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SPECTROSCOPIC CONFIRMATION AND DETAILED STUDIES OF THE PROPERTIES OF VERY MASSIVE GALAXIES IN THE FIRST 2 Gyr OF COSMIC HISTORY

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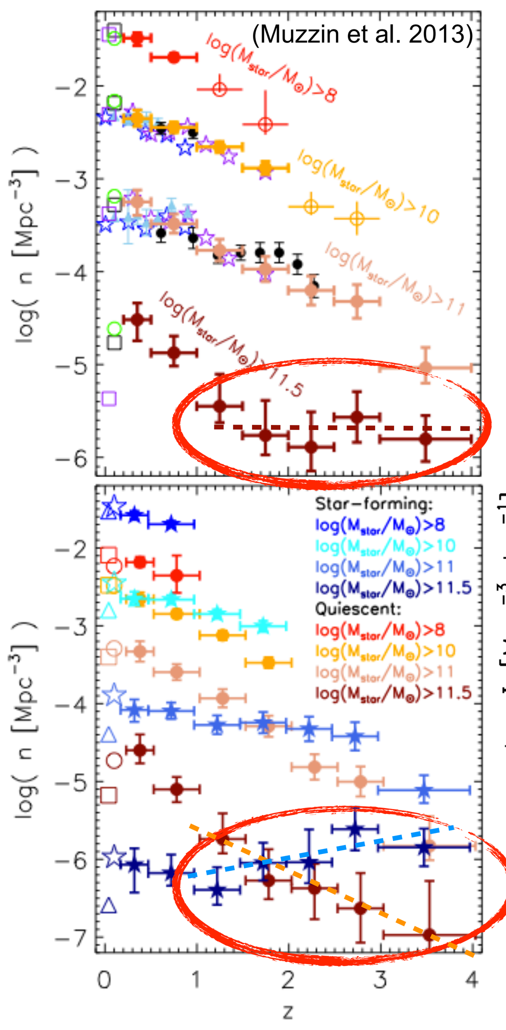
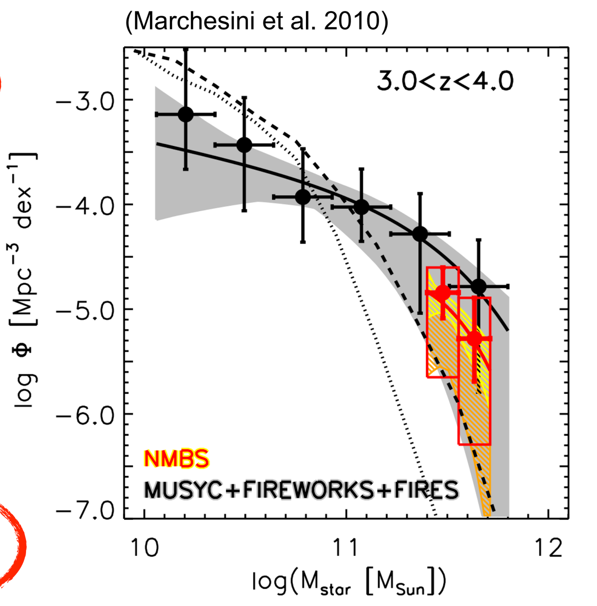
1. VERY MASSIVE GALAXIES AT z>3:

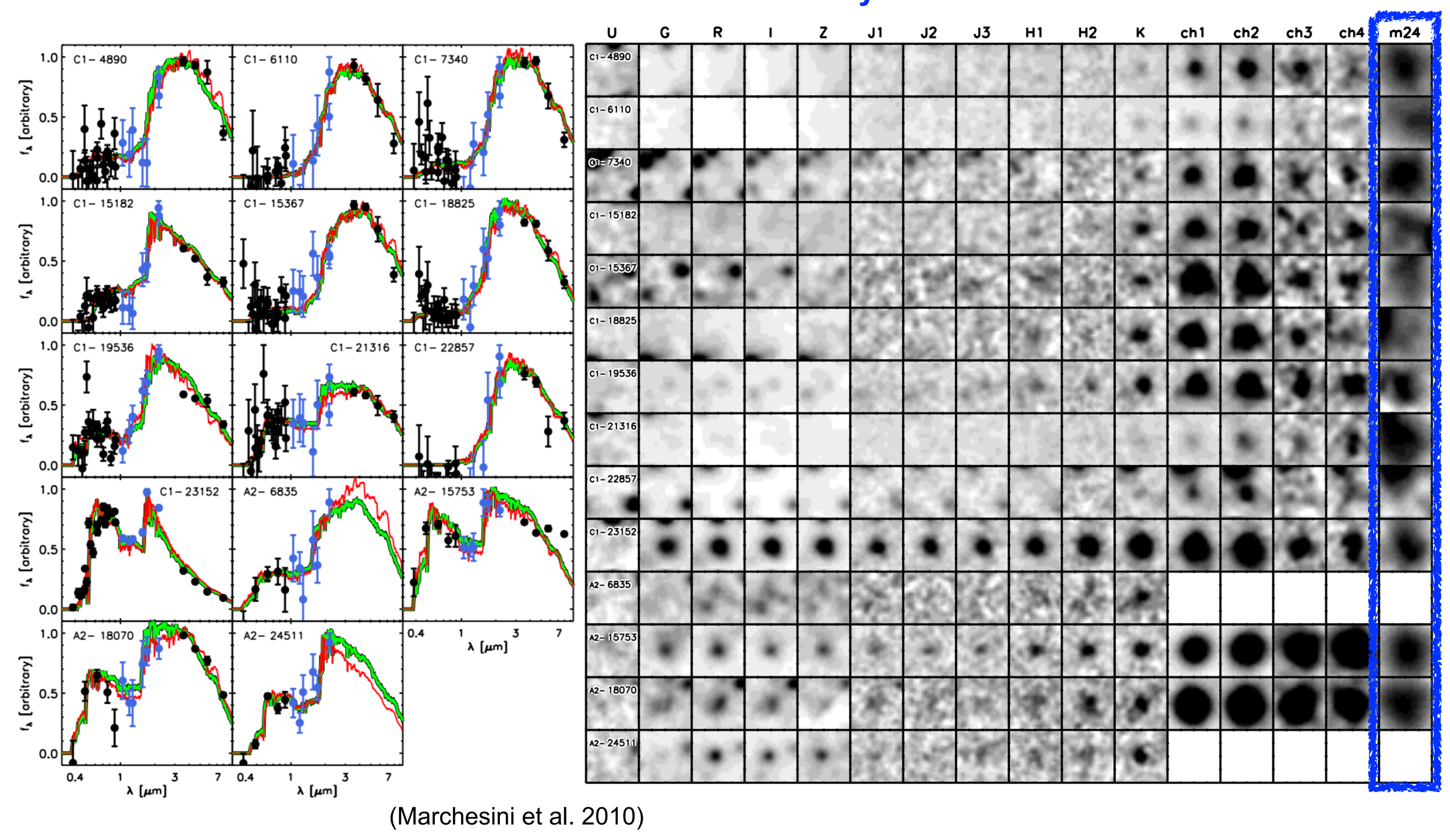


One of the most controversial questions in galaxy formation and evolution is when and how today's most massive galaxies formed. In the last decade, multi-wavelength surveys have allowed us to measure the evolution of the stellar mass function of galaxies over the last ~12 billion years of cosmic history since z~4. **Surprisingly, it appears that the number density of the most massive galaxies (Mstar>3x10^11 Msun) has evolved very little from z~4 to z~1.5, suggesting that very massive galaxies were already in place at z~3.5** (e.g., Marchesini et al. 2009; Muzzin et al. 2013).



In more recent years, **a population of very massive galaxies at z>3 has been robustly discovered** by progressively deeper and wider surveys, providing better sampled spectral energy distributions (SEDs) that result in more accurate photometric redshifts and estimated stellar population properties (e.g. Marchesini et al. 2010). **Recent investigations of the properties of massive galaxies at z>3 indicate that this population is heterogeneous, including both quiescent and star-forming galaxies, with varying degree of dust extinction and large infrared luminosities** (also **indicative of powerful active galactic nuclei, AGNs**; e.g., Marchesini et al. 2010).

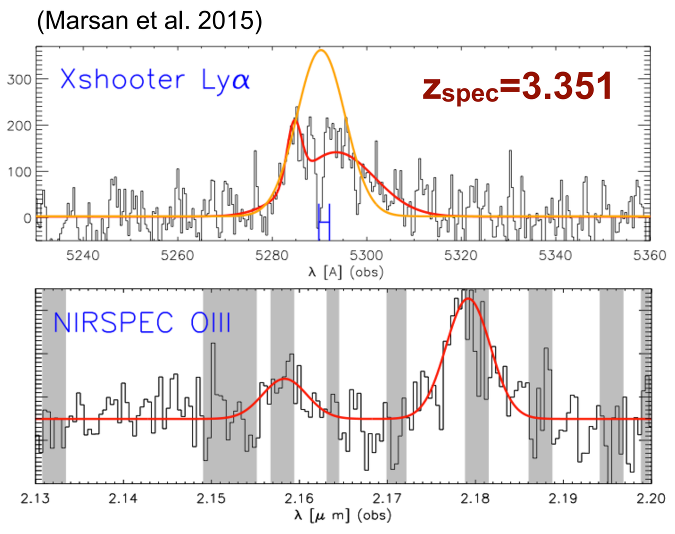
Sample of galaxies at 3<z<4 with log(M_{star}/M_{Sun})>11.4 presented in Marchesini et al. (2010) constructed from the NEWFIRM Medium-Band Survey in the COSMOS and AEGIS fields:



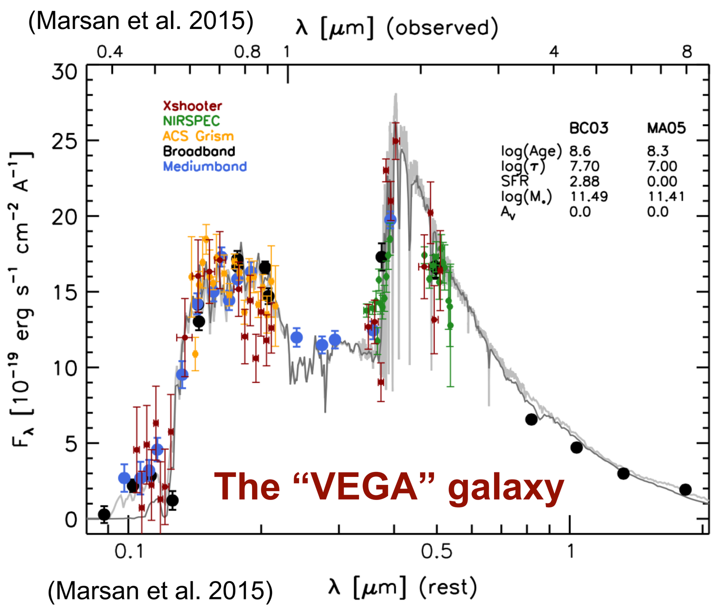
(Marchesini et al. 2010)

2. FIRST SPECTROSCOPIC CONFIRMATION of an ULTRA-MASSIVE GALAXY at z>3:

In the last few years, we have conducted a spectroscopic follow-up survey of robust candidates of very massive galaxies at z>3, necessarily targeting the brightest handful of objects in the sample from Marchesini et al. (2010).
Marsan et al. (2015) presented the first spectroscopic confirmation of an ultra-massive (lg(M_{star}/M_{Sun})=11.5) galaxy at z_{spec}=3.351, dubbed the "Vega" galaxy for its SED closely resembling the spectrum of the A0V star Vega. **The Vega galaxy was found to be very compact (r_e~1 kpc) and with suppressed star formation, about to enter a post-starburst phase, and hosting a very powerful hidden active galactic nucleus (AGN) potentially responsible for the quenching of the star formation. This object likely represents the prototype of the progenitors of local giant ellipticals in the first 2 Gyr of cosmic history, having formed most of its stars at z>4 in a highly dissipative, intense, and short burst of star formation.**

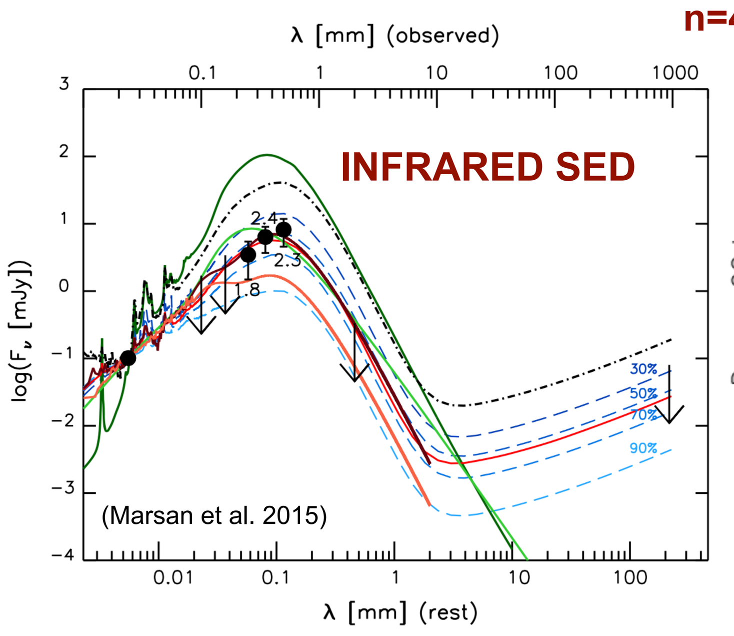


Left: Observed 1D spectra in the region around the considered spectral features. The gray shaded regions indicate regions of the spectra significantly affected by telluric sky lines. Top panel shows high S/N detection of the **Ly-alpha in the VLT-Xshooter spectrum**; bottom panel shows robust detection of the **[OIII] doublet from the Keck-NIRSPEC spectrum.**

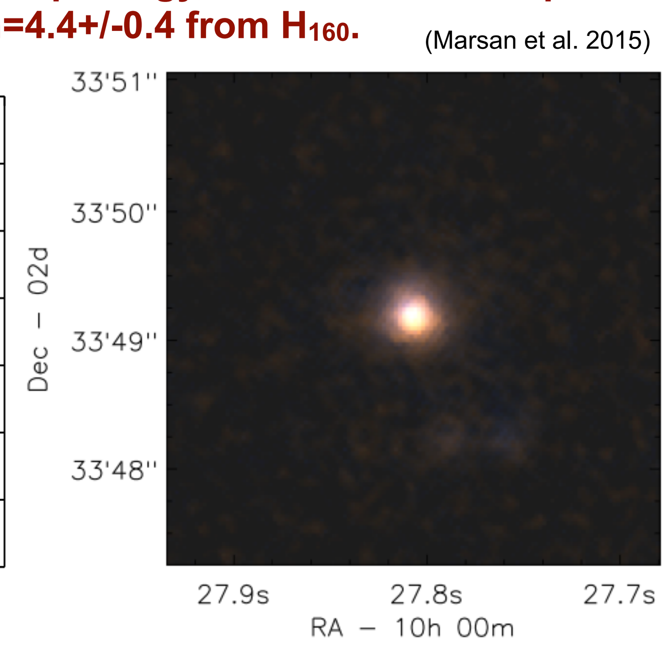


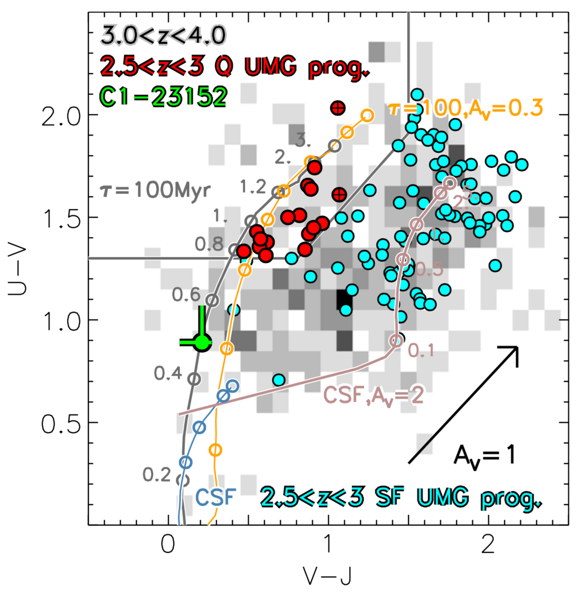
Left: Observed SED from the combination of the medium- (blue filled circles) and broad-band (black filled circles) photometry from the NEWFIRM Medium-Band Survey and the binned spectra (NIRSPEC in green; ACS grism in orange; and Xshooter in maroon) redshifted to the rest frame. The light and dark gray curves represent the best-fit models adopting Bruzual & Charlot (2003) and Maraston (2005) stellar population models, respectively, with an exponentially declining SFH and free metallicity. **The modeling results in M_{star}=3.1$^{+0.6}_{-0.7}$x10^{11} M_{Sun} and SFR<7 M_{Sun} yr^{-1}. The stars appear to have formed in a short (~50 Myr) intense burst ~300-500 Myr prior to the observation epoch, setting z_{form}~4.1.**

Right: **Infrared SED of the Vega galaxy** (Spitzer MIPS 24, Herschel PACS 100 and 160, SPIRE 250, 350, and 500, GISMO 2mm, and 320 GHz GMRT). The starburst template from Magdis et al. (2012; solid dark green), the high-z composite AGN template from Kirkpatrick et al. (2012; orange curve), the mean template from Dale & Helou (2002; black dot-dashed), and the mean templates from Dale et al. (2014) with varying degrees of AGN contribution (30%, dark blue, to 90%, light blue) are plotted. The red solid curve shows the best-fit template from Dale et al. (2014) with f_{AGN}=60%. **IR templates with only obscured star formation cannot model the full observed IR SED; an AGN contribution of >50% is required to reproduce the observed IR SED.**



Bottom: Color image from the combination of the HST ACS I_{814} and WFC3 H_{160} bands. **C1-23152 shows a smooth and round morphology, with r_e=1.0+/-0.1 kpc and n=4.4+/-0.4 from H_{160}.** (Marsan et al. 2015)





Left: **Rest frame U-V versus V-J color-color diagram.** The grayscale representation indicates the distributions of galaxies with log(Mstar/MSun)>10.7 at 3.0<z<4.0 from UltraVISTA (Muzzin et al. 2013). The green point indicates the color of C1-23152 (aka Vega). Red and cyan filled points are the quiescent and star-forming progenitors, respectively, of local UMGs at 2.5<z<3 from Marchesini et al. (2014).

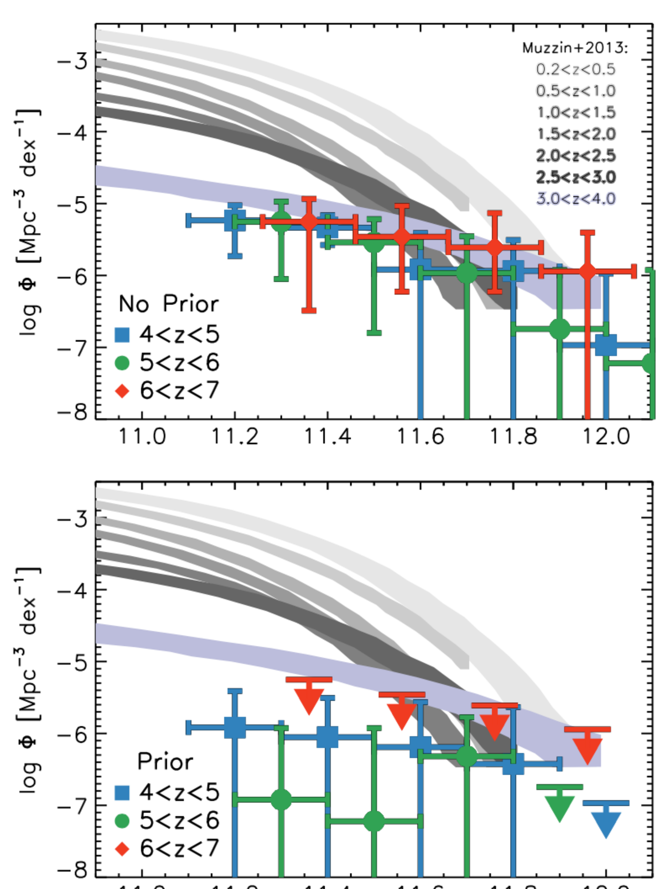
The stellar population properties (i.e., age, SFR, colors) of C1-23152 are qualitatively and quantitatively consistent with it being the progenitor of the already quiescent progenitors of local UMGs at z=2.75.

Marsan et al. (2015b, in prep.) will present the results from the whole spectroscopic campaign of candidates of very massive galaxies at 3<z<4, with the spectroscopic confirmation of four very massive galaxies at z>3 from the sample of Marchesini et al. (2010) in addition to the Vega galaxy.

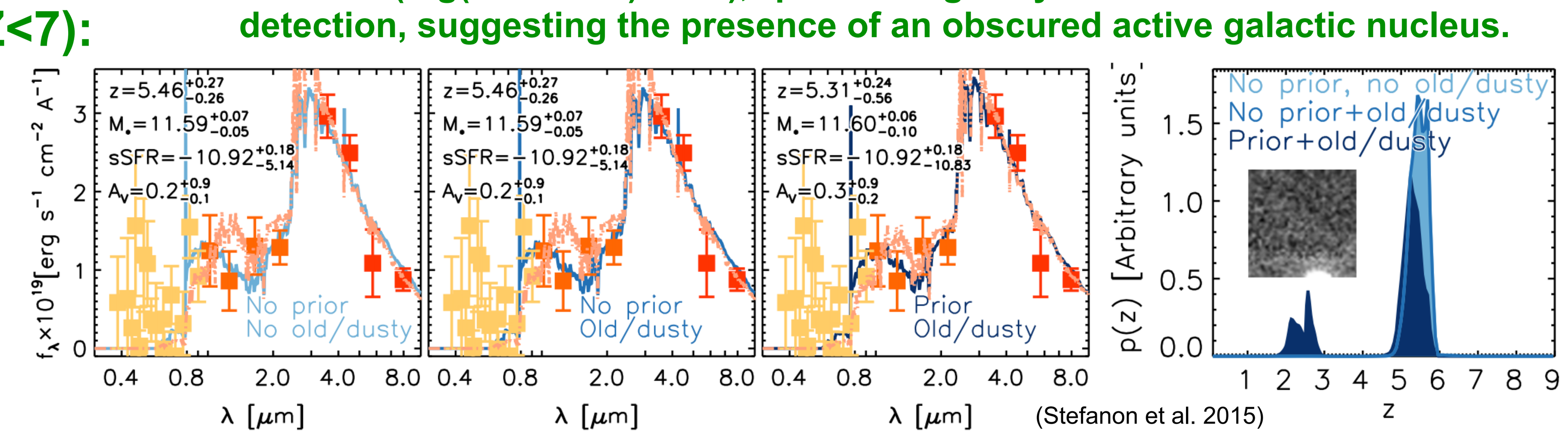
3. SEARCHING FOR VERY MASSIVE GALAXIES AT EVEN EARLIER TIMES (4<Z<7):

Stefanon et al. (2015) extended the search for massive (log(M_{star}/M_{Sun})>11) galaxies at even earlier times (out to z~7) using an IRAC-selected catalog of the UltraVISTA DR1 survey. To identify massive galaxies at 4<z<7 with log(M_{star}/M_{Sun})>11, they considered the **systematic effects on photometric redshifts from the introduction of an old and dusty template and of a bayesian prior on luminosity, as well as the systematic effects from different star formation histories and from nebular emission lines on the stellar population properties.** These effects, particularly the old and dusty template and the luminosity prior, reduce the number of candidates of z>4 massive galaxies by 83%, and **imply a rapid growth of massive galaxies in the first 1.5 Gyr of cosmic history.**

(Stefanon et al. 2015)

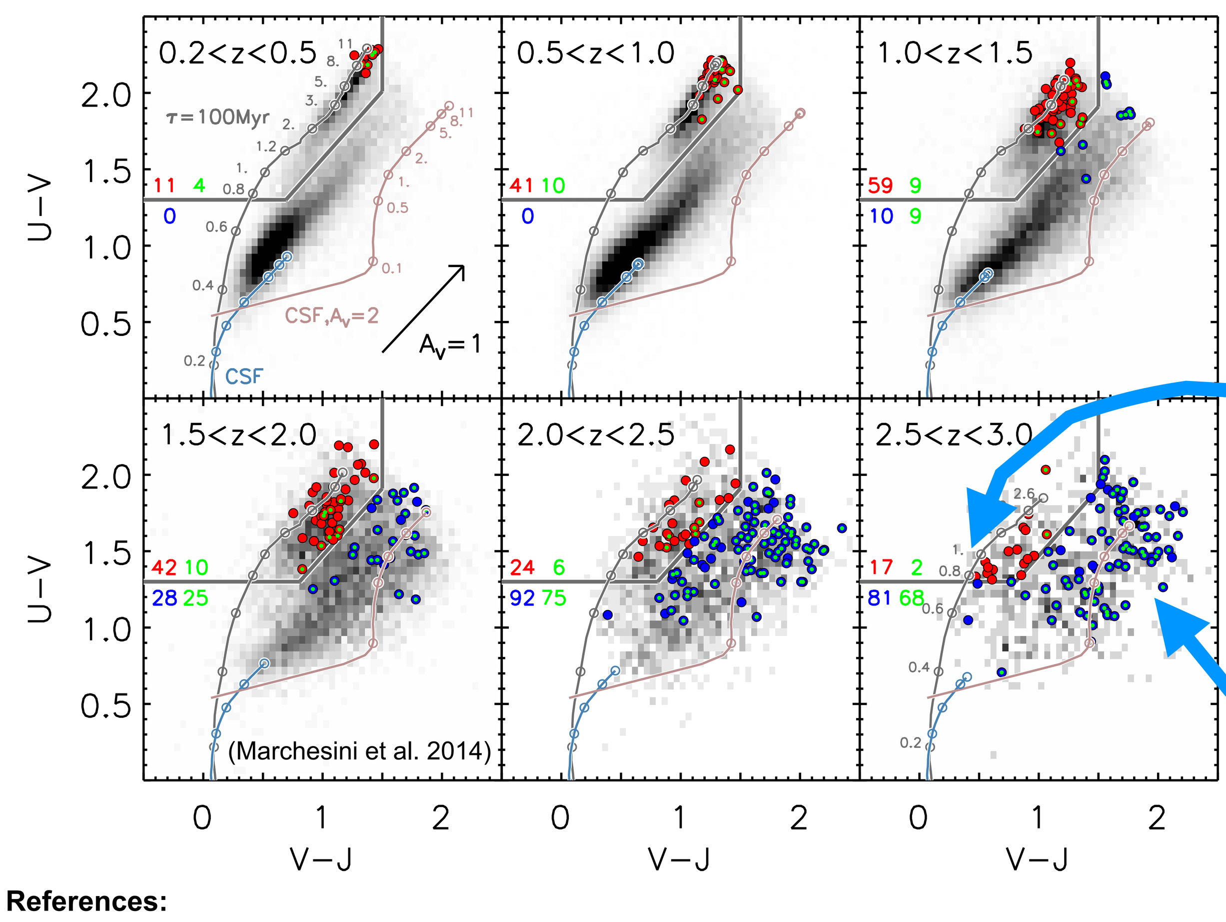


Bottom: **The stellar-mass complete sample include one candidate of a very massive (log(M_{star}/M_{Sun})~11.5), quiescent galaxy at z~5.4 with MIPS 24 micron detection, suggesting the presence of an obscured active galactic nucleus.**

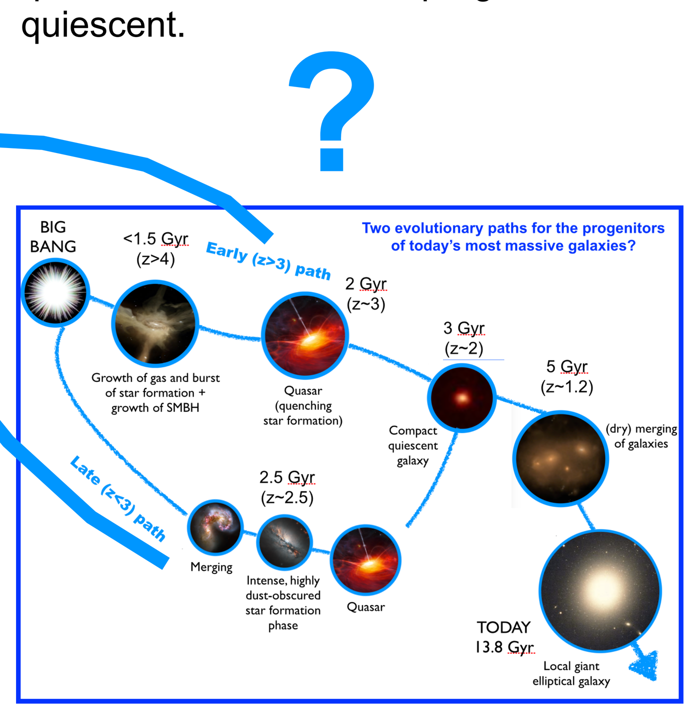


(Stefanon et al. 2015)

4. EVOLUTION OF THE PROGENITORS OF TODAY'S ULTRA MASSIVE GALAXIES:



Evolution in the (U-V) vs. (V-J) diagram of the progenitors of today's ultra-massive galaxies (log(M_{star}/M_{Sun})~11.8) At 2.5<z<3, 85% of the progenitors are dusty, highly star-forming galaxies, although ~15% are already quenched; at z<1, all progenitors are quiescent.



5. JWST PROGRAMS TO STUDY MASSIVE GALAXIES AT z>3:

Despite the recent progress in theoretical models of galaxy formation and evolution, **there is still significant tension between observed and predicted number densities of massive galaxies in the early universe.** However, there are many **systematic uncertainties preventing further understanding of the early phases of the formation of today's most massive galaxies,** e.g., systematic errors in photometric redshifts and stellar population synthesis modeling, emission line contamination, dust content, and blending of close pairs. **The imaging and spectroscopic capabilities of JWST will allow us to study in details the population of very massive galaxies in the first 2 Gyr of cosmic history, confirming their existence, constraining their masses and stellar population properties, robustly measuring their number density, and firmly investigating their AGN content.**

References:
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