Wandering in the Redshift Desert

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The cosmic star formation rate, active galactic nuclei activity, galaxy growth, mass assembly and morphological differentiation all culminate at redshift $z \sim 2$. Yet, the redshift interval $1.4 < z < 3$ is harder to explore than both the closer and the more distant Universe. In spite of so much action taking place in this spacetime portion of the Universe, it has been dubbed the "redshift desert", as if very little was happening within its boundaries. The difficulties encountered in properly mapping the galaxy populations inhabiting the desert are illustrated in this paper, along with some possible remedies.

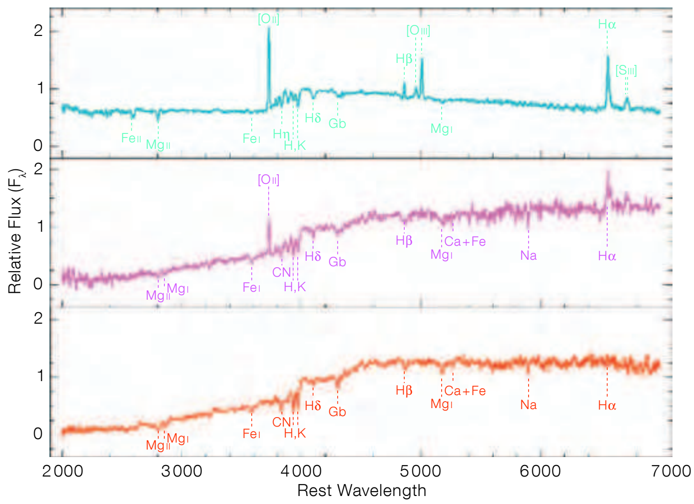

Figure 1. The template spectra of actively star-forming (top), moderately star-forming (middle) and passively evolving galaxies (bottom). From Mignoli et al., 2005.

Optical spectroscopy of $1.4 < z < 3$ galaxies

Figure 1 shows typical FORS2 spectra of actively star-forming, moderately star-forming, and passively evolving galaxies at $z \lesssim 1$ (Mignoli et al., 2005). The strongest, most easily recognisable features in these spectra are the [O II] 3727 Å line in emission, the Ca II H&K doublet, and next to it the 4000 Å break. These are the features that allow spectroscopists to measure reliable redshifts even on relatively low signal-to-noise (S/N) spectra. Provided, of course, these features are included in the observed spectral range.

As redshift increases beyond $z \sim 1$ all these features become harder to recognise in observed spectra, as they enter a wavelength region where the sensitivity of CCDs starts to drop, detector fringing complicates life, and the sky deteriorates. At this point we are already in quite an arid environment (redshift-wise), though still manageable thanks to the collective power of our very large telescopes, routinely applied dithering patterns, and the like. But a little further out in redshift our preferred spectral features move beyond 1 μm, i.e., into the near-infrared, and we are in full desert.

Still, survival with optical spectrographs is hard, but not completely impossible. While we have lost, beyond 1 μm, the strong features, other, albeit less prominent, ones have entered our optical range coming from the restframe ultraviolet (UV). Just as opportunistic organisms still find their ecological niche in the driest desert, so we currently rely on weak, restframe UV features to explore the redshift desert. In the case of actively star-forming galaxies at $z \gtrsim 1.4$, these are several narrow absorption lines across the UV continuum, most of which originate in the interstellar medium of these galaxies (see Figure 2). In the case of passively evolving elliptical galaxies at $z > 1.4$, the strongest feature in the observed optical spectral range is a characteristic feature at 2600–2800 Å, due to neutral and singly ionised magnesium and iron (see Figure 3). Thanks to these features, we can survive in the desert, but it is not an easy life.

First of all, it is quite awkward to use narrow, weak absorption lines to obtain

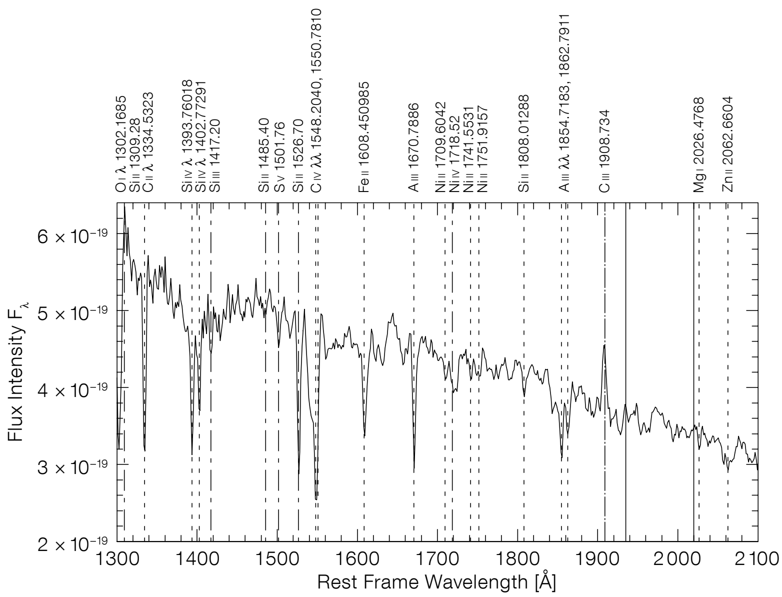

Figure 2. The co-added FORS2 spectrum of 75 star-forming galaxies at $z \sim 2$, corresponding to 1652.5 hours of integration (from Halliday et al., 2008). The main spectral features are indicated, including the weak blend of Fe III lines that originate in the photosphere of the OB stars responsible for the UV continuum.

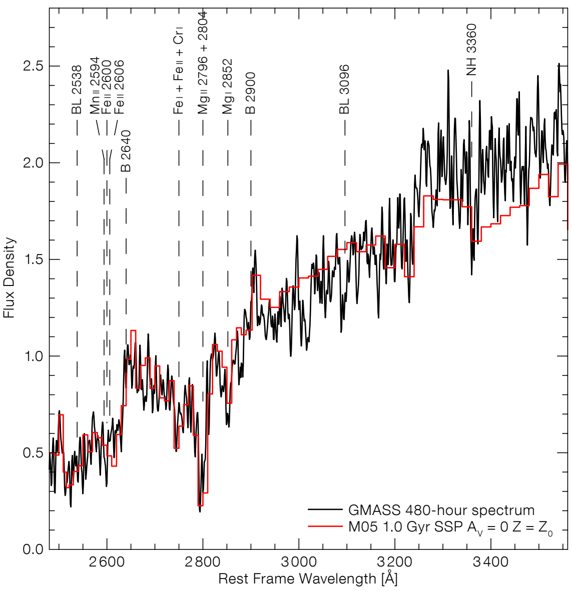

Figure 3. The co-added FORS2 spectrum of 13 passively evolving galaxies at $z \sim 1.6$, corresponding to 480 hours of integration (from Cimatti et al., 2008). The main spectral features are indicated, along with the synthetic spectrum of a 10 Gyr old, solar metallicity stellar population model (Maraston et al., 2005).

redshifts of star-forming galaxies that have strong emission lines elsewhere in their spectrum, or absorptions on a very faint UV continuum for galaxies that are intrinsically very red. These are indeed the cases shown in Figues 2 and 3! But this is not the whole story. In order to make the fairly good S/N spectra shown in these figures from the GMASS Large Programme, Cimatti et al. (2008) had to co-add the spectra of several galaxies, each integrated from a minimum of 30 to a maximum of 60 hours. Thus, the spectrum of star-forming galaxies in Figure 2 is the result of co-adding 75 spectra of individual galaxies for a total integration time of 1652.5 hours (!). Similarly, the spectrum of passive galaxies in Figure 3 was obtained by co-adding the spectra of 13 galaxies, for a total integration time of 480 hours (!). Clearly, journeys in the redshift desert take time nowadays.

In the case of star-forming galaxies a little relief may be offered by Ly-α, if the spectrograph is efficient enough in the UV. Indeed, even if not in emission, Ly-α is such a strong feature that it helps a lot in getting redshifts. However, in a spectrograph such as e.g., VIMOS, Ly-α does not enter before $z \sim 1.8$, hence the range $1.4 < z < 1.8$ is perhaps the harshest part of the redshift desert.

Drawbacks

For quite a few years we have known that at $z \sim 2$ galaxies with star formation rates (SFR) as high as some ~ 100 $M_\odot$ yr^{-1} are quite common, and, by analogy with the rare objects at $z \sim 0$ with similar SFRs, many of us believed they were caught in a merger-driven starburst. It was quite a surprise when one of these galaxies (BzK-15504 at $z = 2.38$) did not show any sign of ongoing merging, but on SINFONI 3D spectroscopy looked like a rather ordered rotating disc (Genzel et al., 2006). But still, its many clumps and a high velocity dispersion make it (like many others, see Förster-Schreiber et al., 2009) quite different from local disc galaxies.

That high SFR in $z \sim 2$ galaxies does not necessarily imply starburst activity became clear from a study of galaxies in the GOODS fields (Daddi et al., 2007a). Figure 4 shows the SFR *v.* stellar mass, M^*, for galaxies at $1.4 \lesssim z \lesssim 2.5$ in the GOODS-South field, where a tight correlation is apparent between SFR and stellar mass. Only a few galaxies are far away from the correlation, most notably a relatively small number of passive galaxies (with undetectable SFR), conventionally placed at the bottom of Figure 4. Among star-forming galaxies, the small dispersion of the SFR for given M^* demonstrates that these objects cannot have been caught in a special, starburst moment of their existence. Rather, they must sustain such high SFRs for a major fraction of the time interval between $z = 2.5$ and $z = 1.4$, i.e. for some 10^9 yr instead of the order of one dynamical time (~ 10^8 yr) typical of starbursts.

In parallel with this observational evidence, theorists are shifting their interest from (major) mergers as the main mechanism to grow galaxies, to continuous cold stream accretion of baryons, hence turned into stars (Deckel et al., 2009). Clearly a continuous, albeit fluctuating SFR such as in these models is far more akin to the evidence revealed by Figure 4, compared to a scenario in which star formation proceeds through a

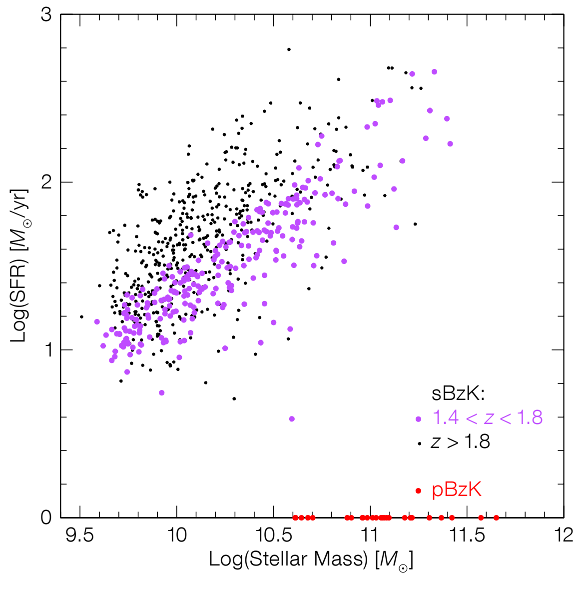

Figure 4. The SFR in $M_\odot$ yr^{-1} *v.* stellar mass for actively star-forming galaxies galaxies (sBzK) in the GOODS-South field and with spectroscopic or photometric redshifts in the range $1.4 < z < 2.5$ (adapted from Daddi et al., 2007a). Passively evolving galaxies (with SFR ~ 0, dubbed pBzKs from Daddi et al., 2004) are conventionally plotted at the bottom as red dots.

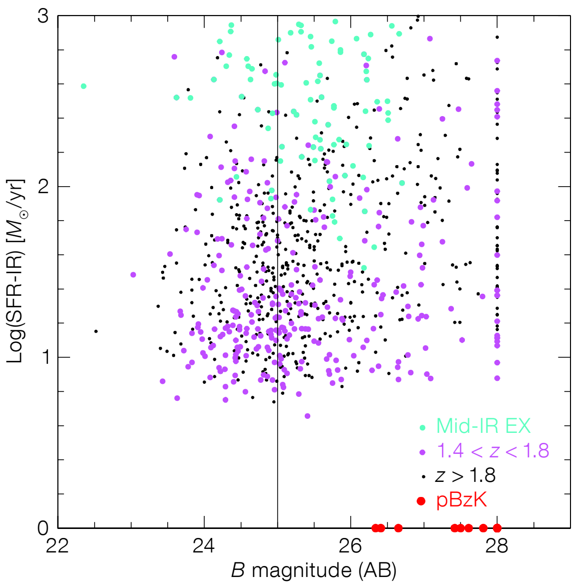

Figure 5. The SFR (here measured from the 24-μm flux as in Daddi et al., 2007a) *v.* the *B* magnitude for $1.4 < z < 2.5$ galaxies in the GOODS-South field. The cyan dots denote galaxies with excess mid-infrared (IR) emission, that according to Daddi et al. (2007b) may be due to a buried, Compton-thick active galactic nucleus (AGN), in which case the SFR may have been overestimated. The vertical line marks the current practical limit of what is doable with the VIMOS instrument.

series of short starbursts interleaved by long periods of reduced activity. This is not to say that major mergers do not play a role. They certainly exist, and can lead to real, giant starbursts corresponding to SFRs as high as ~ 1000 $M_\odot$ yr^{-1}, currently identified with submillimetre galaxies (e.g., Tacconi et al., 2008).

This paradigm shift, from mergers to cold streams, adds flavour to a thorough exploration of the redshift desert, an enterprise which is at the core of the zCOSMOS-Deep project (Lilly et al., 2007), the largest ongoing spectroscopic survey of the desert. This survey is targeting star-forming galaxies whose spectrum is pretty much like that shown in Figure 2, and does so with VIMOS for objects down to *B* magnitudes ~ 25 with 5-hour integrations. The success rate of zCOSMOS-Deep (i.e., the fraction of targets for which a reliable redshift is obtained) is ~ 2/3 (Lilly et al., in preparation), not bad at all for objects in the desert! Still, we wonder what we get, and what we miss.

Figure 5 shows the SFR *v.* *B* magnitude for the same $1.4 < z < 2.5$ GOODS galaxies shown in Figure 4. Clearly, the vast majority of actively star-forming galaxies in the desert are fainter than $B = 25$ mag, and they include several among the most active galaxies (here and elsewhere magnitudes are in the AB system). Those brighter than $B = 25$ mag account for just ~ 16 % of the global SFR of the whole sample, hence ~ 84 % of it remains out of reach. But why is the *B* magnitude (i.e., the restframe UV) such a poor indicator of SFR? This is so because lots of gas is needed to sustain high SFRs, but gas is accompanied by dust, and dust is a potent absorber of UV radiation.

Figure 6 shows the dust reddening E(B–V) for the same set of GOODS galaxies as Figure 5, as a function of SFR (from Greggio et al., 2008). Indeed, the star-forming galaxies with the highest star formation rates are also those with the most extinction, which makes it difficult to obtain redshifts from *B*-band spectroscopy. Such a strong correlation of extinction and SFR has been recently quantitatively confirmed using the dust-free 1.4 GHz flux as a SFR indicator (Pannella et al., 2009). What is said for the SFR also holds true for the stellar mass. Figure 7 shows *M** *v.* *B* magnitude, and again most of the stellar mass is in galaxies fainter than $B = 25$ mag, including many among the most massive galaxies.

Usually, when extinction bothers us it helps to go into the near-infrared. Figures 8 and 9 are analogous to the previous two figures, but SFR and *M** are now plotted *v.* the *J*-band magnitude instead of the *B*-band. Clearly, whereas a $B < 25$ mag selection misses most of the SFR and most of the stellar mass at $z \sim 2$, a $J < 24$ mag selection would pick up most of them. In particular, note that most of the highest star formation and most massive galaxies are fainter than $B = 25$ mag, but are instead among the brightest in the *J*-band. Thus, a $B < 25$ mag selection picks up a fair number of massive, star-forming galaxies at $z \sim 2$, but misses the majority of them, and in particular may miss several of the most massive and most star-forming ones.

It is worth emphasising that a comparison of Figures 7, 8 and 9 shows that all passive galaxies (the pBzKs of Daddi et al., 2004) are among the faintest objects in the *B*-band, but are among the brightest ones in the *J*-band. Being fainter than $B = 25$ mag, all passive

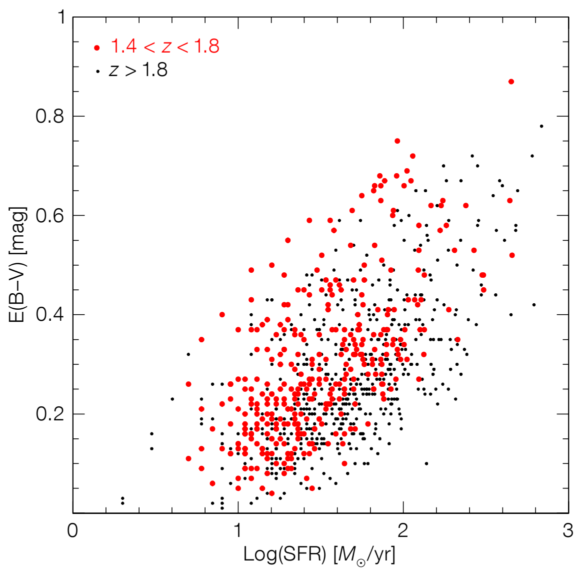

Figure 6. The global reddening E(B–V) derived from the slope of the rest-frame UV continuum as a function of the star formation rate for the same objects shown in Figure 5.

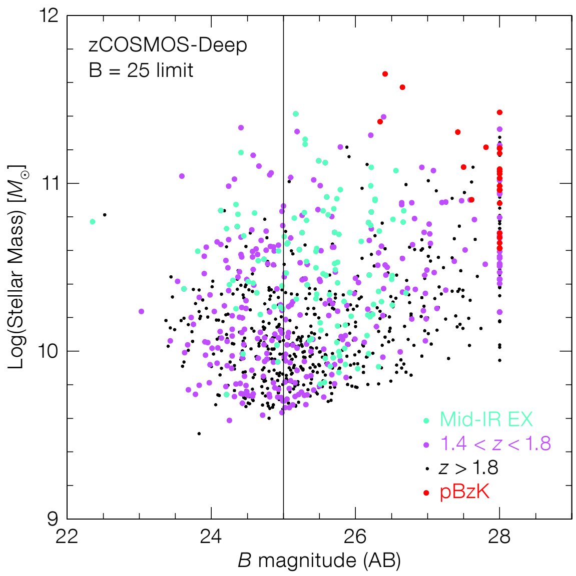

Figure 7. The stellar mass *v.* *B* magnitude for the same objects shown in Figure 5.

galaxies at $z > 1.4$ are automatically excluded from e.g., the zCOSMOS survey. Now, there are over 3000 such galaxies in the COSMOS field (McCracken et al., 2009), and if we wanted to make, over the whole COSMOS field (7200 arcminute^2), the same effort that GMASS did on one FORS2 field of view (49 arcminute^2), investing over 100 hours of VLT time, then it would take well over 15000 hours (!) of telescope time. Passive galaxies at $z > 1.4$ are the most massive galaxies at these redshifts, and they likely mark the highest density peaks in the large-scale structure, but we suspect that this argument would not be sufficient for the Observing Programmes Committee to recommend the allocation of over 1500 VLT nights to such a project ...

With reference to the COSMOS field, using COSMOS data for 30866 star-forming galaxies Figures 10 and 11 further illustrate the differences between *B*-band and *J*-band limited samples of $z \sim 2$ galaxies. Galaxies are first selected with the BzK criterion of Daddi et al. (2004) from the COSMOS *K*-band catalogue (McCracken et al., 2009), which is complete down to $K = 23.5$ mag. Then multi-band photometric redshifts from Ilbert et al. (2009) are used. Notice that the full range of masses and SFRs are still sampled for a selection down to a limiting magnitude as bright as $J = 22$–23 mag. In Figures 8–11 the vertical line at $J = 24$ mag is meant for objects that would be detected with S/N = 5 with 10-hour integrations with the FMOS *J*-band spectrograph at the SUBARU telescope (Kimura et al., 2003). This may well be a rather optimistic limit for a robust detection of the continuum and the absorption lines of passive galaxies. But for star-forming galaxies, the [O II] emission line would help greatly in measuring redshifts, hence a $J = 24$ mag limit may not be a mere dream for such objects.

Remedies

We understand that many may prefer to leave deserts as uncontaminated as possible, rather than crowded by swarms of all-inclusive tourists. But, what options do we have if we really want to colonise the redshift desert fully?

One possibility would be to use VIMOS with much longer integrations compared to the 5 hours currently invested by the zCOSMOS project, i.e., $\gtrsim$ 30 hr as used for the GMASS project. But before doing so, VIMOS would have to be made at least as efficient as FORS2 in the red, a good thing that may happen anyway. With respect to field of view, VIMOS is like 4 FORS units, hence doing all the COSMOS pBzKs (and along with them a much larger number of star-forming galaxies in the desert) would take about a quarter of the time we have estimated above for FORS2, i.e., some 350 VLT nights. This still looks like a lot of time, yet is somewhat more affordable than a mere FORS2 brute force effort. After all, VIMOS was conceived and built primarily for making large redshift surveys, hence, why not this one? But, how many years are 350 nights? We can scale from zCOSMOS, whose 640 hours (~ 75 nights) were reckoned to complete the project in four semesters. Suppose (a big if) VIMOS could be used for zCOSMOS whenever the COSMOS field is +/–4 hours from the meridian. But because of bad weather, competition from projects working on objects at the same right ascension, and instrument downtime, it is now taking five years to finish

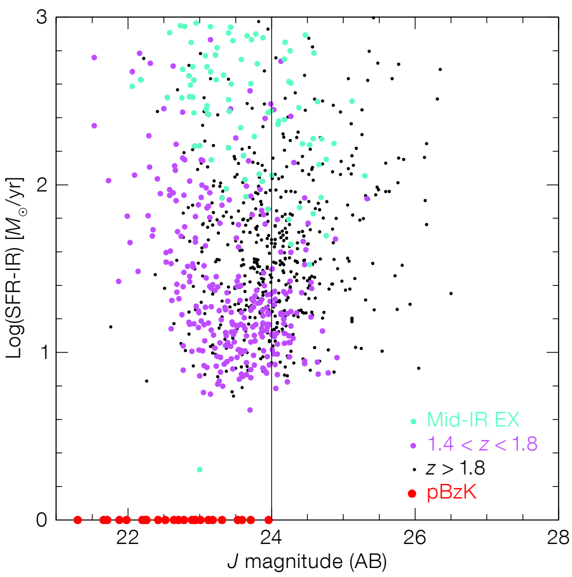

Figure 8. The same as in Figure 5, but now plotted *v.* the *J* magnitude. The vertical line at *J*(AB) = 24 mag marks the limit expected for reaching S/N = 5 with 10-hour integration with the FMOS *J*-band spectrograph at the SUBARU Telescope.

zCOSMOS. By the same token, it would then take ~ 25 years for an upgraded VIMOS to do justice to the COSMOS field alone.

Thus, what we would really need is a high-multiplex instrument able to sample the strongest spectral features of galaxies in the $1.4 < z < 2.5$ desert, i.e., [O II] 3727 Å for the overwhelming population of star-forming galaxies, and Ca II H&K and the 4000 Å break for the passive ones. All these features fall in the *J*-band for the galaxies in the desert, thus a cryogenic instrument would not be necessary. Without having to bother about the thermal background, a room temperature instrument could then cover wide fields in a single telescope pointing. A preliminary knowledge of the distribution of the [O II] line flux for star-forming galaxies in the desert would be critical for properly planning a spectroscopic survey targeting them. Such information is not yet to hand.

The surface density of these objects for the full COSMOS sample down to *K* ~ 23.5 mag is 4 per arcminute, or ~ 1 per arcminute for the brighter portion down to *J* = 22. Thus, the ideal VLT instrument would be one able to exploit fully the largest field of view of the VLT (i.e., ~ 500 arcminute^2 at the Nasmyth focus) with a multiplex ≳ 1 arcminute^{-2}, or ~ 500 objects over the whole field. This can be achieved only with a fibre-fed *zJ*-band spectrograph, not too different from the FMOS instrument on SUBARU. A *camel* of this species may offer the best, short-term possibility of wandering in the redshift desert.

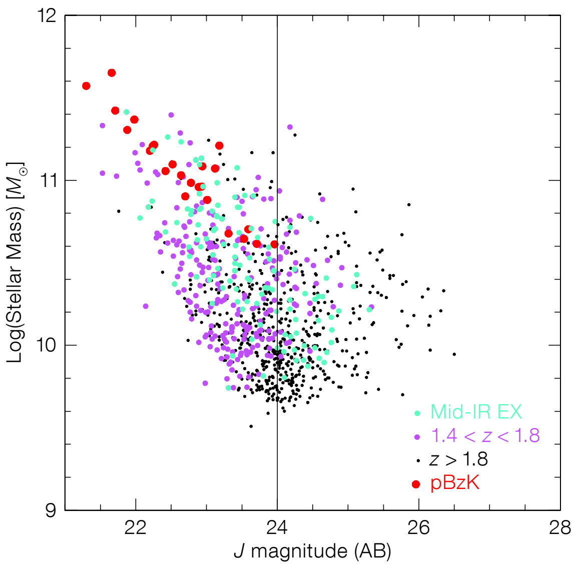

Figure 9. The same as in Figure 7, but now plotted against the *J*-band magnitude.

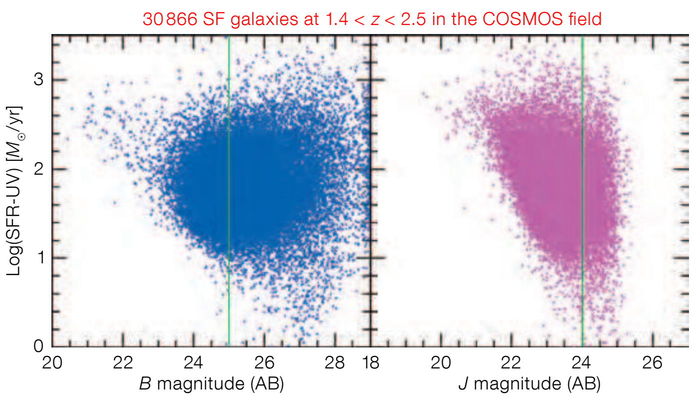

Figure 10. The SFR from the UV diagnostics for SF galaxies at $1.4 < z < 2.5$ in the COSMOS field *v.* their *B*-band magnitude (left) and their *J*-band magnitude (right). A plume of objects brighter than *B* ~ 22 mag are likely to be AGN.

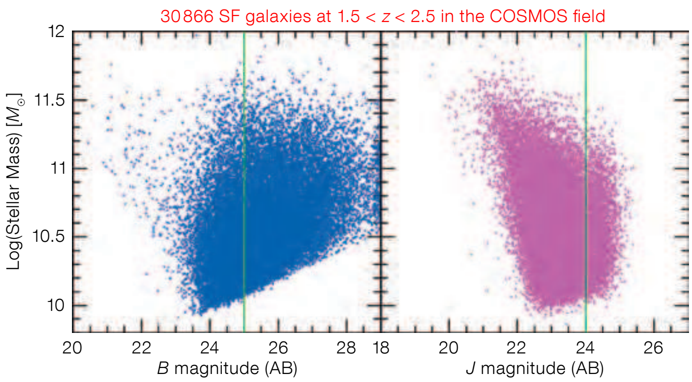

Figure 11. The same as in Figure 10, but now the stellar mass *v.* the *B*- and *J*-band magnitudes are plotted.

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