# Resolving Morphology Transformation in Massive Gas-Rich Galaxy Mergers:
## Imaging the Structures & Determining the Sources of Molecular Feeding & Feedback in Local (U)LIRGs

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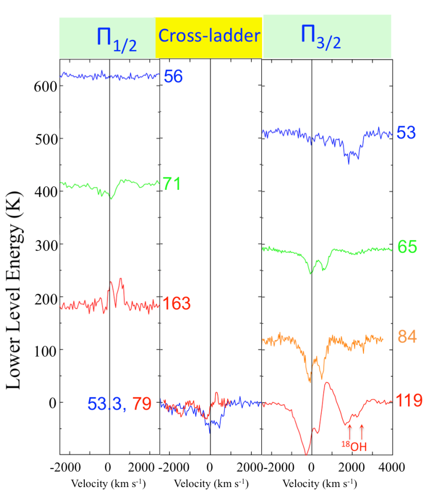
### Summary and Recommendations

One of the key questions in galaxy evolution studies involves the question of galaxy transformation during the merging of gas-rich galaxies, feedback processes, and termination of the prodigious star formation process that occurs during the early phases of the merger process. Cosmological surveys produce number counts of galaxies in this luminous stage of galaxy evolution, but a key part of the puzzle remains elusive: what are the key focussing and kinematic structures involved in the feedback process? Here we discuss the reasons that spatially resolved far-infrared spectroscopic studies of these structures in local mergers is a key and unique tool for characterizing and understanding this process. A space-based far-infrared interferometer with resolution of 0.02 arc seconds or better, across the far-infrared range, is needed for these observations.


**Herschel breakthroughs:** **One of the exciting results of the Herschel mission was the discovery of massive, high velocity (v ~ 1000 km/sec) molecular outflows in ultraluminous infrared galaxies (ULIRGs), [1], [2], [3], [4]. [5]. These outflows, powered by stellar processes or by AGN, are so far, best traced by radiatively pumped far–IR OH transitions and are observed in numerous far-infrared transitions as P–Cygni, absorption, or emission line profiles. Based on modeling of the lines and continuum, the OH observations imply short gas depletion times, mass loss rates at least several times higher than the star formation rates, and appear most powerful in AGN dominated ULIRGs. On the other hand, in the LIRG NGC 4418, the excited molecular lines do not show indications of outflow while the absorption in low-lying OH doublets and [O I] 63 $\mu$m line are redshifted, indicating inflow at a rate of ~ 12 $M_\odot$/yr [6].**

**Unanswered critical questions:** **These mergers of massive gas–rich galaxies have been caught in the act of dispersing their star–forming molecular fuel as they evolve toward becoming massive, gas–poor ellipticals [7]! Are the outflows driven by radio jets or radiation pressure due to a partially buried AGN or are compact super–starburst winds carving out a view to a previously hidden AGN?**

**Why is far-infrared spectroscopy critical?:** **Although these outflows have also been subsequently probed by collisionally excited emission lines of CO and other molecules with the IRAM Plateau de Bure Interferometer [8], [9] and will be studied with ALMA, far-IR transitions of species such as OH and $H_2O$ that are radiatively pumped and whose transitions thus appear as P-Cygni or pure absorption profiles have unique capabilities in that 1) they can differentiate between outflow and inflow because of the high far-IR continuum optical depth and 2) they probe more compact regions of the outflows, where the radiation density is high. With lines throughout the FIR at varying lower level energies (see examples of OH and $H_2O$ in the ULIRG Mrk 231 below), profiles of these species can constrain the outflow and focussing morphological and kinematic structures.**




OH far-IR line profiles in Mrk 231
(wavelengths in microns are indicated.
Rest velocity is marked for the blue component of the OH Λ doublets.)

### What measurement capabilities are needed?:

**Assuming spherical symmetry, modeling efforts have provided estimates of the sizes, outflow rates, and timescales of this morphology-changing feedback, but sensitive, high spatial resolution FIR imaging of these nuclear regions is necessary to determine the true geometry and driving sources of this critical stage of galaxy evolution. Based on modeling and some OH maser imaging (e.g. in Mrk 231), the extents of the thick disks / tori being dispersed by these outflows are of order 100 pc [10], [5], [6], or about 0.06 arc seconds at a distance of about 300 Mpc, which includes the local ULIRGs in the Revised Bright Galaxy Sample [11]. Thus spatial resolution of order 0.02 arc seconds or better across the far-infrared range would isolate these structures and provide a unique probe of the geometry of these critical phases of galaxy evolution that can then be extrapolated to the large surveys that will be done to study them in the distant Universe.**


### References.

[1] Fischer, J. et al. (2010), *A&A*, 518, L41. [2] Sturm, E. et al. (2011), *ApJL*, 733, L16. [3] Veilleux, S. et al. (2013), *ApJ*, 776, 27. [4] Spoon, H. et al. (2013), *ApJ*, 775, 127. [5] González-Alfonso, E. et al. (2014), *A&A*, 561, A27. [6] González-Alfonso, E. et al. (2012), *A&A*, 541, A4. [7] Rothberg, B. et al. (2013), *ApJ*, 767, 72. [8] Cicone, C. et al. (2014), *A&A*, 562, A21. [9] Feruglio, C. et al. (2010), *A&A*, 518, L155. [10] Klöckner, H.-R., Baan, W. A., & Garrett, M. A., (2003), *Nature*, 421, 821. [11] Sanders, D. B. et al. (2003), *ApJ*, 126, 1607.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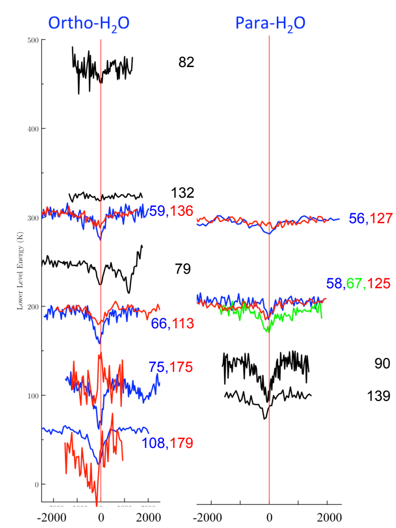


$H_2O$ far-IR line profiles in Mrk 231
Systemic velocities are thought to probe a disk or Torus, outflows are probed by the blueshifted wings.