Dissecting the Epoch of Reionization with Discrete, Embedded Sources

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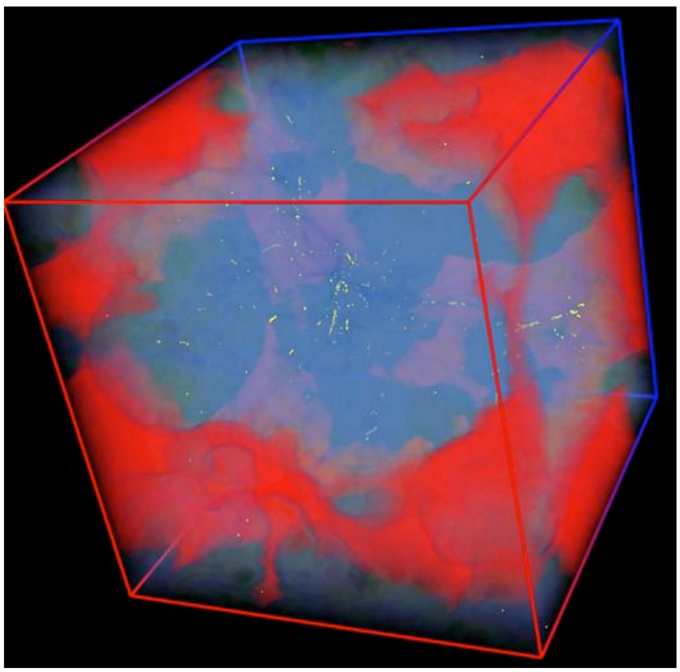

Science Frontier Panels:
PRIMARY: Cosmology and Fundamental Physics (CFP)
SECONDARY: Galaxies across Cosmic Time (GCT)

Projects/Programs Emphasized:
1. The Synoptic All-Sky Infrared Imaging Survey (SASIR); `http://sasir.org`
2. The Near-Infrared Sky Survey (NIRSS)
3. The Giant Segmented Mirror Telescope Program; `http://www.gsmt.noao.edu`

In the upcoming decade, researchers will make great strides in studying the epoch of reionization. Fundamental questions such as the precise timing of this phase transition, its topology, and the nature of the ionizing sources are likely to be revealed. In this white paper, we describe advances that can be made through the study of discrete, embedded sources.

Key Questions:
1. How and when did reionization occur?
2. What is the nature and role of quasars during reionization?
3. How did reionization affect the evolution of galaxies and the IGM?

Introduction:

With the discovery of high redshift ($z \sim 2$) quasars and the subsequent identification of an undulating Lyα forest, astronomers established that the gas between galaxies (the intergalactic medium; IGM) is highly ionized. Current wisdom is that an intense extragalactic UV background (EUVB) generated by quasars and star-forming galaxies maintains the diffuse IGM as a warm ($T \sim 10^4$ K) and highly ionized plasma. In the past decade, spectra of even more distant quasars have revealed that the IGM is highly ionized to at least $z = 6$ and possibly beyond (White et al., 2003; Becker et al., 2007). As one reaches back in time to the first UV emitting sources, however, the EUVB must decline until it can no longer maintain a fully ionized universe. This phase transition defines the epoch of reionization ($z_{\rm reion}$).

Empirical understanding of the epoch of reionization currently comes from analysis of CMB polarization, the Lyα opacity and metal-enrichment of the IGM at $z \approx 6$, and estimates of the EUVB from surveys of $z > 6$ quasars and Lyα emitting galaxies (see Fan et al., 2006, for a review). These studies provide only loose constraints on the time when reionization initiated, the nature and distribution of the sources, and the duration and completion of the phase transition. Significant effort is underway to characterize the epoch of reionization and evaluate its impact on the universe at $z \lesssim z_{\rm reion}$. Several of the above questions are likely to be addressed by experiments that study the global evolution of reionization, i.e. all-sky maps of the CMB and 21cm emission from Hydrogen at $z > 6$. These contributions will be powerful probes of reionization but will challenged to study the small-scale astrophysics of reionization. This white paper describes research that would focus on the detailed aspects of reionization, e.g. the physical attributes of the sources, the characteristics of AGN, the enrichment and evolving ionization state of the IGM. The science of 21cm emission will be reviewed by other white papers to Astro2010 and a companion white paper discusses the role of GRB research to probe reionization.

The Topology of Reionization: How and When Did It Occur?

Reionization is thought to proceed inhomogeneously, as star-forming galaxies (and/or quasars) generate ionized "bubbles" in the IGM which ultimately merge to complete the process. Hydrodynamical numerical simulations mimic this process in detail (e.g., cover figure) and show that the properties of the bubbles trace the properties of the sources driving reionization (e.g., bubbles are larger if more massive galaxies drive reionization; Furlanetto et al., 2006a) and of the IGM (as the Lyα forest forms during the final phases of reionization Choudhury et al., 2008). Probing these features is known as exploring the topology of reionization.

As these 'bubbles' grow, sources embedded within them emit Lyα radiation that may escape by redshifting out of resonance before scattering off the neutral IGM. Because the Lyα opacity is so large, the presence of such emission lines indicates directly that the IGM is locally ionized within ~ 1 proper Mpc of the galaxy (Miralda-Escudé & Rees, 1998; Gnedin & Prada, 2004). As a result,

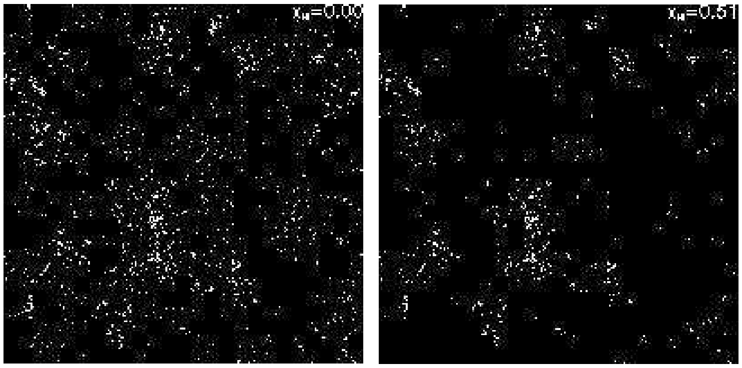

Figure 1: Simulated maps of Lyα-emitting galaxies during and after reionization (Mesinger & Furlanetto, 2008). *Left:* Lyα lines are unattenuated while *Right* includes IGM absorption (51% neutral). Each white dot corresponds to a galaxy; IGM absorption obscures many of the galaxies early in reionization, especially outside of large groups. This $z = 9$ slice is 250 Mpc across ($\sim 1.5\,\mathrm{deg}$) and 20 Mpc thick (corresponding to a narrow-band filter width $R \sim 125$).

mapping these sources provides a direct probe of the growth of these bubbles (e.g. Furlanetto et al., 2004). The two panels of Fig. 1 illustrate the effect: in the left (after reionization is complete), many more galaxies are visible than in the right (midway through reionization), especially in regions with low source densities. Fig. 1 therefore suggests three techniques to study reionization with galaxy surveys (for $z_{\rm reion} > 6$, these bubbles grow during the epochs when Lyα appears in the near-IR.)

<u>The luminosity function of Lyα-emitting galaxies:</u> The disappearance of Lyα emission as the Universe becomes more neutral is a strong prediction of all reionization models (Furlanetto et al., 2006b). Unfortunately, properly interpreting such a decline requires a "control" sample of galaxies whose selection is independent of reionization; current limits are ambiguous (McQuinn et al., 2007; Mesinger & Furlanetto, 2008). The next generation of large near-IR telescopes will provide just such an opportunity by pushing the high-z frontier farther back. Shortward of 2.2μm, 25-30-meter ground-based telescopes will be the most sensitive instruments for blind, narrow-band ($R \sim 300 - 1000$) searches for Lyα sources at $z > 7$ between the strong night sky lines. Depending on the properties of the emitters, GSMTs will reach roughly an order of magnitude fainter, into a regime in which significant Lyα counts are expected by theory.

<u>Clustering measurements of Lyα-emitting galaxies:</u> Careful examination of Fig. 1 shows that the Lyα emitters do not vanish uniformly across the sky throughout reionization: rather, large groups of sources sit inside of large ionized bubbles that permit their Lyα photons to escape even early in reionization. This effect manifests itself as a change in the *clustering* of these galaxies and can be measured with deep, wide surveys (Furlanetto et al., 2006b). Direct measurement of the clustering requires large, narrow-band surveys ($\sim 1\,$sq. deg across; McQuinn et al. 2007), possible with modest allocations of observing time on planned GSMTs. Targeted deep "near-neighbor" searches near previously-identified bright sources provide another, potentially more efficient, strategy to measure this increased clustering and hence take the first steps toward mapping the ionized bubbles. Following up the $\sim$ Mpc environments of ~ 100 bright sources will allow clear detections of neutral gas (Mesinger & Furlanetto, 2008).

<u>Targeted exploration of individual IGM bubbles:</u> By the 2018 era, sensitive broad-band imaging available from large near-IR surveys (e.g. SASIR, NIRSS) will likely reveal the presence of the largest 'clusters' of galaxies at $z > 7$. These clusters provide logical starting points for direct mapping of *individual* bubbles across several redshifts using the Lyα emission lines of cluster members, especially through comparison to continuum detections. This approach provides much more detailed views of individual regions than are possible with, e.g., 21 cm emission maps, where only the most unusual regions can actually be imaged in detail. Bubbles as small as ~ 1 proper

Mpc will be visible. These pointed observations will have the added advantage of indicating regions of the universe where Lyα is least likely to be scattered, allowing more accurate measurements of the ratios of Lyα to other lines. For example, a search for Population III star formation via the HeII (1640 Å) emission line will help reveal some of the earliest stars to form in the Universe [see a companion Population III WP]. At the redshifts of interest, 25-30-meter-class GSMTs will likely represent the most sensitive instrumentation for these studies, and will allow high-resolution spectroscopic follow-up of the discovered sources.

Finding Quasars in the Dark Ages:

Although consensus holds that bright quasars have insufficient number density at $z > 5$ to drive reionization (e.g., Faucher-Giguère et al., 2008), AGN remain the only extragalactic source known to have high escape fractions of ionizing radiation. Furthermore, surveys to date for $z > 5$ quasars have only observed the most luminous sources leaving the faint-end of the luminosity function essentially unconstrained. If the faint-end steepens (as observed for high redshift galaxies in the ultraviolet) or if entirely different classes of AGN (e.g. mini-quasars; Madau et al., 2004) exist at early times, these would contribute to the EUVB at $z > 5$. In addition, high z AGN are sources of radiative and kinematic feedback that modify the characteristics of the IGM on large-scales (via X-ray heating) and can affect the formation of new structures on smaller scales. Finally, surveys for $z > 6$ quasars have great value independent of reionization, e.g. as tracers of the growth of the supermassive black holes that populate modern galaxies. During the next decade, it will be possible to determine *what is the nature and role of quasars during reionization?*.

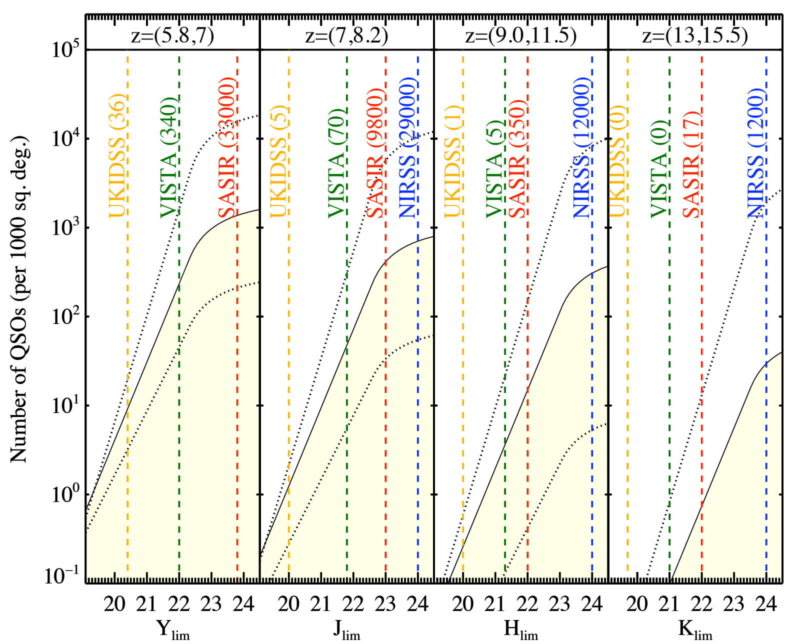

Figure 2: Predicted surface density of quasars (solid black line) per 1000 sq. deg as a function of limiting magnitude assuming a double-power law luminosity function with $\beta_l = -1.64$, $\beta_h = -3.2$, with $M^*_{1450} = -24.5$ and 6×10^{-10} quasars brighter than $M = -26.7$ (Fan et al., 2004). The curves also assume a redshift evolution in the number density $\propto \exp(-0.43z)$. The dotted lines indicate more optimistic and pessimistic assumptions on the number density and redshift evolution. The vertical lines indicate the magnitude limits of various ongoing, planned, and proposed deep, near-IR surveys with the number in parenthesis presenting an estimate of the numbers one might detect assuming the proposed survey area. Only the SASIR and NIRSS surveys will have the depth and sky coverage to provide a meaningful sample of $z > 7$ quasars and have a legitimate chance of detecting sources at $z > 10$.

Searches for quasars in the reionization era are challenged by three effects: (i) cosmological dimming; (ii) a very low number density; and (iii) their extremely red apparent color. Together, these attributes imply that surveys for high z quasars demand deep near-IR and optical imaging over a very large area of sky. While surveys like SDSS and 2DF (and the upcoming Pan-Starrs project) provide large areas of optical imaging, no project has achieved comparable depth and area in the near-IR. The nearly completed UKIDSS project and the upcoming VISTA surveys (a joint UK/ESO venture) should markedly increase the current samples, but these programs also lack sufficient depth and/or area to meaningfully constrain the quasar population, especially at $z > 7$ (Figure 2). It is evident that a systematic study of AGN during the reionization era will require a deeper, wider near-IR survey. Figure 2 presents the predicted number of quasars that could be discovered from two proposed surveys: (i) The Synoptic All-Sky Infrared Imaging Survey (SASIR; a ground-based survey proposed for San Pedro Martir) and (ii) The Near-Infrared Sky Survey (NIRSS; an all-sky, satellite mission).

At $z \sim 6$, such surveys would establish the shape of the quasar luminosity function (the proposed Pan-STARRS and LSST surveys could also contribute significantly here). At higher redshifts, a deep near-IR survey is essential to sample even the brightest sources. These measurements would be compared against estimates of the black-hole merger rate at $z \approx z_{\rm reion}$ from gravitational-wave experiments (e.g. LISA).

While wide-area, multi-band near-IR imaging is the crucial first step toward surveying $z > 6$ quasars, candidate confirmation and and characterization demands follow-up near-IR spectroscopy. The brightest targets are within the reach of existing or planned near-IR spectrometers on the world's suite of 8m-class telescopes. But the majority of the candidates, especially those at $z > 7$, will require larger aperture (e.g. GSMT) and/or space-borne instrumentation (e.g. JWST). Because quasars are point sources, these observations would significantly benefit from diffraction limited spectroscopy (e.g., with next generation adaptive optics) to minimize the bright, near-IR background.

The high z quasars discovered in these surveys are likely to mark the first perturbations which become non-linear in the primordial matter density field (e.g., Trenti & Stiavelli, 2007). This would imply that one might expect an overdensity of (Lyα-emitting) galaxies around the highest-redshift quasars. Competing against this effect is the fact that quasars are not "quiet neighbors" (e.g., Kim et al., 2008). The intense emission of ionizing radiation associated with QSOs ionizes the surrounding IGM and may even photo-evaporate gas in neighboring dark matter halos before it has an opportunity to cool and form stars. One might therefore expect an underdensity of (Lyα-emitting) galaxies around the highest-redshift quasars, despite the fact that the quasars reside in some of the largest halos at their cosmic epoch. In fact, since reionization is expected to rapidly change the neutral hydrogen fraction of the IGM, these two effects might rapidly shift balance, with an enhancement prior to reionization rapidly shifting to a suppression after reionization. Surveys and next-generation facilities over the next decade should allow significant advances in such studies, studying larger samples out to higher redshifts and thus directly mapping the role of feedback in the first stages of galaxy formation, at the epoch of reionization.

Quasars as Probes of the High z IGM:

Independent of whether $z > 6$ quasars drive reionization, these sources permit detailed analysis (via absorption-line spectroscopy) of the physical conditions of the IGM at $z \approx z_{\rm reion}$. In turn, this analysis constrains all three of the *key questions* considered by this WP. Quasar spectra are highly complementary to proposed 21cm observations, since (due to the much larger Lyα oscillator strength) they are most powerful precisely when the hydrogen neutral fraction, and hence the 21cm signal, are fading. As such, they are ideal for probing the tail end of reionization, when the transition from the 'bubble-dominated' topology of reionization to the 'web-dominated' topology characteristic of lower redshifts takes place.

<u>Lyα Analysis:</u> Detailed spectroscopy of luminous quasars and AGNs at $z > 7$ can provide powerful probes to the neutral era of the IGM. The classic Gunn-Peterson test saturates at volume averaged neutral fraction $x_{HI} \sim 10^{-3}$. However, new approaches such as dark gap statistics and HII region sizes around luminous quasars offer tests that are sensitive to IGM with higher neutral fraction. Gallerani et al. (2008) show that the distribution functions of dark gaps are dramatically different for different reionization. In order to characterize dark gap distribution, spectra with moderate (R of a few thousand) and high S/N (> 30) are needed. Even with the largest ground-based telescope and JWST, such data are only possible with the most luminous, and rarest quasars. Sizes of HII region around quasars are sensitive to IGM neutral fraction of order unity. Bolton & Haehnelt (2007) presents the Lyα near-zone sizes in luminous quasars as a function of x_{HI} based on synthetic spectra extracted from cosmological reionization simulations that include detailed radiative transfer models. It both shows the promise – HII regions are only few physical Mpcs for neutral IGM, comparing to tens of Mpcs for a mostly ionized IGM; and uncertainties – large scatter on individual HII region sizes due to density and radiative transfer effects. The study shows the need of samples of a few dozen quasars to average out these large scatter. The advantage of HII region size measurement is that it can be applied to fainter AGNs, since low S/N, low resolution spectra are all that are needed to measure the regions with flux transmission around quasars. Measurements of neutral fraction using either dark ages or HII regions are likely to be highly model dependent, but they also have the advantage that they are directly linked to the HI optical depth.

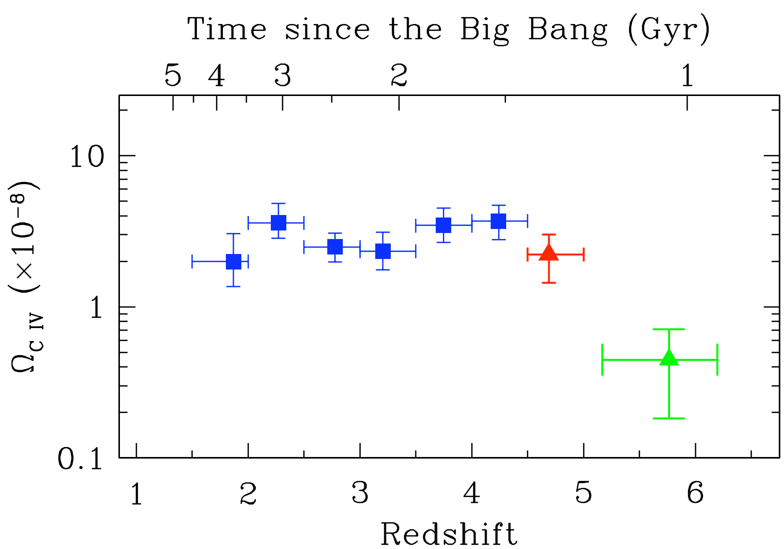

Figure 3: Mass density of CIV relative to the critical density ($\Omega_{\rm CIV}$) as measured from quasar spectroscopy (compiled by Ryan-Weber et al., 2009). The universe exhibits a roughly constant $\Omega_{\rm CIV}$ from $z \approx 2 - 5$ and new near-IR spectroscopy suggests a steep decline at $z > 5$ (Becker et al., 2008; Ryan-Weber et al., 2009). Future observations will test this result and examine whether it indicates a marked decrease in the EUVB at $z \approx 6$ highlighting the end of reionization.

<u>Metal-Line Analysis:</u> At $z > 6.5$, the overwhelming opacity of the Lyα forest precludes its analysis with the Lyman series. Instead, one must focus on metal-line transitions that lie redward of Lyα to reveal characteristics of the IGM. This has two implications for research on the universe at $z \approx z_{\rm reion}$: (i) high resolution, high signal-to-noise near-IR spectroscopy will be essential; and (ii) there is a limited set of diagnostics for analysis. Together, these issues make studies of the $z > 6.5$ IGM significantly more challenging than at $z \sim 3$.

An area of obvious (and current) research is to track the incidence of highly ionized species (e.g. SiIV, CIV) which are known to trace the IGM at $z < 6$. If C and Si nuclei are in place at

$z \approx z_{\mathrm{reion}}$, then their relative ionization states should indirectly trace the history of reionization by constraining the shape and intensity of the EUVB. Recent surveys of CIV toward $z \sim 6$ quasars already suggest that there is a steep decline in the incidence of CIV absorption beyond $z \approx 5$ (Fig 3; Becker et al., 2008; Ryan-Weber et al., 2009). If confirmed, this may signify a steep decline in the EUVB at $z \approx 6$. Further exploration is currently limited by the number of known $z \gtrsim 6$ quasars, but the sample will markedly increase in the upcoming decade (see above).

While assessment of the evolution in CIV provide a simple and straightforward investigation of the reionization epoch, the spectra include additional diagnostics for study. For example, a decline in CIV due to evolution in the EUVB (as opposed to changes in metallicity) should be reflected in a corresponding rise in the incidence of lower ionization states (e.g., CII, OI; Oh, 2002; Furlanetto & Loeb, 2003, ; Fig. 4). This could be assessed in a population of absorbers (i.e. by comparing the CII/CIV ratio versus redshift) or by surveying various ions with redshift. Another area of research would be to measure the relative abundances of Si, C, and O through modeling of the observed ions in individual absorbers. These measurements may reveal the IMF of the stars that pollute the $z \approx 6$ universe. Finally, and perhaps most valuable, the metal-lines serve as simple signposts for follow-up searches of $z > 6$ galaxies. One could search, in principle, for the galaxy that produced the metals (e.g. with AO assisted spectral-imaging to minimize the quasar glare) and/or the Mpc-scale environment.

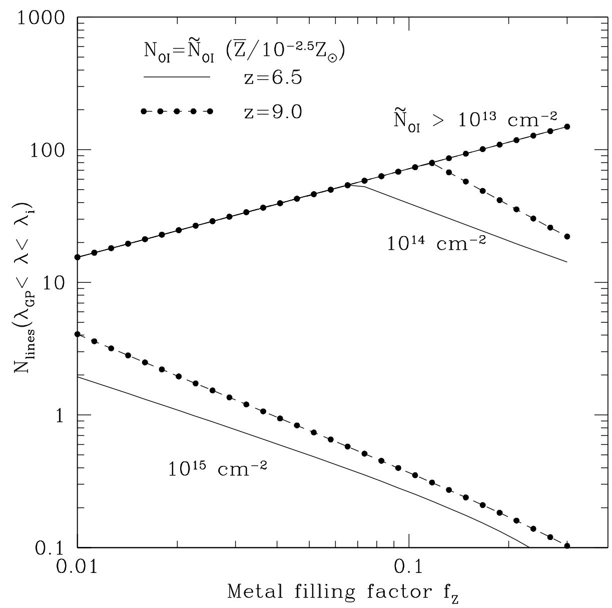

Figure 4: Number of OI lines above a given column density N_{OI} observable in the pre-overlap phase, when metal-polluted high density regions are still largely neutral, as a function of the volume filling factor of metals f_Z. Solid lines are for $z = 6.5$, dashed lines for $z = 9$. The column density scales directly with the assumed mean metallicity $\bar{Z}$. The number of lines with similar equivalent widths is comparable for CII, and roughly half for SiII. From Oh (2002); see paper for explanation of change in slope of relation at high f_Z.

There are a number of advances that could and should be made in the upcoming decade to pursue this science. First, there is a scarcity of $z > 6$ quasars for spectroscopic observation. As described above, this will improve with the UKIDSS and VISTA surveys but a qualitative advance will demand a new, wide-area near-IR survey. Second, the studies of $z \sim 6$ quasars to date have required many nights of near-IR spectroscopy on 10m class telescopes to generate samples that are small and have data quality that is poor in comparison to optical spectroscopy of the $z \sim 3$ IGM. Expected advances in near-IR spectrometers will improve observing efficiency, but a major advance in this area will demand sensitive spectrometers on larger aperture telescopes. Third, and perhaps most important, the paucity of empirical diagnostics (especially the absence of Hydrogen) limit the power of the observations to directly constrain physical characteristics of the IGM at $z \approx z_{\rm reion}$. All of the diagnostics are associated with metal-line transitions which bias the studies to chemically enriched regions of the universe.

Proper interpretation of these data is likely to require comparisons with cosmological models of structure formation at $z_{\rm reion}$ (e.g., Oppenheimer et al., 2009). These simulations must include accurate treatments of radiative transfer and prescriptions for metal production and transport from the first stars and galaxies This is a challenging set of requirements for simulations, both in terms of the dynamic range of timescales and spatial scales. Nevertheless, advances in algorithms and computing power should make this feasible in the upcoming decade.

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