Simulating the Gas Cycle in Galaxies

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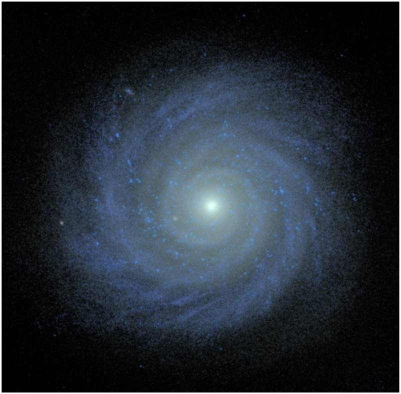
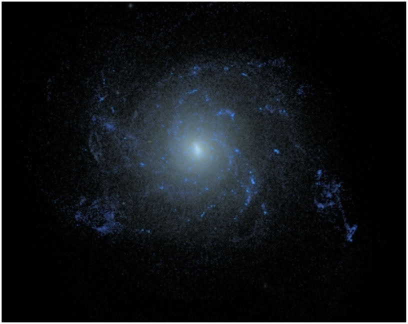
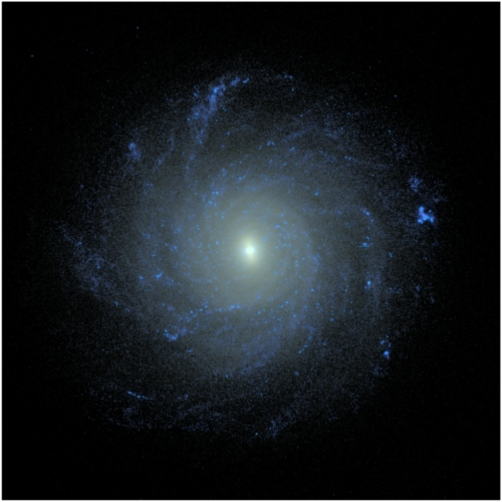
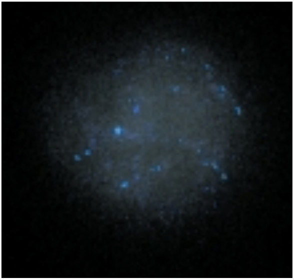
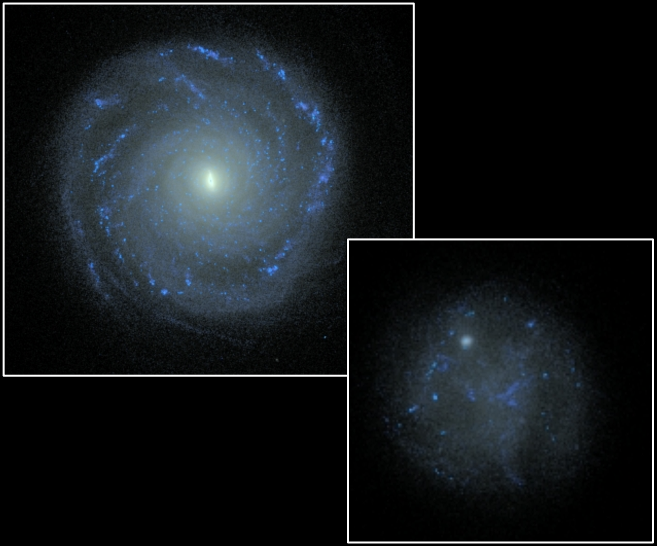
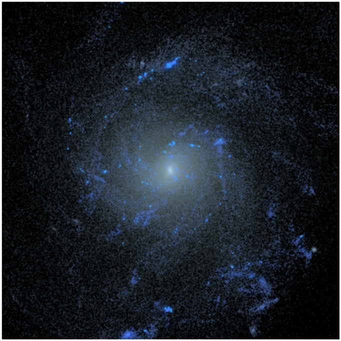
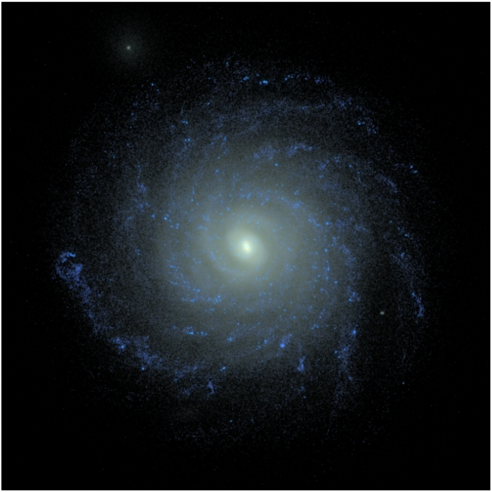
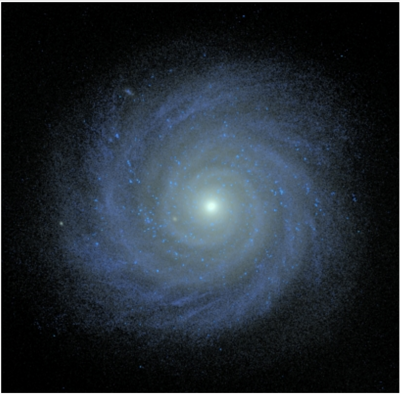
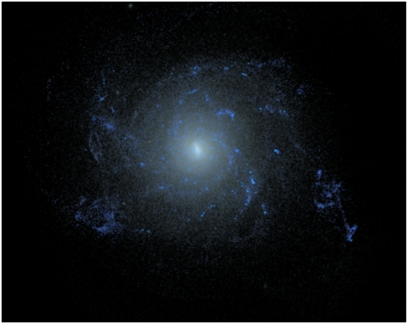
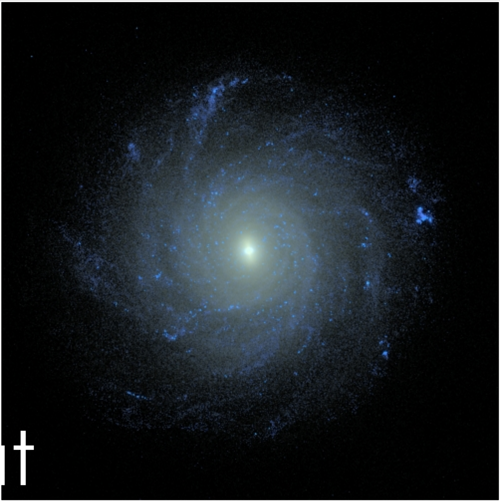
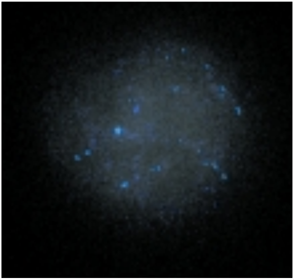




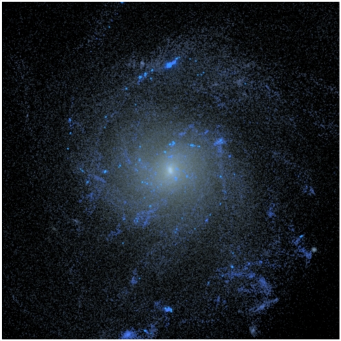
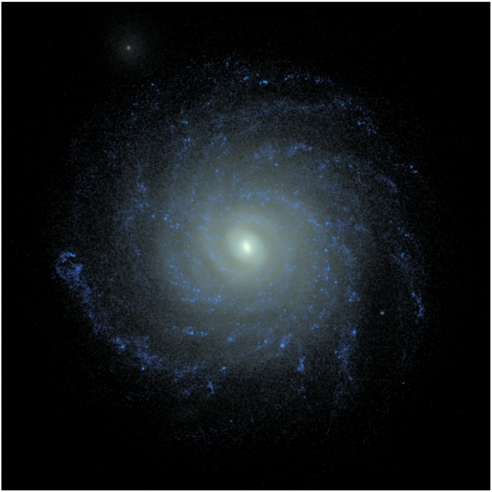
What are the accretion and outflow histories of baryons in galaxies, and what are the properties of the (re)accreting and outflowing gas?

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 & inflow properties*



Code: Gasoline

- SPH code (Wadsley+ 2004)
- Cosmic UV background radiation
- H & He ionization; non-equilibrium H_2 (Christensen+ 2012)
- Metal line cooling and metal diffusion. O and Fe abundances tracked. (Shen+ 2010)
- Probabilistic star formation based on free-fall time and H_2 abundance, $c^* = 0.1$ (Christensen+ 2012)
- Supernovae feedback (blastwave, $E_{SN}=10^{51}$ ergs) (Stinson+ 2006)
  - 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)
- No AGN feedback here . . .

Simulations

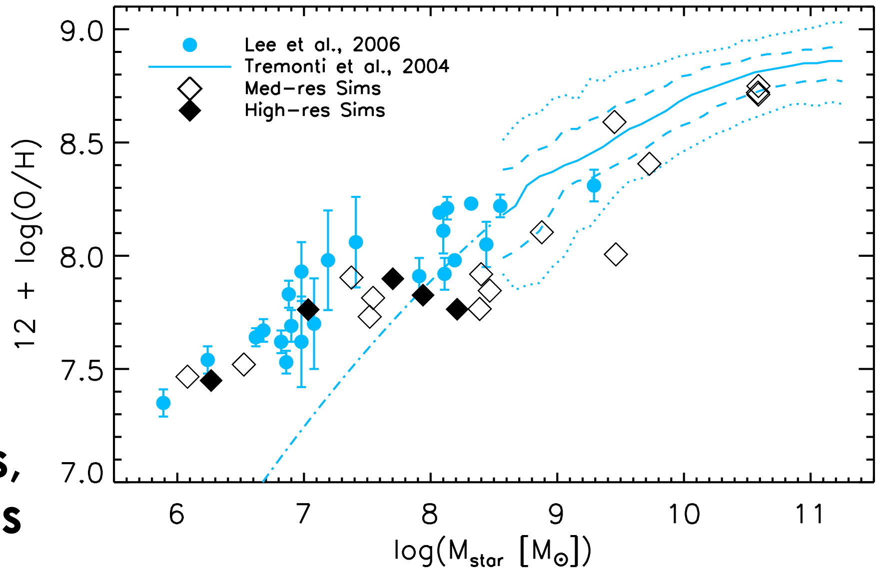
- 20 central galaxies from zoom-in, cosmological simulations.
- Virial masses at $z = 0$ from $5\times10^{9} - 10^{12}\ M_{\odot}$
- Gas particle masses: $3300 M_{\odot}$ or $25{,}000 M_{\odot}$
- Softening lengths: 87 or 170 pc, smoothing lengths > 0.1 softening lengths

Observed relations of global properties at z = 0

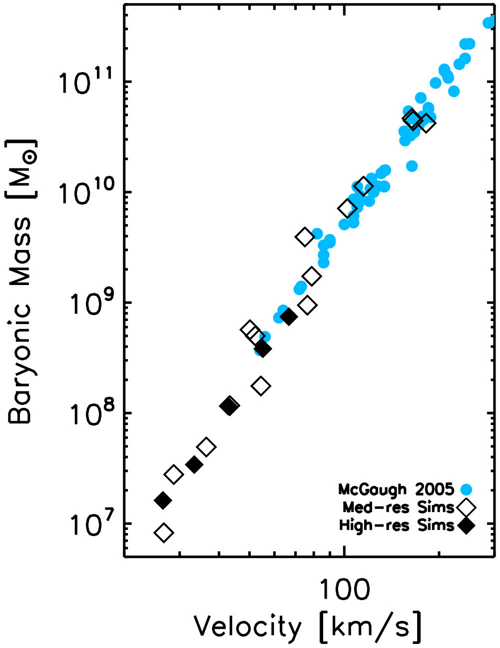
(1st order galaxy formation)

Also: realistic sizes, velocity dispersions, gas fractions, & HI disk sizes

Stellar Mass-Metallicity Relation



Baryonic Tully-Fisher



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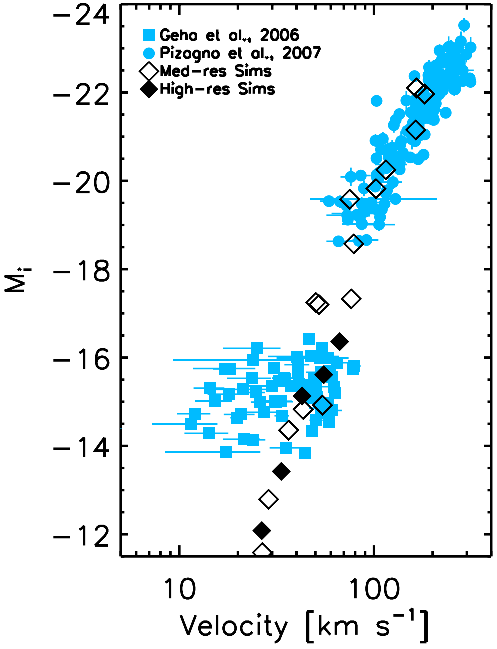
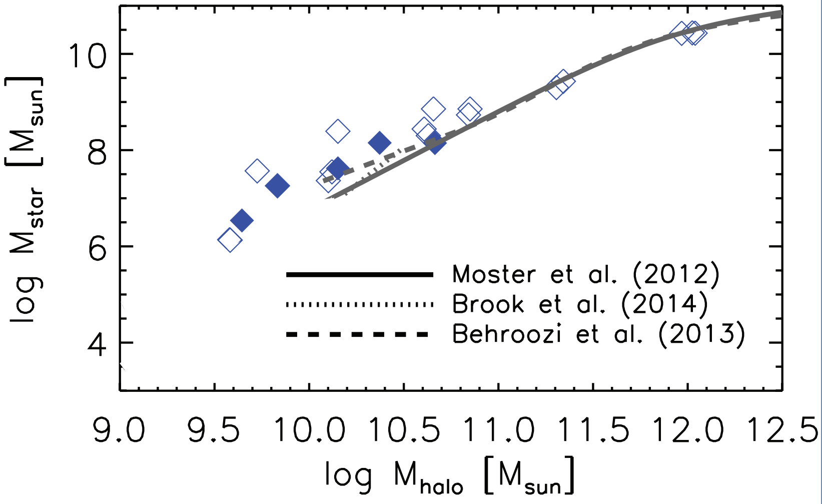


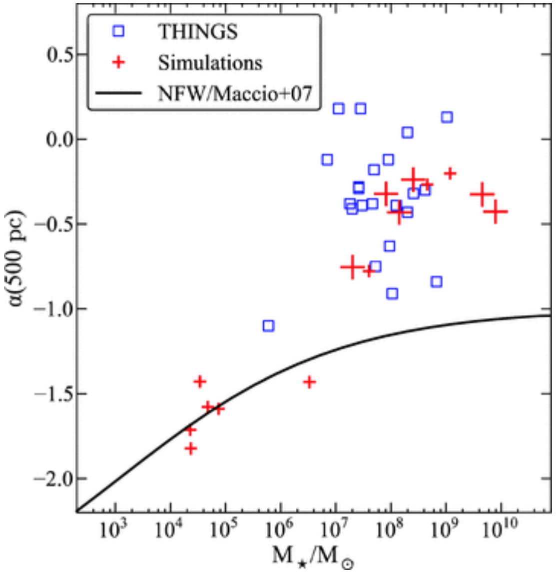
Stellar Mass-Halo Mass Relation



Christensen et al, 2015

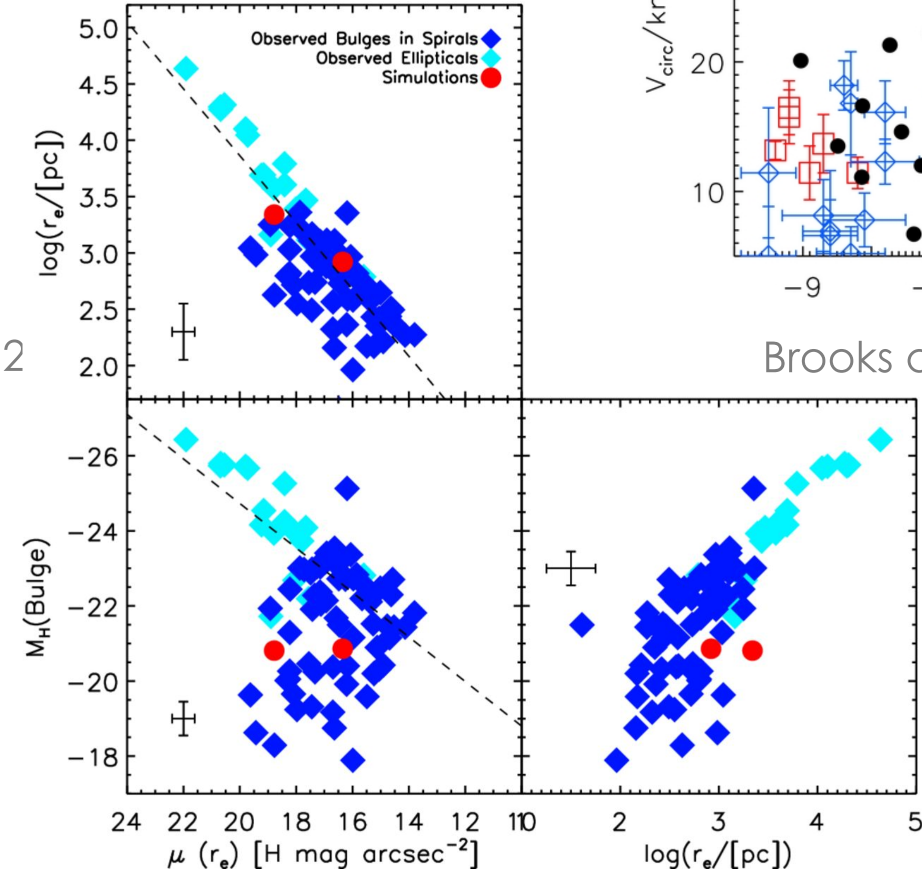
Matter Distribution within Galaxy

Cored Profiles



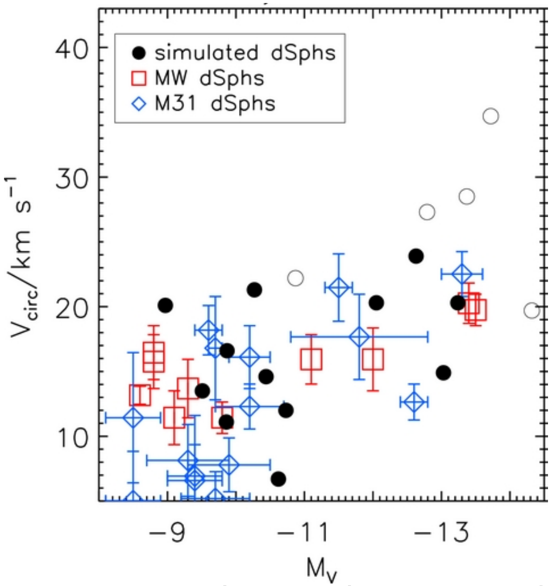
Governato+ 2012

Appropriately Shaped Bulges



Christensen+ 2014

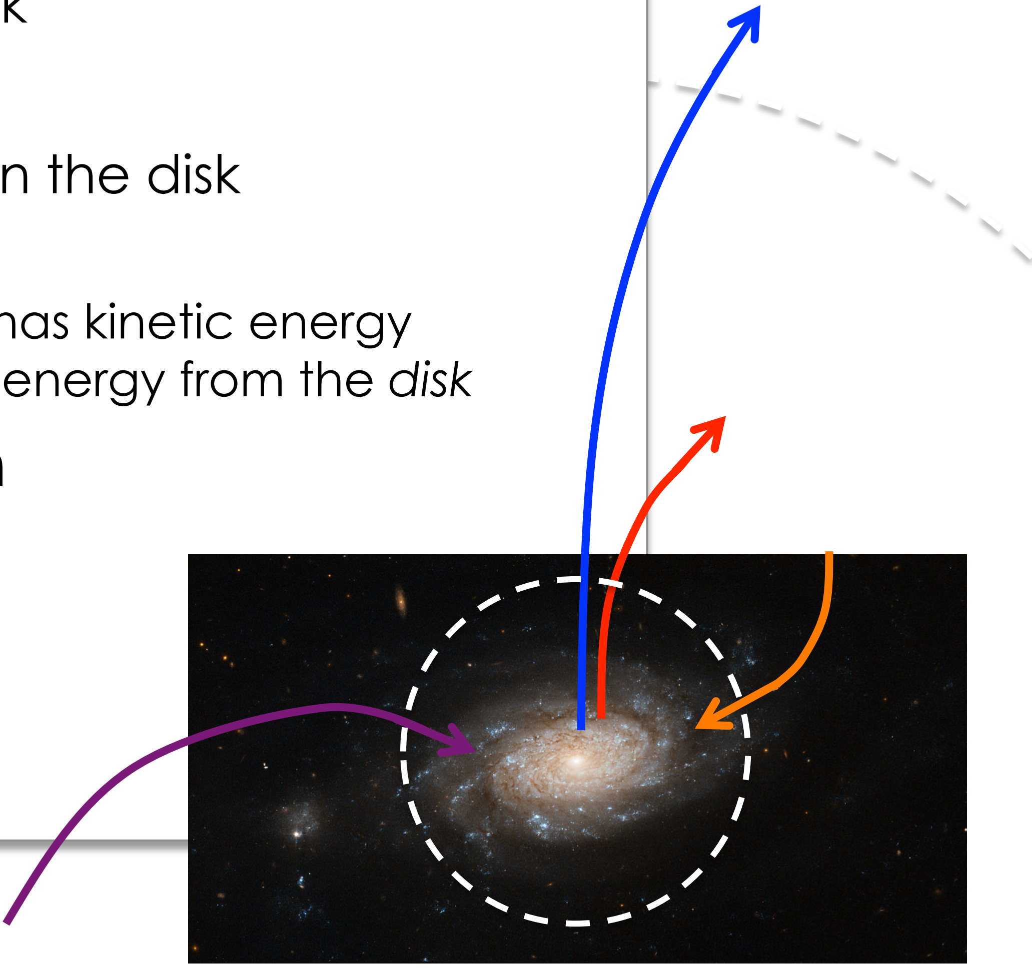
Circular Velocity of Satellites



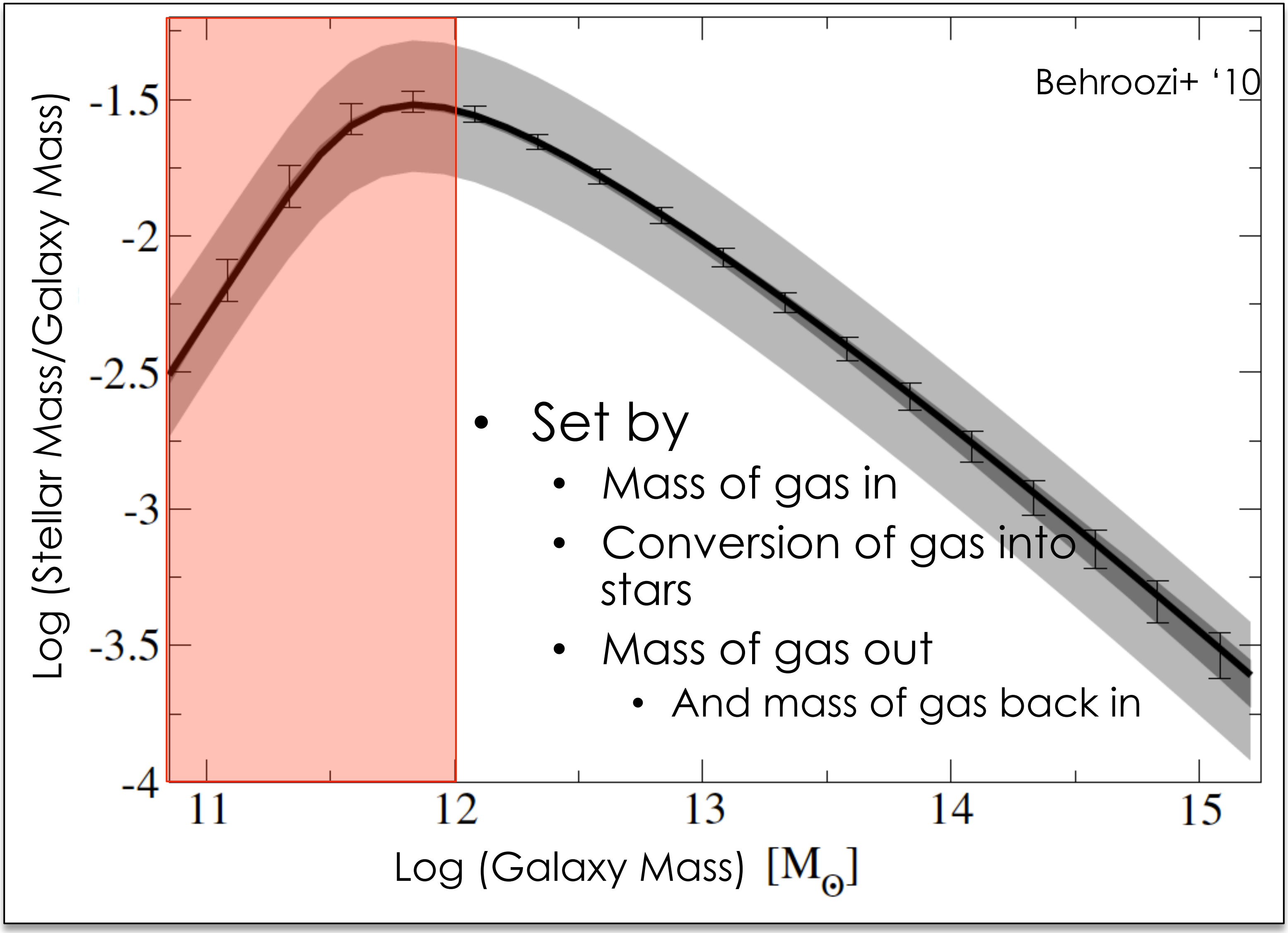
Brooks and Zolotov 2014

Particle Tracking

- Inflowing gas:
  - First step included in disk
- Outflowing gas:
  - Must have once been in the disk
  - Ejected from disk:
    - Outflowing gas which has kinetic energy greater than potential energy from the *disk*
- 100 Myr time resolution
- Start at z = 3

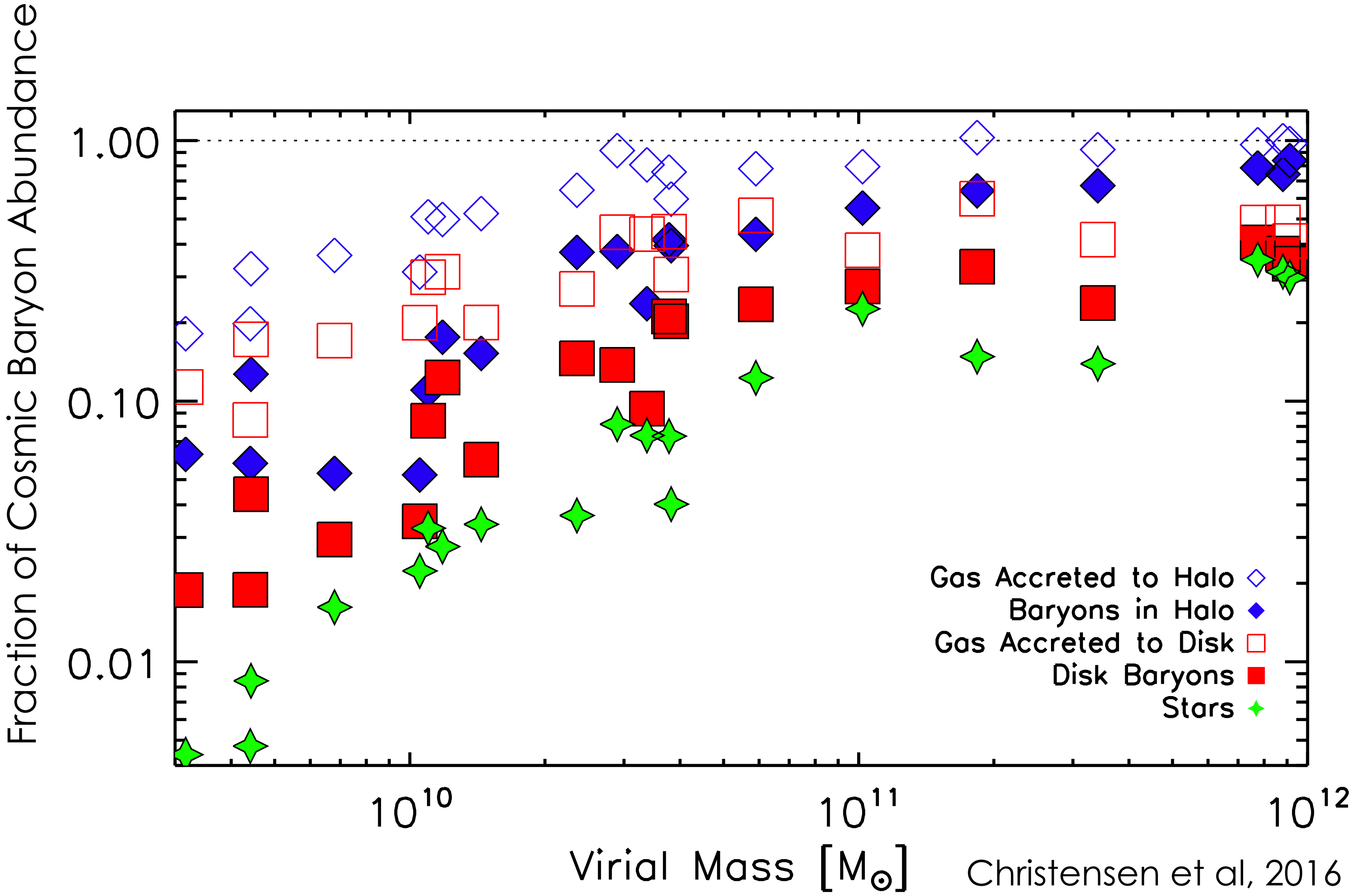


Stellar Mass Fraction vs. Halo Mass



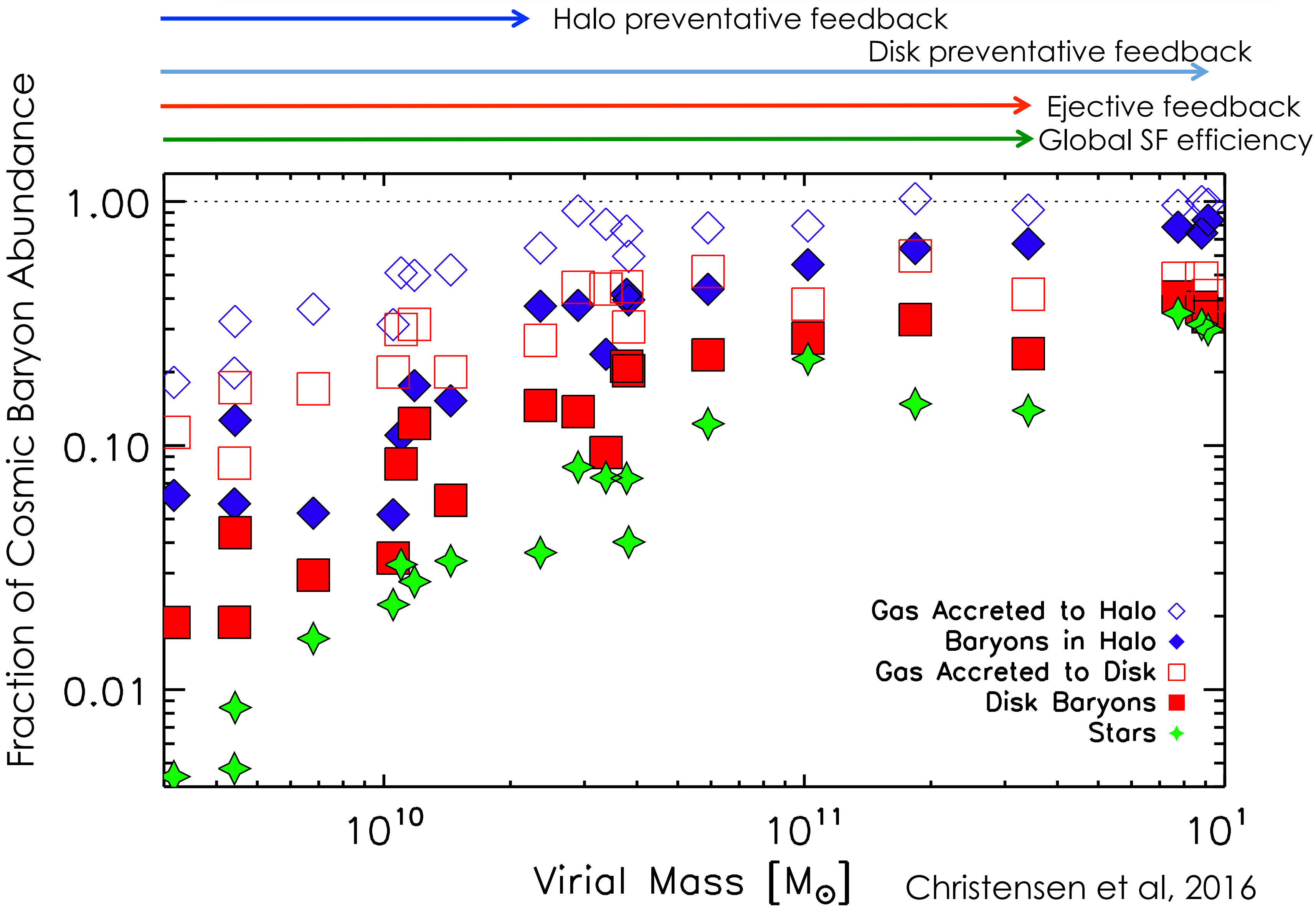
- Set by
  - Mass of gas in
  - Conversion of gas into stars
  - Mass of gas out
    - And mass of gas back in

Baryonic Fraction



Christensen et al, 2016

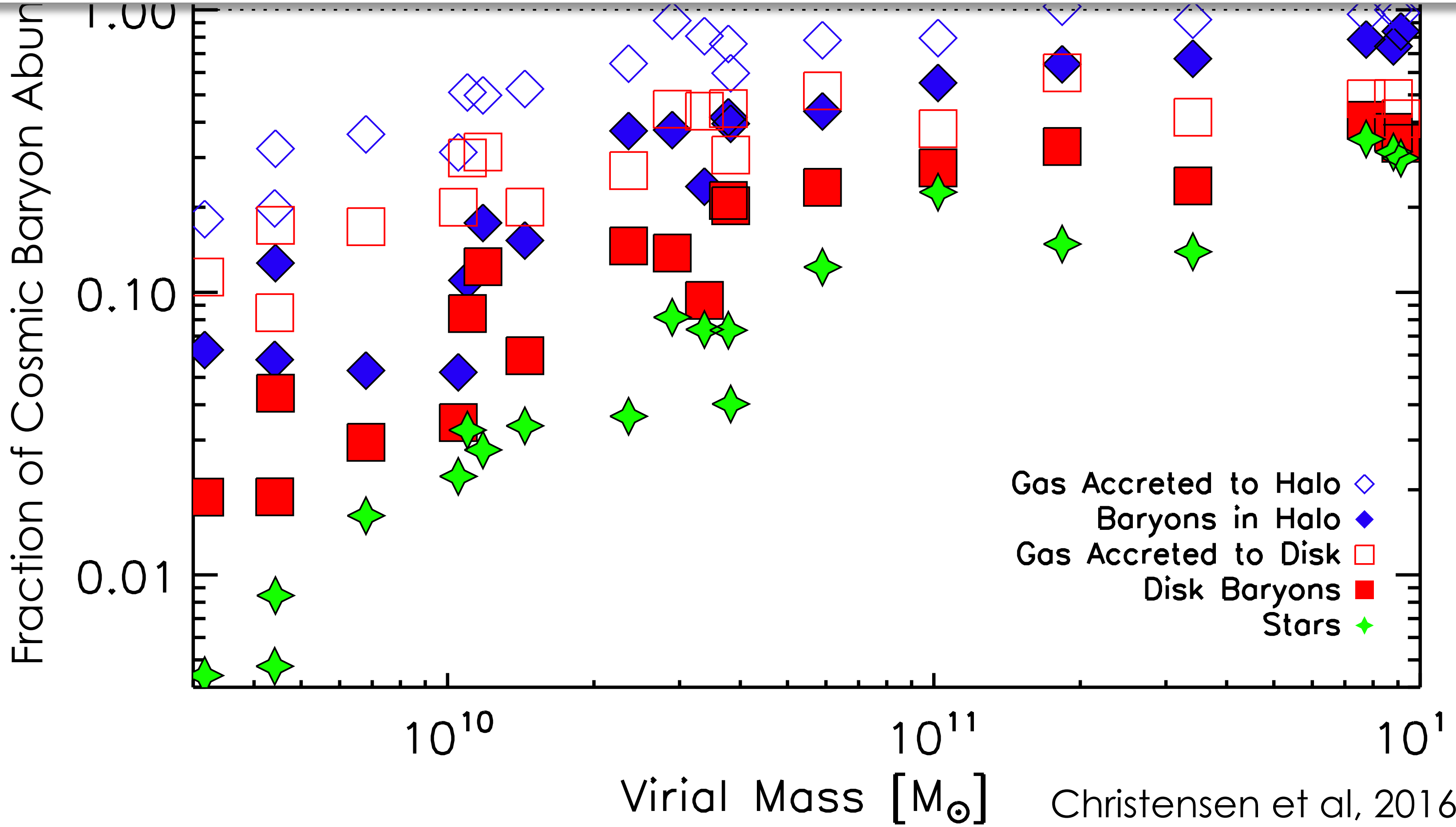
Baryonic Fraction



Christensen et al, 2016

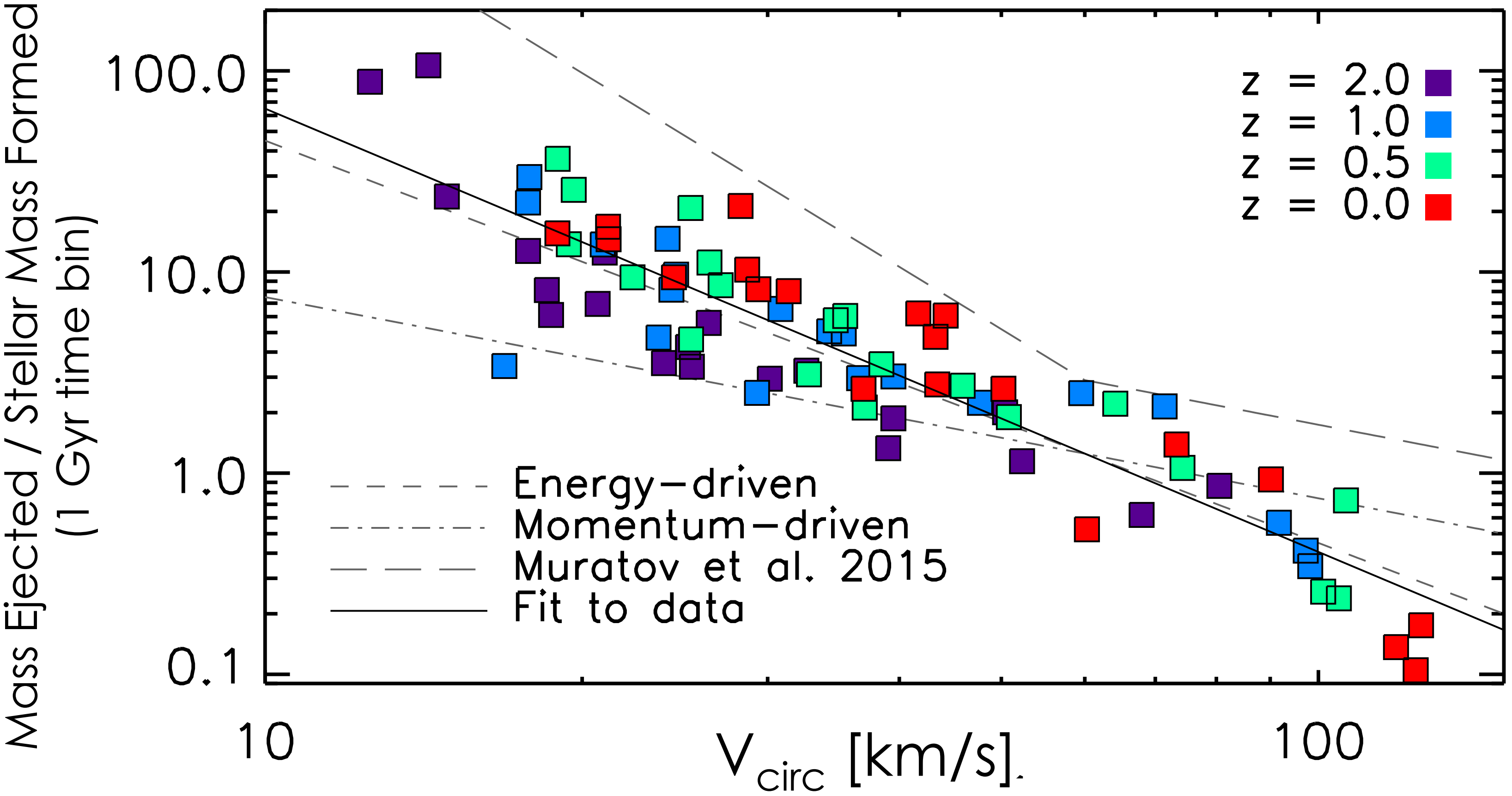
Baryonic Fraction

- Halo preventative feedback dominates at small masses
- Disk preventative feedback similar over all mass range studied
- Global star formation efficiency and ejective feedback are similarly effective and have decreasing efficiency with increasing galaxy mass



Christensen et al, 2016

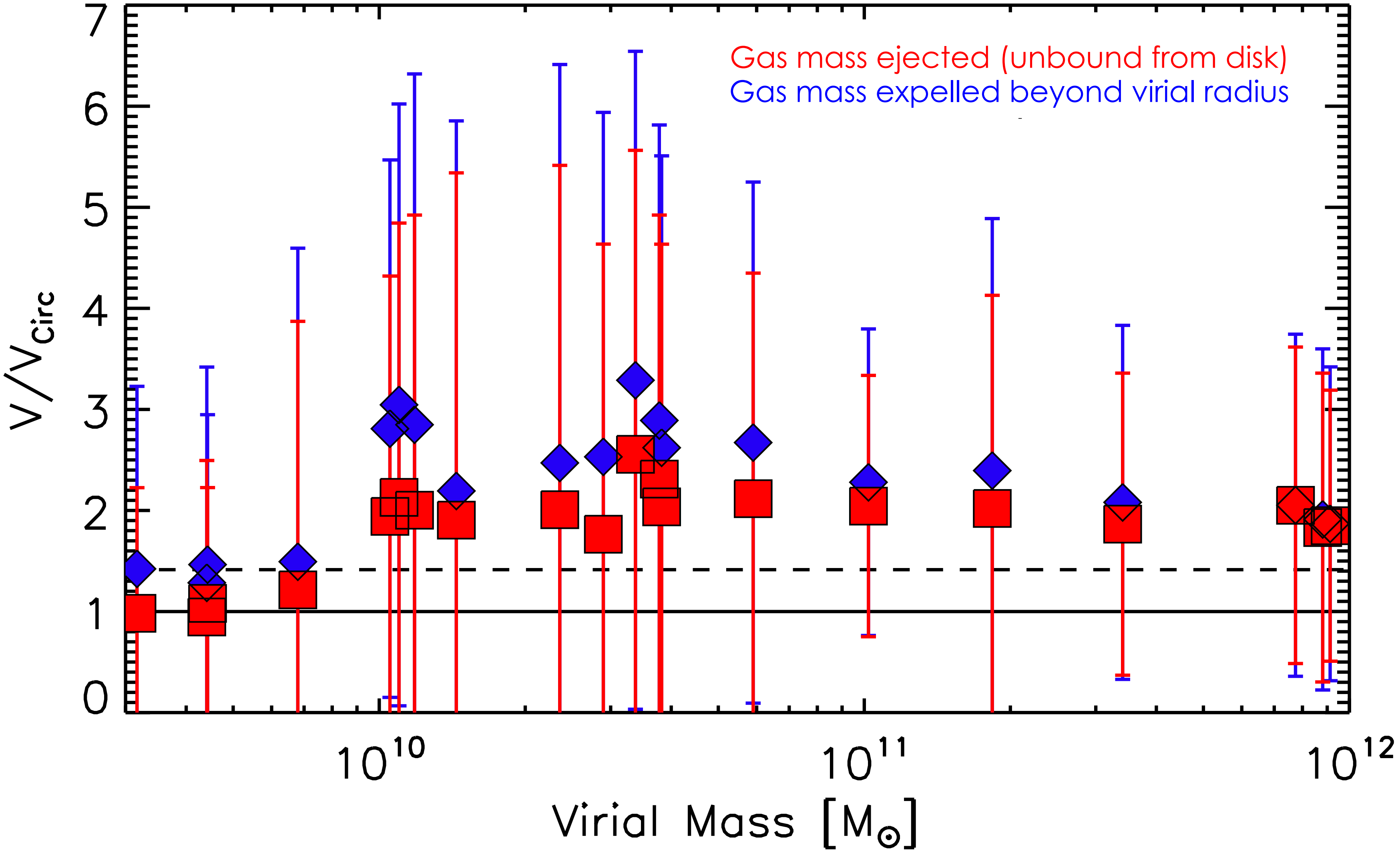
Mass Loading Factor for Ejected Material



$\eta_{\text{ejected}}\ \alpha\ v_{\text{circ}}^{-2.2}$, close to energy driven
No redshift evolution

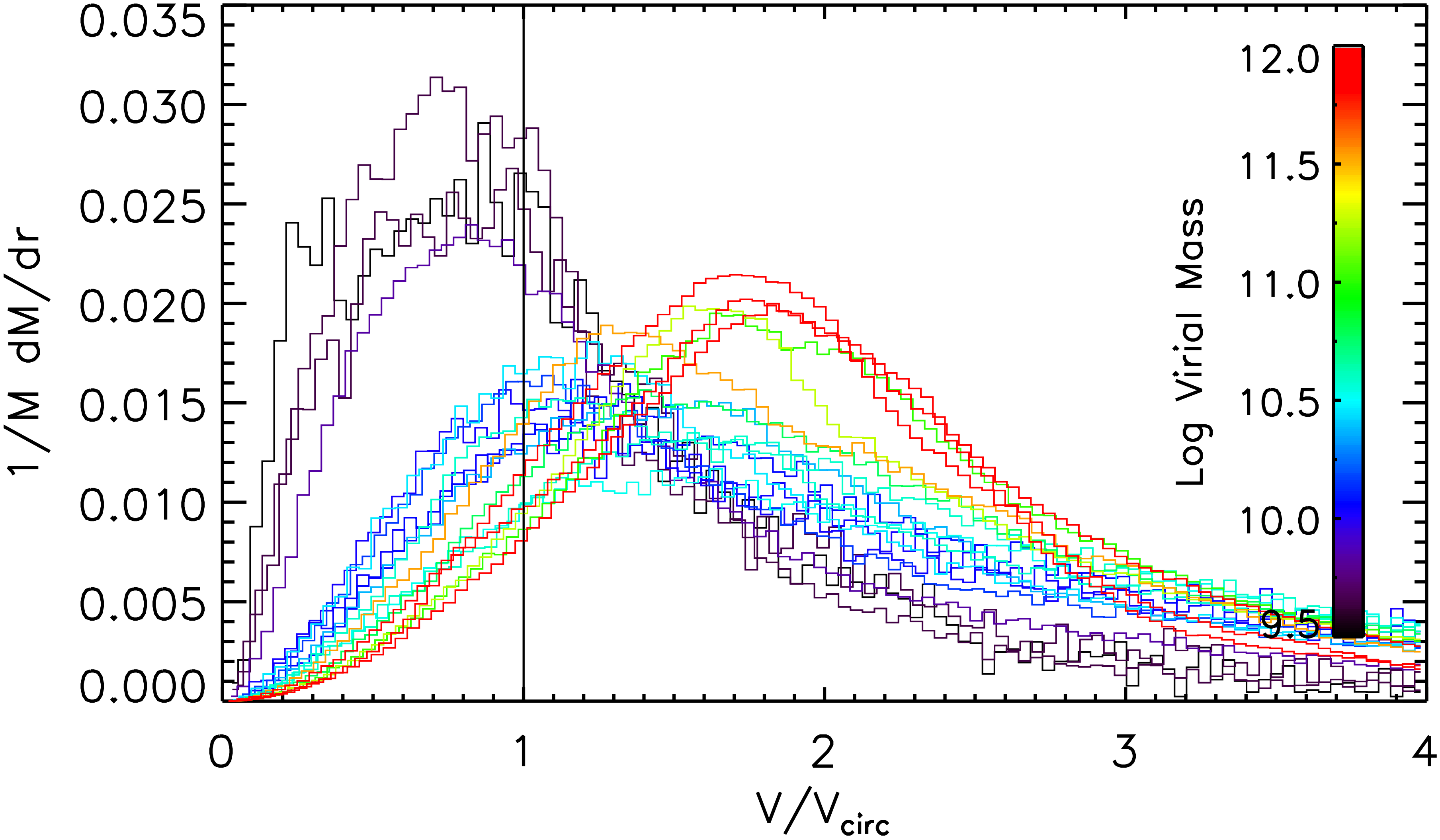
Christensen et al, 2016

Velocity of outflows



Christensen et al, 2016

Velocity of outflows



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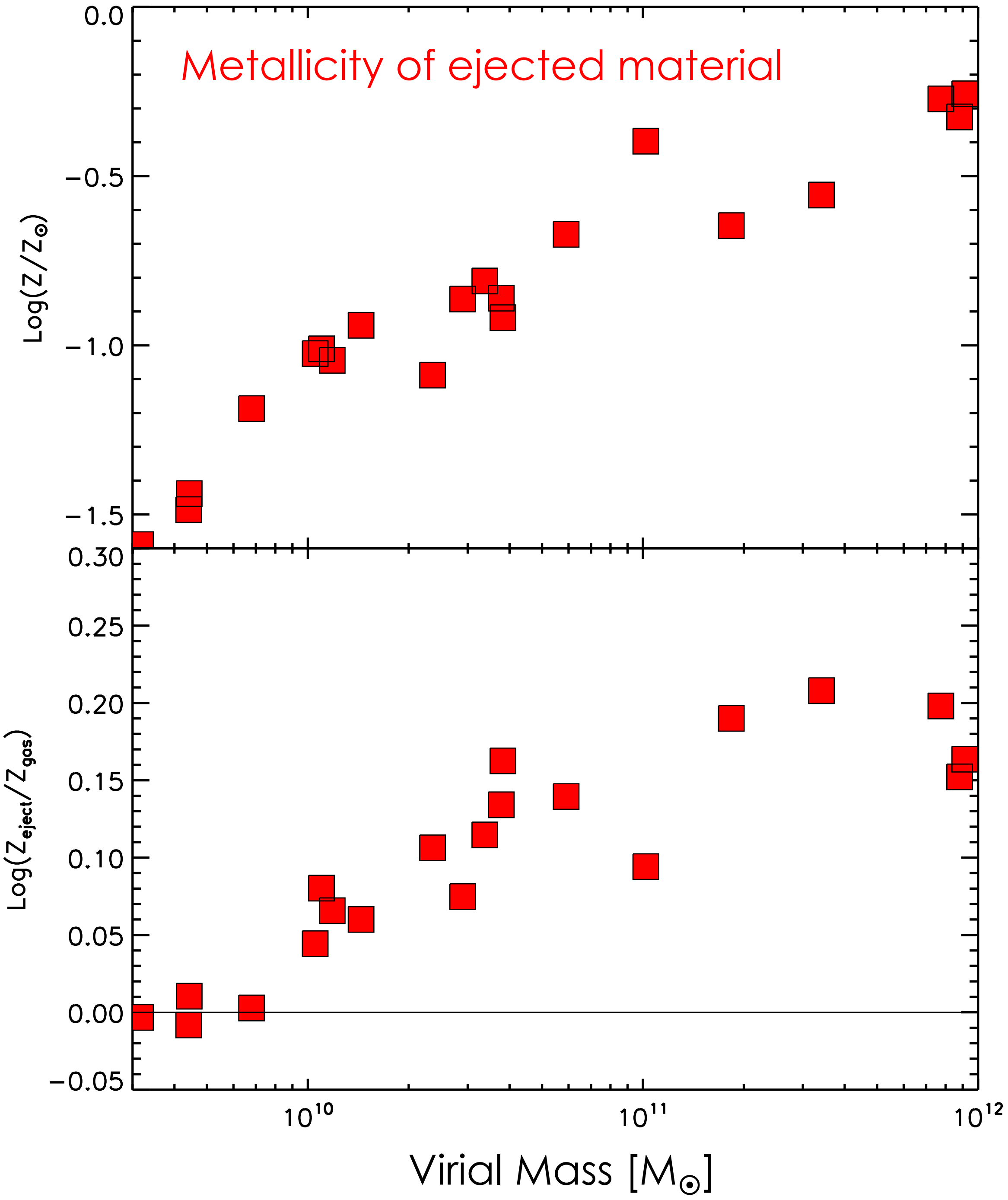
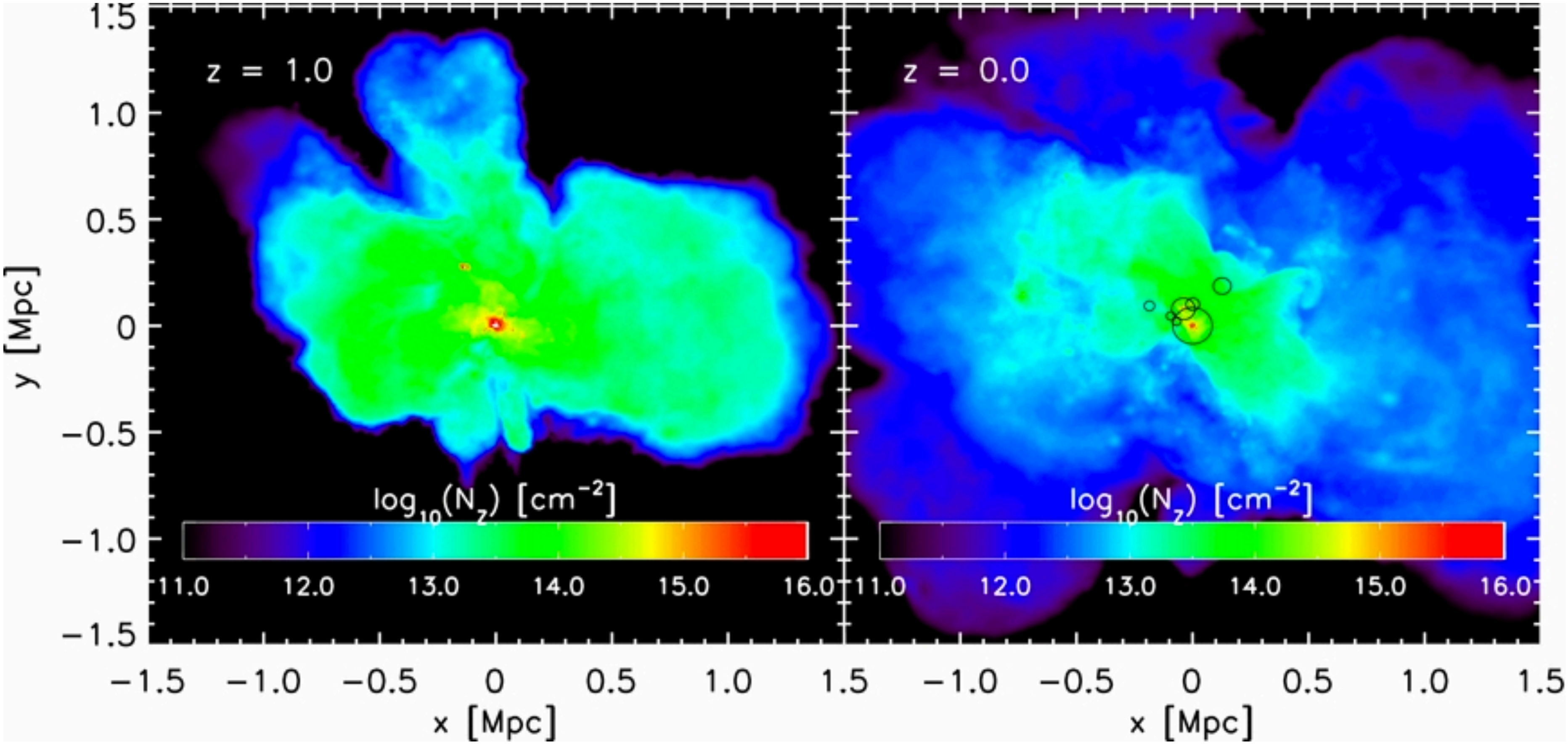
Metal Enrichment of Outflows

Outflows can be metal-enhanced compared to source ISM up to a factor of ~1.6.

Less metal enhancement for dwarfs – because of greater mass loading? Greater entrainment?

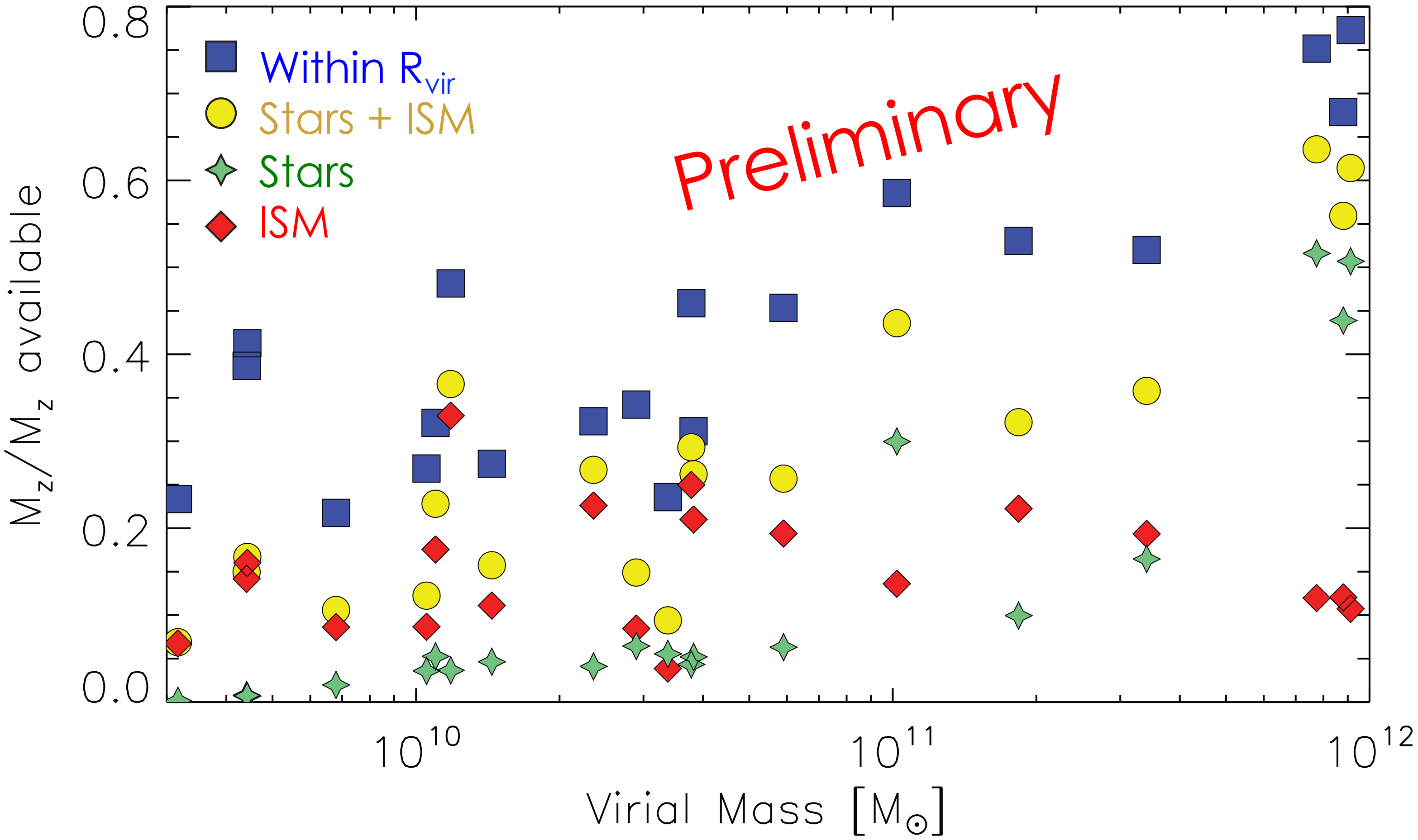


Metal enrichment around simulated dwarfs



“By z = 0, >87% of all the metals produced are spread over a region of 3 comoving Mpc across” Shen et al., 2014

Eventual Location of Metals



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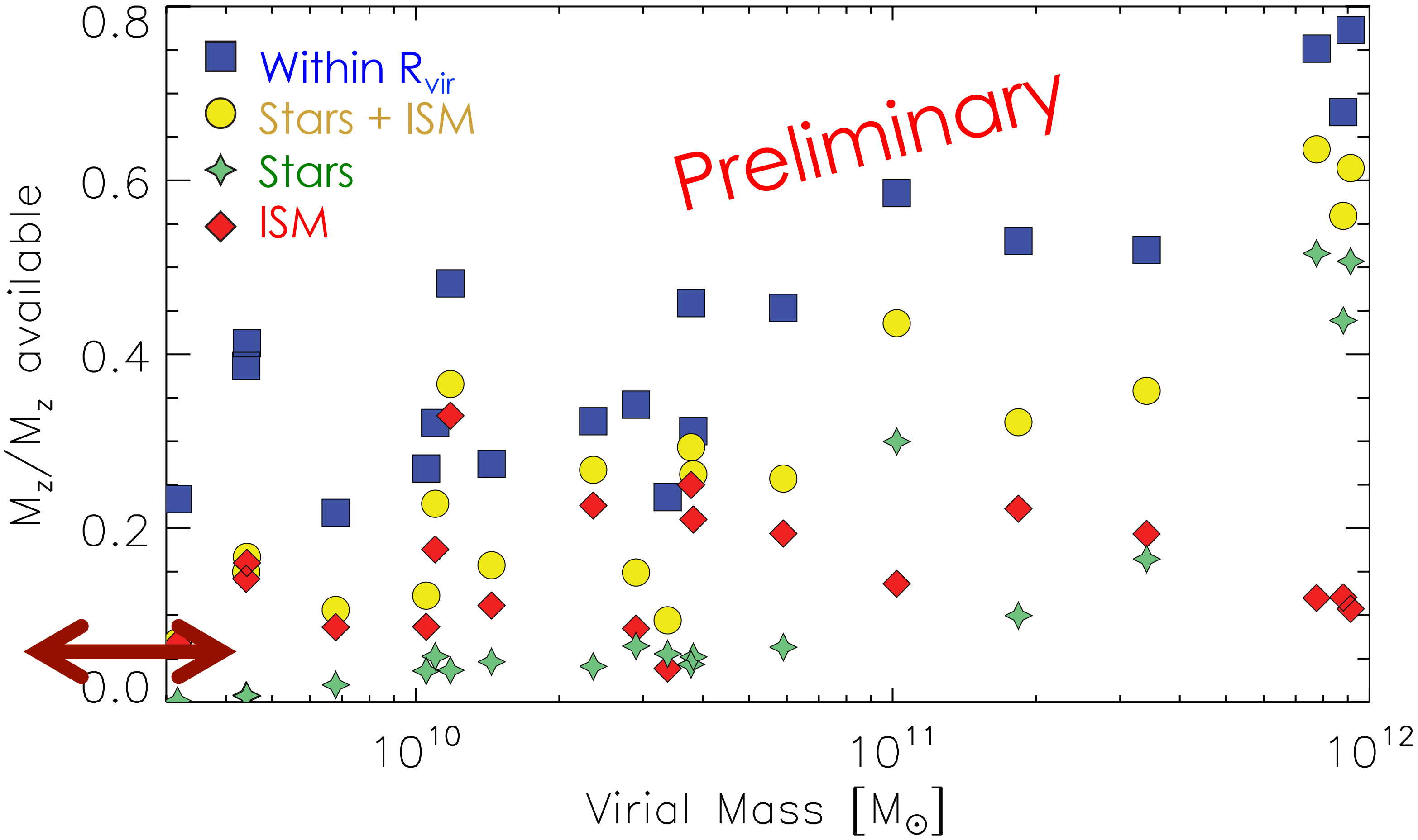
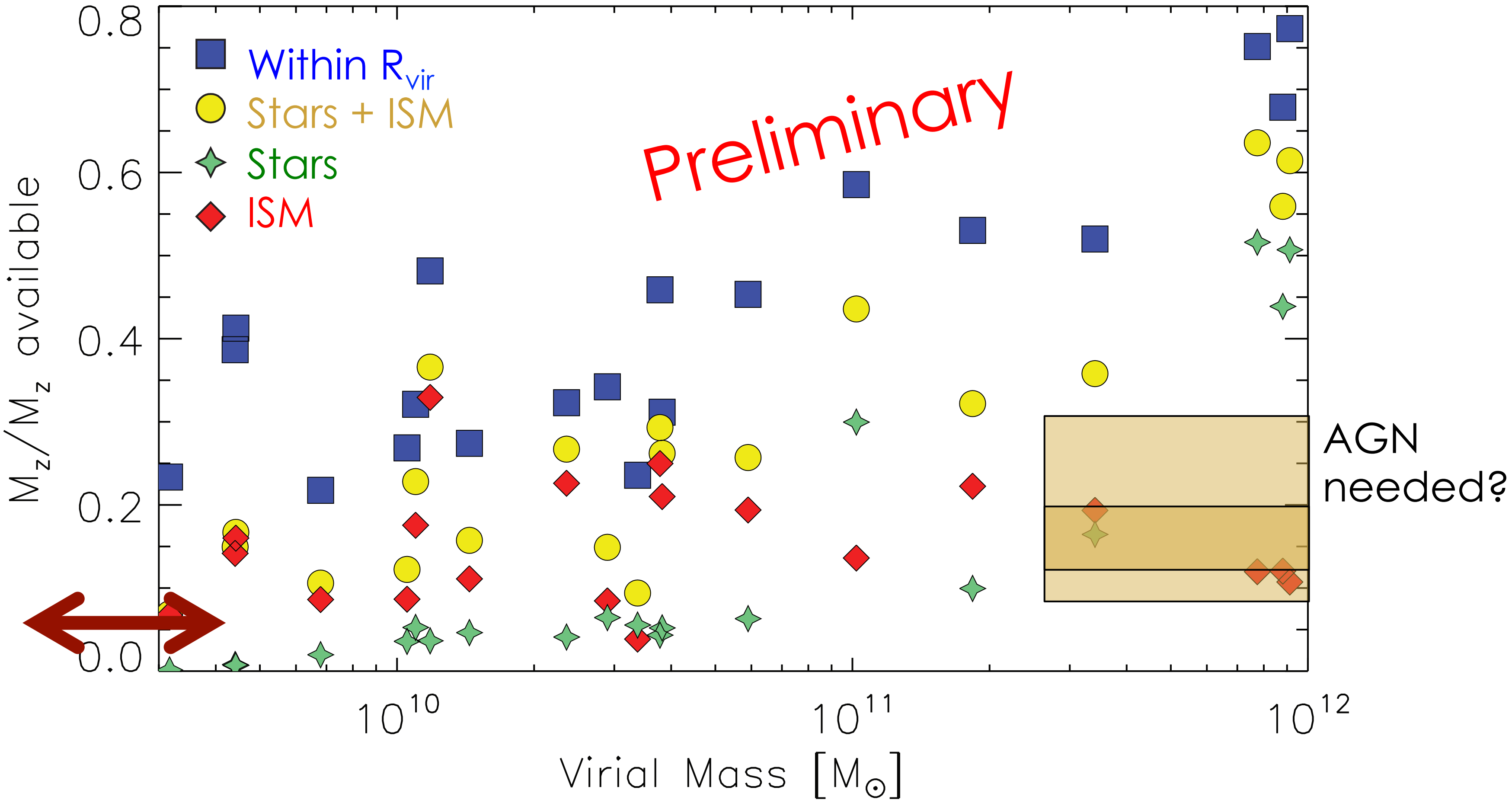


Leo P: $M_* = 5.7 \times 10^5\ M_\odot$
5% O in disk gas, 1% in stars
(McQuinn+ 2015)

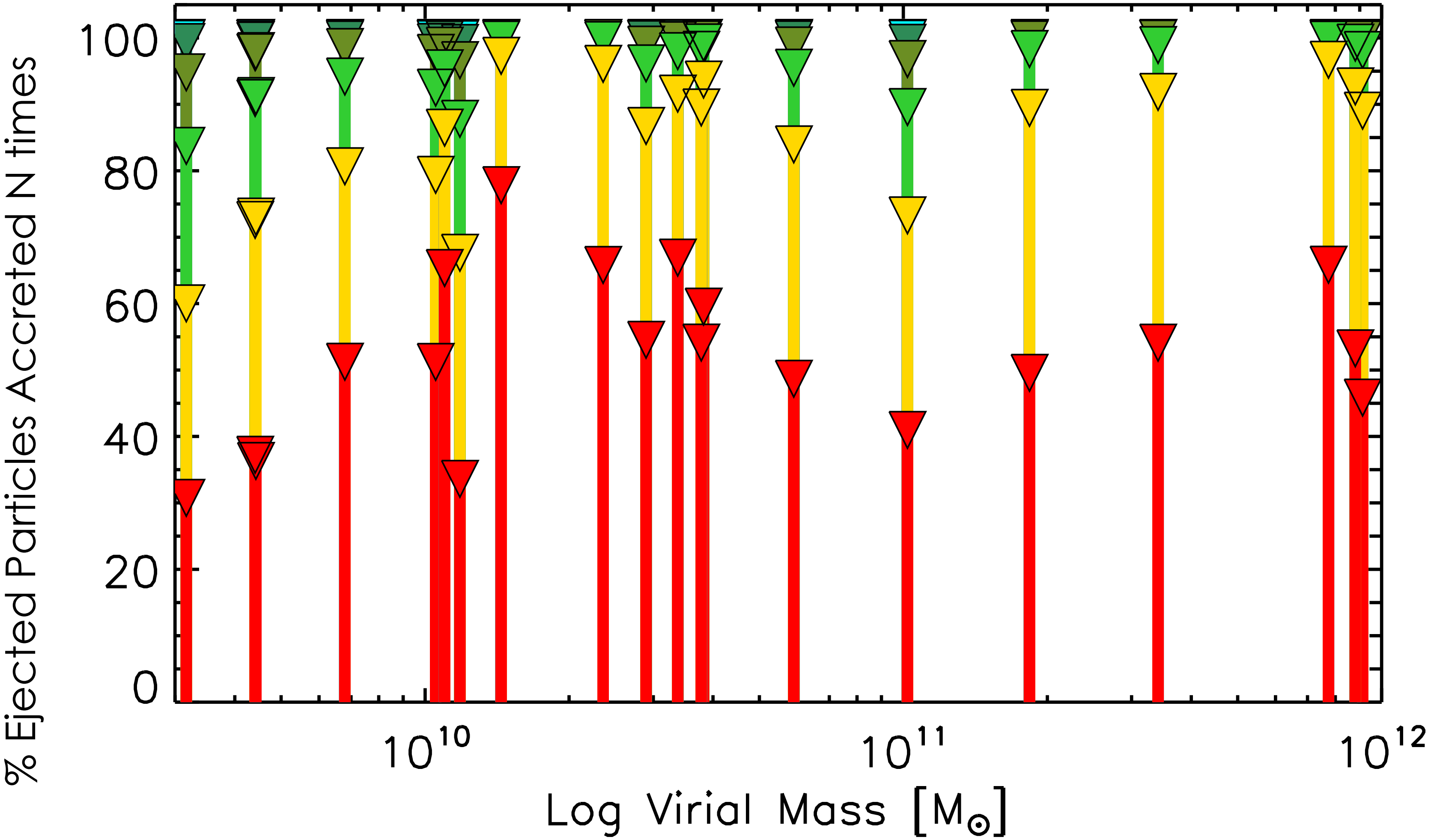
Eventual Location of Metals



Leo P: $M_* = 5.7 \times 10^5$ $M_\odot$
5% O in disk gas, 1% in stars
(McQuinn+ 2015)

$M_* \geq 10^{9.3}$ $M_\odot$: 15 – 30 % of metals remain in disk gas or stars
(Peeples+ 2014)

Number of Times a Particle is Reaccreted

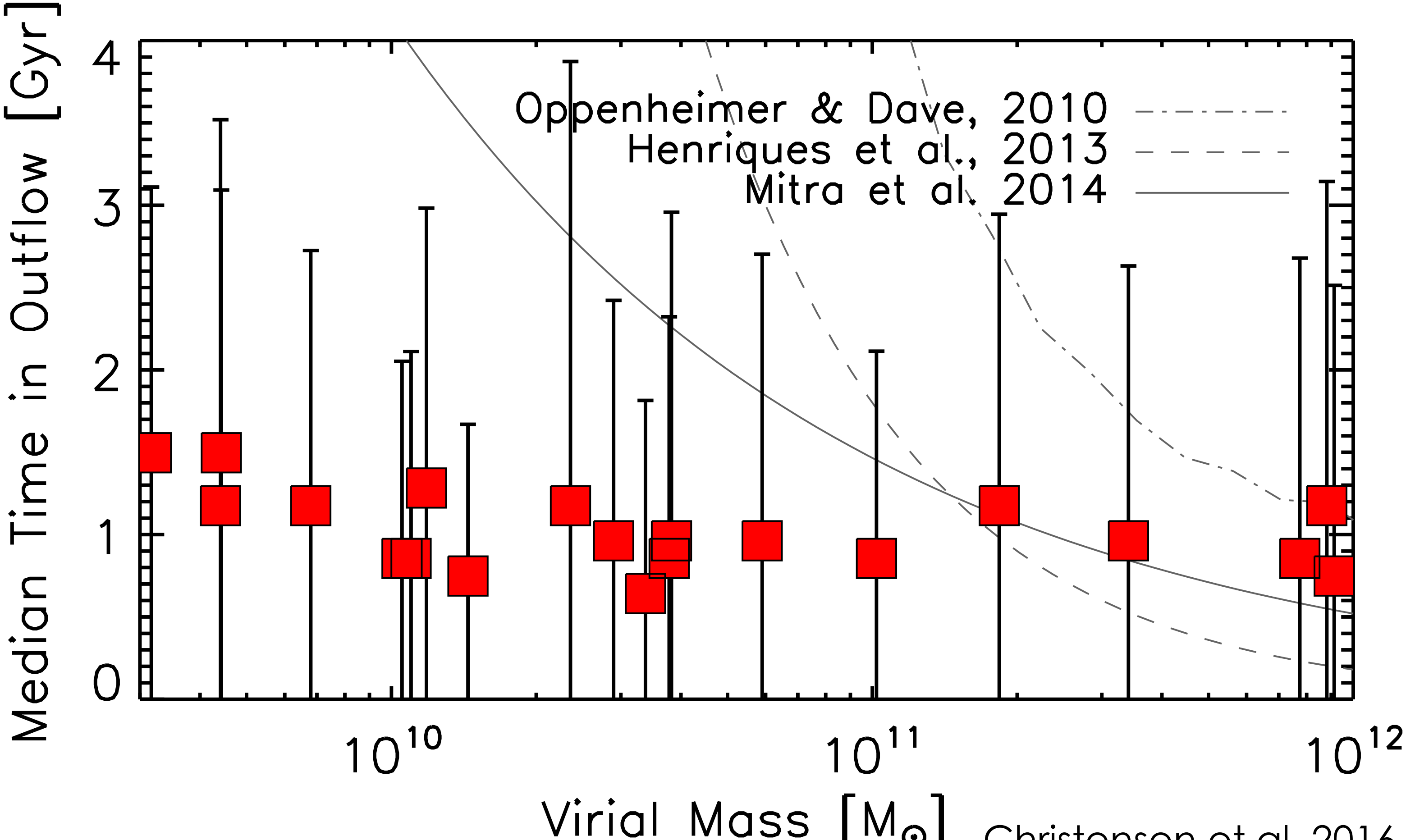


Never Reaccreted Reaccreted once Reaccreted twice . . .

Christensen et al, 2016

Amount of Time Before Reaccretion

Very little mass-dependency in reaccretion time: $\alpha\ M_{halo}^{-0.1}$
Similar to previous models at high mass, much lower at low mass



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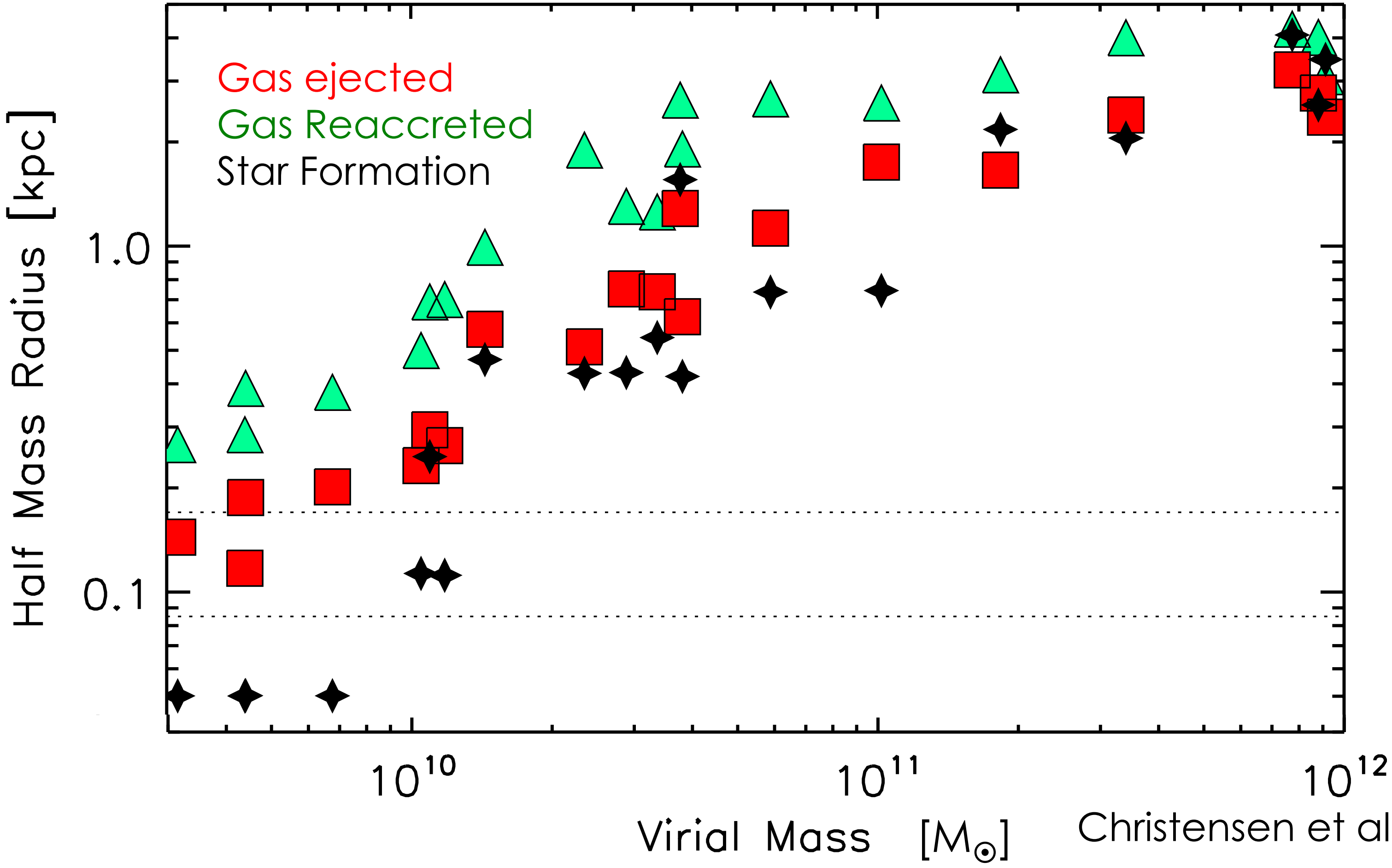
Source of ejected material/location of Reaccreted material

Outflows originate where stars form
Low-mass galaxies eject from slightly broader region
Reaccreted at systematically higher radii



Christensen et al, 2016

Summary

- Ejective feedback comparable to global SF efficiency in regulating SF
- Mass loading consistent with energy driven analytic scaling produces realistic galaxies
- Metals extremely efficiently removed from galaxies
- Feedback preferentially removes matter from center; capable of limiting bulge growth

- Scaling of mass loading at high gas surface densities and the amount and time scale of recycling are heavily model dependent in simulations
- Need for comprehensive model of winds
- CGM and ISM may be way to distinguish between wind models