The cycling of gas and metals in simulated dwarf and spiral galaxies

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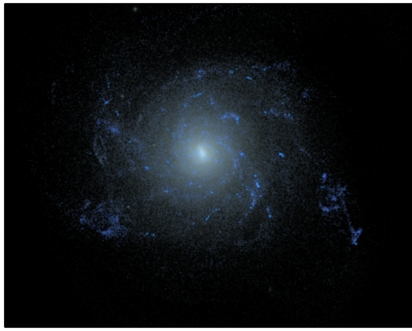
Premise

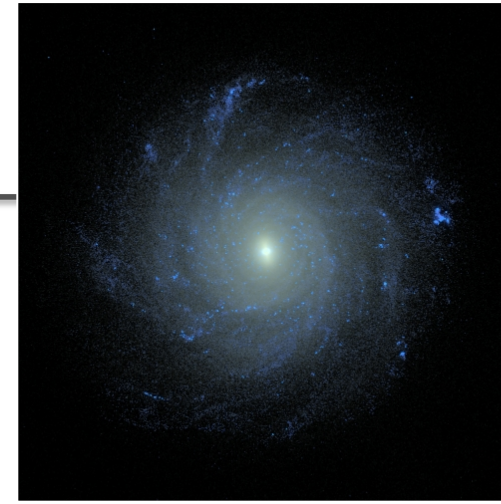
- Given a hydrodynamic code that produces galaxies with reasonably realistic properties, using a physically-motivated, tuned model for stellar feedback, *let's back out information about outflow properties as a function of halo mass*
  - Amount of ejection and recycling
  - Source of gas
  - Metallicity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

Code: Gasoline

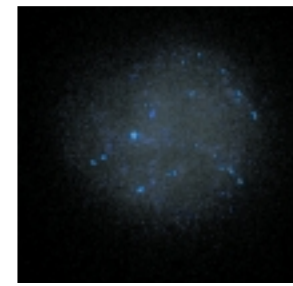
- SPH code (Wadsley+ 2004)
- Cosmic UV background radiation
- H & He ionization; non-equilibrium H_2 (Christensen+ 2012)
- Metal line cooling and metal diffusion. O and Fe abundances tracked. (Shen+ 2010)
- Probabilistic star formation based on free-fall time and H_2 abundance (essentially, dust shielded fraction), $c^* = 0.1$ (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)

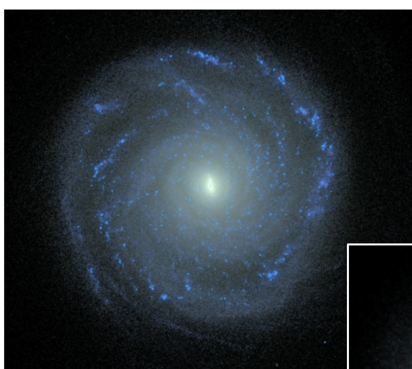


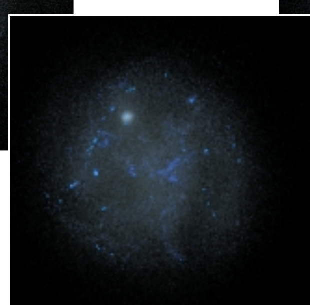
Simulations

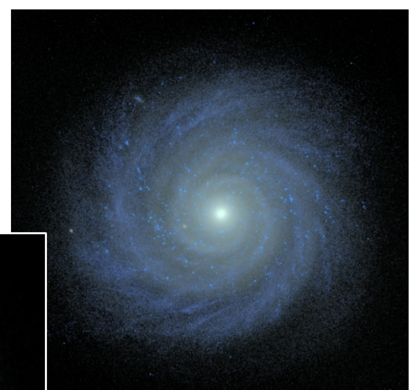


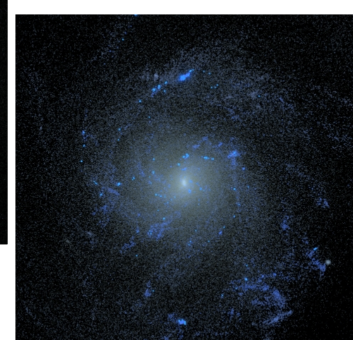
- 20 central galaxies from zoom-in, cosmological simulations.
- Virial masses at $z = 0$ from $5\text{x}10^{9} – 10^{12}\ M_{\odot}$
- Gas particle masses: $3300 M_{\odot}$ or $25{,}000 M_{\odot}$
- Softening lengths: 87 or 170 pc, smoothing lengths > 0.1 softening

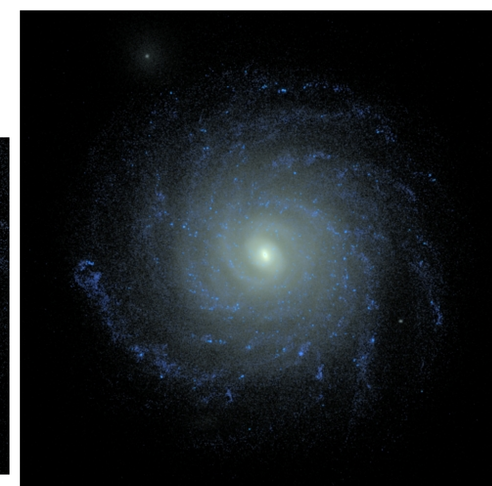








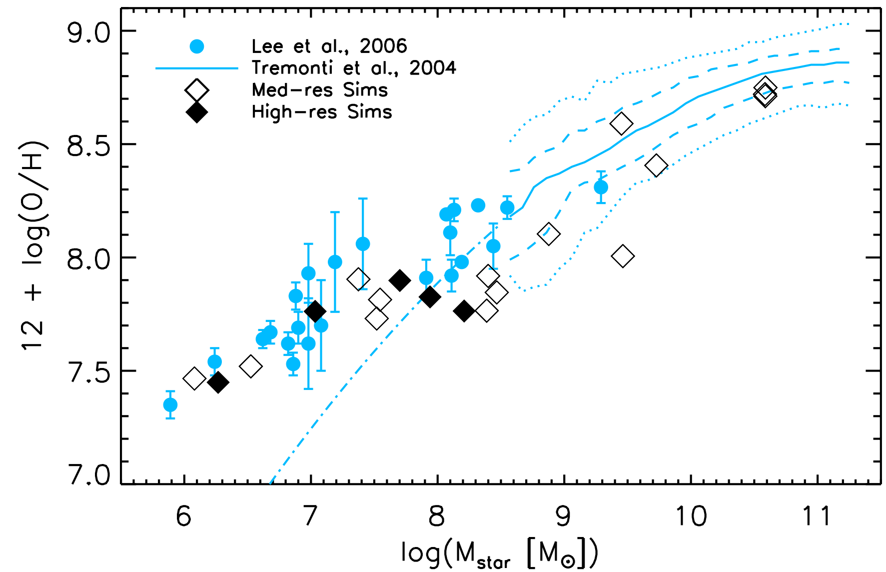




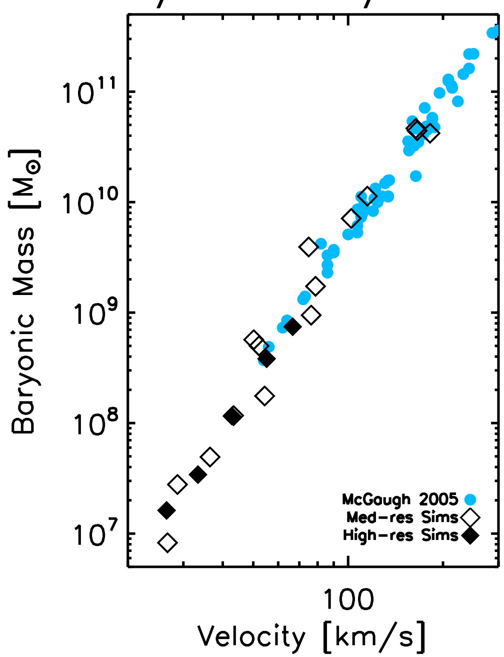
Observed relations of global properties at z = 0 (1st order galaxy formation)

Also: realistic sizes, gas fractions, and velocity dispersions

Stellar Mass-Metallicity Relation



Baryonic Tully-Fisher



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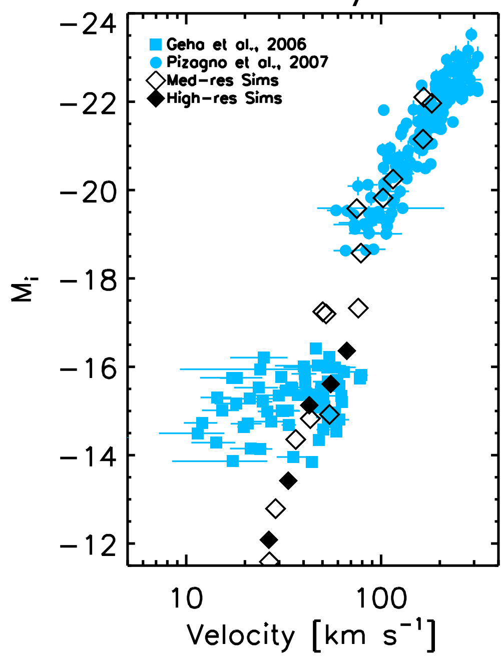
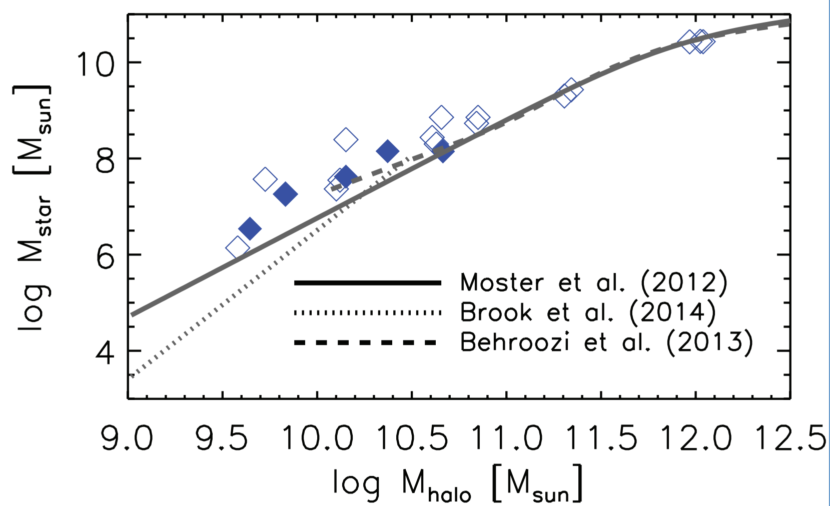


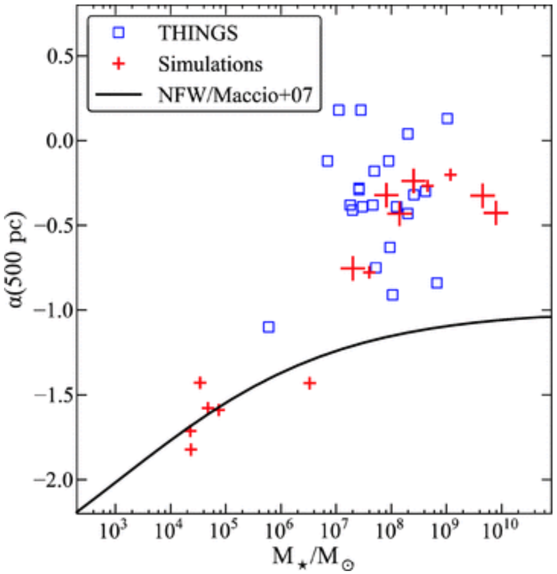
Stellar Mass-Halo Mass Relation



Christensen et al, 2015

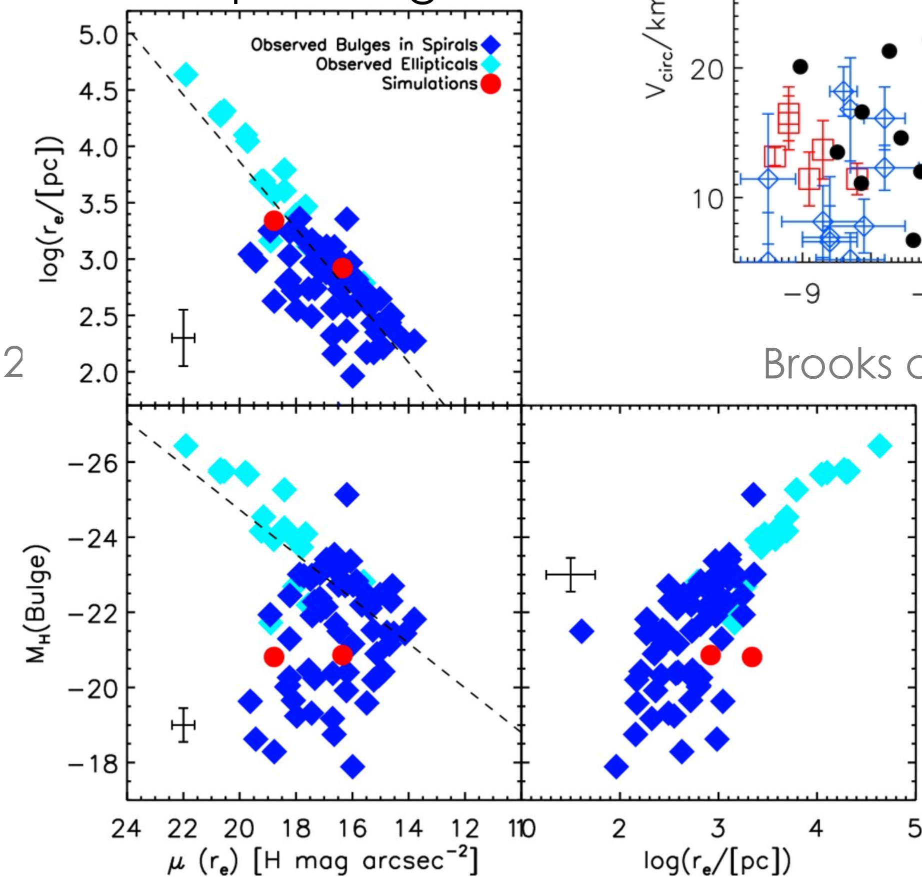
Matter Distribution within Galaxy

Cored Profiles



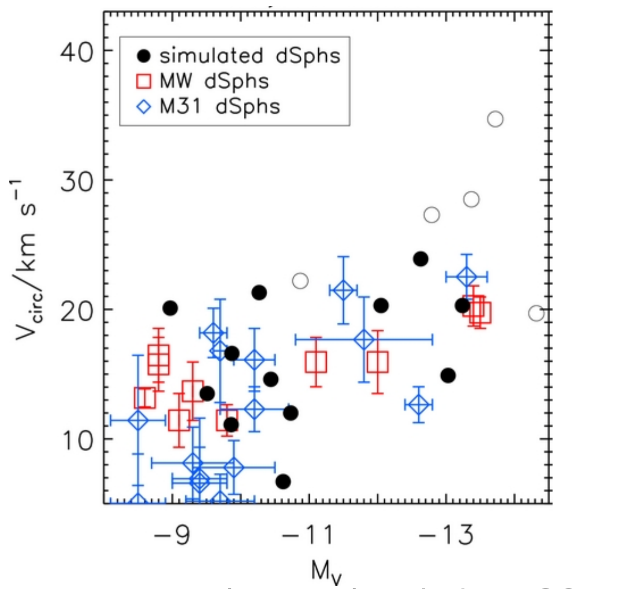
Governato+ 2012

Appropriately Shaped Bulges



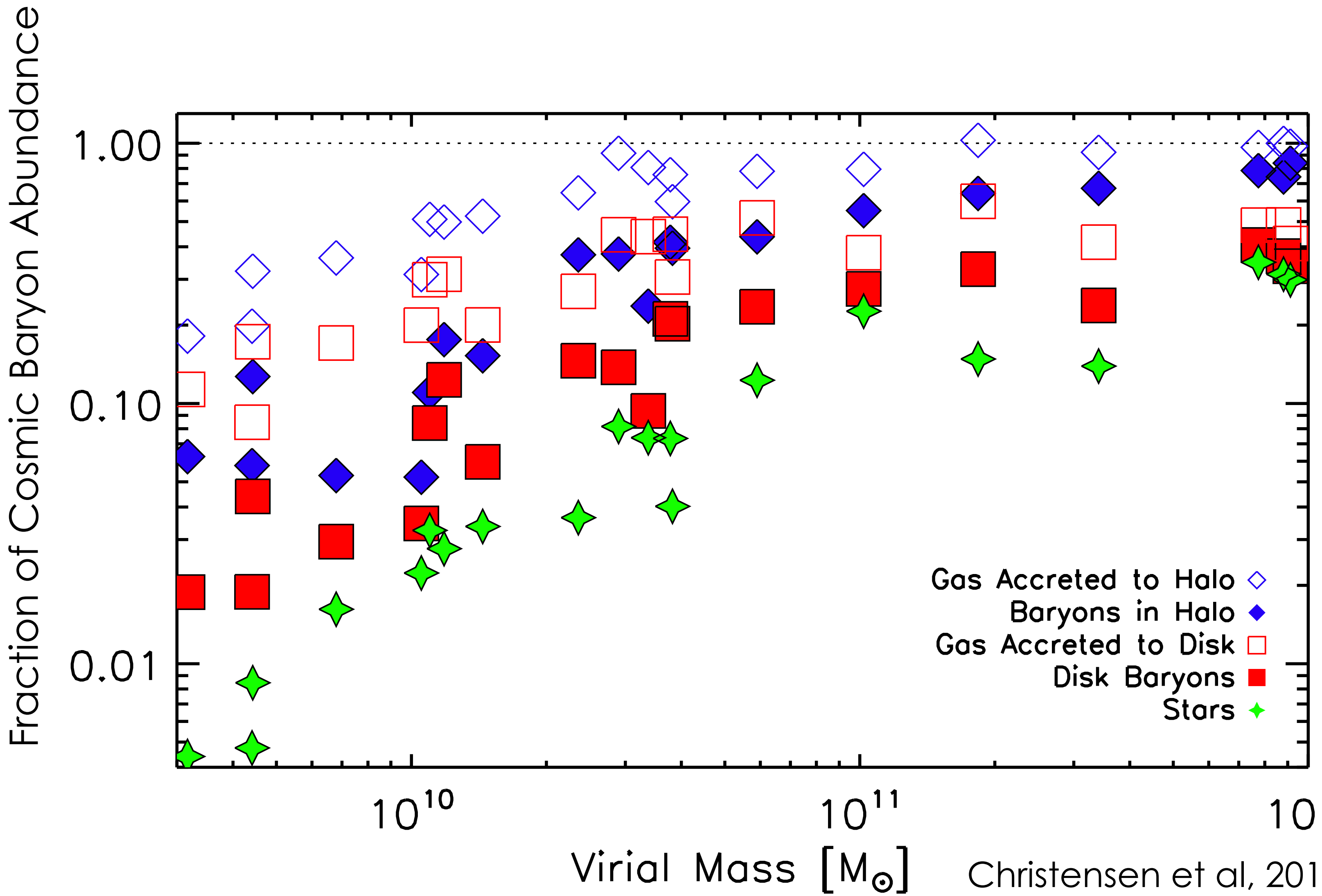
Christensen+ 2014

Circular Velocity of Satellites



Brooks and Zolotov 2014

Baryonic Fraction



Christensen et al, 2016

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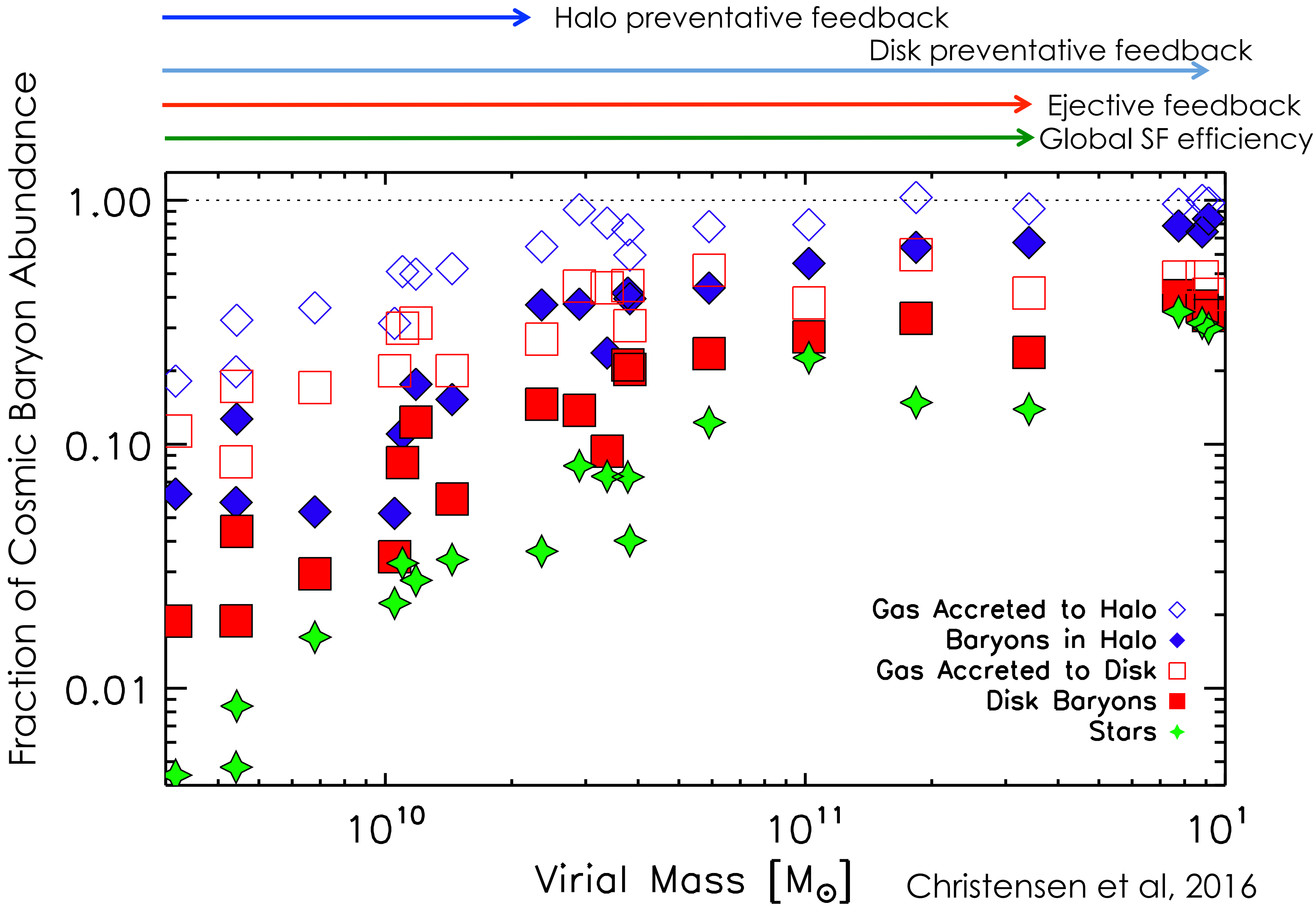
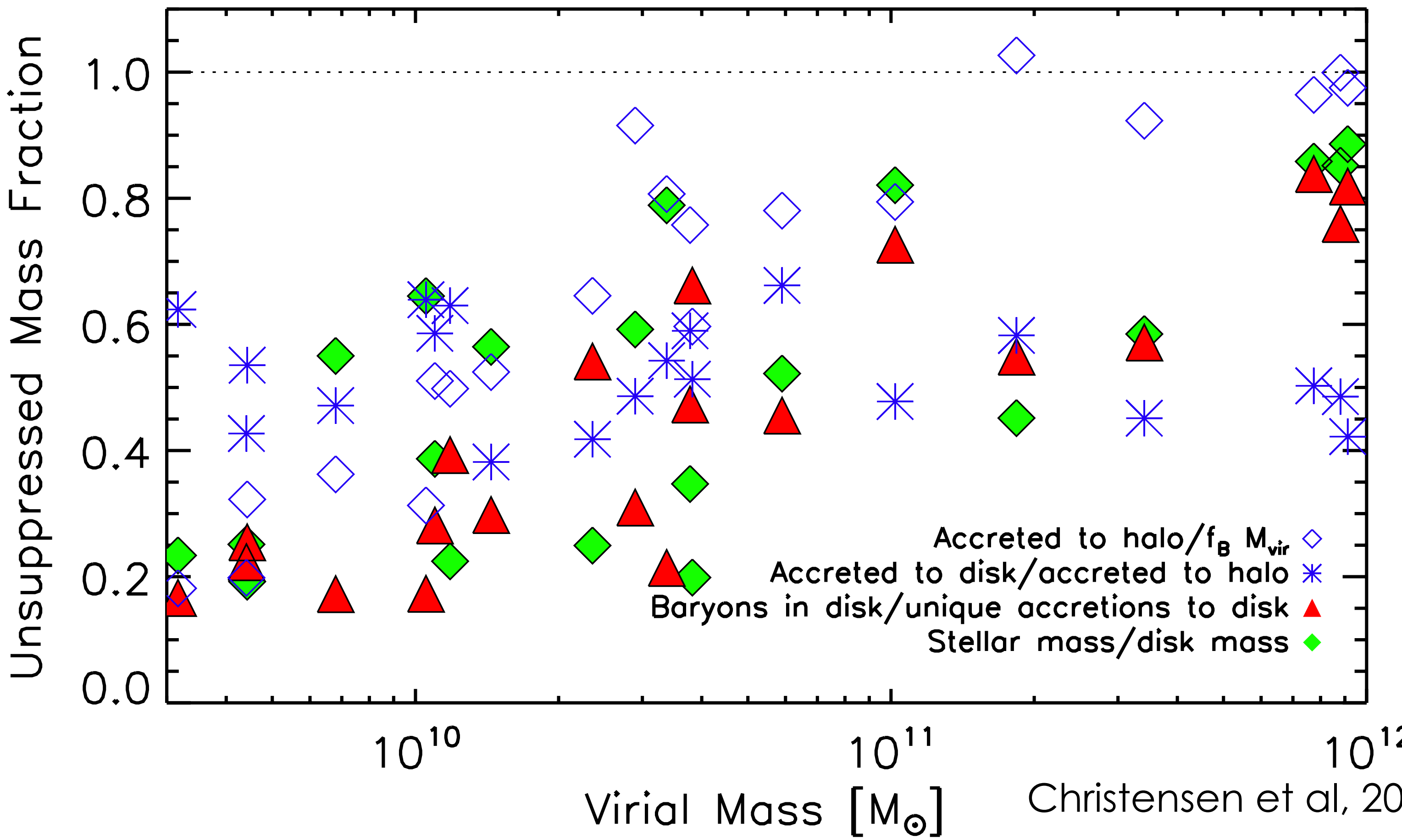


Christensen et al, 2016

Relative efficiency at suppressing SF

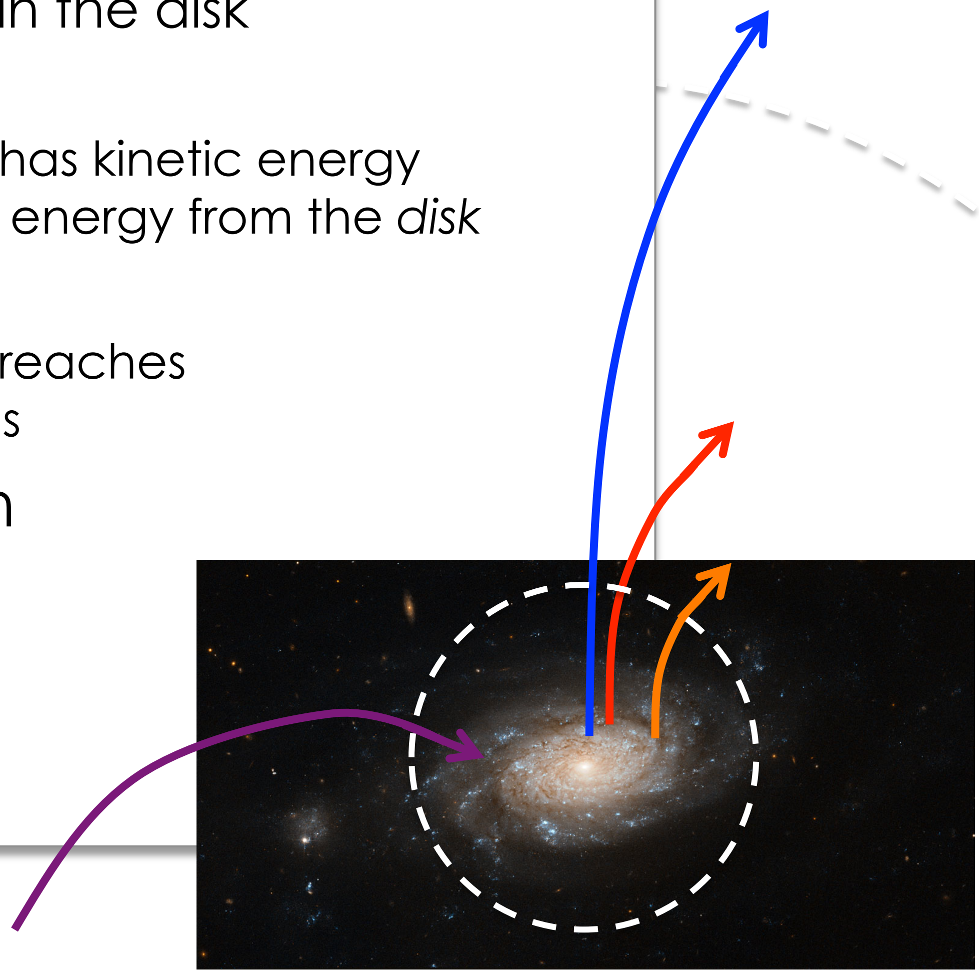
- Halo preventative feedback dominates at small masses
- Disk preventative feedback similar over all mass range studied
- Global star formation efficiency and ejective feedback are similarly effective across mass range



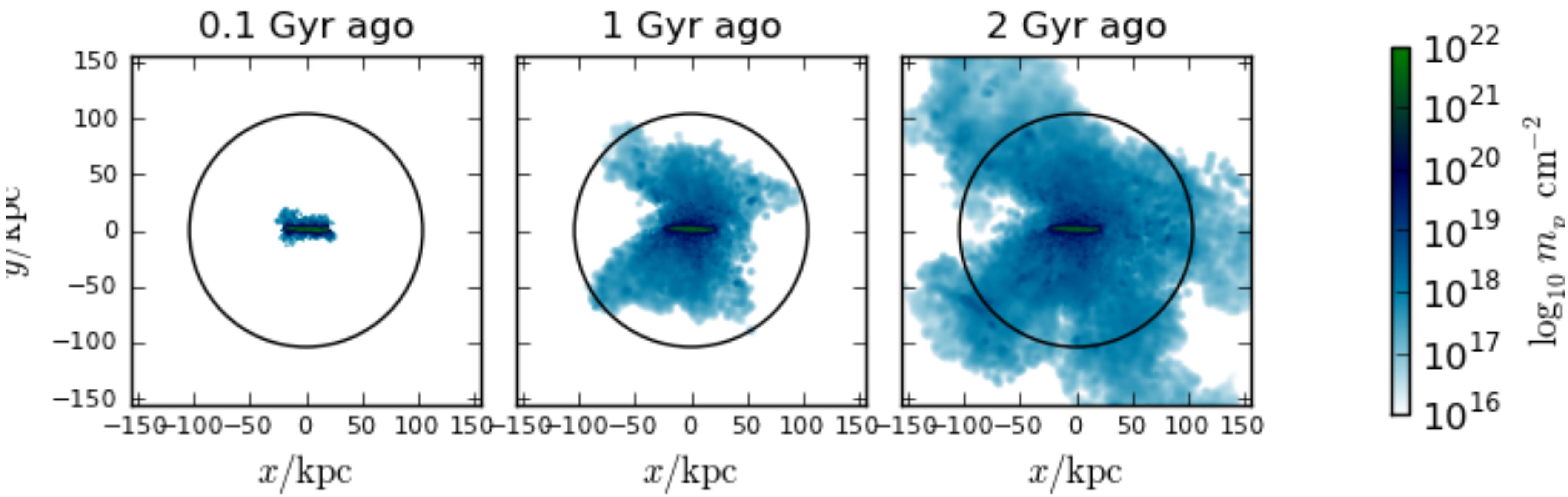
Christensen et al, 2016

Particle Tracking

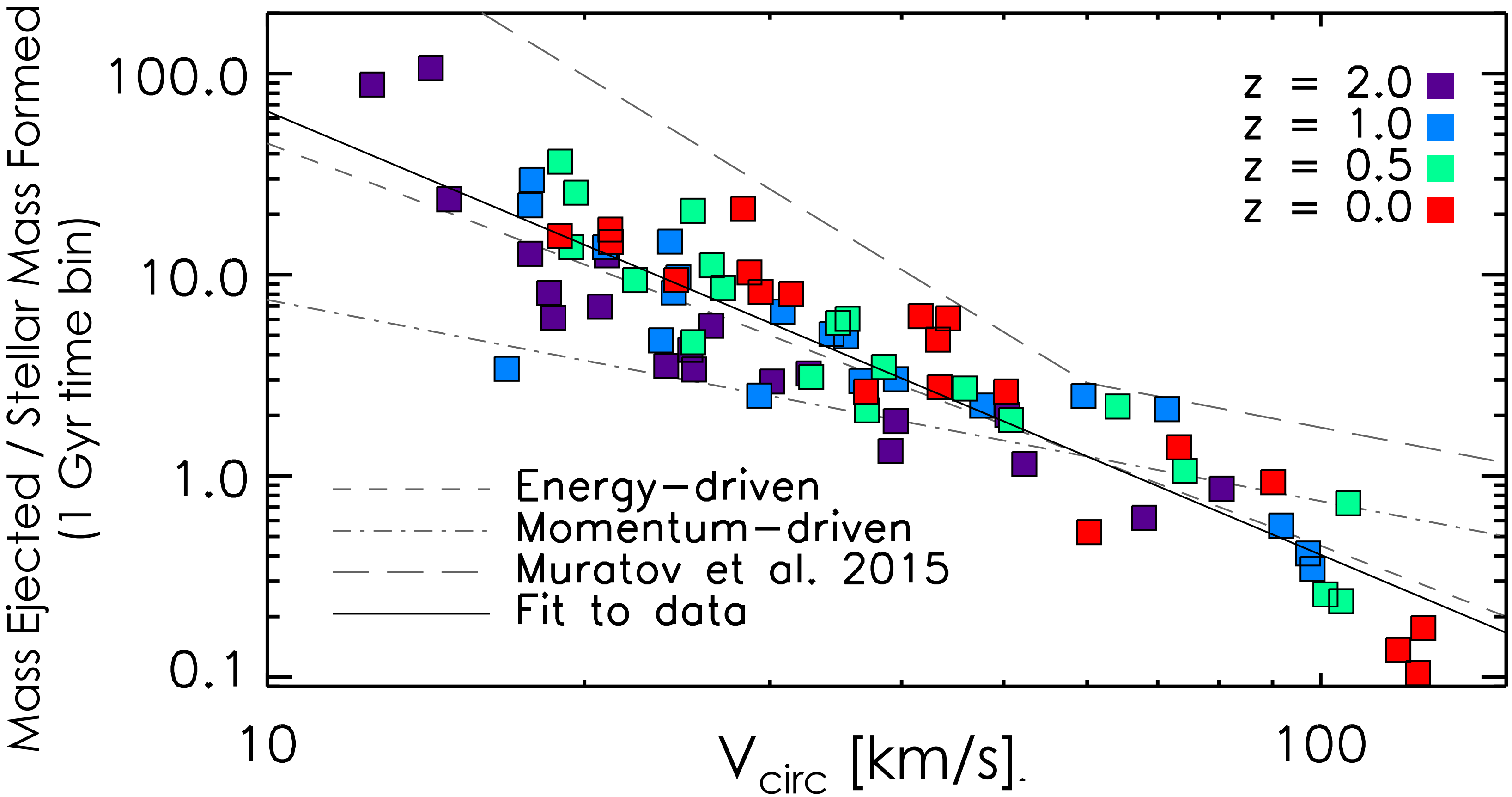
- Outflowing gas:
  - Must have once been in the disk
  - Ejected from disk:
    - Outflowing gas which has kinetic energy greater than potential energy from the *disk*
  - Expelled:
    - Outflowing gas which reaches beyond the virial radius
- 100 Myr time resolution
- Start at z = 3



Spread of outflow material



Mass Loading Factor for Ejected Material

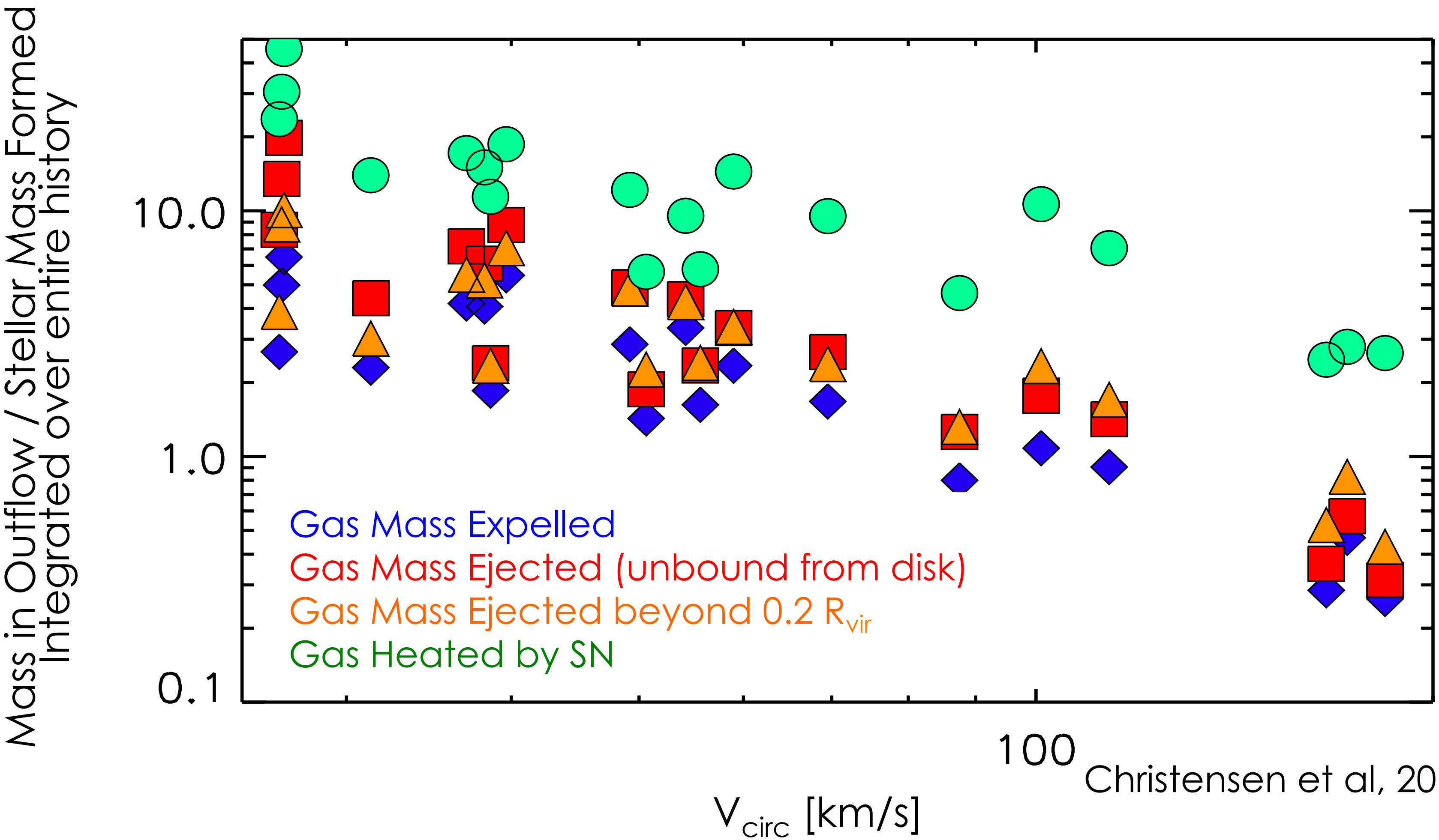


$\eta_{ejected} \propto v_{circ}^{-2.2}$, close to energy driven
No redshift evolution

Christensen et al, 2016

For what is η measured?

We want a way to compare outflows across models
We need a more comprehensive picture of outflows



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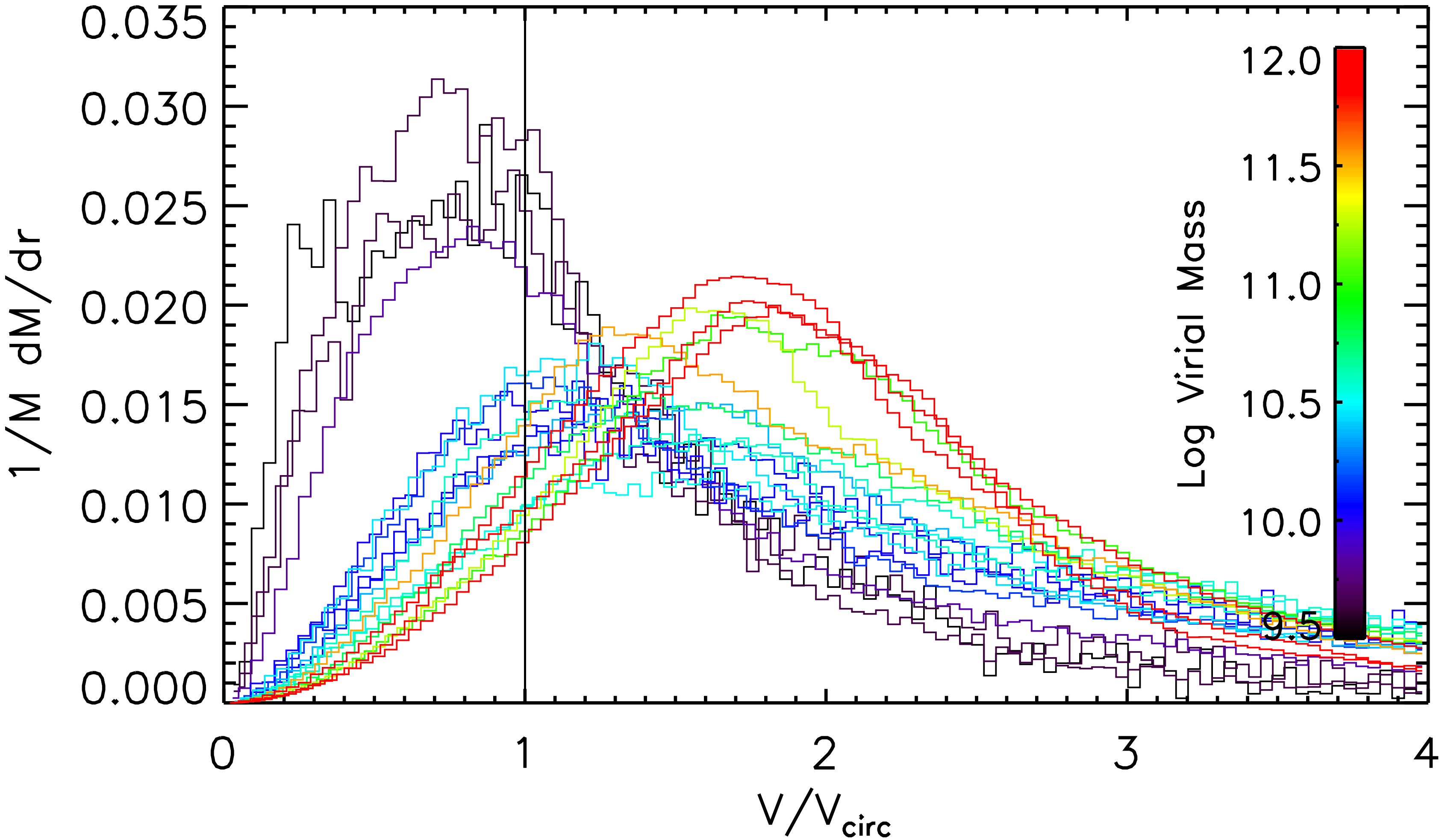
Velocity of outflows



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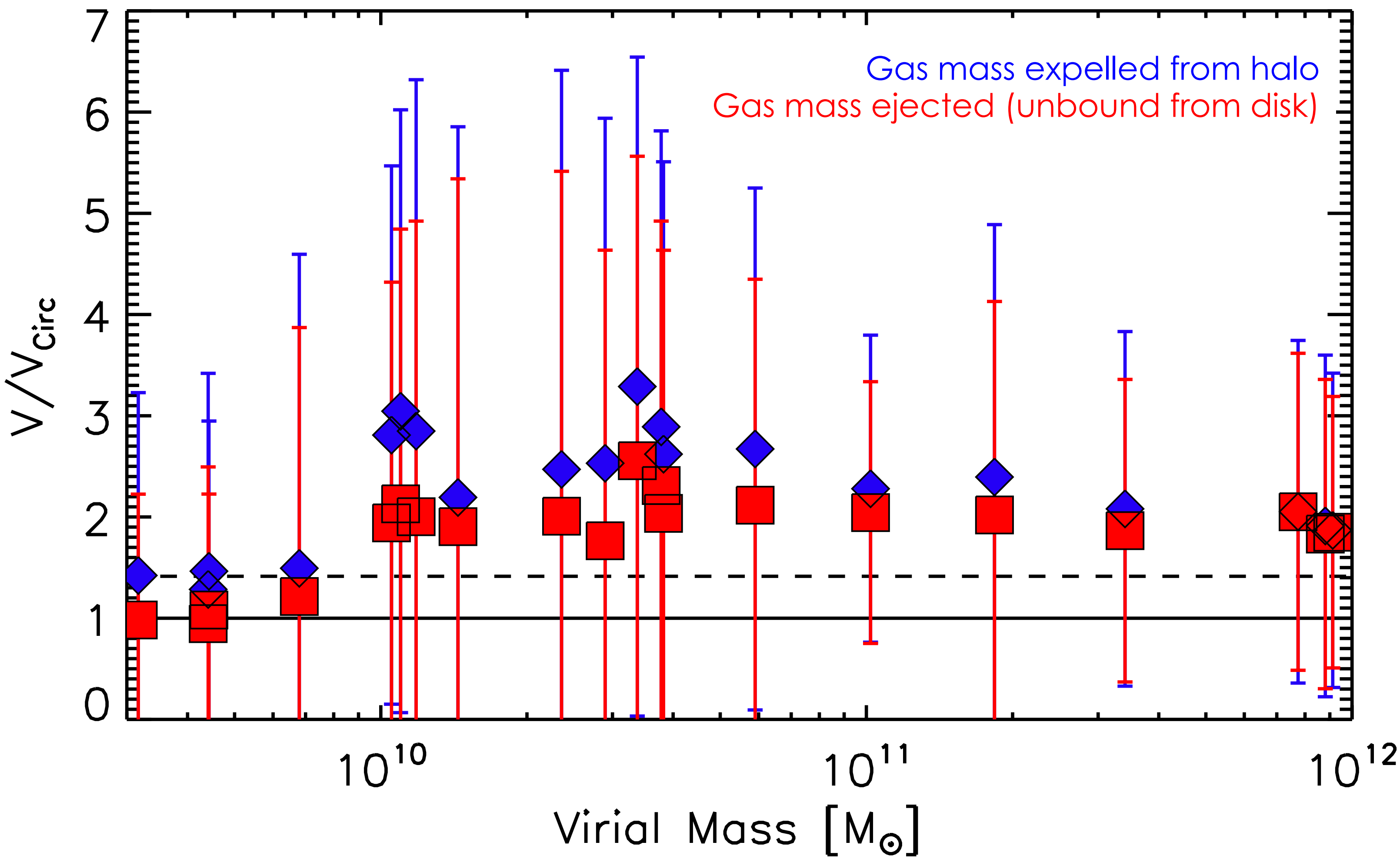

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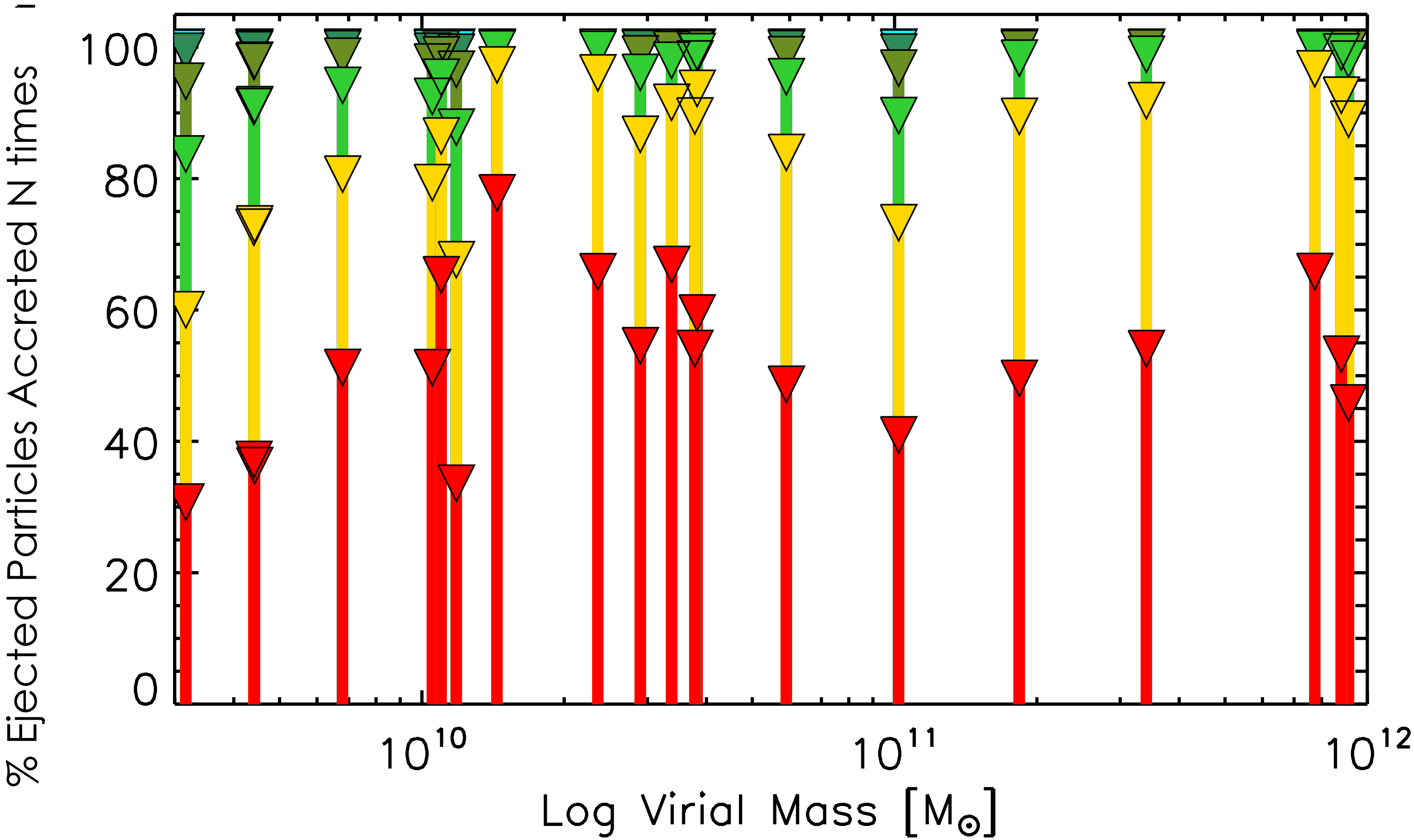
Number of Times a Particle is Reaccreted



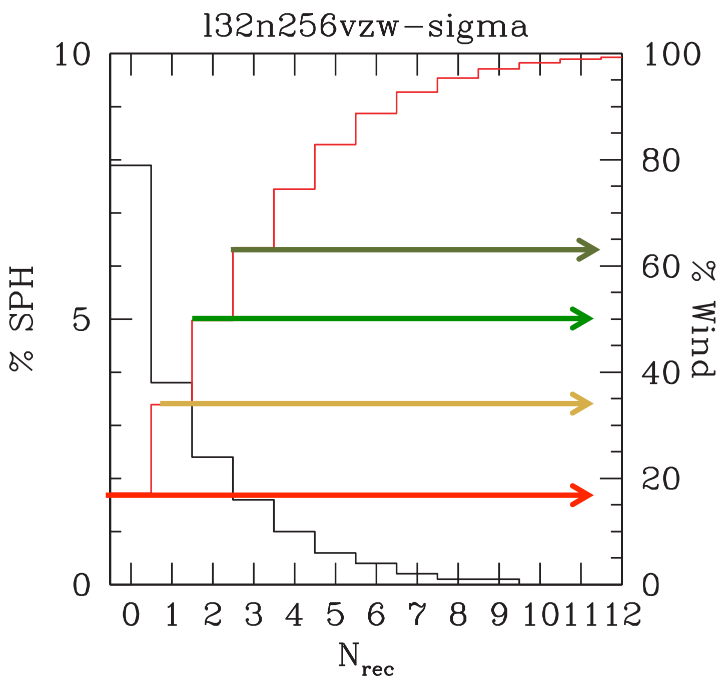
Never Reaccreted Reaccreted once Reaccreted twice . . .

Christensen et al, 2016

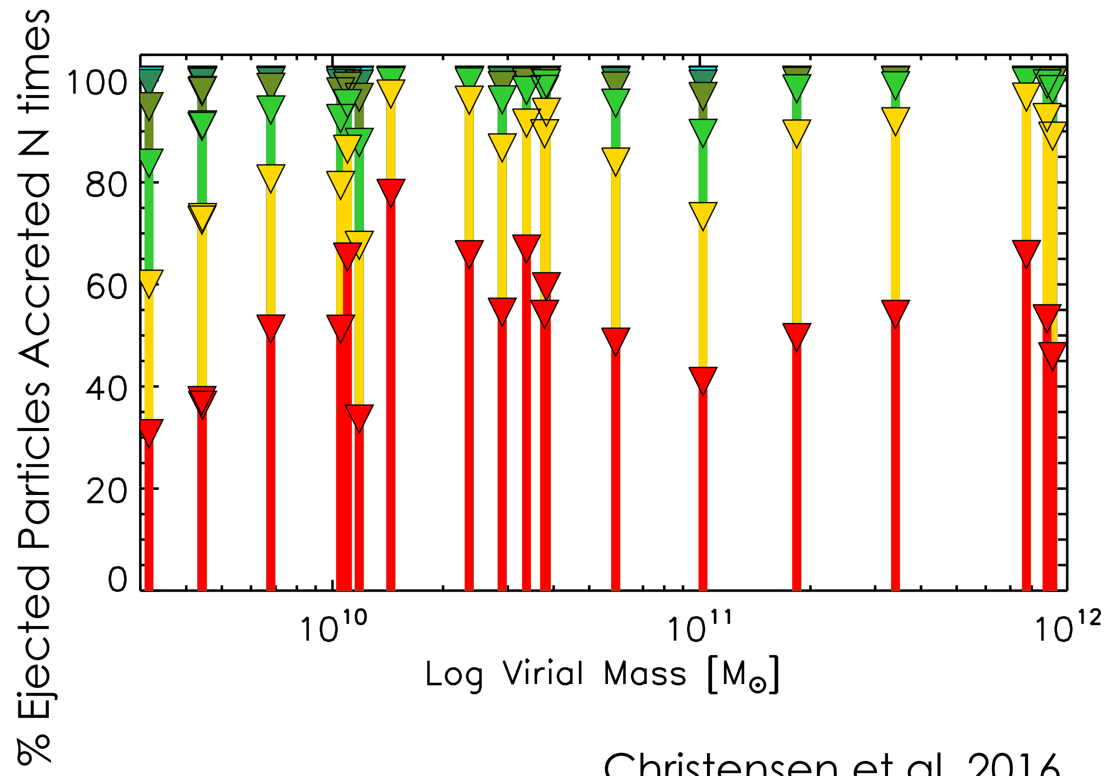
Number of Times a Particle is Reaccreted

Reaccretion is important to galaxy evolution
However, fraction reaccreted is highly dependent on

- feedback model
- selection of outflows



Oppenheimer & Dave, 2008



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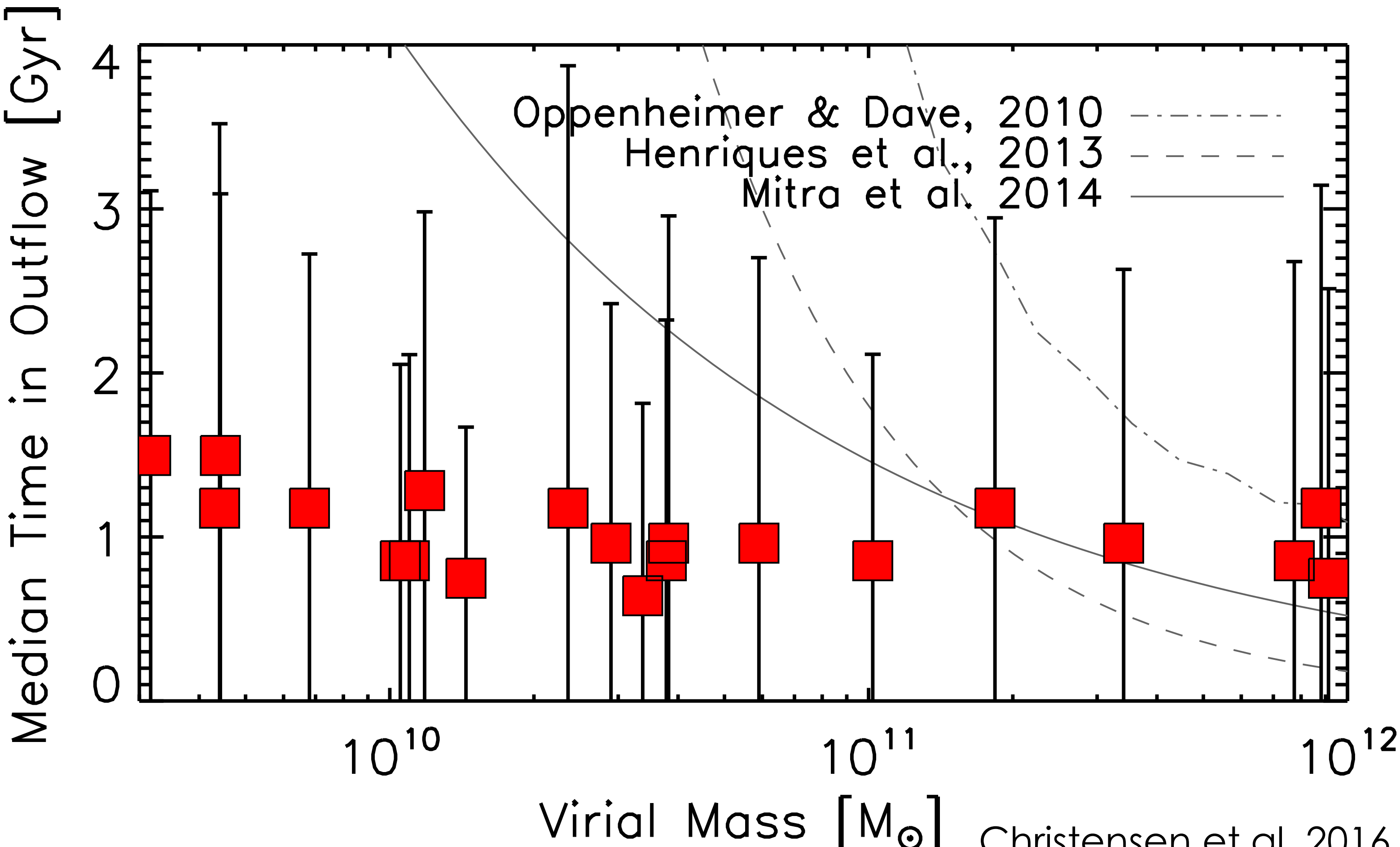
Amount of Time Before Reaccretion

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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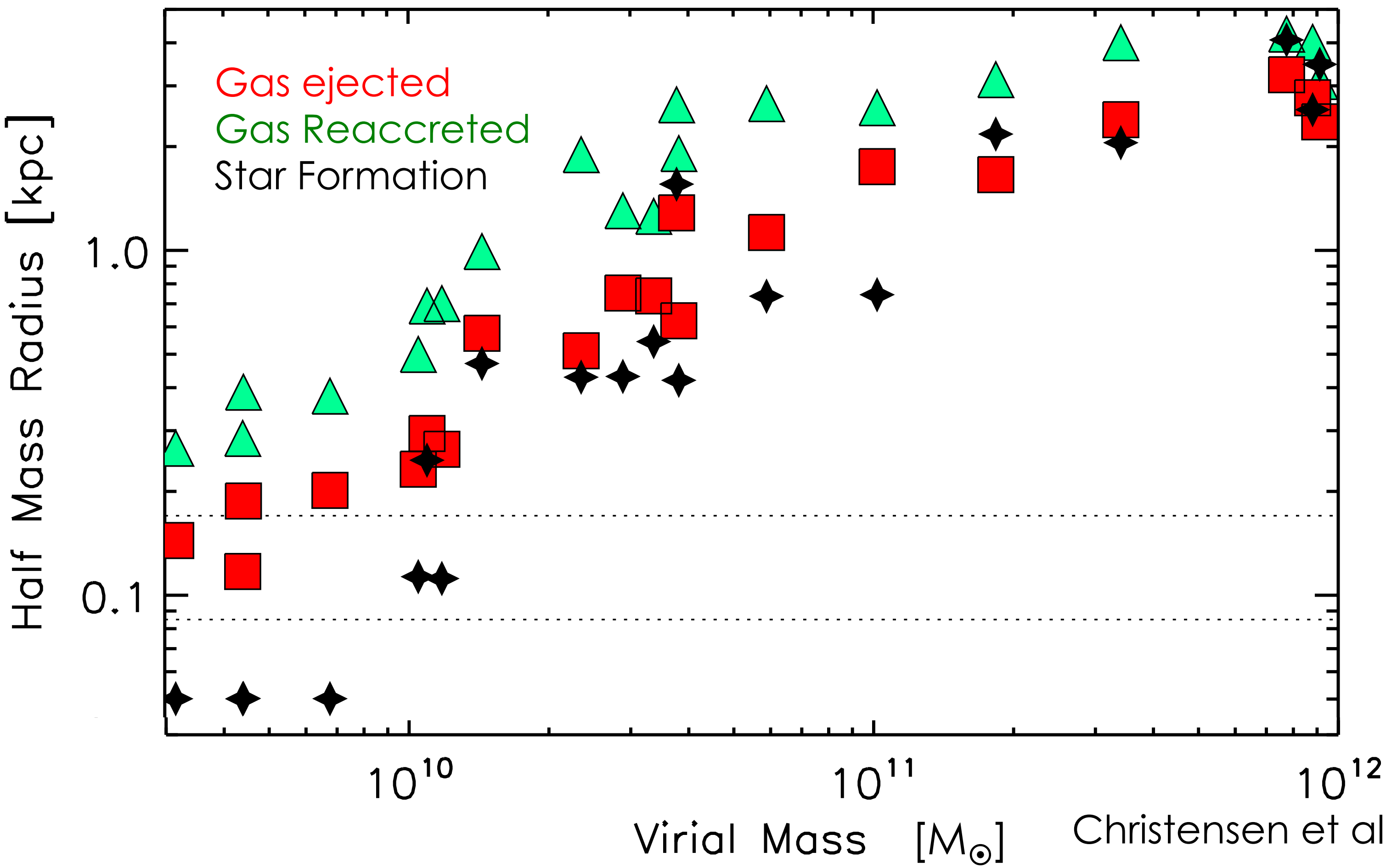
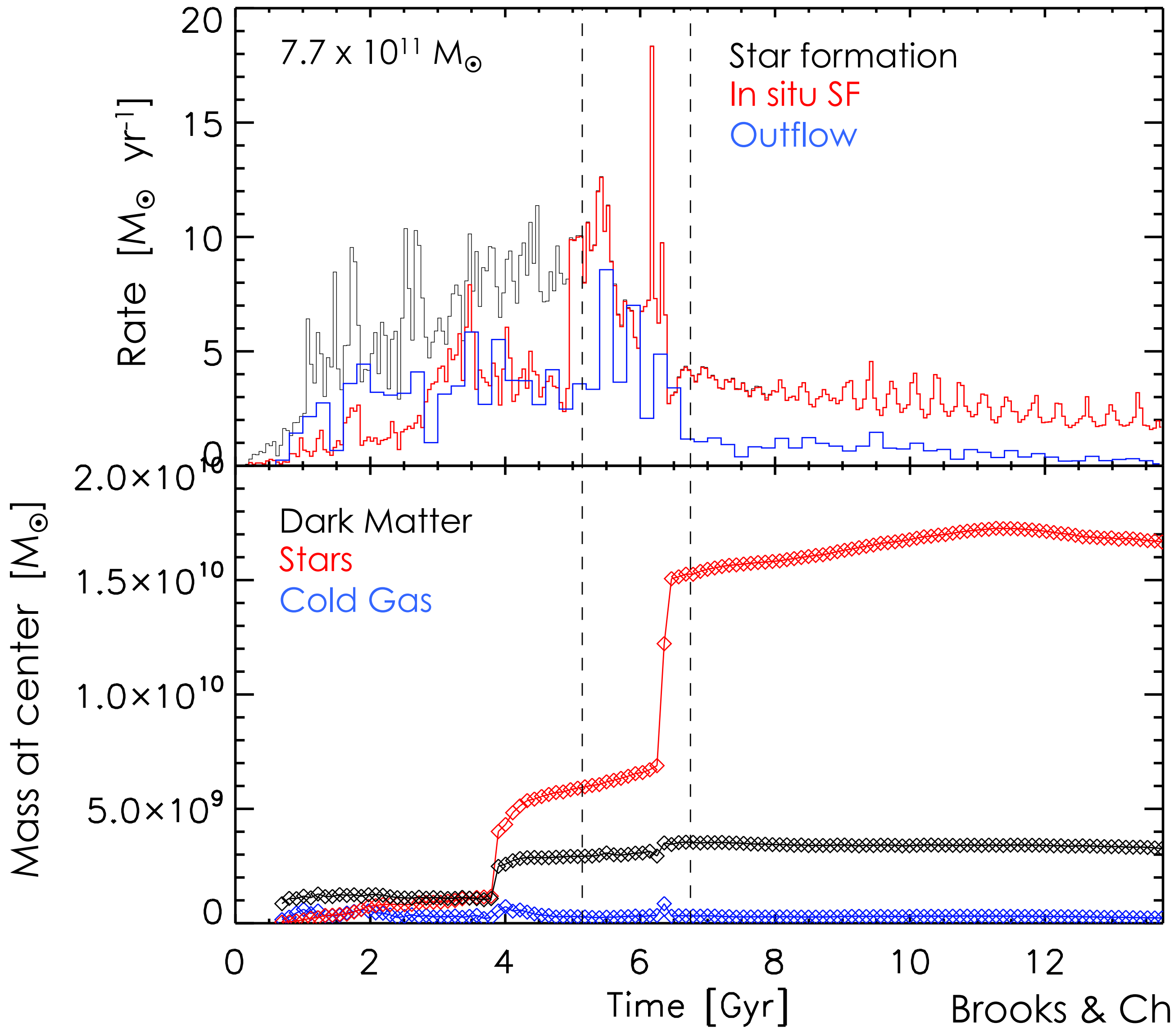
Source of ejected material/location of Reaccreted material

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



Christensen et al, 2016

Feedback-limited bulge growth?



Brooks & Christensen, 2015

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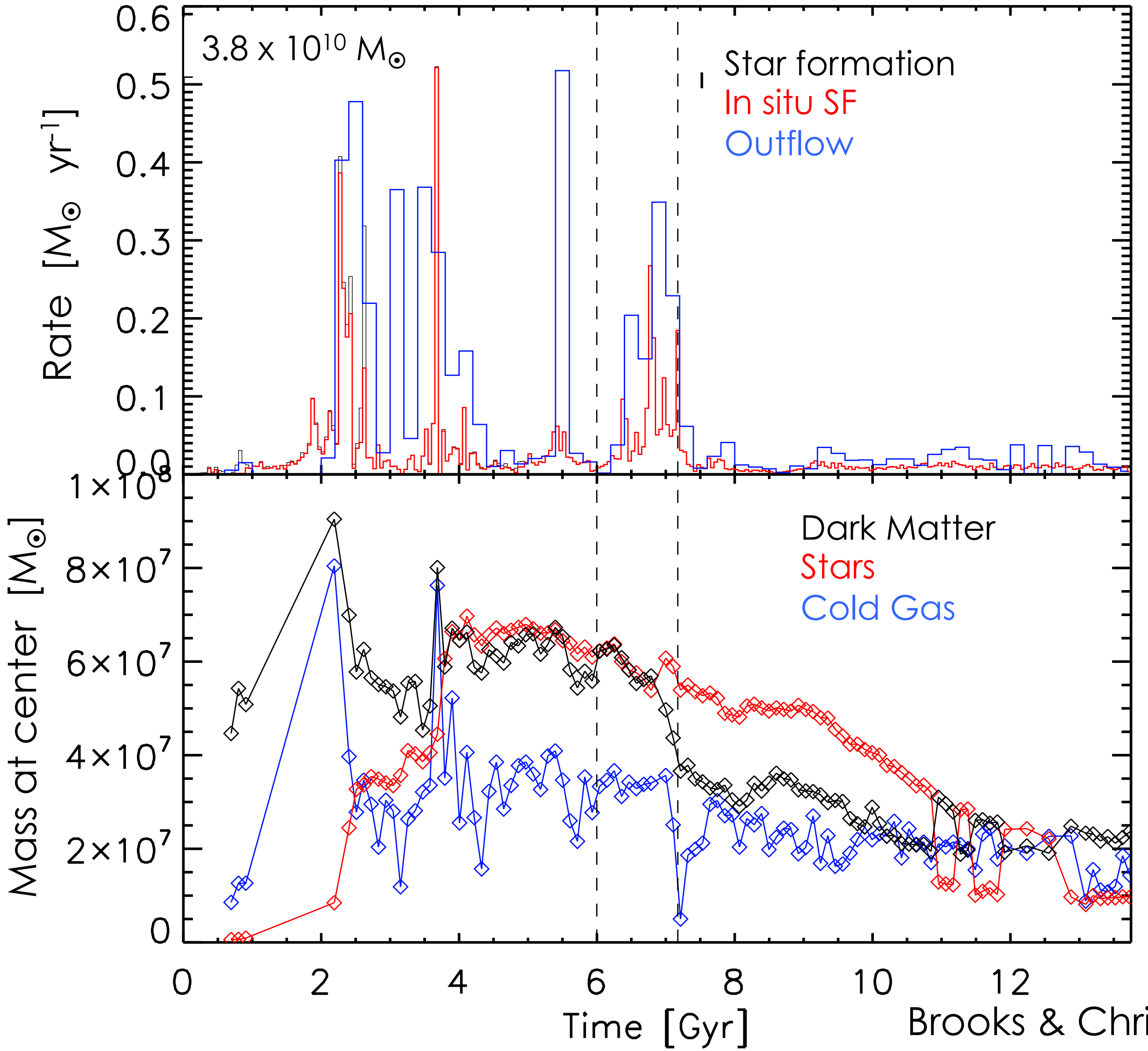


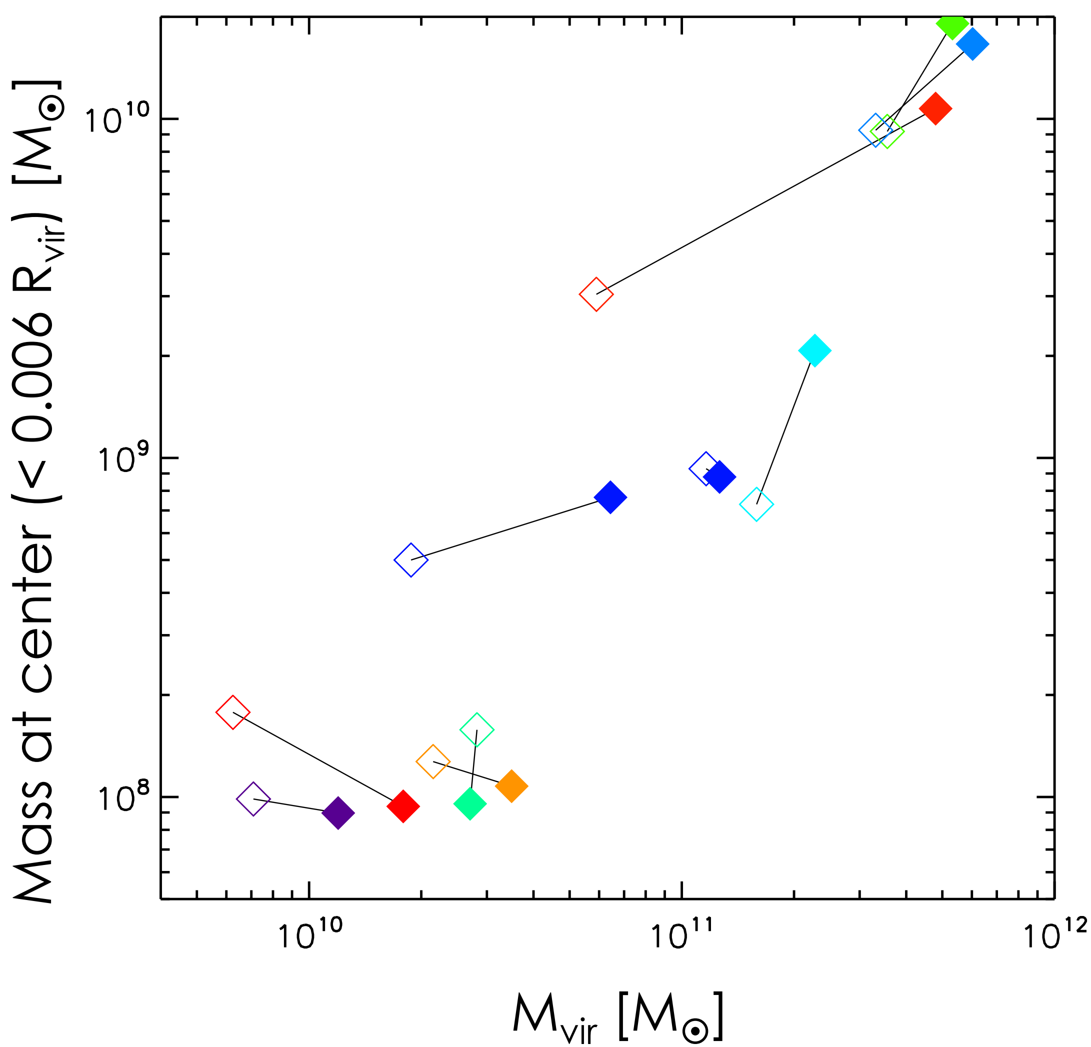
Brooks & Christensen, 2015

Feedback-limited bulge growth?

Outflows are able to prevent bulge growth during mergers for galaxies with about $M < 10^{9.5} M_\odot$.

Result of higher mass loading in low-mass galaxies.

Can help explain mass-dependency of bulge fraction



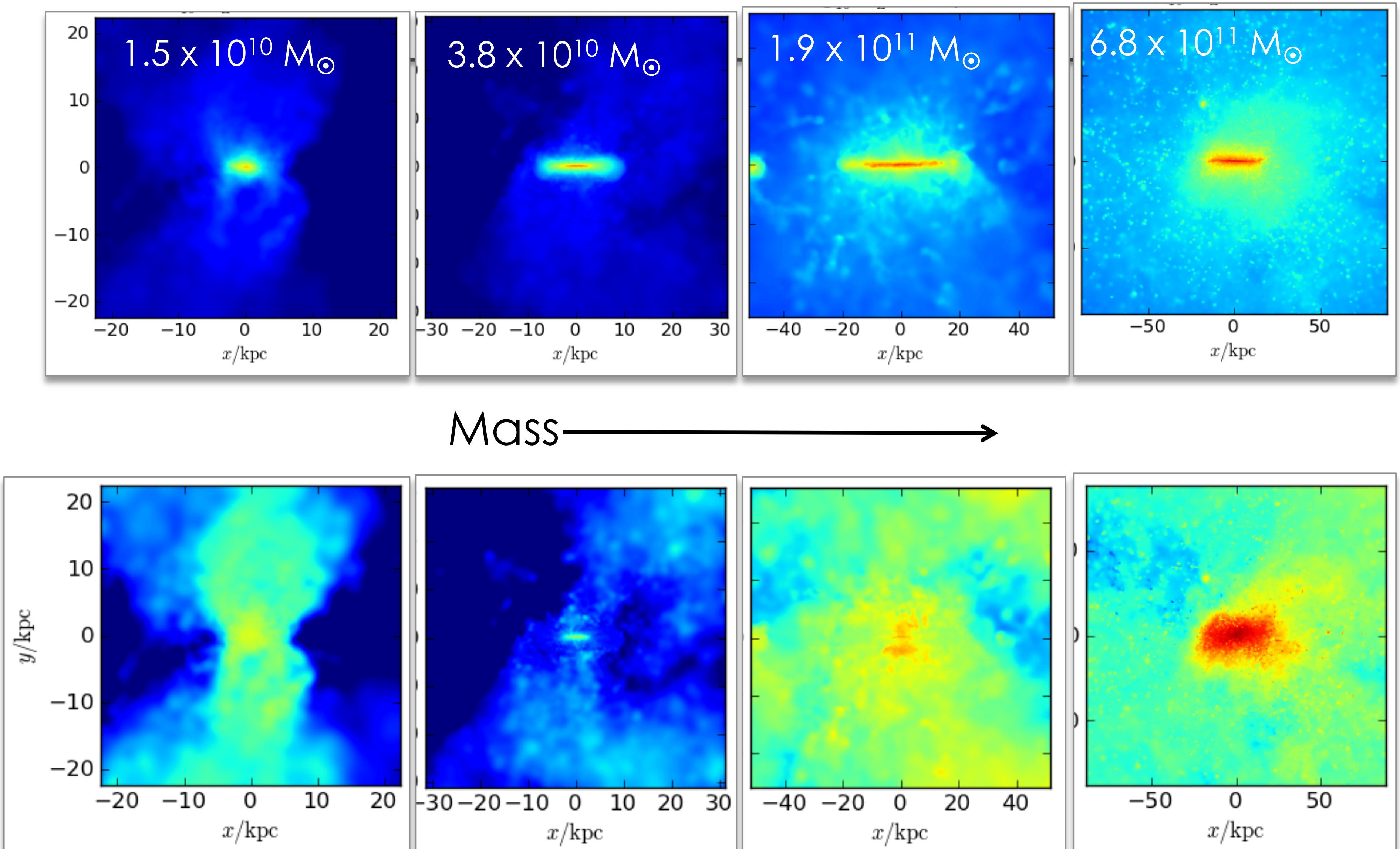
Brooks & Christensen, 2015

Credit: Fabio Governato

Stars

Gas colored by metallicity

Metal Surface Density

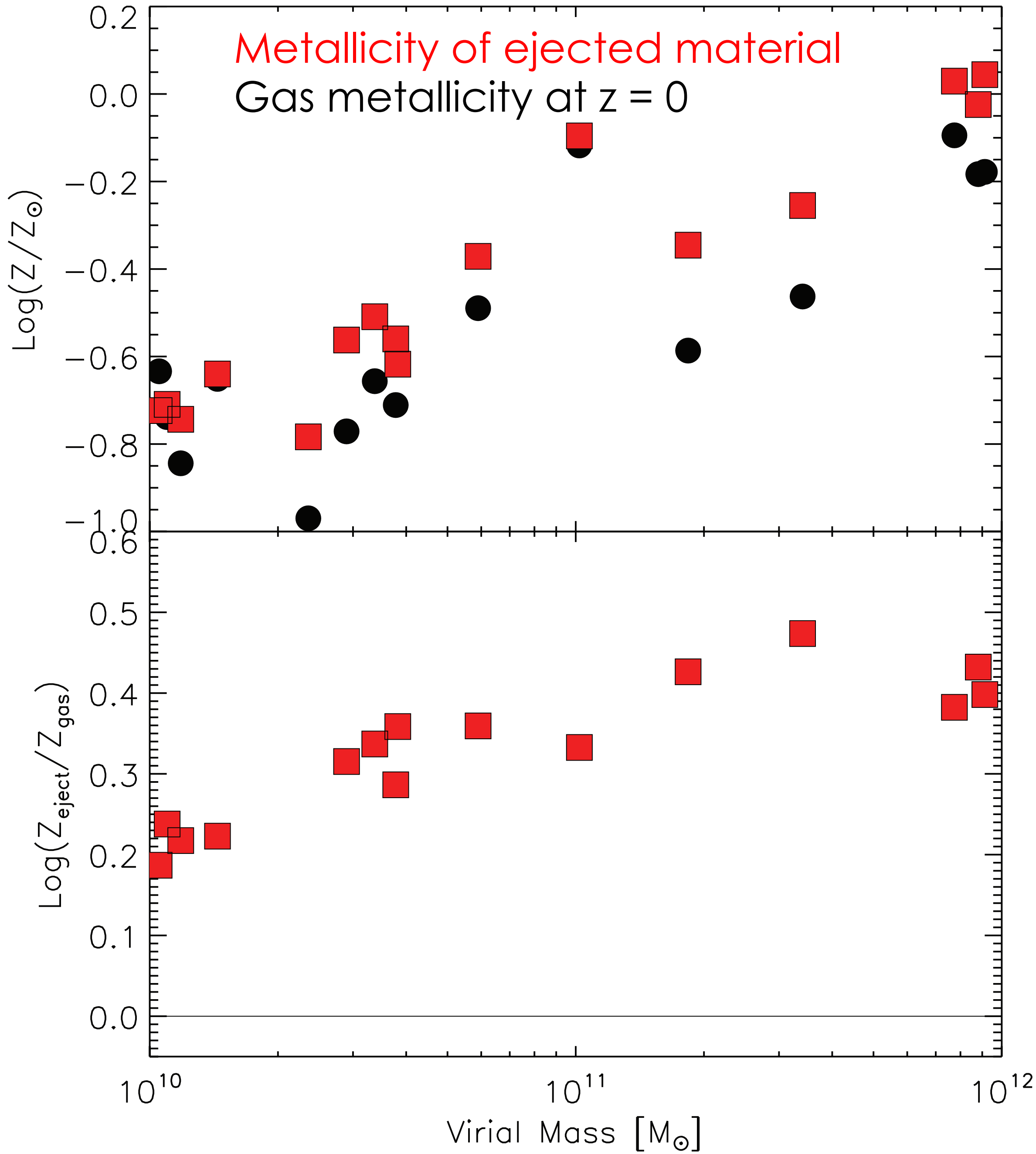


Log Metallicity of Gas (slice through center of galaxy)

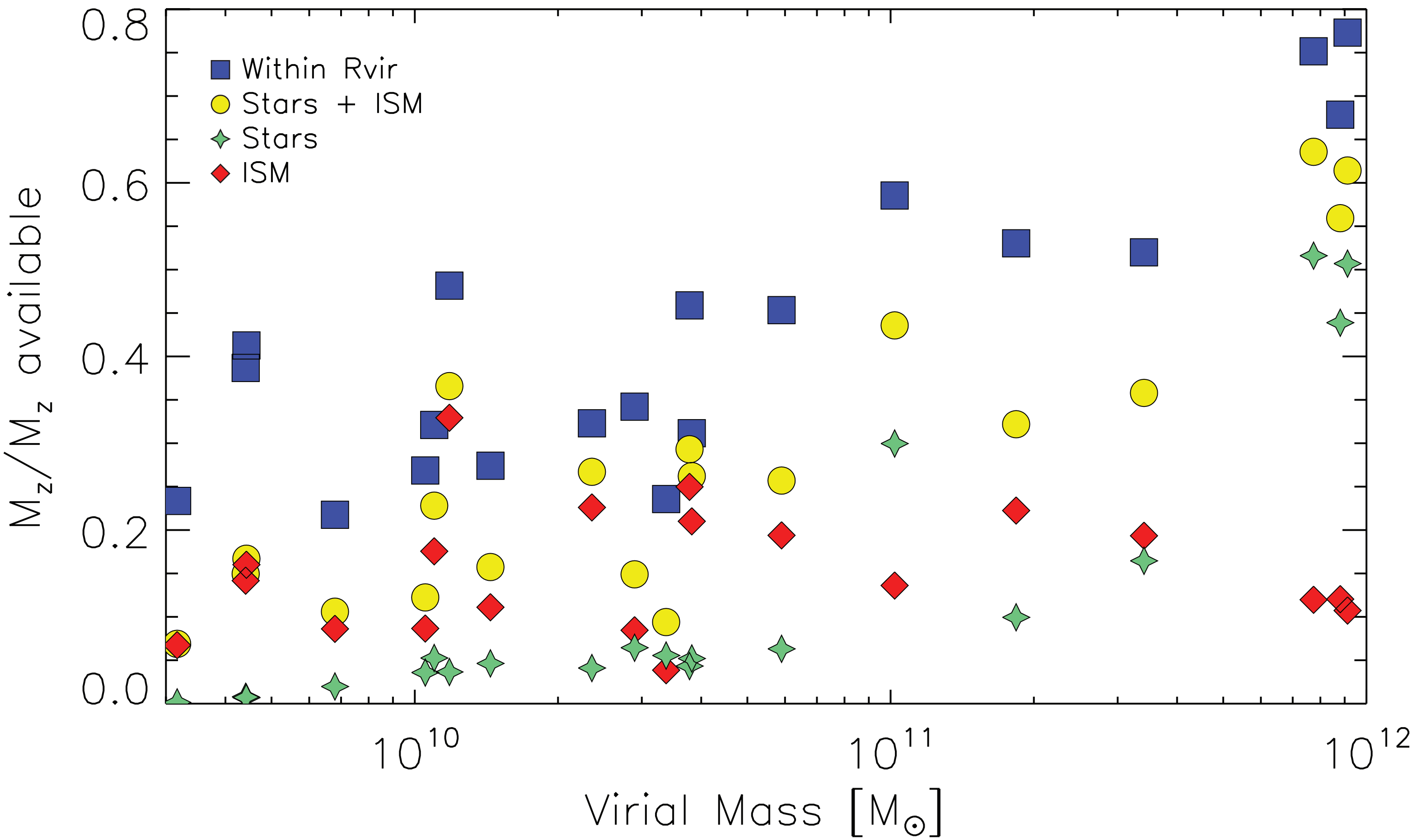
Metal Enrichment of Outflows

Outflows are metal-enhanced compared to source ISM by a factor of ~1.6 to 3.

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



Eventual Location of Metals



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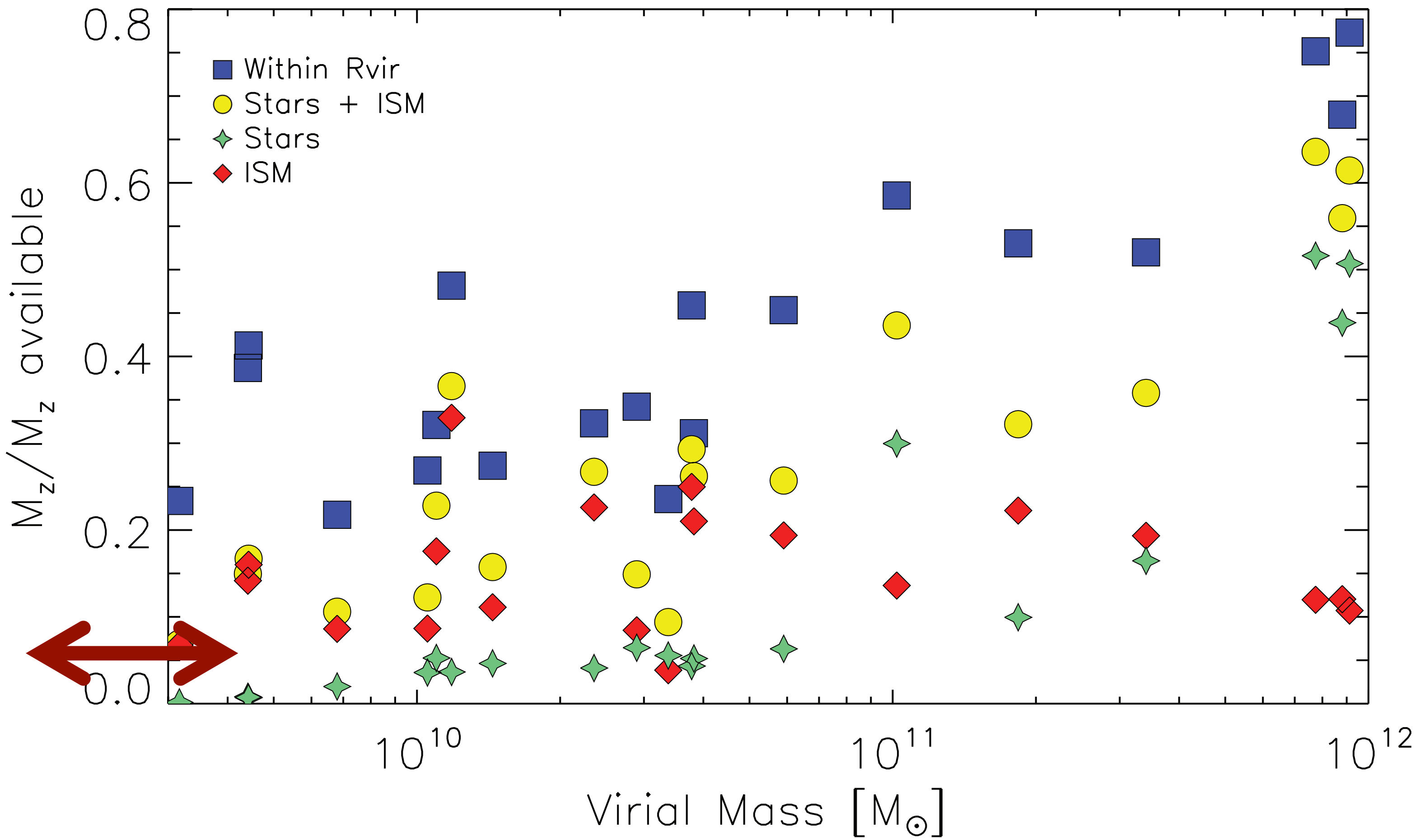

Leo P: $M_* = 5.7 \times 10^5\ M_\odot$
5% O in disk gas, 1% in stars
(McQuinn+ 2015)

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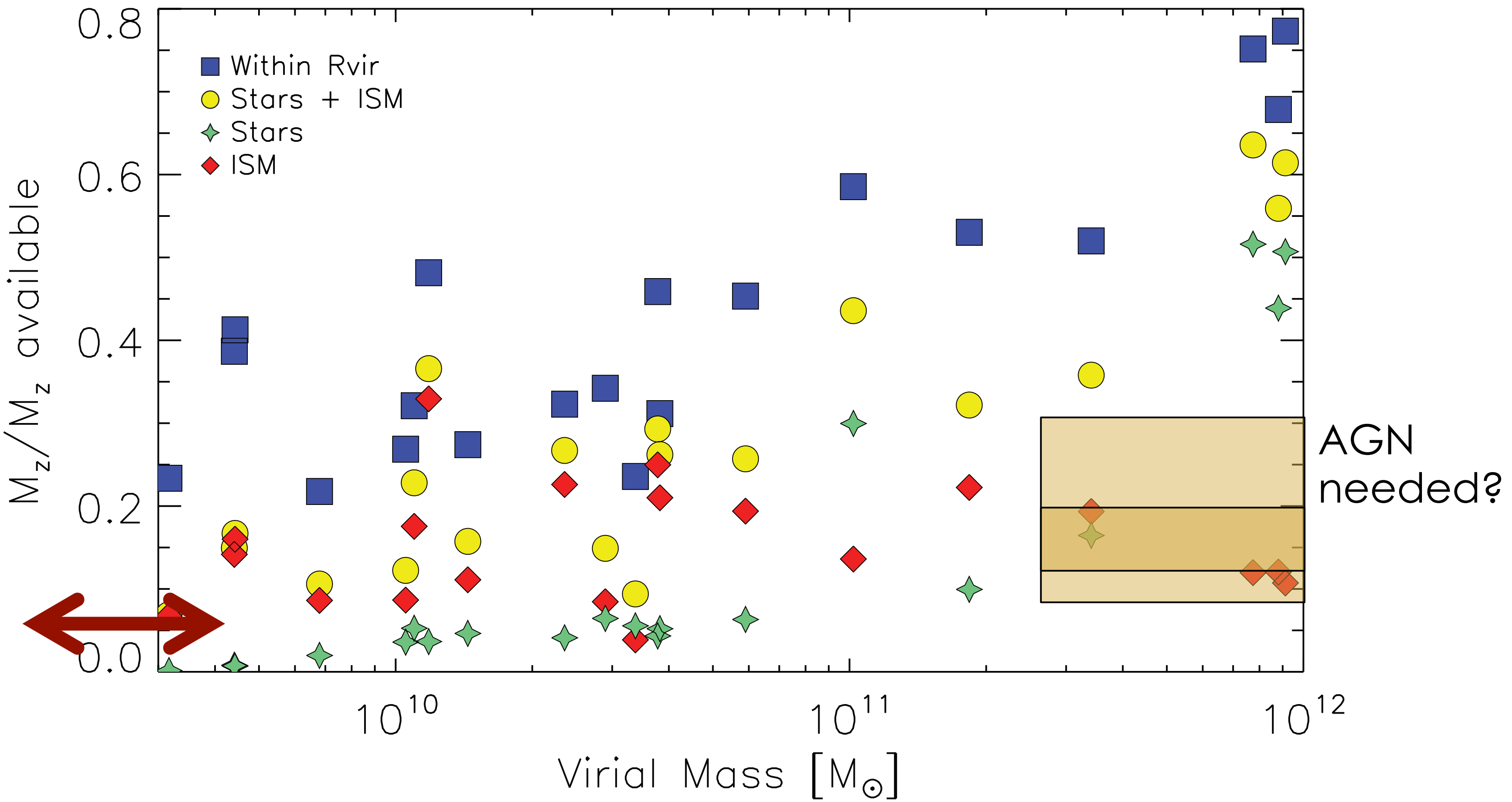

Leo P: $M_* = 5.7 \times 10^5\ M_\odot$
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$M_* \geq 10^{9.3}\ M_\odot$: 15 – 30 % of metals remain in disk gas or stars
(Peeples+ 2014)

Summary

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

- $\eta^{?}$(z?): tension between models at high gas surface densities
- Feedback model sensitive to amount and time scale of recycling
- Need for comprehensive model of winds and a way to compare between models
- CGM and ISM may be way to distinguish between FB models (see Agertz . . .)