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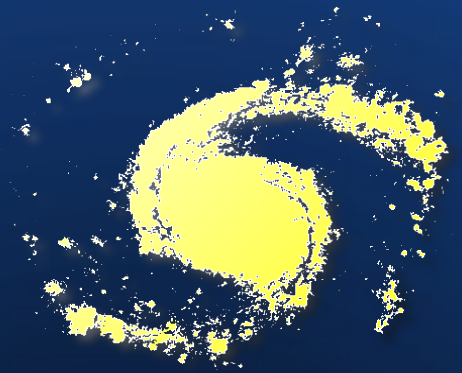
The Galaxy-Halo Connection: Semi-Analytic Models



Andrew Benson

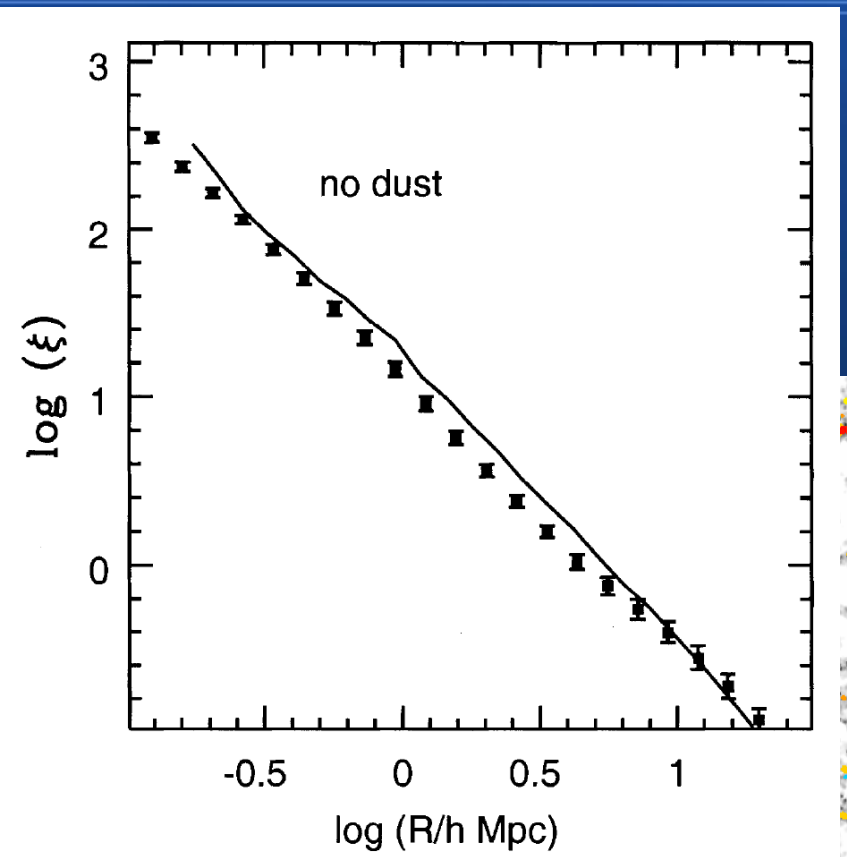
CARNEGIE SCIENCE | The Carnegie Observatories

Challenge……

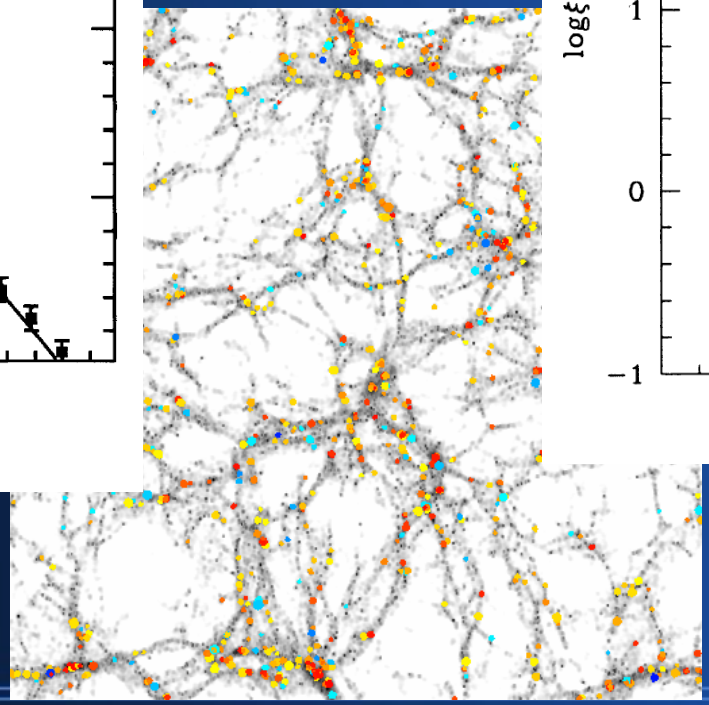
Origins in work attempting to use the galaxy distribution to test the CDM hypothesis, and constrain cosmological parameters:

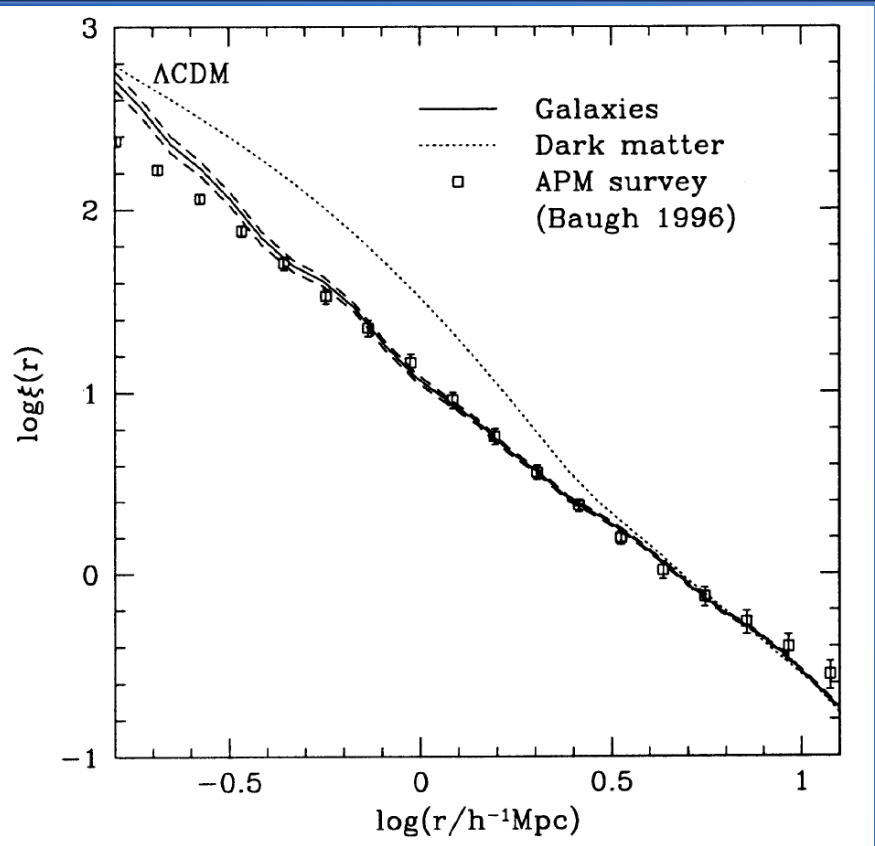
> Clearly, what is now required is a proper physical model for galaxy formation which can be grafted onto simulations to see if the distribution of our “galaxies” is indeed realistic.
>
> – *Davis, Efstathiou, Frenk & White (1985; ApJ; 292; 371)*

….Accepted



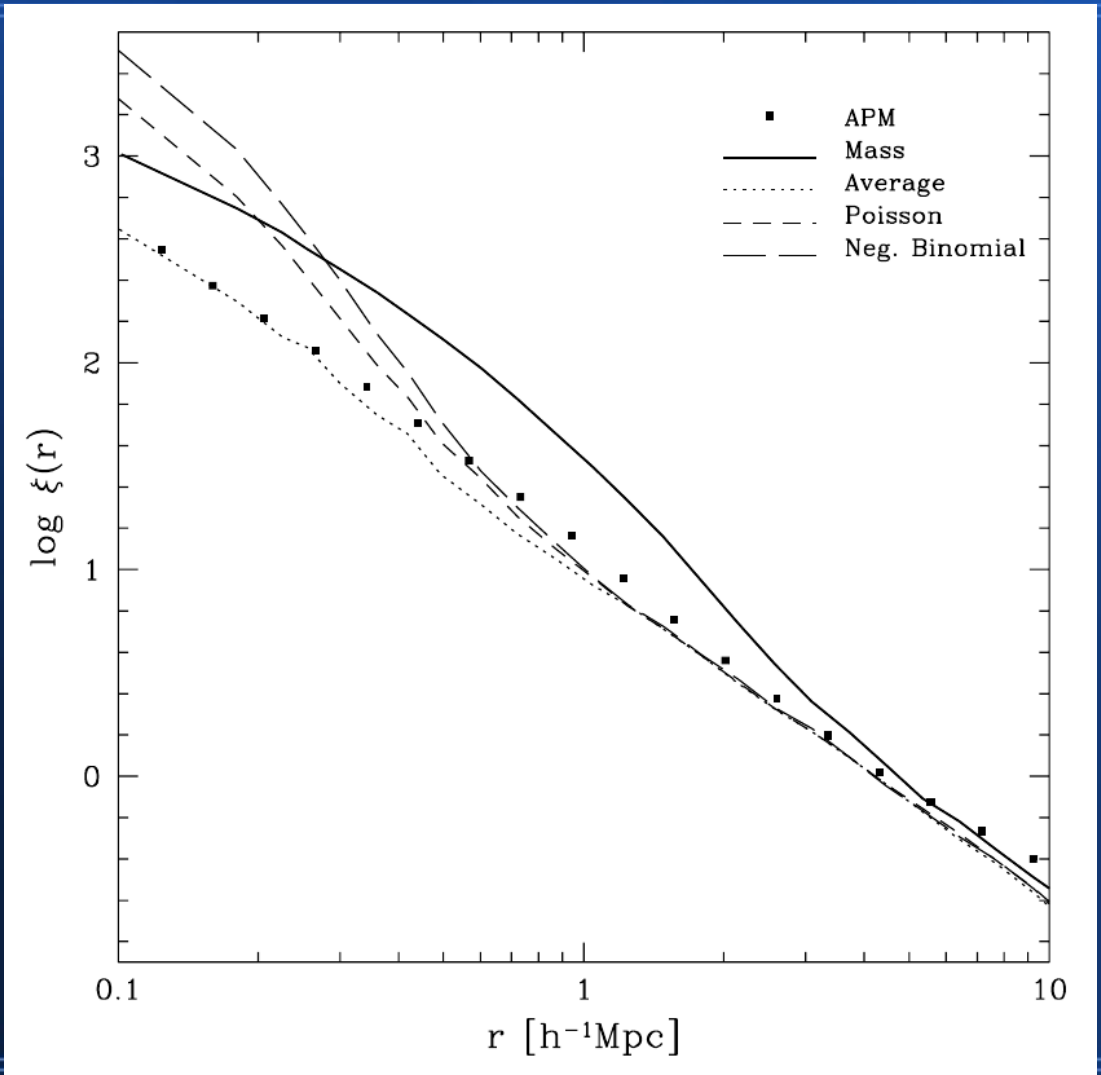
Kauffman et al. (1999)





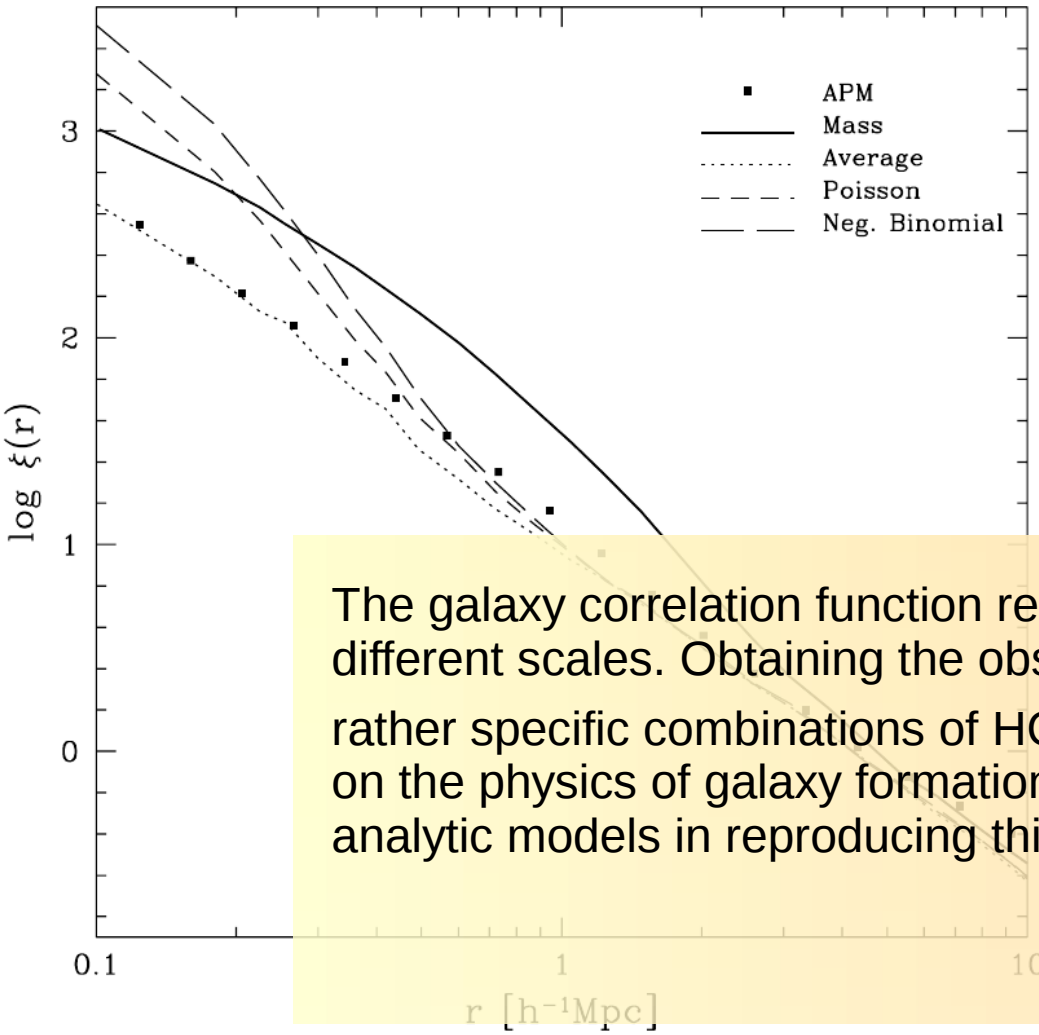
Benson et al. (2000)

Connection to the HOD



Berlind & Weinberg (2002; ApJ; 575; 587)

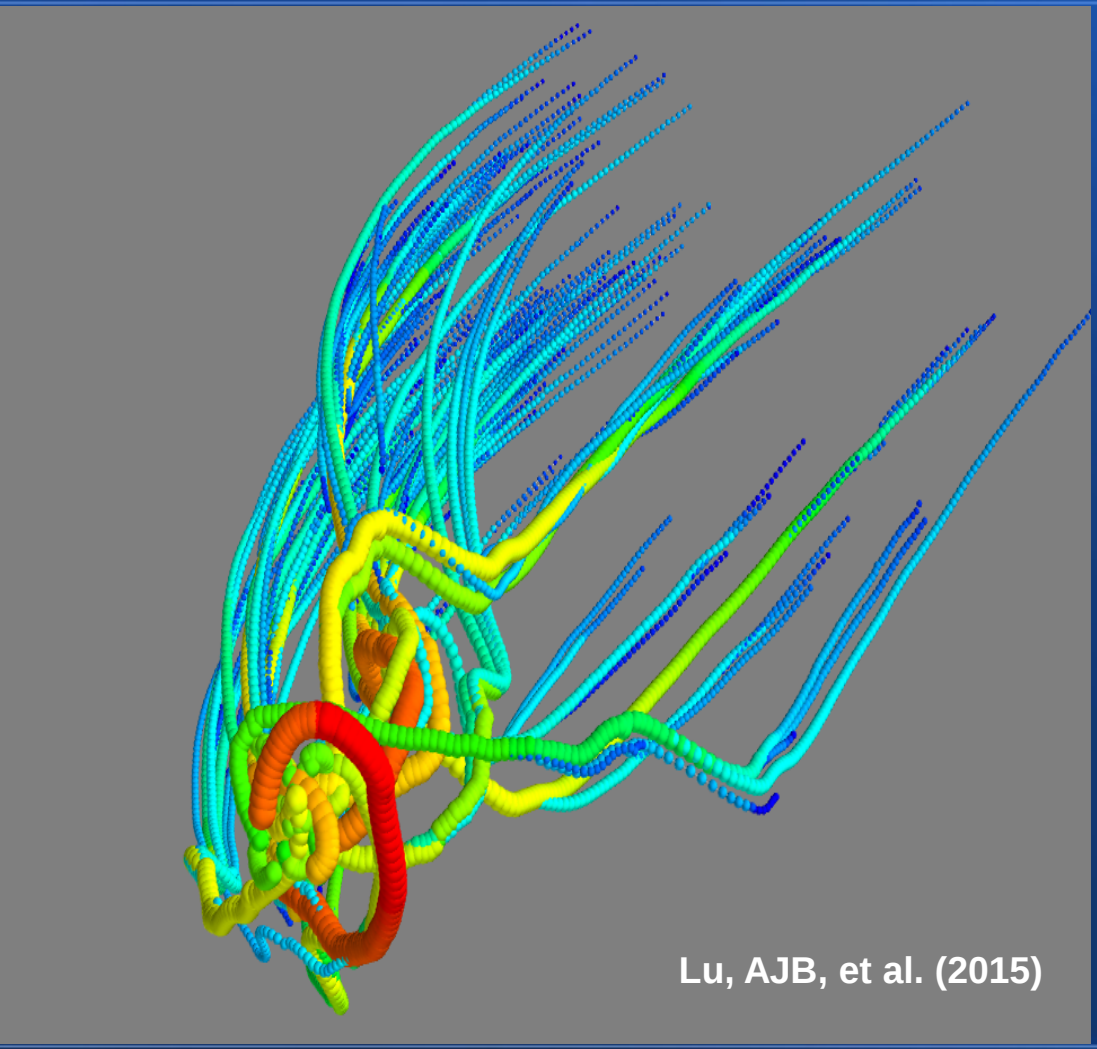
Connection to the HOD



The galaxy correlation function responds to different aspects of P(N|M) on different scales. Obtaining the observed power-law form of $\xi_g(r)$ requires rather specific combinations of HOD parameters, implying a strong constraint on the physics of galaxy formation; the success of numerical and semi-analytic models in reproducing this form is entirely non-trivial.

– *Berlind & Weinberg (2002; ApJ; 575; 587)*

What Does “Semi-Analytic” Mean Anyway?



Lu, AJB, et al. (2015)

- Attempt to model some coarse-grained properties of galaxies:
  - Mass of stars
  - Mass of ISM
  - Characteristic size
- Describe evolution by some set of ODEs, plus impulsive events (mergers)
- Solve that system along branches of merger trees

ODEs: Mass

$$
\begin{aligned}
\dot{M}_{\mathrm{v}} &= +\dot{M}_{\mathrm{v,tree}} \\
\dot{M}_{\mathrm{f}} &= +\dot{M}_{\mathrm{sup}} - \dot{M}_{\mathrm{rec}} \\
\dot{M}_{\mathrm{h}} &= +\dot{M}_{\mathrm{IGM}} + \dot{M}_{\mathrm{rec}} - \dot{M}_{\mathrm{inf}} + \dot{M}_{\mathrm{inc}} - \dot{M}_{\mathrm{str}} - \dot{M}_{\bullet,\mathrm{acc,h}} - \dot{M}_{\bullet,\mathrm{rdo}} \\
\dot{M}_{\mathrm{o}} &= -\dot{M}_{\mathrm{inc}} + \sum \dot{M}'_{\mathrm{str}} + \textstyle\sum_i (1 - f_{\mathrm{str}}) \dot{M}_{\mathrm{out},i} + \sum_i f'_{\mathrm{str}} \dot{M}'_{\mathrm{out},i} + \dot{M}_{\bullet,\mathrm{qsr}} \\
\dot{M}_{\mathrm{d,g}} &= +\dot{M}_{\mathrm{inf}} - \dot{M}_{\mathrm{sf,d}} - \dot{M}_{\mathrm{out,d}} - \dot{M}_{\mathrm{g,ins}} \\
\dot{M}_{\mathrm{d},\star} &= +\dot{M}_{\mathrm{sf,d}} - \dot{M}_{\star,\mathrm{ins}} \\
\dot{M}_{\mathrm{s,g}} &= -\dot{M}_{\mathrm{sf,s}} - \dot{M}_{\mathrm{out,s}} + \dot{M}_{\mathrm{g,ins}} - \dot{M}_{\bullet,\mathrm{acc,s}} - \dot{M}_{\bullet,\mathrm{qsr}} \\
\dot{M}_{\mathrm{s},\star} &= +\dot{M}_{\mathrm{sf,s}} + \dot{M}_{\star,\mathrm{ins}} \\
\dot{M}_{\bullet} &= +\textstyle\sum_j \dot{M}'_{\bullet,\mathrm{acc},j} - \dot{M}_{\bullet,\mathrm{jet}} .
\end{aligned}
$$

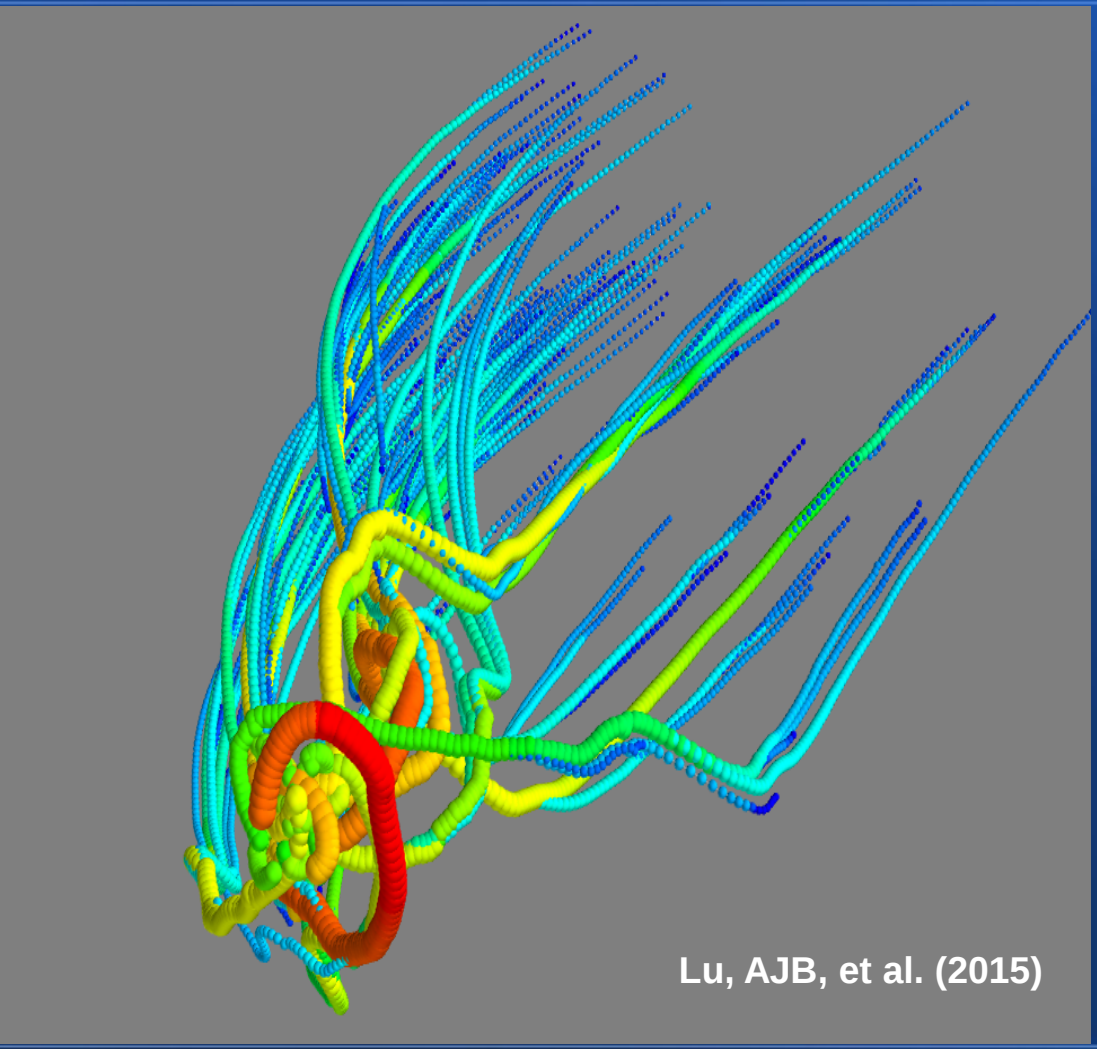
ODEs: Metals

$$
\begin{aligned}
\dot{M}_{Z,\mathrm{h}} &= -\dot{M}_{Z,\mathrm{inf}} + \dot{M}_{Z,\mathrm{inc}} - \dot{M}_{Z,\mathrm{str}} - \dot{M}_{Z,\bullet,\mathrm{acc,h}} - \dot{M}_{Z,\bullet,\mathrm{rdo}}, \\
\dot{M}_{Z,\mathrm{o}} &= -\dot{M}_{Z,\mathrm{inc}} + \sum \dot{M}'_{Z,\mathrm{str}} + \sum_i (1 - f_{\mathrm{str}}) \dot{M}_{Z,\mathrm{out},i} + \sum_i f'_{\mathrm{str}} \dot{M}'_{Z,\mathrm{out},i} + \dot{M}_{Z,\bullet,\mathrm{qsr}}, \\
\dot{M}_{Z,\mathrm{d,g}} &= +\dot{M}_{Z,\mathrm{inf}} - \dot{M}_{Z,\mathrm{sf,d}} + \dot{M}_{Z,\mathrm{yld,d}} - \dot{M}_{Z,\mathrm{out,d}} - \dot{M}_{Z,\mathrm{g,ins}}, \\
\dot{M}_{Z,\mathrm{d},\star} &= + \dot{M}_{Z,\mathrm{sf,d}} - \dot{M}_{Z,\star,\mathrm{ins}}, \\
\dot{M}_{Z,\mathrm{s,g}} &= - \dot{M}_{Z,\mathrm{sf,s}} + \dot{M}_{Z,\mathrm{yld,s}} - \dot{M}_{Z,\mathrm{out,s}} + \dot{M}_{Z,\mathrm{g,ins}} - \dot{M}_{Z,\bullet,\mathrm{acc,s}} - \dot{M}_{Z,\bullet,\mathrm{qsr}}, \\
\dot{M}_{Z,\mathrm{s},\star} &= + \dot{M}_{Z,\mathrm{sf,s}} + \dot{M}_{Z,\star,\mathrm{ins}},
\end{aligned}
\tag{A6}
$$

ODEs: Angular Momentum

$$
\begin{aligned}
\dot{J}_{\rm h} &= +\dot{J}_{\rm IGM} + \dot{J}_{\rm rec} - \dot{J}_{\rm inf} + \dot{J}_{\rm inc} - \dot{J}_{\rm str} - \dot{J}_{\bullet,{\rm acc,h}} - \dot{J}_{\bullet,{\rm rdo}}, \\
\dot{J}_{\rm o} &= -\dot{J}_{\rm inc} + \sum \dot{J}'_{\rm str} + \textstyle\sum_i (1 - f_{\rm str}) \dot{J}_{{\rm out,i}} + \sum_i f'_{\rm str} \dot{J}'_{{\rm out,i}} + \dot{J}_{\bullet,{\rm qsr}}, \\
\dot{J}_{\rm d,g} &= +\dot{J}_{\rm inf} - \dot{J}_{\rm out,d} - \dot{J}_{\rm g,ins}, \\
\dot{J}_{\rm d,\star} &= -\dot{J}_{\star,{\rm ins}}, \\
\dot{J}_{\rm s,g} &= - \dot{J}_{\rm out,s} + \dot{J}_{\rm g,ins} - \dot{J}_{\bullet,{\rm acc,s}} - \dot{J}_{\bullet,{\rm qsr}}, \\
\dot{J}_{\rm s,\star} &= +\dot{J}_{\star,{\rm ins}}, \\
\dot{a}_\bullet &= +\textstyle\sum_j \dot{a}_{\bullet,{\rm acc},j} - \dot{a}_{\bullet,{\rm jet}} \,.
\end{aligned}
$$

What Does “Semi-Analytic” Mean Anyway?



Lu, AJB, et al. (2015)

- Forward modeling is crucial, and a primary strength of semi-analytic modeling
- Allows:
  - Incorporation of physical models
  - Prediction of complex joint distributions
  - Modeling of observational selection effects
  - Interpretation of data

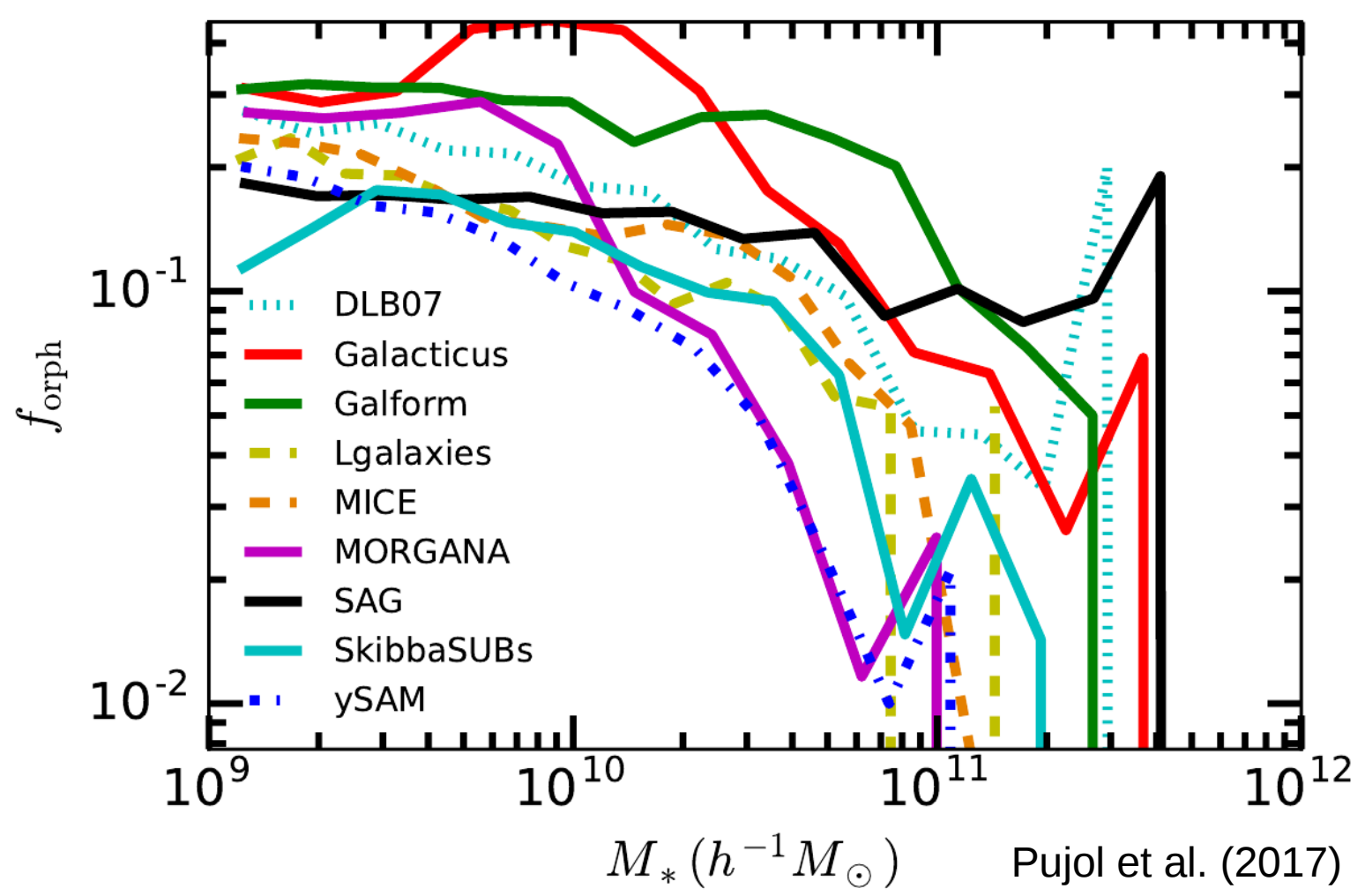
Galaxy-Halo Connection: Goals/Applications

- Survey Simulation
  - Necessary to define and calibrate surveys
    - LSST
    - WFIRST
    - Euclid
  - Allow for accurate/robust marginalization
- Galaxy Physics
  - How galaxies populate halos is *one of the keys* to understanding galaxy formation

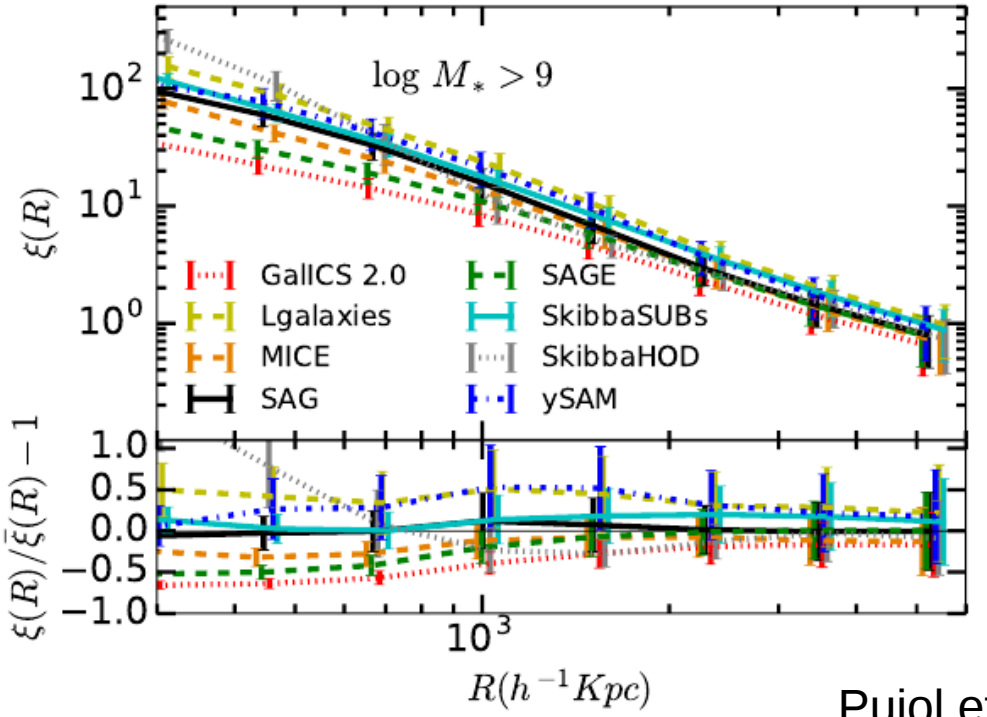
Challenges

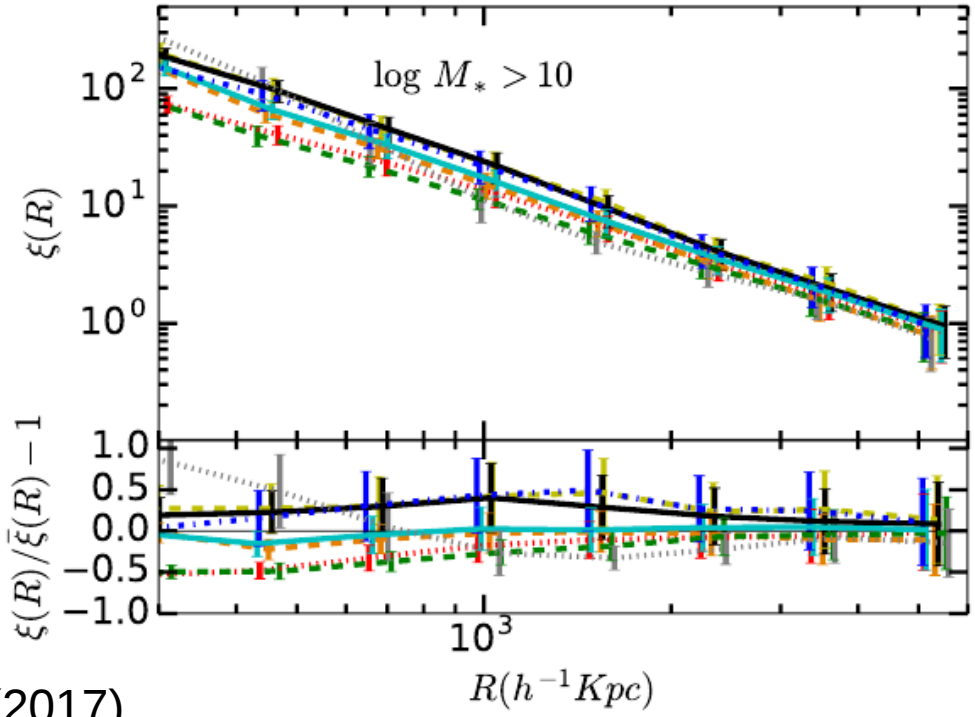
- Incomplete understanding of galaxy formation physics
- Resolution (mass/time)
- Numerical robustness/convergence
- Calibration

Orphans


$f_{\rm orph}$
10^{-1}
10^{-2}
DLB07
Galacticus
Galform
Lgalaxies
MICE
MORGANA
SAG
SkibbaSUBs
ySAM
10^{9}
10^{10}
10^{11}
10^{12}
$M_*\,(h^{-1}M_\odot)$
Pujol et al. (2017)

Robustness



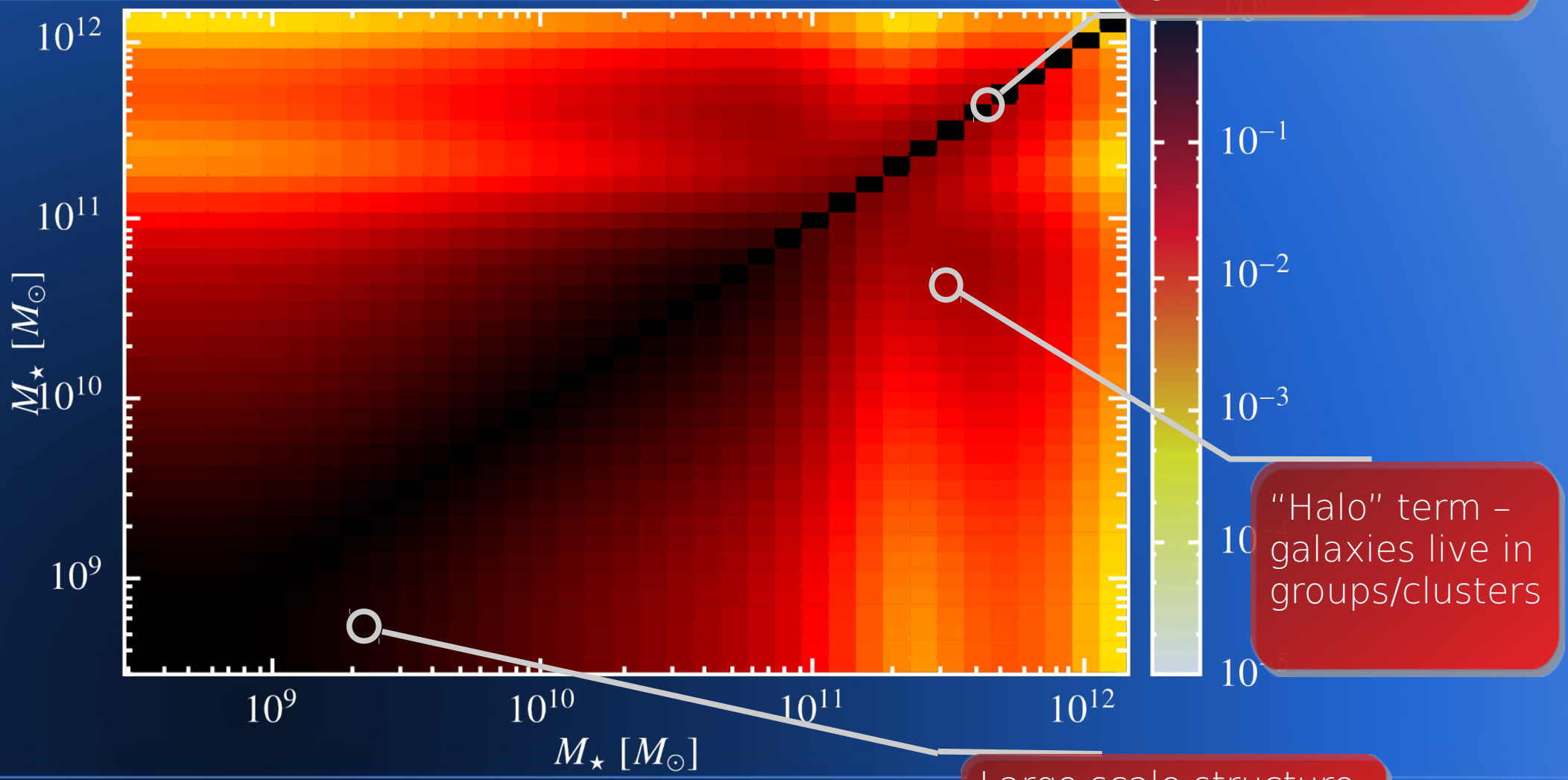


Pujol et al. (2017)

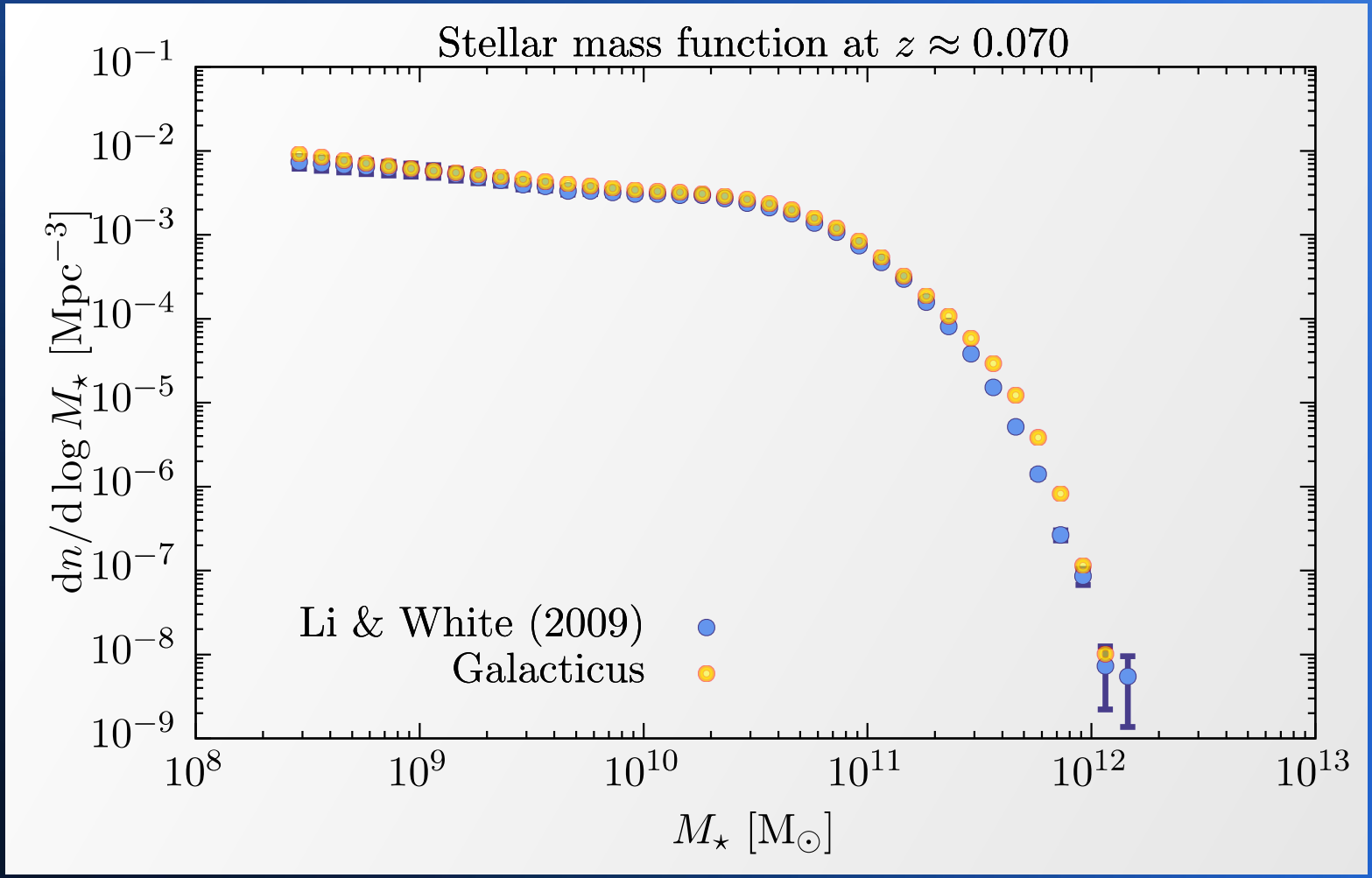
Constraints

- Ongoing work to provide precise calibrations to key physical properties (stellar mass, HI mass, sizes, clustering)
- Careful consideration of:
  - Covariances
  - Systematics
  - Observational biases/errors

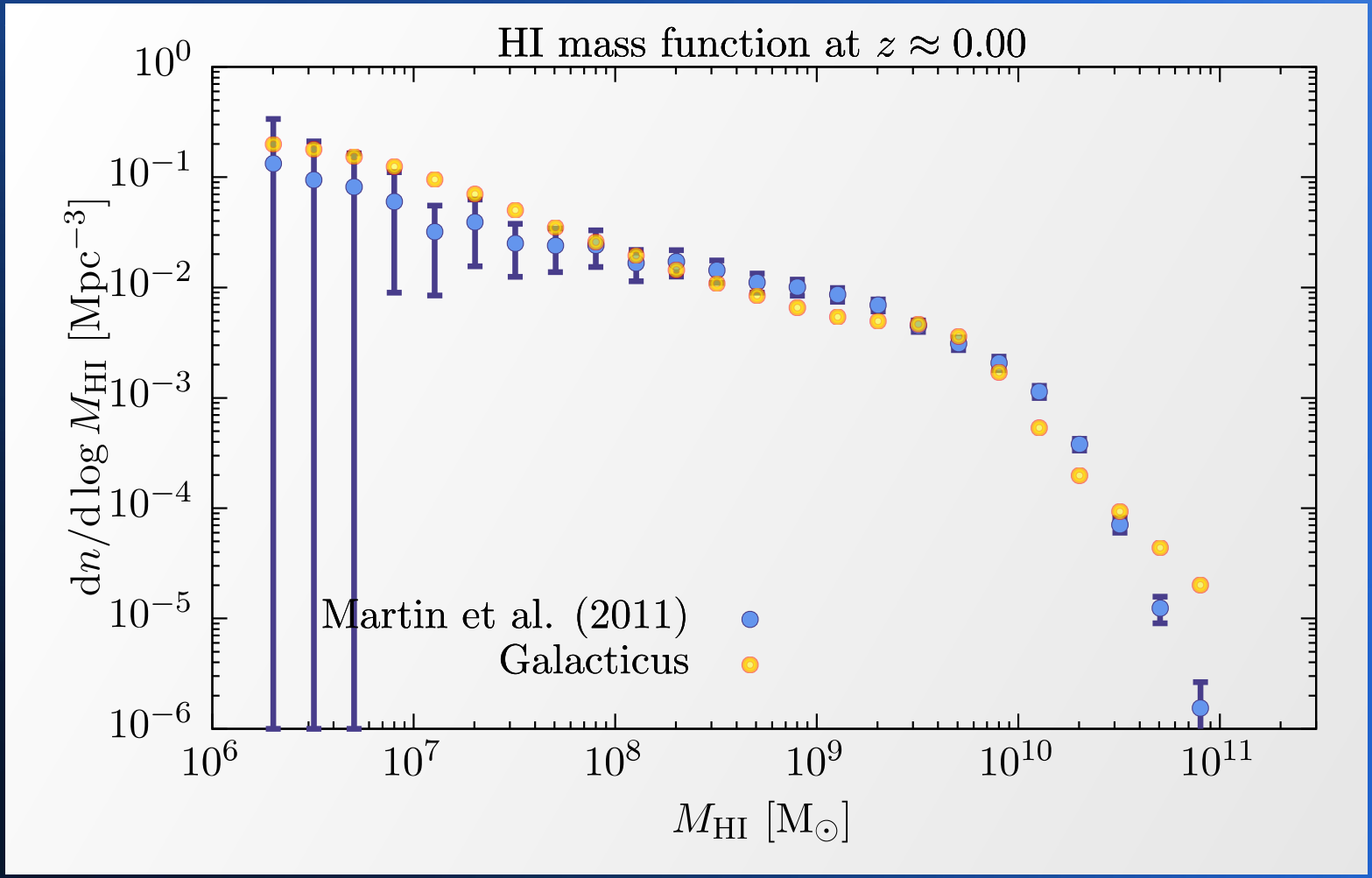
Constraints



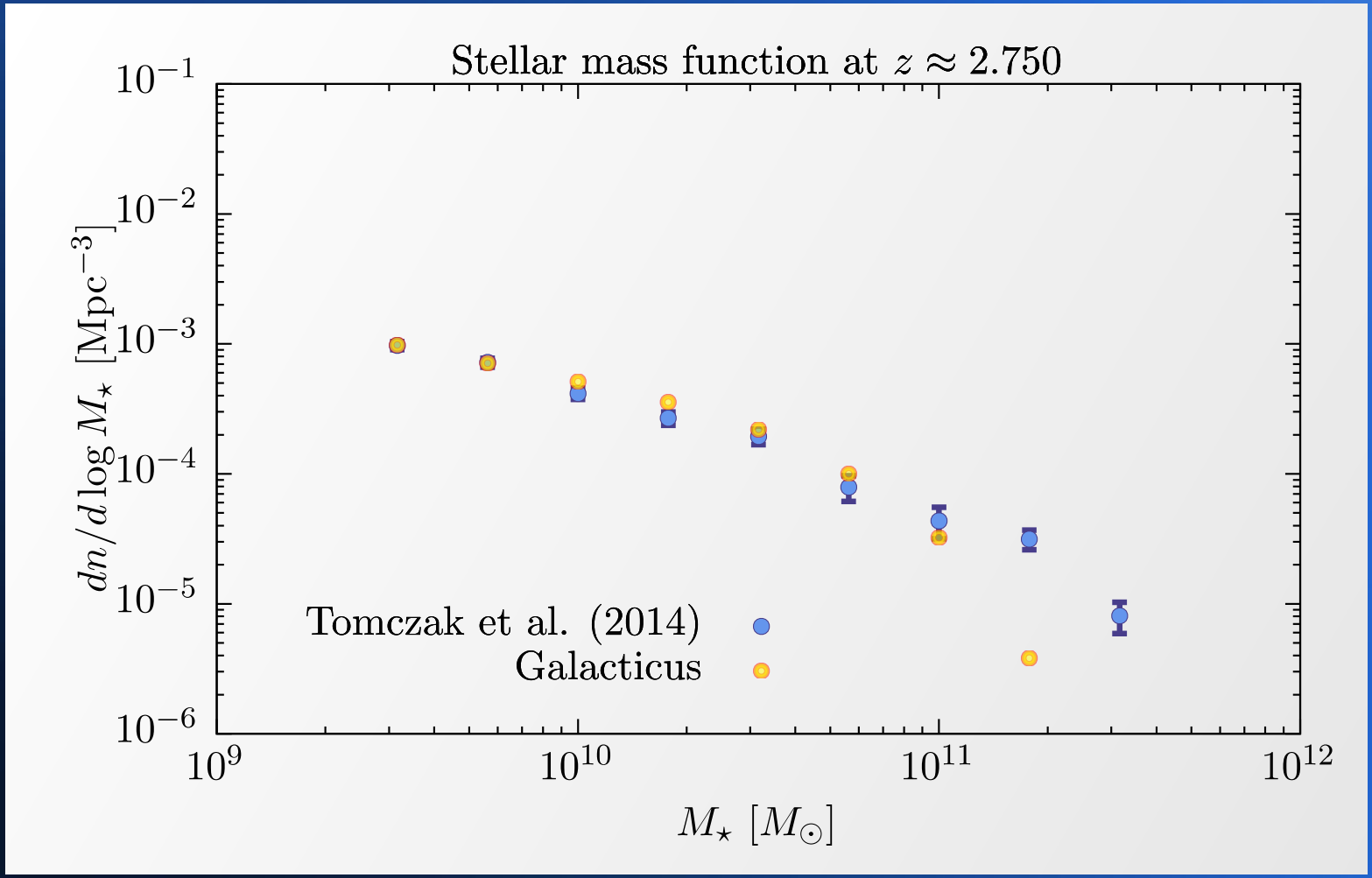
Constrained models...



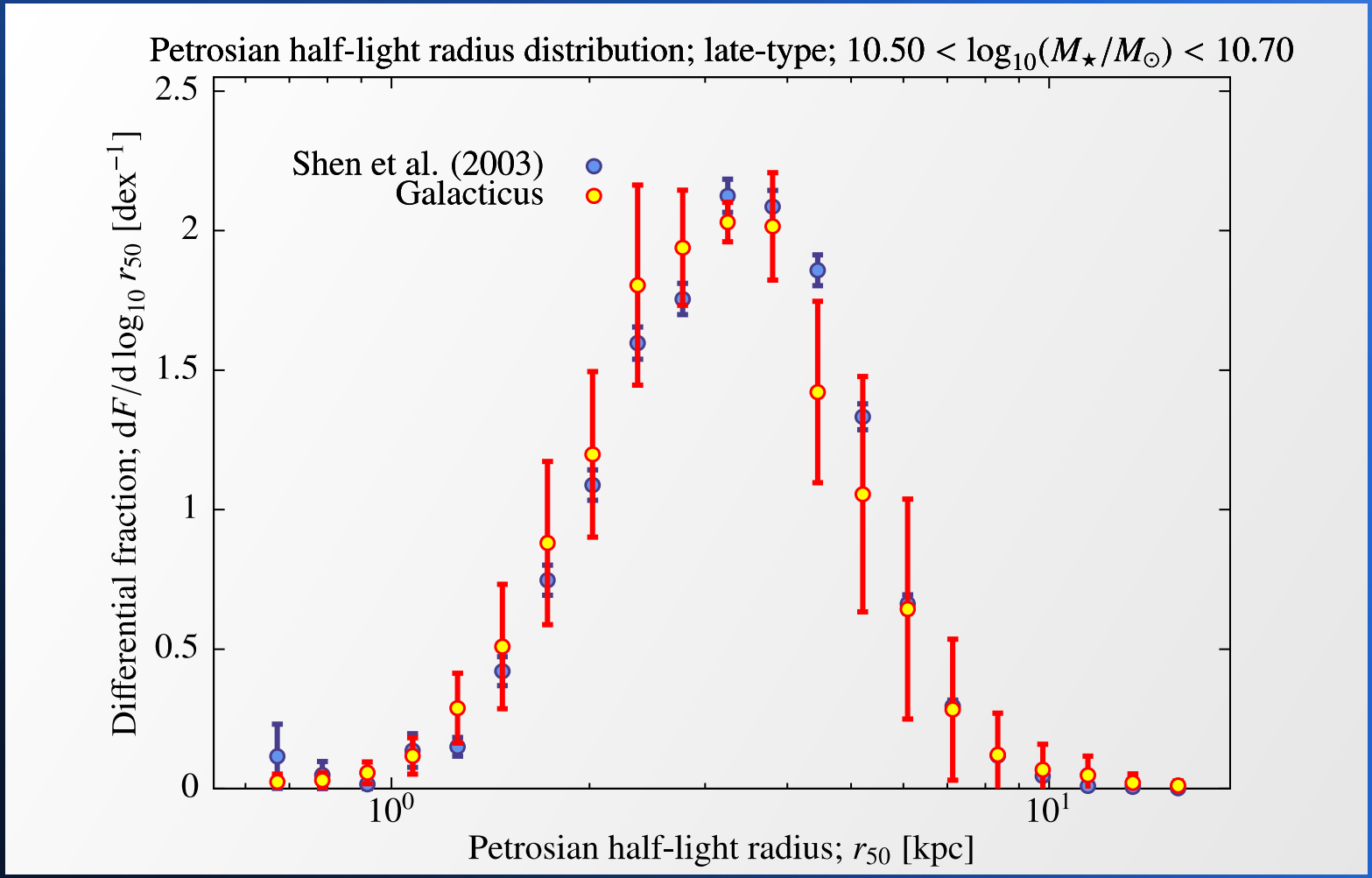
Constrained models...



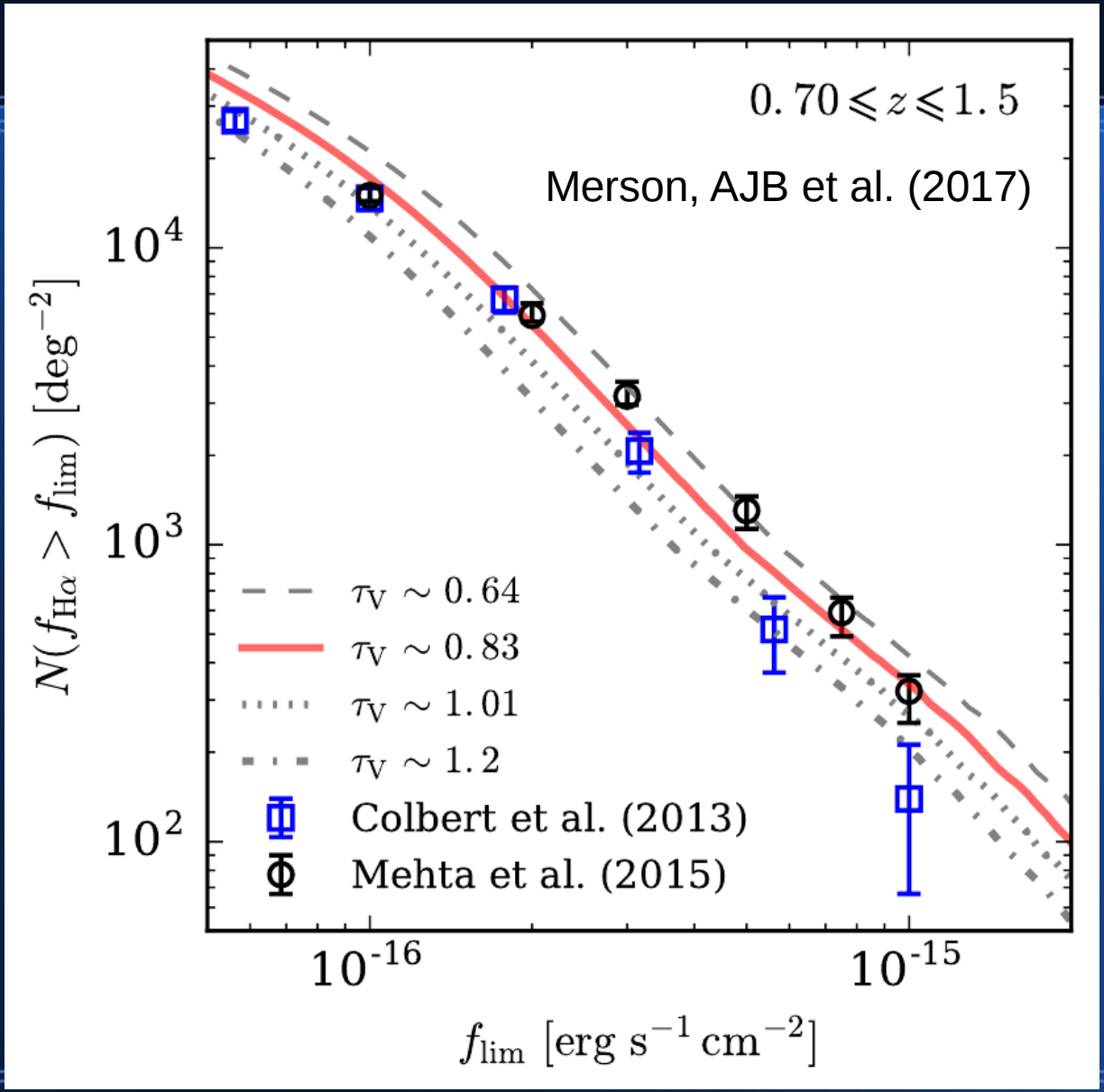
Constrained models...



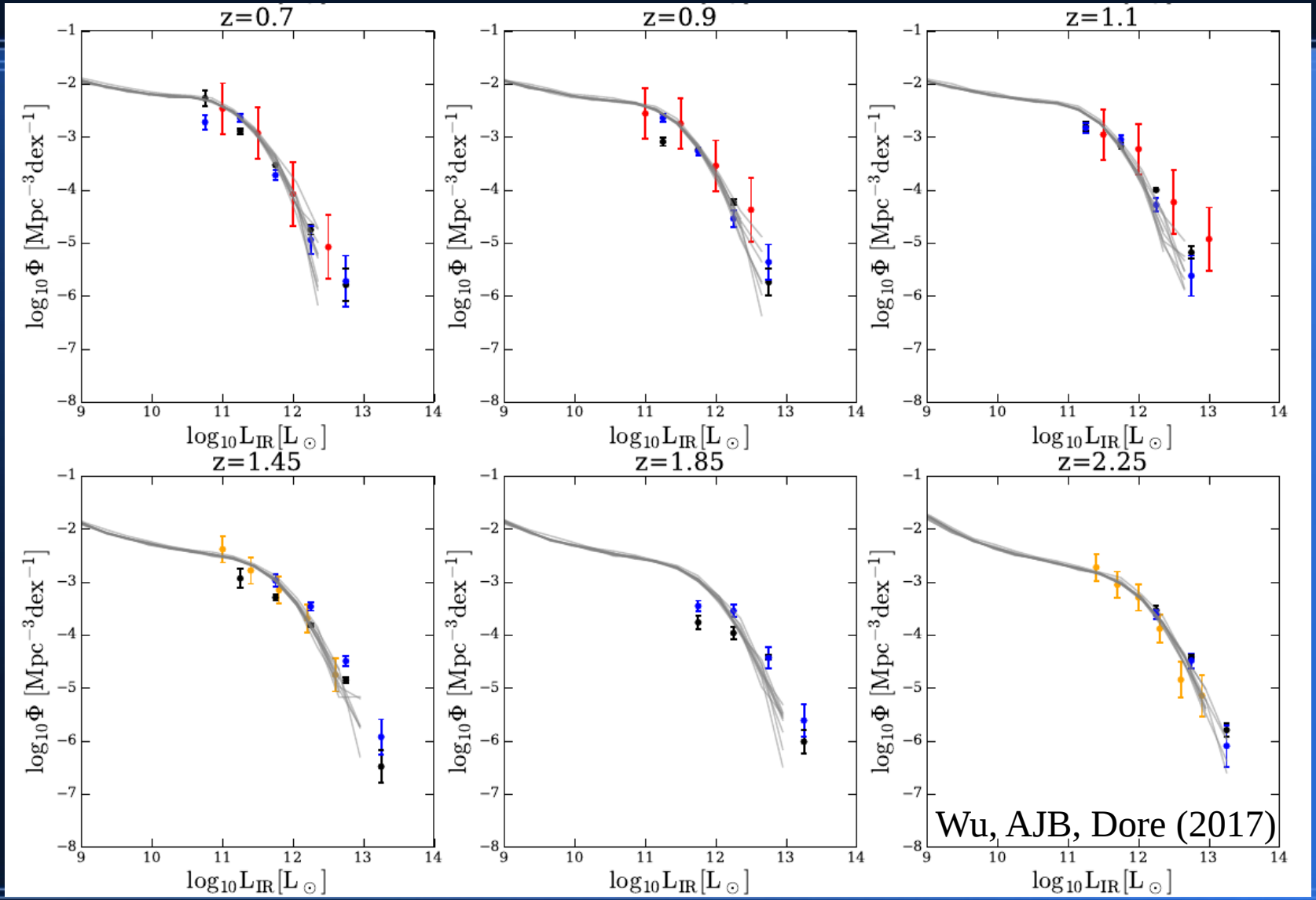
Constrained models...



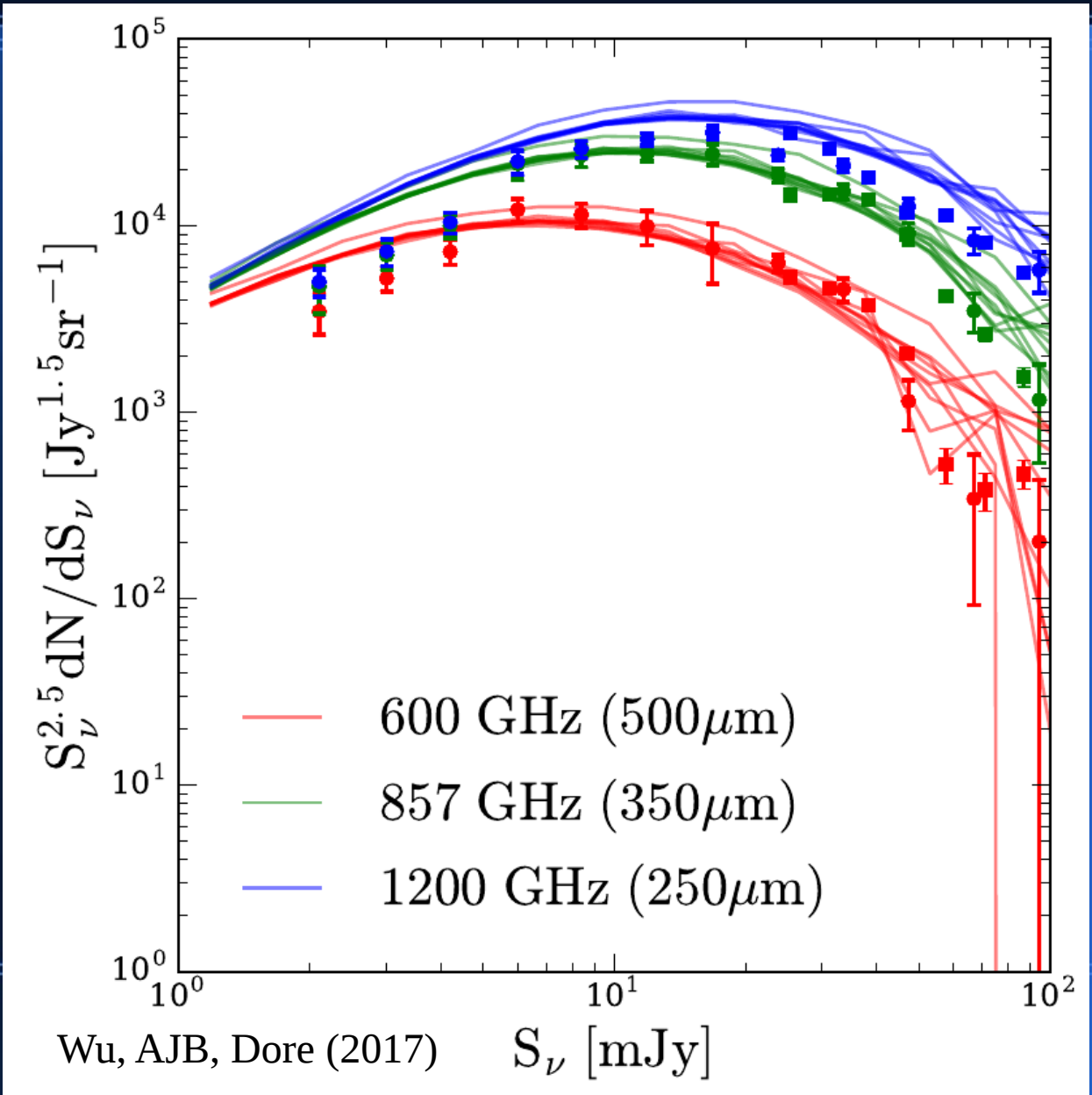
Emission Line Surveys



Infrared Luminosity Functions

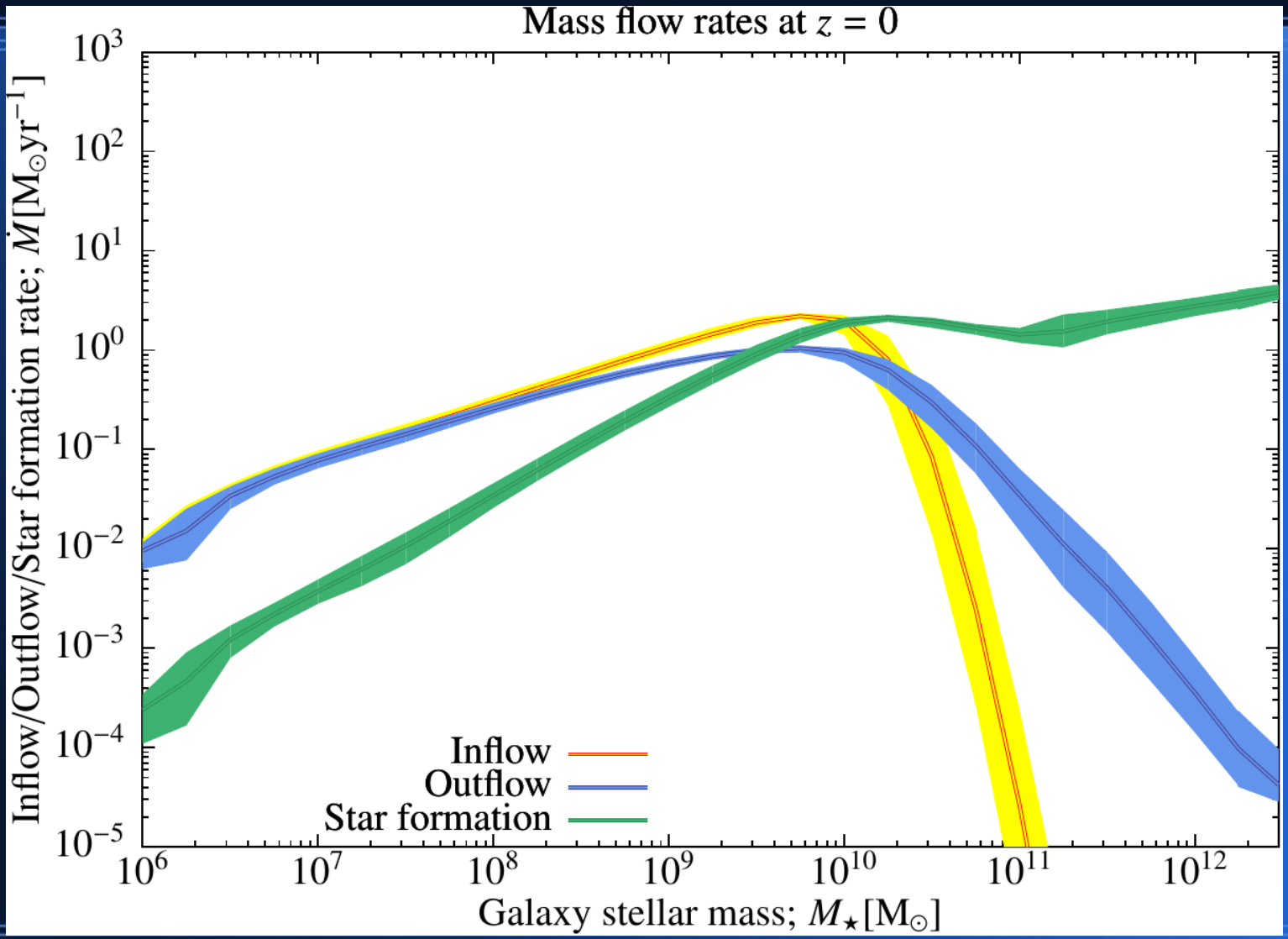


Infrared Number Counts

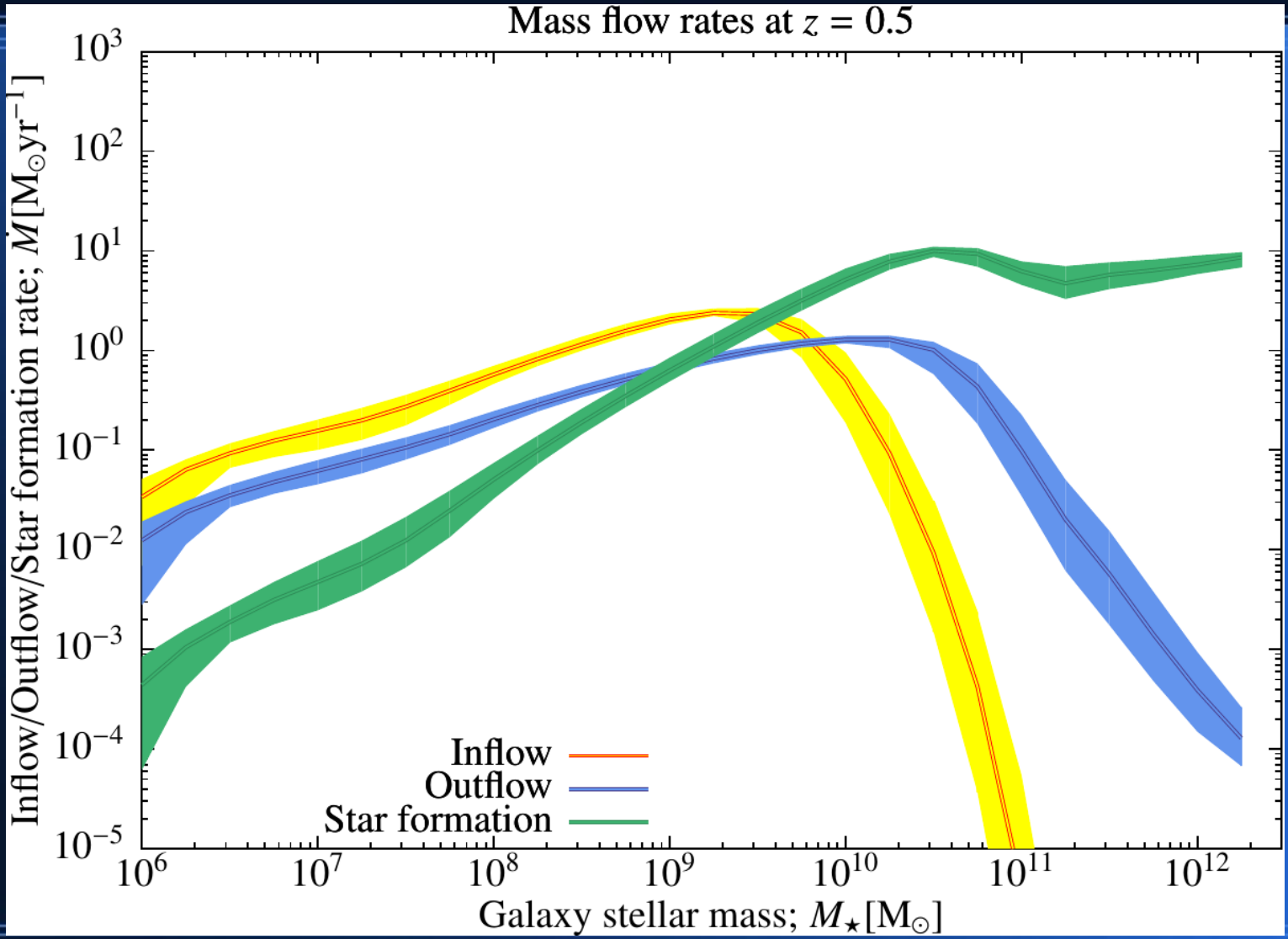


Wu, AJB, Dore (2017)

Inflow/Outflow



Inflow/Outflow



Conclusions

- Semi-analytic models
  - Attempt to predict galaxy-halo connection *ab initio*
  - But, limited by understanding of galaxy physics...
  - ...and ability to accurately constrain
  - Potential to provide insight into the physics of galaxy formation via galaxy-halo connection

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