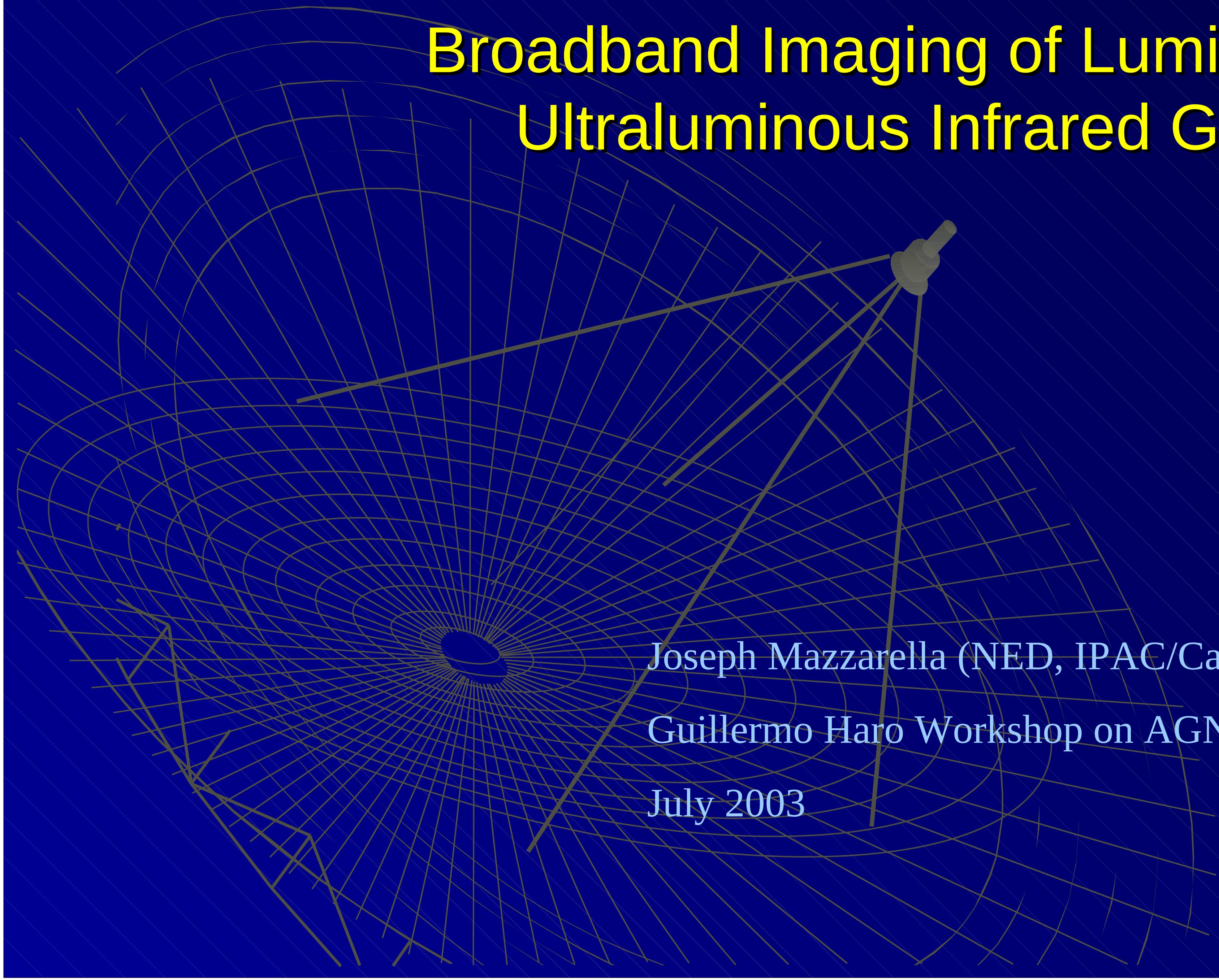
Molecular Gas and Multiwavelength Broadband Imaging of Luminous & Ultraluminous Infrared Galaxies



Joseph Mazzarella (NED, IPAC/Caltech/JPL)

Guillermo Haro Workshop on AGN Surveys

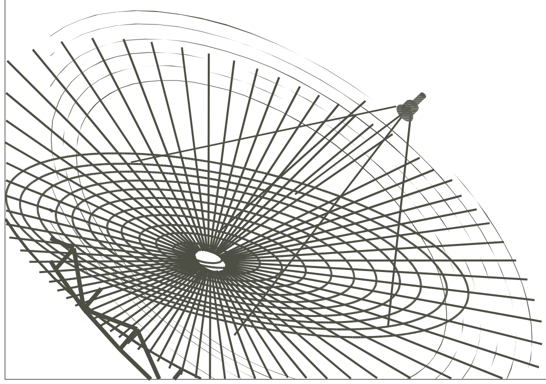
July 2003

Talk Outline

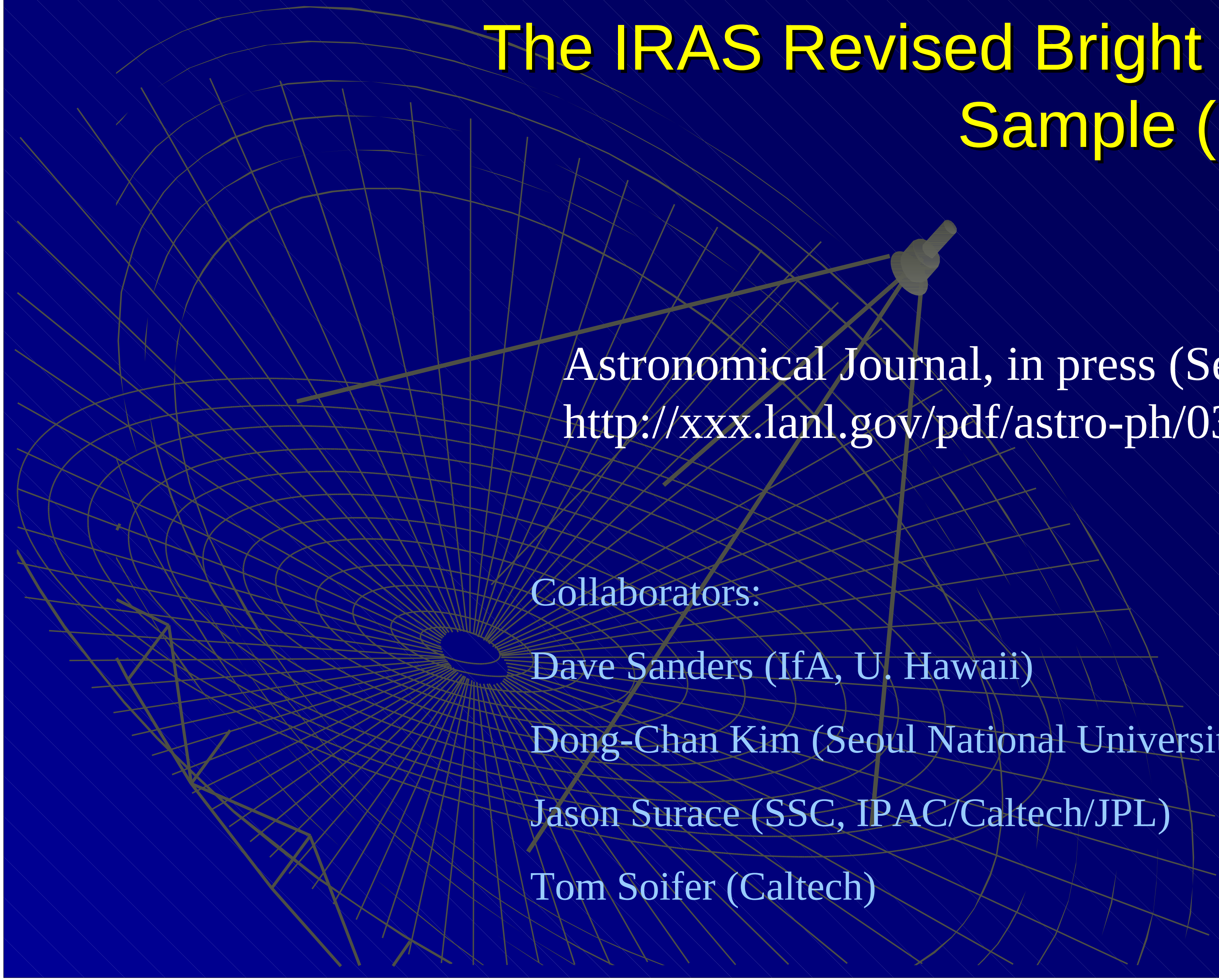
- Introducing the IRAS Revised Bright Galaxy Sample

- Mapping Molecular Gas: ULIGs --> Ellipticals?

- In progress... Multiwavelength Broadband Imaging of RBGS LIGs & ULIGs



The IRAS Revised Bright Galaxy Sample (RBGS)



Astronomical Journal, in press (Sept. 2003)
http://xxx.lanl.gov/pdf/astro-ph/0306263

Collaborators:

Dave Sanders (IfA, U. Hawaii)

Dong-Chan Kim (Seoul National University, Korea)

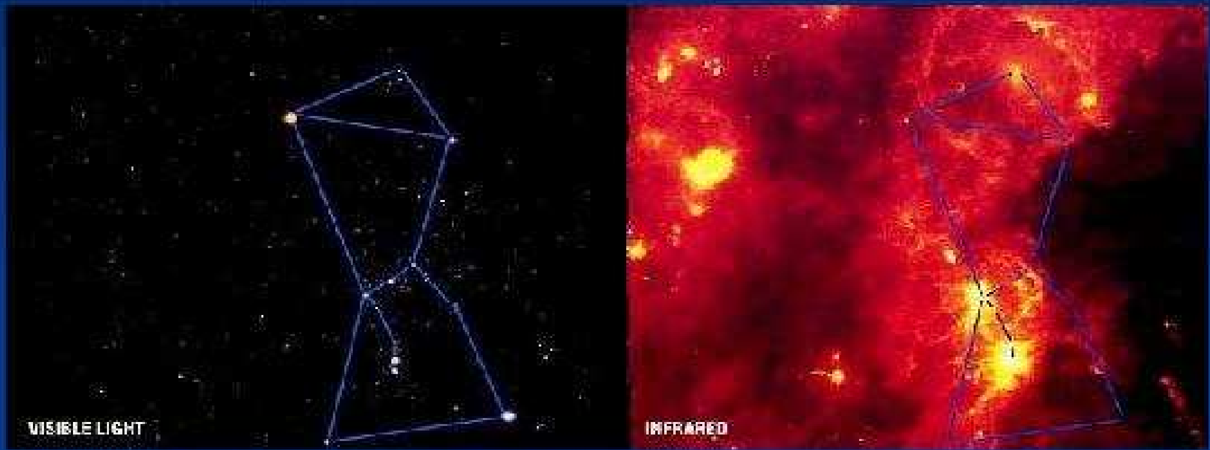
Jason Surace (SSC, IPAC/Caltech/JPL)

Tom Soifer (Caltech)

Overview of the IRAS Revised Bright Galaxy Sample

- What is the IRAS Bright Galaxy Sample (BGS)?
- Why a Revised BGS (RBGS)?
- The Nature of Luminous Infrared Galaxies (LIGs)

InfraRed Astronomical Satellite (IRAS) – 1983

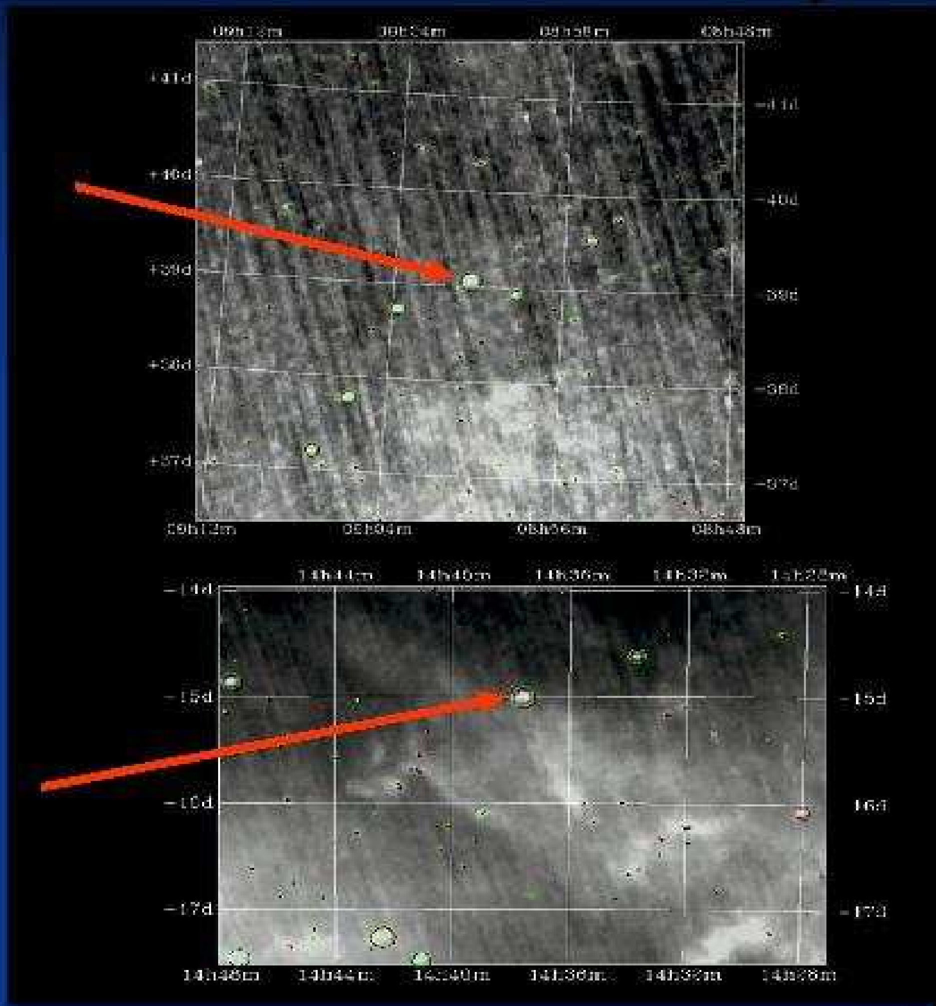


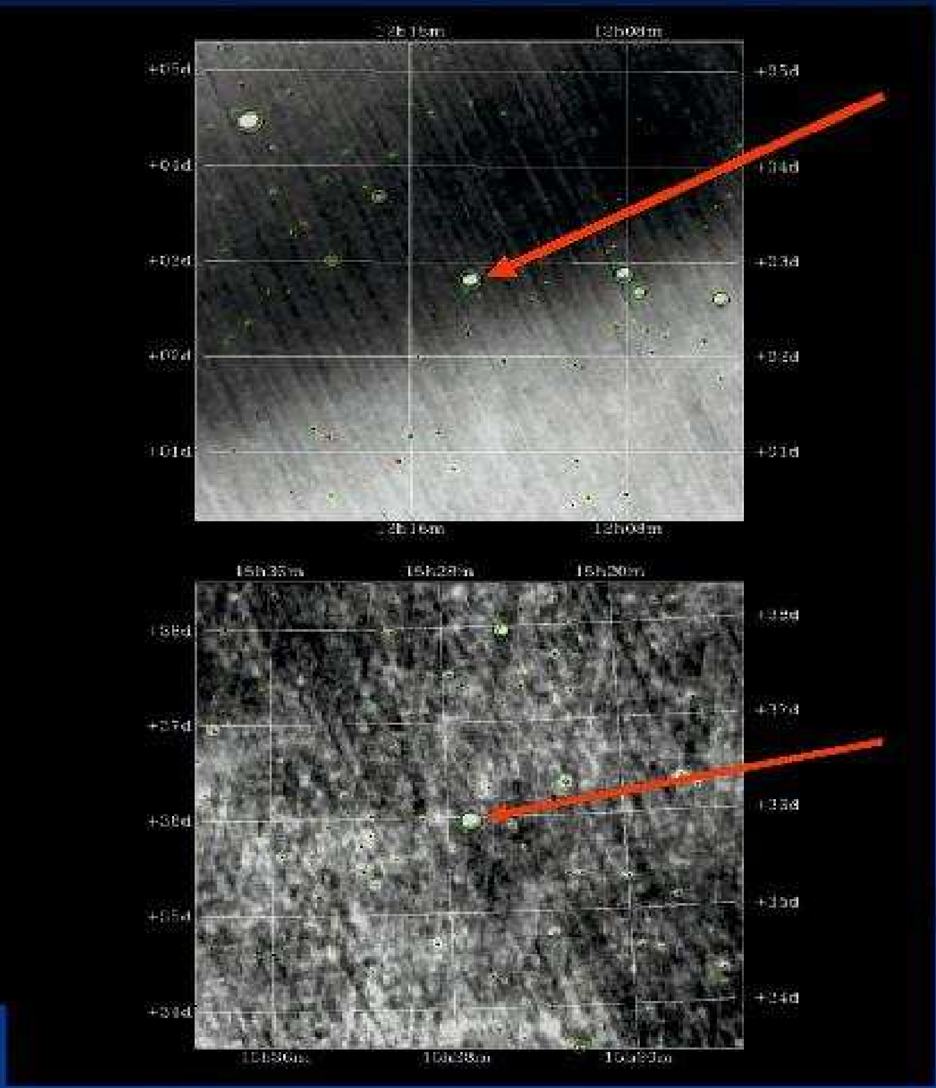
Orion Star Formation Regions

Andromeda Galaxy (M 31)

- Observed the sky at 12, 25, 60, 100 microns
- Emission from dust
- Revealed imbedded star formation
- And…

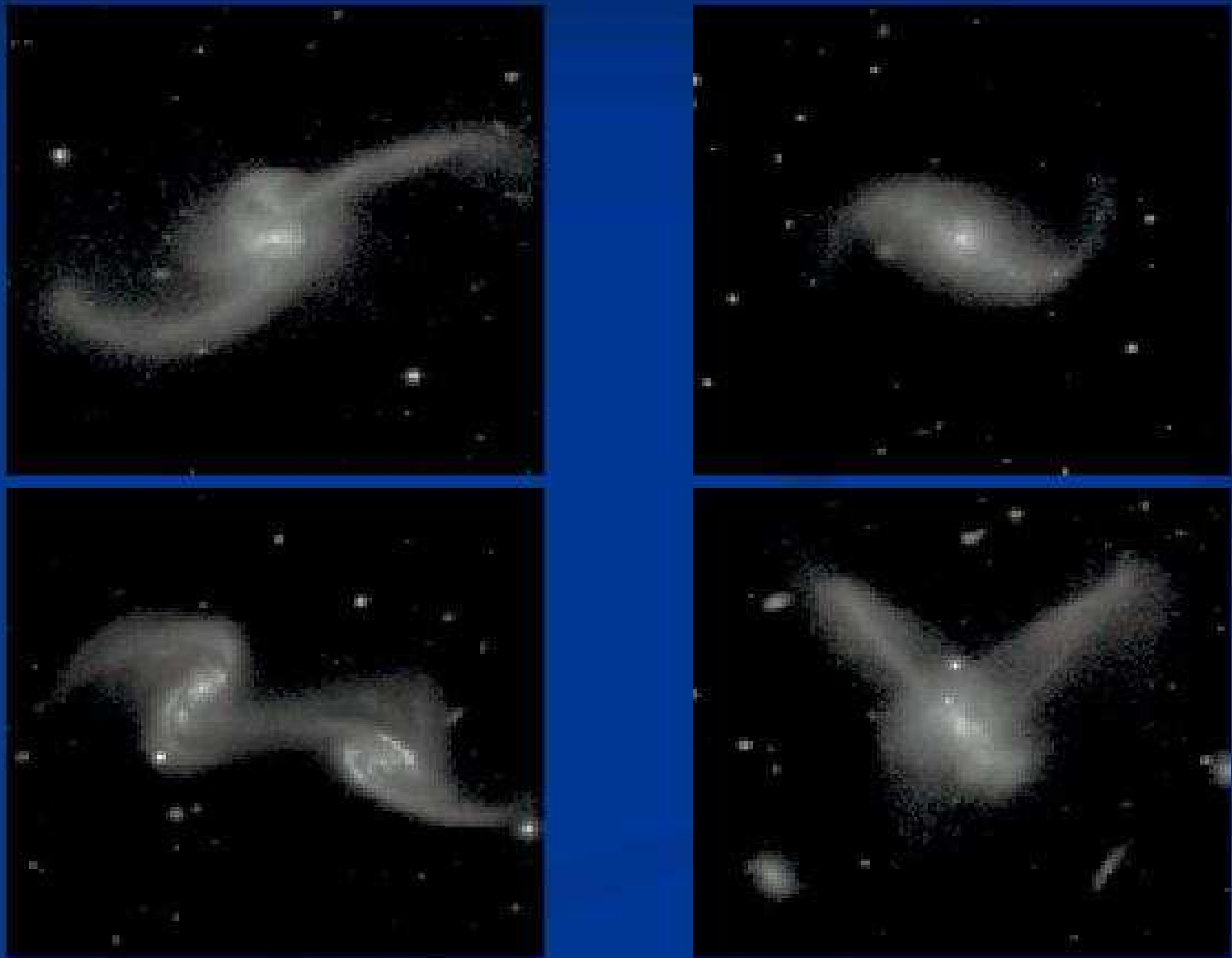
… Some other, unknown sources.



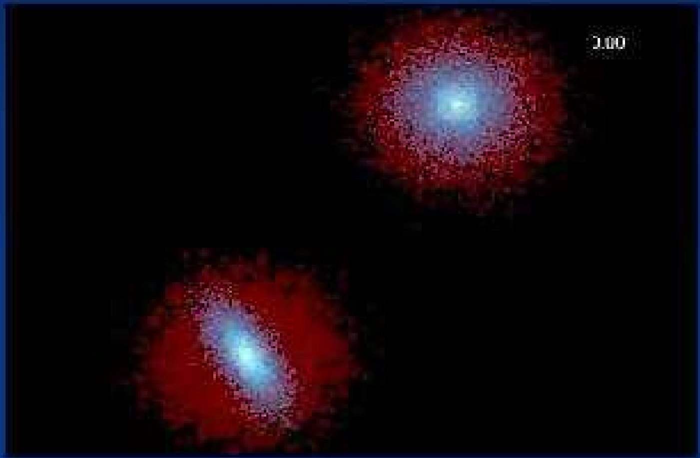


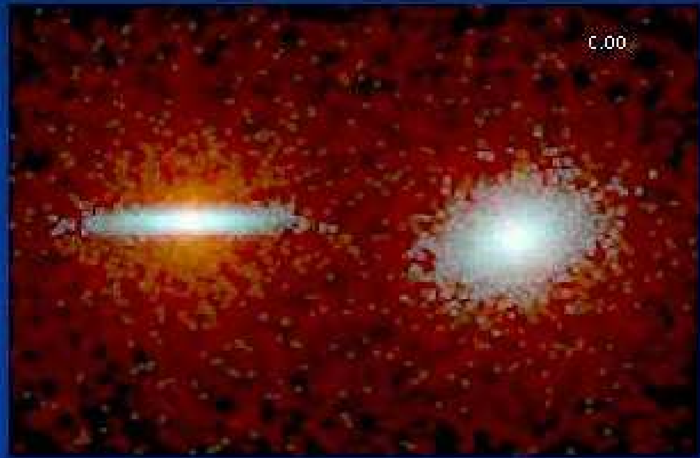
IRAS – 60 micron images

Optical follow-up revealed a population of infrared bright, interacting galaxies

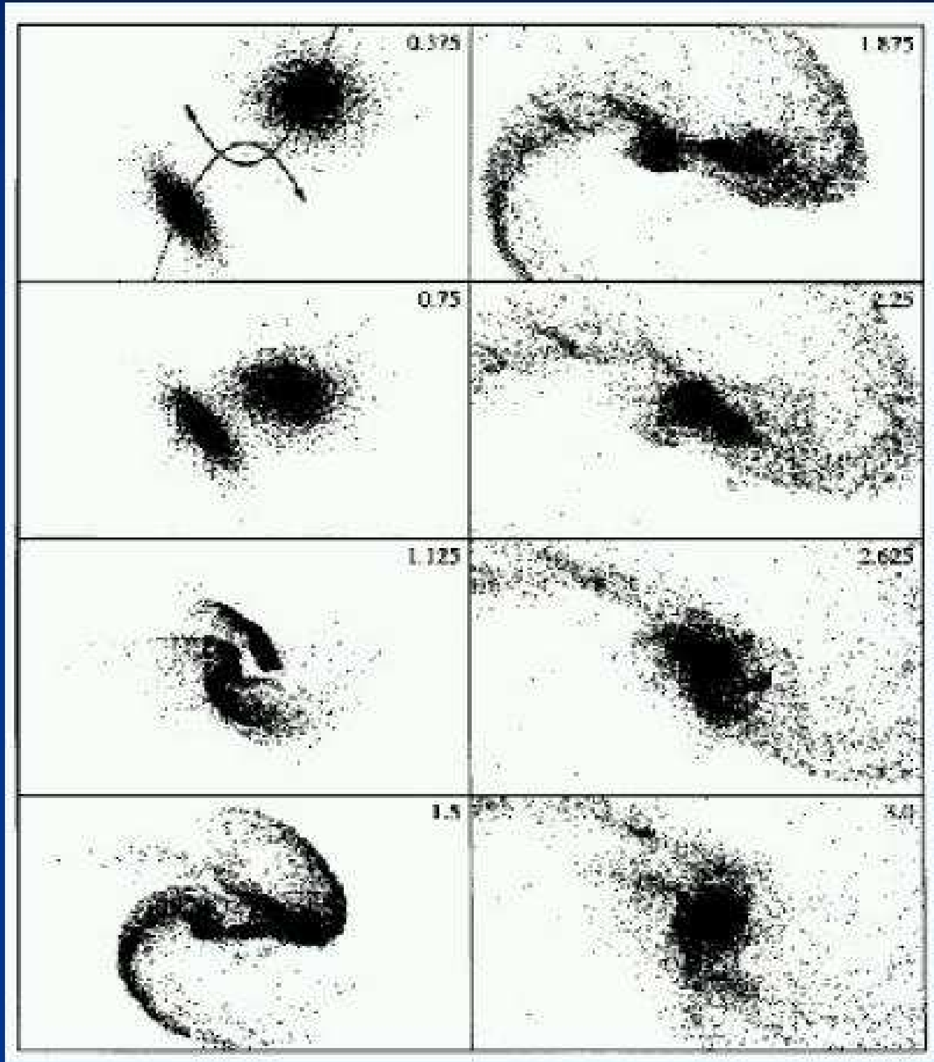


How do we know that they are interacting/merging?





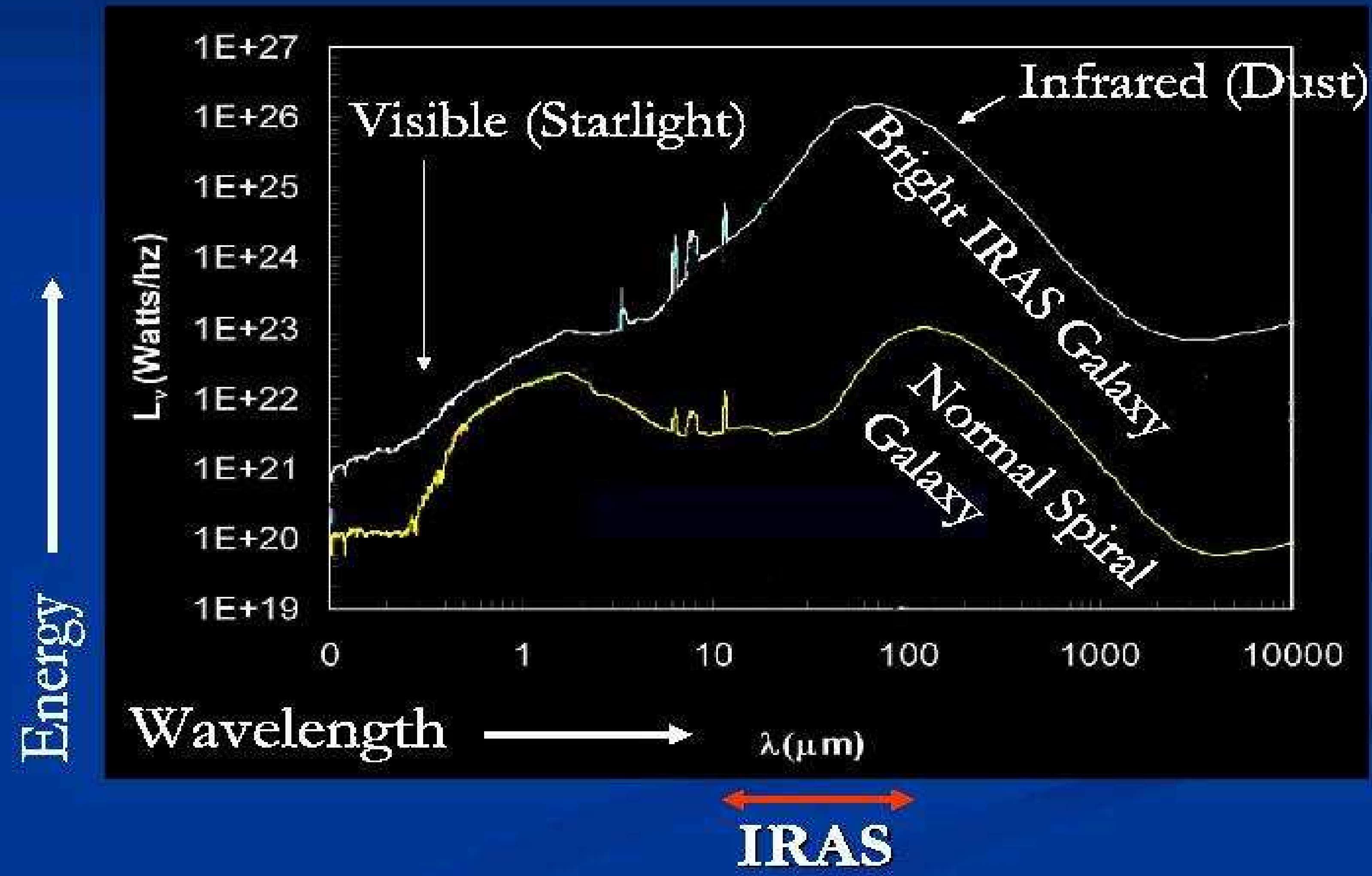
Simulations of Merging Disk Galaxies



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

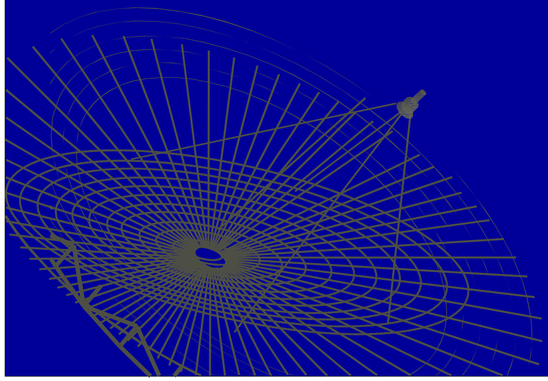
(e.g. Toomre & Toomre 1972; Barnes & Hernquist 1996; Mihos & Hernquist 1996)

Why were these galaxies easy for IRAS to detect?



What is the IRAS Bright Galaxy Sample?

- BGS1 (Soifer et al. 89, 87): 313 extragalactic sources with $f_{\upsilon}(60\mu m) \geq 5.24$ Jy in a ~14,500 sq.deg. area with Dec > -30 deg and |b| > 30 deg.
- BGS2 (Sanders et al. 95): 288 sources with same 60um flux limit and Dec <= -30 deg, 5 <= |b| <= 30 deg.
- This is ideally an excellent sample to study the properties of infrared bright galaxies, except there were a number of problems...



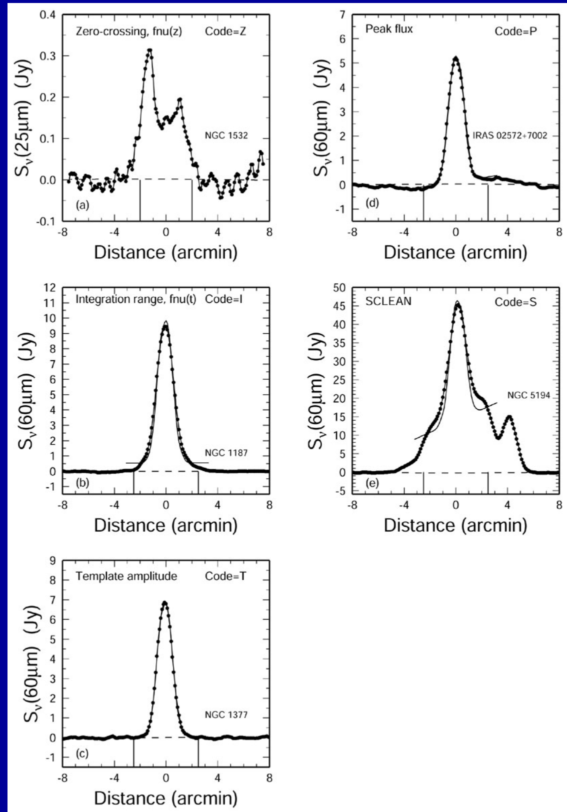
Why a Revised BGS?

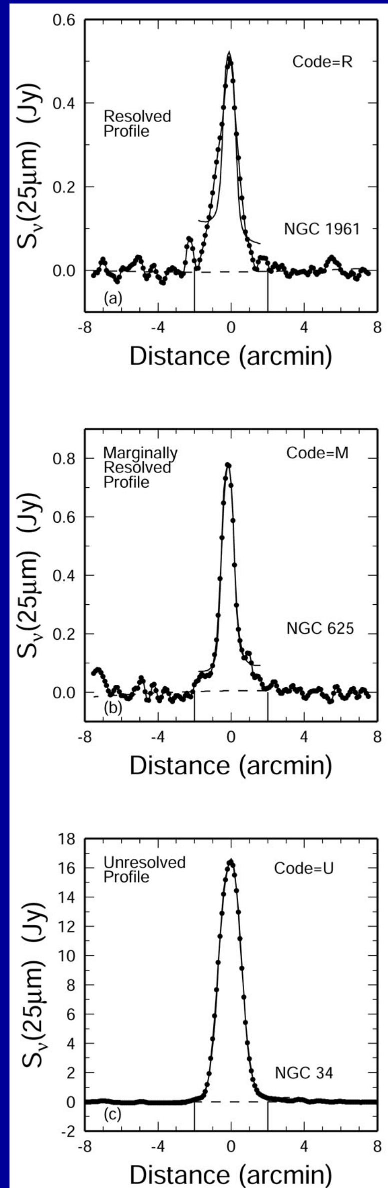
- Limitations of BGS1+BGS2 (601 sources):
  - Coadded IRAS measurements based on ADDSCAN/SCANPI processing before final PASS3 calibration of "Level 1 Archive" (May 1990)
  - Searches for extended objects (underestimated fluxes in PSC/FSC) 4′-8′ in diameter was incomplete. => Maximize use of NED and IRAS catalogs: 28 missed objects ("stragglers") found.
  - SCANPI's total in-band flux, fnu(t) used for resolved objects (other than galaxies with D>8′ [Rice et al. 1989]) underestimated emission for many objects. => Use interactive SCANPI and a computer program to choose zero-crossing flux when fnu(z) >= [fnu(t) + 2*sigma] (Fig. 1.).
- Result: Revised IRAS measurements for a complete sample of 629 extragalactic objects with |b| > 5 deg.
- Distance and luminosity estimates updated using flow model (Mould et al. 2000) to account for deviations from Hubble law due to "attractors"

RBGS Properties – IRAS Resolved Emission

Extended/resolved IRAS emission detected in many objects:

Band	Size	%Extended
12um	>0.77'	61%
25um	>0.78'	54%
60um	>1.44'	48%
100um	>2.94'	30%



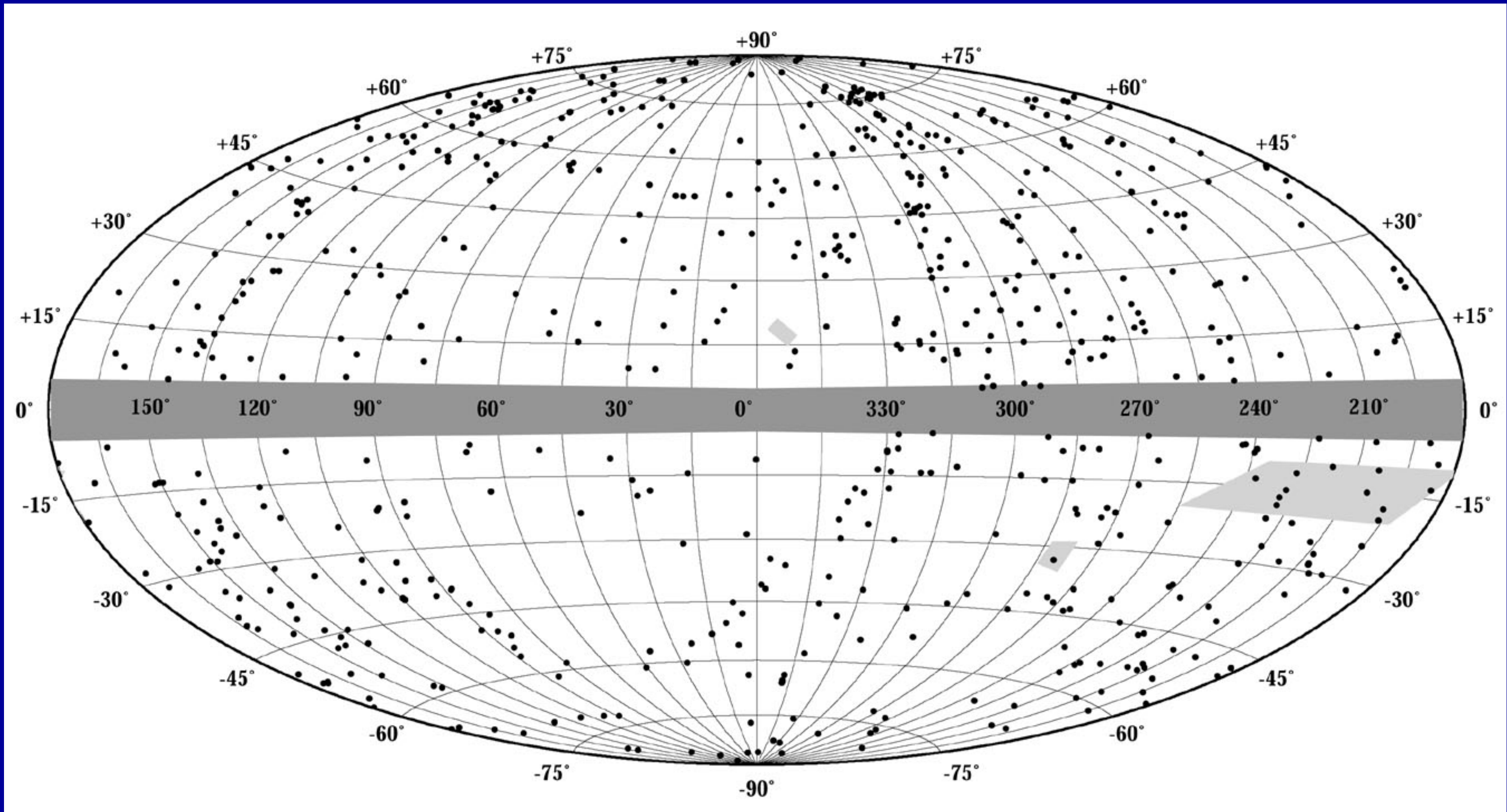


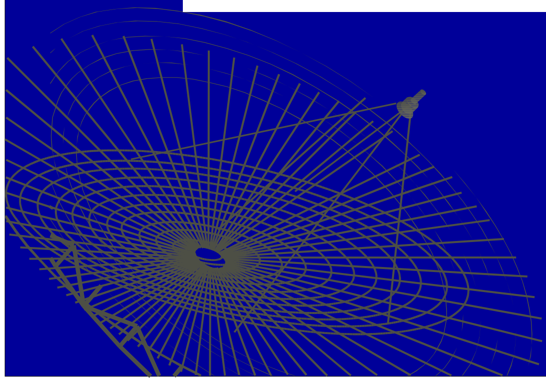
Lesson:

The IRAS PSC and FSC underestimate the total IRAS flux for most objects at 12um and ~1/2 of objects at 25 & 60um.

==> Use the RBGS flux values!

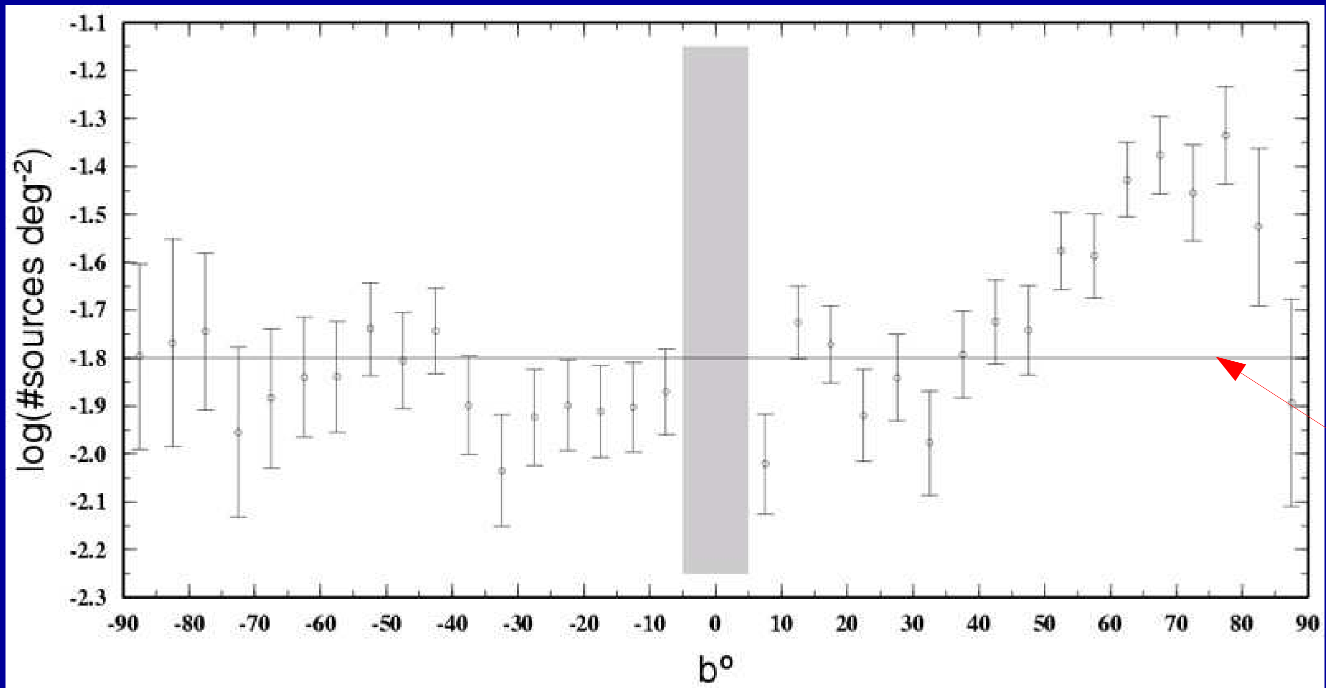
Aitoff projection in Galactic coordinates for 635 objects in the RBGS





37,658 degrees^2 ~ 91% sky

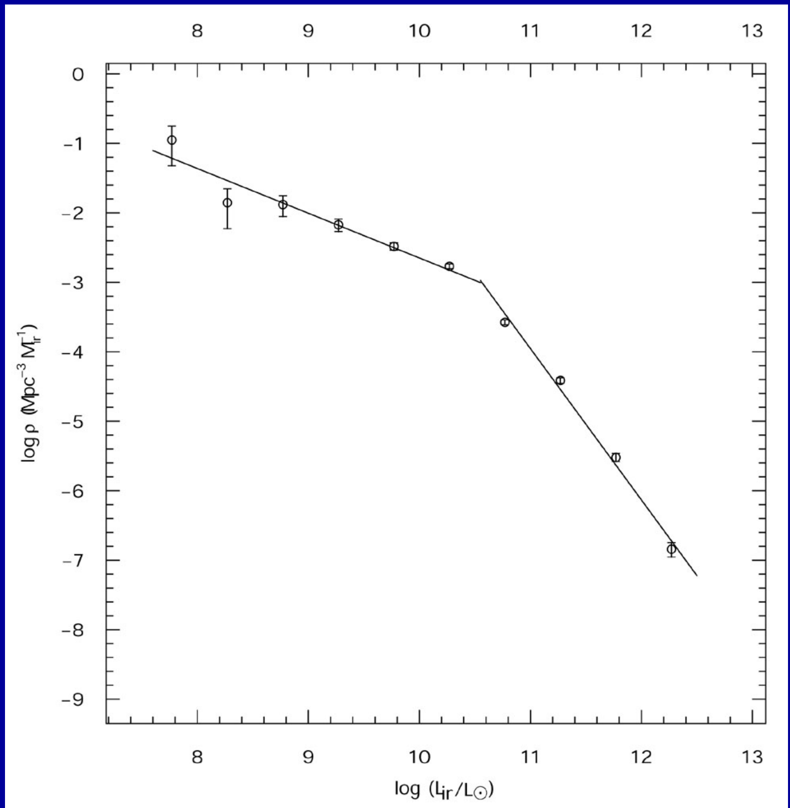
Surface Density of IRAS RBGS Objects



Median = 0.016 objects/deg^2

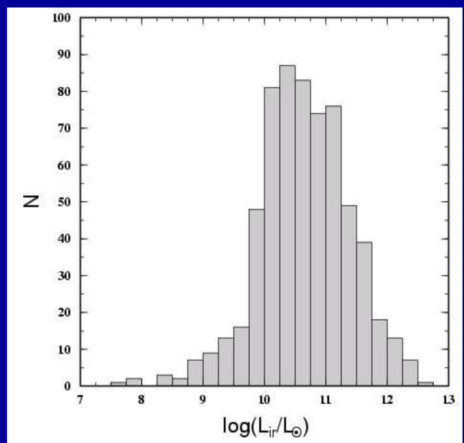
- The Local Supercluster produces a large (~30%) overdensity of objects in the NGP region compared to the SGC.
- Busswell et al. (2003, astro-ph/0302330) find a similar result using large optical surveys, but they call it a "hole" in the south.

RBGS Properties



Bolometric (L_{ir}[8-1000 μm]) luminosity function:

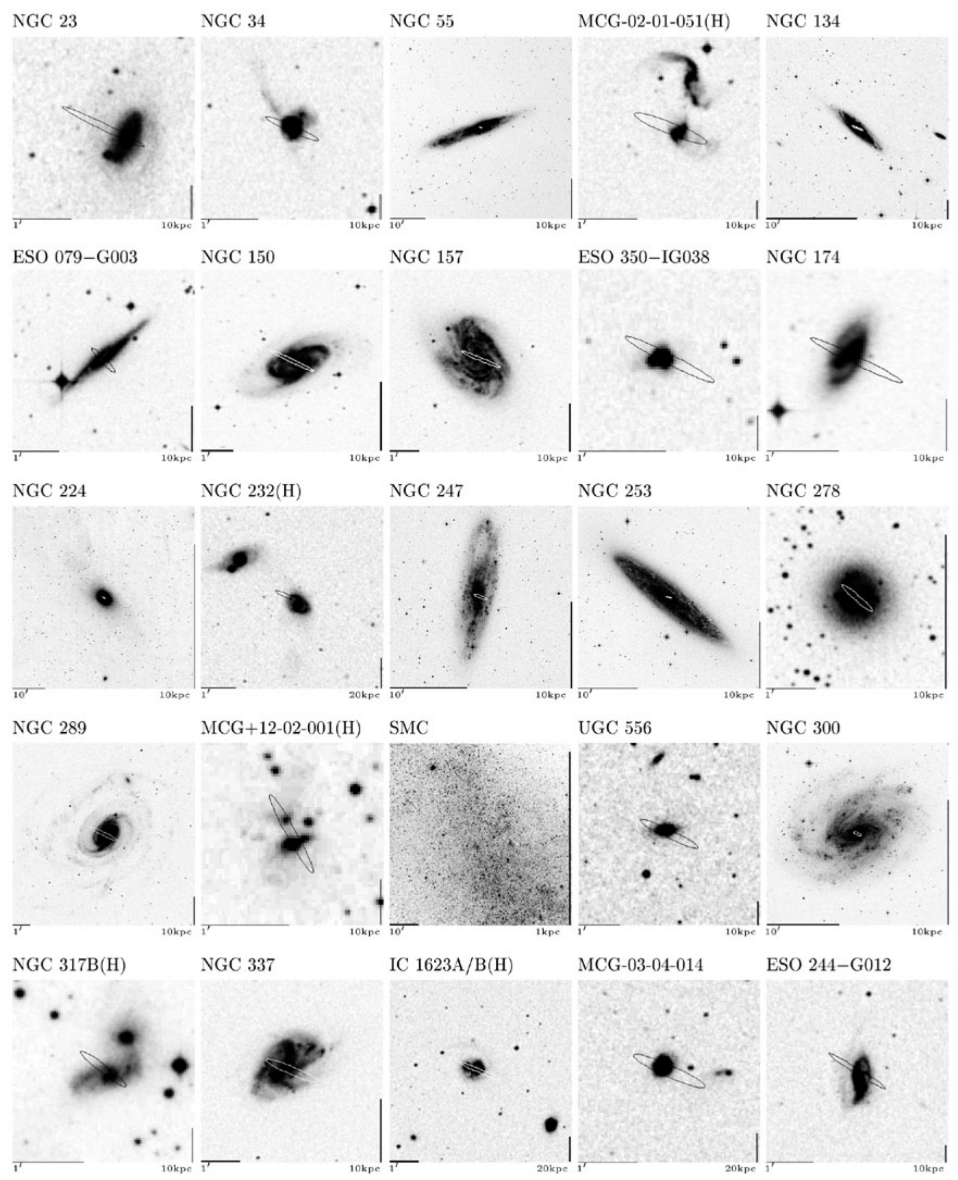
- Best fit with double power laws: α = (-1.5, -2.1)
- Log(L_{ir}/$L_\odot$) < 10.7: SD of RBGS ~= SD of optically selected Sy & SB
- Log(L_{ir}/$L_\odot$)> 11.5: SD of RBGS >= SD of optically selected Seyferts
- Log(L_{ir}/$L_\odot$) > 12.0: SD of RBGS ~= 2*SD of optically selected QSOs

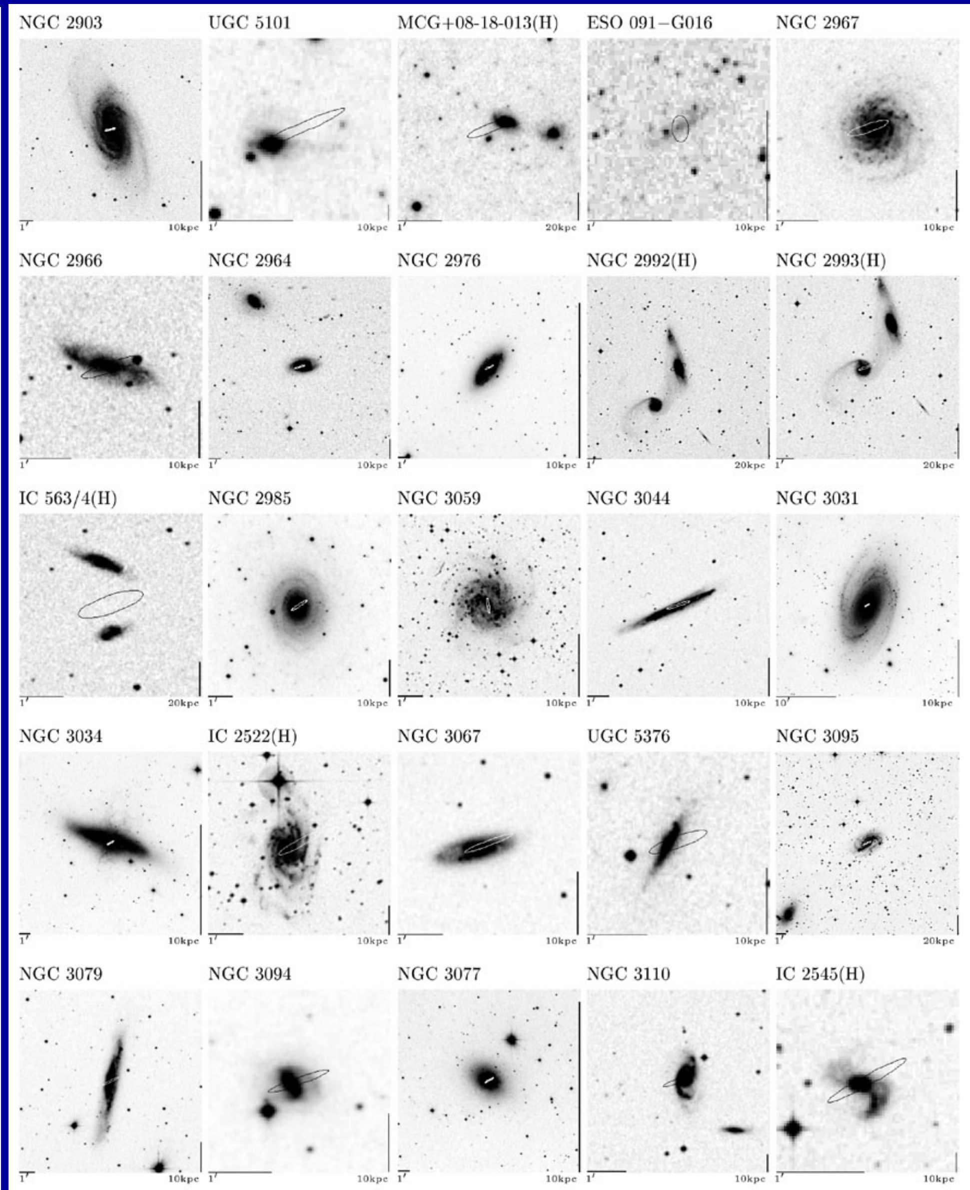


RBGS

- The RBGS represents a complete sample of the brightest extragalactic objects in the sky, offering the best sources for detailed, close-up study of IR emission processes, and for multiwavelength observations.
- Thus, in the far-infrared the RBGS is analogous to the RSA catalog for optically selected galaxies, or the 3CR survey of extragalactic radio sources.

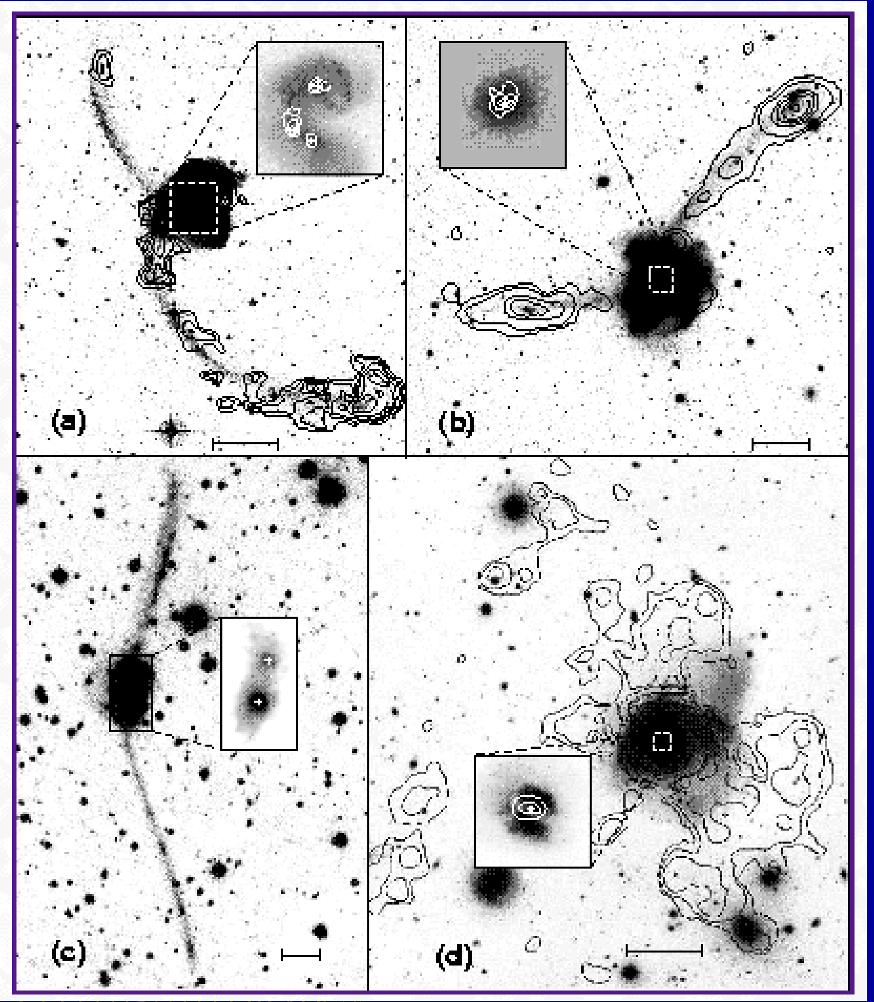
RBGS Properties -- Sample DSS Images





Atlas of DSS1 images with IRAS positional uncertainty ellipses and scale bars: note variation among pairs, etc.

RBGS Properties –Well Studied Mergers



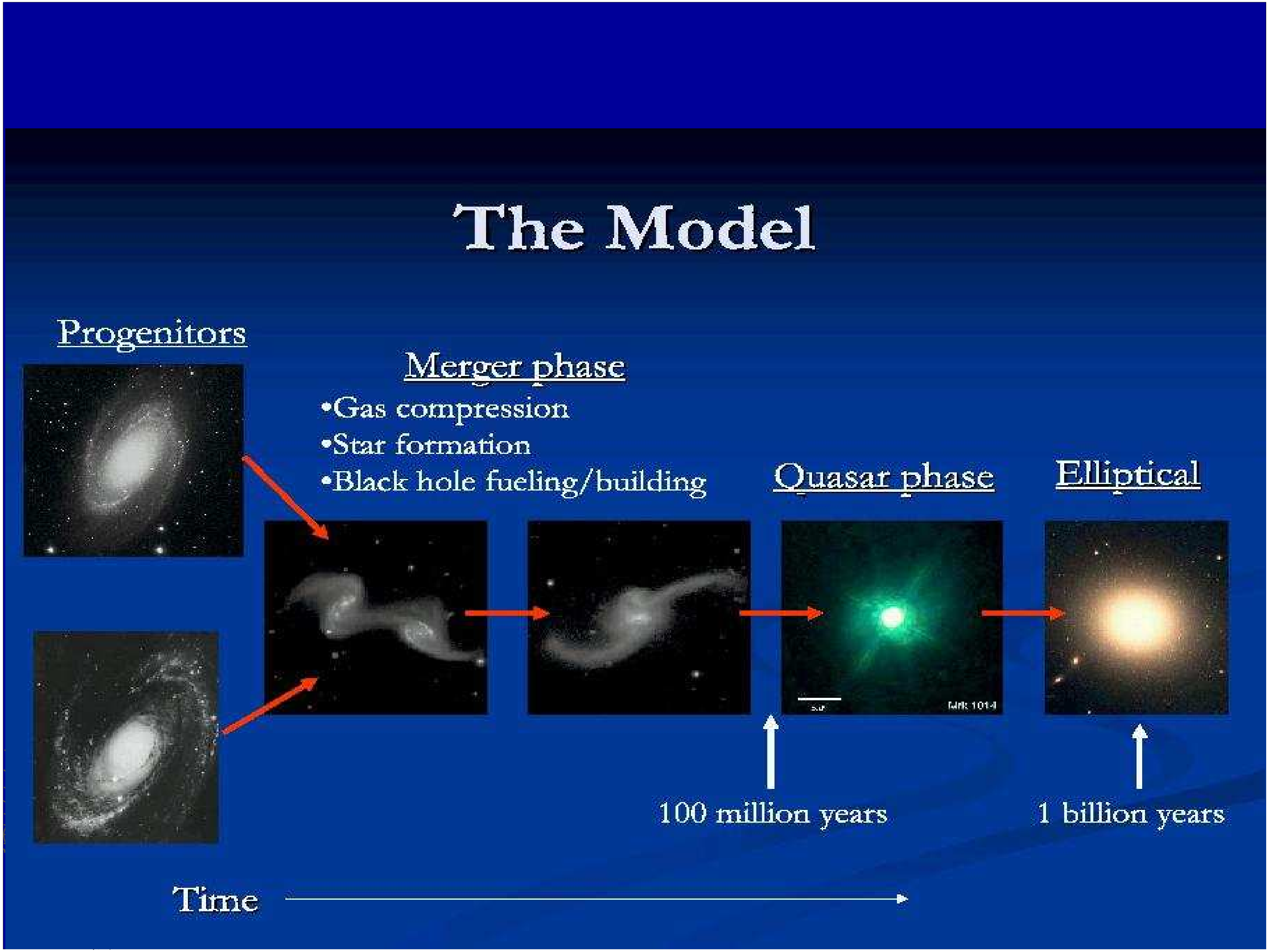
(a) NGC 4038/39=Arp 244= ``The Antennae";
(b) NGC 7252=Arp 226 = ``Atoms for Peace";
(c) IRAS 19254-7245= ``The Super Antennae";
(d) IC 4553/54 = Arp 220.

Contours: H I 21-cm line column density
Grayscale: deep optical (r-band) images

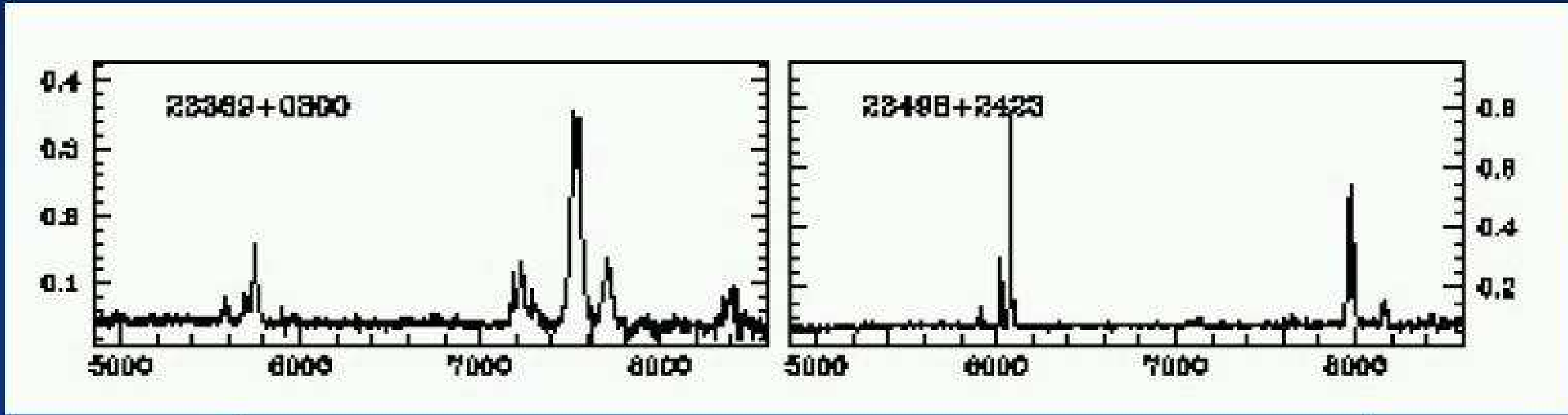
INSERTS: K-band (2.2µm) of nuclear regions of NGC 4038/39, NGC 7252, & IRAS 19254-7245, r-band (0.65 µm) of Arp 220. White contours: CO(1->0) line from OVRO mm-wave interferometer.

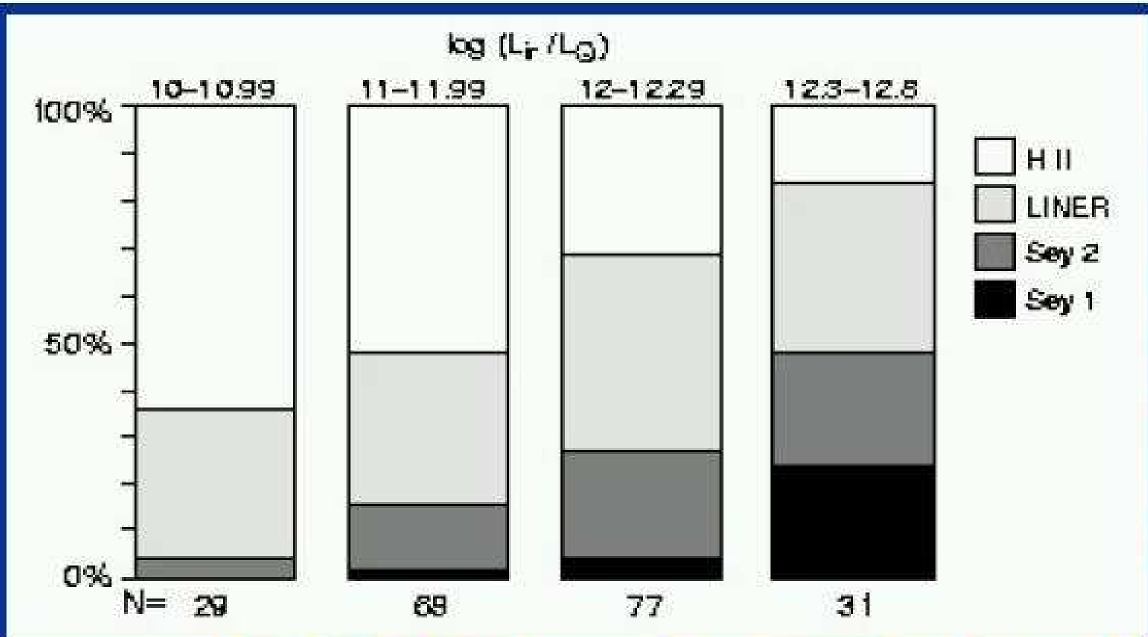
The scale bar represents 20 kpc.

From Sanders & Mirabel (1996, ARA&A)


The Model
Progenitors
Merger phase
•Gas compression
•Star formation
•Black hole fueling/building
Quasar phase
Elliptical
Mrk 1014
100 million years
1 billion years
Time

4. Increase in AGN Fraction with Increasing Infrared Luminosity





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

RBGS Properties Vs. L_{ir}

		10.5-10.99	11.0-11.49	11.5-11.99	12.0-12.50
	log (L_{ir} / $L_{\odot}$)				
No. of objects [a]		50	50	30	40
Morphology	merger	12%	32%	66%	95%
	close pair	21%	36%	14%	0%
	single (?)	67%	32%	20%	5%
Separation [b]	[kpc]	36.	27.	6.4	1.2
Opt Spectra	Seyfert 1 or 2	7%	10%	17%	34%
	LINER	28%	32%	34%	38%
	H II	65%	58%	49%	28%
L_{ir} / L_{B} [c]		1	5	13	25
L_{ir} / L'_{CO} [c]	[$L_{\odot}$ (K km s^{-1} $pc^{2})^{-1}$]	37	78	122	230

[a] Objects in the *IRAS* BGS plus additional ULIGs from Kim & Sanders (1996).

[b] Mean projected separation of nuclei for mergers and close pairs only.

[c] Mean values

Mapping Molecular Gas in Infrared Ultraluminous Galaxies with Merging Nuclei

Collaborators:

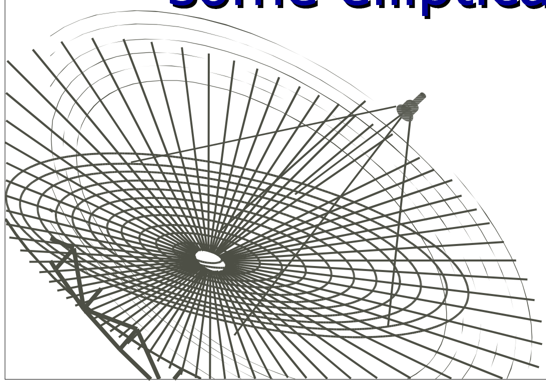
Aaron Evans (SUNY, Stony Brook)

Dave Sanders (IfA, U. Hawaii)

Jason Surace (SSC, IPAC/Caltech/JPL)

The Most Luminous Objects in the Local Universe

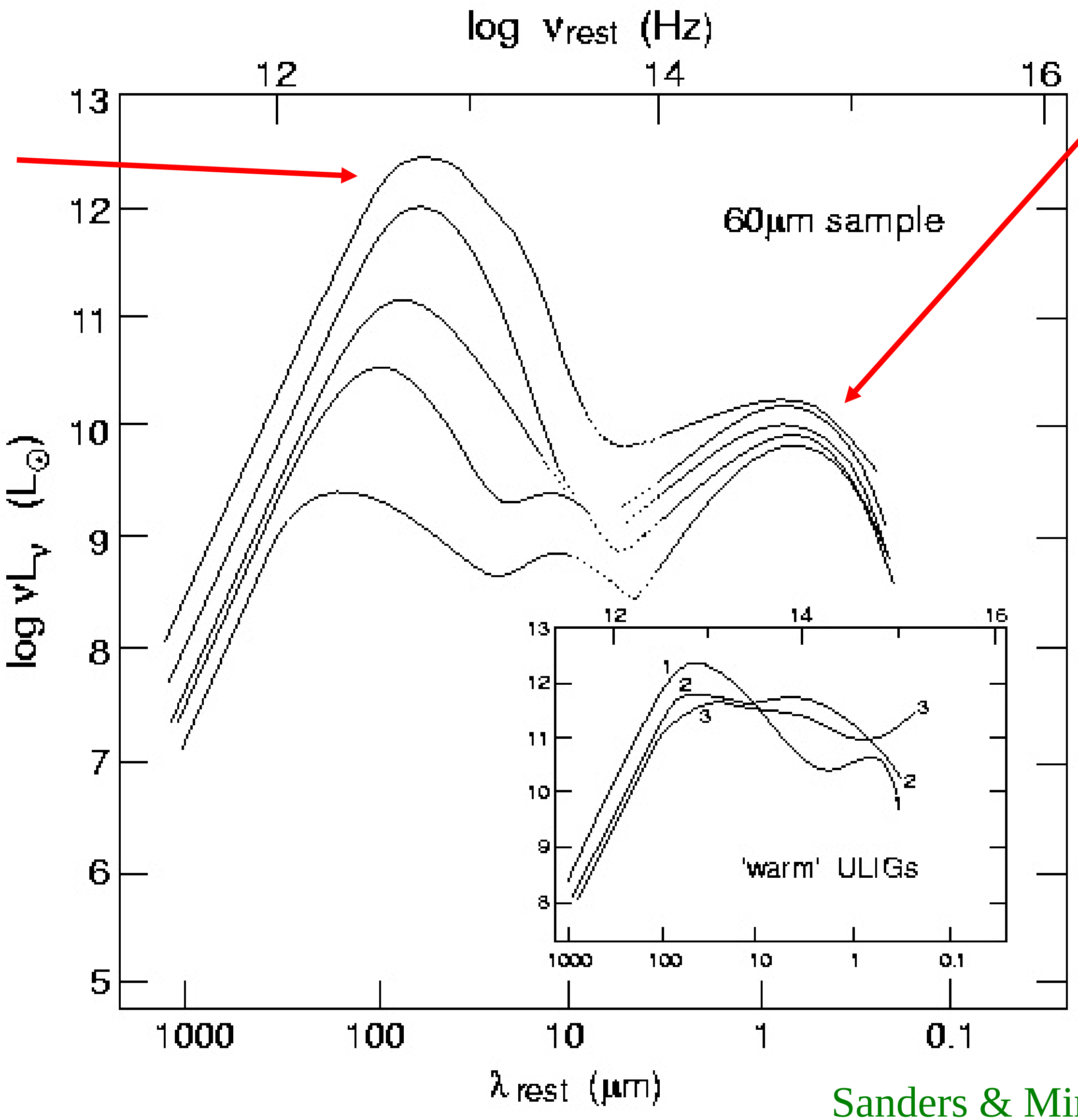
- Ultraluminous Infrared Galaxies (ULIGs): $L_{IR} > 10^{12}\ L_{\odot}$
- Luminous Infrared Galaxies (LIGs): $L_{IR} = 10^{11.00\text{-}11.99}\ L_{\odot}$
- The luminosity function of ULIGs is comparable to classic UV-excess QSOs (e.g., PG quasars)
- "Cool" ($f_{25}/f_{60} < 0.2$) and "warm" ($f_{25}/f_{60} > 0.2$) ULIG varieties may represent earlier and later stages in an evolutionary sequence as QSOs emerge from their dusty nursery in merging disk galaxies (Sanders et al. 1988a, b)
- LIGs and ULIGs may also play a key role in the formation of some elliptical galaxies



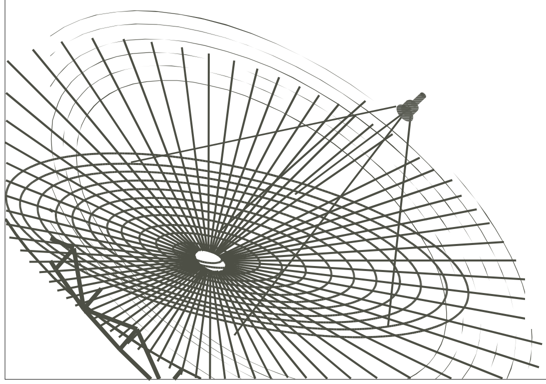
Spectral Energy Distribution of ULIGs

Peak Emission in the FIR (60 μm)

Optical



Sanders & Mirabel 1996

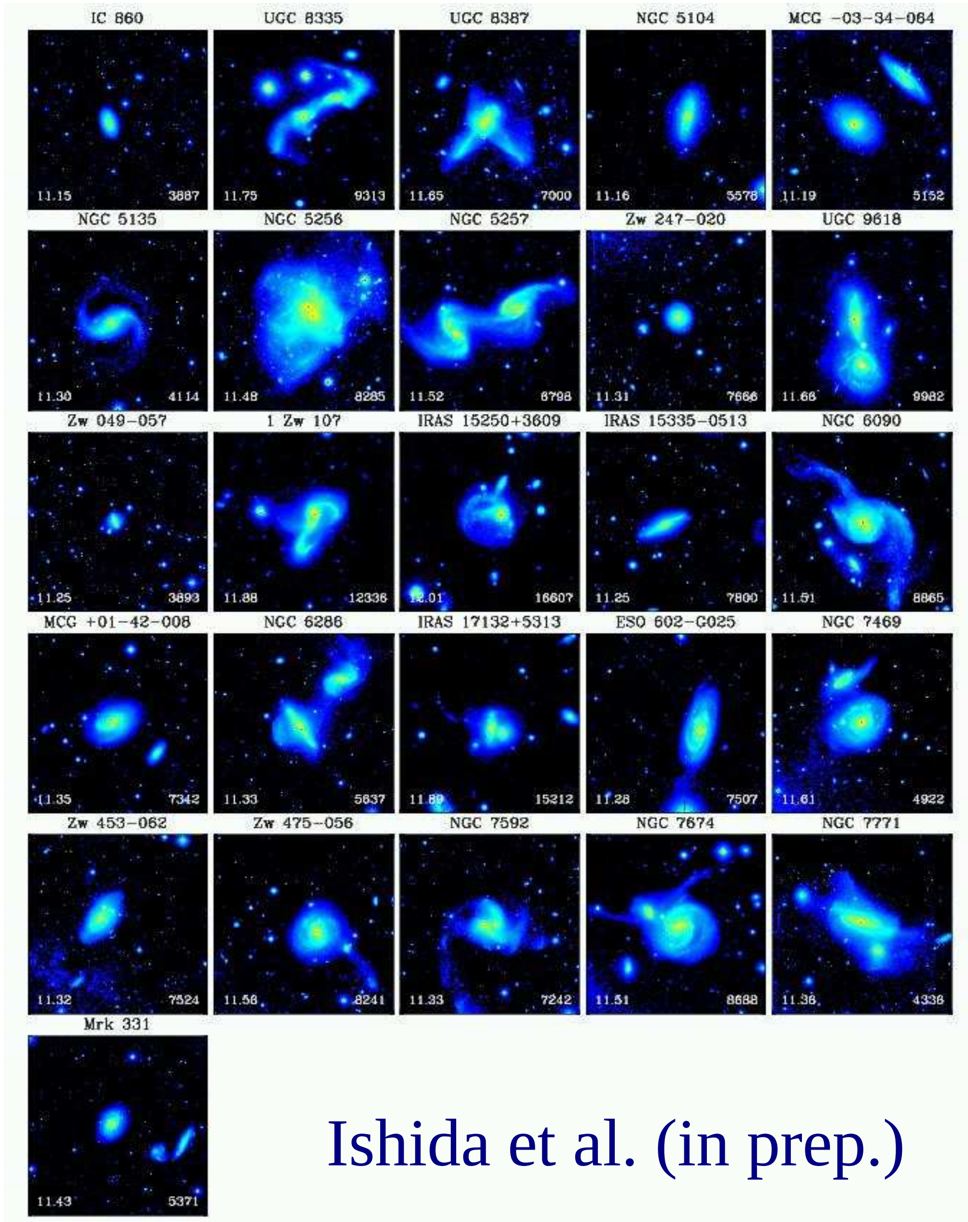


Visual Images of ULIGs

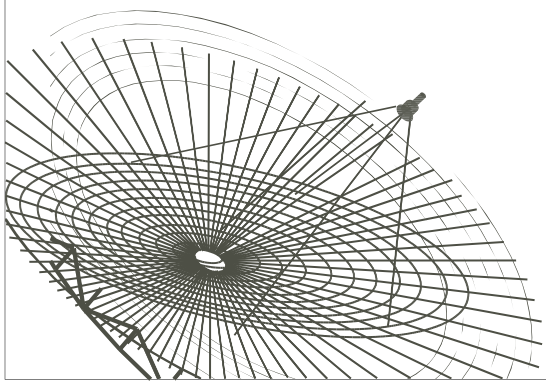
- Evidence for ongoing galaxy mergers: tidal tails and double nuclei

- Emission lines show Seyferts, LINERs, and starburst (H II) activity; the AGN fraction increases with L_{ir}

- Powered by AGNs and/or starbursts that require vast amounts of fuel...



Ishida et al. (in prep.)



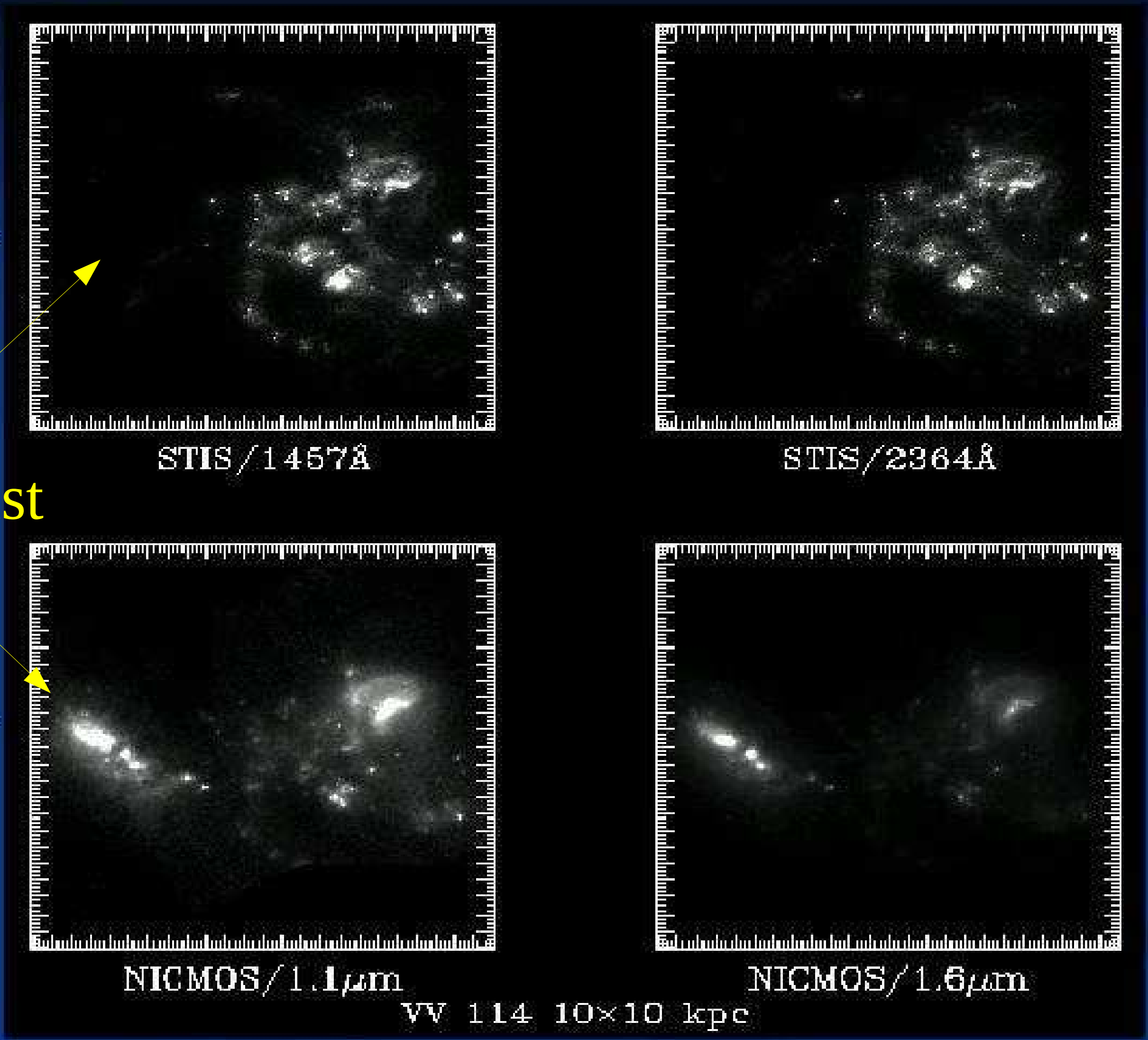
The effects of dust.

Ultraviolet (0.1-0.2 µm)

AGNs can hide behind dust

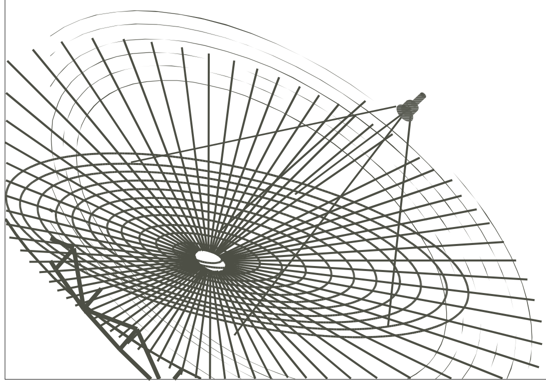
Near-Infrared (1 – 2 µm)

(Note: Optical = 0.55 µm)



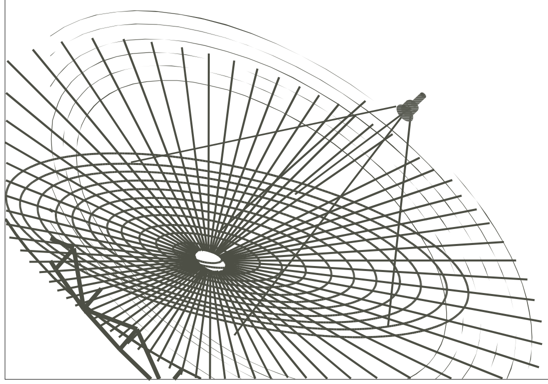
The Importance of Molecular Gas

- Within giant molecular clouds, cool interstellar gas provides the fuel for star formation
- 3mm CO(1-0) emission line is collisionally excited by H_2 and thus provides a convenient tracer of the molecular gas abundance in galaxies
- Single-dish CO observations of ULIGs indicate:
  - Few x 10^9 - 10^{10} $M_\odot$ of gas
  - SFRs ~ 100s of $M_\odot$/yr
  - Depletion times ~ 10^7 - 10^8 yr



Motivation

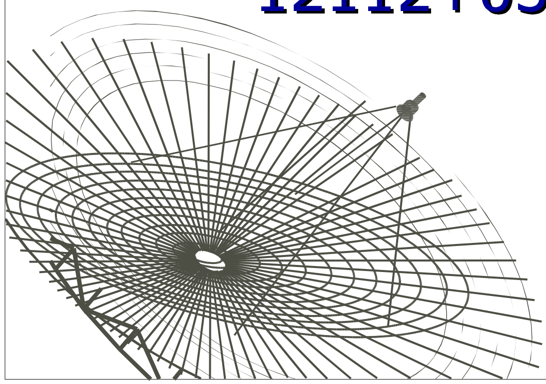
- What is the spatial and kinematic distribution of the molecular gas in ULIGs?
- Do CO properties correlate with merger phase?
- Is molecular gas important in fueling AGN?
- Do CO observations provide clues that ULIGs are evolving into elliptical galaxies?



Sample

Among 21 ULIGs in the IRAS Bright Galaxy Sample (f60μm > 5.24 Jy: Soifer et al. 1987) selected by Sanders et al. (1988a) and the IRAS Warm Galaxy Sample (f60μm > 1.5 Jy and f25μm/f60μm > 0.2 (Sanders et al. 1988b) we require:

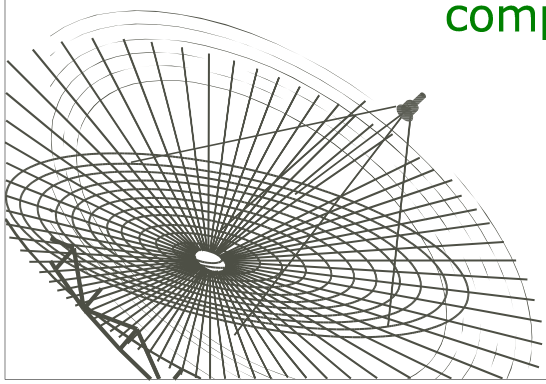
- Confirmed strongly interacting/merging pairs with extensive multi-wavelength data available for study with CO
- Nuclei with separations that can be resolved with the OVRO mm array (R > 2”)
- Five objects satisfy these criteria: IRAS 08572+3915, IRAS 13451+1232 (PKS 1345+12), Mrk 463, IRAS 12112+0305, and IRAS 14348-1447.



Owens Valley Radio Observatory (OVRO) Millimeter Array Observations

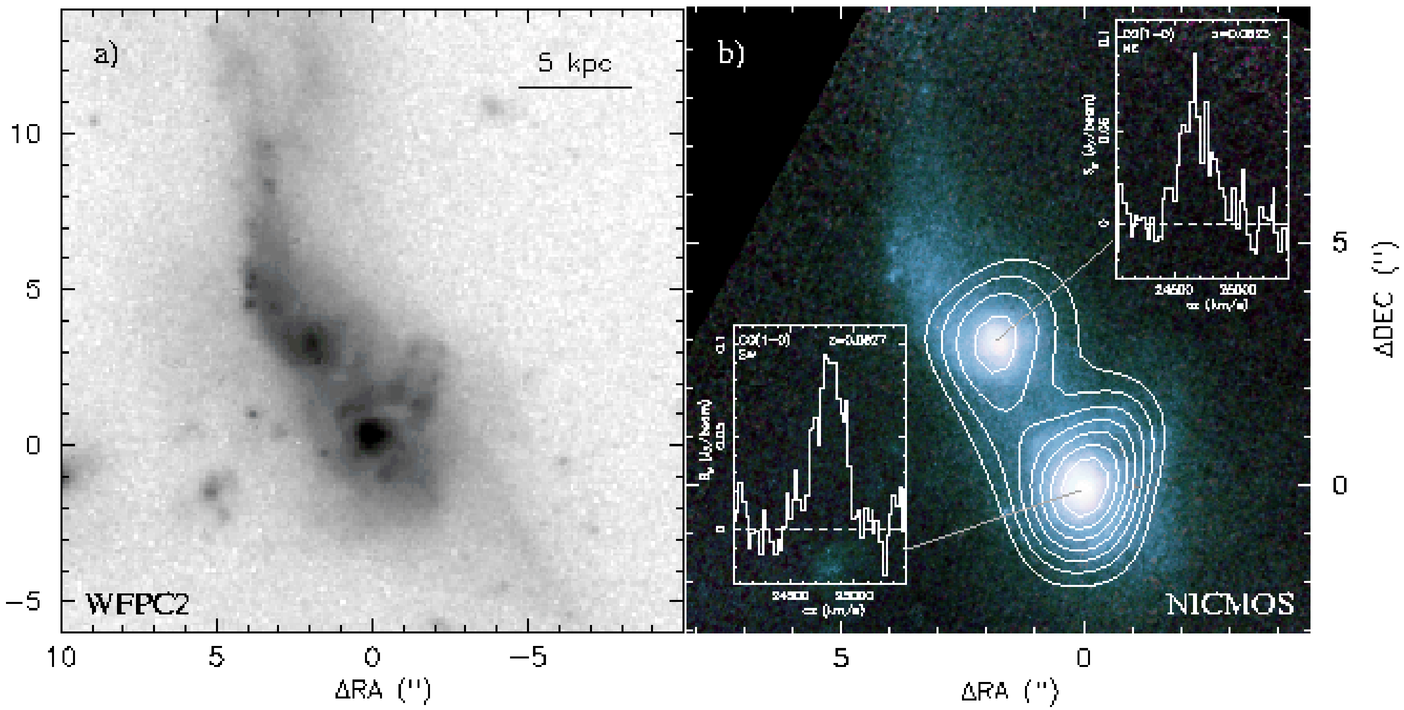
- Five observing periods from Nov. 1996 - Apr. 1999
- Six 10.4m telescopes; longest baseline was 242m
- Low-res configuration provided ~ 4” FWHM sythesized beam
- High-res configuration provided ~ 2” FWHM beam
- QSOs observed every 25 min. to monitor phase and gain variations
- Uranus used for flux calibration
- Data reduction using MMA (Scoville et al. 1993), mapping with DIFMAP (Shepherd et al. 1995) and spectra extraction with AIPS (NRAO)

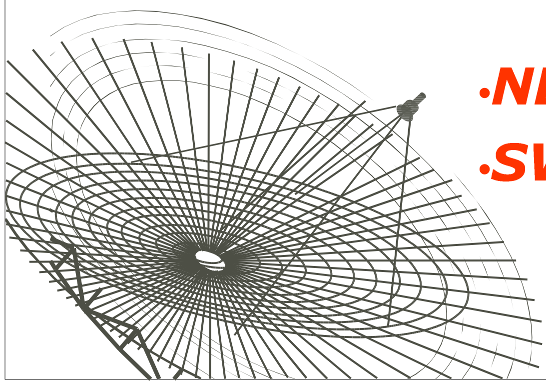
HST WFPC and NICMOS broadband images used for comparison with CO



OVRO Results - IRAS 14348-1447

- $z=0.0825$, D=335 Mpc, Lir = 1.9×10^{12} $L_\odot$
- Cool ULIG ($f25\mu m/f60\mu m < 0.2$)
- Two nuclei separated by 3.5” (4.8 kpc)
- Total $M(H_2)=3.2\times10^{10}$ Msun (14 x H_2 mass of Milky Way)



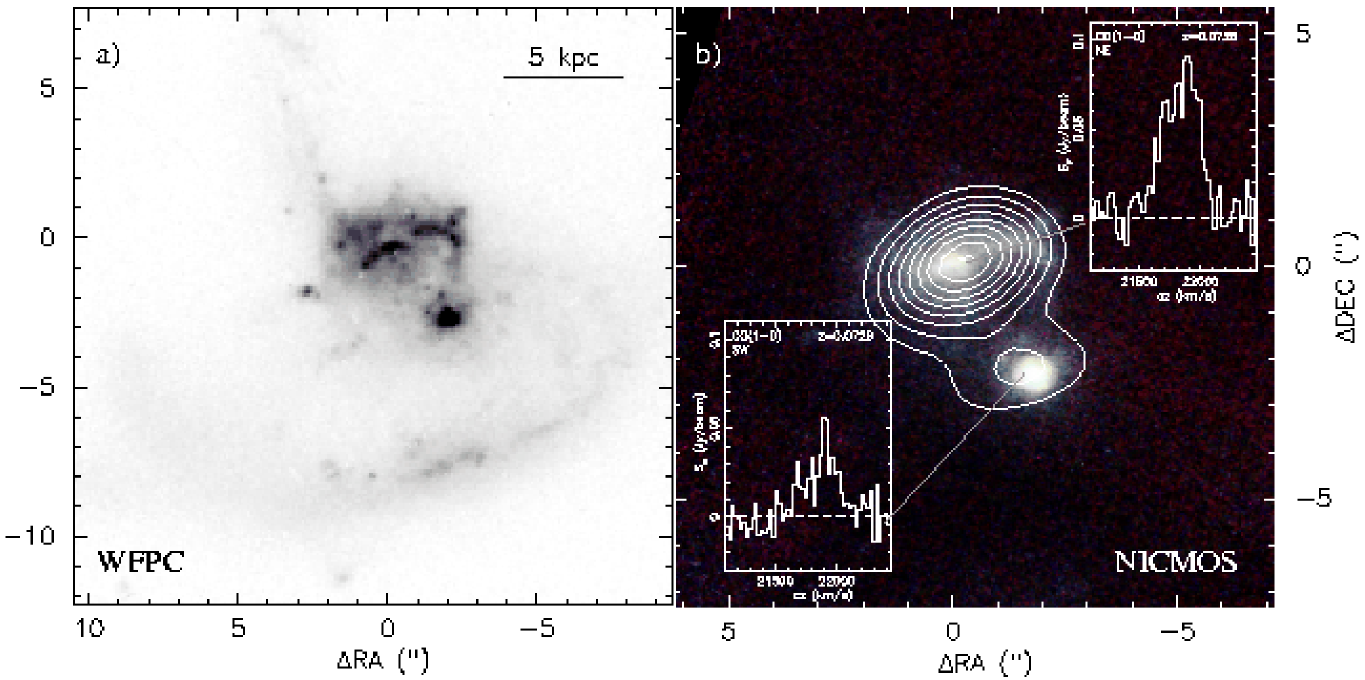


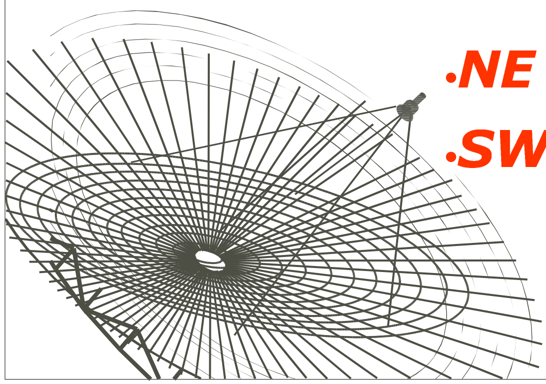
- ***NE nucleus (LINER) has $M(H_2)= 1.2\times10^{10}$ Msun***
- ***SW nucleus (LINER) has $M(H_2)= 2.0\times10^{10}$ Msun***

Evans, A. S., Surace, J. A.,& Mazzarella, J. M., 2000, ApJ, 529, L85

IRAS 12112+0305

- z=0.0728, D=296 Mpc, $L_{ir} = 1.8x10^{12}\ L_\odot$
- Cool ULIG (f25μm/f60μm < 0.2)
- Two nuclei separated by 2.9" (3.7 kpc)
- Total $M(H_2)=1.7x10^{10}$ M



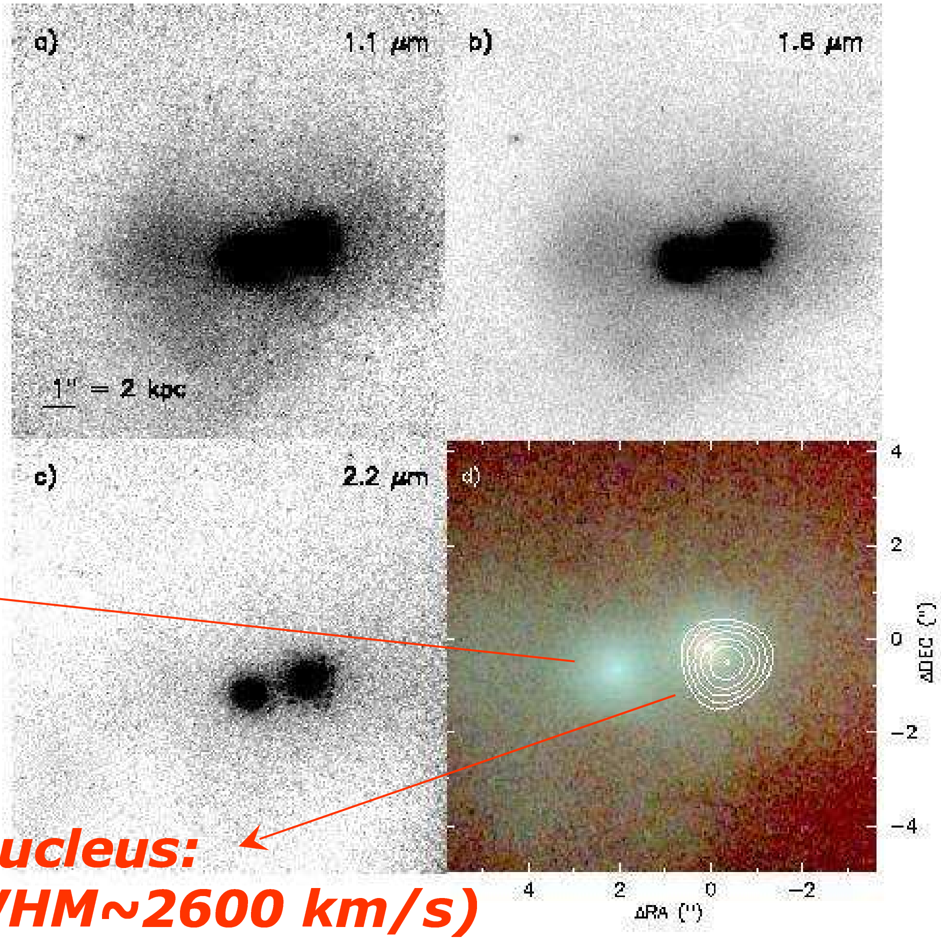


- ***NE nucleus (LINER) has $M(H_2)= 1.3x10^{10}\ M_\odot$***
- ***SW nucleus (LINER) has $M(H_2)= 4.4x10^{9}\ M_\odot$***

Evans, A. S., Mazzarella, J. M., Surace, J. A. & Sanders, D. B. 2002, ApJ, 580, 749.

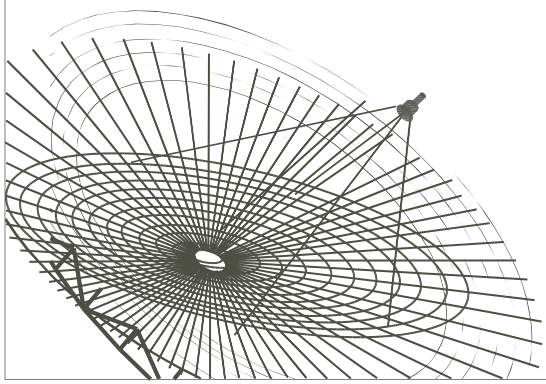
IRAS 13451+1232=PKS 1345+12

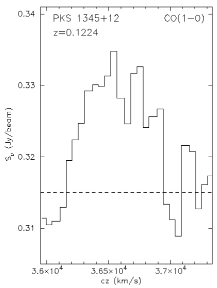
- $z=0.1224$, D = 503 Mpc, $L_{ir} = 1.7\times10^{12}\ L_\odot$
- Warm ULIG (f25μm/f60μm > 0.2)
- P(408 MHz) = 2.4×10^{26} W/Hz
- Two nuclei separated by 2" (4 kpc)
- Prime candidate for link between ULIGs and powerful radio galaxies



SE nucleus undetected:
$M(H2) < 1.2\times10^{9}\ M_\odot$

All detected CO is on the NW nucleus:
dust-enshrouded QSO (Paα FWHM~2600 km/s)





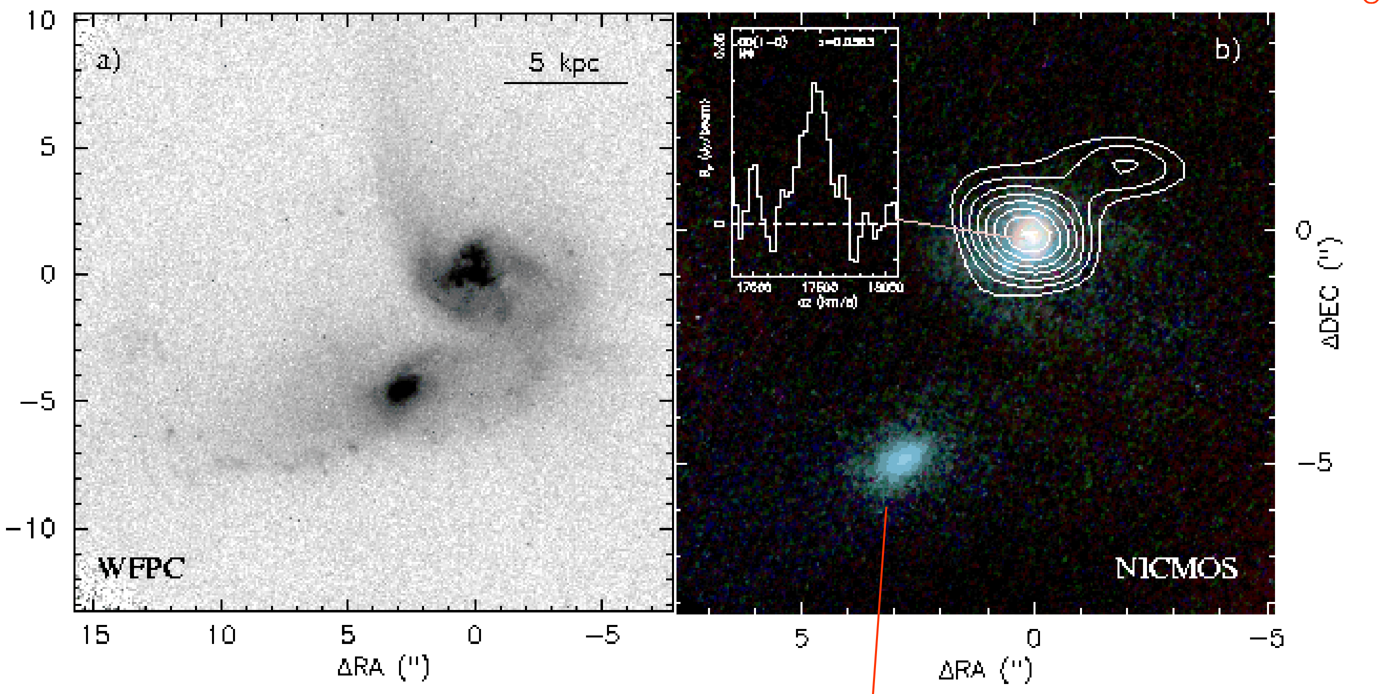
- **CO(1-0) emission and 2.7 mm continuum unresolved with OVRO 2.2" beam**
- **$M(H_2)=3.3\times10^{10}\ M_\odot$ (14 x H_2 mass of MW)**
- **$M(H_2)$ concentration > 2000 $M_\odot\ pc^{-2}$**

Evans, A. S., Kim, D.-C., Mazzarella, J. M.,
Scoville, N. Z., & Sanders, D. B., 1999, ApJ, 521, L107

IRAS 08572+3915

- $z=0.0583$, D = 236 Mpc, $L_{ir} = 1.3\times10^{12}\ L_\odot$
- Warm ULIG (f25μm/f60μm > 0.2)
- Two nuclei separated by 5.4” (5.6 kpc)
- Total $M(H_2)=3.5\times10^9\ M_\odot$

All detected CO is on the NW nucleus (LINER): $3.5\times10^9\ M_\odot$



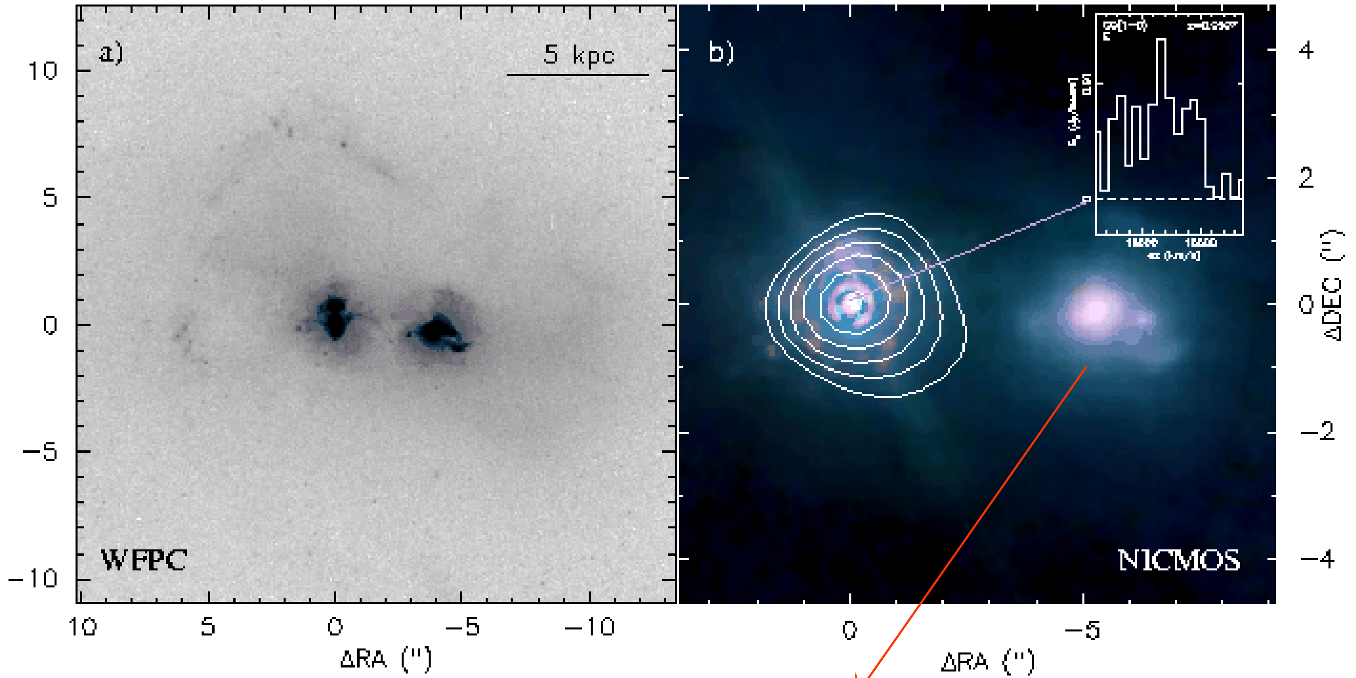
SE nucleus (LINER) undetected: $M(H_2) < 5.0\times10^8\ M_\odot$

Evans, A. S., Mazzarella, J. M., Surace, J. A. & Sanders, D. B. 2002, ApJ, 580, 749.

IRAS 13536+1836 = Mrk 463

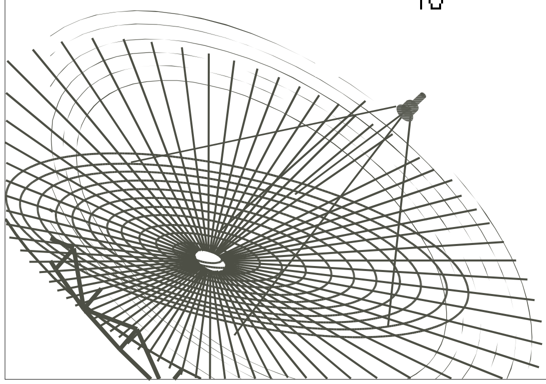
- $z=0.0509$, D = 206 Mpc, $L_{ir} = 5.8 \times 10^{11}\ L_\odot$
- Warm ULIG (f25μm/f60μm > 0.2)
- Two nuclei separated by 4.1" (3.7 kpc)
- Total $M(H_2)=1.3 \times 10^9\ M_\odot$

All detected CO on the E nucleus (dust-enshrouded QSO): $1.3 \times 10^9\ M_\odot$



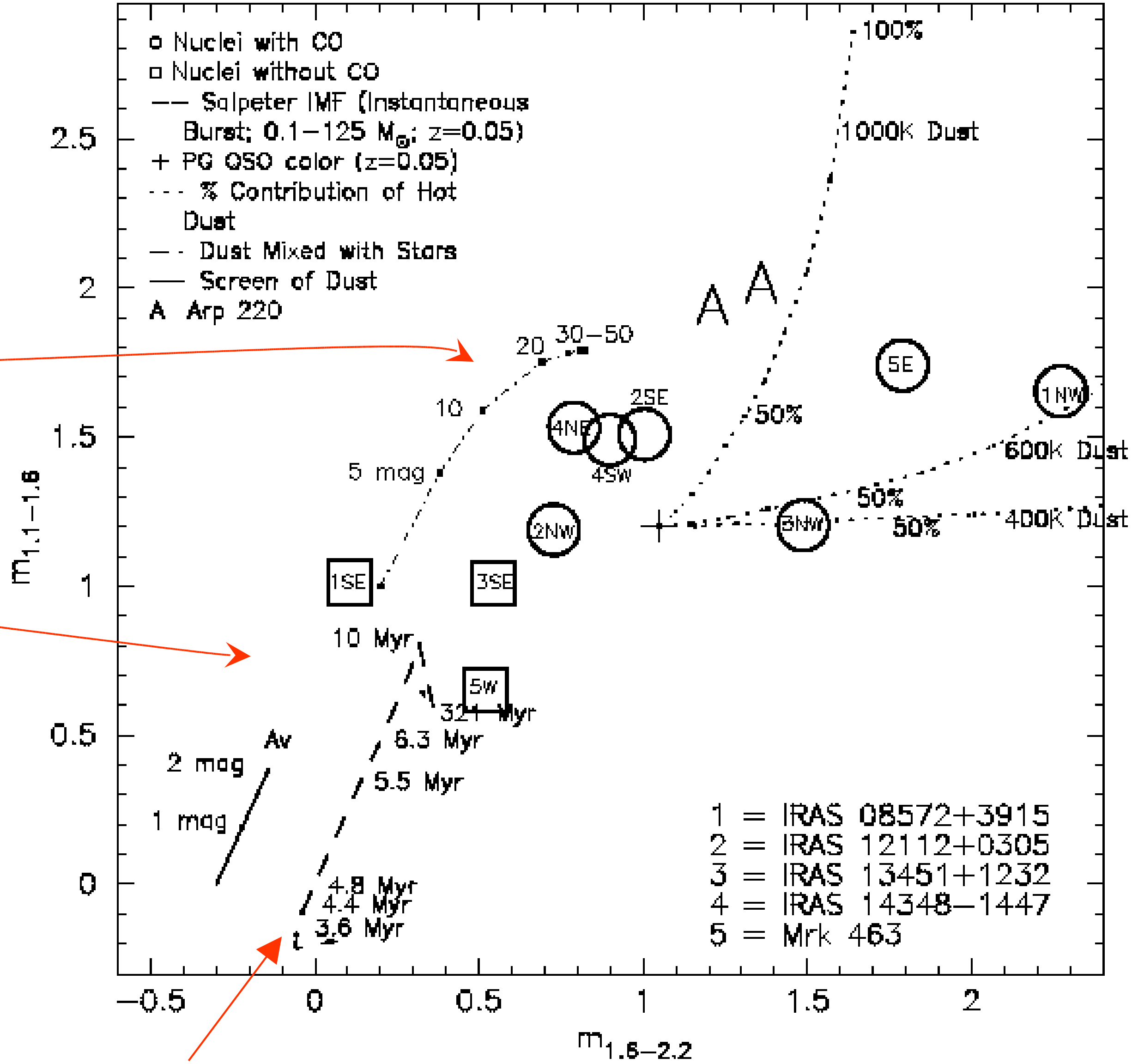
W nucleus (Sy 2/LINER) undetected: $M(H_2) < 2.6 \times 10^8\ M_\odot$

Evans, A. S., Mazzarella, J. M., Surace, J. A. & Sanders, D. B. 2002, ApJ, 580, 749.



Near-Infrared Colors for ULIG Nuclei

- Fluxes measured in 1.1" diameter apertures from HST NICMOS images
- Nuclei with detected CO are consistent with heavily reddened QSOs
- Nuclei without detected CO are in the region of less reddened starbursts



Evolution of instantaneous starburst with Salpeter IMF

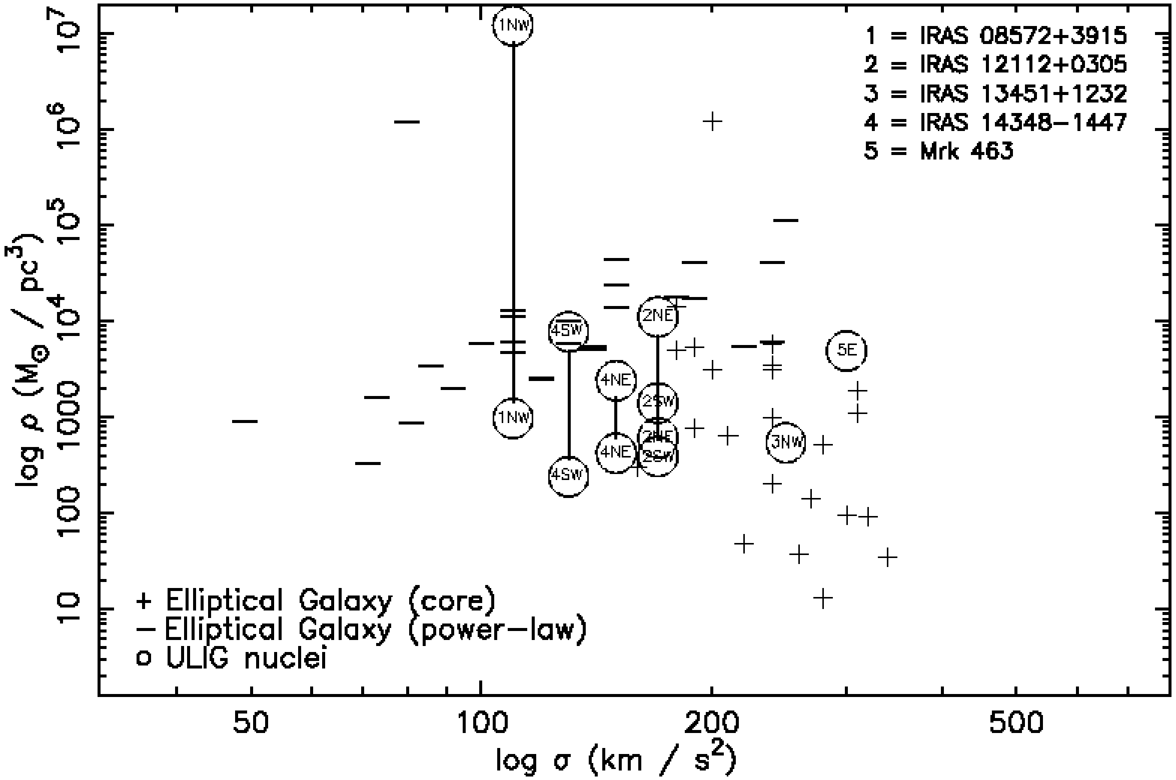
Adapted from Scoville et al. 2000, AJ, 119, 991

Molecular Gas in ULIGs Has High Enough Mass Density to Form the Stars in Elliptical Galaxy Cores

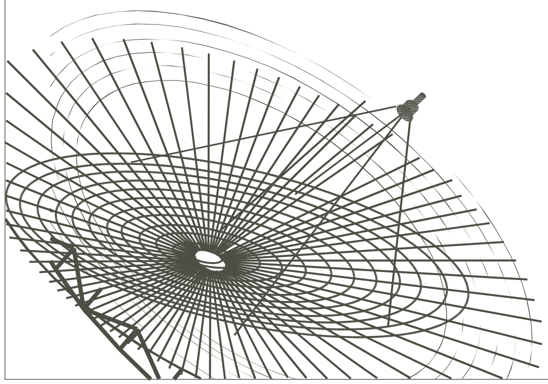
Gas mass density estimated using 3 techniques:

- CO size constraint
- 8.4 GHz size constraint
- Assume optically thick thermalized gas with filling factor = 1 and T(bb)=T(dust)

Methods 2 and 3 agree within 2-3x, but method 1 gives densities 5-20x larger. ==> CO emission regions much smaller than OVRO beam.



Line-of-sight CO velocity dispersion estimated by treating line profiles as Gaussian {σ=ΔV(FWHM)/2.354}

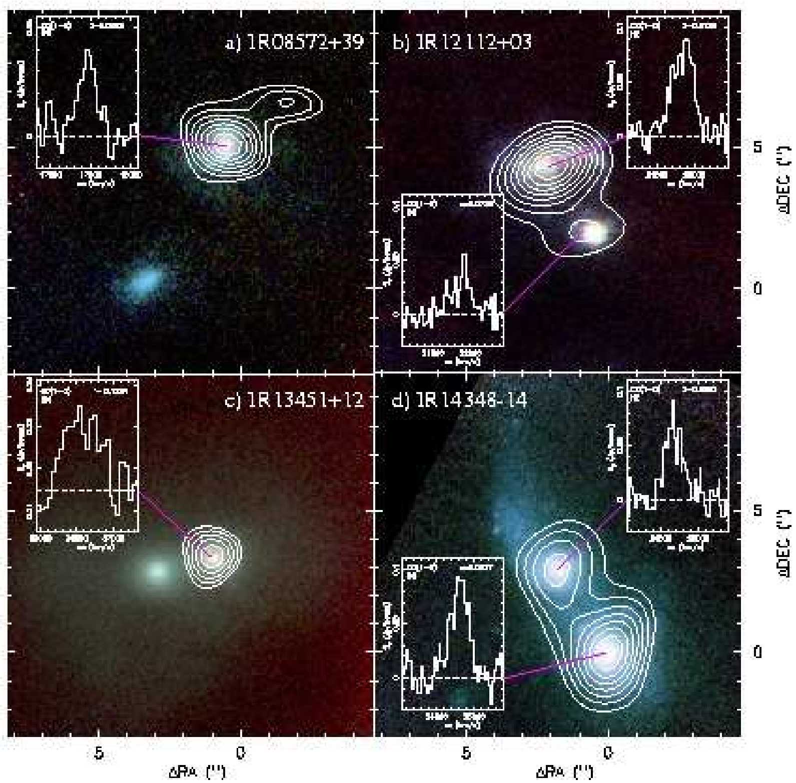


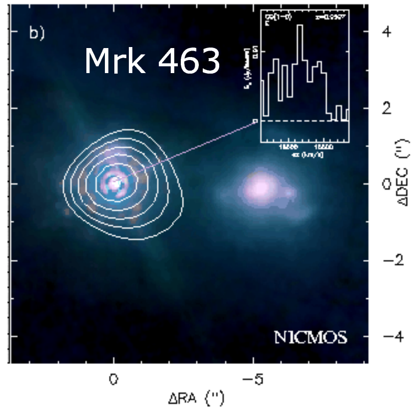
Evans, A. S., Mazzarella, J. M., Surace, J. A. & Sanders, D. B. 2002, ApJ, 580, 749..

Summary

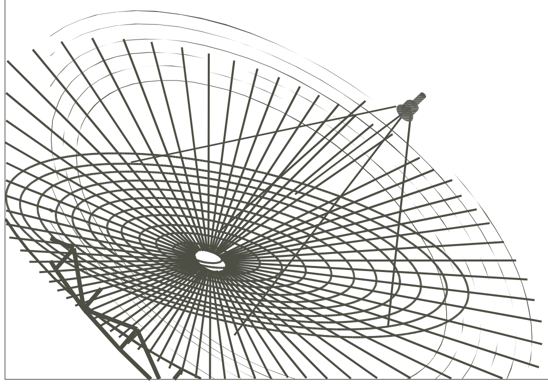
- **Molecular gas is a fuel source for star formation and AGNs**
- ***Molecular gas in ULIGs is not detected between the nuclei*** as found in some LIGs: Antennae (e.g., Gao et al. 2001), NGC 6090 (Bryant & Scoville 1999)
- **Gas-poor nuclei are found in 3 warm ULIGs**, but not in 3 cool ULIGs mapped in CO

Warm ULIGs Cool ULIGs



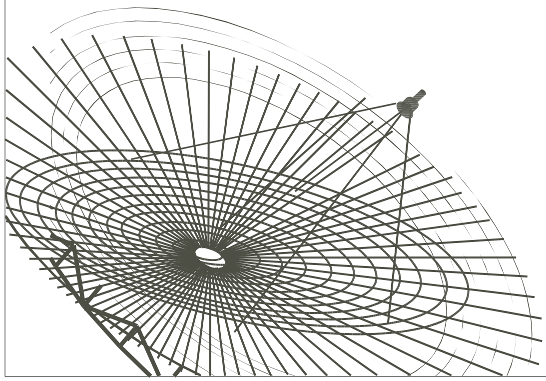


Arp 220 (Sakamoto et al. 1999, ApJ, 514, 68



Summary (cont.)

- If the nuclei of the warm ULIGs had the same CO luminosity ratios as in the cool ULIGs, both nuclei in the warm objects would have been detected
- The three undetected galaxies/nuclei have inferred molecular gas mass upper limits 5-10 times less than the H_2 mass of the Milky Way ($2 \times 10^9\ M_\odot$), indicating they are ***gass poor***
- Yet optical and near-IR observations provide evidence that the nuclei deficient in CO reside in massive disk galaxies roughly comparable to their CO-rich companions
- This is very mysterious...



Summary (cont.)

Why are IRAS 08572+3915E, Mrk 463W, and PKS 1345+12SE deficient in CO? Possibilities:

- They entered the merger as gas-poor disks
- The gas has been consumed in an earlier starburst or an AGN that is now in a relatively quiescent state
- One nucleus has transferred the bulk of its gas to its companion, perhaps contributing to the fuel needed to boost the emission to a ULIG level

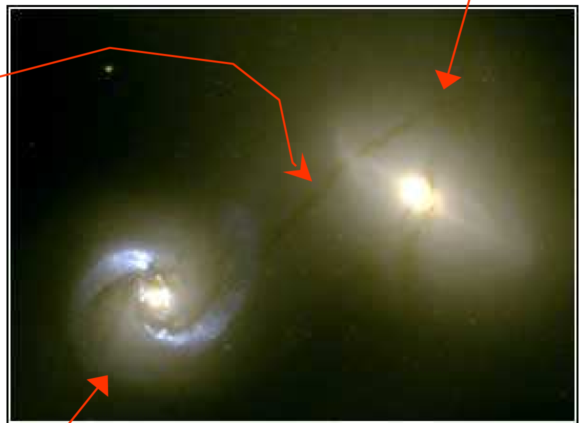
A possible relative (but a very low mass transfer rate):

HST STIS and WIYN imaging and spectroscopy by Bill Keel shows:

·Prograde encounter

·~0.02 $M_{\odot}$/yr being transferred along a "pipeline" between the galaxies

NGC 1409 capturing gas

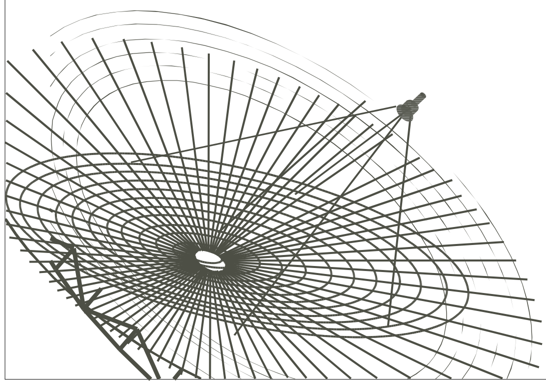


NGC 1410 (Sy 2) donating gas

Keel 2000

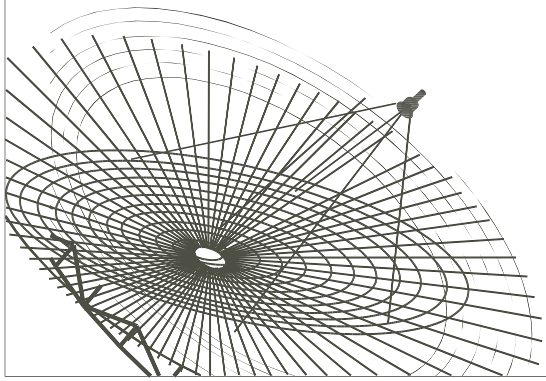
Summary (cont.)

- The presence of LINERs and Seyfert nuclei combined with the high central concentration of CO provides evidence that molecular gas is important in fueling AGNs in ULIGs
- Consistency arguments suggest that CO emission regions are smaller than the current OVRO beam size (< 2”, 0.6-2 kpc) and estimated star formation rates are 30-470 $M_\odot$/yr per nucleus
- Nuclei with detected CO are significantly redder than companions that are deficient in CO, suggestive of dustier environments and hotter dust in the former
- Column density estimates yield ~ 10^{25} cm^{-2}, corresponding to greater than 1000 mag visual extinction



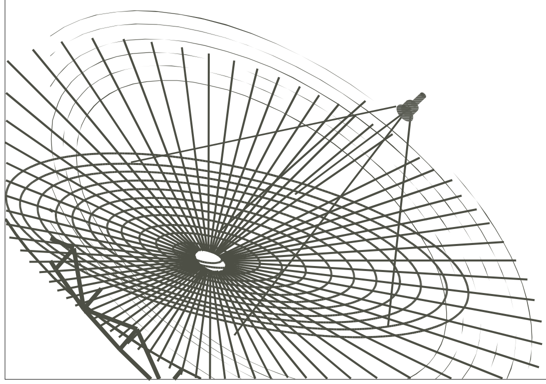
Summary (cont.)

- Gas mass densities are ~ 100 - 10,000 $M_{\odot}$ pc^{-3}
- Such high densities, combined with line-of-sight CO (1-0) velocity dispersions, are comparable to the stellar mass densities and velocity dispersions in elliptical galaxies with $M(V) < -19$ mag.
- Thus, molecular gas has a sufficiently high phase-space density to form the stars in elliptical galaxies

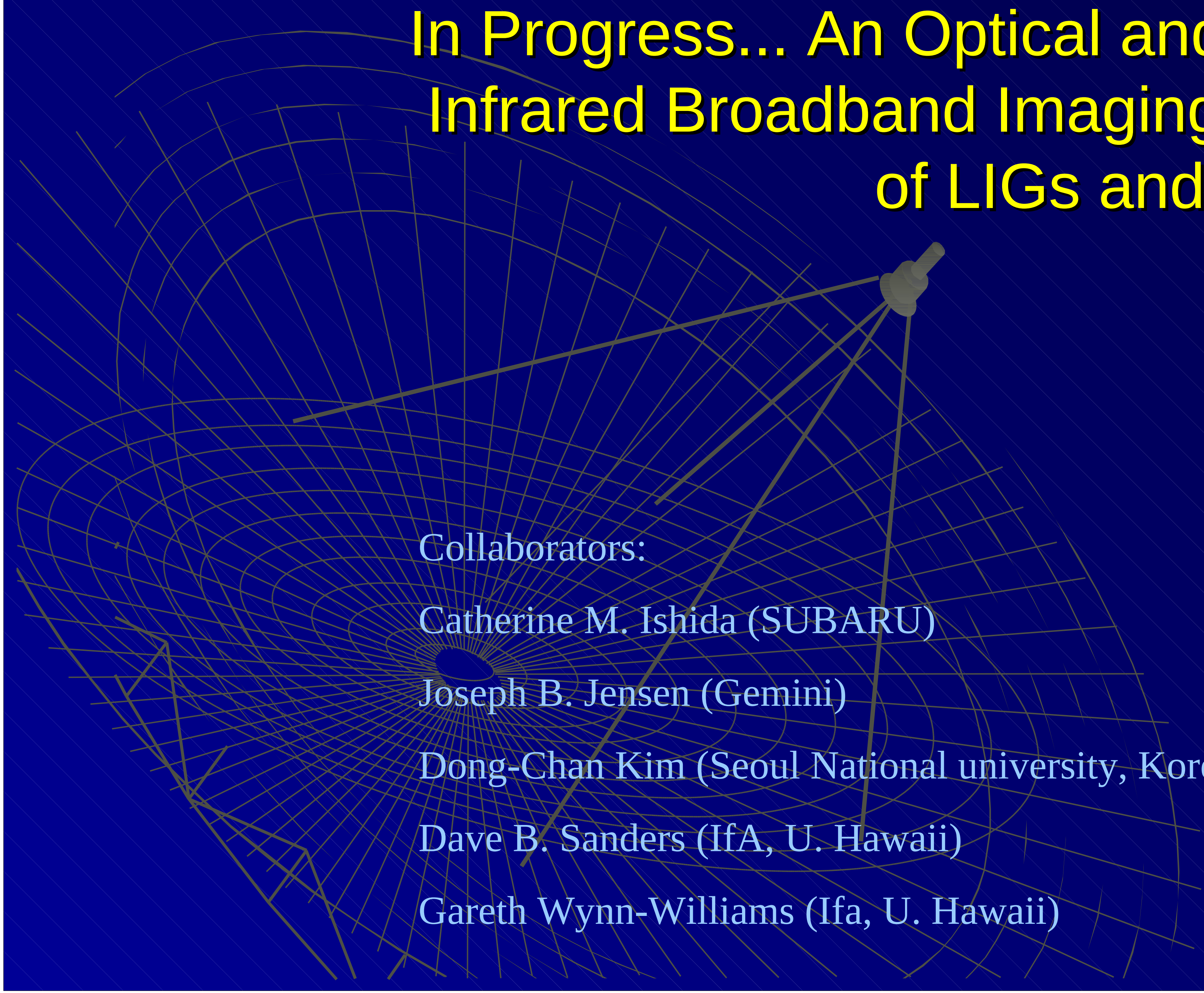


Future

- The present sample size is small (5 galaxies, 10 nuclei), so these interesting results need a larger, more statistically significant sample of intermediate-stage ULIGs
- A CO survey is underway to observe all ULIGs in the IRAS 2 Jy Sample (Strauss et al.) that can be resolved by OVRO
- The CO data will be analyzed with multi-wavelength information as done here
- Improvements to these observations will be possible with the Smithsonian SubMillimeter Array (SMA), enabling CO resolutions approaching that of the $2\mu m$ NICMOS images



In Progress... An Optical and Near-Infrared Broadband Imaging Study of LIGs and ULIGs



Collaborators:

Catherine M. Ishida (SUBARU)

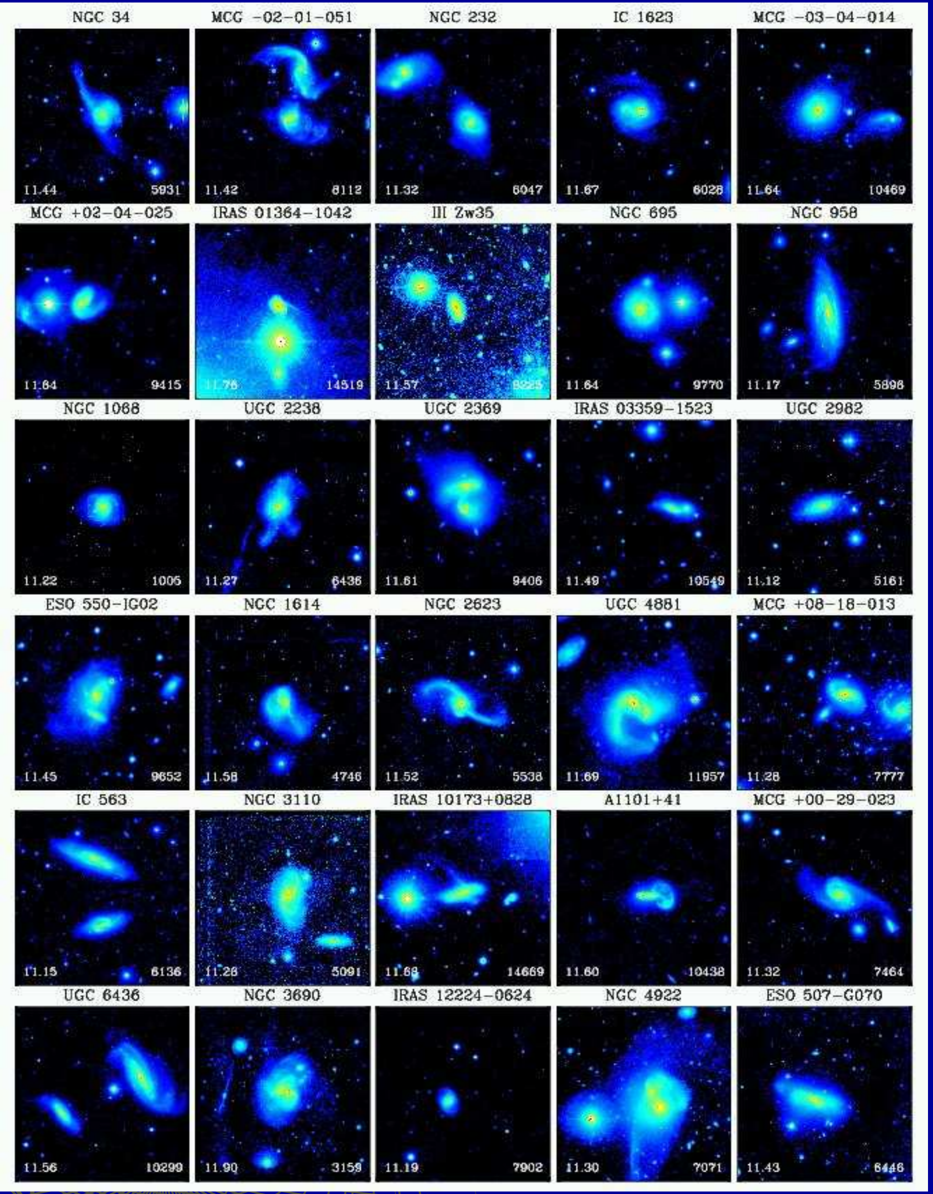
Joseph B. Jensen (Gemini)

Dong-Chan Kim (Seoul National university, Korea)

Dave B. Sanders (IfA, U. Hawaii)

Gareth Wynn-Williams (Ifa, U. Hawaii)

Broadband Imaging of LIGs and ULIGs



- A complete sample of LIRGs and ULIRGs drawn from the RBGS and observable from Mauna Kea (Dec > -40 deg)
- Deep B, V, R, I and K' images
- Photometry
- Radial brightness and color profiles
- We are studying how these parameters change during the merger process
- The majority, if not all, are interacting/merging systems, but...
- Can we distinguish pre-ULIGs from post-ULIGs?

Broadband Imaging of LIGs and ULIGs

A wide range of ratios between components and morphologies are present even among $L_{ir} \sim 10^{11.5} L_\odot$ systems