Cold Gas in High-z Galaxies: The CO Gas Excitation Ladder and the need for the ngVLA

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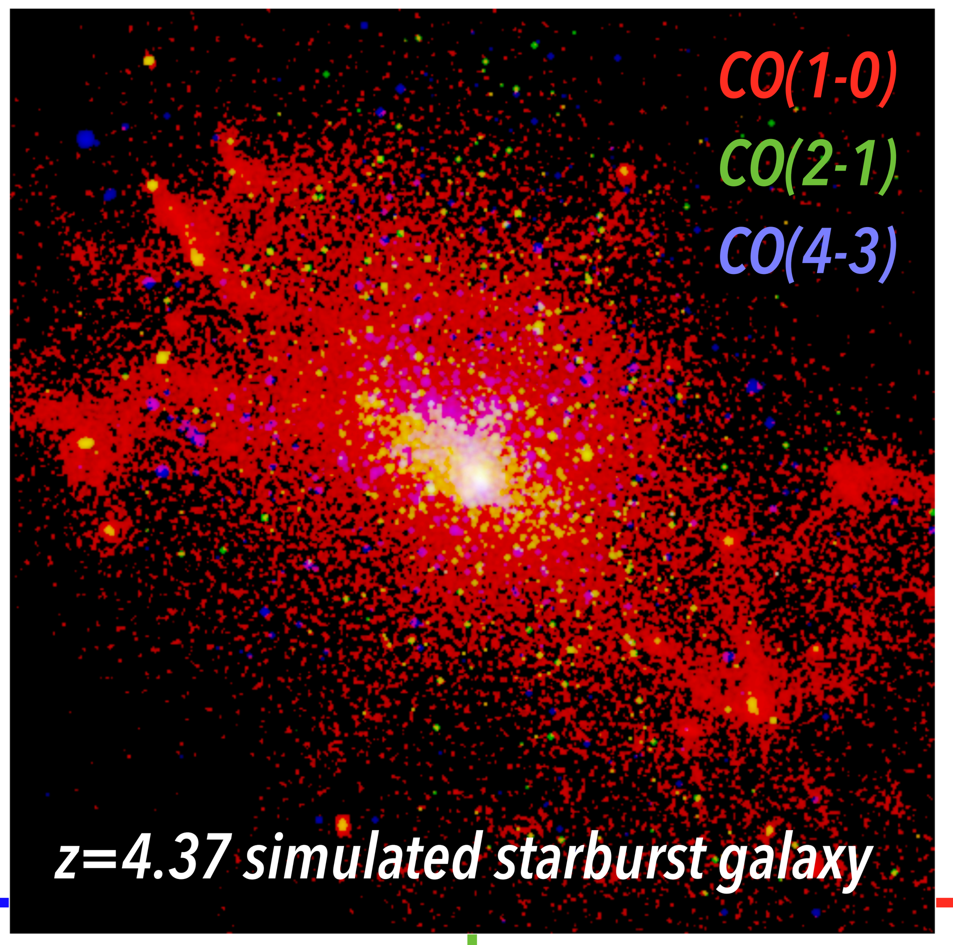
next generation VLA Extragalactic Imaging

The next generation Very Large Array (ngVLA; Carilli et al. 2015) will revolutionize our understanding of the distant Universe via the detection of cold molecular gas in the first galaxies (Casey et al. 2015). Its impact on studies of galaxy characterization via detailed gas dynamics will provide crucial insight on dominant physical drivers for star-formation in high redshift galaxies, including the exchange of gas from scales of the circumgalactic medium down to resolved clouds on mass scales of ~10^5 M . Based on a direct comparison between the inferred results from our mock observations and the cosmological simulations, we investigate the capabilities of ngVLA to constrain the mode of star formation, dynamical mass, and molecular gas kinematics in individual high-redshift galaxies using cold gas tracers like CO(1-0) and CO(2-1) in comparison to commonly-observed high-J CO tracers like CO(4-3). The factor of 100 times improvement in mapping speed for the ngVLA beyond the Jansky VLA and the proposed ALMA Band 1 will make these detailed, high-resolution imaging and kinematic studies routine at z=2 and beyond.

What is the relative role of major mergers versus secular disk evolution to galaxies in the early Universe? This question applies not only to the most massive, dust-obscured starbursts (e.g. Narayanan et al., 2010; Davé et al., 2010; Hayward et al., 2012), but also to the general mass assembly of galaxies at z > 1 (e.g. Förster Schreiber et al., 2009; Dekel et al., 2009), when half of the stellar mass in galaxies was assembled. While the JVLA can already spatially resolve emission on scales as small as 0.05′′ (equivalent to ~400pc at a redshift of z~1), it lacks the surface brightness sensitivity to use this capability on the faint, extended gas reservoirs in even the most CO-luminous high-redshift galaxies.

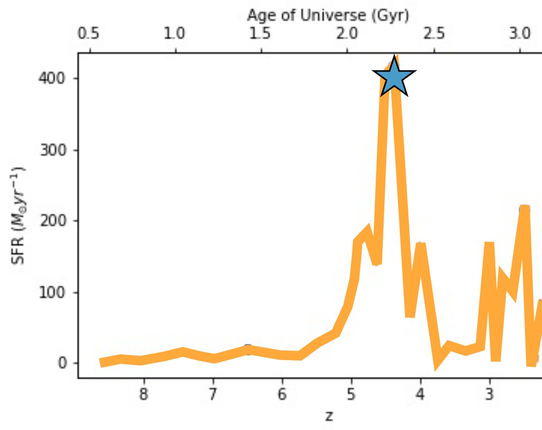
The ngVLA will provide this sensitivity.



Hydrodynamic Zoom Simulation of Gas in a High-z Galaxy

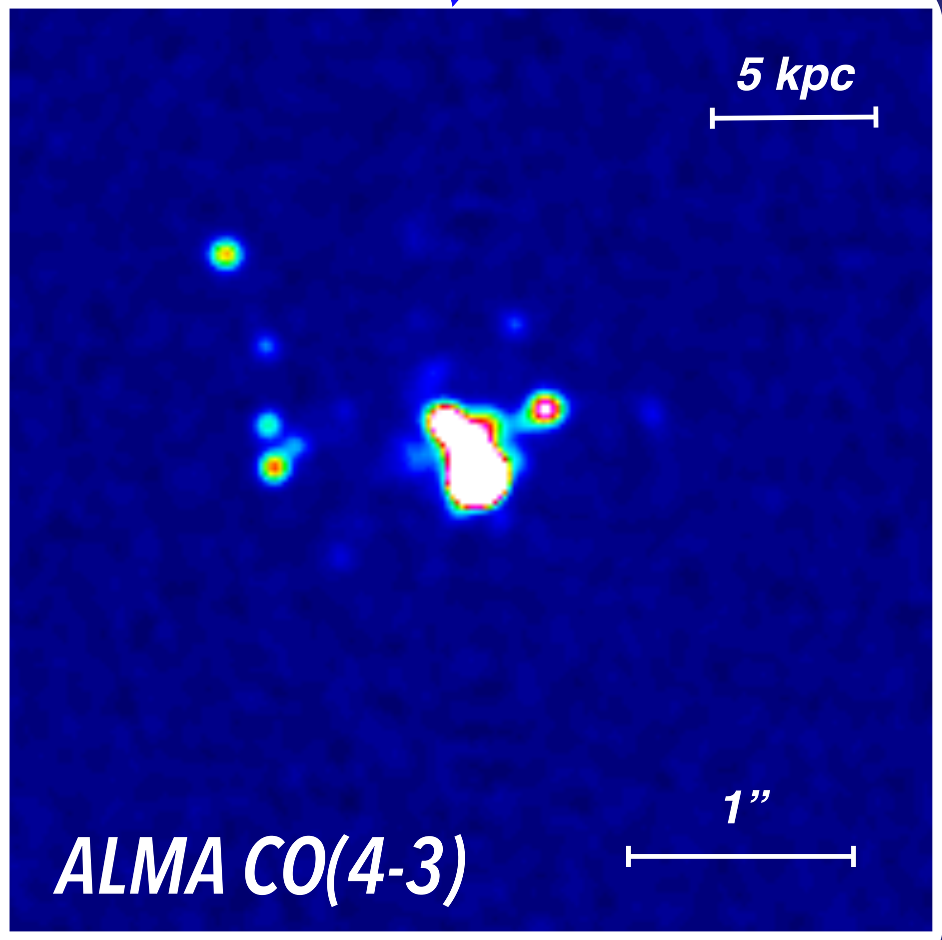
We employ a series of high-resolution, cosmological, hydrodynamic zoom simulations from the MUFASA simulation suite and a CASA simulator to generate mock ngVLA observations. Based on a direct comparison between the inferred results from our mock observations and the cosmological simulations, we investigate the capabilities of ngVLA to constrain the mode of star formation, dynamical mass, and molecular gas kinematics in individual high-redshift galaxies using cold gas tracers like CO(1-0) and CO(2-1). Using the Despotic radiative transfer code that encompasses simultaneous thermal and statistical equilibrium in calculating the molecular and atomic level populations, we generate parallel mock observations of high-J transitions of CO and C+ from ALMA for comparison.

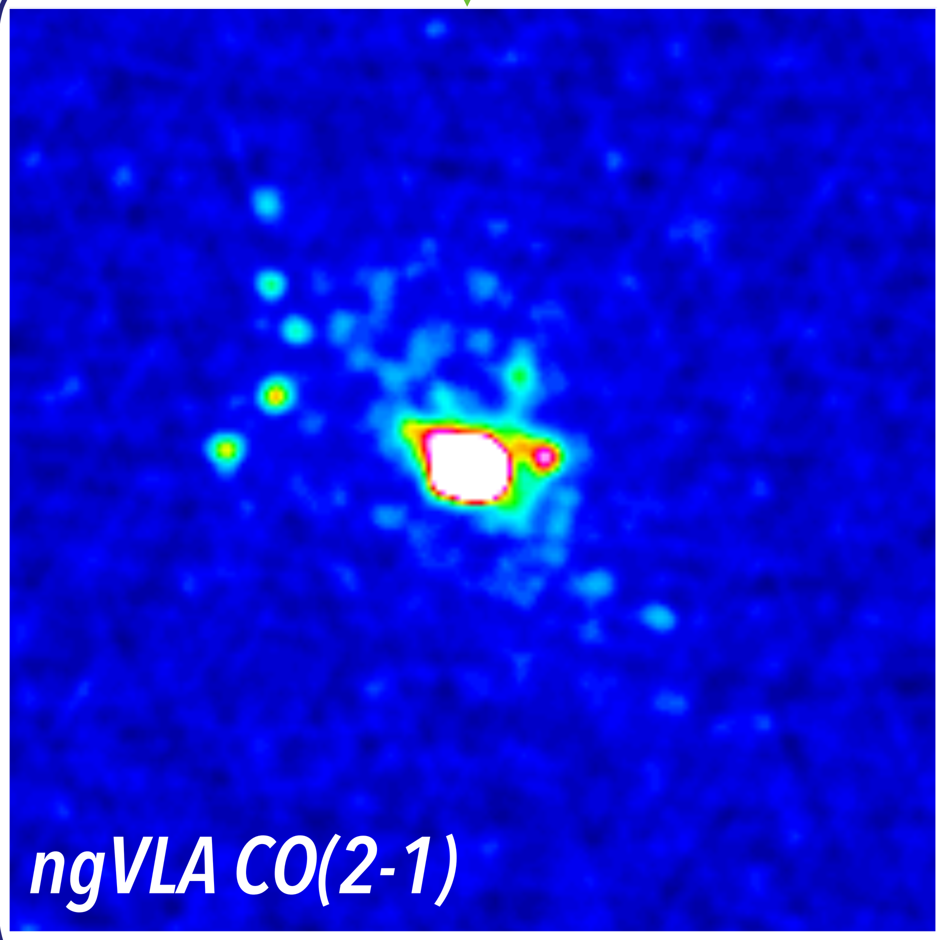
The image at left is a false-color snapshot of a zoom-in simulation for a z=4.37 starbursting galaxy (star-formation history at right). Emission in the ground-state of CO(1-0) gas is shown in red, while CO(2-1) is green and high-J CO(4-3) is shown in blue. The entire gas reservoir emits somewhat uniformly in CO(1-0), indicative of diffuse gas in the galaxy's interstellar and circumgalactic mediums, rendering this tri-color image largely red. When this snapshot is passed through a CASA simulator – mimicking sample observations of this galaxy with ALMA and the ngVLA – we see a stark difference between low-J and high-J tracers of molecular gas.

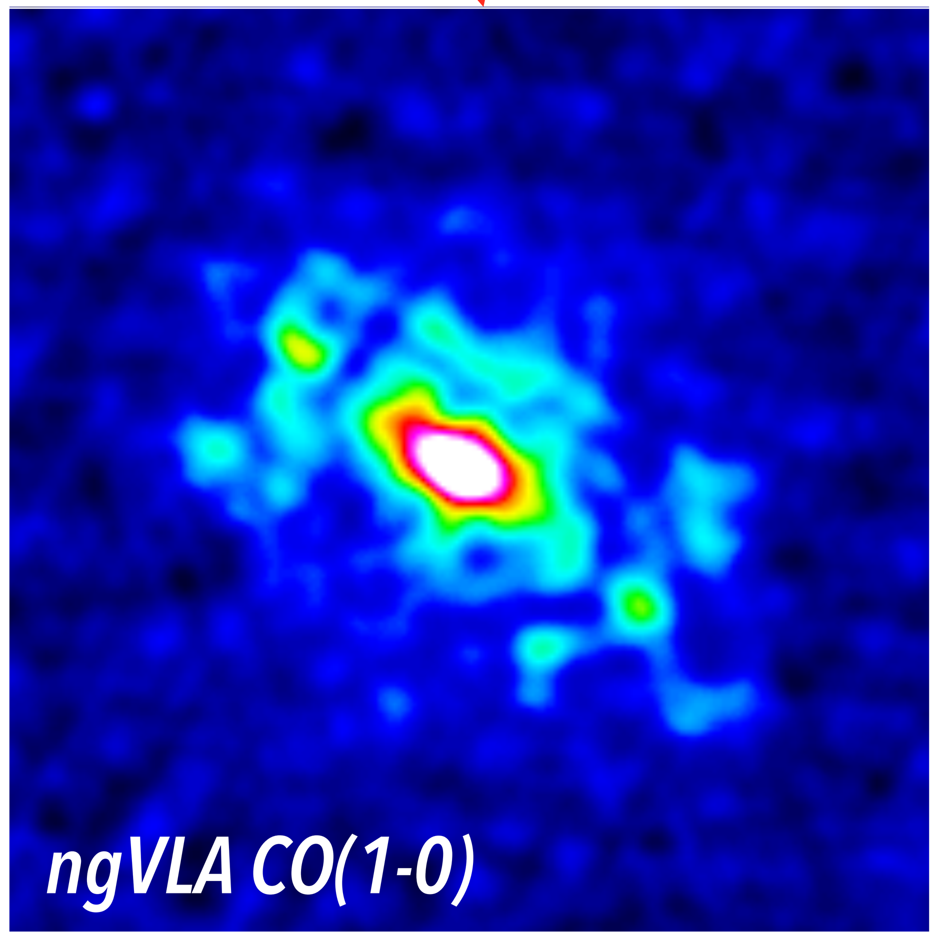


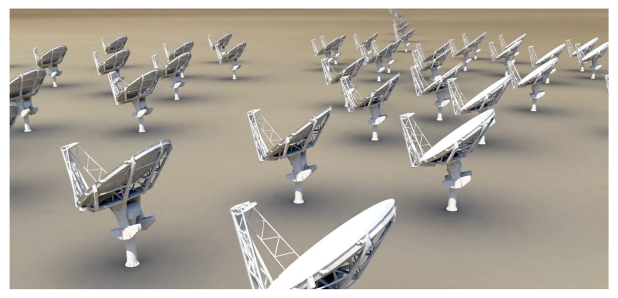
ALMA: traces highly-excited gas at early epochs

ALMA has now made it possible to routinely map molecular gas via high-J CO lines in high-redshift galaxies in less than an hour of on-source observing time. This insight is unmatched by previous facilities, but it is still fundamentally limiting, because highly-excited gas does not necessarily trace the underlying mass of cold, star-forming H_2 gas in a galaxy well (and it suffers from uncertainties in unknown excitation, as well as the CO-to-H_2 conversion factor).









ngVLA: probes ground-state cold gas reservoirs

Because much of the gas in the large scale environment is below the effective excitation conditions for dense gas tracers (even CO(3-2), or in this case CO(4-3), with ALMA), probing the environment of the most extreme star-formers in the Universe at high-redshift will **require observing the ground state CO transition**. Here it is clear that CO(1-0) emission extends well beyond what is visible in high-J tracers.

References / Acknowledgements

This work in progress has drawn substantially from the following references:
Carilli et al. (2015) NRAO ngVLA memo #5: arXiv/1510.06438
Casey et al. (2015) NRAO ngVLA memo #8: arXiv/1510.06411
Davé et al. (2010) MNRAS, 404, 1355
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Narayanan et al. (2010) MNRAS, 401, 1613
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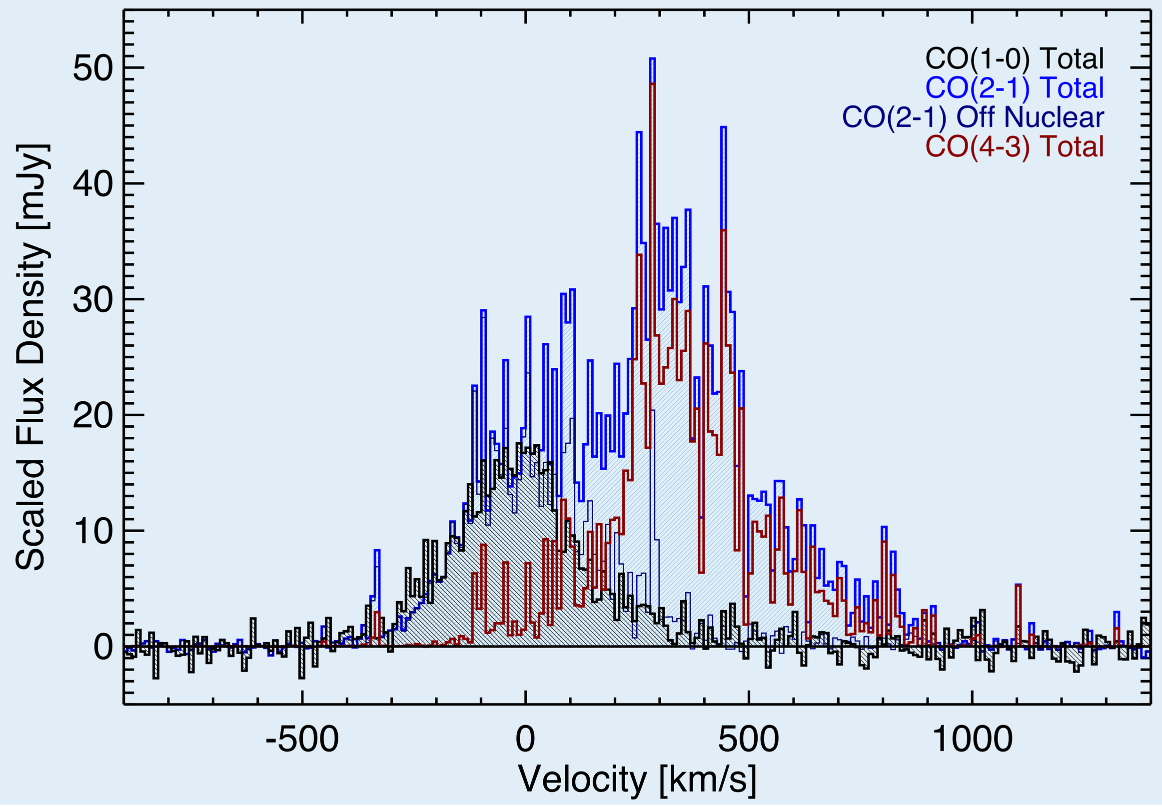
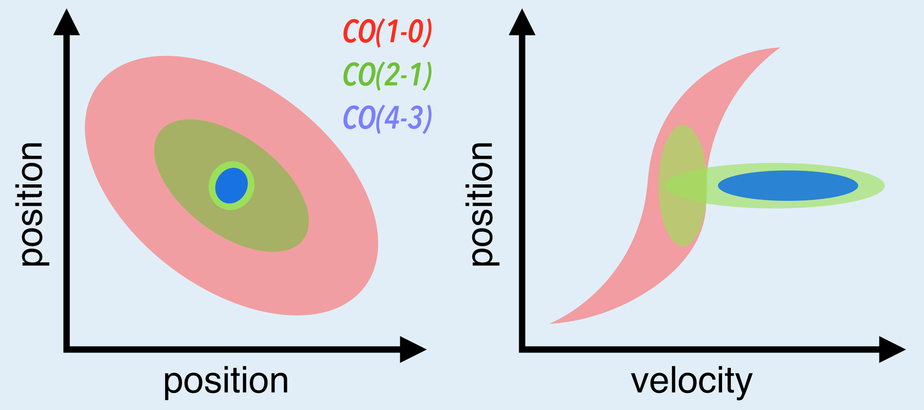


kinematically distinct gas reservoirs

In this particular case-study, the moment 0 line intensity maps shown above already highlight fundamental differences between different CO tracers in a high-z starbursting system. However, these differences are not isolated to the spatial extent of the gas. At left, we show the spectra for each of the three lines and highlight how they are also kinematically distinct. The ground-state transition of CO, extended ~13 kpc along the semi-major axis of the galaxy, is centered on 0 km/s with a 300 km/s FWHM. CO(2-1) exhibits a very different kinematic signature, comprised of two components – gas that is kinematically aligned with the CO(1-0) emission, and gas that is substantially offset at +350 km/s, as well as significantly brighter. Higher-J lines, like the ALMA-observed CO(4-3) traces _only_ this offset component, which is perfectly aligned with the galaxy's nucleus.

This has very important implications on deriving dynamical masses, inferring kinematics of galaxies, and measuring gas masses, depletion times, and star-formation efficiencies for galaxies at high-z, because the vast majority of high-z galaxies are and will be characterized by their high-J CO tracers, and not CO(1-0). This demonstrates a key need for the ngVLA: tracing the fundamental cold gas reservoir in high-z galaxies as a core focus of extragalactic astrophysics.



A cartoon depiction of the kinematic breakdown of our case-study starburst at z=4.37 shown above. CO(1-0) emission is extended spatially much more than the higher-J transitions. CO(1-0) is also kinematically distinct, exhibiting rotation on large scales, while CO(2-1) and CO(4-3) are much more sensitive to the dispersion-dominated galaxy nucleus.

ngvla

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