Formation & evolution of galaxies & SMBHs

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Outline of lectures

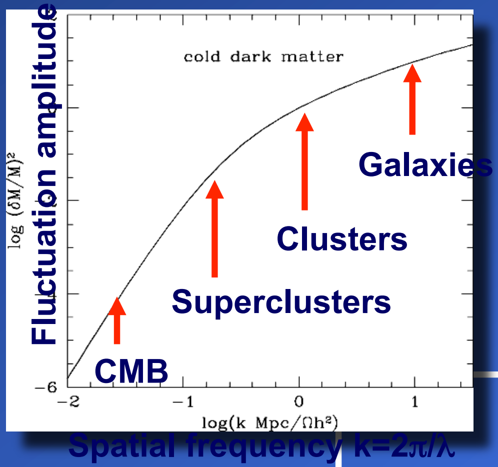
1. Structure formation & assembly of dark halos
2. Gas cooling & angular momentum
3. Star formation & feedback
4. Galaxy mergers & morphologies
5. Cosmic evolution of galaxies
6. Formation of black holes
7. BH binaries & spin
8. Co-evolution of galaxies & AGN

Lecture 5:
Evolution of the galaxy population

Topic 5 outline

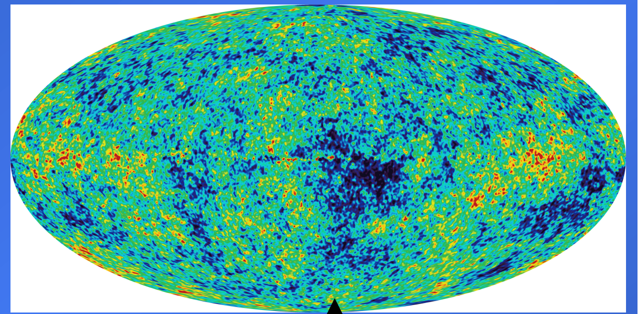
- summary of physical processes in galaxy formation
- galaxy properties at z~0
  - luminosity functions
  - bimodality in colours & SFRs
- cosmic star formation history
- evolution of stellar mass density

Modelling galaxy formation



Cosmological model

(Ω, Λ, h) dark matter



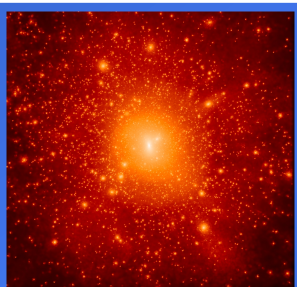
Primordial fluctuations

δρ/ρ(M, t)

Evolution of dark matter halos

Dynamics of cooling gas

N-body simulations



- Gasdynamic simulations
- Semi-analytic modelling

Star formation, feedback, evolution of stellar pops

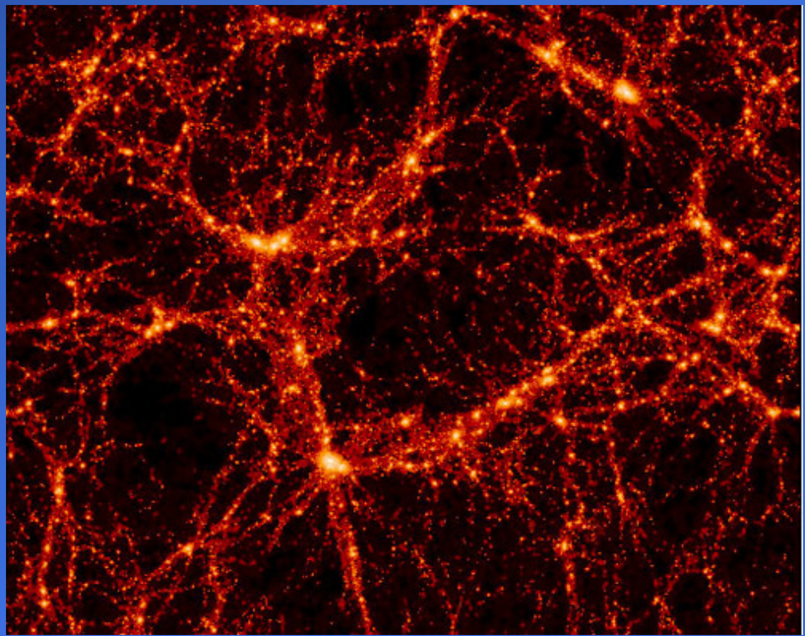
Galaxy mergers

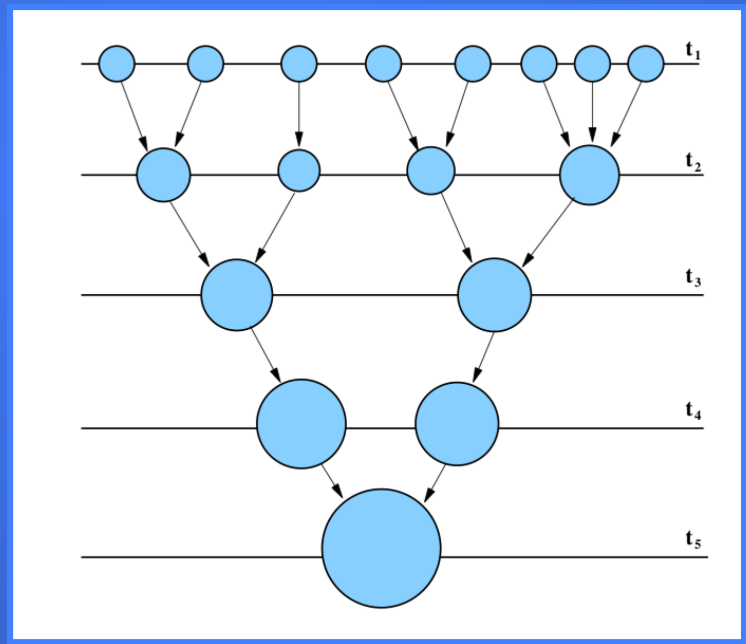
Formation and evolution of galaxies

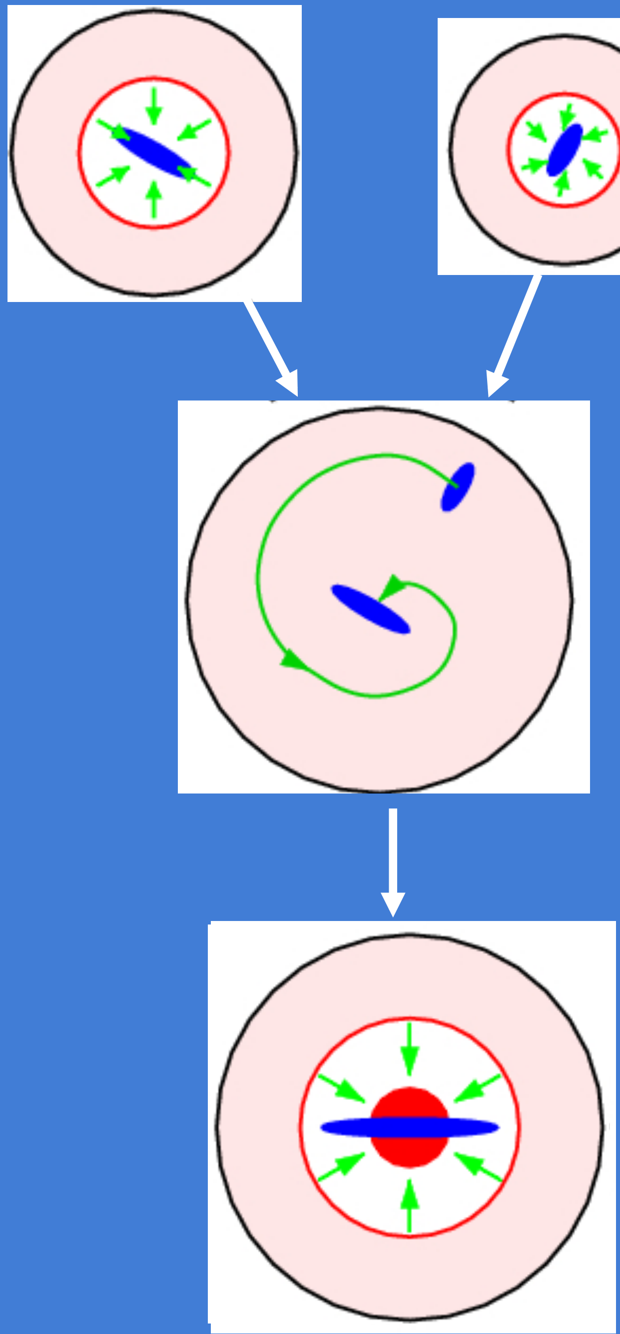
Galaxy formation in the CDM model: key physical processes

- Assembly of dark matter halos
- Shock-heating and radiative cooling of gas within halos
- Star formation and feedback
- Production of heavy elements
- Galaxy mergers

Assembly of dark matter halos: Merger trees







Galaxy formation: the basics

Infalling gas shock-heated to T_{vir}

Gas cools radiatively onto central galaxy and forms disk, conserving J

→ $r_{disk} \sim \lambda_h r_{cool}$

Stars form in disk

And give rise to feedback effects

Satellite sinks by dynamical friction and merges onto central galaxy

Mergers trigger central starburst

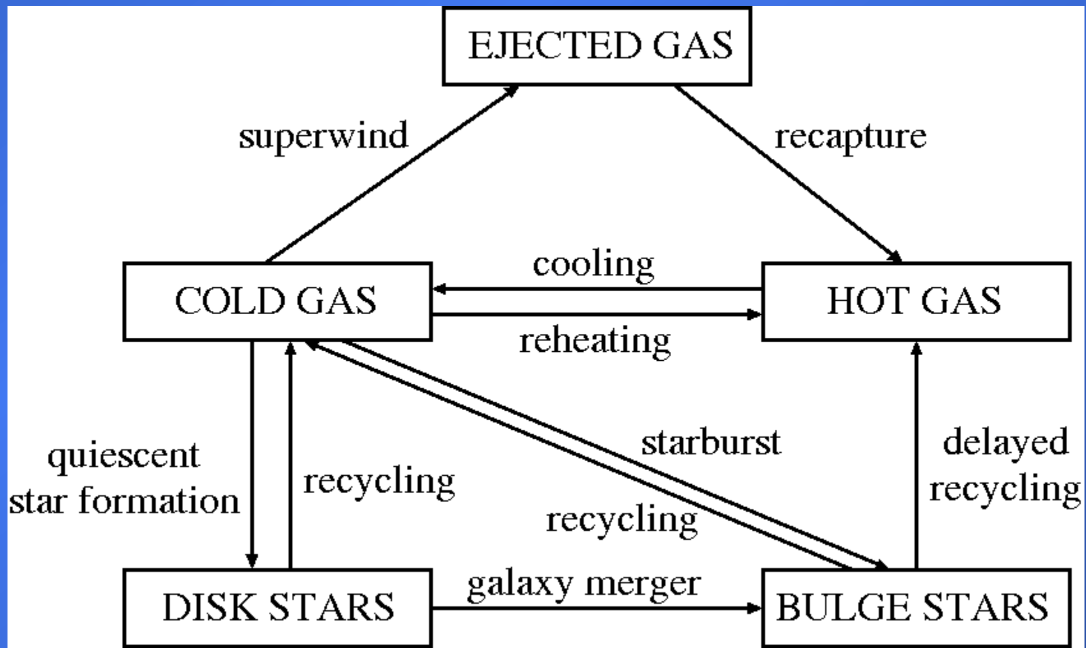
In major mergers, stellar disks → spheroids

New disk may form by gas accretion

Chemical Enrichment of stars & gas

- Chemical enrichment of ISM from metals ejected by dying stars: SNII, SNIa & AGB star winds

- yields of different elements depend on IMF



Properties of present-day galaxies

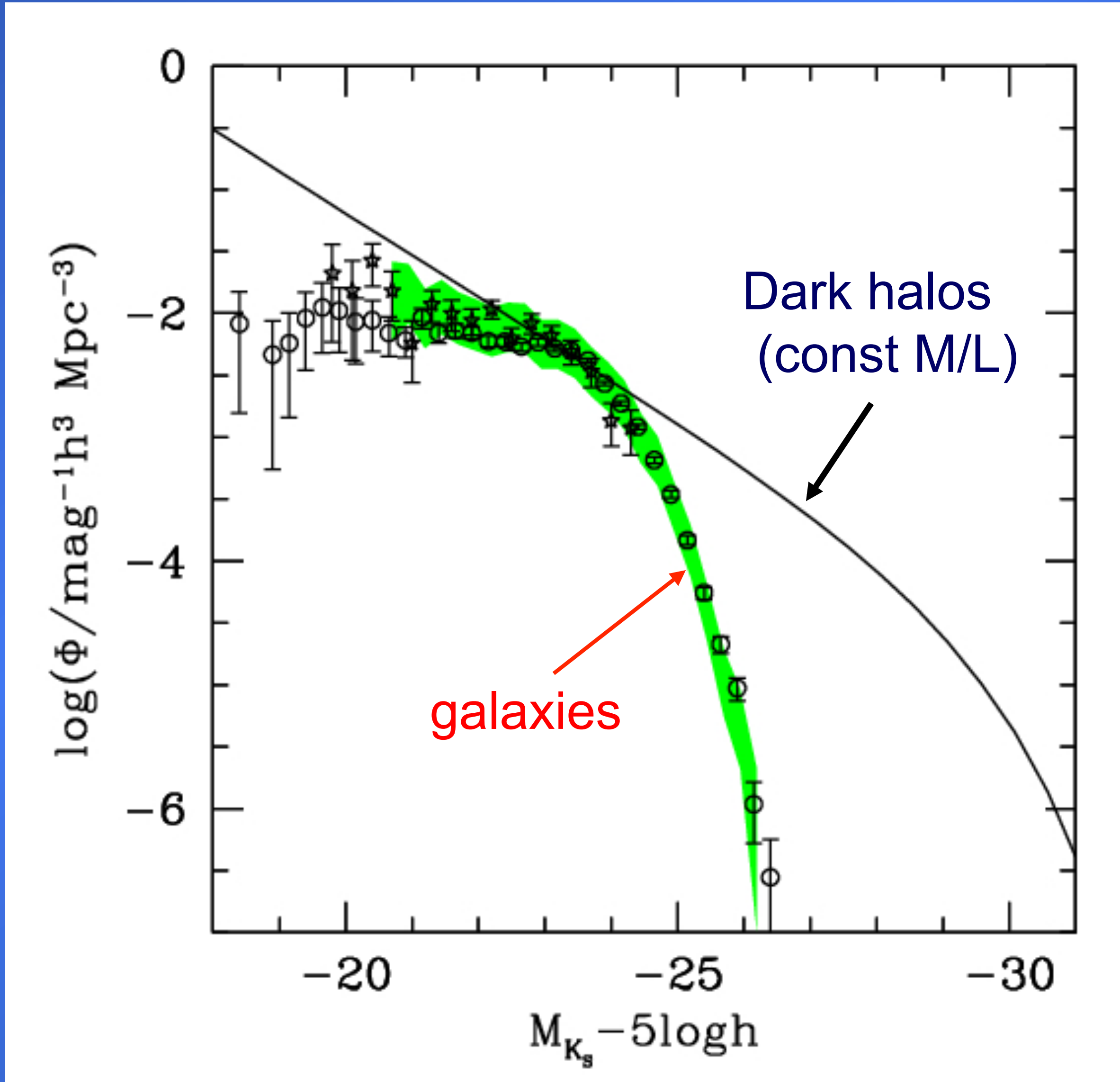
Galaxy luminosity function

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

⇨

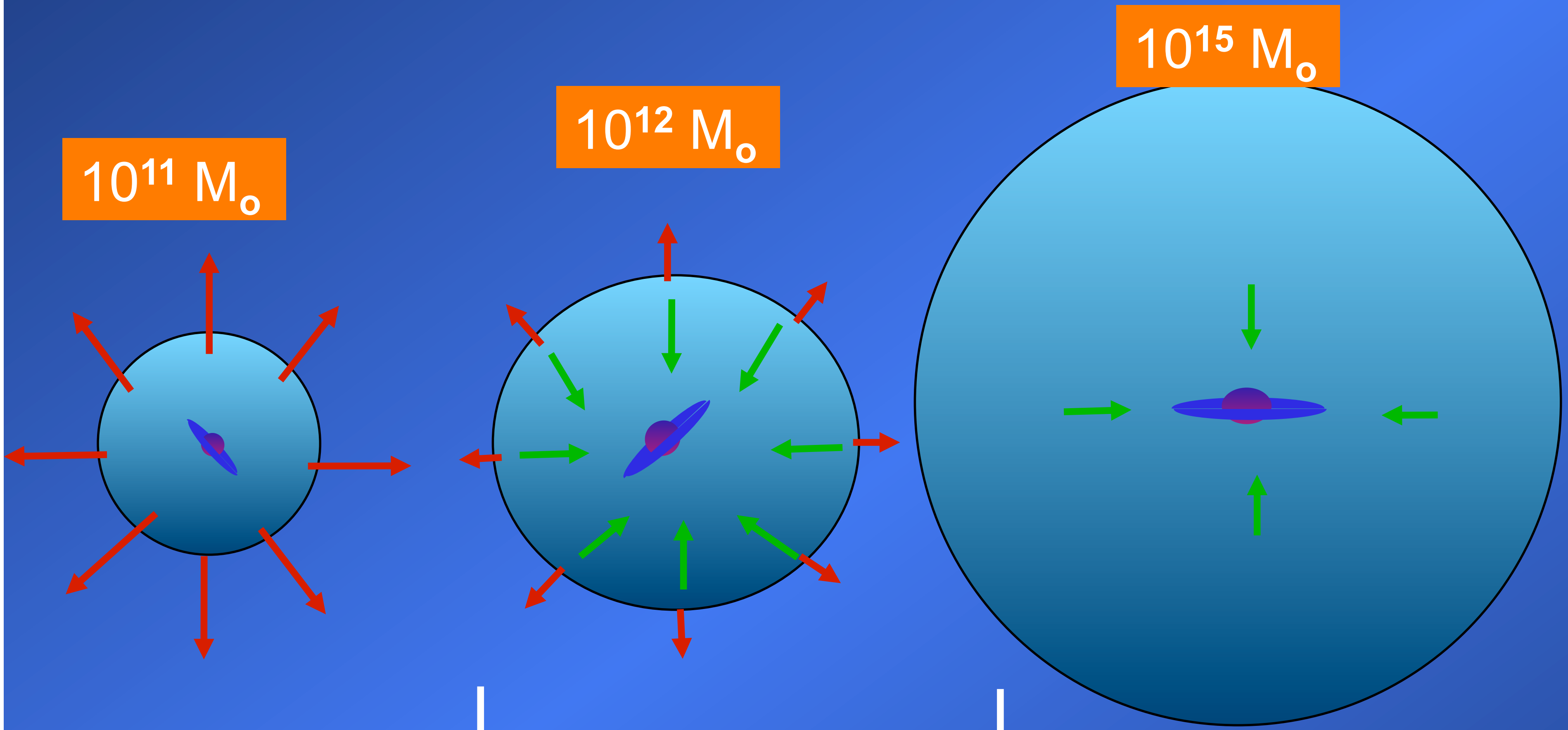
Complicated variation of M/L with halo mass

- this is result of cooling & feedback effects



Benson et al 2003

Efficiency of galaxy formation

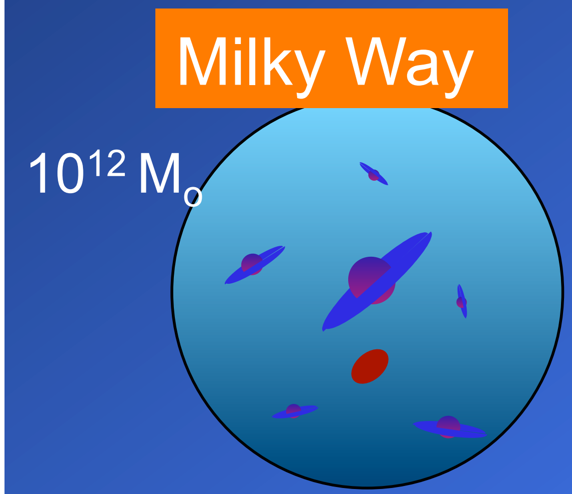


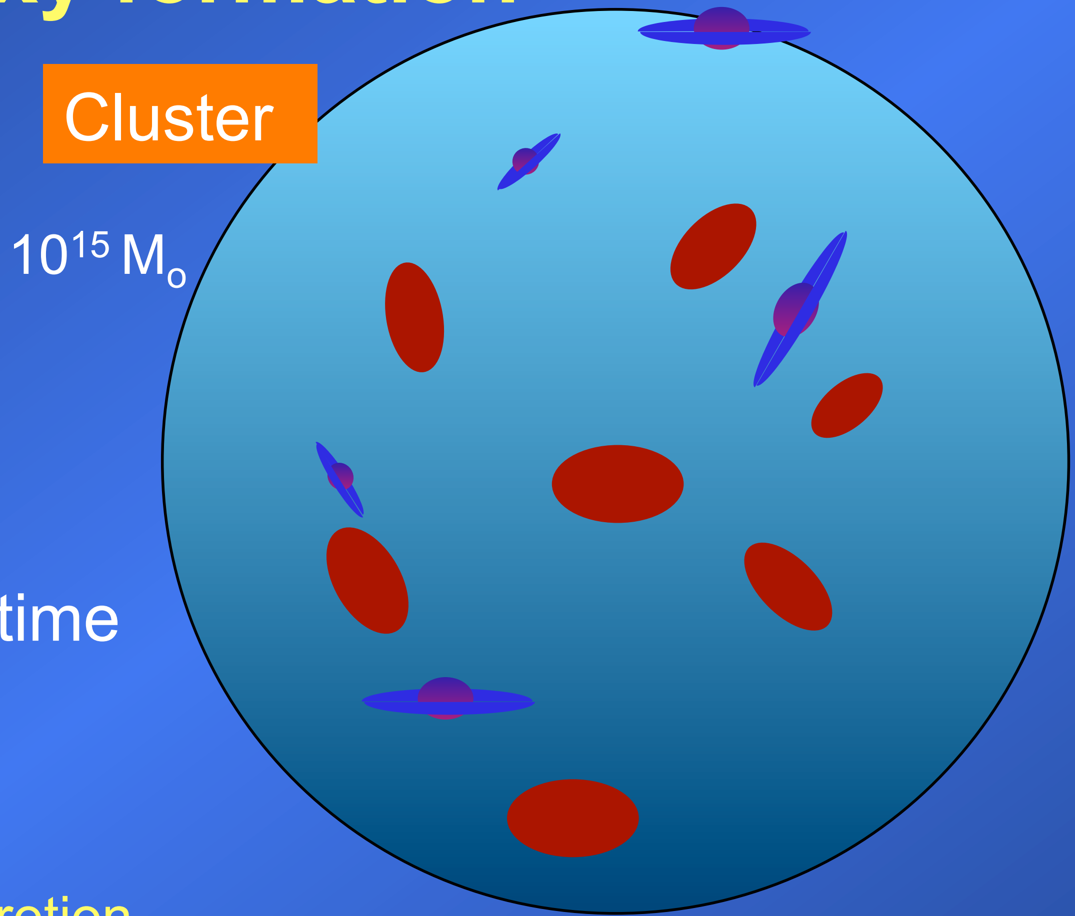
Cooling: +++
SN Feedback: - - - -
Gal. Formation:
Inefficient

Cooling: ++
SN Feedback: - -
Gal. Formation:
Efficient

Cooling: +
SN Feedback: -
Gal. Formation:
Inefficient

Galaxy formation





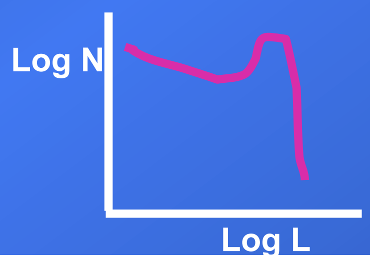
Cooling time ~ dynamical time

→ Gas cools efficiently

Formed early:

→ Central galaxy grows by accretion and mergers

→ Satellites dimmed by feedback



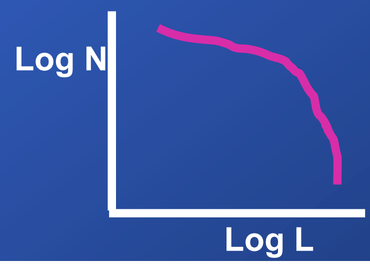
Cooling time >> dynamical time

→ Gas does NOT cool efficiently

Formed late:

→ Fewer mergers

→ Brighter satellites

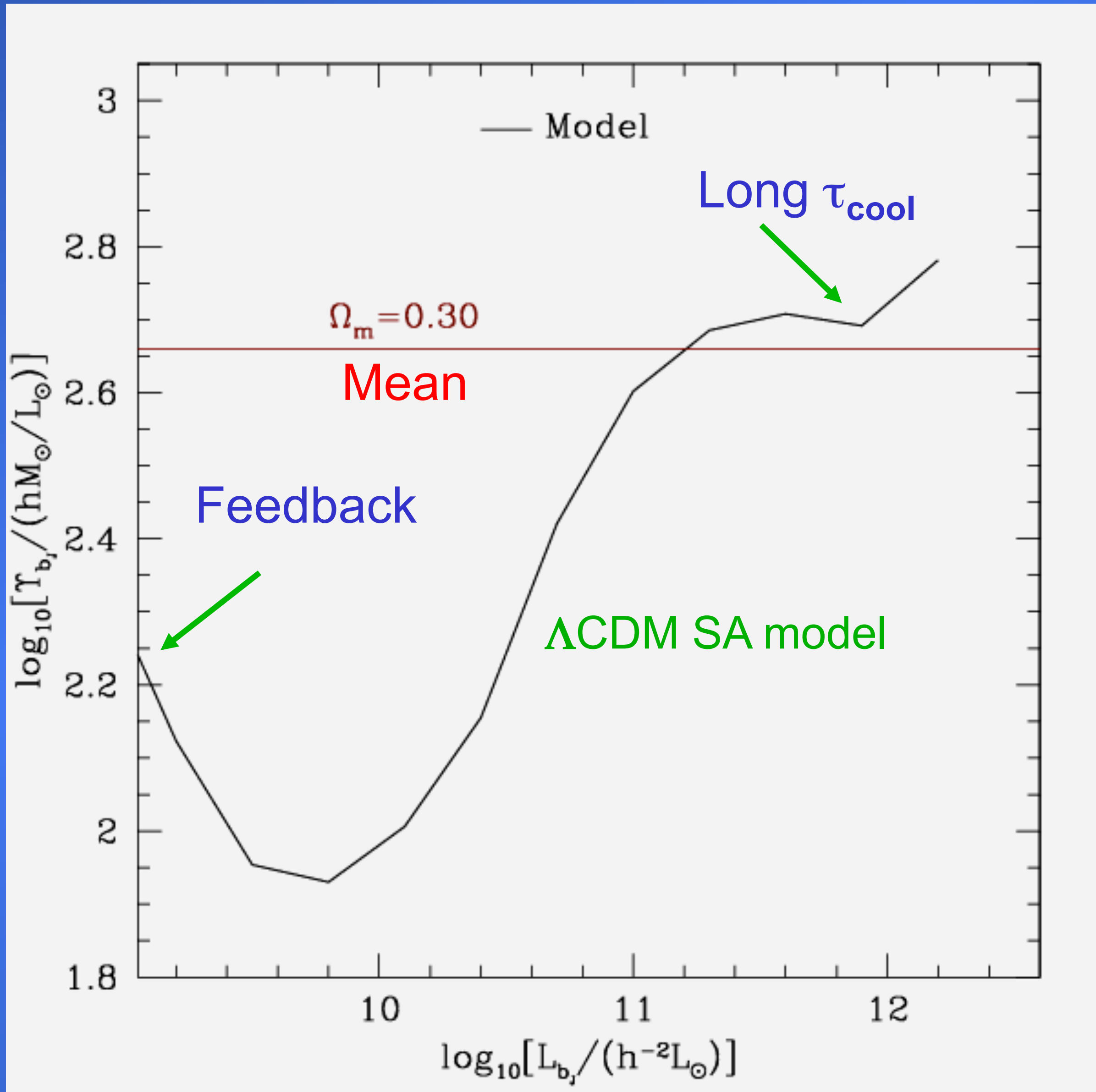


Halo mass-to-light ratios

Theoretical prediction

- Halo M/L obtained by summing light from all galaxies in halo
- Galaxy formation is most efficient (=> M/L lowest) in ~10^{12} M_o halos, corresponding to galaxy groups with L(group) ~ $10^{10}L_o$

Efficiency of galaxy formation



Benson et al 2000

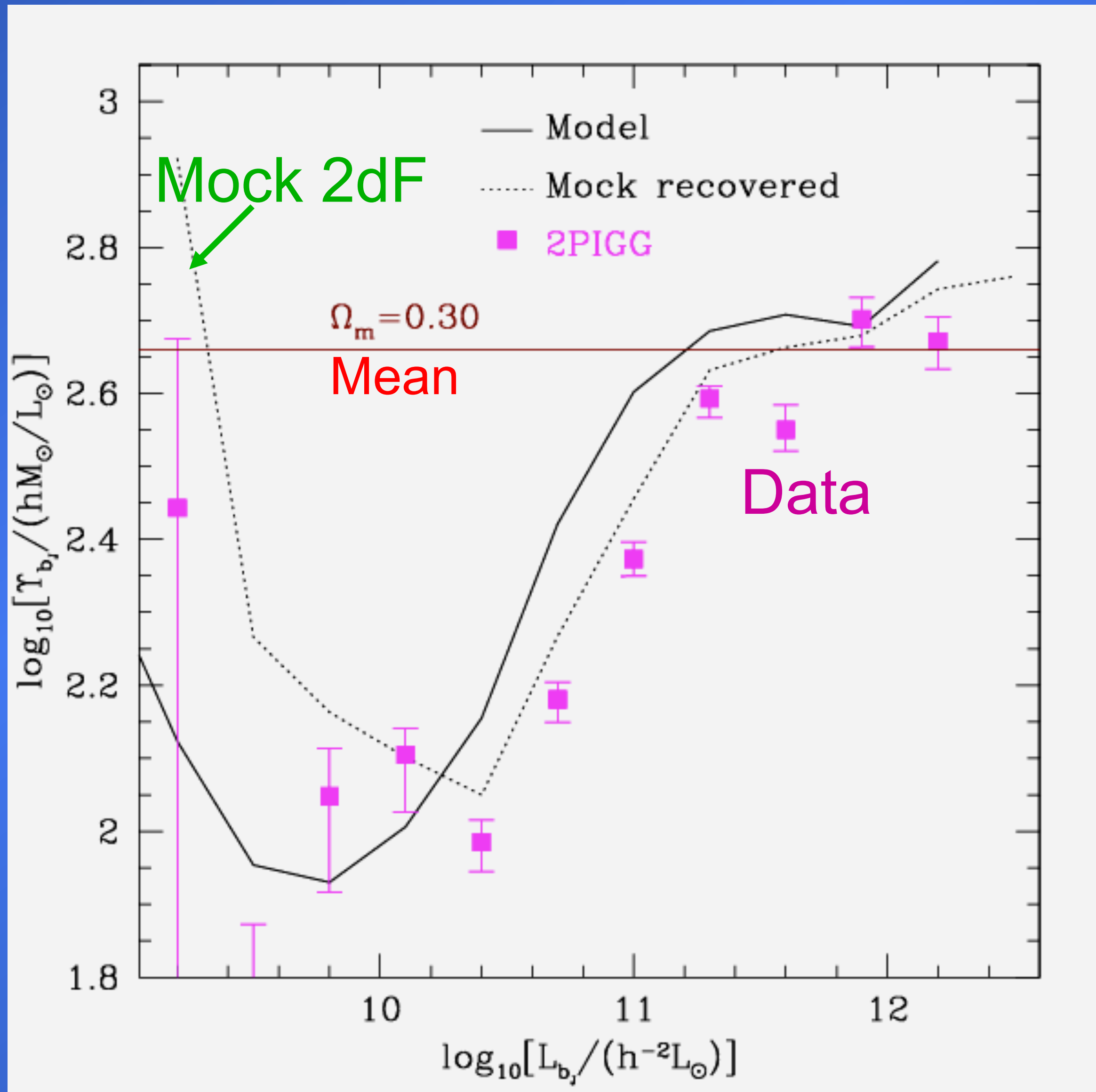
Group luminosity

Halo mass-to-light ratios - test against observed groups & clusters

Mocks and data agree well!

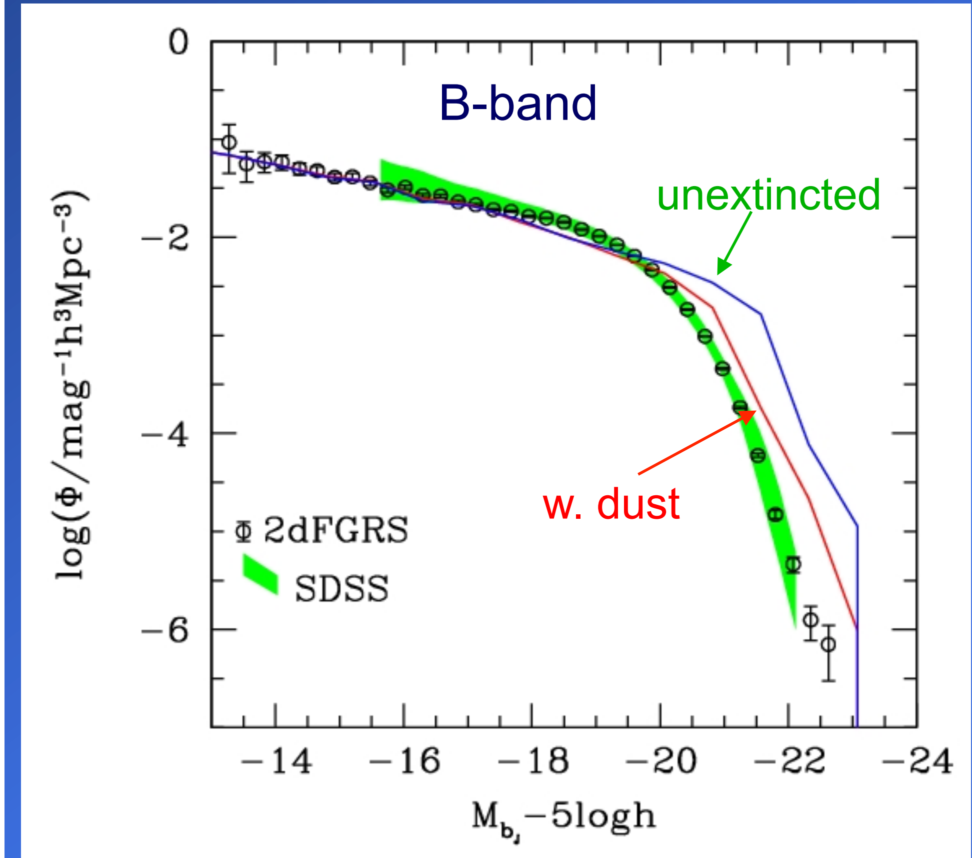
Factor of 4 decrease in M/L from rich clusters to poor groups

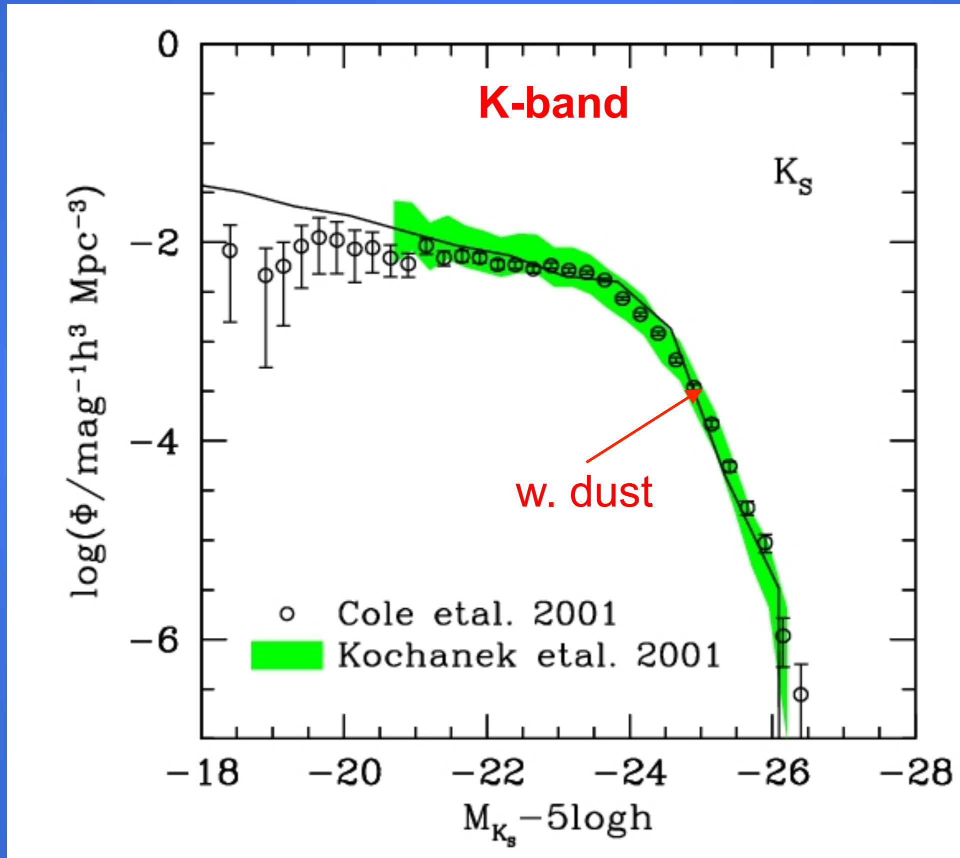
Data consistent with existence of a minimum



Group luminosity

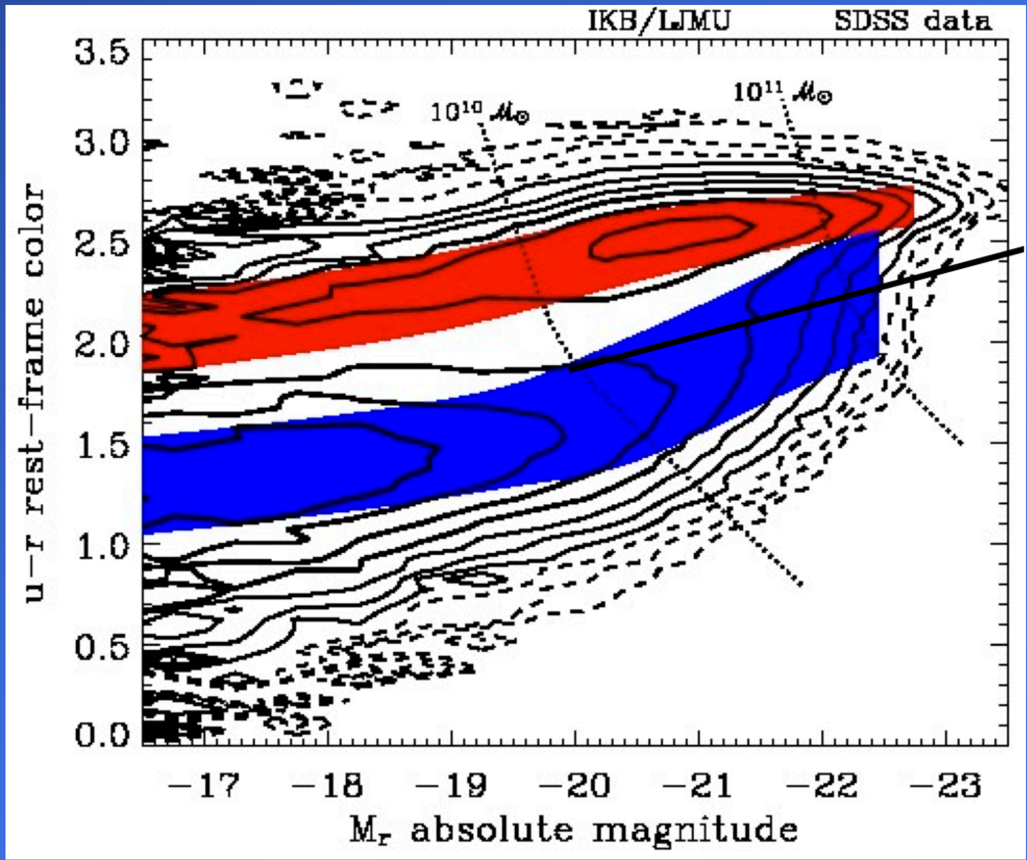
Galaxy luminosity function





Models including these effects can give good match to lum fn at z=0, when include AGN feedback also

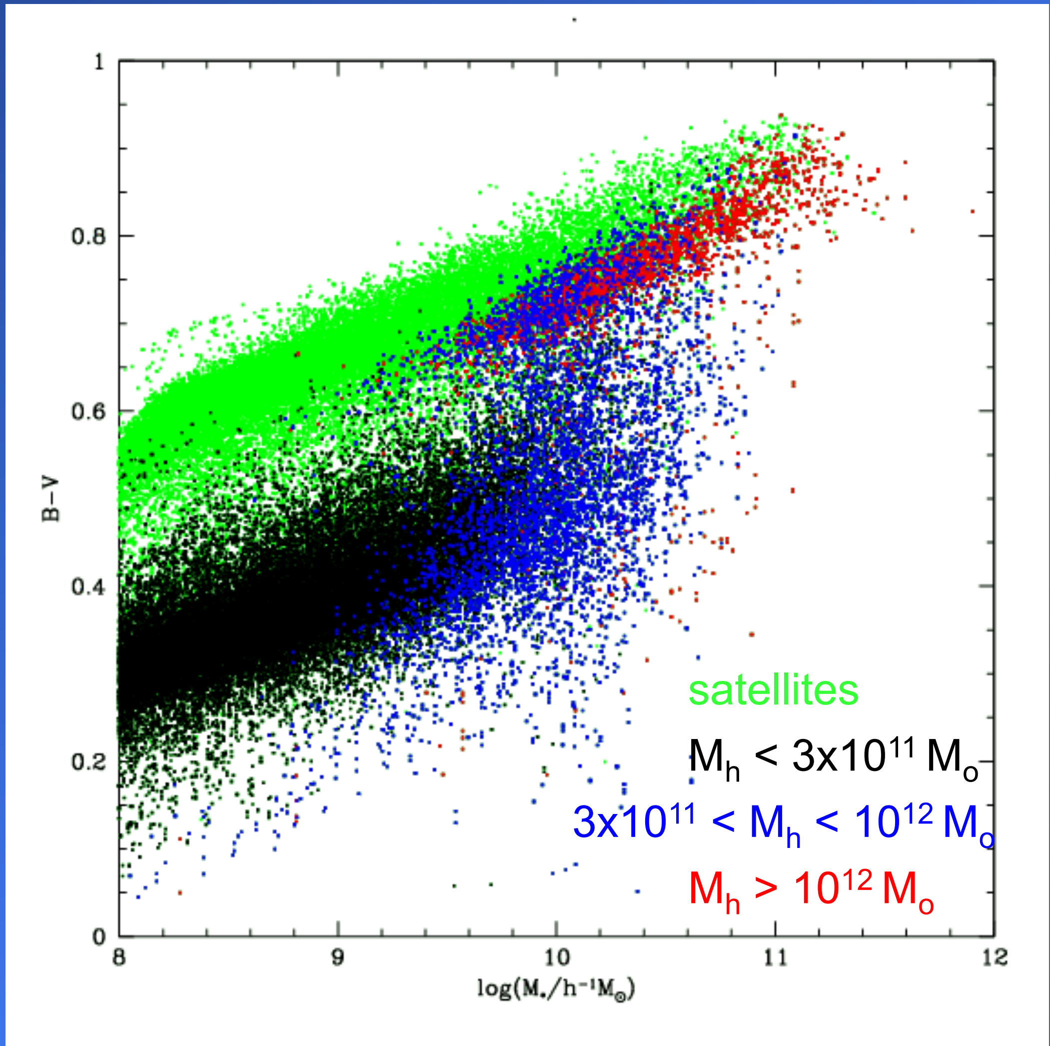
Bimodal colour distribution of galaxies - observations



Baldry etal 2004 - SDSS

- most galaxies at low z lie on either RED or BLUE sequence
- determined by recent star formation history
- RED = passive, insignificant recent star formation
- BLUE = active, ongoing star formation
- bimodal colours due to bimodal SFR/M_*

Bimodal colour distribution in models



- galaxy formation models can reproduce bimodal colour distribution
- satellite galaxies nearly all red, because gas cools only onto central galaxies
- blue sequence dominated by central galaxies in halos which still have gas cooling onto them
- need AGN feedback to suppress star formation in most massive galaxies & make them red

Bower etal 2006

Cosmic star formation history

Star Formation Indicators

Several tracers of star formation:

- Ultraviolet emission
- Radio continuum emission (from SNe)
- Emission lines: Hα, [OII] 3727 (from HII regions)
- Mid- or far-infrared emission (from dust)

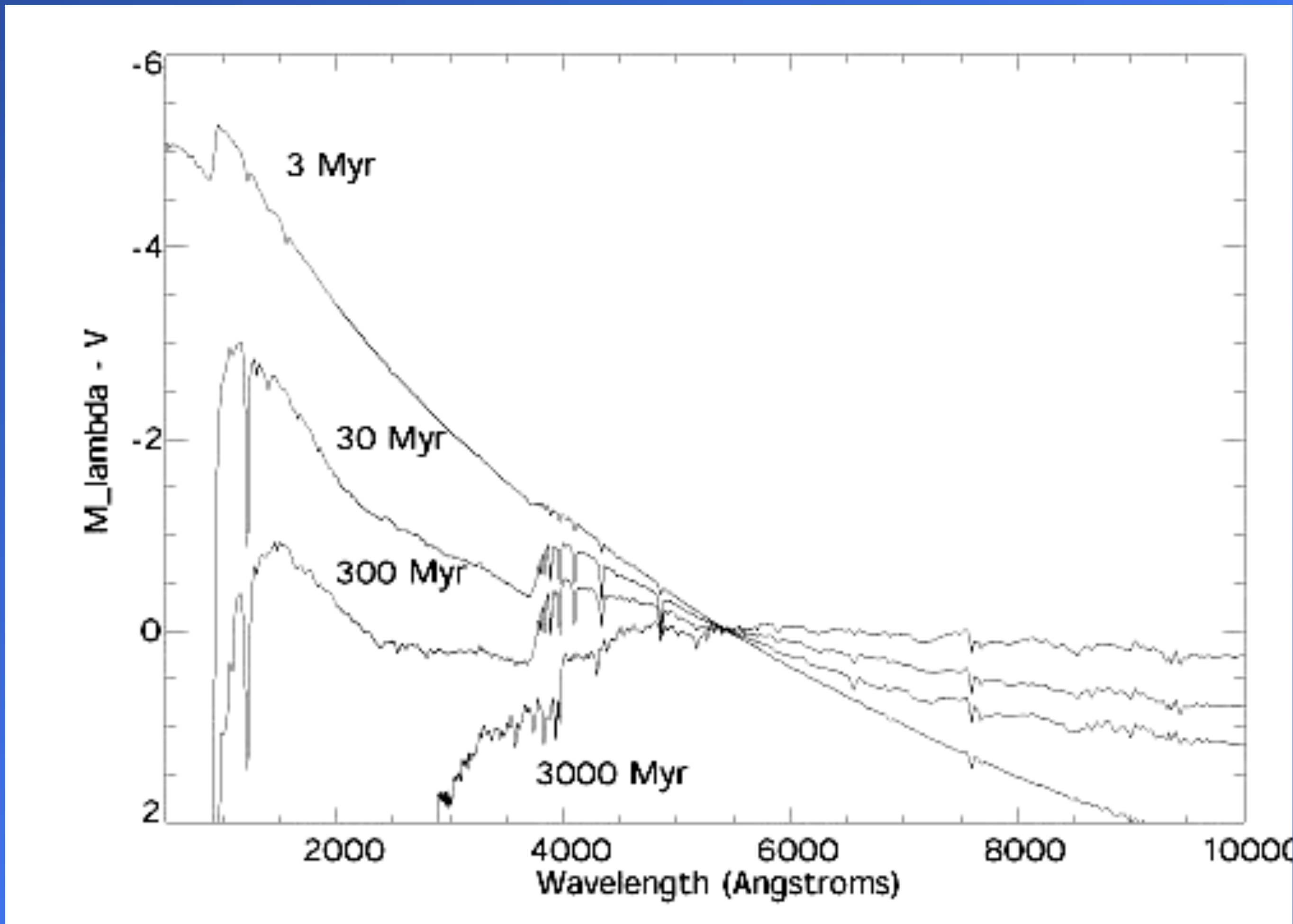
Different indicators used at different redshifts

Ideally want an SFR indicator which:

- is relatively immune to dust extinction
- is sensitive (avoid large extrapolations of LF)
- can be studied over a wide range in redshift

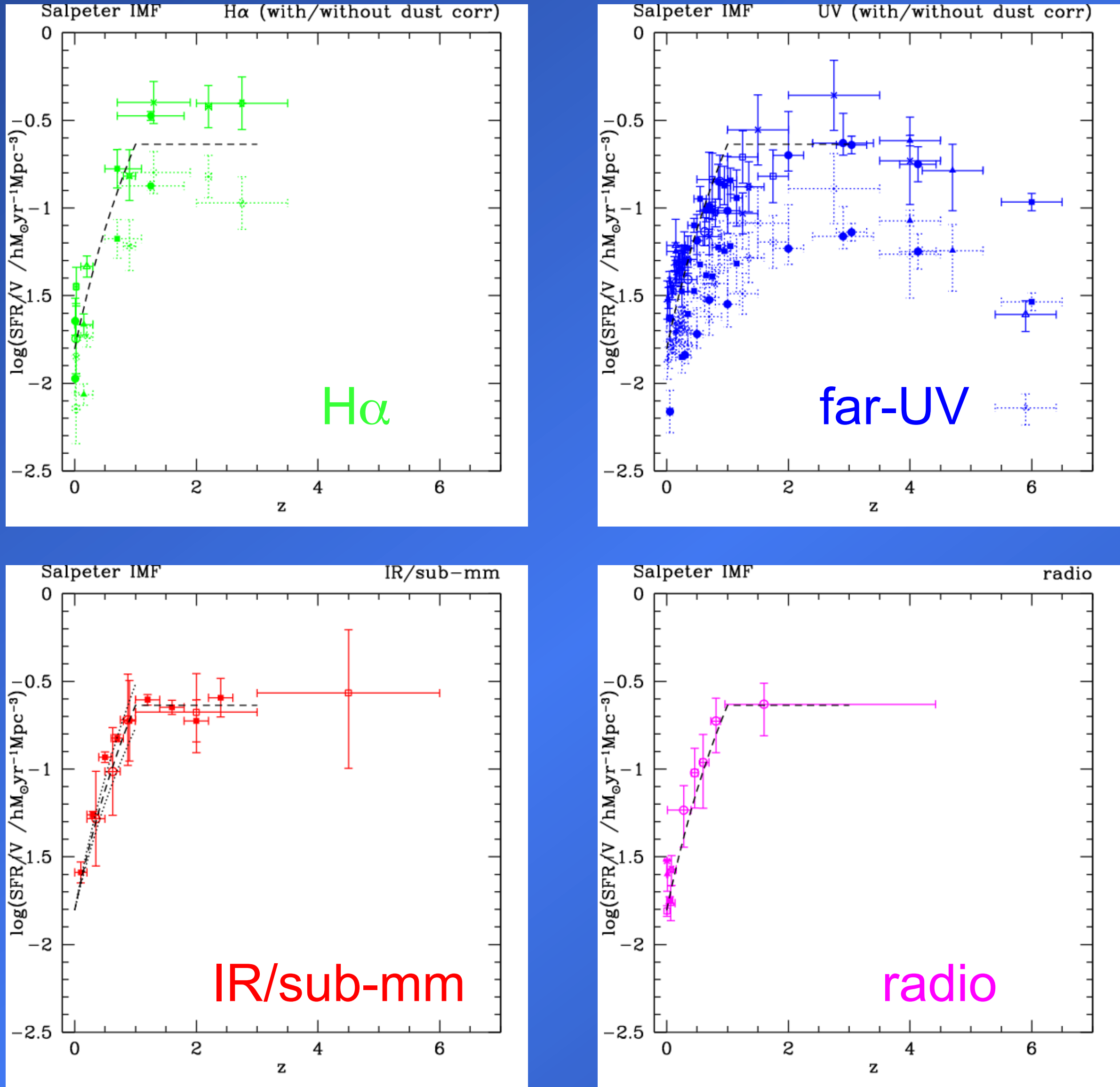
All of these are sensitive to massive (> 5 M_o) stars only – need to assume Initial Mass Function (IMF)

UV tracers of SFR



SFR_{UV} ($M_\odot$ yr^{-1}) = 1.4×10^{-28} L_ν ($ergs^{-1}$ s^{-1} Hz^{-1}) at 1500–2800 Å (for Salpeter IMF). Remember also: $L \propto M^{3.5}$ so the luminosity of a stellar population is dominated by most massive stars.

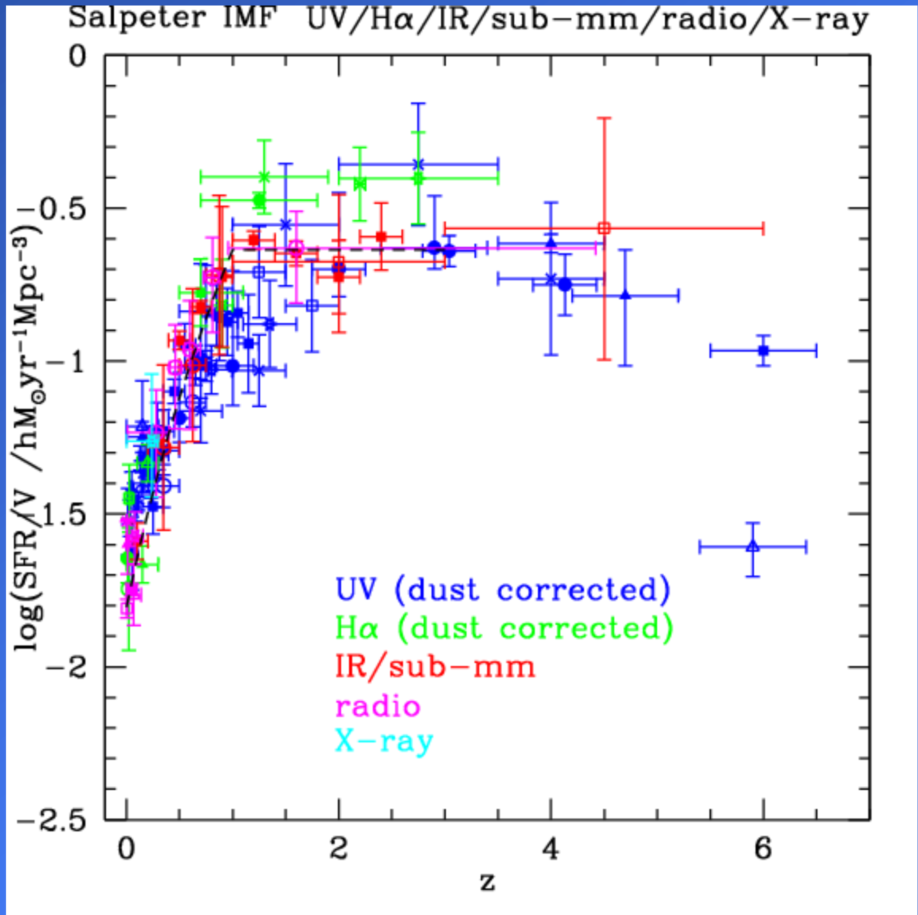
Cosmic SFR history – comparison of different SFR tracers



- different observational tracers of SFR density fairly consistent for z<2 (but some calibrations have been adjusted to achieve this!)
- for z>2, far-UV is currently only available tracer

Hopkins 2006

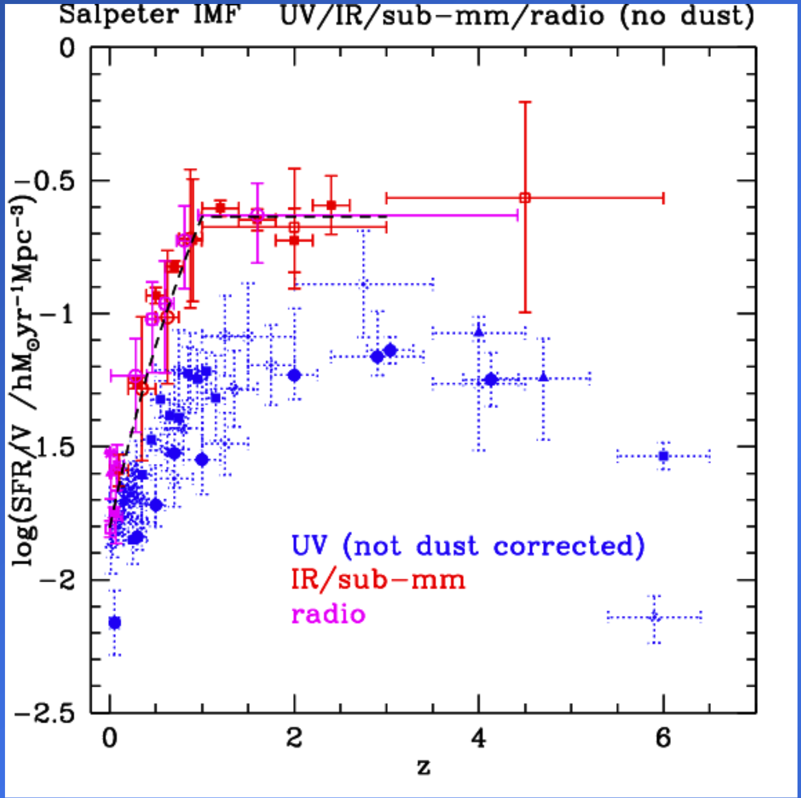
Cosmic SFR history – comparison of different SFR tracers



- SFR density inferred from observations peaks at z~2
- increases by factor 10-20 from z=0 to z~2
- gradually declines at z>2

Hopkins 2006 compilation

Cosmic SFR history - effects of dust

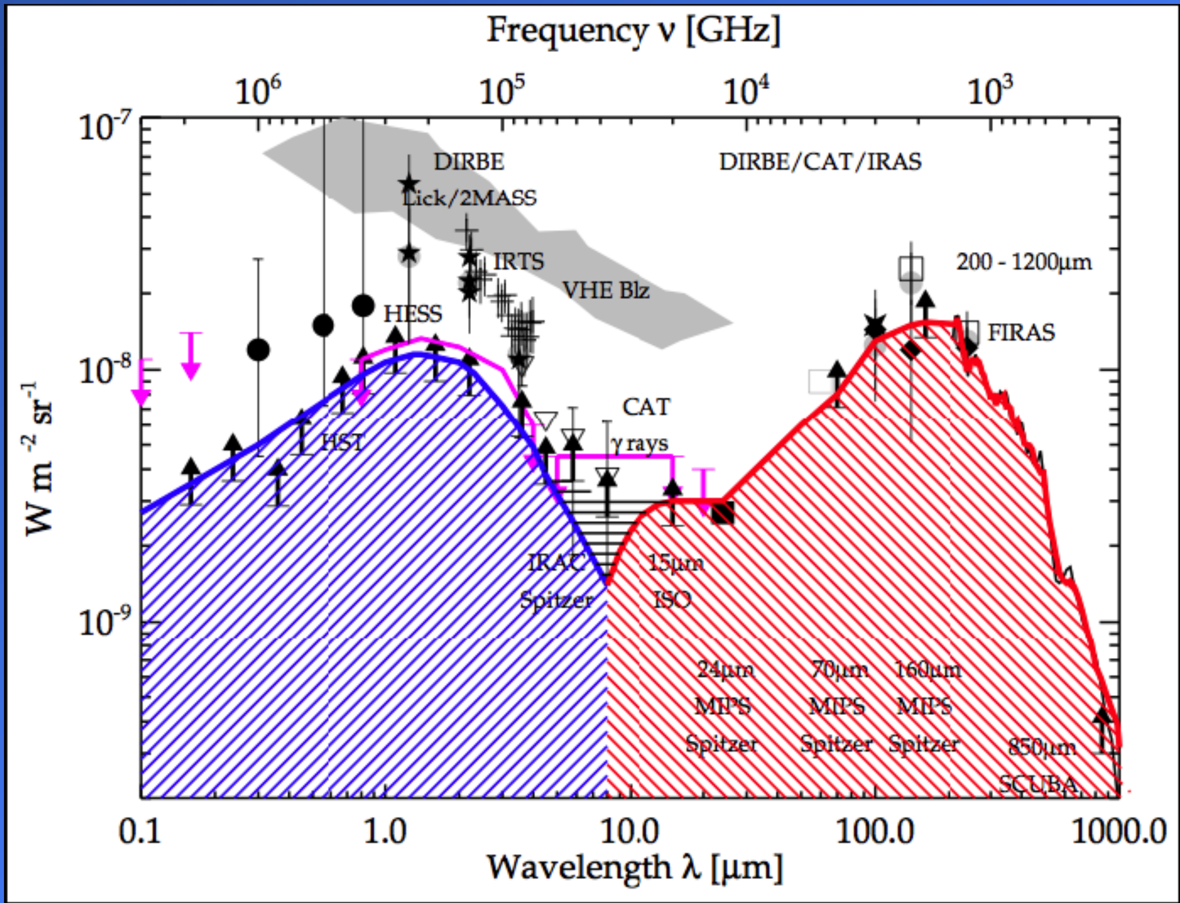


- SFR estimates from rest -frame UV heavily affected by dust (~ 1-2 mag)
- UV extinctions difficult to estimate from obs
- estimates from mid-IR/sub -mm depend on assumed SED shape

Obs compilation: Hopkins 2006

Effects of dust: cosmic optical & IR backgrounds

Optical/IR extragalactic background

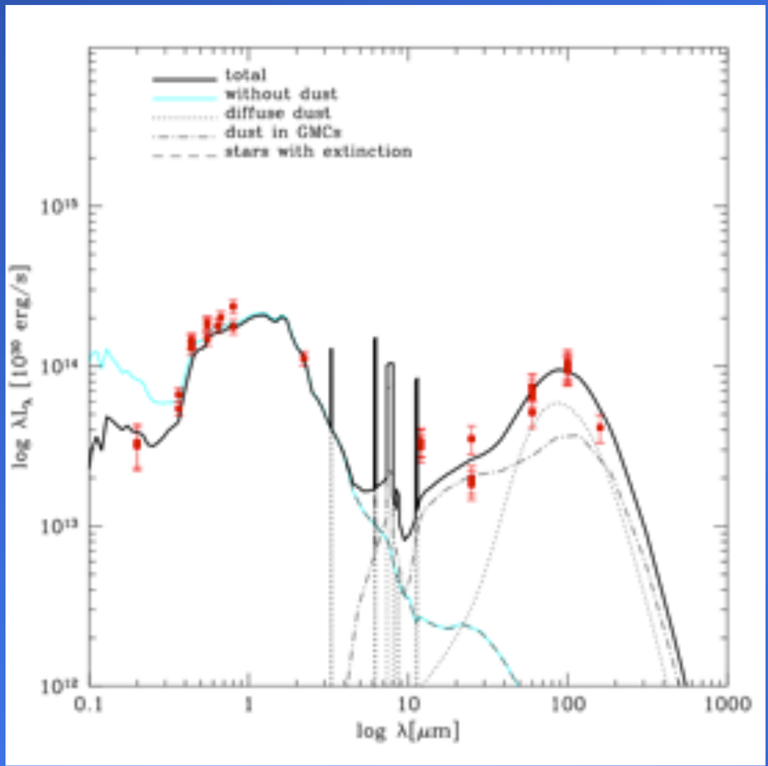


- cosmic far-IR background ~ 1-2x UV -opt-NIR background
- implies most of light from young stars has been reprocessed by dust
- so to understand cosmic star formation history, need to include effects of dust in galaxies

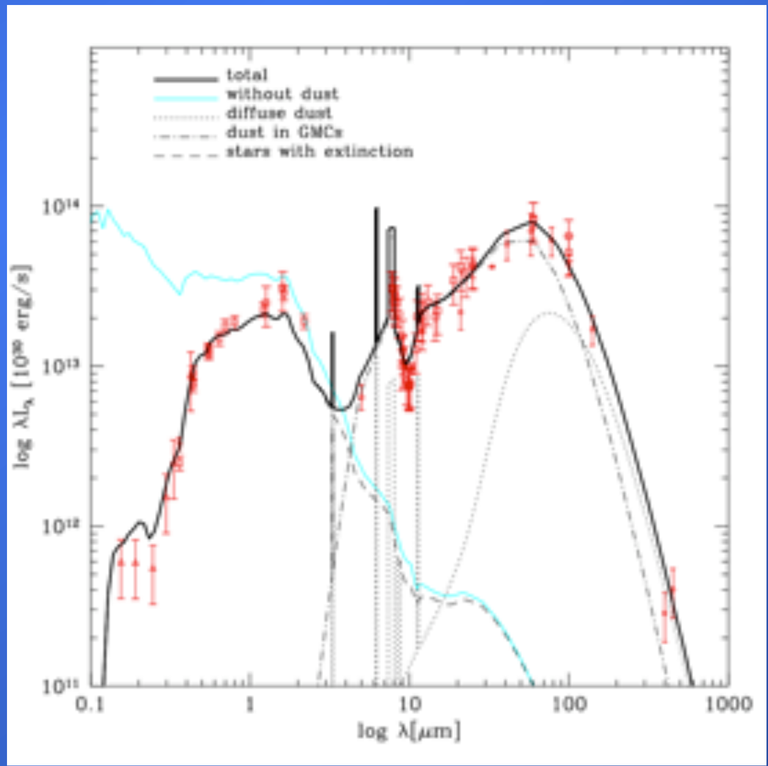
Effects of dust: SEDs of star-forming galaxies

Silva et al 1998

M100 (spiral)

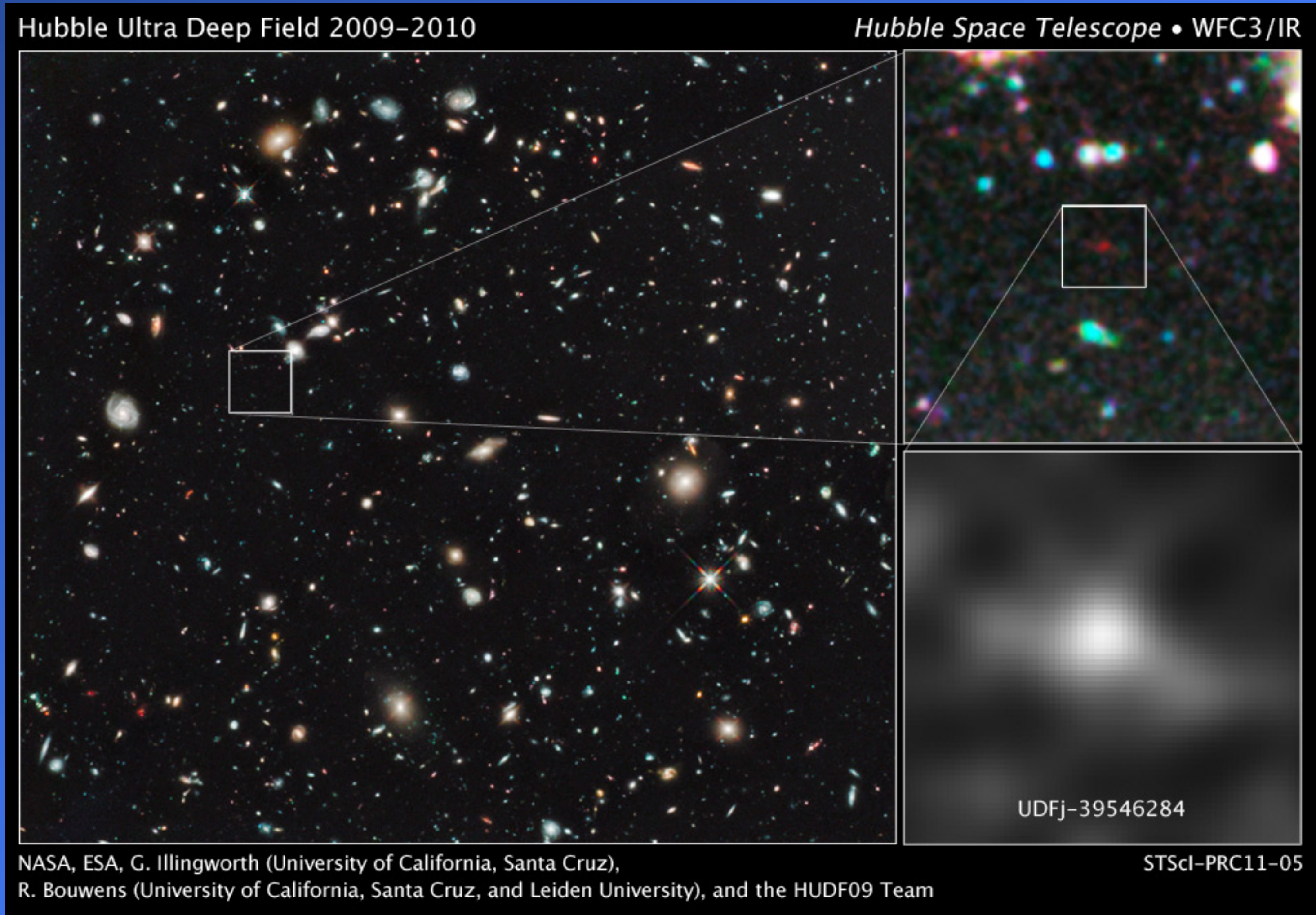


M82 (starburst)



star-forming galaxies have IR luminosities from dust comparable to UV/optical luminosities from stars

Measuring the SFR density to z~10 using Lyman-break galaxies (LBGs)



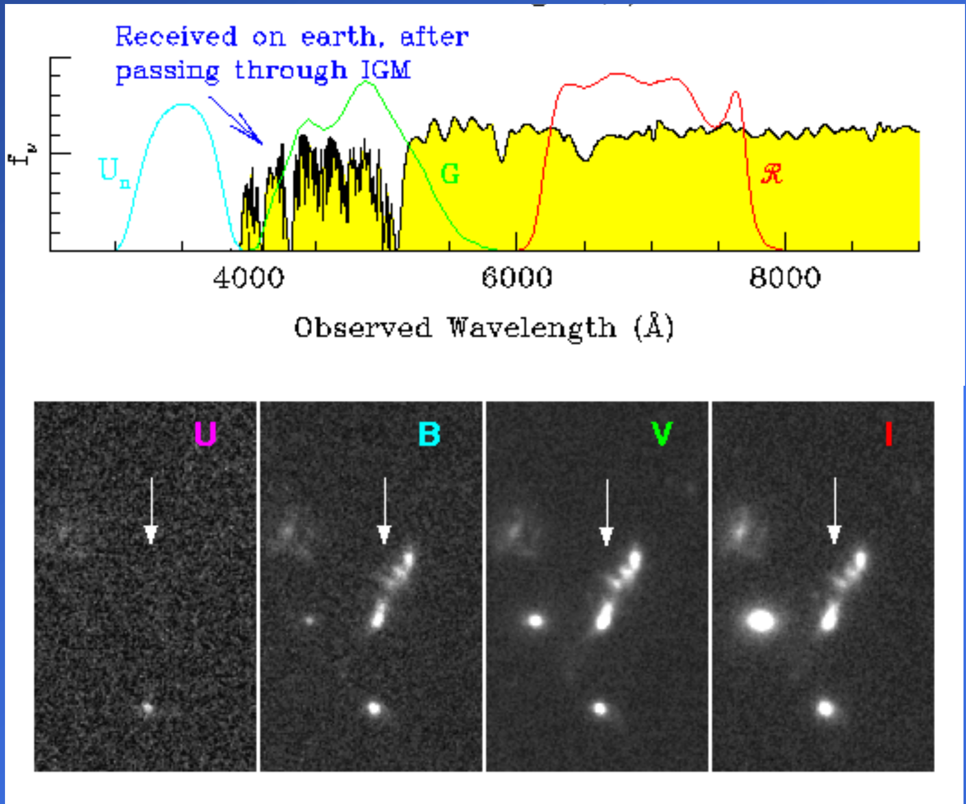
LBG at z~10 in Hubble Ultra-deep field

Bouwens etal 2011

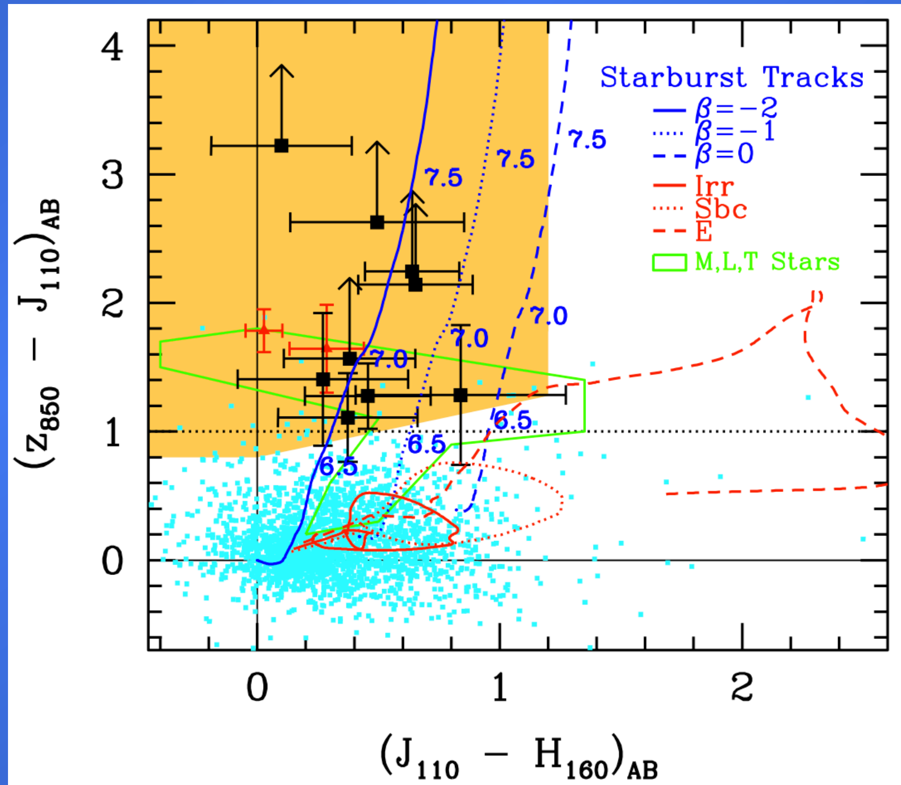
main obs technique to measure SFR history at z~3-10 uses far-UV luminosities of galaxies detected as LBGs

Lyman-break selection

z~3 LBG



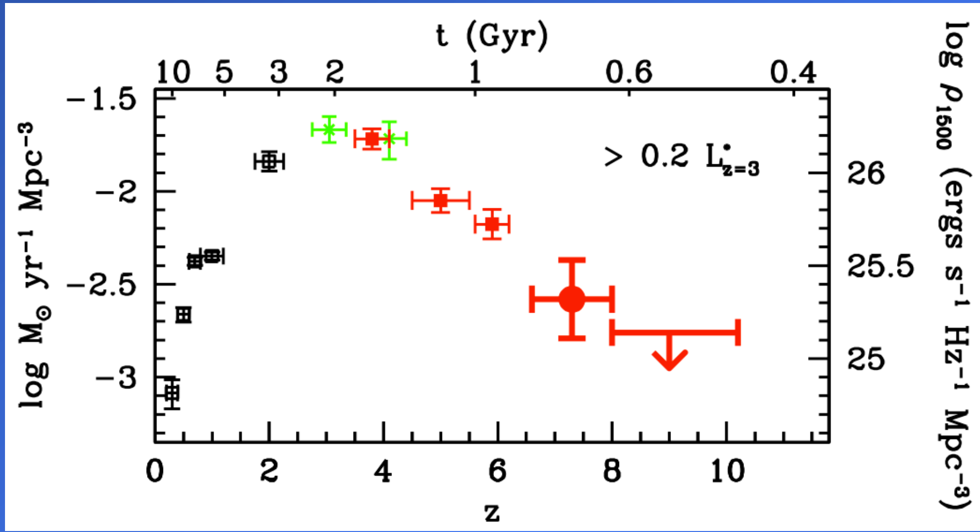
z~8 LBG



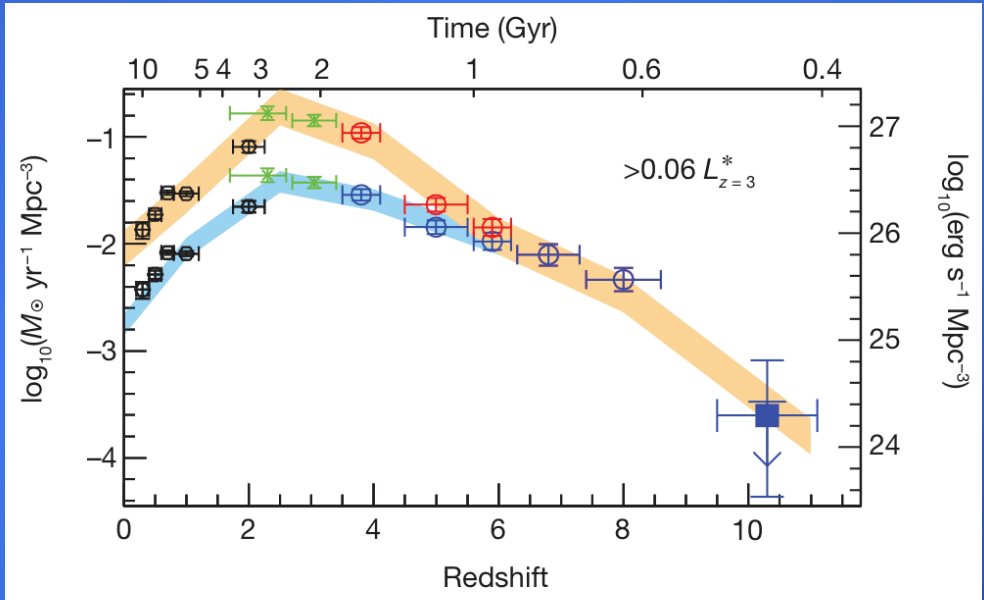
- use multi-band imaging to search for objects with break in SED corresponding to Lyman break (912A or 1216A) in rest-frame of galaxy – should select star-forming galaxies at that redshift
- use 2-colour selection to exclude other types of object

Evolution of observed far-UV luminosity density & SFR density

UV luminosity density (not corrected for dust)



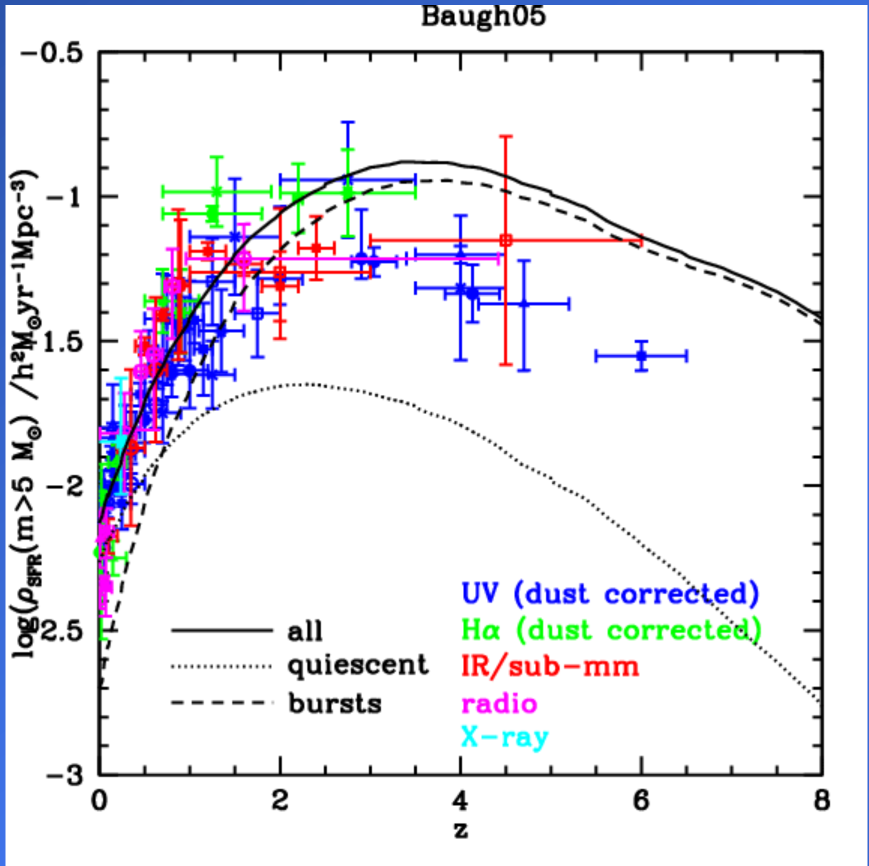
inferred SFR density (with & without correction for dust extinction)



UV luminosity & SFR densities decline by factor 10-100 from z~2 to z~10

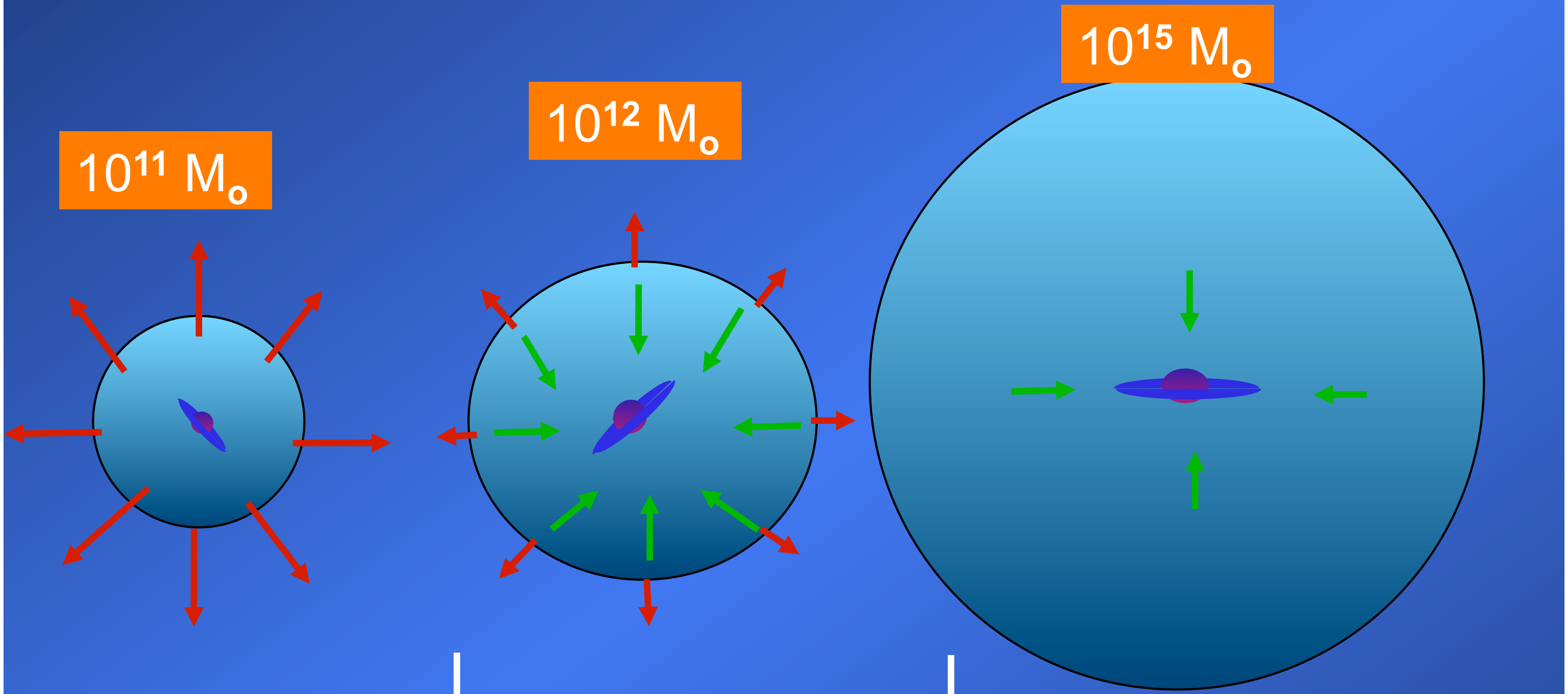
Bouwens etal 2008, 2011

Cosmic SFR history: comparison with galaxy formation models



- evolution of SFR can be understood in terms of:
  (a) growth of typical halo mass with time
  (b) varying efficiency of galaxy formation with halo mass due to cooling & feedback
- decline to high-z due to increasing efficiency of SN feedback
- decline to low-z due to increasing cooling time

Efficiency of galaxy formation



Cooling: +++

SN Feedback: - - - -

Gal. Formation:

Inefficient

Cooling: ++

SN Feedback: - -

Gal. Formation:

Efficient

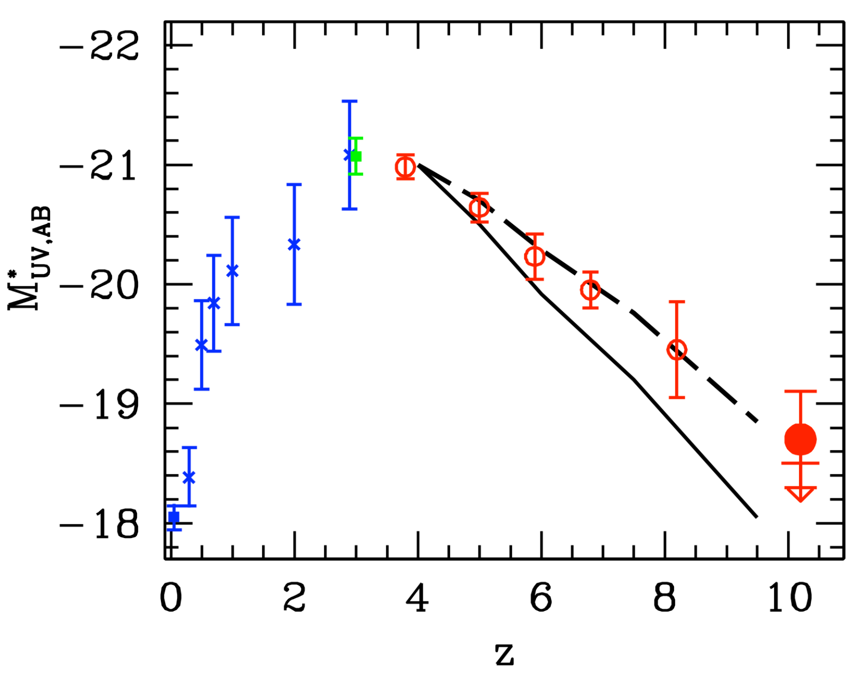
Cooling: +

SN Feedback: -

Gal. Formation:

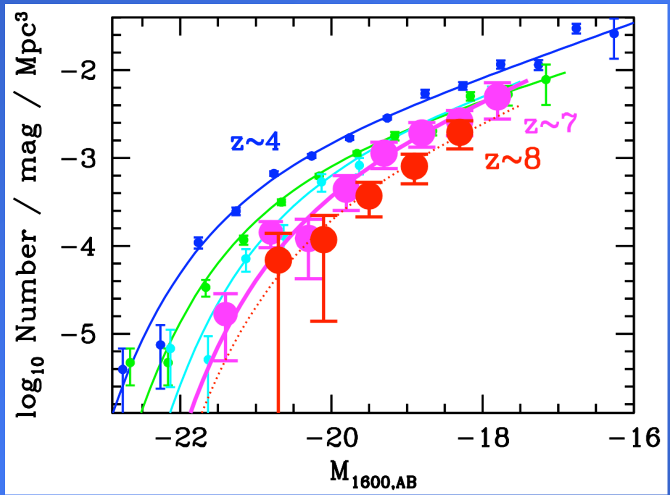
Inefficient

Evolution of characteristic UV luminosity of galaxies



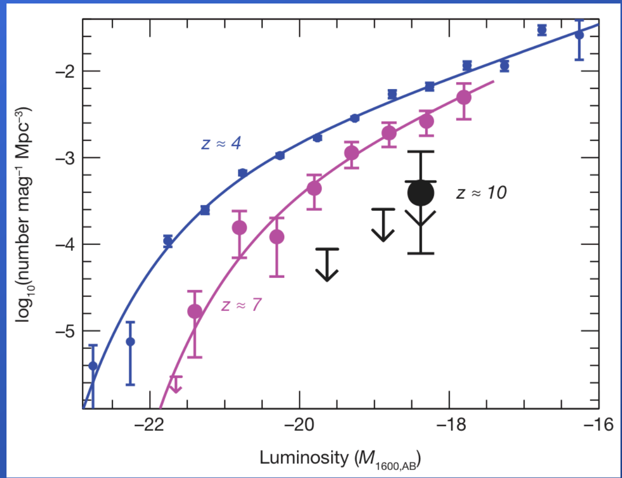
- characteristic L_{UV} evolves in similar way to ρ_{UV}

=> typical SFR of star-forming galaxies increases to peak at z~3 & then declines

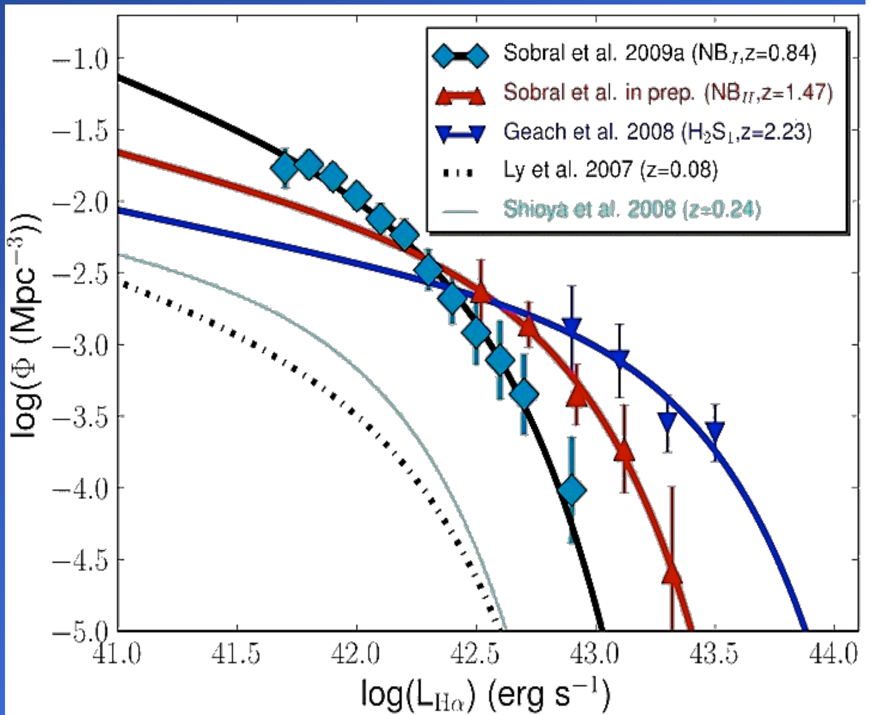


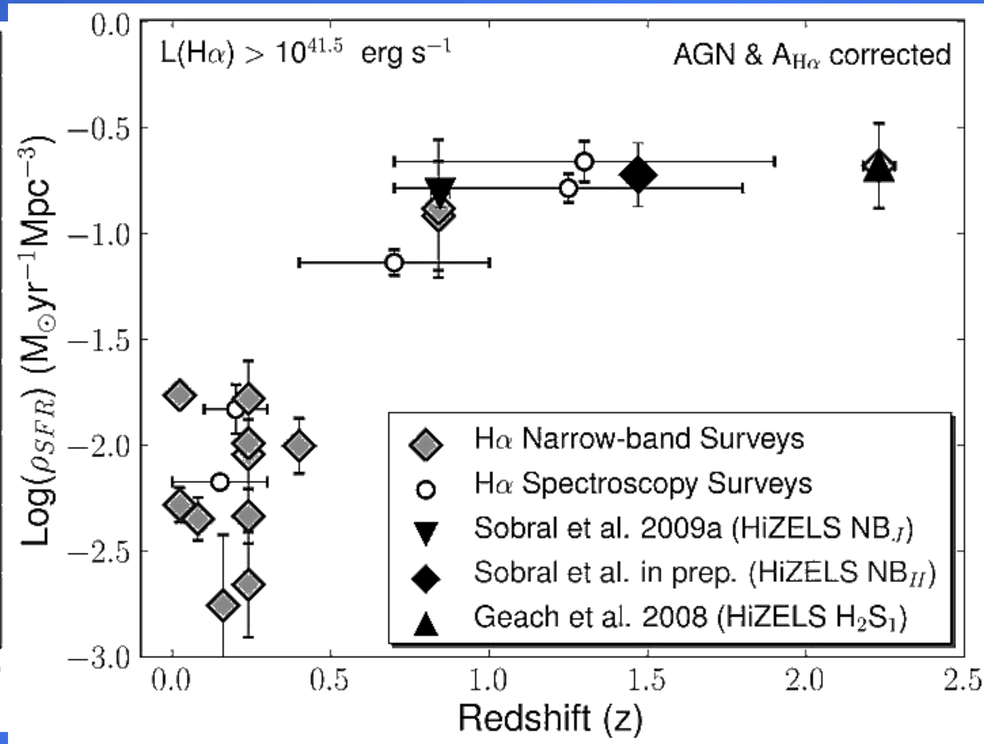
evolution of observed far-UV LF of LBGs

Bouwens etal 2011



Hα SFRD Evolution





*L** increases to z>2

φ* increases to z~1, then decreases

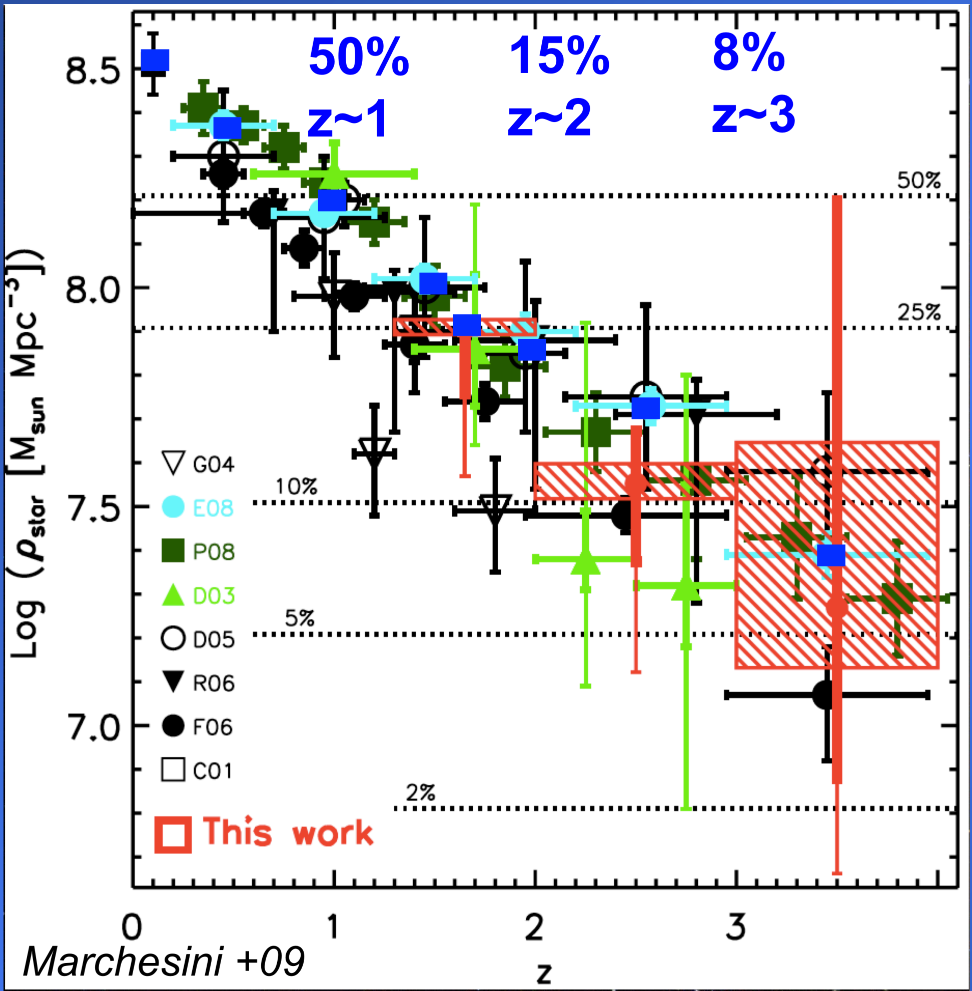
Evoln in SFRD slightly faster than canonical UV-derived $(1+z)^4$ out to z~1 and then levelling.

Evolution of stellar mass density & stellar mass function of galaxies

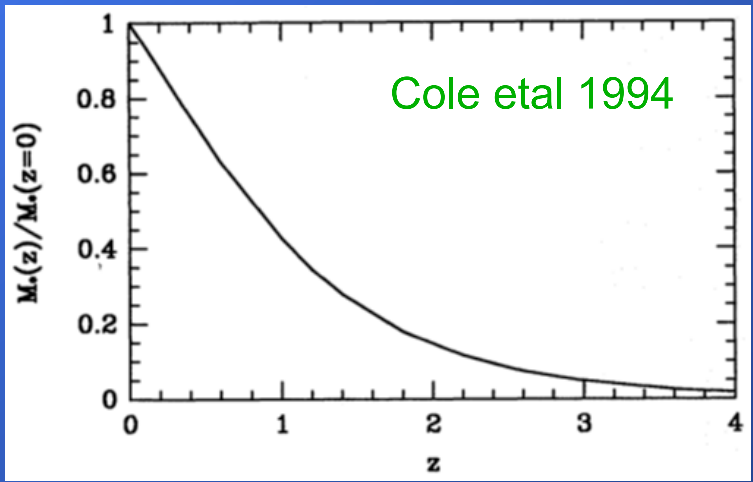
Measuring stellar masses for high-z galaxies

- stellar masses of galaxies estimated PHOTOMETRICALLY
- measure galaxy SED using multi-band photometry
- estimate stellar mass by fitting stellar population model, varying galaxy age, star formation history, dust extinction
- answer depends on assumed IMF & metallicity
- often estimate redshift using same photometric data

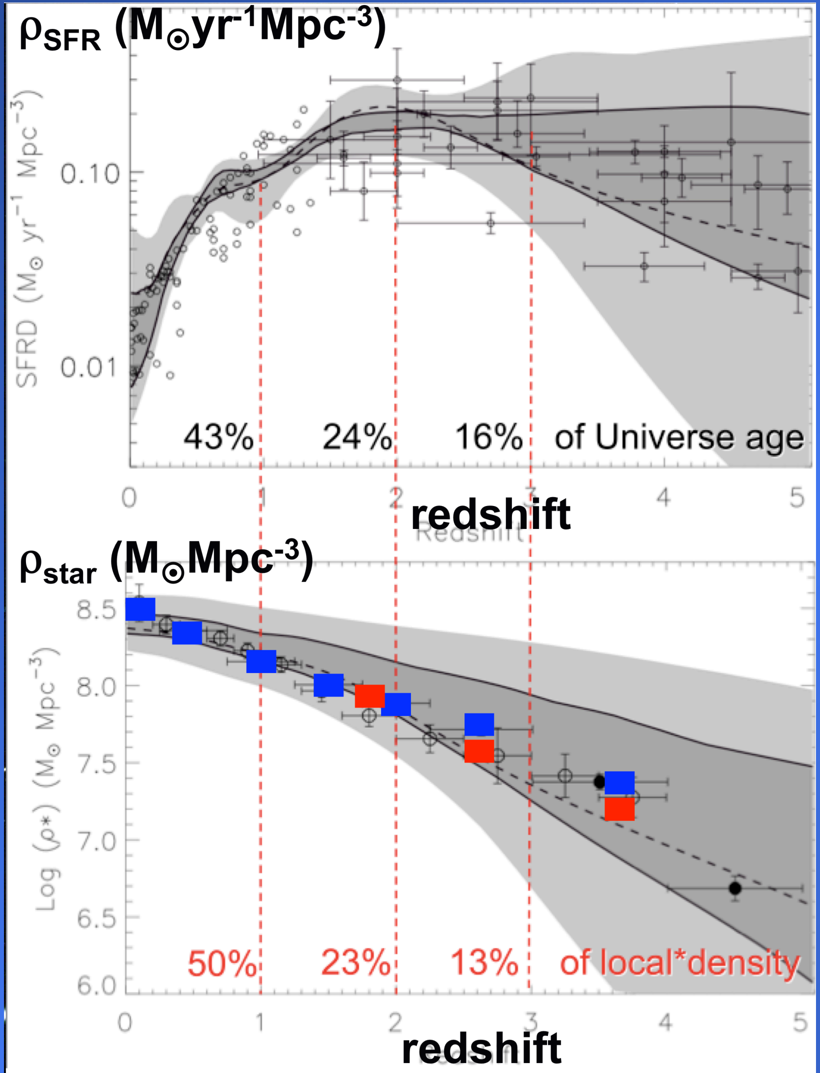
Observed evolution of stellar mass density



obs => 50% of stellar mass formed since z~1,
90% since z~3
- agrees with predictions from CDM-based galaxy formation models e.g. Cole etal 1994



SFR density vs stellar mass density



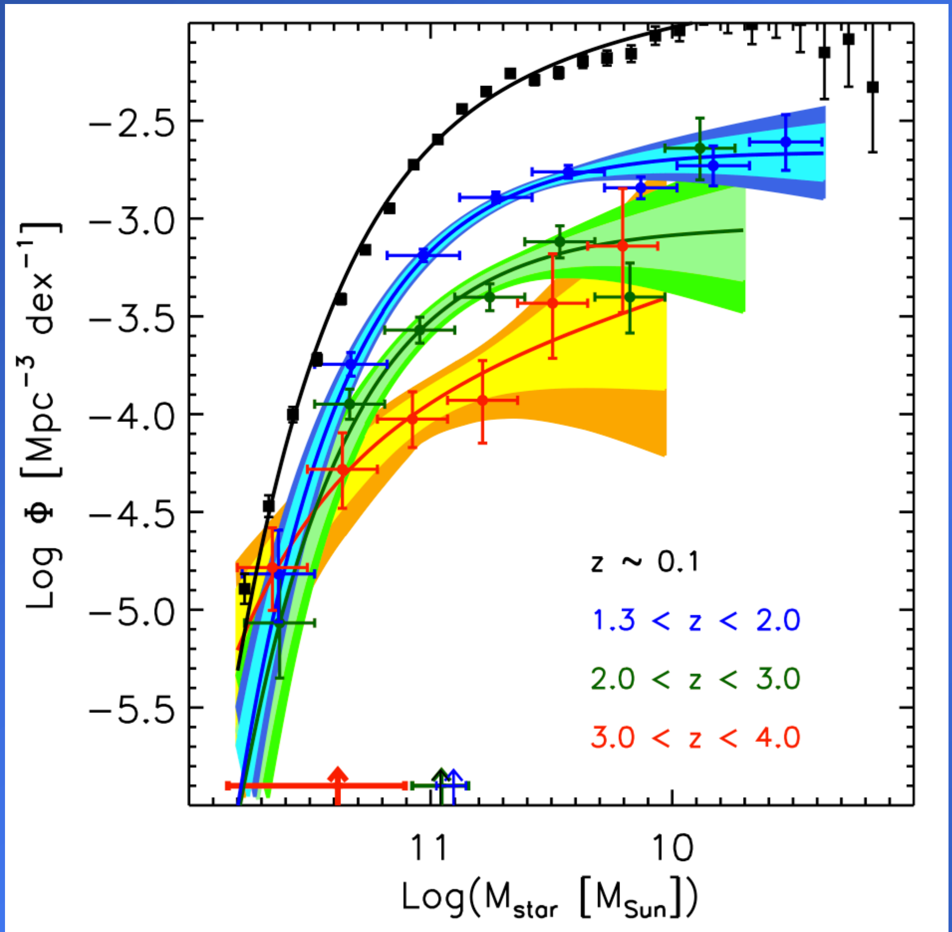
Le Borgne, Elbaz, Ocvirk, Pichon 10

- theoretically:

$$\rho_*(t) = \int_0^t \rho_{SFR}(t')\,dt'$$

- current observational estimates of SFR & stellar mass density histories appear roughly consistent with this

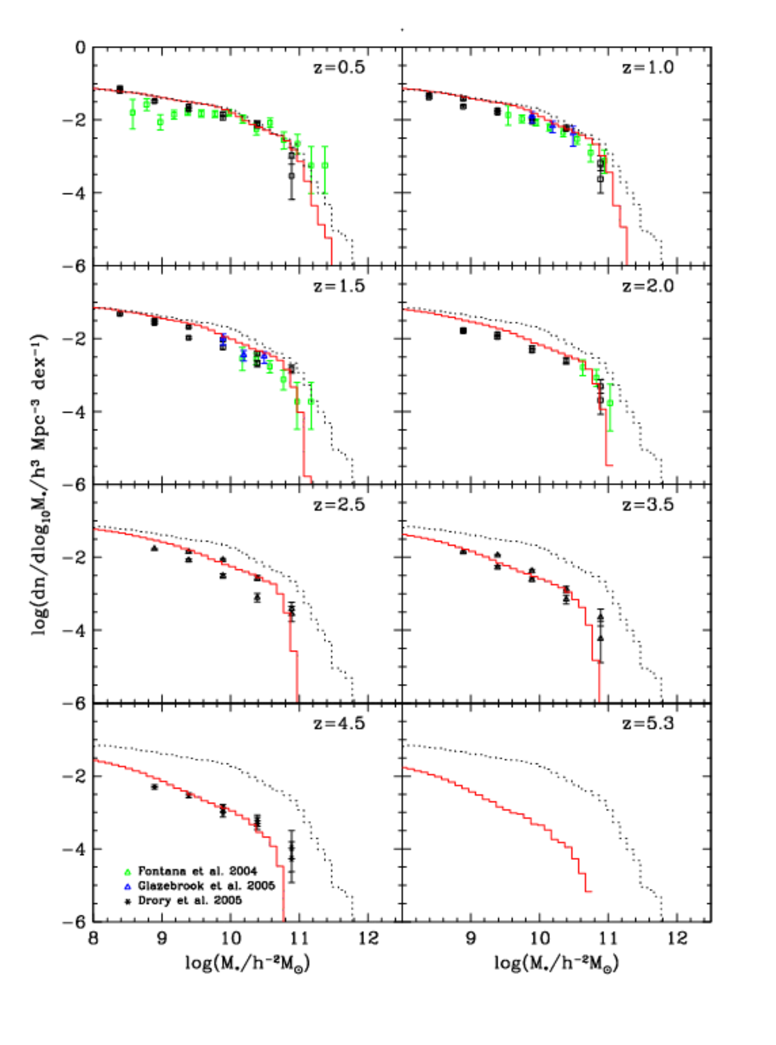
Observed evolution of stellar mass function of galaxies



- obs => stellar mass function at z<4 evolves more strongly at low than high mass – DOWNSIZING
- contrary to simple theoretical expectations based on hierarchical structure formation

Marchesini etal 2009

Evolution of stellar mass function in galaxy formation models



Bower etal 2006

- stellar mass function & halo mass function evolve differently due to effects of cooling and feedback
- models including AGN feedback for high-mass galaxies appear more successful in explaining observed evolution of stellar mass function