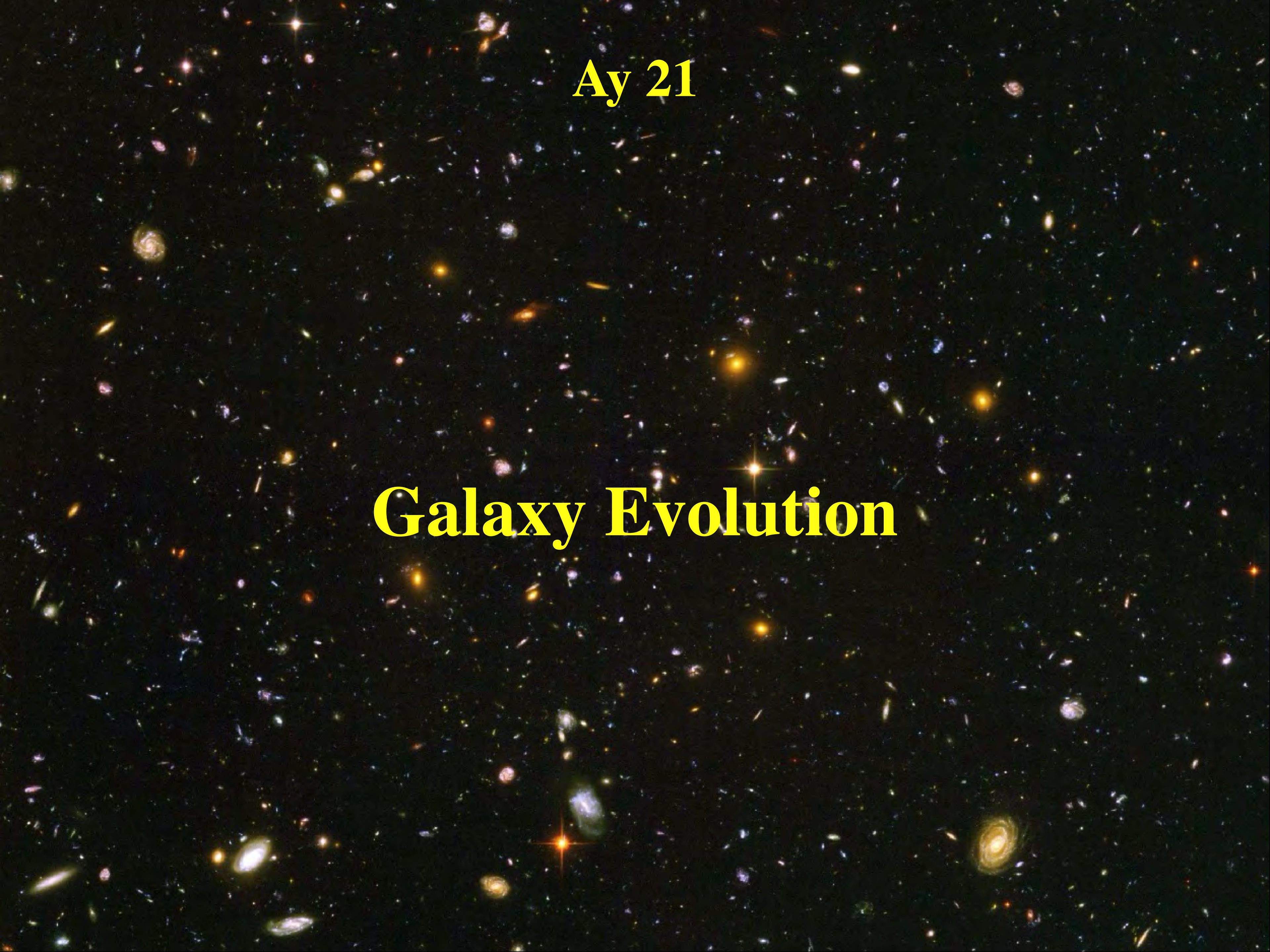


Ay 21

Galaxy Evolution

Galaxies Must Evolve

- Stars evolve: they are born from ISM, evolve, shed envelopes or explode, enriching the ISM, more stars are born…
- Structure evolves: density fluctuations collapse and merge in a hierarchical fashion

Galaxy Evolution

Assembly of the mass

Conversion of gas into stars and v.v., feedback processes

DM dominated
Cannot be observed directly, but may be inferred
Easy to model, mainly dissipationless

This is what is observed, and where energy is generated
Dissipative, and very hard to model

Evolution Timescales and Evidence

Timescales for galactic evolution span wide range:

~ 100 Myr - galaxy free-fall and cooling time scales

10 -100 Myr - lifetimes of massive stars

10 -100 Myr - lifetime of the bright phase of a luminous Active Galactic Nucleus (?)

Few x 100 Myr - rotation period of spiral galaxy

~ Gyr - time required for two galaxies to merge

~ 10 Gyr - age of the Universe

Observational evidence for evolution is found in:

- Stellar populations in the Milky Way (e.g., metallicity as a function of stellar age, etc.)
- Systematics of nearby galaxy properties
- **Properties of distant galaxies seen at earlier epoch**

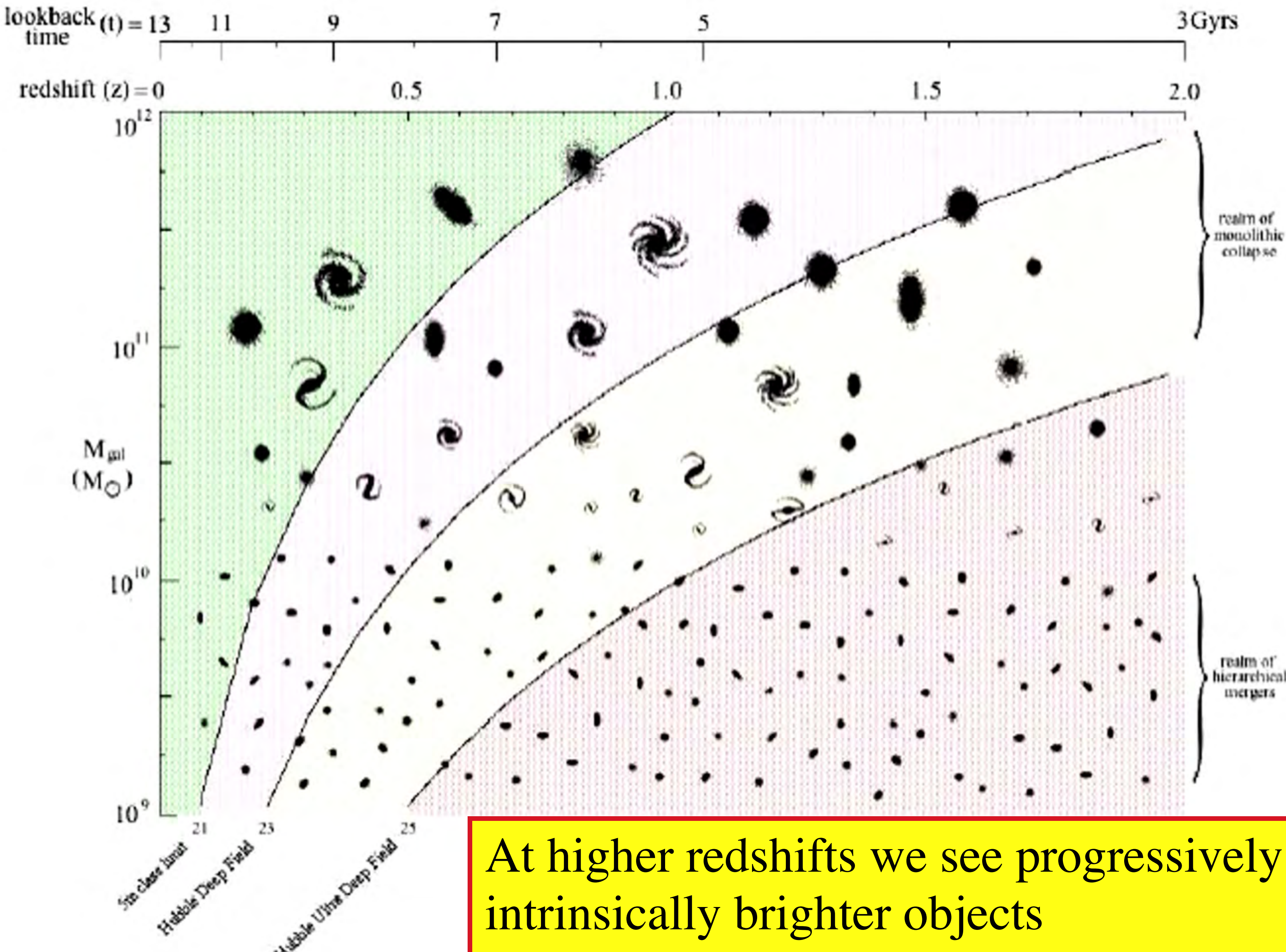
Theoretical Tools and Approaches

1. **Assembly of the mass:** numerical modeling of structure formation. Fairly well advanced, but it is hard to treat any dissipative processes very accurately. Well constrained from cosmology (LSS formation)
2. **Evolution of stellar populations:** based on stellar evolution models, and fairly well understood. Lots of parameters: the stellar initial mass function, star formation history, stellar evolutionary tracks and spectra as functions of metallicity. Poorly constrained a priori.
3. **Hybrid schemes,** e.g., "semi-analytical" models. Use both of the above to assemble comprehensive models, but not constrained very well

Observational Tools and Approaches

- **Deep imaging surveys** and source counts, at wavelengths from UV to FIR
  - Sources are always selected in emission, and any given band has its own selection effects and other peculiarities
  - With enough bandpasses, one can estimate "photometric redshifts", essentially very low resolution spectroscopy; may be unreliable
  - Measurements of clustering provide additional information
- **Deep spectroscopic redshift surveys**: redshifts are usually obtained in the visible, regardless of how the sources are selected
  - As a bonus, one can also estimate current star formation rates and rough chemical abundances from the spectra
- **Diffuse extragalactic backgrounds:** an integrated emission from all sources, regardless of the flux or surface brightness limits
  - Extremely hard to do
  - No redshift information

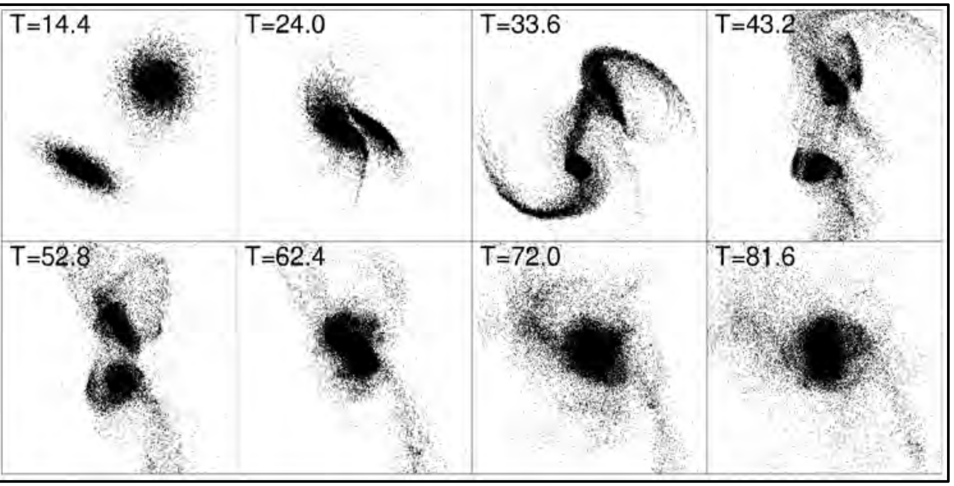
Beware of the Selection Effects



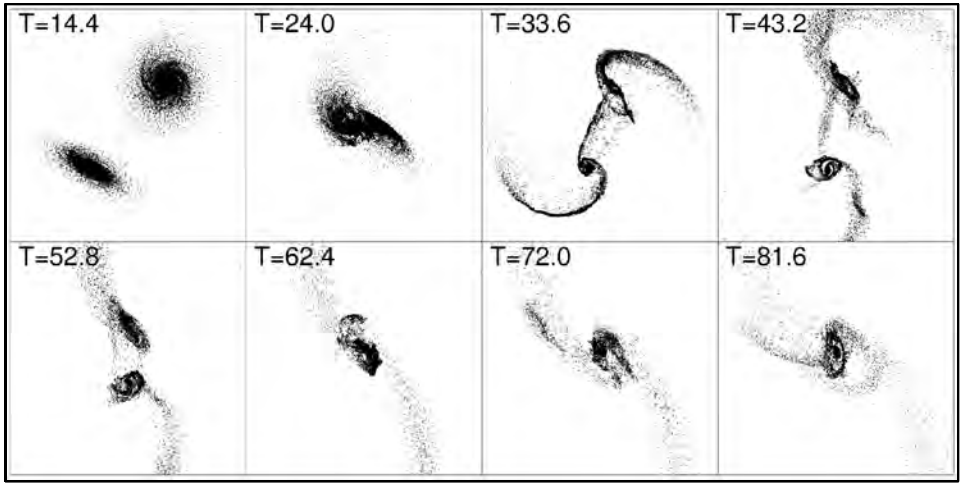
At higher redshifts we see progressively intrinsically brighter objects

Galaxy Merging / Dynamical Evolution

- Commonly observed today, and must have been more important in the past, a part of the overall hierarchical structure formation
- Mergers change the numbers and mass distribution function of galaxies, and their internal structure/morphology
- Dissipative merging can lead to starbursts and feeding of AGN



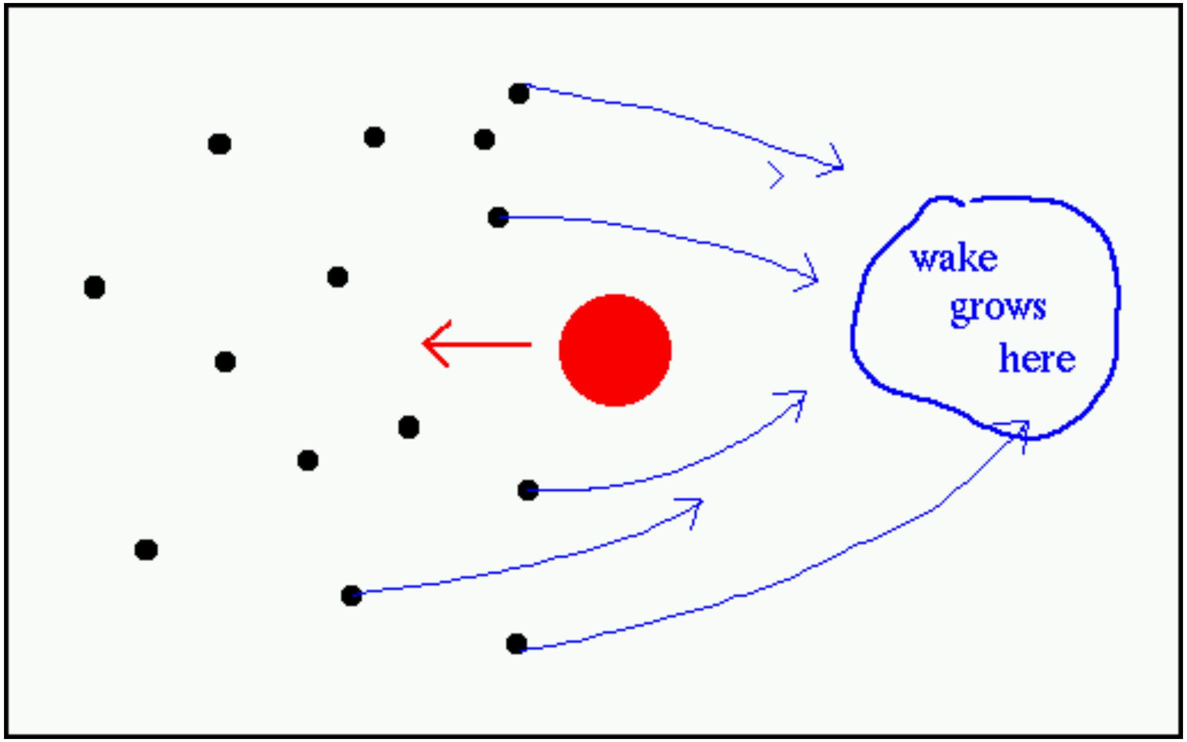
Stars and DM (Dissipationless)

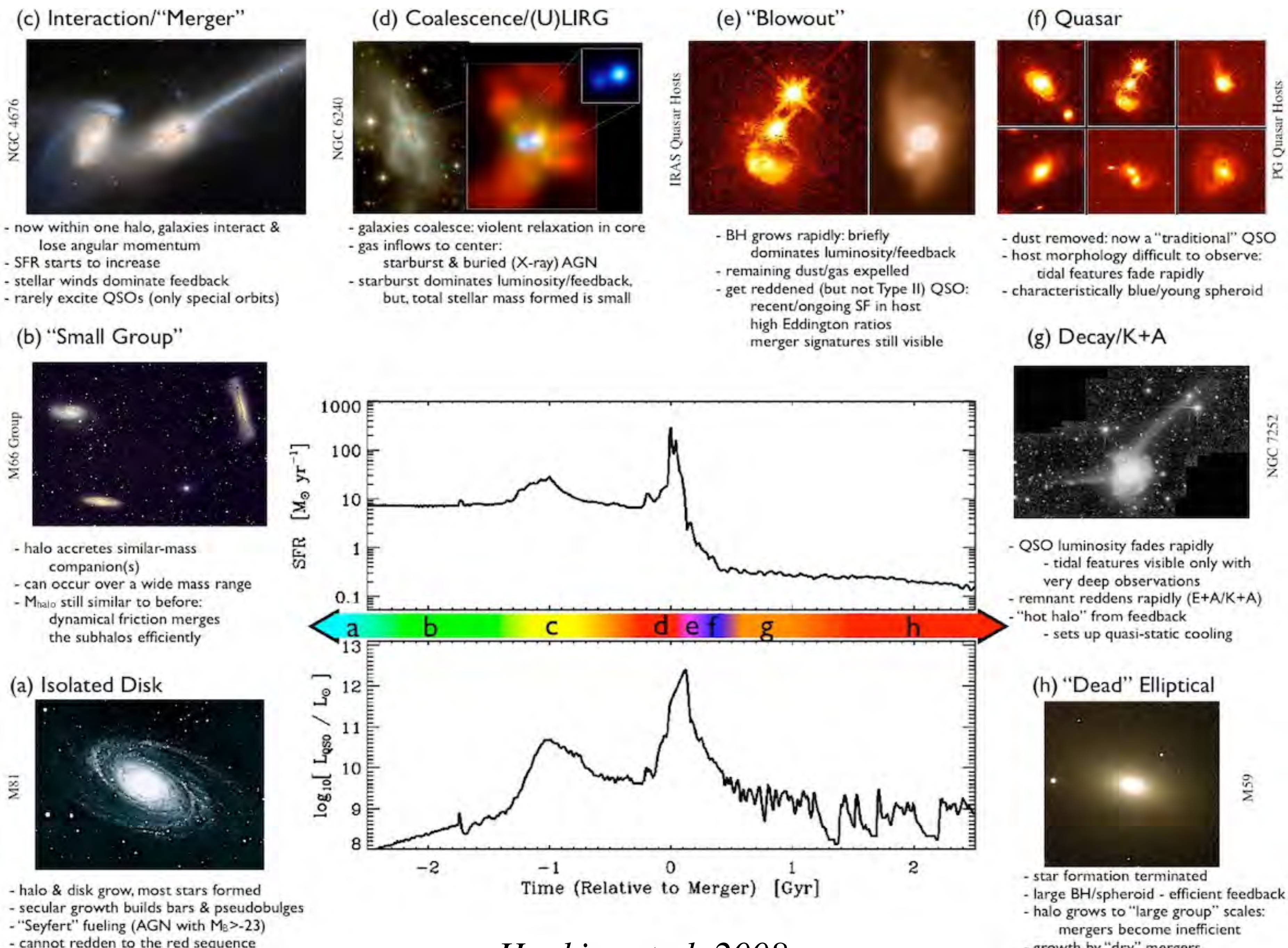


Gas (Dissipative)

Dynamical Friction

- As a massive galaxy moves through a "sea" of stars (and the dark halo), it causes a wake behind it increasing the mass density behind it; the same effect applies to galaxy pass-bys
- This increase in density causes the galaxy to slow and lose its orbital kinetic energy; lower encounters are more effective
- The galaxy will eventually fall in and merge with its companion
- Typical time scales ~ 1 Gyr
- Local example: the Magellanic Clouds

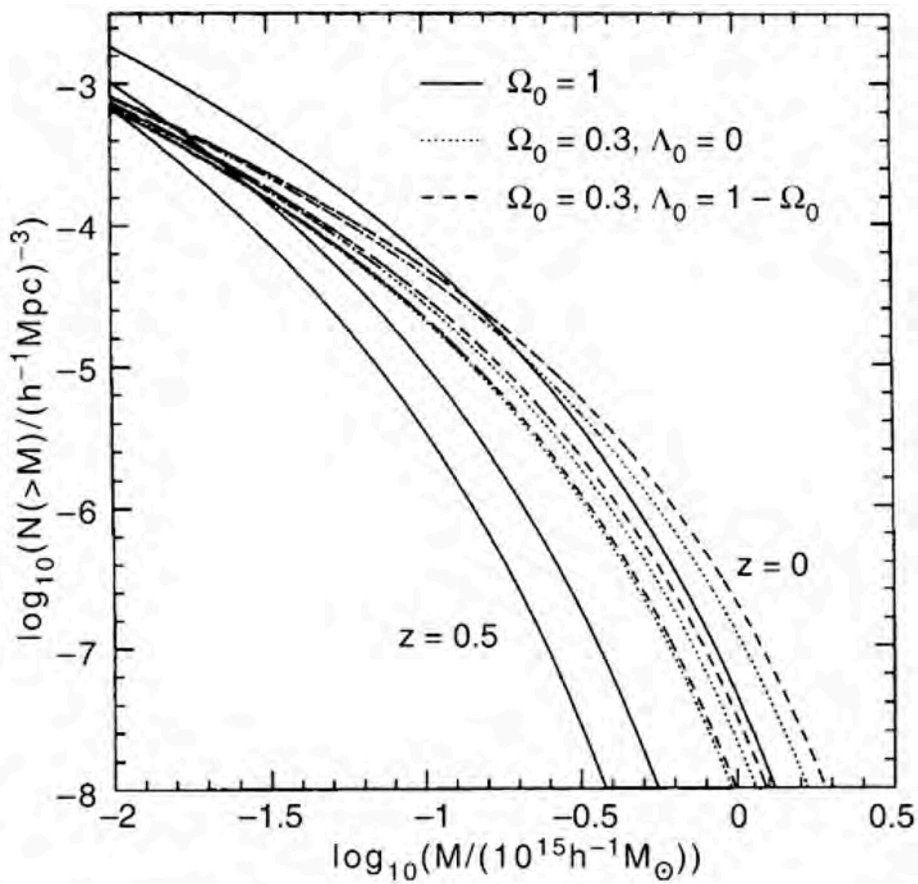




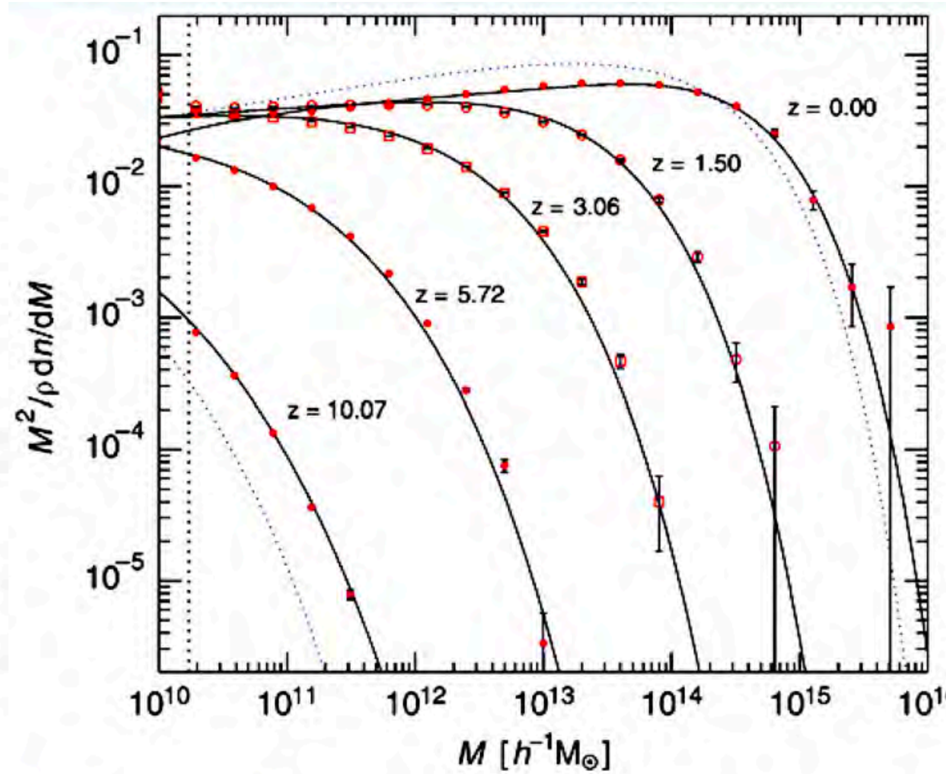
Hopkins et al. 2008

Dark Halo Mass Function

Press-Schechter model: Evolving number density of dark halos as a function of mass and redshift:



As seen in numerical simulations:



The number of halos on any mass *grows in time*, but the changes are *greater at the higher halo masses*

Cosmology dependence: the effect is stronger for higher density models

Galaxy Luminosity Function

Distribution of galaxy luminosities (not masses)

Characterizes *galaxies as a population* and it is bandpass-dependent

It is well fit by the **Schechter luminosity function:**

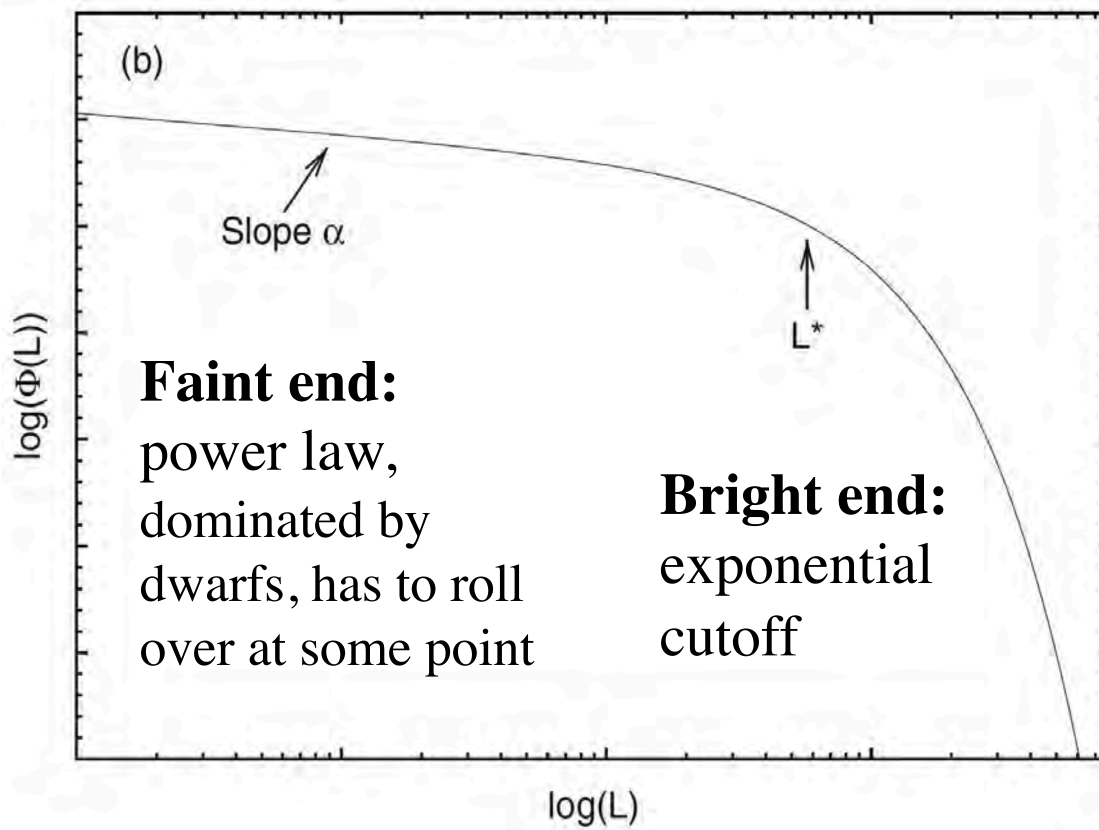
$$\Phi(L) = \left(\frac{\Phi^*}{L^*}\right)\left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-L/L^*\right)$$

L^* = characteristic luminosity

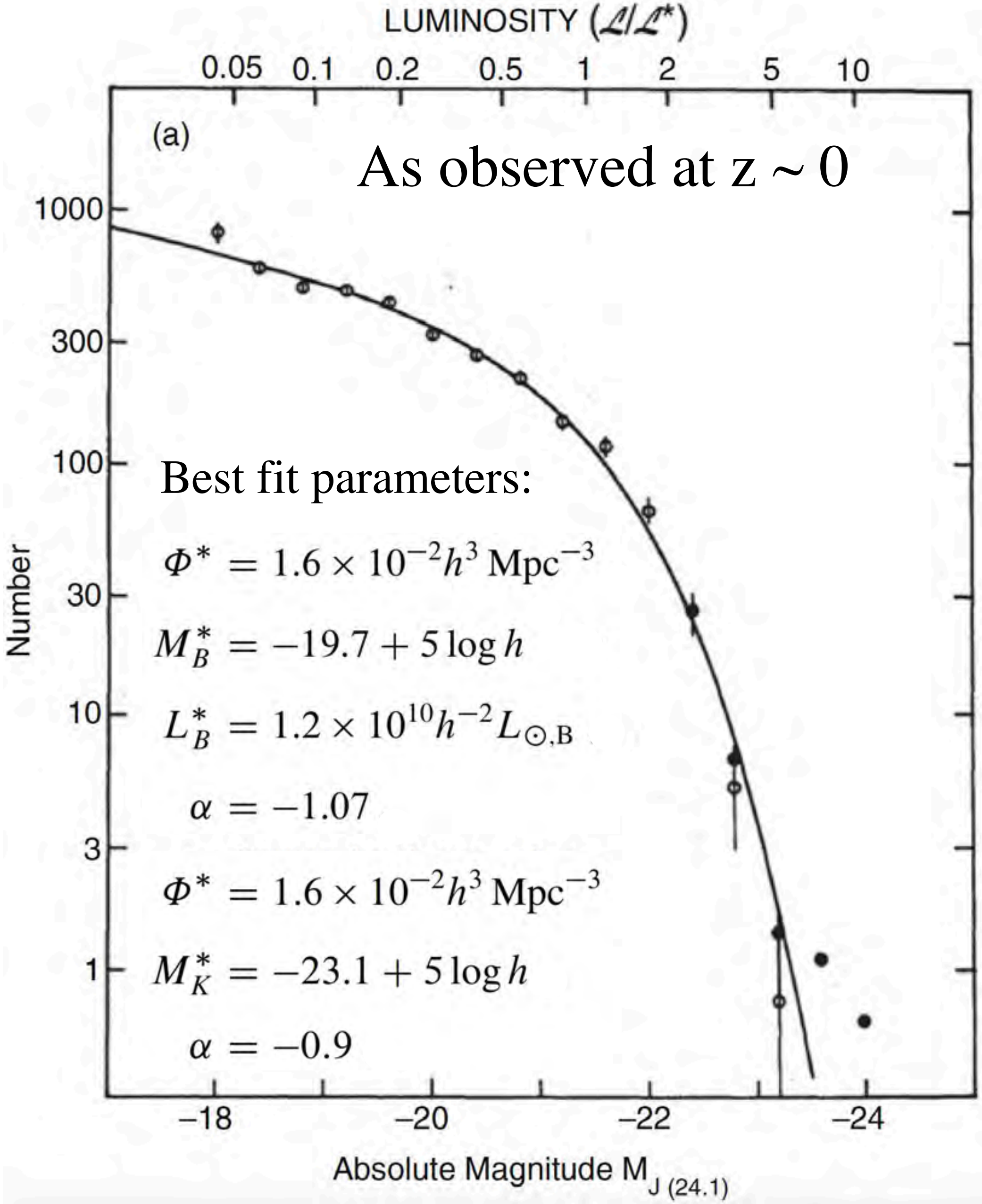
Φ^* = number density at L^*

Note: this is an *empirical* fit, similar but distinct from the Press-Schechter formalism for halo mass distributions (theoretical)

It is *expected to evolve* with redshift, as galaxies evolve



Galaxy Luminosity Function



As observed at z ~ 0

Best fit parameters:

$$\Phi^* = 1.6 \times 10^{-2} h^3\,\mathrm{Mpc}^{-3}$$

$$M_B^* = -19.7 + 5 \log h$$

$$L_B^* = 1.2 \times 10^{10} h^{-2} L_{\odot,\mathrm{B}}$$

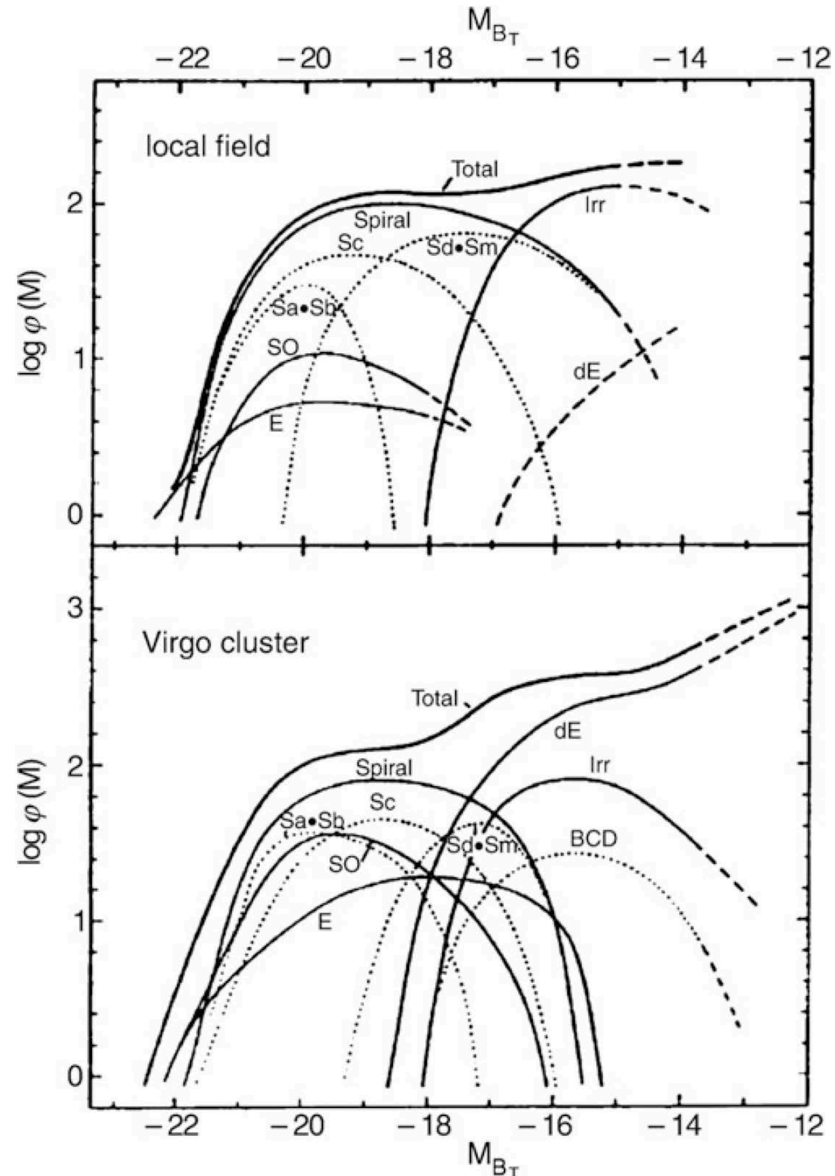
$$\alpha = -1.07$$

$$\Phi^* = 1.6 \times 10^{-2} h^3\,\mathrm{Mpc}^{-3}$$

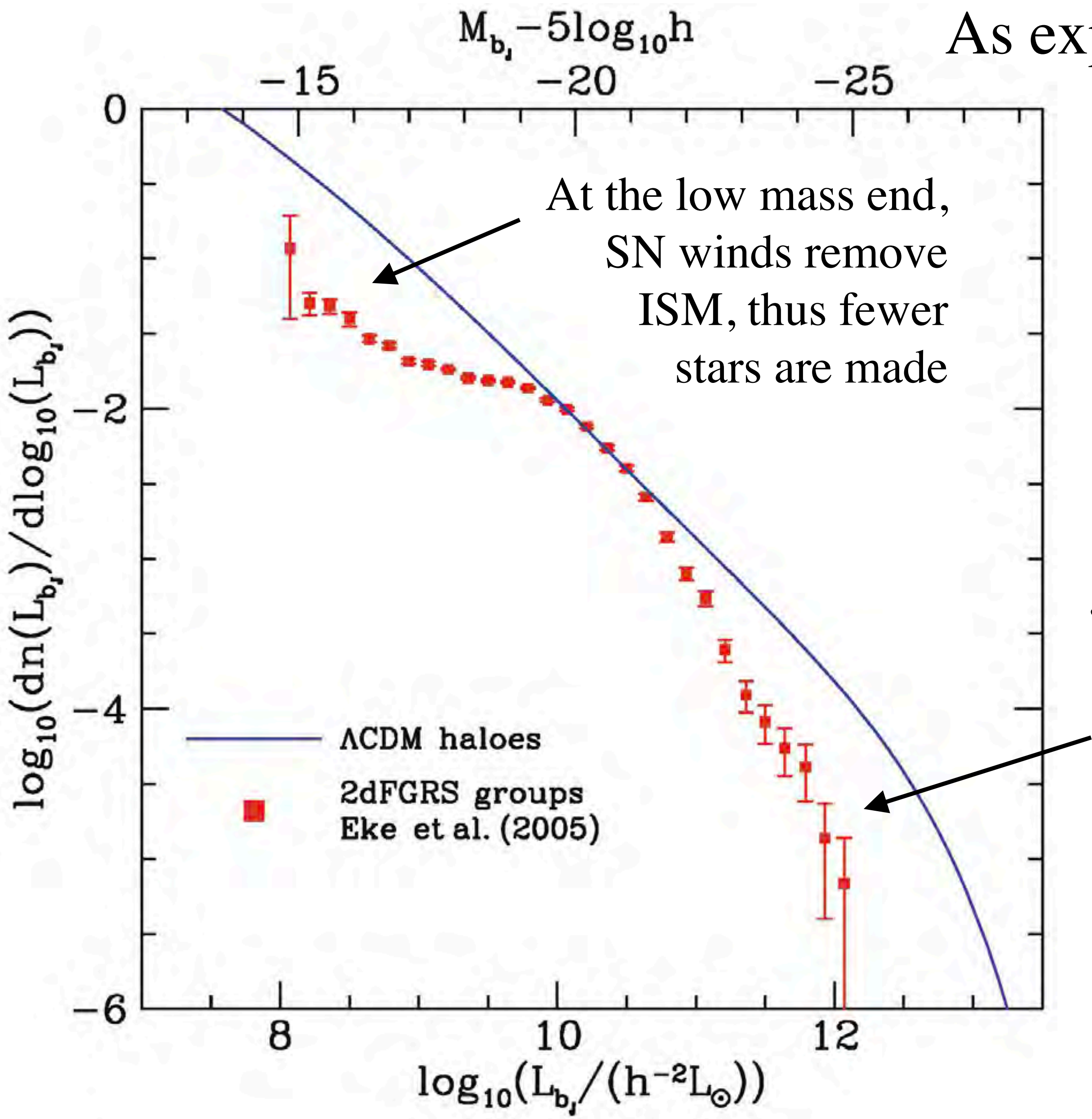
$$M_K^* = -23.1 + 5 \log h$$

$$\alpha = -0.9$$

Type dependence:



Mass Function vs. Luminosity Function



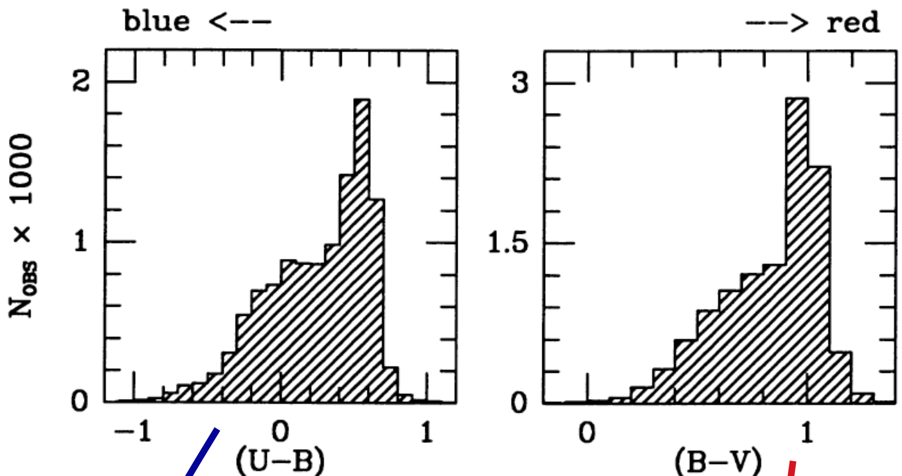
As expected, light roughly traces the mass

However, there are "deficiencies" at both bright and faint ends

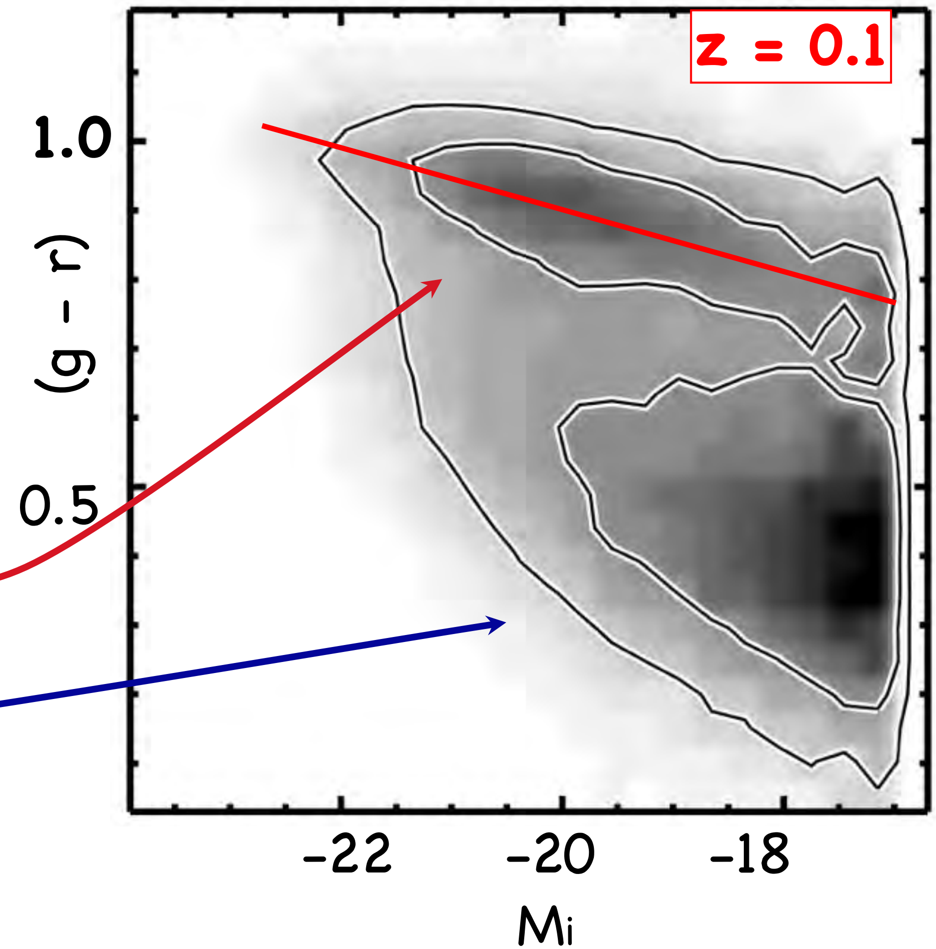
This is understood as the consequences of ***feedback***

Colors of Stellar Populations: Differences in Star Formation Histories

z ~ 0 galaxies, Djorgovski 1992



SDSS, Blanton et al. 2002



The red sequence: mostly E's, no active star formation

The blue sequence: mostly Sp's, with active star formation

Stellar Population Synthesis Models

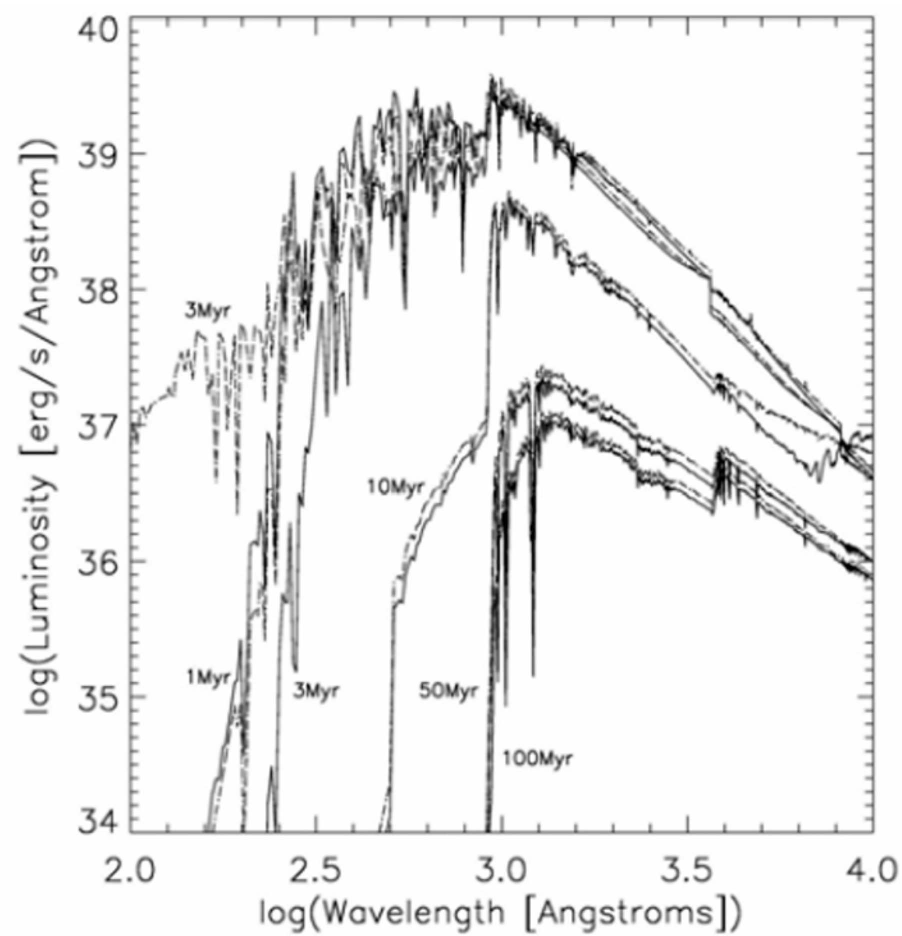
- We can ***synthesize predicted galaxy spectra*** as a function of time by assuming the following:
  - Star formation rate (as a function of time)
  - Initial mass function
  - Libraries of stellar spectra for stars of different masses and metallicities and ages, etc.
  - Stellar evolutionary tracks (isochrones)
- A simple stellar population (SSP) is the result of an instantaneous burst of star formation
- We can model more complex star formation histories by adding together multiple SSPs, parameterize star formation rate as a function of time as:
  - $dM/dt \sim \exp(-t/\tau)$ where t is the time since the start of star formation and τ is the star-formation time scale

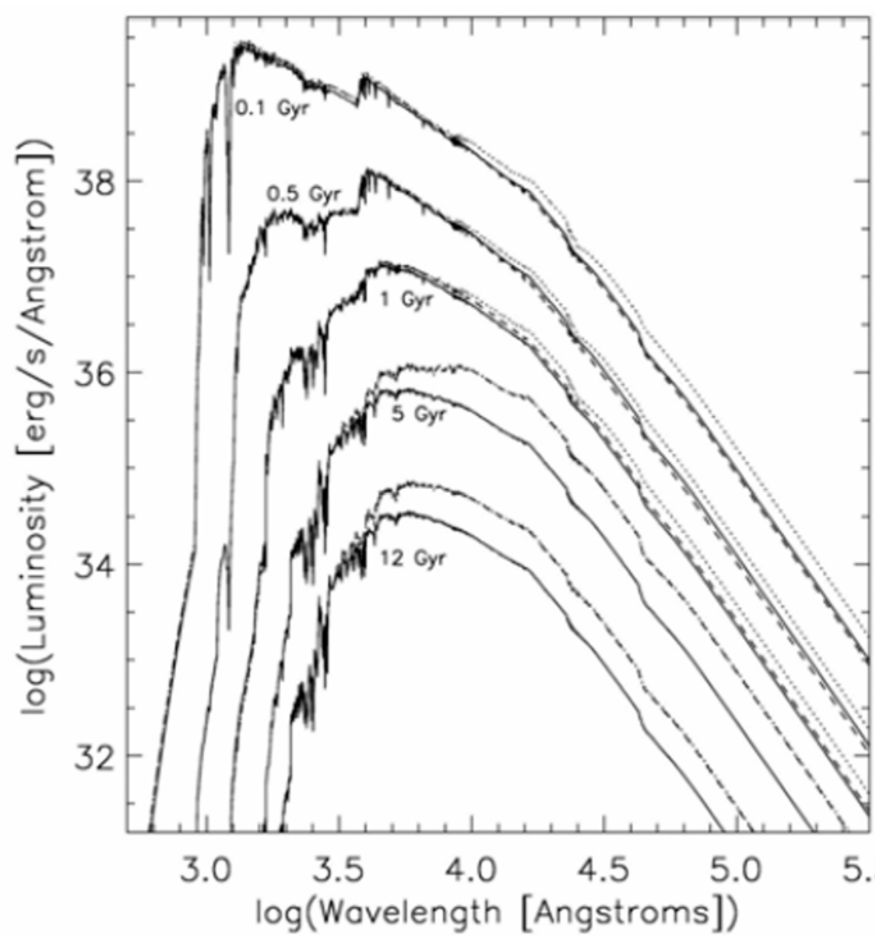
Modeling Evolution of Stellar Pop's

- Stellar evolution is relatively well understood both observationally and theoretically; the key points to remember:
  - Massive stars are very hot, blue, very luminous, and have very short lives; they dominate the restframe UV light
  - Thus we expect largest effects in the bluer parts of the spectrum
  - But there are still some modest disagreements among the models
- **Star formation histories are a key assumption**:
  - Ellipticals are best fit by a burst of early star formation followed by "passive evolution" where they fade and get redder with time $\tau \sim 1$ Gyr or less
  - Spirals are best fit by $\tau \sim 3$-10 Gyr – they stay bluer and don't fade as much
  - Irregulars are best fit by constant star formation rates

Predicted Spectral Evolution

for a simple stellar population (SSP):
a δ-function burst with a fixed metallicity and IMF





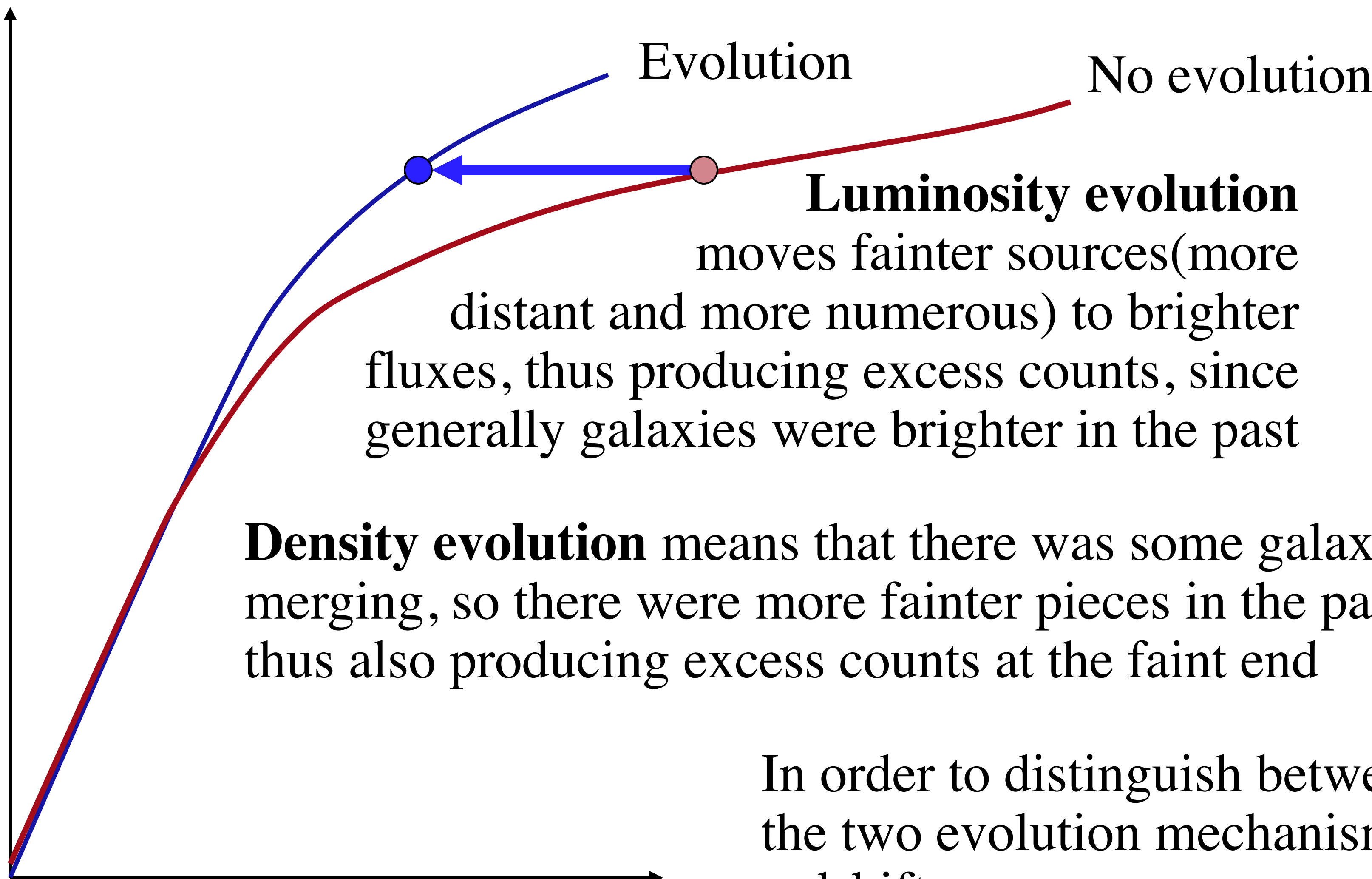
Observing Galaxy Evolution

- If redshifts are not available, we can do *source counts* as a function of limiting flux or magnitude; and colors as a function of magnitude (acting as a proxy for distance - not a great approximation)
- But to get a true evolution in time, and disentangle the various evolution effects, we need *redshifts*
- The field is split observationally:
  - **Unobscured star formation** evolution: most of the energy emerging in the restframe UV, observed in the visible/NIR
  - **Obscured star formation**: energy from young stars reprocessed by dust to emerge in FIR/sub-mm
  - They have different limitations and selection effects
  - We now know that *roughly a half of the star formation in*. *the universe was obscured by dust*

Source Counts: The Effect of Evolution

(at a fixed cosmology!)

log N (per unit area and unit flux or mag)



🡸 ***log f*** or magnitude 🡺

Luminosity evolution moves fainter sources(more distant and more numerous) to brighter fluxes, thus producing excess counts, since generally galaxies were brighter in the past

Density evolution means that there was some galaxy merging, so there were more fainter pieces in the past, thus also producing excess counts at the faint end

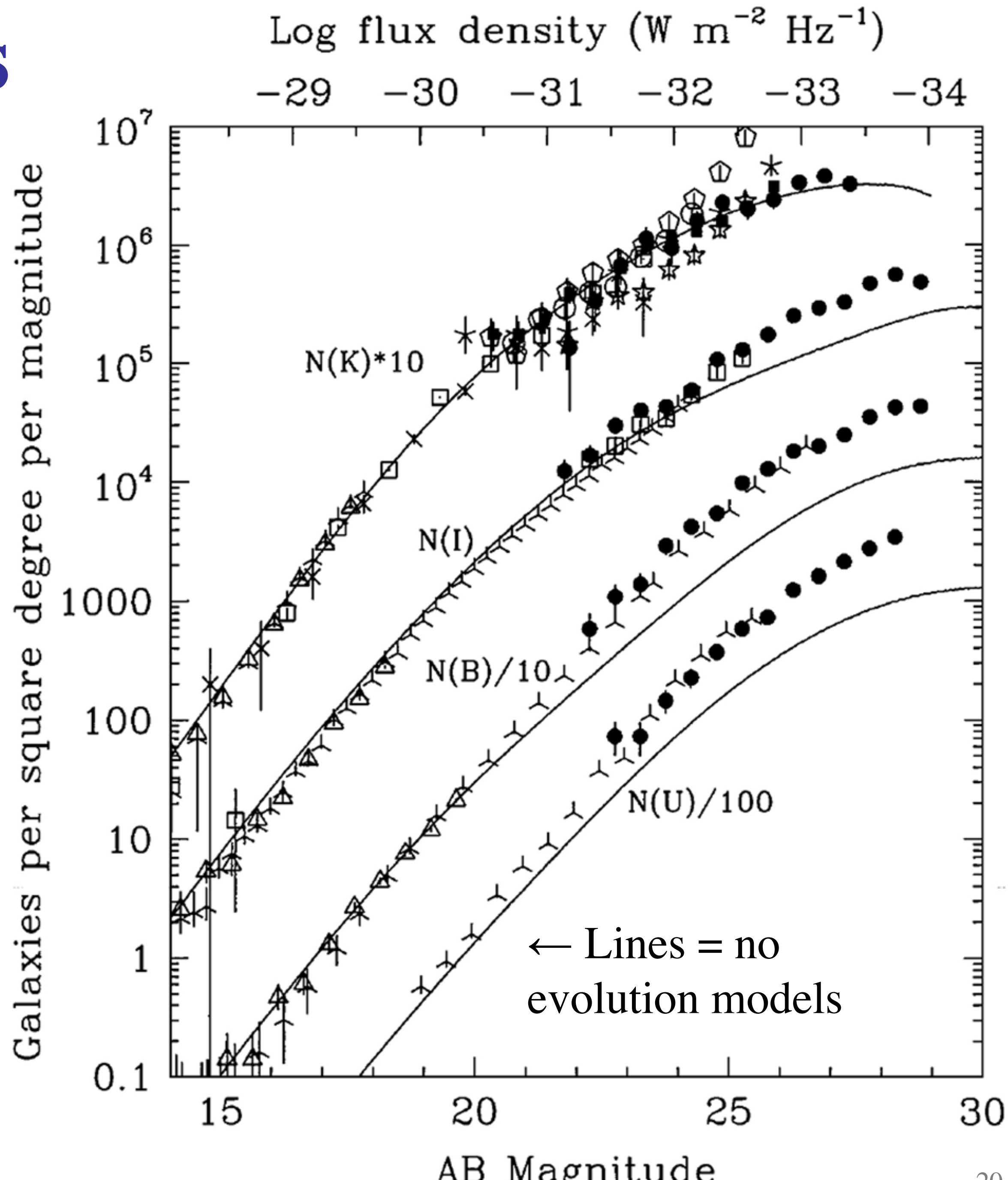
In order to distinguish between the two evolution mechanisms, redshifts are necessary

Galaxy Counts in Practice

The deepest galaxy counts to date come from HST deep and ultra-deep observations, reaching down to ~ 29th mag

All show excess over the no-evolution models, and more in the bluer bands

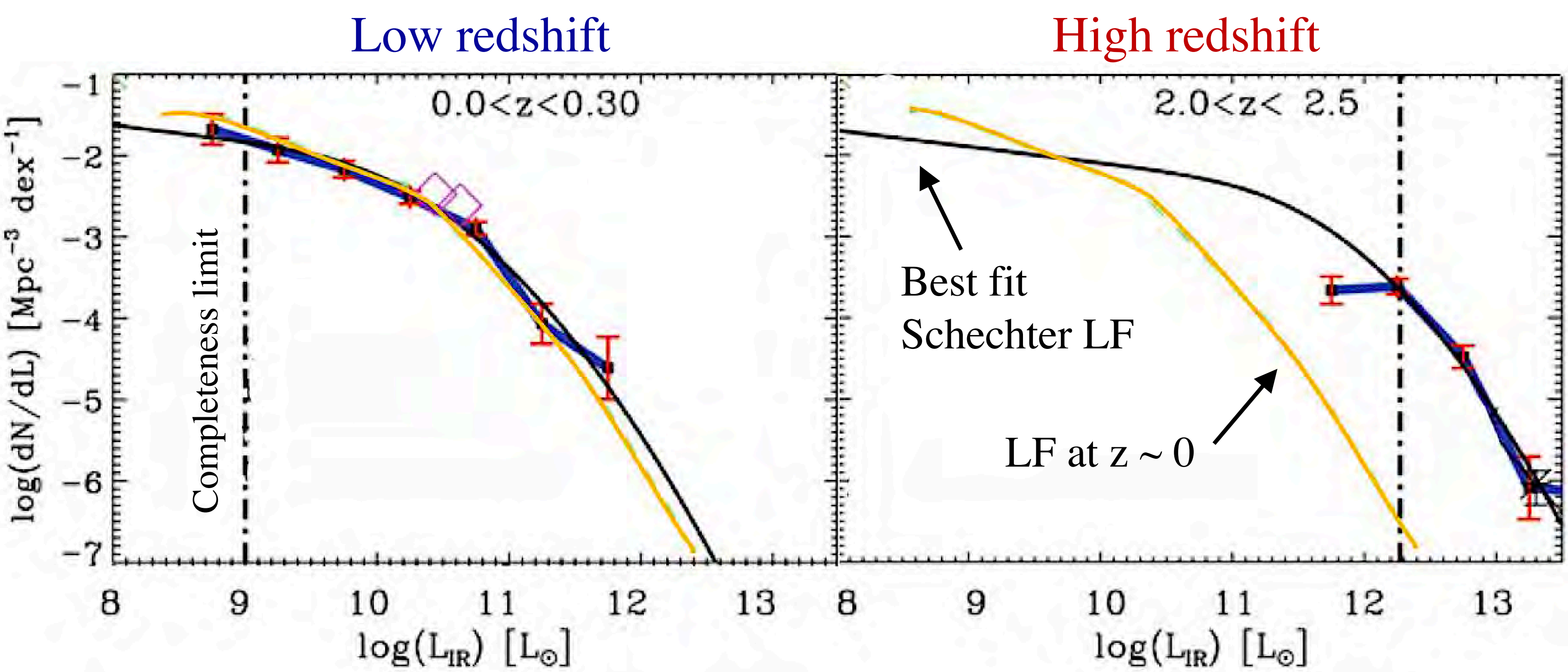
The extrapolated total count is ~ 10^{11} galaxies over the entire sky



Evolution of Galaxy Luminosity Func.

There as an overall brightening of galaxies at higher redshifts, but the effect is strongest for the dwarf galaxies

There is also a flattening of the faint end slope of the LF



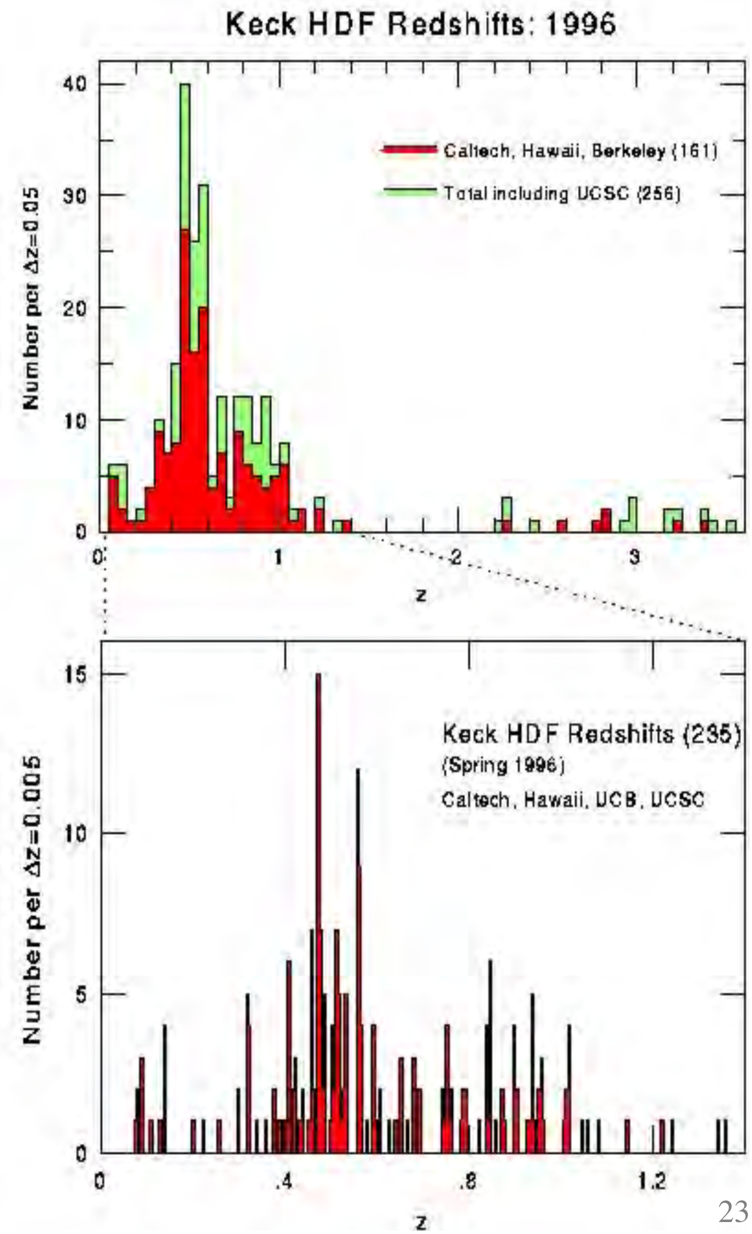
The bulk of the regular, "Hubble sequence" galaxies did not evolve much since $z \sim 1$

Deep Redshift Surveys

To really understand what is going on, separate the effects of luminosity and density evolution, and break the degeneracy between distance and intrinsic luminosity at a given flux, we need *redshifts*

A proven powerful combination is to use deep HST imaging (e.g., HDF N and S, HUDF, GOODS field, etc.) and Keck or other 6 to 10-m class telescope for spectroscopy

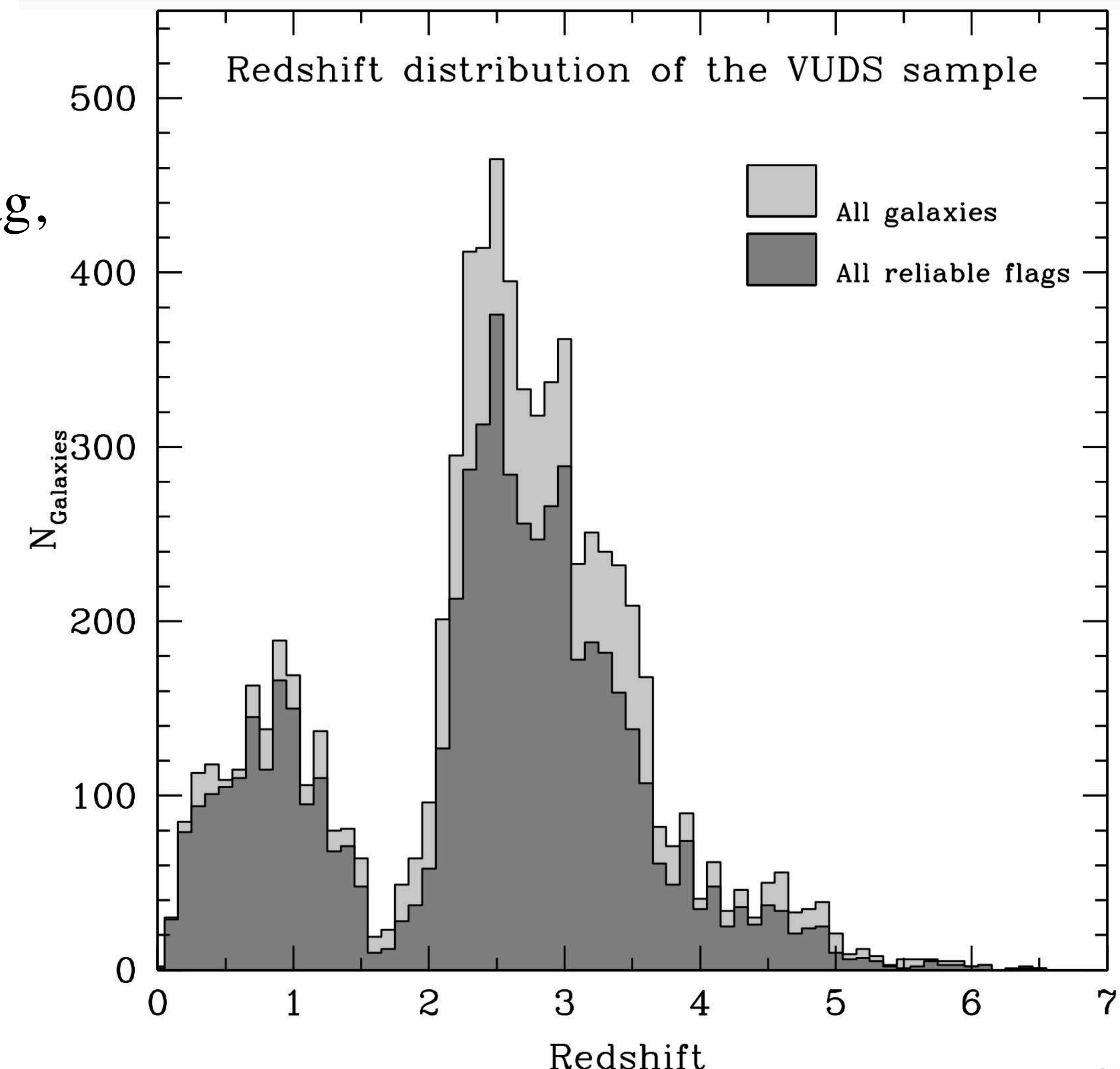
Hubble Deep Field With Keck Redshifts



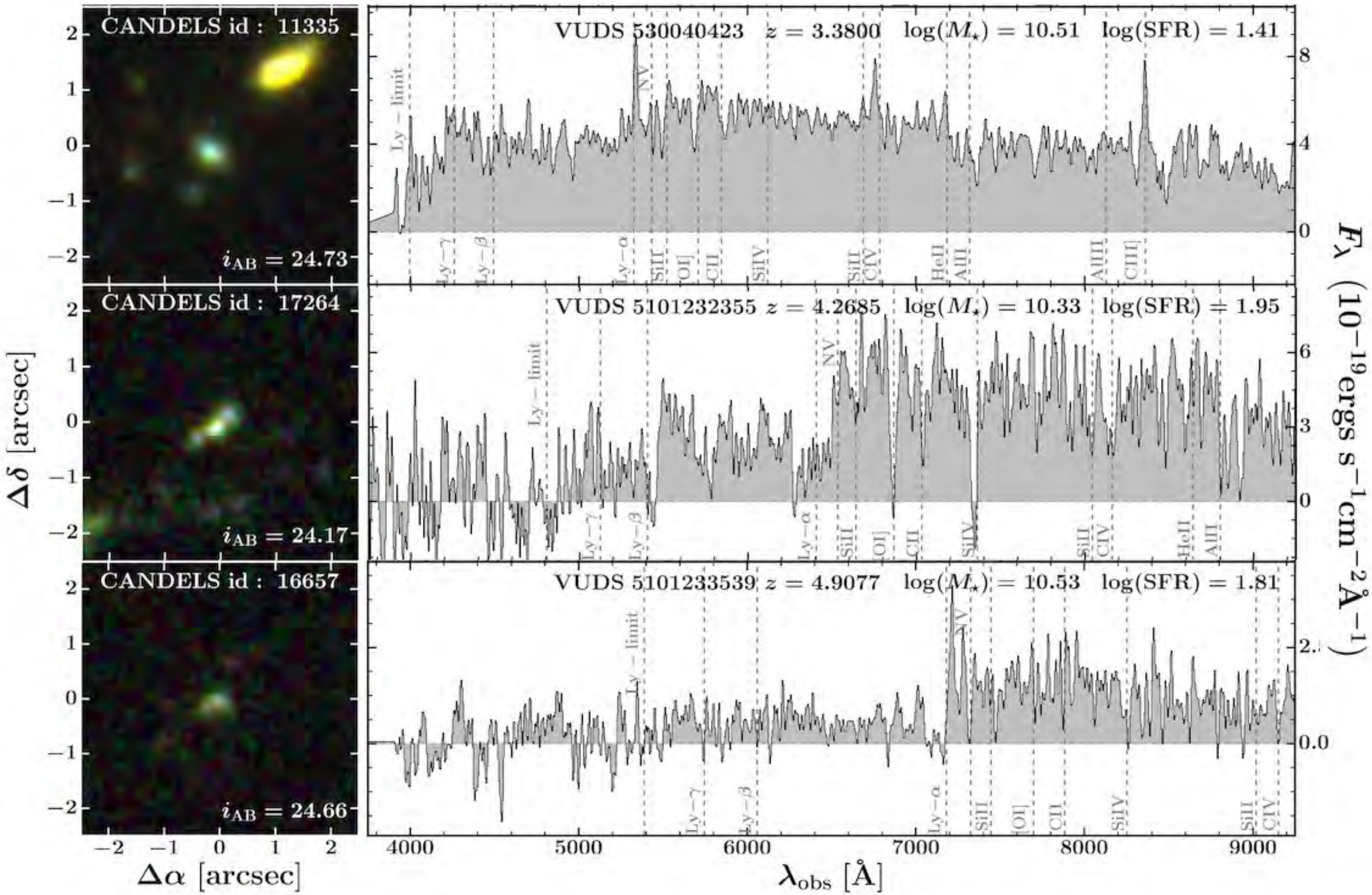
The VLT Ultra-Deep Survey (VUDS)

(Le Fevre et al. 2015)

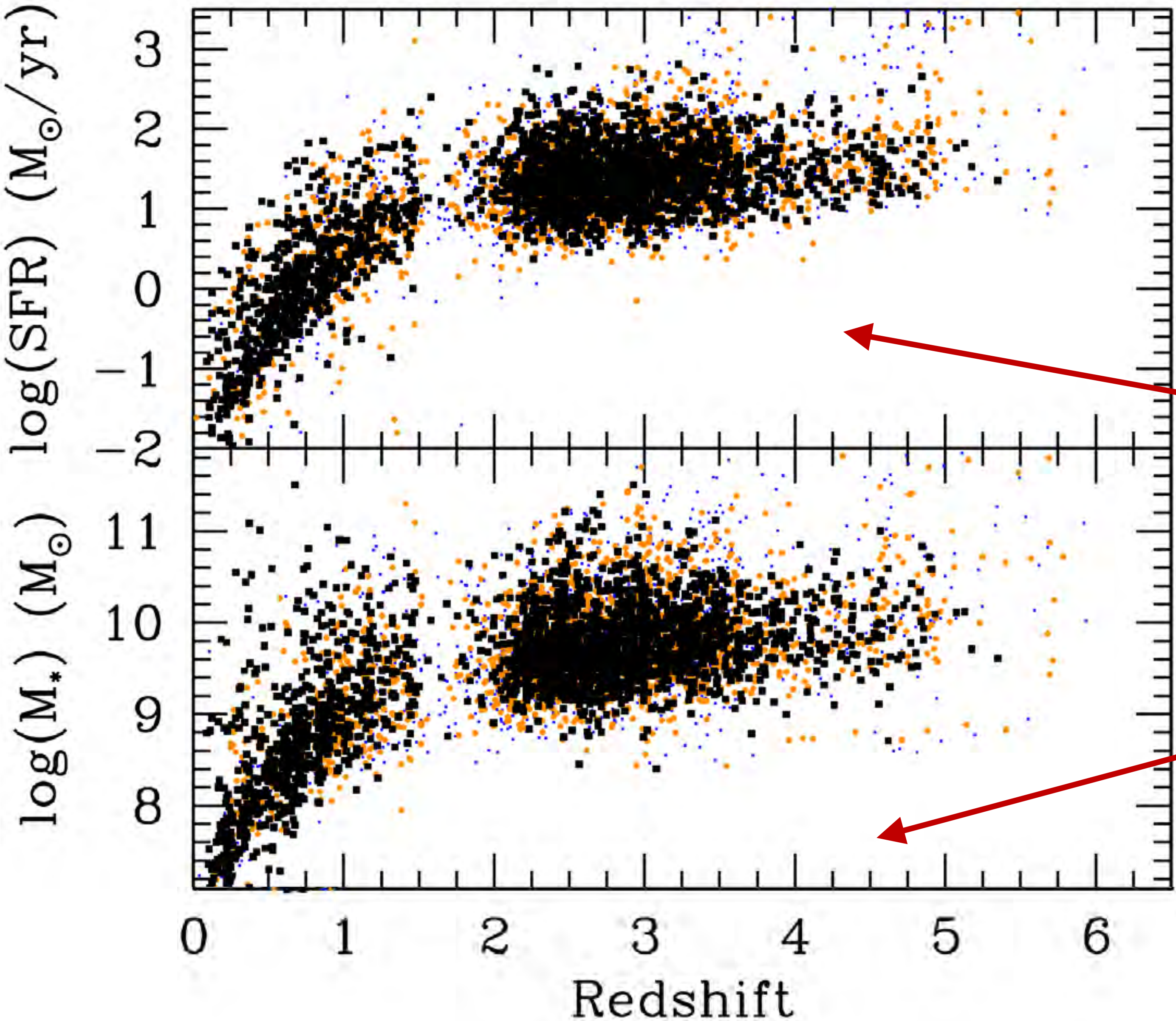
- 10,000 galaxies in 3 Hubble deep fields
- Complete to $i = 25$ mag, reaching out to $i \sim 27$ mag
- Mostly $0 < z < 5$, but reaching out to $z \sim 6.5$



Examples of VUDS Spectra



Properties of VUDS Galaxies



Galaxies here missing due to the sample depth (too faint)

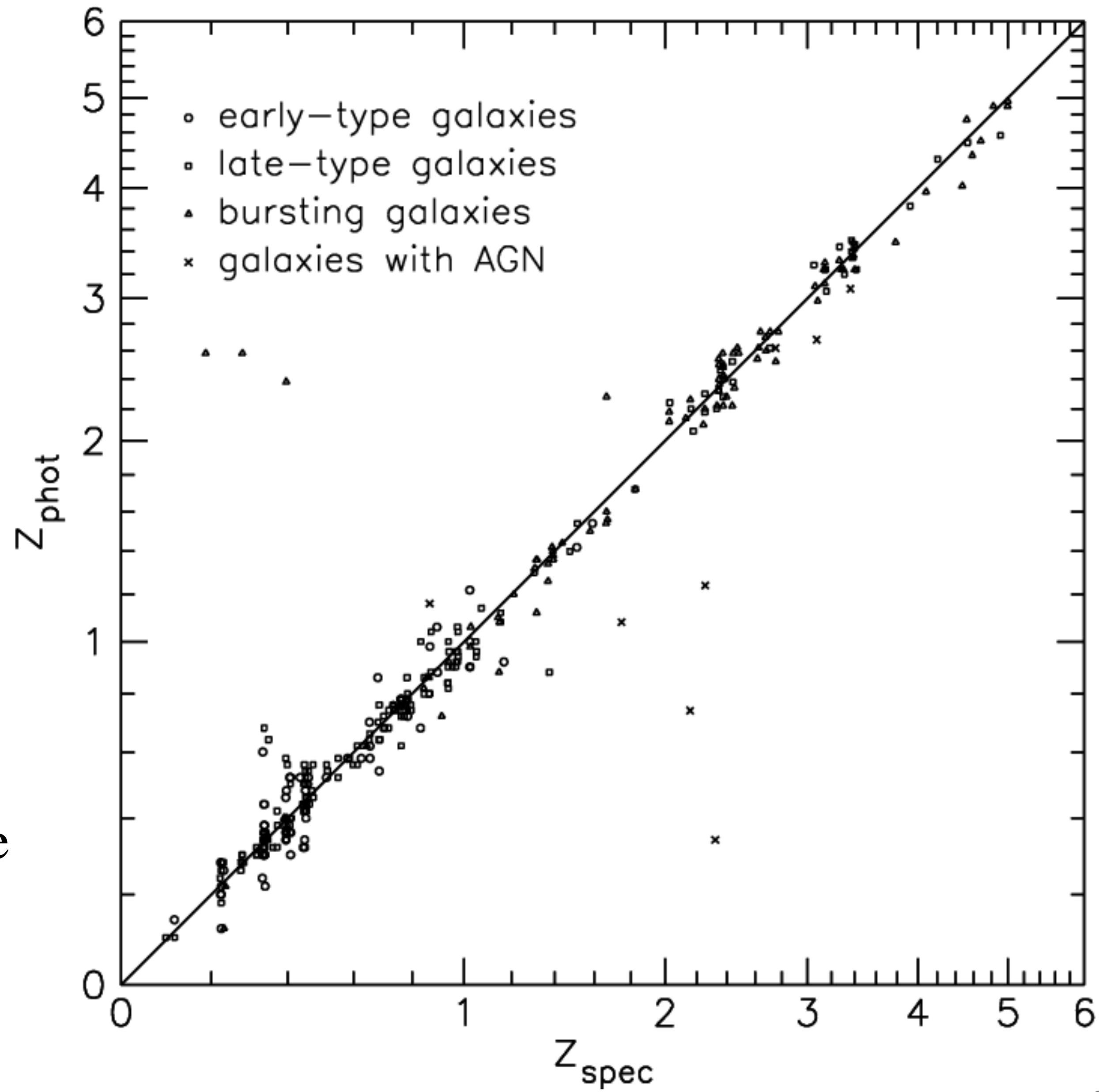
Photometric Redshifts

Fit galaxy model spectra at different *z*'s to observed colors

Given enough bands, and good photometry, one can do remarkably well, but some outliers will always happen

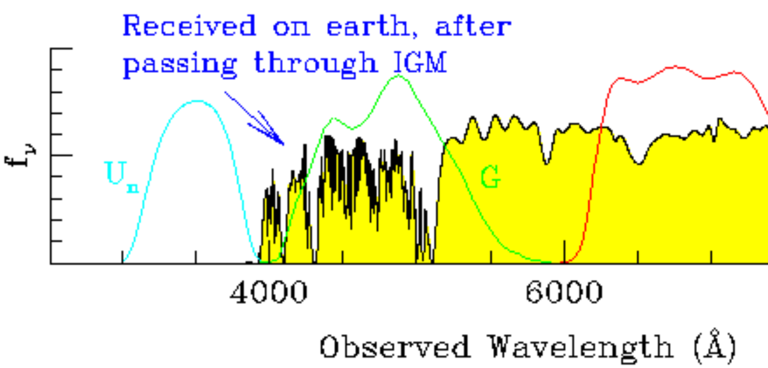
Still, this is a lot cheaper than doing a real spectroscopy…

Modern approaches use machine learning and a lot of statistical modeling

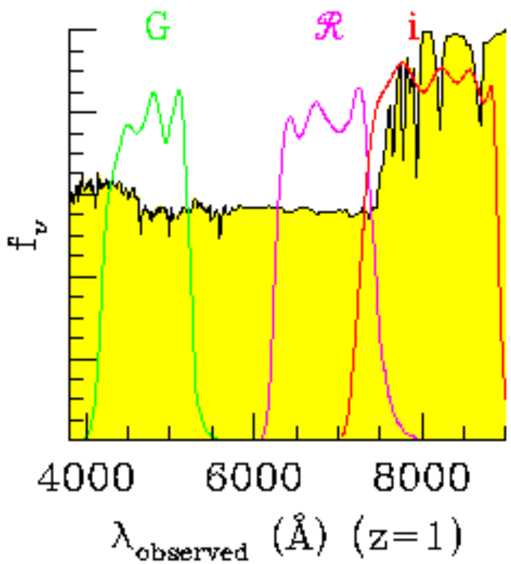


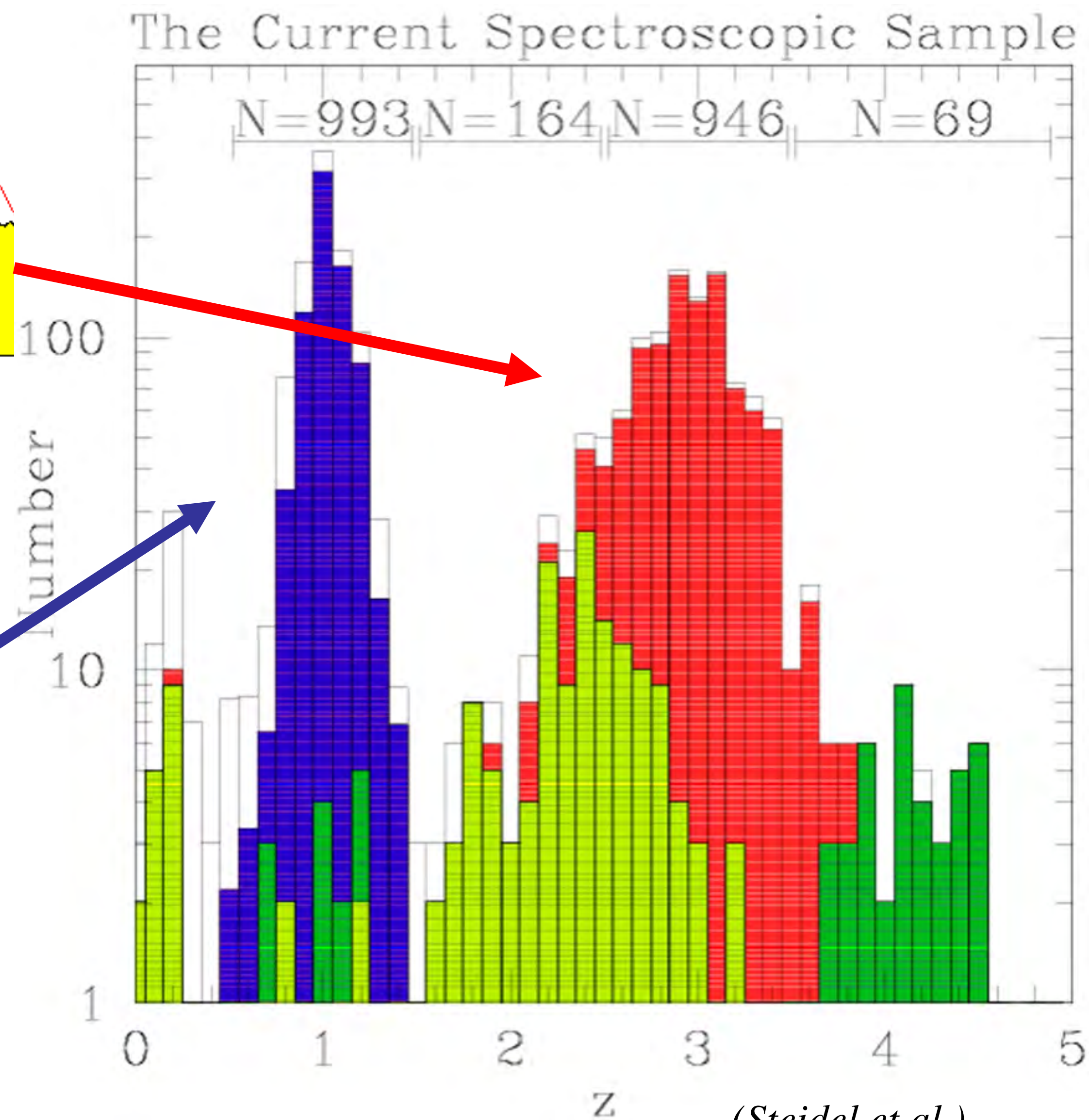
Presence of continuum breaks is an especially powerful in photometrically selecting galaxies in some redshift range

Lyman break



Balmer break

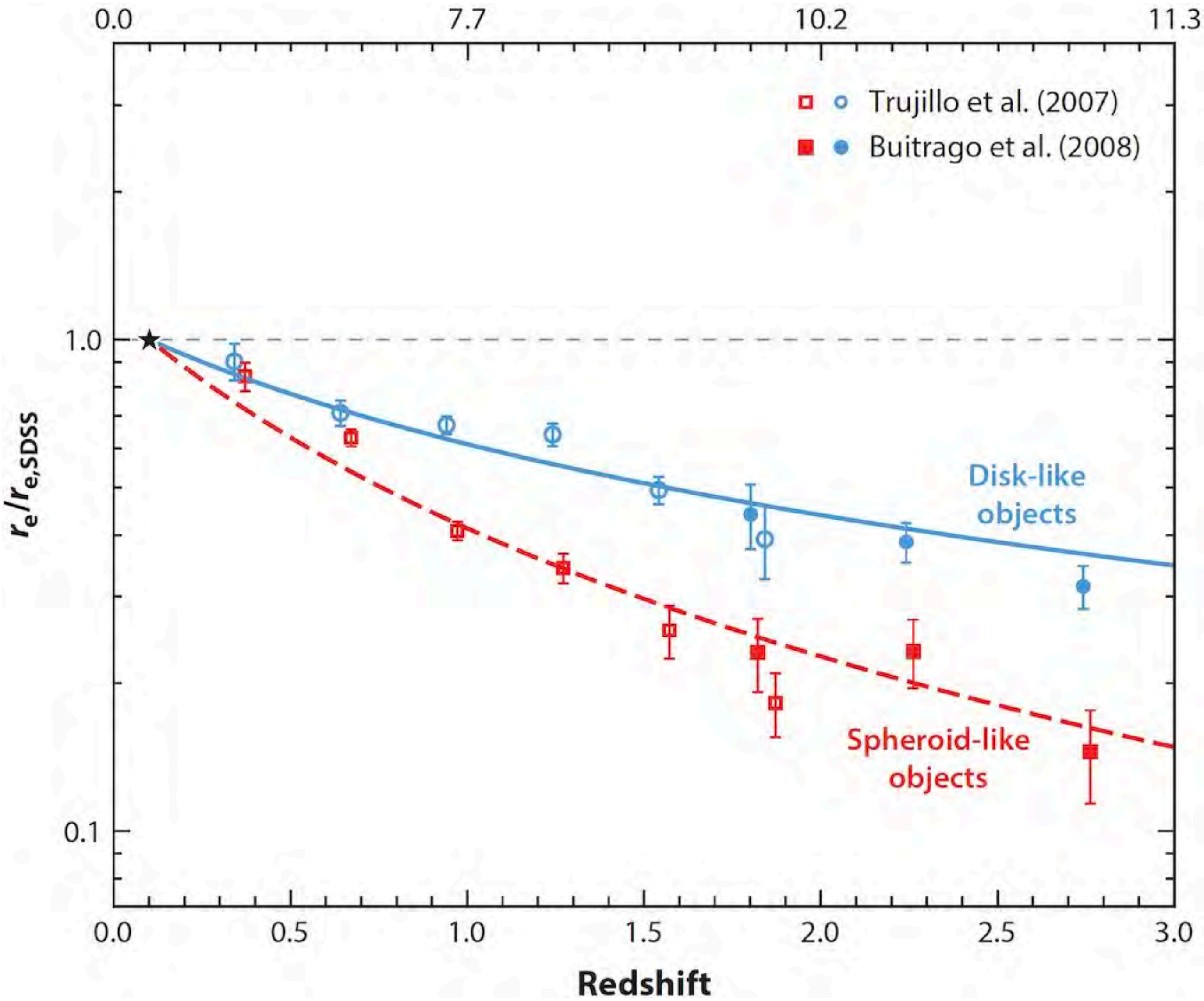




(Steidel et al.)

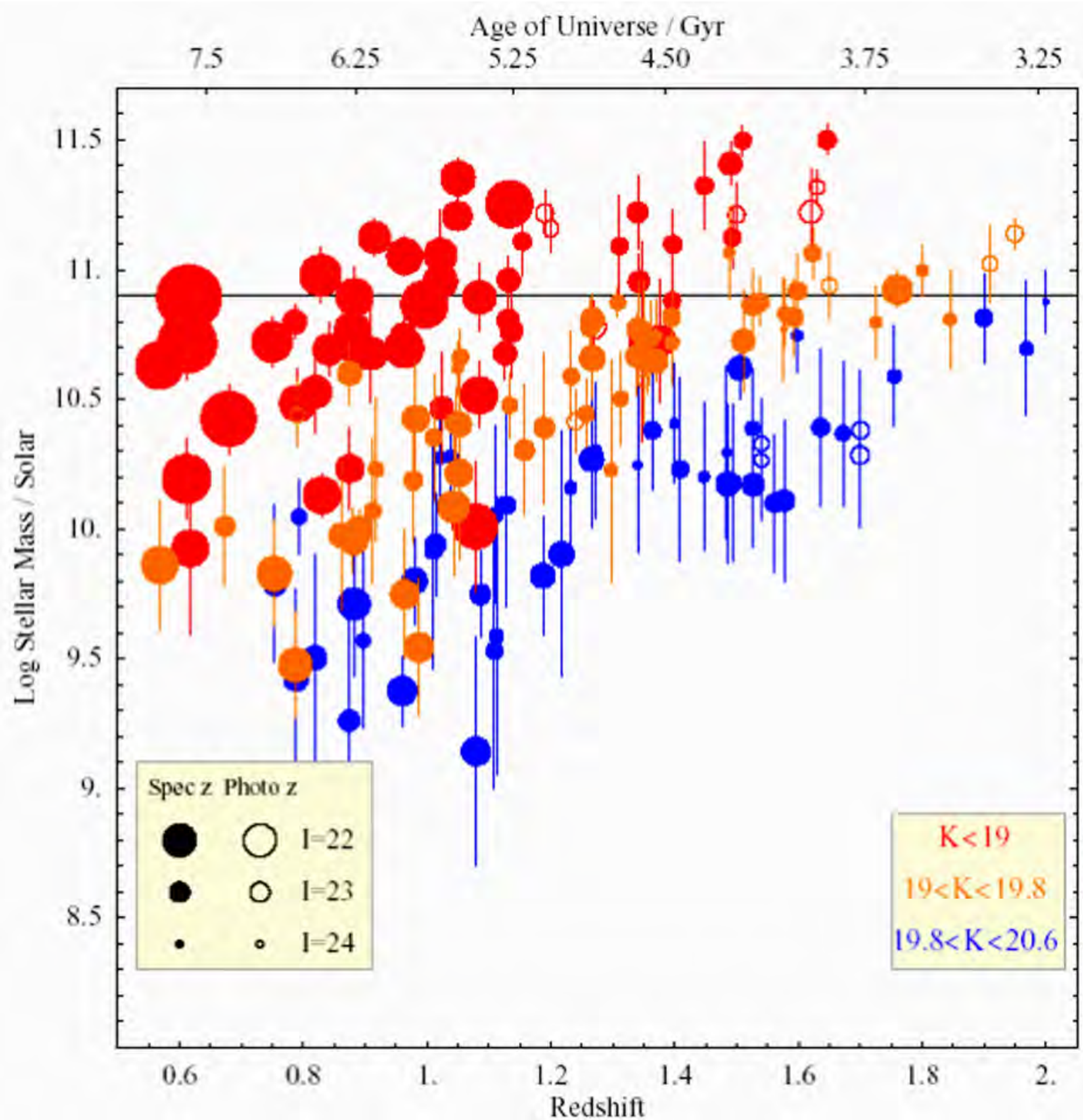
Evolution of Galaxy Sizes

HST imaging suggests that *galaxies were smaller in the past*



Evolution of Galaxy Masses

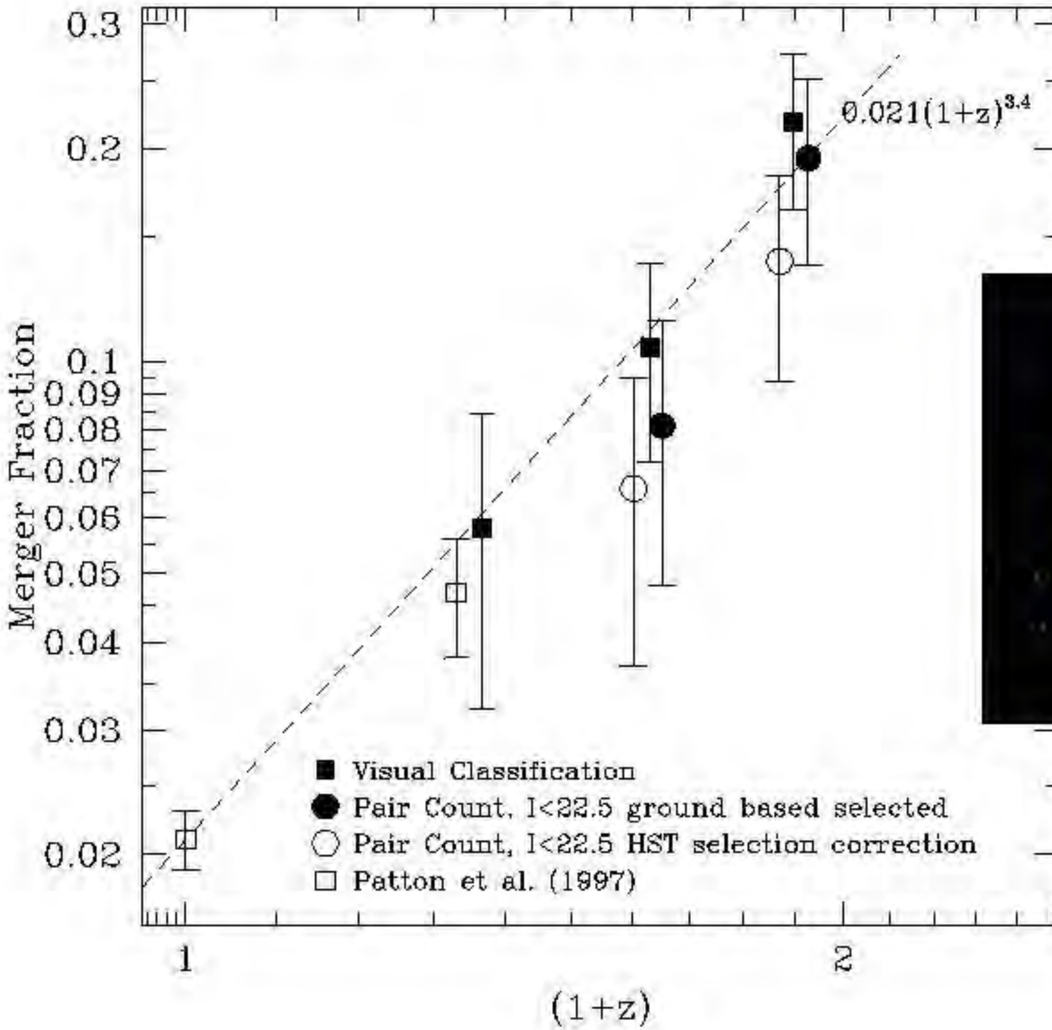
The more massive galaxies evolve less, i.e., they are already in place at $z \sim 1$ - 2, whereas most of the evolution at lower z' s is for the low mass systems - seemingly opposite from what one may expect in the hierarchical scenario! (this is caled "*galaxy downsizing*")



Evolution of the Merger Rate

Merger fraction

~ (1 + z) $^{3.4}$

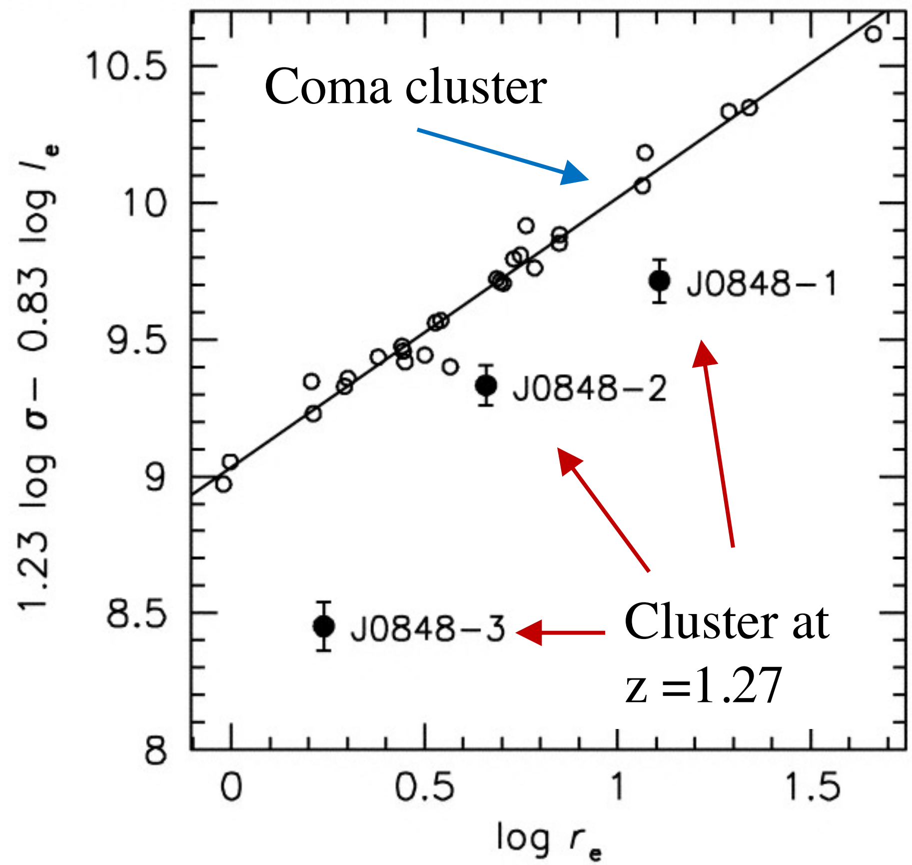


(LeFevre et al. 2000)

Good evidence for a rapid rise in merging fraction at higher z's, but conversion to mass assembly rate is not straightforward

Scaling Relations as Evolution Probes

They are our sharpest probe of galaxy properties - and thus potentially of galaxy evolution (note that the relations themselves may be evolving!)



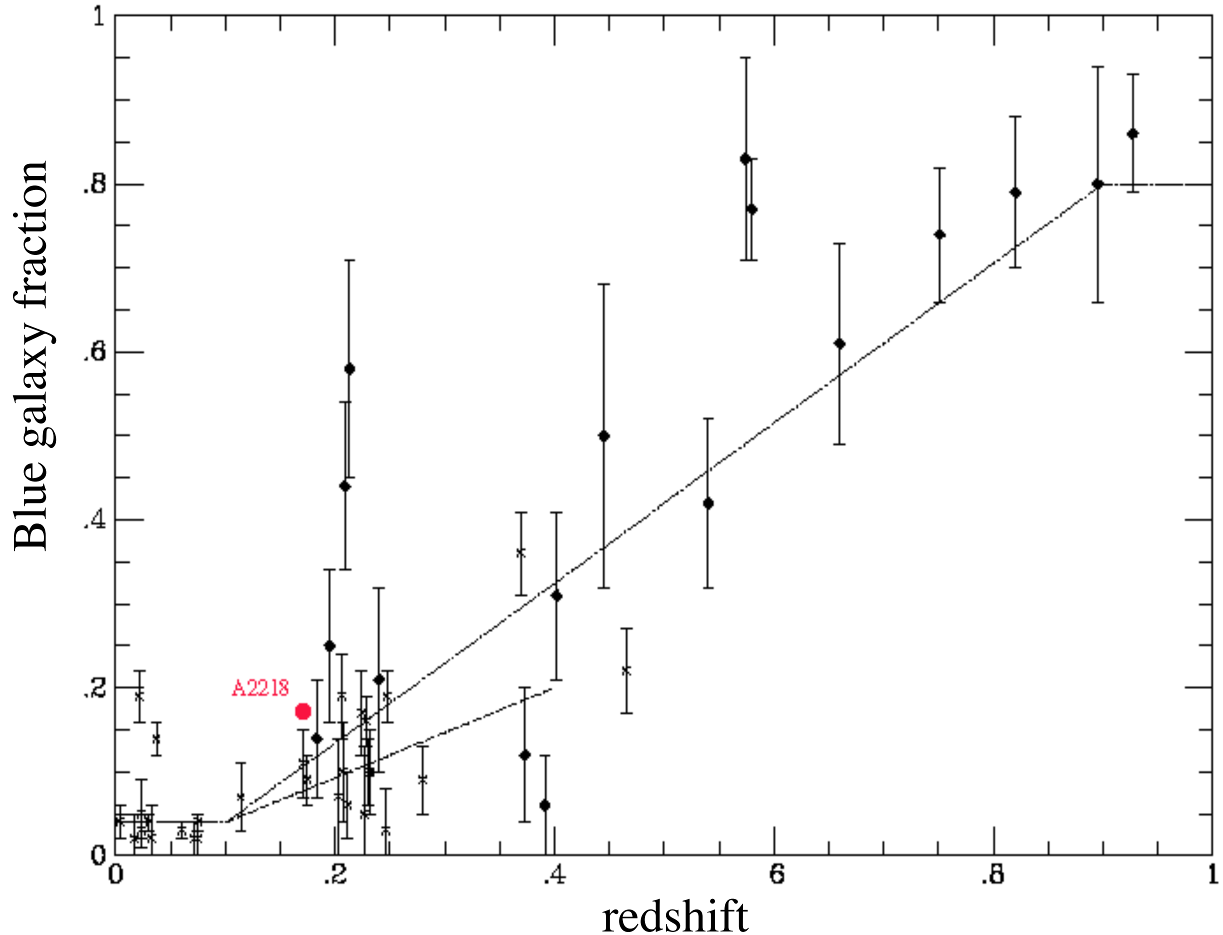
Fundamental Plane evolution →

van Dokkum & Stanford, 2003

Studies of the FP in both clusters and field out to $z > 1$ indicate that ellipticals were brighter in the past, but the data are consistent with a model where they are formed at high redshifts ($z > 3$, say) and evolve nearly passively since then

Galaxy Evolution in Clusters

Generally, we may expect a systematic difference in galaxy evolution processes in different large-scale environments, due to galaxy encounters, gas ram pressure stripping in clusters, etc.

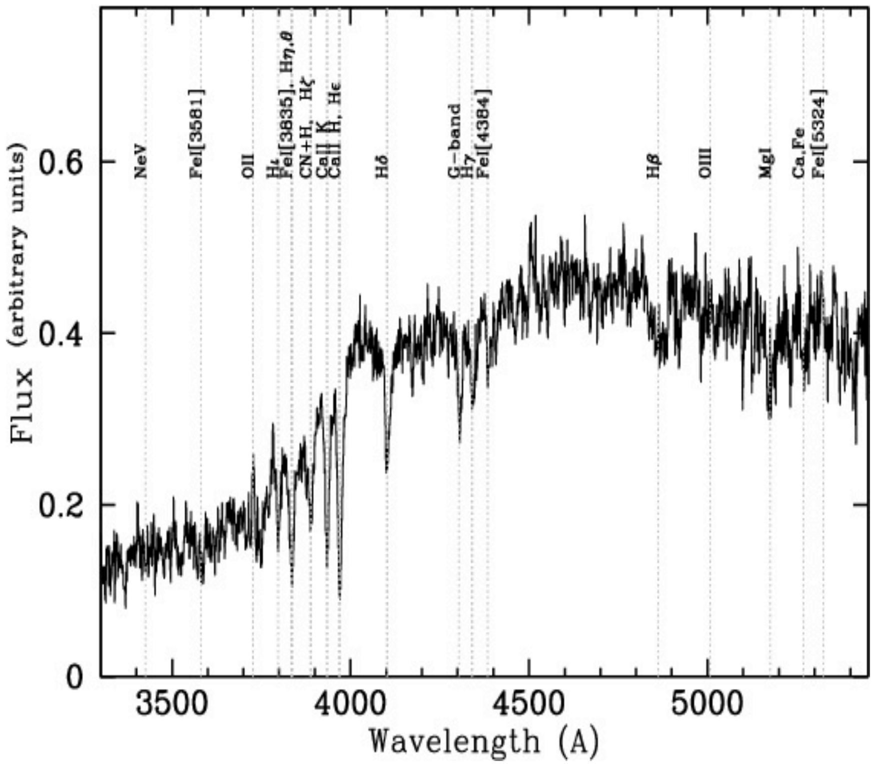


The first observational evidence was the **Butcher-Oemler effect:** the fraction of blue galaxies in clusters increases dramatically at higher redshifts

Post-Starburst Galaxies

- These blue galaxies in distant clusters are a mix of regular star-forming spirals, some AGN, and a *new type:*

- There is a significant population of ***post-starburst galaxies*** in distant clusters (~20%), these have K+A (or E+A) spectrum, showing both the features of a K-star (typical E galaxy spectrum) plus the strong Balmer absorption lines of an A star (~ 1 Gyr old)

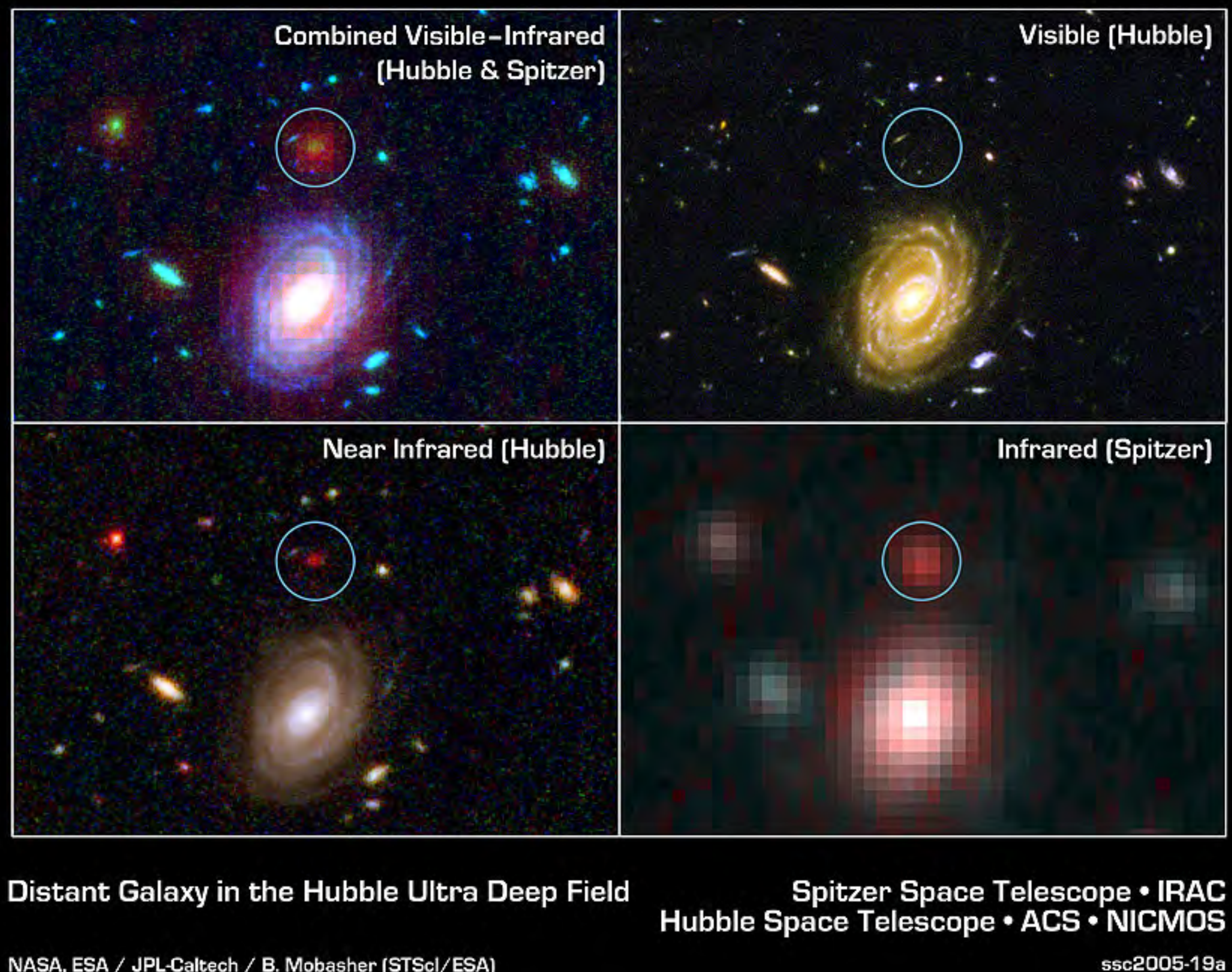


- This is probably related to the conversion of S0 to S galaxies (morphology density) and the Butcher-Oemler effect

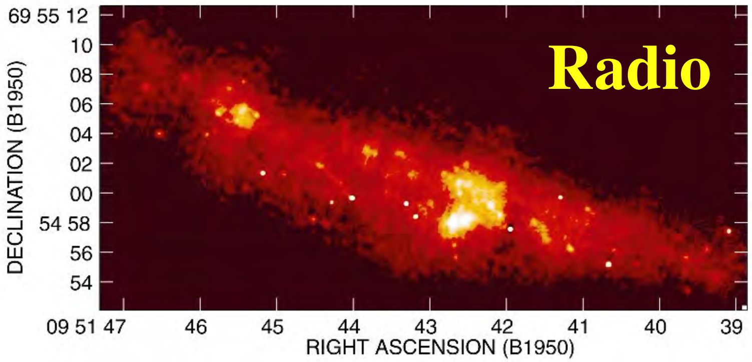
Evolution of Spirals in Cluster Environment

- Possible scenario for spirals transforming into S0's:
  - Infalling spiral galaxies at $z \sim 0.5$
  - Triggering star formation
  - Starburst (emission-line galaxies)
  - Gas is stripped by intracluster medium
  - Post-starburst galaxies
  - Tidal interactions heat disk
  - Stars fade
  - The products are S0's at $z \sim 0$
  - Morphological segregation proceeds hierarchically, affecting richer, denser clusters earlier. S0's are only formed after cluster virialization
- But there are S0's also in group environments, so this is not the only way to make them

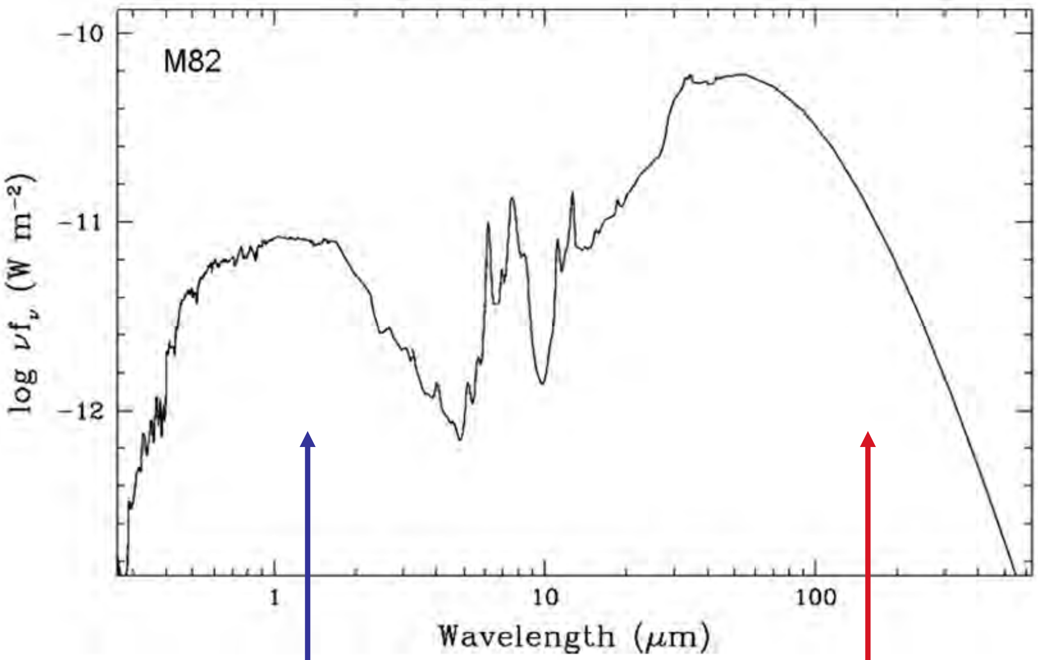
Dust Obscured Galaxies



M82, a Prototypical Starburst Galaxy



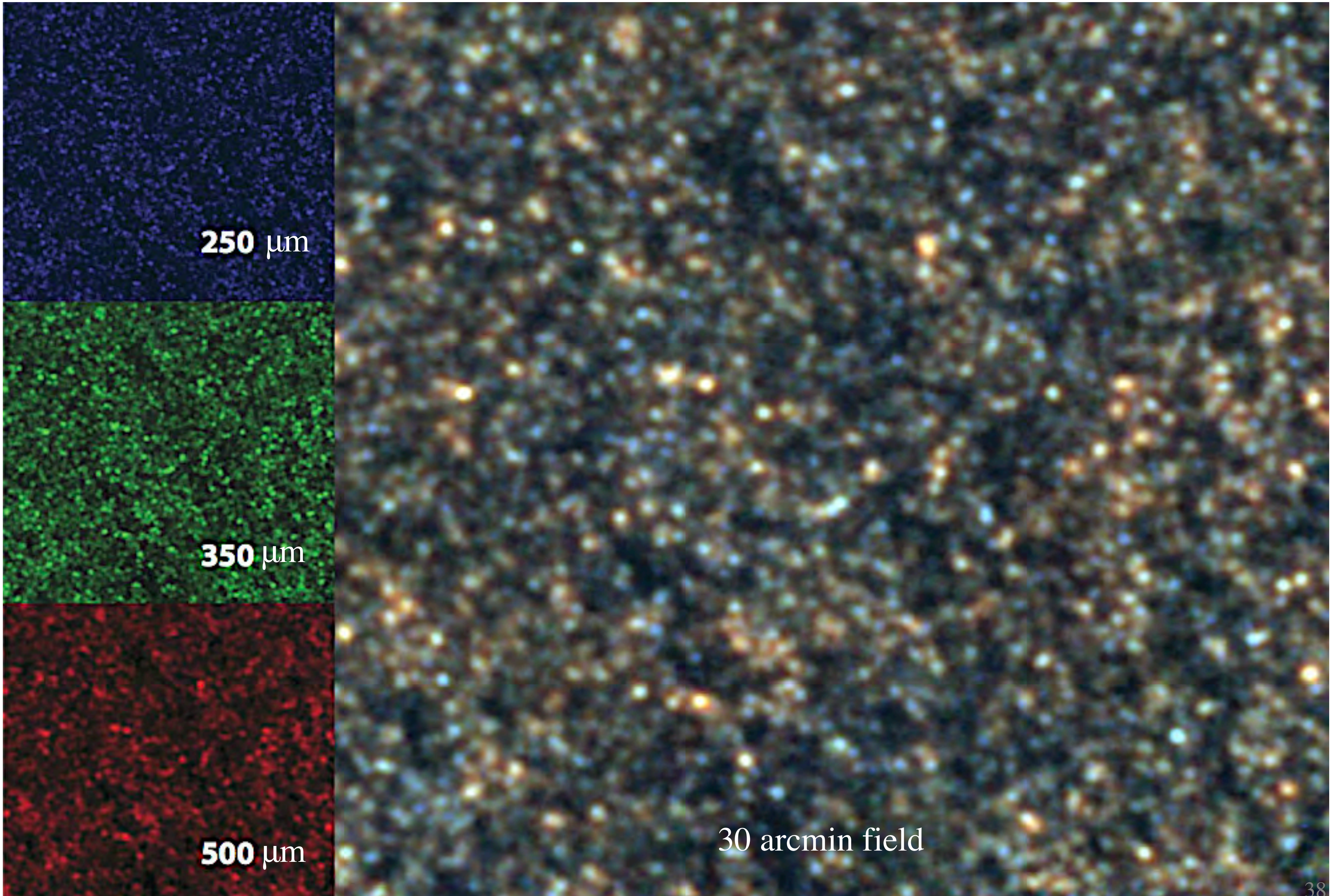
The spectrum of M82, UV to sub-mm



Unobscured starlight

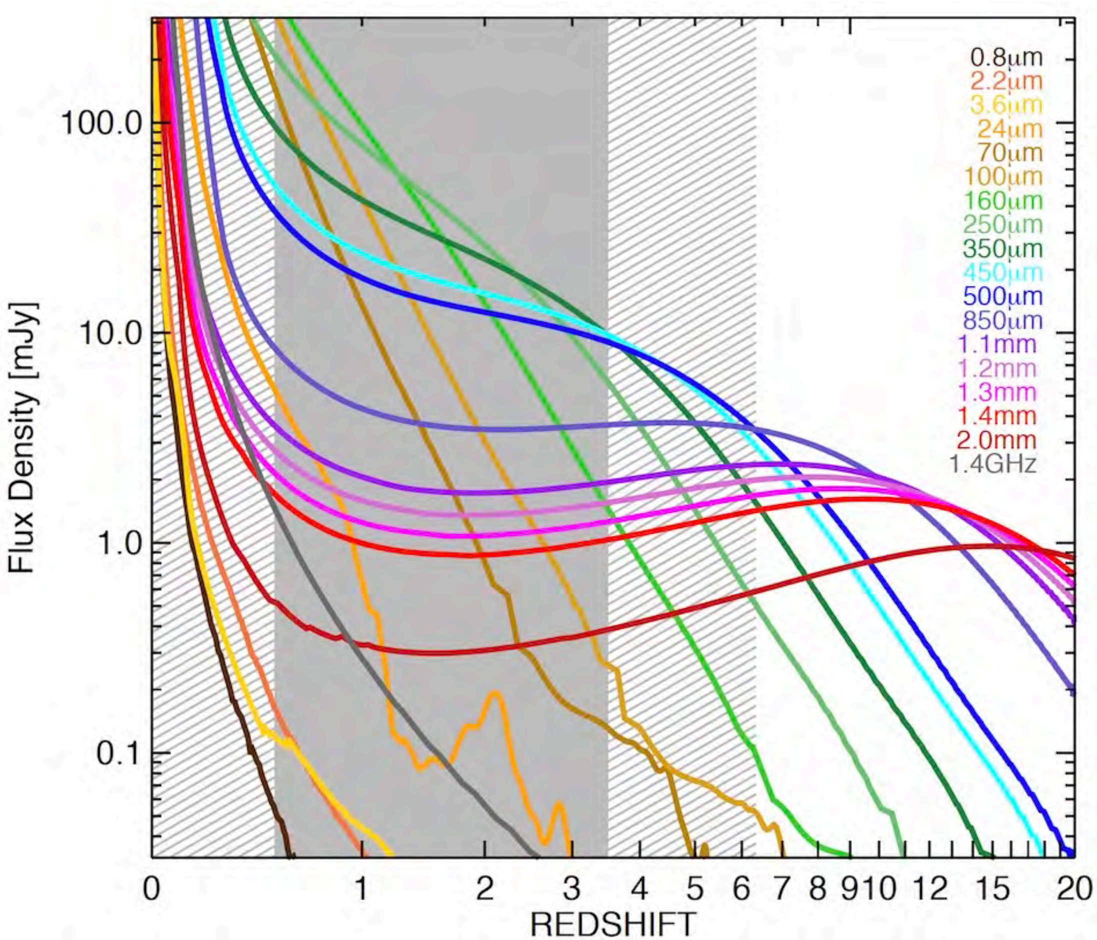
Reprocessed radiation from dust

Herschel FIR Image of the GOODS-N Deep Field



Sub-mm K-Corrections

As dusty galaxies are redshifted, the observed bandpass climbs the Wien side of their thermal emission spectrum, resulting is a negative K-correction - so distant obscured sources may even get brighter at higher z' s, and easier to detect

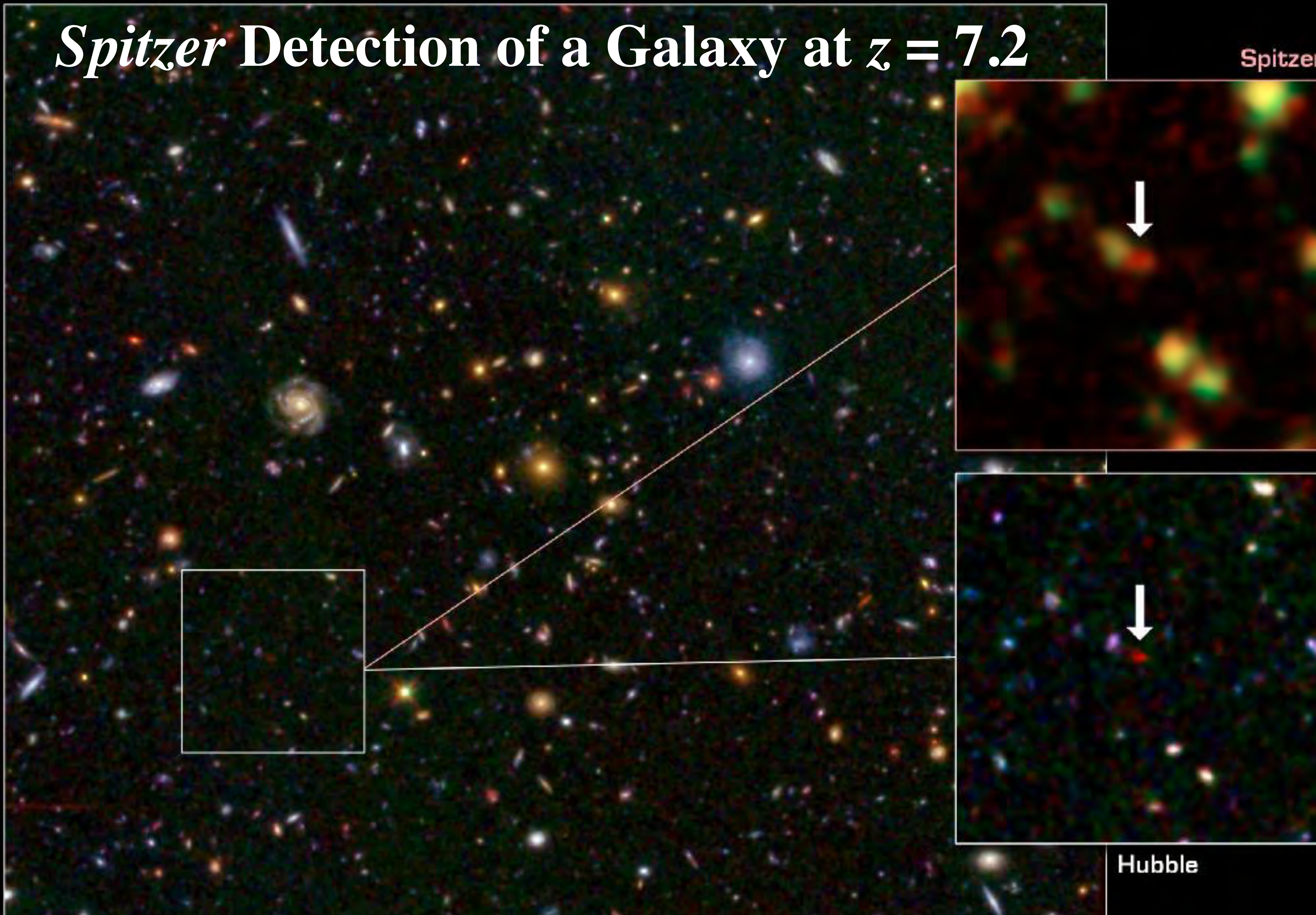


← At the shorter wavelengths sources get dimmer at higher redshifts

← But at the longer wavelengths they can get brighter

This enables their detections out to very high redshifts

Spitzer Detection of a Galaxy at $z = 7.2$



And Now With the JWST

Galaxy Evolution: Key Points

- Two aspects: *assembly of the mass through a hierarchical merging* (relatively easy to model), and *the evolution of their stellar population and gas content* (mush messier and harder to model)
- *Stellar population synthesis* is well established, but it requires assumption about the star formation history, stellar IMF, etc.
- Observational probes include *deep galaxy counts: fainter galaxies are bluer*, indicating *more star formation in the past*
- *Deep redshift surveys are necessary* to separate the effects of the luminosity and density evolution, but they are observationally expensive. *Photometric redshifts* can be a good substitute
- *Dust-obscured star formation* is a key issue
- Galaxy evolution is *different in the clusters and the lower density regions*, due to the dynamical processes