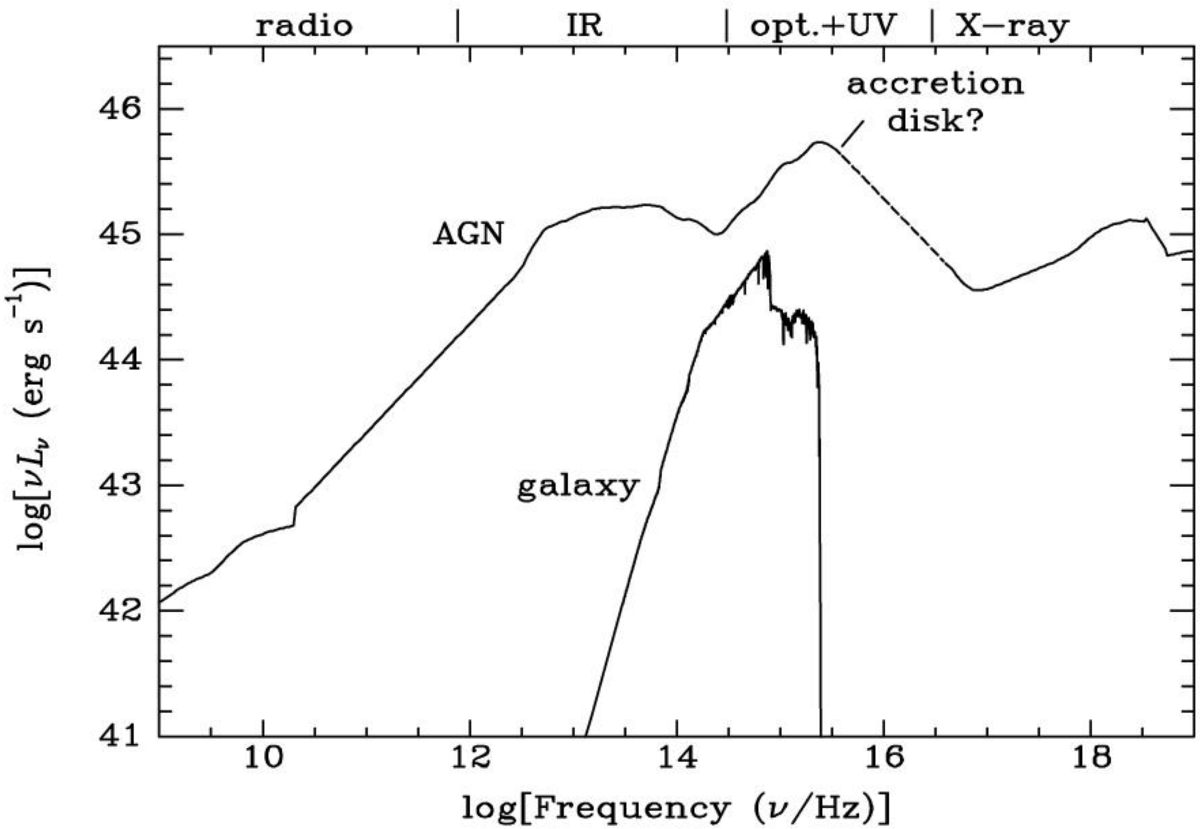
Outline

- Go over problem 9.4
- Quasars
  - Absorption lines
  - Diffuse intergalactic medium
- Finding high z galaxies
  - Lyman break galaxies (LBGs)
  - Photometric redshifts
  - Deep fields
- Starburst galaxies
  - Extremely red objects (EROs)
  - Sub-mm galaxies
- Lyman α systems

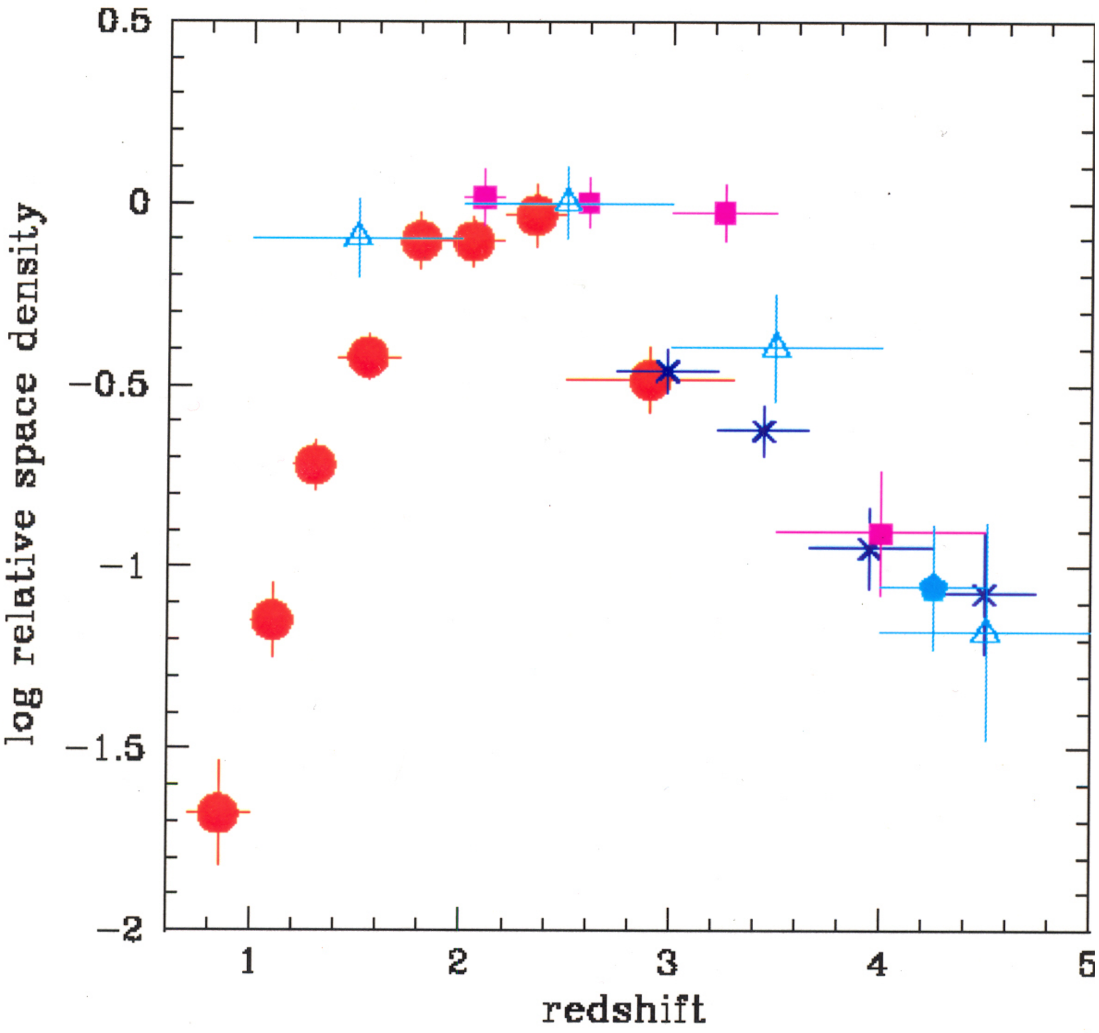
Quasars



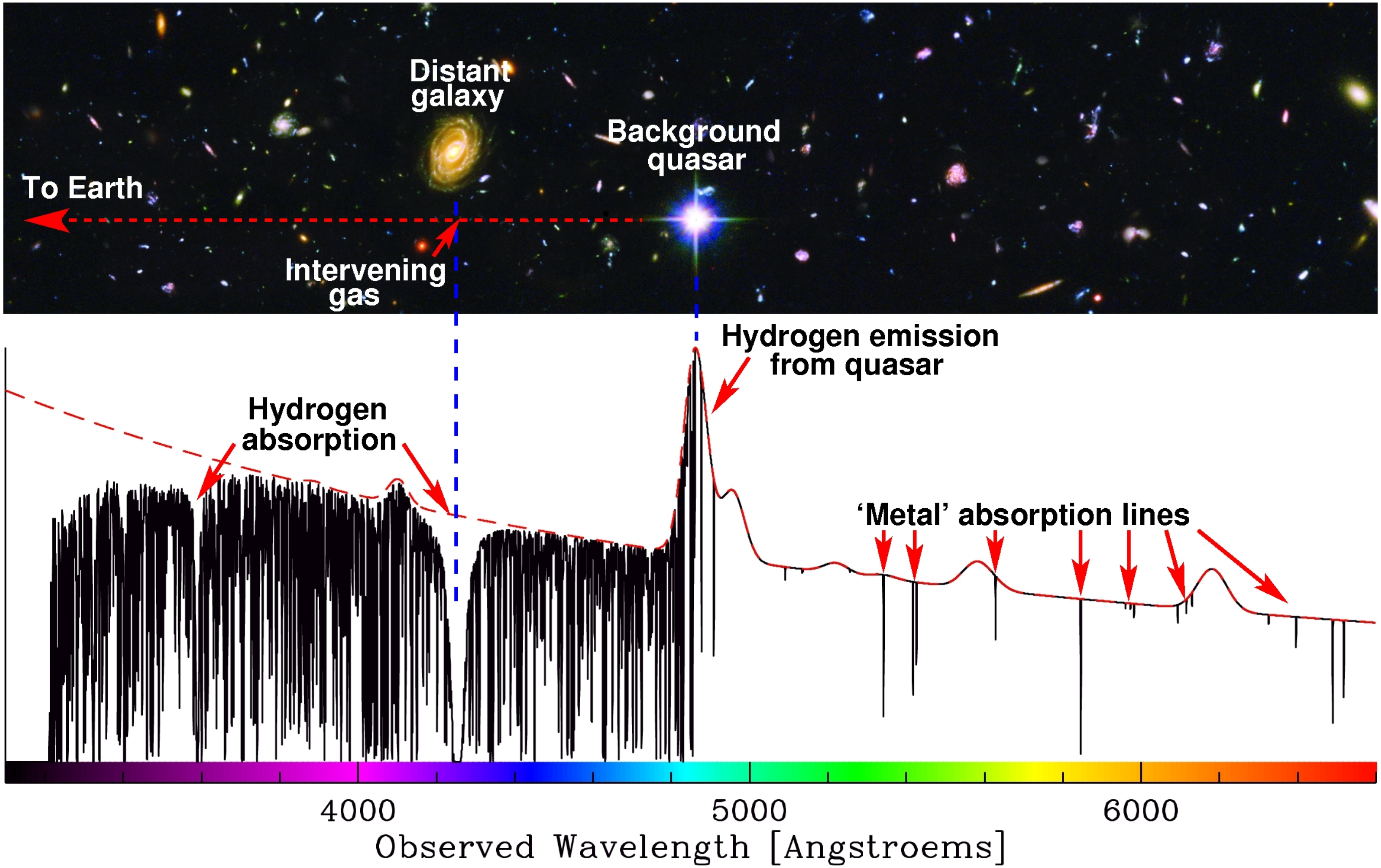
- Quasars or active galactic nulcei are bright at radio, IR, optical/UV, X-rays (sometimes gamma-rays).
- Quasars can be extremely luminous and, thus, can be seen out to large redshifts.

Quasars

- Quasars were more active in the past.
- Space density of AGN peaks at z = 2-3.
- Density declines at very high redshifts, due to limited time to form supermassive black holes.



QSO absorption lines



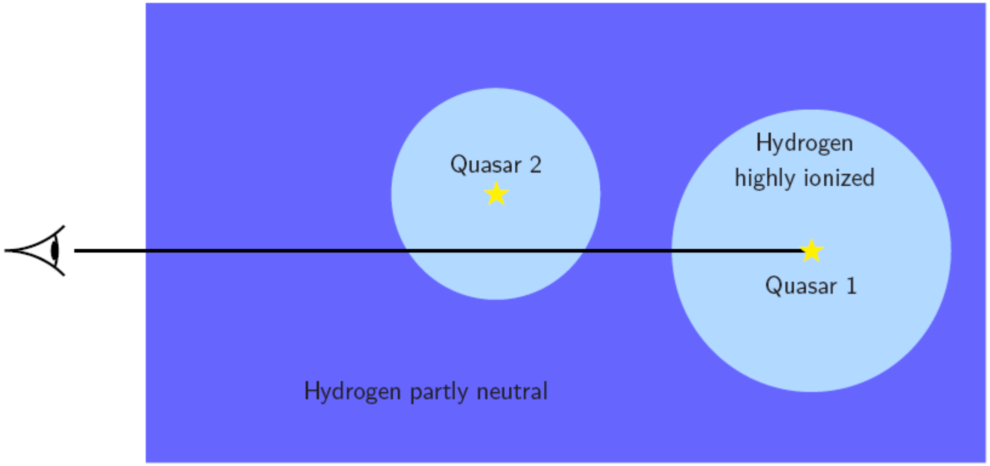
- Gas within quasars or in gas clouds or galaxies between us the and quasar can produce absorption lines.

Diffuse intergalactic medium

- If diffuse IGM is neutral, it should absorb light shortward of Lyα, $\lambda < 1216$ Å.
- Expect jump in continuum radiation from quasars between the red and blue sides of their Lyα line, S(blue)/S(red) = $e^{-\tau}$ where $\tau \sim 6\times10^{10}$ (n_{HI}/cm^{-3}) at $z = 0$.
- If $\Omega_{HI} \geq 10^{-6}$ then $\tau > 1$ and universe is opaque.
- For $z < 3$, find $\tau < 0.05$; for $z \sim 5$, find $\tau < 0.1$.
- From these limits, find n_{HI}(comoving) $< 3\times10^{-13}$ cm^{-3} or $\Omega_{HI} < 3\times10^{-8}$.
- Compare with baryon density from BBN, $\Omega_b = 0.04$.
- Hydrogen in a diffuse component of the intergalactic medium must be essentially fully ionized.

- Searching for this gas in the nearby universe ($z \sim 0$), figuring out when the ionization occurred ("reionization"), and explaining what caused reionization are major topics of current interest.

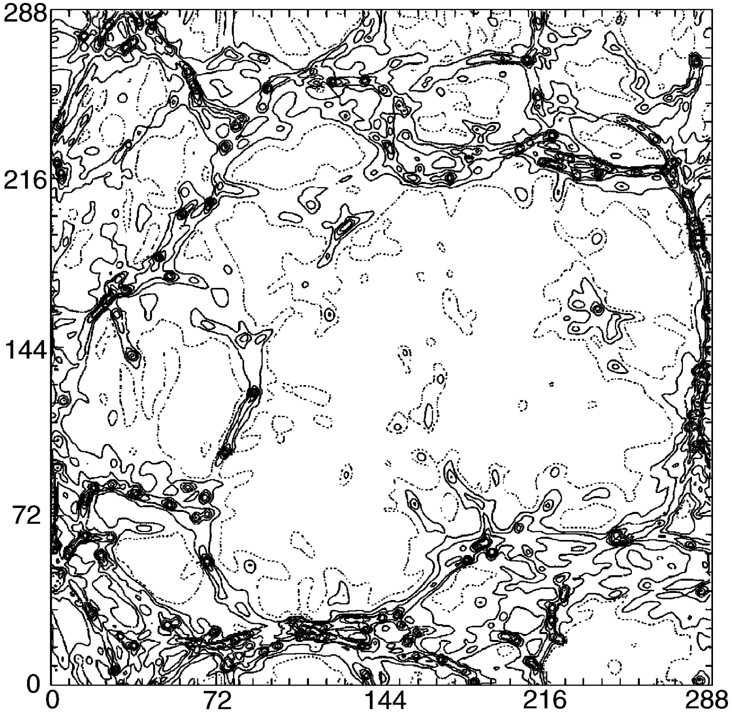
Lyman α forest



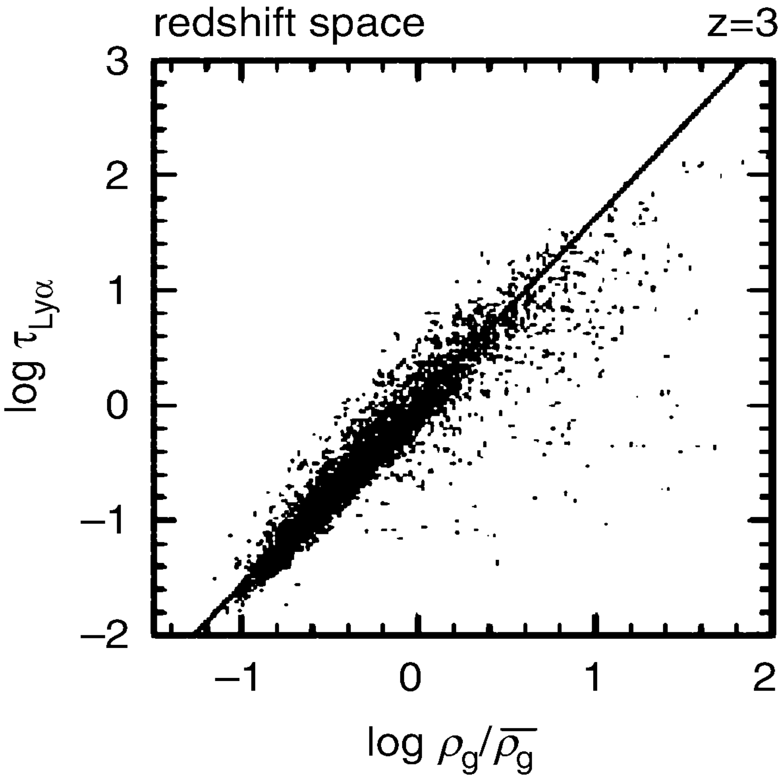
- We do see Lyα absorption features in spectra of distant quasars.
- Can determine HI column density from line strength.
- Widths of lines often ~ 10,000 km/s, origin?
  - Massive cluster, outflow, or thermal (~10^4 K)
- Proximity effect: quasars ionize nearby gas, suppressing Lyα forest.

Lyman α forest

- How did Lyα forest arise?
- Galaxies and clusters formed when baryons fell into dark matter gravitational potential wells after recombination.
- Gas clouds in the Lyα forest formed the same way. However, smaller density perturbations produced smaller baryon concentrations.
- These smaller perturbations are better described by linear theory.
- Lyα forest can be probed to higher *z* than galaxy and cluster distributions, up to *z* ~ 4.
- Can do same sorts of statistics (power spectrum, correlation function) as with galaxies but have disadvantage that probes are along a limit number of lines of sight.



Lyman α forest



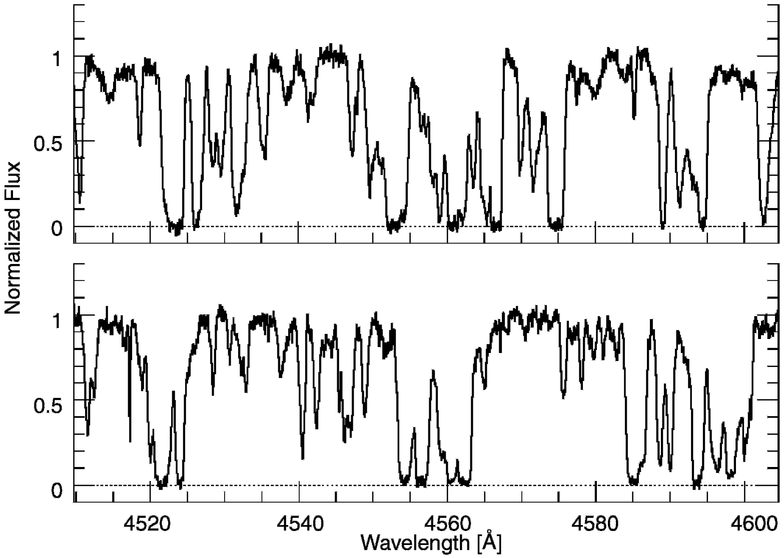
- Simulations follow evolution of dark matter. Must convert dark matter perturbations into gas density perturbations and then into the observable which is optical depth of Lyα absorption.

- Optical depth of absorption depends on density of gas and path length through the gas = size of region.

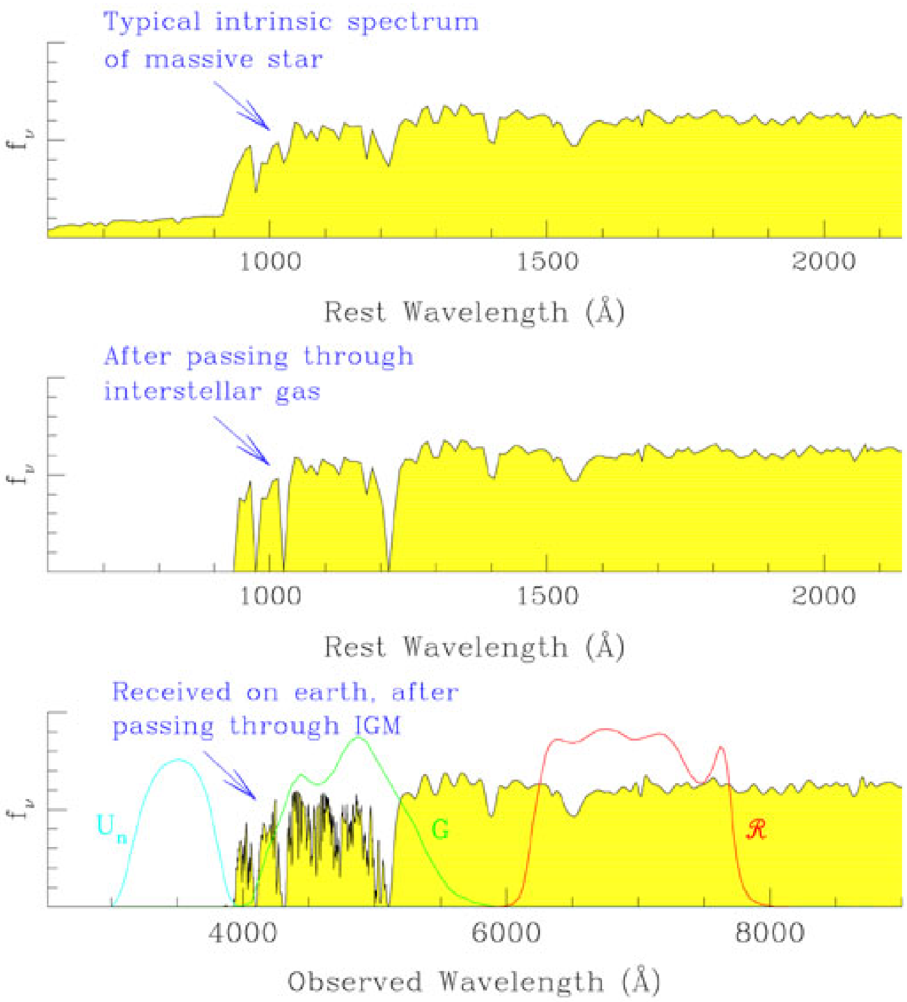
- As gas falls into potential well, it gains energy and heats up. Thus, temperature depends on density.

- This provides relation to convert simulation results into simulated spectra.

- Figure shows two spectra, one simulated, one observed.

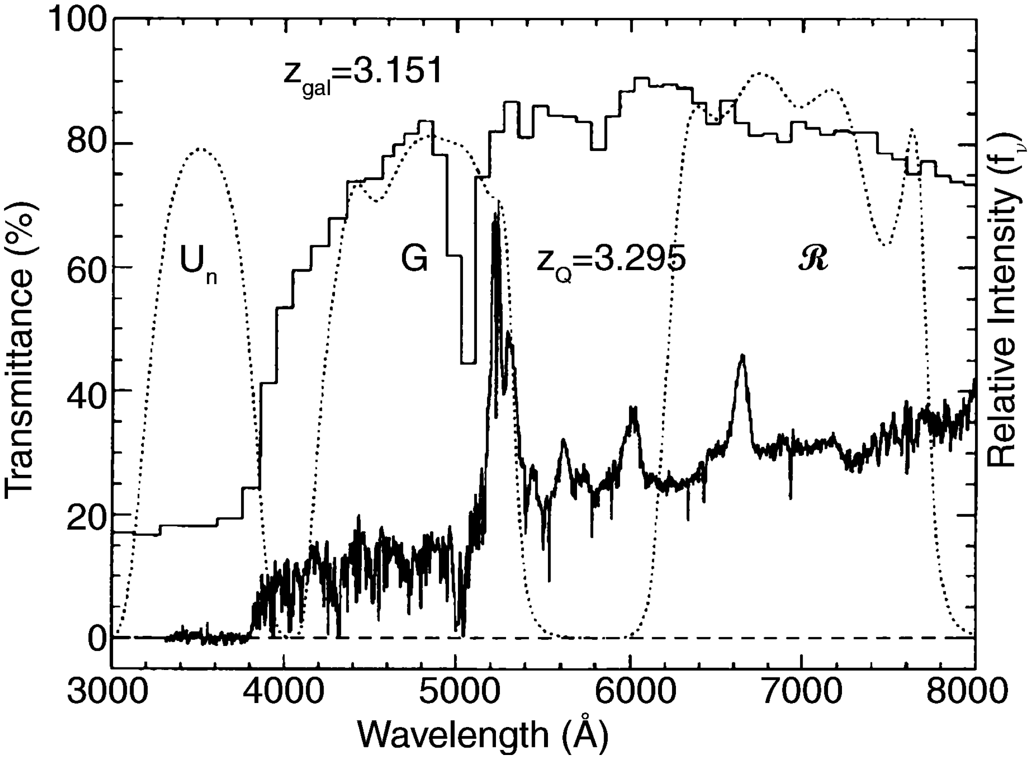


Galaxy Spectra



- Could measure spectra of lots of galaxies and search for redshifted lines. Inefficient. Why?
- What sort of galaxies does one expect at high redshifts?
- Emission is mostly from massive stars.
- Spectra of massive stars extend into the UV, but are cut off at the "Lyman break" by interstellar gas. Why?
- How to search for Lyman break?

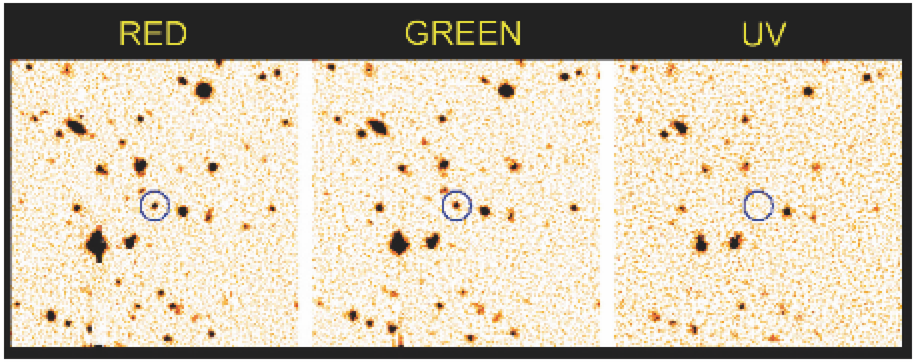
Finding high *z* galaxies

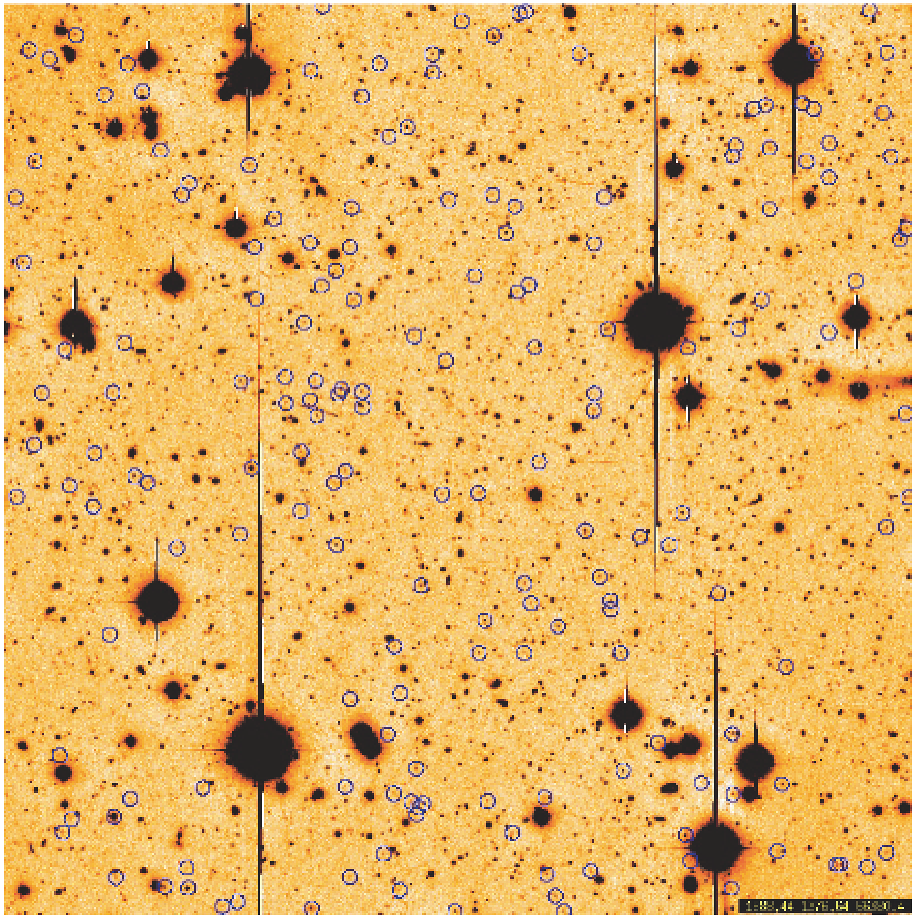


- Search for cutoff in spectrum at Lyman limit 912 Å
  - Requires hydrogen gas in galaxy or IGM
  - Requires emission extending to the UV – star forming galaxies
  - Need 3 filters: $\lambda_1 < (1+z)\, 912Å < \lambda_2 < \lambda_3$

Lyman break galaxies

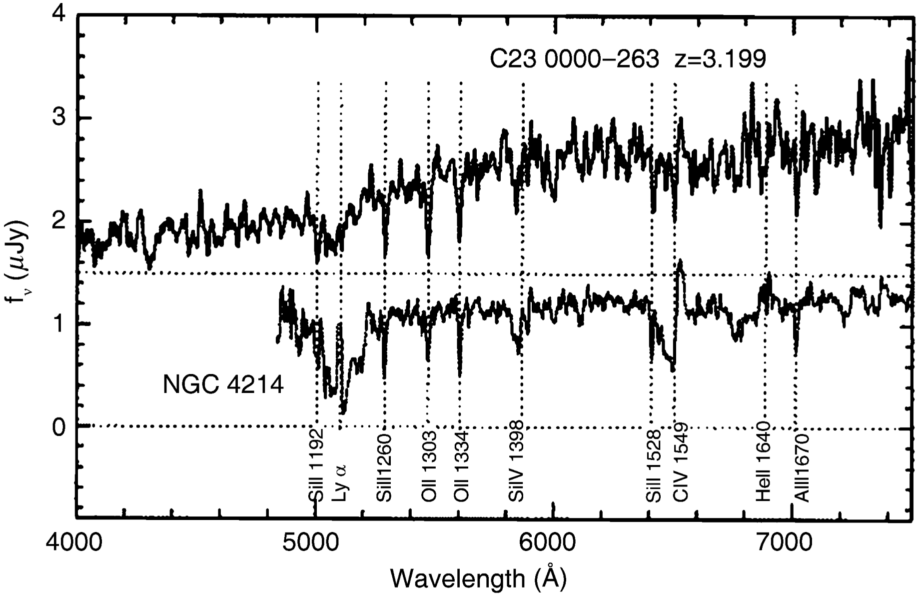
- Galaxy is visible in the two longer wavelength filters.
- Due to young stellar population, galaxy appears blue in these two filters.
- Expect galaxy to be brighter at shorter wavelengths, but it disappears or “drops out” due to absorption shortward of Ly α.
- Called Lyman break or drop out galaxies.
- Very effective technique to find large numbers of high *z* galaxies.
- Select *z* of interest by choosing filter bands.
- First done with U-band, so Lyman break often refers to galaxies found at *z* ~ 3.

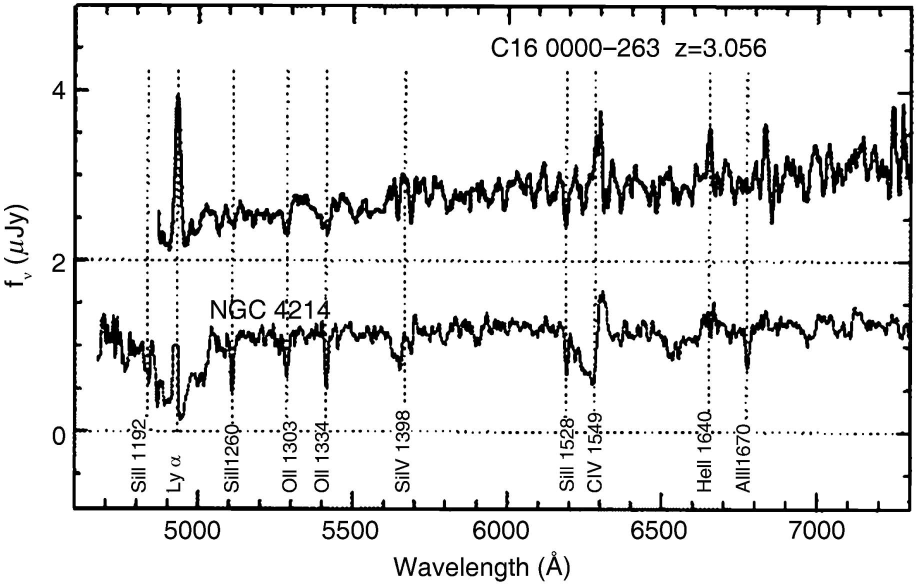




Lyman break galaxies

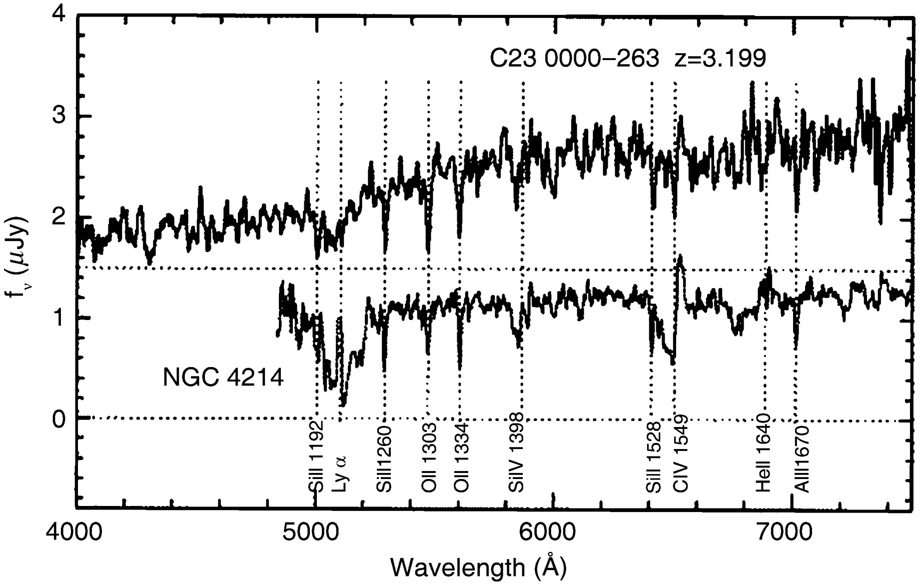
- Redshifts can be confirmed spectroscopically.
- Spectrum also reveals galaxy type.
- Tend to find star forming galaxies.
- Spectra are (typically) very similar to nearby star forming galaxies.
- Many of the galaxies lack a Ly α emission line.



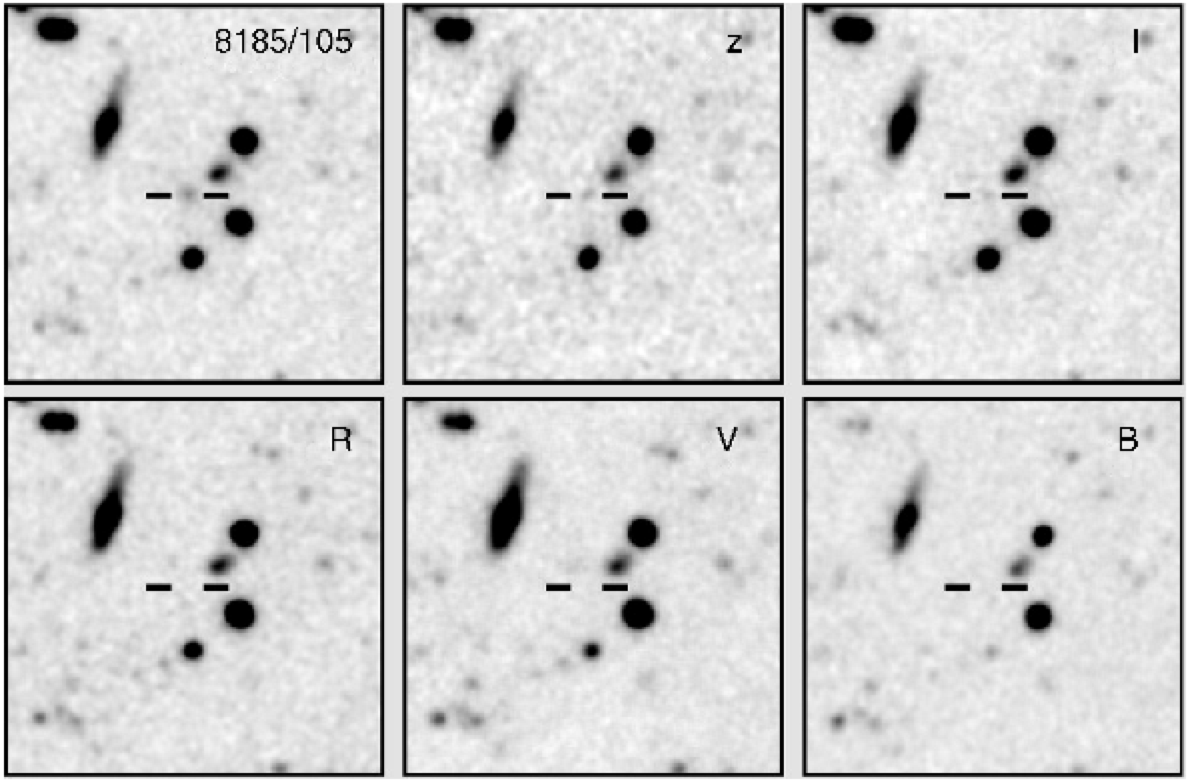


Winds from LBGs

- Spectra of some LBGs reveal features due to winds: broad emission line with absorption on blue wing (p-Cygni profile).
- Expect large numbers of supernovae due to high star formation rates.
- These SN release kinetic energy into the ISM that can drive winds either from the star forming region or whole galaxy.
- These winds provide a means to transport metals into the intergalactic medium.
- Supporting evidence for winds transporting metals at least 40 kpc from LBGs come from quasar absorption lines close to LBGs that show metal absorption lines.



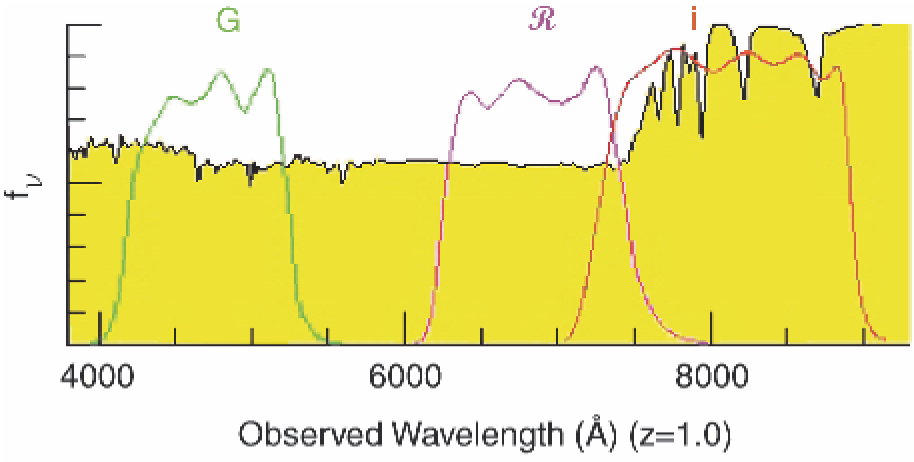
LBGs at high and low *z*

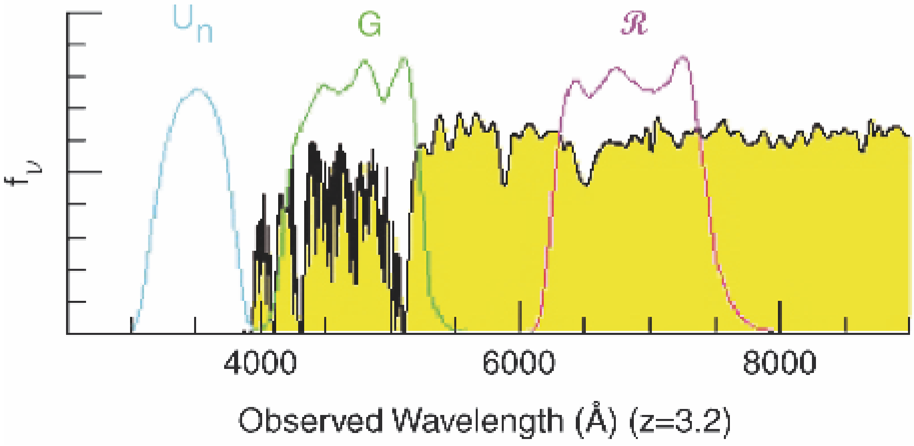


- Local analogs to LBGs can be found by looking in the UV. This became possible with flight of the GALEX satellite that did several (not all sky) surveys in the far UV.
- UV-selected galaxies show an inverse correlation between stellar mass and surface brightness – low mass UV-selected galaxies have more concentrated star formation.
- Compact UV-selected galaxies have properties similar to LBGs, e.g. low metallicity.
- Find LBGs at high *z* by adjusting choice of filters. B-band drop outs → *z* ~ 4.5. I-band drop outs → *z* ~ 5.5, but difficult to do from ground due to night sky.

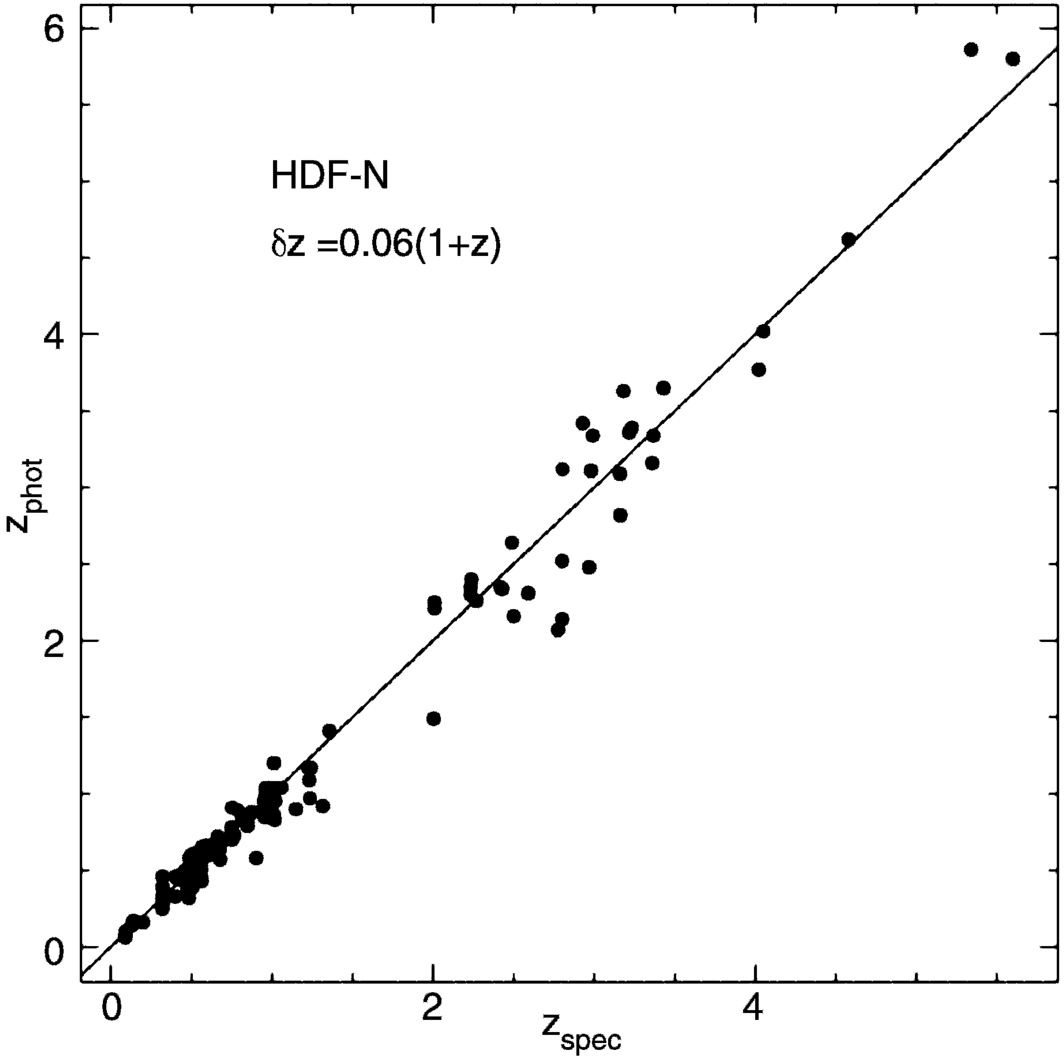
Photometric redshifts

- Galaxies tend to have spectral features at the Lyman edge (~1000 Å) and at the Balmer edge (~4000 Å).
- Using photometry in multiple bands, preferably covering the optical and NIR, one can use these features to determine the galaxy redshift.
- The overall shape is determined by the galaxy type, so one fits for redshift and galaxy type simultaneously.



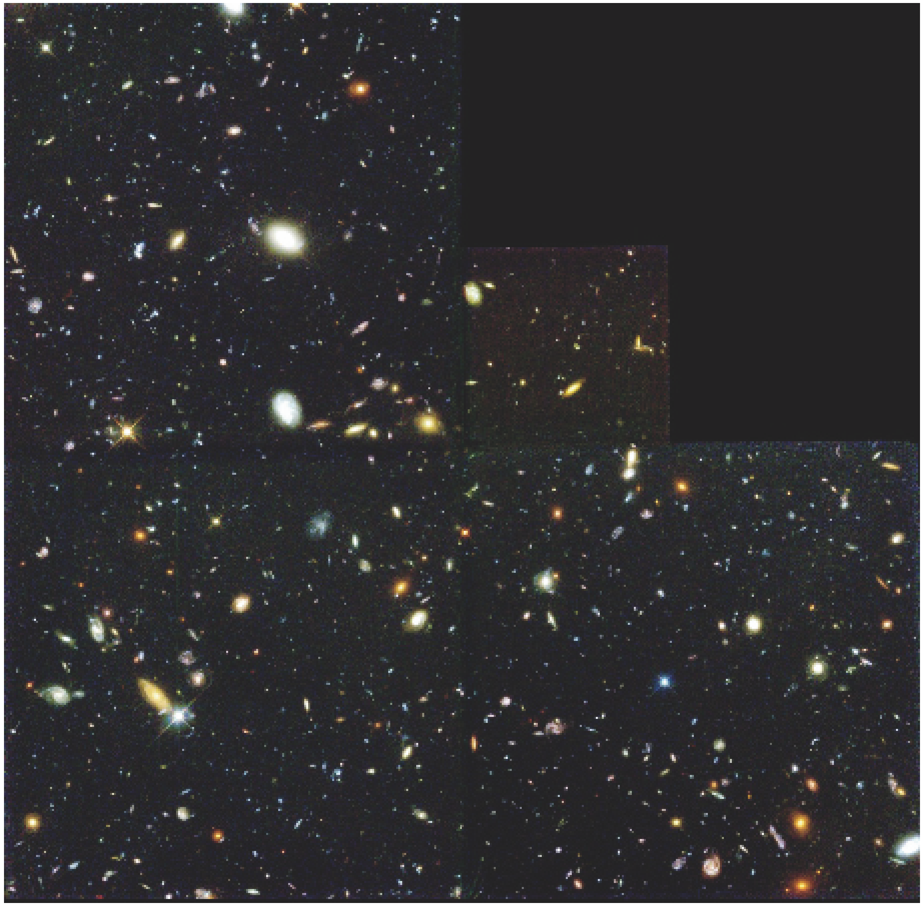


Photometric redshifts



- Photometric redshifts, “photo-*z*s”, can be determined to 0.03(1+*z*) using multiple, narrow filters with excellent photometry.
- More typically, the accuracy is ~0.1(1+*z*).

Hubble deep field



- Images in 4 bands with deep exposures, total of 10 days.
- Data publicly available immediately.
- Field contains ~3000 galaxies and less than 20 stars.
- Has ~30 galaxies with $z > 2$.
- Followed by HDF-S and Hubble Ultra-Deep Field.

Hubble ultra-deep field

Hubble Ultra Deep Field HST · ACS

NASA, ESA, S. Beckwith (STScI) and The HUDF Team STScI-PRC04-07a

- Larger field (3.4') due to installation of ACS and one magnitude deeper than HDF.
- More than ~10,000 galaxies, redshifts as high as 6.
- Wider surveys:
  - GOODS: two 10' by 16' fields with HST, Chandra, Spitzer, ….
  - COSMOS: 2 $\deg^2$ field with HST, Spitzer, XMM-Newton, Chandra, GALEX, ...

Homework

For next class: problems 9.5 and 9.6