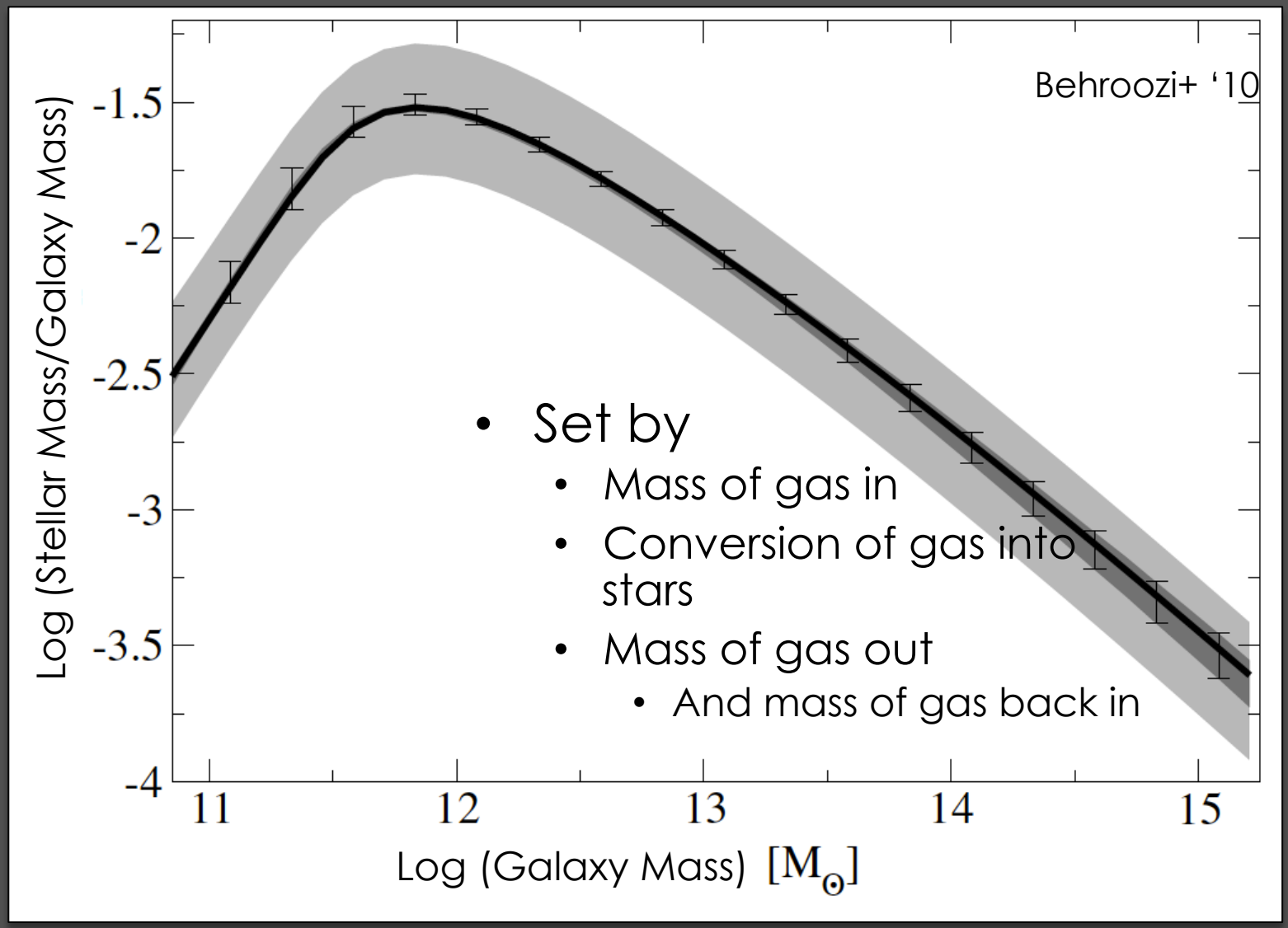
Galaxy growth as seen through simulations and models

Charlotte Christensen

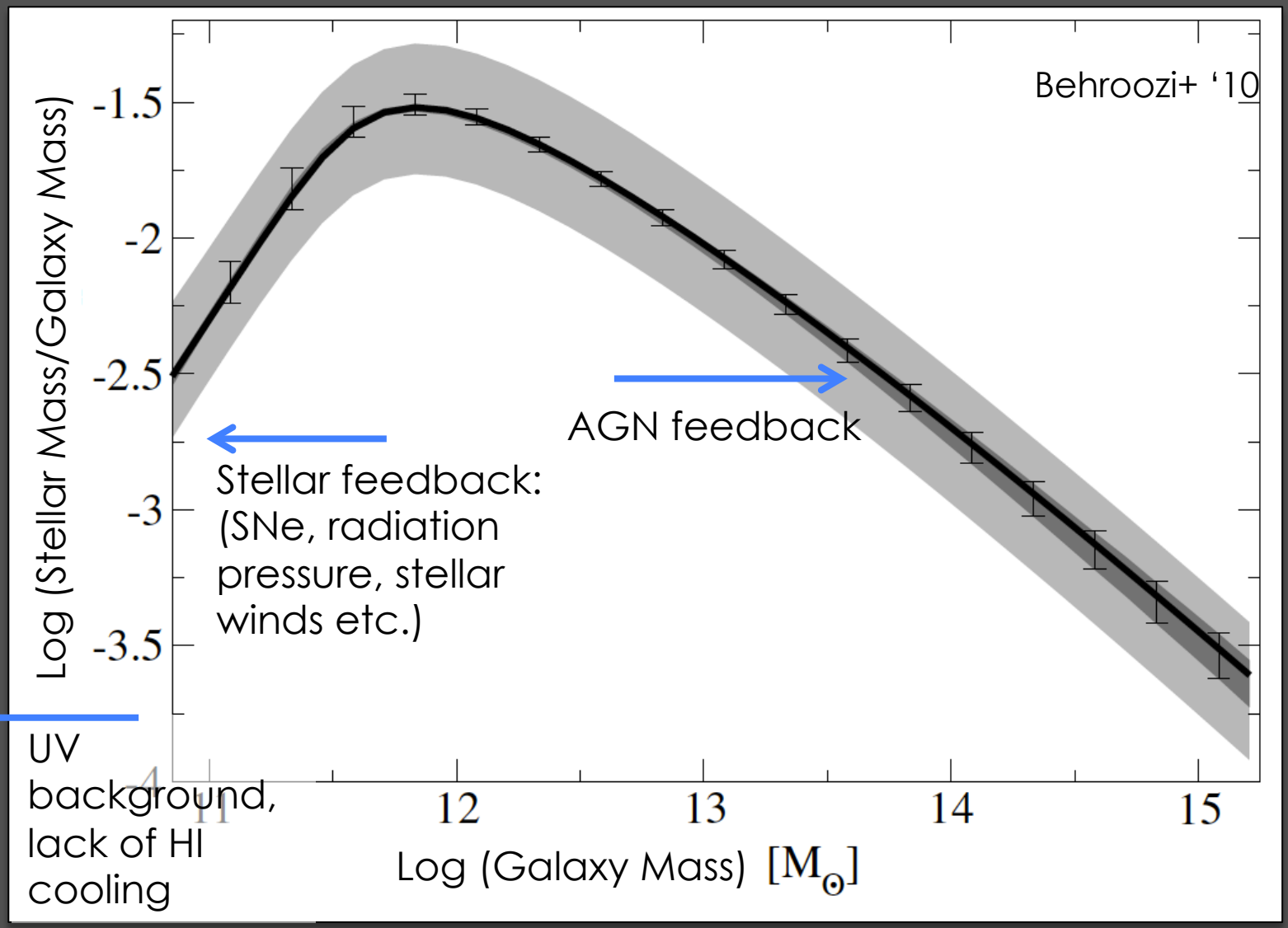
Grinnell College

Romeel Davé, Alyson Brooks, Andrew Pontzen, Fabio Governato

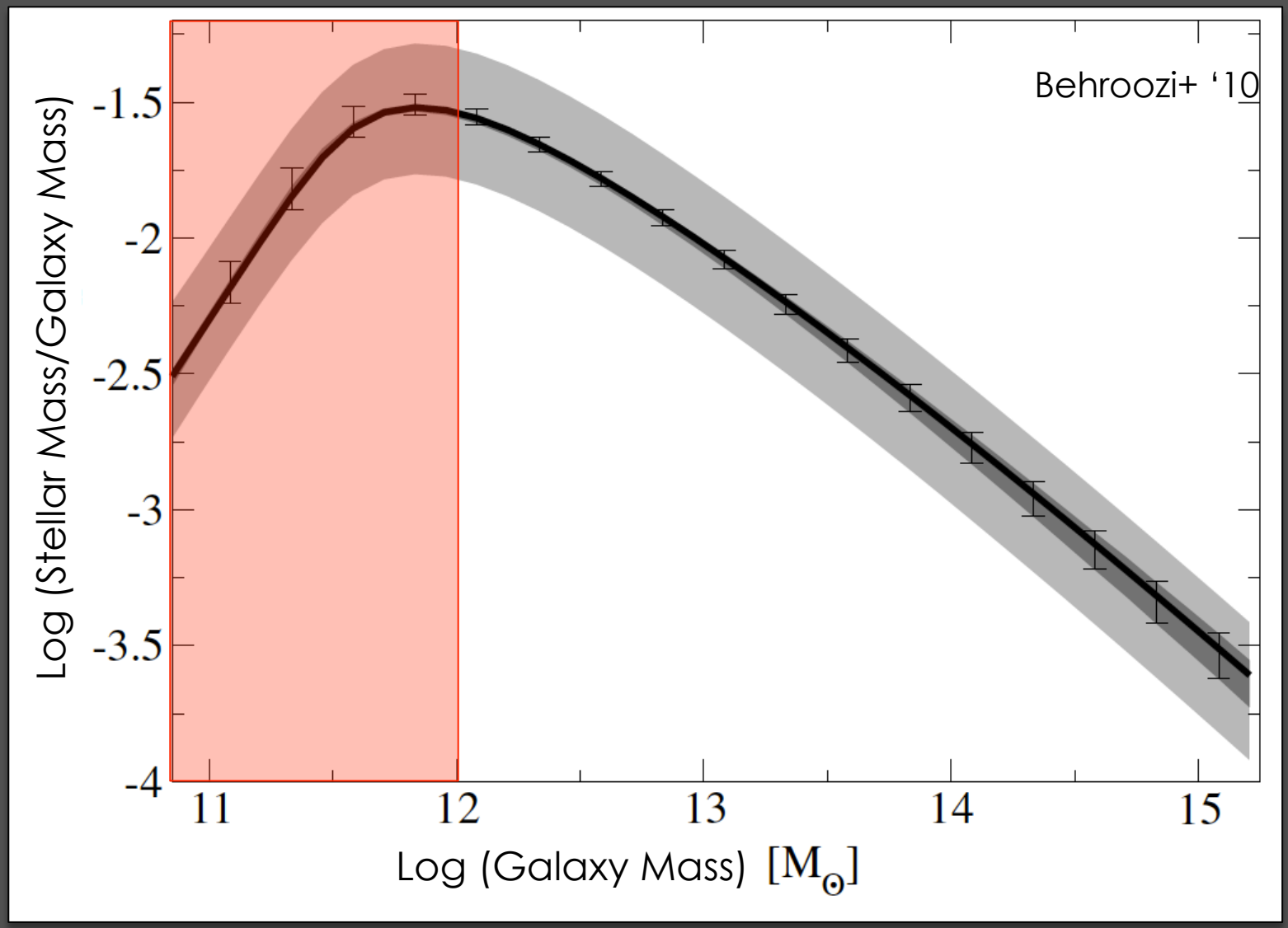
Stellar Mass Fraction vs. Halo Mass



Stellar Mass Fraction vs. Halo Mass

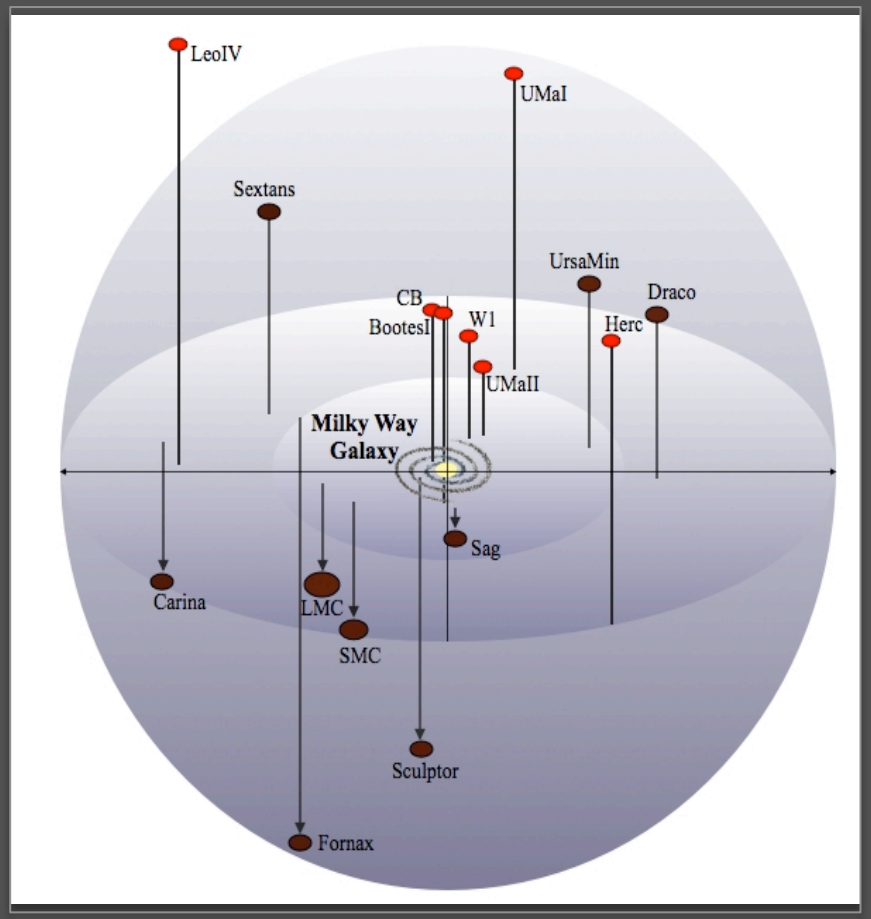


Stellar Mass Fraction vs. Halo Mass



Dark Matter only models predict: Missing satellites

Milky Way

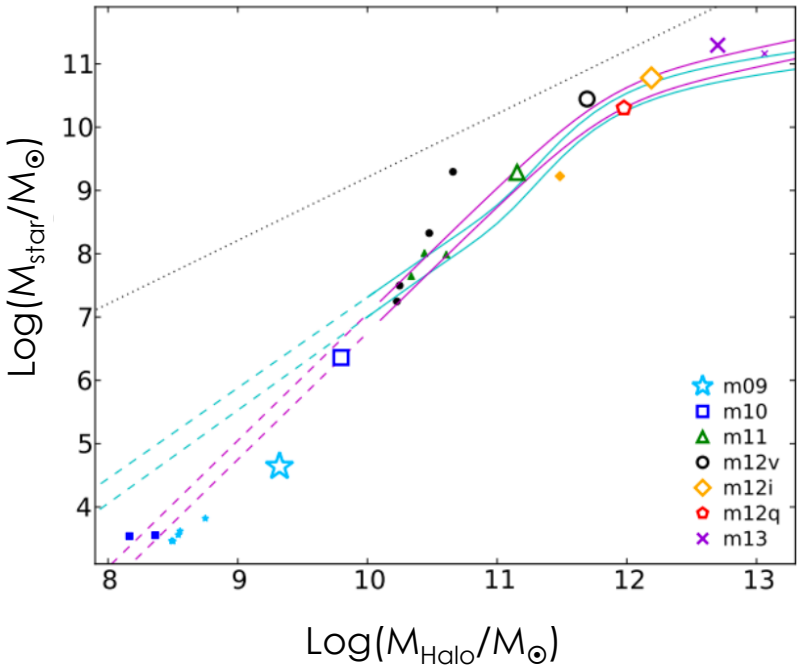


Simulations

Moore et al., 1999

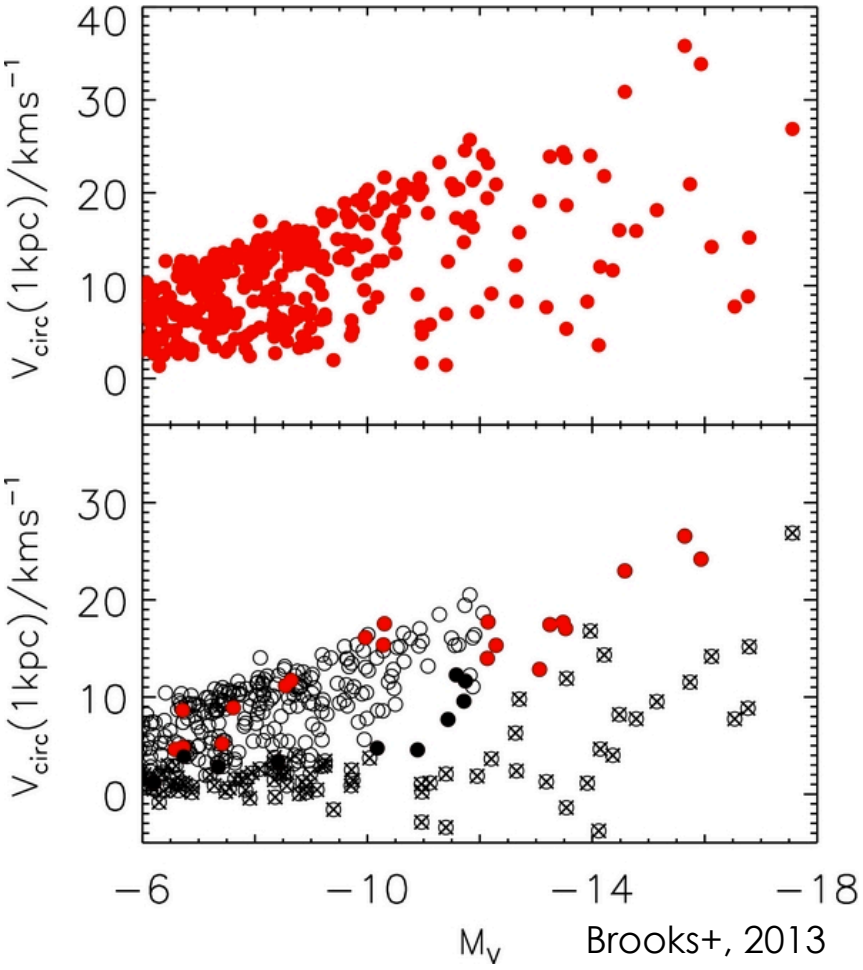
Stellar feedback results in

Smaller stellar mass/halo mass in low-mass galaxies



Hopkins+, 2014

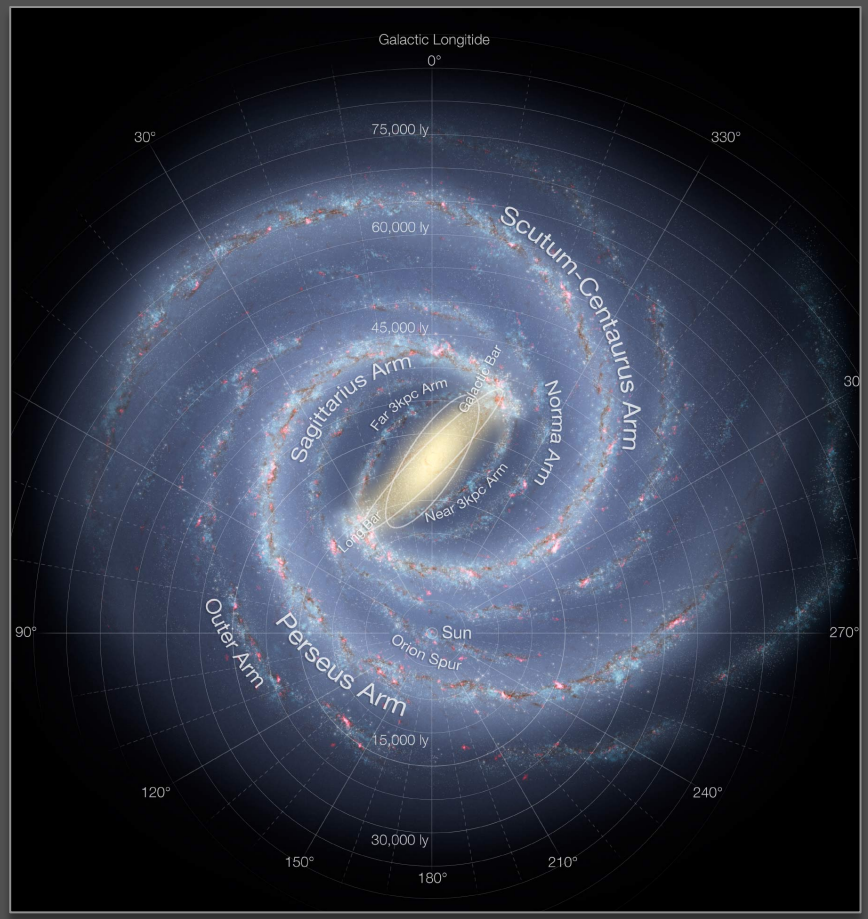
Fewer observable satellites



Brooks+, 2013

Dark Matter only models predict: Too concentrated of galaxies

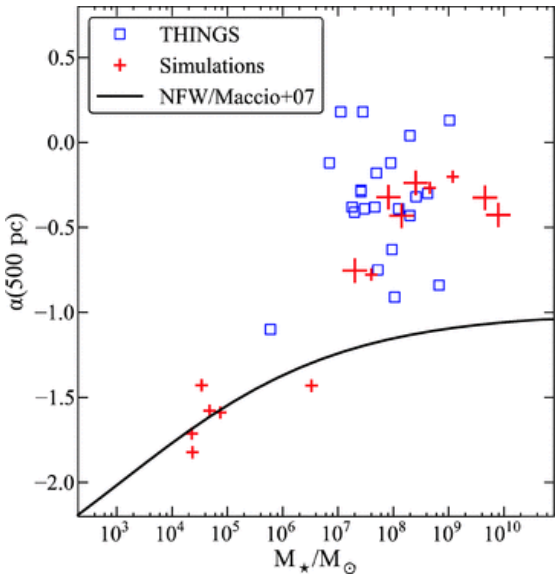
- Milky Way



- Simulations

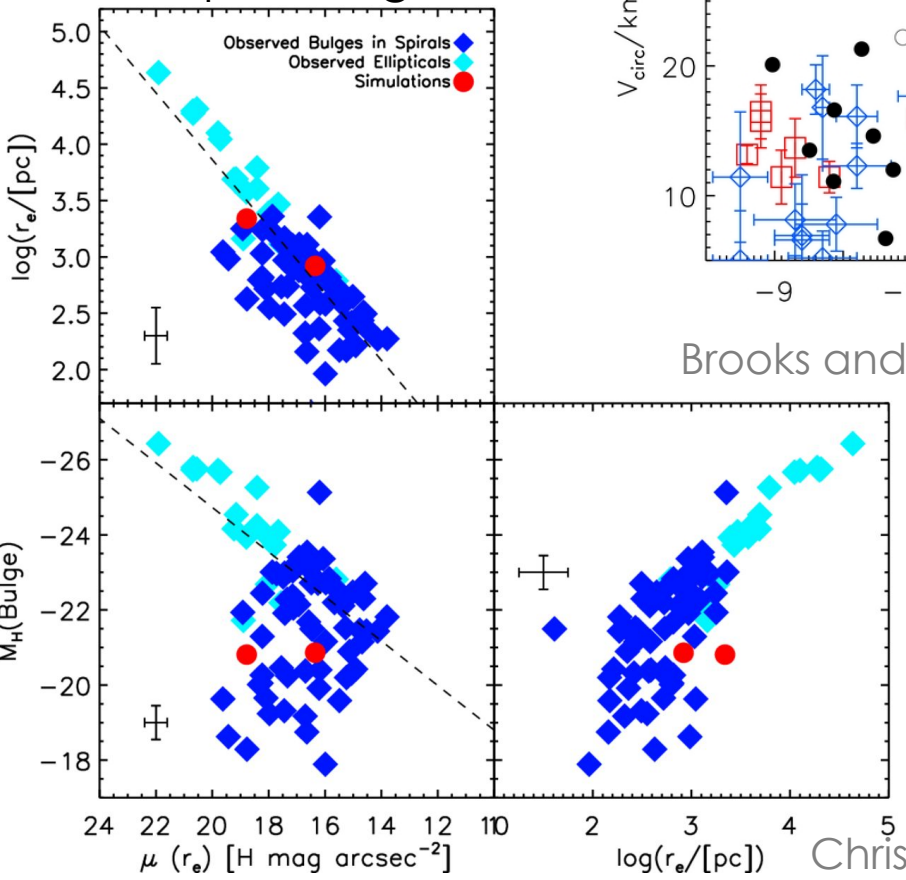
Stellar feedback results in

Cored Profiles



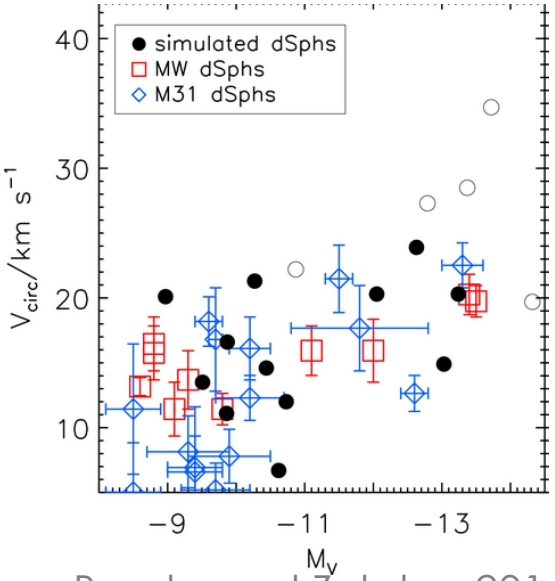
Governato+ 2012

Appropriately Shaped Bulges



Christensen+ 2014

Appropriate Circular Velocity of Satellites



Brooks and Zolotov 2014

For discussion on outflows changing central density, see Governato+ '10, Guedes+ '11, Brook+ '11, Pontzen+ '12, Teyssier+ '13, Anglés-Alcázar+ '13, Christensen+ '13

What would a theorist like to have?

- Spatially resolved star formation histories for a range of galaxies including ellipticals and extremely isolated faint dwarf galaxies.
- Observations of sites of outflows
- Measurements of the CGM

A simulator's approach

- Given a hydrodynamic code that produces galaxies with reasonably realistic properties, using a physically-motivated, tuned model for stellar feedback, *let's back out information about outflow properties as a function of halo mass*
  - Amount of ejection and recycling
  - Source of gas
  - Metallicity of gas

Code: Gasoline (Wadsley+ 2004)

- SPH code
- Cosmic UV background radiation
- H & He ionization; non-equilibrium H_2 (Christensen+ 2012)
- Metal line cooling and metal diffusion (Shen+ 2010)
- Probabilistic star formation based on free-fall time and H_2 abundance (shielded fraction) (Christensen+ 2012)
- Supernovae feedback from type II and type Ia (blastwave, $E_{SN}=10^{51}$ ergs) (Stinson+ 2006)

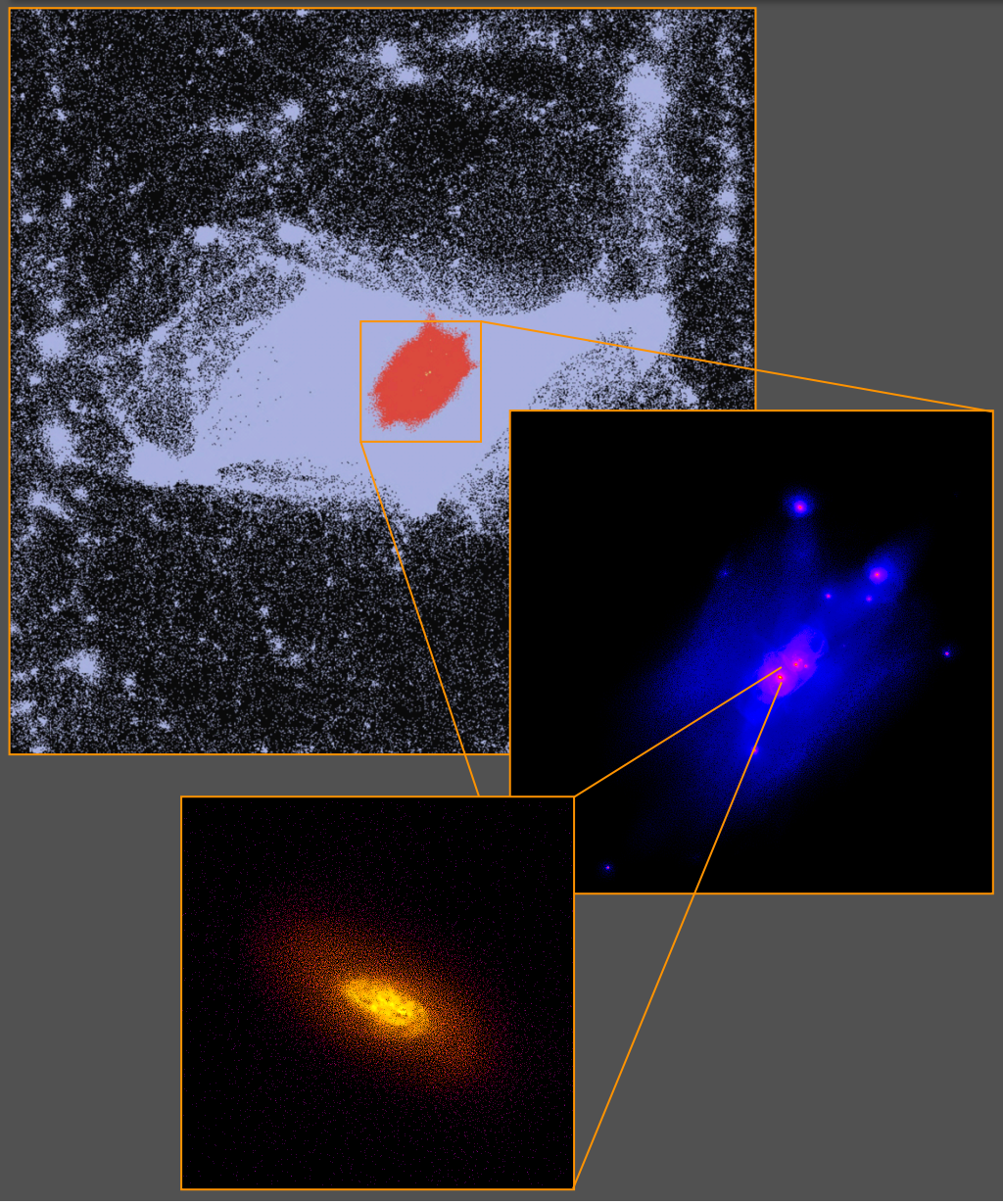
Blastwave Model for Feedback

- Thermal energy is transferred to gas particles near the star
- Cooling is disabled for the period of time equal to the momentum-conserving (snowplow) phase of the blastwave
  - function of E, P and ρ (McKee and Ostriker 1977)

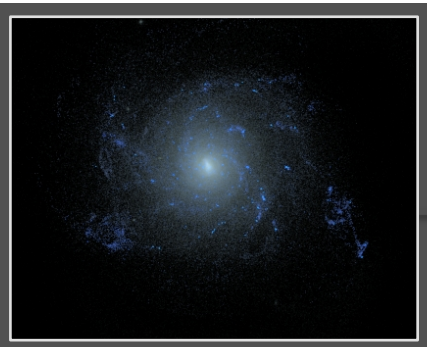
$$t_{\max} = 10^{6.85} E_{51}^{0.32} n_0^{0.34} \tilde{P}_{04}^{-0.70} \text{ yr.}$$

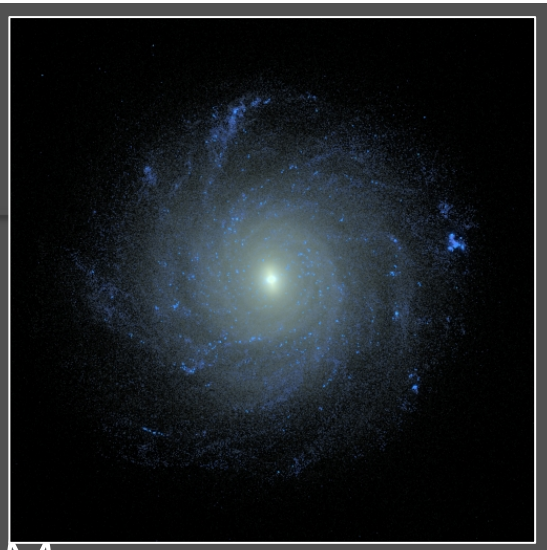
- The hot particle will naturally rise from the disk (no kick needed, no information about the halo included)

Cosmological Simulations

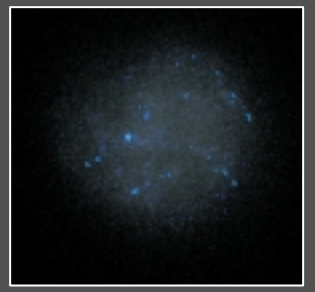


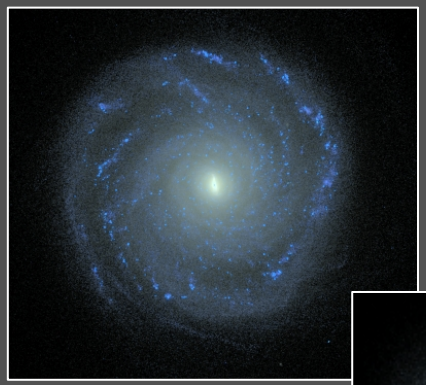
Simulations

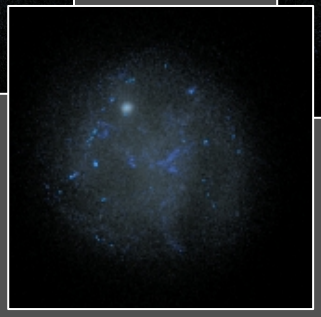


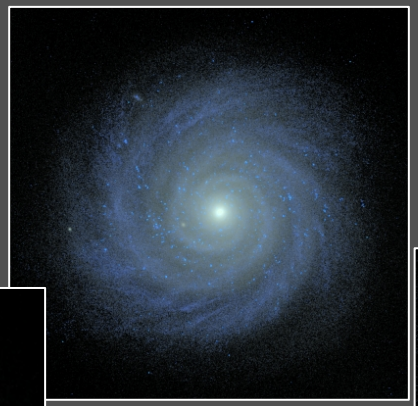


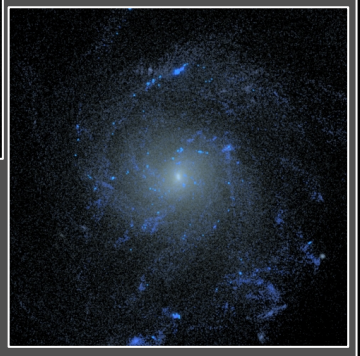
- 20 central galaxies from zoom-in, cosmological simulations.
- Virial masses at z = 0 from 5×10^9 – 10^{12} $M_\odot$
- Gas particle masses: 3300$M_\odot$ or 25,000$M_\odot$
- Softening lengths: 87 or 170 pc

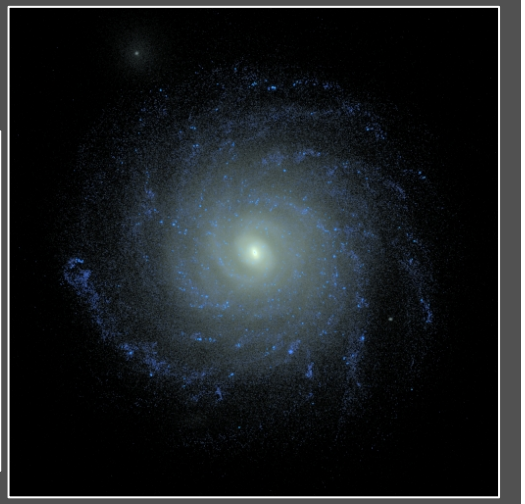








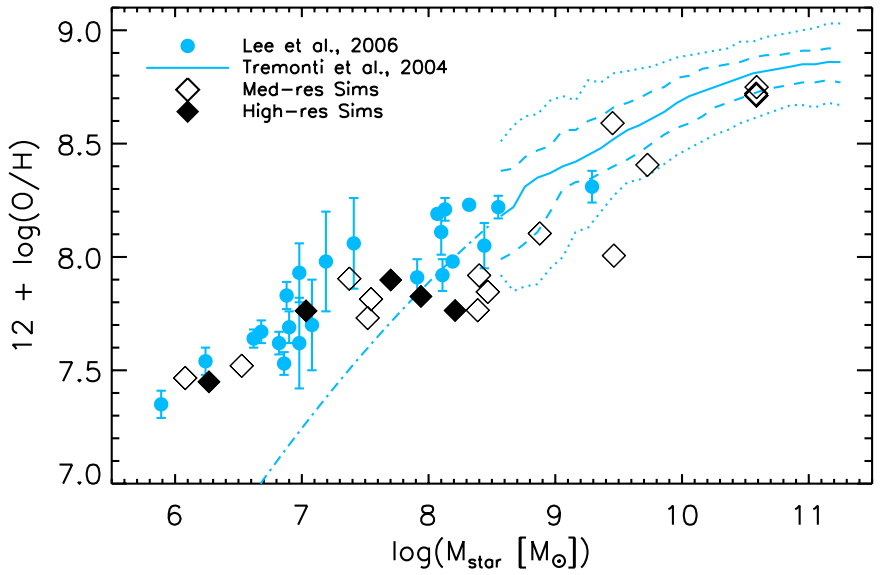




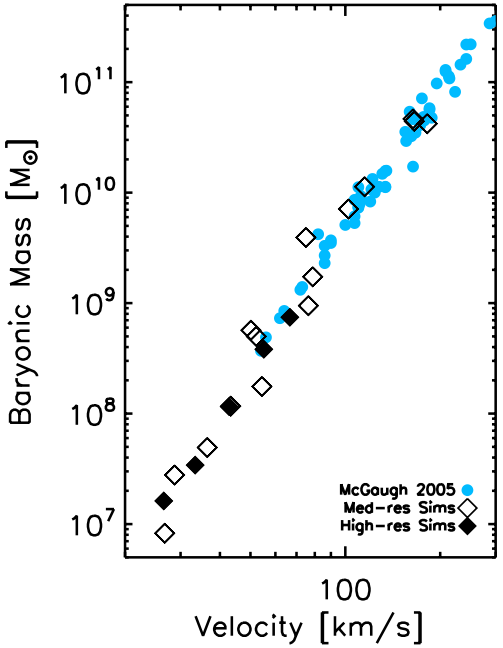
Observed relations of global properties at z = 0

Also, realistic sizes, and gas fractions

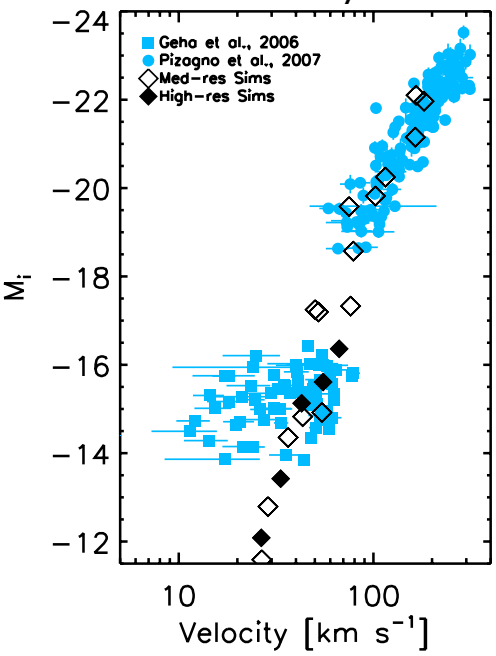
Stellar Mass-Metallicity Relation



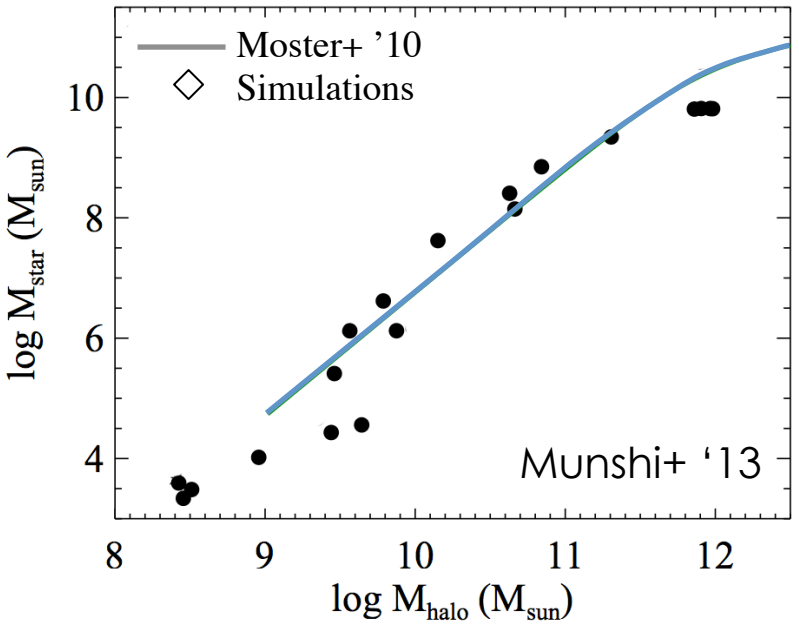
Baryonic Tully-Fisher



Stellar Tully-Fisher



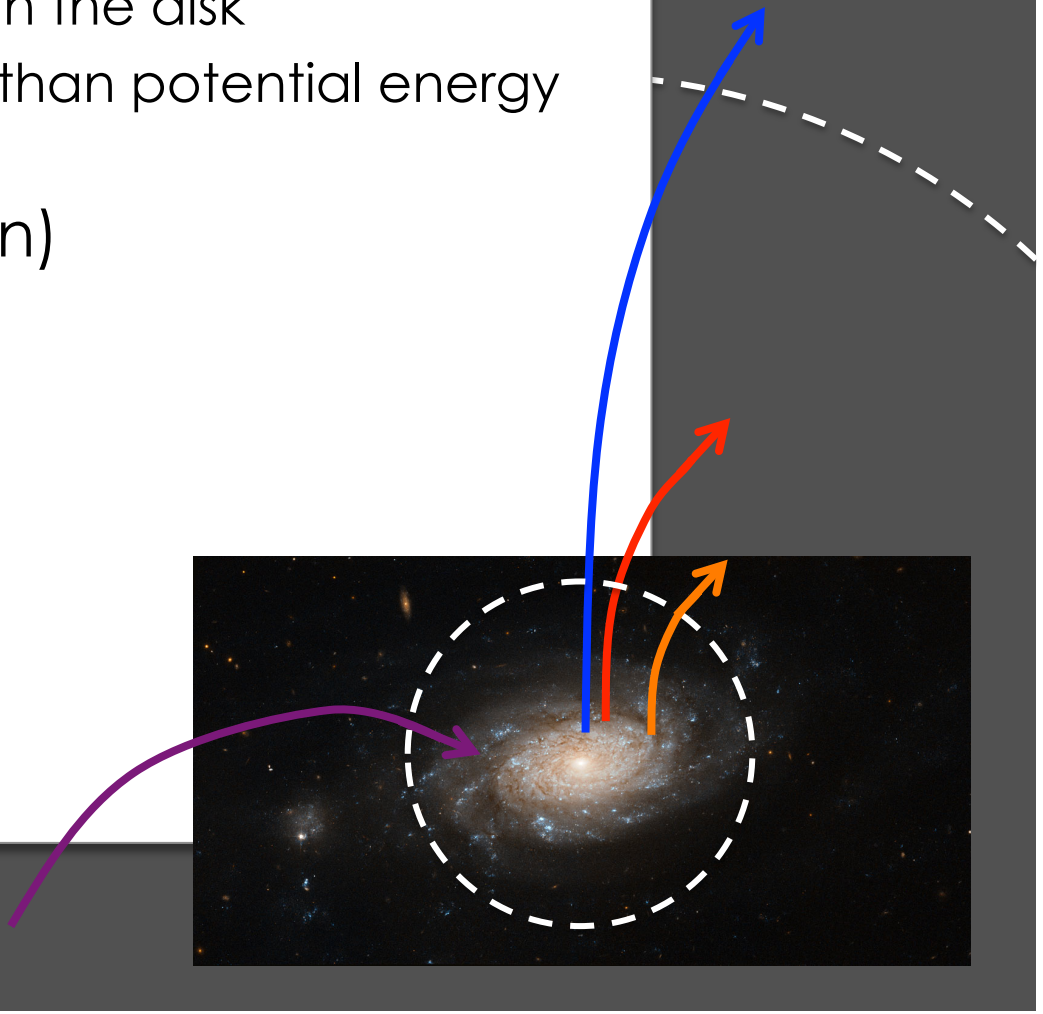
Stellar Mass-Halo Mass Relation



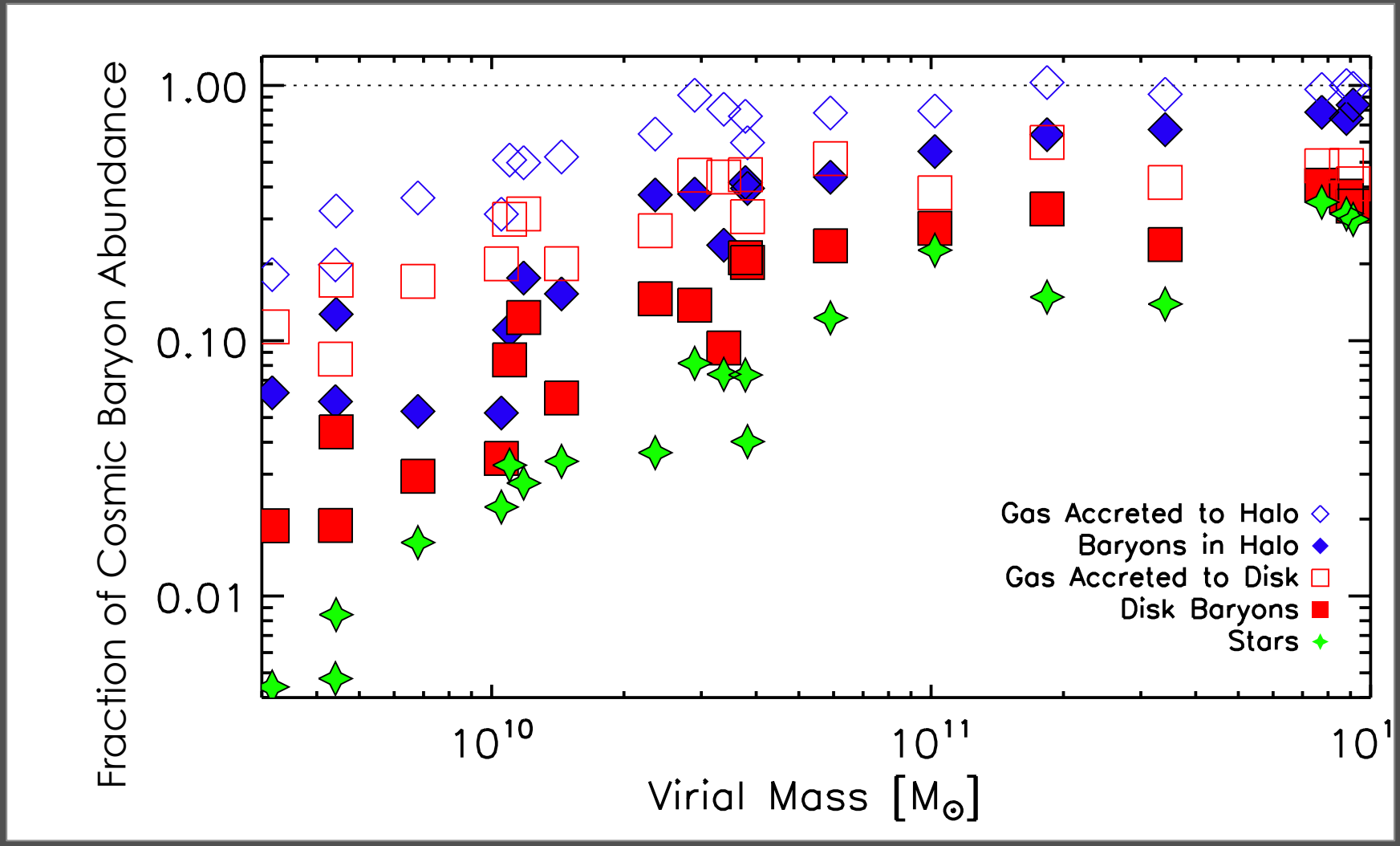
Christensen et al, 2015

Tracking Particles

- Ejected gas:
  - Must have once been in the disk
  - Kinetic energy greater than potential energy from the *disk*
- (100 Myr time resolution)

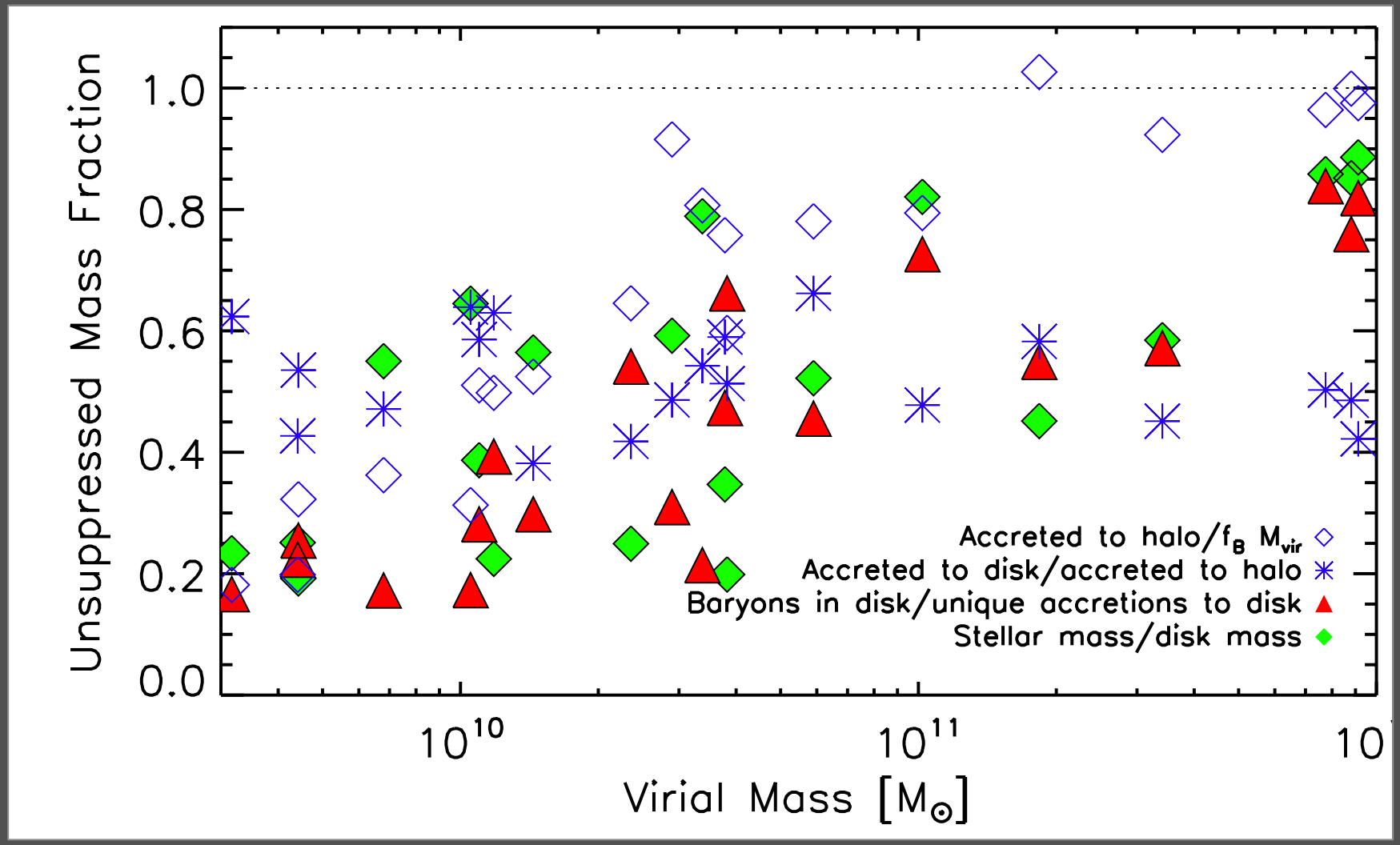


Baryonic Fraction



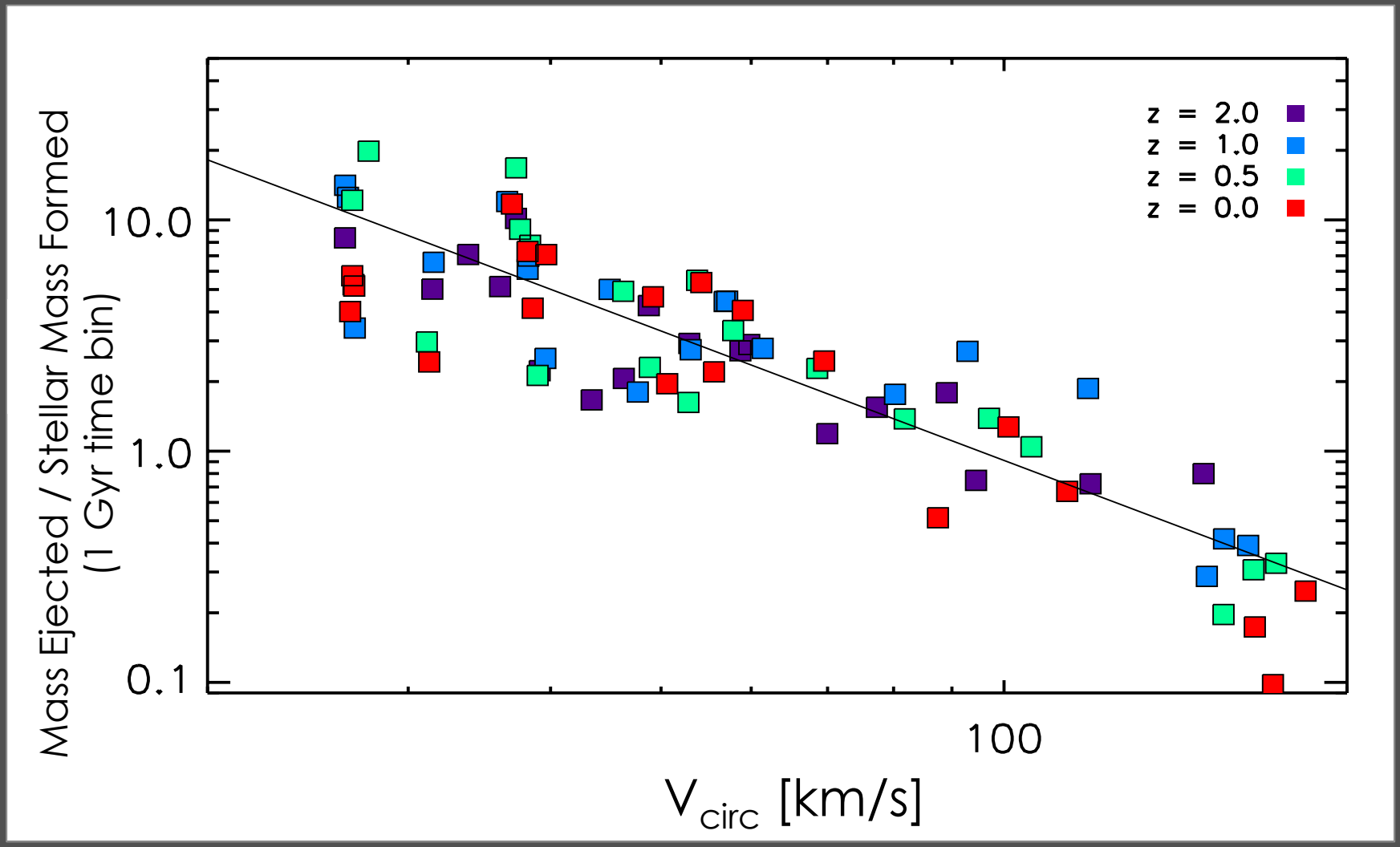
Christensen et al, 2015

Baryonic Fraction



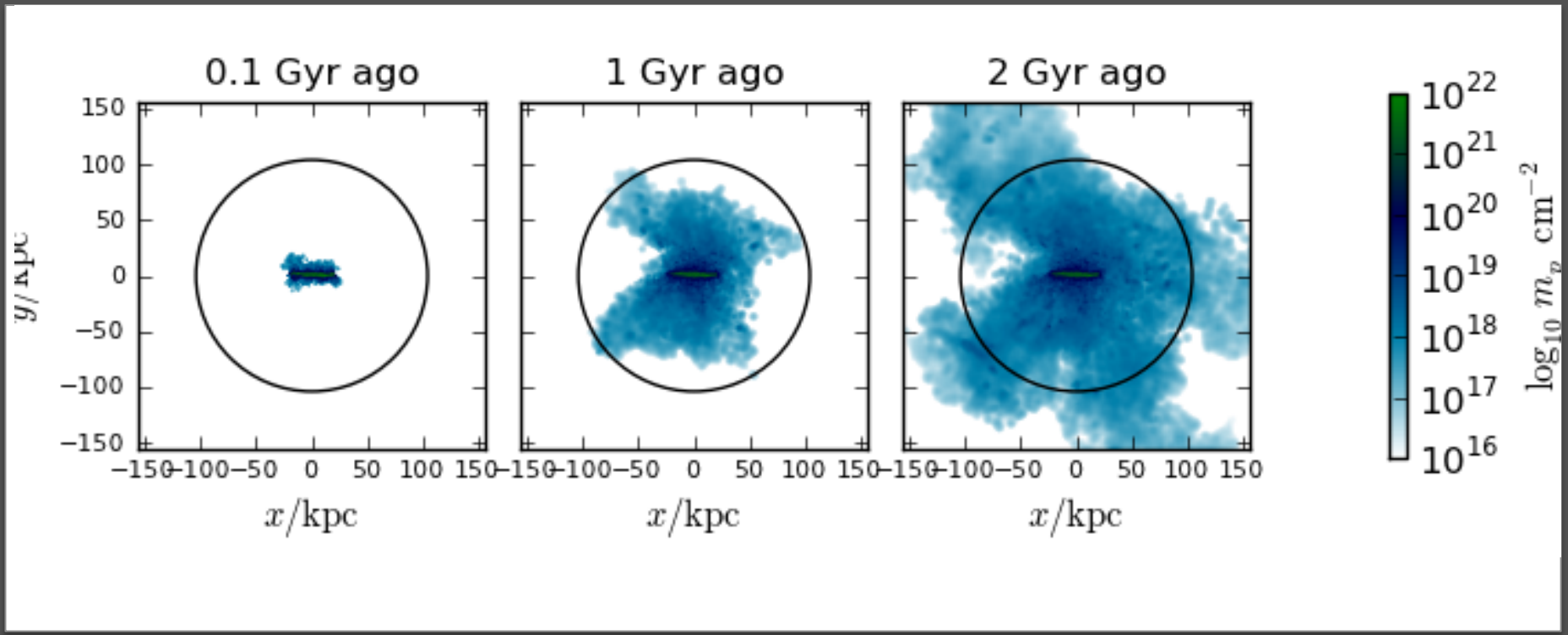
Christensen et al, 2015

Mass Loading Factor for Ejected Material

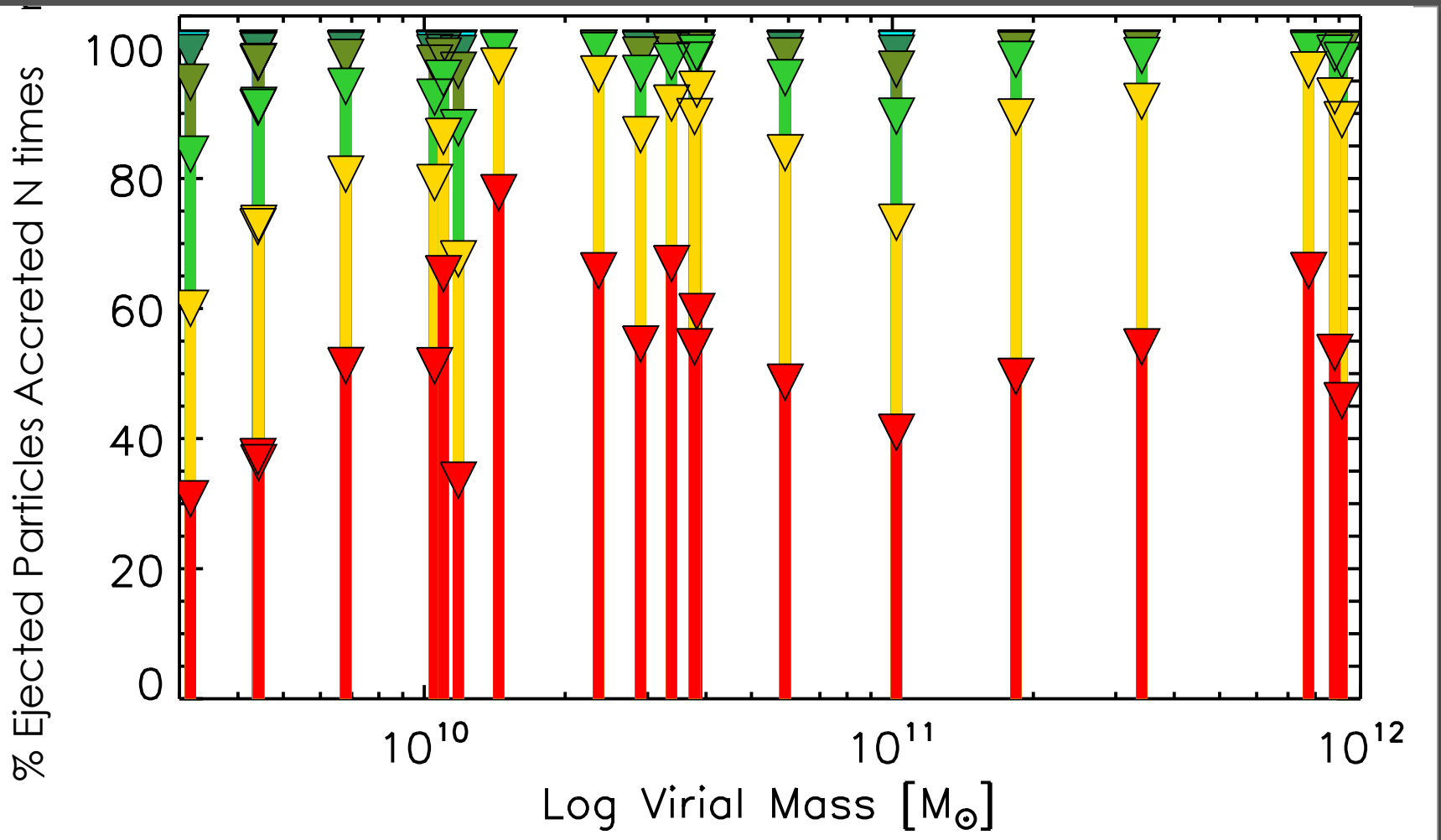


Christensen et al, 2015

Spread of outflow material



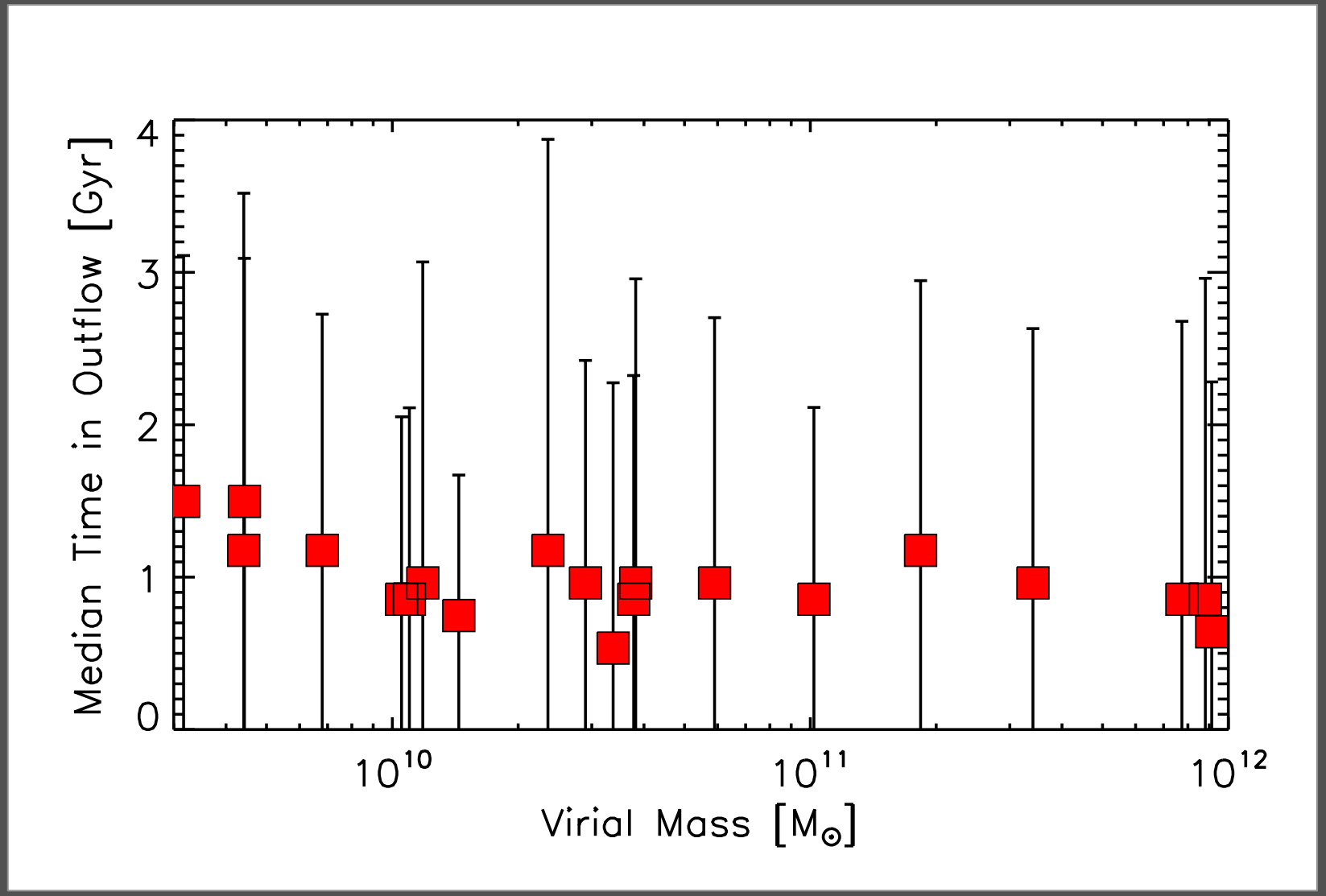
Number of Times a Particle is Reaccreted



Never Reaccreted Reaccreted once Reaccreted twice . . .

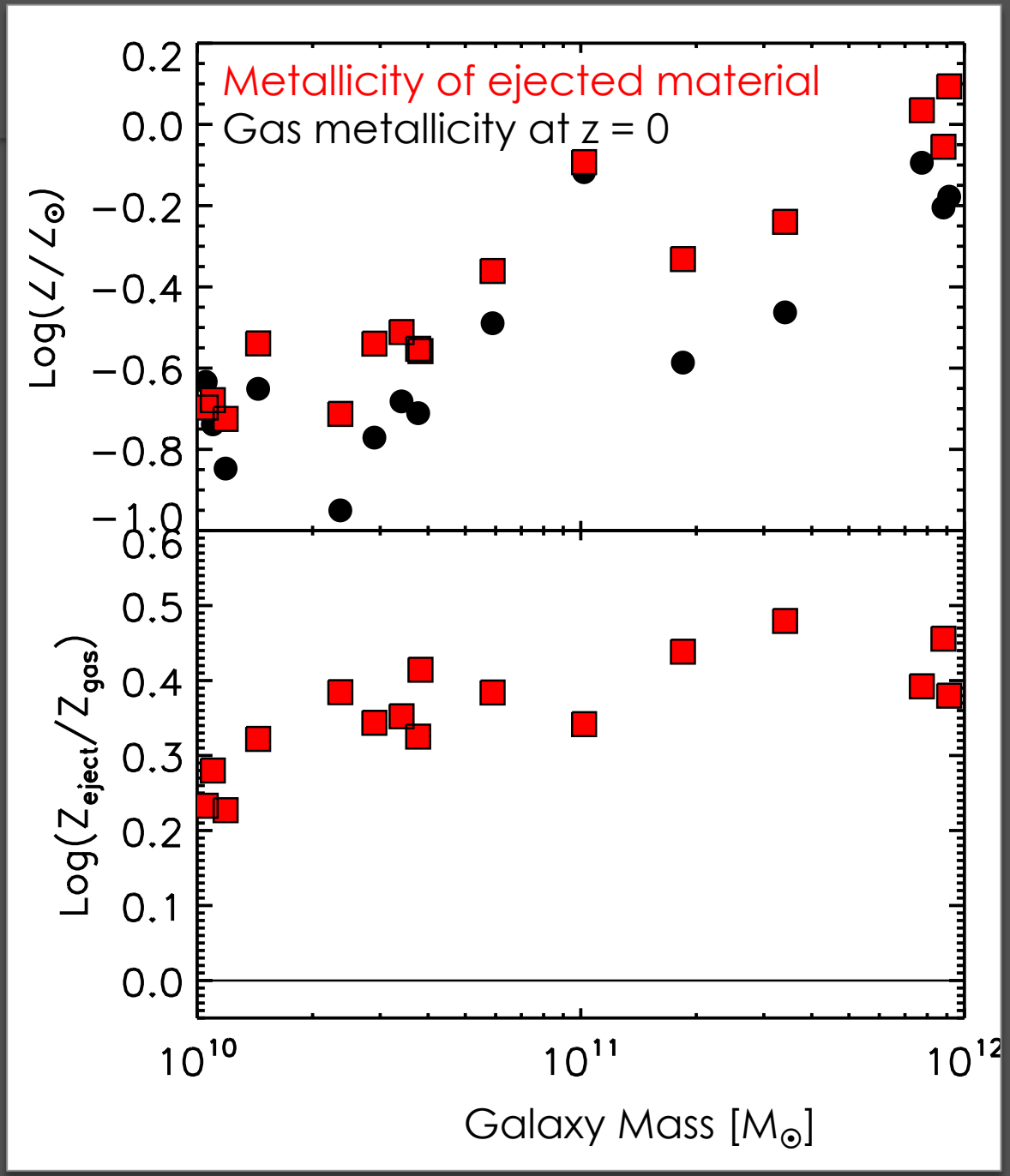
Christensen et al, 2015

Amount of Time Before Reaccretion

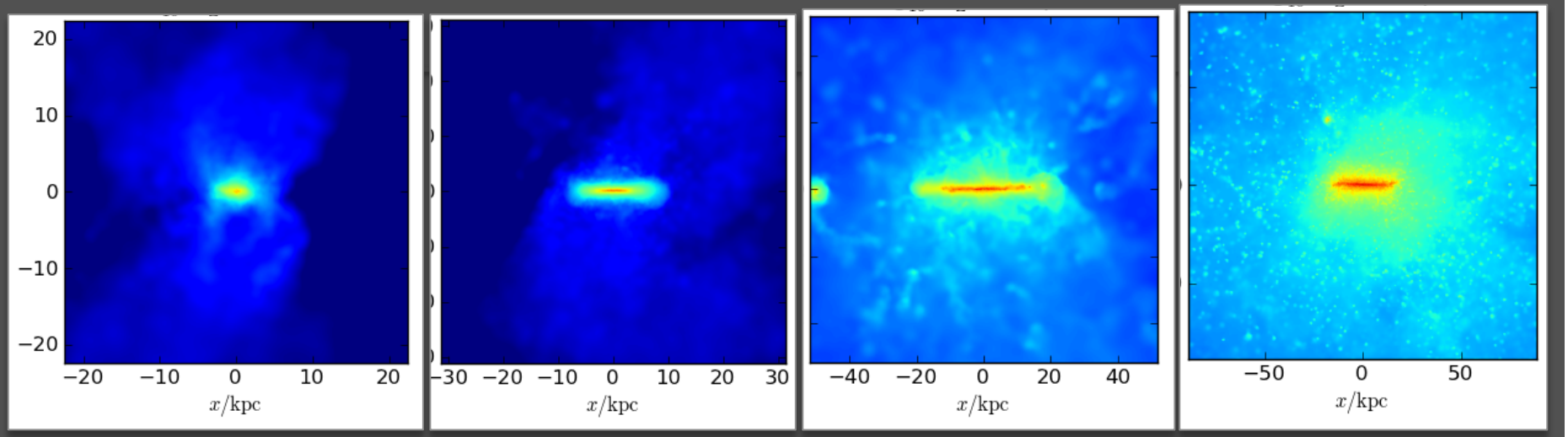


Christensen et al, 2015

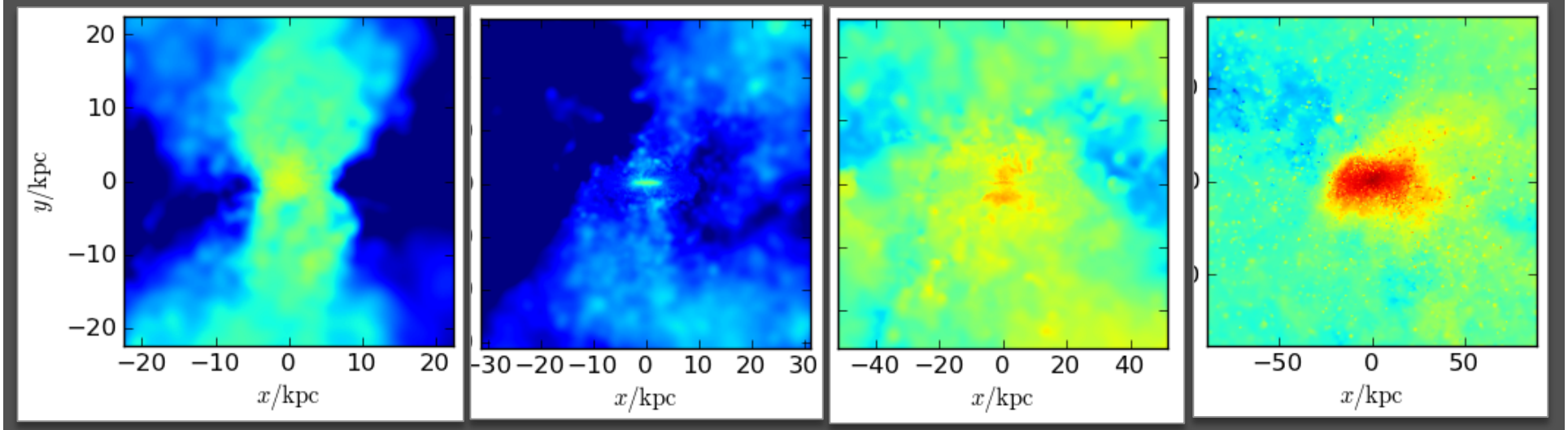
Metal Enrichment of Outflows



Metal Surface Density

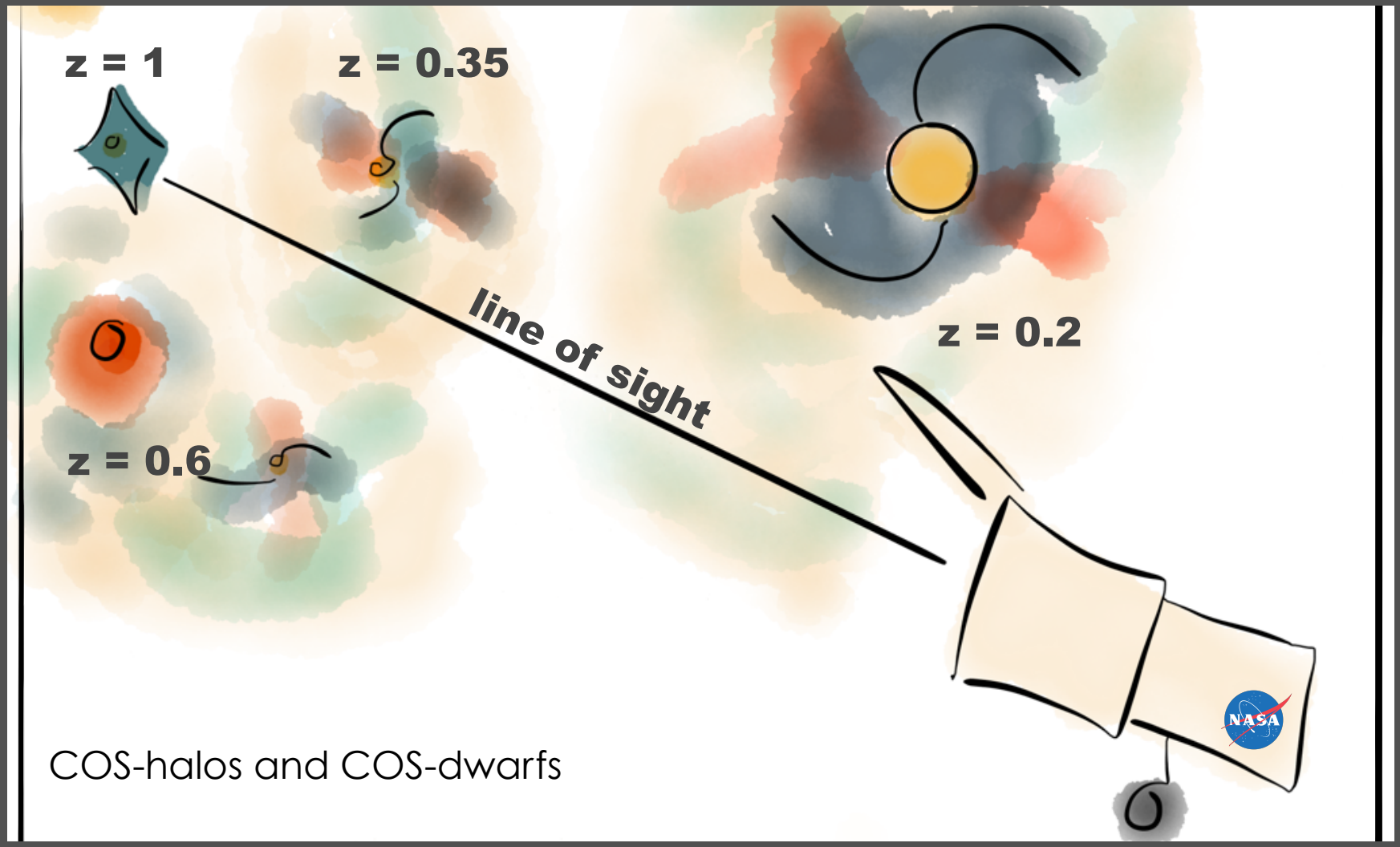


Mass →



Log Metallicity of Gas (slice through center of galaxy)

Observations of CGM through Quasar Absorption Line Spectra

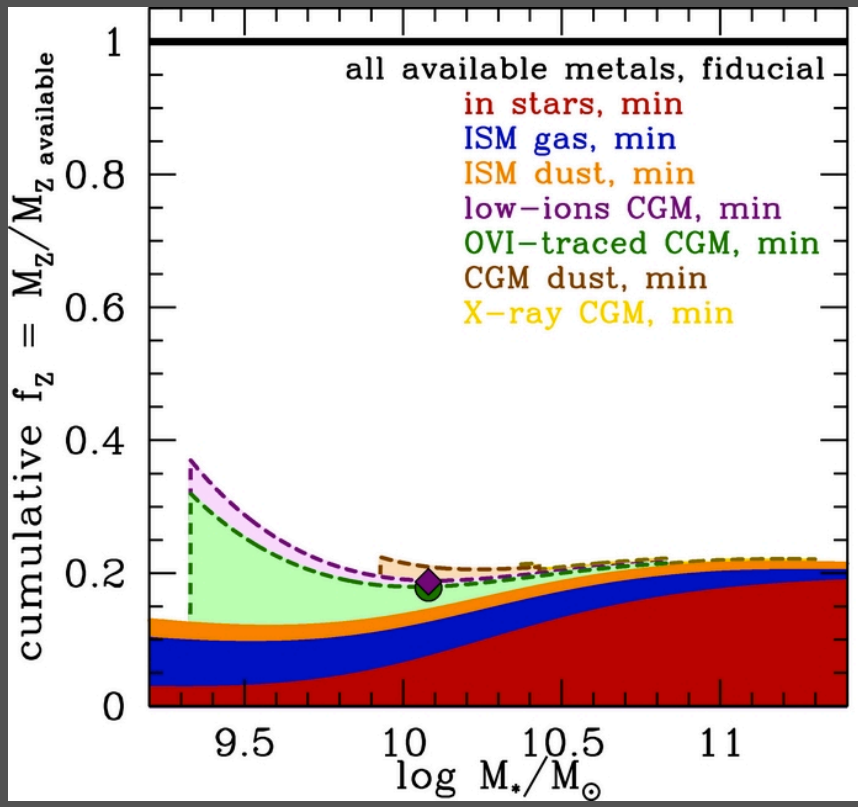


COS-halos and COS-dwarfs

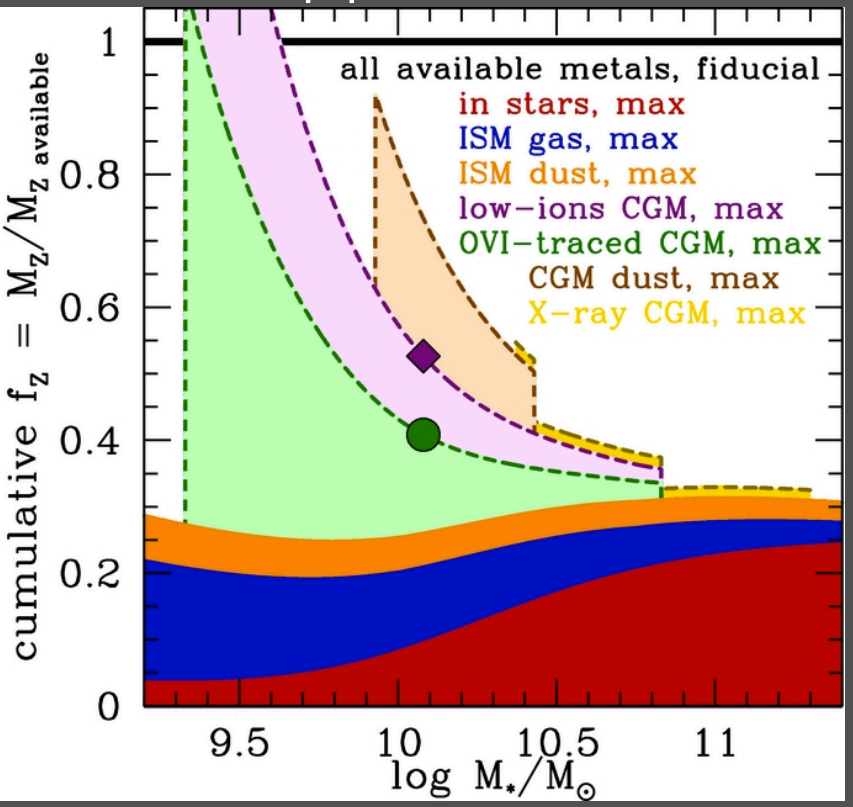
Image from Jessica Werk

Metal budget

Lower estimate



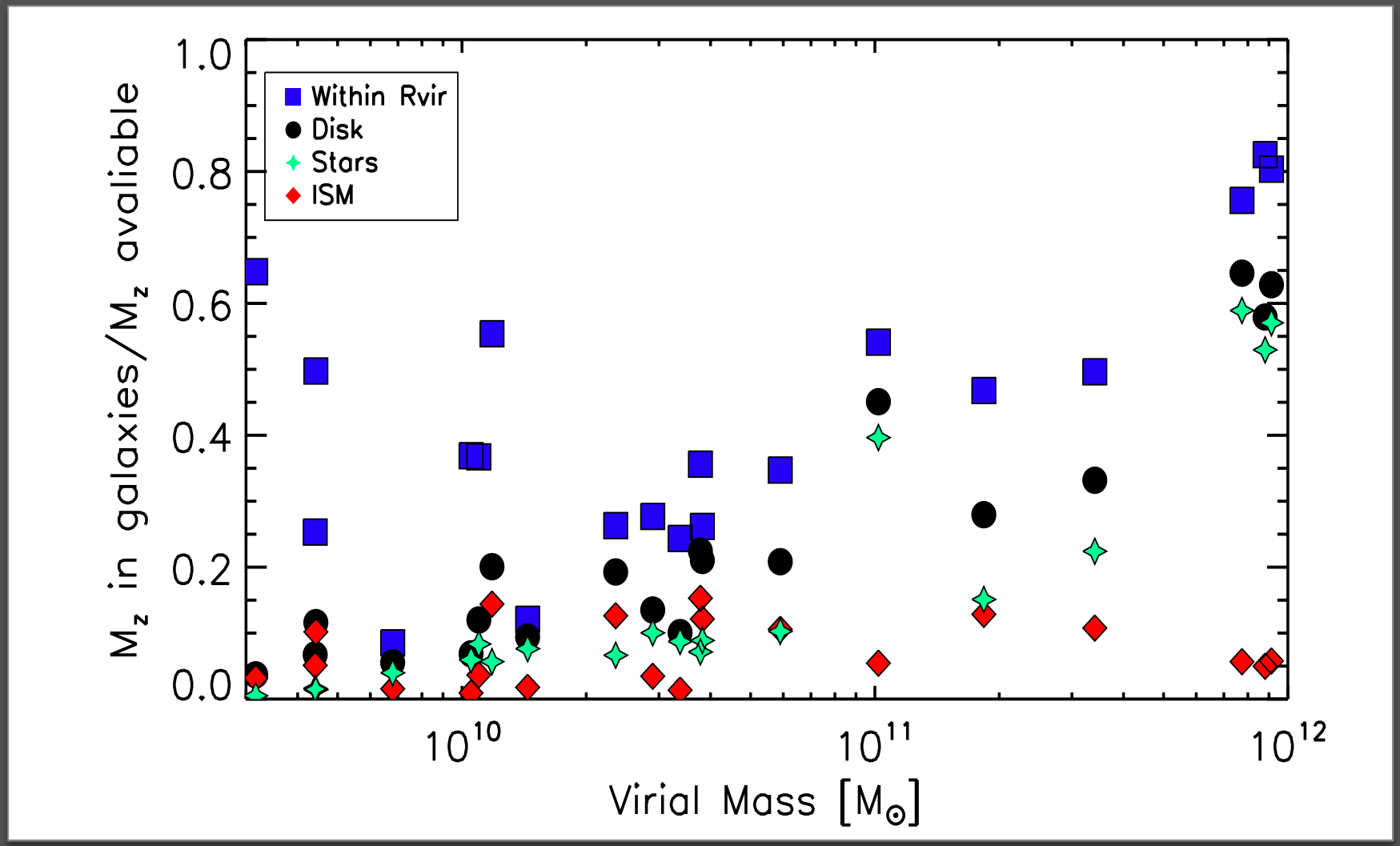
Upper estimate



Peeples+2014

Compare with McQuinn+ 2015 of Leo P

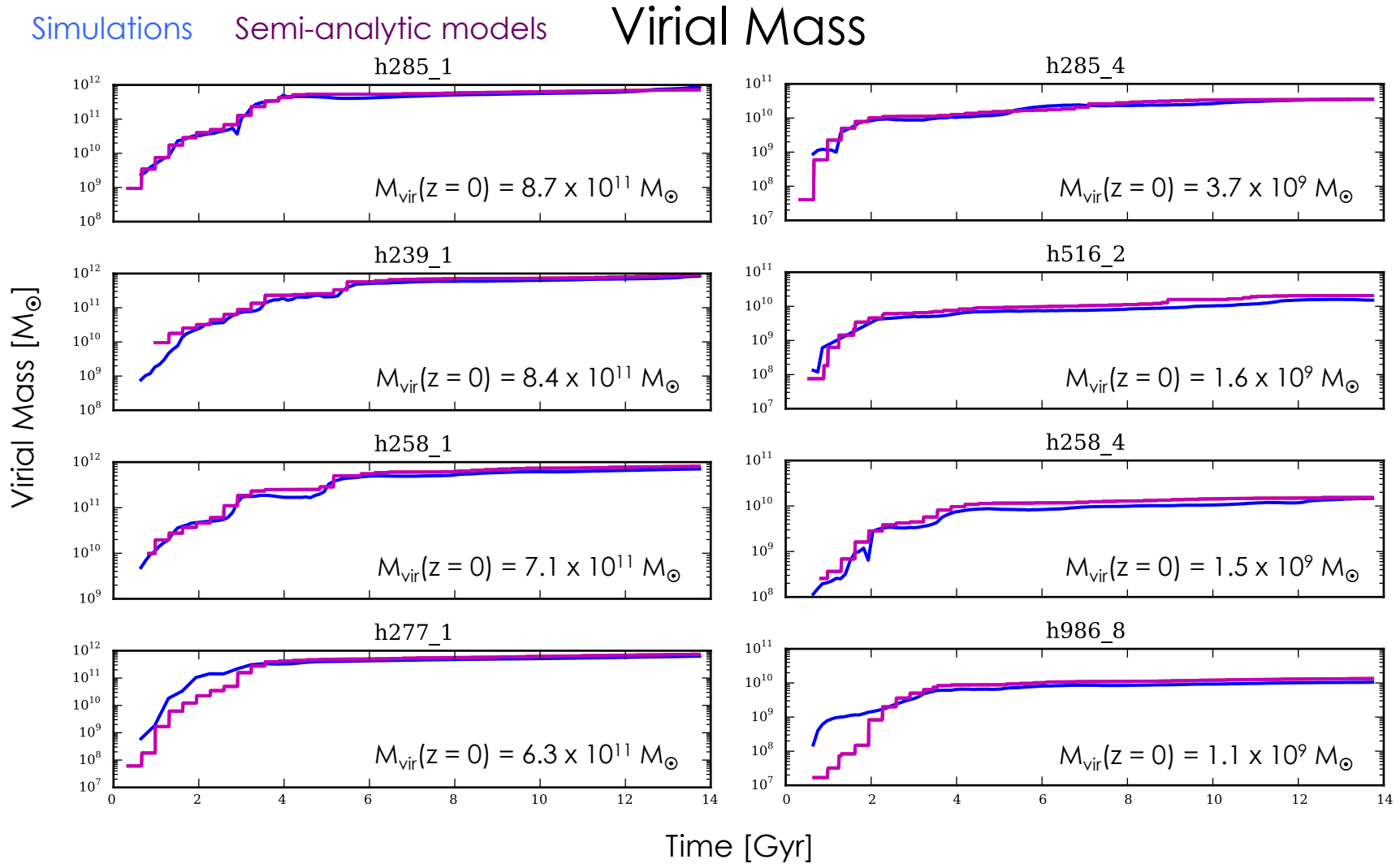
Eventual Location of Metals



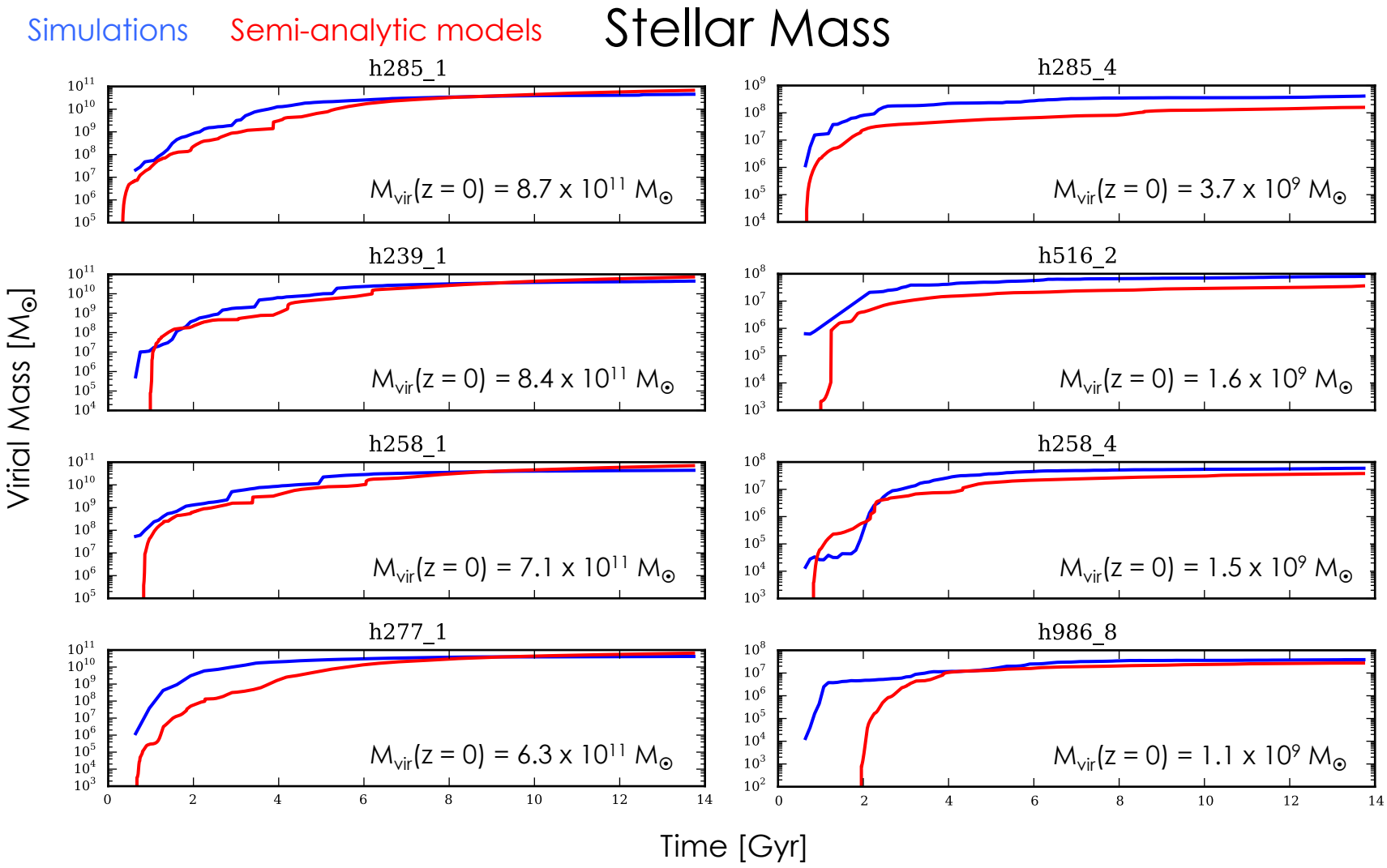
Working with semi-analytic models

- What SAMs add
  - Dramatically increase statistics
  - Allows for testing of individual prescriptions
  - Results in develop analytic models
- Using simulations to inform SAMs
  - Input models derived from simulations into SAM
  - Select merger history from dark matter and re-simulate with SAM
- Work done by Yotam Cohen with Rachel Somerville and myself

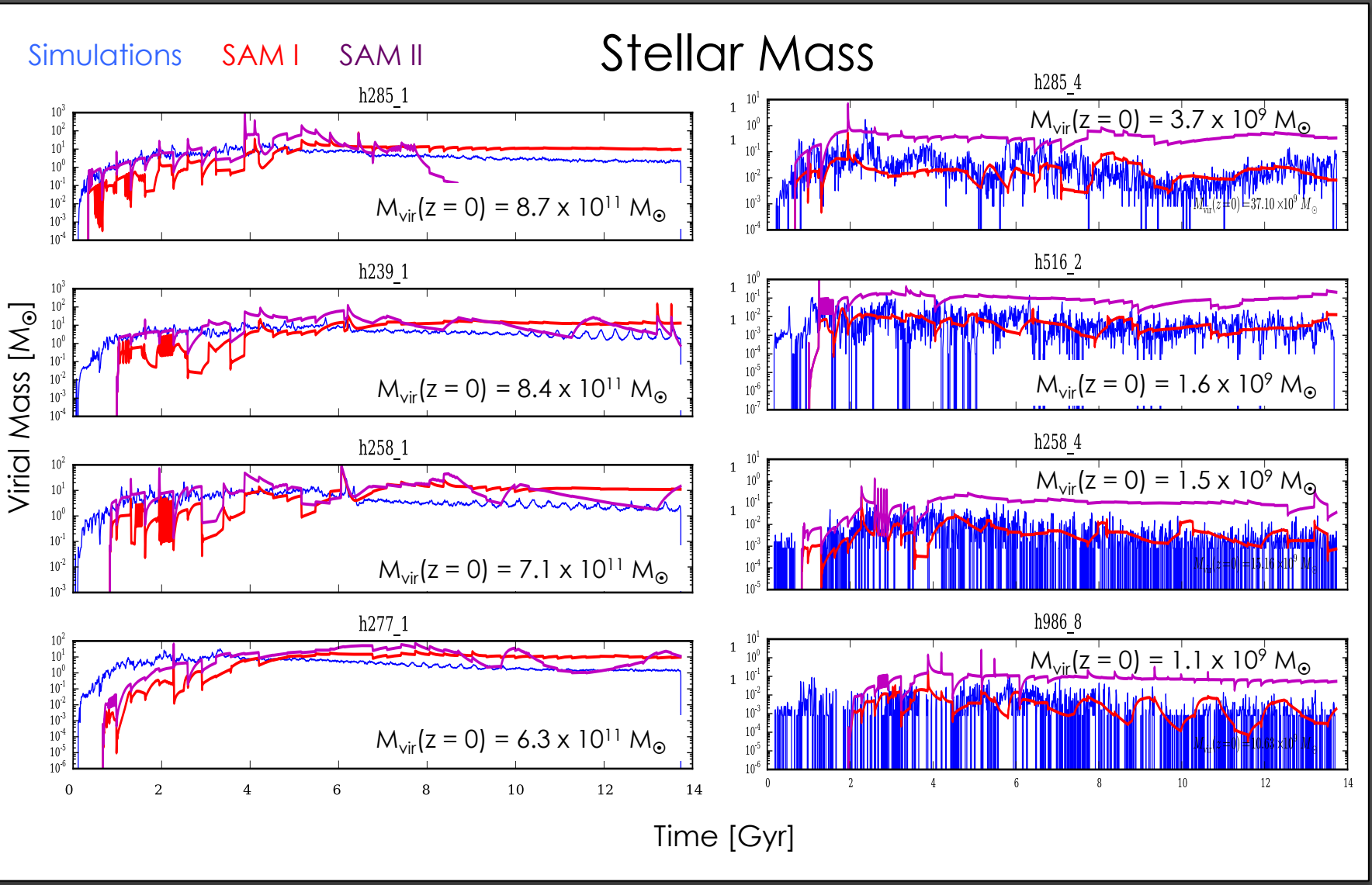
Comparing Sims and SAMs



Comparing Sims and SAMs



Comparing Sims and SAMs



Summary and plan for future

- We know that stellar feedback has a profound effect on galaxy growth and structure and yet is poorly understood
- Use detailed simulations to measure properties of outflows and the resulting CGM
- Apply models derived from simulations to SAMs to produce populations of galaxies and to interpret the simulations
- In an ideal future, combine with measurements of resolved star formation histories, outflowing gas, and the CGM