

# Fast, Accurate Galaxy Power Spectra with Cosmic Emulation

Juliana Kwan

Hal Finkel, Nicholas Frontiere, Salman Habib, Katrin Heitmann, Nikhil Padmanabhan, Adrian Pope

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Argonne National Laboratory

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# Preparing for Precision Cosmology

- Next generation surveys will deliver precision measurements of large scale structure.
- To fully exploit these datasets, we need to model the non-linear regime.
- Fitting formulae: difficult to find a general enough formula.
- Perturbation theory is only suitable for mildly non-linear regimes.
- Halo model not accurate enough on small scales.
- Brute force approach too slow.
- Emulator reduces calculation from ~ hour to be almost instantaneous on a single processor.

### How the emulator works:

- Set of high precision measurements (e.g. from N-body simulation) made according to a design.
- A Gaussian Process maps the parameter space.
- The hyperparameters are conditioned according to the measurements from N-body simulations.
- Predictions are made by locating the new parameters in the design matrix and recalculating the covariance function using the known hyperparameters.
- The emulator is only conditioned once to set the hyperparameters, so each prediction is actually quite fast.

## Some Examples

We have already produced emulators for

- Matter power spectrum [Heitmann et al. (2009,2010) and Lawrence et al. (2010), Heitmann et al. (2013)]
  - ► 1% accuracy out to  $k = 1 \text{ Mpc}^{-1}$ , 3-5% accuracy out to  $k = 10 \text{ Mpc}^{-1}$ .
  - Redshift range: 0 < z < 4.
- c-M relation [JK et al. 2013 (1210.1576)]
  - Accurate up to  $\sim$ 3% at z = 0 and  $\sim$ 13% at z = 1.
  - Mass range  $2 \times 10^{12} 10^{15} M_{\odot}$ .
- ► HOD galaxy power spectrum [JK et al., 2013, (1311.6444)] We are working on:
  - Redshift space HOD power spectrum
  - Covariance matrix for weak lensing (see talk on Friday)

The emulator is publicly available at

http://www.hep.anl.gov/cosmology/CosmicEmu/emu.html.

### How to Model Galaxies?

We use the Zheng et al. (2009) Halo Occupation Distribution (HOD) model:

$$\langle n_{cen} \rangle = \operatorname{erfc} \left( \frac{\log M - \log M_{cut}}{\sqrt{2}\sigma} \right)$$

$$\langle n_{sat} \rangle = \left( \frac{M - \kappa M_{cut}}{M_1} \right)^{\alpha}$$

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## HOD emulator

- Galaxy power spectrum from  $0.01 \le k < 1 \text{ Mpc}^{-1}$  from  $0 \le z \le 1$ .
- HOD parameter ranges:

12.85	$\leq \log(M_{cut}) \leq$	13.85
13.3	$\leq \log(M_1) \leq$	14.3
0.5	$\leq \sigma \leq$	1.2
0.5	$\leq \kappa \leq$	1.5
0.5	$\leq \alpha \leq$	1.5

- These are chosen to fit the resolution of the simulations.
- But they also fit some interesting observational samples as well, e.g. BOSS (White et al., 2011).

## Building the Emulator

- Our N-body simulation:
  - ACDM cosmology
  - L = 2100 Mpc, 3200<sup>3</sup> particles
- From our FOF halo catalogue, 100 HOD models per snapshot are generated as design points.
- We measure the power spectrum from each model.
- Each power spectrum is then smoothed.
- Repeat process for 6 snapshots between  $0 \le z \le 1$ .

#### The emulator is accurate to $\sim$ 3%

The emulator is tested against 5 new models not included in the original design.



## Comparison to Halo Model

We now compare the emulator to halo model predictions (Zheng 2004 model).

$$P_{gal}(k) = P_{gal}^{1h}(k) + P_{gal}^{2h}(k);$$

$$P_{gal}^{1h} = \int n(m) \frac{\langle N_{gal} (N_{gal} - 1) | m \rangle}{\bar{n}} |u(k|m)|^p dm$$
$$P_{gal}^{2h} = P_L \left[ \int n(m) b(m) \frac{\langle N_{gal} | m \rangle}{\bar{n}} u(k|m) dm \right]^2,$$

### Comparison to Halo Model

- Large scale bias (Tinker 2010) is accurate to  $\sim$ 3% to  $k \sim 0.1 \text{ Mpc}^{-1}$ .
- On smaller scales, 1-halo term and scale dependent bias fails to describe small scale clustering.



## Sensitivity of HOD parameters



#### Galaxy bias

The emulator can also give us the galaxy bias:

$$b(k) = \sqrt{\frac{P_{gal}(k)}{P_m(k)}}$$



### Conclusions

- We have presented a means of predicting galaxy power spectra to ~3% accuracy.
- Our HOD emulator is faster than the brute force approach and faster and more accurate than the halo model.
- All our emulators are available for download at: http://www.hep.anl.gov/cosmology/CosmicEmu/emu.html
- Still to come: redshift space HOD emulator.