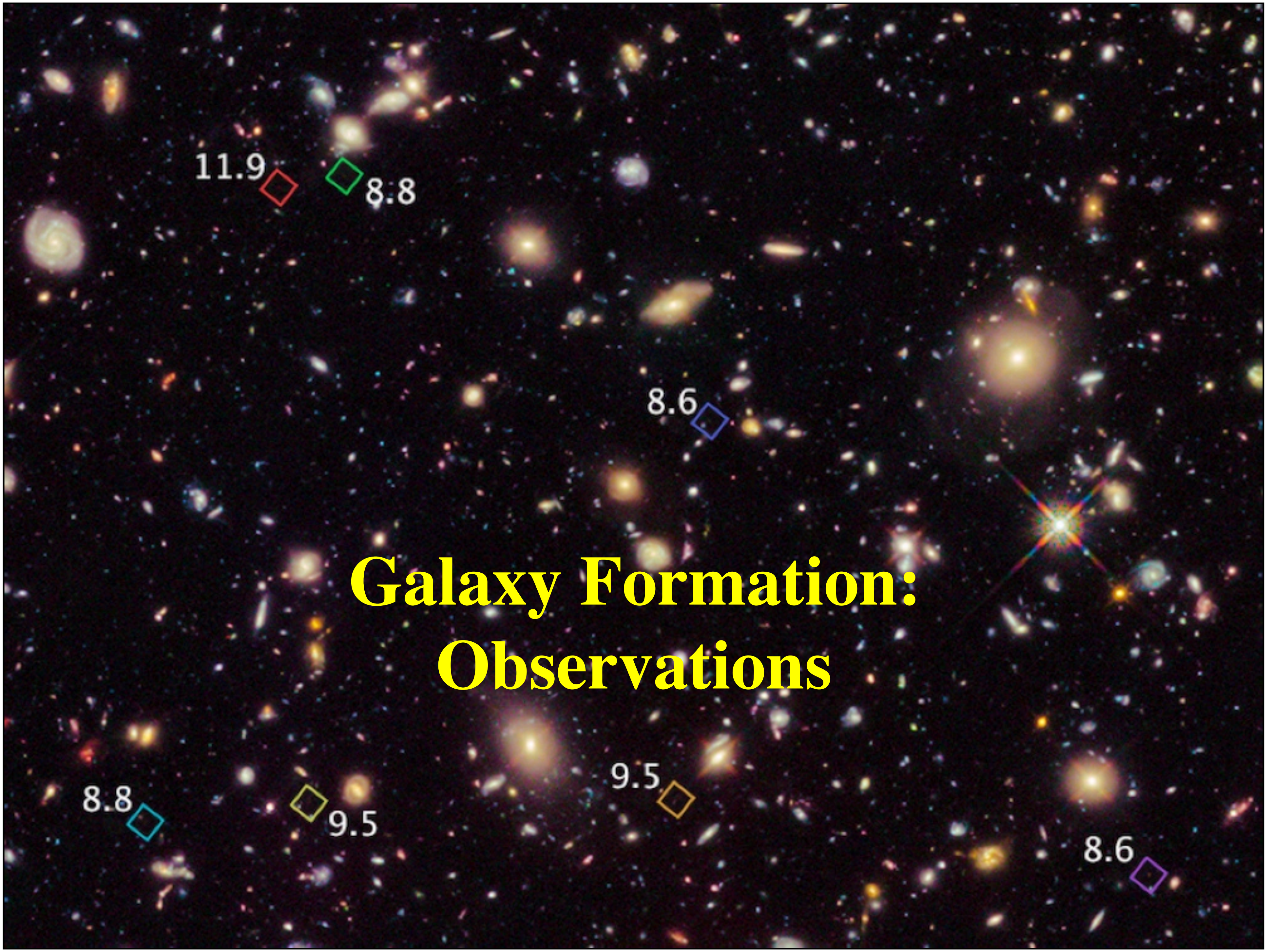
Galaxy Formation: Observations



Expected Observable Properties of PGs

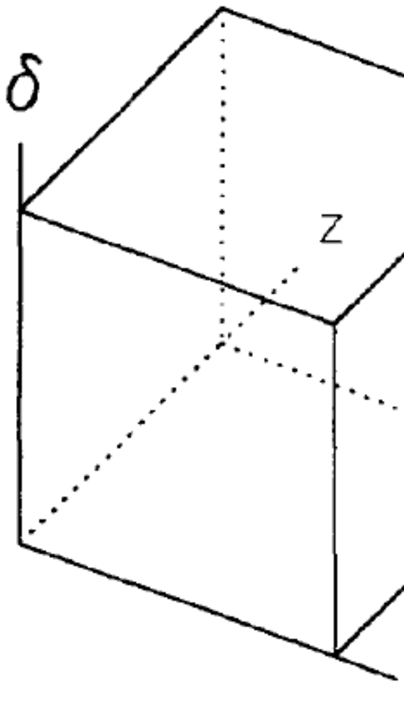
- We expect a release of $\Delta E \sim 10^{60}$ ergs from a typical proto-elliptical (or a large bulge); but over what time scale?
  - The starburst time scale of ~ 10^7 - 10^8 yrs
  - The free-fall time scale of ~ 10^8 yrs
  - The merging time scale of ~ 10^9 yrs
- Since luminosity is $L \sim \Delta E/\Delta t$, we estimate typical

$$L_{PG} \sim 10^{11} - 10^{12}\ L_{\odot},$$

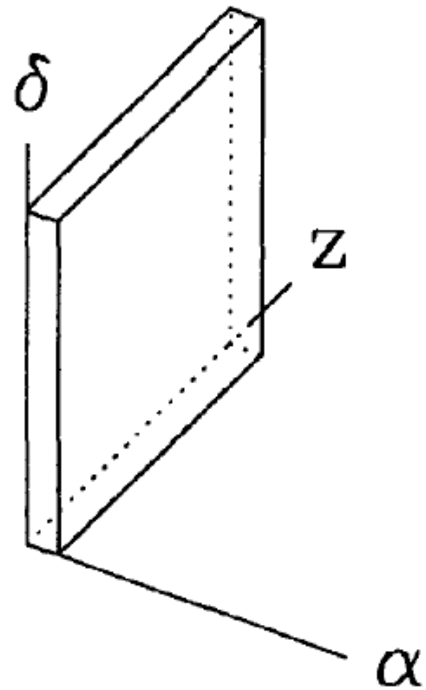
or absolute magnitudes $M \sim -22$ to -25 mag

- Given the luminosity distances to z ~ 6 - 8, the expected apparent magnitudes are in the range ~ 26 to 30 mag
- A few % of the total energy is in recombination lines, e.g., Lyα
- But the **Big Question** is: ***is this luminosity obscured by dust?***
  - No: optical surveys
  - Yes: sumb-mm/FIR surveys

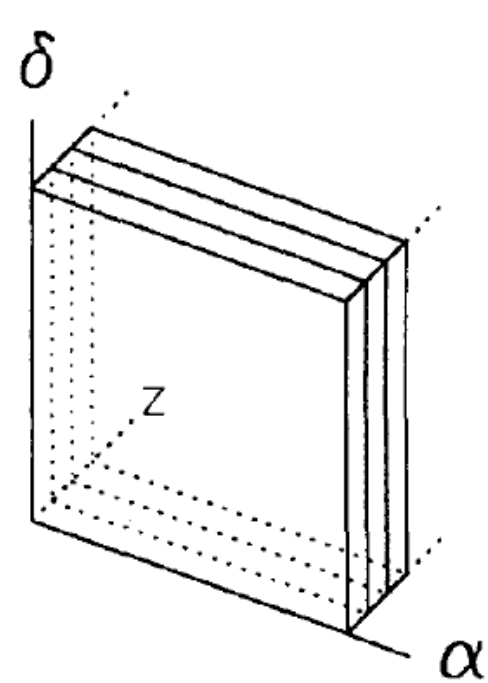
Emission Line Search Methodologies



Slitless spectroscopy:
Large volume, but low S/N (~ depth)



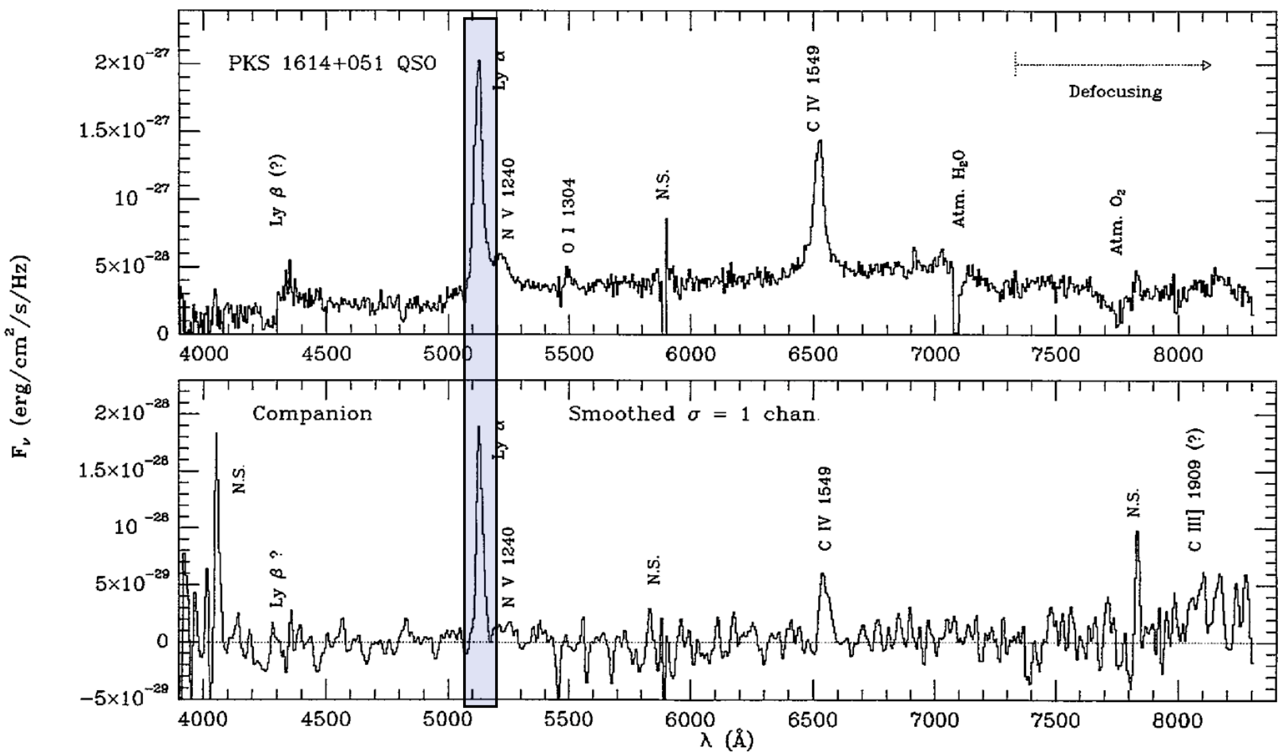
Long-slit spectroscopy:
Small volume,
large redshift range,
good depth

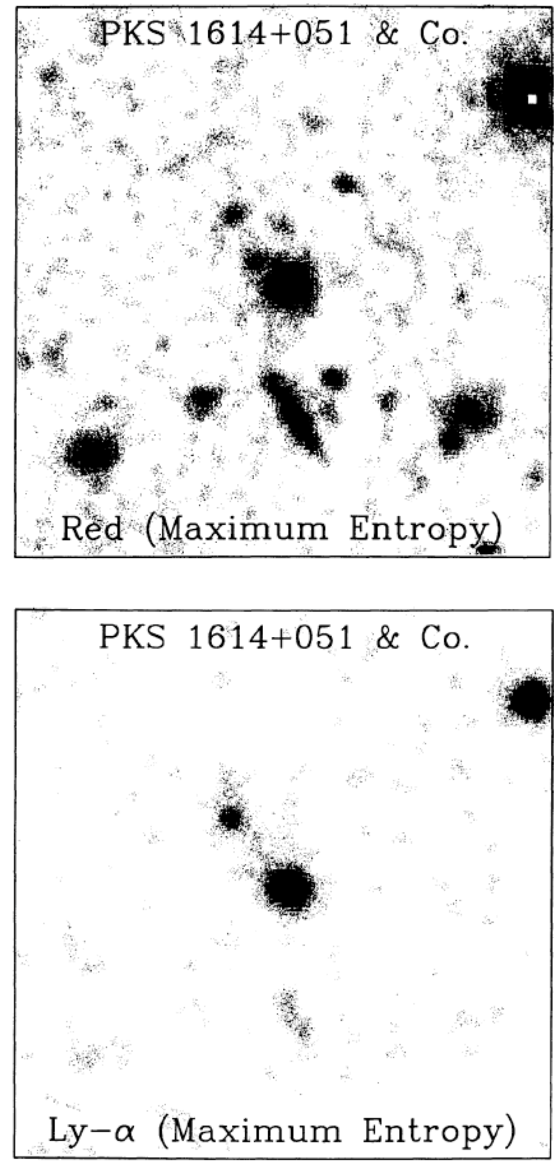


Narrow band imaging:
Moderate volume,
small redshift range,
good depth

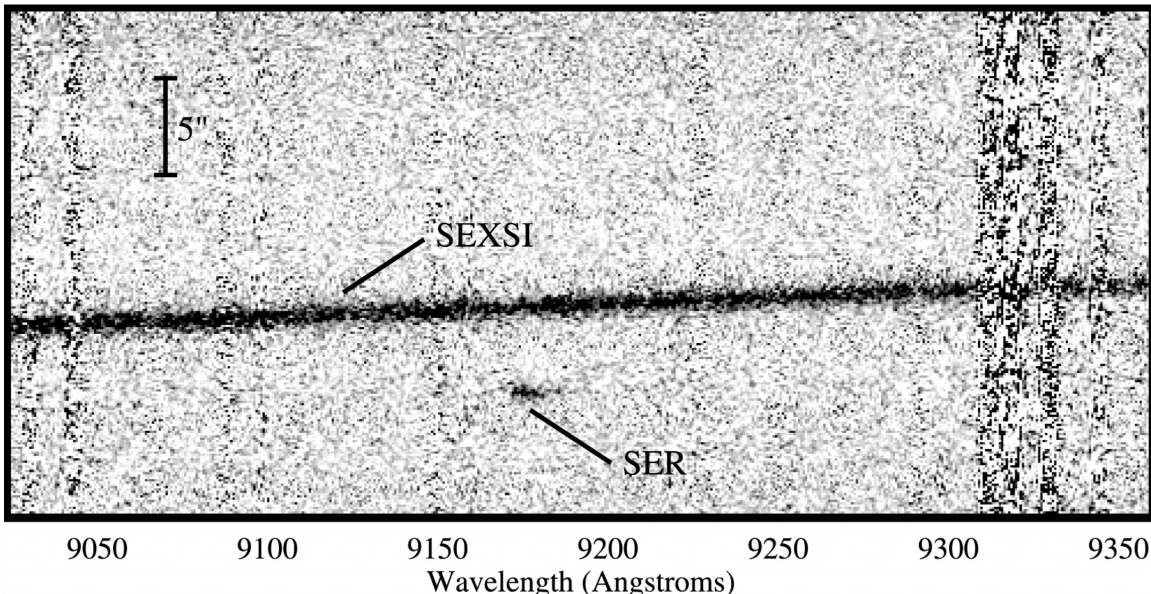
Narrow-Band Imaging

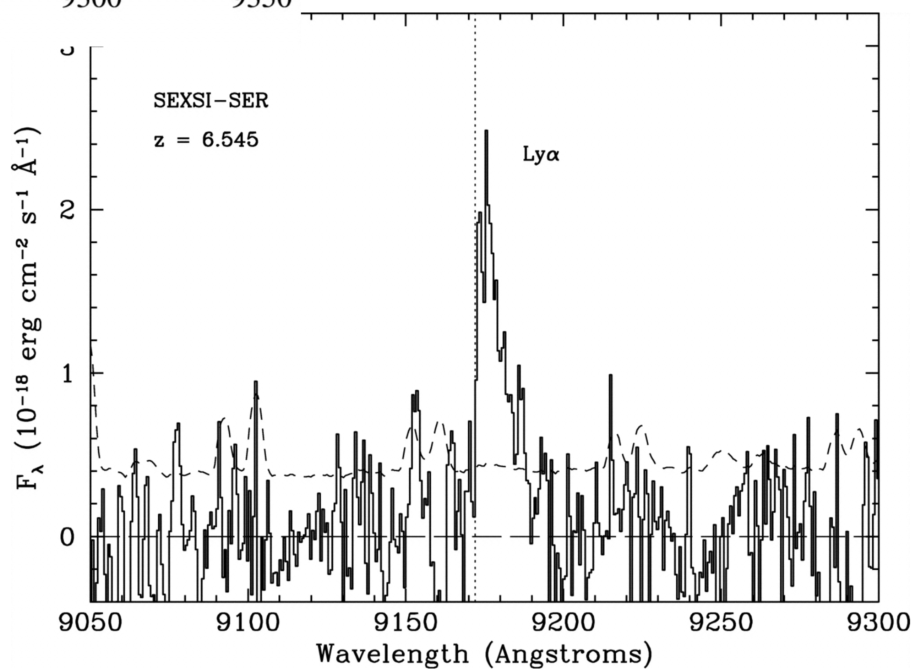
A greatly increased contrast for an object with a strong line emission





Long-Slit Spectroscopy + Serendipity



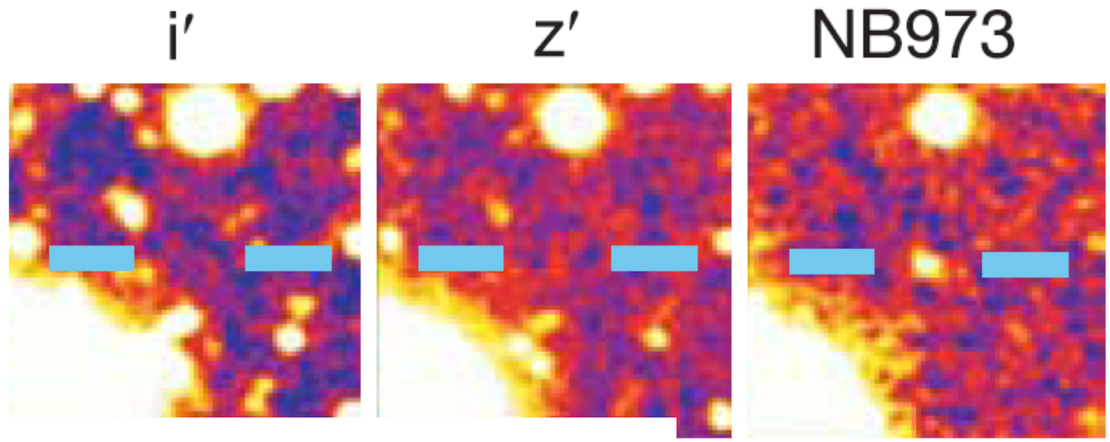


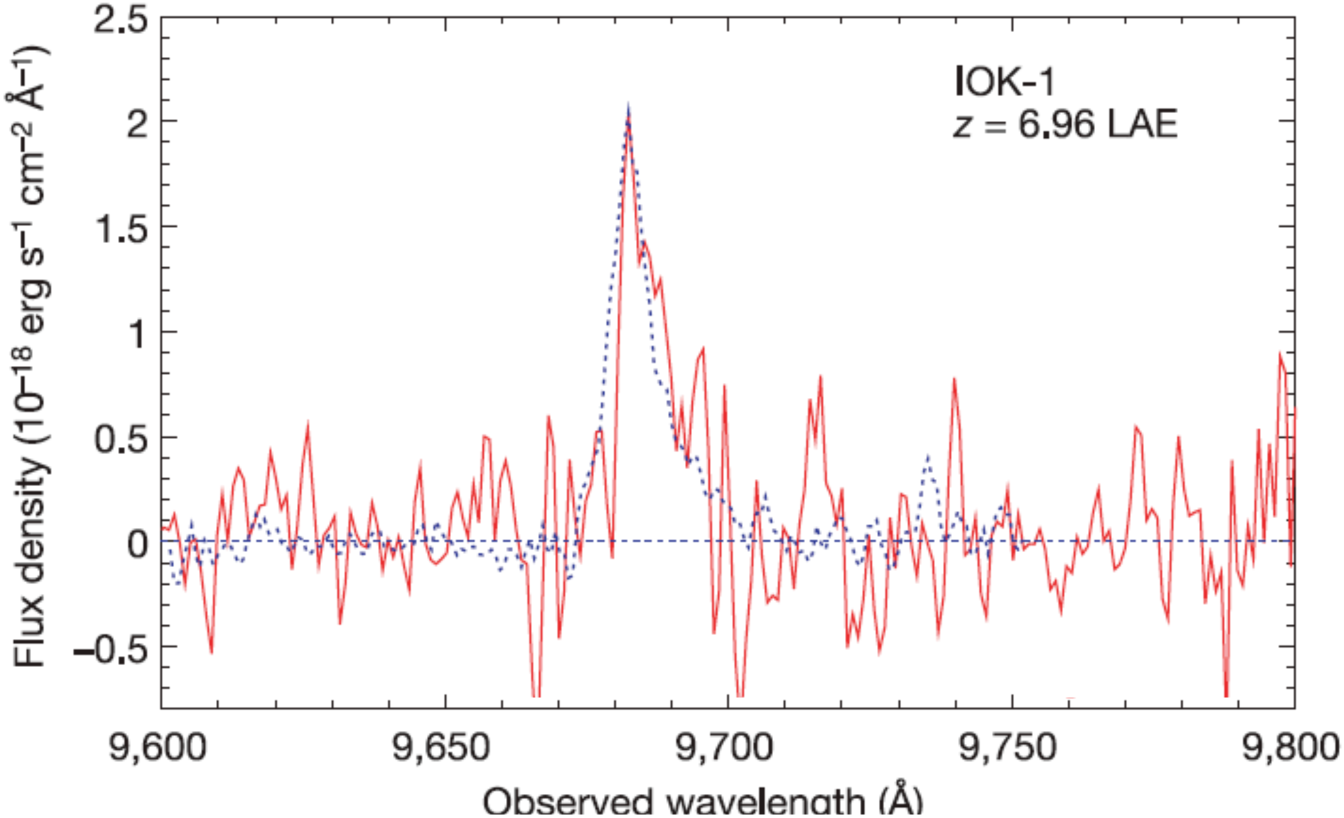
A Galaxy at z ~ 7

IOK-1 at z = 6.96

(Iye et al. 2006; Subaru)

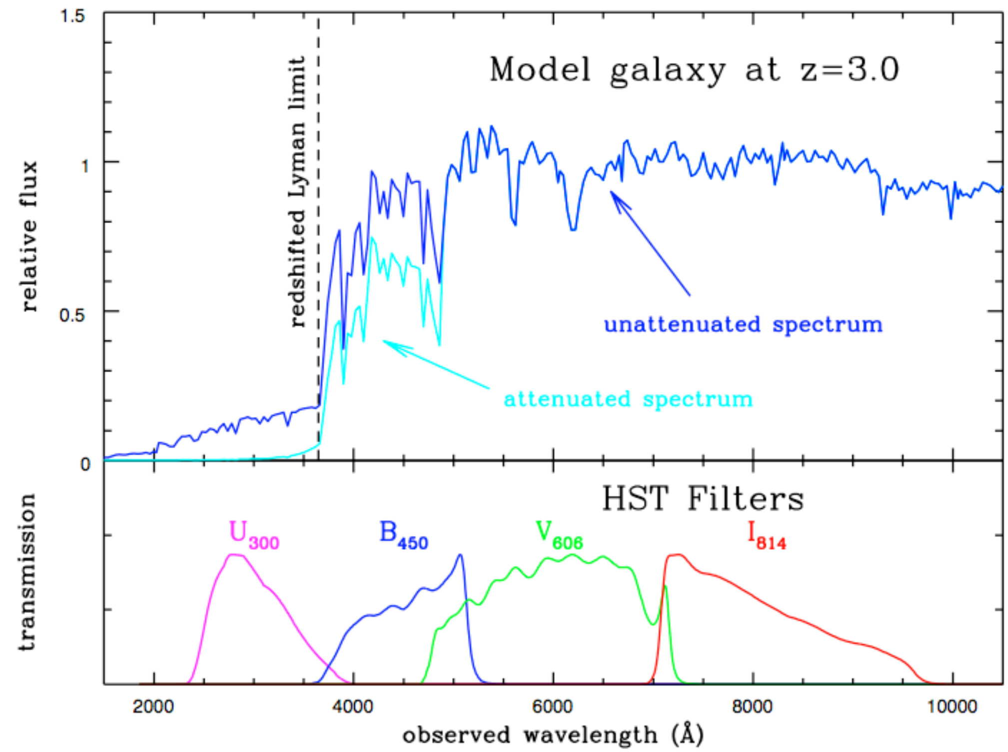
Discovered using narrow band imaging technique

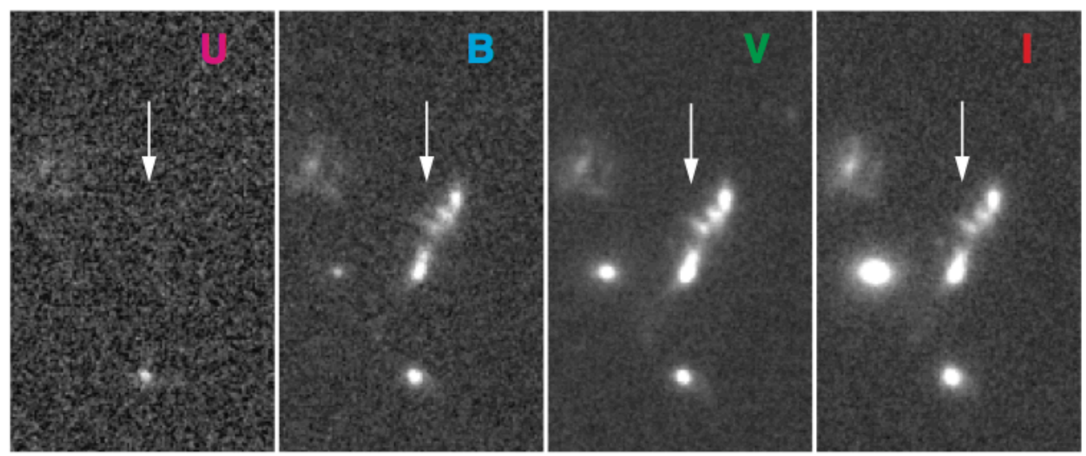




The Lyman-Break Method

Absorption by the interstellar and intergalactic hydrogen of the UV flux blueward of the Ly alpha line, and especially the Lyman limit, creates a continuum break which is easily detectable by multicolor imaging

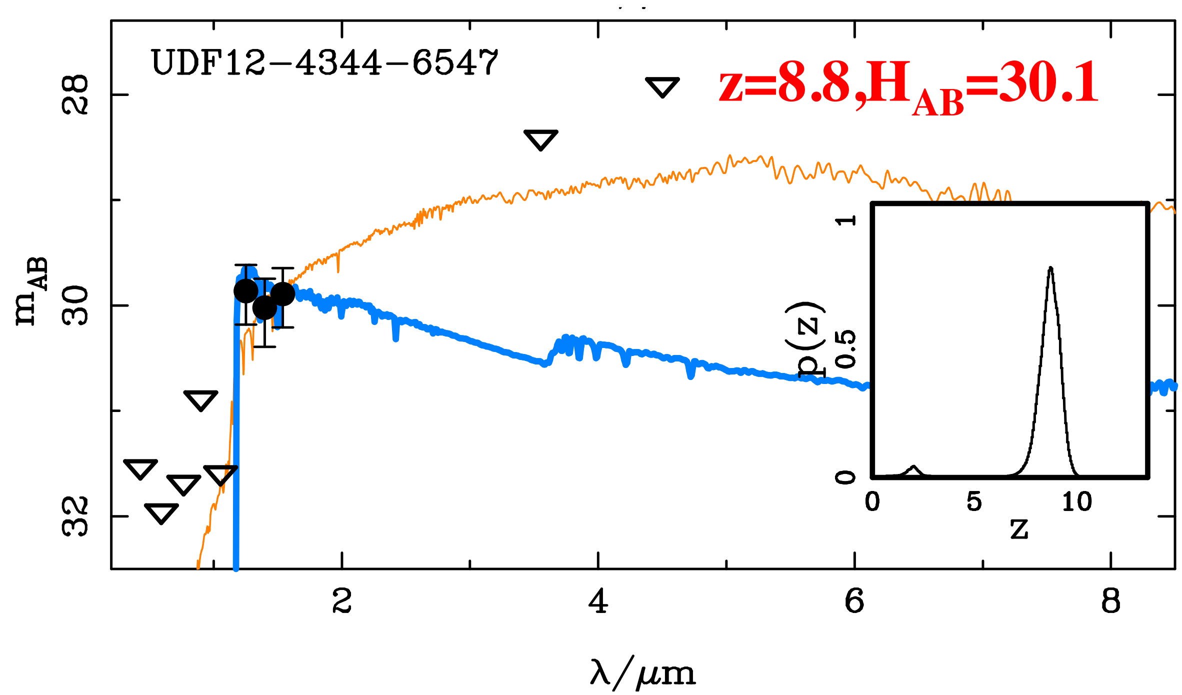


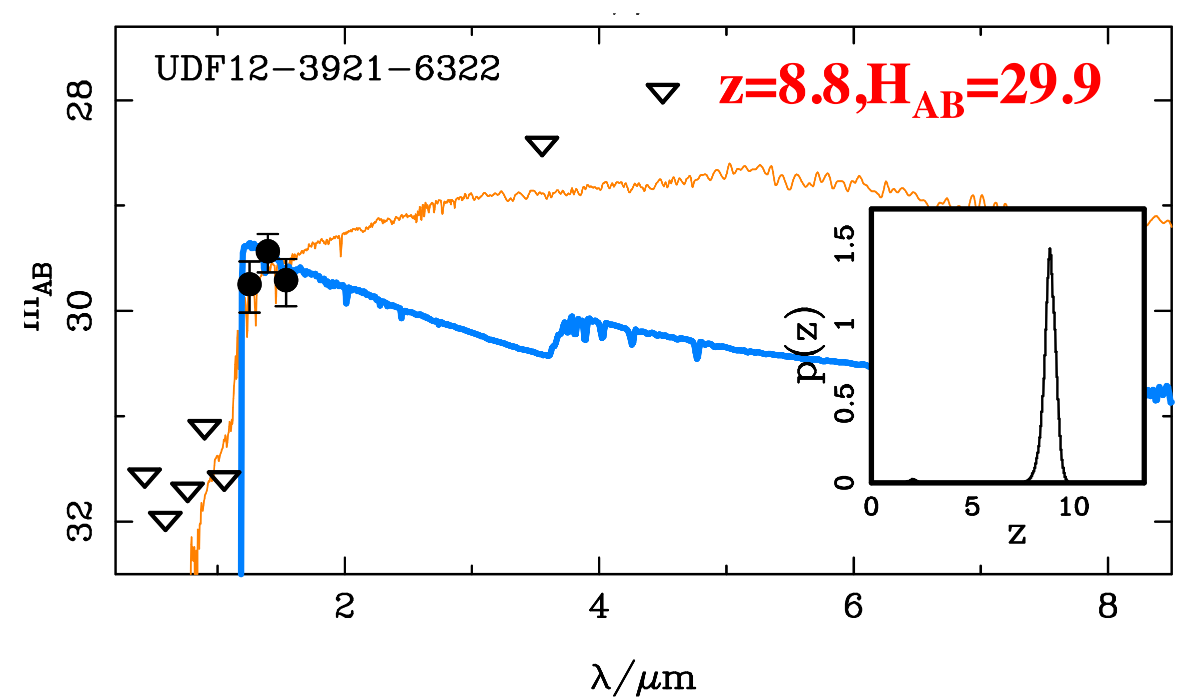


Photometric Redshifts

Using the combination of 4 optical and 4 infrared filters, the redshifts of individual galaxies can be estimated for systems well beyond current spectroscopic reach

(from R. Ellis)





Color-Selected Candidate High-z Galaxies

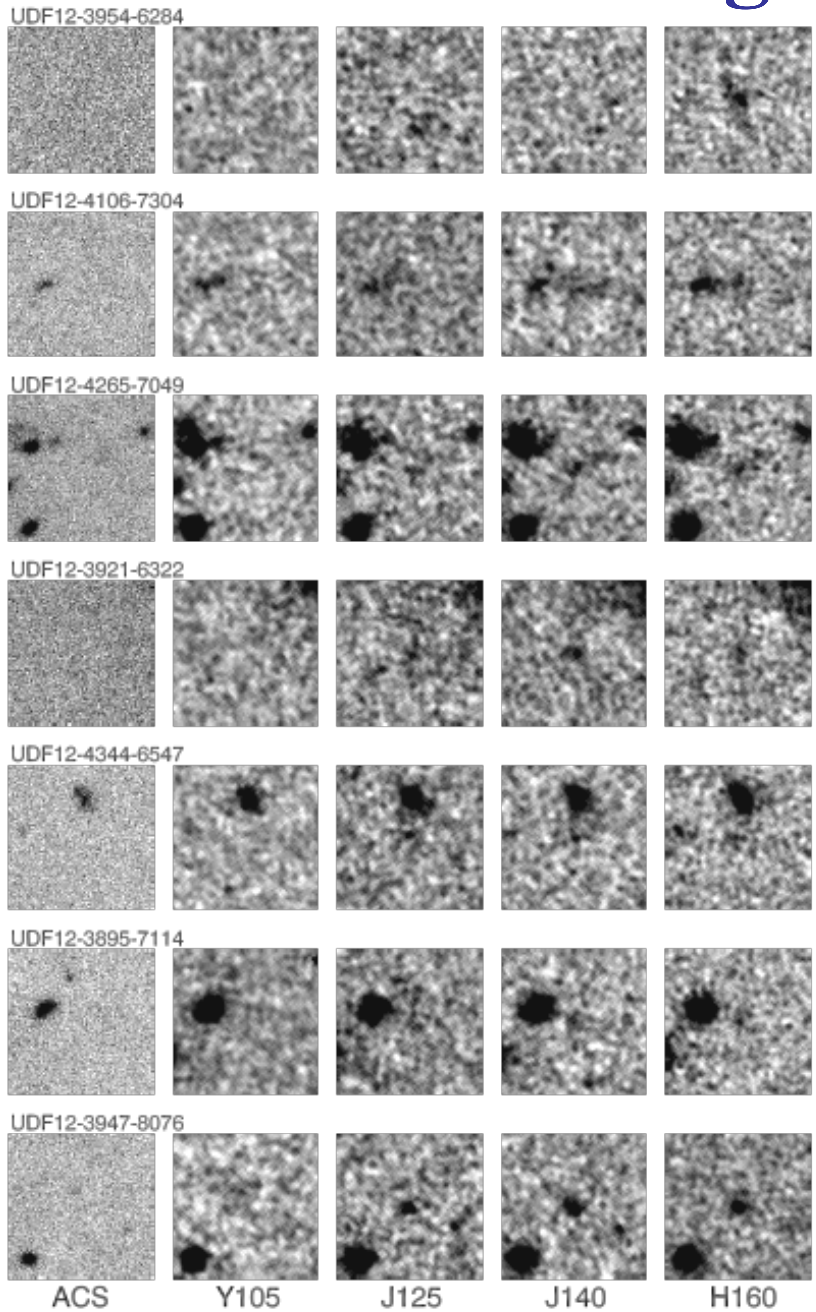
7 star-forming galaxies located 8.5<z<12

5σ detections in (160W+140W +125W) stack (m_{AB} < 30.1)

2σ rejection in ultradeep F105W (m_{AB} > 31.0)

2σ rejection in ACS BViz (m_{AB} > 31.3)

Ellis et al (2013) Ap J Lett 763, L7



z=11.9? 380 Myr

z=9.5 520 Myr

z=9.5 520 Myr

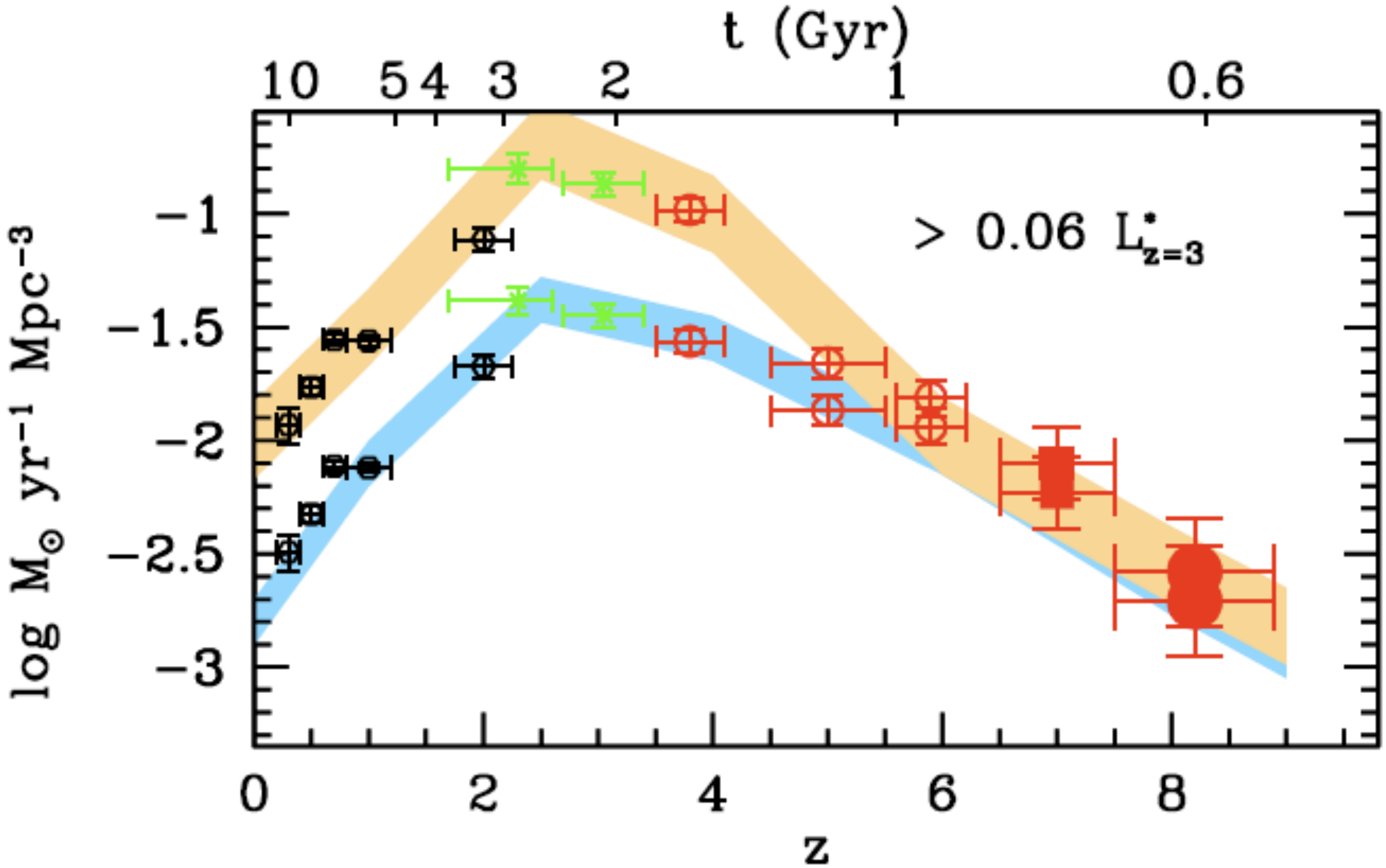
z=8.8 570 Myr

z=8.8 570 Myr

z=8.6 590 Myr

z=8.6 590 Myr

Star formation density of LBGs

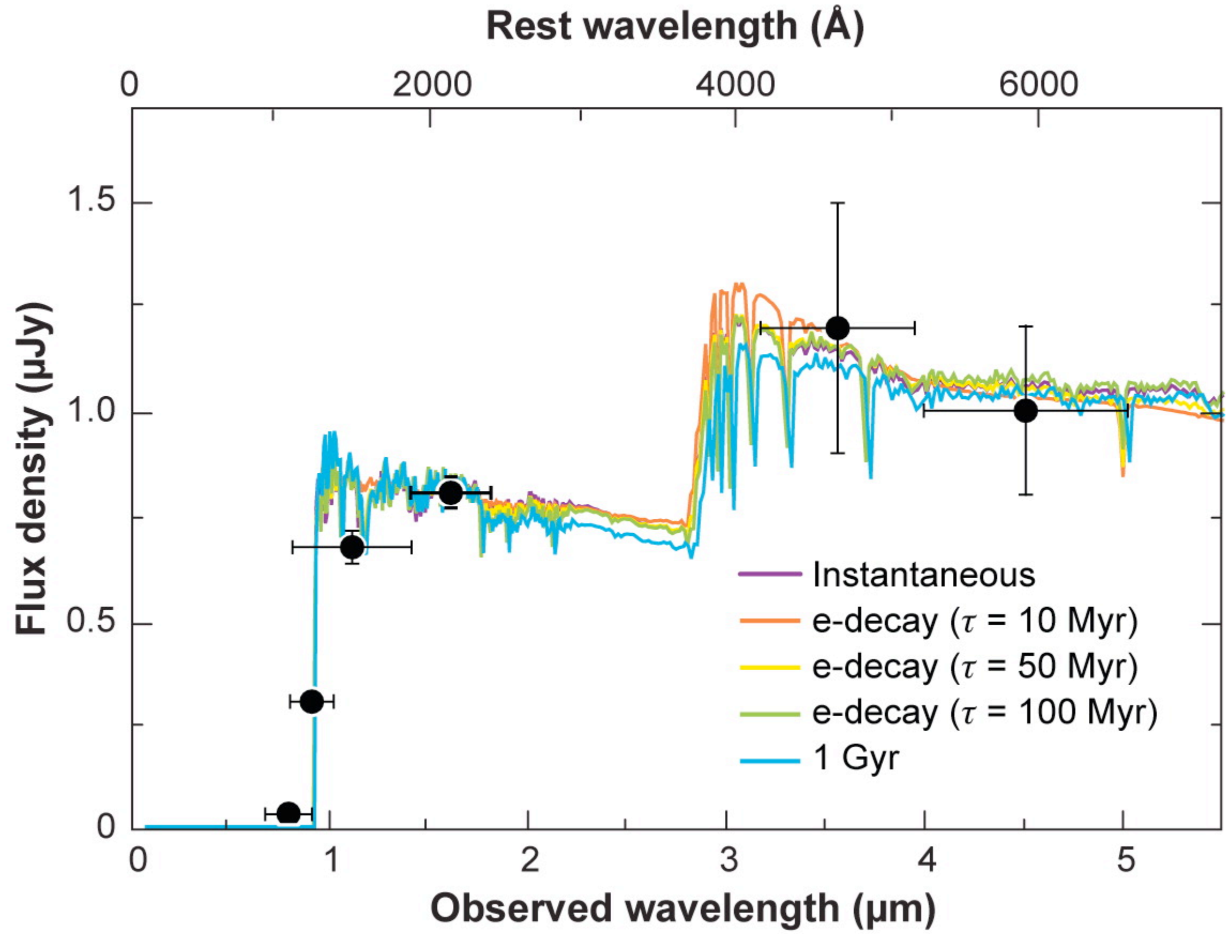


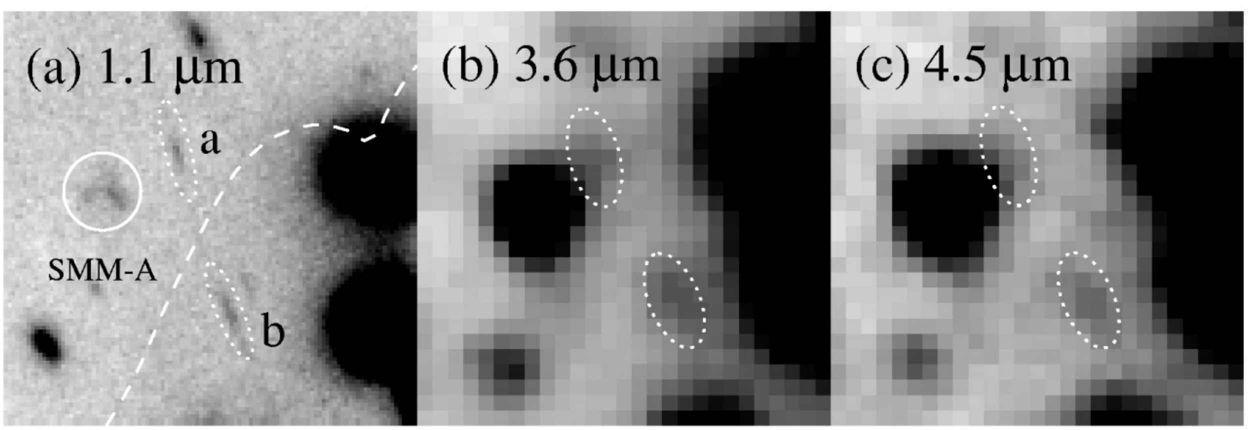
Monotonically declining population to z ~ 6 and beyond

Drop of ×8 in UV luminosity density over 2 < z < 6

Bouwens et al (2009, 2011)

However, even some galaxies at $z > 6$ seem to have been forming stars for a while, indicating a very early onset of galaxy formation





Lensed arc galaxy at $z \sim 6.7$ (?) behind A2218

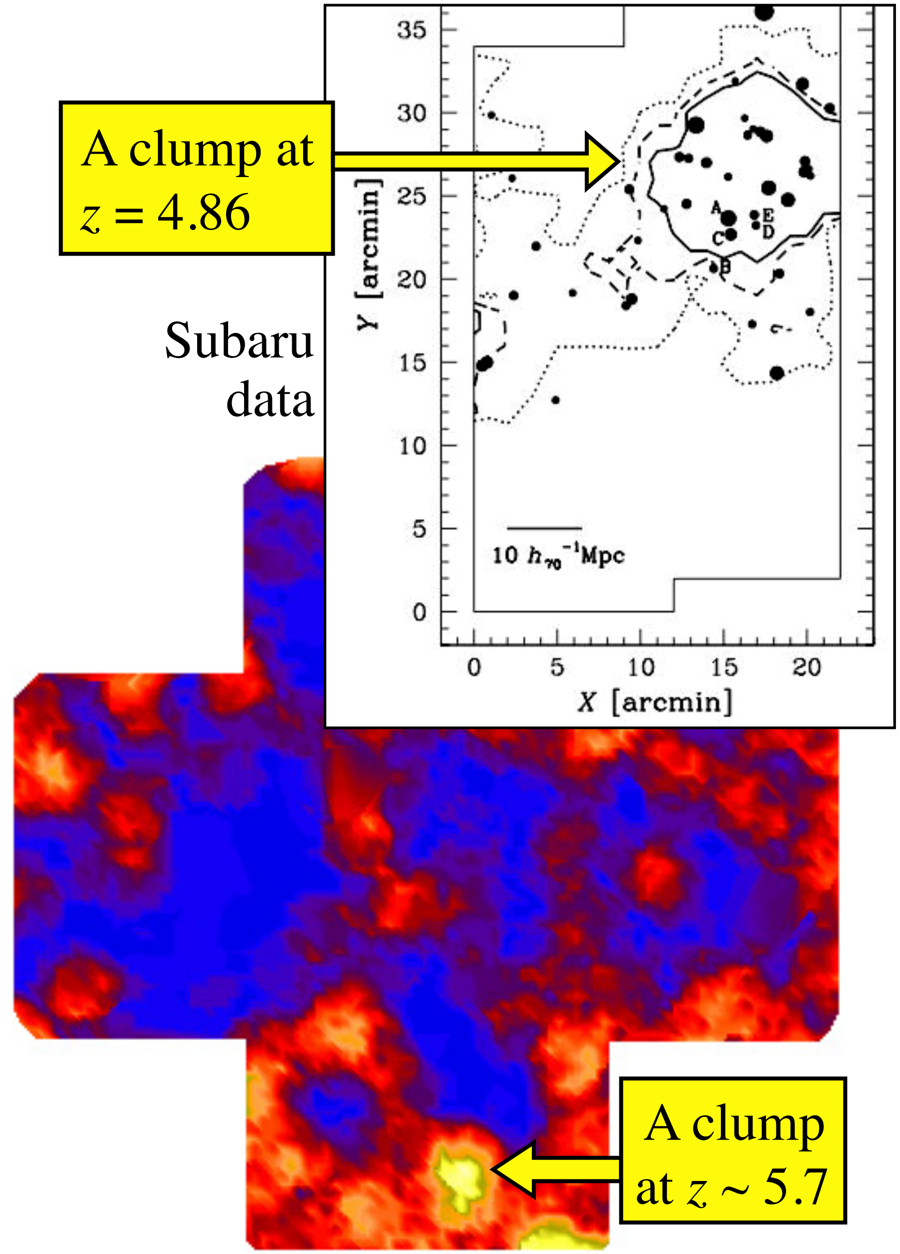
(Egami et al. 2005)

Biasing and Early Structure Formation

- ***Strong, bias-driven clustering*** of the first luminous sources is generally expected in most models
- There is a lot of evidence that this does occur at $z \sim 4 - 6$, from clustering of Lyα galaxies, to clustering of Ly-break galaxies around high-z QSOs
- This may lead to a ***clumpy reionization***, which among other things would produce a rise in the cosmic variance of the IGM transmission in the approach to reionization
- There is some evidence that this indeed does occur, from the spectra of z ~ 6 QSOs - and this may help improve our understanding of the final phases of reionization

Evidence for a Strong Biasing at High *z*'s

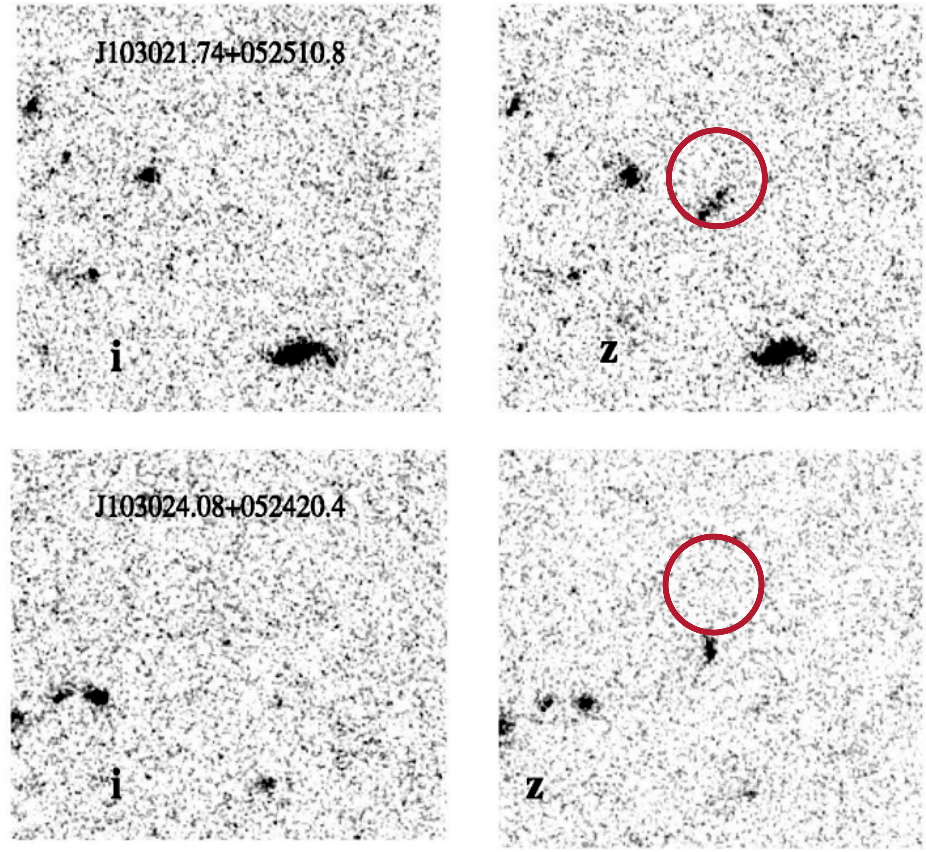
- LBGs at $z \geq 3$, ~ Mpc scales *(Steidel, Adelberger, et al.)*
- Clustered QSO companions at $z \sim 4$ - 6, scales ~ 0.1 - 1 Mpc *(Djorgovski et al., Stiavelli et al., etc.)* ; and also radio galaxies at similar *z*'s *(Venemans et al.)*
- Clustered Lyα and LB galaxies at z ~ 4.9 - 5.7, scales ~ a few Mpc *(Shimasaku et al., Ouchi et al., Hu et al., etc.)*
- Estimated **bias factors *b* ~ 3 - 6**, but could be as high as ~ 10 - 30!

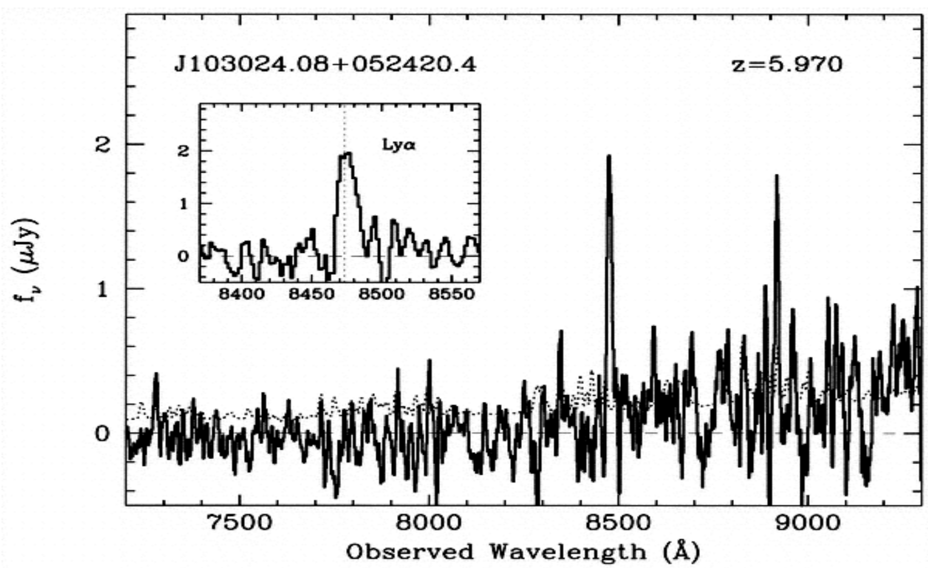


Protoclusters Around z ~ 6 QSOs?

Evidence for an excess of color-selected galaxies in the fields of $z \sim 6$ QSOs

Examples of color-selected candidates ➡





⬅ Spectroscopic confirmations

(Stiavelli et al. 2005, Bouwens et al. 2005, Kim et al. 2009)


Next:
Reionization Era: The First Stars