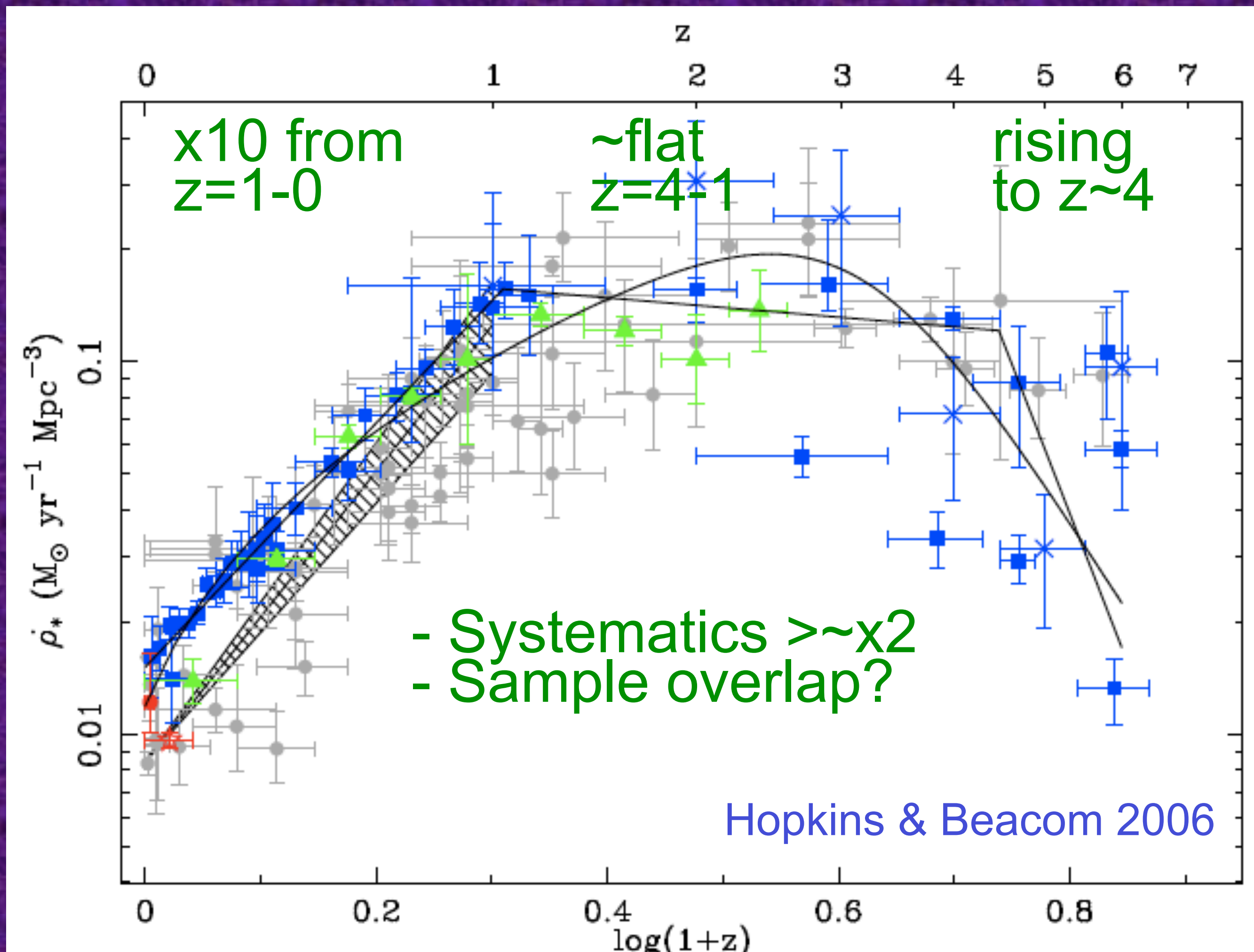
movie by B. Oppenheimer

Star Formation at High Redshift: *Observational Progress and Theoretical Perspectives*

Romeel Davé

From first light to Newborn Stars

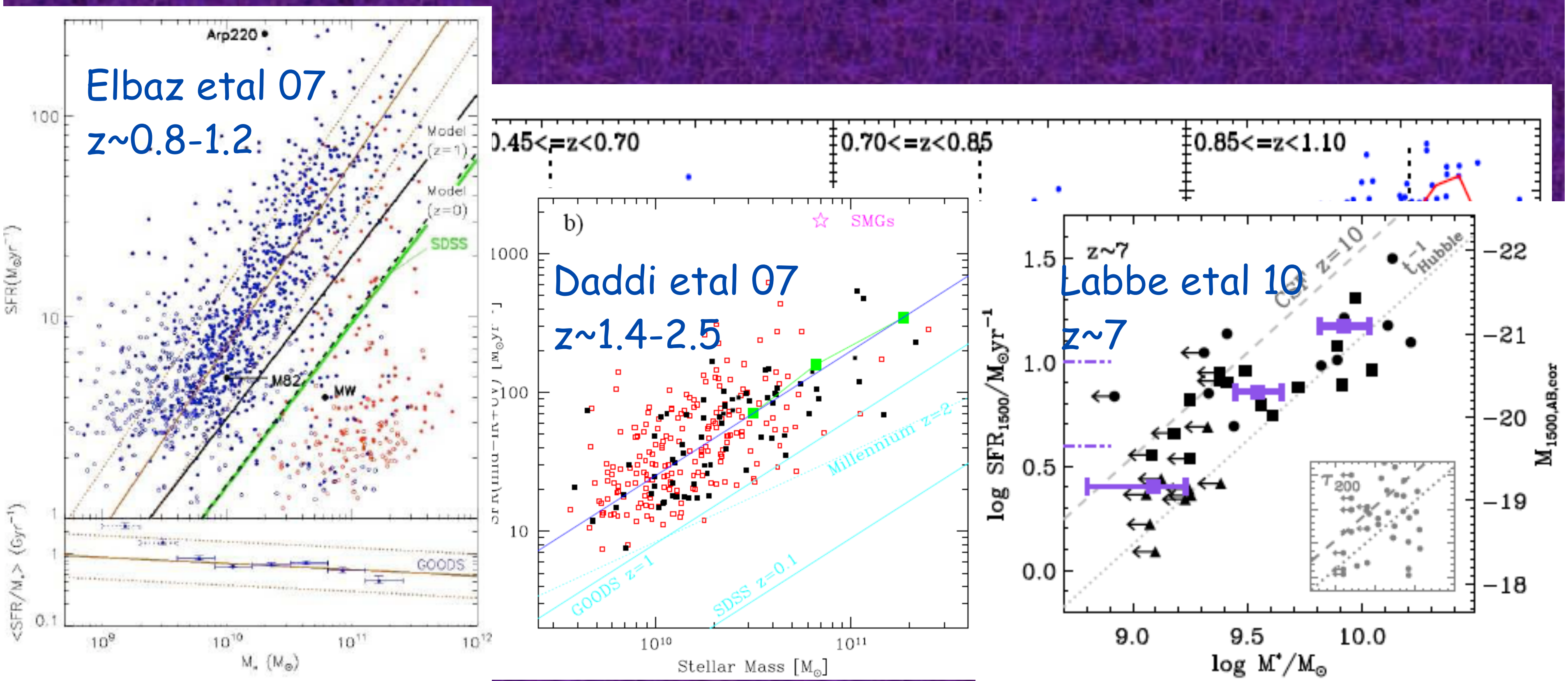
Cosmic SF History



Breaking down cosmic SF

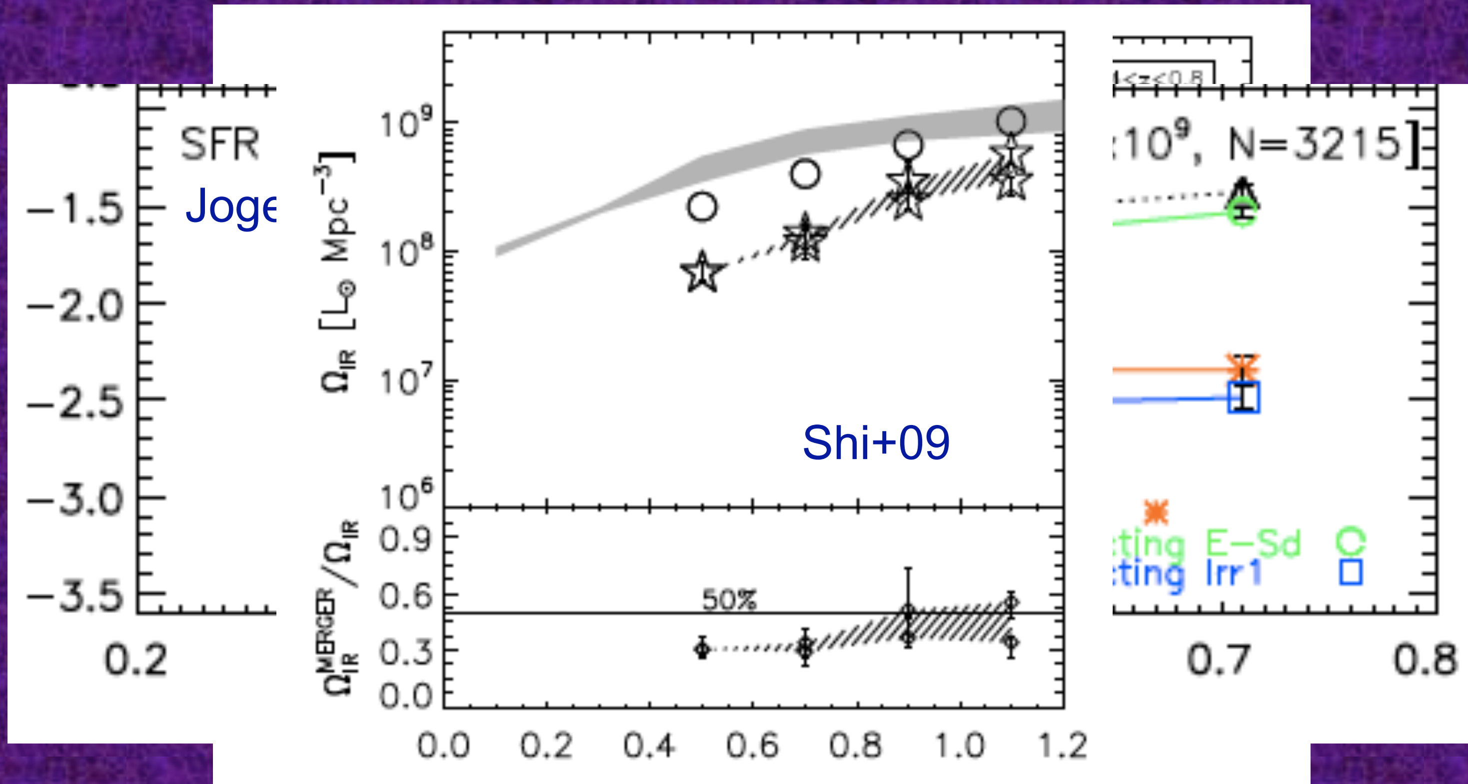
- Bursty or quiescent?
- How important are mergers?
- How much is obscured?
- Stellar mass growth vs. SFR?
- Is hi-z SF systematically different?

Main Sequence of Galaxy Formation



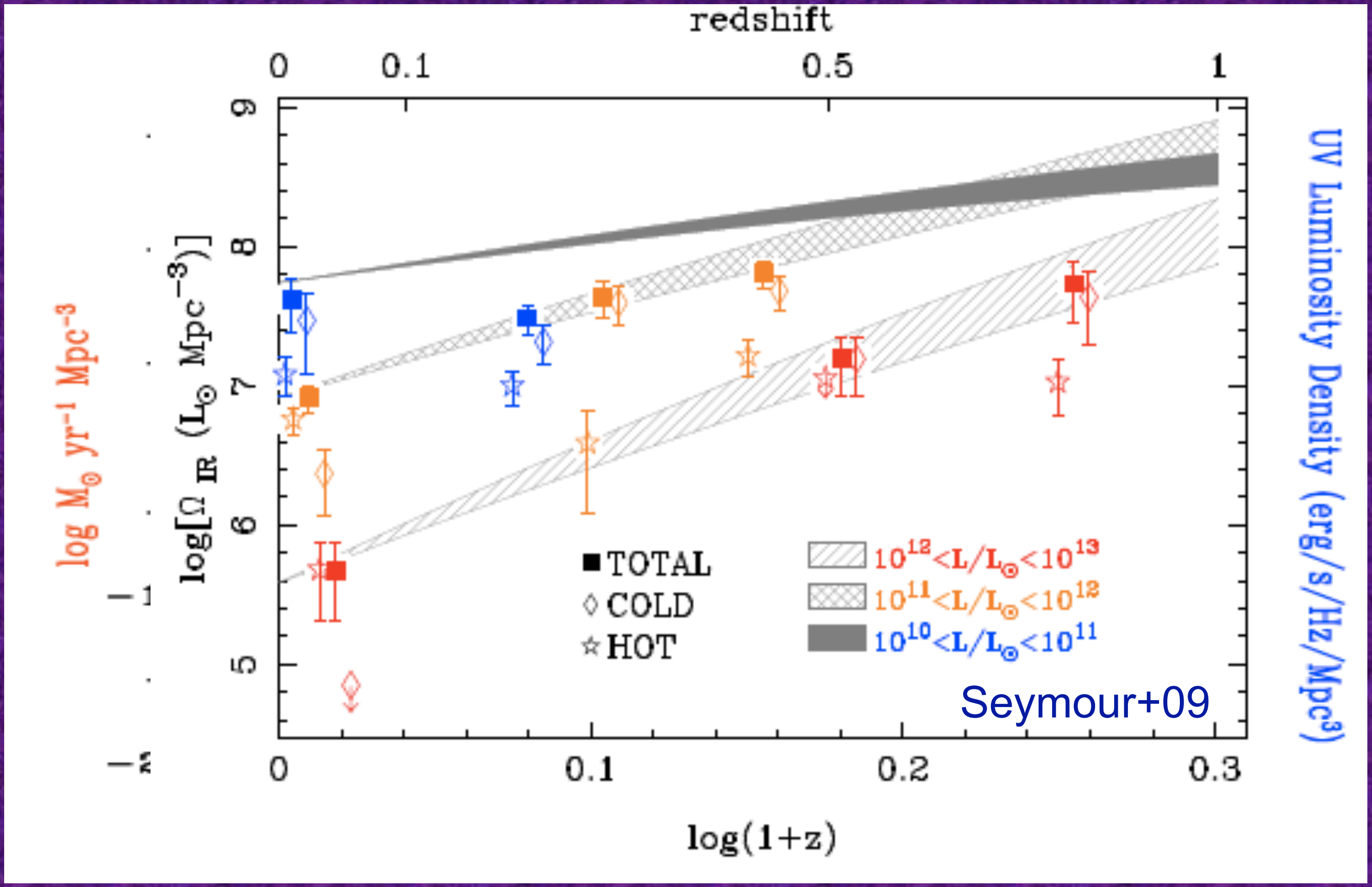
- SFR ~ $M_*^{0.7\text{-}0.9}$, scatter 0.3 dex.
- Evolves down independently of M_*
- *SFR quiescent, not burst, dominated*

SFR from mergers?



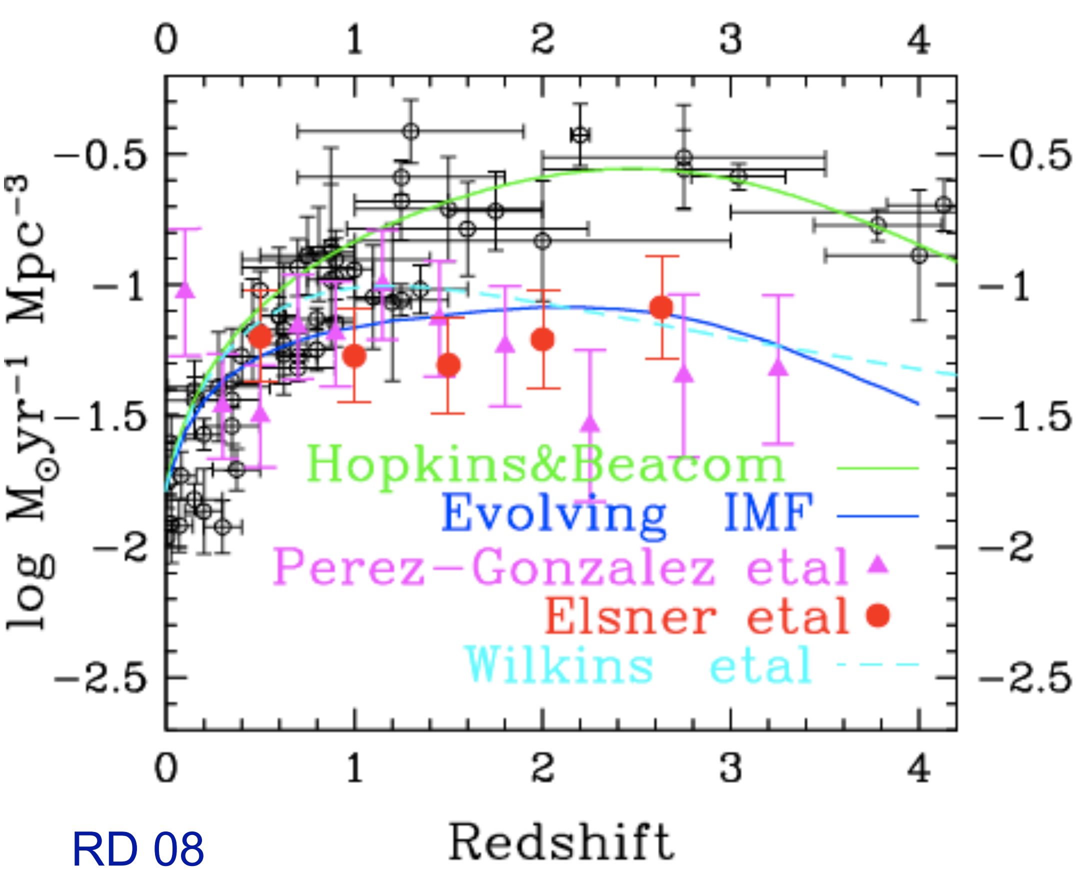
- Close pairs: <10% global SF in >3:1 mergers
- Morphological: <30% global SF in interacting
- BUT– Asymmetry: ~50% z~1 SF in "mergers"
- *Non-interacting galaxies dominate SFRD*

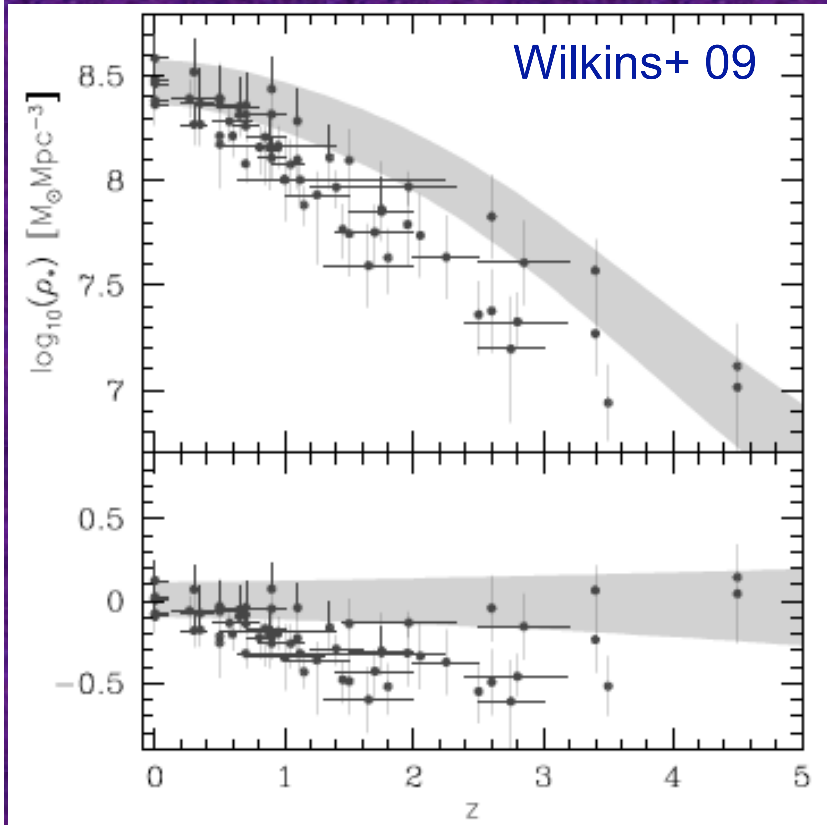
Obscured star formation



- Most SF obscured; peaks at z~2.
- LIRGs/ULIRGs dominate to z~1,2…but don't interpret as local ULIRG analogs!

SFR vs. dM*/dt





- dM*/dt << SFR (+IMF) at z~2-3
- Completeness? (Reddy+09)
- Is SFR at z~2-3 fundamentally different?

How Do We Understand All this?

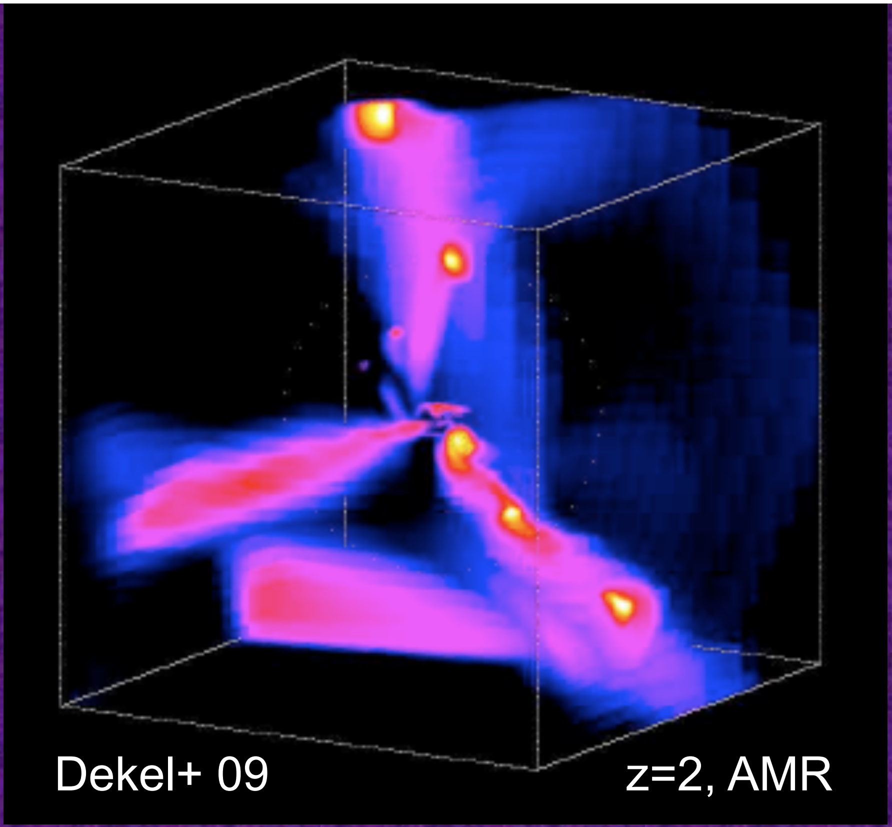
- Computers!

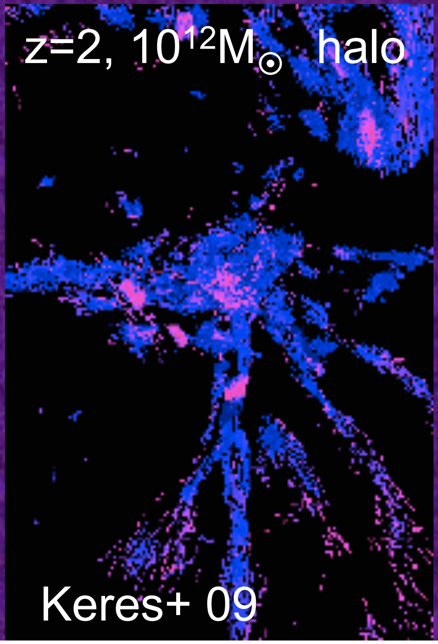
A Not-totally-wrong Story for Star-forming Galaxies

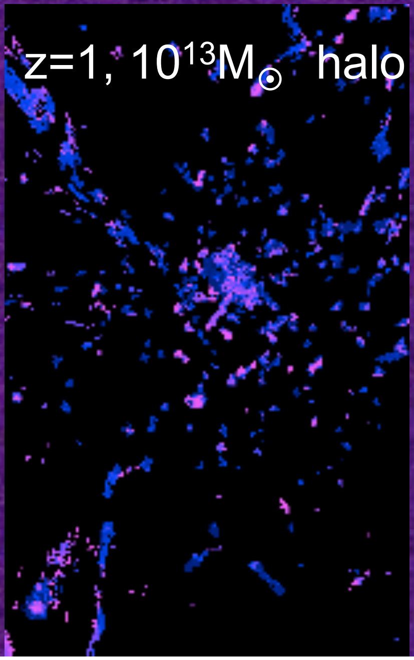
- Cold flows
- Smooth accretion
- Regulation by galactic outflows
- The Galaxy-IGM connection
- Truncation by mergers/AGN

Cold mode accretion

- Cold flows dominate gas infall for *ALL* star-forming galaxies.
- Hot halos for $>10^{12}\ M_\odot$







- At z>~1-2, flows penetrate hot halo.
- At low-z, flows break up into clouds (HVCs?)

Cold Mode -- in every hydro sim ever done

DISSIPATIONAL GALAXY FORMATION. I. EFFECTS OF GASDYNAMICS

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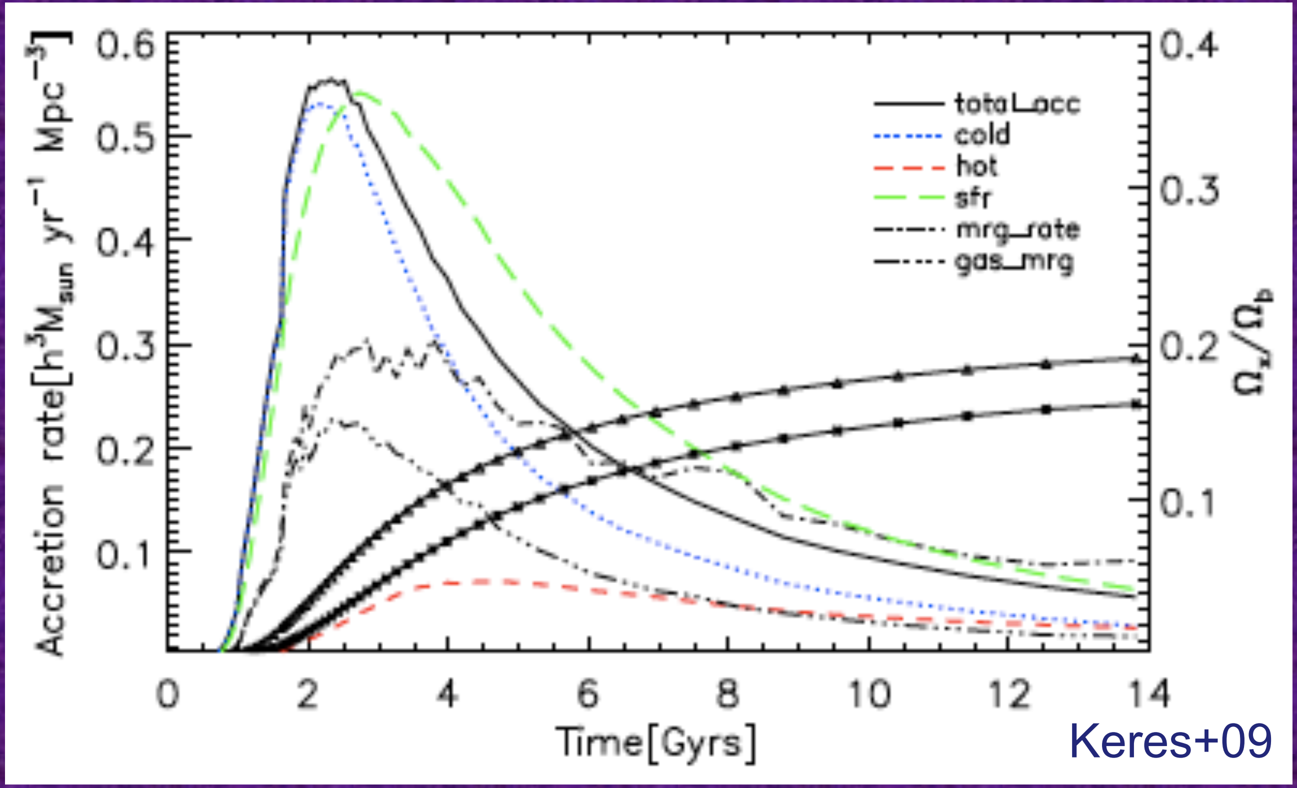
ABSTRACT

We present numerical simulations of hierarchical galaxy formation including gasdynamics. These simulations are conducted using a new, general-purpose program for evolving self-gravitating systems in three dimensions. The gravitational forces are calculated with a hierarchical tree algorithm, while the gasdynamic properties are determined by an approach known as smoothed particle hydrodynamics. In this method the complete thermodynamic state of the gas is known everywhere, so dissipational effects can be included by allowing the gas to cool radiatively. We use standard cooling curves that include Compton, as well as radiative, cooling.

These simulations model the collapse of isolated constant density perturbations, initially in solid-body rotation and in Hubble-flow. The perturbations consist of dark and baryonic matter in a 10 to 1 ratio. Small-scale power is added using the Zel'dovich approximation assuming a power-law slope of either -2.5 or 0. We are successful in making two component systems that resemble spiral galaxies: a thin disk made of gas and a dark matter halo. The disk transfers more than 50% of its original angular momentum to the dark halo and forms at an angle of $\sim 30°$ to the rotation axis of the dark halo. The disks form with a warp that is also a consequence of the angular momentum transport that acts during the collapse. Beyond ~ 5 kpc the gaseous disk has a flat rotation curve and an exponential surface density profile. Due to the efficient cooling that acts during the collapse, the gas never heats to the virial temperature but remains at less than 30,000 K.

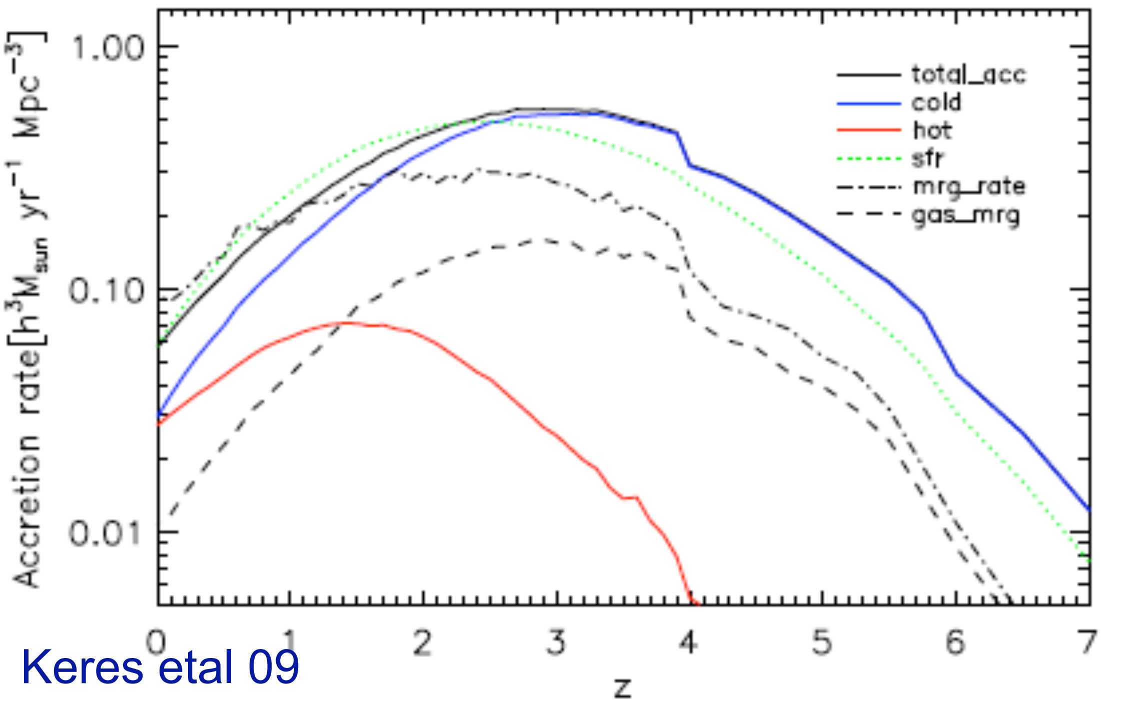
Subject headings: galaxies: formation — hydrodynamics — numerical methods

SFR tracks accretion

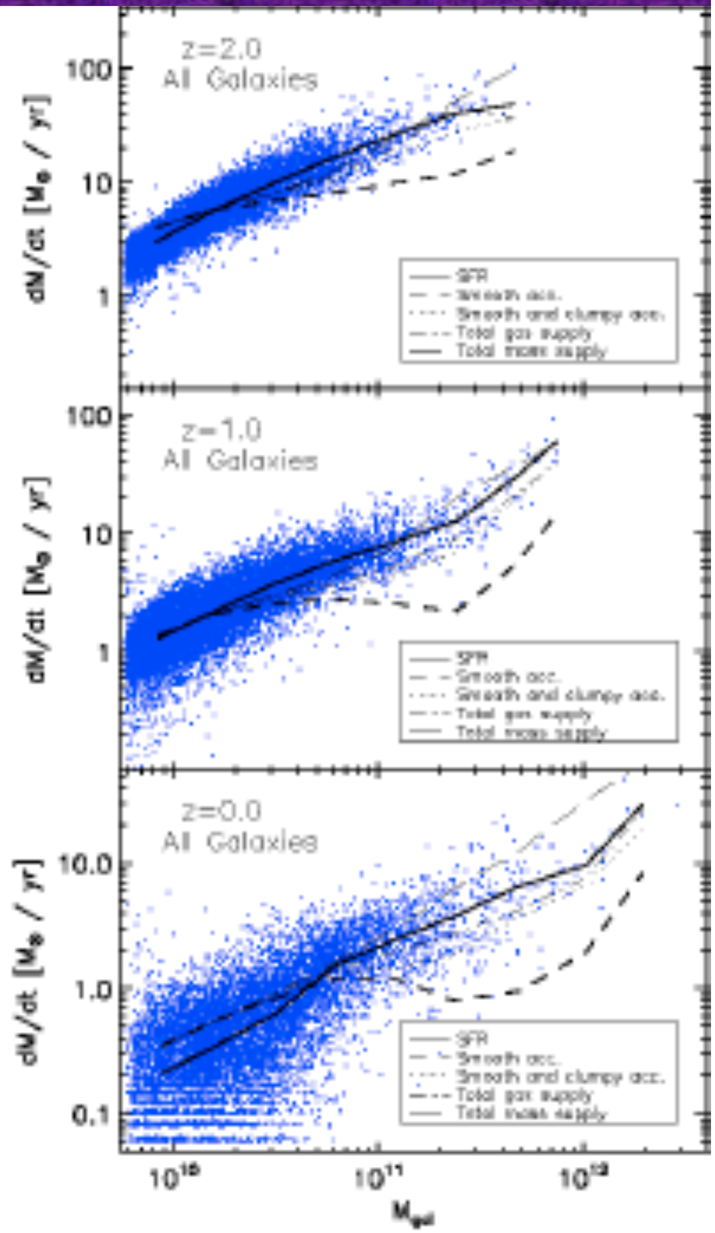


- SFGs at all masses, epochs process accreted gas into stars on $t \ll t_H$

Accretion is Smooth



Keres etal 09



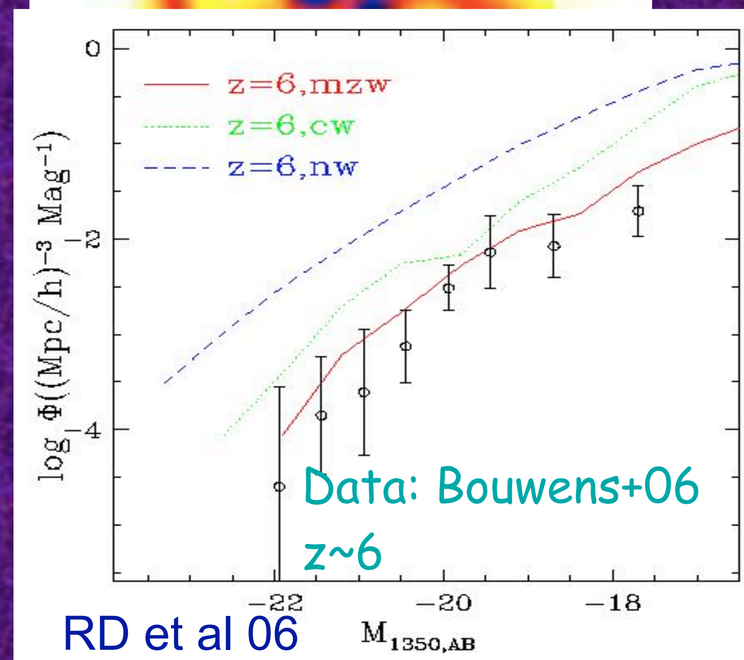
- Accretion is ~smooth (& filamentary).
- Mergers subdominant.

Generic predictions

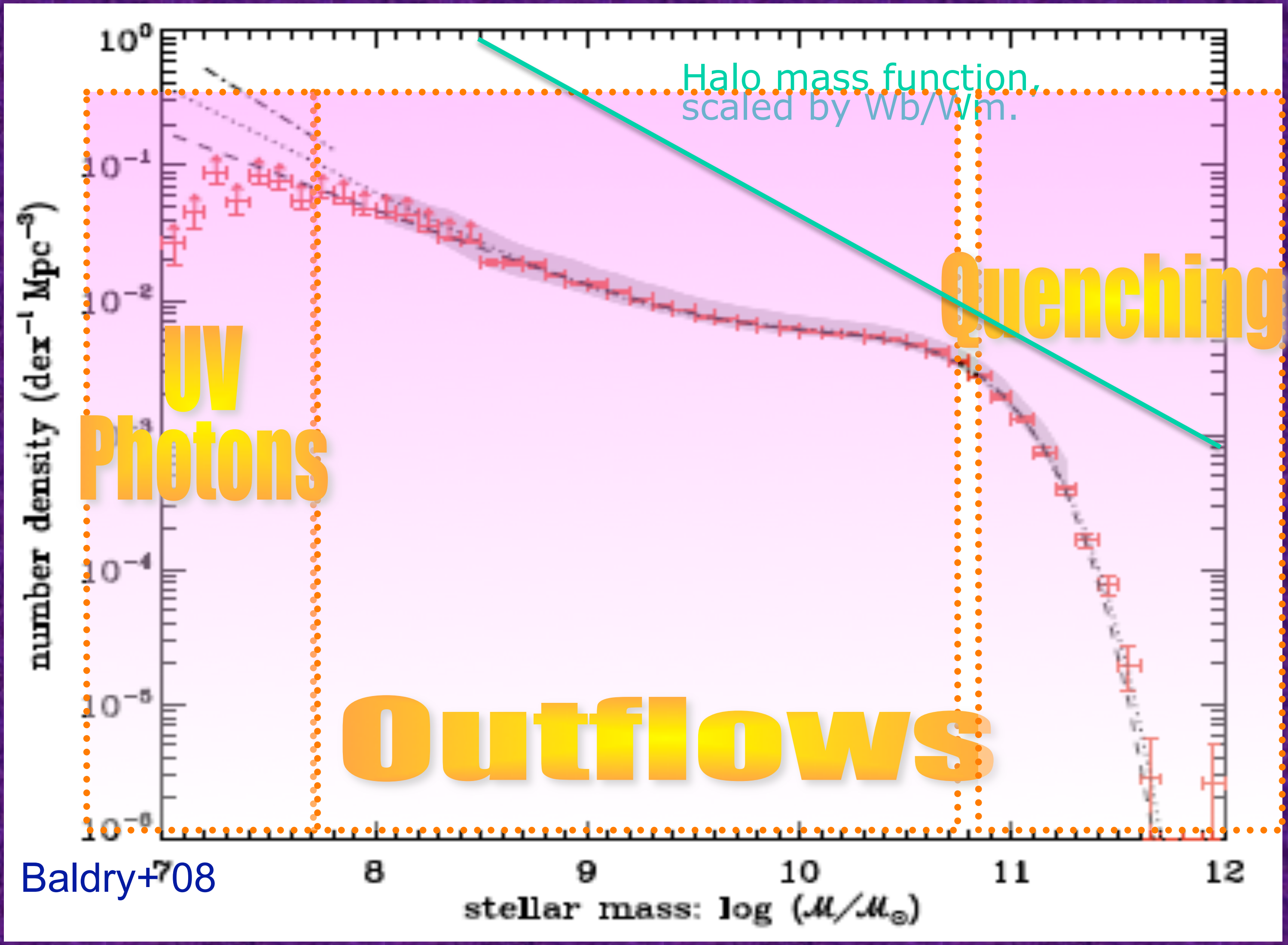
- Tight SFR-M$_*$ relation, evolves indep of M$_*$
- Mergers/bursts sub-dominant in SFRD.
- Disturbed morphology due to rapid accretion
- Early galaxies grow rapidly.

- … *too* rapidly!

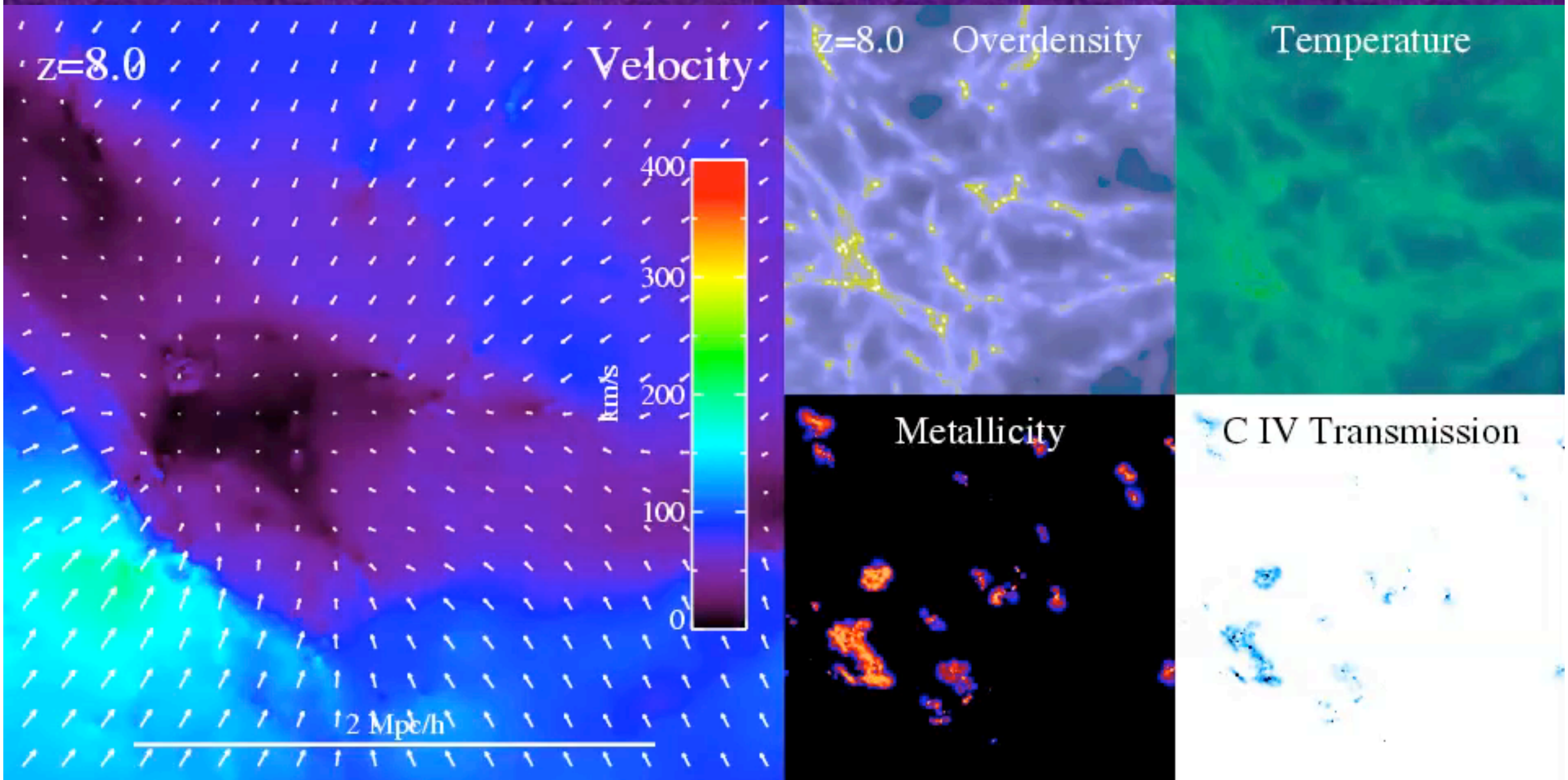
- Need feedback.



Feedback Regulates SF



Cosmic Feedback Cycle



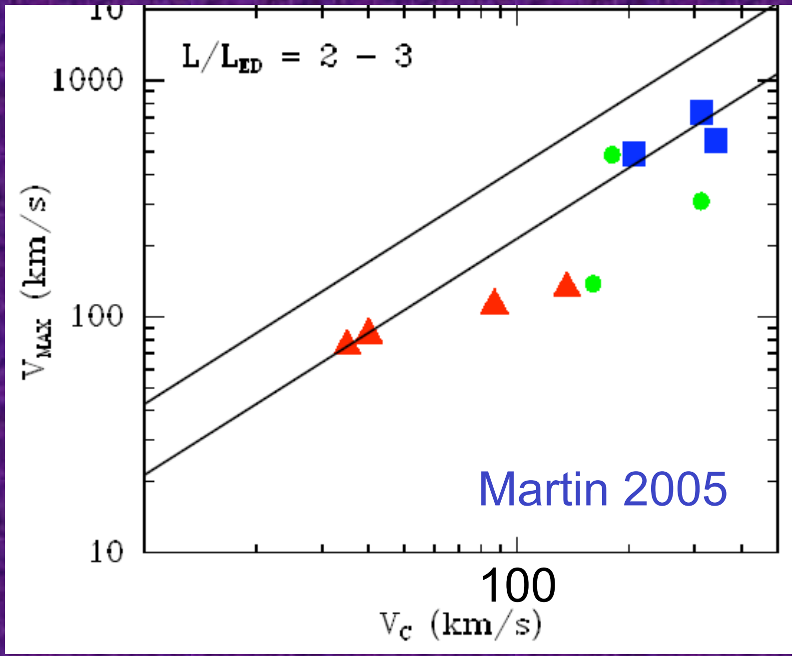
Outflows: Observations & Implications

- Common at z~1+:
  - $\Sigma_{SFR} >> 0.1\ M_{\odot}/kpc^2$
  - $\Delta v_{ISM} \sim$ hundreds km/s
- Local SBs, z~1 SFG:

  $v_w \propto v_{circ}$

  Momentum-driven winds?
- If so, *mass loading factor*

  $\eta \propto 1/v_{circ}$
- Note: Similar scalings may arise from other physical mechanisms.



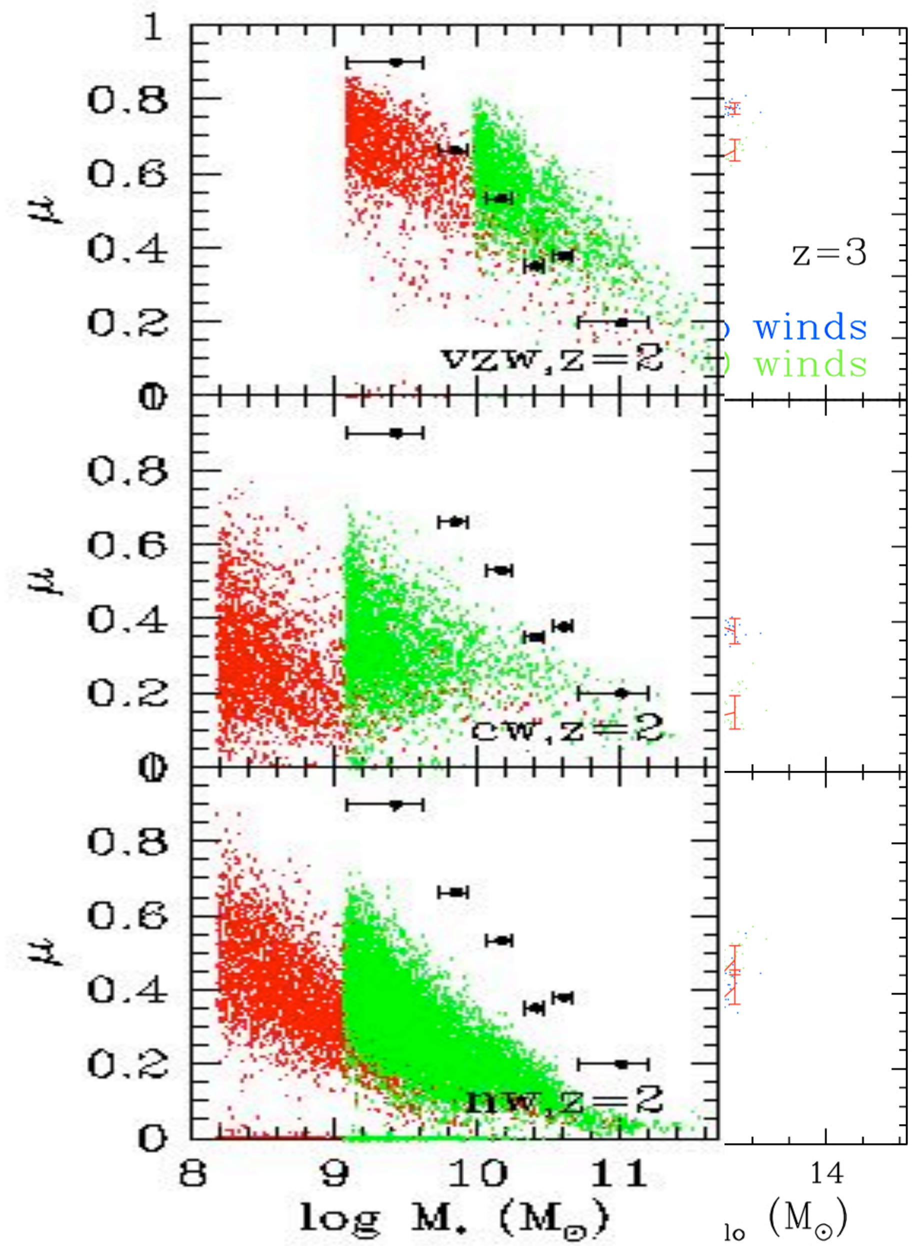
Such Outflows Yield...

- Correct (early) evolution of cosmic SFR
- IGM enriched to match CIV, OVI absorbers
- Mass-metallicity with right slope & scaller
- High gas fractions in low-M galaxies
- DLA kinematics w/enough wide systems
- Non-grav entropy in intracluster gas

… all from including one simple scaling of outflows with galaxy mass.

... Some Surprising Implications

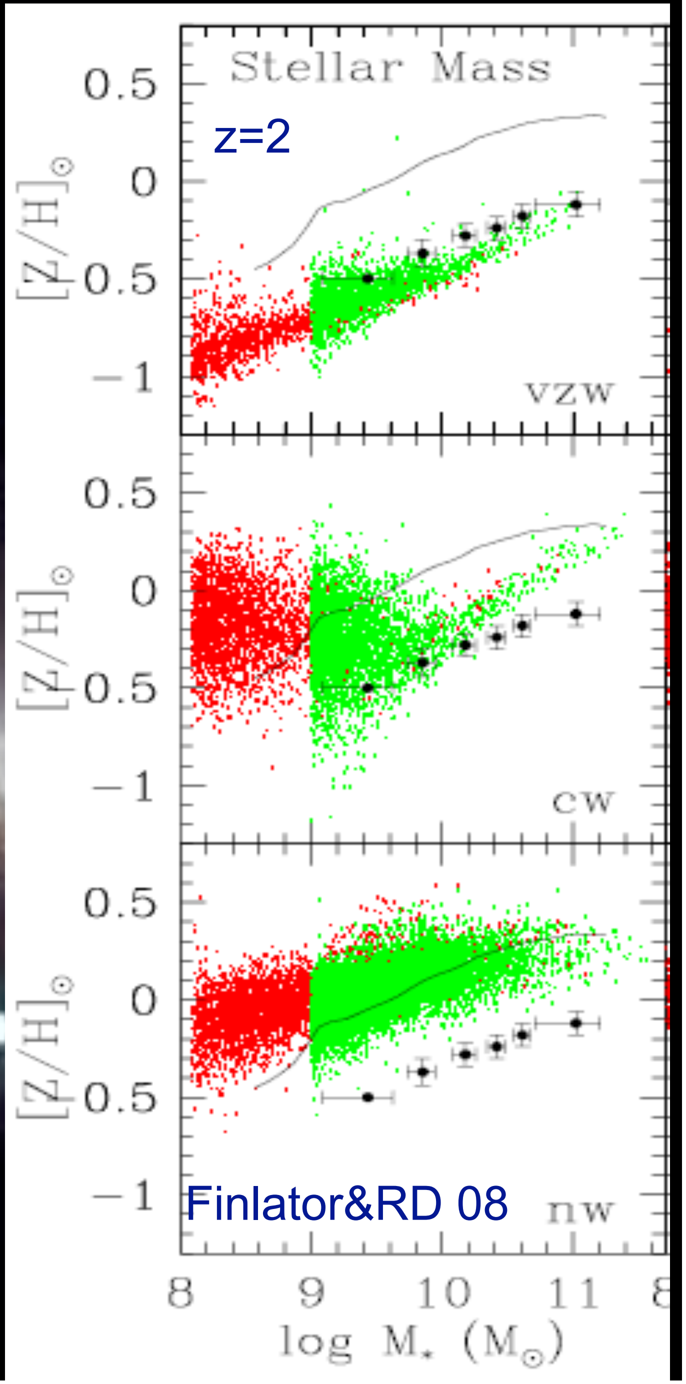
- Mass in outflows >> Mass in stars
- Winds recycle a lot; recycled wind accretion dominates at z<~1.
- Many baryons blown out of even large halos
- Outflows keep galaxies gas rich (not poor).
- MZR set by balance of inflows and outflows, not gas processing rate



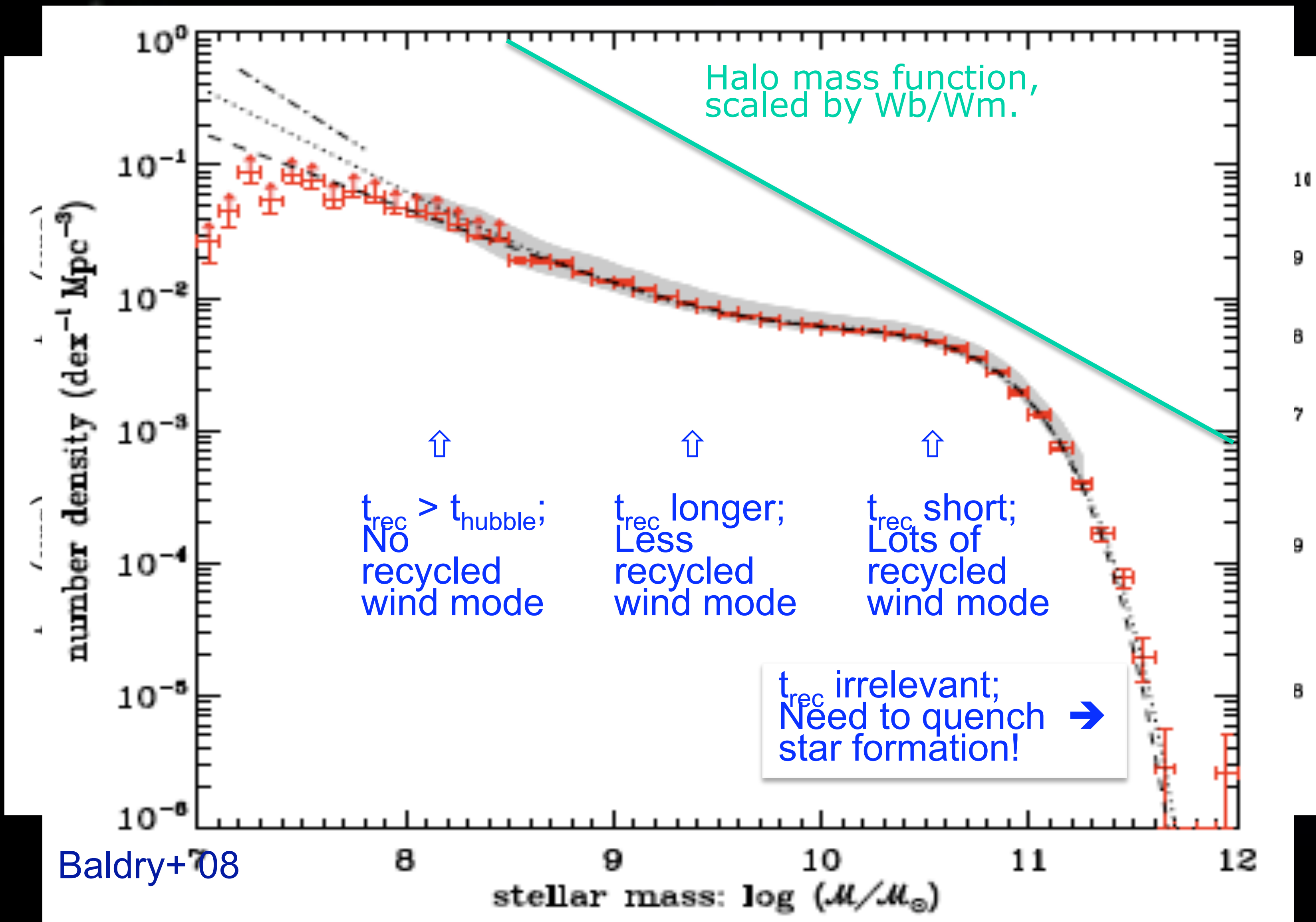
The "Equilibrium" MZR Model

- $Z \sim y\, \dot{M}_* / \dot{M}_{acc} \sim y\,(1+h)^{-1}$
- If $v_w > v_{esc}$, constant h → constant Z. For $v_w < v_{esc}$, h→0, Z→y. Produces a feature in MZR-- not seen.
- For mom-driven winds:

  $h \sim M_*^{-1/3} \sim v_c^{-1} \rightarrow Z(M_*) \sim M_*^{1/3}$
- Z_{gas} set by an *equilibrium* between *recent* inflow and outflows.



Recycling sets the GSMF

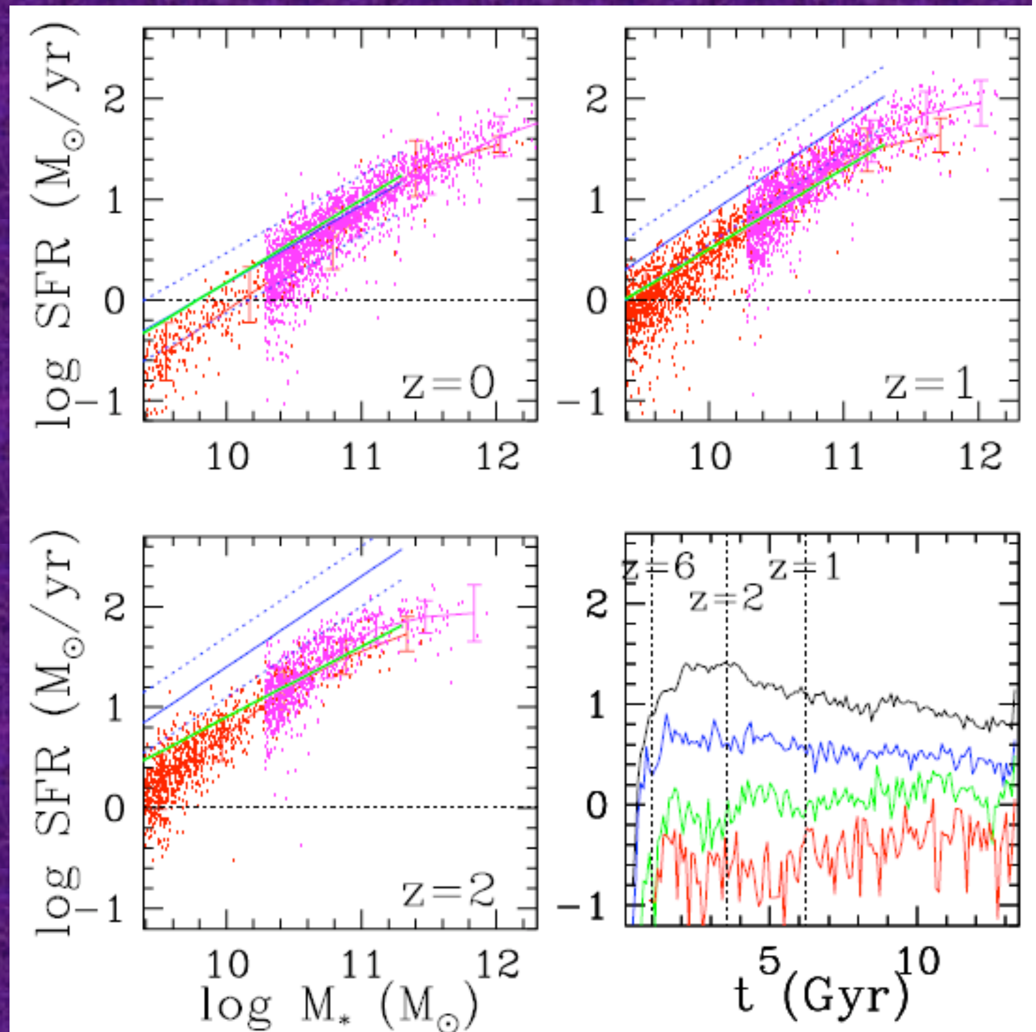


Galaxies as "Gas Processing Engines"

- *Obtain gas via cold, smooth accretion*
  - Creates tight evolving M_*-SFR relation.
- *Process into stars (some) or eject into outflows (most) on a short timescale.*
  - SFR, gas content, metallicity set by balance of inflow vs outflow.
- *Ejected material recycles, moreso in larger galaxies.*
  - Sets shape and evolution of galaxy stellar mass function.

SFR-M_*: Close but no cigar

- Models get right:
  - Slope
  - Scatter
  - General evolution
- But *amplitude evolution is wrong!*
- Data has higher SFR at given M*.
- But wait… cold accretion sets *maximum* rate!

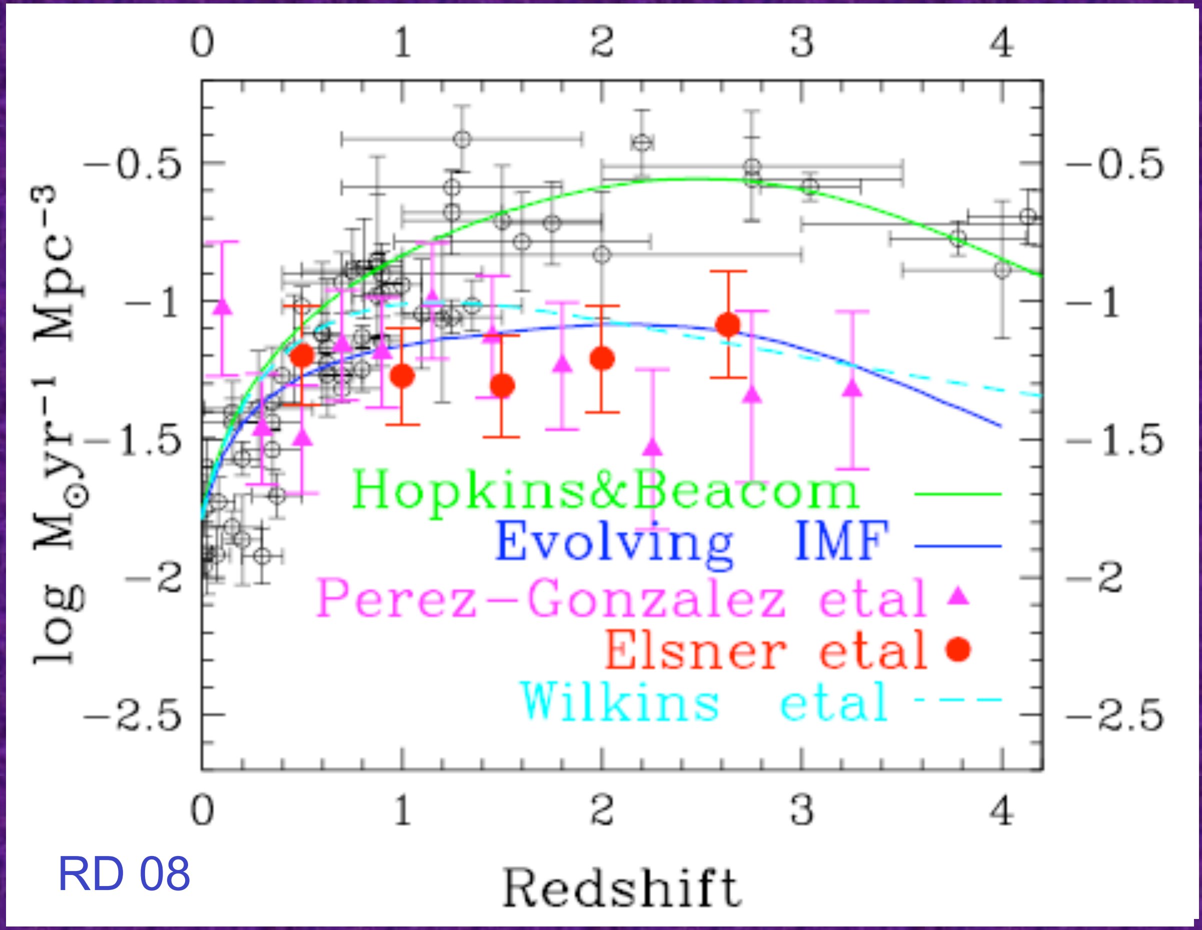


·Green: Millenium SAM

·Red, magenta: SPH sims

·Blue: Data ([illegible]=0.3)

Birthrate evolution: Huh?



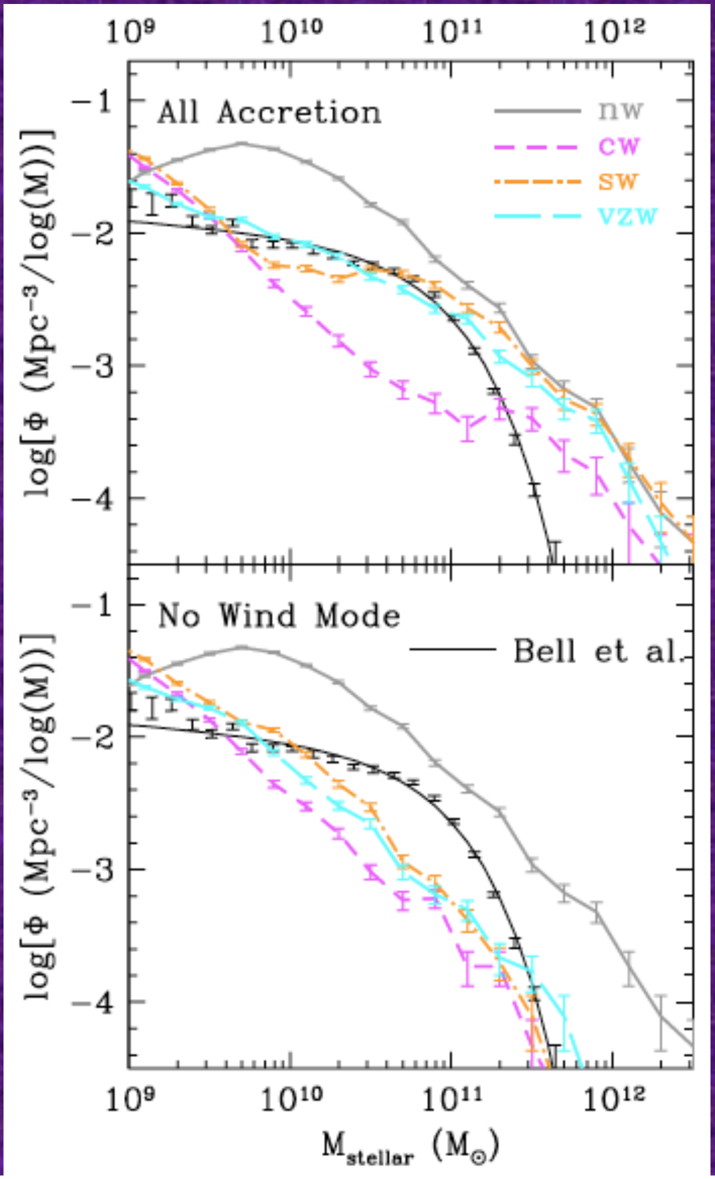
- Discrepant during the peak dusty SF epoch.
- Something different? Calibrations? IMF?

Summary

- 3 regimes of cosmic SFH: Early growth (z>4), rapid phase (1<z<4), late decline (z<1)
- Dominated by fairly smooth, filamentary cold accretion. Mergers & bursts subdominant.
- Dust embedded SF peaks @ z~2. Before that, less dust; after, SF morphology change?
- Generally, trends well explained by
  - Cold mode accretion, smooth & filamentary
  - Outflows that eject more mass from small gals.
- Mismatch between SFR and M* evolution, both vs. data and theory?

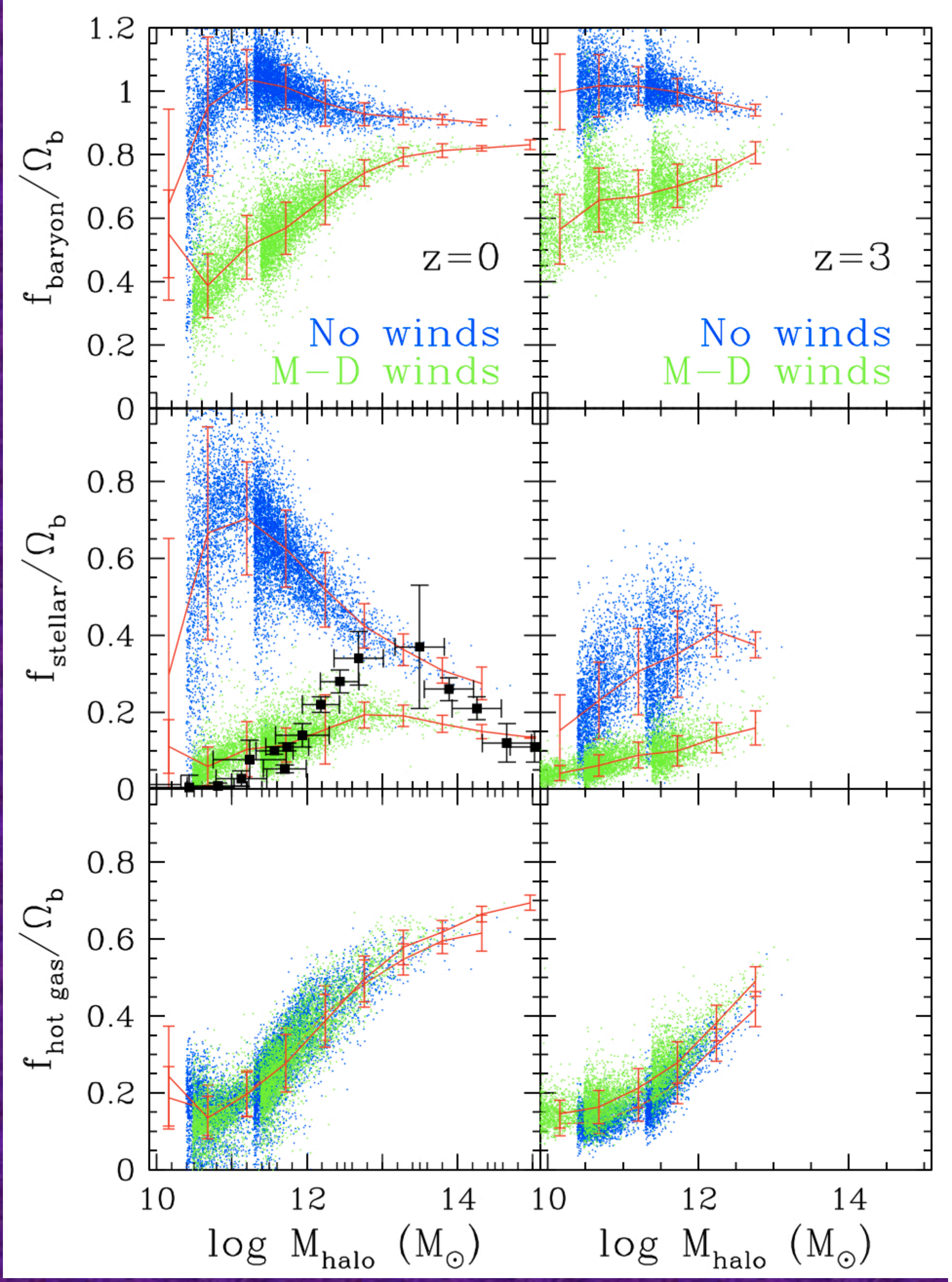
Diff recycling governs GSMF

- Without wind mode, GSMF~halo MF (scaled).
- Wind recycling boosts higher M* galaxies, flattens GSMF.
- Once $t_{recyc} > t_{Hubble}$, reverts to steep slope, modulated by outflows (vzw shallower since $h \sim 1/v_{circ}$).



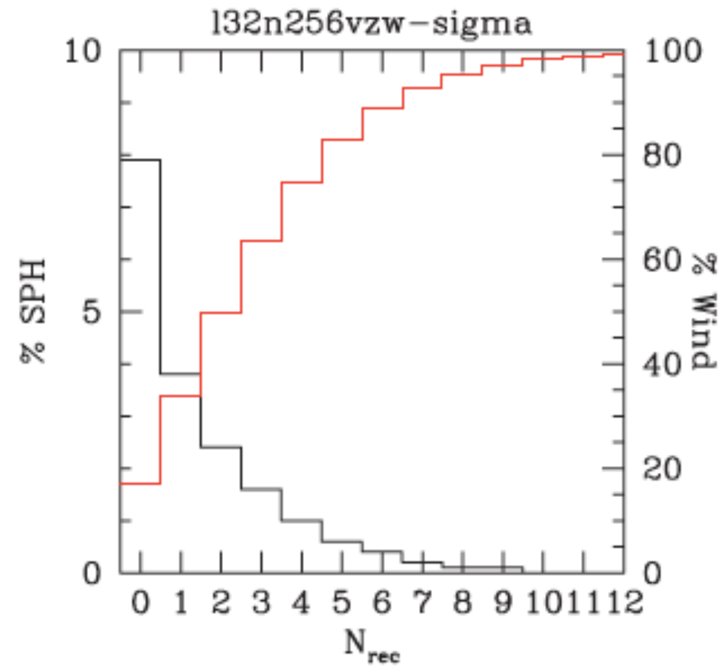
Halo baryon content

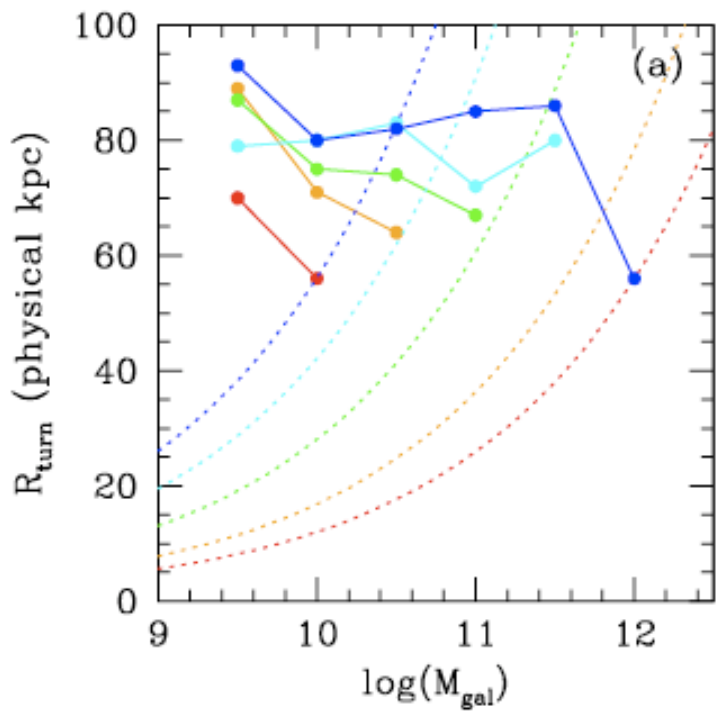
- Winds drive lots of baryons out of halos.
- Big galaxies lose baryons early.
- MW-like halo today has lost ~½ baryons
- Peak SF "efficiency" @ $10^{13}M_\odot$.
- Qualitatively similar to observations.



Winds recycle!

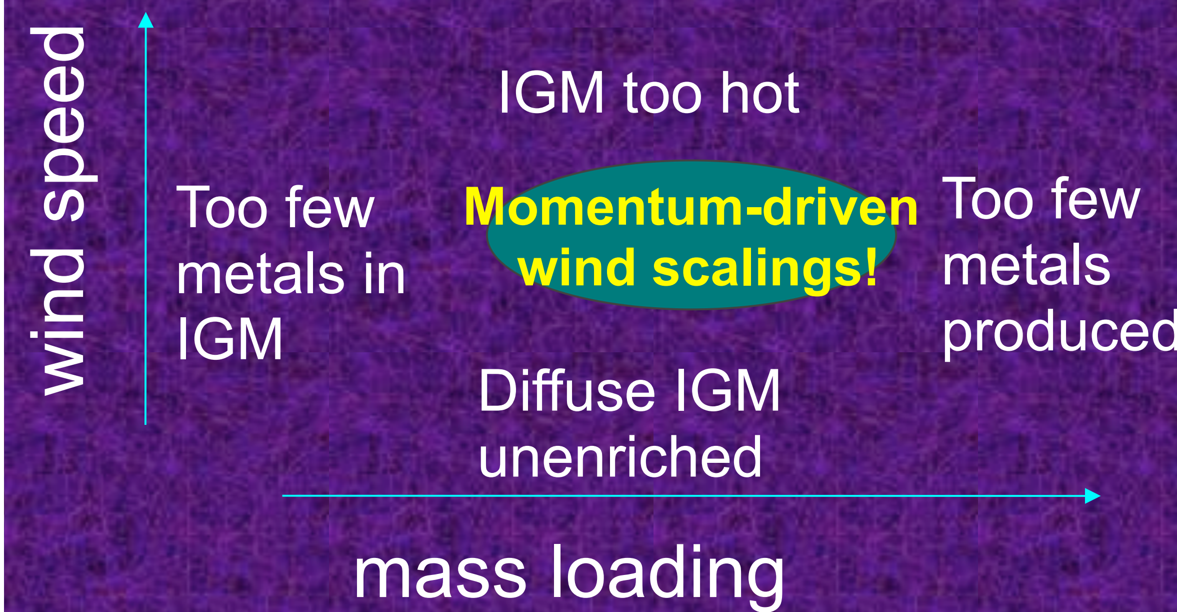
- $M_{winds} >> M_{stars}$
  - $\Omega_{wind} \sim 0.2\ \Omega_b$
  - $\Omega_{ejected} \sim 0.5\ \Omega_b$
  - Compare: $\Omega_* \sim 0.08\ \Omega_b$
- Median # ejections: 3
- Turnaround radius ~100 physical kpc
  - high-z: Enrich IGM
  - low-z: Halo fountains
- Median $t_{recyc} \sim 1$ Gyr

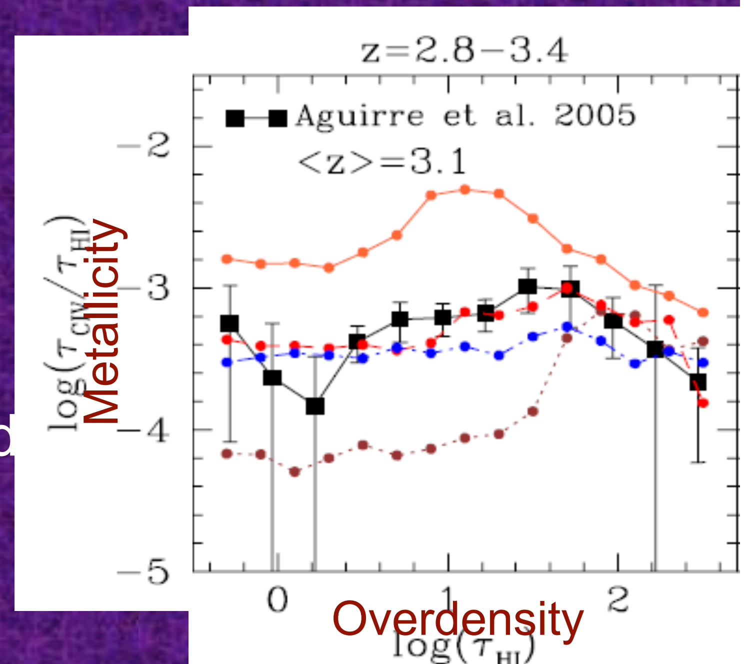




Constraints from IGM enrichment

- Outflows are the only way to enrich IGM
- z~2-4 CIV absorbers *very* constraining; favors **momentum-driven wind scalings: $v_w \sim v_{circ}$, $h \sim v_{circ}^{-1}$.**

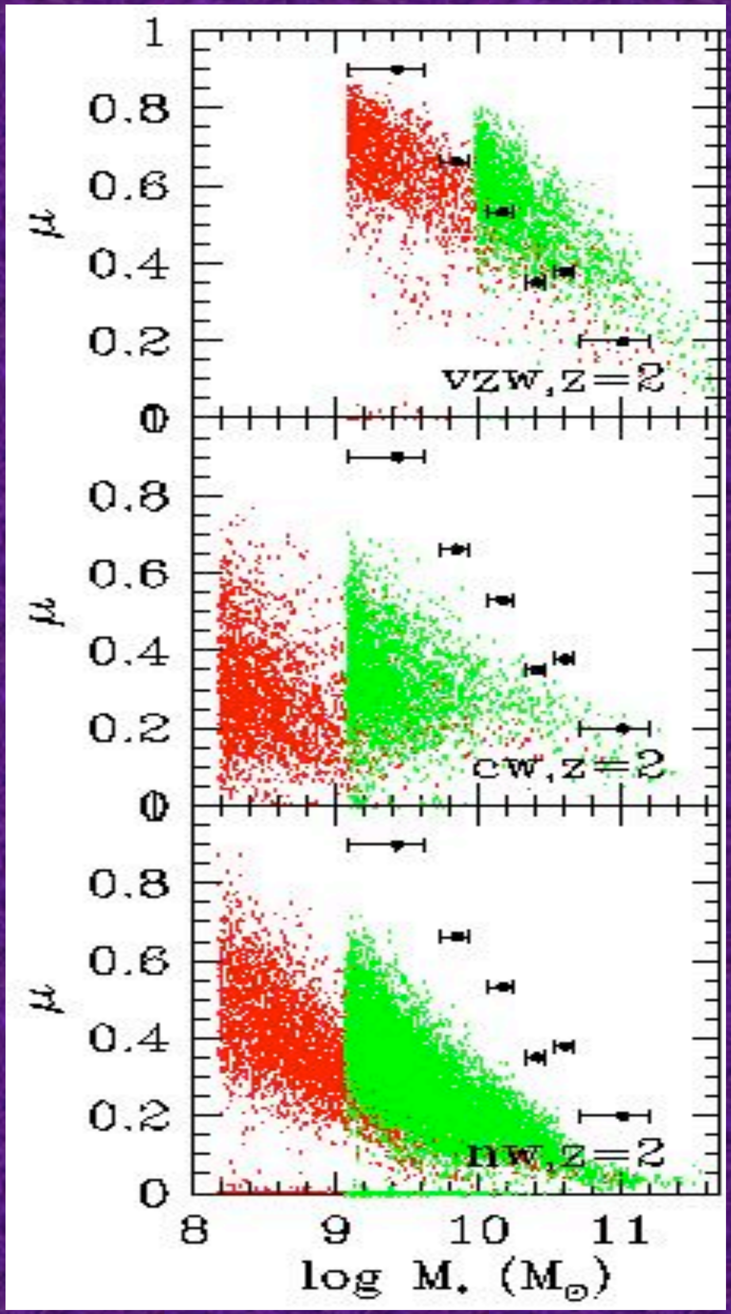




Oppenheimer & RD 2006
Oppenheimer & RD 2008
Oppenheimer & RD 2009a,b

Gas content

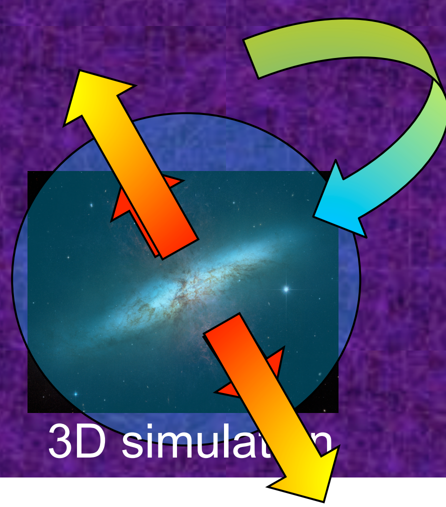
- $f_{gas}(M_*)$ strongly dependent on outflows.
- M-D winds keep low-mass galaxies gas rich by suppressing SF.
- Strong outflows make galaxies gas *rich*, not gas *poor*.
- Galaxies are the antithesis of closed boxes: They process gas as supplied.



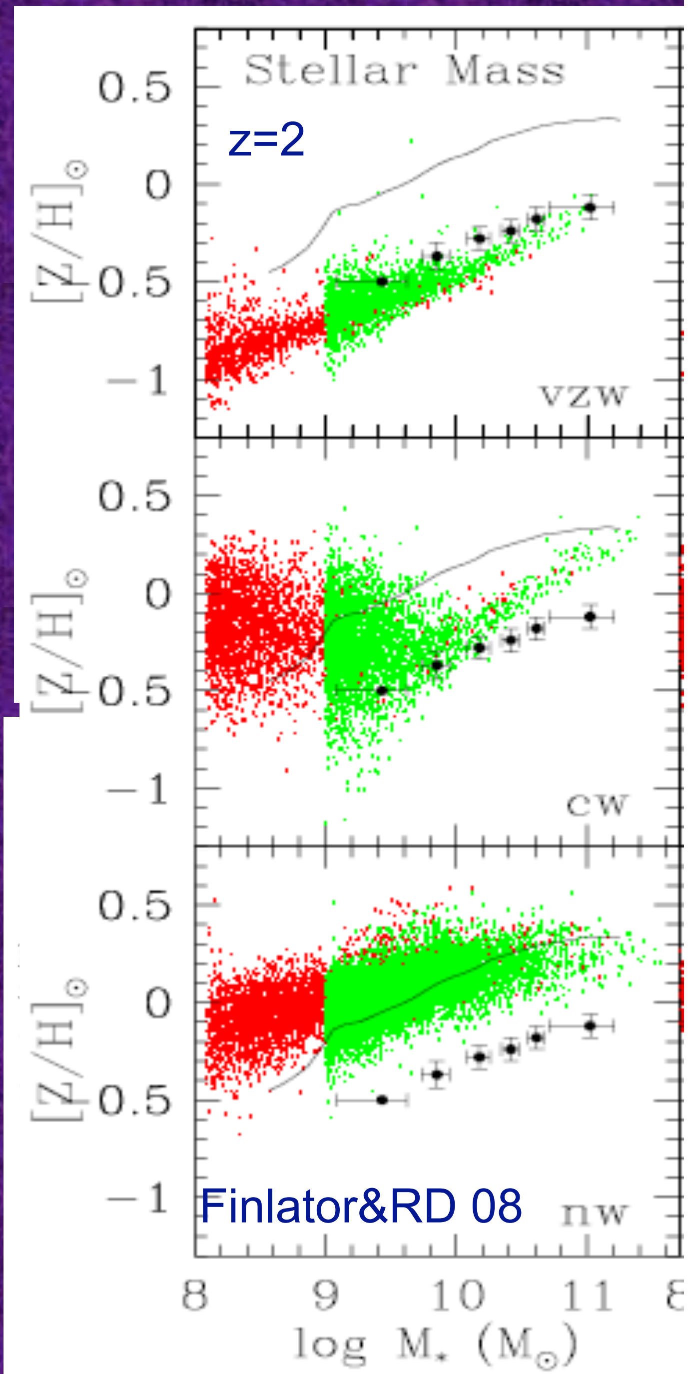
Mass-Metallicity Relation

- Conventional thinking:
  - Z_{gas} reflects stage of processing
  - Galaxies lose metals based on F.
- NO! Why? Outflows are greedy & destructive:
  - They don't share their energy -- they blow holes!

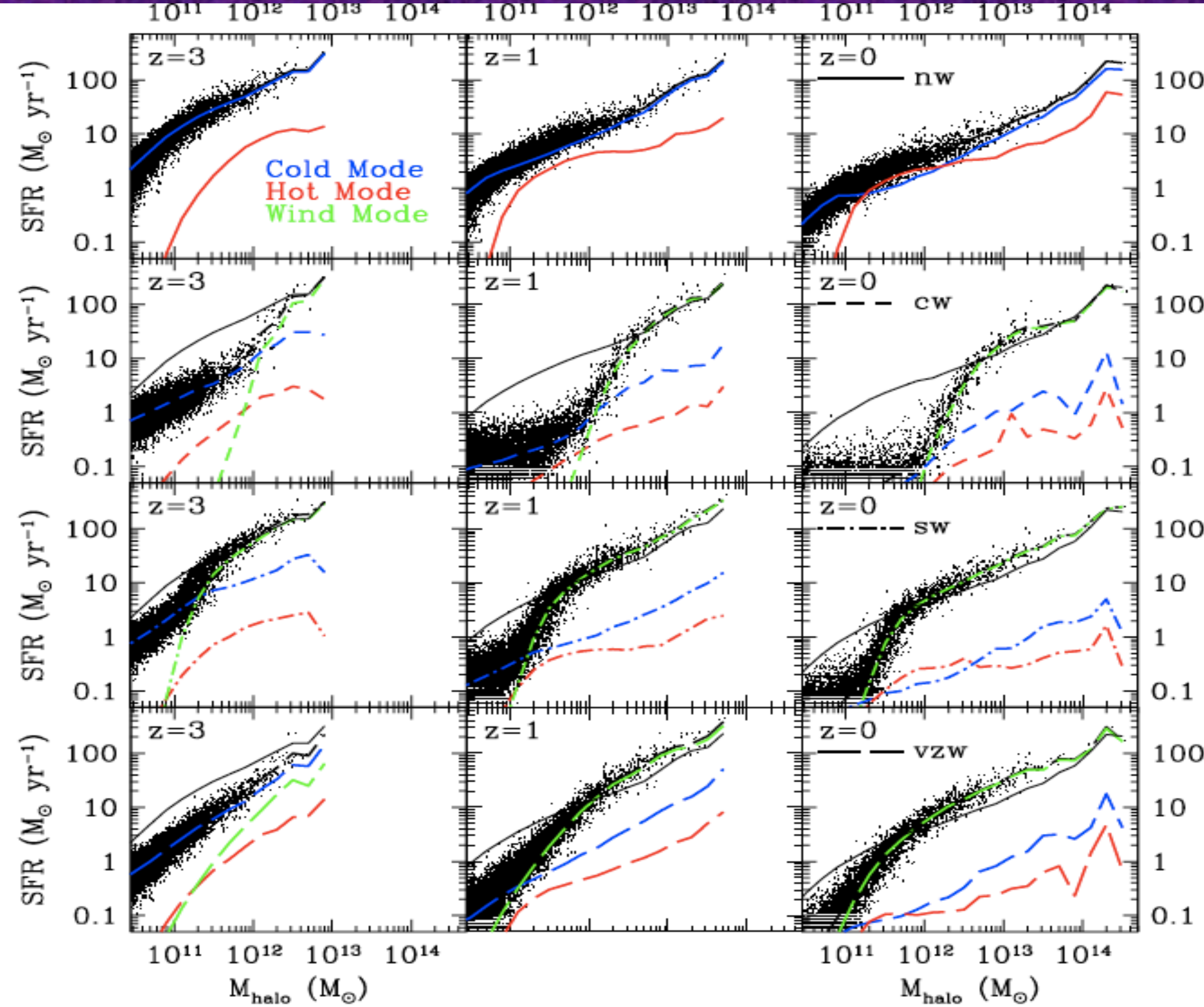
Analytic



3D simulation

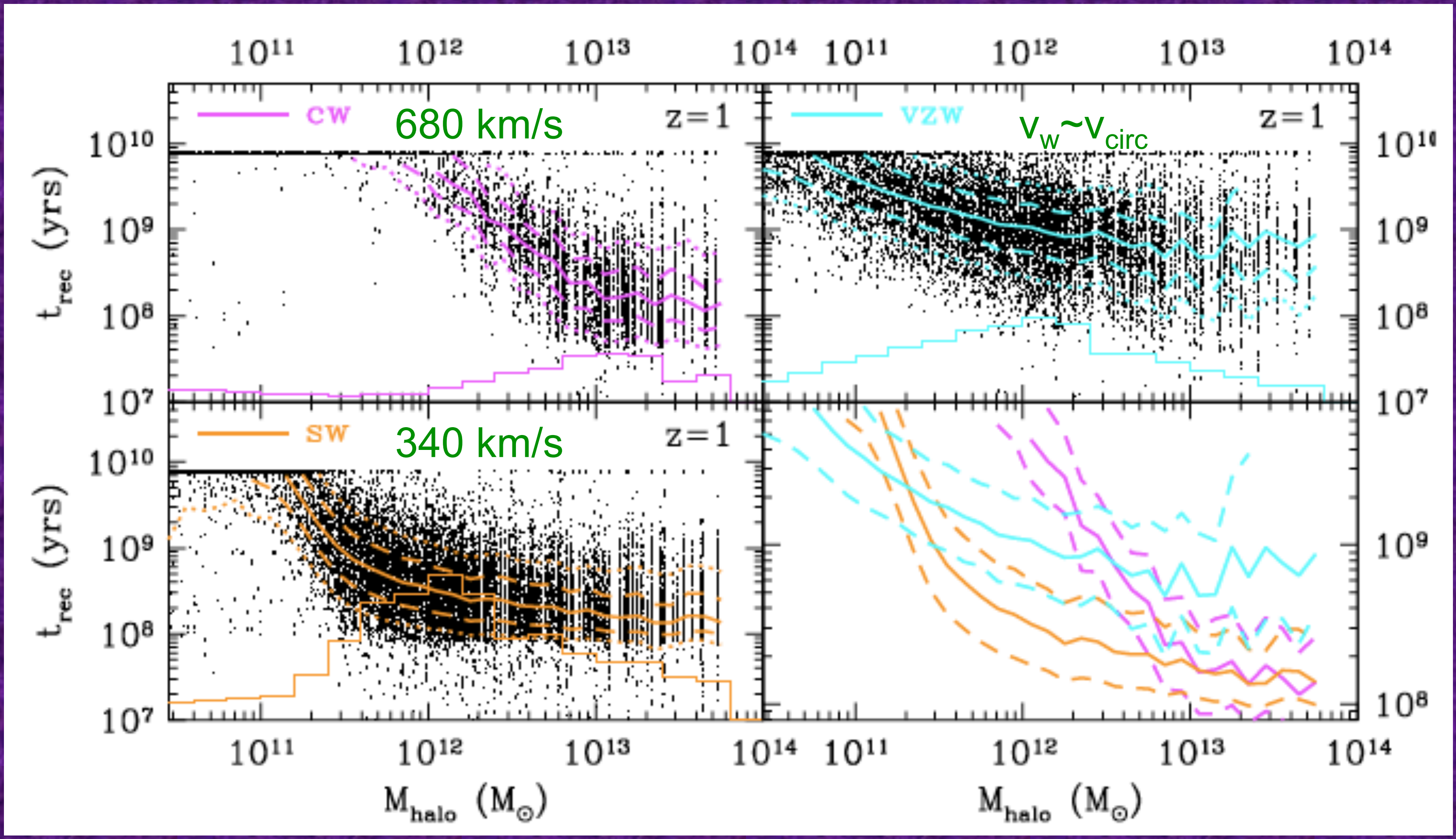


"Wind mode" accretion



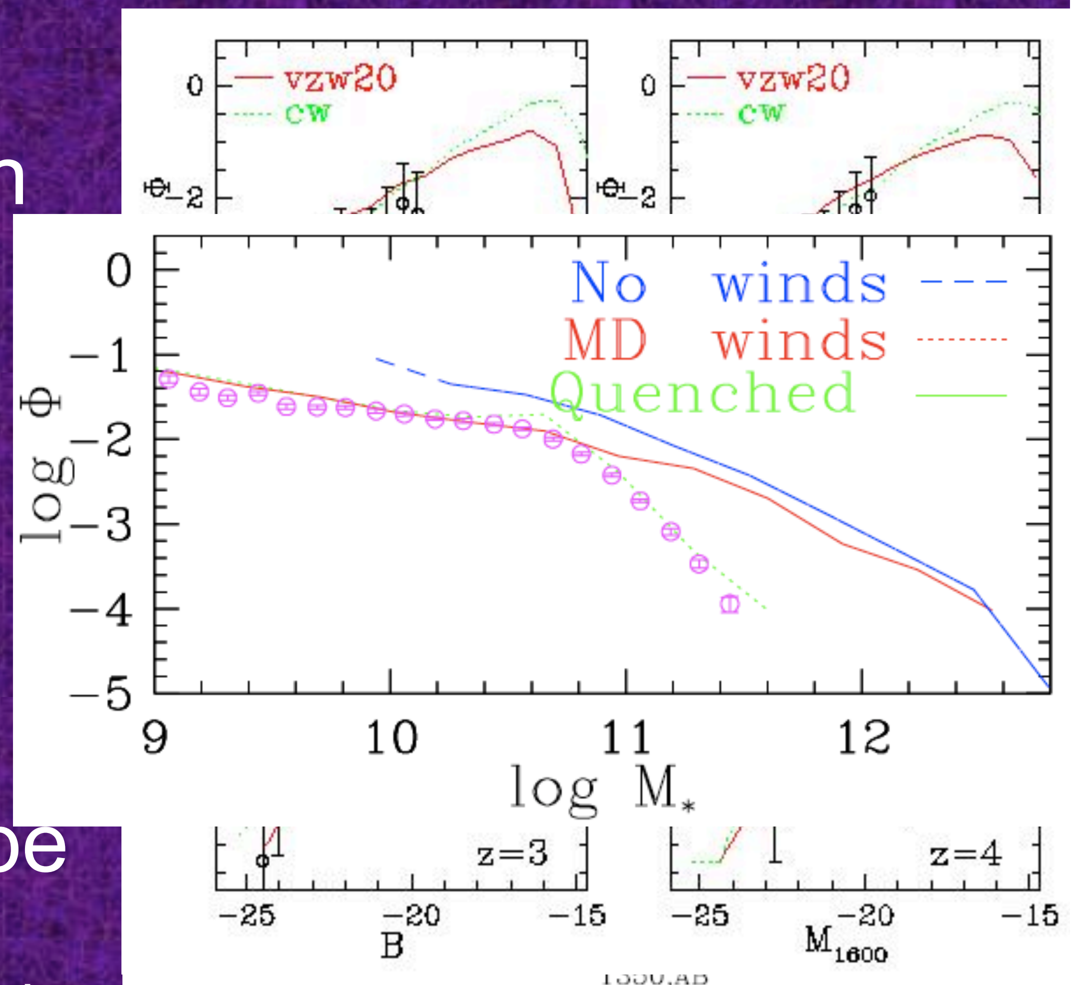
Differential Recycling

- $t_{recycling}$ goes inversely with mass



Luminosity functions

- $z\sim6$: Large SF suppression.
- Rapid consumption ➔ must *eject* gas.
- $\dot{M}_{acc} = \dot{M}_{*}+\dot{M}_{outflow}$ ➔ $SFR \propto (1+h)^{-1}$
- $z\sim2$-4:
  - Const h ➔ a~2+
  - $h \sim v_c^{-1}$ ➔ a~1.7
- $z=0$: Faint end slope a~1.3; less steep!
- (bright end?…fugly)

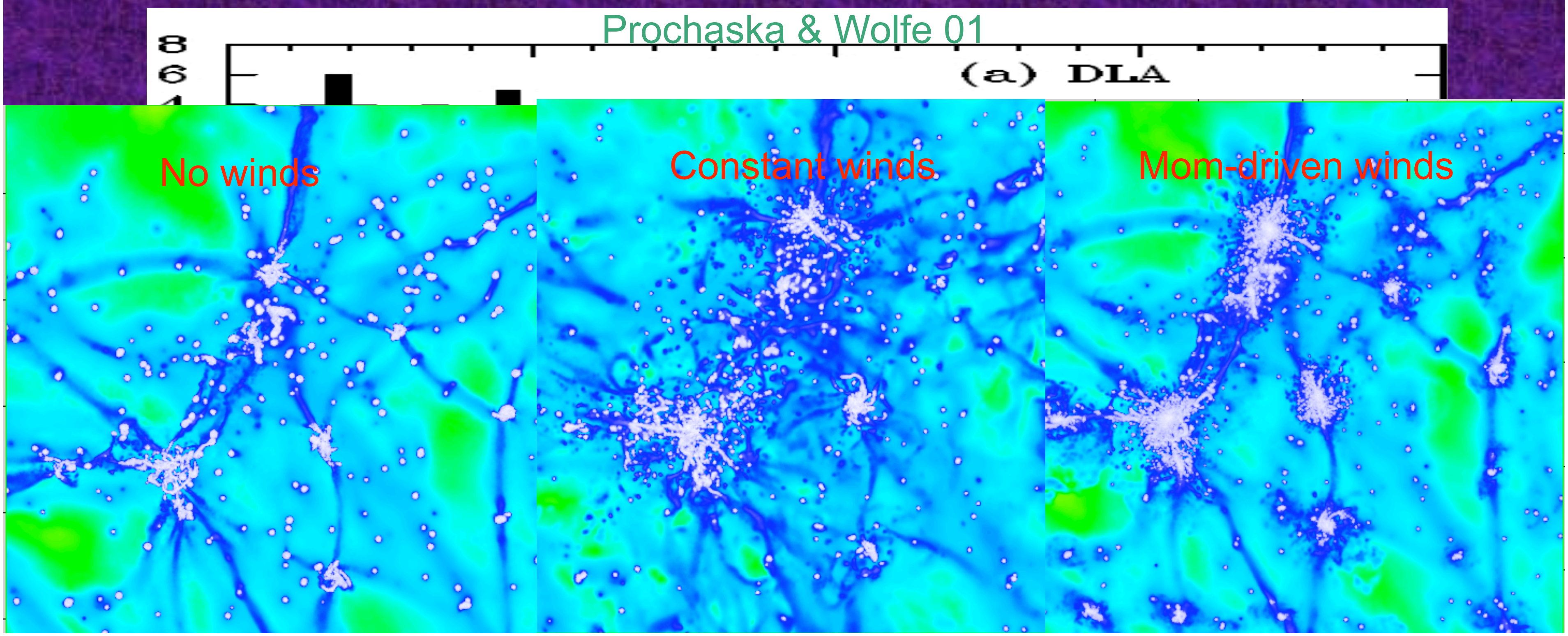


RD, Finlator, Oppenheimer 06

DLA Kinematics: Outflows?

- Wide separation ($\Delta v > v_{rot}$) DLAs hard to produce; protogalactic clump infall fails (eg Pontzen etal).
- Momentum-drive winds puff out gas, produces wide-separation systems.

S. Hong, Katz, RD etal, in prep



Feedback Tomography

- Background sources observe outflows in action.
- Tough now, but will become routine at z~2+ in 30m era.
- COS enables at z<1
- Also possible in emission around galaxies.
- The next frontier of observational galaxy formation!