Andrew Bunker,
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Title: “T.B.D.”

TIARA Winter School, Feb '12

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How to find high reshift galaxies:

The First Billion Years of History - seeing Galaxies Close to the Dawn of Time

TIARA Winter School, Feb '12

Re-ionization: star forming galaxies at z~6?

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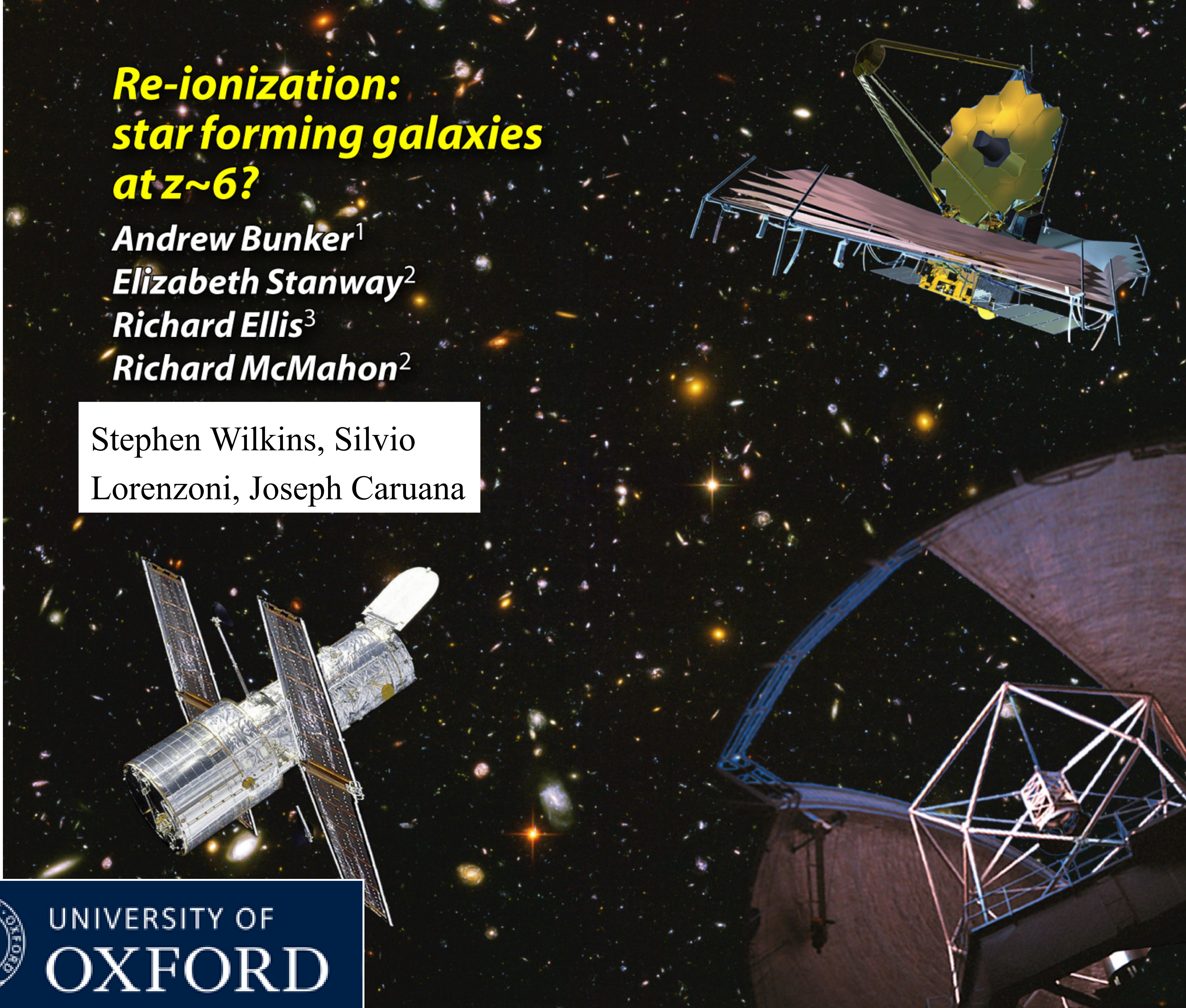

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AAO

Plan of Lectures

- Basics - what is galaxy evolution (what are the properties of galaxies and how do they change with cosmic epoch)
- Observations - how do we observe galaxies (imaging, spectroscopy) and how do we interpret these observations
- The evolution of the star formation rate
- Finding distant galaxies - search strategies
- Discovering galaxies in the reionization epoch
- Contribution of galaxies to reionization
- Future observational prospects

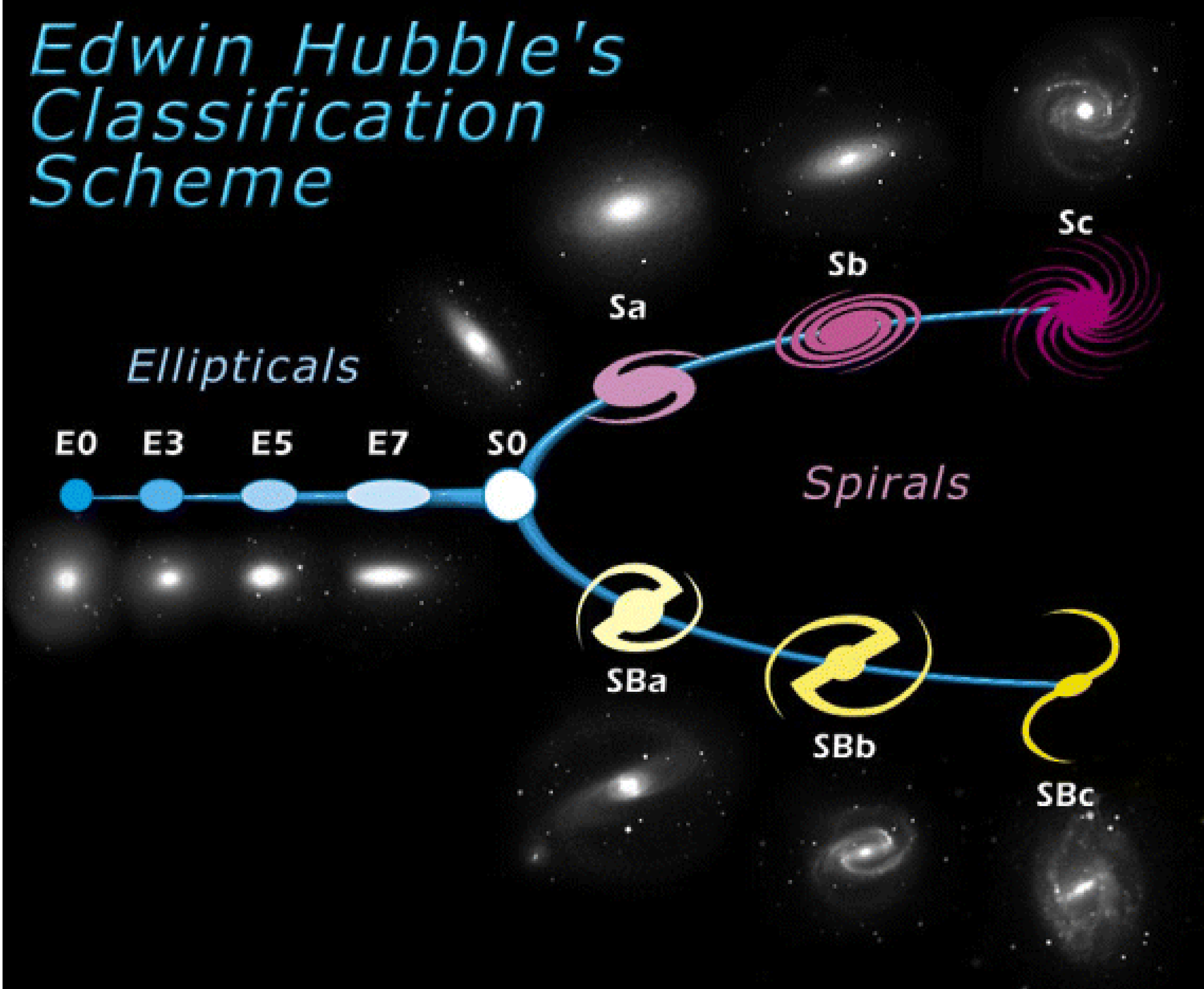
Introduction & Basics

- Definitions & Observables
- Galaxy Shapes - morphology & the Hubble sequence

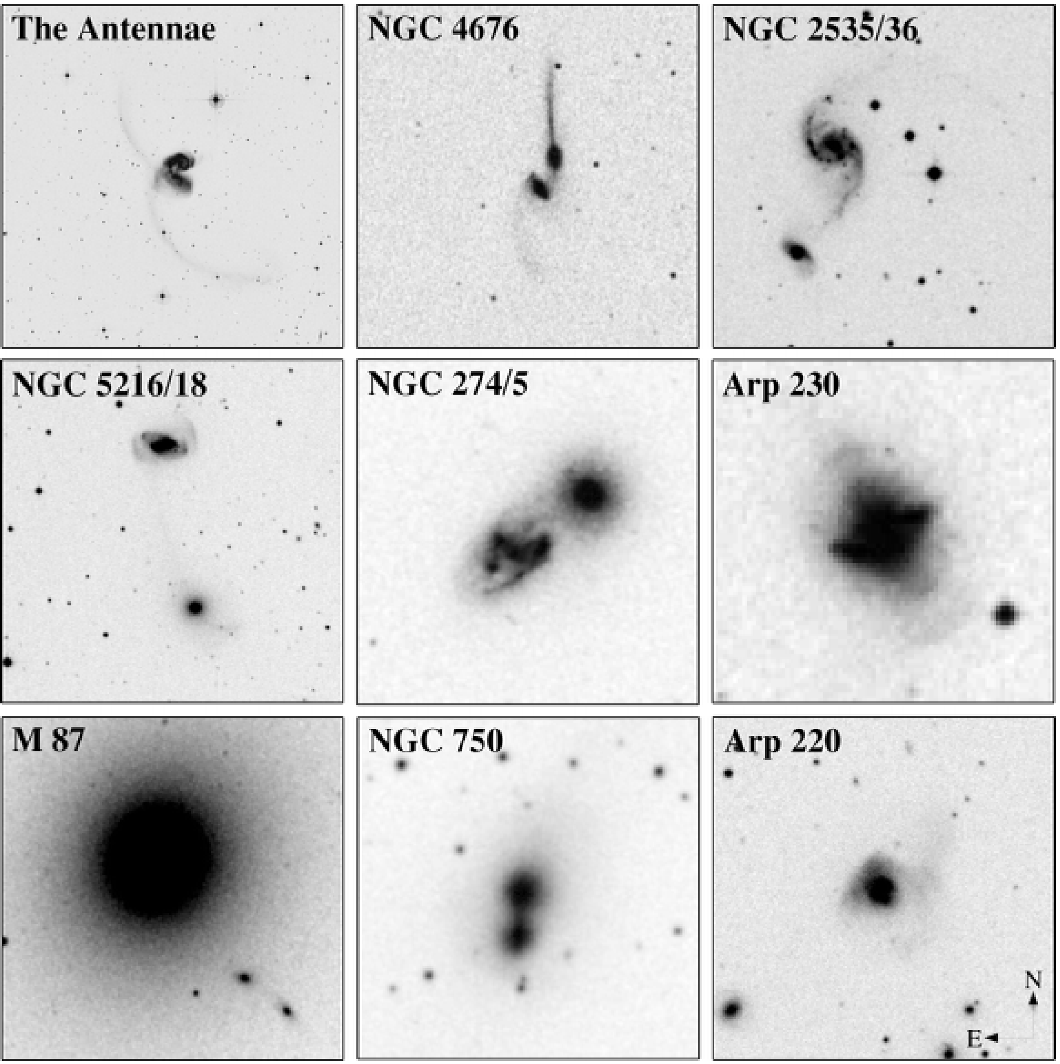
Galaxies composed of gas, stars, dust (& dark matter)

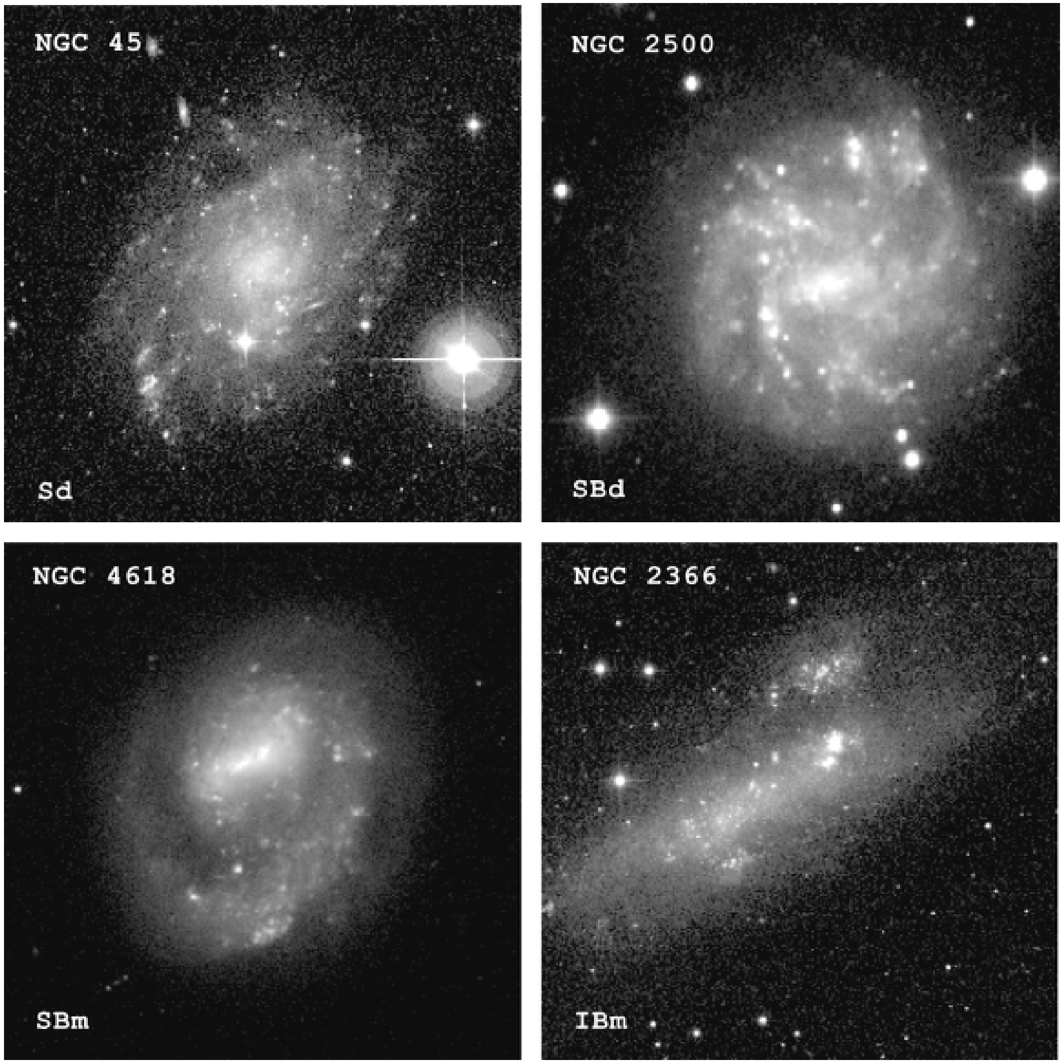
Galaxy Evolution - *What is it, and why do we need it?*

- *Dynamical processes (internal & external, e.g. mergers)*
- *Gas consumption (star formation)*
- *Stellar evolution (feedback)*
- *Chemical enrichment*

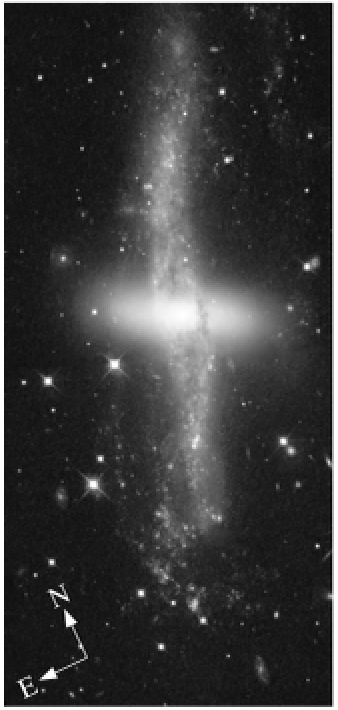

Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

Peculiar & Irregular Galaxies

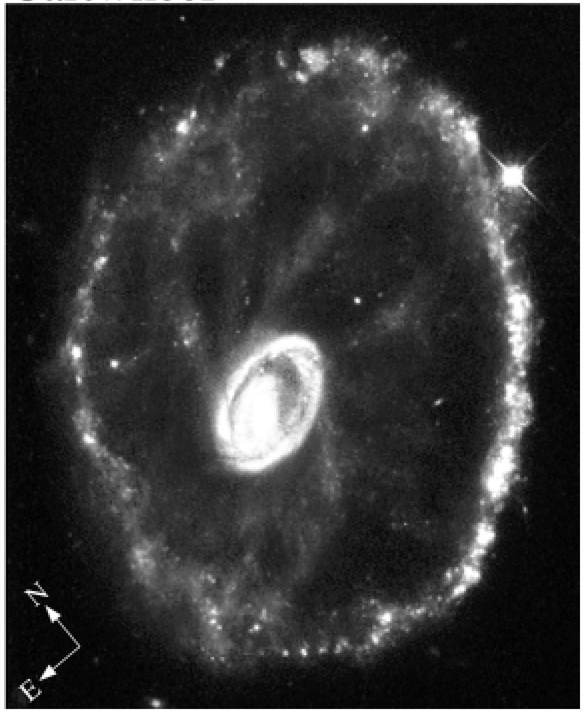




NGC 4650A



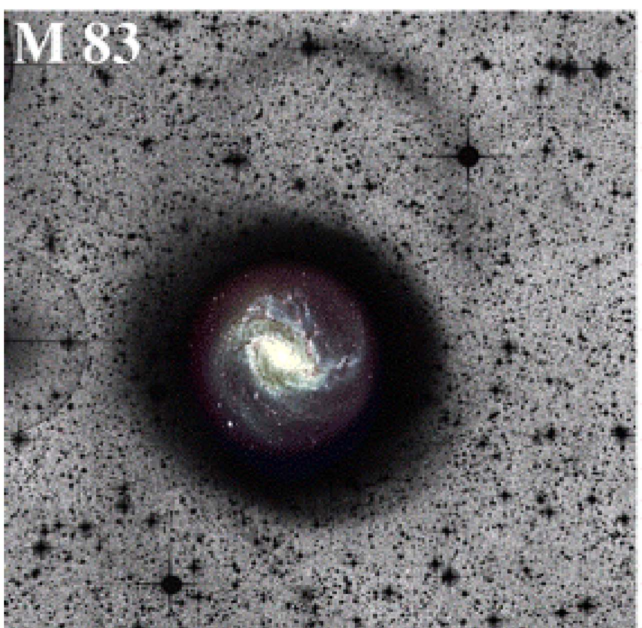
Cartwheel

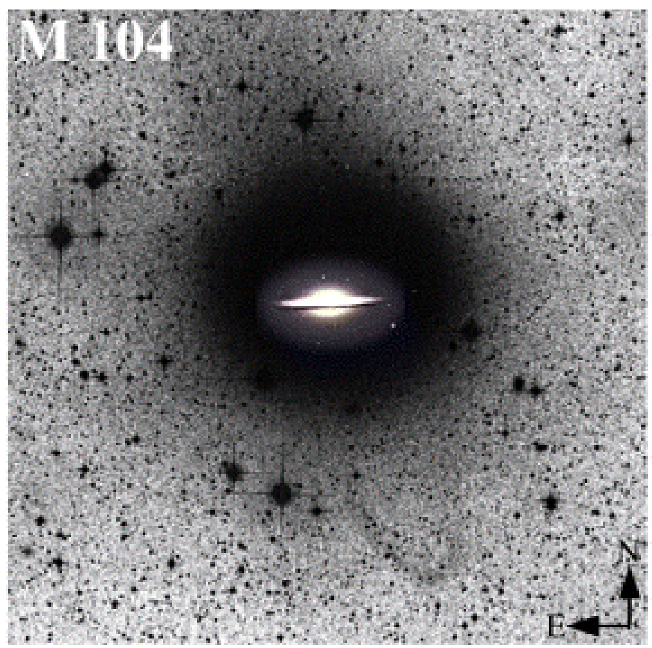


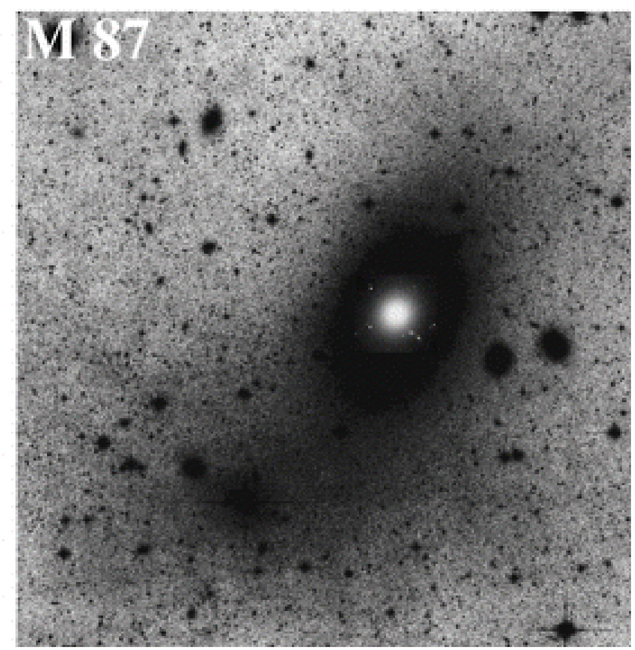
Collisions, Rings & Shells

<u>Left:</u> Some spectacular interactions

<u>Below:</u> Even apparently normal local galaxies have low-surface brightness shells around them - relics of consumed dwarf galaxies? Revealed through unsharp-masking (D. Malin)

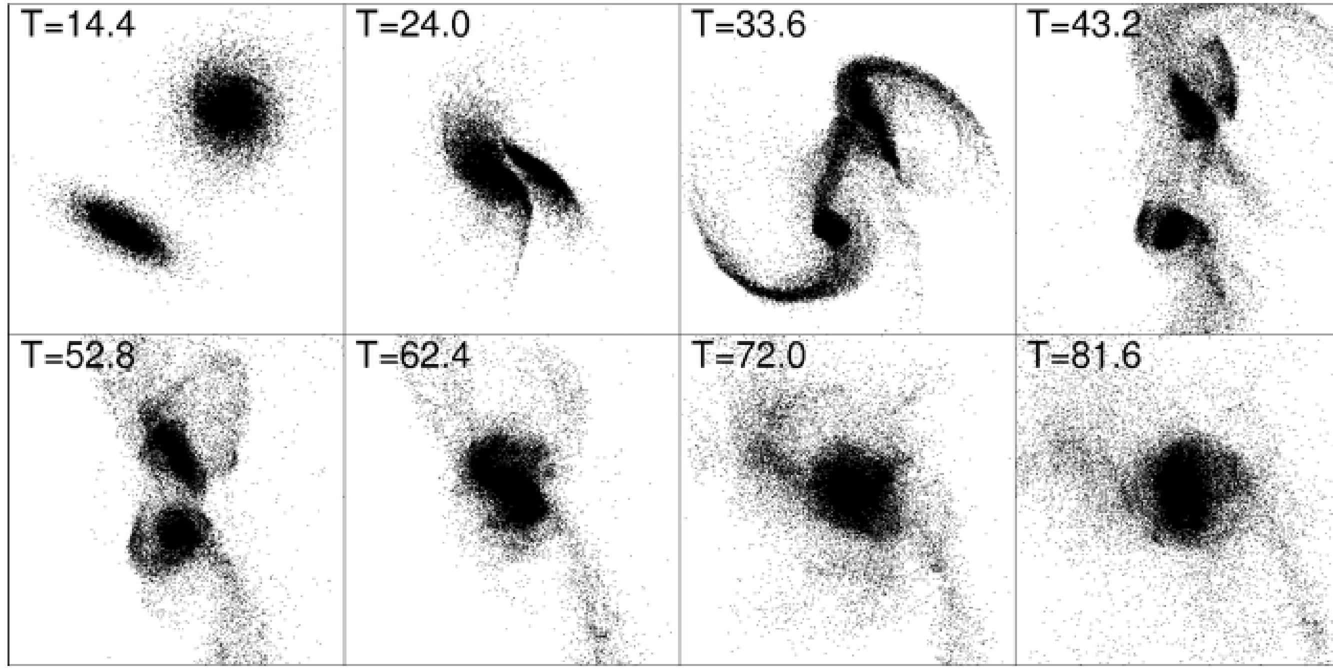


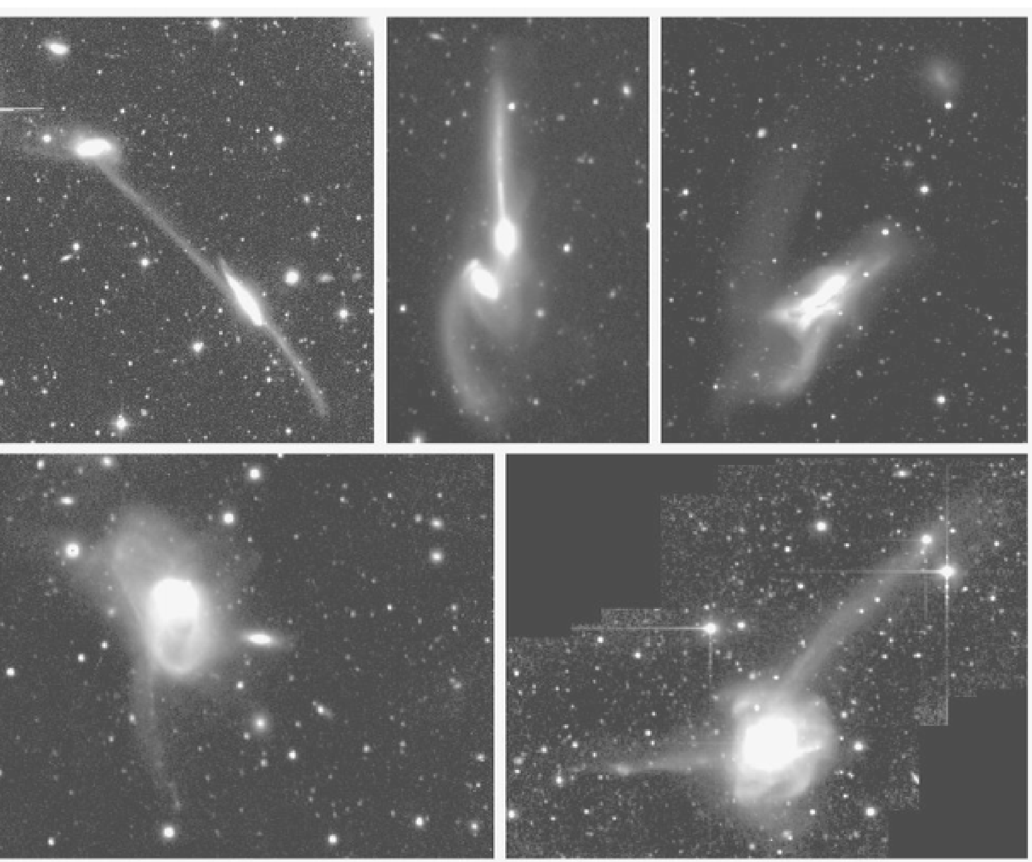




Mergers

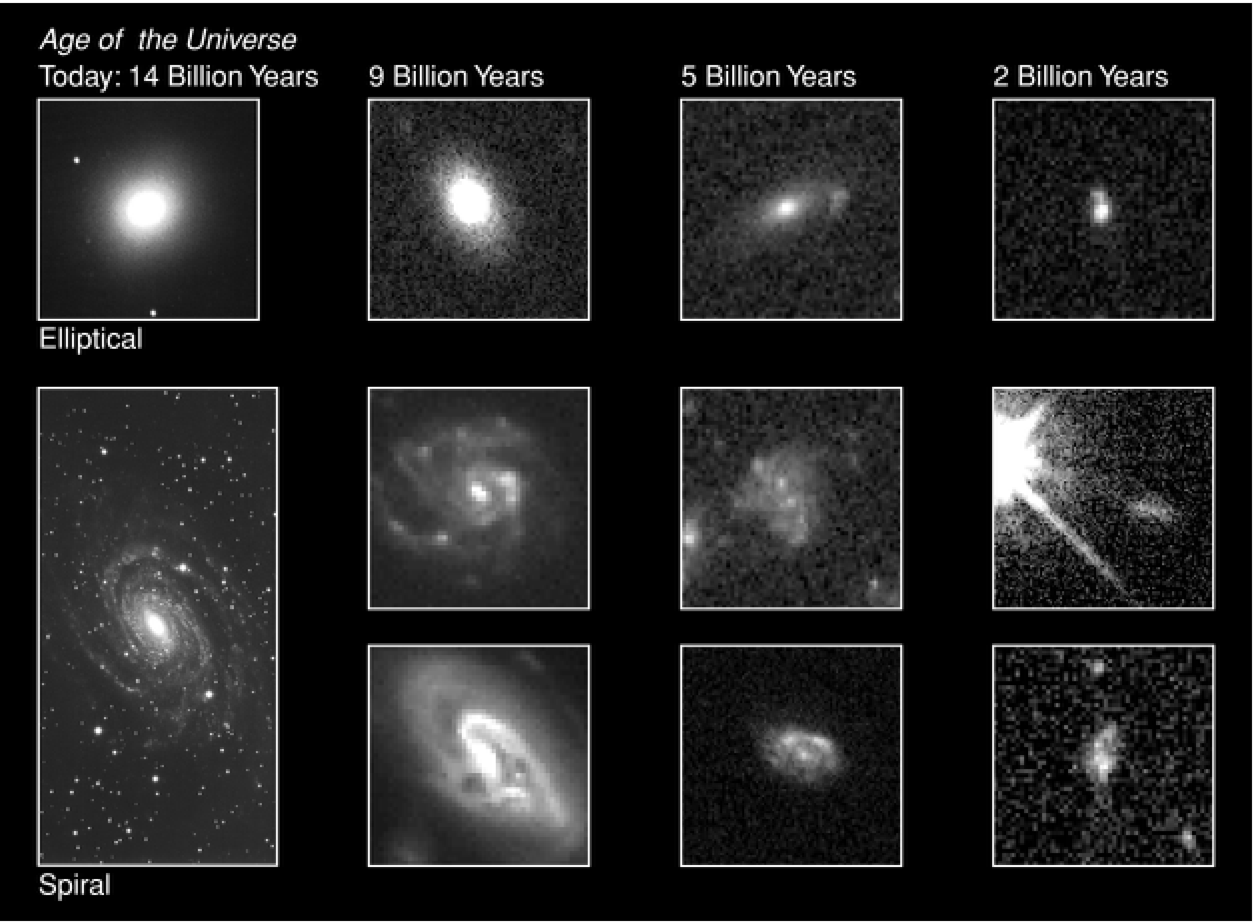
Right: *N*-body simulation of two equal-mass merging disk galaxies (time units: 10million years) - from C. Mihos





Left: Real galaxy interactions, producing tidal tails. Such galaxies are relatively uncommon at low redshift. At earlier times, interacting systems may have been much more common

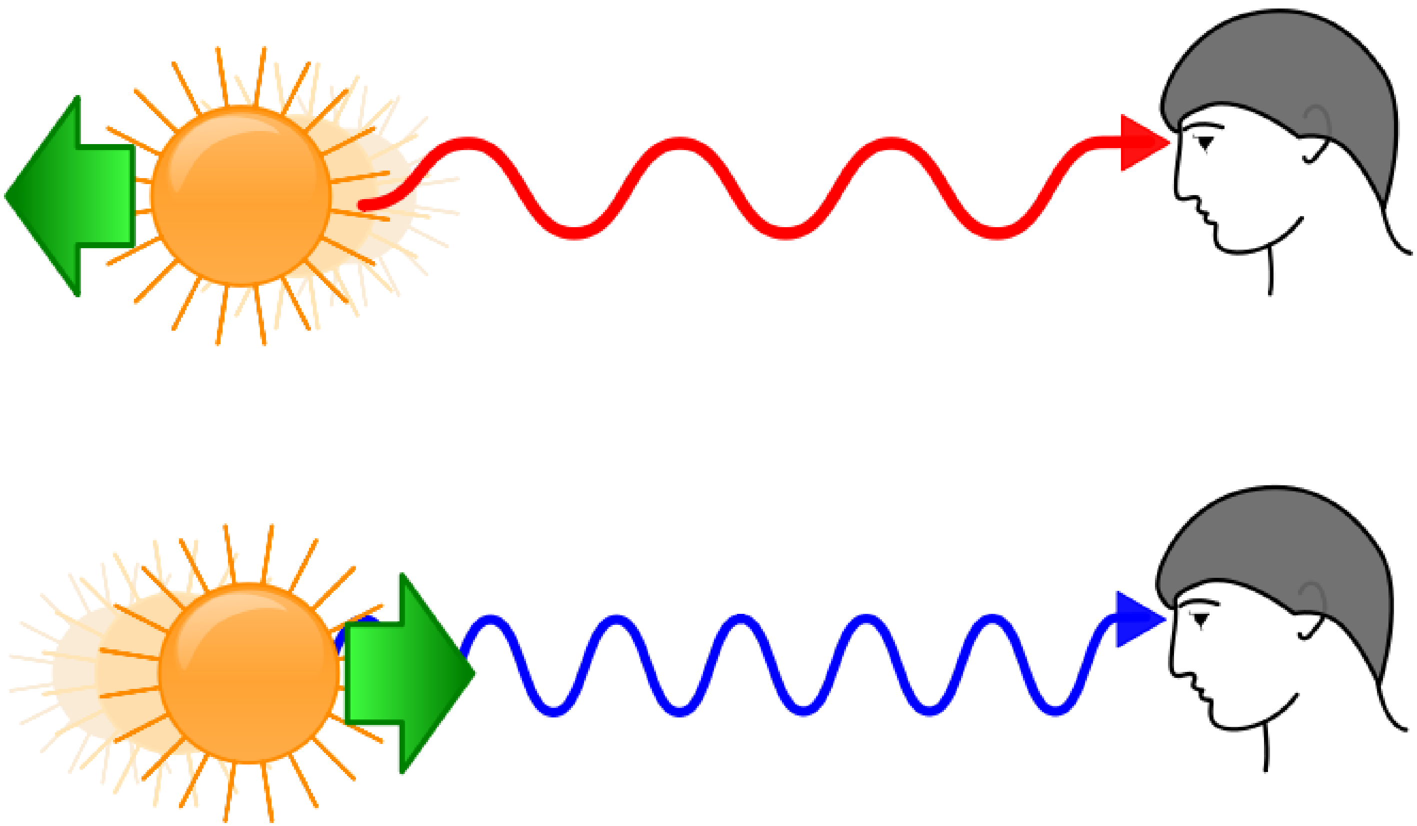
The Disintegration of the Hubble Classes?



- *Angular resolution & depth of Hubble Space Telescope imaging measures morphology of faint distant galaxies*
- *By I~24mags, most galaxies no longer fall within the Hubble tuning-fork classes*
- *Need to correct for redshift (band-shifting effects :* ***morphological k-corrections****)*
- *Real evolution:galaxies in the past (at high redshift) more peculiar*

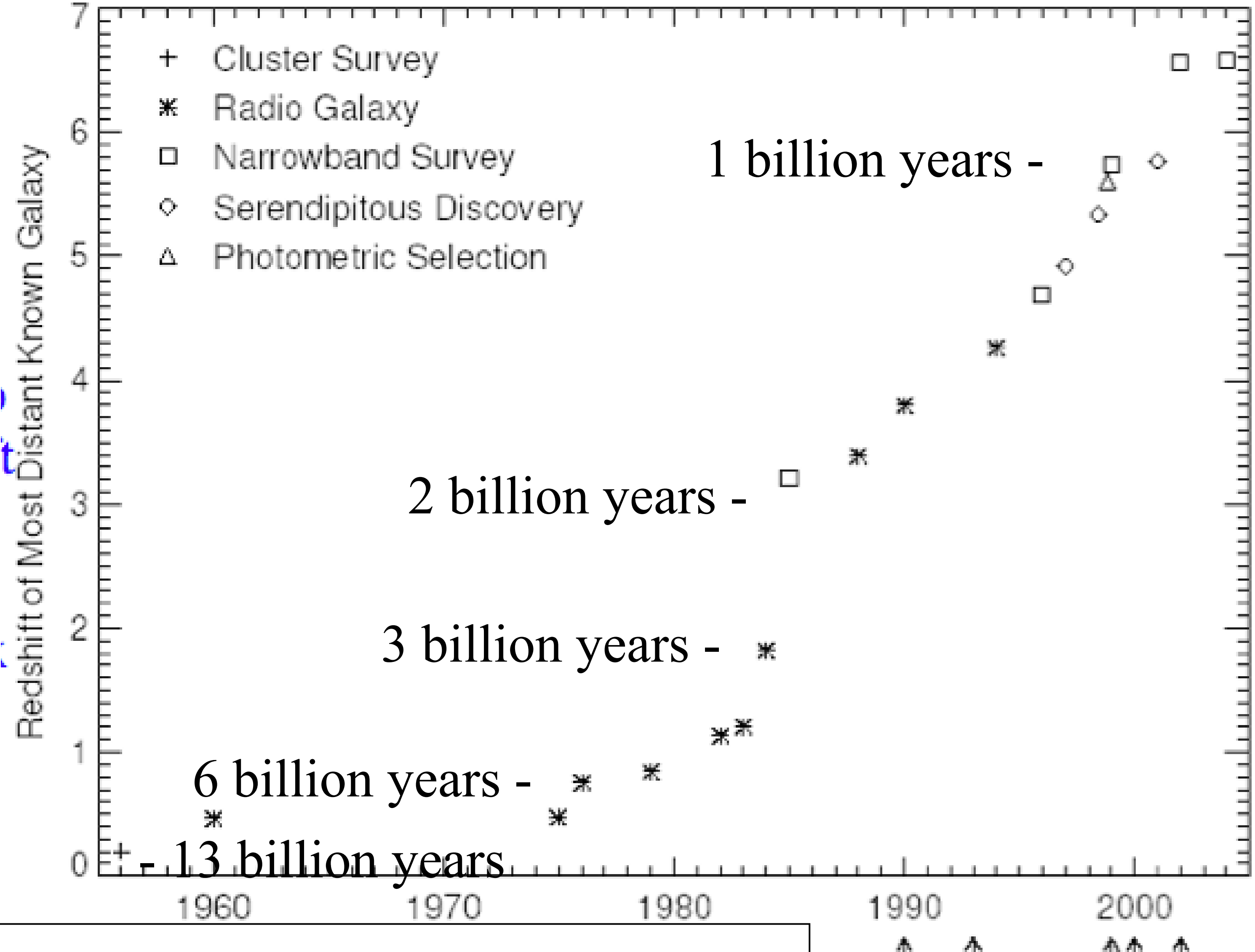
Speed away produces a Redshift of light

Expansion of Universe: further the object, the faster it moves away



Credit: wikipedia

Redshift - the stretching of space. The distance record!



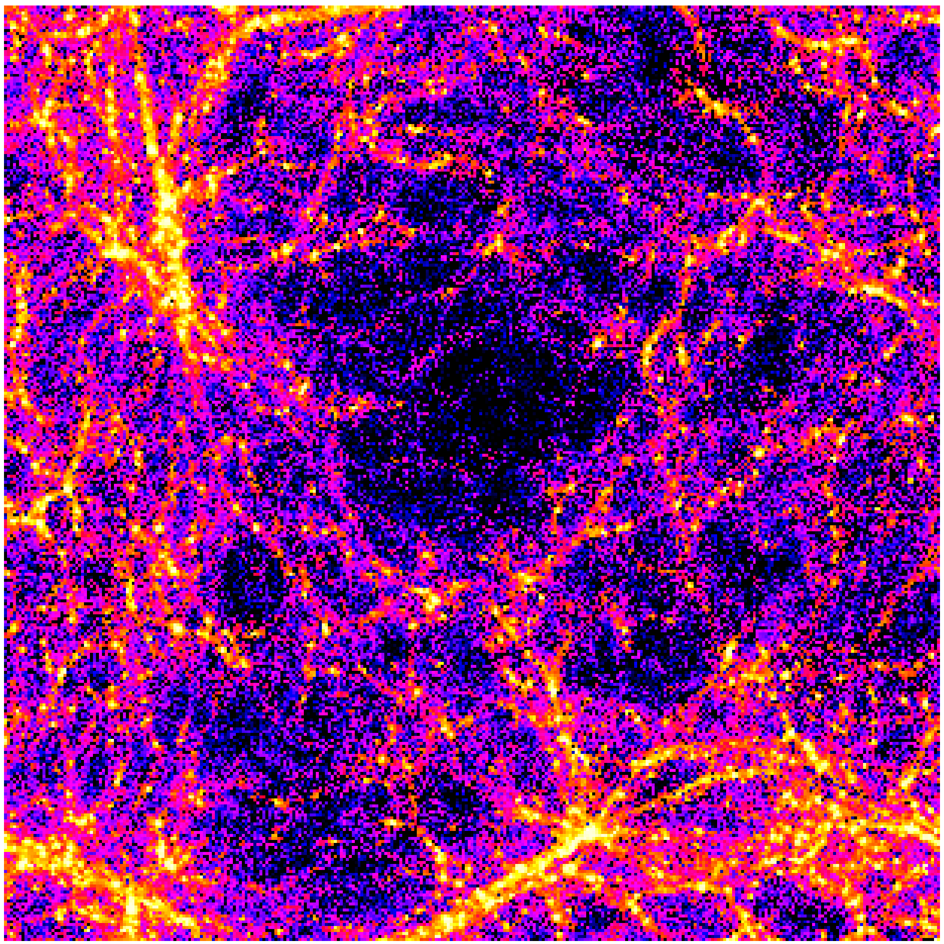
Space itself expanding after Big Bang

Photons stretched out (redder wavelengths)

Galaxy Formation & Evolution

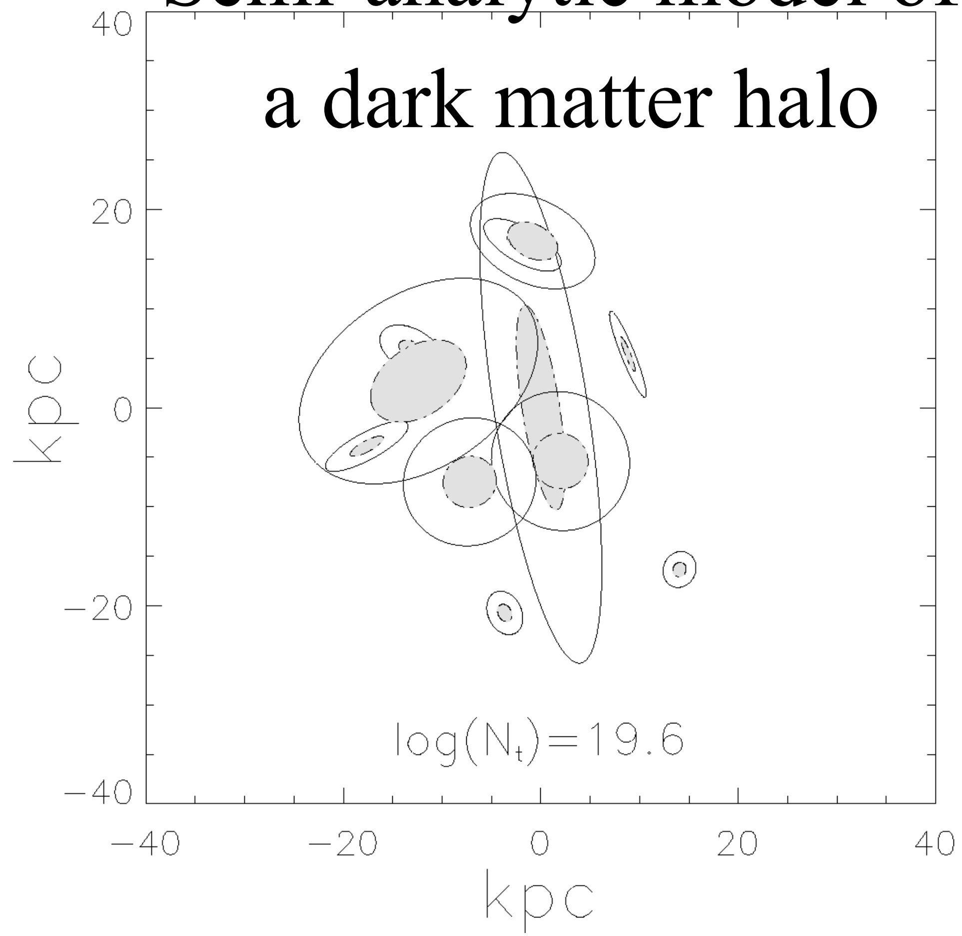
Advances in Theory

Ly-α forest simulation



(Tom Theuns)

Semi-analytic model of a dark matter halo



(Rachel Somerville)

ASIDE: The Magnitude System

$m_1 - m_2 = -2.5 \log_{10}(f_1/f_2)$ N.B. $\Delta m \approx \Delta f / f$

$f_1/f_2 = (d_2/d_1)^2$ from inverse-square law, lum: $L = f/(4\pi d^2)$

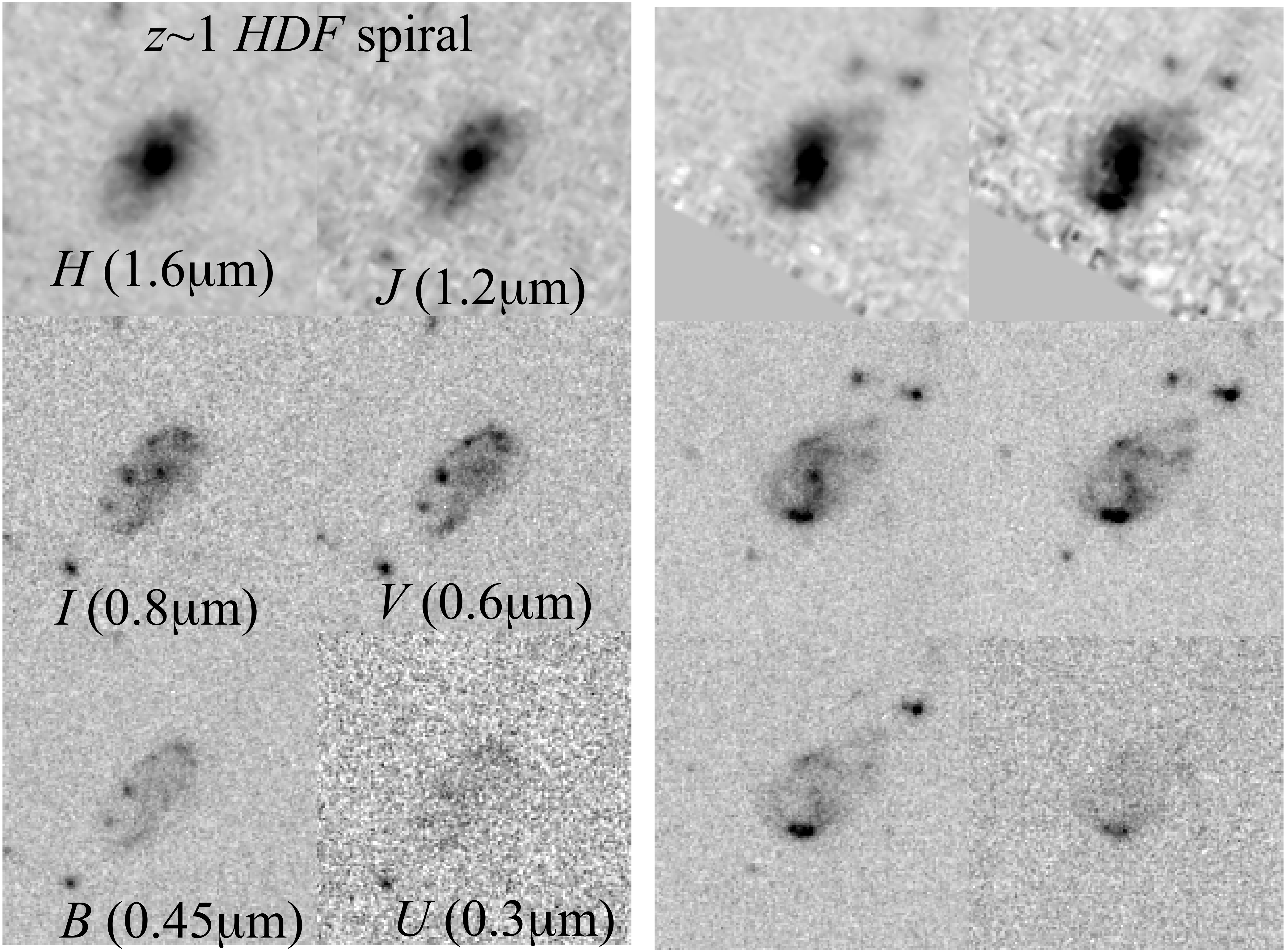
Define "ABSOLUTE MAGNITUDE" (M - related to intrinsic luminosity) as being apparent magnitude (m) when viewed at 10 parsecs

[1 parsec (pc) is the distance at which the Earth-Sun distance (Astronomical Unit, AU) subtends an angle of 1 arcsec: 1pc $=3.09\times10^{16}$m=206265 AU]

$m - M = 5 \log_{10} d_L - 5$ = "distance modulus"

Arbitrarily zero-pointed to the star Vega (A0)

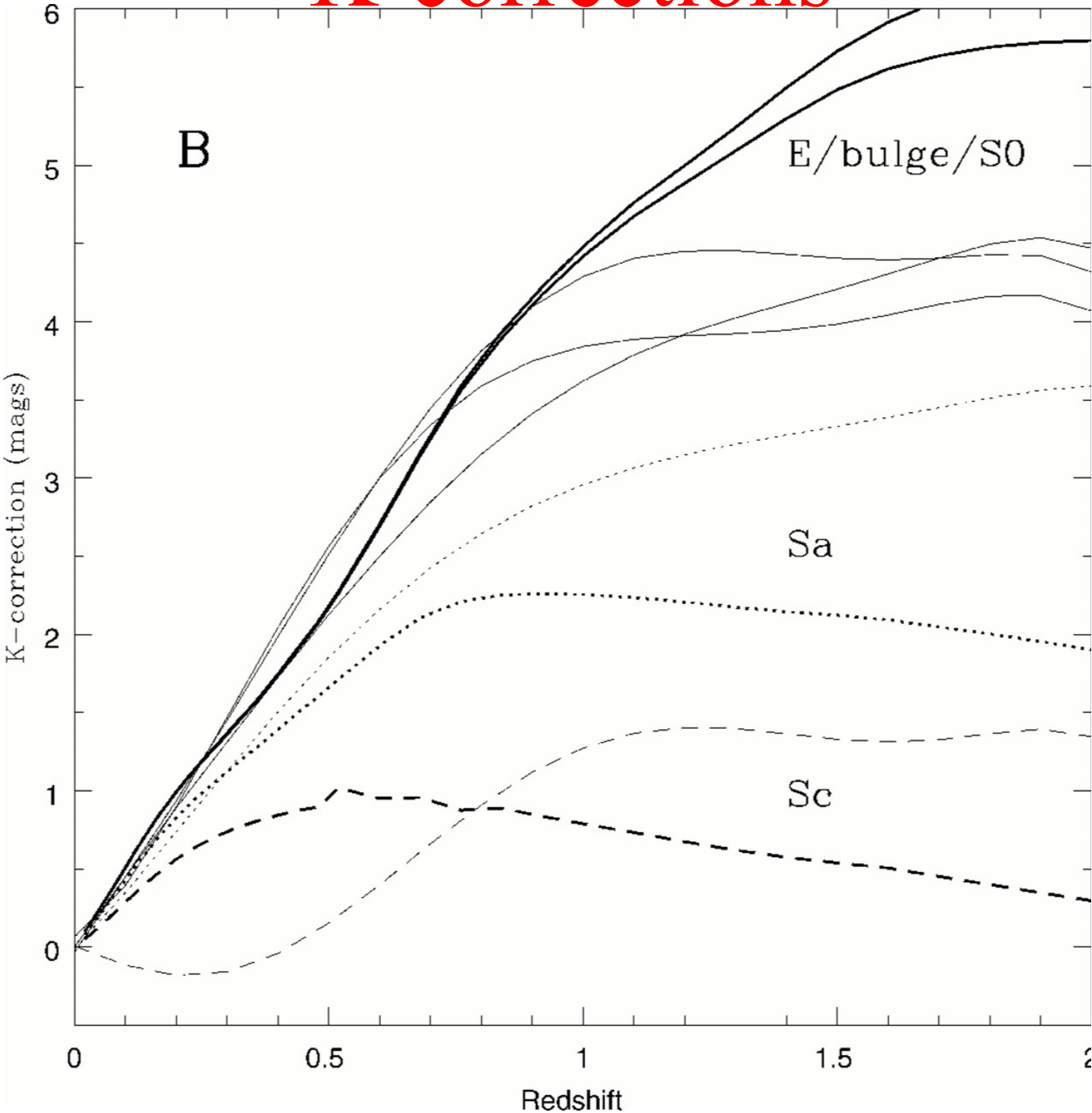
Now often use AB system - flat in f_ν is zero colour (flux



z~1 HDF spiral
H (1.6μm)
J (1.2μm)
I (0.8μm)
V (0.6μm)
B (0.45μm)
U (0.3μm)

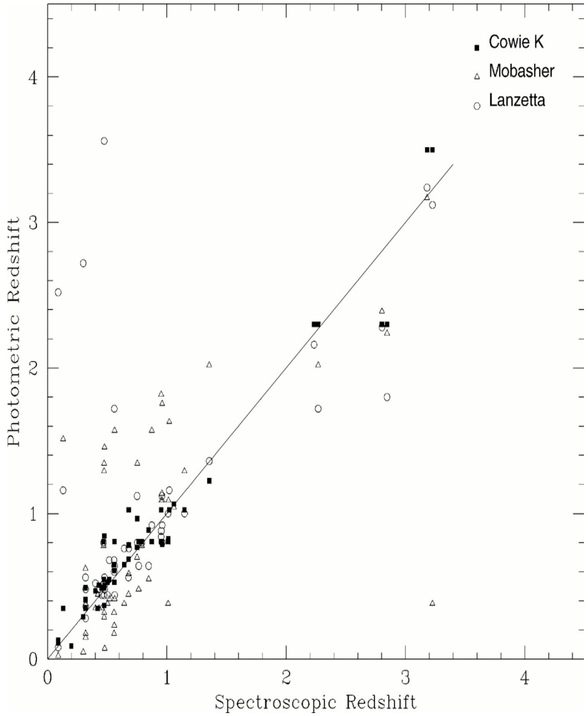
K-corrections

Need to correct apparent magnitude for band-shifting effects due to redshift. Right: Type-dependent k-corrections for the B band using two different approaches. Bold lines indicate corrections based on model SEDs that reproduce integrated broadband colors; non-bold lines indicate corrections derived from aperture spectrophotometry analyzed in conjunction with color data (Kinney *et al.* 1996)

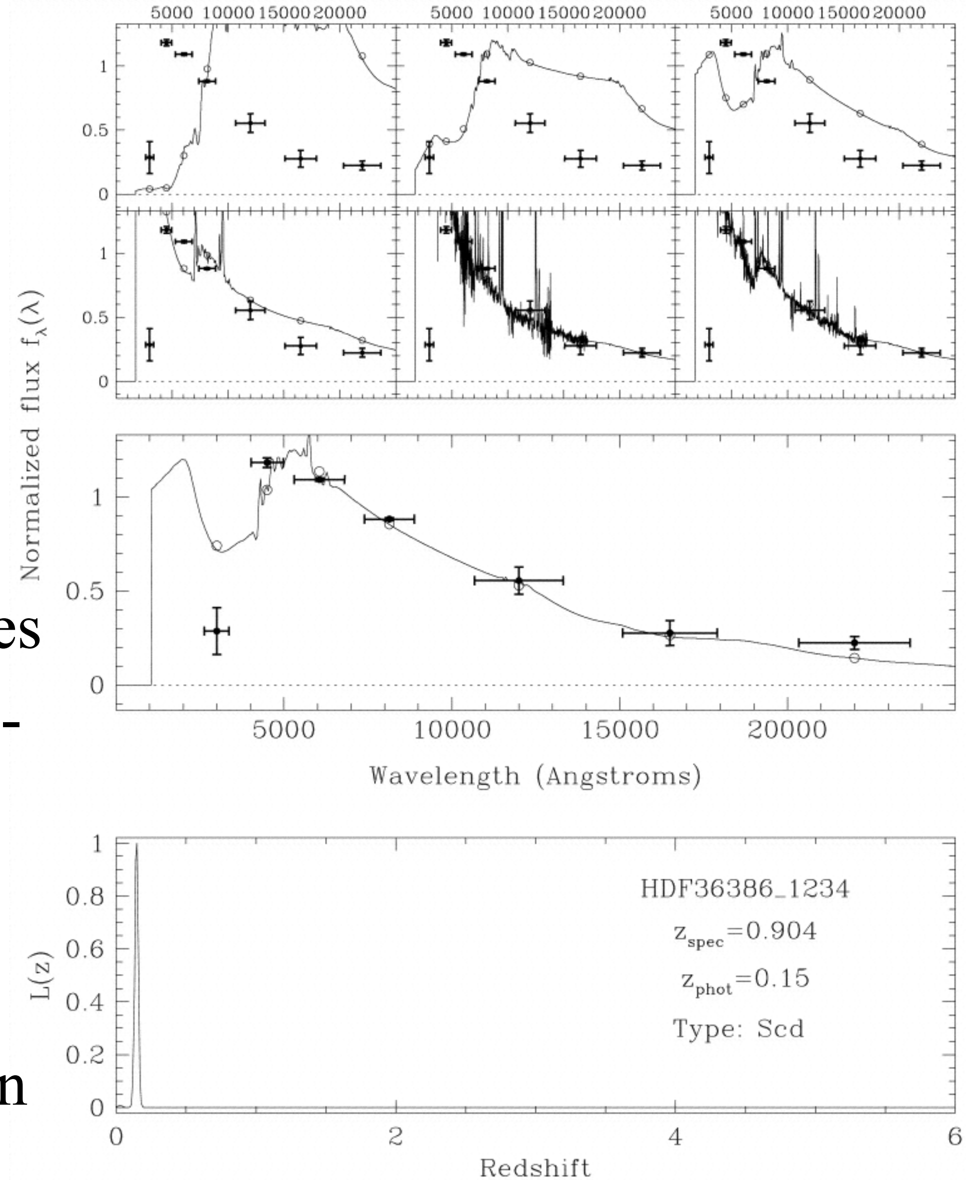


Poggianti (1997)

Photometric Redshifts

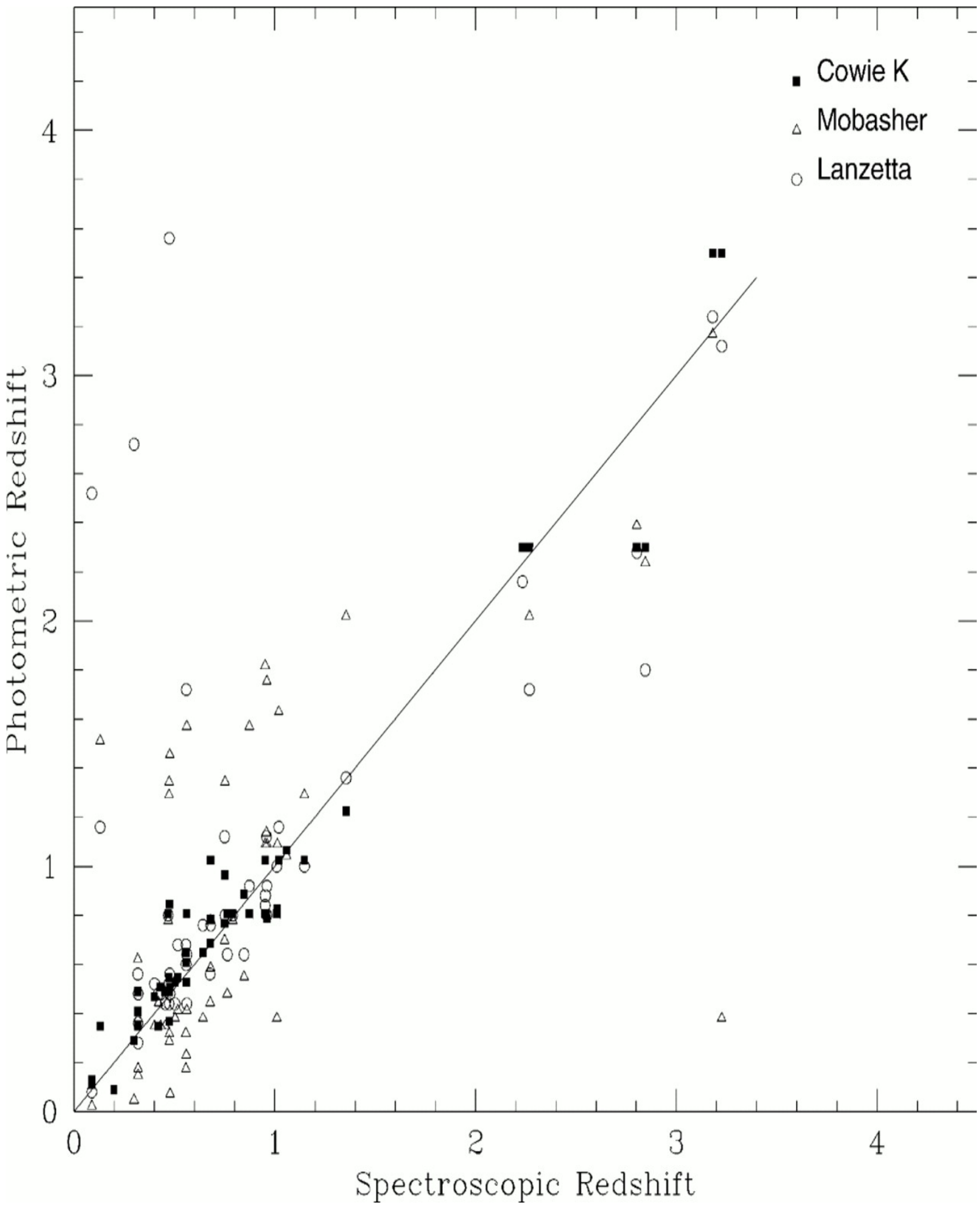


Ellis (1997)



Fernández-Soto *et al*. (2001)

Way of estimating redshifts of faint galaxies based on their brightness in different wave-bands (filters) – using broad-band colours (sensitive to spectral breaks) instead to of time-consuming spectroscopy (which measures spectral features such as emission & absorption lines). It puts those K-corrections to good use! This has rapidly developed in the past 15 years.

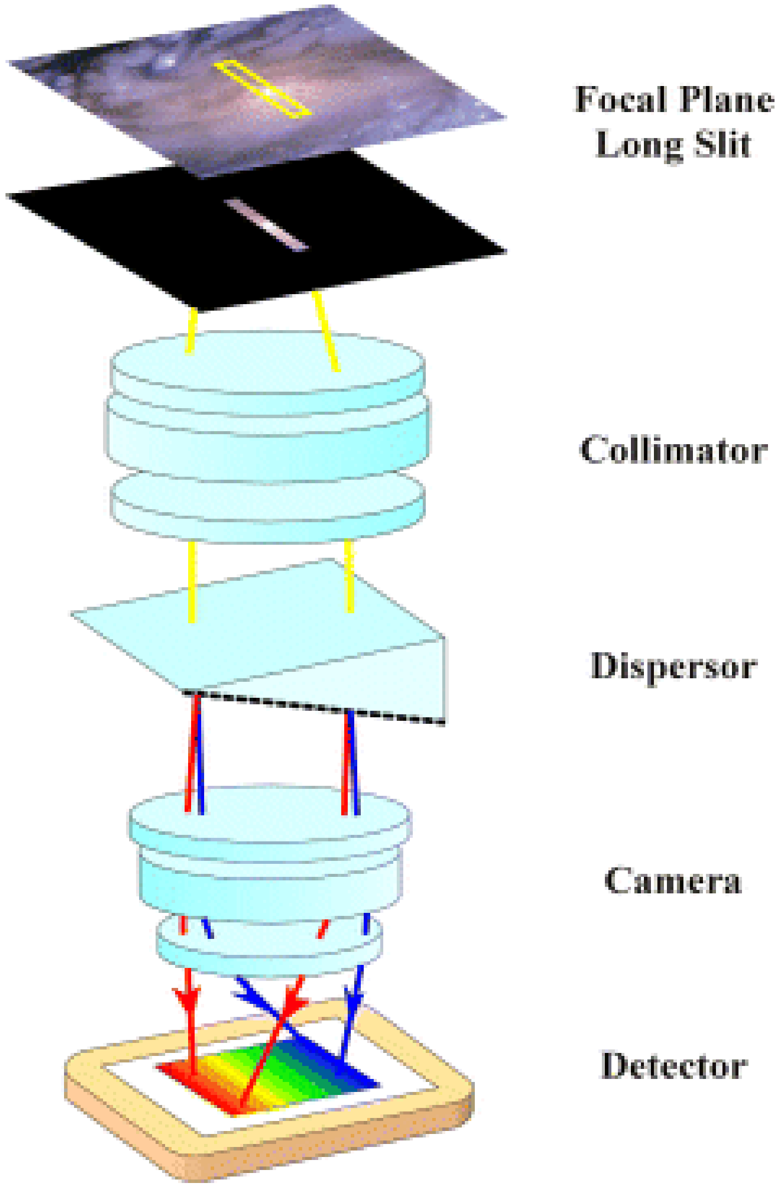

Cowie K
Mobasher
Lanzetta
Photometric Redshift
Spectroscopic Redshift
0
1
2
3
4
0
1
2
3
4

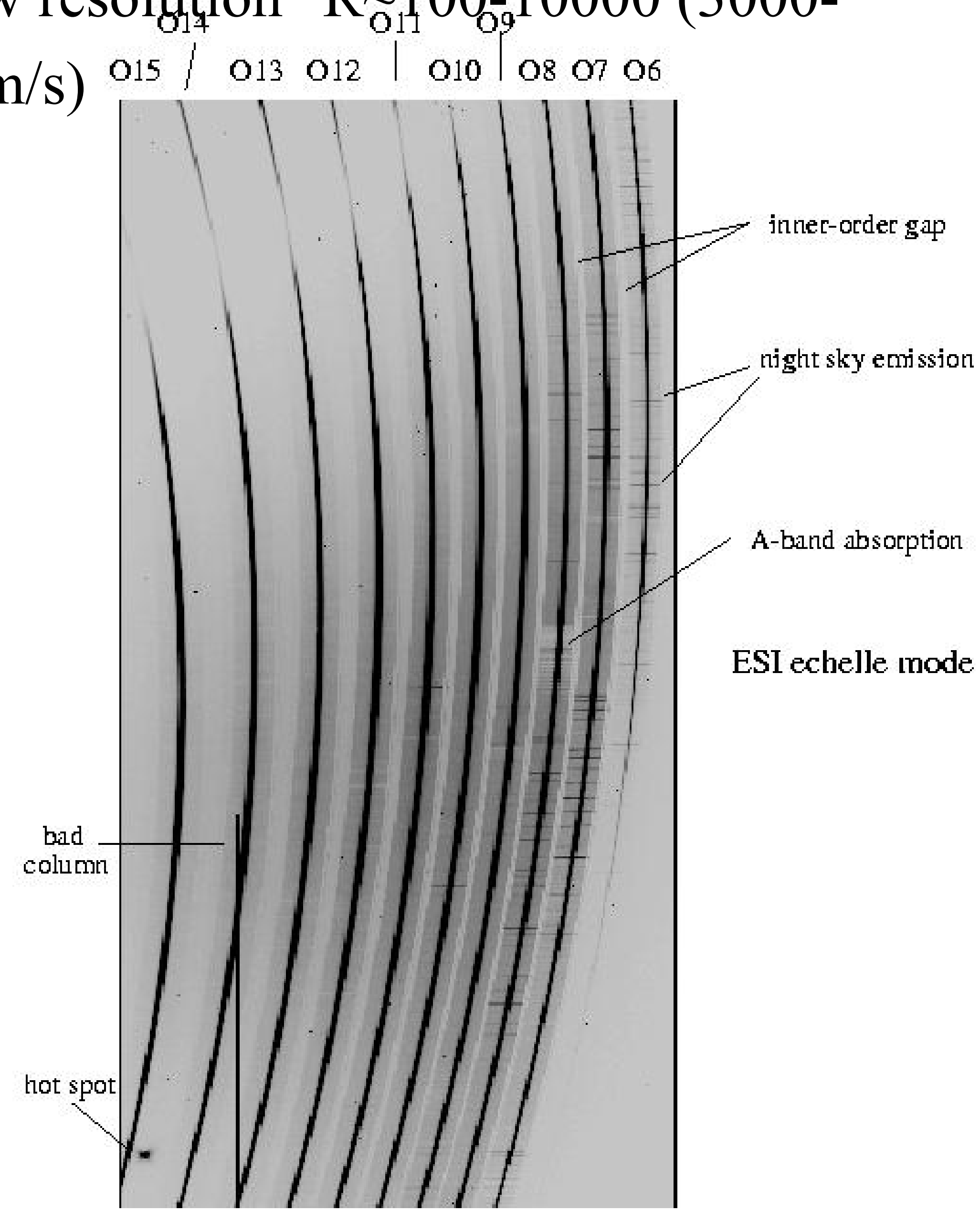
Galaxy Spectra

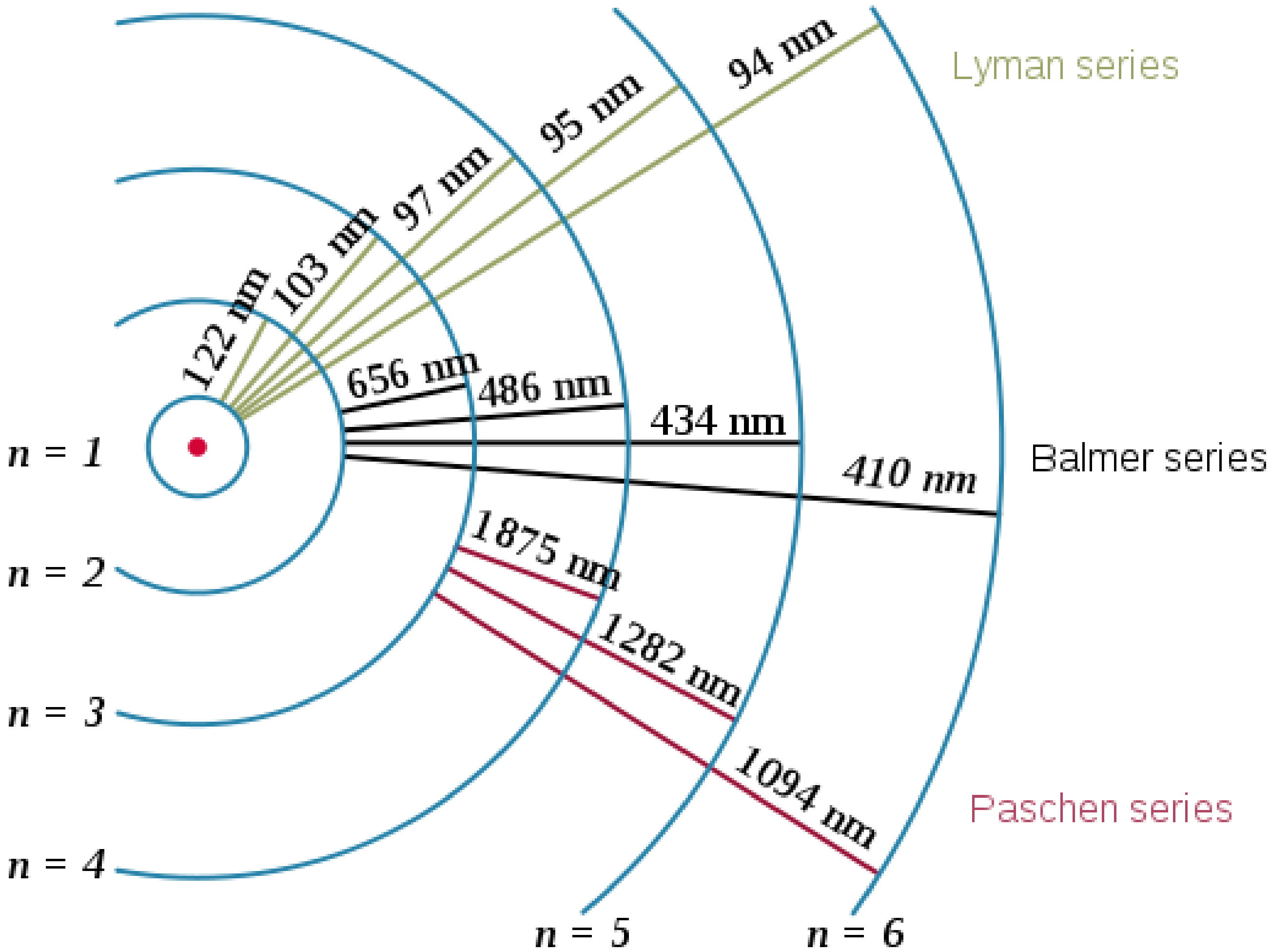
- Emission & absorption lines
- Dust & interstellar medium (ISM)
- Star formation
- Metallicity & chemical evolution
- Stellar populations & initial mass function (IMF)
- Internal dynamics
- Cosmological redshift (& peculiar motions at low-z)

Spectrographs

- Resolving power: $R=\lambda/\Delta\lambda_{FWHM}$
- "Low resolution" R~100-10000 (3000-30km/s)







Credit: wikipedia

Spectral Features: What are the main observables?

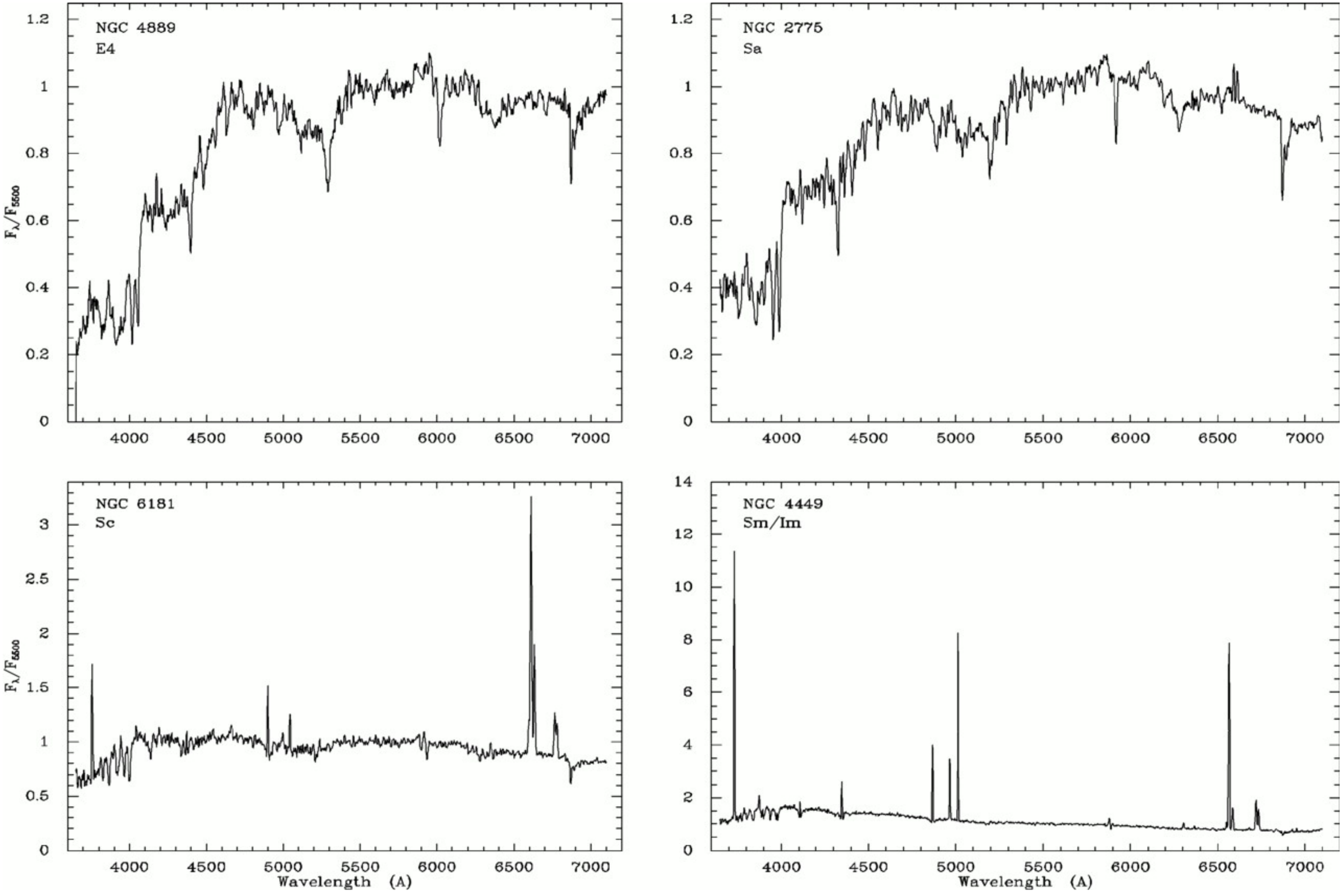
- Continuum shape ("red" or "blue") black body/thermal?
- Absorption lines - stellar photospheres (spectral classification)
- Emission lines (powered by UV - hot stars - excitation/ionization)
- Line widths ⇒ dynamics of stars or gas
- Line ratios ⇒ reddening/metallicity/electron density/temperature "diagnostics"
- Compare with rest wavelength, measure redshifts - stretching by **(1+*z*): Doppler shift recession** velocities/expansion of the Universe

Why do galaxy spectra look different?

- Contributions from stars of different temperatures
- Different metallicities (chemical composition/abundances)
- Effects of dust (in our Galaxy and the distant one) & ISM
- Nebula emission
- Active Galactic Nucleus (AGN) contribution
- Intervening clouds along the line of sight

Galaxy Spectra and Morphology

Integrated galaxy spectra correlate with morphological type (star formation history?)



Kennicutt (1992) ApJ Supp **79**, 255

Untangling Galaxy Spectra

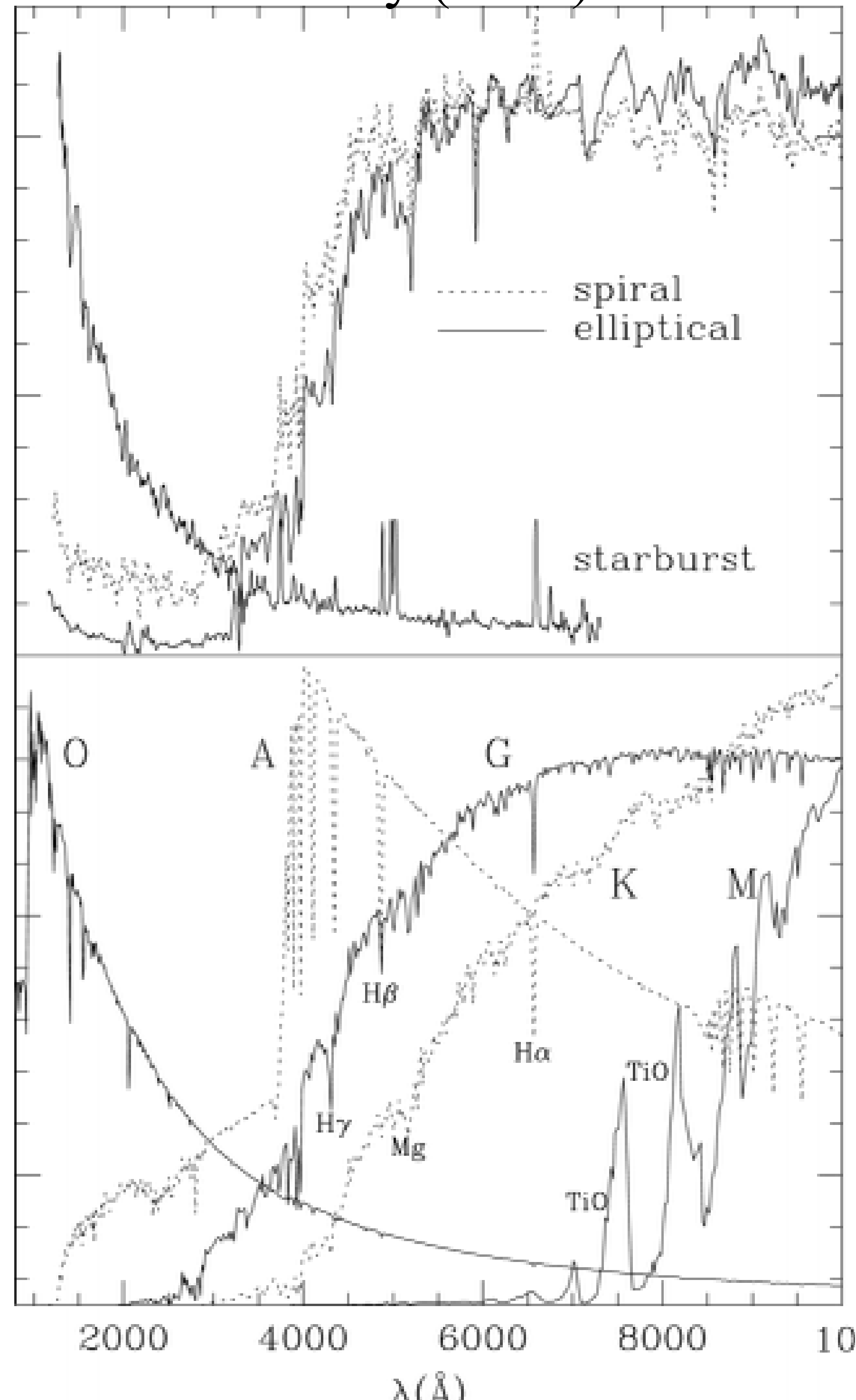
- For galaxies and clusters outside the local group, ***cannot* study individual stars**. Instead, we see the sum of the light from all of the stars. How do we extract information from the ***integrated*** starlight?
- Can determine ages or heavy-element abundances through comparison with models - synthetic representations of the numbers and types of stars present.
- These models of integrated galaxy spectra are developed from spectra of nearby stars and star clusters, also from stellar evolution theory and stellar atmospheres.

Underlying Stellar Types

Starbursts - Most of energy in UV: OB-type stars (young, hot, massive, blue). Emission lines from photoionization

Ellipticals - G+K stars; also cool M-stars (TiO features). Absorption lines. Red spectral shape

Worthy (2000)



Stellar Populations

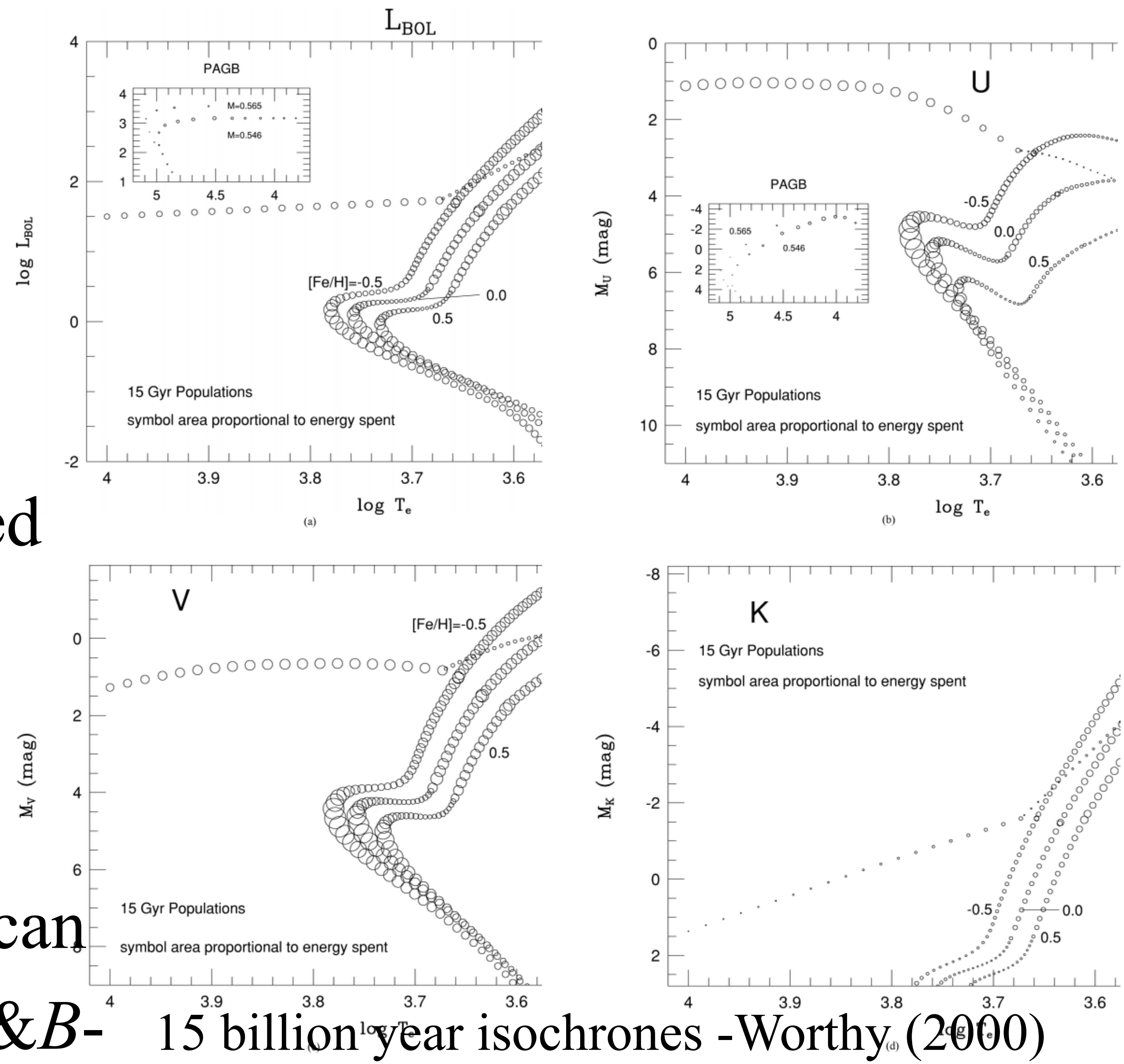
Stellar population - set of stars of the same age and chemical composition. Born together at some point in a galaxy, share the same kinematic properties (e.g. star clusters - OB associations, globular cluster etc.)

Population synthesis - constructing a model of a galaxy from its constituent stellar populations, pioneered by Tinsley. Models a galaxy as the sum of its stellar populations of a particular age, weighted by the ***Star Formation Rate*** at that epoch.

Chemical enrichment history should also be accounted for.

What Dominates the Spectrum?

Stars near main sequence turn-off usually dominate, except for old populations (>500 Myr) where cool red giant stars are prominent at long wavelengths. Horizontal branch can be significant in *U&B*-bands.

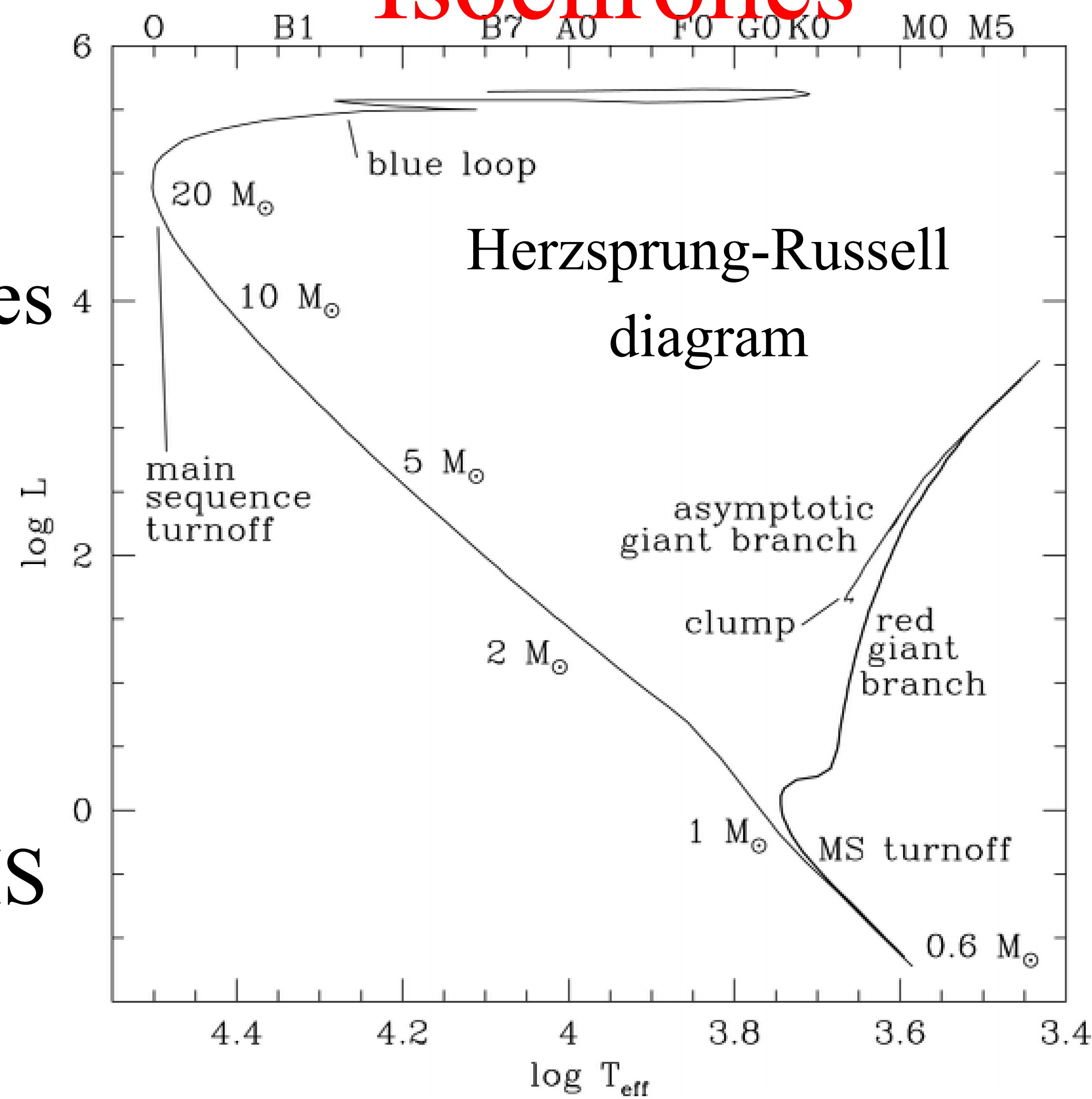


15 billion year isochrones -Worthy (2000)

Isochrones

Isochrone - locus of luminosities and temperatures at one instant in time for stars of all masses (mimics a star cluster or a single-age stellar population).

Massive stars have shorter main sequence lifetimes: MS turn-off becomes dimmer and cooler with time.



Isochrones for solar composition at 5×10^6 & 15×10^9 years Worthy (2000)

Initial Mass Function (IMF)

Number of stars which exist at each mass at zero age - determines rate of dimming (impact of different IMFs becomes irrelevant after 1Gyr). IMF still uncertain - might vary with environment.

Normalize: $\int_{low}^{up} m\,\Phi(m)\,dm = 1$

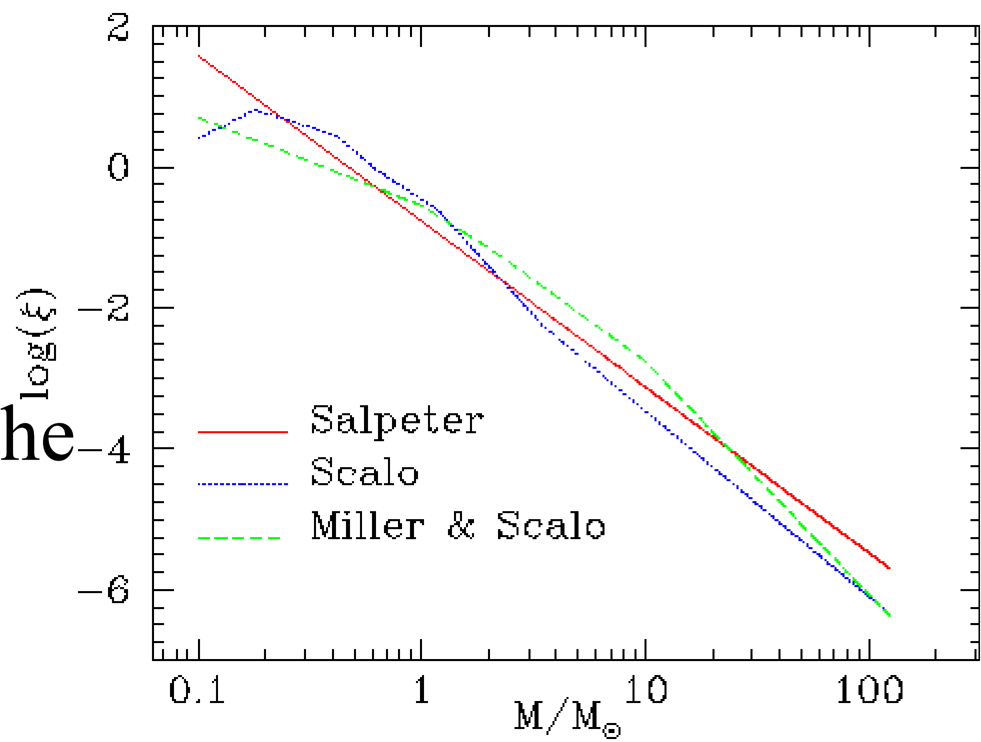
Simple power-law representation

$\Phi(m)=m^{-(1+x)}$= fraction of stars in the mass range $m \rightarrow m+\delta m$

where x is "slope"

x=1.35 - Salpeter IMF

(Scalo is 3-component IMF).



Bruzual & Charlot (1993)

Population Synthesis

Model simple stellar population (SSP), constructing by summing individual stellar spectra l_λ (depends on surface temperature, surface gravity & metallicity) over the mass function Φ

$$L_\lambda = \Sigma_i \Phi(M, \delta M) \; l_\lambda(T_{eff}, g, Z)$$

Put in time evolution of SSP. A galaxy has more complicated star formation history $\Psi(t)$ - do convolution integral to get spectral evolution:

$$f_\lambda = \int^t_0 \Psi(t-\tau) \; f_\lambda(\tau) d\tau$$ approach of Bruzual & Charlot (1993)

Problem: "mean ages" derived too young, as young populations are brighter and dominate light (thus get more weight - luminosity weighting...)

Spectral Evolution with Stellar Age

- Stellar populations generally become dimmer & redder with age.
- Neutral metal lines increase in strength.
- After 100million years, Balmer (hydrogen) absorption lines decrease in strength (before that, OB stars can power line emission which "fills-in" absorption).
- Balmer absorption line strength sets stellar class OBAFGKM (A-stars have strongest absorption)
- 4000 Å break develops in old stars - line-blanketting by metals, (Balmer break in post-starburst galaxies at similar wavelength). Spectral discontinuity in continuum.

Metallicity

- Enrichment of heavy elements - stellar nucleosynthesis (Big Bang only gets as far as Be...) These are dispersed by supernovæ, winds and loss of outer envelopes.
- Subsequent generations of stars have different chemical composition.
- Model this: mass in stars increases with star formation rate, decreased with ejection rate. Gas is depleted, replenished by infall. Often assumes "***instantaneous recycling approx***"
- Returned fraction: 10-30% eventually gets returned to ISM
- Yield: fraction of mass turned into heavy elements

Definition: $[Z/H]=\log_{10}\{n(Z)/n(H)\} \ / \ \log_{10}\{n(Z_{\odot})/n(H_{\odot})\}$

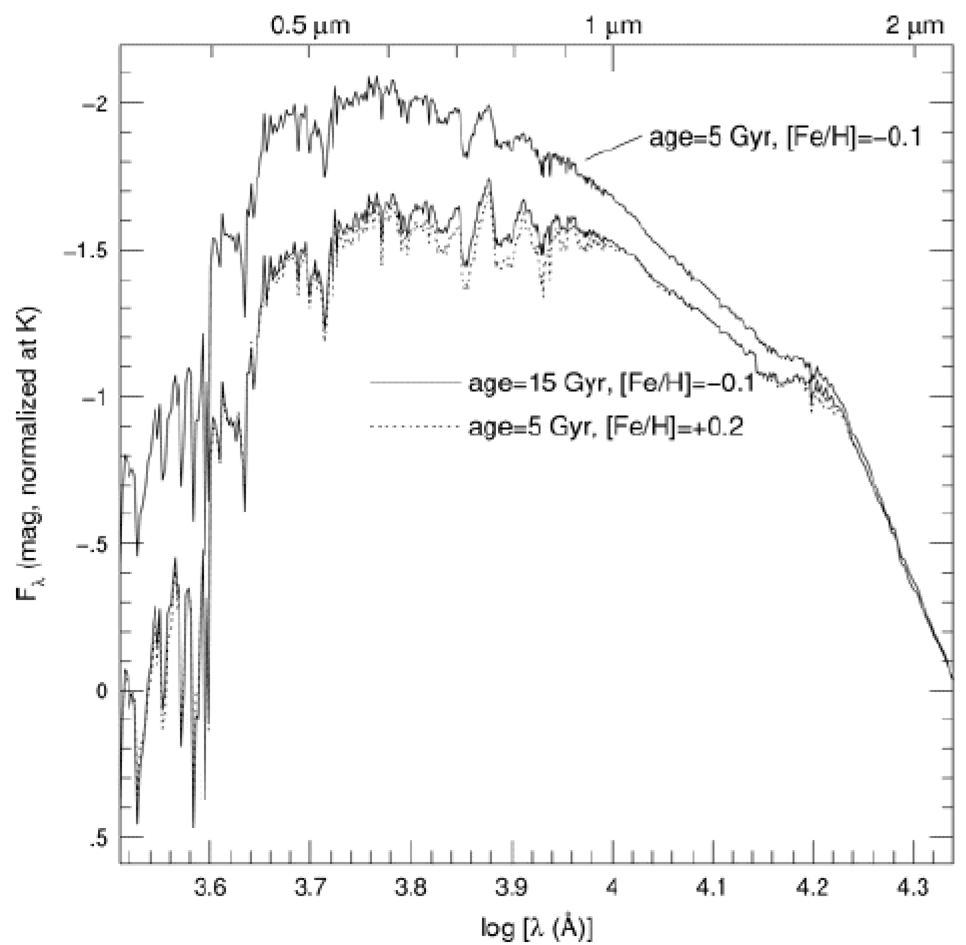
Problem: different element ratios have different evolution (O in massive stars, 10Myr; Fe in type 1a SNe, 1Gyr)

Age-Metallicity Degeneracy

Changes in age and metal abundance have very similar, almost indistinguishable, effects on the integrated spectrum, so that an old, metal poor population may very closely resemble a young, metal-rich population.

Stellar population becomes dimmer and redder with both increasing age & metallicity Z

$\log(\text{age}) \propto 3/2 \log(Z)$

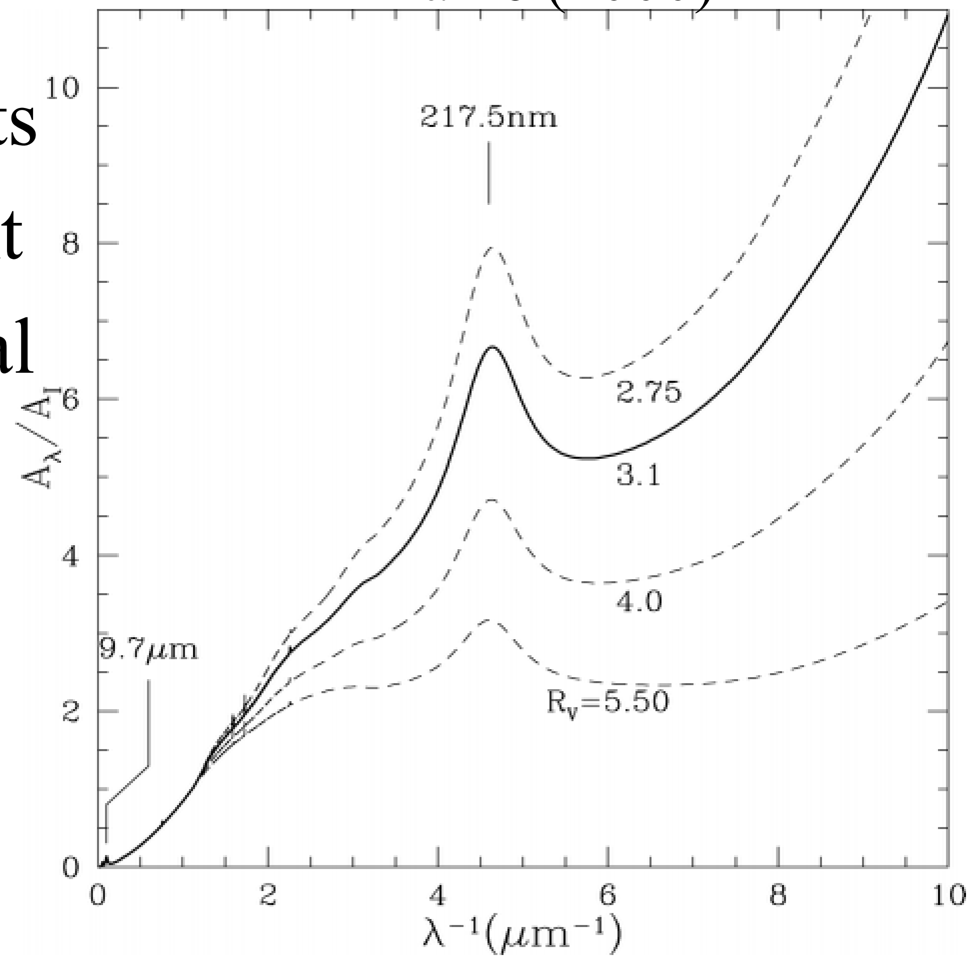


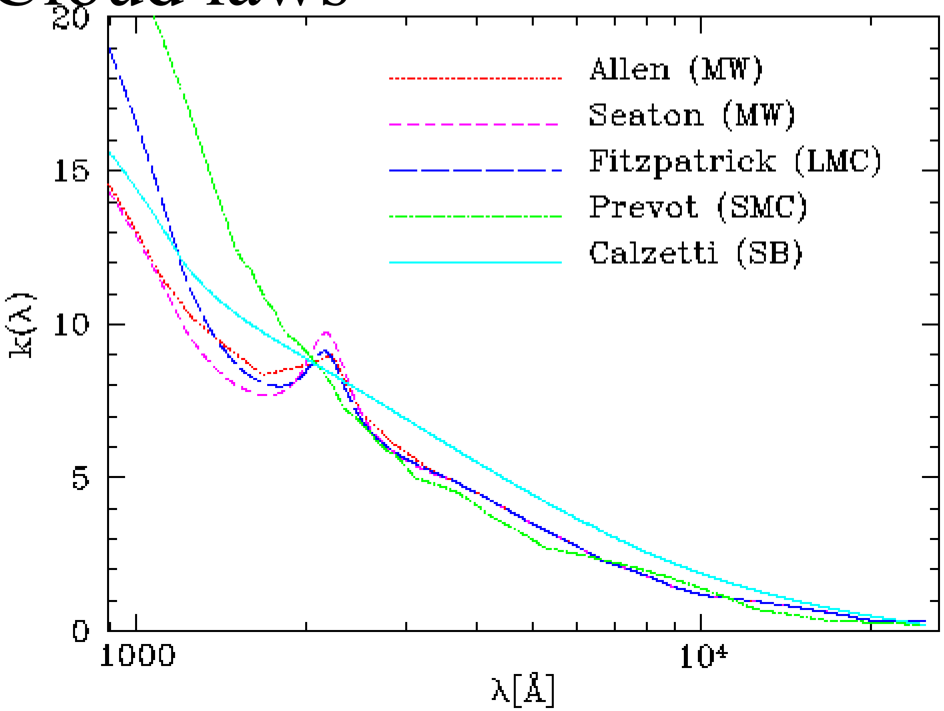
Worthy (2000)

Dust Reddening

Dust can scatter and absorb starlight. Often modelled as a foreground screen: over-simplification of geometry, particularly for starbursts where dust is intermixed - different extinction law (Calzetti) from usual Milky Way or Small Magellanic Cloud laws

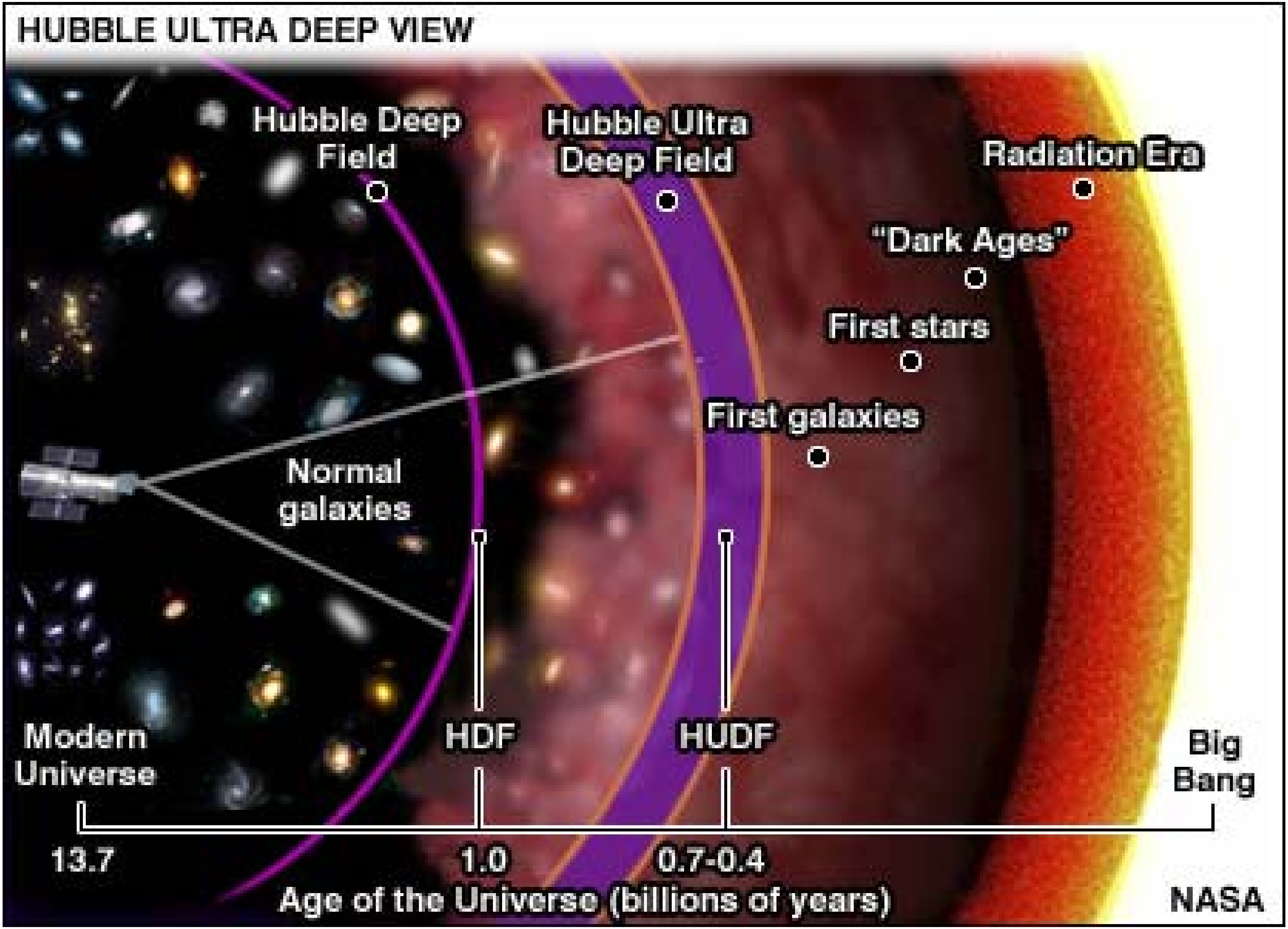
Draine (2000)





Emission Lines

- Photoionzing flux (e.g. From massive short-lived stars) - recombination lines, HII region, particulary the Balmer lines of hydrogen (transitions to n=2) in the optical Hα 6563Å, Hβ 4861Å. In the UV, Lyα 1216Å is important (n=1).
- Flux in these lines proportional to ionizing photons - and so to the number of OB stars. These are a measure of near-instantaneous star formation rate (rate of conversion of gas to stars, units: solar masses per year) Kennicutt 1983.
- In starbursts, also see forbidden lines which are collisionally de-excited: prominent are [OIII]5007/4959Å, [OII]3727Å


HUBBLE ULTRA DEEP VIEW
Hubble Deep Field
Hubble Ultra Deep Field
Radiation Era
"Dark Ages"
First stars
First galaxies
Normal galaxies
Modern Universe
HDF
HUDF
Big Bang
13.7
1.0
0.7-0.4
Age of the Universe (billions of years)
NASA

A Brief History of the Star Formation History

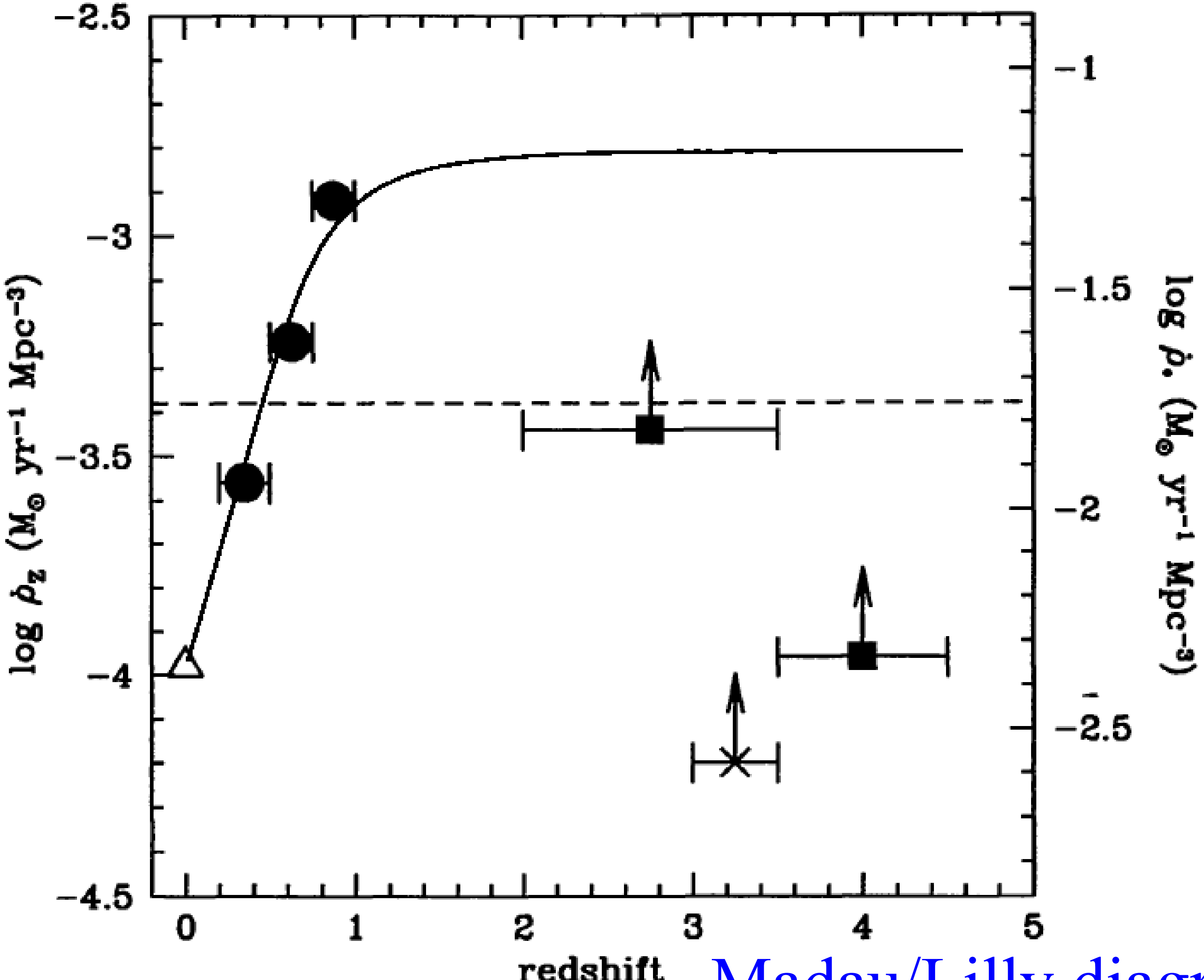
Proxies for star formation rate (SFR) used in individual galaxies (H-alpha, [OII], UV continuum)... usually to measure number of short-lived massive stars (>8M_sun). Use IMF to infer total - e.g. Kennicutt work (1983, 1998)

Evolution in galaxy colours invoked to explain number counts (e.g. "Faint blue galaxies" problem)

By mid-1990s, redshift surveys (e.g. CFRS, Lilly et al 1996) and multi-colour deep fields (HDF, Madau et al 1996) with photometric redshifts were getting comoving density of rest-UV light to z>1

Strong evolution in average SFR per unit volume

The Star Formation History of the Univese



Madau/Lilly diagram

Limitations of the Madau-Lilly Plot

Different star formation indicators in different redshift bins

Different luminosity limits

Dust & metallicity not properly incorporated

Tells you about integrated SFR - not the nature of the galaxies hosting the star formation

Should NOT be regarded as the star formation history of a single galaxy - different galaxies active at different times

Says nothing about merging history and evolution of mass function & luminosity function

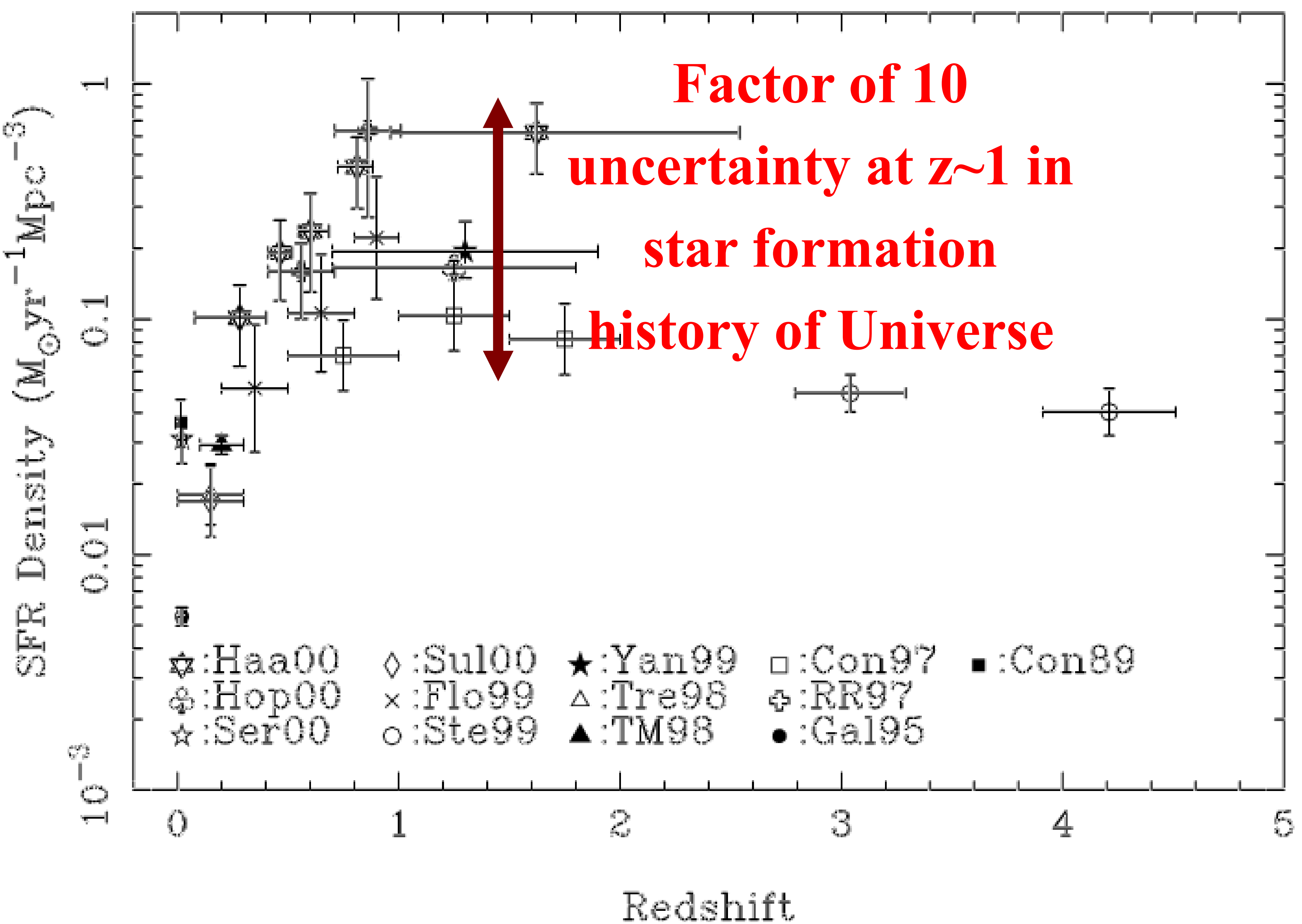
Background

Key problem in observational cosmology
=> At what epoch did majority of stars form?

- Star formation rate (SFR) higher in recent past => peaks around z=1-2?

- Large discrepancies between SFR estimates obtained from different methods

=> different indicators have uncertain relative calibration and are differently affected by dust extinction



Madau-Lilly diagram (updated by Hopkins et al. 2001)

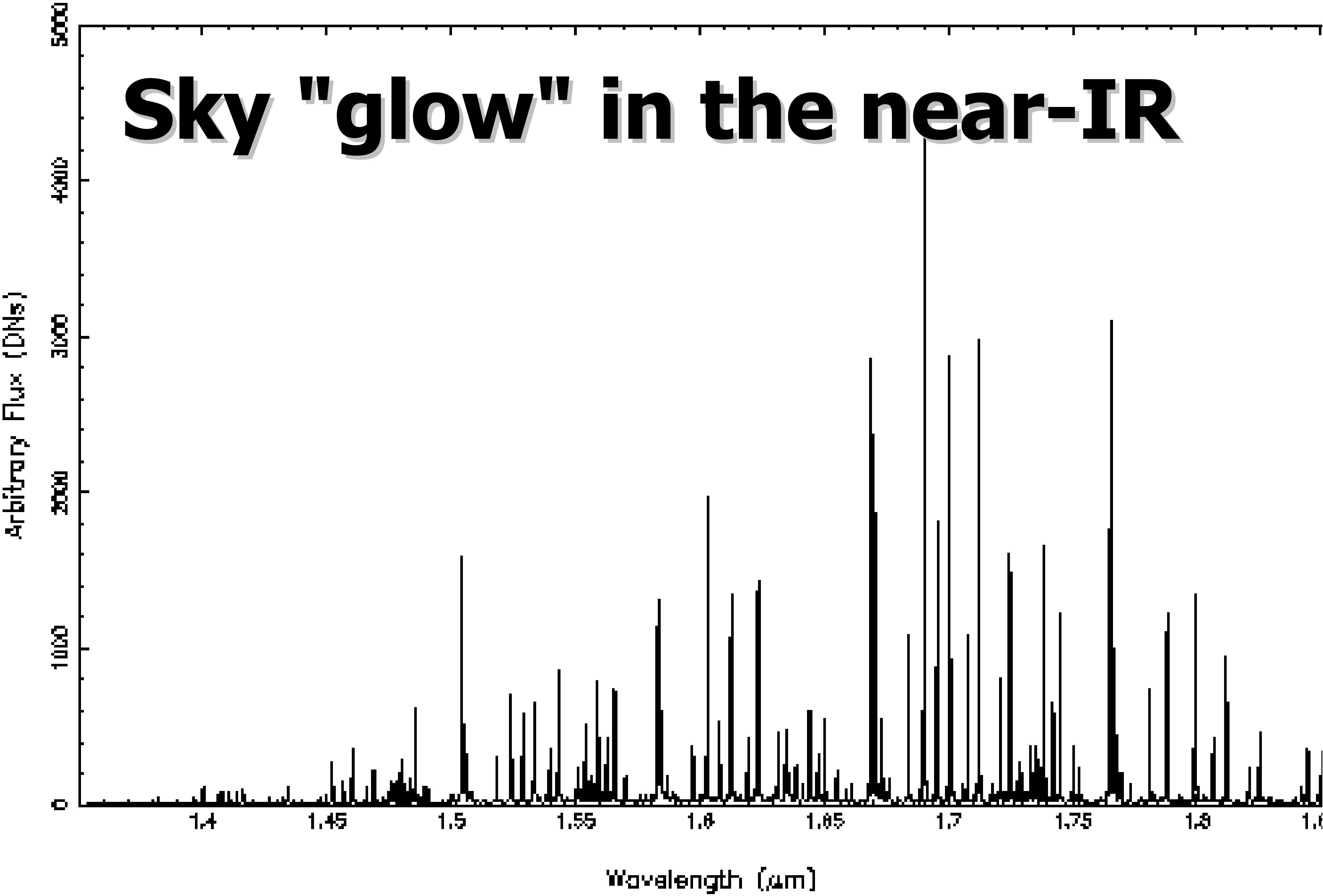
Hα as an SFR indicator

Hα luminosity proportional to ionising flux from massive stars

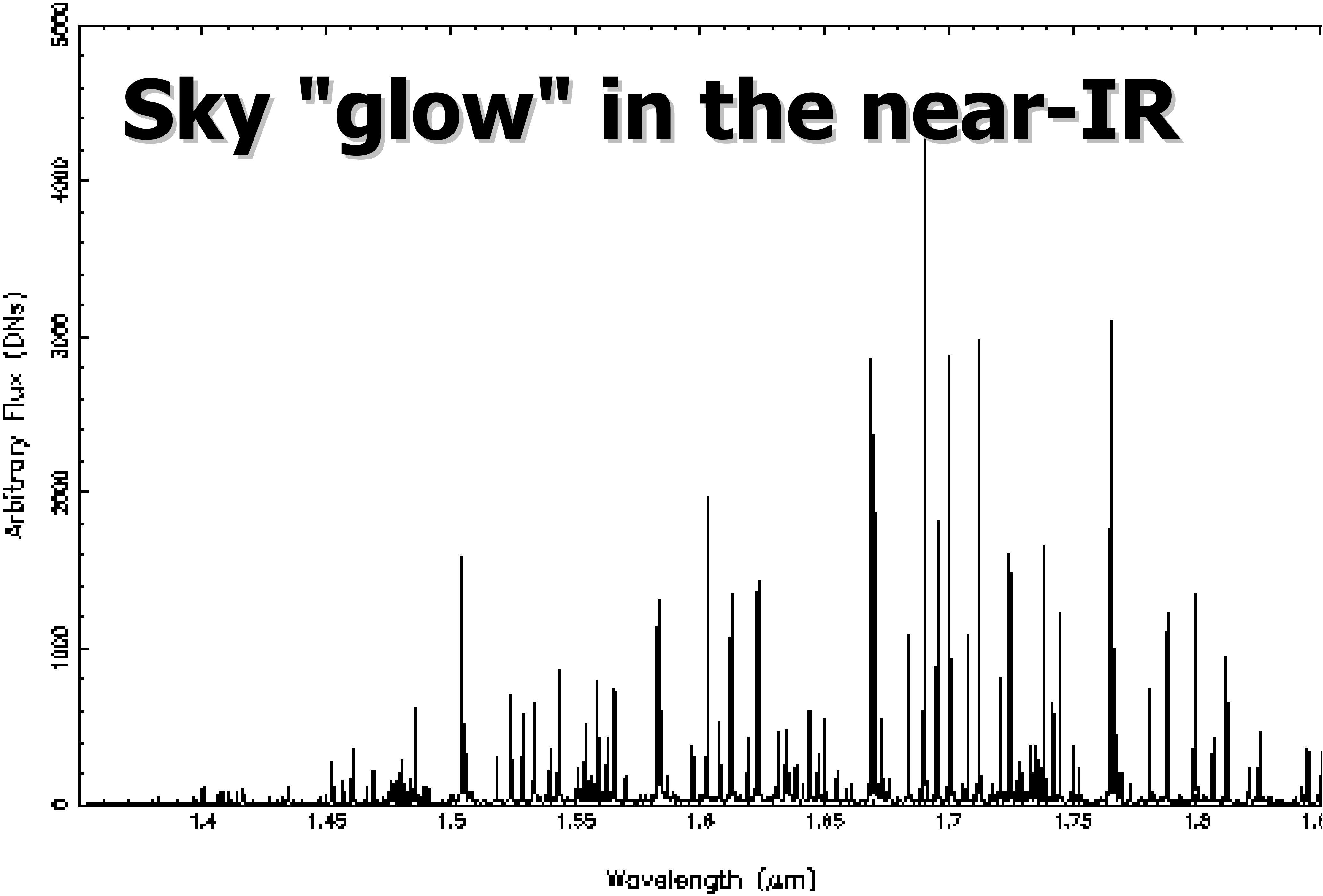
=> instantaneous SFR

- Relatively immune to metallicity effects
- Less susceptible to extinction than rest-UV
- tracing Hα to early epochs forces a move to near infrared at $z>0.6$
- Need a large sample (several hundred!) to address the issue properly

Sky "glow" in the near-IR



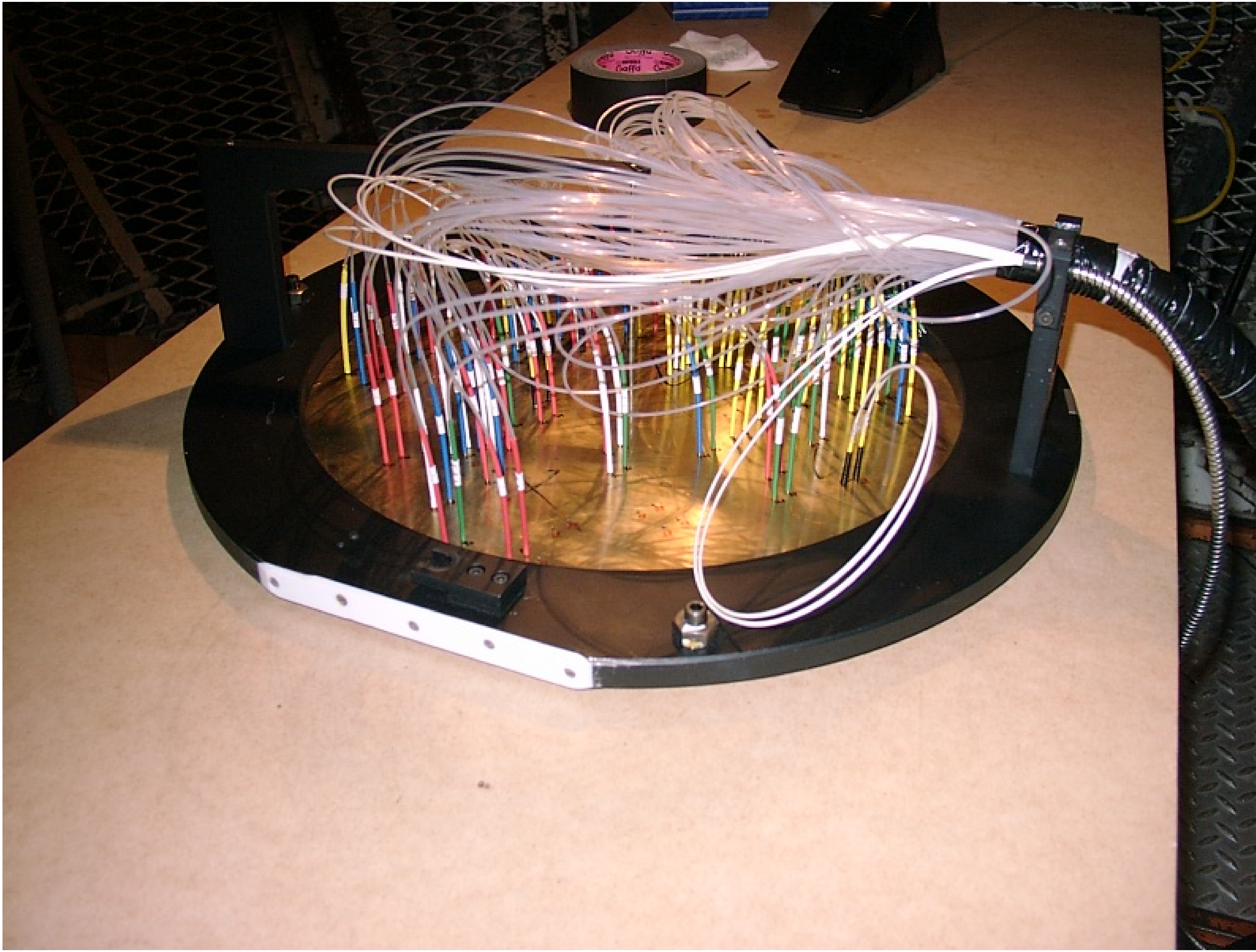
Sky "glow" in the near-IR



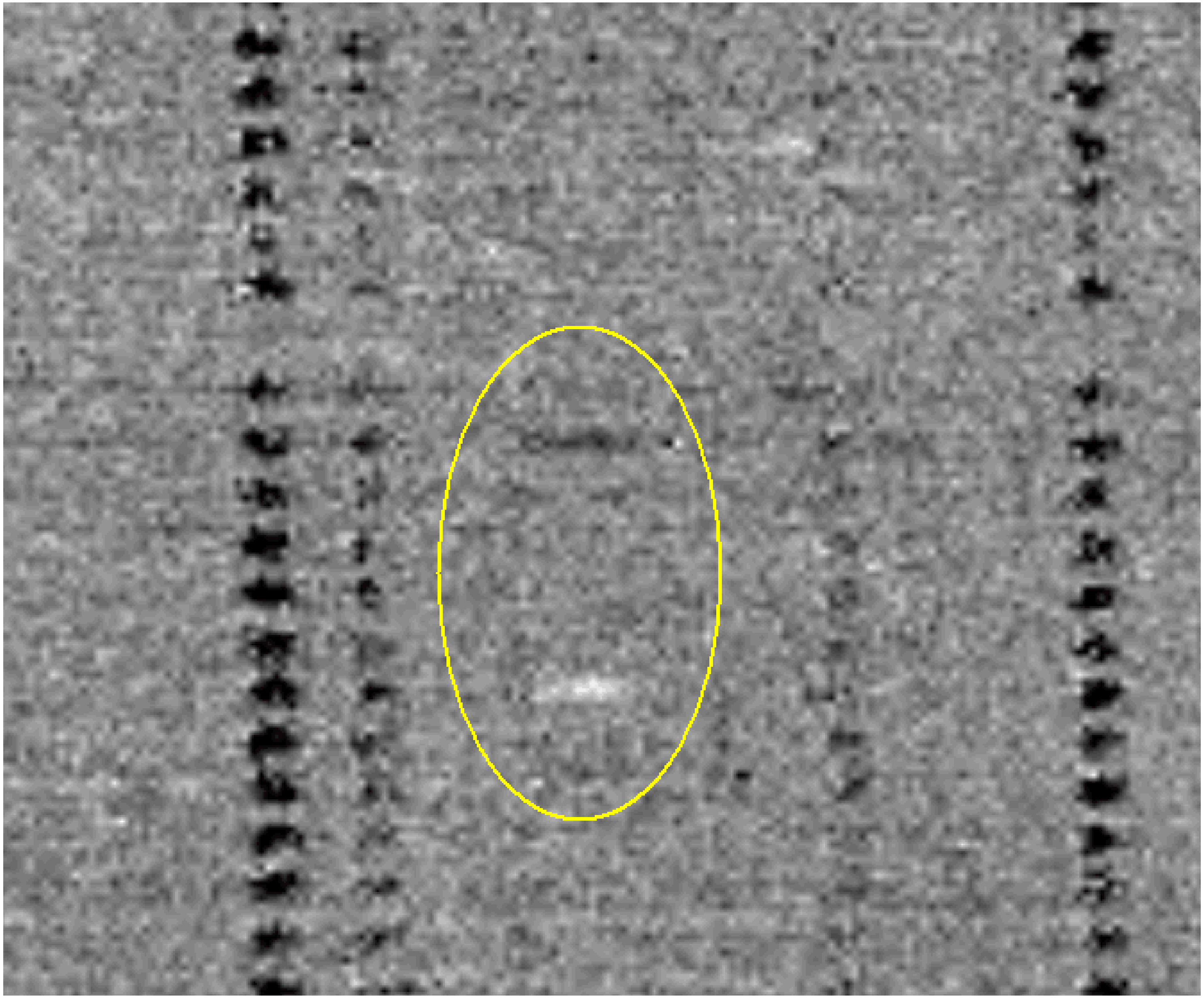
Hα in the Infrared

Previous IR Hα surveys restricted to small samples

- Narrow-band work still to yield large numbers as volumes are small (Bunker et al.; Mannucci et al.; Teplitz et al. in the mid-1990s)
- Single-object long slit work important but laborious (e.g. Glazebrook et al. (1999), Tresse et al. (2002) @z~**1** , Erb et al. (2003) @z~**2**
- Can do slitless surveys on HST with NICMOS (Yan et al; McCarthy et al.) but spectral resolution poor
- Multi-object near-IR spectroscopy just starting on the ground (fibre-fed IoA CIRPASS on WHT & AAT, fore-runner of FMOS on Subaru; cold slitmasks too LIRIS on WHT, IRIS2 on AAT; MOIRCS on Subaru



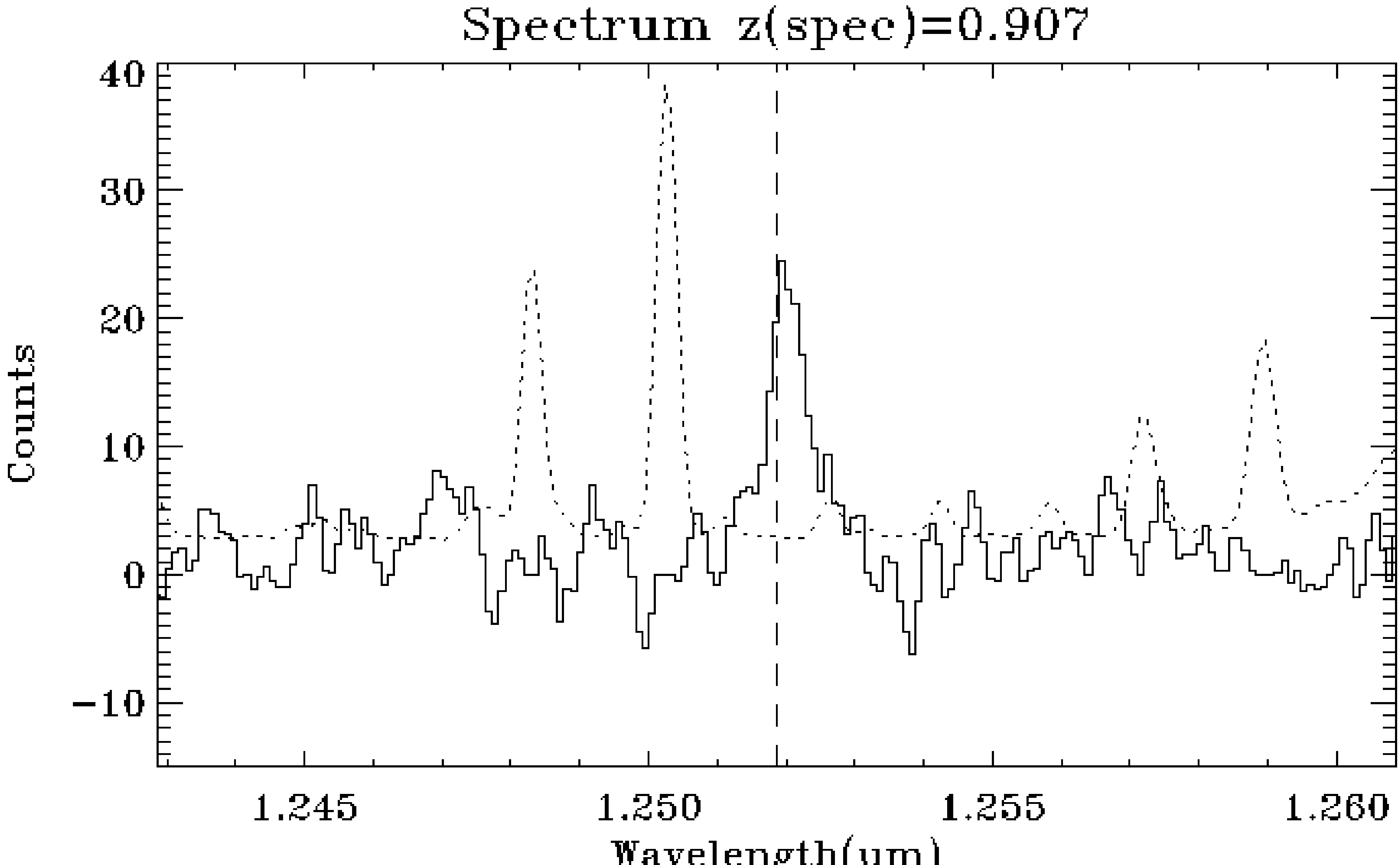
Human fibre positioners with CIRPASS



"Beam switching" between pairs of fibres. Sky lines burn only ~10% - no need for OH suppression at R~5000

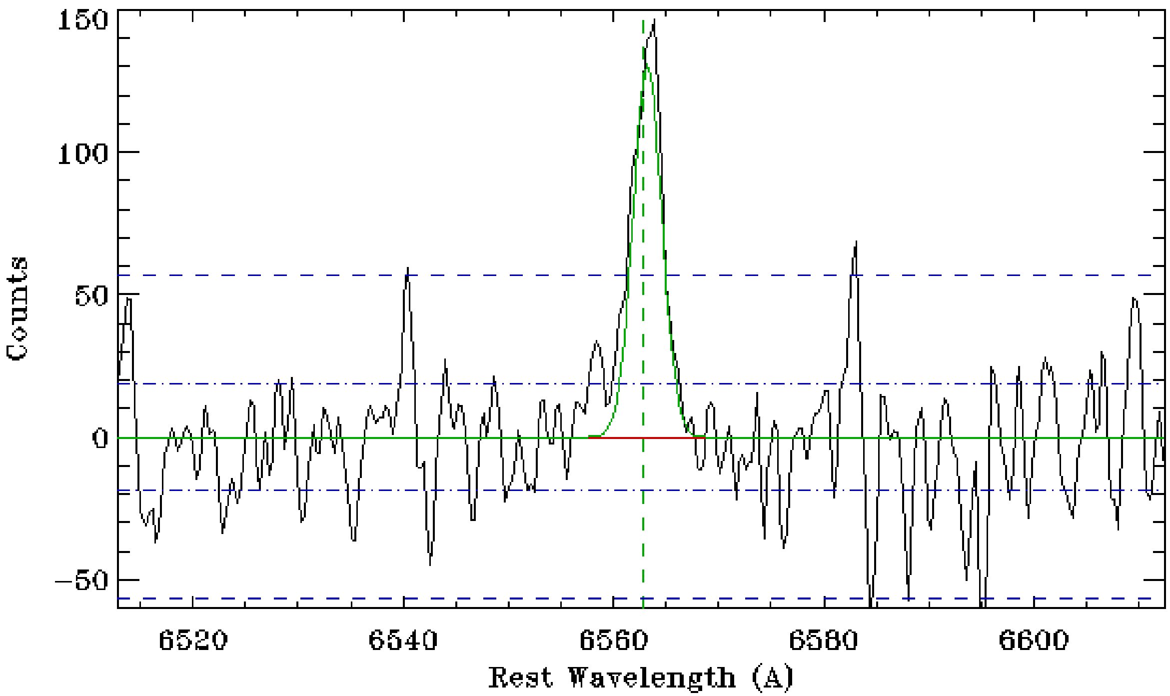
HDF-N galaxy, observed in Hα

with CIRPASS on WHT



Doherty, Bunker, Sharp, Parry et al. 2005

Survey Science



We have a spectroscopic sample in HDFN, complete to a mag limit (I~24 mag) - redshifts known from optical, want true star formation rates: can stack Hα lines

=> Next step at z~1-1.5 (Hα in J & H): move to an 8-m.

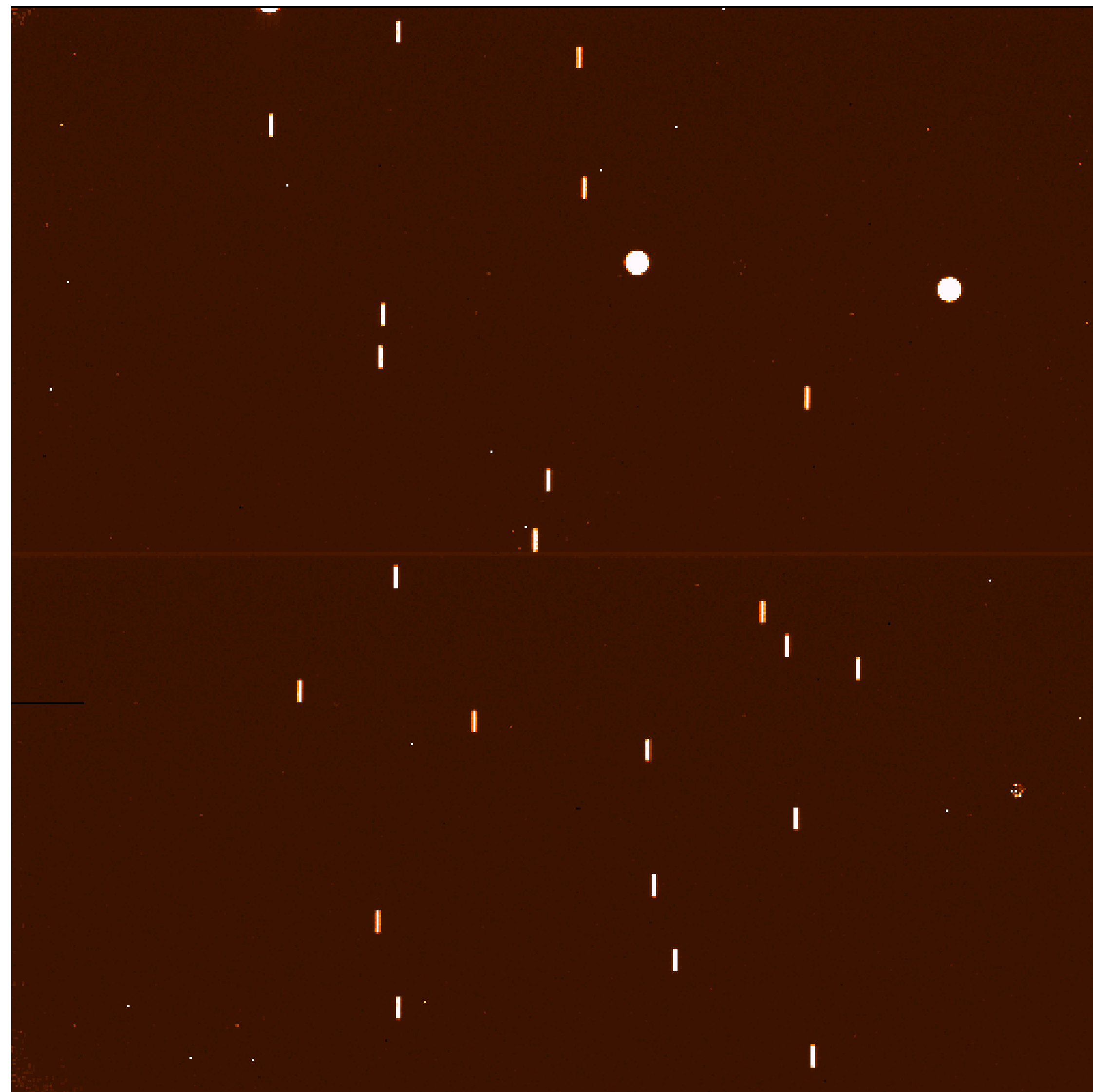
FMOS on Subaru based on CIRPASS design

Pushing to Higher Redshifts

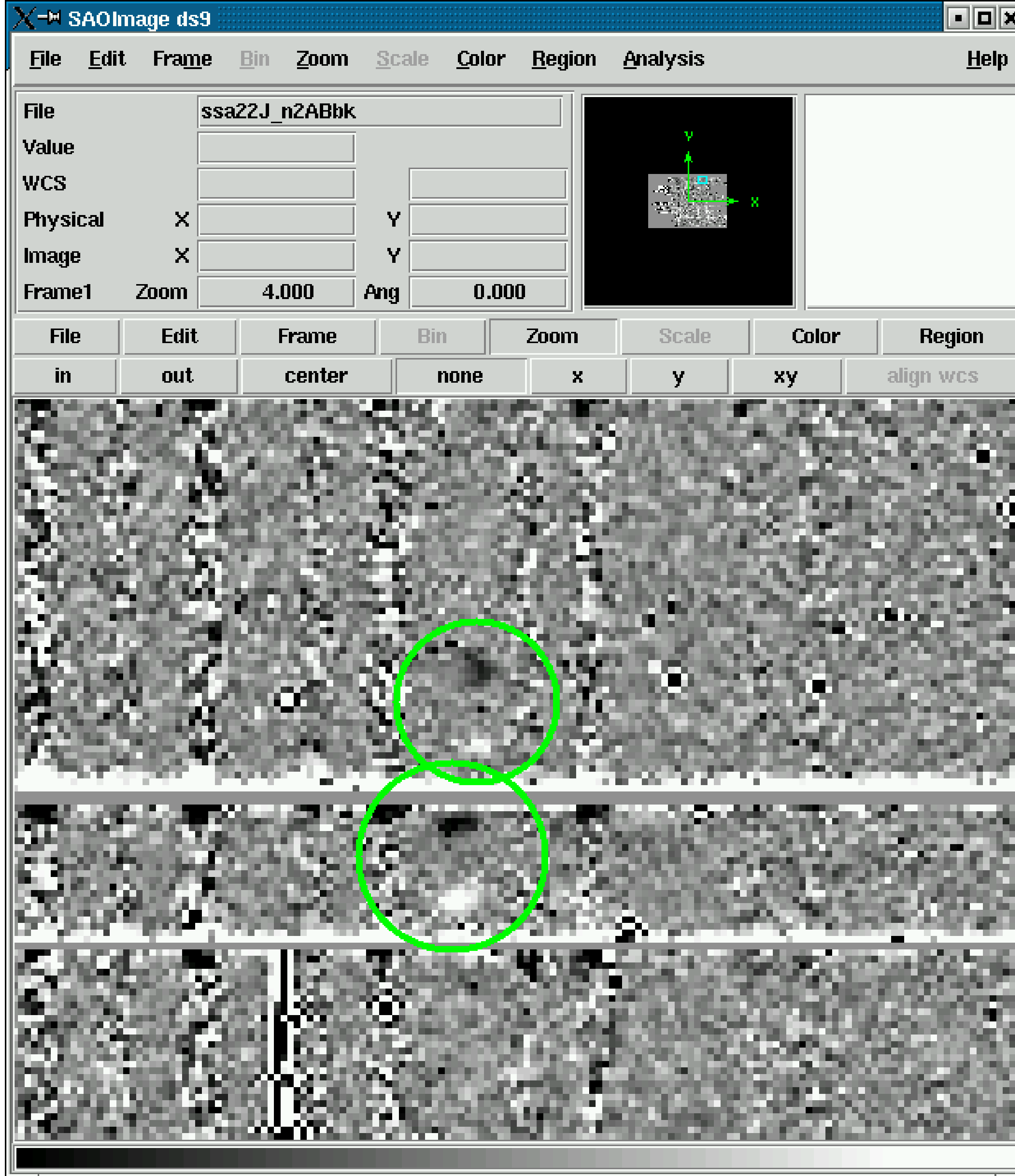
- CIRPASS and FMOS are fibre-fed, do not work well in thermal IR (wavelengths beyond 2microns, K-band)
- Rules out studying $z>1.6$ in $H\alpha$

=> Next step: cold slitmasks rather than fibres, to get K

IRIS2 on AAT

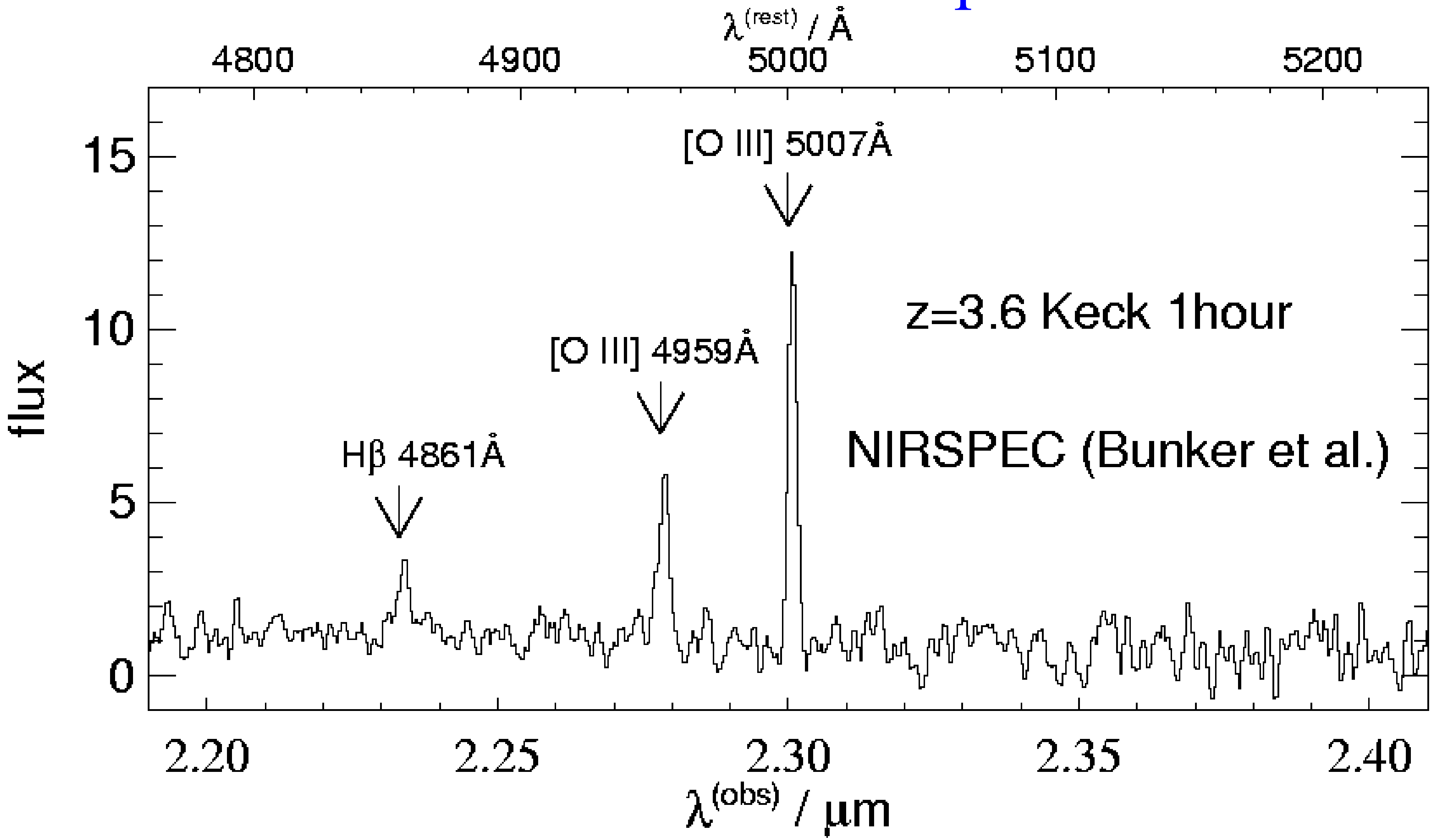


Bunker, Sharp & Doherty (in prep)



Emission lines ⇒ Star formation rates (hot, massive stars), metal lines, dust extinction;

line widths/rot curves ⇒ speeds/masses



Spectra with FMOS on 8-m Subaru (Japanese telescope in Hawaii)

Push to 2microns K-band (z~2) with IRIS2/AAT, MOIRCS/Subaru, KMOS/VLT, Keck/MOSFIRE, Gemini/FLAMINGOS-2

Evolution of Star-formation & Metallicity in the Universe at high Reshift with FMOS

evol SMURF

Ongoing Studies

- Sloan & 2dF spectra, local universe
  Low/intermediate-z UV luminosity function (GALEX)
  z~1: spectroscopic surveys, mag limited (or colour pre-selected) VVDS/VIMOS-VLT & DEEP2/DEIMOS-Keck
- Reprocessed dust emission: Spitzer/MIPS, SCUBA (SHADES)
- SEDs of galaxies from deep fields (HST, Spitzer...) - "photometric redshifts" or ground-based spectra
- Red objects (DRGs, EROs - UKIDSS)
- Rest-frame optical lines out to high-z with near-IR spectrographs (happening now: FMOS/Subaru)

Distant Galaxies...

... and How to Find Them

Search Techniques for Galaxies at High Redshift

- Motivation for studying distant objects
- Possible observational signatures of "protogalaxies"
- Searches based on line emission
- Continuum searches (broad-band imaging)
- Photometric redshifts
- The Lyman-break population

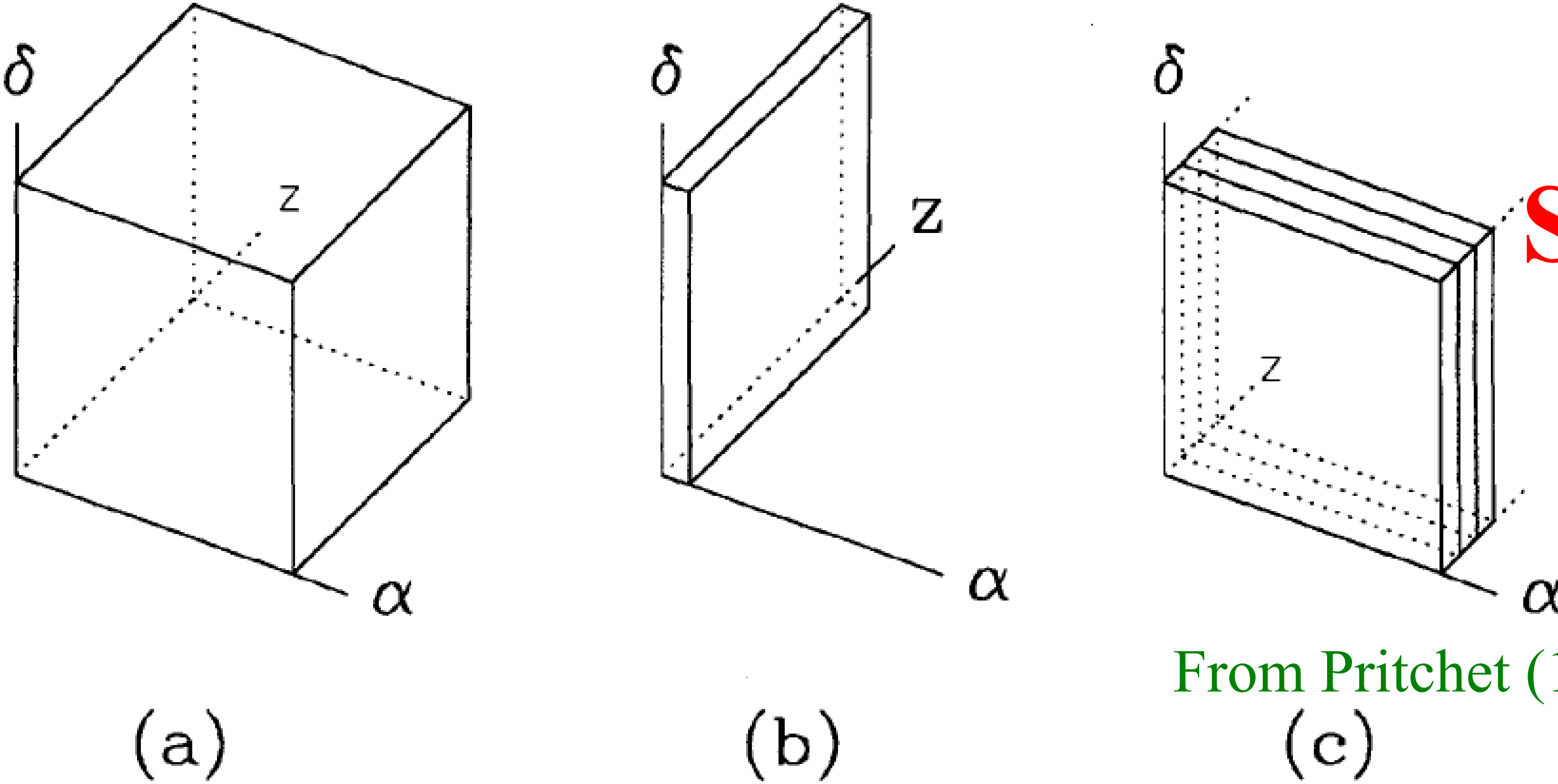
Why Look for Distant Galaxies

- Study galaxies when Universe was young
- About half stellar mass today is "old" (bulge, stellar halos...) and must have formed early (at high-redshift)
- *Primeval* or *proto-galaxies*: progenitors of present-day (normal) galaxies, in early stages of formation
- Hard to define - first major burst of star formation? Peak merging epoch? Dark matter overdensity seeding galaxy collapse? Gas cloud prior to star formation?
- Want a history of the assembly of galaxies (& large-scale structure)
- Want history of star formation and chemical enrichment
- Is there an *"epoch of galaxy formation"*?

So, how do you go about finding a distant galaxy?

How do you prove it really is distant? (high redshift)

Search Strategies



From Pritchet (1994)

Many searches based on looking for line emission from star formation - juggle depth, survey area and redshift coverage (together affect survey volume).

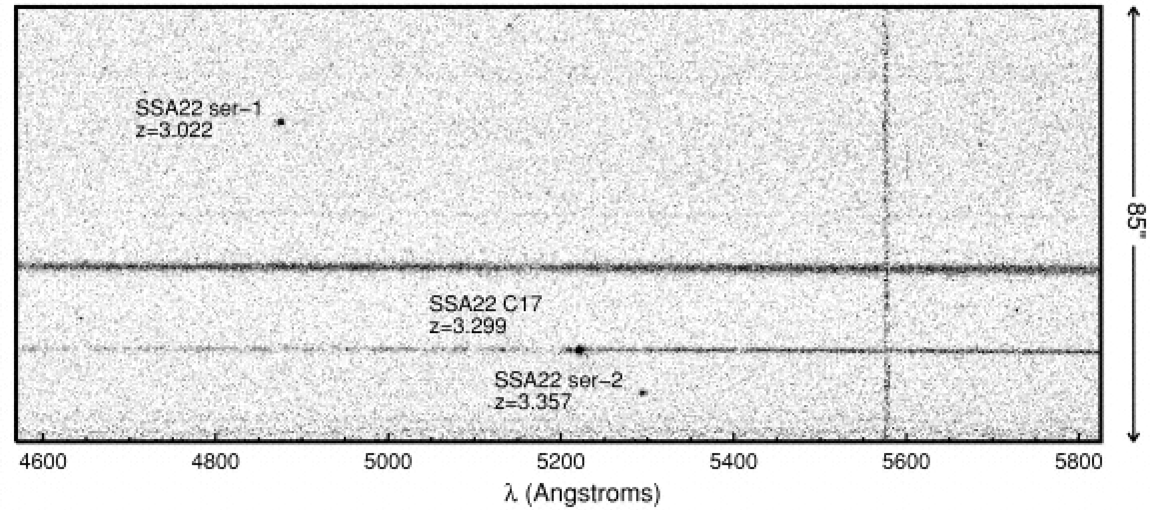
Slitless spectroscopy or broad-band imaging (a);

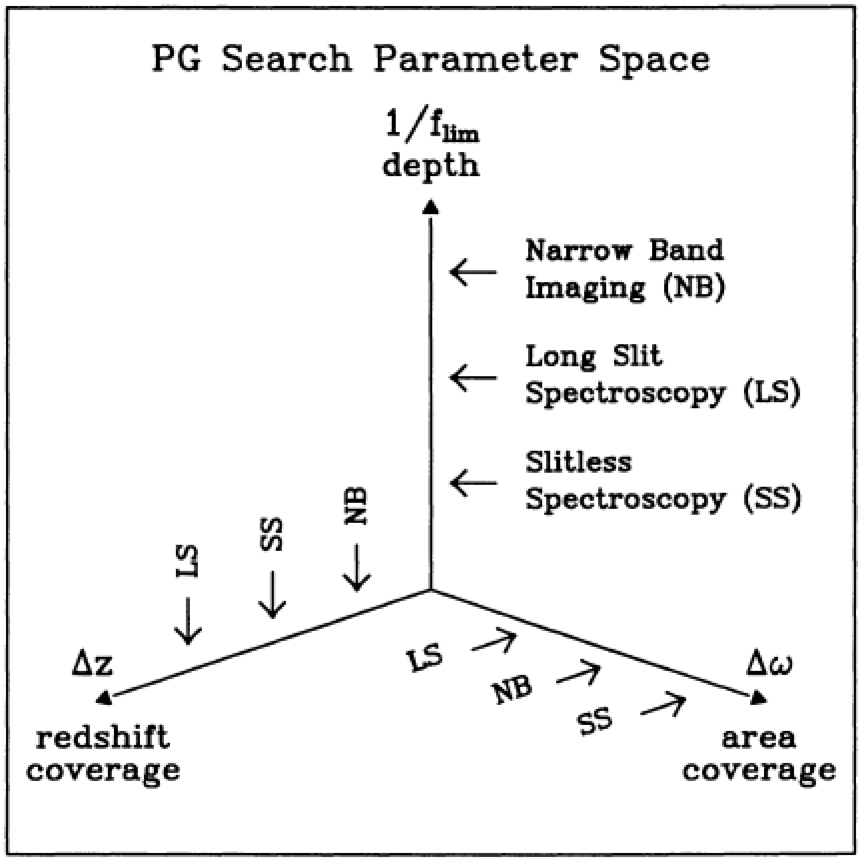
long-slit spectroscopy (b) covers ~1arcmin x 1arcsec;

narrow-band imaging (c) $\lambda/\Delta\lambda \sim 1\%$ filter (~3000km/s)

From Manning *et al.* (2000)

Survey Parameter Space

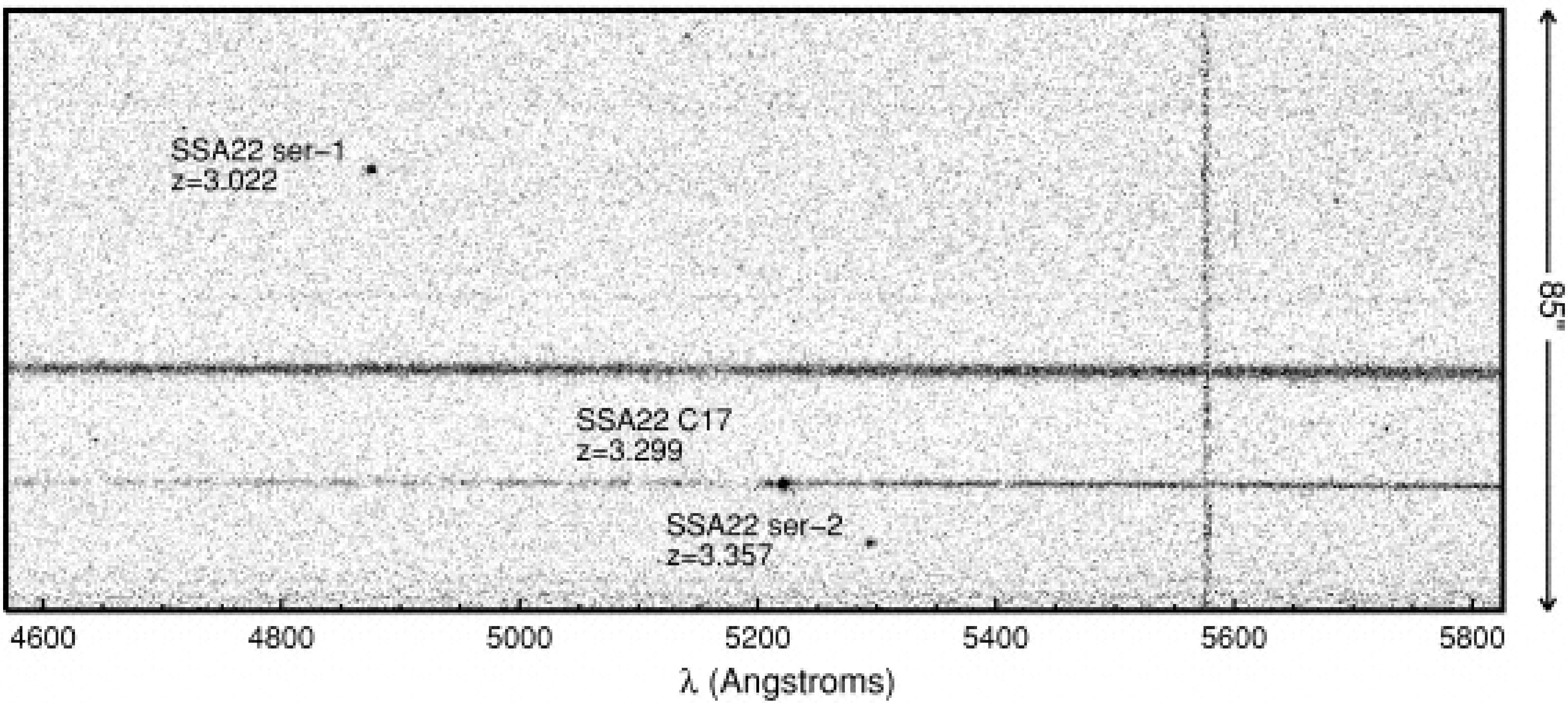




From Djorgovski (2000)

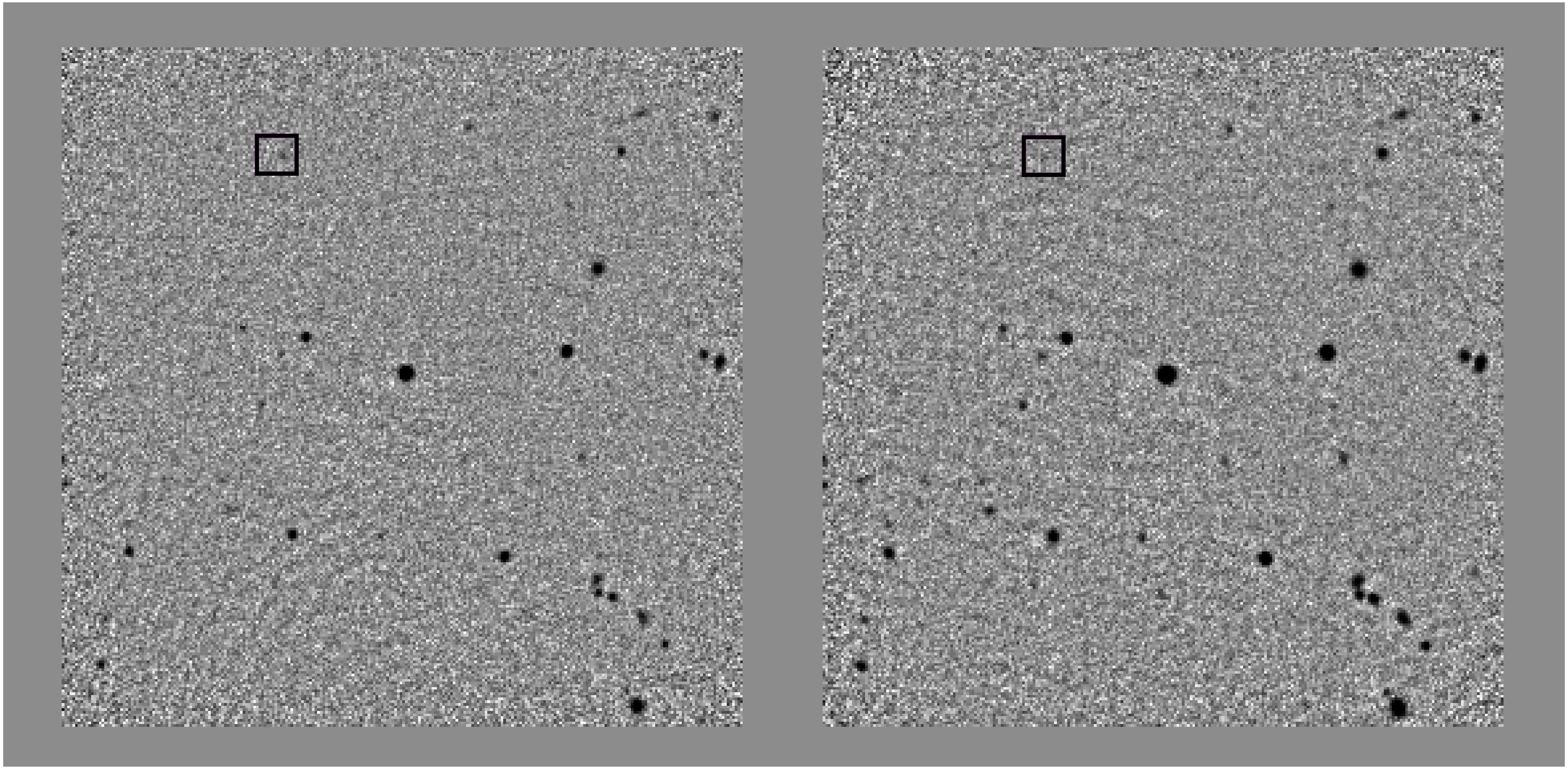
Starburst galaxies might have ~5% of their bolometric flux emerge in emission lines (concentrated into a few Å).

For line emission, look for contrast against continuum - use spectral resolution (either a narrow filter, or a spectrograph).

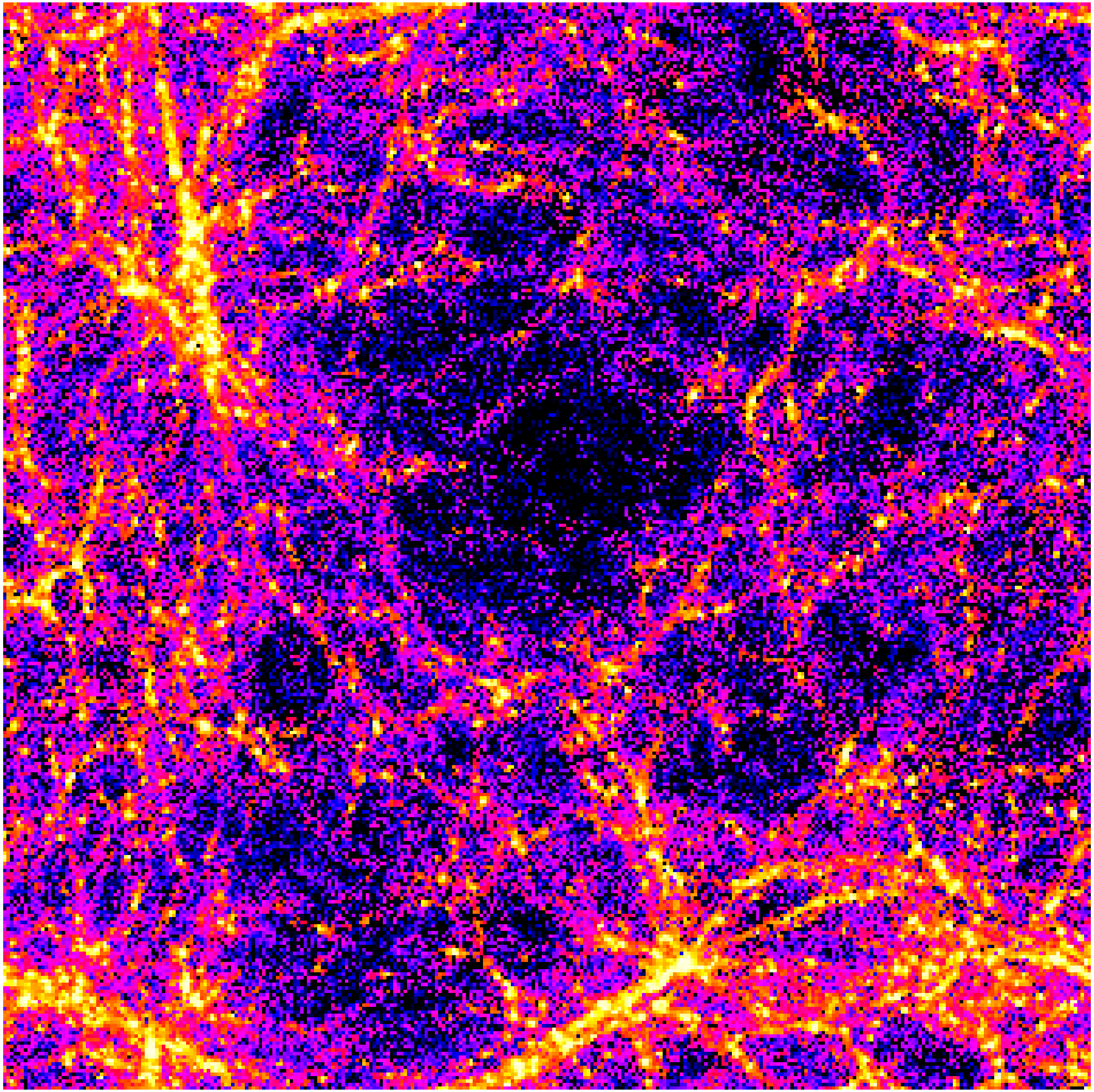


SSA22 ser−1
z=3.022
SSA22 C17
z=3.299
SSA22 ser−2
z=3.357
85"
4600
4800
5000
5200
5400
5600
5800
λ (Angstroms)

Narrow-Band : Find the z>2 Galaxy!



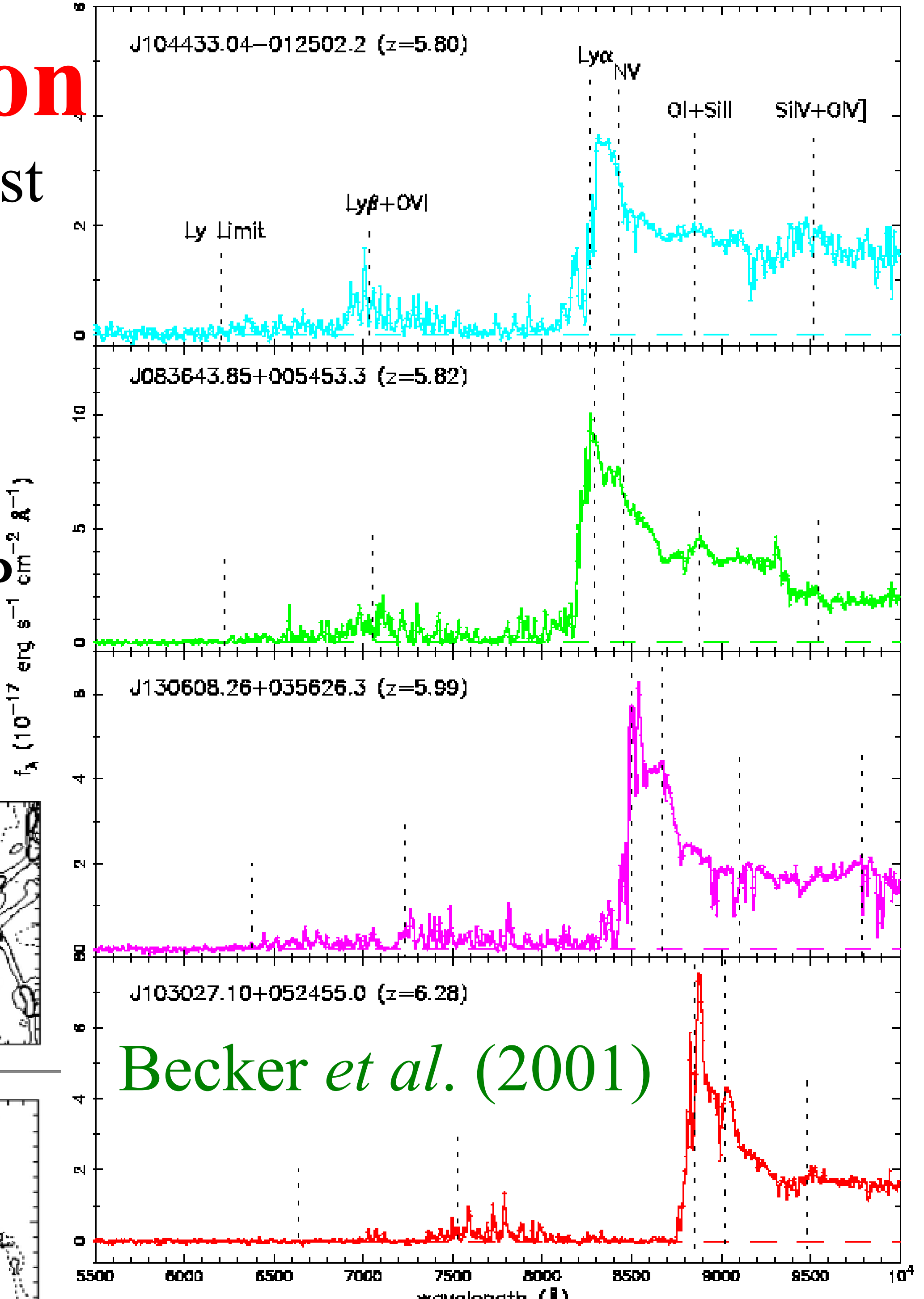
From Bunker *et al*. (1995), using a narrow-band filter (left, λ=2.177μm) to look for Hα6563Å at z=2.31. Compare with the broad-band K-image (right) to find line emission source



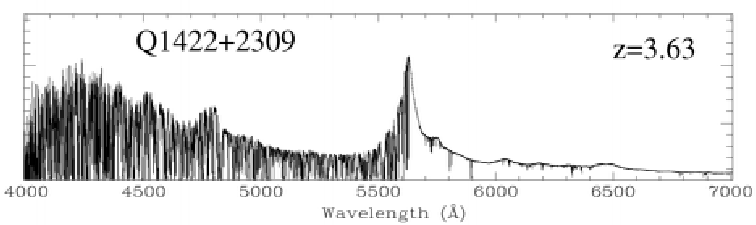
Neutral gas simulation at z~3, Theuns et al.

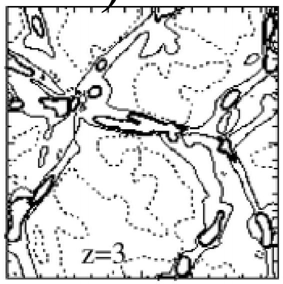
Intervening Absorption

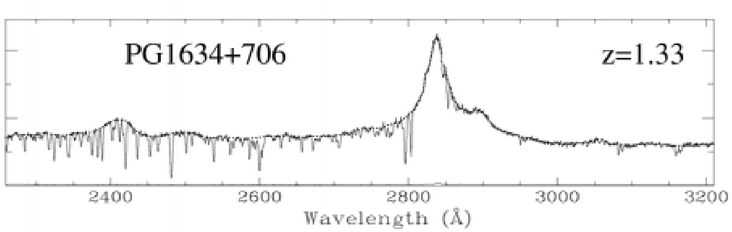
At high-redshift, the Lyman-α forest can absorb most of the flux below λ_{rf}=1216Å. Indications from *z*=6.3 SDSS QSO that Universe may be optically thick at z~6. Also WMAP CMB satellite: reionization z~10? (Kogut et al. '03, Dunkley '09)

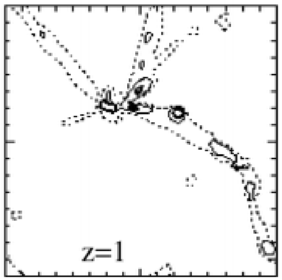


Becker *et al*. (2001)

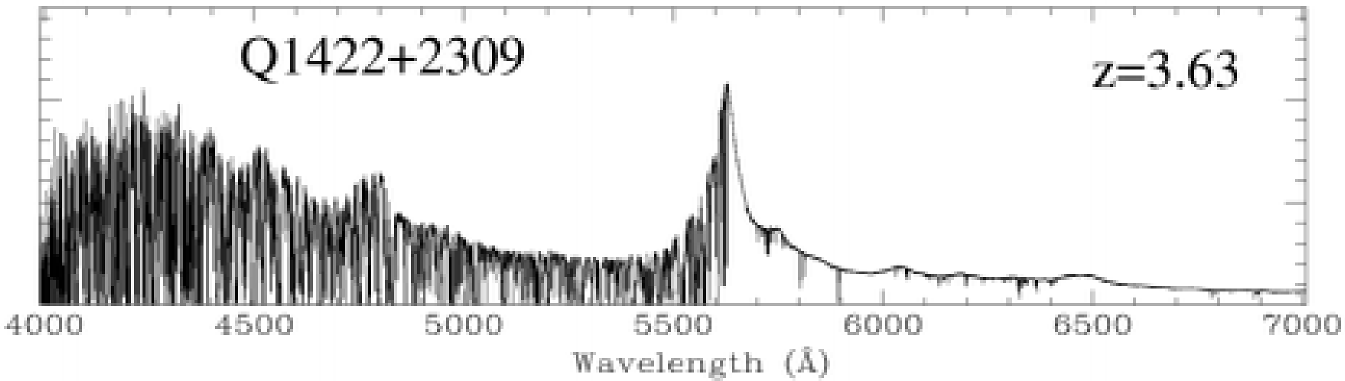


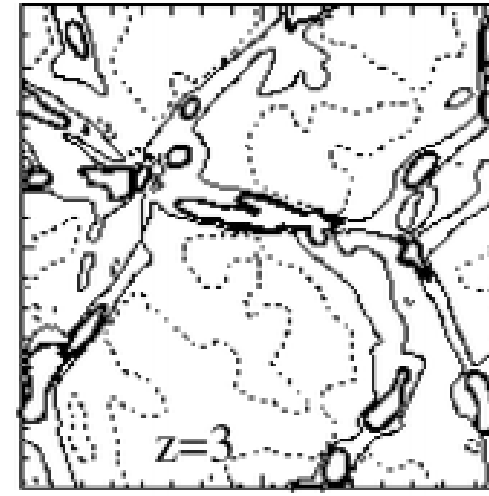


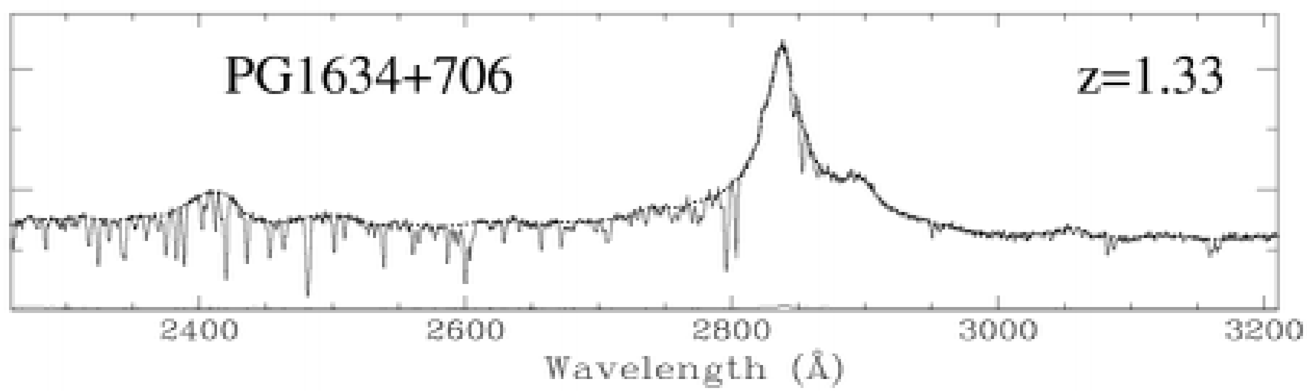


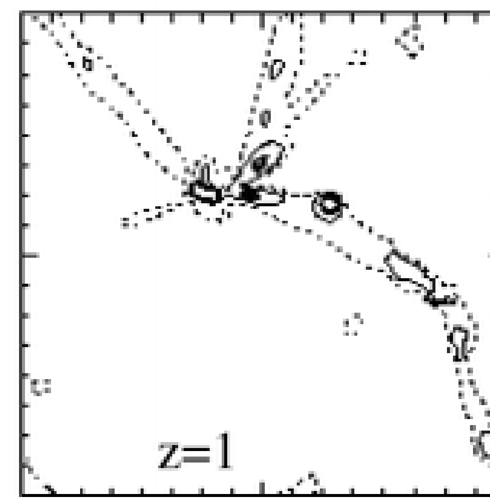


Charlton & Churchill (2000)

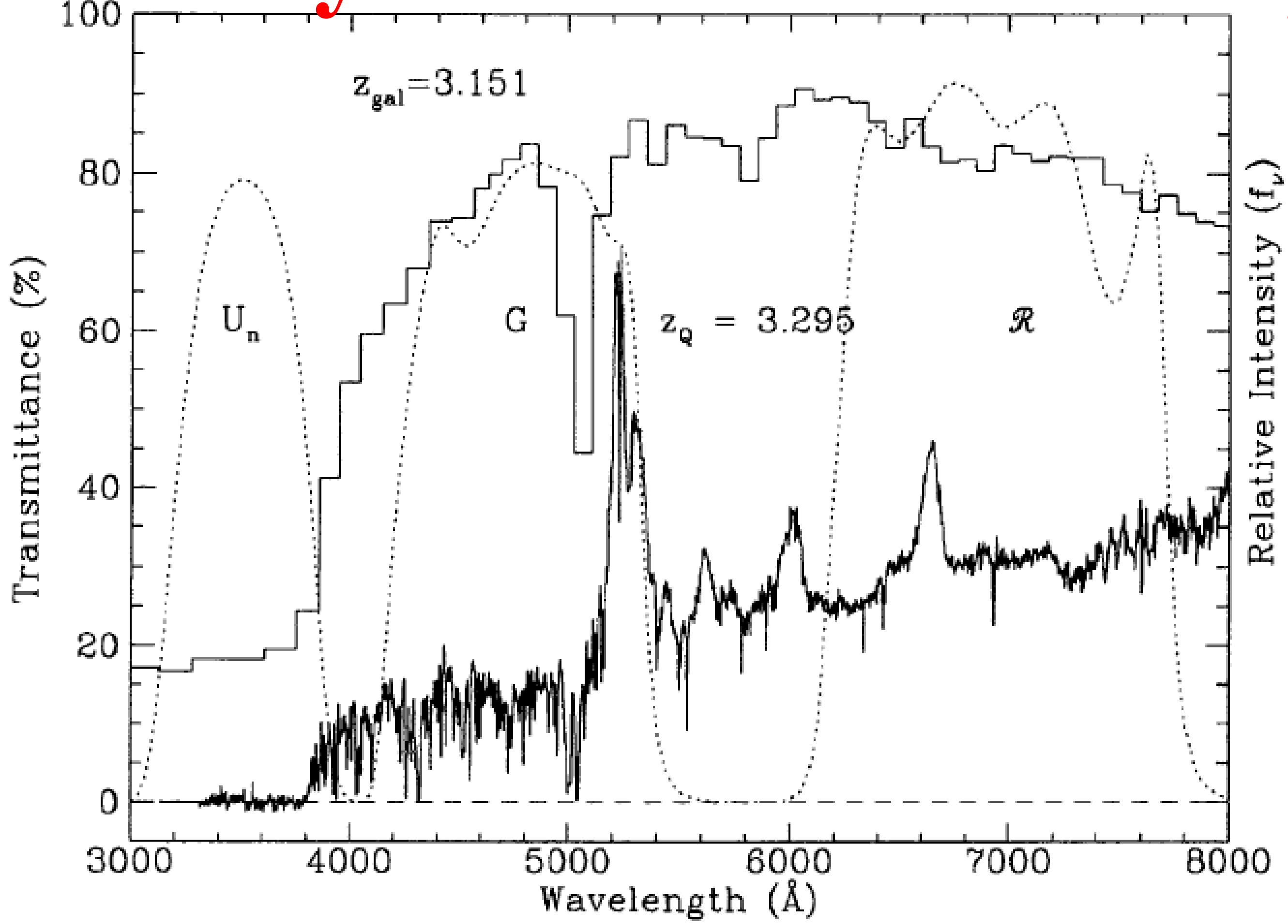

Q1422+2309
z=3.63
4000
4500
5000
5500
6000
6500
7000
Wavelength (Å)


z=3

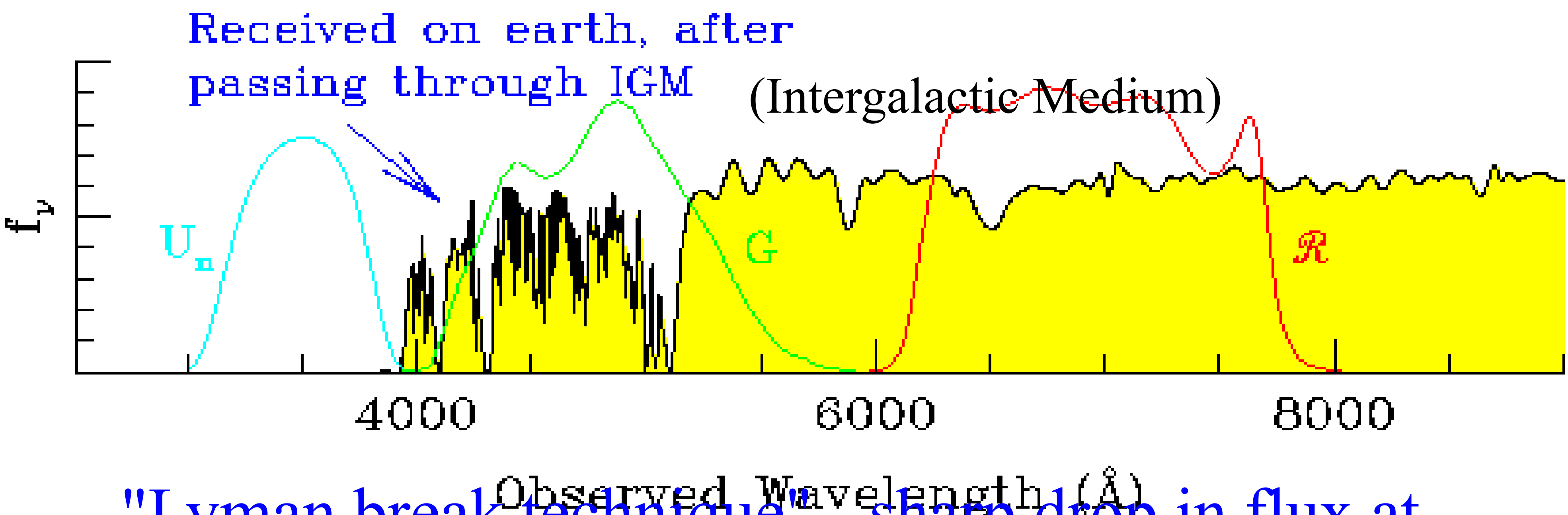

PG1634+706
z=1.33
2400
2600
2800
3000
3200
Wavelength (Å)


z=1

The Lyman Break Technique



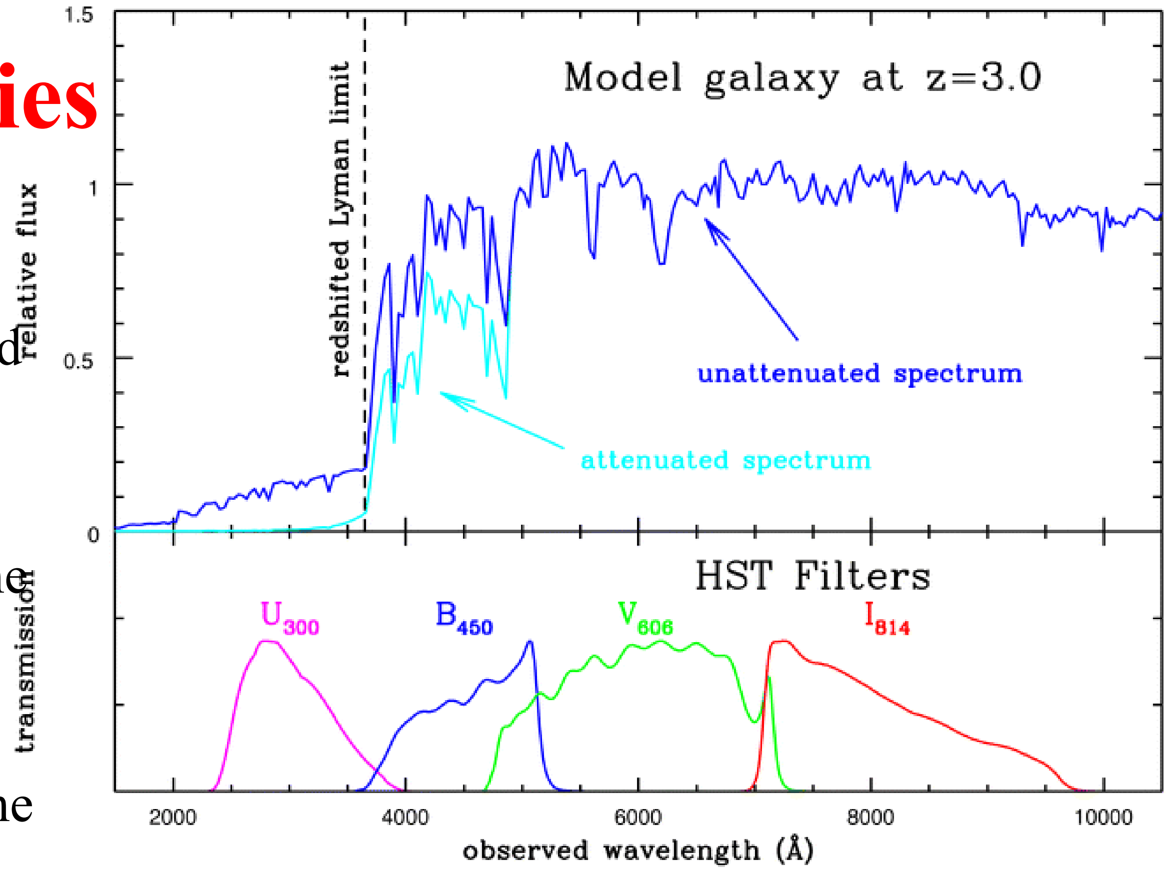
Steidel & Hamilton (1992): technique which revolutionized the field, finding first galaxies at z>3 (spectroscopically-confirmed by Steidel *et al*. 1995). Based on imaging below Lyman-break (λ_{rest}=912Å), above Lyman-α (1216Å) and with intermediate filter



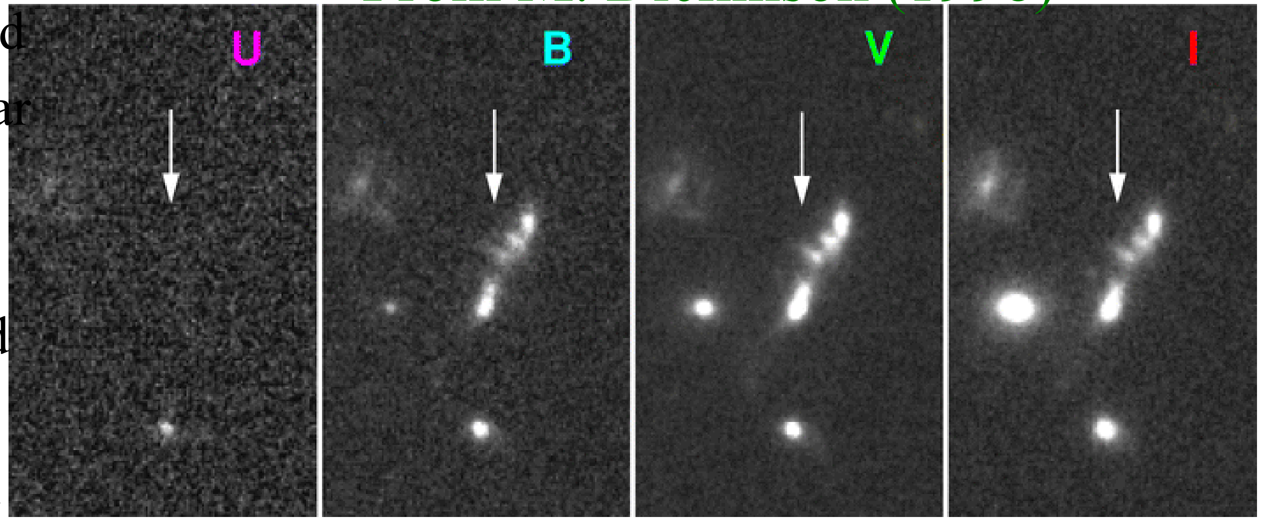
"Lyman break technique" - sharp drop in flux at wavelengths less than Ly-α - hydrogen gas between us and the distant object absorbs light at the energy of quantum electron transitions. Lower redshift, so shorter wavelength. A distant (high redshift) object should have no detectable emission at short wavelength

Lyman Break Galaxies

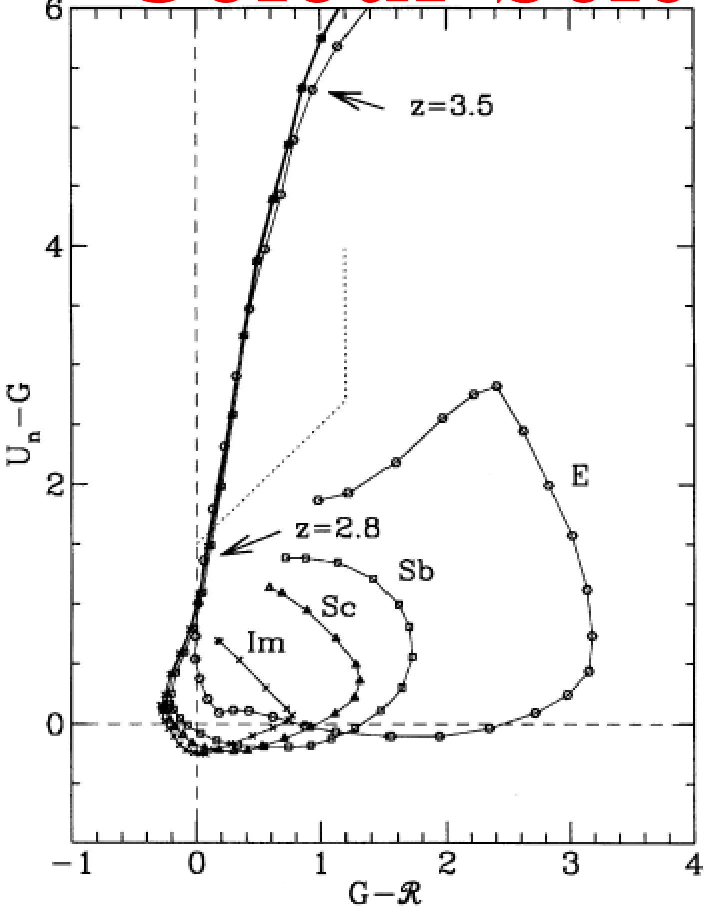
The top panel shows a population synthesis model spectrum of an actively star-forming galaxy redshifted to z=3, with and without attenuation due to the Lyα Forest. Note the sharp drop in the continuum shortward of the Lyman break, at the observed wavelength of 912 Å ×(1+z). A set of transmission curves of filter used in the imaging of the Hubble Deep Field is shown below the spectrum. One would expect that such a galaxy would appear about equally bright in the B, V and R filters, but be practically undetectable in the U filter. This is indeed observed in the actual images of a galaxy at z=2.8 found in the Hubble Deep Field images, shown in the bottom row.

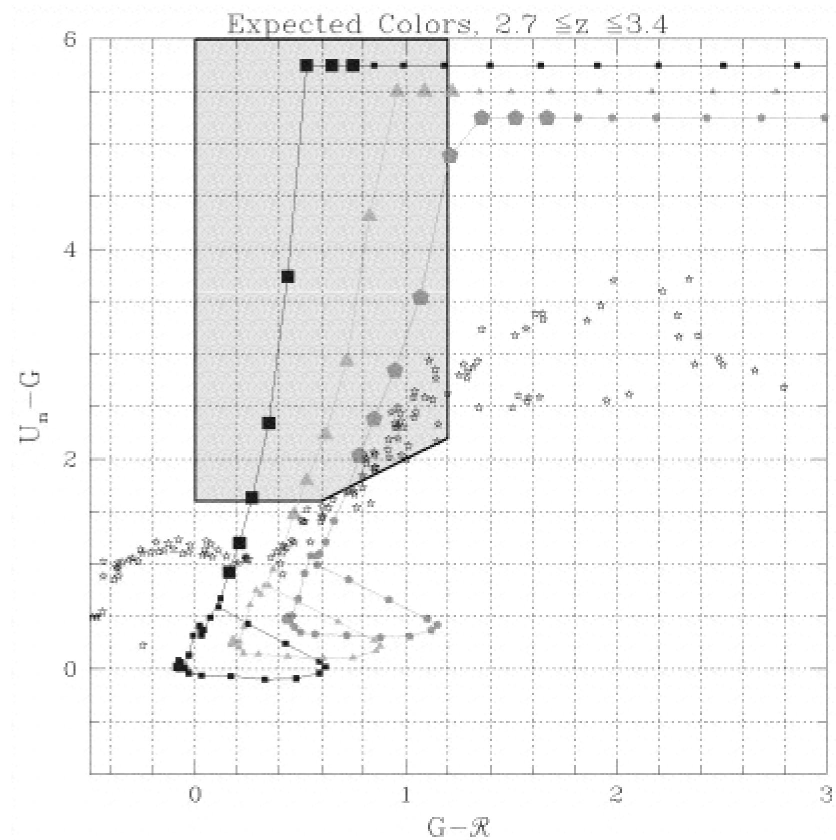


From M. Dickinson (1998)



Colour Selection of High-*z* Galaxies

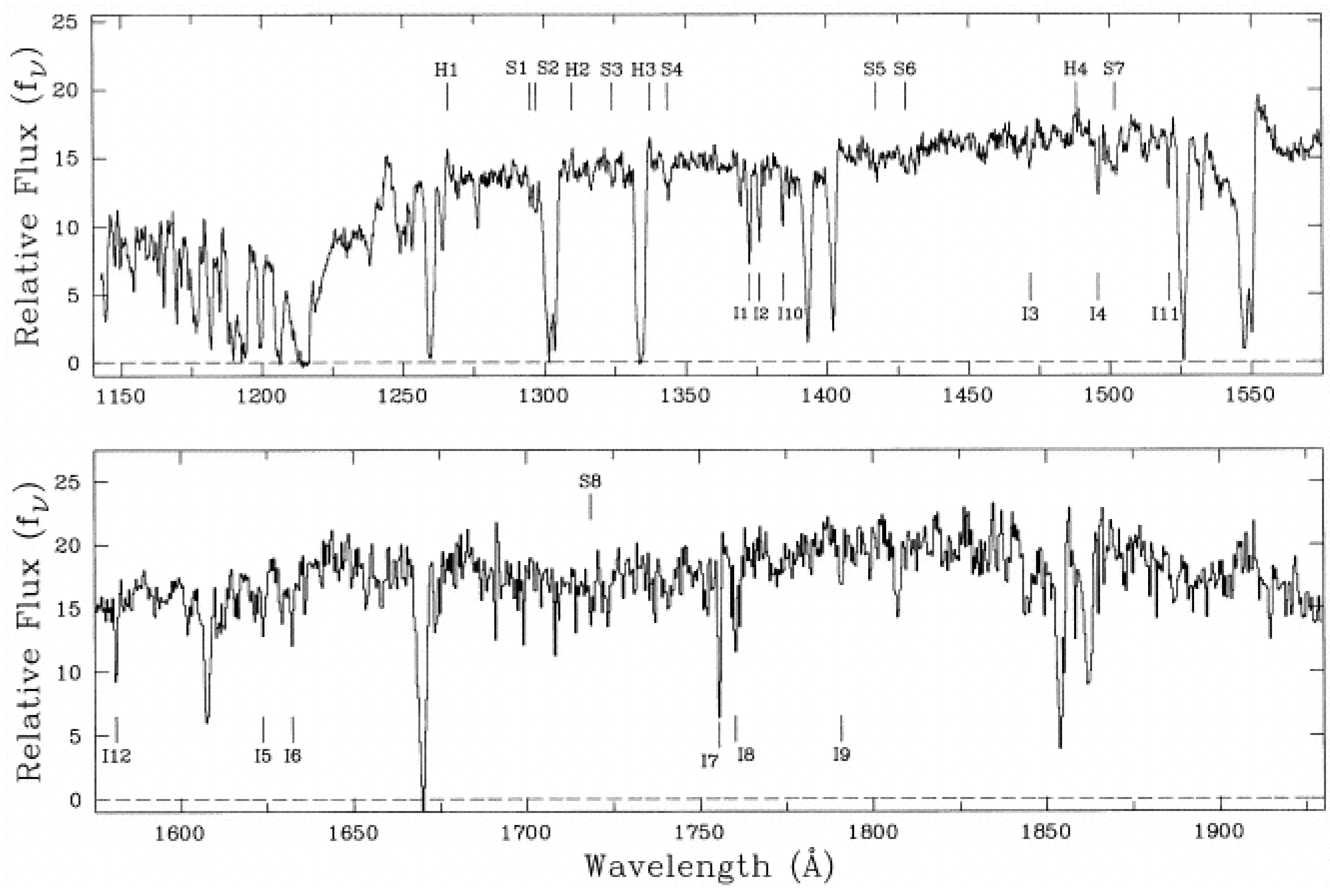




Unobscured star-forming galaxies at z~3-3.5 occupy a distinct region in colour:colour space, with few "contaminants". From Steidel, Pettini & Hamilton (1995) and Steidel *et al*. (1999).

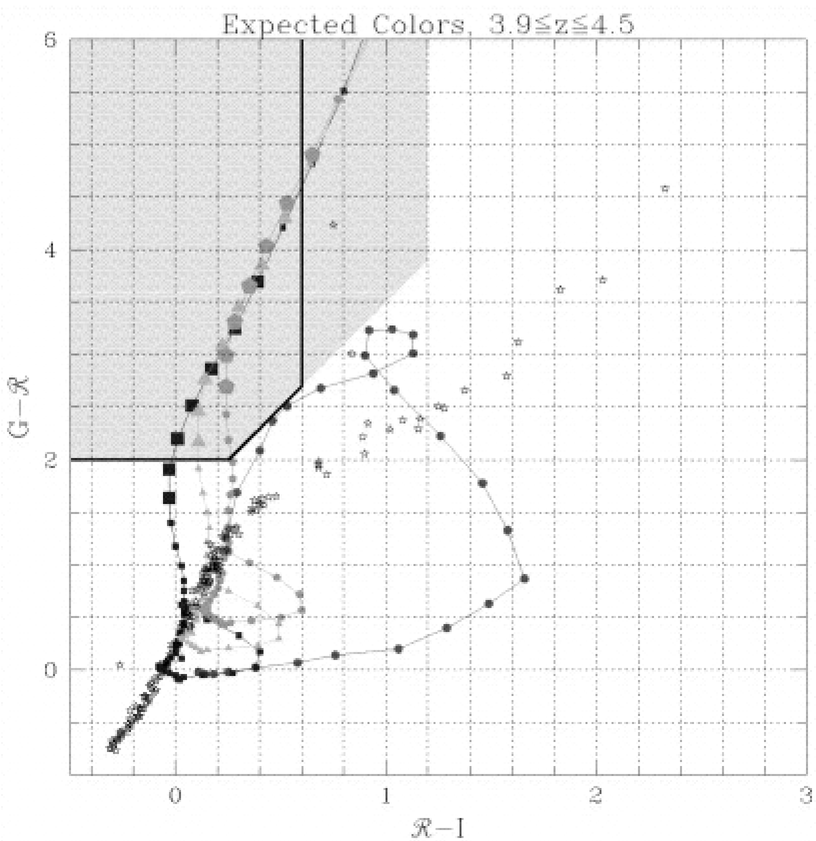
Optical Spectroscopy of z~3 Galaxies

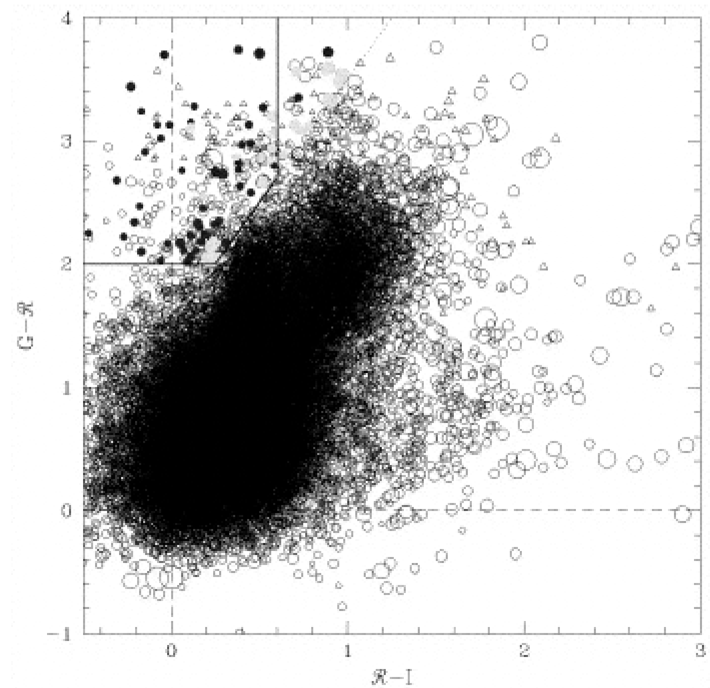
"MS1512-cB58" From Pettini *et al*. (1999) - a lensed galaxy at z=2.72



Optical spectroscopy samples the rest-frame UV - see a wealth of metal absorption features (many are ISM lines, a few are photospheric). Some have P-Cygni profiles

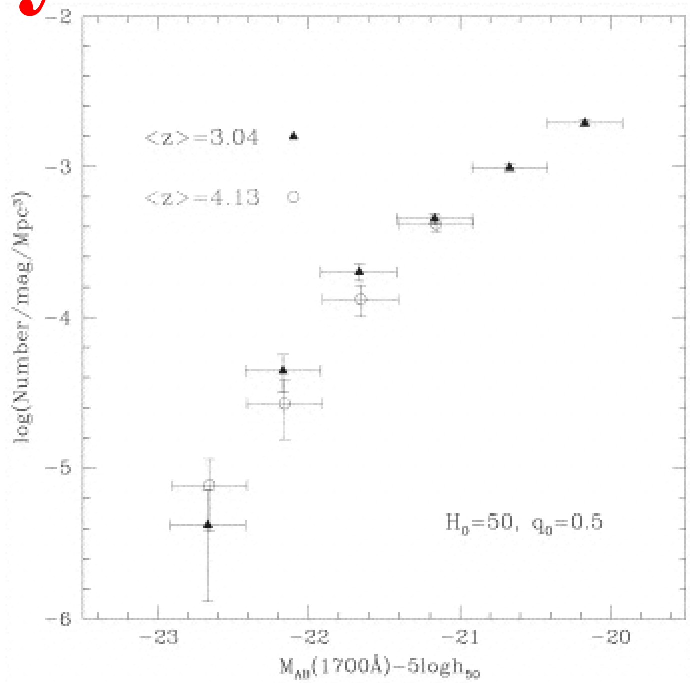
Pushing Lyman Limit Selection to z~4

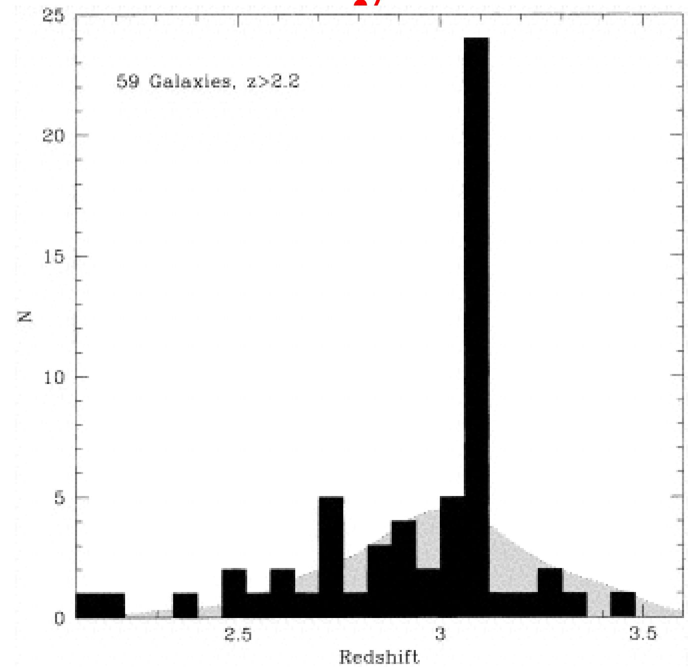




Shifting the filters to longer wavelength, you can look for "***B***-drops" at z~4-4.5 rather than "***U***-drops" at z~3-3.5 From Steidel *et al*. (1999)

Ly-Break Galaxy Luminosity Function

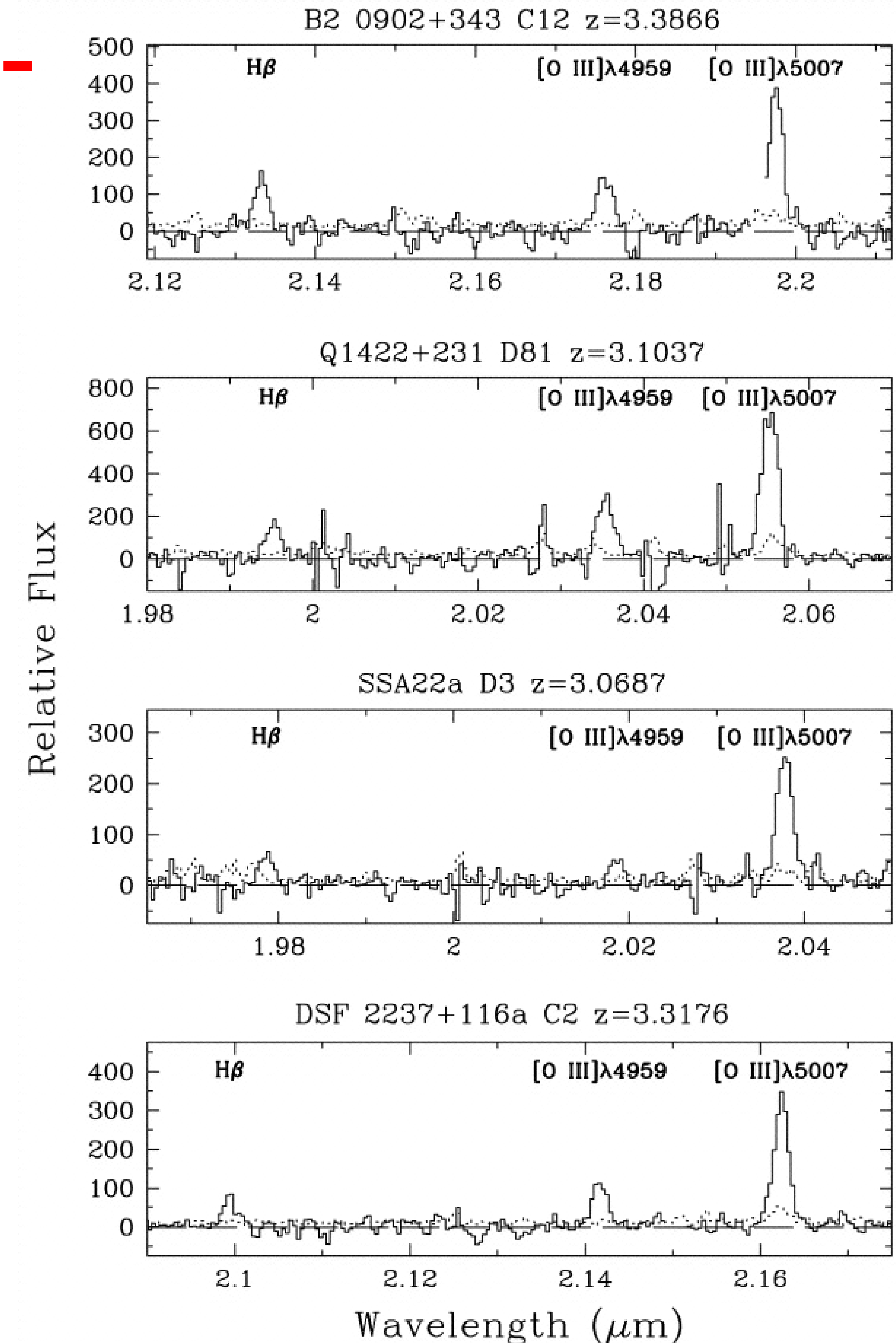




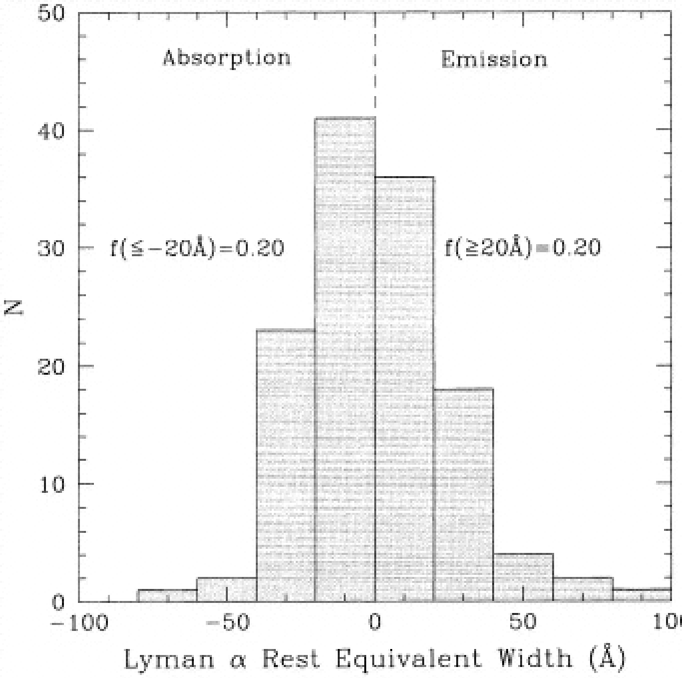
Many hundred Ly-break galaxies confirmed spectroscopically - can construct a luminosity function (N.B. based on UV continuum magnitude, related to the star formation rate rather than the mass). The redshift distribution also exhibits "spikes" (clustering over-densities). From Steidel *et al*. (1998 & 1999)

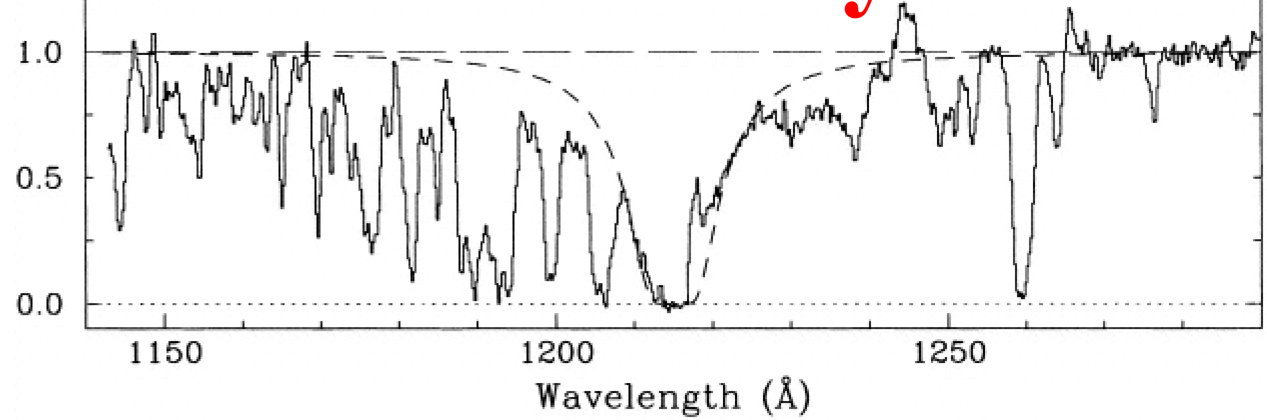
Galaxies in the Rest-Frame Optical

At z>3, must move to near-infrared to study rest-frame optical spectrum. The familiar Balmer and oxygen lines for starbursts studied with near-IR spectroscopy by Pettini *et al*. (2001) - show that dust has a modest effect on rest-UV, and that metallicities are relatively high (>1/3 solar).

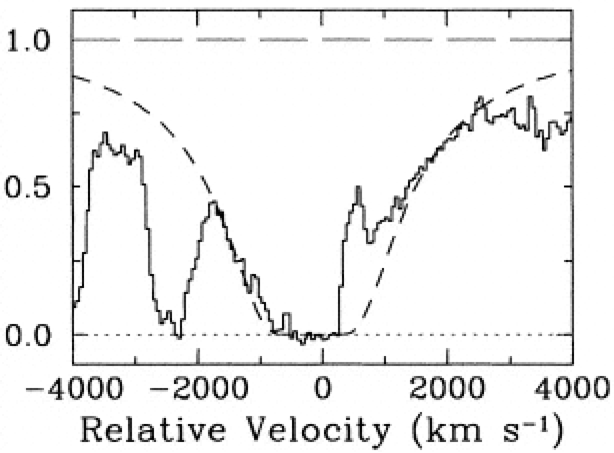


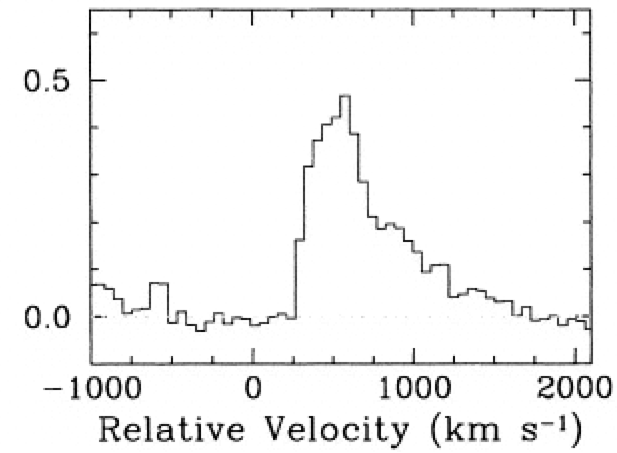
Why Did Ly-α Searches Mostly Fail?





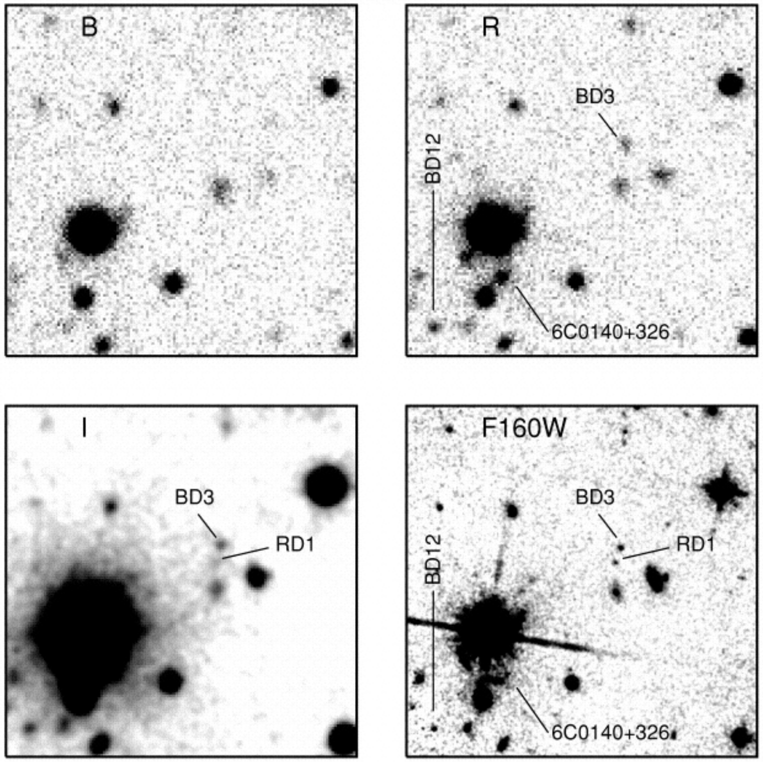
Lyman-α is easily extinguished by dust: it is in the UV, and is resonantly scattered by HI). Whether it emerges at all depends on topology, kinematics and enrichment of the ISM.

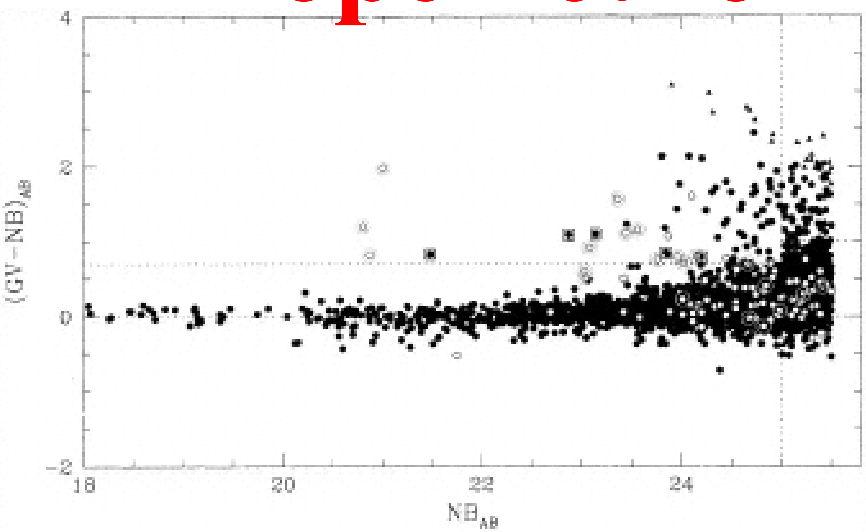




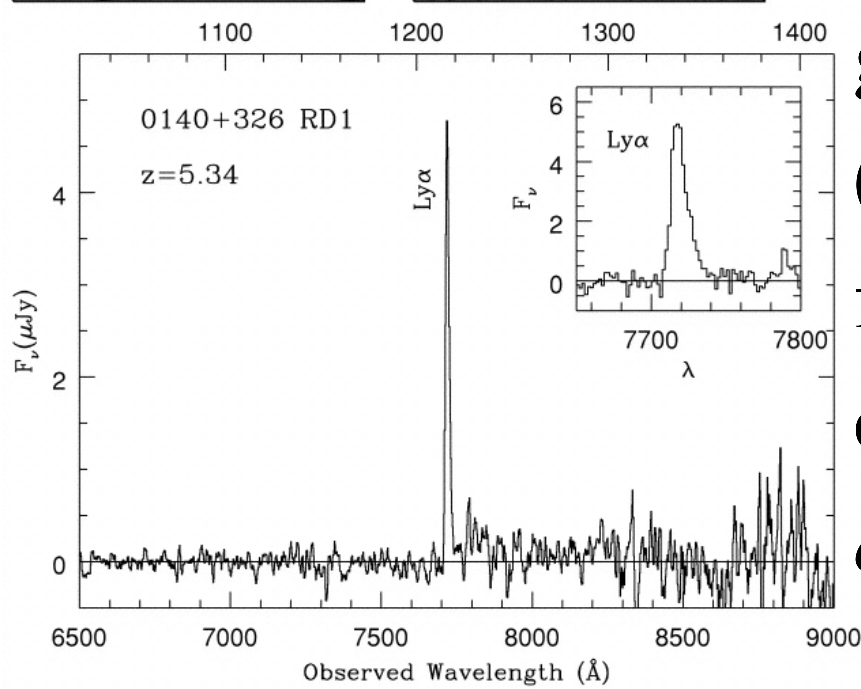
From Steidel *et al*. (1999) & Pettini *et al*. (2000)

Hope Yet for Ly-α ?

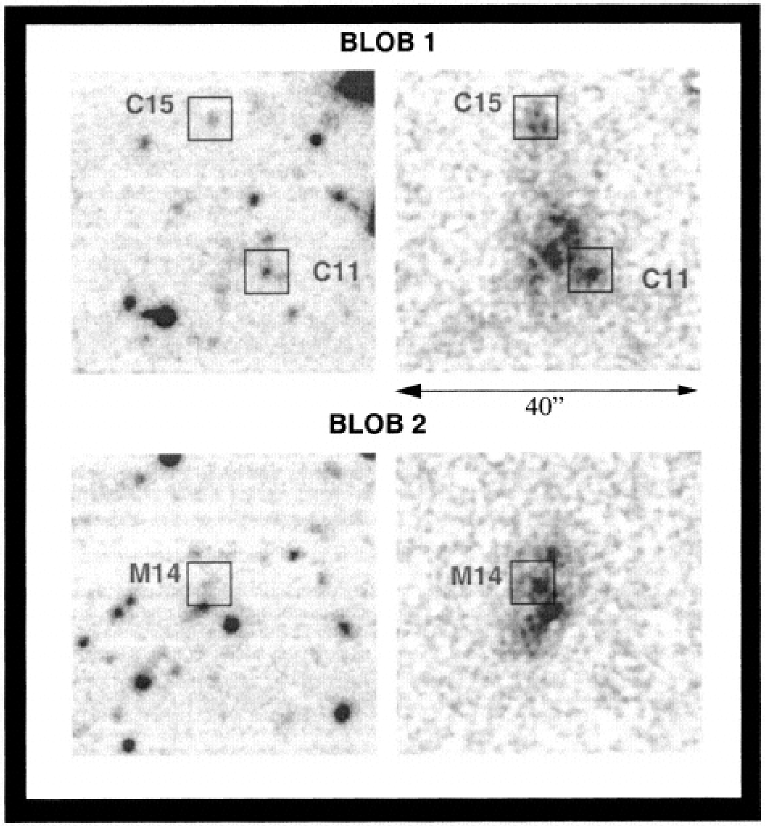


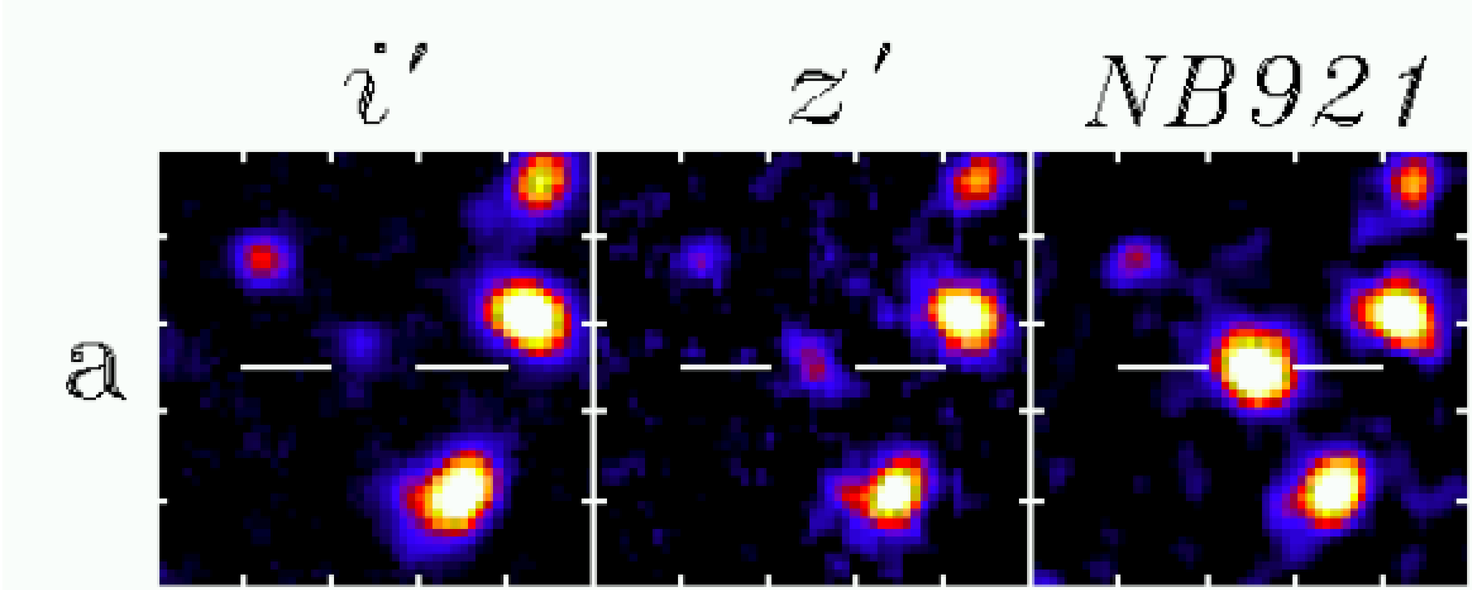


Ly-α blobs found in z=3 cluster - Steidel *et al*. (2000)



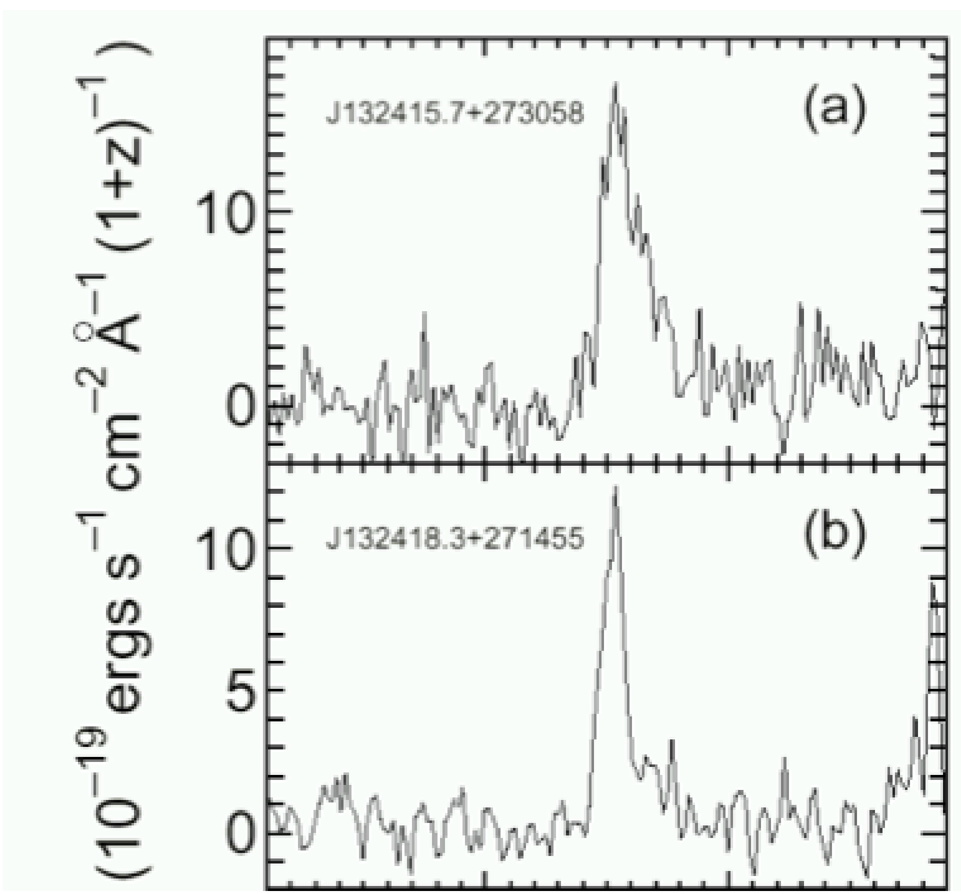
Left: first z>5 galaxy (z=5.34) found by chance: Dey *et al*. (1998)





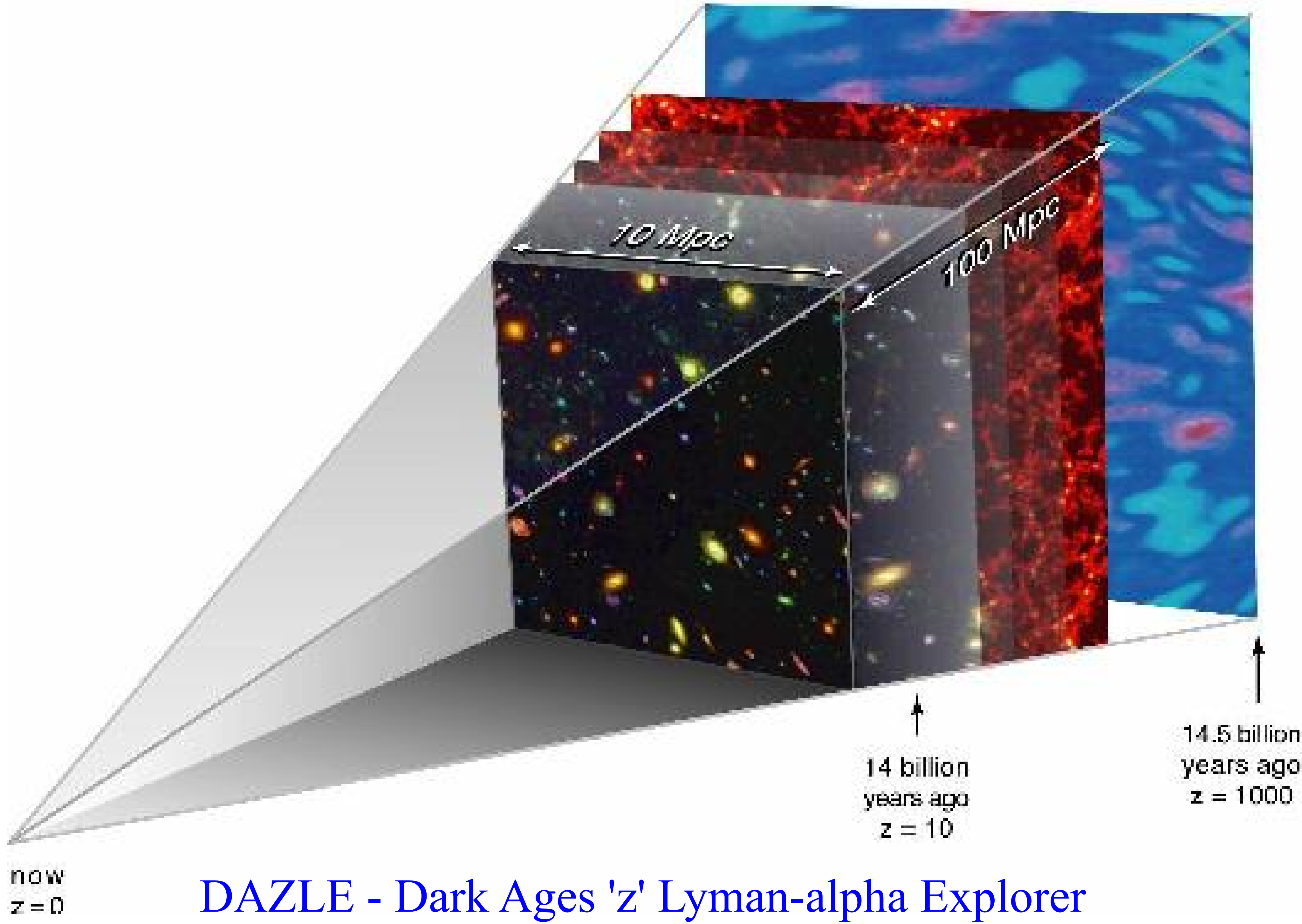
Kodaira et al. (2003) z=6.58 Ly-alpha galaxy (narrow-band)

Current narrow-band record now z=6.96



Also: Hu et al. (2002) z=6.56, lensed by Abell 370 cluster

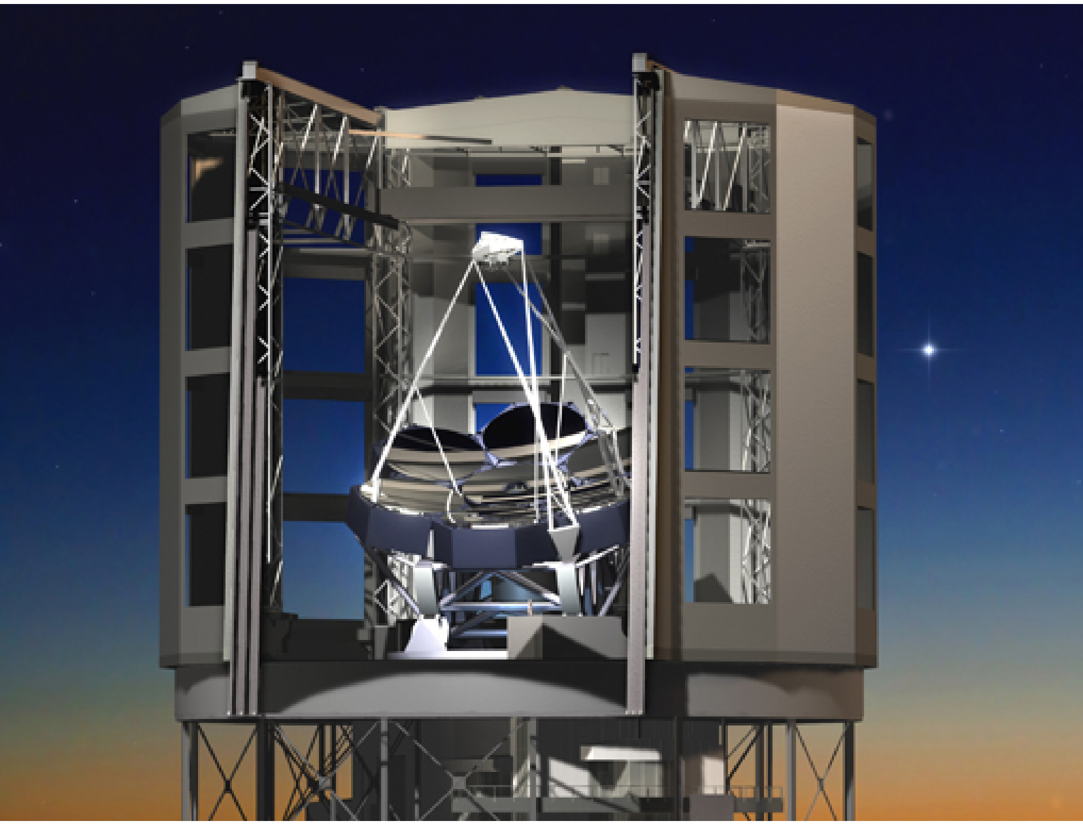
Both use narrow-band filter in low-background region between sky lines, and follow-up spectra

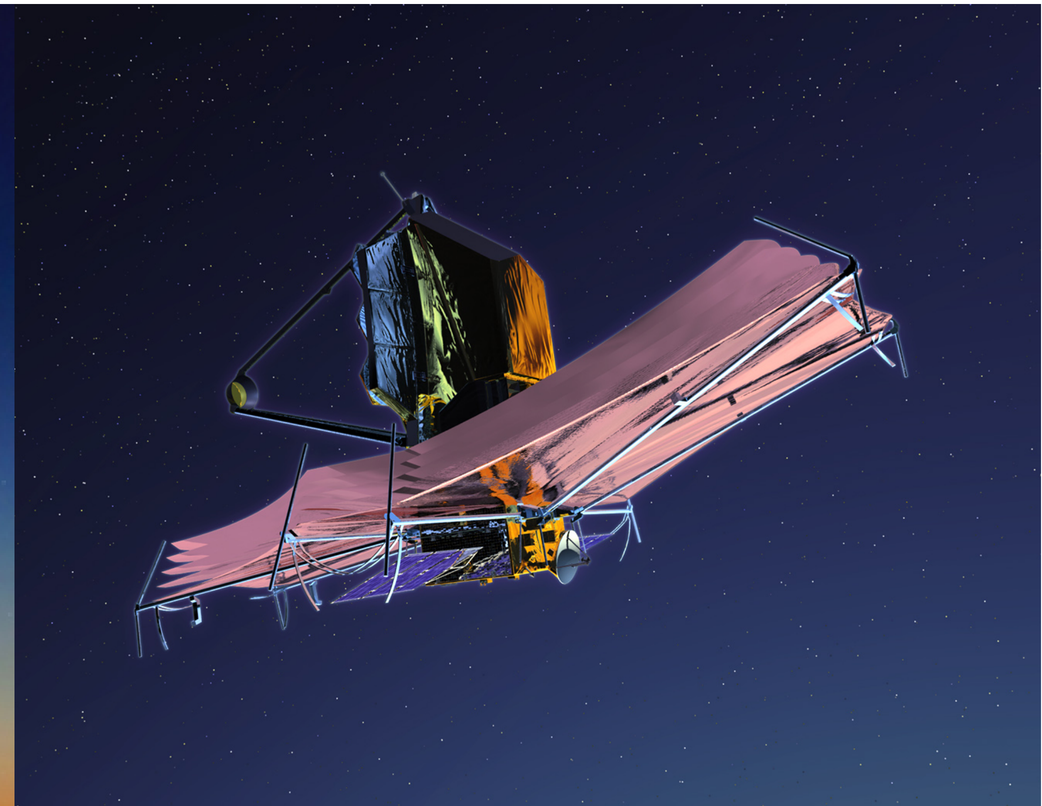


DAZLE - Dark Ages 'z' Lyman-alpha Explorer

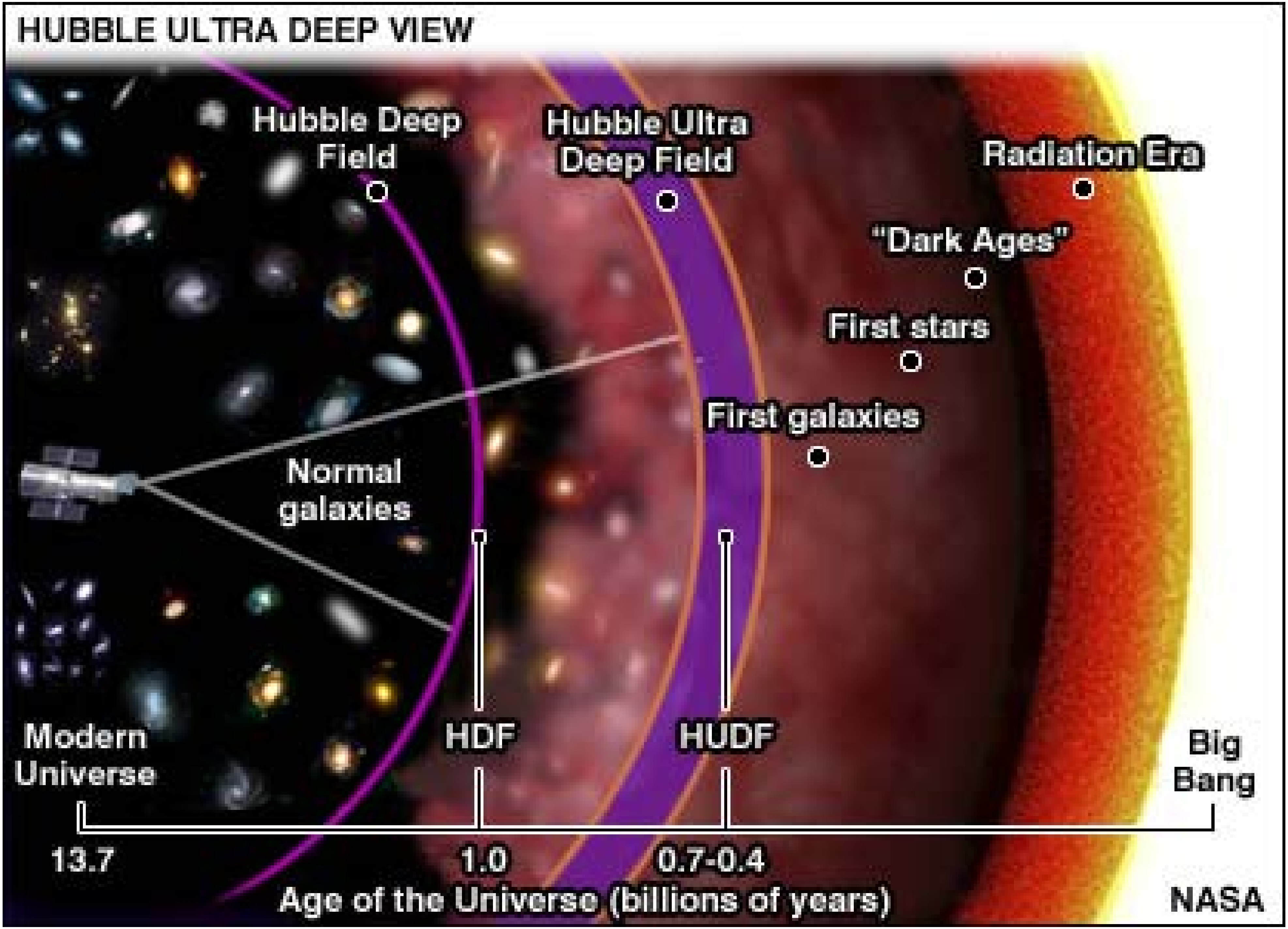
IoA - Richard McMahon, Ian Parry; AAO - Joss Bland-Hawthorne

Galaxies within the Reionization Epoch: Exploring the High-Redshift Universe with HST, Keck and (ultimately) ELTs & JWST

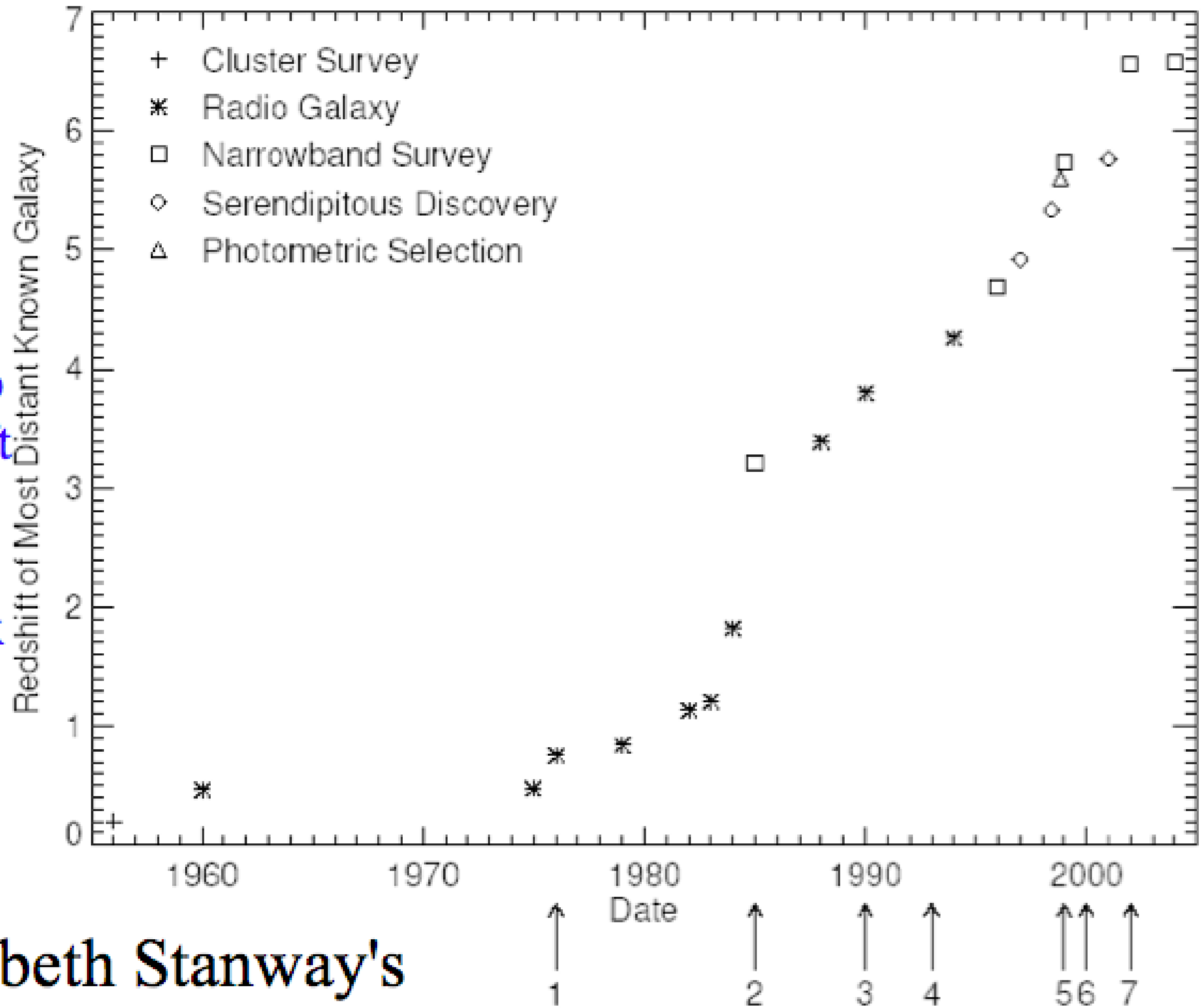




Andrew Bunker (Oxford)


HUBBLE ULTRA DEEP VIEW
Hubble Deep Field
Hubble Ultra Deep Field
Radiation Era
"Dark Ages"
First stars
First galaxies
Normal galaxies
Modern Universe
HDF
HUDF
Big Bang
13.7
1.0
0.7-0.4
Age of the Universe (billions of years)
NASA

Early strategy: most massive short-lived OB stars produce ionizing UV photons. Want to find high-redshift star forming galaxies, and measure UV flux (or recombination lines e.g. Ly-α)



From Elizabeth Stanway's thesis (2004), updated from review of Stern & Spinrad

The z~5 "Barrier"

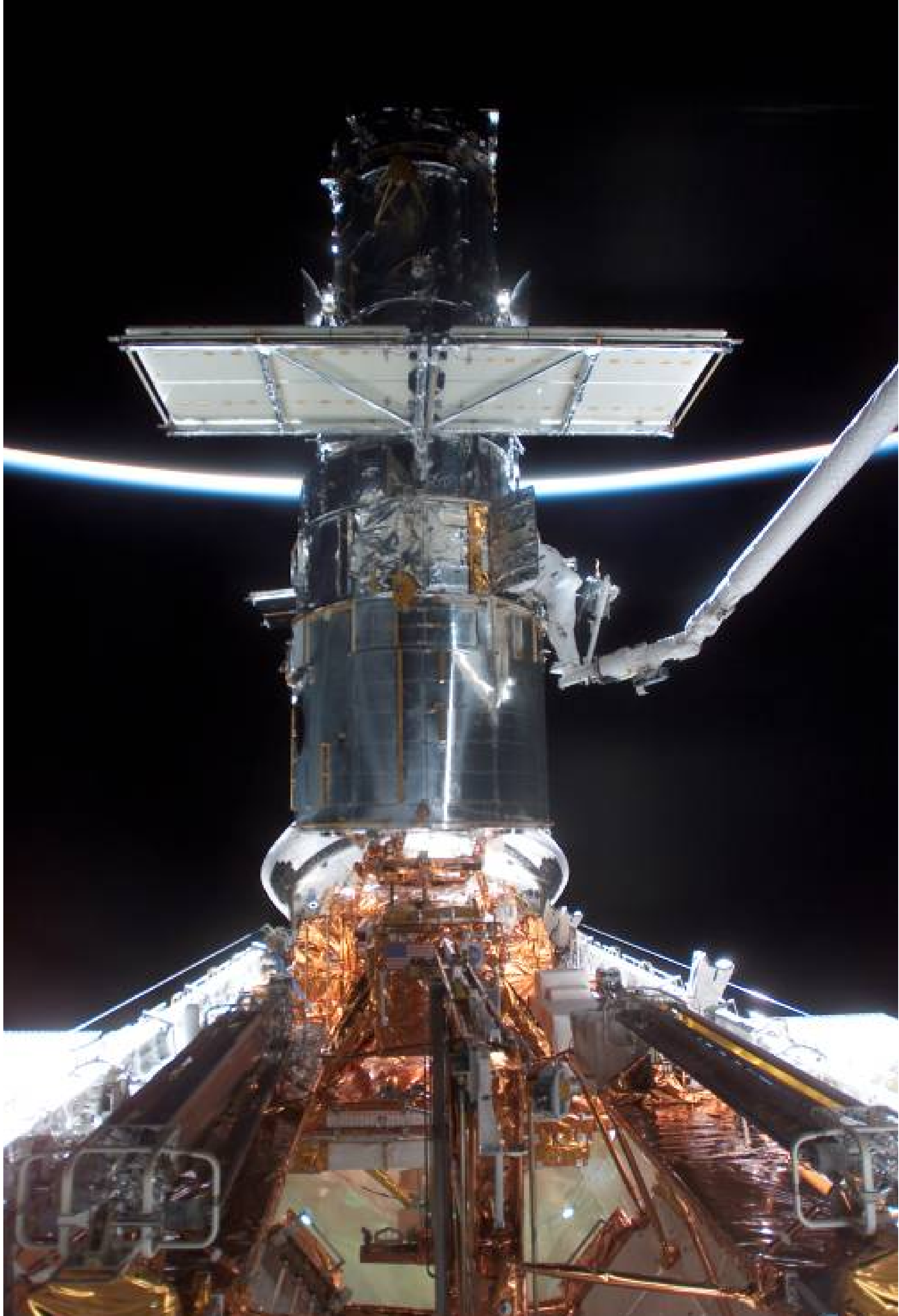
"Hubble Deep Field" (Williams et al. 1996) contained only one galaxy confirmed to be at z>5.5 (Weymann et al 1998). Small field of view and choice of filters with WFPC2.

CCDs inefficient at ~0.9-1.0 micron, which is Lyman-alpha and rest-frame UV continuum at z~6.

Advanced Camera for Surveys (ACS) on HST offered SDSS filters and good senstivity at long wavelengths

Coupled with better spectrographs on the ground (DEIMOS on Keck, and nod&shuffle technique with GMOS on Gemini to beat sky lines)

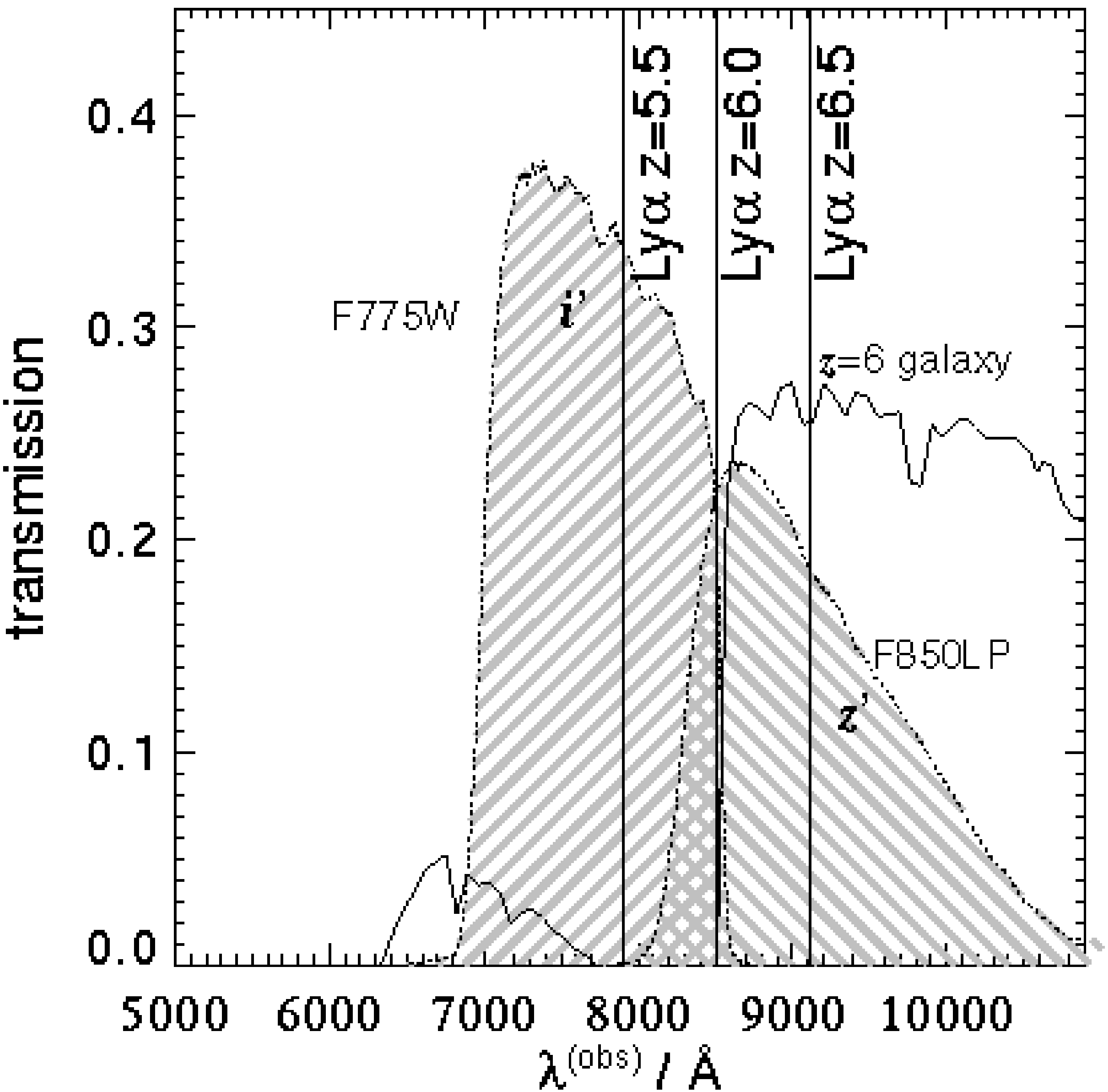

HUBBLE SPACE
TELESCOPE
9 07:06:57

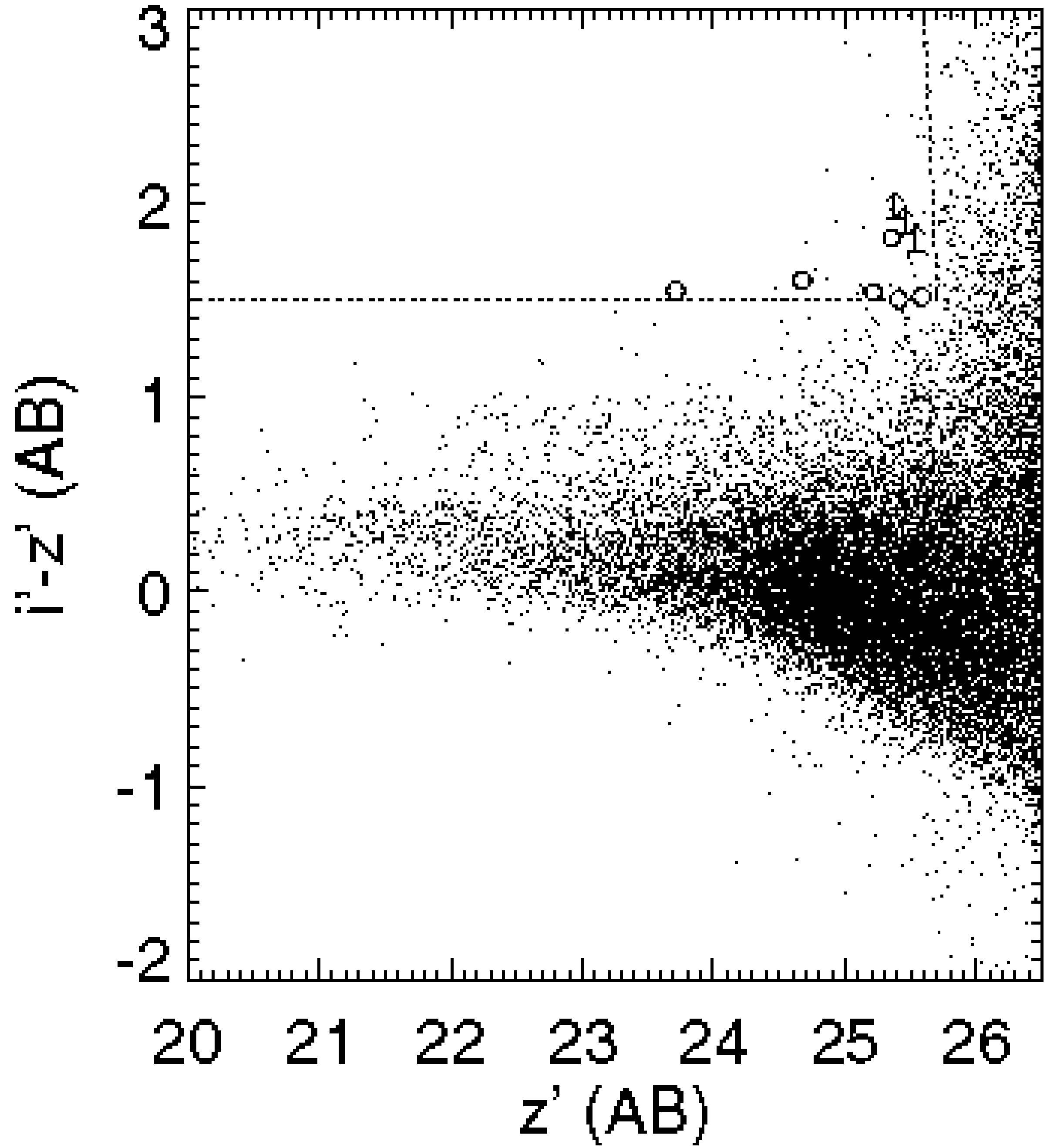



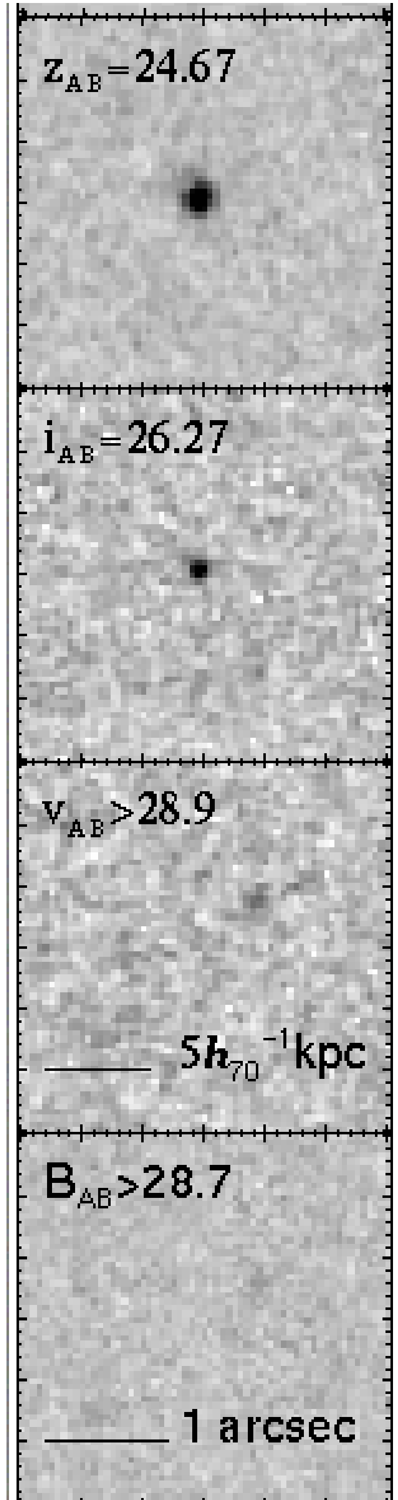
S109E5660

"Lyman break technique" - sharp drop in flux at λ below Ly-α. Steidel et al. have >1000 z~3 objects, "drop" in U-band.

Pushing to higher redshift- Finding Lyman break galaxies at z~6 : using *i*-drops.







Using HST/ACS GOODS data - CDFS & HDFN, 5 epochs B,v,i',z'