With photometric sky surveys, the two-dimensional distribution of galaxies on the sphere can be mapped. To also determine the third spatial coordinate, it is necessary to measure the redshift of the galaxies using spectroscopy, deriving the distance from the Hubble law (or some model of $a(t)$). Actually performing such (spectroscopic!) surveys is daunting, and was not practical until the advent of CCDs and high-multiplexity spectrographs, which could take spectra of several thousand objects simultaneously. Modern surveys are defined by two parameters: the angular size of the sky covered, and the brightness cutoff of objects being observed.

Major galaxy surveys include the two-degree Field Galaxy Redshift Survey (2dFGRS, or 2dF for short), which covered approximately 1500 square degrees and objects with $B \lesssim 19.5$, and the Sloan Digital Sky Survey (SDSS), which covered a quarter of the sky, with a limiting surface brightness of about 23 magnitudes/arcsec^2 (SDSS 2012).

1.18.2. *What about three or higher point correlation functions?*

This information is from Schneider (2006), pg. 282.

Higher point correlation functions can be defined in the same manner that we have defined the two point correlation function. It can be shown that the statistical properties of a random field are fully specified by the set of all n-point correlations. Observationally, these functions are significantly harder to map, though.

1.19. *Question 18*

QUESTION: Consider a cosmological model including a positive cosmological constant. Show that, in such a model, the expansion factor eventually expands at an exponential rate. Sketch the time dependence of the expansion factor in the currently favoured cosmological model.

This question as been entirely answered in Secs. 1.1.4 and 1.10. Followups can be found there as well.

1.20. *Question 19*

QUESTION: Define and describe the epoch of reionization. What are the observational constraints on it?

This information is from a collection of sources (mostly Schneider (2006)); see my other document for details.

After recombination (3.8×10^5 yrs after the Big Bang) the vast majority of matter in the universe was neutral hydrogen. The epoch of reionization is the period in the universe's history over which the matter in the universe became ionized again. An understanding of reionization is important because of the role reionization plays in large-scale structure formation. The nature of reionization is directly linked to the nature of the reionizing sources, the first stars and active galactic nuclei in the universe (studies could shed light into everything from the early stages of metal enrichment in the uinverse and the clumpiness of the IGM, to the formation of the first supermassive black holes). Moreover, IGM ionization and temperature regulate galaxy formation and evolution.

It is currently believed that the first several generations of stars were the primary produces of photoionizing radiation during the epoch of reionization. The pre-population III star universe was a metal-free environment, meaning that the only methods of cooling involved H and He. All collapsing dark matter halos in the early universe had small masses, corresponding to low virial temperatures on the order of 10^3 K. Only H_2 emission cools baryons at $T_{\rm vir} \approx 10^3$ K efficiently; as a result, the baryon clouds formed $\gtrsim 100$ $M_\odot$ stars. When the baryon clouds corresponding to these small CDM halos collapse to form population III stars, the immediate regions surrounding these halos is ionized by the stars' radiation. Moreover, the radiation dissociates most of the H_2 in the universe (the dissociation energy is 11.3 eV, below the 13.6 eV minimum absorption energy of neutral ground-state H, so H_2-dissociating photons can travel without impedement) and prevent further star formation. After they die, population III stars seed the IGM with metals, which provide cooling for gas at much higher virial temperatures. Therefore baryons associated with larger halos can now collapse to form stars. The greater volume of ionizing photons from these stars begins ionizing more and more of the IGM. Eventually different expanding patches of ionized IGM merge, greatly accelerating reionization (since photos can now freely travel between bubbles). Eventually the last regions of the universe become fully ionized. This process can be seen in cartoon form in Fig. 26.

Because the recombination time for the IGM becomes longer than a Hubble time at z $\sim$ 8, very complicated reionization histories are allowed, and it is unclear exactly how longer reionization took. We know that reionization must occur over a time period of longer than $\Delta z > 0.15$, but it is very likely much longer.

Despite the fact that the universe is now fully ionized, the average density of HII in the universe is too low for the universe to again become opaque; assuming the universe somehow remained ionized *ad infinitum*, it would still have become transparent after 20 Myr.

Observational constraints on reionization include:

- **Ly-α observations** constrain the redshift at which recombination must have ended. Ly-α absorption lines (and, at high column densities, continuum absorption due to the Lyman limit at 912 Å) are created in quasar spectra by

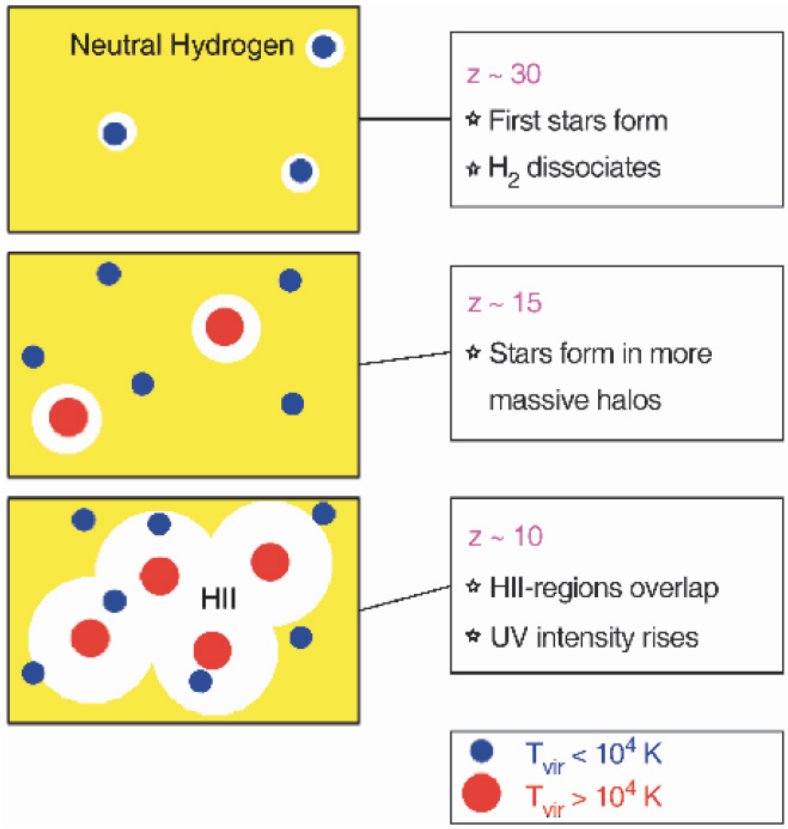

FIG. 26.— A cartoon of the two-step reionization process. At z $\gtrsim$ 12 population III stars form in low-mass halos, ionizing the nearby universe and dissociating H_2 across the universe. When these stars die, they seed the IGM with metals, allowing more metal-rich stars to form in much more massive halos. These metal-rich stars eject many more ionizing photons, and are primarily responsible for reionizing the entire universe. From Schneider (2006), his Fig. 9.30.

the H I floating in the line-of-sight between us and the quasar (neither free-free absorption nor scattering produces absorption lines). The n = 1 to n = 2 transition for a neutral H atom translates to a photon of $\lambda_{Ly\alpha} = 1216$ Å, meaning that for a QSO at $z = z_{\rm QSO}$, we could expect any QSO emission between $\lambda_{Ly\alpha}(1+z_{\rm QSO})^{-1}$ and $\lambda_{Ly\alpha}$ to potentially be absorbed by lines. If there were a large amount of H I at all redshifts from 0 to $z_{\rm QSO}$, the absorption lines would merger together into a trough - the fact that we do not see this at z $<\sim$ 5 (despite there being enough hydrogen density) indicates that the universe is currently ionized (the Gunn-Peterson test); otherwise the various pockets of overdense HI would create a "forest" of absorption lines (Schneider 2006). However, for spectra of QSR at z $\gtrsim$ 6, we see signs of strong Gunn-Peterson troughs, indicating that dense patches of H I still existed at z $\gtrsim$ 6. From this we can set the lower limit for the completion of reionization at z $\sim$ 6. Unfortunately, Ly-α emission cannot penetrate past regions with neutral fractions greater than about 10^{-3}, meaning that it cannot be used to probe the era of reionization itself. See Fig. 27.

- **The proximity effect** is when the QSO ionizes nearby H I clouds, reducing the Ly-α absorption at redshifts close to the emission redshift of the QSO spectrum. The size and shape of this damping can tell us the fraction of hydrogen that is neutral in the space around the QSO (giving us an indication of how far reionization has progressed).

- **CMB polarization** measurements can be used to constrain the start of reionization. H II region electrons have a tendency to Thomson scatter incoming CMB photons. Since this scattering is isotropic, Thomson scattering blends photons from different regions of the CMB together, washing out anisotropies. Thomson scattering also has a natural polarization axis. If in the electron rest frame the CMB were isotropic, no net polarization would be created, but since the CMB itself is anisotropic, CMB radiation can become polarized. The degree of CMB polarization is directly related to the Thomson scattering optical depth, which is related to when a significant amount of H II existed in the universe. WMAP three-year observations of CMB polarization suggest the depth is fairly large, indicating that reionization may have started quite early. Because it is measuring an integrated quantity (degree of polarization along the line of sight) WMAP results cannot easily constrain the period of time over which reionization occured - if it was instant, WMAP gives $z = 11.3$; if it occurred over an extended period of time from z $\sim$ 7 onward, reionization could have begun closer to $z = 15$.

- **21-cm line emission and absorption** from H I could prove an invaluable tool to studying reionization. In

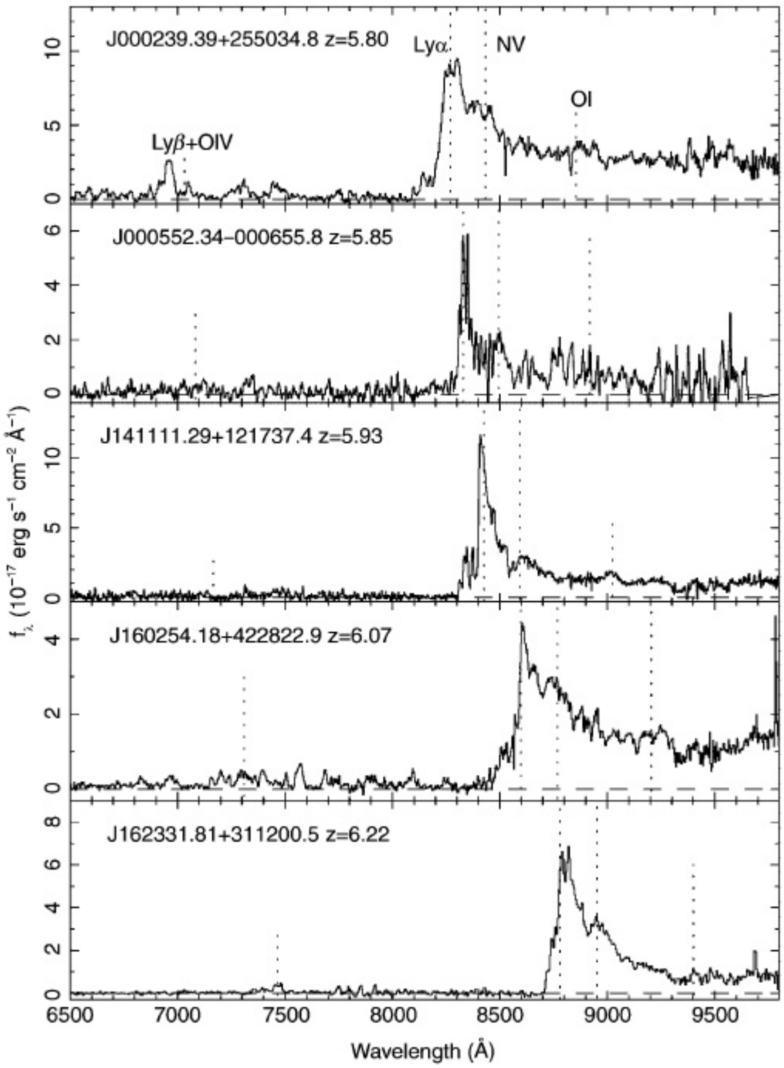

FIG. 27.— UV spectra of QSOs near z = 6. Each spectrum contains a prominent and broad Ly-α emission line (intrinsic to the quasar emission spectrum **(CHECK) THIS**), preceded by a Ly-α forest at lower wavelengths. Near z = 6 the forest is thick, and overall absorption along the line of sight is significant. Note in some cases there is slightly less absorption right near the Ly-α emission line - this is due to the proximity effect, where the QSO ionizes it surrounding IGM (this effect can be used to separate the ionizing flux of photons from the particular QSR and from the background). The forest flattens near z = 6, indicating the creation of significant Gunn-Peterson troughs past that redshift from passing the emission through thick HI regions. This indicates the universe became fully ionized around z = 6. From Schneider (2006), his Fig. 9.28.

the late ($z \lesssim 9$) reionization epoch, the 21-cm line intensity is simply proportional to the ionized fraction, and therefore it is straightforward to translate fluctuations in 21-cm emission to the progression of reionization. While QSO observations are restricted to $z \lesssim 6$ and CMB observations are integrated, 21-cm line emission and absorption could probe to much higher redshifts while maintaining fidelity in both time and space.

1.20.1. *What about He reionization?*

This information is from **?**.

HeII has an ionizing potential energy of 54.4 eV, and the soft emission from population III stars is unable to ionize it (in contrast, population III stars can easily ionize HeI, with an ionizing potential of 24.6 eV) (Furlanetto & Oh 2008). As a result He only fully ionizes when the quasar population is large enough for large numbers of hard quasar-emitted photons to percolate the universe, which occurs at z $\sim$ 3. The most significant observation evidence for reionization completion at z $\sim$ 3 comes from far-UV studies of the He Ly-α forest along lines of sight to bright quasars, which show a significant increase in HeII optical depth near z $\sim$ 3. Other, more controversial evidence also exists (such as a decrease in the HI recombination rate (which corresponds to a change in HI opacity), a change in the hard photon opacity in the universe, and a change in IGM temperature; observations of these effects are not as conclusive as the Ly-α studies). Despite the lack of theoretical studies done on He reionization, it should be noted that the universe at z = 3 is easier to understand and observe than z $\gtrsim$ 6, and therefore the physics of reionization can be constrained by further study of He reionization.