MBH Growth in Gas-Rich Galaxy Mergers

Dave Sanders

University of Hawaii, Institute for Astronomy

GMU June, 2017

MBH – SMBH Growth in IR-Luminous, Gas-Rich Galaxy Mergers
(in the local universe)
(and at "high" redshift)

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Outline

1. A brief Retrospective –
   (U)LIRGs @ 30

2. New Results for Local (U)LIRGs –
   updated morphology, molecular gas fractions (GOALS)

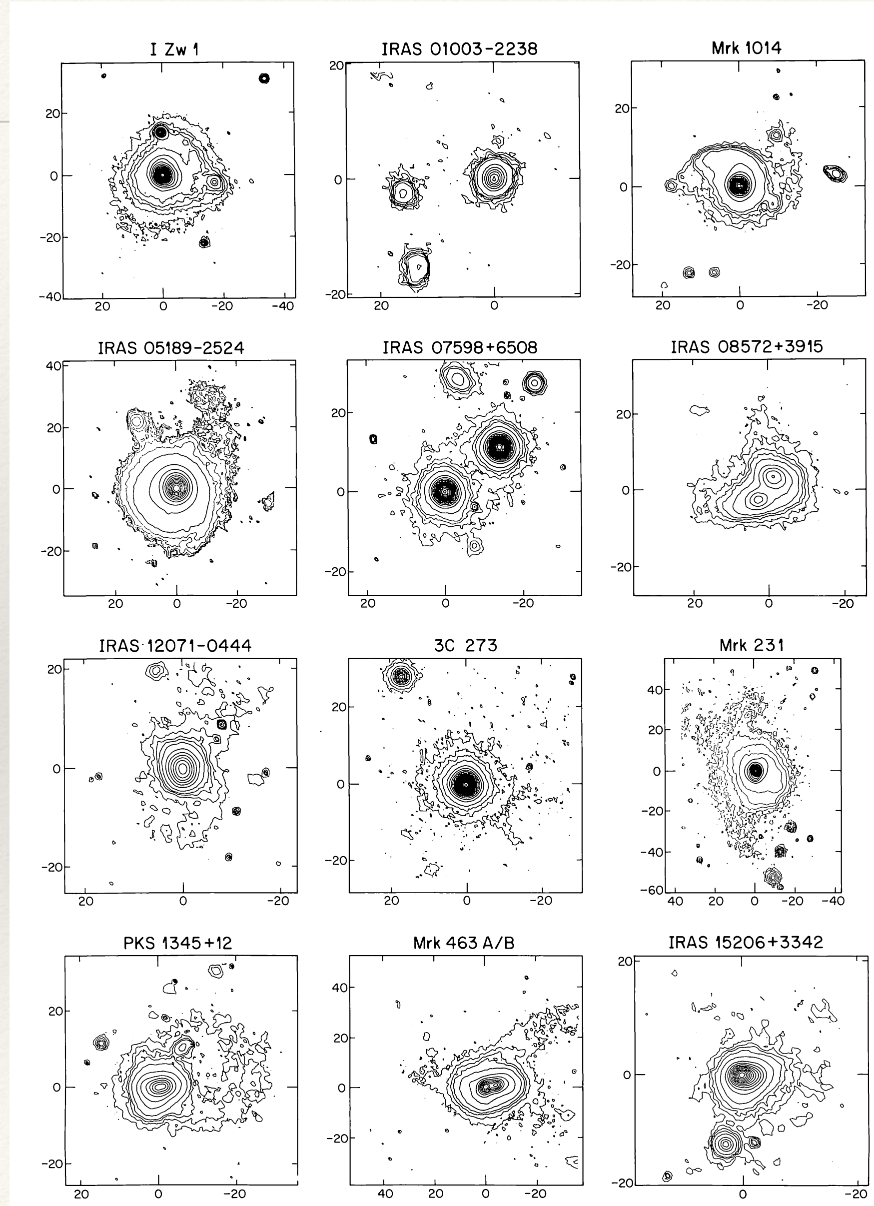
3. Newer Results for Local (U)LIRGs –
   high resolution NIR and submm spectroscopy/imaging

4. Morphology and Spectroscopy of (U)LIRGs at z ~ 0 – 1.5

Discovery of “FIR-Extreme” Objects: ULIRGs, IRQSOs, HyLIRGs, …

Late 1980s

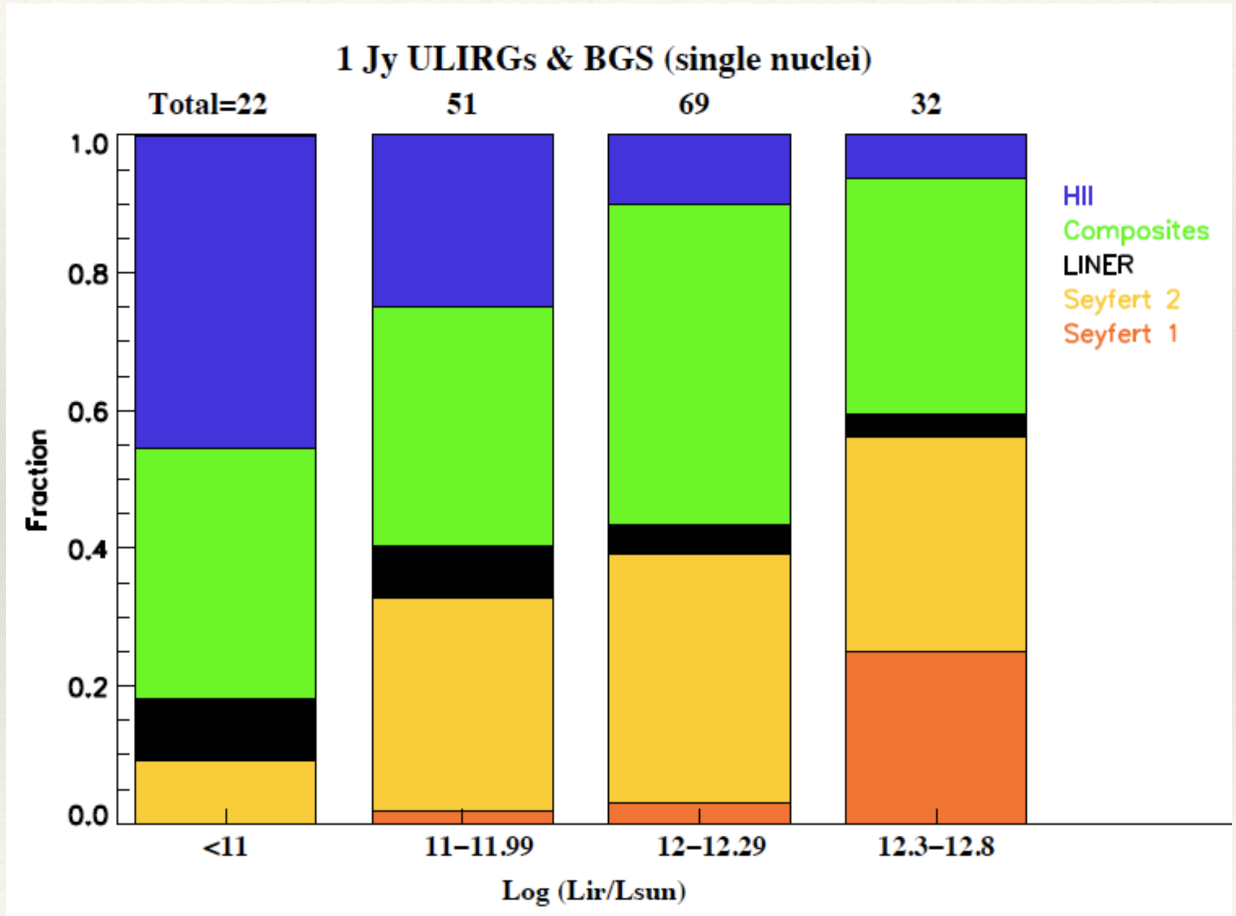
IRAS follow-up



Properties of Local (U)LIRGs

- Fraction of (U)LIRGs with AGN increases with L_{IR}
  - Veilleux et al. 1995, 1999; Yuan et al. 2010

- **Definite AGN (orange + yellow)**
  - $< 20\%$ for $L_{IR} < 10^{11}\ L_{\odot}$
  - $> 50\%$ for $L_{IR} > 10^{12.3}\ L_{\odot}$
- **Large fraction of composites (green)**
  - Mix of SF, AGN, shocks
  - Difficult to disentangle



Yuan et al. 2010

My interest was in molecular gas (GMCs)

L_{FIR} vs. L_{CO} plot

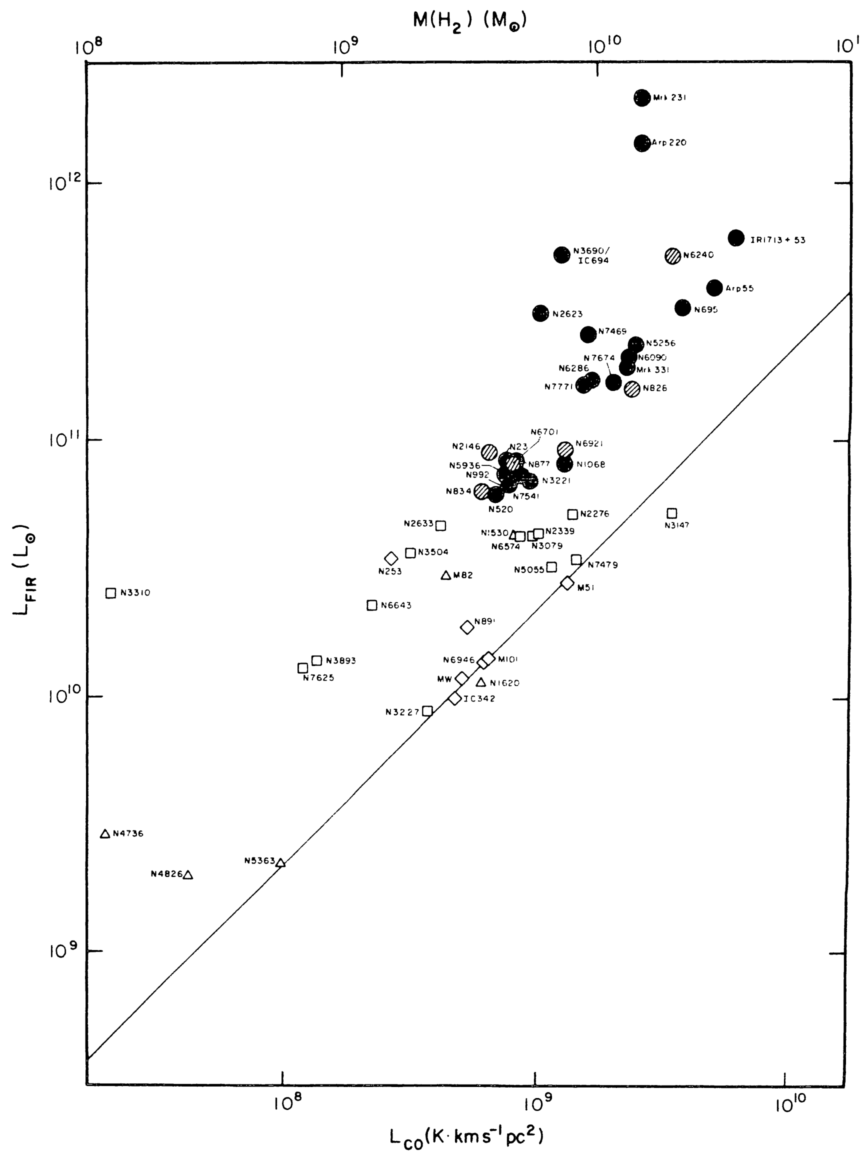
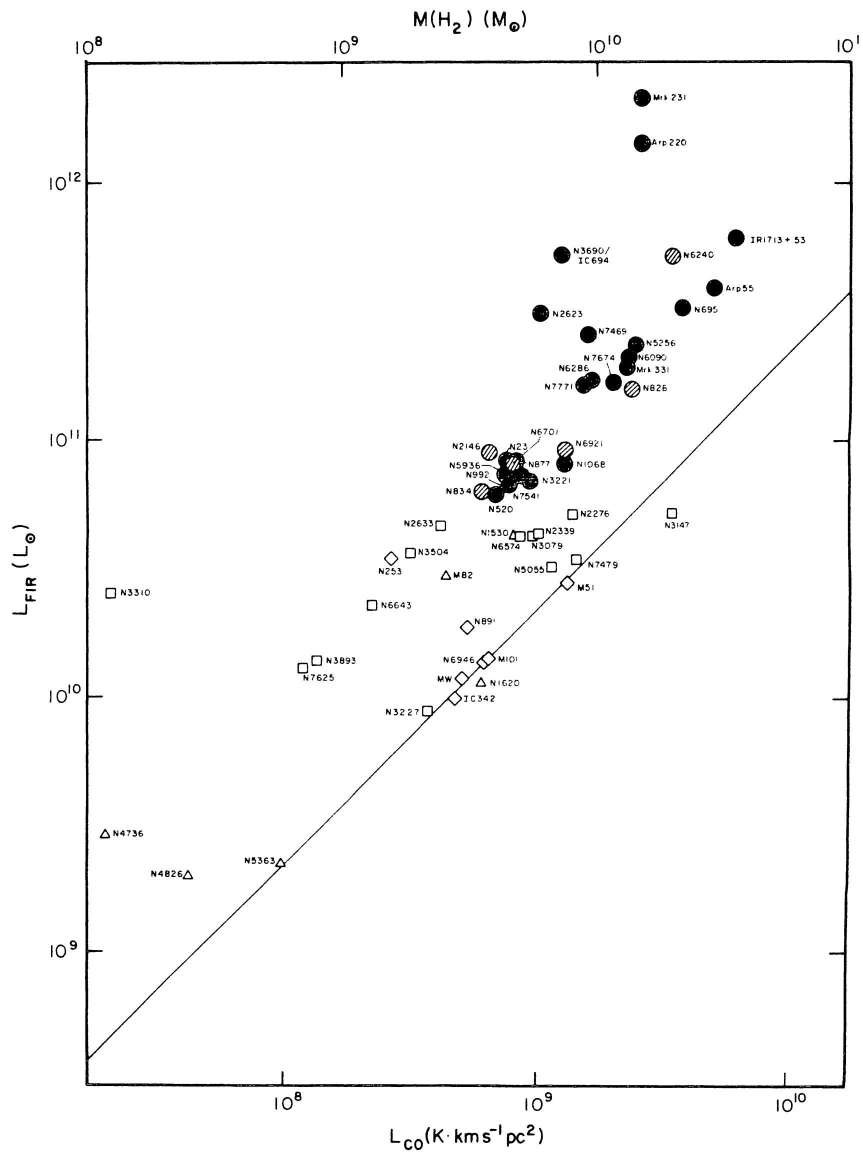


Figure 3: The total far-infrared luminosity determined from IRAS data vs CO luminosity and the total mass of H_2 in molecular clouds. Circles represent high luminosity IRAS galaxies which are an unbiased sample of all galaxies with L_{FIR} (40-400μm) $\geq 7 \times 10^{10}$ $L_\odot$. All other symbols represent CO observations of lower luminosity bright IRAS galaxies with known and unknown selection bias (see Sanders *et al.* 1986a).

A “MW Sequence” of star formation in GMCs

L_{FIR} vs. L_{CO} plot



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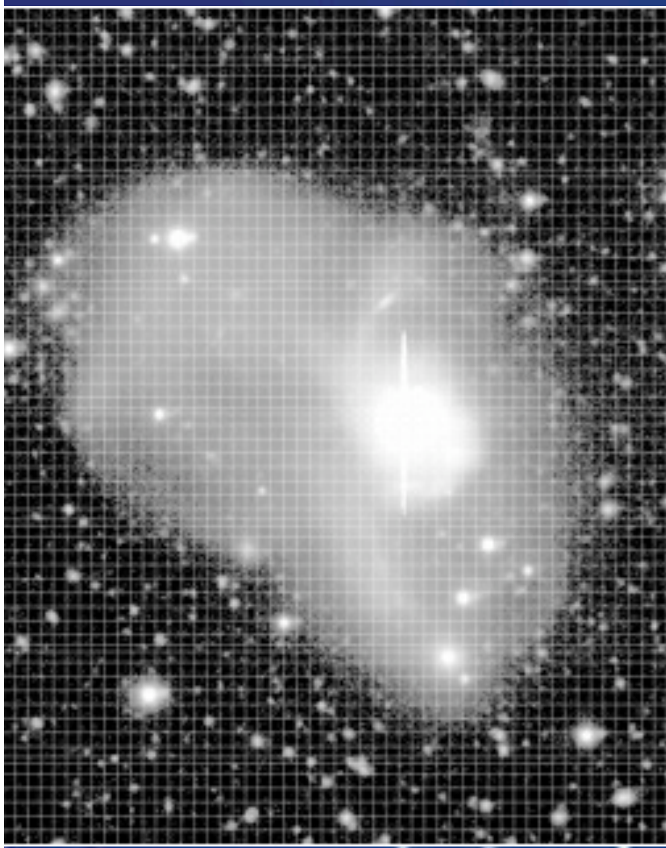
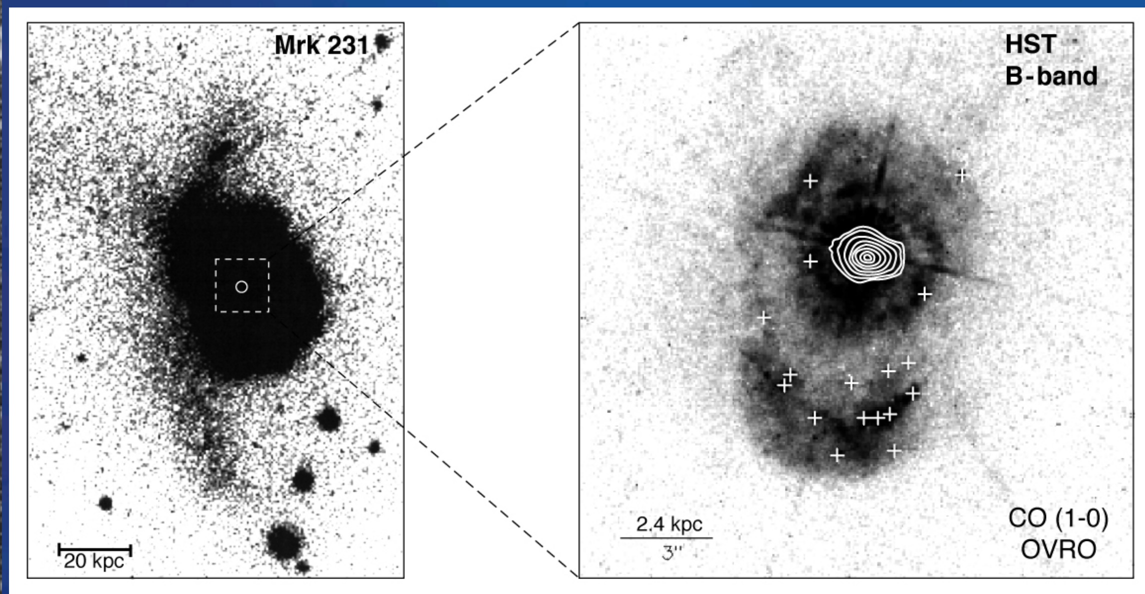
UGC 83038 = Mrk 231

Log ($L_{IR}/L_{\odot}$) = 12.57
"warm" ULIRG



Jin Koda
Subaru r-band



Sanders et al.
Hutchings & Neff

Scoville et al.
Surace et al

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

- M_{nuc} = 1 – 3 x 10^{10} M_{sun}
- $\langle \sigma (H_2) \rangle$ ~ 0.65 – 2 x 10^{10} M_{sun}
- M_{nuc}/M_{tot} = 40 – 100 %
- $\langle n\, (H_2) \rangle_{spherical}$ ~ 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

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 to develop better diagnostic measures to separate the ES from AGN.

Summary 1

It has been 30 years since ***IRAS*** provided a complete census of Luminous Infrared Galaxies (LIRGs: $L_{IR} > 10^{11}\ L_{\odot}$) in the Local Universe, ($z < 0.1$)
[IRAS RBGS: L_{IR}, M^*, Morphology, $M_T(H_2)$, $M_{nuc}(H_2)$]

~10 years since ***Spitzer*** confirmed strong evolution in the space density of LIRGs out to $z \sim 3$, and **<5** years since ***Herschel*** expanded these results to even higher redshifts by providing more sensitive, and higher resolution sky maps at 70-500μm.

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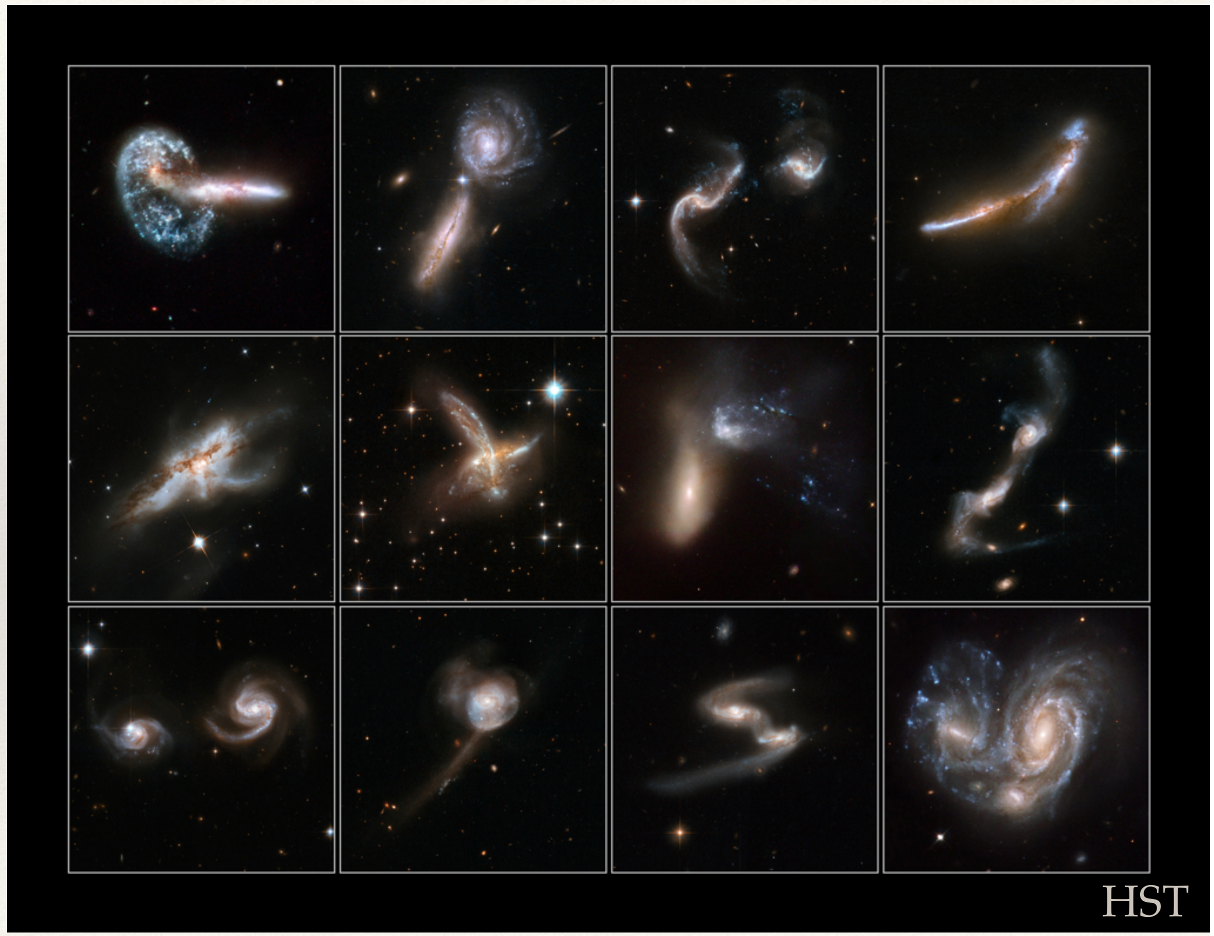
GOALS Great Observatory All-sky LIRG Survey

- GOALS is a sample of 203 (U)LIRGs with $L_{IR} > 10^{11}\ L_\odot$ and $z < 0.088$
- Northern sub-sample of 65 (U)LIRGS from GOALS
- Contains galaxies in every interaction stage

Evans+ 2017, ApJS



Morphology and Molecular Gas Fraction of Local Luminous Infrared Galaxies

Kirsten Larson, Dave Sanders, Josh Barnes,

+ GOALS Team (ApJ, 2016)

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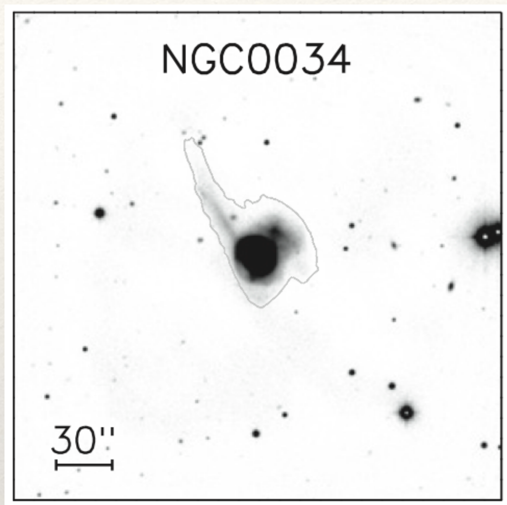
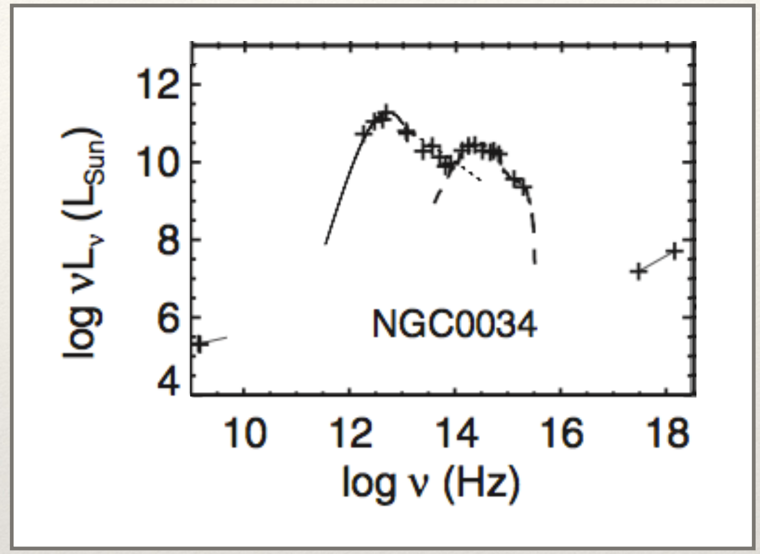
Multi-wavelength Photometry



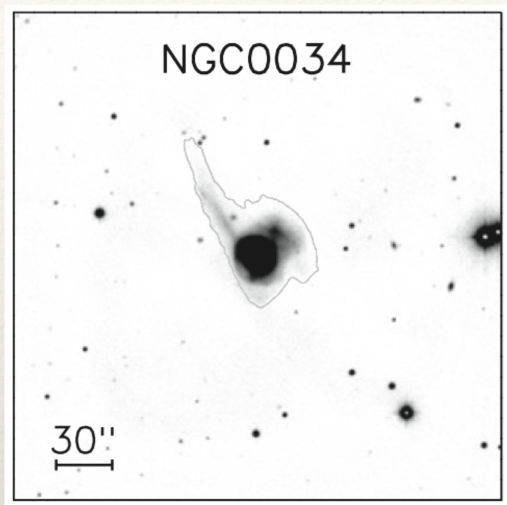


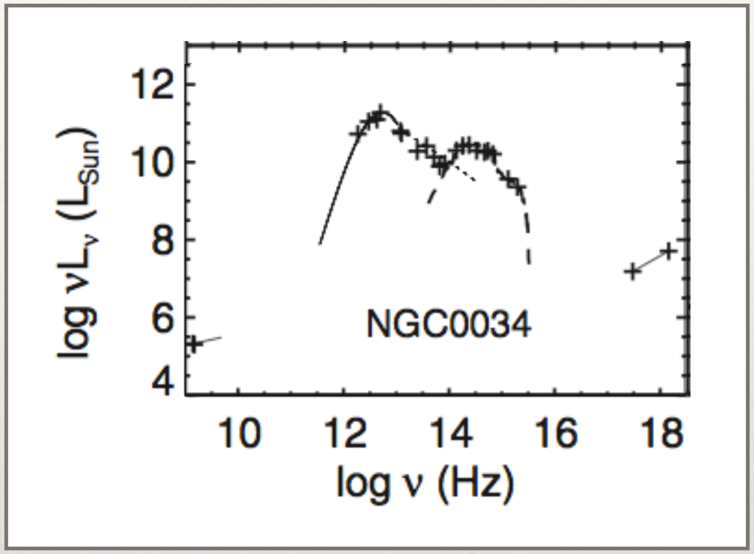
X-ray, FUV, NUV, UBVI , JHK , IRAC1234, MIPS, IRAS, SCUBA

U+12, ApJ

- Full SEDs for all 65 galaxies
- Data from Xray, UV – IR, radio
- Measure accurate L_{IR} and M^*

Multi-wavelength Photometry



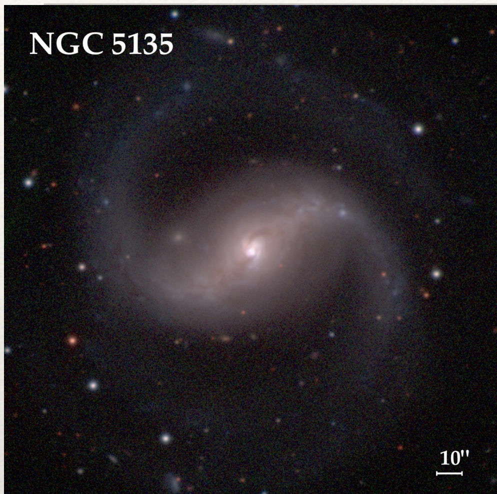


IRAC1234, WISE, MIPS24, PACS+SPIRE

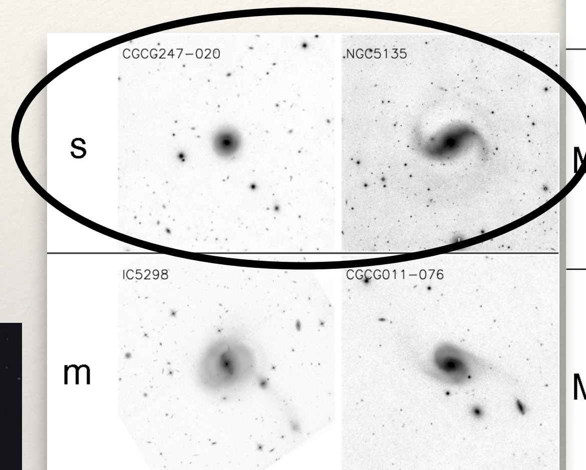
- Full SEDs for all 203 GOALS galaxies
- Data from the NIR - submm
- Measure more accurate SEDs + L_{IR}, T_{dust}

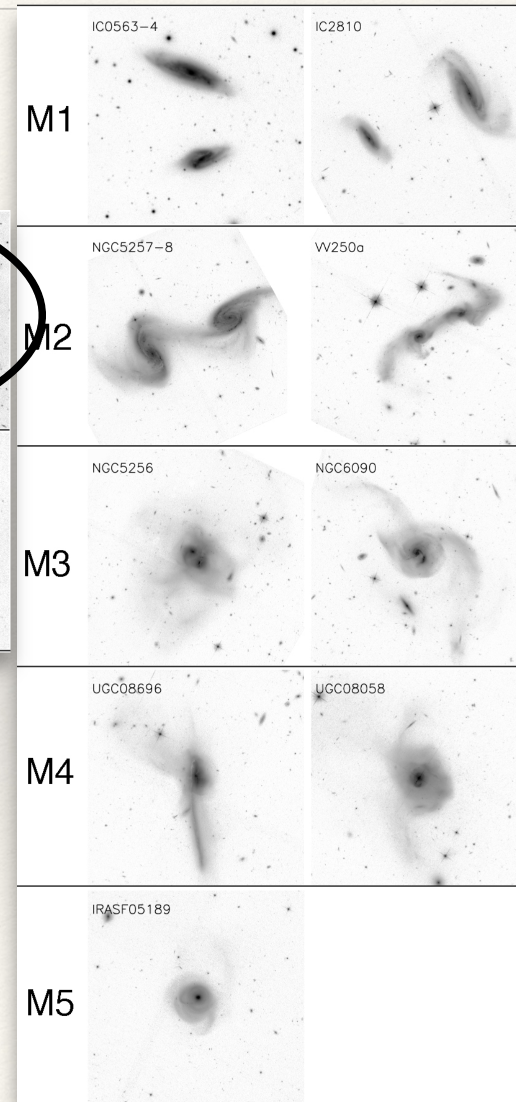
Chu+17, ApJS

Visual Classification Scheme



- single — s

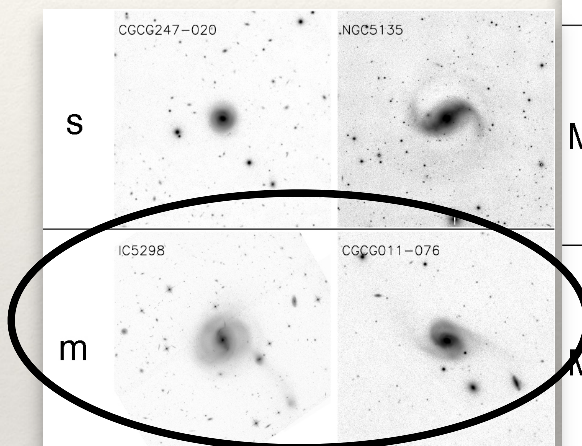


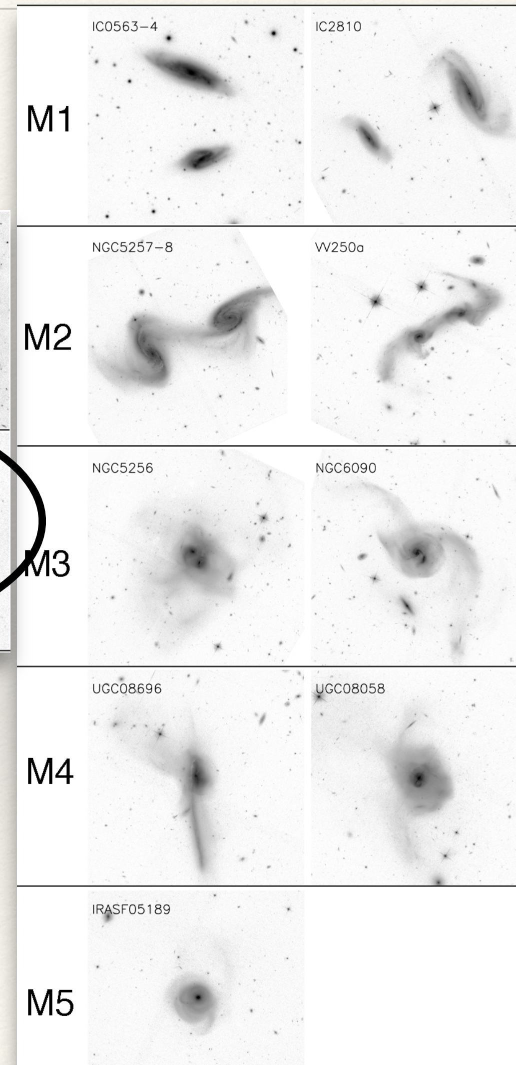


Visual Classification Scheme

❖ minor merger: m

NGC 1614

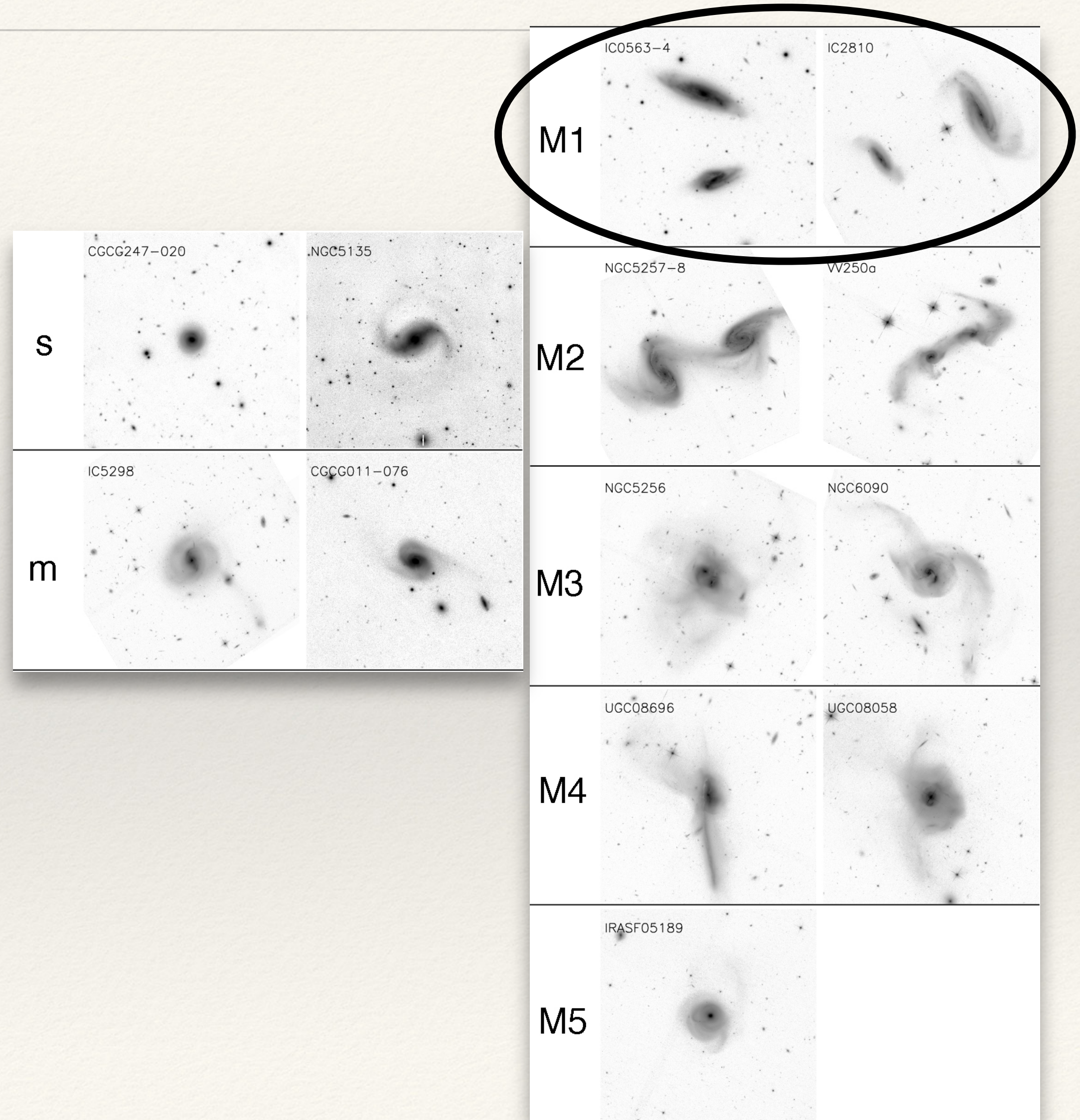




Larson et al 2015a *Submitted*

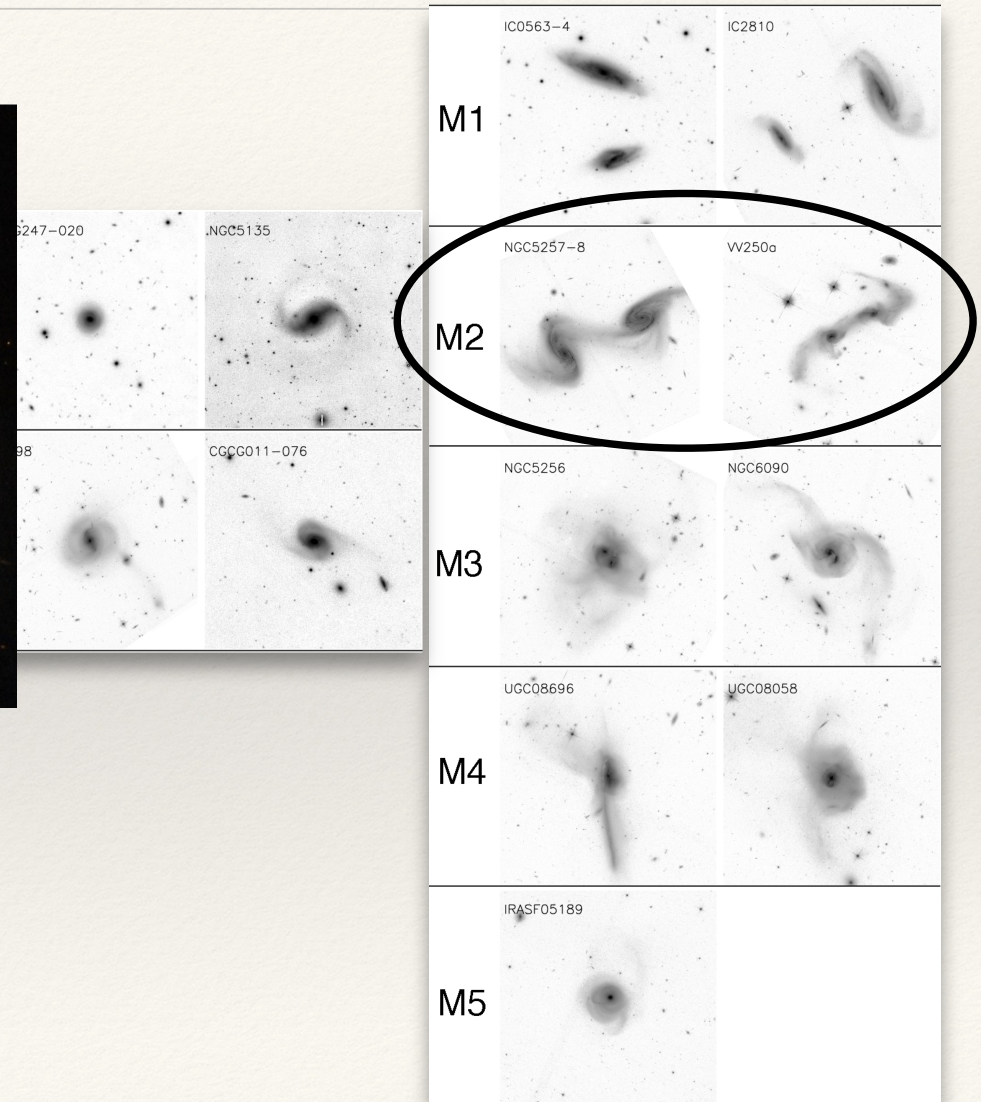
Visual Classification Scheme

❖ Major Merger : M1



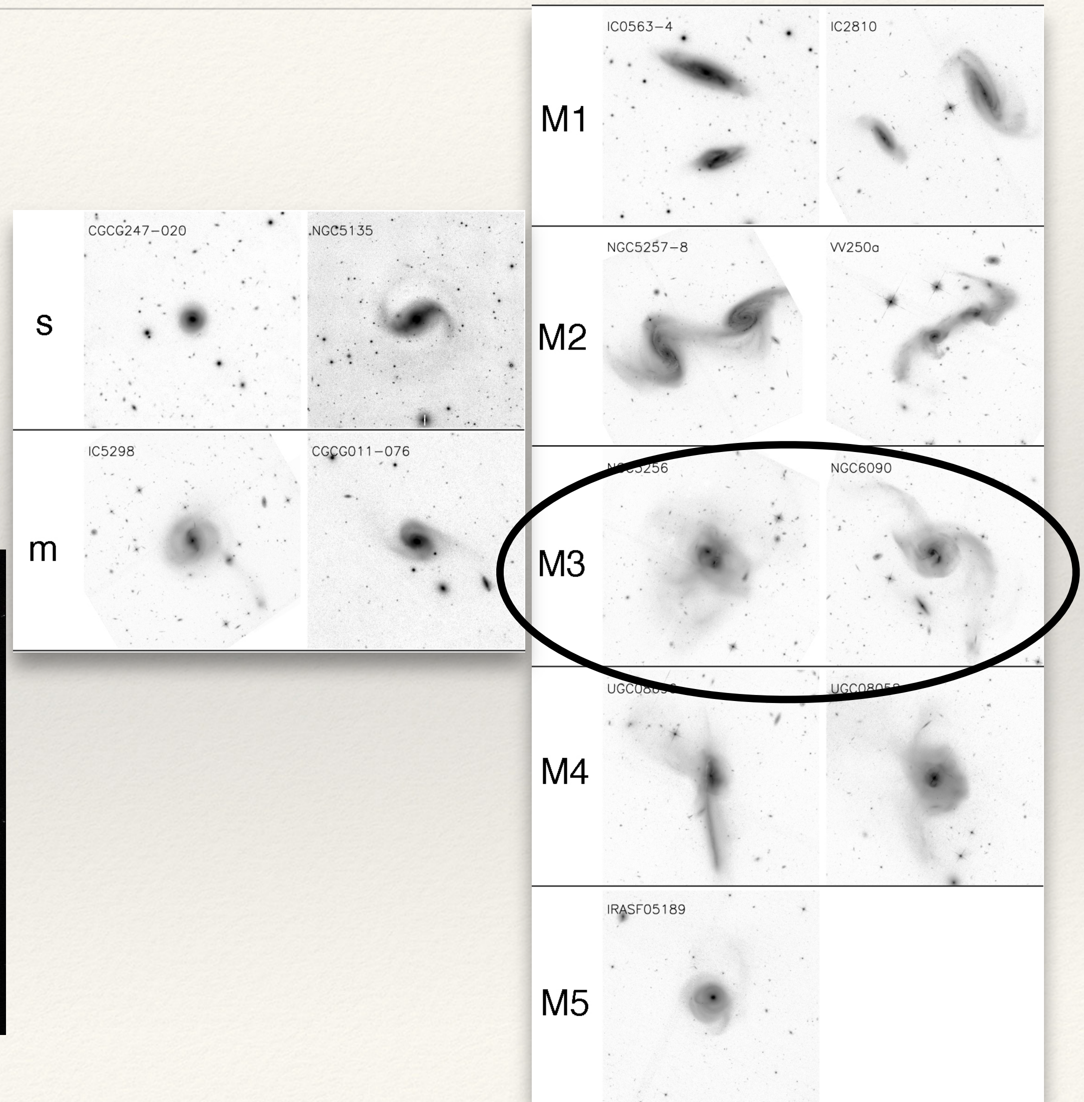
Visual Classification Scheme

- Major Merger : M2



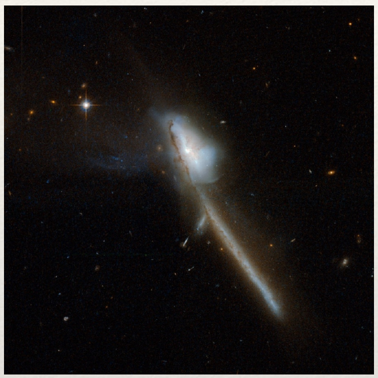
Visual Classification Scheme

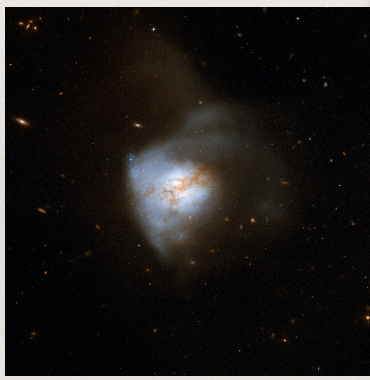
- Major Merger : M3

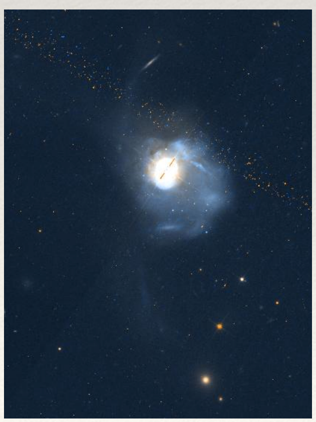


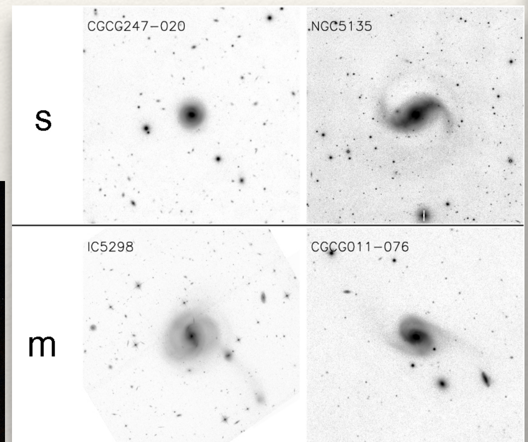
Visual Classification Scheme

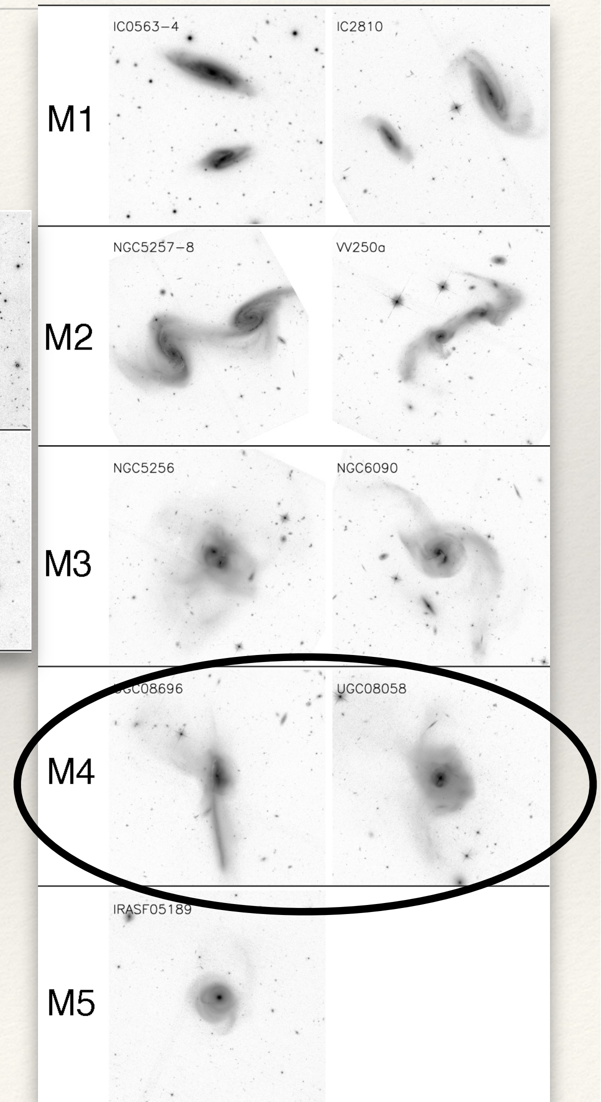
❖ Major Merger : M4





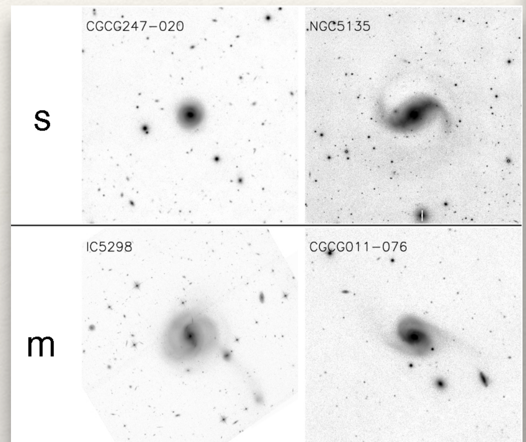


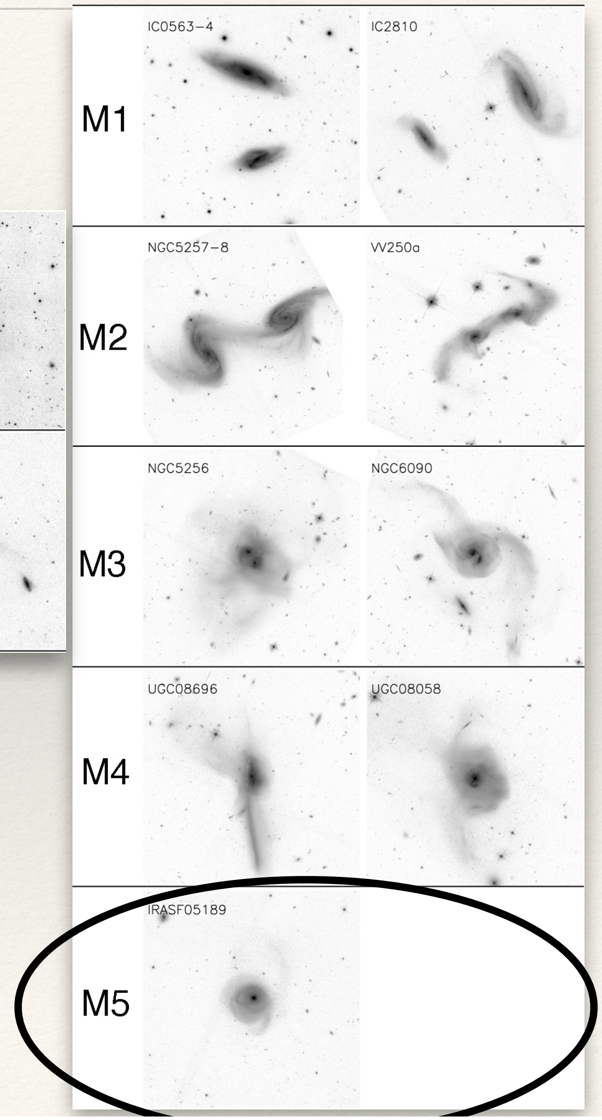




Visual Classification Scheme

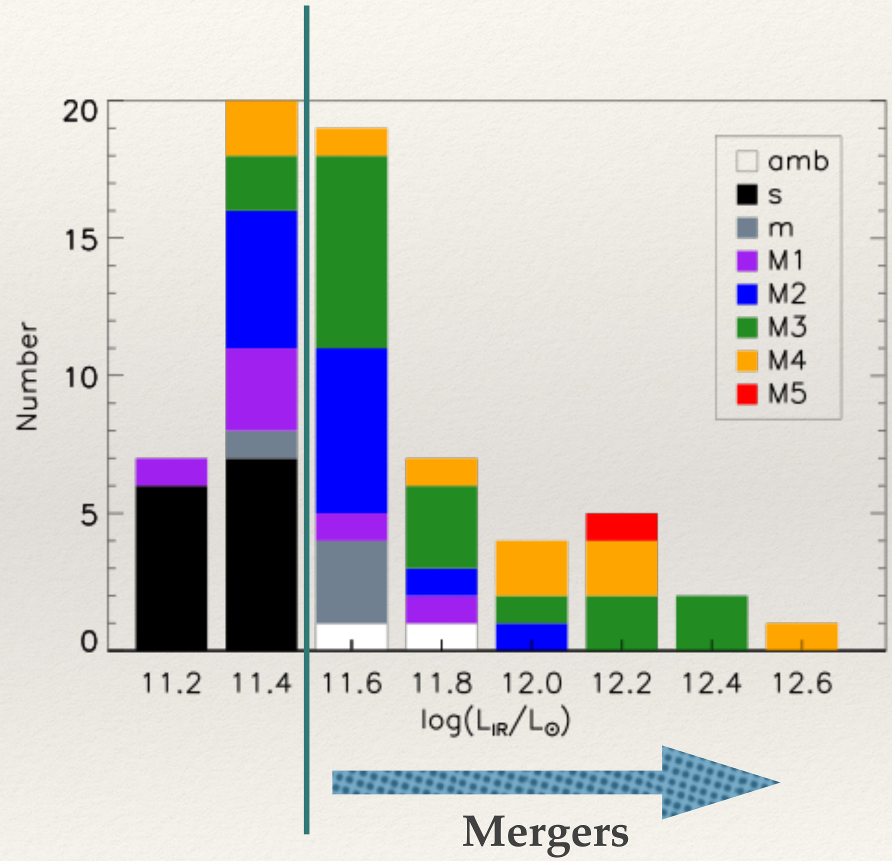
- Major Merger : M5





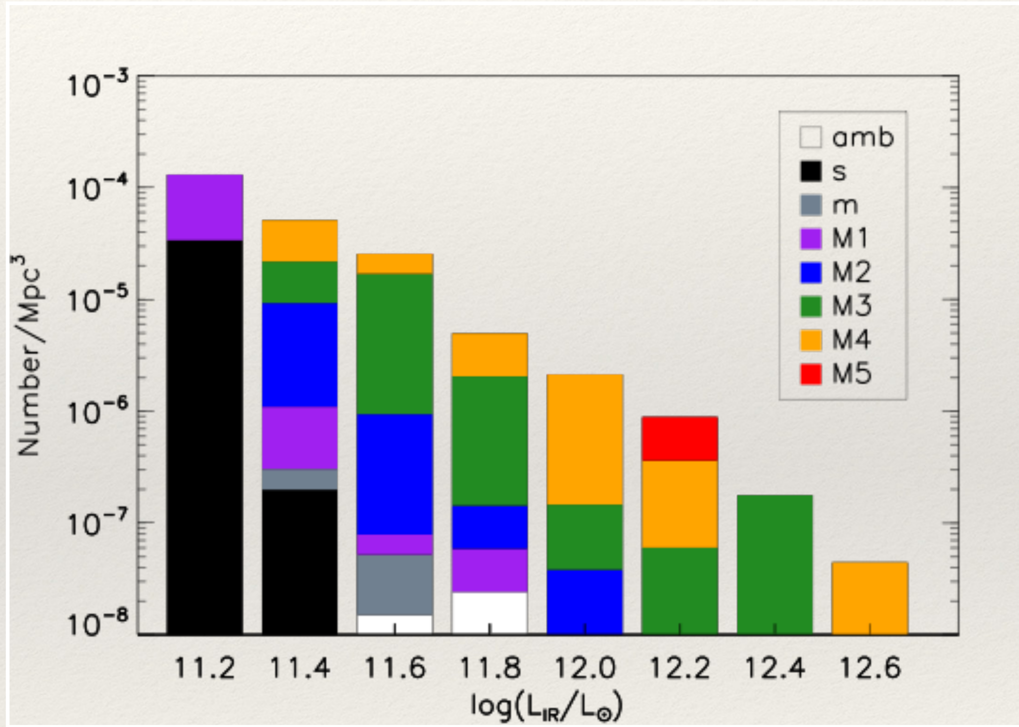
Morphology vs. Infrared Luminosity

- All galaxies with log ($L_{IR}/L_{\odot}$) >~ 11.5 are mergers.
- Our sample of galaxies is flux limited and incomplete in the lowest luminosity bin

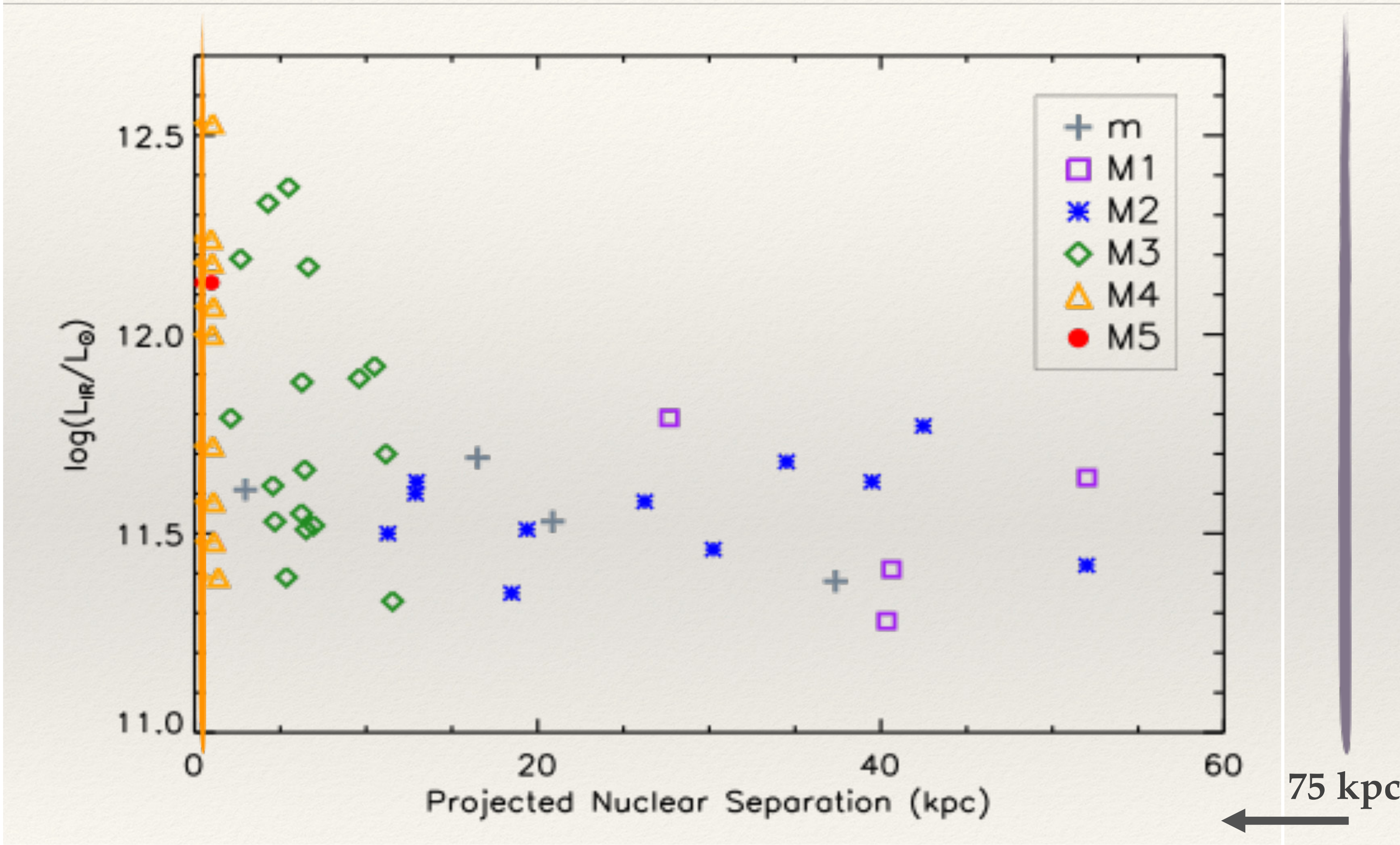


Morphology vs. Infrared Luminosity

- **Volume Corrected sample:**
- **Below log ($L_{IR}/L_{\odot}$) ~ 11.5 non-interacting galaxies dominate the volume.**



Nuclear Separation



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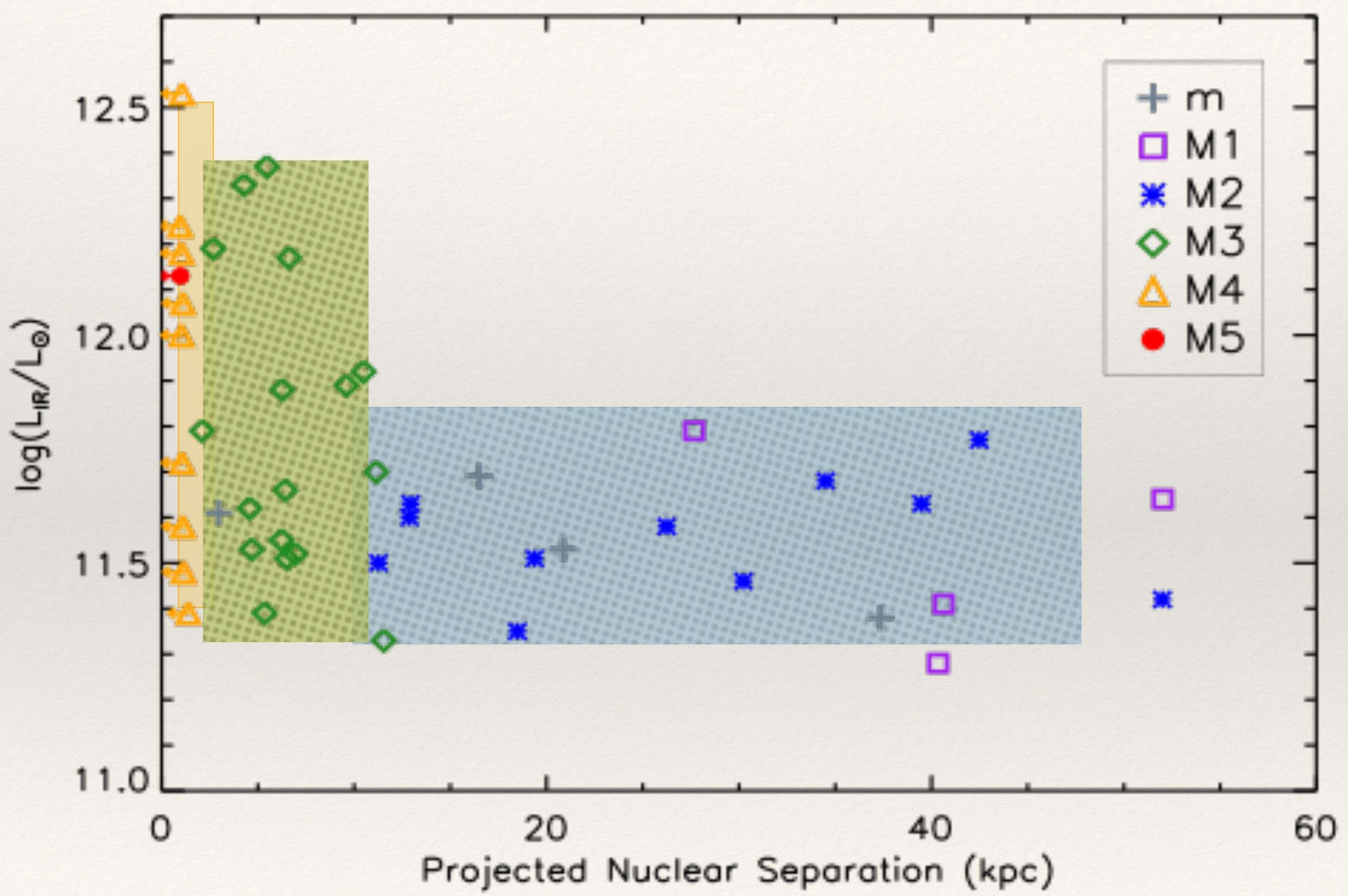
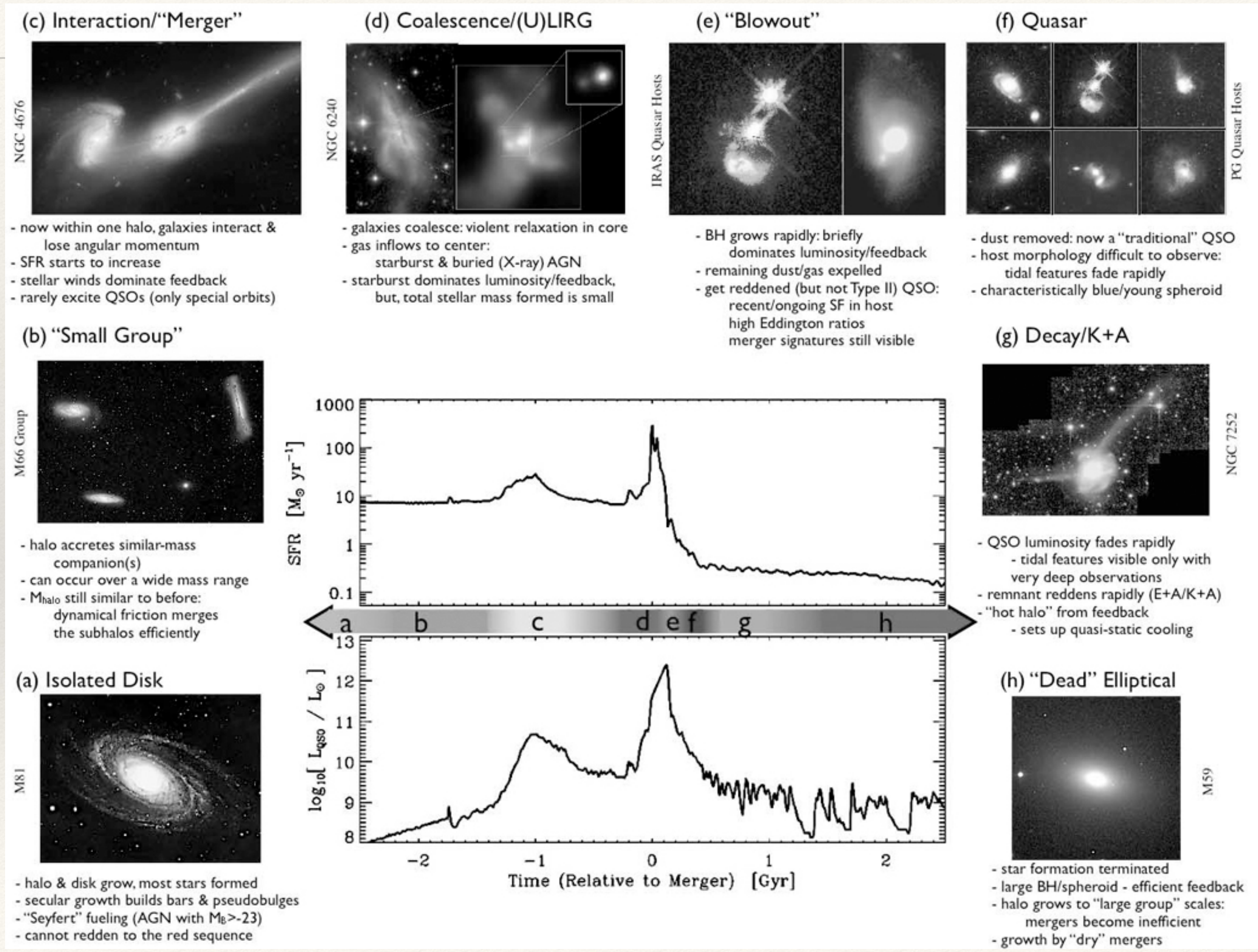


The Merger Sequence paradigm for (U)LIRGs

Credit: P. Hopkins



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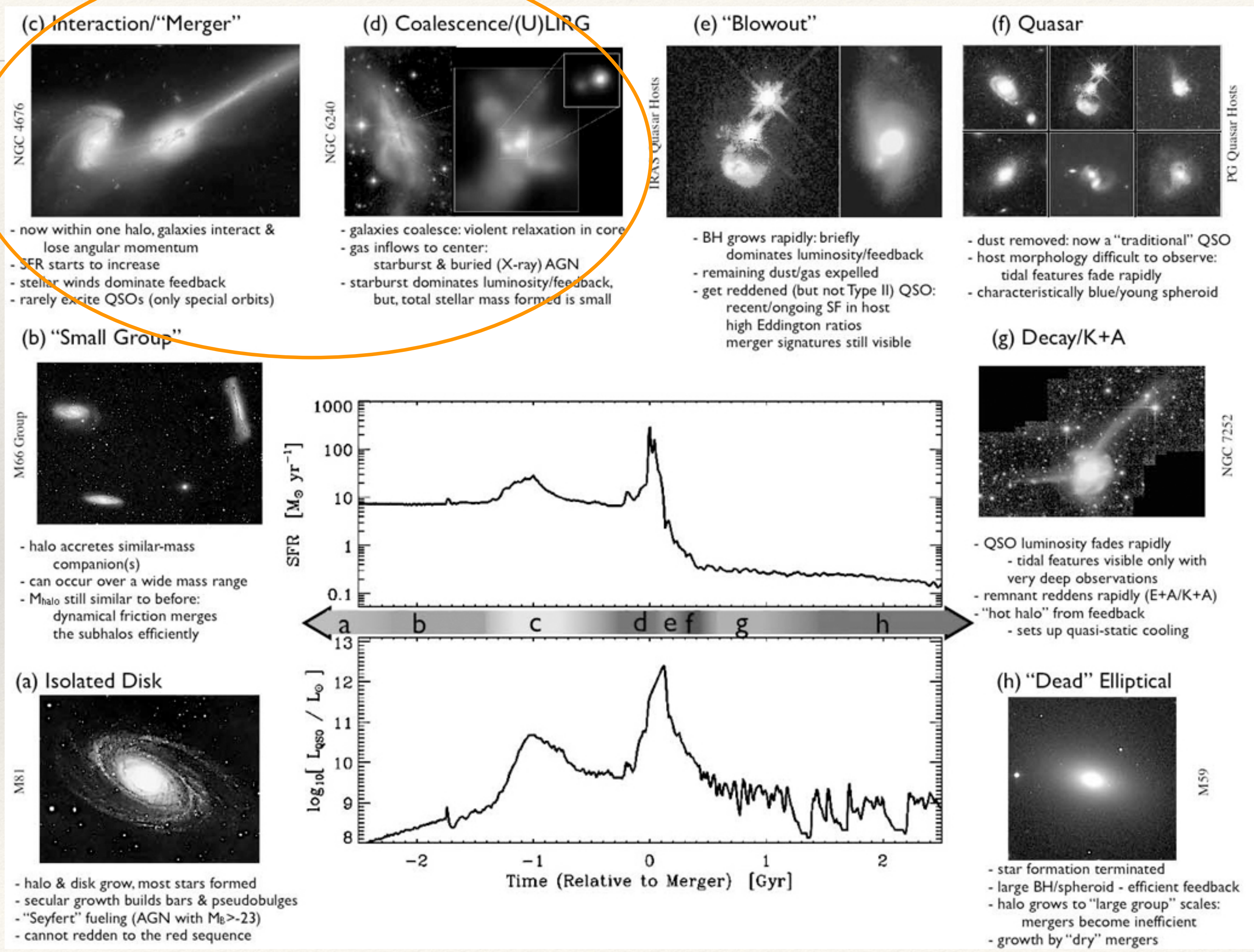


Credit: P. Hopkins

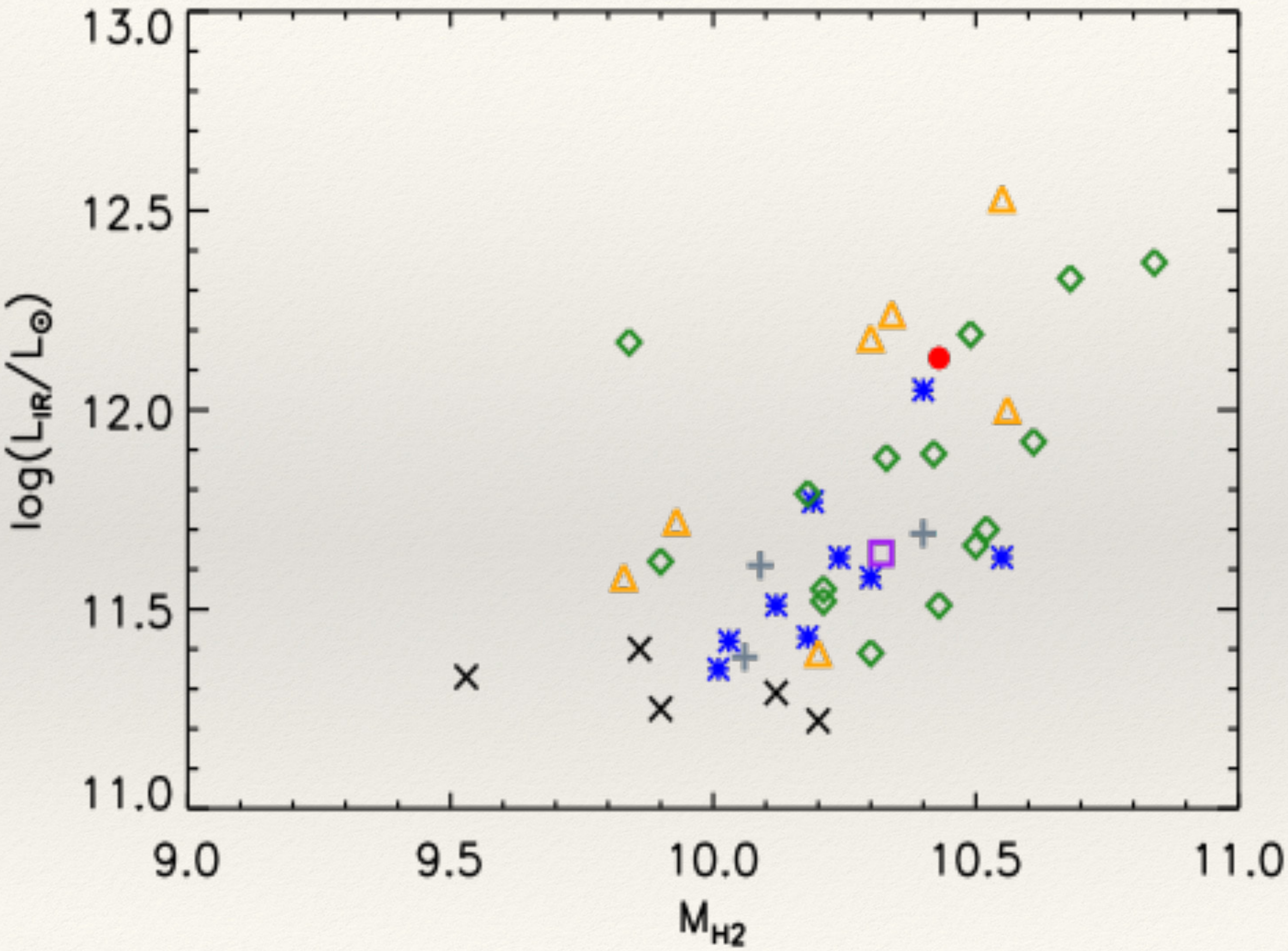
CO Data

(Molecular gas fractions)

- Single dish CO (1-0) line measurements
- Used a constant CO-H_2 conversion factor for all galaxies

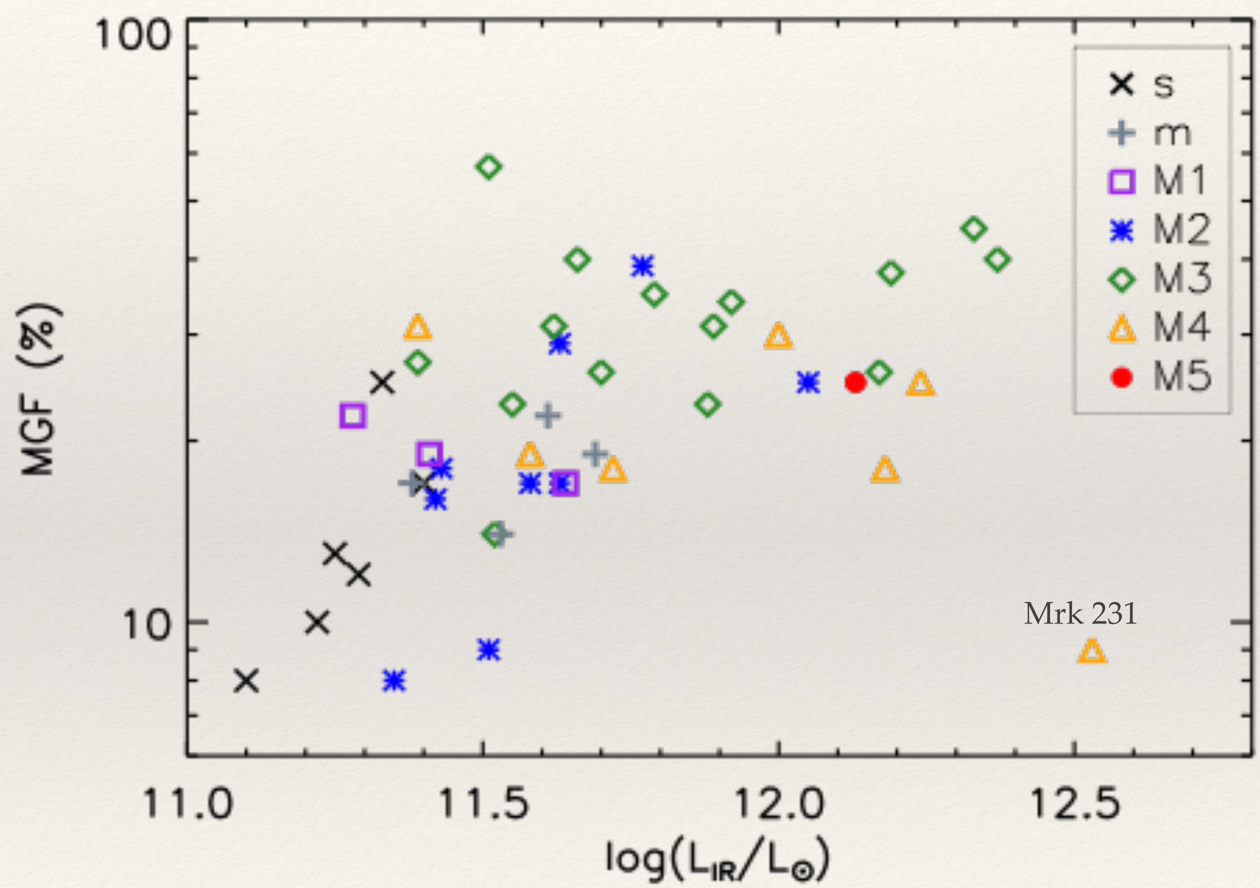
$X_{CO} = 3.0 \times 10^{20}\ H_2\ cm^{-2}\ (K\ km\ s^{-1})^{-1}$

Molecular Gas



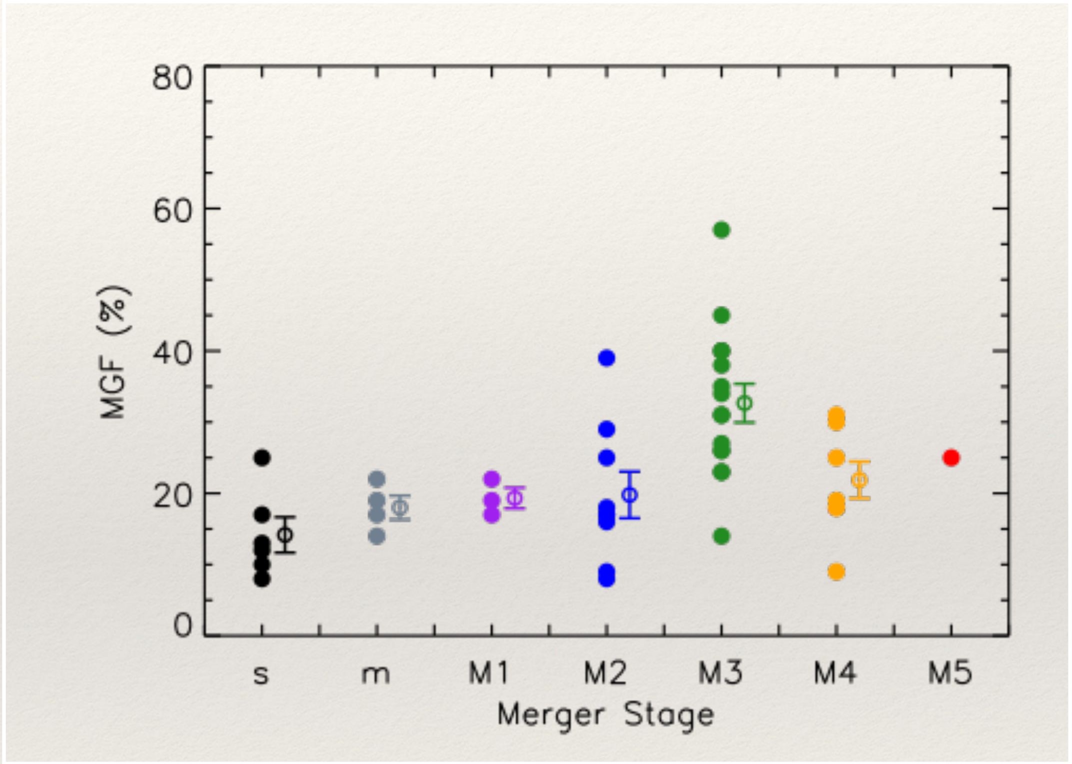
Molecular Gas Fraction

$$MGF = \frac{M_{H2}}{(M_{H2} + M_{*})}$$



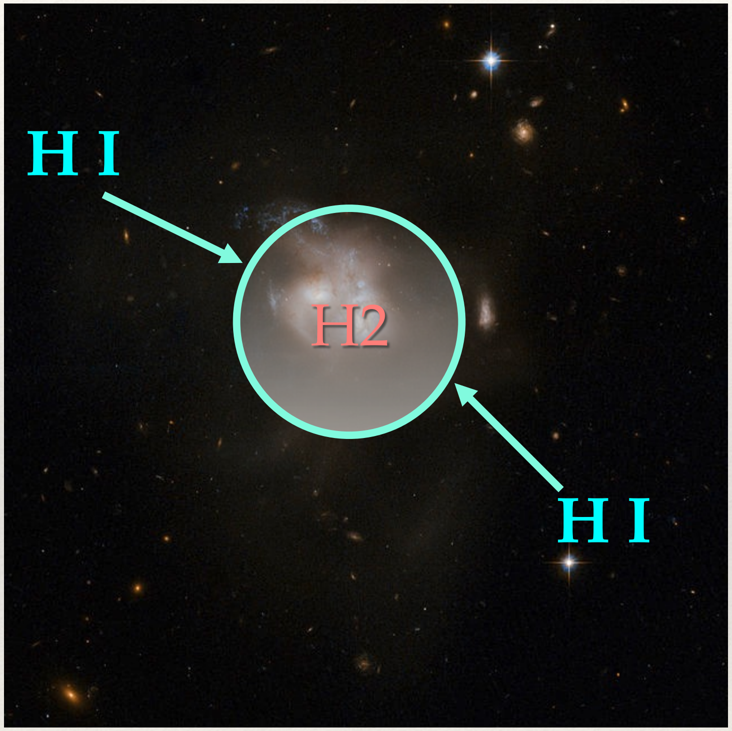
Molecular Gas Fraction

s	0.14
M2	0.20
M3	0.33
M4/5	0.22



Molecular Gas Fraction

Merger stage: M3



HI → **H2**

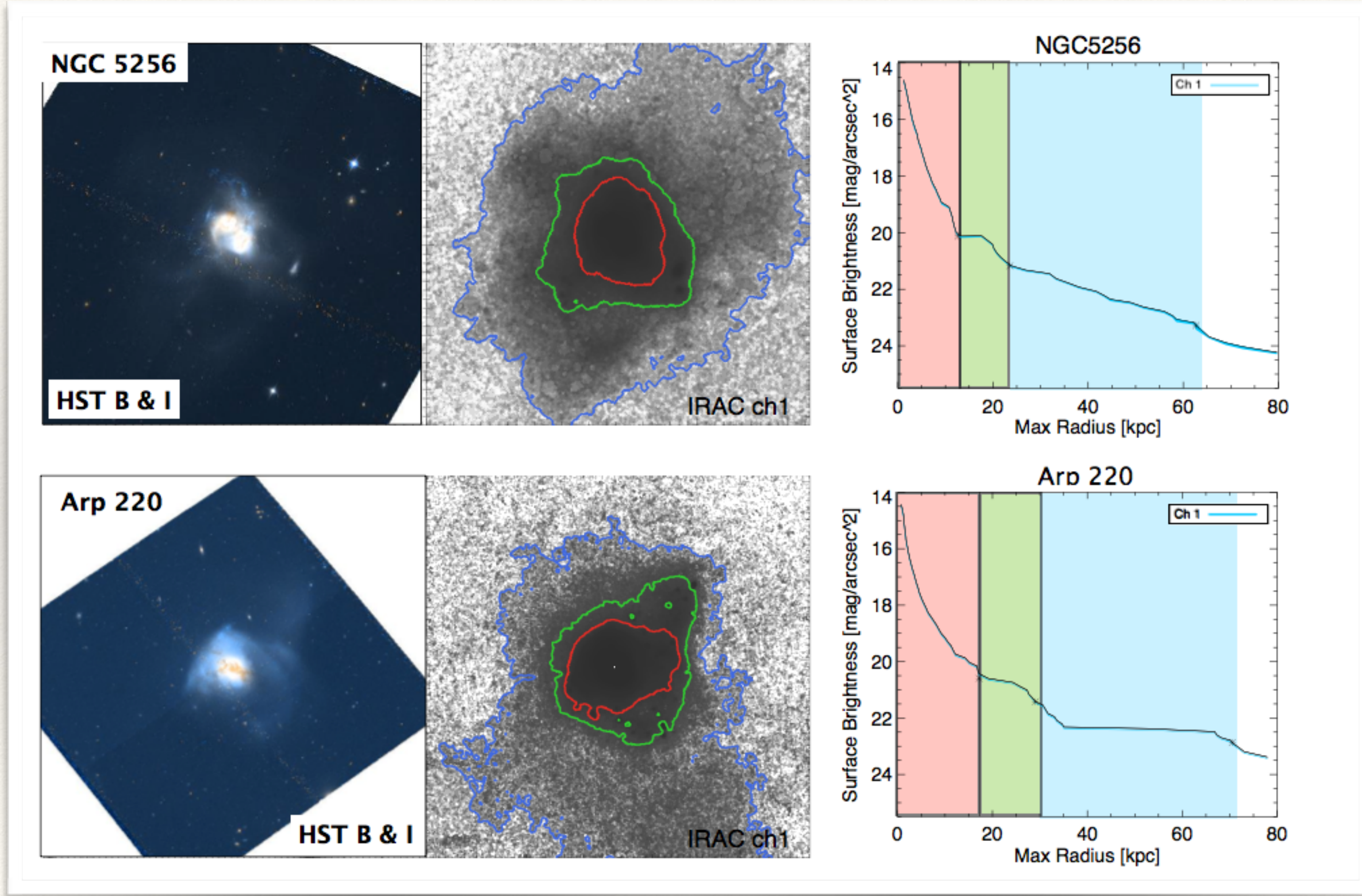
MGF ↑

Extended (100 x 100 kpc) Tidal Debris Fields

Stage

M3

M4



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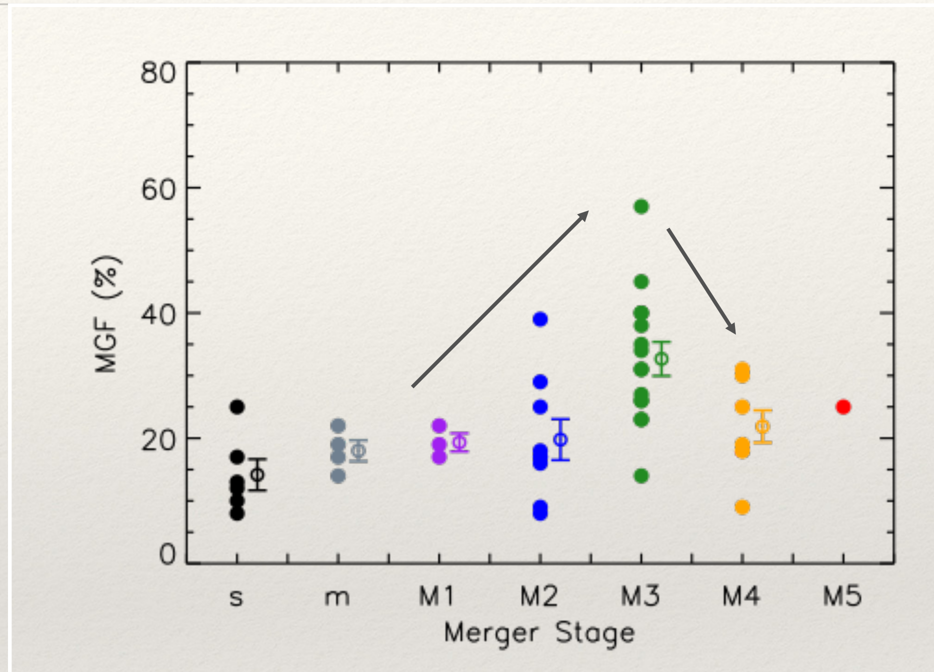

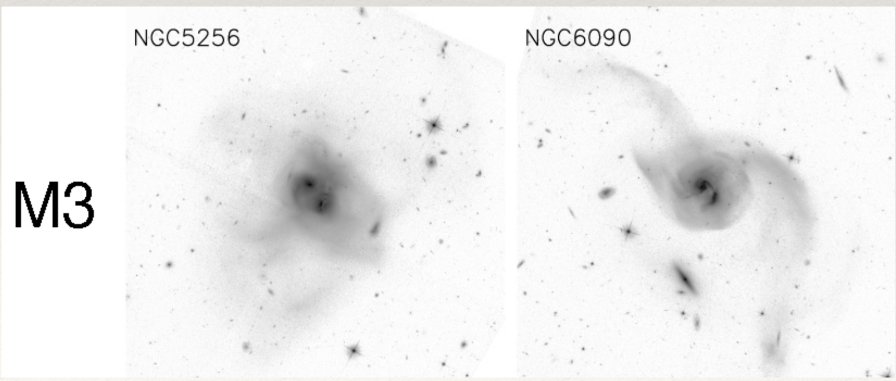

Summary 2

- Larson+16 analyzed the visual morphologies of 65 local (U)LIRGs
- All systems with log $(L_{\rm IR}/L_{\odot}) > 11.6$ are major mergers
- It is not until merger stage M3 that we see an increase in log$(L_{\rm IR}/L_{\odot})$ above 12.0
- The molecular gas fraction (MGF) increases during the merging process, peaking at merger stage M3 with $< MGF > \sim 33\%$

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Keck-AO (+SMA) High-Resolution Observations of Molecular Gas and MBH in Luminous Infrared Galaxies

Vivian U, Anne Medling, Claire Max,
Giovanni Fazio, Aaron Evans, Lisa Kewley

GOALS – Great Observatories All-Sky LIRGs Survey

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

$L_{ir} > 10^{11} L_{sun}$ (203 objects) ($z < 0.1$)

http://www.ipac.caltech.edu/goals

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Keck NIR AO Campaign

Vivian U, Anne Medling et al. 2010 - 2017

- Goals: nuclear morphology, black hole masses, SB vs. AGN

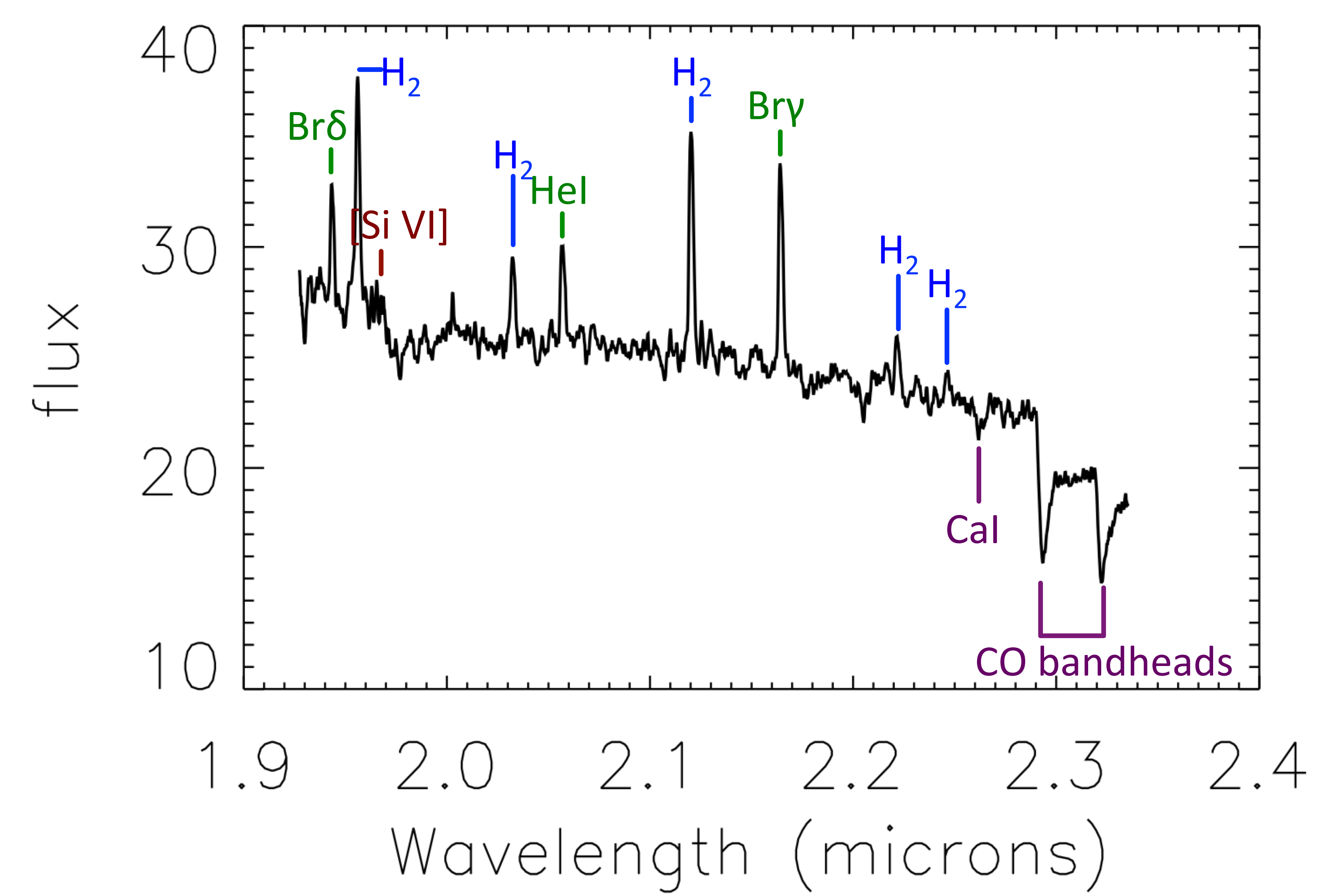
- ***Strategies:***
  - ***OSIRIS, LGS(NGS)AO (FWHM ~0.05")***

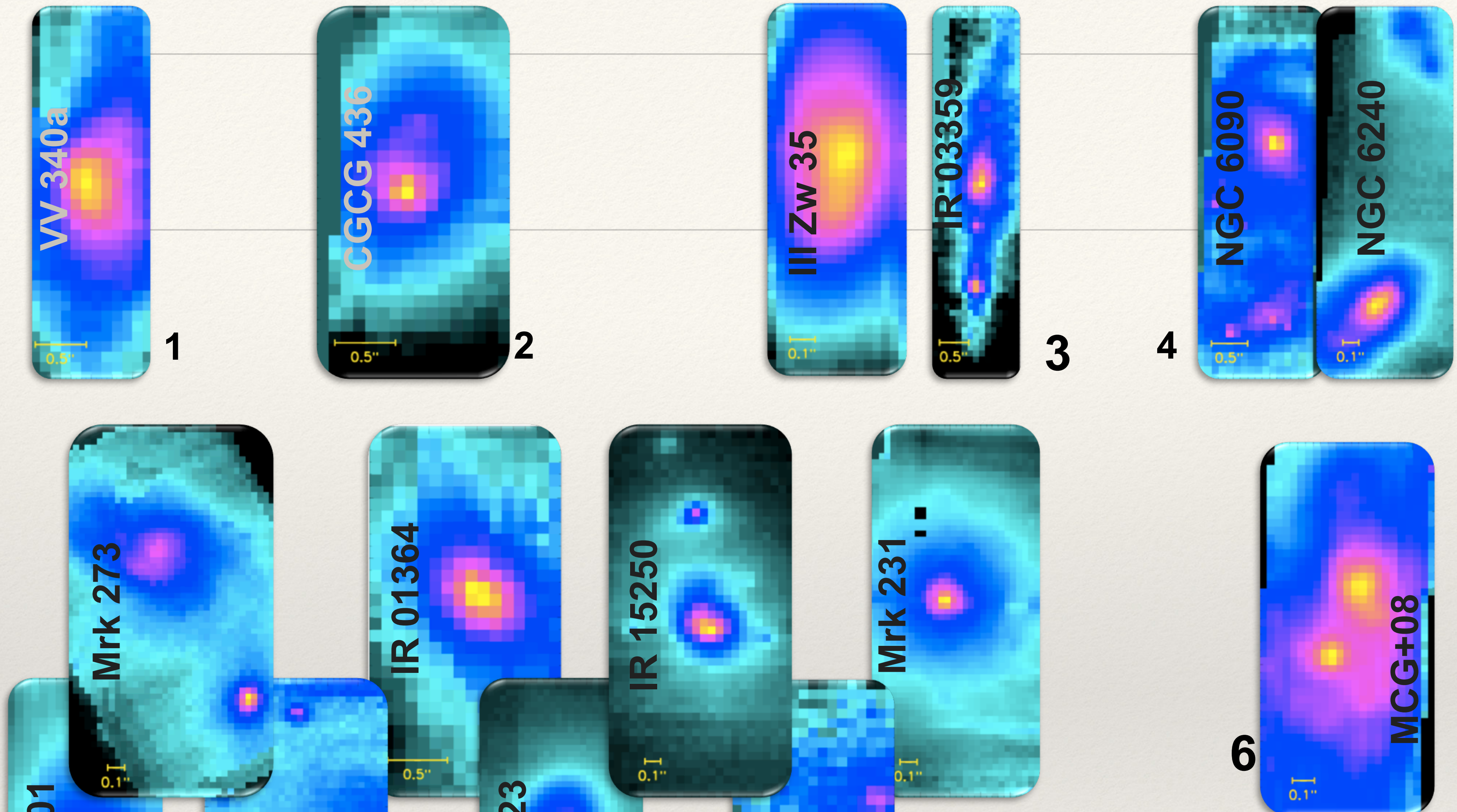
    K broadband, 0.050"-0.100" (H_2, Br, HeI, [Si VI], etc.)

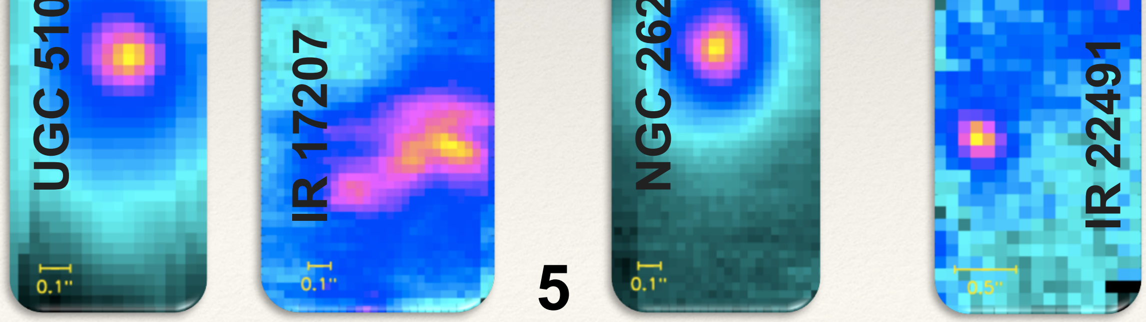
    H or K narrowband, 0.035" (CO bandheads)

U (Hawaii), Medling (UCSC), Sanders (IfA), Armus (SSC), Max (UCSC), Evans (NRAO/UVa), Iwasawa (IEEC-UB), Kewley (IfA), Mazzarella (IPAC), Surace (SSC), Inami (SSC/JAXA), Stierwalt (SSC), Barnes (IfA), and the GOALS Team

Keck NIR AO Campaign







- Observed at least 1 nucleus in all systems
- **Ubiquitous nuclear disks, 200 - 700pc radius**

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Black Hole Dynamical Mass

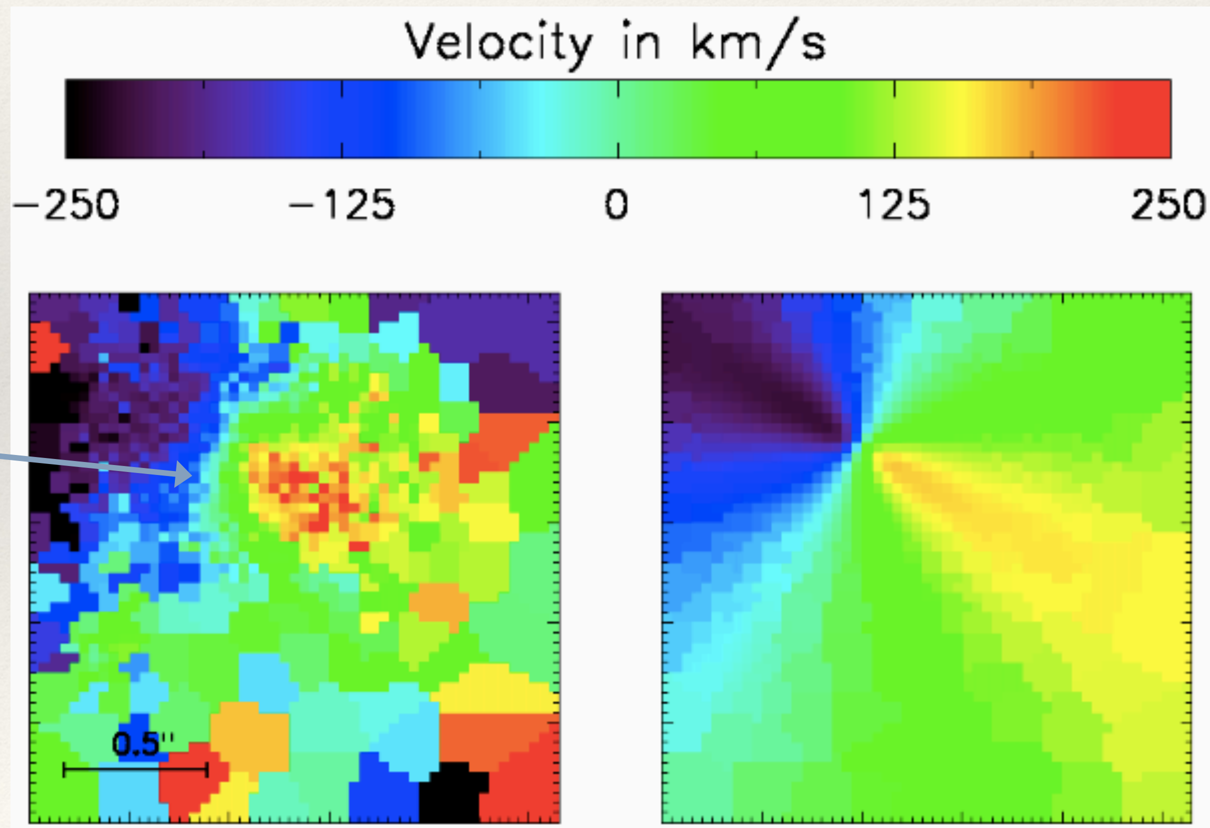
$$v = \sqrt{\frac{GM_{encl}(r)}{r}}$$

$$M_{encl}(r) = M_{BH} + \rho_0 r^{\gamma}$$

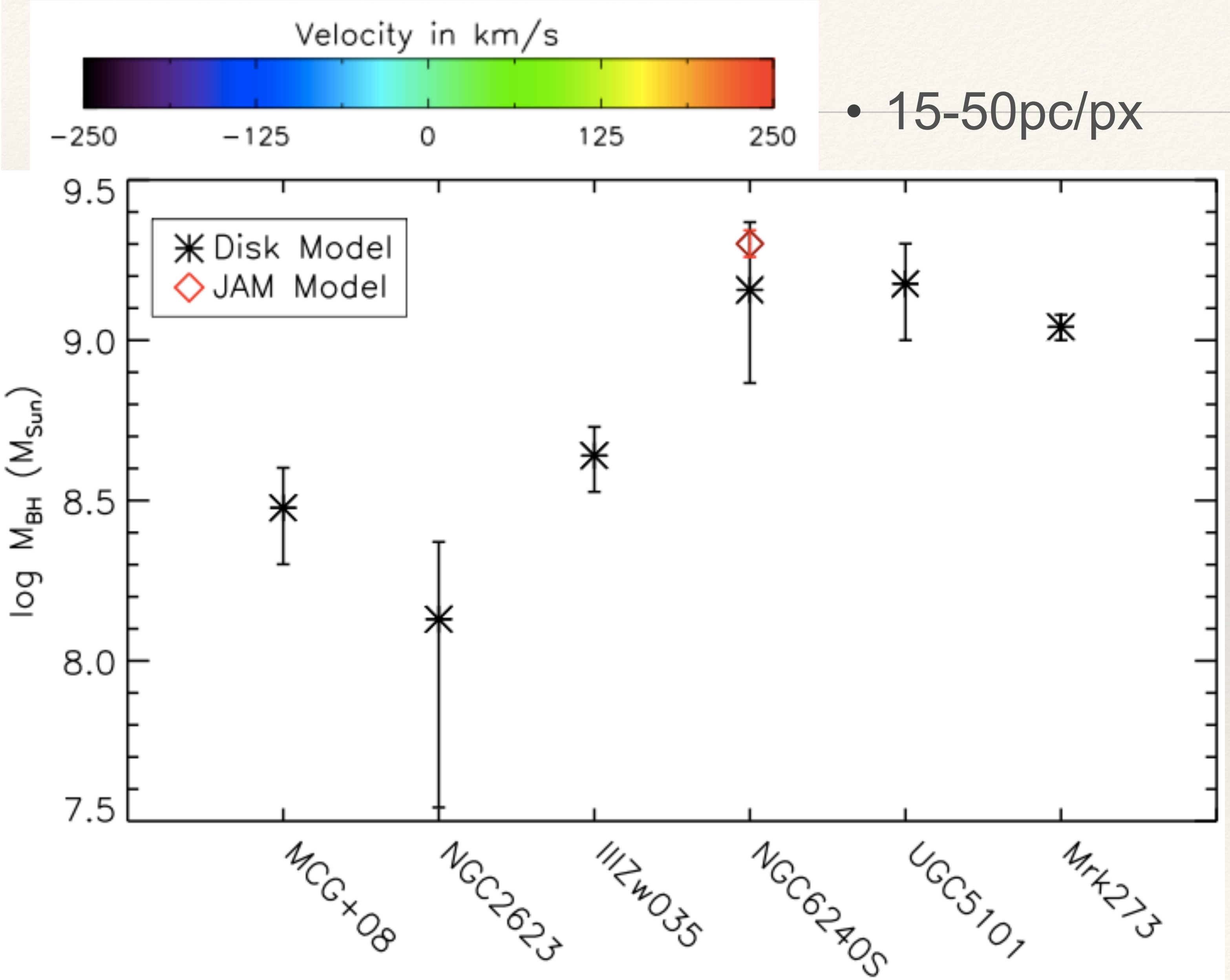
Spatial resolution: 28pc/px, resolving within sphere of influence!

$M_{BH} = 1.1 \pm 0.1 \times 10^9\ M_{\odot}$

From OH maser (Klockner & Baan 04):
$M_{BH} = 1.39 \pm 0.16 \times 10^9\ M_{\odot}$



Black Hole Mass Measurement



- 15-50pc/px

SMA CO Campaign

Vivian U et al. 2010 - 2014

- Goals: gas morphology and kinematics, *how much* gas is concentrated in nuclei?

- ***Strategies:***
  - ***VEX (0.3-0.4") or EXT (0.7-1") at 345 or 230 GHz***
  - ***Build on Wilson+08 sample (i.e. add high resolution)***
  - ***Expand from Wilson+ 08 sample (dimmer (U)LIRGs)***

Sanders (IfA), Wang (CfA), Chung (Yonsei), Petitpas (SMA), Iono (Nobeyama), Gao (PMO), Kewley (IfA/ANU), Huang (CfA), and the GOALS Team

SMA CO Survey

1. Detected compact CO(3-2) or CO(2-1) “disks” in all 10 (U)LIRGs
2. Rotating disks:

   R_e ~1–2 kpc, v ~ 100 – 250 km/s, σ ~ 70 – 160 km/s

3. M_{H2} ~ 1.2 – 12.9 x 10^9 $M_\odot$

-> plenty of gas to fuel star formation and build supermassive black holes !

Summary 3

All late-stage mergers contain compact gas-rich nuclear disks:

compact	$R_e \leq 200$ pc
rotationally supported	$v/\sigma \sim 2 - 5$
gas rich	$M(H_2)$ $10^{8.5} - 10^{10}$ M_{sun}
young stellar ages	< 30 Myr
massive black holes	$M_{BH} \sim 10^{8.5} - 10^{9.5}$ M_{sun}

Earl(ier) merger stages contain less compact gas-rich nuclear disks:

Larger nuclear disks	R_e ~ 200 – 1800 pc
Smaller black holes	$M_{BH} \sim 10^{6.5} - 10^{7.5}$ M_{sun}

MBH -> SMBH growth phase (x 30-100) occurs during the (U)LIRG phase over a timescale of 3-8 x 10^8 years

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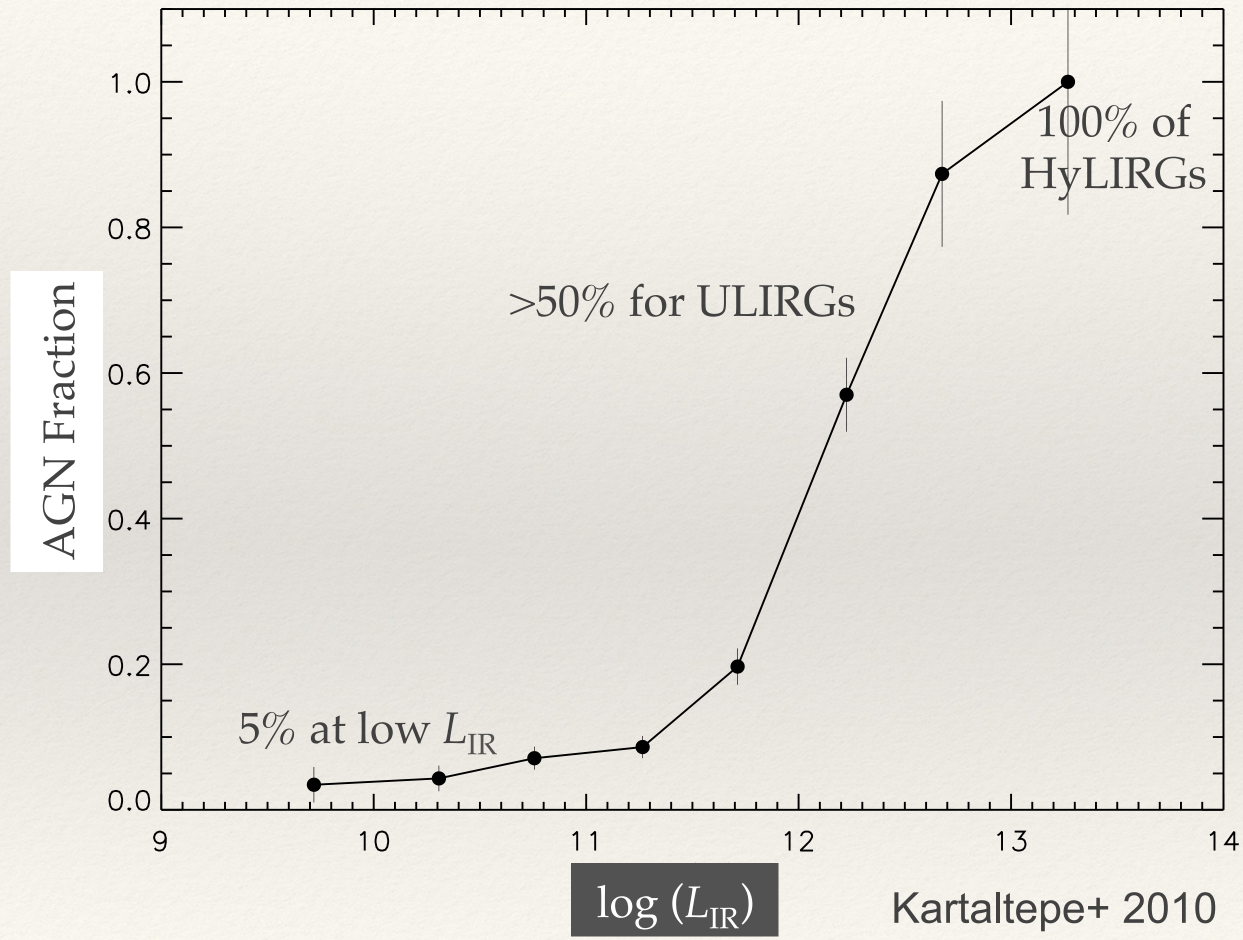
The role of AGN and galaxy mergers in massive galaxies at "high redshift" ($z = 0 – 1.3$)

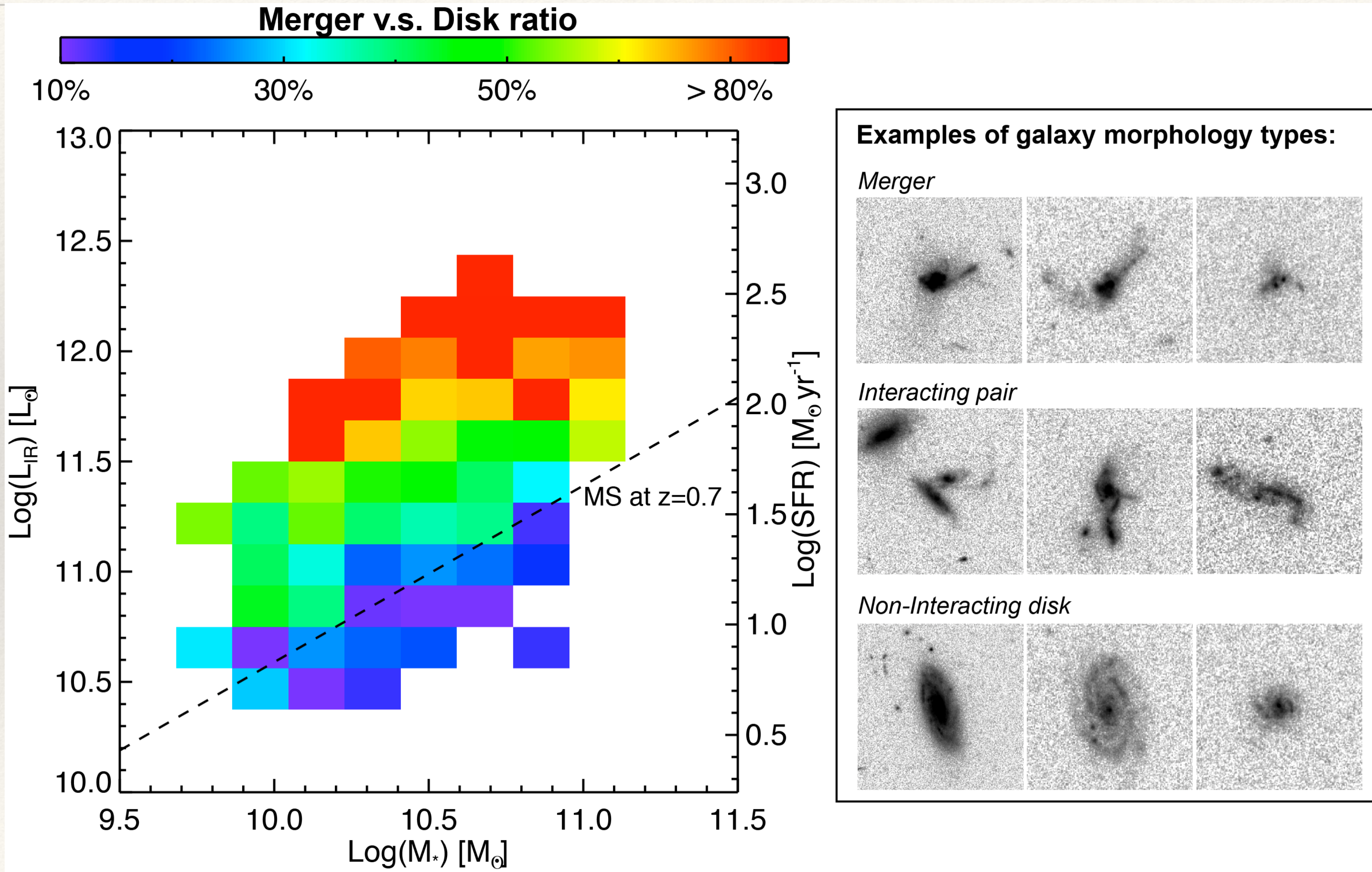
- AGN fraction vs. L_{IR} – Kartaltepe+10, 15
- Number density vs. redshift – Kartaltepe+11
- Morphology vs. L_{IR} and M^* – Hung+13

AGN Fraction at High(er) Redshift
(z ~ 0.3 – 1.3)



AGN Fraction increases systematically with L_{IR} (as it does locally)!

The *Herschel+Spitzer* COSMOS Surveys
Morphology vs. "main sequence" $z \sim 0.4 - 1.0$ (Hung+13)



Summary 4

- Increase in AGN vs. L_{IR} seen at $z \sim 0$ continues out to $z \sim 1$
- Increase in Major Mergers vs. L_{IR} seen at $z \sim 0$ continues out to $z \sim 1$
- Merger rate α $(1+z)^3$

Talk Summary

1. **Gas-rich, major mergers play a major role in the evolution of massive galaxies at *ALL* redshifts**

2. **Gas-rich, major mergers play a dominant role in fueling luminous Nuclear Starbursts and MBH -> SMBH at *ALL* redshifts**

3. **MBH -> SMBH growth phase (x 30-100) occurs during the (U)LIRG phase over a timescale of 3-8 x 10^8 years**

The next decade -> ALMA and JWST !!