Starting Point: the present-day galaxy population

- Different properties of individual galaxies are strongly correlated
  - formerly known as the 'Hubble sequence'
  - M_*, L, M/L, t_{age}, SFR, size, shape, [Fe/H], σ, v_{circ}

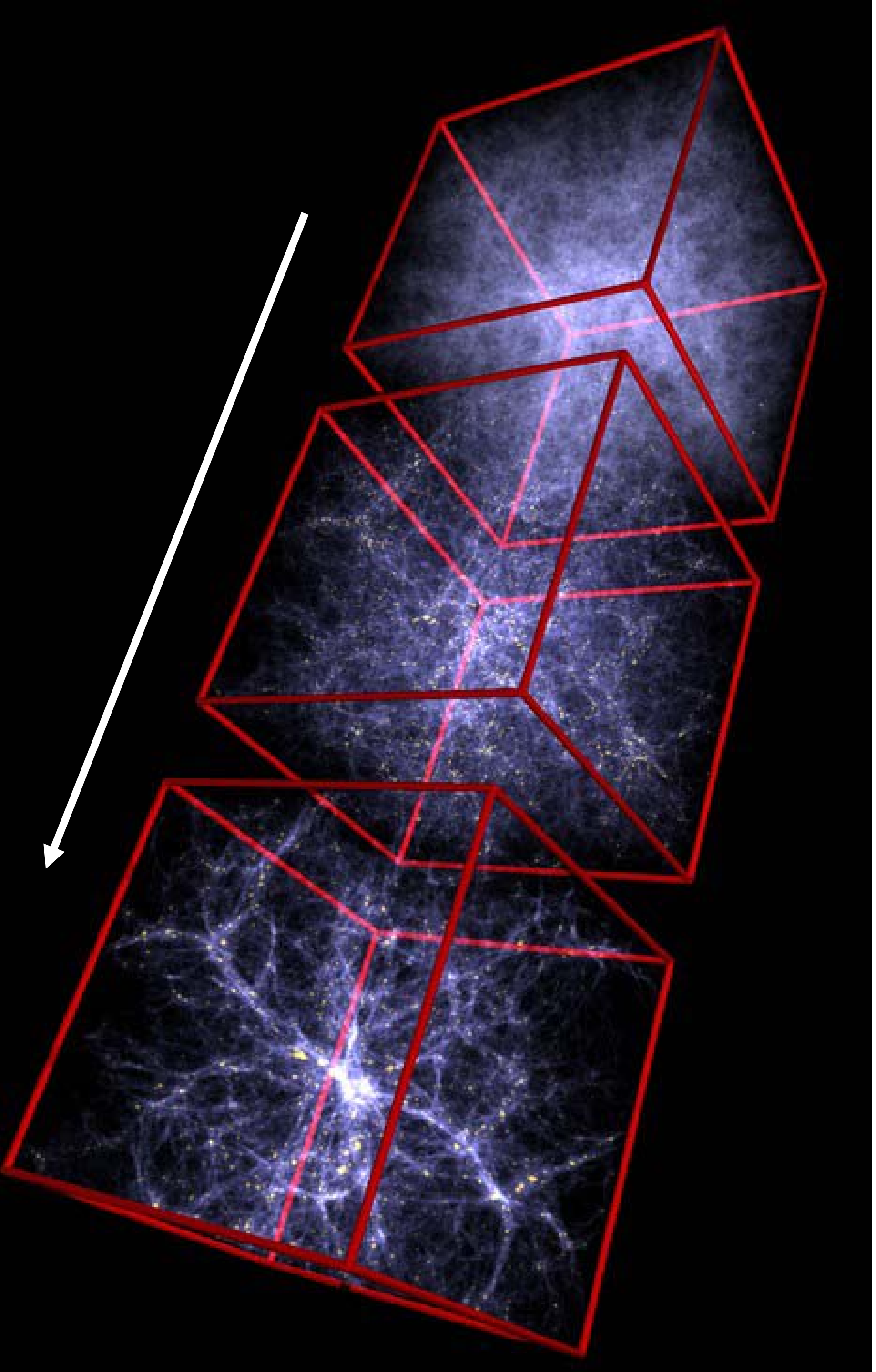
- 'Mass' is the decisive parameter in setting properties
  - M_* or M_{halo}
  - Most stars live in massive galaxies ($10^{10.5}$ M_o)
    - Most massive galaxies don't form stars anymore ('early types')
  - 1000 M_0 < M_* (galaxy) < 10^{12} M_0

- Galaxies and the DM Cosmogony
  - can match galaxies ← → halos by abundance or clustering

    → vastly different efficiencies in turning baryons into stars, peaking at M_{halo} ~ $10^{11.5} M_o$
  - LCDM: massive halos (+ galaxies) preferentially found in dense & early-collapsed regions.

Exploring Galaxy Evolution: Approaches

- **How did the present-day galaxy population come into being?**
- Evolution of galaxies is not observable!
- Evolution of population properties **is** observable.
- **Experiment:** Look-back observations (high redshift)
  - Fine enough time/redshift-resolution to see gradual population changes
- **Modelling:** how well can galaxy population properties be explained by:
  - Initial conditions: density fluctuations and cosmological params.
  - Non-linear (hydro-) dynamical simulations + sub-grid-physics



Why detailed empirical data are needed

Good ab-initio cosmological models exist, describing:

- Initial fluctuation spectrum
- Ω, Λ, Ω_b, H_0
- Growth of structure

But the baryonic component is iffy

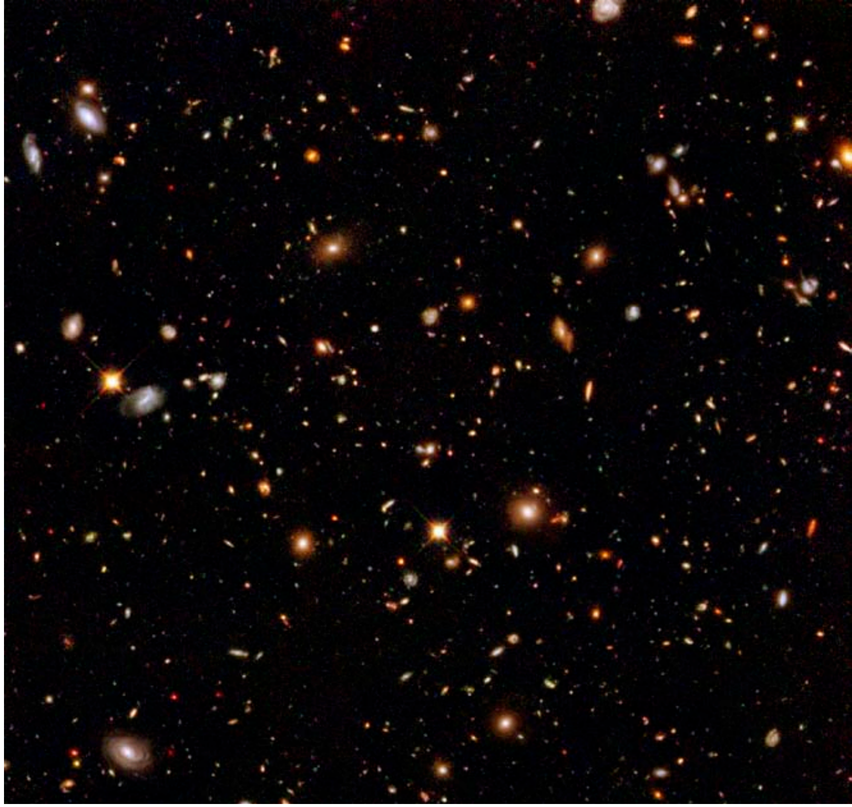
- sets observable galaxy properties
- physics on 1 M_o and 10^{11} M_o strongly coupled
- models barely getting good at 'post-diction'

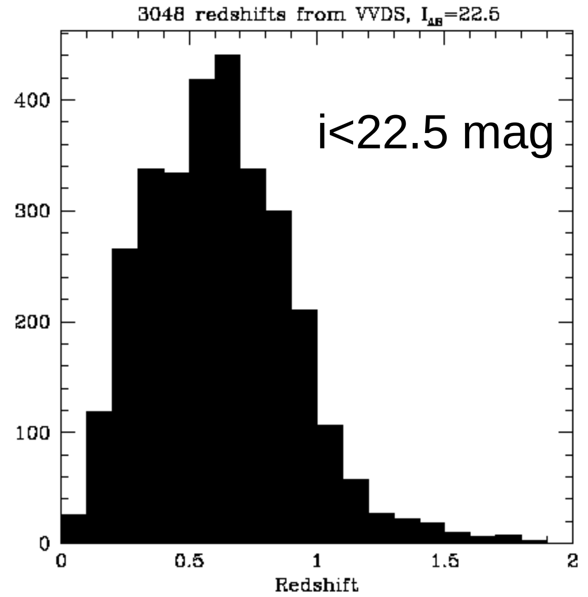
z: 49.5

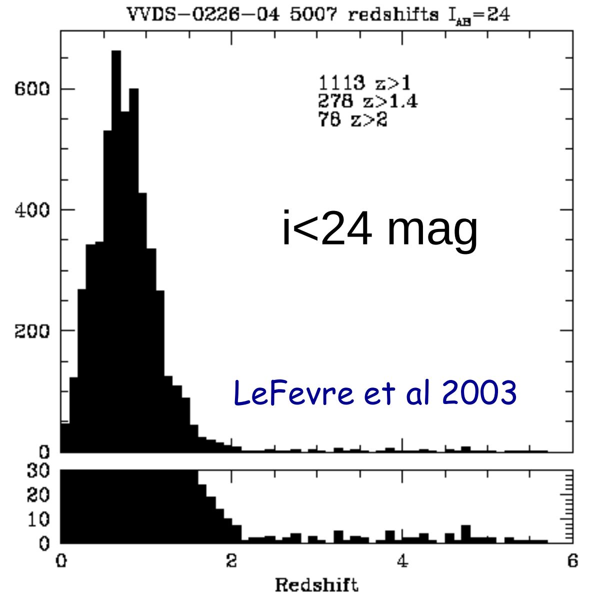
To study galaxies at early epoch (=high redshift), you have to find them first …

- Distant galaxies are faint
  → deep fields (Hubble Deep field, Chandra Deep Field South, …)

- “Foregrounds” dominate
  → Need pre-selection technique

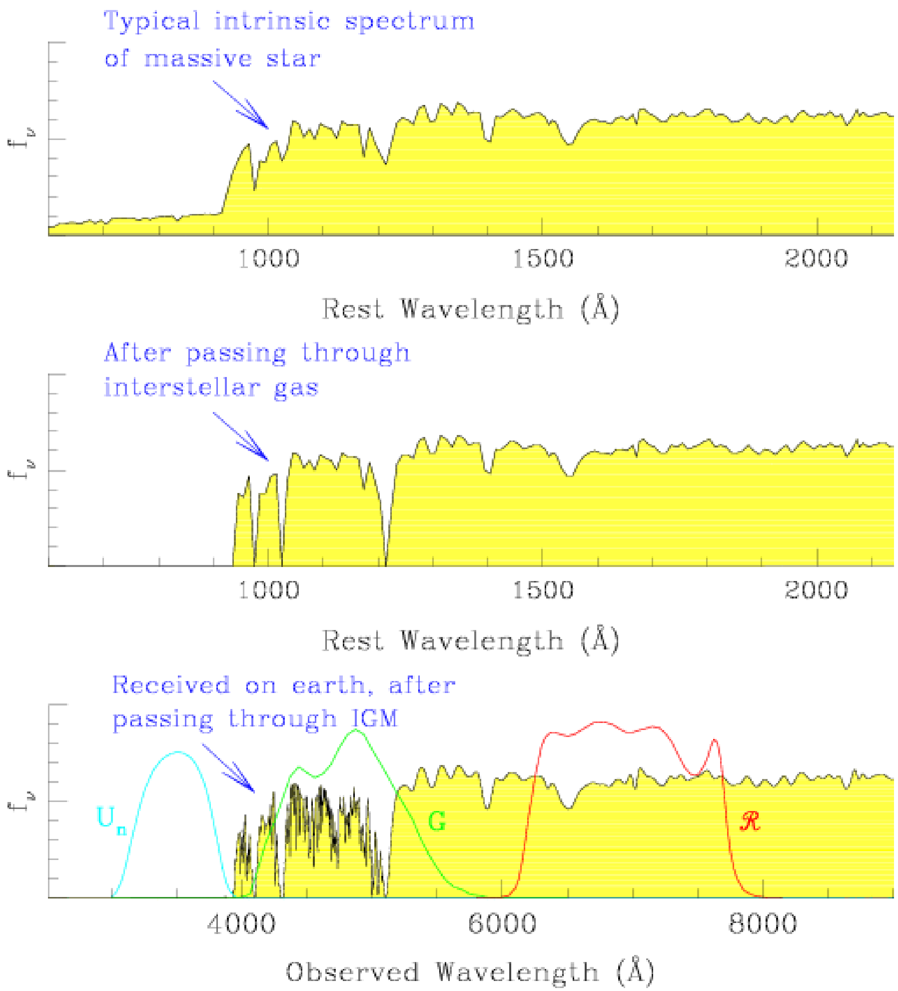


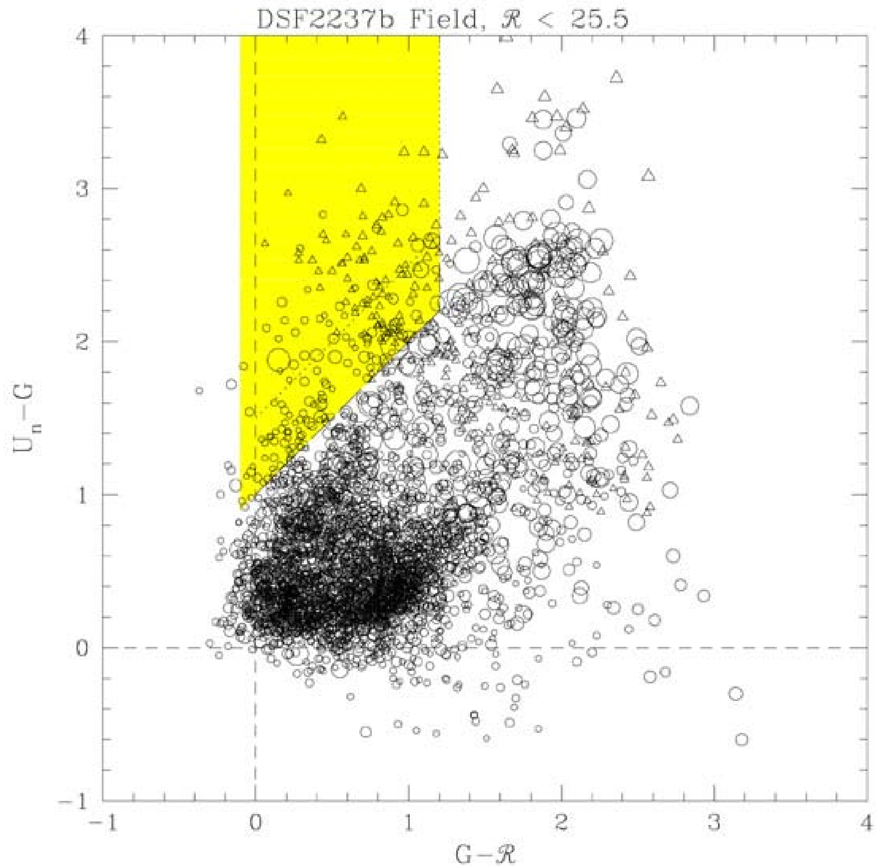




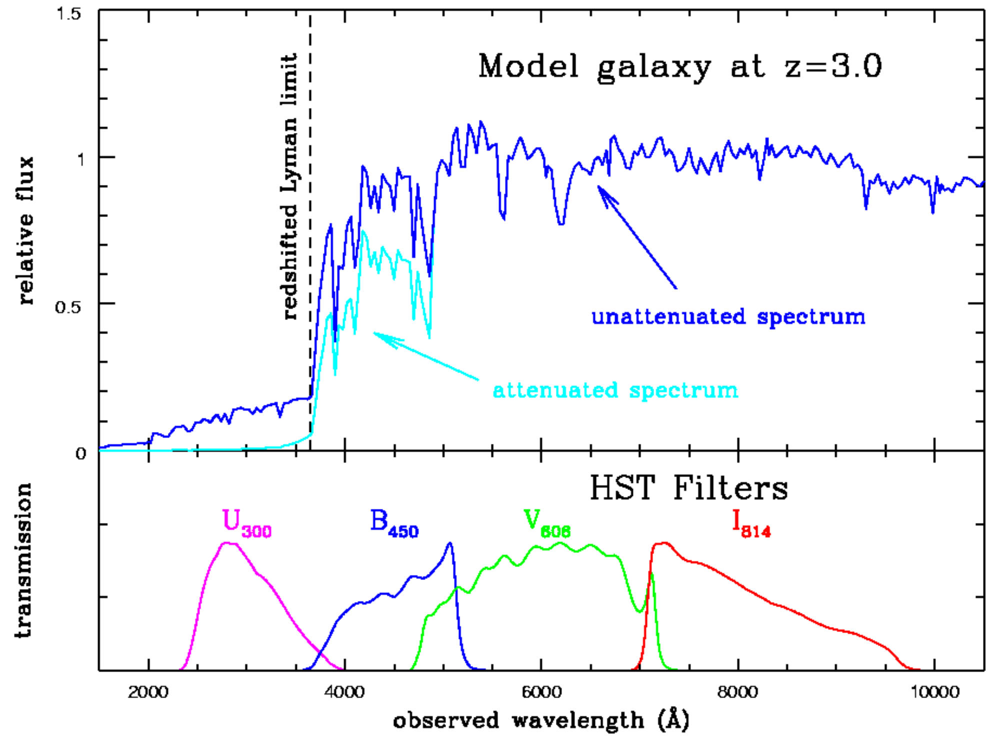
The first steps in finding high-z galaxies

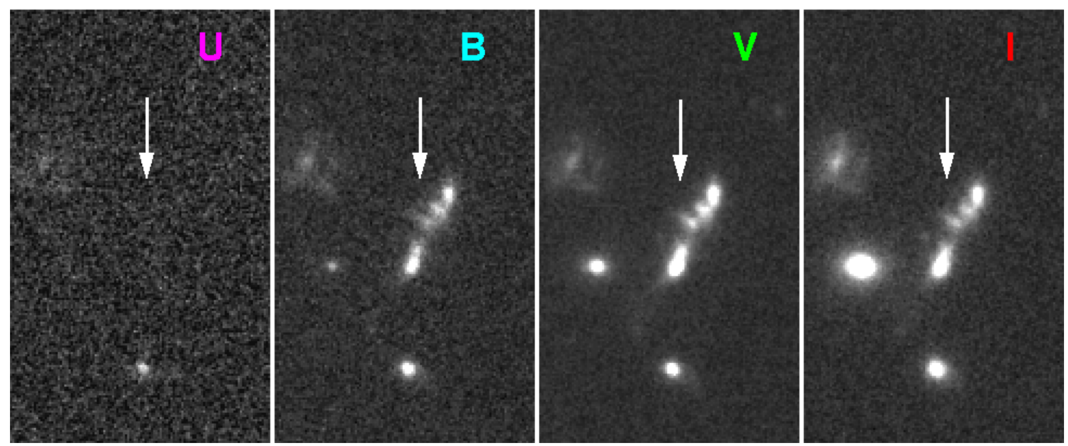
Lyman Break Technique (Steidel 1996)





- Example: what Ly-brak galaxies look like
- In 1996 we knew galaxies to z<0.4 and z>3
- They looked very different!
- How to connect them?





Jerusalem 2004
Hans-Walter Rix - MPIA

Mapping the evolution of the galaxy population over the last half of the Universe's age

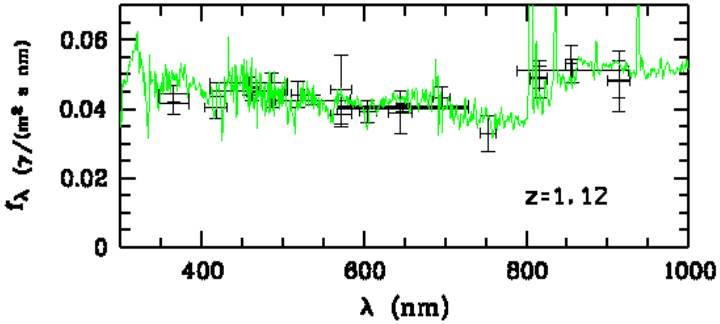
What is needed to map the evolution of the galaxy **population** properties?

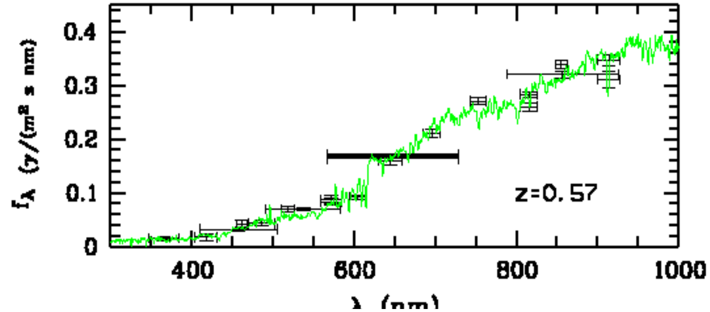
- $>10^4$ galaxies with
  - Redshifts (to 1-2%)
  - Luminosities/stellar masses
  - Spectral energy distributions (=SEDs)
    - → star-formation rates (SFR) and stellar ages?
- field(s) size >> corr. length → proper volume average
- structural/morphological parameters (<<1” resolution)

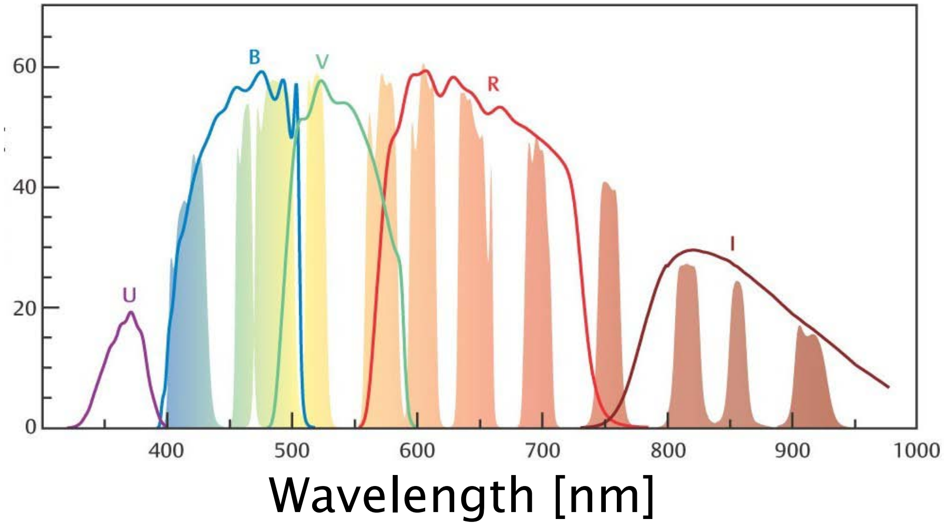
COMBO-17

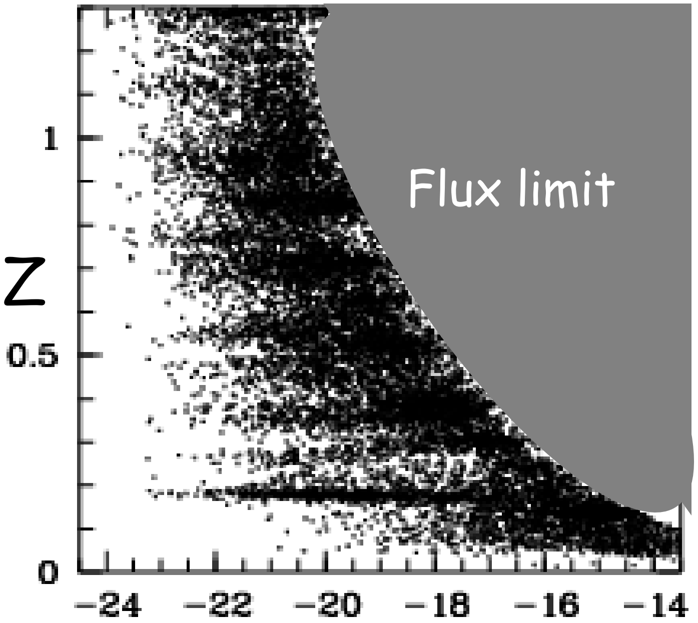
Wolf, Meisenheimer, Rix et al. 02/04

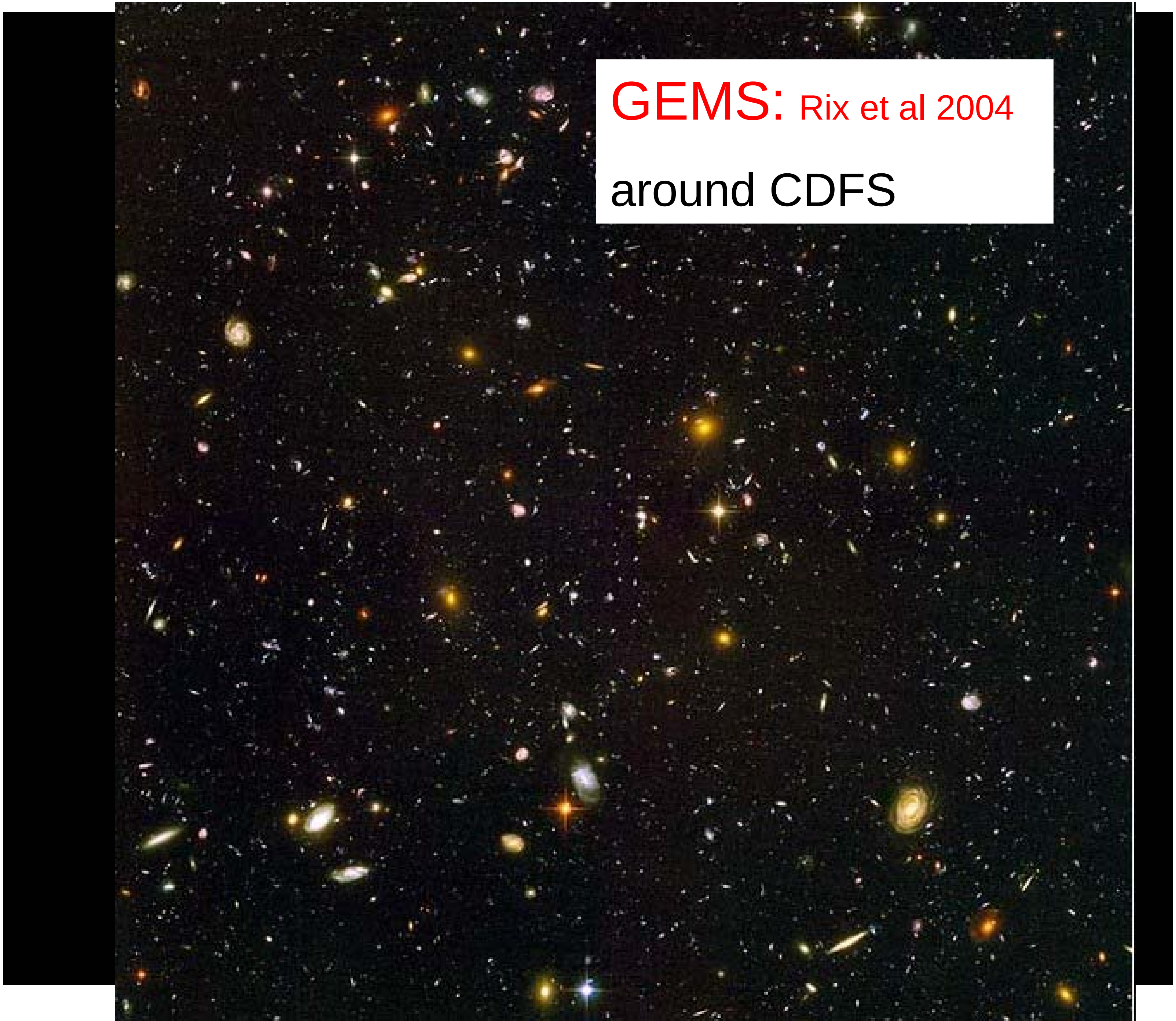
- 3 fields @ 30'x30'
- 17 filters to m_r~23.6
- ~10.000 redshifts + SEDs per field










GEMS: Rix et al 2004
around CDFS

The Galaxy Population 6Gyrs ago

Wolf et al 2003; Bell et al 2004

L_V and rest-frame color

from 3 disjoint COMBO-17 fields

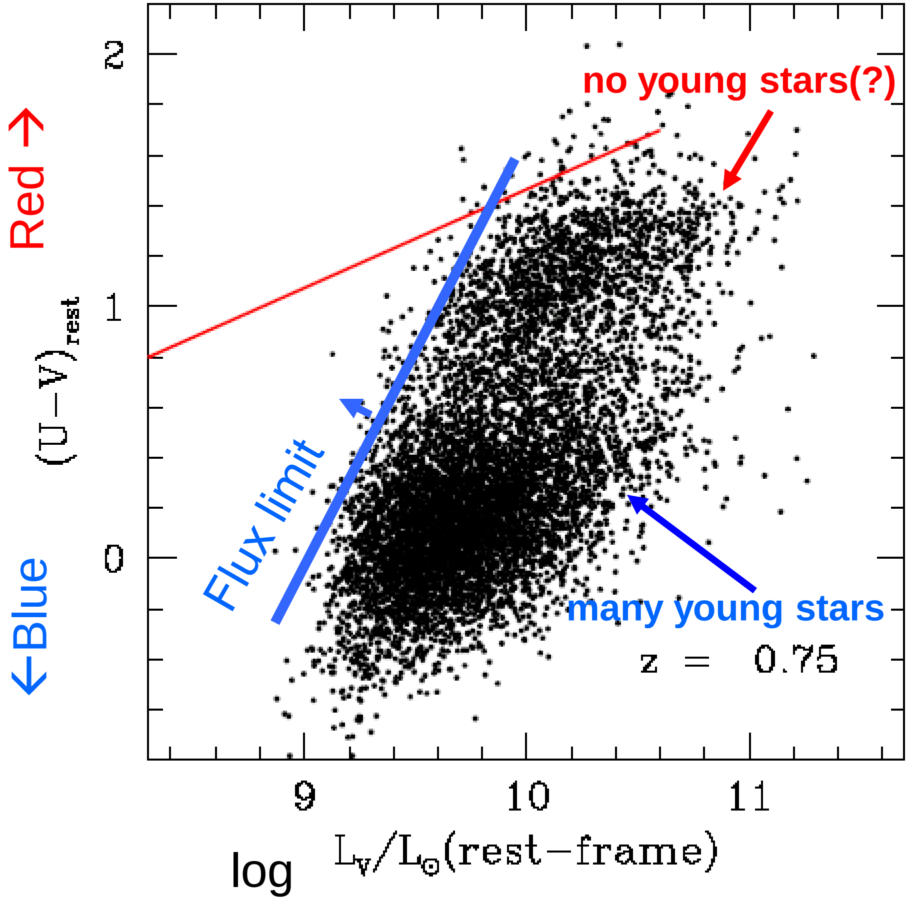
32.000 galaxies to z~1.2

Galaxy color distribution is bi-modal

(as in the local universe; e.g. Strateva et al. 2001)

Note: the red(est) galaxies were not as red as they are at the present epoch, as Δt=6Gyrs

Galaxies in the Luminosity – Color Plane



Galaxy Mass vs Presence of Newly Formed Stars at z~1

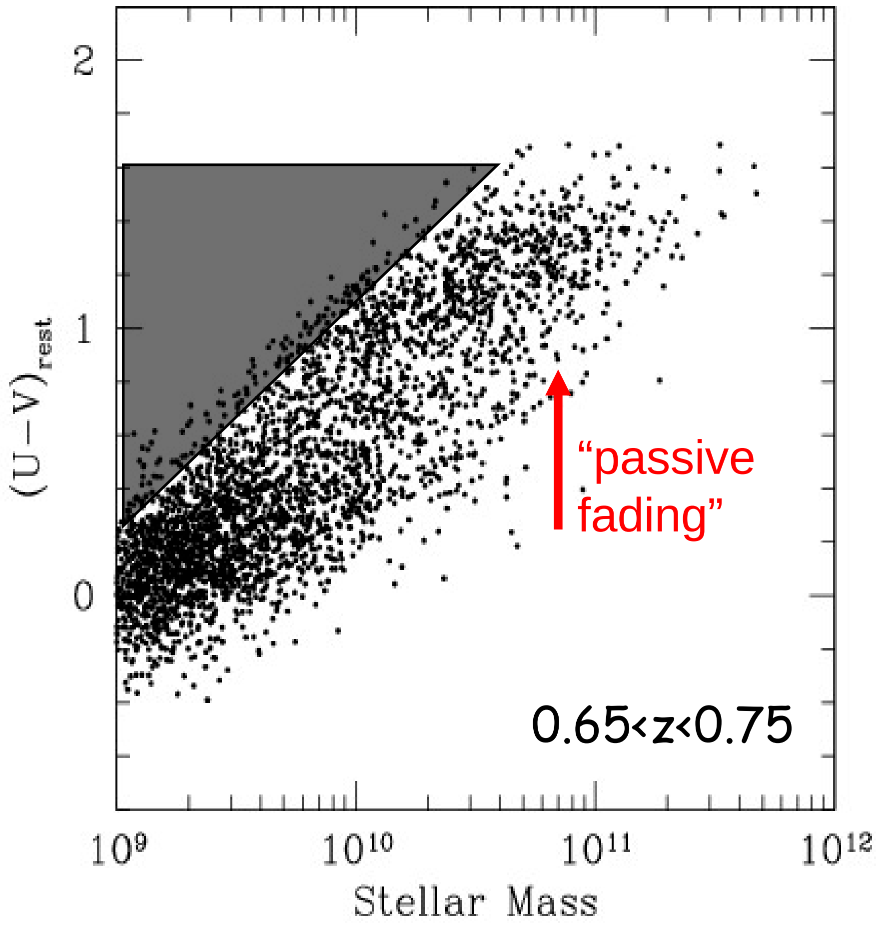
Borch, HWR, et al 2006

- Use SED to estimate the M/L
  - cross-check with dynamical mass estimates OK

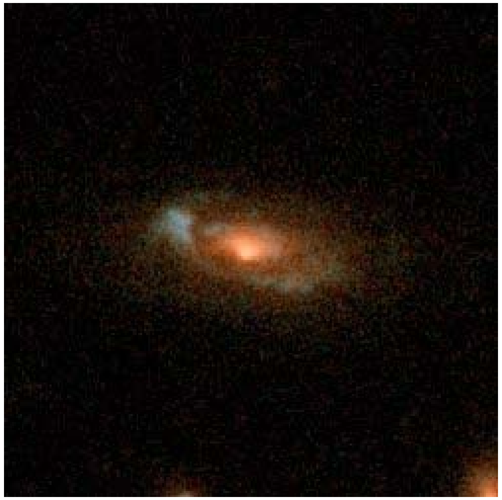
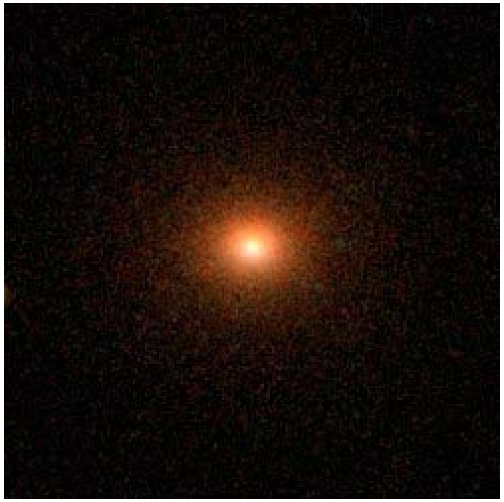
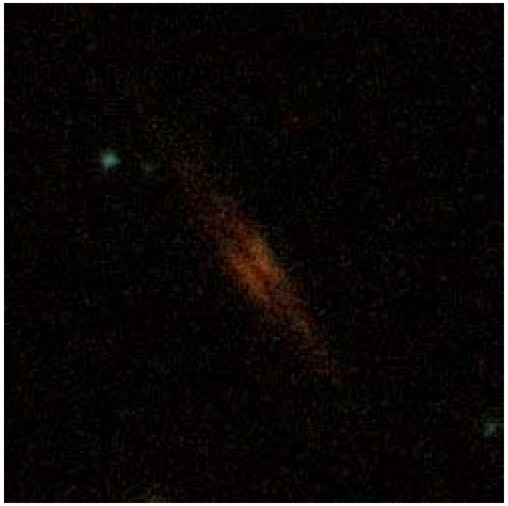
  (van der Wel, Franx, Rix, et al 2005)

- Most very massive galaxies have been red, at least since z~1

- Total mass in the "red-sequence" is ½ of present value



Red = “Dead” or Dusty ?

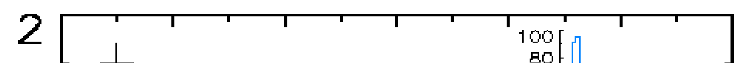
Red/Dusty or Red/Dead ?

(Bell et al 2004b)

Pick thin redshift slice (0.7) to eliminate

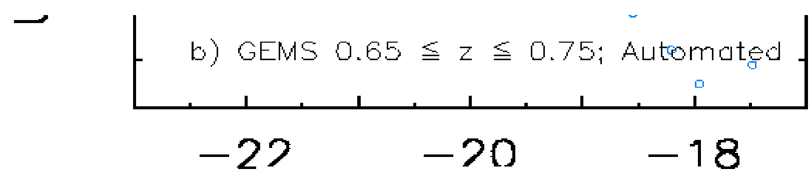
- differential band-shifting
- differential $(1+z)^4$ dimming

Classification visually + concentration index



85% of the red sequence at z~0.7 are *early types*,

i.e. `red and dead`



← luminosity

Massive galaxies at z~1

1/2 t_{Hubble} ago

- Most of the massive galaxies at z~1 are red == not/hardly forming new stars

- BUT, only half as many stars (per unit volume) are on the "red seqence" as at present.

Questions

I. Why have massive galaxies stopped forming stars?

II. How did the "red sequence" mass get augmented?

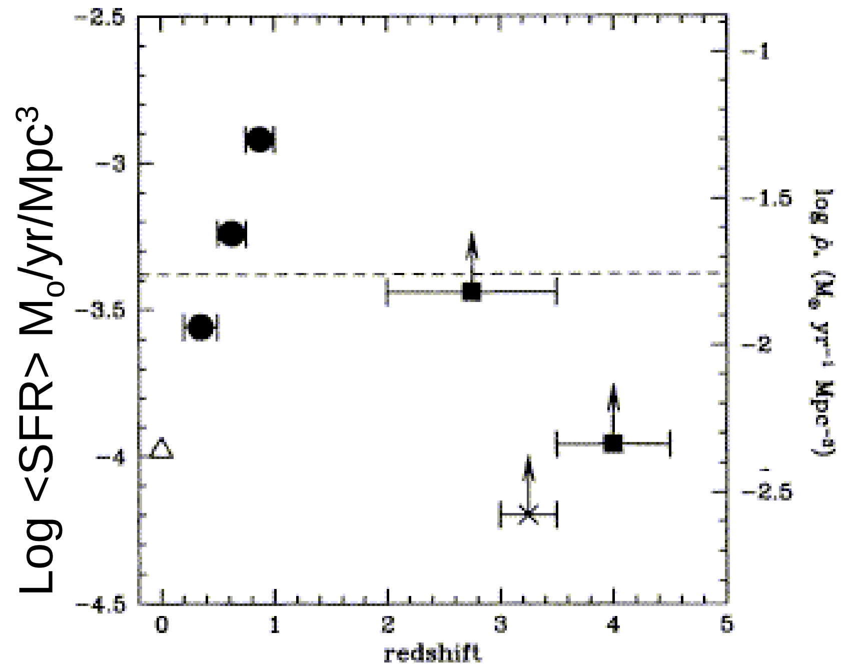
III. When did they form their stars?

II. How to increase the total (stellar) mass in massive galaxies

- Galaxies can grow in mass by
  - forming new stars
  - coalescence (merging) of pre-existing bits

Why did the global SFR decrease towards the present epoch?

- At z~0.75 the <SFR> was 5x higher than it is now (Lilly et al 96, Madau et al 96)



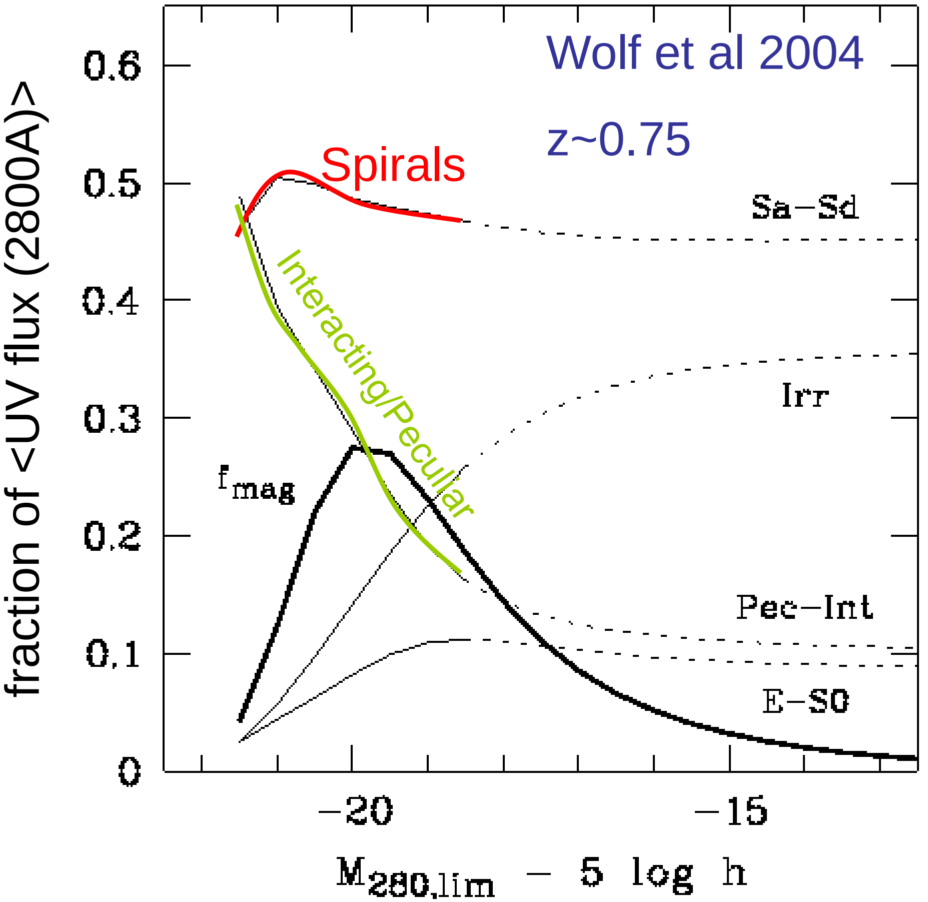
- Did it drop because there were fewer merger-driven starbursts?

- Did it drop because 'quiescent' disk galaxies formed fewer stars?

- At M_V>-19 and z~0.75
  - ½ the UV flux comes from seemingly normal spirals
  - 20% from visibly interacting systems

- only minority of UV flux from interacting systems at z~0.75

→drop in merger rate unlikely cause for large drop in SFR (=UV flux)



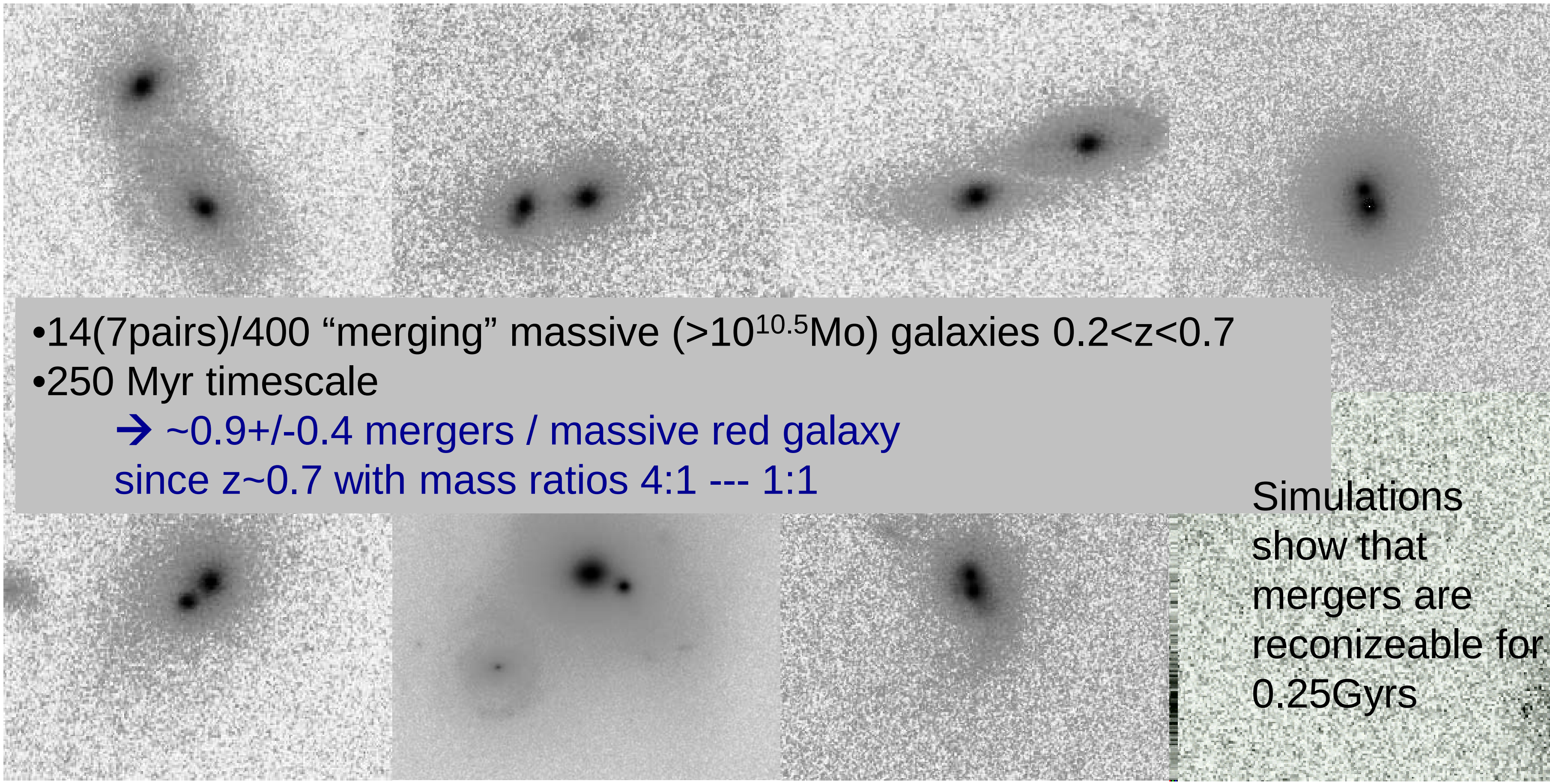
II. How to increase the total (stellar) mass in massive galaxies

- Galaxies can grow in mass by
  - forming new stars
  - coalescence (merging) of pre-existing bits

- Can we estimate a merger rate for massive galaxies?
  - Steps:
    - Devise quantifiable definition of “ongoing merger”
    - Estimate a timescale for this phase: incidence → rate
    - Quantify how the ongoing merger changes the probability of entering sampe: **e.g. merger → star-formation→ lumosity boost**

Actually observed “dry” mergers at z<0.7 in GEMS

Bell, HWR et al 2005



- 14(7pairs)/400 “merging” massive (>$10^{10.5}$Mo) galaxies 0.2<z<0.7
- 250 Myr timescale

  → ~0.9+/-0.4 mergers / massive red galaxy since z~0.7 with mass ratios 4:1 --- 1:1

Simulations show that mergers are reconizeable for 0.25Gyrs

Massive galaxies since z~1: upshot

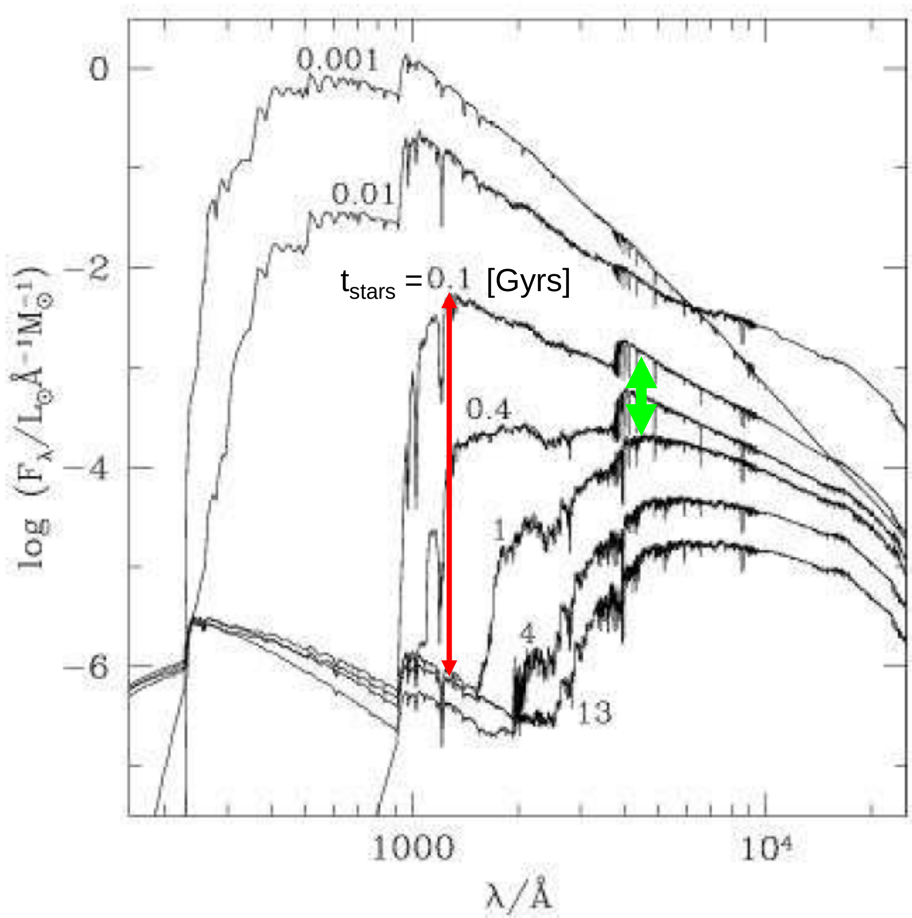
- Star-formation has essentially stopped in most massive galaxies since z~1 (7Gyrs)
  - "need" missing ingredient to stop/quench star-formation --- central black hole feed-back?
- Overall stellar mass density in *red'n'dead* galaxies has doubled since z~1
  - Source: galaxies that have stopped forming stars
- Typical massive galaxy has undergone *one* (major, dry) merger since z~1
  - Boost total red sequence mass at the most massive end

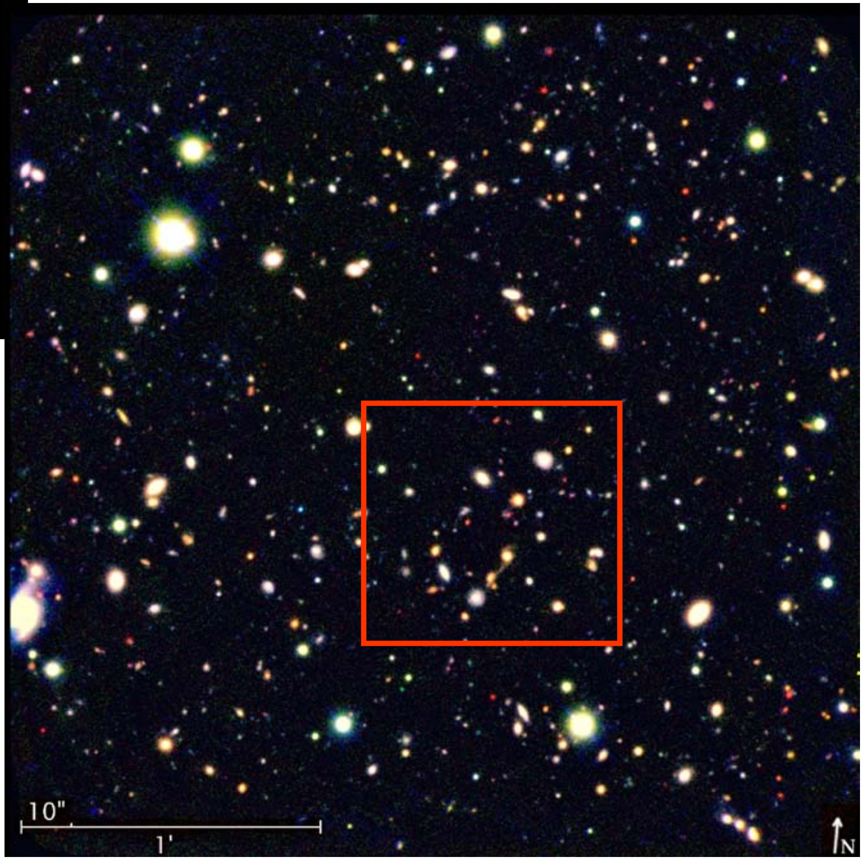
III. What Questions Arise for Earlier Epochs?

- When did most of the stars form that are in massive galaxies today?
- How rapidly did they form?
  - How many episodes?
  - Early periods of quiescence?

$$t_{form} \propto M_* / \dot{M}_* \quad \text{vs} \quad t_{\text{dyn}} \approx 100 Myrs$$

Why similar experiments get harder for z>1

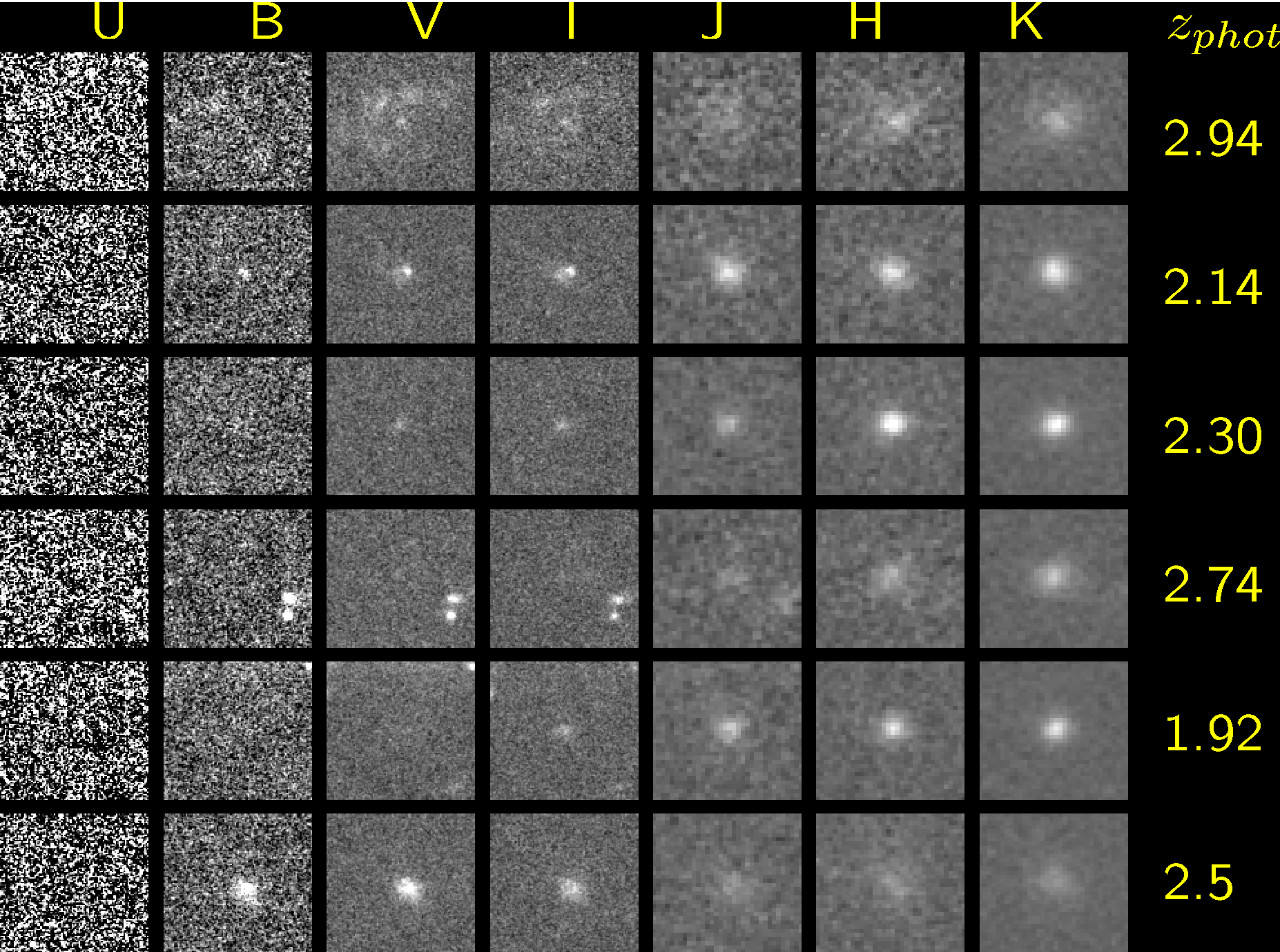




Faint InfraRed Extragalactic Survey

Franx (PI), Rix, Labbe, Foerster-Schreiber, Rudnick, et al. 2002-2006

Red galaxies in HDF-South


U
B
V
I
J
H
K
z_{phot}
2.94
2.14
2.30
2.74
1.92
2.5

Characteristic Properties of “Distant Red Galaxies”

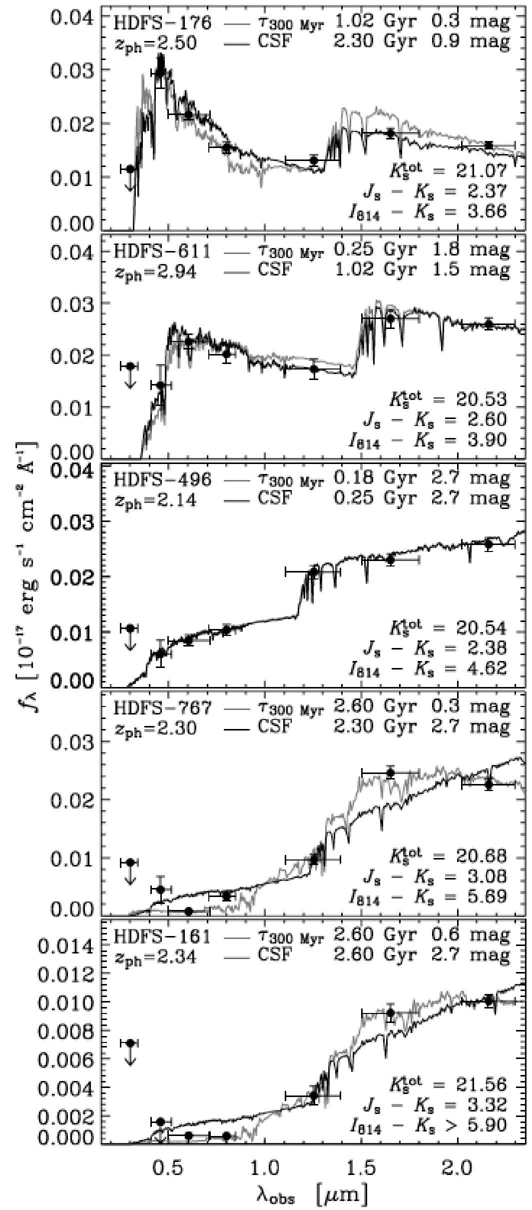
(Franx et al 2003, van Dokkum et al 2004, Foerster-Schreiber et al 2005, Labbe et al 2005)

- Epoch: Z~2.5
  - SED fitting to get M*, SFR,τdust
- M_{*}~$5x10^{10}$ – $2x10^{11}$ M_{o}
  - Nearly as massive as most massive galaxies today
  - Contain the bulk of stars at those epochs
- Star-formation rate ~ 50-150 M_{o}/yr
  - Dust extinction important A_V~2 mag
  - SFR cross-checked with thermal-IR
- For SFR ~ $e^{-t/\tau}$ → τ_{fit}~500Myr

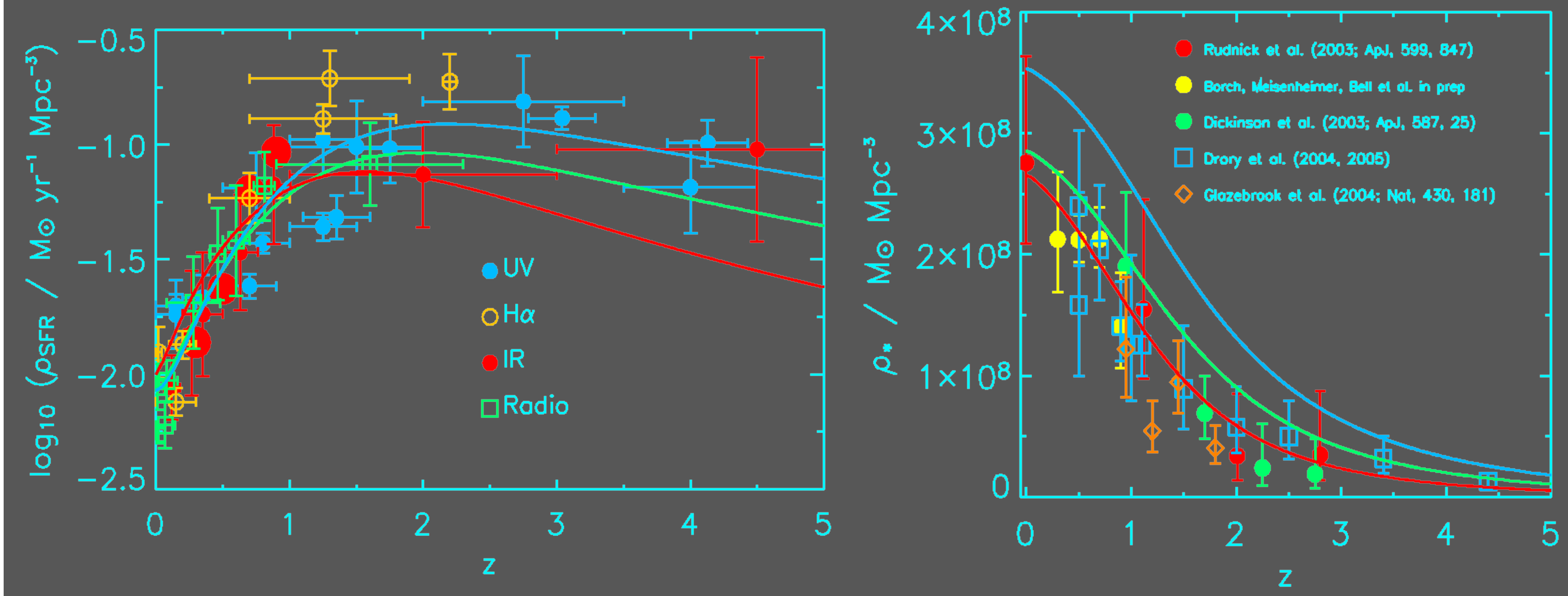
  → Mass build-up:

  SFR x τ ~ 10^{10-11}Mo (!!!)

Finally: the epoch when massive galaxies are forming stars at a high rate!



The 'Cosmic Star Formation History' and the Build-Up of Stellar Mass

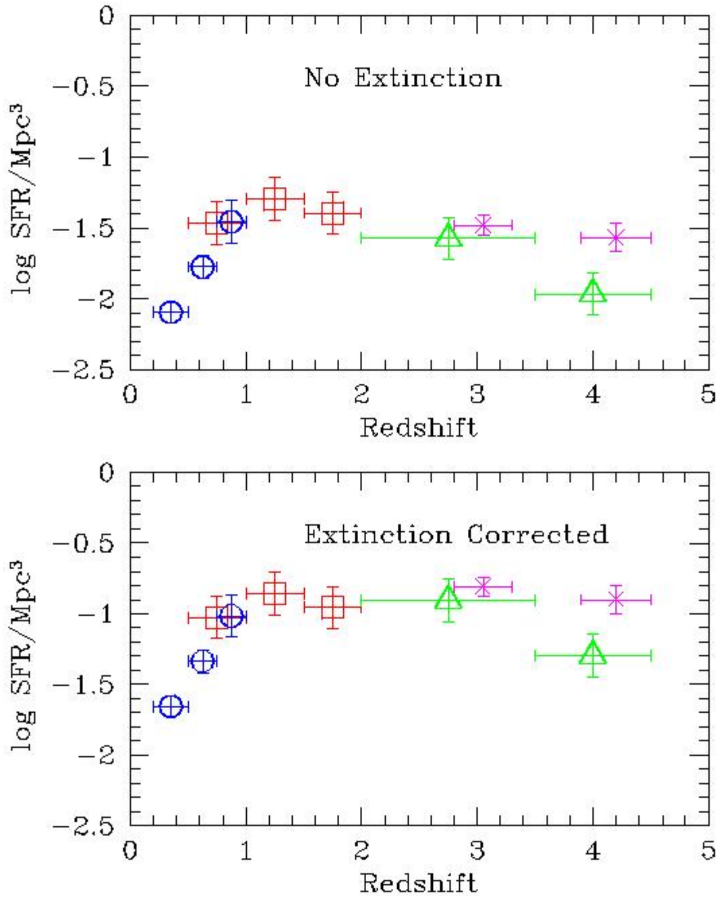


Borch et al. 2006

Galaxies Block Course March 09
Eric Bell

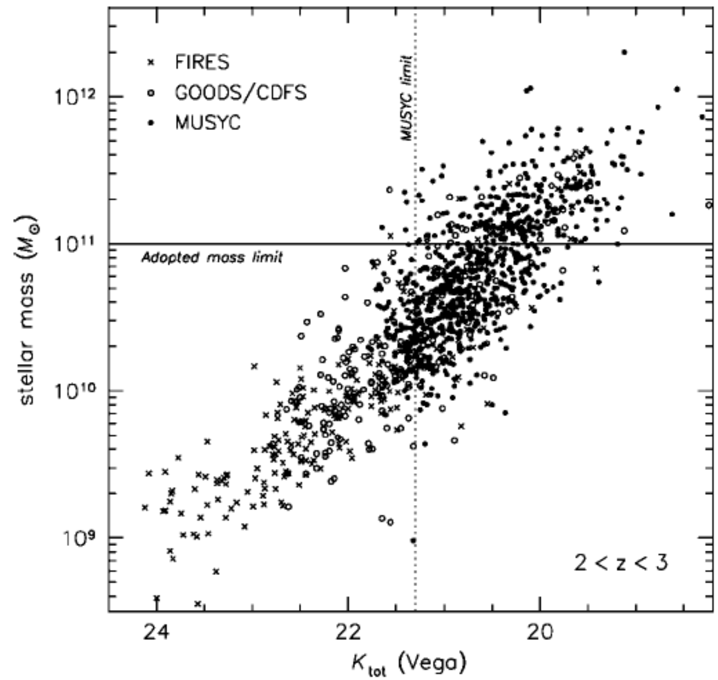
Main Issues in Assembling the Cosmic Star Formation History

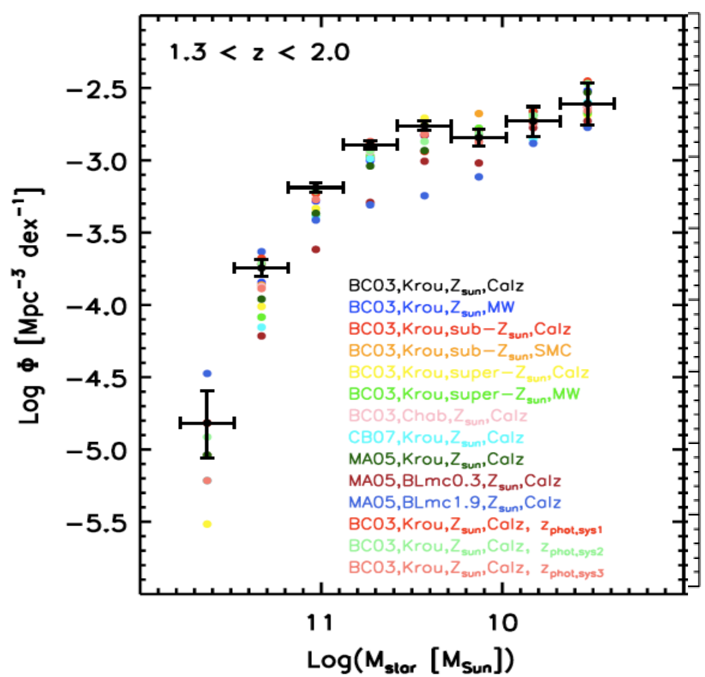
- Different redshifts: different technique for finding galaxies and SFR estimates
- Correct for dust extinction
- Which fraction of <SFR> comes from faint galaxies?
  - Count the effect of the UV photons on the IGM (tomorrow)



The Galaxy Mass Function at Earlier Epochs
(e.g. Marchesini et al 2009)

- At present: galaxy mass function is
  - 'Schechter function'
  - most stars in $M_{gal}=10^{10.5}M_o$
- At earlier epochs:
  - Define M_*-limited sample, independent of SFR (which brightens galaxies)
  - → near-IR selection is needed
- Results:
  - Galaxy mass function looks similar 0<z<4
  - 'characteristic mass' was only slightly lower at high-z
  - Co-moving density was considerably lower
- Most stars were always in the most massive galaxies!
  - At least for z<4, since when 95% of all stars formed



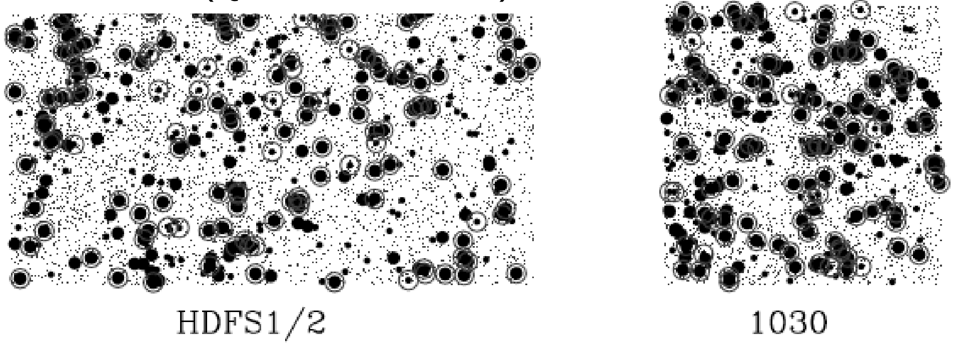


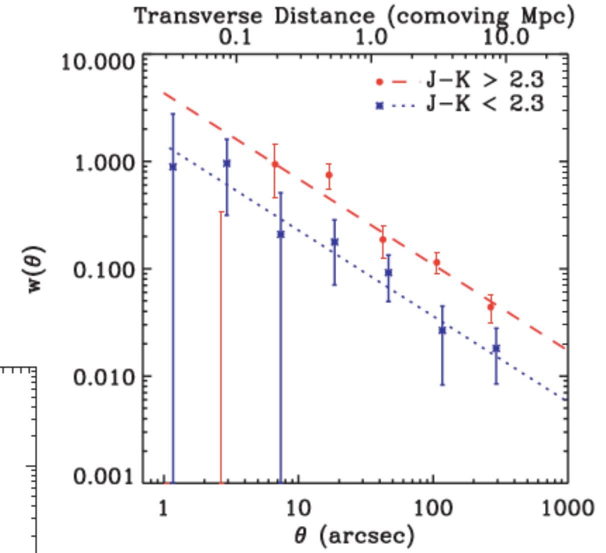
Matching Galaxy Populations across different redshifts

- If we observe a 'galaxy population' (a certain L,z,color range), into which counter-parts should they evolve at z=0?

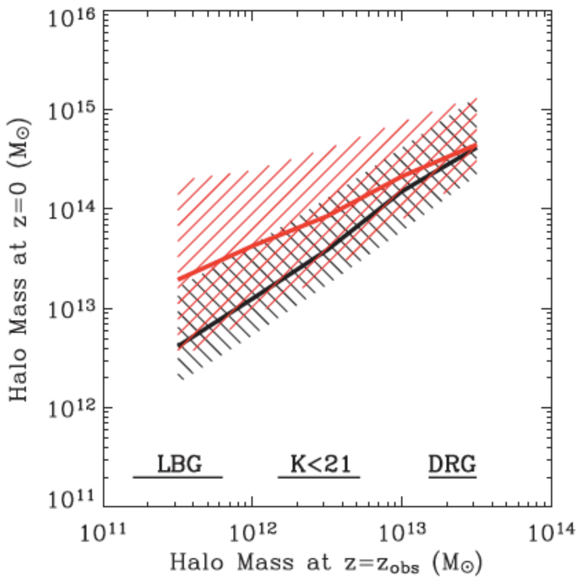
- Approach:
  - Isolate a sub-population of galaxies
  - Determine through clustering in which halos they sit at z~3
  - Follow halo evolution through large-scale DM simulations → ha

On-sky distributions of galaxies at 2<z<3.5 (Quadri et al 2008)





—Angular correlation function for 2 < z_{phot} < 3.5 galaxies that meet



Summary

- We've mapped most of the cosmic star formation history
  - 90% of all stars formed since z~3
  - SFR has dropped by ~10x since z~1.
- The most massive galaxies are seen to
  - Grow mostly by merging z<1
  - Form stars vigorously at z>2
  - Also at earlier epochs: most stars lived in the most massive galaxies at the time