Galaxy Formation: Ins and Outs

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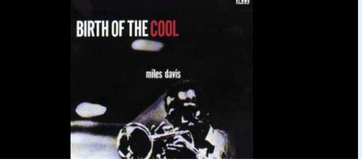
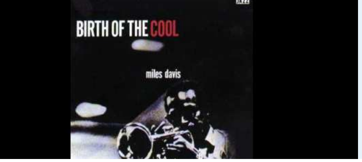


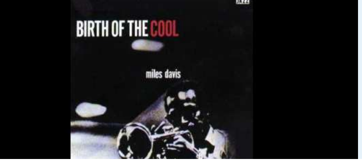
There are two types of feedback in this world . . .

- Bouncer Feedback: gas comes in but gets thrown out
  - Supernova winds
  - AGN: quasar mode?



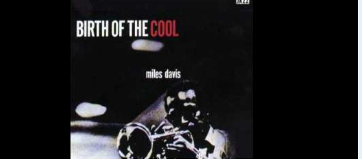
There are two types of feedback in this world . . .

- Bouncer Feedback: gas comes in but gets thrown out
  - Supernova winds
  - AGN: quasar mode?
- Velvet Rope Feedback: the gas never makes it in
  - AGN: radio mode
  - Preheating



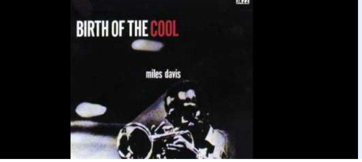
Halo gas vs. feedback type

- "Bouncer" Feedback should mostly affect low mass halos.
    - At low z these are all the cold mode halos.
    - Only energetics determine whether or not winds escape cold mode halos.
    - Quasi-spherical hot halo makes winds hard to escape.

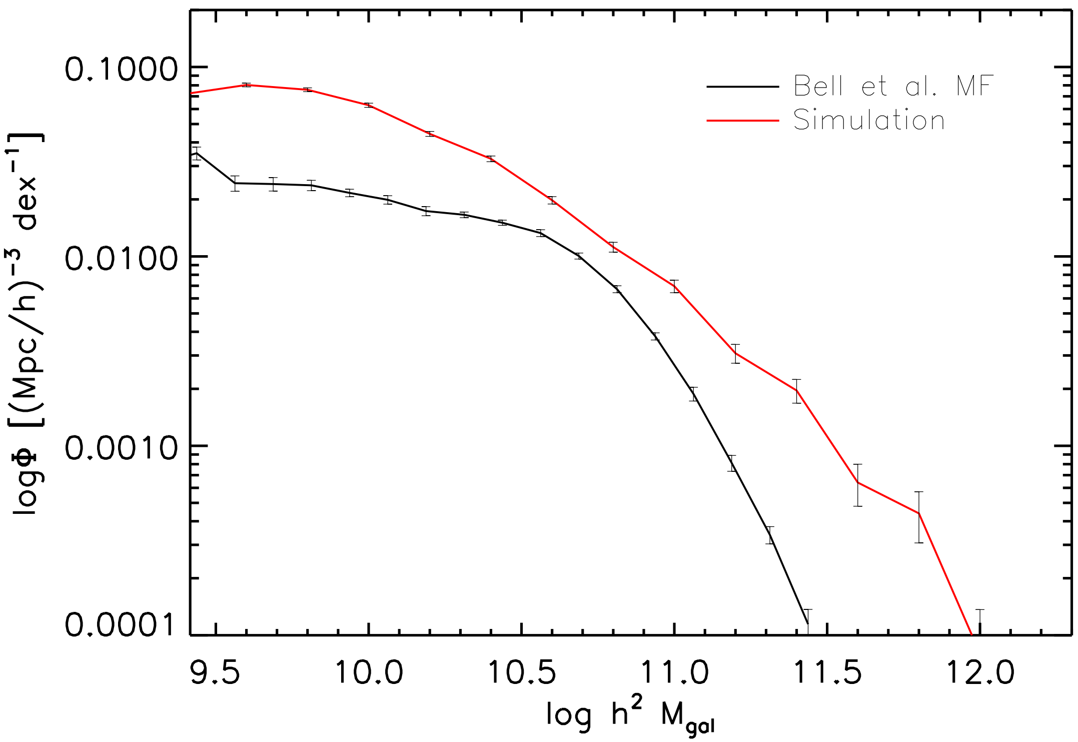


Halo gas vs. feedback type

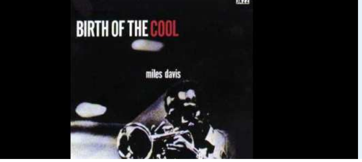
- "Bouncer" Feedback should mostly affect low mass halos.
  - At low z these are all the cold mode halos.
  - Only energetics determine whether or not winds escape cold mode halos.
  - Quasi-spherical hot halo makes winds hard to escape.
- At low z "Velvet Rope" Feedback should mostly affect hot mode galaxies.
  - Easier to prevent quasi-spherical gas from cooling.
- At high z, "Velvet Rope" Feedback will not operate efficiently.
  - Hard to prevent cold mode from entering except perhaps by preheating.



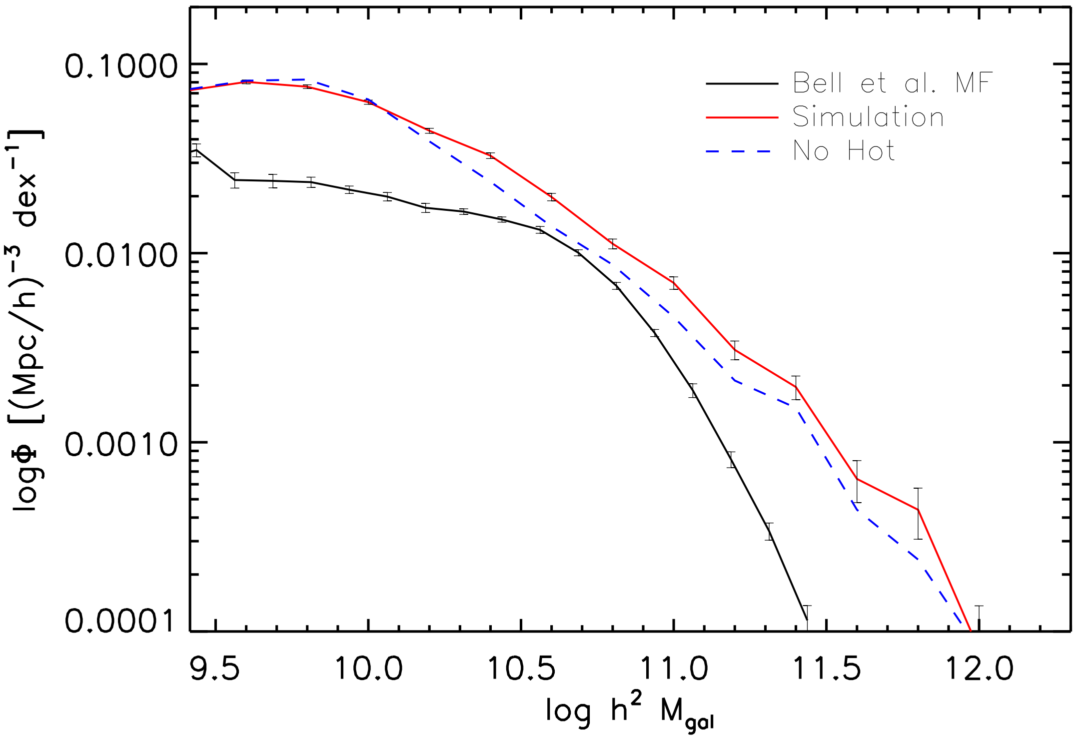
Stellar Mass Function



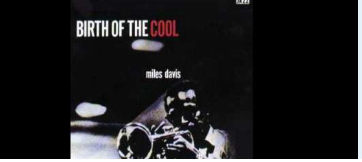
- Terrible match at all masses!
- Need to lower masses at both the high and low mass ends.
- Typically: SN winds for low mass end and AGN radio mode for high mass end.



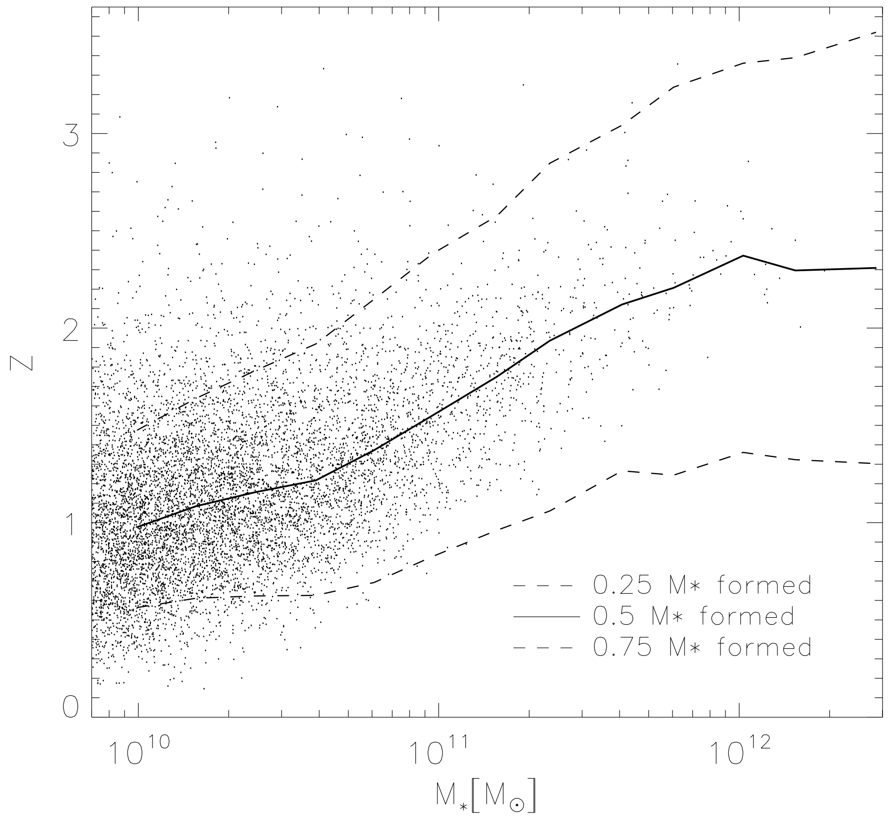
Stellar Mass Function: No hot mode



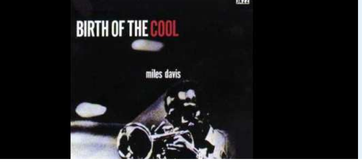
- Remove hot mode accretion to approximate maximum AGN feedback.
- Lowers mass function at the high end but not enough.
- High mass galaxies grow through merging, not through accretion.
- Need to remove or prevent cold mode accretion.

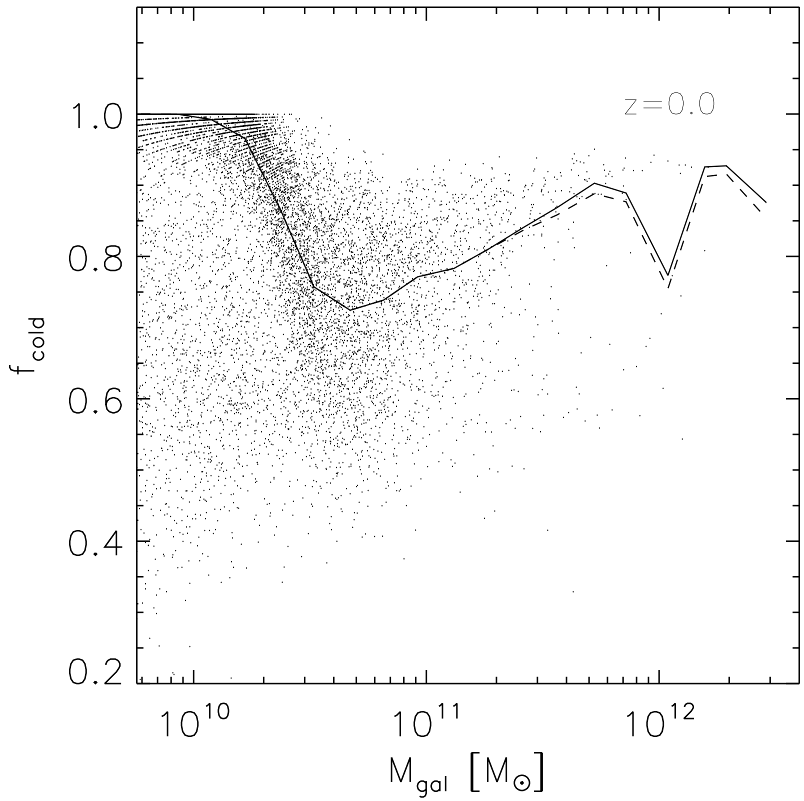


We can downsize too!

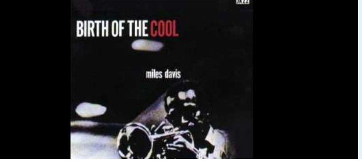


- Massive galaxies form most of their stars at high redshift.
- Need to remove or prevent cold mode accretion to match massive end.
- Cold mode removal should probably happen more at high *z* and not too much at low *z* to fix high mass end.

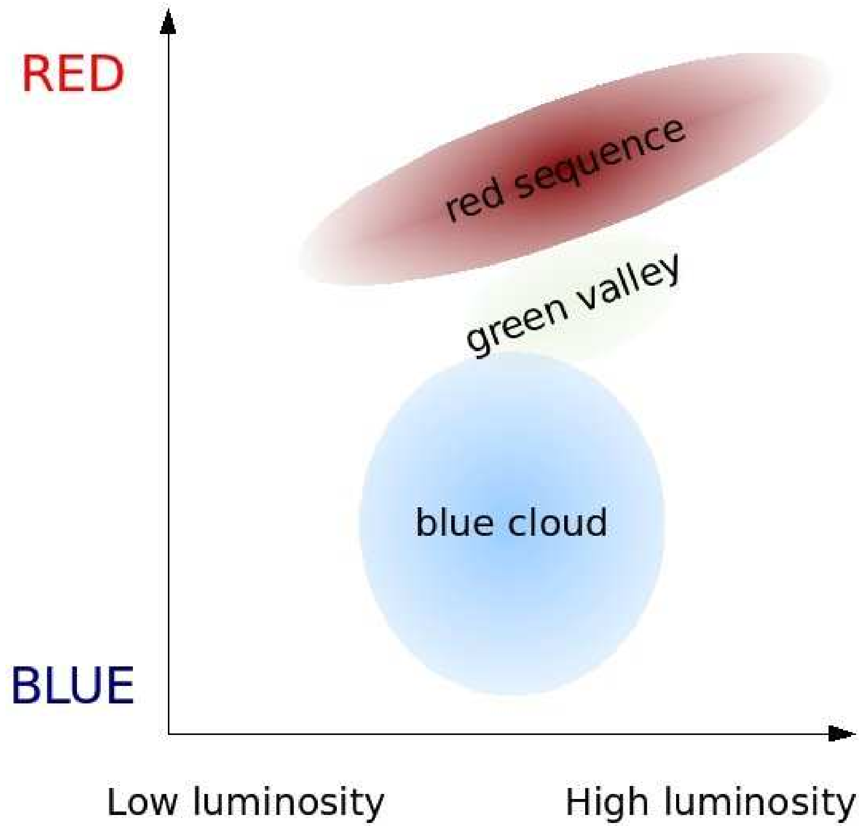




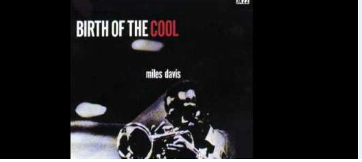
- Cold mode dominates hot mode by a large factor at all redshifts.
- This explains why removing hot mode did not have a large effect.



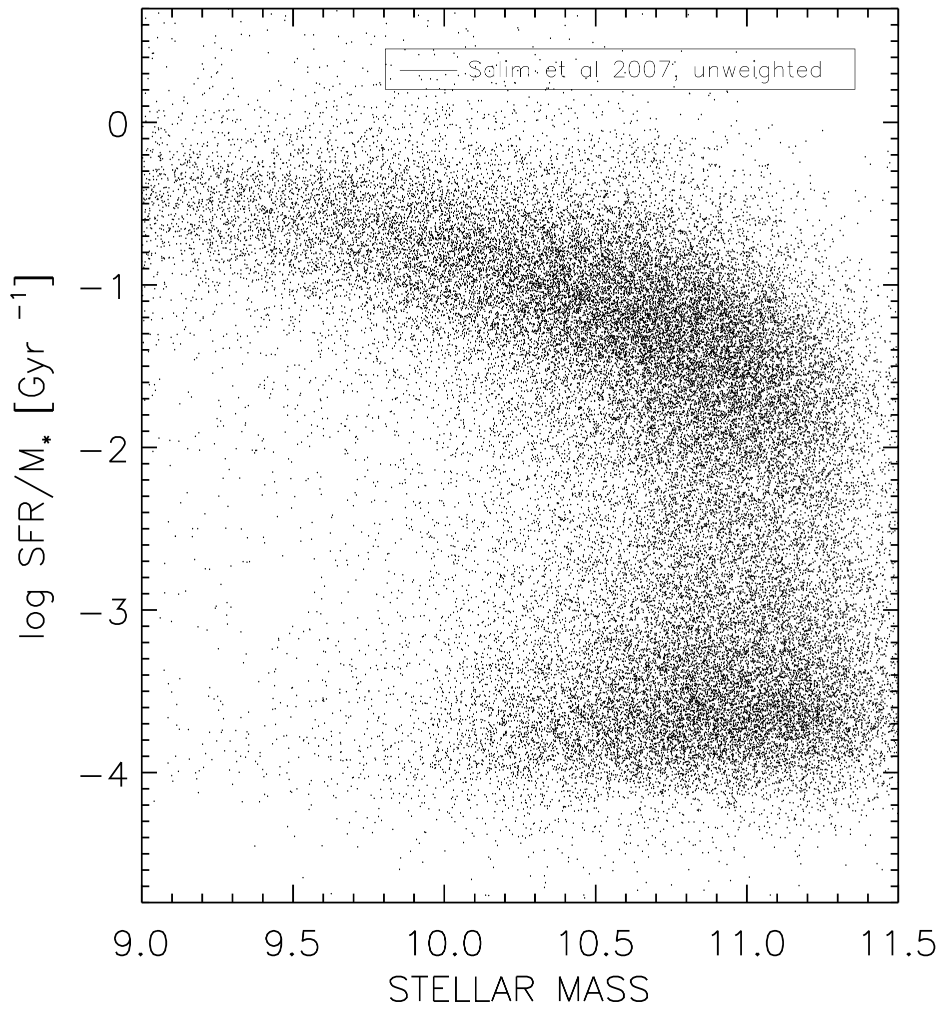
There are two types of galaxies in this world ...



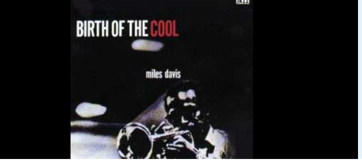
- Observed color-magnitude diagram of galaxies is bimodal.
- Almost all galaxies either in the red sequence or the blue cloud.



Theorist's color-magnitude diagram



- Observed from Salim et al, not volume corrected.



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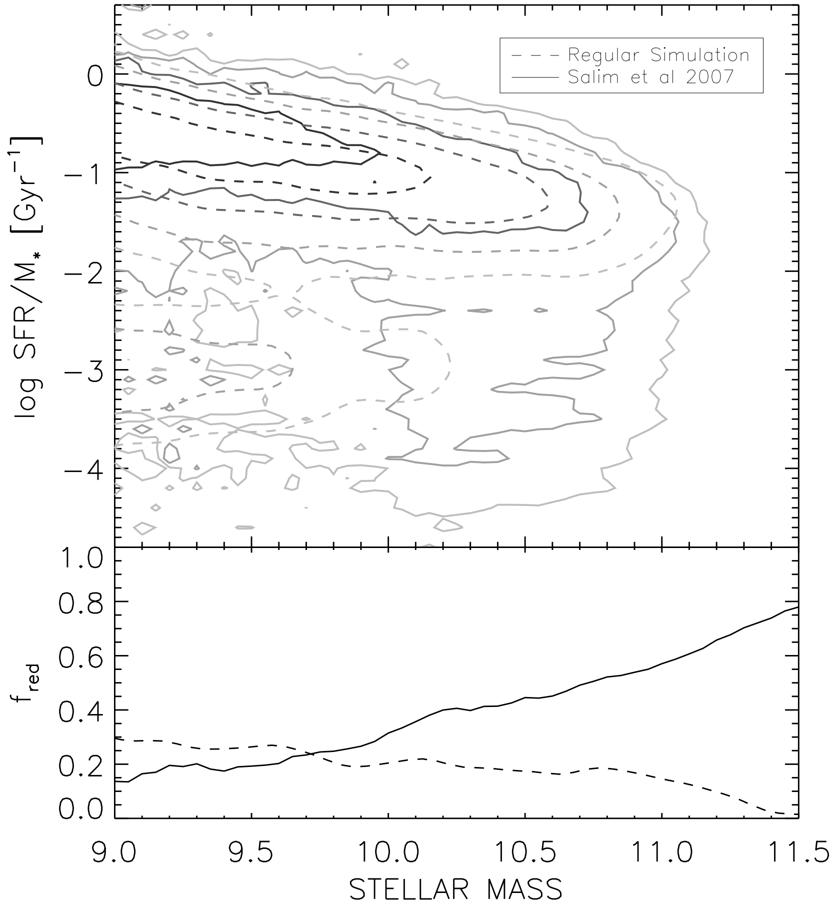
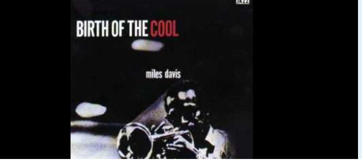
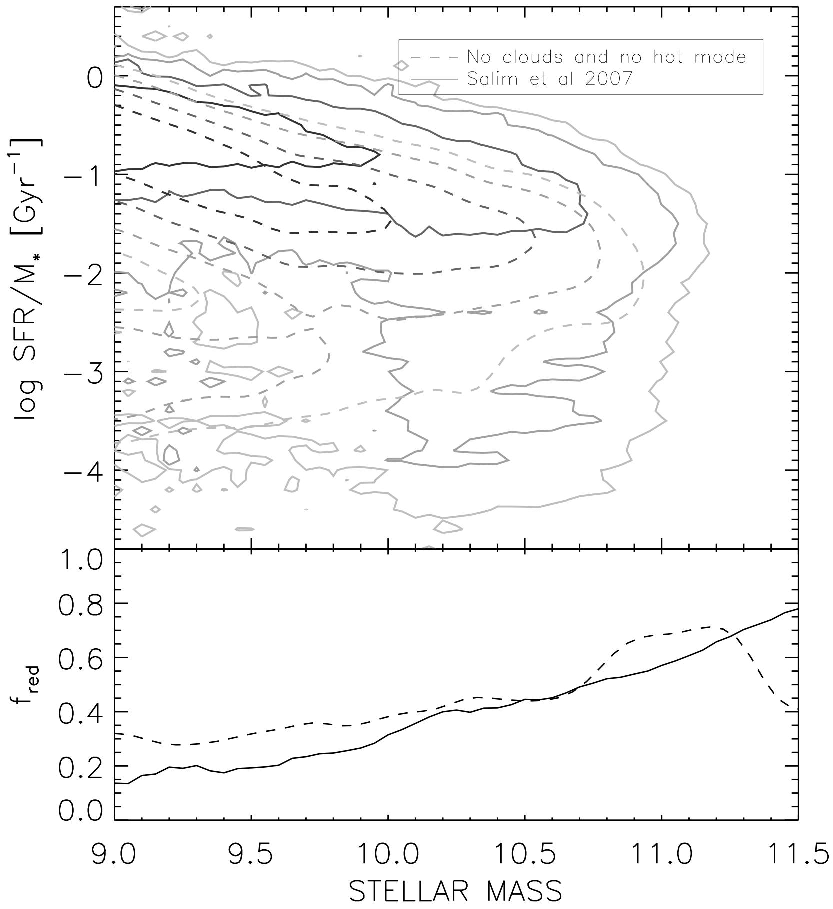


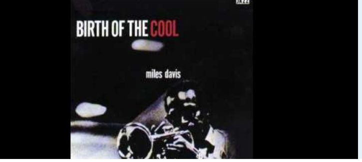
- Observations are not bimodal.
- Rescaled simulated galaxy masses to match observations.
- Simulation does not have enough high mass red galaxies.



Theorist's color-magnitude diagram: No hot

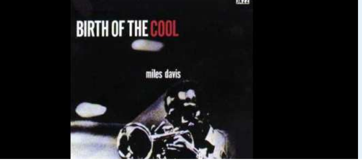


- Remove hot mode accretion: ∼maximum AGN feedback.
- Makes large galaxies redder but simulation is still not red enough.
- Red enough at all but the highest masses.

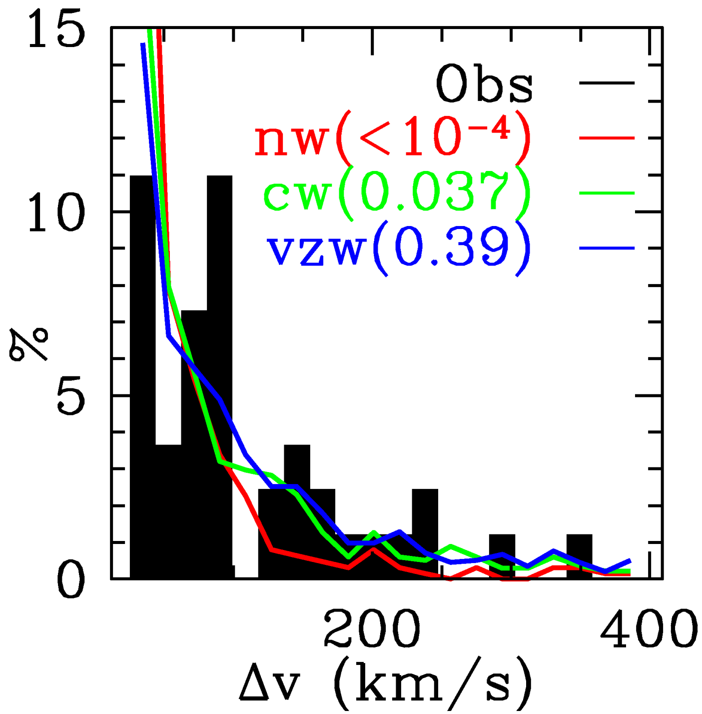


A cold wind blows some good

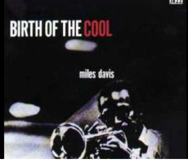
- Wind mass flux $\dot{m}_{wind} = \eta \dot{m}_\star$.
- Launch wind particle in direction $\vec{v} \times \vec{a}$.
- Temporarily turn off hydro forces at launch.
- Use momentum driven wind scalings.
  - $v_{wind} \approx 3\sigma$
  - $\eta = 150 \text{ kms}^{-1}/\sigma$
  - Successfully matches IGM metal observations at high and low z.
  - Reproduces the galaxy mass-metallicity relation.
  - Better matches the detailed low ion kinematics of damped Lyman alpha systems.



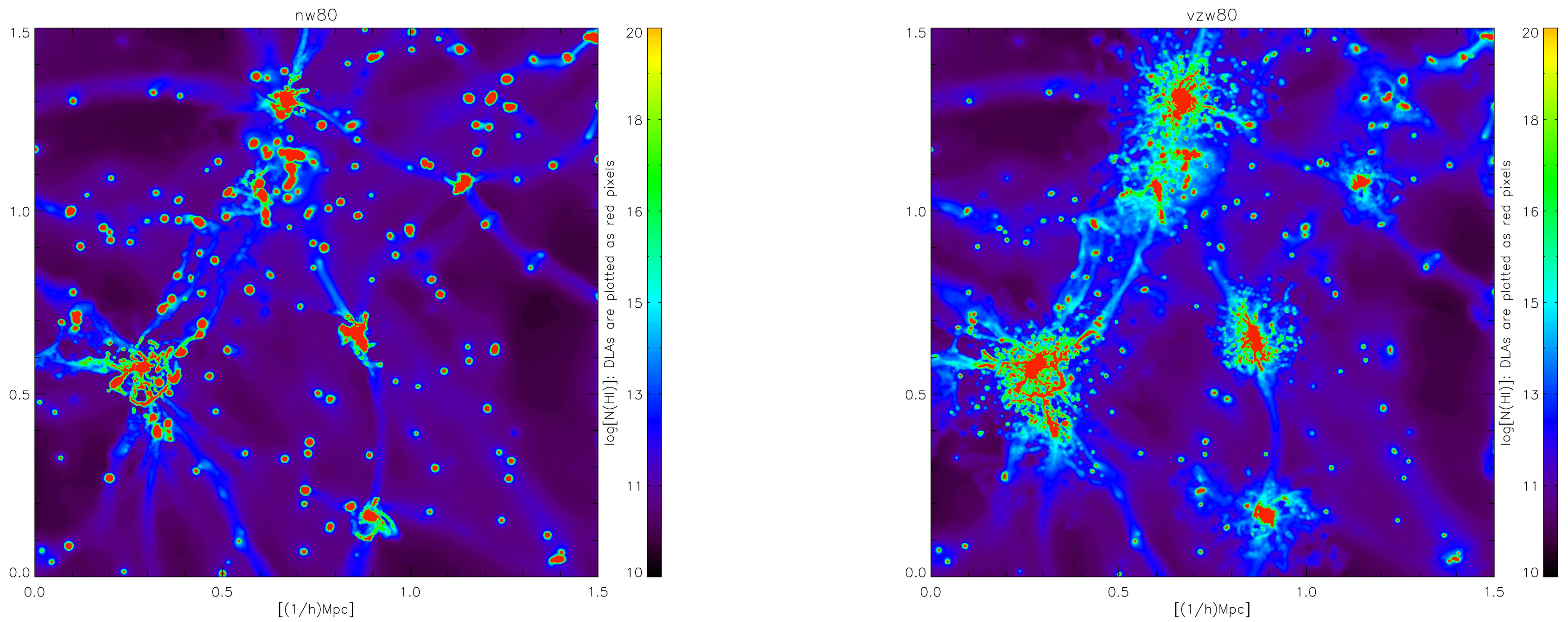
Damped Lyman alpha kinematics



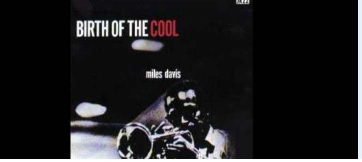
- Measure line widths of damped absorption systems using low ionization metal lines.
- Without winds too many small systems; too few large systems.
- Adding constant winds helps match observations.
- Momentum driven wind scalings do even better.



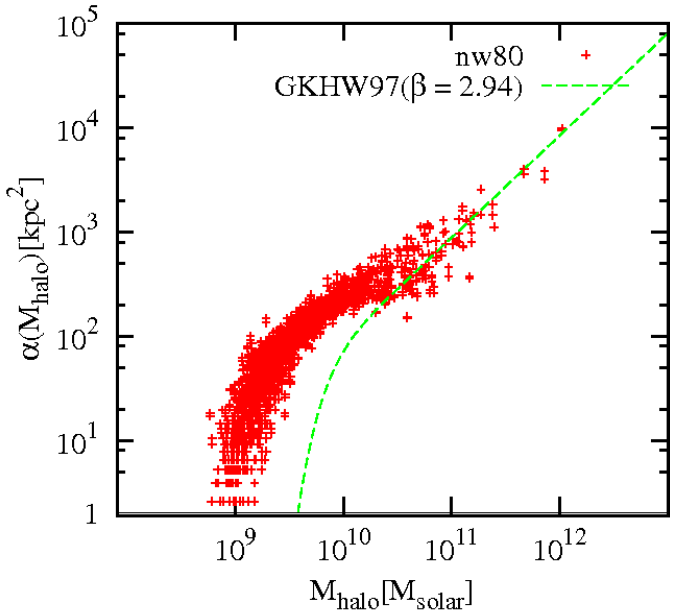
A picture’s worth a thousand words

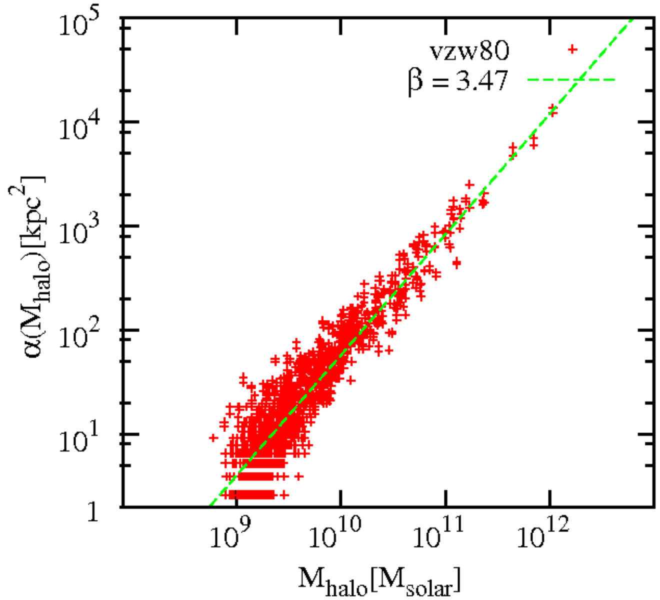


- Adding winds removes small damped systems.
- Adding winds increases the damped cross section of larger systems.

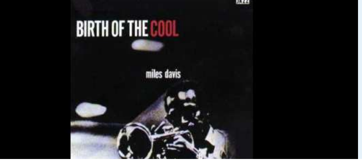


Damped Lyman alpha cross sections

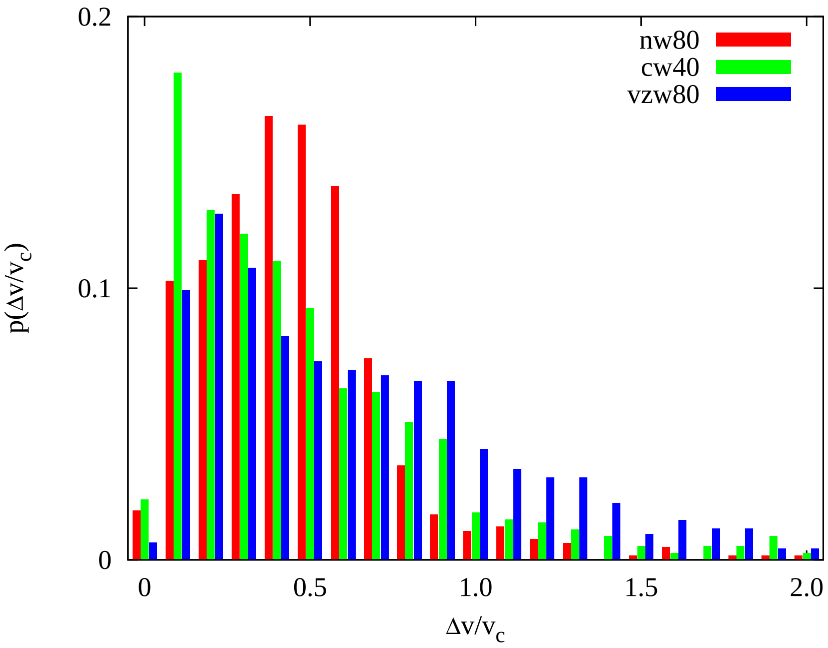




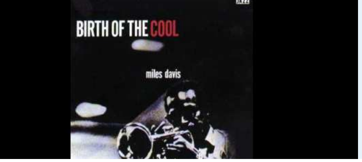
- Winds remove material from small galaxies.
- With winds the cross section to damped absorption remains a power law with halo mass down to small masses.
- Constant winds are not as efficient at removing material from small galaxies; have intermediate properties.



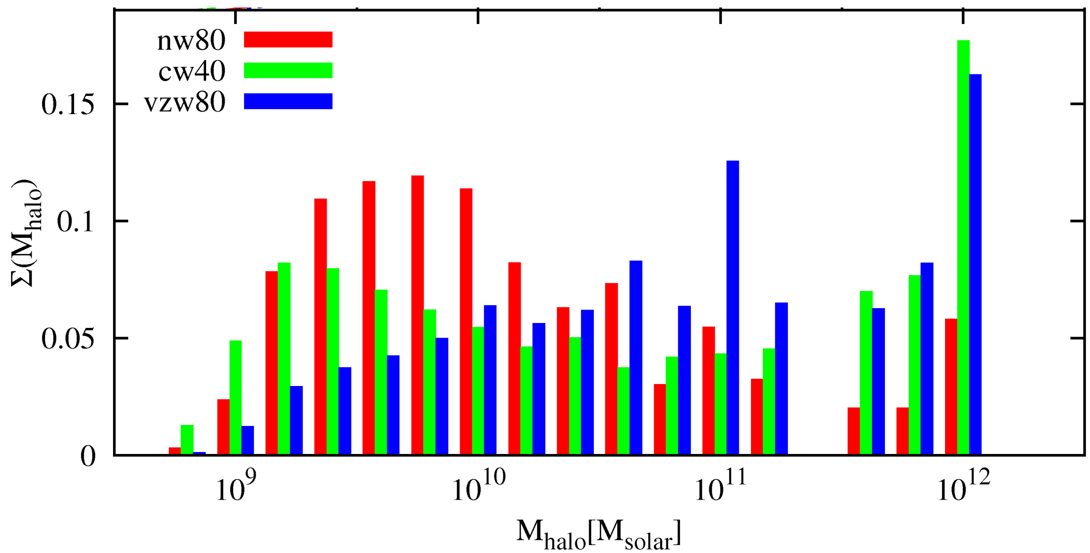
These winds really blow



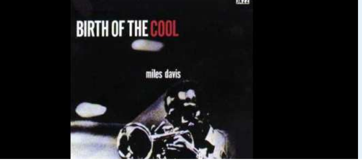
- Without winds line widths can rarely be larger than v_{circ}; mergers.
- Constant winds can marginally increase the incidence.
- Momentum driven wind scalings greatly increase the incidence because the winds themselves have a substantial damped cross section.



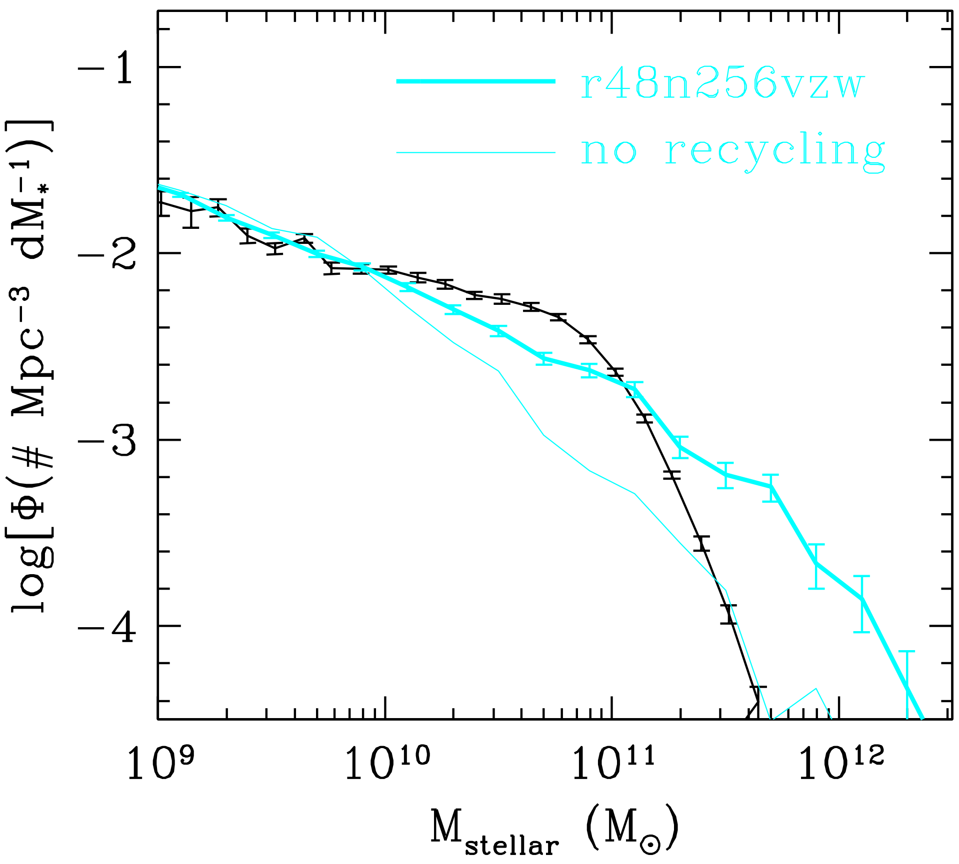
Damped Lyman alpha kinematics



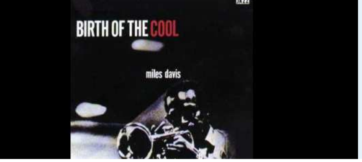
- Winds with momentum driven scalings can match the data because:
  - They are more efficient at removing mass from small halos owing to the σ^{-1} mass loading.
  - The winds have lower velocities so are cool enough to have a significant HI content and hence their velocities can add to the measured line widths for intermediate mass halos.
  - They boost the damped cross section for larger halos.



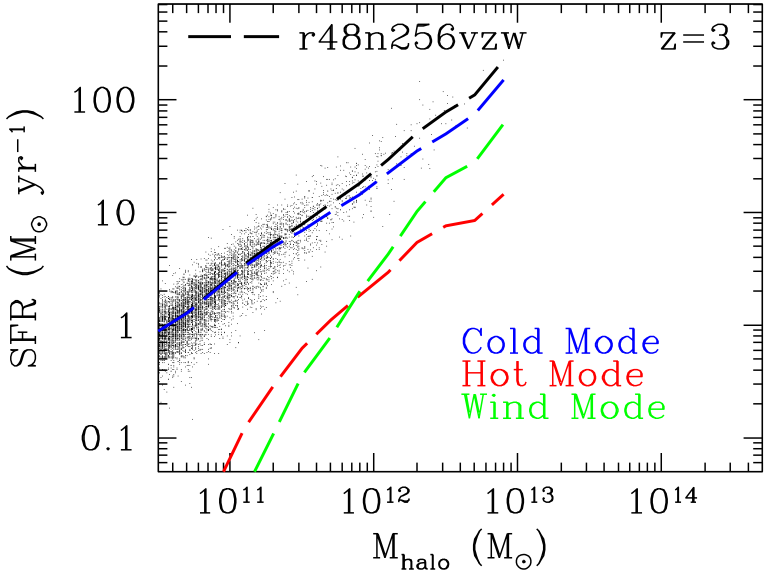
I’ll huff and I’ll puff and I’ll blow your gas out

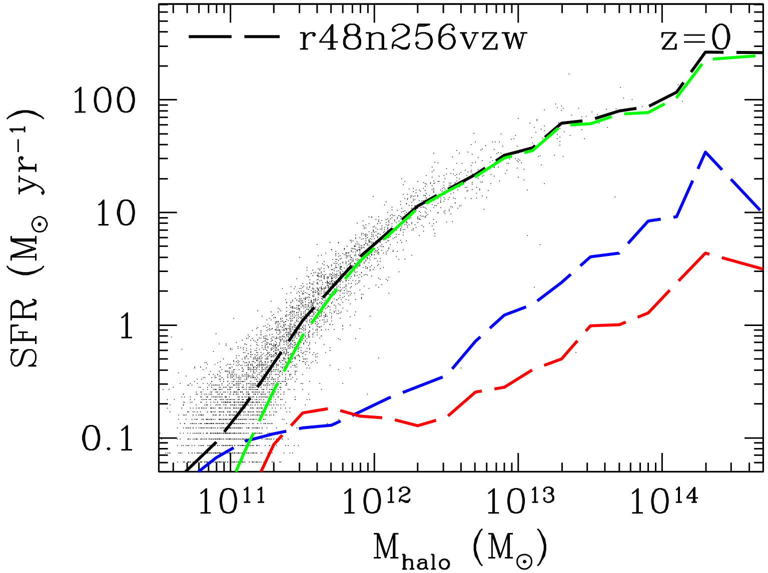


- Winds lower masses at low mass end as desired.
- At high mass end wind recycling negates help from winds.

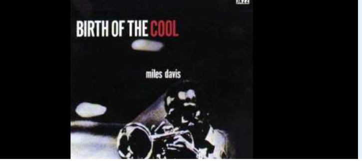


What goes up must come down

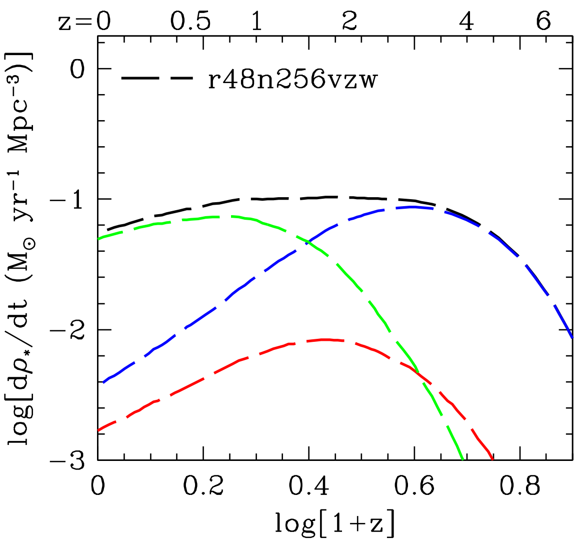


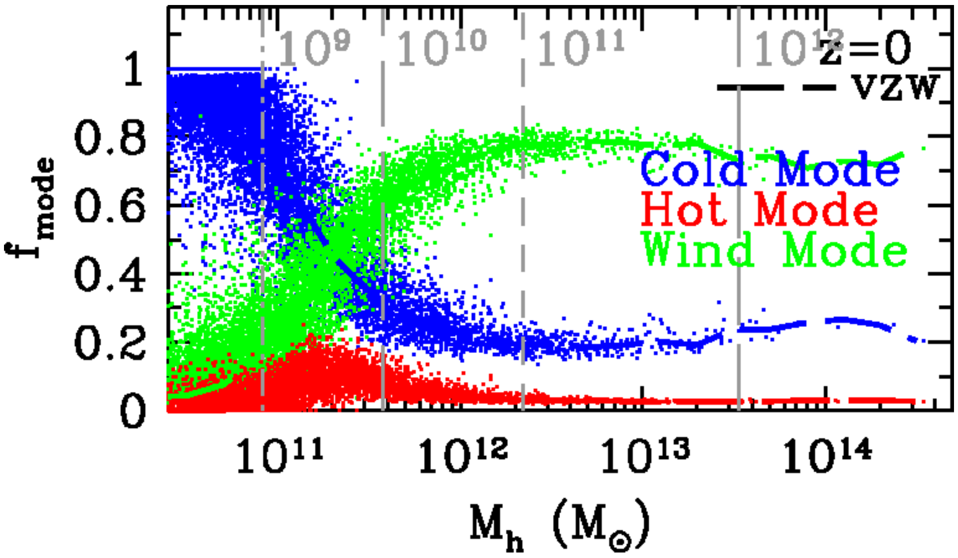


- At high *z*: cold mode accretion dominates star formation.
- At low *z*: reaccreted wind material dominates star formation at all but lowest masses.

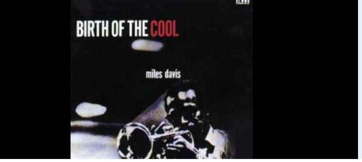


What is old is new again

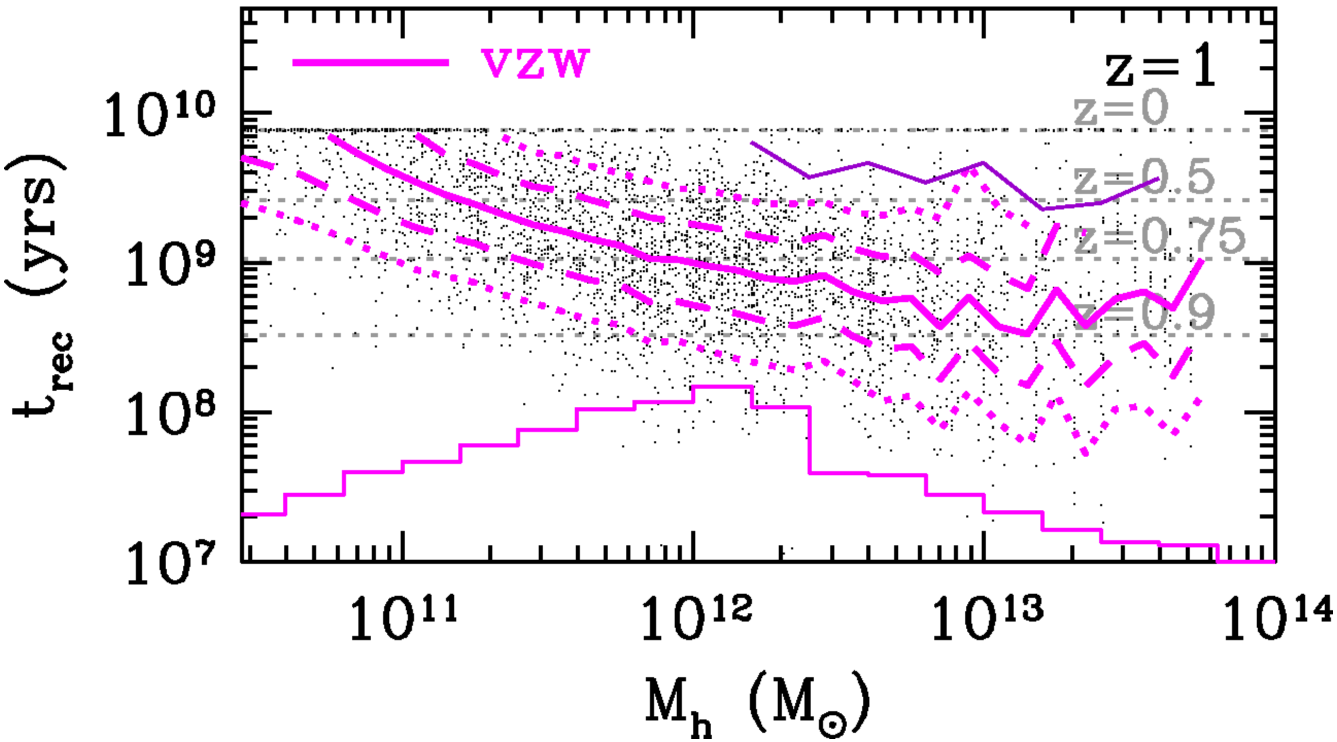




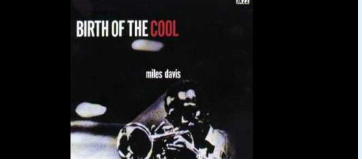
- Globally, reaccreted winds dominate star formation at $z < 1.5$
- Very important for massive galaxies, $M_{\rm stellar} > 10^{10.5} {\rm M}_\odot$



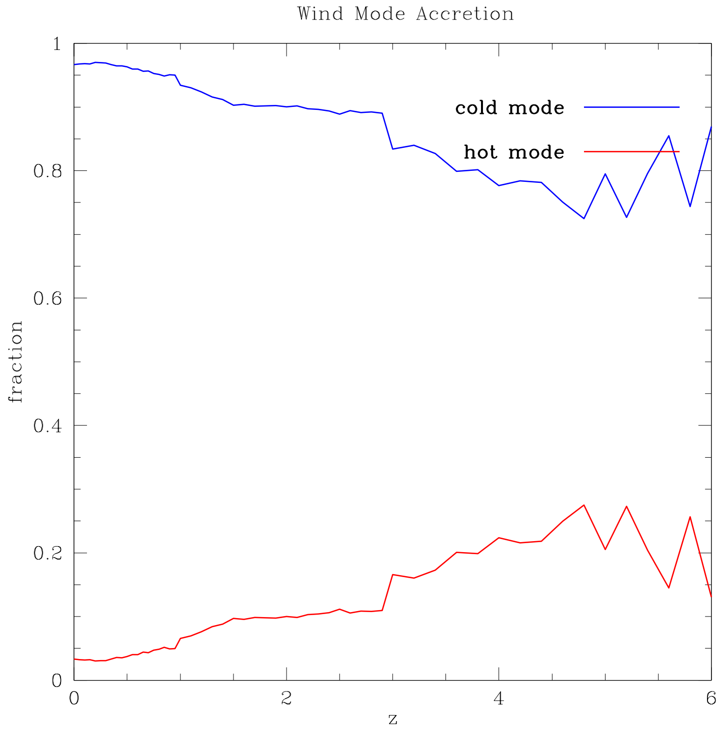
I'll be back



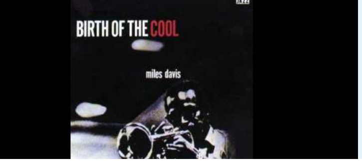
- 83% of wind particles are reaccreted.
- A typical wind particle recycles 3 times.
- Recycle times are shorter in more massive halos.
- Winds interact with hot halo gas.



A cold rain is going to fall

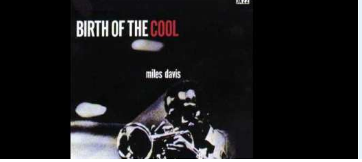


- In simulations, most reaccreted wind material stays cold.
- Need a feedback process to stop this reaccretion.
- Standard AGN feedback is unlikely to work.
- Are the numerics correct?



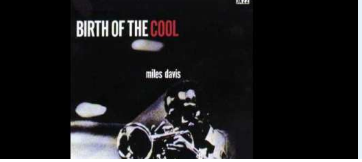
Nobody’s perfect

- SPH designed to represent fluid elements represented by 32 or more particles; wind particles are very different than their surroundings.
- SPH has known difficulties treating two-phase media; suppresses Kelvin-Helmholtz instabilities.
- The ram pressure on under resolved clumps can be underestimated, e.g. cold drizzle.
- The metallicity of the wind particles is high and cannot mix; could cause too much cooling.



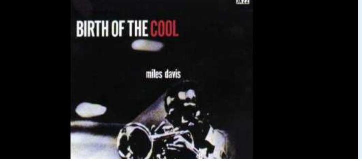
Phenomenologically Obtained Winds (POW)

- Do not have the resolution to correctly model superwinds leaving galaxies so we develop a phenomenological model.
- Want the model to be limited by our physical assumptions and not numerics.
- Want a method that must be as independent of resolution as possible.
- Want to try to limit the number of parameters.
- Want it to globally conserve mass, momentum, and energy.



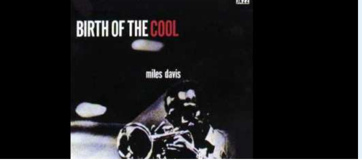
Simulations, soon with POW

- Assume each wind particle made of many spherical clouds with mass M_c, temperature T_c, uniform density, ρ_c, and radius R_c.
- Assume clouds in pressure equilibrium with ambient medium, with temperature T_a and density of ρ_a, and the ram pressure.
- Wind particles launched as before.
- Evolved analytically using microphysics.
- Do not become ordinary SPH gas particles until they are similar to their surroundings.



POW: its physics

- Cloud motion affected by:
  - gravity,
  - ram pressure.
- Cloud temperature affected by:
  - radiative heating and cooling,
  - adiabatic heating and cooling,
  - ram pressure heating,
  - conduction.
- Cloud mixes thermal energy and metals with surroundings owing to:
  - Kelvin-Helmholtz instabilities,
  - Conductive evaporation.



Conclusions

- AGN feedback alone is unlikely to solve the massive galaxy problem.
- Adding AGN feedback makes massive galaxies red but not red enough especially at the high mass end.
- Need a process to reduce cold mode accretion whenever it occurs, particularly at high redshift in addition to AGN feedback.
- Reaccreting wind material dominates star formation at $z < 1.5$ so need a process to stop it.
- Low mass end probably needs an additional process: preheating?
- Damped Lyman Alpha kinematics are better fit when momentum driven wind scalings are used.
- Need a more robust way to include winds in cosmological hydrodynamic simulations.
- Much work remains to be done.