Precision Cosmology with Cosmic Emulators

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Cosmic Calibration Framework

What is an Emulator?
Matter Power Spectrum
c-M relation
Cosmic Emulators: galaxy power spectrum

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 won't be enough; they have uncontrolled errors outside the range of acceptable parameters.

- ▶ Perturbation theory is only suitable for mildly non-linear regimes.

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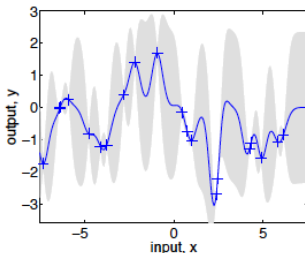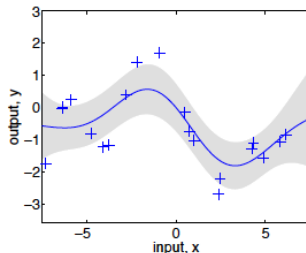
How the Emulator works: Brief Overview

- ▶ We have developed the Cosmic Calibration Framework (CCF) to solve inverse problem.
- ▶ Set of 37 carefully chosen N-body simulations of volume (1.3 Gpc)^3 with 1024^3 particles.
- ▶ Simulations span a range of 'likely' wCDM cosmologies:

$$
\begin{aligned}
0.12 &< \omega_m < 0.1155 \\
0.0215 &< \omega_b < 0.0235 \\
0.85 &< n_s < 1.05 \\
-1.3 &< w < -0.70 \\
0.61 &< \sigma_8 < 0.9
\end{aligned}
$$

- ▶ We have already built emulators for the matter power spectrum and c-M relation.

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How the emulator works: Gaussian Process Interpolation

- ▶ Interpolate over simulation results with Gaussian Process modelling.
- ▶ Gaussian process returns a function that fits the input points.
- ▶ How closely the input points are fitted is controlled by the covariance matrix.

(b), $\ell = 0.3$

(c), $\ell = 3$

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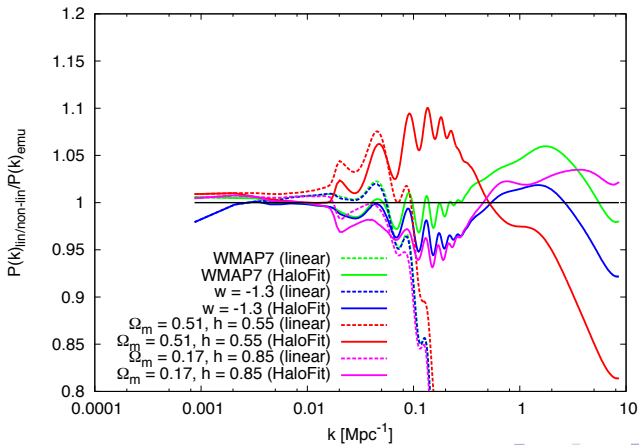
How the emulator works: Making Predictions

► The hyperparameters are conditioned according to the measurements from N-body simulations.

► The N-body measurements act as known points in a distance matrix.

► Predictions are made by locating the new parameters in the design matrix and adjusting the weights of existing simulations according to the distance from the new point to the existing points.

► The emulator is only conditioned once to set the hyperparameters, so each prediction is actually quite fast.

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What is an Emulator?
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Cosmic Emulators: Power spectrum

- ▶ Two emulators for the matter power spectrum have been built:

  - ▶ Coyote Emulator [Heitmann et al. (2009,2010) and Lawrence et al. (2010)]
    - ▶ 1% accuracy out to $k = 1$ Mpc^{-1}.
    - ▶ Redshift range: $0 < z < 1$.
    - ▶ Shear power spectrum emulator also available from Eifler (2011).
  - ▶ Coyote^{++} Emulator [Heitmann et al. (2013)]
    - ▶ 3% accuracy out to $k = 8.6$ Mpc^{-1} (fixed h).
    - ▶ 5% accuracy out to $k = 8.6$ Mpc^{-1} (free h).
    - ▶ Redshift range: $0 < z < 4$.

- ▶ Emulator available from
  http://www.hep.anl.gov/cosmology/CosmicEmu/

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Cosmic Emulators: Power spectrum

Comparison between Halofit (Takahashi et al., 2012) and Coyote[++]:

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Cosmic Emulators: c-M relation

The statistics of massive dark matter haloes can also be useful for cosmology, e.g: halo mass function, halo profiles.

▶ The mass profile of a dark matter halo (in a simulation) is given by
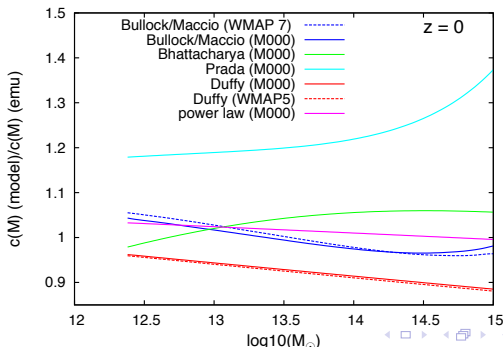
$$\rho(r) = \frac{\delta \rho_c}{(r/r_s)(1 + r/r_s)^2}$$

according to Navarro, Frenk and White (1997).

▶ The concentration of a dark matter halo is defined as $c = R_{200}/r_s$

▶ From the halo catalogue of the Coyote and Coyote[++] simulations, we have measured the concentrations of haloes in the mass range $2 \times 10^{12} - 10^{15} M_\odot$.

▶ These were incorporated into an emulator for the c-M relation over wCDM cosmologies [arXiv:1210.1576].

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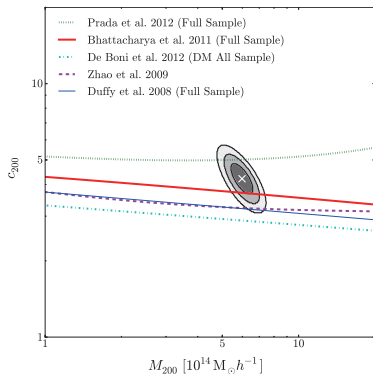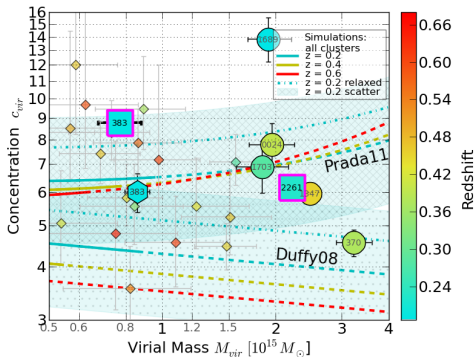**c-M relation**
Cosmic Emulators: galaxy power spectrum

Emulator accuracy

▶ The emulator is accurate up to $\sim 3\%$ at $z = 0$ and $\sim 13\%$ at $z = 1$.

▶ Consistent with existing fitting formulae to 10%, apart from Prada et al. (2012).
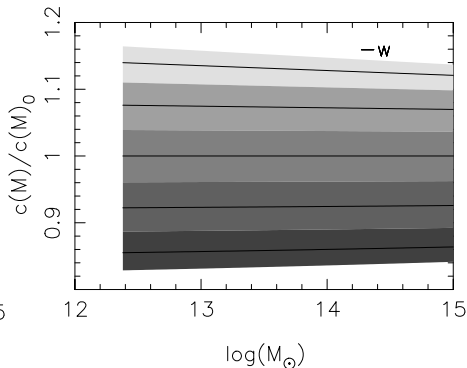
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Cosmic Emulators: c-M relation

Coe et al. (2012)

Okabe et al. (2013)

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Sensitivity to cosmology
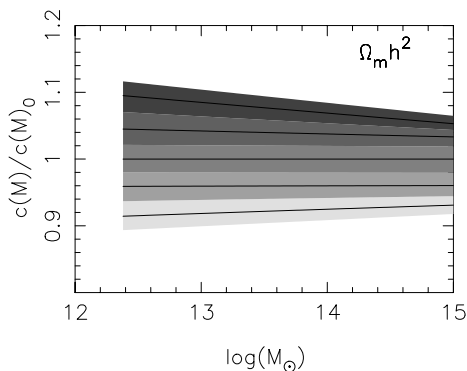
(JK, Bhattacharya, Heitmann & Habib, 2012, [arXiv:1210.1576])

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Cosmic Emulators: galaxy power spectrum

How can we insert galaxies into our simulations?

- ▶ N-body simulations are only capable of modelling dark matter content of our Universe.
- ▶ Cosmological simulations containing fully self consistent baryonic physics are still very far away.
- ▶ There are three main methods for inserting galaxies into simulations:
  - ▶ Halo Occupation Distribution (HOD) model.
  - ▶ Halo abundance matching, e.g. SHAM.
  - ▶ Semi-analytic galaxy formation models, e.g. GALFORM, Galacticus.

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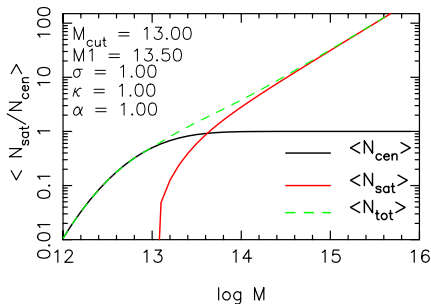
The Halo Occupation Distribution Model

- ▶ In the HOD model, galaxies are placed into dark matter haloes.
- ▶ The halo mass determines the number of galaxies it will host; more the massive a halo, the greater the number of galaxies it will contain.
- ▶ The first galaxy in a halo is placed in the center, (central galaxy), subsequent galaxies are located in the surrounding dark matter halo (satellite galaxies).

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Matter Power Spectrum
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Cosmic Emulators: galaxy power spectrum

How Many Galaxies?

We use the Zehavi et al. (2009) HOD model:

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

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

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▶ We would like to produce two emulators:
  1. HOD parameters only: $M_{cut}, M_1, \sigma, \kappa, \alpha$
  2. HOD + cosmology: $M_{cut}, M_1, \sigma, \kappa, \alpha, \Omega_m h^2, \Omega_b h^2, n_s, \sigma_8, w$.

▶ The emulator will be useful for:
  ▶ Producing a fast estimate of the non-linear galaxy power spectrum.
  ▶ Fitting for the HOD parameters from an observed galaxy sample.
  ▶ Determining cosmological and HOD parameter degeneracies.
  ▶ Fisher matrix forecasts.
  ▶ Any application in which a galaxy power spectrum is needed.

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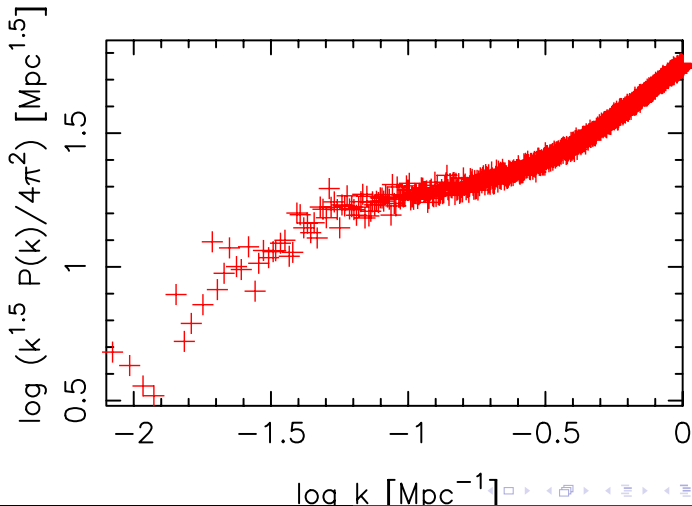c-M relation
Cosmic Emulators: galaxy power spectrum

▶ We populate each simulation in the Coyote Universe with a 100 HOD models and measure their power spectra.

▶ The HOD parameters ranges are:

$$
\begin{array}{rcl}
12.85 & \leq log(M_{cut}) \leq & 13.85 \\
13.3 & \leq log(M_1) \leq & 14.3 \\
0.6 & \leq \sigma \leq & 1.2 \\
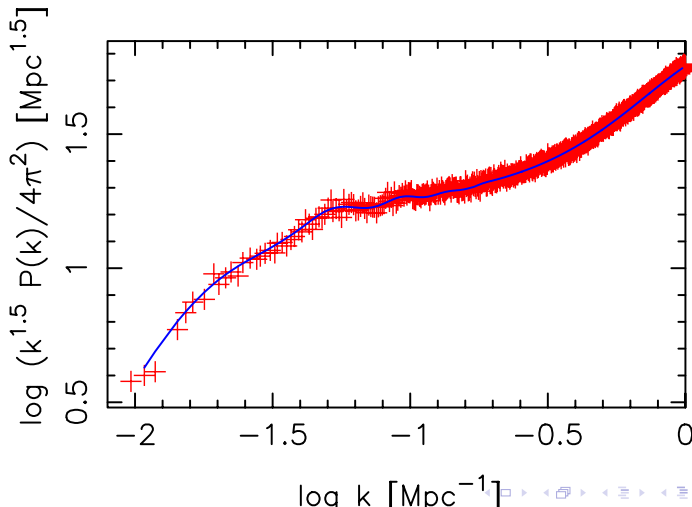0.5 & \leq \kappa \leq & 1.5 \\
0.5 & \leq \alpha \leq & 1.5
\end{array}
$$

▶ 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).

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Each galaxy power spectrum must be smoothed; this is to avoid modelling the noise in the power spectrum in the final product.

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The procedure is:

- ▶ Remove cosmic variance using the matter power spectrum (which we know to 1% accuracy from the previous Coyote emulator.)
- ▶ Cubic spline captures the broadband shape of the power spectrum.
- ▶ Model the region $0.01 < k < k_{max}$ Mpc^{-1} using a renormalized PT scheme [McDonald (2006)] for the galaxy power spectrum:
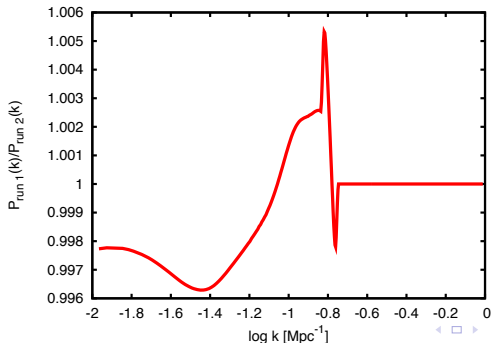
$$P_g(k) = b_1{}^2 P_m(k) + \frac{1}{2} b_1{}^2 b_2{}^2 \int \frac{d^3\mathbf{q}}{(2\pi)^3} P(q) \left[P(|\mathbf{k} - \mathbf{q}|) - P(q) \right]$$
$$+ 2b_1{}^2 b_2 \int \frac{d^3\mathbf{q}}{(2\pi)^3} P(q) P(|\mathbf{k} - \mathbf{q}|) J_s^{(2)}(\mathbf{q}, \mathbf{k}) + N.$$

- ▶ b_1, b_2, N are free parameters that must be fitted to the power spectra; we do this with a Markov Chain Monte Carlo exploration of the posterior.
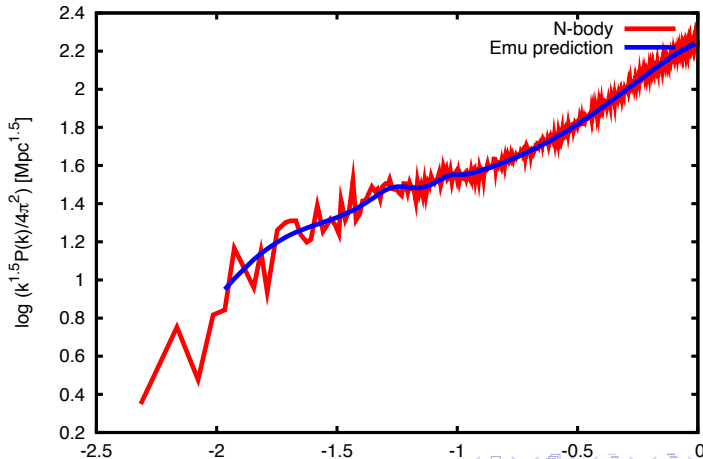- ▶ Derivatives are matched at both sides of the joining region.

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Emulator accuracy

Some sources of error to watch out for:

1. Width in the distribution of b_1, b_2, N affects power spectrum on large scales.
2. The mass of low particle number FOF haloes is biased high.
3. Shot noise in the power spectrum

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Cosmic Emu: Results

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Conclusions

▶ Cosmic emulators can make a non-linear prediction for any observational quantity that can be measured from a N-body simulation.

▶ This is particularly important for highly non-linear effects, such as RSD.

▶ We have already produced emulators for the matter power spectrum and the c-M relation.

▶ All emulators will be publicly available, please check our website: http://www.hep.anl.gov/cosmology/CosmicEmu/

▶ We plan to extend our suite of N-body simulations with more cosmological parameters, e.g. neutrino mass, dynamical dark energy and models of gravity e.g. $f(R)$.