Galaxy Formation (Lecture II)

Gas cooling and AGN feedback

Outline

- Exploring feedback
  - Developing a feeling for how feedback affects the mass function
- Gas cooling
  - How and why?
  - Characteristic scales
  - Why its not so important!!
- AGN feedback
  - Why its needed…
  - Quasars vs Radio Galaxies
  - Connection to the X-ray universe
- Comparison to observations
  - Which observations are most important?
  - How do the models perform?

Part V

Cooling and thermal instability

Gas Cooling Processes

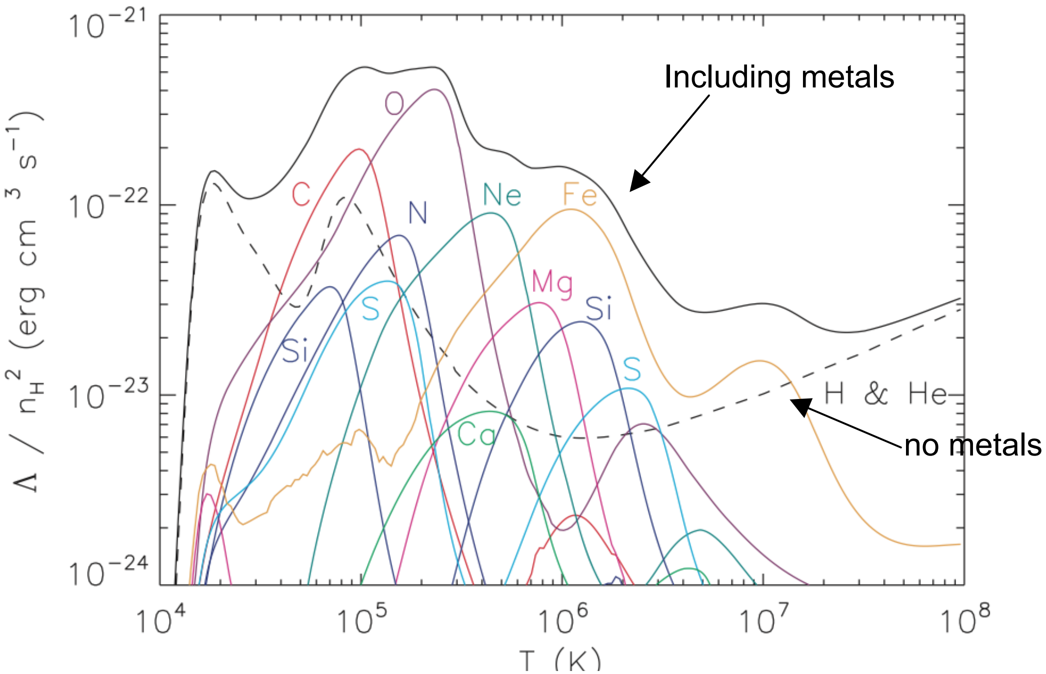
- Thermal bremstrahlung
  - Scattering of a free electron by a nucleus
  - Dominates cooling in high-mass haloes
- Recombination
  - Electron is captured by a nucleus
  - Electron makes a transition between shells
  - Very important at 10^4 - 10^7 K
  - Metal enrichment of the universe has a big effect!
- Inverse Compton effect
  - Scattering microwave background to higher energies
  - Only important at high redshifts
- Below 10^4
  - most gas is atomic
  - cooling is strongly suppressed

The cooling function

Collissional process

$$\epsilon = n_H^2 \Lambda(T, Z)$$

Accounts for temperature and metall dependent effects



$$\Lambda \approx 3 \times 10^{-23} (T_8^{1/2} + 0.5 f_m T_8^{-1/2}) \, \mathrm{erg\,cm^3\,s^{-1}}$$

Peacock et al 2009; Wiersma et al., 2009

Some cooling basics

$$t_{\rm cool} \equiv \frac{\frac{3}{2} n\, k_B T}{n_H^2 \Lambda}$$

$$T \approx 1.6 \times 10^7 \left(\frac{M_v}{10^{14}\, M_\odot} \right)^{2/3} \mathrm{K}$$

$n = \frac{\rho_g}{0.59 m_p}$ and $n_H = \frac{\rho_g}{1.33 m_p}$

$$t_{\rm cool} \sim 16 \left(\frac{\rho_g}{(10^{14}\, M_\odot\, \mathrm{Mpc}^{-3})} \right)^{-1} \left(T_8^{-1/2} + 0.5 f_m T_8^{-3/2} \right)^{-1} \mathrm{Gyr.}$$

For comparison $\rho_{\rm crit,0} = \frac{3H_0^2}{8\pi G} \approx 1.0 \times 10^{-26}\ \mathrm{kg\,m^{-3}}$
$\approx 1.5 \times 10^{11}\, \mathrm{M_\odot\, Mpc^{-3}}$

Implication: Present-day massive haloes can only cool a fraction of their virialised gas content.

More cooling basics…

Compare cooling time to orbital time…

$$t_{\rm cool} \sim 16 \left(\frac{\rho_g}{(10^{14}\, M_\odot\, {\rm Mpc}^{-3})} \right)^{-1} \left(T_8^{-1/2} + 0.5 f_m T_8^{-3/2} \right)^{-1} {\rm Gyr.}$$

$$t_{\rm dyn} = \frac{1}{\sqrt{G\rho_m}} \approx 2 \left(\frac{\rho_g}{10^{14}\, M_o {\rm Mpc}^{-3}} \right)^{-1/2} {\rm Gyr}$$

As the density increases, or T decreases, eventually, $t_{dyn} > t_{cool}$… such gas in these haloes cools faster than it can flow to the center of the potential - either they fragment, or the gas is never able to heat up.

A simple model (eg., White & Frenk 1991)

- Compute the radius within which the cooling time is sufficiently short:

$$t_{cool}(r_{cool}) = t_{halo}$$

- The rate of change of the cooling radius gives the rate at which mass flows to the center:

$$\dot{M}_{cool} = 4\pi . r_{cool}^{\ \ 2} . \rho(r_{cool}) \frac{dr_{cool}}{dt}$$

- Can improve by actually computing the difference in mass, and by using a merger tree to compute the age of the halo

Clearly this is dumb!

•As gas cools out, new material flows in to take its place

•As gas cools it becomes denser and cooling accelerates

•As the gas cools it is squashed, PdV work is done on it

•The halo isn't static and doesn't have a well defined age

Cold Flows (are very old news)

- So what happens if

$$r_{cool} > r_{vir}$$

- In this regime, the gas cools out and the supply of cold gas is limited by the growth of the halo, not by the cooling time
- In practice there's a transition mass in which the hydrostatic halo and the cold flow co-exist

We distinguish two different cases. When $r_{\rm cool}$ is larger than the virialized region of a halo, cooling is so rapid that infalling gas never comes to hydrostatic equilibrium. The supply of cold gas for star formation is then limited by the infall rate rather than by cooling. When $r_{\rm cool}$ lies deep within the halo, the accretion shock radiates only weakly, a quasi-static atmosphere forms, and the supply of cold gas for star formation is regulated by radiative losses near $r_{\rm cool}$.

We consider the virialized part of a halo to be the region within which the mean overdensity is 200. Its radius and mass are therefore defined by

$$\begin{aligned} r_{\rm vir} &= 0.1H_0^{-1}(1+z)^{-3/2}V_c\ , \\ M_{\rm vir} &= 0.1G^{-1}H_0^{-1}(1+z)^{-3/2}V_c^3\ . \end{aligned} \qquad (18)$$

This choice is motivated by the simple spherical collapse model discussed above (before eq. [3]). However, additional support comes from simulations of the collapse of rich clusters carried out with a hybrid *N*-body/smoothed particle hydrodynamics code (Evrard & Davis 1988; Evrard 1989). These models show the accretion shock to be close to, but perhaps a little outside, the radius given by equation (18). Thus, when $r_{\rm cool} \gg r_{\rm vir}$, we are in the accretion-limited case in which infalling gas never reaches hydrostatic equilibrium. We obtain an expression for the accretion rate by differentiating the second of equations (18) with respect to time, and multiplying by the fraction of the mass of the universe which remains in gaseous form:

$$\dot{M}_{\rm inf}(V_c, z) = 0.15 f_g \Omega_b V_c^{-3} G^{-1}\ . \qquad (19)$$

Note that, except for the weak time dependence of f_g, this infall rate does not depend on redshift.

White & Frenk, 1991

Implication…

- So the details of cooling in small haloes are unimportant since the gas cools before it becomes stable
- The details of cooling would be important at higher masses,
- But AGN feedback is important then also….

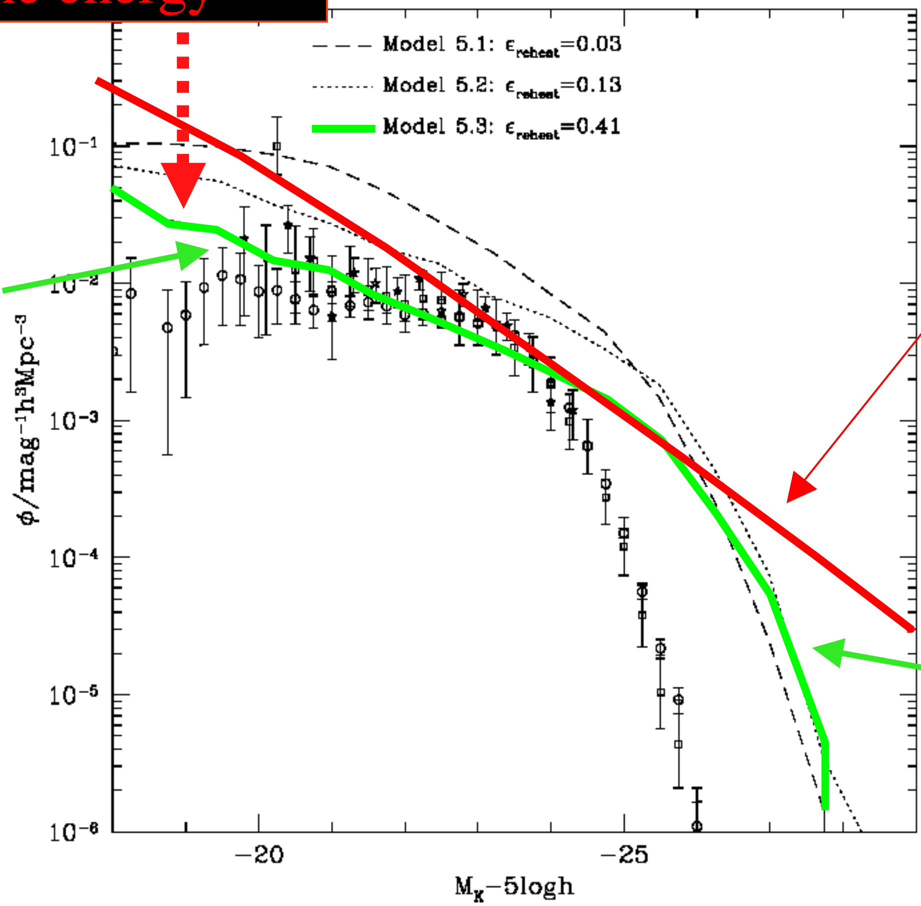
Part VI

AGN feedback

Why AGN feedback is needed

Formation of faint galaxies supressed by Sne energy

feedback has sucessfully depressed galaxy formation in small haloes



dark matter mass function (fixed M/L)

NB: exacerbated by the high value of WMAP Ω_b

but cooling is now too effective in high mass haloes (there's more gas left over)

Benson et al 2003

The same problem is seen in simulations: Balogh et al., 2001; Springel & Hernquist 2003

The three problems of galaxy formation

1. The bright end of the luminosity function
   - What sets the break in the galaxy luminosity function?
2. The “cooling flow” problem
   - Why don’t cooling flows result in bright blue galaxies at the centres of clusters?
3. The “hierarchy” problem
   - Why are the brightest galaxies old and red?

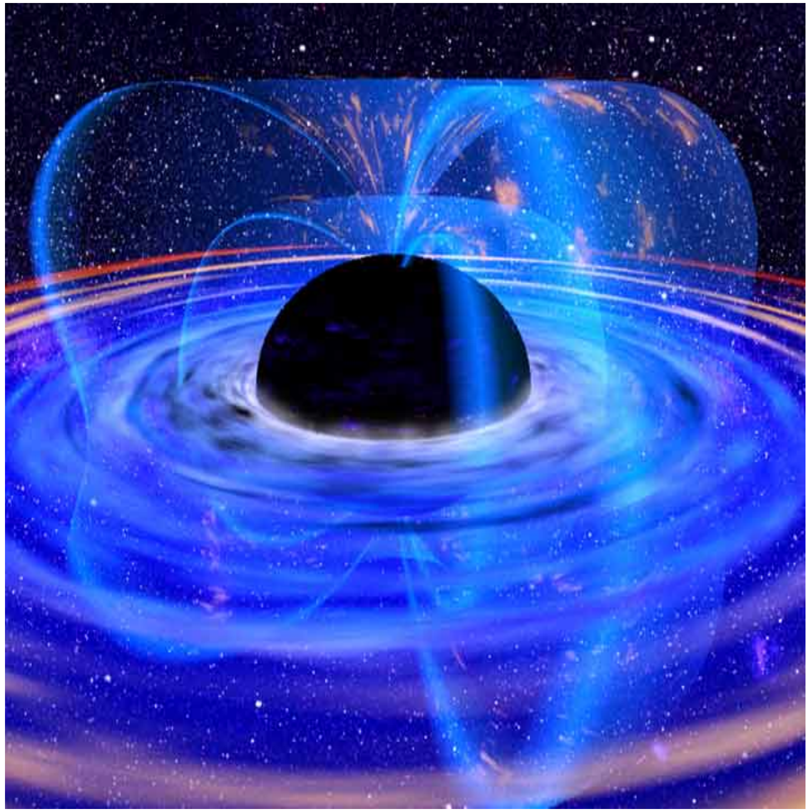
4. Only 10% of the baryons form into stars!!! Where are the other baryons? what are their properties?

These problems are closely interconnected: do AGN provide the solution?

AGN feedback

Heating clusters and groups

- What could possibly do this.
- Star formation - not enough energy
- But black holes…



Comparison of energies:

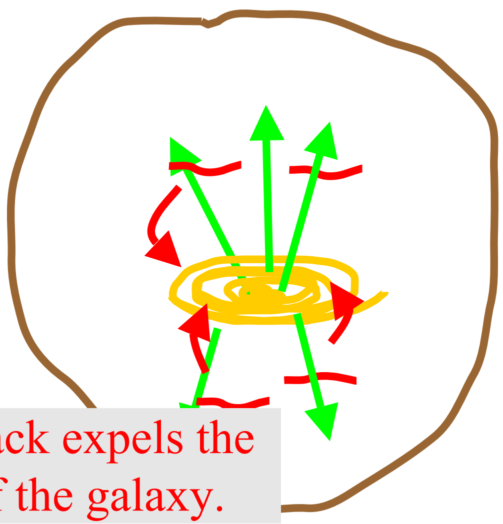
Thermal energy of a 10^{13} M_o halo
… 10^{61} erg

Accretion energy of a 10^{9} M_o black hole
… 2×10^{62} erg

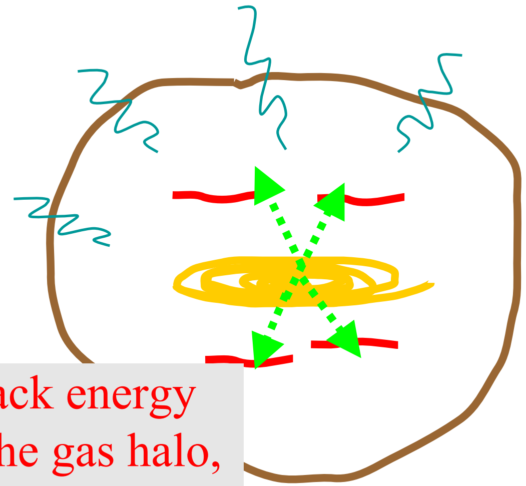
- Surely not a coincidence!

AGN feedback

- Two possible modes
  - “quasar” or “burst-mode” feedback
  - “radio galaxy” or “hot halo mode” feedback



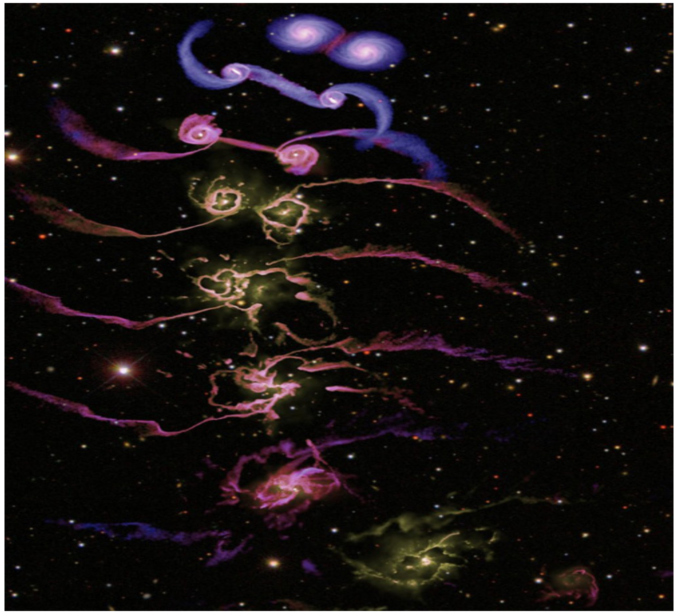
Feedback expels the ISM of the galaxy.

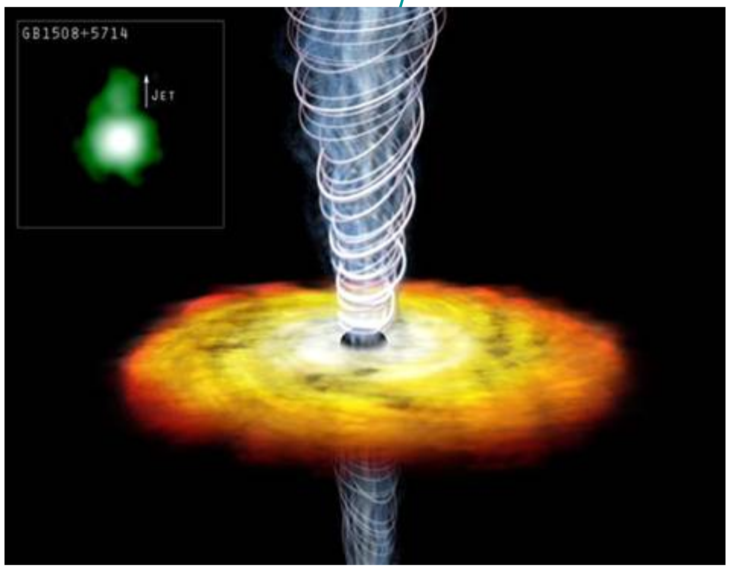


Feedback energy heats the gas halo, cancelling radiative cooling

AGN feedback

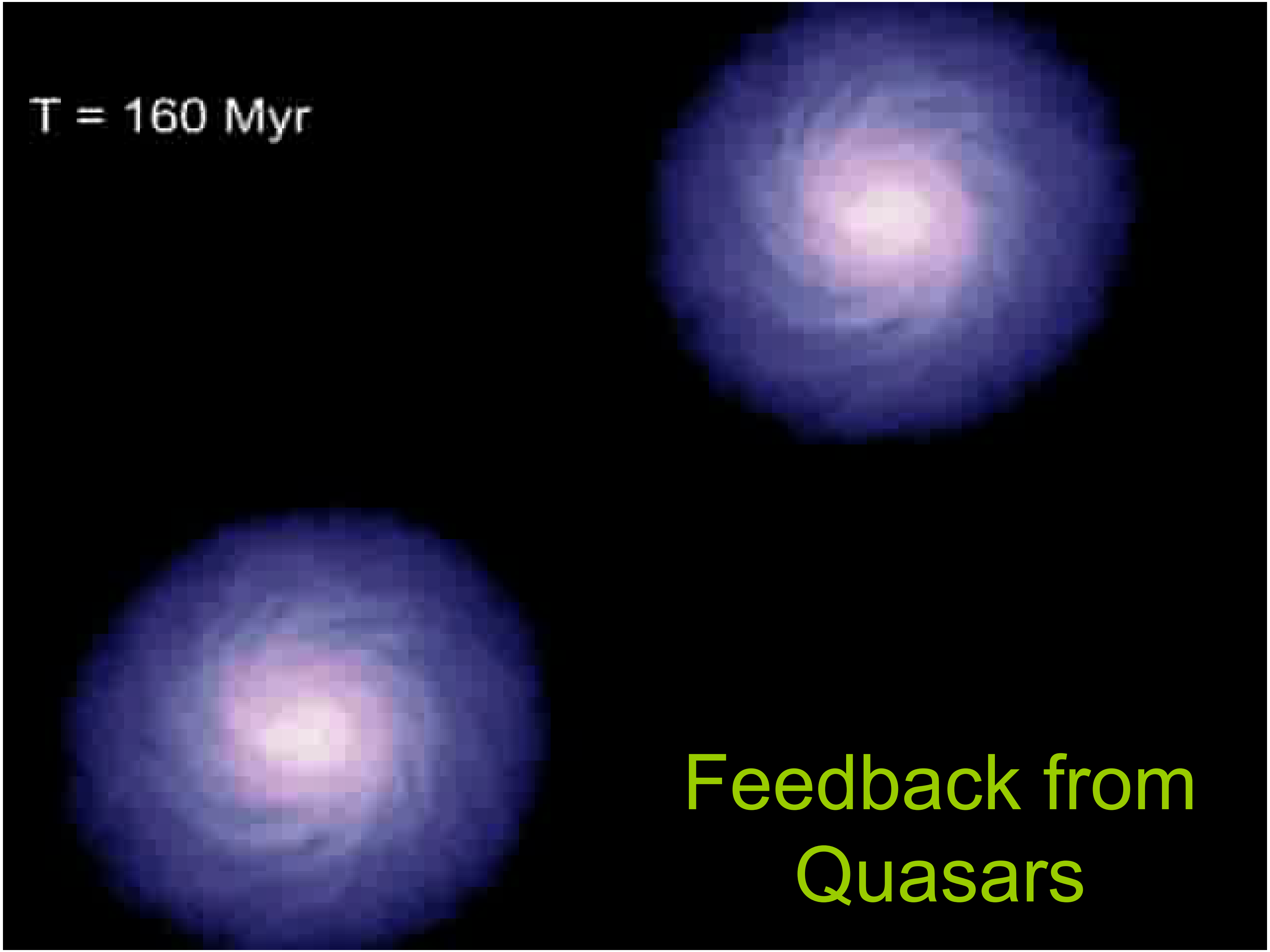
- Two possible modes
  - "quasar" or "burst-mode" feedback
  - "radio galaxy" or "hot halo mode" feedback





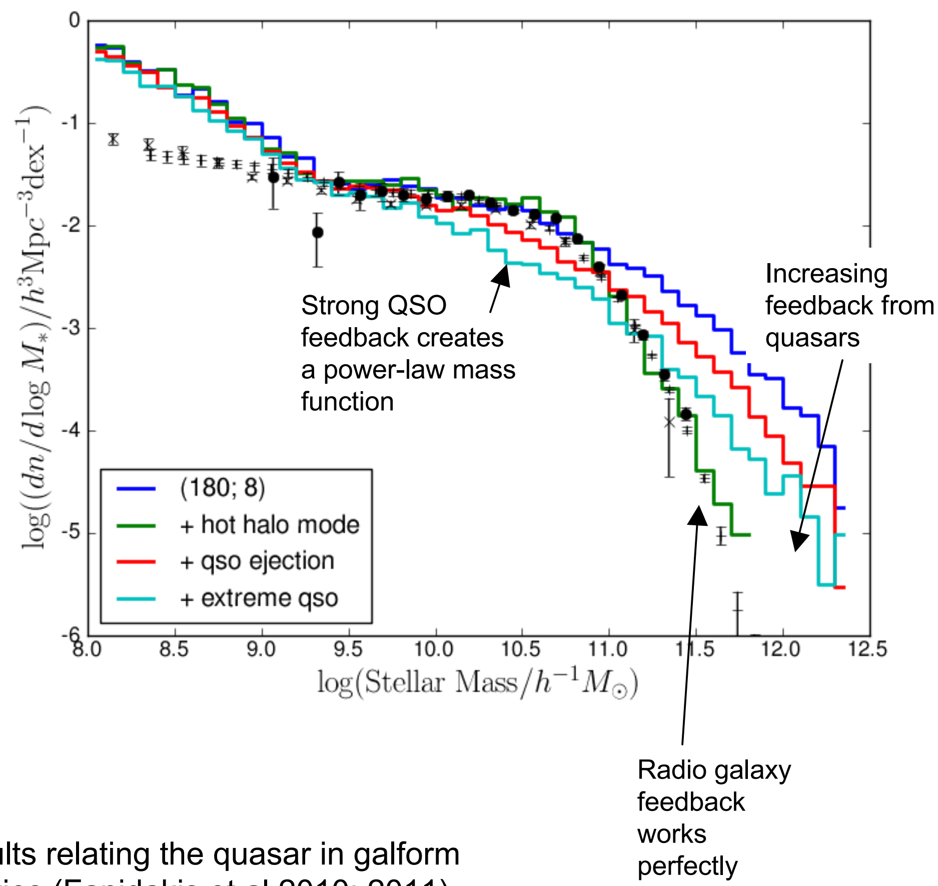
The two types of AGN feedback

- Low accretion rates onto massive BH
  - Geometrically thick disks
  - Deep threading of the BH by the ergo-sphere
- High accretion rates
  - Limited by the Eddington luminosity
  - Photon flux generates wind


T = 160 Myr
Feedback from Quasars

Feedback from Quasars?

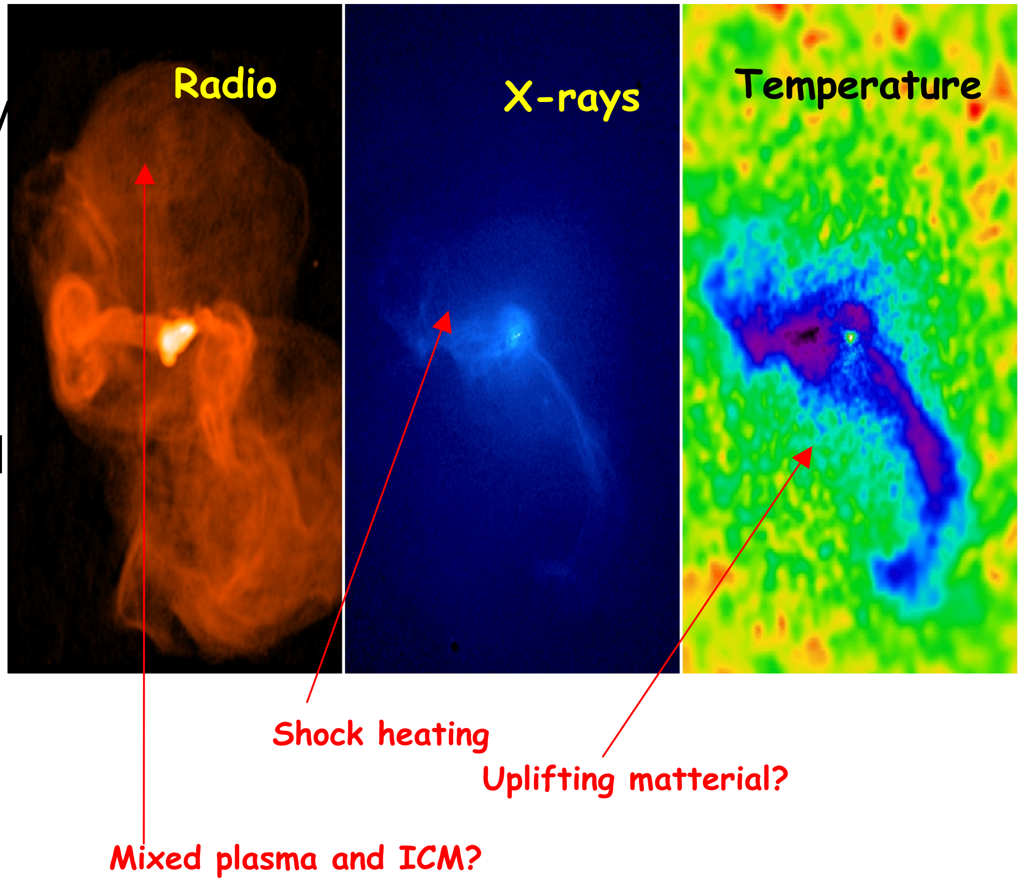
- Why should it work? BH is very small, why should it couple to the whole galaxy?
- The BH grow stochastically, so effect of the QSO is short lived. Galaxy recovers quickly
- Strongest QSO are in the galaxies where we need least feedback!
- It doesn't work anyway!! (at least not as the complete solution)



…but there are still lots of exciting results relating the quasar in galform to observations, and to their host galaxies (Fanidakis et al 2010; 2011)

Observing the “radio mode”

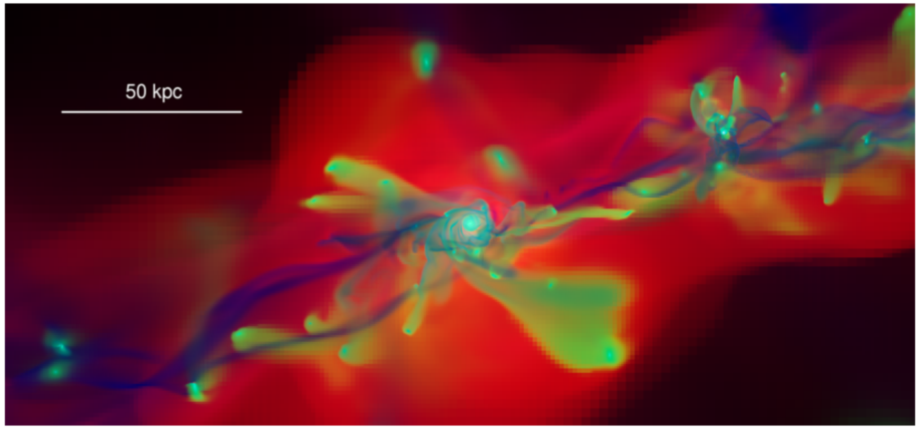
- Radio emision traces relativistic plasma ejected by the black hole
- X-ray image shows cavities where the ICM has been pushed aside
- Energy deposited in the ICM as bubbles rise displacing cooler gas



M87: Forman et al 2006;
Perseus: Fabian et al 2000, 2006

The “radio mode”

- Rapid and slow cooling in haloes
  - Compare cooling time and dynamical time
  - Two very different way that galaxies get their gas
- “cold accretion”
  - Does the accreted material ever heat up?
  - Accretion is not spherical!
- “cooling flows”
  - Cooling time in clusters < age of the cluster
  - Yet cnetral galaies have little cold gas and young stars - why?



“Cold Flows” in action: Keres et al., Dekel et al., Agertz et al

AGN in galaxy formation models

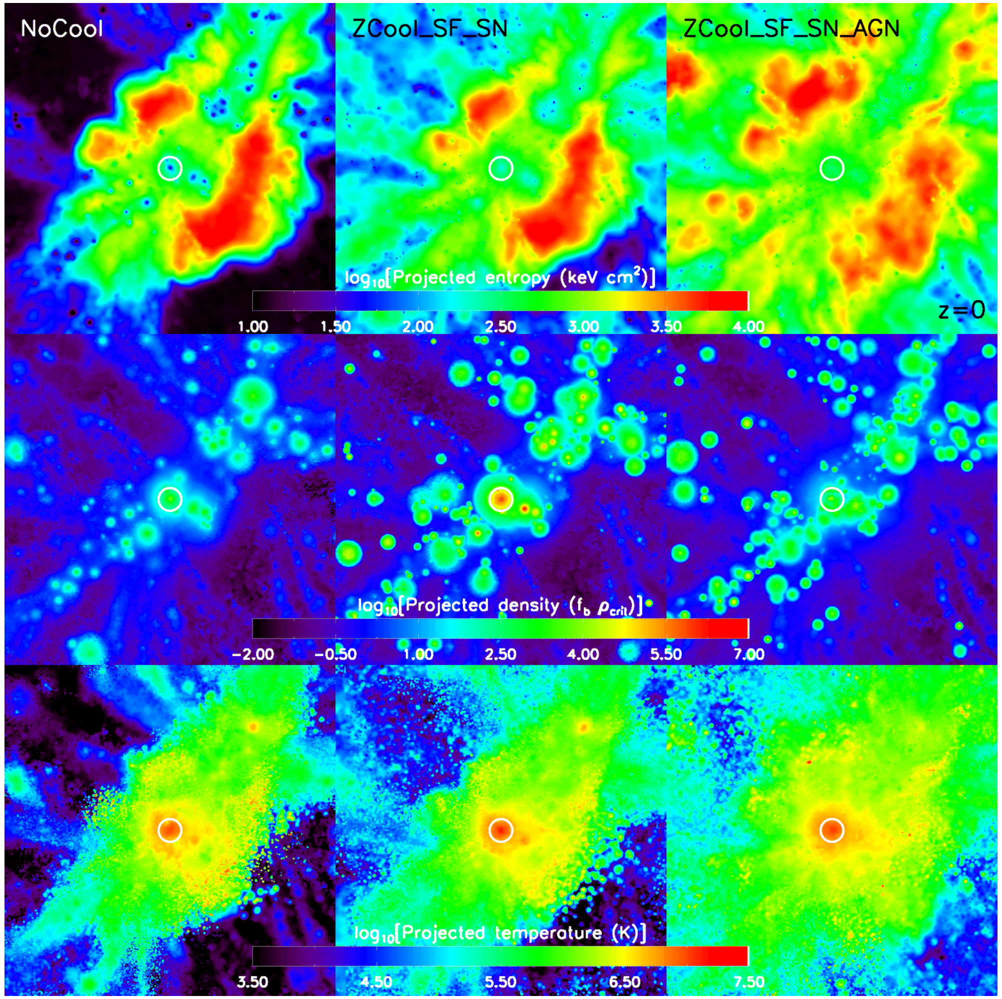
- The simple approach:
  - AGN shuts off cooling in hydrostatic haloes
- More complete approach,
  - AGN ejects material from halo until cooling rate drops

Part VII

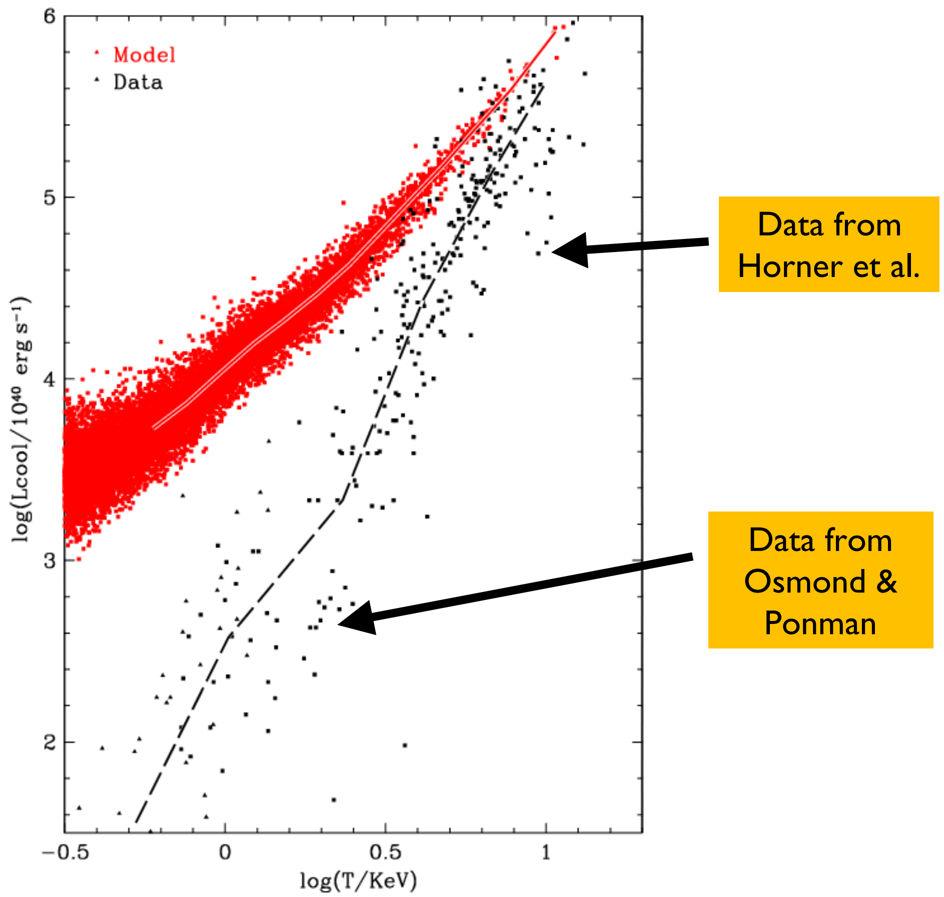
The X-ray View of Feedback

The X-ray view of feedback

- Groups and clusters
  - The Lx-T relation
  - Gas mass content
- Individual galaxies



the X-ray universe (ssshhh!)

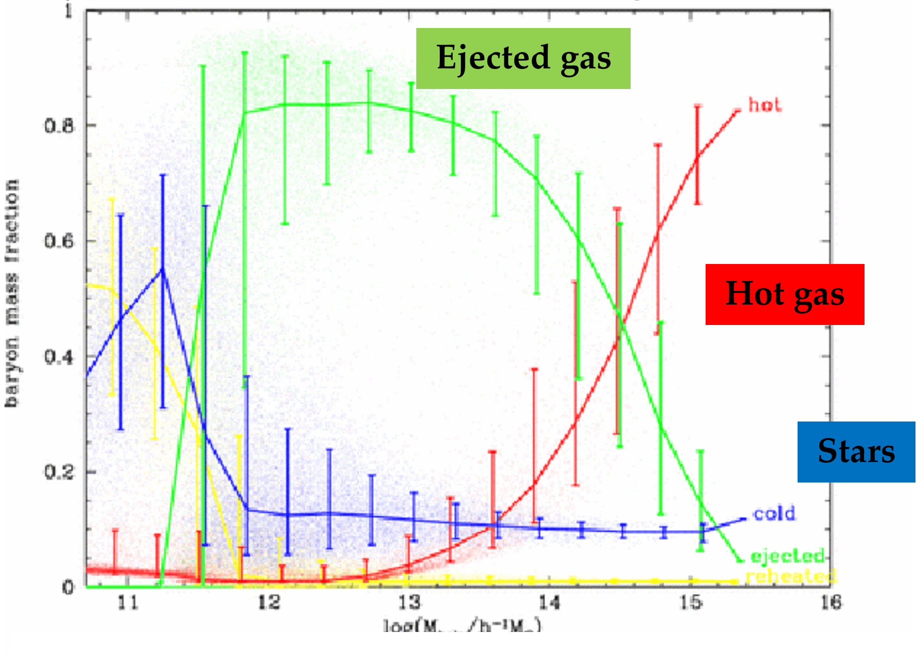


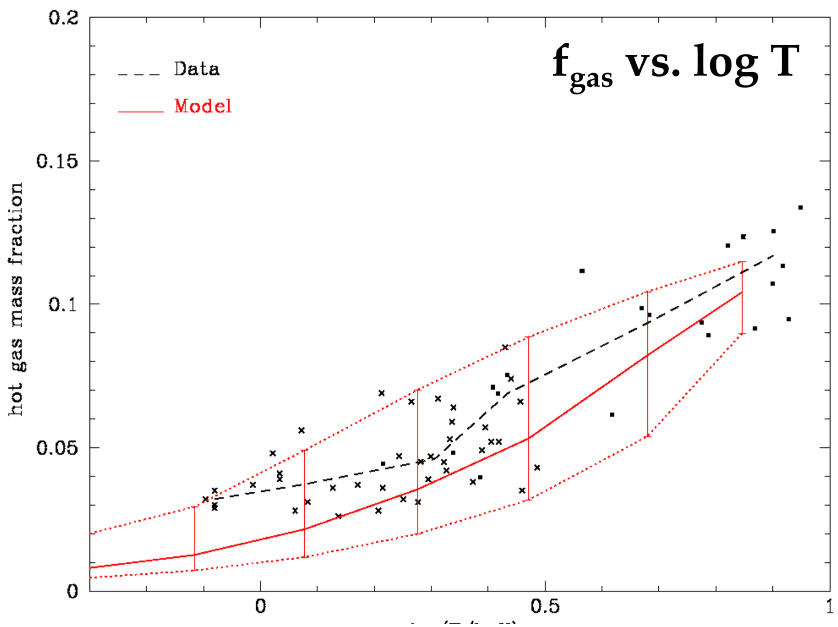
Bower et al. (2008)

- Typically, in SAMS heating of hot gas does not occur. "Heating" merely stops cooling. (Can heat cold gas to T_{vir}, but that's it.)

- What happens when excess energy is allowed to heat/eject gas?

Ejection dominates below log M < 14.5





Allowing for gas ejection

Bower et al. (2008)

L_{heat} is the smaller of:

$$\varepsilon_{SMBH} L_{Eddington}$$

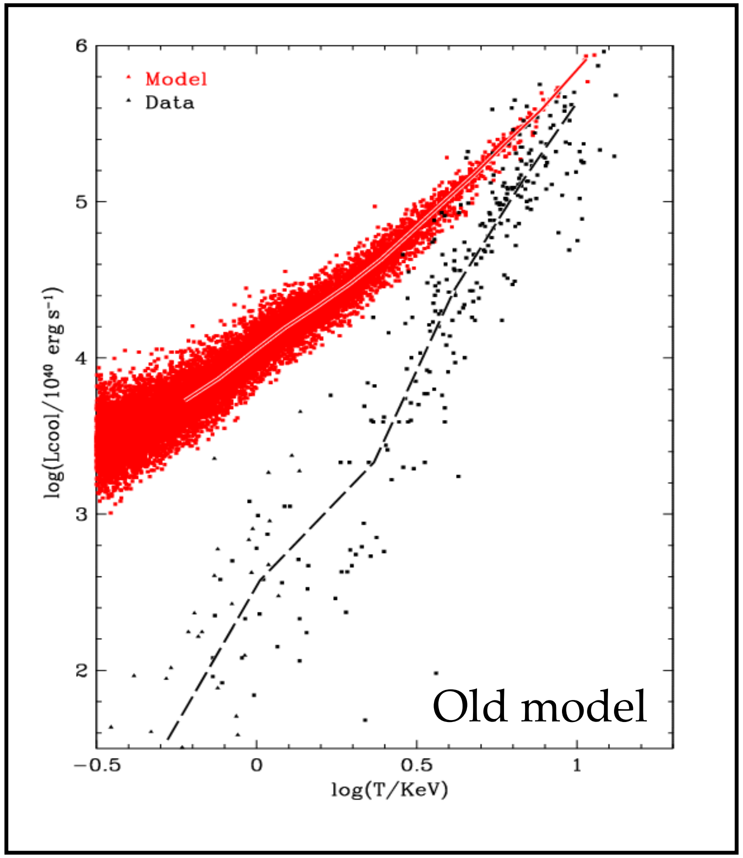
$$\eta_{SMBH} 0.1 \dot{M}_{cool} c^2$$

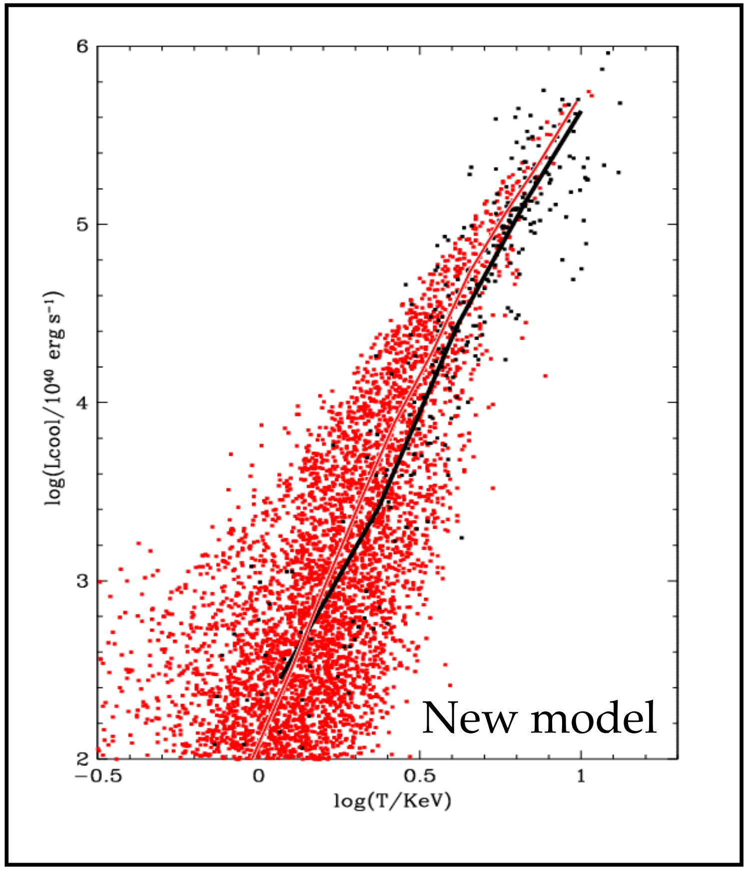
If $L_{heat} > L_{cool}$, gas is “ejected” from the system at a rate:

$$\frac{dM_{gas}}{dt} = \frac{L_{heat} - L_{cool}}{v_{halo}^2 / 2}$$

Gas can return later, if the halo grows significantly.

the X-ray universe, revisited

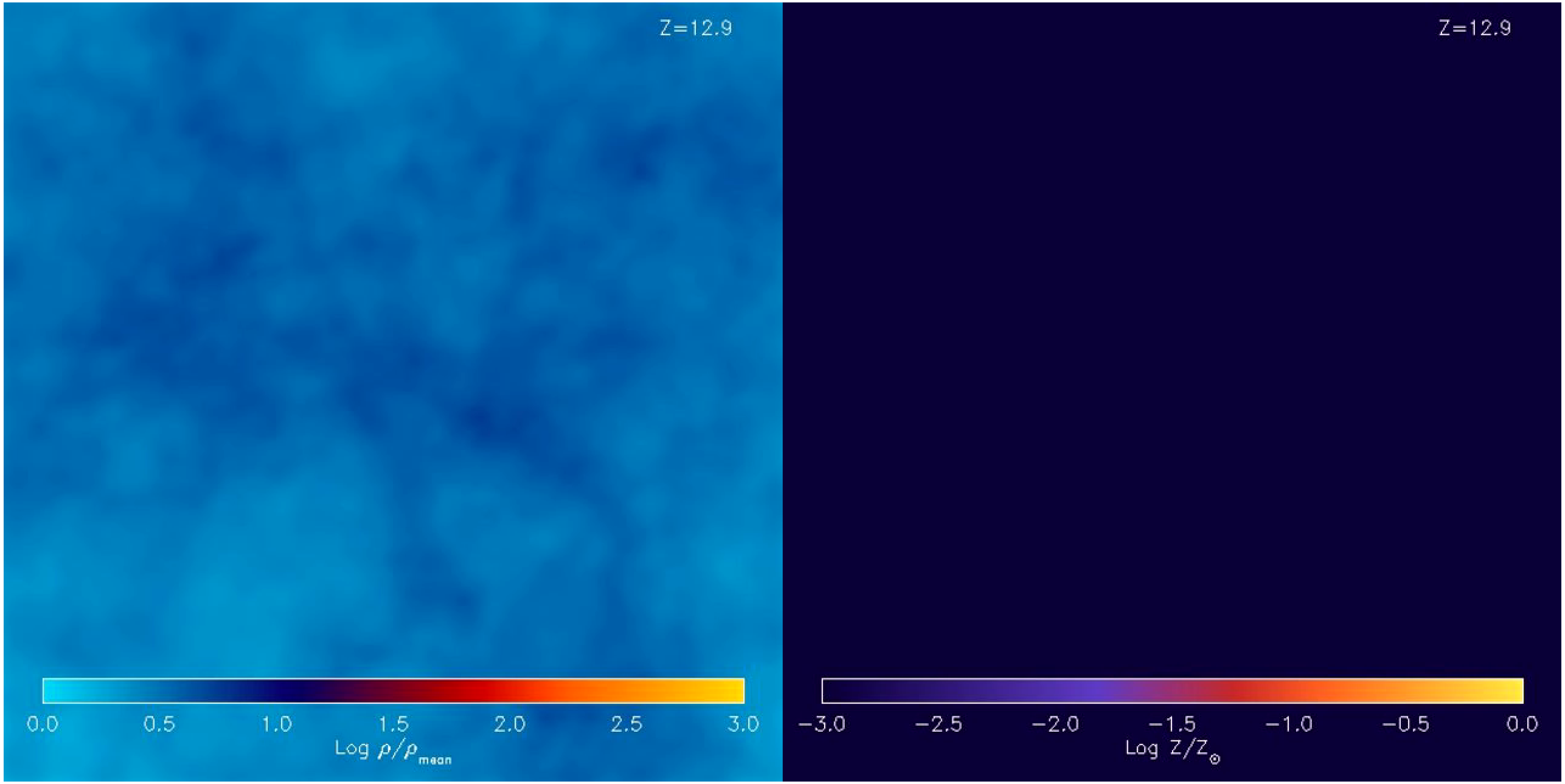




- Other parameters of the model (e.g., merger timescale, yields, SN efficiency) need to be modified to maintain match to galaxy LF.
- BH scalings differ between B06 and B08 (linearity breaks down at high halo mass) in new model, a consequence of requiring more energy to eject gas.

How it works - the movie!

This is a hydro-simulation, not!! GALFORM, but its similar

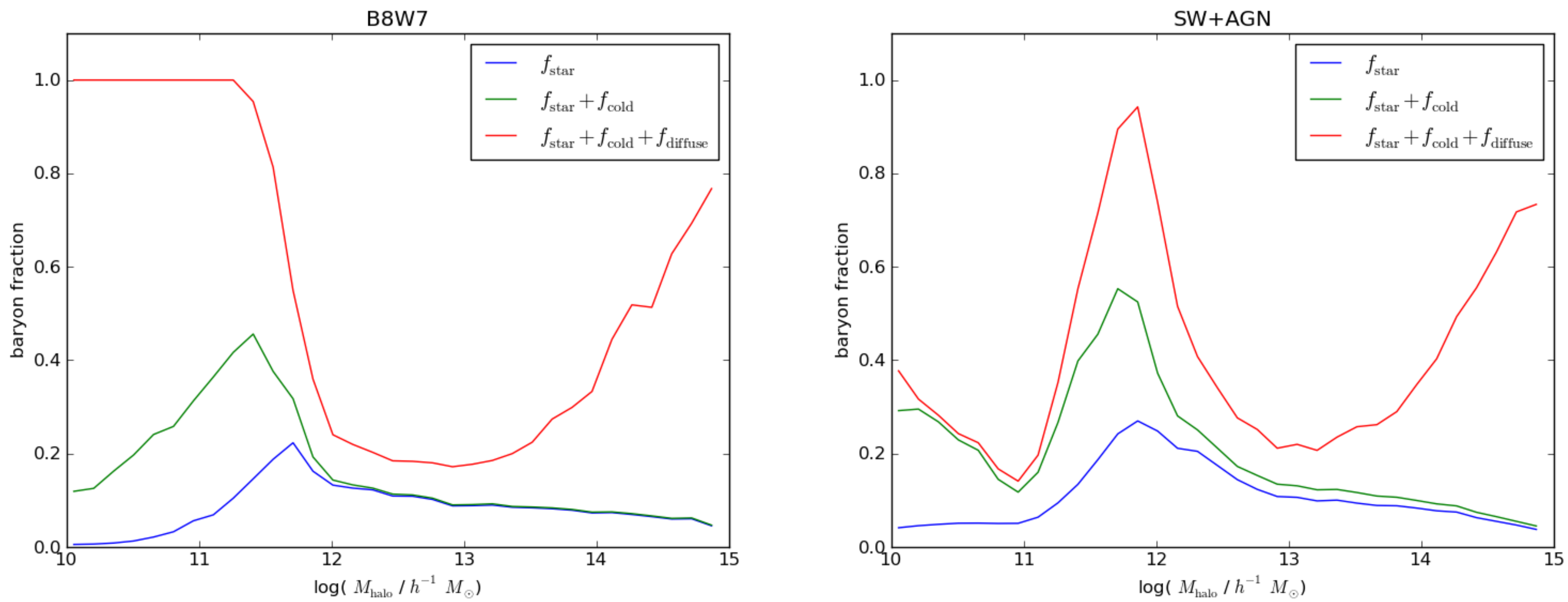


Gas density

metalicity

Movie credit Craig Booth. The OWLS project
(McCarthy et al 2011)

Where are the baryons?



- Combine the feedback schemes and ask where the baryons are

Summary (a good paradigm)

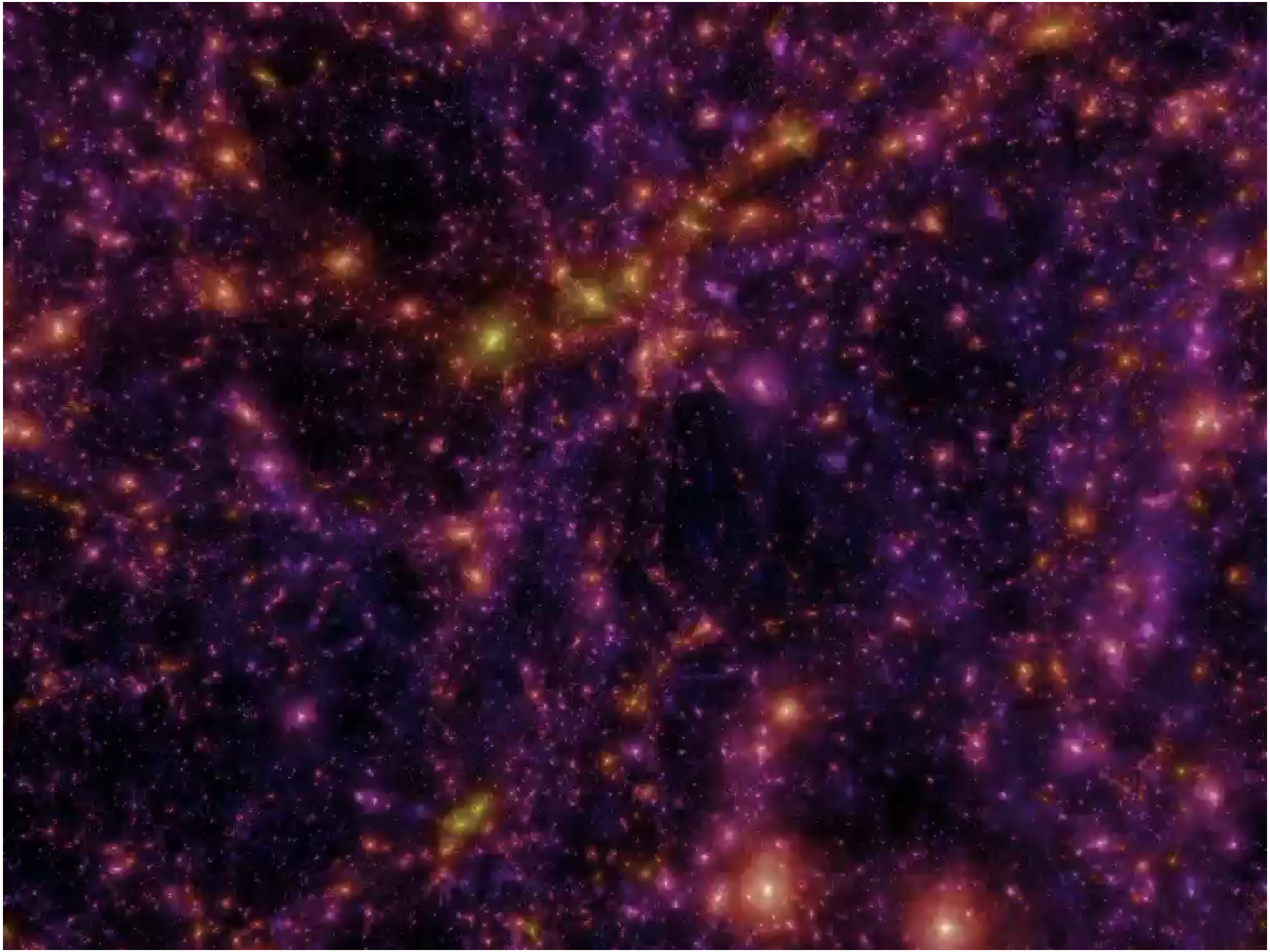
- Feedback is essential to reconcile the shape of the mass function with the galaxy mass function
  - Formation of the smallest galaxies is suppressed by re-ionisation.
  - Supernova-driven winds regulates the formation of small galaxies
  - Jets from Radio Galaxies prevent cooling (and eject gas) in hydrostatic haloes.
- The issue is to understand how these components link together, and to demonstrate that the “story” really holds true

Well done!

Now you can see the movie

Joel Snape & Mark Swinbank

+ the GALFORM team



Part IV

Exploring feedback

Feedback - some equations

- Adopt an empirical approach - what is needed to match the stellar mass function?

Mass loading of the wind: how much material is carried away

$$\dot{M}_{wind} = \beta \dot{M}_*$$

$$\beta = \beta_{200} \left(\frac{v_{\rm halo}}{200 \text{ km/s}} \right)^{-\alpha_{\rm hot}}$$

Wind speed (or specific energy): determines if it escapes

$$v_{wind}^{\ 2} = v_{200}^{\ 2} \cdot \left(\frac{v_{\rm halo}}{200 \text{ km/s}} \right)^{\alpha_{\rm expel}+2}$$

$$\alpha_{\rm expel} + 2 = \alpha_{\rm hot}$$

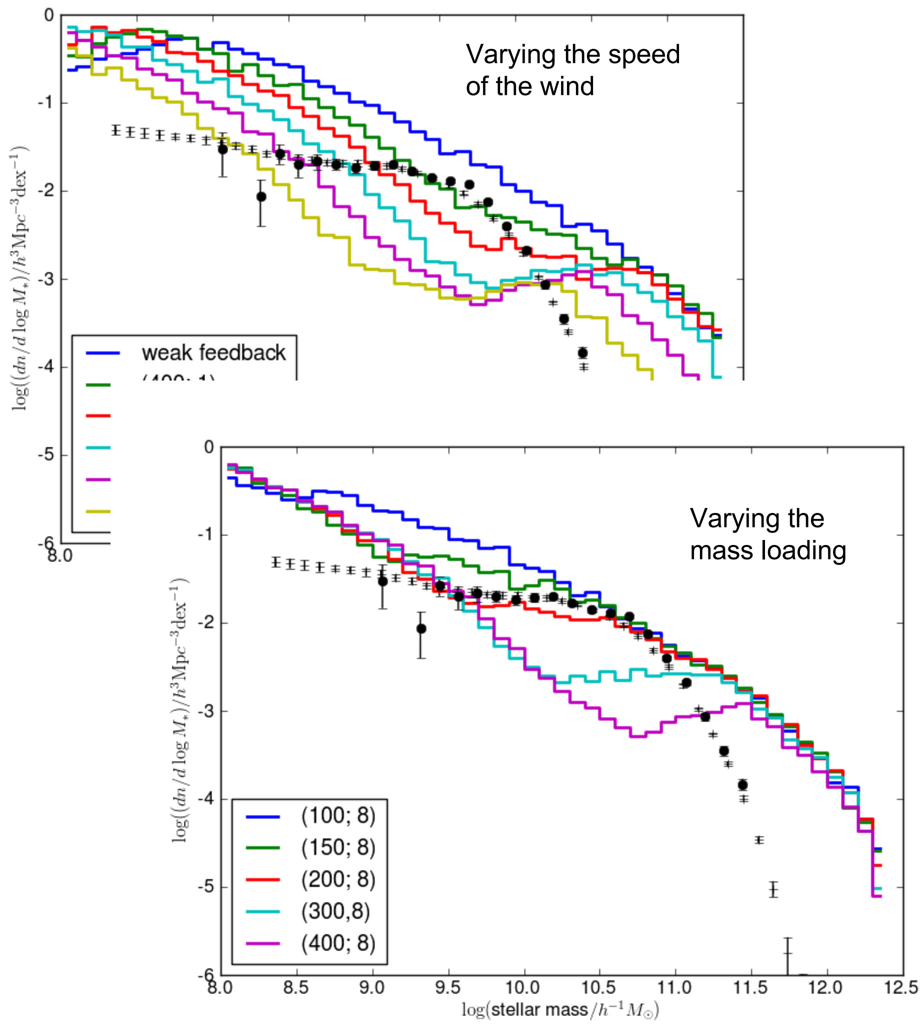
Energy conservation

or if it is recaptured!

Exploring Feedback

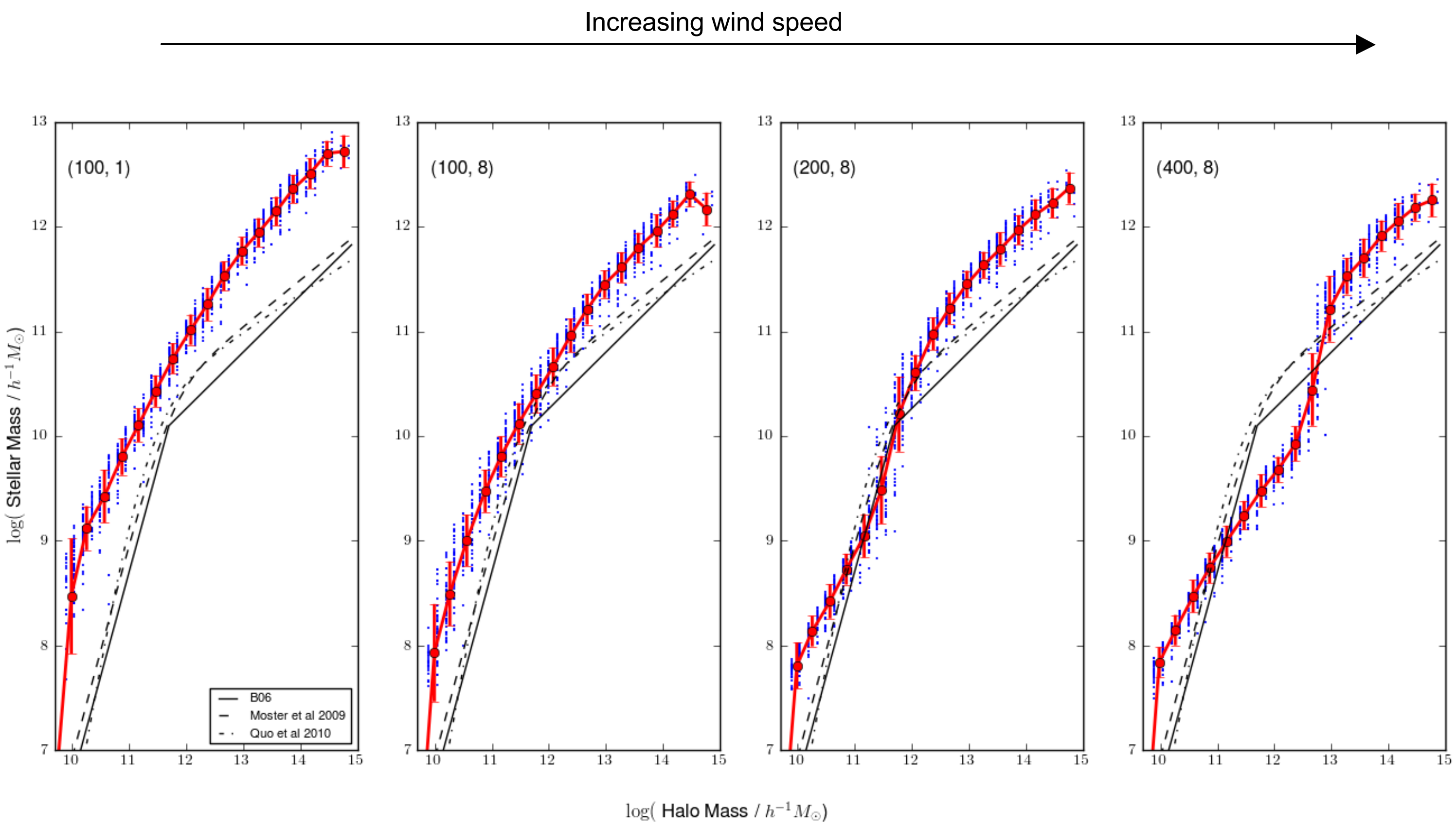
- Assume that supernovae drive a wind with fixed speed, and a mass-loading proportional to the star formation rate.

$$\beta = \frac{\dot{M}_{out}}{\dot{M}_*}$$

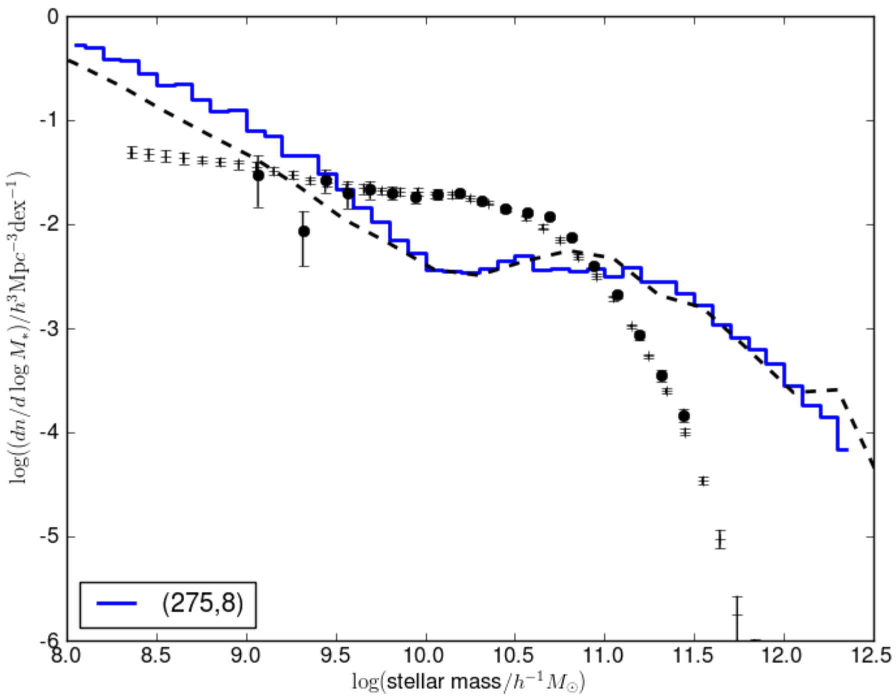


Bower et al 2012

A better way to think about feedback

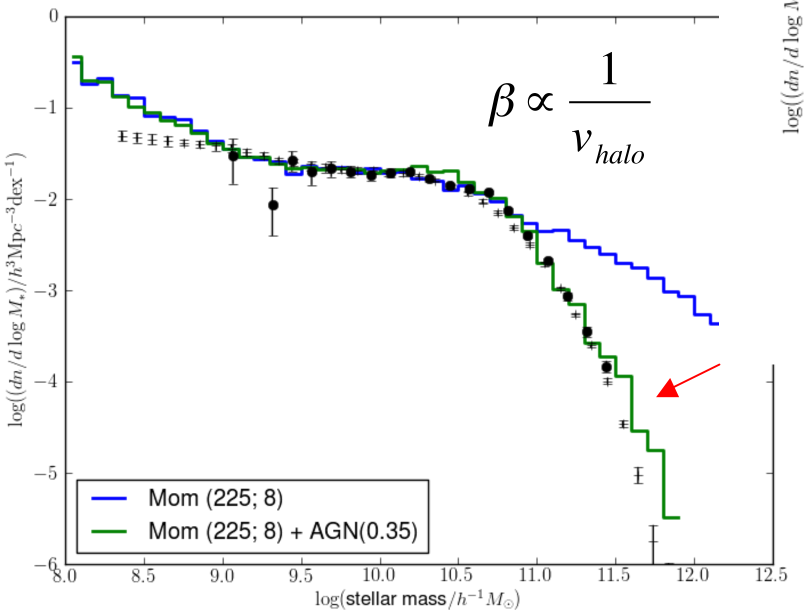


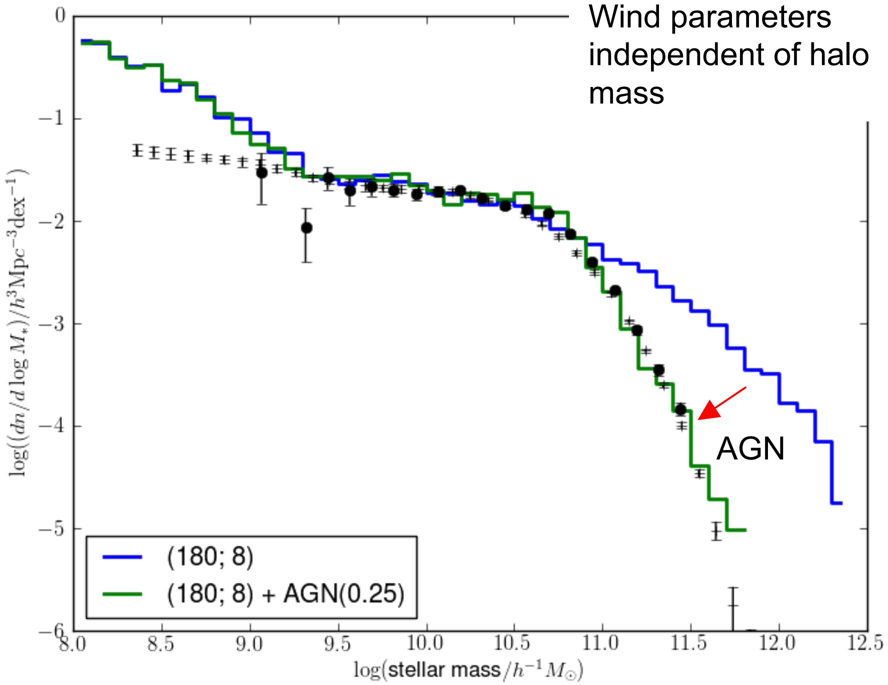
Aside: Comparing Galform and GIMIC



- Can "semi-analytic" models reproduce the results of numerical simulation?

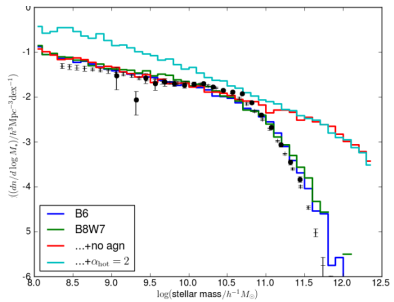
So is it possible to fit the mass function?





Wind parameters independent of halo mass

B06 model



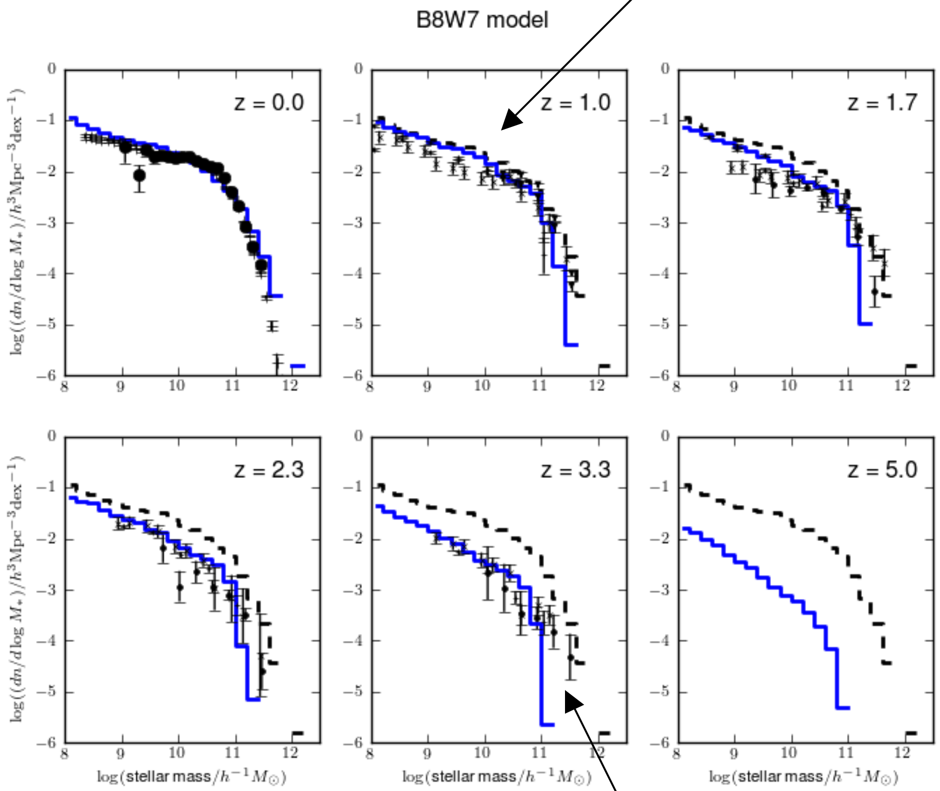
Part VIII

Comparing with data

Beyond the stellar mass function

All the models struggle to match the mass function normalisation at z=1-2

- Other observational tests
  - Evolution of the stellar mass function
  - Specific star formation rates
  - Evolution of the star formation rate density



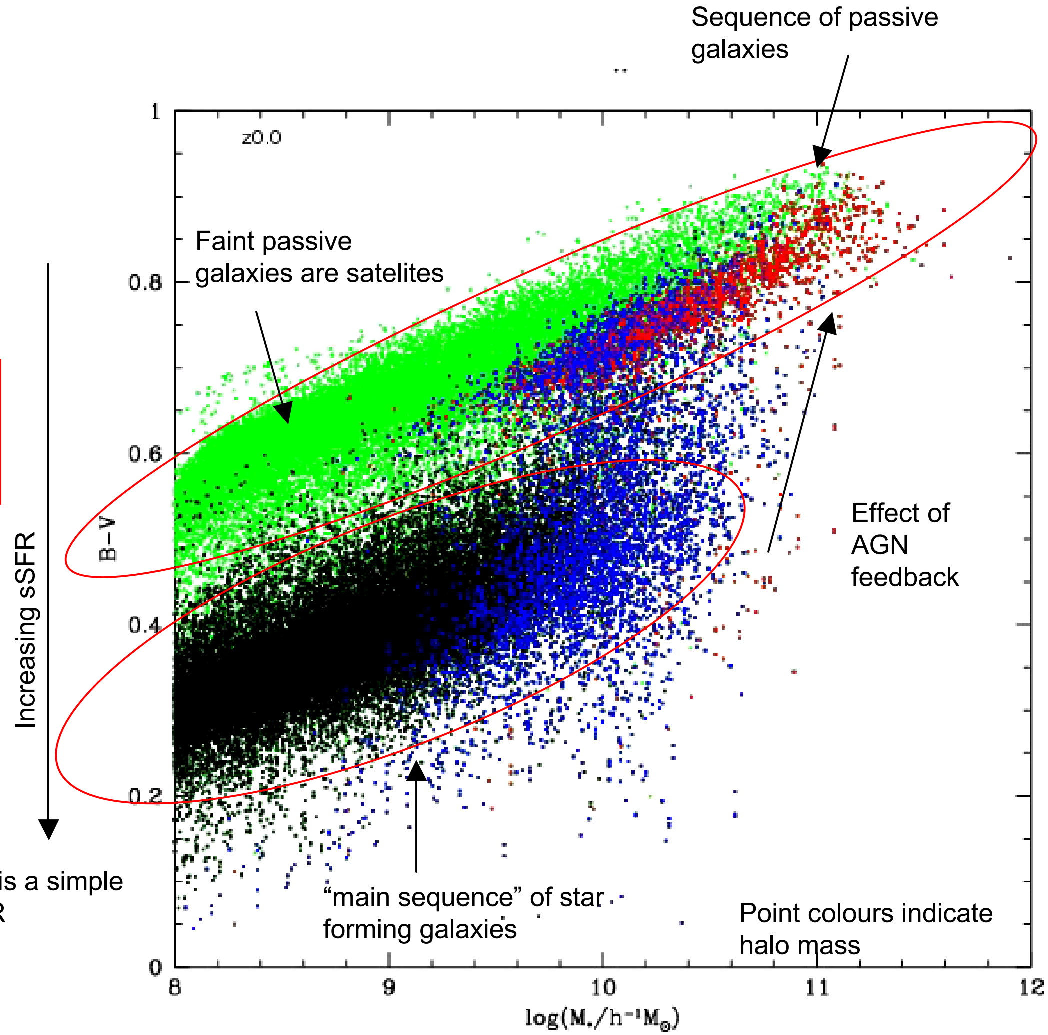
Three models shown: SW = fixed wind parameters, MS= weak mass dependence, B8W7 = strong dep.

B8W7 model best succeeds at reproducing the abundance of massive galaxies at high-z

Beyond the stellar mass function

- Other observational tests
  - Evolution of the stellar mass function
  - Specific star formation rates
  - Evolution of the star formation rate density

$$\mathrm{sSFR} = \frac{\dot{M}_*}{M_*}$$
$$= \frac{1}{t} \quad \text{if} \quad \dot{M}_* = \text{const}$$



Galaxy colour is a simple proxy for sSFR

Beyond the stellar mass function

- Other observational tests
  - Evolution of the stellar mass function
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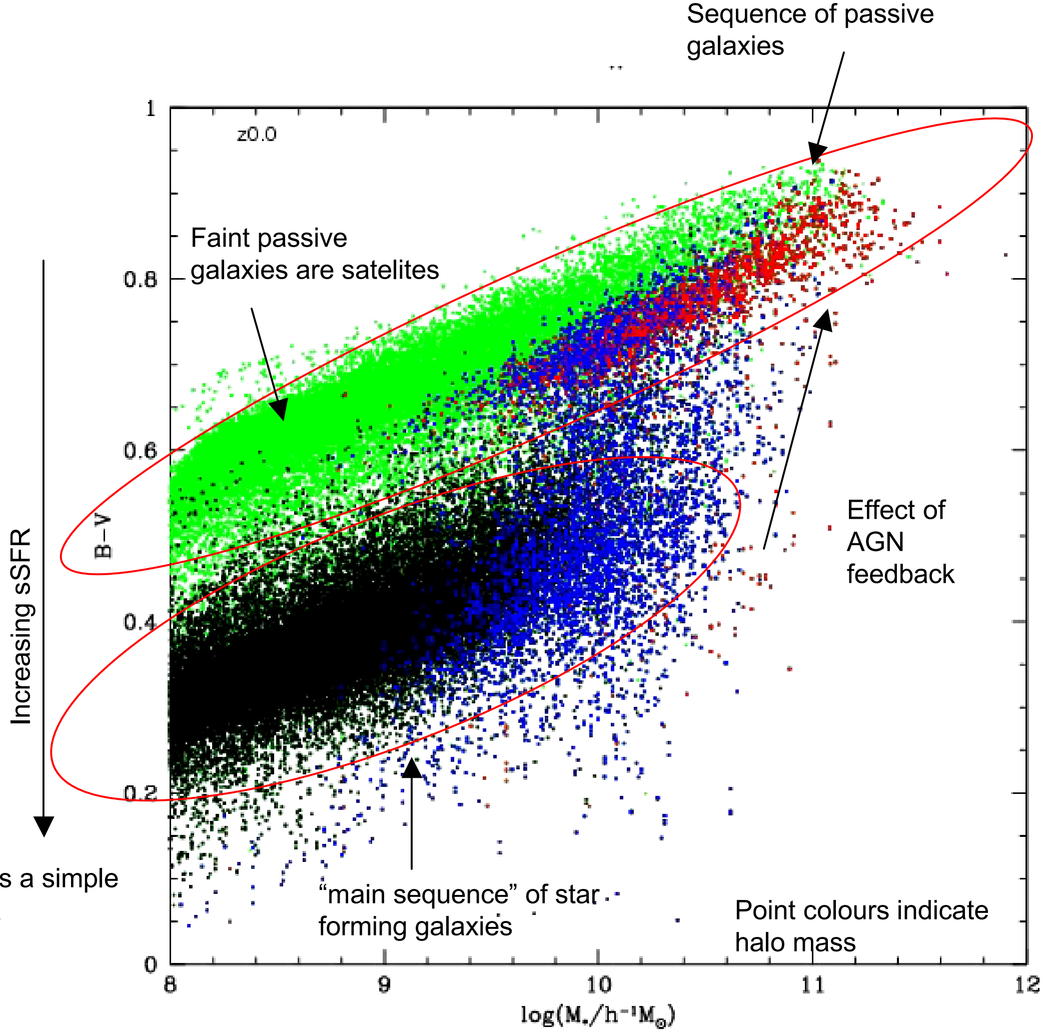
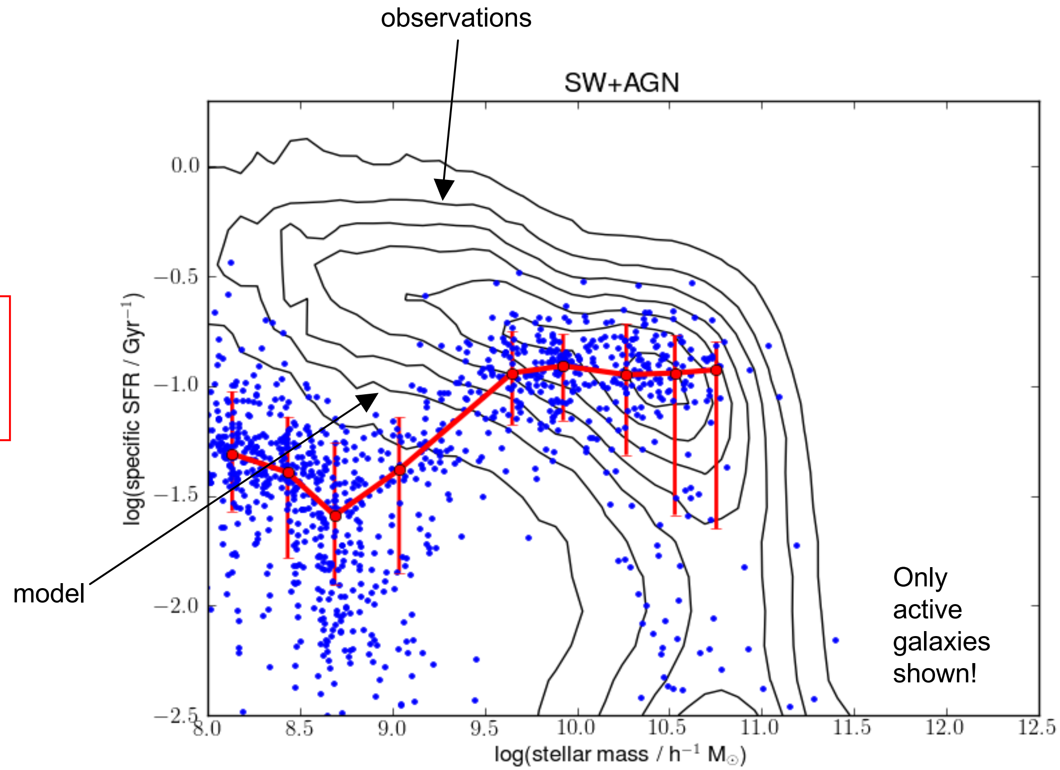
Galaxy colour is a simple proxy for sSFR



Beyond the stellar mass function

- Other observational tests
  - Evolution of the stellar mass function
  - Specific star formation rates
  - Evolution of the star formation rate density

$$
\begin{aligned}
sSFR &= \frac{\dot{M}_*}{M_*} \\
&= \frac{1}{t} \quad \text{if} \quad \dot{M}_* = \text{const}
\end{aligned}
$$



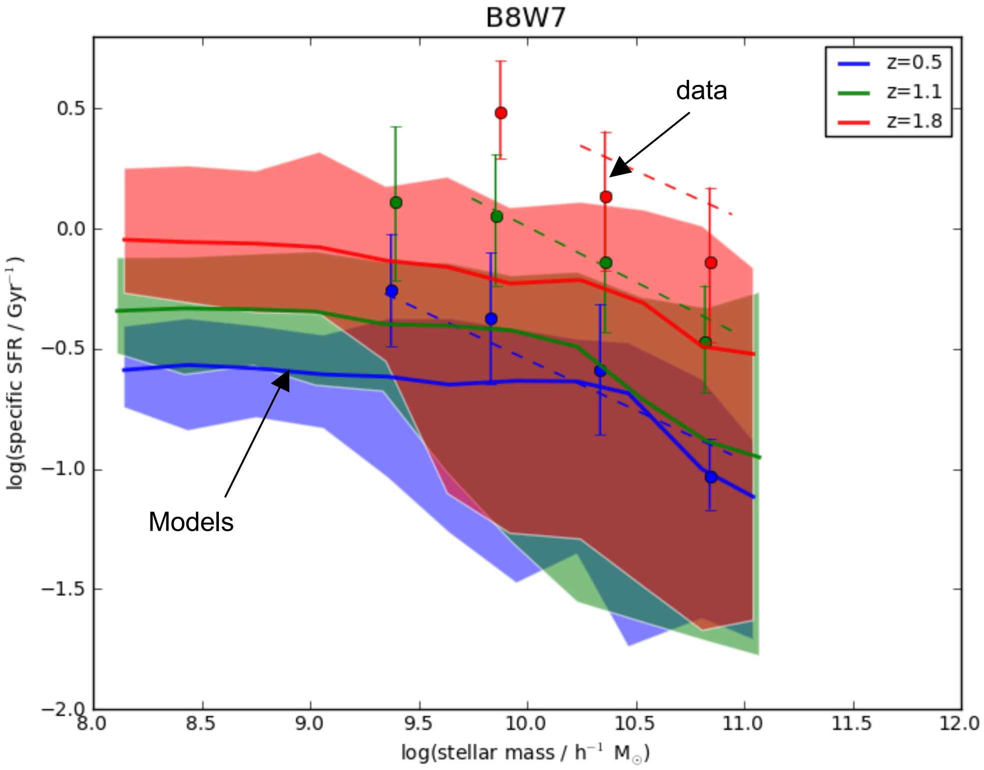
Model sequence is too flat compared to the data! (worse for other feedback schames considered)

Beyond the stellar mass function

- Other observational tests
  - Evolution of the stellar mass function
  - Specific star formation rates
  - Evolution of the star formation rate density

$$\mathrm{sSFR} = \frac{\dot{M}_*}{M_*}$$
$$= \frac{1}{t} \quad \text{if} \quad \dot{M}_* = \text{const}$$

Models struggle to reproduce the rapid increase in specific star formation rates. Is this a selection effect?

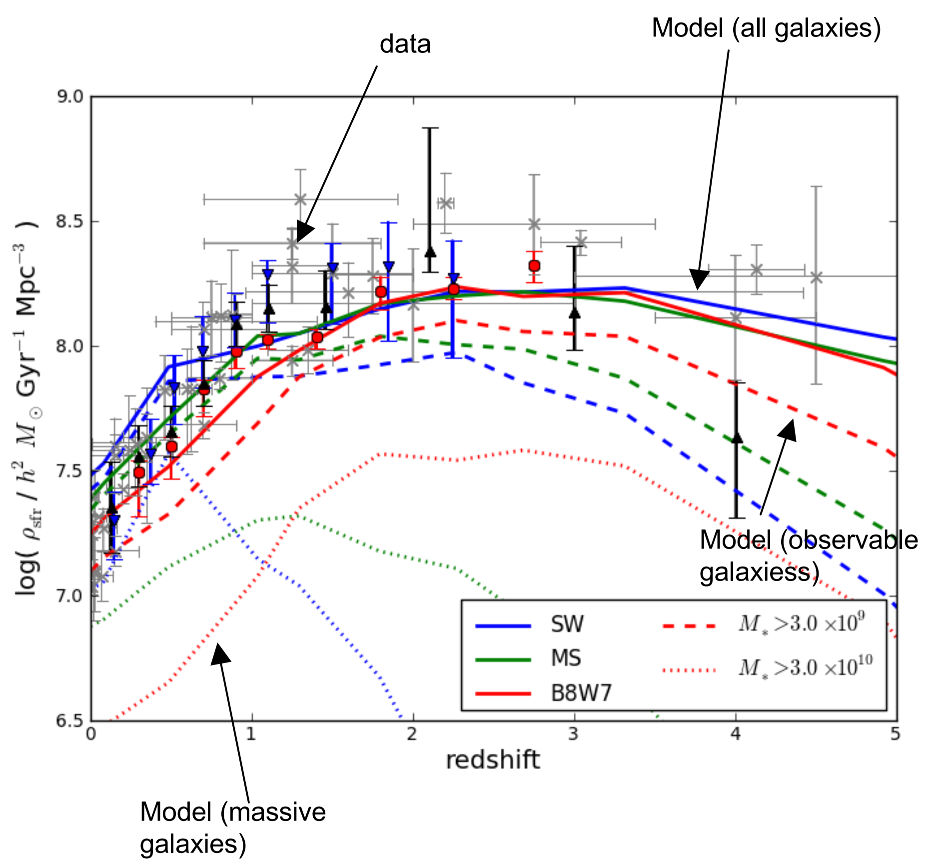


Data from Rohdigiero et al. 2011; Karim et al 2011; Lin et al 2011.

Beyond the stellar mass function

- Other observational tests
  - Evolution of the stellar mass function
  - Specific star formation rates
  - Evolution of the star formation rate density

Combines the two other measures!



Model does not fit the data particularly well.
Is this due to limited depth of observations?

Beyond the stellar mass function

- Other observational tests
  - Evolution of the stellar mass function
  - Specific star formation rates
  - Evolution of the star formation rate density

Conclusions? B8W7 works best:

•Good stuff:-

- •Mass function generally looks good
- •(some) Massive galaxies formed early
- •sSFR is has the right average value
- •Contributions to cosmic SFR about right

•Bad stuff:- (could do better)

- •Rapid evolution of stellar mass function between z=0 and z=1-2
- •Slope and rapid evolution of sSFR
- •Steep decline of the cosmic SFR

Summary