The gas and stellar content of a metal-poor galaxy at $z = 8.496$ as revealed by JWST and ALMA

K. E. Heintz[1,2] C. Giménez-Arteaga[1,2] S. Fujimoto[3,1,2] G. Brammer[1,2] D. Espada[4,5]
S. Gillman[1,6] J. González-López[7,8] T. R. Greve[1,6] Y. Harikane[9] B. Hatsukade[10]
K. K. Knudsen[11] A. M. Koekemoer[12] K. Kohno[10,13] V. Kokorev[14] M. M. Lee[1,6]
G. E. Magdis[1,6,2] E. J. Nelson[15] F. Rizzo[1,2] R. L. Sanders[16,17] D. Schaerer[18,19] A. E. Shapley[16]
V. B. Strait[1,2] S. Toft[1,2] F. Valentino[1,2,20] A. van der Wel[21] A. P. Vijayan[1,6] D. Watson[1,2]
F. E. Bauer[22,23,24] C. R. Christiansen[1,2] and S. N. Wilson[1,2]
[1]Cosmic Dawn Center (DAWN), Denmark

[Reasons for selecting this paper]
- Similar features with Yun's target:
  - low-mass (log(M*) = 7.2-8.0) + high sSFR (log(SFR)=0.46) + metal-poor
- Analyzed the galaxy at z = 8.496 (galaxy name: S04590) by combining JWST and ALMA

[Introduction]
Important line from JWST
[1]. auroral [O III] λ4363 emission line
➔ measure electron temperature (Te)
➔ measure metallicity (from Te)

z > 6 galaxies with ALMA: information on gas and dust.
(1). [C II] 158 µm luminosity
1. Estimation of galactic ISM kinematics and total gas mass is possible. (Capak et al. 2015; Smit et al. 2018; Matthee et al. 2019; Knudsen et al. 2016; Dessauges-Zavadsky et al. 2020; Heintz et al. 2021, 2022a)
2. [C II]: strong correlation with the star formation rate (SFR) at z ~ 0–8. (Stacey et al. 1991; De Looze et al. 2014; Cormier et al. 2015, Schaerer et al. 2020)

(2). FIR continuum
1. Dust mass
2. Dust temperature
(Draine & Li 2007; Scoville et al. 2014; Bakx et al. 2021)

[Data]
1. JWST data:
NIRSpec, NIRCam, and NIRISS observations of the galaxy cluster SMACS J0723 obtained as part of the JWST Early Release Observations (ERO) (Pontoppidan et al. 2022).
- Data reduction:
  - wavelength calibration, flat-field correction, flux calibration -> use JWST offical pipeline
  - 2D spectrum, optimal 1D spectrum -> use script of Brammer(2022)

2. ALMA data:
Cycle 8 DDT program, published by Fujimoto et al. (2022b)
  - Data reduction: CASA(version 6.4.1.12) pipeline

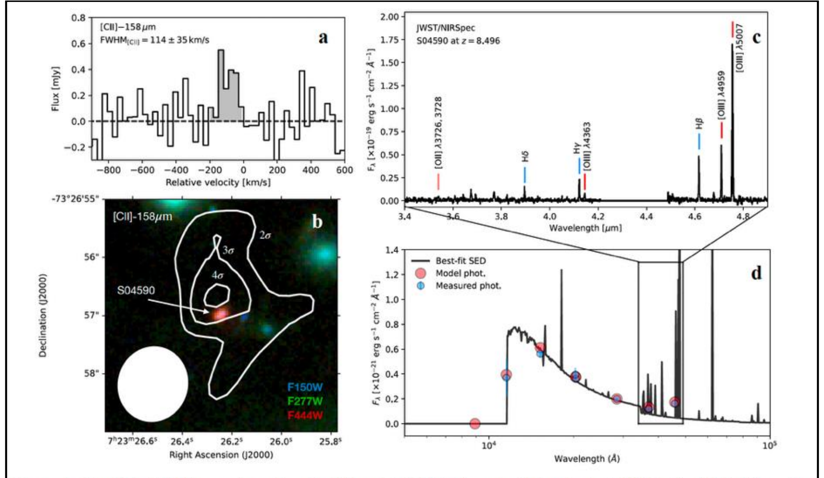

Figure 1. Panel (a): [C II] line spectrum from the 30 km s^{-1} ALMA data cube (Fujimoto et al. 2022b). Panel (b): False-color RGB JWST/NIRCam image zoomed in on S04590(blue: F150W; green: F277W; red: F444W), overlaid with the 2σ, 3σ, and 4σ contours of the [C II] moment-0 map with the beam size represented by the white ellipse. Panel (c): JWST/NIRSpec spectrum with the most prominent nebular and auroral emission lines marked. Panel (d): Best-fit SED model (black curve) and model photometry (red points) based on the derived JWST/NIRCam+NIRISS photometry (blue points) using Bagpipes (Carnall et al. 2018) and assuming the dust attenuation curve from Salim et al. (2018).

[Method for determining physical properties]
1. JWST/NIRCam photometry + JWST/NIRISS photometry/spectroscopy
→ SED (Bagpipes)
→ stellar mass & age

2. JWST/NIRSpec
→ Emission lines: Hβ, Hr, [OIII], [OII], [O III]4363 aurora line
→ metallicity (from [O III]4363 emission line), ionization parameter, dust (Balmer decrement from Hγ/Hβ), electron density

3. ALMA
→ [CII] 158 µm, dust continuum
→ gas mass, ISM distribution, dynamical mass

[Results]
- NIRCam -> Galfit (Peng et al. 2002) -> $r_e \simeq 0.11$ kpc -> compact dwarf galaxy
- [OIII]/Hβ=3.65
- Mass-Metallicity Relation: consistent with the FIRE simulation
- metallicity from Fundamental metallicity relation (FMR): 7.76 but in real 7.16 -> likely indicating substantial infall of neutral, pristine gas diluting the metallicity at z>5 (Heintz et al. 2022b)
- metallicity: 12+log(O/H) = 7.16
  ➔ a state in which chemical enrichment has barely progressed
- Young stellar population: tens of Myr

- Dynamical mass:
  - Assuming that [C II] traces the ISM of galaxy
  - Note: [CII] exhibits an offset and a 90 km/s blueshift compared to UV.
    - Possibility: gas reservoir, outflow, shock, merger

$$M_{\rm dyn} = 1.16 \times 10^5 v_{\rm circ}^2 D_{\rm [CII]}$$

Wang et al. (2013) and Willott et al. (2015)

$$v_{\rm circ} \approx 0.52 \times {\rm FWHM}_{\rm [CII]}$$

(Decarli et al. 2018, Neeleman et al. 2021).

circularized [C II] effective radius of 0.69″ ± 0.42″ in the image plane (Fujimoto 2022b)

- [C II] distribution: about 10 times more extended than UV -> cold gas is distributed over a much wider area than star-forming regions.
- Gas mass (M_{gas}): M_{gas} = M_{dyn} - M* (assume : do not consider dark matter mass)
- Estimate ISM metal mass ($M_{Z,\,ISM}$) using metallicity and gas mass (Sanders et al. 2023)

$$M_{\rm Z,ISM} = M_{\rm gas} \times 10^{12+\log{\rm (O/H)}-8.69} \times Z_\odot = (3.2 \pm 1.6) \times 10^5 M_\odot$$

  - This value similar with total Type II supernova metal production estimated by Peeples et al. (2014)

$$M_{\rm Z,SN} = (7.6 \pm 1.9) \times 10^5\ M_\odot,$$

  ➔ majority of the produced metals remain within the galaxy's interstellar medium (ISM).
- Dust continuum: almost not detected from ALMA
  - only upper limit: $M_{\rm dust} < 1.2 \times 10^5 M_\odot$
- Large gas fraction: f_{gas}=M_{gas}/(M_{gas} + M*) > 90%,

➔ This suggests that a dwarf galaxy in the early universe is continuously being supplied with gas and forming stars.
  - The gas mass fraction is similar to I Zw18.
  - I Zw18: local extreme low-metallicity dwarf galaxy

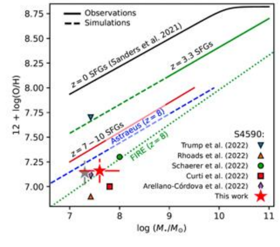

Figure 2. Mass-metallicity (MZ) relation of S04590. For comparison, we show the various preexisting MZ estimates for S04590 from the literature, which highlights the uncertainties from the various methods used. We also show various MZ relations either observed for galaxies at $z \approx 0$ and $z \approx 3.3$ (black and green, respectively; Sanders et al. 2021) and at $z \approx 7-10$ (Heintz et al. 2022b) or predicted from the Astraeus (Ucci et al. 2023) and FIRE (Ma et al. 2016) simulations, extrapolated to $z \approx 8$. The local, metal-poor galaxy I Zw 18 is marked by a gray star symbol, showing an MZ relation consistent with that of S04590. Both are consistent with the predictions for the high-z MZ relations.

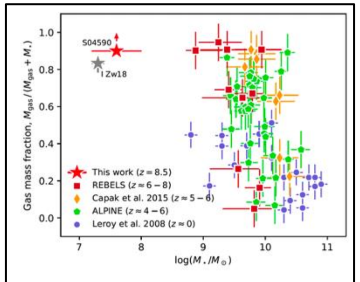

Figure 4. Gas mass fraction, $f_{\rm gas} = M_{\rm gas}/(M_{\rm gas} + M_\star)$, as a function of stellar mass. The symbol notation follows Fig. 3. We observe an overall anticorrelation of $f_{\rm gas}$ with stellar mass for both the low- and high-z galaxy samples, though with an offset due to the redshift evolution of $M_{\rm gas}/M_\star$. S04590 and I Zw 18 are both clear outliers, with low stellar masses $M_\star = 1-2 \times 10^7\ M_\odot$ and high gas fractions $f_{\rm gas} \gtrsim 90\%$, but seem to follow the overall trend.