Molecular gas dynamics and AGN/starburst mechanism in a strongly-lensed wet merger: bridging the gap between local ULIRGs and high-z systems

PI: T. K. Daisy Leung

Missing link between mergers/ULIRGs and their high-z analogues Ultraluminous infrared galaxies (ULIRGs: $L_{\rm IR} \geq 10^{12} L_\odot$) have been regarded as analogues of high-redshift (z) starbursts given the similarities in their interstellar medium (ISM; e.g. $L_{\rm IR}/L'_{\rm CO}$). As such, detailed studies of ULIRGs are important to gain more detailed insight into the early universe and in studies of galaxy evolution over cosmic time. Since mergers are believed to play an important role in giving rise to these dusty galaxies (e.g. Sanders & Mirabel 1996). Yet, merger-induced effects on the physical mechanisms and chemistry that drive the starburst (SB) and active galactic nucleus (AGN) activities on small scales are still unclear. Thus characterizing the properties of the molecular gas that fuels star-formation (SF) and AGN is crucial to understand the interplay between AGN and SB and their relation to the ISM properties of galaxies across cosmic time.

While the ISM in local ULIRGs has been studied in great detail, forming a rich inventory of molecular transitions that serves as the template for studying high-z galaxies (e.g. Rangwala et al. 2015), a wide knowledge gap persists between z=0 and the epoch when most stars are formed in the universe (z∼2). Hence, understanding galaxy populations at which the build-up of stellar mass is steeply rising is critical and we here aim to bridge this gap by testifying correlations and properties found locally out to high redshift by observing the dynamical structure and properties of the ISM of the quadruply lensed galaxy RXJ1131-1231 and its dust-obscured companion at $z_{\rm CO}$∼0.65.

Molecular gas in AGN/SB Owing to the high molecular gas fractions in ULIRGs, their extreme SFRs are a natural consequence of either gas is being converted into stars more efficiently and/or their molecular gas content. Fragmentation of giant star-forming clumps and turbulent conditions are also expected from gravitational instability of these gas-rich bodies. In fact, studies of the ISM kinematics at z=1-2 find clumps of size scale ∼few kpc (Swinbank et al. 2012a,b). Resolving the gas dynamics on hundred pc scales is therefore an important first step to understanding the mechanisms and physical processes taking place on different scales and how the ISM physical conditions are related to the SB in ULIRGs at this epoch.

While ^{12}CO emission traces the total molecular distribution and dynamics, high-dipole moment molecules such as HCN and HCO^+ are expected to trace the denser, actively star-forming gas. Indeed, a tight correlation between HCN(J=1→0) and $L_{\rm IR}$ (proxy for SFR) has been found in nearby galaxies and local giant molecular clouds (GMC; Gao & Solomon 2004, hereafter GS04; Wu et al. 2005), suggesting HCN is a faithful tracer of the star-forming dense gas. However, HCN(J=4→3) observations of (U)LIRGs have revealed a wide range of excitation conditions that may render the ground state transition of HCN and HCO^+ poor proxies of the dense gas mass (Papadopoulos 2007, hereafter P07). In this light, higher-J transitions (e.g. J=4→3) have been suggested to be better probes since they trace the much denser gas (n$\gtrsim 10^5 - 10^7$ cm^{-3}) that is thought to be the immediate fuel for SF in turbulent GMCs (Shirley et al. 2003; Krumholz & McKee 2005). This has been supported by the linear correlations found in $L_{\rm IR}$-$L'_{\rm HCN(\mathit{J}=4\rightarrow3)}$ and $L_{\rm IR}$-$L'_{\rm HCO^+(\mathit{J}=4\rightarrow3)}$ (Zhang et al. 2014, hereafter Z14). Since the ground state lines are redshifted to frequencies beyond the spectral coverage of ALMA at z>0.06, it is also necessary to establish diagnostics using these mid-J lines to study distant galaxies. Additionally, due to the difference in abundances and excitation conditions of HCN and HCO^+ in star-forming versus AGN regions, the line ratio HCN(J=4→3)/HCO^+(J=4→3) (Imanishi & Nakanishi 2014; García-Burillo et al. 2014; Viti et al. 2014) have been proposed as a diagnostic tool to reveal deeply buried AGNs at the cores of ULIRGs (Izumi et al. 2016; Imanishi et al. 2016).

Prior to ALMA, studies of dense gas were largely limited to the local universe ($z \lesssim 0.1$) with only five detections at $z \gtrsim 0.3$ (Riechers et al. 2006, 2007, 2010; Wagg et al. 2005; Gao et al. 2007). Moreover, none of these spatially resolve the emission, rendering it difficult to draw conclusions on the dense gas properties of galaxies at high redshift. Even with ALMA, such studies will remain challenging, but by combining with the magnification provided by gravitational lensing and the exceptional spatial resolution and sensitivity of ALMA, studies of dense molecular gas in distant galaxies are now possible, as proposed here.

Science Target RXJ 1131-1231: a demonstrative case at high-z

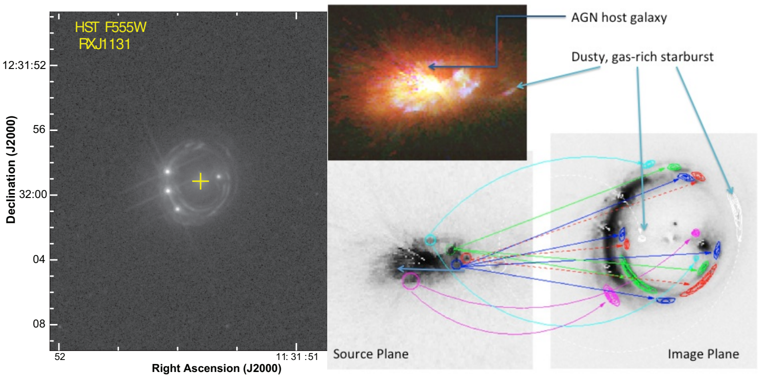

Figure 1: **Stellar light distribution in the AGN host galaxy of RXJ 1131-1231 and its reconstructed source plane morphology** *Left:* The rest-frame UV emission (tracing recent star formation) is lensed into an almost complete Einstein ring with diameter ∼3.8”. *Right:* Lens modeling of the optical emission identifies complex structures in the host galaxy and an optically faint companion (white; Claeskens et al. 2006), which we have recently confirmed by modeling CO(J=2→1) emission detected with NOEMA (Fig. 3; Leung & Riechers, in prep.). We here propose to study the ISM conditions in this AGN-starburst merger and offers an unparalleled view into the early universe, with finer detail than otherwise possible with current facilities.

RXJ 1131-1231 is a quadruply imaged AGN with its host galaxy lensed into a partial Einstein ring (Fig. 1). HST observations (rest-frame UV) have revealed distinct emission from recent star formation (lensing arcs) and from the AGN (bright knots) in the background galaxy (Sluse et al. 2003), demonstrating the great potential for probing its ISM conditions in detail. Lens modeling carried out on optical images shows that the AGN resides in a star-forming region of size ∼1 kpc in its host galaxy, which itself is 7 kpc across, and made it possible to identify seven distinct structures in the source plane (Fig. 1). Remarkably, emission from a spatially offset region (∼2.4 kpc away from the AGN host galaxy) has been identified and found to be ∼700 pc in size (Brewer & Lewis 2008), indicating a companion galaxy. We have recently confirmed that both galaxies are at the same redshift by detecting their CO(J=2→1) emission and lens-modeling their gas distribution in velocity space (Fig. 3f), and verfiied that the both are gas-rich (Leung & Riechers, in prep.). Our SED modeling of the dust continuum emission up to 500 μm finds $L_{\rm IR} \sim 6{\times}10^{12}{\rm L}_{\odot}$ (corrected for lensing). Hence, this target is a gas-rich ULIRG merger at z∼0.7 caught in the act.

Proposed Observations and Science Goals We here propose to map (1): CO(J=5→4) at 0.15” resolution (∼500pc at z∼0.7 in the source plane) and (2): HCN(J=4→3) and HCO$^+$(J=4→3) emission and the underlying continuum at 0.7” resolution (2.5 kpc in the source plane). The continuum traces the dust emission, providing better constraints on the the gas-to-dust ratio, dust temperature(s), dust mass, and its spatial extent (and thus the surface density of the SFR). These quantities are key to investigate how the ISM vary as galaxies evolve across cosmic time. In conjunction with the large set of ancillary data from rest-frame UV to radio wavelength and our recent observations of CO(J=2→1) and CO(J=3→2), our proposed observations are designed to investigate the gas-rich merger aspects listed as follows.

Dynamics and kinematics: Our recently obtained CO(J=2→1) data shows an asymmetric double-horned line profile (Fig. 3a). Given the 1$^{\rm st}$ moment map observed and the velocity gradient across the source plane in our model (Fig. 3c & 3f), this is indicative of a kinematically ordered galaxy but its emission has been lensed differentially. Limited by the spatial resolution of this data, it is insufficient to infer the true kinematics due to beam smearing. Furthermore, the unusually high velocity dispersion $\gtrsim$400km s^{-1} at the central region (Fig. 3d) hints at perturbations from the AGN and/or internal turbulence due to interactions with the companion and/or instability due to the huge gas reservoir. Thus higher-resolution imaging, as proposed here, is needed to distinguish between a merger-driven and a turbulent clumpy disk starburst, since we will be able to obtain a detailed dynamical lens modeling of the system, probing at sub-kpc scale.

The CO(J=5→4) observations will be tracing emission on the size scale of high-z GMCs, allowing us to compare the spatial distributions between recent star-formation (from HST) and star-forming gas clumps. Since CO(J=5→4), HCN and HCO$^+$ trace the warm, excited, dense molecular gas, this will as well allow us to compare against the relatively unperturbed large-scale molecular environment and dynamical mass using our existing low-J CO data. Such comparisons are the key to understand different processes regulating star-formation in ULIRGs/mergers and examine how they differ from other galaxy populations.

AGN/SB diagnostic: At the proposed resolution, we will be able to distinguish HCN(J=4→3) and HCO^+(J=4→3) emission originating from the AGN host galaxy (and within) and from its companion. By observing spatial variations in this line ratio across the AGN host galaxy, we will be able to assess its fidelity as an AGN/SB diagnostic, at higher redshift than current studies, since an elevated HCN(J=4→3)/HCO^+(J=4→3) is expected in nuclear regions near an AGN. By measuring this ratio in the companion, we will as well examine the possibility of a heavily-obscured AGN at its center. Since the HCN vibrational line (v_2=1) falls within the targeted frequency range, we will use it to independently confirm the AGN in the companion, given that this line is excited by infrared pumping (easily achieved near an AGN) and is the cause of the elevated HCN(J=4→3)/HCO^+(J=4→3) (Sakamoto et al. 2010; Imanishi & Nakanishi 2013).

The high spin rate of the central black hole in RXJ1131-1231 (over half the speed of light; Reis et al. 2014) suggests that the black hole has grown via merger (i.e., the galaxies may have already encountered previously). In this scenario, we might be witnessing a second encounter of two AGN host galaxies if we find evidence of a buried AGN in the companion, which the proposed observations are needed to provide such clues.

Line ratios and physical conditions: [In addition, we will measure spatially resolve line ratios (HCN/CO and HCO^+/CO) within the AGN host galaxy as proxies of its very dense (cores; $\sim 10^5$-10^7 cm^{-3}) versus the less dense (clumps; $\sim 10^4$ cm^{-3}) gas content and their spatial distributions.] OR [In addition, we will measure spatially resolve line ratios (HCN/CO and HCO^+/CO) within the AGN host galaxy to constrain the density gradients from $n \sim 10^5$-10^7 to $\sim 10^4$cm^{-3}.]

We will also measure the linewidths of the very dense gas (traced by HCN and HCO^+), the excited gas (traced by CO(J=5→4)), and the more-extended, less-perturbed molecular gas (traced by low-J CO) at various locations to constrain the kinematics and relative mass-fractions of different gas phases, which are indications of the evolutionary stage of a galaxy. Since CO(J=5→4) is excited in higher temperature than the HCN and HCO^+ lines (e.g. in X-ray dominated regions (XDRs) near an AGN), variations in HCN/CO will allow us to constrain the spatial extents of photon dominated regions (PDRs from starbursts) and XDRs. Due to differential lensing, we will be able obtain kinematical information on spatial scales smaller than the beam, as seen in our CO(J=2→1) data (Fig. 3b & Fig. 3c; the blue-shifted emission arises from a region that is positioned differently with respect to the caustic than the red-shifted emission), thereby enabling us to probe the aforementioned variations and gradients in the inner molecular disk (near the AGN).

Differential lensing between HCN, HCO^+, and CO emission is also expected as they trace different emitting regions and are arising from two galaxies. Hence, high spatial resolution is necessary to accurately measure their intrinsic line fluxes (free from differential lensing biases) as it enables a detailed lens modeling on each line emission. Such measurements are vital to reveal how galaxy interactions drive gas into inner disks to initiate starbursts and AGN activities and how the ISM differ from normal star-forming galaxies. We will also combine CO(J=5→4) with our existing CO data to constrain the gas density (n_{H_2}) and kinetic temperature by performing radiative transfer modeling.

The SK Law: The Schmidt-Kennicutt (SK) relation ($\Sigma_{\rm SFR}$=$A\Sigma^N_{\rm gas}$) is one of the key ingredients for theoretical models as it encodes the physical processes and timescales regulating star-formation and their dependence on the ISM (e.g. Narayanan & Krumholz 2014). However, the surface densities of gas at high densities ($n_{\rm crit} \sim 10^7$cm^{-3}; $\Sigma_{\rm dense}$; and thus $\Sigma_{\rm SFR} \propto \Sigma^N_{\rm dense}$) are currently poorly constrained due to the lack of (spatially resolved) observations of the much weaker emission from high critical density tracers. It is thus unclear how the power-law index of the SK law should change depending on the critical density of the tracer used to probe the SF gas (e.g. Krumholz & Thompson 2007). and how the SFR surface density should depend on the global dynamical time scales in normal galaxies and in merges. To further underline the problem, the integrated form (log$L_{\rm IR}$ =α log$L'_{\rm X}$+β; Kennicutt 1998) has been commonly used as a proxy to the true SK relation, for which correlations found for dense gas tracers are incompatible with model predictions (Fig. 2; Z14; Greve et al. 2014) and largely based on constraints from local galaxies. At the proposed resolutions, we will spatially resolve, for the first time, the *true surface density version of the*

SK relation using tracers with $n_{\rm crit} \gtrsim 10^5 {\rm cm}^{-3}$ in a high-z merger: $\Sigma_{\rm SFR} \propto \Sigma^N_{\rm CO(5\rightarrow4)}$ in each of the interacting galaxies, and $\Sigma_{\rm SFR} \propto \Sigma_{\rm HCN(4\rightarrow4)}$ and $\Sigma_{\rm SFR} \propto \Sigma_{\rm HCO+(4\rightarrow3)}$ within the AGN host galaxy and investigate potential variations in the power-law index.

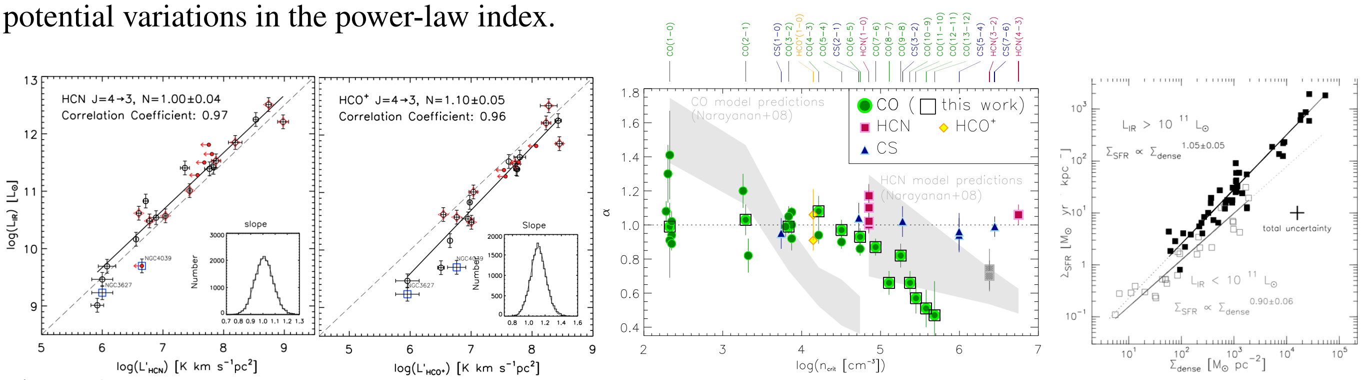

Figure 2: *Left:* **The SK proxy: log $L_{\rm IR}$ = α log $L'_{\rm X}$+β.** Linear correlations in $L_{\rm IR}$-HCN(J=4→3) and $L_{\rm IR}$-HCO$^+$(J=4→3) have been established toward nearby galaxies (Z14), suggesting a single star-formation efficiency for all galaxies and demonstrating the utility of mid-J lines in tracing the star-forming dense gas, which will be routinely mapped in high-z galaxies with ALMA. *Middle panels:* **Constraints on the SK relation with line transitions of different $n_{\rm crit}$.** Most observations are incompatible with model predictions (gray shaded), especially for HCN(J=4→3) (Greve et al. 2014). *Right:* **The true SK relation for the dense gas using HCN(J=1→0)** While constraints on the power-law index from gas of different densities are important for star-formation models, current studies are only able to constrain the true SK law using the ground state HCN line ($n_{\rm crit} \sim 10^4$) and largely limited to nearby measurements (Graciá-Carpio et al. 2008). Our proposed observations will, for the first time, spatially resolve the true SK relation with high critical density tracers in a merger at z∼0.7, exploring potential deviations in SK relation at higher redshift, providing key constraints for models of galaxy evolution.

Technical overview We estimate the line widths and fluxes based on our CO(J=2→1) data, and a source size from our lens model. We thus expect the source to be resolved over 153 beams and 7 beams at 0.15” and 0.7”, respectively (see TJ for details). We adopt conservative line ratios measured for high-z galaxies for CO(J=5→4) line (Carilli & Walter 2013) and those based on (U)LIRGs for HCN(J=4→3) (GS04; P07). For HCO$^+$(J=4→3), we adopt the line ratio HCN(J=4→3)/HCO$^+$(J=4→3) found in ULIRGs (Greve et al. 2009). We use the most stringent sensitivity estimates among HCN(J=4→3) and HCO$^+$(J=4→3) as our sensitivity goal for science goal 1. To secure enough S/N for lens modeling, we require a minimum of 8σ of 0.47 mJy beam^{-1} and 0.07 mJy beam^{-1} per 150 km s^{-1} channel for the science goals, respectively.

References • Brewer et al. 2008, MNRAS, 390, 39 • Carilli et al. 2013, ARA&A, 51, 105 • Claeskens et al. 2006, A&A, 451, 865 • Gao et al. 2007, ApJ, 660, L93 • Gao et al. 2004, ApJ, 606, 271 • García-Burillo et al. 2014, A&A, 567, A125 • Graciá-Carpio et al. 2008, A&A, 479, 703 • Greve et al. 2014, ApJ, 794, 142 • Greve et al. 2009, ApJ, 692, 1432 • Imanishi et al. 2013, AJ, 146, 91 • Imanishi et al. 2014, AJ, 148, 9 • Imanishi et al. 2016, ArXiv e-prints • Izumi et al. 2016, ApJ, 818, 42 • Kennicutt, Jr., R. C. 1998, ApJ, 498, 541 • Krumholz et al. 2005, ApJ, 630, 250 • Krumholz et al. 2007, ApJ, 669, 289 • Narayanan et al. 2014, MNRAS, 442, 1411 • Papadopoulos, P. P. 2007, ApJ, 656, 792 • Rangwala et al. 2015, ApJ, 806, 17 • Reis et al. 2014, Nature, 507, 207 • Riechers et al. 2007, ApJ, 671, L13 • Riechers et al. 2006, ApJ, 645, L13 • Riechers et al. 2010, ApJ, 725, 1032 • Sakamoto et al. 2010, ApJ, 725, L228 • Shirley et al. 2003, ApJS, 149, 375 • Sluse et al. 2003, A&A, 406, L43 • Swinbank et al. 2012a, ApJ, 760, 130 • Swinbank et al. 2012b, MNRAS, 426, 935 • Viti et al. 2014, A&A, 570, A28 • Wagg et al. 2005, ApJ, 634, L13 • Wu et al. 2005, ApJ, 635, L173 • Zhang et al. 2014, ApJ, 784, L31

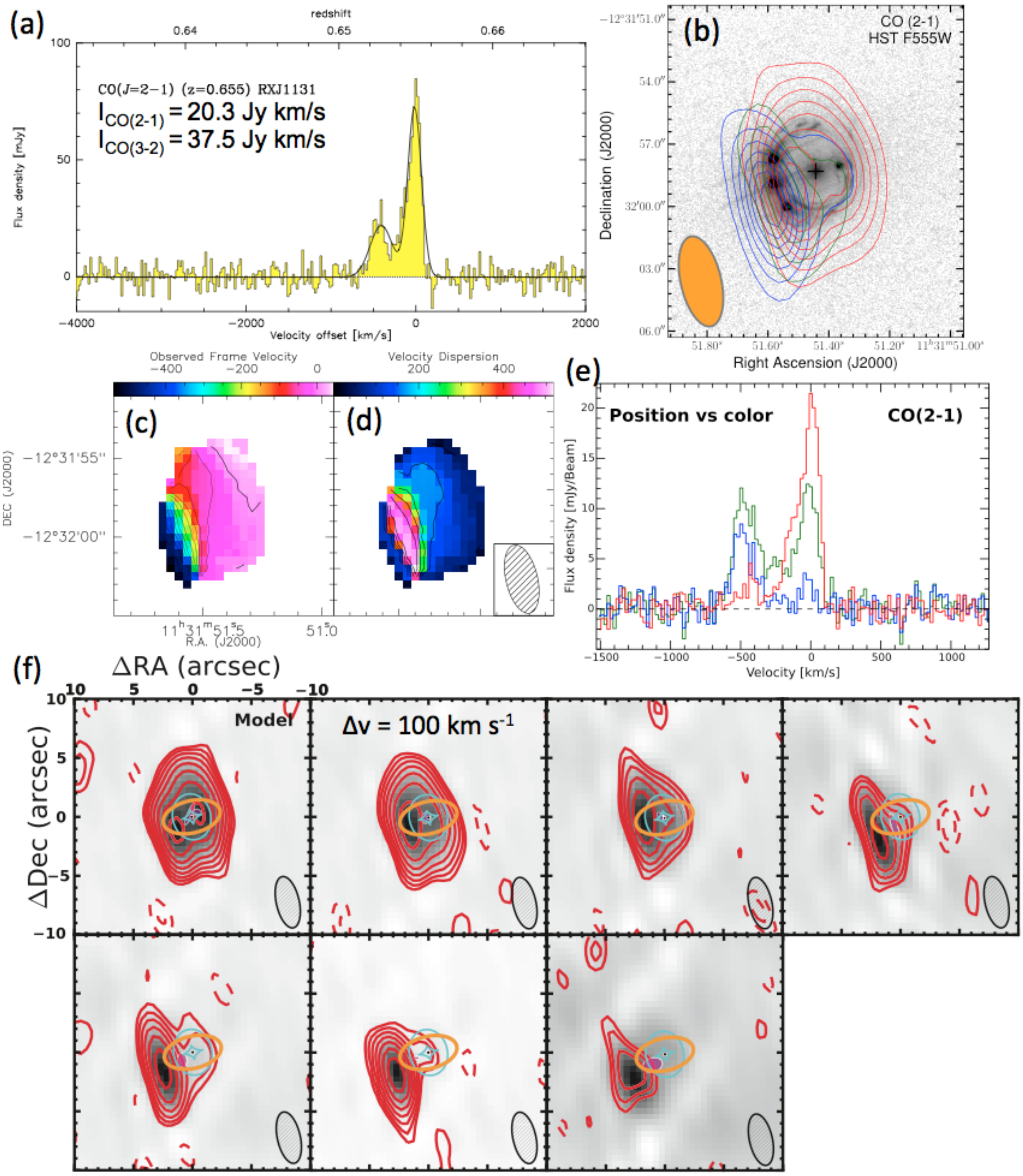

Figure 3: **CO(*J*=2→1)** *(a):* A double-horned, asymmetric line profile arising due to differential lensing. *(b):* Observed spatial variations across the channels, as shown by the red (red-shifted), green (line center), and blue (blue-shifted) contours. *(c):* The observed velocity gradient is suggestive of a kinematically ordered disk at the current resolution limit. Spatial variations across different kinematic components are also see within the beam, indicating the spectrally resolved lensed emission allows us to probe dynamical structures on smaller spatial scales than otherwise possible. *(d):* An usually high velocity dispersion is observed but the true dynamics is unclear due to beam smearing effects. *(e):* Spectra taken at three locations along the strongest velocity gradient, demonstrating differential lensing of the kinematic components of the gas-rich "disk". *(f):* Channel maps of the CO emission (red) overlaid on our best-fit lens models (grayscale). The foreground lensing galaxy is represented by a black dot. The reconstructed source morphology (magenta ellipses) is also suggestive of a "disk". Given the presence of a companion galaxy within 2.4 kpc and beam smearing effects, high-resolution imaging is necessary to unambiguously determine the nature that gives rise to the observed velocity gradient and dispersion, as proposed here. This will allow us to investigate the mechanisms responsible for the starburst in the AGN host galaxy (e.g. GMC-like in a rotating disk or due to fragmentation of dynamically unstable gas-rich disk) and its ISM conditions as it interacts with the companion. We therefore aim to spatially resolve the gas dynamics, kinematics and ISM conditions in a merger, providing observational constraints on the star-formation processes at the epoch where the SFR density is steeply rising across cosmic times.