# GMT Science Use Case

# Measuring the Faint End Slope of the Lyα Luminosity Function at z ~ 6

**Abstract:** The source of reionization at z > 6 remains uncertain as the present suite of telescopes and instruments appear to be unable to probe deep enough to reach the relevant population. The most likely source of reionization is a faint population of star forming galaxies at redshifts above six. The Lyα luminosity at z~6 provides a probe of the production rate, and escape fraction, of ionizing photons at the end of the dark ages. A steep faint end slope would produce enough photons to reionize the IGM; if the faint end of the LF is shallow then some other population must be identified. GMACS on the GMT can measure the faint end slope at z ~6 in as few as four nights. In this use case we describe an example program and provide sensitivity estimates and simulated spectra that demonstrate how such a program might be carried out.

**Motivation:** Reionization is one of the major transition points in the evolution of the baryonic content of the Universe. Our empirical knowledge of the timing of reionization and the source of the ionization itself are quite rudimentary. Observations of the Gunn-Peterson effect place a lower bound of z ~ 6.4 for the end of the reionization era and observations electron scattering in the CMB suggest an upper limit of z ~ 12. Attempts to isolate the population of objects responsible for a sufficient flux of ionizing photons have been indeterminate. The space density of high luminosity sources such as bright quasars is too low. The importance of more abundant systems like UV luminous galaxies depends strongly on the escape fraction below the Lyman limit. Estimates of the total energy density in ionizing photons from UV bright galaxies depend strongly on the shape of the luminosity function and the slope at the faint end in particular. As the total UV luminosity density is determined by the integral of the LF, the faint end slope is critical; if the LF is shallow the integral is dominated by sources near $L^*$, if it is steep the faint sources can make an important, even dominant, contribution.

Our present understanding of the faint-end slope for the galaxy and AGN luminosity functions at z ~ 5 is rather limited. Luminosity function for continuum selected objects are based on their deep imaging studies and photometric redshifts, or extrapolations of the luminosity functions at z ~ 3. The Lyα LF is more relevant as it is pre-selected for objects with non-zero escape fractions. At present our understanding of the faint end of the Lyα LF is limited to very small sight lines along strong gravitational lensing caustics in massive clusters. At the bright end the LF is determined from wide-area searches with narrow band filters and somewhat deeper spectroscopic surveys, both confined to narrow slices of redshift in which the sky is dark. In Figure 1 we show the Lyα luminosity function from Malhotra & Rhoads (2007). The faint end is determined by detections of only ~ 11 objects from gravitational lensing studies. The errorbars are dominated by the small number statistics. There are additional errors associated with uncertainties in the magnification corrections. The extant data favor a steep slope, but the range of slopes allowed is quite large.

**Approach:** GMT provides the collecting area needed to detect faint Lyα emission directly without the need for gravitational lensing. GMACS, with its large field of view can sample a large number of Ly alpha emitters in a single exposure. The large wavelength coverage enabled by the red and blue channels also allows one to reject confusing sources (e.g. other lines) with high efficiency.

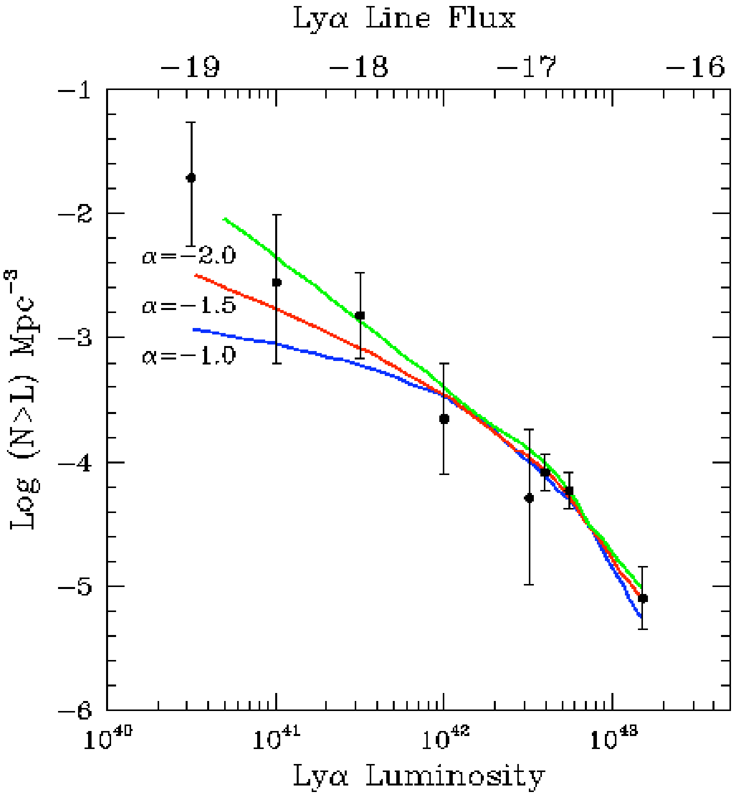

**Figure 1. The Lyα luminosity function at z = 5.7 from Malhotra & Rhoads (2007). The faint points come primarily from cluster lensing studies. Three Schechter function fits with faint end slopes of –1, -1.5, and –2 are shown. The top axis shows the line flux corresponding to the luminosities on the bottom axis for z = 5.7.**

The field of view of GMACS is 9′ x 18′, for a total field area of 162 square arcminutes. The co-moving volume covered in a single GMACS pointing in the redshift interval from $5 < z < 6$ is 460,000 Mpc$^3$. Many recent Lyα searches have been confined to narrow dark regions between the OH bands. One dark region spans the redshift range from z = 5.68 to z = 5.8. In this limited region the volume sampled by a single GMACS field is about 50,000 Mpc$^3$. If the faint-end slope is as steep as –2 the number of objects in a GMACS field of view is fairly large, as listed in Table 1. In its baseline configuration GMACS can accommodate 360 6-arcsecond-long slits with full spectral coverage if they are uniformly distributed in the field. In practice the actually slit-packing efficiency is roughly half that of the optimal, so one might expect to be able to place slits on ~ 180 targets in a GMACS field of view. In the most conservative case, limiting oneself to the narrow redshift range allowed in the dark OH region at 8200A, the expected number of targets within reach of a ~30 hour GMACS integration is ~ 150 (see below). Thus the field of view is not the limiting factor in this case. The use of band-limiting filters could improve the slit density by a fairly large factor.

**Table 1. Number of Lyα Emitters per GMACS Field of View**

| Log L(Lyα) | φ(α = -2) | N (5 < z < 6) | N(5.68 < z < 5.8) |
|---|---|---|---|
| 42.5 | -4.20 | 29 | 3 |
| 42.0 | -3.45 | 163 | 18 |
| 41.5 | -2.86 | 635 | 70 |
| ***41.2*** | ***-2.53*** | ***1357*** | ***149*** |
| 41.0 | -2.30 | 2300 | 250 |
| 40.5 | -1.86 | 6350 | 698 |

One can see from Table 1 that GMACS is well suited to probing the faint end of the LF in as few as one deep pointing. A proper sampling of the bright end would require a different strategy, although it is likely that other programs will accurately characterize the $L \sim L^*$ of the LF in the coming years.

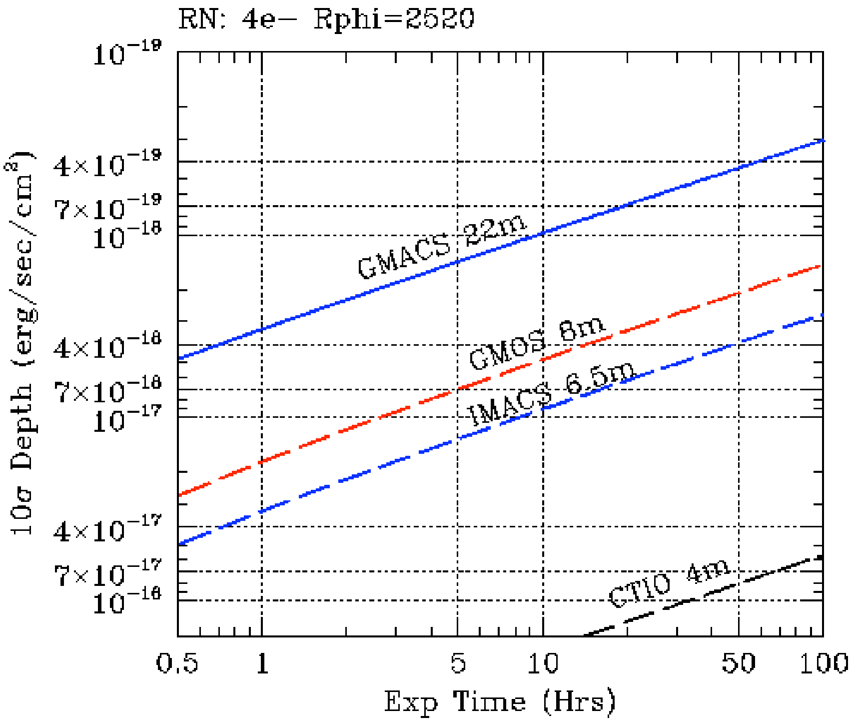

**Figure 2. Predicted sensitivity for unresolved emission lines for GMACS and similar spectrographs on telescopes ranging in size from 4 to 22m. These estimates are based on a 1″ slit resolving power of R = 2500 and a detector read noise of $4e^-$. The predicted sensitivity for GMOS is not far from that derived from the UDF observations.**

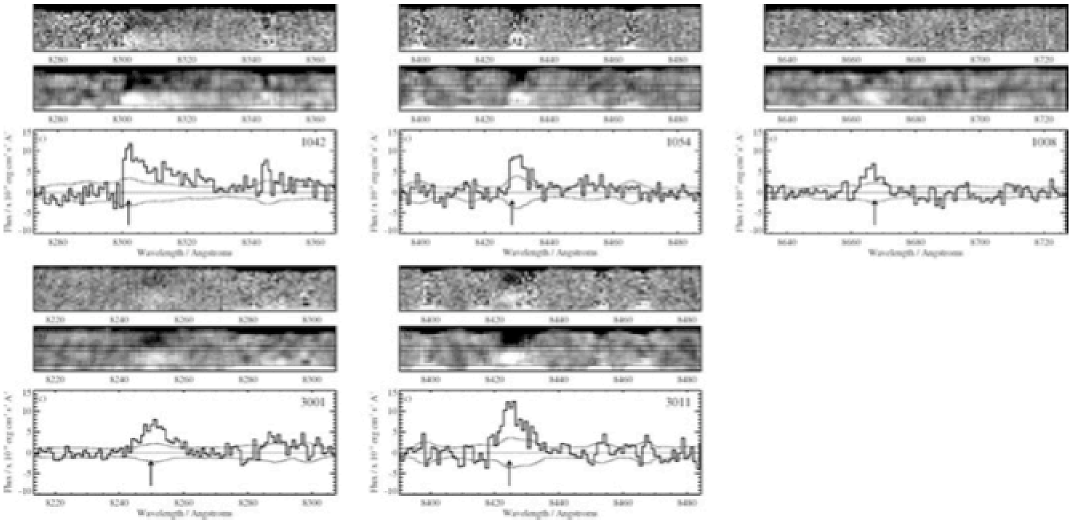

**Figure 3. Spectra of Lyα emission-lines in the UDF taken with GMOS on Gemini South. The observations were performed with nod & shuffle and each emission line is shown with a positive and negative image. The integration time was roughly 35 hours and the faintest emission-lines have fluxes of ~5 x $10^{-18}$ ergs/sec/cm$^2$. From Stanway et al. (2007).**

**Sensitivity:** The critical question in evaluating the viability and cost of a program such as this one is the expected sensitivity of the observations. We have estimated the sensitivity of the GMT using the parameters for the GMACS spectrograph. Figure 2 shows the expected sensitivity to unresolved emission-lines for GMACS along with similar numbers for GMOS on Gemini, IMACS on Magellan and a similar spectrograph on a 4m telescope. The calculations all use an Rϕ product of 2500; the GMACS and GMOS sensitivities are based on a 0.5" wide slit, while the IMACS and 4m numbers use 0.75" and 1.2" slit widths, respectively. One can see that in 10 hours GMACS can reach a limiting line flux of a $10^{-18}$ erg/sec/cm$^2$.

A useful benchmark is provided by deep observations of Lyα emitters at z = 5 in the UDF with GMOS on Gemini. Examples are shown in Figure 3, where integrations as long as 35 hours in duration reach a limiting flux of 5 x $10^{-18}$ ergs/sec/cm$^2$. In this same time GMACS should reach a depth on order of magnitude deeper for unresolved lines.

We have simulated spectra of Lyα emitters at z = 6 using the baseline properties of GMACS. The details of the simulations will be described elsewhere but, in brief, we use the basic properties of GMACS along with a flux calibrated sky spectrum from Gemini. Slit losses are included and a range of seeing and slit widths and on-chip binning combinations were considered. The spectrograph throughput was set at 30%, conservative compared to state-of-the-art spectrographs today. The observations are simulated at a resolution of ~ 4000 and, after sky subtraction, are rebinned to lower resolution. The brighter objects were rebinned to R = 1200, the fainter objects were binned to lower resolution. We modeled the Lyα emission lines as having a FHWM =

500 km/s, before passing through the IGM and a modest equivalent width (~30A in the rest-frame). The data were scaled according to the line flux before attenuation by the IGM. We treat the Lyα forest absorption at 100% for simplicity and obscure all photons more than 100 km/s to the blue of the line center. The results are shown in Figure 4. From this figure we conclude that a reasonable limiting line flux is ~ 4 x $10^{-19}$ in a 30 hour integration. With overheads in a fully queue schedule operation this observation would cost the equivalent of four full nights of telescope time.

**Measuring the Luminosity Function:** As shown in Table 1, in the most conservative case there would be ~ 150 targets within a single GMACS field of view for $\alpha$ = -2. We would like to determine the LF with reasonable statistical significance over bins no more than a factor of two wide in luminosity. In this case these would be distributed in flux such that approximately 50% of the objects would be in the last bin, 25% in the next faintest bin and so on until, in the brightest bin there would be only a handful of objects. This is illustrated in Table 2 below.

**Table 1. Statistics of Luminosity Function Determinations**

| Log L(Lyα) | Fraction | N(4 nights) | σ(%) | N(8 nights) | σ(%) |
|---|---|---|---|---|---|
| 41.2 | 0.57 | 85 | 10 | 85 | 10 |
| 41.5 | 0.25 | 37 | 16 | 37 | 16 |
| 41.8 | 0.10 | 15 | 30 | 30 | 18 |
| 42.1 | 0.05 | 7 | 40 | 35 | 15 |
| 42.4 | 0.03 | 4 | 50 | 20 | 20 |

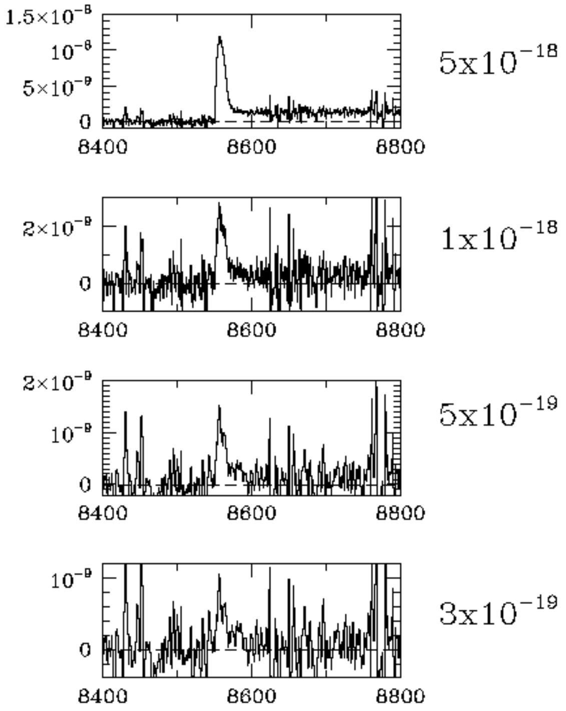

**Figure 4. Simulated Lyα spectra with GMACS for line fluxes ranging from 5 x $10^{-18}$ to 5 x $10^{-19}$ erg/sec/$cm^2$. The line profiles are modeled with a FWHM of 500 km/s and are attenuated by the IGM. The simulated exposure time is 30 hours and the data are observed at R = 4000 and then, after sky subtraction, rebinned to R = 1200 or lower resolution, depending on the initial signal-to-noise ratios.**

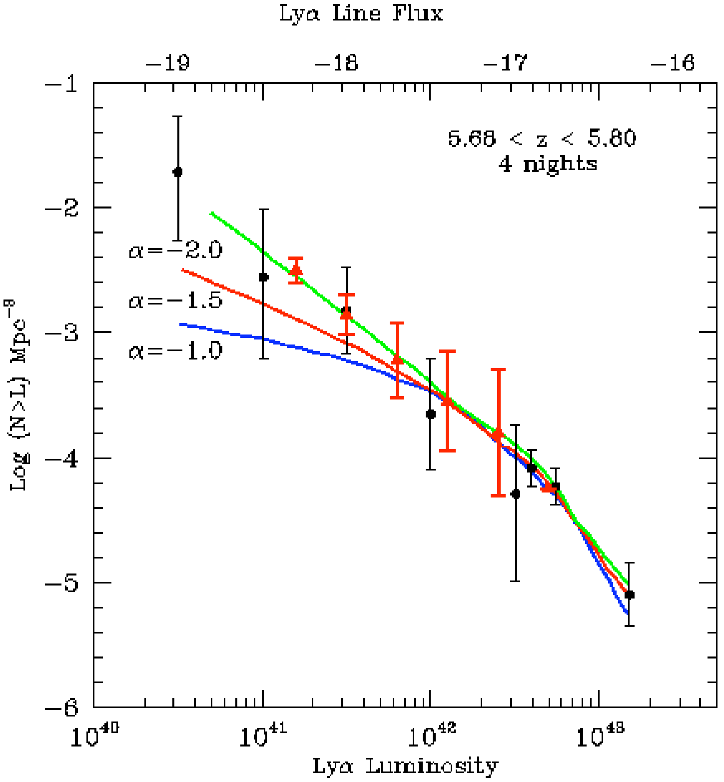

**Figure 5. Simulated measurements of the Lya luminosity function at z = 5.7 based on a single GMACS pointing and a 30-hour integration for an intrinsic faint end slope of –2. The statistical errors in the faintest bin are roughly 10%, while the bin sizes are half that of the Malhotra & Rhoads bins. From this one could distinguish between faint end slopes of –1, -1.5 and –2 with high confidence levels. The errors near L*, however, are not much improved from current studies.**

One can see from Table 2, deep observations with GMACS can determine the faint end of the LF with ~10% uncertainties in an single mask. The brighter bins, those near L* are poorly sampled simply because the volume in a single pointing is too small. This is illustrated graphically in Figure 5 where we show the LF from Malhotra & Rhoads with our putative simulated measurements from a single field superposed. The errors in the faintest bins are dramatically reduced while those in the bins near L* are not improved the same degree.

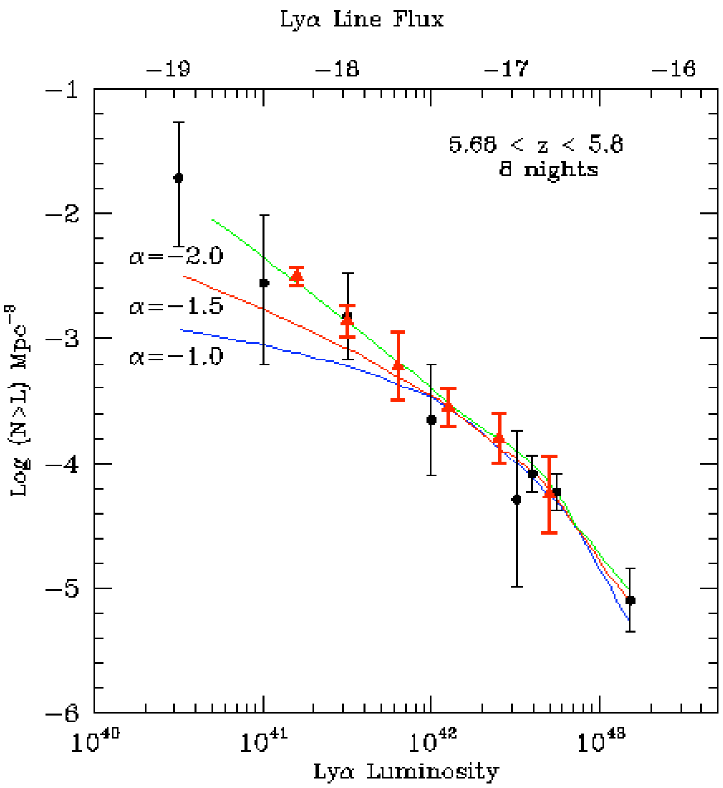

**Figure 6. The same plot as in Figure 5, except in this case we include four extra pointings of six hours each along with the original deep pointing. The combination produces nearly constant statistical errors in each of the bines and determines the LF with high precision.**

A somewhat longer program that combined four shorter pointings, of say six hours each, with the single deeper pointing could provide nearly constant statistical errors in all of the bins. This program would cost a total of 8 nights of telescope time, assuming reasonable overheads. The power of these extra pointings is illustrated in the right two columns of Table 2 and in Figure 6 above.

**Target Selection:** Defining a suitable set of targets is often the most challenging part of surveys for distant Lyα emitters. In this example we have assumed that a narrow-band imaging program using a 150A wide filter has been used to identify a list of emission-line candidates and deep continuum imaging has filtered out most of the outliers. The deepest narrow-band imaging surveys to date on 8m telescopes reach 5σ limits of ~ $10^{-18}$ and so a deeper set of imaging observations are needed to provide the target list for this experiment. Spectroscopic searches in conjunction with intermediate band-filters provide better sensitivity than narrow-band imaging surveys, but the volume sampled is rather limited.

**Summary:** We have shown that with a single pointing and a long, but not unprecedented, exposure time one can measure the faint-end slope of the Lyα luminosity function with a precision of 10%. This will allow one to distinguish between slopes of –1 to –2 with a high degree of confidence. The total cost of this measurement is equivalent to four nights of observing time, not an unreasonable expectation for a small group of investigators. Adding another four nights would allow one to measure the full LF to high significance and would provide a sample large enough to examine the clustering of faint Lyα emitters just after the end of the reionization era.