Tracking Outflow Properties Across Galaxy Mass

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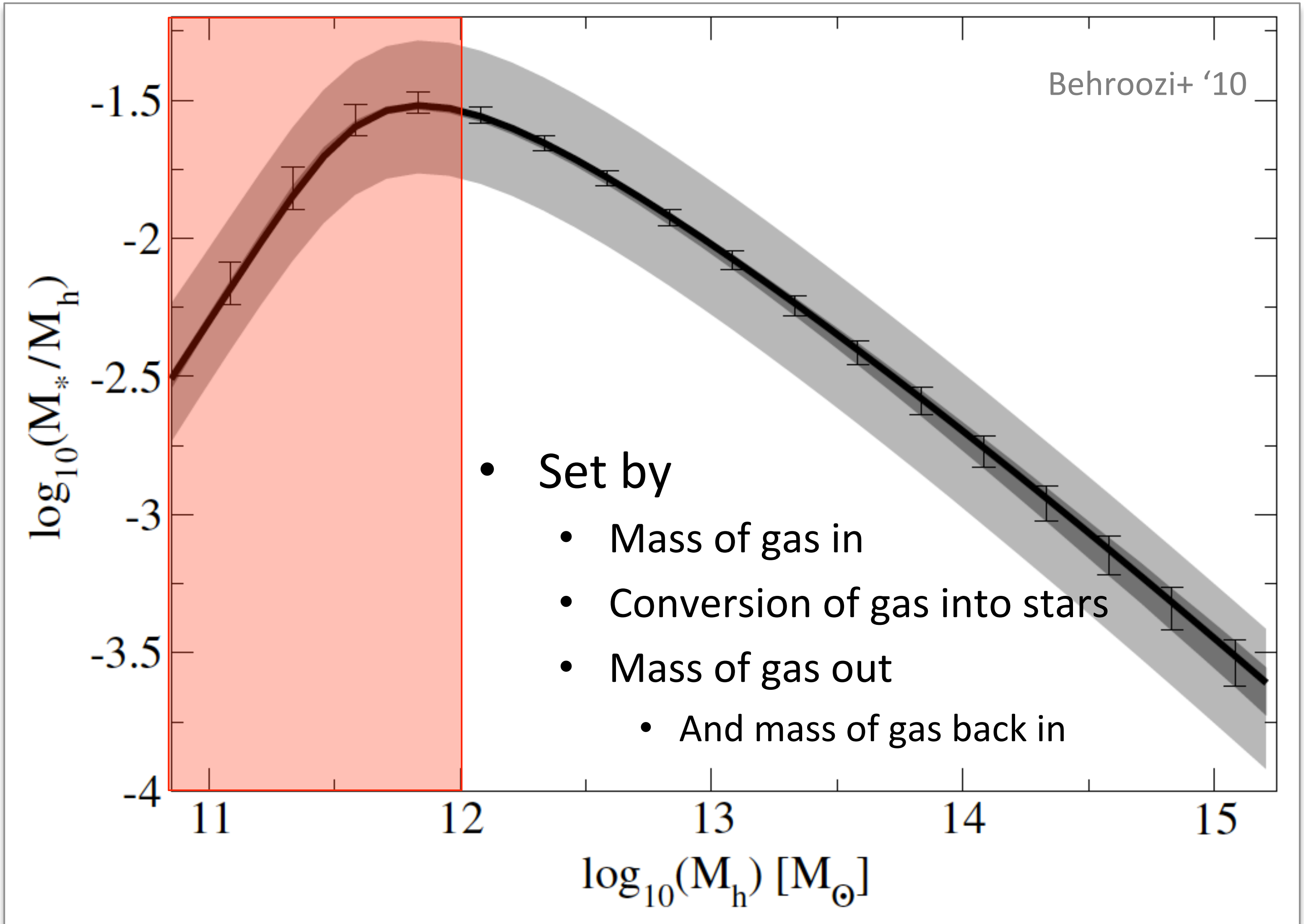
Stellar Mass Fraction vs. Halo Mass



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

Outflow Mass Scaling with Halo Mass

- Greater gravitational potential with increasing halo mass
- Higher density environment with increasing halo mass (Oppenheimer+ ’10)

- Over virial masses from $5x10^9 – 10^{12}$ M_{sun}, how do outflow properties scale?
  - Outflow Mass
  - Mass Loading
  - Velocity
  - Recycling
  - Metallicity
  - Origin

Modeling Stellar Feedback

- 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*

Code: Gasoline

(Wadsley+ 2004)

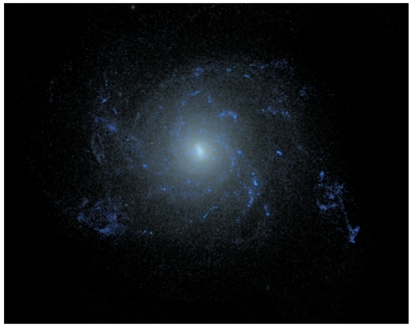
- SPH code
- Cosmic UV background radiation
- H & He ionization; non-equilibrium H_2 (Christensen+ 2012)
- Metal line cooling and metal diffusion (Shen+ 2010)
- Probabilistic star formation based on free-fall time and H_2 abundance (shielded fraction) (Christensen+ 2012)
- Supernovae feedback from type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

Blastwave Model for Feedback

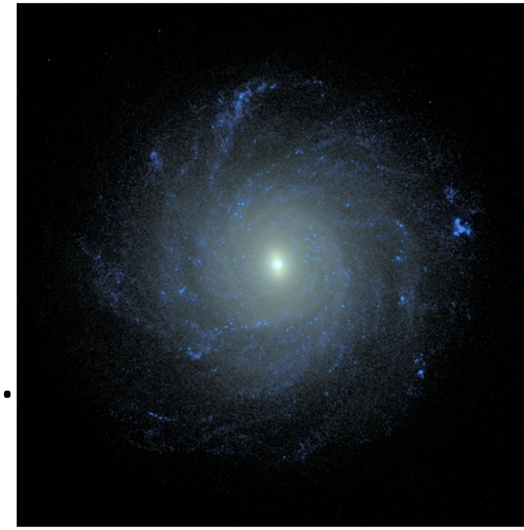
- Thermal energy is transferred to gas particles near the star
- Cooling is disabled for the period of time equal to the momentum-conserving (snowplow) phase of the blastwave
  - function of E, P and ρ (McKee and Ostriker 1977)

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

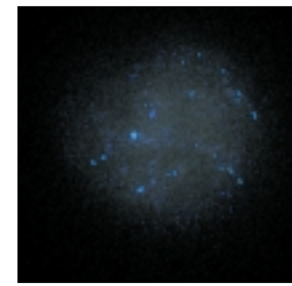
- The hot particle will naturally rise from the disk (no kick needed, no information about the halo included)

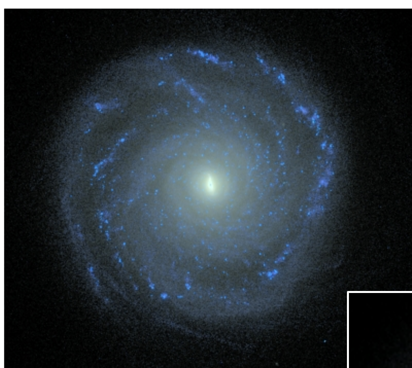


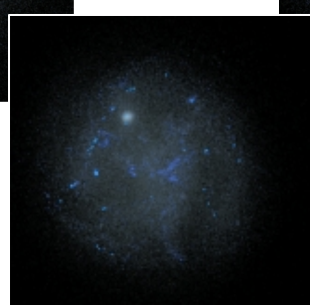
Simulations

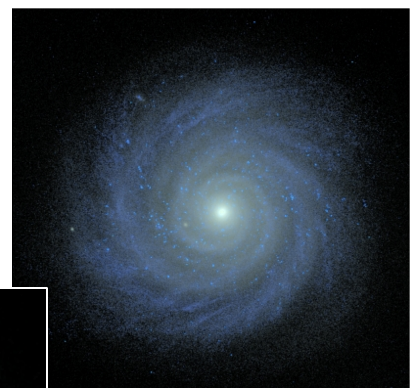


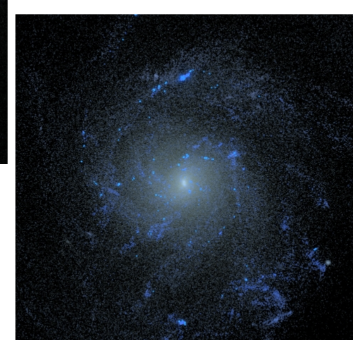
- 20 central galaxies from zoom-in, cosmo sims.
- Virial masses at z = 0 from $5\text{x}10^{9} – 10^{12}\ M_{\odot}$
- Gas particle masses: $3300M_{\odot}$ or $25{,}000M_{\odot}$
- Softening lengths: 87 or 170 pc

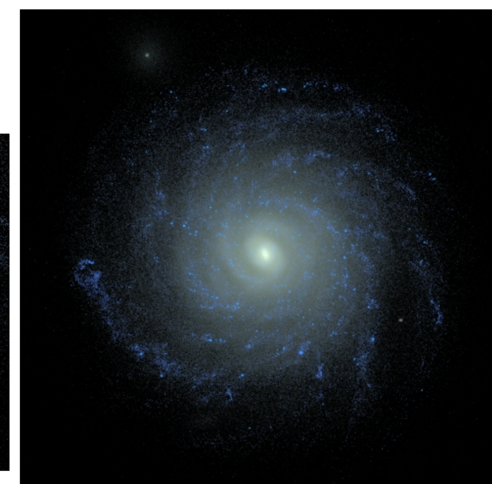








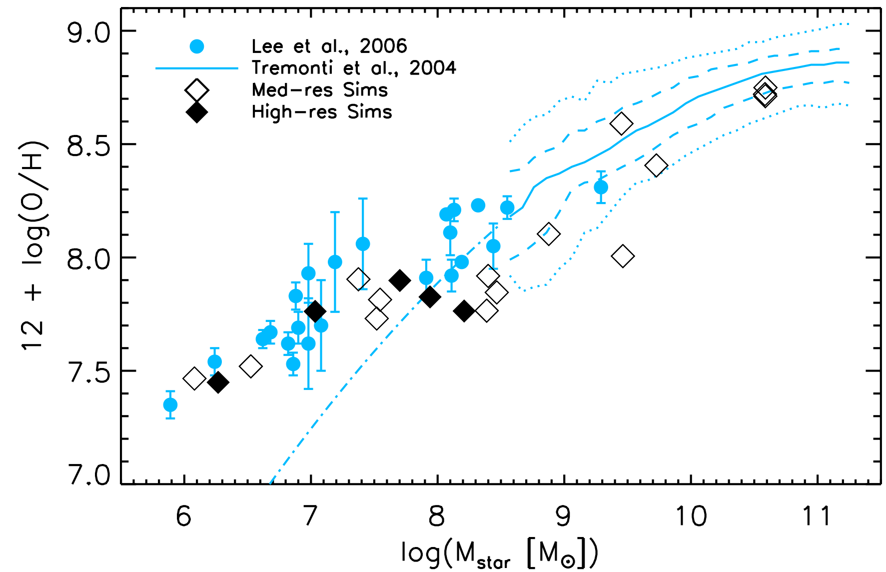




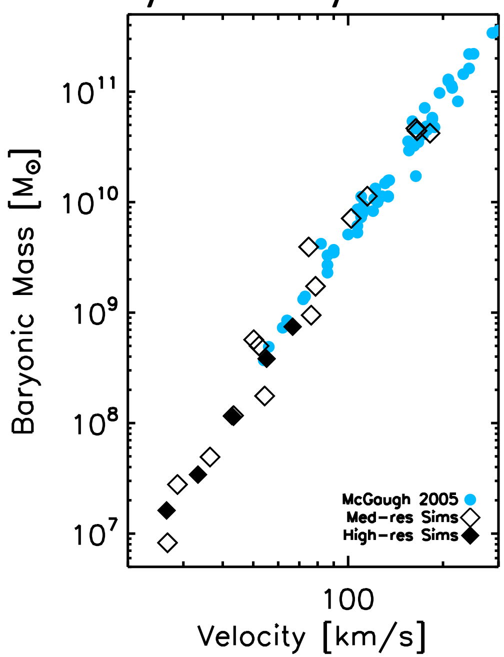
Observed relations of global properties at z = 0

Also, realistic sizes, and gas fractions

Stellar Mass-Metallicity Relation



Baryonic Tully-Fisher



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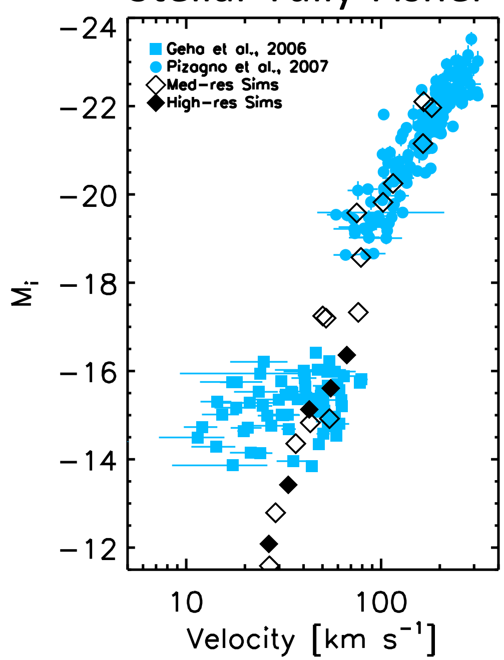
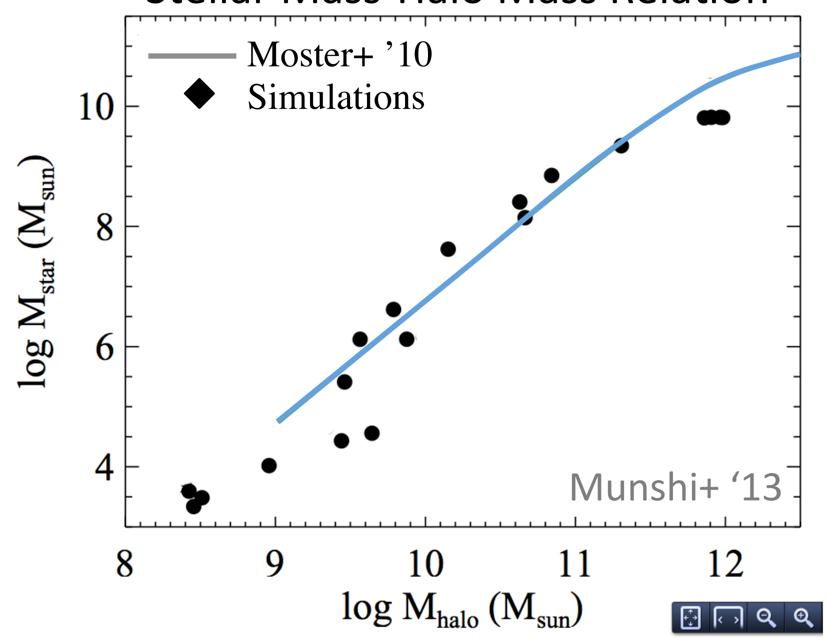
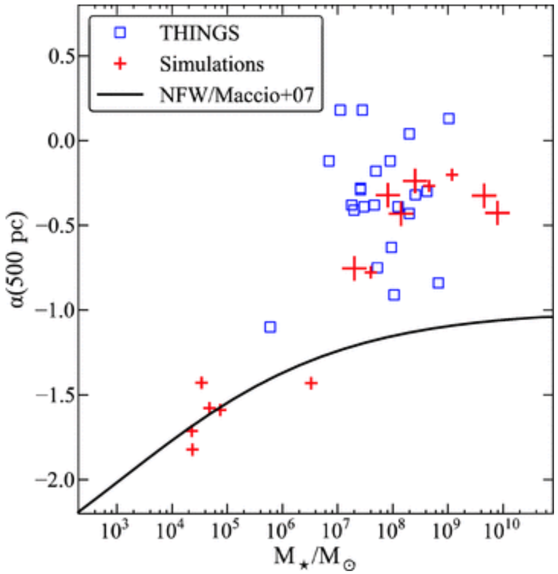


Stellar Mass-Halo Mass Relation



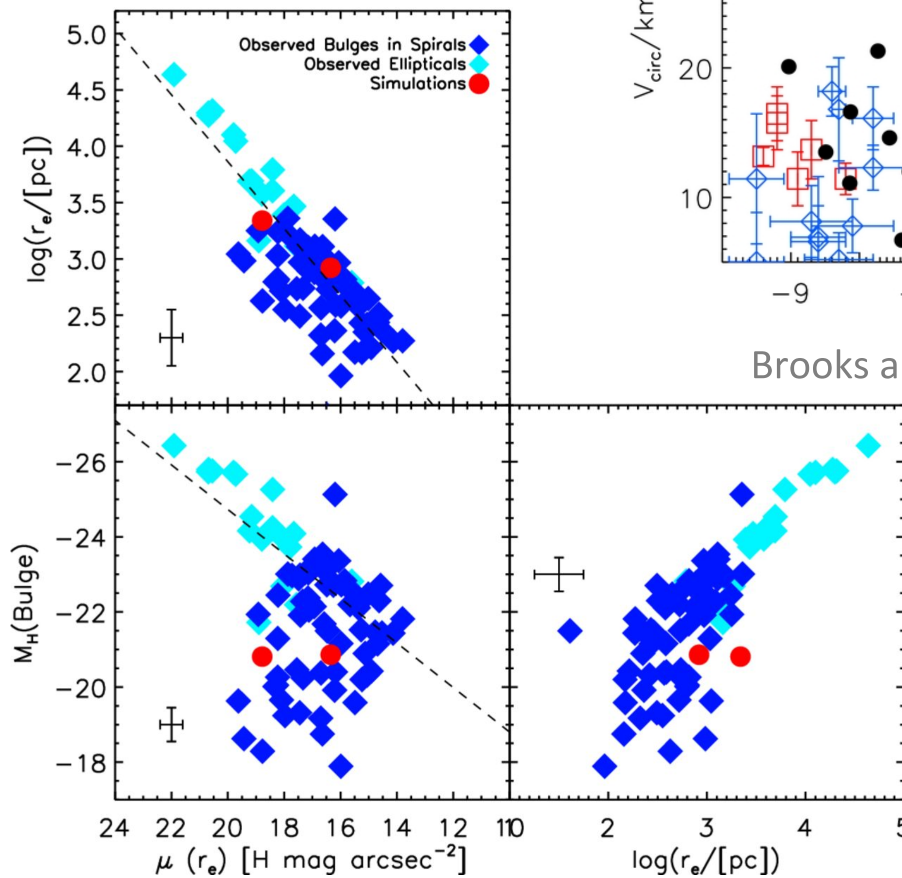
Matter Distribution within Galaxy

Cored Profiles



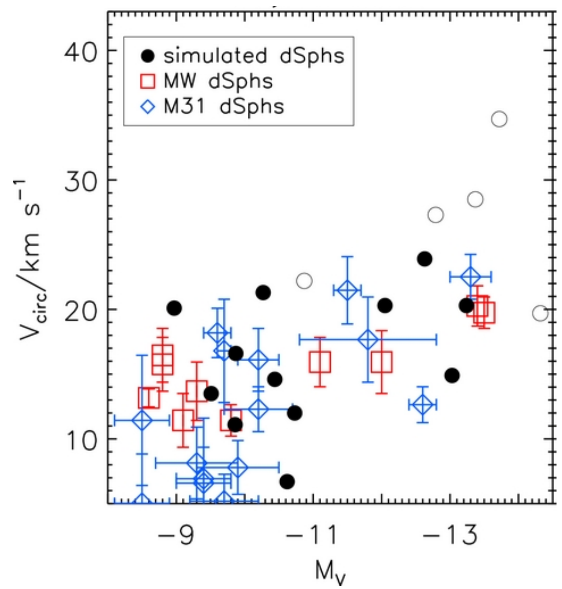
Governato+ 2012

Appropriately
Shaped Bulges



Christensen+ 2014

Circular Velocity of Satellites

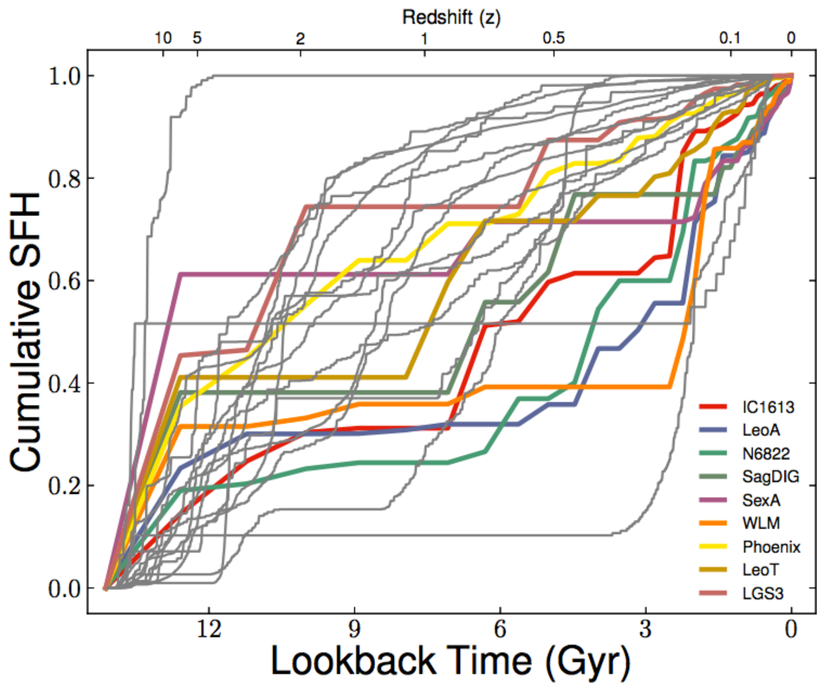


Brooks and Zolotov 2014

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

Star Formation Histories

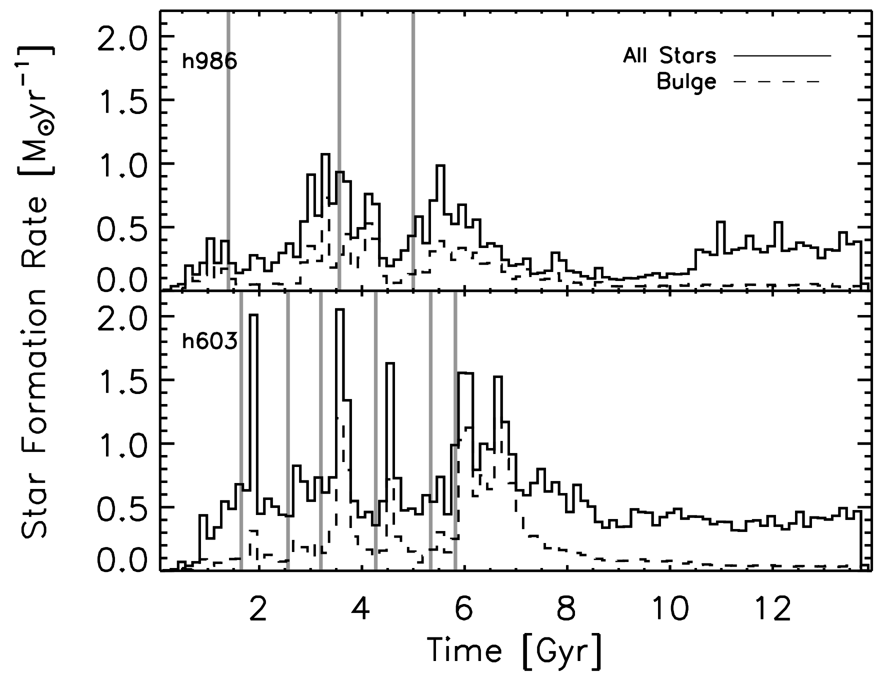
Dwarf Galaxies



Brooks, A., Weisz, D. et al, *in prep*

See also Shen+ 2014

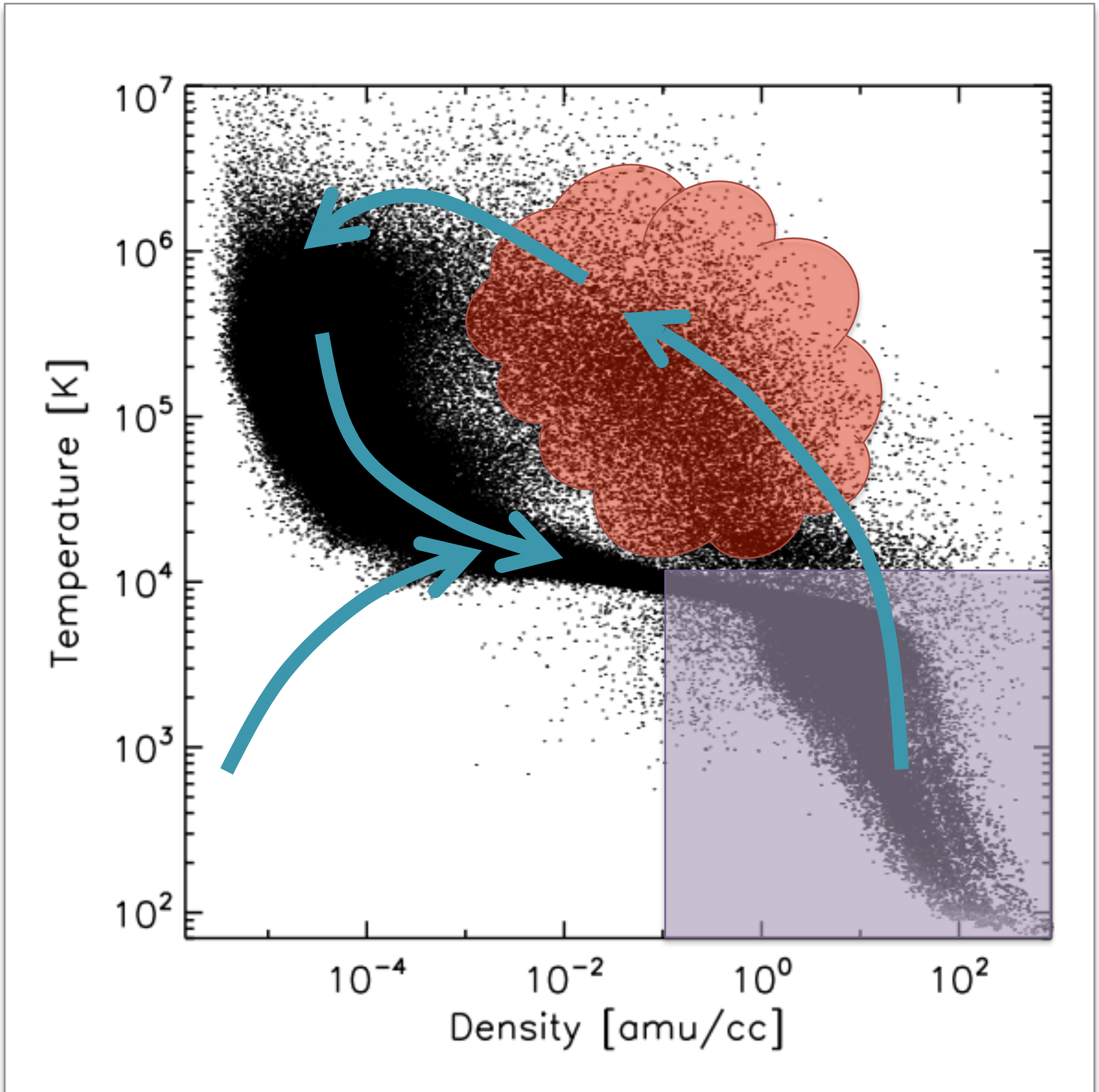
Low-mass (2e11 $M_\odot$) Galaxies



Christensen+ 2014

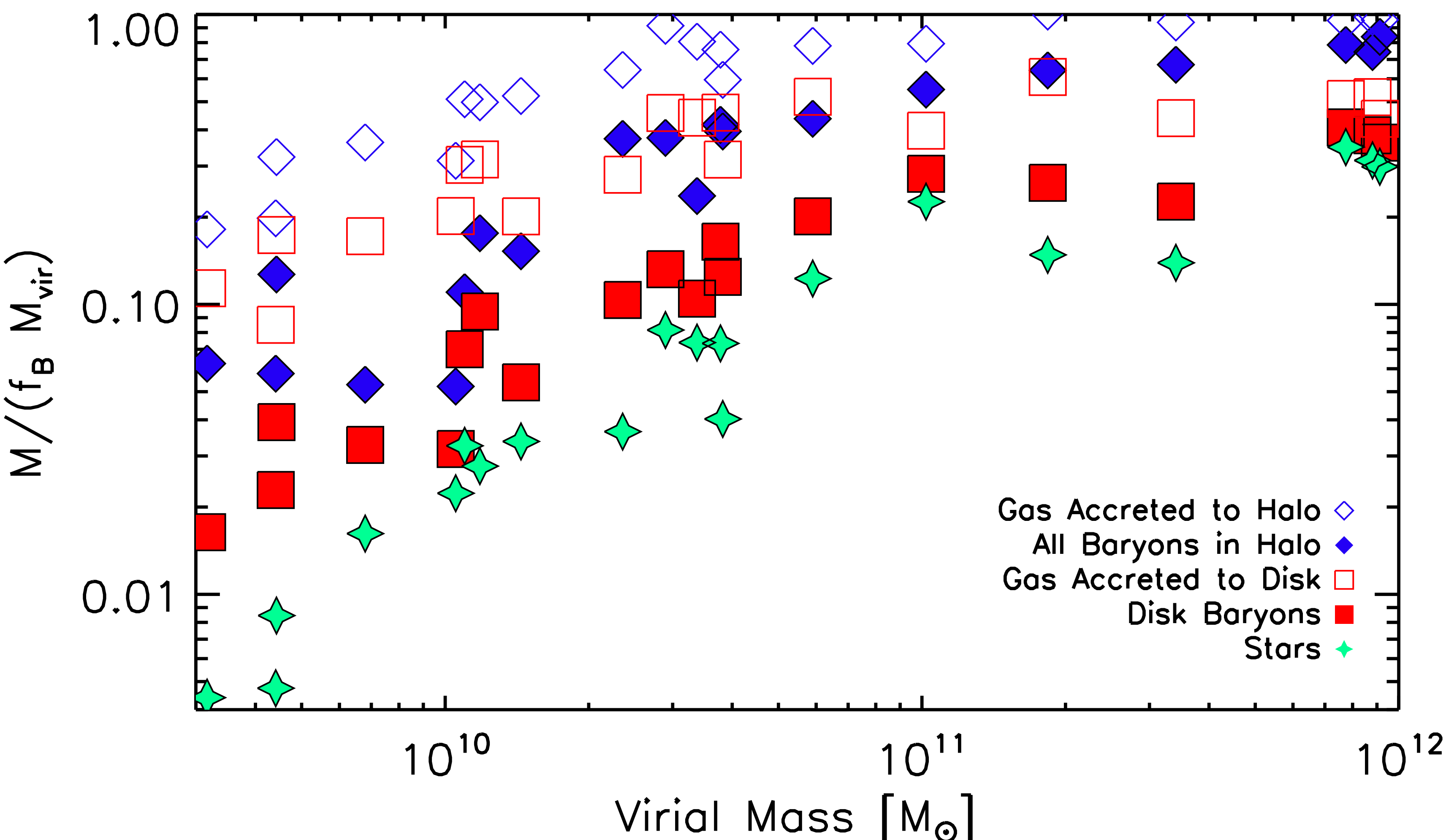
Current blastwave feedback model may be insufficient to properly reduce SF at high-z (high Σ?) in larger mass galaxies. (See Stinson+ 2012, Hopkins+ 2013, Agertz+ 2014 for discussion on effects of early stellar feedback and Keller+ 2014 for another approach).

Phase Diagram



Disk Gas:
- ρ > 0.1 amu/cc
- T < 1.2×10^4
- spatial cut

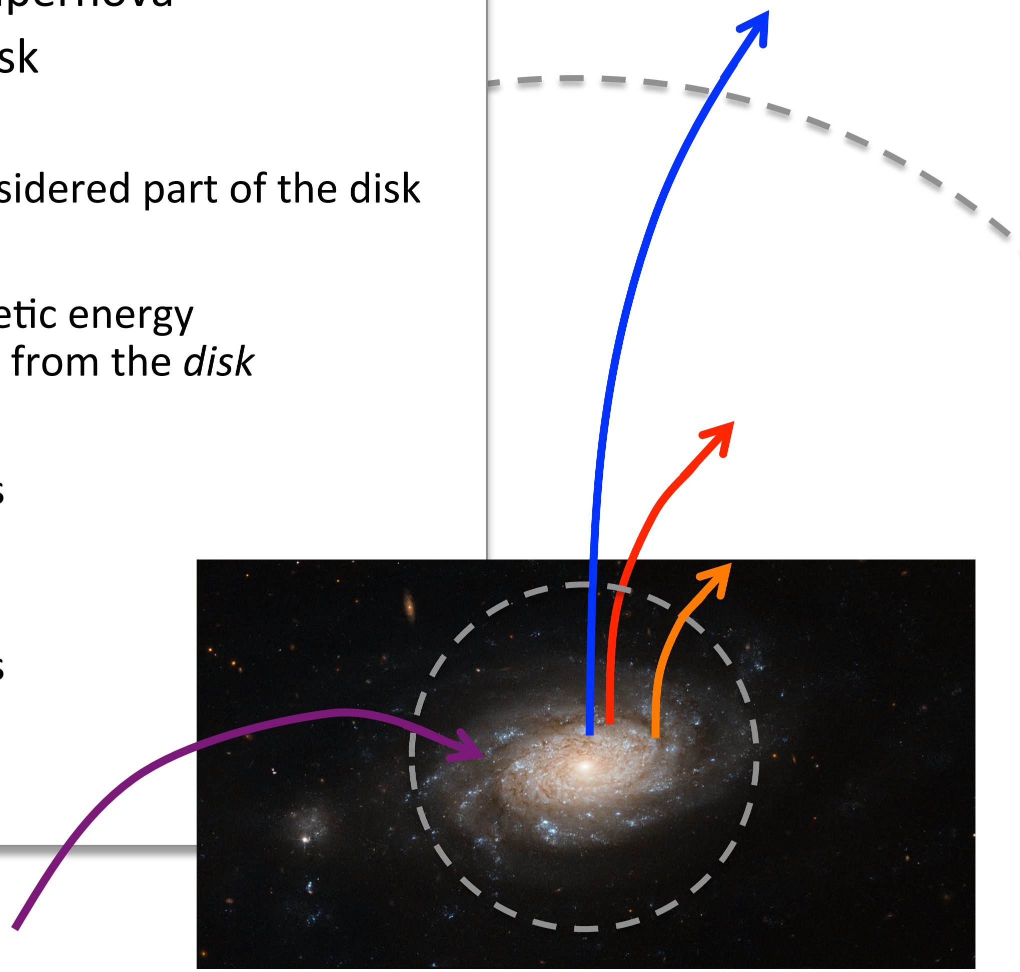
Baryonic Fraction



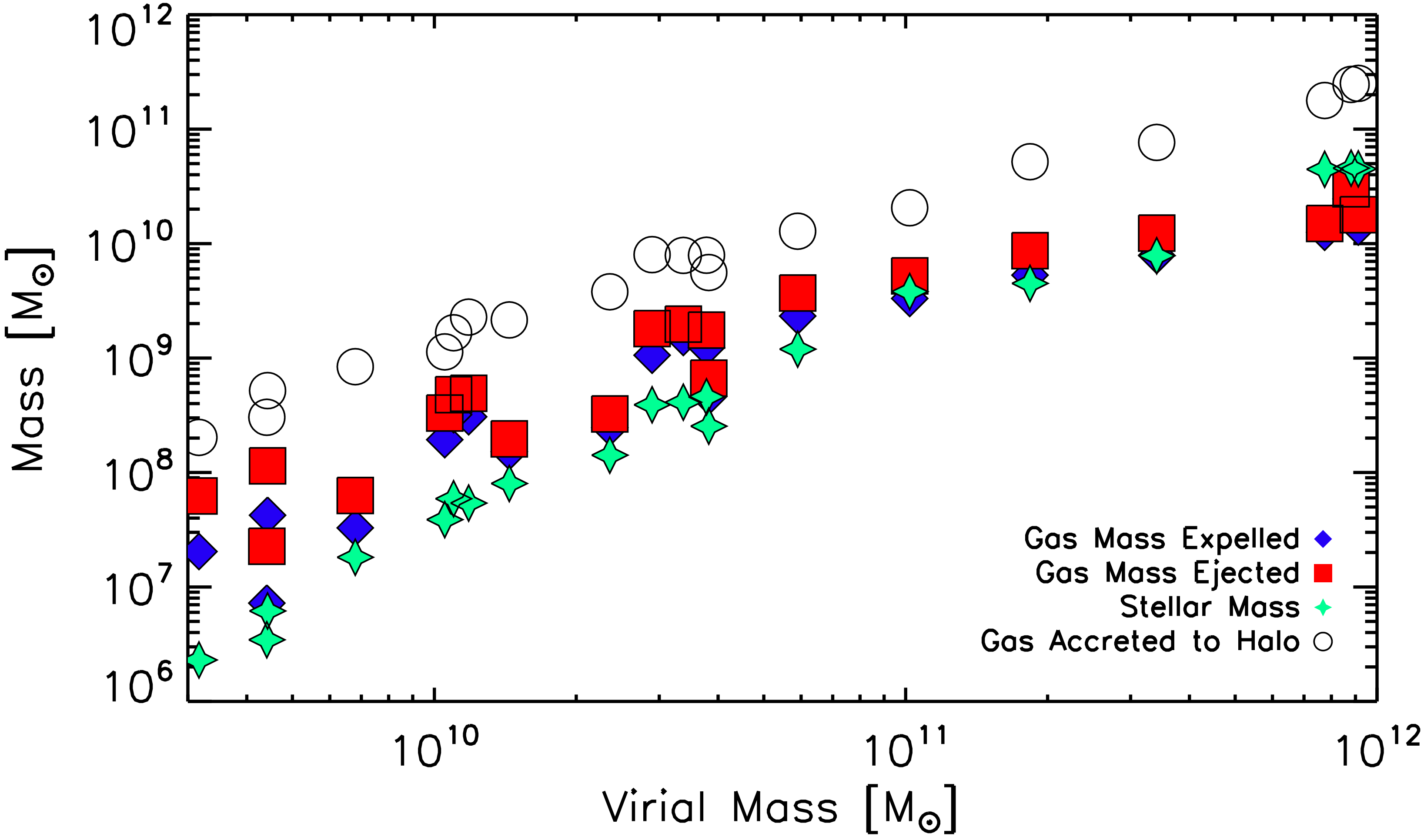
- Lower rates of accretion in smaller galaxies
- Gas outflows are critical to further suppressing baryon fraction

Tracking Particles

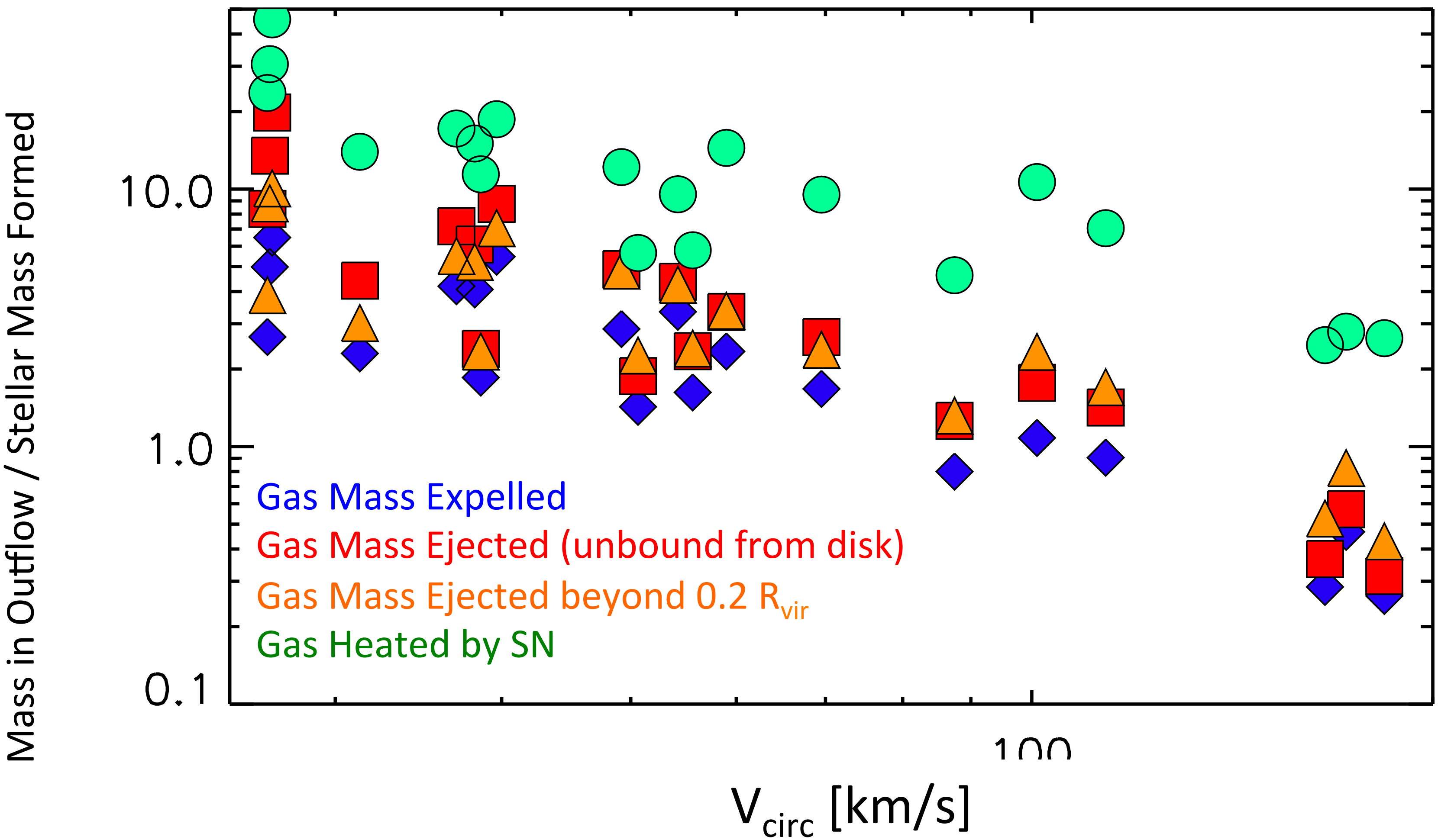
- Outflowing gas:
  - Must have been affected by supernova
  - Must have once been in the disk
  - Heated:
    - Outflowing gas no longer considered part of the disk
  - Ejected from disk:
    - Outflowing gas which has kinetic energy greater than potential energy from the *disk*
  - Ejected beyond 0.2*R_{vir}
    - Outflowing gas which reaches beyond 0.2 * the virial radius
  - Expelled:
    - Outflowing gas which reaches virial radius
- (100 Myr time resolution)



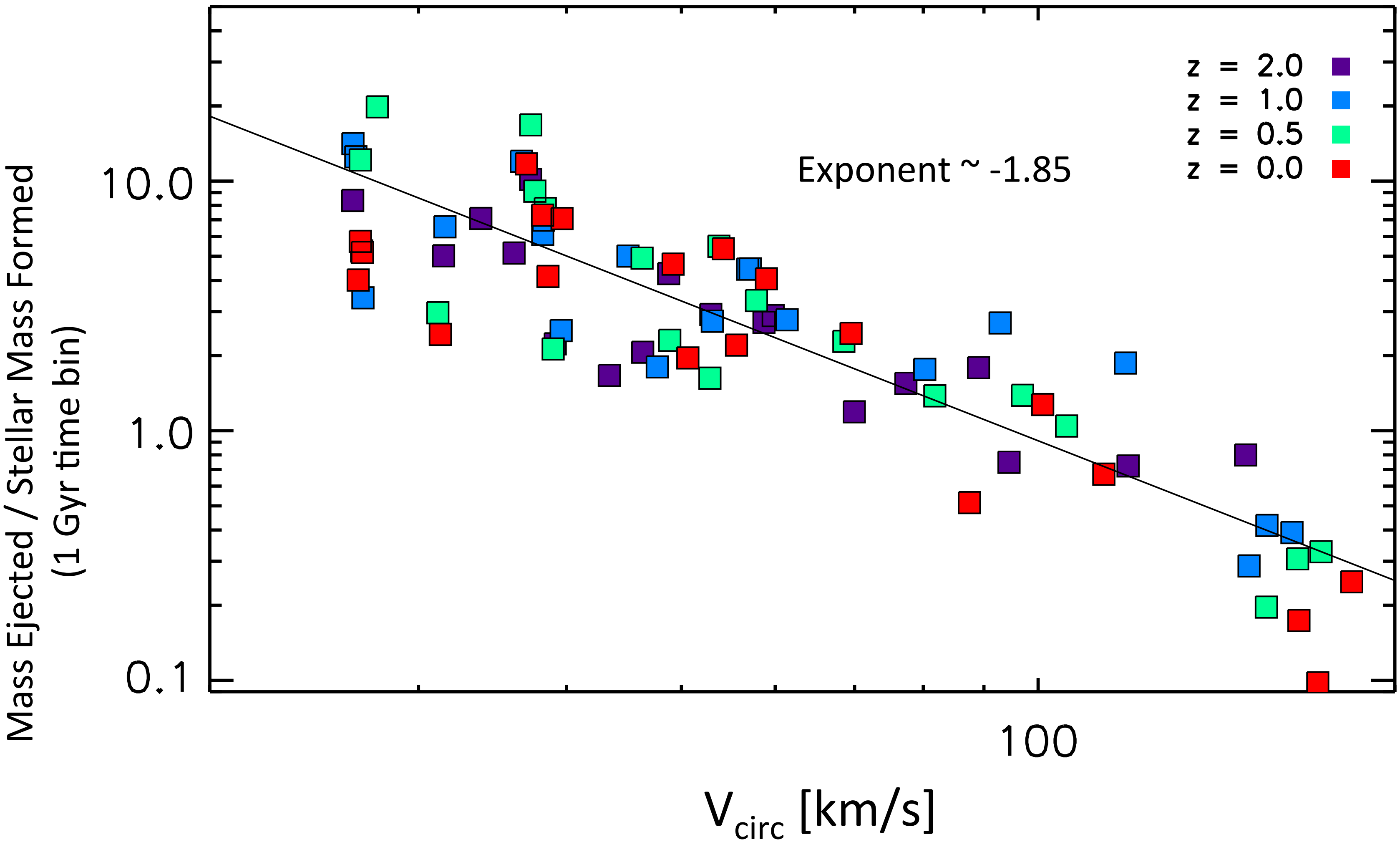
Total Mass Ejected and Expelled



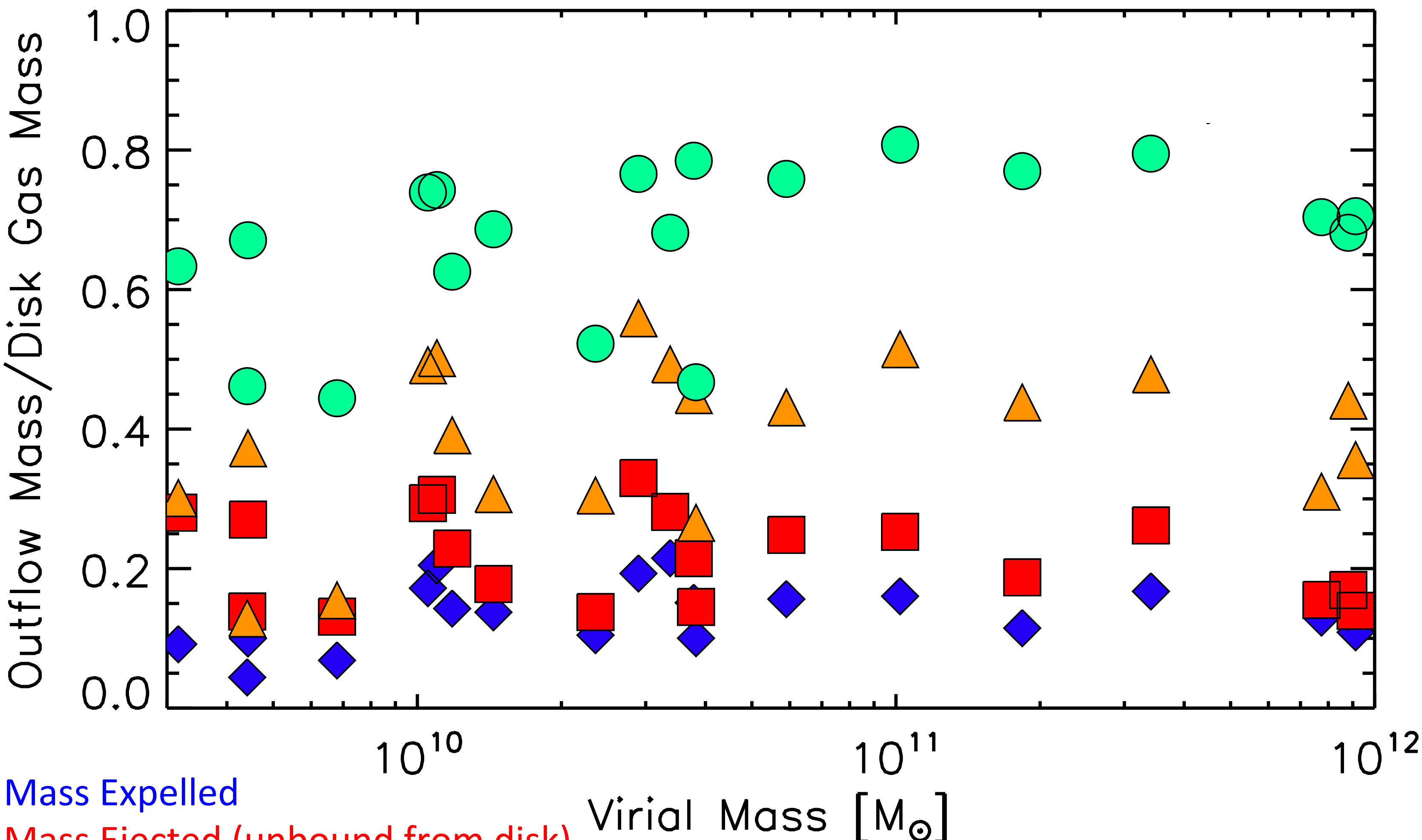
Mass Loading Factor for Ejected Material



Mass Loading Factor for Ejected Material



Fraction of Disk Gas Ejected/Expelled



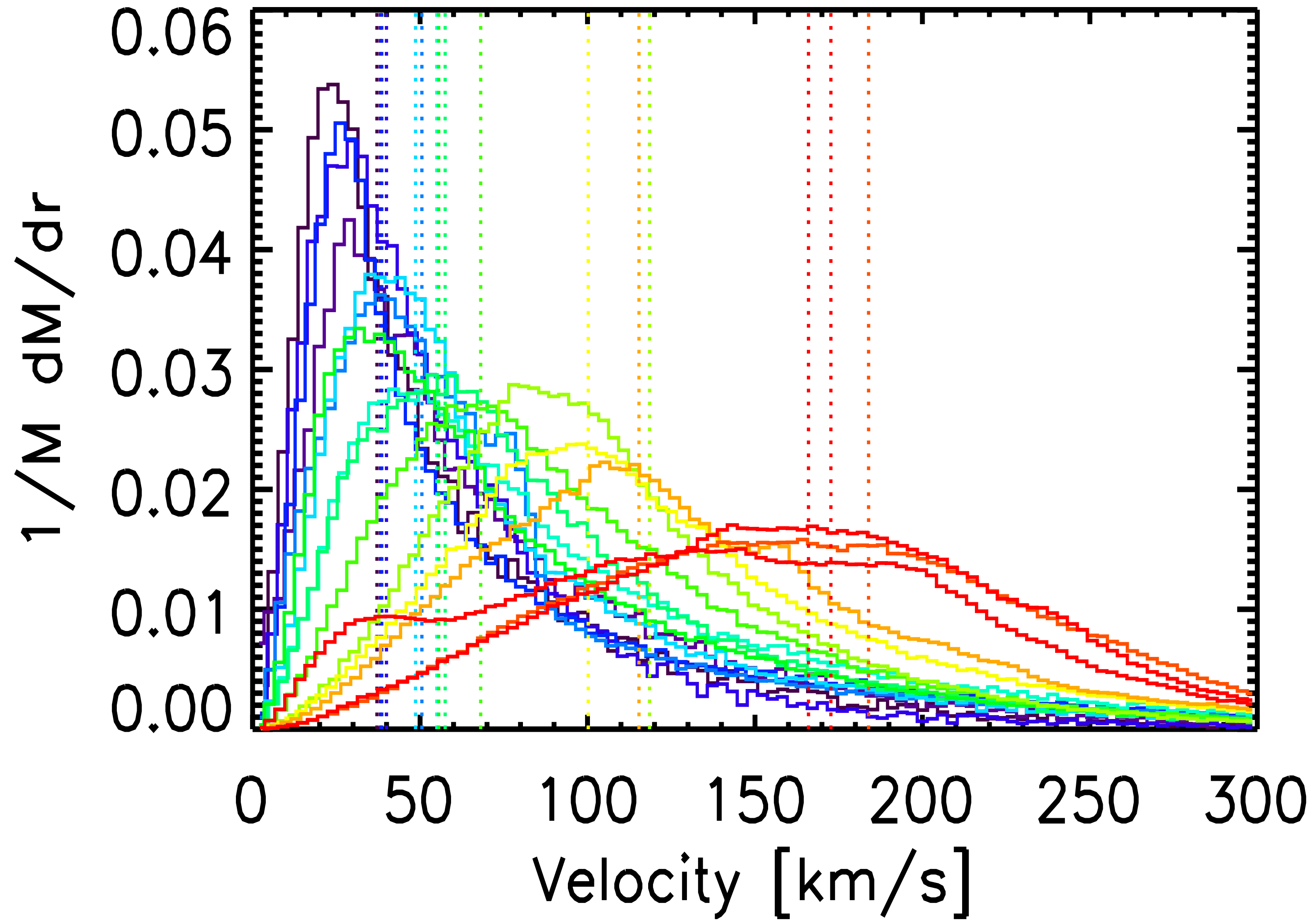
Gas Mass Expelled

Gas Mass Ejected (unbound from disk)

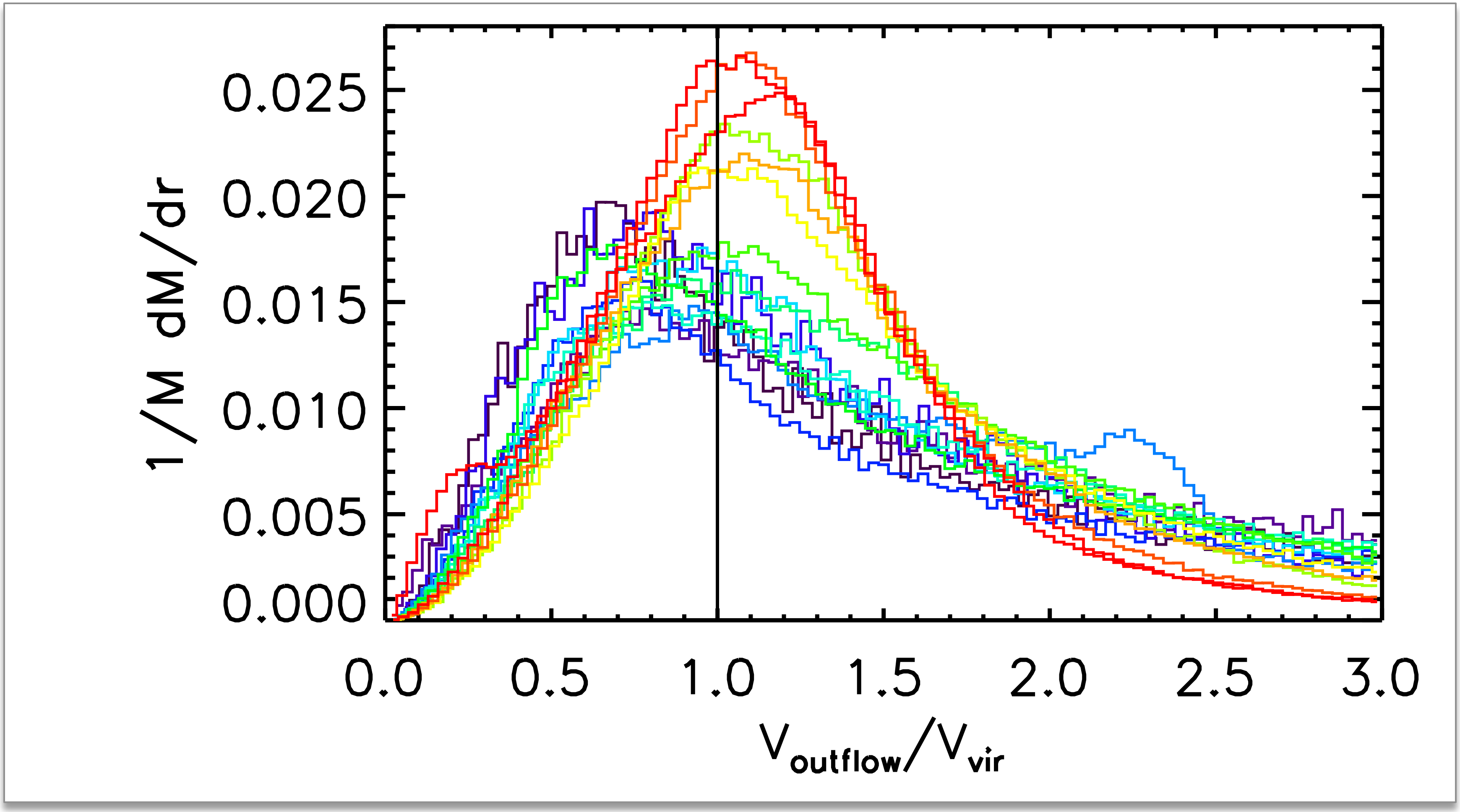
Gas Mass Ejected beyond 0.2 R_{vir}

Gas Heated by SN

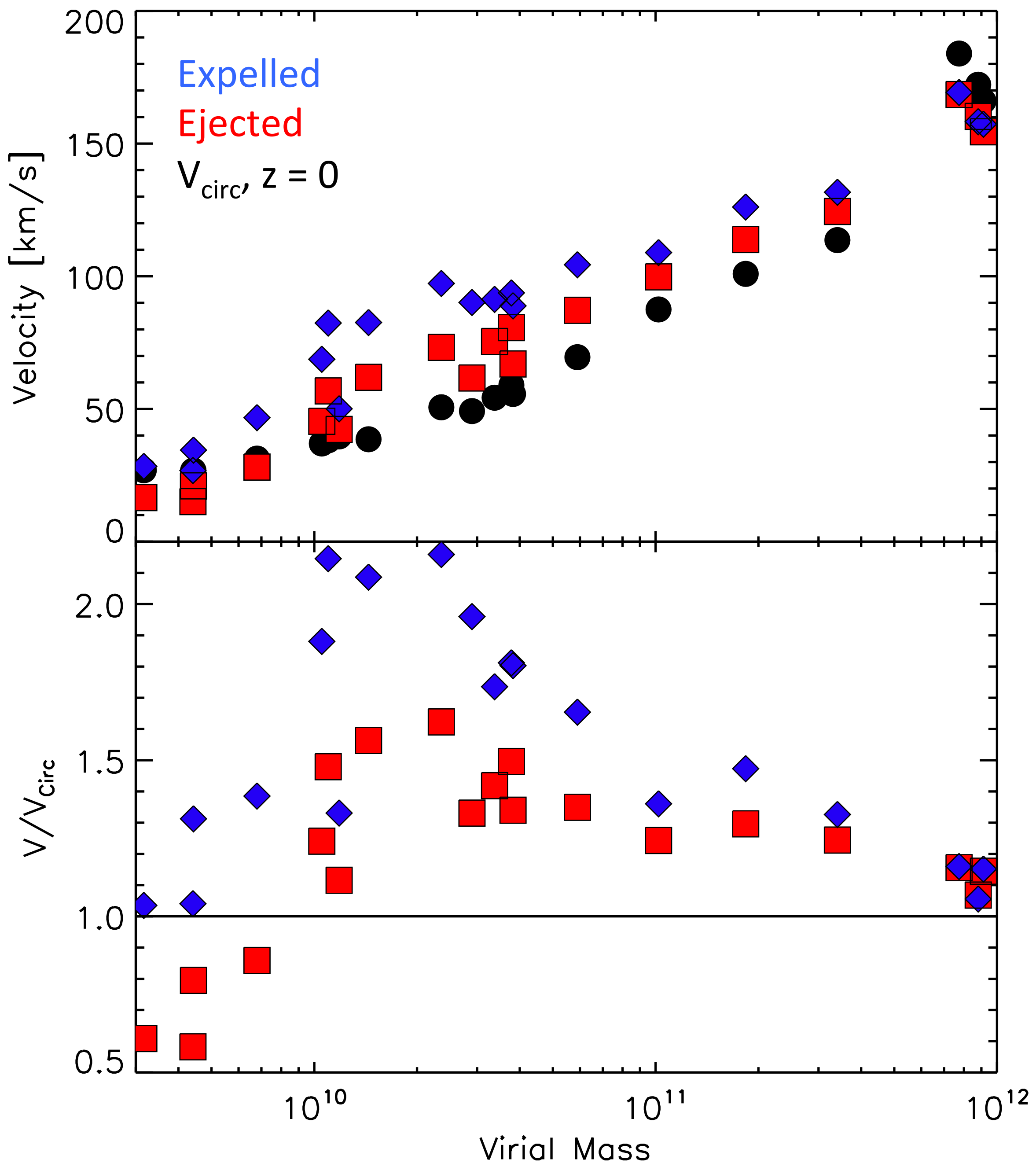
Velocities of Ejected Material



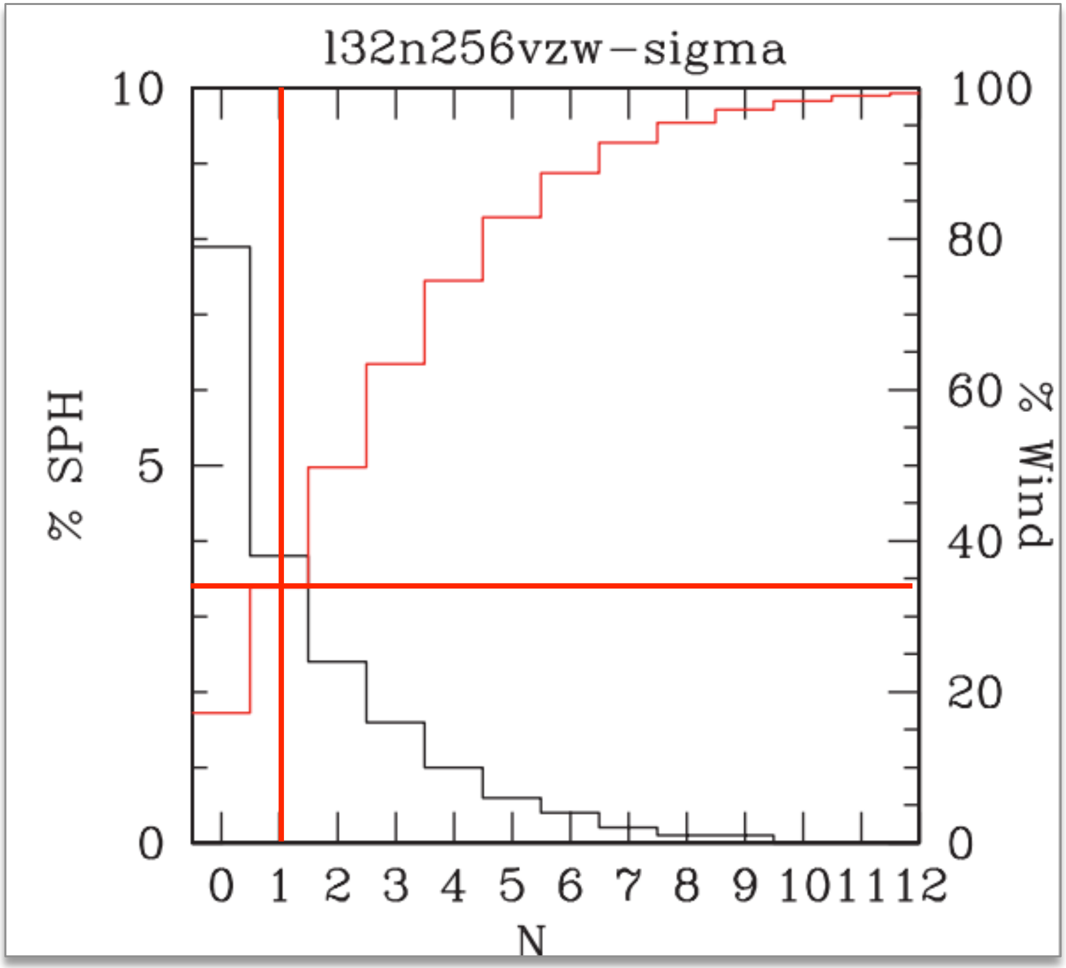
Velocities of Ejected Material Scaled by Circular Velocity



Median Velocities of Ejected and Expelled Gas *immediately* after they leave the disk

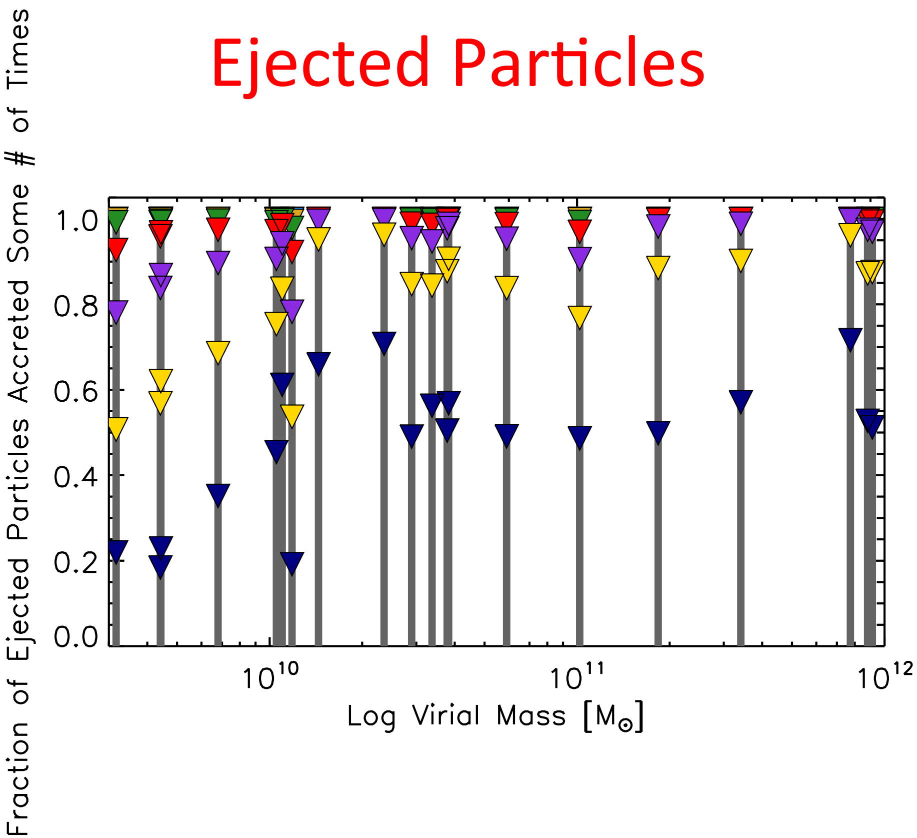


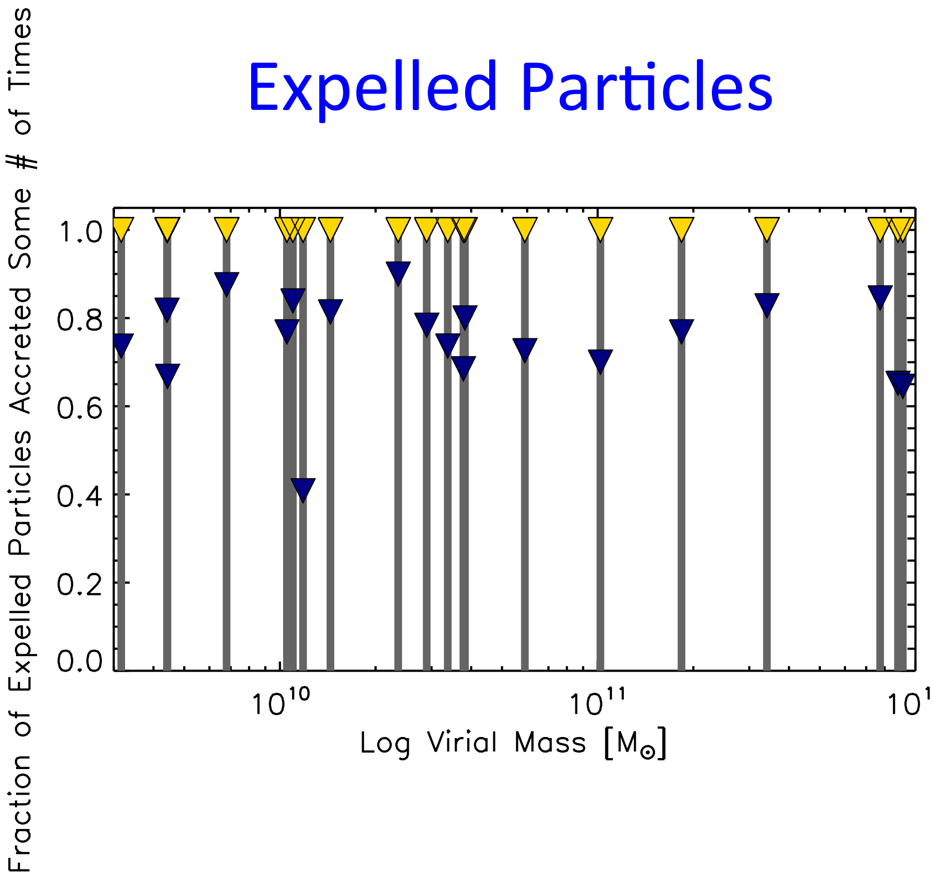
How much of the ejected gas is later recycled?



Oppenheimer et al, 2008

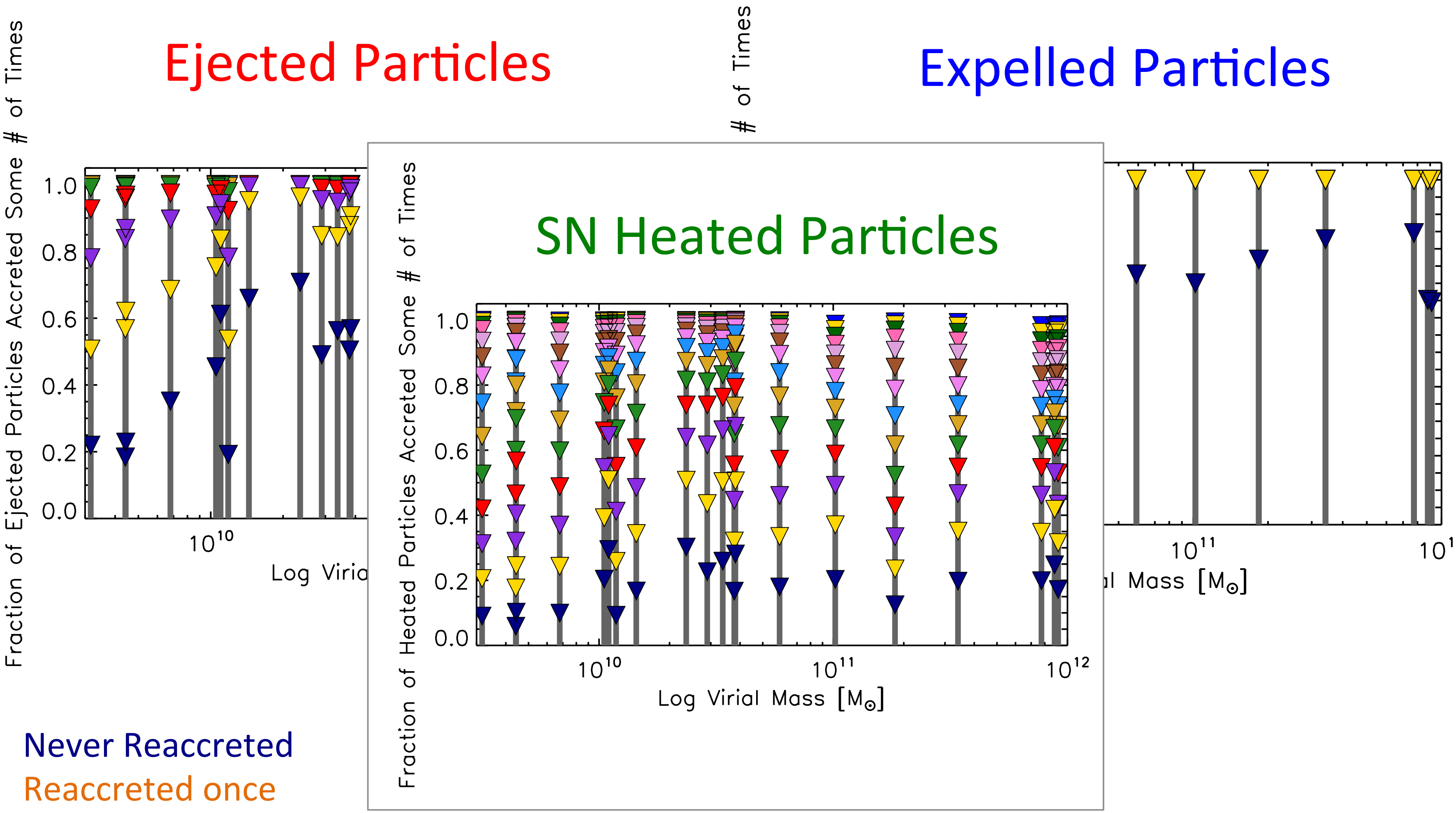
Number of Times a Particle is Reaccreted





Never Reaccreted
Reaccreted once
Reaccreted twice
Reaccreted three times . . .

Number of Times a Particle is Reaccreted



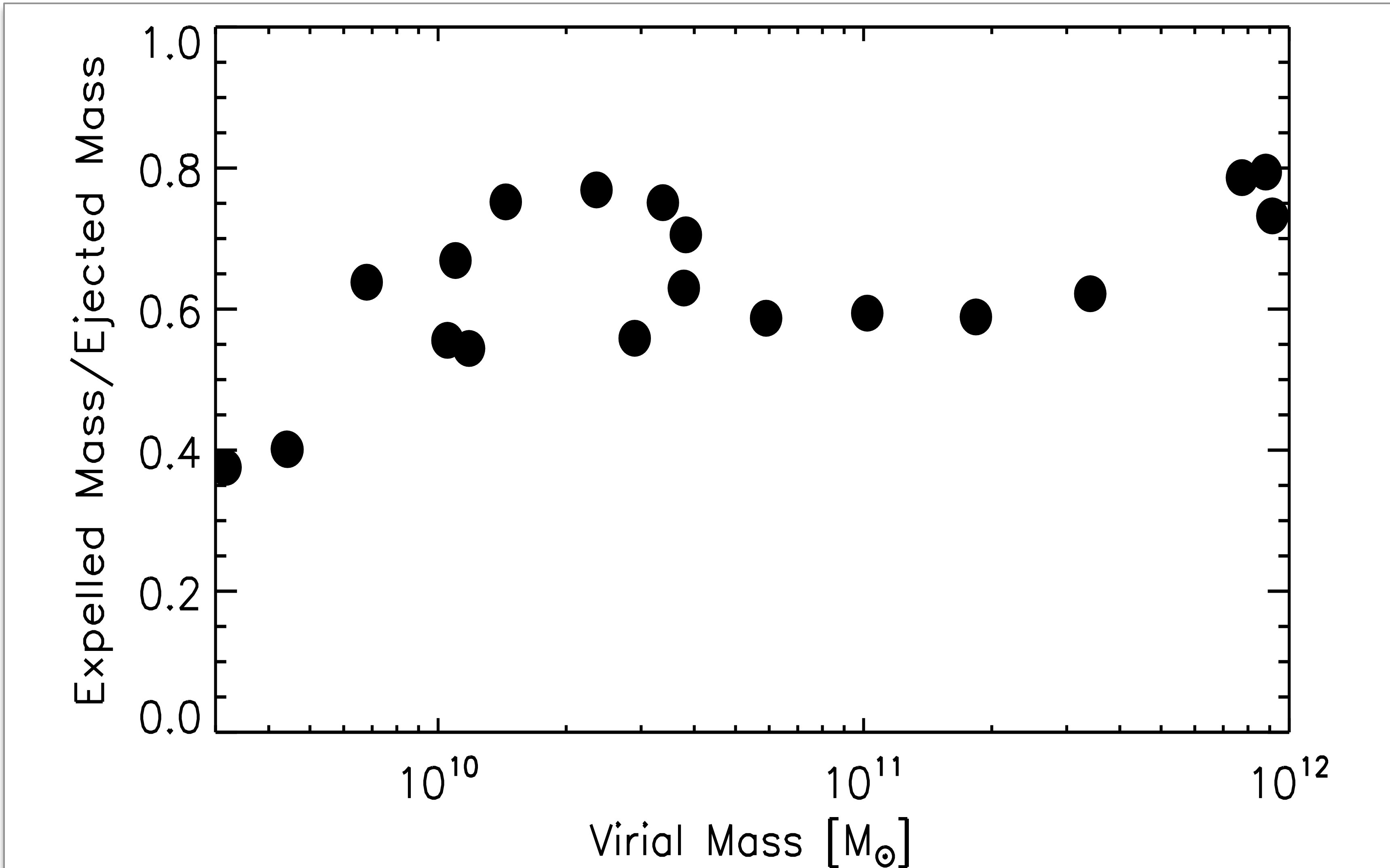
Never Reaccreted

Reaccreted once

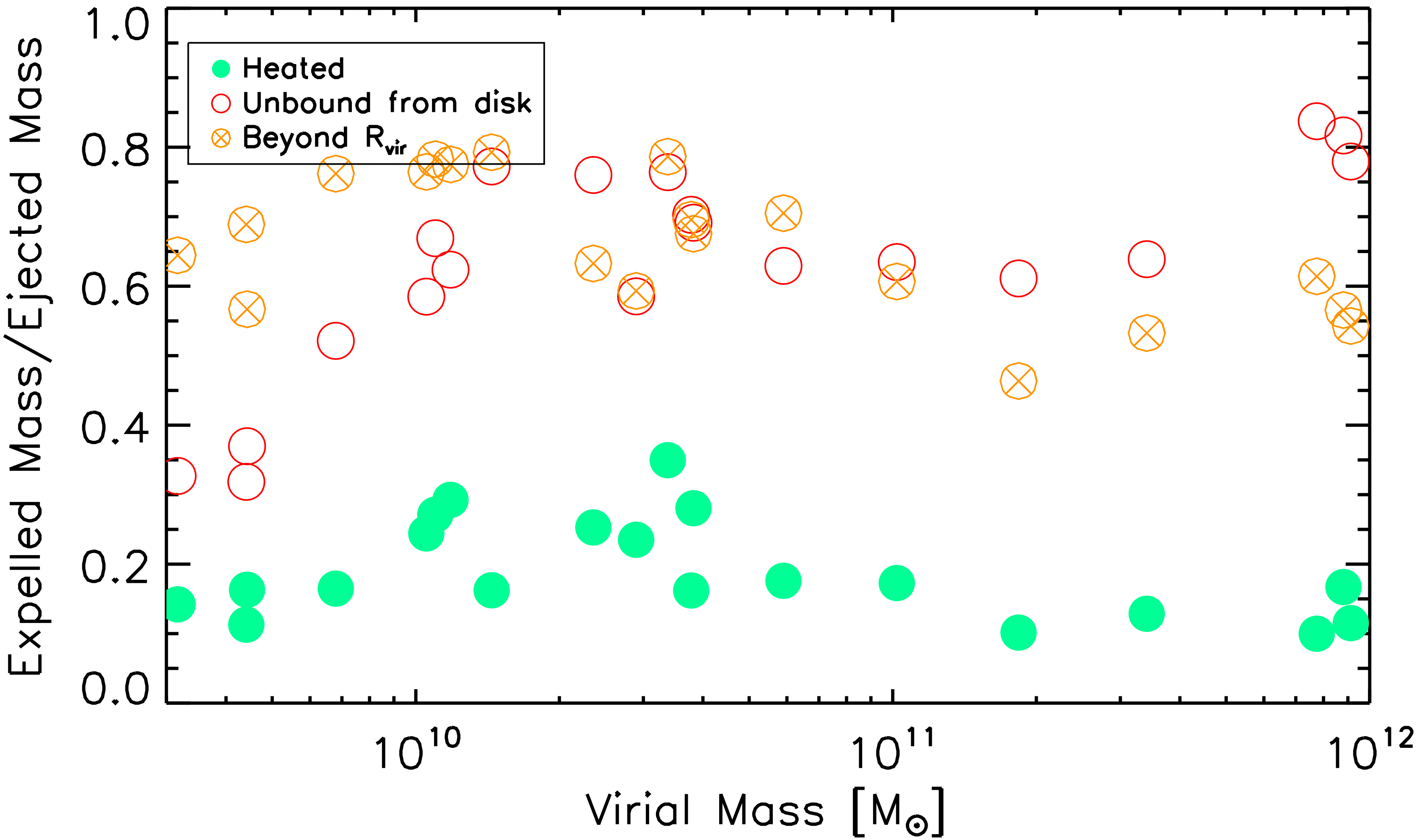
Reaccreted twice

Reaccreted three times . . .

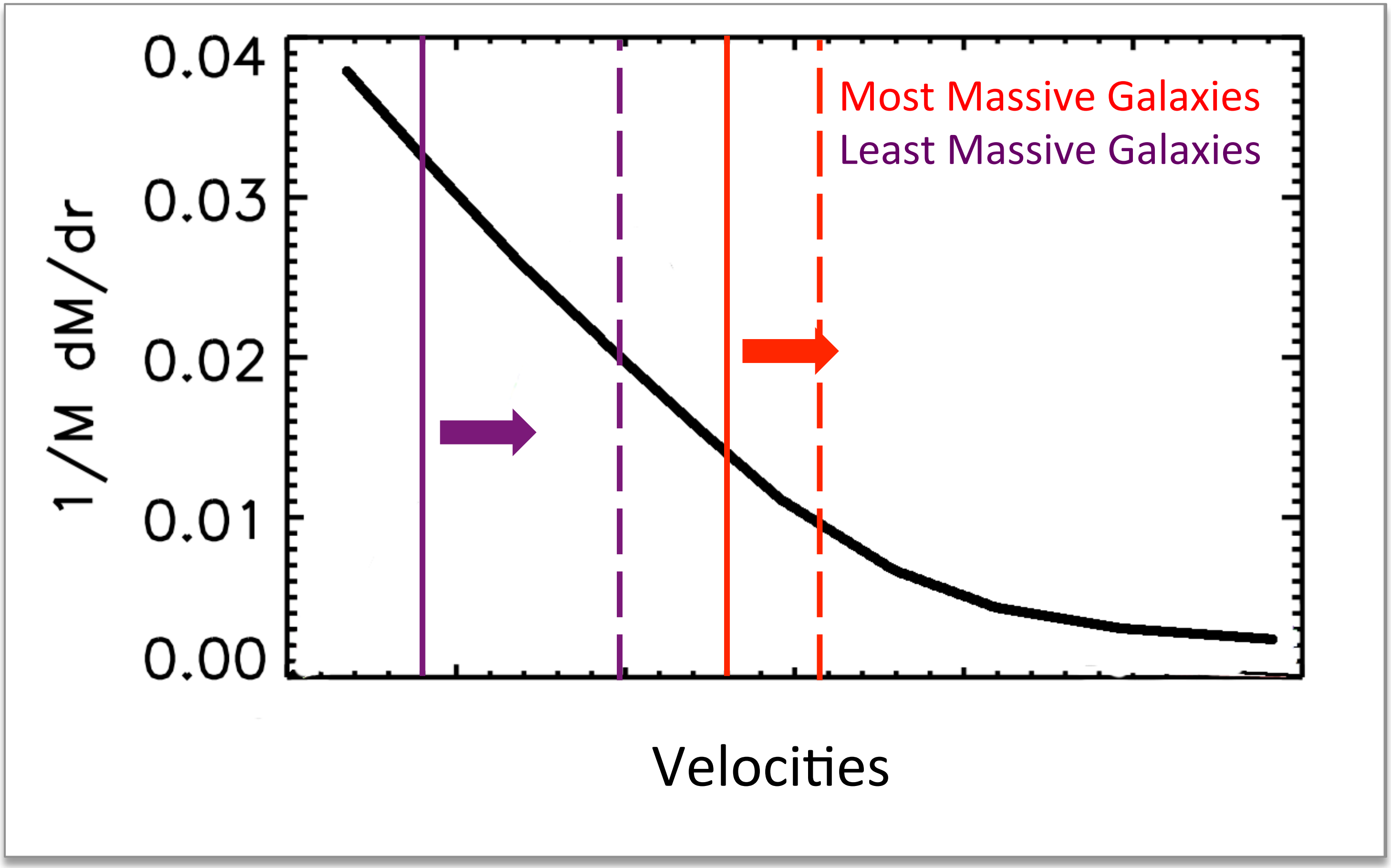
Fraction of Ejected Gas Eventually Expelled



Fraction of Ejected Gas Eventually Expelled

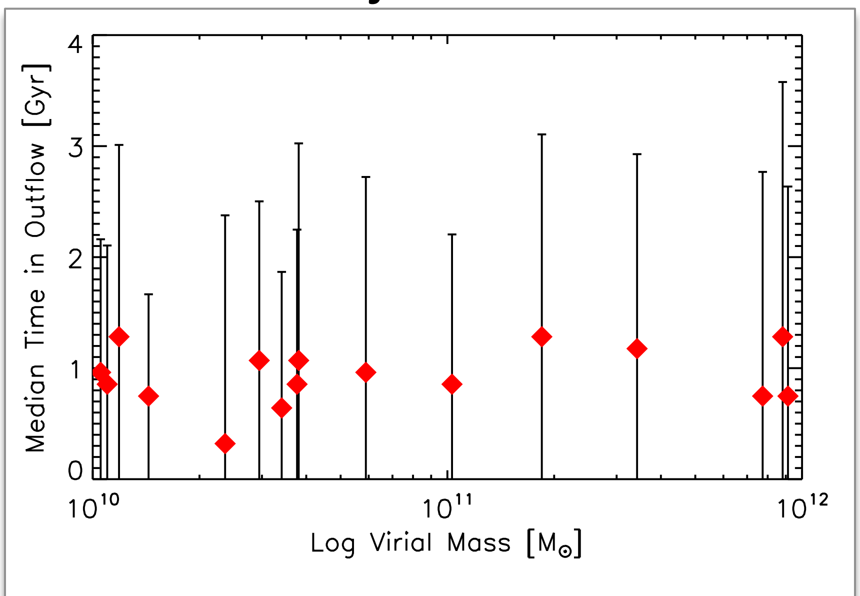


As halo mass increases, a *higher* fraction of the gas with velocities sufficient to escape the disk is able to escape the halo

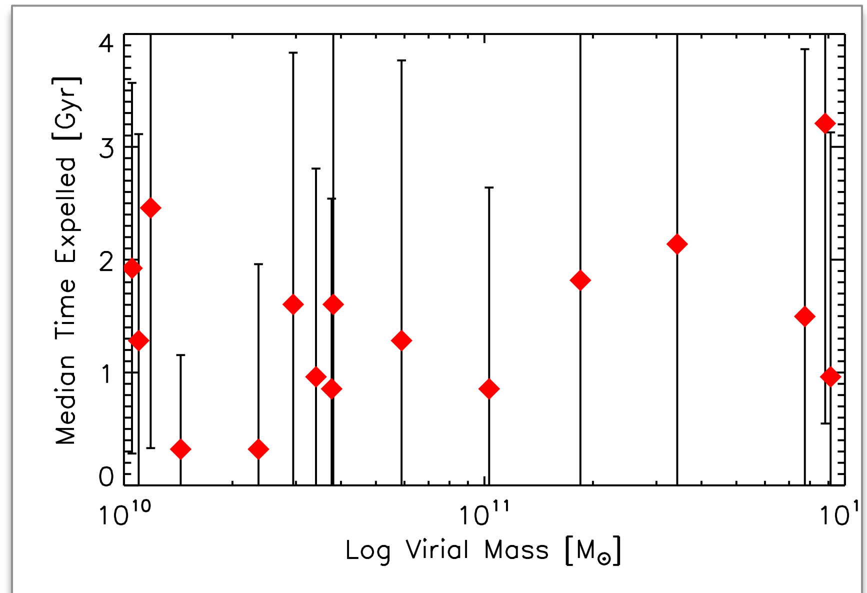


Amount of Time Before Recreation after Ejection or Expulsion

Ejection



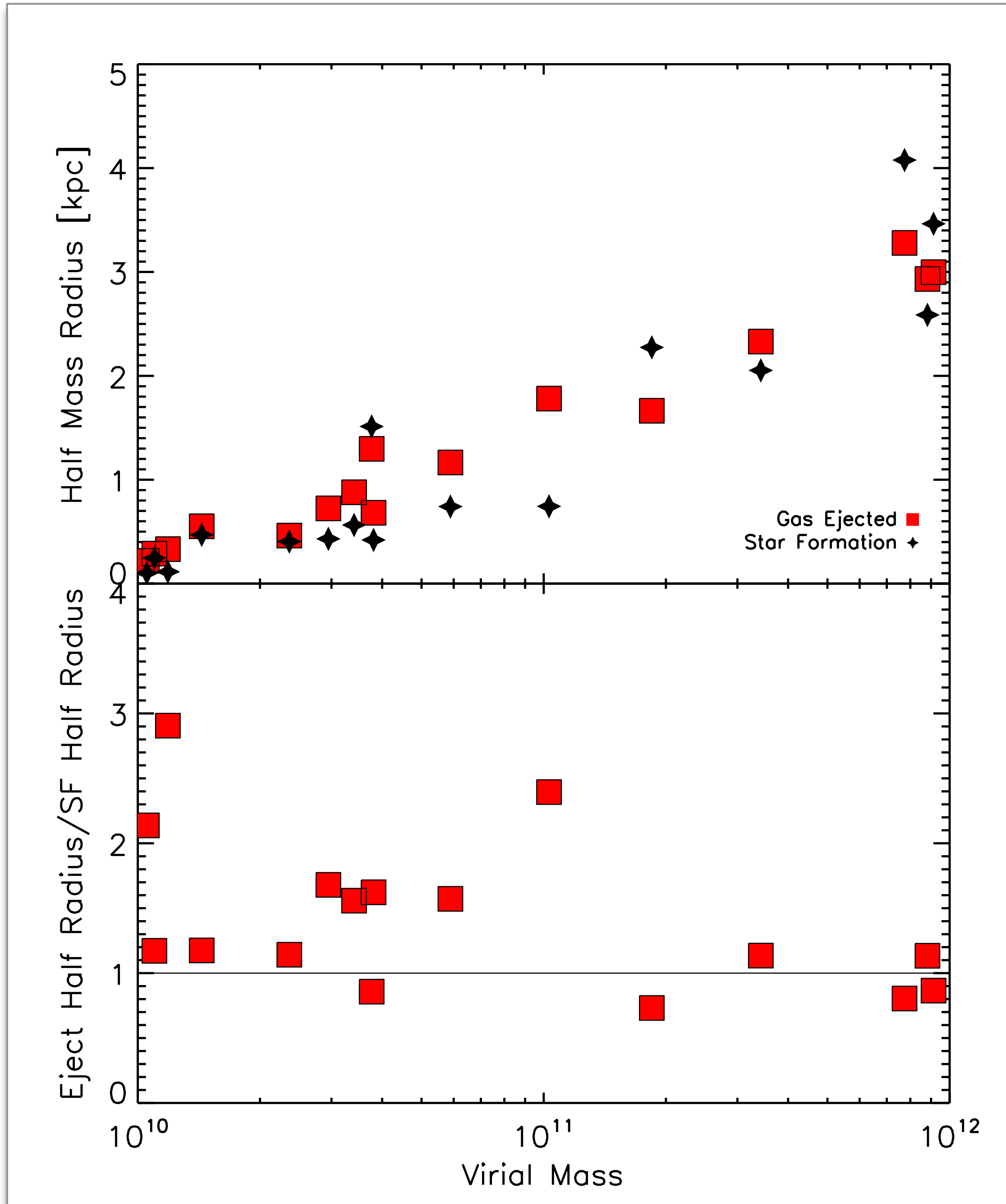
Expulsion



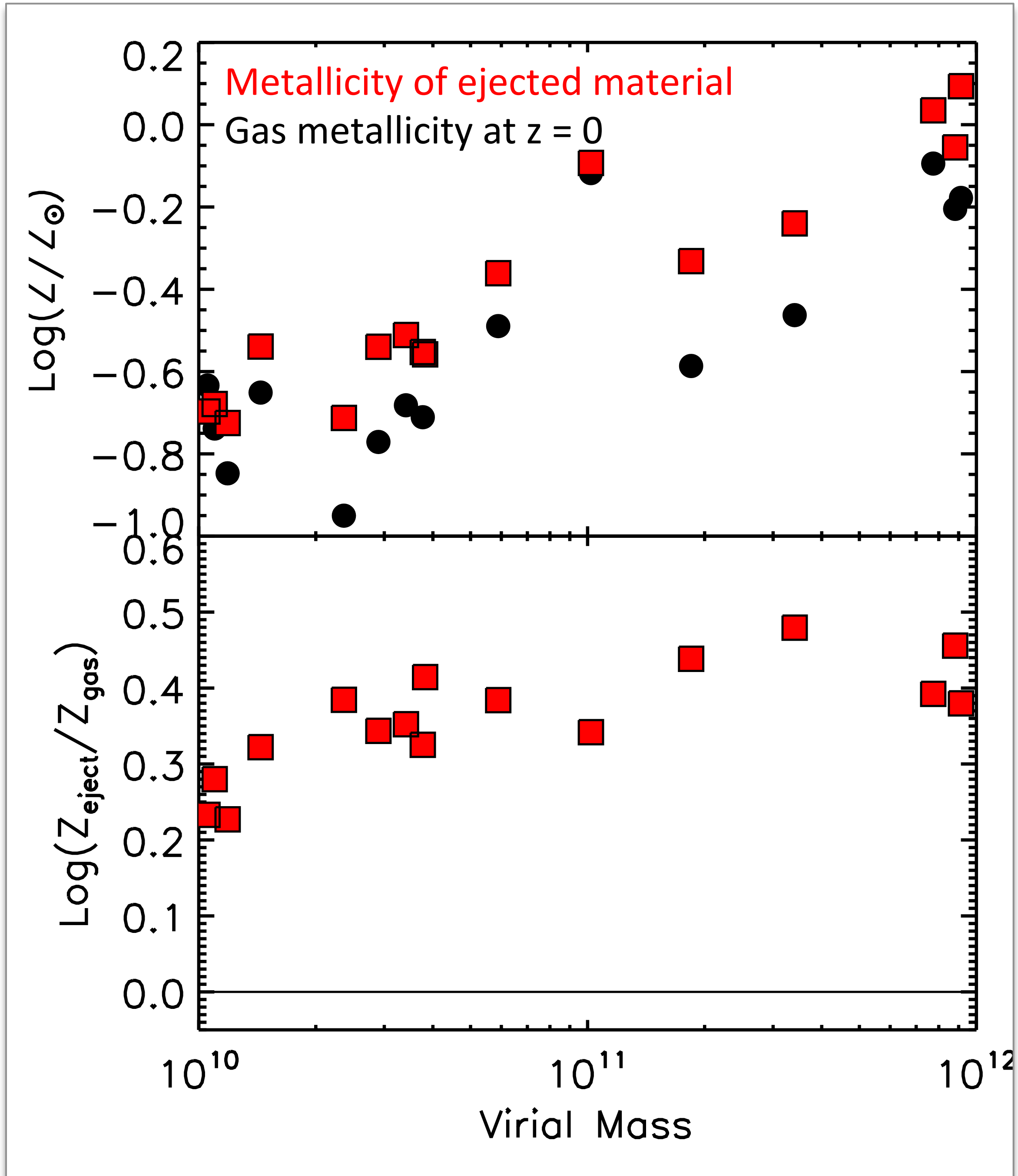
- Wide spread in reaccretion time scales (non-gaussian distribution with tail towards long times).
- Typical time scales of reaccretion on the order of a gigayear or so.
- Dependent on feedback implementation (see Ben Oppenheimer's talk).

Source of Ejected Material

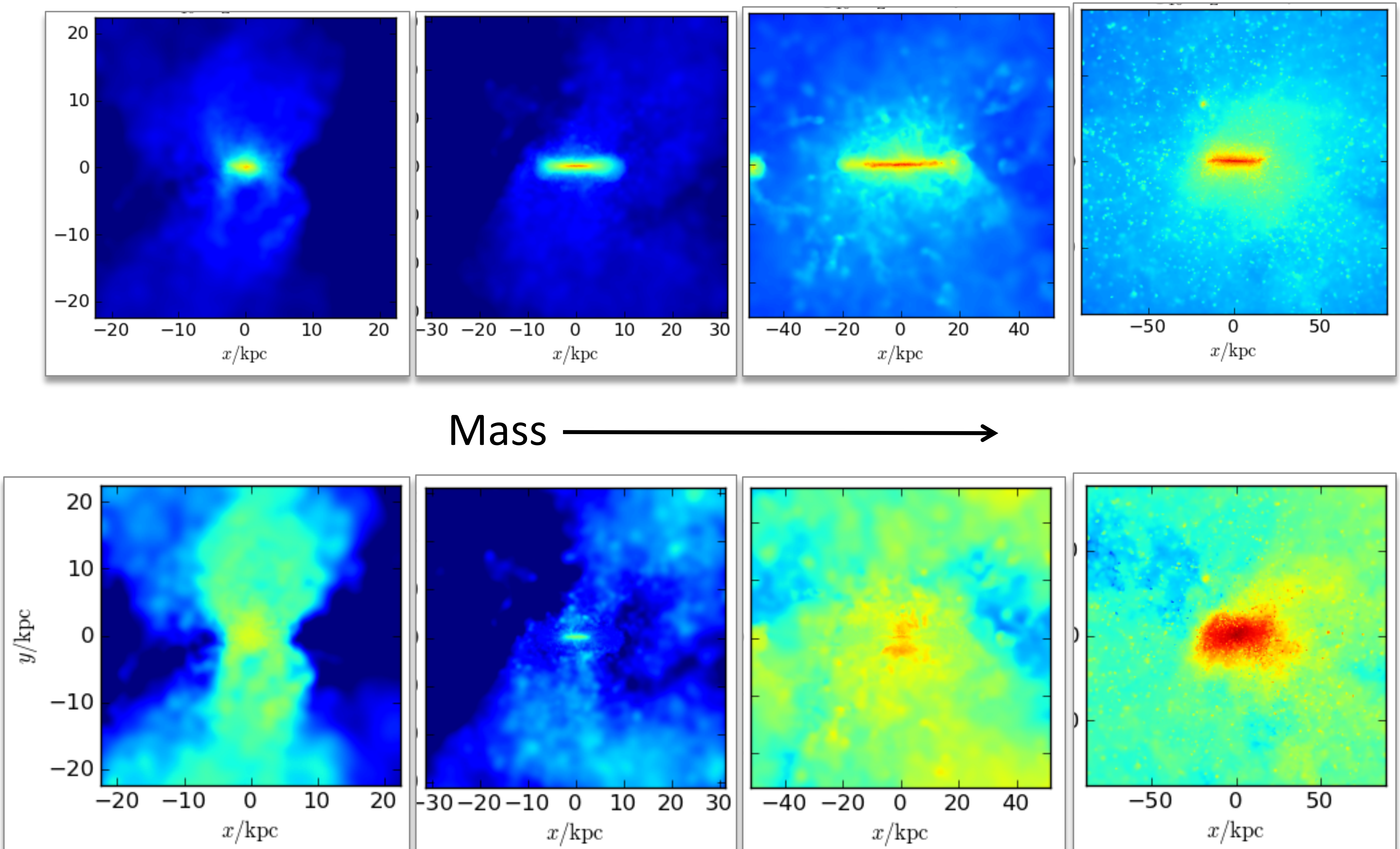
Ejected gas originates from approximately the same area as star formation



Metal Enrichment of Outflows

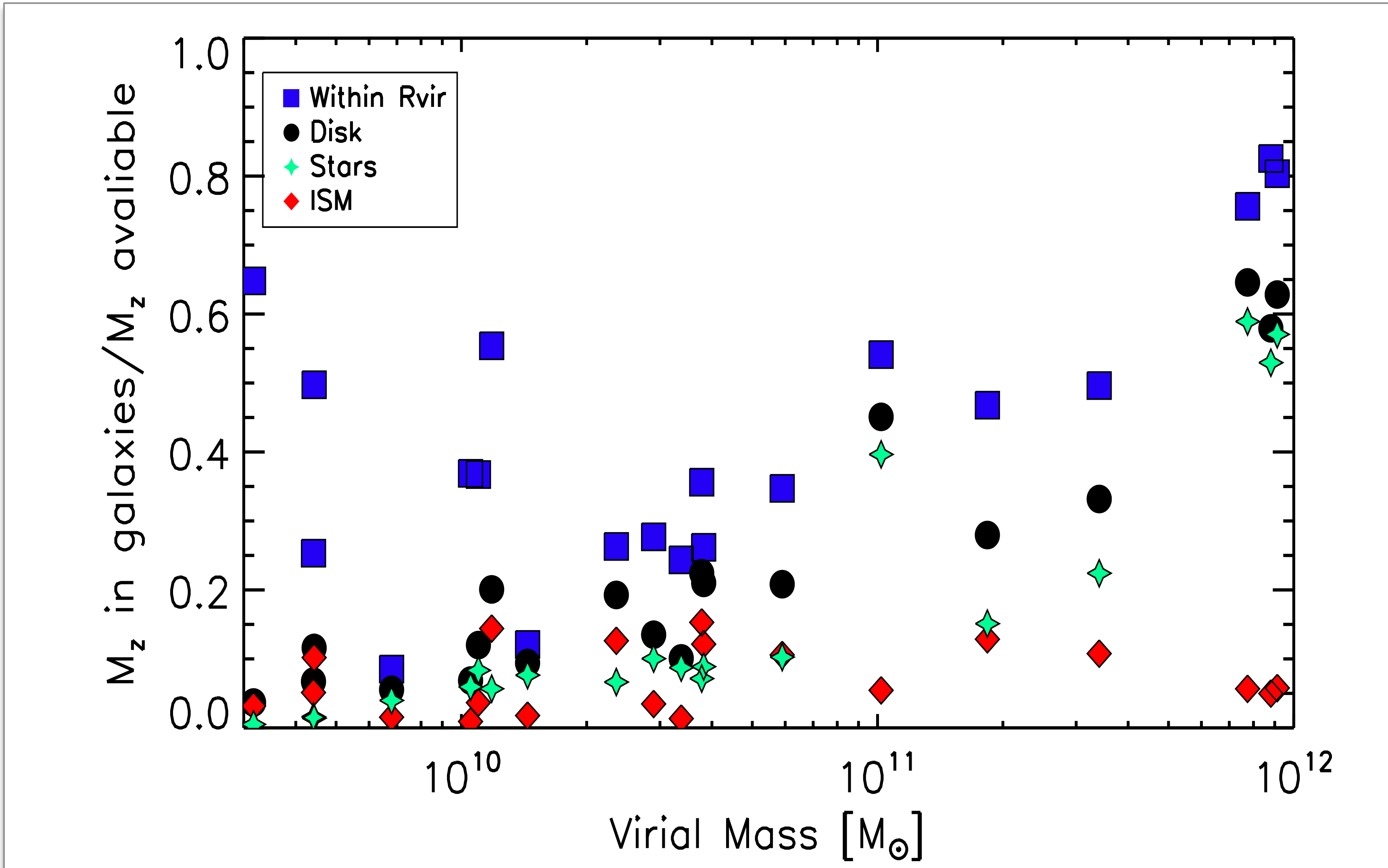


Metal Surface Density

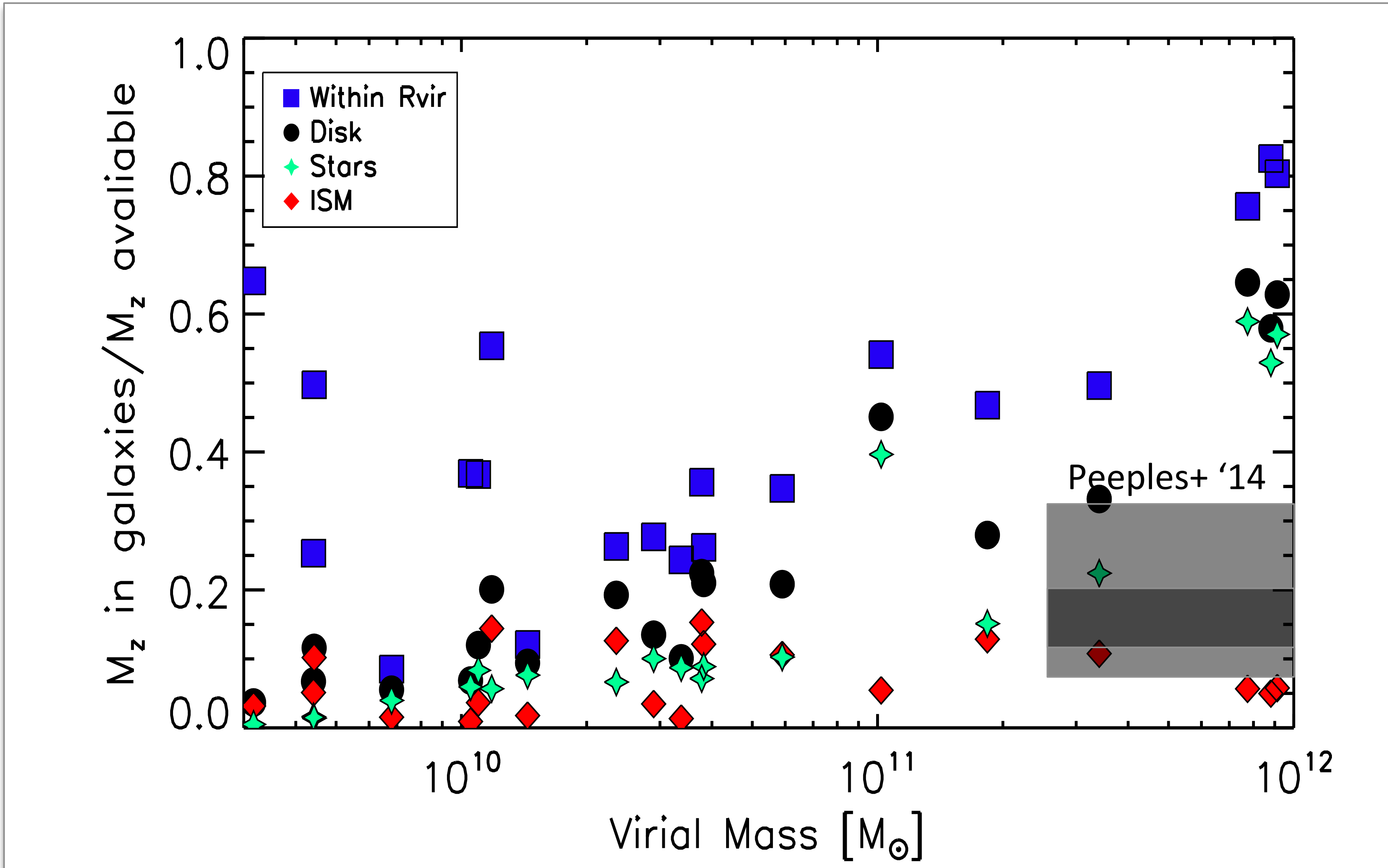


Log Metallicity of Gas (slice through center of galaxy)

Eventual Location of Metals



Eventual Location of Metals



Note that Peeples+ '14 does not include stellar remnants in analysis

Summary

- Power-law relation between virial mass and mass loading, similar to energy-driven winds
  - However, lower SFRs in dwarf galaxies also reduce mass loss
- Gas cycling is significant but lower than in previous works
  - Median recycling timescales of 1 Gyr
  - Sensitive to feedback implementation, CGM properties, gas cooling etc.
- Evidence for enhanced fraction of gas in dwarf galaxies able to escape disk but not halo
- Outflows primarily originate from the same area as star formation
- Outflows have substantially higher metallicity than disk gas
  - More metals locked up in stars than observations suggest

- *Open problems*
  - *Comparing to observations*
  - *Higher redshifts evolution (can SFHs be affected by cycling?)*