Cosmic Calibration

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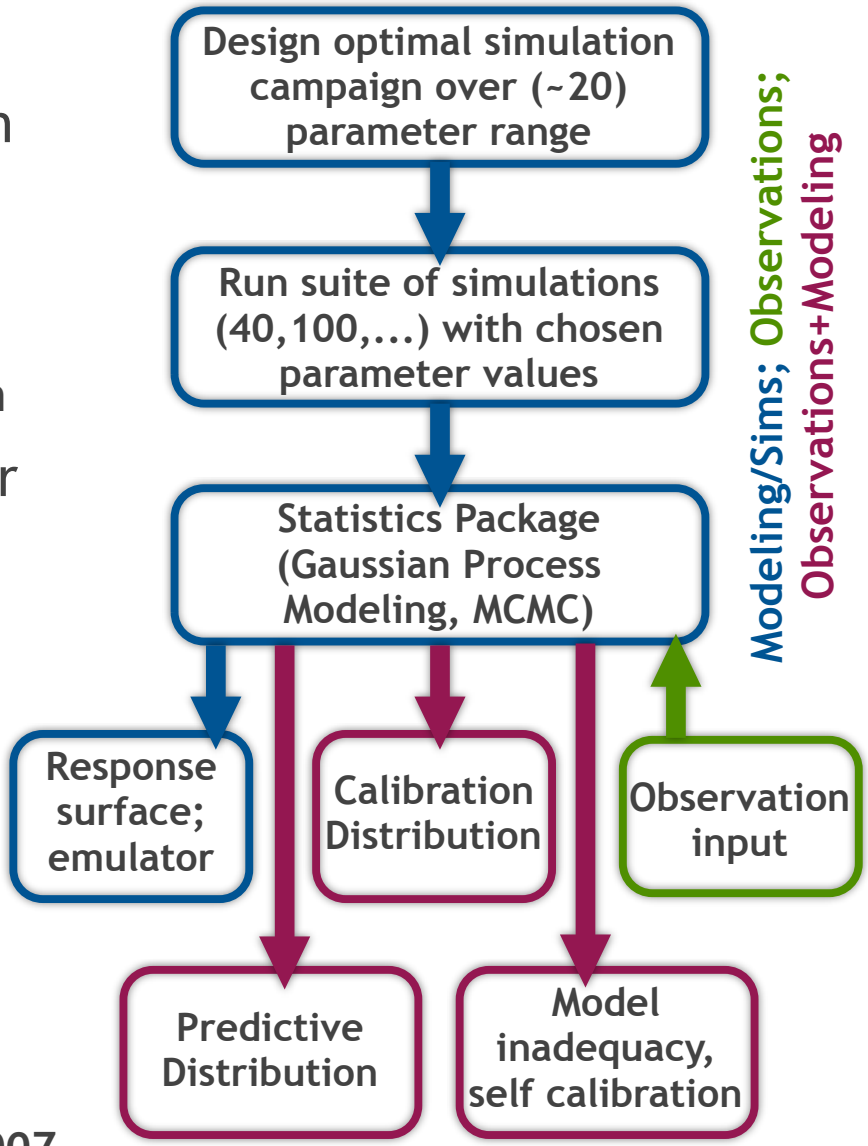
Physicists, Statisticians

Cosmic Calibration: Solving the Inverse Problem

- **The "cosmological inverse problem":** We observe one Universe (at different wavelengths) and want to infer the physics underlying the content and evolution of the Universe
- **Nonlinear regime of structure formation** holds wealth of information, but requires very costly simulations
- **"CMB approach":** To extract cosmological constraints from observations, run Markov Chain Monte Carlo; input: 10,000 - 100,000 different models
- **Brute Force in the nonlinear regime:** Simulations, ~30 years on 2000 processor cluster ---
- **Current Strategy:** Fitting functions, e.g. for power spectrum, accurate at 10% level, not good enough! Theory has to be at least as accurate as observations
- **Our Solution:** Precision emulators, built from a small set of very accurate simulations

Cosmic Calibration and Emulation, Concepts

- **Simulation design:** For a given set of parameters to be varied and a certain number of simulation runs, at what setting should the simulations be performed?
  - Orthogonal-array Latin hypercube design
- **Interpolation scheme:** Predictions for observables, e.g. P(k), for any cosmology within the priors
  - Principal components, Gaussian process modeling
- **Uncertainty and sensitivity analysis**
- **Calibration:** Combine emulator and observations to obtain cosmological and modeling parameters

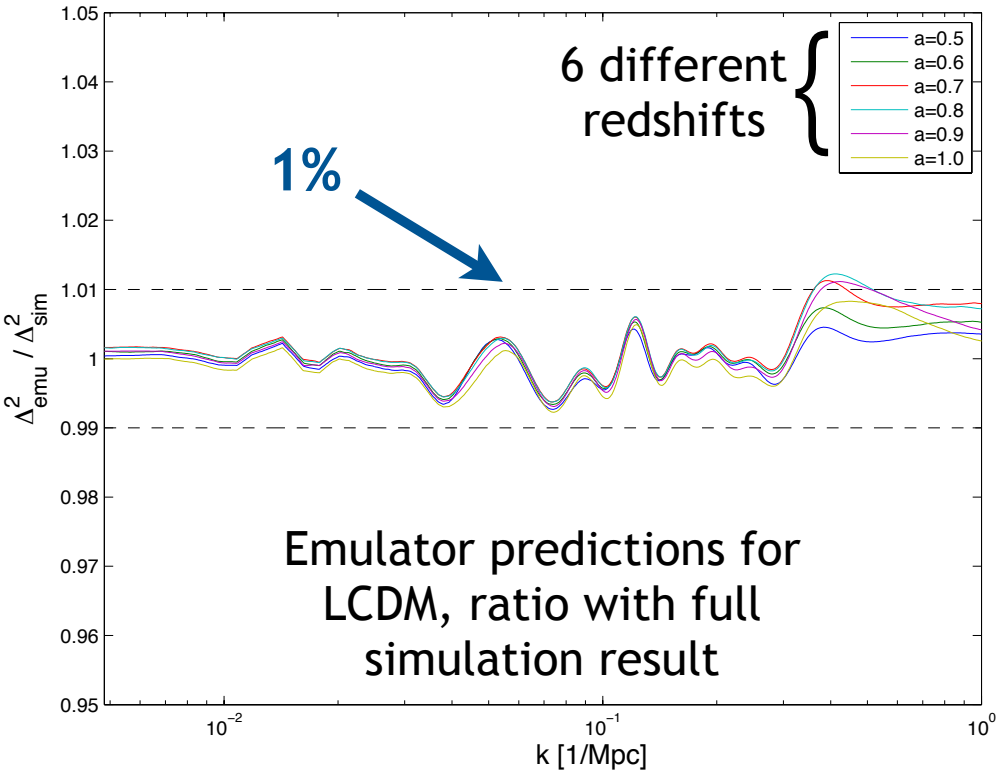


Heitmann et al. ApJL 2006, Habib et al. PRD 2007

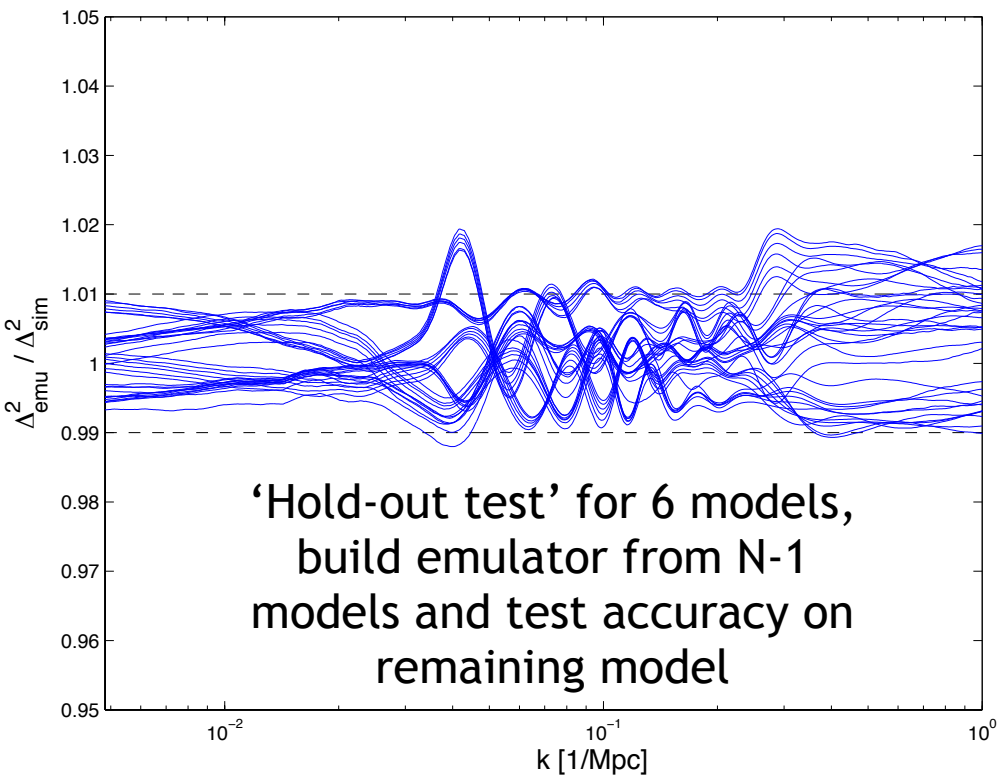
Cosmic Emulator in Action

- Instantaneous ‘oracle’ for nonlinear power spectrum, easy to use, reduces run time from weeks to ‘zero’, 1% accurate to k~1/Mpc for wCDM cosmologies -- based on ~1000 simulation runs for 38 cosmologies
- For the first time enables direct MCMC with results from full simulations

Cosmic Emulator Accuracy



Emulator predictions for LCDM, ratio with full simulation result



'Hold-out test' for 6 models, build emulator from N-1 models and test accuracy on remaining model

- 'CMBfast' for large scale structure probes at high accuracy
- Currently: derive emulator for concentration-mass relation for dark matter halos

Cosmic Emulators for Future Surveys

- **Extension Beyond wCDM:**

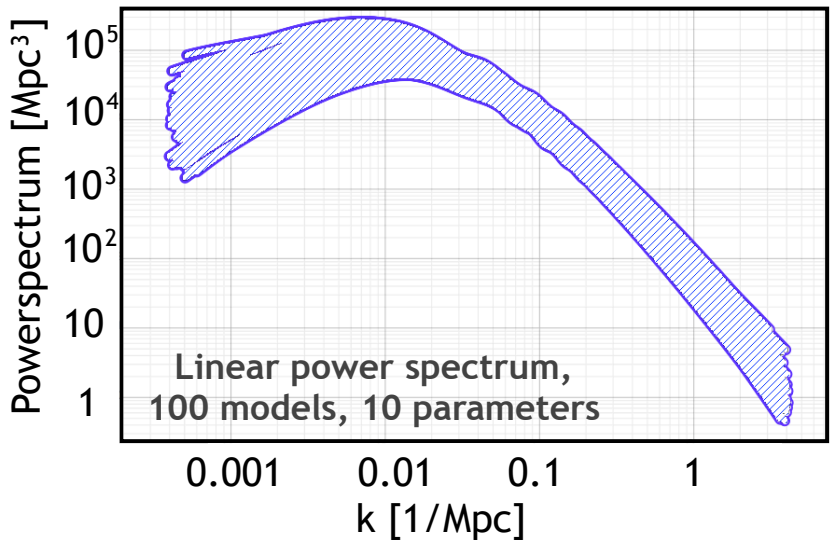
$$\theta = \{\omega_m, \omega_b, n_s, w_0, \sigma_8,$$
$$w_a, dn_s/d\log k, h, \Omega_k, f_\nu\}$$

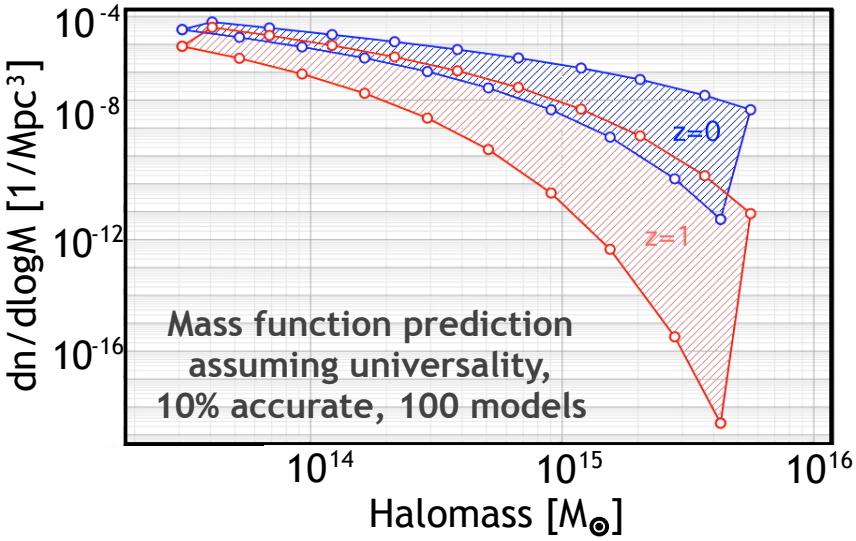
  Currently fine-tuning number of models and parameter ranges via convergence tests

- **Emulators for a Variety of Observables:** Power spectrum, mass function (different mass definitions), shear power spectrum, peak statistics, bias, ---

- **Extension of Range of Validity:** Higher resolution, baryonic physics

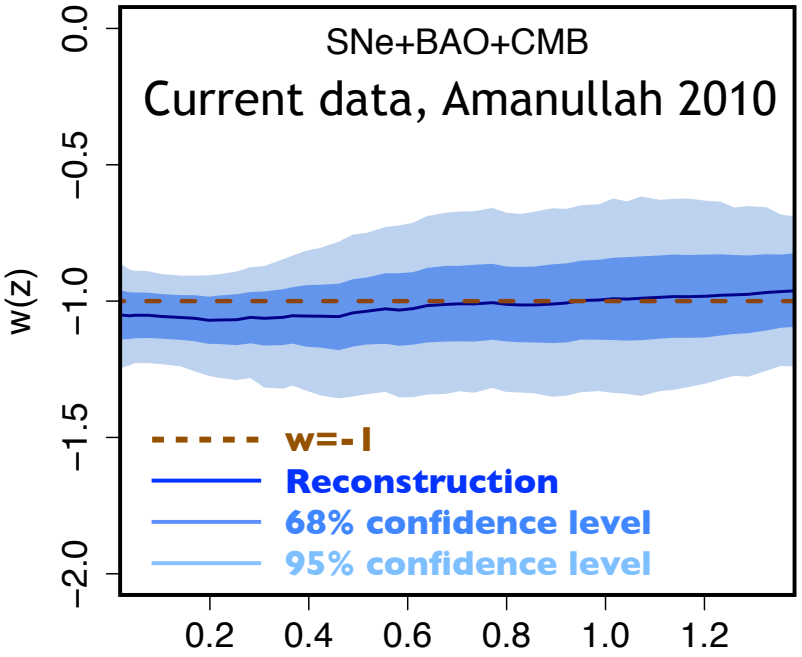
- **Early Science Project on Mira will enable this important next step**

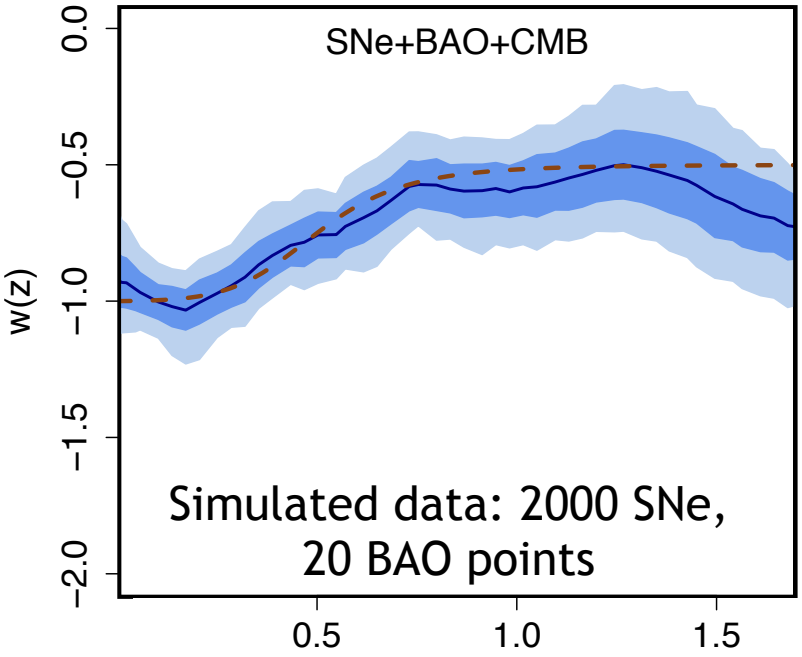




Nonparametric Reconstruction of the Dark Energy EOS

Holsclaw et al. PRD 2010, PRL 2010, PRD 2011 submitted





$$\mu(z) = 25 + 5\log_{10}\left((1+z)\frac{c}{H_0}\int_0^z ds\left[\Omega_m(1+s)^3 + (1-\Omega_m)(1+s)^3\exp\left(3\int_0^s \frac{w(u)}{1+u}du\right)\right]^{-\frac{1}{2}}\right)$$

- **Challenge:** Measurement and quantity of interest are two integrals apart, assuming parametric form for w(z) can lead to biases
- **New nonparametric approach** based on Gaussian Process Modeling
- Test on simulated data and analysis of real data

Summary and Outlook

- **Enable:** Cosmic emulators will be crucial for the analysis of current and upcoming dark energy surveys, already used by the community for weak lensing, lots of requests to extend range of validity
- **Unique:** Building emulators requires cross-disciplinary effort by physicists, statisticians, and computer scientists, ANL provides the needed supercomputing resources as well as expertise in large data bases
- **Data release:** Coyote Universe database has been very useful for University collaborators (velocity statistics, new power spectrum analysis, weak lensing for DES,...)
  - Ported data base from LANL to ANL (help from Computation Institute (CI), UoC, 3GB/s data transfer rate!), first analysis tests carried out on Eureka, ANL's analysis and visualization supercomputer
  - Collaboration with MCS division and CI to build efficient data base
- **New simulations beyond wCDM underway!**