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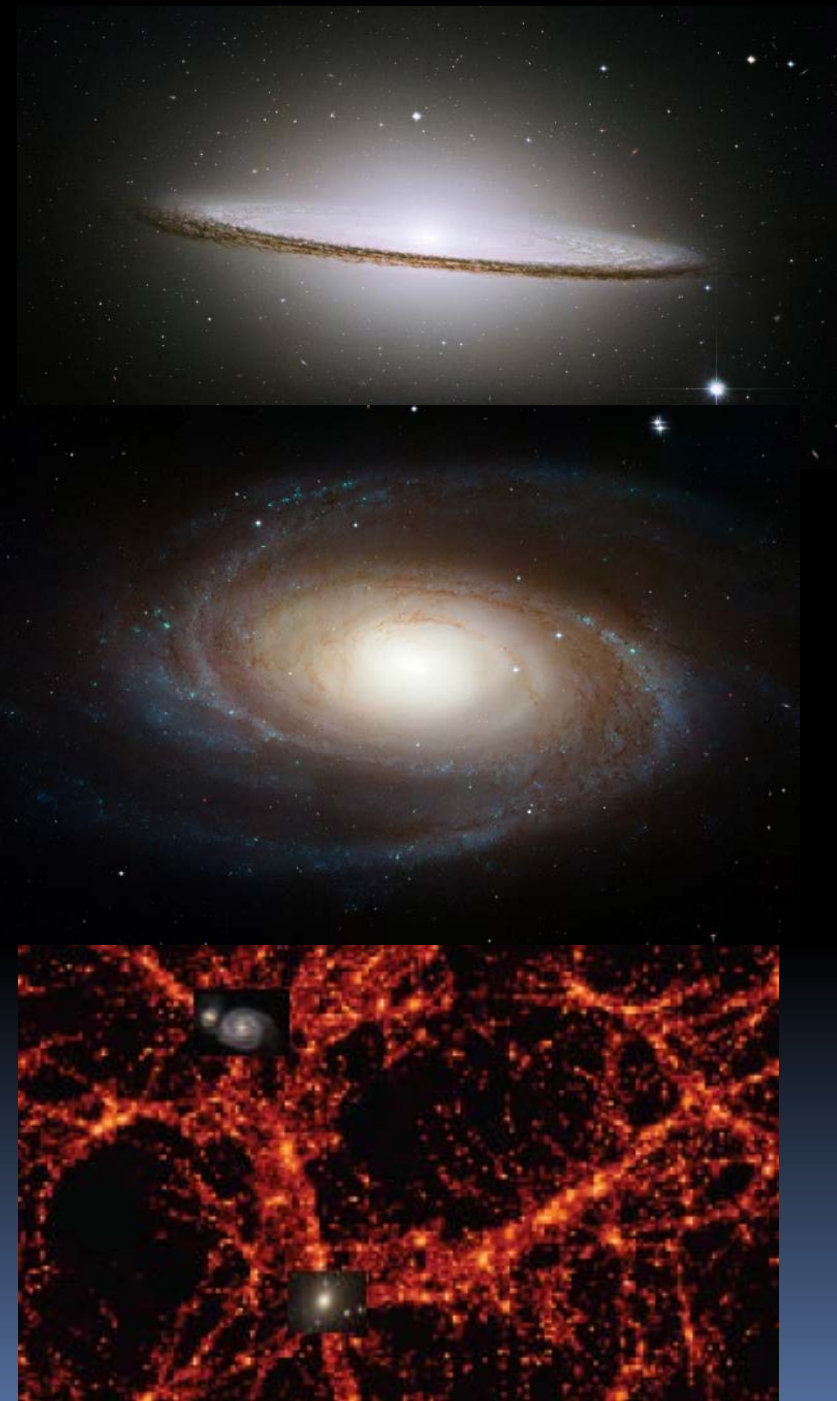
# STATISTICAL PROPERTIES OF GALAXIES AND EVOLUTION SINCE $z \sim 4$

1. Context
2. Main evolution drivers
3. Statistical description of the galaxy population
4. Deep galaxy surveys and galaxy evolution

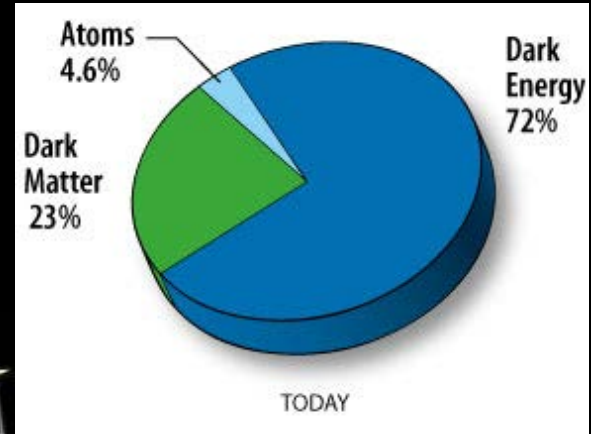
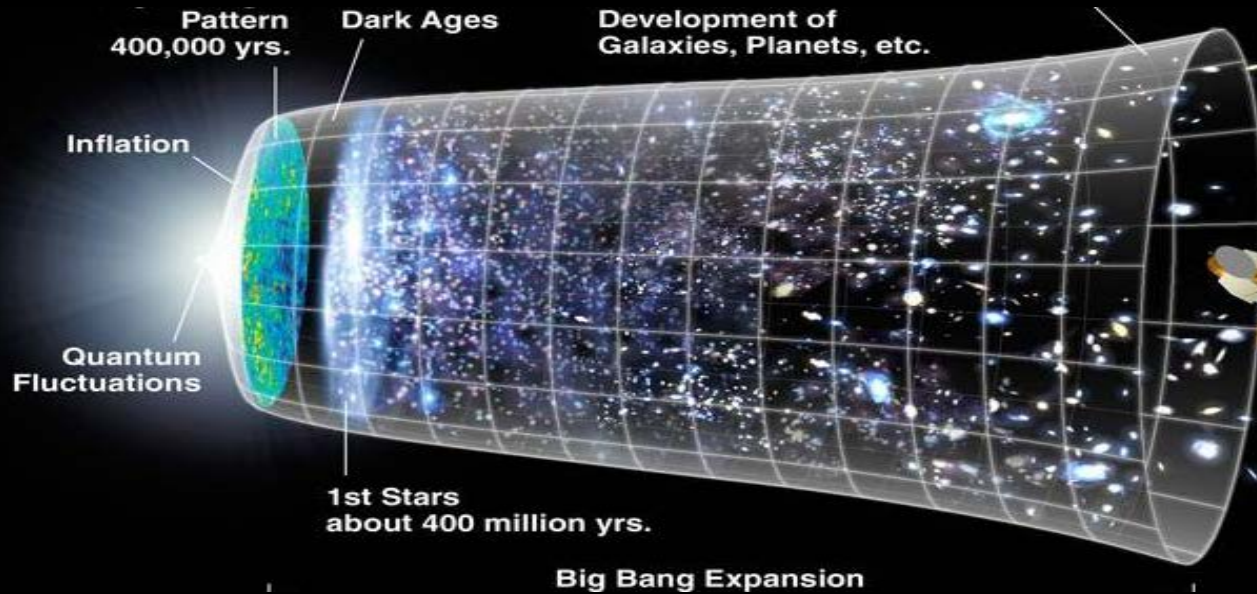


# Introduction

- Cosmological context
  - Galaxies are made of baryonic matter and dark matter
  - Interplay of BM and DM shapes galaxies in the context of hierarchical clustering
- What is the origin of the Hubble sequence ?
  - When did most stars form ?
  - How and when did galaxies assemble most of their mass ?
  - What are the main physical processes at play ?

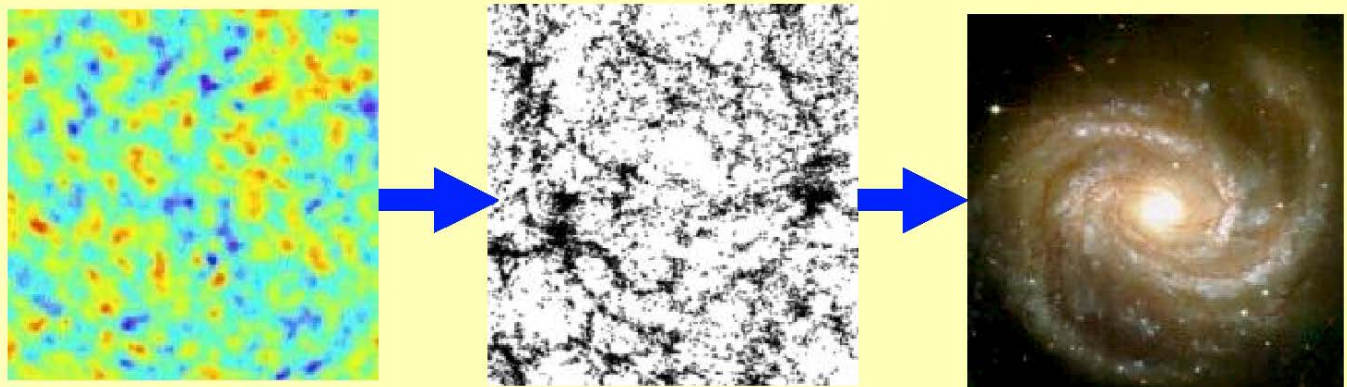


# Cosmological context

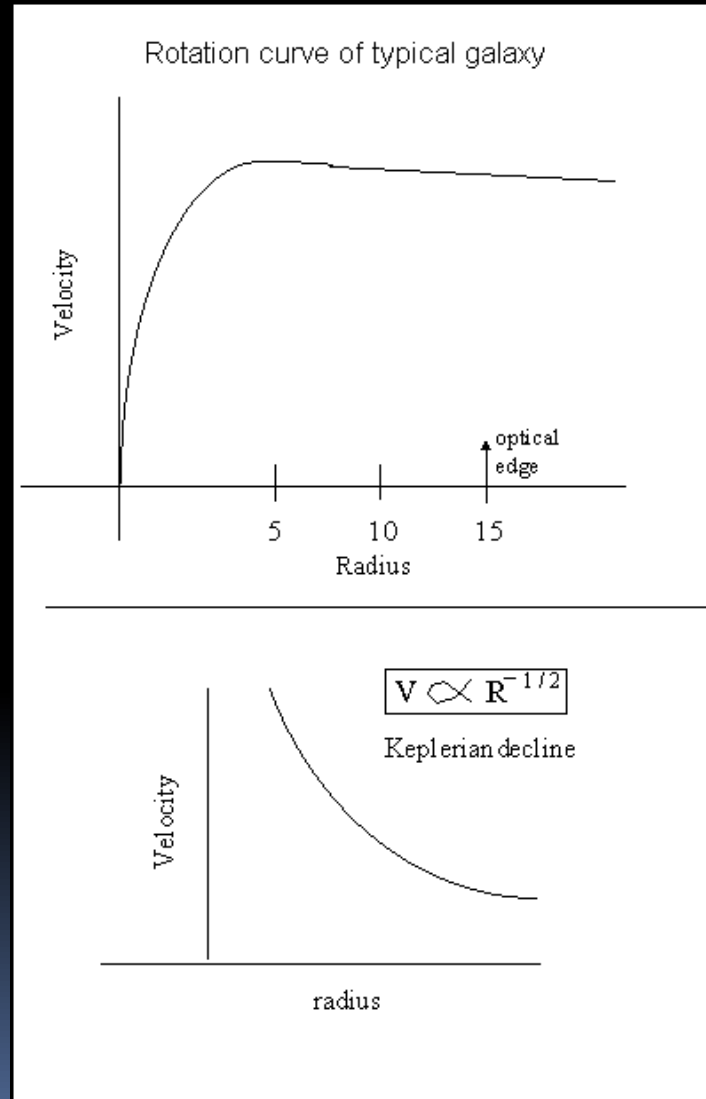


- Expanding Universe
- Accelerated expansion

Mostly Dark Matter and Dark Energy

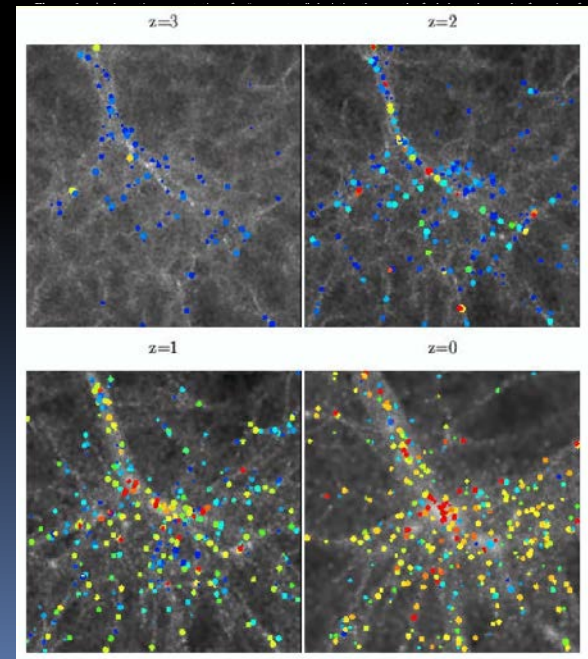
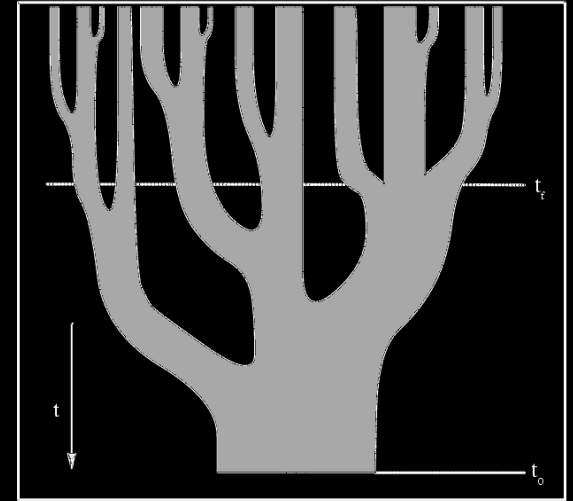


# Rotation curves in galaxies: dark matter !

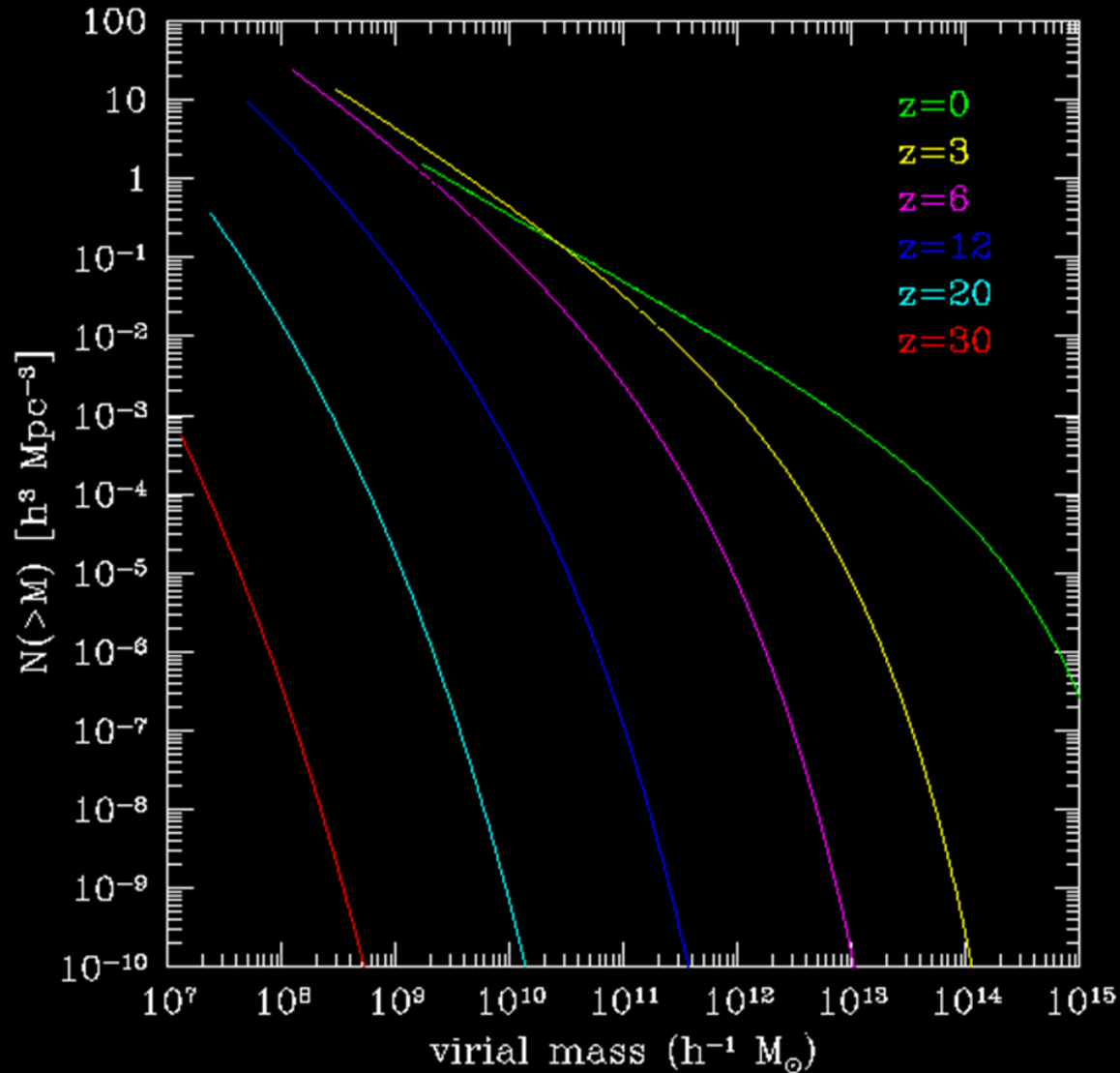


# Hierarchical clustering

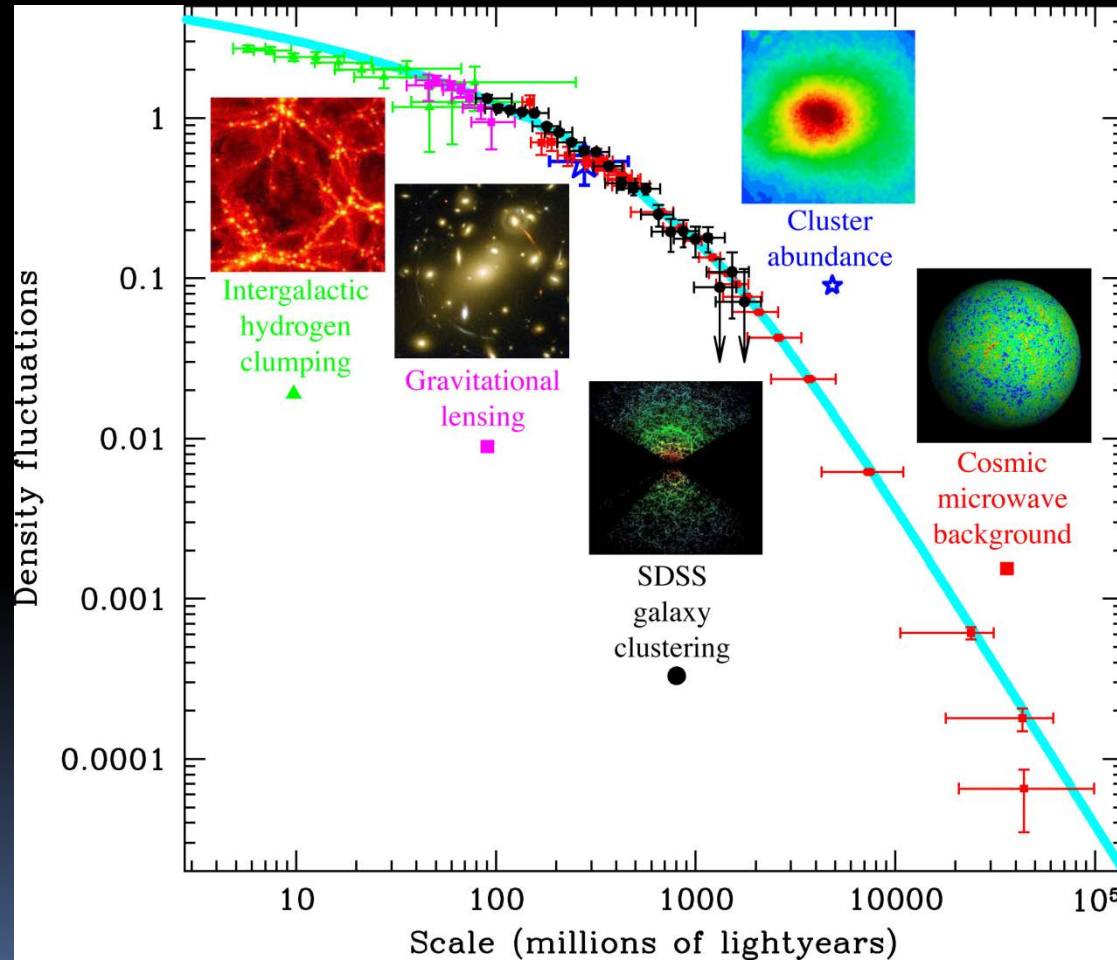
- Growth of dark matter halos following a merger tree
- DM halos merge to form more massive ones
- Matter flows along the cosmic web
- Galaxies in DM halos follow this process

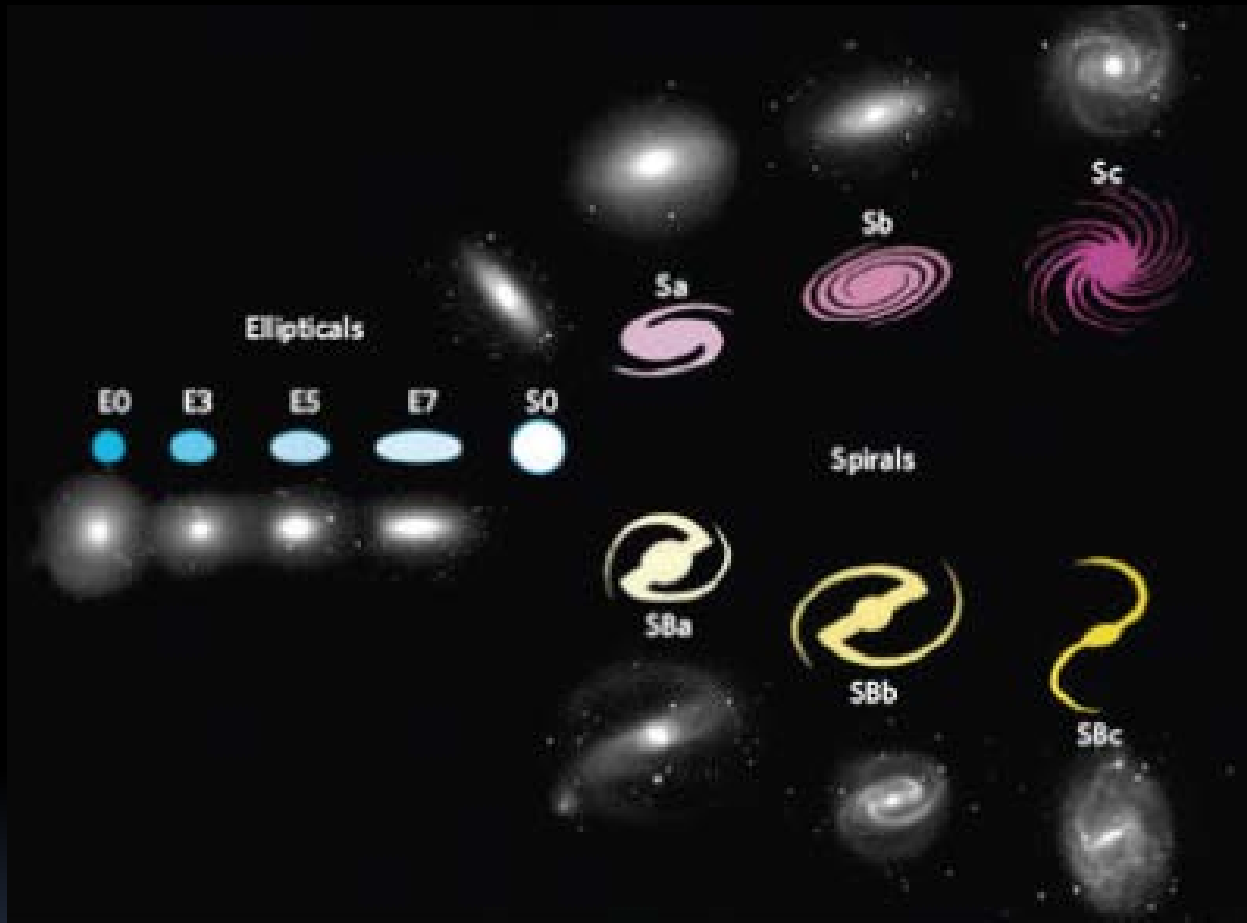


# Predicts the cumulative mass function in DM halos and its evolution with redshift



# Density fluctuations and large scale structures

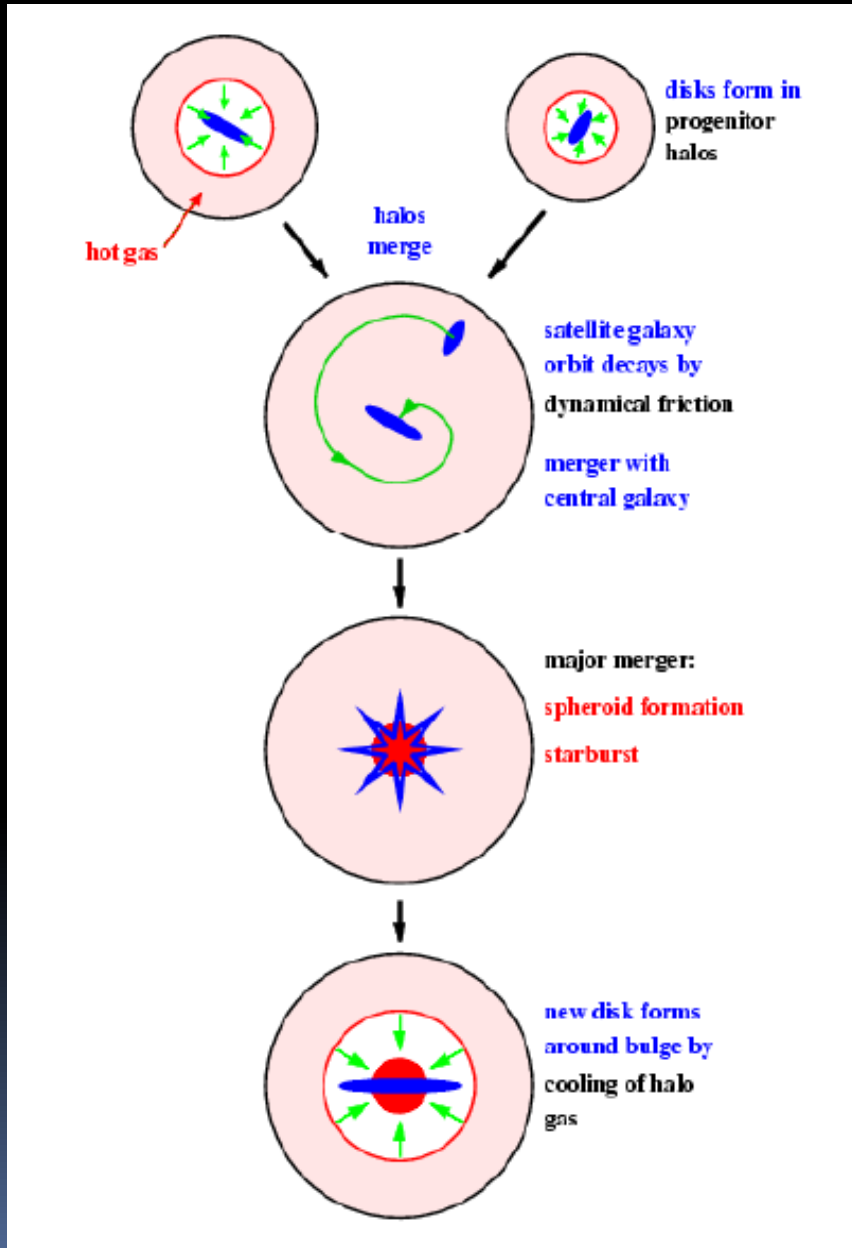




Hubble sequence of galaxy morphologies at present day  
What is its origin ?

# Main physical processes driving evolution

- Hierarchical assembly by merging
  - Increases mass “catastrophically”
- Stellar evolution
  - Luminosity / color, lifetime
- Cold accretion along the cosmic web
  - Fuels star formation
  - Increases mass continuously
- Feedback
  - AGN
  - Supernovae (explosion)
- Environnement,  $f(\text{density})$ 
  - Quenching, Harassement, Stripping,...



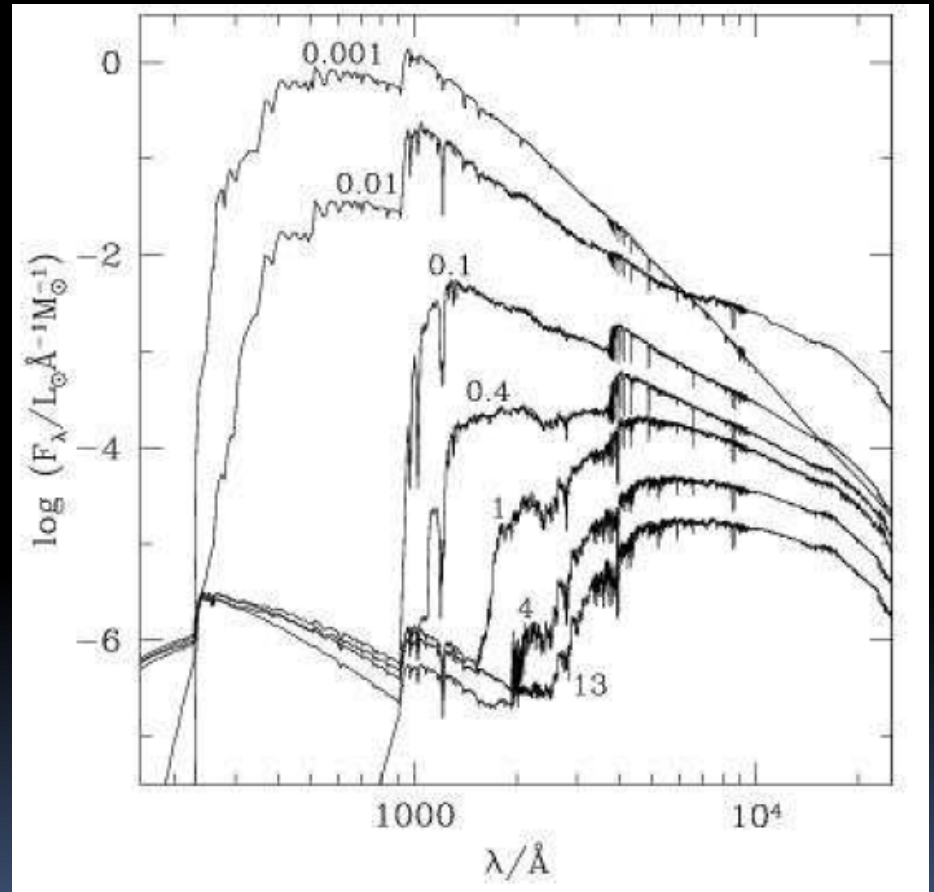
# Hierarchical merging

- Merging of DM halos
- Galaxies merge by dynamical friction
- Major mergers can produce spheroids from disks
- Merging increases star formation
- Increases mass
  - Major merging: equal mass
  - Minor merging: small companions
- $MR \propto (1+z)^m$

# Evolution of stellar populations

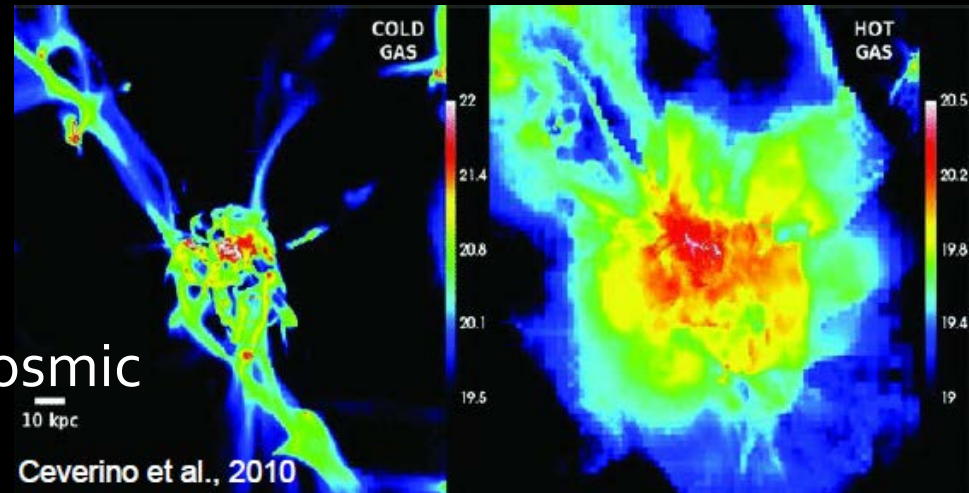
Stellar population synthesis models:  
(Bruzual&Charlot, Maraston,...)

- Luminosity evolution
- Color evolution



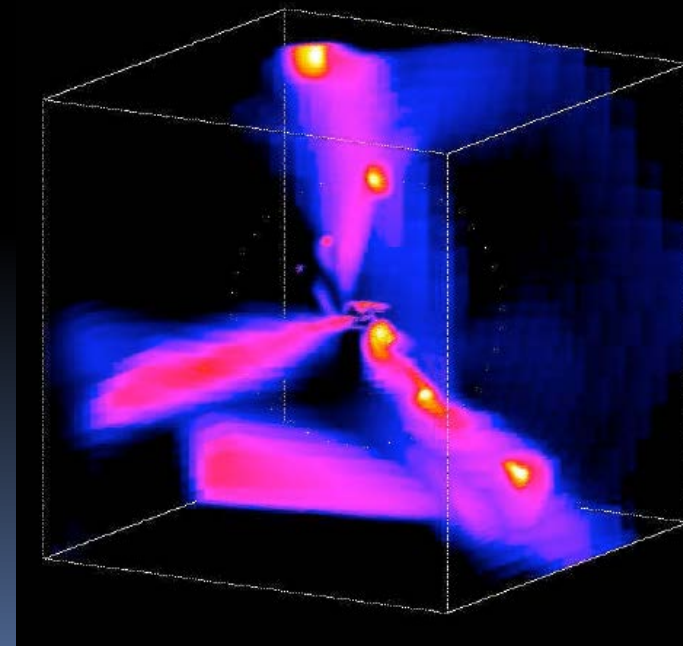
BC<sub>03</sub>

# Cold gas accretion



- Along the filaments of the cosmic web
- Steady flow for some billion years can accumulate a lot of gas
- Gas transforms into stars
- Produces important mass growth
- From Press-Schechter theory

## Simulations



$$\dot{M} \simeq 6.6 M_{12}^{1.15} (1+z)^{2.25} f_{b,165} M_{\odot} \text{ yr}^{-1}$$

$$M_{12} \equiv M_v / 10^{12} M_{\odot}$$

$$f_b = 0.165$$

At  $z \sim 2$   $\dot{M} \simeq 200 M_{\odot} \text{ yr}^{-1}$

Dekel et al., 2009

# Feedback

- Takes material out of a galaxy back to DM halo
- May quench star formation ?
- AGN feedback

$$\dot{E}_{\text{feed}} = \epsilon_f L_r = \epsilon_f \epsilon_r \dot{M}_{\text{BH}} c^2$$

$\epsilon_f=0.05$  (thermal coupling efficiency)

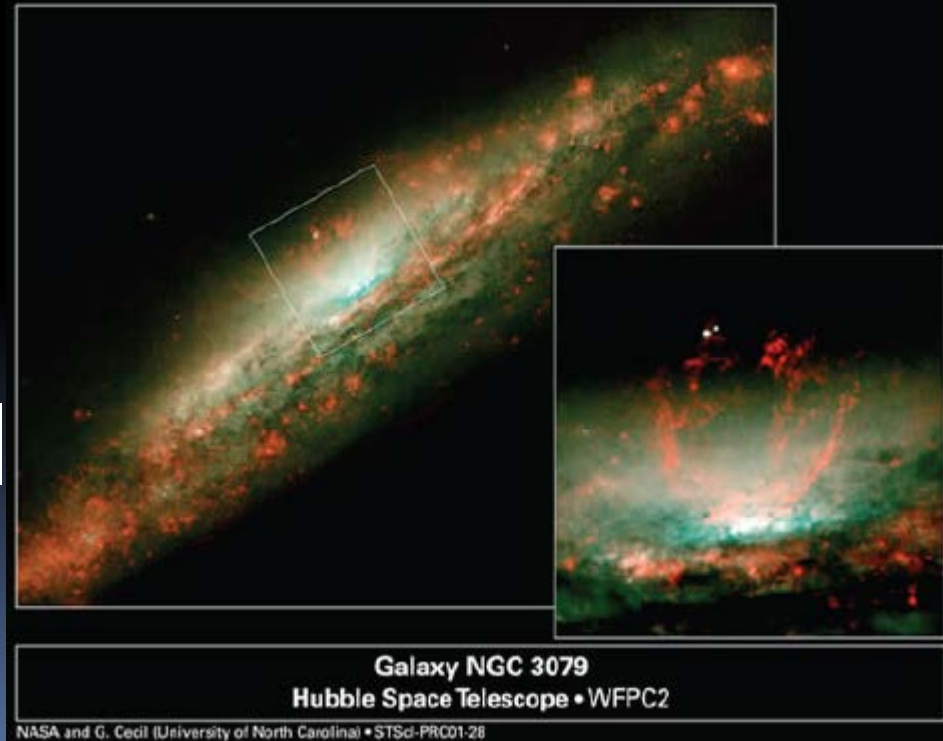
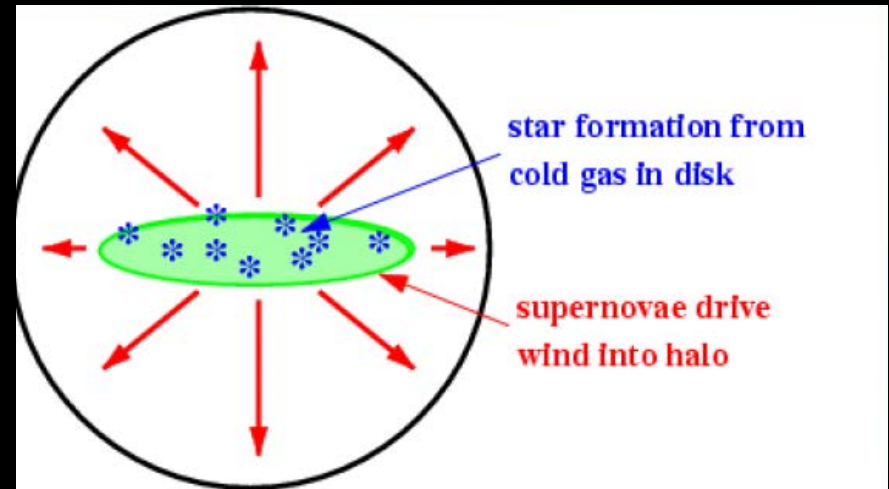
$\epsilon_r=0.1$  (radiative efficiency)

- SNe feedback

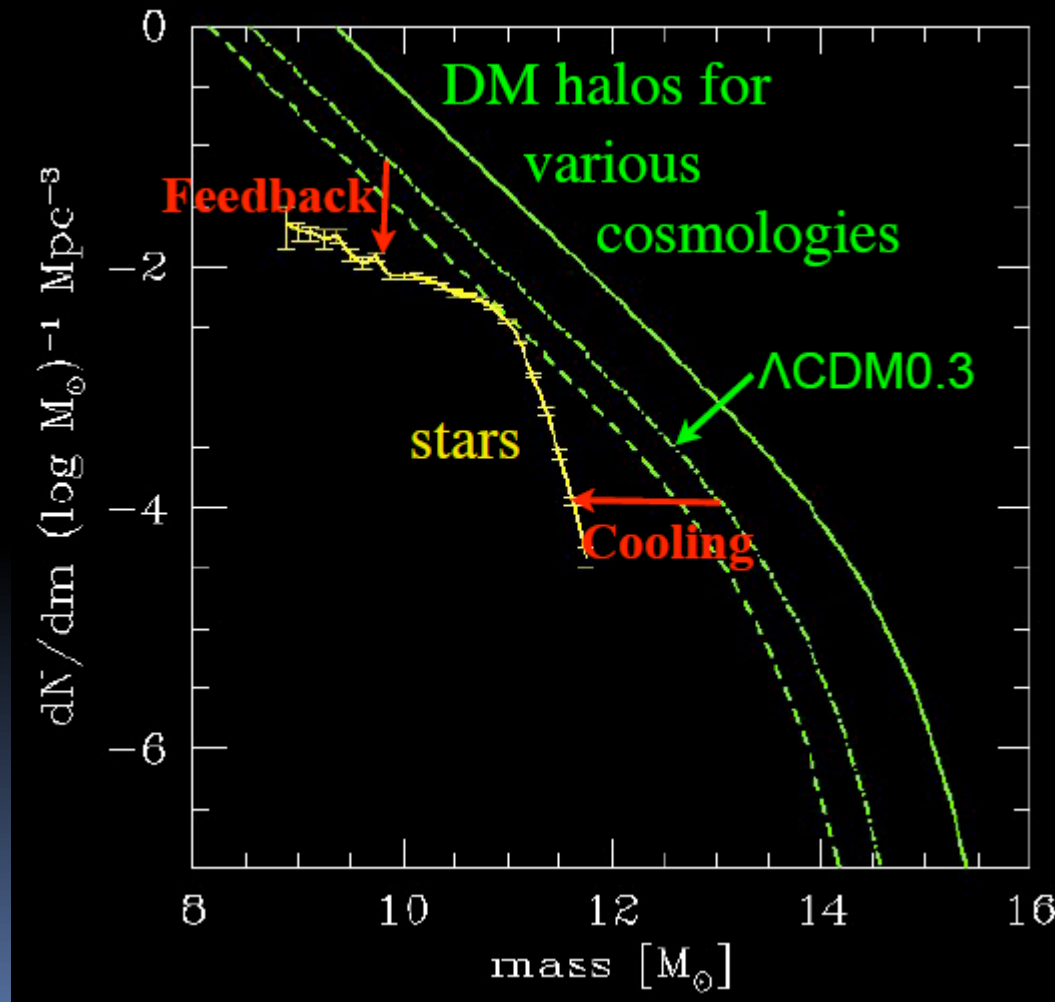
$$\dot{M}_{\text{eject}} = \beta \psi \quad \psi: \text{instantaneous SFR}$$

feedback efficiency  $\beta = (V_{\text{disk}}/V_{\text{hot}})^{-\alpha_{\text{hot}}}$

$V_{\text{hot}}=485\text{km/s}$  and  $\alpha_{\text{hot}}=3.2$



# Effect of feedback and cooling on mass function



# Measuring galaxy evolution

- Deep galaxy surveys
  - Imaging: Spectral Energy Distribution, photo-z
  - Spectroscopy: spectro-z, line properties
- Large volumes
  - Minimize cosmic variance
- Large numbers
- Measure properties at different epochs to trace evolution

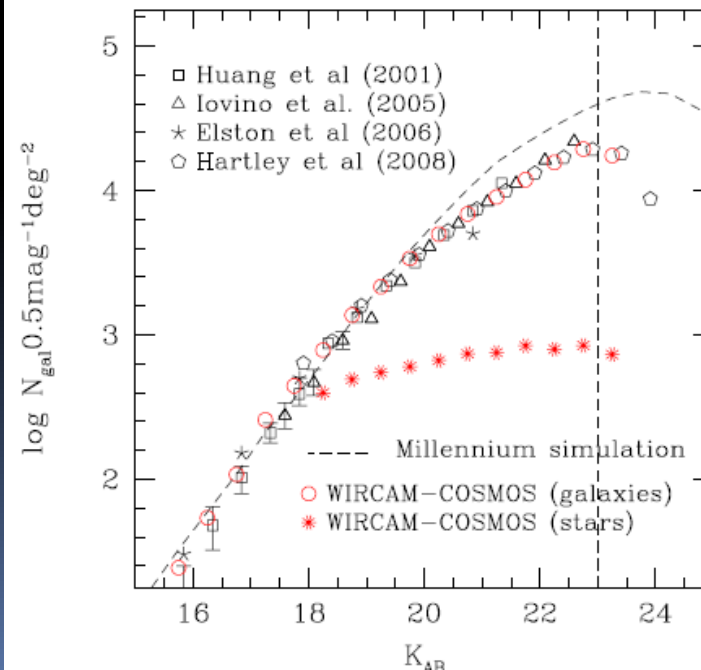
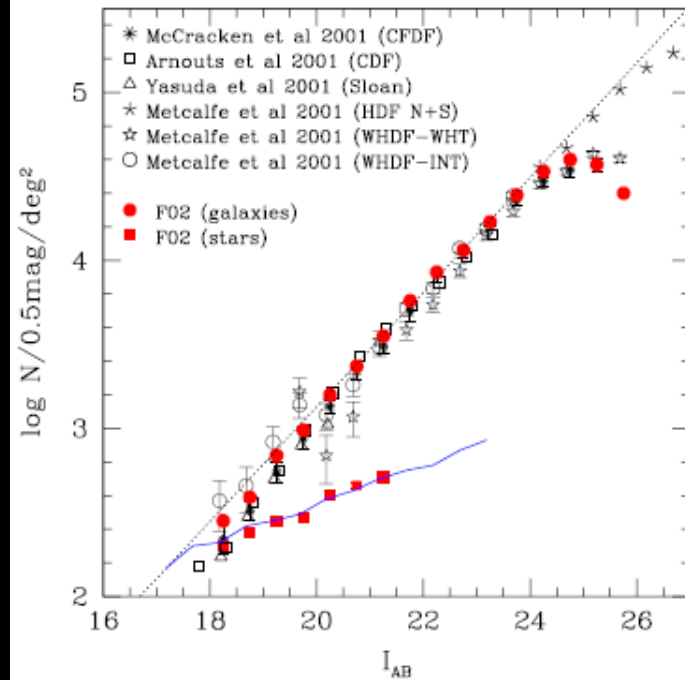
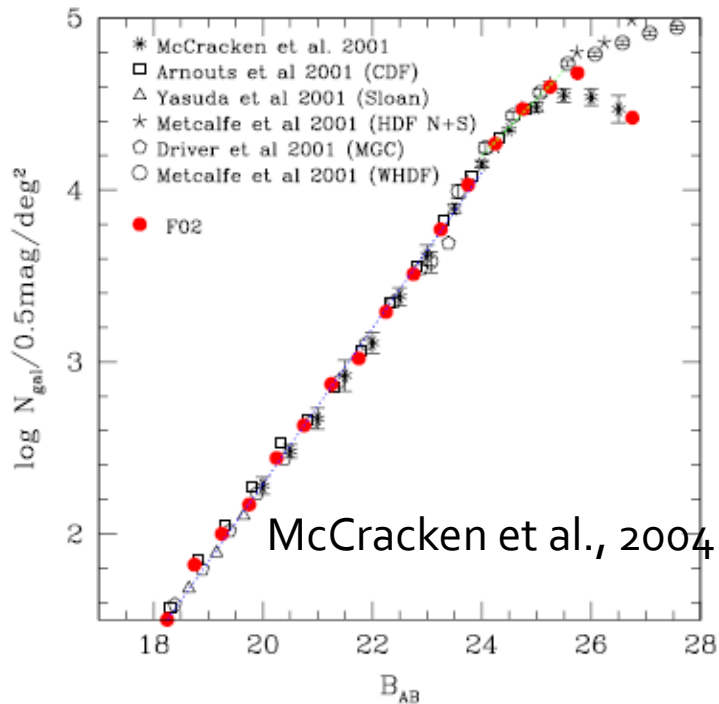
# Statistical properties of galaxy populations and evolution

- Galaxy counts  $N(m)$
- Color distribution
- Redshift distribution  $N(m, z)$
- Luminosity function and star formation rate evolution
- Mass function and evolution of the stellar mass density
- Galaxy merger rate evolution
- Effect of environment: evolution of the morphology – density relation
- Correlation function

- SFH: Star Formation history
  - From SFRD: Star Formation Rate Density
- Mass assembly history
  - From Stellar Mass Density
- Merger rate history

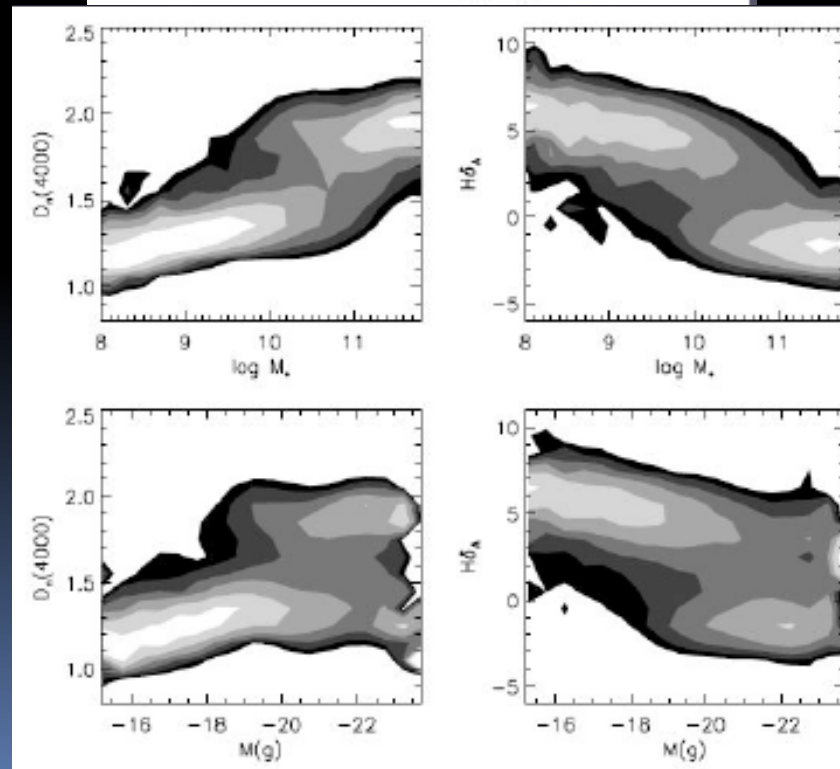
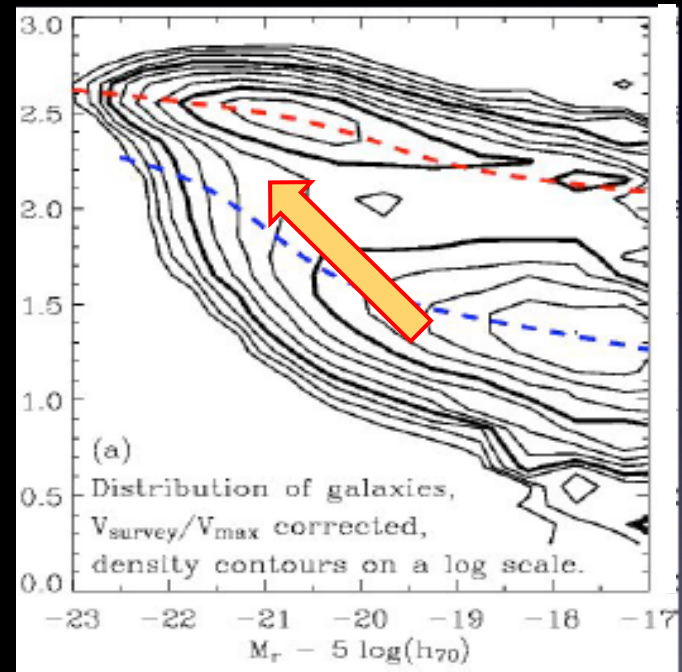
# Galaxy counts $N(m)$

- Faint blue galaxy excess counts (in the ~80s)
  - Too many faint galaxies compared to “no-evolution” or pure luminosity evolution
  - Understood if galaxies were more actively forming stars in the past



# Color distribution

- At low- $z$ : strong color-magnitude bimodality
  - Red sequence and blue cloud
- At  $z \sim 1$  red sequence exist but less populated
- Are galaxies moving from the blue cloud to the green valley and then to the red sequence ?



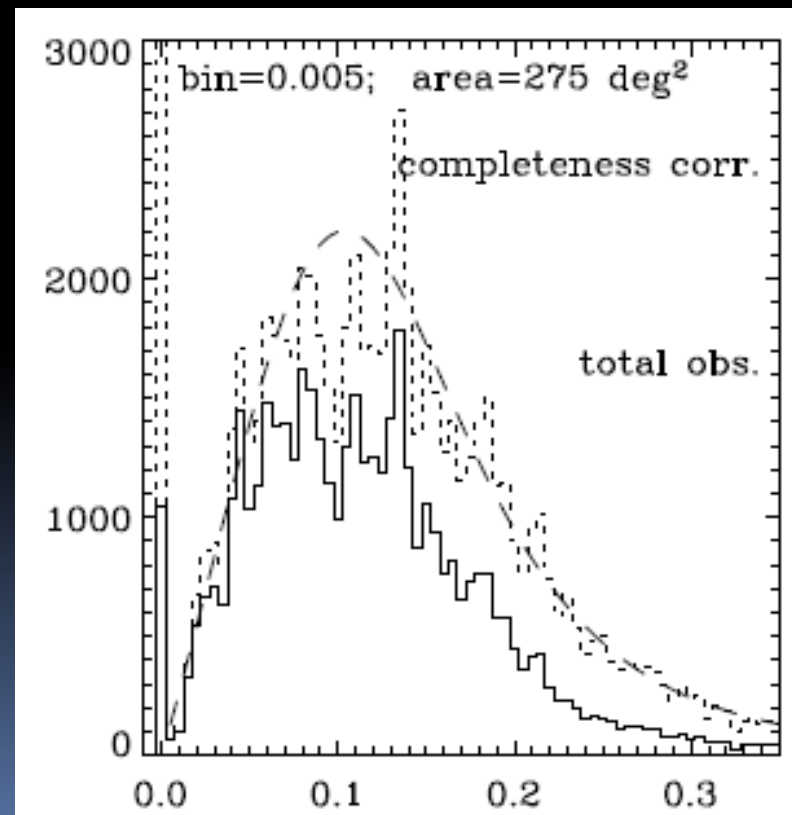
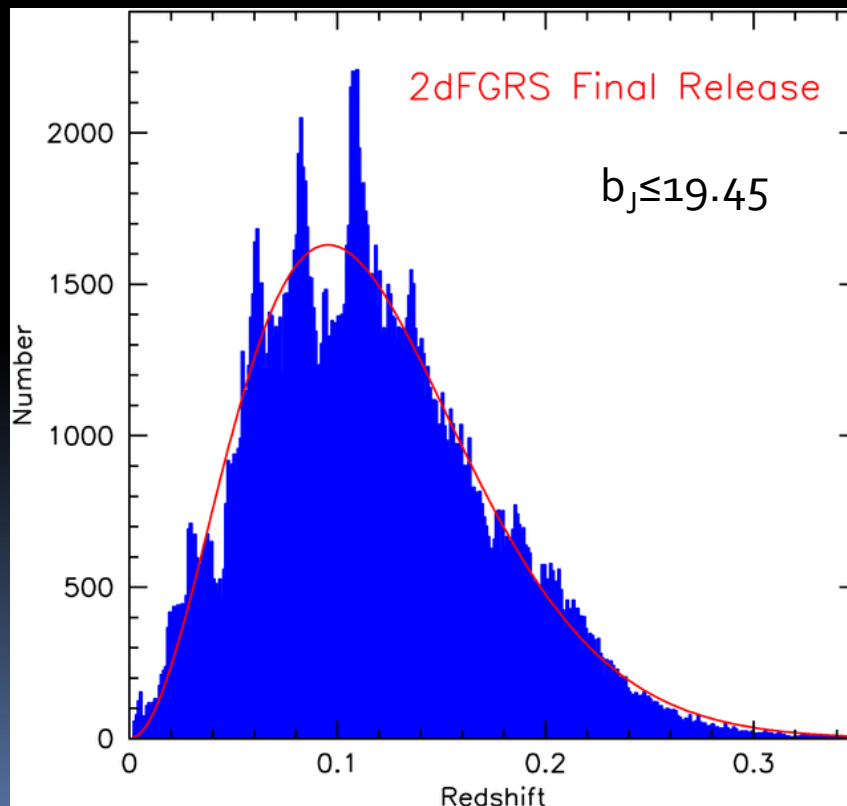
Baldry et al., 2005  
Kauffmann et al., 2003

# Redshift distributions

*magnitude selected samples: Local*

- $N(m,z)$  includes evolution signatures
- SDSS, 2dFGRS: Large volumes

SDSS,  $u < 20$ , Baldry et al., 2005



# Redshift distributions

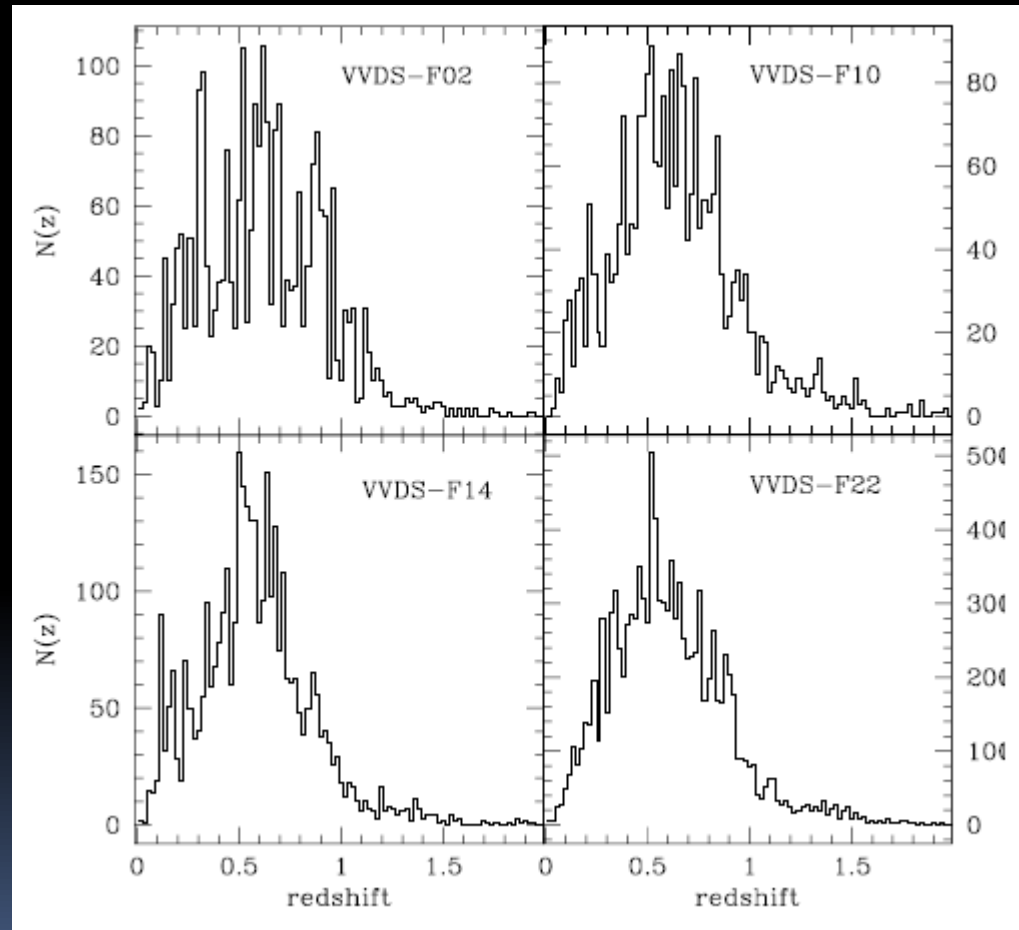
*magnitude selected samples: medium-z*

$$i_{AB} \leq 22.5$$

- CFRS
- VVDS-wide
- zCOSMOS-bright

$$\langle z \rangle = 0.55$$

Cosmic variance on 1deg scale still a limiting factor



VVDS: Garilli et al., 2008

# Redshift distributions

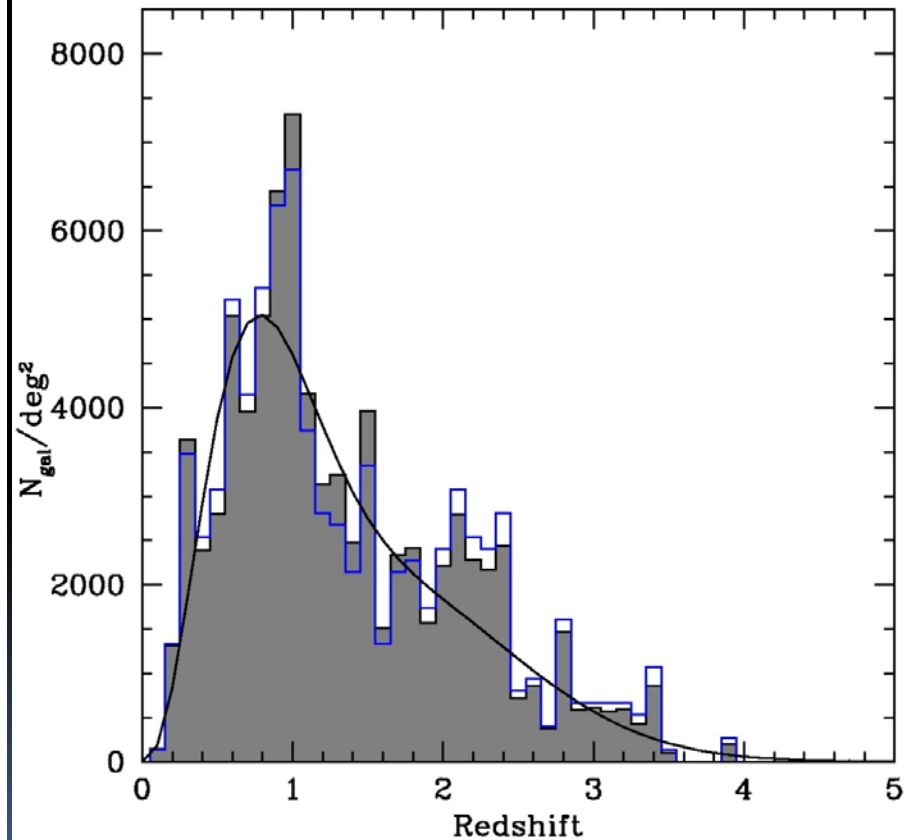
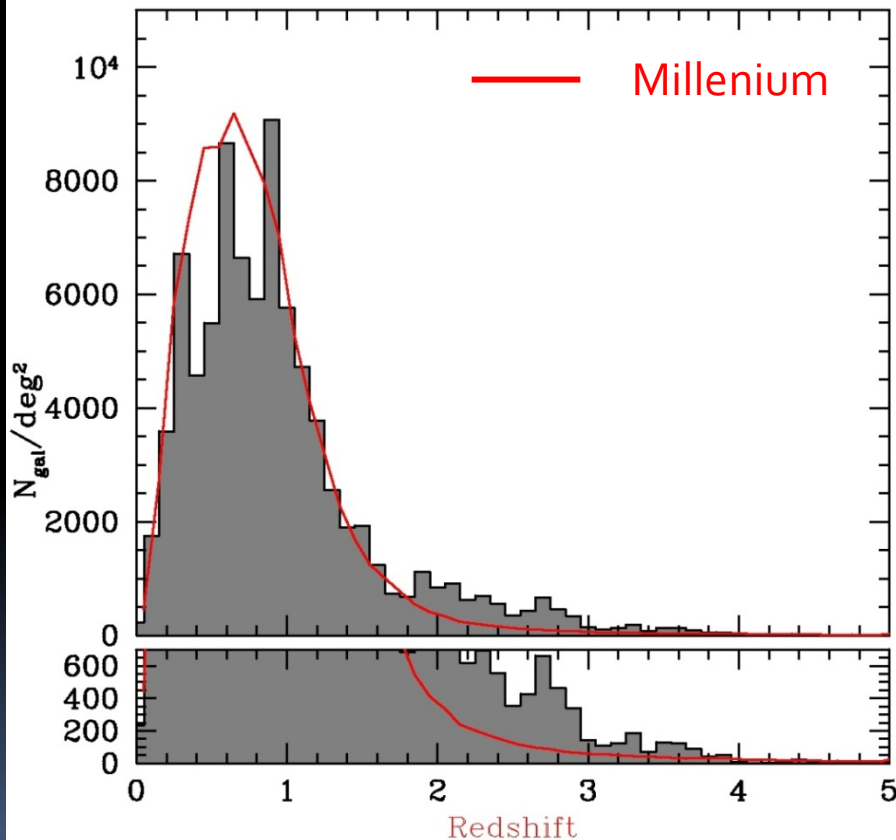
*magnitude selected samples: high-z*

$$i_{AB} \leq 24$$

■  $\langle Z \rangle = 0.8$

$$23 \leq i_{AB} \leq 24.75$$

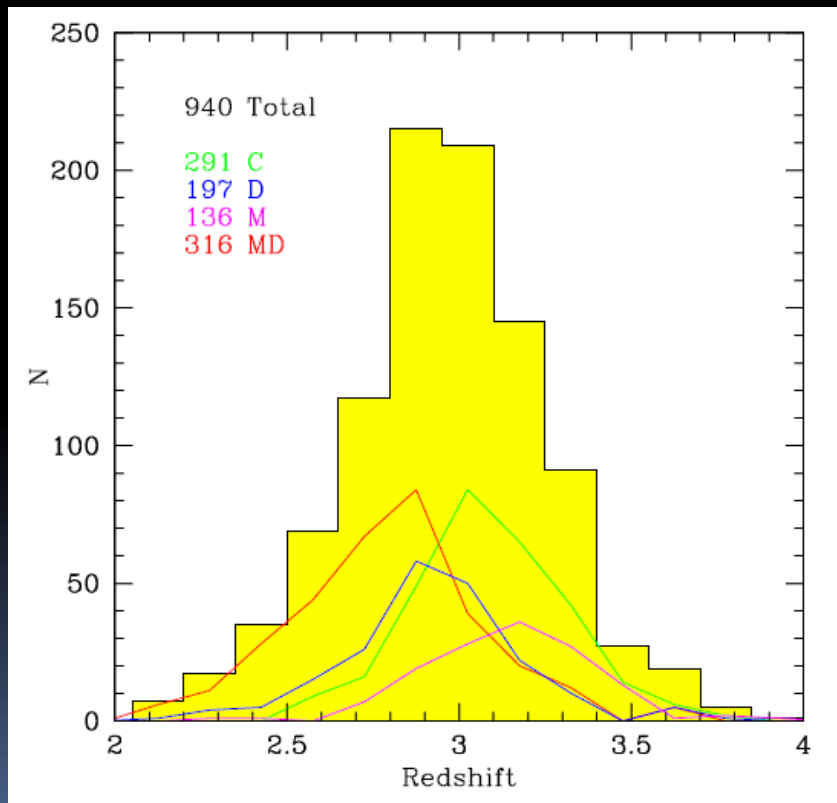
■  $\langle Z \rangle = 1.3$



# Redshift distributions

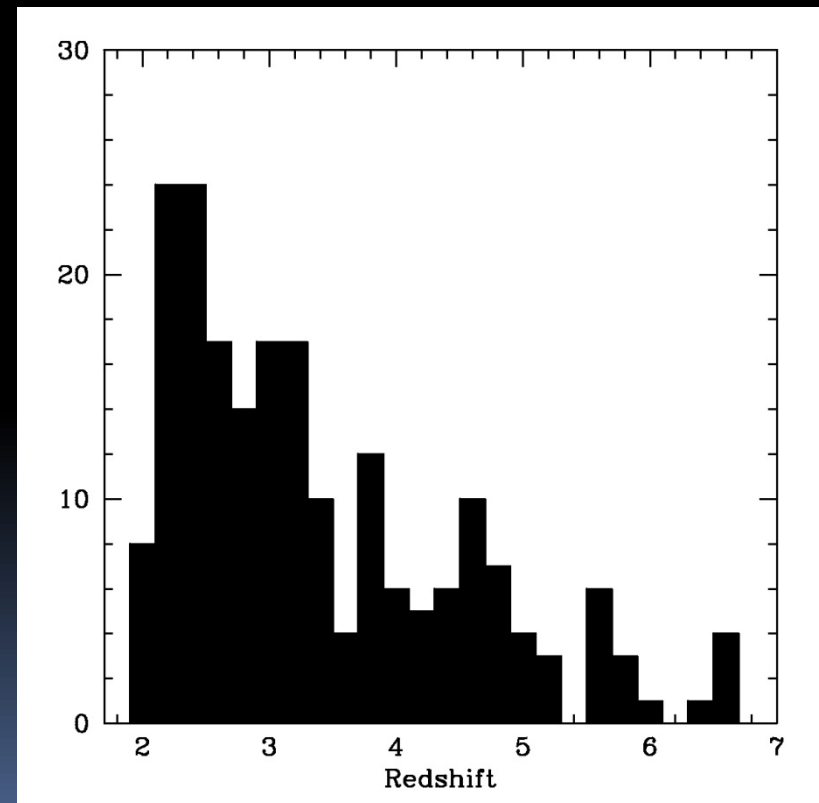
*high-z samples*

LBG: UGR color-color  
Lyman-break selection



Steidel et al., 2003

LAE: Lyman- $\alpha$  emitters  
serendipitous discovery



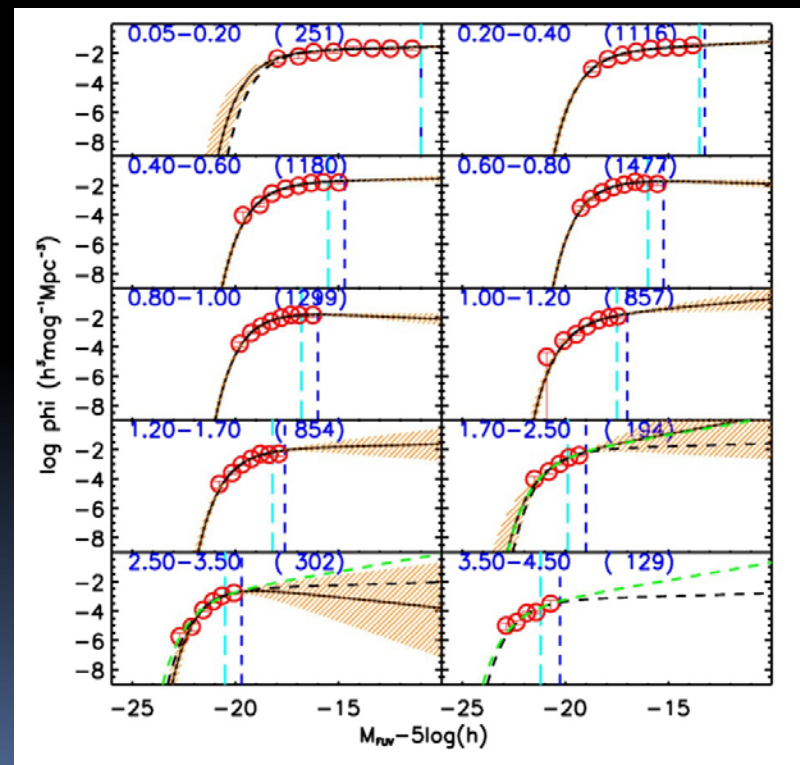
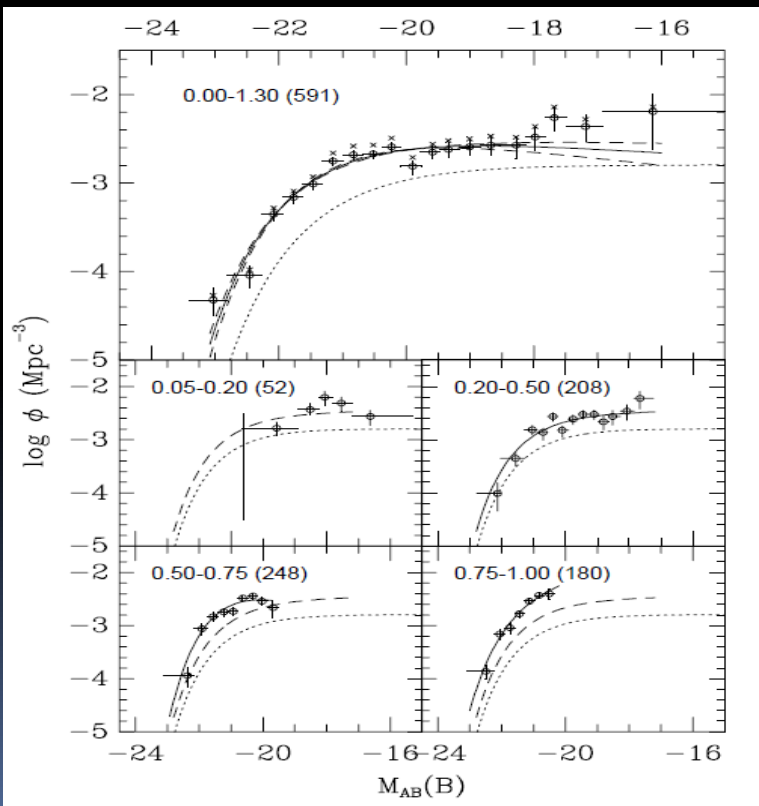
Cassata et al., 2011

# Evolution of the luminosity function

- Important evolution probe
- Described by the Schechter function
- Evolution identified in 1995 (Canada-France Redshift Survey)
  - $L_{*is}$  1 magnitude brighter at  $z \sim 1$
- 15 years later: LF up to  $z \sim 7$ !

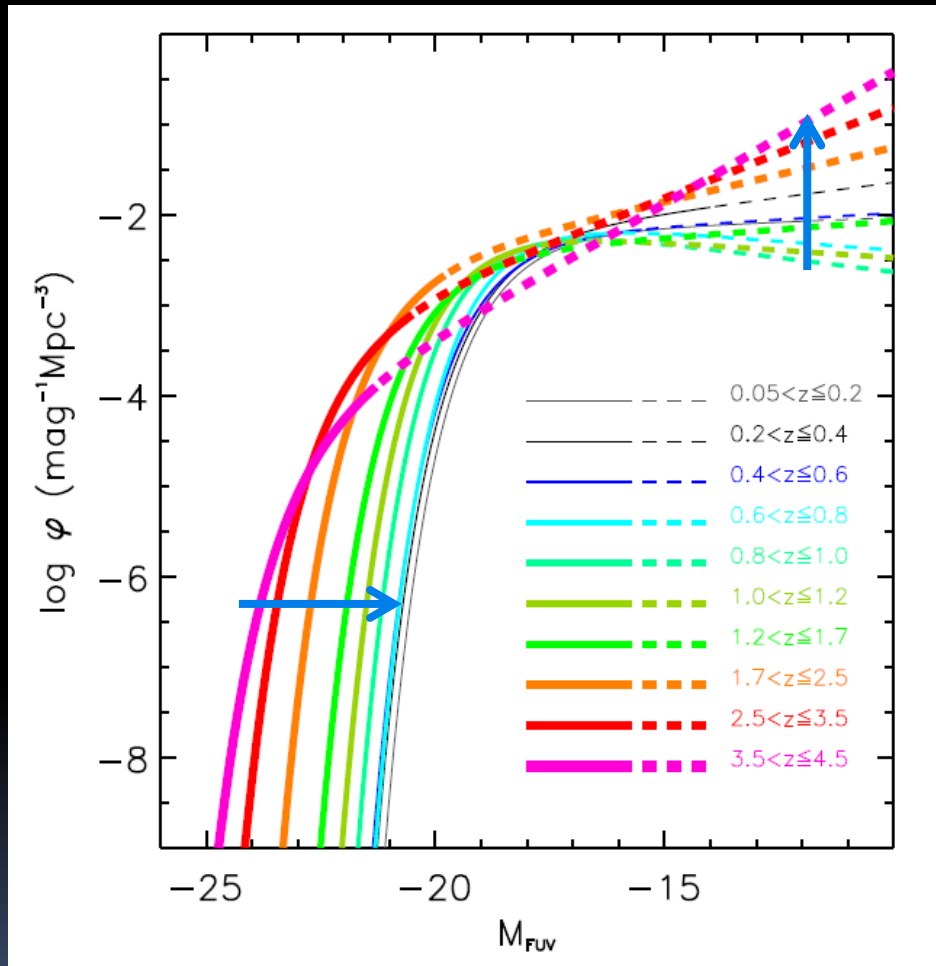
$$\phi(L)dL = \phi_* \left( \frac{L}{L_*} \right)^\alpha \exp \left( -\frac{L}{L_*} \right) \frac{dL}{L_*}$$

- 3 parameters:
- $\phi_*$ : volume density
  - $L_*$ : characteristic luminosity
  - $\alpha$ : slope at low L



Cucciati et al., [arXiv:1109.1005](https://arxiv.org/abs/1109.1005)

# LF evolution for normal galaxies



“Normal” at  $z > 2$  means “star forming” when selected from optical bands (rest-frame UV continuum)

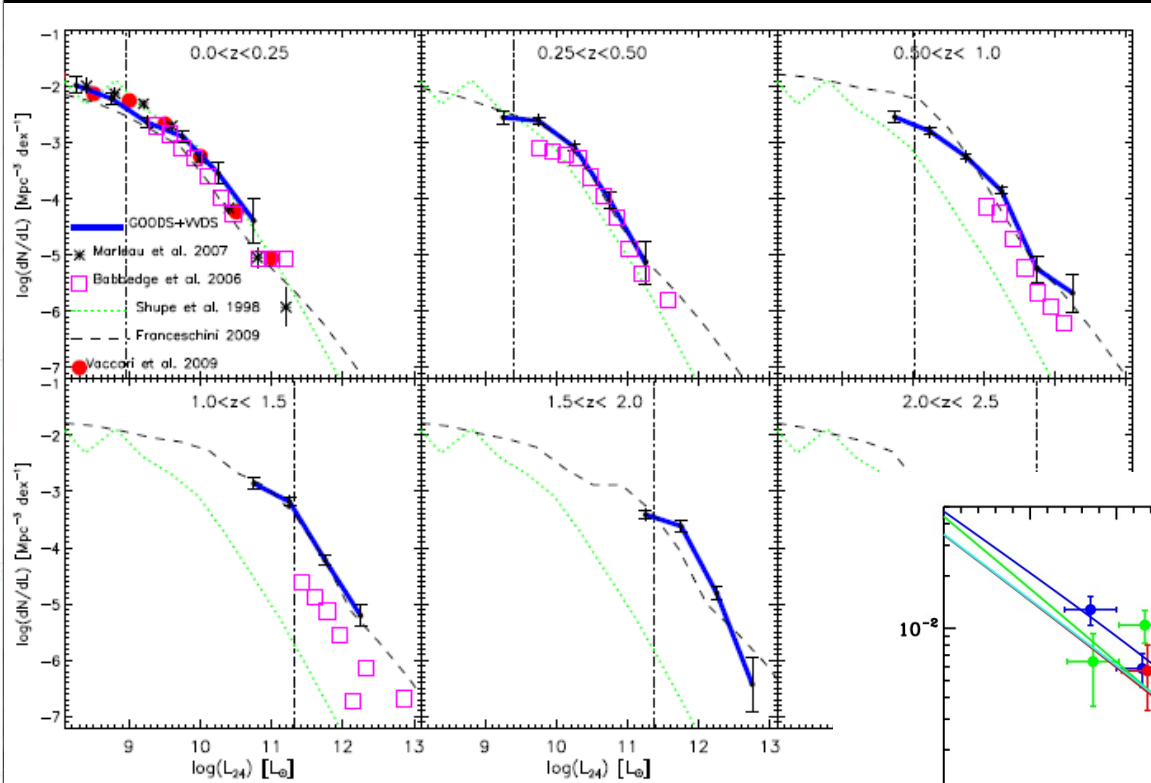
- $L_*$  decreases with  $z$
- Slope  $\alpha$  is steeper at high  $z$

At higher  $z > 4$ :  
see Bouwens et al. 2006+

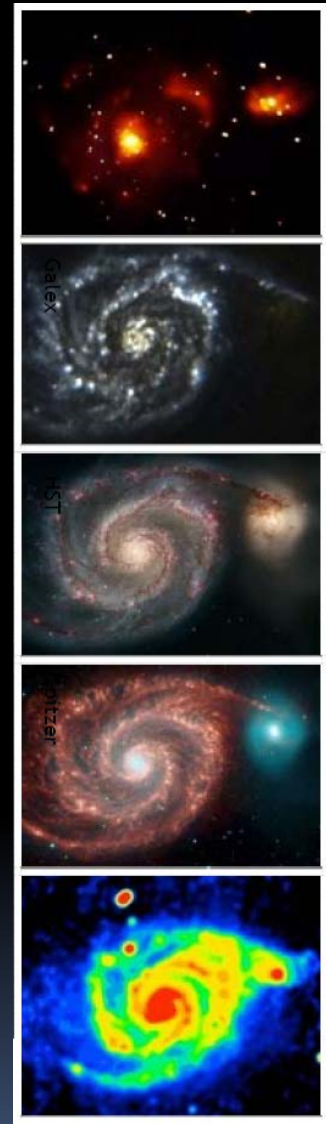
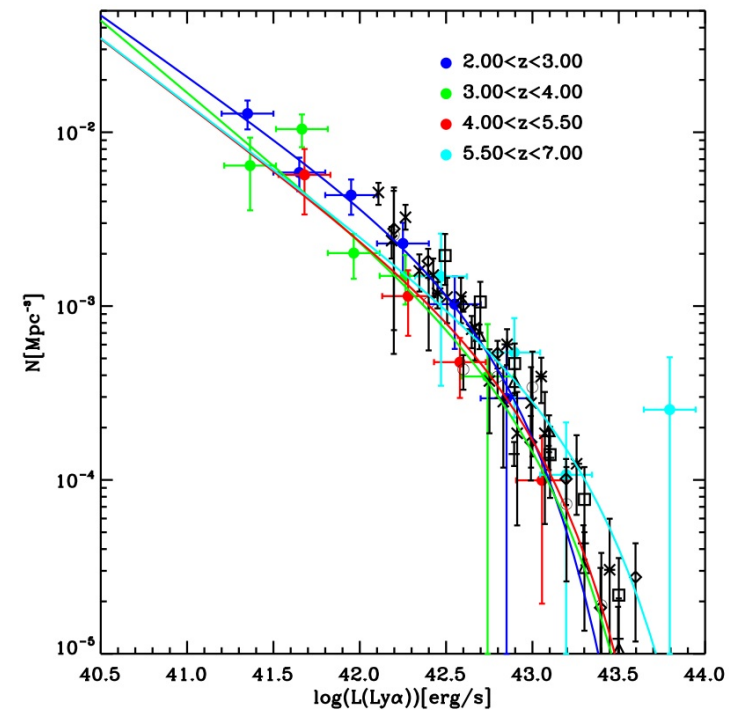
Cucciati et al., [arXiv:1109.1005](https://arxiv.org/abs/1109.1005)

# LF depends on selection function

24 $\mu$ m  
Rodighiero  
et al., 2010

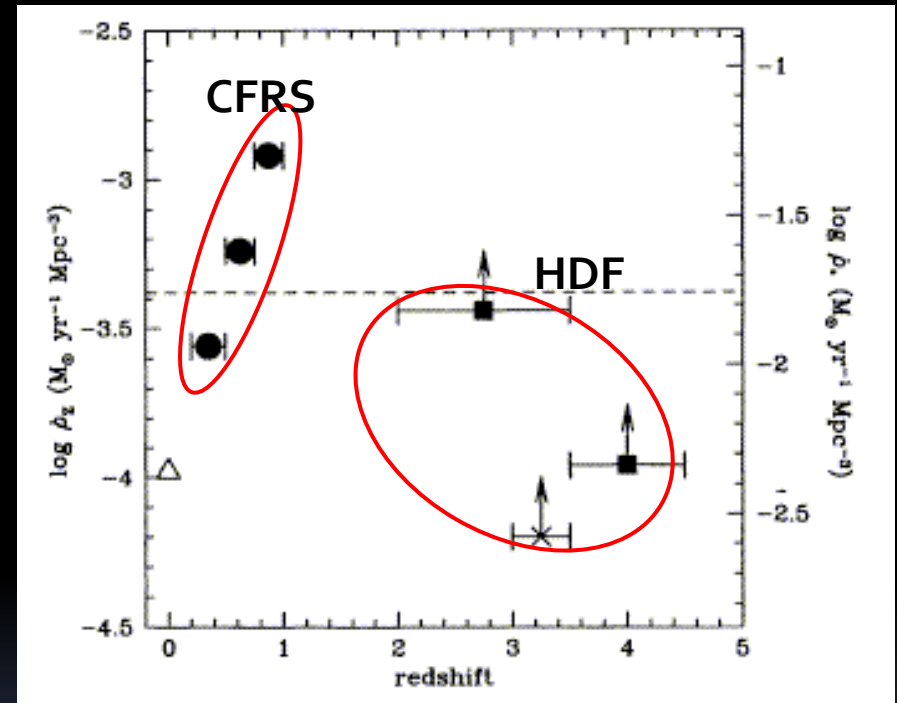


Lyman- $\alpha$  flux  
Cassata et al., 2011



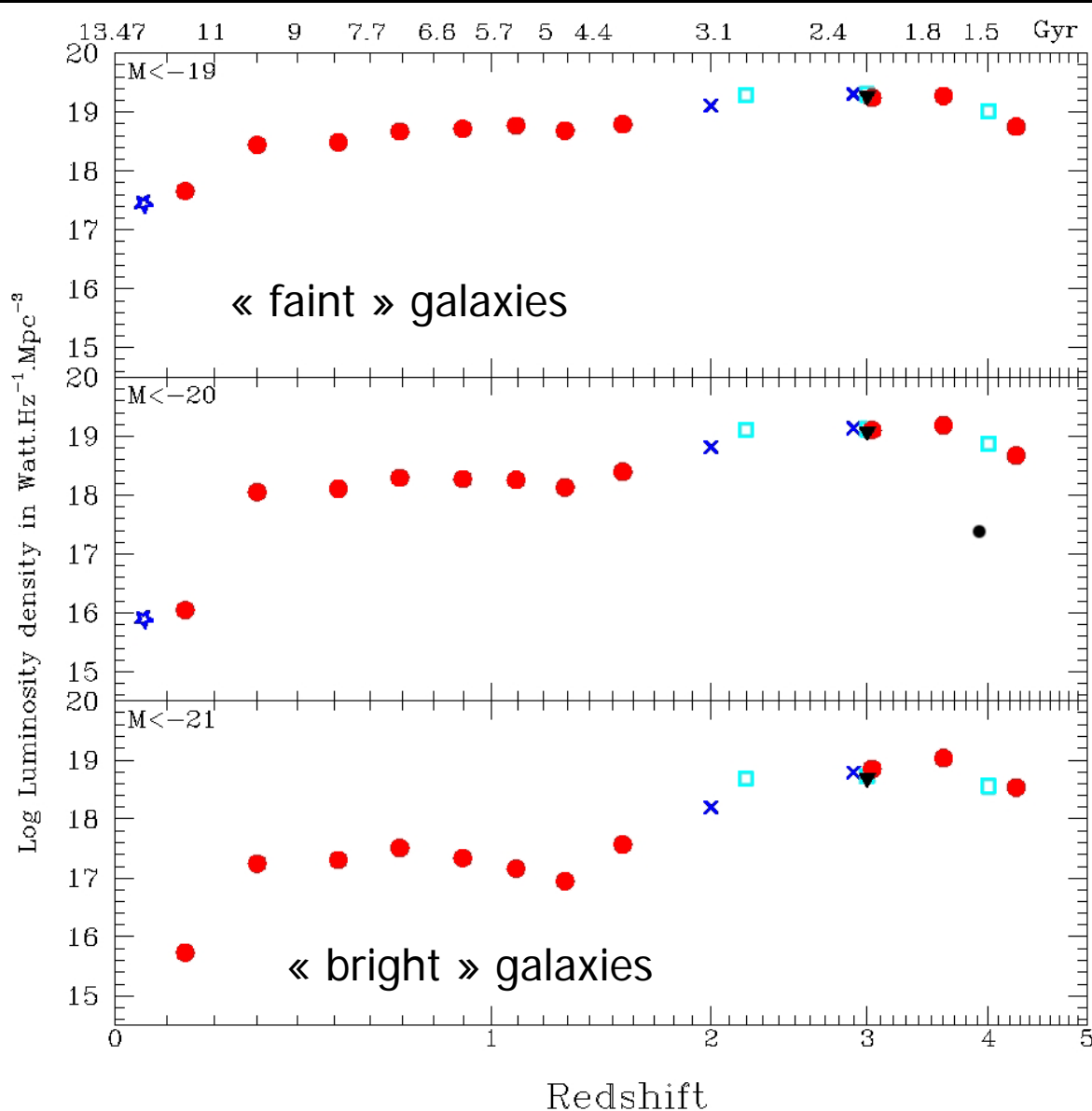
# SFH: Star Formation History

- A key evolution indicator
- Compute luminosity density  $LD = \int \phi(L) dL$  from LF and transform luminosity density into star formation
  - Uncertainties linked to dust attenuation and Initial Mass Function
- Full history? Contribution of different populations?



Madau diagram (Madau, 1996)

# FUV global luminosity density since $z=4$



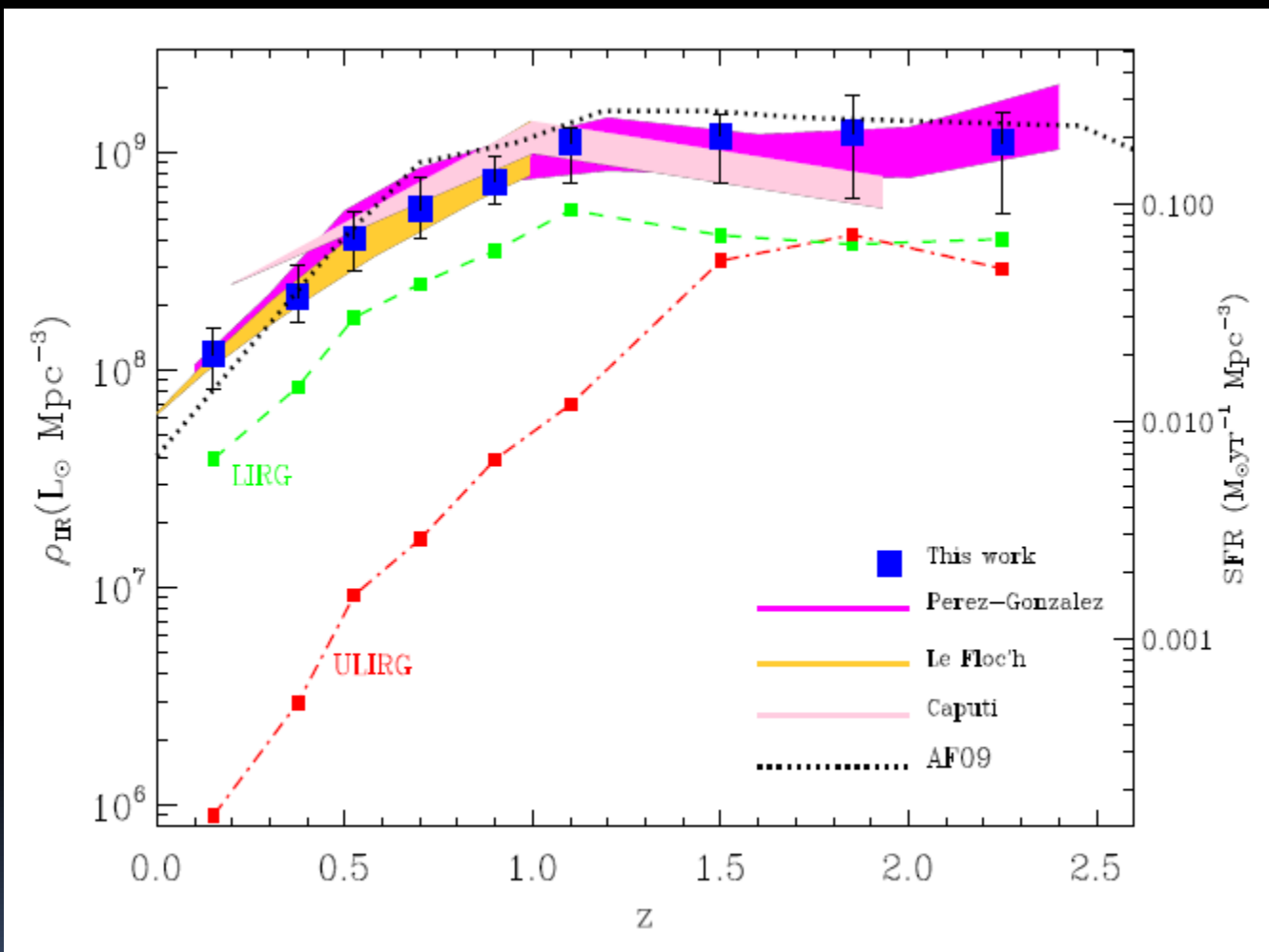
Downsizing :

Luminous galaxies form most of their stars early

Faint galaxies contain more star formation at low  $z$

Downsizing trends observed from various indicators

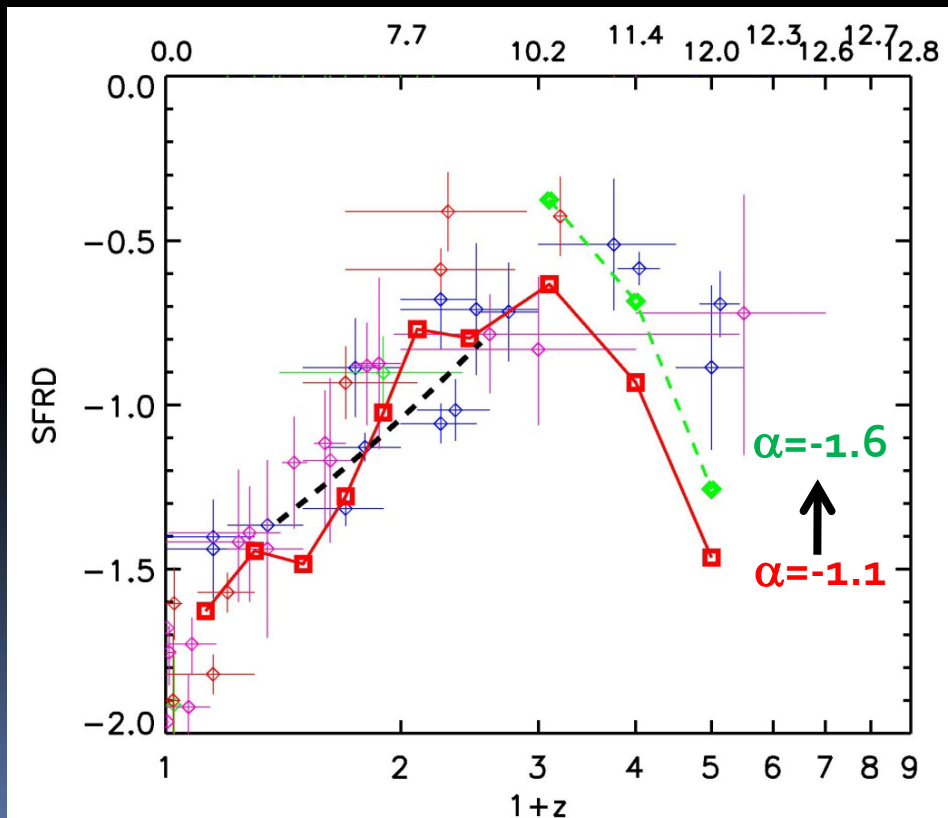
*Tresse et al., 2007*



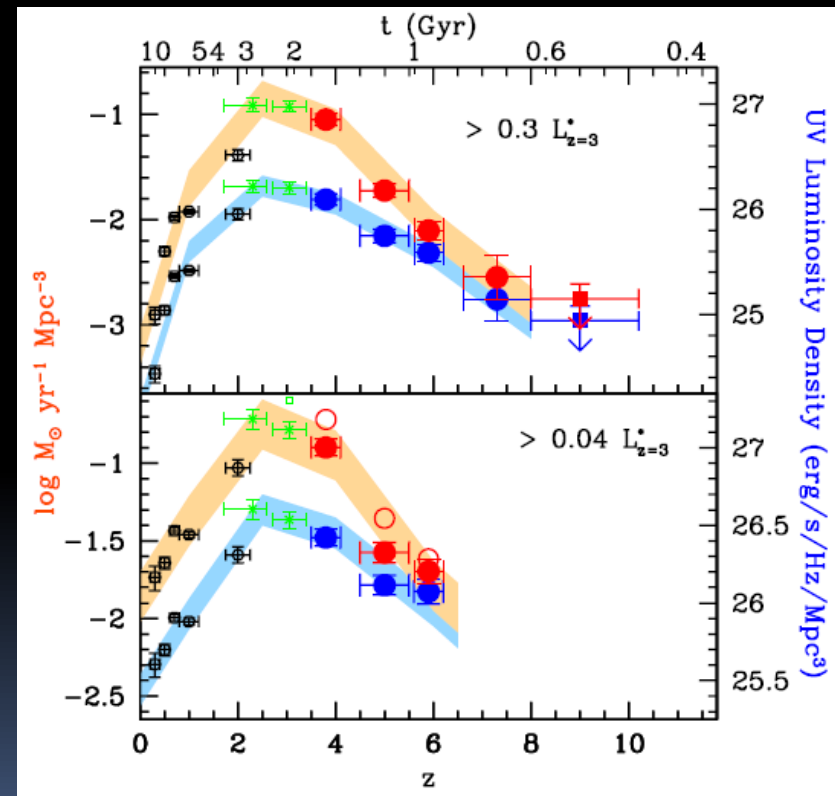
Evolution of the IR luminosity density (Rodighiero et al., 2010)

# Evolution of the SFRD

- Several key epochs:
  - $0 < z < 1$ : rise by a factor  $\sim 10$
  - $1 < z < 2.5$ : plateau
  - $z > 2.5$ : decrease ?
- Main uncertainty: slope  $\alpha$



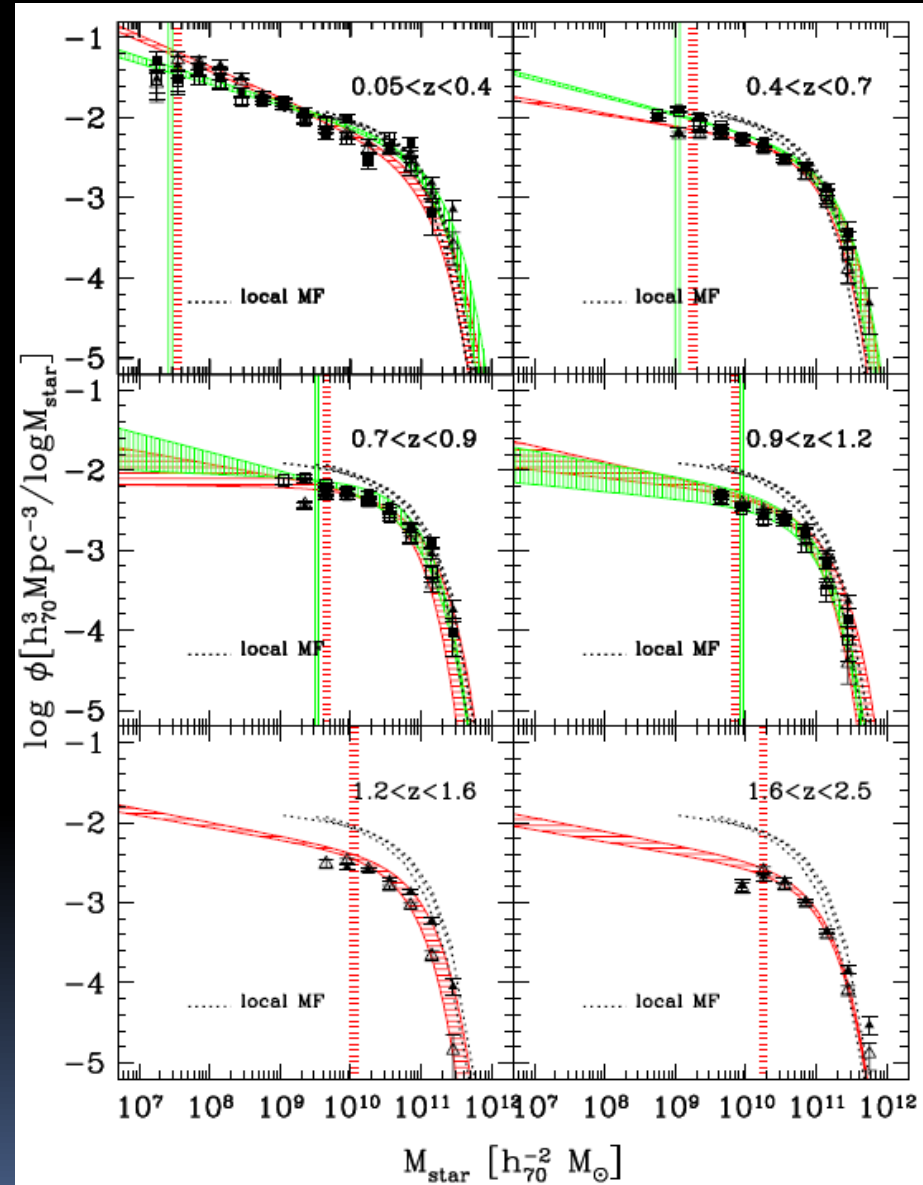
Bouwens et al., 2009



Cucciati et al., [arXiv:1109.1005](https://arxiv.org/abs/1109.1005).

# Evolution of the stellar mass function

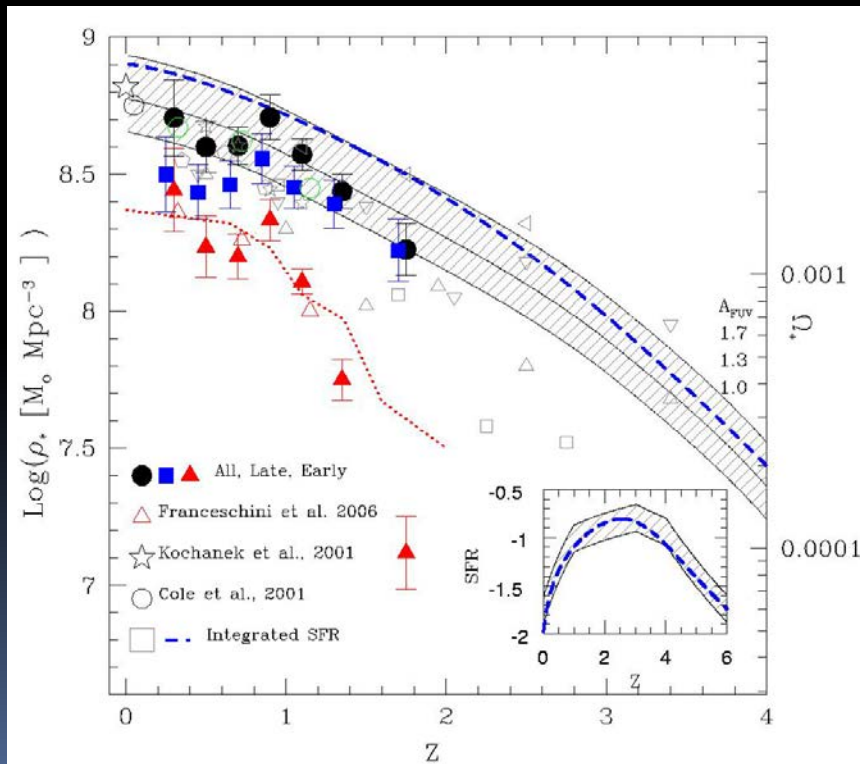
- Stellar mass of a galaxy computed from SED fitting using templates
  - Large uncertainties
- Massive galaxies in place at  $z \sim 1$
- Evolution at the low mass end



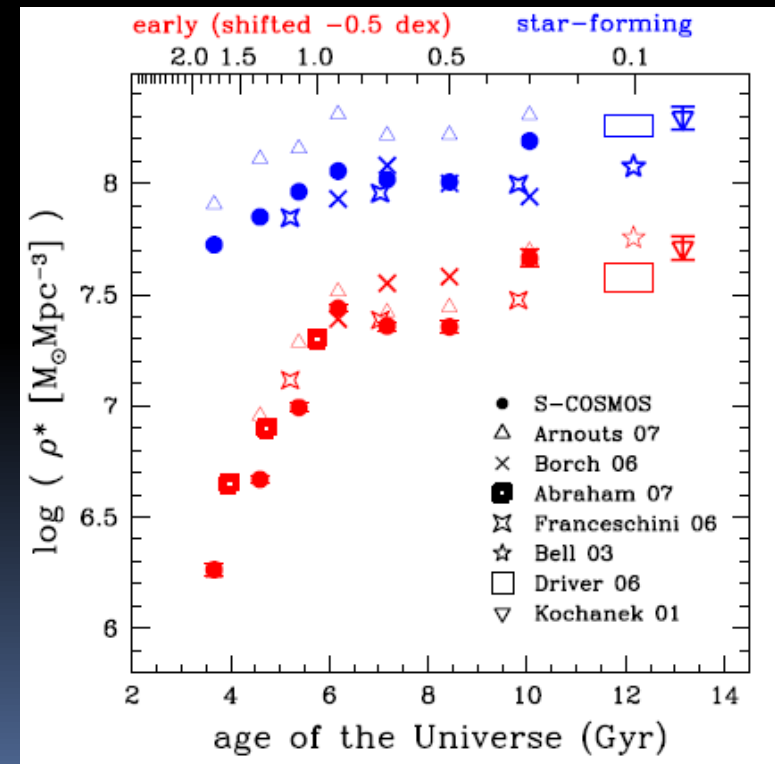
Pozzetti et al., 2007

# Stellar mass assembly history

- Stellar mass density  $\rho_* = \int_{10^3}^{10^{13}} \phi(M) dM$
- Fast rise of the stellar mass density for early type / red in  $1 < z < 2$ : the epoch of elliptical galaxies formation
- Continuous increase of stellar mass in star forming galaxies



VVDS, Arnouts et al., 2007

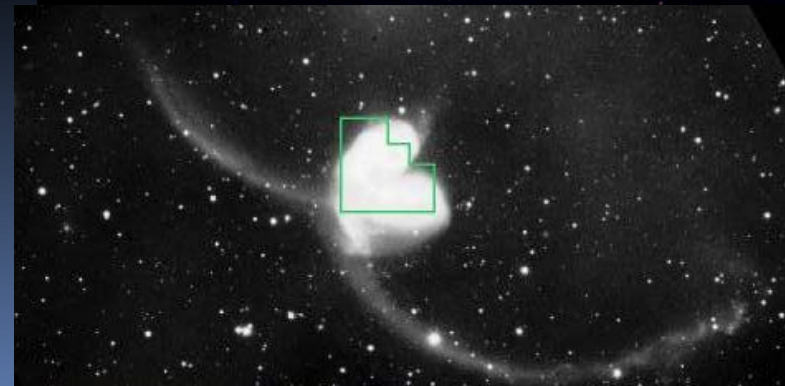


COSMOS, Ilbert et al. 2010 31

# GMRH: Galaxy Merger rate history

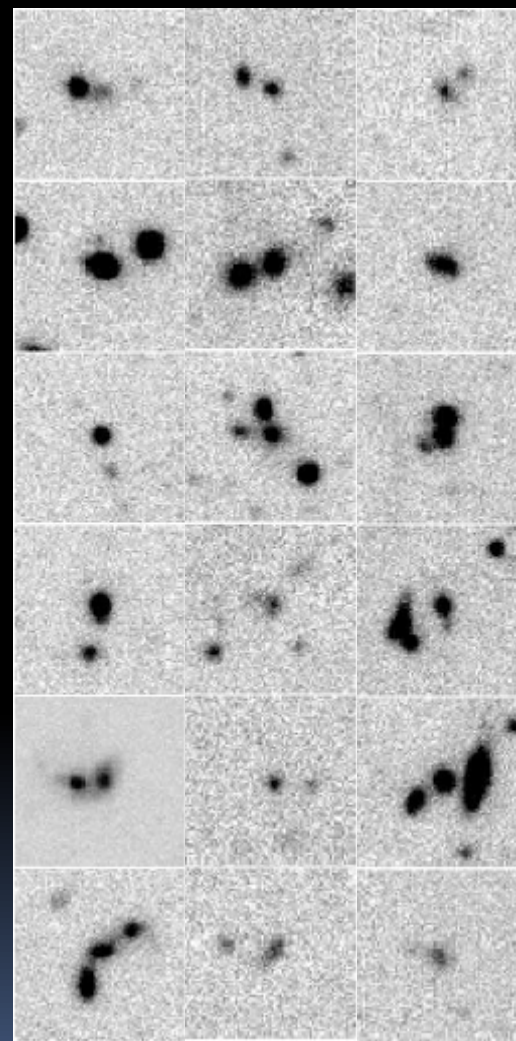
- How many mergers along cosmic time ?
  - Major
  - Minor
- What is the contribution of mergers to mass assembly ?

Simple questions, but not so easy to answer



# Measuring the evolution of the galaxy merger rate

- Method 1, A priori:  
**pairs of galaxies**
- Method 2, A posteriori:  
**merger remnants, shapes**
- Both methods require a *timescale*
  - Timescale for the pair to merge (vs. mass and separation)
  - Timescale for features visibility (vs. redshift, type of feature...)
- At high redshifts  $z > 1$ : pairs
  - Faint tails/wisps lost to  $(1+z)^4$  surface brightness dimming

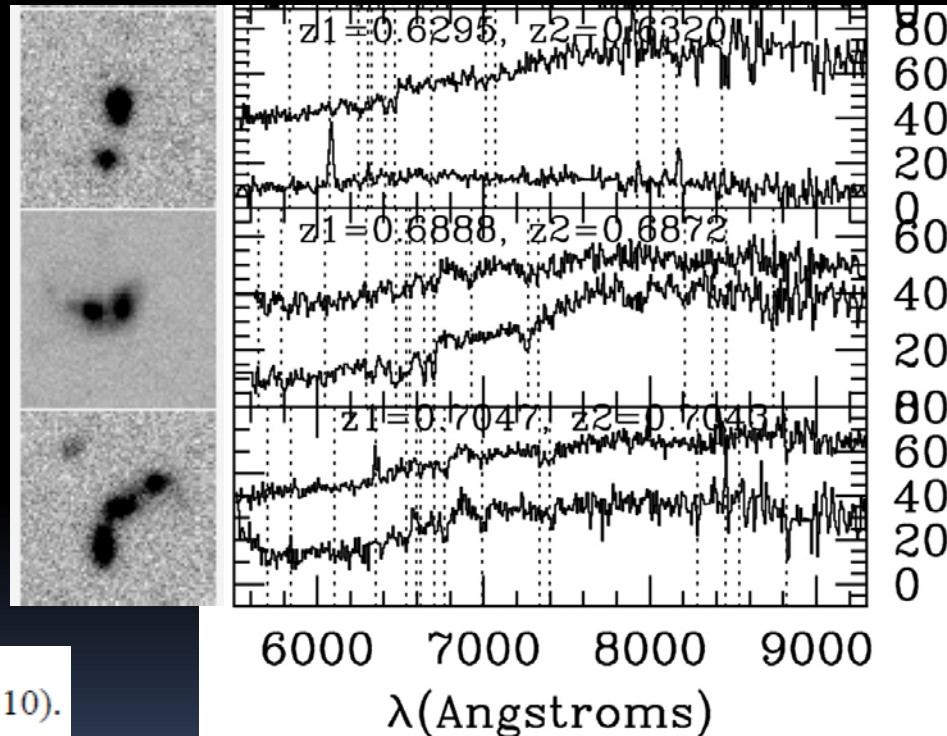


# Merging rate from pair count

- Spectroscopy to confirm physical (rather than projected) pairs
  - Major (ratio > 1/4), and minor (ratio < 1/4) mergers

$$N_{mg}(z) = C_{mg} \times \frac{(N_P^{corr} - N_{triplets}^{corr})}{N_g^{corr}} \times n(z) \times T_{mg}^{-1}$$

$$T_{mg}^{-1/2} = T_0(r_p^{max})^{-1/2} + f_1(r_p^{max}) \times z + f_2(r_p^{max}) \times (\log M_* - 10).$$



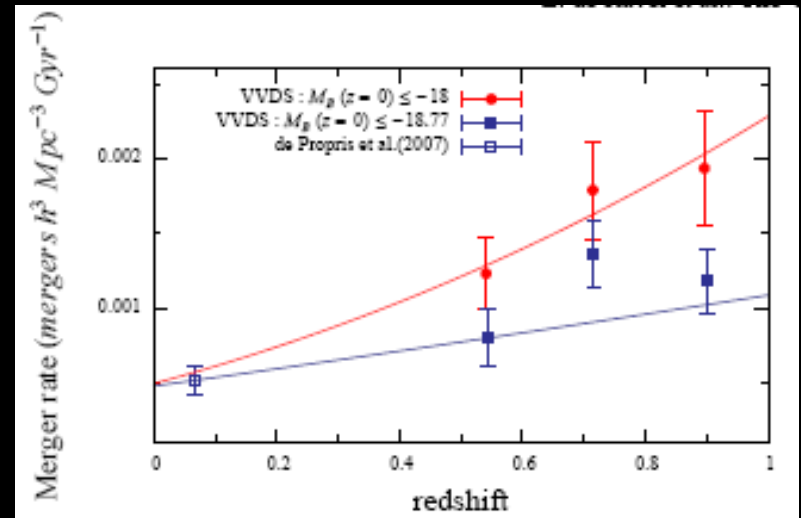
De Ravel et al., 2009  
Kitzbichler et al., 2008

Spectroscopy to avoid  
projection effects

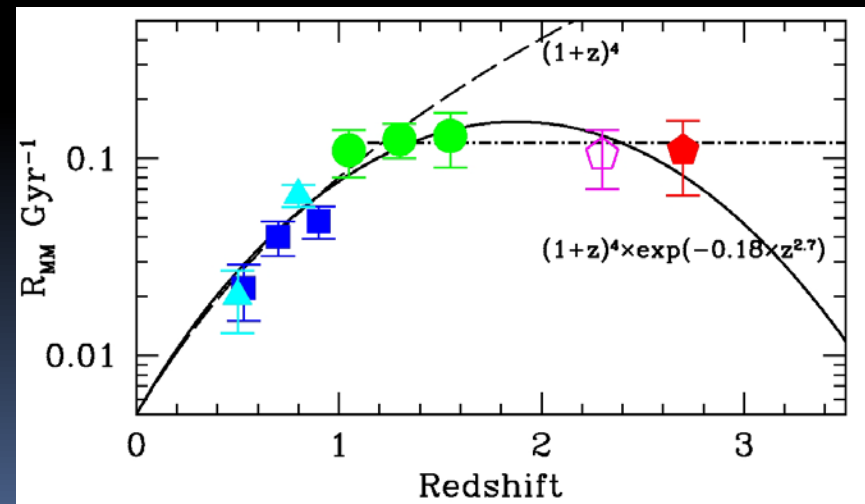
# GMRH: galaxy merger rate history

- Merger rate depends on mass / luminosity
- Peak in GMR at  $z \sim 1.5$
- The mass in galaxies with  $L_B \geq L_B^*$  has increase by 25% since  $z \sim 1$  by mergers (1/4 mineur, 3/4 majeur)
- Mass increase by major mergers more important for early types (40%) than for late-types (20%)

*Mergers are an important contributor to mass assembly*

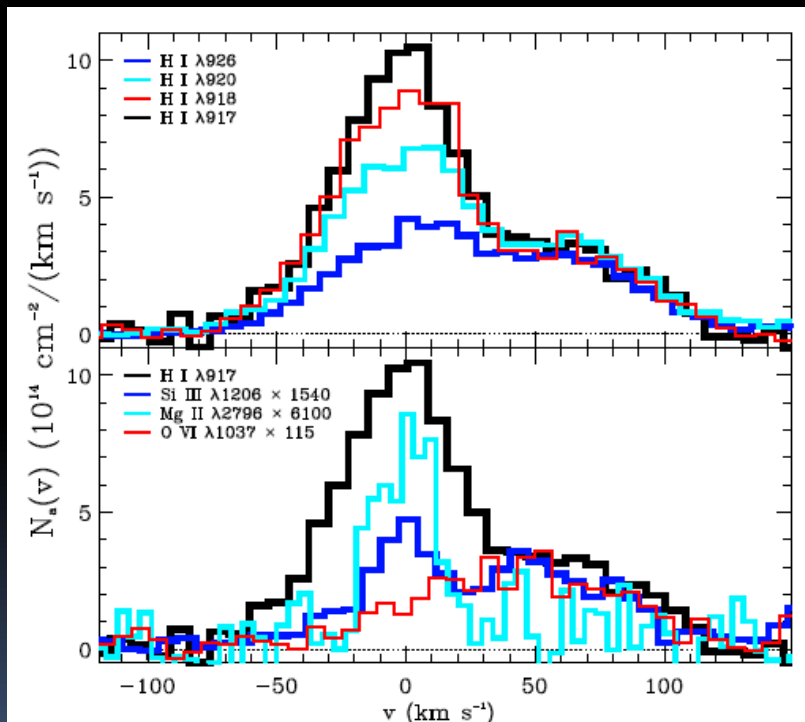


Major mergers, de Ravel et al. 2009

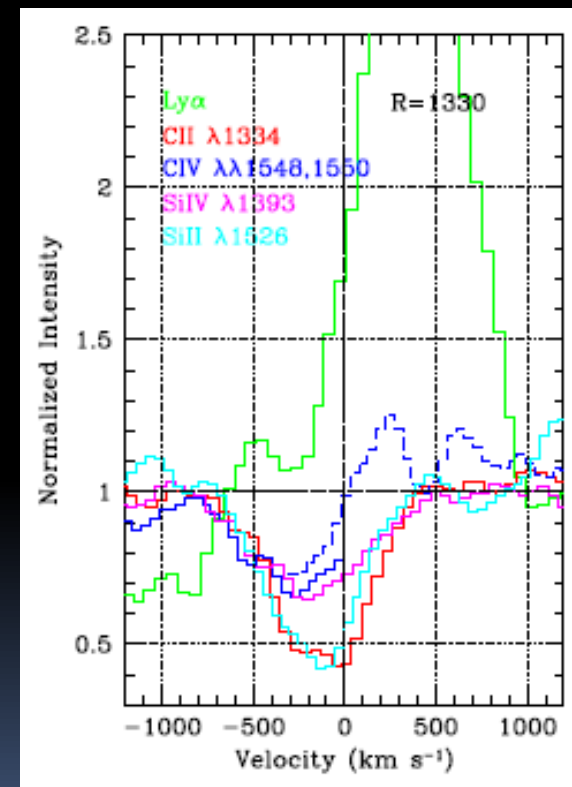


# Evidence for cold gas accretion ?

- Direct evidence for accretion at low-z, not yet at high-z
- Evidence for feedback



Infall,  $z=0.27$   
Ribaudo et al., 2011

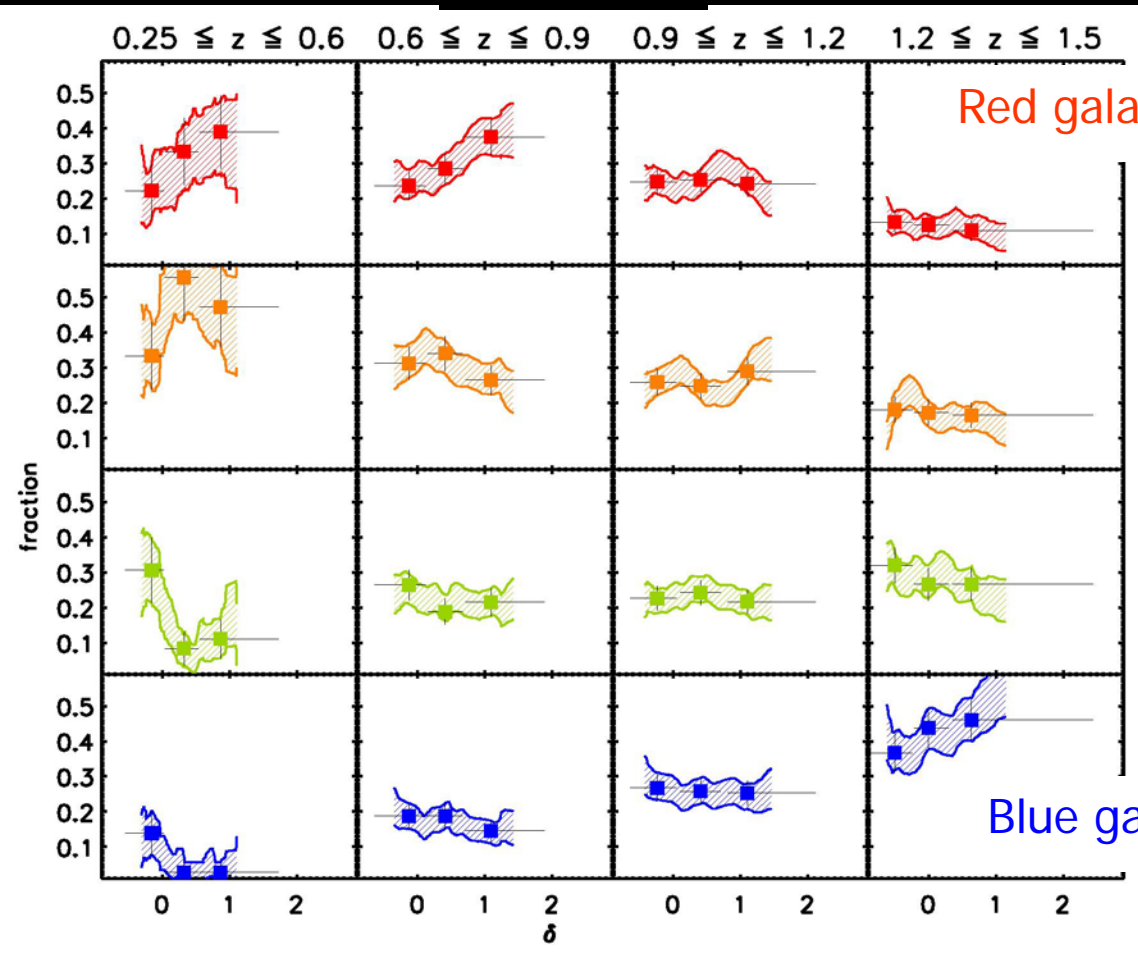


Out-flows,  $z=3$   
Steidel et al., 2011



# the build-up of the Colour-density relation

Redshift



Red galaxies

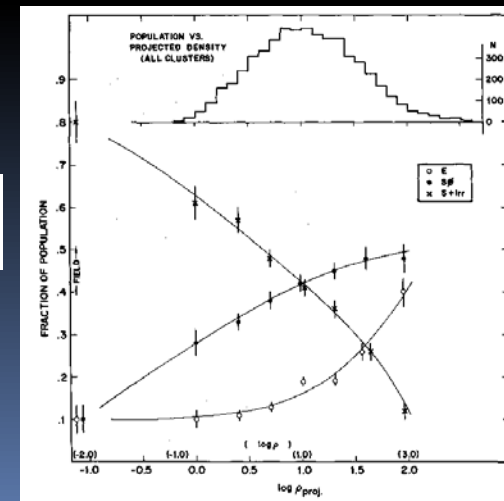
*VVDS: Cucciati et al., 2006*

*DEEP2: Cooper et al., 2006*

*Dressler, 1980*

Blue galaxies

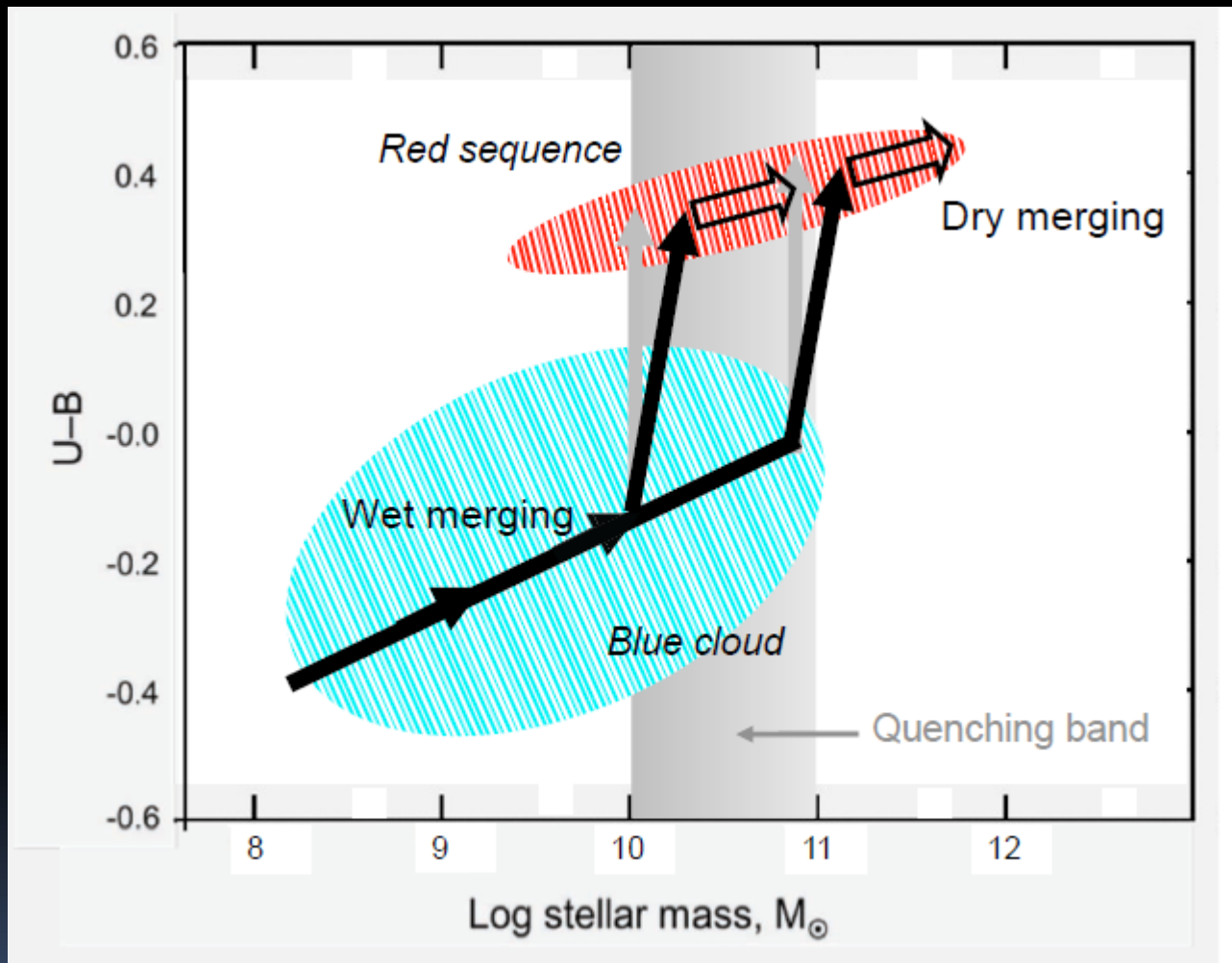
Density contrast





# Building a galaxy evolution scenario ?

- Several key processes have been identified,
  - Direct: mergers, stellar evolution
  - Indirect: accretion, feedback, environment
- Properties have been quantified over  $>12$ Gyr
  - Observational references exist to confront models
- Semi-analytical models
  - Take the DM halo evolution
  - Plug-in the physical description of processes
  - Get simulated galaxy populations
- Semi-successful... some lethal failures
  - Over-production of low-mass/low-z and under-production of high-mass/high-z galaxies
  - Reproducing low-z LF/MF AND high-z LF/MF



Faber et al.

(c) Interaction/"Merger"



- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

(b) "Small Group"



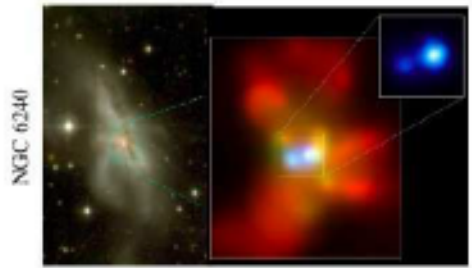
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- $M_{halo}$  still similar to before: dynamical friction merges the subhalos efficiently

(a) Isolated Disk



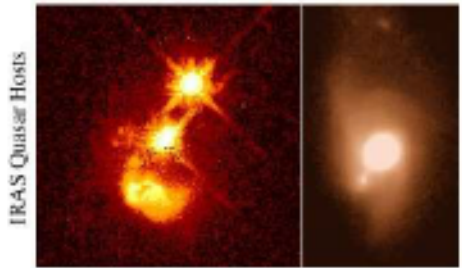
- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with  $M_{\bullet} > 23$ )
- cannot redden to the red sequence

(d) Coalescence/(U)LIRG



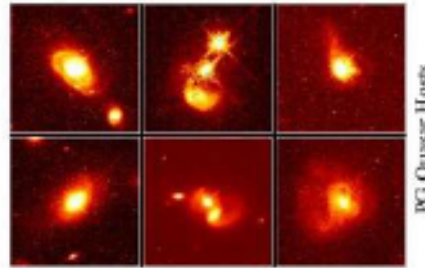
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small

(e) "Blowout"



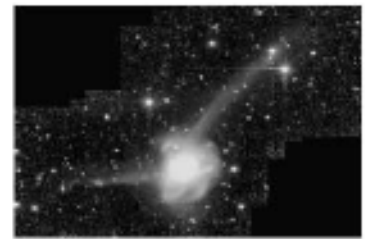
- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host
- high Eddington ratios
- merger signatures still visible

(f) Quasar



- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid

(g) Decay/K+A

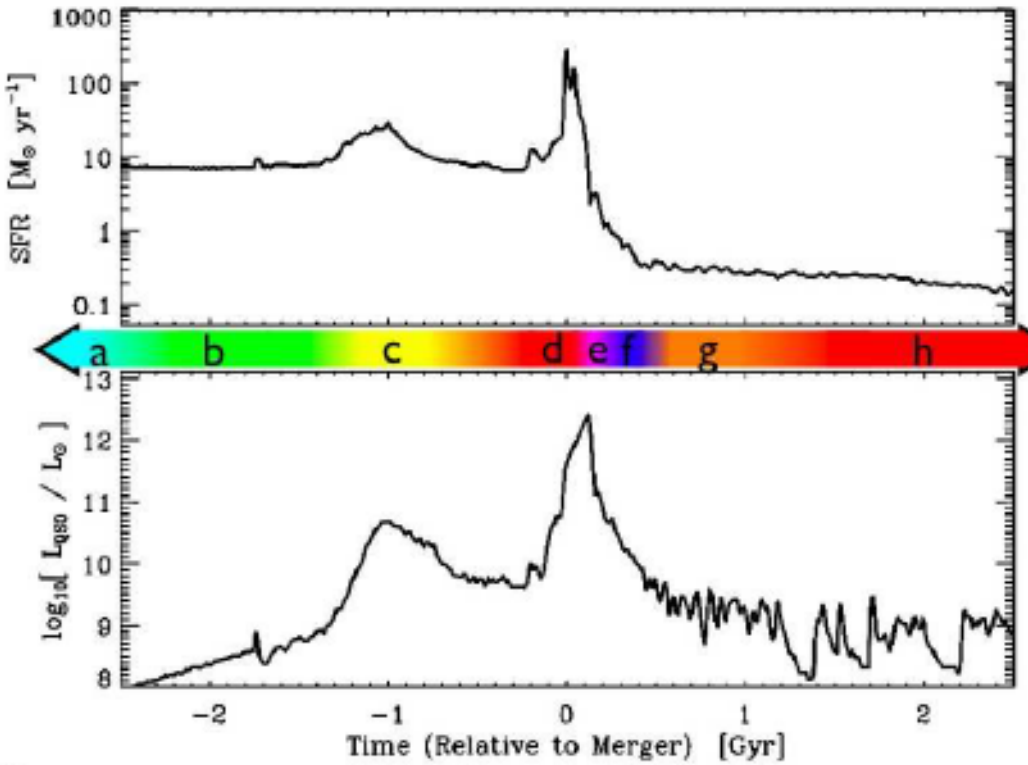


- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant reddens rapidly (E+A/K+A)
- "hot halo" from feedback
- sets up quasi-static cooling

(h) "Dead" Elliptical



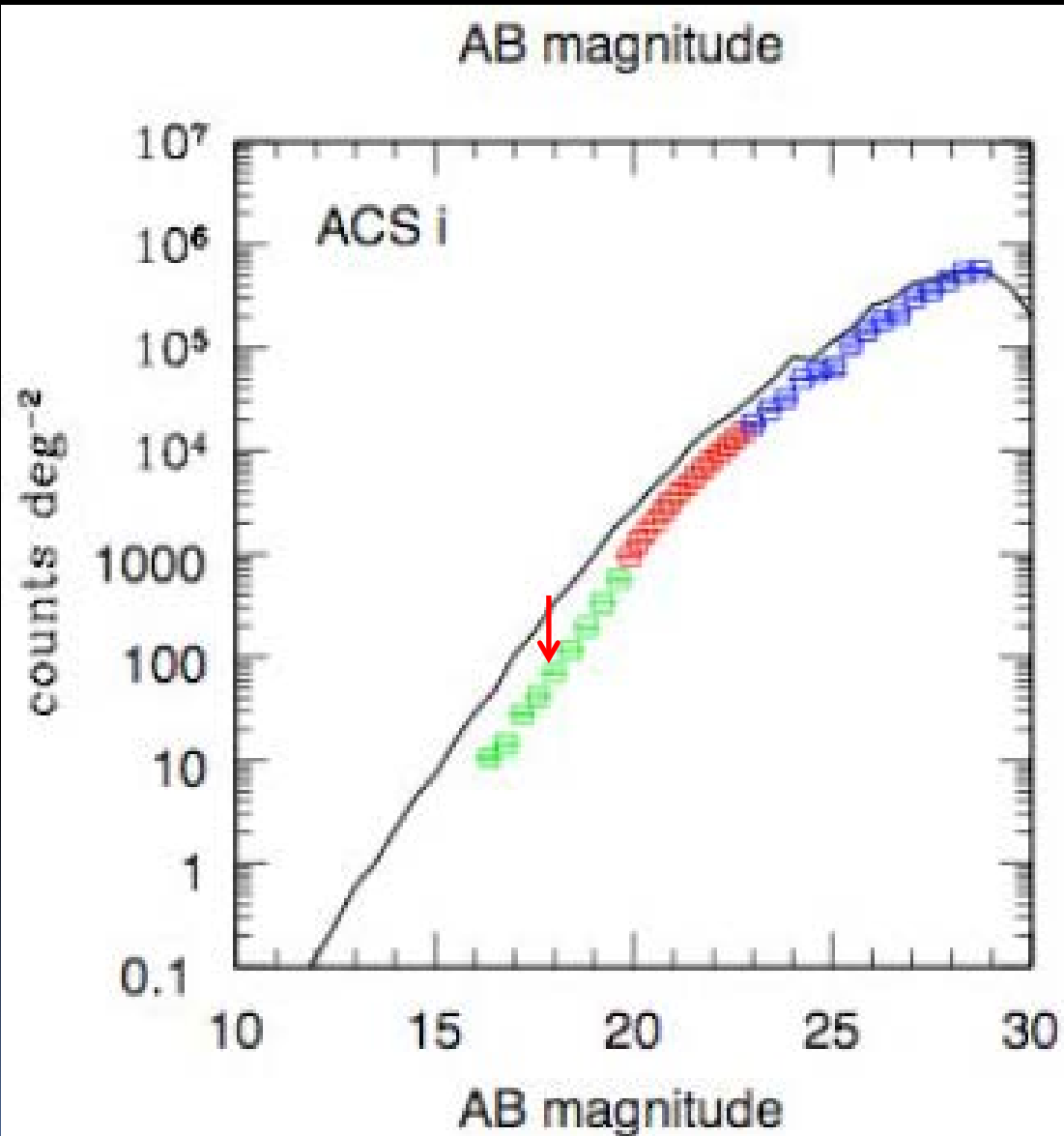
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers



Beware of the details in models comparison to observations...

Log plots: missing factors of 2-5 on galaxy i-band counts at  $15 < AB < 20$  !

“no name” example



# Galaxy evolution since $z \sim 4$

## *Summary*

- The statistical properties of galaxies are well measured ( $\sim 10-20\%$ ) up to  $z \sim 1.5$
- They are reasonably constrained to  $z \sim 4-5$  ( $\sim \times 2$ ) but significant uncertainties remain on census of star formation and mass assembly
  - Larger samples in larger volumes
  - Multi-wavelength (UV vs. IR)
  - Fainter samples: faint end – low mass of LF/MF
- The relative effects of physical processes vs. cosmic time remain to be quantified
  - For different galaxy types
- Need a comprehensive approach to compare models and observations, towards a robust scenario for galaxy evolution