Outline

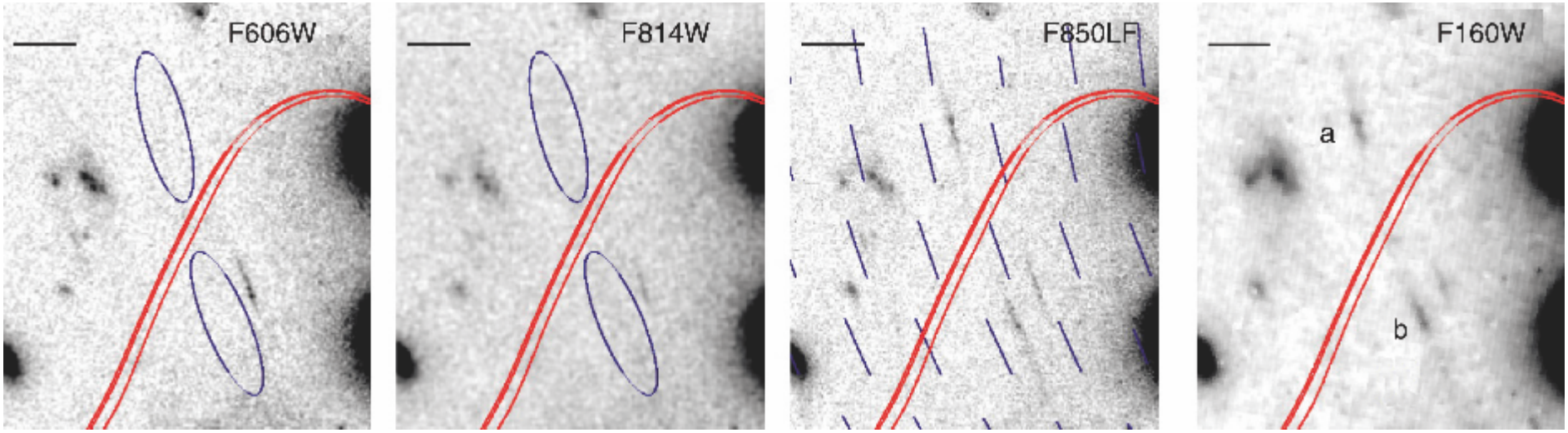
- Go over problems 9.5 and 9.6
- Other ways to find high z galaxies
- Gravitational lensing
- Starburst galaxies
  - Extremely red objects (EROs)
  - Sub-mm galaxies
- Lyman α systems

Hubble ultra-deep field

- How can one go deeper than HST?

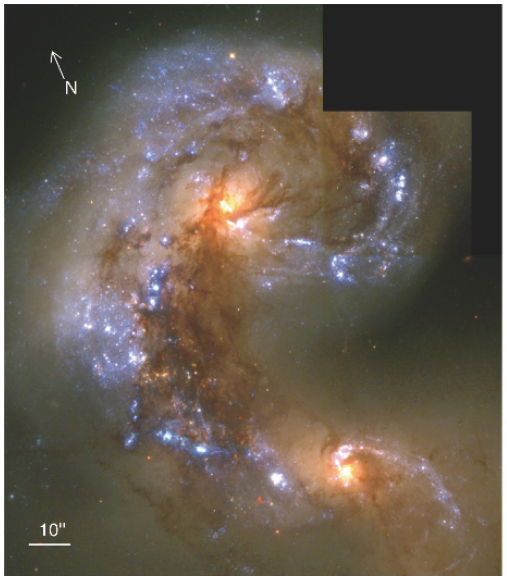

Abell 2218
HST WFPC2 ACS
200,000 light-years
70,000 parsecs
21″
At the distance of Abell 2218
2 billion light-years or
600 million parsecs
N
E

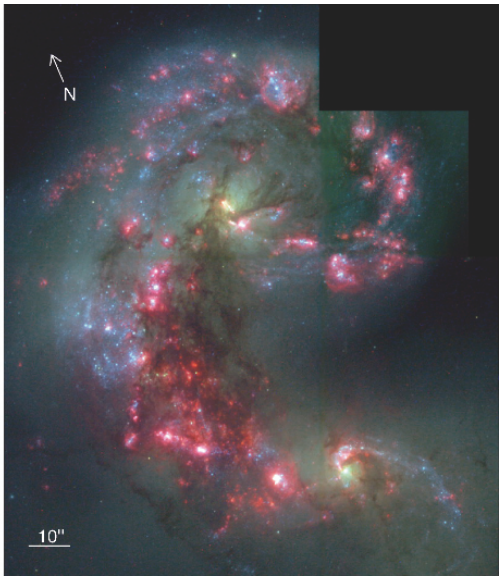
Gravitational lenses

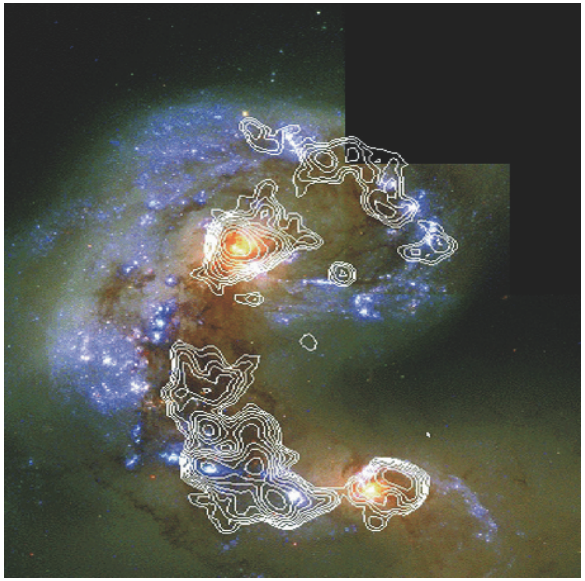


- High *z* galaxies observed tend to be at the high end of luminosity distribution.
- Feasible to get spectra for L* galaxies to $z \sim 3$.
- Gravitational lensing can magnify by factors > 5.
- Factor of 5 flux increase leads to decrease in exposure by factor of 25.
- Galaxy shown here is magnified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

Starburst galaxies







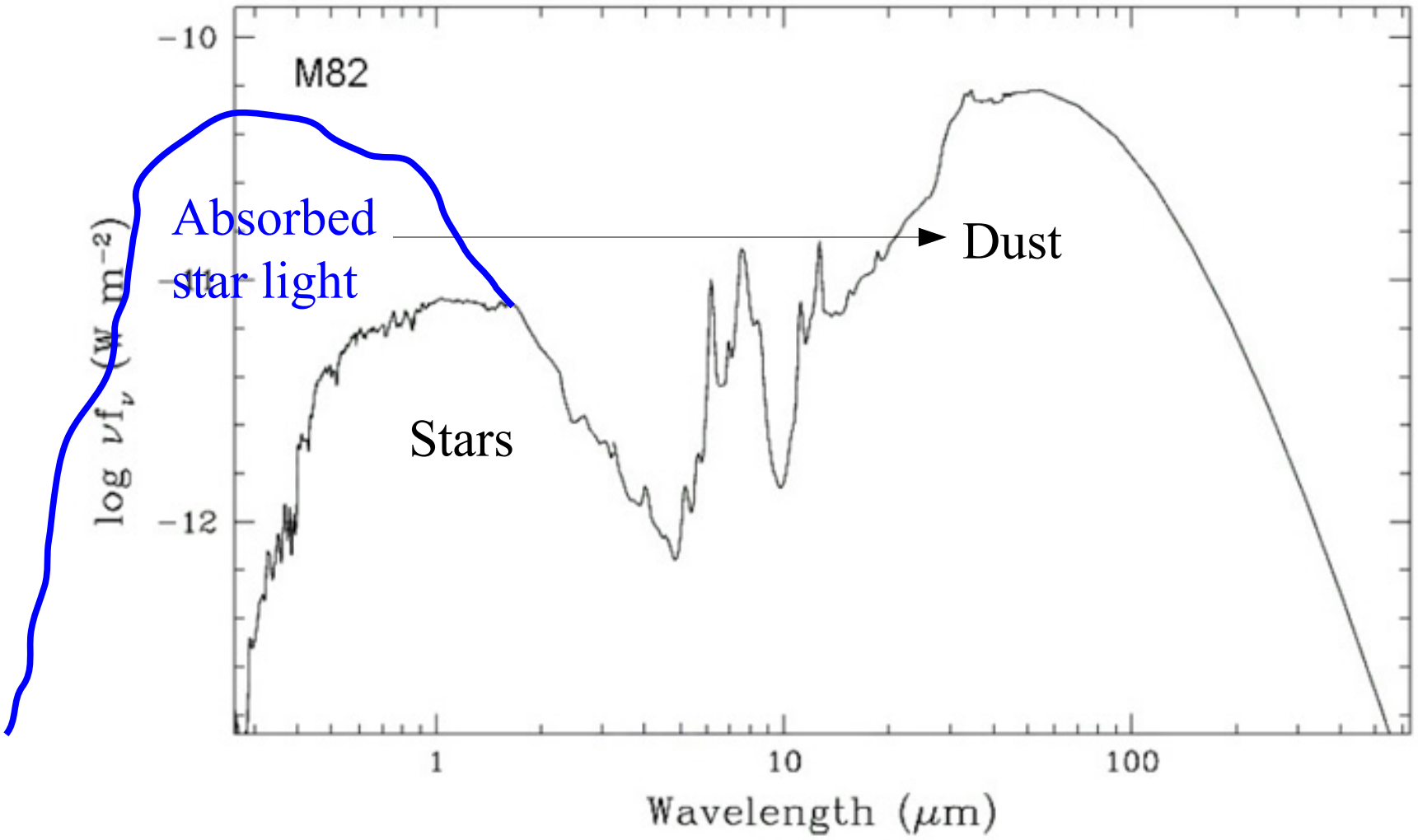
Optical

Red = Hα

Contours = IR

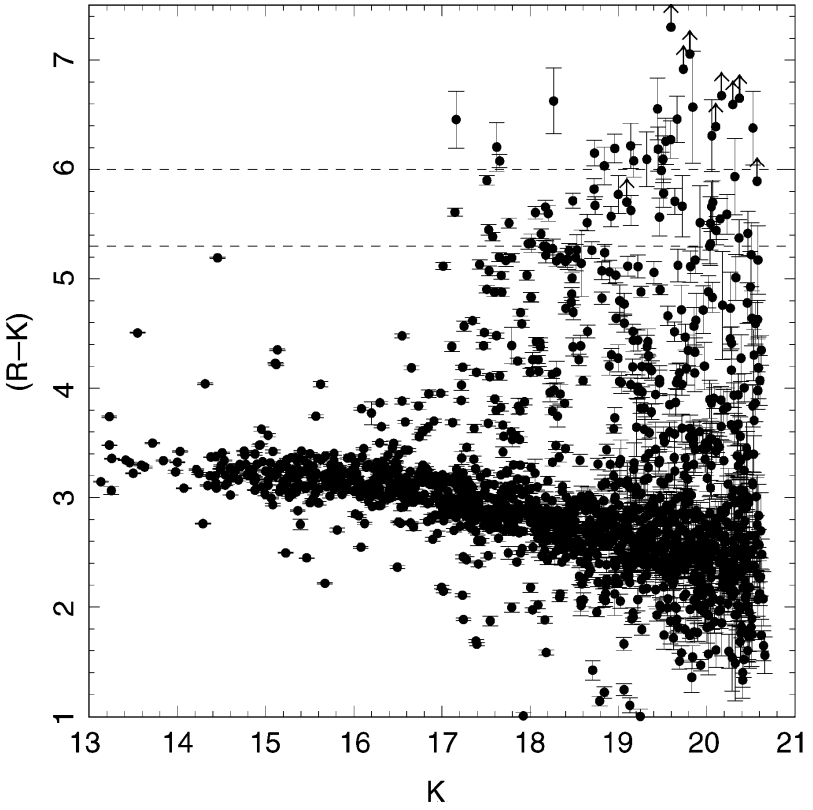
- Images of Antennae galaxies – interacting and starburst
- Young stars 5-10 Myr, also an older population 100-500 Myr
- Active star formation in regions of high gas and dust density
- UV/blue radiation reprocessed into IR

Spectral energy distribution of M82



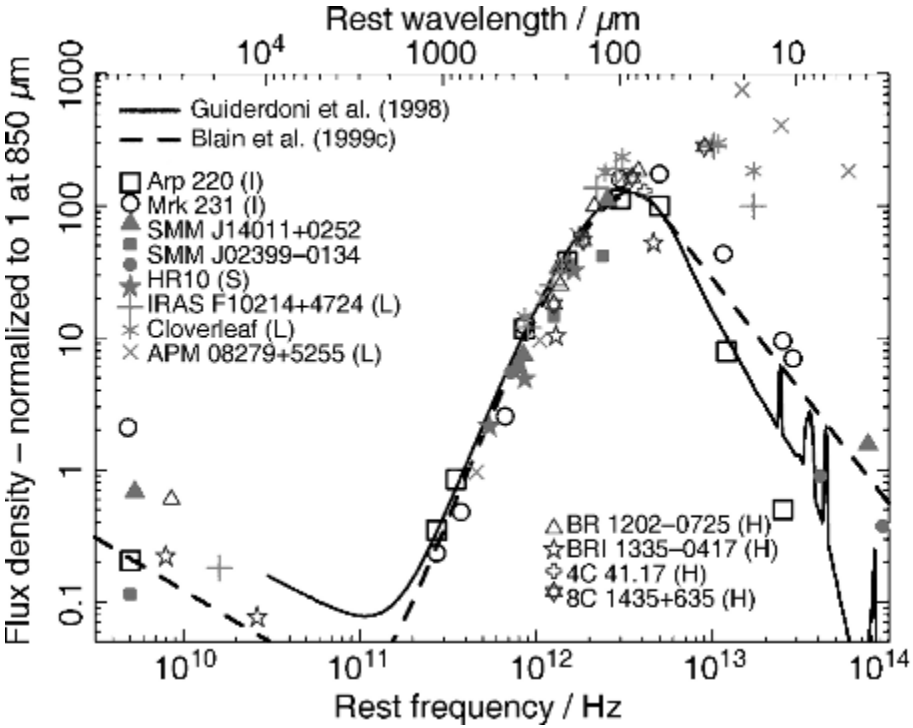
Absorbed star light heats dust clouds that radiate in the IR

Extremely red objects (EROs)



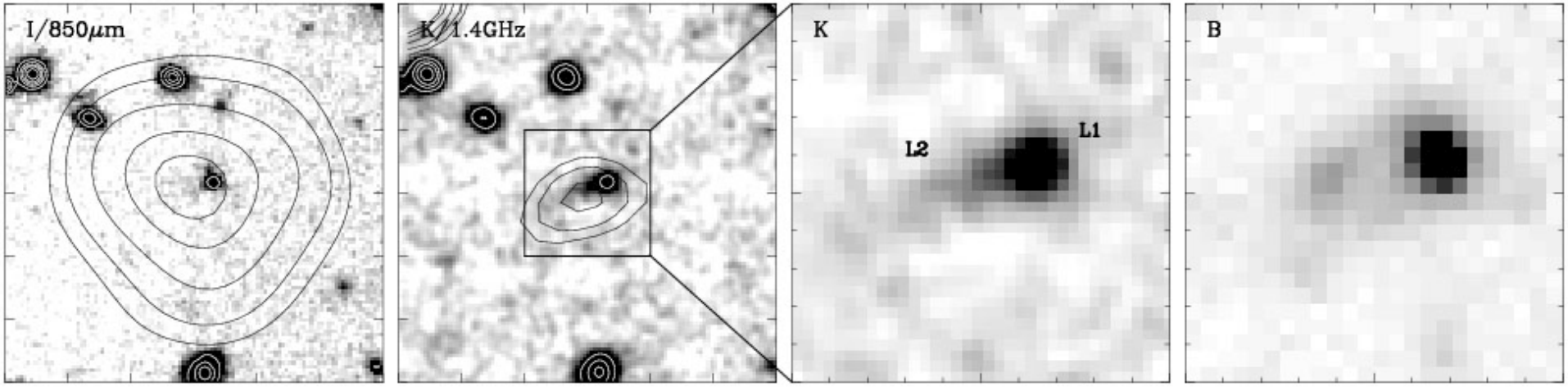
- NIR surveys reveal EROs, dim objects with R-K > 5. (K = 2.2 μm).
- Half are elliptical galaxies with 4000 Å break between R and K.
  - Galaxies are at $z \sim 1$ and have old stellar populations that formed at $z > 2.5$.
- Half are star-forming galaxies with star formation enshrouded by gas and dust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

Sub-mm galaxies



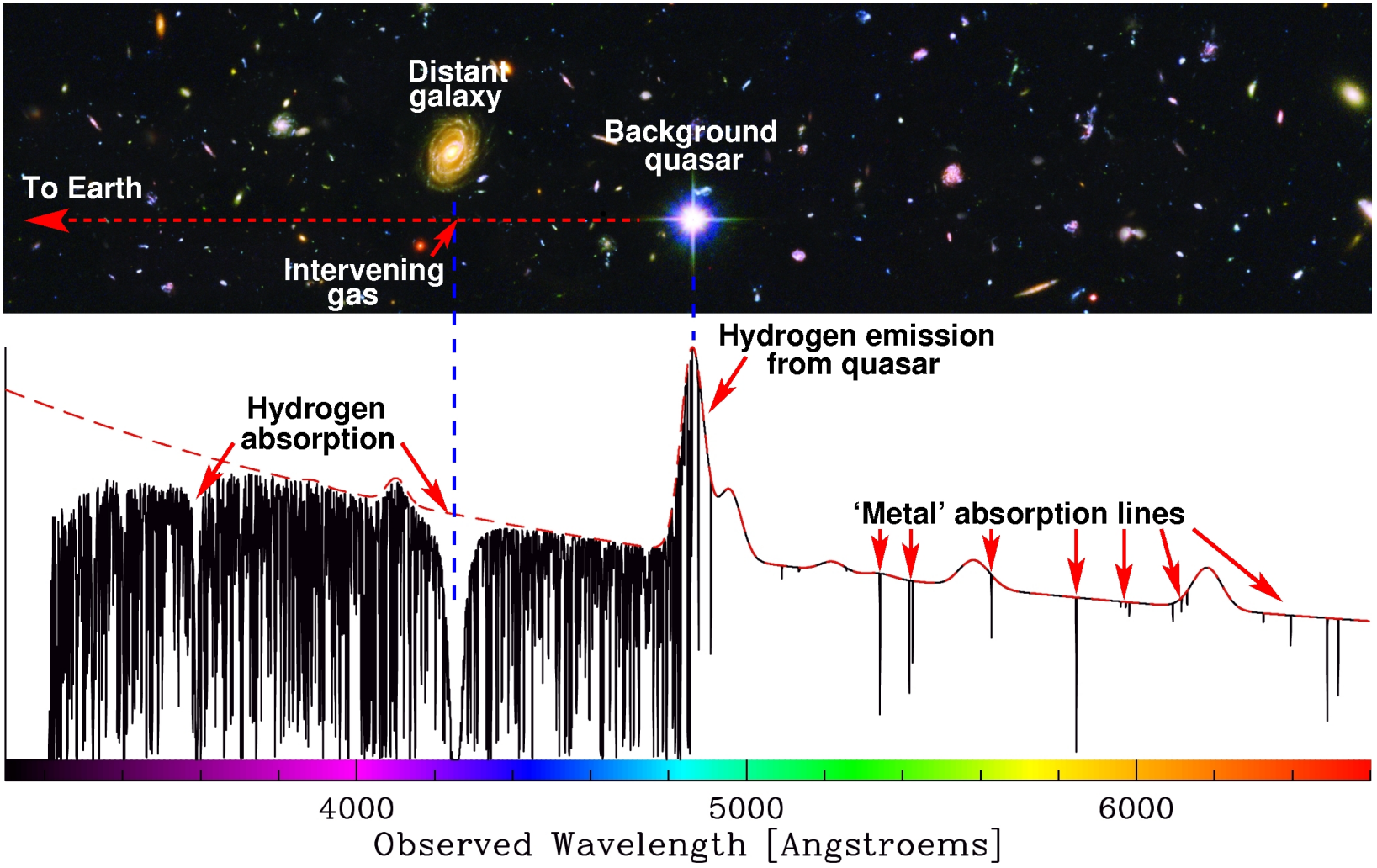
- Sub-mm telescopes (SCUBA) operating at 0.4-1.3 mm mainly see dust at 20-40 K.
- Spectrum $S_\upsilon \sim \upsilon^{2+\beta}$ with $1 < \beta < 2$. Redshift increases rest-frame υ and increasing spectrum leads to a higher luminosity density for sources at higher redshift.
- For $z_{max} > z > 1$, flux 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 $\sim 10^{11}\ M_{\rm Sun} \sim 10\times$ 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.

QSO absorption lines



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

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

Homework

For next class: problems 9.7