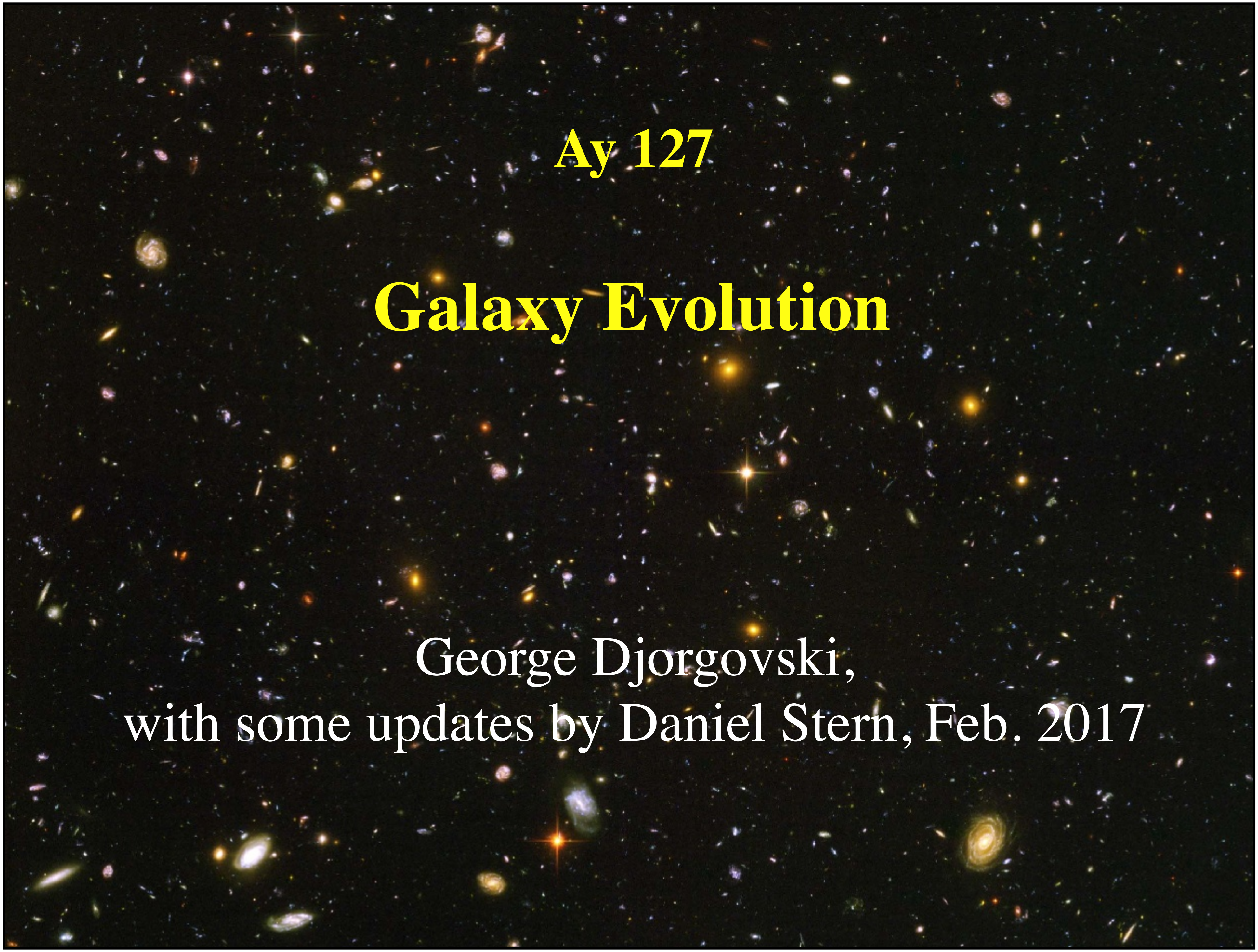

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Galaxy Evolution

George Djorgovski,
with some updates by Daniel Stern, Feb. 2017

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

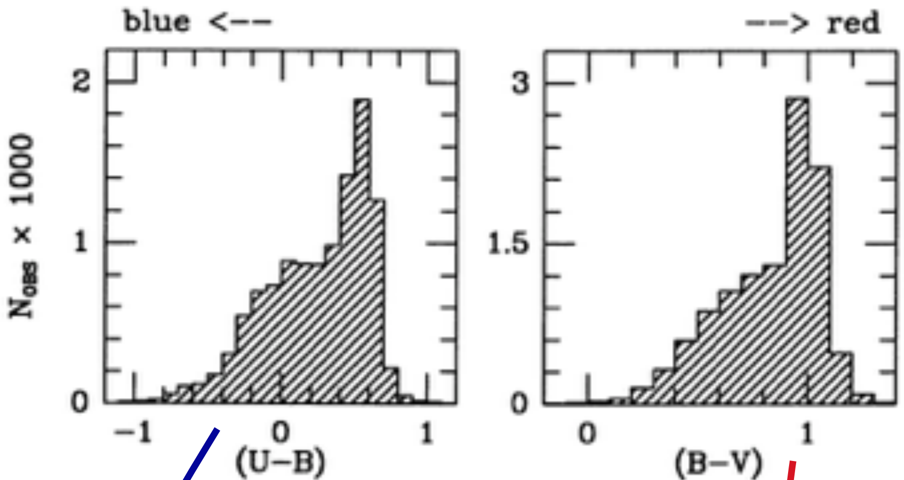
1. **Assembly of the mass:** numerical modeling of structure formation. Fairly well advanced, but it is hard to treat any dissipative processes very accurately. Well constrained from cosmology (LSS formation).
2. **Evolution of stellar populations:** based on stellar evolution models, and fairly well 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

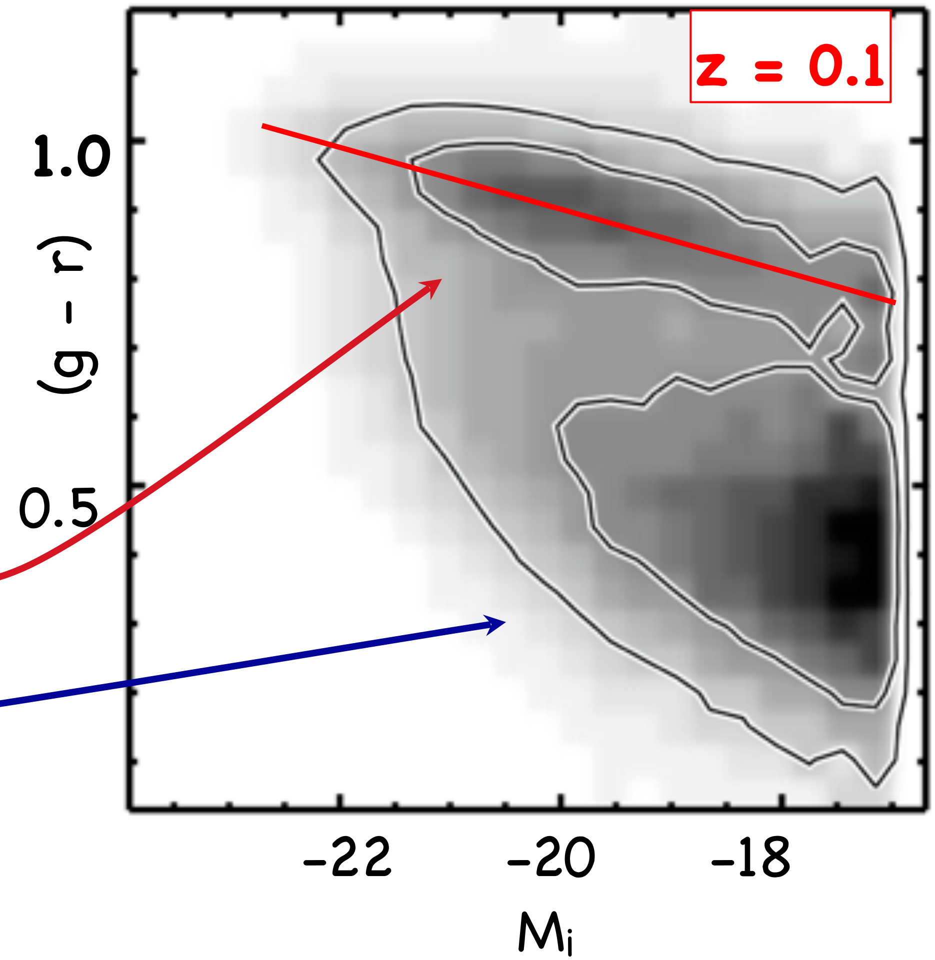
- **Deep imaging surveys** and source counts, at wavelengths from UV to FIR
  - Sources are always selected in emission, and any given band has its own selection effects and other peculiarities
  - With enough bandpasses, one can estimate "photometric redshifts", essentially very low resolution spectroscopy; 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 (**)

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 rest-frame 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

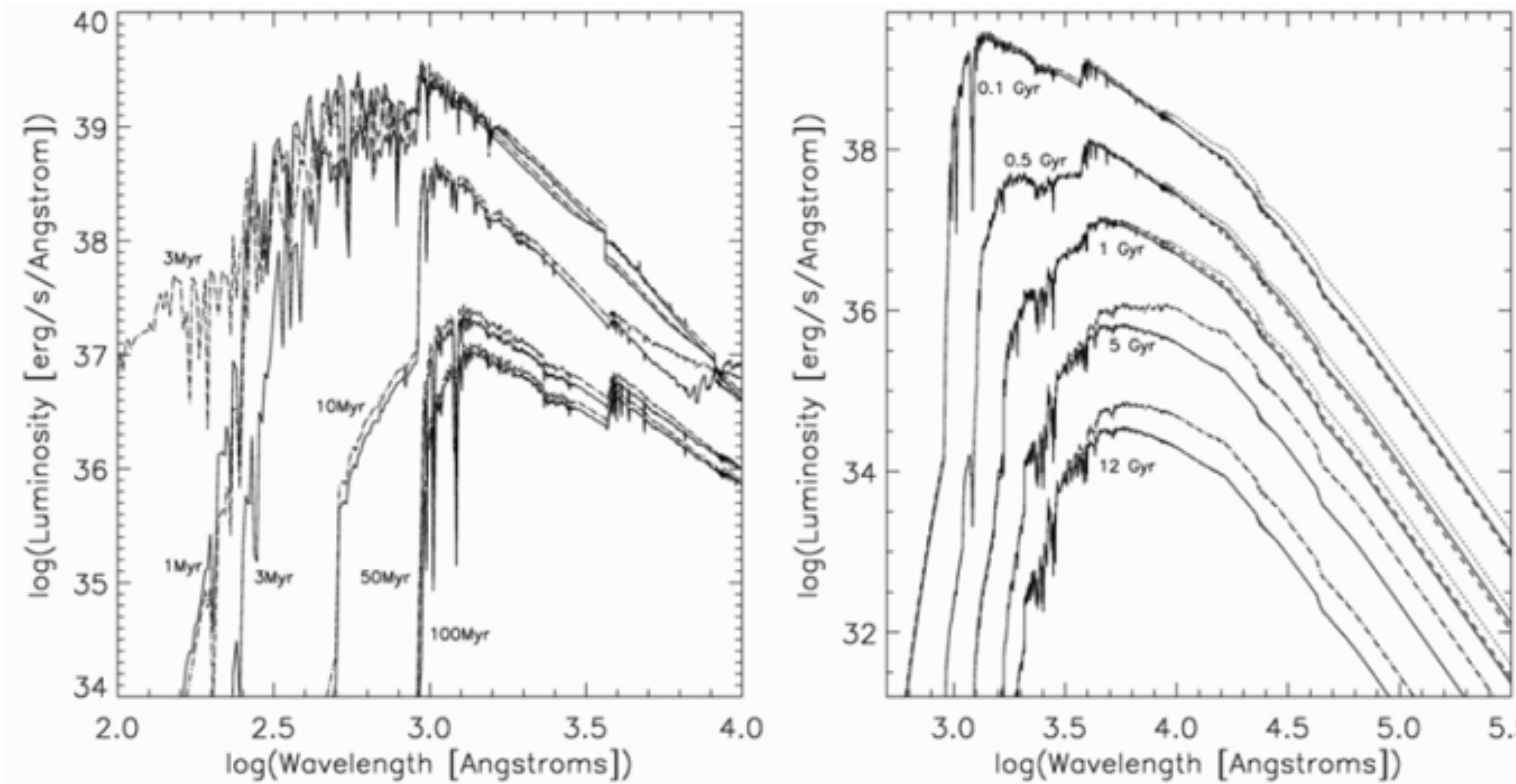
What We Need

- Stellar theory predicts the evolution or (***stellar tracks***) of stars of a given mass. There is some variation among different theoretical models (**)
- Observations give us ***libraries of stellar spectra*** as a function of age, mass, metallicity, etc.
- We need the ***initial mass function (IMF)*** of stars
- All of these are uncertain at very low metallicities and high stellar masses
- We have to assume some ***star formation rate (SFR)*** as a function of time. Popular choices include a sharp burst, a constant SFR, or an exponentially declining one:

$$\frac{\partial M}{\partial t} \propto \exp\left(-\frac{t}{\tau}\right)$$

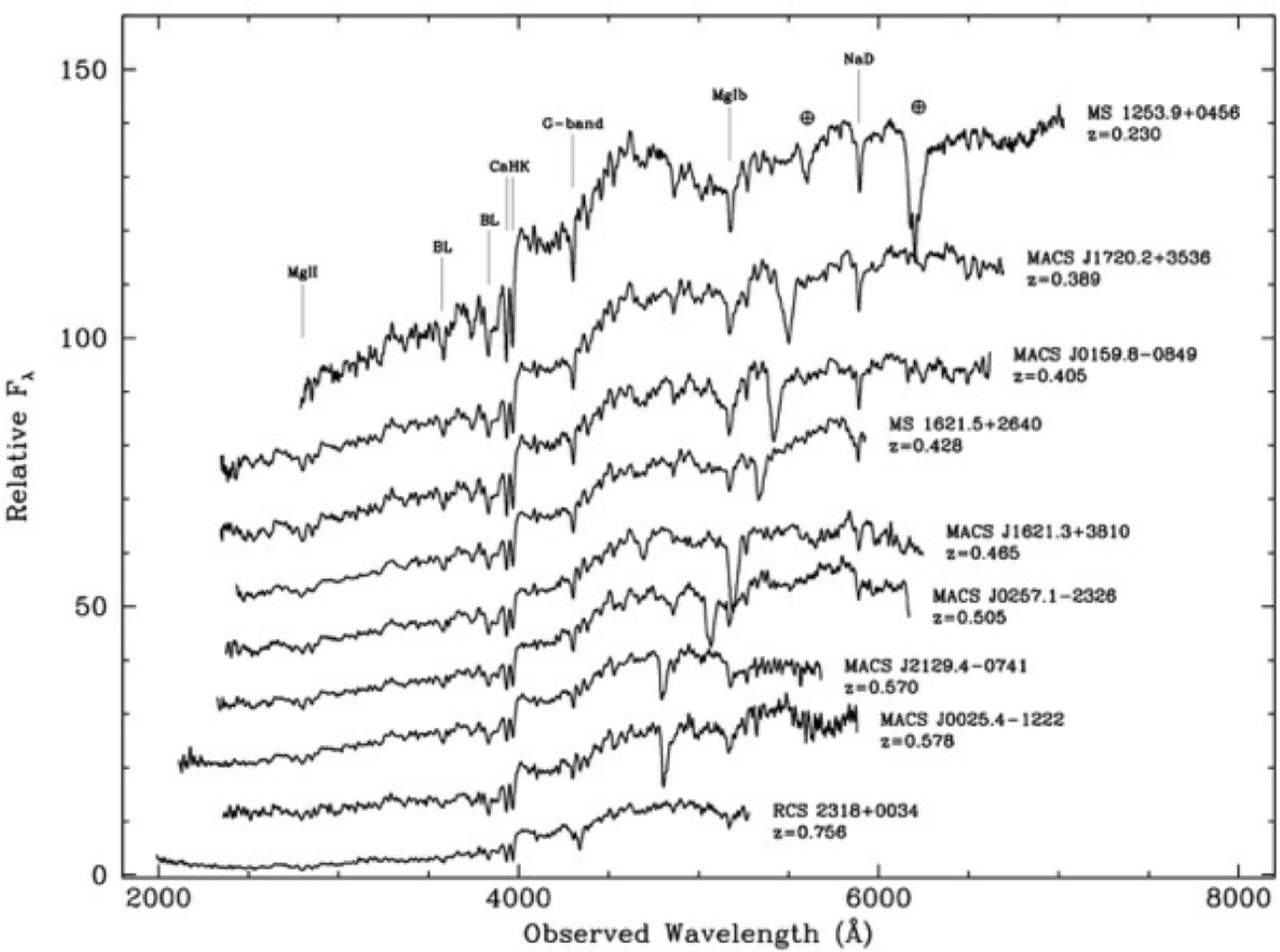
Predicted Spectral Evolution

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



Observed Spectral Evolution

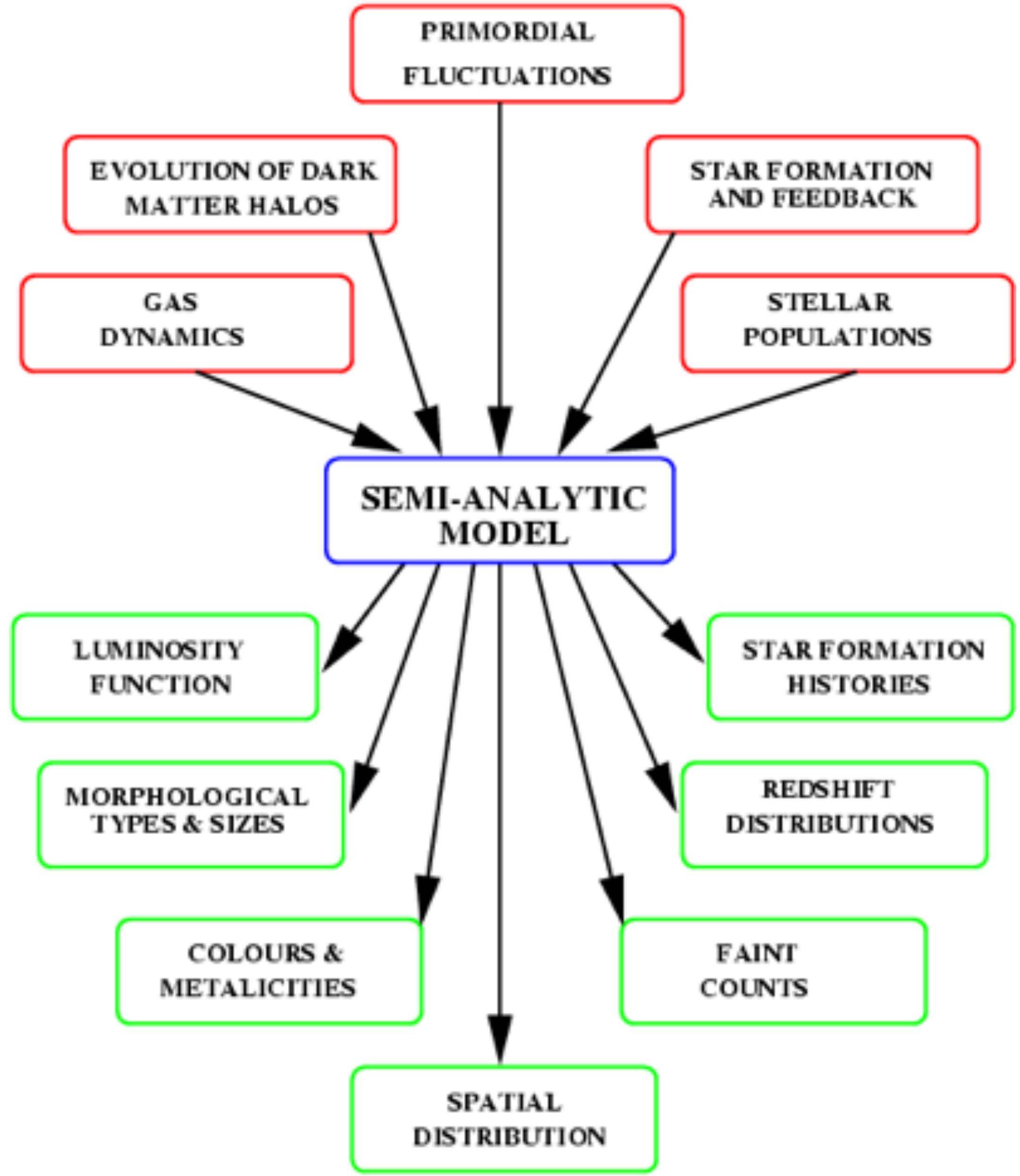
early-type galaxies in massive galaxy clusters (0.23 < z < 0.76)



Semi-Analytical Models

Semi-analytical models claim to match observations using prescriptive methods for star formation and morphological assembly

Warning: Star formation is a complex, poorly constrained phenomenon: provides a weak test of the theory (age of stars ≠ age of structures)

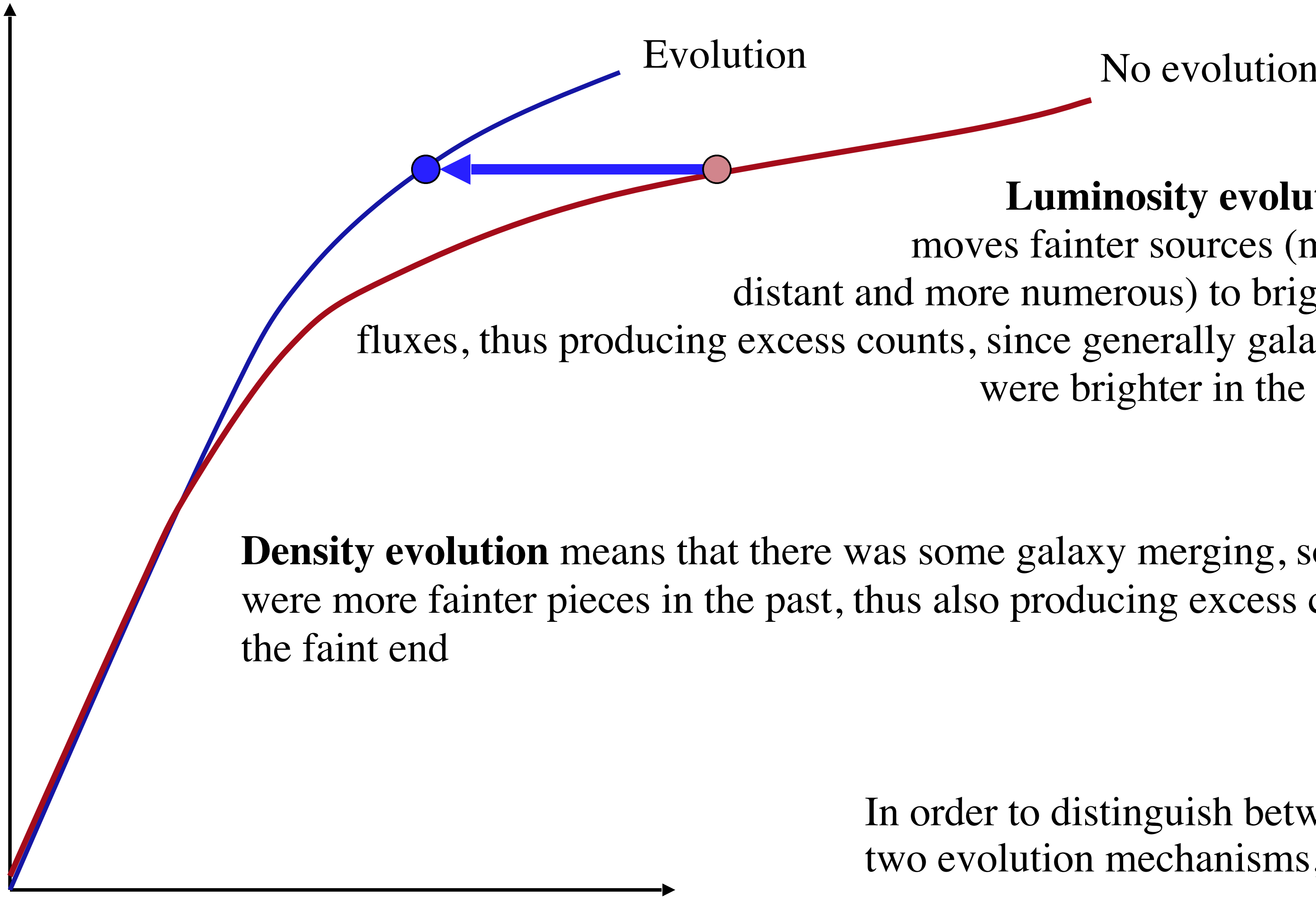


Observing Galaxy Evolution

- 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 you really do need redshifts, to get a true evolution in time, and disentangle the various evolution effects
- The field is split observationally:
  - **Unobscured star formation** evolution: most of the energy emerging in the rest-frame 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

Source Counts: The Effect of Evolution

(at a fixed cosmology!)



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

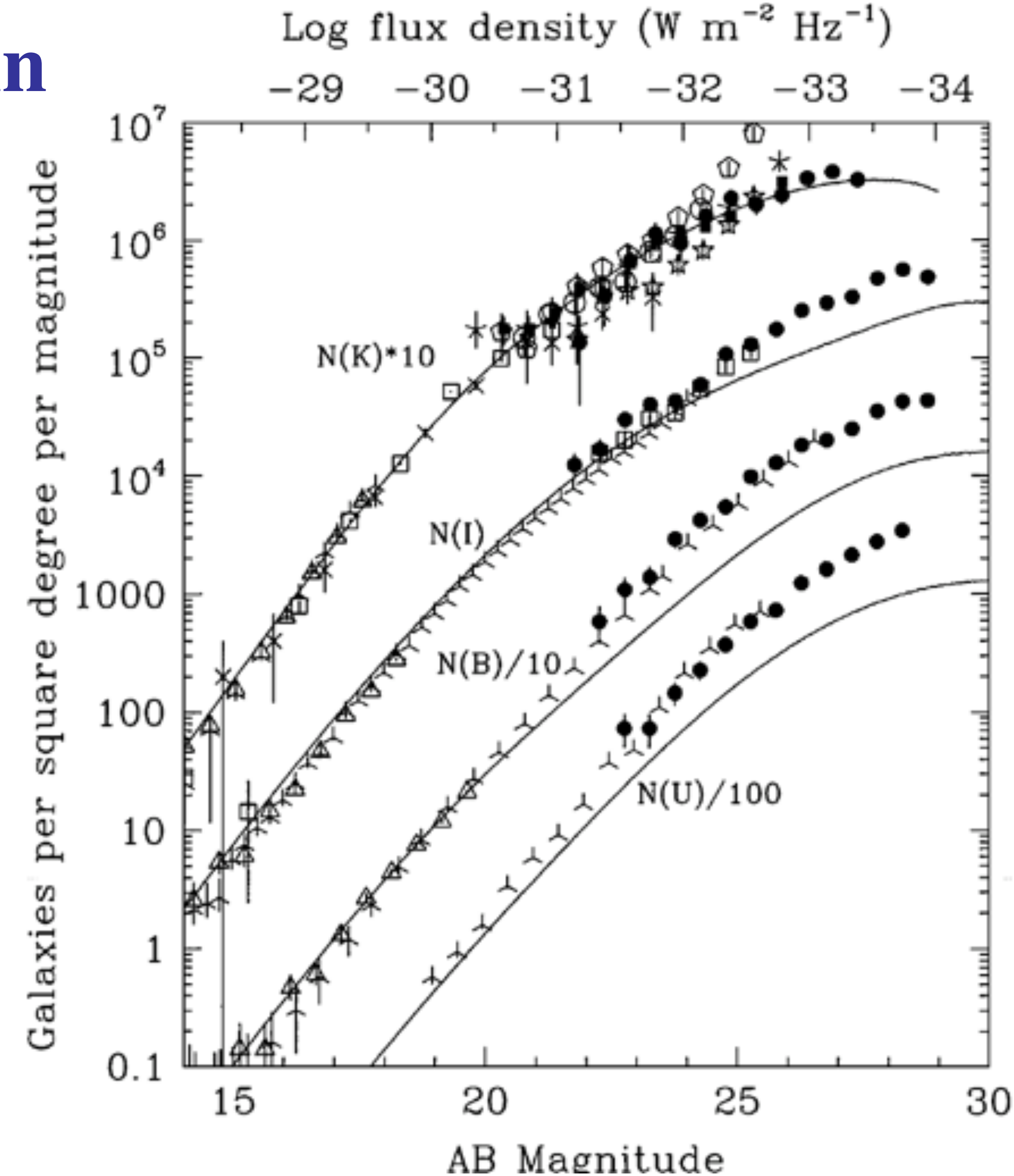
In order to distinguish between the two evolution mechanisms, redshifts are necessary

Galaxy Counts in Practice

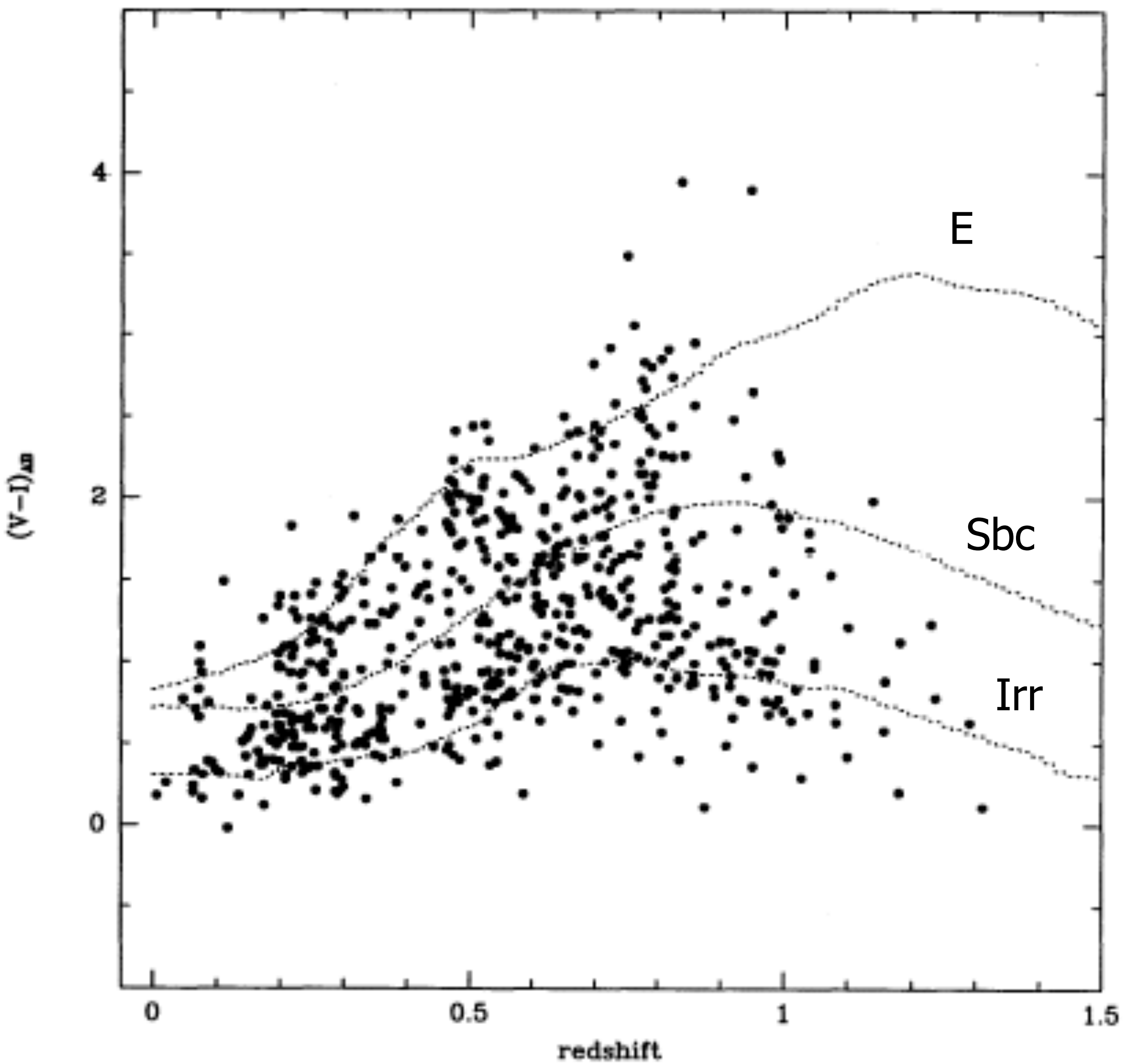
The deepest galaxy counts to date come from HST deep and ultra-deep observations, reaching down to ~ 29th mag

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



Galaxy Colors vs. Redshift

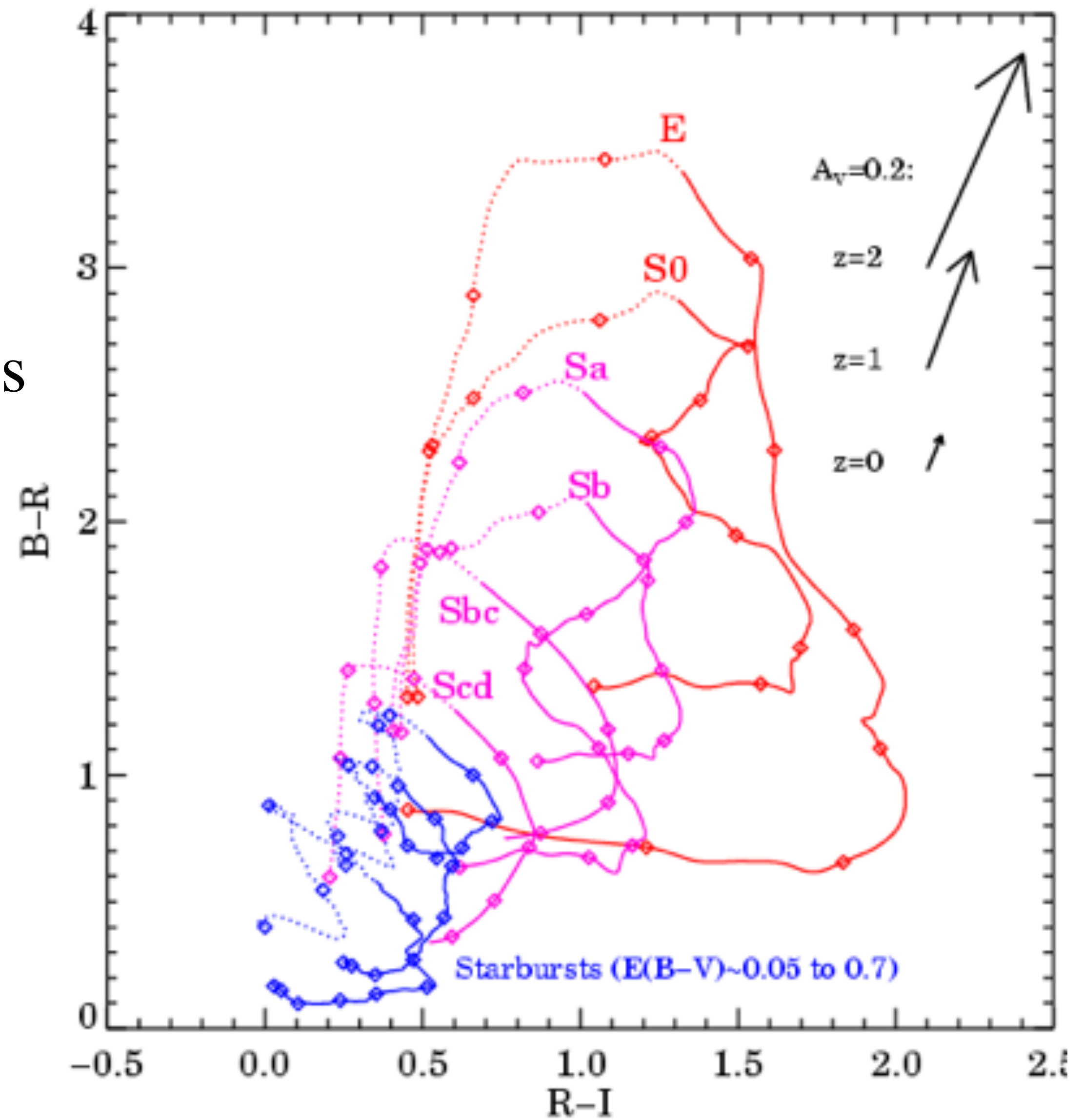


Morphological mix comparable to that at z ~ 0 extends out to z ~ 1, with little apparent evolution

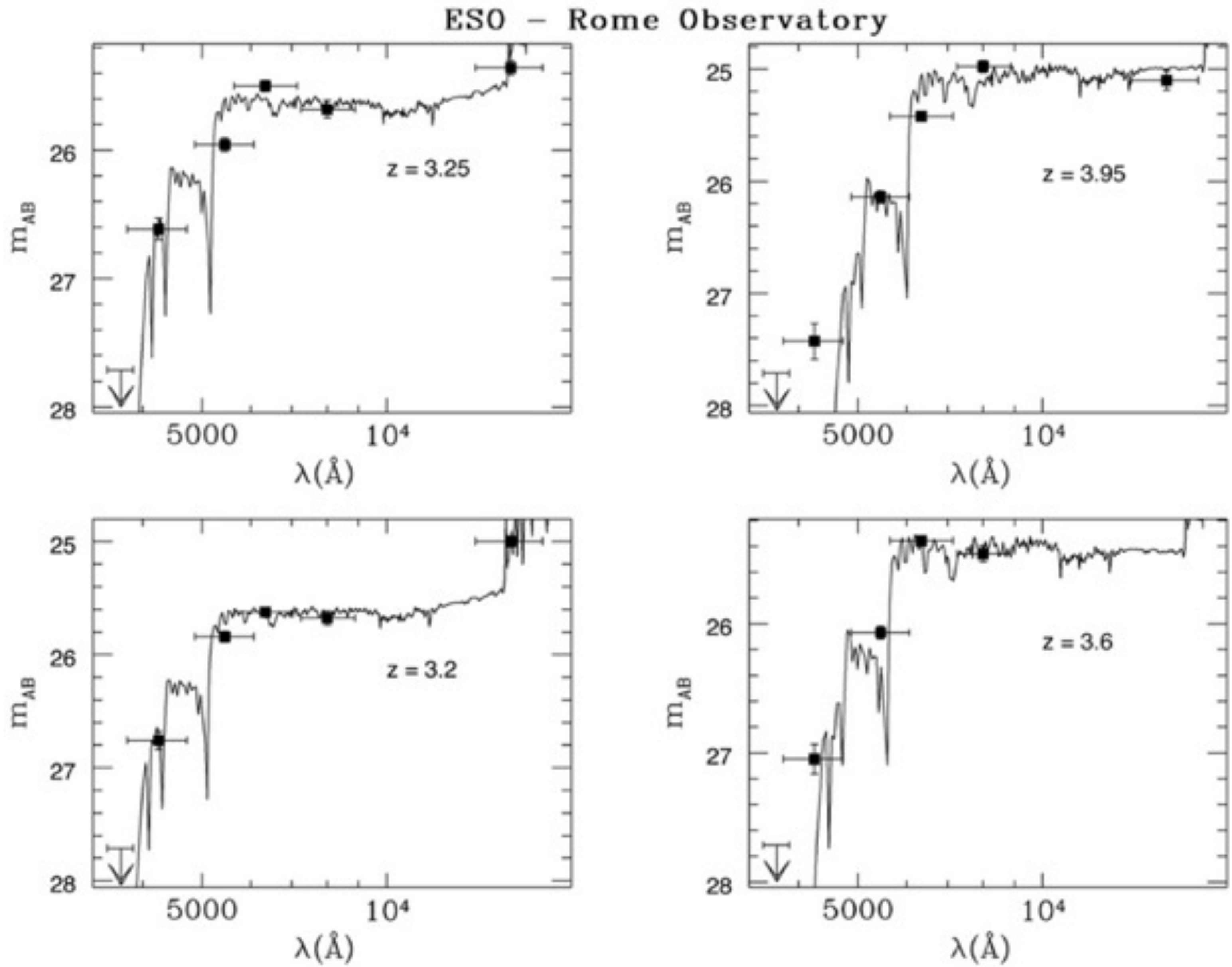
Faint Galaxy Colors

We can use the synthesis models to predict colors of galaxies at high redshifts, and then use color-color diagrams to select objects is some likely redshift range

This leads to an estimation of ***photometric redshifts***



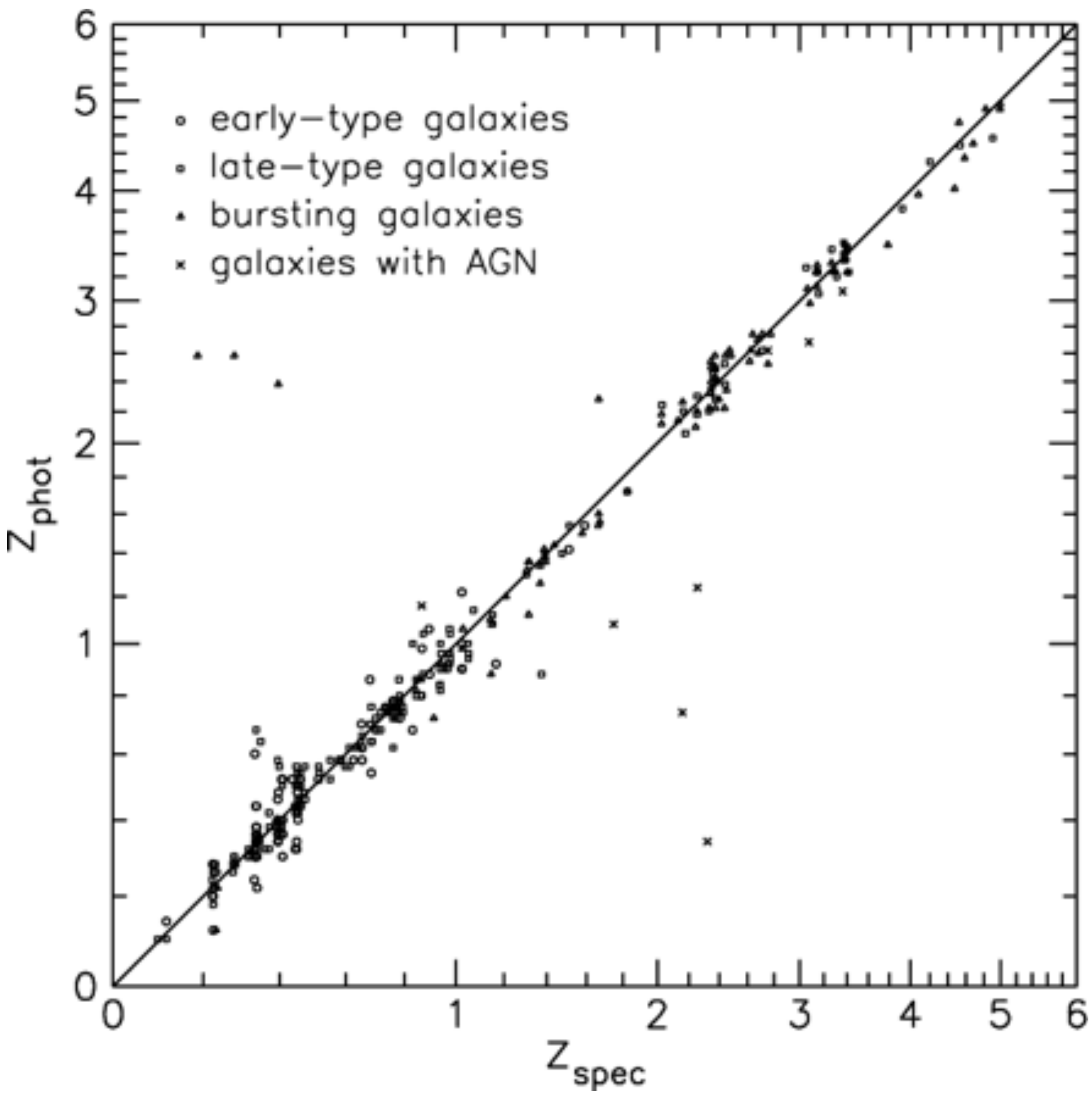
Examples of Spectral Energy Distributions Fits to Photometric Data



Photometric Redshifts

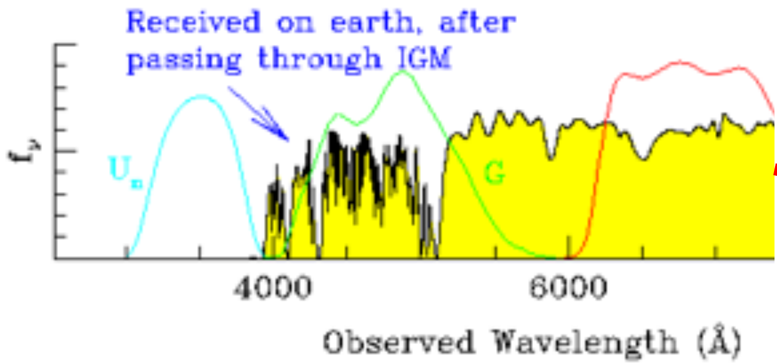
Given enough bands, and good photometry, one can do reasonably well, but some outliers will always happen

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

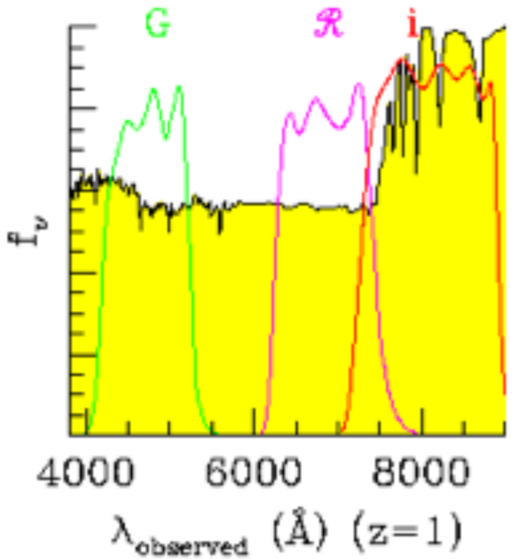


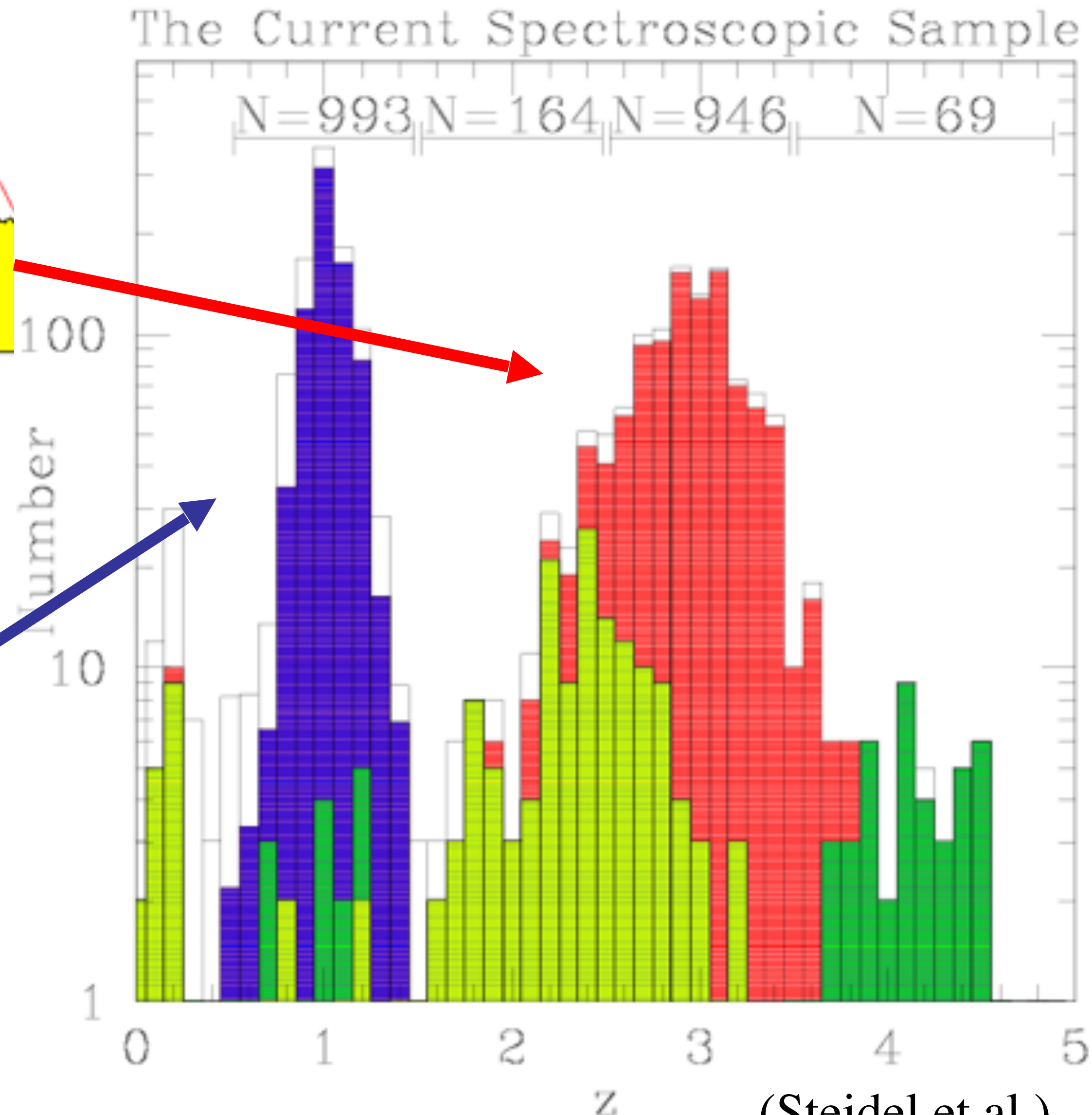
Presence of continuum breaks is an especially powerful in photometrically selecting galaxies in some redshift range

Lyman break



Balmer break

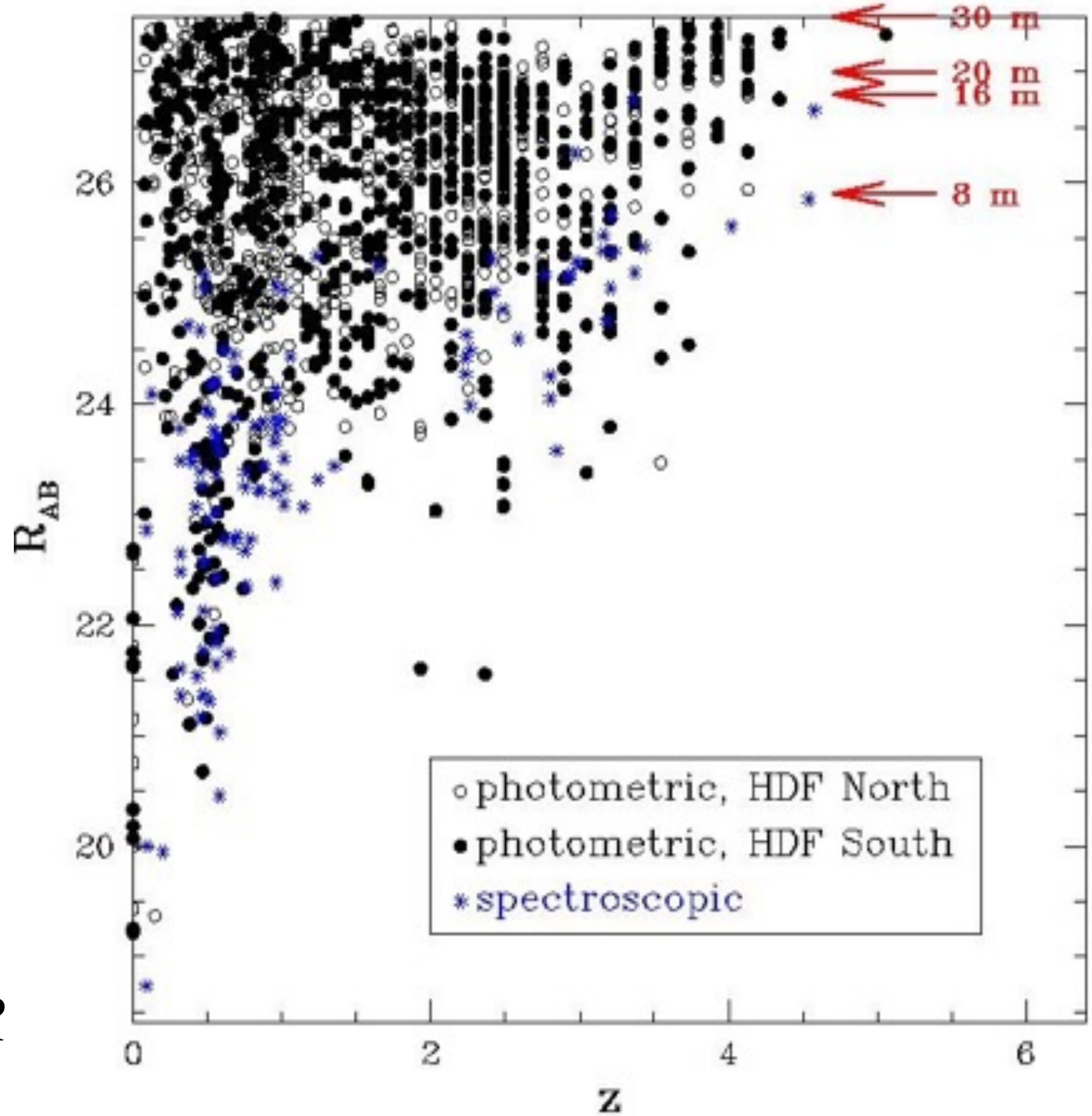




(Steidel et al.)

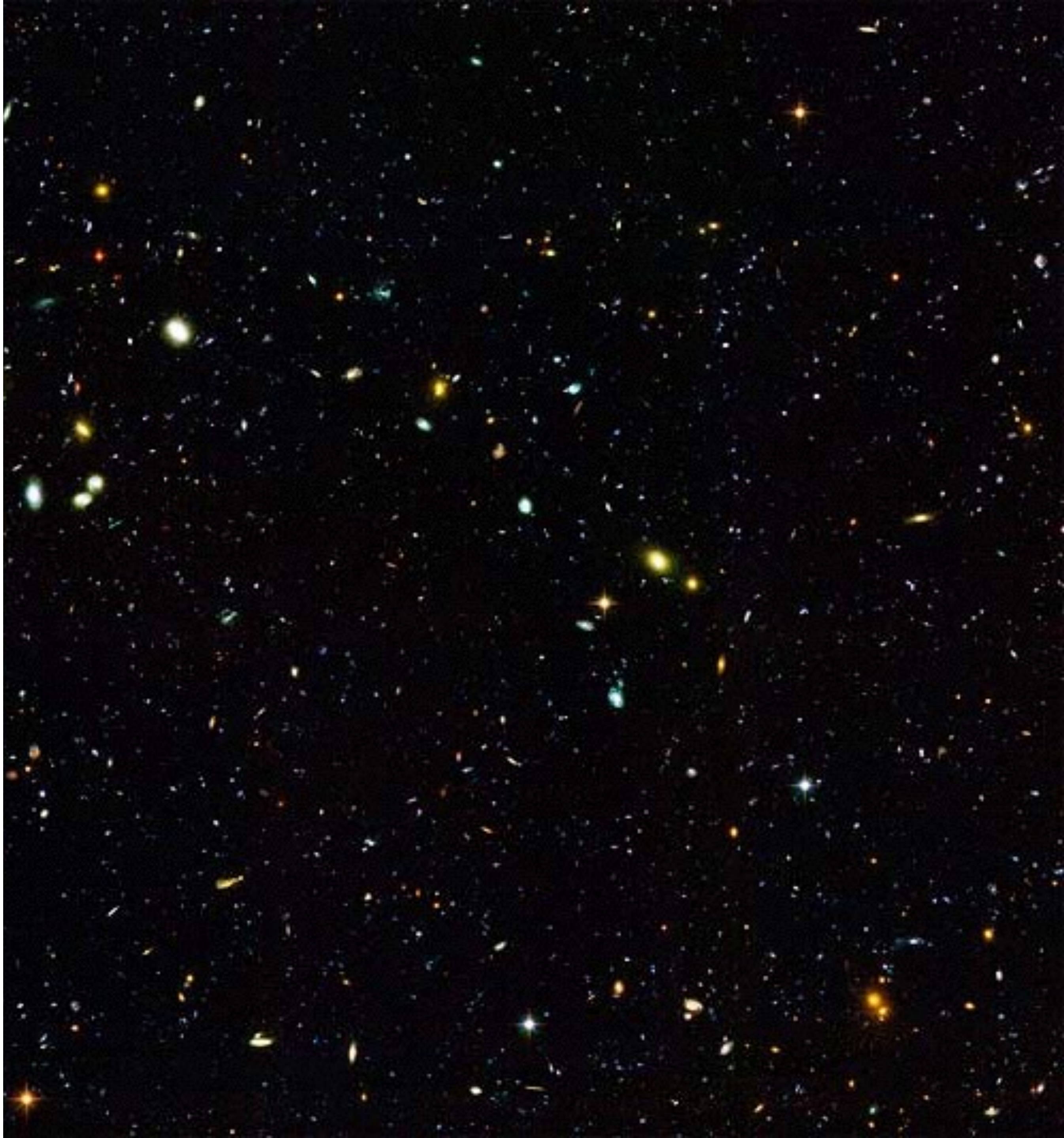
Deep Redshift Surveys

- 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
- To go beyond $z > 1$, we have to go faint, e.g. to $R > 23$ - 24 mag

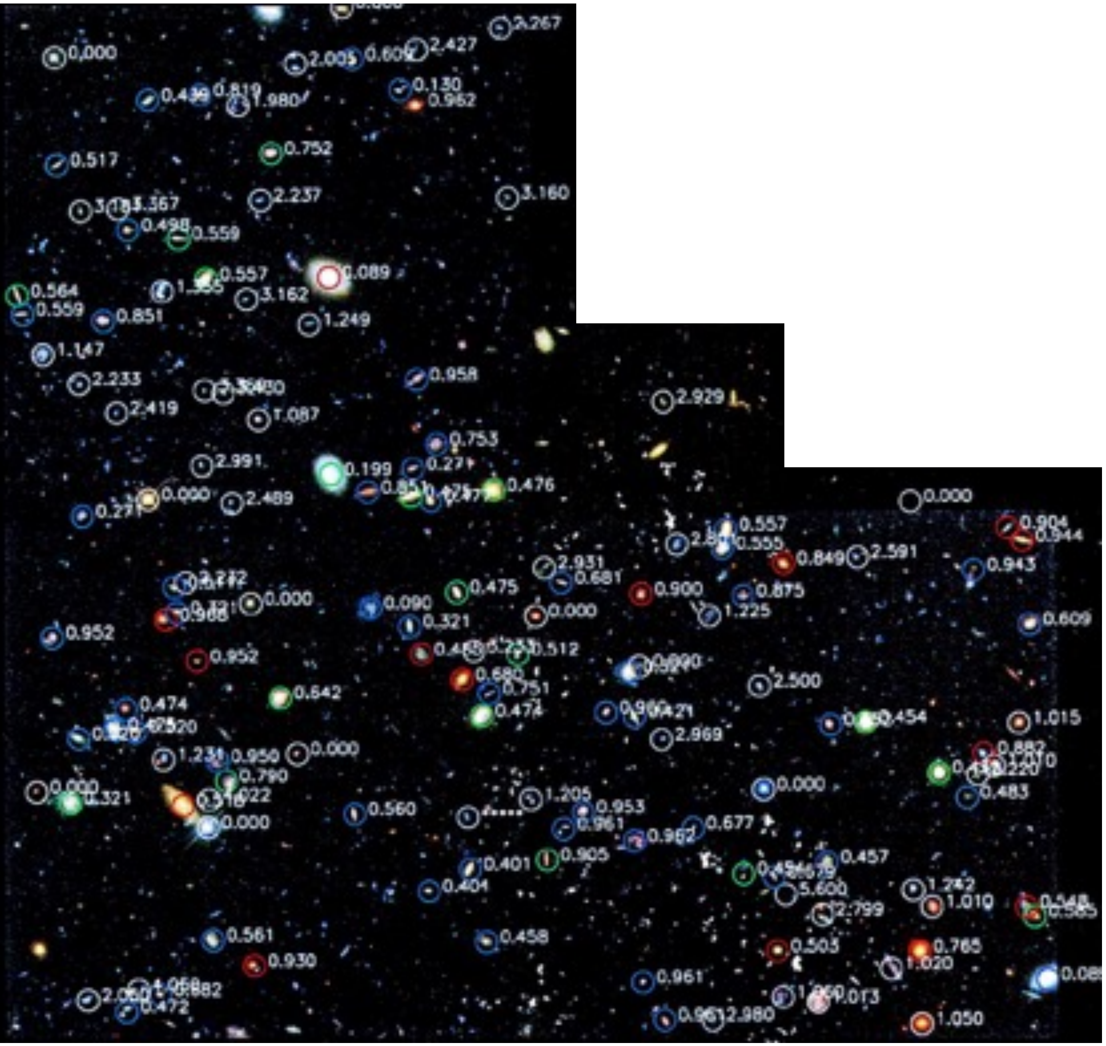


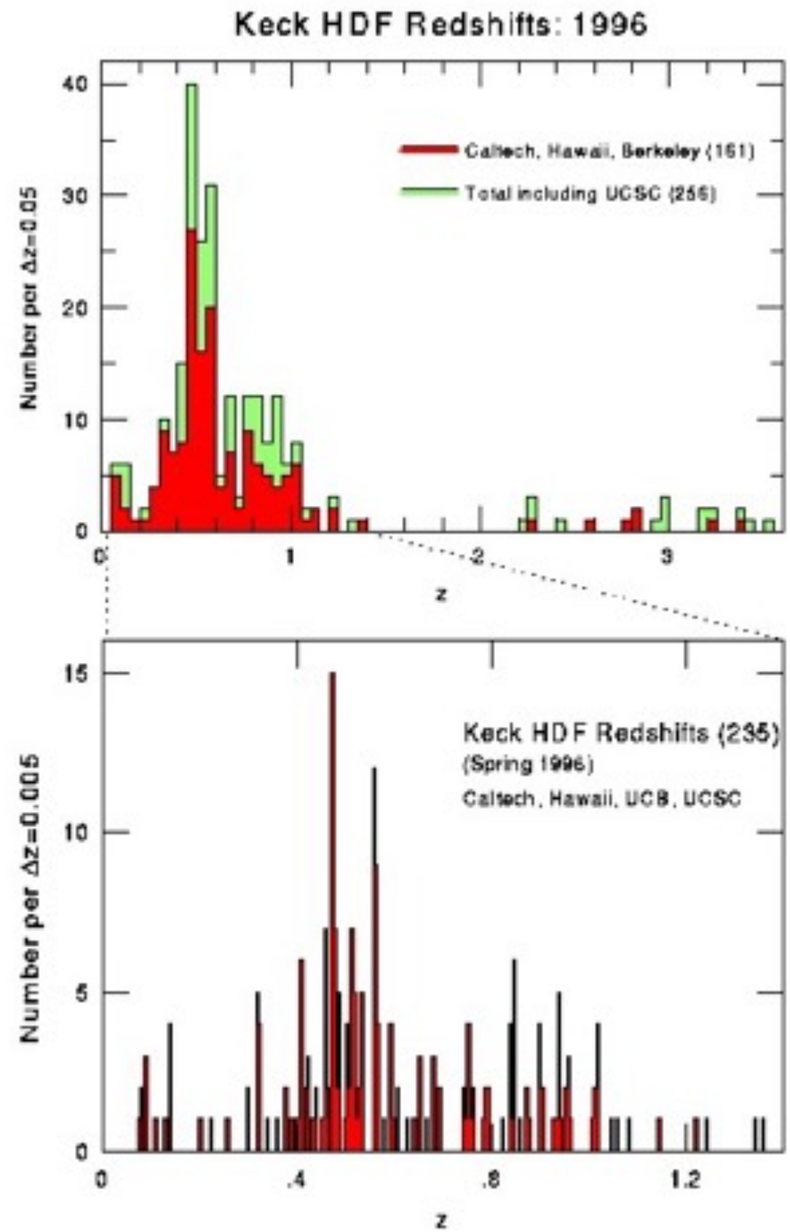
A proven powerful combination is to use deep HST imaging (e.g., HDF N and S, HUDF, GOODS field, etc.) and Keck or other 6 to 10-m class telescope for spectroscopy.

Various deep fields also have multi- wavelength data from Chandra, VLA, Spitzer …



Hubble Deep Field With Keck Redshifts





GOODS Field Redshifts

The Team Keck Redshift Survey of the GOODS- North Field
(Wirth et al. 2004)
Spectroscopic redshifts in the ACS-GOODS region of the HDF-N
(Cowie et al. 2004)
VIMOS VLT Deep Survey: redshifts in the CDFS
(Le Fevre et al. 2004)

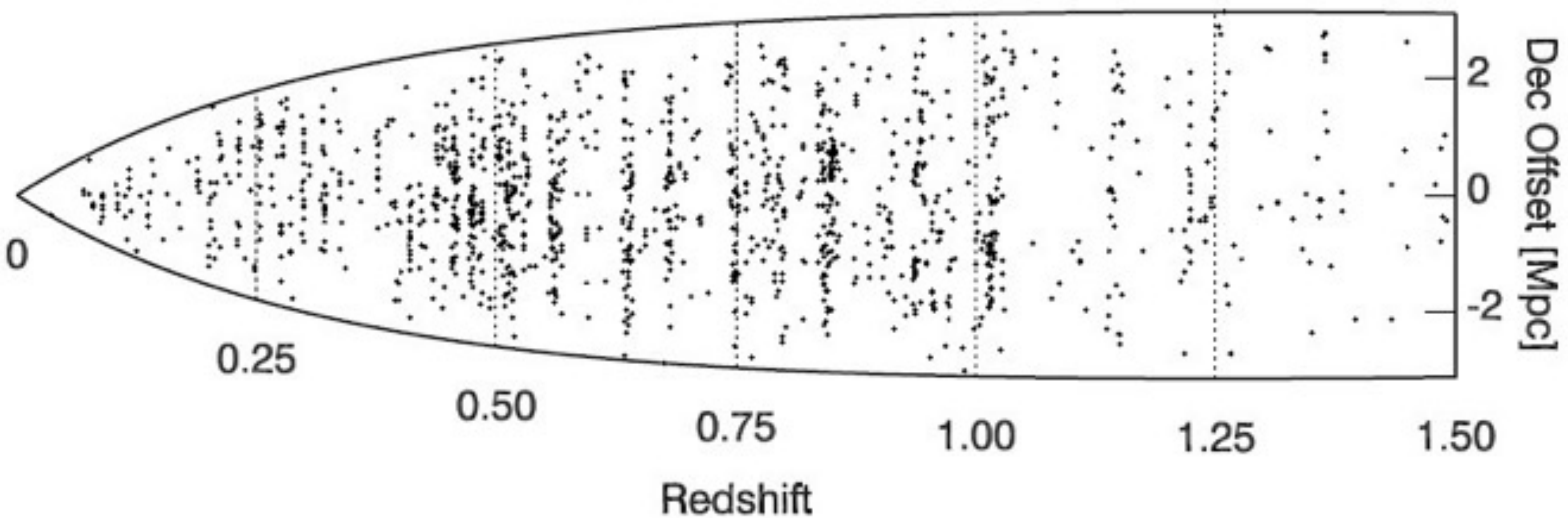
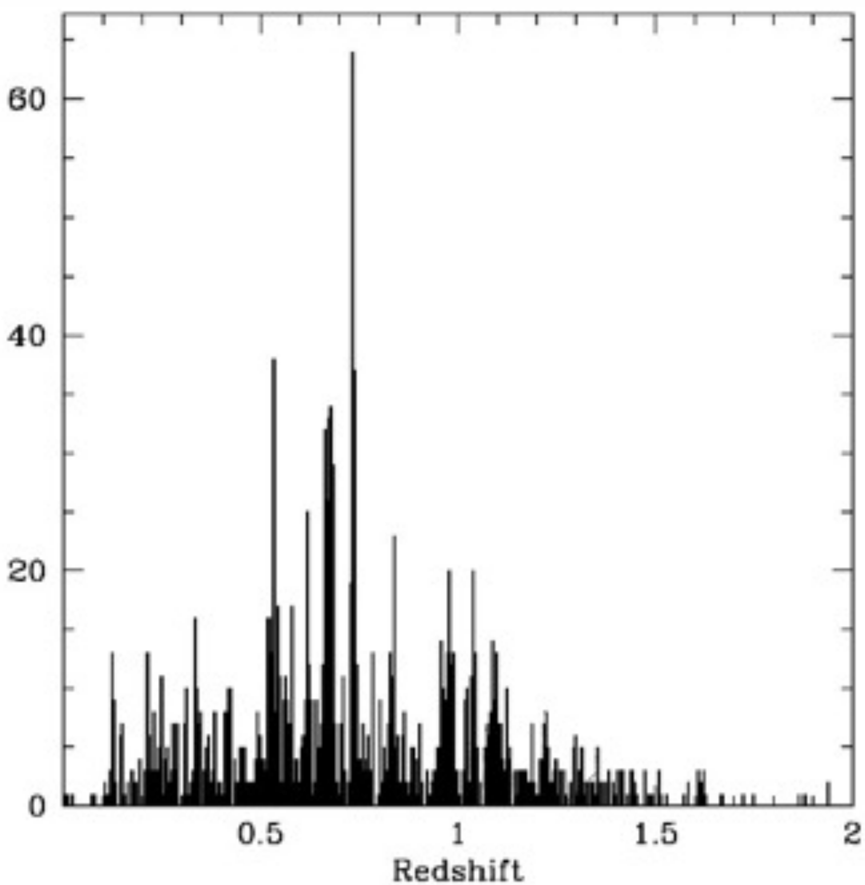
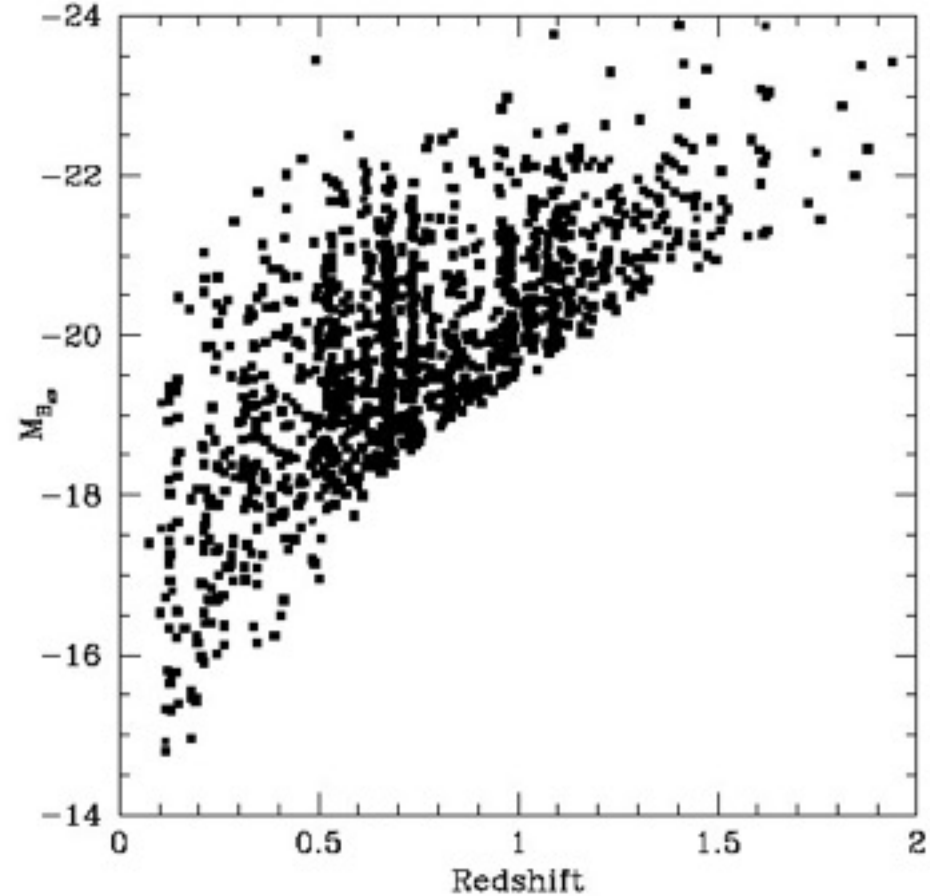


FIG. 16.— Pie diagrams showing the spatial distribution as a function of redshift for all galaxies with secure measurements in our survey. (a) Projected distance of each galaxy from the center of the GOODS-N field in the direction of Right Ascension vs. redshift. (b) Same, for Declination. In each plot, the outer envelope represents the linear separation corresponding to the 18.′4 width of the field at that redshift. Note the numerous walls correponding to peaks in the marginal distribution of redshifts seen in Fig. 15. Dotted lines indicate lines of constant redshift. Cosmological parameters $h_0 = 0.75$ and $q_0 = 0.5$ are assumed in computing the spatial offsets.

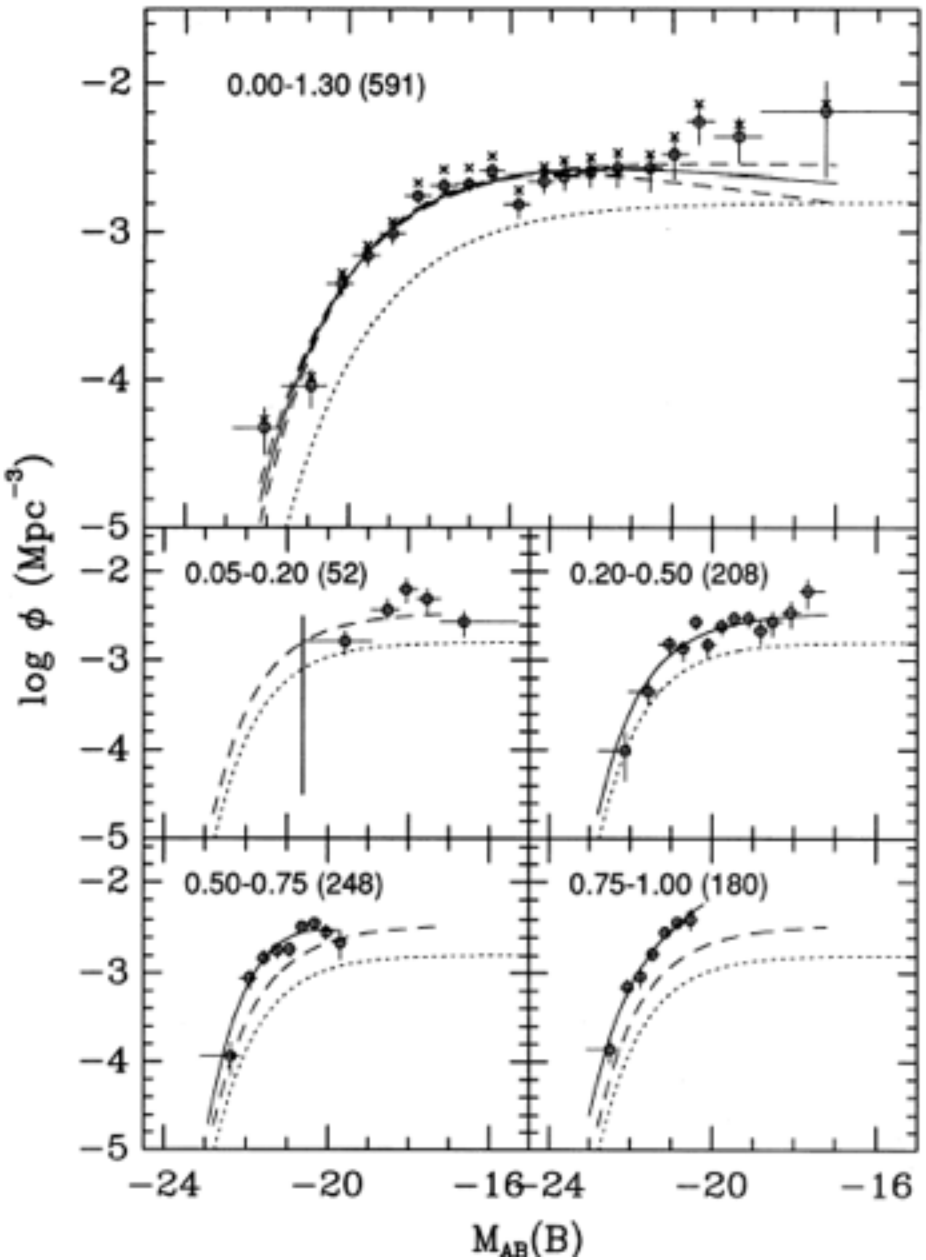
VVDS: redshift distribution of galaxies and absolute magnitude – redshift distribution





Modern deep redshift surveys reach ~ L_* galaxies out to z ~ 1

Evolution of Galaxy Luminosity Function



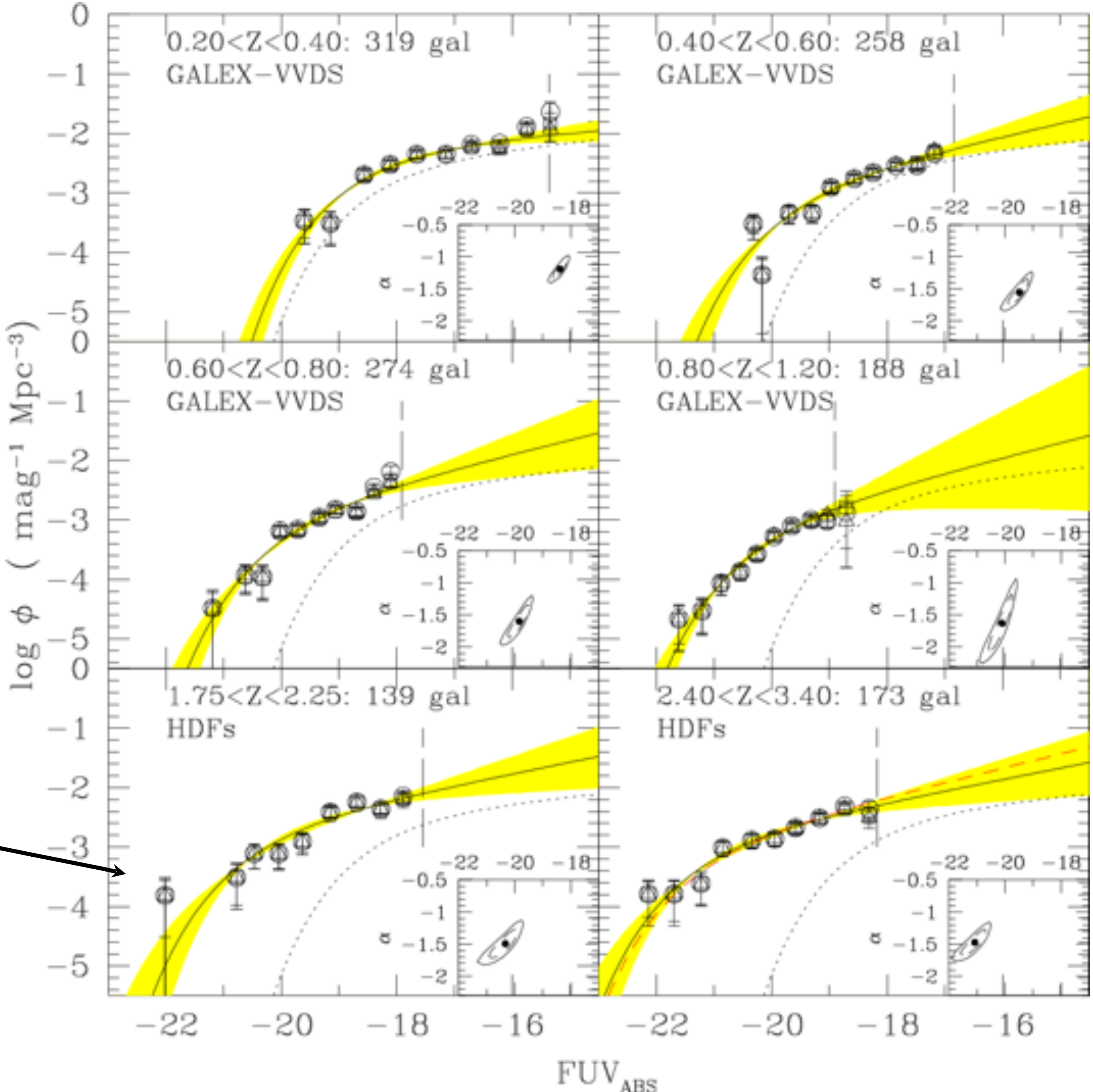
There as an overall brightening of galaxies at higher redshifts, but the effect is strongest for the dwarf galaxies at $z > 0.5$ ("downsizing")

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

Evolutionary effects are the strongest for the late Hubble types

CFRS, Lilly et al. 1995

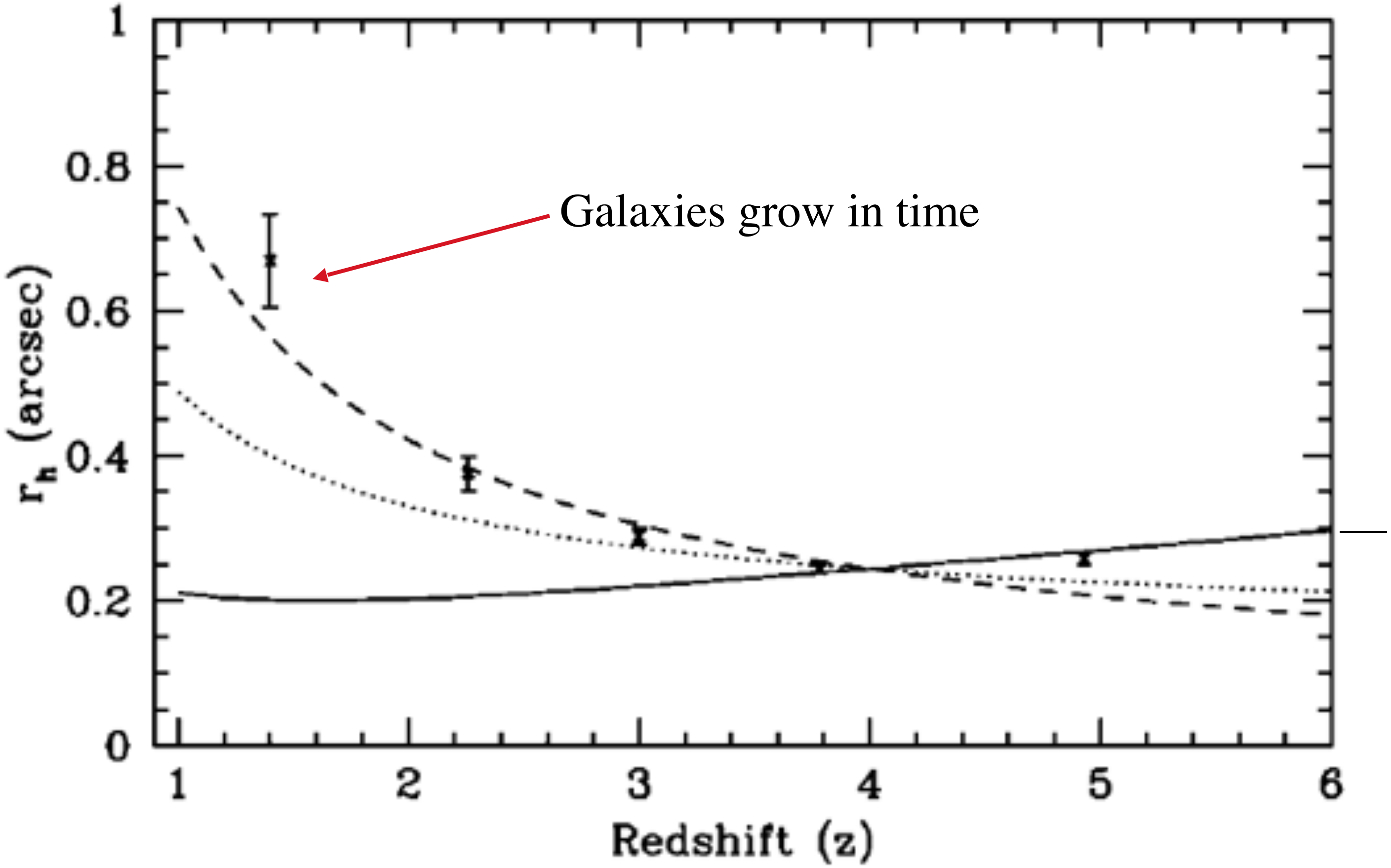
But at higher redshifts, there is a brightening of the bright end of the LF



Arnouts et al. 2005

Evolution of Galaxy Sizes

HST imaging suggests that galaxies were smaller in the past

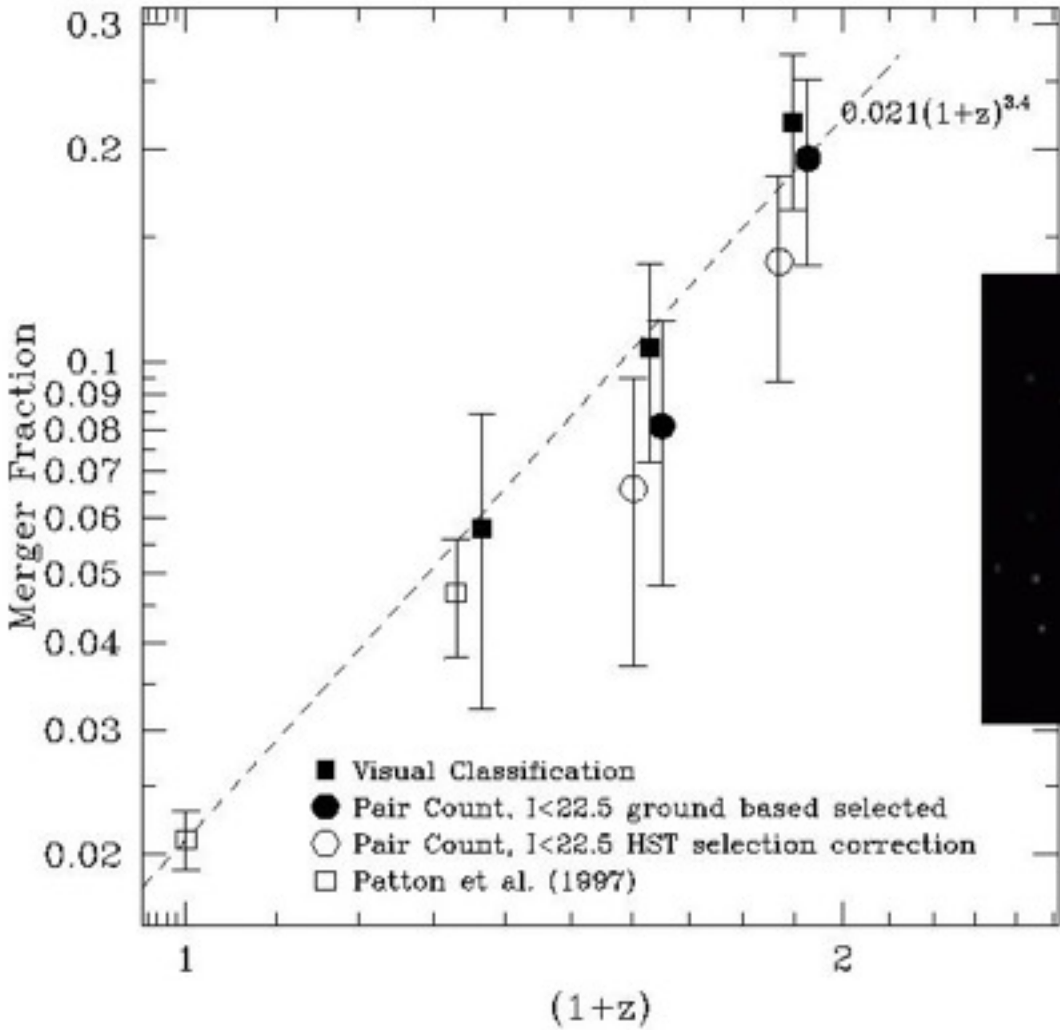


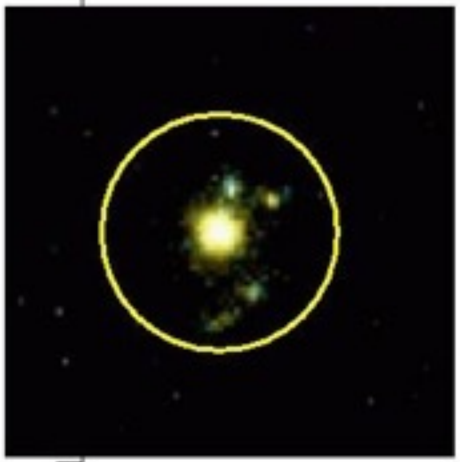
Solid line: Expected if galaxies have a fixed size in proper coordinates

Evolution of the Merger Rate

Merger fractio

$\sim (1 + z)^{3.4}$



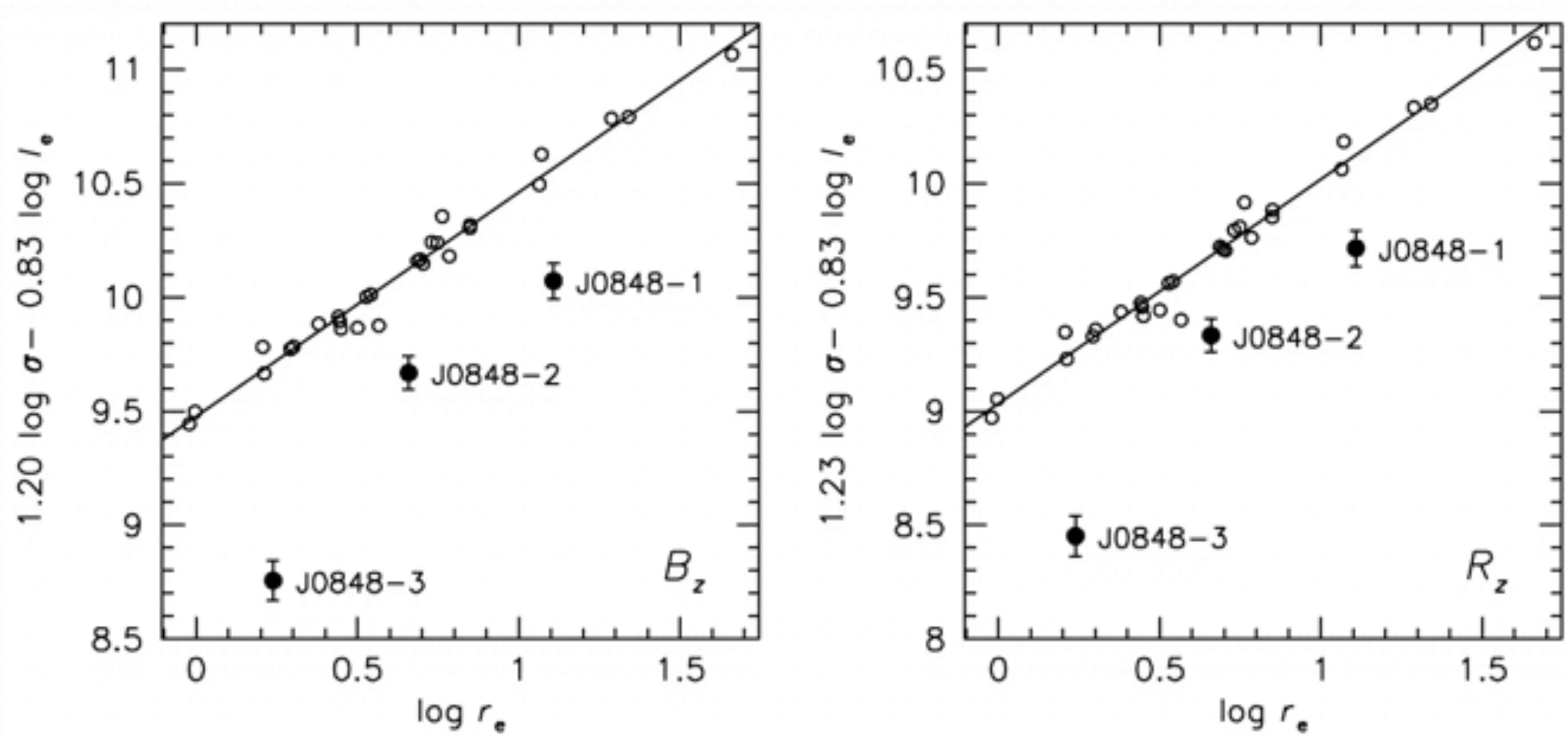


(LeFevre et al. 2000)

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

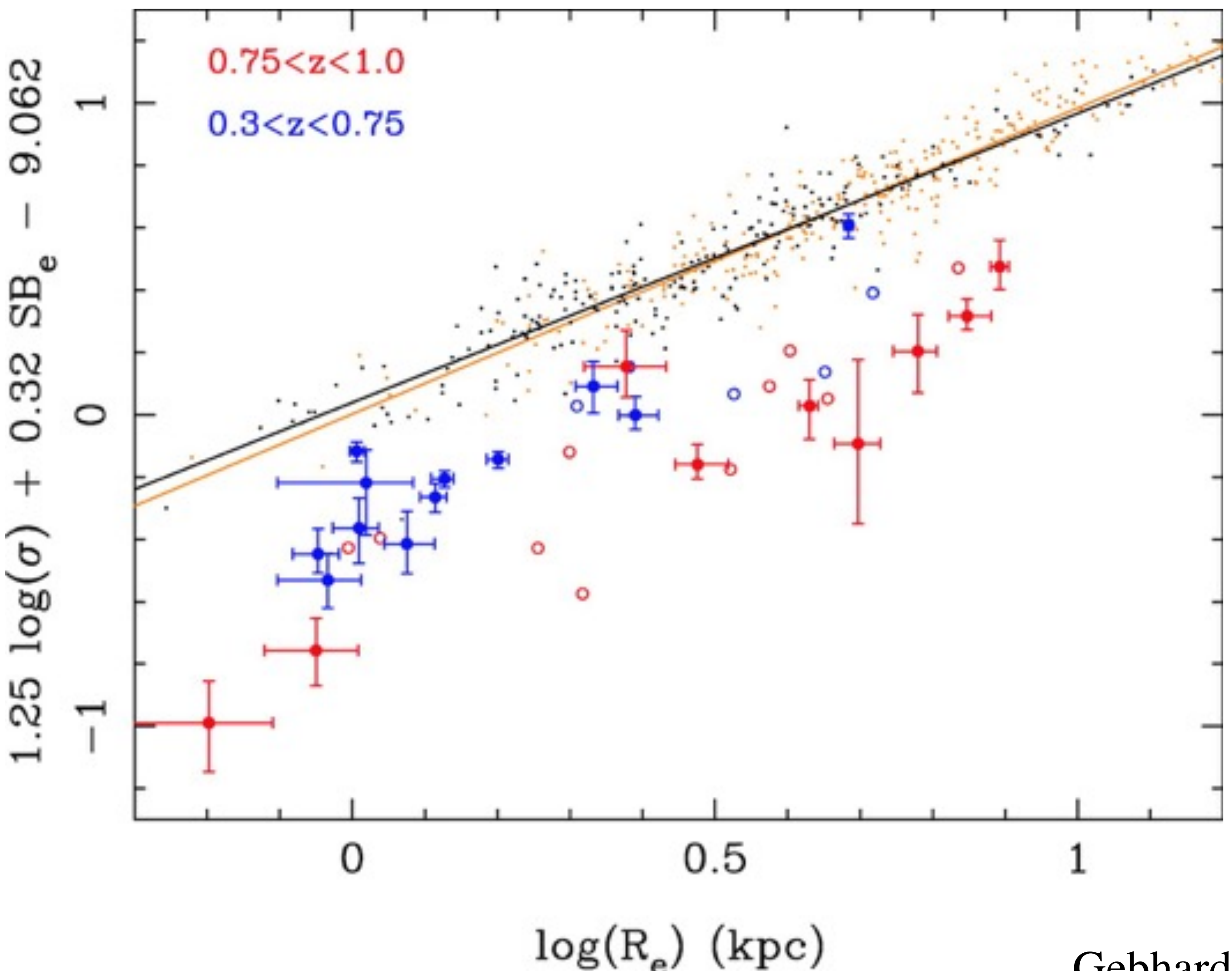
By design, they are our sharpest probe of galaxy properties - and thus potentially of galaxy evolution (note that the relations themselves may be evolving!)



Cluster at z =1.27

van Dokkum & Stanford, 2003

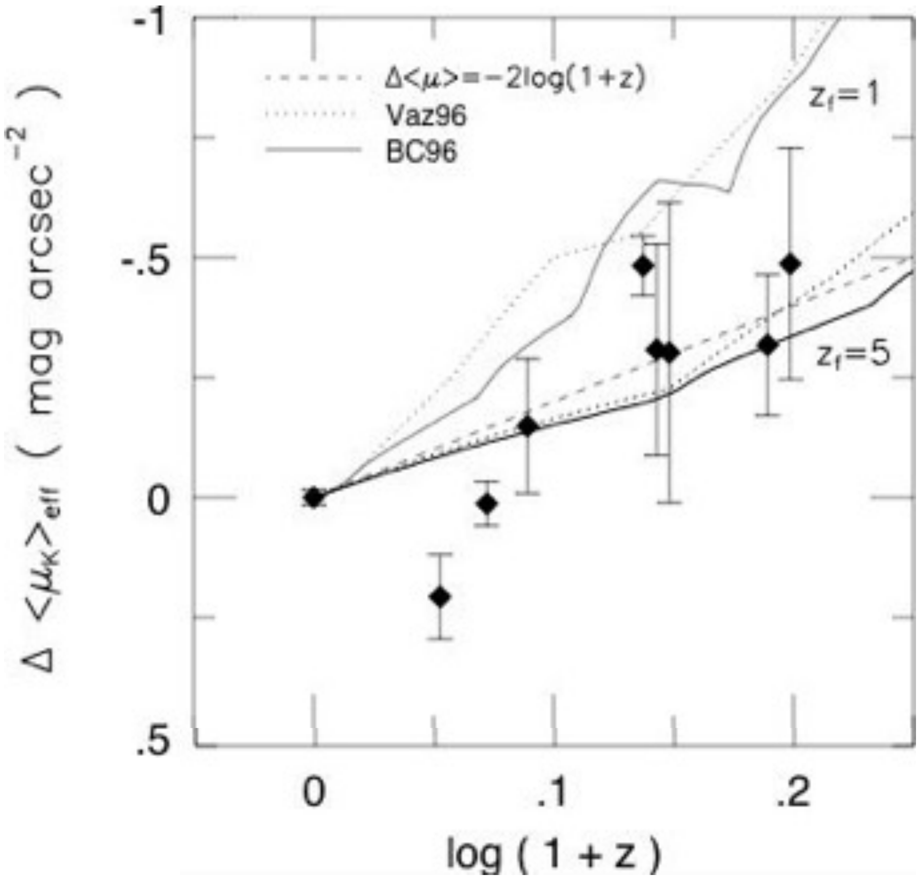
Evolution of the FP of Field Ellipticals

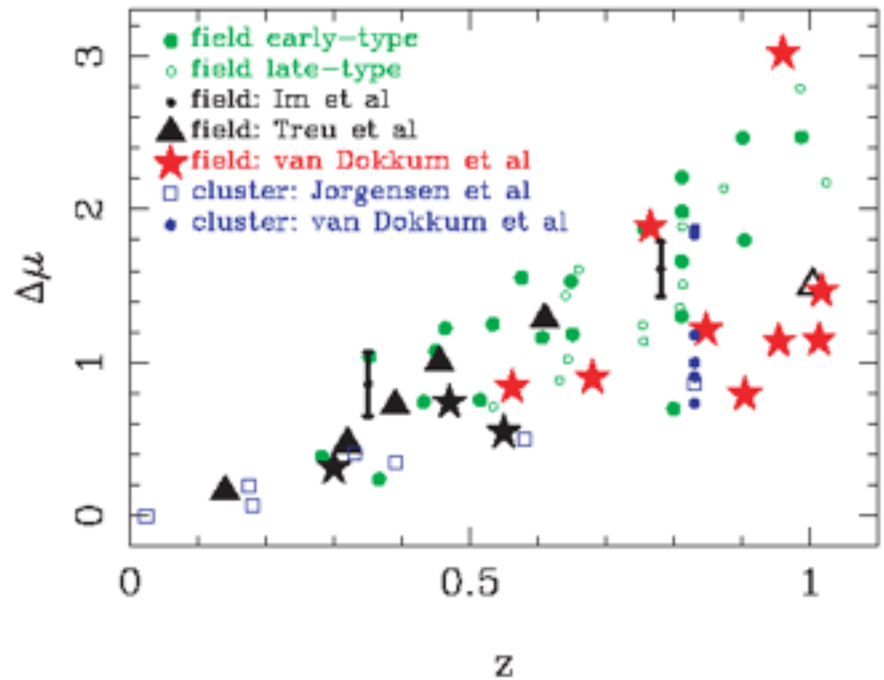


Gebhardt et al. 2004

Fundamental Plane Evolution

The data indicate a brightening of E's at higher redshift, as reflected in their surface brightness at a fixed r_e and σ. The brightening rate is consistent with passive evolution starting at a high redshift





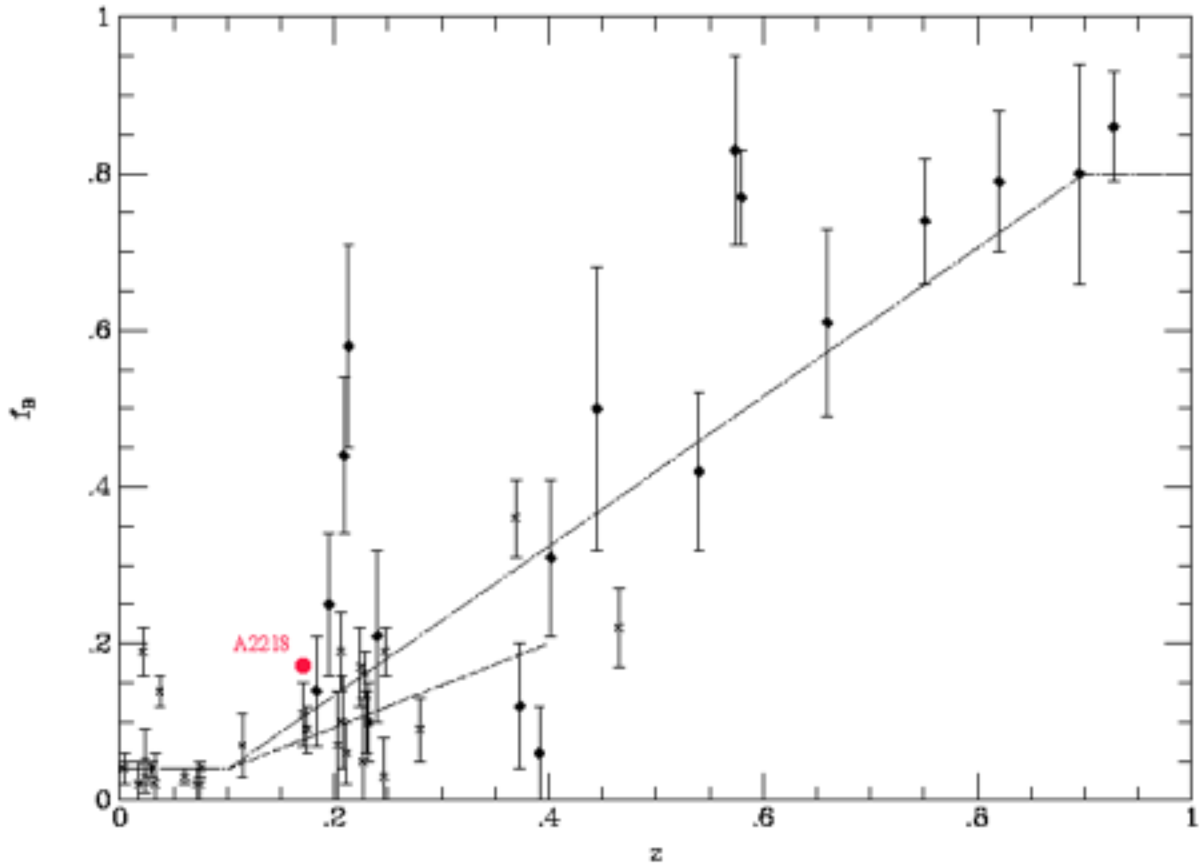
Scaling Relations as Evolution Probes

- 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
- Data on galaxy colors and line strengths are also consistent with that picture
- There is a gradual rotation of the FP, in the sense that the lower mass E's are younger - galaxy downsizing again
- Studies of the ***Tully-Fisher relation*** at high z's are much less conclusive: the TFR appears to be noisier in the past, and spirals somewhat brighter, but the situation is not clear yet

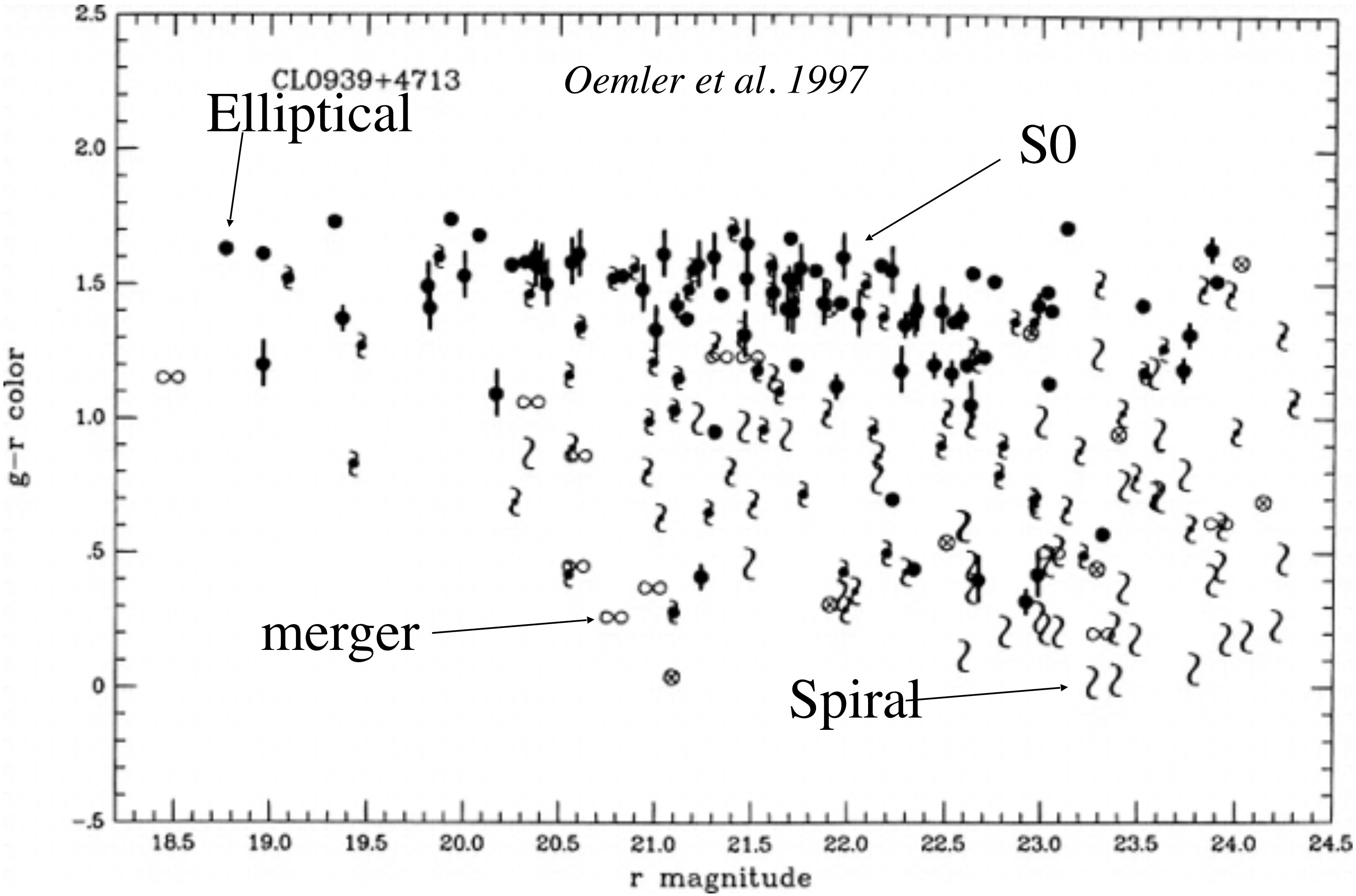
Galaxy Evolution in Clusters

Generally, we may expect a systematic difference in galaxy evolution processes in very different large-scale environments, mainly due to different dynamical effects.

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



Color-magnitude diagram for CL0939+4713, z ~ 0.41



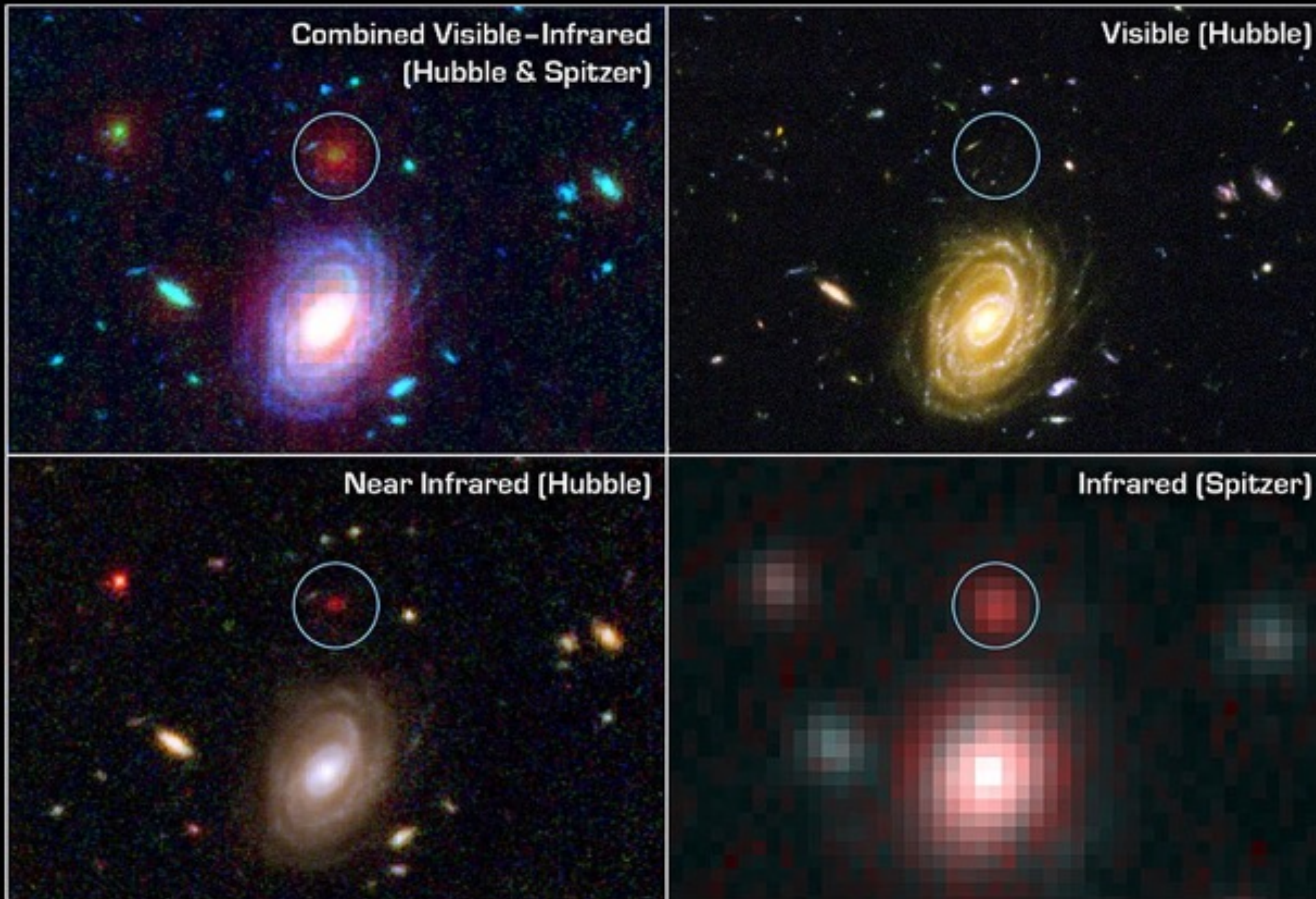
There is a systematic conversion of regular spirals into S0 and E galaxies in time, but at any fixed redshift, richer and denser clusters have fewer spirals

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
- This would only be seen in a galaxy that was forming stars in the recent past (<1.5 Gyr) but the star formation was truncated
- 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 @ z~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~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



Distant Galaxy in the Hubble Ultra Deep Field

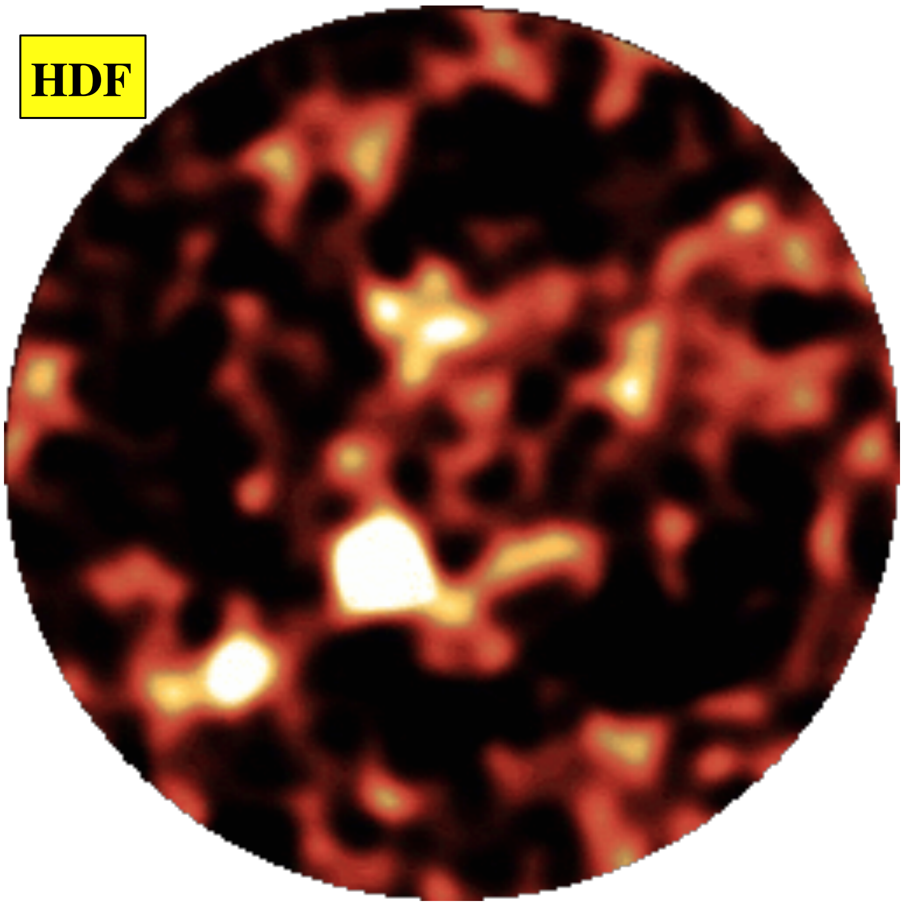
Spitzer Space Telescope • IRAC
Hubble Space Telescope • ACS • NICMOS

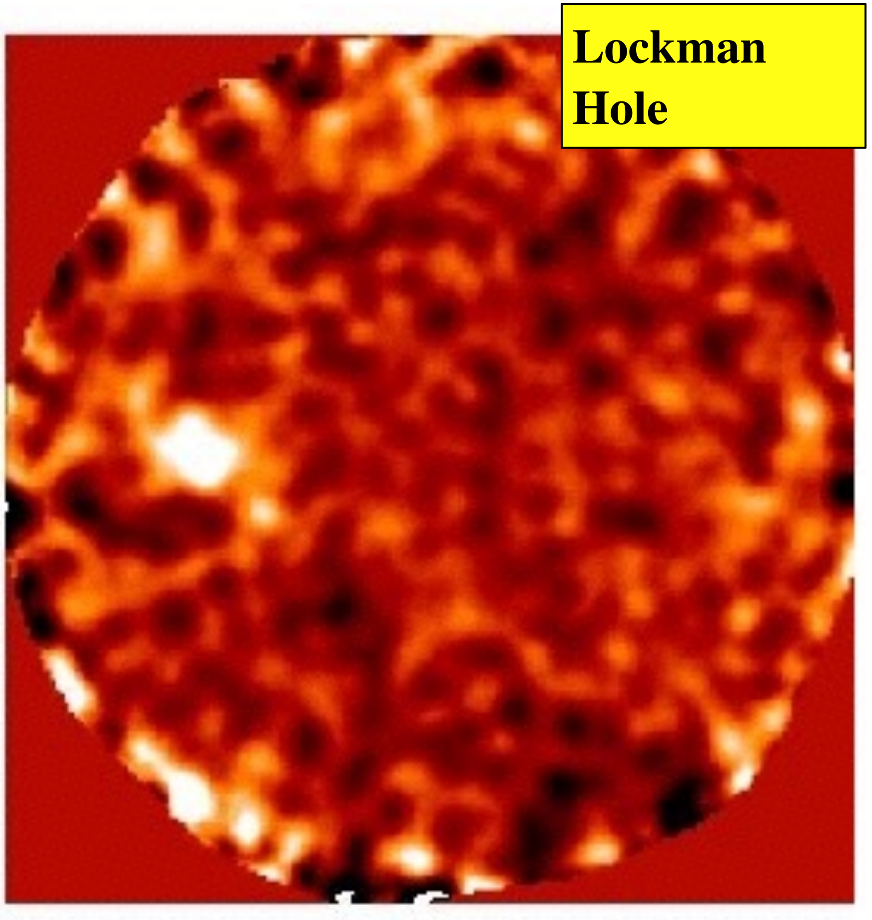
NASA, ESA / JPL-Caltech / B. Mobasher (STScI/ESA)

ssc2005-19a

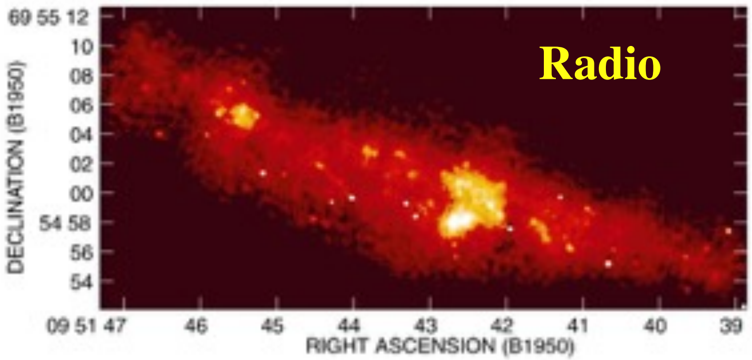
Obscured Galaxy Populations

- We know that a lot of star formation locally is obscured by dust
- Sub-mm observations, e.g., at CSO or JCMT using SCUBA instrument reveal a population of luminous obscured sources

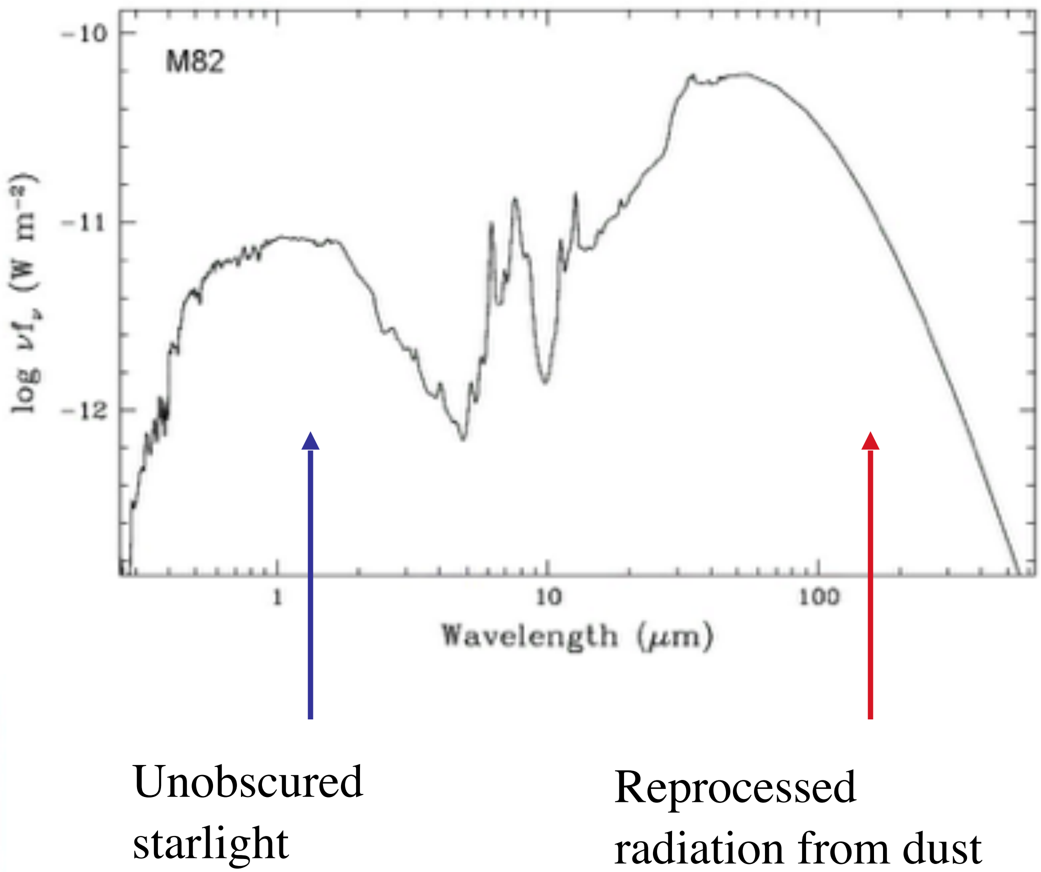




M82, a Prototypical Starburst Galaxy

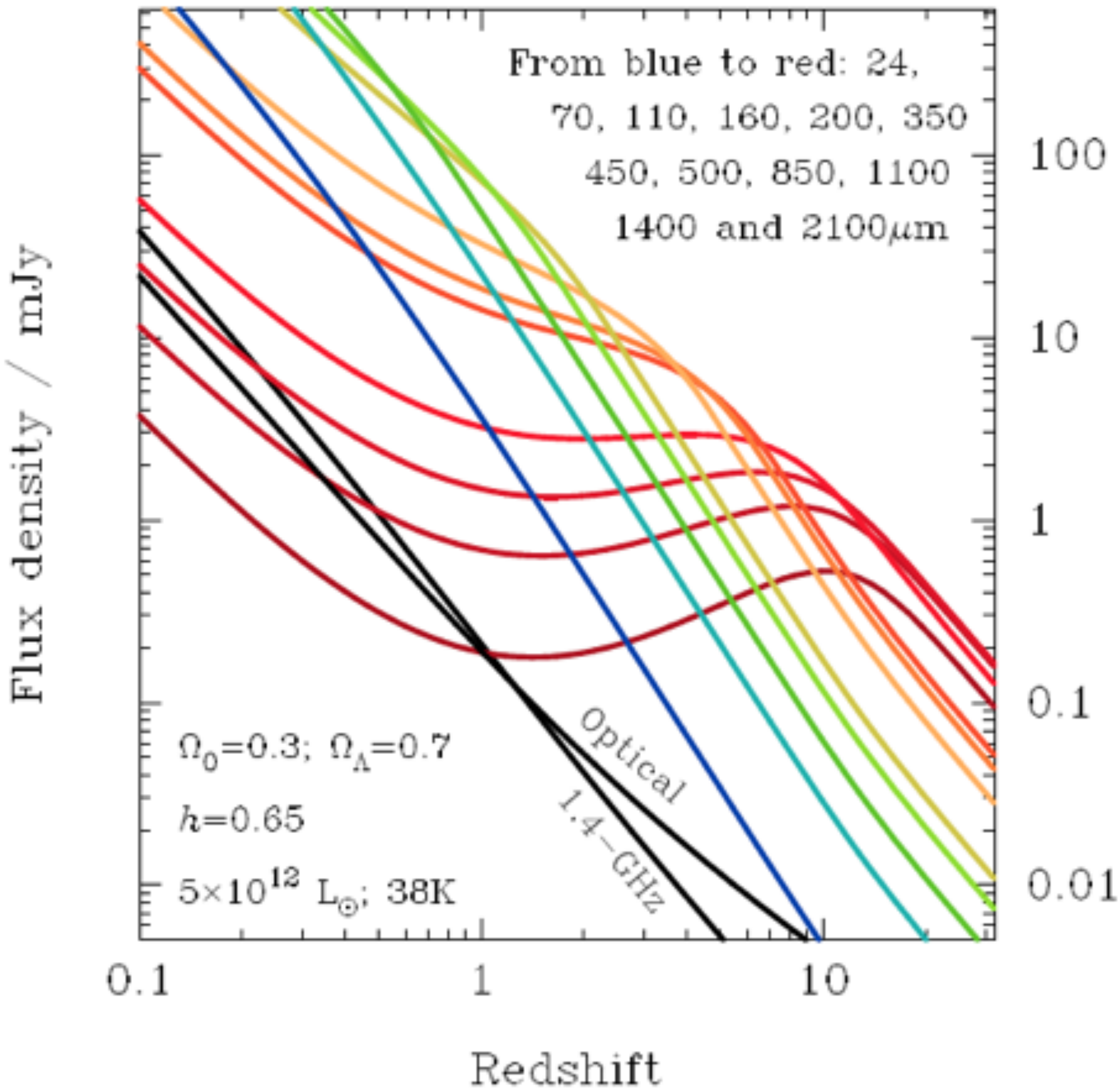


The spectrum of M82, UV to sub-mm



Sub-mm K-Corrections

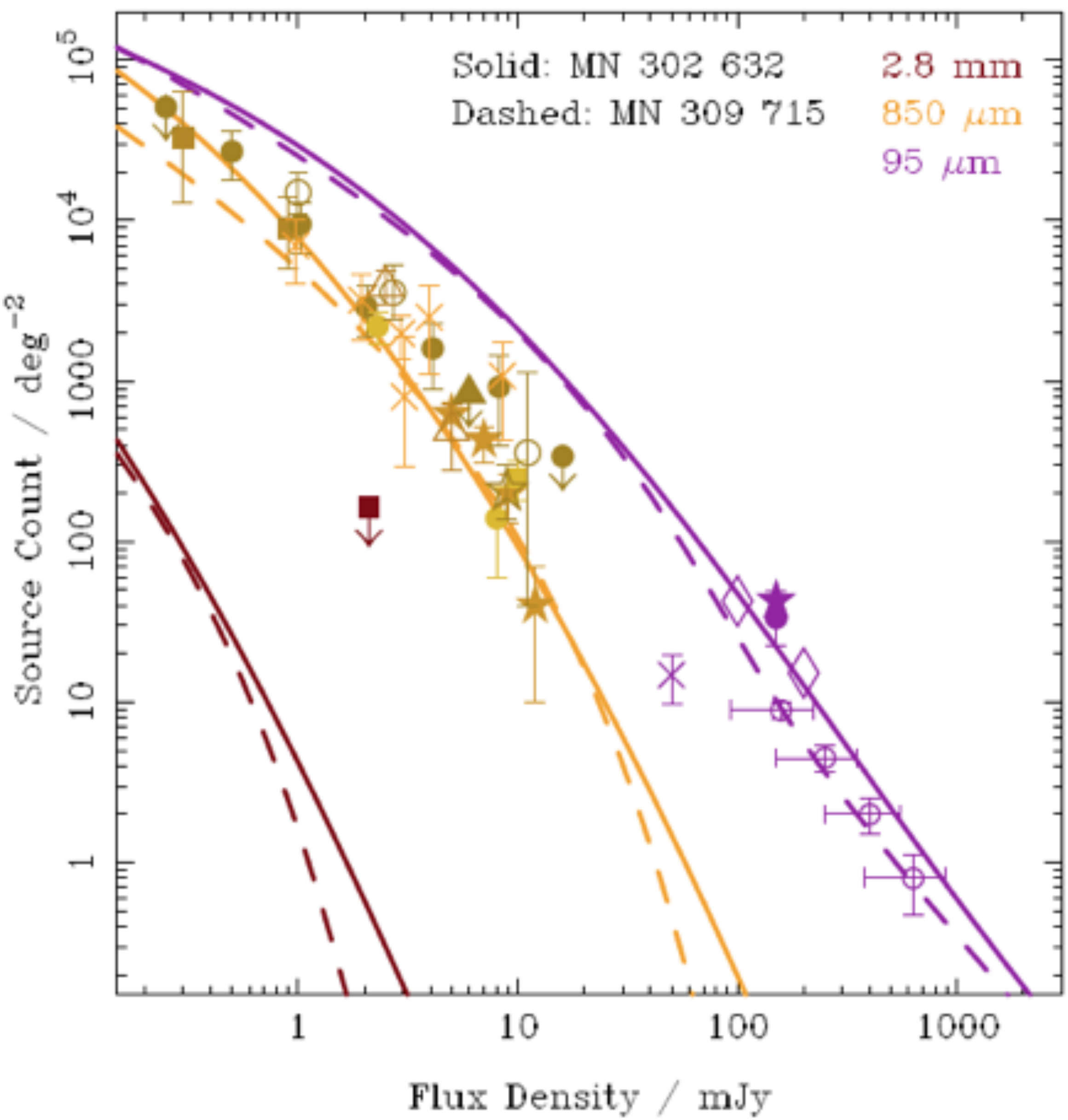
As dusty galaxies are redshifted, the observed bandpass climbs the Wien side of their thermal emission spectrum, resulting is a negative K-correction - so distant obscured sources may even get brighter at higher *z*’s, and easier to detect



Sub-mm Source Counts

Current technology limits us to only the most luminous obscured sources at high redshifts (and redshifts for most of them are still unknown)

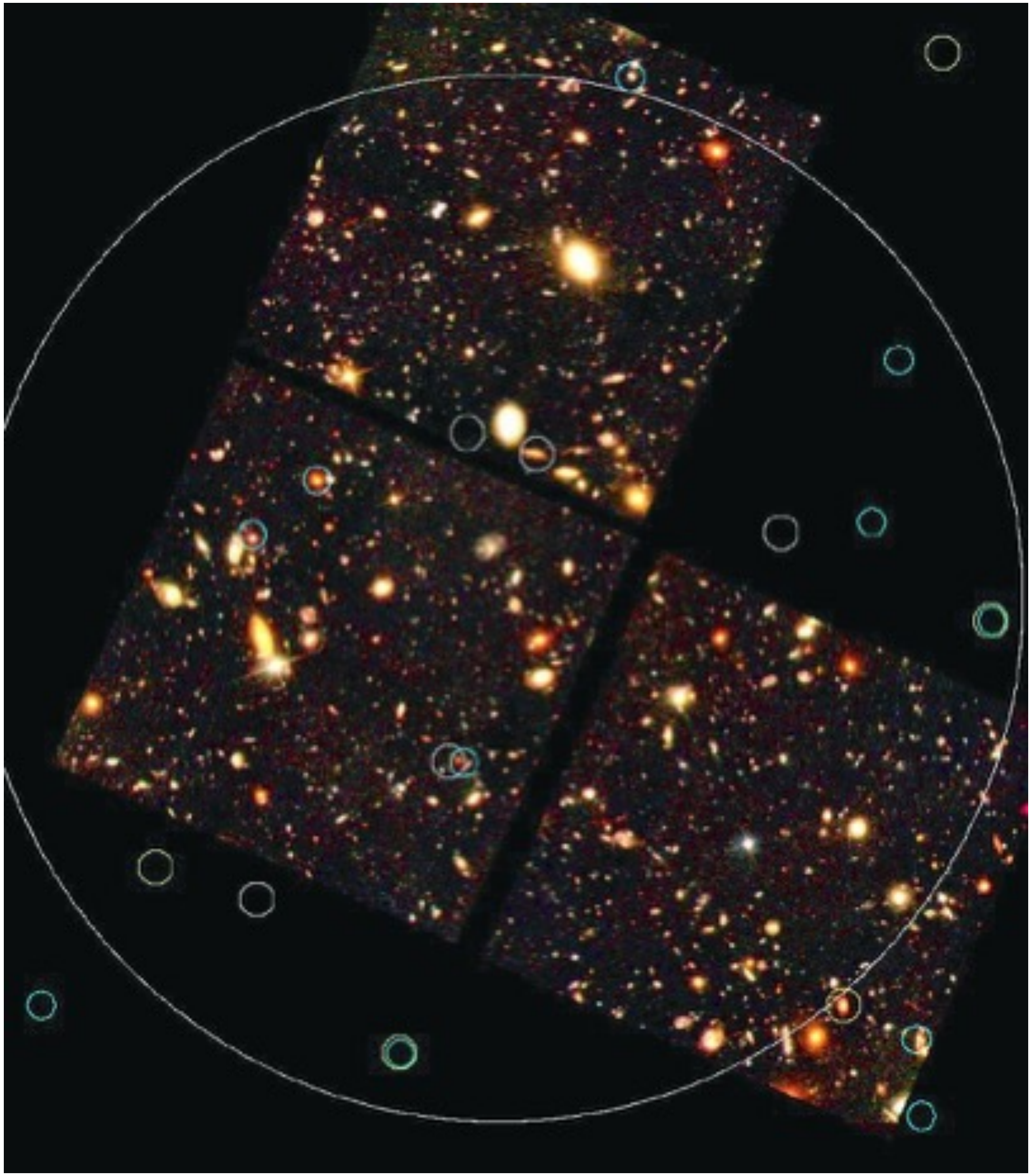
Thus, one has to model their counts and evolution using a lot of assumptions …



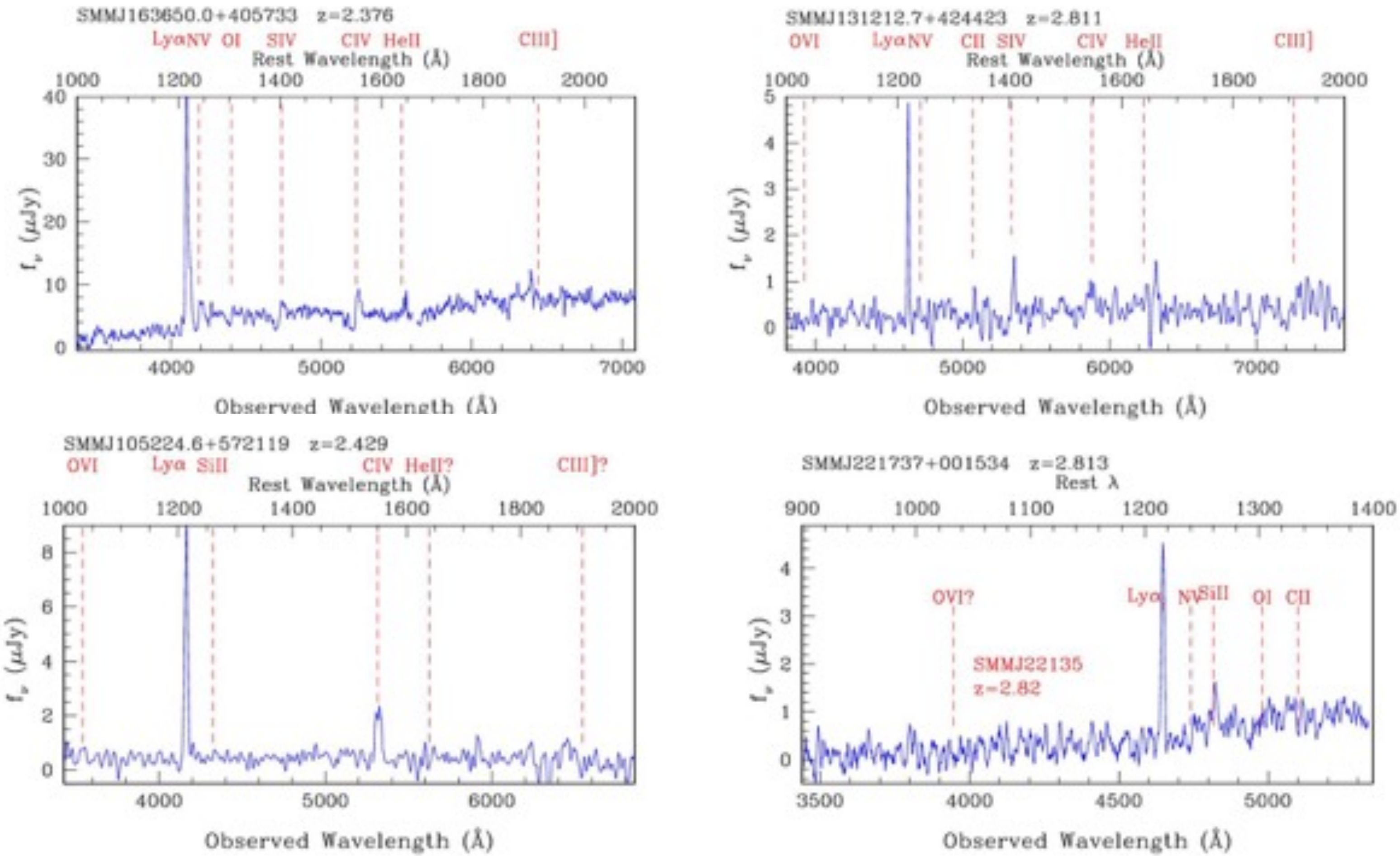
Optical IDs of SCUBA Sources

Given the poor angular resolution of the current sub-mm telescopes, optical IDs and thus redshifts for many of these sources are highly uncertain

Sometimes one can use radio IDs from VLA as a step towards getting the optical IDs and then the redshifts

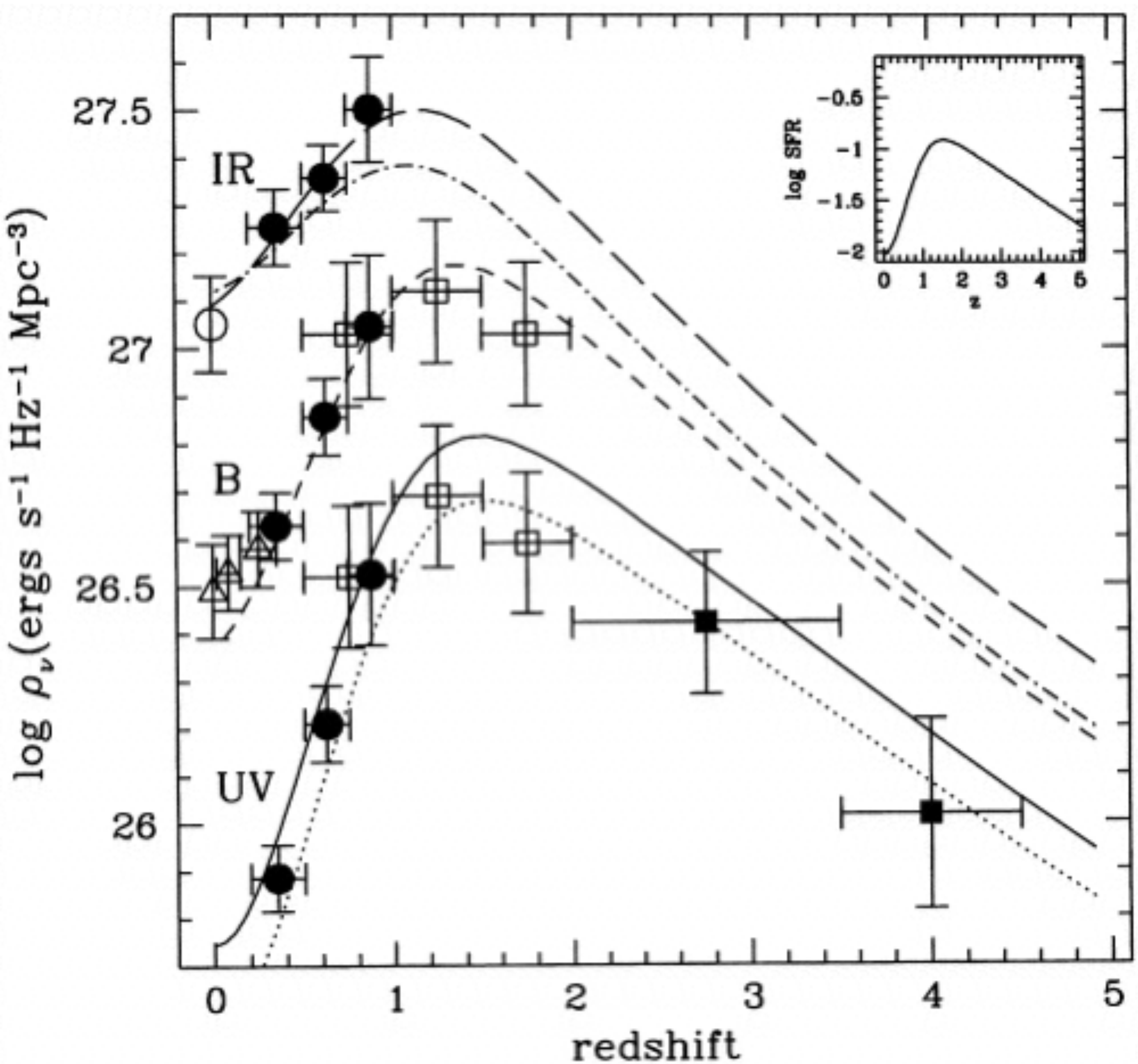


Redshifts for Radio-Selected SCUBA Sources



- VLA positions for 70% of f(850μm) > 5 mJy (20% b/g)
- **Redshifts are typically *z* ~ 2 - 3** (as expected)
- **Many SCUBA sources seem to contain active nuclei**

The History of Star Formation



This is often called the "Madau diagram"

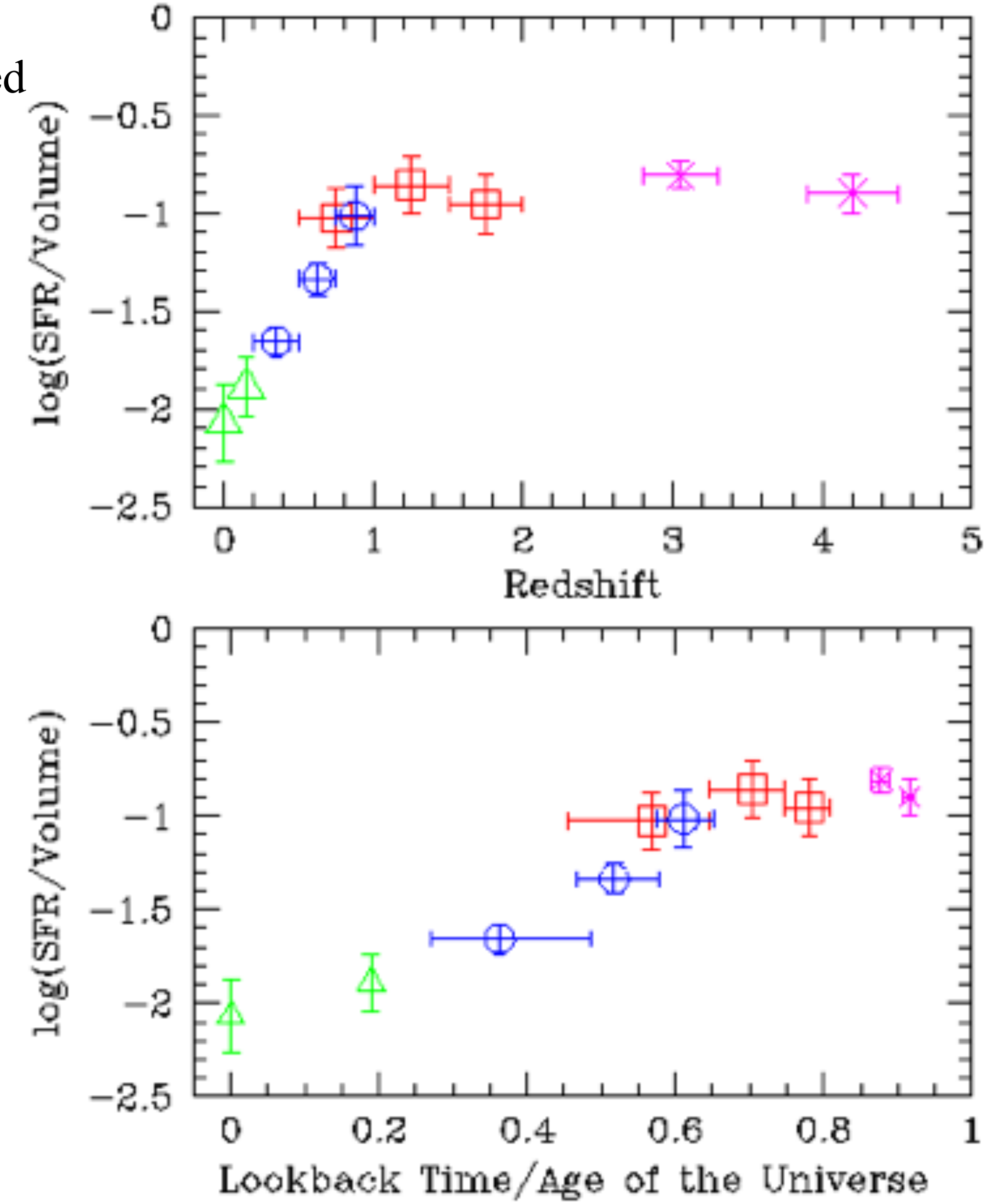
These data and models are ***not*** corrected for extinction

Cosmic Star Formation History

From various luminosity densities converted to star formation rates, we can construct a possible history of the comoving SFR density

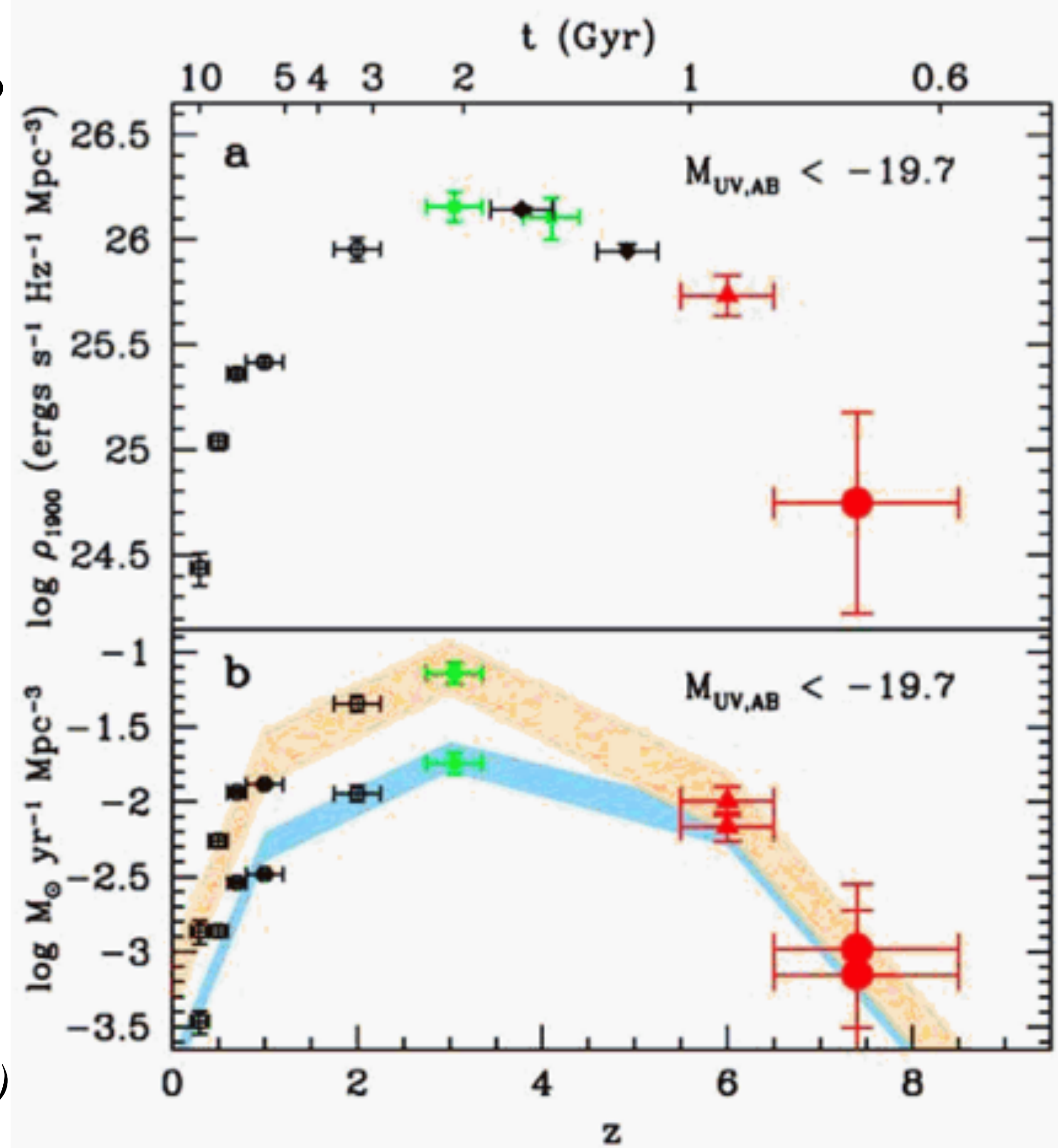
At face value it implies the universe was much more active in the past (z ~1 - 2) but what happens earlier is unclear

There are many complications of interpretation, including the reliability of each SFR diagnostic, dust extinction, incompleteness, etc.



Now pushing to z ~ 6 (and beyond?)

Use the color dropout technique to identify high-z galaxy candidates in deep HST images: different color bins give different redshift shells. Then add up the light.

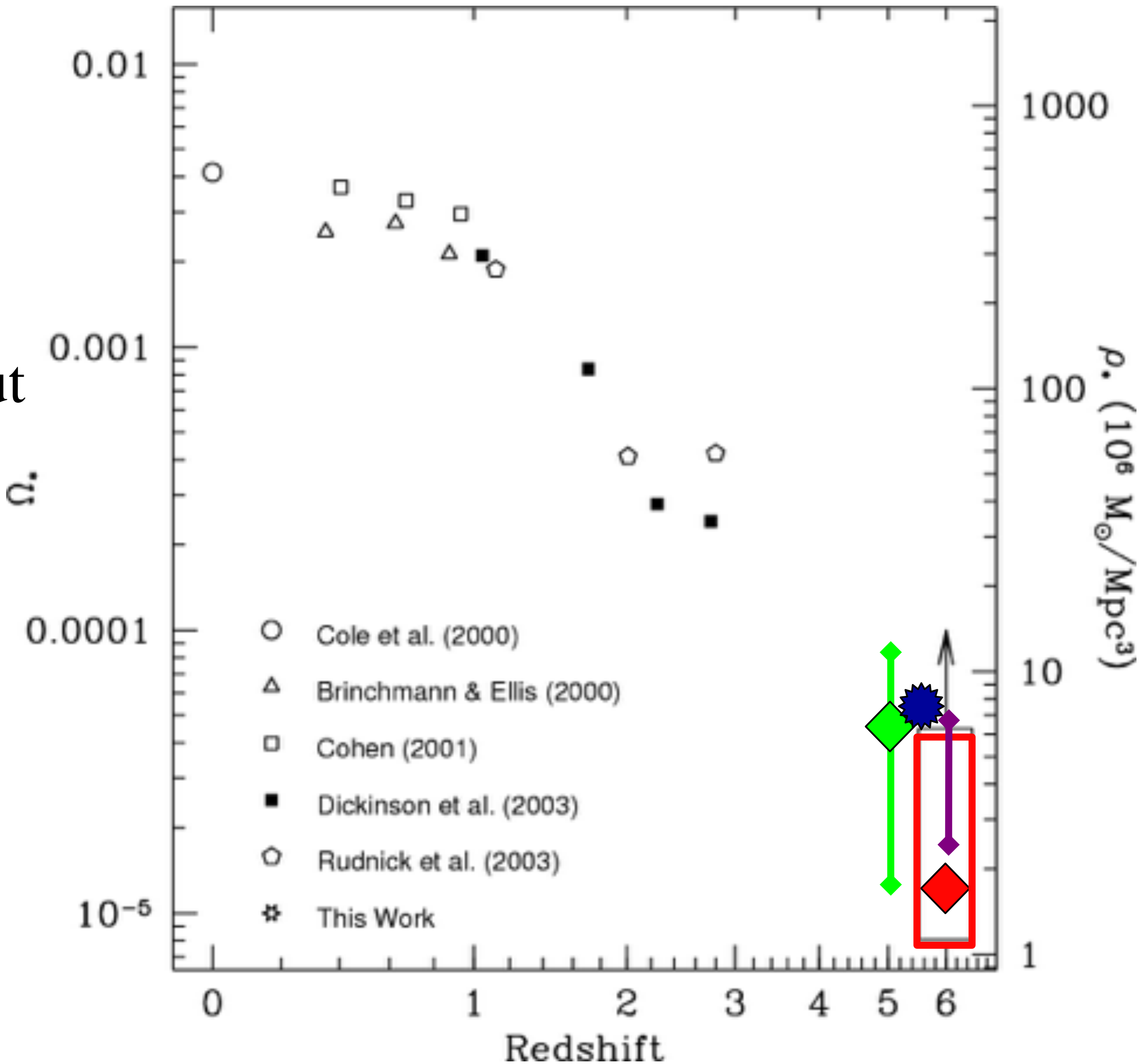


There seems to be a rollover at z > 5 - 6: the epoch of the initial galaxy build-up?

(Bouwens & Illingworth 2006)

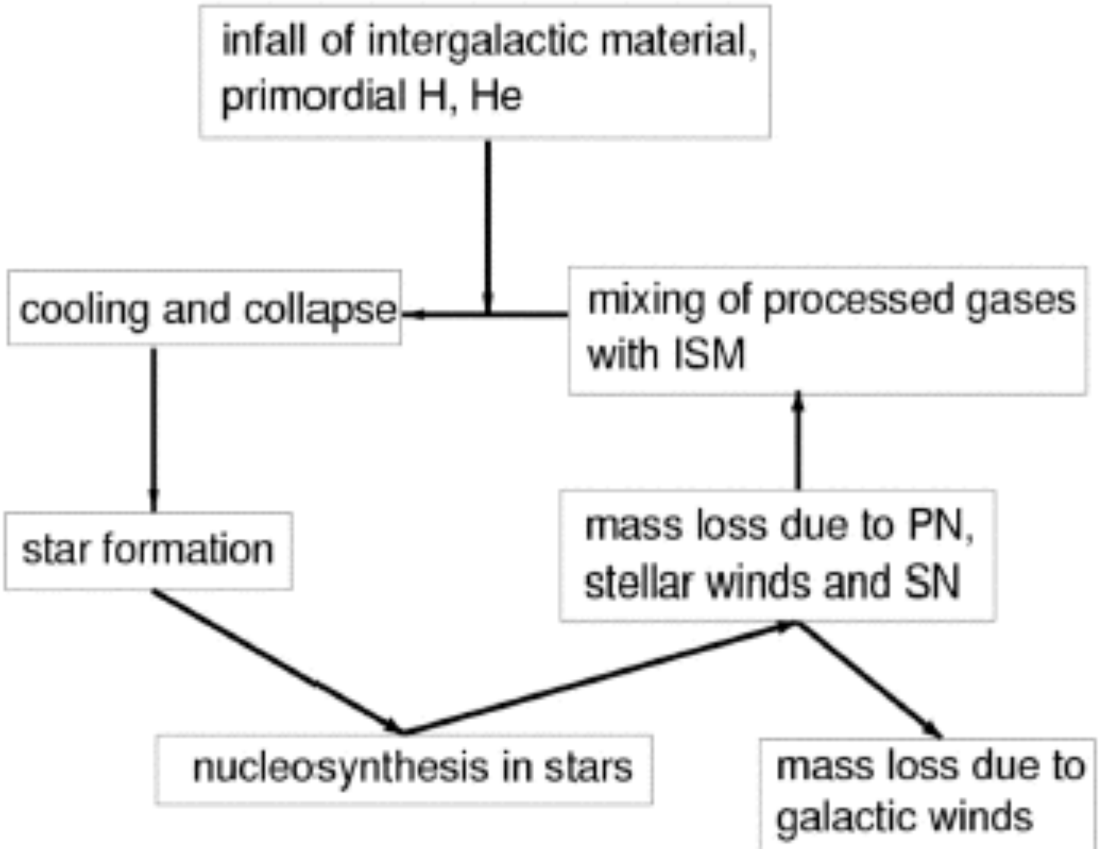
Build-up of Stellar Mass Density

Co-moving stellar mass density grew rapidly from z ~ 6 (and probably higher) to z ~ 1, but has not changed much since then



The Cosmic Chemical Evolution

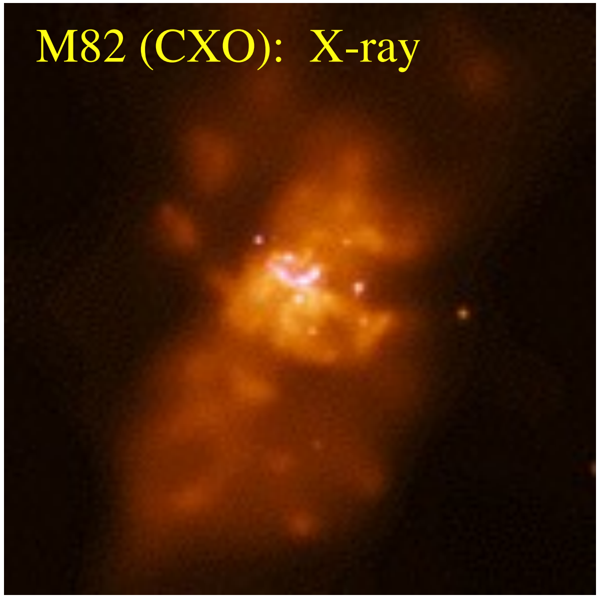
A schematic view:

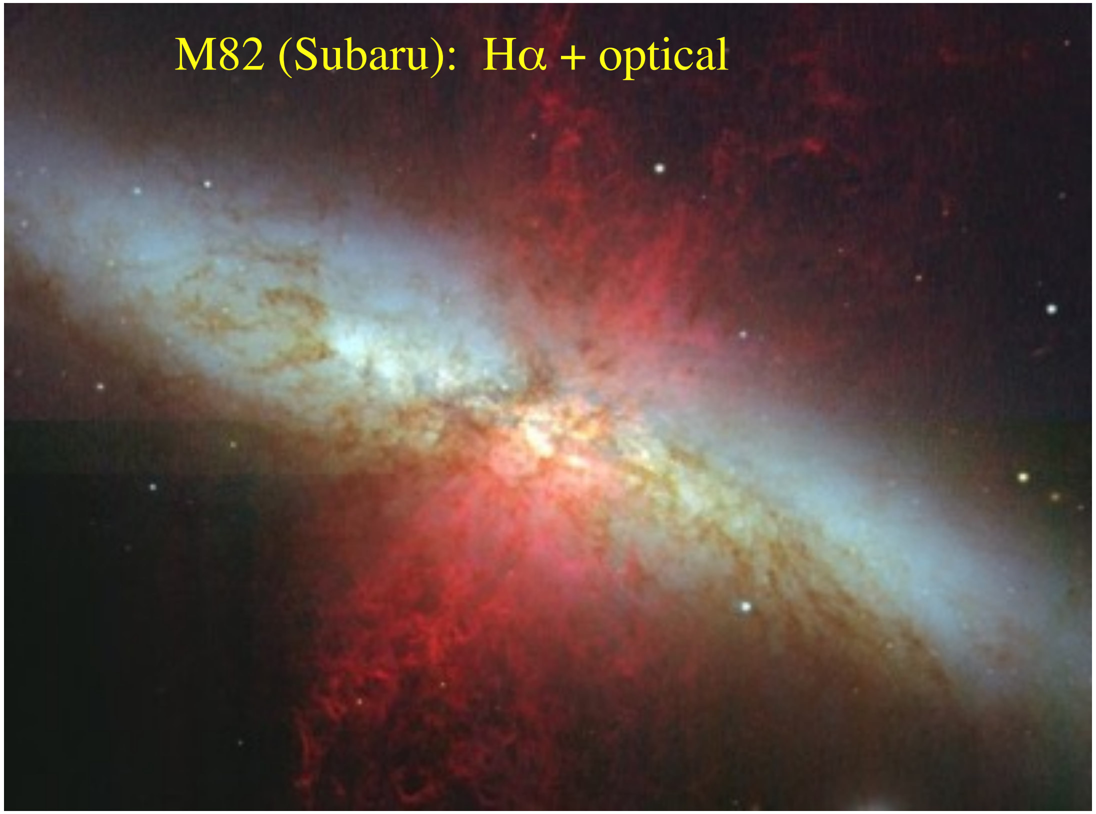


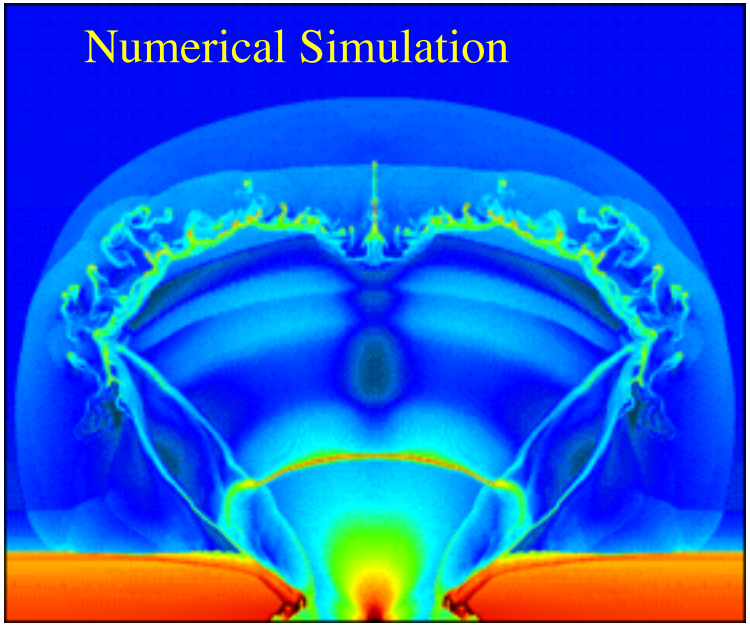
Details of these processes are very messy and hard to model or simulate. So, simplified (semi)analytical models and assumptions are often used, e.g., the “closed box” model, or the “instanteneous recycling” approximation.

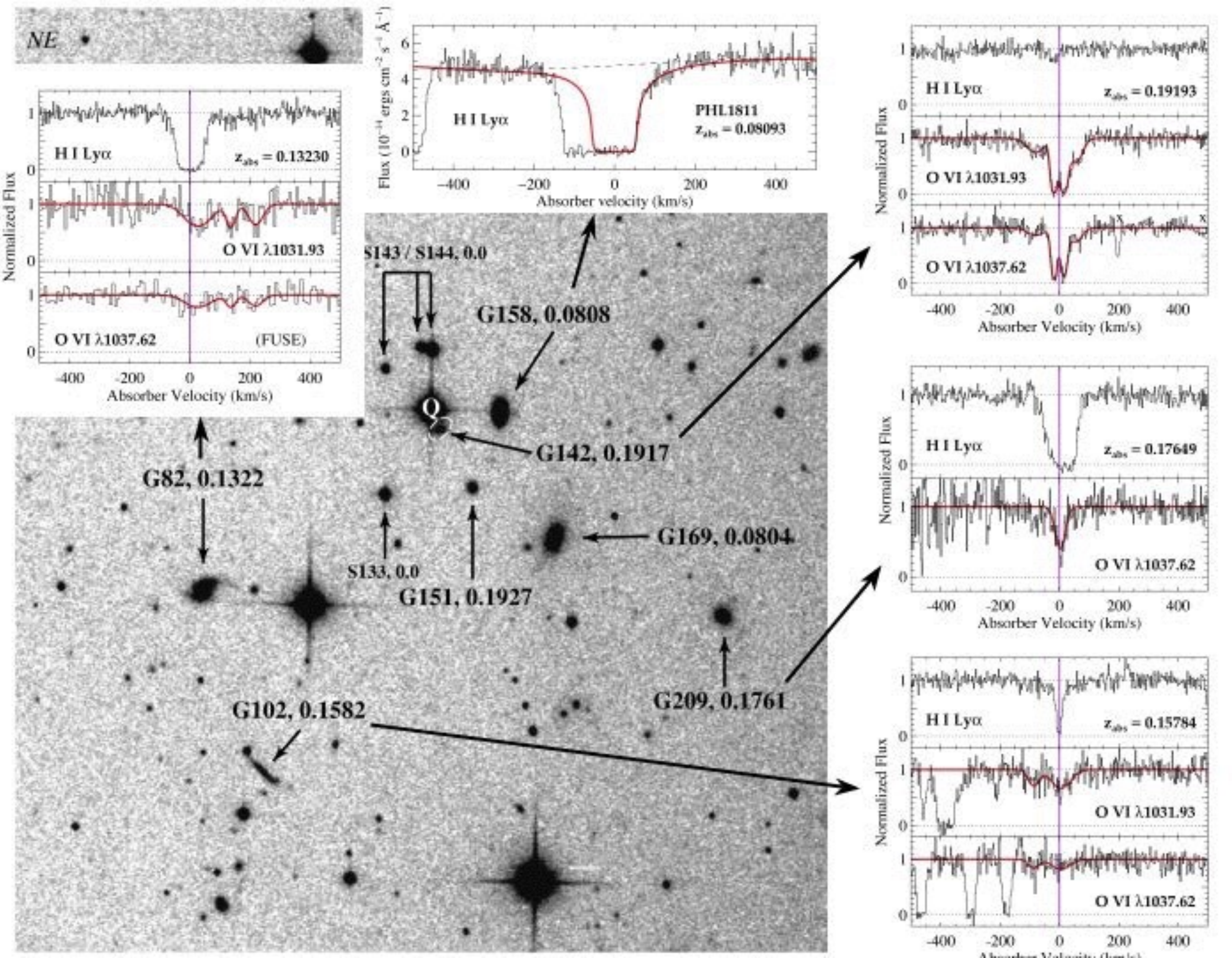
Galactic Winds

Starburst can drive winds of enriched gas (e.g., from supernova ejecta) out to the intergalactic medium. This gas can then be accreted again by galaxies. In a disk galaxy, the winds are generally bipolar outflows



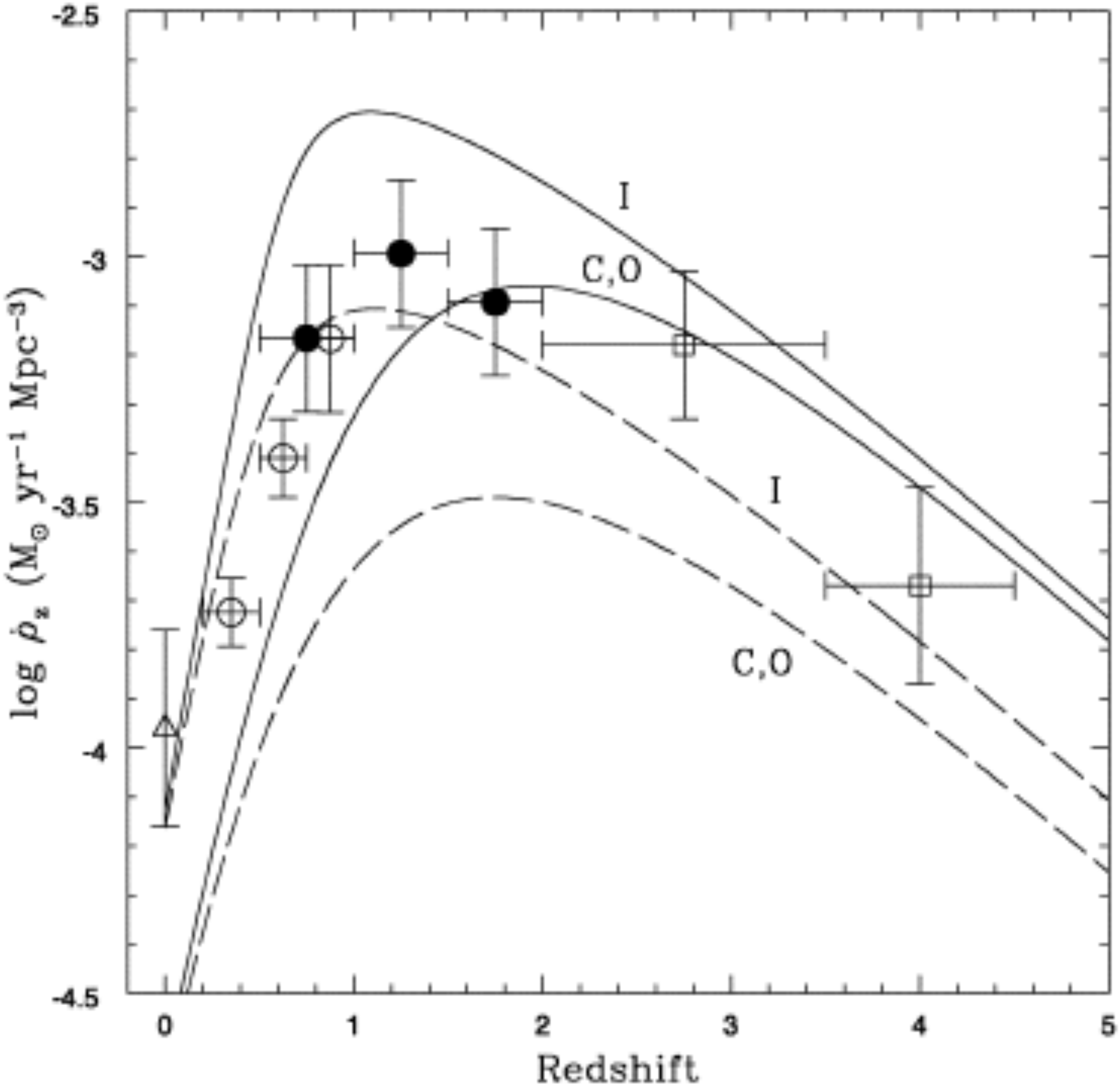






NE
H I Lyα
z_abs = 0.13230
O VI λ1031.93
O VI λ1037.62
(FUSE)
Normalized Flux
Absorber Velocity (km/s)
Flux (10^-14 ergs cm^-2 s^-1 Å^-1)
PHL1811
z_abs = 0.08093
Absorber velocity (km/s)
z_abs = 0.19193
z_abs = 0.17649
z_abs = 0.15784
S143 / S144, 0.0
G158, 0.0808
Q
G142, 0.1917
G82, 0.1322
G169, 0.0804
S133, 0.0
G151, 0.1927
G209, 0.1761
G102, 0.1582

Evolution of the Metal Production



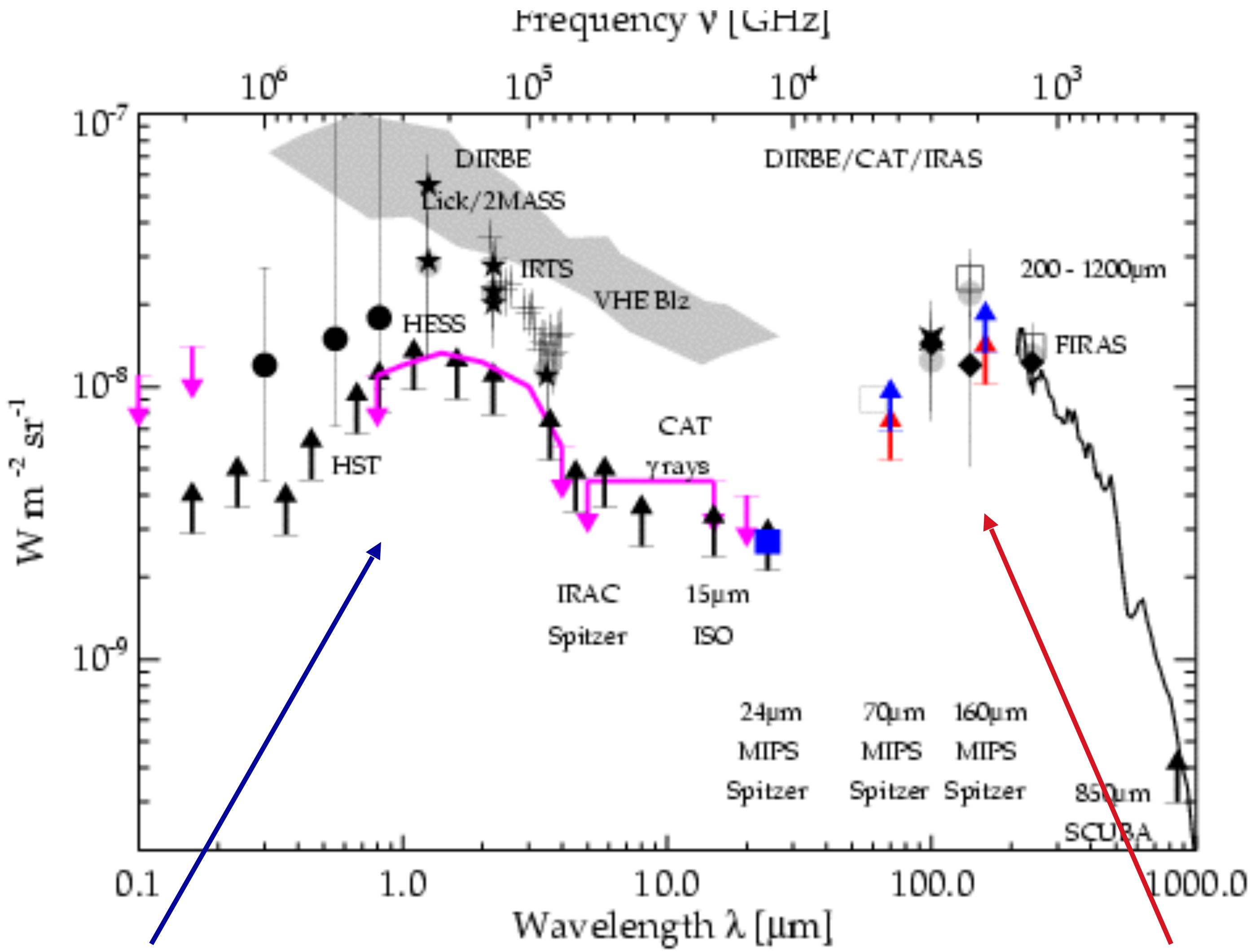
It must track the star formation in galaxies …

Connolly et al. (1997)

All Starlight in the Universe

- Any deep survey is limited in flux and surface brightness: some fainter and/or more diffuse sources are likely missed; thus, our source counts give us only a lower limit to the total energy emitted by evolving galaxies
- An alternative approach is to measure ***integrated diffuse backgrounds, due to all sources***
  - This is really hard to do, for many reasons
  - Redshifts are lost, but at least the energy census is complete
- The total energy in the diffuse extragalactic backgrounds from UV to sub-mm is ~ 100 nW m^{-2} sr^{-1} (±50% or so)
  - This is distributed roughly equally between the UV/Opt (unobscured SF) and FIR/sub-mm (obscured SF)
  - A few percent of the total is contributed by AGN
  - This is only a few percent of the CMB

Diffuse Optical and IR Backgrounds



Unobscured component
(restframe UV, obs. Optical/NIR)

Obscured component
(restframe FIR, obs. FIR/sub-mm)