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MAGAZ3NE: Massive, Extremely Dusty Galaxies at $z \sim 2$ Lead to Photometric Overestimation of Number Densities of the Most Massive Galaxies at $3 < z < 4$*

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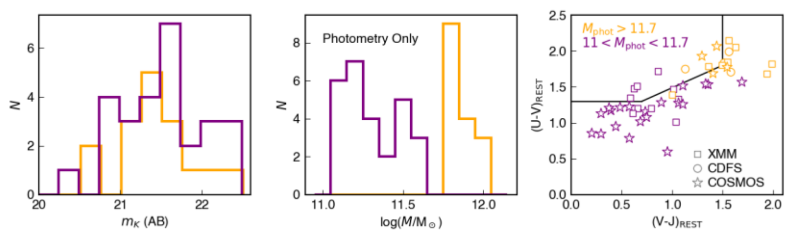
We present rest-frame optical spectra from Keck/MOSFIRE and Keck/NIRES of 16 candidate ultra-massive galaxies targeted as part of the Massive Ancient Galaxies at $z > 3$ Near-Infrared (MAGAZ3NE) Survey. These candidates were selected to have photometric redshifts $3 \lesssim z_{\rm phot} < 4$, photometric stellar masses $\log(M_*/M_\odot) > 11.7$, and well-sampled photometric spectral energy distributions (SEDs) from the UltraVISTA and VIDEO surveys. In contrast to previous spectroscopic observations of blue star-forming and post-starburst ultramassive galaxies, candidates in this sample have very red SEDs implying significant dust attenuation, old stellar ages, and/or active galactic nuclei (AGN). Of these galaxies, eight are revealed to be heavily dust-obscured $2.0 < z < 2.7$ galaxies with strong emission lines, some showing broad features indicative of AGN, three are Type I AGN hosts at $z > 3$, one is a $z \sim 1.2$ dusty galaxy, and four galaxies do not have a confirmed spectroscopic redshift. In fact, none of the sample has $|z_{\rm spec}\text{-}z_{\rm phot}| < 0.5$, suggesting difficulties for photometric redshift programs in fitting similarly red SEDs. The prevalence of these red interloper galaxies suggests that the number densities of high-mass galaxies are overestimated at $z \gtrsim 3$ in large photometric surveys, helping to resolve the 'impossibly early galaxy problem' and leading to much better agreement with cosmological galaxy simulations. A more complete spectroscopic survey of ultramassive galaxies is required to pin down the uncertainties on their number densities in the early universe.

Spectroscopic confirmation of misidentification of Ultra-massive galaxies at z~3-4

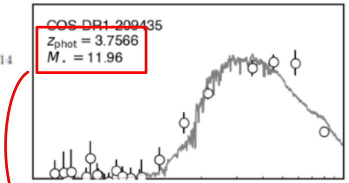
- Multi-color photometric catalogs indicate the presence of a larger number of most massive galaxies than previously been spectroscopically confirmed at 3<z<4.
- Those number densities (high-mass end of the stellar mass function) are significantly higher than simulations.
  → called '**impossibly early galaxy problem**'.
- Spectroscopic confirmation is needed to clarify the cause: the simulations are missing something? Or more simply, photo-z ($z_{\rm phot}$) are overestimated?

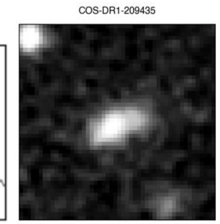
- Using Keck/MOSFIRE and NIRES, spec-z ($z_{\rm spec}$) are obtained for 16 most massive (and less massive) galaxies at 3 < $z_{\rm phot}$ < 4 in three deep photometric fields (COSMOS, XMM, CDF-S).
- FAST++ is used to obtain best-fit SED models.



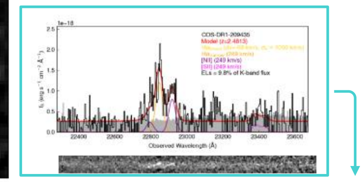
↑ Fig.1: Ultra-massive galaxies (UMG; 11<log$M$*<11.7) and Super-UMG (S-UMG; 11.7<log$M$*).

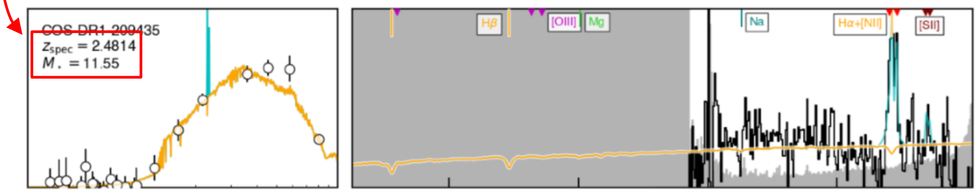
↓Fig.2: Photometric SED fitting





↓Fig.3: Multiple emission line fitting





↑Fig.4: Photometric & continuum spectral SED fitting (but without lines) with z fixed at $z_{\rm spec}$.

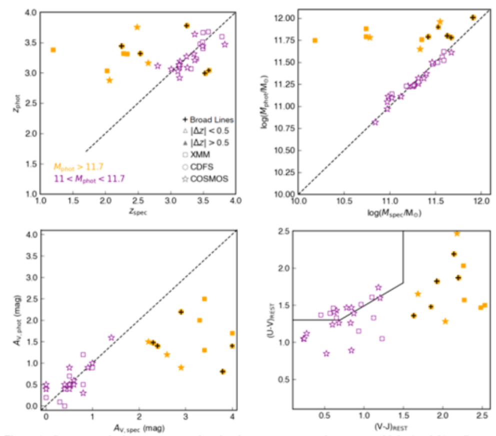


Figure 5. Comparison of galaxy properties with and without spectroscopic information - redshifts (top left), stellar masses (top right), and dust attenuation values (bottom left) are shown. Marker shape indicates the field, color indicates the stellar mass estimated from photometry alone, and a filled symbol represents objects with $|z_{\rm phot}\text{-}z_{\rm spec}| > 0.5$. A clear discrepancy is seen between the UMG candidates (studied in previous works; purple points), which have generally good agreement, and the S-UMG candidates (the focus of this paper; yellow markers), which typically have different redshifts, lower stellar masses, and greater dust attenuation than predicted from photometry. Spectra exhibiting broad lines from AGN activity are marked with a cross. The bottom right panel shows the spectroscopically derived rest-frame colors for comparison with Figure 1. The redshift interlopers have extremely red rest-frame colors.

← Fig.5: Comparison of properties obtained from SED fitting w/ and w/o spectroscopic data.

- UMGs show good agreement b/w photometric and spectroscopic results.
- S-UMGs have huge deviations (lower-z, lower-M*). None of them have $|z_{\rm spec} - z_{\rm phot}| < 0.5$.

Possible contributions to the fitting failure:
- Emission lines from SF and AGN
- Degeneracies b/w redshift, extinction, and AGN activity (?)

→ Photometric data alone would produce more massive galaxies at higher z.
→ High-mass end of the stellar mass function at early universe would become inaccurate and unreliable.

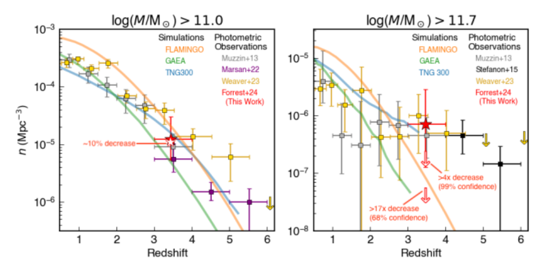


Figure 8. The number density of massive galaxy candidates in the COSMOS field. **Left:** Literature values for galaxies with $\log(M_*/M_\odot) > 11$ from Muzzin et al. (2013a), Marsan et al. (2022), and Weaver et al. (2022) are shown as gray, purple, and gold squares, respectively. Values from the FLAMINGO, GAEA, and TNG300 simulations convolved with a mass uncertainty of 0.25 dex are shown as orange, green, and blue lines, which truncate when the number of galaxies above the mass threshold drops below ten. The filled red star is the average number density from the seven COSMOS catalogs and SED modeling characterizations considered in Section 4, while the unfilled red star on the left panel shows the correction to this number density for galaxies with $\log(M_*/M_\odot) > 11.0$ based on MAGAZ3NE spectroscopic success rate, a correction of $\sim 10\%$. **Right:** Literature values for galaxies with $\log(M_*/M_\odot) > 11.7$ from Muzzin et al. (2013a), Stefanon et al. (2015), and Weaver et al. (2022) are shown as gray, black, and gold squares, respectively. The unfilled red arrows show the spectroscopic correction for galaxies with $\log(M_*/M_\odot) > 11.7$, which suggest a decrease of at least 4× (99% confidence) and possibly more than 17× (68% confidence).

←Fig.8: Number densities of UMGs and S-UMGs.
UMGs are almost consistent with the literature and simulations.
S-UMGs will agree with simulations by correcting for the misidentifications.

- Redder, massive populations may be missing from current SED models.
- Also, those galaxies have similar JWST/NIRCam colors with z~2 hot DOGs (dust-obscured galaxies).

→ Although MBFs and NBFs may reduce the severity of this issue, JWST/NIRSpec confirmation is crucial.