Galaxy Formation and Evolution

PG lecture course, 2013

Peder Norberg

(based on Ian Smail's slides)

1. Classifying Galaxies: Diversity at z=0
2. Empirical Galaxy Evolution
3. Cosmic Star Formation History
4. Stellar Mass Assembly
5. Theoretical models I (CGL)
6. Theoretical models II (CGL)

Outline

Can we find evidence for evolution in galaxies?

Benchmark based on local galaxy properties & "No Evolution" model

Low-z redshift surveys -> e.g. galaxy luminosity function

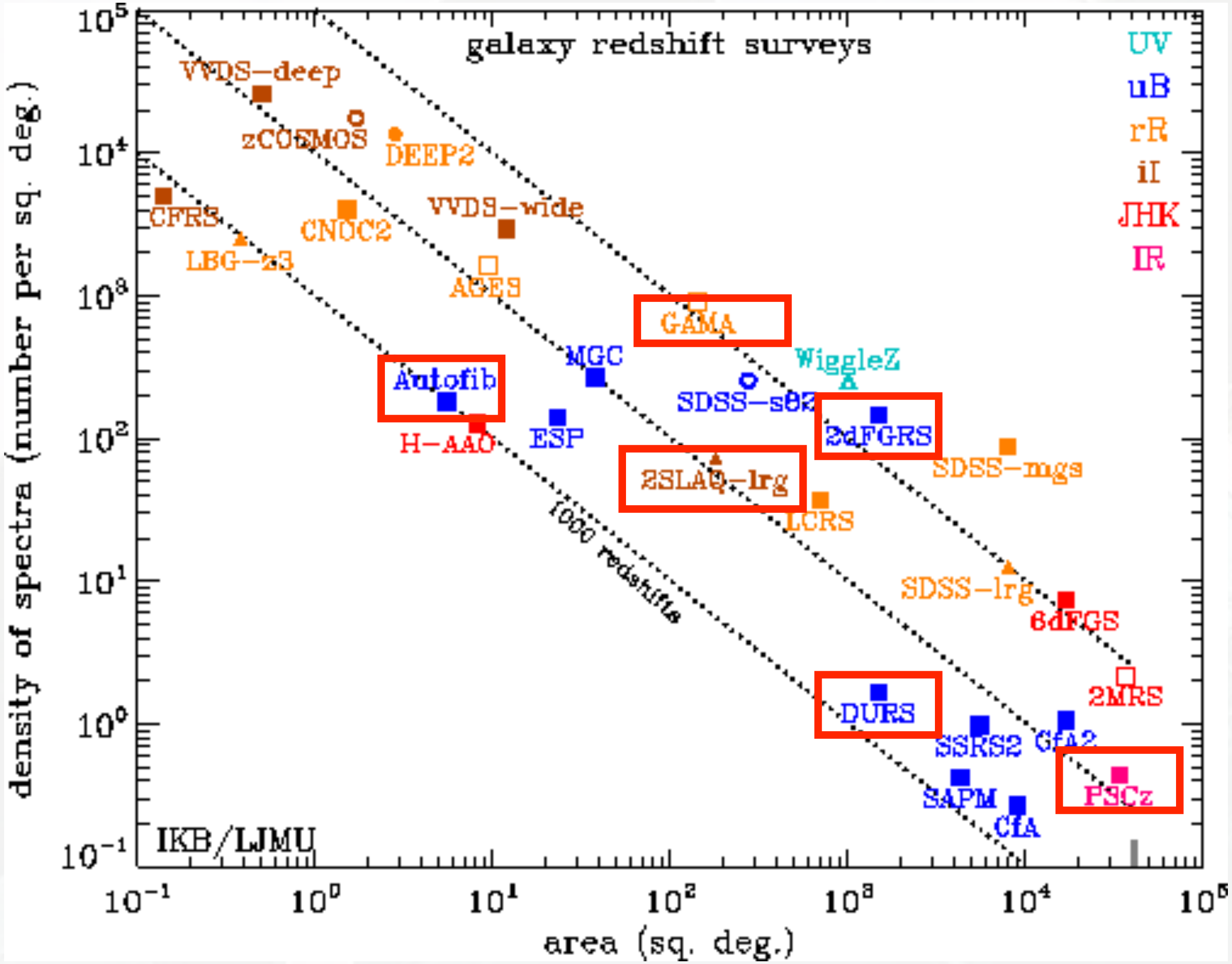
Compare the model to the observed properties of distant galaxies to see if they have evolved:

- number counts,
- colours,
- clustering,
- sizes,
- morphologies,
- ….

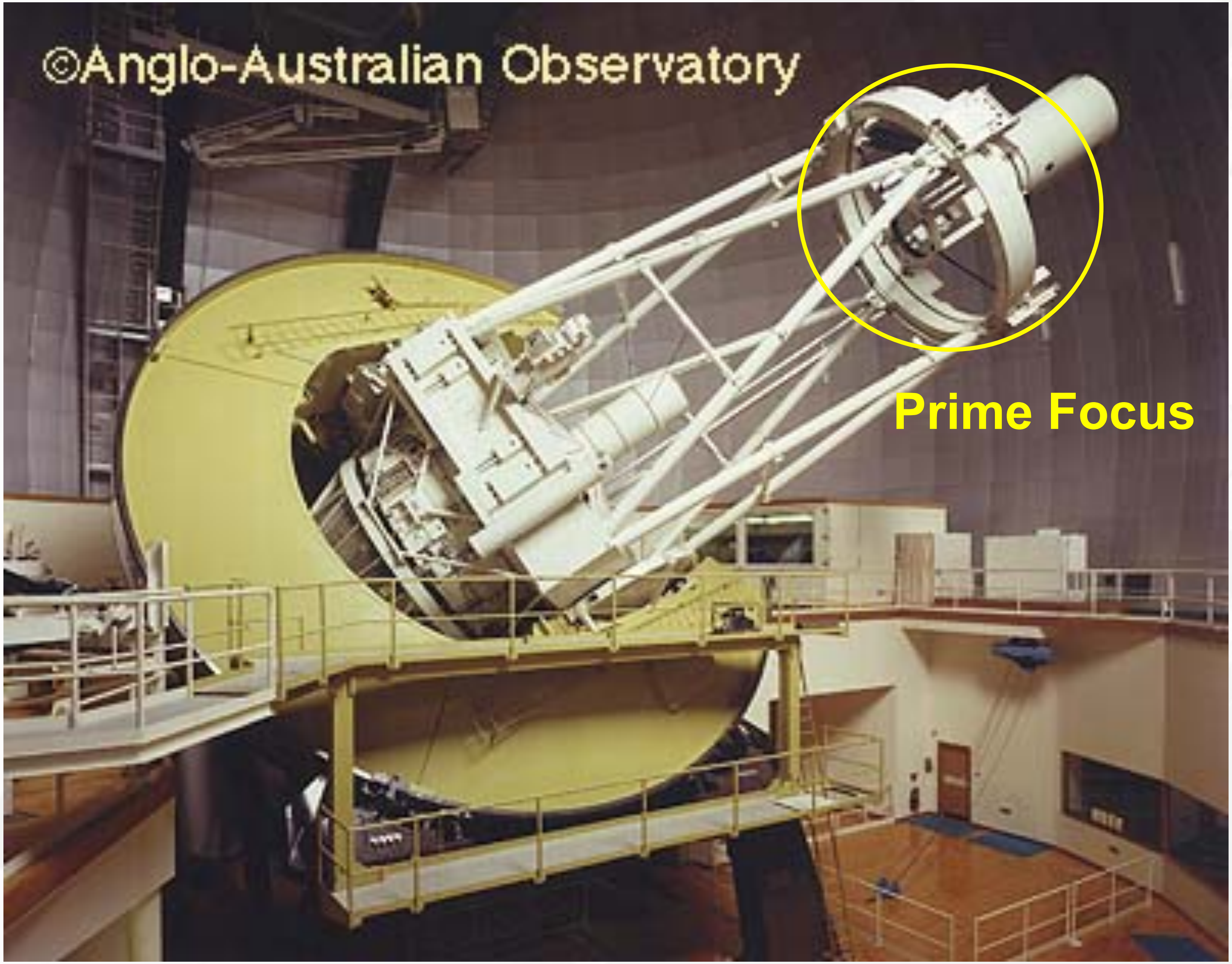
Redshift Surveys

Wide-field (and deep) redshift surveys are Durham speciality (Shanks, Ellis, Edge, Frenk, Norberg)

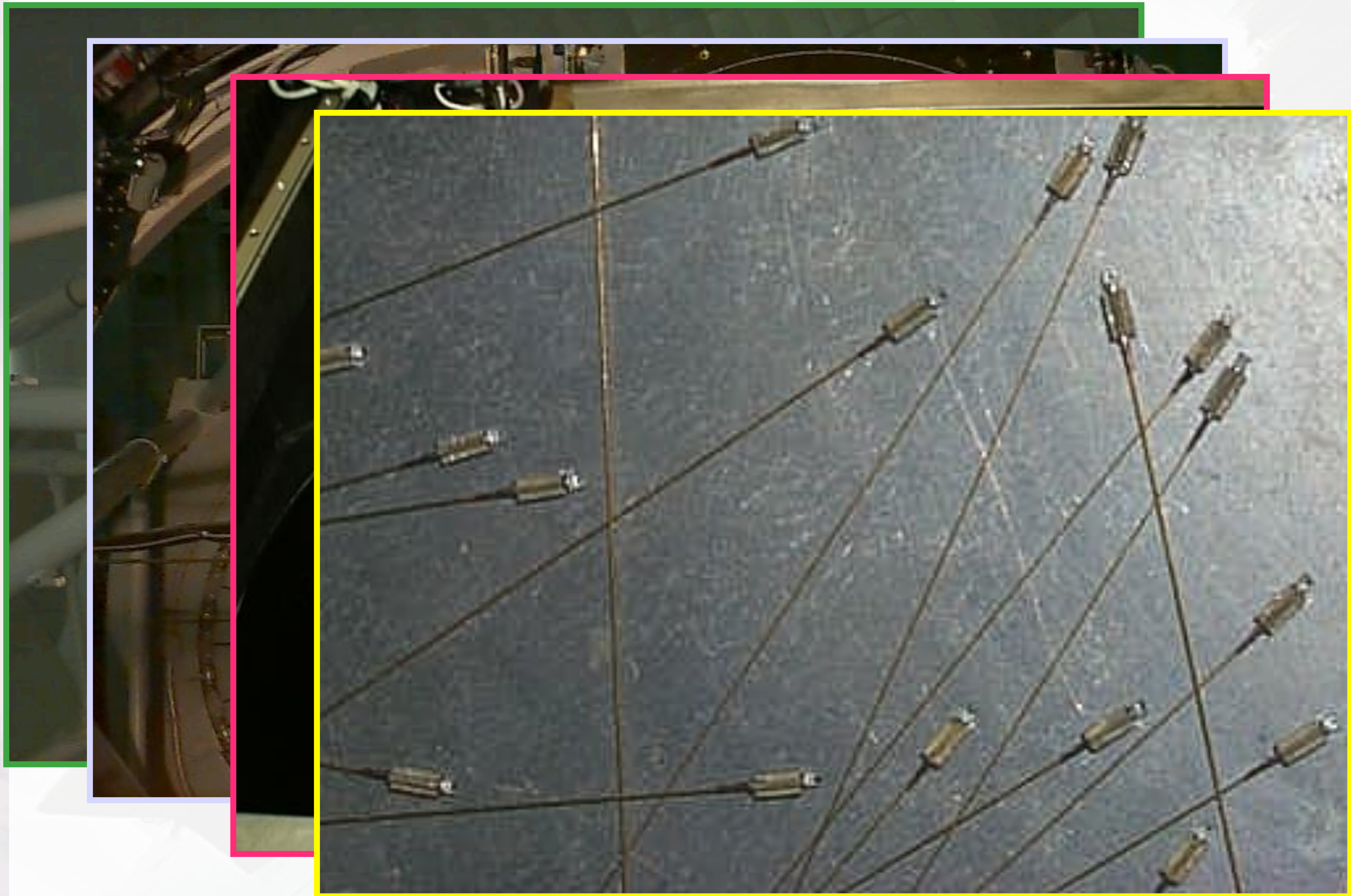
Autofib, DURS, FSCz, 2SLAQ-LRG, 2dFGRS, GAMA

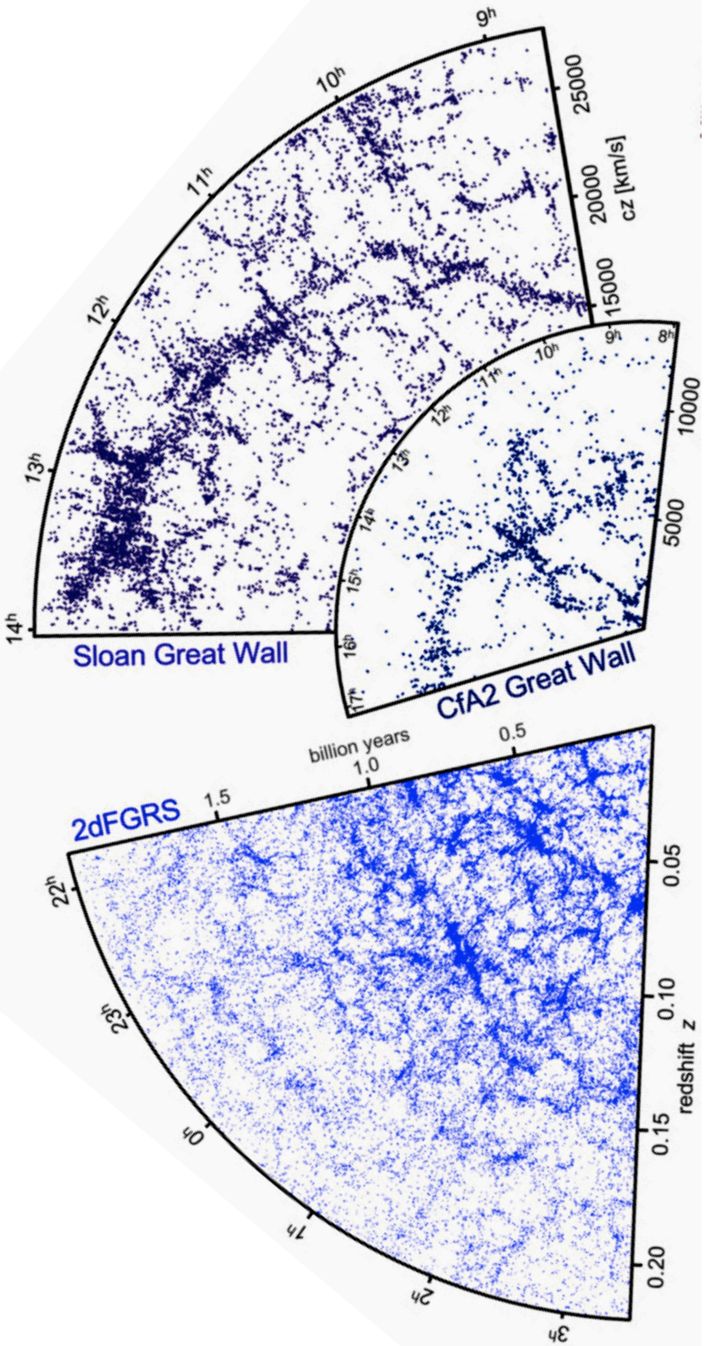


The 2-degree Field Spectrograph



2dF on the AAT





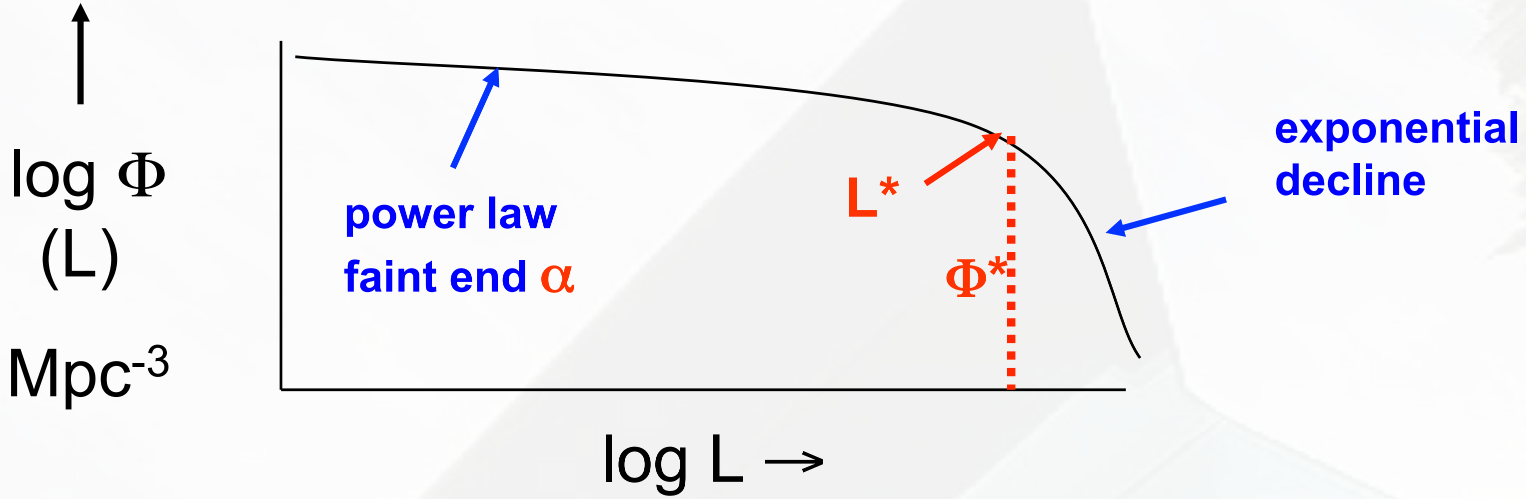
Redshift Surveys

2dFGRS & Sloan Digital Sky Survey (SDSS) have now measured redshifts for > ~10^6 galaxies.

These can be used to produce detailed maps of the Universe. Find strong "filamentary" structures, with walls and filaments surrounding empty voids.

These surveys are key to determine galaxy luminosities from their distances and apparent magnitudes.

Galaxy Luminosity Function



The field galaxy luminosity function is defined: $\Phi(L)\, h^{-3}\, \mathrm{Mpc}^{-3}$

Schechter's function (differential form):

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

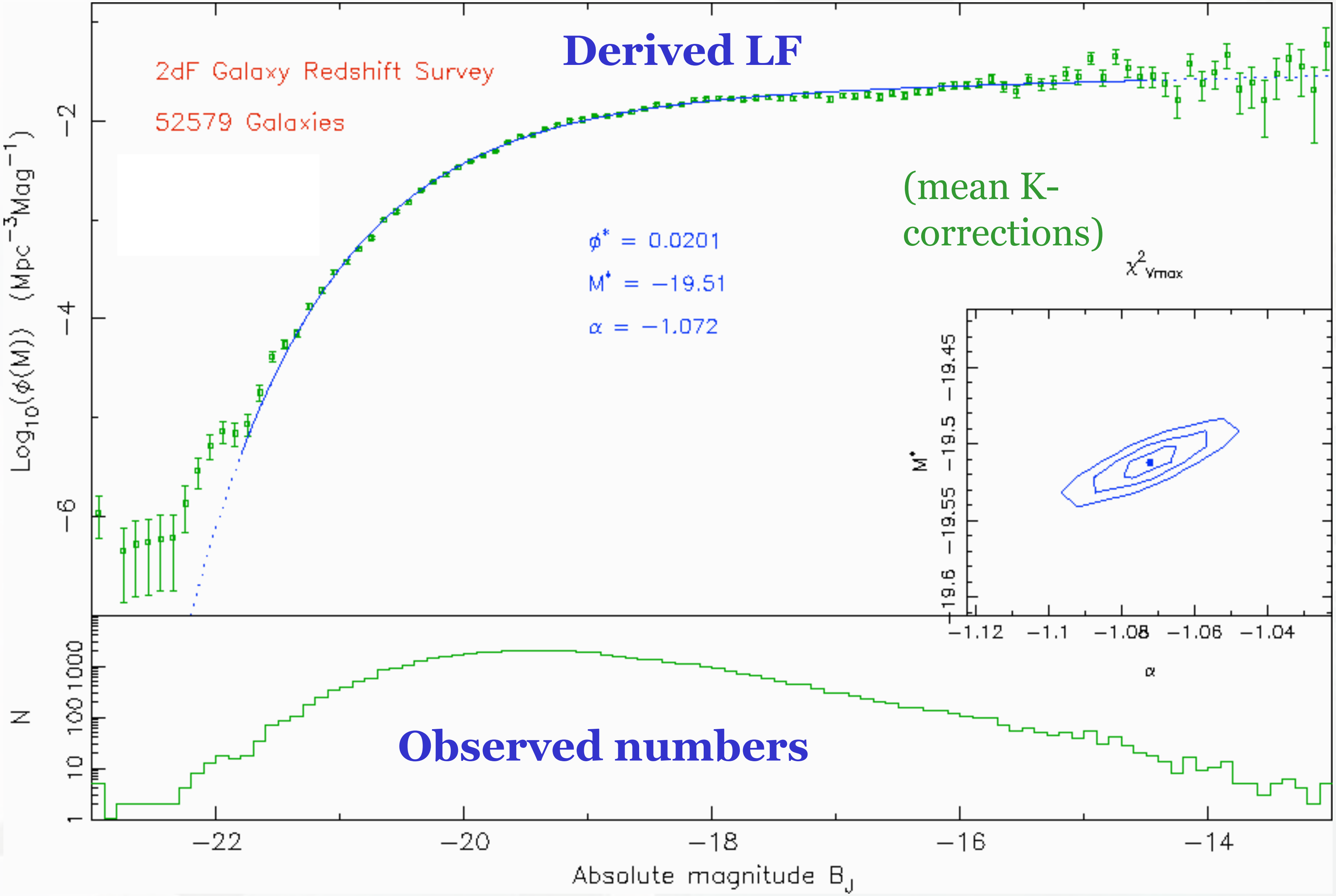
where Φ^* is the normalisation, α is a faint end slope and L^* is a characteristic luminosity

Total galaxy density $\quad N_{Tot} = \int \Phi(L)\, dL = \Phi^* \Gamma(\alpha + 1)$

Luminosity density $\quad \rho_L = \int \Phi(L) L\, dL = \Phi^* L^* \Gamma(\alpha + 2)$

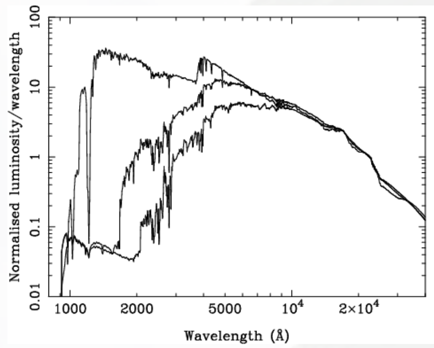
(N_{Tot} diverges if $\alpha < -1$ whereas ρ_L diverges only if $\alpha < -2$)

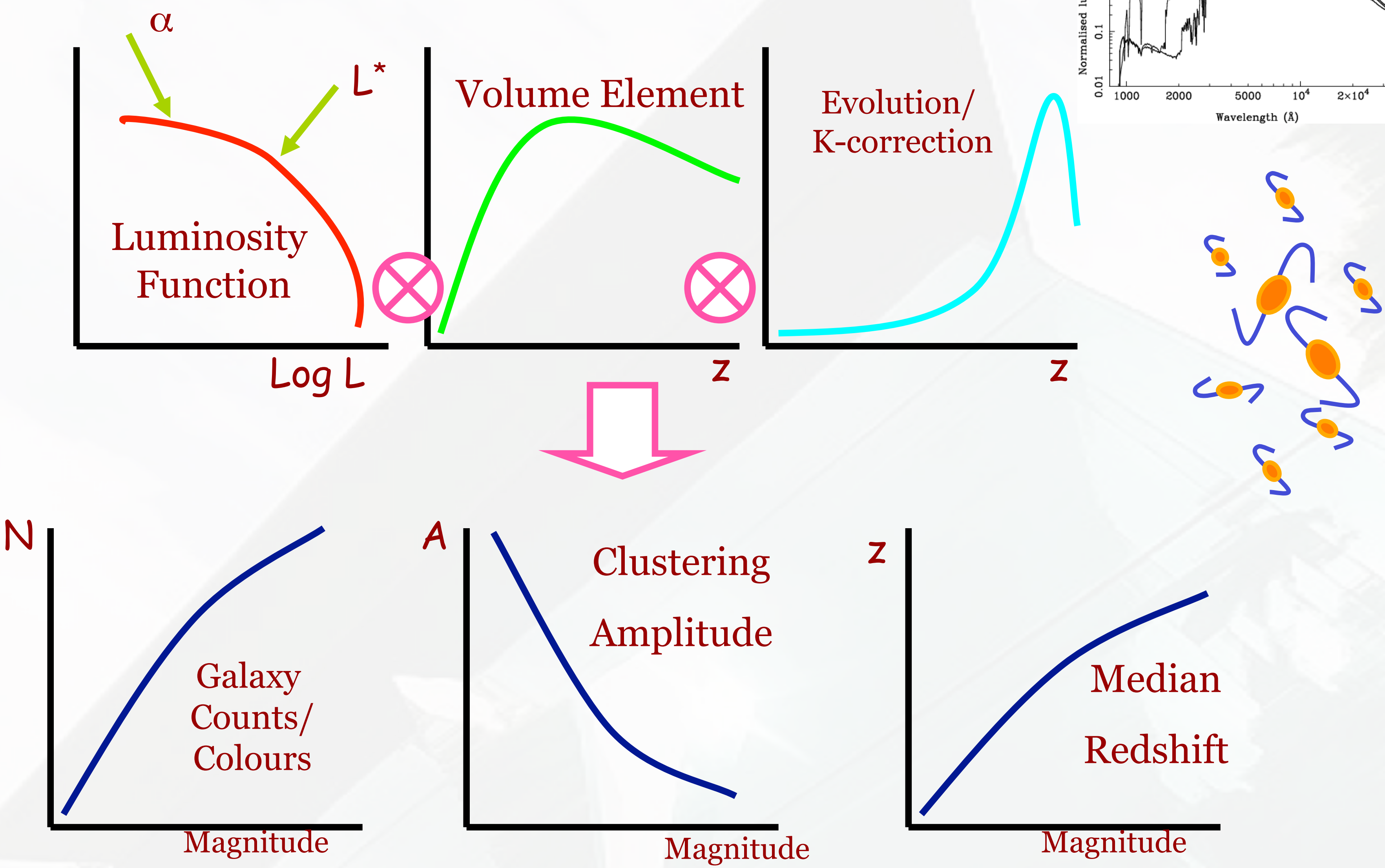
2dF Galaxy Luminosity Function



← Luminosity

Distant Galaxies Observables





Searching for Galaxy Evolution

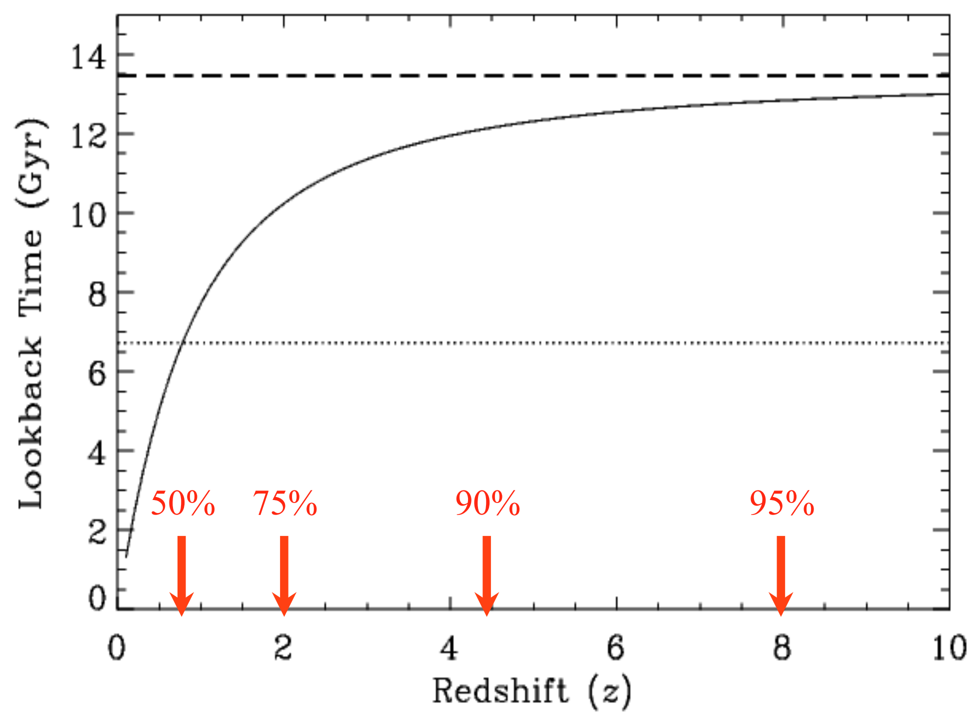
Cosmological Scales

WMAP cosmology:

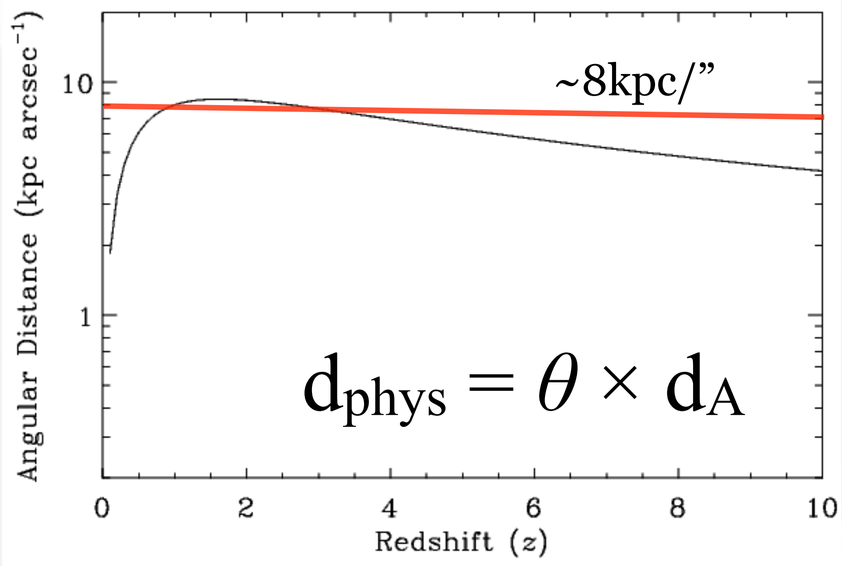
$\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$

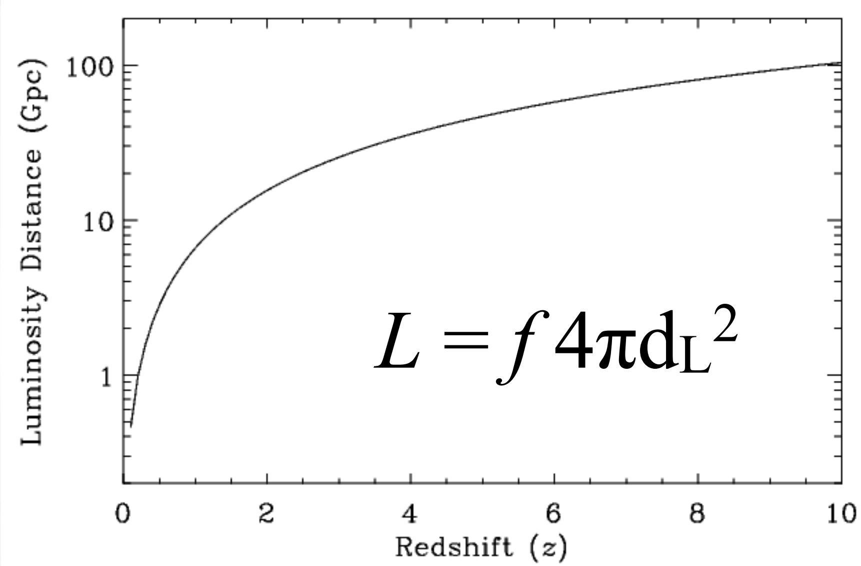
$H_0 = 70$ km s^{-1} Mpc^{-1}

Age of Universe = 13.4 Gyr

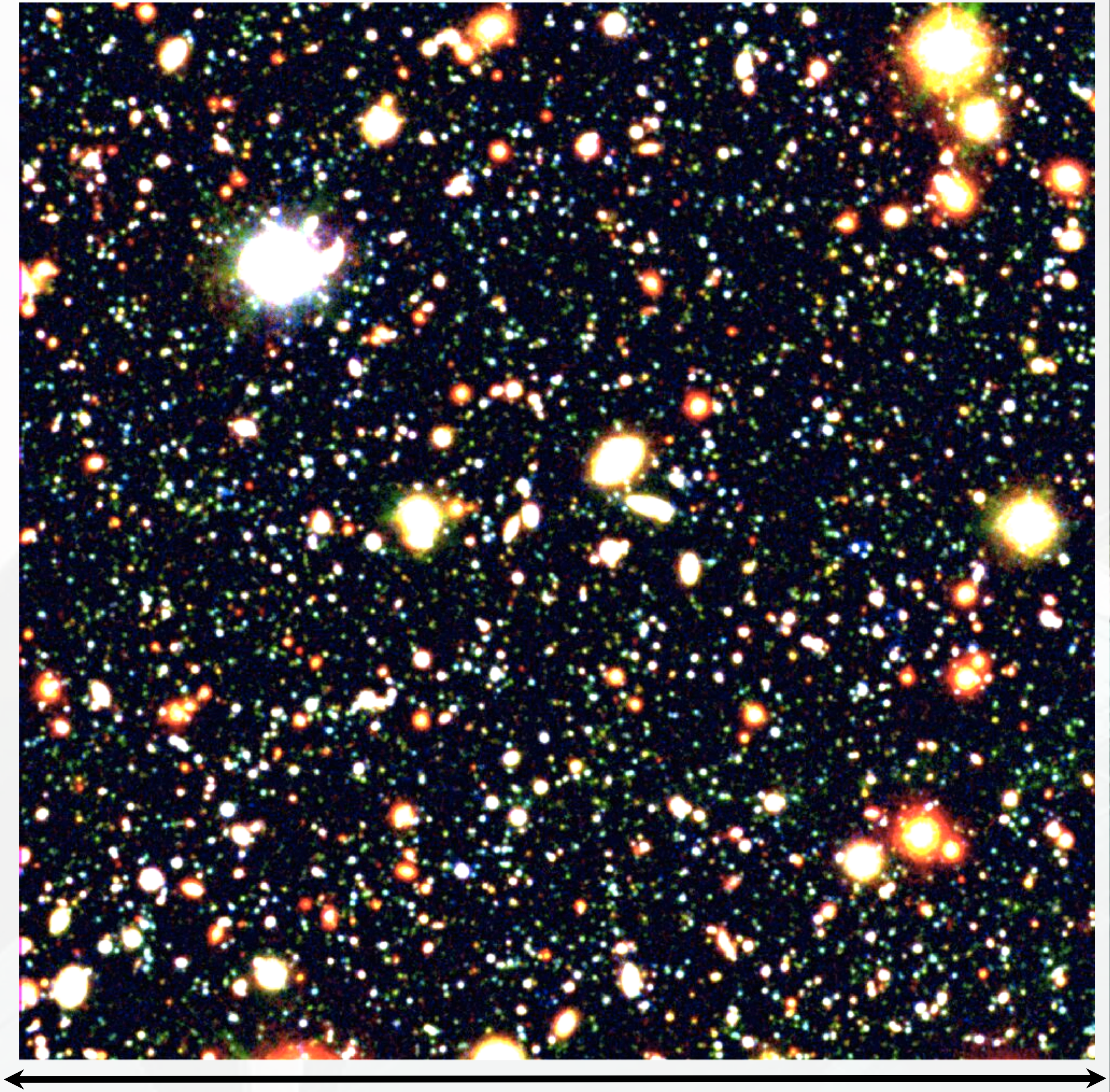


-> time ~ log (1+z)





Deep (ground-based) images of the Universe

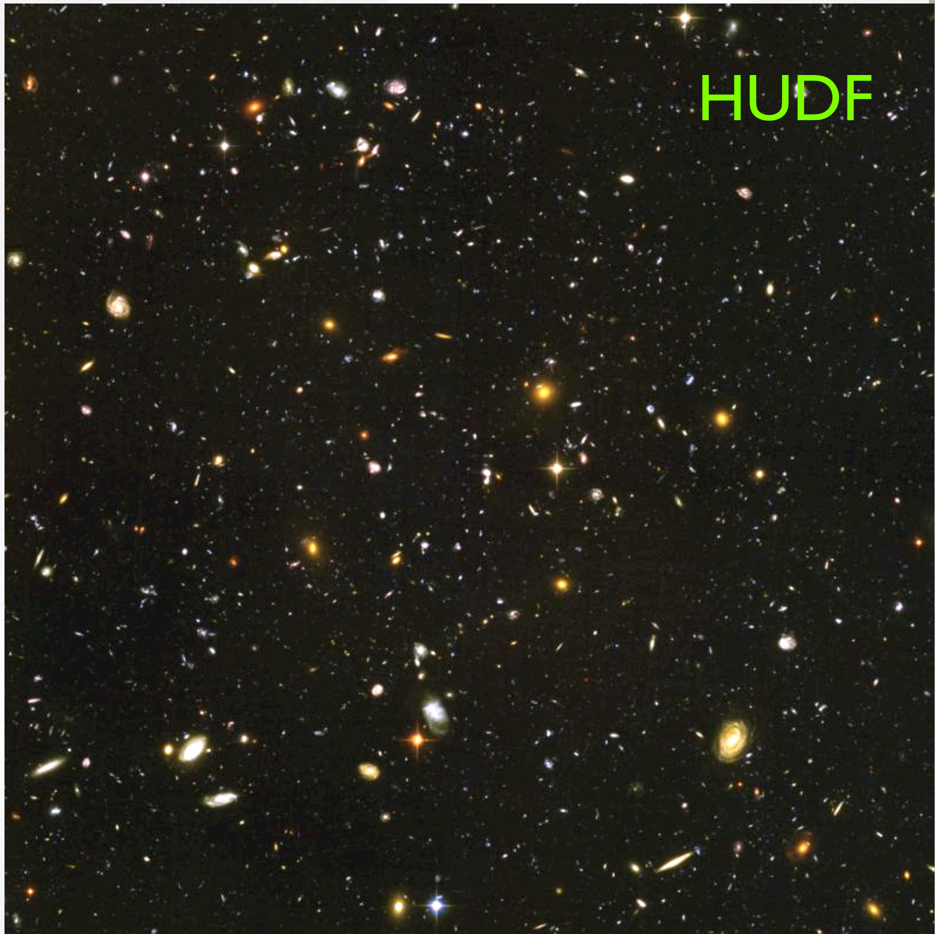


Metcalfe/Shanks et al.   WHDF: 7 arcmin

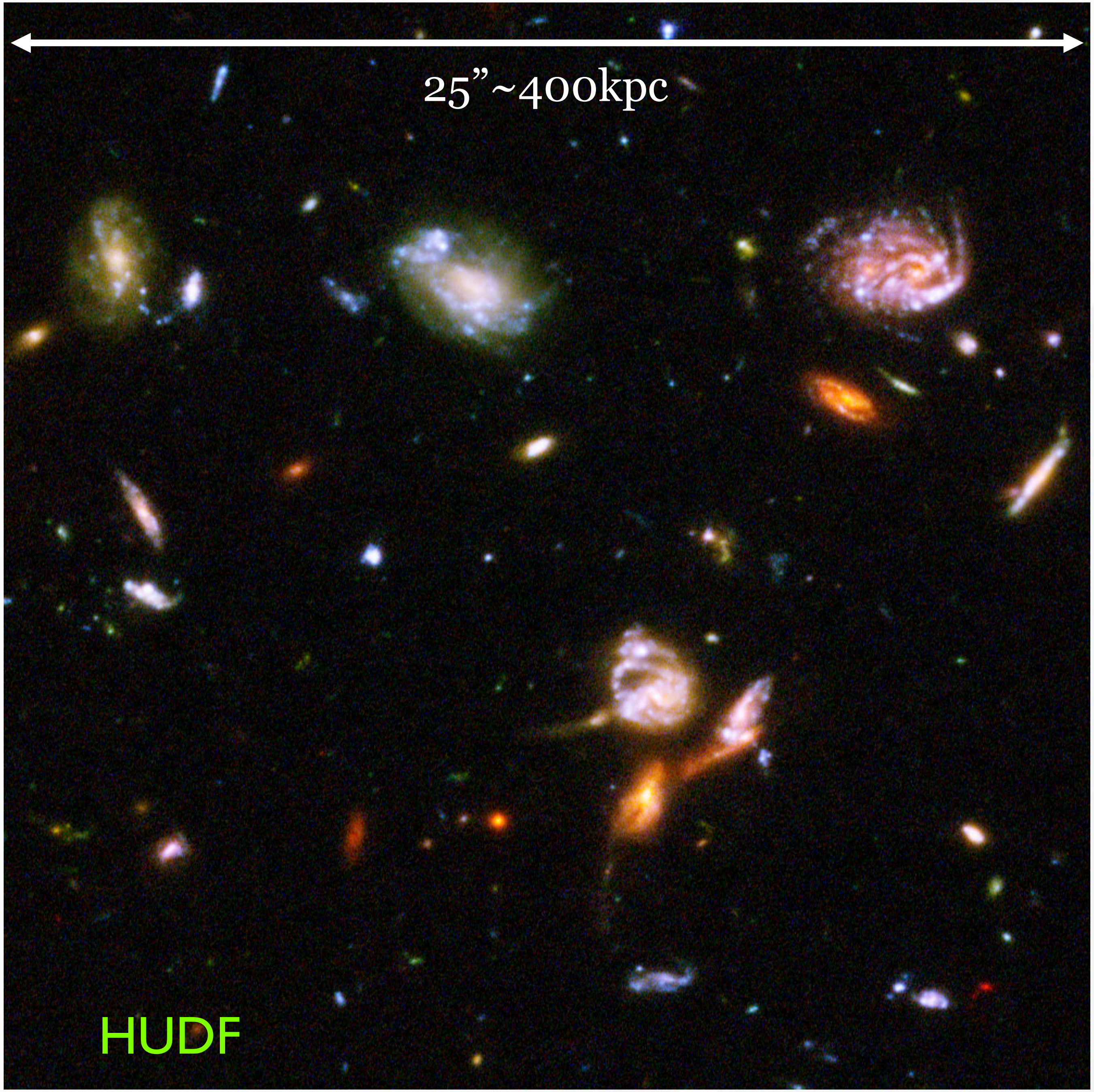
Deepest Images of the Universe

WFPC2: 2.5 arcmin (0.1 arcsec FWHM)

ACS: 3.5 arcmin (0.1 arcsec FWHM)



More of the fainter galaxies appear blue and compact



Deepest Images of the Universe

Note there is blank sky between the galaxies!

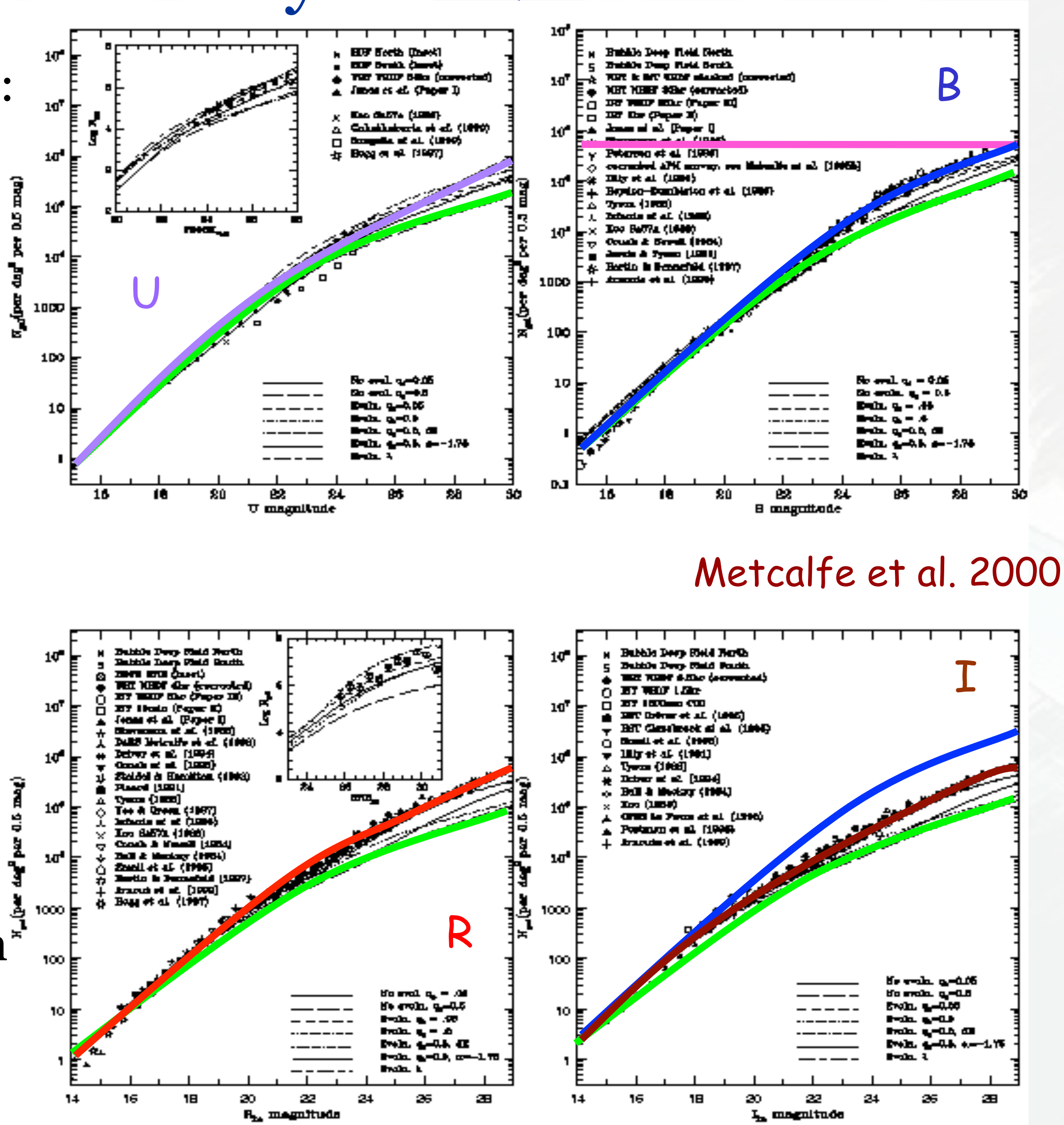
Differential Galaxy Number Counts

dN/dm in different filters:
$dN/dm \sim 10^{A-C*mag}$

Slope, C, steeper in bluer passbands:
C=0.4 in B,
C=0.32 in R and
C=0.27 in I
-> fainter galaxies bluer

Counts exceed No Evolution model at faint end, 2x @ R=22

Cumulative surface density reaches >200 sq. arcmin by B~30 about 8-10x more than No Evolution model



Why so many galaxies?

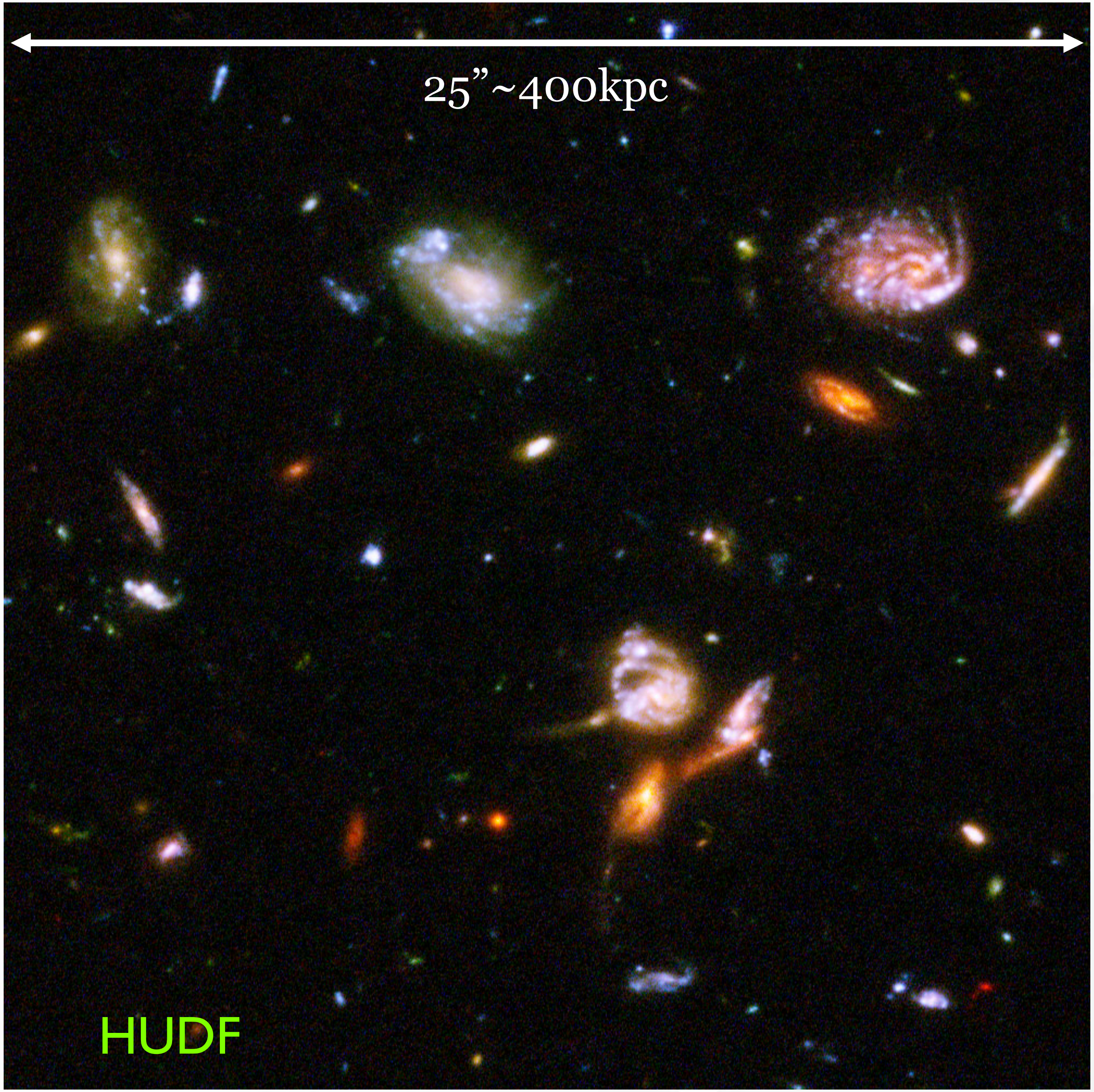
Many more (> 10x) galaxies than expected from "No Evolution" model:

i. Population of "proto-galaxies" at high-redshifts which are bright because of enhanced SF?

ii. Population of dwarf galaxies at intermediate redshifts which fade/merge by present day?

iii. Underdensity in local Universe - so "No Evolution" model under predicts counts?

iv. Something even odder?



The Faintest Galaxies

Equivalent to 10^{10} galaxies over whole sky.

Or >1 per 4x4-arcsec box (30-kpc)

Why are there 10x more than we expect from NE?

What are they? Are they galaxies?

Colours of Faint Galaxies

Counts steeper in bluer filters

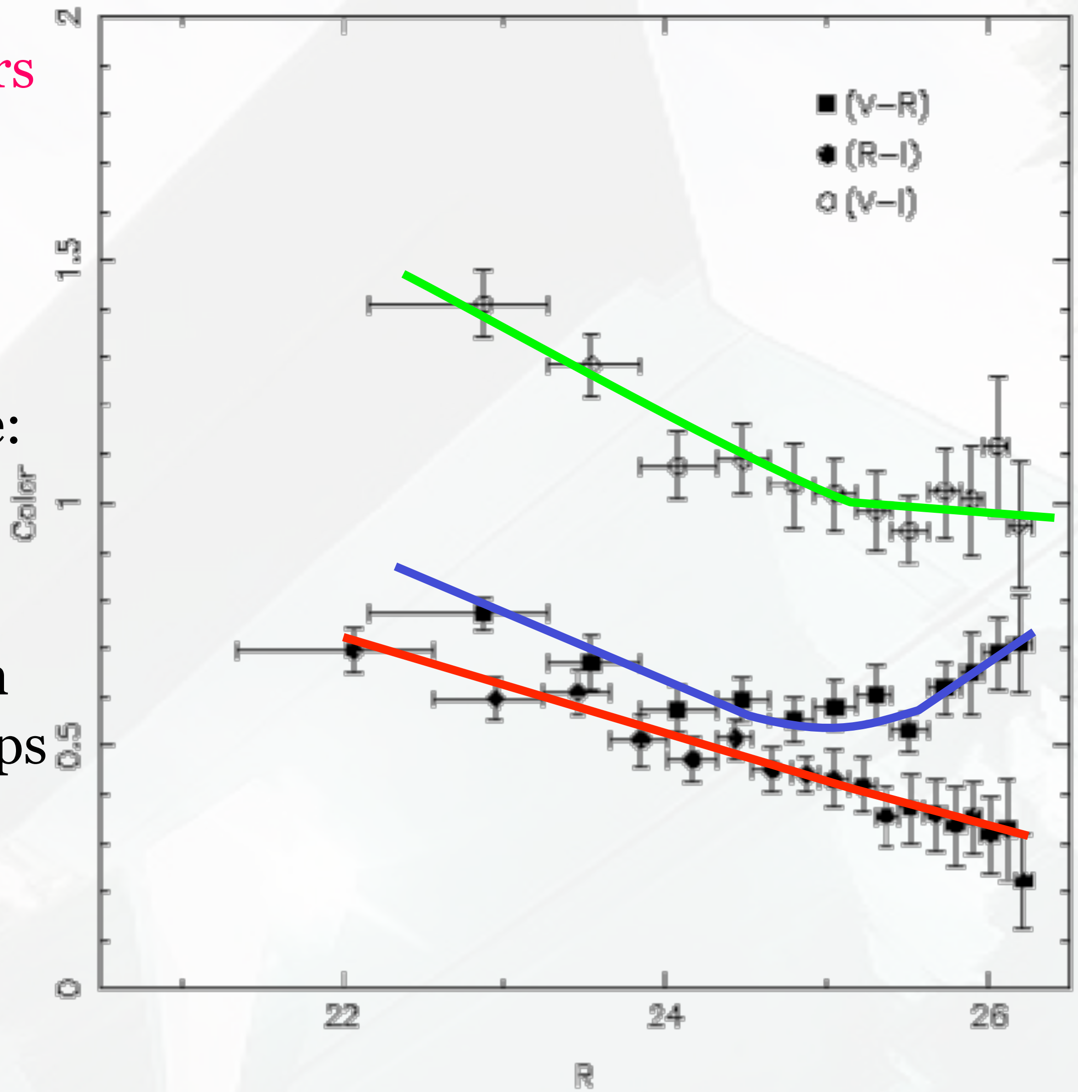
-> galaxies become bluer on average as we go fainter.

Variation in median colour with apparent magnitude:

-> Galaxies bluer in all passbands to R~24.5

At R>24.5 the count slope in the bluest passbands drops – due to:

- volume element?
- evolution?
- redshift limit?



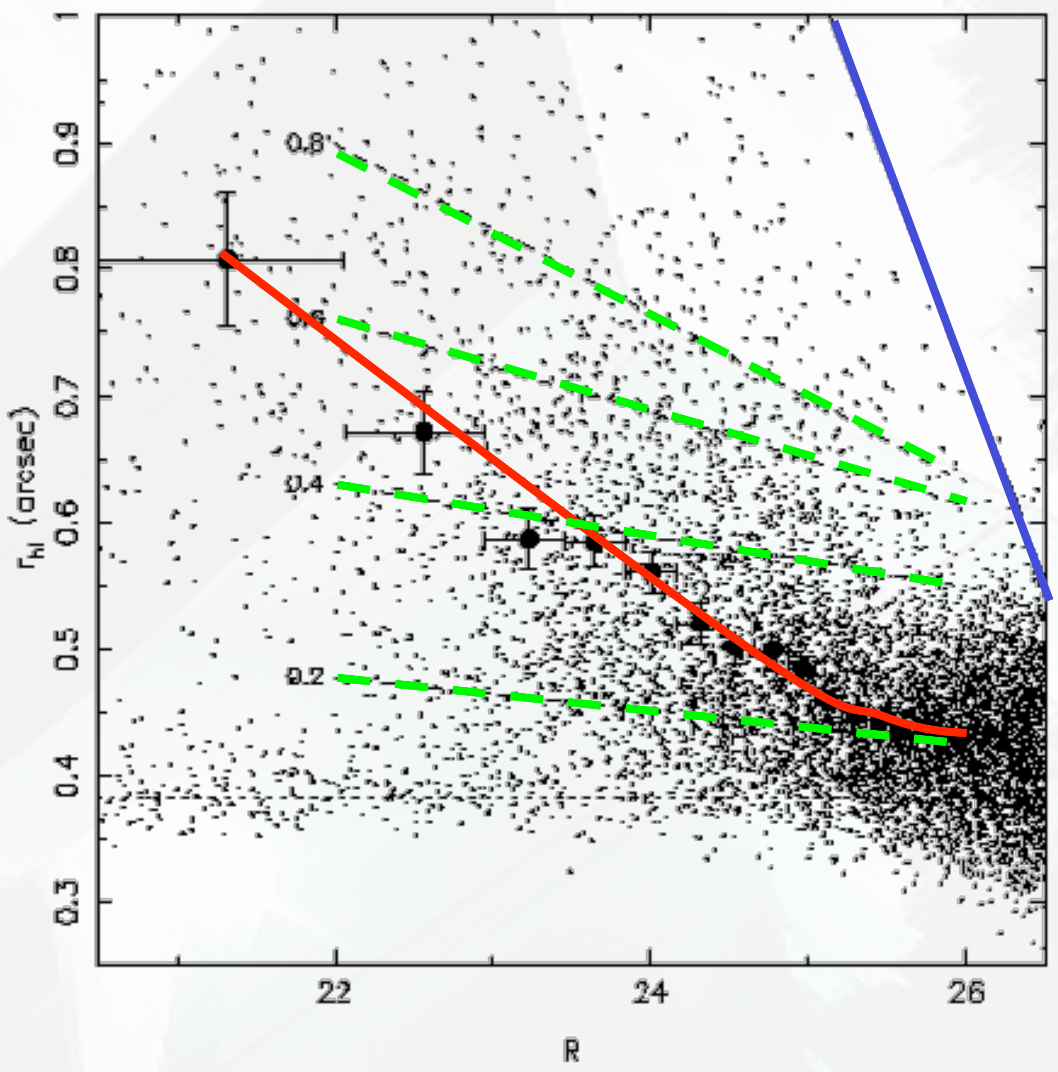
Angular Sizes

In best seeing ground-based images we can resolve faint galaxies

Median half-light size vs apparent magnitude:

Gradual decline, i.e. fainter galaxies are smaller (hence why HUDF has blank sky)

Intrinsic sizes of 0.2” are <3kpc (dwarfs) at any redshift and in any cosmology



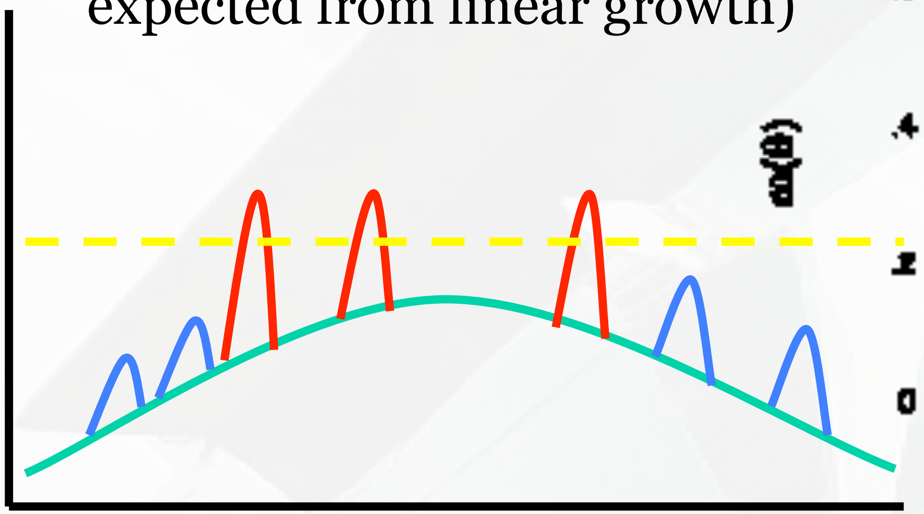
Angular Clustering I

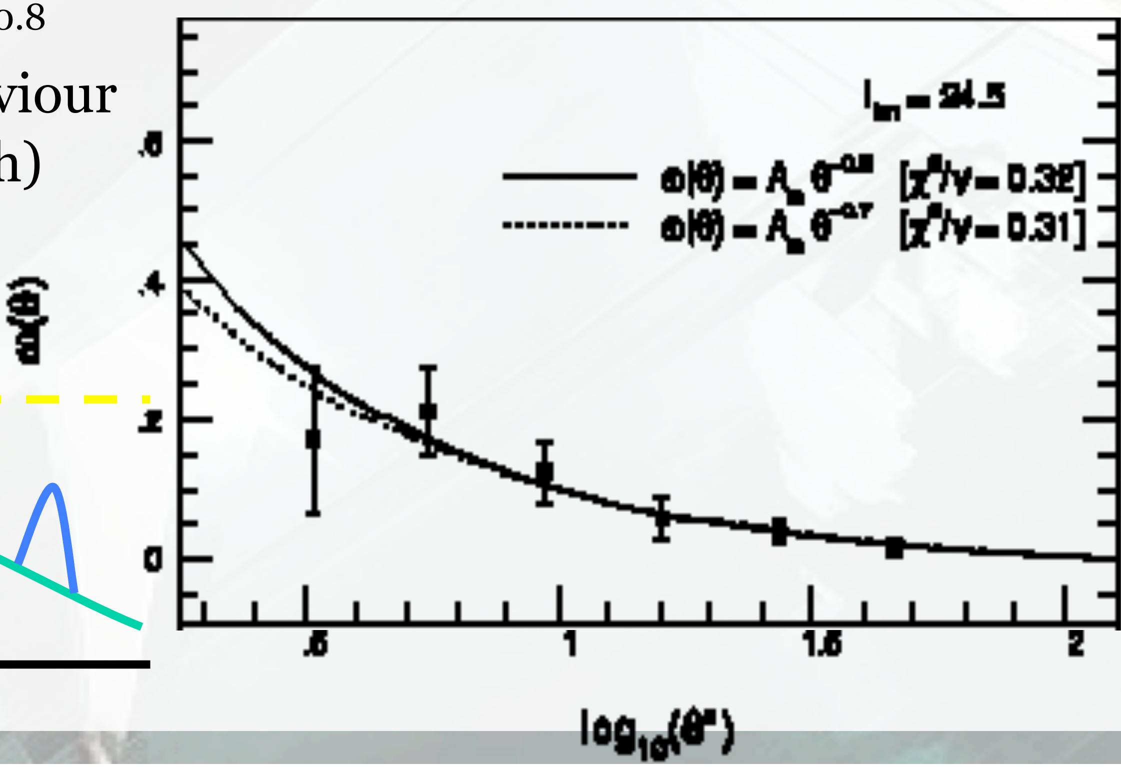
ω(θ) measures the probability of finding a 2nd galaxy within θ±dθ of the first

$$\omega(\theta)=DD/DR-1$$

Apparent clustering relates to intrinsic clustering of the population (and hence to bias/mass) and volume surveyed

Fit functional form: $\omega(\theta)= A\theta^{-0.8}$ (power law clustering behaviour expected from linear growth)





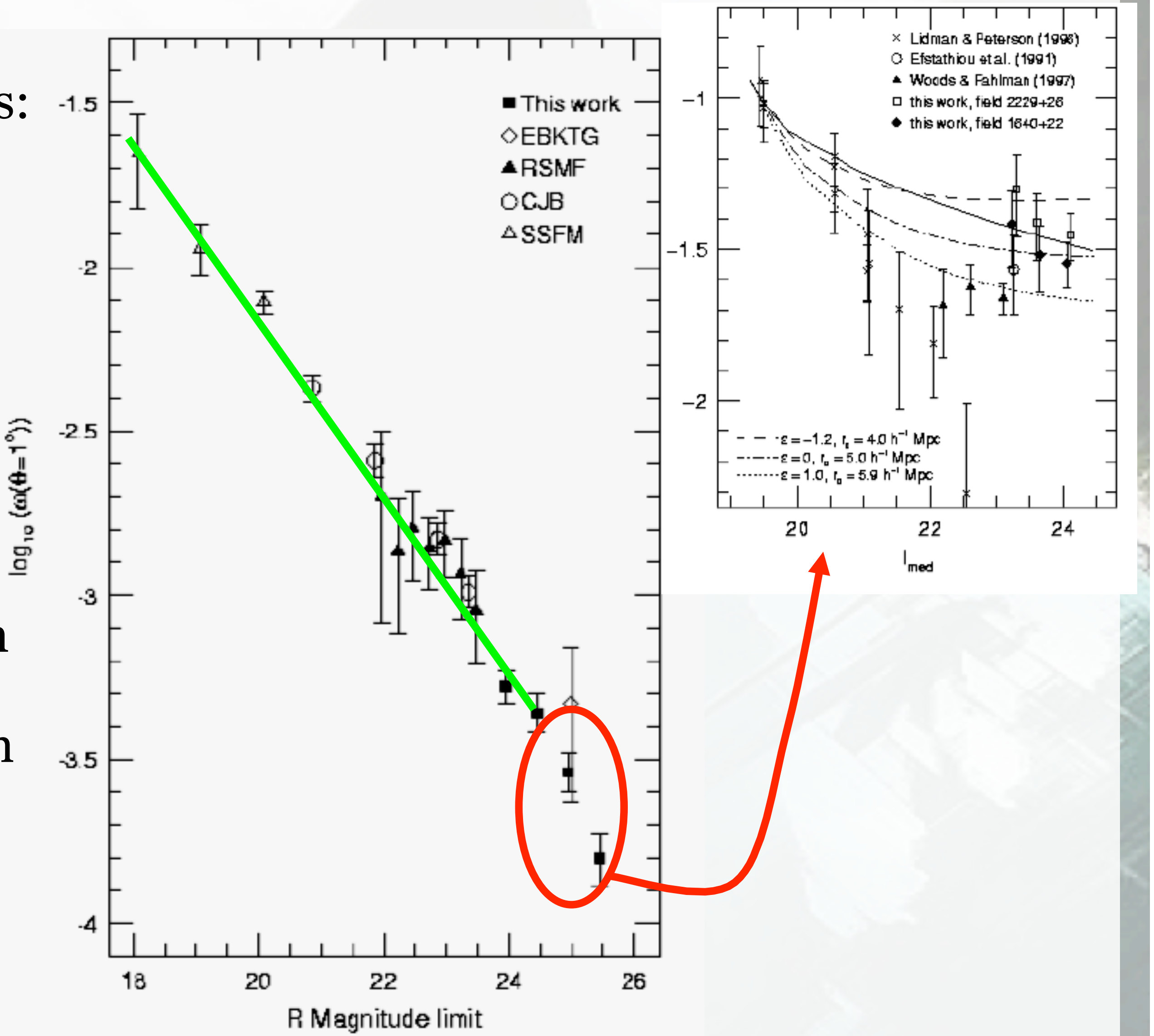
Angular Clustering II

Amplitude, A, vs sample depth compared to models:

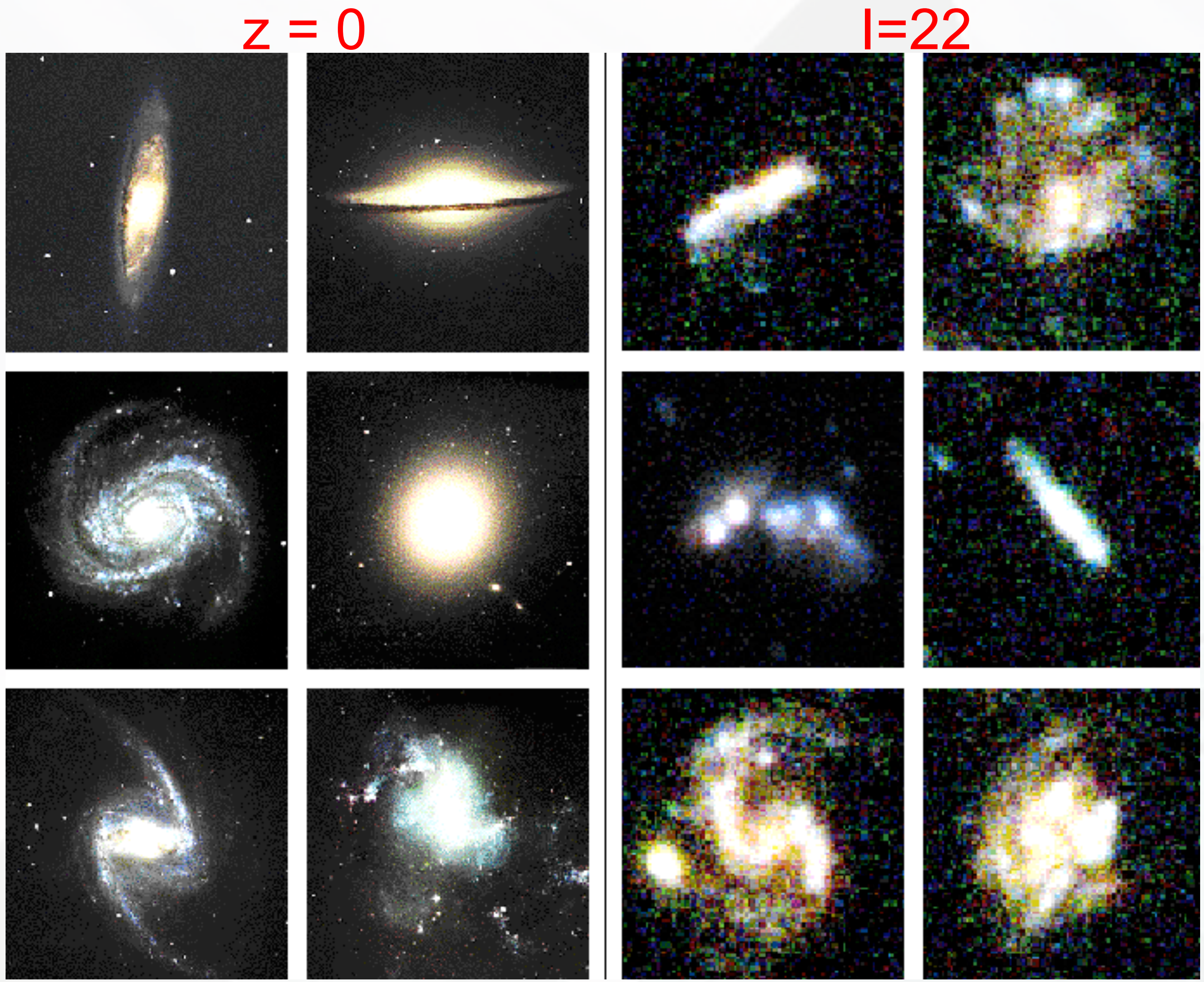
Clustering declines for fainter galaxies as the volume washes out the intrinsic signal

Consistent with No Evolution and dwarf correlation length

Is decline slowing down in faintest samples – are we seeing right through the volume?

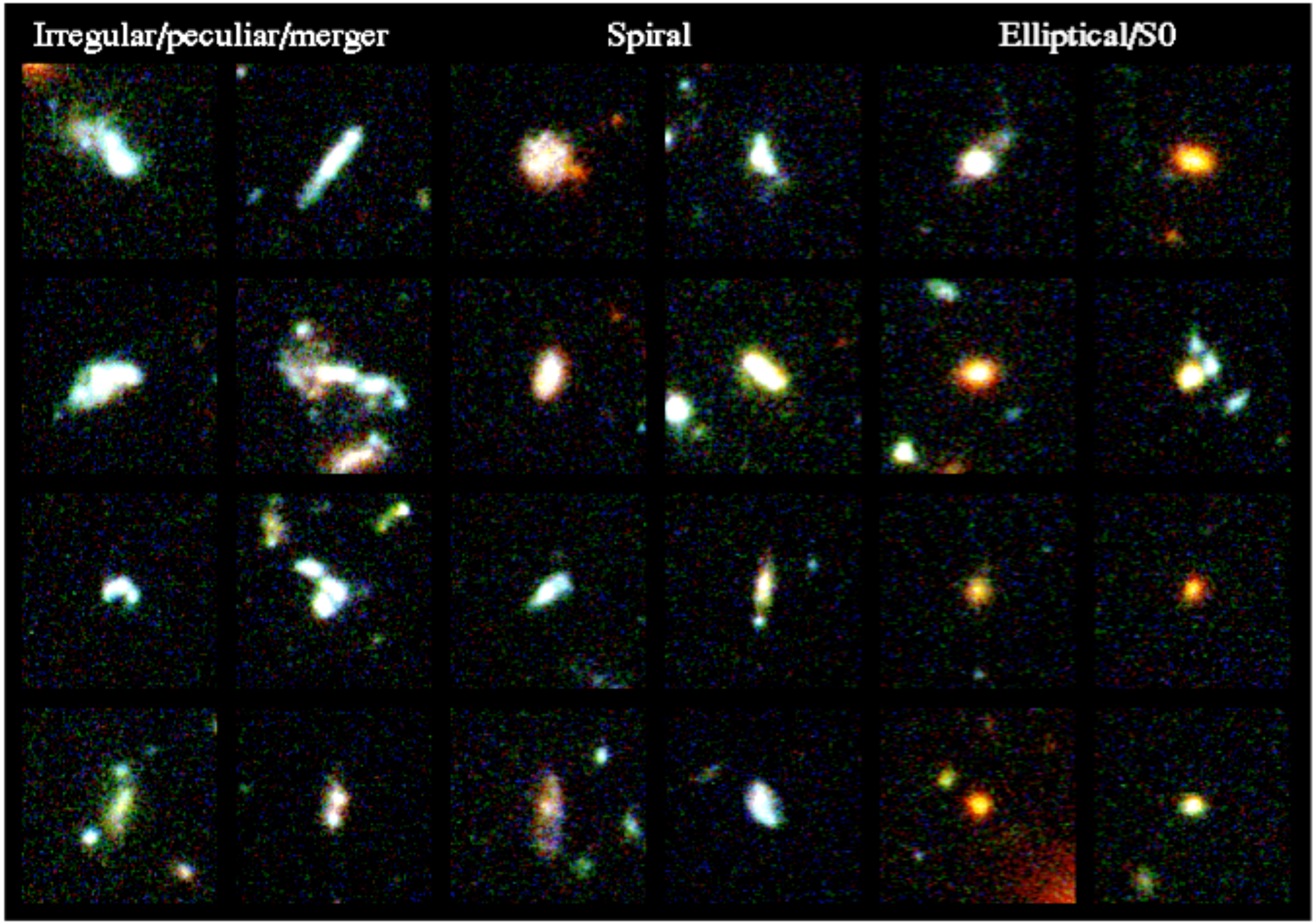


Morphological Evolution



With correction of Hubble primary mirror it was possible to start studying morphologies of faint galaxies

Galaxy Morphologies



Classify faint galaxies onto traditional Hubble "tuning-fork" morphological scheme. Then determine number counts of each type.

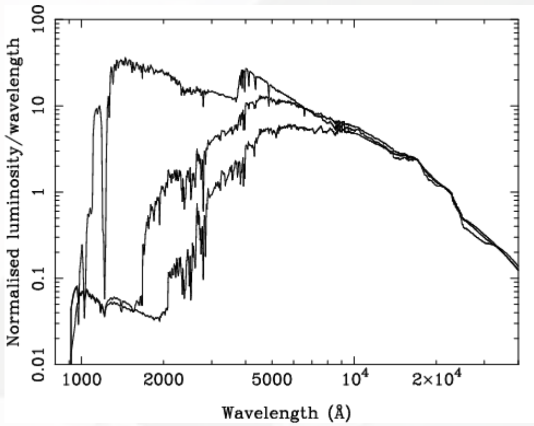
Morphological Counts

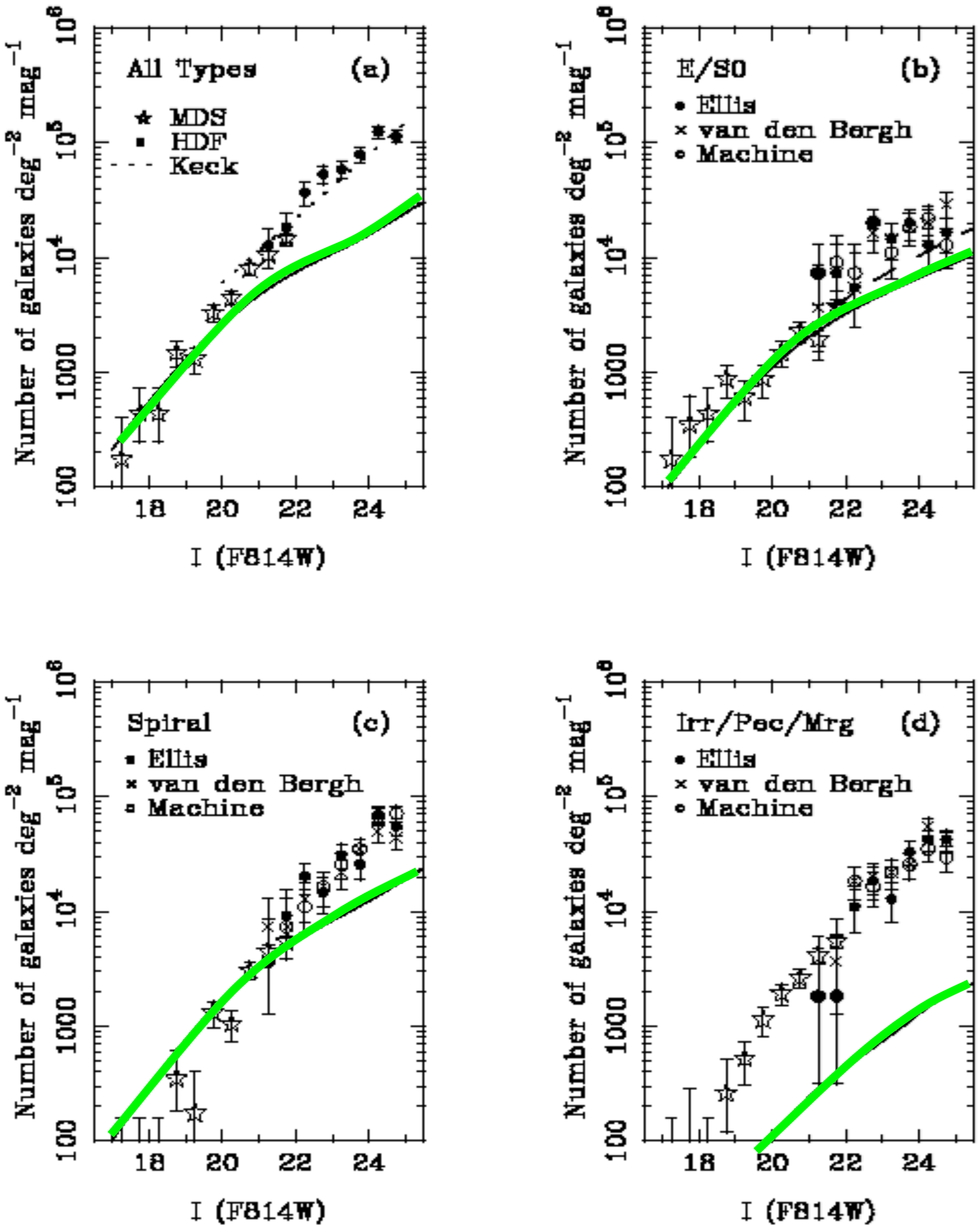
Spirals and E+S0 roughly follow
No Evolution model

Strong rise, at faint limits, in number of apparently disturbed or merging systems

Concern about effect of K-correction on morphologies?

SED to show K corr



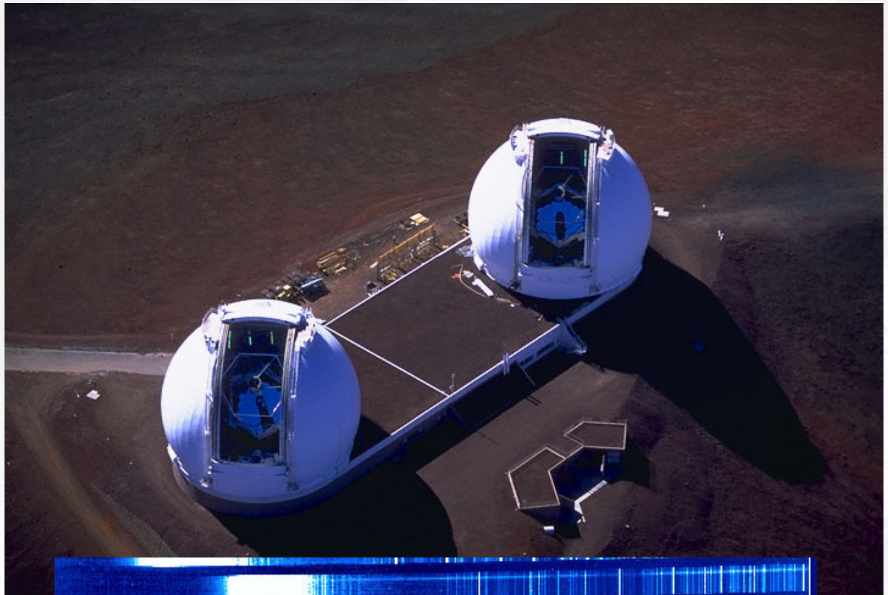


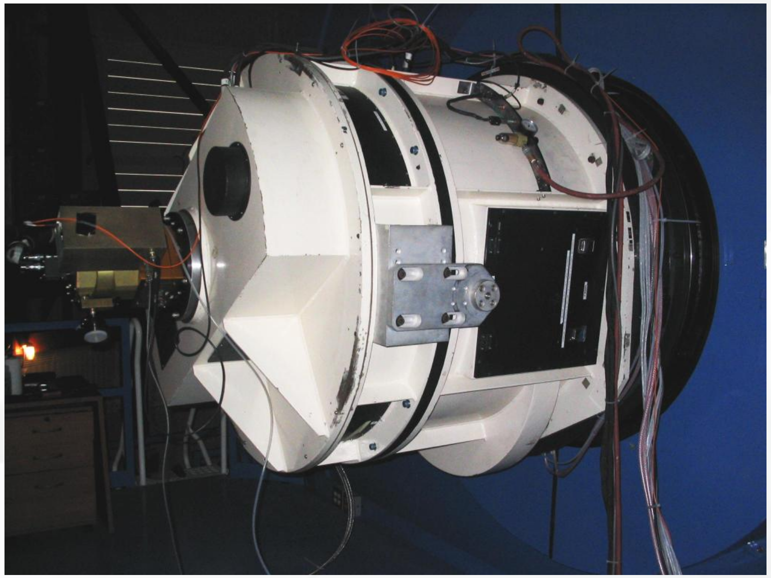
Abraham et al. 1996

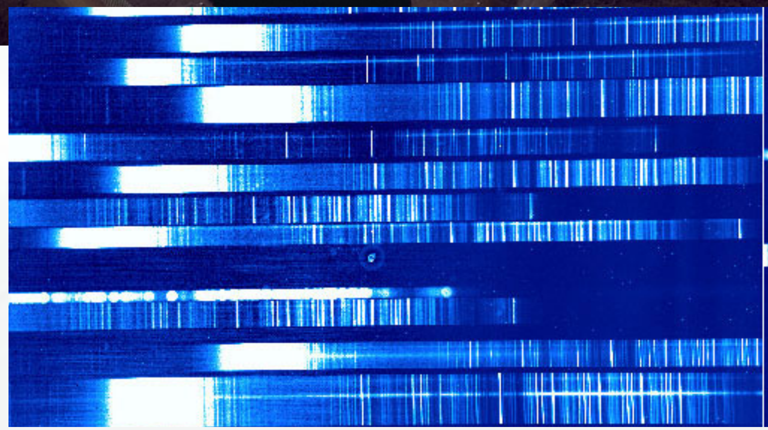
Redshifts

Deep redshift surveys

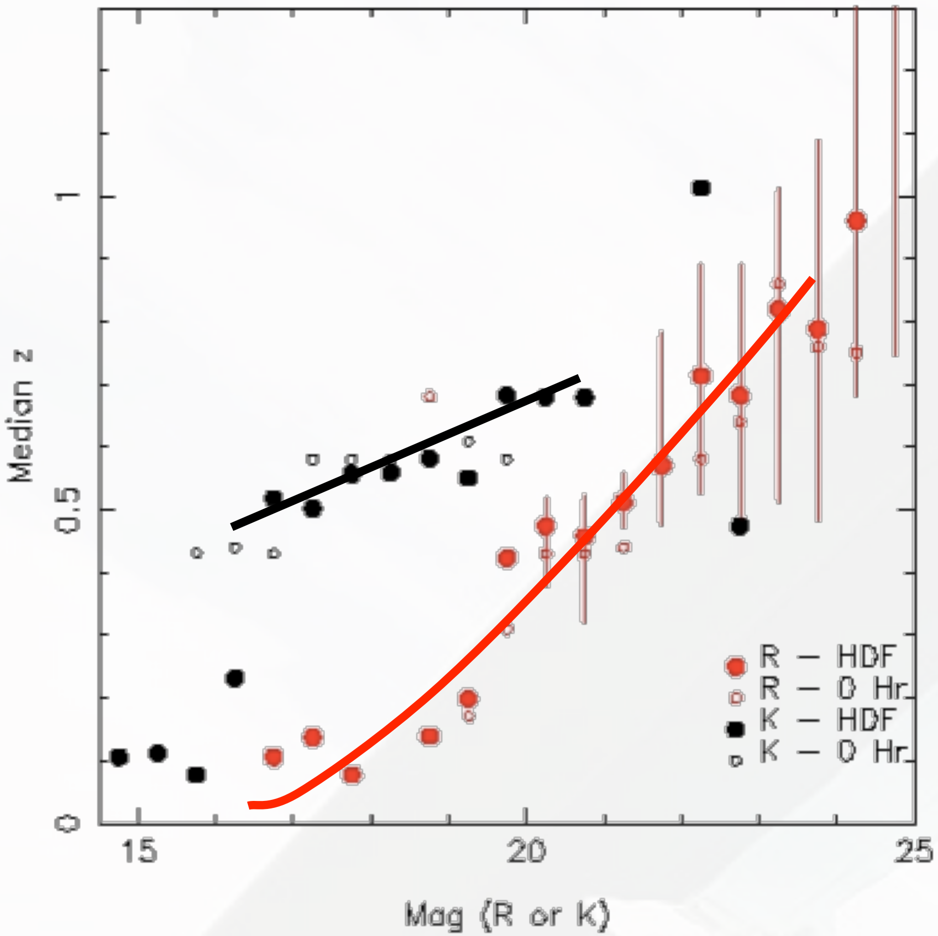
Availability of efficient multi-object spectrographs on 4-m (and then 8-10m telescopes) meant redshift surveys could be pushed beyond the B~20-22 limit of fibre-based surveys (eg 2dFGRS)







Median redshift of faint galaxies

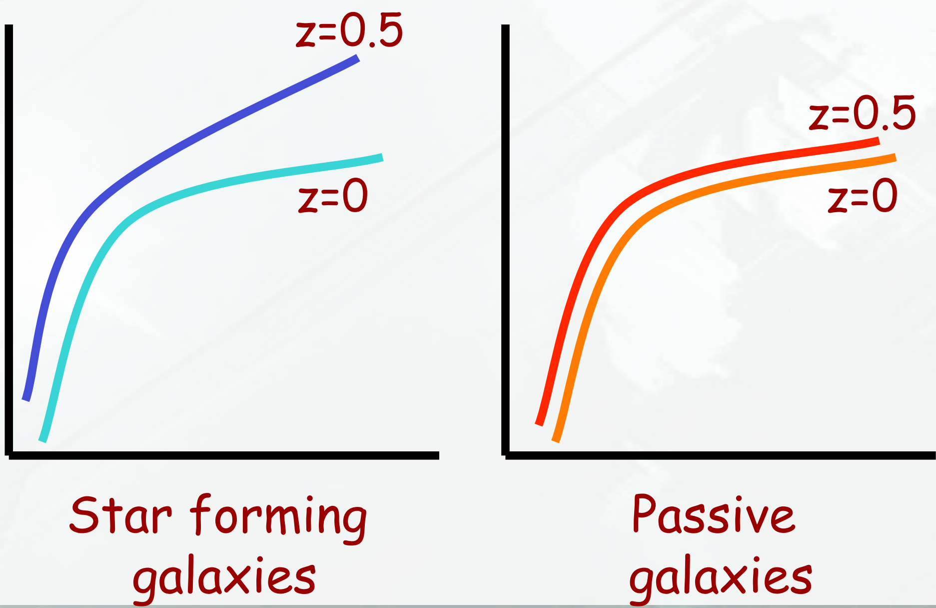


Median redshift for R<24 sample is close to No Evolution expectation

So counts say more galaxies than NE model, but redshifts say they are in the same volume as NE prediction…

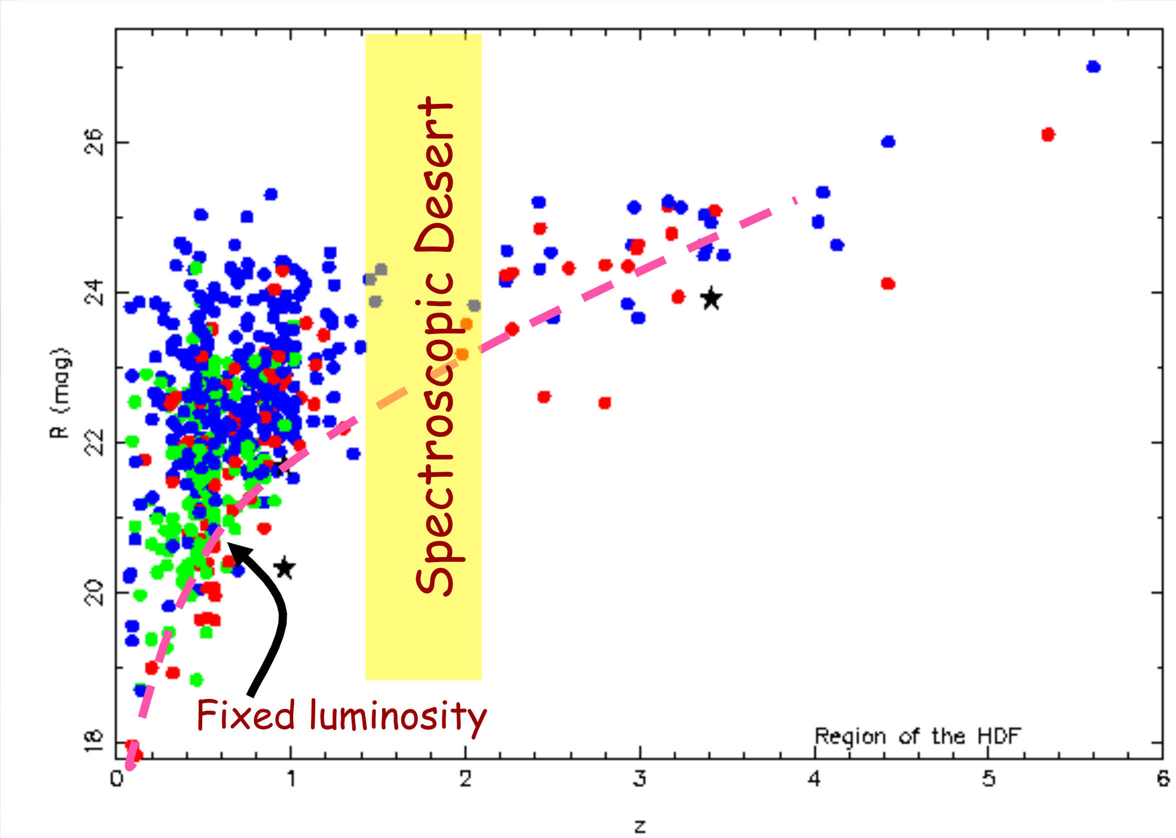
Increase in number density – or differential luminosity evolution

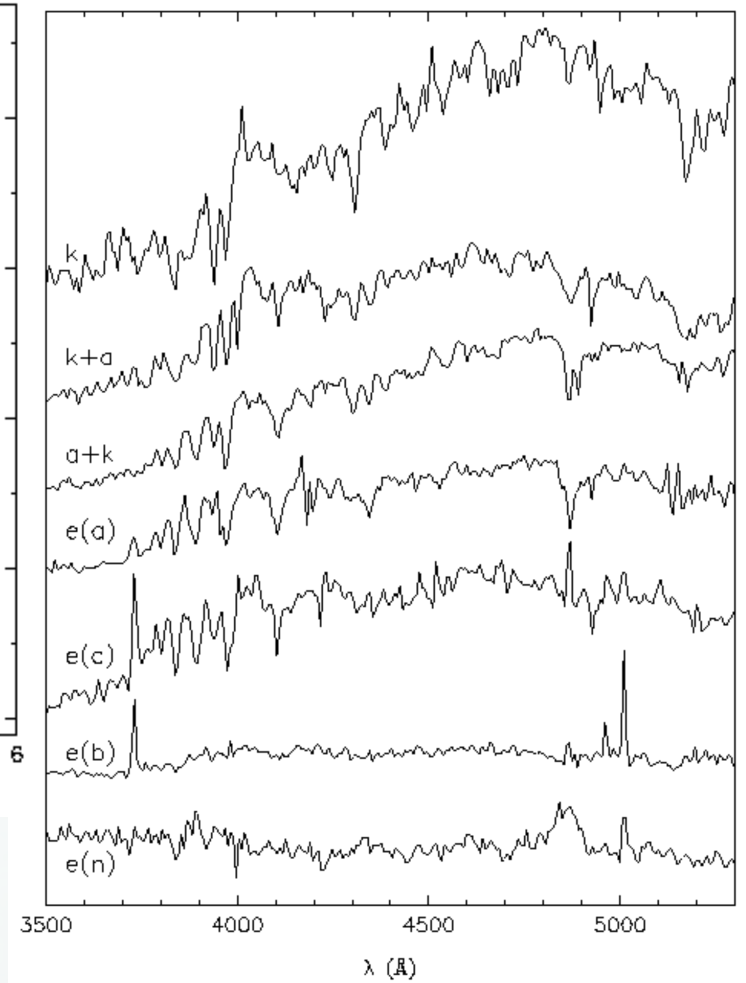
To R<24 it appears that much of the evolution arises from increase in star-forming dwarf galaxies at z<1… but what is happening at fainter magnitudes/higher-z?



Pushing Redshift Surveys to R>24/z>1

Deep redshift surveys II



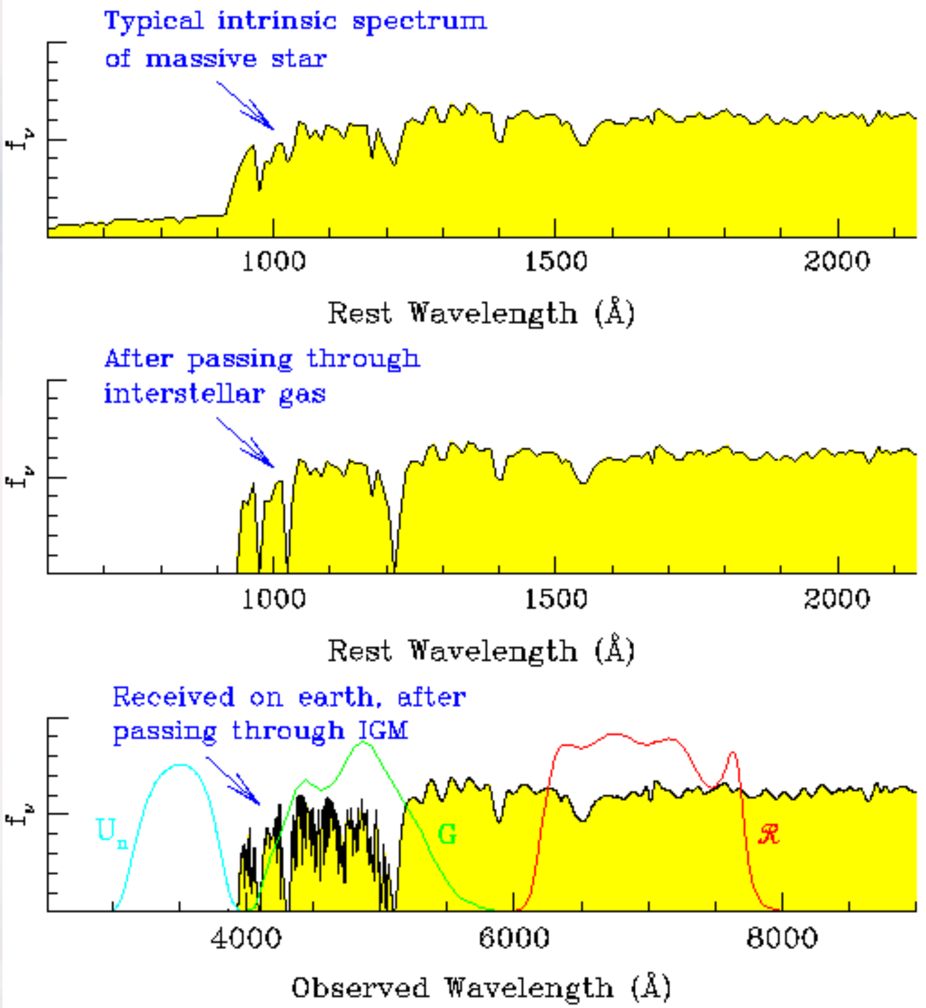


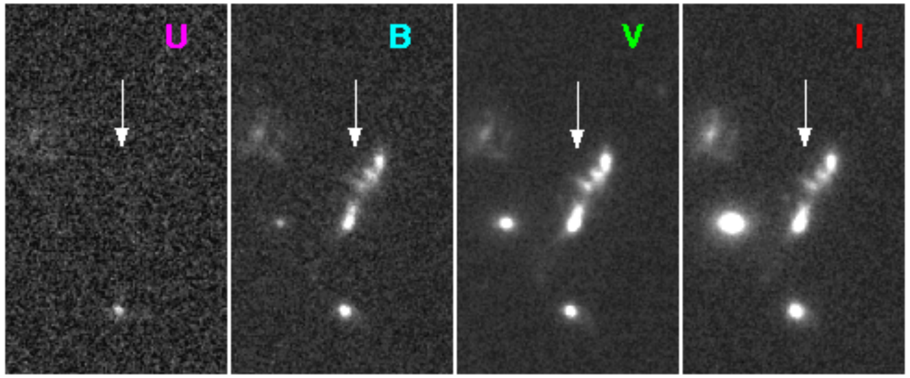
Magnitude-limited redshift surveys pick up lots of z<1 galaxies

Spectroscopic incompleteness against faintest passive galaxies and emission line galaxies at z>1.4 due to "spectroscopic desert"

Need a new technique to identify high-z galaxies...

Finding star-forming galaxies at high z



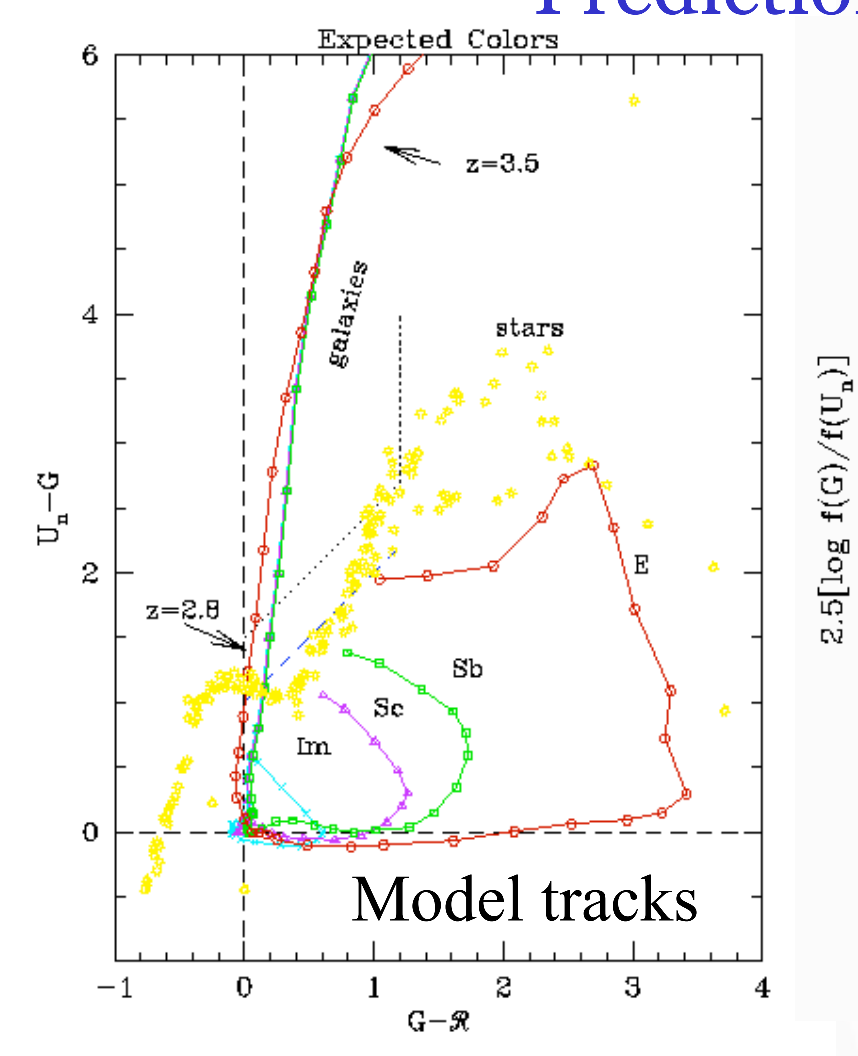


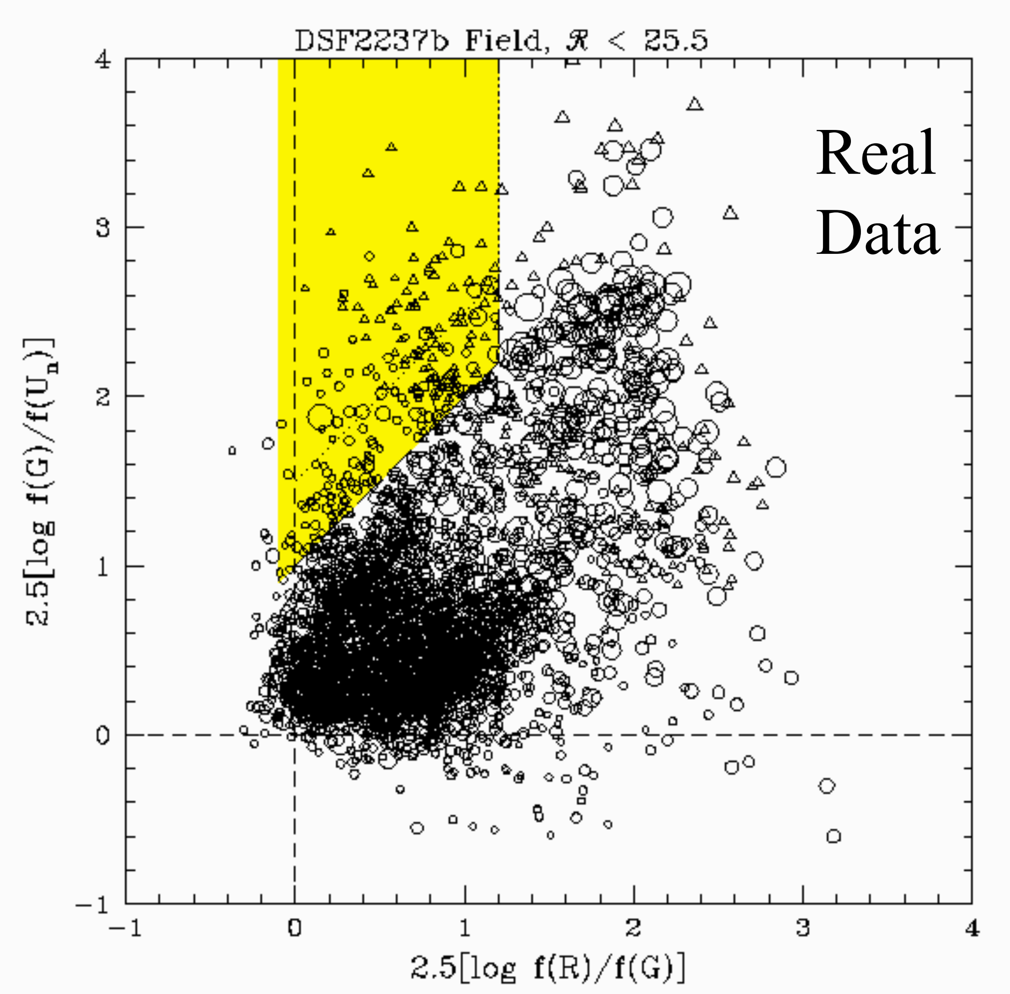
Steidel et al 1999a,b; 2003

The Lyman continuum discontinuity (912A "Lyman Break") is particularly powerful for isolating star-forming high redshift galaxies ("Dropouts").

From the ground, we have access to the redshift range z=2.5-6 in the 0.3-1 micron range.

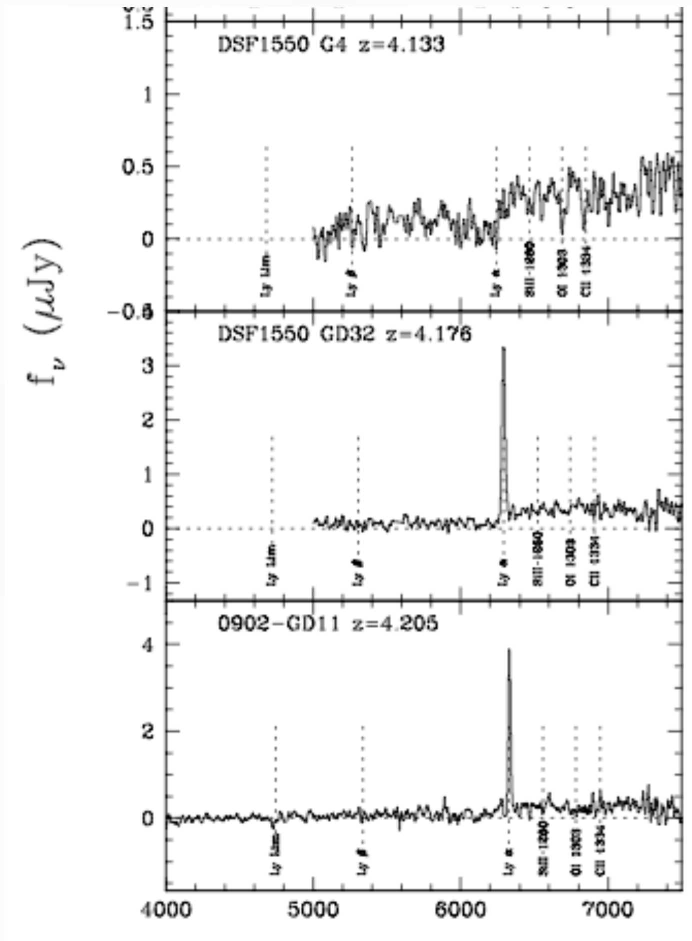
Lyman Break Galaxies (LBG): Prediction and Practice



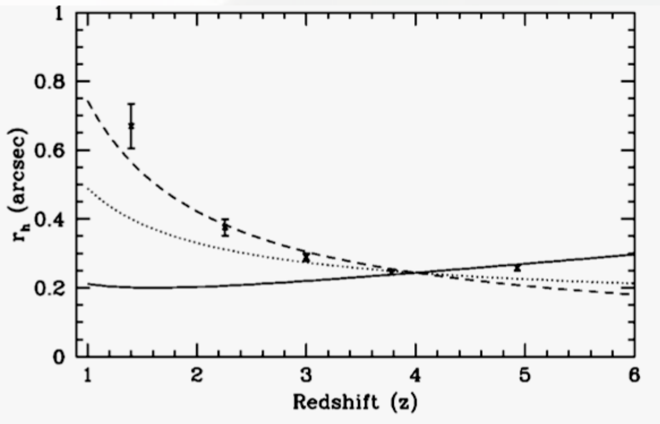


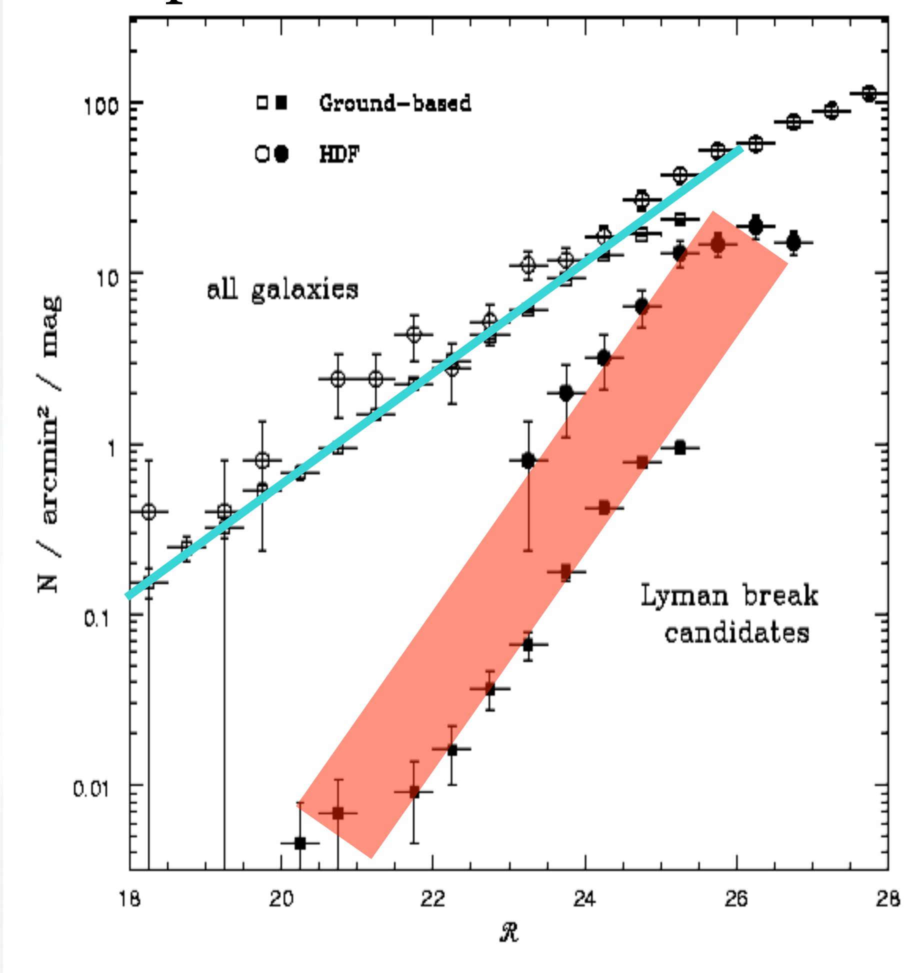
Spectral energy distributions allow us to predict where distant SF galaxies lie in colour-colour diagrams such as (*U-V* vs *V-R*) (Steidel et al 1996)

Properties of LBGs



- ~10% of galaxy population at R~24
- ~30% of galaxy population at R~26
- Moderate SFRs (> 1 $M_\odot$ yr^{-1}) (UV em.)
- Sizes of ~2 kpc



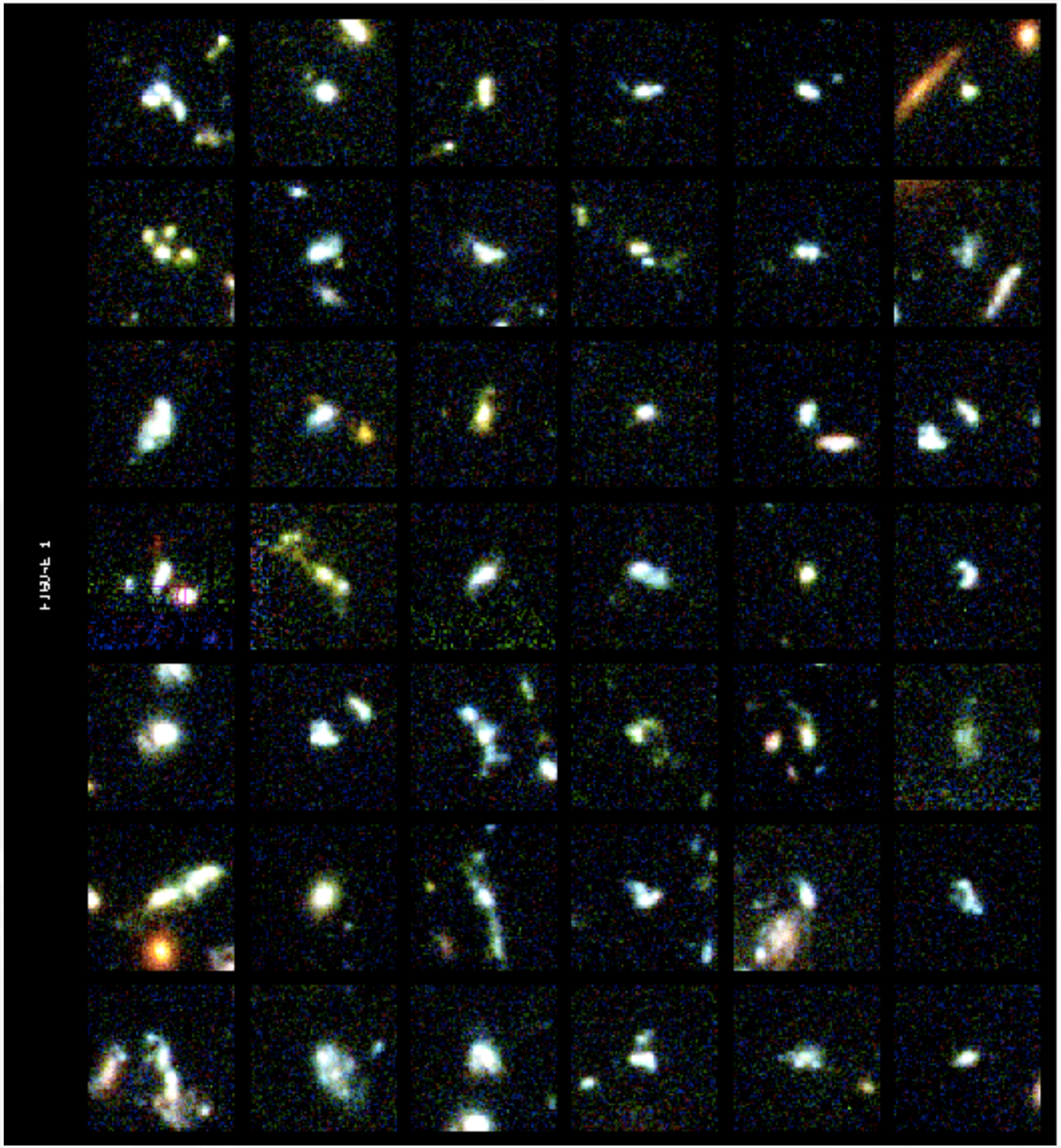


HST images of spectroscopically-confirmed “Lyman break” galaxies with z>2 in HDF/HUDF revealing small physical scale-lengths and irregular morphologies.

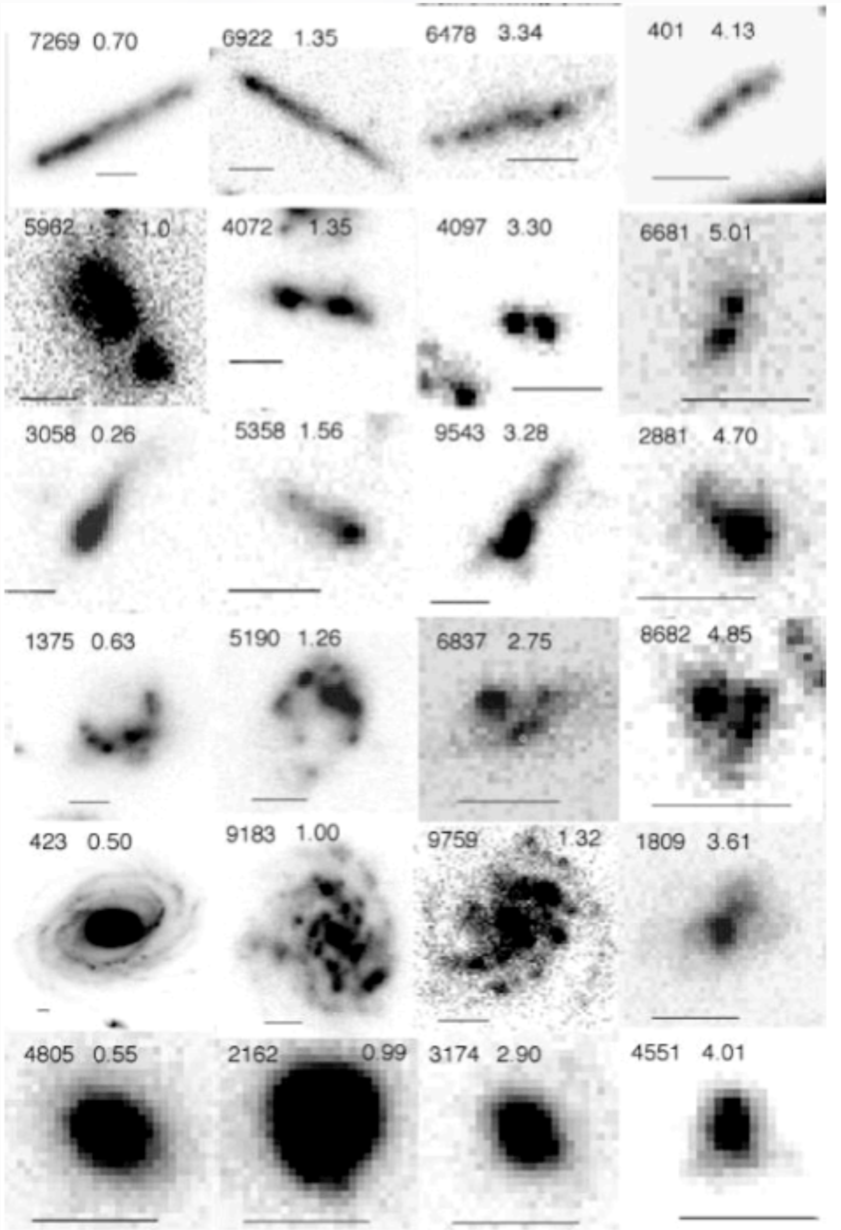
No big disks?

By z>2 are we finding “sub-galactic” components - which explains why there are so many and they’re so small?

What happens at z~1-2?



High-z Galaxy Morphologies



With complete redshift coverage, go back to the morphologies of galaxies in the deepest Hubble images.

Extend "Hubble-type" morphologies with new classes :

chains: lumps of emission observed in a line.

doubles: pairs of galaxies that seem to be interacting.

tadpoles: galaxies with extended tails.

clump-cluster: galaxies with giant clumps of emission.

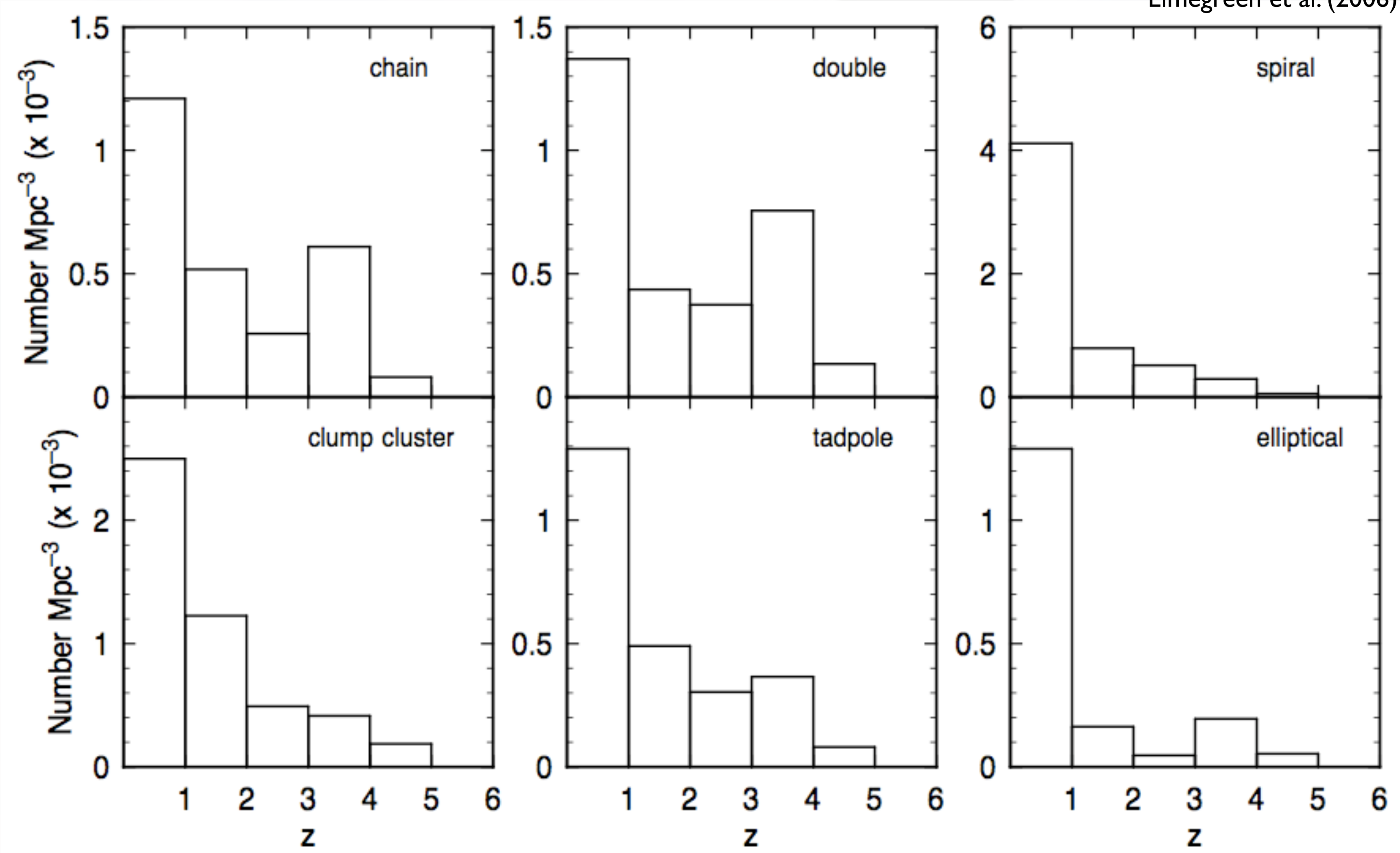
spirals: similar to local spirals

ellipticals: similar to local ellipticals

More exotic morphologies are seen more commonly at $z > 1$.

High-z Galaxy Morphologies

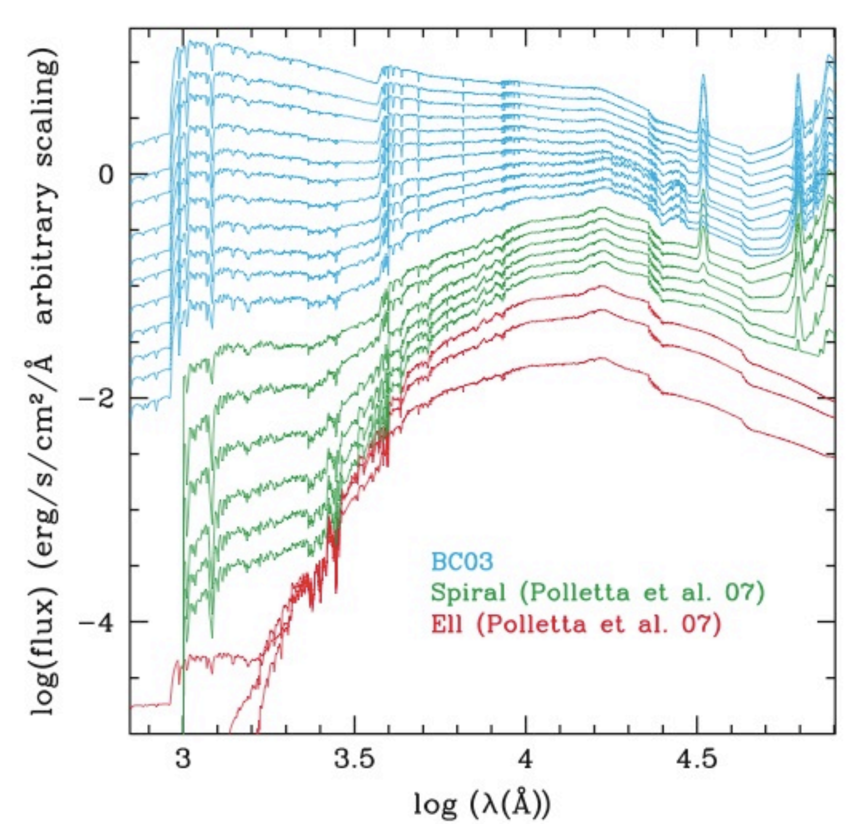
Elmegreen et al. (2006)

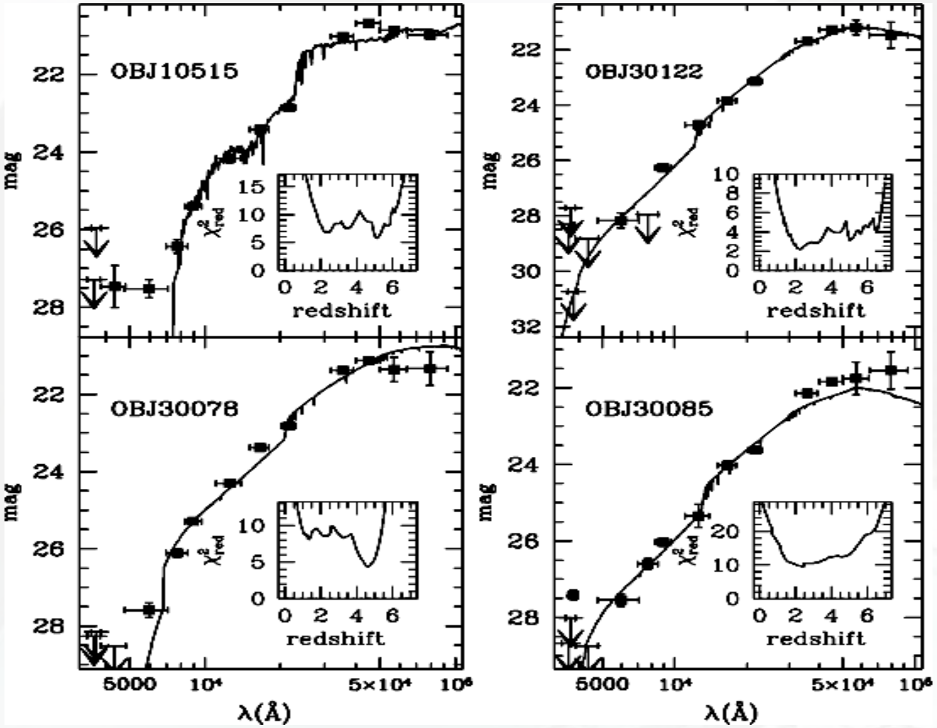


Traditional Spiral/Ellipticals disappear beyond z~1 and we get a wide variety of apparently merging/interacting systems made up of small components (sub-galactic fragments?)

Redshift Surveys without spectroscopy: Photometric redshift surveys

Photometric Redshifts (photo-z)



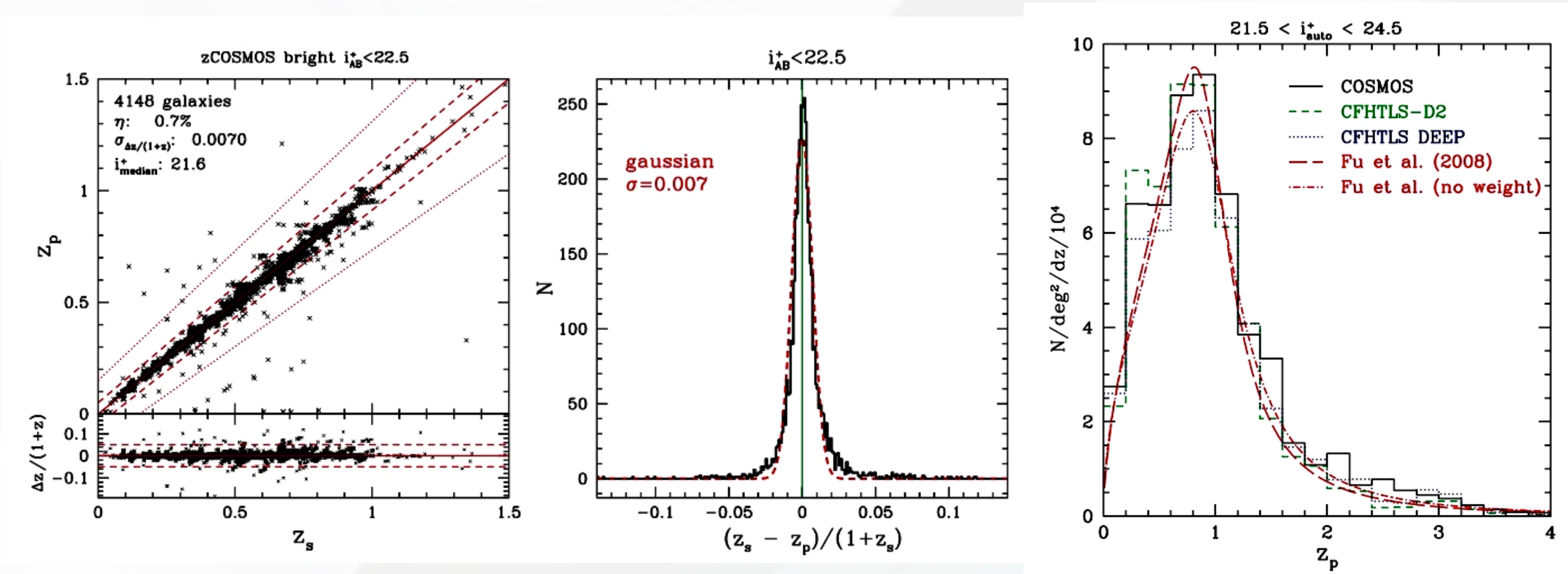


Use broadband photometry and fit a range of model/real SEDs at different z's to observations to try to determine redshift

Various limitations:

- No features = no precise photo-z
- Not very accurate on individual basis: dz/(1+z) ~0.01 to ~0.2...
- Template fitting methods limited to the templates used....

Photometric Redshifts (photo-z)



Cheap & sometimes very successful (usually for ~0.2 < z <~1.5):
photo-z for ~100k galaxies in a few hours (as opposed to a few weeks!!!)

Blind test of 30 colour photometry from COSMOS:
dz/(1+z)~0.01 (NB: spec-z have dz/(1+z) ~ 0.0003 or better)

Many photo-z surveys:
- broad-band: PS1, DES, ...
- narrow band: Combo-17, Alahmabra, PAUS,...

Ilbert et al. 2009

Summary

Observations of faint galaxies suggest strong evolution.

We see an increasing number of blue, compact, weakly-clustered galaxies at faint magnitudes. Sizes and clustering suggest that at R~24 these are "dwarf" star-forming galaxies.

Redshifts for R<24 galaxies confirm that the number density of galaxies increases out to z~1 due to increased star-formation activity (much of it in dwarfs).

Using Lyman-break or photo-z at fainter magnitudes we pick up a population of z>1 galaxies, with disturbed structures (few if any have regular spiral or elliptical morphologies).

Many of these likely correspond sub-galactic fragments which are interacting/merging to form "normal" galaxies.

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