Semi-Analytic Galaxy Formation - are we kidding ourselves?

Health warning - not a proper review; not a complete bibliography

Thanks to the Galform team: Carlton Baugh, Andrew Benson, Shaun Cole, Andreea Font, Carlos Frenk, Juan Gonzalez, John Helly, Cedric Lacey, Rowena Malbon, Ian McCarthy, (this talk in no way reflects the views of the group!)

What this conference is all about…

- What are semi-analytic models for?
  - A means of predicting the properties of the universe?
  - The ultimate multiscale simulation technique?
  - A tool for interpreting observational data?
  - A tool for understanding numerical simulations?
  - A tool for assessing telescope proposals?

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Something to think about…

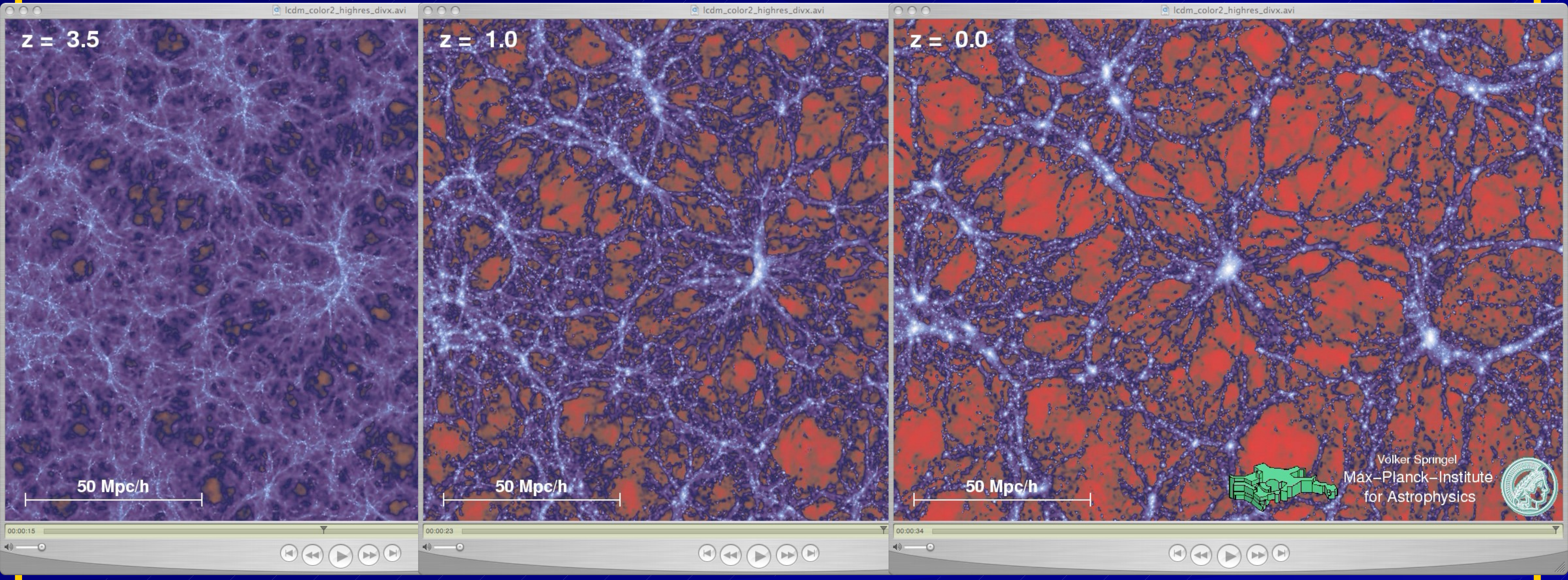
- If you ran the perfect simulation:
  - real Hydrodynamics
  - 1 Mo resolution, 1pc smoothing
  - Magneto-hydrodynamics
  - Black holes (relativistic magnetohydrodynamics)
- …and matched every piece of observational data
- Would you have learned anything?

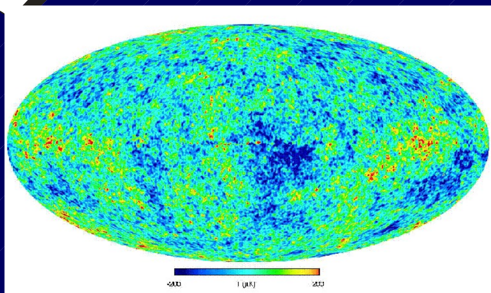
What are Semi-Analytic Simulations?

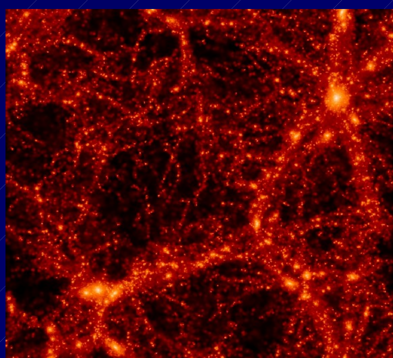
…take a few steps backwards…

Structure formation is hierarchical

- Small things form first
- Big things form later







Cosmological model

$(\Omega_m, \Omega_\Lambda, h)$; dark matter

Primordial fluctuations

$\delta \rho / \rho \; (M, t)$

Well established

Dark matter halos

(N-body simulations)

Well understood

Gas processes

(cooling, star formation, feedback)

Gasdynamic simulations

Semi-analytics

Formation and evolution of galaxies

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Two approaches for populating the Dark Universe with galaxies

- Semi-analytics
  - Encapsulate physics in simple equations. Link them in a network.
  - Fast!
  - Easy to explore different parameters and new physical effects
  - Populate a vast volume with galaxies

- Direct simulation
  - Start from fundamental physical laws
  - Gives the “correct” solution (for the input physics, resolution, numerical accuracy etc)
  - Need to add “subgrid” physics to stabilise the solution.

Complementary not Adversary!!!

(the boundaries are blurring)

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What's the problem?

- So few stars
  - Only 10% of the baryons form into stars (Balogh et al 2001, Cole et al 2001, Lin et al 2003)
- "Down sizing"
  - "As the universe ages star for smaller objects" (Cowie et al 1996)

But is this really what the data show? Is it just the maximum star forming mass that increase with redshift? – or is it just the mass threshold for star formation?

- "Anti-hierarchical"
  - "the big galaxies form first, while in CDM the large dark matter haloes form last"

But the first haloes to form are now incorporated into the largest haloes today!

- "The Broken Hierarchy"
  - "baryon physics introduces extra scales"

(Rees & Ostriker 1978, Binney 1977, Silk 1977, White & Rees 1978, White & Frenk 1991)

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Other problems for galaxy formation

- Related problems:
  - The shape of the luminosity function
  - The “cooling flow” problem
- Unrelated problems (?):
  - The density-morphology relation
  - “(pre-)heating” the intra-cluster medium

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Recent progress in semi-analytics

Feedback - regulating the formation of galaxies is the key issue

The galaxy luminosity function

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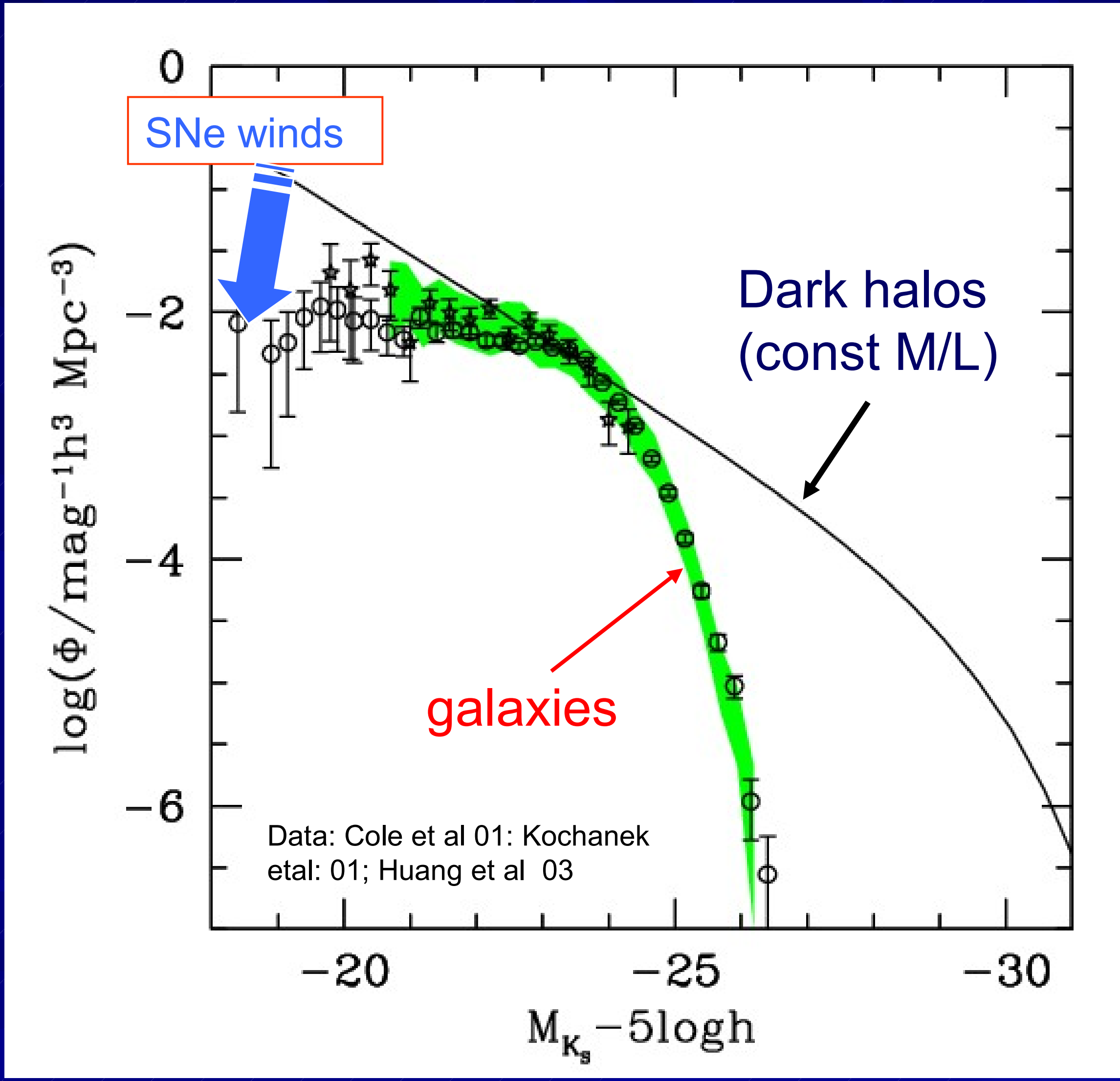
The halo mass function and the galaxy luminosity function have different shapes

⇨

Complicated variation of M/L with halo mass

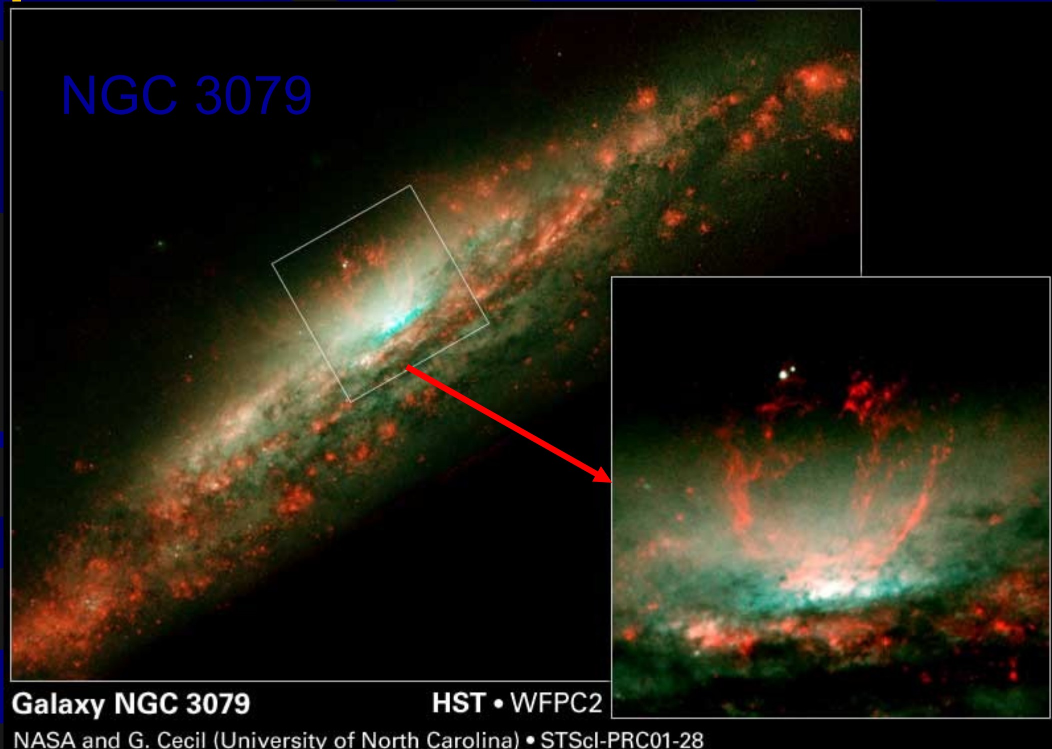


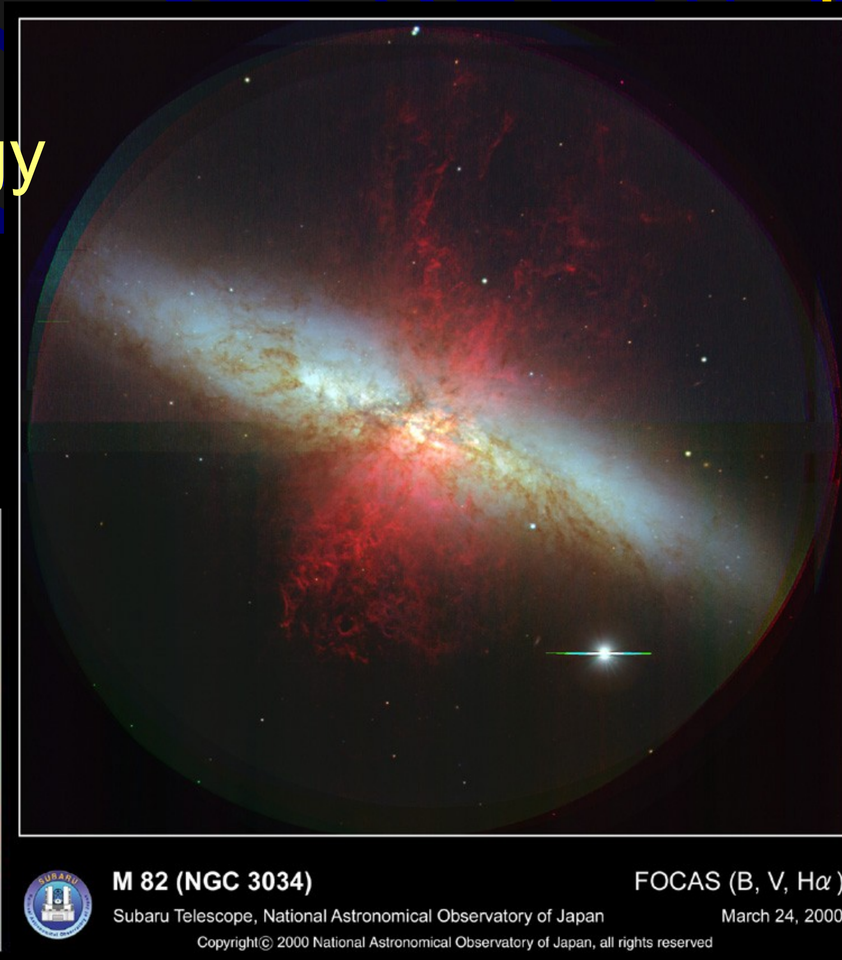
Benson et al '03

Feedback in galaxy formation

The faint end of luminosity function:

White & Rees '78 $\Rightarrow$ Injection of supernovae/stellar wind energy





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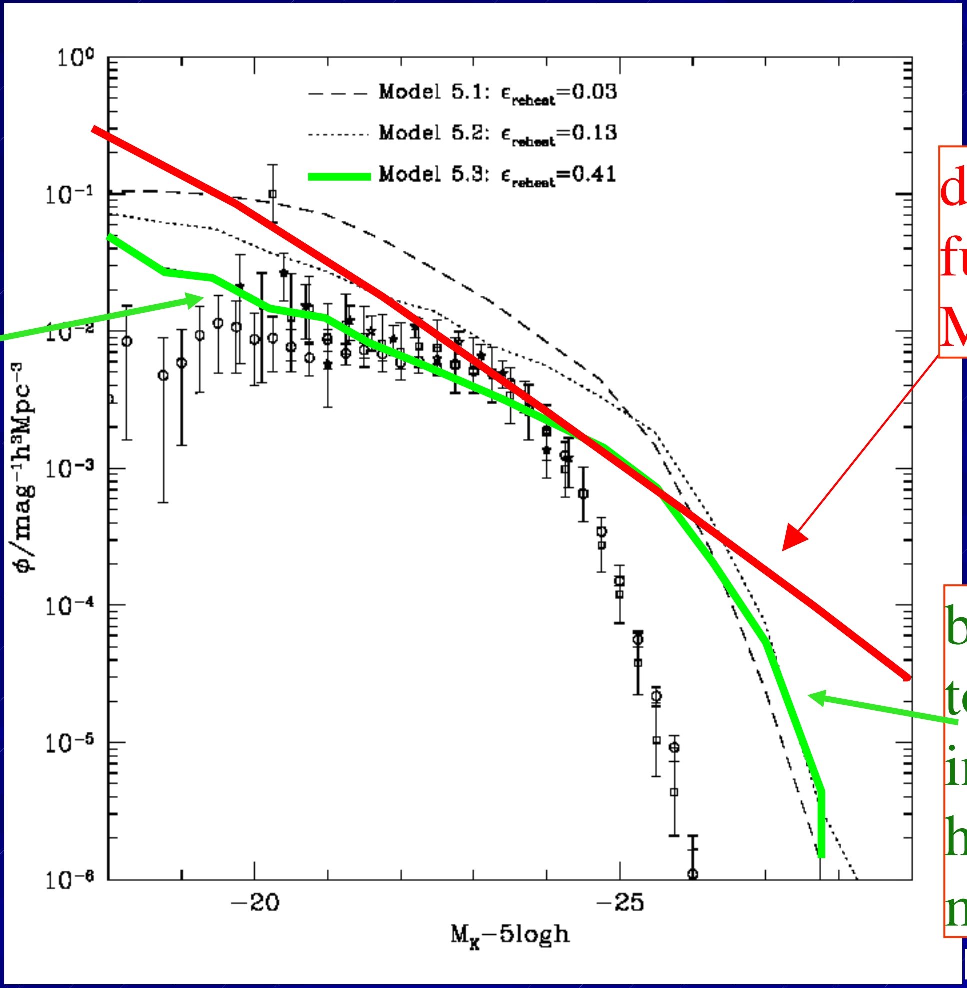
What cooling+feedback need to do!

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)

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

Benson et al 2003

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A solution: AGN

The two modes of AGN accretion

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The GALFORM family

- Cole et al 2000
  low baryon fraction
  - Benson et al 2003
    Superwinds/conduction
  - Baugh et al 2005
    Superwinds
    - Lacey et al 2008
      (Spitzer & IR)
  - Bower et al 2006
    AGN feedback
    - Font et al 2008 (environment)
      Bower et al 2008 (X-rays)

Superwinds

Radio Mode AGN

Many recent papers have their own implementation of AGN “radio mode” feedback,
eg. Crotton et al 2006, Cattaneo et al 2006, Kang et al 2007; Sommerville 2008

The Power of AGN

Comparison of energies:

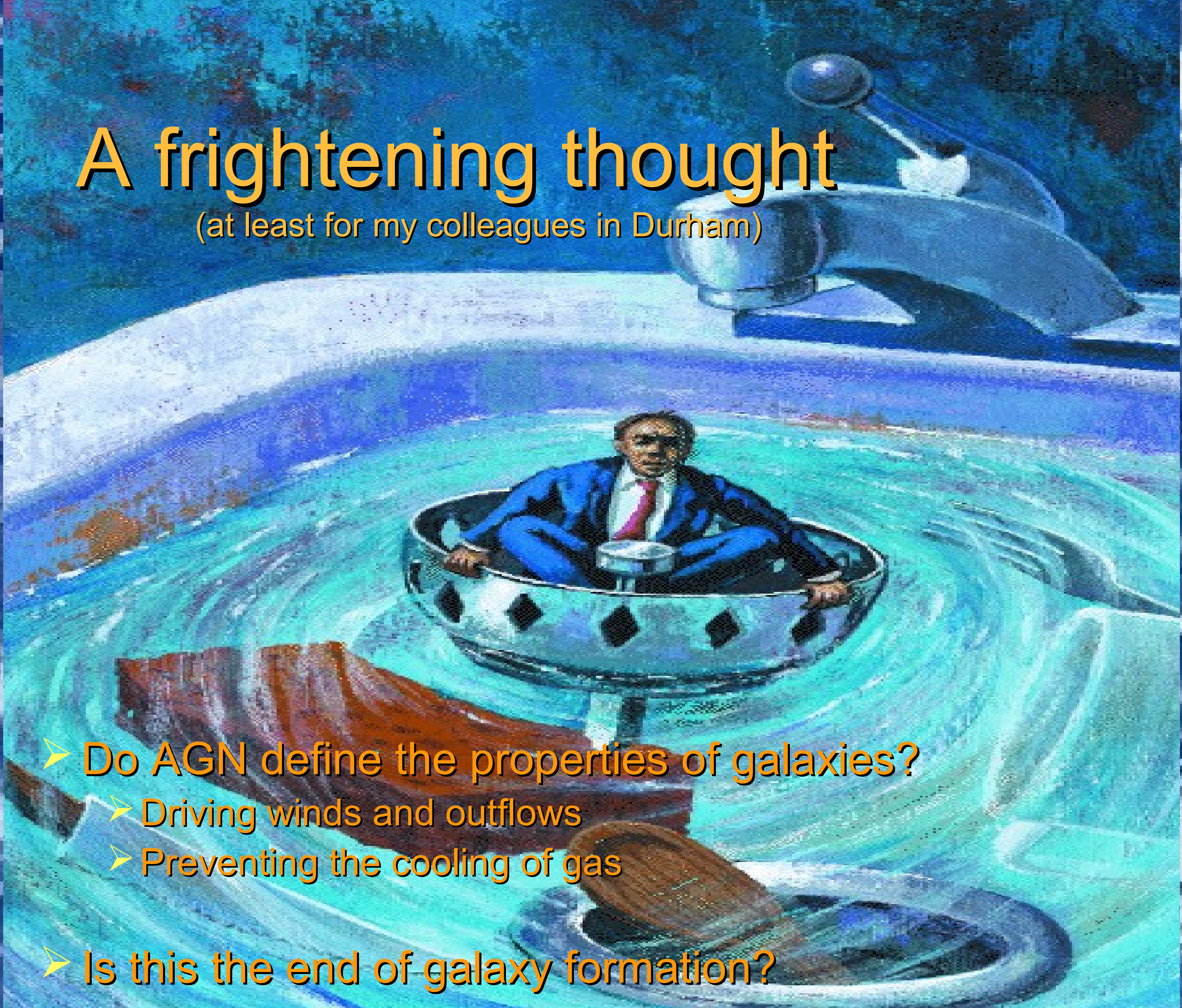
Thermal energy of a 10^{13} M_o halo … 10^{61} erg

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

It seems unlikely that AGN are unimportant!

A frightening thought

(at least for my colleagues in Durham)



- Do AGN define the properties of galaxies?
  - Driving winds and outflows
  - Preventing the cooling of gas
- Is this the end of galaxy formation?

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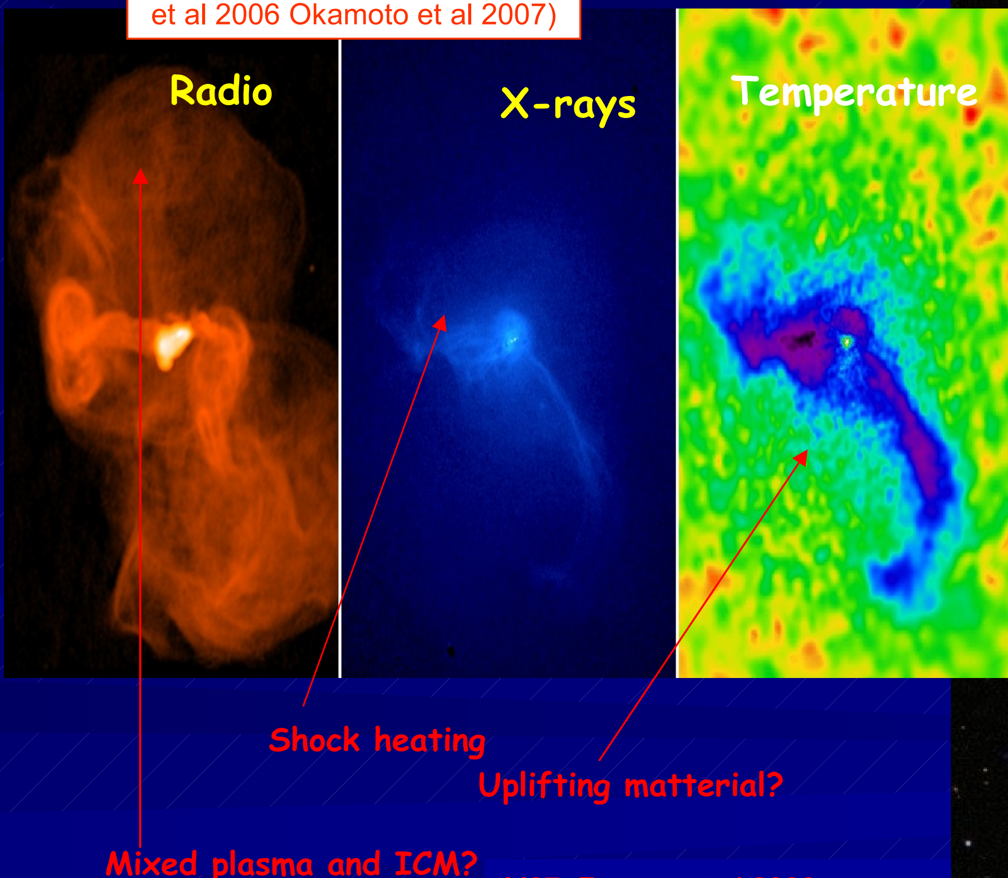
The two forms of AGN feedback

“Radio” mode feedback

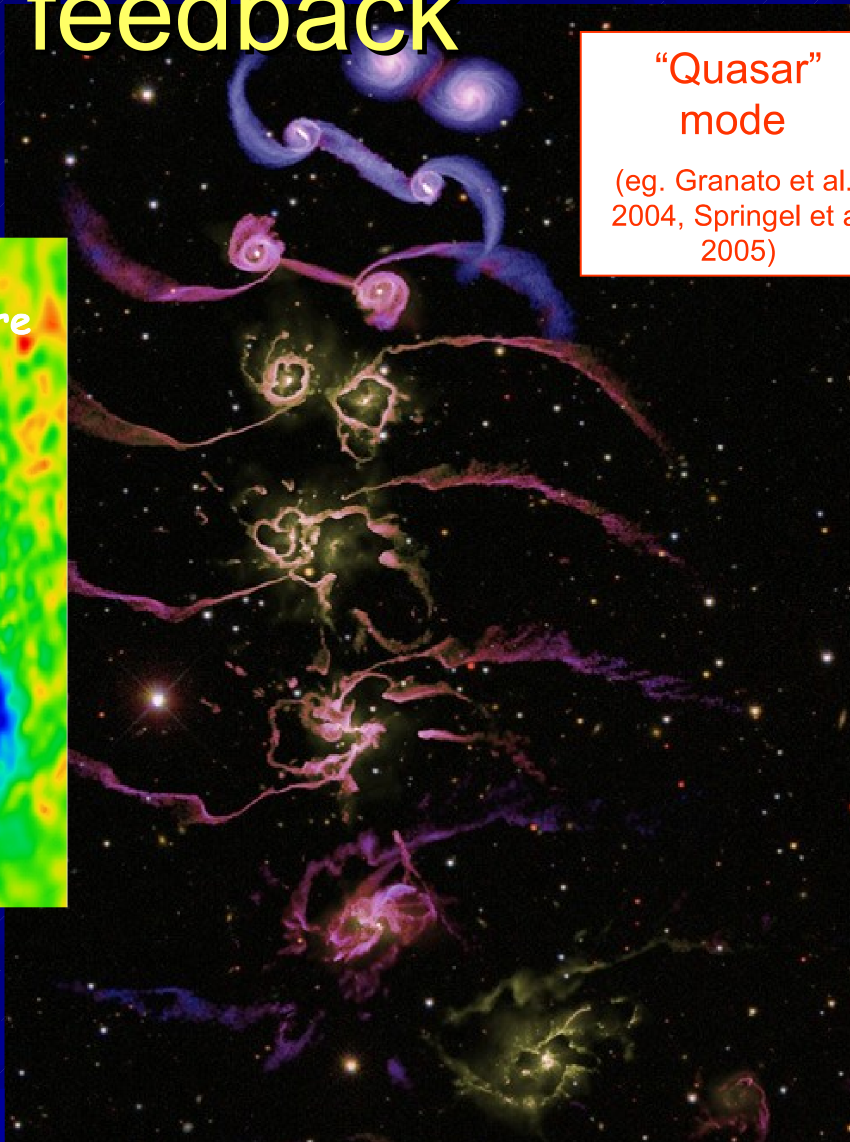
(eg. Croton et al 2006, Bower et al 2006 Okamoto et al 2007)



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

“Quasar” mode

(eg. Granato et al., 2004, Springel et al 2005)



Springel et al 2005

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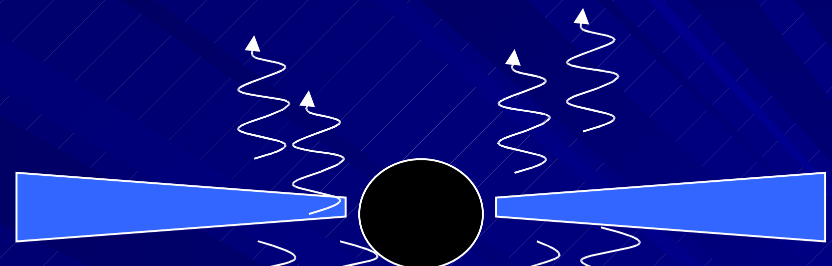
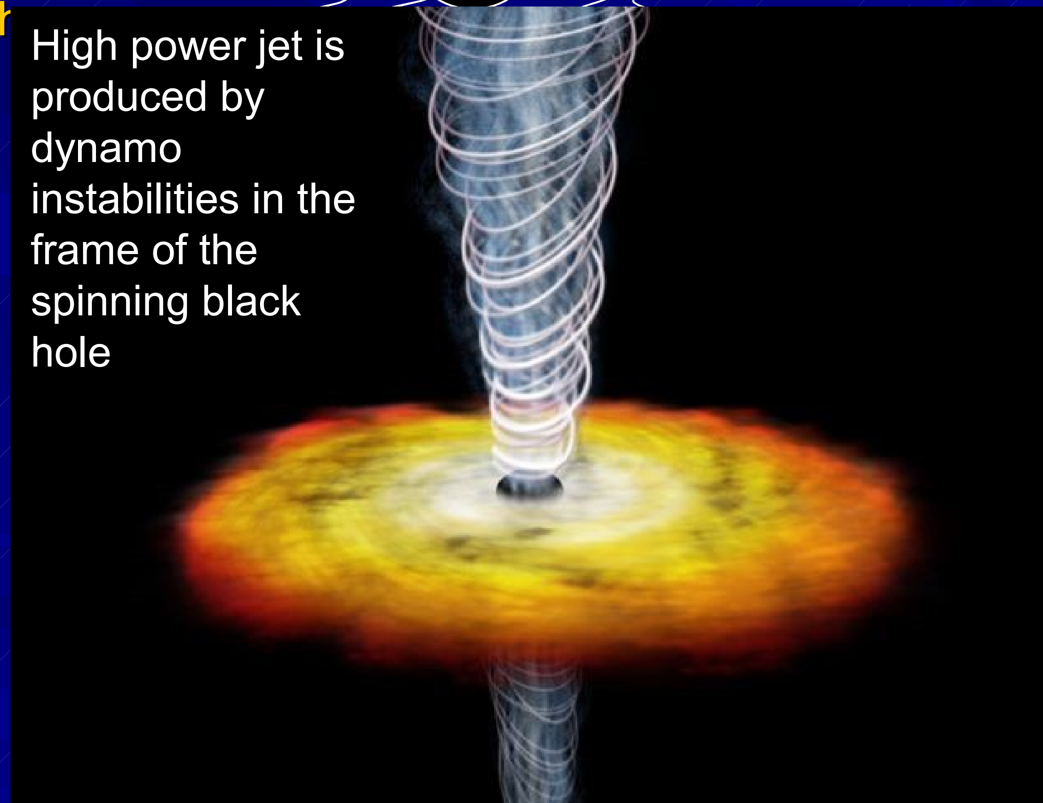
The two modes of AGN feedback



High accretion rate

Radiatively efficient flows
- •"normal" Shakura-Sunyaev disk
- •Geometrically thin
- •Heat generated by th flow is radiated
- •The disk stays cool and thin



Radiatively inefficient flows
- •Geometrically thick
- •Heat generated by the flow is trapped and advected into the black hole
- •The disk becomes hot and thick

(ADAF: Narayan & Yi 1995; RIAF: Blandford & Begelman 1999)

Low cretion rate

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1983, Meier 1999, 2001)

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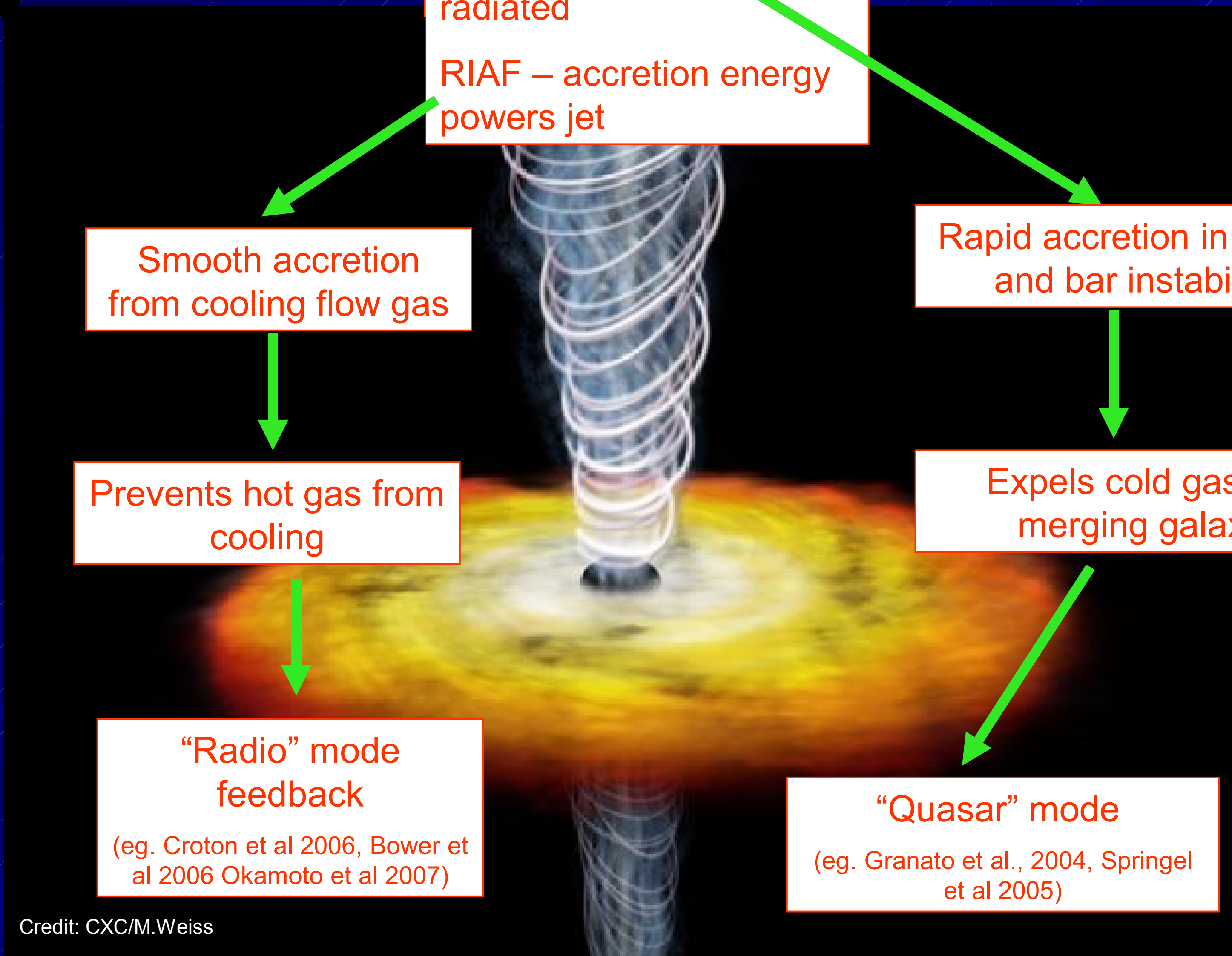
Two types of accretion?

SS – accretion energy is radiated

RIAF – accretion energy powers jet



Smooth accretion from cooling flow gas

Prevents hot gas from cooling

“Radio” mode feedback

(eg. Croton et al 2006, Bower et al 2006 Okamoto et al 2007)

Rapid accretion in mergers and bar instabilities

Expels cold gas from merging galaxies

“Quasar” mode

(eg. Granato et al., 2004, Springel et al 2005)

Credit: CXC/M.Weiss

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Why does the "radio mode" work?

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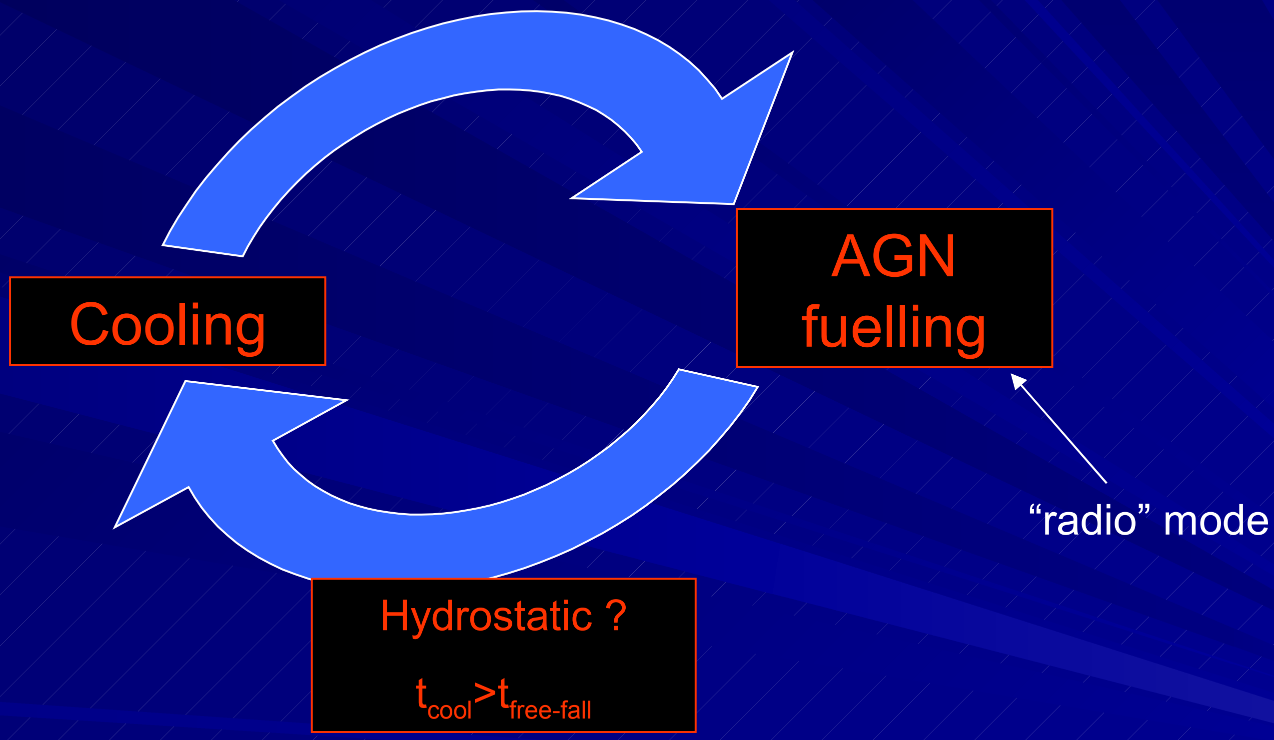
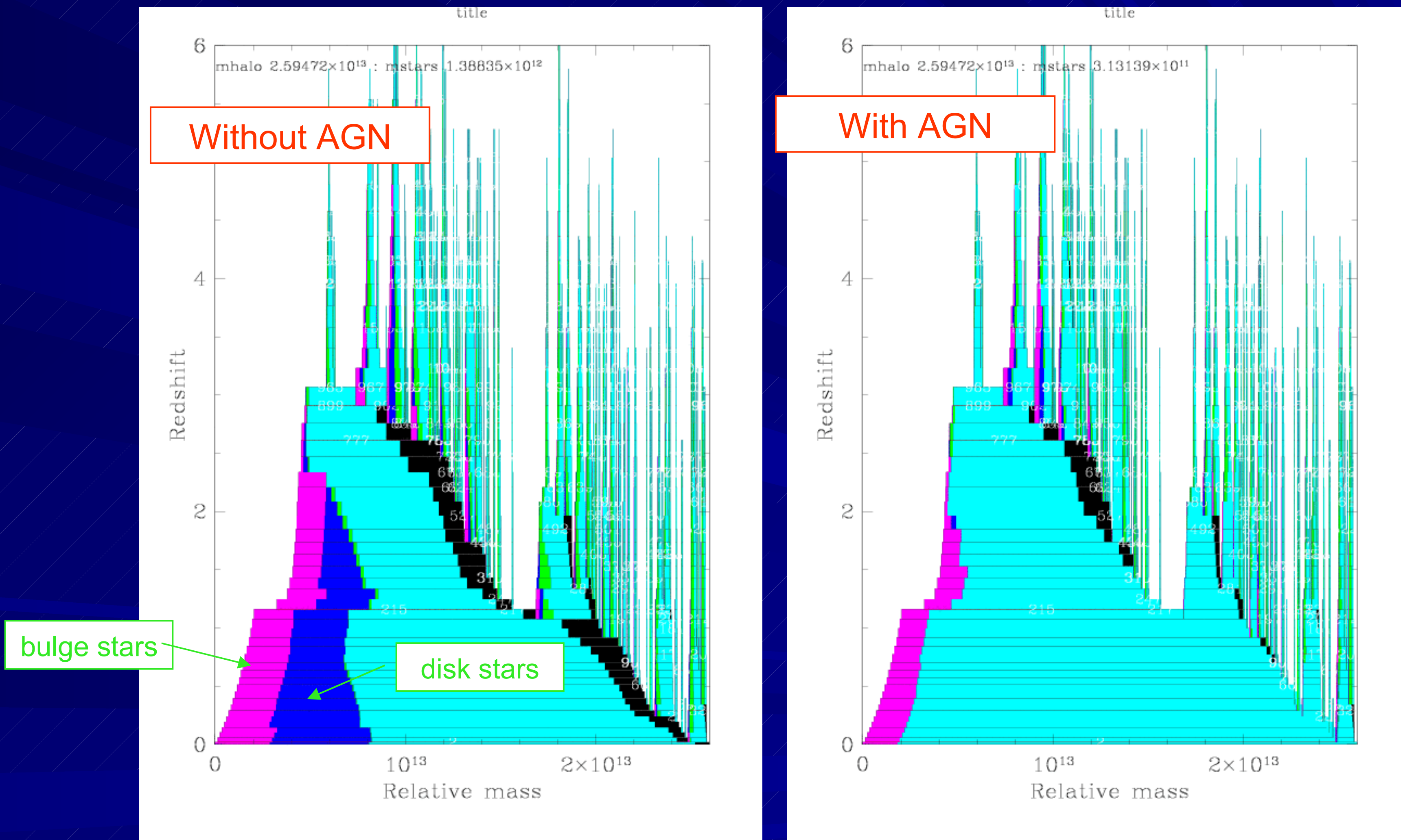
The AGN feedback loop



Keres et al 2003; Dekel & Birnboim 2003; Binney 2004

The impact of AGN Feedback: An Example



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Example from Cattaneo et al 06

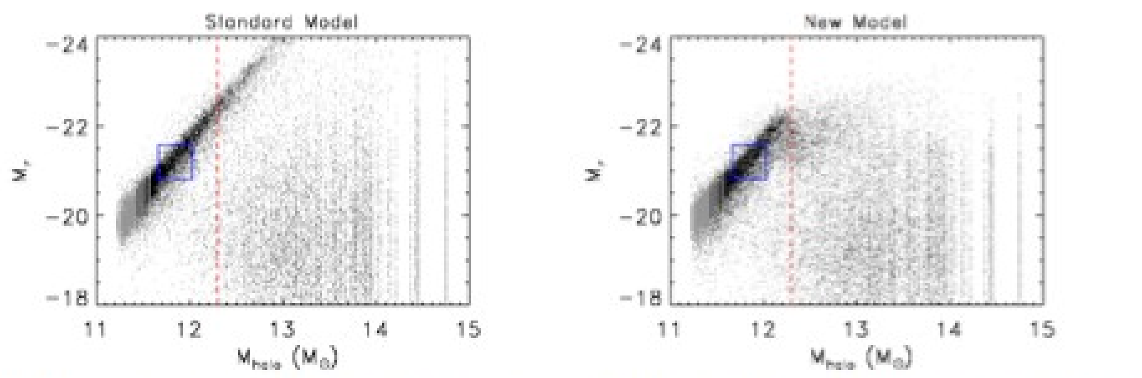


Figure 1. Galaxy luminosity versus halo mass for the "standard" model (left) and the "new" model (right). The blue square refers to the Milky Way (Binney & Merrifield 1998; Dehnen & Binney 1998). The vertical dashed line marks the shock-heating scale. The main difference between the two models is in the break in the relation at $M_{\rm halo} > M_{\rm shock}$ due to the shutdown above $M_{\rm crit}$ (Eq. 3). Some differences also show up below $M_{\rm shock}$ because of the shutdown of cooling in galaxies where the bulge is the dominant component.

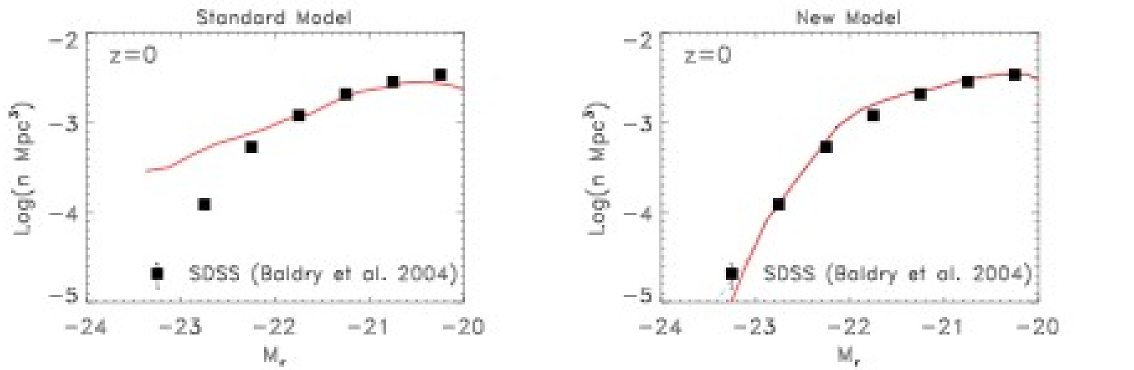
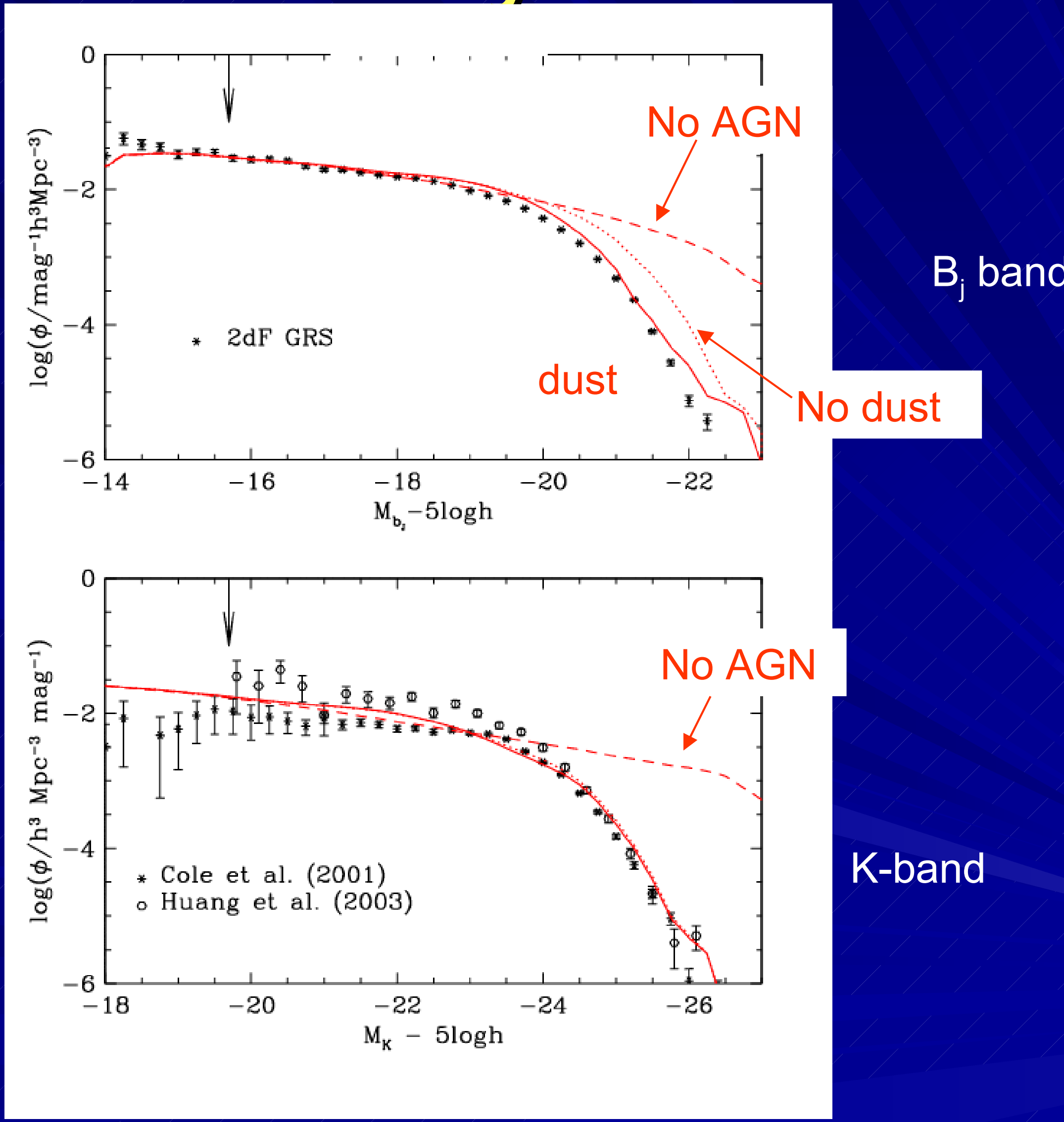


Figure 2. Luminosity function in the r−band. The model predictions (solid line, red) for the "standard" model (left) and for the "new" model with shutdown in massive haloes (right) compared to the observed luminosity function (symbols) observed by SDSS (Baldry et al. 2004). The dotted-dashed line (right) illustrates the effect of lowering the critical redshift from $z_c = 3.2$ to $z_c = 3$.

Similar plots in Croton et al 06

Present-day Galaxies

- Bj and K luminosity functions
- Switching “radio” feedback off leads to a population of very bright galaxies formed in cooling flows
- But position of the LF break is set by the division between rapid and hydrostatic cooling haloes.



Different implementations - same aim

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- RGB
  - AGN “radio mode” offsets hydrostatic cooling if BH is sufficiently massive
- Croton/De Lucia
  - Compute “radio mode” feedback energy from mass of halo and black hole (loosely based on bondi accretion of multiphase gas)
- Cattaneo et al
  - Separate hot and cold accretion above a (redshift dependent) threshold mass.
- Kang/Summerville
  - Radio mode driven by multiphase bondi accretion model
- Menci/Monaco(/Baugh05)
  - BH(SN) driven superwinds
- Etc…

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Are the semi-analytic recipies justified?

- “Gastrophysics” is still a difficult problem
  - How does the thermal energy from Sne couple with the ISM?
    - If resolution is low, this energy is just radiated away
  - How does the AGN interact; how is it triggered?
- Still hard (impossible) to simulate a significant population of galaxies with adequate resolution
- The prospects for “ab initio” simulation of galaxies
  - Learn and embed in semi-analytics
  - Embed sub-grid semi-analytics in simulation

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How well does it work?

Comparison with data

- Cirasulo et al.

Faint end overshoots - but see Khochfar 08 et al

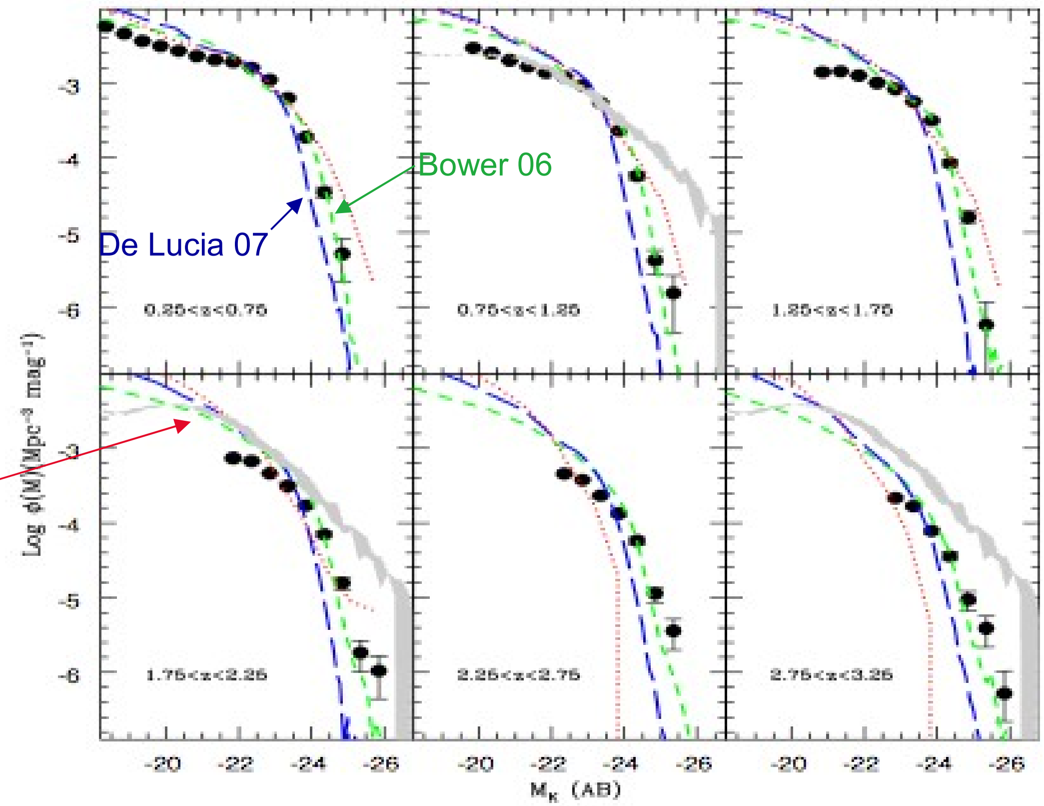
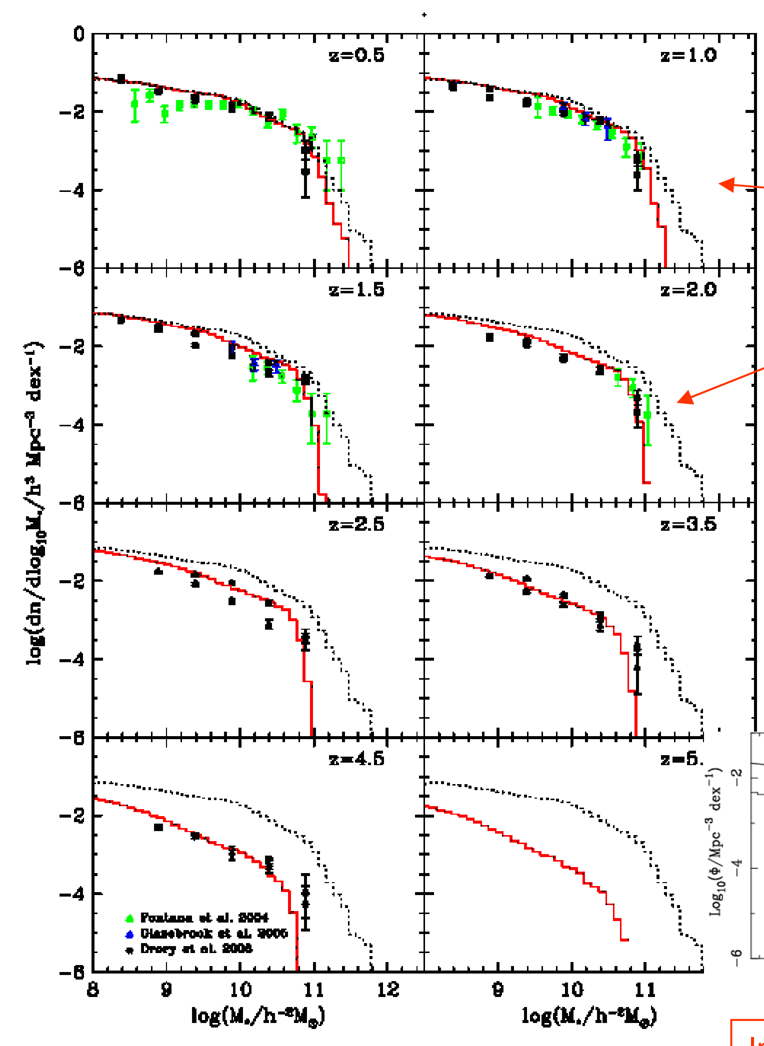


Figure 6. Comparison of our determination of the K-band LF (solid dots) with predictions of theoretical models. Short and long dashed lines are the predictions obtained by Bower et al. (2006) and De Lucia & Blaizot (2006), respectively. The predictions by Monaco et al. (2007) are shown with a dotted red curve. The gray area shows the prediction obtained by hydrodynamical simulations (Nagamine et al. 2006; Cen & Ostriker 2006).

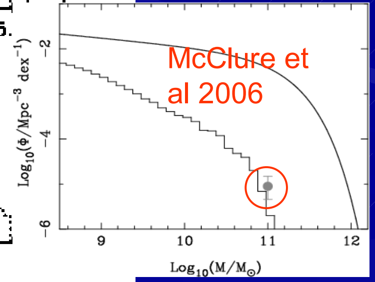
Evolution of the Stellar Mass Function

- The evolution of the stellar mass function from Drory et al 2005.



z=0

AGN model



McClure et al 2006

Integrated SMD agrees with Stark et al 2006

Evolution of rest-frame K-band LF

Bright galaxies are in place at high-z

At hi-z:

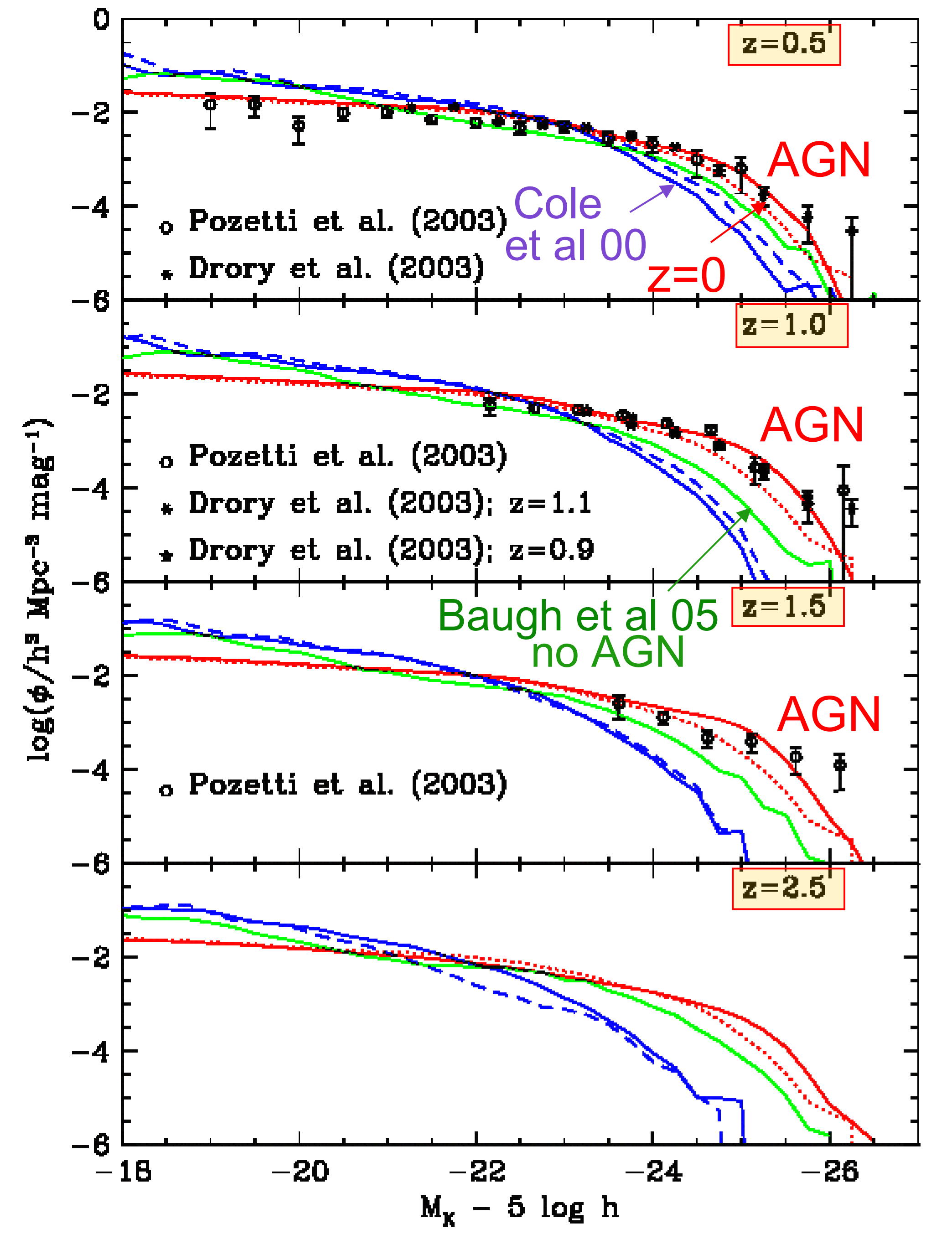
- Improved gas cooling model

⟹ more efficient star formatn

- Halos less likely to be hydrostatic & have small BHs

⟹ no AGN feedback

⟹ Gals form efficiently at hi-z



Bower et al 06

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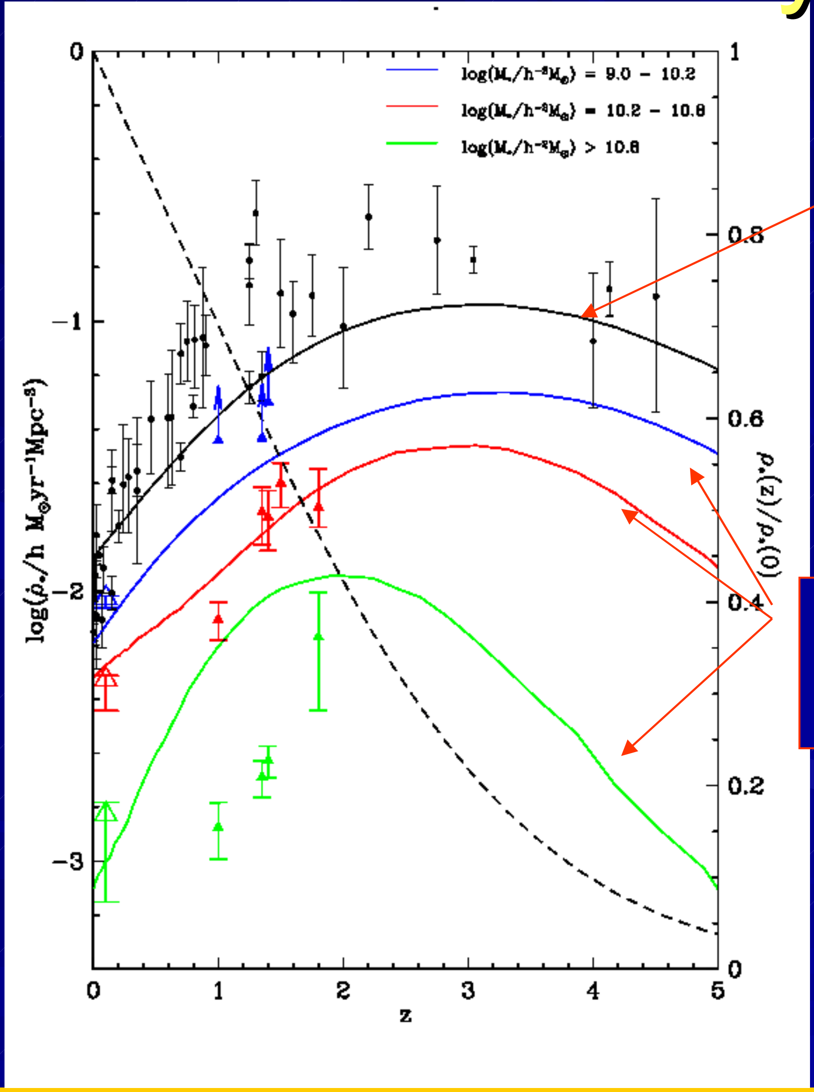
The evolution of star formation history

- Star formation History
- Juneau et al use GDDS to divide this by mass.
- AGN model works well.
- Massive galaxies have higher SFR in the past
- … but small galaxies always dominate!



Global average

Contribution from different mass ranges

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Evolution of colours

- Evolution of red sequence tracks passive evolution
- …but the blue sequence also get bluer – matches the increase in SFR density

QuickTimeS and a decompressor are needed to see this picture.

Bower et al 2006 & De Lucia et al 2006 galaxy catalogues are public!
www.mpa-garching.mpg.de and www.icc.dur.ac.uk

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Problem solved?
No Way!

Challenges for galaxy formation models

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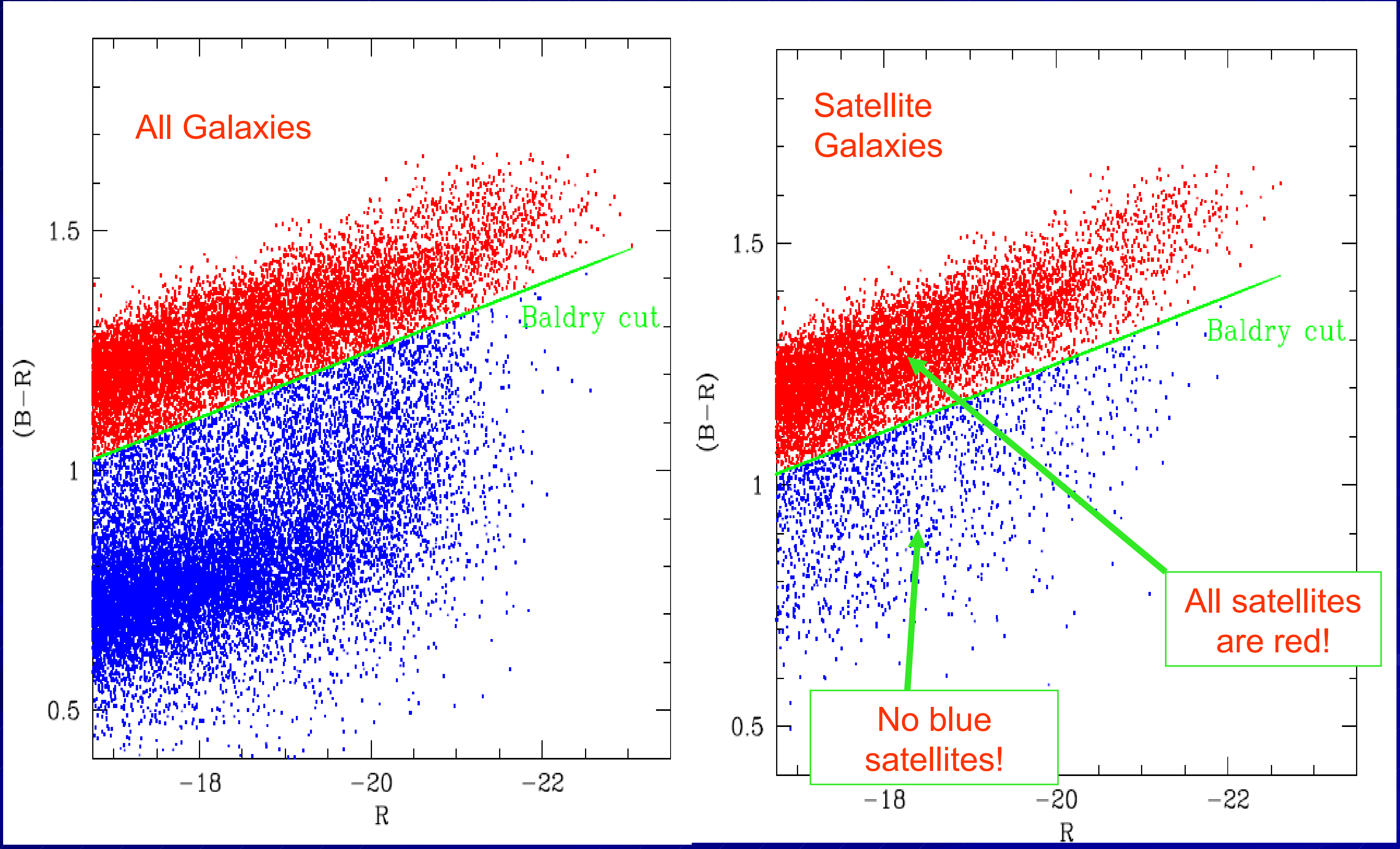
Environment

Models need more sophisticated treatment of environmental effects:

Kang et al

Font et al

Environmental Physics is not correctly handled



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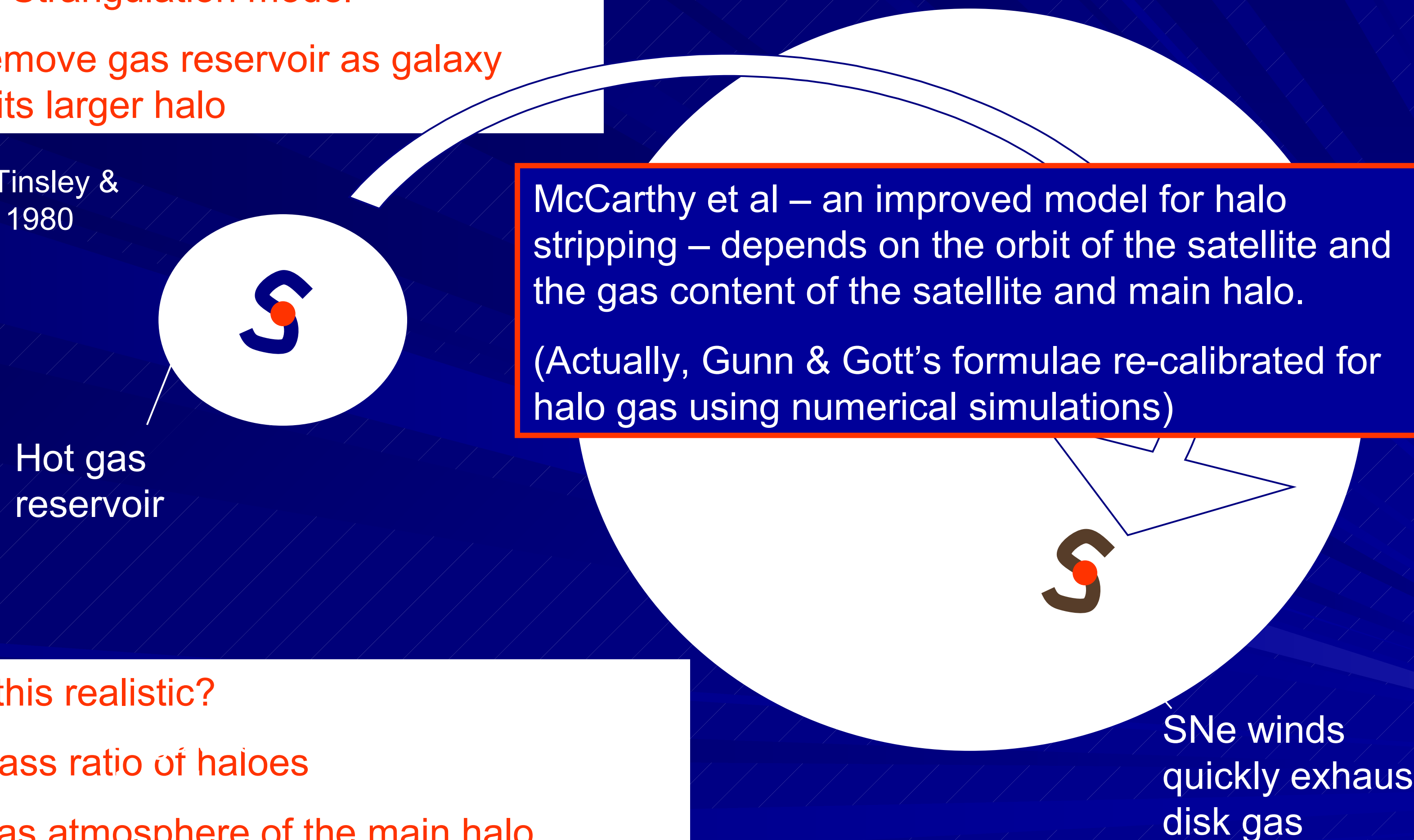
Environmental Physics is not correctly handled

Old Strangulation model

•Remove gas reservoir as galaxy orbits larger halo

Larson, Tinsley & Caldwell 1980



McCarthy et al – an improved model for halo stripping – depends on the orbit of the satellite and the gas content of the satellite and main halo.

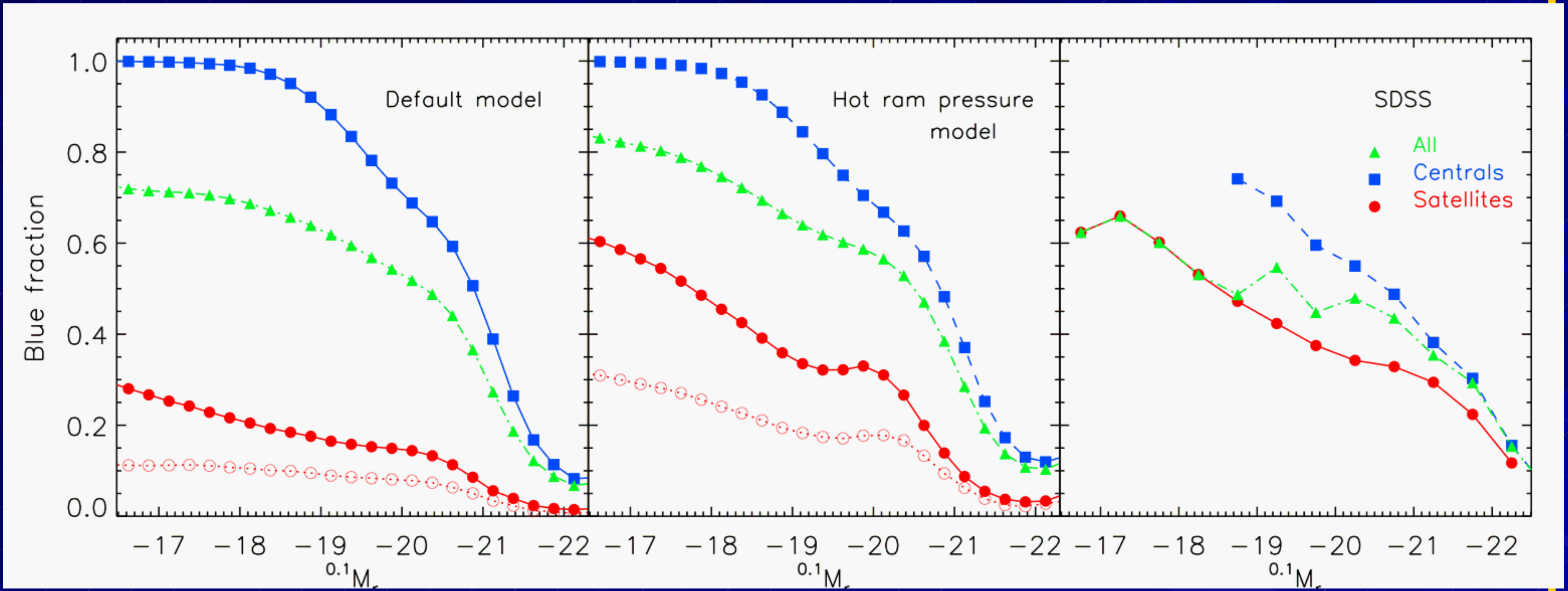
(Actually, Gunn & Gott's formulae re-calibrated for halo gas using numerical simulations)

Is this realistic?

•Mass ratio of haloes

•Gas atmosphere of the main halo

Blue galaxy fraction with an improved treatment of environment



Weinmann et al 2006; Font et al, 2008

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X-rays emission from groups and clusters

The Achilles' heal of these models???

X-ray Emission from Groups and Clusters

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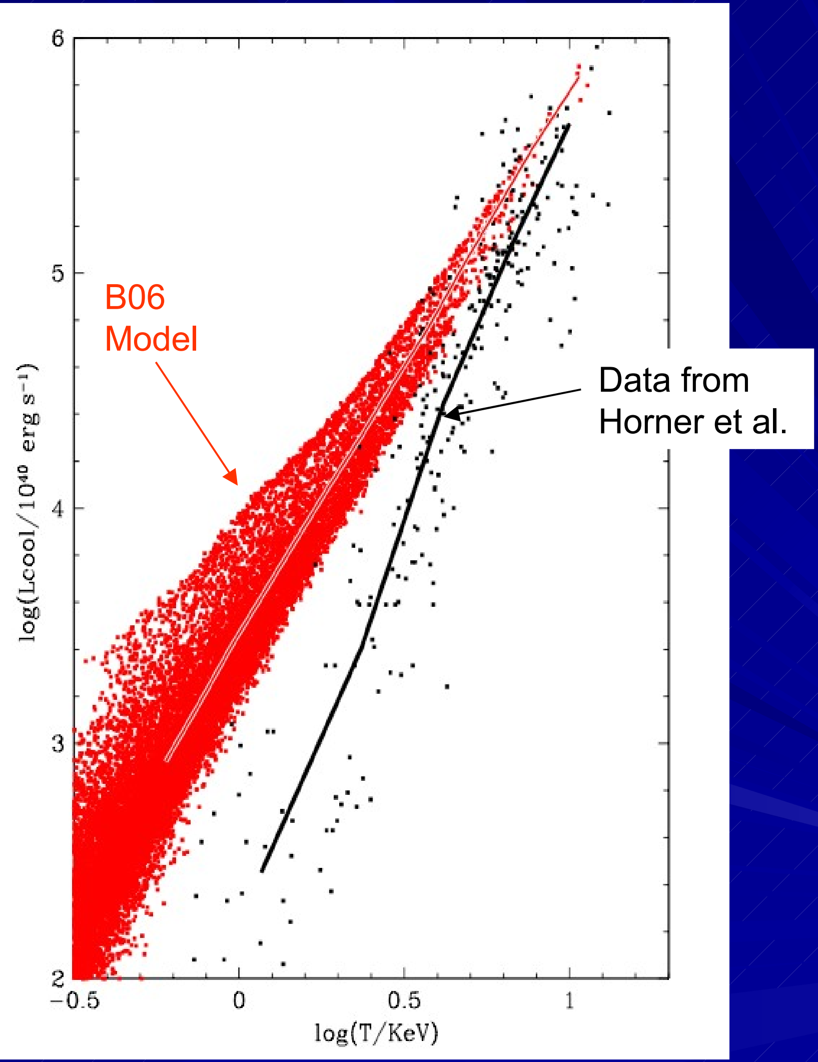
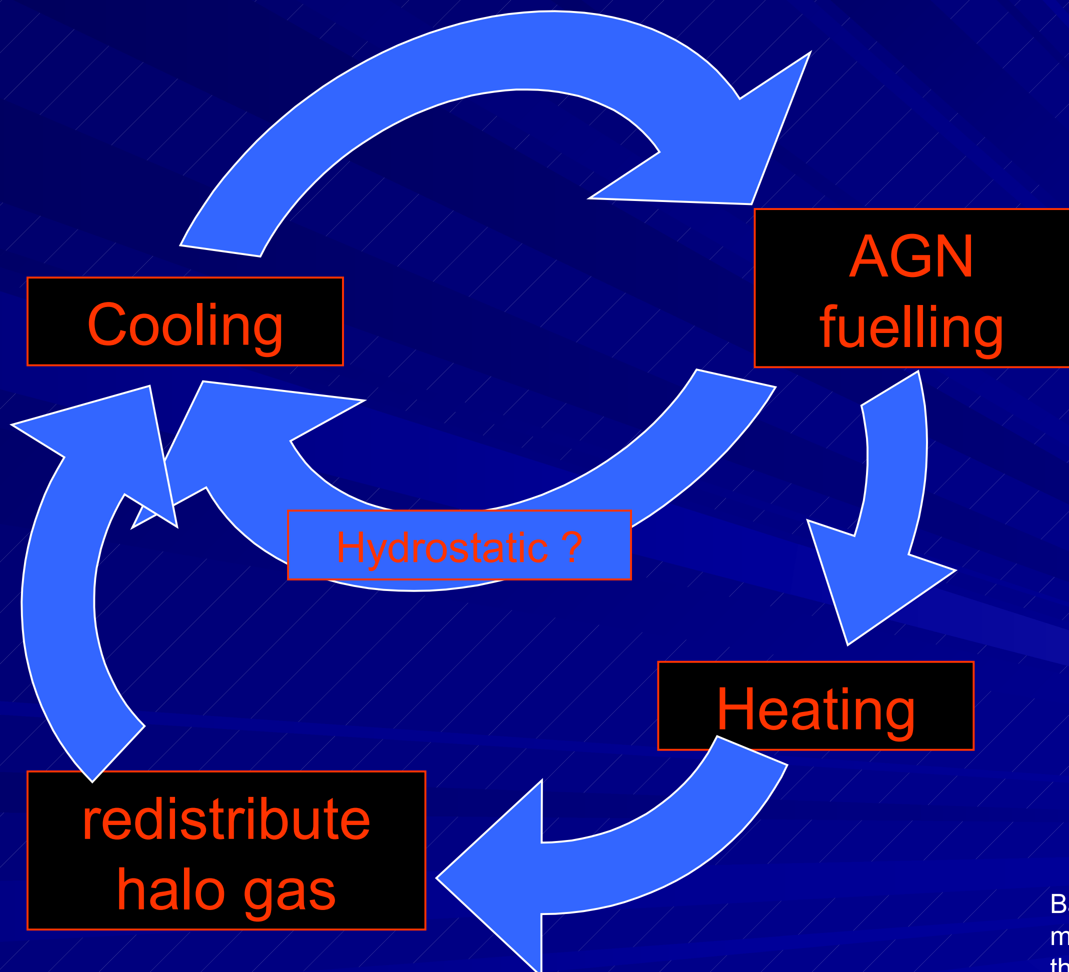
- L-T relation : well known that the self-similar relation fails
- AGN: standard model just prevents cooling… it doesn't affect the X-ray luminosity



The AGN feedback loop (new version)



Based on the "excess energy" method (Wu et al 1999), plus the hydrostatic criterion

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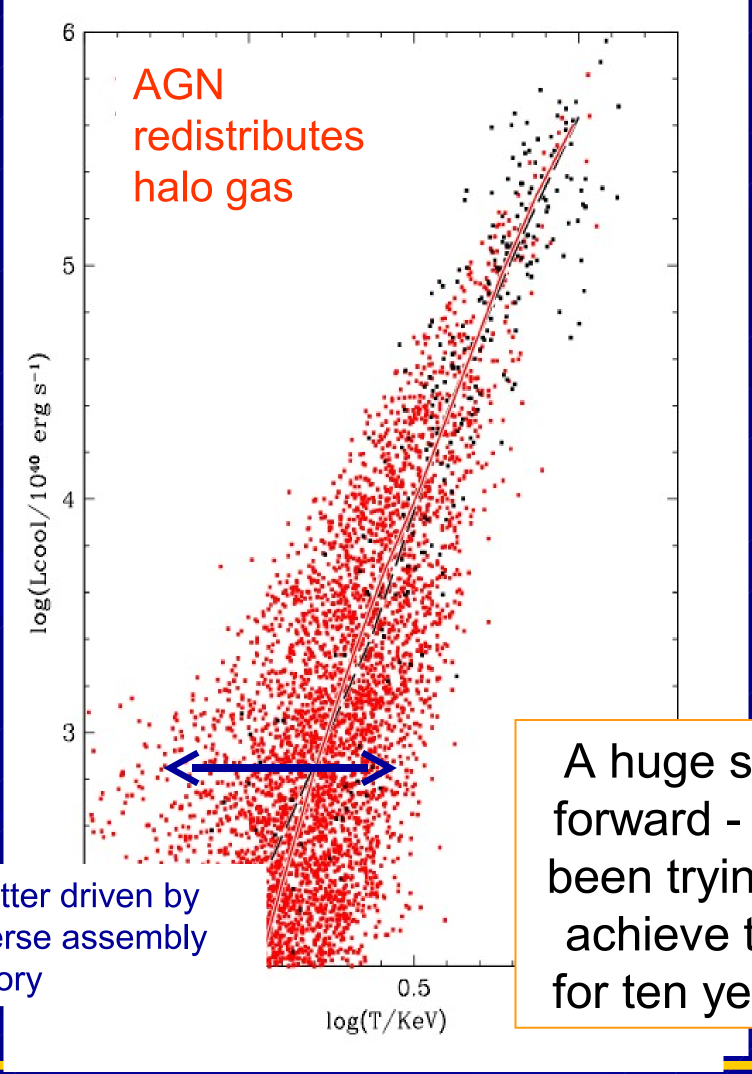
X-ray Emission from Groups and Clusters

- L-T relation : well known that the self-similar relation fails
- AGN: standard model just prevents cooling
- Revised model, AGN feedback redistributes halo gas until the cooling rate drops and AGN power is cut off



Scatter driven by diverse assembly history

A huge step forward - I've been trying to achieve this for ten years!

Voit & Bryan 2001; Bower et al 2008, submitted

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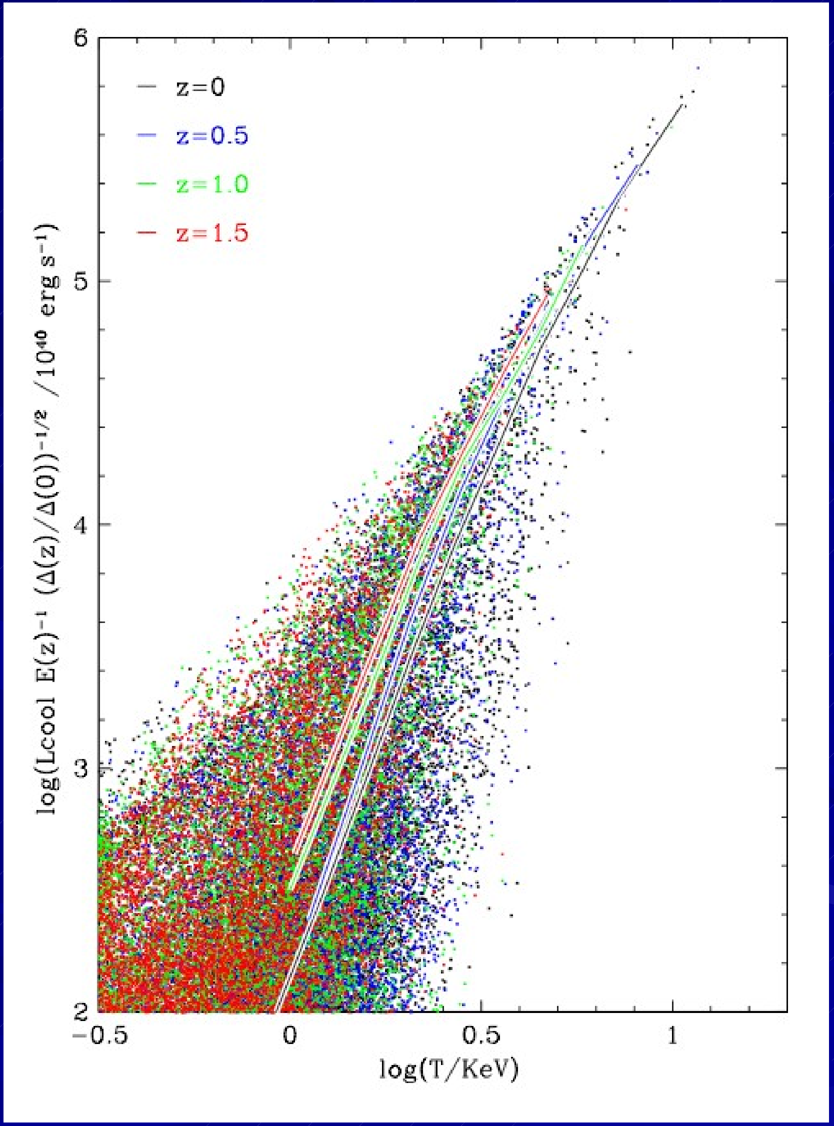
Evolution!

- An important test - if halo gas has only been ejcted recently, model will fail.
- Colour indicate redshift (0,0.5,1.0,1.5)
- L_x evolution is not quite described by the "self-similar" evolution factor.
- Compatible with current data, but is this detectable?



The baryon content of haloes - where are all those baryons?

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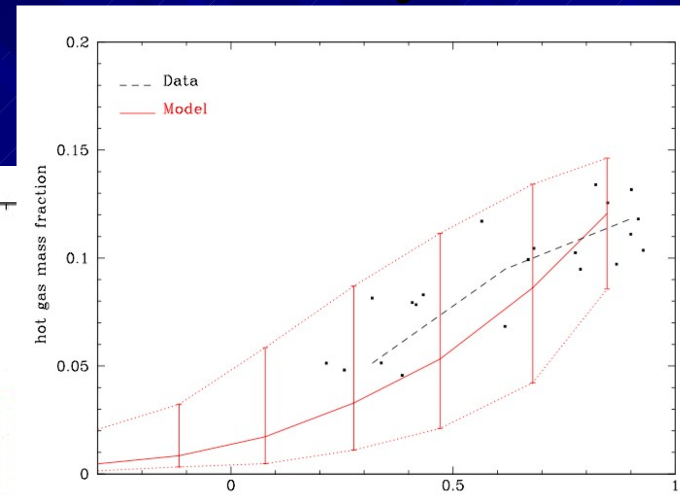
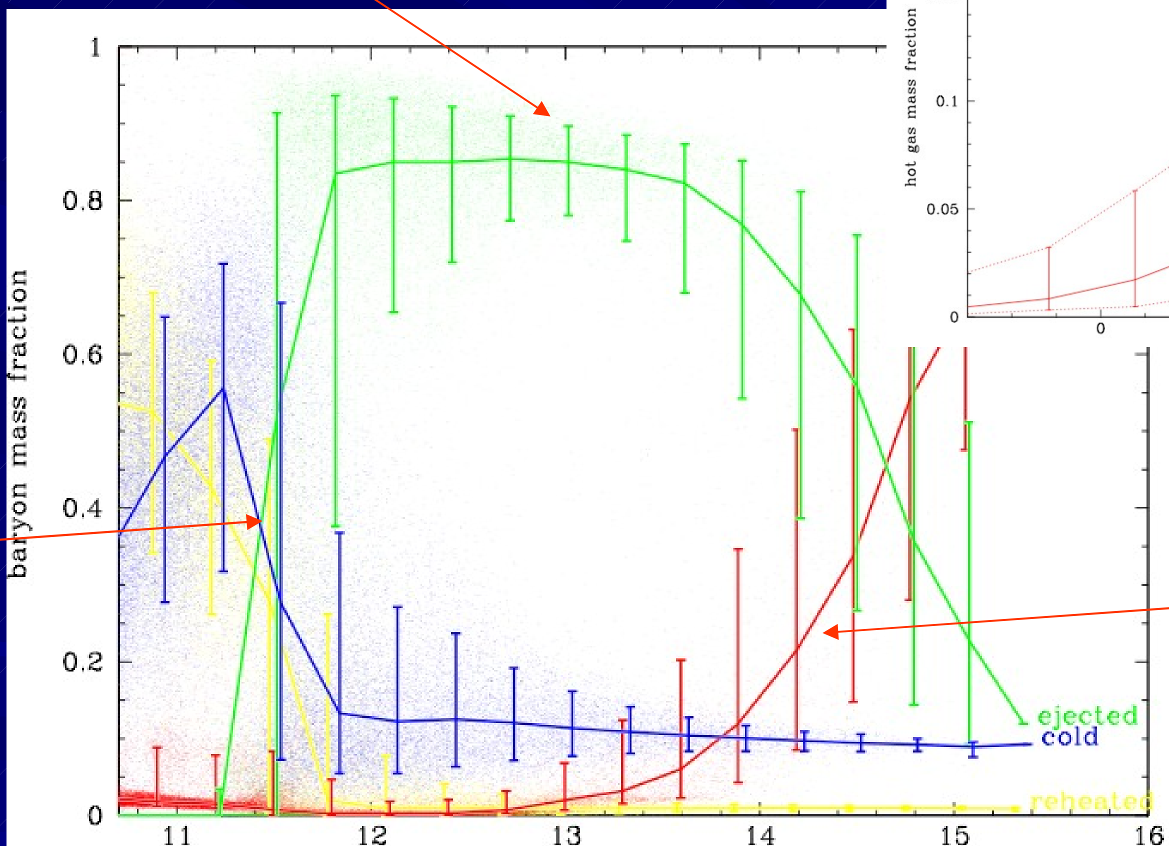
“Ejected” gas



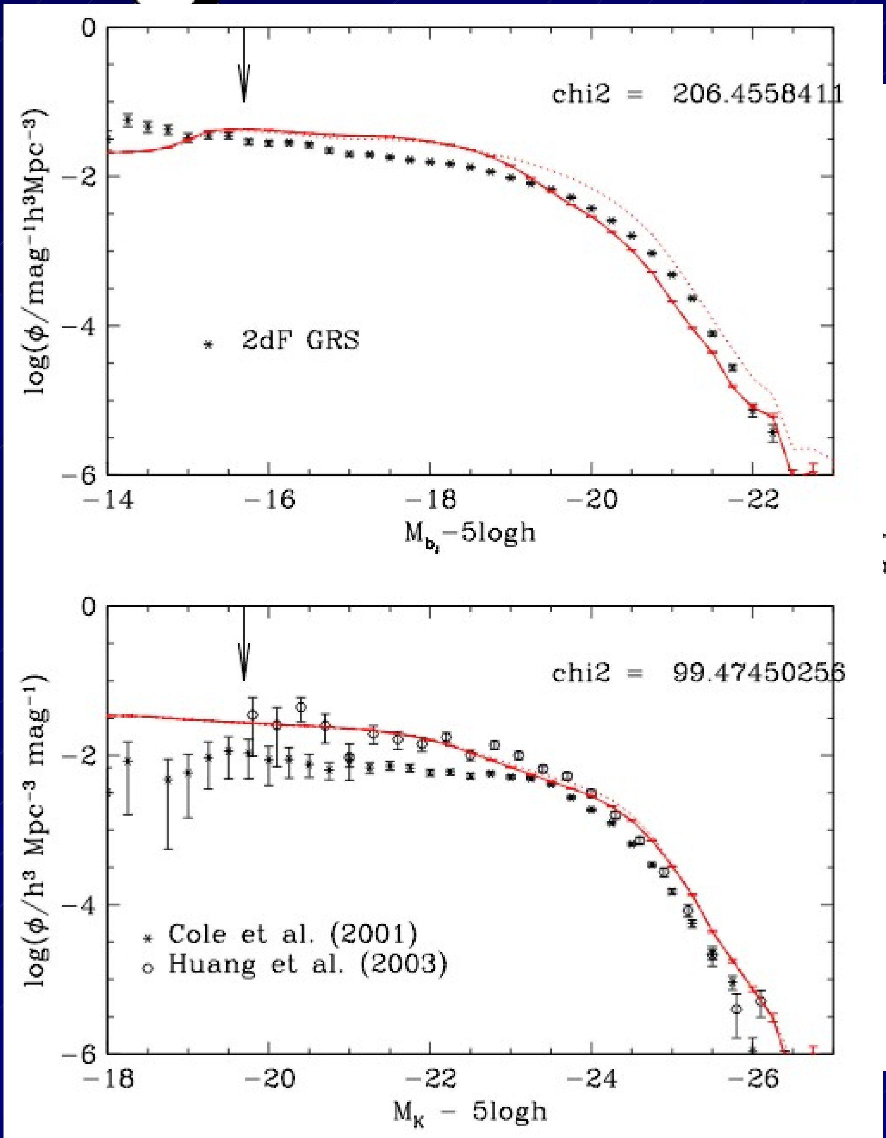


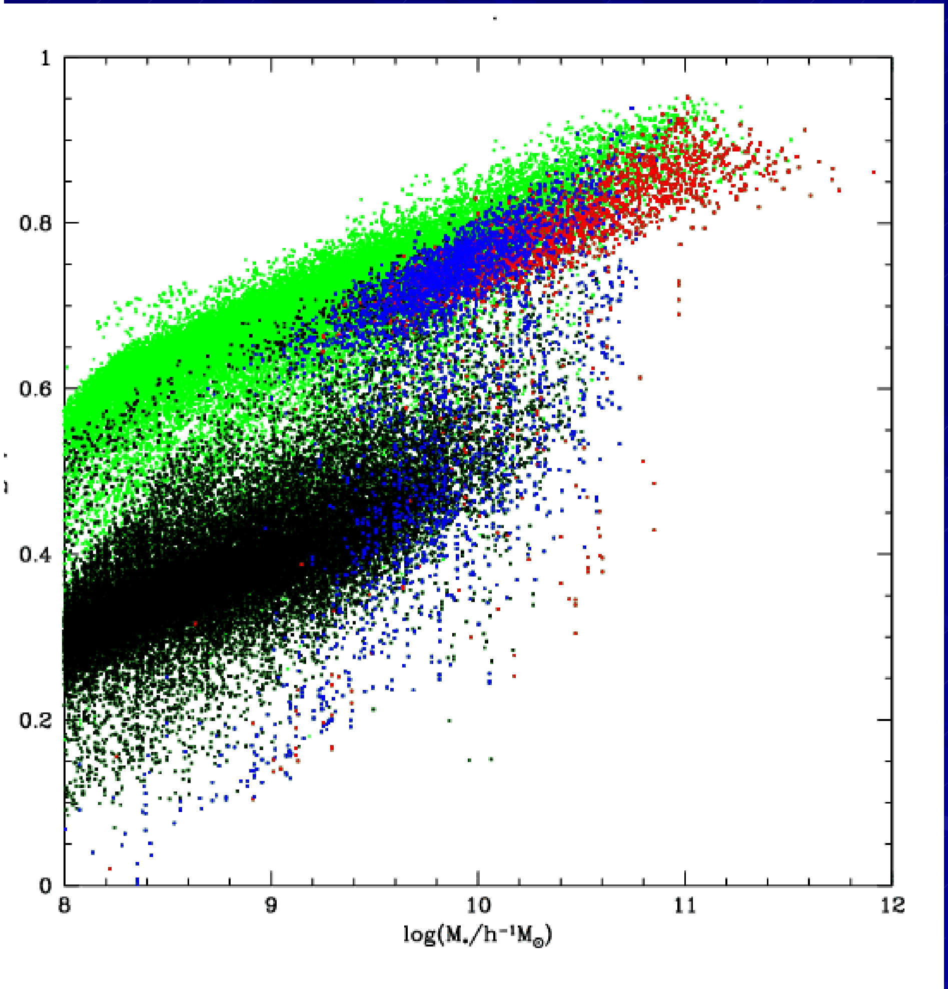
Stars and cold gas

Hot X-ray emitting gas

Halo mass

What about the galaxies?





But note! The parameters have all changed!

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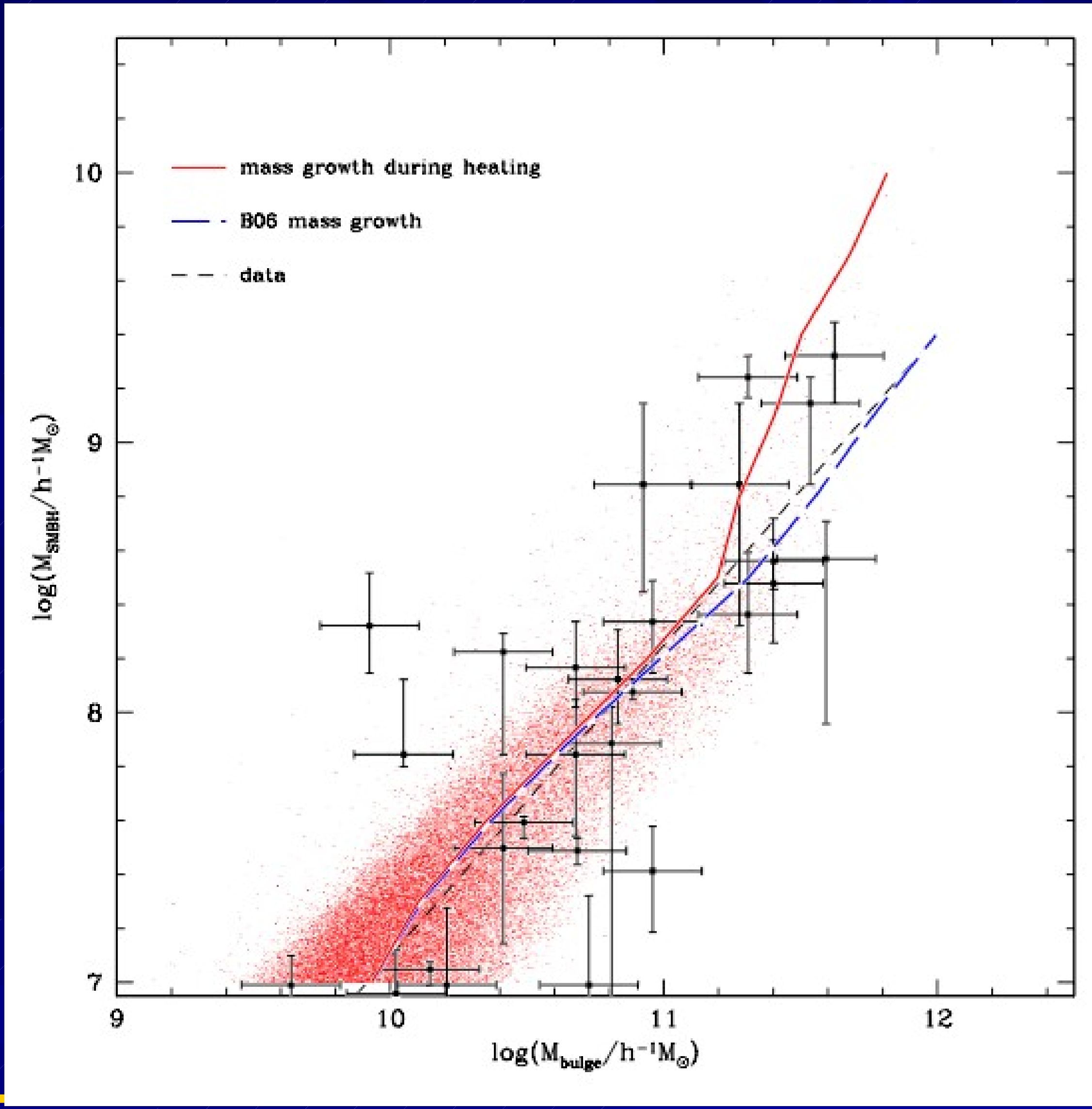

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Where are we?

- Semi-analytics working well in many respects
- Many aspects are coming out well!
- Almost justified by numerical simulations (…discuss…)

- But there are plenty of problems…
  - SCUBA galaxies
  - Morphology/Sizes (both in SA and numerical models)
  - Narrowness of the CMR
  - understanding BH accretion (Bondi can't be correct!)
  - All the other problems…

I don’t believe any of this…

with so many parameters you can fit anything!

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Just how many parameters are there?

- Not all parameters are equal
  - Some are set by external simulations
  - Some have a very weak effect
  - Some are physically degenerate

- Just how many are there?
  - Input file contains 50 numbers (but many are legancy for older versions)
  - It makes sense to vary 20 parameters
  - 8 parameters dominate the variance
  - But acceptable models occupy less than 1% of the parameters space

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The space of acceptable models

- The methods…
  - Use model runs to sample the surface.
    - Latin hypercube provide maximum information on parameter dependencies
  - Construct "emulator" to interpolate between runs
    - Use low-order polynomial plus "Gaussian process".
  - Rule out "implausible" regions of parameter space
    - Allow for emulator uncertainty make conservative choice
  - Limit region of interest and generate a new wave of runs
    - surface is smoother and so emulator is more accurate

- "What's the answer"
  - How unique is the Bower06 model?
  - How much do other properties vary within acceptable models?
  - Do parameter degeneracies have a physical interpretation?

With Ian Vernon & Michael Goldstein, Maths.

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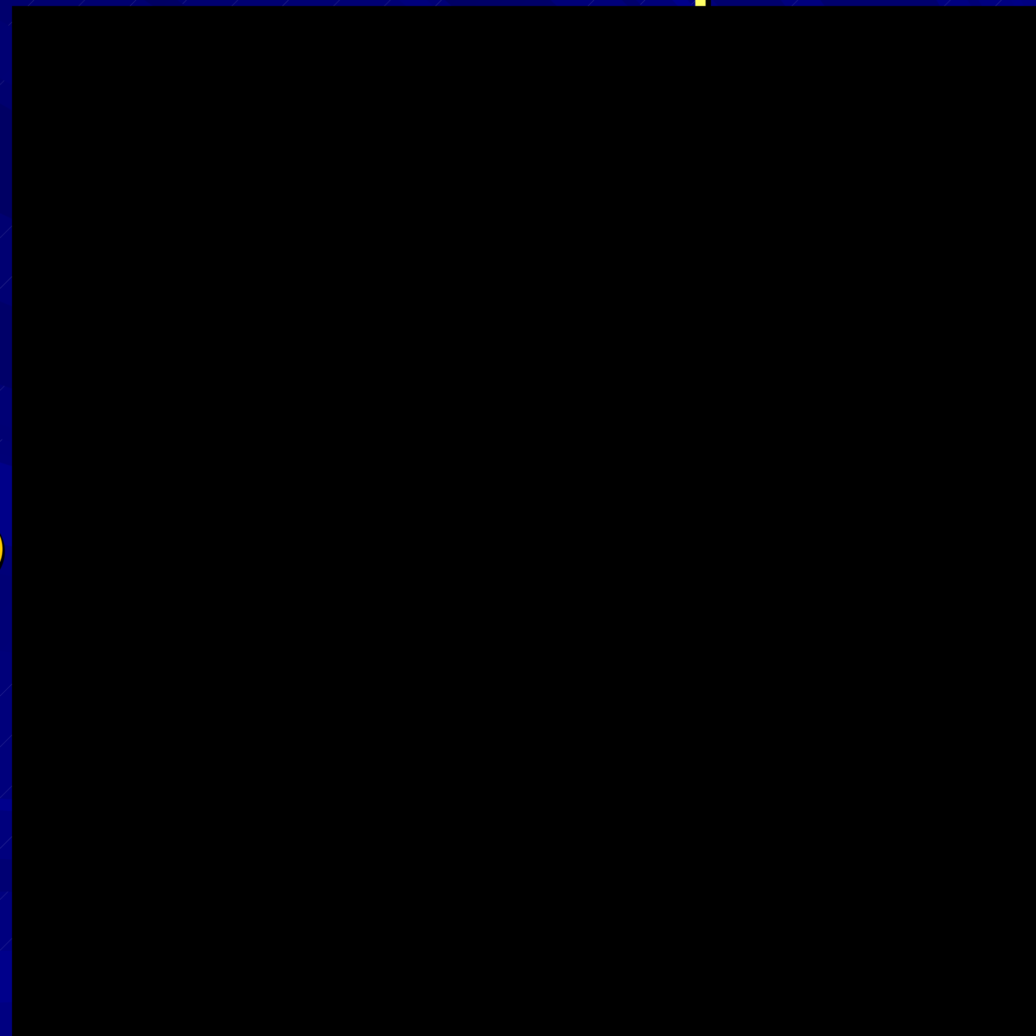
The Galform Parameter Space

- 2-sigma discrepant models occupy 1% of the volume.
- Difficult to visualise an 11-d space!
- Project to 3-d using the least discrepant point (still hard to fully sample!)
- x,y,z = $v_{hot}, \alpha_{reheat}, \alpha_{hot}$



The Galform Parameter Space

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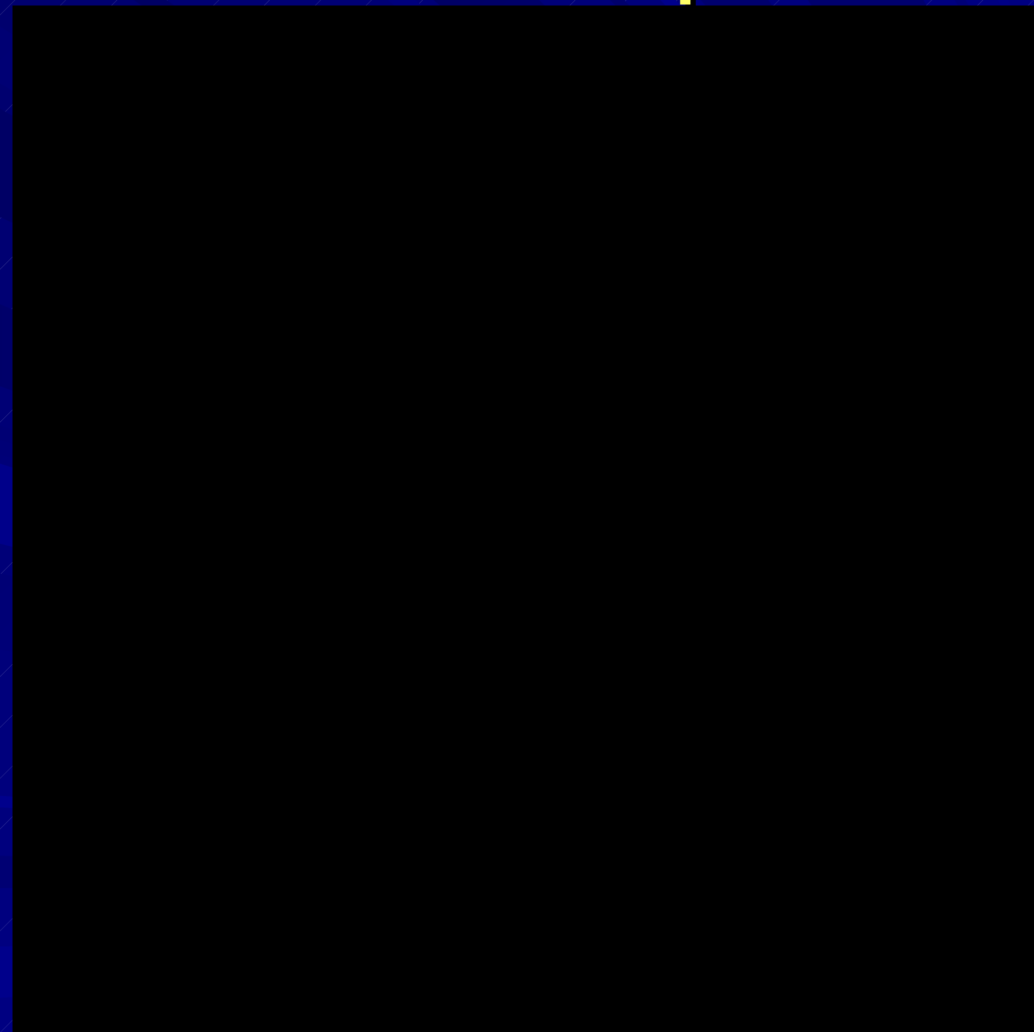

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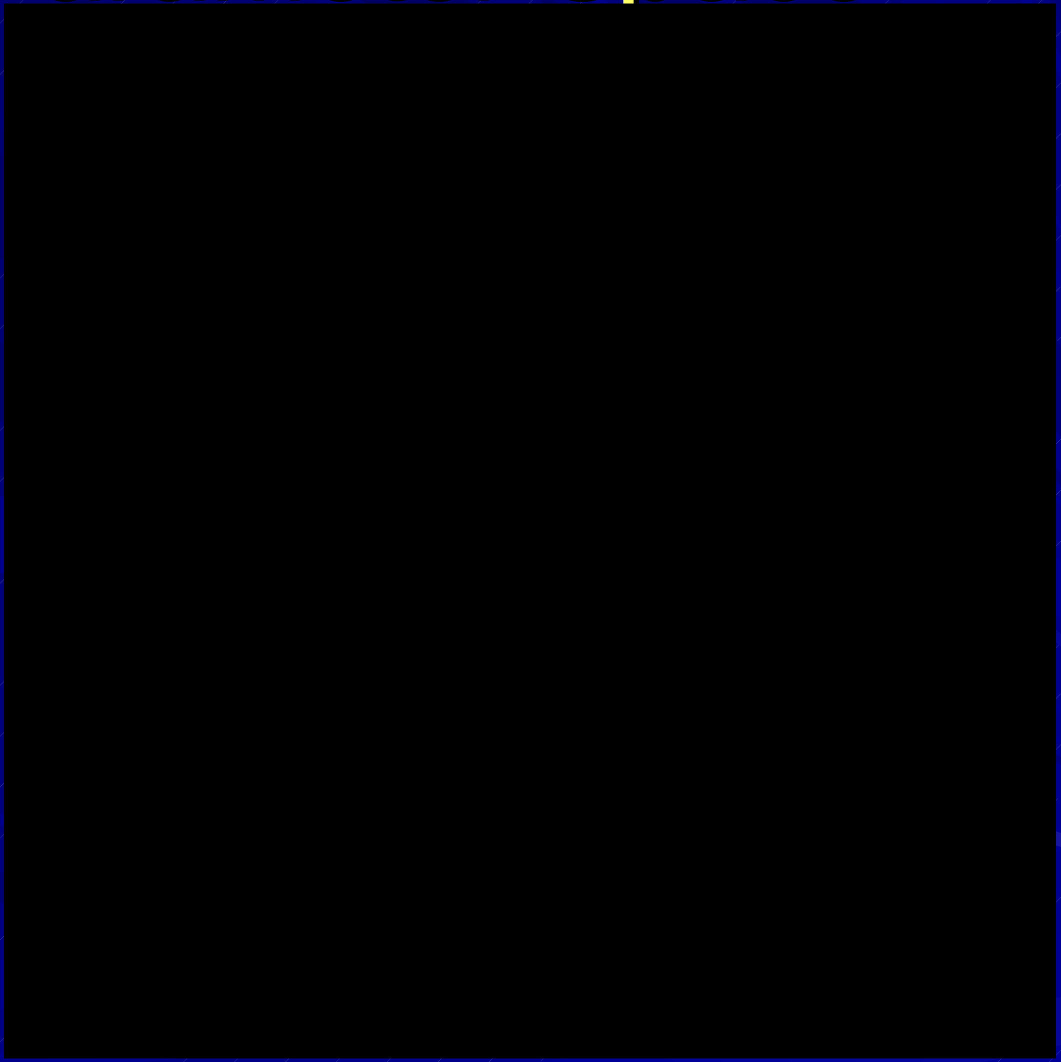
The Galform Parameter Space



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- $x,y,z = v_{hot}, \alpha_{reheat}, \alpha_{hot}$

Conclusions

Semi-Analytic models - are we kidding?

Semi-Analytic Models: "are we kidding?"

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- What I've told you:
  - Gas physics is difficult
  - Semi-analytics vs direct simulation
  - The challenges for galaxy formation models
  - Where we stand & future challenges
    - Environment
    - X-ray emission
  - Systematically exploring the parameter space…
- Why you should listen!
- Semi-analytic models are:
  - A fact of life
    - We need them!
    - Where do we draw the boundaries?
  - A method for multi-scale simulation
  - A tool for understanding physics
  - A tool for understanding observations

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Thank you!