Molecular gas dynamics and excitation and star-formation mechanism in a strongly-lensed wet merger

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Missing link between mergers/ULIRGs and their high-z analogues Ultraluminous infrared galaxies (ULIRGs: $\mathrm{L_{IR}} \geq 10^{12}\mathrm{L_\odot}$) have been regarded as analogues of high-redshift (z) starbursts given their similarities in $\mathrm{L_{IR}}/L'_{\mathrm{CO}}$ and other physical properties. Hence, they are commonly used as templates for their high-z counterparts, which are expensive to study. As such, detailed studies and characterization of ULIRGs are extremely important to gain insights into the early universe and study how galaxies evolve over cosmic time. It is now 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 and AGN activities on small scales are still unclear. Thus characterizing the properties of the molecular gas that fuel star-formation and AGN is crucial for understanding the interplay between these activities and their relation to the ISM content across cosmic times.

While local ULIRGs has been studied in great details with multi-transitions of different molecular species, and increasingly more so with the advent of 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 out to 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 redshifts.

Various molecular gas phases and the star-formation law Owning to the high molecular gas fraction in ULIRGs and their high-z analogues, their extreme SFRs is a natural consequence of either gas is 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 a promising 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 SFRD is steeply rising).

While ^{12}CO emission traces the total molecular distribution and dynamics, molecules such as HCN, HNC and $\mathrm{HCO^+}$ are expected to trace the properties of the denser star-forming gas. Indeed, a tight correlation between HCN(J=1$\rightarrow$0) and $\mathrm{L_{IR}}$ (SFR tracer) has been found in nearby galaxies and local GMCs (Wu et al. 2005), suggesting HCN is a faithful tracer of the star-forming dense molecular gas. However, the origin of such correlation is still under debate (Kohno 2005, Papadopoulos 2007; hereafter P07; Costagliola et al. 2011). Meanwhile, an elevated $\mathrm{L_{IR}}/L'_{\mathrm{HCN}(J=1\rightarrow0)}$ in (U)LIRGs and high-z galaxies (Riechers et al. 2007; Gao et al. 2007; hereafter G07; Graciá-Carpio et al. 2008) imply that the star-formation law of dense gas (based on HCN) (Σ_{SFR} - Σ_{dense}) breaks down above $\mathrm{L_{IR}} > 10^{11}\mathrm{L_\odot}$, calling questions into the reliability of HCN(J=1$\rightarrow$0) as a dense gas tracer and $\mathrm{L_{IR}}/L'_{\mathrm{HCN}(J=1\rightarrow0)}$ as a diagnostic of the star formation efficiency of dense gas (Graciá-Carpio et al. 2006).

In addition, HCN(J=4$\rightarrow$3) observations of (U)LIRGs have revealed a wide range of excitation conditions for their dense gas phase that may render the ground state transition of HCN and $\mathrm{HCO^+}$ poor proxies of the dense gas mass (P07). In this light, higher-J transitions (e.g. J=4$\rightarrow$3) have been argued to be necessary to scrutinize the reliability of HCN(J=1$\rightarrow$0) as dense gas mass tracer since the mid-J transitions trace the much denser (n$\gtrsim 10^5 - 10^6$ cm^{-3}) molecular gas that is thought to be the immediate fuel for star-formation in turbulent GMCs (Shirley et al. 2003; Krumholz & McKee 2005). Besides, since the ground state lines are redshifted to frequencies beyond spectral coverage of ALMA for z >0.06, it is also necessary to establish diagnostics using mid-J lines to study distant galaxies.

Prior to era of ALMA, studies of dense gas are largely limited to the local universe (z $\lesssim$0.1) except for detections in five IR-luminous lensed galaxies (Riechers et al. 2006, 2007; Wagg et al. 2005; G07), such small sample with limited resolution renders it extremely difficult to draw conclusions on the dense gas properties at high redshifts. Even with ALMA, it will remain challenging to carry out similar studies at high redshifts, e.g. line ratio maps tracing spatial variations on few tens of pc scales, resolving gas clumps in GMCs and the dynamics and excitation conditions at high resolution. Yet, the magnification provided by gravitational lensing enables one to further exploits the exceptional spatial resolution of ALMA, enabling studies of distant galaxies to be carried out beyond the capabilities of current instruments. We here propose a detailed study of the ISM properties in the quadruply lensed galaxy RXJ1131-1231 and its dust-obscured companion at $z_{\rm CO}{\sim}0.65$ to bridge the gap between nearby ULIRGs and their high-z analogues.

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

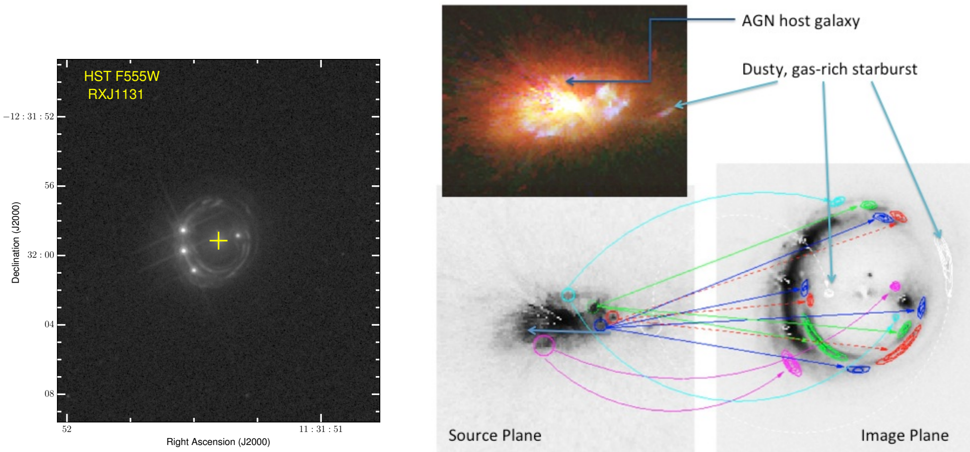

Figure 1: **RXJ1131-1231 stellar distribution and its reconstructed source plane morphology** *Left:* An optical image reveals the background AGN (knots) and its host galaxy (arcs) with highly complex structures. The rest-frame UV emission (tracing recent star formation) is lensed into an almost Einstein ring with radius $\sim$ 3.8". *Right:* A lens modelling with the optical image identify an optically faint companion (white; Claeskens et al. 2006), which we have recently confirmed with our dynamical lens model using CO(J=2$\rightarrow$1) emission (Fig. 3) and is extremely dusty ($L_{\rm IR}$ $\sim$6$\times$10^{12}$L_\odot$) and gas-rich (Fig. 4; Leung & Riechers, in prep.). A source plane reconstruction also shows seven spatially distinct components, highlighting the potential of our science target for studying the ISM conditions near starburst and AGN activities 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 an Einstein Ring (Fig. 1). HST observations (rest-frame UV) have revealed distinct emission from recent star formation (arcs) and the AGN (knots) in the background galaxy (Sluse et al. 2003), demonstrating the complexity and the immense potential for probing the ISM conditions at astounding level of detail. Lens modelling carried out with the optical images show that the AGN resides in a star-forming region of $\sim$0.15" ($\sim$1 kpc) in its host galaxy which is 1" across ($\sim$7 kpc), and identify seven spatially distinct structures in the source plane of size $\sim$0.1" (Fig. 3). Remarkably, emission originating from a spatially offset region from the AGN host galaxy has been identified at $\sim$ 2.4 kpc away, of $\sim$ 700 pc in size (Brewer & Lewis 2008), indicating a nearby counterpart, which we have recently confirmed with the CO(J=2$\rightarrow$1) emission and our dynamical lens model, verifying the two host massive cool gas reservoirs and are at similar redshifts (Fig. 4 & Fig. 3; Leung & Riechers, in prep.). Our SED modelling of the dust finds $L_{\rm IR}$ $\sim$ 6$\times$10^{12}$L_\odot$ (corrected for lensing). Hence, this target is a gas-rich ULIRG merger caught in the act.

Proposed Observations and Immediate Objectives We here propose to map (1): CO(J=5$\rightarrow$4) at 0.15" resolution ($\sim$500pc in the source plane) and (2): HCN(J=4$\rightarrow$3) and HCO$^+$(J=4$\rightarrow$3) emission at 0.7" resolution (2.5 kpc). The underlying continuum will addtionally provide better constrain on the dust emission and distribution and thus surface density of the SFR. In conjunction with the large set of ancillary data obtained spanning from rest-frame UV to radio and spectral line observations of CO(J=2$\rightarrow$1) and CO(J=3$\rightarrow$2), our proposed observations will address many questions in various aspects (see below). The weak H_2O line falls in the same sideband as CO(J=5$\rightarrow$4), and thus our observations will as well provide constrains on the line strength and thus AGN feedback/excitation, albeit the small number of detections at high redshift (R06?).

Dynamics and kinematics:

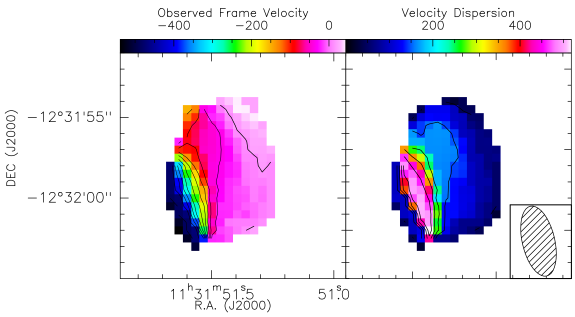

Figure 2: **RXJ1131-1231 kinematics and dynamics in CO(J=2→1)** *Left:* The observed velocity gradient is suggestive of a kinematically ordered disk. Limited by current spatial resolution, the intrinsic velocity gradient may be smaller than the beam size such that the smaller gradient are not resolved, which may led to misinterpretation of the system to be rotationally supported. *Right:* 2^{nd} order moment map showing the velocity dispersion in 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. High resolution is thus necessary to distinguish the dichotomy between a rotating disk and mergers and/or the effect of a companion on the internal dynamics of the AGN host galaxy. This will enable us to understand the mechanisms driving the starburst and investigate whether dominant mode of star formation is like GMC in a stable disk or by fragmentation of dynamically unstable gas-rich disk.

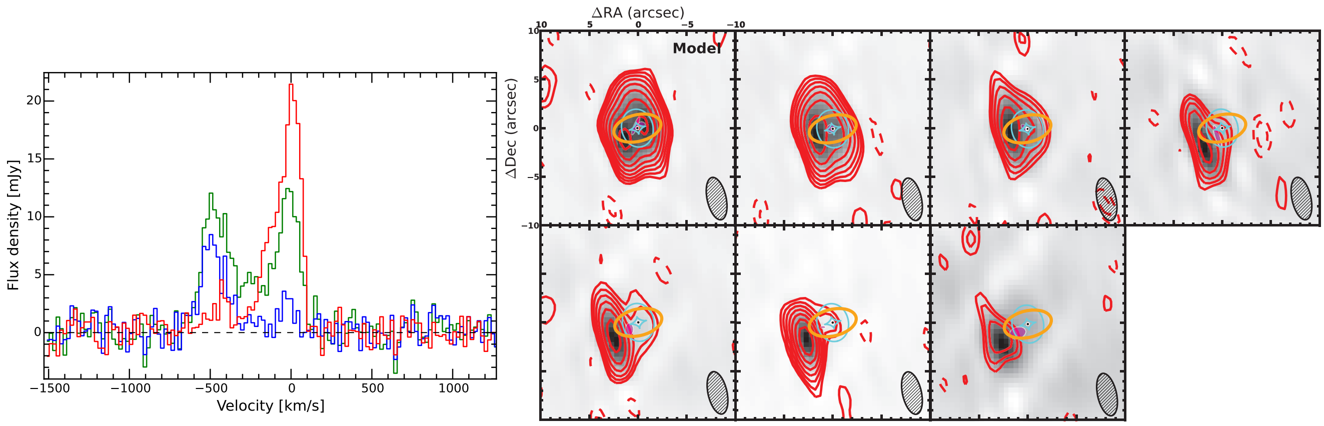

Figure 3: **Differential lensing with spatial variations and dynamical lens model** *Left:* Overlay of spectra taken at various spatial positions along the strongest velocity gradient, demonstrating differential lensing of the different kinematic components of the galaxy. Hence, higher resolution imaging of this source will allow us to probe the gas distribution. *Right:* Velocity channels of the CO emission toward the gas-rich merger (red contours) overlaid on our best-fit lens model (grayscale). Clearly, there are spatial variations across different kinematic components, which is likely due to differential lensing. The foreground lensing galaxy is represented by a black dot, and the beam size is shown in the bottom right corner. The velocity across the panels decreases from top left (red wing) to bottom right (blue wing), with $\Delta v \sim$100 km s^{-1}. The reconstructed source morphology (magenta ellipse) is suggestive of a kinematically ordered galaxy. However, at the spatial resolution of our data, we cannot definitively infer its true morphology due to beam smearing. Higher-resolution imaging is needed to unambiguously determine the nature that gives rise to the observed velocity gradient. The proposal observations will confirm if the system is rotationally supported or highly turbulent (due to AGN or tidally disrupted if merging with the companion).

The CO emission shows an asymmetric double-horned line profile (Fig. 4), which indicates the effect of differential lensing and that the cool gas is spatially distributed (Fig. 3). Hence, our proposed observations will probe the spatial variations of the molecular gas. The 1st moment map (Fig. 2) and the velocity gradient across the source plane (Fig. 3) in our model suggests that our source is kinematically ordered (reminiscent of a rotating disk). Yet, the spatial resolution of this data is insufficient to infer the true kinematics due to beam smearing. Besides, an unusually high velocity dispersion $\gtrsim$400km s^{-1} at the central region(Fig. 2) hint 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. Higher-resolution imaging is absolutely necessary to to unambiguously determine the nature that gives rise to the observed velocity gradient and confirm if the galaxy is disk-like but disrupted or merging and whether it is dominated by internal random motions (in addition to large-scale orbital velocity, if confirmed to be disk-like in 1st moment map) to distinguish the major mechanism driving the starburst: merger-driven versus gas-rich clumpy disk, which show similar velocity profile in low-resolution data.

We also aim to spatially separate/resolve the kinematic signatures of the gas clumps in the AGN host galaxy to probe the kinematical and dynamical state of the gas, and how the gas distribution is affected. At the proposed resolutions, we will also obtain a better-constrained dynamical lens model and be able to probe the gas in the kinematically related companion and its internal dynamics. The proposed observations will also highly complementary to optical image, allowing a comparison between the gas and stellar distribution.

Physical properties and dense gas line ratio maps: Since the critical densities of HCN rotational transitions are $\sim$5 times higher than HCO^+, they trace different gas phases. The line fluxes and spatially resolved line ratio maps will thus enable us to constrain the density and temperature of the molecular gas around the AGN, its star-forming host galaxy, and in its companion, providing perceptive clues to how these activities and galaxy interactions alter the chemical composition of the ISM/ISM chemistry (e.g. HCN and HCO^+ enhancements in different regions), and thus the evolution these ubiquitous dusty mergers. Due to the difference in abundances and excitation conditions of these molecules, HCN(J=4$\rightarrow$3)/HCO^+(J=4$\rightarrow$3) can be used to separate activities/emission originating from AGN or starburst (Imanishi et al. 2010; Izumi et al. 2013), which sheds light on AGN and star-formation feedbacks and clues to interpret the evolutionary stage of the galaxy (Baan+08).

Excitation conditions: The line ratio ^{12}CO (low-J)/HCN probes the dense gas fraction, abundance, and excitation. Thus, we will map out the spatial variations and gradients in the physical conditions of the gas within the galaxies, providing extra constraints on the star-formation activity.

We will combine these data [tracing the excited emission] with our existing lower-J CO data to diagnose the excitation conditions and the heating source of the gas. [Since the high-density tracers probe the star-forming molecular dense gas regions and the low-density tracers probe the relatively unperturbed larger-scale molecular environment.]

Star-formation Law: Our proposed observations will furnish data to carry comparative studies between the L_{IR}, SFR_{IR}, SFR_{UV}, surface densities of SFR, CO, HCN and HCO^+, providing stringent constraints on the relation between molecular gas and star-formation on sub-kpc scales and on the mechanisms driving the mammoth SFR at earlier epochs, giving rise to the observed stellar-assembly history.

Our proposed observations therefore provide an exceptional opportunity to investigate the physical properties and dynamical structures of different gas phases in the ISM of mergers and distant galaxies with exquisite details. These are vital to improve our current understanding on the star-formation processes at the cosmic epoch where the contribution of dusty, star-forming galaxies to the cosmic SFR density is steeply rising (Le Floc'h et al. 2005). This will also provide a benchmark in utilizing high-dipole moment molecules as routine tracers to study star-formation in relatively poorly-studied high-z populations and demonstrate the capabilities of ALMA in mapping these much fainter emission in distant galaxies. The proposed observations with our science target will therefore provide a giant leap on our understanding – putting high-z systems into the context of nearby studies and lay the groundwork to routinely perform such studies at higher redshifts in the ALMA full operations cycle in the near future.

Potential for publicity I will publish a paper on this if I get the data I need. SOME TEXT The proposed observations will serve as a demonstrative case of the dense, excited gas in high-z galaxies at high resolution. high potential for publicity.

References • **Brewer et al. 2008,** MNRAS, **390, 39** • **Claeskens et al. 2006,** A&A, **451, 865** • **Costagliola et al. 2011,** A&A, **528, A30** • **Gao et al. 2007,** ApJ, **660, L93** • **Graciá-Carpio et al. 2006,** ApJ, **640, L135** • **Graciá-Carpio et al. 2008,** A&A, **479, 703** • **Imanishi et al. 2010,** PASJ, **62, 201** • **Izumi et al. 2013,** PASJ, **65** • **Kohno, K. 2005,** AIP Conf. Proc., **783, 203** • **Krumholz et al. 2005,** ApJ, **630, 250** • **Le Floc'h et al. 2005,** ApJ, **632, 169** • **Papadopoulos, P. P. 2007,** ApJ, **656, 792** • **Rangwala et al. 2015,** ApJ, **806, 17** • **Riechers et al. 2007,** ApJ, **671, L13** • **Riechers et al. 2006,** ApJ, **645, L13** • **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** • **Wagg et al. 2005,** ApJ, **634, L13** • **Wu et al. 2005,** ApJ, **635, L173**

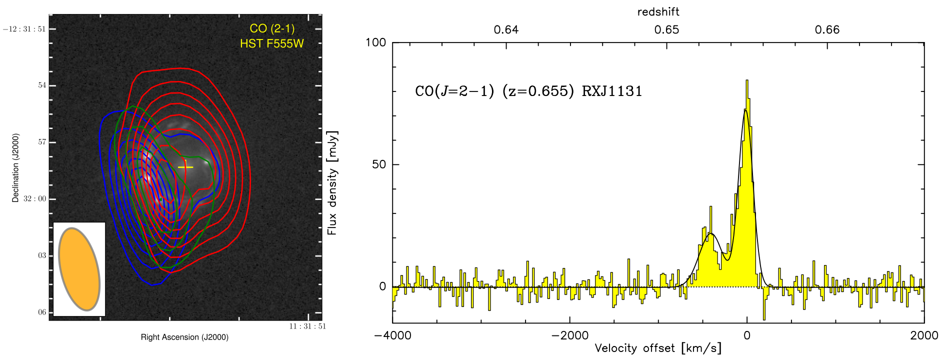

Figure 4: **Detection of a gas-rich merger with spatial variations traced by CO(J=2→1)** *Left:* The (red, green, blue) contours correspond to the velocity-integrated line flux of different velocity channels (red wing, line center, blue wing) in our CO(J=2→1) data. Strikingly, the spatially-resolved molecular gas emission shows a different lensing configuration than in the optical. The counter-arc structure as shown by the red wing and its redshift (see right) is evident of a gas-rich source. This companion galaxy is consistent with the dusty source discovered with *Herschel*, which is faint in the optical as expected (the white component in Fig. 1). *Right:* The continuum-subtracted spectrum shows a double-horned profile, where the red wing is significantly brighter. Our lens modelling suggests that this arises due to differential lensing across the kinematic components of the source. Our proposed observations will allow us to investigate the fuel and mechanisms responsible for the intense star-formation in the AGN host galaxy. We here aim to spatially and dynamically resolve the dense, excited gas emission, which will allow us to unambiguously examine the dynamic structure of the ISM in the distant merger and provide observational constants on the star-formation and stellar-assembly history at the epoch where the SFR density is steeply rising across cosmic times.