Clustering as a constraint for galaxy formation

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CLUSTERING AS A CONSTRAINT

- Clustering observations offer complentary constraints to traditional data (e.g. stellar mass function, colours), because they encode spatial information

- But: two-point function, so much harder to sample for – taking a sizeable volume (or several) might work, but that takes too long for use in MCMC

- Solution: use sampled haloes as input to a **halo model** and predict the clustering that way

HALO MODEL

- Ingredients needed by the halo model:
  - Linear matter power spectrum
  - Halo mass function
  - Halo bias
  - Halo occupation distribution for galaxies (HOD)
  - Halo profile

- Possible extensions/corrections: nonlinear bias, assembly bias, halo triaxiality, halo exclusion, satellites decoupled from halo profile...

HALO MODEL

- Many different models already exist for each ingredient

- However, our goal is unusual: we want to model the galaxy clustering of the **simulation**, not of the real Universe!

- This means we can measure the dark matter properties directly from Millennium: **realized** initial power spectrum, halo mass function

- We also know how to scale these with cosmology (Angulo & White 2010)

HALO MODEL

- Left to sample: HOD, satellite profile

- Clustering of galaxies is **very** sensitive to the HOD and small changes in the profile, especially on small scales, where most of the constraining power is

- Important therefore to treat centrals and satellites separately, and to use a custom satellite profile (i.e. not NFW or Einasto, and not cut off at virial radius)

- Lots of galaxy information available for sampled haloes to fit to!

HALO MODEL

$$P^{1h}_{gal}(k) = 2\int n(M)\frac{\langle N_{cen}N_{sat}|M\rangle}{\bar{n}^2_{gal}}[u_{gal}(k|M)-W_R(k)]\,\mathrm{d}M +$$

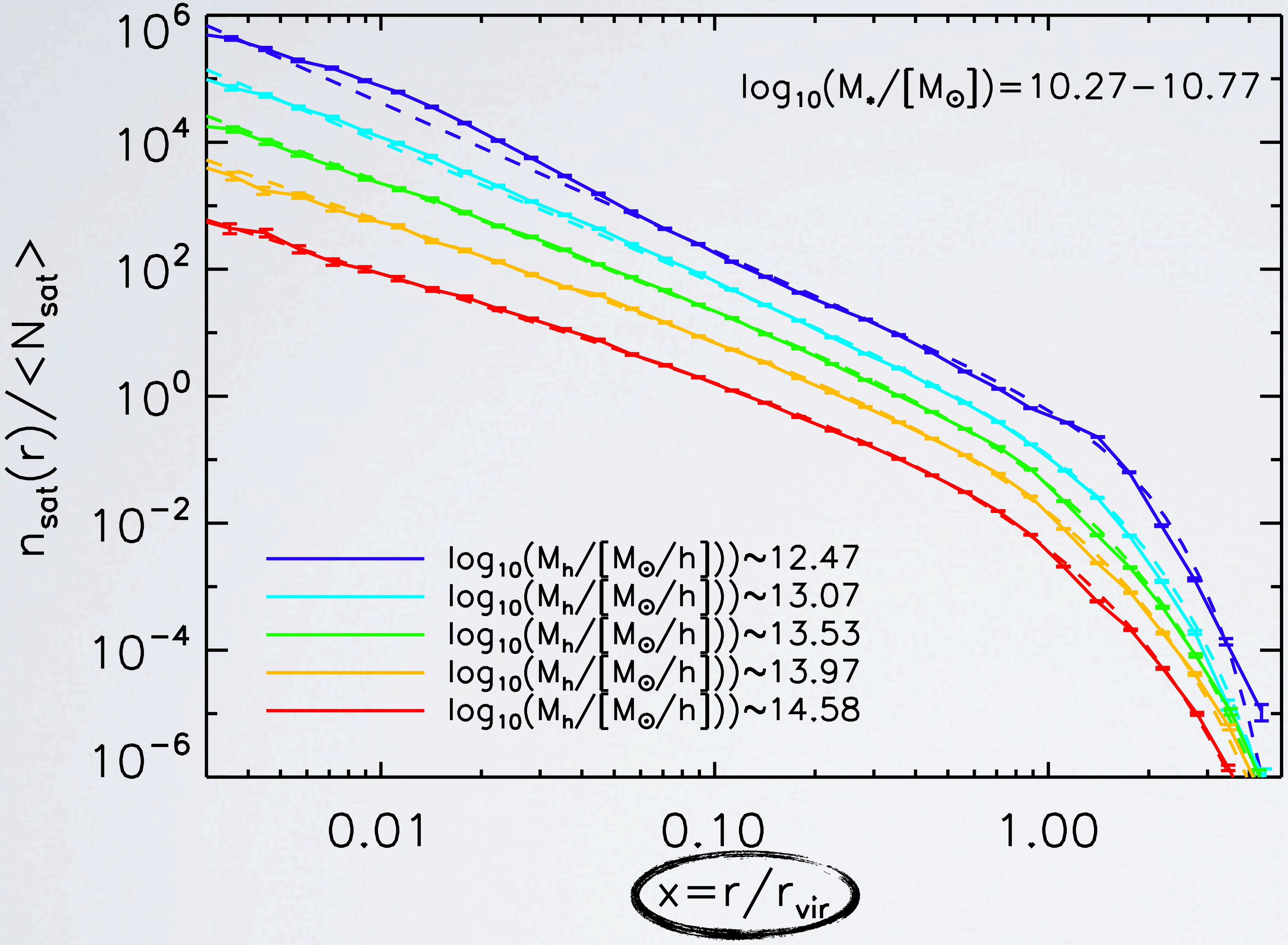
$$\int n(M)\frac{\langle N_{sat}(N_{sat}-1)|M\rangle}{\bar{n}^2_{gal}}[u_{gal}(k|M)^2-W_R(k)^2]\,\mathrm{d}M$$

$$P^{2h}_{gal}(k) = P_{lin}(k)\left[\int n(M)b(M)\frac{\langle N_{cen}|M\rangle}{\bar{n}_{gal}}\mathrm{d}M + \right.$$

$$\left.\int n(M)b(M)\frac{\langle N_{sat}|M\rangle}{\bar{n}_{gal}}u_{gal}(k|M)\mathrm{d}M\right]^2$$

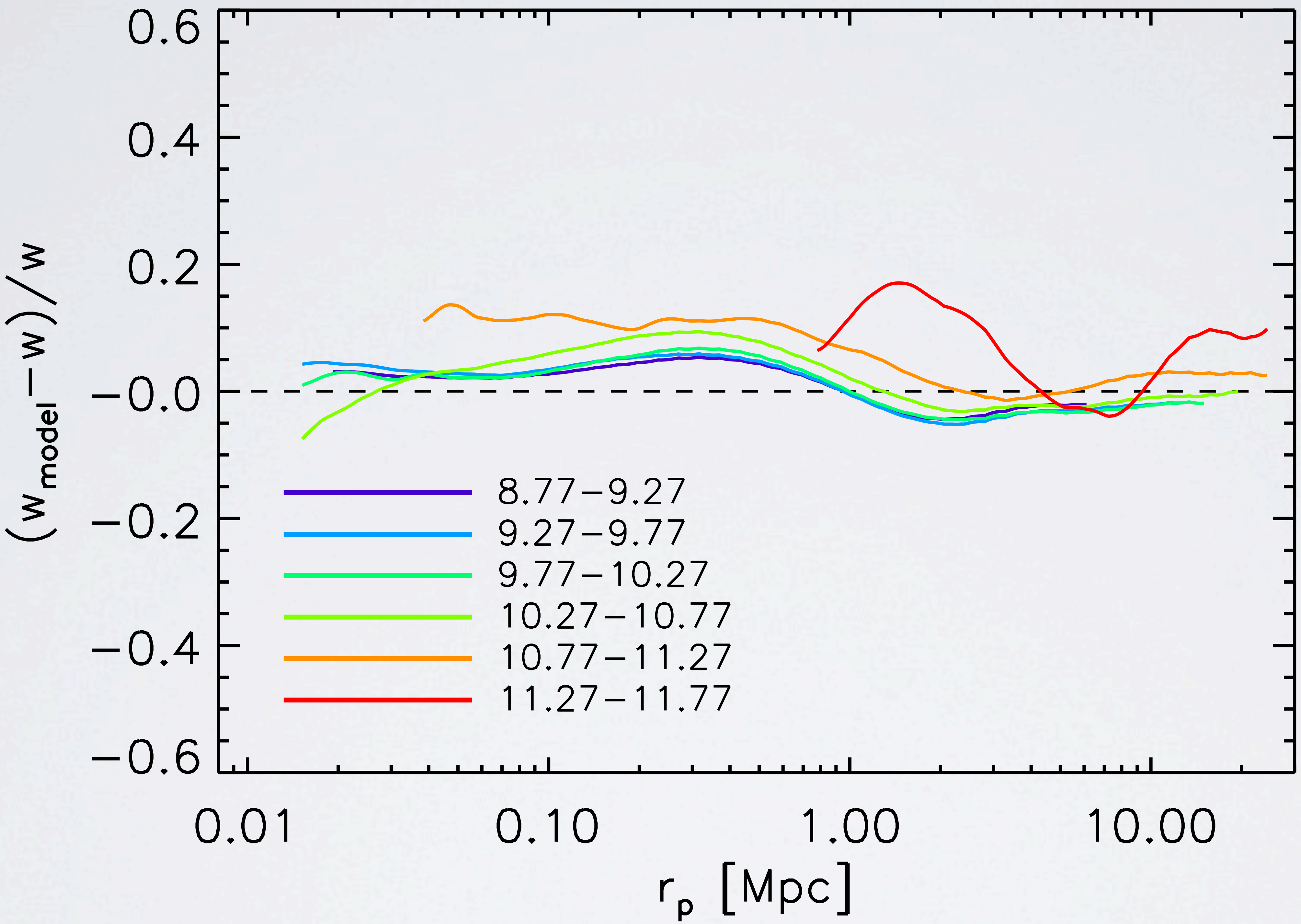
+ corrections!

SATELLITE PROFILE

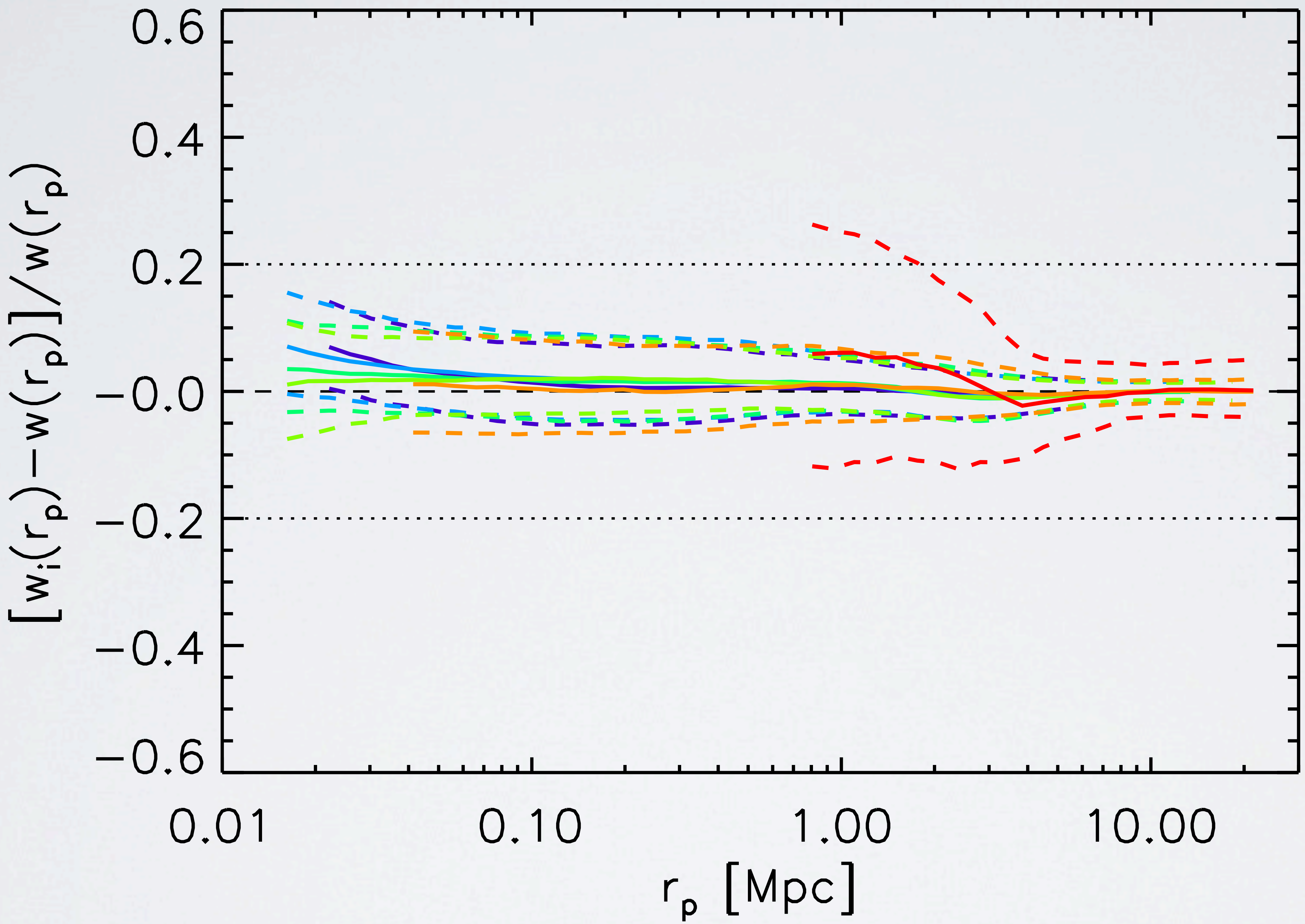


$$\frac{n_{\rm sat}(r)}{\langle N_{\rm sat}\rangle} \propto \left(\frac{x}{b}\right)^{a-3} \exp\left\{-\left(\frac{x}{b}\right)^{c}\right\}$$

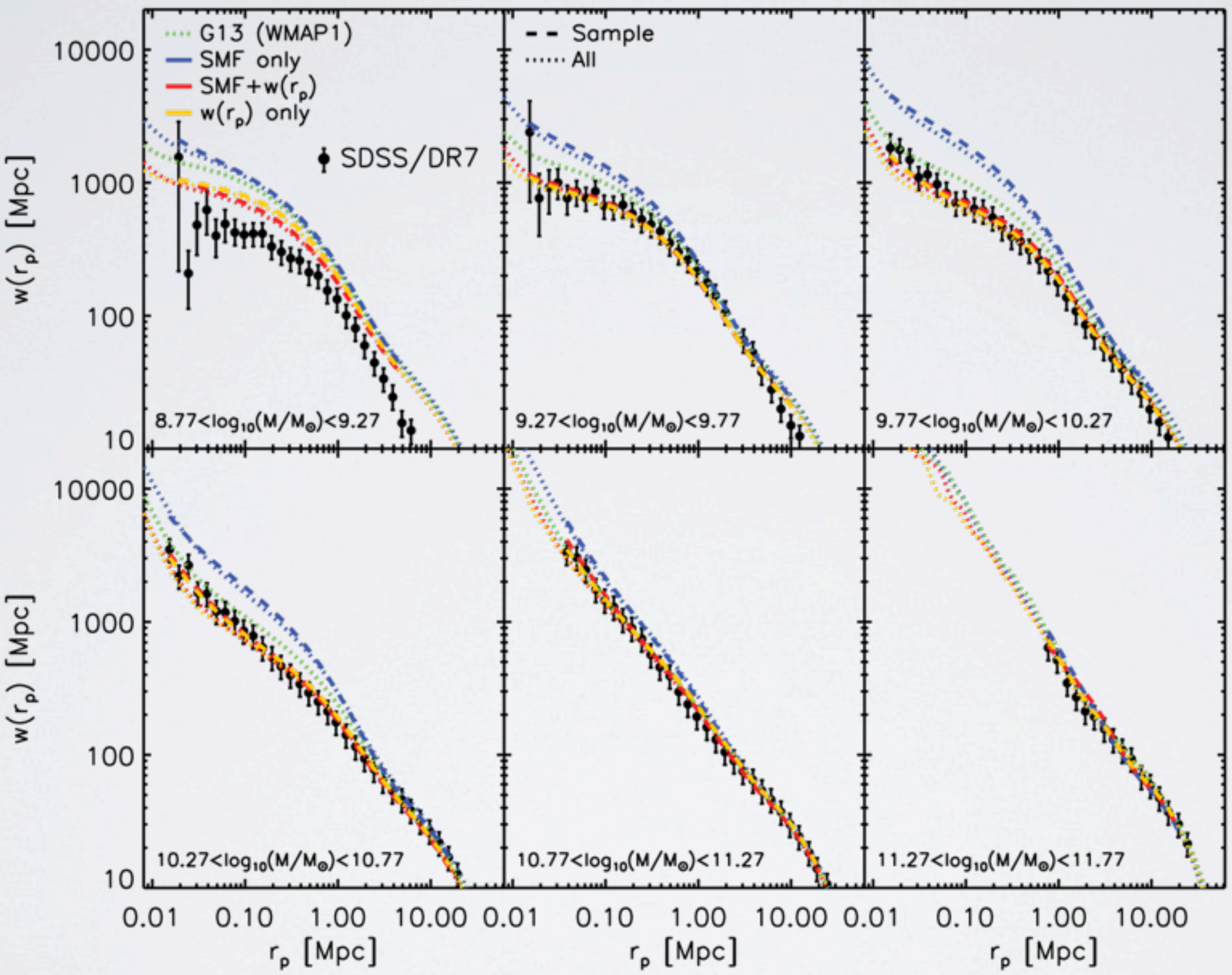
ESTIMATOR ACCURACY



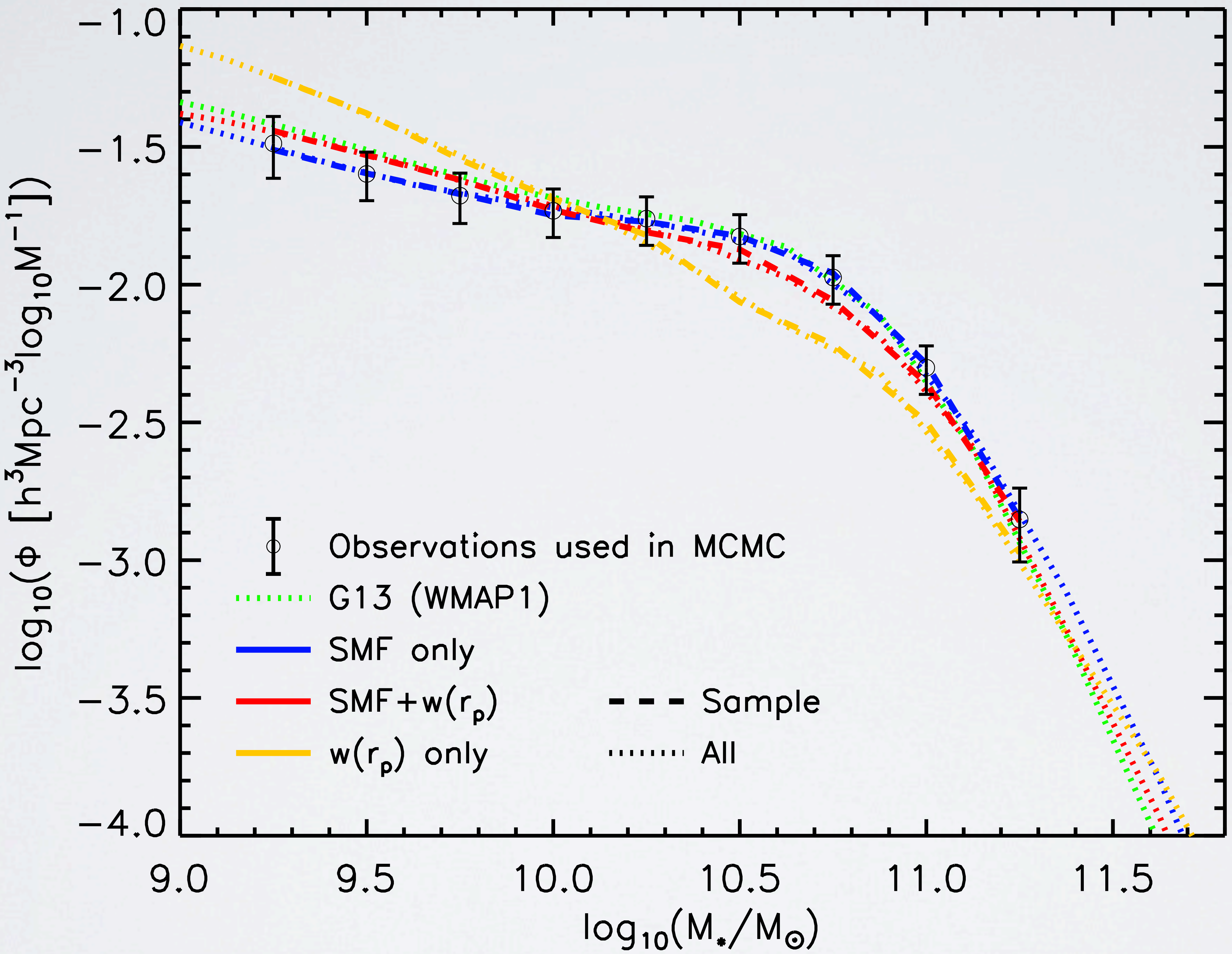
ESTIMATOR ACCURACY



RESULTS

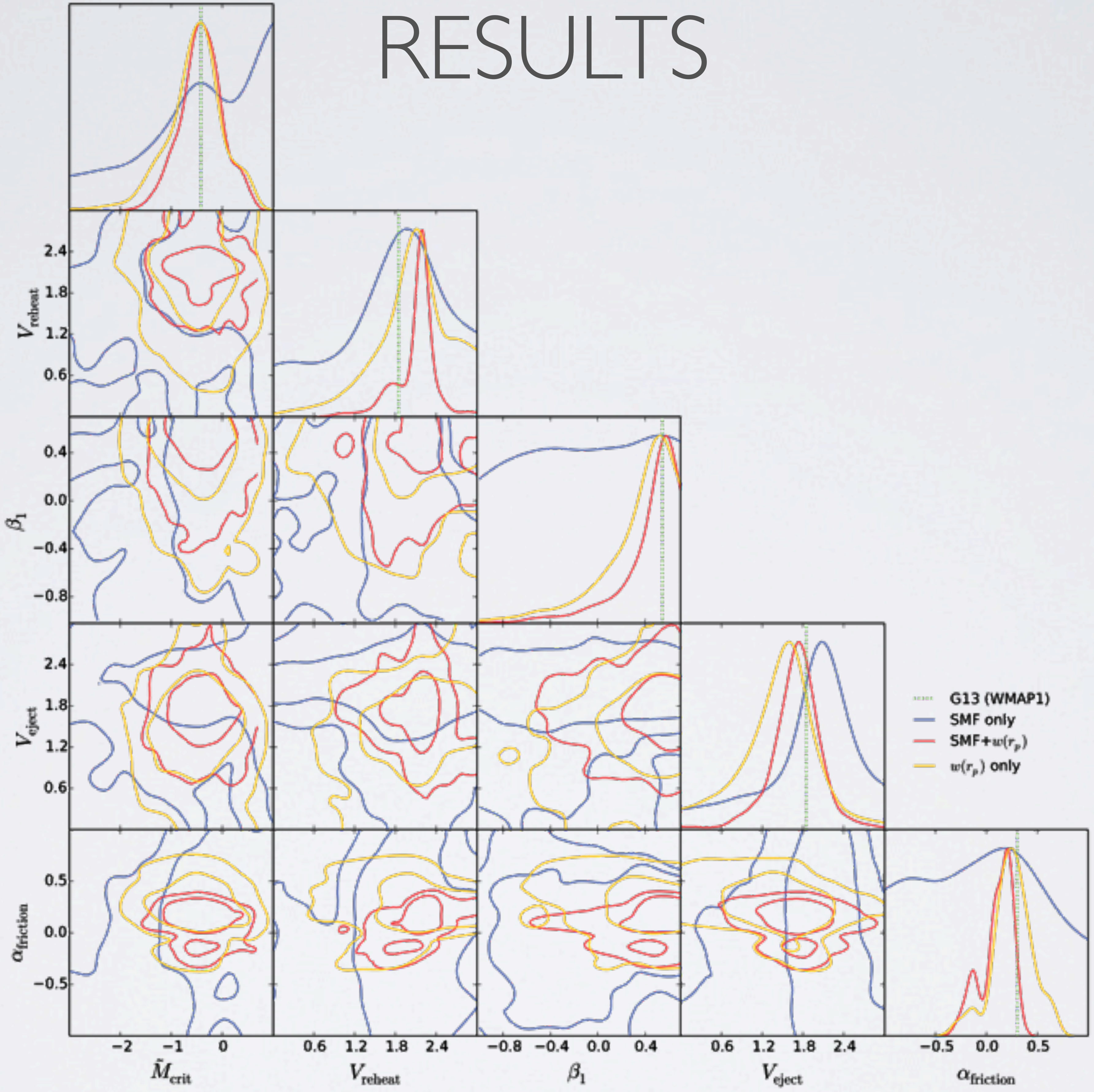

G13 (WMAP1)
SMF only
SMF+w(r_p)
w(r_p) only
SDSS/DR7
Sample
All
$8.77<\log_{10}(M/M_\odot)<9.27$
$9.27<\log_{10}(M/M_\odot)<9.77$
$9.77<\log_{10}(M/M_\odot)<10.27$
$10.27<\log_{10}(M/M_\odot)<10.77$
$10.77<\log_{10}(M/M_\odot)<11.27$
$11.27<\log_{10}(M/M_\odot)<11.77$
w(r_p) [Mpc]
r_p [Mpc]
10000
1000
100
10
0.01
0.10
1.00
10.00

RESULTS



−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
$\log_{10}(\Phi\ [h^3 Mpc^{-3} \log_{10} M^{-1}])$
9.0
9.5
10.0
10.5
11.0
11.5
$\log_{10}(M_*/M_\odot)$
Observations used in MCMC
G13 (WMAP1)
SMF only
SMF+w(r_p)
w(r_p) only
Sample
All

RESULTS



G13 (WMAP1)
SMF only
SMF+$w(r_p)$
$w(r_p)$ only
$\tilde{M}_{crit}$
V_{reheat}
β_1
V_{eject}
$\alpha_{friction}$

HOW THE ESTIMATOR WORKS

`mcmc.c`, main function

`initialize_halomodel()`

```
#ifdef MCMC
void Senna()
{
  int ii, jj, snap, IndividualAcceptRate = 0, TotAcceptRate = 0;
  FILE *fmcmc;
  char buf[1000];
  char DirNum;
  time_t local_initial, final;
  double lhood2, qratio, AcceptanceProbability, ran;
  int AcceptanceLogic;

  if(ThisTask==0)
  {
        printf("\n\n\n");
        printf("************************************************************\n");
        printf("*                                                          *\n");
        printf("*                      Starting Senna                      *\n");
        printf("*                                                          *\n");
        printf("*                 MCMC parameter estimation                *\n");
        printf("*  Applied to a Semi-Analytic Model of Galaxy Formation    *\n");
        printf("*                                                          *\n");
        printf("************************************************************\n\n");
  }

  MCMCseed = -((ThisTask+FirstChainNumber) * 100 + 25);

#ifdef HALOMODEL //to compute correlation function for MCMC
  initialize_halomodel();
  printf("halo model initialized\n");
#endif
```

HOW THE ESTIMATOR WORKS

- `initialize_halomodel` reads in the linear power spectrum, FoF mass function, and power spectrum corrections, scales these with cosmology, and spline-interpolates them

- In `mcmc_likelihood.c`, at each step in the chain, `correct_for_correlation` is called (line 113 ➔ 781)

- This ensures the centrals are indexed, and each FoF group knows how many satellites follow

- Finally, `compute_correlation_func` is called for each stellar mass bin, which in turns calls `halomodel` (the main estimator function) and outputs the result (lines 216-227➔ line 847) – which is then given a χ^2 value by comparing to observations

HOW THE ESTIMATOR WORKS

`mcmc_halomodel.c`

RUNNING THE ESTIMATOR

- Setup:
    - Download "Representative sample of trees for clustering+MCMC mode" (4.44GB), **put files in folders indicated in readme.txt files**
    - In `Makefile`, make sure `include My_Makefile_options_MCMC` is active
    - In `My_Makefile_options_MCMC`, check that:
        - `OPT += -DNOUT=1`
        - `OPT += -DGUO13`
        - `OPT += -DMCMC`
        - `OPT += -DHALOMODEL`
    - Below the latter, add: `OPT += -DPROJLIMITS`
    - Run `Make`
    - Change `FileWithOutputRedshifts` in the input file (below) to `input/MCMC_inputs/desired_output_redshifts_for_MCMC_Halomodel.txt`
    - Run `echo "0.0" > input/MCMC_inputs/desired_output_redshifts_for_MCMC_Halomodel.txt`
- Use `input/MCMC_inputs/input_Guo13_mcmc_halomodel_MR_W1_W1.par` as input to LGalaxies (check `input/MCMC_inputs/HaloModel_MCMCObsConstraints.txt` for 1's)