Modeling galaxy redshift space distortions for WFIRST

Nick Hand
UC Berkeley
March 3, 2016

with Uros Seljak, Yu Feng, and Grigor Aslanyan
Galaxy clustering with WFIRST

the ultimate goal: measure expansion history and growth rate with sub-percent level precision

BAO as standard ruler

redshift space distortions

Anderson et al. 2014

Planck Collaboration XIII 2015
Uncertainties in the forecasting of RSD constraints

- small scales contaminated by non-linear effects, but have greater statistical precision

- theoretical systematics implicitly forecasted through value of $k_{\text{max}}$

source: Weinberg et al. 2013
RSD constraints have great potential

- need full P(k) analysis to fully capture information

- factor of \(~3\) improvement in dark energy FOM when using full P(k) shape measurements (assuming GR)

- full shape analysis provides information on neutrino masses and expansion through AP test

source: Wang et al. 2010
A new scheme for modeling RSD

1. Approximate N-body solver with halo formation model that is both sufficiently fast and accurate enough to extract galaxy statistics.

2. Physical model for galaxy-halo connection that is general enough to avoid the many unknown aspects of galaxy formation.

3. Simultaneously sample the posterior distribution and emulate the slow evaluation of the data likelihood.
FastPM: fast simulations of halos

- an approximate particle mesh N-body solver that enforces the correct large-scale linear growth at each time step

- written from scratch to exhibit strong-scaling — nearly linear scaling with the number of CPUs allows for fast simulations

- benchmarks with 10 time steps produce halo catalogs that are very close to the exact (N-body) solution

- simulations led by Yu Feng at UC Berkeley, with publication coming soon

find the project on github: https://github.com/rainwoodman/fastpm
Nick Hand, UC Berkeley

FastPM: fast simulations of halos

Feng et al. 2016 (in prep.)

<table>
<thead>
<tr>
<th>Simulation</th>
<th>40 Steps</th>
<th>10 Steps</th>
<th>5 Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>B=1</td>
<td>8.06x</td>
<td>19.2x</td>
<td>3.88x</td>
</tr>
<tr>
<td>B=1,2</td>
<td>17.1x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B=2</td>
<td>24.8x</td>
<td>71.5x</td>
<td></td>
</tr>
<tr>
<td>B=3</td>
<td></td>
<td></td>
<td>6.97x</td>
</tr>
</tbody>
</table>

Preferred configuration takes $\sim 100$ CPU-hours $\rightarrow$ typically $O(1 \text{ min})$
FastPM: benchmarks for halo catalogs

Feng et al. 2016 (in prep.)

at z = 0
the galaxy - halo connection: HOD formalism

- flexible enough to immunize constraints against galaxy formation uncertainties:
  1. velocity bias for centrals/satellites
  2. central galaxy incompleteness
  3. satellite profile uncertainties
  4. assembly bias —> decorated HODs (see Hearin et al. 2015, 1512.03050)
  5. others?

- populate FastPM halo catalogs using as many features as needed using Halotools software (led by Andrew Hearin)

- simplified HOD-modeling already successful in extending RSD constraints to smaller scales: Reid et al. 2014, Guo et al. 2014.

Halotools: https://github.com/astropy/halotools
from simulation to clustering observables

- fast power spectrum measurements via FFTs via nbodykit
- population + power spectrum steps take $O(\text{seconds})$

**to do:**
- tailor to WFIRST
- volume, HOD masses, observational effects, etc

nbodykit: https://github.com/bccp/nbodykit
Combining the pieces with Cosmo++ emulator

- a combined sampler and emulator for data likelihood using training set of exact results produced during sampling procedure

- robust error control of emulation errors that are propagated to posterior probability distribution

- exact solution computed if error model predicts an unacceptable emulation error

- “learn-as-you-go”: updates error model and training set given new, exact solutions

Aslanyan et al. 2015, 1506.01079
https://github.com/aslanyan/cosmopp
Combining the pieces with Cosmo++ emulator

led by Grigor Aslanyan at UC Berkeley

applied to CMB likelihoods in 1506.01079

Aslanyan et al. 2015
Conclusions

- RSD analyses can provide powerful constraints on dark energy and General Relativity tests with WFIRST, if theoretical uncertainties can be controlled
- Key challenge: accurate modeling of non-linear effects and galaxy formation physics on small-scales
- Developing a simulation-based RSD model that is both computationally tractable and sufficiently accurate
  1. FastPM simulations produce halo catalogs in $O(\text{minutes})$
  2. HOD population and power spectrum estimation in $O(\text{seconds})$
  3. Combine these steps in learn-as-you-go emulator to simultaneously sample the posterior and emulate the non-linear galaxy power spectrum
FastPM: benchmarks for halo catalogs

\[ \sim 0.18 \text{ dex scatter in halo mass corresponds to:} \]
\[ \text{stochasticity } \sim 0.10, 0.18, 0.22 \text{ in } 10^{12}, 10^{13}, 10^{14} \text{ M}_{\odot}/h \text{ halos} \]
Modeling assembly bias with decorated HODs

\[ M > 10^{10.5} \, M_\odot \]

\[
\frac{\Delta \xi_{gg}}{\xi_{gg}}
\]

\[
R \, [\text{Mpc}]
\]
the current status of growth rate results

best uncertainty on $f\sigma_8(z=0.57)$ is $\sim 8\%$, fitting to $k_{\text{max}} = 0.24 \, h/\text{Mpc}$
BAO systematics are well-controlled

simulations indicate reconstruction eliminates systematics to the \(~0.1\%\) level

source: Mehta et al. 2011
nbodykit software tools

- python tools for N-body simulations + LSS surveys
- parallelized with MPI and designed to run on super-computers

- available tools/features:
  - periodic and windowed power spectra
  - correlation functions
  - FOF halo finder
  - sub-halo finder
  - running above algorithms in parallel across nodes in batch mode

available at [github.com/bccp/nbodykit](https://github.com/bccp/nbodykit)