Deep ALMA redshift search of a $z \sim 12$ GLASS-JWST galaxy candidate

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ABSTRACT
The JWST has discovered a surprising abundance of bright galaxy candidates in the very early universe ($\leq 500$ Myr after the Big Bang), calling into question current galaxy formation models. Spectroscopy is needed to confirm the primeval nature of these candidates, as well as to understand how the first galaxies form stars and grow. Here we present deep spectroscopic and continuum ALMA observations towards GHZ2/GLASS-z12, one of the brightest and most robust candidates at $z > 10$, identified in the GLASS-JWST Early Release Science Program. We detect a 5.8$\sigma$ line, offset 0\arcsec 5 from the JWST position of GHZ2/GLASS-z12, that associating it with the [O III] 88 $\mu$m transition, implies a spectroscopic redshift of $z = 12.117 \pm 0.001$. We verify the detection using extensive statistical tests. The oxygen line luminosity places GHZ2/GLASS-z12 above the [O III]-SFR relation for metal-poor galaxies, implying an enhancement of [O III] emission in this system while the JWST-observed emission is likely a lower-metallicity region. The lack of dust emission seen by these observations is consistent with the blue UV slope observed by JWST, which suggest little dust attenuation in galaxies at this early epoch. Further observations will unambiguously confirm the redshift and shed light on the origins of the wide and offset line and physical properties of this early galaxy. This work illustrates the synergy between JWST and ALMA, and paves the way for future spectroscopic surveys of $z > 10$ galaxy candidates.

Key words: techniques: spectroscopic – dust, extinction – galaxies: distances and redshifts – galaxies: evolution – galaxies: formation – galaxies: high-redshift.

1 INTRODUCTION
The JWST recently opened a new window to the Universe with unprecedented sensitivity and angular resolution at near-infrared (NIR) wavelengths. The public release of the JWST Early Release Observations (ERO) and the Director’s Discretionary Early Release Science Programs (DD-ERS) have unlocked new searches for the faintest, rarest, and most distant galaxies ever found. Notably, the high sensitivity of the NIRCam instrument (Rieke, Kelly & Horner 2005) and its wavelength coverage (reaching up to $\sim 5\mu$m) make NIRCam ideal for the identification of candidate galaxies at redshifts above ten. To date, several $z > 10$ galaxy candidates have been reported (Adams et al. 2023; Castellano et al. 2022; Donnan et al. 2022; Finkelstein et al. 2022a; Morishita & Stiavelli 2022; Naidu et al. 2022...
2 SUMMARY OF JWST OBSERVATIONS

The GLASS-JWST program represents the deepest extragalactic survey of the ERS campaign and consists of NIRISS (Roberts-Borsani et al. 2022a) and NIRSpec spectroscopy observations centred on the cluster A2744 with parallel NIRCam imaging offset from the cluster centre. The multiband strategy of the NIRCam observations (Merlin et al. 2022), which include imaging in seven wide filters (F090W, F115W, F150W, F200W, F277W, F356W, and F444W) allows the identification of $z > 10$ galaxy candidates via colour-colour diagrams and/or SED fitting techniques. The NIRCam images used in this paper were reduced as described by Merlin et al. (2022), who constructed a multiband photometric catalogue. High-$z$ candidates were selected by Castellano et al. (2022) using a combination of colour cuts, and photometric redshifts designed to minimize contamination by lower redshift interlopers.

As mentioned above, GHZ2/GLASS-z12 was identified as a $z \sim 12.5$ candidate by several teams using independent reductions of the GLASS data (Donnan et al. 2022; Harikane et al. 2022; Naidu et al. 2022a). Santini et al. (2022) presented the physical properties of this galaxy, which we update here using the most recent photometric calibrations (Rigby et al. 2022). From our best-fit SED, we constrain the following physical properties: a star formation rate of $SFR = 19^{+14}_{-10} M_{\odot} \text{yr}^{-1}$, $M_* = 1.6^{+1.9}_{-0.3} \times 10^9 M_{\odot}$, and absolute magnitude $M_{1500} = -21.0^{+0.2}_{-0.5}$ AB (Santini et al. 2022).

3 ALMA OBSERVATIONS AND DATA REDUCTION

ALMA observations were carried out between 2022-08-03 and 2022-08-05 as part of the DDT project 2021.A.00020.S (Baxx & Zavala), and are summarized in Table A.1. The spectral setup consists of four adjacent tunings covering a total bandwidth of $\sim$30 GHz from 233.4 to 263.0 GHz in the ALMA Band 6. This range covers the expected (redshifted) frequency of the [OIII] $\lambda 88\mu$m ($\nu_{\text{rest}} = 3393.0062$ GHz) from $z = 11.9$ to $z = 13.5$, where our target was expected to be (covering $\sim$98 per cent of the posterior distribution function of the photometric redshift). Each of the tunings was observed for around 2.2 h on-source ($\sim 4$ h per tuning including the overheads).

Based on the photometric redshift analysis by Castellano et al. (2022) and Naidu et al. (2022a) conducted with EAZY and ZPHOT, we expect only a 2 per cent chance that the line be redshifted below or above our observing window. The initial results from the PROSPECTOR fit (Naidu et al. 2022a) suggest a slightly greater probability within $z \sim 13.5$–14.5, although improved photometric estimates have now removed this redshift solution. In addition, potential systematic errors in the photo-$z$, or selection effects altering the prior distribution could lead to underestimating these probabilities. Despite this, we believe the chances of the redshift being outside our window of observation are minor, because the marginal detection in F150W and the clear photometric break tightly constrain the photometric redshift regardless of the prior and template choice.

Data reduction was performed following the standard procedure and using the ALMA pipeline. Then, we use CASA for imaging the $uv$-visibilities using Briggs weighting with a robust parameter of 2.0 (to maximize the depth of the observations at the expense of slightly increasing the final synthesized beam size). This process results in a typical depth of 0.1 mJy beam$^{-1}$ in 35 km s$^{-1}$ channels with a mean synthesized beam size of $\theta \approx 0.34 \times 0.30$. In addition to have a better sensitivity to extended emission beyond the $\sim 0.3$ arcsec beam and to broad emission lines, we explore $uv$-tapering at 0.3, 0.5, and 1.0 arcsec, and we create several cubes varying the velocity binning across the full frequency coverage, creating cubes with 15, 50, 100, 150, 300, and 400 km s$^{-1}$ channels. Finally, we combine the four different tunings to create a single continuum image (at a representative frequency of $\nu_{\text{obs}} = 248$ GHz) adopting Briggs weighting with a robust parameter of 2.0. The final continuum image has a root-mean-square of $4.6 \mu$Jy beam$^{-1}$ and a beam size of $\sim 0.34 \times 0.31$.

4 LINE SEARCH AND DUST CONTINUUM EMISSION

We look for the emission of [OIII] at and surrounding the JWST position of GHZ2/GLASS-z12 using different velocity binnings (including velocity offsets) and taperings. We find an emission line offset from the source by a projected $\sim 0.5$ arcsec and perform extensive statistical tests to verify its robustness. We further discuss the properties of this detection and its potential caveats, as well as, the lack of any dust or line emission at the source position.
We use a 0.3 arcsec tapered data cube with a velocity sampling at 150 km s$^{-1}$. We normalize the entire data cube to the per-frequency standard deviation to account for the inhomogeneous noise-profile of the emission due to observational and atmospheric effects. We then manually define a square aperture in both x-, y- and frequency pixels. Here we mask out a single emission line in the north-west of the cube associated with a bright foreground galaxy, and proceed to take one million samples across the data cube at off-line positions. We then fit the relative signal-to-noise distribution of all the one million measures with a Gaussian profile, to have an estimate of the normalized noise distribution across the whole data cube, taking into account the aperture size effects. This would account for any coherent noise in the system missed in either direct line fitting or 2D fitting. As shown in Fig. 3, the normalized signal-to-noise of our signal is 5.8σ, with no single other aperture matching the emission at both positive and negative signal-to-noise, confirming the robustness of the line.

In the Appendix B, we expand upon this analysis in order to investigate the wide line-width of the line. There, we try the line fitting for different frequency bounds on the aperture. Appendix Fig. B1 shows the effect of changing the integration velocities from $-450$ to $+750$ at 150 km s$^{-1}$ intervals for a total of 36 different integration configurations. Even with a 150 km s$^{-1}$ line velocity, we find a $>5\sigma$ detection and a total of six such configurations resulting in a line significance in excess of 5σ.

4.1.3 On the line-width, size, and spatial offset

The emission line is significant, however here we note several caveats: (1) the line is spatially-offset from the JWST detection. (2) The large velocity width is in excess of what is seen for systems with stellar masses of $\sim 10^6$ M$_{\odot}$. For comparison, Inoue et al. (2016), Laporte et al. (2017), Laporte et al. (2021), Hashimoto et al. (2018), Tamura et al. (2019) report values between 50 and 320 km s$^{-1}$. And finally, (3) the emission appears spatially more extended than the size inferred from the JWST images of GHZ2/GLASS-z12 (Yang et al. 2022).
While these line properties are surprising for a $z \sim 12$ galaxy, we discuss some possible explanations. First, we note that spatial offsets between emission lines [O III], [C II], Lyα, and the UV or dust continuum have been reported both in observations (e.g. Carniani et al. 2017) and simulations (e.g. Katz et al. 2019; Pallottini et al. 2019; Arata et al. 2020) at $z = 7–8$. These offsets are typically understood to be due to chemically-evolved components with high-dust-obscuration or by outflows of chemically-enriched gas. Indeed, an outflow-scenario would be able to explain not only the large spatial offset but also the large line width and spatially-extended emission. Similarly, the observed line properties could be the result of a galaxy interaction. In this case, it would require the presence of a heavily-obscured component to explain the non-detection in the NIRCam filters, and a weak dust emission contrast against the CMB to explain the non-detection of dust continuum (e.g. da Cunha et al. 2013; Zhang et al. 2016, see Section 4.3). To further explore these possibilities, we show the moment zero, one and two maps of the emission line in Fig. 4, as well as the map of undetected dust emission. The emission line is offset by 1.5 kpc, and has a clumpy structure extending to the north. A modest velocity gradient ($\sim 15\, \text{km}\, \text{s}^{-1}$) appears in the direction away from the JWST source. Meanwhile, the velocity dispersion of the emission line varies little across the emission line region. There are no indications of rotation, while the velocity gradient could be caused by a decelerating outflow. Although it is certainly possible that early phases of galaxy evolution are dynamically complex (e.g. Arata et al. 2019; Ziparo et al. 2022), making these scenarios conceivable, further observations of the peculiar nature of this emission line are needed to discern between these various interpretations.

Finally, it is worth noting the relatively large uncertainties in the measured line velocity and spatial extension. Therefore, it is also possible that the true line velocity could be lower given the relatively-large errors in the velocity width (400 ± 70 km s$^{-1}$), and line significance even at smaller integration velocities (Appendix Fig. B1). The same is true for the extended emission which is only marginally larger than the beamsize (see Fig. 4).

4.2 The lack of [O III] emission at the position of GHZ2/GLASS-z12

No obvious emission line is seen at the JWST position of GHZ2/GLASS-z12, as shown in Appendix Fig. C1. The spectrum of GHZ2/GLASS-z12 extracted from an aperture centred on the JWST-position with a circular size of 0′′35 selected to match the average synthesized beam size. We show this aperture relative to the background JWST image in Fig. 5. Similarly, no emission is
Figure 4. The line associated with GHZ2/GLASS-z12, seen untapered with robust = 2 (white contours) and tapered at 0.5 arcsec (black contours), drawn at ±3, 4, 5σ levels. The central black plus indicates the JWST position. **Left:** The line emission (moment-0 map) is offset from the JWST-source and appears extended. The dashed box indicates the region used for the analysis in Fig. 3 discussed in Section 4.1.2. **Middle left:** The velocity gradient (moment-1 map) of the line shows little gradient in the velocity profile of the line. **Middle Right:** The velocity dispersion (moment-2 map) of the line shows an average velocity dispersion of 180 km s$^{-1}$ across the source. **Right:** No dust emission is seen at the JWST position, nor at the position of the spectral line.

Figure 5. A 2′:5 × 2′:5 JWST/NIRCam composite image of GHZ2/GLASS-z12 is shown in the background (F150W in blue, F277W in green, and F444W in red) along with the dust-continuum signal-to-noise ratio as white contours. Since there is no dust continuum emission above ±3σ, only ±2σ contours are shown. To illustrate the offset and the significance of the tentative emission line at $z = 12.117$, we also plot ±3, 4, and 5σ levels of the moment-0 map (with 0.5 arcsec tapering) across 258.5 to 259.0 GHz as green contours. The beam sizes for the (untapered) continuum map and the tapered moment-0 map are represented by the dark and light ellipses on the bottom left. The 0′:35 aperture used to extract the upper limit at the JWST position is also illustrated with a yellow dotted circle.

seen in any of the resampled spectra with different velocity binnings (including velocity offsets) and taperings.

In order to evaluate the intrinsic properties of the UV-bright component of GHZ2/GLASS-z12, we also estimate an [O III] line luminosity upper limit at the exact JWST position. We use the standard-deviation of the map at each frequency to evaluate the [O III] luminosity upper limit. We find no redshift dependency, although the atmospheric windows and instrumental sensitivity slightly vary across the spectral windows. The average 5σ line luminosity upper limit across the entire window is estimated to be $1.7 \times 10^8 L_\odot$ assuming a line velocity of 100 km s$^{-1}$ and no spatially-extended emission. Assuming a wider line-width of 200 km s$^{-1}$ would increase the derived upper limit by ~40 per cent.

4.3 Search for dust continuum emission

No dust emission is seen in the collapsed (multifrequency synthesis) continuum image down to 13.8 μJy at 3σ. The lack of dust emission provides further credence to the high-redshift solution at $z = 12.117$. Assuming a typical dust thermal emission SED (e.g. Casey et al. 2012), we derive an upper limit on the dust-obsured star formation of <2–5 M$_\odot$ yr$^{-1}$ at 3σ for low-redshift interlopers ($z < 6$), depending on the galaxy model. Hence, these observations rule out the possibility of a low-redshift interloper associated with a dusty star-forming galaxy, where the observed break in the NIRCam photometry would be rather associated to the Balmer break combined with high-dust attenuation (e.g. Zavala et al. 2022).

The dust non-detection is fully consistent with the blue colours and multiple JWST detections redwards of the strong Lyman break, which also rule out a $z \sim 4$ quiescent galaxy. Furthermore, the compact size of 0.047 ± 0.006 kpc (corresponding to 0.17 ± 0.02 kpc at $z \sim 12$; Yang et al. 2022) is much more compatible with a high-redshift source than with a one at much lower redshift. The contamination from a dwarf star has also been ruled out since dwarf SED templates do not provide a good fit to the NIRCam data points, moreover the source is clearly resolved. Again, this is consistent with a $z = 12.117$ identification for GHZ2/GLASS-z12.

5 DISCUSSION

5.1 Metallicity and the [O III]-SFR relation

Fig. 6 shows the [O III] emission line and the upper-limit of [O III] emission at the position of GHZ2/GLASS-z12 against the star-formation estimate from JWST observations. The line emission and the on-source upper-limit from Sections 4.1 and 4.2 are compared to local starbursting galaxies (De Looze et al. 2014), metal-poor galaxies (Cormier et al. 2019; Harikane et al. 2020), and a reference sample of $z > 6$ Lyman-break selected galaxies from Harikane et al. (2020). Below we discuss the interpretation of such measures and the derived constraints on the gas-phase metallicity.
Figure 6. Star-formation rate of distant galaxies as a function of [O\text{iii}] 88 \mu m emission. The line emission lies at the top end of the scaling relations from metal-poor galaxies (Cormier et al. 2019; Harikane et al. 2020), and the range seen for z \approx 6–9 galaxies (grey squares; Harikane et al. 2020 and references therein). The red fill indicates our 5 through 1σ upper limit on the Oxygen luminosity at the position of the JWST emission. The upper limit coincides with observed distant galaxies as well as the scaling relation for starburst galaxies (De Loore et al. 2014).

5.1.1 Metallicity estimate of the line-emitting region

As shown in Fig. 6, the line detection lies slightly above the scaling relation for metal-poor galaxies when adopting the JWST-based SFR of 19\,\text{M}_\odot\,\text{yr}^{-1} (Santini et al. 2022, although still consistent within the error bars). This could suggest an enhancement of [O\text{iii}] emission in this system.

If we use instead the 3σ limit of SFR \textless 11\,\text{M}_\odot\,\text{yr}^{-1} based on non-detection of dust emission at the position of the line emission and, following equation (2) of Jones et al. (2020), the emission line corresponds to a 3σ lower limit on the metallicity of 12 + log O/H > 8.8, i.e. a supersolar oxygen abundance (adopting electron temperature T_e = 1.5 \times 10^4 K, gas density n_e = 250 cm^{-3}, and an ionization correction factor of 0.17 dex from O^{++} to total Oxygen abundance, with solar metallicity 12 + log O/H_\odot = 8.69; Asplund et al. 2009). However, the uncertainty arising from unknown physical conditions is of order 0.4 dex, which could significantly reduce the lower limit on the metallicity. Assuming extreme nebular densities and temperatures (n_e = 1 \text{ cm}^{-3}, T_e = 2.5 \times 10^4 K), the associated abundance would be half the solar value (i.e. 12 + log O/H_\odot > 8.4).

A high metallicity is surprising given the lack of any stellar emission at the position of the line-emitting region, particularly at this high redshift. And while some recent studies have suggested an early onset of star formation and a rapid evolution in z > 10 galaxies (Boylan-Kolchin 2022; Ferrara et al. 2022; Finkelstein et al. 2022a; Harikane et al. 2022; Labbe et al. 2022; Mason et al. 2022; Pérez-González et al. 2022), it may suggest that this line does not arise from star-forming H II regions (e.g. with ionized outflows as an alternative scenario instead; e.g. Fiore et al. 2022; Ziparo et al. 2022). The high-metallicity estimate from the wide, offset emission line is also affected by the star-formation rate estimates (based on a ∼50 K dust temperature) and the correct line velocity. These affect the metallicity linearly with both an increase in star-formation, and a decrease in line width decreasing the estimated metallicity. Similarly, the assumed electron temperatures, gas densities and O^{++}-to-Oxygen abundances might vary, even relative to the z = 6–9 Universe.

5.1.2 Metallicity estimate at the JWST position

In contrast to the high metallicity associated with the emission line, the 5σ line flux limit implies an oxygen abundance 12 + log O/H < 7.6. Same as above, the uncertainty arising from unknown physical conditions is of order 0.4 dex (Jones et al. 2020). This limit corresponds to <0.1 times the solar value, and is comparable to the typical metallicities inferred for luminous [O\text{iii}] emitters at z ∼ 8 (Jones et al. 2020).

Our metallicity limit implies that the JWST-visible component of GHZ2/GLASS-z12 is likely to be in an early stage of chemical enrichment. From a simple closed-box chemical evolution model, assuming oxygen yields Y_O = 0.007–0.039 from low-metallicity stars (Vincenzo et al. 2016), the metallicity of GHZ2/GLASS-z12 suggests only <2–14 percent of its gas has been processed into stars (i.e. >90 per cent gas fraction; the constraint becomes >82 per cent for the case of a 400 km s^{-1} line width). However, effects of gaseous inflows and outflows can permit smaller gas fractions; the low metallicity may thus indicate accretion and outflow rates, which are comparable or larger than the SFR. In any case, the non-detection of [O\text{iii}] at the JWST position suggests that the metal abundance of GHZ2/GLASS-z12 might not yet be as high as those seen in z = 6–9 Lyman Break Galaxies (Harikane et al. 2020; Jones et al. 2020). This is expected given that only ∼400 Myr elapsed from the Big Bang to the time of observation, leaving little time to form heavy elements (Maiolino & Mannucci 2019; Ucci et al. 2023). Our low-metallicity limit further corroborates the young age based on SED fitting (Santini et al. 2022).

5.1.3 Observed metallicity gradient across GHZ2/GLASS-z12

The large variation in star-formation and oxygen-emission properties of the line-emitting and JWST-observed regions of GHZ2/GLASS-z12 suggest a metallicity gradient exists across the source (if the [O\text{iii}] emission arises from star-forming H II regions), even considering the uncertainties in the metallicity estimates since we need to assume many galaxy properties. Previous observations at lower redshift suggest pre-existing stellar populations formed at redshifts z > 10 enrich galaxy systems (Hashimoto et al. 2018; Hoag et al. 2018; Tamura et al. 2019; Roberts-Borsani, Ellis & Laporte 2020; Pérez-González et al. 2022) as well as episodic star-formation (Arata et al. 2019; Katz et al. 2019; Pallottini et al. 2019) distributing the chemicals efficiently (Sun et al. 2022; Ziparo et al. 2022). The detection of galaxies by strong Lyman-breaks further selects towards young stellar populations, which might not spatially coincide with these older enriched populations.

5.2 Lack of dust in the cosmic dawn?

The lack of a dust detection (down to a 3σ limit of 13.8 \mu{Jy}; see Fig. 5) suggests an upper limit of 1.5 \times 10^3 \text{ M}_\odot \,\text{M}_\odot\,\text{yr}^{-1} of interstellar dust, a far-infrared luminosity less than 6.5 \times 10^{10} \text{ L}_\odot, and a dust-obscured star-formation rate of 11 \text{ M}_\odot\,\text{yr}^{-1}. This explains the blue UV slope (β_{UV} \approx -2.4) suggesting little dust obscuration of the young (∼70 Myr; Naidu et al. 2022a) stellar population. This assumes a dust temperature of 50 K, although average temperatures could rise
We report on the ALMA band six redshift search for the spectroscopic redshift of GHZ2/GLASS-z12 through the [O iii] emission line covering 30 GHz contiguous. Our deep observations ($\sigma = 0.1 \, \text{mJy beam}^{-1}$ in 35 km s$^{-1}$ channels) revealed a 5.8σ line at 258.7 GHz and, associating it with the [O iii] 88 μm line, infer a spectroscopic redshift of $z = 12.117 \pm 0.001$.

The projected offset nature of the line ($0.5$ or $1.5$ kpc) could be caused by an outflow or pre-existing but JWST-dark stellar components. Assuming star-forming H ii regions as the origin of the [O iii] emission requires a high metallicity in the line-emitting region of $12 + \log O/H > 8.4$. At the JWST position, the [O iii] luminosity upper-limit from our observations suggest a metal-poor system ($12 + \log O/H < 7.83$) in the distant universe, with a lower line luminosity compared to $z \approx 6-9$ galaxies. The lack of dust emission, even with our deep observations, contrasts with lower redshift galaxies, implying a very low-dust content and a negligible dust-obscuration at this early epoch, potentially due to the short cosmic time.
We have also discussed potential strategies for deriving spectroscopic redshifts of $z \gtrsim 11$ candidates, the necessity of improving current instruments’ capabilities, and the importance of combining multi-wavelength observations to constrain the physical properties of the earliest galaxies in the Universe.

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**DATA AVAILABILITY**

The data are publicly available through the ALMA science archive and the MAST portal managed by Space Telescope Science Institute. Other calibrated products used in this article will be shared upon request.

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**APPENDIX A: ALMA OBSERVATION TABLE**

In this appendix we summarise the ALMA observations, given in Table A1.

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Table A1. Parameters of the ALMA observations.

| UT start time     | Baseline length | N_{ant} | Frequency [GHz] | T_{int} [min] | PWV [mm] |
|-------------------|-----------------|---------|-----------------|--------------|----------|
| [YYYY-MM-DD h:min:s] | [m]             |         |                 |              |          |
| Tuning 1          |                 |         |                 |              |          |
| 2022-08-03 06:33:45 | 15–1301        | 43      | 233.42–237.14 & 248.22–251.94 | 44.30       | 0.82     |
| 2022-08-03 07:48:41 | 15–1301        | 43      | 233.42–237.14 & 248.22–251.94 | 44.37       | 0.94     |
| 2022-08-03 09:03:07 | 15–1301        | 43      | 233.42–237.14 & 248.22–251.94 | 44.38       | 0.97     |
| Tuning 2          |                 |         |                 |              |          |
| 2022-08-03 10:42:26 | 15–1301        | 43      | 237.12–240.84 & 251.92–255.64 | 43.88       | 1.03     |
| 2022-08-03 12:03:52 | 15–1301        | 43      | 237.12–240.84 & 251.92–255.64 | 43.90       | 1.15     |
| 2022-08-04 06:50:26 | 15–1301        | 44      | 237.12–240.84 & 251.92–255.64 | 43.83       | 0.57     |
| Tuning 3*         |                 |         |                 |              |          |
| 2022-08-04 08:14:20 | 15–1301        | 44      | 240.82–244.54 & 255.62–259.34 | 44.87       | 0.56     |
| 2022-08-04 09:32:36 | 15–1301        | 44      | 240.82–244.54 & 255.62–259.34 | 44.85       | 0.57     |
| 2022-08-04 10:48:43 | 15–1301        | 44      | 240.82–244.54 & 255.62–259.34 | 44.87       | 0.62     |
| Tuning 4          |                 |         |                 |              |          |
| 2022-08-05 06:57:24 | 15–1301        | 46      | 244.52–248.24 & 259.32–263.04 | 44.05       | 0.48     |
| 2022-08-05 08:01:01 | 15–1301        | 46      | 244.52–248.24 & 259.32–263.04 | 44.02       | 0.45     |

*Note.* *Containing the [O III] 88 μm emission line at 258.7 GHz.

**APPENDIX B: VARIABLE-FREQUENCY EXTRACTION OF THE EMISSION LINE**

We apply the method of Section 4.1.2 assuming different velocity integration boundaries to test the veracity of the line, as shown in Fig. B1. The colour scale indicates the significance of the emission line, ranging from $-2$ to $>5\sigma$, when integrating from the lower velocity limit (x-axis) to the upper velocity limit (y-axis). There exist single velocity bins that are in excess of $5\sigma$, i.e. from 150 to 300 km s$^{-1}$ integration. The aperture was manually optimized for the $-150$ to $300$ km s$^{-1}$, the highest significance bin, and indubitably the significance of the other bins could be improved with further manual optimization.

*Figure B1.* The line significance for different velocity integrals from the lower velocity limit (x-axis) to the upper velocity limit (y-axis). The line significance is indicated in a colour-scale ranging from $-2$ to $>5\sigma$. Stars indicate velocity integration bounds resulting in a significance in excess of $>5\sigma$, with the larger star indicating the maximum significance at $5.8\sigma$. 
APPENDIX C: LINE SPECTRUM AT THE JWST POSITION

We present the line spectrum at the JWST position, extracted from a 0.35′′ aperture at the JWST position. No emission line above 4σ is visible in this spectrum.

Figure C1. Similar to Fig. 1 Top: The full ALMA spectrum covers 233.42 to 263.04 GHz across four tunings of GHZ2/GLASS-z12. The red and blue fill show the spectrum at 35 and 150 km s\(^{-1}\) bins, respectively. The on-source spectrum (extracted from an aperture centred on the JWST position) does not show any statistically significant emission features across the full frequency coverage. An emission feature is seen 0.5 north-east of the JWST position, extended across ~0.4 arcsec. The tentative line is at 258.7 GHz, implying a spectroscopic redshift of \(z = 12.117\) if this is a true [O\(\text{III}\)] 88 μm emission line. This spectrum is shown with a 1 mJy offset for visualization. Note that the larger standard-deviation is caused by the larger aperture used to extract the tentative line. We stress that further observations are necessary to rule out a spurious signal and the association with the target, as discussed in detail in the main text. Bottom: The atmospheric transmission at 0.5 mm precipitable water vapour – similar to the ALMA observing conditions (see Table A1) – shows only minor absorption features (<10 per cent). The four tunings span the redshift range 11.9–13.5, covering 98 per cent of the confidence limits predicted from multiple photometric redshift methods (Castellano et al. 2022; Naidu et al. 2022a).

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