Early Evolution of Massive Galaxies

Romeel Davé
Kristian Finlator
Ben D. Oppenheimer
University of Arizona

Early (z>2) Massive Galaxies: Questions for Theory

- How do galaxies obtain fuel?
- Can large stellar masses be produced at early times?
- How do they become so metal enriched?
- What are their SFHs as a function of mass and environment?

Understanding high-z galaxy formation provides the initial conditions for studying new issues arising at low-z.

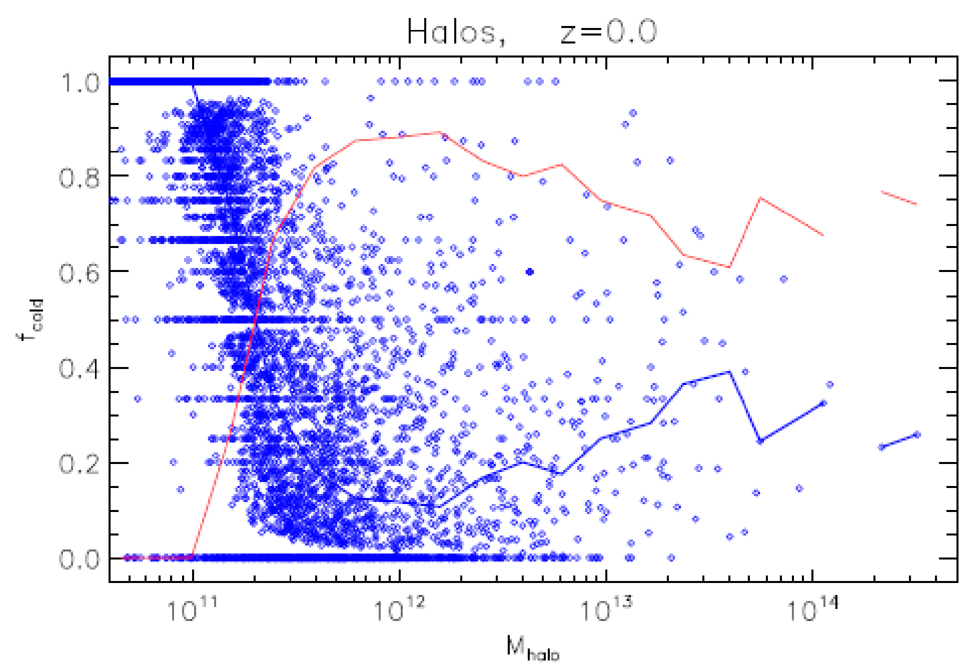
Physics of Early Massive Galaxies in Simulations

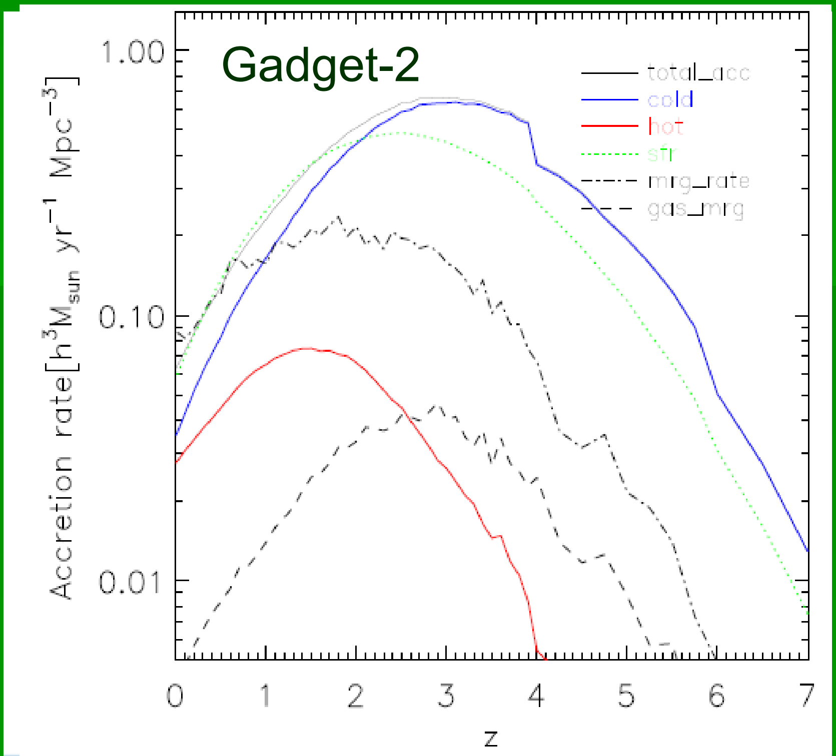
- *Cold, smooth accretion.*
  - SFR ∝ M_* (with little scatter).
  - LBGs are massive; age ~ ½ t_{Hubble}.
  - [Merging plays minor role during SF'ing phase.]
- *Ubiquitous and highly-loaded outflows.*
  - Suppress overcooling.
  - Enrich IGM.
  - Establish mass-metallicity relation.
  - Keep galaxies gas-rich.

Is this plausible, and is this sufficient?

Cold Accretion: The Gadget story

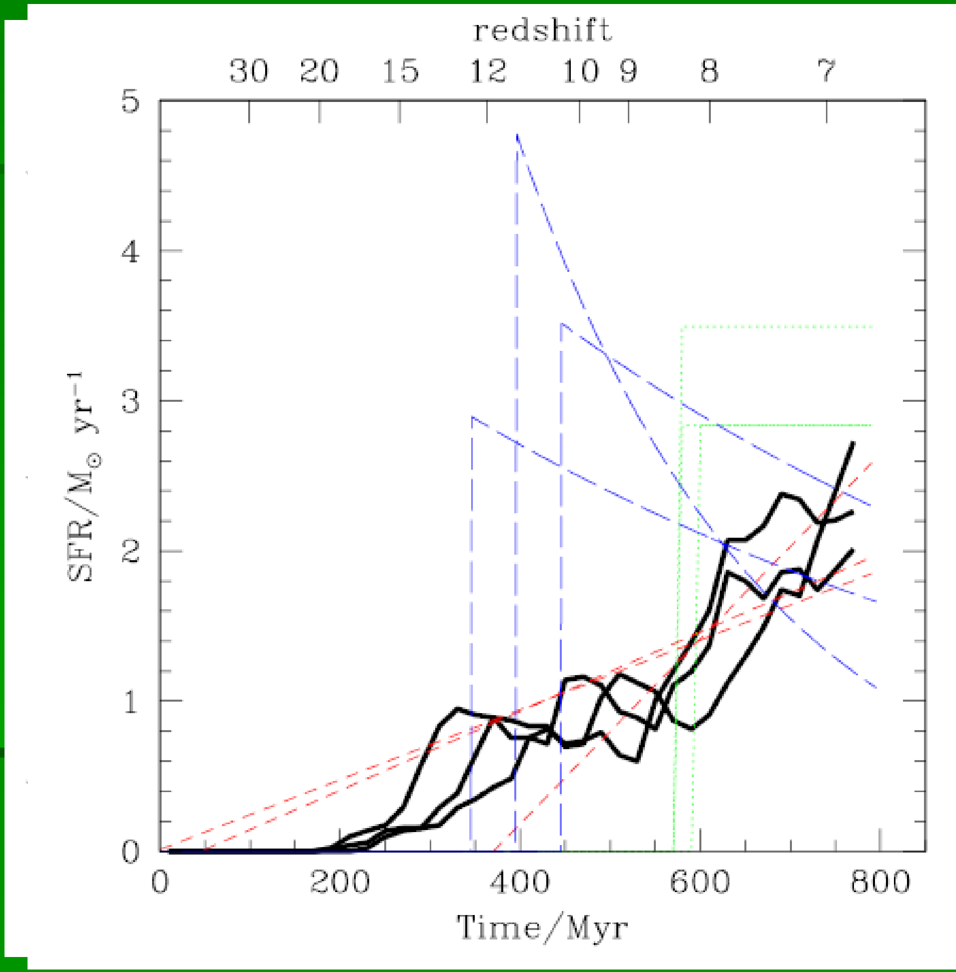
- Cold mode: No virial shock; t_{dyn}-limited.
- Hot mode: t_{cool}-limited.
- Keres et al: Transition $M_{halo} \sim 10^{11.4} M_{\odot}$, hot mode dominates at z<2.
- Gadget's entropy-conservative SPH greatly reduces hot mode.
- Suppressing hot mode alone unlikely to solve red & dead problem.





Rapid accretion ⇒ Rapid early growth

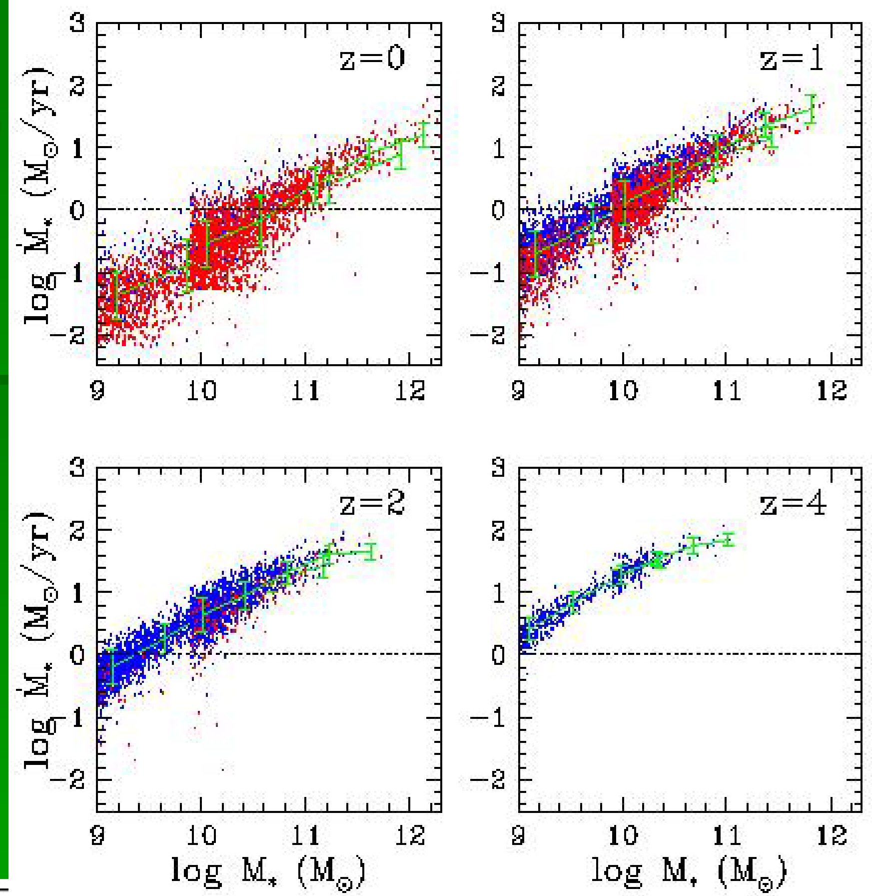
- WMAP-3 Gadget simulations vs. z>5.5 galaxies w/IRAC data.
- In most cases, simulated galaxies provide good fit ($\chi_\nu^2<1$).
- Best-fit galaxies…
  - are fairly massive,
  - have older stars,
  - show 4000Å break.
- Typical SFH is constantly rising.

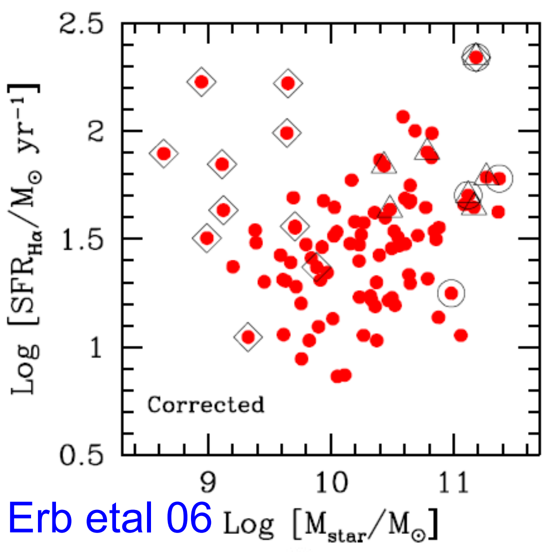


Finlator, RD, Oppenheimer 06

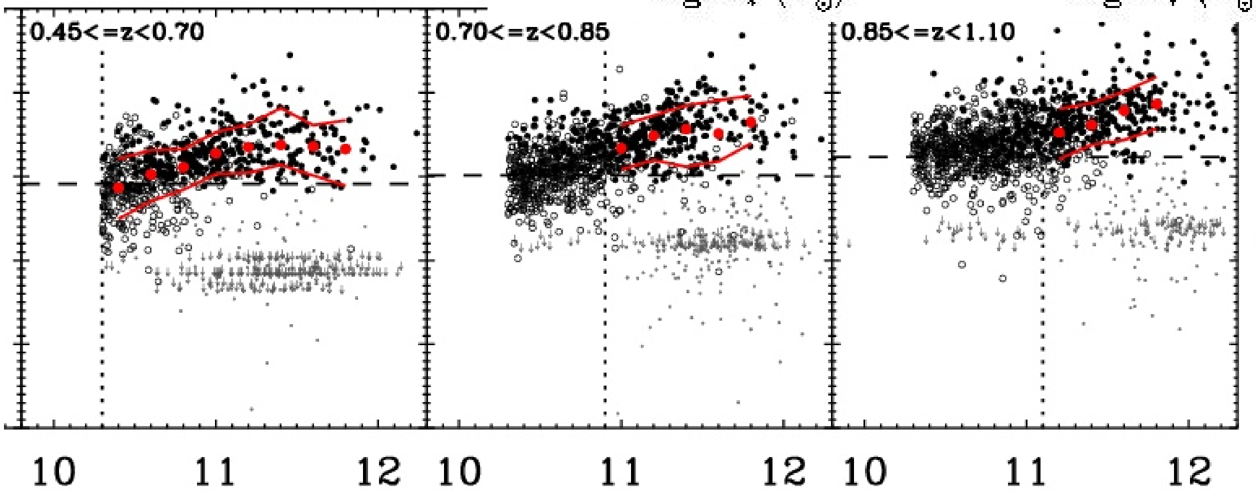
Quiescent SFH?

- SFR ∝ M_*: Cold mode.
- Mergers/bursts *not* a significant driver of SF.
- True? At z~0-1, yes. At z~2, more confusing.
- Amplitude too low?





Erb etal 06

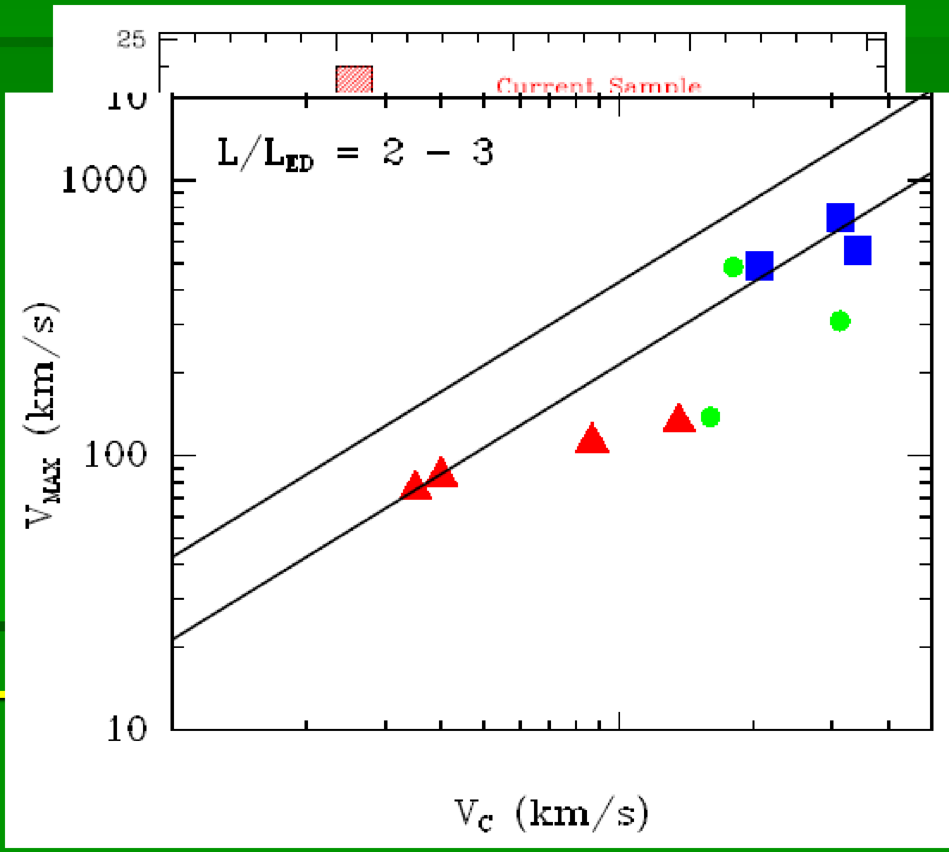


Noeske et al. 2006

The Impact of Outflows

- Needed to regulate SF, alleviate overcooling.
- Common/expected in z~2+ galaxies.
- Defined by outflow speed (v_w) and mass loading factor (η).
- Local starbursts: $v_w \propto v_{circ} \Rightarrow$ Momentum-driven winds?
- How to constrain? **Track the metals!**

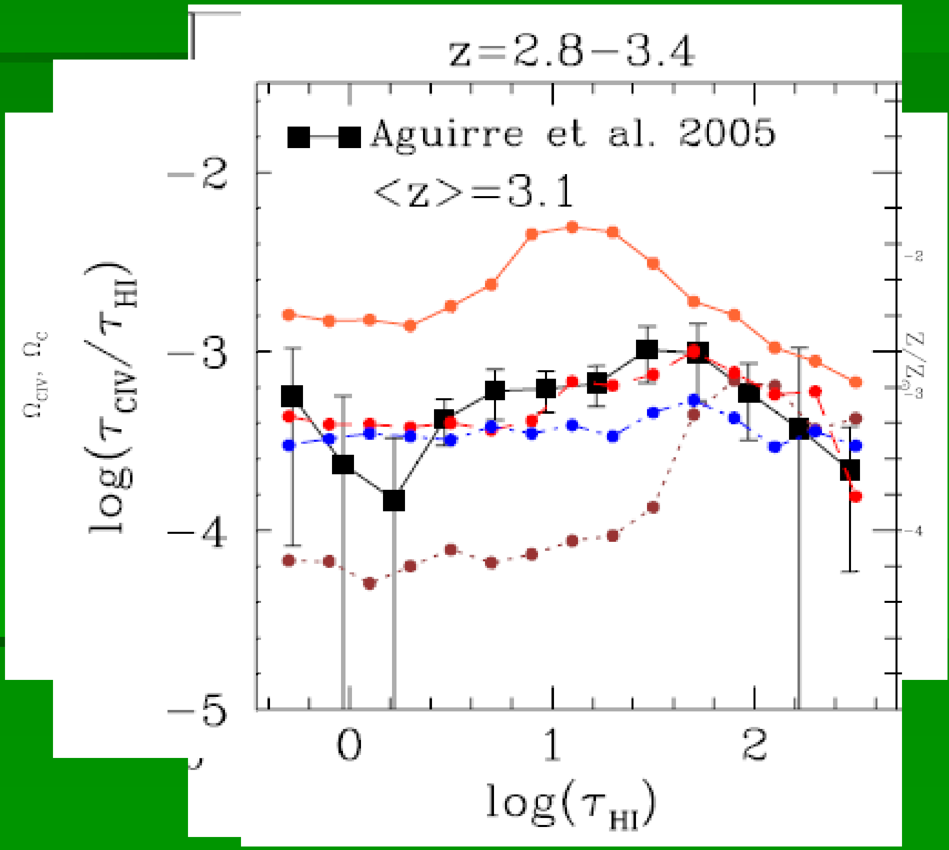
Erb et al 2006



Martin 2005

Outflows and IGM Metals

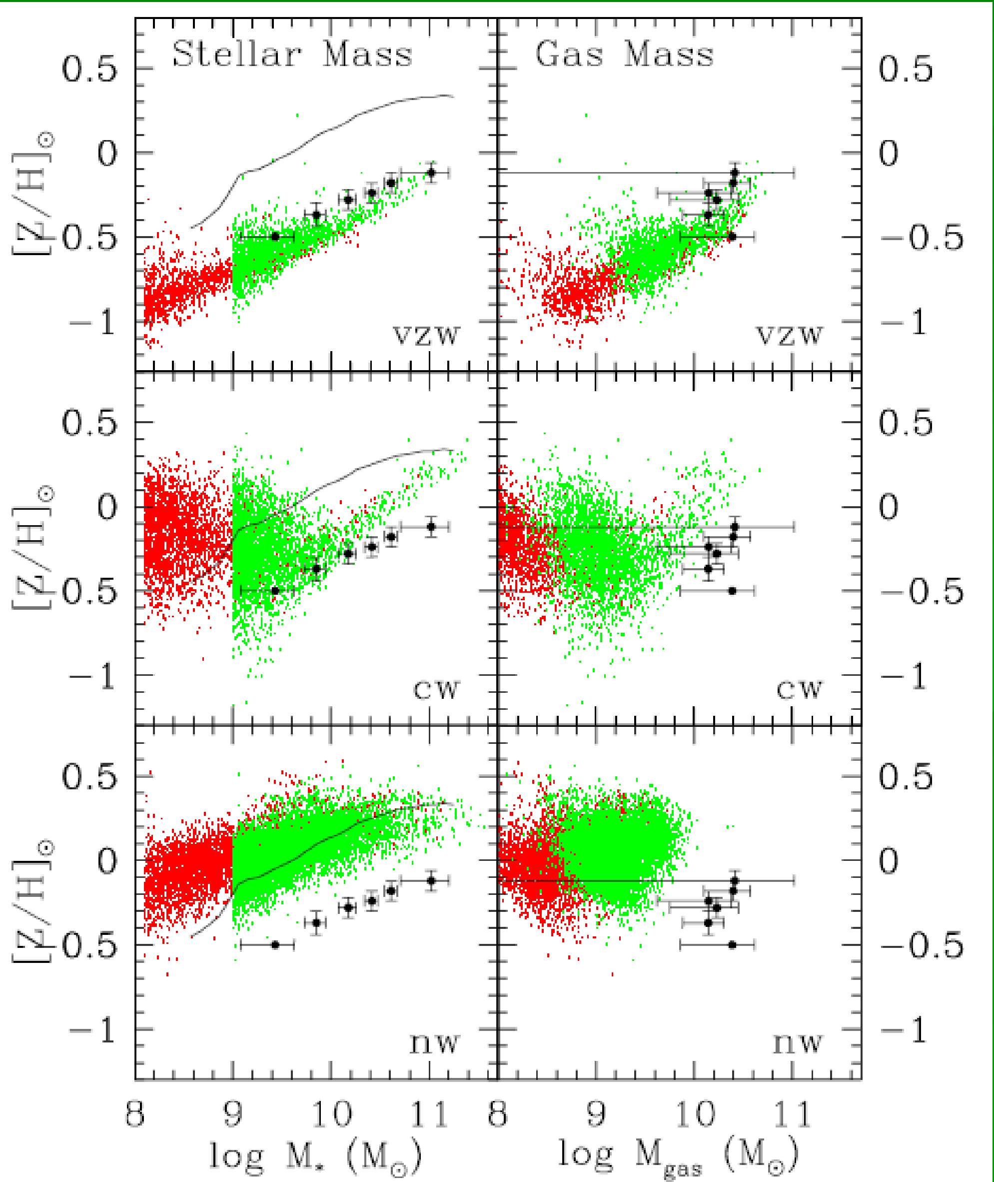
- Gadget + winds from star forming galaxies.
- Momentum-driven winds ($v_w \propto \sigma, \eta \propto 1/\sigma$) vs. v_w, η = constant
- Must inject metals early: High η.
- Must not overheat IGM: Low v_w.
- CIV POD ⇒ spatial distribution of metals; constrains wind model.



Oppenheimer & RD 06

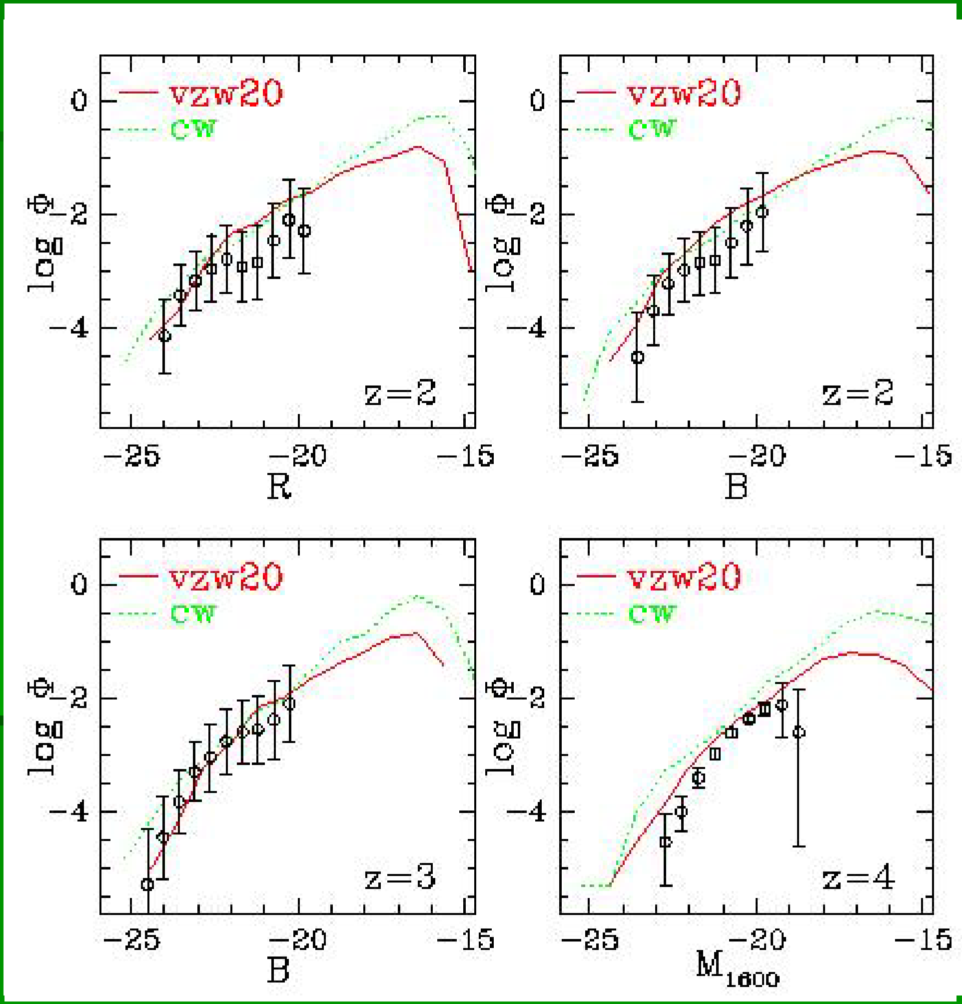
Mass-Metallicity Relation

- Galaxies enrich early, and $M \propto Z^{0.3}$ established early on.
- Why so *much* evolution observed from $z=2 \rightarrow 0$?
- Outflows affect (set?) M-Z relation.
- Momentum-driven wind scalings work!
- In addition to metals, winds also keeps galaxies gas-rich.



Luminosity functions

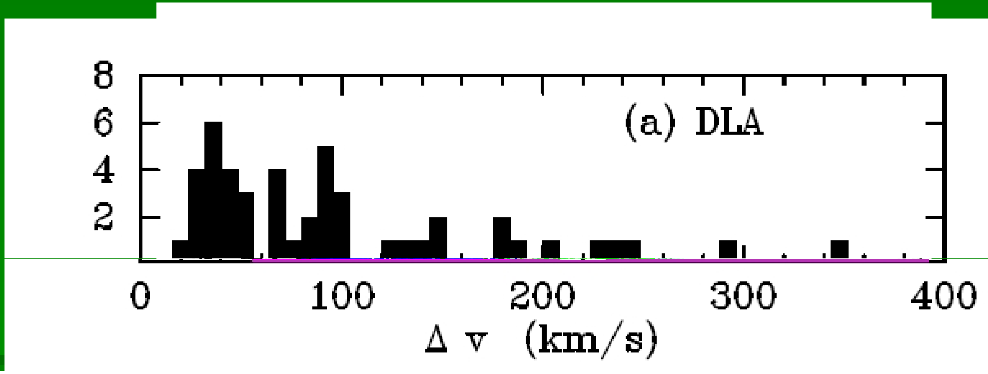
- z~6 UVLF seems to indicate some SF suppression required: Outflows?
- z~2-4 rest-optical LF's agree with data.
- Outflows affect faint end of LF: prefers higher η in small galaxies.

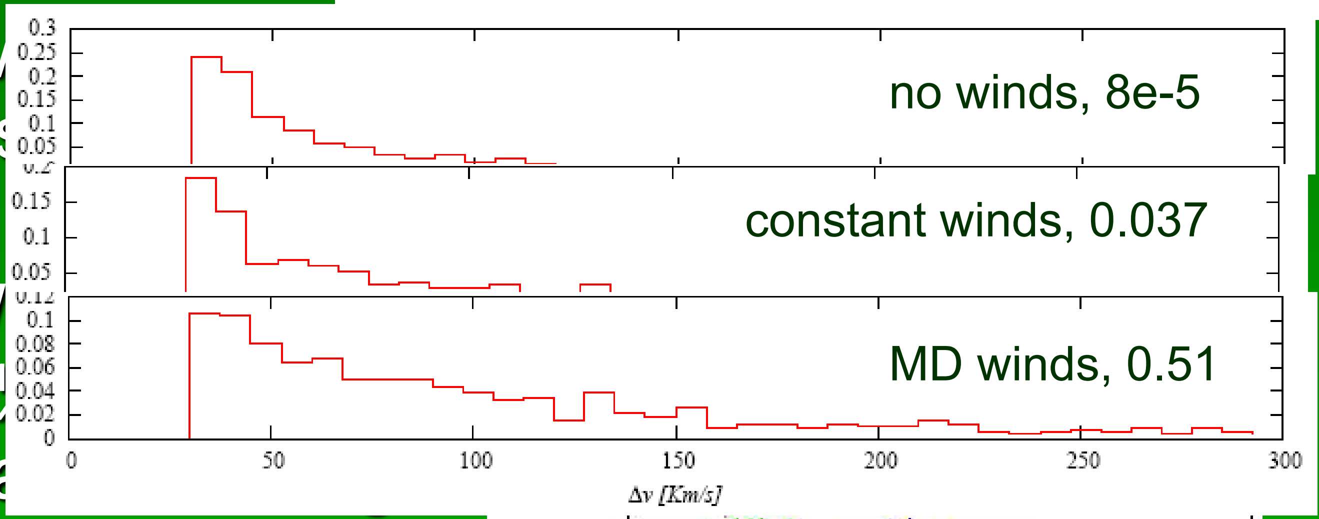


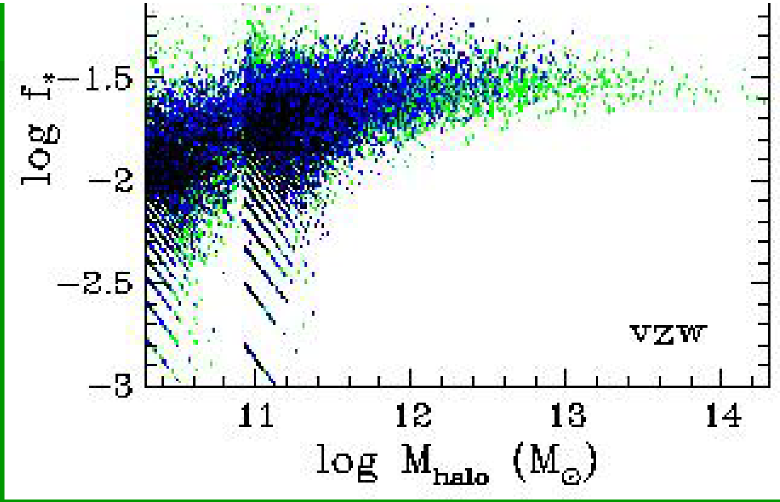
RD, Finlator, Oppenheimer 06

Baryon fractions

- Winds throw baryons outs Is this real?
- By z~0, MW have only ~1 They really a
- Evidence for baryons, not just metals, being ejected at z~3: DLA kinematics (Sungryon Kim et al, in prep).

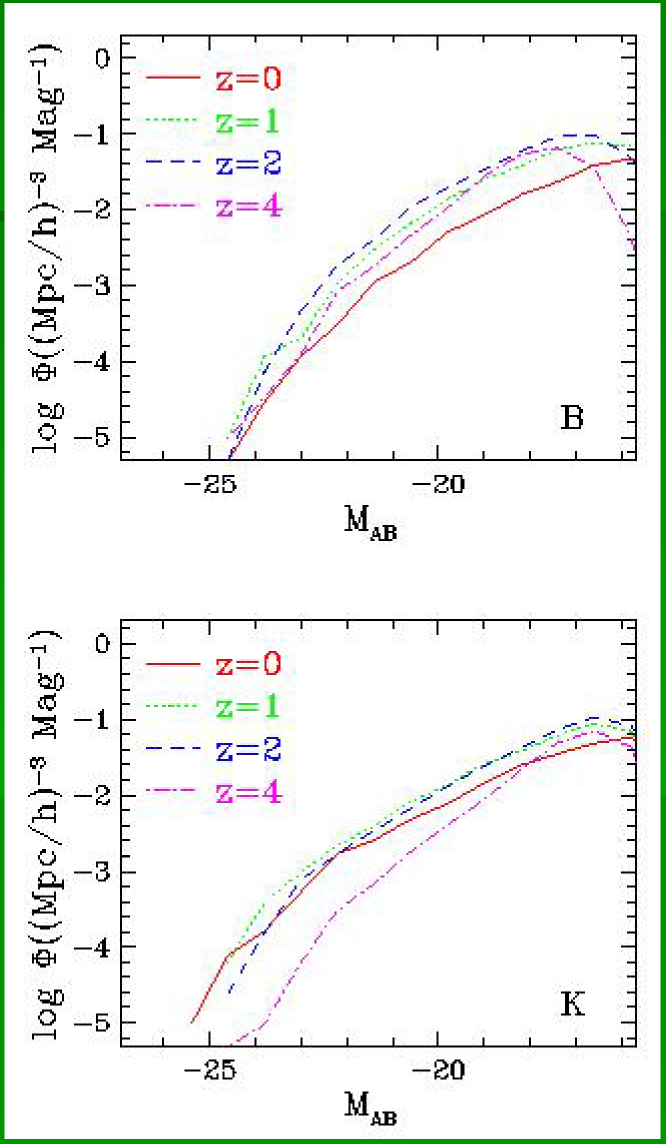






Summary

- Galaxy formation at high-z seems to be driven by (at least):
  - Cold accretion
  - Strong and ubiquitous outflows
- Direct observational evidence of these are sparse, but many indirect constraints.
- Not clear that it's solved; simulations may be limited by numerics, or physical processes may be absent.
- High-z galaxy formation presents own challenges apparently separate from low-z.



log Φ((Mpc/h)^-3 Mag^-1)
z=0
z=1
z=2
z=4
B
M_AB
-25
-20
0
-1
-2
-3
-4
-5
K