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Galacticus in the MultiDark Database
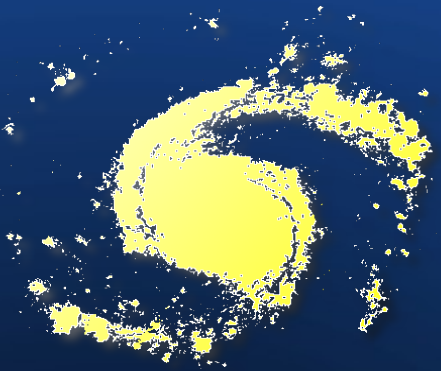
Andrew Benson

CARNEGIE SCIENCE | The Carnegie Observatories

The Galacticus SAM

- Open source SAM

- Operates on *N-body* or Press-Schechter-type merger trees (or analytic MAHs, or hand-built merger trees, or halos in static universes)

- Baryonic physics modeled as network of ODEs

- Includes all the usual suspects (star formation, feedback, AGN, chemical enrichment, merging, etc.)

- Modular in nature, so easy to construct models of varying complexity

Mass Evolution

$$\dot{M}_{\rm v} = +\dot{M}_{\rm v,tree} \qquad\qquad ,$$

$$\dot{M}_{\rm f} = +\dot{M}_{\rm sup} -\dot{M}_{\rm rec} \qquad\qquad ,$$

$$\dot{M}_{\rm h} = +\dot{M}_{\rm IGM}+\dot{M}_{\rm rec}-\dot{M}_{\rm inf}+\dot{M}_{\rm inc}- \dot{M}_{\rm str} \qquad - \dot{M}_{\bullet,{\rm acc,h}}-\dot{M}_{\bullet,{\rm rdo}},$$

$$\dot{M}_{\rm o} = -\dot{M}_{\rm inc}+\sum \dot{M}'_{\rm str} +\sum_i(1-f_{\rm str})\dot{M}_{{\rm out},i}+\sum_i f'_{\rm str}\dot{M}'_{{\rm out},i} \qquad +\dot{M}_{\bullet,{\rm qsr}},$$

$$\dot{M}_{\rm d,g} = +\dot{M}_{\rm inf} -\dot{M}_{\rm sf,d}- \dot{M}_{\rm out,d} -\dot{M}_{\rm g,ins} \qquad ,$$

$$\dot{M}_{\rm d,\star} = +\dot{M}_{\rm sf,d} -\dot{M}_{\star,{\rm ins}} \qquad ,$$

$$\dot{M}_{\rm s,g} = -\dot{M}_{\rm sf,s}- \dot{M}_{\rm out,s} +\dot{M}_{\rm g,ins}- \dot{M}_{\bullet,{\rm acc,s}}-\dot{M}_{\bullet,{\rm qsr}},$$

$$\dot{M}_{\rm s,\star} = +\dot{M}_{\rm sf,s} +\dot{M}_{\star,{\rm ins}} \qquad ,$$

$$\dot{M}_{\bullet} = +\sum_j \dot{M}'_{\bullet,{\rm acc},j}-\dot{M}_{\bullet,{\rm jet}} .$$

Metal Evolution

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

$$(\text{A6})$$

Angular Momentum Evolution

$$\dot{J}_{\rm h} = +\dot{J}_{\rm IGM} + \dot{J}_{\rm rec} - \dot{J}_{\rm inf} + \dot{J}_{\rm inc} - \quad \dot{J}_{\rm str} \qquad\qquad\qquad\qquad - \quad \dot{J}_{\bullet,{\rm acc,h}} - \dot{J}_{\bullet,{\rm rdo}},$$

$$\dot{J}_{\rm o} = \qquad\qquad\qquad -\dot{J}_{\rm inc} + \sum \dot{J}'_{\rm str} + \sum_i (1-f_{\rm str})\dot{J}_{\rm out,i} + \sum_i f'_{\rm str}\dot{J}'_{\rm out,i} \qquad\qquad +\dot{J}_{\bullet,{\rm qsr}},$$

$$\dot{J}_{\rm d,g} = \qquad\qquad +\dot{J}_{\rm inf} \qquad\qquad - \qquad\qquad \dot{J}_{\rm out,d} \qquad -\dot{J}_{\rm g,ins} \qquad ,$$

$$\dot{J}_{\rm d,\star} = \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad -\dot{J}_{\star,{\rm ins}} \qquad ,$$

$$\dot{J}_{\rm s,g} = \qquad\qquad\qquad\qquad\qquad - \qquad\qquad \dot{J}_{\rm out,s} \qquad +\dot{J}_{\rm g,ins} - \quad \dot{J}_{\bullet,{\rm acc,s}} - \dot{J}_{\rm g,qsr},$$

$$\dot{J}_{\rm s,\star} = \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad +\dot{J}_{\star,{\rm ins}} \qquad ,$$

$$\dot{a}_{\bullet} = \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad +\sum_j \dot{a}_{\bullet,{\rm acc},j} - \dot{a}_{\bullet,{\rm jet}} .$$

Calibration

- Current catalog based on "by-eye" calibrations
- Ongoing work to provide precise calibrations to key physical properties (stellar mass, HI mass, sizes, clustering)
- Careful consideration of:
  - Covariances
  - Systematics
  - Observational biases/errors
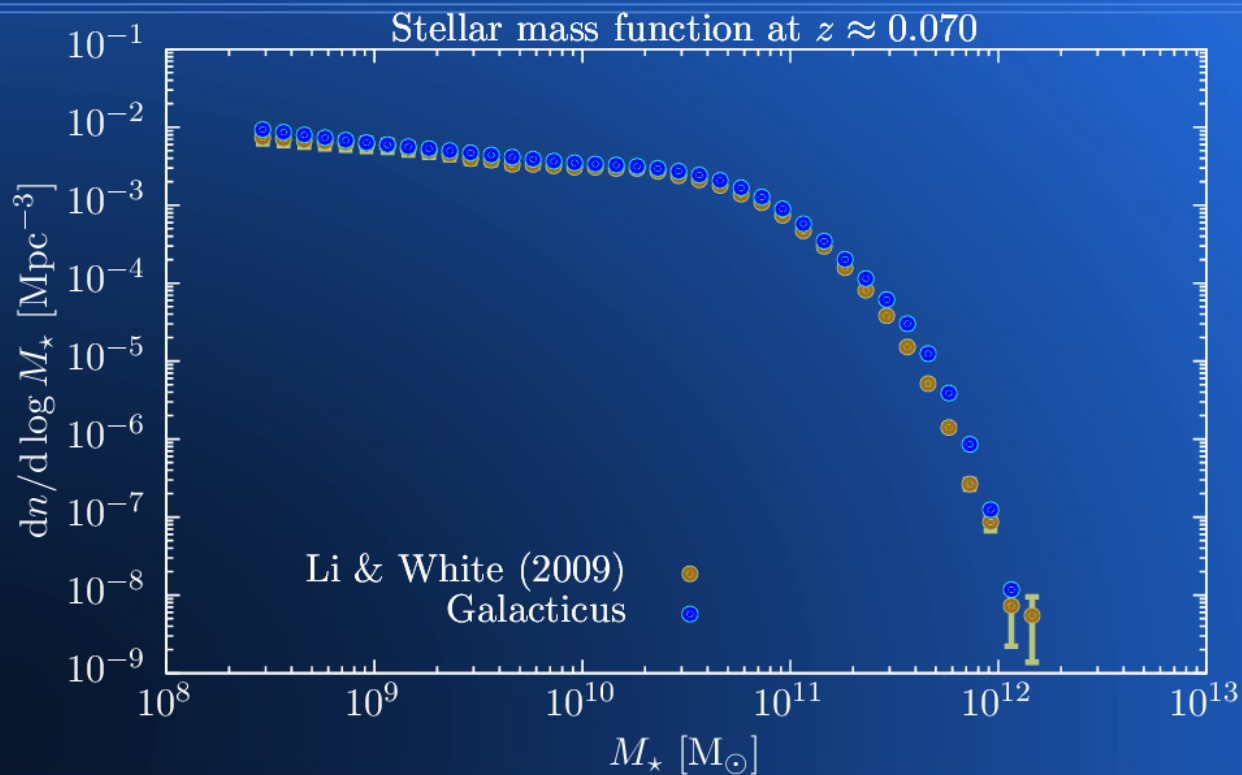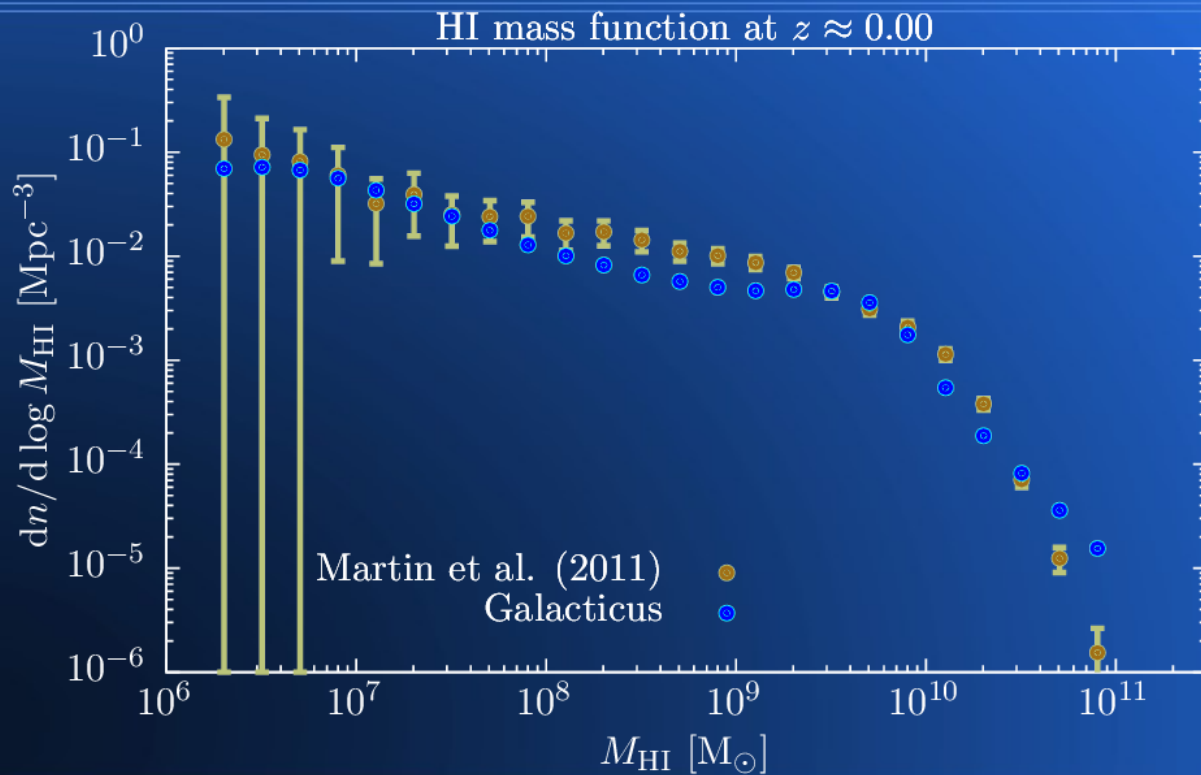
Calibration of the Model

High-mass bins dominated by Poisson term

"Halo" term – galaxies live in groups/clusters
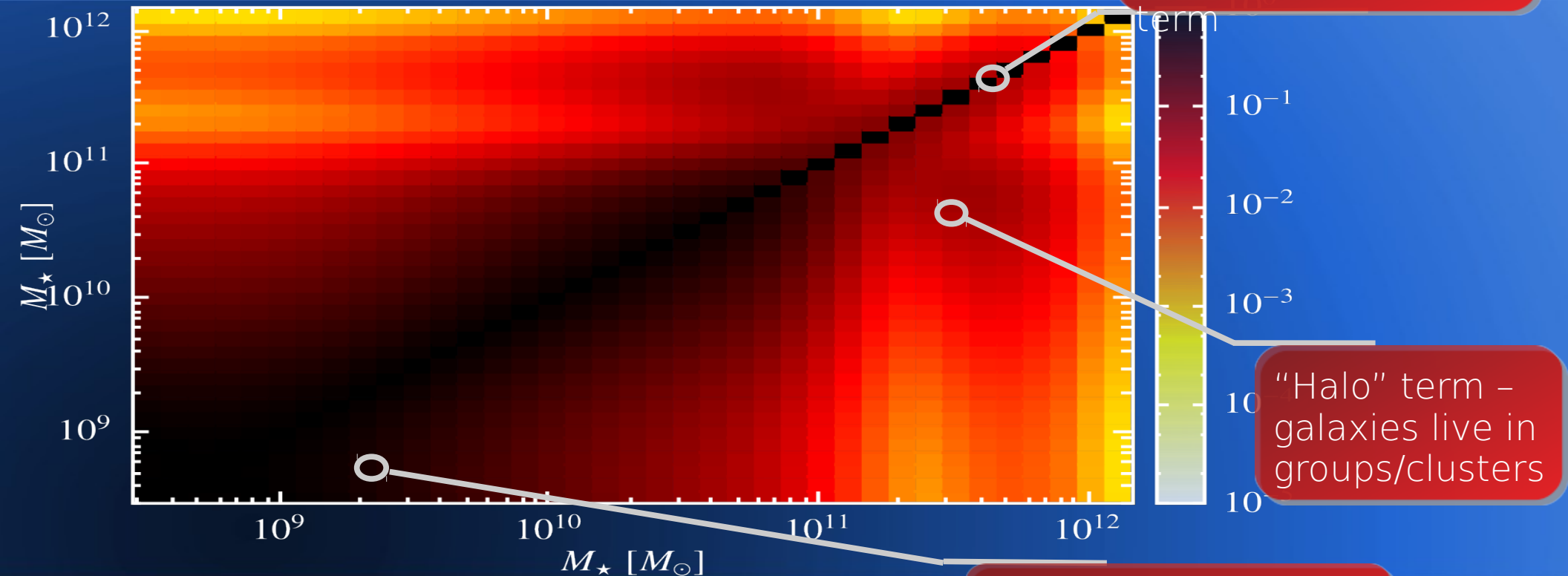
Large scale structure contribution

Galacticus in MultiDark

Calibration of the Model

Stellar mass function at $z \approx 0.070$

Calibration of the Model

HI mass function at $z \approx 0.00$

Martin et al. (2011)
Galacticus

$dn/d\log M_{HI}$ [Mpc^{-3}]

M_{HI} [M$_\odot$]

Calibration of the Model

Stellar mass function at $z \approx 1.125$

Calibration of the Model

Stellar mass function at $z \approx 4.625$

Calibration of the Model

Projected correlation function at $z \approx 0.07$ for $\log_{10}(M_\star/M_\odot) > 9.8$

Hearin et al. (2013)
Galacticus

Calibration of the Model

Petrosian half-light radius distribution; late-type; $10.50 < \log_{10}(M_\star/M_\odot) < 10.70$

y-axis: Differential fraction; $\mathrm{d}F/\mathrm{d}\log_{10} r_{50}$ [dex^{-1}]

x-axis: Petrosian half-light radius; r_{50} [kpc]

Legend: Shen et al. (2003); Galacticus
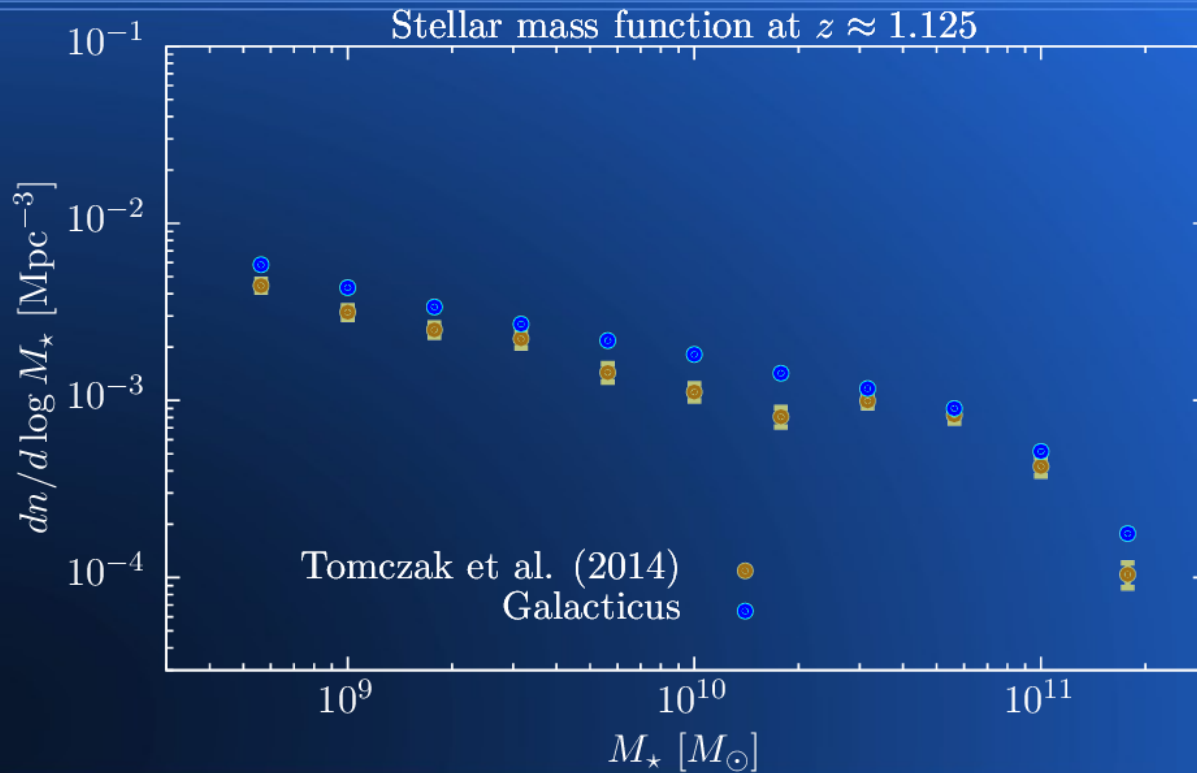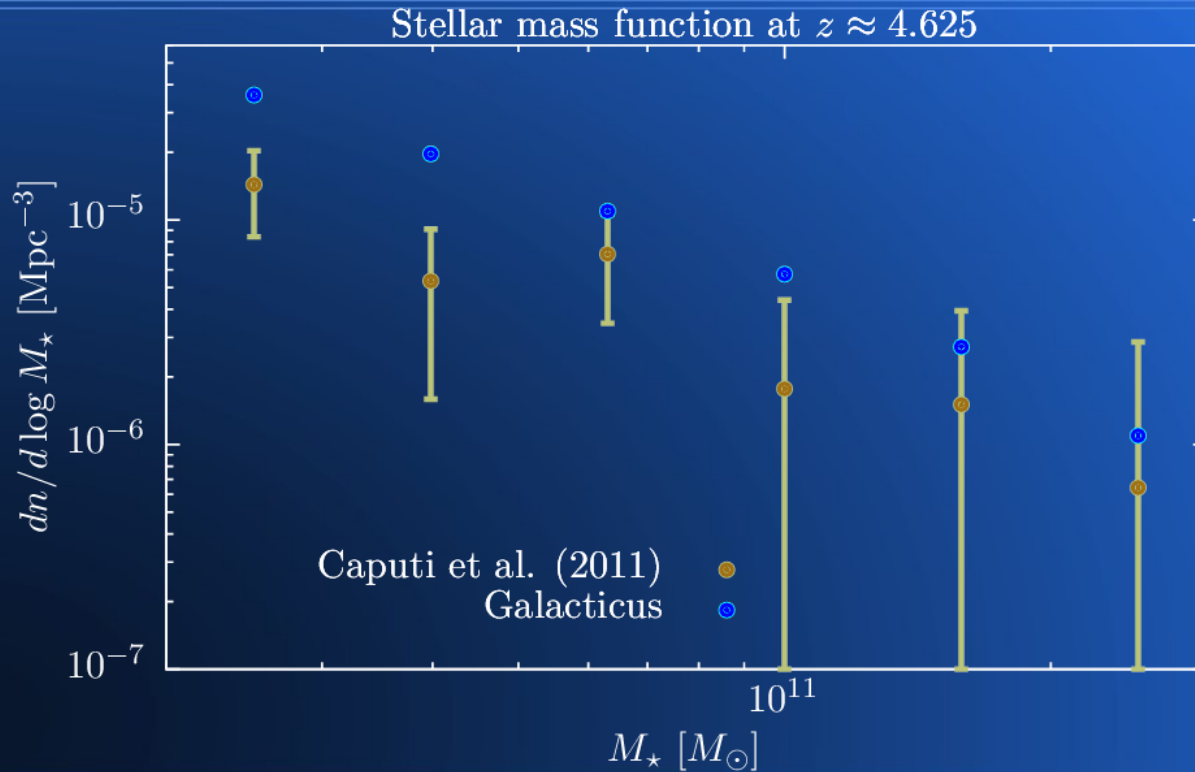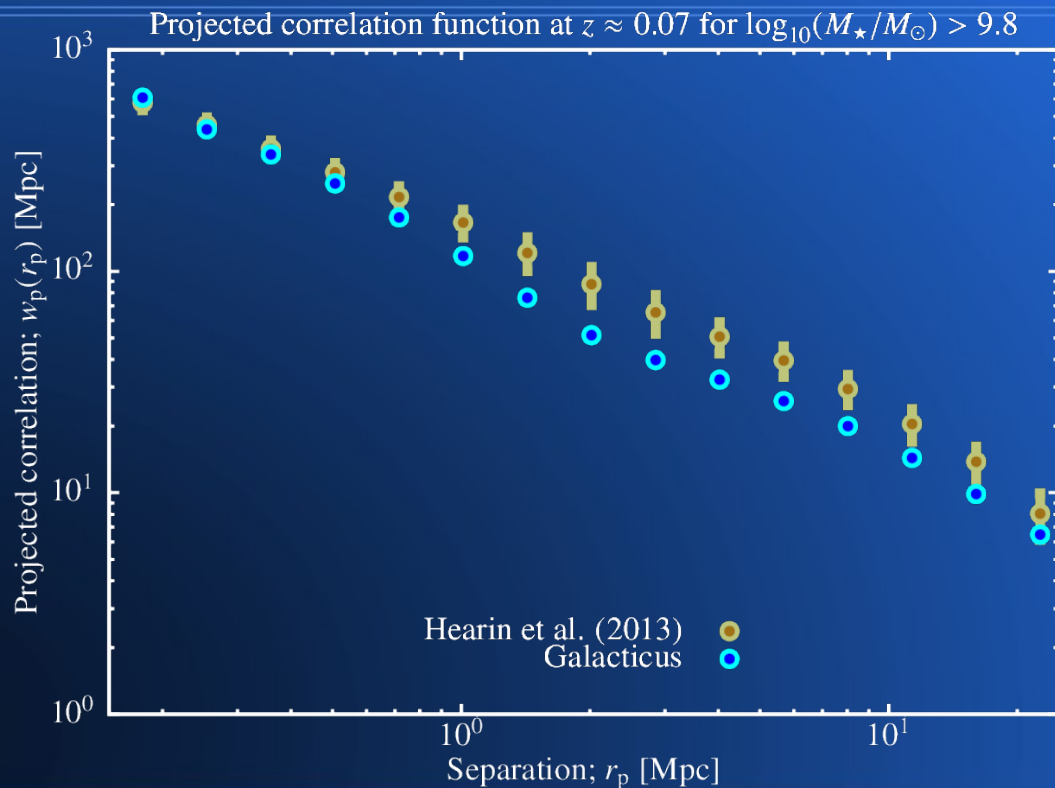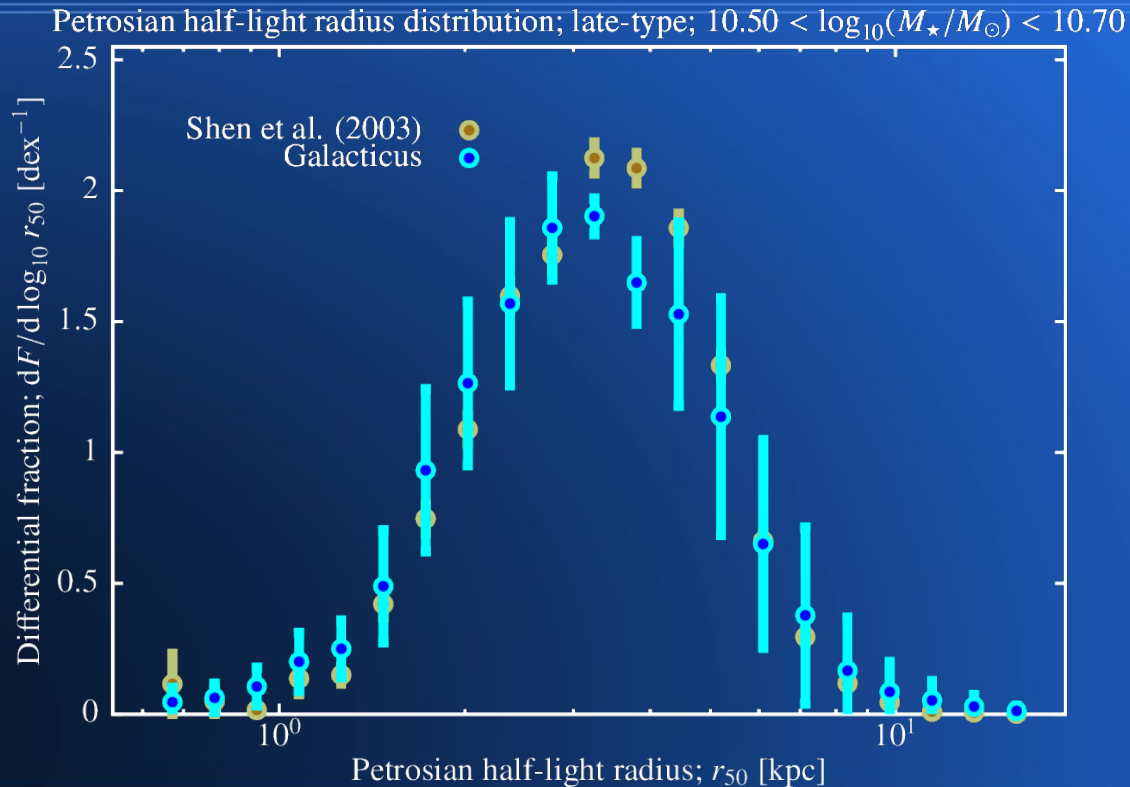
Future Catalogs?

- Improved calibrations

- Resolution independence?

- More observables

    - AGN luminosities

    - Emission lines

    - IR/Sub-mm luminosities

    - Rotation curves?