Dissecting an Extremely-Lensed Dusty Star-Forming Galaxy at z=4.7

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Abstract

The strong lensing effect provided by massive clusters magnifies high-redshift galaxies in the background, allowing investigations in great detail. In this work, we present a multi-wavelength study of a strongly-lensed dusty star-forming galaxy (DSFG), HLSJ0257-2209 (hereafter HLS0257) at z = 4.69. Discovered by the *Herschel Lensing Survey* (HLS), it is lensed by the cluster MACSJ0257-2209 into 5 images with an astonishing **total magnification factor of μ~180.** Our ALMA observations resolved its CO (5-4), CO (12-11), [CII] 158 μm and [NII] 205 μm emission spectrally and spatially, detecting a rotating disk of molecular gas coincident with the luminous dust continuum. The spatial distributions and intensity ratios of these lines demonstrate the presence of a highly excited interstellar medium with a solar-like metallicity. In the source plane where the lensing effect is corrected, we detect five [CII]-emitting clumps with a linear scale of ~100 pc each, which may indicate the existence of compact, luminous star-forming gaseous clouds around the galaxy. Moreover, our HST/WFC3 near-IR images show a bright rest-frame UV continuum source ~650 pc from the DSFG, revealing a significantly reddened (i.e., dusty) Lyman break galaxy (LBG) at the same redshift. Compared with the past studies of individual high-redshift DSFGs, this interacting galaxy pair is of more representative mass and star-formation rate (~47 and ~6 $M_\odot\,yr^{-1}$), offering us an excellent test case to track the evolution of non-extreme dusty star-forming galaxies at z~5.

(1) Discovery

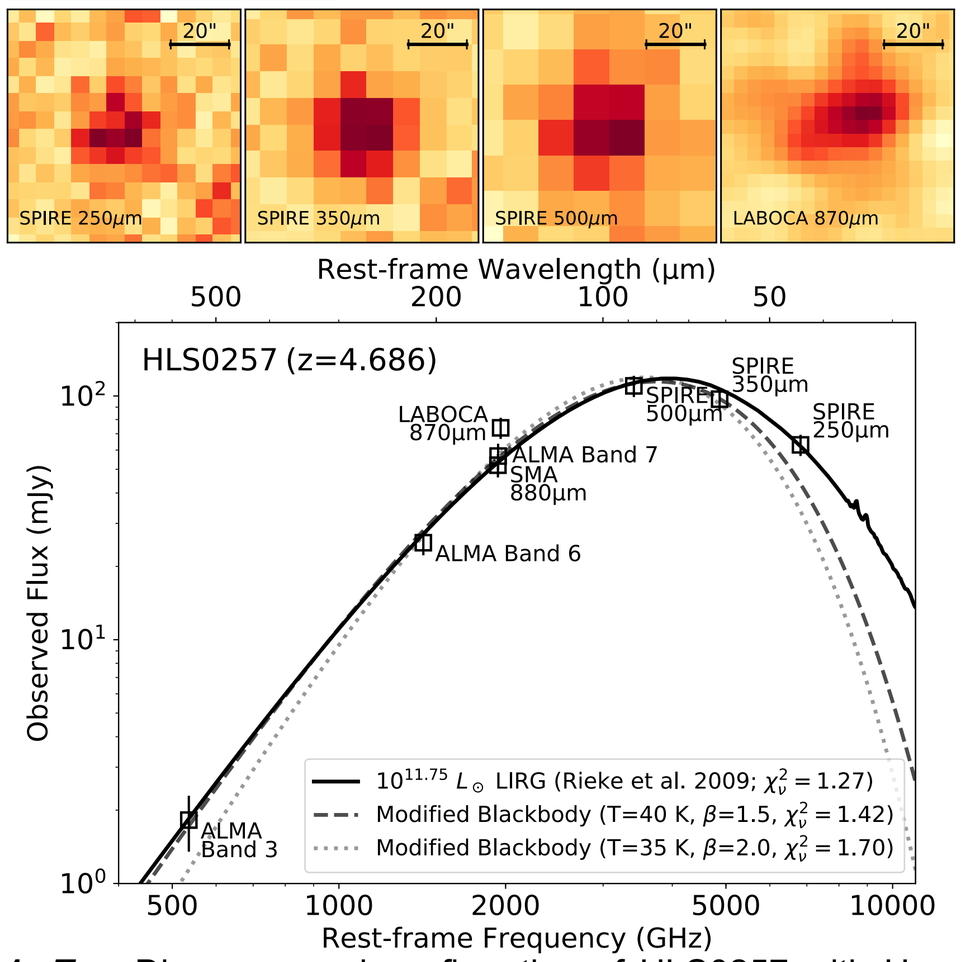

Fig 1. *Top:* Discovery and confirmation of HLS0257 with Herschel Lensing Survey (Egami et al. 2010) and LABOCA/APEX. *Bottom:* Dust continuum SED fitting of HLS0257. Best-fit model suggests a dust temperature of 40K, total-IR (8~1000μm) luminosity of $10^{11.67}\,L_\odot$, and **SFR_{IR} of 47±2 $M_\odot\,yr^{-1}$** (lensing magnification is corrected).

(2) Near-IR Follow-up

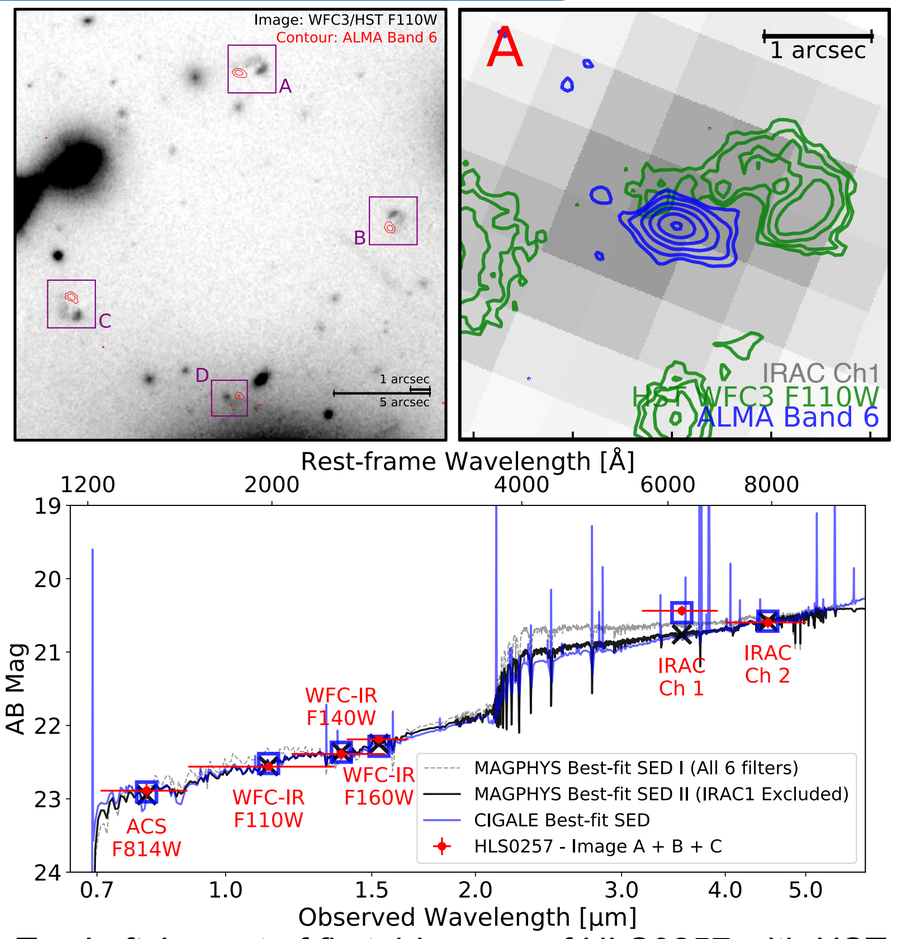

Fig 2. *Top Left:* Layout of first 4 images of HLS0257 with HST (grey-scale image) and ALMA (red contours). *Top Right:* Zoom-in view of HLS0257 Image A at rest-UV (HST, green contours), rest-optical (IRAC1, grey-scale image) and FIR (ALMA, blue contours). *Bottom:* Near-IR SED fitting of HLS0257. Best-fit model suggests a dusty UV continuum (**β=–1.0**), a stellar mass of $2.6\times10^9\,M_\odot$, and **SFR_{UV} of 6±1 $M_\odot\,yr^{-1}$** (lensing magnification is corrected).

➢ **Dusty UV continuum, sub-kpc offset from DSFG**

(3) Resolved Features in the Source Plane

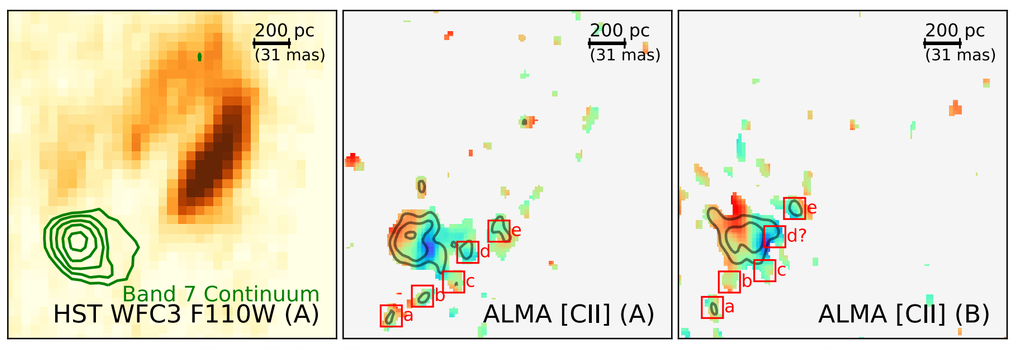

Fig 3. *Left*: HST WFC3 F110W (heat map) and ALMA Band 7 (green contours) source plane image, constructed from HLS0257 Image A (magnification μ_A~50). Intrinsic physical scale is noted on upper-right corner. *Middle & Right:* ALMA $[CII]_{158\mu m}$ velocity map in source plane, constructed from Image A & B. Contour levels are 3, 5, 8σ of RMS noise, and velocity range is -200~+200 km/s. Note that the **five 100-pc scale [CII] clumps** noted in red square shows consistency in their relative positions and velocity.

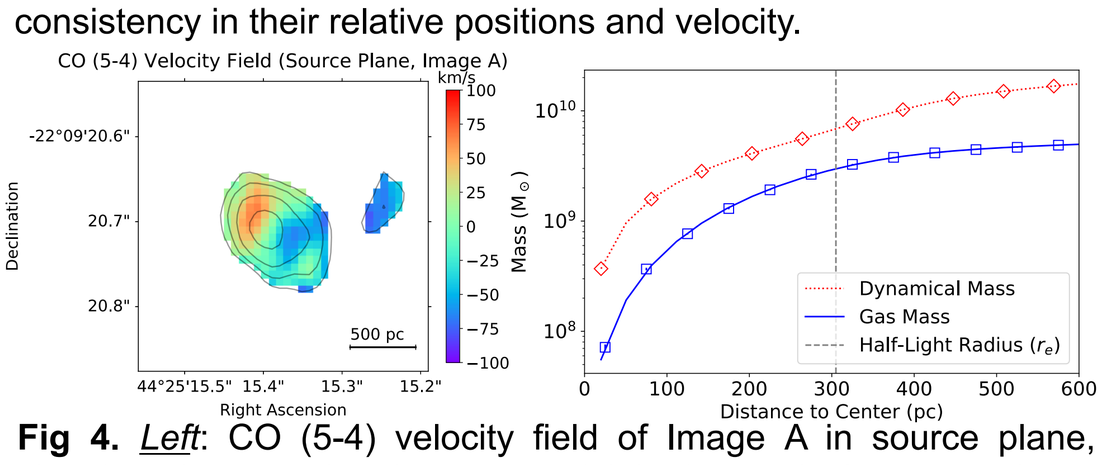

Fig 4. *Left*: CO (5-4) velocity field of Image A in source plane, showing clear rotational structure. *Right:* Dynamical mass and gas mass profile of HLS0257, inferred from ALMA CO (5-4) observation. The gas mass fraction of HLS0257 is then estimated as 36%, with a depletion time of 132±13 Myr.

➢ **Rotating disk and 100-pc clumps**

(4) ISM Excitation and Ionization

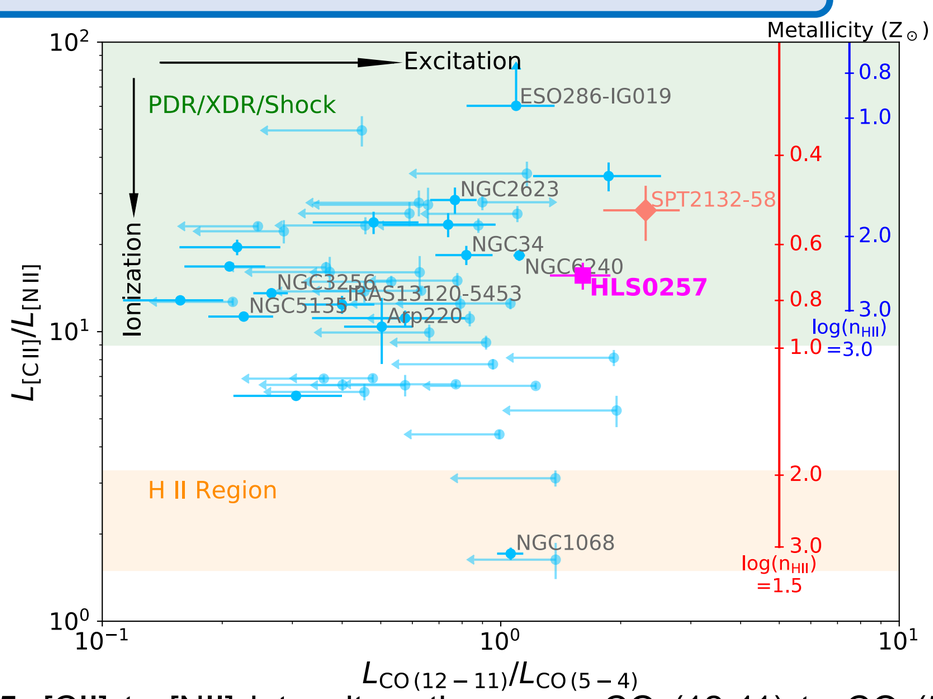

Fig 5. [CII] to [NII] intensity ratio versus CO (12-11) to CO (5-4). HLS0257 (this work) and SPT2132-58 at z=4.7 (Béthermin et al. 2016) are specially noted. Blue circles stand for *GOALS* sample (Díaz-Santos et al. 2013). Metallicity inferred from [CII]/[NII] ratio (modelled by Nagao et al. 2012) is also noted. The shallow green and orange filled region represent the [CII]/[NII] range of PDR and HII-dominated ISM, respectively (Decarli et al. 2014).

➢ **High excitation, PDR dominated, Solar-like metallicity**

References: [1] Béthermin, M. et al. 2016, A&A, 586, L7; [2] Decarli, R. et al. 2014, ApJL, 782, L17; [3] Díaz-Santos, T. et al. 2013, ApJ, 774, 68; [4] Egami, E. et al. 2010, A&A, 518, L12; [5] Nagao, T. et al. 2012, A&A, 542, L34; [6] Rieke, G. H. et al. 2009, ApJ, 692, 556.