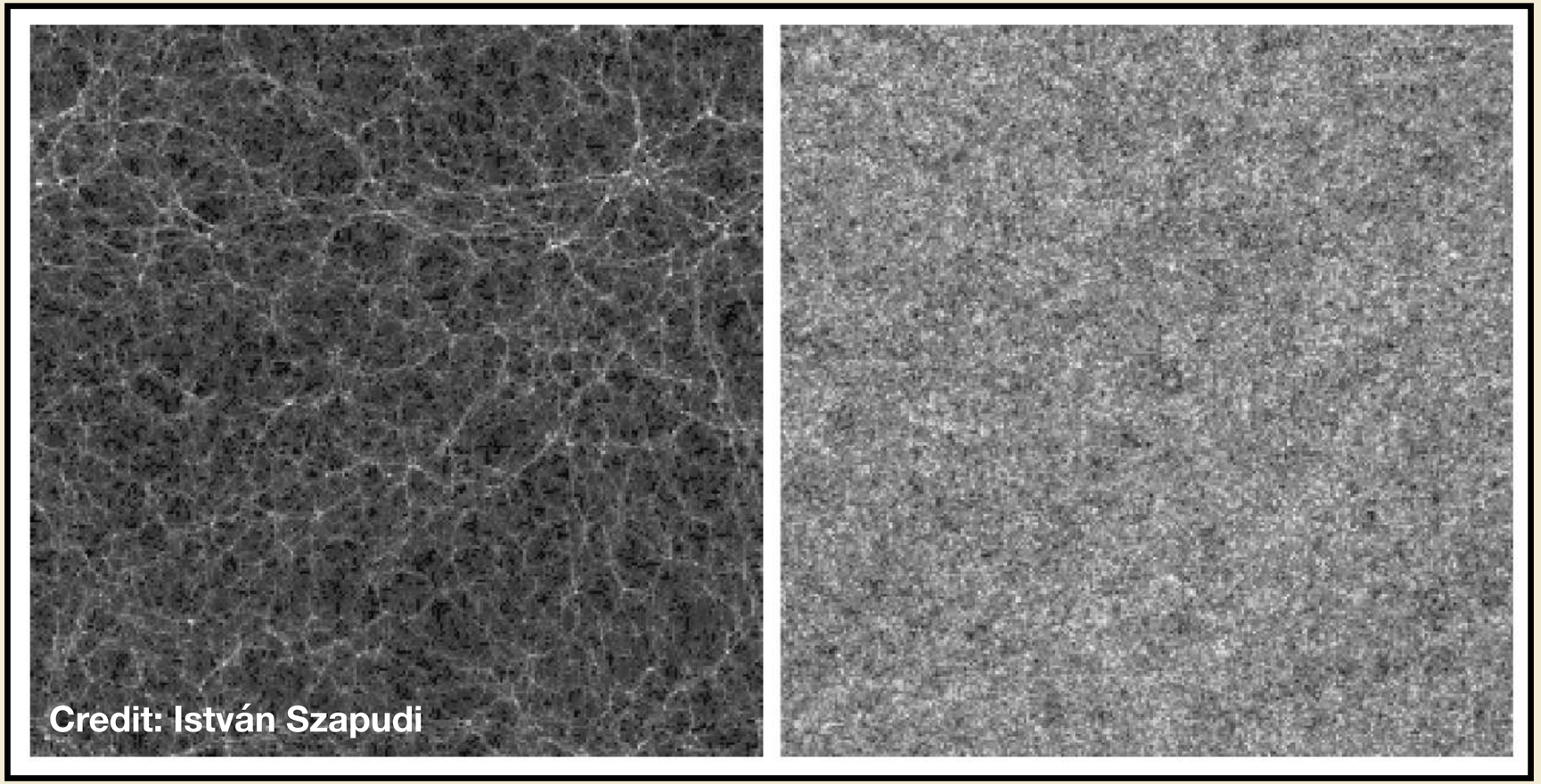
Late-time Universe: Non-Gaussian density field. Non-linear evolution governing small scales.



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.

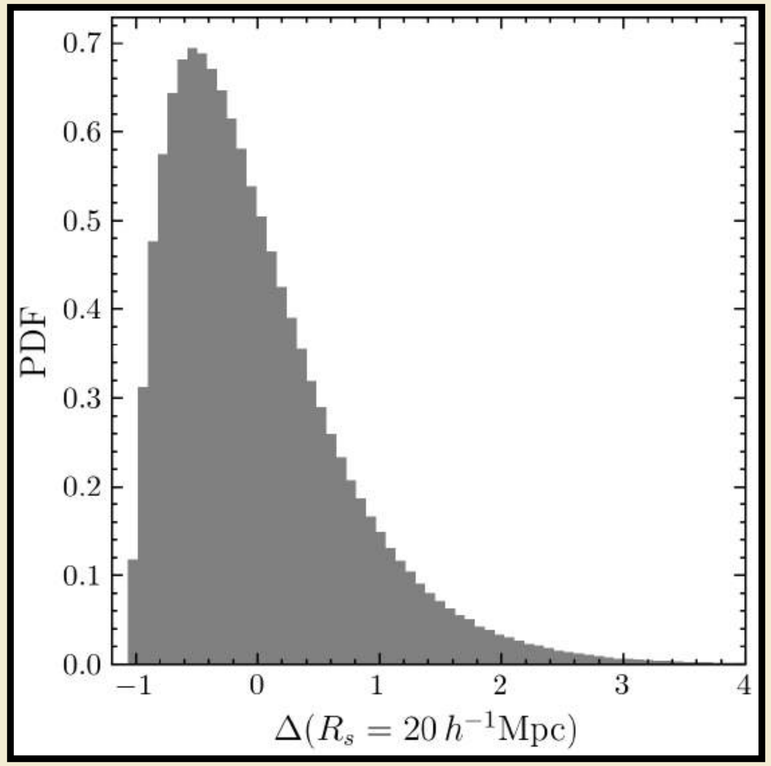
- N-point correlation functions, polyspectra
- Non-linear transformations of the density field
- Counts-in-cells statistics
- Separate Universes

- Density field reconstruction
- Cosmic voids
- Marked correlation functions
- Wavelet-based methods
- Nearest-neighbour statistics

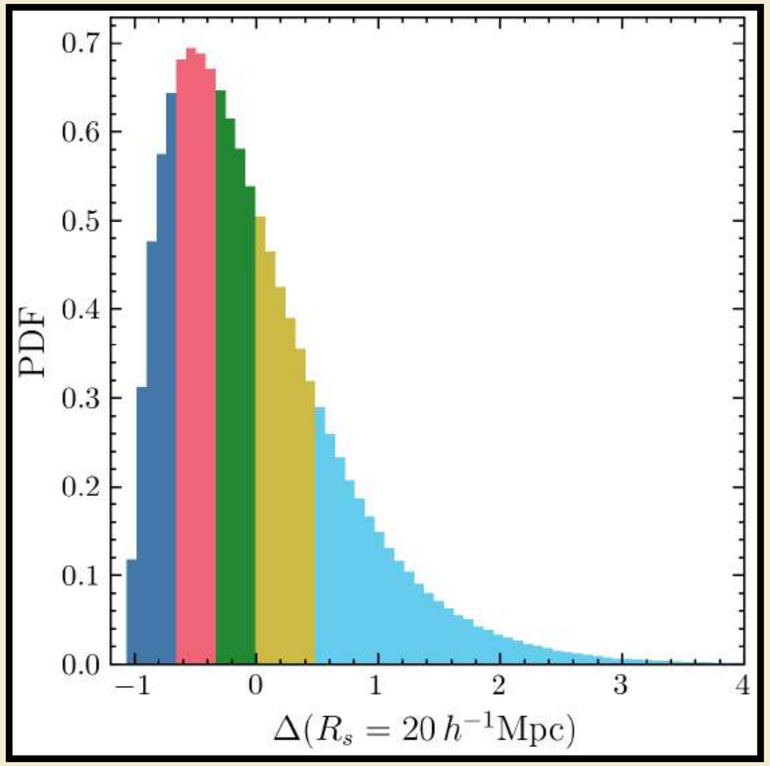
Density-split clustering

- The density-split clustering method combines galaxy clustering statistics from regions of different environmental density.
- Its sensitivity to non-Gaussian features of the galaxy field allows for extraction of information that is not readily captured by the power spectrum.
- Builds upon existing ideas in the literature, such as weak lensing density split statistics, the separate Universe approach, and counts-in-cells.

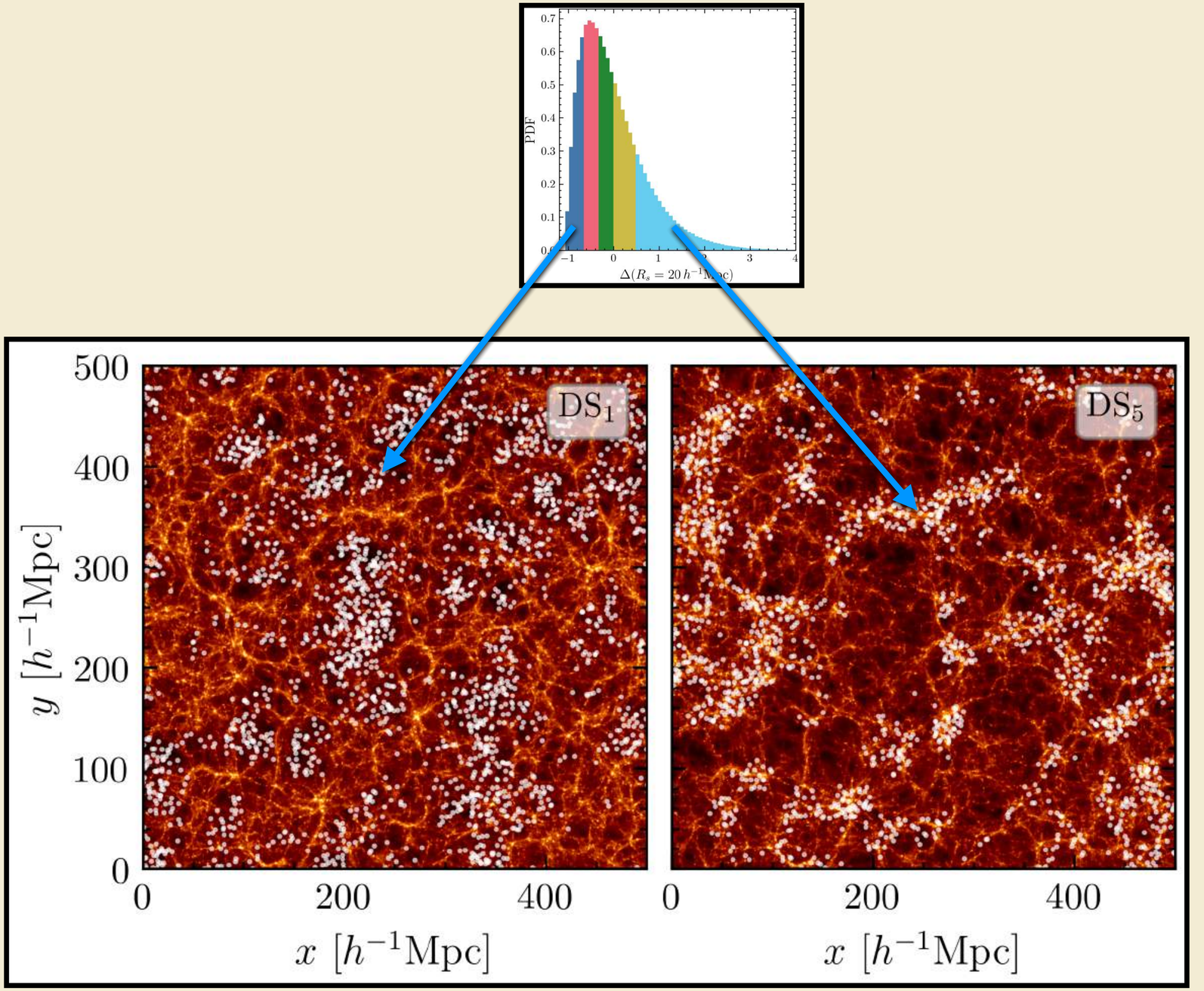
1 Splitting the density field



Galaxy overdensity measured at random query positions



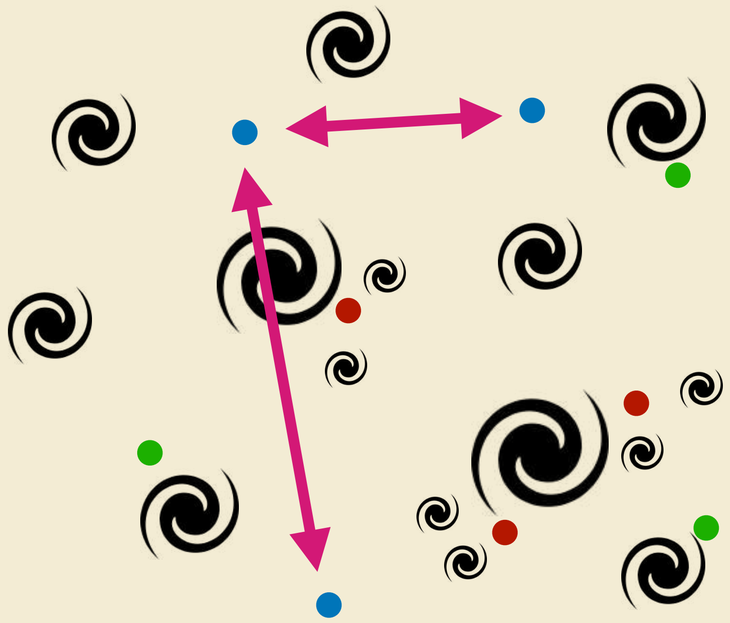
Query points are split into quintiles


PDF
$\Delta(R_s = 20\,h^{-1}\mathrm{Mpc})$
DS_1
DS_5
$y\ [h^{-1}\mathrm{Mpc}]$
$x\ [h^{-1}\mathrm{Mpc}]$
$x\ [h^{-1}\mathrm{Mpc}]$

2 Clustering statistics

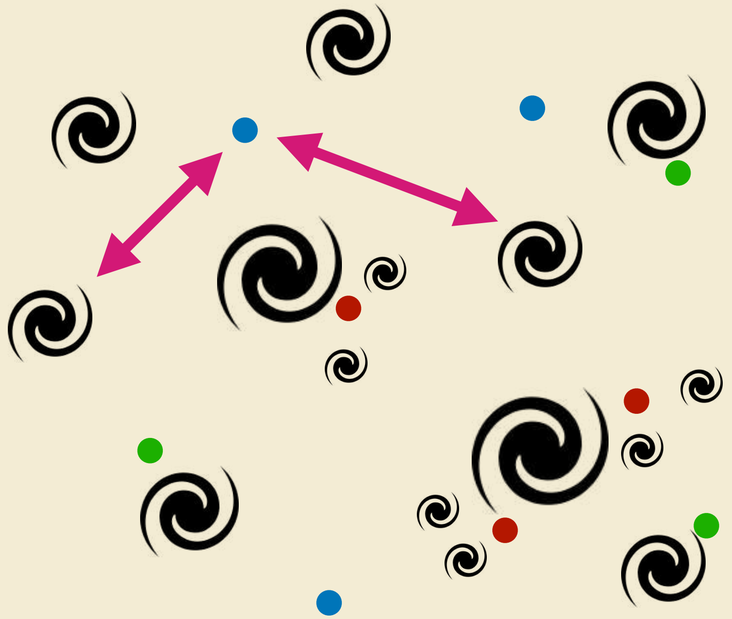
$\xi^{qq}(s)$

Quintile autocorrelation function

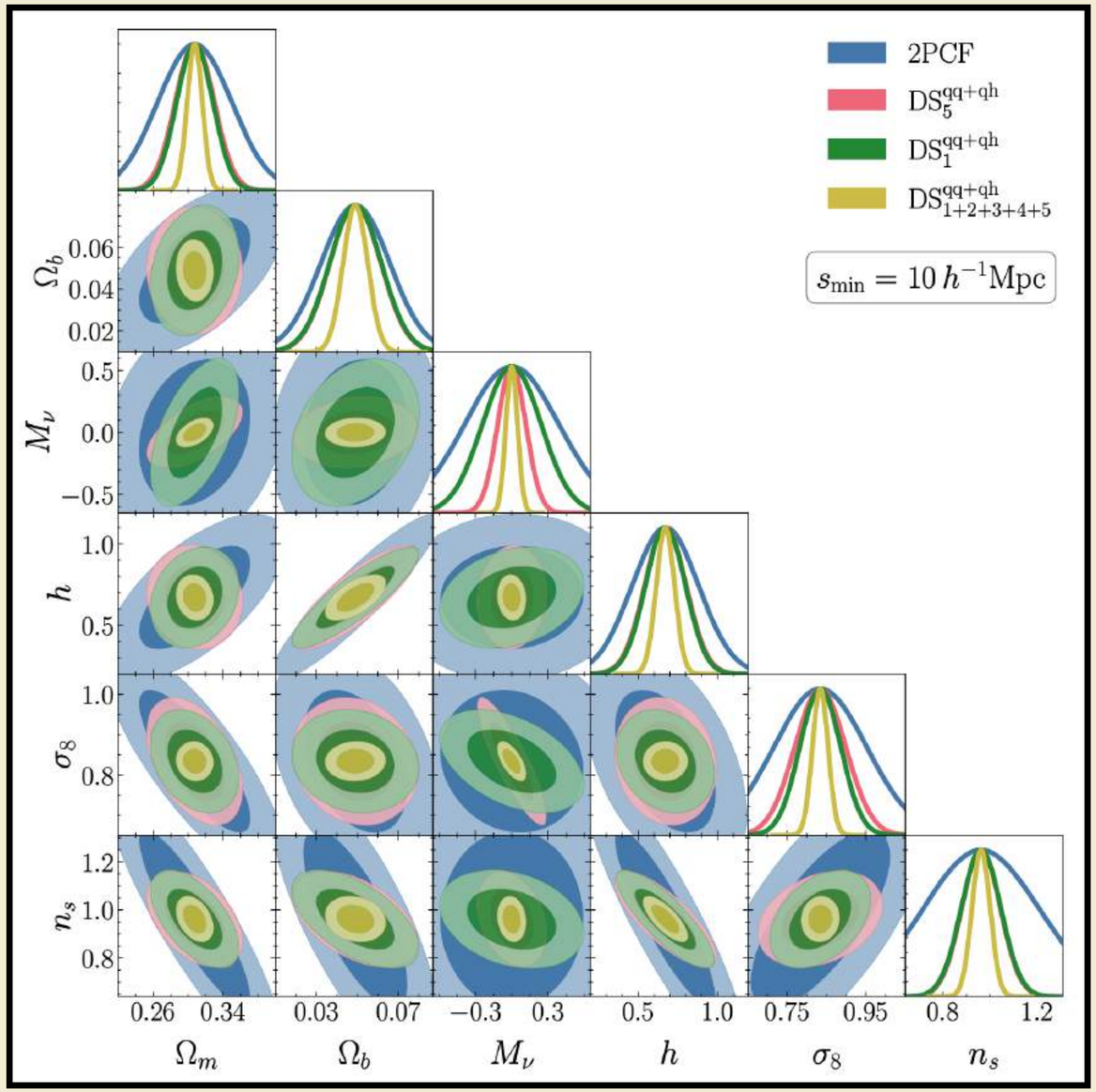


$\xi^{qg}(s)$

Quintile-galaxy cross-correlation function



Paillas et al. (2023)



Fisher forecasts based on the Quijote cosmological simulations

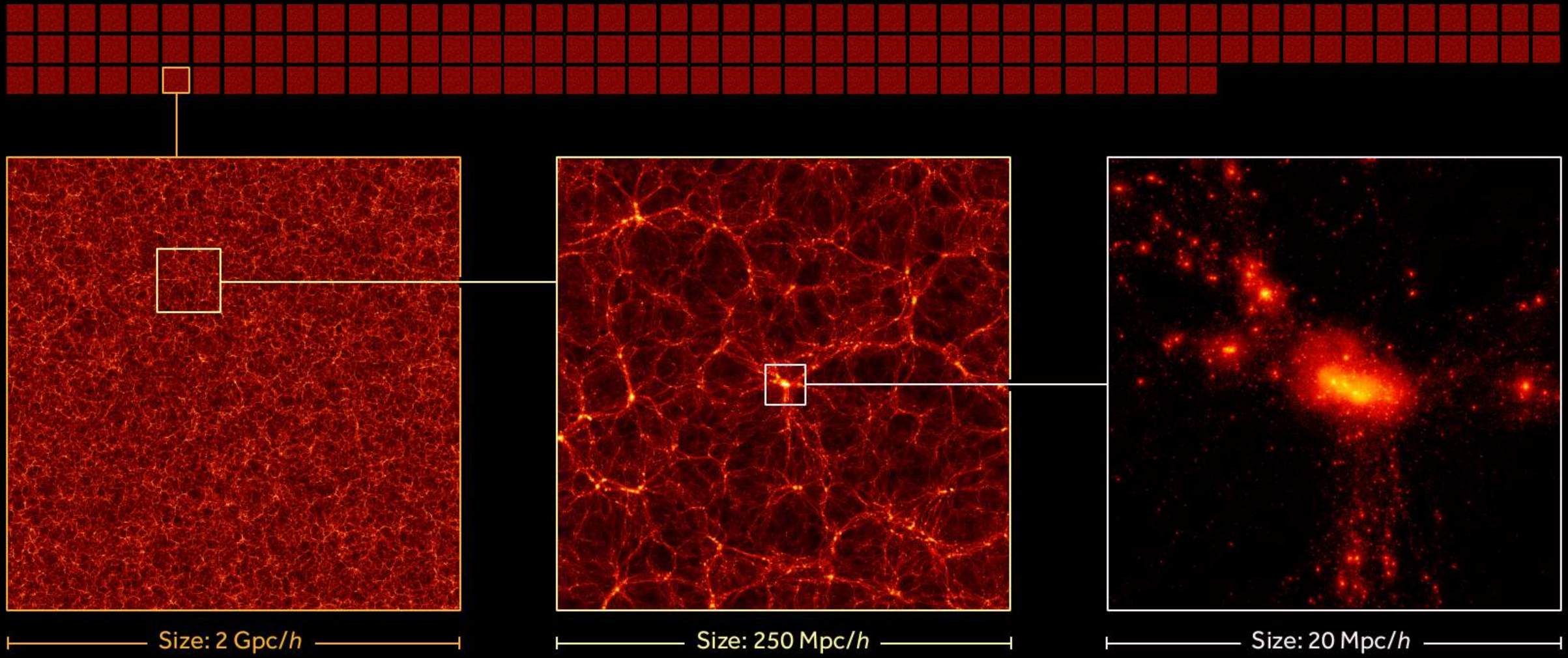
- DS provides more precise constraints on the parameters of the ΛCDM model compared to the 2PCF.
- DS improves the constraints on the sum of neutrino masses by a factor of 8 and by factors of 5, 3, 4, 6, and 6 for Ω_m, Ω_b, h, n_s, and σ_8, respectively.

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

OAK RIDGE National Laboratory | ABACUSSUMMIT

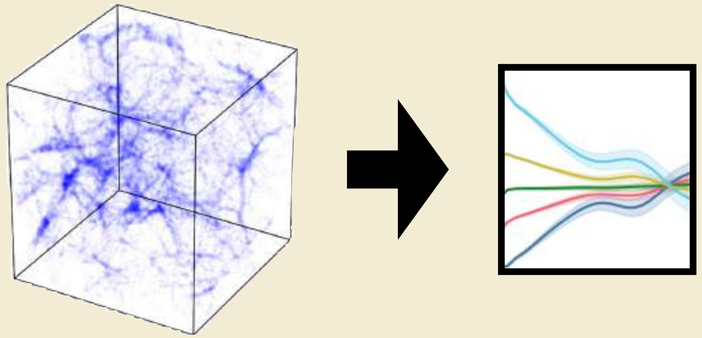
139 base simulations | 60 trillion particles | 97 cosmologies | 67 billion halos | Particle mass 2 x $10^9 h^{-1} M_\odot$ | AbacusSummit.readthedocs.io



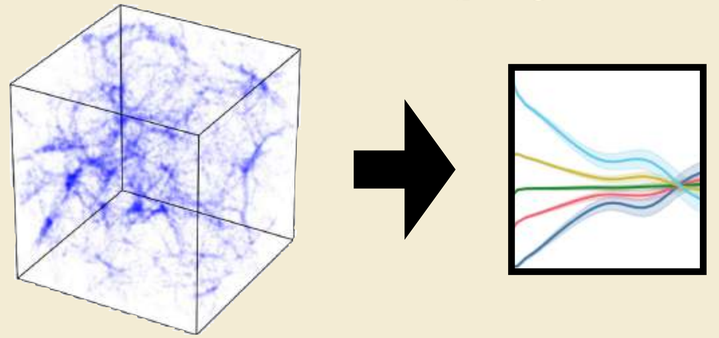
A simulation-based model for DSC

85 simulations with same initial conditions, but different cosmological parameters

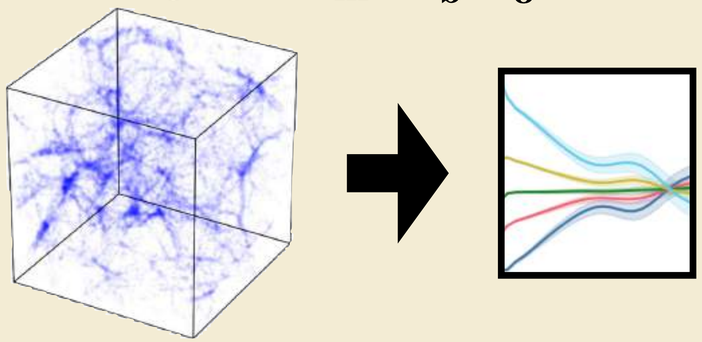
$\theta_1 = \{\Omega_{\rm m}^1, \Omega_{\rm b}^1, \sigma_8^1, \dots\}$



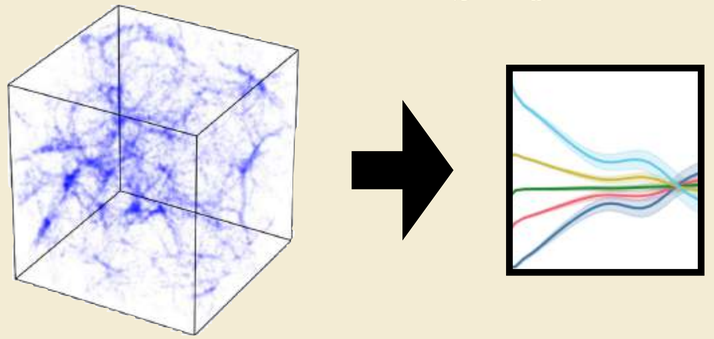
$\theta_2 = \{\Omega_{\rm m}^2, \Omega_{\rm b}^2, \sigma_8^2, \dots\}$



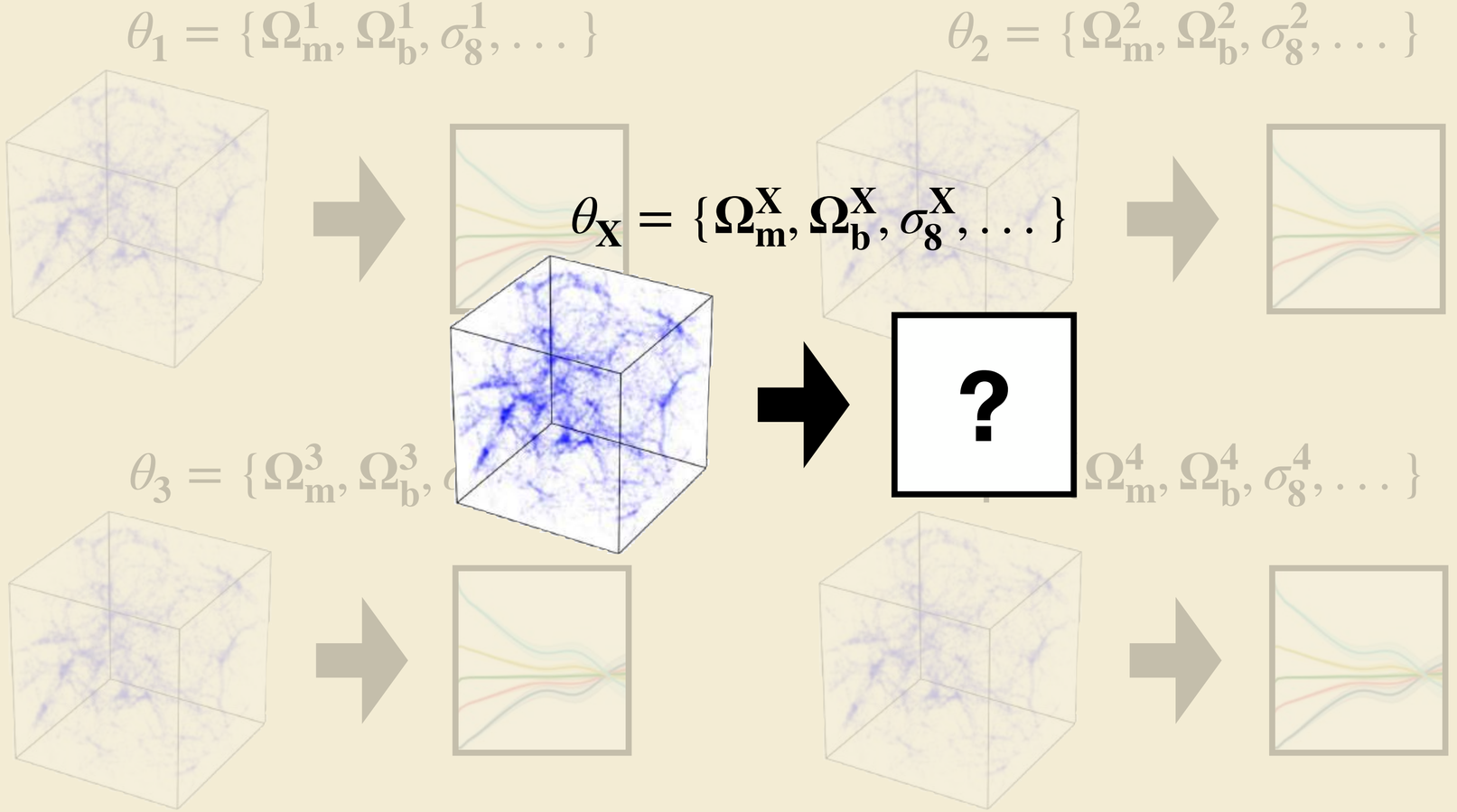
$\theta_3 = \{\Omega_{\rm m}^3, \Omega_{\rm b}^3, \sigma_8^3, \dots\}$



$\theta_4 = \{\Omega_{\rm m}^4, \Omega_{\rm b}^4, \sigma_8^4, \dots\}$



A simulation-based model for DSC



Using neural networks to emulate clustering statistics

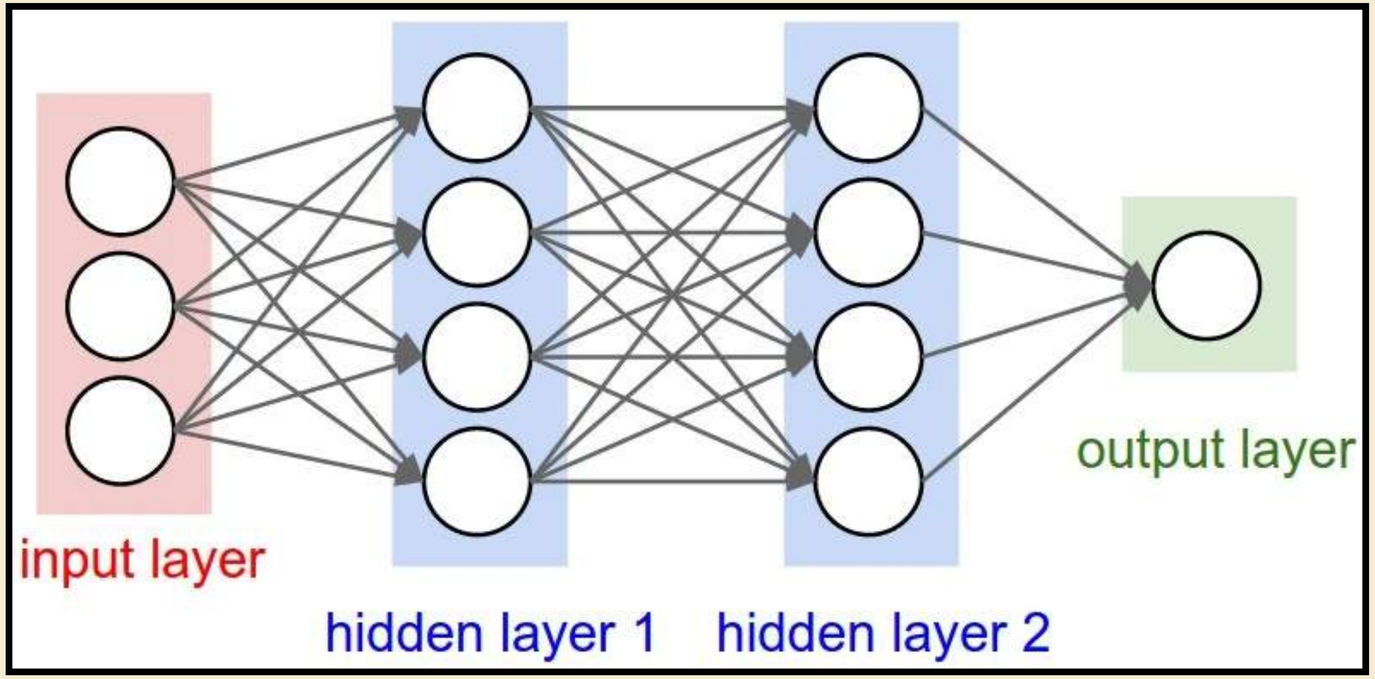
ω_b

$\omega_{\rm cdm}$

n_s

σ_8

...



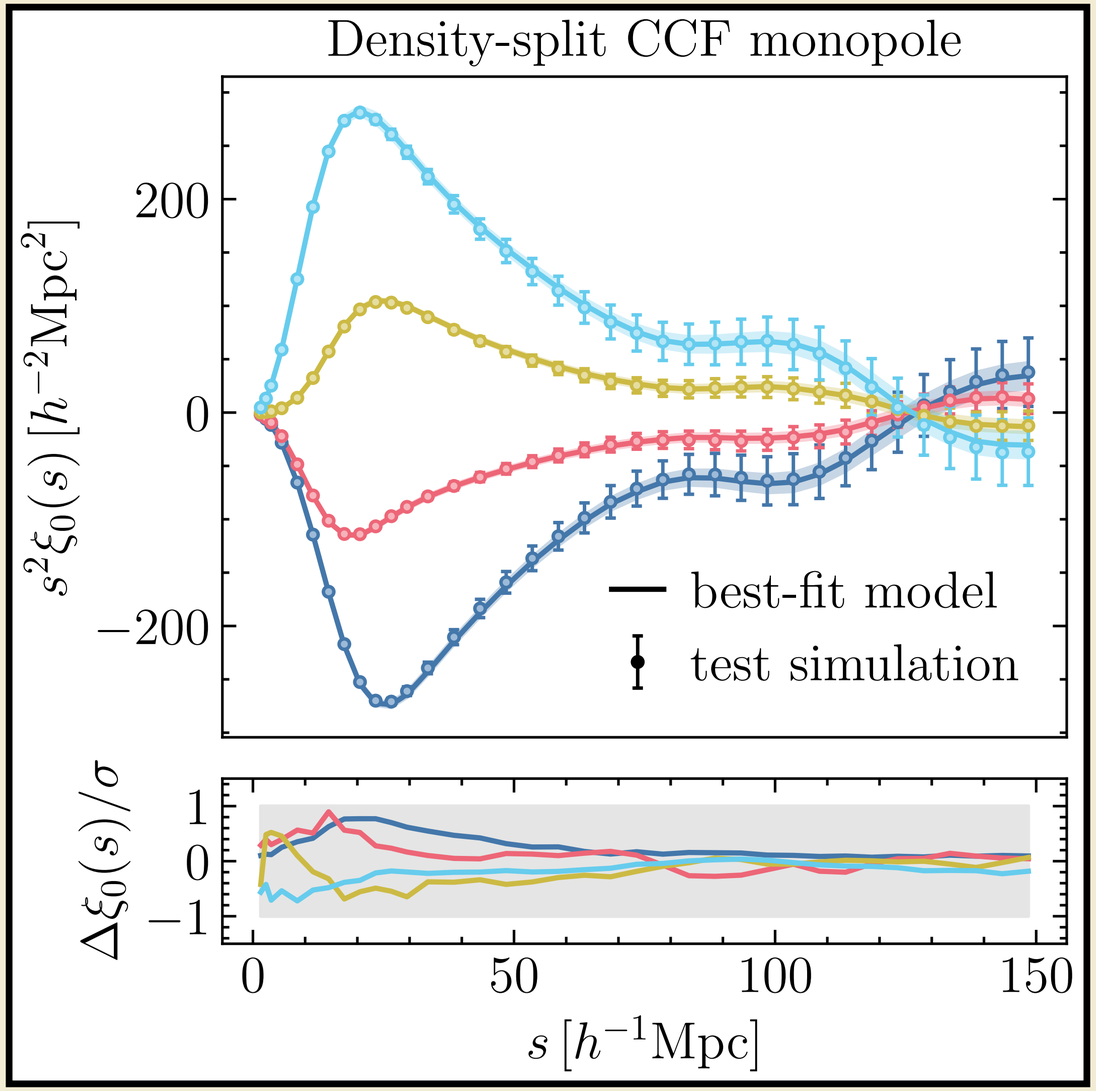
$\xi_0(s)$

$\xi_2(s)$

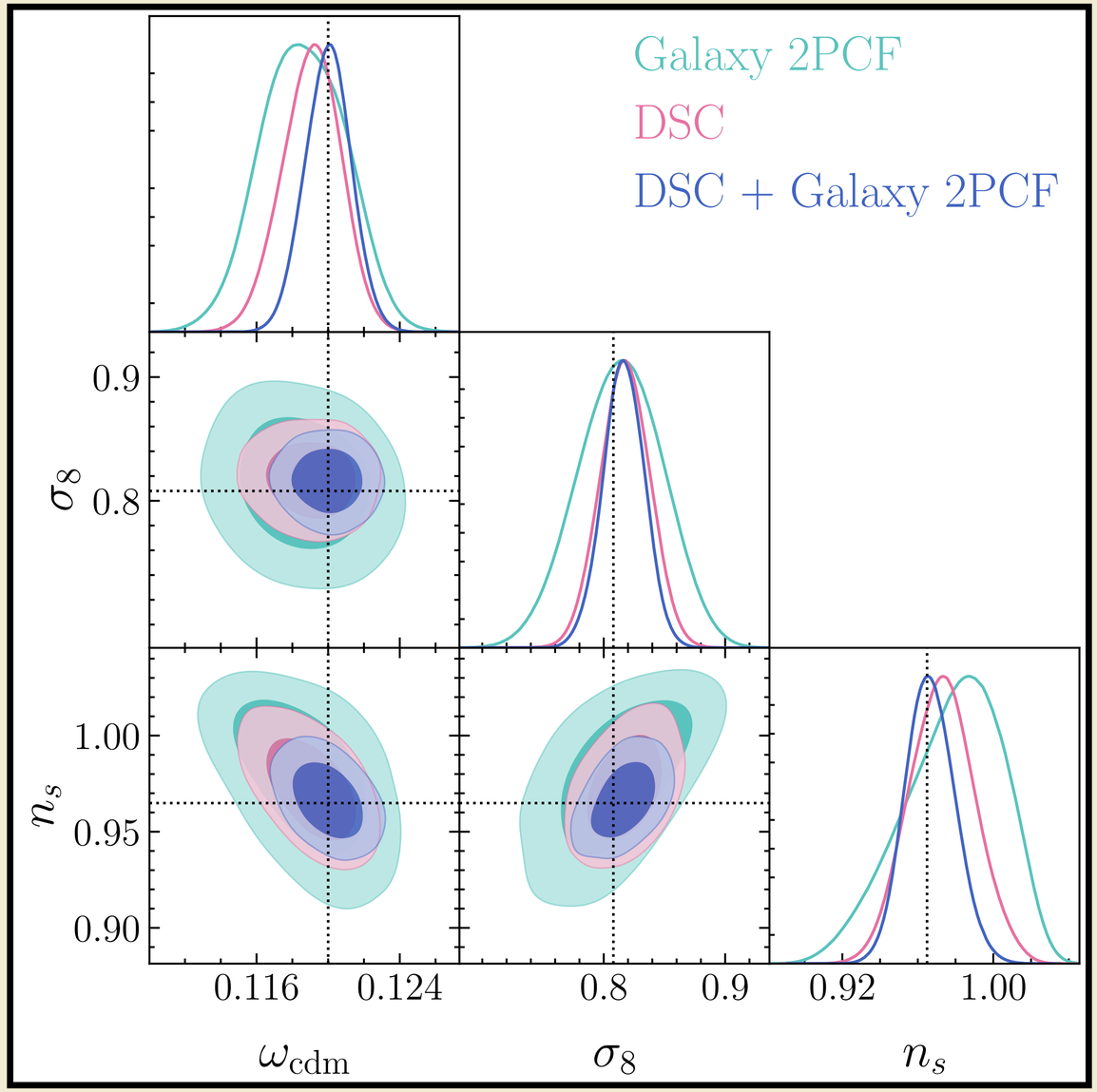
Loss function

$$\mathcal{L} = \frac{1}{N}\sum_{i=0}^{N} |y^i_{\rm true} - y^i_{\rm predicted}|,$$

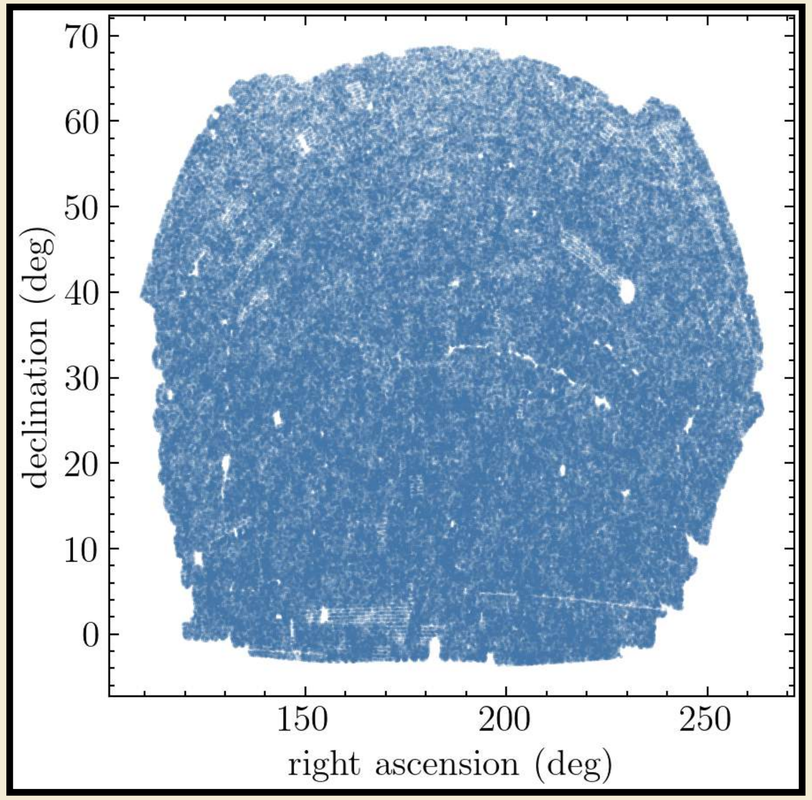
Cuesta-Lazaro et al. (in preparation)



Cuesta-Lazaro et al. (in preparation)

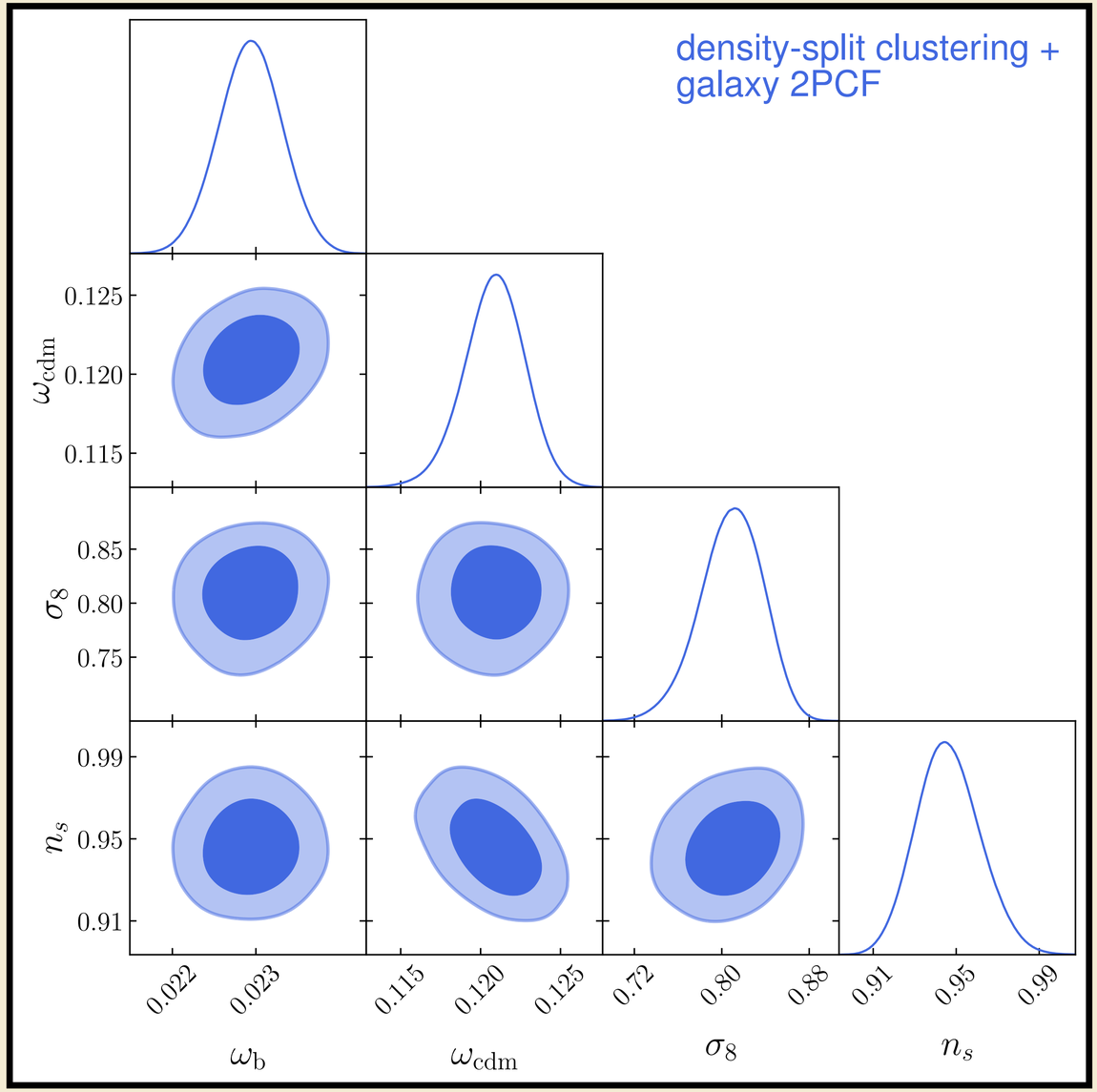


Density-split clustering in BOSS CMASS



Angular footprint of CMASS galaxies

Paillas et al. (in preparation)



Summary and conclusions

github.com/epaillas

enrique.paillas@uwaterloo.ca

- 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, providing accurate and precise cosmological constraints down to small scales.