Development of the accurate emulator for the redshift-space power spectrum of dark matter halos

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Redshift-Space Distortion

- Galaxy Redshift Survey

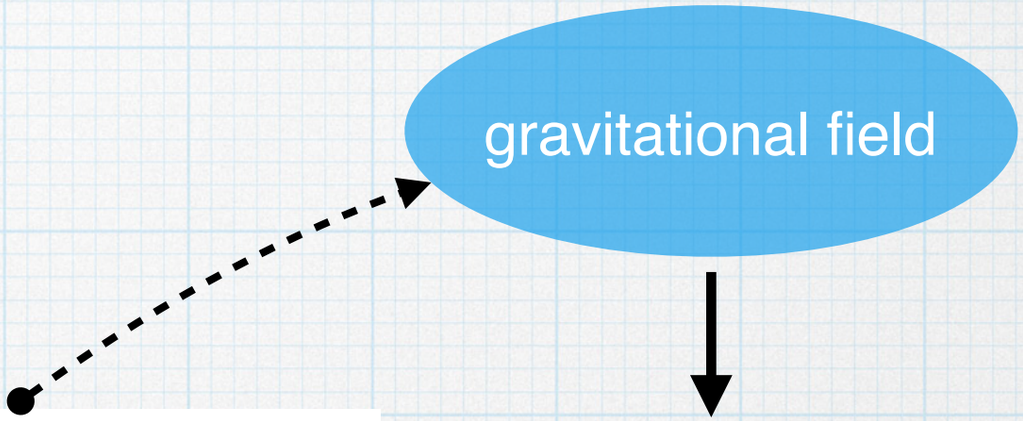
  Doppler shift due to peculiar velocities of galaxies

$$z_{\rm obs} = z + \frac{\overrightarrow{v}}{\mathscr{H}} \cdot \overrightarrow{e}_{\rm LoS}$$

  → galaxy clustering in redshift space

- Statistical anisotropy: distorted in LoS direction

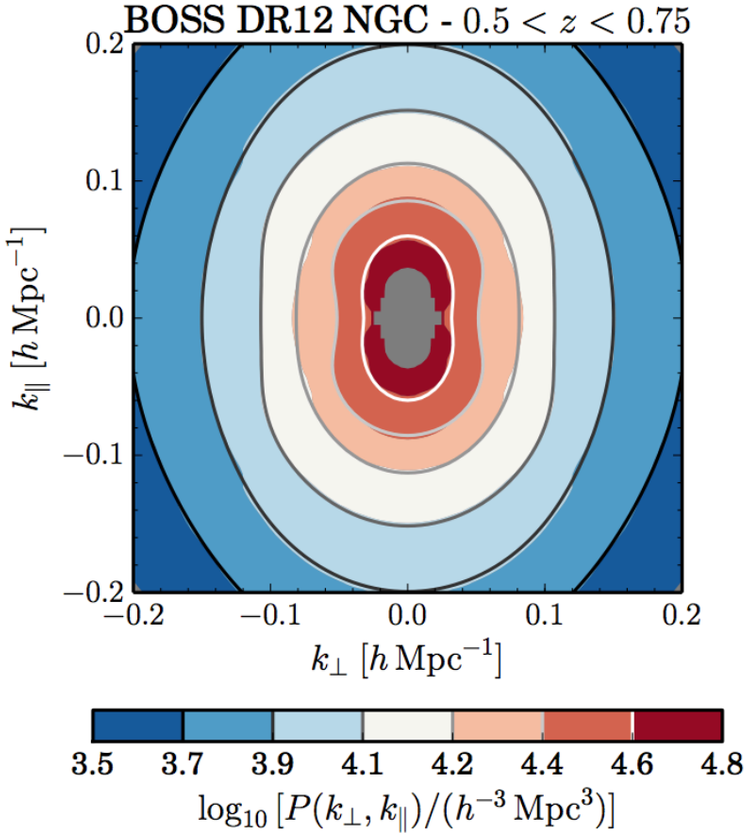
Redshift-Space Distortion (RSD) due to gravity

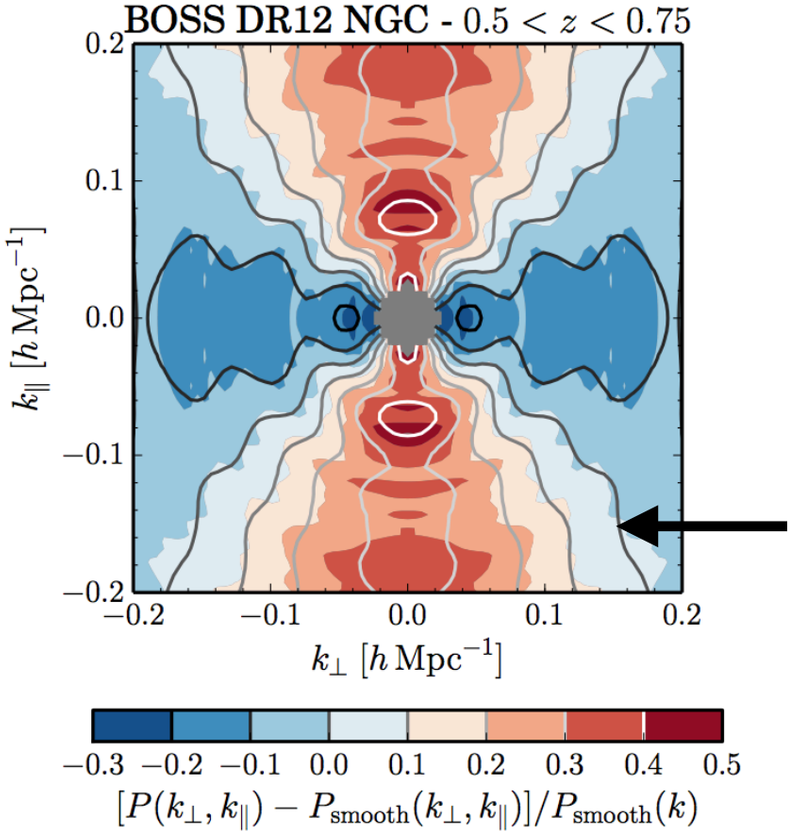


Linear theory

$$\boldsymbol{v} = -\frac{\mathcal{H} f}{4\pi G a^2 \overline{\rho}} \nabla \Phi$$

Peculiar velocity field of galaxies





Alam et al. 2017

Modeling of Redshift-Space Power Spectrum

Power spectrum in redshift space

$$\delta_D(\boldsymbol{k}) + P^s(\boldsymbol{k}) = \int d^3r e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \left\langle e^{-ik\mu\Delta u_z}[1+\delta(\boldsymbol{x})][1+\delta(\boldsymbol{x}')]\right\rangle$$

Linear theory $P^s(k,\mu) = (1+f\mu^2)^2 P(k)$ (Kaiser 1987)

-> in non-linear scales…

Problems

Gravitational non-linear evolution

- break-down of perturbative expansion (k > 0.2 h/Mpc or so) (e.g. Carlson et al. 2009)
- difficult to develop the analytic model to predict multi-streaming, halo-scale clustering

Galaxy bias uncertainty

- due to the poor understanding of galaxy formation, we cannot model the galaxy distribution within halos from the first principles.

  -> we must treat e.g. the velocity dispersion as nuisance parameters (c.f. Hand et al. 2017)

Solution

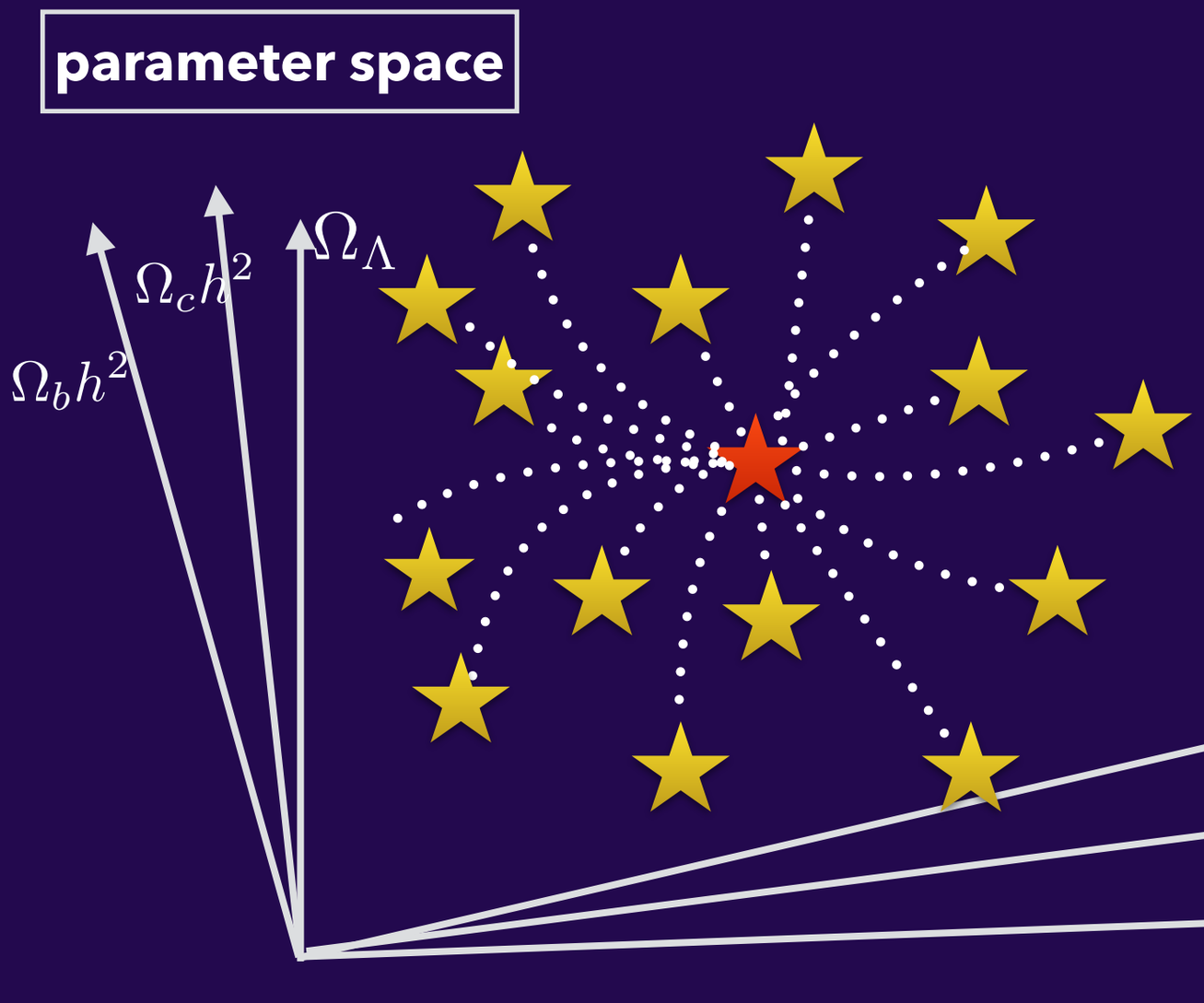
: Modeling the halo power spectrum in redshift space based on N-body simulations, and exploit the simulations as much as possible

Dark Quest (Nishimichi et al. 2018)

Development of ‘Dark Emulator’ based on the large N-body simulation suite

Simulation + Machine learning scheme
-> accurate prediction of various statistics of dark matter halos

eg. mass function, correlation function



Dark Quest Simulation

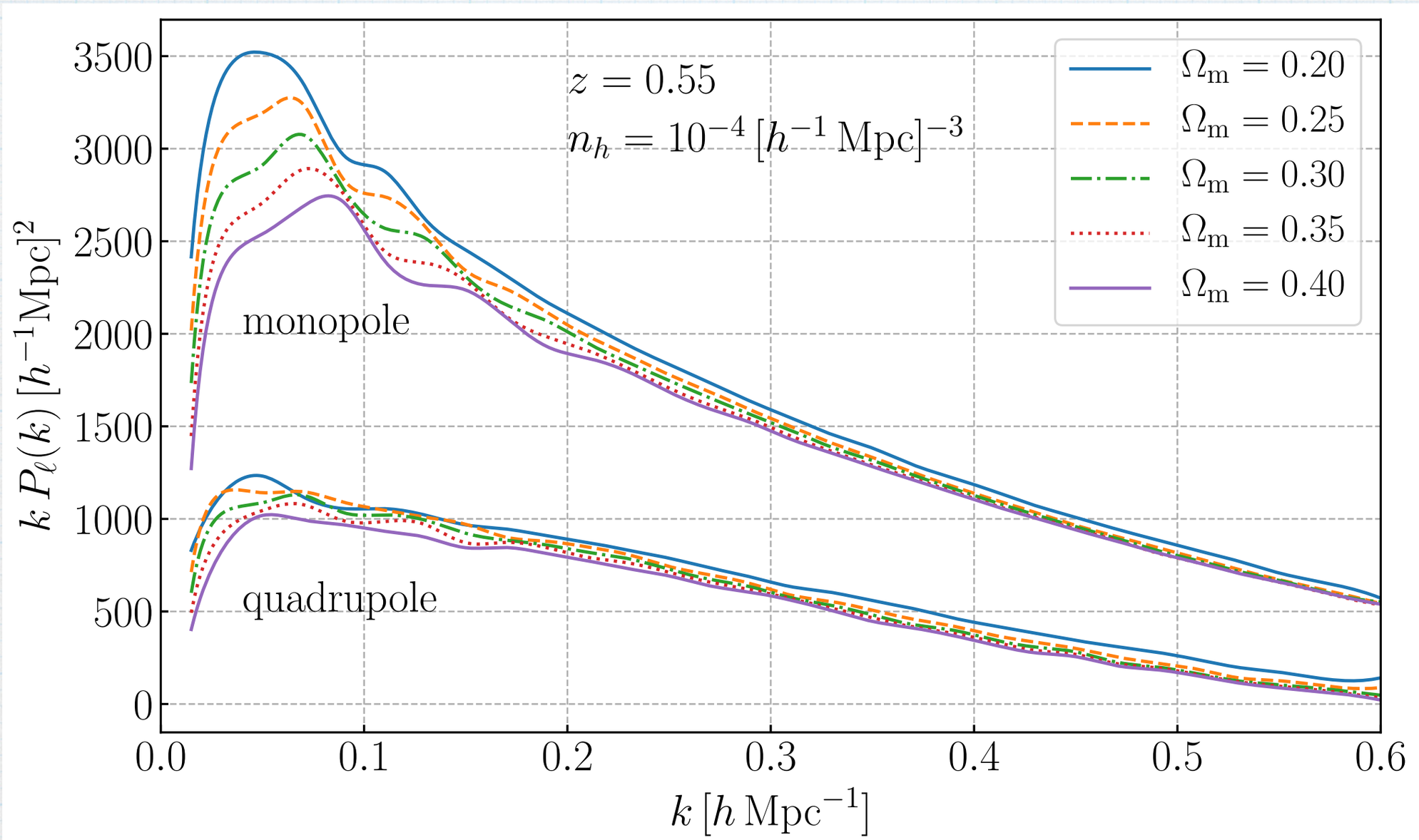
- Gadget-2 2048^3 particles
- 1 or 2 Gpc/h cubic box
- 101 cosmologies
around Planck 2015 flat ΛCDM
- Rockstar halo identification
+ post processing

Emulator of Halo Power Spectrum

Construct an 'emulator' to predict the dependence on

- **cosmology** (6 parameter flat wCDM, around Planck 2015)
- **redshift**
- **halo mass (number density)**

of the redshift-space halo power spectrum, in non-linear scales.



Emulator Construction using Neural Network

Traditionally, the Gaussian process regression is used to construct the emulator

e.g. Mira-Titan Universe, Aemulus

GP often requires some dimensionality reduction of the training data, i.e., data compression

Instead of GP, we introduce a simple feed-forward neural network as a regression model.

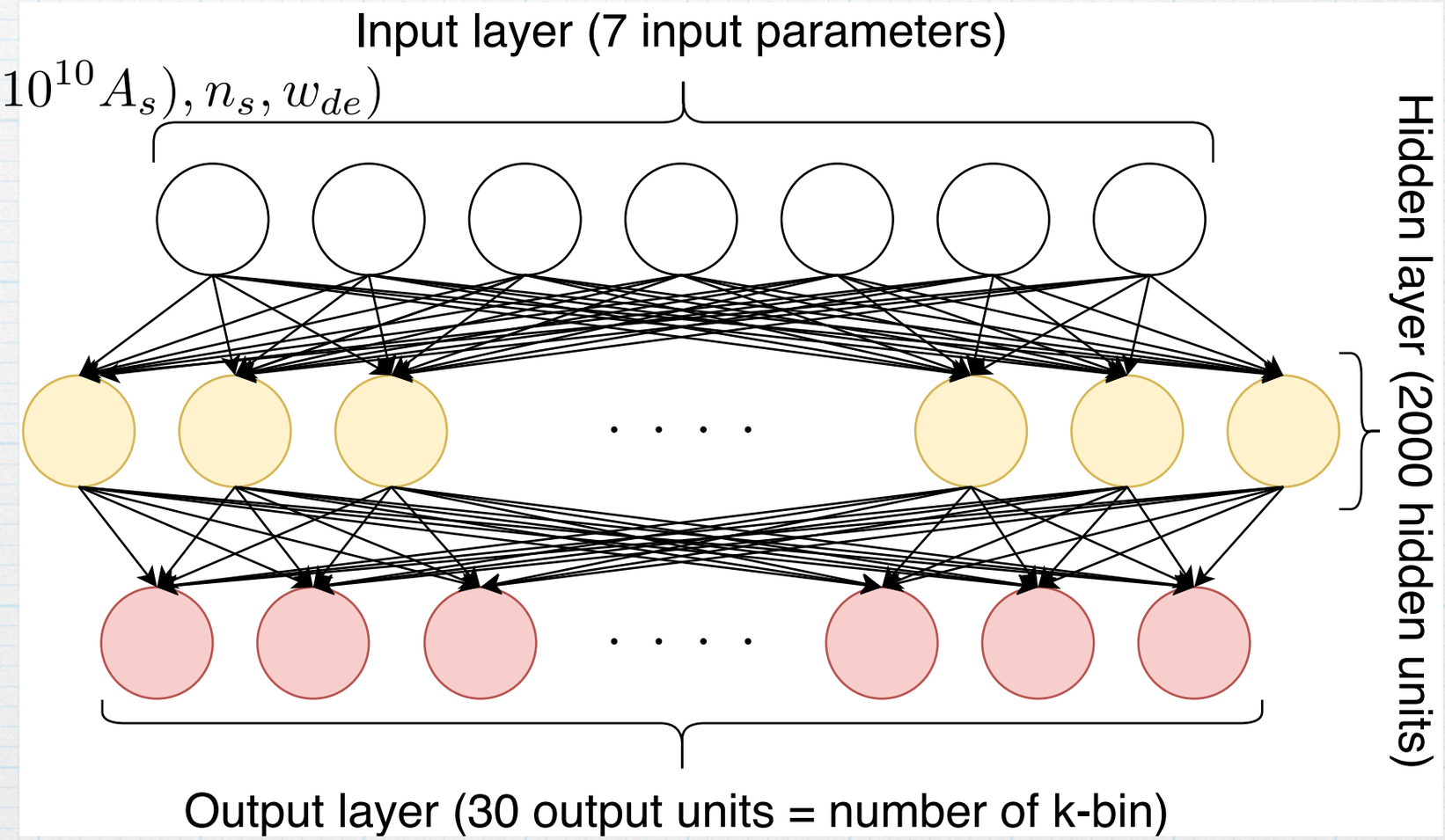
7D input $(\boldsymbol{p}_{cosmo}, z)$

$\boldsymbol{p}_{cosmo} = (\Omega_b h^2, \Omega_c h^2, \Omega_\Lambda, \ln(10^{10} A_s), n_s, w_{de})$

cosmology
97

redshift
21

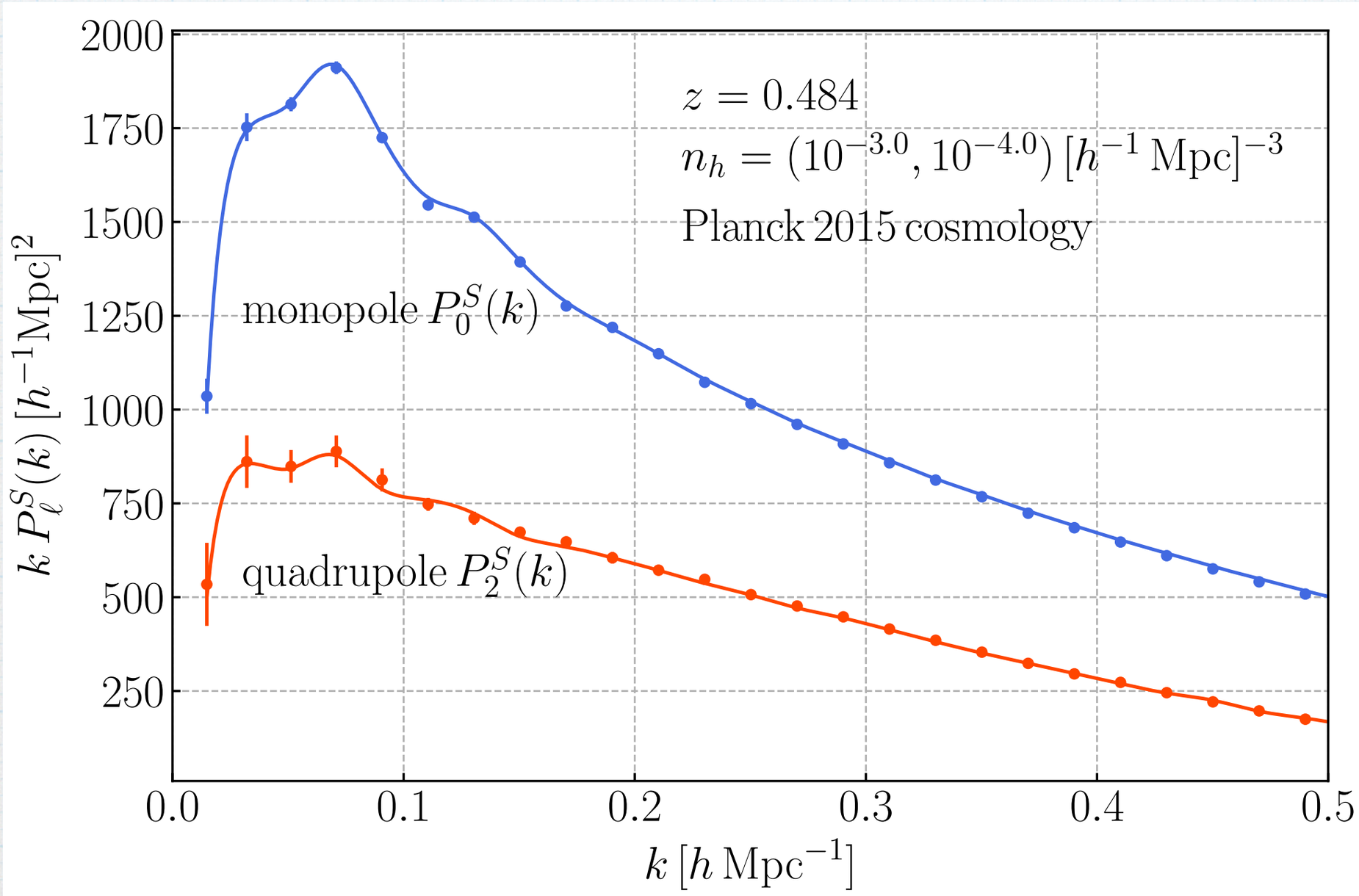
Spline interpolation in k & number density



Result: Emulator of Halo Power Spectrum

The emulator accurately predicts the redshift-space power spectrum in non-linear scales.
-> to be complementary to the perturbative analytic models.

$$P_\ell^S(k) = \frac{2\ell+1}{2}\int_{-1}^{1} \mathrm{d}\mu P^S(k,\mu)\mathscr{L}_\ell(\mu)$$



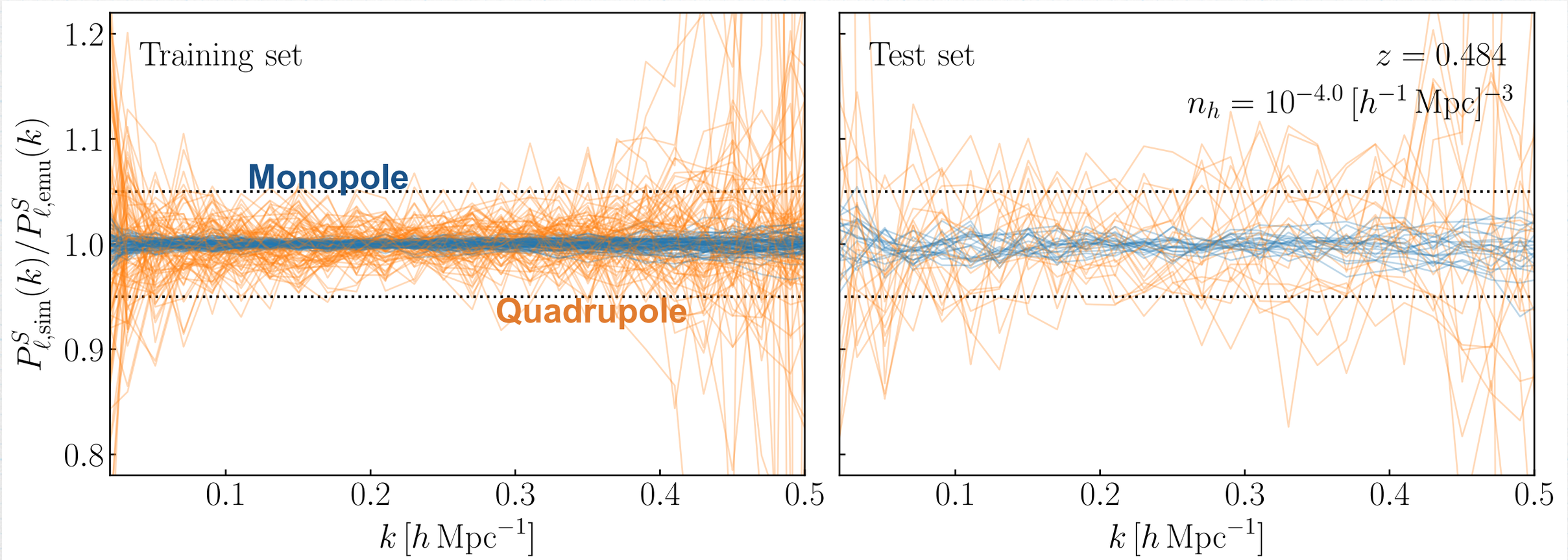
Validation of Emulator Performance

Testing the emulator with the test data set.

We split ~ 100 cosmologies into training & test data sets.

~ 80 cosmologies: training set

~ 20 cosmologies: test set



-> ~1% for the monopole, and ~5% for the quadrupole in non-linear scales.

Preparation for BOSS Analysis: Fisher Forecast

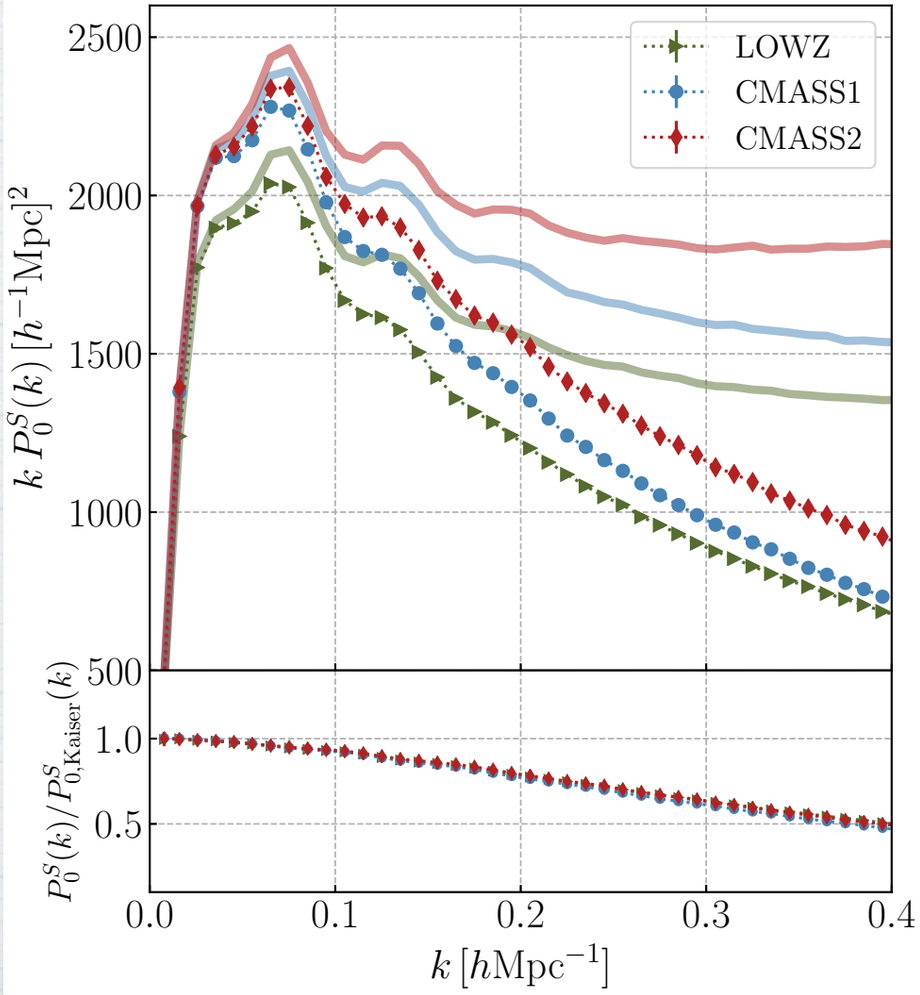
Fisher analysis using the mock galaxy measurements as the model

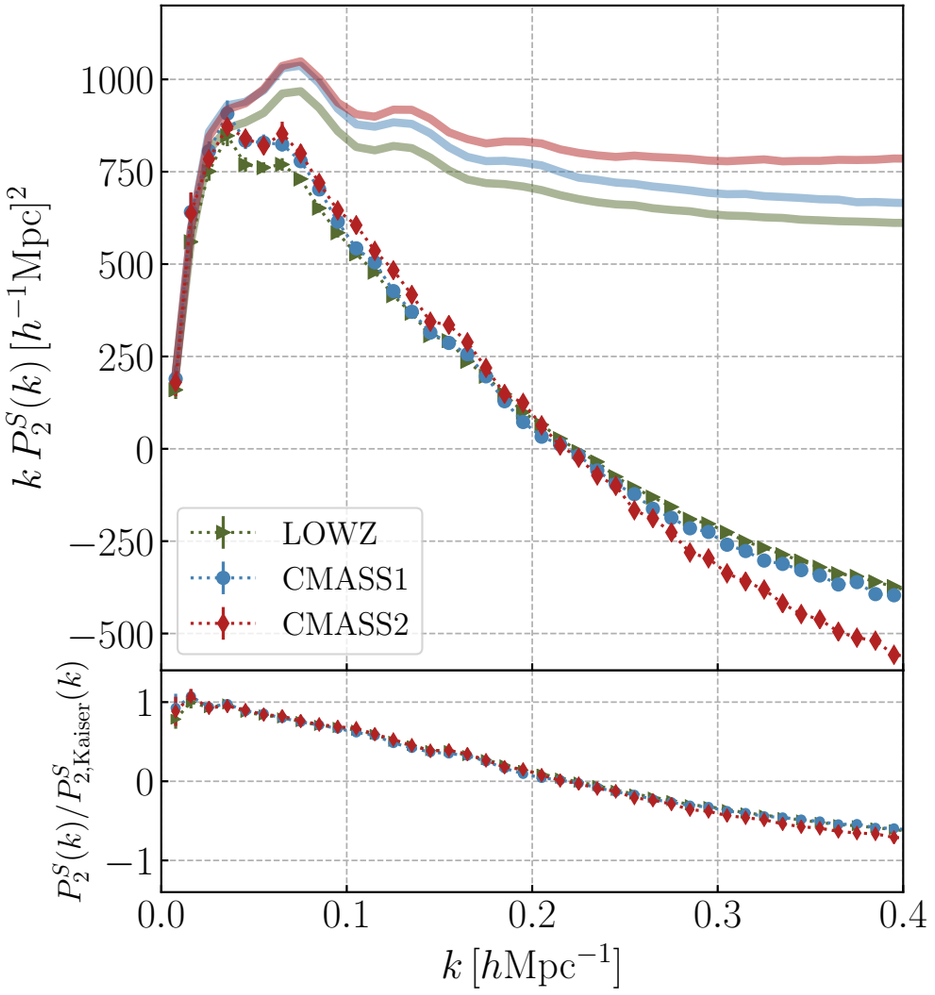
Mock generation

$$p_\alpha = \{\Omega_{\rm m}, \sigma_8, D_A(z), H(z), \log M_{\rm min}, \sigma_{\log M}, \log M_{\rm sat}, \log M_1, \alpha, c_{\rm conc}, c_{\rm vel}, p_{\rm off}, \mathscr{R}_{\rm off}, P_{\rm SN}\}$$

- Planck 2015 simulation halo catalogs (a part of Dark Quest)
- NFW density profile
- HOD of BOSS galaxies (LOWZ, CMASS1 & CMASS2 volume limited)

-> What information would be obtained from the signals in non-linear scales, when we marginalize the model uncertainty in the galaxy-halo connection?

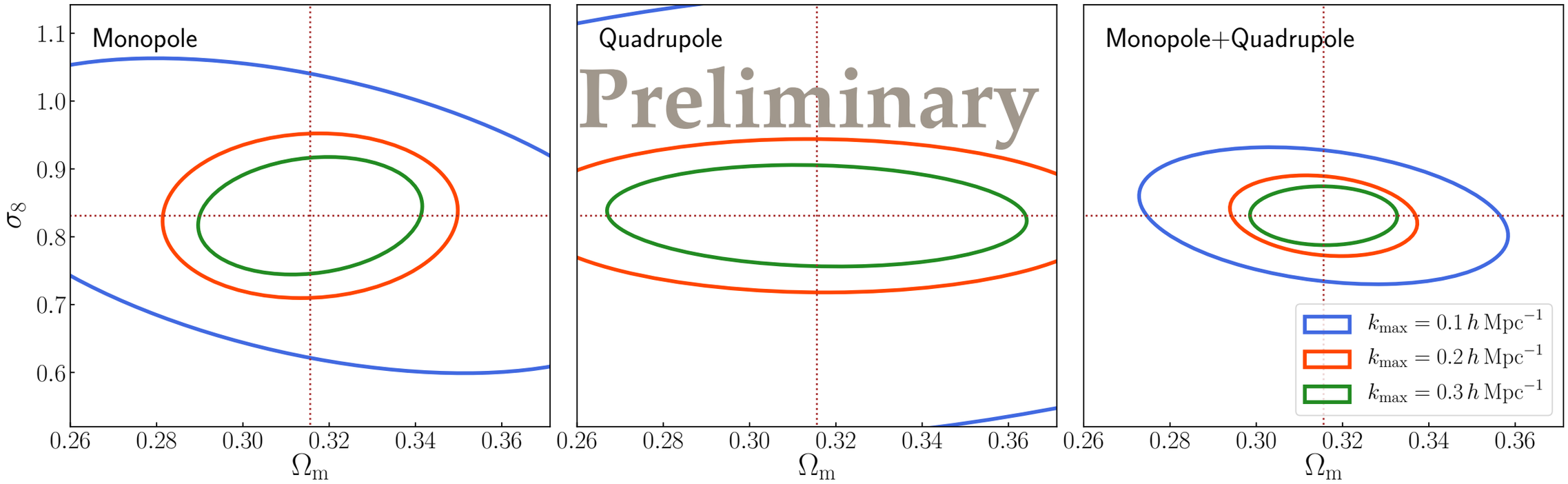


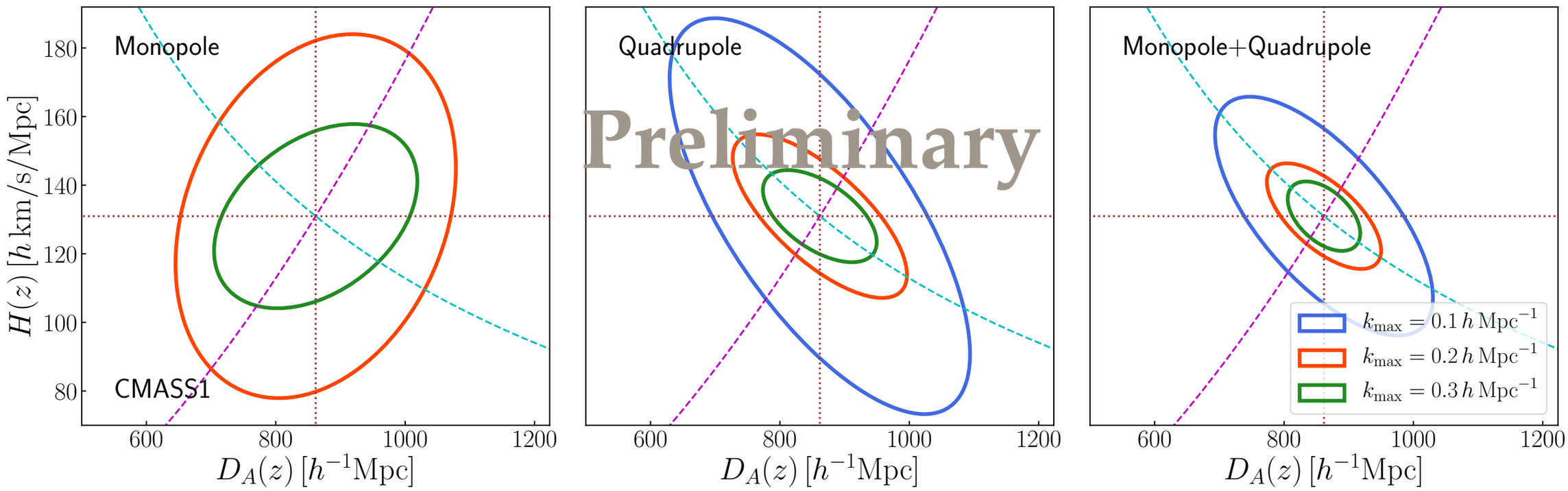


Fisher Forecast from BOSS-like galaxy mocks

Fisher analysis using the mock galaxy measurements as the model

$$p_\alpha = \{\Omega_{\rm m}, \sigma_8, D_A(z), H(z), \log M_{\rm min}, \sigma_{\log M}, \log M_{\rm sat}, \log M_1, \alpha, c_{\rm conc}, c_{\rm vel}, p_{\rm off}, \mathscr{R}_{\rm off}, P_{\rm SN}\}$$





Summary & Future Work

We develop an emulator which predicts the redshift-space non-linear power spectrum of halos, based on the Dark Quest simulation suite and a simple neural network.

It achieves ~ 1% (5%) prediction accuracy for the monopole (quadrupole) power spectrum in non-linear scales ($k < 0.4$ Mpc/h).

It is expected that the emulator performance will be improved by the additional realizations of the N-body simulations

Future Work

Implementation of the HOD galaxy power spectrum based on the emulator

Cosmology analysis of BOSS galaxy clustering using the emulator, including halo assembly-bias mock challenge

- Searching for a more automated learning pipeline for the emulator constructions