The nature of (sub)millimetre galaxies in hierarchical cosmologies

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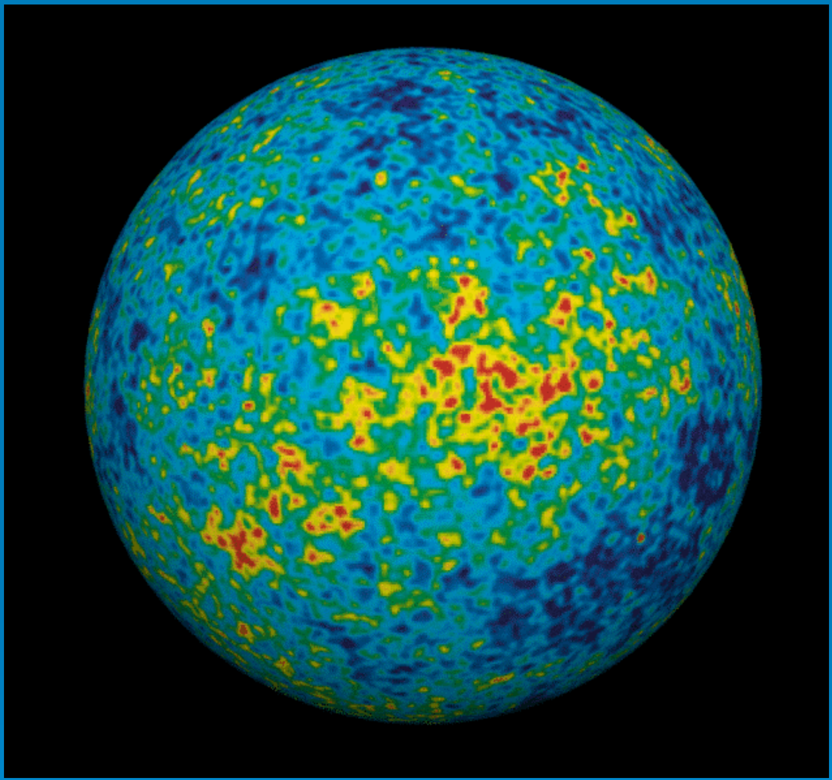
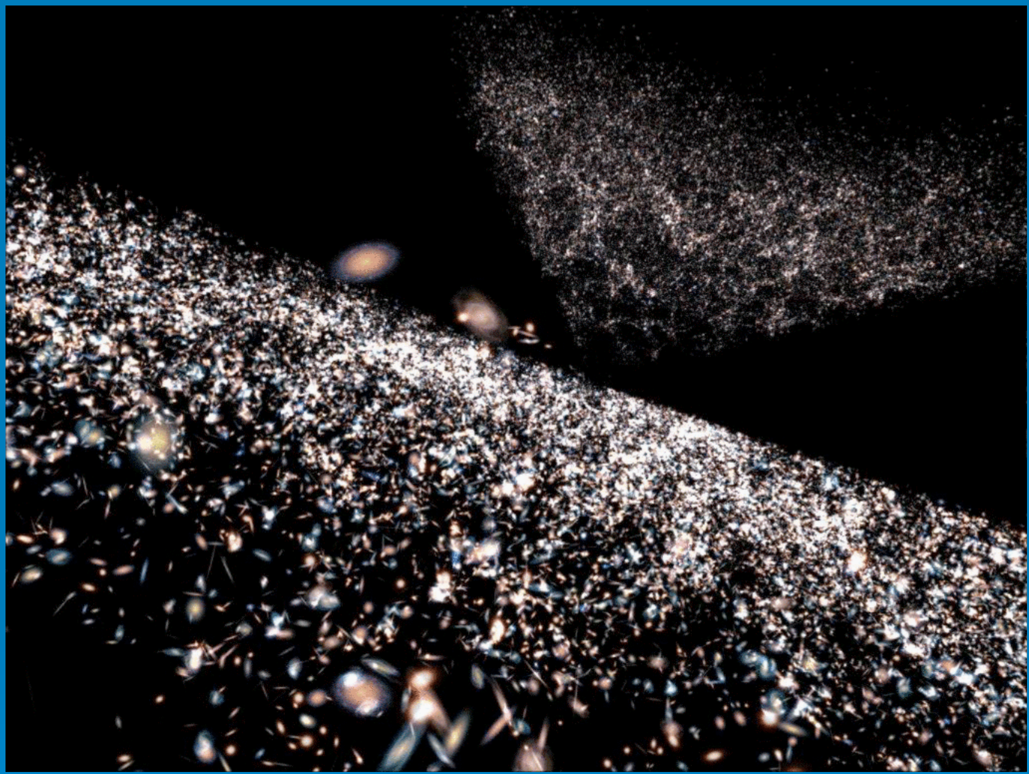
Outline:

- Why do we think structure formation is hierarchical?
- Why do we need "complicated" models?
- How do we model galaxy formation?
- A problem making massive galaxies?
- The challenge of (sub)millimetre observations

Why do we think structure formation is hierarchical?

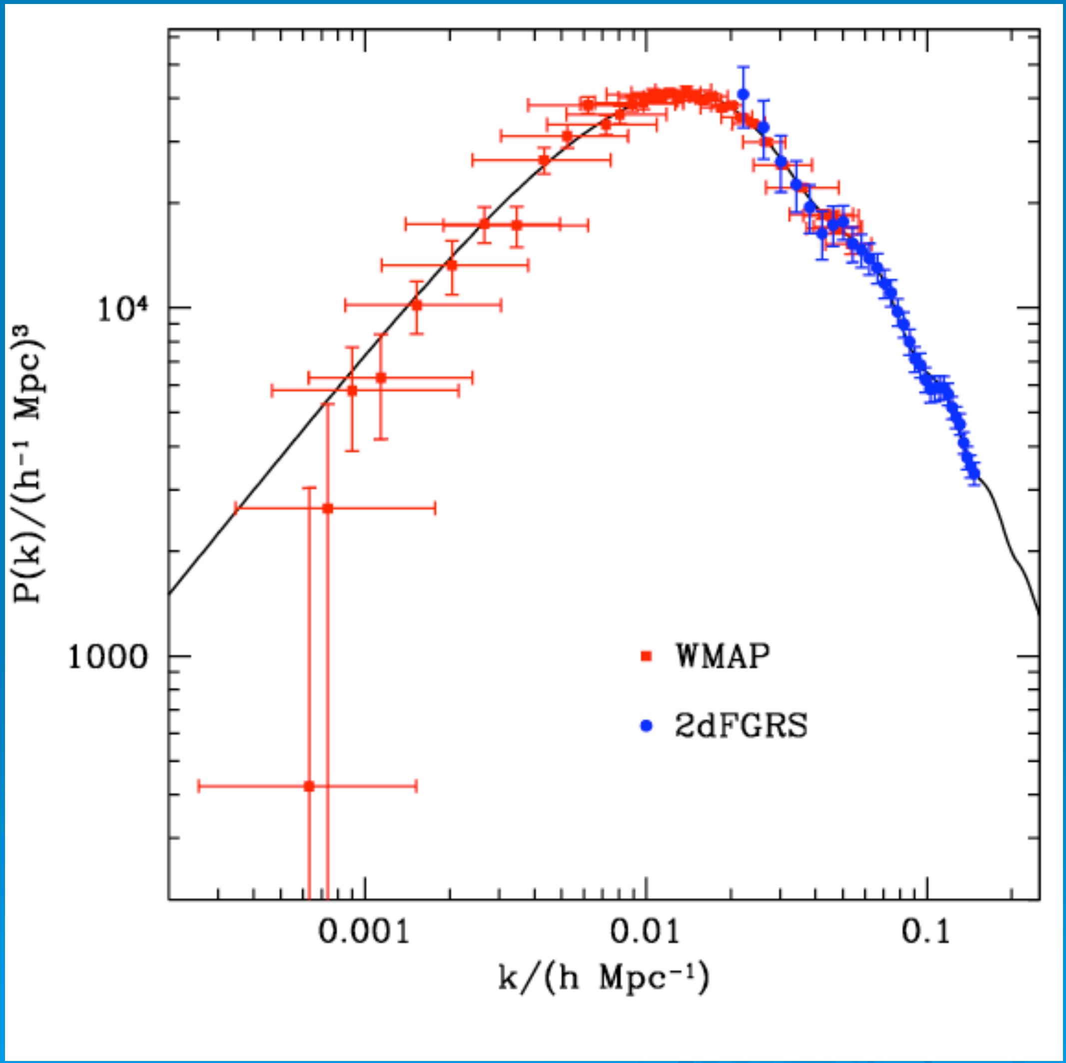


CMB WMAP
Fluctuations 1 part in 100,000
400,000 years after Big Bang



Galaxy map of local universe: 2dFGRS
Fluctuations of order unity
13.7 billion years after Big Bang

Why do we think structure formation is hierarchical?

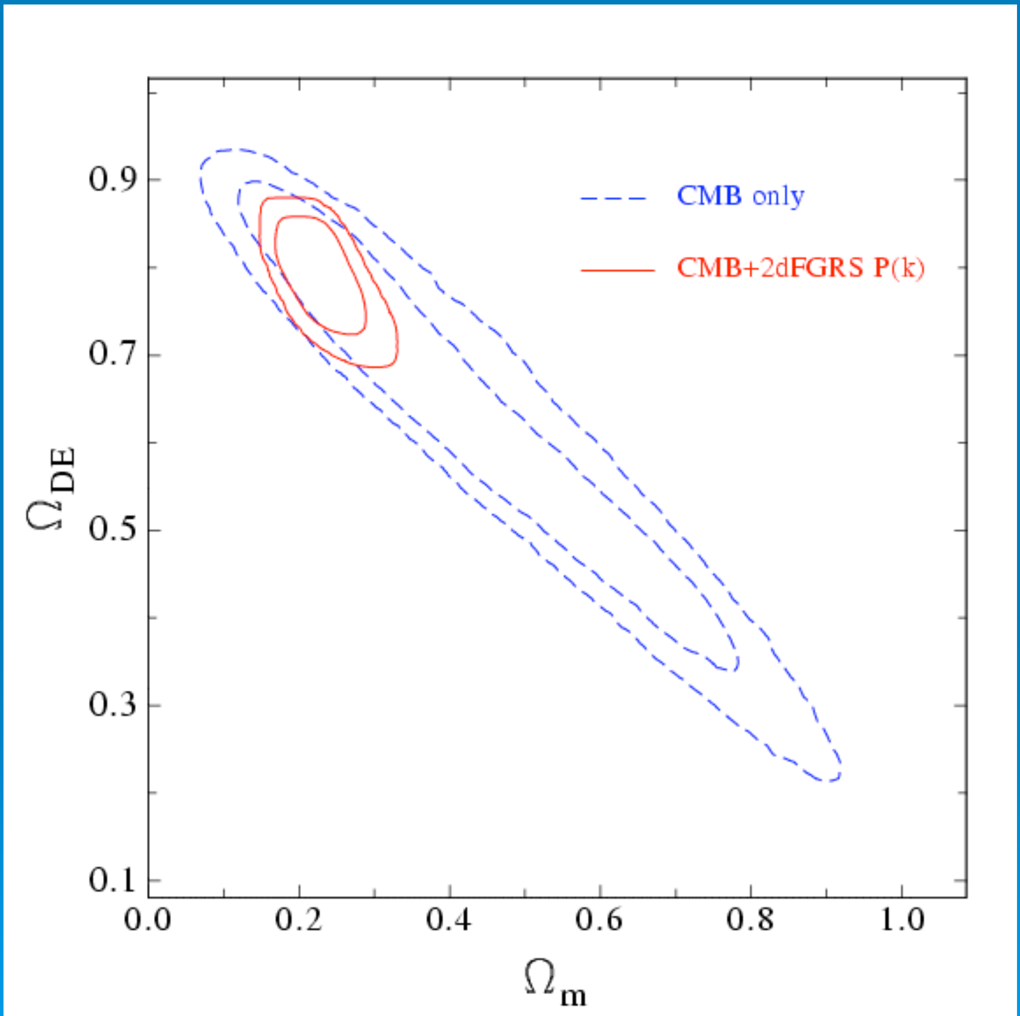


CMB dt/t and galaxy power spectrum plotted in same units.

CDM theory can describe density fluctuations in the early universe and their subsequent growth due to gravitational instability.

Sanchez et al. 2006, MNRAS, In press. astro-ph/0507583.

Why do we think structure formation is hierarchical?



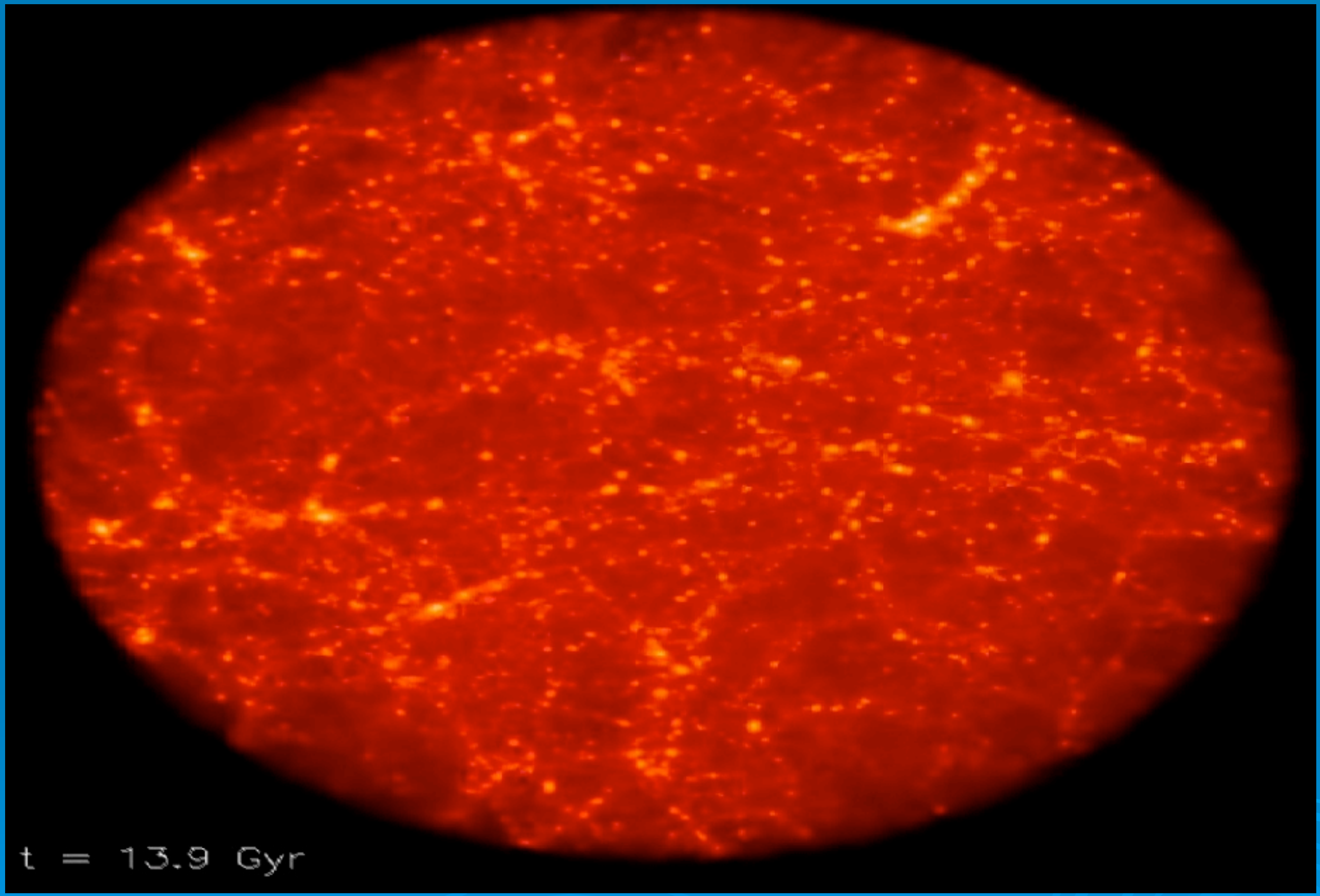
A new era of precision cosmology.

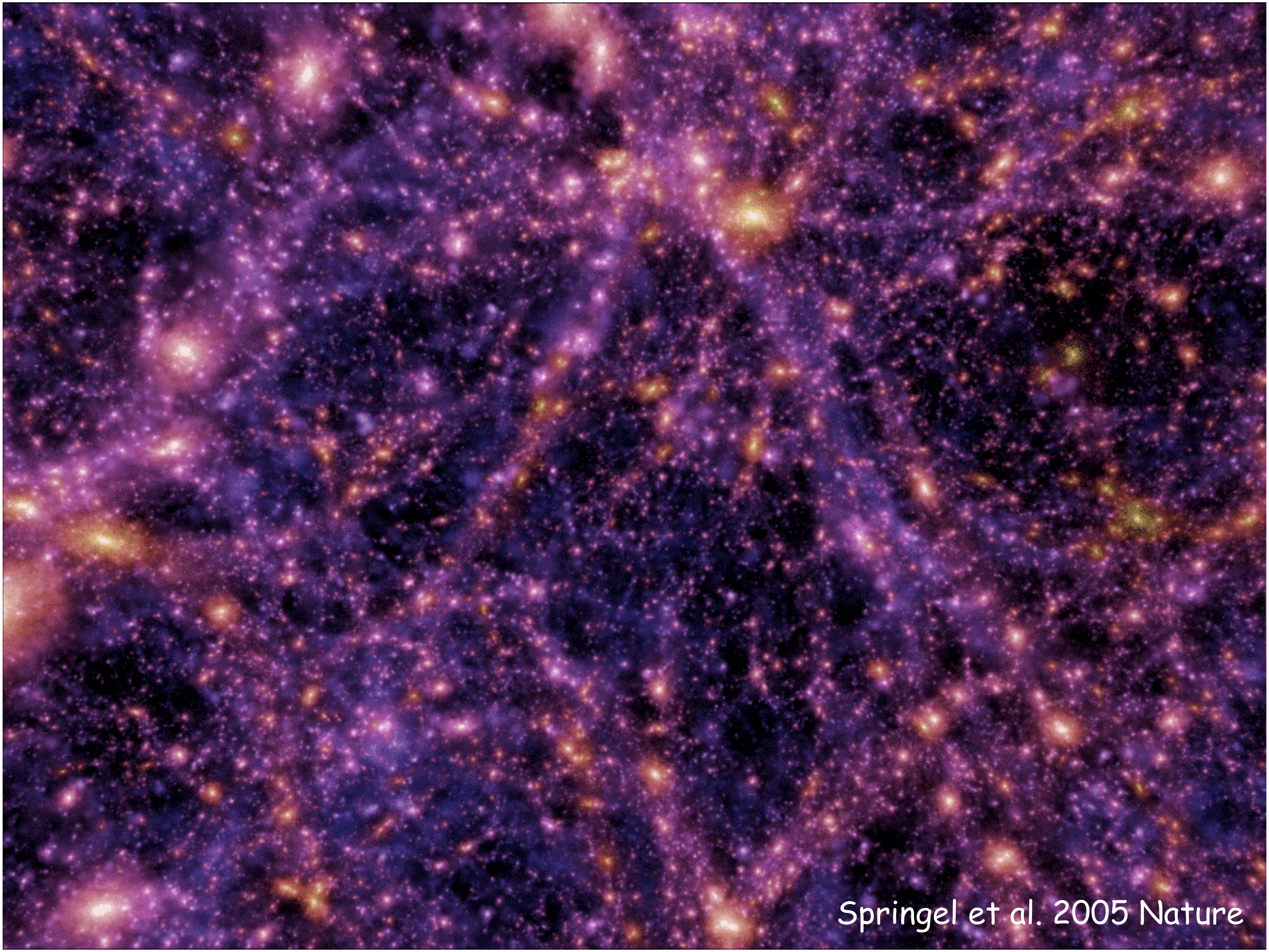
Combining CMB and P(k) data from different epochs tightens constraints.

Cosmology fixed: can concentrate on the "gastrophysics" of galaxy formation.

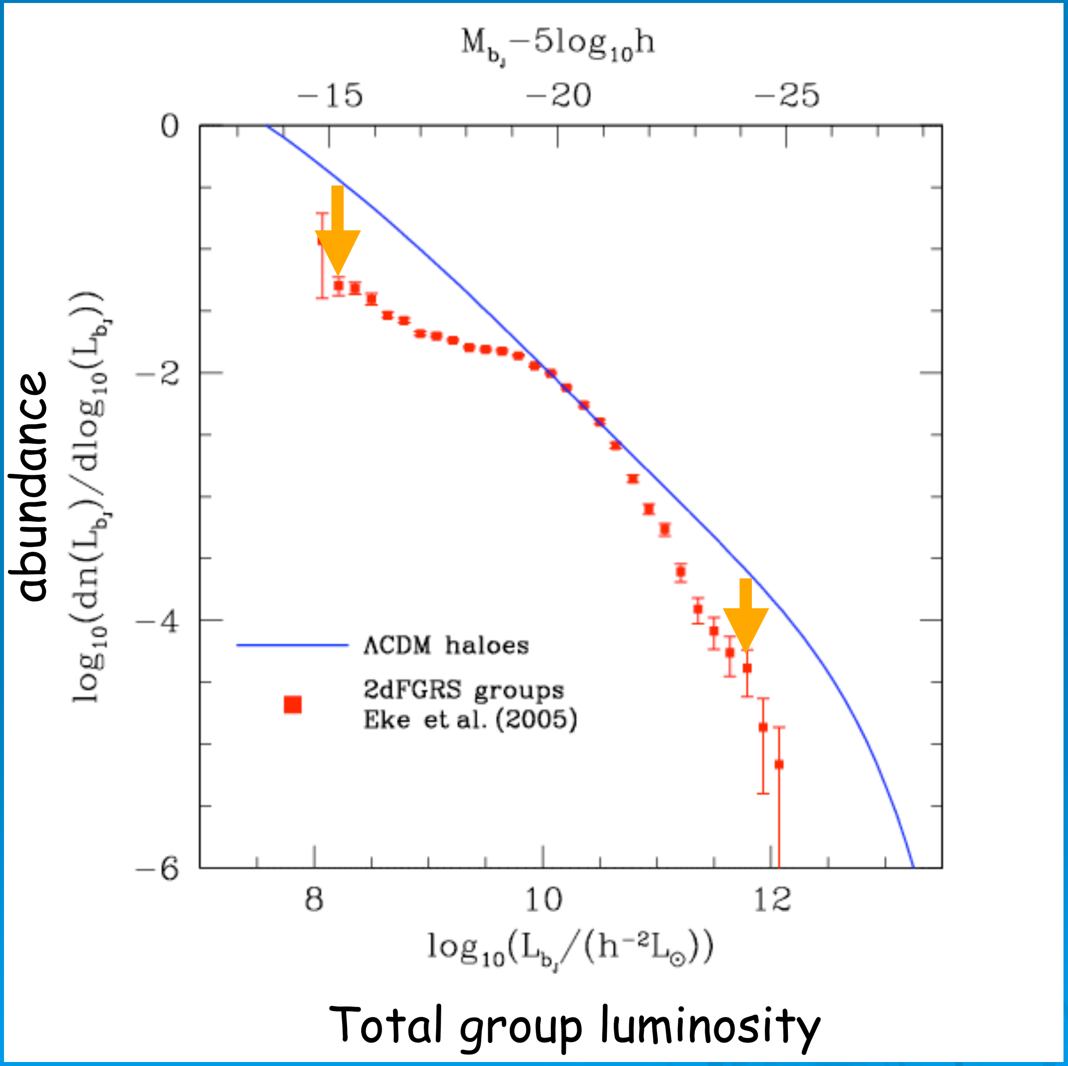
Sanchez et al. 2006, MNRAS, In press. astro-ph/0507583.

Gravitational instability in a Lambda-CDM universe




Springel et al. 2005 Nature

Why do we need "complicated" models?



Galaxy group luminosity function
Measured from 2dFGRS by
Eke et al. 2004, 2005

Simple prediction:
Take DM halo mass function
plus fixed M/L ratio

<u>Galaxy formation TOO efficient in both low and high mass haloes</u>

Why do we need "complicated" models?

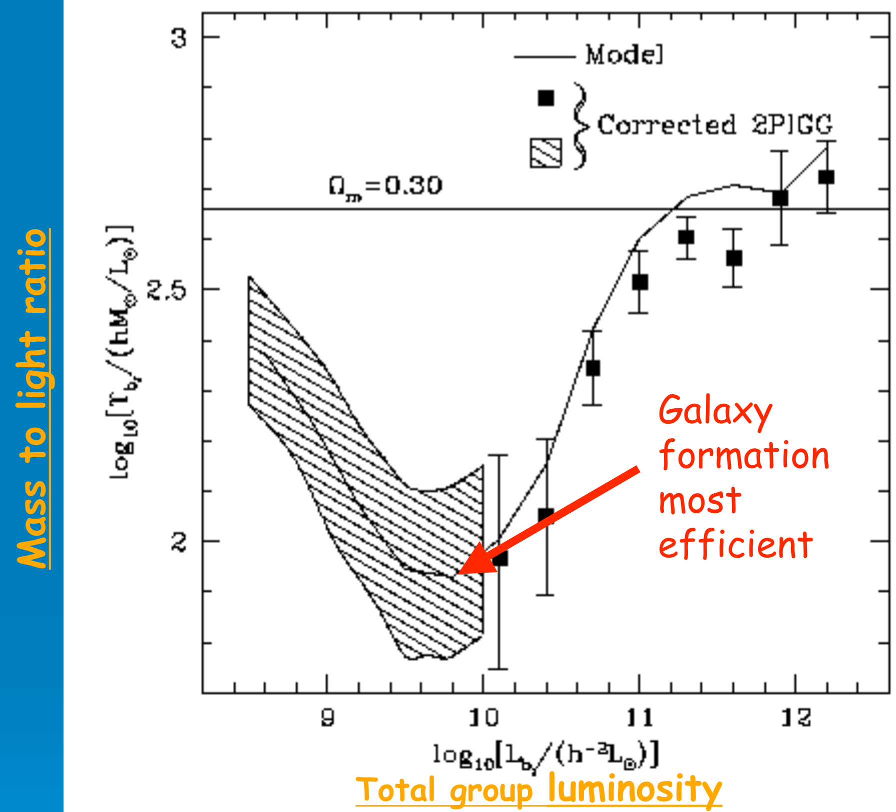


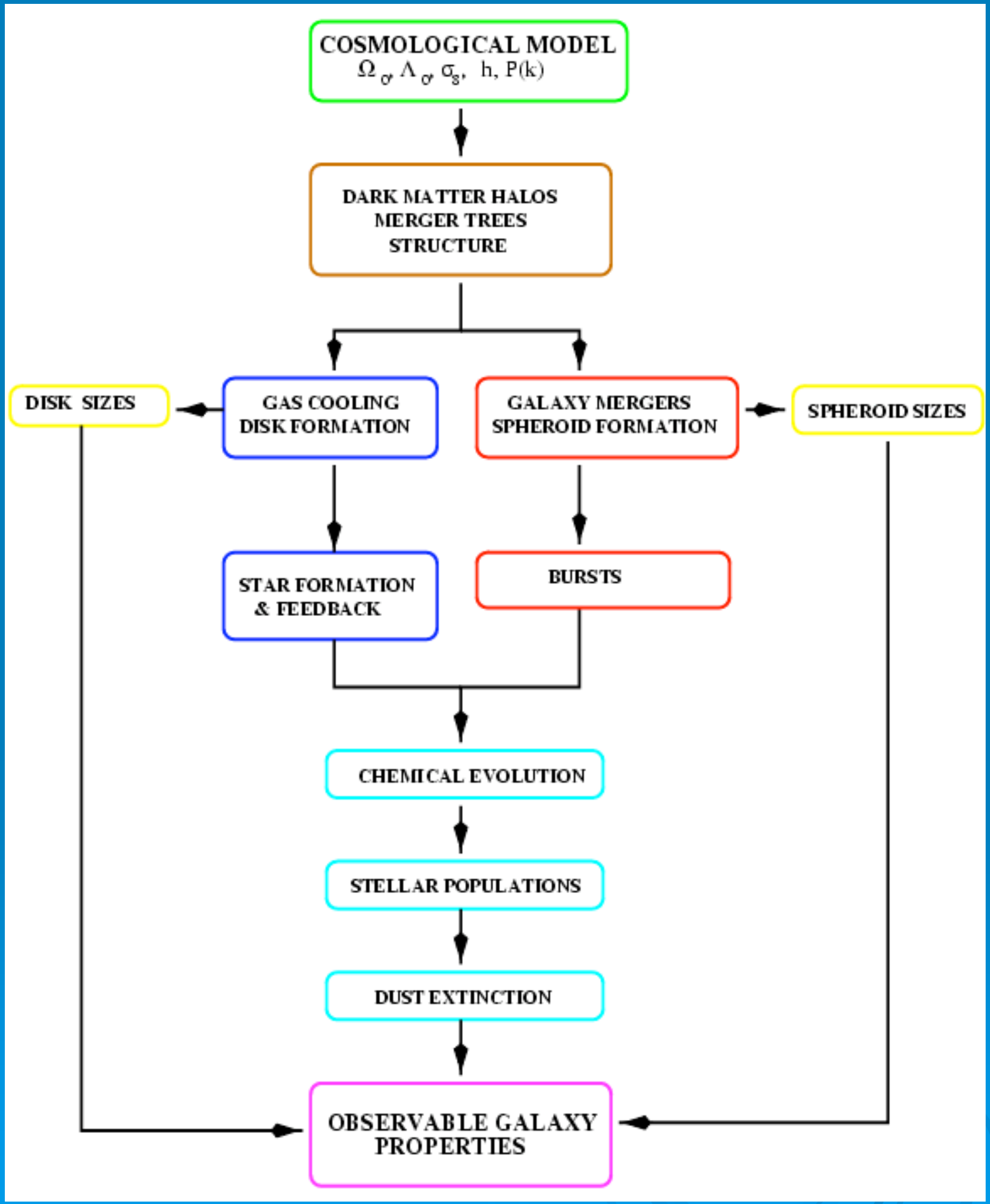
Figure 15. The 'corrected' mass-to-light ratio as a function of group luminosity for the 2PIGG sample. The error bars include the statistical errors added in quadrature to the uncertainty in the systematic shift applied to 'correct' the measurements. Directly measured mass-to-light ratios are shown with points, whereas those inferred assuming that the global halo mass function is given by the fitting function of J01 are shown by the shaded region.

Variation of M/L with total group luminosity shows how the efficiency of galaxy formation should depend on halo mass.

Effectiveness of feedback processes and variation in gas cooling time within haloes of different mass drive change in M/L

Eke et al. 2004, 2005

How do we model galaxy formation?



Combination of simulations, analytic results and recipes with parameters

Cole et al. 2000

A problem making massive galaxies?

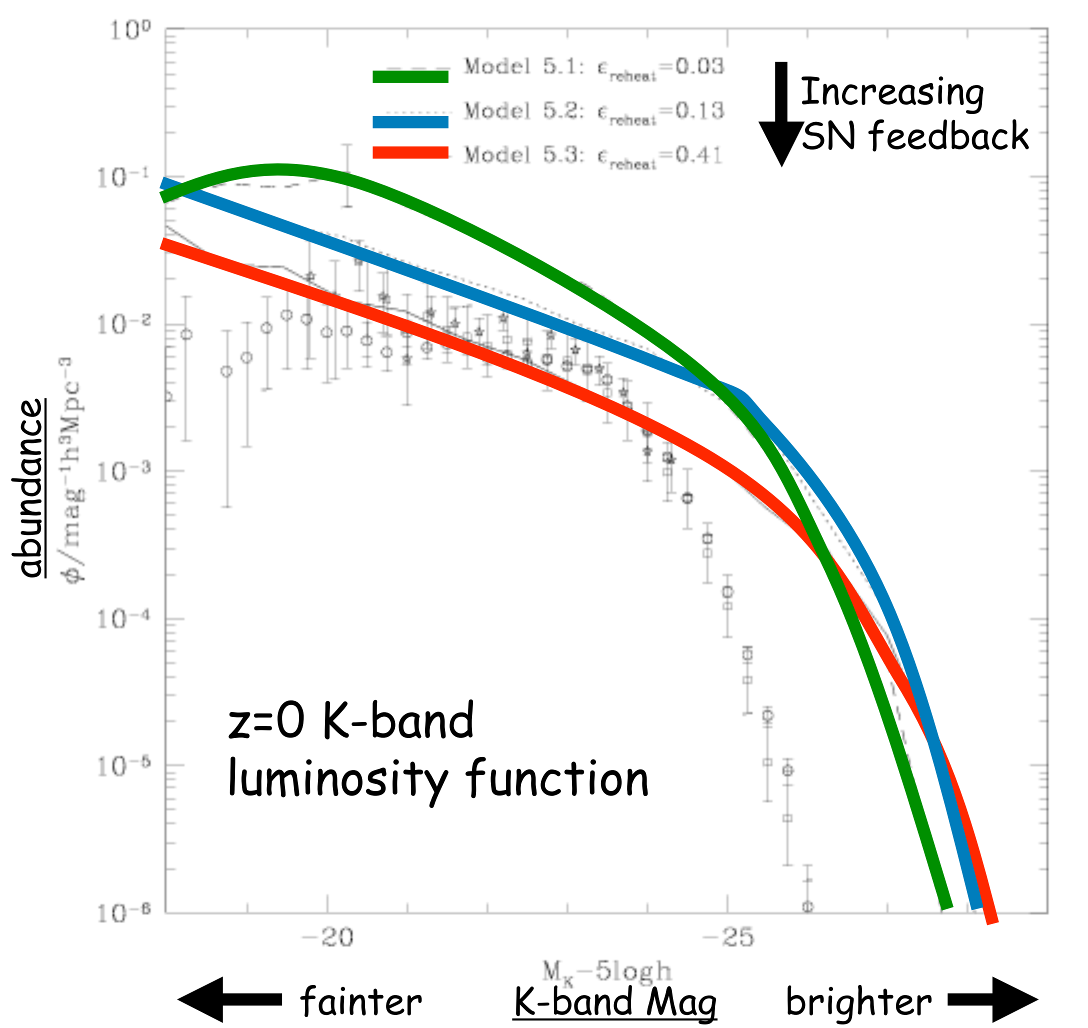


FIG. 2.—Model 5. Starting from model 4, disk reheating is added in order to suppress the formation of small galaxies. Results are shown for three levels of energy input (ϵ_{reheat} = 0.03, 0.13, and 0.41). The data points are the same as in Fig. 1.

With current best fit value for baryon fraction, predict far too many bright galaxies

Increasing supernovae feedback which heats disk gas just reduces number of faint galaxies

Benson et al. 2003

A problem making massive galaxies?

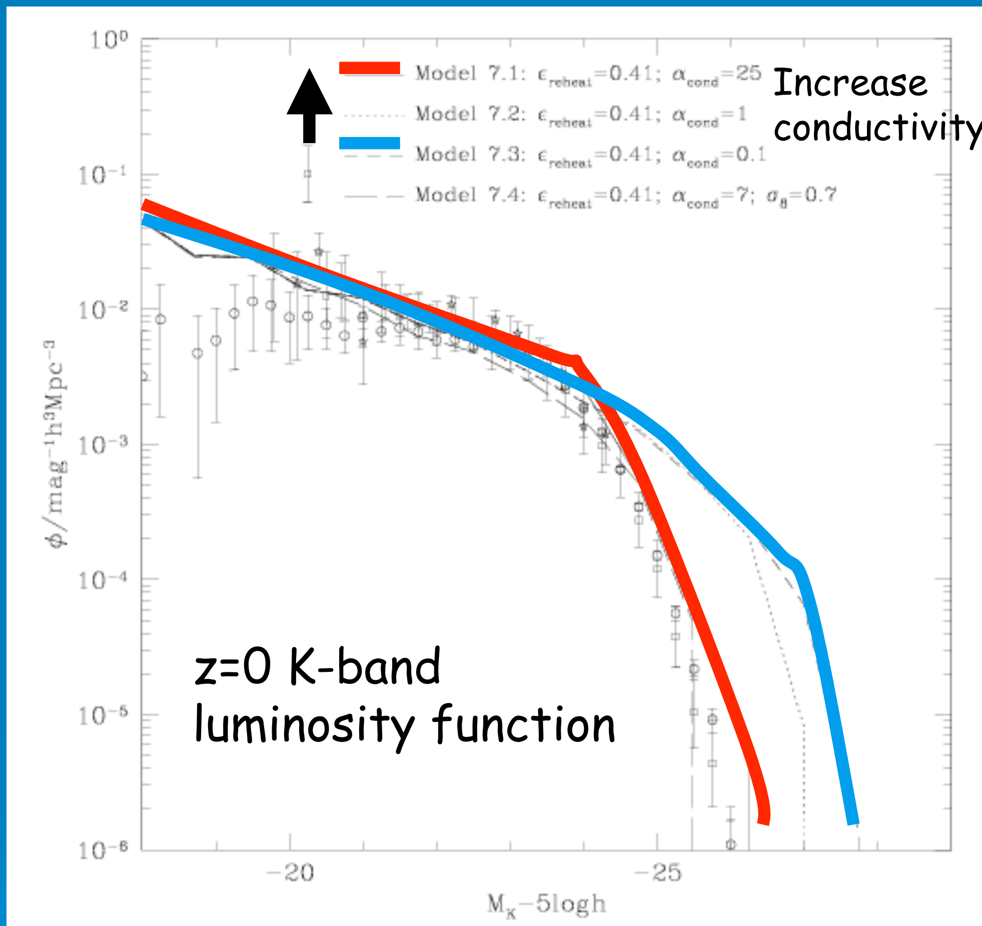


FIG. 4.—Model 7. These models illustrate the effect of thermal conduction. In model 7.3 ($\alpha_{cond} = 25$), conduction is assumed to be highly efficient (it is unlikely that such a high efficiency is physically plausible). More realistic conduction efficiencies are illustrated in models 7.2 ($\alpha_{cond} = 1$) and 7.1 ($\alpha_{cond} = 0.1$). For model 7.4, we adopt a lower value for σ_8; a conduction efficiency of $\alpha_{cond} = 7$ then gives a reasonable match to the observed

With current best fit value for baryon fraction, predict far too many bright galaxies

Thermal conduction balances cooling luminosity of gas: requires implausibly high conduction efficiency

Benson et al. 2003

A problem making massive galaxies?

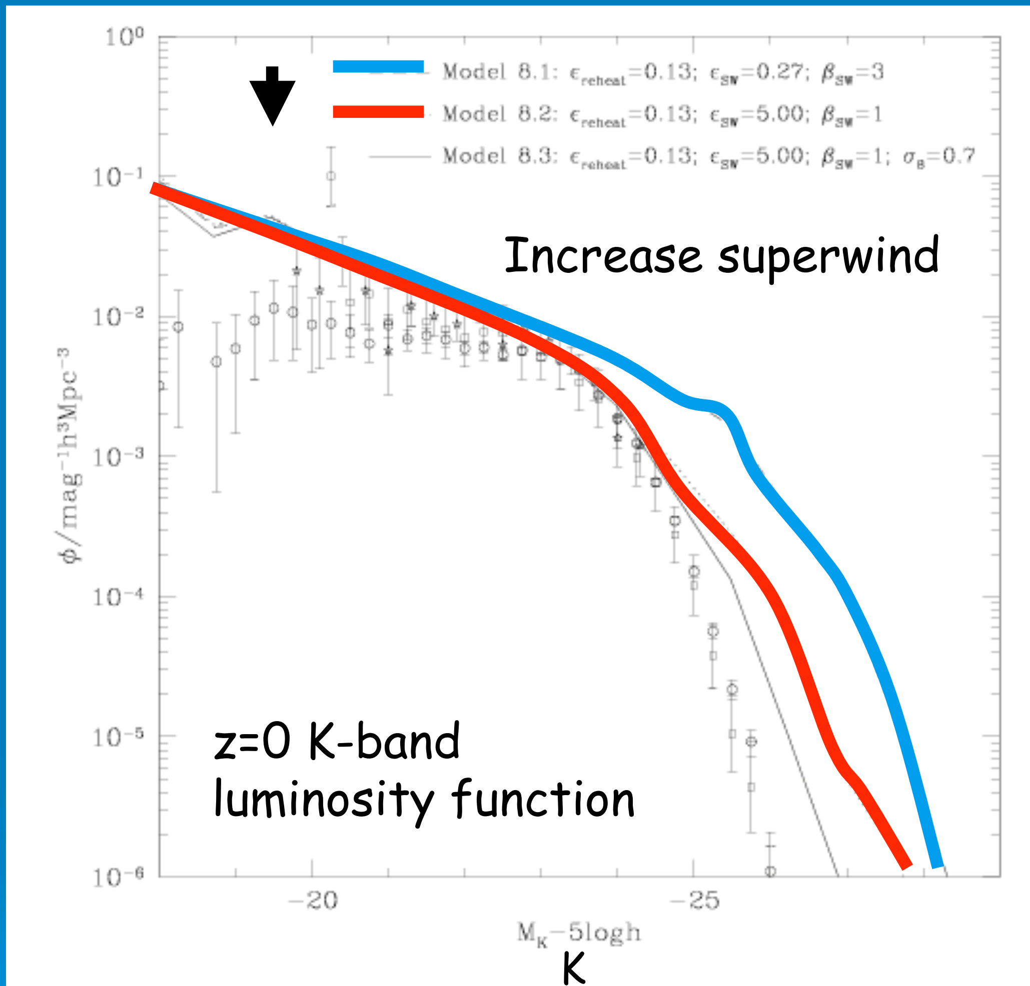


FIG. 5.—Model 8. These models illustrate the effect of superwinds. In model 8.1, an energy of $\epsilon_{sw} = 0.27$ drives a weak superwind (with $\beta_{sw} = 3$); disk reheating has efficiency $\epsilon_{reheat} = 0.13$, and there is no heating of the diffuse halo ($\epsilon_{halo} = 0$). A much more powerful wind is needed to create a break in the luminosity function. Model 8.2 ($\epsilon_{sw} = 5.0$; $\beta_{sw} = 1$) illustrates the effect of increasing the superwind power. An improved match to the

With current best fit value for baryon fraction, predict far too many bright galaxies

Superwind drives gas out of large galaxies: requires all energy from SNe to go into wind

Benson et al. 2003

An alternative energy source: AGN feedback

Bower et al. 2005

If the available AGN power is greater than the cooling luminosity, we assume that the cooling flow is indeed quenched. We parametrise the available AGN power as a fraction of the Eddington luminosity of the central galaxy's black hole, ϵ_{SMBH}. A halo is prevented from cooling if:

$$r_{\mathrm{cool}}(t) < r_{\mathrm{ff}}(\alpha_{\mathrm{cool}} t) \qquad (2)$$

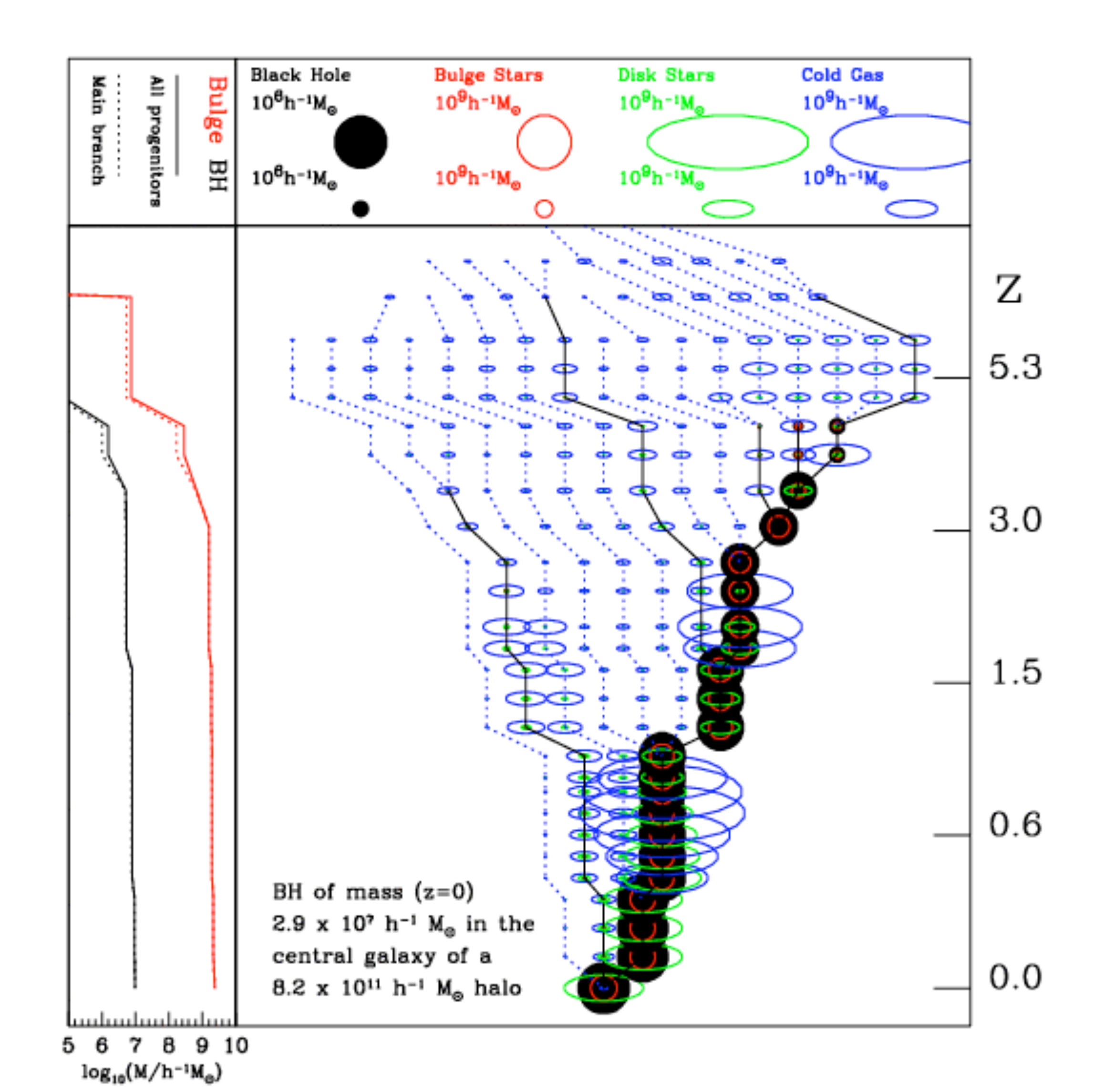
and

$$L_{\mathrm{cool}} < \epsilon_{\mathrm{SMBH}} L_{\mathrm{Edd}}. \qquad (3)$$

- Need model to track growth of black holes in galaxy mergers
- Haloes with quasi-static hot gas halo: t(cool) > t(free-fall)
- Rate at which gas cools is quenched, depending on size of black hole
- AGN emits luminosity that balances cooling luminosity radiated by gas

See also Granato et al. 2004; Croton et al. 2006, MNRAS; de Lucia et al. 2006, MNRAS

Tracking the growth of black holes in hierarchical models



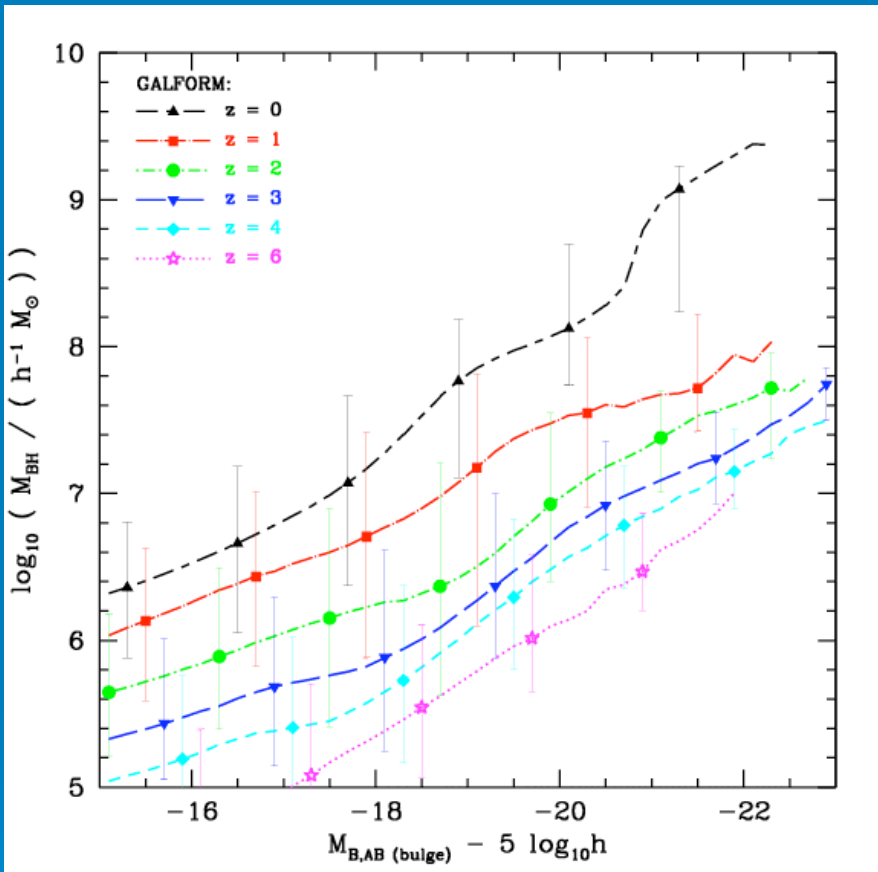
Black holes grow by:

- Cold gas accretion in galaxy mergers
- Mergers of black holes

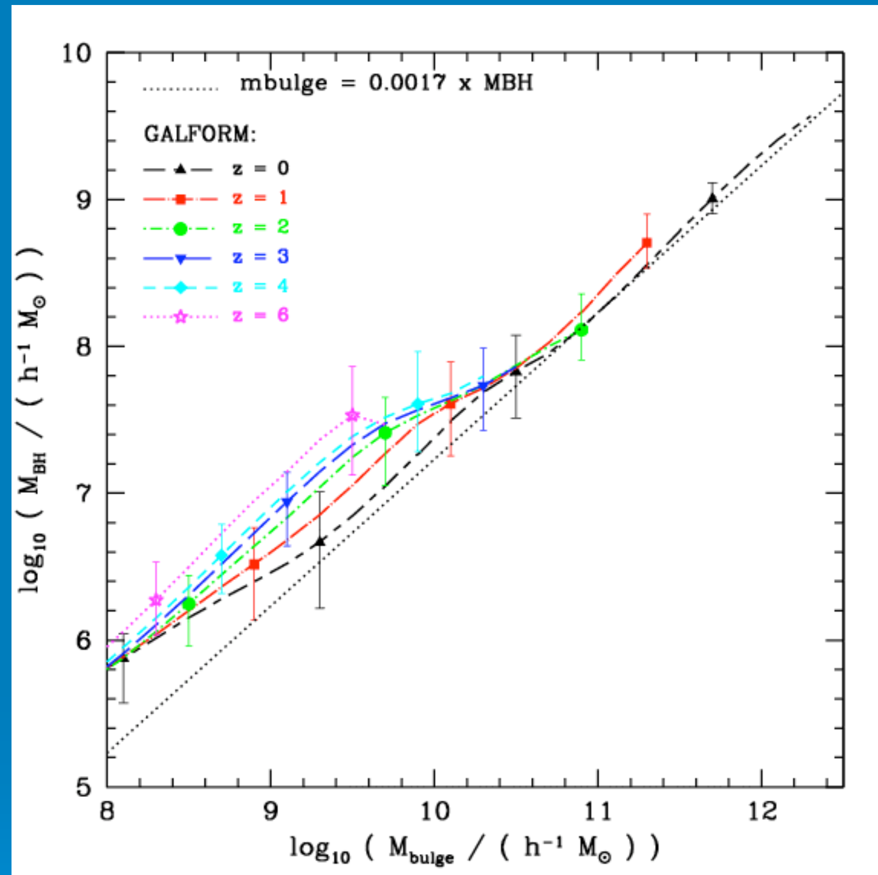
Kauffmann & Haehnelt 2000
Cattaneo et al. 2005

Rowena Malbon et al. 2006

Evolution of the Magorrian relation



Rest frame B-band



Bulge stellar mass

Rowena Malbon et al. 2006

The impact of AGN feedback on gas cooling

Gas cooling rate

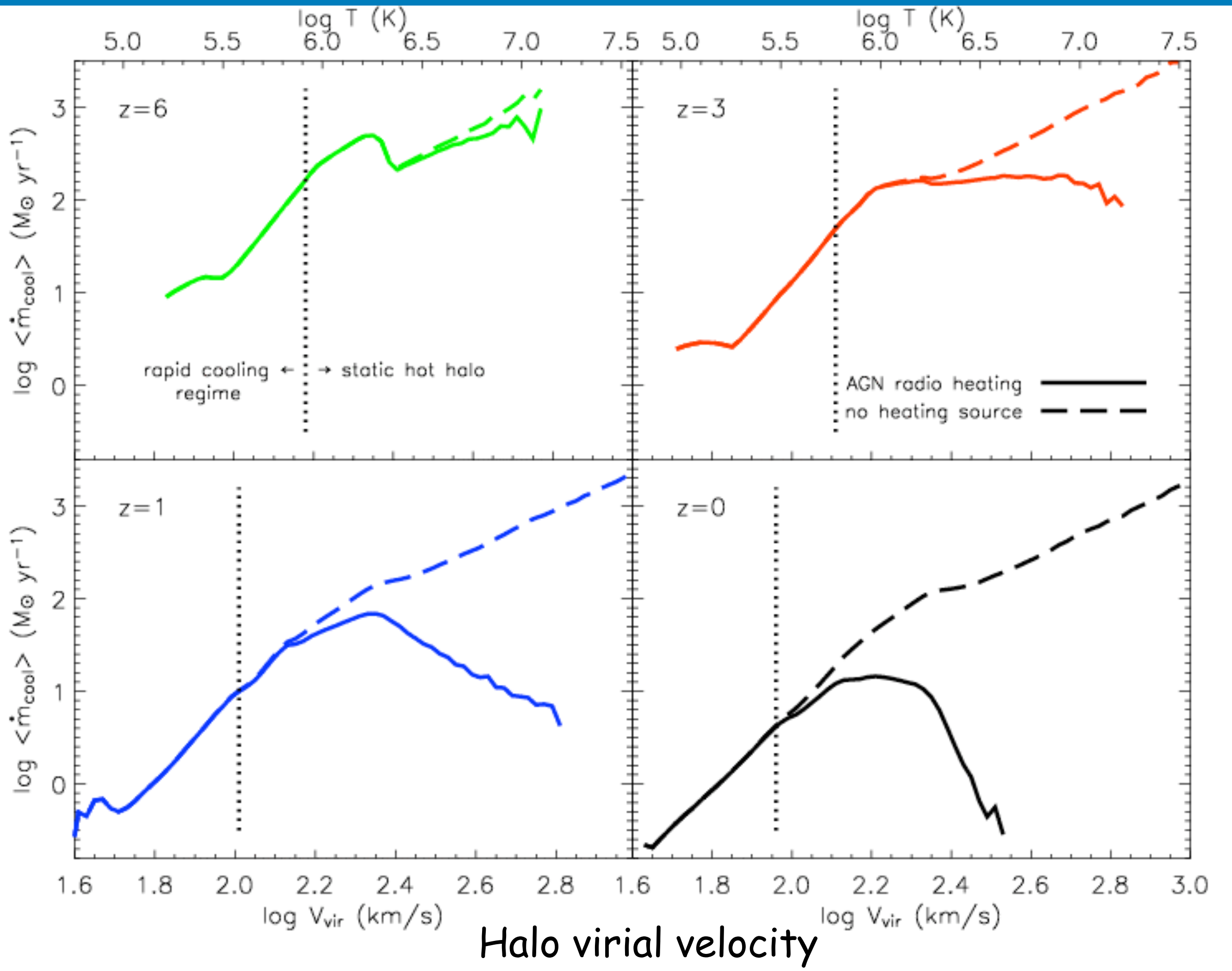
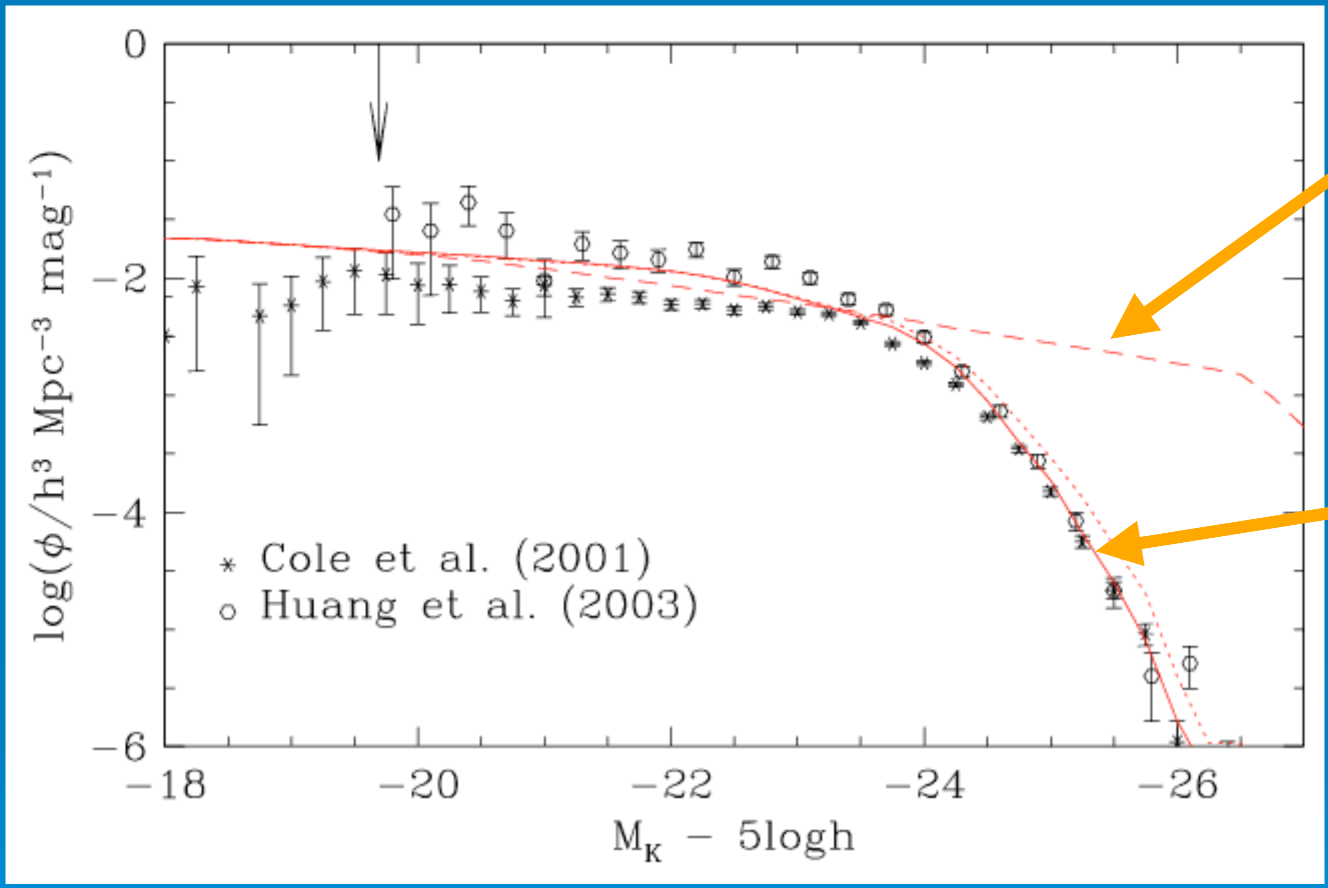


Figure 7. The mean condensation rate, $\langle \dot{m}_{\rm cool} \rangle$ as a function of halo virial velocity $V_{\rm vir}$ at redshifts of 6, 3, 1, and 0. Solid and dashed lines in each panel represent the condensation rate with and without 'radio mode' feedback respectively, while the vertical dotted lines show the transition between the rapid cooling and static hot halo regimes, as discussed in Section 3.2. This figure demonstrates that cooling flow suppression is most efficient in our model for haloes with $V_{\rm vir} > 150\,{\rm km\,s^{-1}}$ and at $z \lesssim 3$.

Croton et al. 2006, MNRAS

The luminosity function with suppression of cooling by AGN



Same parameters but turn off AGN feedback

With AGN feedback

Present day K-band field luminosity function

Bower et al. 2005

The challenge of (sub)millimetre galaxies

A DEEP SUB-MILLIMETER SURVEY OF LENSING CLUSTERS:
A NEW WINDOW ON GALAXY FORMATION AND EVOLUTION

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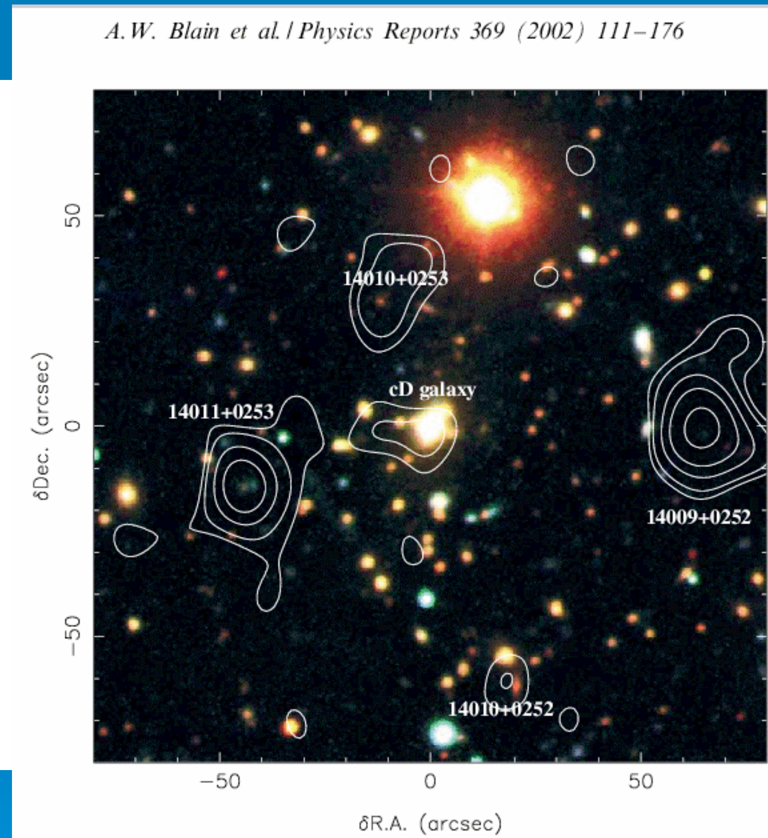
ACCEPTED VERSION

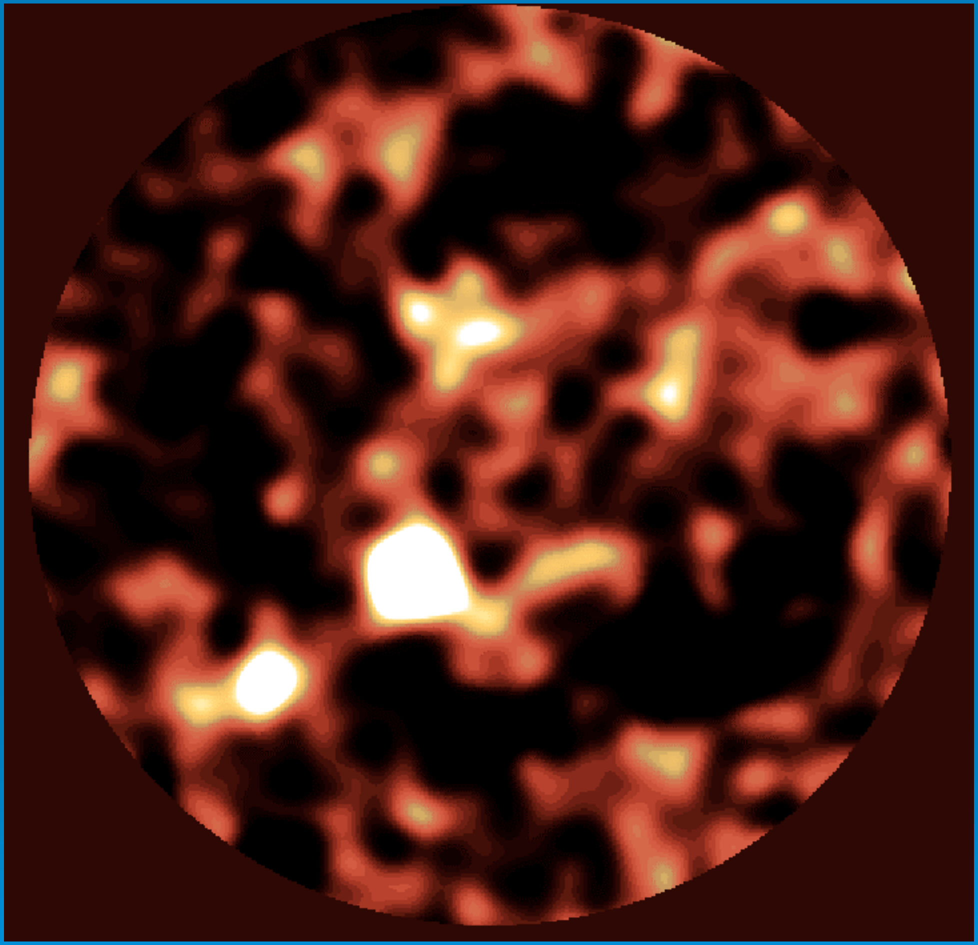
ABSTRACT

We present the first results of a sub-millimeter survey of distant clusters using the new Sub-mm Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope. We have mapped fields in two massive, concentrated clusters, A370 at $z = 0.37$ and Cl 2244−02 at $z = 0.33$, at wavelengths of 450 and 850 μm. The resulting continuum maps cover a total area of about 10 arcmin^2 to 1σ noise levels less than 14 and 2 mJy beam^{-1} at the two wavelengths, 2–3 orders of magnitude deeper than was previously possible. We have concentrated on lensing clusters to exploit the amplification of *all* background sources by the cluster, improving the sensitivity by a factor of 1.3–2 as compared with a blank-field survey. A cumulative source surface density of $(2.4 \pm 1.0) \times 10^3$ degree^{-2} is found to a 50% completeness limit of $\sim$ 4 mJy at 850 μm. The sub-mm spectral properties of these sources indicate that the majority lie at high redshift, $z > 1$. Without correcting for lens amplification, our observations limit the blank-field counts at this depth. The surface density is 3 orders of magnitude greater than the expectation of a non-evolving model using the local *IRAS* 60 μm luminosity function. The observed source counts thus require a substantial increase in the number density of strongly star-forming galaxies in the high-redshift Universe and suggest that optical surveys may have substantial underestimated the star formation density in the distant Universe. Deeper sub-mm surveys with SCUBA should detect large numbers of star-forming galaxies at high redshift, and so provide strong constraints on the formation of normal galaxies.

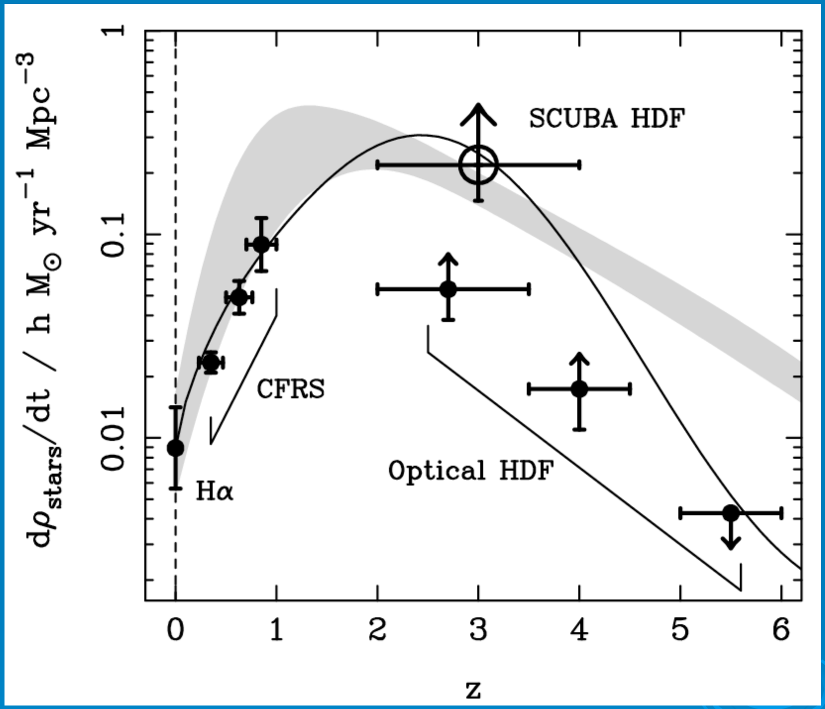
Subject headings: cosmology: observations — cosmology: early universe — galaxies: evolution — galaxies: formation — gravitational lensing — radio continuum: galaxies



The challenge of (sub)millimetre galaxies



SCUBA image of HDF



More star formation at high-z?

Hughes et al. 1998; Barger et al. 1998

The challenge of (sub)millimetre galaxies

*Population of sources missed by Lyman-break dropout & UV imaging

*Possibly more star formation at high redshift than previously thought

*Inferred SFRs huge ~ 1000 Msun/yr!

*Is all emission due to starburst or is some from an AGN?

*Is a SCUBA source an elliptical galaxy in formation?

*Massive galaxies in place at high-z?

How can SCUBA sources be accommodated in hierarchical models?

Modelling dust extinction and emission

*Naïve model: assume dust temperature

$$L_\nu \propto \nu^{2+\beta} L_d / T_d^{3+\beta} \rightarrow T_d^{-5}$$

*Physically inconsistent!

*Dust temperature should be determined by thermal equilibrium between heating and cooling of grains

*With the bolometric luminosity and dust mass as parameters, and with the dust in thermal equilibrium,

$$L_d \propto M_d T_d^{\beta+4}$$

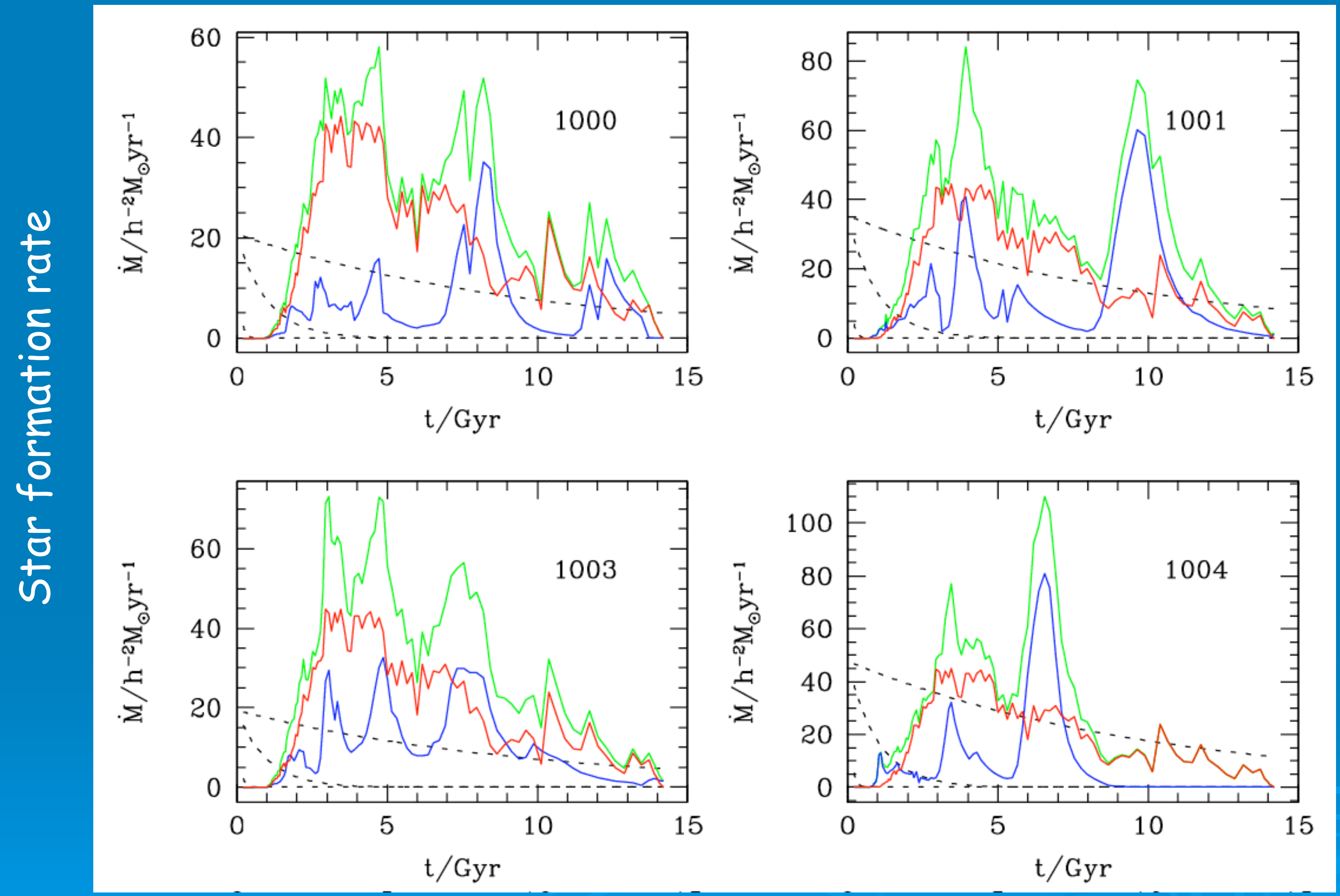
Which gives :

$$L_\nu \propto \nu^{2+\beta} M_d^{(3+\beta)/(4+\beta)} L_d^{1/(4+\beta)}$$

Modelling dust extinction and emission

1. Complete star formation history of galaxy, including starbursts triggered by galaxy mergers

Examples of predicted star formation histories



GREEN: total

RED: Starbursts

BLUE: Quiescent Disks

Age of universe →

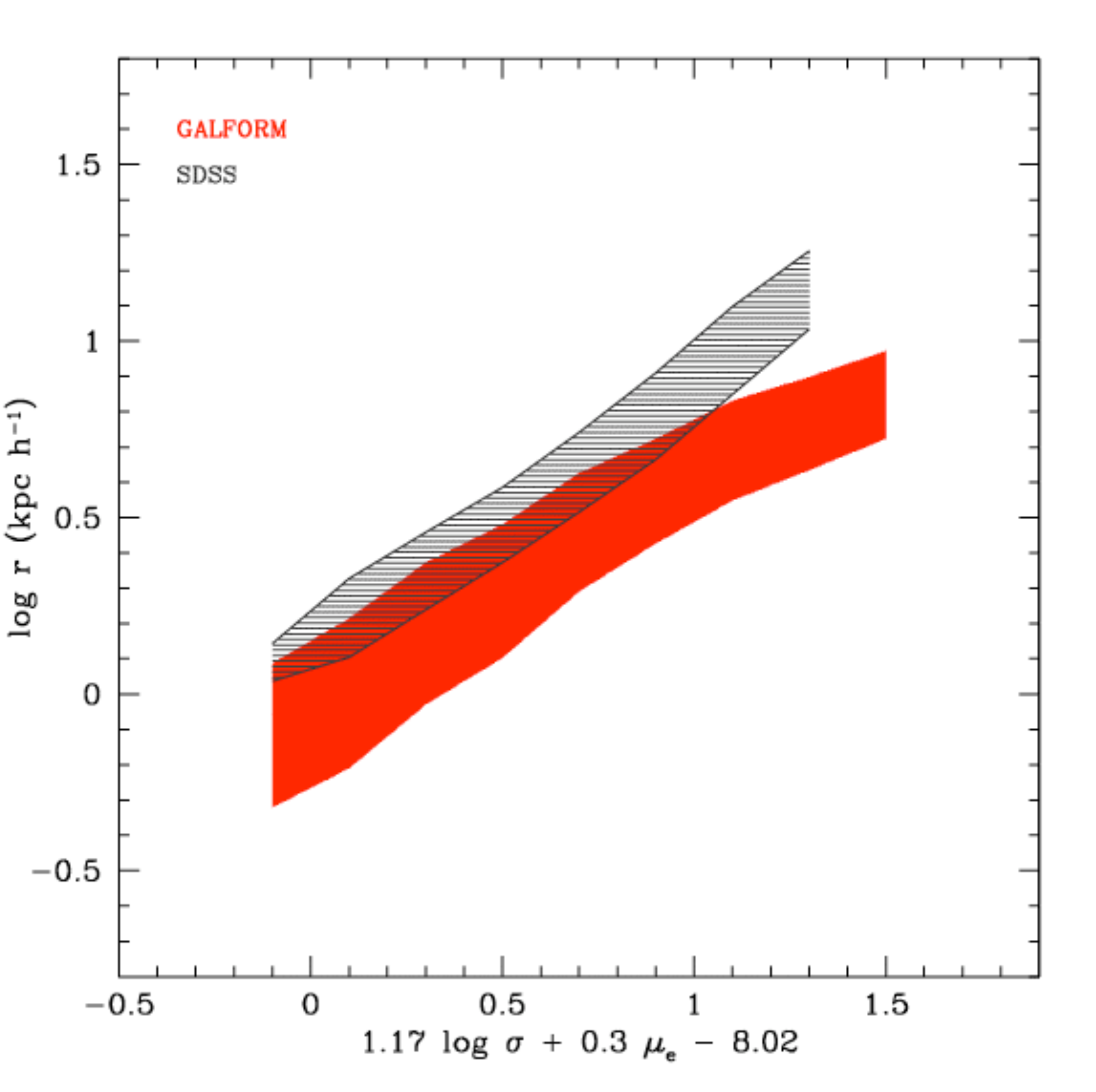
Baugh 2006 Rep. Prog. Phys.

Modelling dust extinction and emission

1. Complete star formation history of galaxy, including starbursts triggered by galaxy mergers.

2. Scale lengths of the disk and bulge components, calculated by conserving angular momentum and applying conservation of energy.

Example of size calculation: Fundamental plane of ellipticals



Comparison of predicted sizes of local bulge dominated galaxies with SDSS analysis by Bernardi et al. 2005

Cesario Almeida et al. 2006

Modelling dust extinction and emission

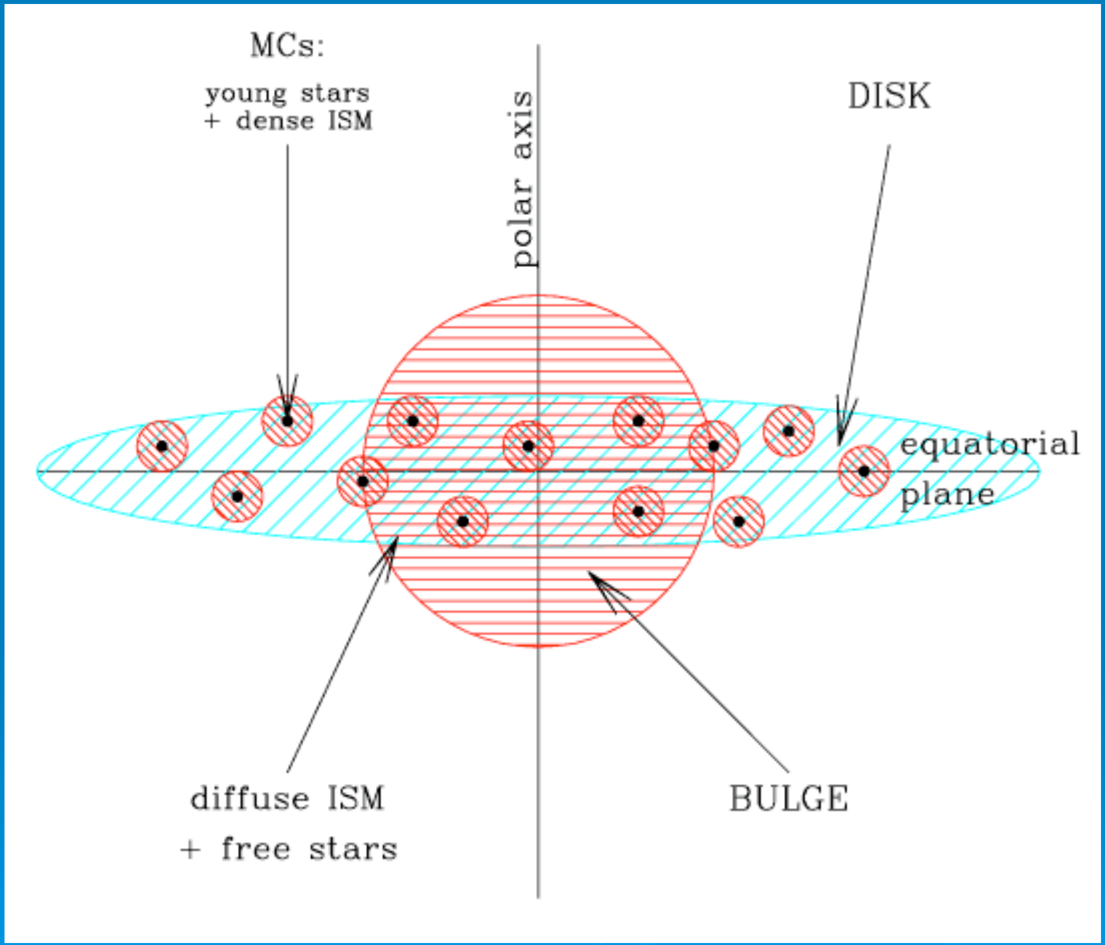
1. Complete star formation history of galaxy, including starbursts triggered by galaxy mergers.

2. Scale lengths of the disk and bulge components, calculated by conserving angular momentum and applying conservation of energy.

3. Metallicity and cold gas mass: dust mass.

4. A spectro-photometric model to compute dust extinction and emission.

Modelling dust extinction and emission

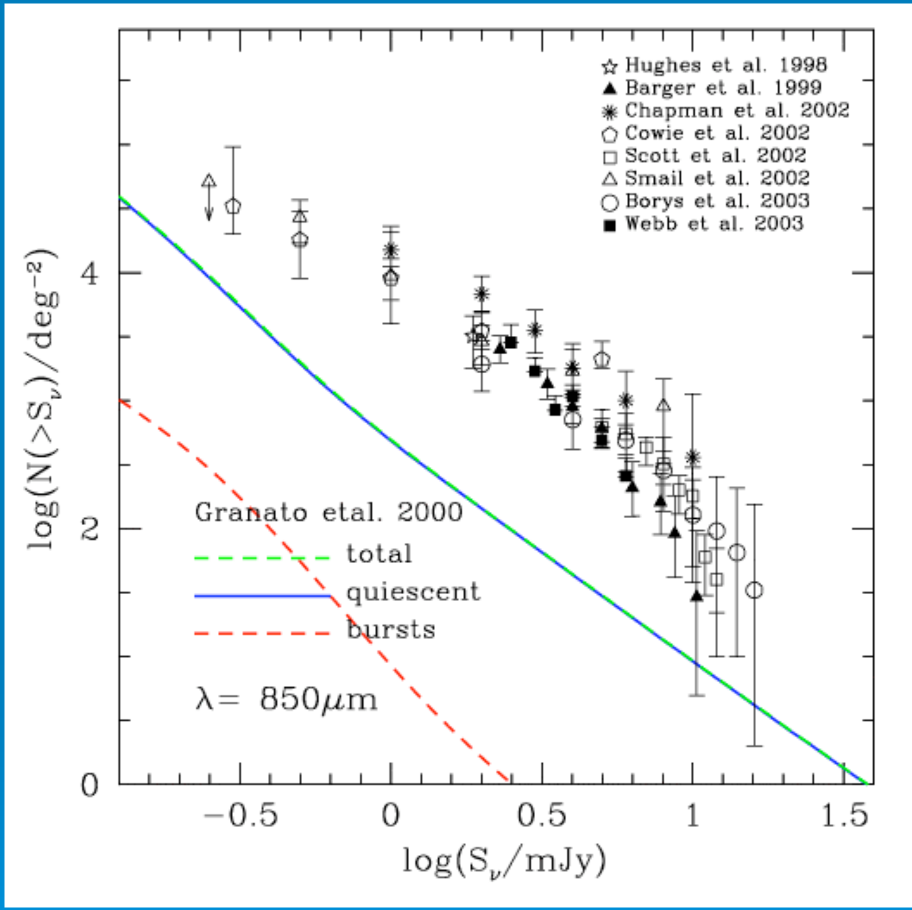


GRASIL : Silva et al. 1998

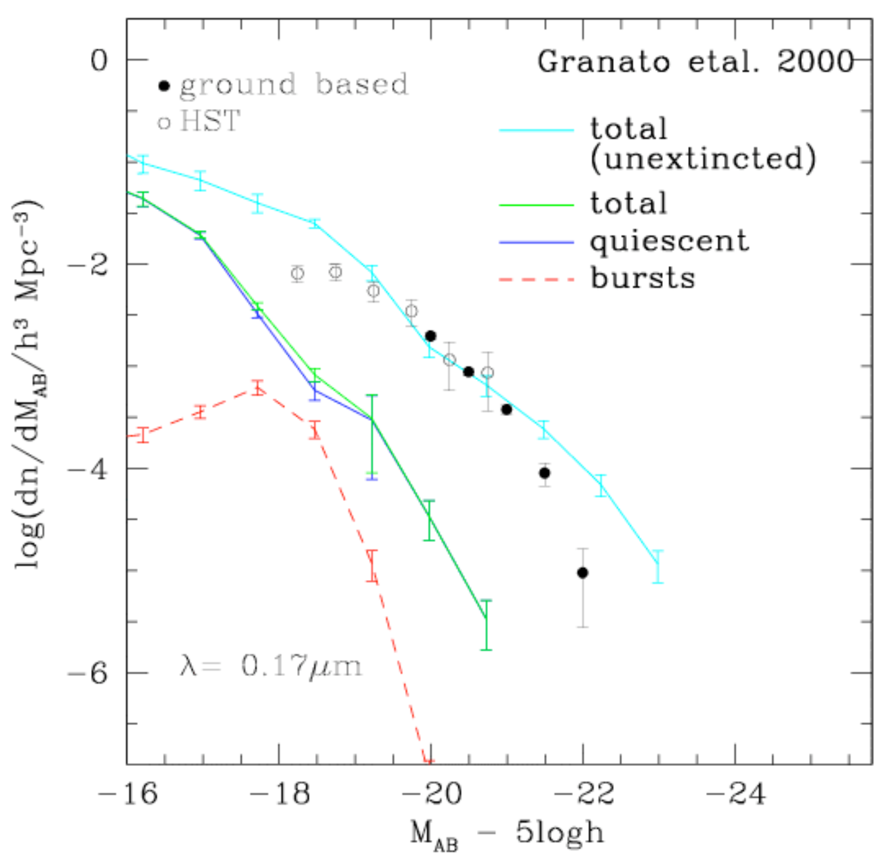
- Emission from stars
- Extinction by dust in two components: clouds & diffuse
- Computes temperature at each location in galaxy applying thermal eqm.
- Composite dust spectrum

Combination of GALFORM & GRASIL : Granato et al. 2000

Standard predictions for the high redshift universe



850 micron counts

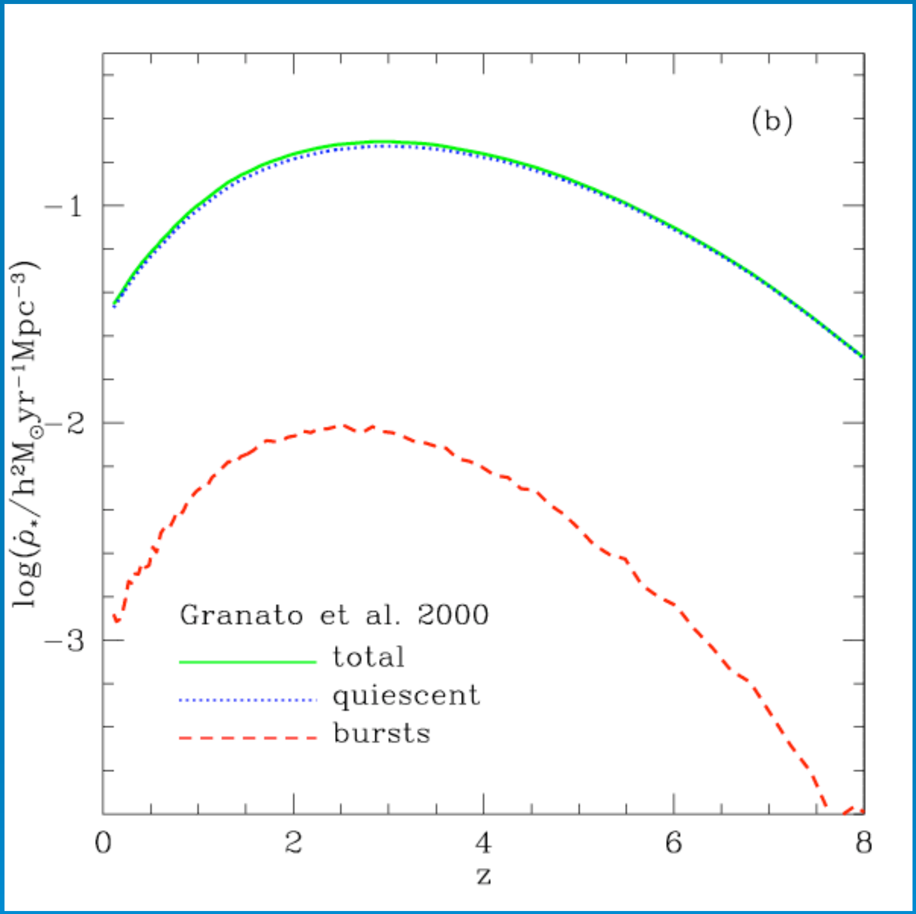


Lyman-break luminosity function at z=3

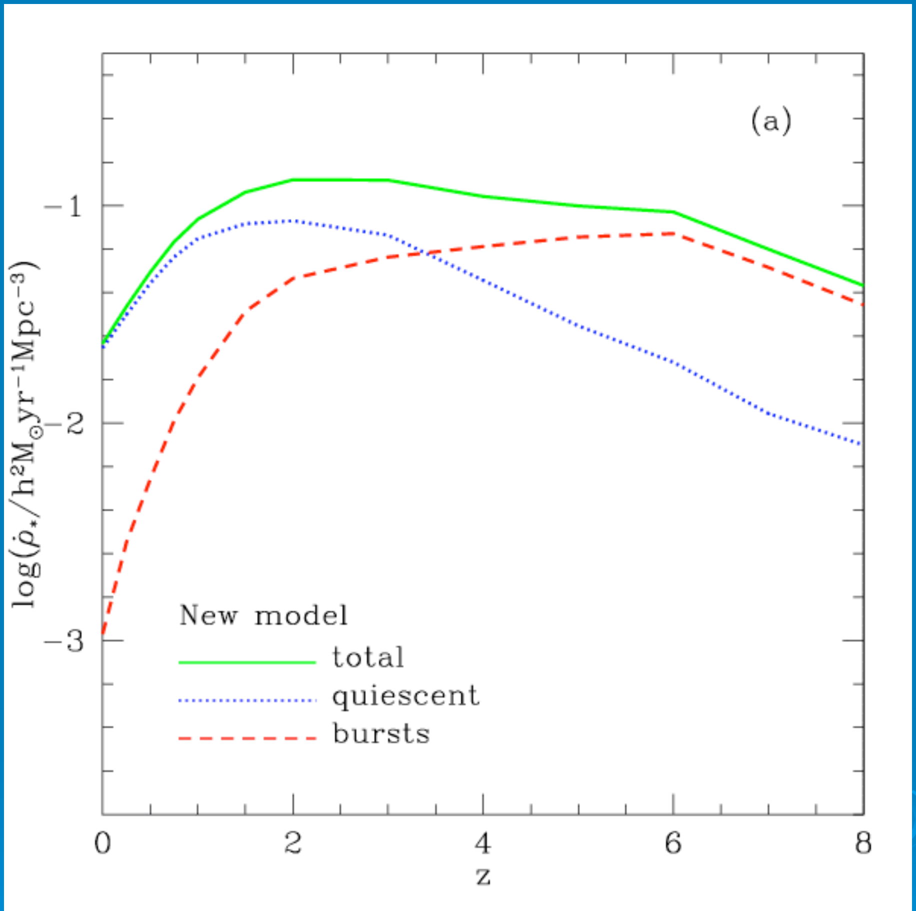
What changes were made to improve these predictions?

1. Change to a constant star formation timescale, rather than one that scales with the dynamical time
2. Minor mergers trigger starbursts in gas rich disks

Global star formation history



Dynamical time scaling



Fixed timescale

Baugh et al. 2005

What changes were made to improve these predictions?

1. Change to a constant star formation timescale, rather than one that scales with the dynamical time

2. Minor mergers trigger starbursts in gas rich disks

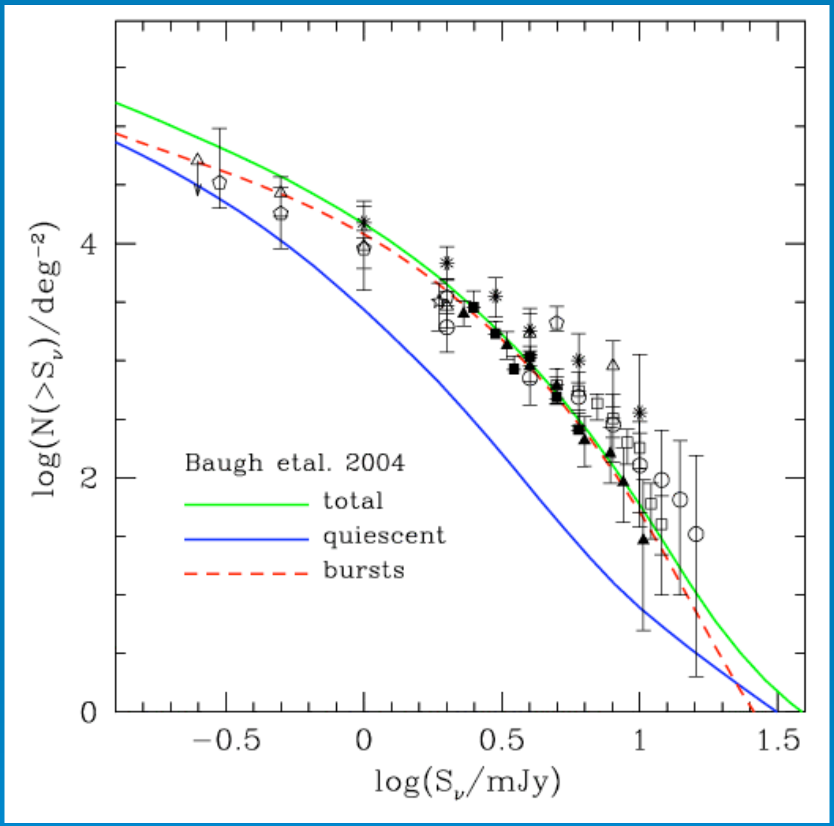
3. Use a flat IMF in starbursts:

   more energy output in UV by high mass stars

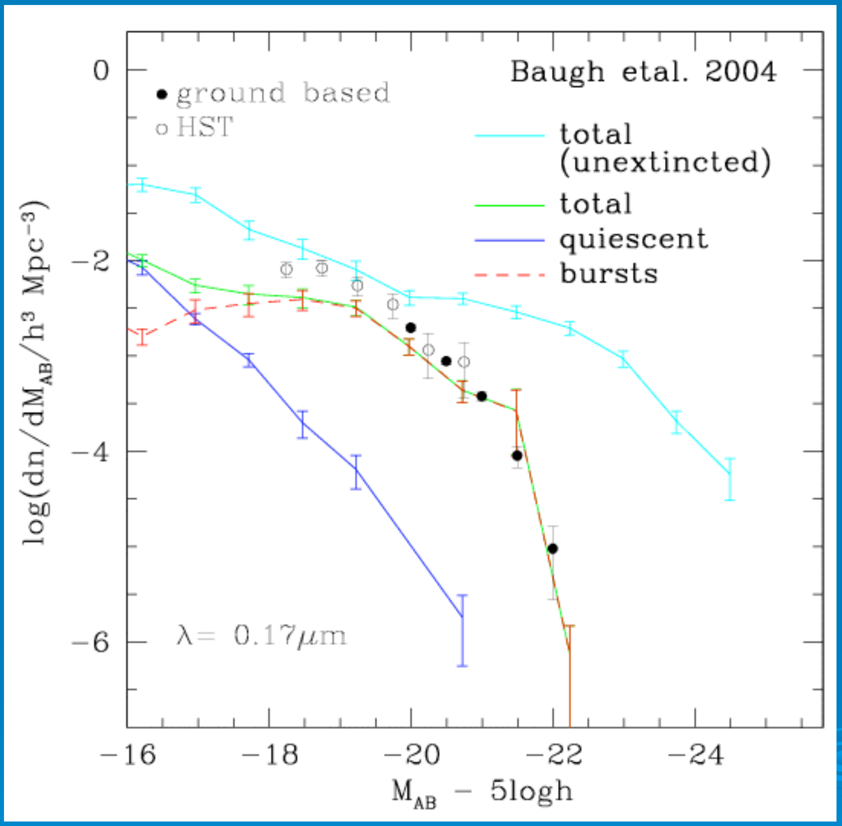
   more energy absorbed by dust

   more dust to prevent heating to too high a temperature

Predictions of the model with a flat IMF in starbursts



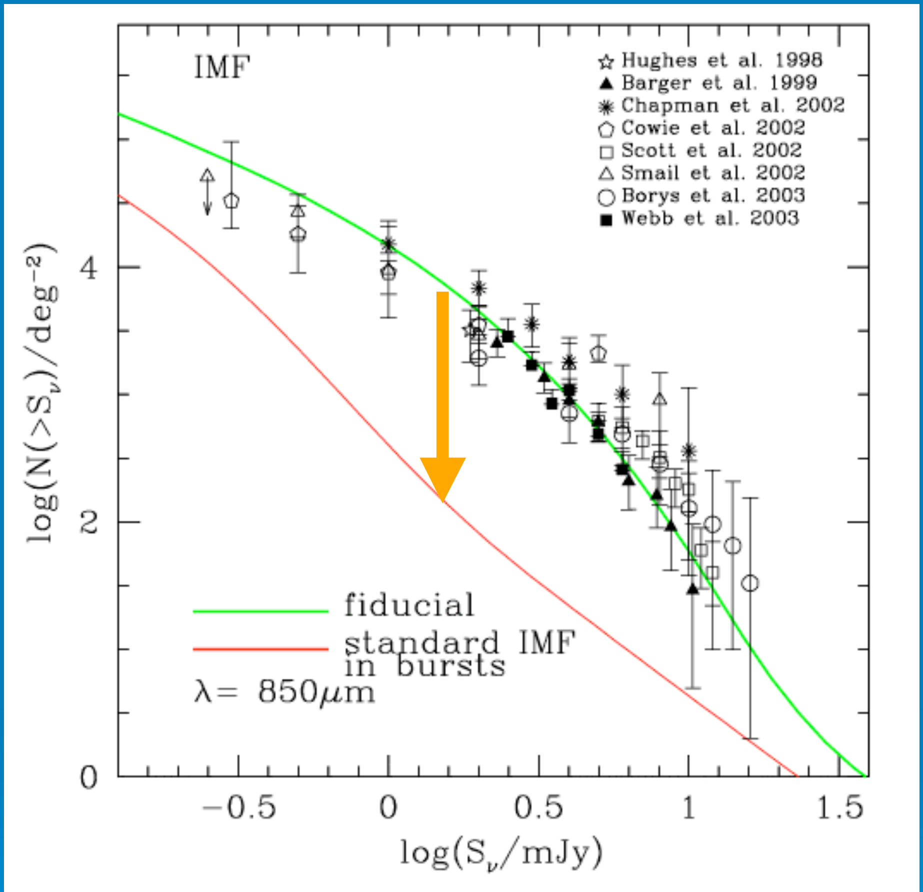
850 micron counts



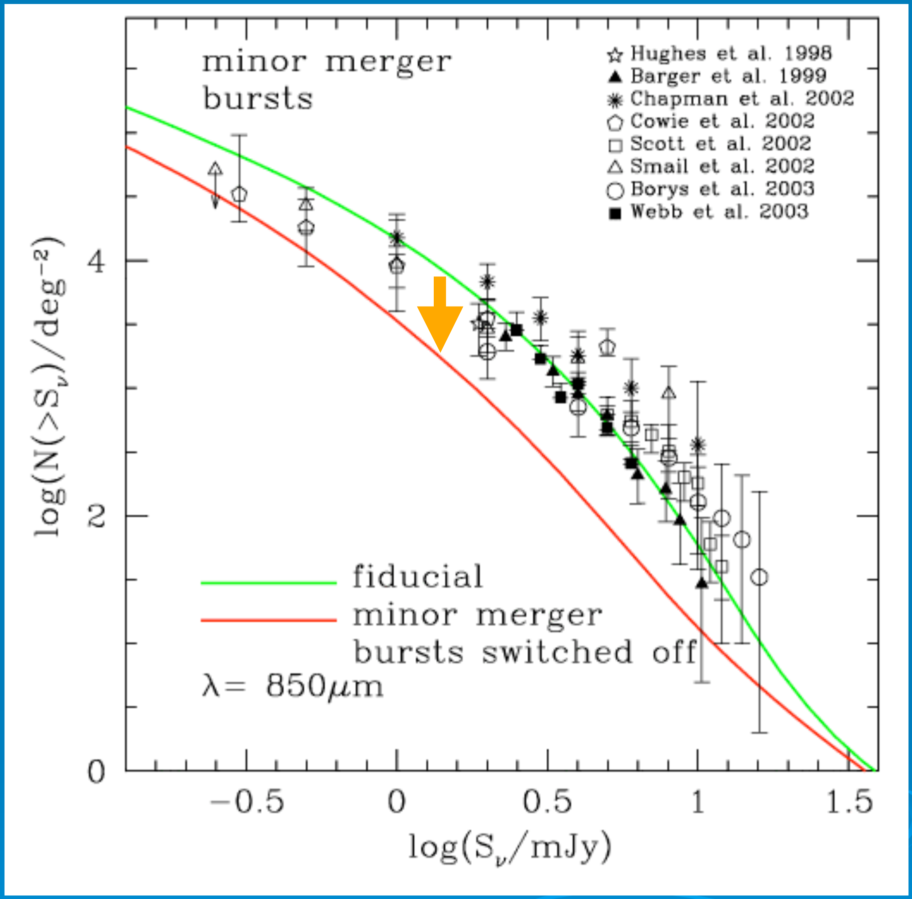
Lyman break LF z=3

Baugh et al. 2005, MNRAS, 356, 1191

Which changes drive the agreement with observations?



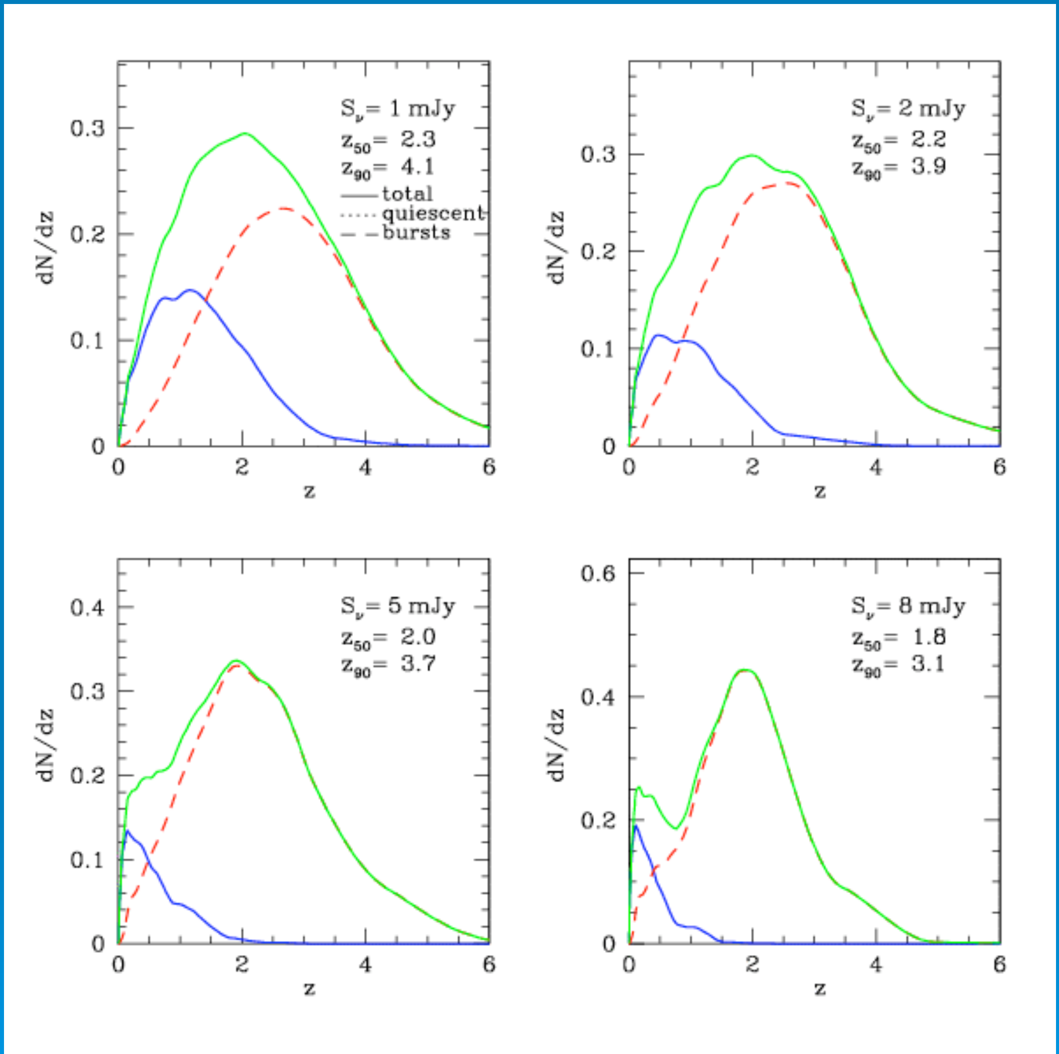
Use standard IMF in bursts



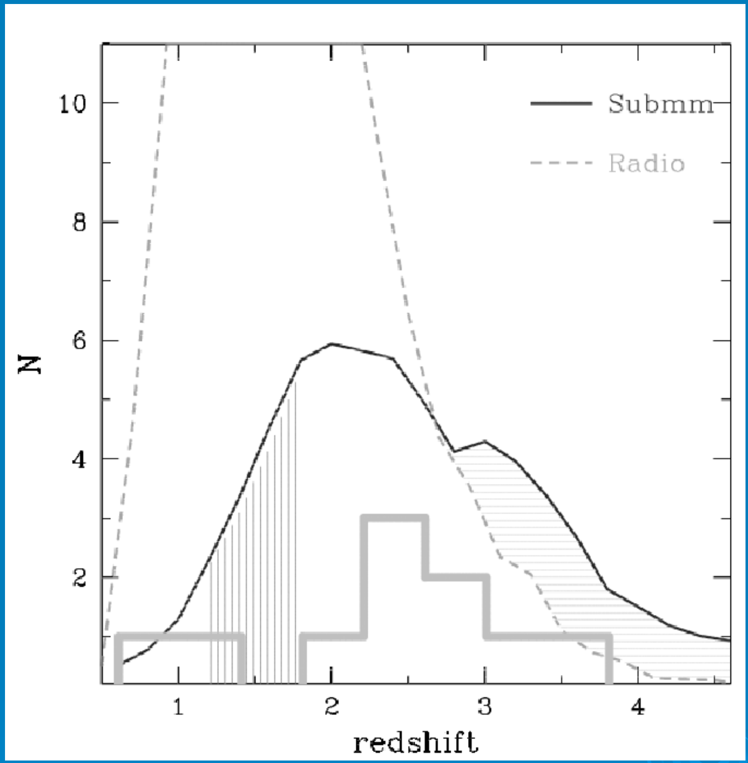
Switch off minor merger bursts

Baugh et al. (2005)

Predicted and observed 850 micron redshift distributions



Baugh et al. (2005)



Chapman et al. (2003)

Predictions at other wavelengths

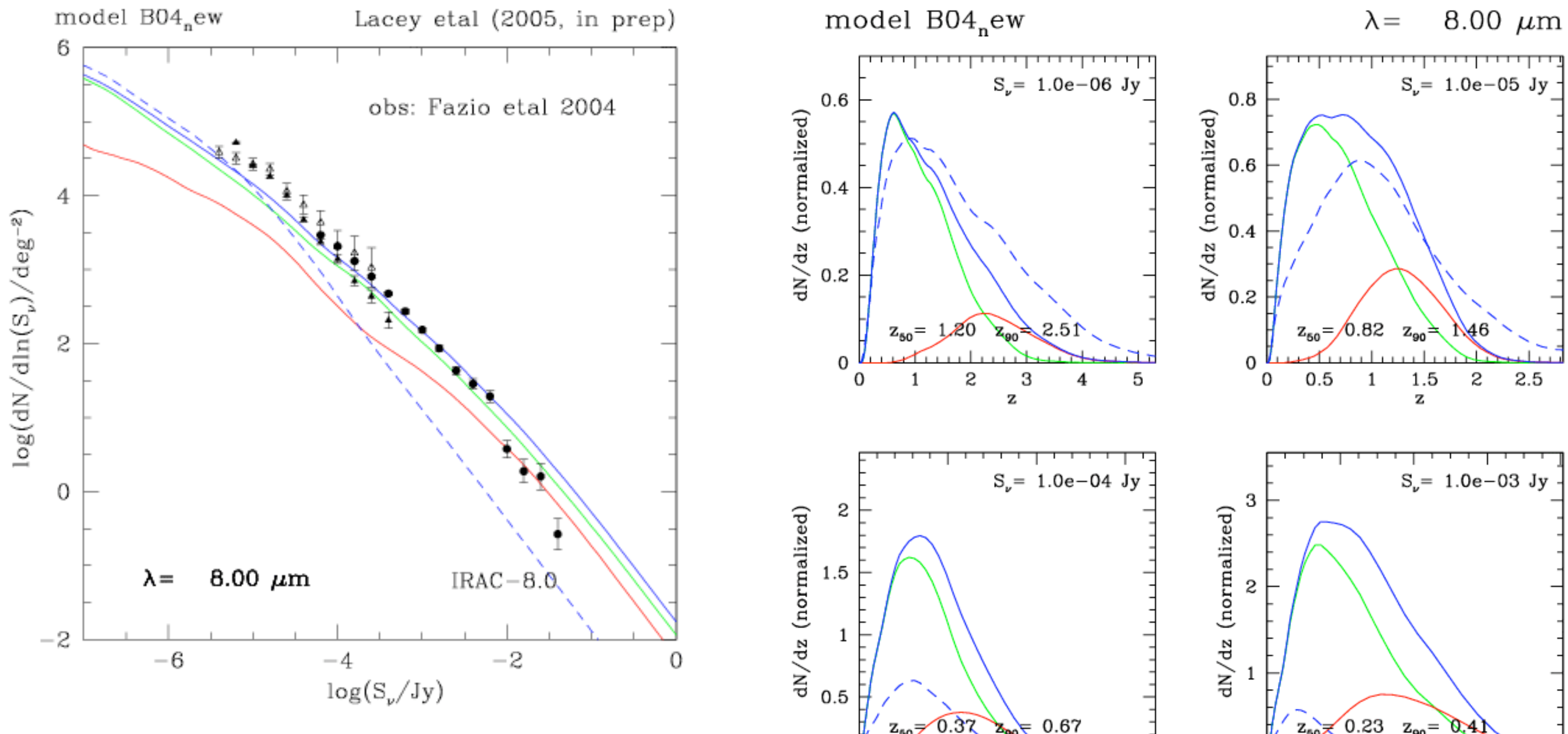


Figure 4. Galaxy differential number counts at 8μm, compared with observational data from (Fazio *et al.* 2004). Model curves as in previous figure.

8 micron counts and N(z) : dust & PAHs start to dominate

Lacey et al. 2006

Predictions at other wavelengths

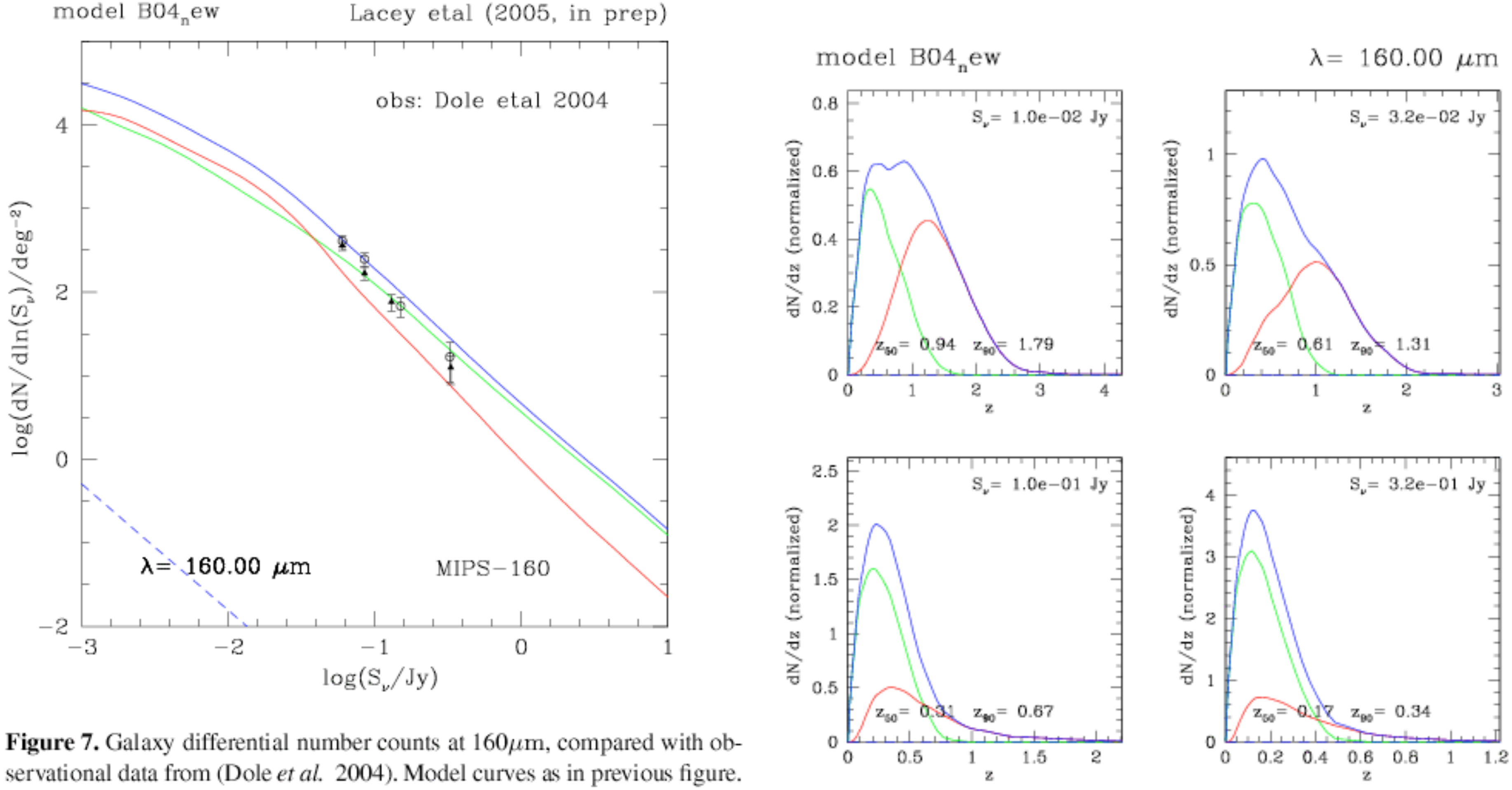


Figure 7. Galaxy differential number counts at 160μm, compared with observational data from (Dole *et al.* 2004). Model curves as in previous figure.

160 micron number counts and redshift distribution

Lacey et al. 2006

Predictions at other wavelengths

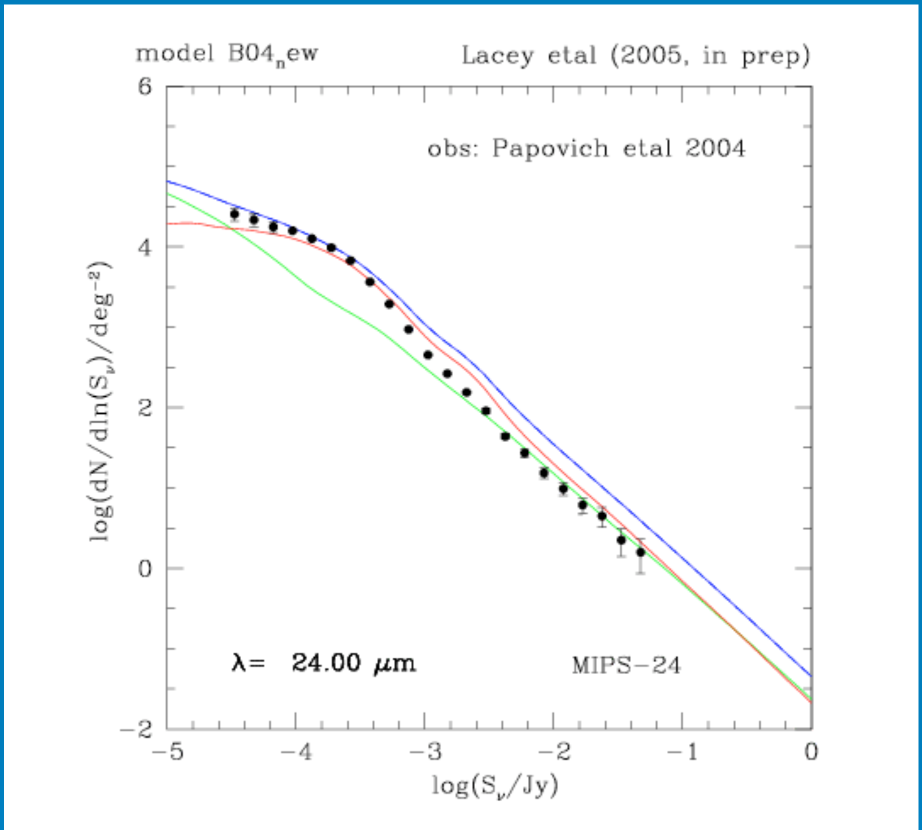
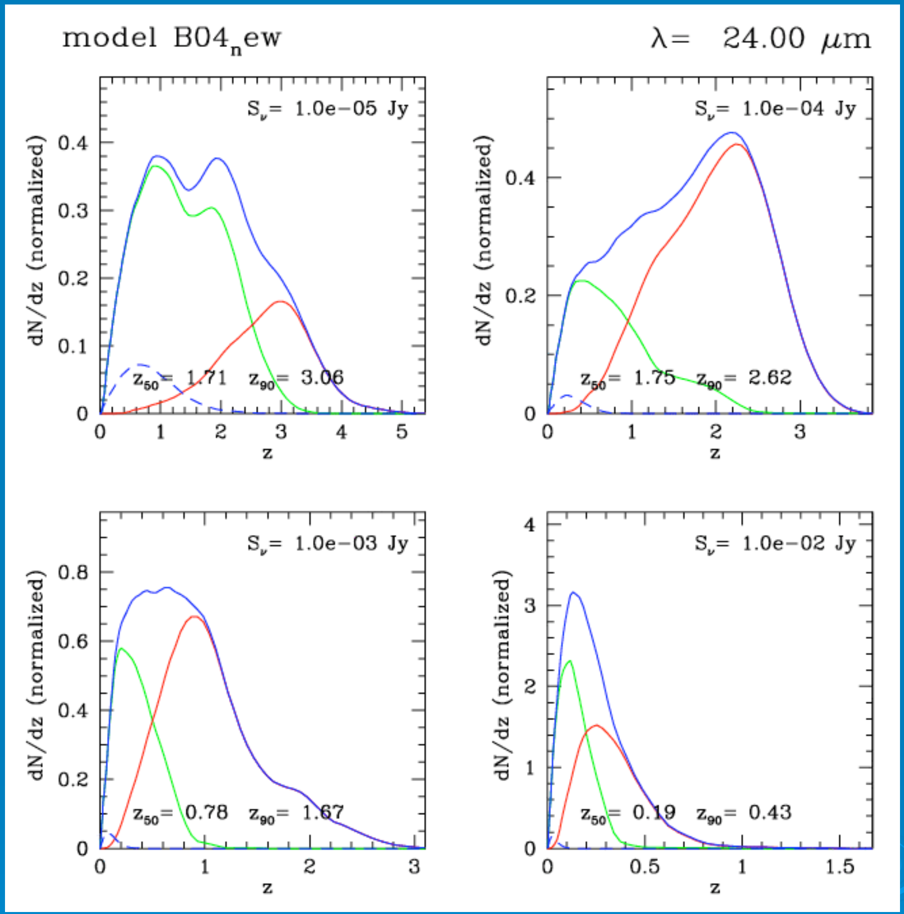


Figure 5. Galaxy differential number counts at 24μm, compared with observational data from (Papovich *et al.* 2004). Model curves as follows:



24 micron number counts and redshift distribution
Accurate modelling of PAHs essential

Lacey et al. 2006

Predictions at other wavelengths

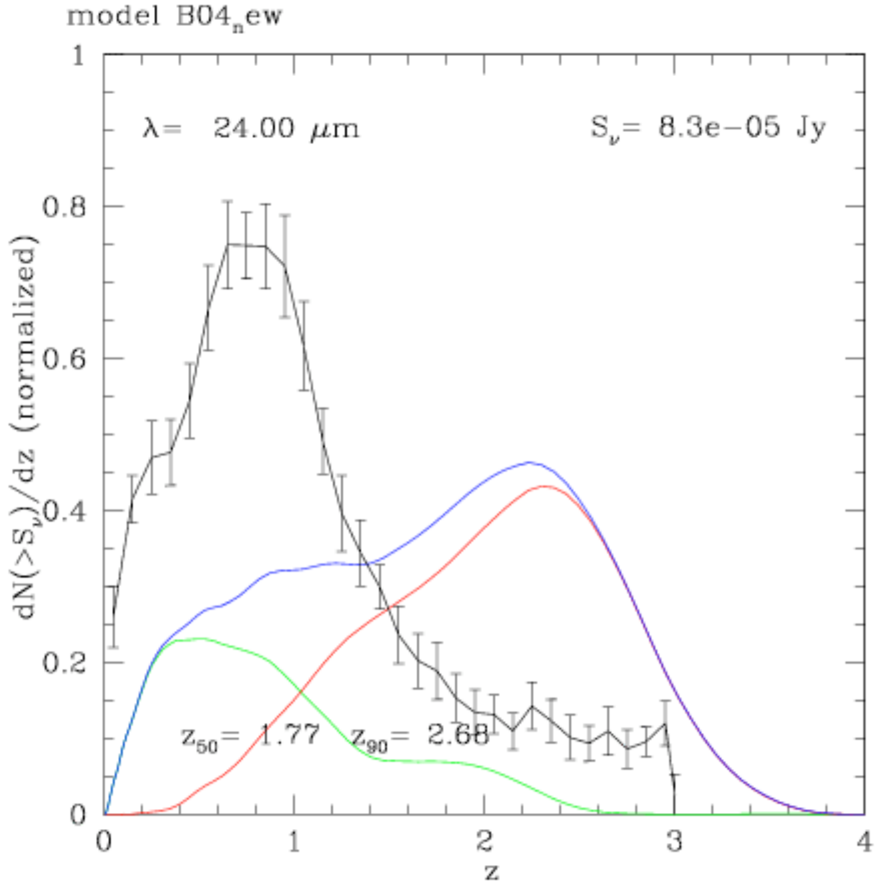


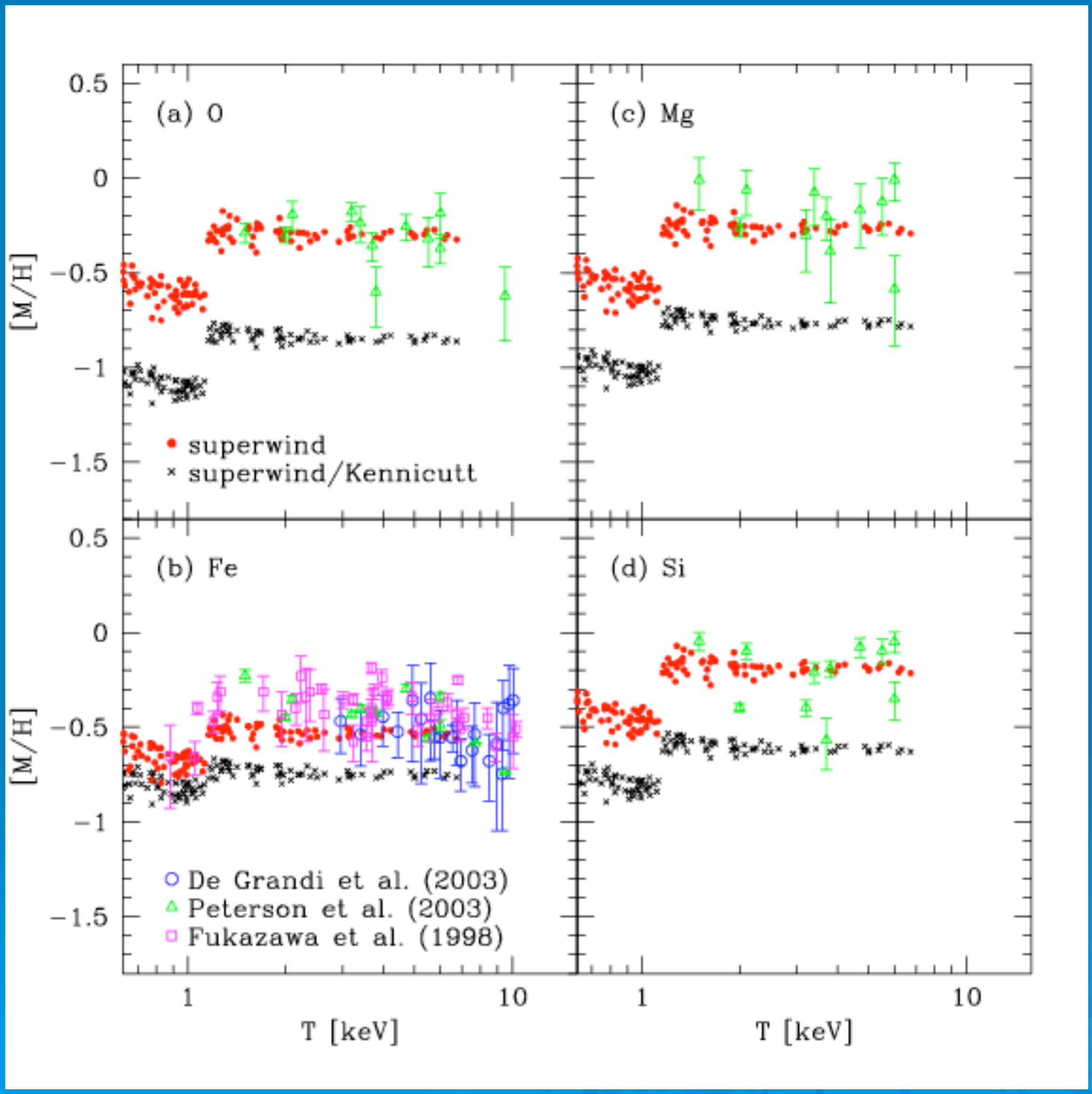
Figure 13. Galaxy redshift distributions at 24μm for galaxies brighter than $S_\nu > 83\mu$Jy. Model curves as follows: solid green: total counts including dust; solid red: ongoing bursts (including dust); solid blue: quiescent galaxies (including dust). Black line with error bars: observational estimate using photometric redshifts from (Perez-Gonzalez *et al.* 2005).

Discrepancy with inferred
Photo-z n(z) at 24 microns

Sources brighter than
83 micro Jy.

Lacey et al. 2006

Other evidence in support of a top-heavy IMF



Model with top-heavy IMF matches metal abundances in ICM

Nagashima et al. 2005

Type I & Type II SN

Summary

1) Structure formation IS hierarchical

2) Lambda-CDM seems like a good bet: working framework

3) Realistic galaxy formation models must be set in hierarchical context

4) Efficiency of galaxy formation depends on halo mass

5) Problem with overproducing bright galaxies today

6) Problem forming massive galaxies at high-z?

7) Model with flat IMF in starbursts has a number of successes:

   * reproduces present day luminosity functions: B, K, 60 micron
   * reproduces 850 micron counts and N(z)
   * reproduces Lyman-break luminosity function
   * good match to SPITZER counts