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

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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 their similarities in $L_{\rm IR}/L'_{\rm CO}$ and other physical properties. As such, detailed studies and characterization of ULIRGs are important to gain more detailed insight into the early universe and in studies of galaxy evolution over cosmic time. It is believed that mergers 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 intense 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 interstellar medium (ISM) properties of galaxies across cosmic time.

While the ISM in local ULIRGs has been studied in great detail with ALMA, forming a rich inventory of molecular transitions that serves as the template for understanding high-z galaxies and galaxy evolution (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$$\sim$2). Understanding galaxy populations at the epoch when the build-up of stellar mass across cosmic time is steeply rising is thus critical and we here aim to bridge this gap by testifying correlations and properties found locally out to high/moderate redshifts by observing the dynamical structure of the different molecular gas components in the quadruply lensed galaxy RXJ1131-1231 and its dust-obscured companion at $z_{\rm CO}$$\sim$0.65.

Molecular gas in AGN/SB Owing to the high molecular gas fractions in ULIRGs and their high-z analogues, 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 $\sim$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 physical conditions are related to the starburst in ULIRGs at this epoch (when the SFR density is steeply rising).

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 properties of the denser, actively star-forming gas. Indeed, a tight correlation between HCN(J=1$\rightarrow$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. This has been supported by the linear correlations in $L_{\rm IR}$-$L'_{{\rm HCN}(J=4\rightarrow3)}$ and $L_{\rm IR}$-$L'_{{\rm HCO^+}(J=4\rightarrow3)}$ found recently (Zhang et al. 2014, hereafter Z14; see Fig. 2), which also highlight the great utility of these mid-J lines observable for galaxies at z>0.06.

Due to the difference in abundances and excitation conditions of HCN and HCO$^+$ in star-forming versus AGN regions, the line ratio HCN(J=1$\rightarrow$0)/HCO$^+$(J=1$\rightarrow$0) has been proposed as a diagnostic tool to separate emission originating from AGN and starburst (Kohno 2005; Imanishi et al. 2010; Izumi et al. 2013). With the frequency coverage of ALMA, some studies have extended this diagnostic to using the J=4$\rightarrow$3 transitions (Imanishi & Nakanishi 2014; García-Burillo et al. 2014; Viti et al. 2014), where an elevated HCN(J=4$\rightarrow$3)/HCO$^+$(J=4$\rightarrow$3) line ratio is also seen in AGNs, suggesting it, too, can be used to reveal a deeply buried AGN 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 IR-luminous lensed galaxies detected at $z \gtrsim 0.3$ (e.g. Riechers et al. 2006, 2007, 2010; Wagg et al. 2005; Gao et al. 2007). However, none of these high-z detections spatially resolve the emission, rendering it difficult to draw conclusions on the dense gas properties of galaxies at high redshifts. 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

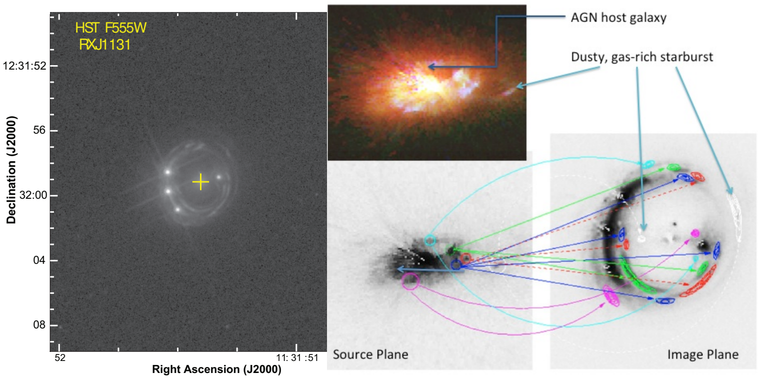

Figure 1: **Stellar light distribution in the AGN host galaxy of RXJ 1131-1231 and its reconstructed source plane morphology** *Left:* The rest-frame UV emission (tracing recent star formation) is lensed into an almost complete Einstein ring with diameter $\sim$ 3.8". *Right:* Lens modeling of the optical 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$\rightarrow$1) emission detected with NOEMA (Fig. 3; Leung & Riechers, in prep.). We here propose to study the ISM conditions in this AGN-starburst composite system 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 the ISM conditions in detail. Lens modeling carried out on optical images shows that the AGN resides in a star-forming region of size $\sim$0.15" ($\sim$1 kpc) in its host galaxy, which itself is 1" across ($\sim$7 kpc), and made it possible to identify seven distinct structures in the source plane (Fig. 1). Remarkably, emission originating from a spatially offset region ($\sim$2.4 kpc away) from the AGN host galaxy has been identified and found to be $\sim$700 pc in size (Brewer & Lewis 2008), indicating a nearby companion galaxy. We have recently confirmed that both galaxies are at the same redshift by detecting their CO(J=2$\rightarrow$1) emission and lens-modeling the distribution of the gas in velocity space (Fig. 3f), verifying 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$10^{12}L$_\odot$ (corrected for lensing). Hence, this target is a gas-rich ULIRG merger at $z$$\sim$0.7 caught in the act.

Proposed Observations and Science Goals We here propose to map (1): CO(J=5$\rightarrow$4) at 0.15" resolution ($\sim$500pc at $z$$\sim$0.7 in the source plane) and (2): HCN(J=4$\rightarrow$3) and HCO$^+$(J=4$\rightarrow$3) emission at 0.7" resolution (2.5 kpc) and the underlying continuum. The continuum emission traces the optically-thick dust emission, which will provide better constraints on the dust temperature(s), dust mass, and spatial distribution, and thus a tighter constraint on the surface density of the SFR and the gas-to-dust ratio. These quantities are key to investigate how the ISM conditions vary as galaxies evolve. In conjunction with the large set of ancillary data from rest-frame UV to radio wavelength and our new spectral line observations of CO(J=2$\rightarrow$1) and CO(J=3$\rightarrow$2), our proposed observations will enable a detailed characterization of merger/ULIRG in the following aspects.

Dynamics and kinematics: Our recently obtained CO(J=2$\rightarrow$1) data shows an asymmetric double-horned line profile (Fig. 3a). Given the observed 1$^{\rm st}$ moment map and the velocity gradient across the source plane in our model (Fig. 3c & 3f), this is indicative of a kinematically ordered (reminiscent of a rotating disk) 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 central AGN and/or internal turbulent motion due to interactions with the companion and/or instability due to the huge gas reservoir. Thus, higher-resolution imaging, as proposed here, will allow us to distinguish the major mechanism driving the starburst: merger-driven versus gas-rich clumpy disk, since we will also be able to obtain a detailed dynamical lens modeling of the system.

The CO(J=5$\rightarrow$4) observations at 0.15" are complementary to the optical images, allowing a comparison between the stellar and gas distribution. Additionally, since CO(J=5→4), HCN(J=4→3) and HCO$^+$(J=4→3) trace the warm, excited, dense molecular gas, this will allow us to compare against the relatively unperturbed large-scale molecular environment and the dynamical mass with our existing lower-J CO data. Such comparison are key to understand the processes and timescales regulating star-formation in ULIRG/merger, and examine how they differ from other galaxy populations.

Line ratios as AGN/starburst diagnostic: By measuring HCN(J=4→3)/HCO$^+$(J=4→3) in the AGN host galaxy, separated from the companion, we will assess its fidelity as a AGN/SB diagnostic at higher redshifts than current studies. We will as well measure this ratio in the companion and examine the possibility of a heavily-obscured AGN at its center. Due to the high critical densities of these high-J transitions ($n_{\rm crit}$ ∼10^8cm^{-3}), the HCN(J=4→3)/CO and HCO$^+$(J=4→3)/CO line ratios are expected to be enhanced in AGNs on a global scale, enabling us to carry out a consistency check against the HCN(J=4→3)/HCO$^+$(J=4→3) line ratio diagnostic.

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 rather than from small episodic accretions (from random directions). In this scenario, the companion and the AGN host galaxy may have already encountered previously. Therefore, our observations will improve our understanding on the formation and evolution of supermassive black holes and the co-evolution with their host galaxies (and mergers). More interestingly, we might be witnessing the pre/post merging/encounter of two AGN host galaxies if we find evidence of a buried AGN in the companion, of which the proposed observations are needed to provide such clues.

Spectral line energy distributions (SLED) and the SF Law: On top of using HCN(J=4→3) and HCO$^+$ as AGN/SB diagnostic, another aspect is to combine them with CO(J=5→4) and our existing low-J CO data to perform radiative transfer modeling to constrain the physical conditions (e.g. density and gas kinetic temperature) of the multi-phase molecular gas. The HCN(J=4→3) and HCO$^+$(J=4→3) lines are essential as they trace beyond the J-transition of the CO SLED turnover (typically beyond J=6→5 in local (U)LIRGs and high-z starbursts; Greve et al. 2014). In addition, since ISM studies of high-z galaxies typically adopt local SLED for comparison (e.g. Bothwell et al. 2013) and/or for asserting assumptions on the conditions of these high-z galaxies. Our observations will thus form a template at z∼0.7 for these high-z studies.

The "star-formation law" (log$L_{\rm IR}$ =α log$L'_{\rm X}$+β) is one of the key ingredients for theoretical models as it encodes the physical processes of star-formation and its dependence on the ISM (e.g. Narayanan & Krumholz 2014). However, the $L_{\rm IR}$-$L'_{\rm X}$ at high critical density are currently poorly constrained due to the lack of observations and are largely limited to the nearby universe (Fig. 2; Greve et al. 2014). Our proposed observations will help delineate the slopes at high critical densities and explore the linear correlations found locally in $L'_{\rm HCN(\it J=4\to3)}$-$L_{\rm IR}$ and $L'_{\rm HCO^+(\it J=4\to3)}$-$L_{\rm IR}$ (Fig. 2; Z14) at higher redshifts.

Technical overview We propose to observe the CO(J=5→4) line at 0.15" resolution and the HCN(J=4→3) and HCO$^+$(J=4→3) lines at 0.7", assuming a line of 700km s^{-1} based on our CO(J=2→1) data and a source size from our lens model (see details in TJ). We thus expect the source to be resolved over 153 beams and 7 beams at 0.15" and 0.7", respectively. We compute the target sensitivities for both science goals based on the CO(J=2→1) line flux. For CO(J=5→4), we adopt conservative line ratios measured for SMGs (Carilli & Walter 2013, see TJ for details), and those based on (U)LIRGs for HCN(J=4→3) (GS04; Papadopoulos 2007). 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. We therefore request a **total time of 7.0 hours**.

Our proposed observations present an exceptional opportunity to investigate the physical properties and dynamical structures of the ISM in mergers at the cosmic epoch where the SFR density is steeply rising (Le Floc'h et al. 2005), connecting high redshift and nearby studies to improve our understanding of galaxy evolution. This will also serve as a benchmark demonstrating the future prospects for ALMA in utilizing

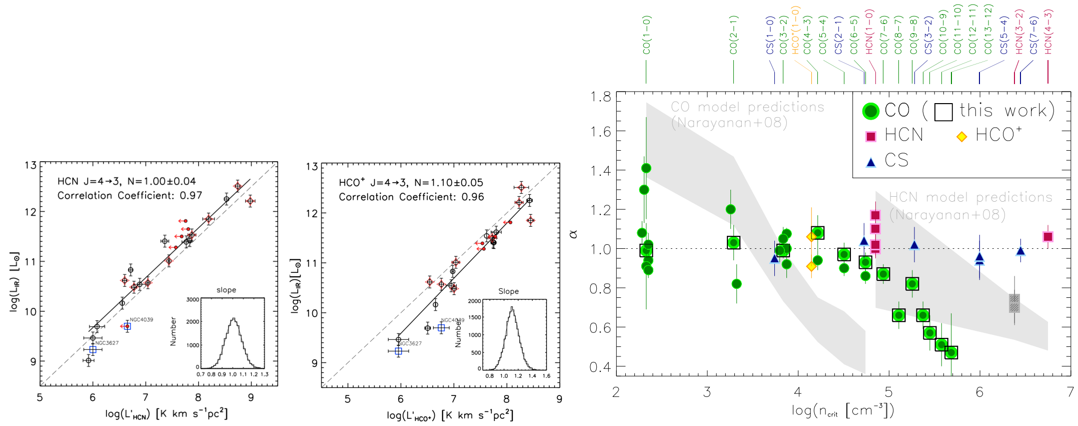

Figure 2: **The SF law: log $L_{\rm IR}$ = α log $L'_{\rm X}$+β.** *Left & middle:* A linear correlation between $L_{\rm IR}$-HCN(J=4$\rightarrow$3) and $L_{\rm IR}$-HCO$^+$(J=4$\rightarrow$3) have been established toward nearby galaxies (Z14), demonstrating the utility of mid-J lines in tracing the star-forming dense gas, which will be routinely mapped in high-z galaxies with ALMA. Our proposed observations will testify the linearity by adding measurements of a ULIRG at z$\sim$0.7, and unveil potential deviations at higher redshift. *Right:* **Constraints on the SF law with line transitions of different $n_{\rm crit}$.** Most observations are incompatible with current model predictions (gray shaded area), especially for HCN(J=4$\rightarrow$3) (Greve et al. 2014). Our proposed observations will thus reduce the uncertainties on the slopes at high critical densities and improve our current understanding of galaxy evolution.

high-dipole moment molecules as routine tracers to study star-formation at high redshifts.

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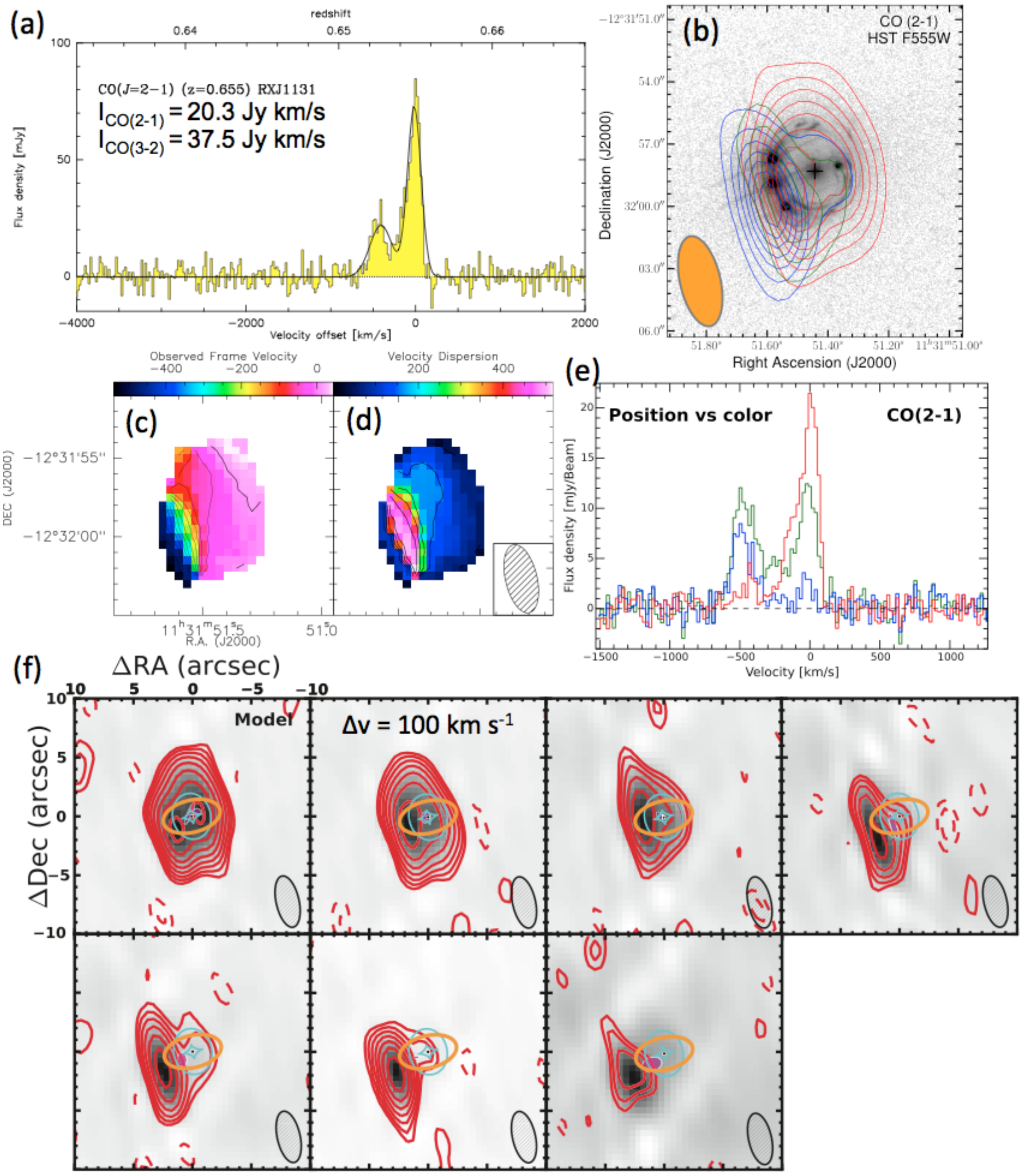

Figure 3: *(a):* The CO(J=2→1) spectrum of RXJ1131-1231 shows a double-horned, highly asymmetric line profile, which arises due to differential lensing. *(b):* Spatial variations traced by CO(J=2→1) as shown by the (red, green, blue) contours corresponding to the line flux of different velocity channels (red wing, line center, blue wing). *(c):* The observed velocity gradient is suggestive of a kinematically ordered disk at the current resolution limit. *(d):* Velocity dispersion map of the CO(J=2→1) emitting gas. However, limited by the spatial resolution, beam smearing strongly decreases large-scale velocity gradients and increases observed dispersion. *(e):* Overlay of spectra taken at three locations along the strongest velocity gradient, demonstrating differential lensing of the different kinematic components of the galaxy. *(f):* Velocity channels of the CO emission toward the gas-rich merger (red contours) overlaid on our best-fit lens model for each velocity bin (grayscale). The foreground lensing galaxy is represented by a black dot, and the beam size is shown in the bottom right corner. Clearly, there are spatial variations across different kinematic components. The reconstructed source morphology (magenta ellipses) is suggestive of a kinematically ordered galaxy. Given the presence of a companion galaxy within 2.4 kpc and beam smearing effects, high-resolution imaging is thus necessary to unambiguously determine the nature that gives rise to the observed velocity gradient and dynamics, as proposed here. This will confirm if the system is rotationally supported or highly turbulent (tidally disrupted) and allow us to investigate the major mechanisms responsible for the starburst in the AGN host galaxy and investigate whether dominant mode of star formation is GMC-like in a rotating disk or due to fragmentation of dynamically unstable gas-rich disk. **We here aim BLAH** and provide observational constraints on the star-formation and stellar-assembly history at the epoch where the SFR density is steeply rising across cosmic times.