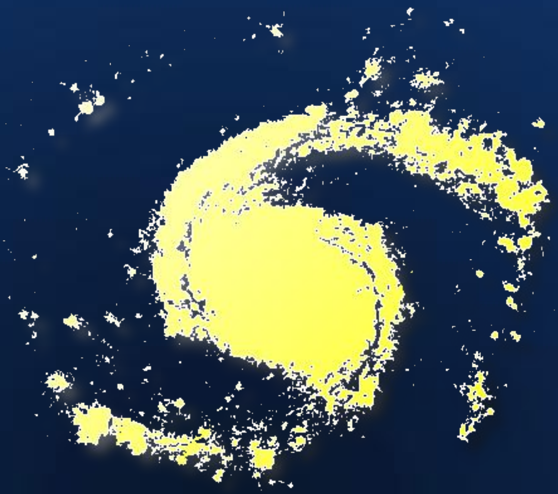
Modeling the Milky Way satellite system: moving from qualitative to quantitative

Andrew Benson



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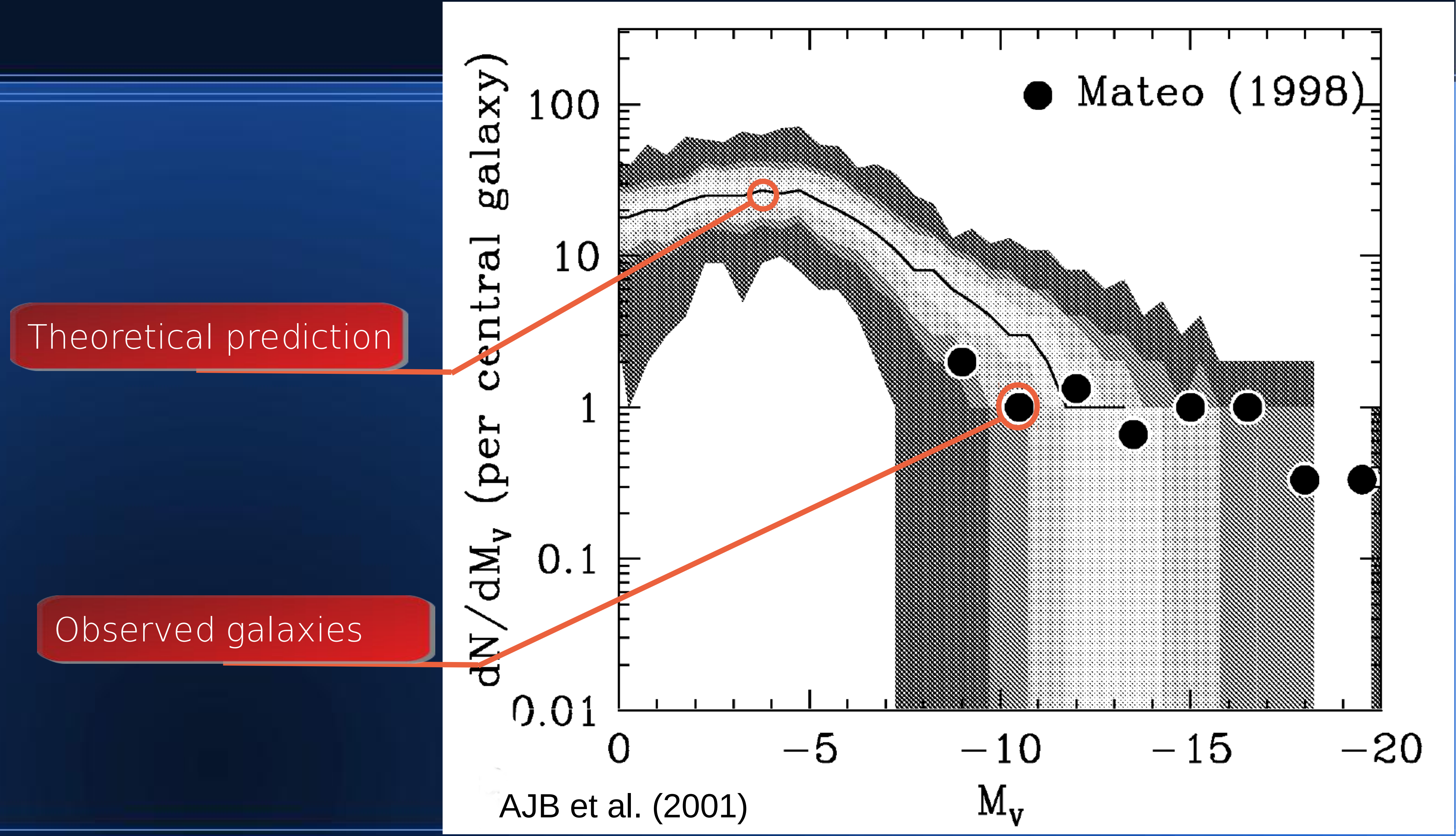
The Missing Satellites Problem



The Missing Satellites Problem

BEASTS OF THE SOUTHERN WILD. DISCOVERY OF A LARGE NUMBER OF ULTRA FAINT SATELLITES IN THE VICINITY OF THE MAGELLANIC CLOUDS.

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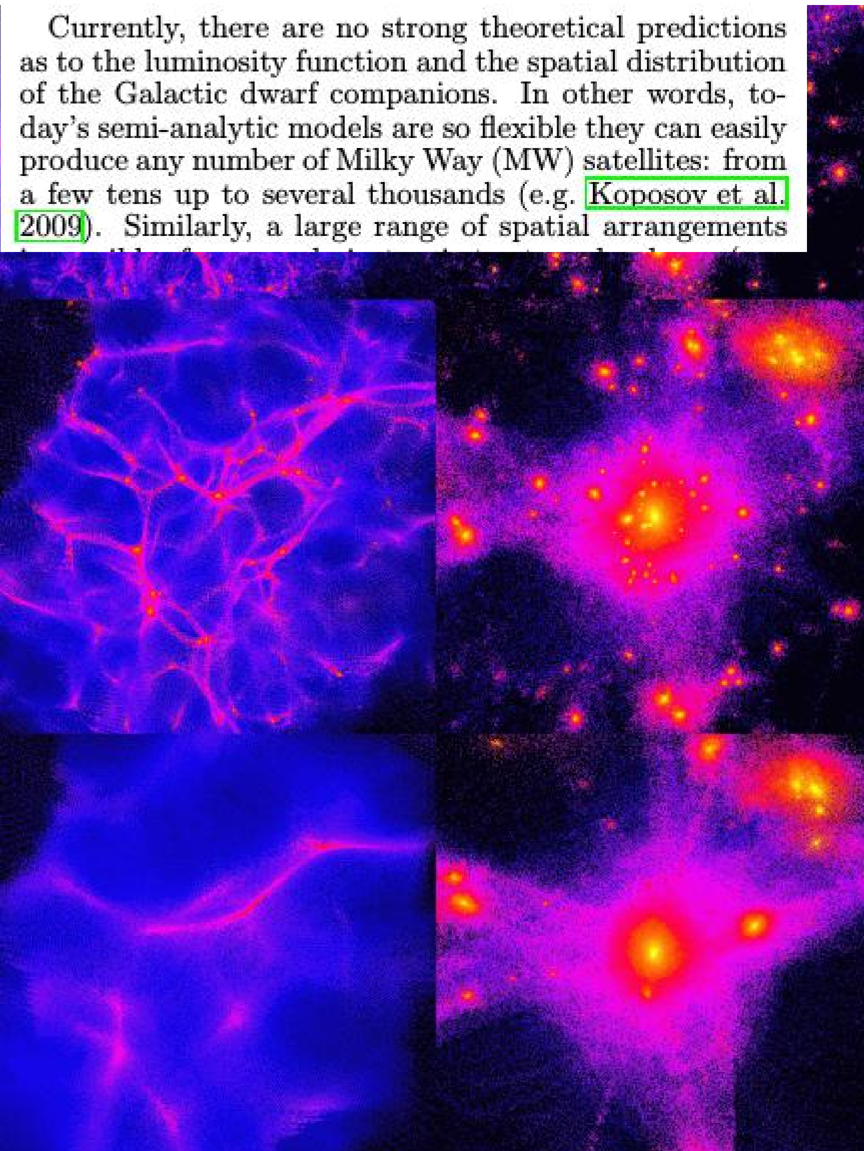
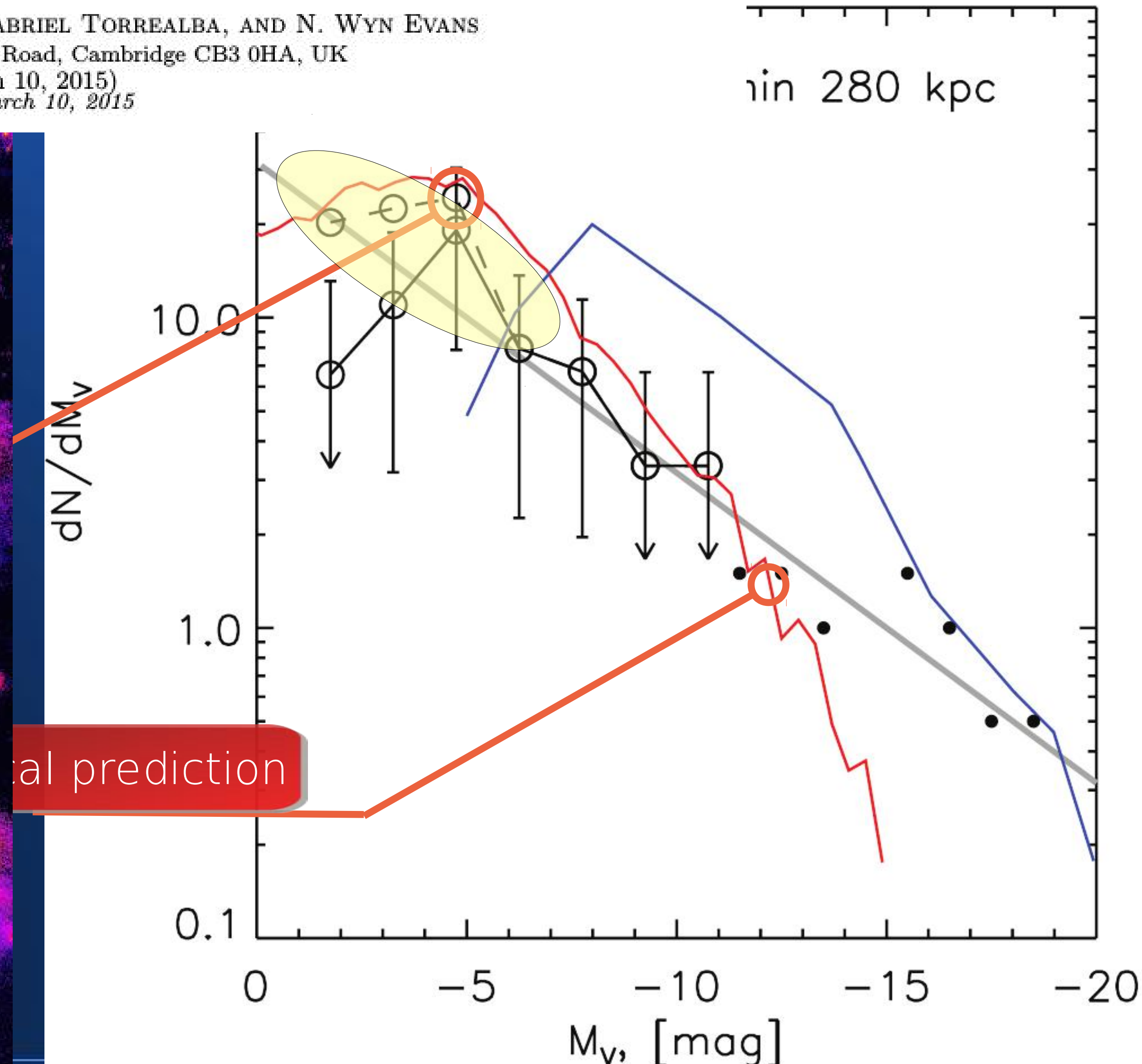
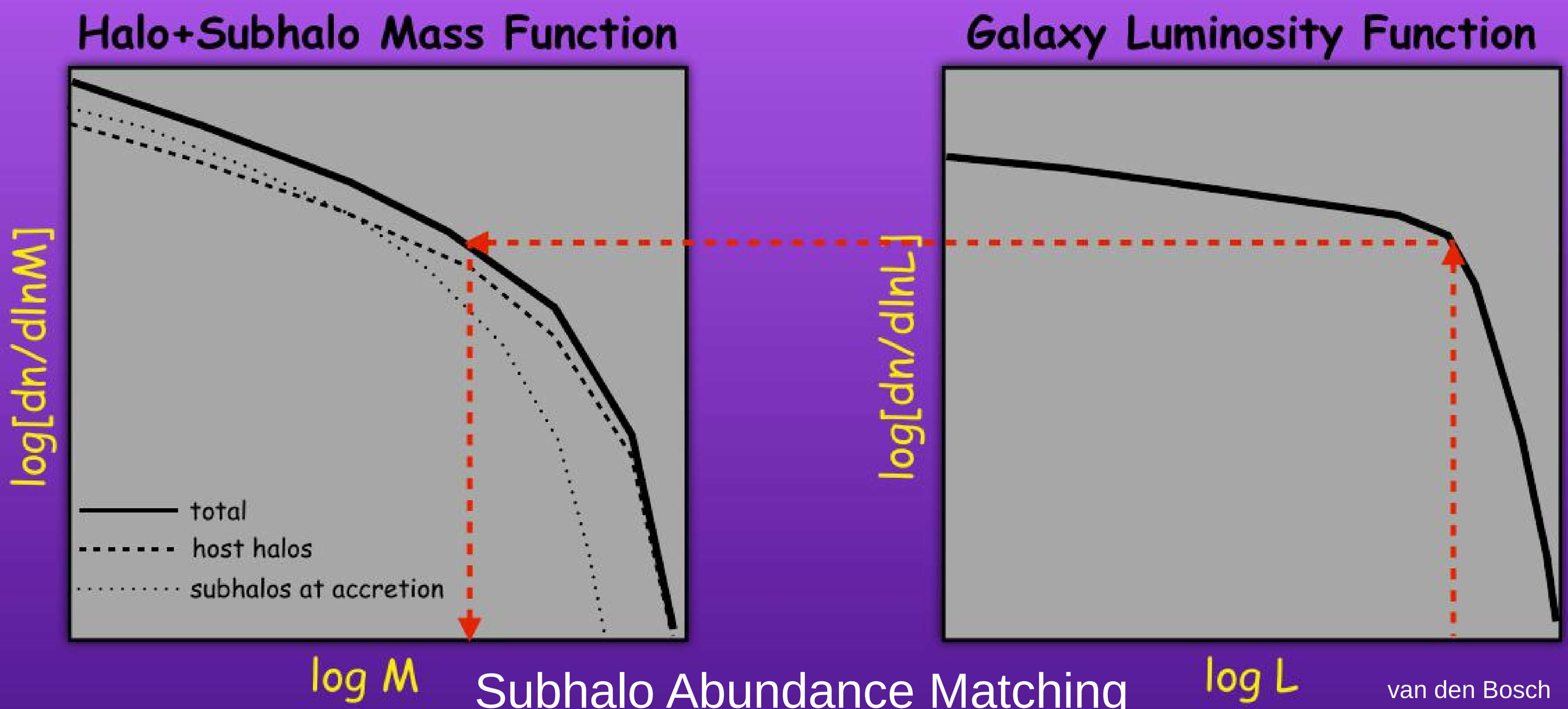
Currently, there are no strong theoretical predictions as to the luminosity function and the spatial distribution of the Galactic dwarf companions. In other words, today's semi-analytic models are so flexible they can easily produce any number of Milky Way (MW) satellites: from a few tens up to several thousands (e.g. Koposov et al. 2009). Similarly, a large range of spatial arrangements





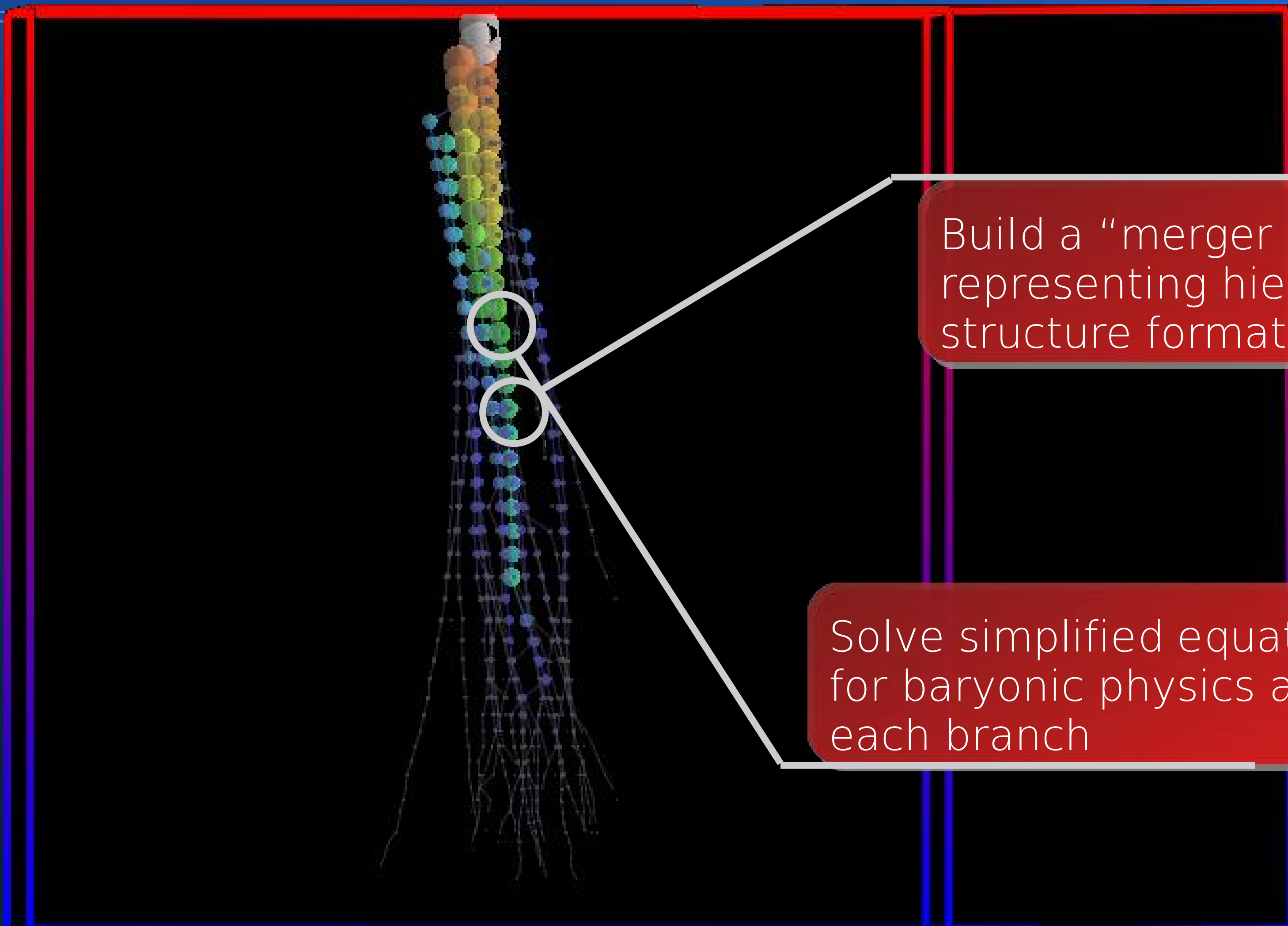
Approaches to Galaxy Formation



Subhalo Abundance Matching

van den Bosch

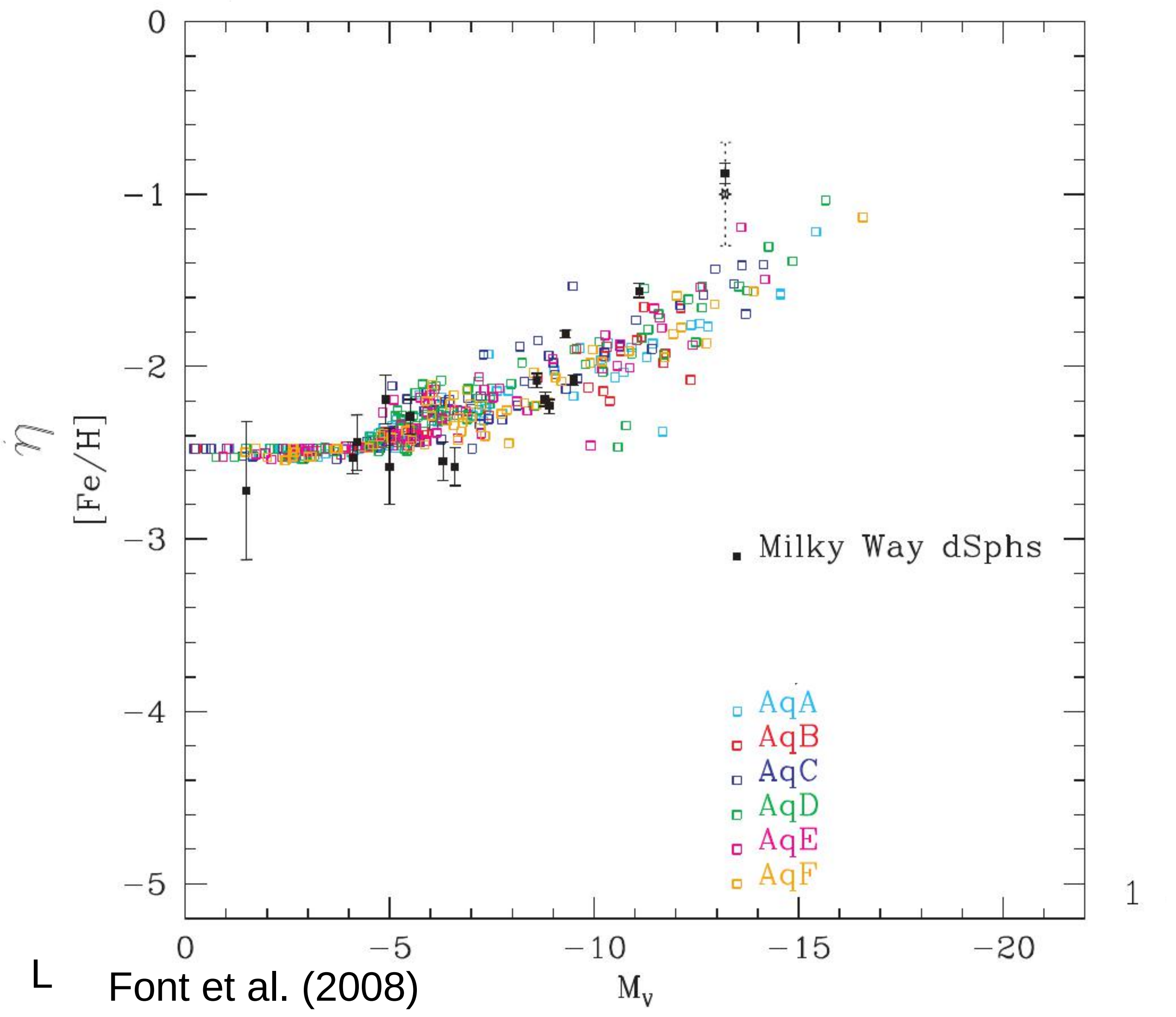
Semi-analytic Modeling



Build a “merger tree” representing hierarchical structure formation

Solve simplified equations for baryonic physics along each branch

Outflows From Galaxies

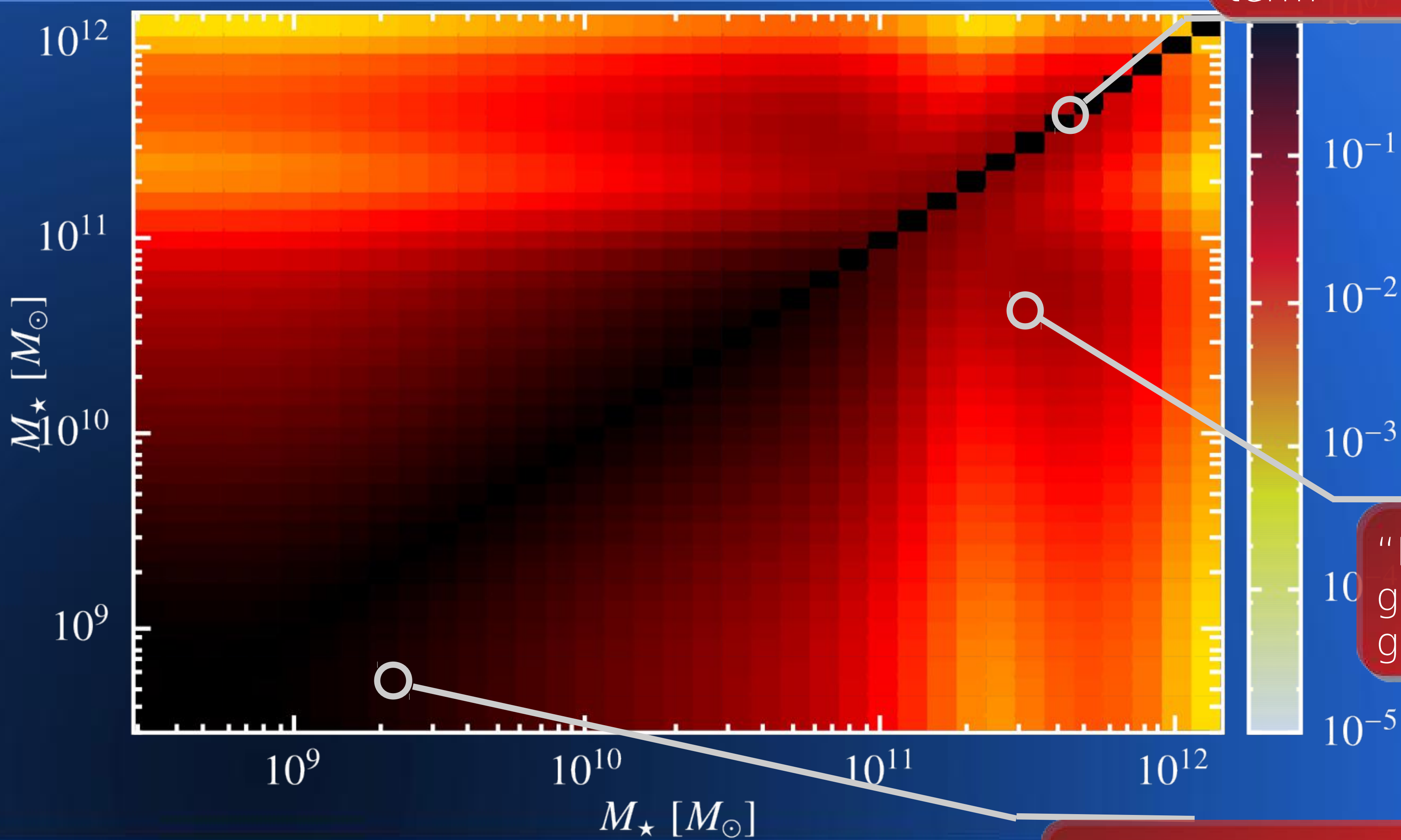


Font et al. (2008)

Likelihood, likelihood, likelihood...

- MCMC techniques powerful way to survey model parameter space
- Results only as good as the likelihood function you put in
  - Covariance
  - Systematics
- Also, your model had better be converged...

Data Covariance Model



High-mass bins dominated by Poisson term

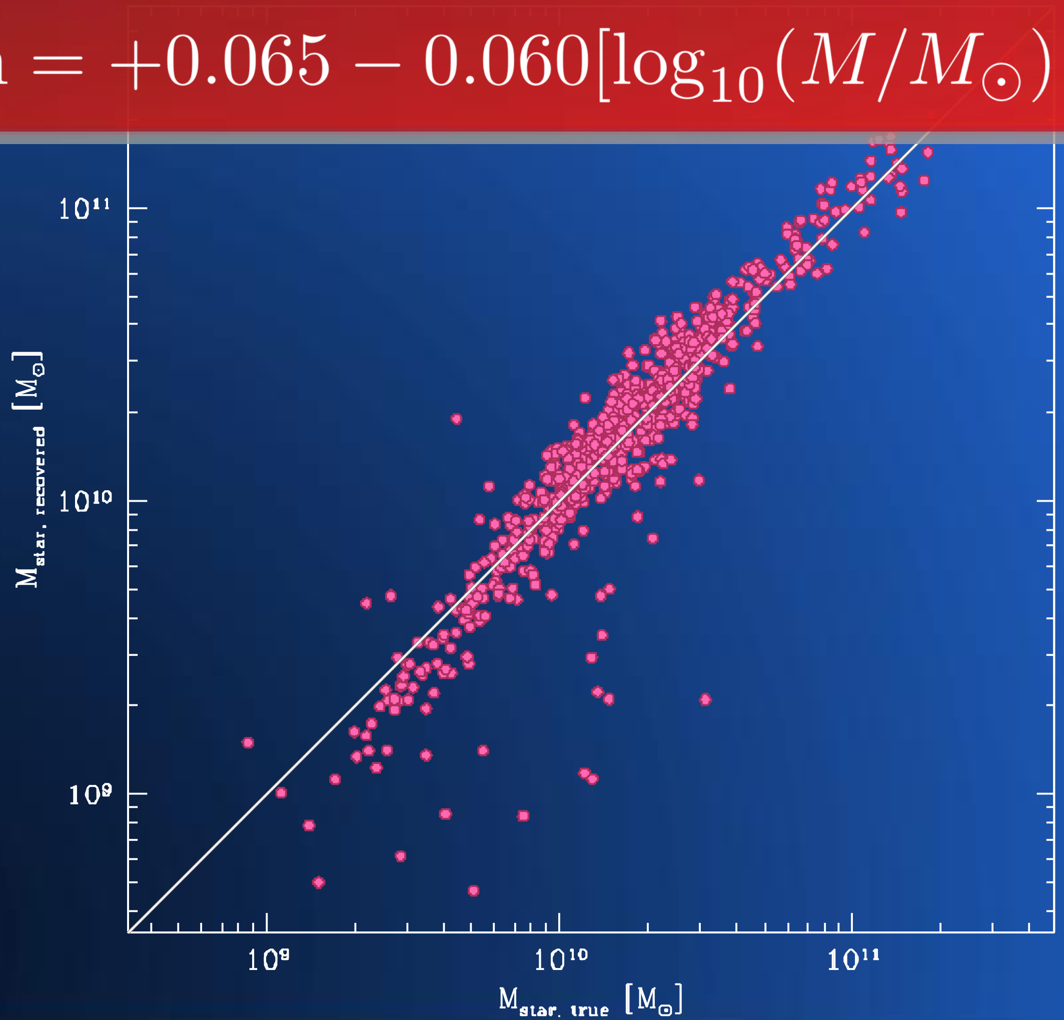
"Halo" term – galaxies live in groups/clusters

Large scale structure contribution

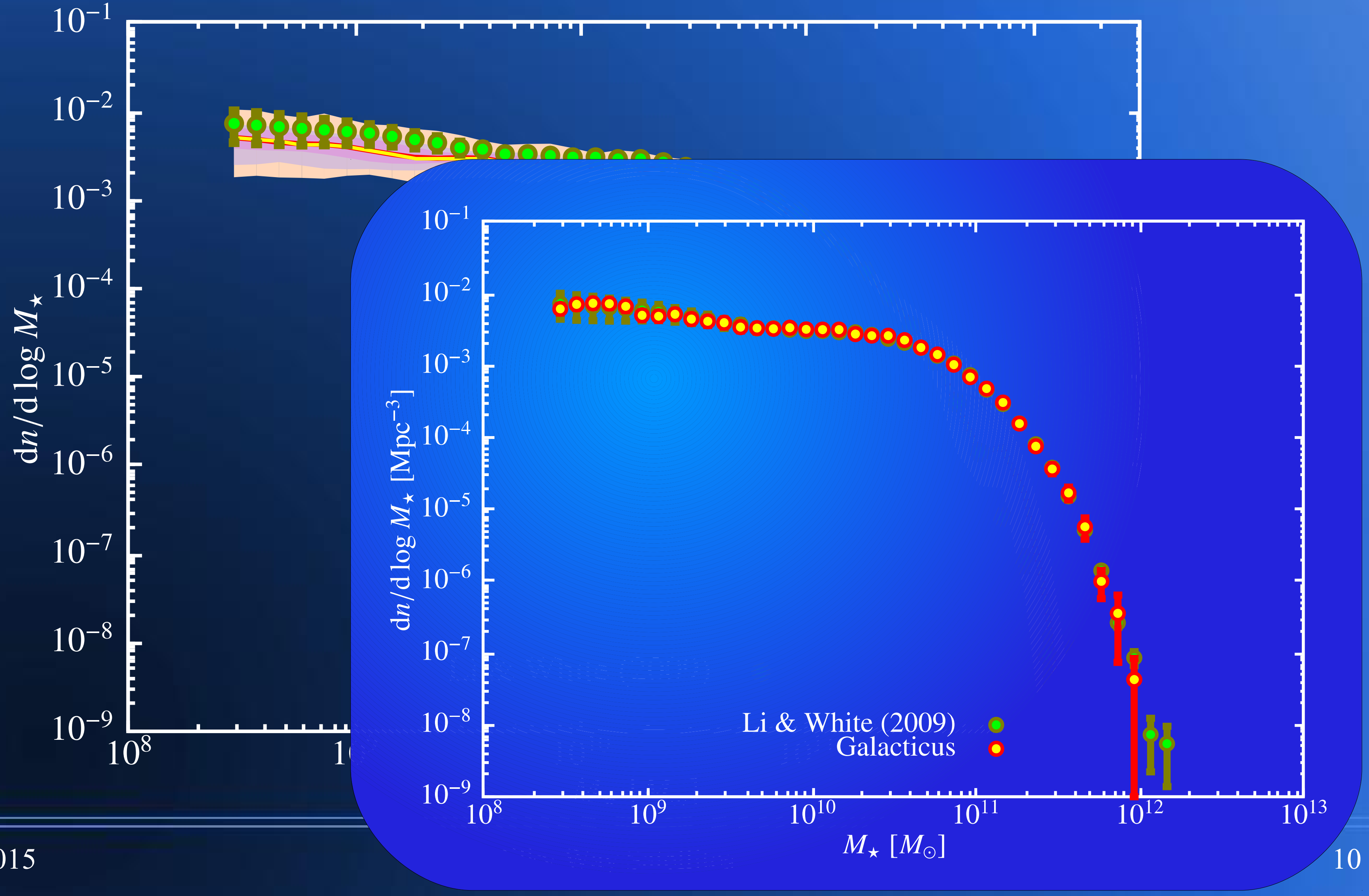
Stellar Mass Systematics

$$\Delta M_\star, \mathrm{sys} = +0.085 + 0.080[\log_{10}(M/M_\odot) - 11.3]\mathrm{dex}$$

$$\Delta M_\star, \mathrm{ran} = +0.065 - 0.060[\log_{10}(M/M_\odot) - 11.3]\mathrm{dex}$$



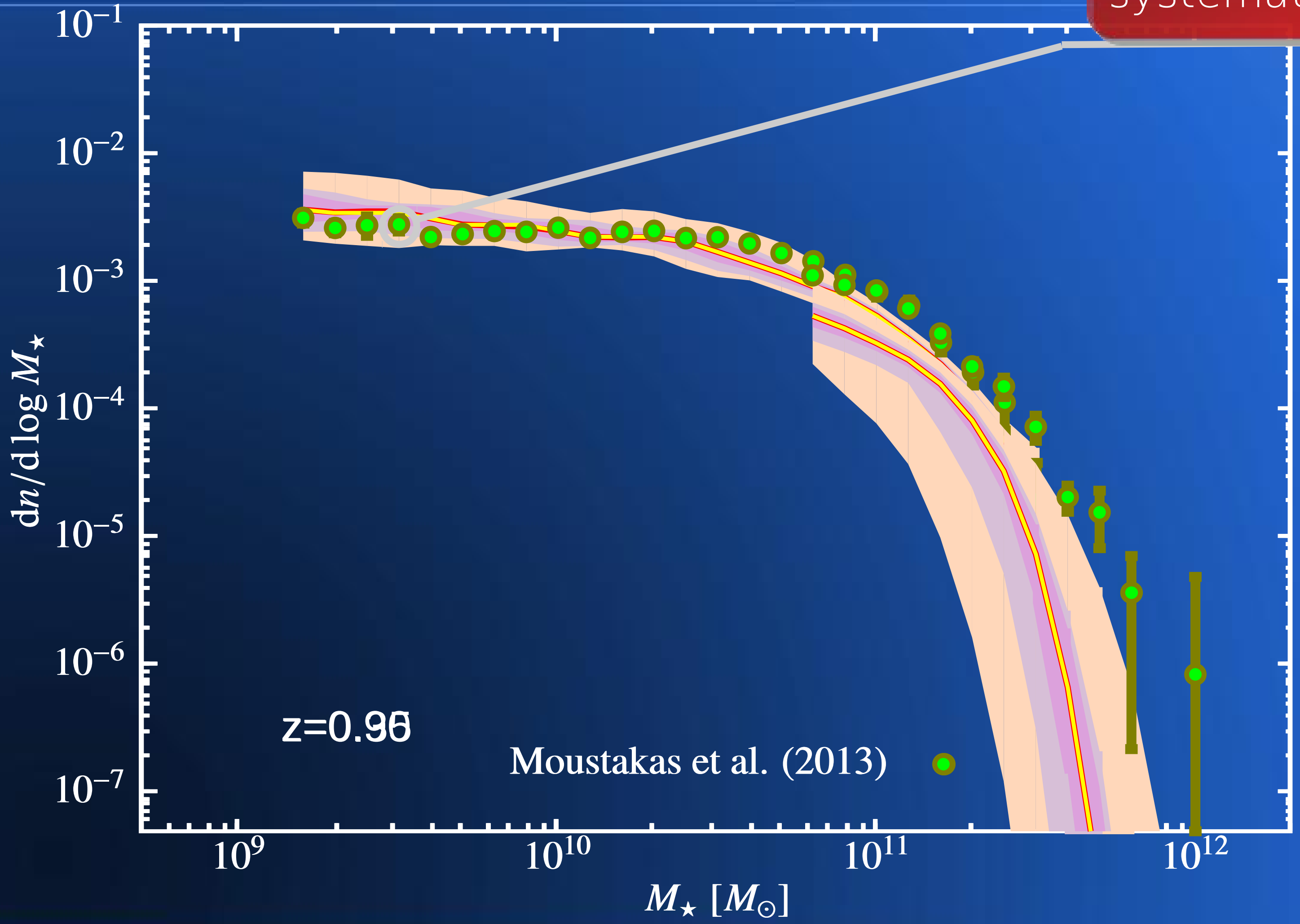
Constraints on the Model



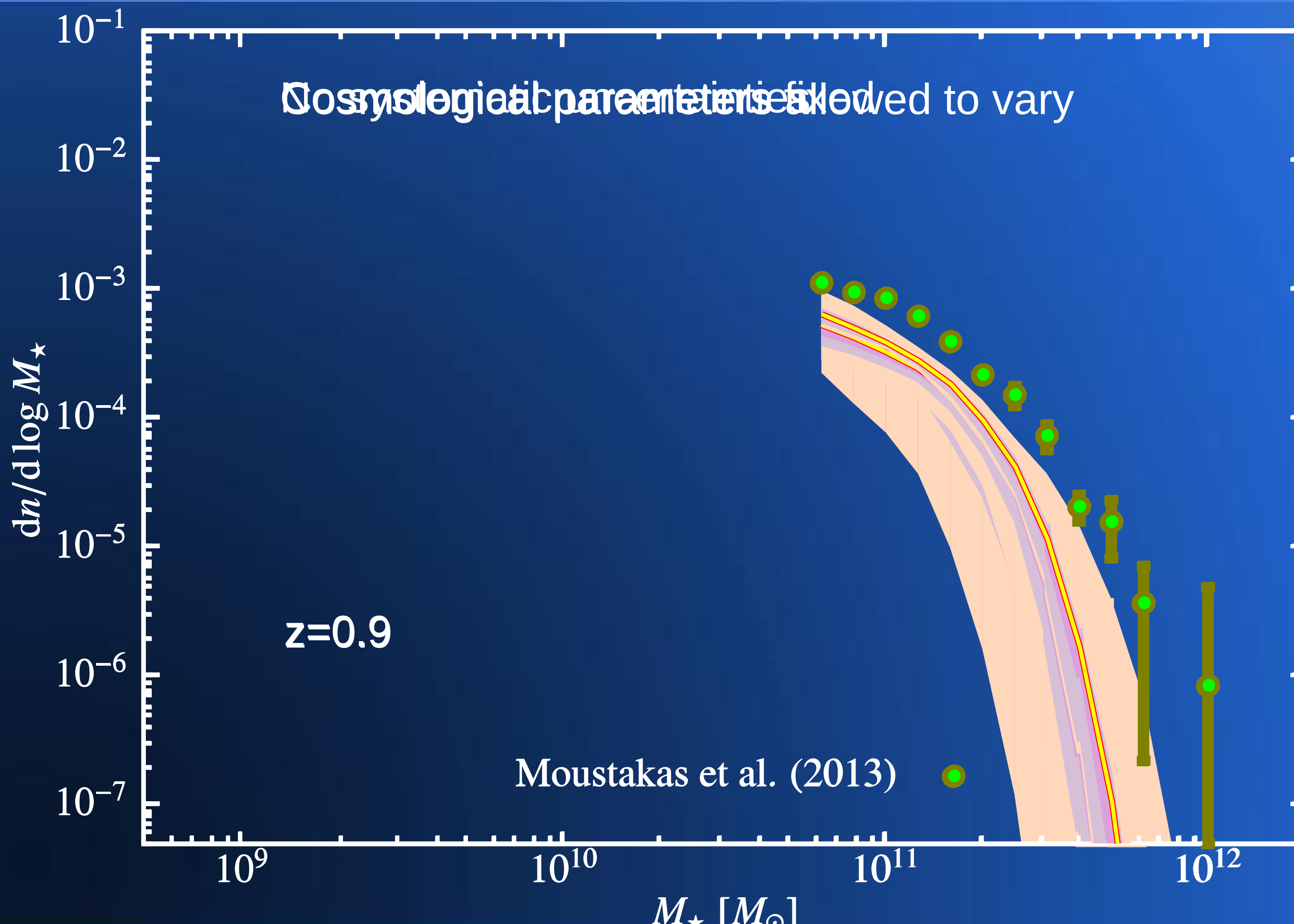
“Predictions”

Goals | Data covariance | Model | Systematics | **Constraining** | Next time.....

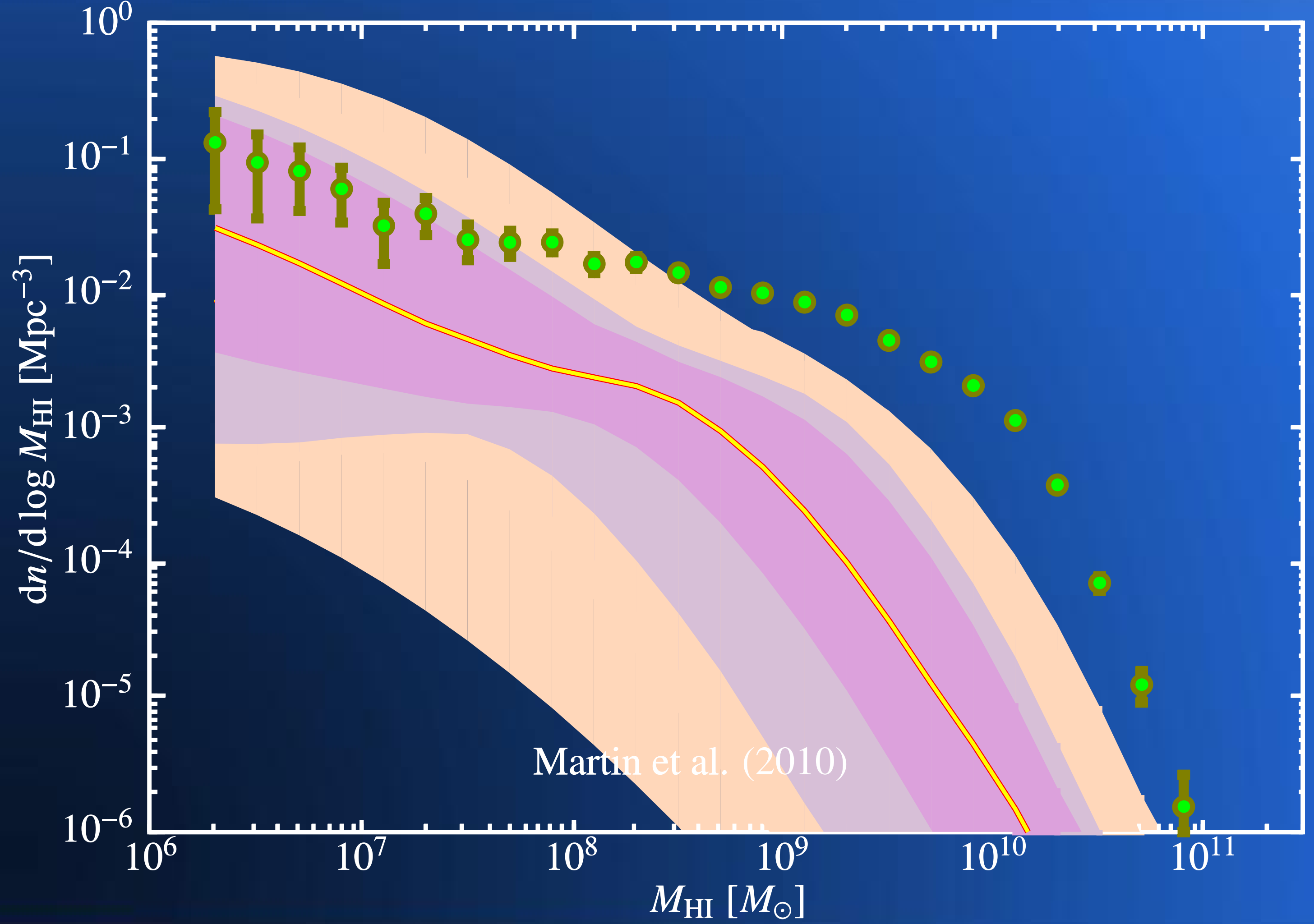
Assumes same systematics as z=0



“Predictions”



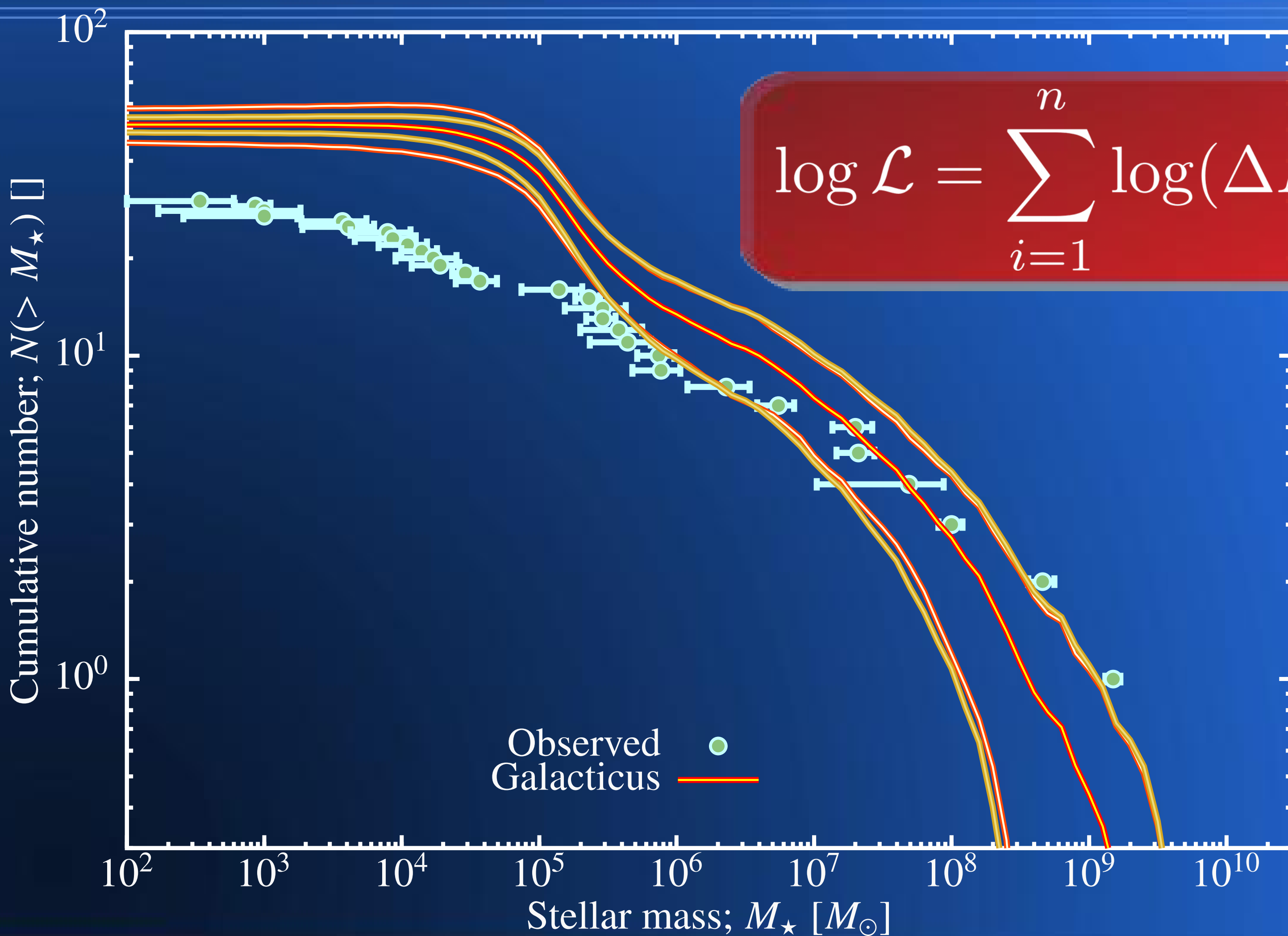
“Predictions”



What's Next?

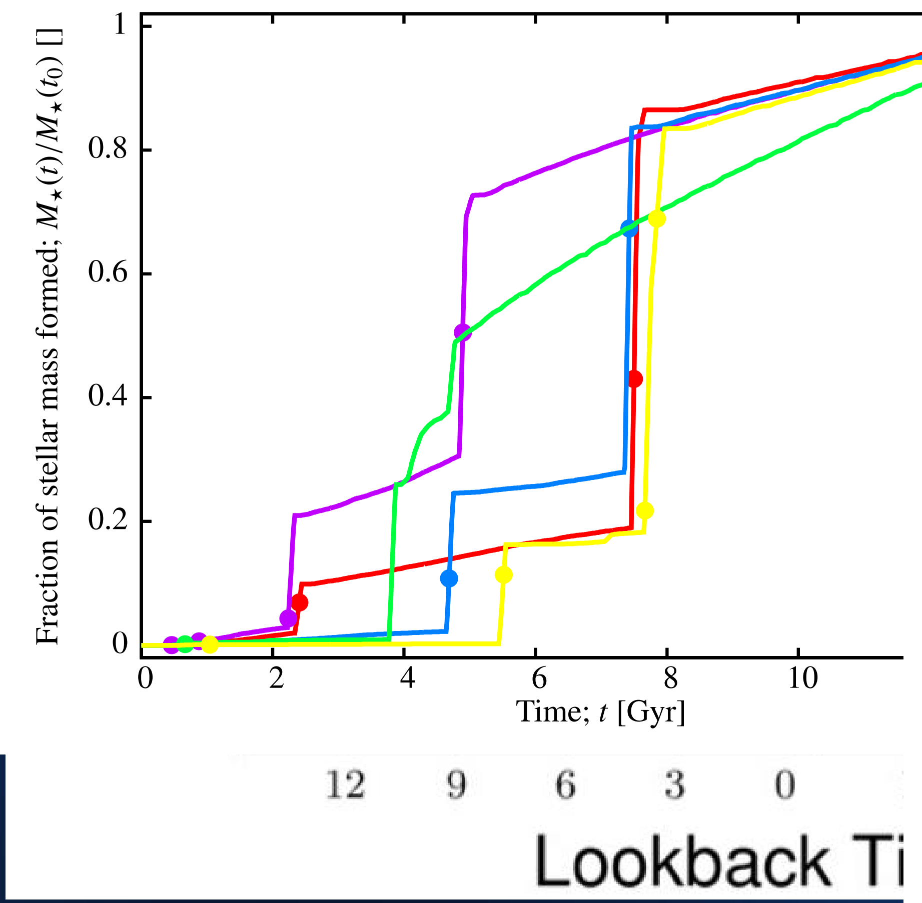
- Build a model that gets key properties
  - Mass (stars and gas)
  - Sizes
  - Densities
  - Evolution
- Introduce physics
- Can we make successful predictions?

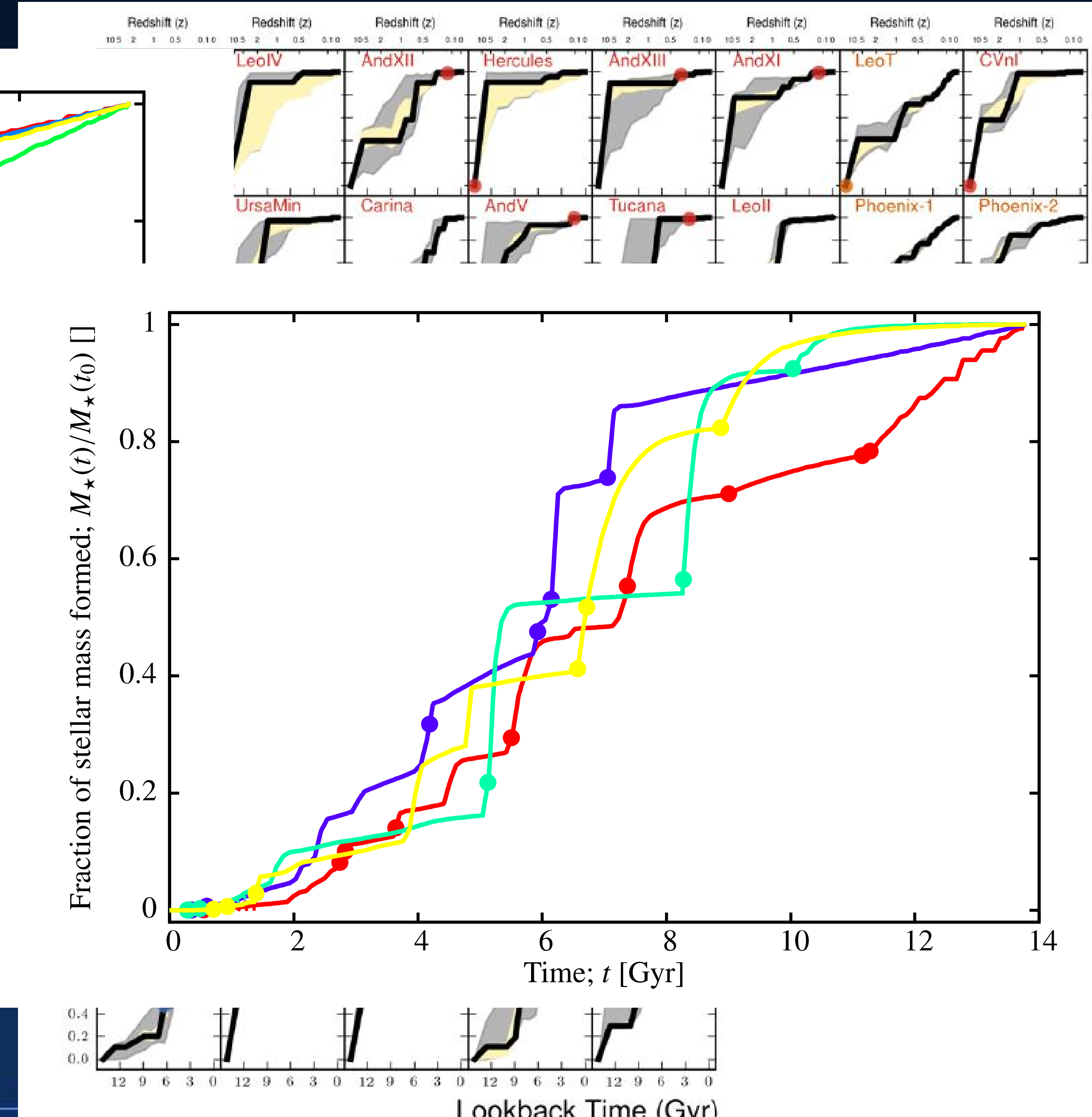
Milky Way/M31 Stellar Mass Functions



$$\log \mathcal{L} = \sum_{i=1}^{n} \log(\Delta \bar{N}_i^\prime) - \Delta \bar{N}_i^\prime$$

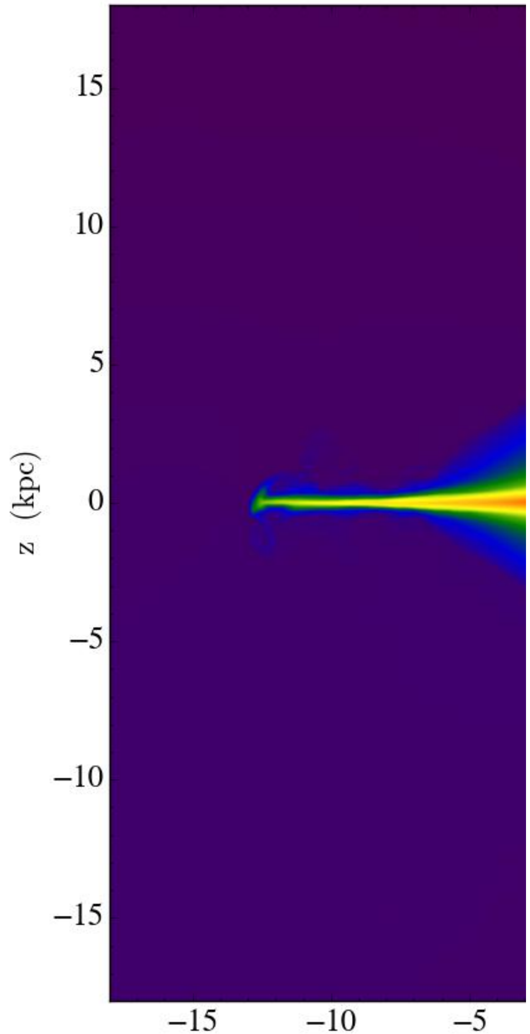
Star Formation Histories



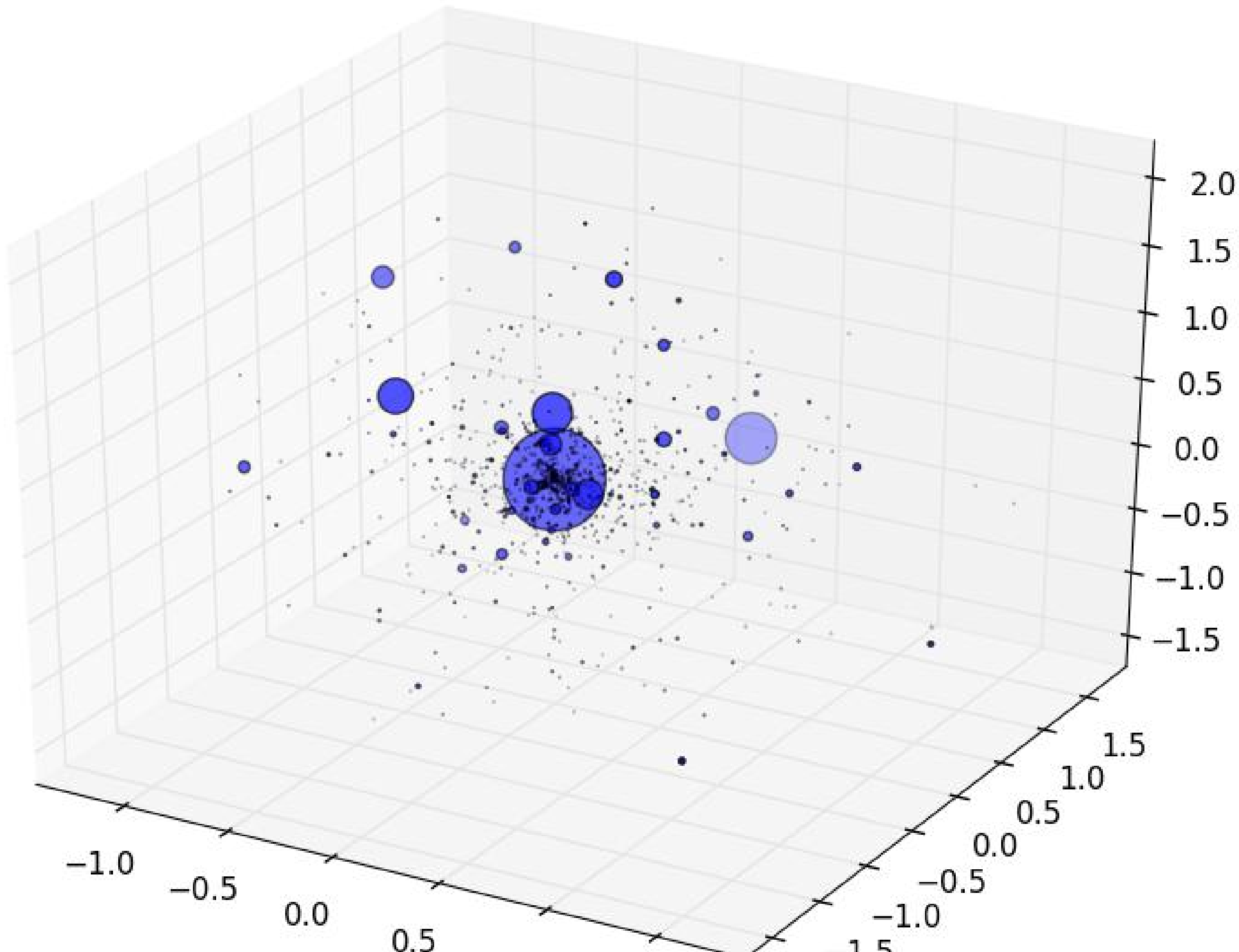


Weisz et al. (2014)

Ram Pressure Stripping



Tonneson

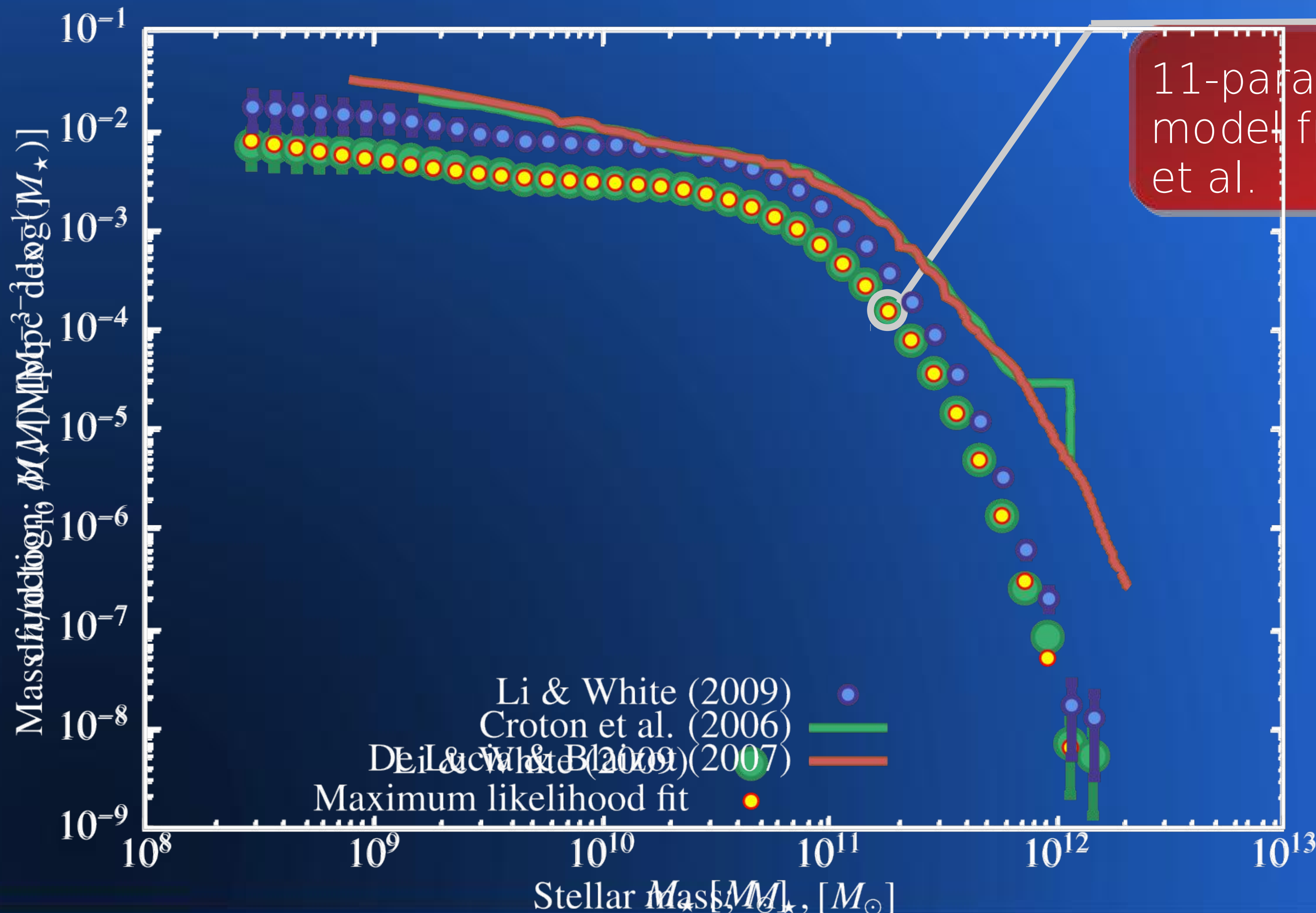


Pullen, Moustakas, AJB (2014)

Summary

- SAMs + MCMC
  - Powerful method to fit observational data
- Crucial to account for
  - Covariance
  - Random errors (data and model)
  - Systematics (data and model)
- Next step: predictions and model testing

Data Covariance Model



11-parameter HOD model from Behzroozi et al.

Data Covariance Model

$$C_{\mu\nu} = \phi_\mu \phi_\nu b^{\rm g}_\mu b^{\rm g}_\nu \sigma^2_{\rm v} + \frac{\phi_\mu \delta^{\rm K}_{\mu,\nu}}{V_{\rm s} \log M^\star_\mu} + \Sigma_{\mu\nu}$$

$$\sigma^2_{\rm v} = \int \frac{{\rm d}^3\mathbf{k}}{(2\pi)^3} |W(\mathbf{k})|^2 P(k)$$

Poisson term

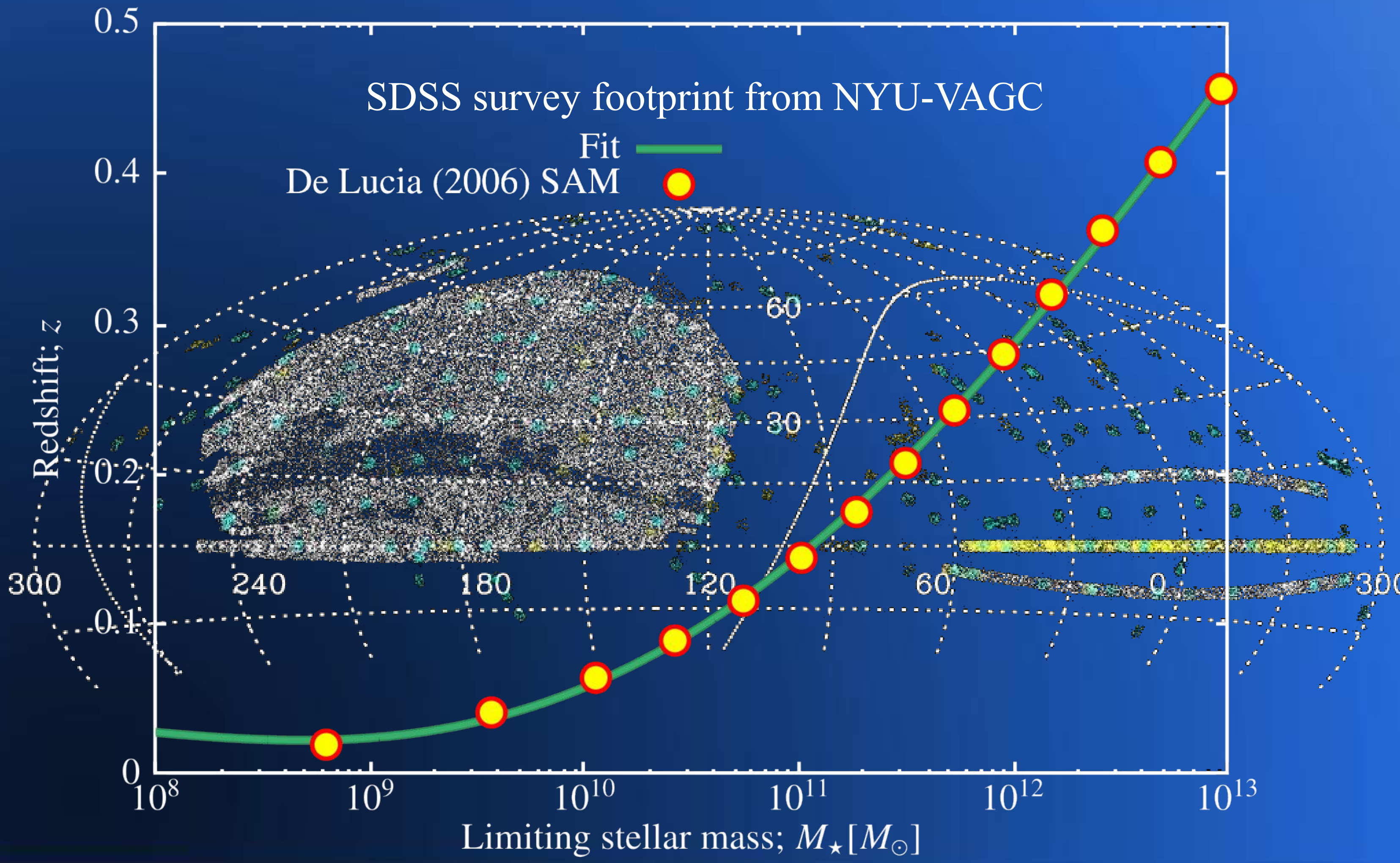
Halo/grouping term

Large scale structure

$$\Sigma_{\mu\nu} = \frac{1}{V_{\rm s}} \int {\rm d}M_1 n(M_1) \Phi(M^\star_\mu|M_1) \Phi(M_\nu|M_1)$$

Smith (2012)

Data Covariance Model



Model: Differential Evolution

$$\dot{M}_{\rm hot} = \dot{M}_{\rm IGM} - \dot{M}_{\rm cool} + \dot{M}_{\rm wind}$$

$$\dot{M}_{\rm ISM} = + \dot{M}_{\rm cool} - \dot{M}_{\rm wind} - \dot{M}_{\rm sf}$$

$$\dot{M}_{\star} = + \dot{M}_{\rm sf}$$

Model: Punctuated Evolution

"Strangulation"

$$M_{\rm hot,host} \rightarrow M_{\rm hot,host} + M_{\rm hot,subhalo}$$
$$M_{\rm hot,subhalo} \rightarrow 0$$

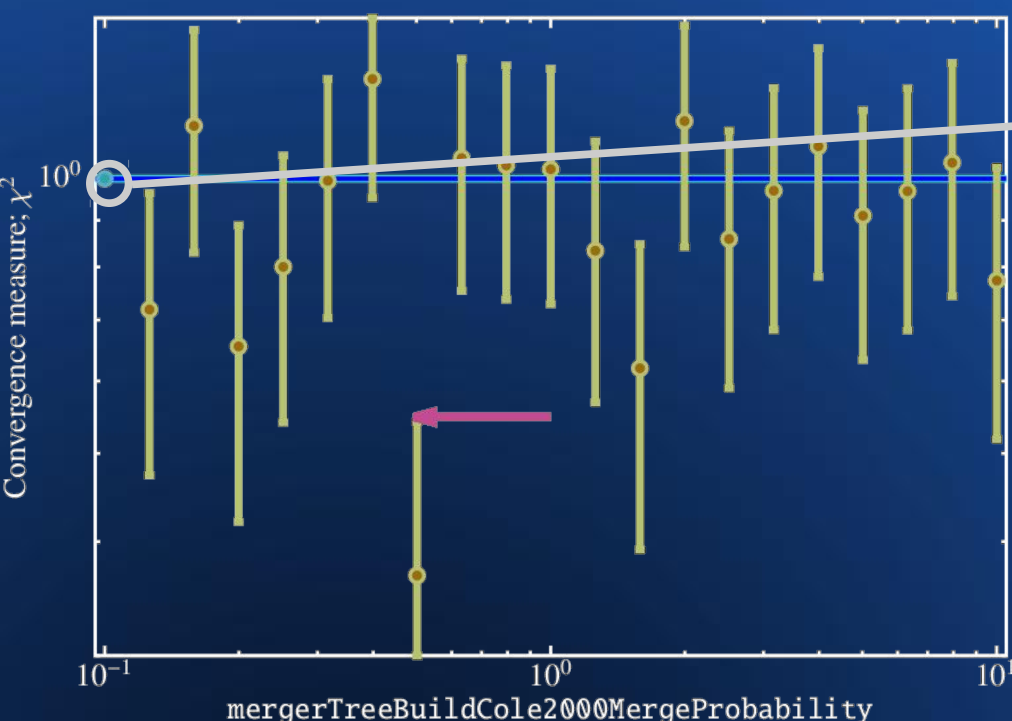
Merging

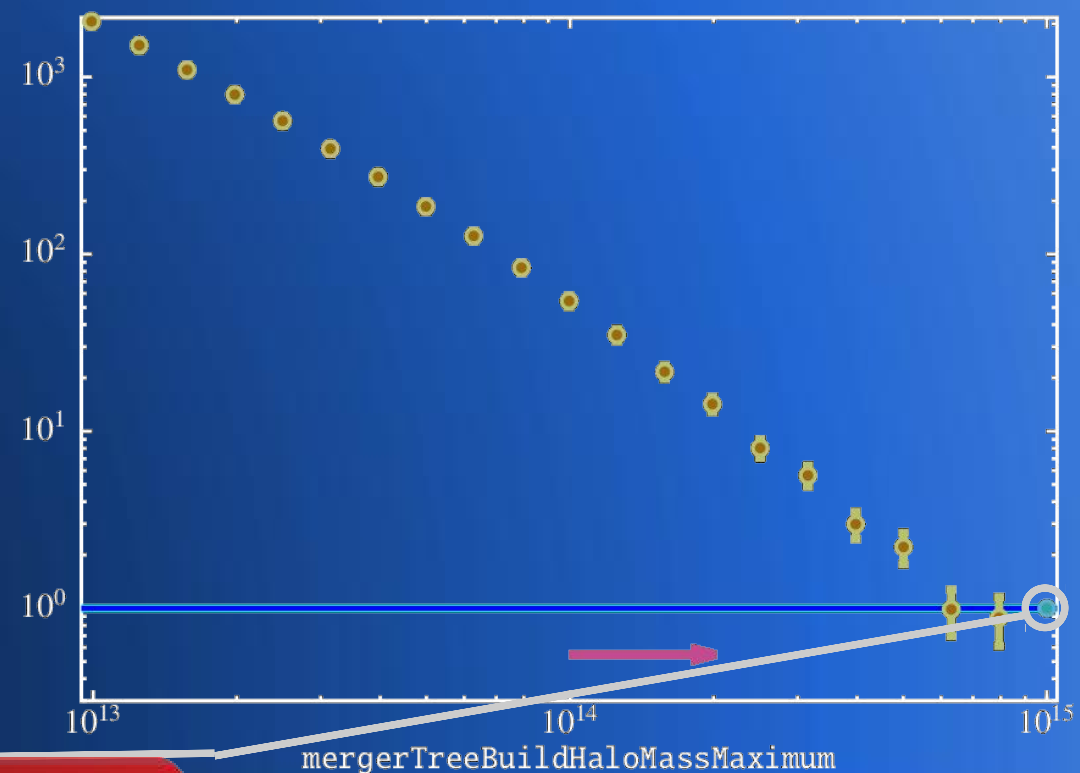
$$M_{\rm ISM,host} \rightarrow M_{\rm ISM,host} + M_{\rm ISM,subhalo}$$
$$M_{\rm ISM,subhalo} \rightarrow 0$$

$$M_{\star,\rm host} \rightarrow M_{\star,\rm host} + M_{\star,\rm subhalo}$$
$$M_{\star,\rm subhalo} \rightarrow 0$$

Model Convergence

Very well converged for default value





Converged – but only just sufficiently

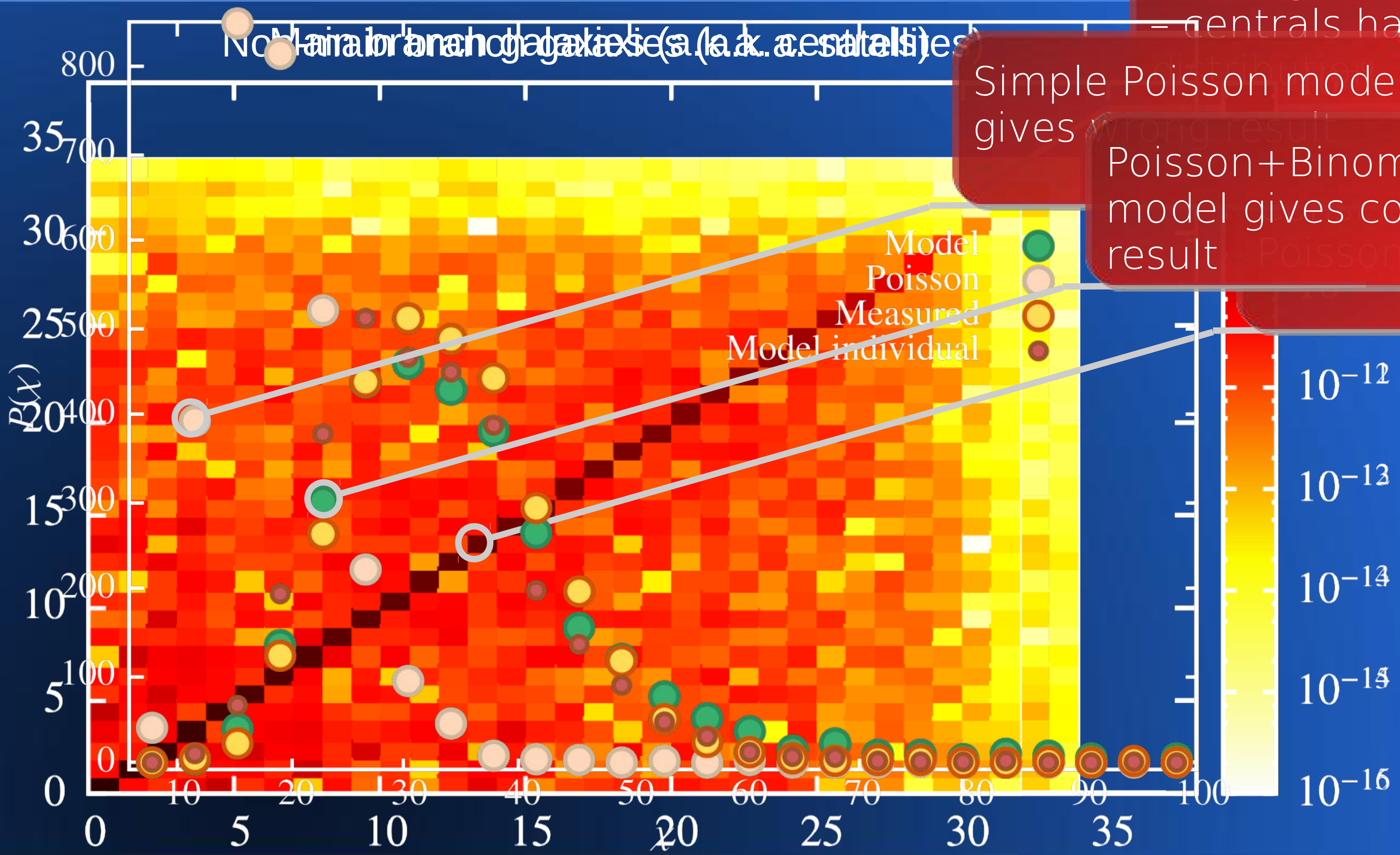
Model Covariance Model

Off-diagonal covariance – centrals have binomial

Simple Poisson model gives wrong result

Poisson+Binomial model gives correct result

Poisson distribution



"Nuisance" Parameters

Systematic Errors in Stellar Masses:

$$\log_{10}(M_\star) \rightarrow \log_{10}(M_\star) + \mu + \kappa \log_{10}\left(\frac{M_\star}{10^{11.3} M_\odot}\right)$$

Systematic Errors in Halo Mass Function:

$$n(M) \rightarrow n(M)[1 + \alpha + \beta \log_{10}(M_{\rm halo}/10^{12} M_\odot)]$$

Random errors on stellar mass accounted for by convolving model mass function with a gaussian

Cosmological Parameters:

$$\Omega_{\rm M}; \Omega_{\rm b}; H_0; n_{\rm s}; \sigma_8; \tau$$

$$\Omega_\Lambda = 1 - \Omega_{\rm M}$$

Modeled as multivariate Gaussian with covariance matrix measured from MCMC chains from WMAP-9 analysis

Model Discrepancies

Known limitations of the model, e.g.:

- Use of extended Press-Schechter merger trees

$\lesssim 1\%$ effect

- Lack of variability in subhalo orbits/merging timescales

$\lesssim 1\%$ effect

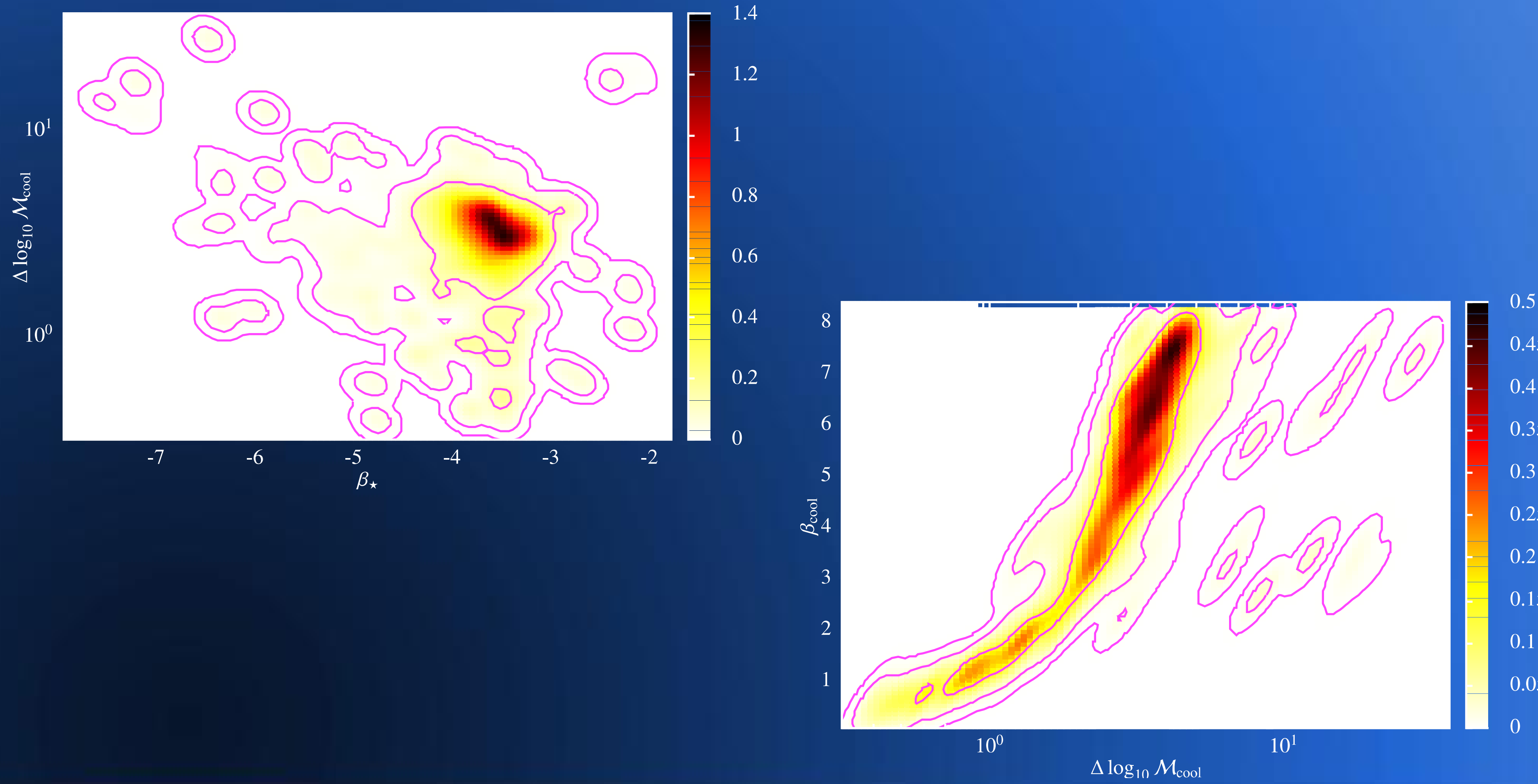
- Finite mass resolution of merger trees

$\lesssim 10\%$ effect

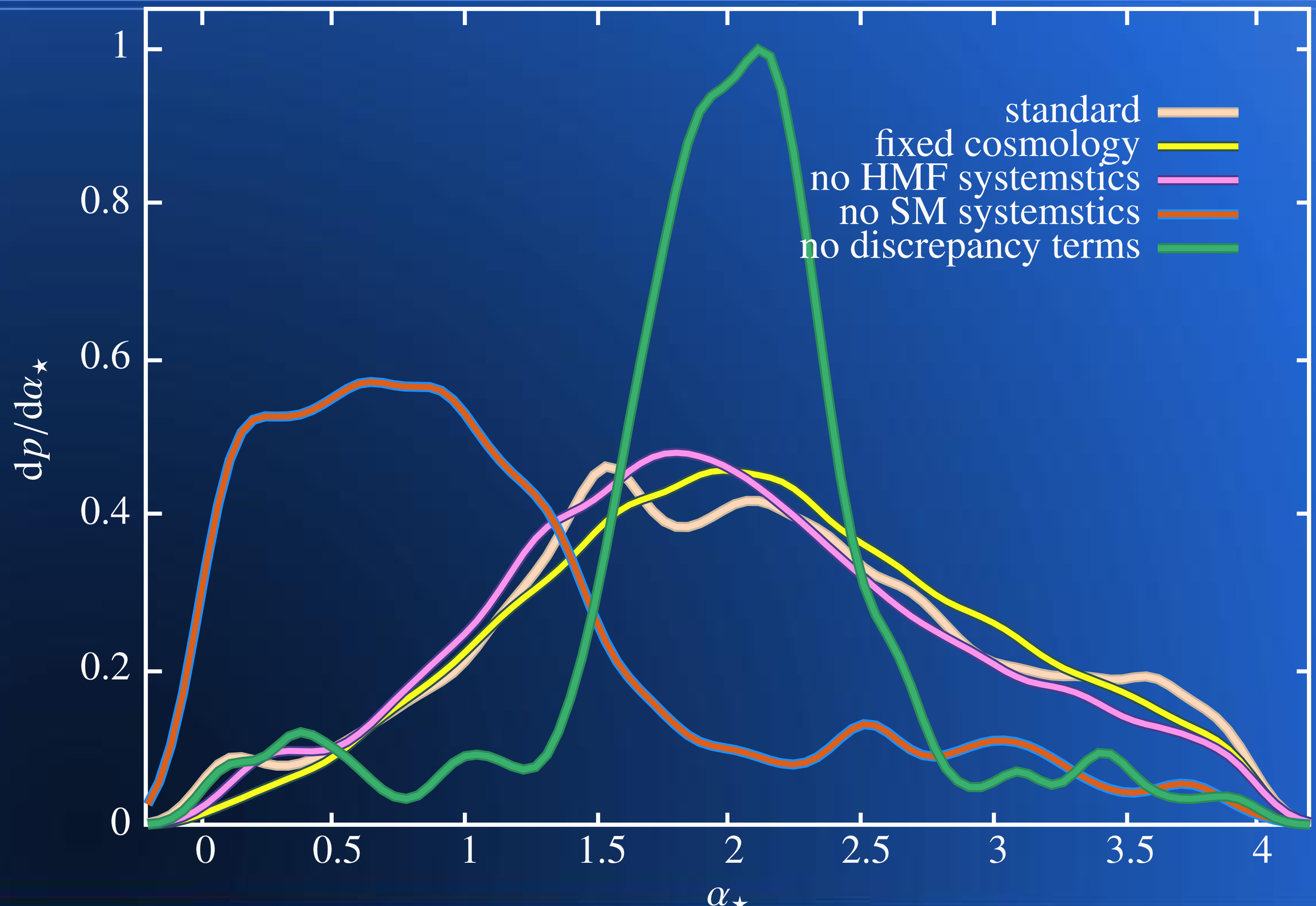
- Fixed cosmology for merger trees

$\lesssim$ few% effect

Posterior Distributions



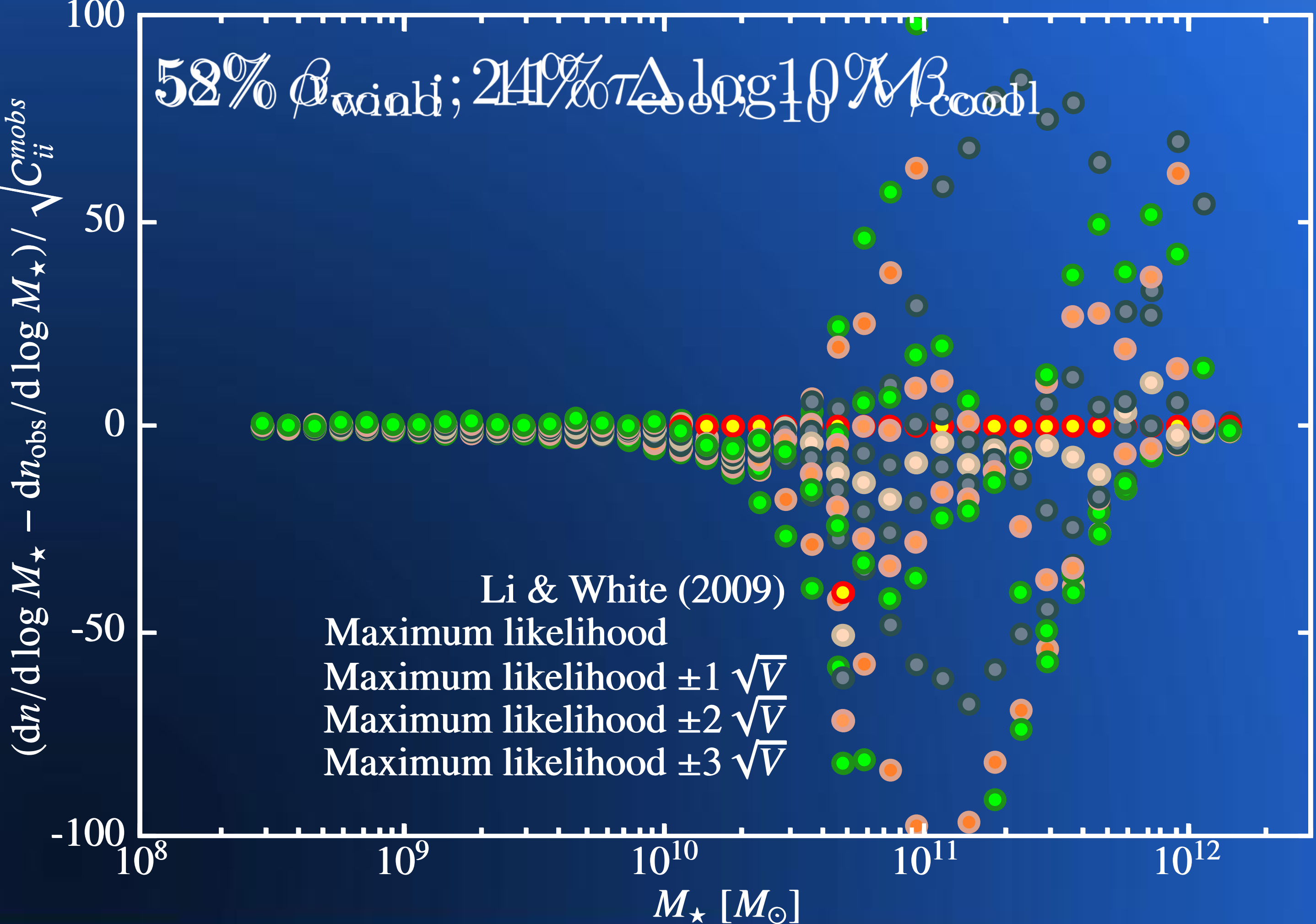
Effect of Systematics



Projections

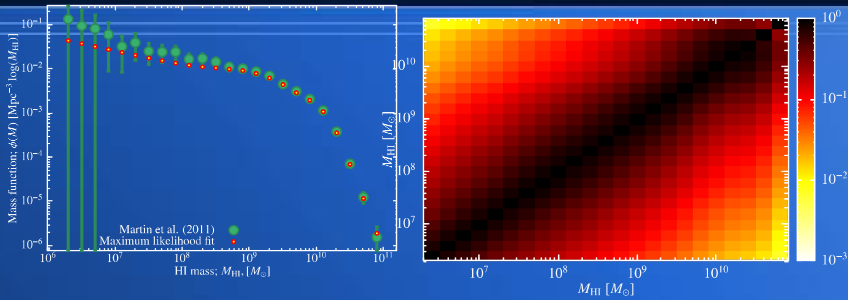
- Which parameter combinations are constrained?
  - And by what?
- Do PCA (i.e. find eigenvectors of posterior)
  - *Minimum* variance vector is most strongly constrained
  - Perturb the model along this vector

Projections

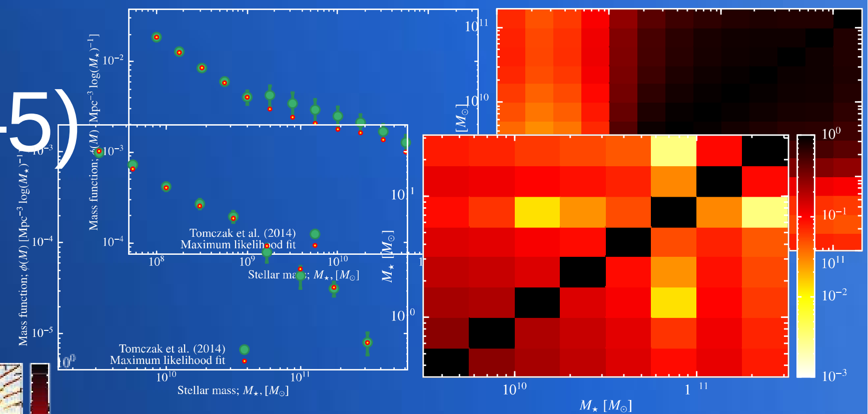


Additional Constraints

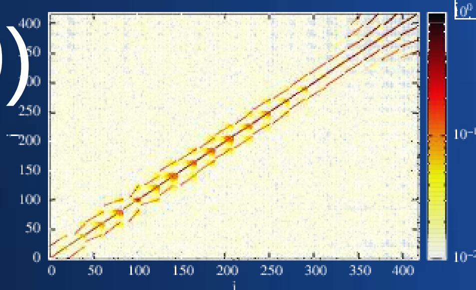
- HI mass function (z=0)



- Stellar mass functions (z=0–5)



- Galaxy sizes (z=0)



- Projected correlation functions