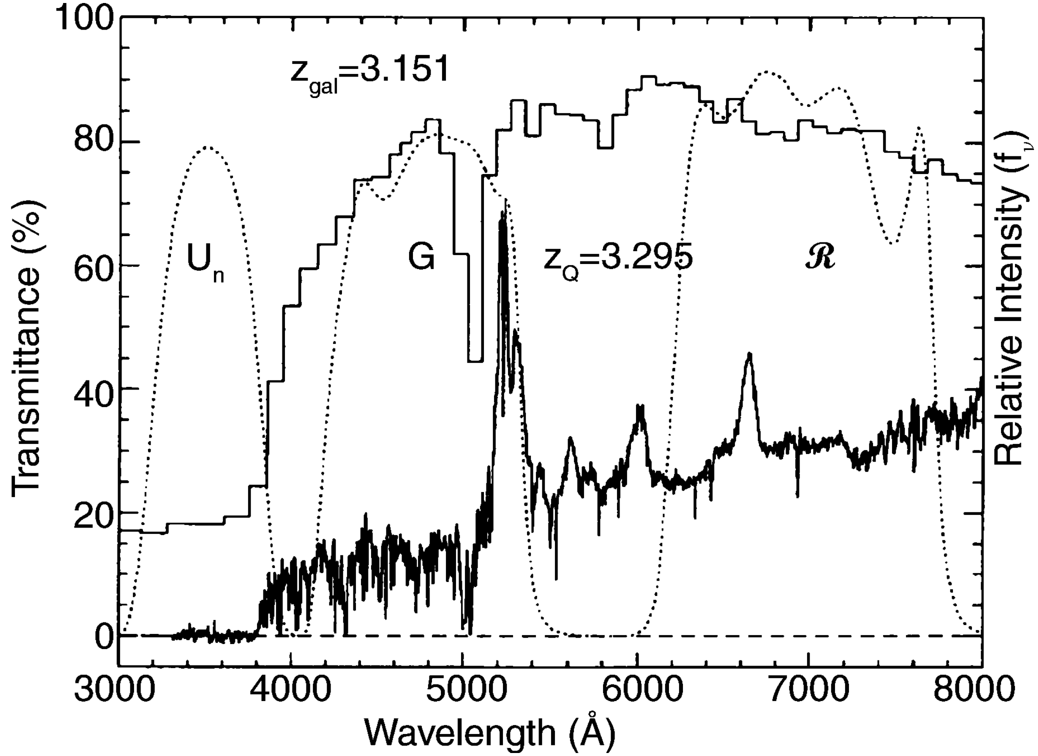
High Redshift Universe

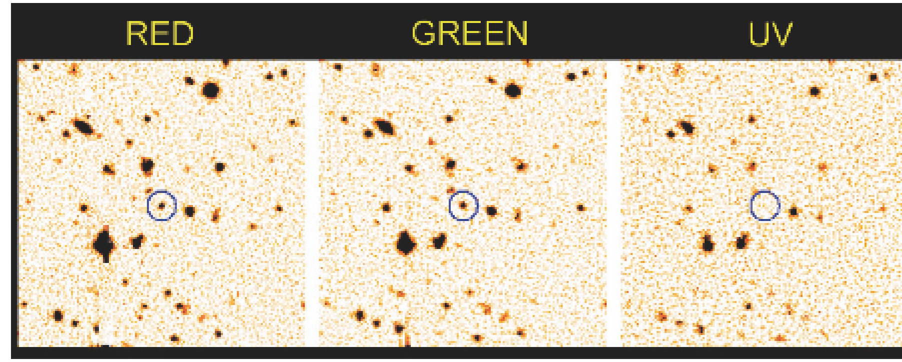
- Finding high *z* galaxies
- Lyman break galaxies (LBGs)
- Photometric redshifts
- Deep fields
- Starburst galaxies
- Extremely red objects (EROs)
- Sub-mm galaxies
- Lyman α systems

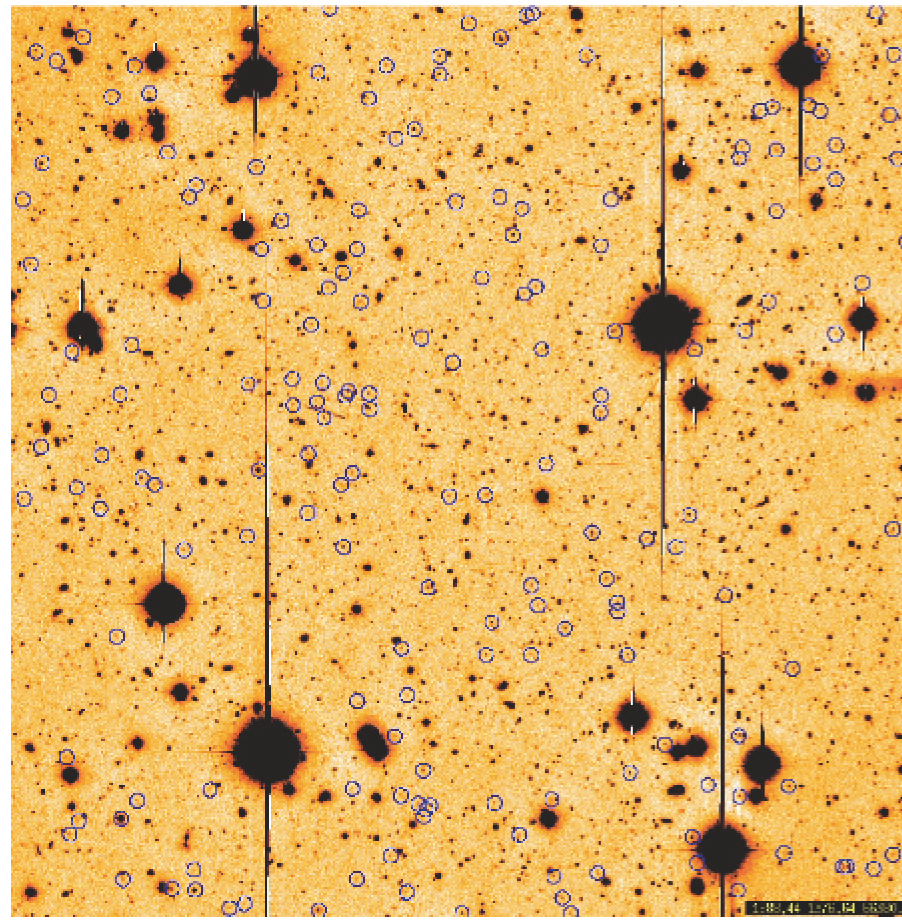
Finding high *z* galaxies



- Take spectra of many galaxies
  - Inefficient and requires time on large telescopes
- Instead, use (narrow band imaging).
- Search for Lyman α line at 1216 Å.
  - Depends on strong line emission from galaxy, is not effective
- 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: $\lambda_1 < (1+z)\,912\text{Å} < \lambda_2 < \lambda_3$

Lyman break galaxies

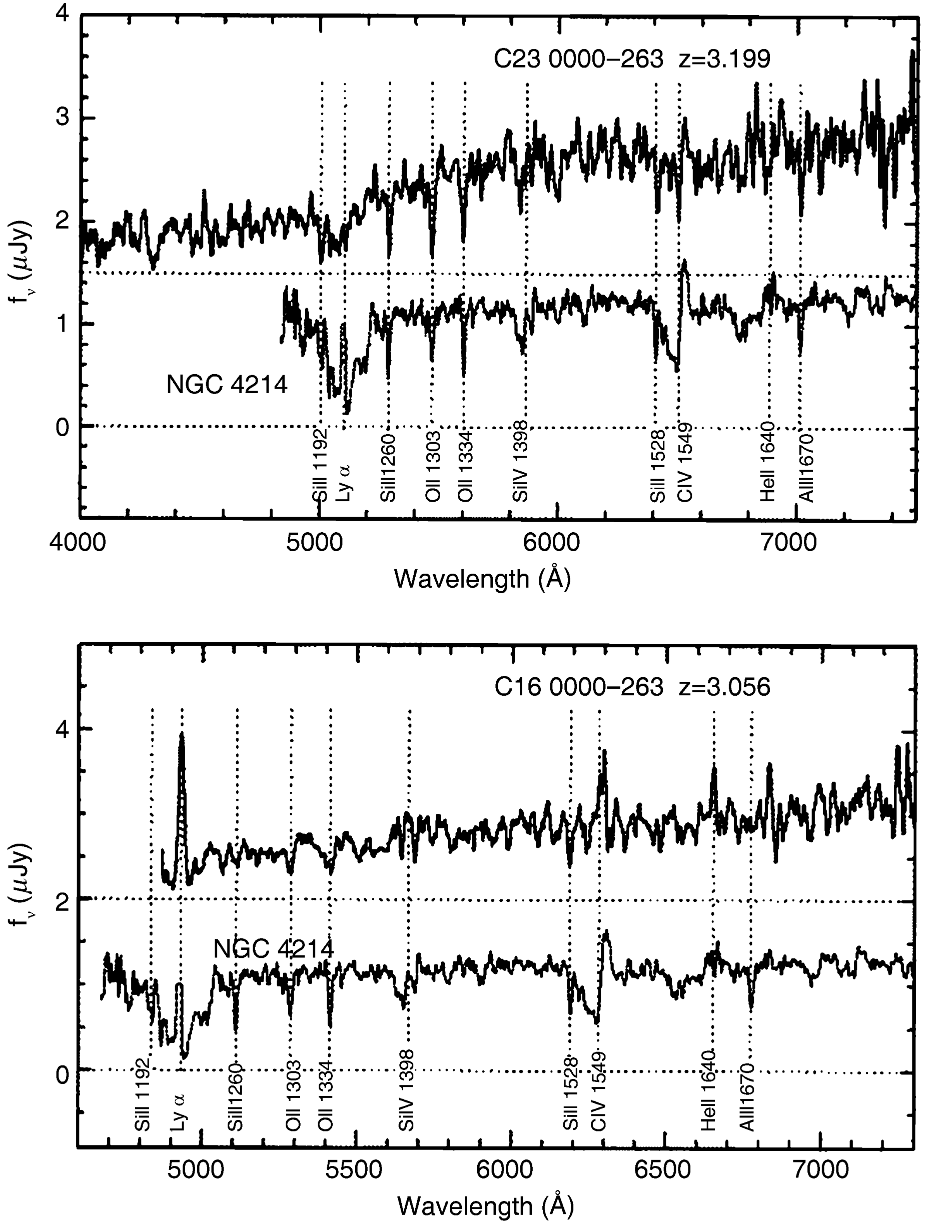




- Galaxy is visible in the two longer wavelength filters.
- Due to young stellar population, galaxy appears blue in these two filters.
- Expect galaxy to be brighter at shorter wavelengths, but it disappears or "drops out" due to absorption shortward of Ly α.
- Called Lyman break or drop out galaxies.
- 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 $z \sim 3$.

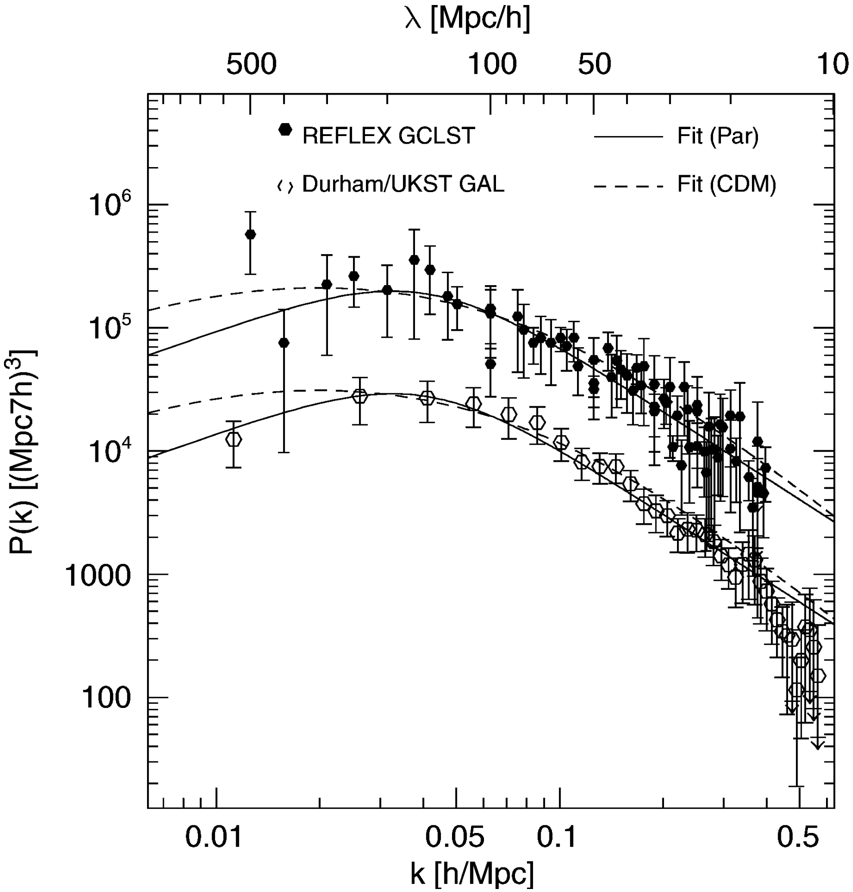
Lyman break galaxies

- 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.



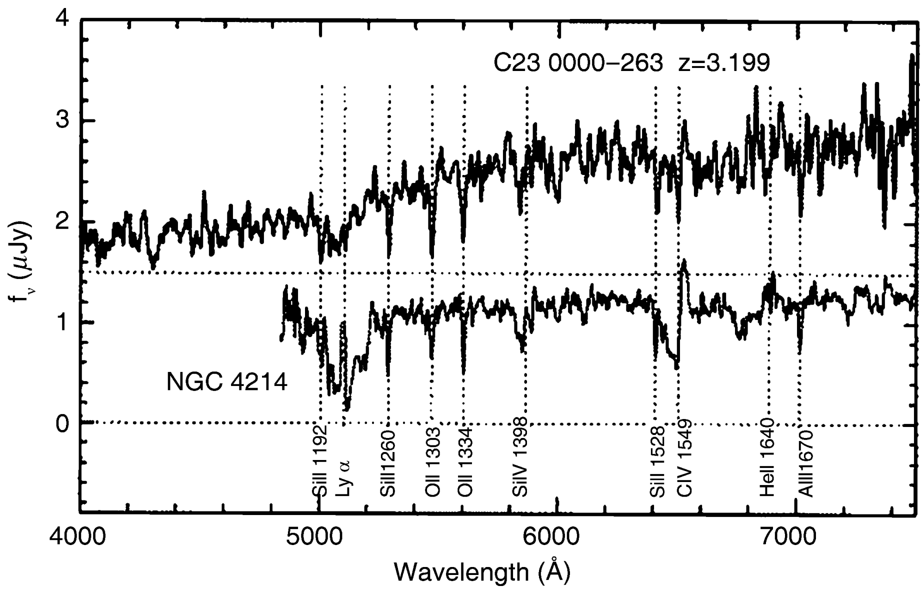
Clustering of Lyman break galaxies

- Recall that power spectrum for clusters has higher amplitude that than for field galaxies.
- This is because clusters correspond to high mass dark matter halos and have a stronger bias, $b_{\text{clus}} \sim 2.6\, b_{\text{g}}$.
- Power spectrum amplitude for LBGs is similar to that of clusters → LBGs correspond to high mass dark matter halos, but not as large as whole clusters.
- Estimate characteristic halo mass to be $\sim 3\times10^{11}$ M_{Sun} at $z \sim 3$ and $\sim 10^{12}$ M_{Sun} at $z \sim 2$.
- Comparing with local correlation function, find that LBGs at $z \sim$ 2-3 are likely progenitors of elliptical galaxies.
- Find concentrations of LBGs.
  - Identify these as proto-clusters.
  - These LBGs have older stars – star formation is faster in dense environments.

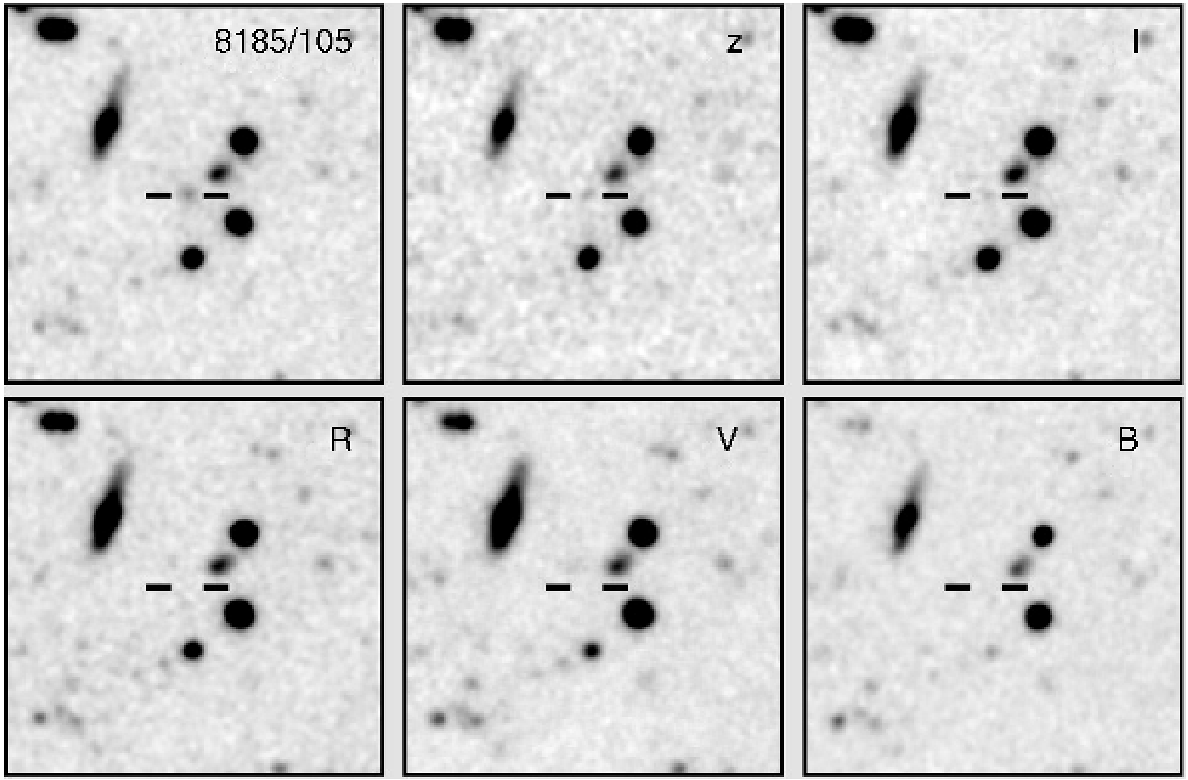


Winds from LBGs

- 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.



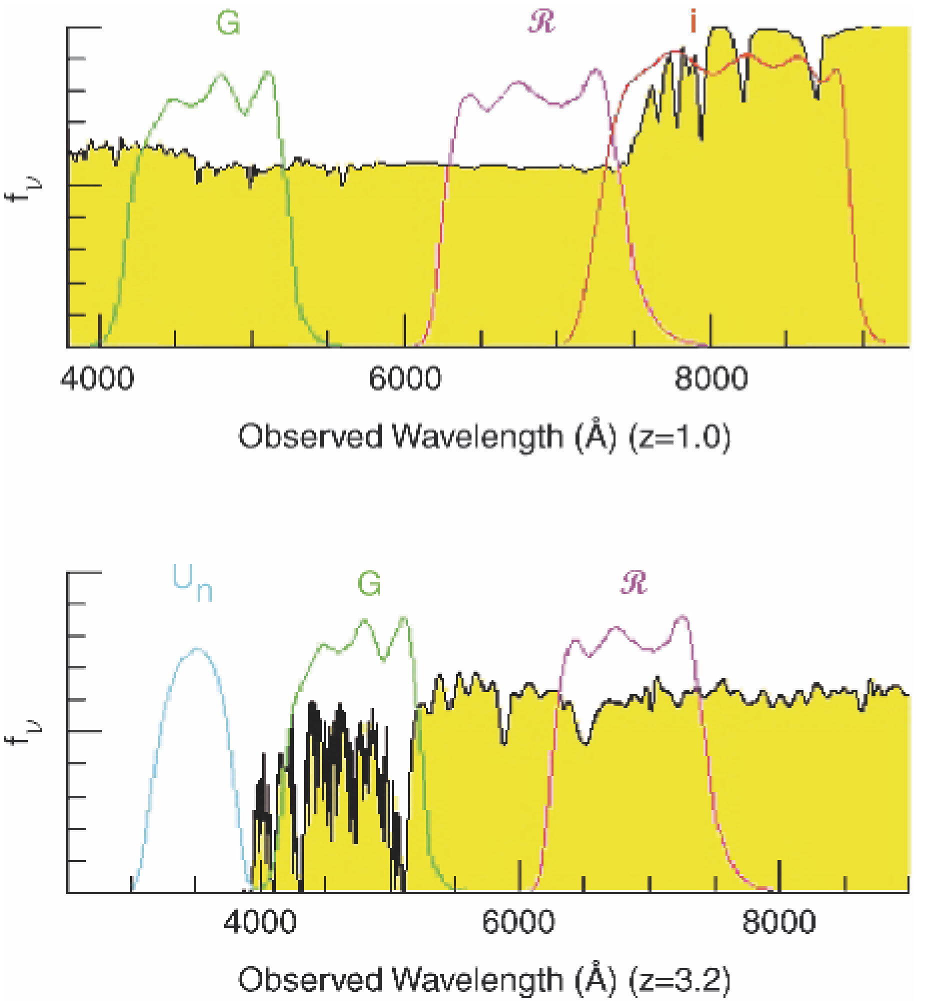
LBGs at high and low *z*



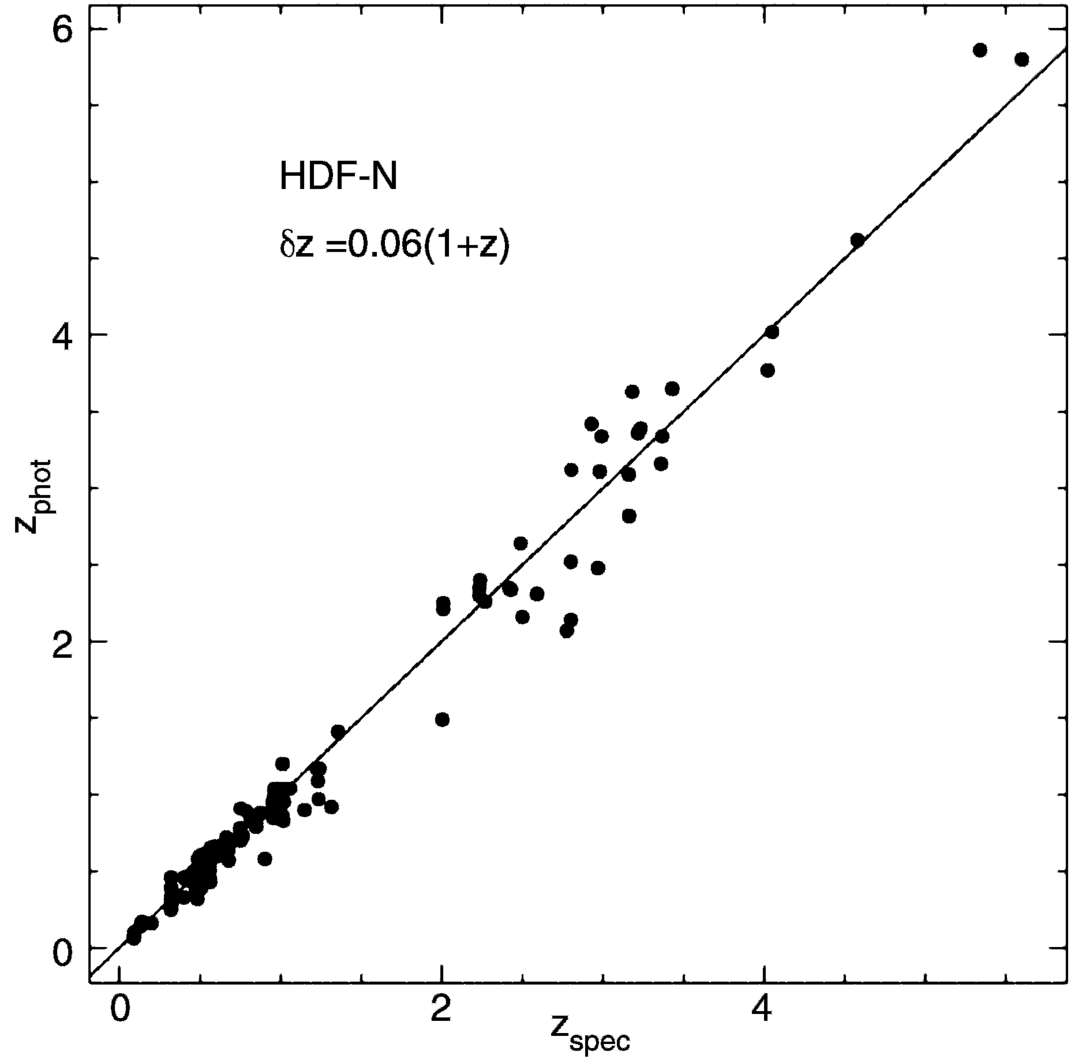
- Local analogs to LBGs can be found by looking in the UV. This became possible with flight of the GALEX satellite that did several (not all sky) surveys in the far UV.
- UV-selected galaxies show an inverse correlation between stellar mass and surface brightness – low mass UV-selected galaxies have 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 → $z \sim 4.5$. I-band drop outs → $z \sim 5.5$, 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.

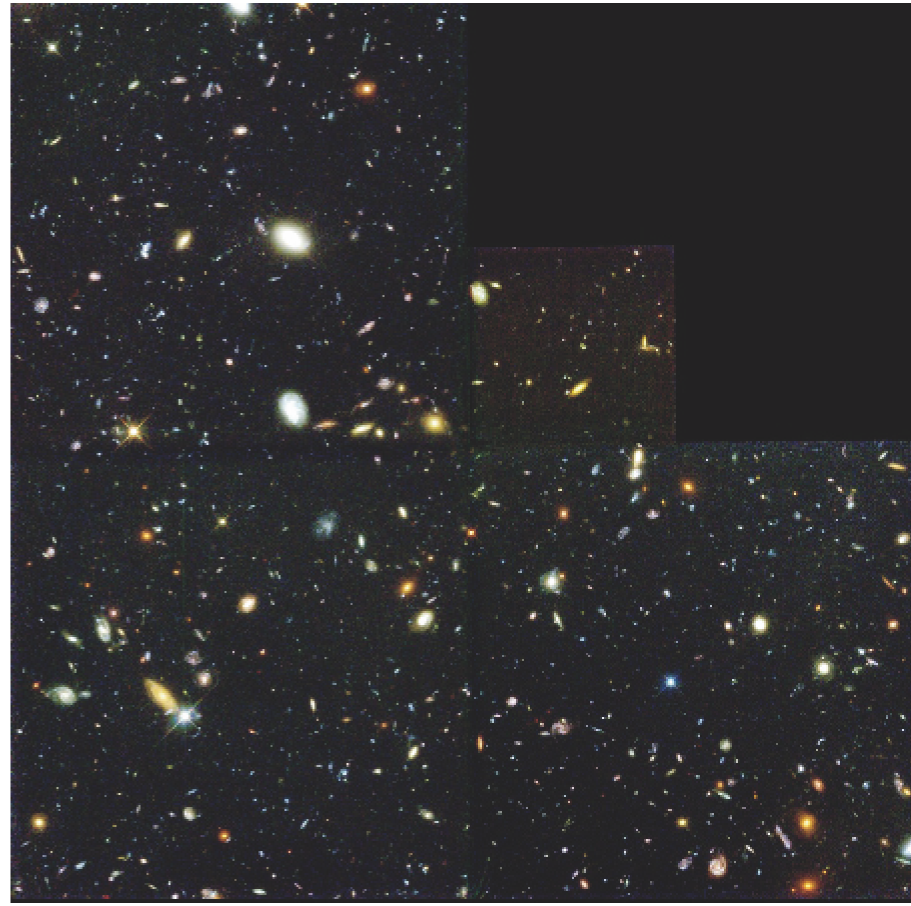


Photometric redshifts



- 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*).

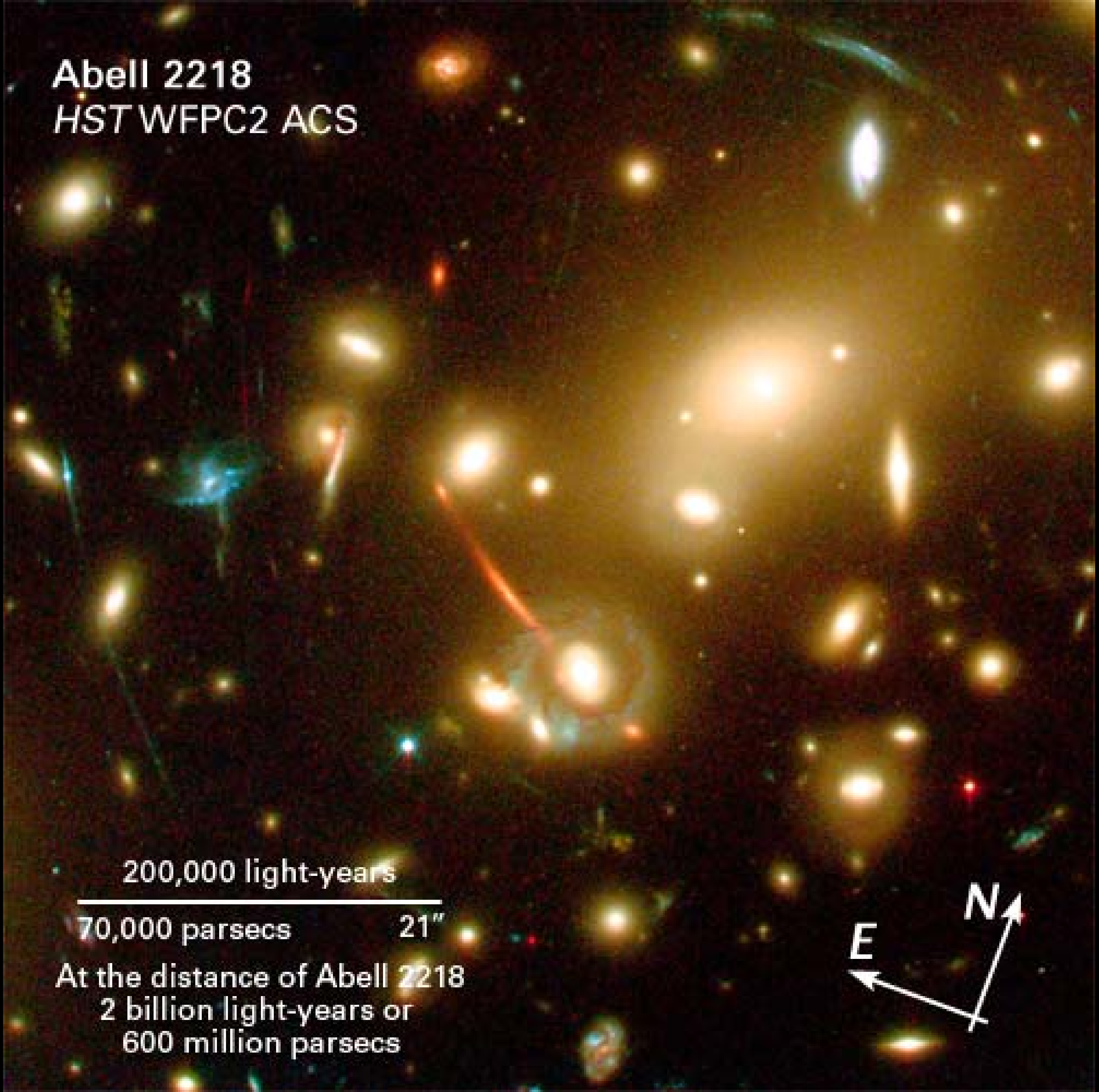
Hubble deep field



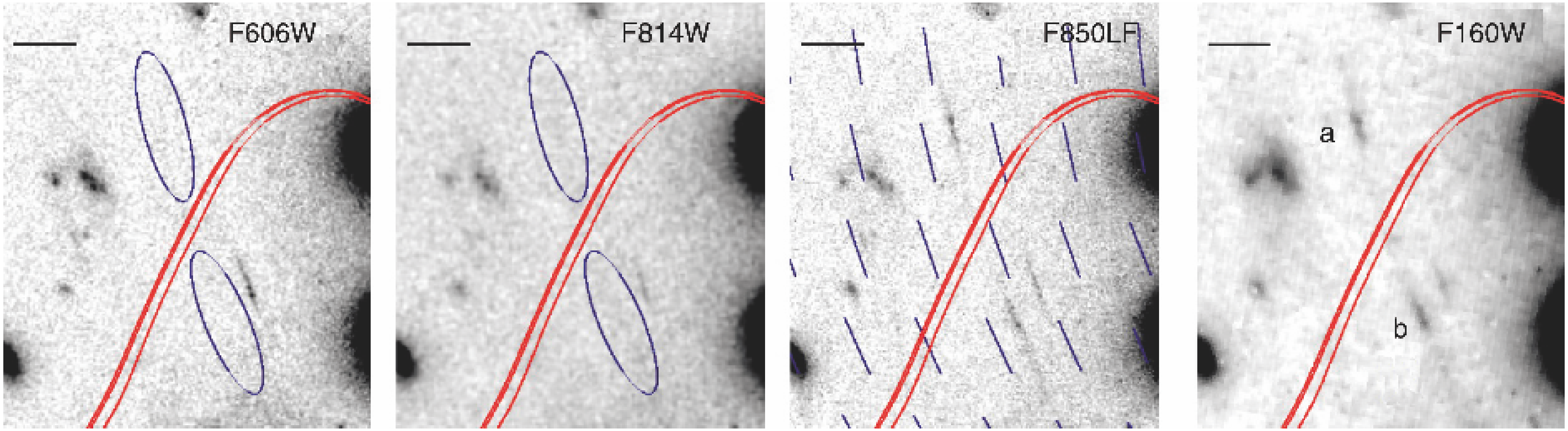
- Images in 4 bands with deep exposures, total of 10 days.
- Data publicly available immediately.
- Field contains ~3000 galaxies and less than 20 stars.
- Has ~30 galaxies with $z > 2$.
- Followed by HDF-S and Hubble Ultra-Deep Field.

Hubble ultra-deep field

- 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, ...

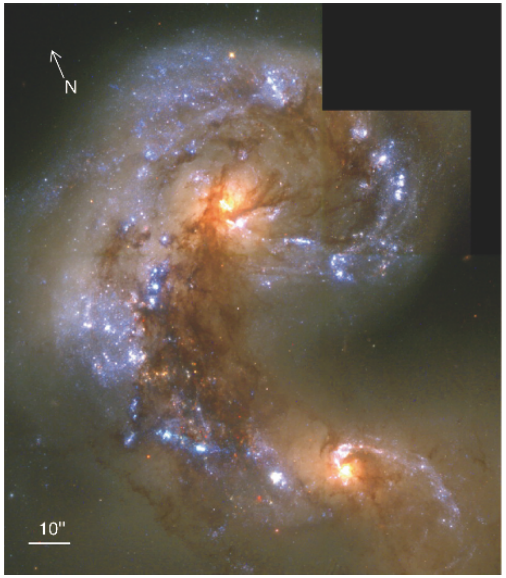

Abell 2218
HST WFPC2 ACS
200,000 light-years
70,000 parsecs
21″
At the distance of Abell 2218
2 billion light-years or
600 million parsecs
N
E

Gravitational lenses

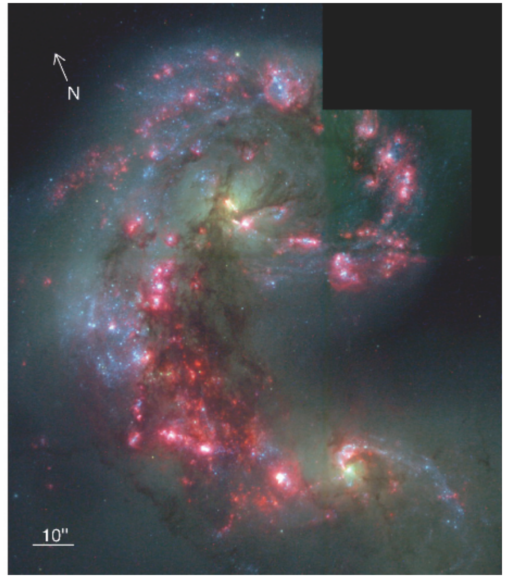


- High z galaxies observed tend to be at the high end of luminosity distribution.
- Feasible to get spectra for L* galaxies to $z \sim 3$.
- Gravitational lensing can magnify by factors > 5.
- Factor of 5 flux increase leads to decrease in exposure by factor of 25.
- Galaxy shown here is magnified by a factor ~25.

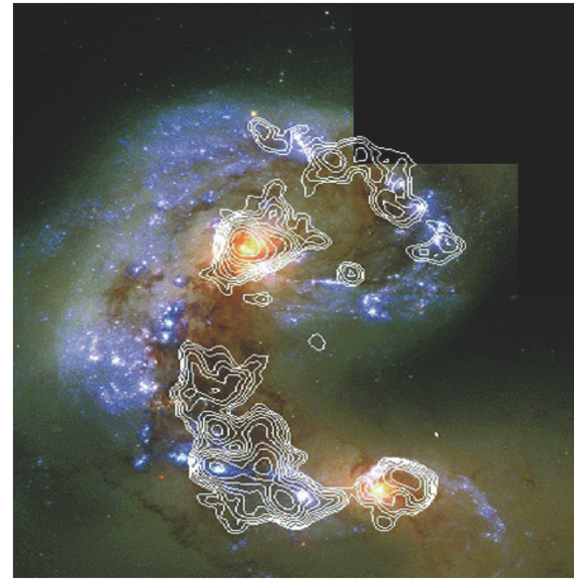
Starburst galaxies



Optical



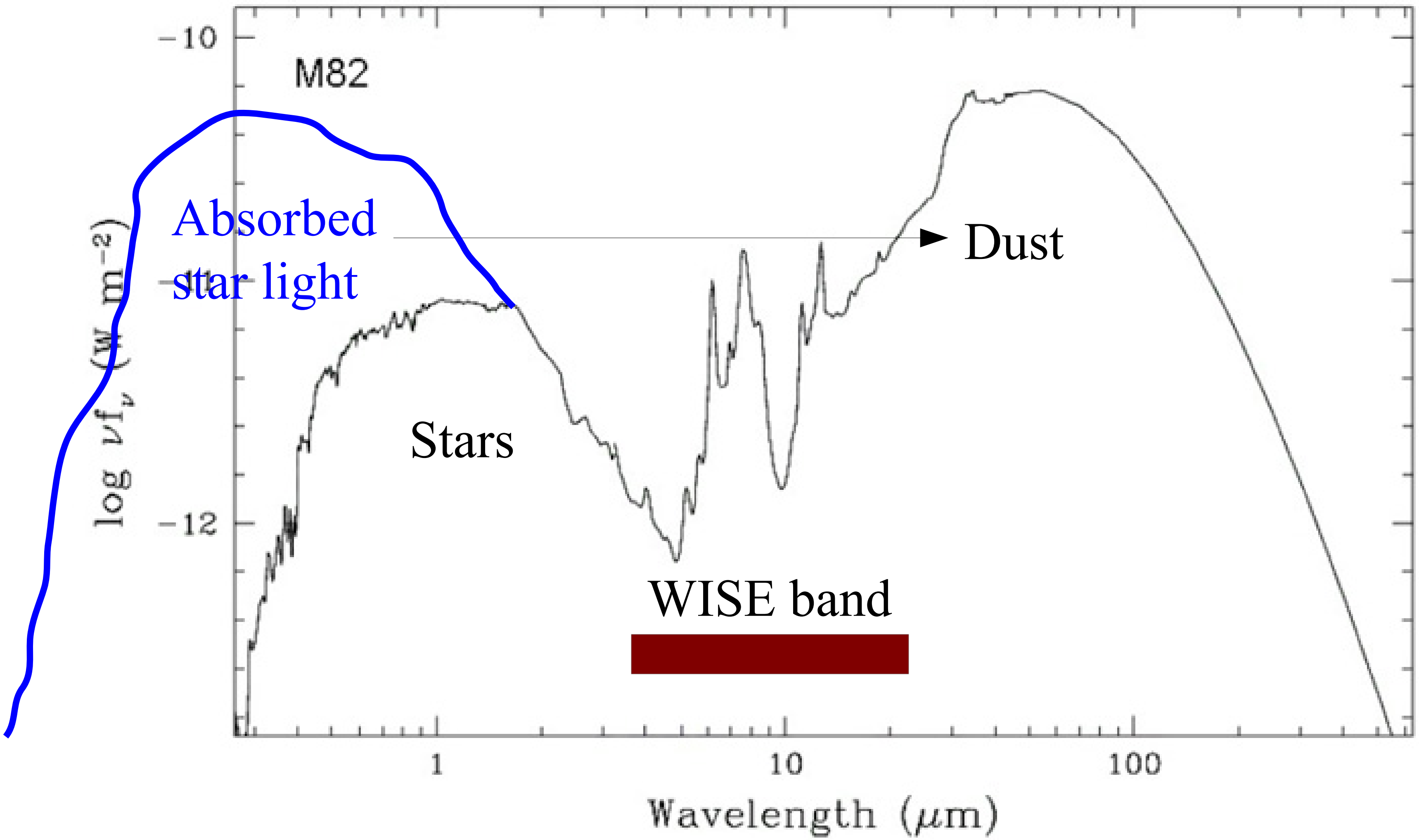
Red = Hα



Contours = IR

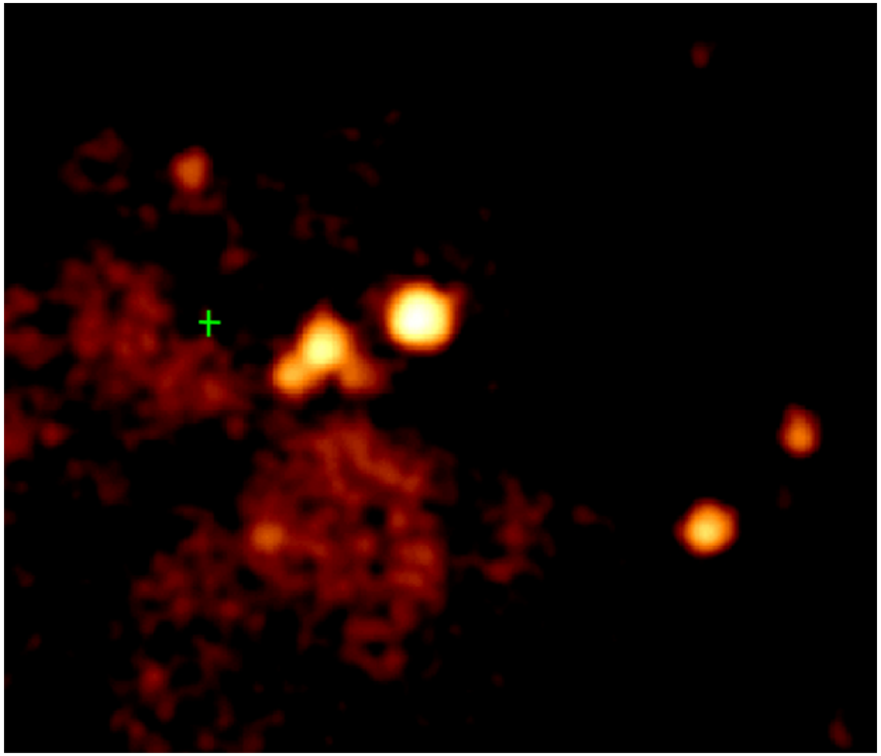
- Images of Antennae galaxies – interacting and starburst
- Young stars 5-10 Myr, also an older population 100-500 Myr
- Active star formation in regions of high gas and dust density
- UV/blue radiation reprocessed into IR

Spectral energy distribution of M82



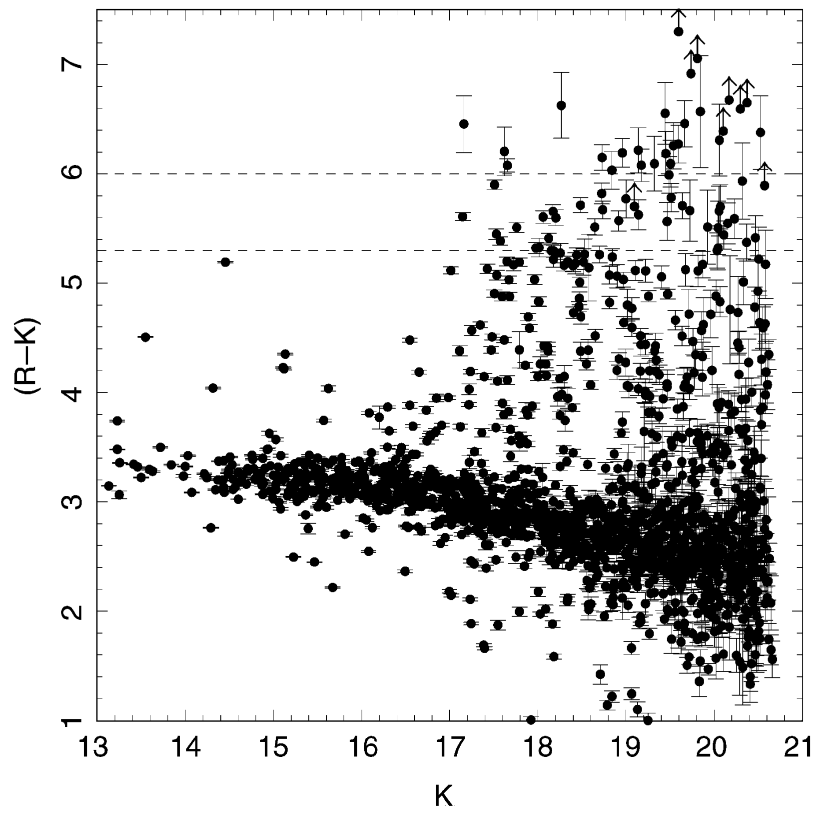
Absorbed star light heats dust clouds that radiate in the IR

Ultraluminous X-ray sources



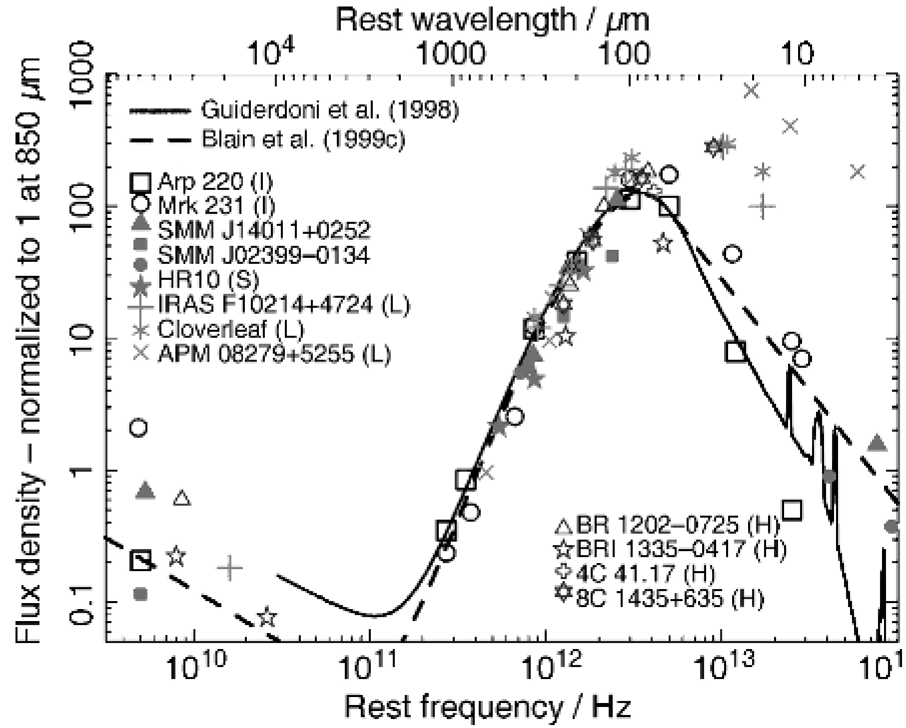
- Starburst galaxies host bright, variable X-ray sources likely to be accreting black holes.
- If emission is isotropic and sources obey the Eddington limit, some of these may be "intermediate mass" black holes with masses > 200 M_{Sun}.
- IMBHs spiral into center of galaxy due to dynamical friction, could be a path for the formation of supermassive black holes.

Extremely red objects (EROs)



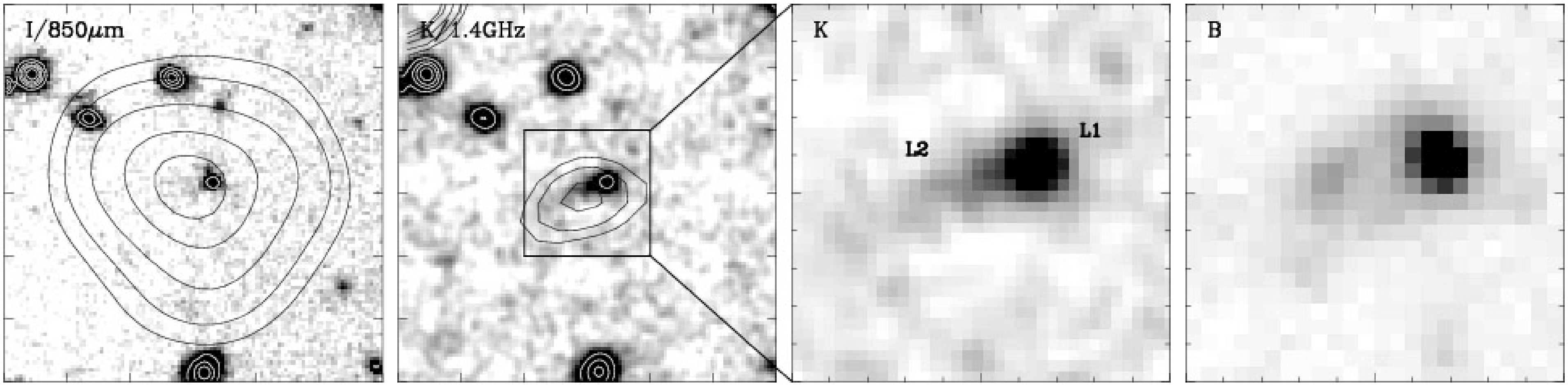
- NIR surveys reveal EROs, dim objects with R-K > 5. (K = 2.2 μm).
- Half are elliptical galaxies with 4000 Å break between R and K.
  - Galaxies are at $z \sim 1$ and have old stellar populations that formed at $z > 2.5$.
- Half are star-forming galaxies with star formation enshrouded by gas and dust
  - Star formation confirmed by radio and [OII] line emission
  - Ultraluminous infrared galaxies (ULIRGs) at ~ 1

Sub-mm galaxies



- Sub-mm telescopes (SCUBA) operating at 0.4-1.3 mm mainly see dust at 20-40 K.
- Spectrum $S_\upsilon \sim \upsilon^{2+\beta}$ with $1 < \beta < 2$. Redshift increases rest-frame υ and increasing spectrum leads to a negative K-correction.
- For $z_{max} > z > 1$, flux stays constant or increases.
- What sets z_{max}? For dust at 40 K and $\lambda \sim 0.85$ mm, $z_{max} \sim 8$.
- Luminosity function $N(>S) \sim S^{-1.1}$.

Sub-mm galaxies



- SCUBA positions good to ~15” making optical identification difficult.
- Counterparts identified in radio with VLA (1.4 GHz, 1”) and then in optical.
- Redshifts from optical or a sort of photo-*z* from radio/sub-mm flux ratio.
- Median $z \sim 2.5$. Galaxy masses ~ $10^{11}\ M_{\mathrm{Sun}}$ ~ 10× mass of LBGs.
- From mass, number density, and optical morphology, sub-mm galaxies are thought to be ellipticals in the process of formation.
- Many sub-mm have AGN revealed in X-rays, but X-ray/sub-mm ratio is low suggesting galaxies are dominated by star formation.

Lyman α systems

- Damped Ly α systems defined as Ly α absorbers with $N_H > 10^{20}$ cm^{-2}.
- Most of the neutral hydrogen visible in quasar absorption lines is in DLAs.
- At current time, neutral hydrogen in damped is 1/3 of hydrogen in stars.
- DLAs have low metallicity, 0.1 solar, suggesting little star formation.
- Line profiles suggest DLAs are disks rotating with speeds ~ 200 km/s.
  - May be spiral galaxies or proto-spirals
- Amount of gas in DLAs with $z < 1.5$ is comparable to HI in local galaxies.
  - Suggests DLAs are gas rich galaxies
  - Nearby DLAs also seen in emission, appear to be normal galaxies
- Amount of gas in DLAs at high z is 2× larger than HI in galaxies.
  - A few high z DLAs seen in emission
  - Unclear if galaxies or proto-spirals
- Lyman α blobs are extended, ~100 kpc, systems seen in Ly α emission
  - Could be misaligned quasars, star-forming galaxies, and/or gas accreted into dark matter halos

For next class

- Project presentations on November 12 (LT, BG, SM) and 14 (BS, MA, DD).
  - Should be full presentations with all results.
  - Each group will have 20 minutes with 5 minutes for questions.
- For after Thanksgiving, read rest of chapter 9 and do HW #9.