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.**
  - \( \text{SFR} \propto M_\star \) (with little scatter).
  - LBGs are massive; age \( \sim \frac{1}{2} t_{\text{Hubble}} \).
  - [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; $t_{\text{dyn}}$-limited.
- Hot mode: $t_{\text{cool}}$-limited.
- Keres et al: Transition $M_{\text{halo}} \sim 10^{11.4} M_\odot$, 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 $\Rightarrow$ Rapid early growth

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

Finlator, RD, Oppenheimer 06
Quiescent SFH?

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

---

Noeske et al. 2006  
Erb et al. 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 ($\eta$).
- Local starbursts: $v_w \propto v_{\text{circ}} \Rightarrow$ Momentum-driven winds?
- How to constrain? Track the metals!
Outflows and IGM Metals

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

Oppenheimer & RD 06
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

- \( z \sim 6 \) UVLF seems to indicate some SF suppression required: Outflows?
- \( z \sim 2-4 \) rest-optical LF’s agree with data.
- Outflows affect faint end of LF: prefers higher \( \eta \) in small galaxies.

RD, Finlator, Oppenheimer 06
Baryon fractions

- Winds throw many baryons outside of halos. Is this real?
- By $z \sim 0$, MW-sized halos have only $\sim 1/2$ baryons. They really are "missing"!
- Evidence for baryons, not just metals, being ejected at $z \sim 3$: 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.