“What Drives the Growth of Black Holes”, Durham 28 July, 2010

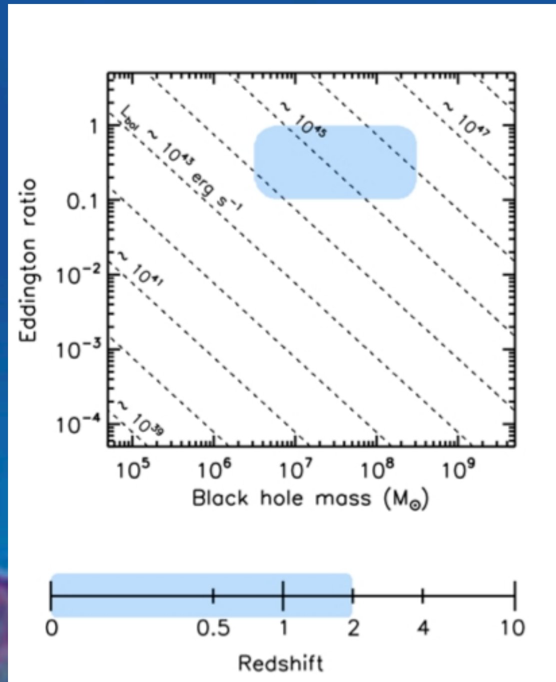
The Growth of Massive Black Holes during Gas-Rich Major Mergers

D. B. Sanders

Institute for Astronomy,
University of Hawaii

Abstract

Massive Black Holes ($> 10^8 M_\odot$) are most likely to have been produced during major mergers ($\sim L^\star$–$L^\star$) of gas-rich spirals. I will review current evidence which suggests that the major growth period of these MBH ($\times 100$) occurs during a time interval of a few $\times 10^8$yrs, coinciding with an ultra-luminous infrared phase when the merger nuclei are still heavily enshrouded in dust.



OUTLINE

- IR Galaxies – Definitions, LF
- Origin & Evolution of (U)LIRGs
- GOALS ⇔ (U)LIRGs at $z < 0.1$
- Spitzer-COSMOS ⇔ (U)LIRGs at $z = 0 \sim 3$)

IRAS	-	ISO	-	SCUBA - MAMBO
(1984)		(1996)		(1997) (1999)
$z < 0.3$		$z < 1.5$		$z < 5$

Spitzer+AstroF	-	*Herschel*	- LMT+ALMA
(2003) (2005)		(2009)	(2011 --)
		$z = 0\text{-}10?$	

Two Surveys:

1. GOALS – Great Observatories All-Sky LIRGs Survey

   IRAS Revised Bright Galaxies Sample ($S_{60} > 5.24$ Jy)

   $L_{ir} > 10^{11}\ L_{sun}$ (~ 200 objects) ($z < 0.1$)

2. S-COSMOS – *Spitzer* IRAC+MIPS Survey of the COSMOS 2-deg^2 Field

   Spitzer 70µm sample ($S_{70} > 5$ mJy)

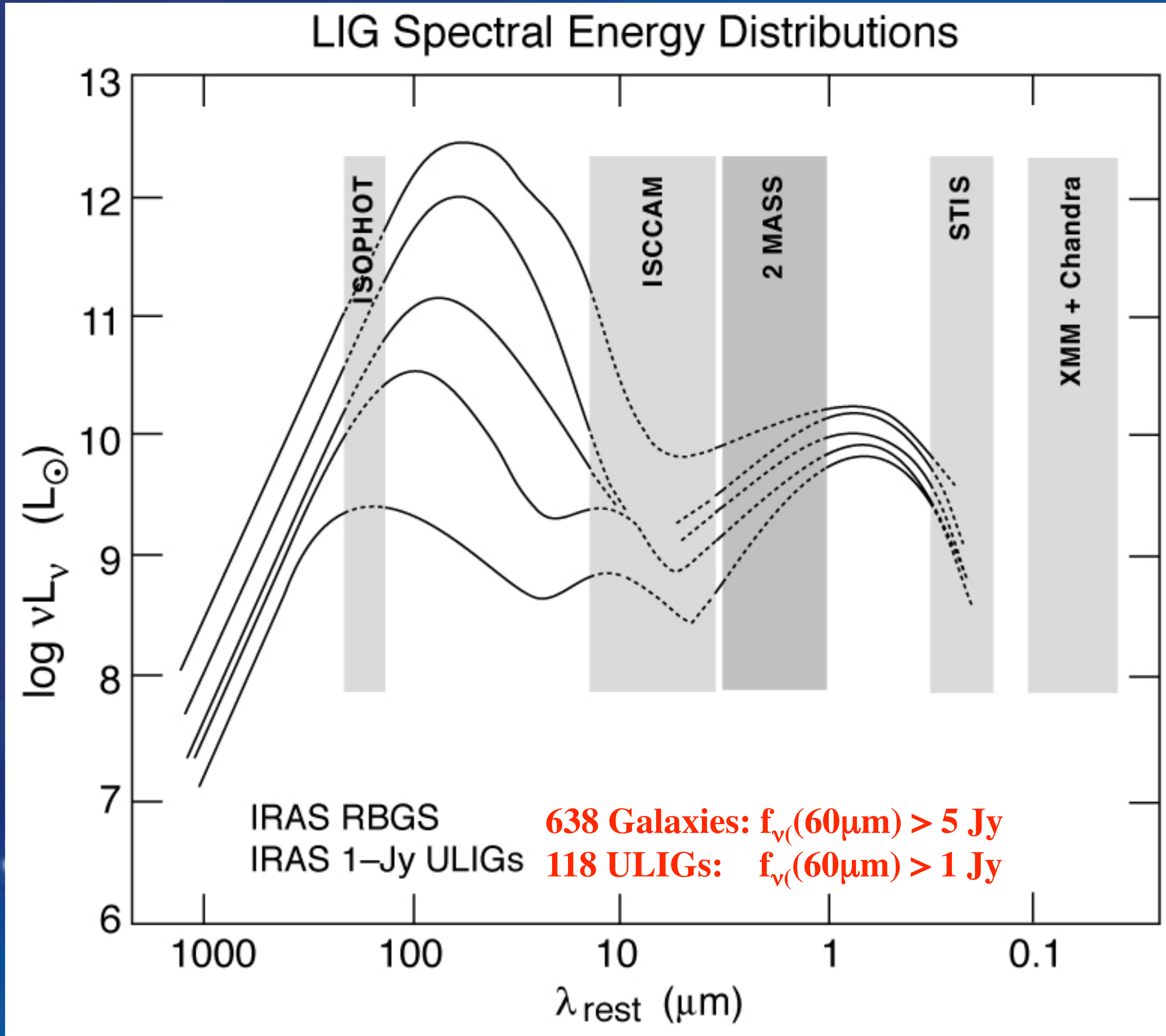
   $L_{ir} > 10^{11}\ L_{sun}$ (~ 2000 objects) ($z \sim 0 – 2$)

+ Call your attention to 2 Posters:

C. Cardamone

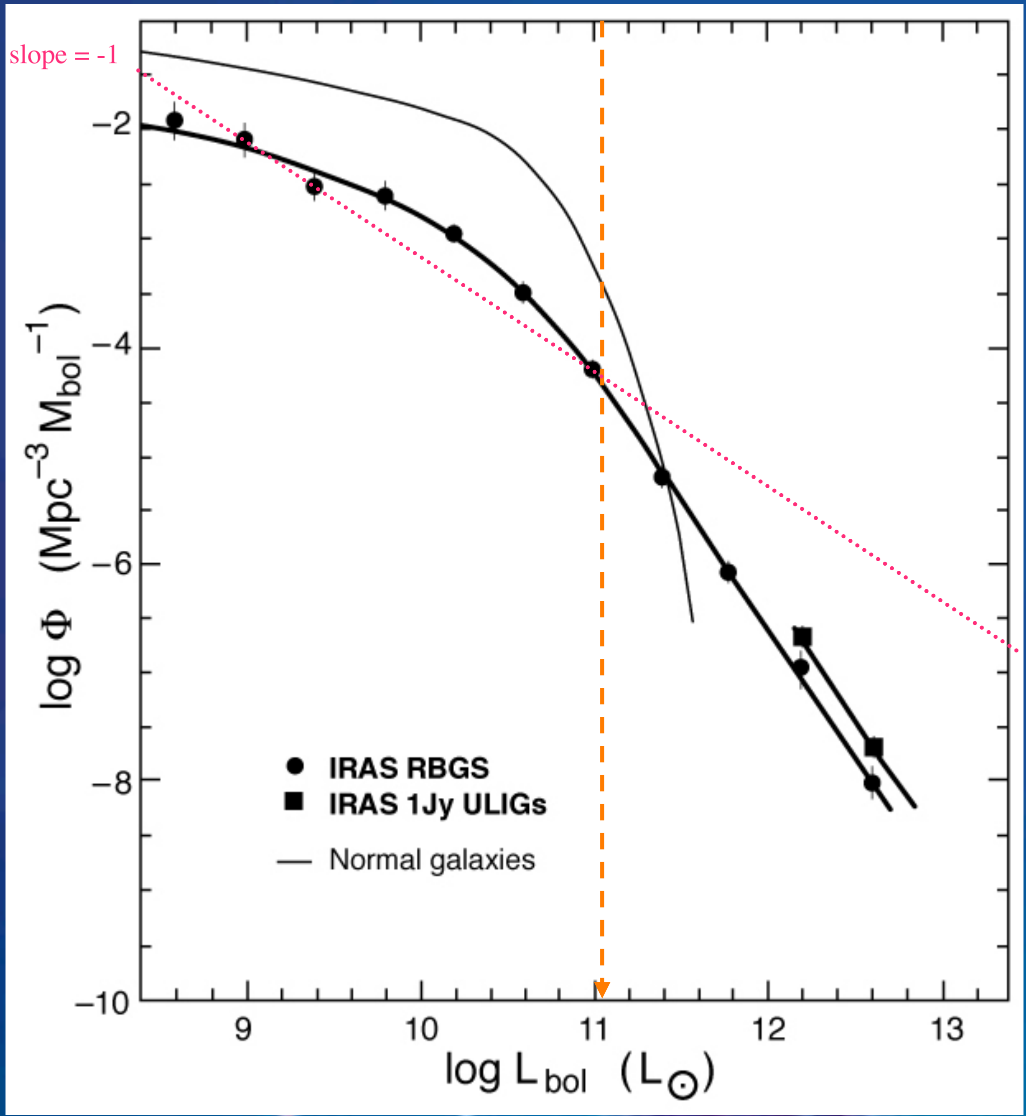
E. Treister

Radio-to-UV SEDs of IRAS Selected Galaxies



"Infrared Galaxies" ≡ $(\nu f_\nu)_{IR} / (\nu f_\nu)_{opt} > 1$

Galaxy Luminosity Functions



L_{FIR} **high luminosity tail:**

$\Phi \propto L^{-2.35}$

$\rho(z) \propto (1+z)^{5 \pm 2.5}$

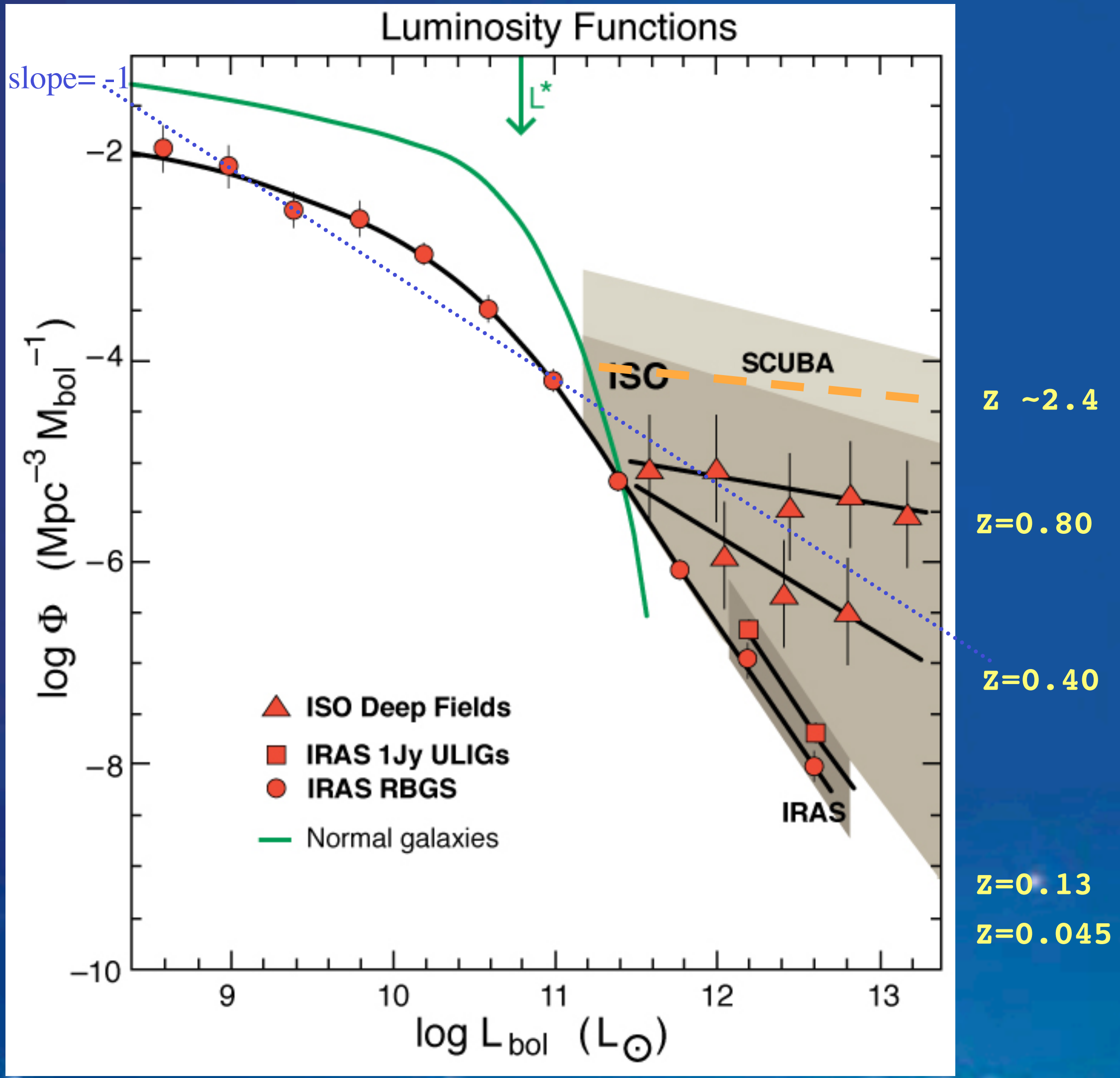
$\sigma(z < 0.2) \sim 0.008 \text{ deg}^{-2}$

Why do we care about

Luminous Infrared Galaxies ?

- Because they rule the Universe at high redshift, when galaxy assembly largely took place ….
- All >*L** ellipticals/spirals likely have gone through at least one luminous infrared phase

Galaxy Luminosity Functions



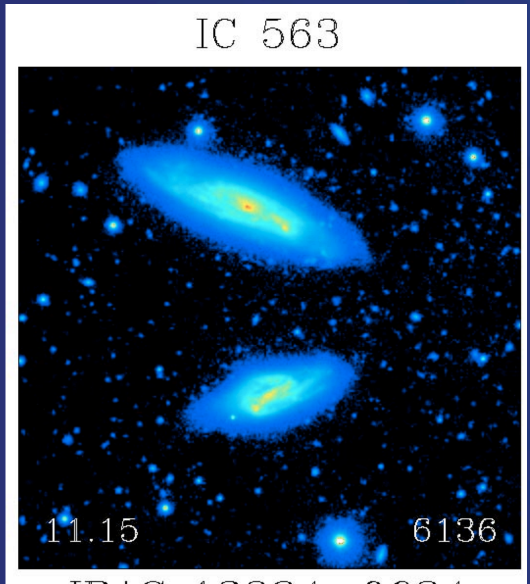
The Origin and Evolution of Luminous Infrared Galaxies

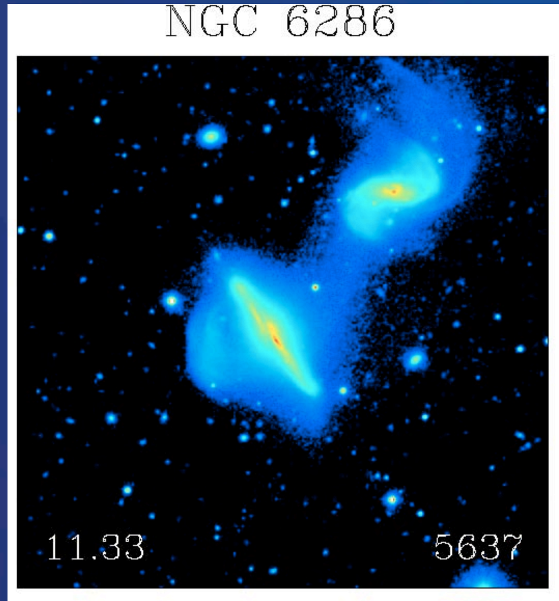
Strong Interactions/Mergers of Molecular Gas-rich Disks

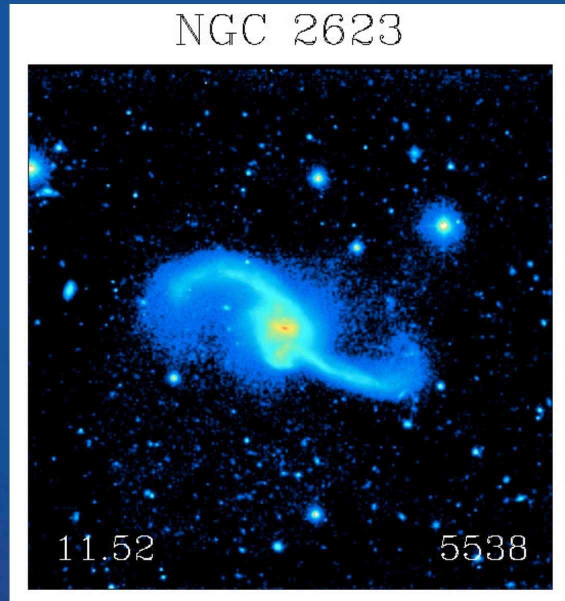
IRAS RBGS

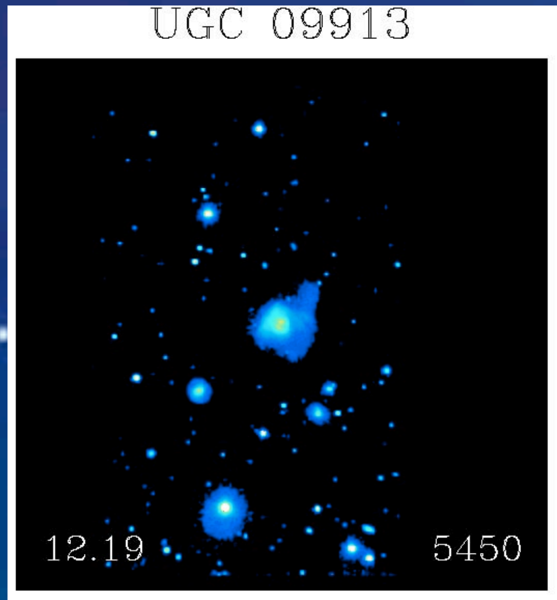
(Ishida, PhD Thesis)

Log (L_{IR}/L_o) = 11.10 - 12.50





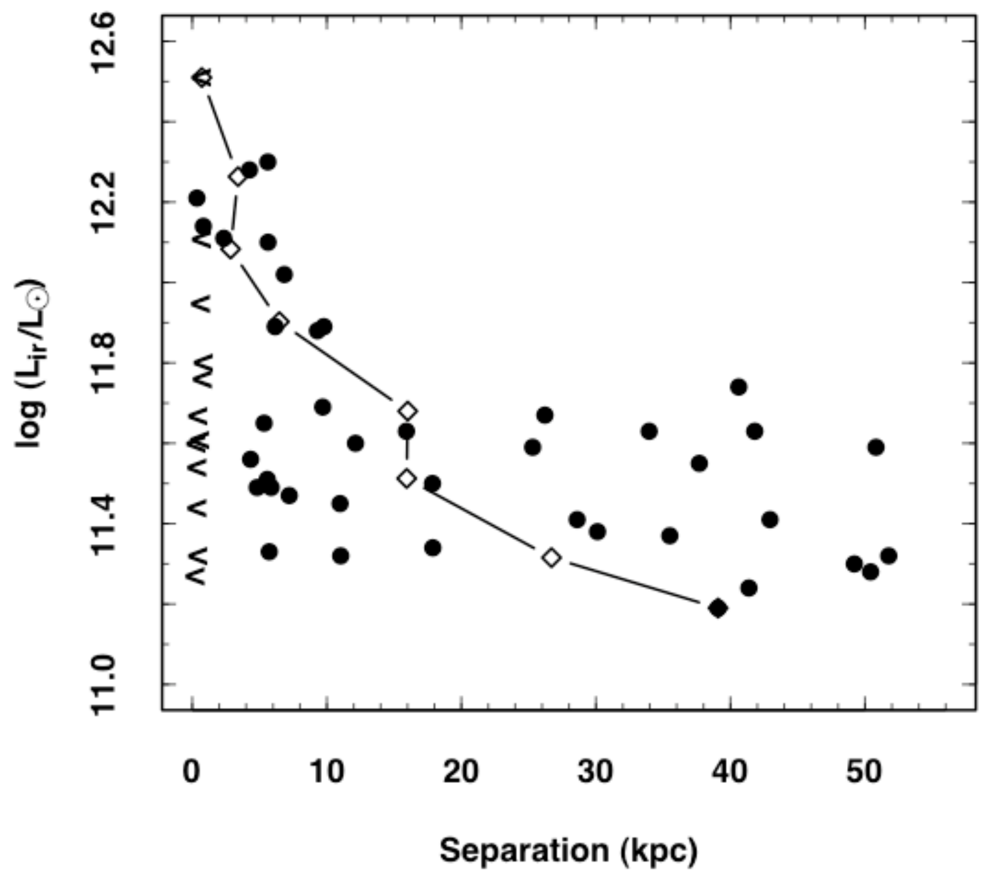




IRAS RBGS

(Ishida 2004)

Nuclear Separation vs. Lir



IRAS RBGS

Ishida (2004), PhD Thesis, U. Hawaii

Conclusions:

In the range log (L_{IR}/L_o) = 11.6 - 12.0, LIRGs are "major mergers" of ~ *L-*L** spirals in the final stages of merging, with a *typical* "pre-merger" time ~ 3-5 x 10^8 years**

At log (L_{IR}/L_o) > 12.0, > 40% of ULIRGs have merged and the remainder will merge within ~ 10^8 years

Sources are predominantly:
$\langle M_K \rangle_{Tot} \sim 2 L_K^*$
M_K pair ratio < 3:1
L_{IR} pair ratio < 5:1
Pairs are predominantly late type spirals
Both components are molecular gas rich ($M_{H2} \sim 10^{9-10} M_{sun}$)

What have we been doing to prepare for the "Herschel+ALMA era" ……

Two Surveys:

1. GOALS – the Great Observatories All-Sky LIRGs Survey

2. S-COSMOS – The Spitzer IRAC+MIPS Survey of the COSMOS 2-sq deg Field

GOALS

Spitzer-IRAC+MIPS+IRS
HST-ACS
Chandra-ACIS

Multiwavelength observations
LIRGs from the IRAS RBGS

Evans, Stony Brook
Mazzarella, Caltech/IPAC
Armus, Caltech/SSC
Sanders, Hawaii

Great Observatory All-sky LIRG Survey

Home | Overview | Observations | Target Lists | Team (Private) | Publications

Spitzer Observing Program Description:

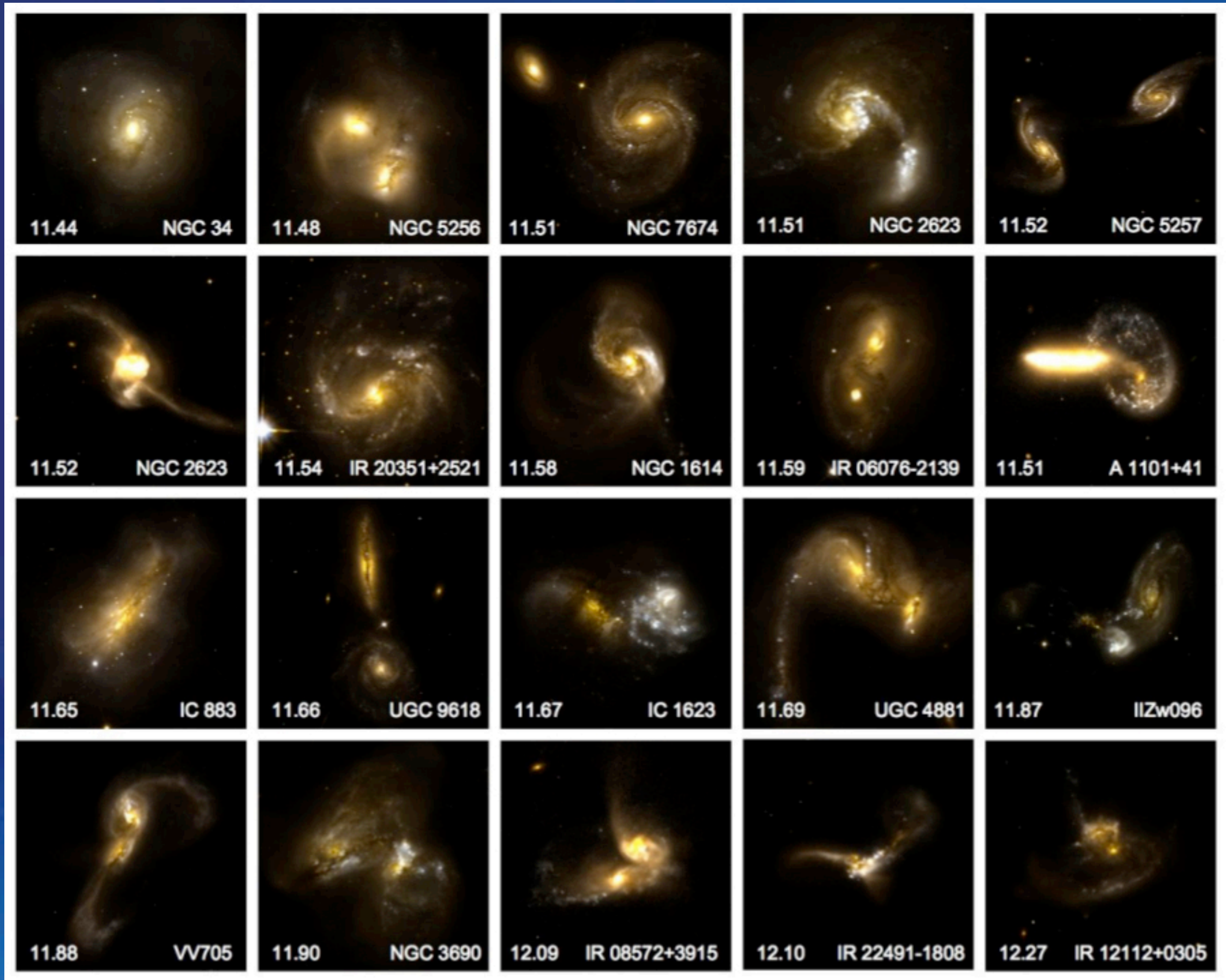
The Spitzer component of GOALS consists of:

(1) **A Cycle 1 GO program (Mazzarella et al., Program ID# 3672)** consisting of imaging and photometric measurements in the 4 channels of IRAC (3.6, 4.5, 5.8, and 8.0 μm) and the 3 channels of MIPS (24, 70 and 160 μm) for the 203 RBGS systems with infrared luminosity greater than 10^{11} $L_\odot$. An overview of the Spitzer imaging and photometric program is provided here.

(2) **A Cycle 3 Legacy GO program (Armus et al., program ID# 30323)** consisting of spectroscopic observations with all four modes of the IRS to collect nuclear spectra of the RBGS systems as well as some of their nearby companions. An overview of the Spitzer spectroscopic program is provided here.

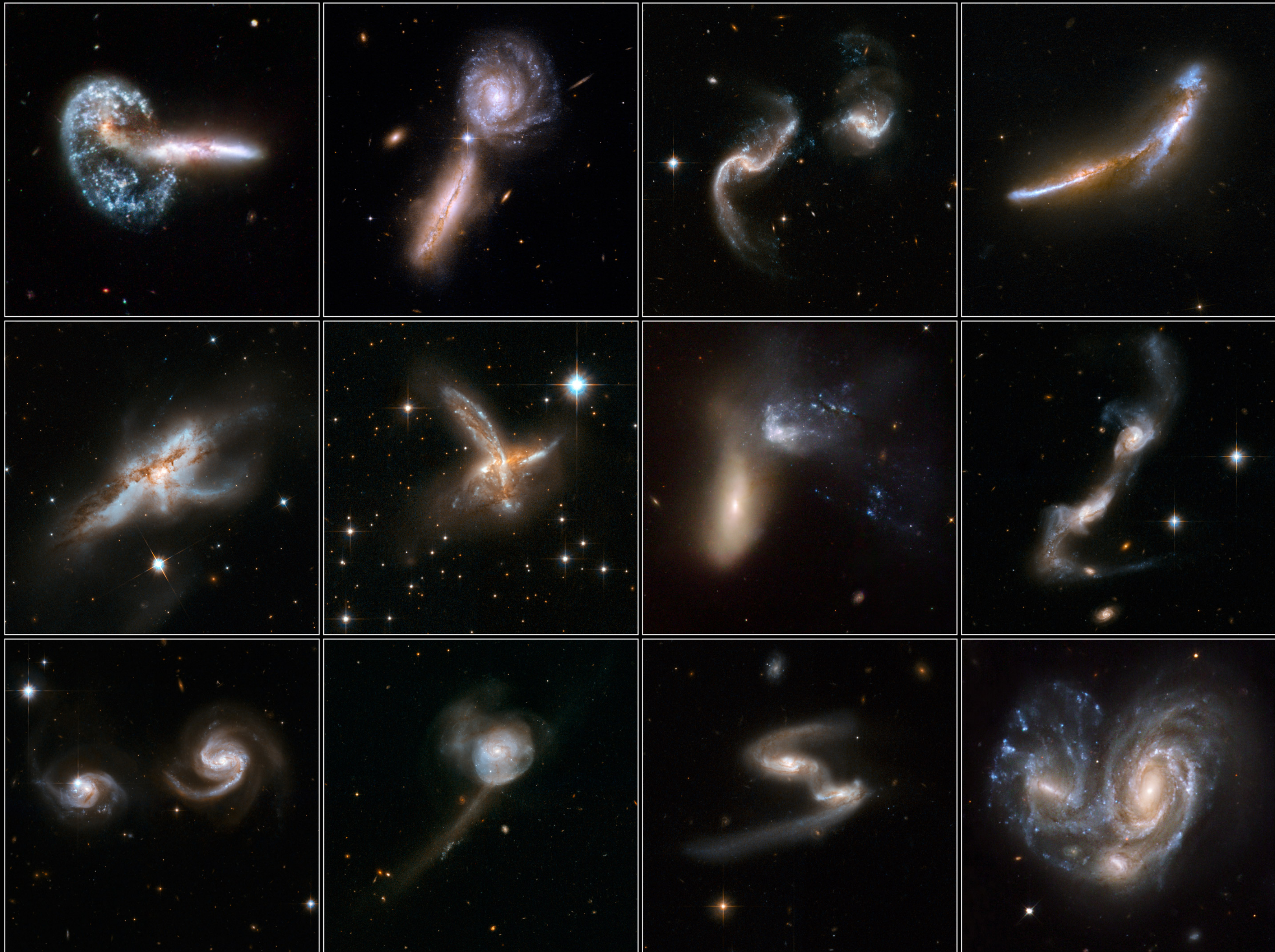
A tabulated target list of the Spitzer imaging and spectroscopy programs is provided here.

GOALS: HST-ACS *BI* images   Evans et al. 2007, in preparation



Interacting Galaxies

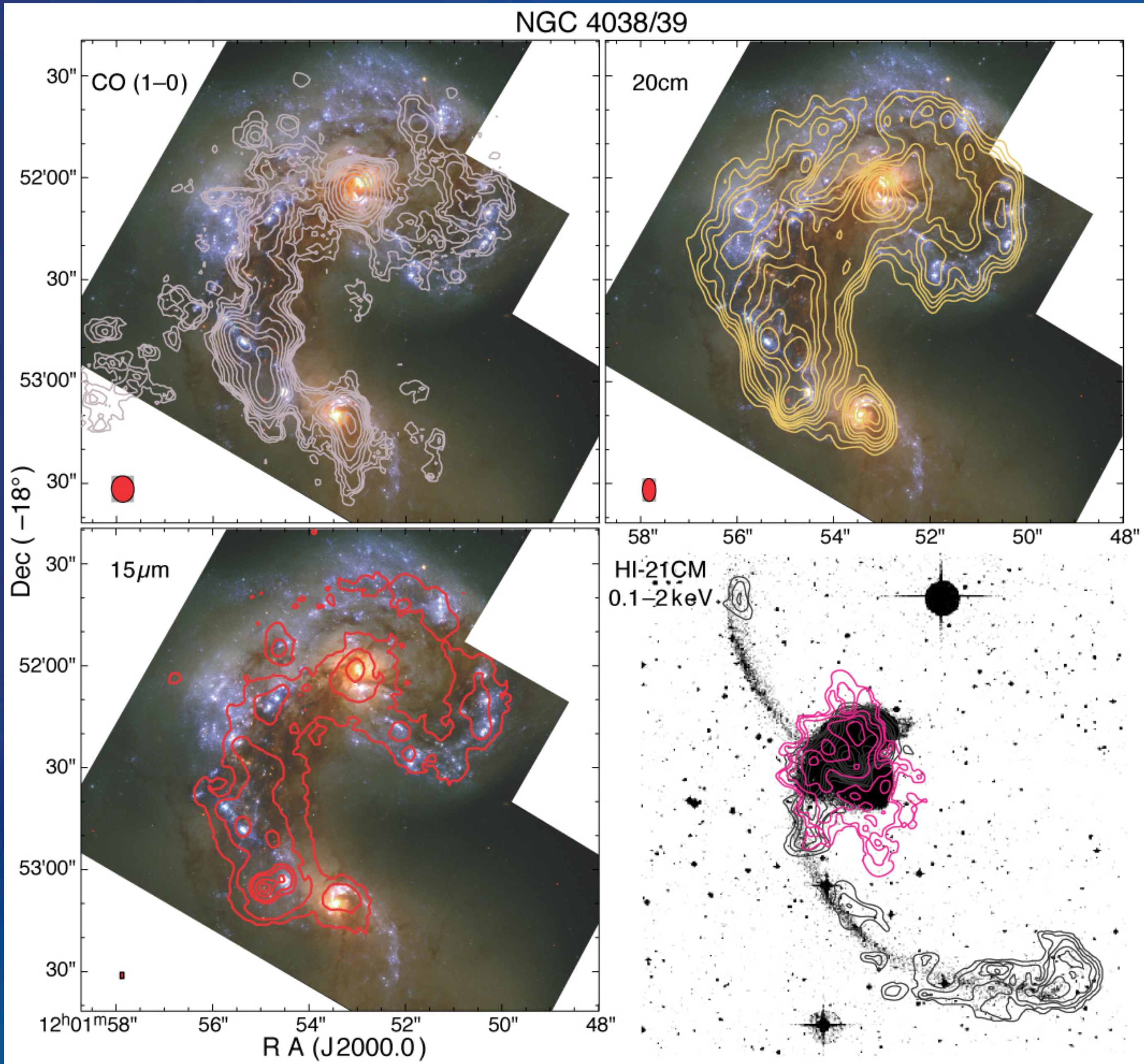
Hubble Space Telescope • ACS/WFC • WFPC2



NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and
A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

STScI-PRC08-16a

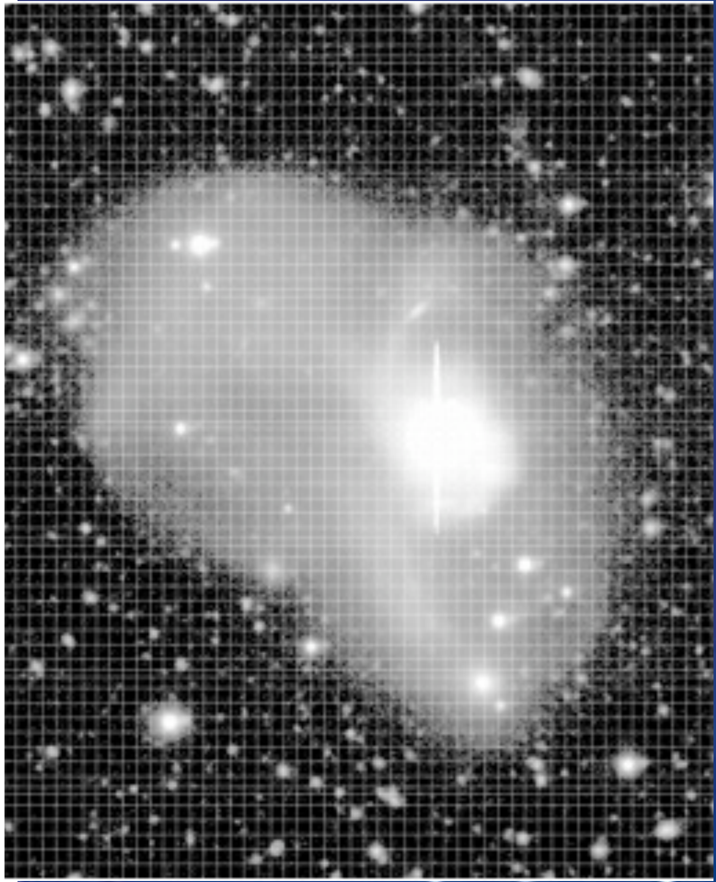
Log (L_{IR}/L_{sun}) = 11.01
Int. Class = 3

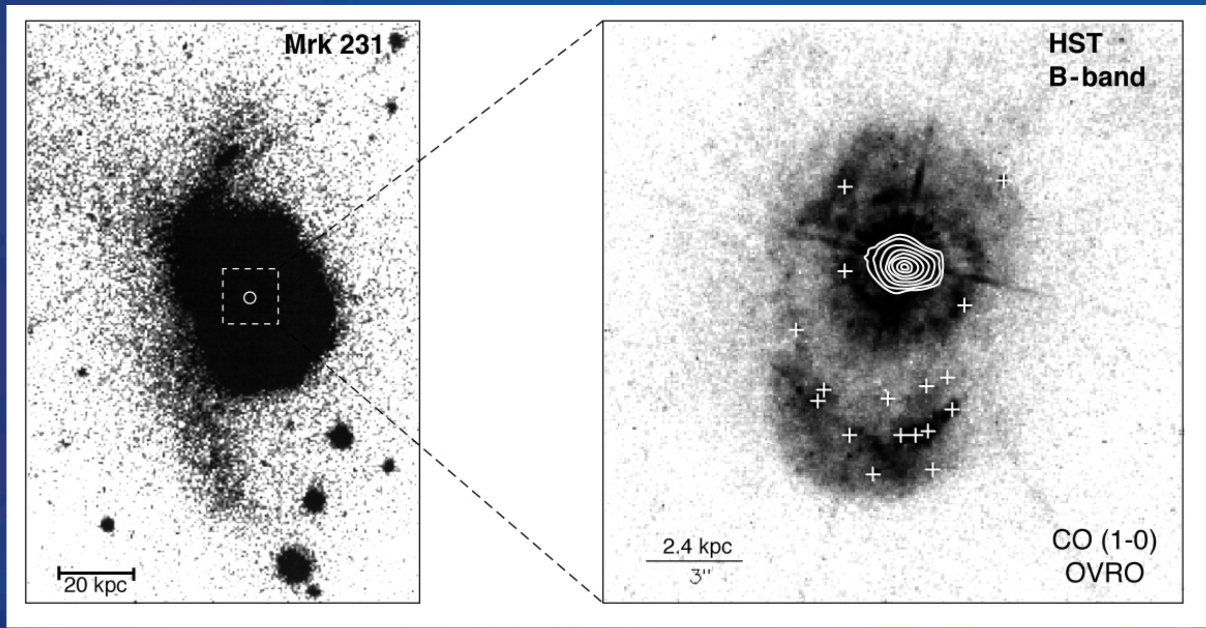


Gao et al.
Mirabel et al.
Hibbard et al.
Ponman et al.

UGC 83038 = Mrk 231

Log (L_{IR}/L_{sun}) = 12.57
Int. Class = 4





Sanders et al.
Hutchings & Neff

Scoville et al.
Surace et al

Jin Koda
Subaru r-band

Nuclear Molecular Gas Concentrations @ r < 700 pc
General Results for ULIRGs

- M_{nuc}/M_{tot} = 40 – 100 %
- M_{nuc} = 1 – 3 x 10^{10} M_{sun}
- $\langle \sigma (H_2) \rangle$ ~ 0.65 – 2 x 10^{10} M_{sun}
- $\langle n (H_2) \rangle_{spherical}$ ~ 130 – 400 cm^{-3}
- => ff_{nuc} ~ 1 (for a population of W3-like GMCs)
- $\langle N (H_2) \rangle_{spherical}$ ~ $10^{23.2 - 23.7}$ cm^{-2}

OVRO Interferometer
Bryant, Scoville et al. 1993-9

The large column densities of gas and dust in the circumnuclear regions of ALL ULIRGs implies that any source of luminosity, whether it be an ES or a powerful AGN, will very likely be heavily obscured (Compton-thick ??); We will need higher resolution data and better diagnostic measures to separate the two.

Black hole in the West Nucleus of Arp 220

D. Downes[1] and A. Eckart[2,3]   **IRAM PdBI**

1kpc x 1kpc

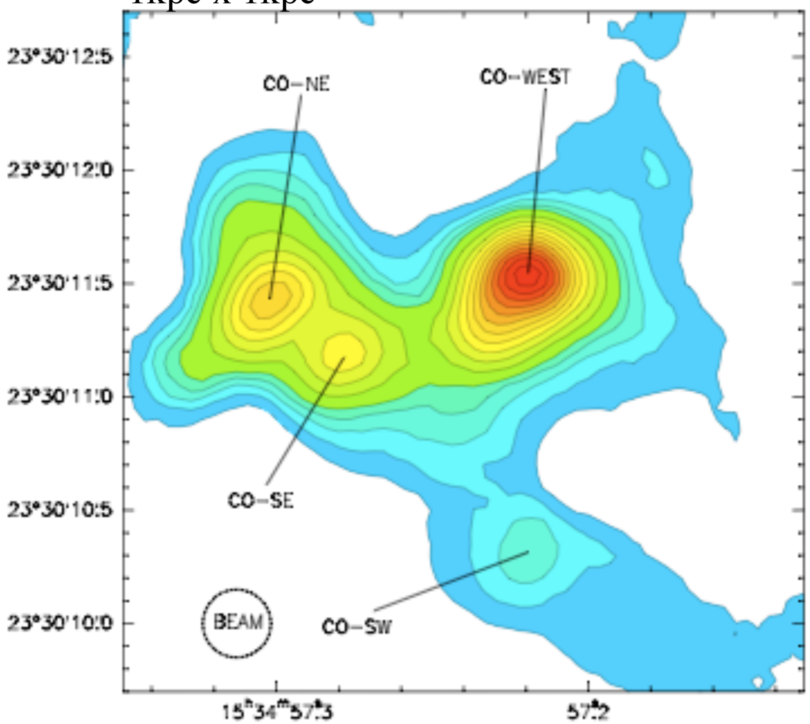


Fig. 1. The central 3″ of Arp 220 in CO(2–1) integrated over 770 km s^{-1}, with the 1.3 mm continuum subtracted. The beam (*lower left*) is 0.30″ with T_b/S = 266 K/Jy. Contours are 2 to 10 by 2, then 14 to 54 by 4 (in Jy km s^{-1}). The CO-West peak is 56.5 Jy km s^{-1}; CO-NE is 33.4 Jy km s^{-1}.

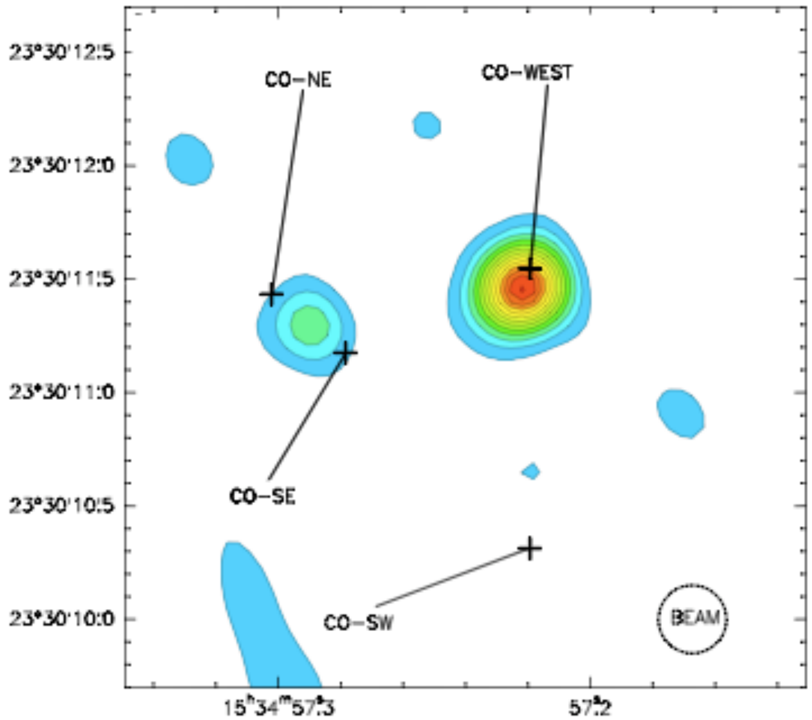
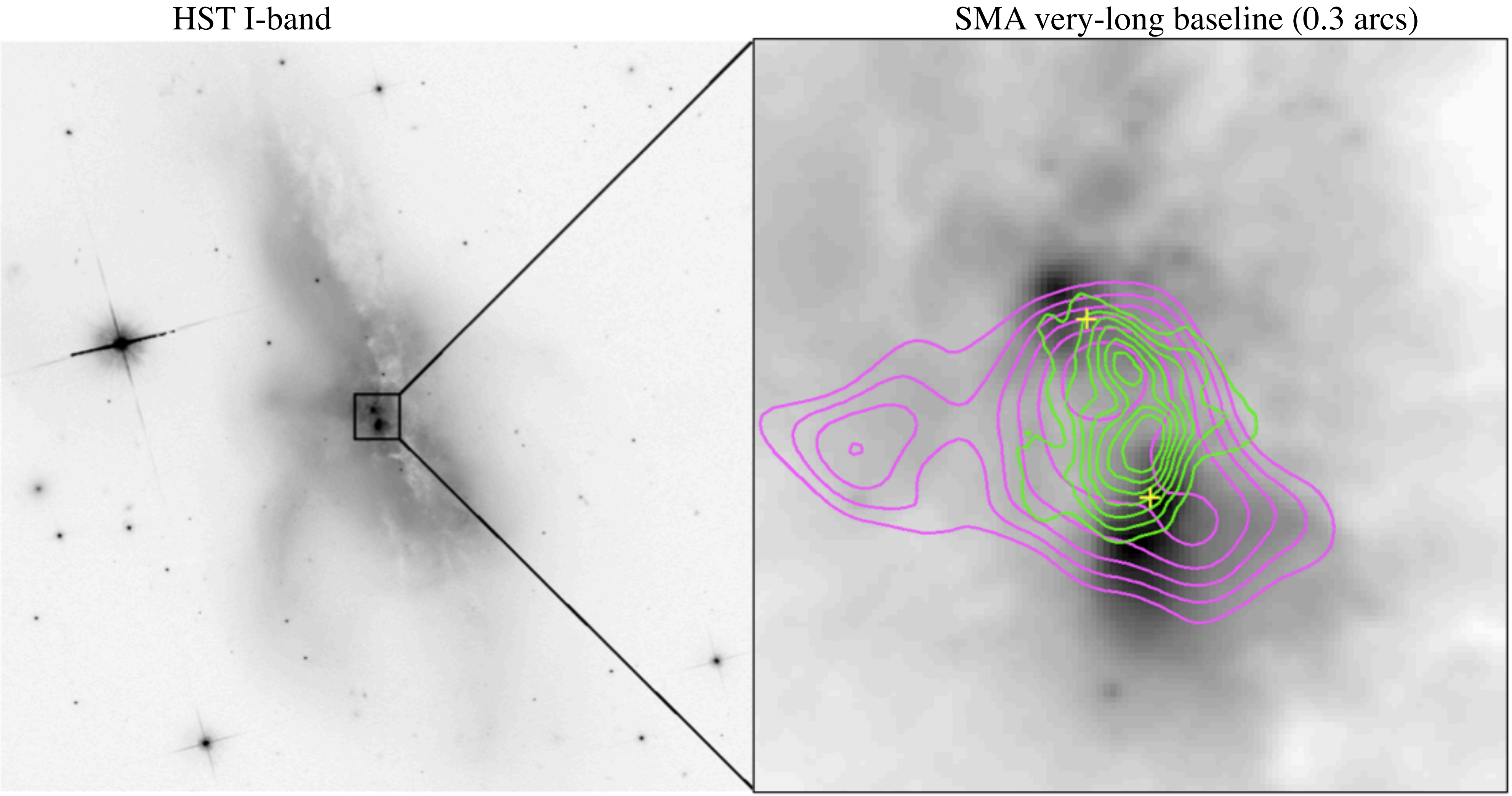


Fig. 2. Continuum map at 1.3mm (229.4 GHz). Contour steps are 6 mJy $beam^{-1}$. The Arp 220-West peak is 79 mJy $beam^{-1}$, and the East peak is 23 mJy $beam^{-1}$. Note that the continuum peaks do not coincide with the CO(2–1) peaks, which are marked with crosses. The beam is 0.30″ (lower right).

0.3 arcs ~ 90 pc

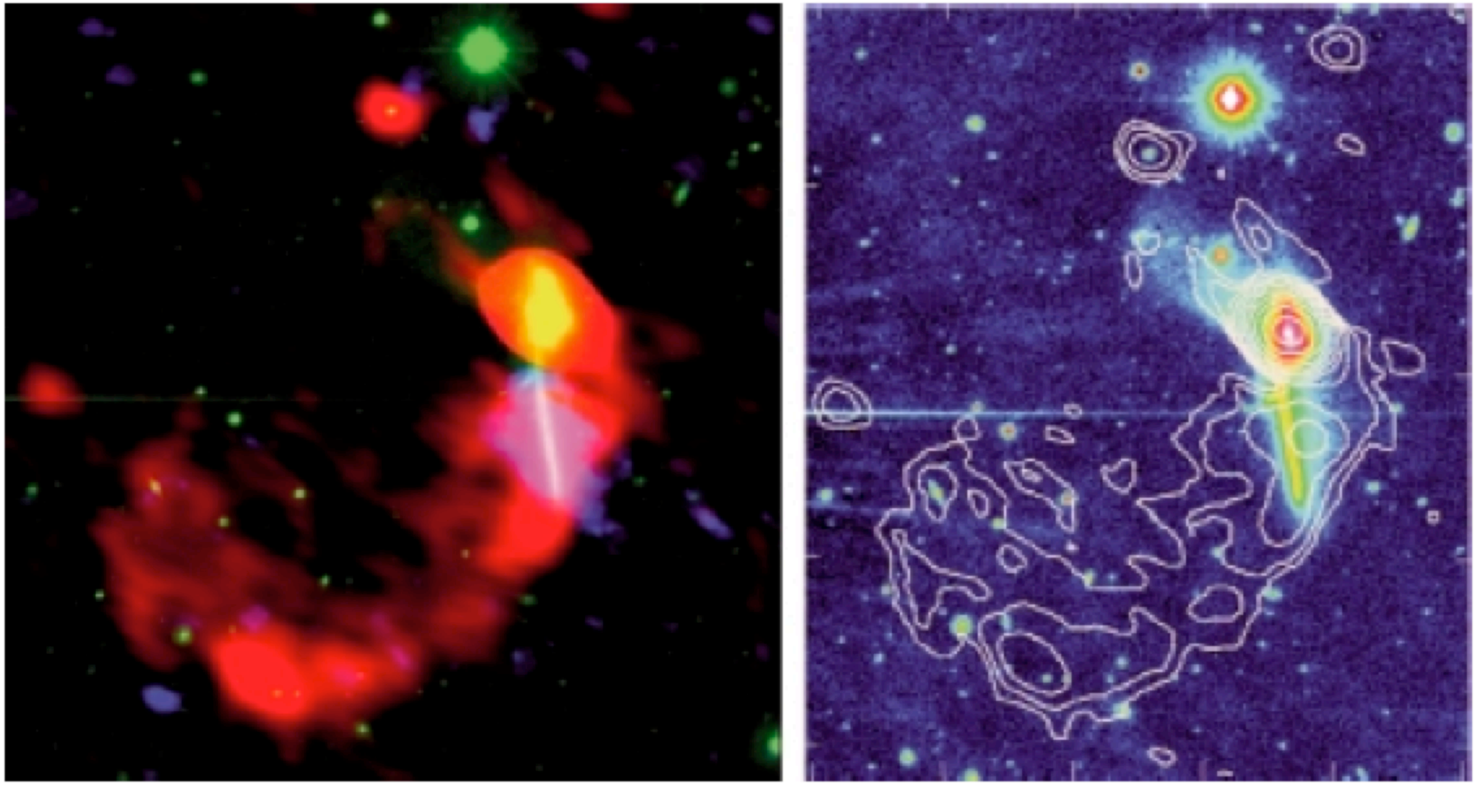
New Results for the binary AGN in NGC 6240 – Vivian U et al. 2010



Purple : 850 μm continuum
Green : CO(3-2) line emission
Yellow + : K-band nuclei

Mrk 273 - Discovery of Giant Radio Continuum “Plumes” - Yun & Hibbard 2000 (!)

April 2000 | **New Results** | **Number 83**



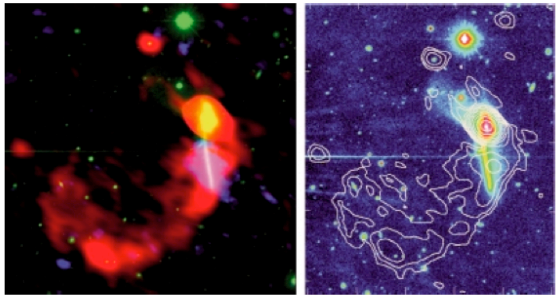
Left: False color RGB image of Mrk 273, with the starlight shown in green, 21cm H I line emission in blue, and 1.4 GHz radio continuum emission in red. Right: optical image of Mrk 273 in spectral colors, with contours of the 1.4 GHz emission superimposed.

200kpc x 200kpc

Red : VLA D-array 1.4 GHz continuum

Blue : VLA HI-21cm line emission

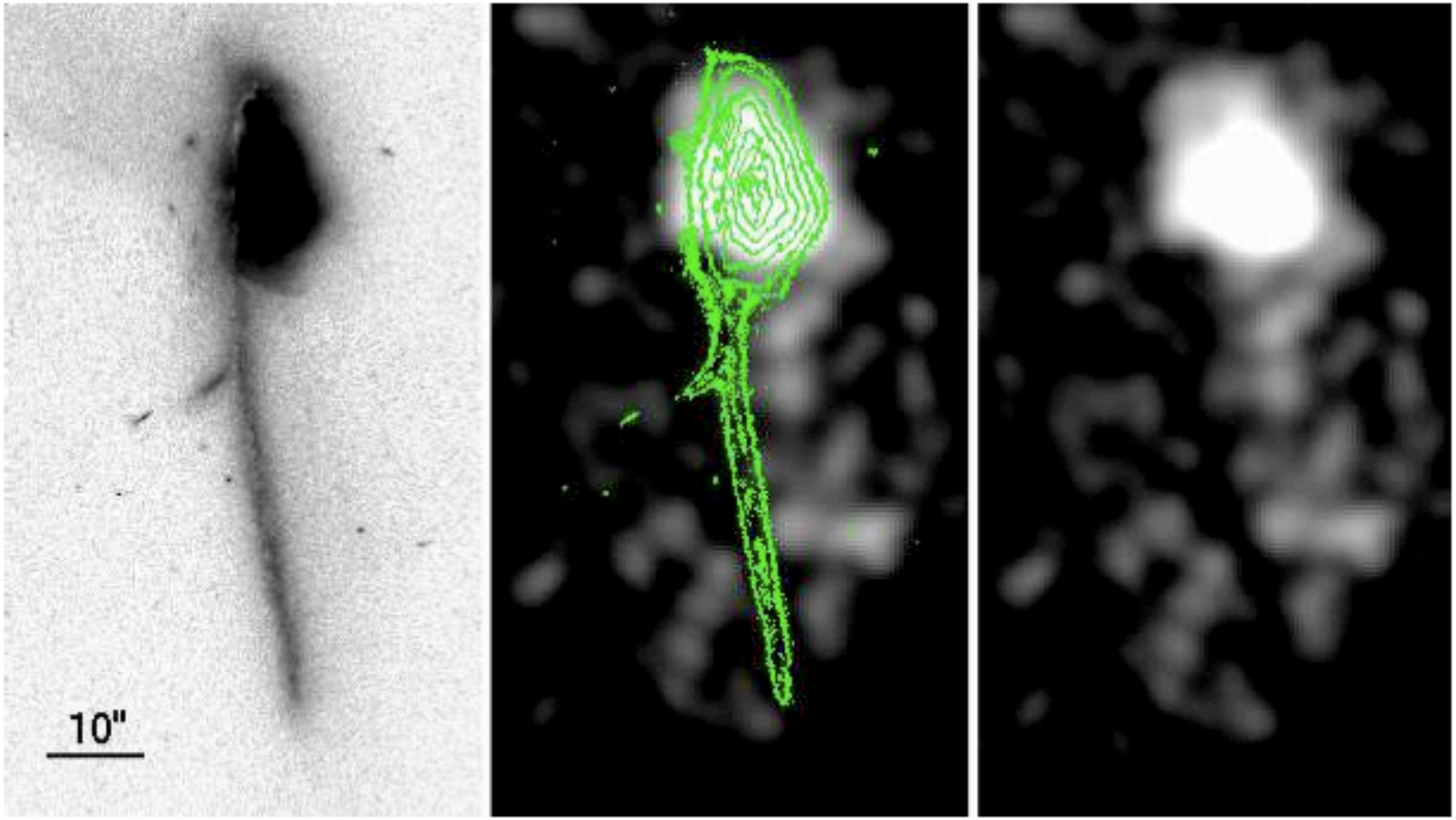
April 2000 New Results Number 83

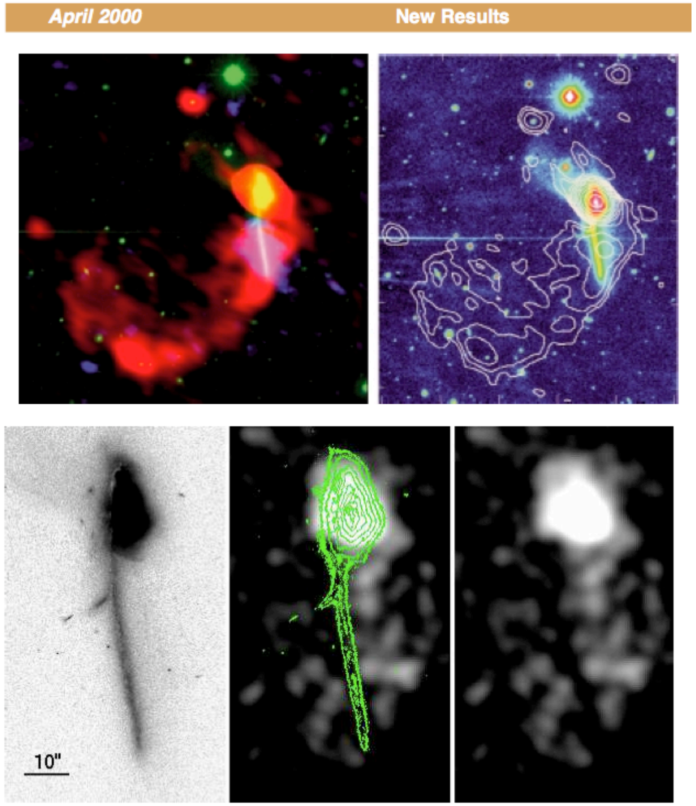


Left: False color RGB image of Mrk 273, with the starlight shown in green, 21cm H I line emission in blue, and 1.4 GHz radio continuum emission in red. Right: optical image of Mrk 273 in spectral colors, with contours of the 1.4 GHz emission superimposed.

Mrk 273 Chandra soft X-ray emission – Iwasawa et al 2010

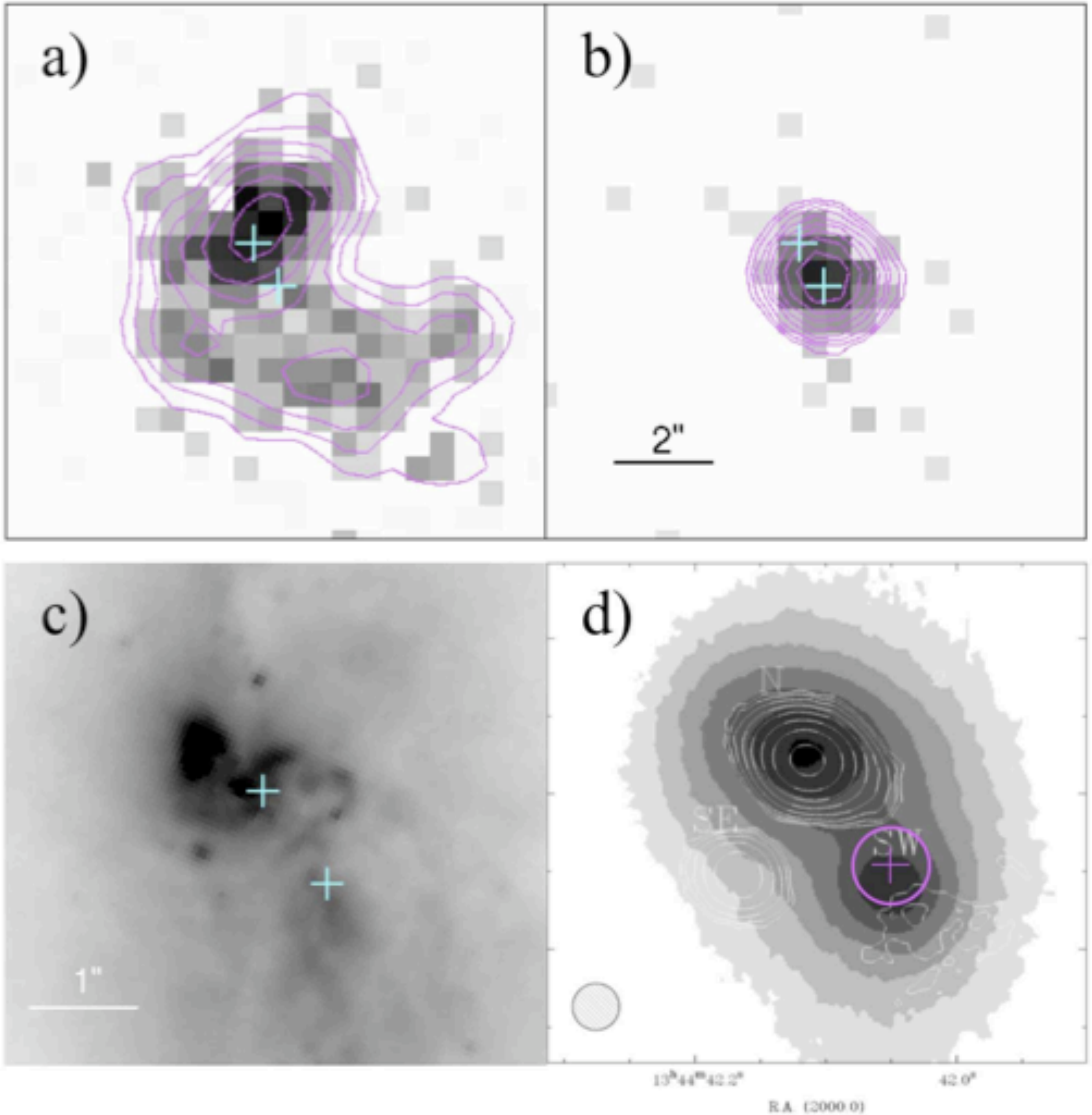
Absorption by the tidal tail





Mrk 273 core - Chandra ACIS   Iwasawa et al. 2010

Soft X-rays   Hard X-rays



HST I-band   + K-band nuclei   + Hard X on K-band image

New Results:

HST-NICMOS (H-band) imaging of the GOALS sample

- Haan, Surace et al. 2010, AJ, submitted

GALFIT measurements of bulge (*L, r, Sersic index*)

Marconni & Hunt : M_{BH} vs. L_{bulge}

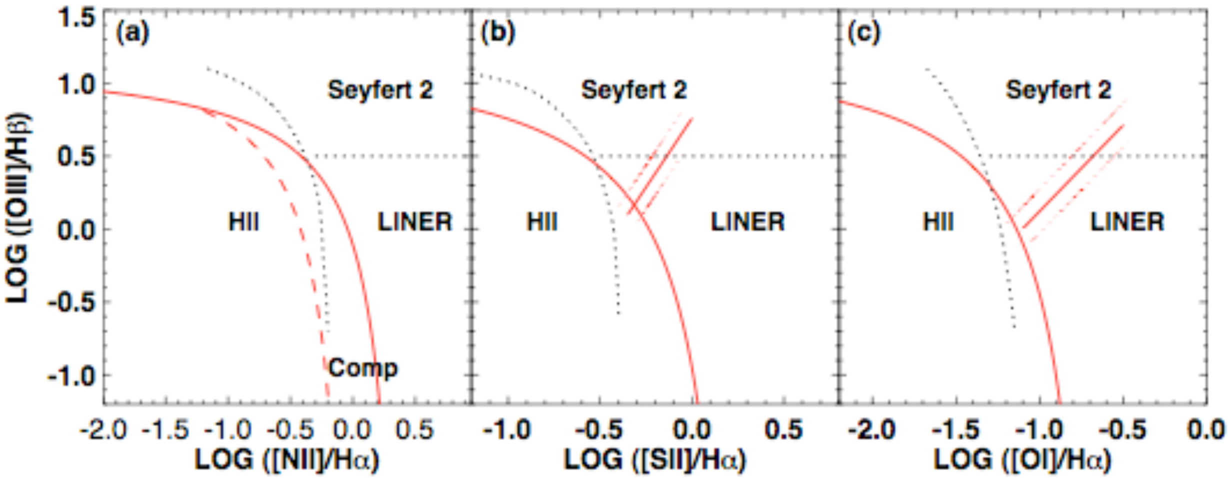
For systems with $L_{IR} = 10^{11.5}$ -- $10^{12.3}$ L_o

M_{BH} grows from 2-4 x 10^7 M_o -> 6-9 x 10^8 M_o

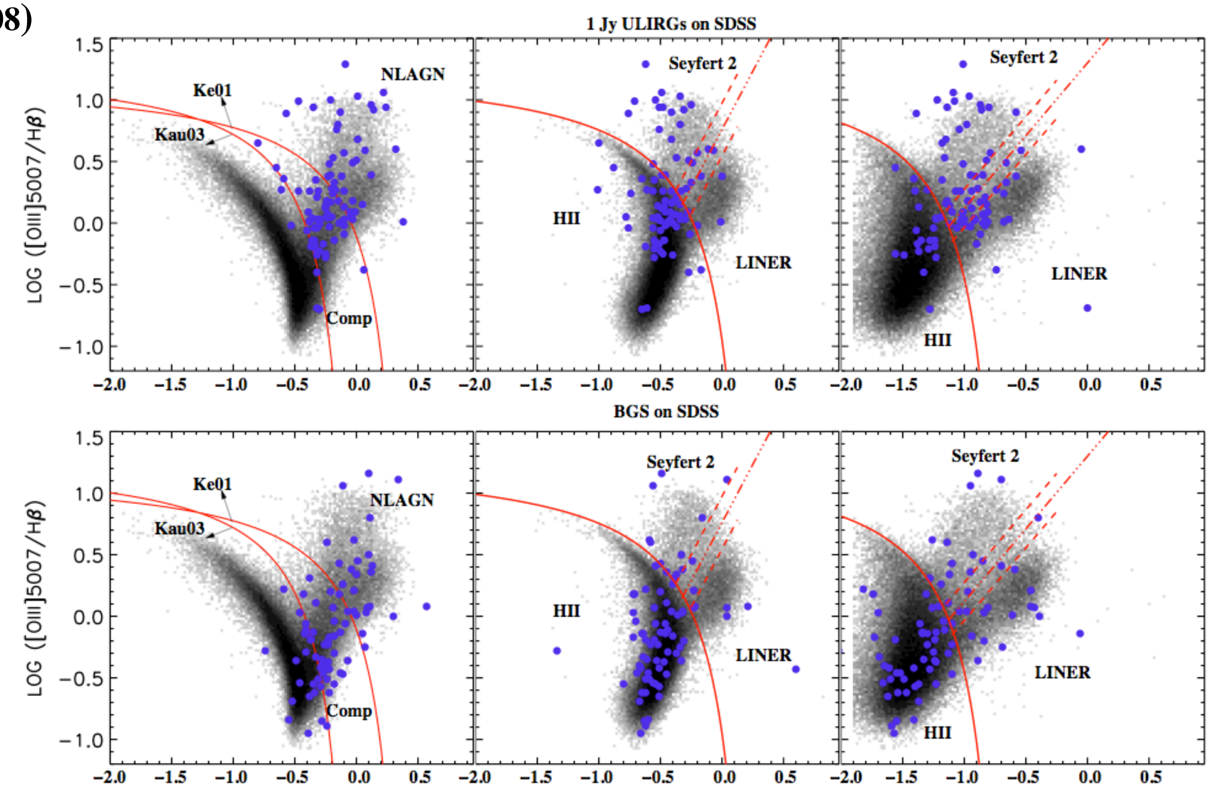
=> A factor of x30 increase in M_{BH} in FIR luminous phase

New optical diagnostic line classification scheme (Kewley et al. 2006)

“the addition of *B/AGN composite objects”



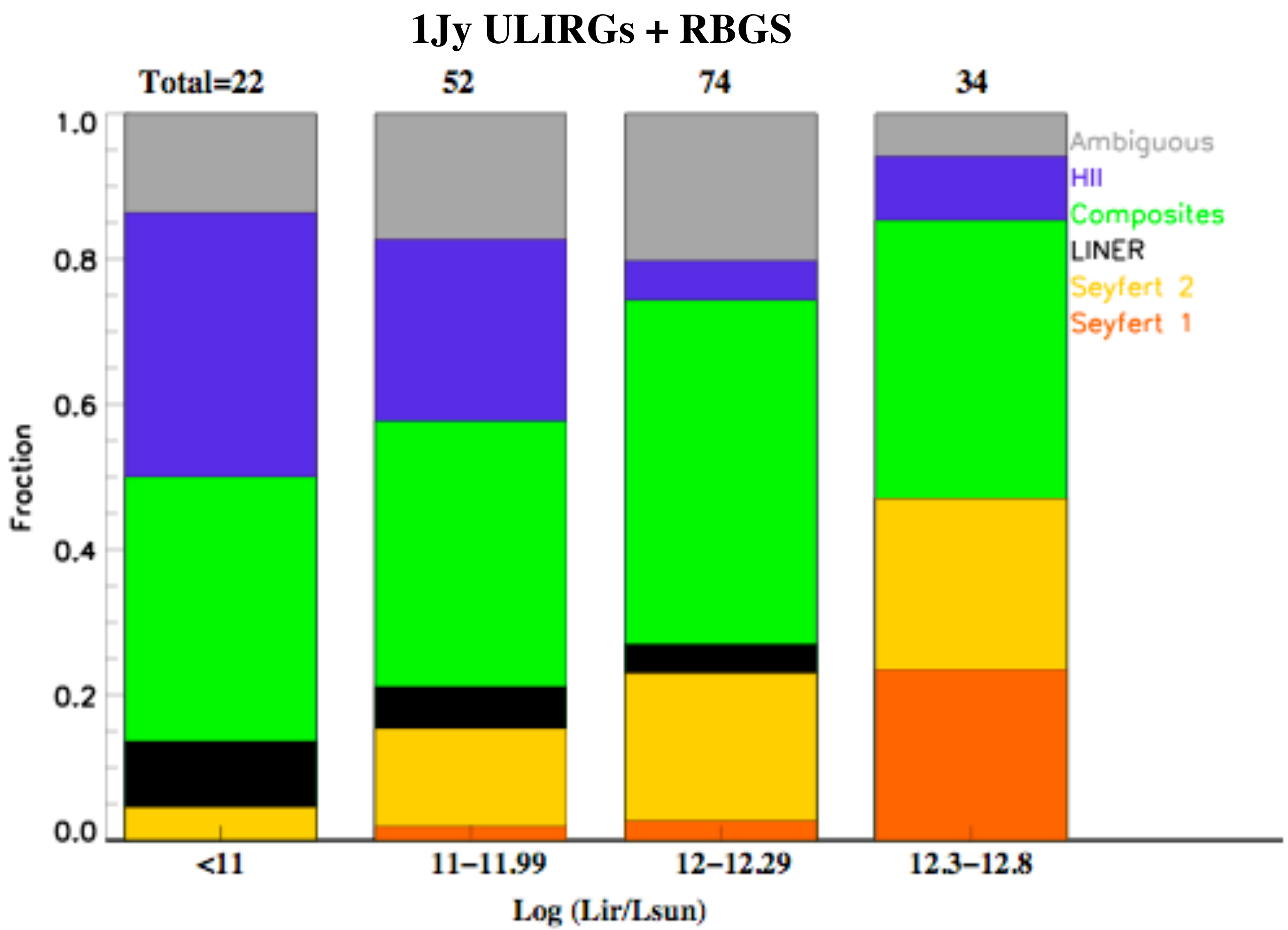
Classification of (U)LIRGs
(Yuan, Kewley&Sanders 2008)



1Jy ULIRGs
+SDSS

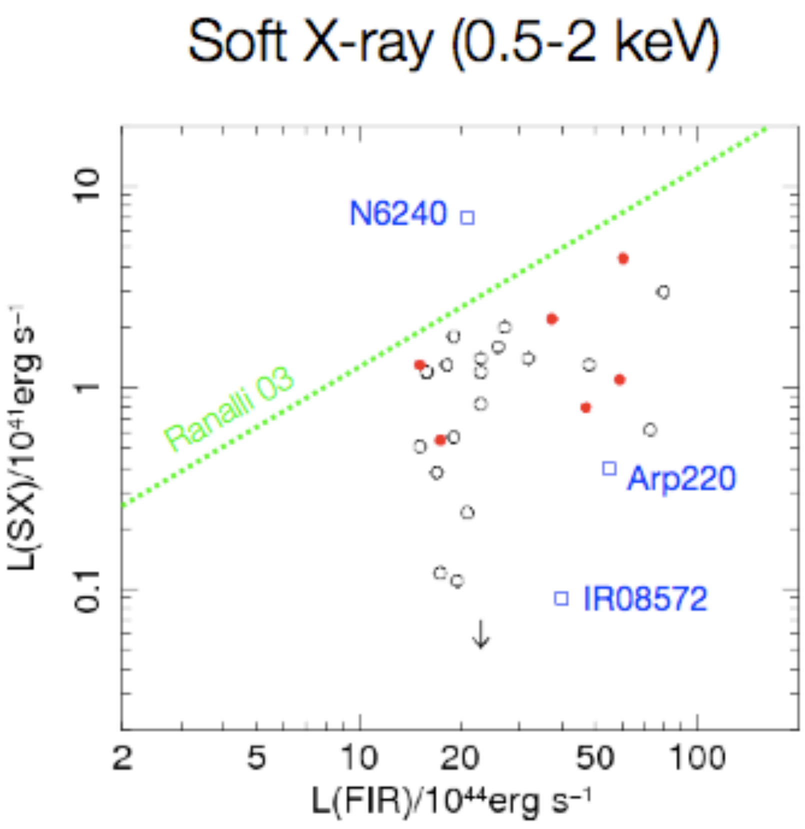
RBGS
+SDSS

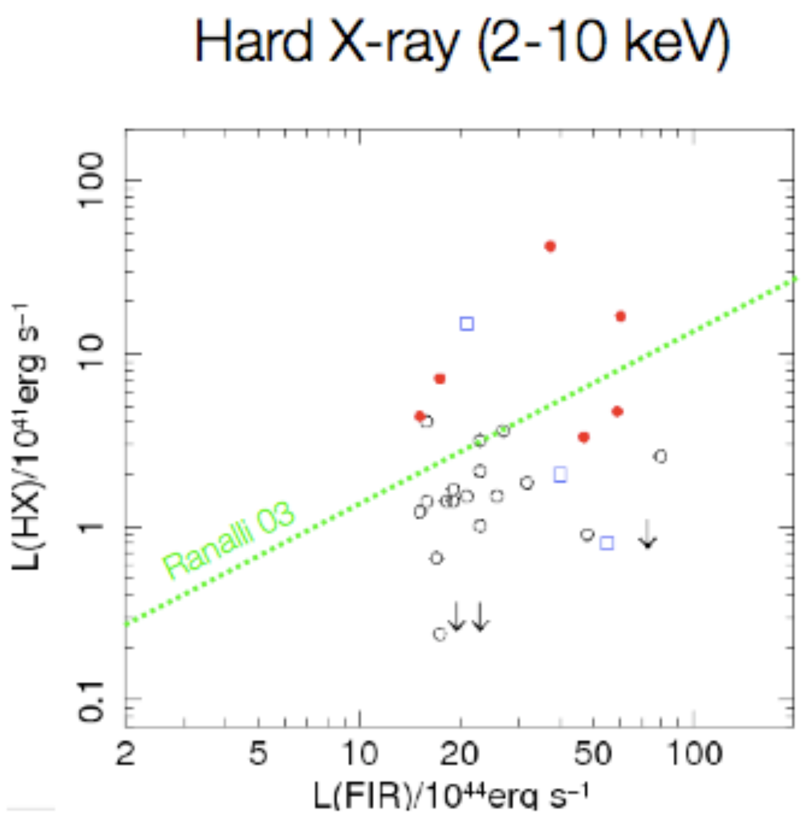
Optical Diagnostic Line Classification of (U)LIRGs (Yuan, Kewley&Sanders 2008)



Chandra-GOALS Iwasawa et al. 2008

X-ray vs Far-IR



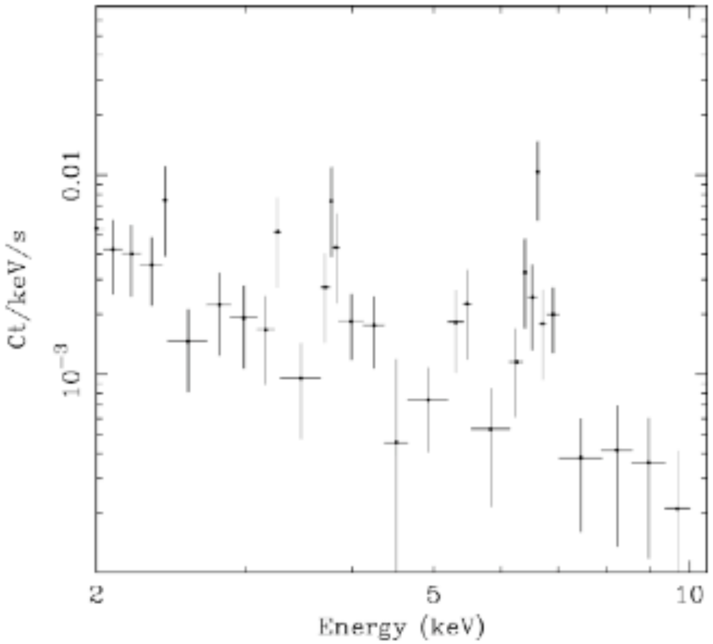


● AGN

*Absorption correction only for Galactic N_H

Arp 220 The template of starburst ULIG ?

XMM-Newton



Iwasawa et al 2005

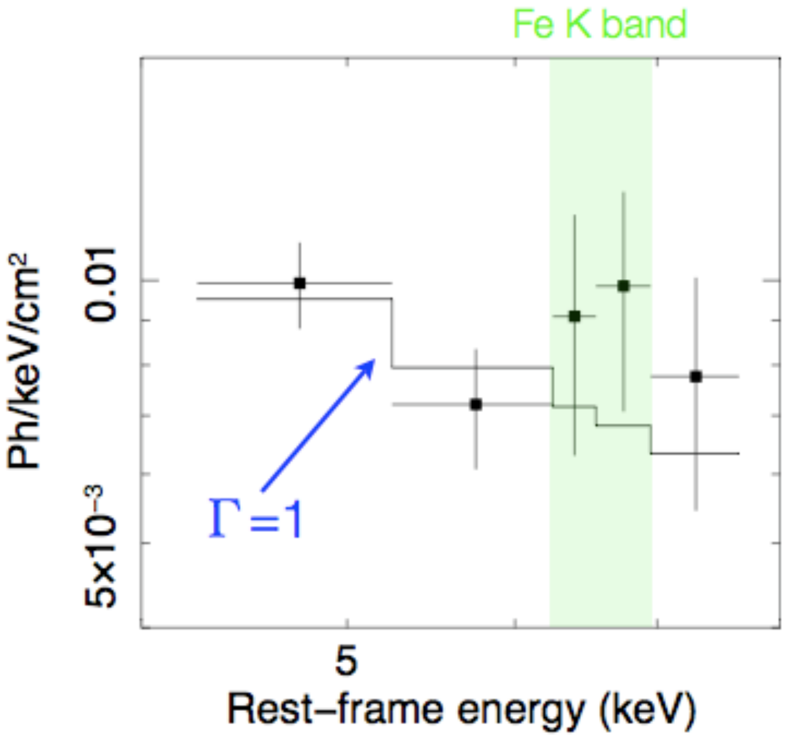
- **X-ray under-luminous** at given L_{IR}
- Hard X-ray spectrum with strong **Fe K** (but at 6.7 keV)

  not compatible with X-ray binary origin

Hard X-ray spectrum of non-AGN sources

20 non-AGN sources stacked

Total 155 counts



Like Arp220?

Two Surveys:

1. GOALS – the Great Observatories All-Sky LIRGs Survey

2. S-COSMOS – The Spitzer IRAC+MIPS Survey of the COSMOS 2-sq deg Field

S-COSMOS

http://irsa.ipac.caltech.edu/data/SPITZER/S-COSMOS/

S-COSMOS Archive

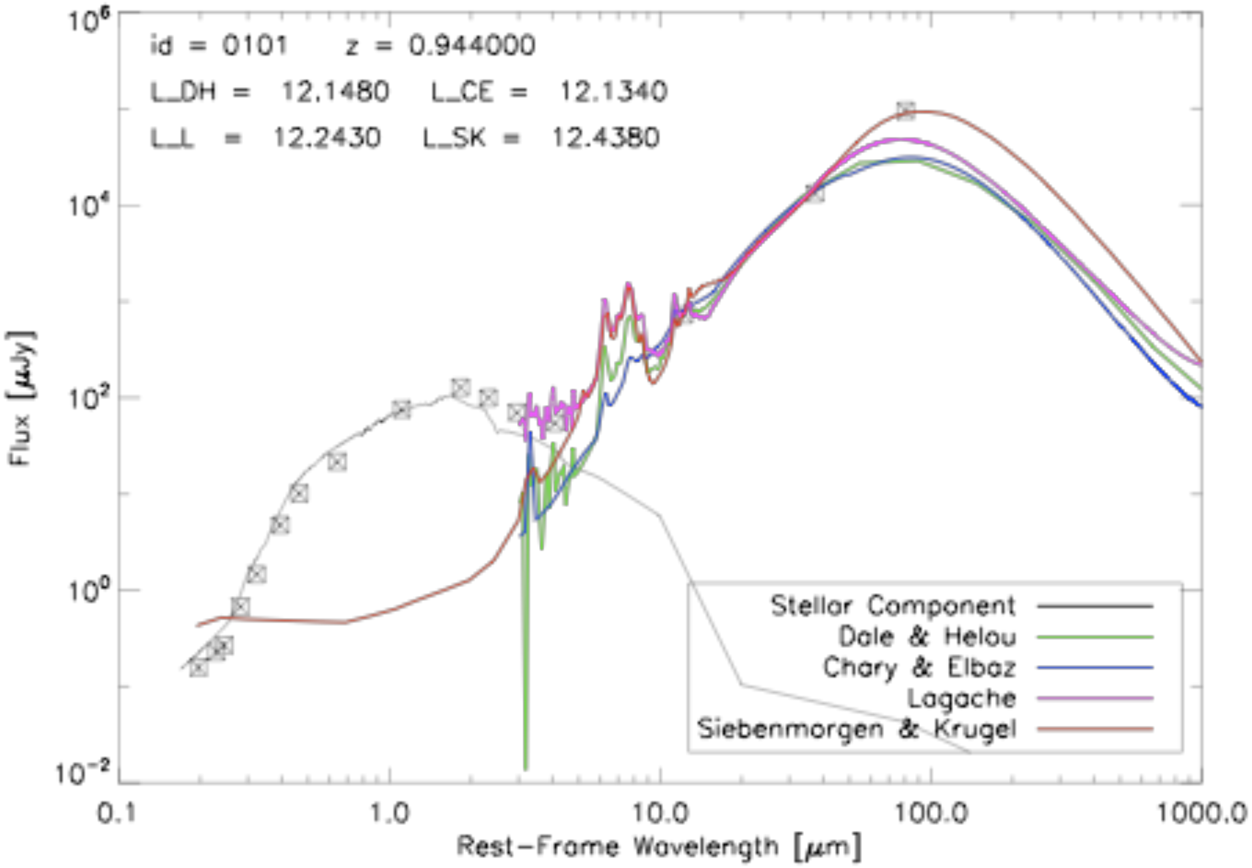
S-COSMOS is a deep infrared imaging survey carried out with the Spitzer Space Telescope. The survey covers the entire 2 square degrees of the **Cosmic Evolution Survey** (COSMOS) field. The S-COSMOS and COSMOS projects are closely coupled; therefore, their data are served as one large **COSMOS Archive**, using IRSA's general search service, Atlas. For more information on S-COSMOS, click here for the project web site. S-COSMOS is part of the Spitzer Legacy Program; these "Enhanced Products" are from the Spitzer Science Center (SSC) public data staging location. The data products released are part of the Spitzer General Observer Cycle 2 (GO2) program, including predominantly IRAC products (images and catalog). MIPS data include shallow images/catalogs covering the entire COSMOS field. There are also deep MIPS images covering only a test field of 0.16 sq. degrees for the coming GO3 program. The GO3 products will be public in September 2008.

COSMOS is an astronomical survey designed to probe the formation and evolution of galaxies as a function of cosmic time (redshift) and large scale structural environment. The survey covers a 2 square degree equatorial field with imaging by most of the major space-based telescopes (Hubble, Spitzer, GALEX, XMM, Chandra) and a number of large ground based telescopes (Subaru, VLA, ESO-VLT, UKIRT, NOAO, CFHT, and others). Over 2 million galaxies are detected, spanning 75% of the age of the universe. The COSMOS survey involves almost 100 scientists in a dozen countries.

S-COSMOS Archive Access

- Spatial Search: S-COSMOS **image** data access within the COSMOS Archive
- Spatial Search: S-COSMOS **image cutouts** within COSMOS Archive using Cutouts Service. IRSA's Cutouts Service is a general tool to create single or multiple small FITS (and JPEGs) image cutouts of datasets archived at IRSA. Note - to get Spitzer-only image cutouts, deselect the rest of the available COSMOS image datasets.
- Advanced Catalog Search: S-COSMOS **catalog** data access using Gator
- Directory Access: S-COSMOS **images** - directory of FITS files

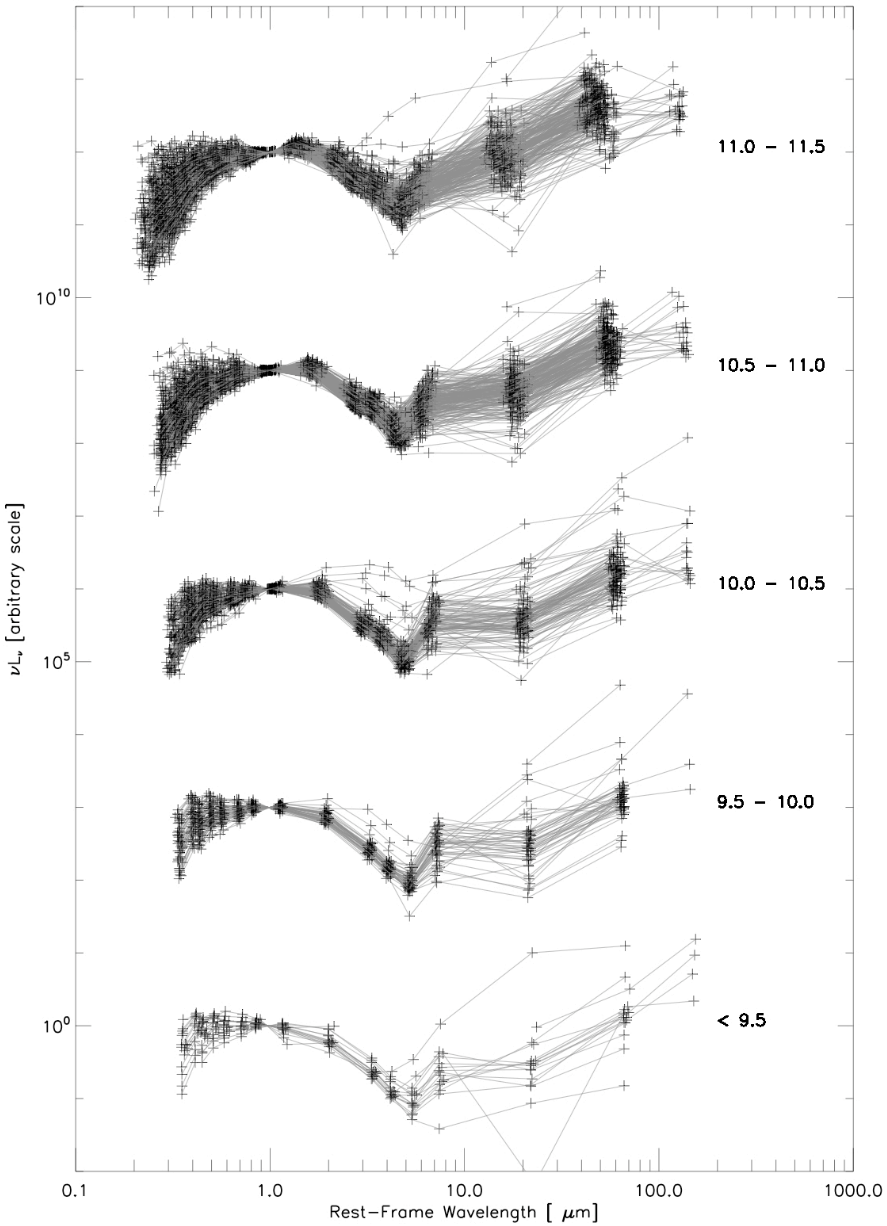
S-COSMOS: SEDs of a complete flux-limited, 70um-selected sample of galaxies ($z < 2$)
J. S. Kartaltepe et al. (2009)

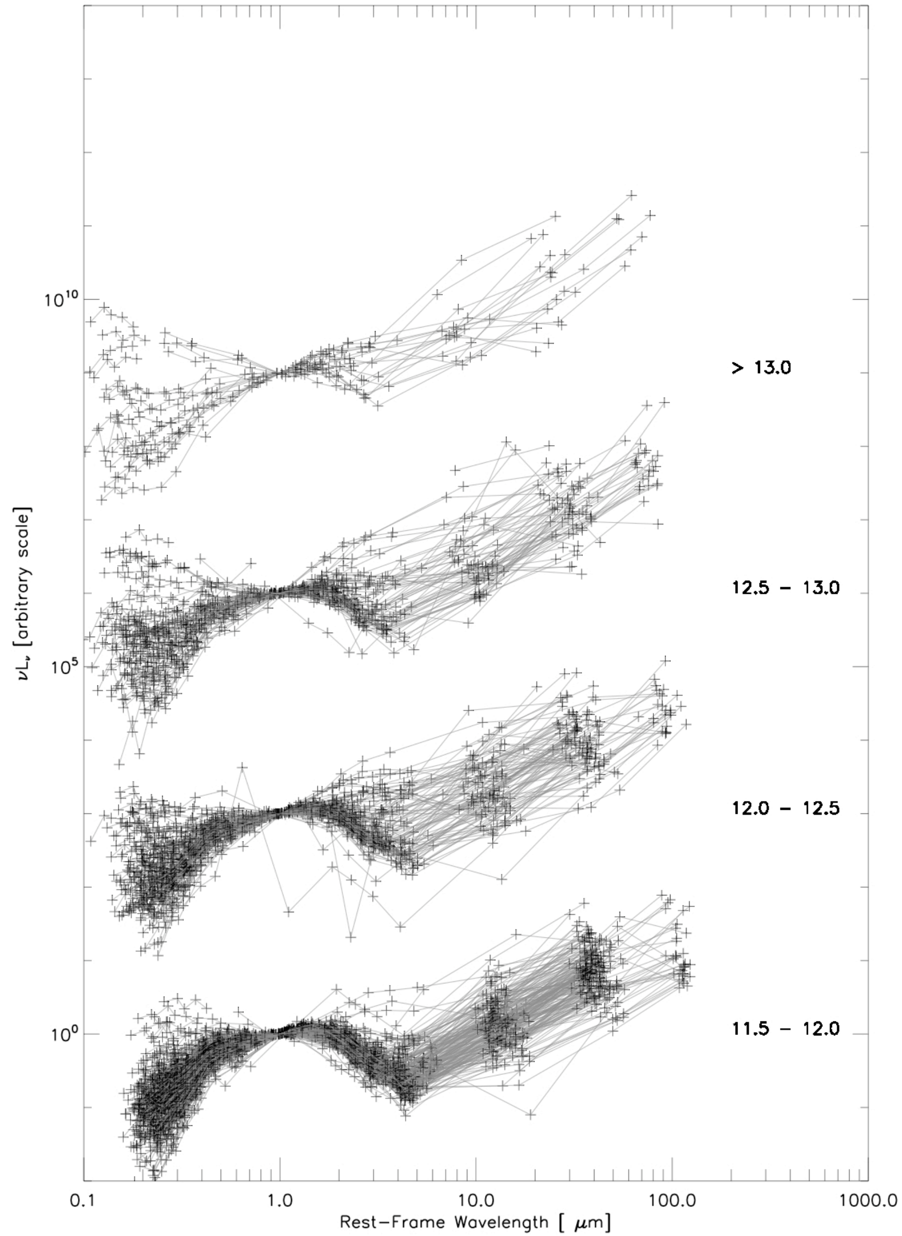


Template fits for photo-z and $L_{\rm FIR}$

S-COSMOS: SEDs of a complete flux-limited, 70um-selected sample of galaxies ($z < 2$)

J. S. Kartaltepe et al. (2009)



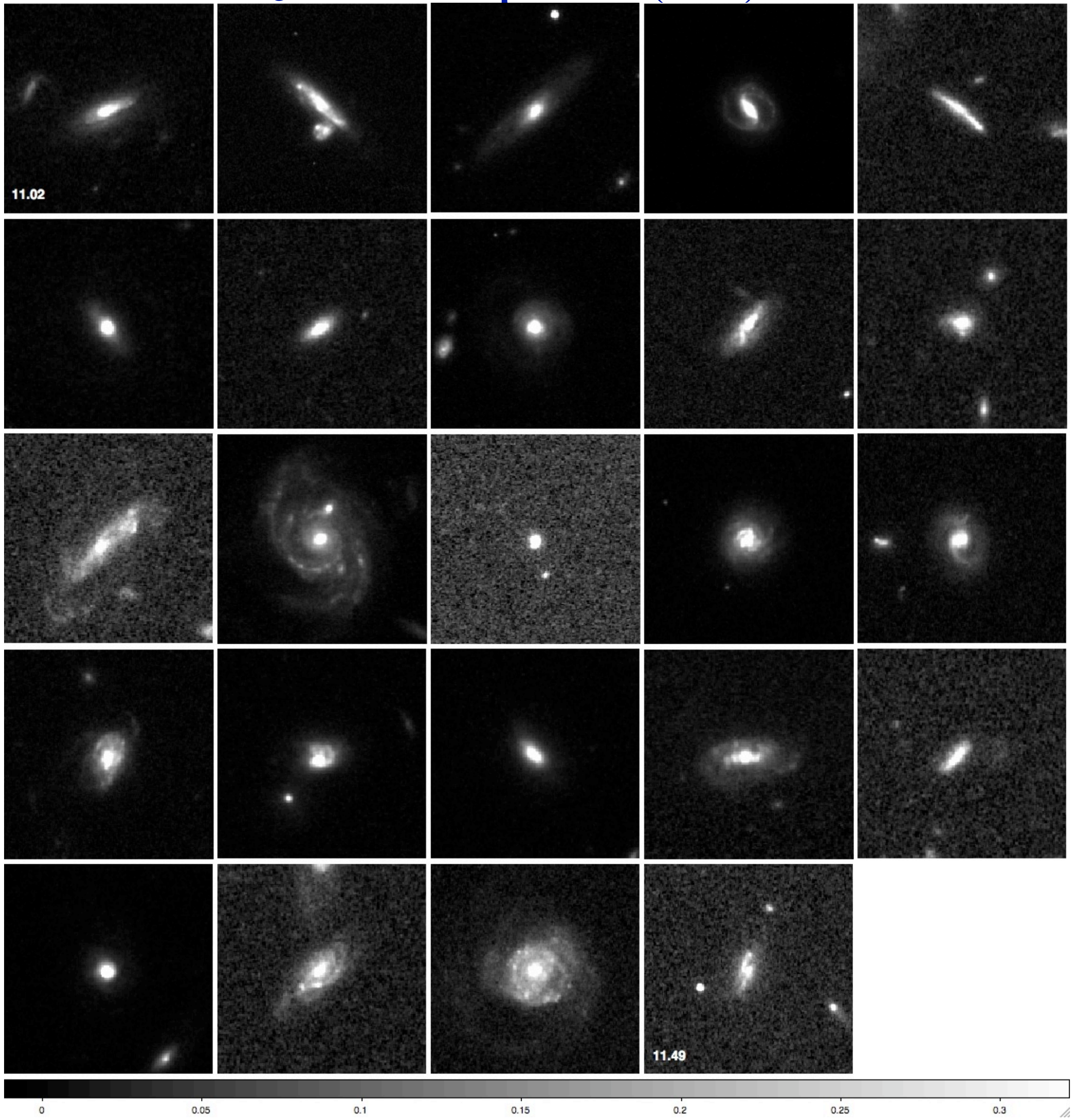


S-COSMOS: 70um-selected sample of galaxies

L_{ir}/L_{sun} = 11.00 – 11.49

J. S. Kartaltepe et al. (2009)

HST I-band morphology

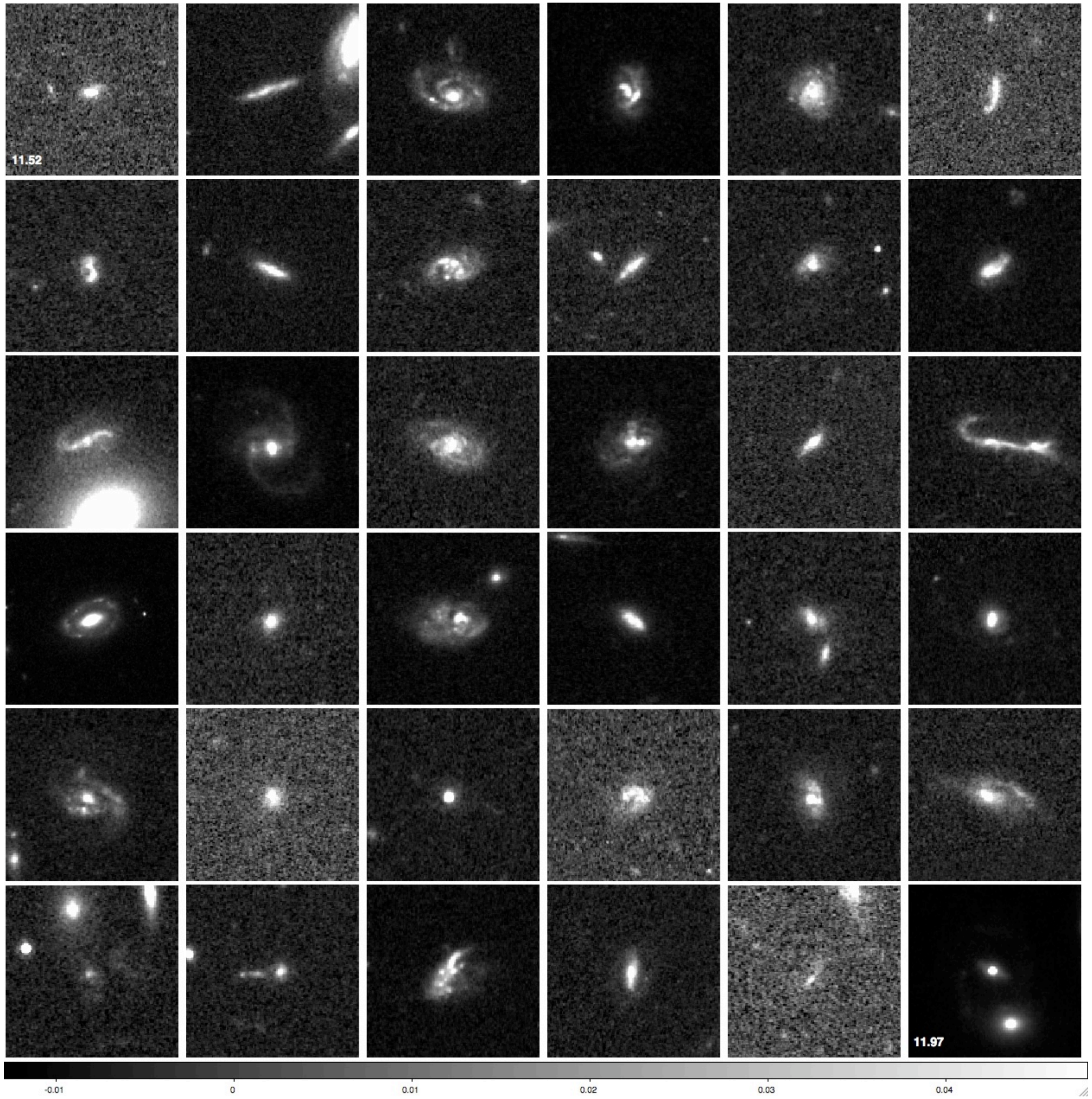


S-COSMOS: 70um-selected sample of galaxies

L_{ir}/L_{sun} = 11.50 – 11.99

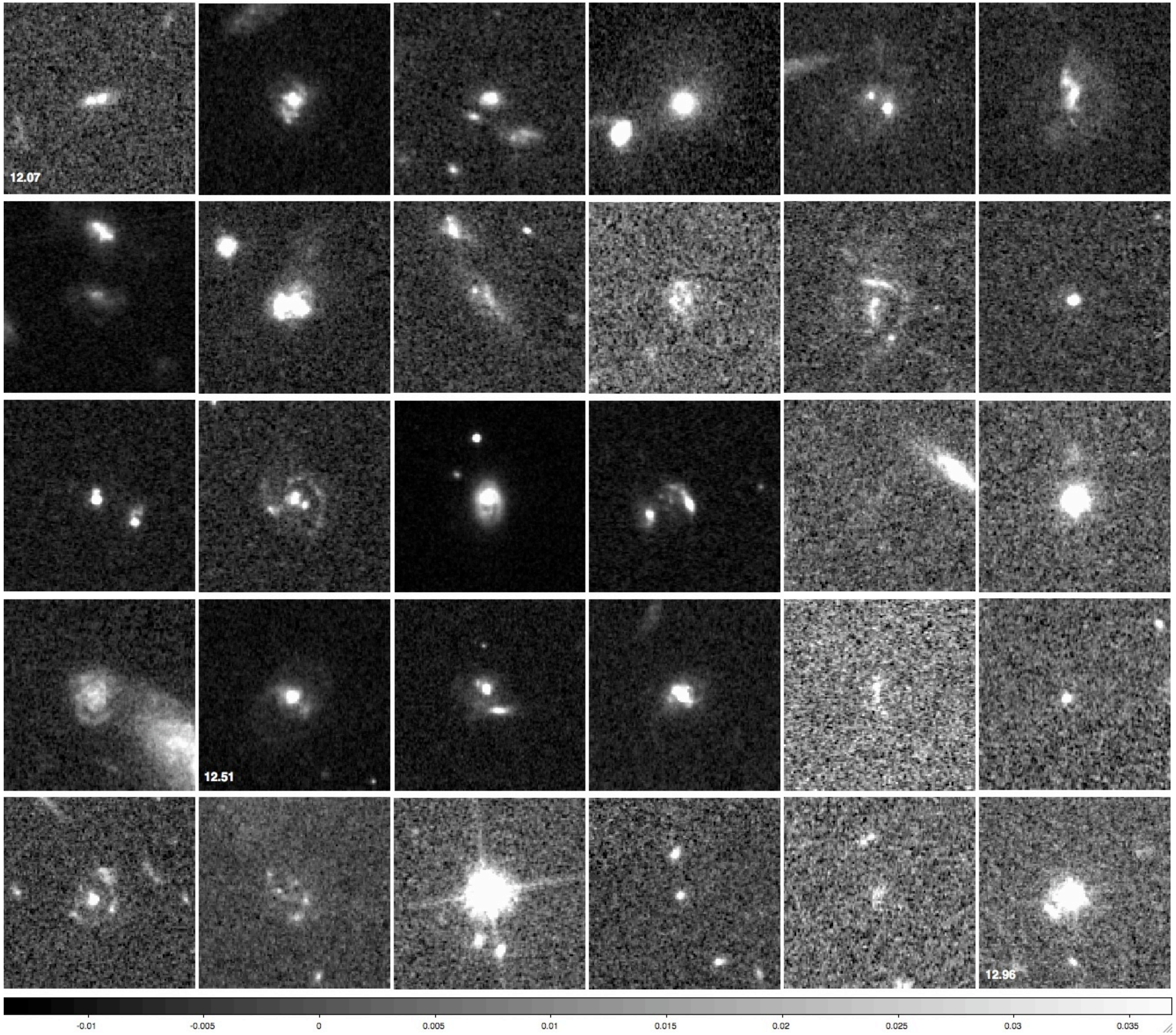
J. S. Kartaltepe et al. (2009)

HST I-band morphology



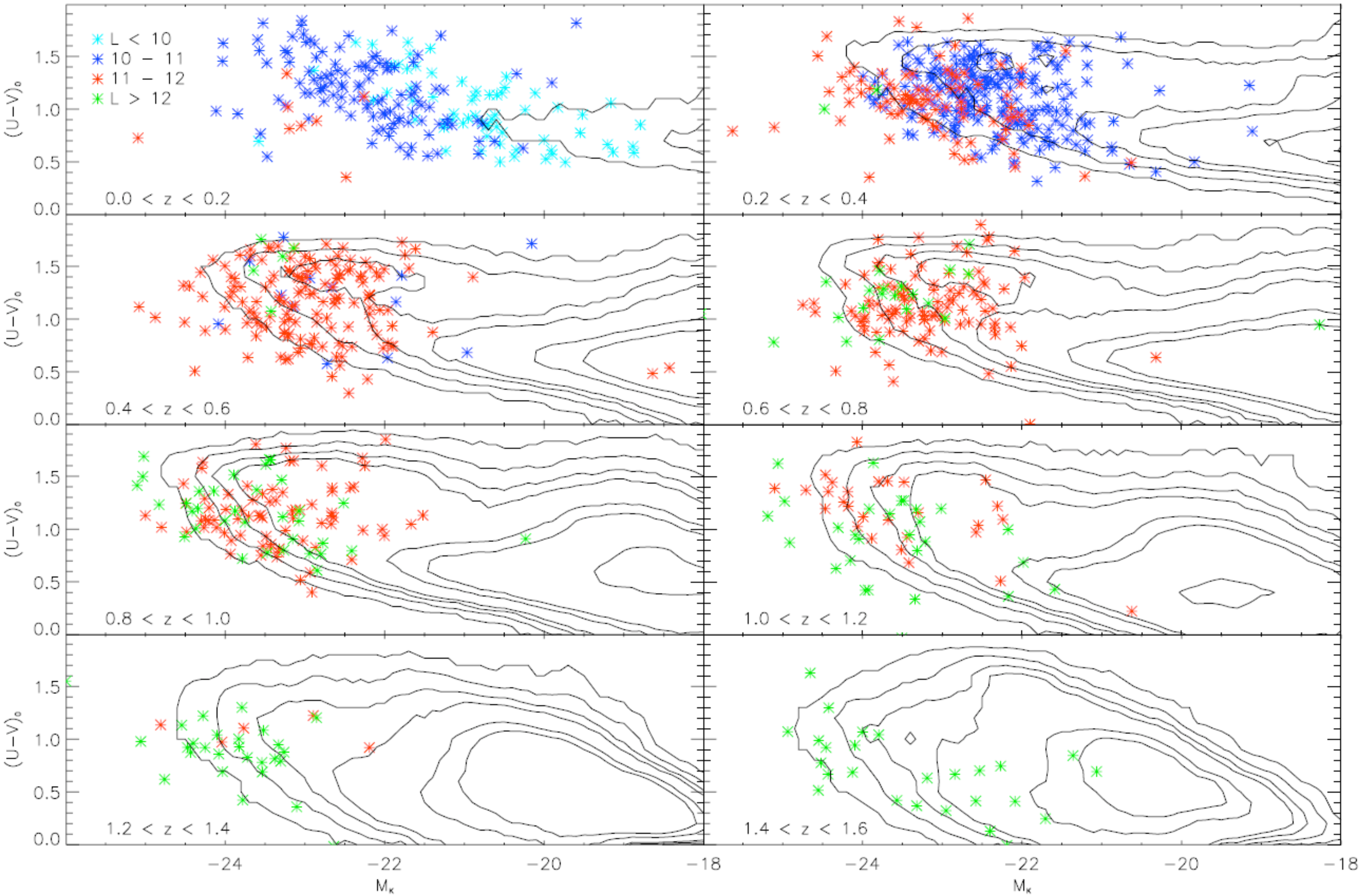
S-COSMOS: 70um-selected sample of galaxies
L_{ir}/L_{sun} = 12.00 – 12.99
J. S. Kartaltepe et al. (2009)

HST I-band morphology



S-COSMOS: $(U\text{-}V)_0$ vs. M_K for a complete flux-limited, 70um-selected sample of galaxies ($z < 1.6$)

J. S. Kartaltepe et al. (2009)



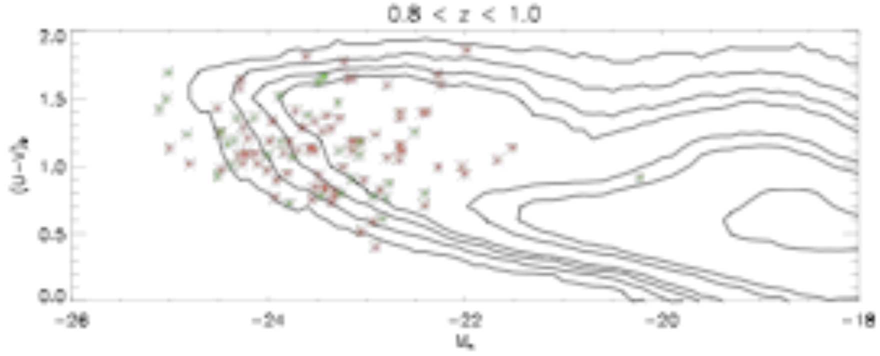


Figure 1. Rest frame $U-V$ vs. M_K color-magnitude diagram for the $0.8 < z < 1.0$ redshift bin. The optically selected sample for the full field is shown by the contours and the asterisks mark the 70 μm selected sources. Red: LIRGs, Green: ULIRGs

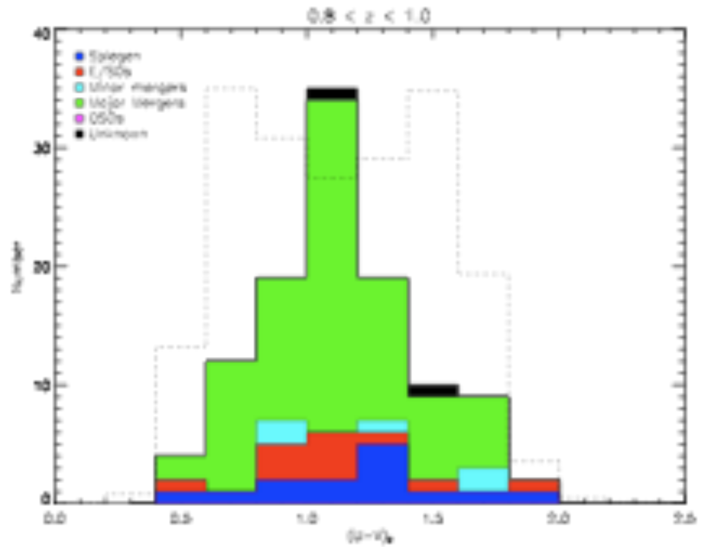
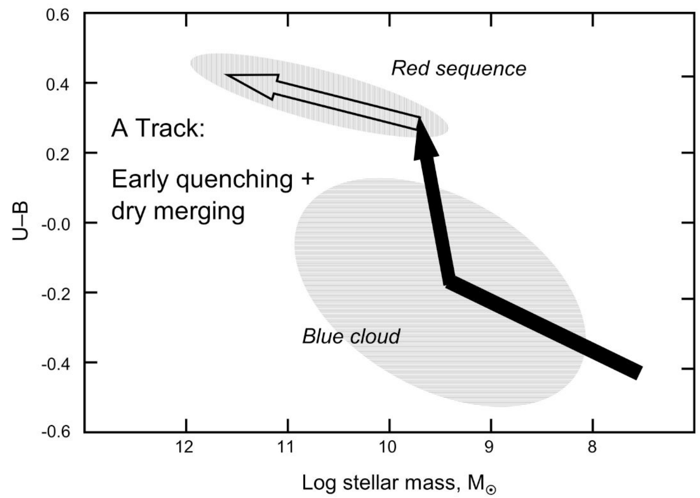
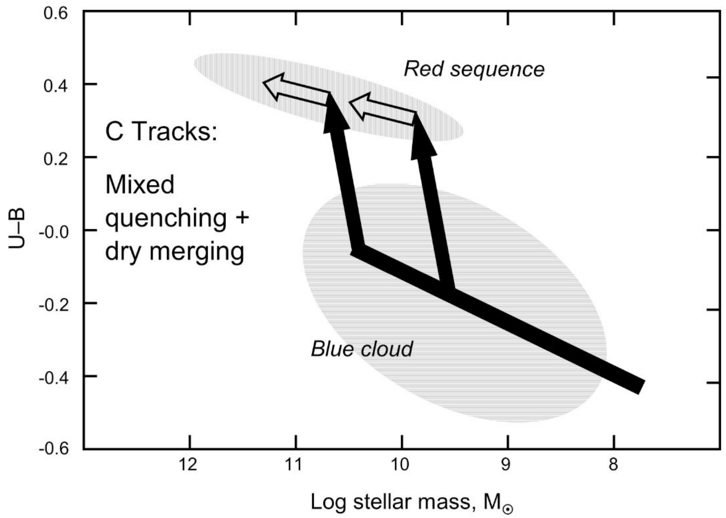


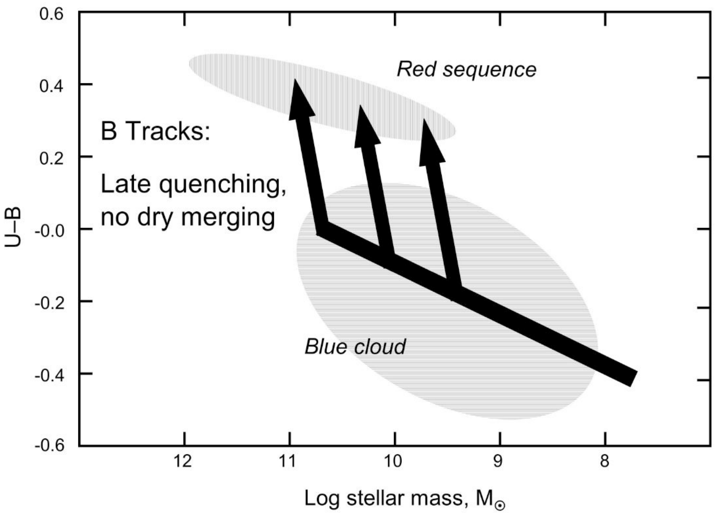
Figure 2. $U-V$ histogram for the 70 μm sample across all M_K values in the $0.8 < z < 1.0$ redshift bin olor coded by morphology. The $U-V$ distribution for the entire optically selected sample over the same M_K range is shown as the dotted line.

Merger Scenarios for the Formation of Elliptical Galaxies
"gas-rich" vs. "gas-poor" mergers

(from Faber et al. 2007, ApJ, 665, 265)



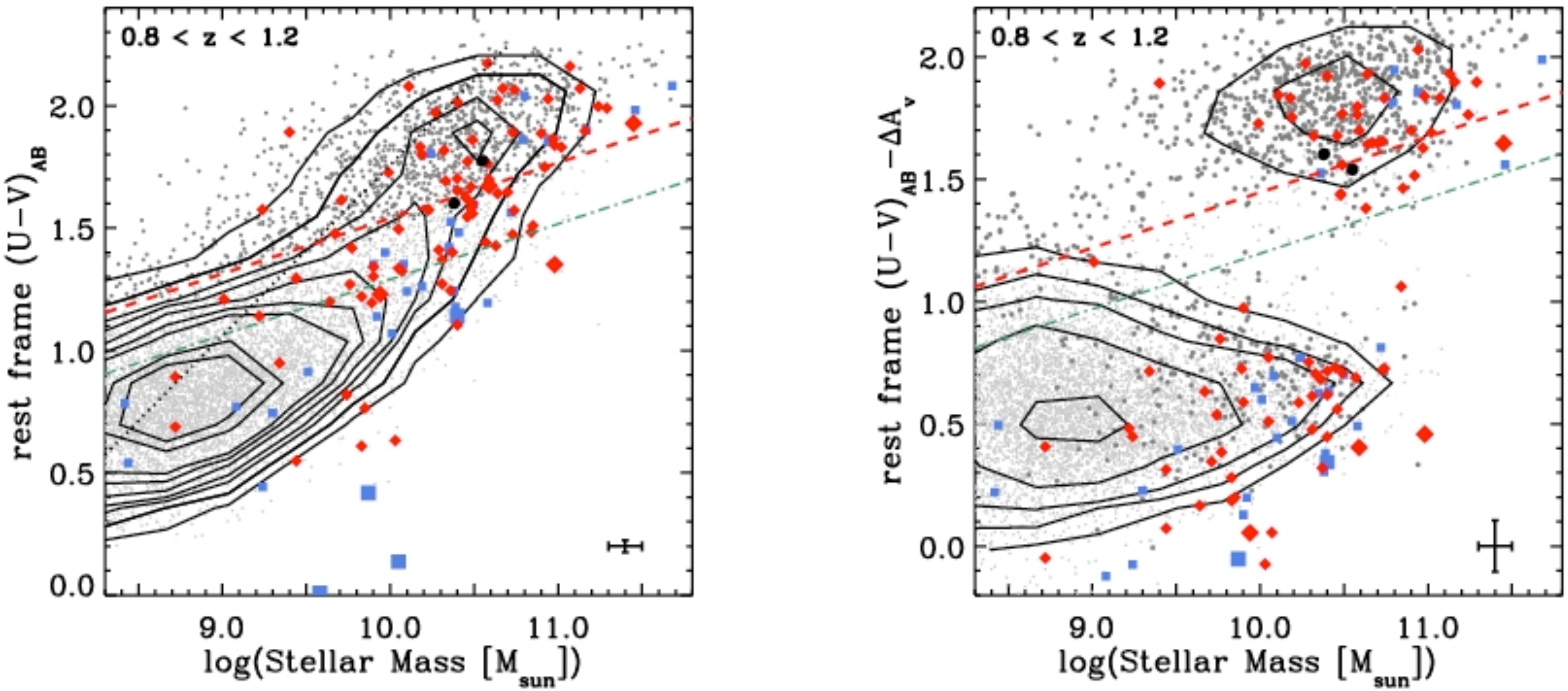




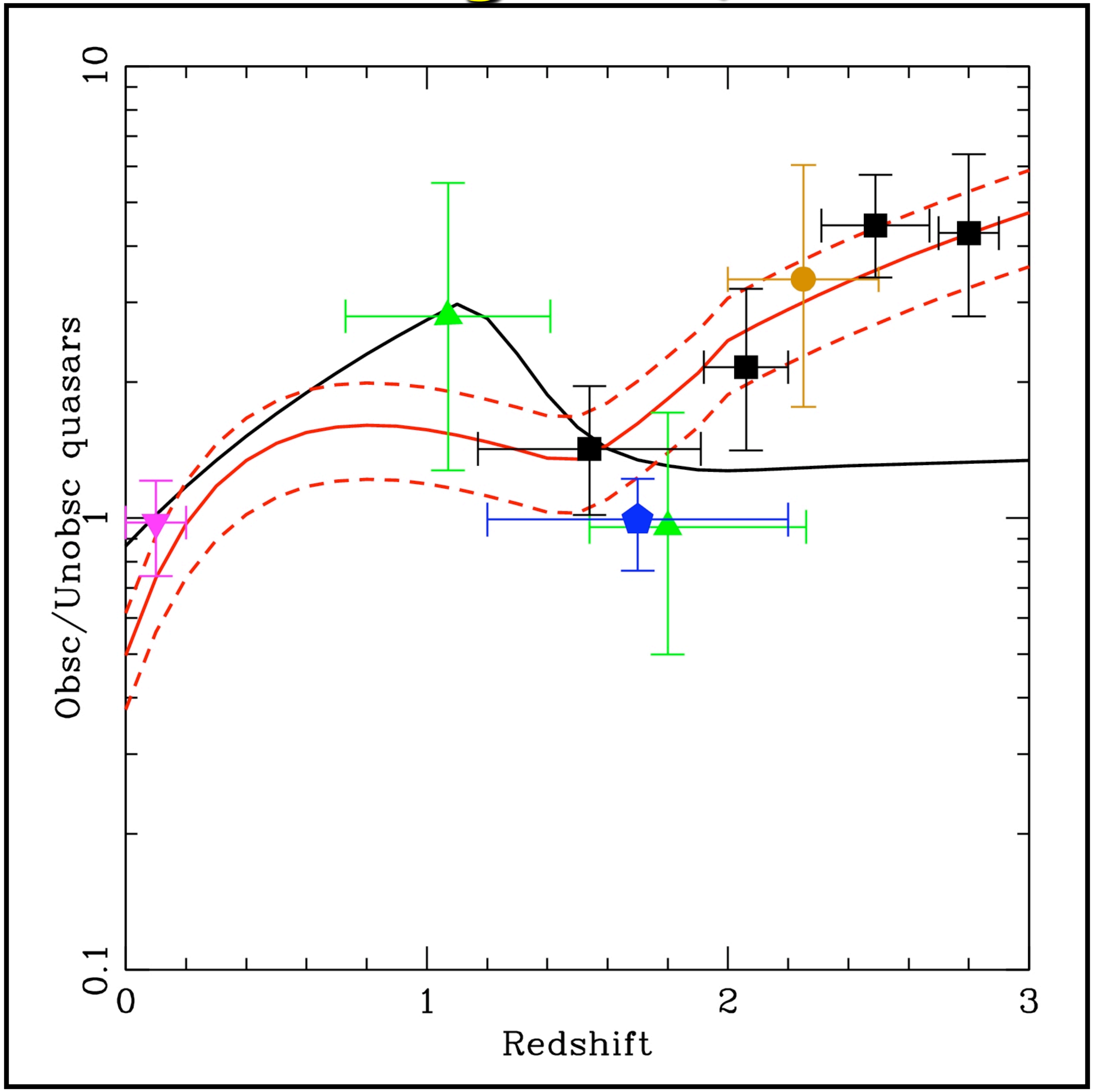
Given that we find a sufficient population of strongly interacting/merging LIRGs in the green valley that appear to span the full range of M_K of the red sequence, we prefer the "B Tracks" scenario shown at the left, and suggest that LIRGs can account for MOST IF NOT ALL 1 - 6 *L ellipticals.**

A caveat: De-reddened Color-Magnitude Diagrams

(from Carrie Cardamone's poster)

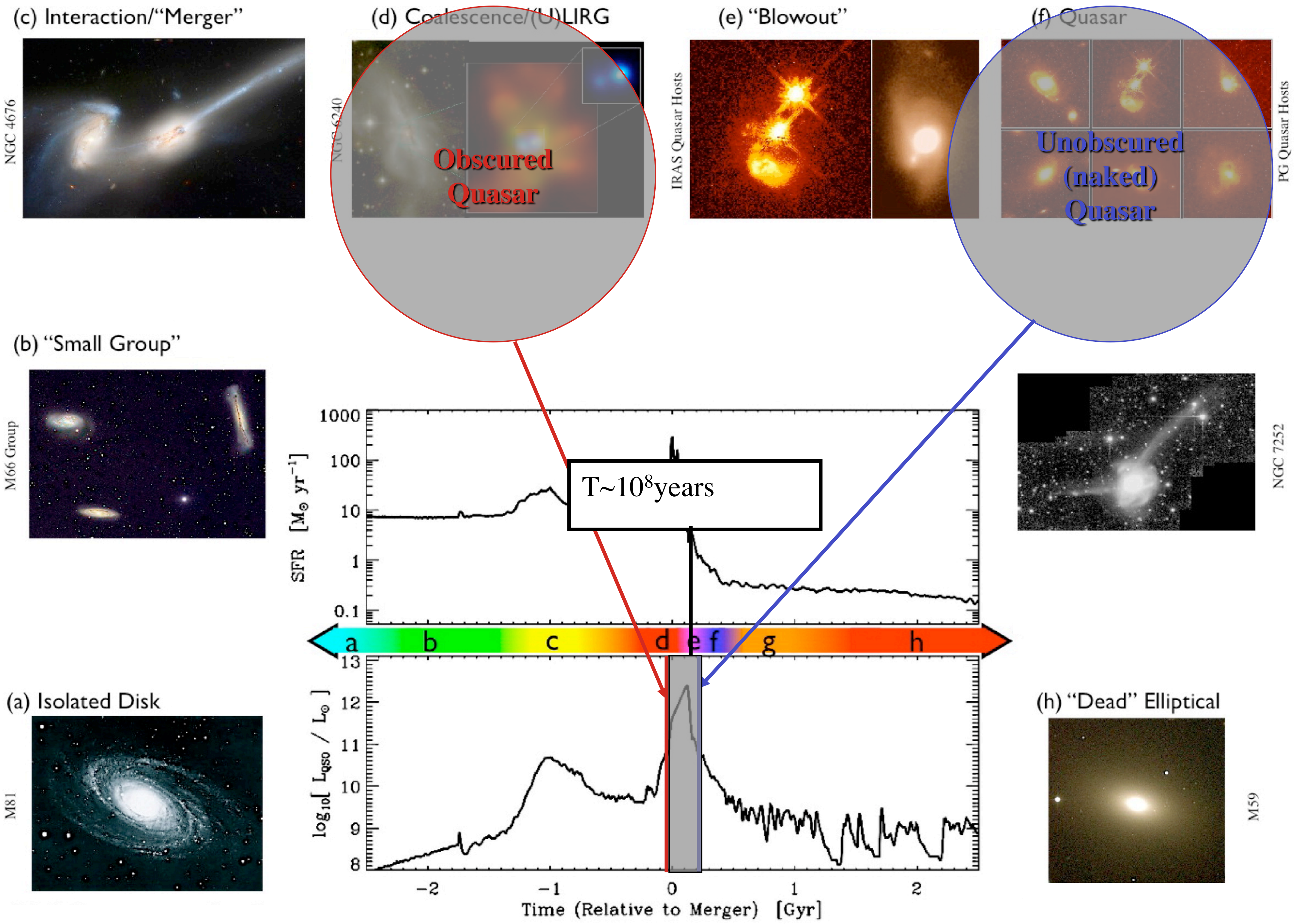


The Merger-Quasar Connection



Treister poster:

Increasing importance of CT sources at high z



Hopkins et al. (2008)

Summary

1. All galaxies in the local universe with log (L_{ir}/L_{o}) > 11.6 are major mergers of gas-rich spirals (typically *L*-L**)

2. Evidence from ISO and Spitzer deep fields suggests strong evolution $(1+z)^{5\pm2}$ of the high luminosity tail of the infrared LF due to major mergers over the redshift range $z = 0 - 2$.

3. Evidence suggests that a substantial fraction of the luminosity emitted by the most luminous IR galaxies may come from a massive black hole(s) accreting at near L_{edd} (many Compton-thick sources)

4. M_{BH} grows by ~ x 30 (3 x10^7 to 9 x10^8 M_o) during the FIR-luminous phase (6-8 x 10^8 years)

5. LIRGs have observed optical colors that lie preferentially in the "green valley"; they are sufficient in number (at a given M_K) to plausibly account for the buildup of "red sequence" Ellipticals through the merger of gas-rich Spirals in the blue cloud.