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GA-NIFS: A smouldering disk galaxy undergoing ordered rotation at $z = 4.26$

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ABSTRACT

Rotating galaxies with relaxed gaseous disks have been discovered across cosmic time, from the local Universe to high redshift ($z > 4$). But few such sources have been confirmed at $z > 4$, making them a precious sample to examine what conditions result in such ordered kinematics in an early, more chaotic Universe. One of the best examples of this sample is the galaxy DLA0817g1 ($z = 4.2603$), which shows remarkably clear rotation in ALMA [C II] data. We present recent JWST/NIRSpec IFU data ($R \sim 2700$) of DLA0817g1, which we combine with archival ALMA [C II] observations to place constraints on its ISM conditions and morpho-kinematics. From a combination of line ratios, we find a high gas-phase metallicity ($\sim 0.7 Z_{\odot}$), high fraction of obscured star formation, low ionisation (compared to other high-redshift galaxies observed with JWST), and no significant evidence for AGN (based on the WHAN diagnostic). Dynamical modelling with ^{3D}Barolo reveal nearly identical rotation in H α and [C II], but with a higher velocity dispersion in the former. Using our metallicity estimate and previous CO and [C II] detections, we derive a new estimate of the molecular gas mass, relieving a previous strain in the mass budget. Altogether, we suggest that this is a ‘smouldering’ galaxy, where past star formation resulted in significant chemical enrichment (i.e., Z_{gas} and M_{dust}), but the current activity is low (i.e., lower ionisation parameter and electron temperature). These new observations have opened a window into questions regarding the interplay of gas, metallicity, star formation, and kinematics in a prototypical early disk galaxy.

Наблюдения:

- JWST, NIRspec/IFU
- ALMA, [CII]

Изображения и поля скоростей в эмиссионных линиях $H\alpha$ и $[CII]$

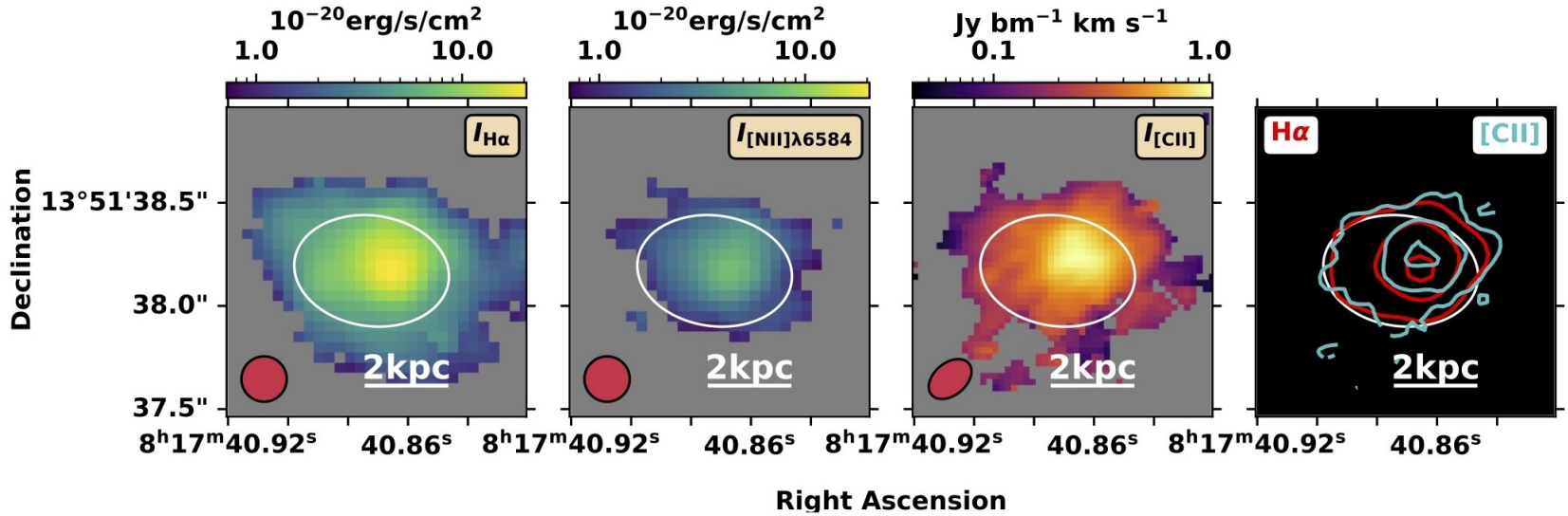


Figure 1. Best fit line intensity maps of $H\alpha$, $[NII]\lambda 6584$, and $[CII]$, where values are given per pixel. In the rightmost panel, we instead compare the $H\alpha$ (red) and $[CII]$ (cyan) emission using contours of $[0.25, 0.50, 0.90] \times$ the peak value of each. In each panel, we show a physical scale of 2 kpc. The PSF is represented as a red circle or ellipse to the southeast (north is up and east is to the left). Our adopted aperture is shown as a white ellipse.

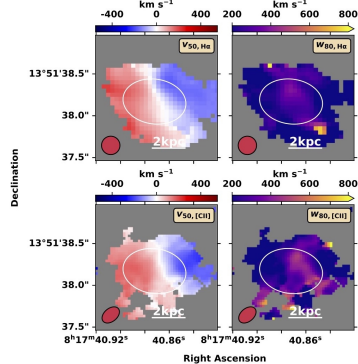


Figure 2. Best fit v_{50} (left column) and w_{50} (right column) maps for $H\alpha$ (top row) and $[CII]$ (lower row). In each panel, we show a physical scale of 2 kpc. The PSF is represented as a red circle or ellipse to the southeast (north is up and east is to the left). Our adopted aperture is shown as a white ellipse.

Property	$H\alpha$	$[CII]$
Ellipticity	0.29 ± 0.02	0.26 ± 0.04
n_s	0.9 ± 0.1	0.8 ± 0.1
$PA [^\circ]$	82 ± 2	89 ± 12
$R_e [']$	0.29 ± 0.01	0.28 ± 0.01
$R_e [kpc]$	2.0 ± 0.1	1.9 ± 0.1

Table 1. Best-fit morphological properties of the $H\alpha$ and $[CII]$ emission, as derived through PYSERSIC fits.

Набор «оптических» линий

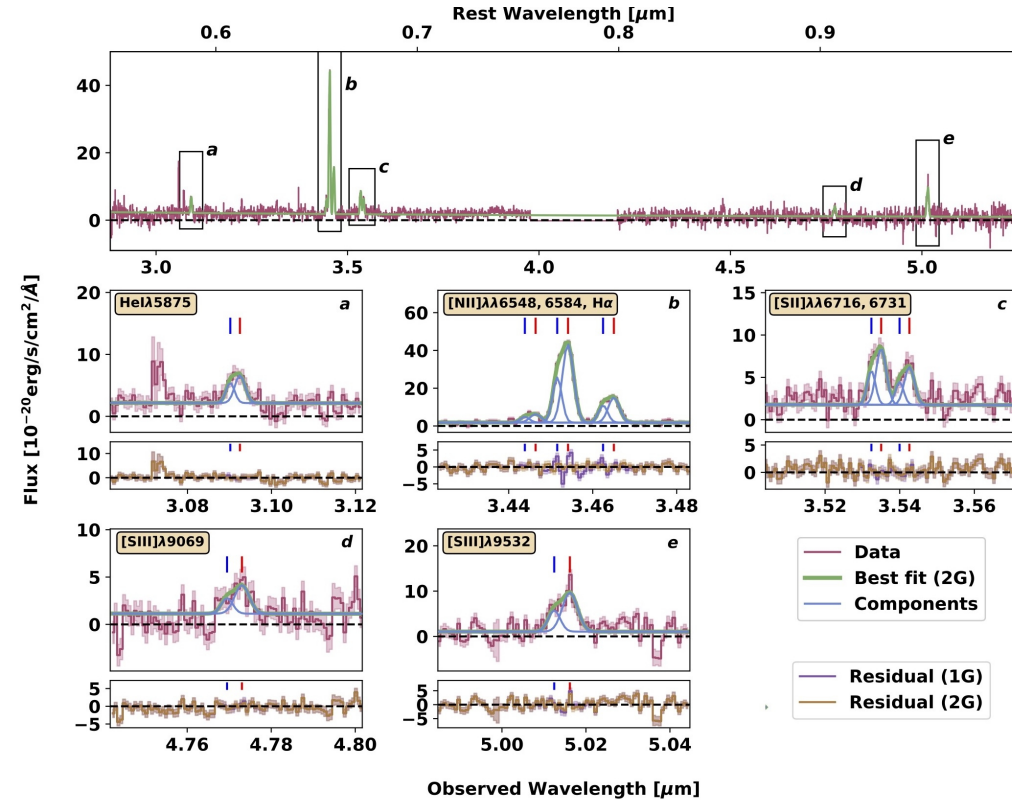


Figure 3. Results of fitting integrated spectrum of DLA0817g1. The top panel shows a full spectrum (pink line with 1σ uncertainty shown as shaded region) along with the best-fit model (green). Panels a-e are zoomed-in views for each line, showing the individual best-fit Gaussian components (light blue) and the centroid wavelength of each of the 2-Gaussian fits (red and blue lines above each spectrum). The lower portion of each panel depicts the residual spectra for a single-Gaussian fit (purple) and out two-Gaussian fit (brown).

Property	Model	Value	Units
z	1G	4.2606 ± 0.0001	
	2G _{blue}	4.2579 ± 0.0003	
	2G _{red}	4.2618 ± 0.0002	
$FWHM_V$	1G	366 ± 6	[km s ⁻¹]
	2G _{blue}	182 ± 25	[km s ⁻¹]
	2G _{red}	241 ± 20	[km s ⁻¹]
$F_{\text{HeI}\lambda 5875}$		221.05 ± 40.20	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]
$F_{\text{[NII]}\lambda 6548}$		227.84 ± 29.79	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]
$F_{\text{H}\alpha}$		2033.84 ± 198.85	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]
$F_{\text{[NII]}\lambda 6584}$		692.29 ± 29.79	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]
$F_{\text{[SII]}\lambda 6716}$		337.78 ± 42.42	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]
$F_{\text{[SII]}\lambda 6731}$		227.21 ± 42.42	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]
$F_{\text{[SIII]}\lambda 9069}$		187.47 ± 32.77	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]
$F_{\text{[SII]}\lambda 9532}$		558.80 ± 32.77	[10 ⁻²⁰ erg s ⁻¹ cm ⁻²]
F_{cont}		1.46 ± 0.03	[10 ⁻²⁰ erg s ⁻¹ cm ⁻² Å ⁻¹]
α_{opt}		-1.47 ± 0.10	[10 ⁻²⁰ erg s ⁻¹ cm ⁻² Å ⁻¹]

Table 2. Best-fit quantities of DLA0817g1, as derived from fits to the integrated spectrum. For the redshift and intrinsic width of each lines (i.e., accounting for the LSF), we list the results for the single Gaussian model (1G) and the two components of the double Gaussian model (2G_{red} and 2G_{blue}). The line fluxes are the total values from the double Gaussian model. No dust correction has been applied.

Property	$E(B - V) = 0$	$E(B - V) = 0.4$	Units
$\log_{10}(S2)$	-0.56 ± 0.06	-0.57 ± 0.06	-
$\log_{10}(S3)$	-0.44 ± 0.05	-0.64 ± 0.05	-
$\log_{10}(S23)$	-0.19 ± 0.05	-0.30 ± 0.05	-
$\log_{10}(S32)$	0.12 ± 0.05	-0.07 ± 0.05	-
$\log_{10}(N2)$	-0.47 ± 0.05	-0.47 ± 0.05	-
$\log_{10}(N2S2)$	0.09 ± 0.05	0.10 ± 0.05	-
$\log_{10}(n_e [\text{cm}^{-3}])$	2.47 ± 0.43	2.45 ± 0.40	-
$12 + \log_{10}(O/H)$	8.52 ± 0.07	8.54 ± 0.09	-
Z	0.68 ± 0.11	0.70 ± 0.14	[Z _⊙]
$SFR_{\text{H}\alpha}$	17 ± 1	59 ± 5	[M _⊙ yr ⁻¹]
$\log_{10}(U)$	-3.43 ± 0.06	-3.64 ± 0.06	-
$\alpha_{\text{[CII]}}(Z)$	5.45 ± 0.34	5.38 ± 0.41	[M _⊙ L _⊙ ⁻¹]
$\log_{10}(M_{\text{H}_2, [\text{CII}]} [\text{M}_{\odot}])$	10.25 ± 0.04	10.24 ± 0.04	-

Диагностика возбуждения

- Никаких признаков AGN!

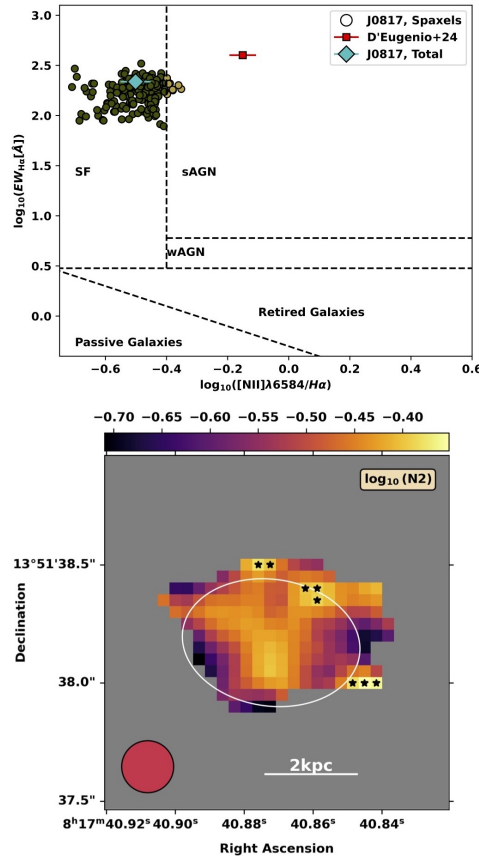


Figure 5. Results of WHAN diagnostics. The top panel show the distribution of spaxel values in the $\log_{10}(EW_{H\alpha}/AA)$ - $\log_{10}(N2)$ space, with the demarcation lines and classifications of Cid Fernandes et al. (2010) included. The circles and blue diamond show the values found through a fit to the spaxel-by-spaxel spectra and the integrated spectrum, respectively. For comparison, we also show the location of a $z = 4.6348$ AGN host galaxy studied with JWST/NIRSpec (red point - Ulema; D'Eugenio et al. 2025). In the bottom panel, we show the spatial distribution of $\log_{10}(N2)$ (i.e., the x-axis of the upper panel), with spaxels that would be classified as 'strong AGN' marked with black stars (and all other coloured spaxels classified as 'SF'). The PSF is represented as a red circle to the southeast (north is up and east is to the left), and we include a physical scale of 2 kpc. Our adopted aperture is shown as the white ellipse.

Результаты IFU

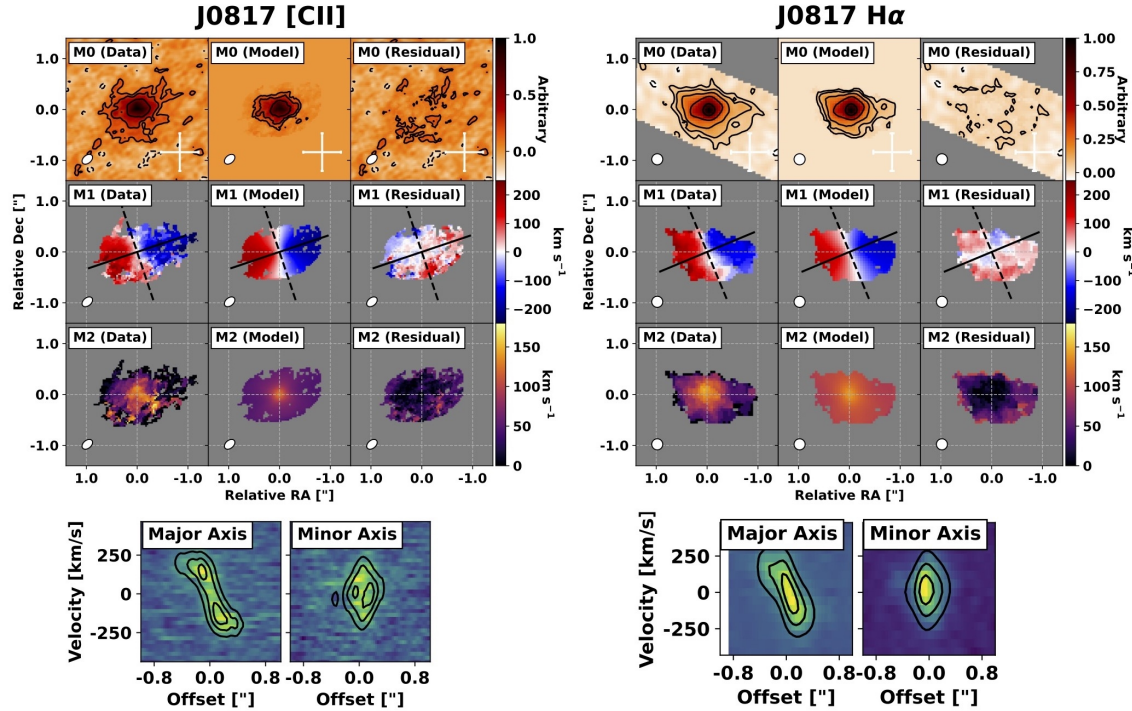


Figure 6. Comparison of 3^{D} Barolo fits to the [C II] (left) and H α (right) data cubes. For each, we present the moment 0 (first row), moment 1 (second row) moment 2 (third row) for the observed data (left column), model (centre column), and the difference between the two (column). The bottom row includes extracted from the observed data cube (colours) and model (contours) along the major (lower left) and minor (lower right) axes. The white crosses in the first row show a scale of $5 \text{ kpc} \times 5 \text{ kpc}$.

Property	H α	[C II]
$i_{\text{morph}} [^{\circ}]$	46 ± 2	46 ± 6
$i_{\text{kin}} [^{\circ}]$	51 ± 6	60 ± 3
$PA_{\text{morph}} [^{\circ}]$	87 ± 2	106 ± 10
$PA_{\text{kin}} [^{\circ}]$	113 ± 8	109 ± 9
$v_{\text{rot}}(R_e) [\text{km s}^{-1}]$	206 ± 14	235 ± 16
$\sigma_o(R_e) [\text{km s}^{-1}]$	97 ± 12	49 ± 11
$v_{\text{rot}}(R_e)/\sigma_o(R_e)$	2.1 ± 0.3	4.8 ± 1.1
$\log_{10}(M_{\text{dyn}}/M_{\odot})$	10.9 ± 0.1	10.8 ± 0.1

Table 5. Best-fit morpho-kinematic properties of the H α and [C II] emission, as derived through our 3^{D} Barolo fits.

Кинематические профили

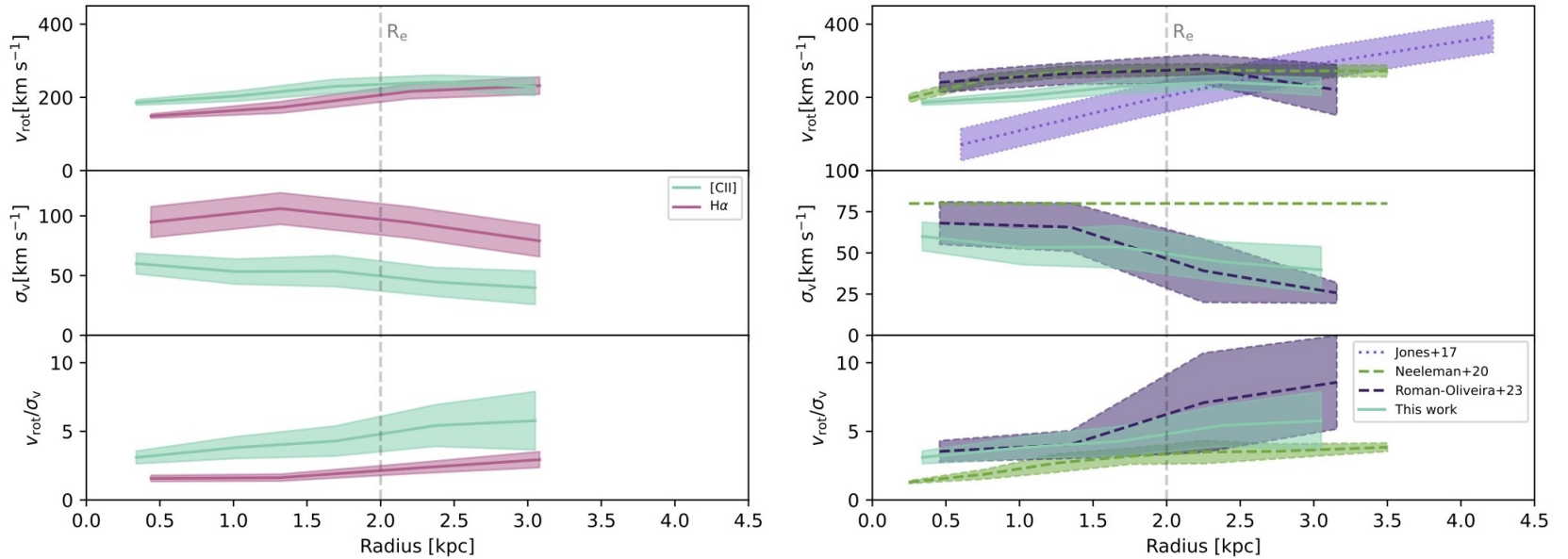


Figure 7. Comparison of best-fit rotation curves (top panels), velocity dispersion profiles (centre panels), and the ratio of the two (lower panels) for the [C II] and H α data studied in this work (left column). In the right column, we compare our [C II] values for DLA0817g1 to those of previous works that studies the same galaxy (Jones et al. 2017; Neeleman et al. 2020; Roman-Oliveira et al. 2023). For each panel, we mark the effective radius of the H α emission (as derived through a Sérsic fit; Section 3.1) with a dashed vertical line.

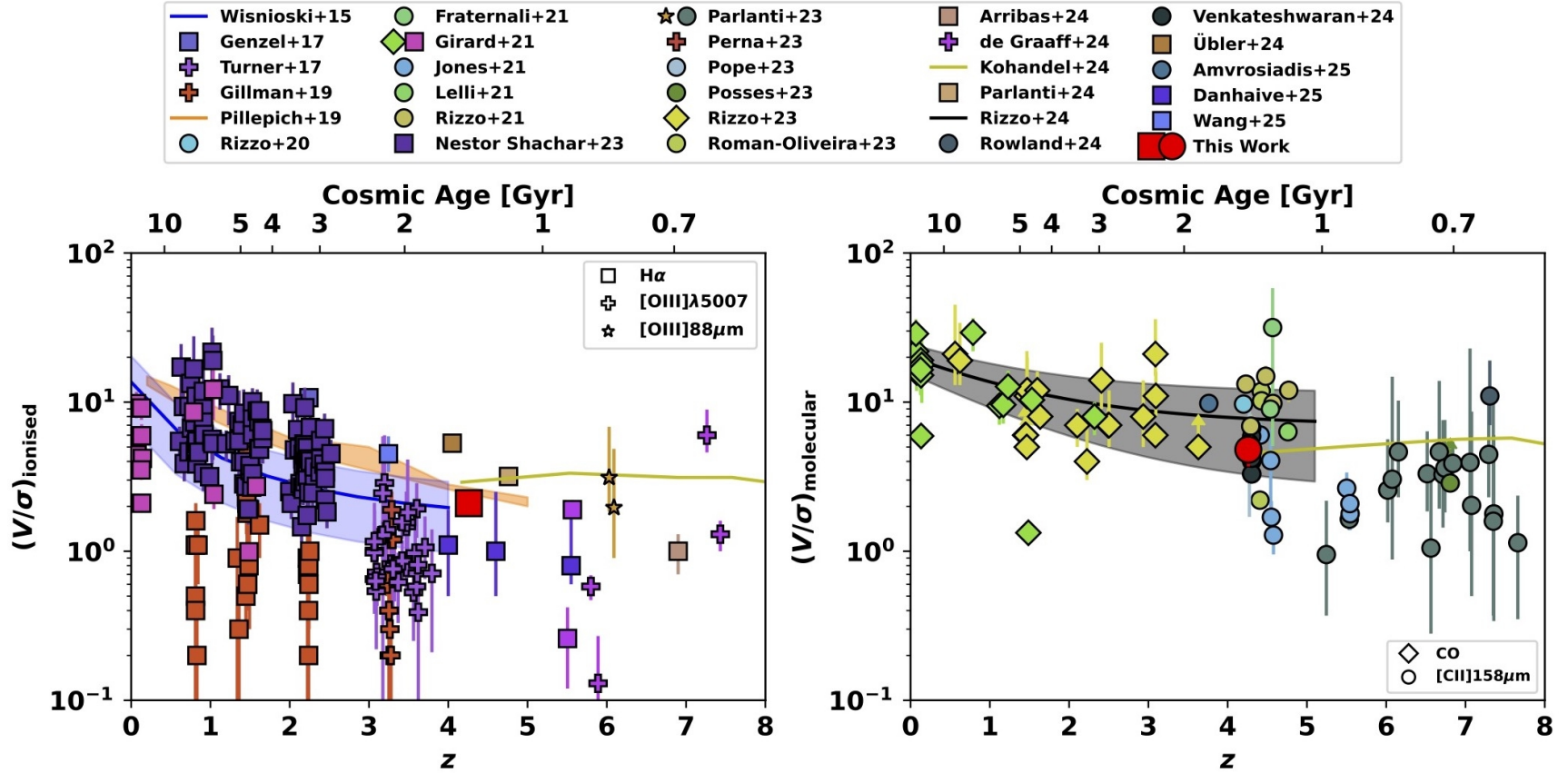


Figure 8. Collection of rotational velocity to velocity dispersion ratios, for ionised (left panel) and molecular gas (right panel). In addition to the values of DLA0817g1 (red points), we include values from literature for ionised gas (Genzel et al. 2017; Turner et al. 2017; Gillman et al. 2019; Girard et al. 2021; Nestor Shachar et al. 2023; Perna et al. 2023; Arribas et al. 2024; de Graaff et al. 2024; Parlanti et al. 2024; Übler et al. 2024; Danhaive et al. 2025; Wang et al. 2025) and molecular gas (Rizzo et al. 2020; Fraternali et al. 2021; Lelli et al. 2021; Rizzo et al. 2021; Jones et al. 2021; Parlanti et al. 2023; Pope et al. 2023; Posses et al. 2023; Rizzo et al. 2023; Roman-Oliveira et al. 2023; Rowland et al. 2024; Venkateshwaran et al. 2024; Amvrosiadis et al. 2025). Some studies present results from both gas phases (Girard et al. 2021; Parlanti et al. 2023). The black line in the right panel depicts the best-fit $(v_{\text{rot}}/\sigma_v)_{\text{molecular}}$ relation from Rizzo et al. (2024), with the reported scatter is depicted as a shaded region. The blue curve in the left panel shows the expected $(v_{\text{rot}}/\sigma_v)_{\text{H}\alpha}$ evolution of $M_* = 10^{10.5} M_\odot$ galaxies (Wisnioski et al. 2015). The observed values are compared to expected ratios from simulations: the orange shaded region in the left panel shows the $\text{H}\alpha$ ratio from TNG50 for $\log_{10}(M_*/M_\odot) = 9 - 11$ galaxies (Pillepich et al. 2019), while the olive lines at $z > 4$ in the left and right panels show $(v_{\text{rot}}/\sigma_v)$ for $\log_{10}(M_*/M_\odot) = 9 - 10$ galaxies from the SERRA simulations for $\text{H}\alpha$ and $[\text{CII}]$, respectively (Kohandel et al. 2024).