The Formation and Evolution of Galaxies in the First Half of the Universe's Age

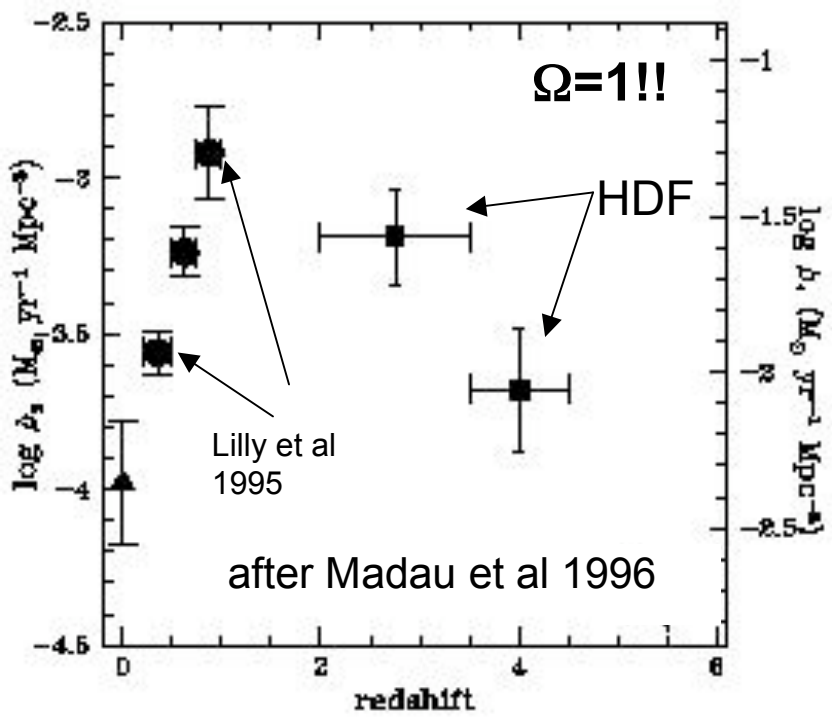
Galaxies Block Course April 4 08
Hans-Walter Rix - MPIA

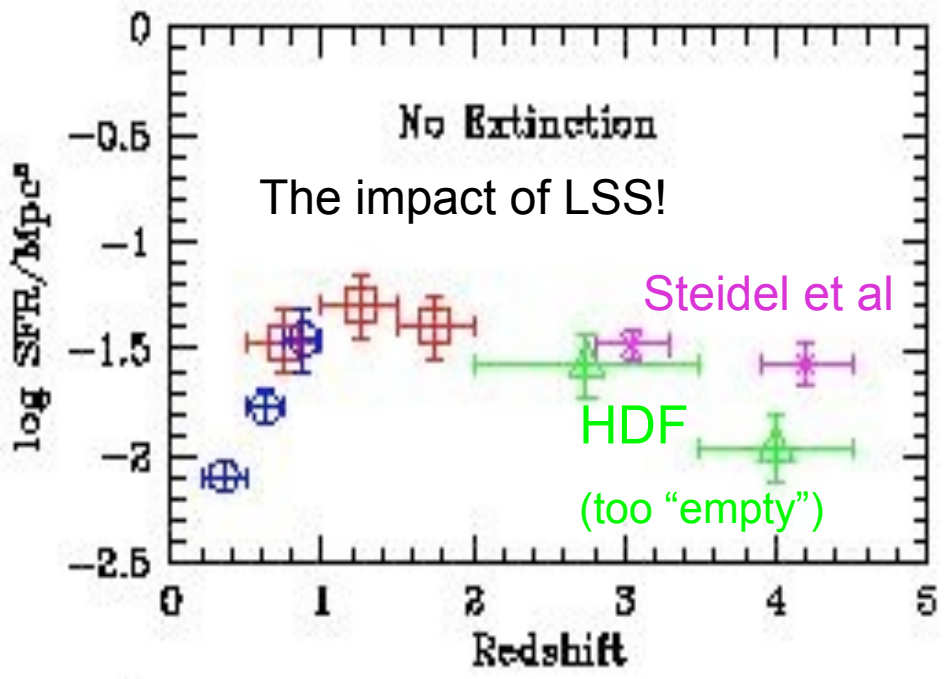
The Evolution of the Cosmic Star Formation Rate

- When did it start / ramp up?
- When were half of the stars formed?
- Can it be understood (in terms of models)?
- When/how did the first stars form?

- Estimating the "cosmic star-formation rate"
  - Estimating the SFRs in individual objects
  - Are all relevant sources included
    - Faint
    - Obscured

First (1996-1997) estimates of the cosmic star-formation history

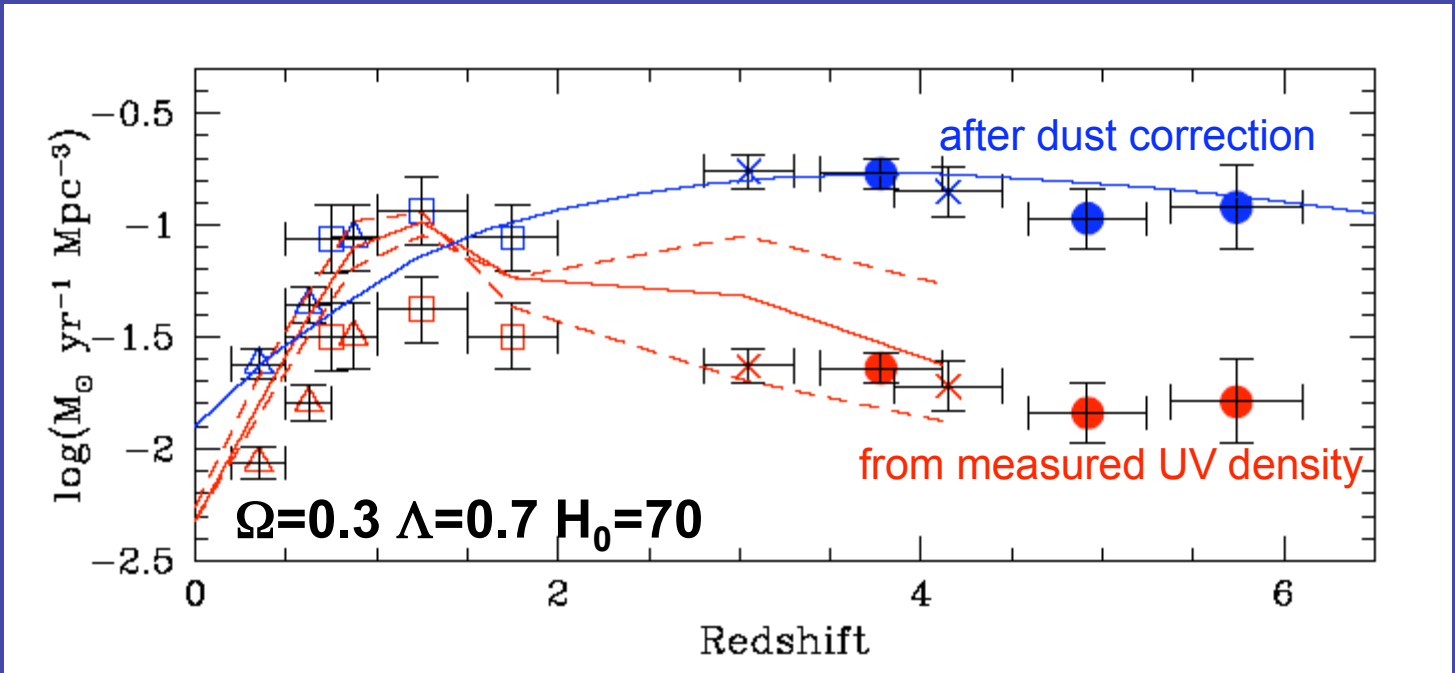




Warning: historical plots. Do not use for research!!

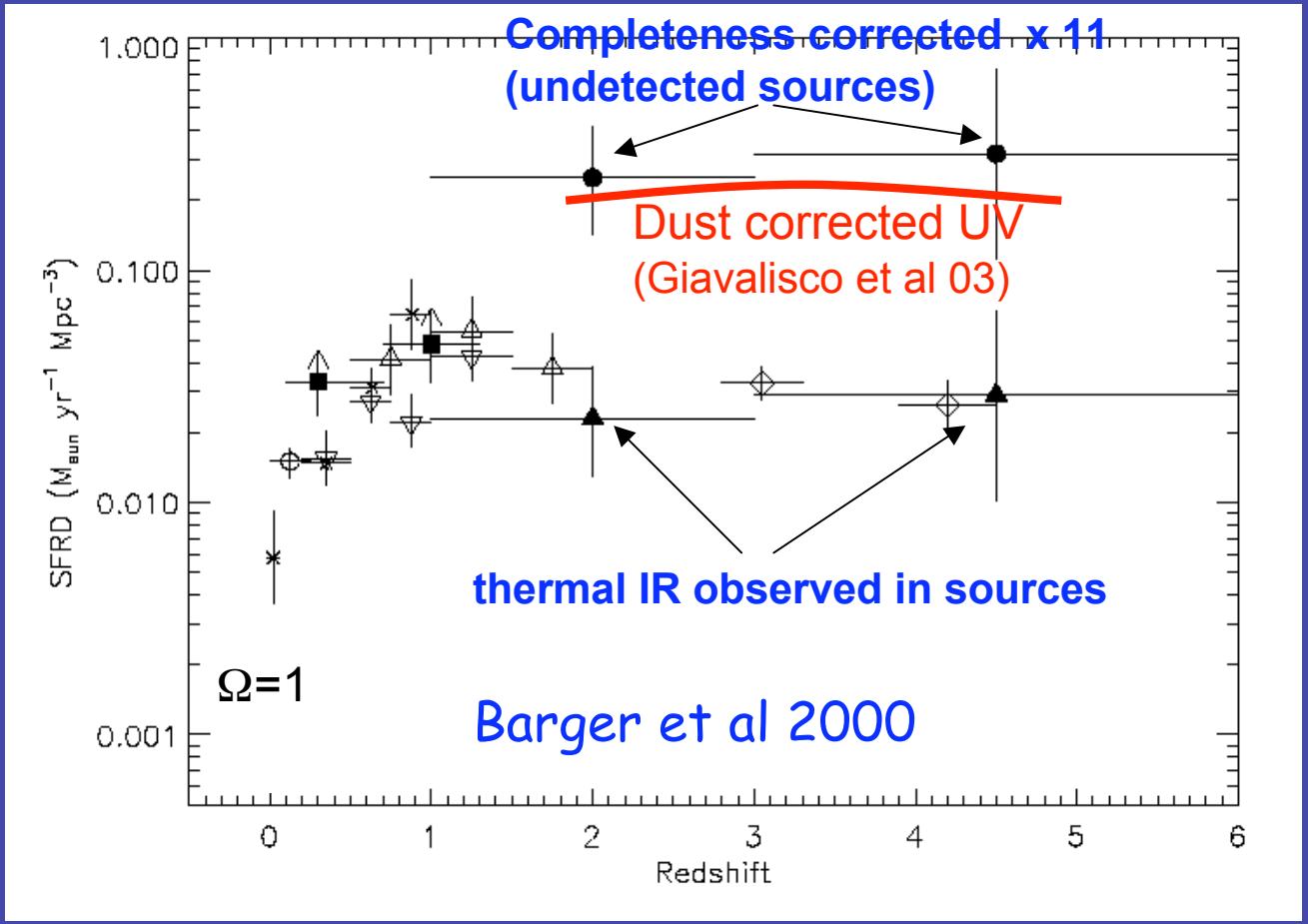
A current "UV-based" version

Giavalisco et al 2003 (GOODS)

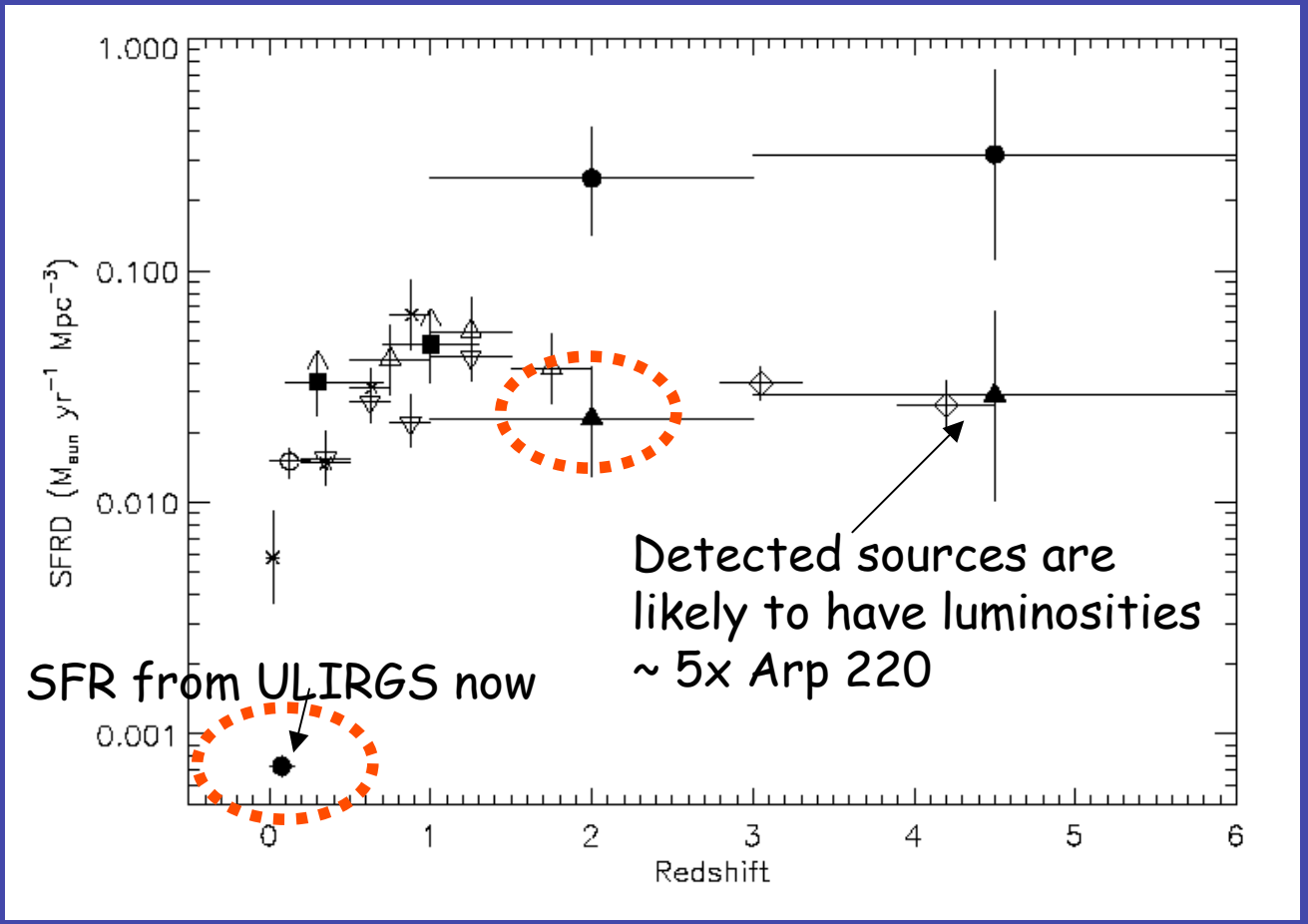


a.k.a. the '(Lilly-)Madau-plot'

And from the perspective of sub-mm (thermal dust emission)



The Evolution of Intense Starbursts



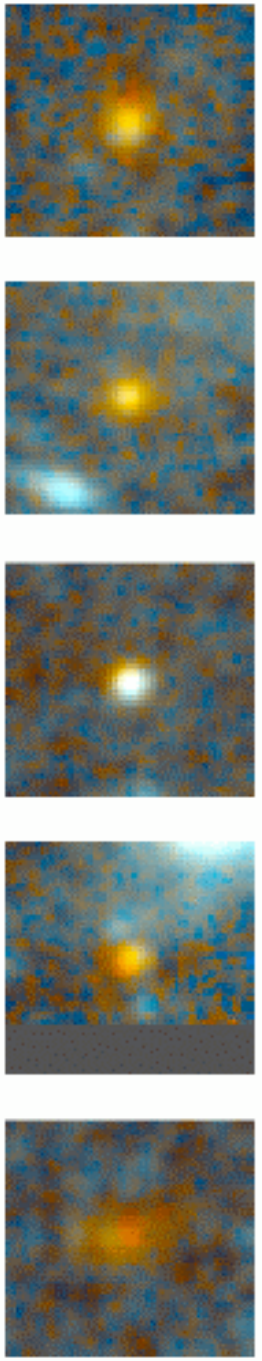
- SFR from ULIRGs has dropped by > 100 since ~3!
- NB: many high-z QSO's also show enormous thermal dust emission → phases of intense SFR

Cosmic Star-Formation History z>1

- UV based estimates (after dust correction by 10) and sub-mm/thermal IR (after incompleteness correction of 10) give consistent <SFR> estimates 2<z<6
- 1.5<z<6 <SFR> approximately constant (~2)
  - Note: there is weak evidence for a drop before z~5
  - Note: there is much less time in interval 5>z>4 than 1>z>0 ….
- ULIRG (>few $100M_{sun}$/yr) mode of star-formation has dropped by >100 since z~3

Brief, but important aside

- Galaxies with low SFR exist at $1<z<3.5$
- they can be found in IR-selected samples
- They seem to make up ½ of the stellar mass (see below) at z~2-3



FIRES: van Dokkum et al 2003 with Spectra

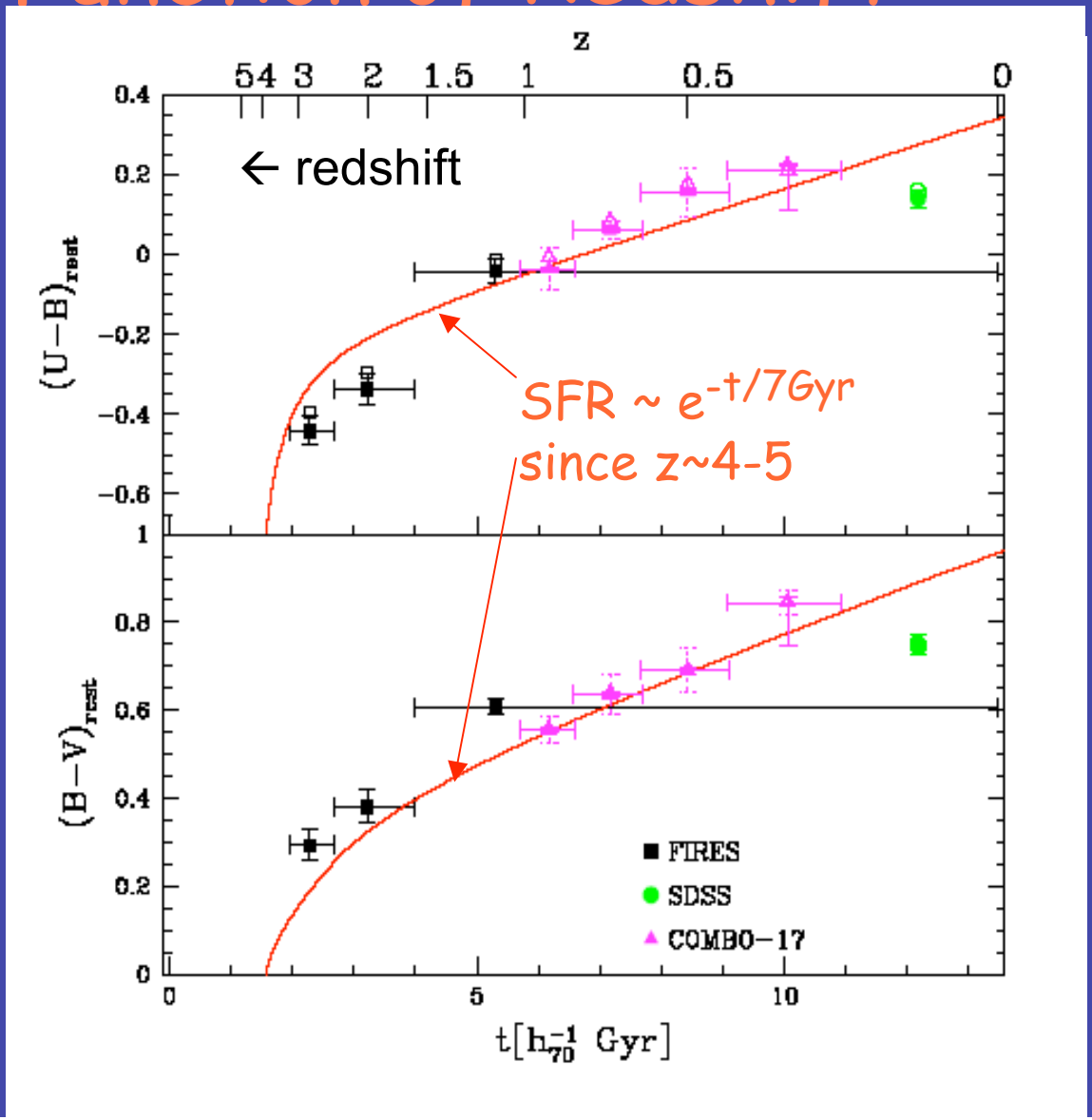
The Build-Up of the Stellar Mass
Step 1

The mean color of galaxies as function of redshift (Rudnick et al 2003):

- Optical colors ← → M/L_B as long as star-formation history is not too "bursty" (Bell and de Jong 2001)
- Individual galaxies may have bursts, but an ensemble of galaxies at a given epoch (say $\Delta z \sim 0.5$) should not have their bursts all at the same time
- → Look at the mean color of the galaxies as a function of

Mean Color of the Galaxy Population as a Function of Redshift

- On average, galaxies were much bluer in the past
- <M/L> was 10 x lower at z~3

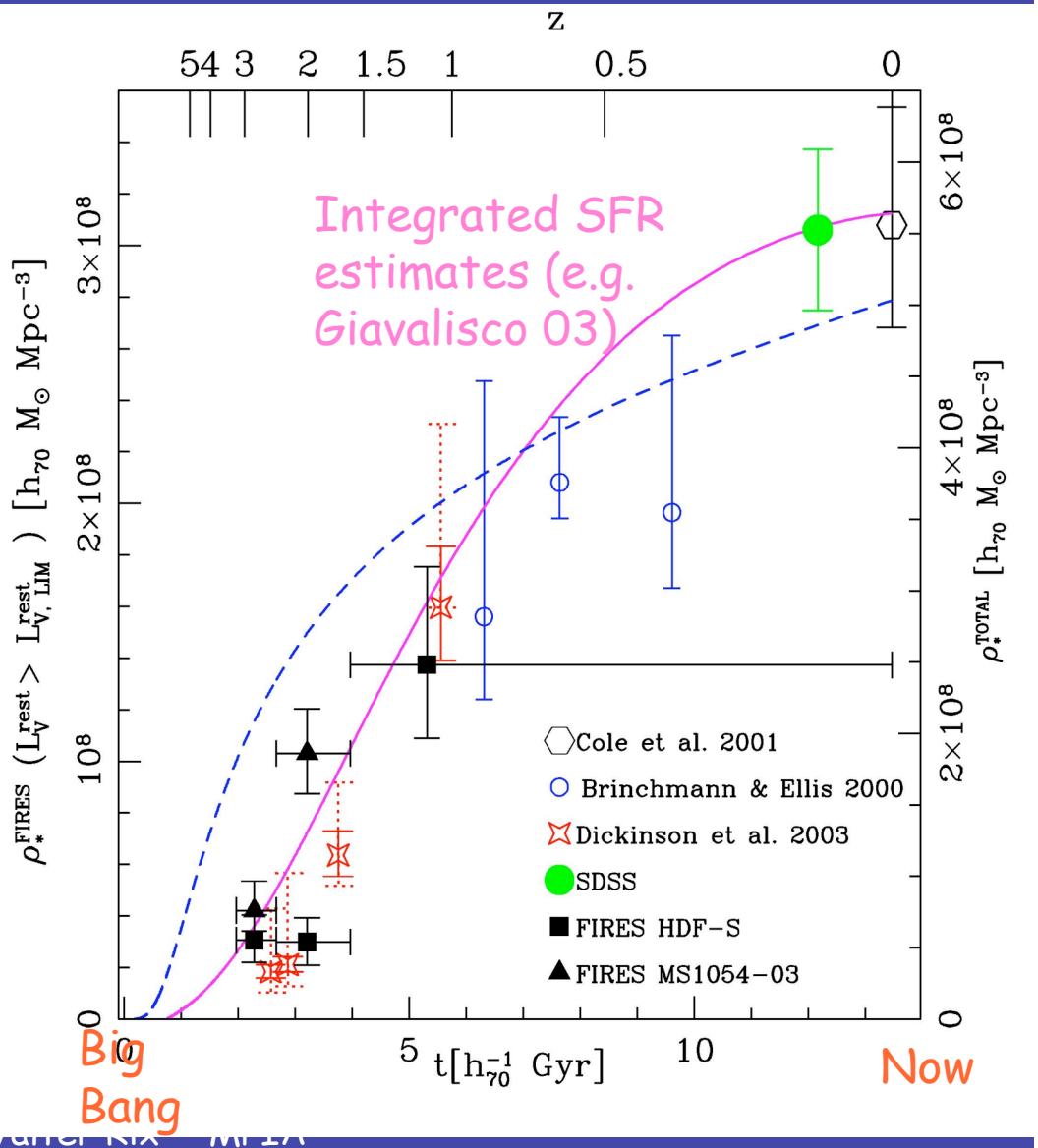


The Build-Up of Stellar Mass

Rudnick et al 2003

- Take IR-selected sample
- Multiply j_V with $\langle M/L \rangle_V$ to get $\langle \rho_* \rangle$

- ½ of stars since z~1.4
- 50% between 2>z>1
- 10% before z~3

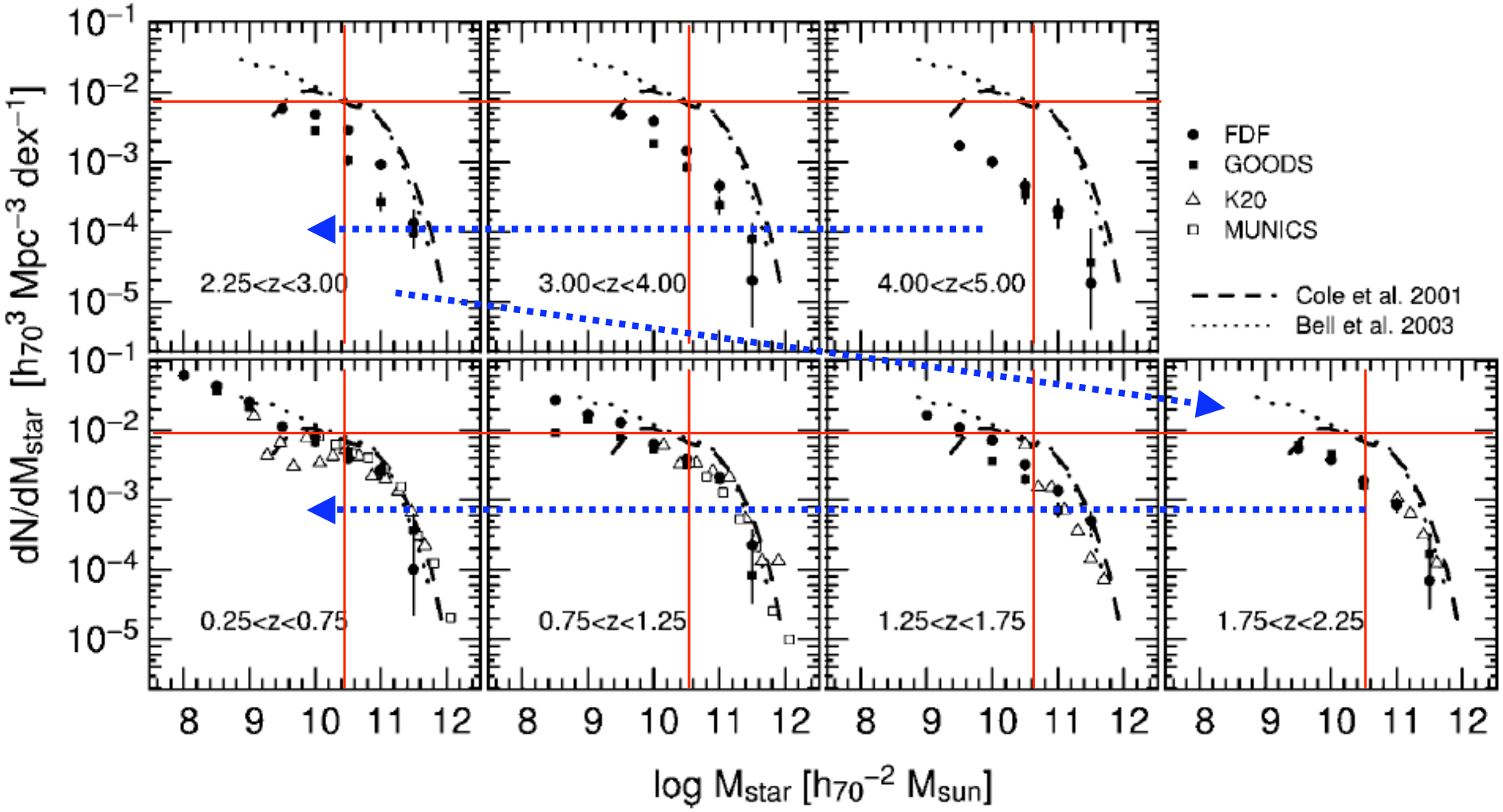


Build up of Stellar Mass

(Drory et al 04)

→ throughout global build-up of stellar mass, most stars have lived in galaxies near the 'characteristic galaxy mass' (now 3-5x10^10Msun) and at z~3 (when ~10% of all stars had formed) factors of a few lower

→the picture 'early on stars were all in 'very small galaxies' is not correct



Modeling/interpreting the <SFR>(z)

- The <SFR> = f(z,M_{halo}) is a consequence of
  - Fluctuation/halo growth
  - Gas cooling in those halos (cold fuel supply)
  - [feed-back]

- Simulation approaches
  - Direct cosmological hydro-dynamical simulations

    (e.g. Springel and Hernquist 2005)
    - Main issues: resolution + star-formation (+feedback 'recipe')

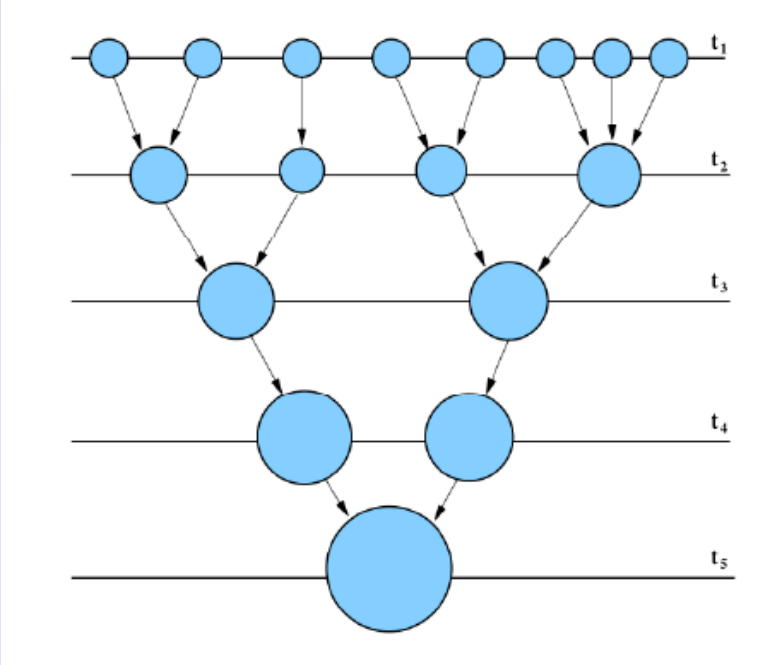
  - Semi-analytic models

    (Kauffmann; Lacey and Cole '93 → Croton et al 06, Somerville et al 08)
    - DM halo abundance and merging from Press-Schechter Theo.
    - Main issues: galaxy merging, spatial information, + star-formation (+feedback 'recipe')

Elements of the Modelling

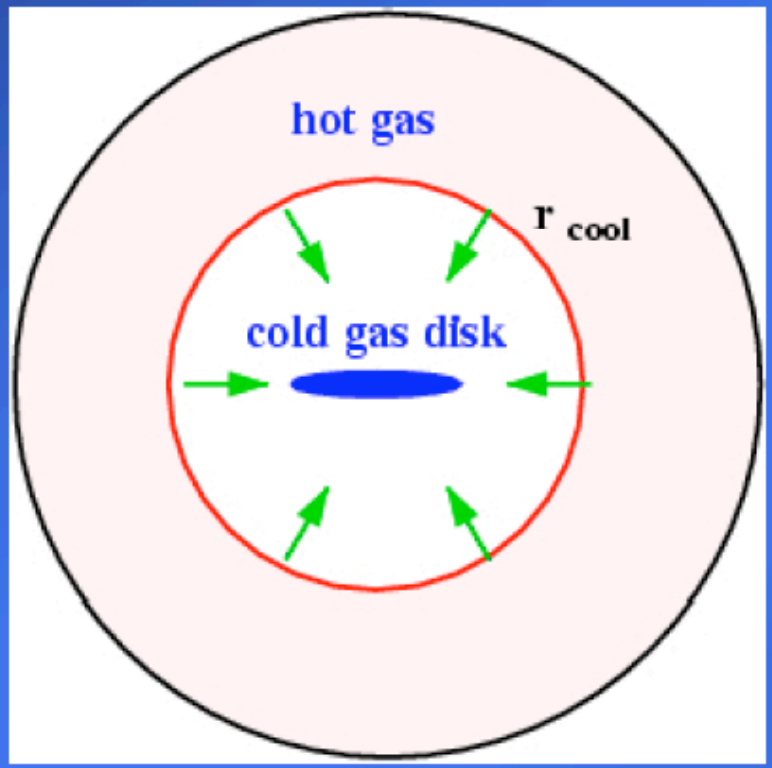
- http://www.daf.on.br/etelles/lectures/lacey-2.pdf

Assembly of dark matter halos: Merger trees



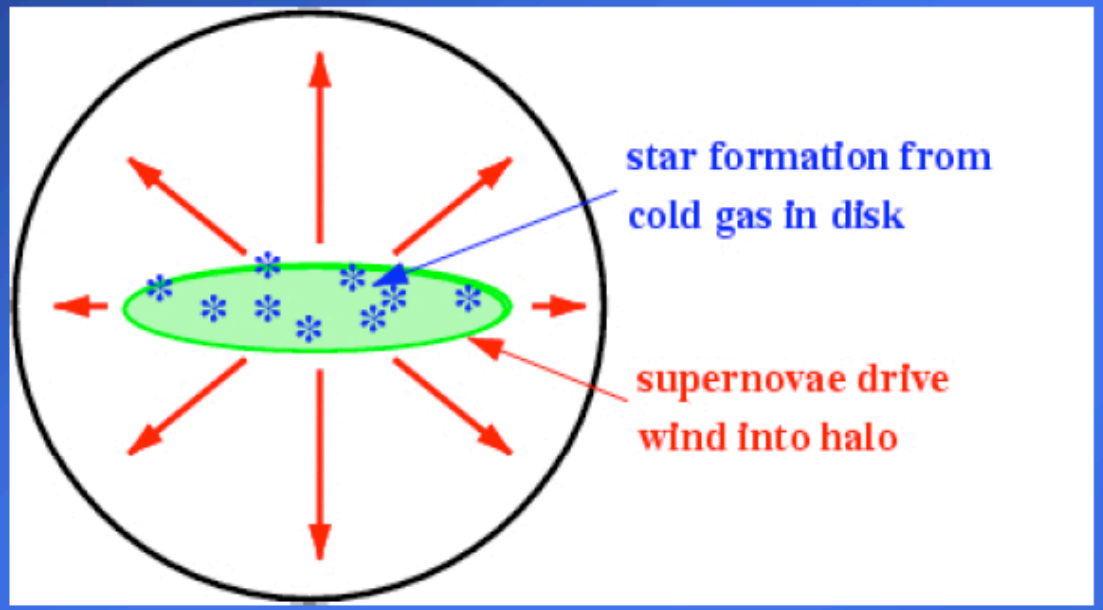
- Assembly history of halo described by merger tree
- 2 approaches:
- **Monte Carlo** based on conditional **Press-Schechter** mass function
- **Extract** from **N-body simulations**
- similar results from both approaches

Shock-heating & cooling of gas in halos



- Infalling gas all shock-heated to halo virial temperature
- Radiative cooling of gas from static spherical distribution
- Disk size related to angular momentum of gas which cools

Star formation & feedback



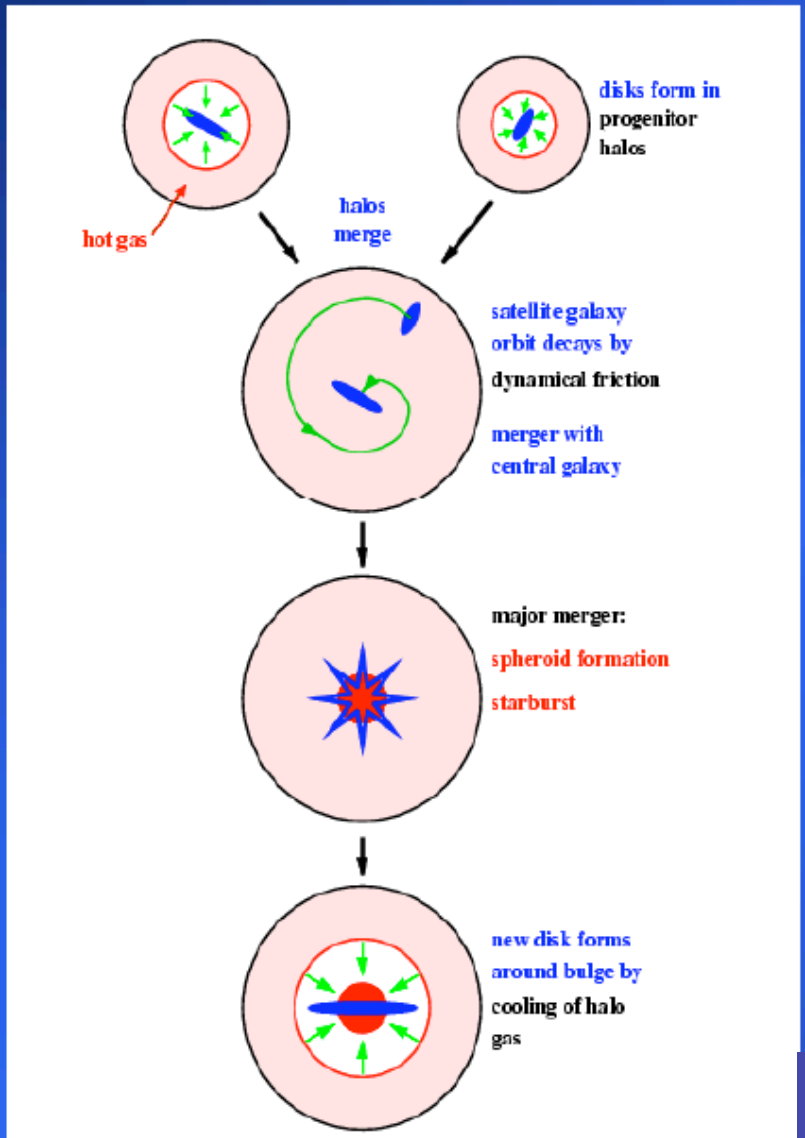
- **stars form in disks**

$$SFR = M_{gas} / \tau_*$$

- **supernova feedback ejects gas from galaxies**

$$\dot{M}_{eject} = \beta(V_c)\, SFR$$

Galaxy mergers & morphology



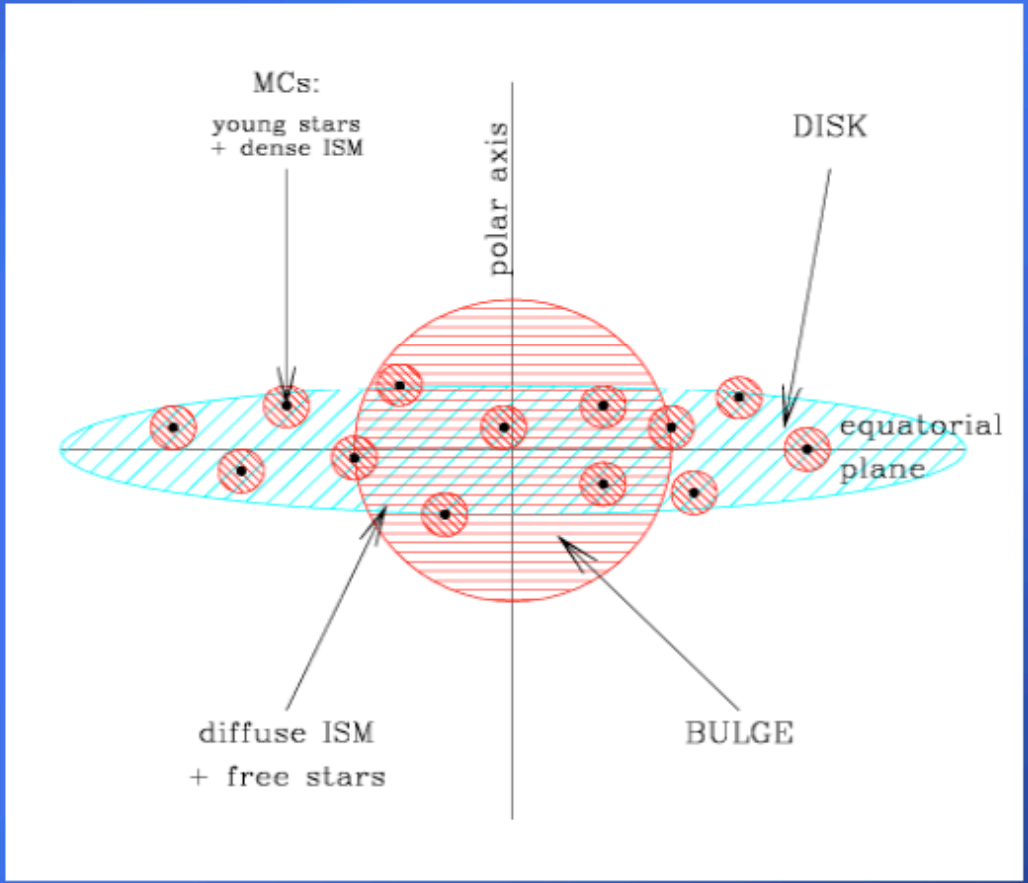
- halos merge
- galaxies merge by dynamical friction
- major mergers make galactic spheroids from disks
- mergers trigger starbursts
- spheroids can grow new disks

Modelling galaxy SEDs

Or other

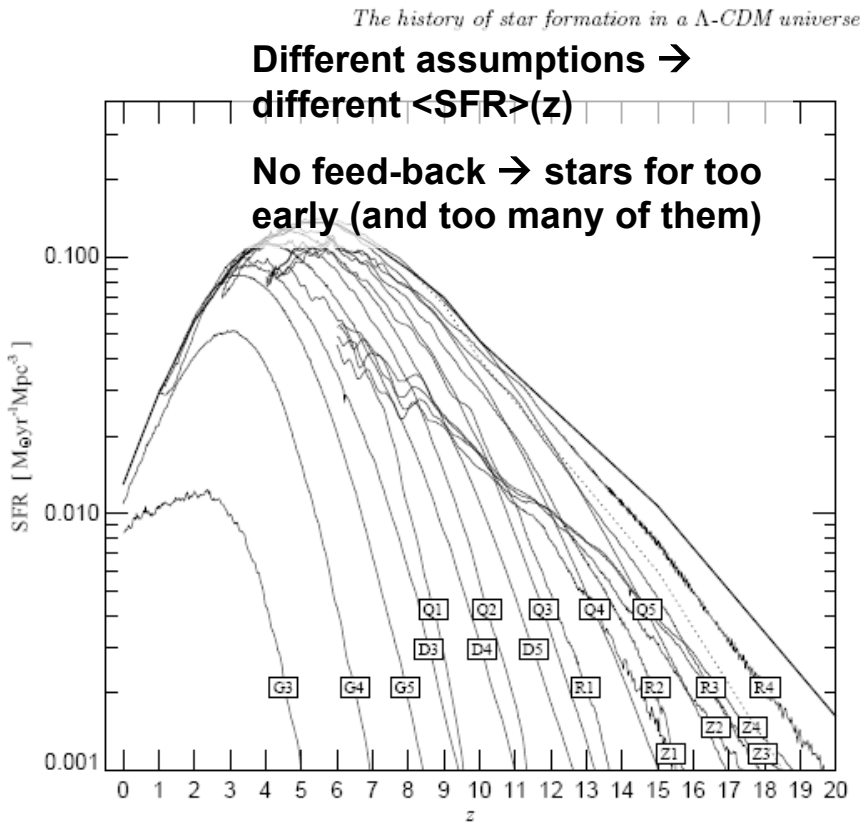
use GRASIL model to compute emission from stars, extinction and emission by dust, and radio emission

(Silva et al 1998)



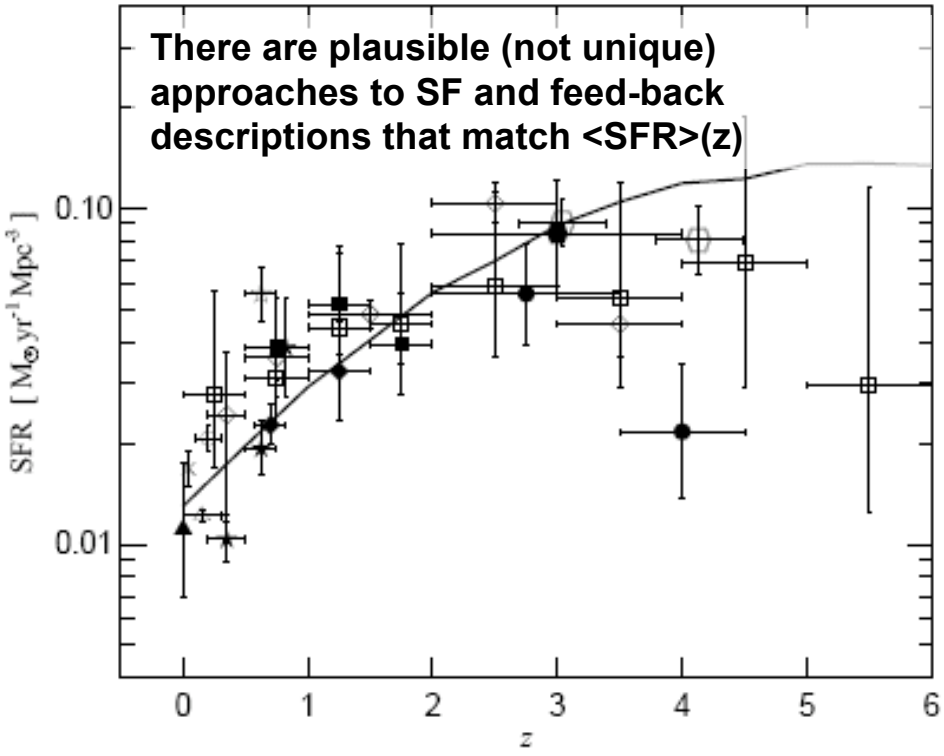
Results of such simulations

1st example: Springel & Hernquist 03



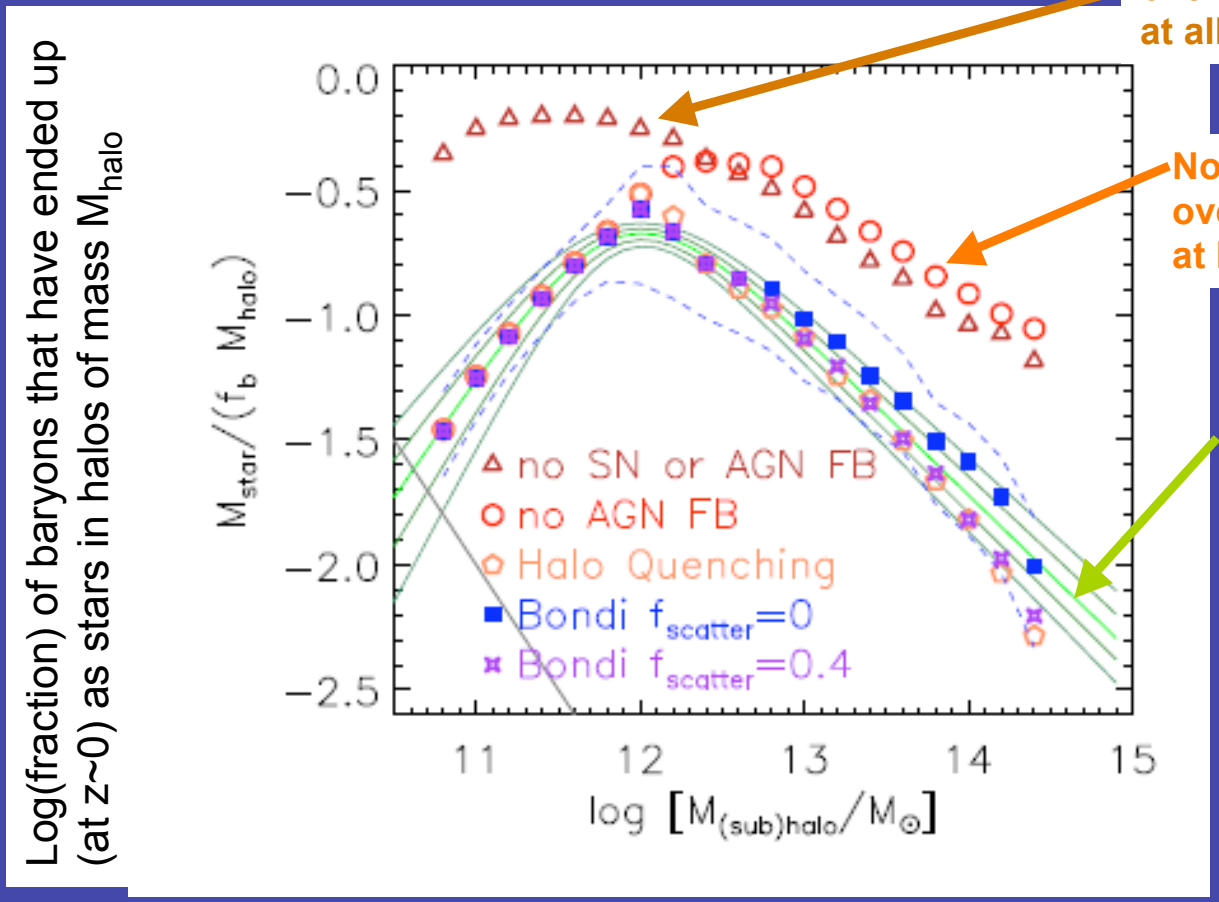
Different assumptions → different <SFR>(z)

No feed-back → stars for too early (and too many of them)



There are plausible (not unique) approaches to SF and feed-back descriptions that match <SFR>(z)

Comparison data—models
(Somerville et al 08)



No feed-back → vast overprediction of stars at all halo masses

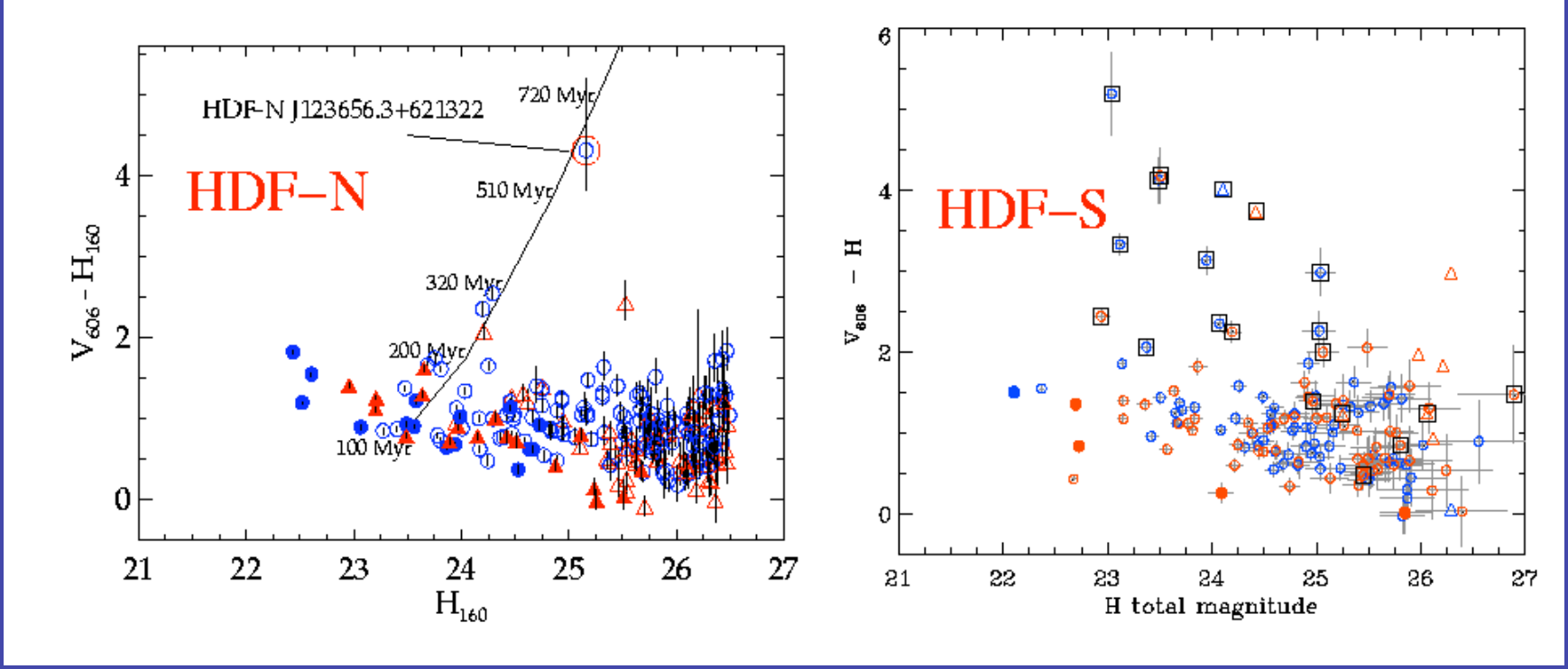
No AGN feed-back → overprediction of stars at HIGH halo masses

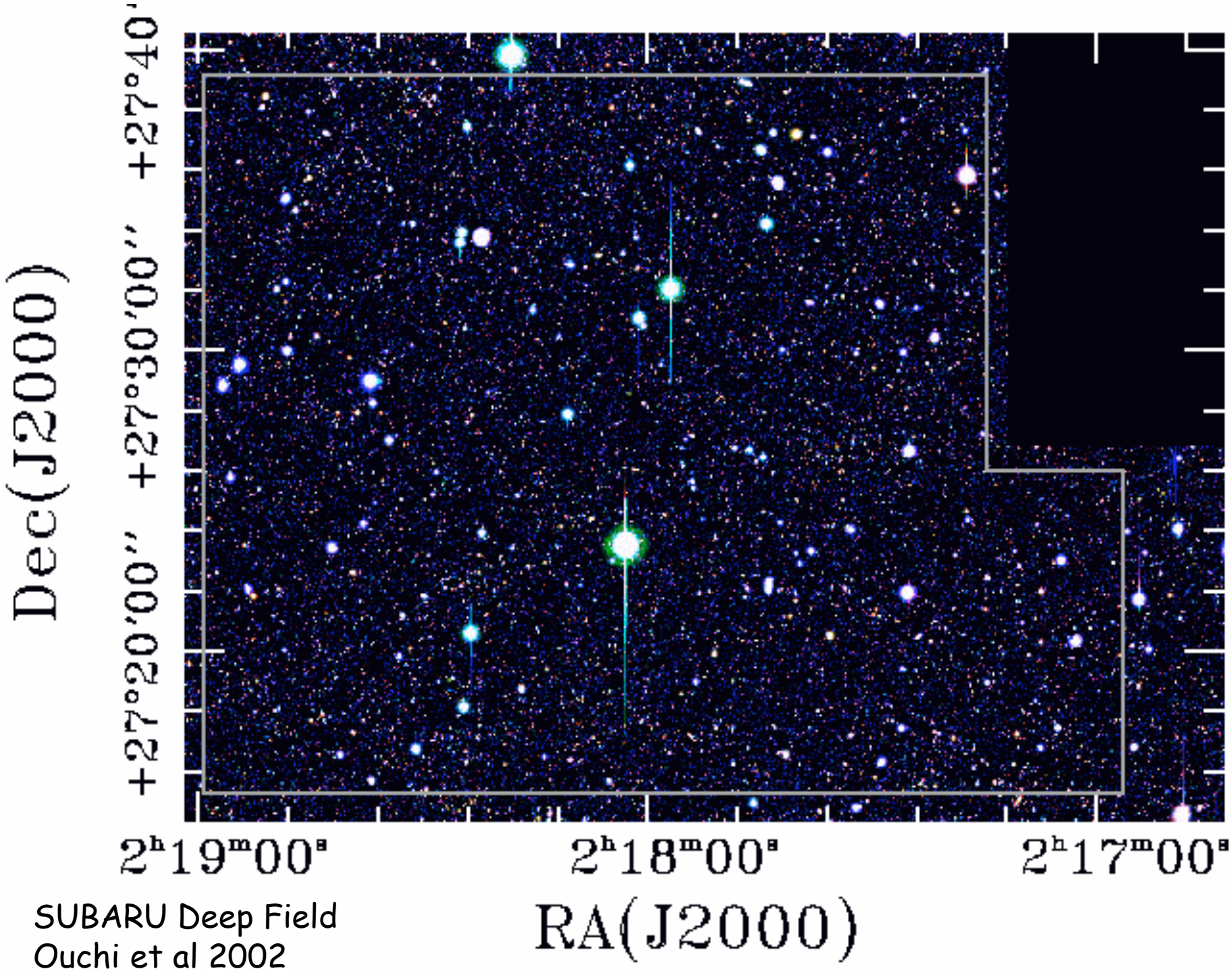
Observational constraint (from B. Moster)

Galaxy Clustering and its Evolution

- **Generic prediction of hierarchical CDM models:**
  - More massive halos (=more luminous galaxies?) are more strongly clustered
  - (Luminous) Galaxies at early epochs are increasingly "biased" → their clustering remains high
- **Present epoch:** redder galaxies are more clustered than blue ones
  - **Has that always been true?**

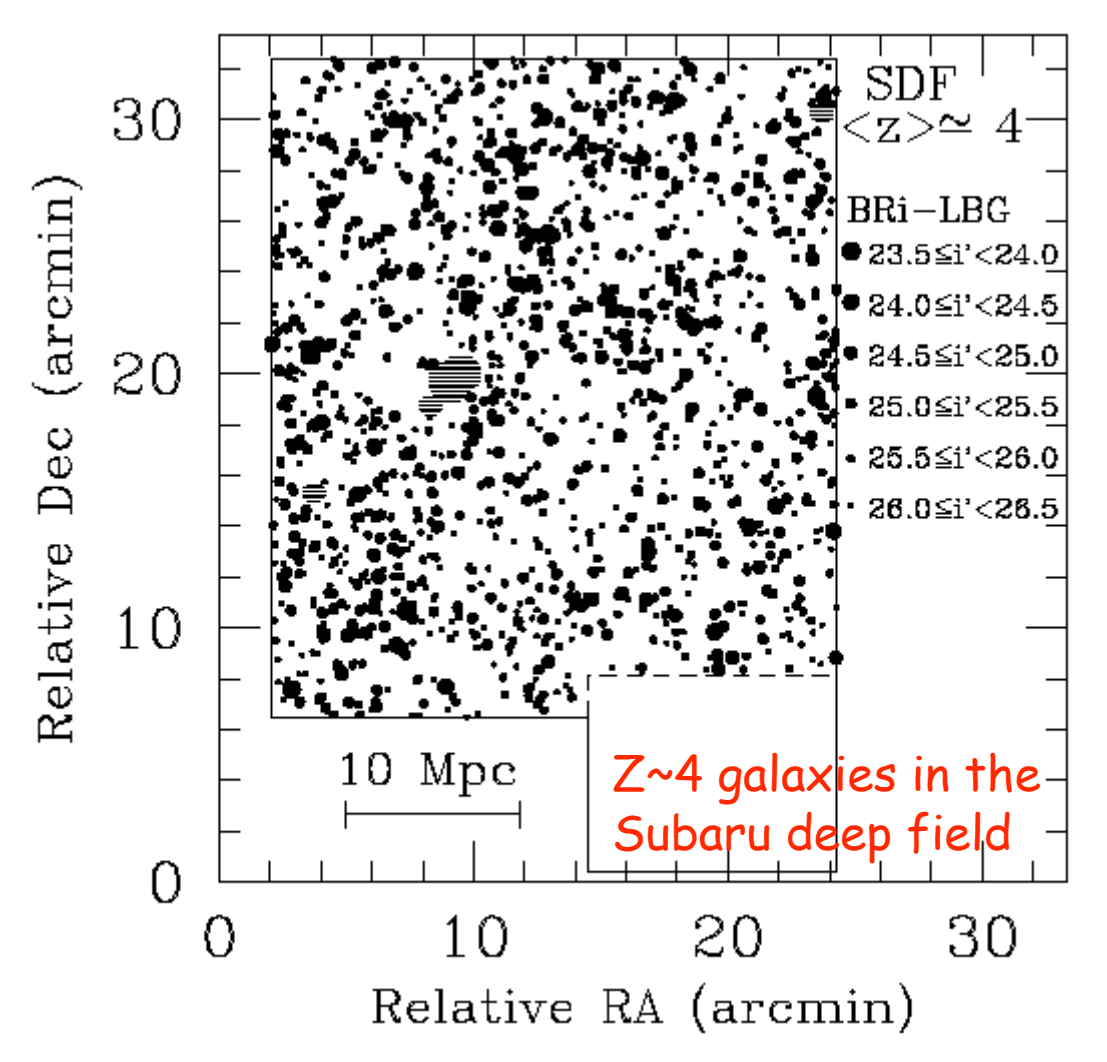
Example: Red Galaxies in the Hubble Deep Field





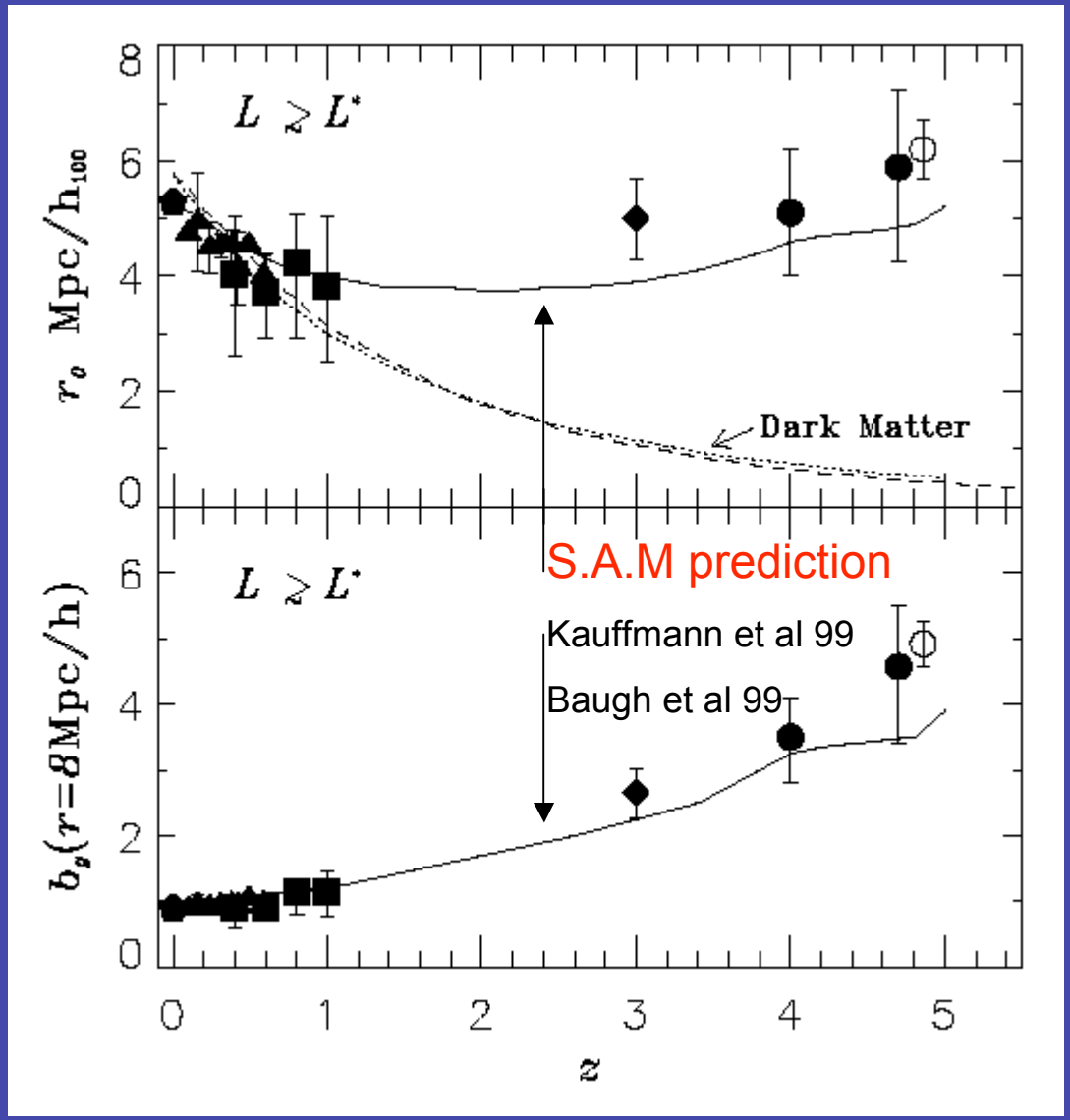
SUBARU Deep Field
Ouchi et al 2002

Ly-break galaxies are observed to be clustered (e.g. Giavalisco et al 1998; Ouchi et al 2003)



Bias

Correlation Length



Ouchi et al 2003

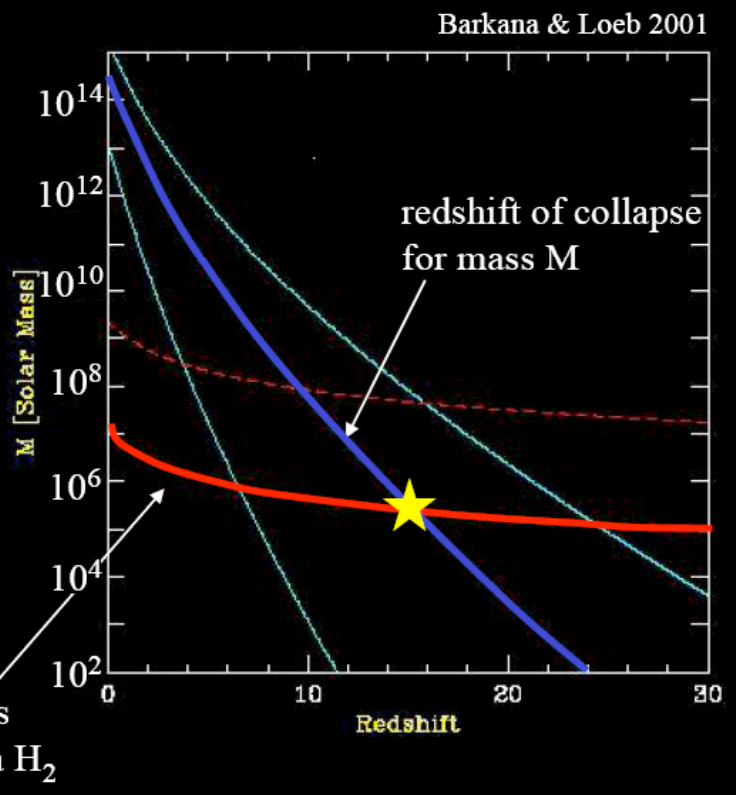
Now .. How did star-formation start at all in the cosmos?

(Tom Abel, Greg Bryant, Volker Bromm etc..)

First Stars: Two mass scales

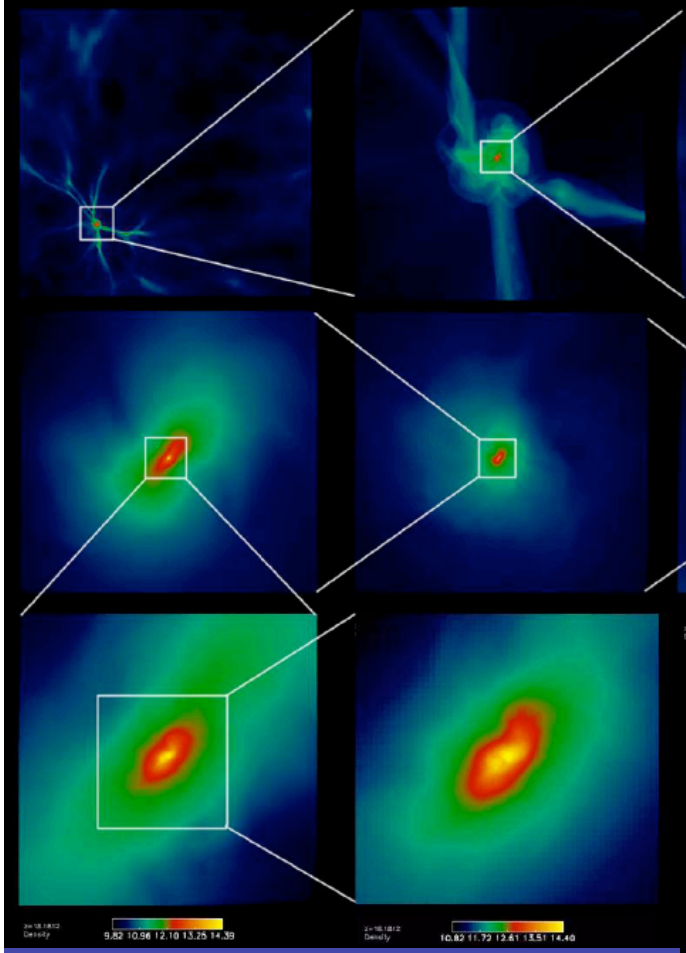
(1) Overall mass of the "microgalaxy" (M_{cloud})

- Gas must be able to cool
- No "heavy" atoms/molecules
- No H line cooling
  - $T_{vir} \sim M^{2/3}(1+z) < 10^4$ K
- H_2 is the primary coolant
  - catalyzed by free electrons
  - cooling strongly T dependent
- Minimum H_2 fraction for efficient cooling:
  - $f(H_2) \sim 10^{-3}$
  - $T_{vir} \sim 1000$ K
- $M_{cloud} \sim 10^6 M_{sun}$
- $z \sim 20$



Greg Bryan - First Stars

First star formation: simulation



Implications:

- $M_* \sim 100\ M_{sun}$ (2-500?)
  - Probable stellar lifetime ~ 3 Myr
  - Ionizes cloud, SN unbinds cloud
- IMF: only one massive cloud
- Star generates:
  - Supernova (Hypernova?): directly observable?
  - BH remnant?
  - Heavy element production -> changes future star formation
  - Ionizing radiation -> early reionization?

Summary

- Cosmic star-formation history and stellar mass build-up have been mapped from z~6 to the present
  - >95% of all stars have formed since then
- Models can match this build up, but only with various (stellar + AGN) feed-back mechanisms
- How the first stars formed, and whether there was a fundamentally different star-formation mode (not metals) is unclear