Motivation

- 40 orbits of UDF observations with the ACS grism
- Spectra for every source in the field.
- Good S/N continuum detections to I(AB) ~ 27; about 30% of UDF sources.
- Spectral identification of every 4<z<7 object to I(AB)=27
- Efficiently identifies spectroscopically interesting sources that might not merit a slit without the grism information:
  - high equivalent width lines;
  - Real z > 6 LBGs among the very red, faint stuff.

GRism ACS Program for Extragalactic Science (GRAPES)

Deepest Unbiased Spectroscopy yet. I(AB) < 27 (UDF)

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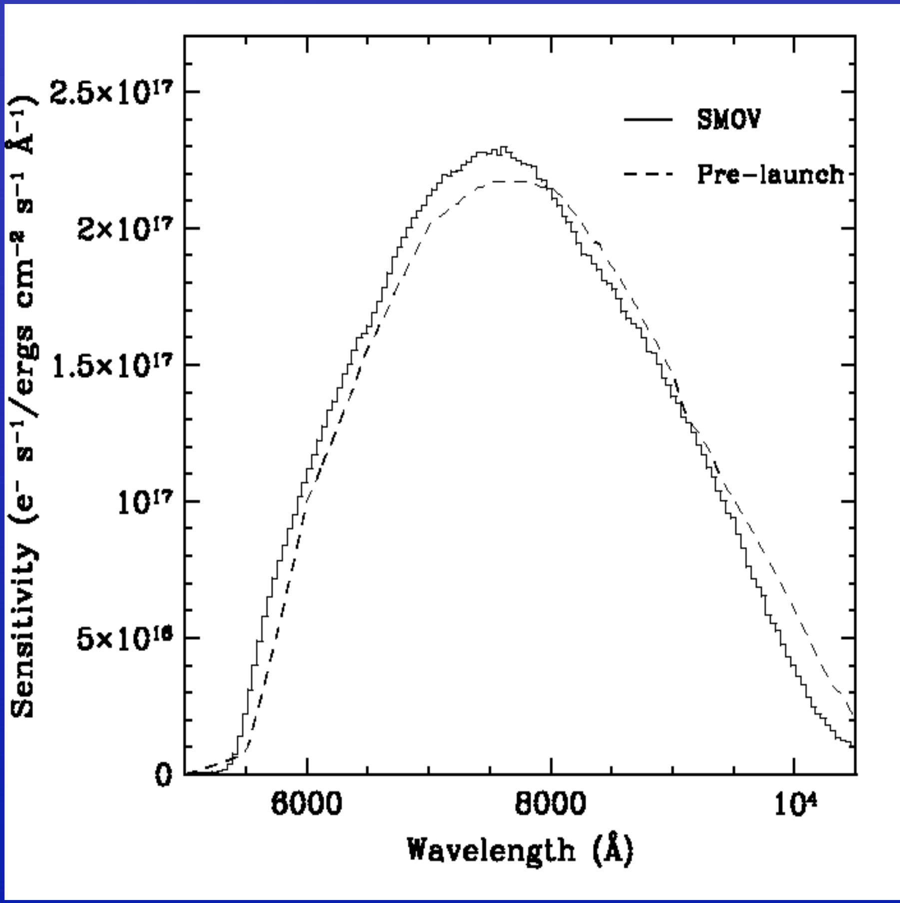
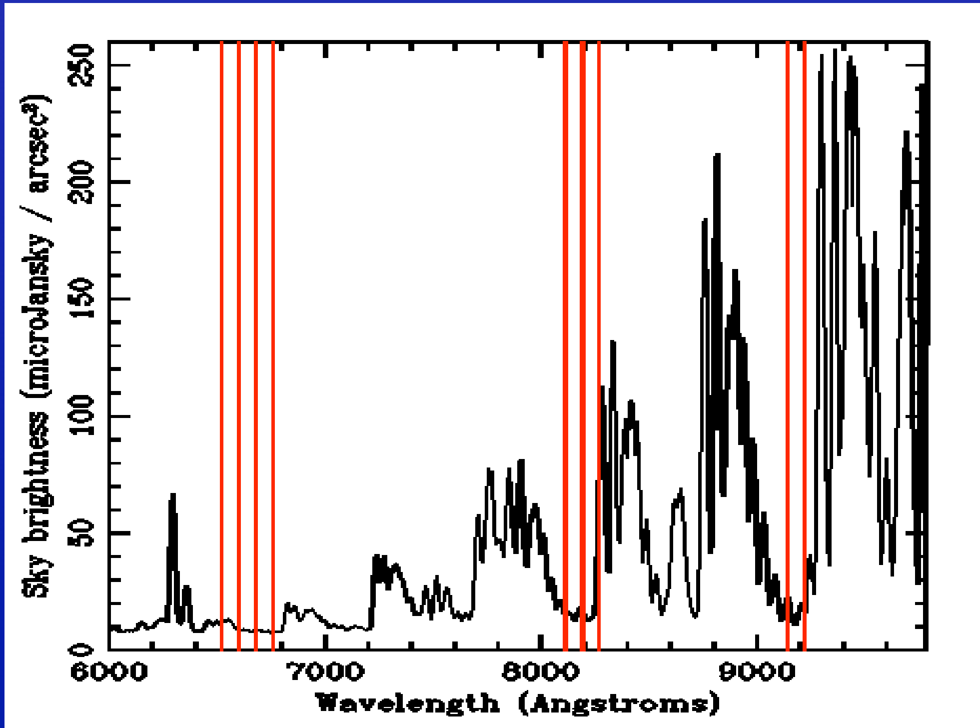
ACS Grism Characteristics
(G800L + WFC)

- Dispersion: 40Å/pixel, Resolution: ~ 80Å (point source; scales with image size).
- Wavelength calibration is accurate ~10Å or Dz~0.001
- Wavelength coverage: ~ 550 nm to 1050 nm at "zero" response; 600 to 930 nm at half max.



Advantages of HST/ACS combination:

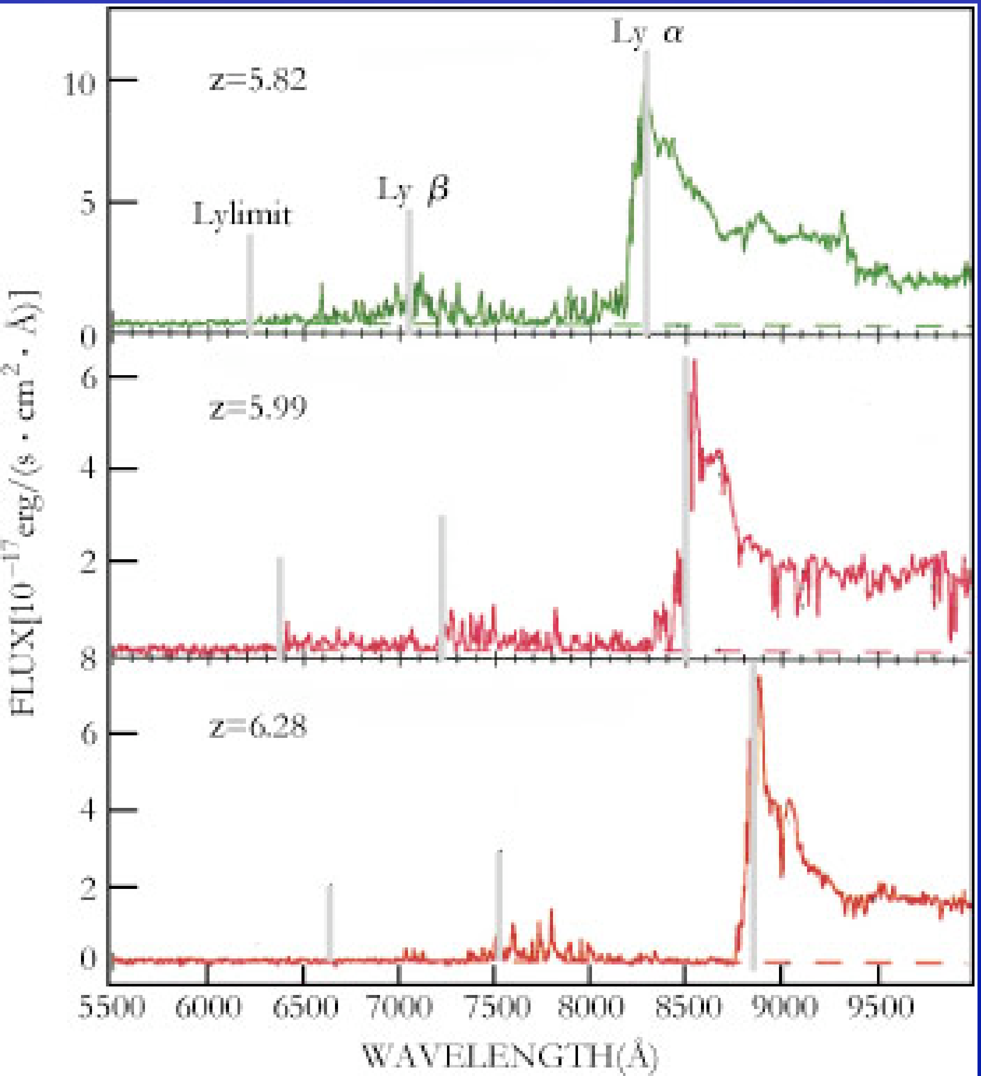
- Low sky background from space
- Red sensitivity of the ACS
- High redshift galaxies are compact, HST PSF helps
- Contiguous wavelength/redshift coverage, unlike ground based instruments.



Science Goals

- Probe reionization era by determining luminosity functions of lyman-α emitters, lyman-break galaxies at $z=4$-7 and low-luminosity AGNs.
- Study star-formation and galaxy assembly at $1<z<2$ by identifying star-forming galaxies with strong emission lines and old populations with strong 4000Å break and any combination of the two.
- Supernovae spectra, M-dwarfs, [your science].

The Epoch of Reionization



- The detection of Gunn-Peterson trough(s) in z ~ 6 quasars show the late stages of H reionization (Becker et al. 2001, Fan et al. 2002.)
- WMAP results indicate substantial reionization at z~15
- Was the universe reionized twice (Cen 2002)?

Epoch of Galaxy formation?

- Early stages of galaxy formation are presumably ongoing at $z \sim 6$.
- Our current samples at this redshift are small: A half dozen $z>5$ galaxies, 6 at $z>6$, quasars at the very brightest end of luminosity function.
- *We would like to determine the epoch and pace of reionization as well as the luminosity function of sources (galaxies/AGNs) responsible for the photons.*

Testing Reionization with Lyman-α emitters

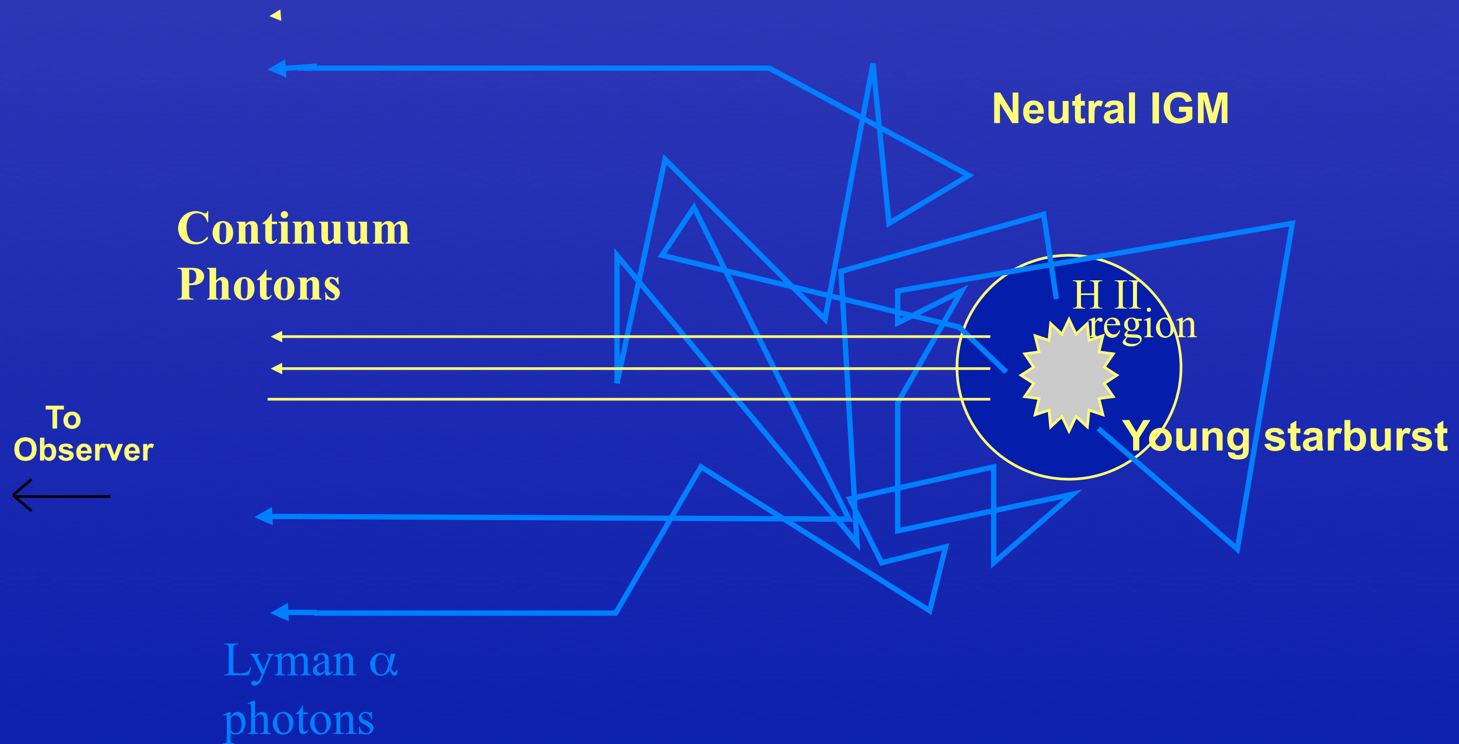
Low luminosity Lyman-α sources should not be visible before reionization:

- Lyman alpha photons resonantly scatter in a neutral universe.
- This means they should not be apparent as compact sources, I.e., we expect a sharp drop in the Lyman alpha source counts at reionization.

(Miralda-Escude 1998; Miralda-Escude & Rees 1998; Haiman & Spaans 1999; Loeb & Rybicki 1999)

- Higher luminosity sources (e.g. quasars) create a local ionized bubble allowing the Lyman-α photons to escape.

Resonant Scattering Before Reionization



Constraining Reionization

- We still see expected number/luminosity of Lyman alpha emitters in our $z=5.7$ sample. Thus, the reionization redshift is $z > 5.7$.

(Rhoads & Malhotra 2001, ApJ Lett 563, L5)

- … extended to z(reionization) > 6.6?

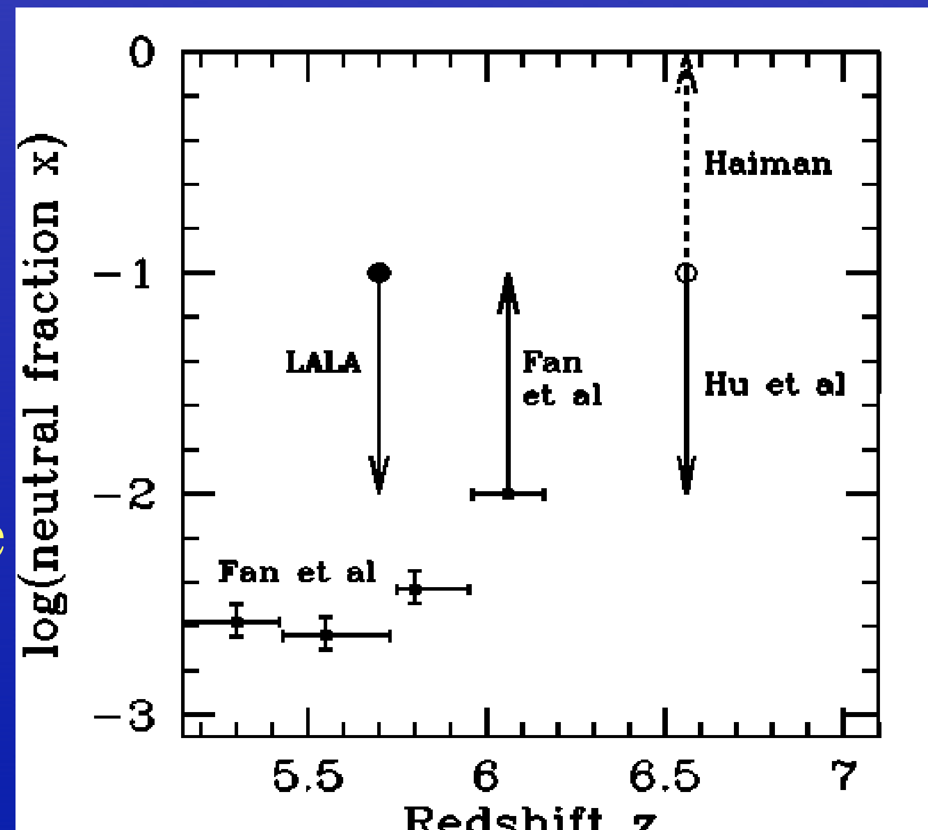
(Hu et al. 2002, Kodaira et al. 2003, Lilly et al. 2003, Cuby et al. 2003, Rhoads et al. 2003)

HII Regions in $z > 5$ Lyman α Samples

- An HII region must be > 1.2 Mpc (non-comoving) to reduce the line center optical depth to $\tau < 1$.
- This requires a minimum value of (L_i t f_{esc}).
- We can constrain all of these quantities in LALA using the observed line luminosities and equivalent width distribution.
- We find that L_i t f_{esc} is < 30% of threshold for the z=5.7 sources, i.e. the sources are too faint to create a large enough HII region.
- The limit for the Hu et al source is similar, thanks to its lower physical luminosity.

The Lyman α Test, First Order Concerns: $\tau \sim 2 < \tau \sim \infty$

- Our threshold HII region size was based on $\tau_0 = 1$ at emitted line center. Lines have finite width, and $\tau < \tau_0$ in the red wing.
- The Hu et al source could be embedded in a fully neutral IGM and still get 10 to 20% of its Lyman α flux out (Haiman 2002).



Testing Reionization

- Statistical test remains: The *observed number* of Lyman α emitters above a fixed threshold will show a dramatic drop at reionization.

- Equivalent width test: Also the equivalent width of the Lyman-α line will also drop at reionization.
- At present 5/6 sources at z>6 have rest equivalent width of the Lyman-α line <50 Å, whereas at z=4.5 median equivalent width is 200 Å (Malhotra & Rhoads 2002). So the line may well be attenuated by the damping wings of the neutral gas. The sixth source has EW>85 Å (Rhoads et al. 2003)

The Lyman α Test, First Order Concerns: Evolution

- The Lyman α test is based on number counts as a function of redshift.
- Strong evolution could cause trouble. In particular, a decrease in n(z) could mimic a neutral IGM.
- However, the intrinsic n(z) is more likely to increase than decrease at reionization:
  - Star formation in small halos is suppressed at reionization;
  - Lyman α galaxies appear to be primitive objects (Malhotra & Rhoads 2002) and should be a larger fraction of galaxies at high z.
- Lyman break galaxies offer a control sample, if we can go deep enough to find them.

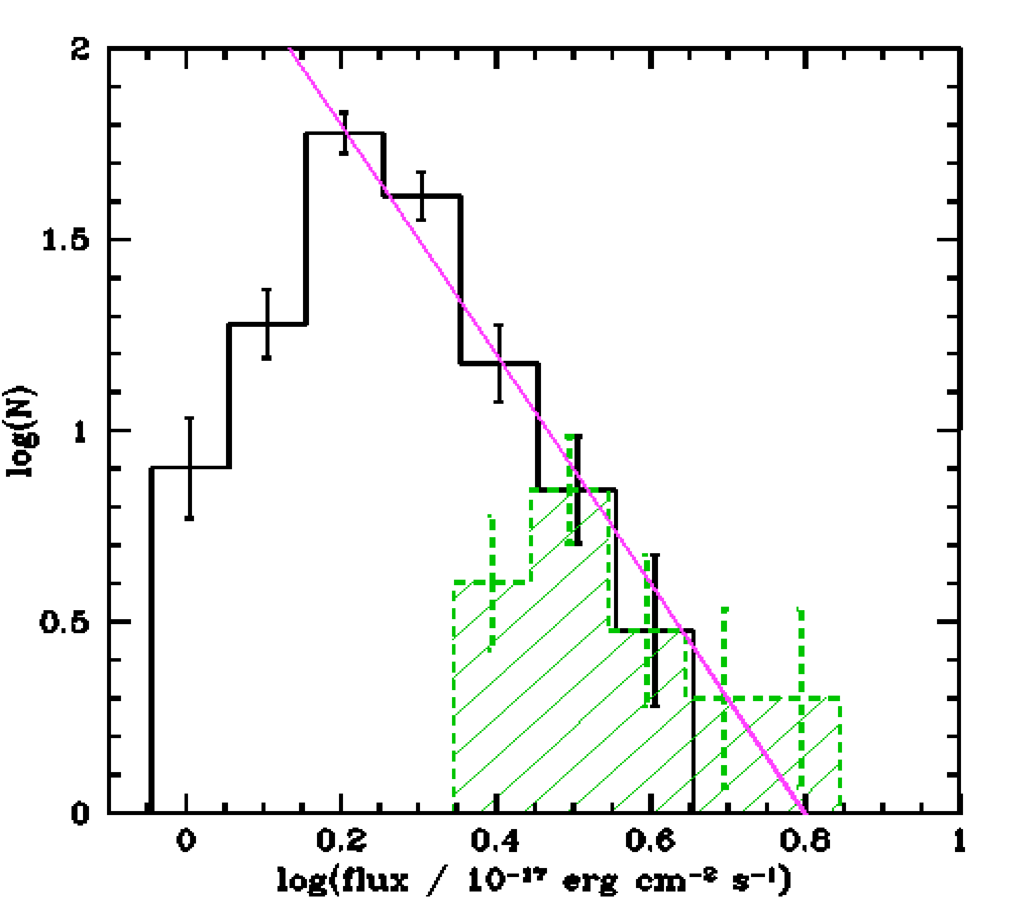
Ultradeep Field Grism Expectations: Lyman Break Galaxies

- Extrapolating from shallower grism data, we estimate that Lyman break galaxies can be reliably identified to I(AB) = 26.9 for breaks near the throughput peak.
- Effective redshift limit around 6.7 (to have some useful wavelength coverage redward of break).
- Compare limit at redshift < 6.0 for i’, z’ two-filter detections.
- Predicted Counts… shortly.

Ultradeep Field Grism Expectations: Lyman α Galaxies

- Isolated emission lines near peak sensitivity would be detected to
  - 8×10^{-18} erg/cm^2/s for compact galaxies
  - 6×10^{-18} erg/cm^2/s for point sources
- Lyman-α galaxy density: ~1 per sq. arcminute per unit z above flux 2×10^{-17} erg/cm^2/s (z=4.5, Rhoads et al 2000).
- A very steep luminosity function observed → expect many objects.

Ultradeep Field Grism Expectations: Lyman-α Galaxies

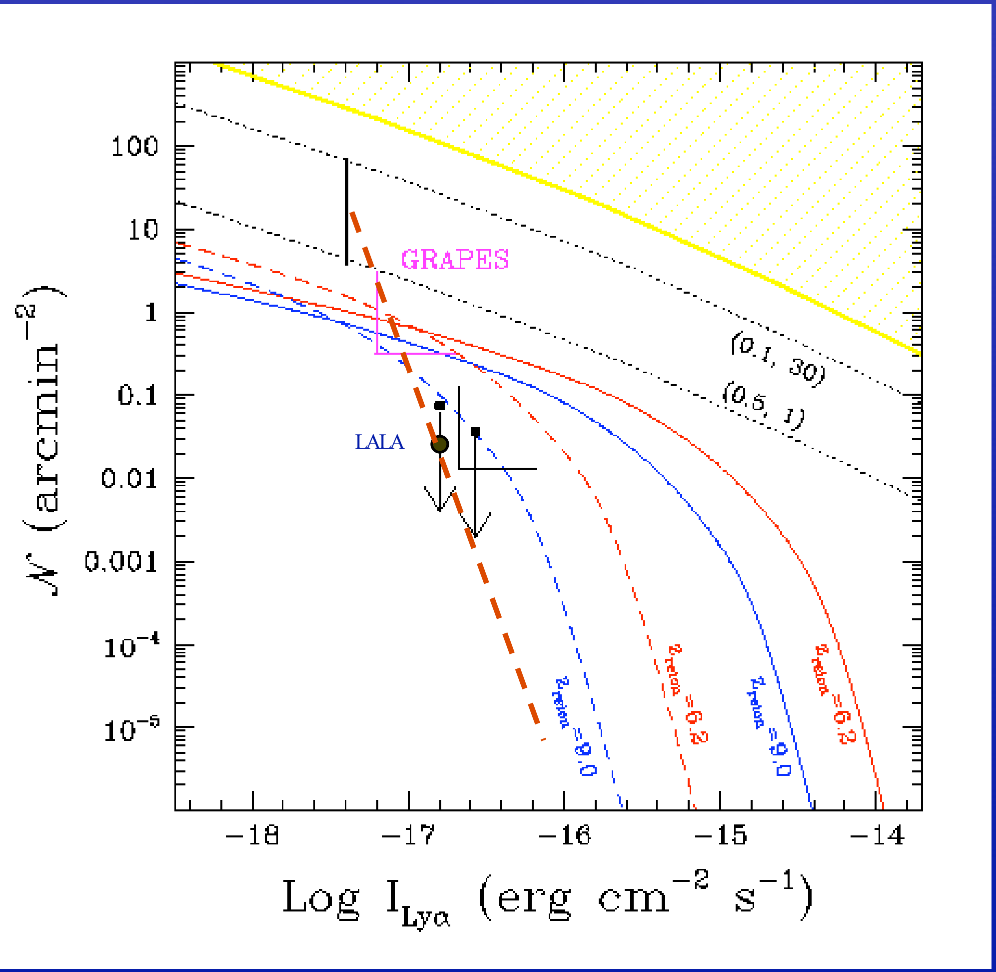


Number-flux relations for Lyman α galaxies from the LALA survey. Scaled to redshift $z=5.7$.

Black: $z=4.5$ data; Green: $z=5.7$ data.

Red line: $N \sim f^{-3}$

Expected Numbers of z>6 Lyman-α emitters



- Adapted from Stiavelli et al. 2003. Upper limits from Hu et al. and detection from the Large Area Lyman Alpha (LALA) survey.
- Grapes should see 3-30 z>6 Lyman-α emitters.

Ultradeep Field Grism Expectations: High Redshift Galaxy Counts

	$4.5<z<5.5$	$5.5<z<6.7$
Lyman-break galaxies	10	10
Lyman-α	60-400	3-30
AGNs	~0.6-4	

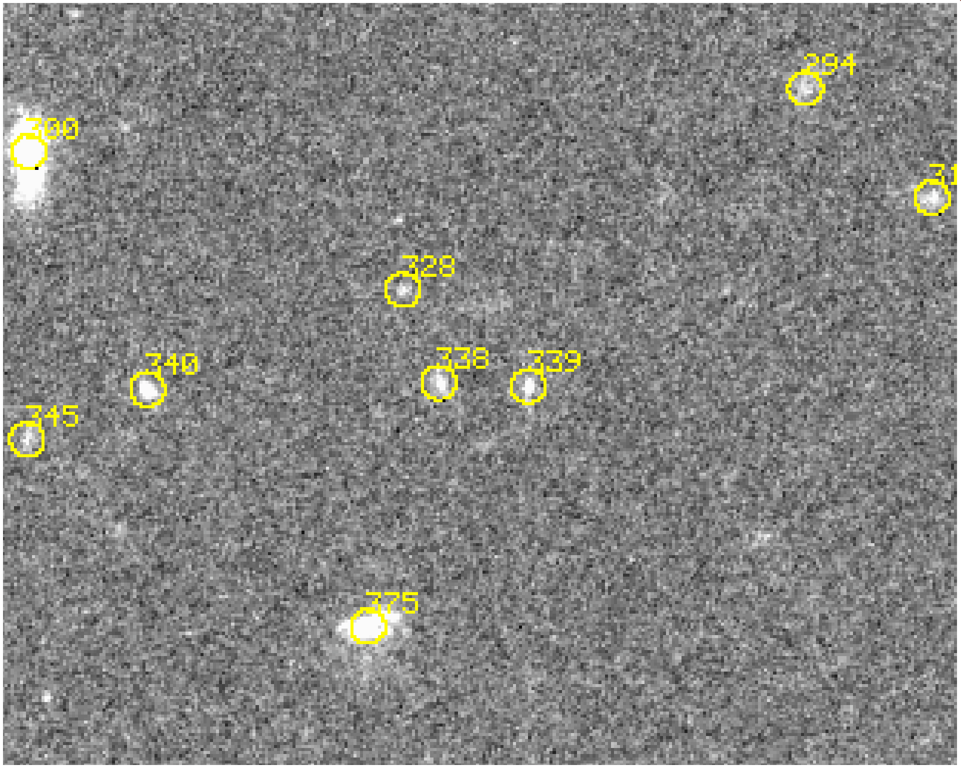
Ultradeep Field Grism Expectations: Foreground ($z \sim 1$) Galaxies

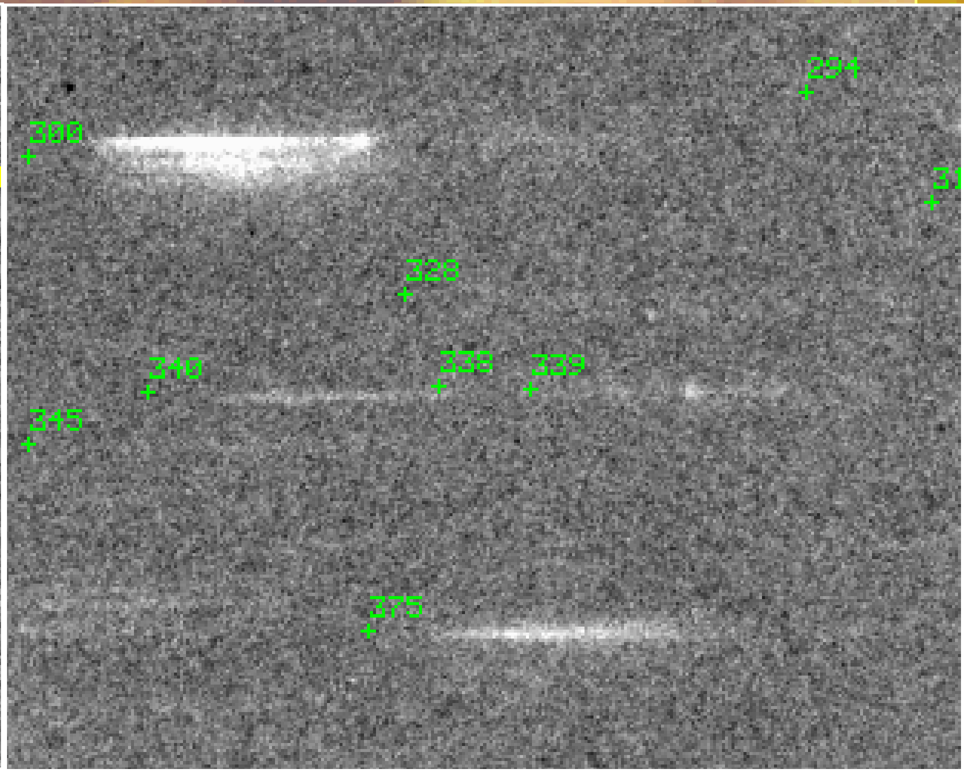
- Most galaxies with a well detected emission line or 4000Å break will yield a redshift.
  - Two lines à redshift;
  - One line → synergy with photo-z (grism redshift is more precise but may be less accurate) and with ground based followup (more wavelength coverage)
- Star formation history from emission lines at $0<z<1.8$;
- Field ellipticals over a similar redshift range.

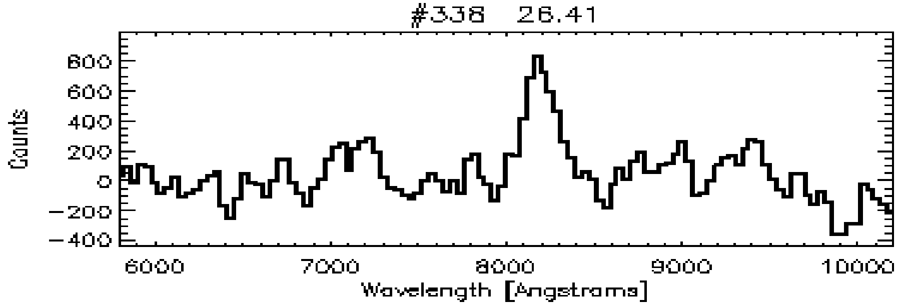
Ultradeep Field Grism Expectations: Faint Quasars?

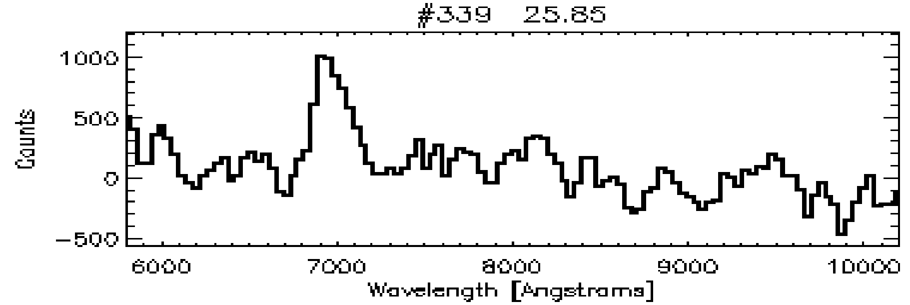
- We have detected a couple of promising high redshift quasar candidates in our deepest cycle 11 parallel grism data.
- Many AGN lines → broad redshift coverage
- Morphology + spectroscopy (+variability) → reliable identifications, completeness.
- Caveat: modest sample size

APPLES (ACS Pure Parallel Lyman-α Emission Survey)

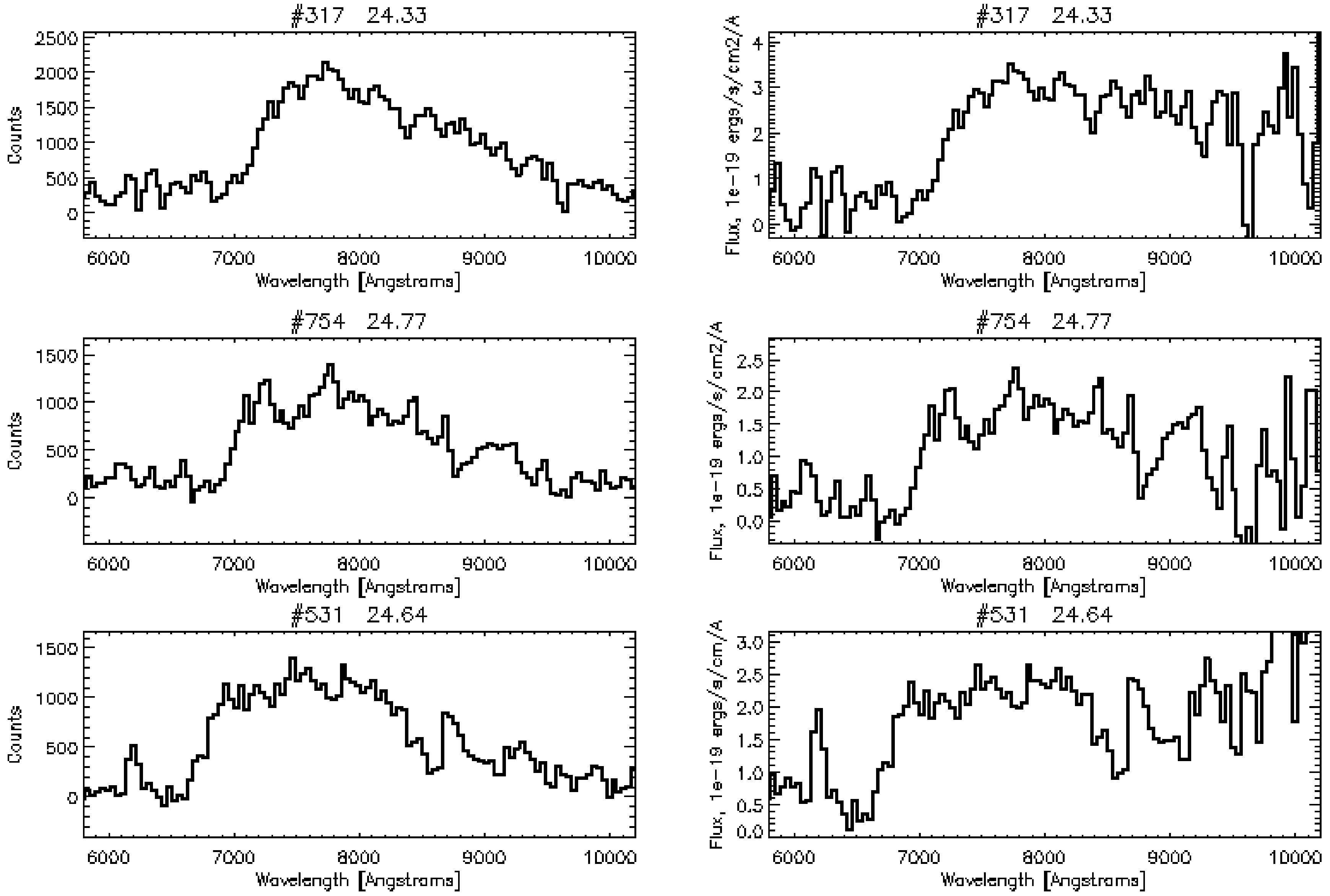




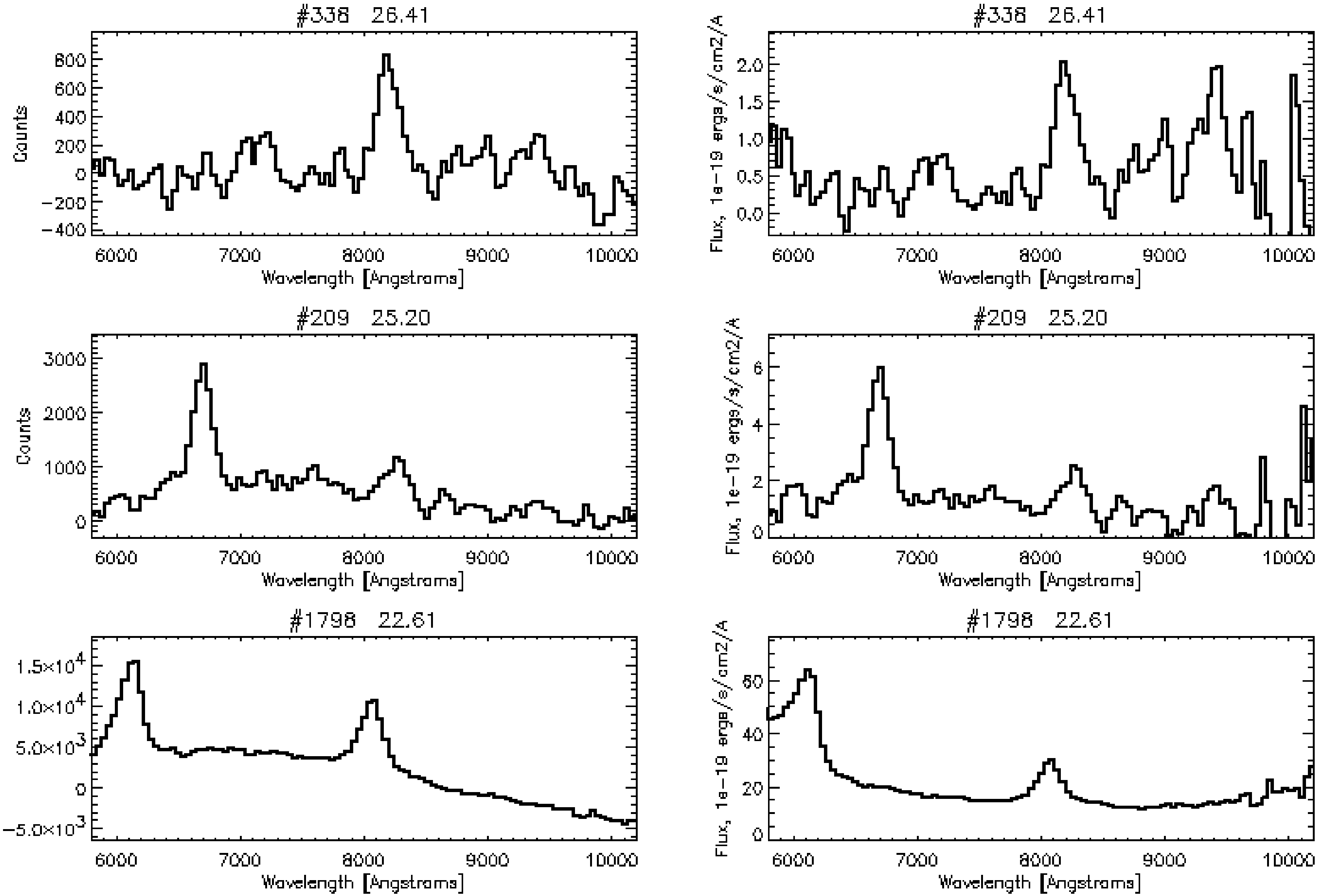




APPLES First-Look Lyman Break Galaxies



APPLES First-Look Emission Line Objects



Synergy with Ground Based Spectra

Grapes will help ground based spectroscopy in at least two ways:

- "Instant" redshifts for ~ 300 to 500 objects; potential savings of time.
- Identification of **which** faint objects are worth a slitlet.

Conversely, ground based data yield more flexible wavelength coverage and higher resolution, offering physical information unavailable with the grism.

Spectrum Overlap and Roll Angles

- Overlap is potentially a problem in slitless spectroscopy.
- Extrapolation from shallower grism fields and simulated GRAPES data both imply 20% contamination in any roll angle.
- Multiple roll angles will resolve source confusion due to overlap for almost all sources.

Science and Data Products

Primary Data Product: Reduced, extracted spectra to go in the public domain.

Science products:

- Spectral identification of galaxies between $4<z<7$.
- Continuous redshift coverage => Clean studies of galaxy evolution.
- Galaxies with old stellar populations, HII region lines or both identified at $z\sim1$.
- M-dwarfs, Supernovae …