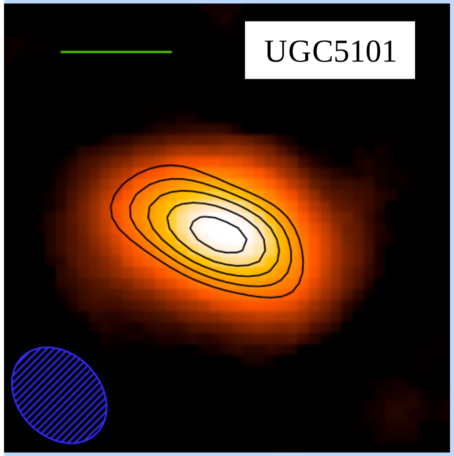
Luminous Infrared Galaxies with the Submillimeter Array: Probing the Extremes of Star Formation



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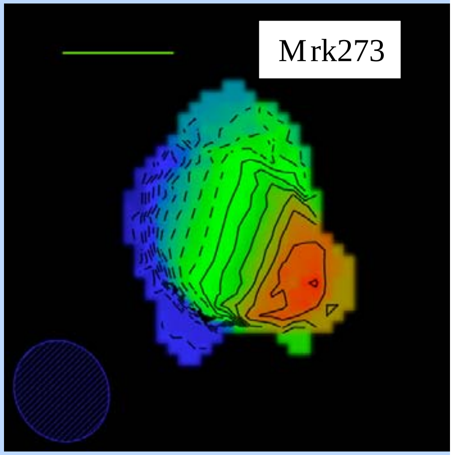

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Luminous Infrared Galaxies with the Submillimeter Array

1. What are Luminous Infrared Galaxies?
2. An SMA Legacy Project: Gas Morphology and Dynamics in U/LIRGs
3. First results: gas-to-dust ratio, comparison to high-redshift submillimeter galaxies
4. Future work and prospects

ULIRGS are galaxy mergers

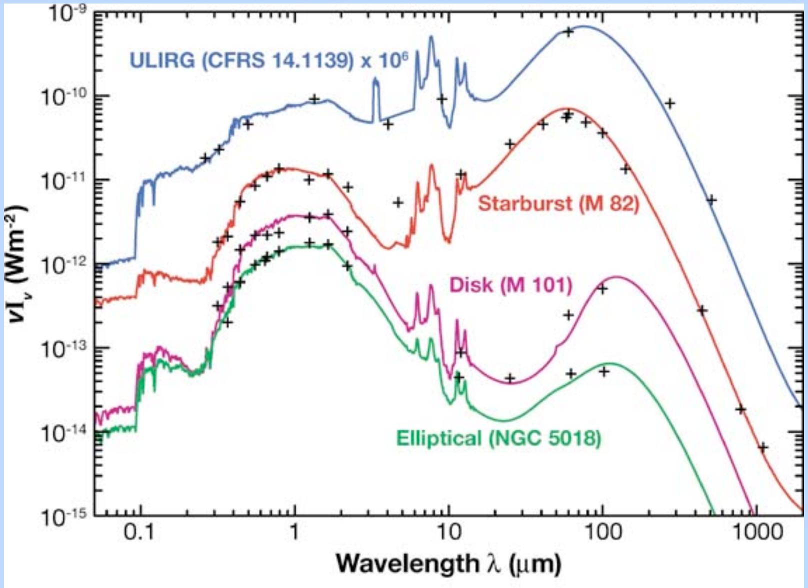
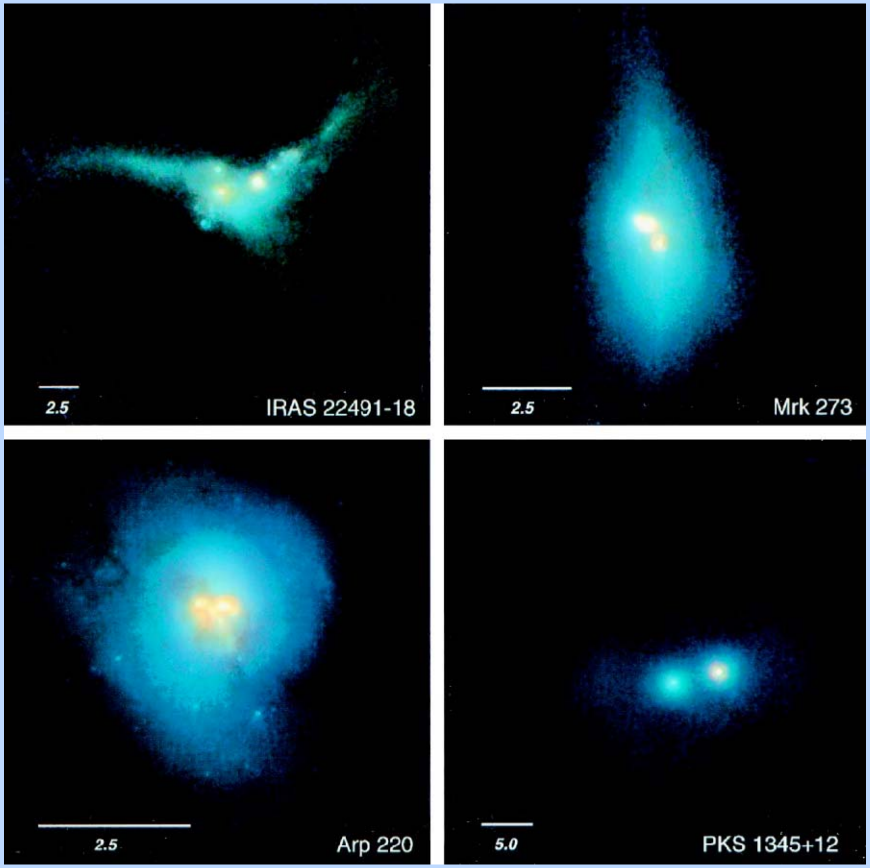


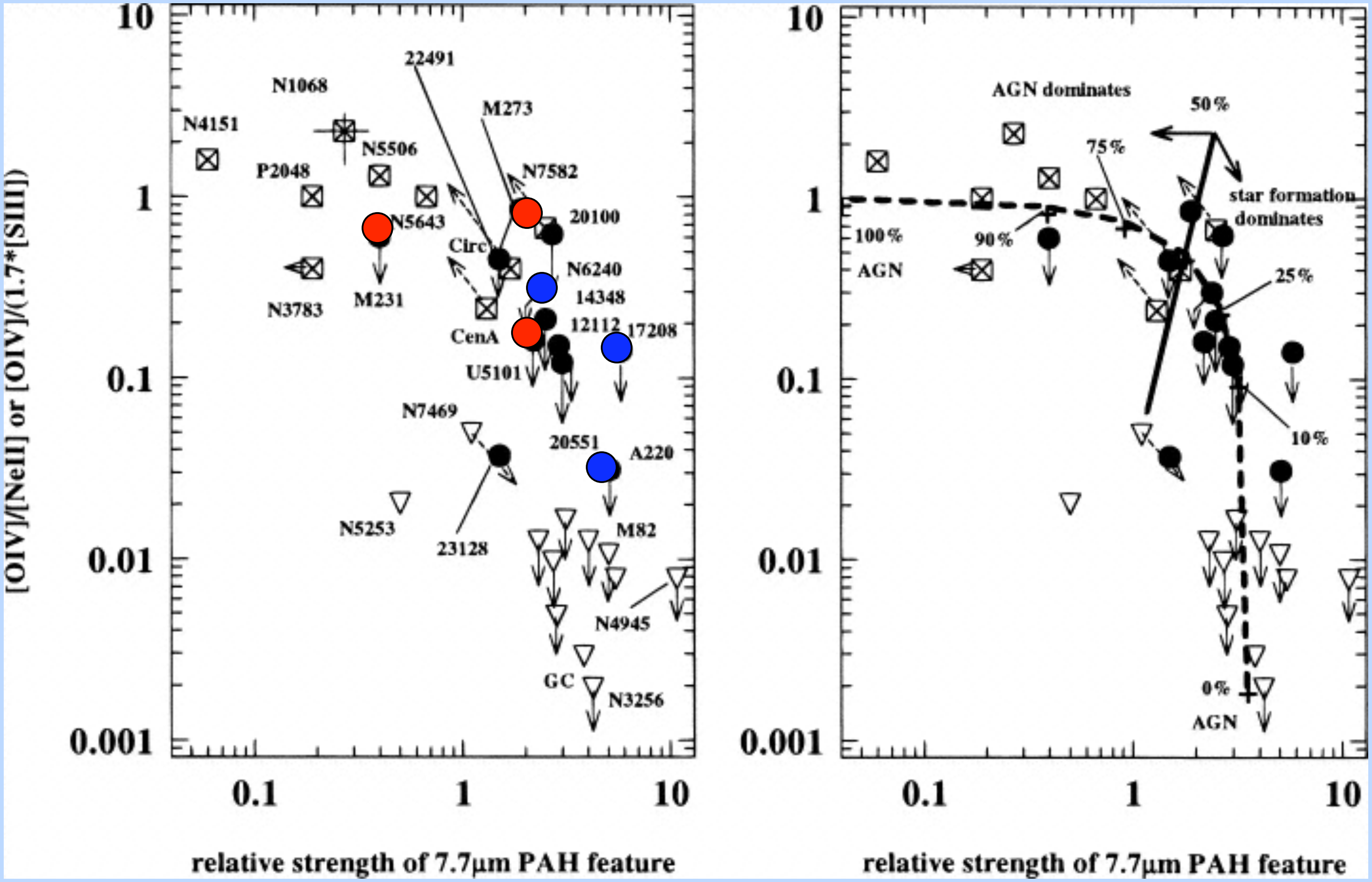
Figure from Galliano 2004



Scoville et al. 2000

All galaxies with $L_{FIR} > 5x10^{11}\ L_o$ are interacting or close pairs *(Sanders et al. 1987)*

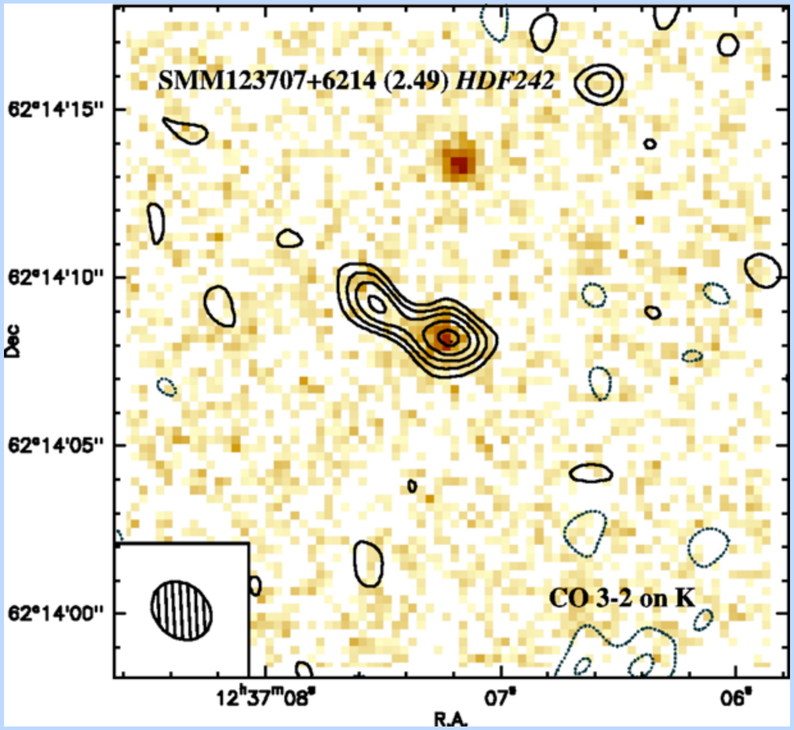
Luminosity Source: Starbursts and AGN



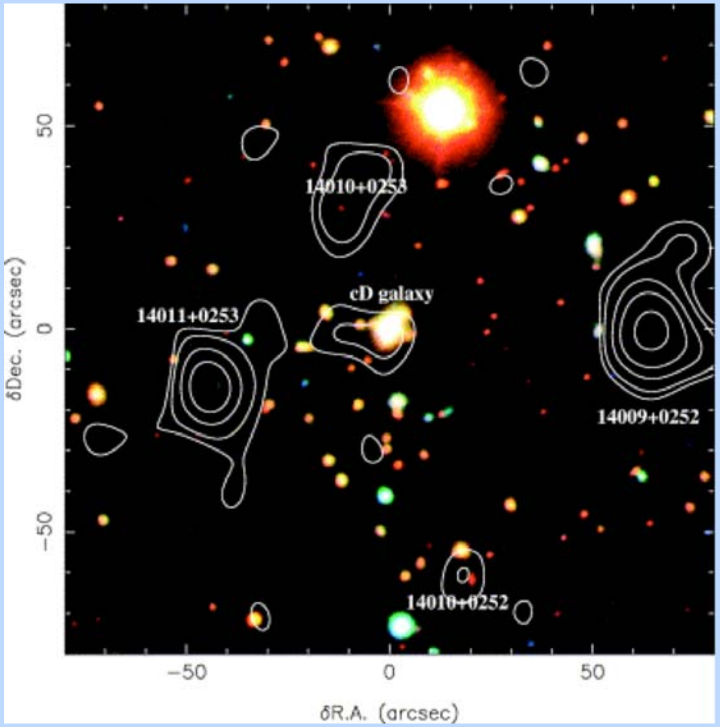
- 70-80% predominantly starbursts
- 20-30% predominantly AGN

Genzel et al. 1998

Dusty galaxies at high redshift: ULIRGs on steroids?



Tacconi et al. 2006



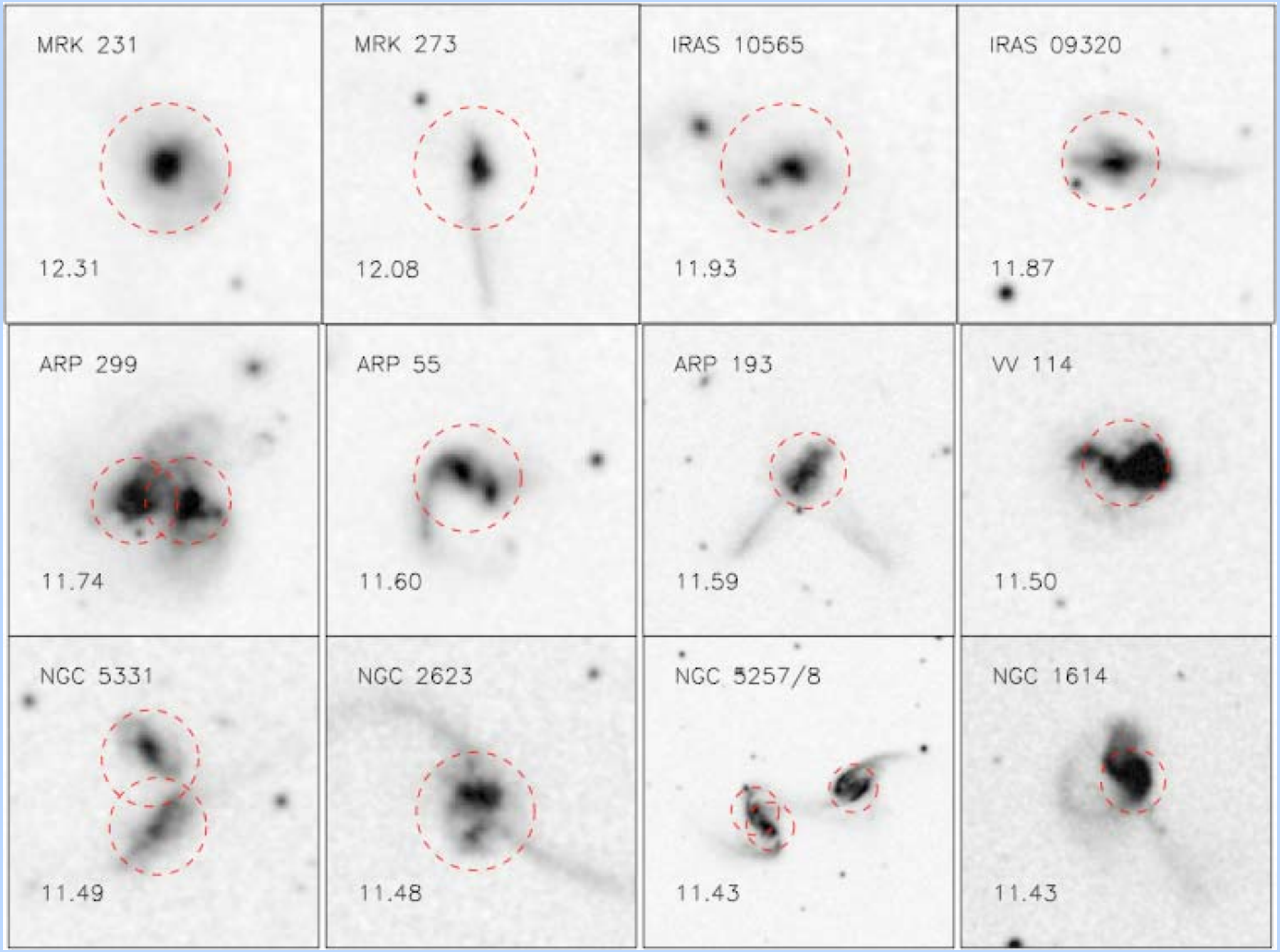
Ivison et al. 2000

- Cosmologically significant population of very luminous dusty galaxies discovered at submm wavelengths
- For z>0.5, 5 mJy at 850 μm implies L > 8×10^{12} L_o

Gas Morphology and Dynamics in Luminous Infrared Galaxies: An SMA Legacy Project

- Representative sample of 14 luminous and ultraluminous infrared galaxies
- D_L < 200 Mpc   (resolution ~ 1 kpc)
- $\log(L_{FIR}) > 11.4$
- All with previous interferometric observations in the CO J=1-0 line

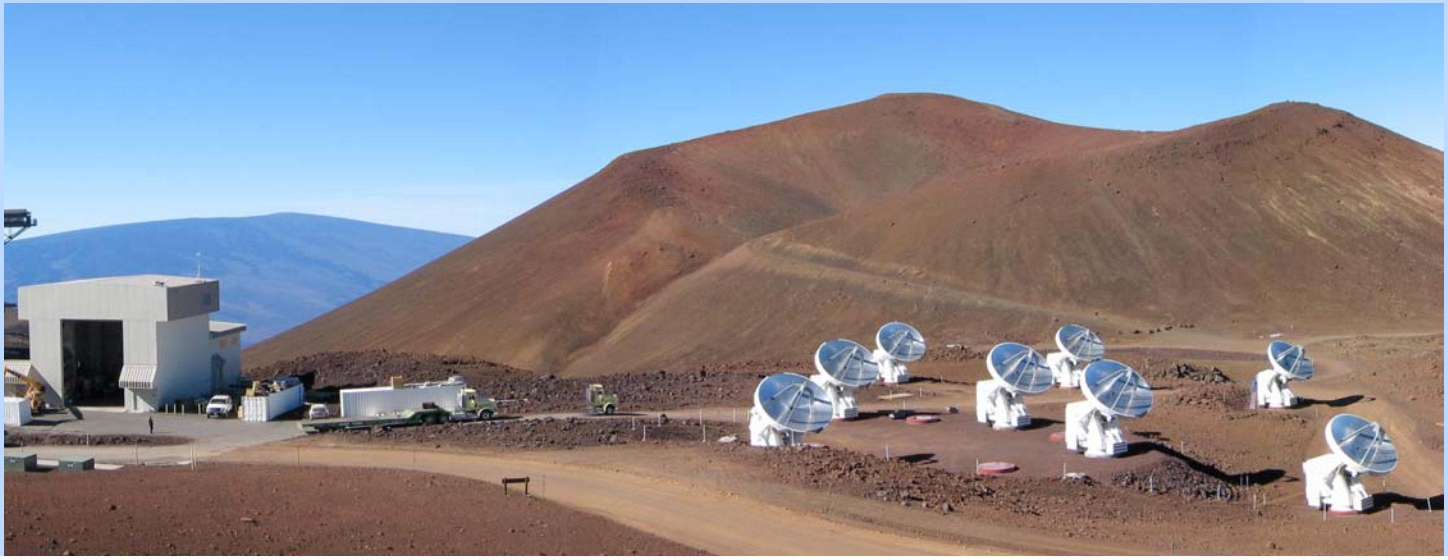
The Nearby Luminous Infrared Galaxy Sample



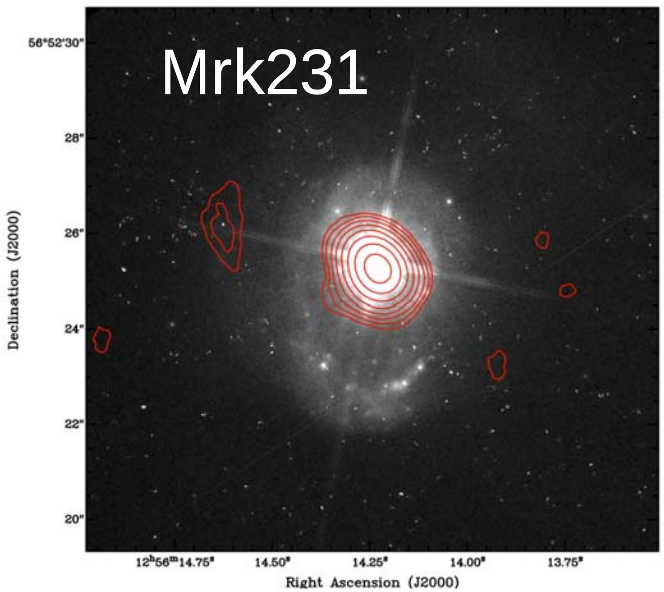
(IRAS17208-0014, NGC6240 not shown)

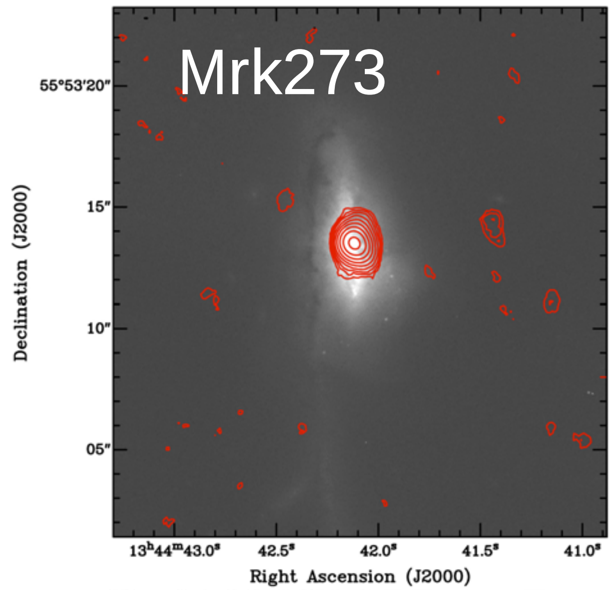
Science Goals of the Survey

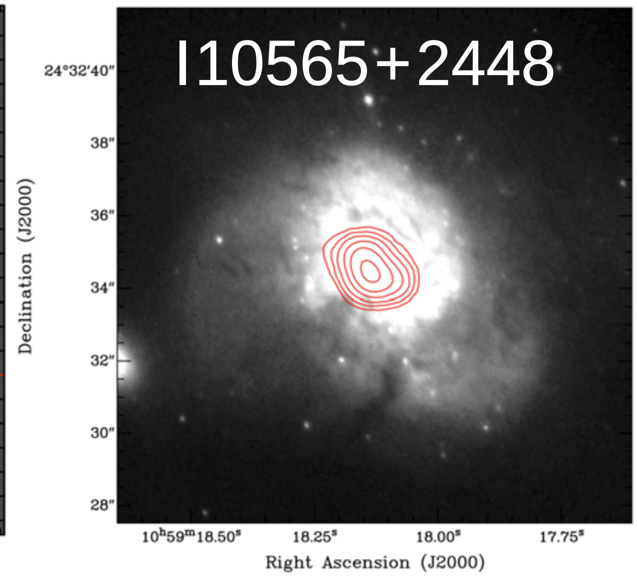
- Determine the distributions, kinematics, and physical conditions of dense molecular gas in U/LIRGs
- Determine the spatial distribution of dust in U/LIRGs
- Constrain the origin of nuclear OH megamasers
- Determine how the gas properties change as the interaction progresses
- Compare the properties of the dense gas in local ULIRGs with the high-redshift submillimeter sources

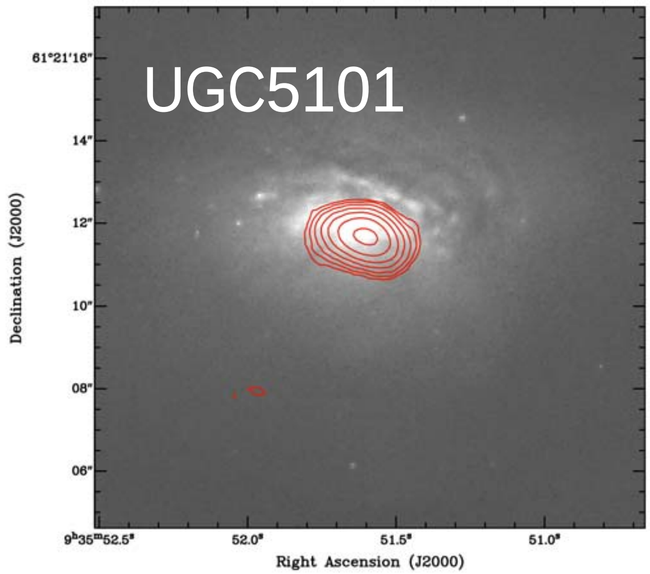


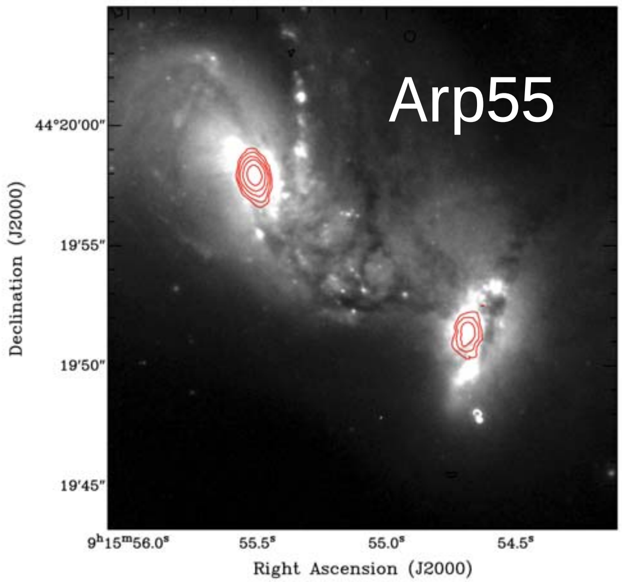
Centrally compact CO 3-2 emission





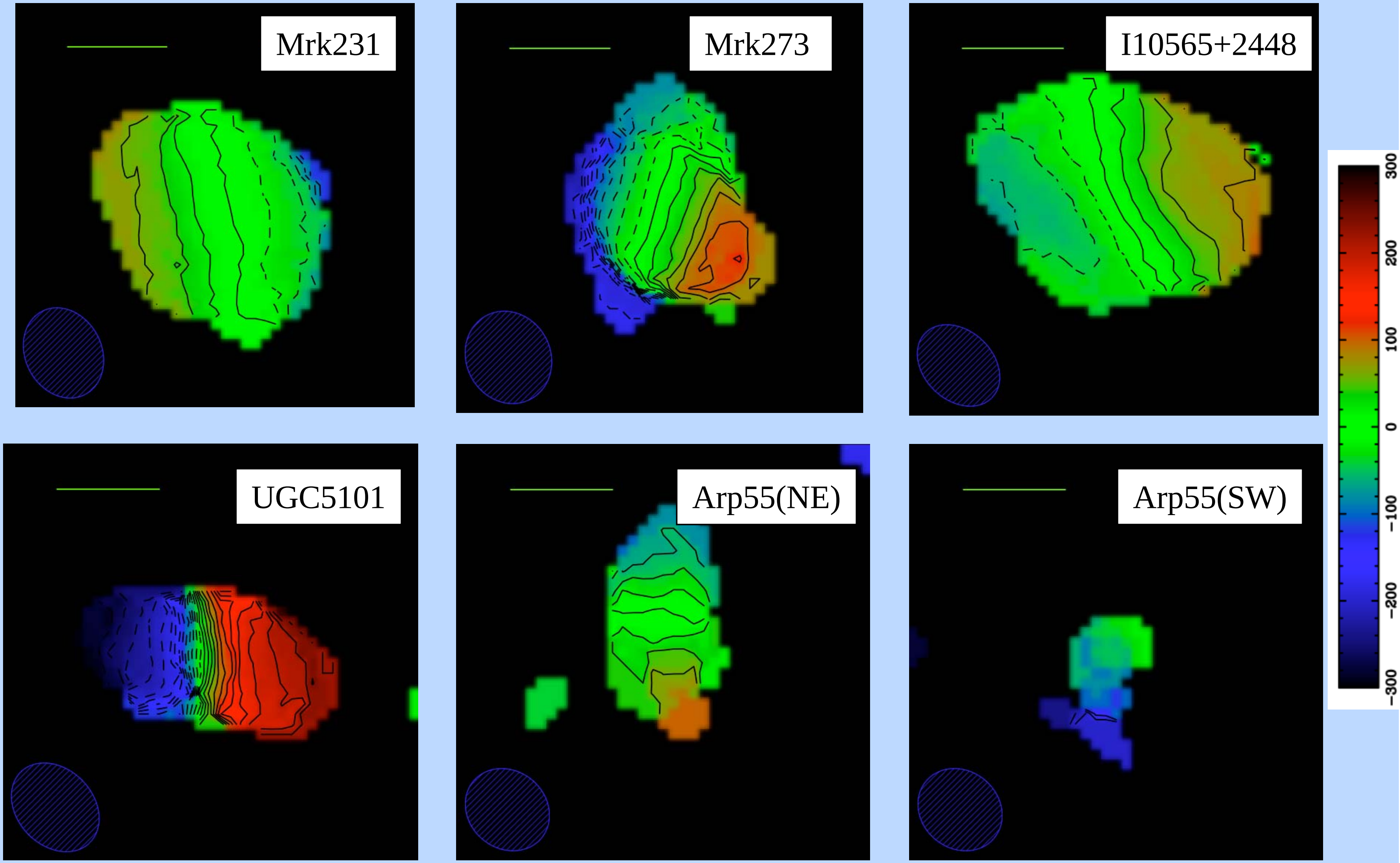




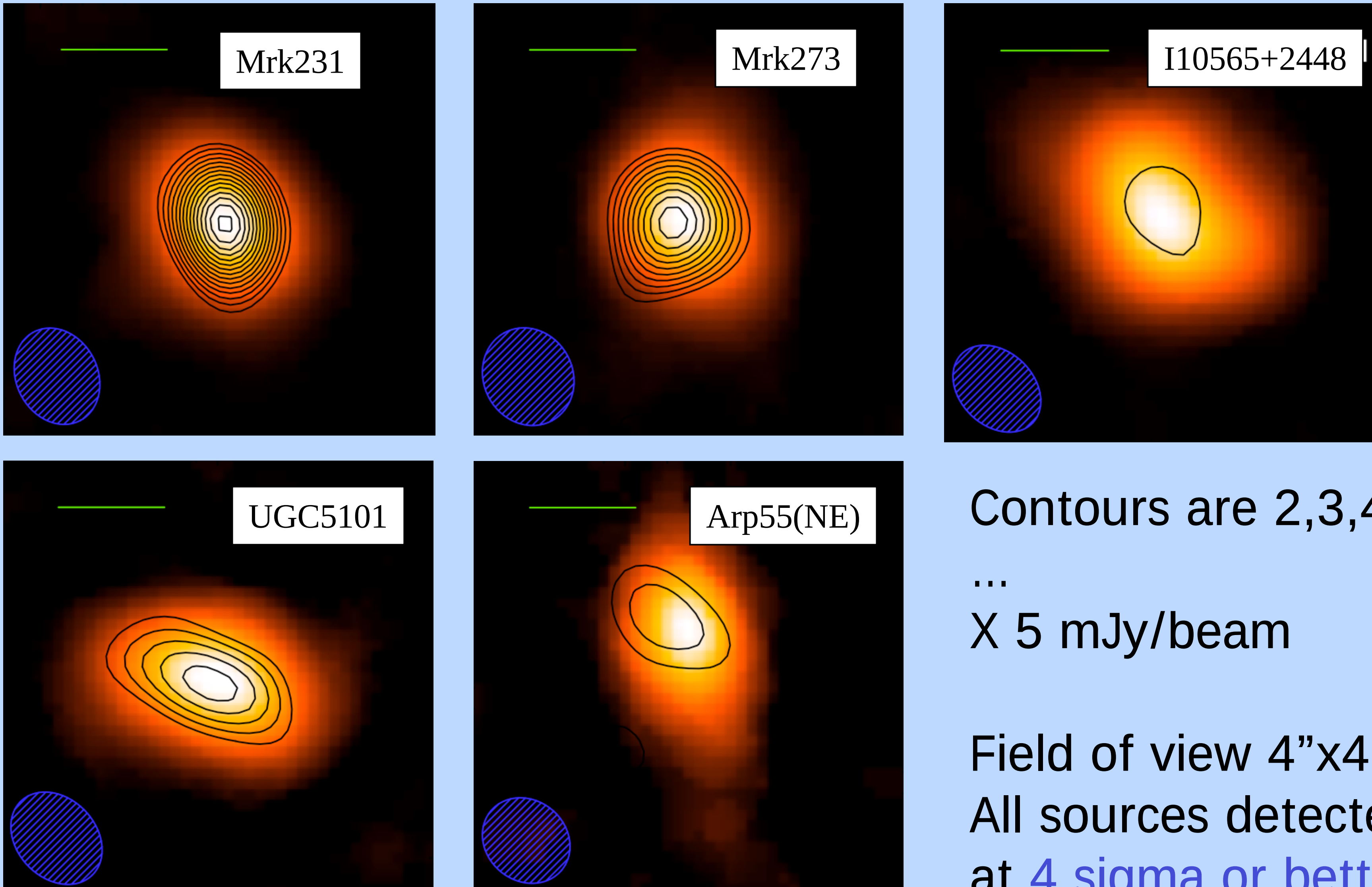


(HST images of Arp55 and I10565+2448 from Evans, Vavilkin, et al., 2006, in prep.)

Velocity Fields within R<1 kpc



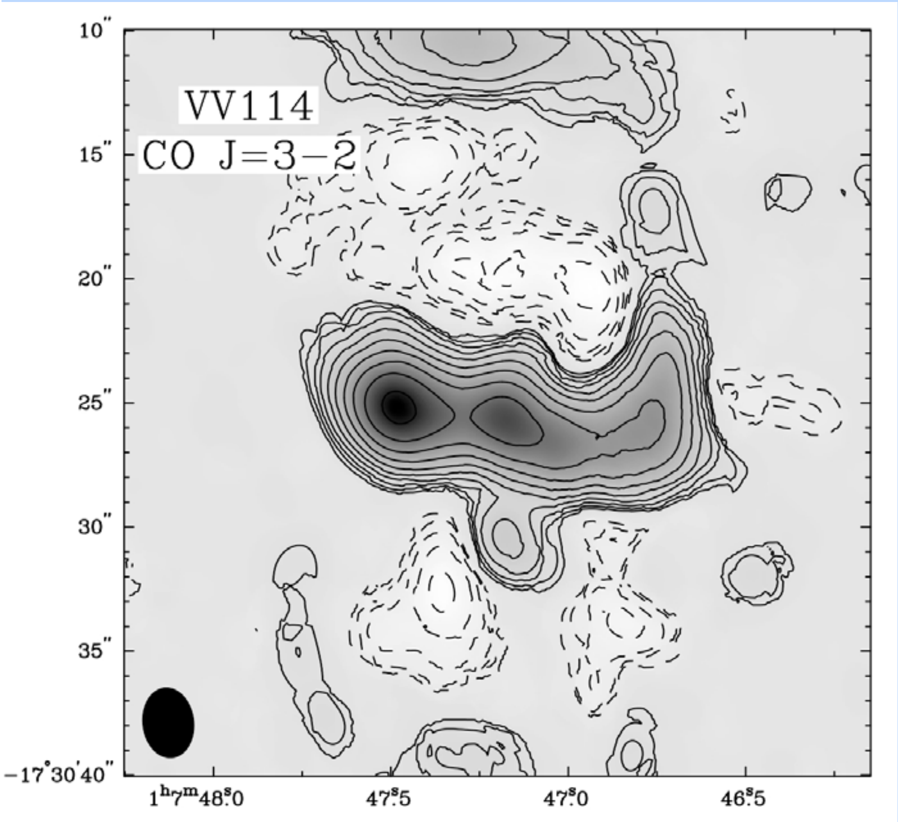
850 μm continuum overlaid on CO3-2

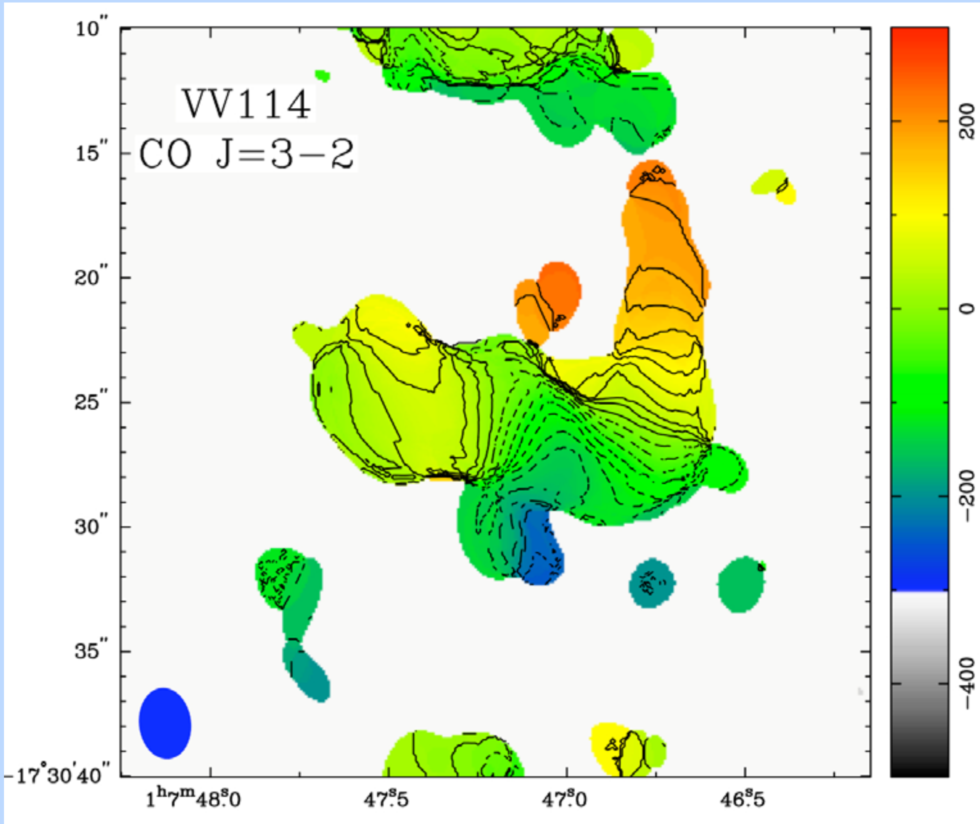


Contours are 2,3,4
...
X 5 mJy/beam

Field of view 4"x4".
All sources detected
at 4 sigma or better.

But some systems are very extended





- CO emission in VV114 shows three peaks spaced over 4 kpc (10")
- 5 out of 14 galaxies in our sample show two or more components

Now for some numbers ... and a caution

- Basic data reduction and measurements are complete
- I'm still working on calculating derived quantities, averages etc.
- So the exact numbers in the next few slides may not be correct (I calculated some of them this morning ...)
- Paper discussing these results should be submitted by the end of October ...

The Gas to Dust Mass Ratio

- M_{dust} assumes κ = 0.9 cm^2/g and T_{dust} from modified blackbody fit to global data from 60 to 800 μm (cf. Klaas et al. 2001)
- $M(H_2)$ = 0.8 L(CO1-0) (Downes & Solomon 1998); assume CO3-2/1-0=0.5 (our data)
- Calculate gas to dust ratio in central beam only (CO much more sensitive than continuum per unit mass)
- Average gas/dust ratio = 120 +/- 30
  - Standard deviation 109: significant scatter

Extremely high central gas surface densities

- Peak gas surface densities range from 10^3 to 10^4 M_o/pc^2 inside 0.5-1.2 kpc^2 area
  - 6×10^{22} - 6×10^{23} H_2/cm^2
  - A_V=70-700 mag
- Average volume density at peak range from 1 to 15 M_o/pc^3
  - n_H = 20 - 300 cm^{-3}
  - Estimated as (gas surface density) / (beam radius)
- Average volume density is comparable to a GMC, but volume is 10^3-10^6 times larger
  - 1 kpc versus 10-100 pc

Star formation rates and efficiencies

- $L_{IR}/M(H_2)$ ranges from 30 to 600 L_o/M_o
  - Total LIR divided by total SMA MH2 ...
- Log(L(IR))= 11.43 -12.41 implies star formation rates of 50 - 450 M_o/yr
  - Kennicutt 1998, ARAA
  - Caution: some L(IR) could be from AGN
- gas depletion times of $1x10^7$ to $2x10^8$ yr
  - Note naïve calculation, does not include possibility of gas recycling

Very high star formation rates and efficiences compared to normal galaxies or GMCs

ULIRGs at low and high redshift

Compare four brightest local galaxies with eight high-redshift galaxies; all in CO 3-2 *(Tacconi et al. 2006, Downes & Solomon 2003, Genzel et al. 2003, Weiss et al. 2003)*

Compared to local galaxies, high-redshift galaxies

- are at least an order of magnitude more luminous in CO 3-2
  - $L_{CO} = 3.5 \times 10^{10}$ versus 2.5×10^{9} K km/s pc^2
- have somewhat broader lines
  - 560+/-90 versus 370 +/-90 km/s
- have much larger FWHM diameters
  - 5 kpc versus 600 pc

ULIRGs at low and high redshift

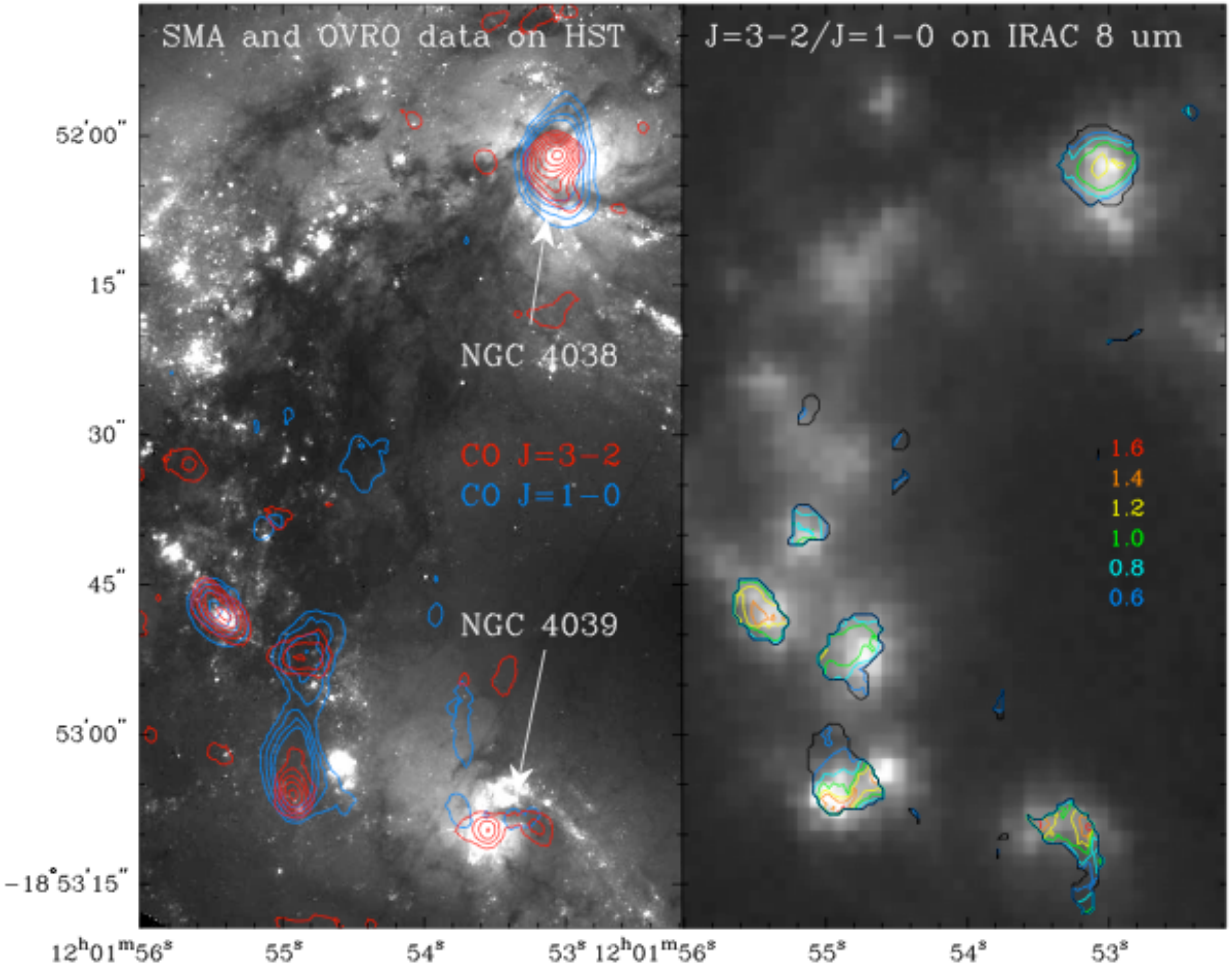
What if we look at our entire local sample?

Compared to local galaxies, high-redshift galaxies

- are at least an order of magnitude more luminous in CO 3-2
  - $L_{CO} = 3.5 \times 10^{10}$ versus 2.6×10^{9} K km/s pc^2
  - Note that average CO luminosity doesn't change much when include L(IR)-fainter galaxies

- Still have much larger FWHM diameters on average
  - 5 kpc versus 900 pc (9 galaxies)
  - 5 galaxies have two nuclei separated by 4-36 kpc
  - Compact galaxies span the full range of L(IR) in our sample, but extended galaxies tend to be at the fainter end

Further analysis: an example



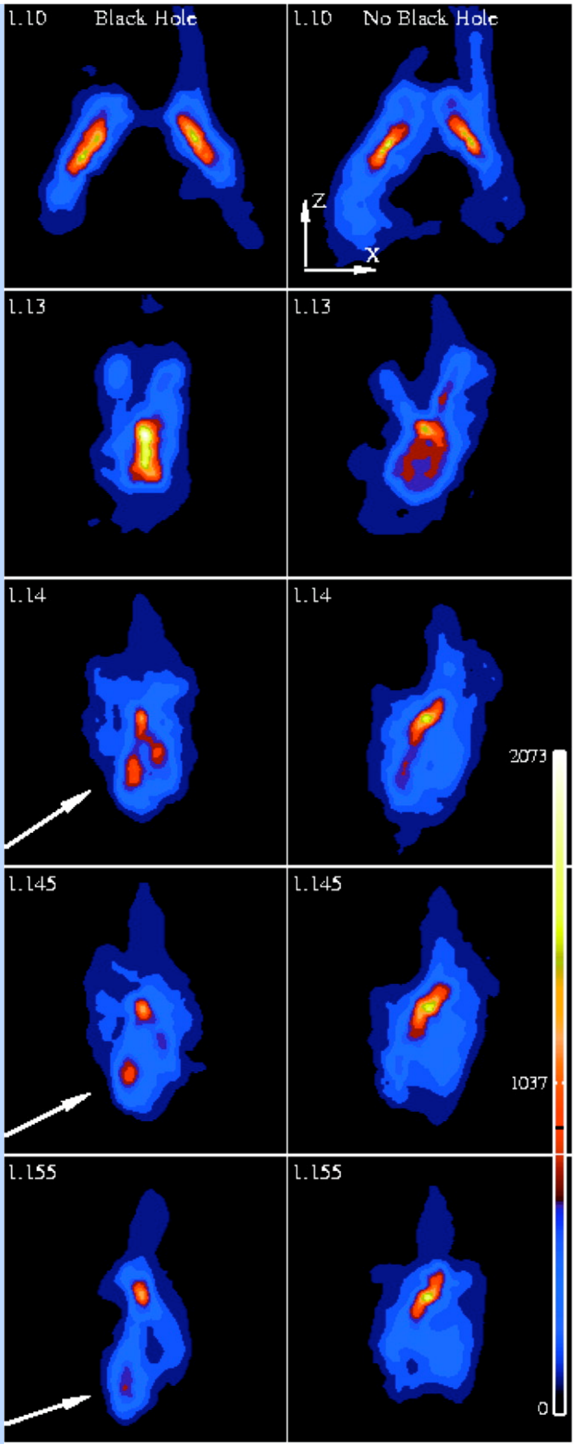
- Combine CO 3-2, 2-1, and 1-0, and ^{13}CO 2-1, to determine the physical properties of the molecular gas

SMA data: Petitpas et al. 2006   Spitzer image: Wang et al. 2004

Further analysis (cont.)

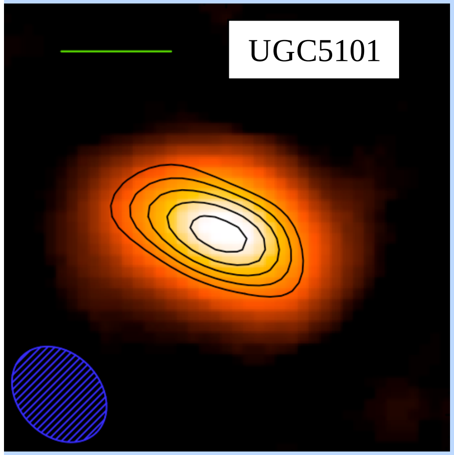
- Compare morphology and kinematics to numerical simulations to constrain merger age and establish a merger sequence
  - Correlate changes in gas physical properties with merger stage
  - Feed results on physical properties back into models to improve gas physics

Narayanan et al. 2006

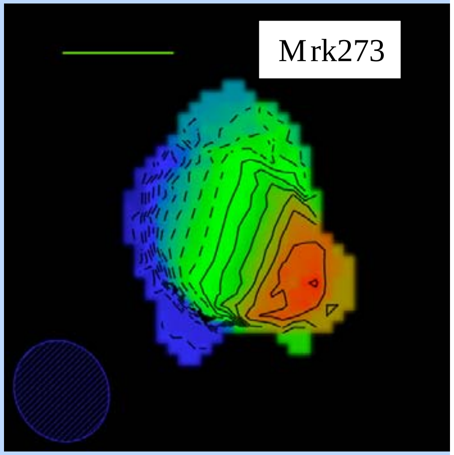


Conclusions

- A large survey of warm dense molecular gas in nearby luminous infrared galaxies shows
  - Gas masses of 1-5x10^9 M_o within central 1kpc
  - Gas to dust mass ratio very similar to Galaxy
  - Very high central gas surface densities and volume densities



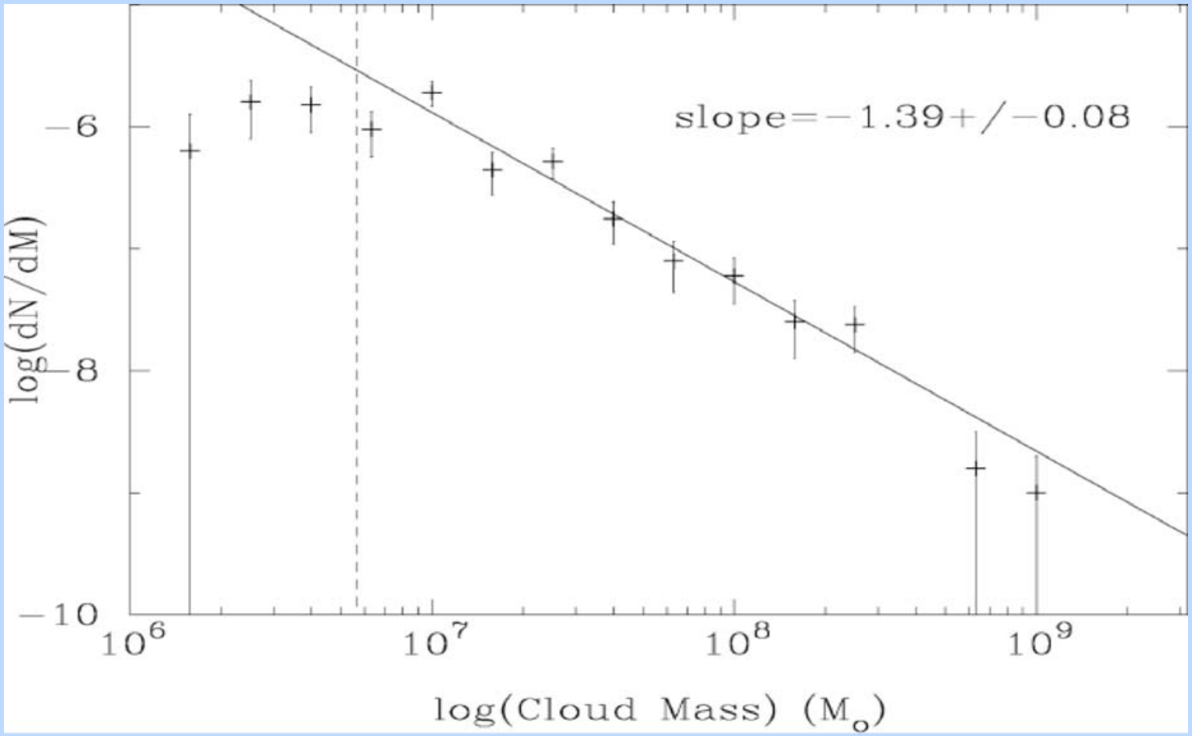
- Direct comparison of CO3-2 shows high-redshift submillimeter galaxies are more luminous and (perhaps) less centrally concentrated than local ULIRGs



The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

The end

ALMA: Mass Function of Super-Giant Molecular Complexes



SGMC mass function in the Antennae

Wilson et al. 2003

ALMA will let us study molecular clouds and complexes in galaxies out to 200 Mpc

- can reach masses as small as 5×10^6 M_o at 200 Mpc in just one hour (3 sigma)

The Gas to Dust Mass Ratio

Galaxy	M_{dust} (10^7 $M_\odot$)	M_{H_2} (10^9 $M_\odot$)	Gas/Dust Ratio
Mrk231	4.43	4.13	93
Mrk273	3.26	5.10	156
10565+2448	1.27	3.10	244
UGC5101	3.45	2.66	77
Arp55(NE)	1.79	1.18	66
Arp55(SW)	$<$0.75	0.65	$>$87

Average gas/dust ratio = 120 +/- 30

- M_{dust} assumes κ = 1 cm^2/g and T_{dust} from blackbody fit to IRAS 60 and 100 μm (Solomon et al. 1997)
- $M(H_2)$ = 0.8 L(CO1-0) (Downes & Solomon 1998); assume CO3-2/1-0=0.5 (our data)