

# Molecular Gas and the Host Galaxies of Infrared-Excess Quasi-Stellar Objects

A. S. Evans (Stony Brook)

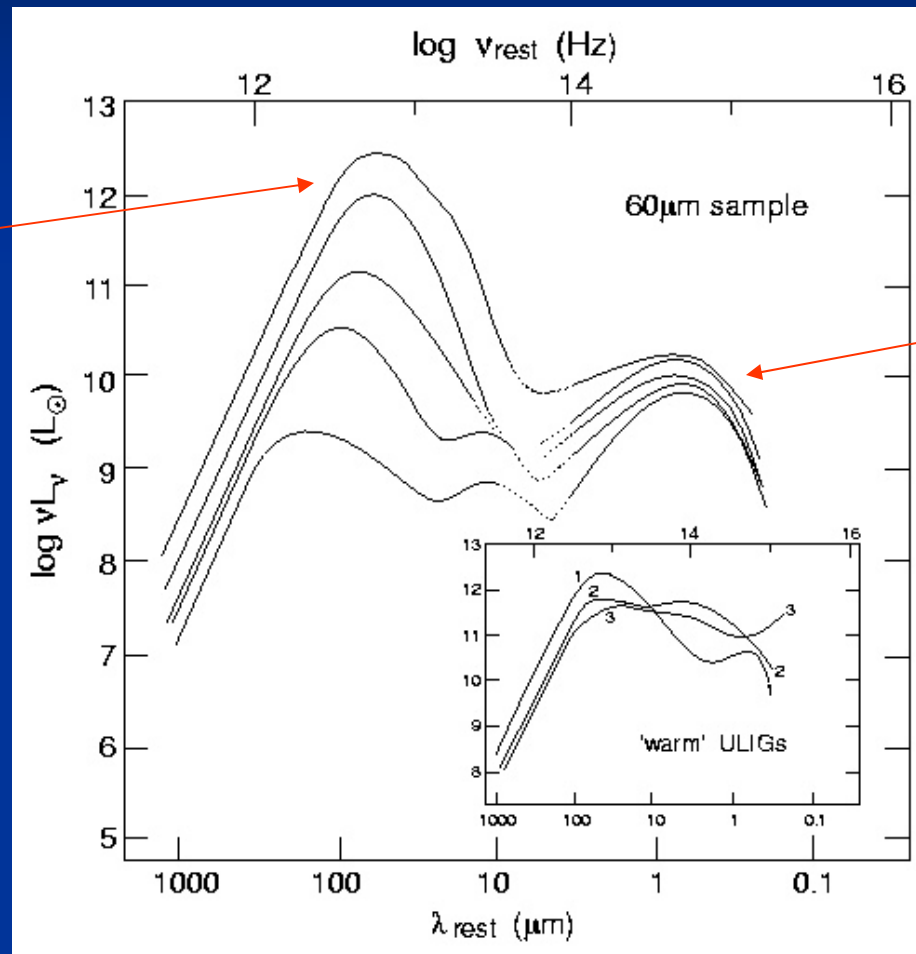
J. A. Surace & D. T. Frayer (Caltech)

D. B. Sanders (Hawaii)

# Luminous Infrared Galaxies

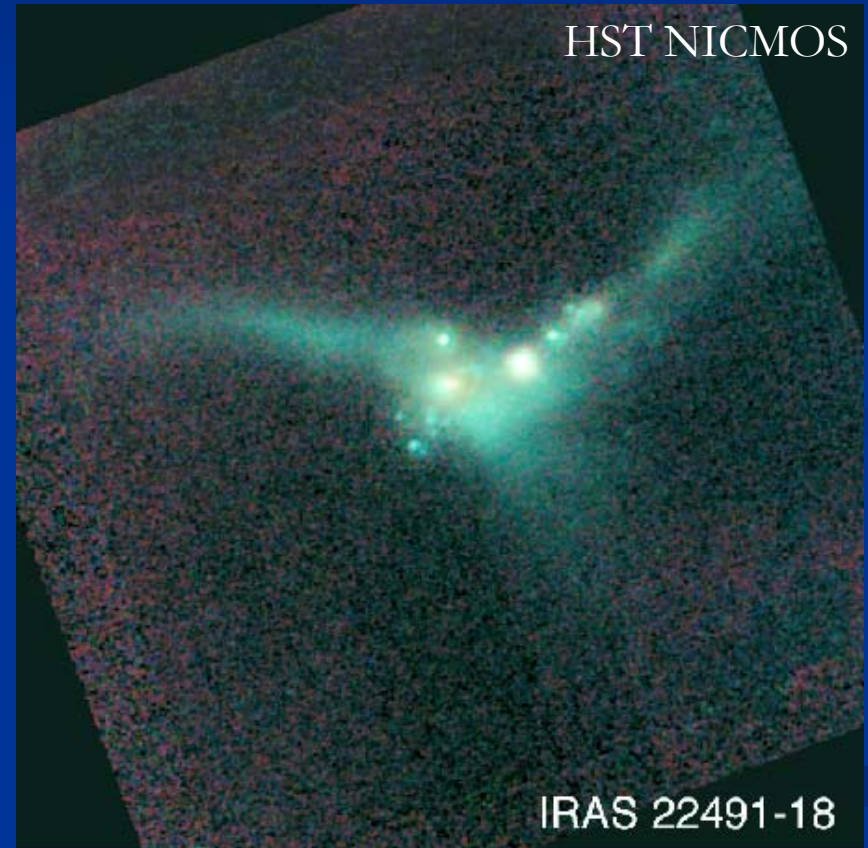
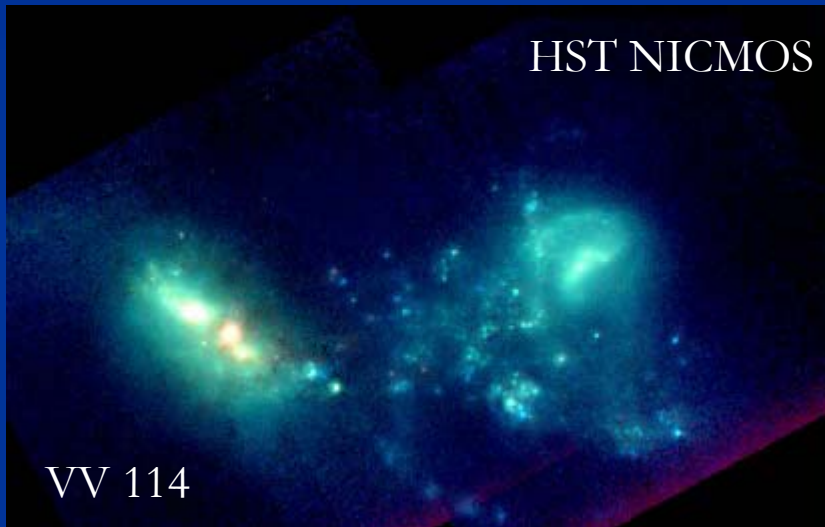
## Properties – 1. Infrared Excess

Infrared



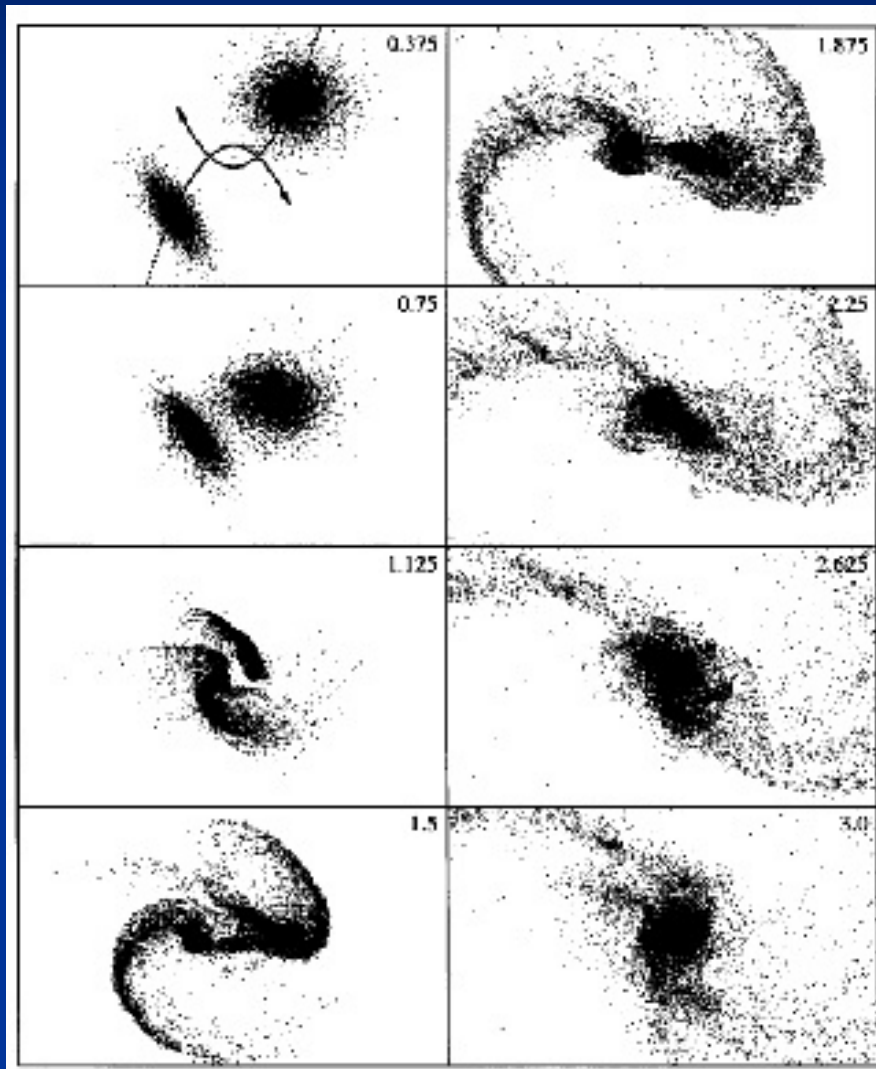
Optical

## 2. Galaxy Mergers with Starburst Activity



(e.g. Scoville et al. 2000)

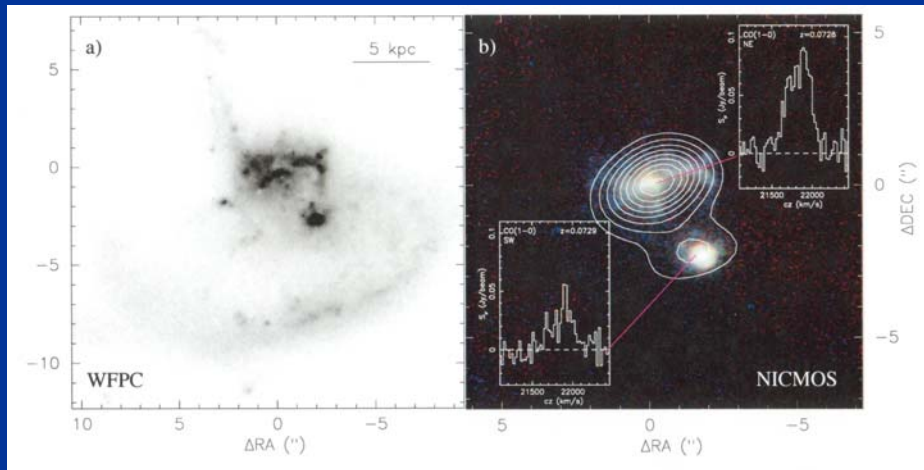
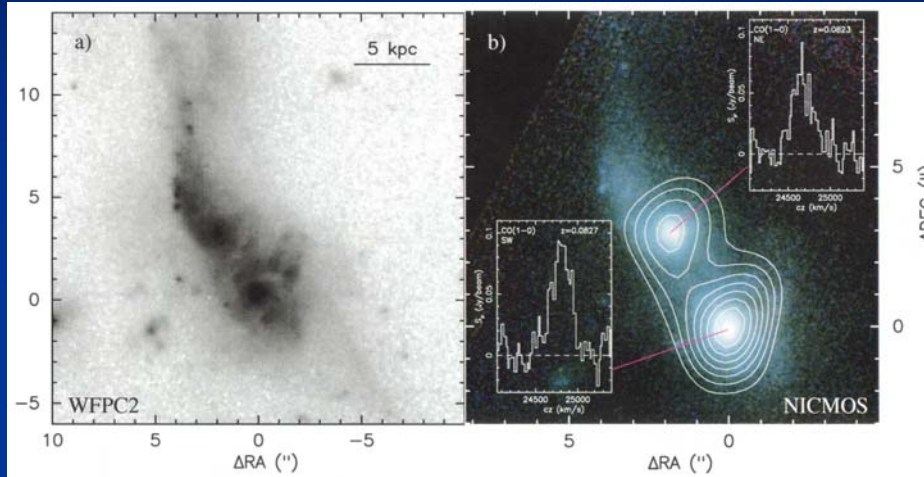
# Simulations of Merging Disk Galaxies



- Double Nuclei
- Tidal Features
- Evolution Toward Galaxies with Elliptical Profiles

(e.g. Toomre & Toomre 1972;  
Barnes & Hernquist 1996;  
Mihos & Hernquist 1996)

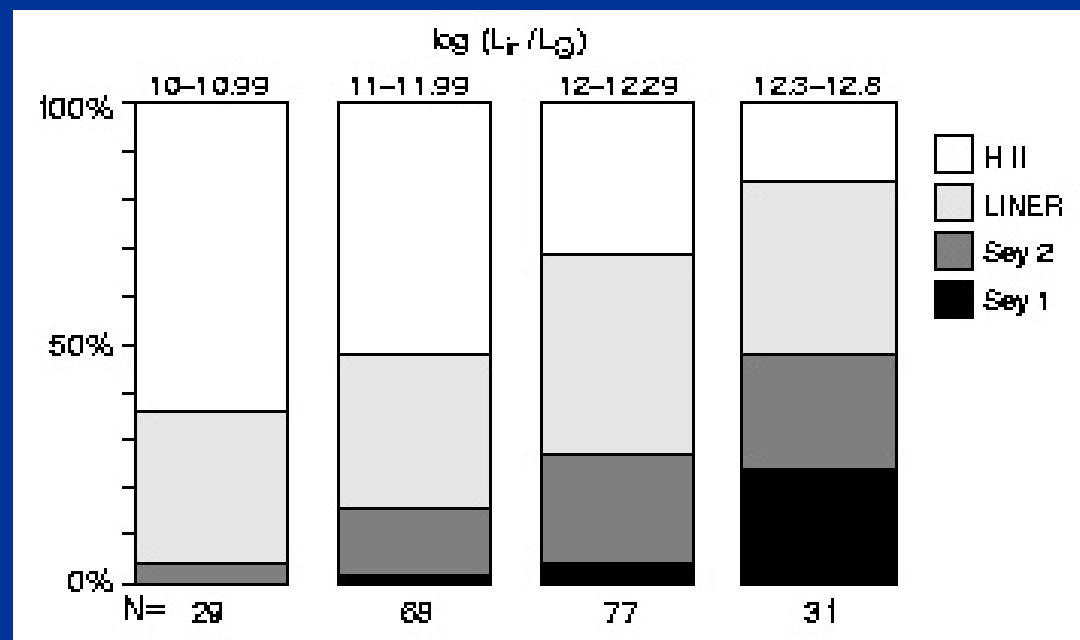
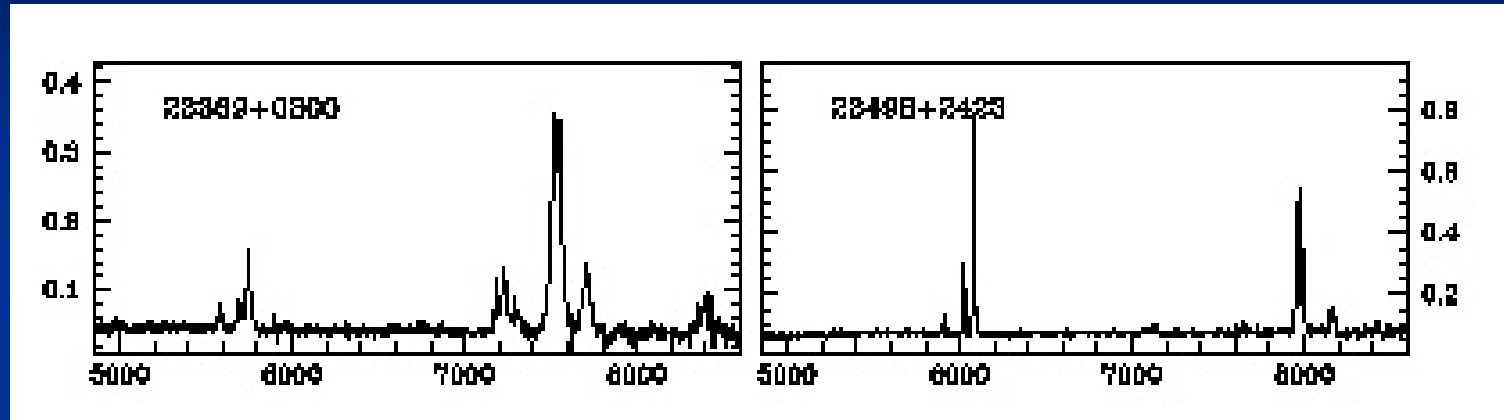
# 3. Significant Quantities of Star-Forming Molecular Gas



- 3mm CO(1-0) Emission Line: Collisionally excited by H<sub>2</sub>
- Few x 10<sup>9-10</sup> M<sub>sun</sub> of Gas
- Star-formation Rates = 100s M<sub>sun</sub> / year
- Depletion Time = 10<sup>7-8</sup> years

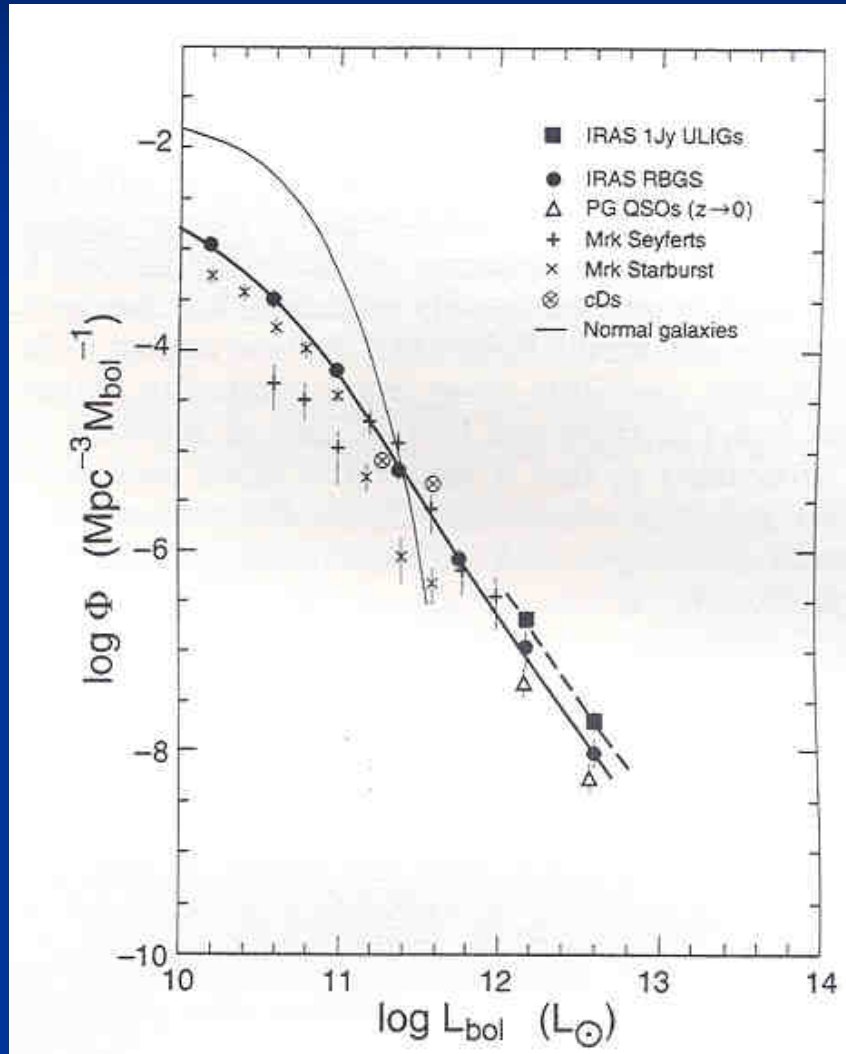
(e.g. Sanders, Scoville, & Soifer 1991  
Evans, Surace, & Mazzarella 2000;  
Evans et al. 2002)

# 4. Increase in AGN Fraction with Increasing Infrared Luminosity



(Veilleux et al 1995; Veilleux, Sanders, & Kim 1998)

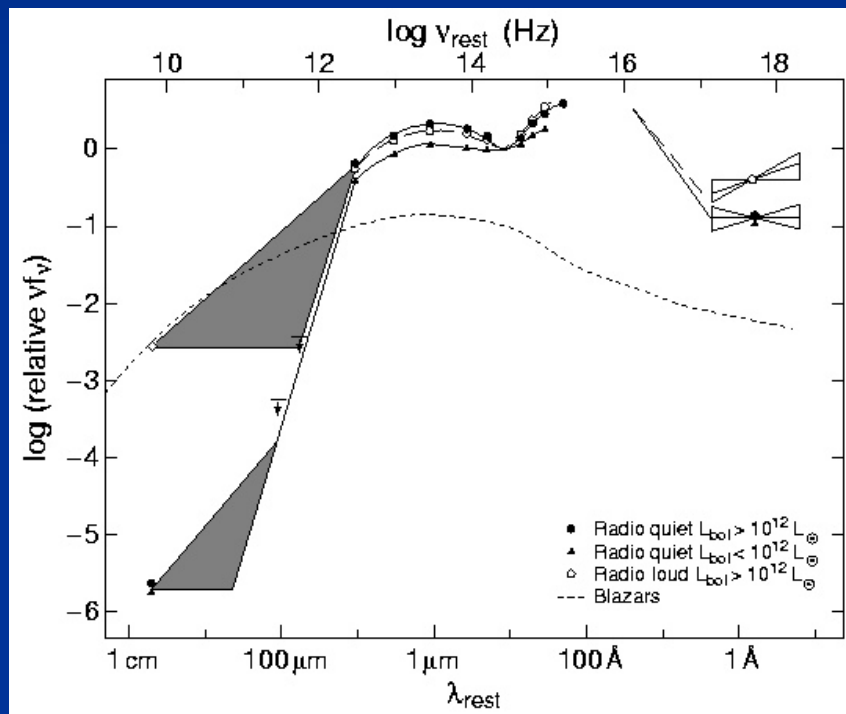
# 5. Luminosity Function at High End Similar to QSOs



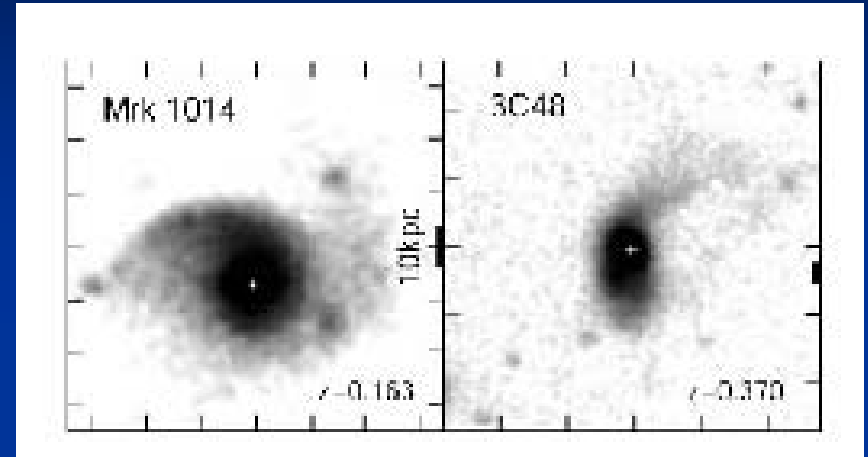
“Ultra”luminous Infrared  
Galaxies (ULIGs:  
 $L_{\text{TR}} [8-1000\mu\text{m}] > \sim 10^{12} L_{\text{sun}}$ )

(Soifer et al. 1987;  
Kim & Sanders 1998)

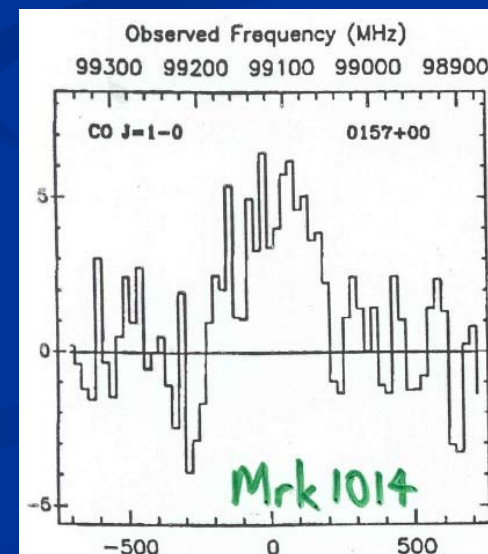
# Properties of Nearby QSOs (1988)



(Sanders et al. 1989)



(e.g. Stockton & MacKenty 1984)



(Sanders, Scoville, Soifer 1988)

# Dust-Enshrouded Quasar Model:

QSOs are the/an Evolutionary By-product of the  
Ultraluminous Infrared Galaxy Phenomenon

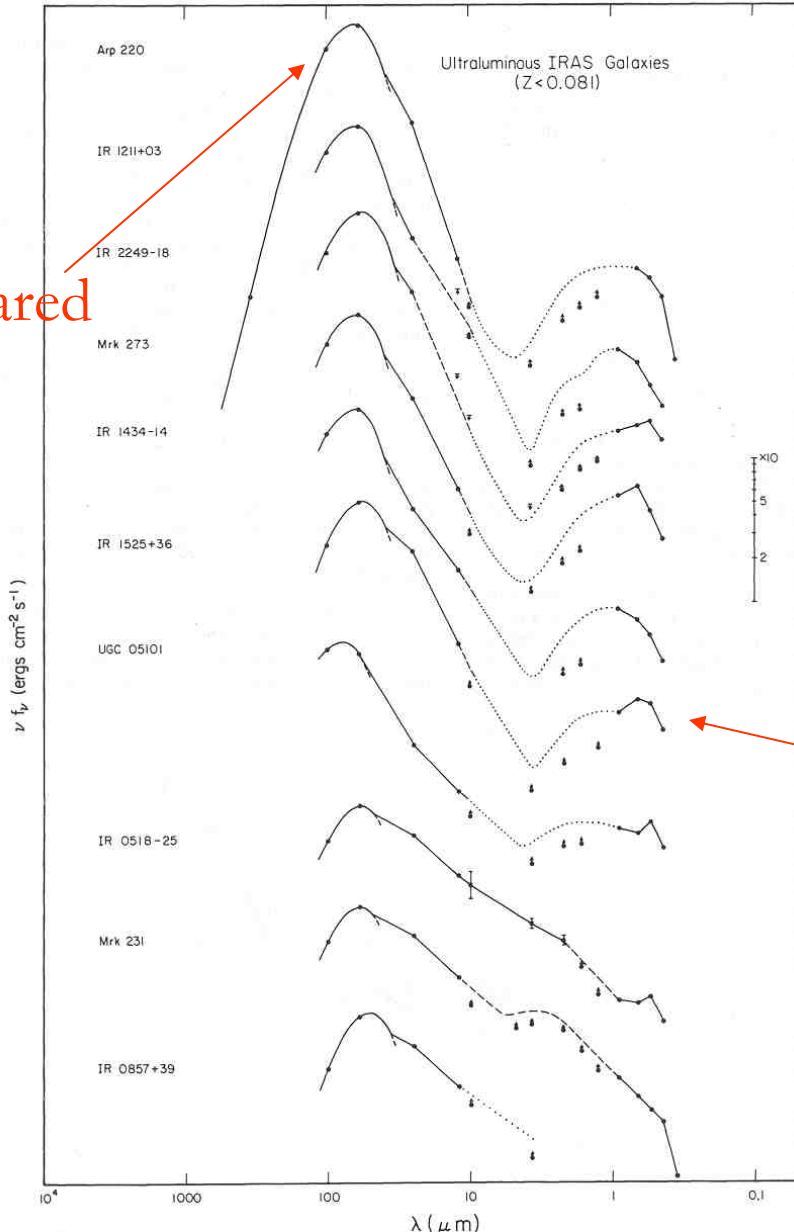
- Similarities in Luminosity Function
- Distorted Stellar Morphologies and Large Amounts of Molecular Gas
- Increased AGN Fraction with Increasing Infrared Luminosity

(Sanders et al. 1988)

# Possible Evolutionary Sequence

Infrared

Progression

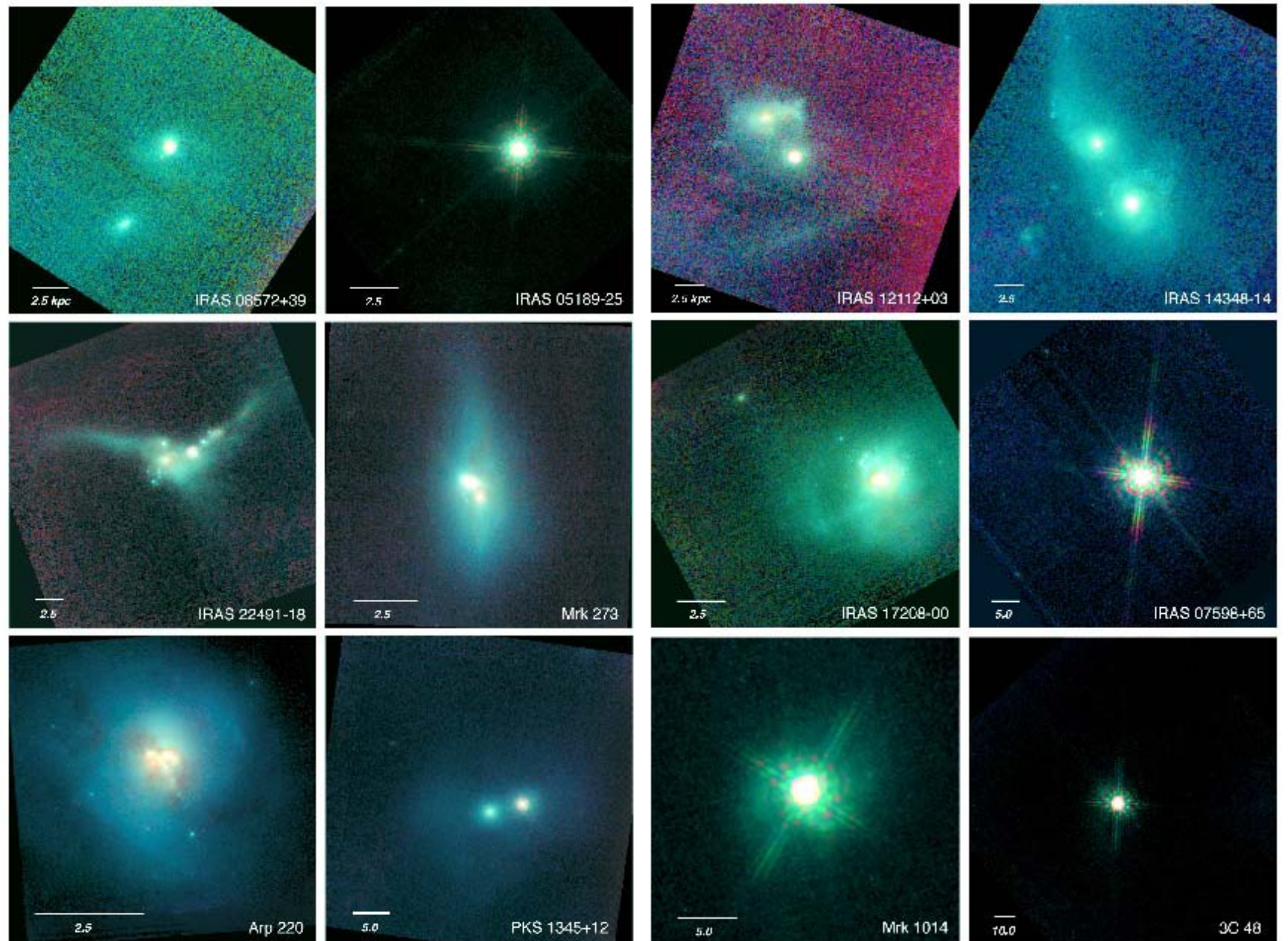


- Cool ULIGs ( $f_{25}/f_{60} < 0.2$ )
- Warm ULIGs ( $f_{25}/f_{60} > 0.2$ )
- UV-Excess QSOs

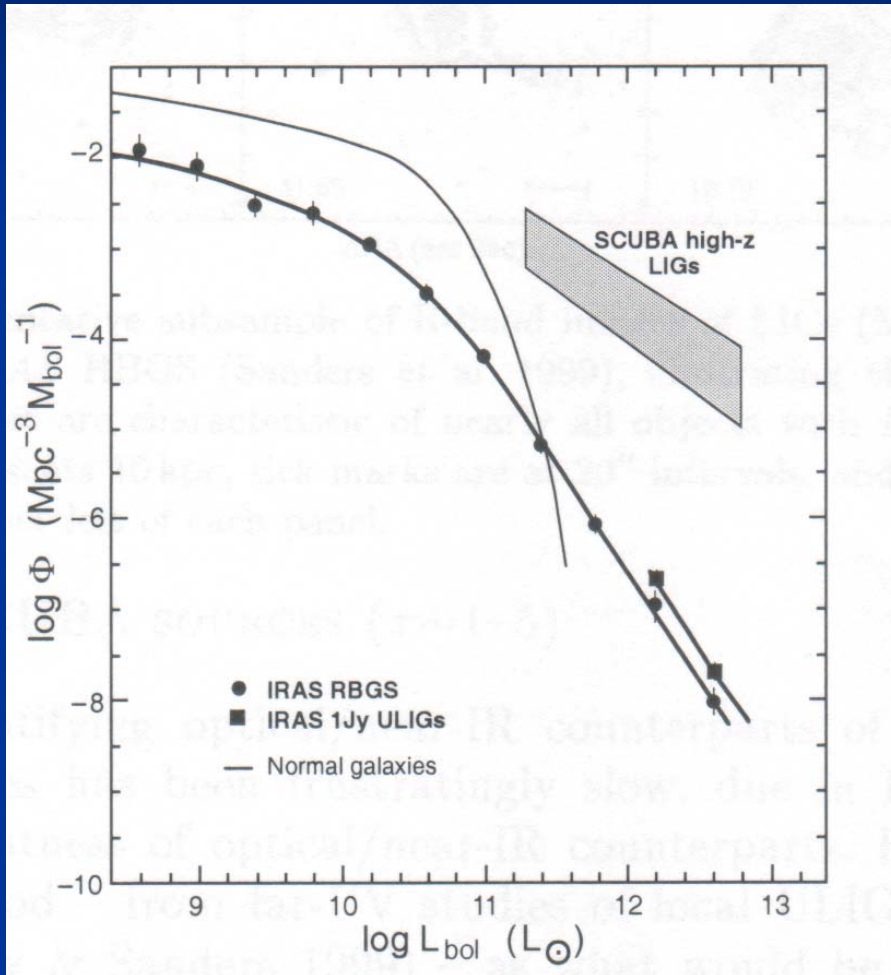
Optical

(Sanders et al. 1988)

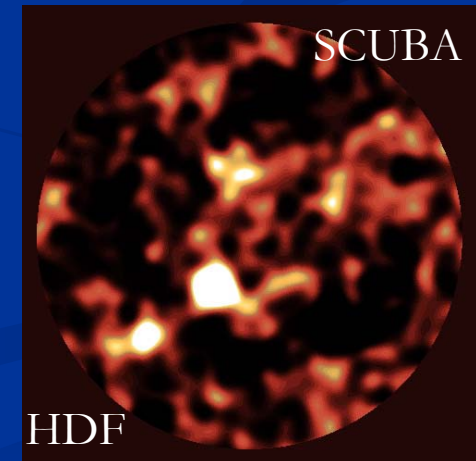
# Warm ULIGs have Bright, Compact Nuclei (Scoville et al. 2000)



# Infrared Galaxies at High Redshift

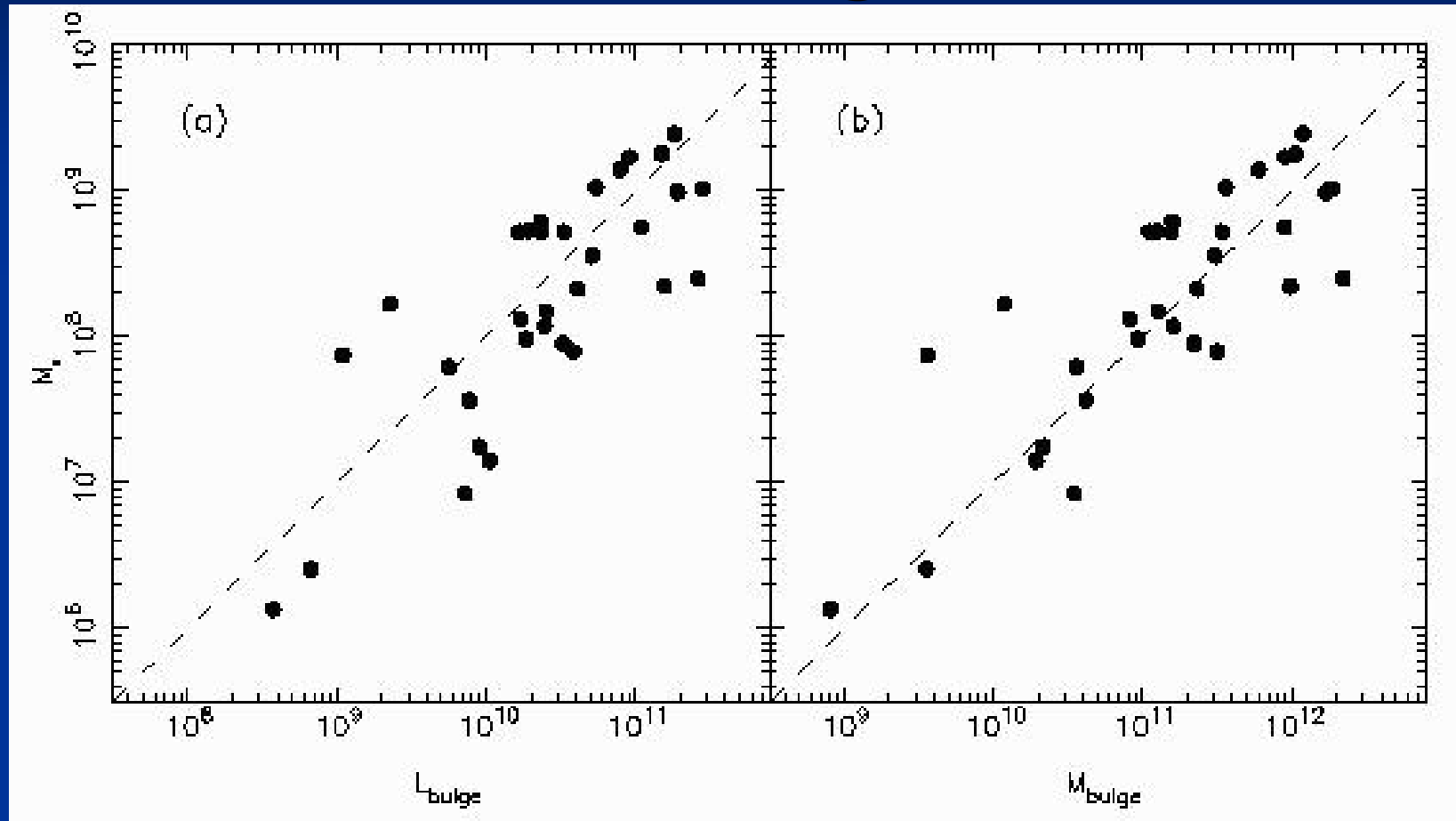


- Space Density of Infrared Galaxies Higher in the Past
- Based on SCUBA and ISO Observations



(Hughes et al. 1998)

# Relationship Between Black Hole Mass and Bulge Mass



I.e., Black Hole Creation is a Standard Part of Galaxy Formation

(e.g. Kormendy & Richstone 1995; Magorrian et al. 1998)

# Comparison of LIG-QSO Datasets (ca. 1998)

Observation Type	Importance	Local LIGs	Local QSOs
Optical/NIR Imaging	Galaxy Type/ Age-Dating	Lots	Substantial (AO, HST)
Optical/IR Spectroscopy	Ionization Mechanism	Lots	N/A
FIR Photometry	$L_{\text{IR}}$	Lots	Lots
CO Spectroscopy	Fuel for Star Formation and AGN?	Lots (i.e. Single Dish)	Several
X-ray, etc...			

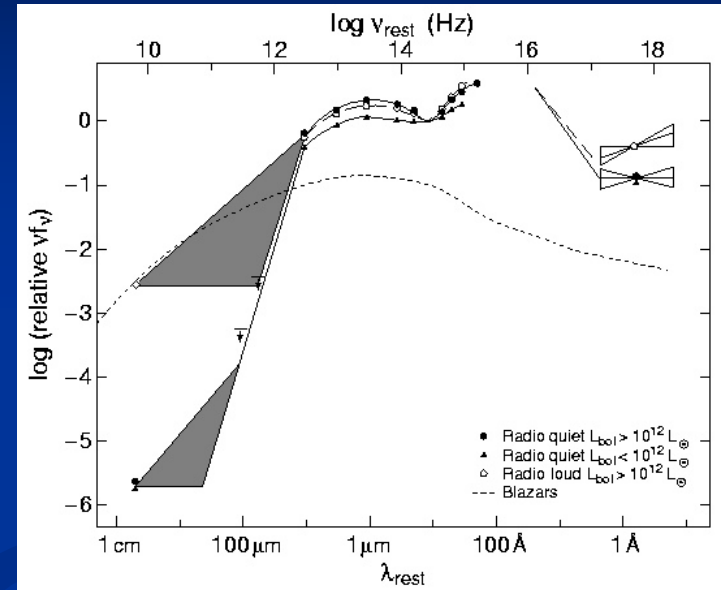
# CO(1-0) Observations of QSOs

- Possible Evolutionary Connection with ULIGs
- Molecular Gas is a Possible Fuel Source for AGN Activity
- Molecular Gas Present if Stars and Black Hole are Co-evolving

(Evans et al. 2001)

# An Infrared-Excess Sample -

- Palomar-Green Quasar Survey
- $L_{\text{IR}} / L_{\text{bbb}} (0.1-1.0 \mu\text{m}) > 0.36$
- Redshift,  $z < 0.17$
- $M_{\text{B}} < -22.0$
  
- 17 QSOs Total, 10 Observed in CO(1-0) thus Far
  
- Note: For PG QSOs,  
 $L_{\text{IR}} = 0.2 - 0.4 L_{\text{bol}}$



# Millimeter (CO) Observations

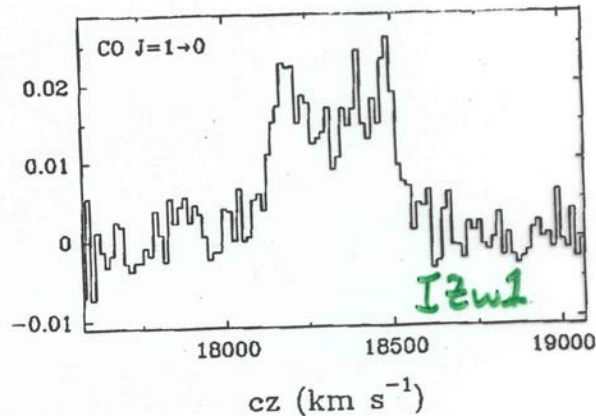
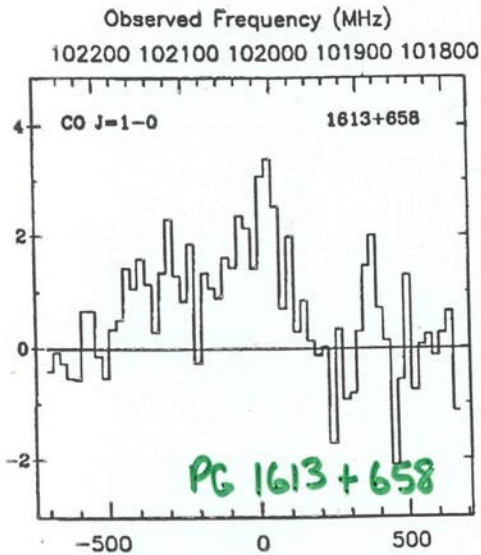
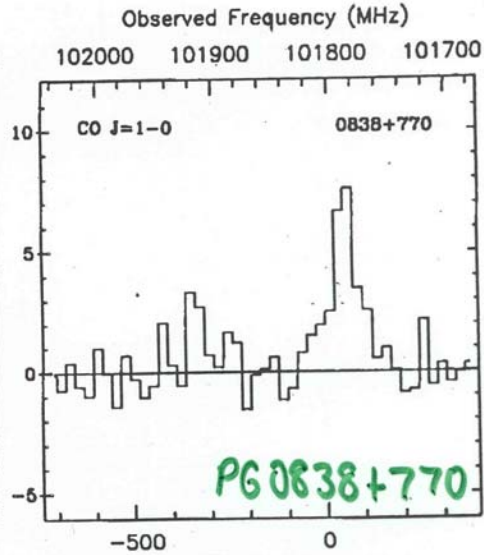
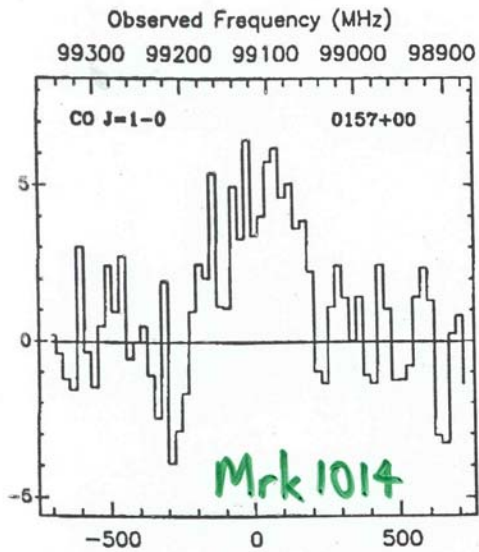


Owens Valley Millimeter Array

- Two Transits/Source
- Beam Size = 4''
- Detection Limit of  $S_{\text{CO}} (3\sigma \text{ rms}) = 8 \text{ mJy}$  with 280 km/s Smoothing
- I.e.,  $M(\text{H}_2) = 10^9 M_{\text{sun}}$  at  $z = 0.1$

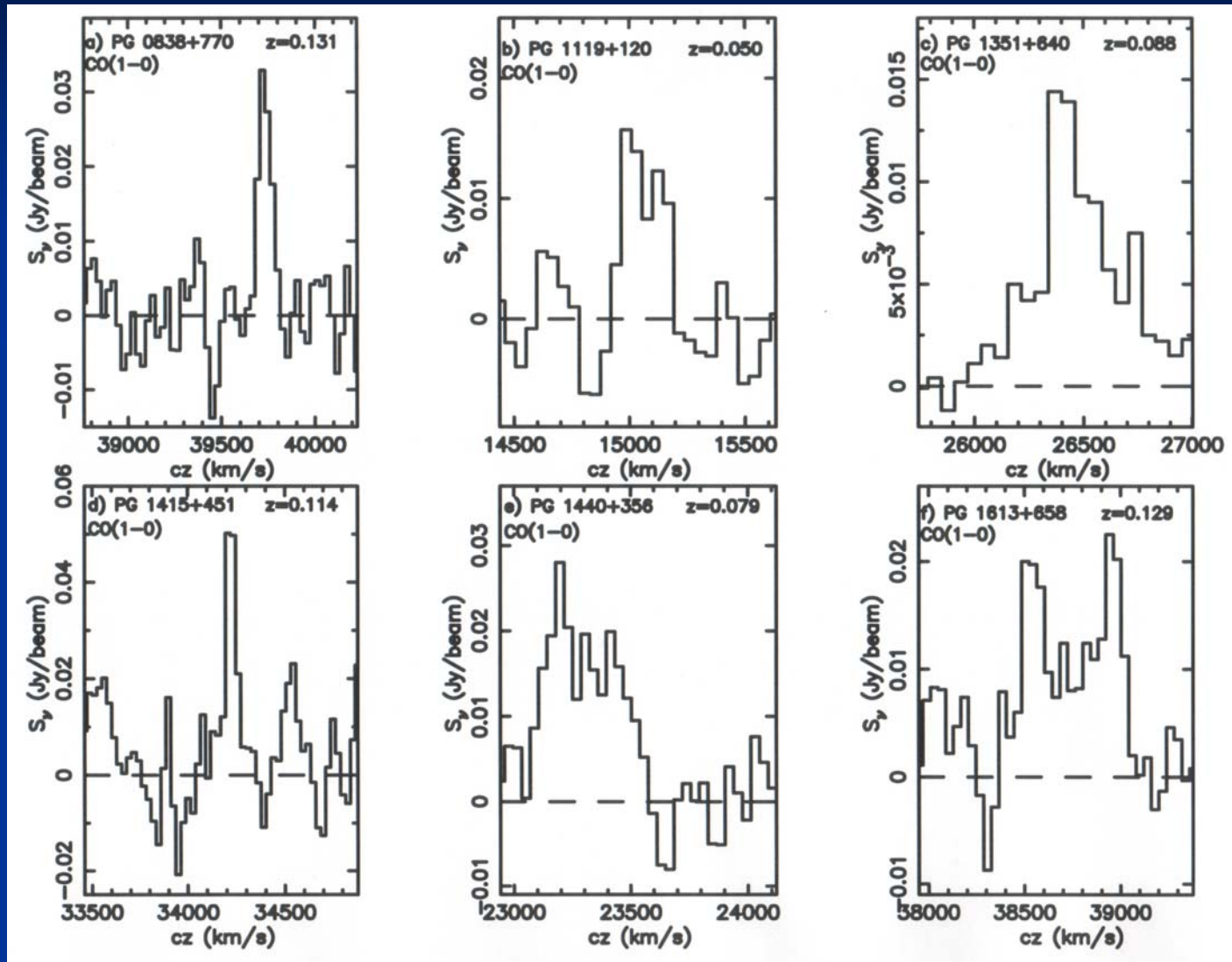
$$(\alpha = 4 M_{\text{sun}} [\text{Km/s/pc}^2]^{-1})$$

# Previous Detections with Single Dish Telescopes (mostly)



(Sanders et al. 1988;  
Barvainis et al. 1989;  
Alloin et al. 1992;  
Solomon et al. 1997;  
Schinnerer et al. 1998)

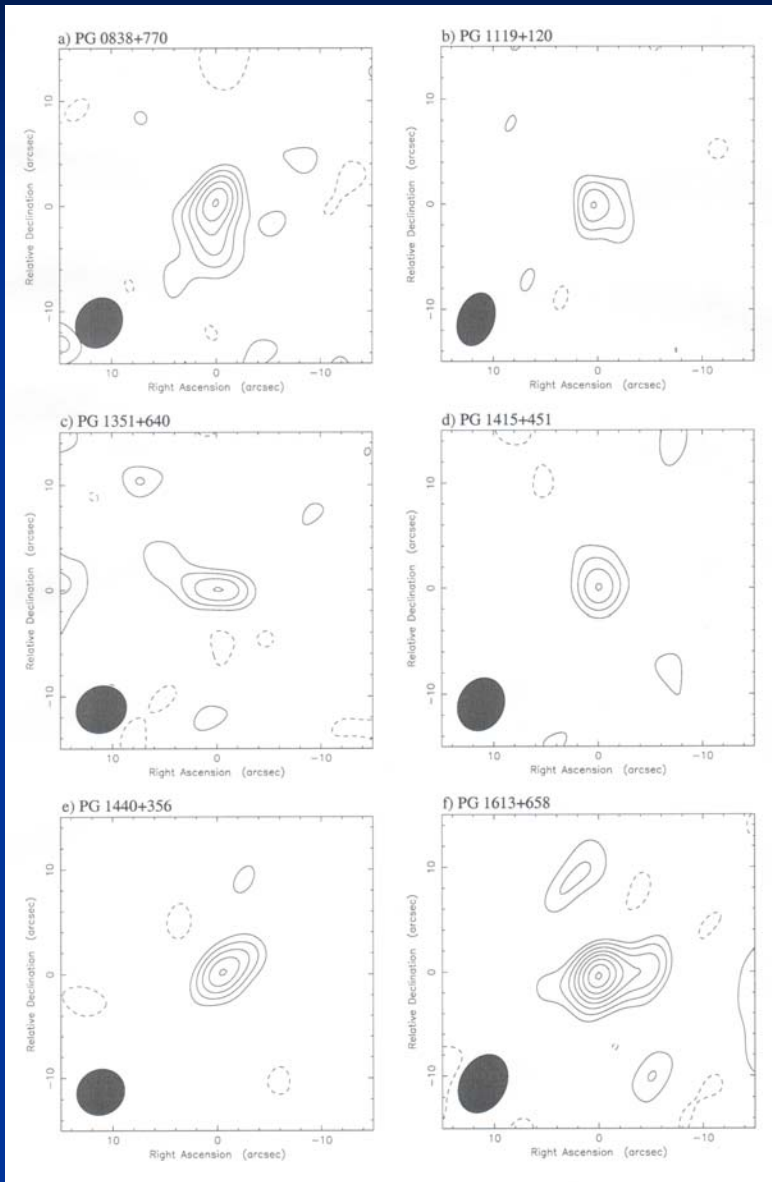
# CO Spectra of IR-Excess QSOs



$$\Delta v_{\text{FWHM}} = 50\text{-}500 \text{ km/s}$$

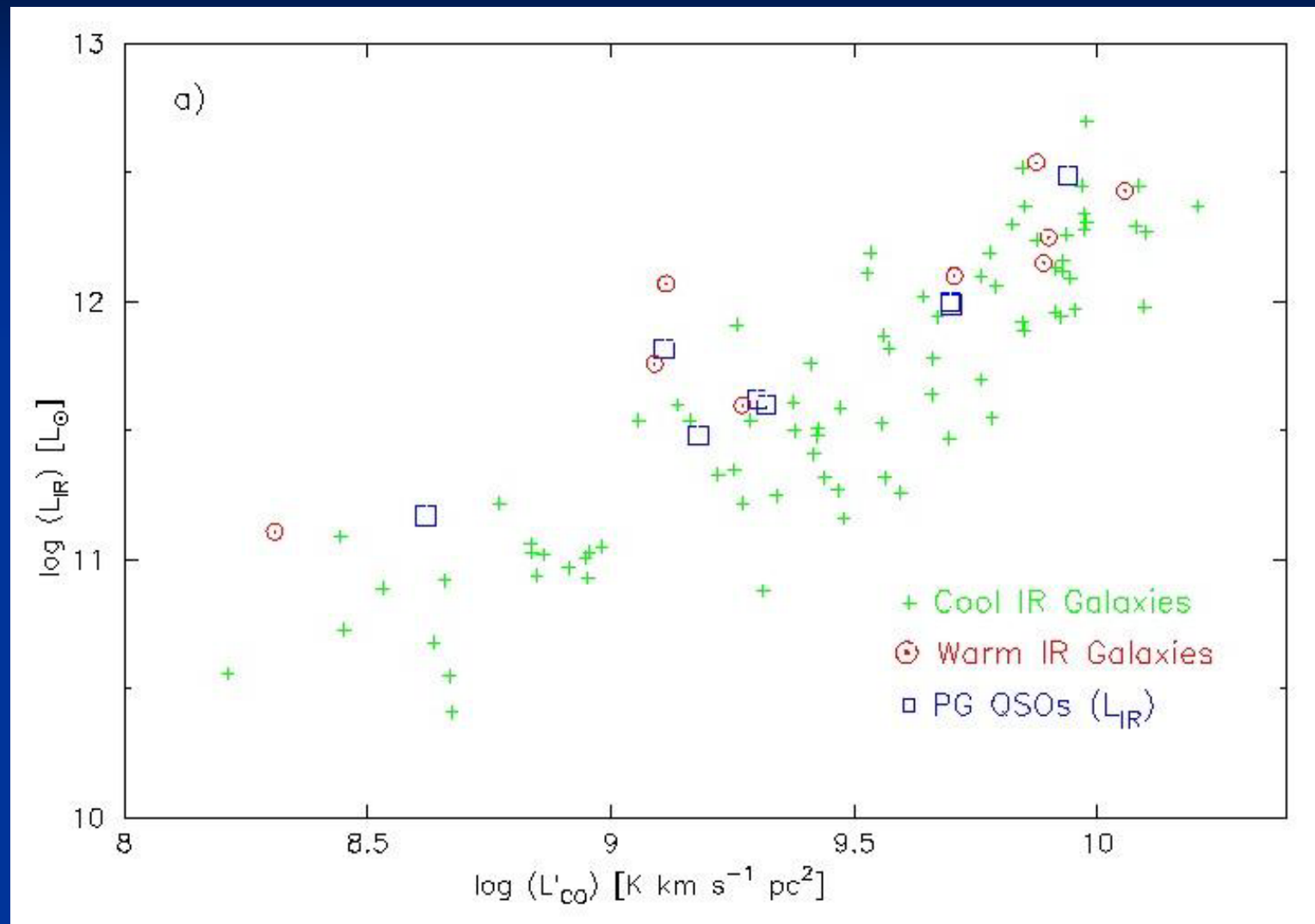
# Synthesized CO(1-0) Maps

- Contours =  $1\sigma$  steps
- Detections =  $4.6 - 8.6\sigma$



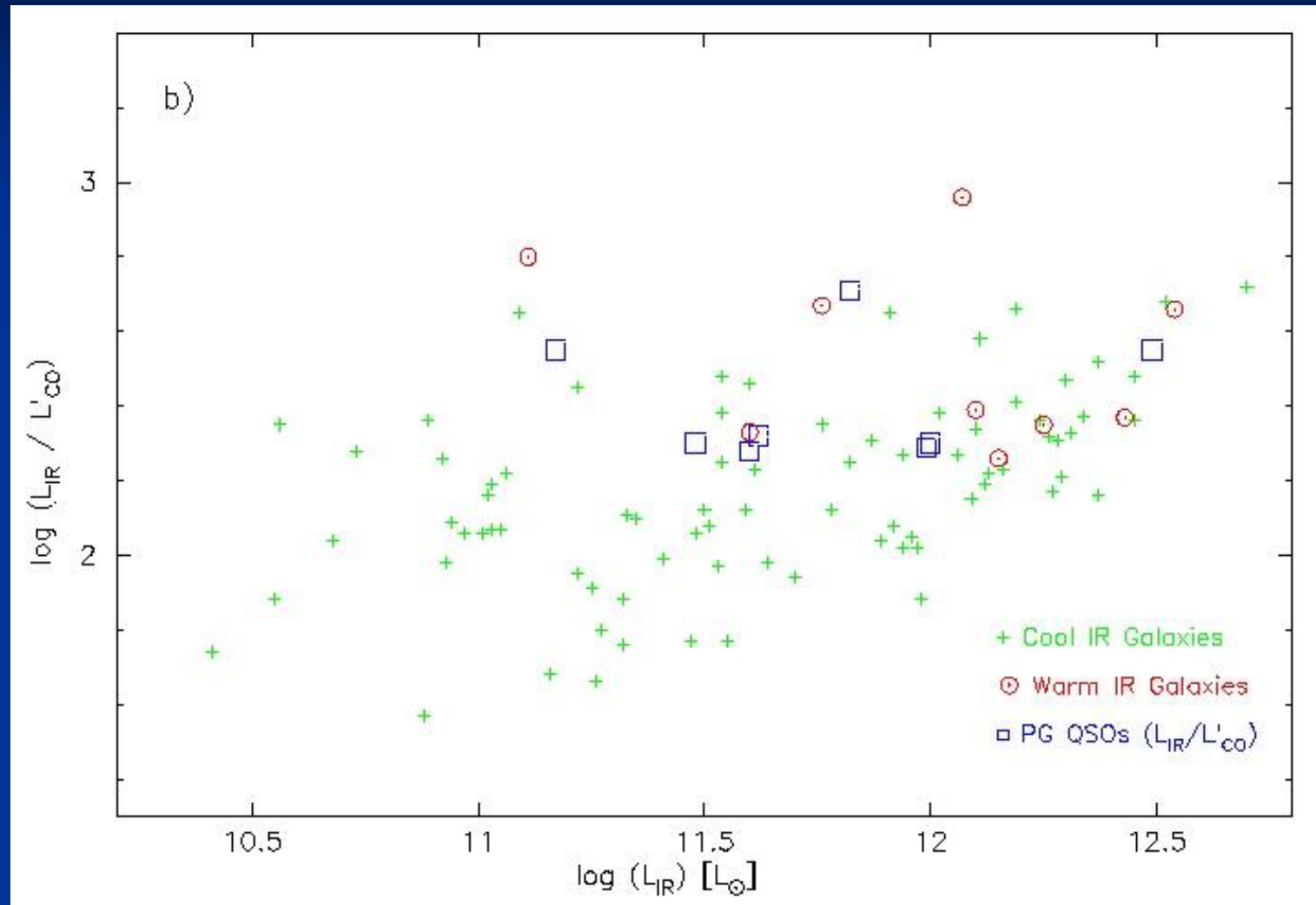


# Log ( $L_{\text{IR}}$ ) vs. Log ( $L'_{\text{CO}}$ )



I.e., Dust Heating vs. Fuel Reservoir

# “Star Formation” Efficiency



...or Significant Heating by AGN?

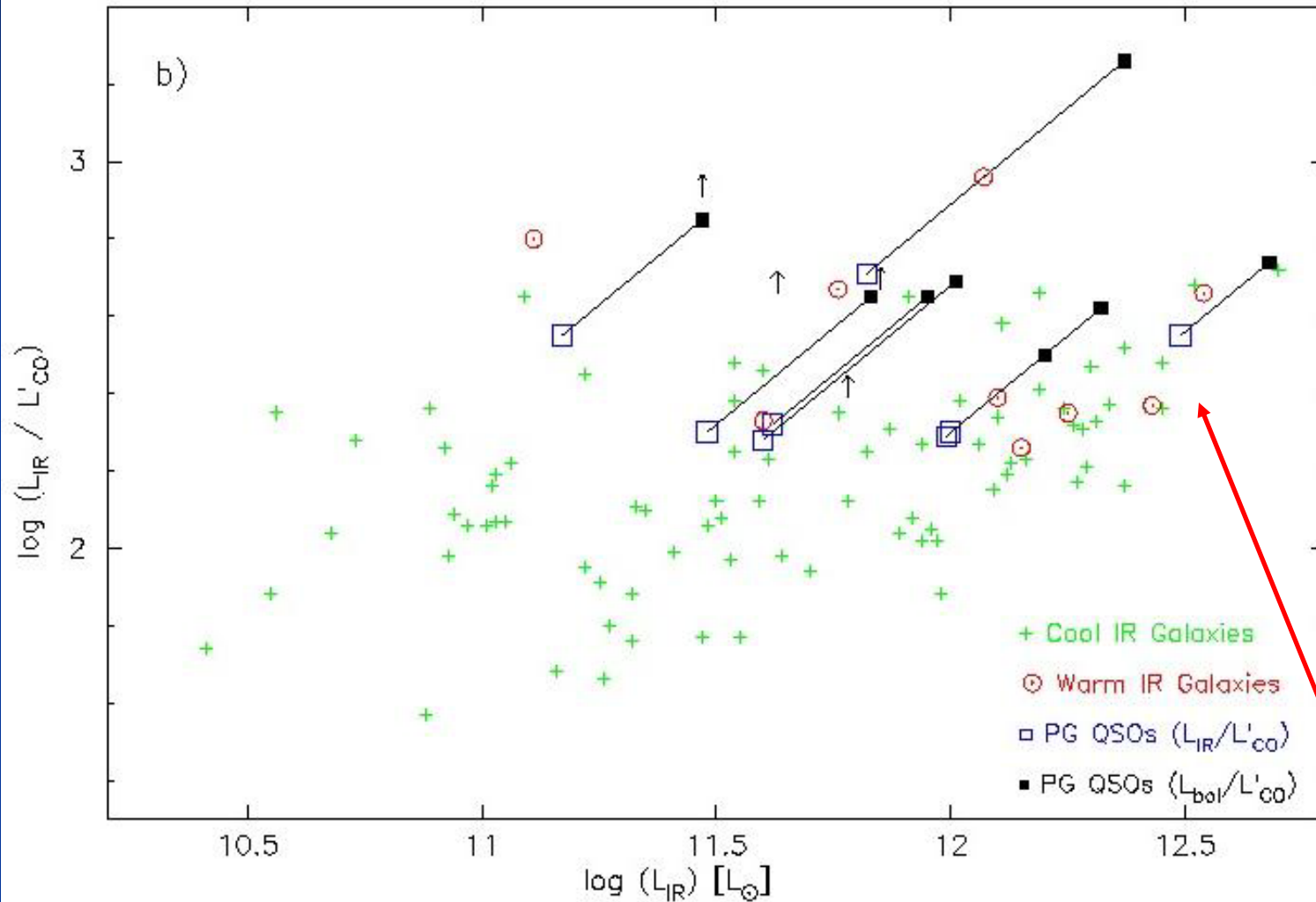
# Can the QSOs Account for most/all of the Bolometric Luminosity?

PG QSO	$M_{\bullet}$	$L_{\text{bol}}/L_{\text{eddington}}$
PG 1226+023	$5 \times 10^8$	0.12
PG 1351+640	$5 \times 10^7$	0.16
PG 1411+442	$8 \times 10^7$	0.04
PG 1613+658	$2 \times 10^8$	0.02
PG 2130+099	$1 \times 10^8$	0.02

From Reverberation Mapping (Kaspi et al. 2000)

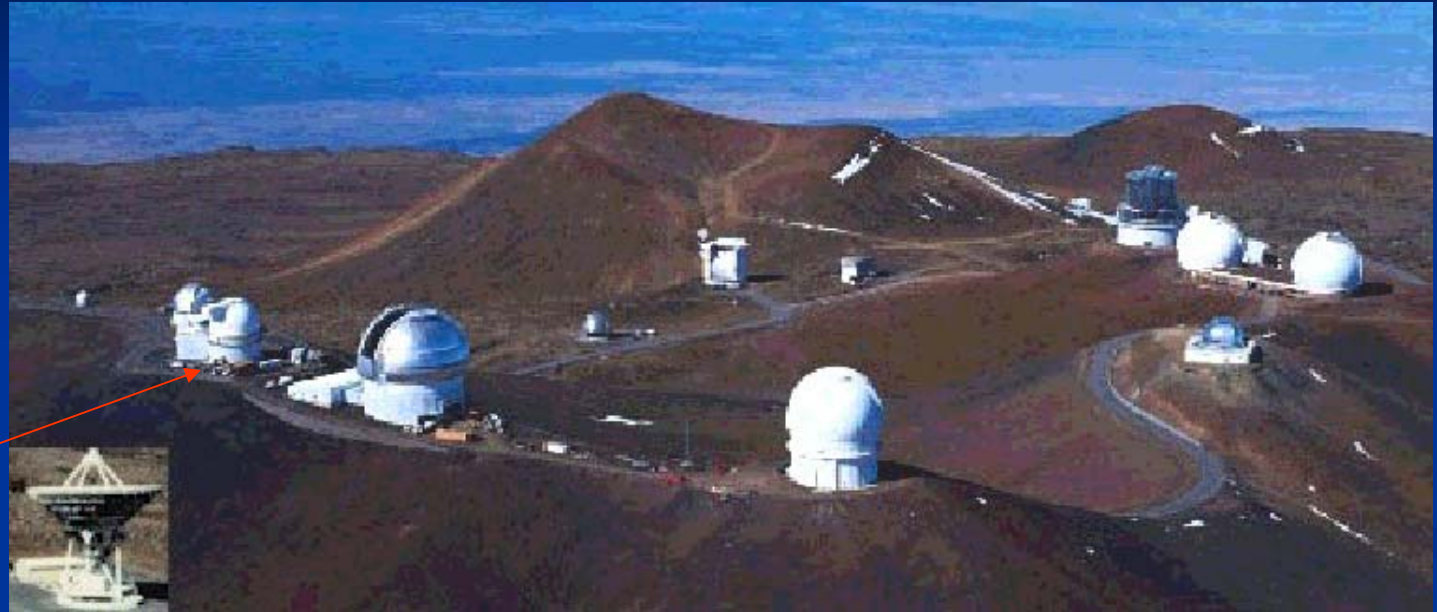
**Answer: Yes.**

# If $L_{\text{IR}} = L_{\text{bol}}$ for QSOs



Regions Occupied by Dust-Enshrouded Quasars?

# Optical/Near-Infrared Imaging

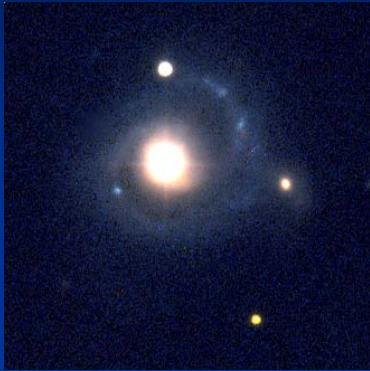


UH 2.2m

- B, I, H, K-Band Filters
- Total Integration Times = 9-54 minutes
- Typical Seeing: I= 0.4-0.9", K=0.25-0.5"

(Surace, Sanders, & Evans 2001)

# Diverse Morphology



Half are in  
spiral galaxies.



And half of  
those are  
barred.

# Diverse Morphology

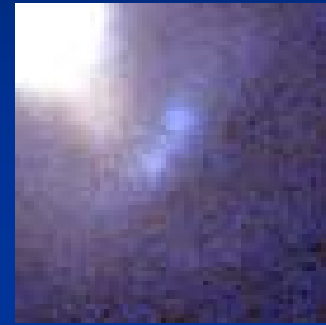


A quarter are in major merger systems as evidenced by tidal tails 20-80 kpc in length.



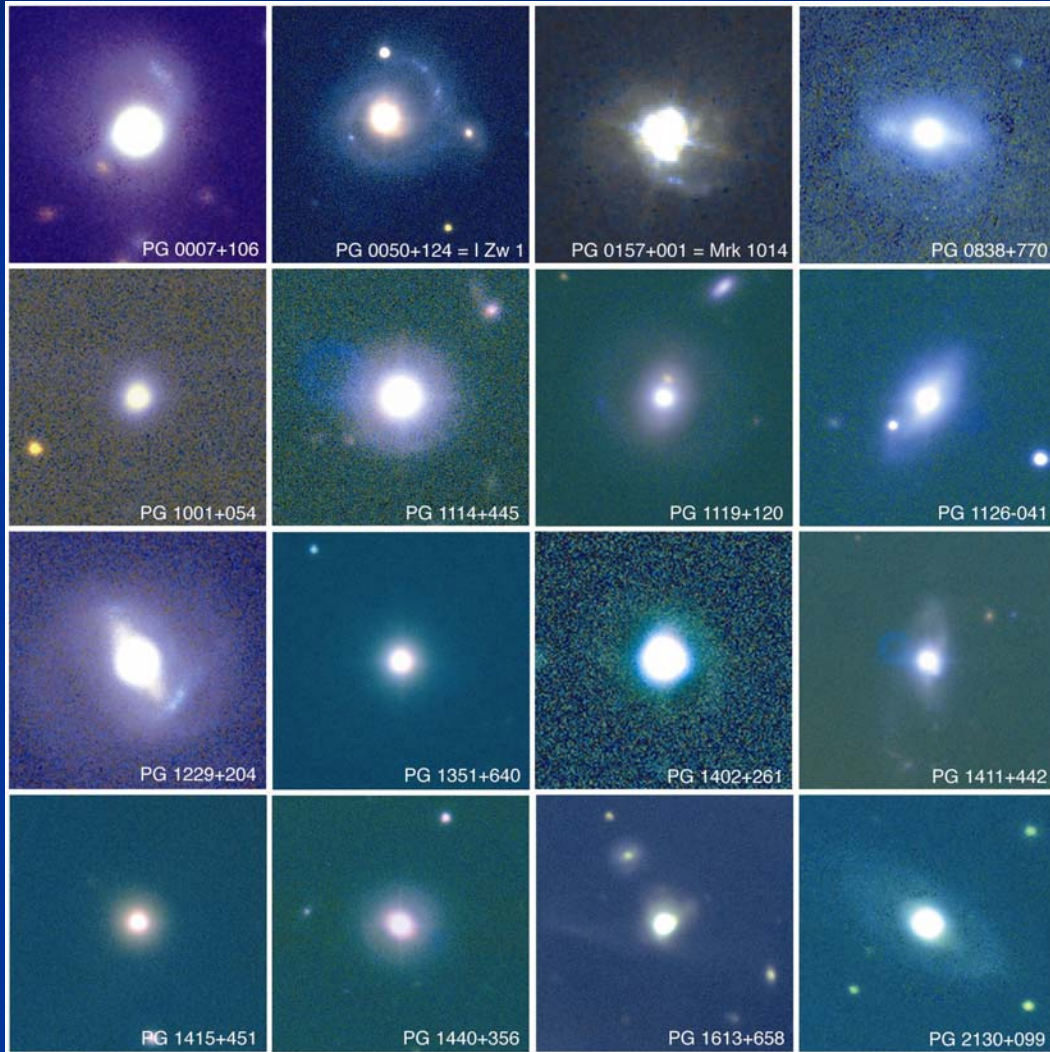
A few are extended but don't look like anything. They have no resolvable structure, and could be ellipticals or unresolved spirals. Radial profiles do not produce very meaningful results due to convolution effects with PSF.

# Small-Scale Structure



In some cases there is resolvable small scale structure similar to the star-forming knots found in ULIRG nuclear regions and tidal structure. In most cases the ages of these knots are probably under 100 Myrs based on 4-color analysis and spectral synthesis models.

# Optical Imaging of QSOs

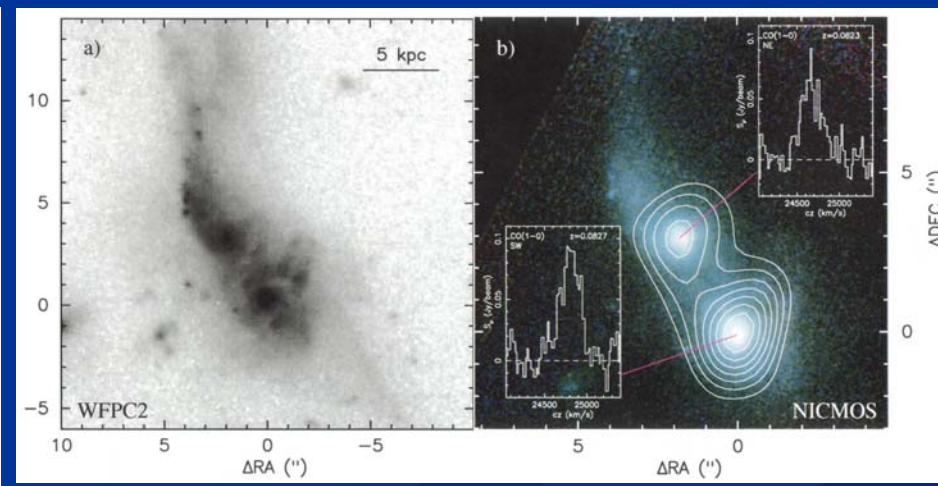
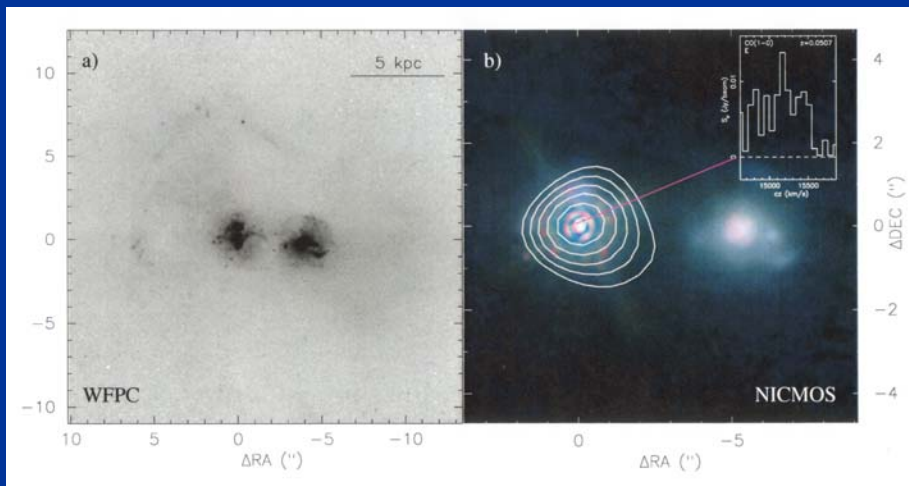
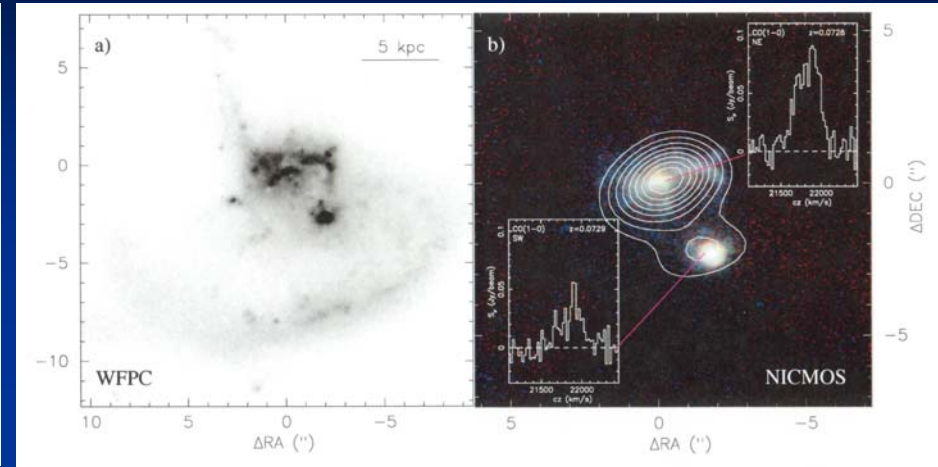
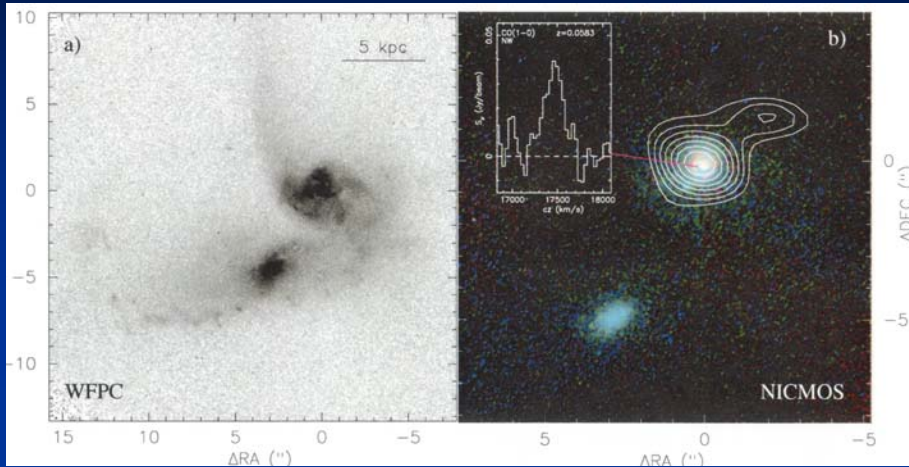


- IR-Excess QSOs Have Spiral, Merger, and “Elliptical” Galaxy Hosts
- 25% - Ongoing Major Mergers

# Improvements to CO Work

- Larger QSO Samples
- Higher Resolution Observations – CO Extent, Column Density
- Other CO Transitions – Density, Temperature
- HCN – Dense Gas ( $10^5 \text{ cm}^{-3}$ )
- Similar Observations of Luminous Infrared Galaxies as a Function of Evolutionary State

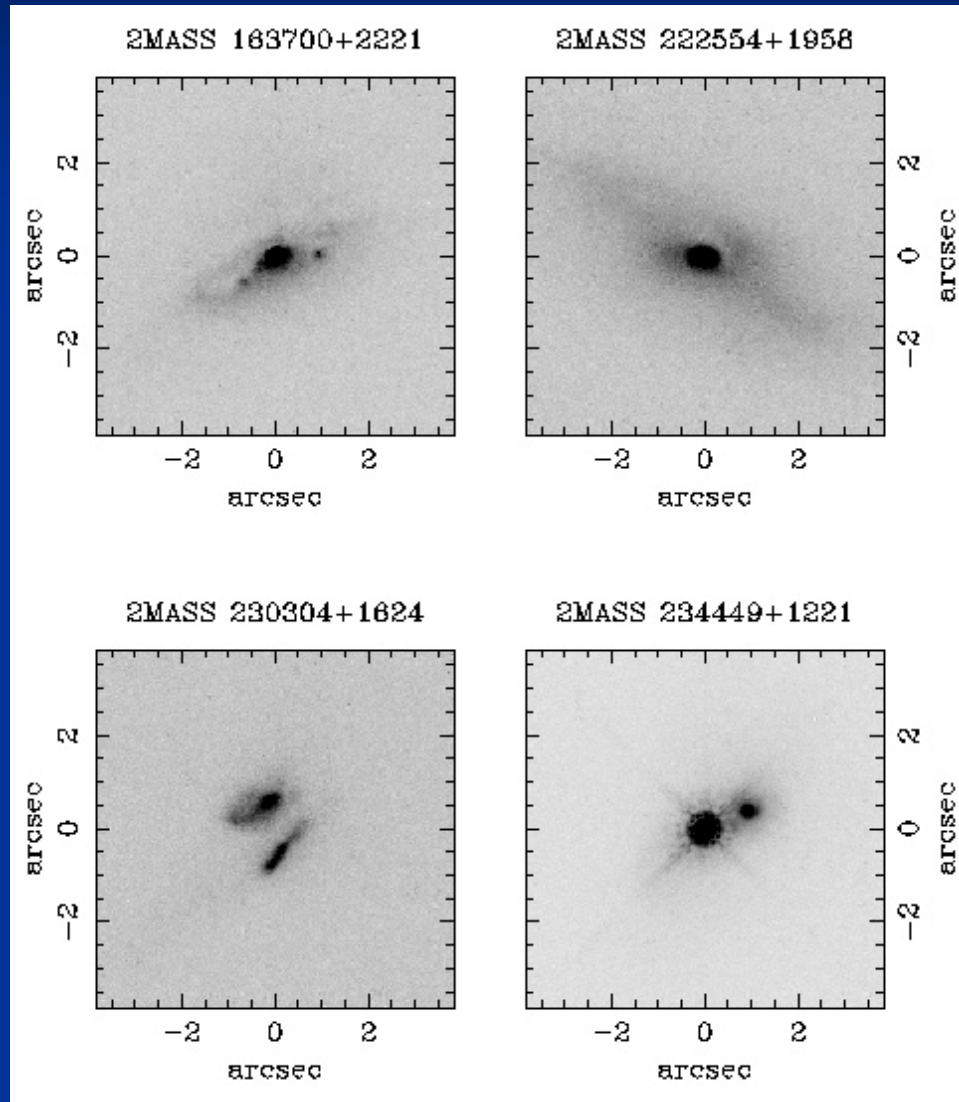
# Improvements:



A Sample of Intermediate Stage ULIGs: Projected Nuclear Separation = 2 – 5 kpc.

# Improvements to Imaging Work

- 2MASS QSOs



(Hines et al. 2002)

# Summary

- Six out of Nine QSOs Detected in CO(1-0) with Molecular Gas Mass  $> 10^9 M_{\text{sun}}$
- High  $L_{\text{IR}} / L'_{\text{CO}}$  of QSOs is Indicative of Dust Heating by an AGN and/or Massive Stars (I.e., High Star Formation Efficiency)
- IR-Excess QSOs have Host Galaxies Which are Spirals, Mergers, and “Elliptical” Galaxies