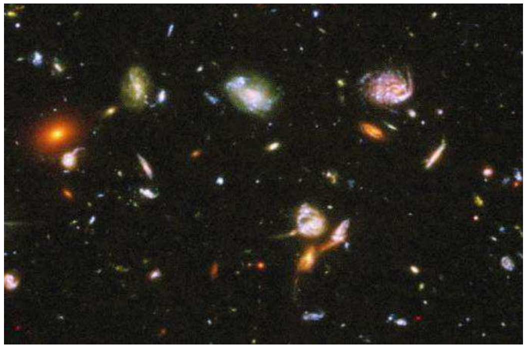


Galaxies at high redshifts

	z	t (Gyr)	t/t$_0$
	0	13.8	1.0
	0.81	6.9	0.50
	1	6.0	0.44
	2	3.4	0.25
HIGH Z ↓	5	1.2	0.09
	7	0.8	0.06
	10	0.5	0.035
	20	0.2	0.013
	30	0.1	0.007

Why search for high-z galaxies?

• Studying distant galaxies can provide important constraints on galaxy formation theory.

• One can obtain important insight into physical processes at early epoch (e.g. star formation).

• Cosmological tests.

To find a distant galaxy, one must have some idea of what one is searching for.

• Surface density

$\sim 10^{5-6}$ galaxies/$\Box^o$ or 1 galaxy per $(5'' - 10'')^2$ (assuming constant space density – no mergers).
Primeval galaxies should be very numerous.

• Redshift of galaxy formation

Two simple arguments:

– *Overlap argument*
The present-day ratio $\frac{distance\ between\ galaxies}{diameter\ of\ a\ galaxy} \sim 10^1 - 10^2$.

Distance between galaxies in expanding Universe changes as $\propto \frac{1}{1+z}$.
Hence at $z \approx 10 - 100$ galaxies must overlap
(assuming constant physical diameters of galaxies).

– *Density argument*
According to spherical collapse model (e.g. Gunn & Gott 1972), self-gravitating, virialized dark halos form when their mean density exceeds ≈200 times the background at formation:

$$\langle \rho \rangle > 200\,\rho_{cr} = 200\,\rho_{cr}^{0}\,(1+z)^3.$$

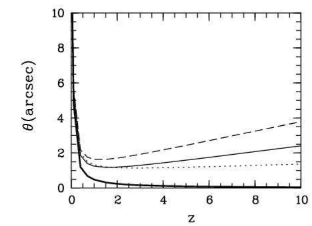
MW: $r = 8$ kpc, $V = 200$ km/s → $\langle \rho \rangle = 10^{-23}$ g/cm^3.
Therefore, $z(MW) \sim 15$

$z \sim 10 - 20$ – epoch of galaxies formation ($\sim 200 - 500$ mln. years)

└Expected properties of high-z galaxies

• **Angular sizes**
If the observable protogalaxy phase were the end product of the monolitic collapse of a massive cloud of gas, then the bulk of its star formation might occur in a small region kiloparsecs in size (1 kpc $\approx 0.''15$ at $z = 5$).
On the other hand, some models of galaxy formation predict that young galaxies will be lumpy in structure and extended in size, primarily due to the fact that in these models galaxy formation is a hierachical process. Such an object would have a size of perhaps $\sim 5'' - 20''$ ($\sim 10 - 100$ kpc).

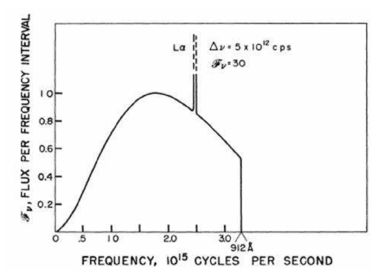
One can resolve galaxy-size object at ANY redshift
(10 kpc vs. z)



└Expected properties of high-z galaxies

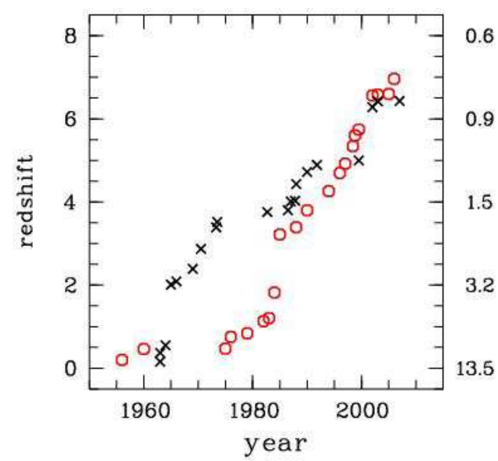
• **Luminosities**
Partridge & Peebles (1967):
"galaxies should go through a phase of high luminosity in early stages of their evolution. The estimated luminosity for a galaxy resembling our own is $\sim 3 \times 10^{46}$ ergs/sec, roughly 700 times higher than the present luminosity."
($M_B \sim -27^m$ and $M \sim 24^m - 25^m$)

• **Spectrum**
Partridge & Peebles (1967):
up to $\sim (5-10)\%$ of the bolometric luminosity may be emitted in Lyα (W(Lyα) $\sim 10{-}100$Å), rendering the line potentially detectable out to the highest redshifts.



└Expected properties of high-z galaxies

The highest redshift objects
(circles – galaxies, crosses – QSOs)



- Cosmological dimming (Tolmen effect)

How does surface brightness depend on distance in a Euclidean static universe?..

In the expanding Universe

$$I_{obs} = \frac{I_{true}}{(1+z)^4}.$$

$$z = 1 \qquad \Delta\mu \approx 3.^m0,$$
$$z = 5 \qquad \Delta\mu \approx 8.^m0.$$

- K-correction

The expansion of the Universe provides astronomers with the benefit that recession velocities can be translated into radial distances. It also presents the challenge that sources observed at different redshifts are sampled, by any particular instrument, at different rest-frame frequencies.
The transformations between observed and rest-frame broad-band photometric measurements involve terms known as "K-corrections".

$$K(z) = -2.5\lg\left[\frac{L(\nu_1)}{L(\nu_0)}(1+z)\right],$$

$L(\nu_1)$ – intrinsic luminosity of the source, $L(\nu_0)$ – observed luminosity (monochromatic correction in mag.).

To determine the appropriate K-corrections, the spectral energy distribution of the galaxy has to be convolved with the transmission function of the filter in the reast-frame and at redshift of the galaxy. This is a simple calculation once *the spectrum of the object is known.*

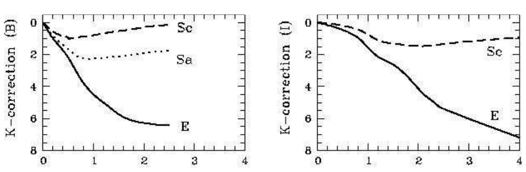
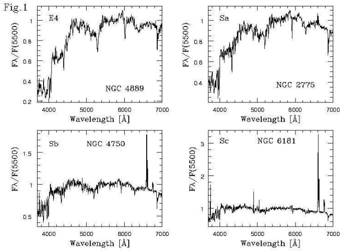
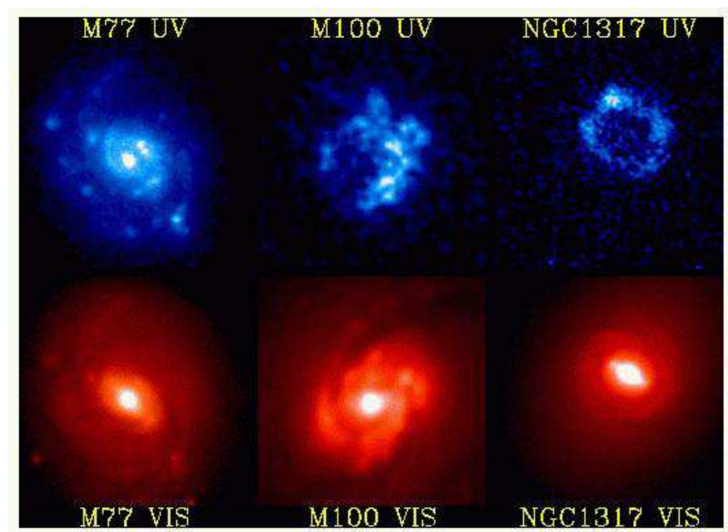


Fig.1



Morphological K-correction:



- Strong Lyα emission

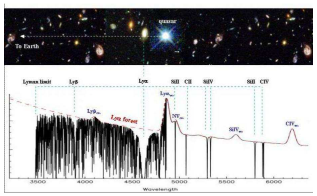
Population synthesis models predict that a young, dust free, star-forming galaxy should show strong Lyα emission with intrinsic W(Lyα)$\approx 100\,$Å.
The flux in the Lyα line is expected to be disrectly proportional to the SFR and 3-6% of the bolometric luminosity are emitted in Lyα.

- An intrinsically flat spectrum for $\lambda > 912\,$Å

Population synthesis models prediction: flat spectral energy distribution between the Lyman-limit and the Balmer-limit (3646Å). This is due to UV-radiation from hot, short-lived ($< 10^8$ yr) massive stars.

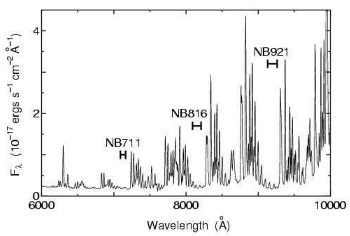
- A pronounced drop of the SED at the Lyman limit, e.g. a complete absence of flux at wavelength below the Lyman limit ($\lambda < 912\,$Å)

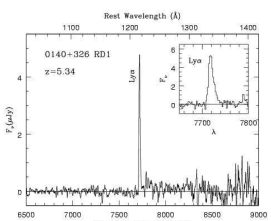
– The feature forms in the stellar atmosphere of massive stars as a result of the hydrogen ionization edge and is quite pronounced, with a discontinuity of an order of magnitude.
– The break in the stellar continuum is made more pronounced by the photoelectric absorption of the interstellar HI gas, which is abundant in young galaxies, and also by intervening HI gas.
– The UV spectrum of sources at high z is also subject to additional opacity owing to line blanketing by the intervening Lyα forest that dims the continuum between 912 Å and 1216 Å by an amount that depends on z.



- **Search for objects with prominent emission lines with narrow-band filters.**

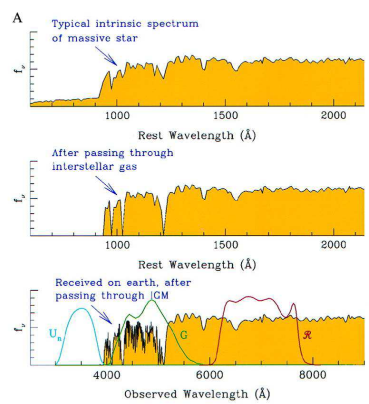
This requires the detection of emission line objects at a wavelength at which the redshifted lines (Lyα, Hα etc.) are expected. One uses narrow band imaging with a spectral resolution of a few handred to several thousand km/s.
Subsequent spectroscopic observations are necessary to establish weather the detected emission line is in fact the high redshift line one was searching for.

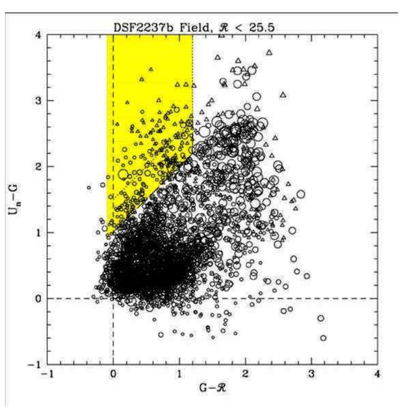




Ly emitters (LAEs)

- **Search for objects with unusual broad-band colors.**



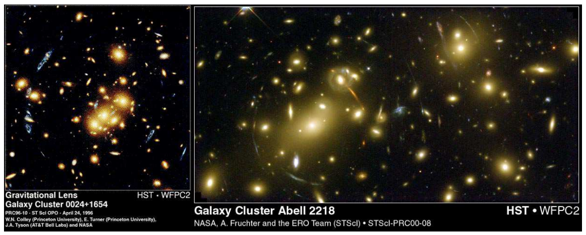


Lyman-break galaxies (LBGs)

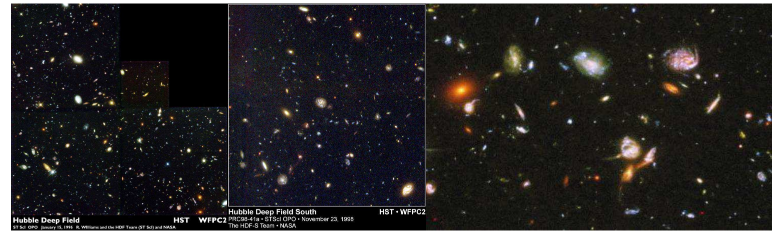
Where to look for distant galaxies?

– Fields in which high-z objects are already detected (clustering of galaxies)

– Search in the surrounding of galaxy clusters (gravitational lensing)



– Extremely deep fields: HDF-N, HDF-S, HUDF, SDF etc.



– Serendipitous discoveries

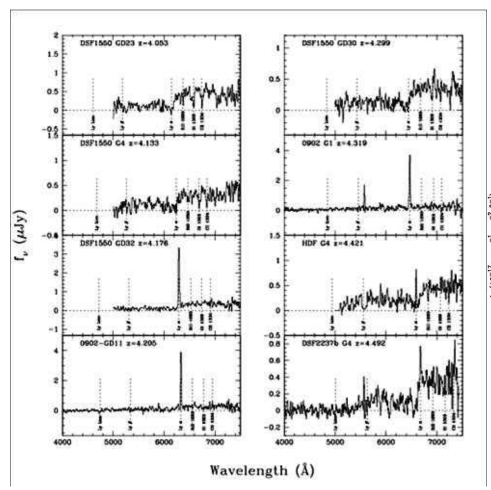
All the methods does work!

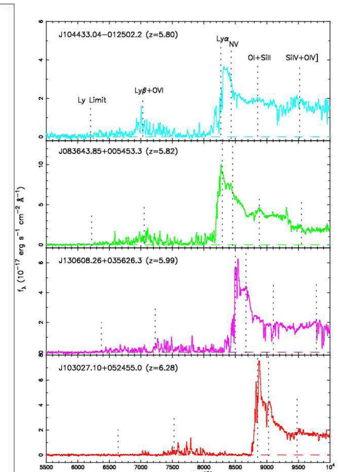
Current status:

$>$50 LAEs at $z > 5$ ($\mathbf{z = 6.96}$ – most distant)

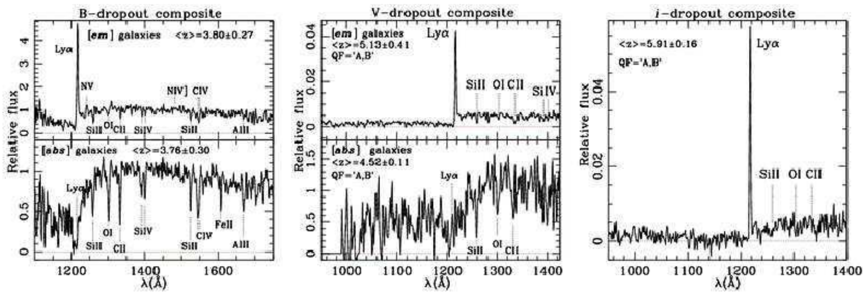
$\sim$5000 LBGs at $z \sim 4$
$\sim$1500 LBGs at $z \sim 5$
$>$500 LBGs at $z \sim 6$
$>$100 LBGs at $z > 5$ with spectroscopically-confirmed redshifts

Examples of spectra





Vanzella et al. (2007): composite spectra of B, V, and i drop galaxies (the success rate of the redshift identifications to be ≈70%).



First modern searches for galaxies at high redshift using the Lyman-break technique – Guhathakurta et al. (1990), Steidel & Hamilton (1992, 1993), etc.

Verma et al. (2007) presented the properties of 21 LBGs at $z \sim 5$ (spectra + 10-band photometry in the range 0.45-8 μm).

Main results: typical SFR ~ 40 M$_\odot$/yr, stellar mass $\sim 2 \cdot 10^9$ M$_\odot$, age < 100 Myr, size $r_{1/2} \sim 1$ kpc.

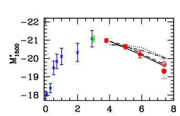
On average, LBGs at $z \sim 5$ are ~10 times less massive and are significantly younger than LBGs at $z \sim 3$.

Progenitors of early-type galaxies or bulges?

Luminosity function of LBGs

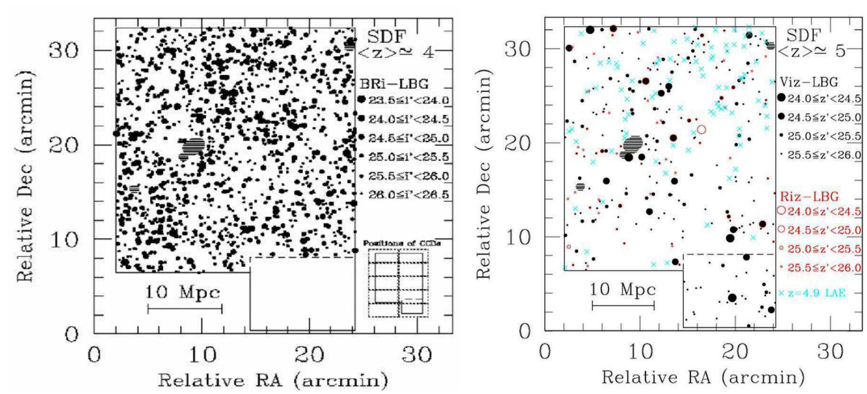
Bouwens et al. (2007): 4671, 1416, and 627 B, V, and i dropouts ($z \sim 4$, $z \sim 5$, and $z \sim 6$) in several deep fields of the HST.
The LF parameters for the rest-frame LFs at different z.

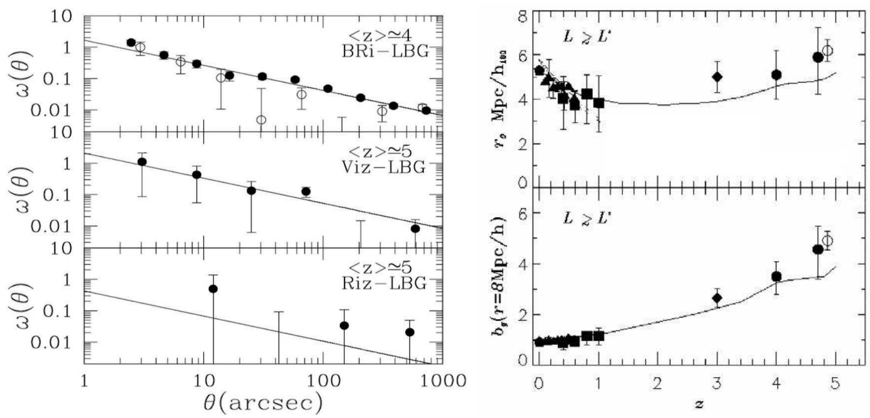
Dropout Sample	$<z>$	M^*_{UV} [a]	ϕ^* (10^{-3} Mpc^{-3})	α
B	3.8	-20.98 ± 0.10	1.3 ± 0.2	-1.73 ± 0.05
V	5.0	-20.64 ± 0.13	1.0 ± 0.3	-1.66 ± 0.09
i	5.9	-20.24 ± 0.19	$1.4^{+0.6}_{-0.4}$	-1.74 ± 0.16
z	7.4	-19.3 ± 0.4	(1.4)	(-1.74)



Spatial distribution

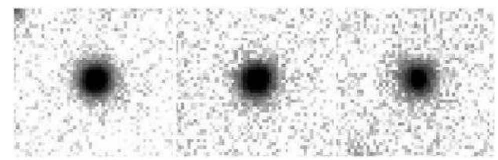
Ouchi et al. (2004): 2600 LBGs with z=3.5-5.2 in the SDF.



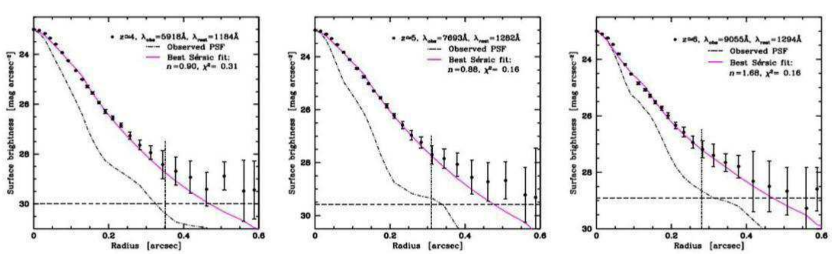


Surface brightness profiles

Hathi et al. (2008) used the stacked HUDF images to analyze the average surface brightness profiles of $z \approx 4-6$ galaxies (30 objects at $z \approx 4$, 30 at $z \approx 5$, and 30 at $z \approx 6$).
0.2cm
From these stacked images, they are able to study averaged radial structure at much higher signal-to-noise ratio than possible for an individual faint object.



Composite images for $z \approx 4$, 5, and 6 (from left to right) objects. Each stamp is 1.″53 on a side.



(a) For $z \simeq 4$ objects. (b) For $z \simeq 5$ objects. (c) For $z \simeq 6$ objects.

Mean surface brightness profiles with a best fit Sérsic profiles for 30 composite images at $z \simeq 4$–6. The thin dot-dash curve represents the ACS V-, i'-, z'-band PSFs, respectively, while the horizontal dashed line indicates the surface brightness level corresponding to the 1σ sky–subtraction error in the HUDF images. The vertical dotted line marks the radius at which the profile starts to deviate significantly from the extrapolation of the inner $r^{1/n}$ profile observed at smaller radii. The n is the best fit Sérsic index.

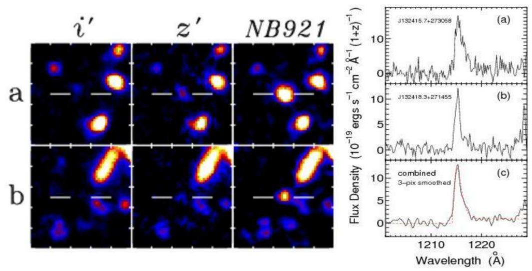
Main conclusions:

– The shape of the average surface brightness profiles shows that even the faintest $z \approx 4-6$ objects are resolved.

– The average surface brightness profiles display breaks at a radius that progresses towards lower redshift from $r = 0.''27$ (1.6 kpc) at $z \approx 6$ to $r = 0.''35$ (2.5 kpc) at $z \approx 4$.
The radius where surface brightness profiles start do deviate significantly from an $r^{1/n}$ profile might serve as a “virial clock” that traces the time since the onset of the last major merger, accretion event or global starburst in these objects.
The limits to dynamical age estimates for the galaxies from their profile shapes (~ 100 Myr) are comparable with the SED ages obtained from the broadband colors.

The systematic search for Lyα-emitting high-z galaxies for a long time been a business without the success expected from early predictions (e.g. Partridge & Peebles 1967). First results – end of 90th (e.g. Hu et al. 1998 with the 10-m Keck telescope).

Kodaira et al. (2003):



(a) $z = 6.541$, FWHM=4.4 kpc, SFR$>9\,$M$_\odot$/yr
(b) $z = 6.578$, FWHM<4.4 kpc, SFR$>5\,$M$_\odot$/yr

Typical characteristics of LAEs

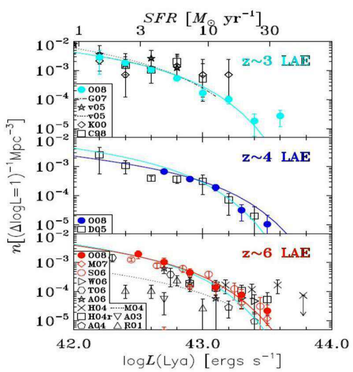
– Compact (~ 1 kpc)

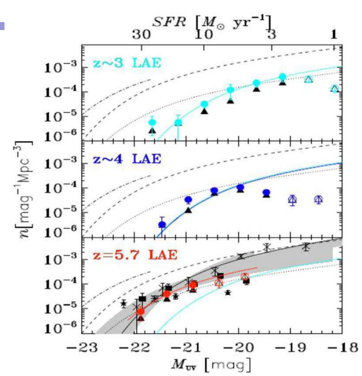
– SFR~2–50 M$_\odot$/yr

– Masses $\sim 10^9 - 10^{10}$ M$_\odot$

– Luminosity function

Ouchi et al. (2008) presented LFs of Lyα emitters at $z \approx 3$, 4, and 6 in a 1 deg^2 sky of the Subaru/XMM–Newton Deep Survey Field (858 photometrically-selected candidates + 84 confirmed LAEs). They derived the LFs of Lyα and UV-continuum ($\approx 1500\,$Å).

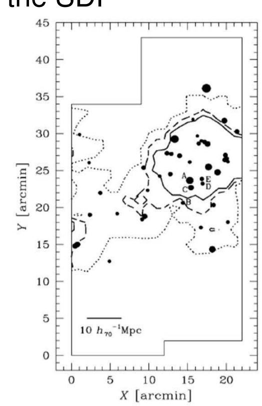




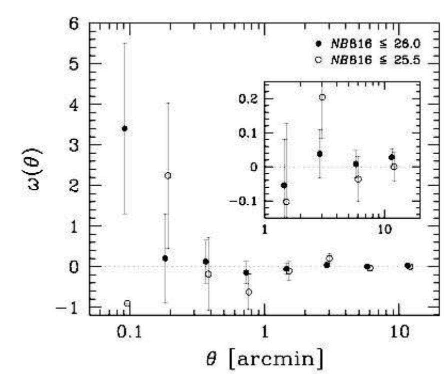
– The apparent Lyα LF shows no significant evolution beween $z = 3$ and 6.
– The UV LF of LAEs increases from $z = 3$ to 6, indicating that galaxies with Lyα emission are more common at earlier epochs.
– The ratio in number density of LAEs to LBGs increases from $z = 3$ to 6: galaxies with Lyα emission are more common at high z.

Spatial distribution

Shimasaku et al. (2003): 43 LAEs at $z = 4.86$ in the SDF



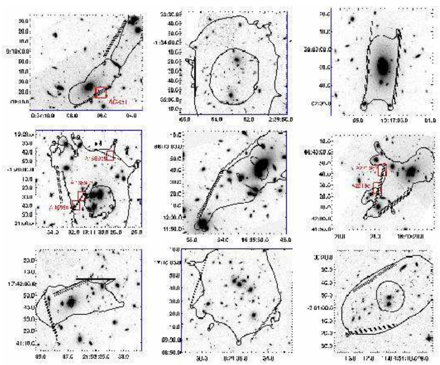
Shimasaku et al. (2006): 89 LAEs at $z = 5.7$ in the SDF



LAEs at $z \sim 9$?

Stark et al. (2007) presented new observational constraints on the abundance of faint high-z LAEs secured from a deep Keck near-infrared spectroscopic survey which utilizes the strong magnification provided by lensing galaxy clusters at intermediate redshift ($z = 0.2 - 0.5$) (9 clusters).

Stark et al. have undertaken a systematic search for line emission in the J-band (1.143-1.375 μm) within carefully-selected regions which offer very high magnifications (10–50 times) for background sources with redshifts $z \approx 10$.

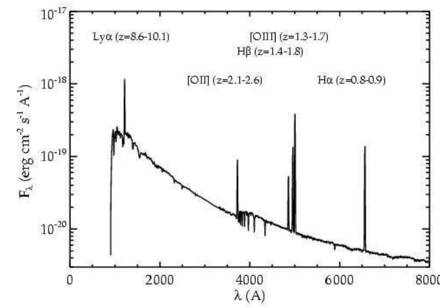


The survey has yielded six promising ($> 5\sigma$) candidate LAEs which lie between $z = 8.7$ and $z = 10.2$.

All but one of the candidates remain undetected in deep HST optical images and lower redshift line interpretations can be excluded, with reasonable assumptions, through the non-detection of secondary emission in further spectroscopy.

At least two of the candidates are likely to be a $z \approx 9$:

8.99 and 9.32.



Main conclusions:

– Assuming two or more of the LAE candidates are real, then the cumulative abundance of low luminosity galaxies (defined as those with $L > 10^{41.5}$ erg/s) is at least 0.3 Mpc^{-3}. Such a large abundance of low luminosity LAEs supports the contention of a steep faint end slope for the star-forming luminosity function at $z \approx 10$.

– The first glimpse at the $z \approx 10$ Universe suggests that low luminosity star-forming galaxies contribute a significant proportion of the UV photons necessary for cosmic reionization.

$z \geq 5$ galaxies:

– compact (∼1–5 kpc)

– asymmetric

– high rest-frame surface brightness and luminosity ($\mu_0(B) \sim 18^m/\square''$, $L \sim L^*$)

– young (~ 100 Myr)

– low mass ($\sim 10^9 - 10^{10}$ M$_\odot$)

– high SFR ($\sim 10^1 - 10^2$ M$_\odot$/yr)

– spatial density $\approx$ spatial density of bright galaxies at $z = 0$

– evidence of LSS

Summary

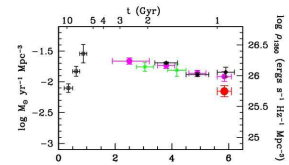
These characteristics are very strongly biased by the selection procedure itself, and it is therefore unclear to what extent they reflect actual properties of all objects located at $z \geq 5$.

The observed objects can be “building blocks” that later merge and accrete the surrounding matter to form the galaxies we now know in our vicinity. On the other hand, some of these objects can represent bulges of massive spirals under formation or elliptical galaxies.

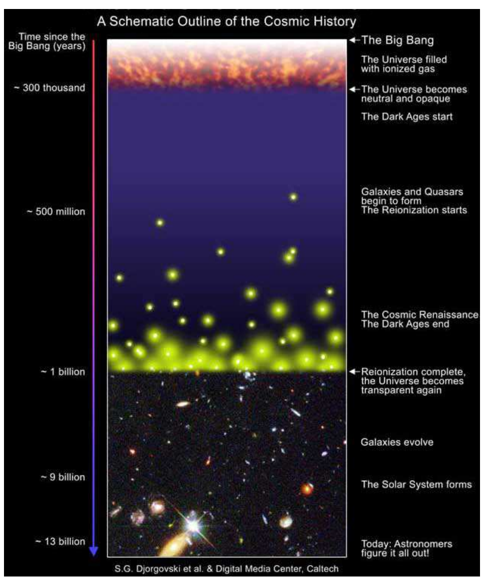
Summary

Some important questions (Schaerer 2007):

- How do different high-z populations such as LAE and LBG fit together? Are there other currently unknown populations? What are the evolutionary links between these populations and galaxies at lower redshift?
- What is the metallicity of the high-z galaxies? Where is Pop III?
- What is the star formation history of the universe during the first Gyr after Big Bang?
- Are there dusty galaxies at $z \geq 6$? How, where, when, and how much dust is produced at high redshift?
- Which are the sources of reionisation? And, are these currently detectable galaxies or very faint low mass objects? What is the history of cosmic reionisation?



Summary



Summary

Useful literature

C.J. Pritchet “The Search for Primeval Galaxies”, PASP 106, 1052, 1994

E. Thommes “Galaxies at high redshifts – observing galaxies in the cradle” astro-ph/9812223

D. Stern, H. Spinrad “Search Techniques for Distant Galaxies”, PASP 111, 1475, 1999

M. Giavalisco “Lyman-Break Galaxies”, ARAA 40, 579, 2002

H. Spinrad “The Most Distant Galaxies”, astro-ph/ 0308411

D. Schaerer “Primeval galaxies”, arXiv:0706.0139v1 [astro-ph]

R. S. Ellis “Observations of the High Redshift Universe”, astro-ph/0701024