HUNTING FOR THE DARK PHASES OF GALAXY FORMATION WITH MUSE: THE HAMMERHEAD FIELD

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ABSTRACT

Theoretical models suggest that the early phases of galaxy formation should involve an epoch when galaxies are gas rich and inefficient at forming stars: a dark galaxy phase. In this work, we present new results on the search for dark galaxies at high redshift (z~3) obtained from the analysis of the Hammerhead MUSE deep field as a part of the Guaranteed Time of Observation (GTO) program. In particular, we take advantage of the quasar-induced, fluorescent Lyman α emission to study and detect such objects otherwise invisible to optical telescopes. Previous pioneering works already showed that dark galaxies are compact, gas-rich, and very inefficient at forming stars but the current sample is very limited. Thanks to the unprecedent capabilities of the MUSE instrument, we are now able to provide a more complete census of fluorescently illuminated dark galaxies as well as to analyze and characterize the main properties of these intriguing objects with a unique spatial and spectral resolution.

DARK GALAXIES

- The densest and most filamentary parts of the Intergalactic Medium (IGM) play a key role in the formation and evolution of galaxies (Meiksin 2009, and references therein). The challenge, however, is to understand how the IGM gas is converted into stars in the high-redshift Universe and what is the efficiency of this process. In most of the studies conducted so far, the proto-galactic phase (Krumholz & Dekel 2012) preceding substantial star-formation is poorly constrained.

- We take advantage of the QSO-induced fluorescent Lyα emission to study and detect in emission these dense gas clouds without "internal" light sources. In other words, we use the ionizing radiation emitted by the QSO as a flashlight to illuminate and to boost the faint signal coming from dark galaxies in a large cosmological volume.

- From pilot observation of Cantalupo et al. 2012 using a 20hr deep narrow-band (NB) image with a custom-built filter on VLT-FORS around the QSO UM287 at redshift 2.4, we have learned that dark galaxies are compact and gas-rich emitters with EW_0 > 240 Å (see Fig. 1) but their current sample is very small (12).

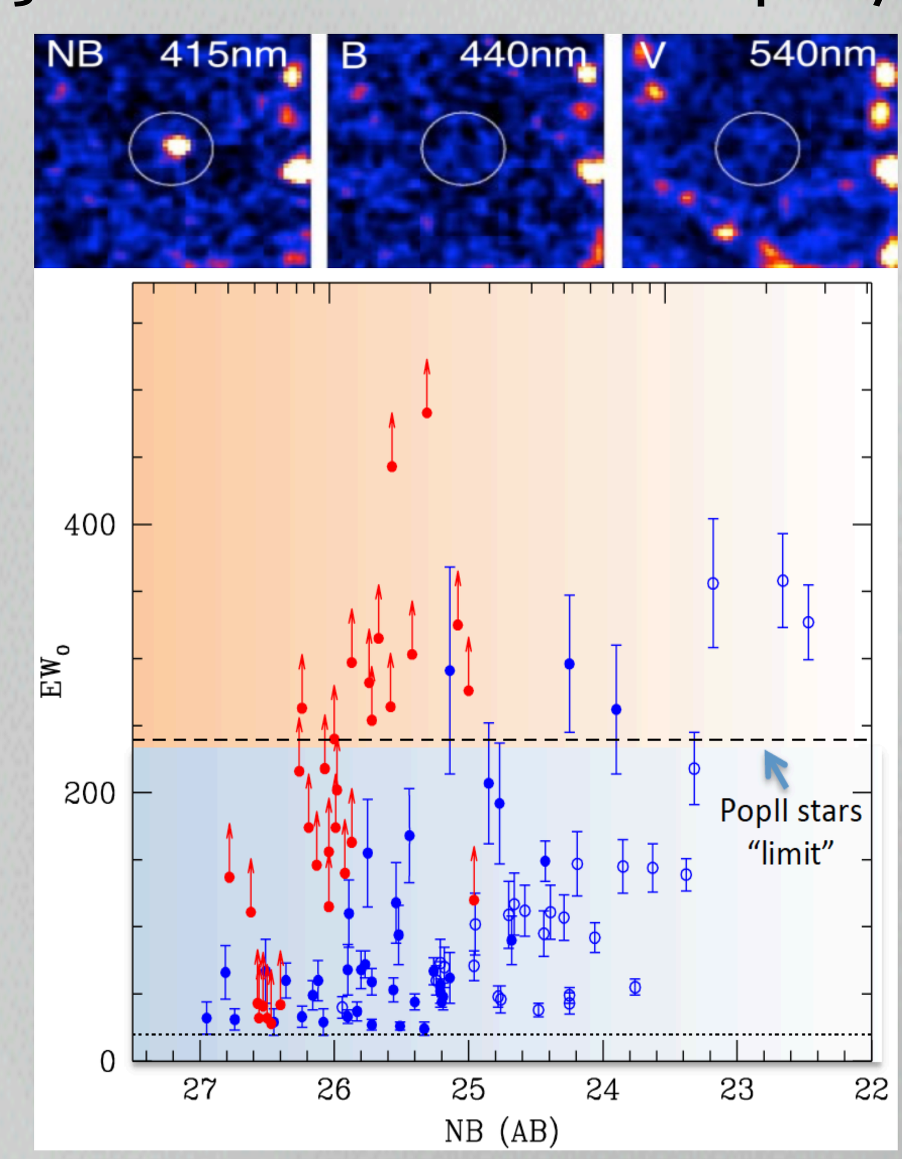


Fig. 1: Top row: Postage-stamp images of one of the 12 dark galaxies discovered in the UM287 field. Left panel shows the positive detection in the narrow-band (NB) image while central and right panels the corresponding expected position in the B- and V- bands, respectively. **Bottom row:** Lyα rest-frame Equivalent Width (EW) versus NB AB magnitude. Blue symbols represent objects with detected continuum, red dots with arrows represent the estimated lower limit on the EW for the objects undetected in the broad-bands. The continuum-undetected objects above the horizontal dashed line (EW_0=240 Å) are the best candidates for dark galaxies fluorescently illuminated by the quasar.

- The MUSE deep cubes (> 9hr) with excellent spatial and spectral information are the best place to search for/analyse these dark galaxies.

THE HAMMERHEAD

The MUSE instrument (Bacon et al. 2010) is the new optical integral field spectrograph on the VLT highly suitable to blindly look for extended line emission. MUSE has been designed to offer a relatively large field of view (1′x1′), wide optical spectral range (4750-9350 Å), relatively high spatial (0.2″) and spectral (R~3000) resolution.

The MUSE performance and stability allowed us to discover, among other results, giant fluorescent Lyα nebulae around QSO (Borisova et al. 2016). The Hammerhead MUSE data were taken as a part of the GTO program (P.I. Simon Lilly) and our 9hr final datacube is the result of the combination of 36 exposures. Figures 2 & 3 show as example the RGB image of the field and the Hammerhead spectrum respectively.

NAME	J2321+0135
CLASS	Radio Quiet QSO
RA (J2000)	23:21:14.7
DEC (J2000)	+01:35:54
REDSHIFT	3.199
OBSERVATIONS	9hr = 36 exposures
SEEING	0.73″
$I_{[AB]}$	18.94 mag

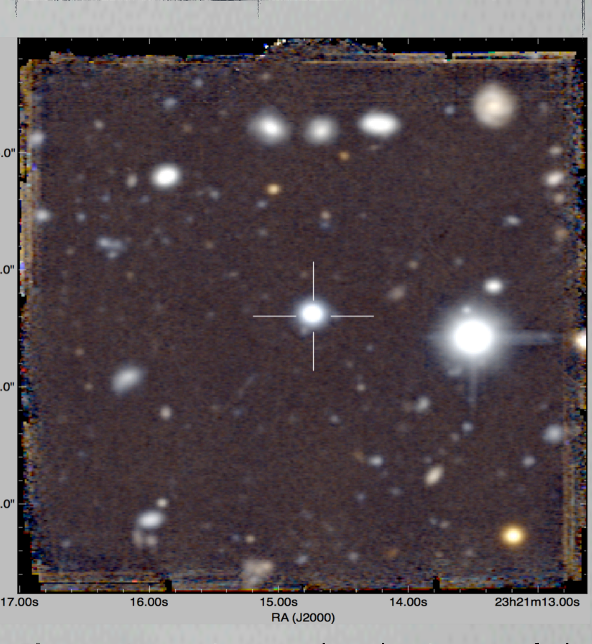


Fig. 2: Composite pseudo-color image of the Hammerhead field. The RGB colors are assigned to V-, I-, and R-band images from MUSE. The white cross points the quasar location. North is up and east to the left.

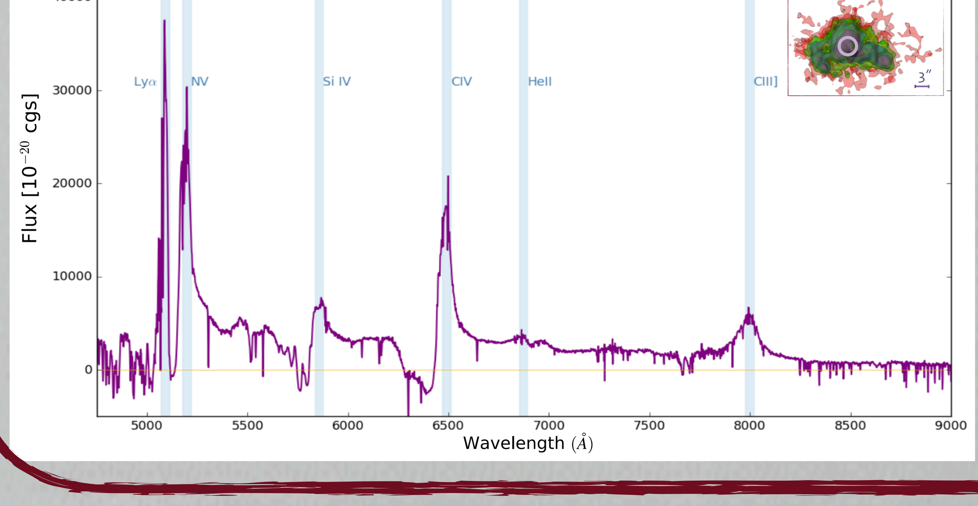


Fig. 3: The MUSE spectrum of the Hammerhead within a 3″ aperture (lilac circle in the inset) is shown. The cyan shadow areas highlight the most prominent emission lines and the QSO Lyα emission at z=3.199 is at λ=5089Å. The inset panel shows the giant Lyα nebula (~25″) found around the QSO.

DATA PROCESSING & ANALYSIS

REDUCTION PROCEDURE	**MUSE Pipeline v1.2** (Weilbacher et al. 2014)
	scibasic & **scipost** packages for bias subtraction, flat-fielding, twilight and illumination correction, and wavelength calibration
POST PROCESSING	**CubExtractor** package (Cantalupo in prep.)
	Astrometric offsets CubeFIX (self-calibration flat-field correction) CubeSHARP (flux-conserving sky subtraction) CubeCombine

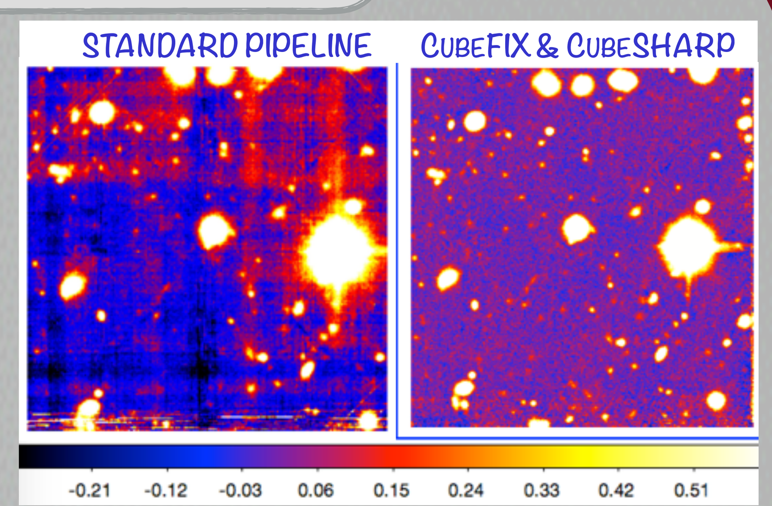


Fig. 4: White light images of one individual datacube. The output of the standard pipeline is shown on the right panel while on the left is the improved results obtained after applying CubeFix (flat-fielding correction) and CubeSharp (sky subtraction) tools.

The QSO contribution and the continuum subtraction of the brightest sources were corrected with the CubePSF and CubeBKG tools, also part of the CubEx package. We start the analysis of the Hammerhead field by splitting our datacube over the λ dimension in 3 sub-cubes (λ_{width}=200Å) in order to study the distribution of the Lyα emitters (LAEs) centred around the QSO in the on-source cube, and also in two control cubes (off-blue and off-red).

The 3D detection and extraction of the LAEs was obtained with CubEx using a S/N=3.5 and 40 minimum connected voxels. Then, we visually inspect the analysis plots (see Fig. 5) to reject possible spurious detections or [OII] and [OIII] emitters and the final catalogue comprises ~100 LAEs.

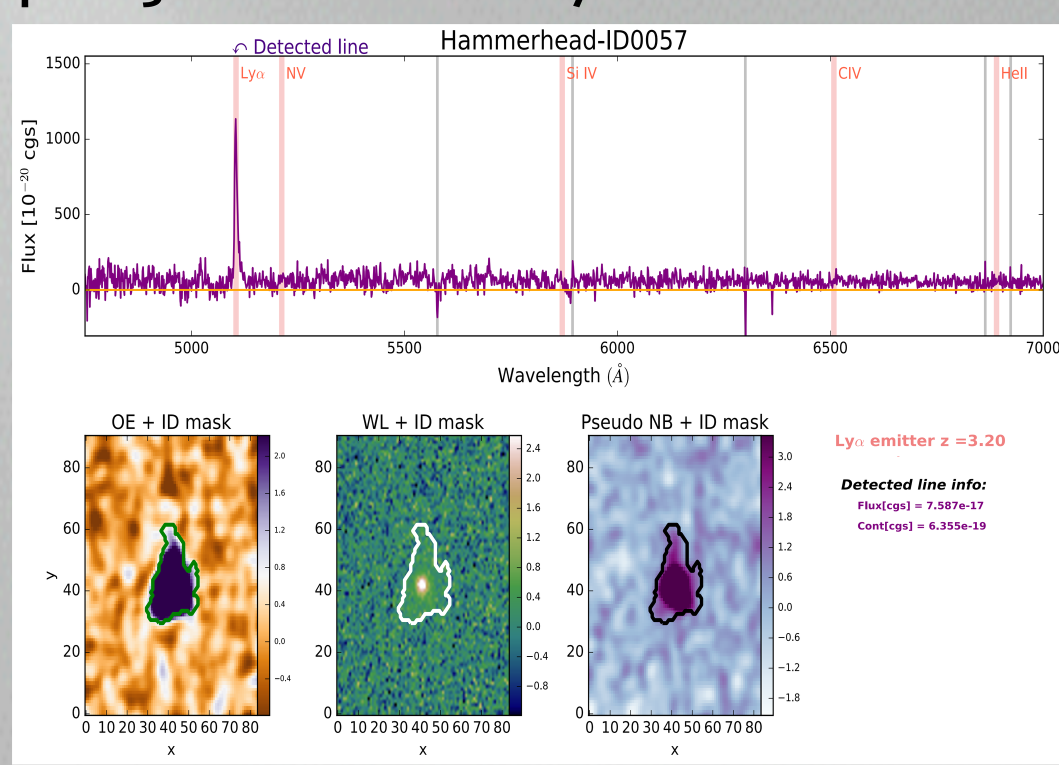
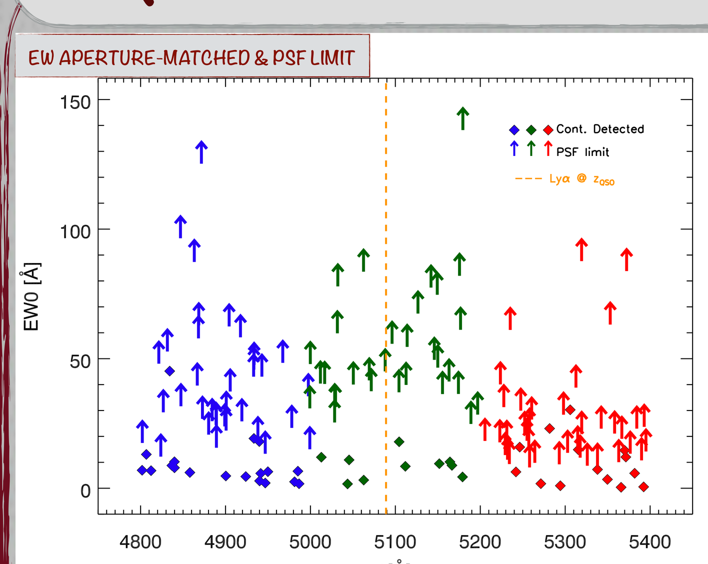
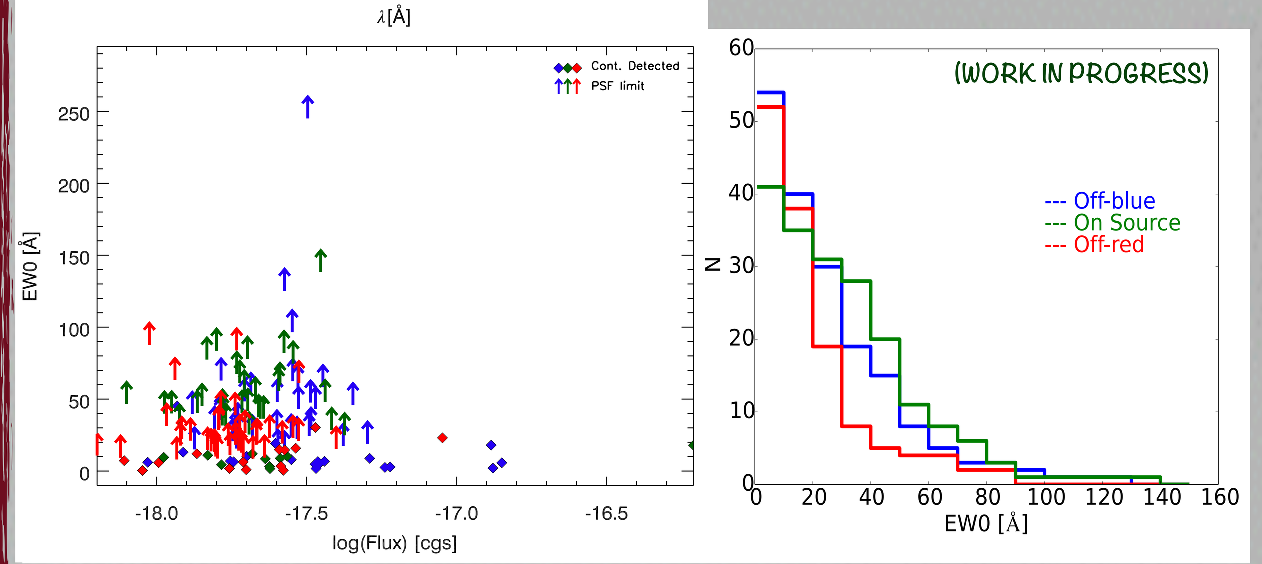


Fig. 5: Analysis plot for one Lyα emitter (ID#57). **Top row:** The MUSE optical spectrum (purple) along with the detected emission lines (pink shadow areas) and the sky-lines residuals (grey vertical lines) is plotted. **Bottom row:** The 'optimally' extracted (OE, right), the white light (WL, central) and the pseudo NB images obtained from the MUSE datacube are shown. The solid contours indicate the 3D mask obtained from CubEx. The 3D mask is also used to extract the spectrum and to measure the Lyα flux and the continuum emission.

EQUIVALENT WIDTHS DISTRIBUTION



- We follow two approaches for the equivalent width (EW, see Fig. 6) measurements:
  - Matched-aperture for the continuum detected candidates (same aperture for $F_{Ly\alpha}$ and F_{cont})
  - PSF limit for the continuum undetected candidates (F_{PSF}> 3σ)
- So far, we have no evidence (yet) at current limits for dark galaxies in the (small) volume probed around the Hammerhead QSO.



- We are working on improving our EW measurements and on extending our analysis to other deep (>9h) QSO MUSE fields. We also plan to compare our results with theoretical model predictions.

Fig. 6: Top row: Rest-frame EW (EW_0) values versus the wavelength of the detected Lyα emission. Blue symbols indicate the off-blue LAEs, green the on-source ones and the red the LAEs detected in the off-red cube. Diamonds represent those targets with continuum counterparts while the arrows show the lower limit on the EW values for undetected-continuum LAEs. The vertical yellow dashed line marks the QSO Lyα emission. **Bottom row:** Left panel shows EW_0 versus the Lyα fluxes whereas on the right the cumulative EW_0 distribution is plotted.

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