

Imaging Study of Luminous Infrared Galaxies

Doctoral Dissertation Work by
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Background

- Accretion and mergers are fundamental to:
 - structure formation in the universe
 - morphological evolution of galaxies
 - star formation history
 - feeding AGN
- IRAS discovered galaxies that emit most of their energy in the far infrared, comparable to star formation rates 5 to 1000 times greater than average spiral galaxies.
- High L_{IR} correlates with nuclear activity, starbursts and morphological peculiarities. At luminosities greater than $\log L_{\text{IR}} (8\text{-}1000 \text{ microns}) > 12.00$, all IRAS galaxies appear to be advanced mergers.
- At $\log L_{\text{bol}} > 11$, IRAS galaxies are more common in the local universe ($z < 0.3$) than other objects with similar bolometric luminosities such as optically selected Seyferts, starbursts and QSOs.

IRAS = efficient detector of star-forming galaxies and star-forming mergers

- Detectes all Sb - Sd spirals and Irregulars, half of S0s and Sals and no Es (from a sample of 165 Shapley-Ames Catalog galaxies, Jong et al 1984)
- High L_{IR} correlates with nuclear activity, starbursts and morphological peculiarities. At luminosities greater than $\log L_{\text{IR}} (8\text{-}1000 \text{ microns}) > 12.00$, all IRAS galaxies appear to be advanced mergers.

Luminous IRAS Galaxies

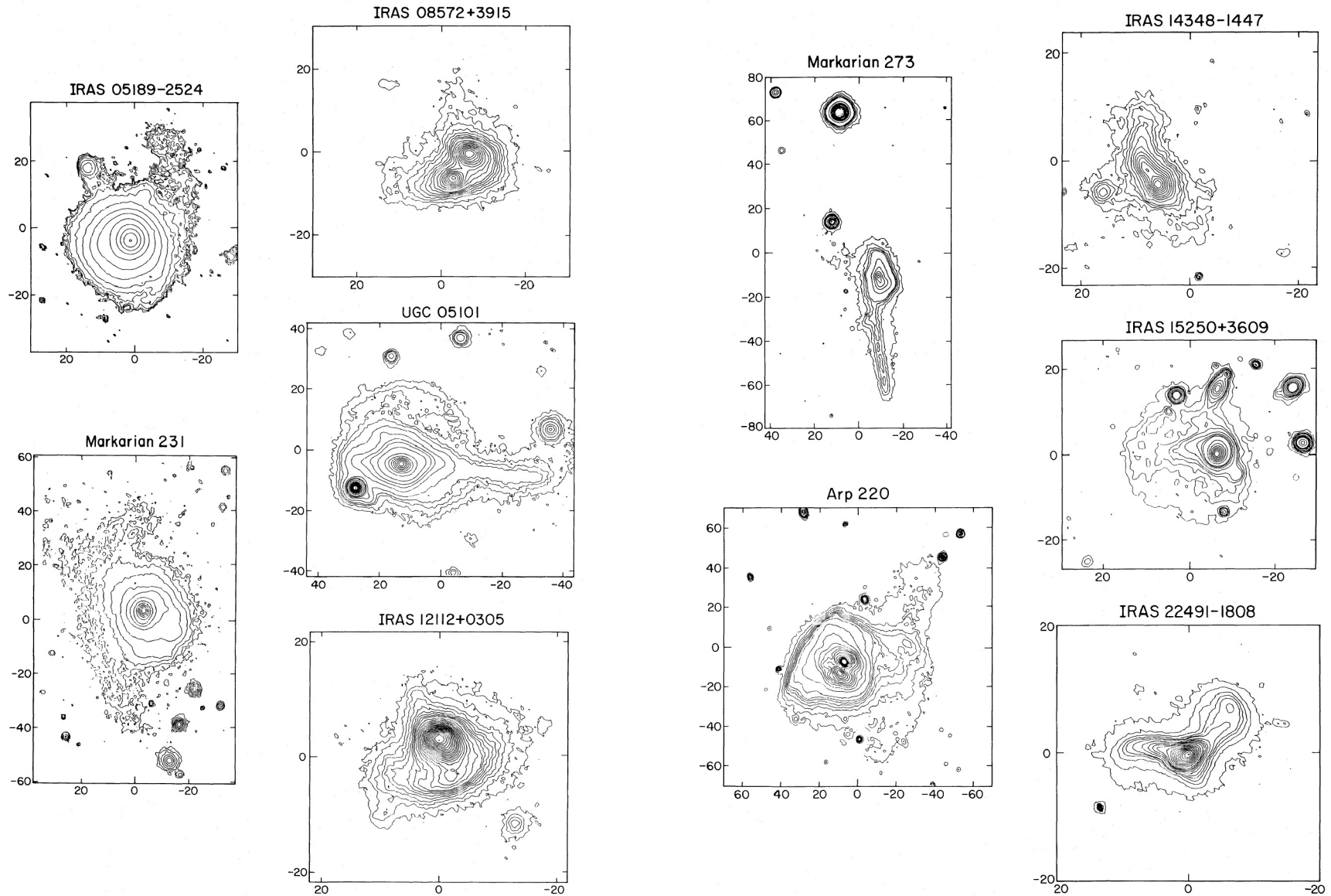
	Log L_IR/L_sun (8-1000 microns)	Examples	% in RBGS
Moderate	10-10.99	M 82 NGC 253	55.5%
Luminous (LIGs)	11-11.99	NGC 1068 NGC 7469	27.2%
Ultraluminous (ULIGs)	12-12.99	Arp 220 Mrk 231	3.5%
Hyperluminous	13-13.99	IR1520+32	0%

IRAS Bright Galaxy Sample:

All galaxies with 60 micron flux densities greater than 5.24 Jy
Brightest and closest and most amenable to detailed study.

Original (Soifer et al. 1987, 313 objects), Revised (Sanders et al. 1996, 602 objects)

ULIGs from the IRAS BGS - Advanced Mergers



Gunn r (Sanders et al, 1988)

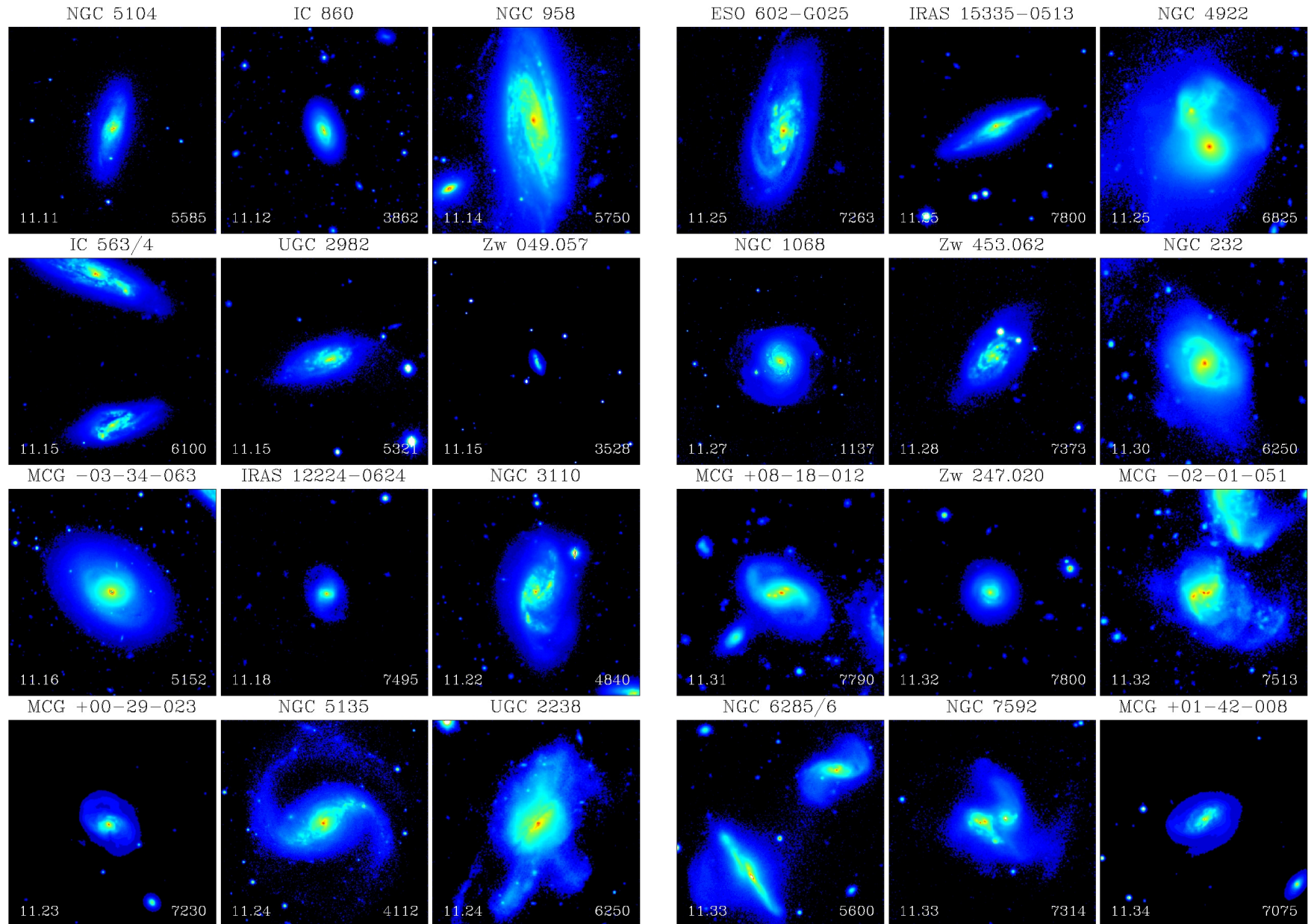
Statistically complete sample of 56 galaxies with $\log L_{\text{IR}}$ 11.10 to 11.99

- Selected from RBGS sample and observable from Mauna Kea
 - $S > 5.24$ Jy at 60 microns
 - $|b| > 30$ degrees
 - declination > -30 degrees
- Lower cutoff eliminates most “normal galaxies” that appear in optically selected samples such as large spirals, Seyferts, and UV-excess galaxies.
- Higher cutoff eliminates ULIGs = Advanced mergers with $10^{10} M_{\text{sol}}$ of molecular gas (Sanders et al 1988)

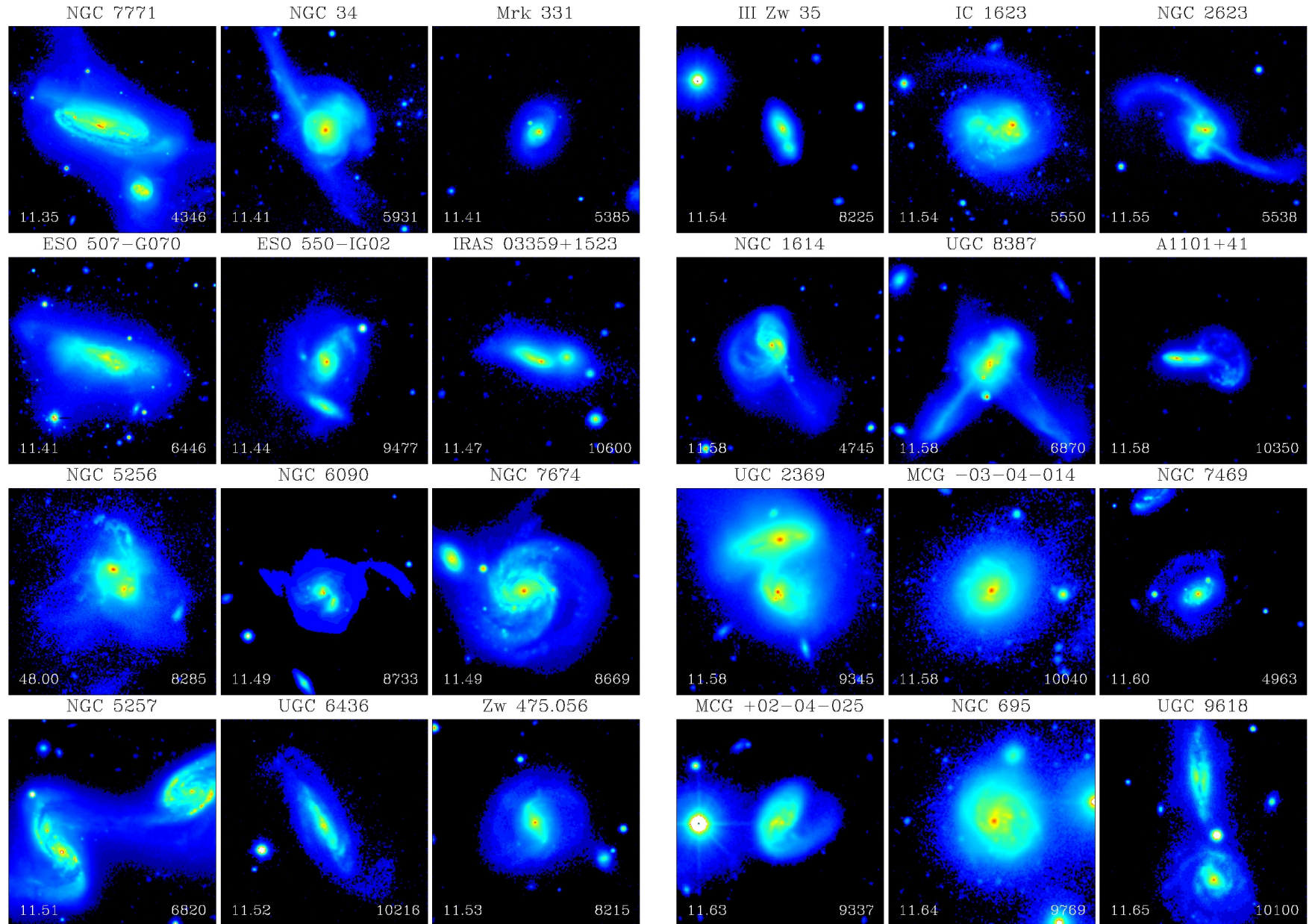
Multi-wavelength data for the sample

- BVRI optical imaging
 - Mazzarella et al. in prep (r-K Atlas), Ishida
 - 100% of sample
- JHKp NIR imaging
 - Mazarella at al. in prep (r-K Atlas), Ishida
 - 100% of sample
- Optical spectra (3750 -8000 Å, 3-5 Å)
 - Kim et al. 1995, Ishida
 - 98% of sample
- 1.49 GHz Radio Continuum
 - Condon et al. 1990, Ishida
 - 100% of sample
- Single dish CO (1- $\rightarrow$ 0) Fluxes
 - Sanders, Scoville & Soifer 1991
 - 61% of sample

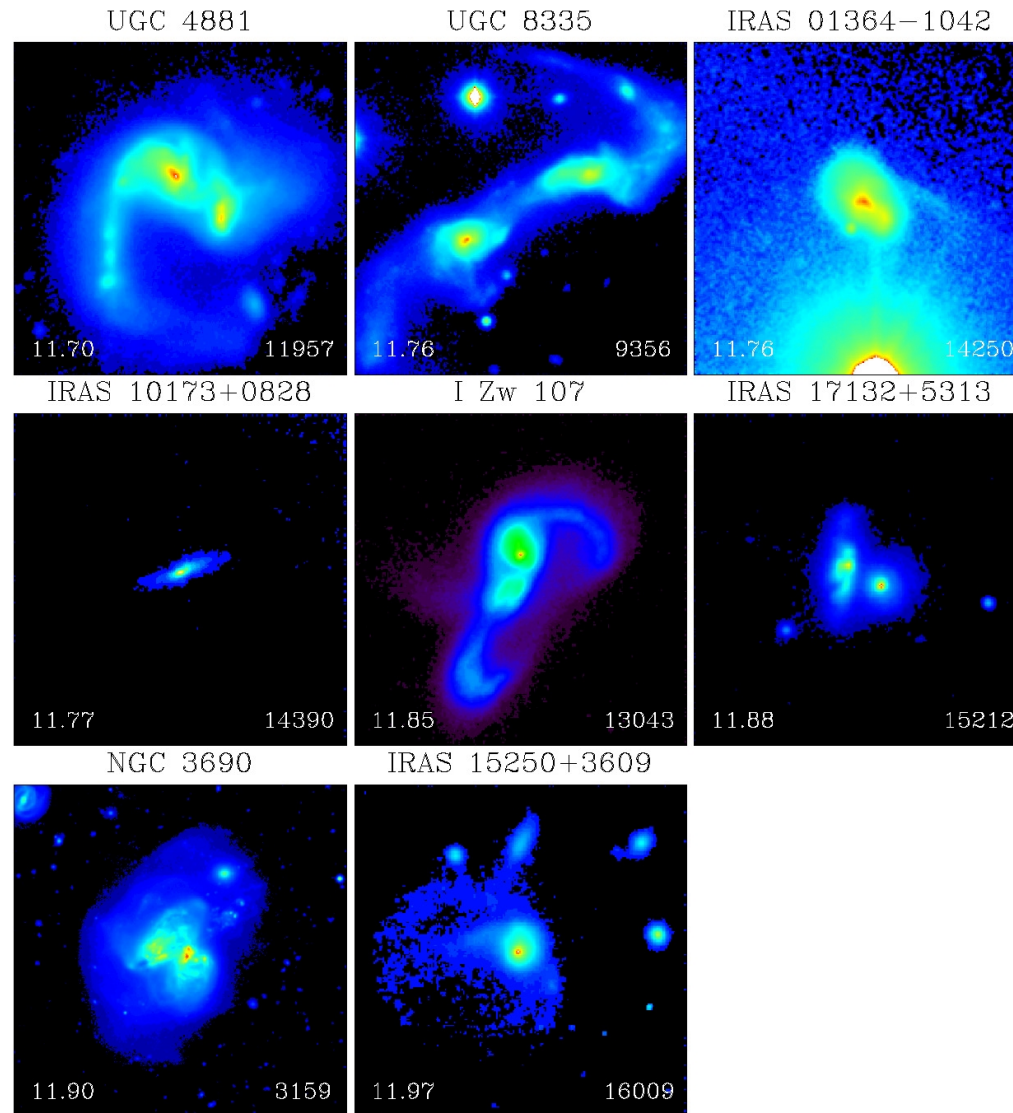
LIGs: 11.10 to 11.34 (50kpc Square)



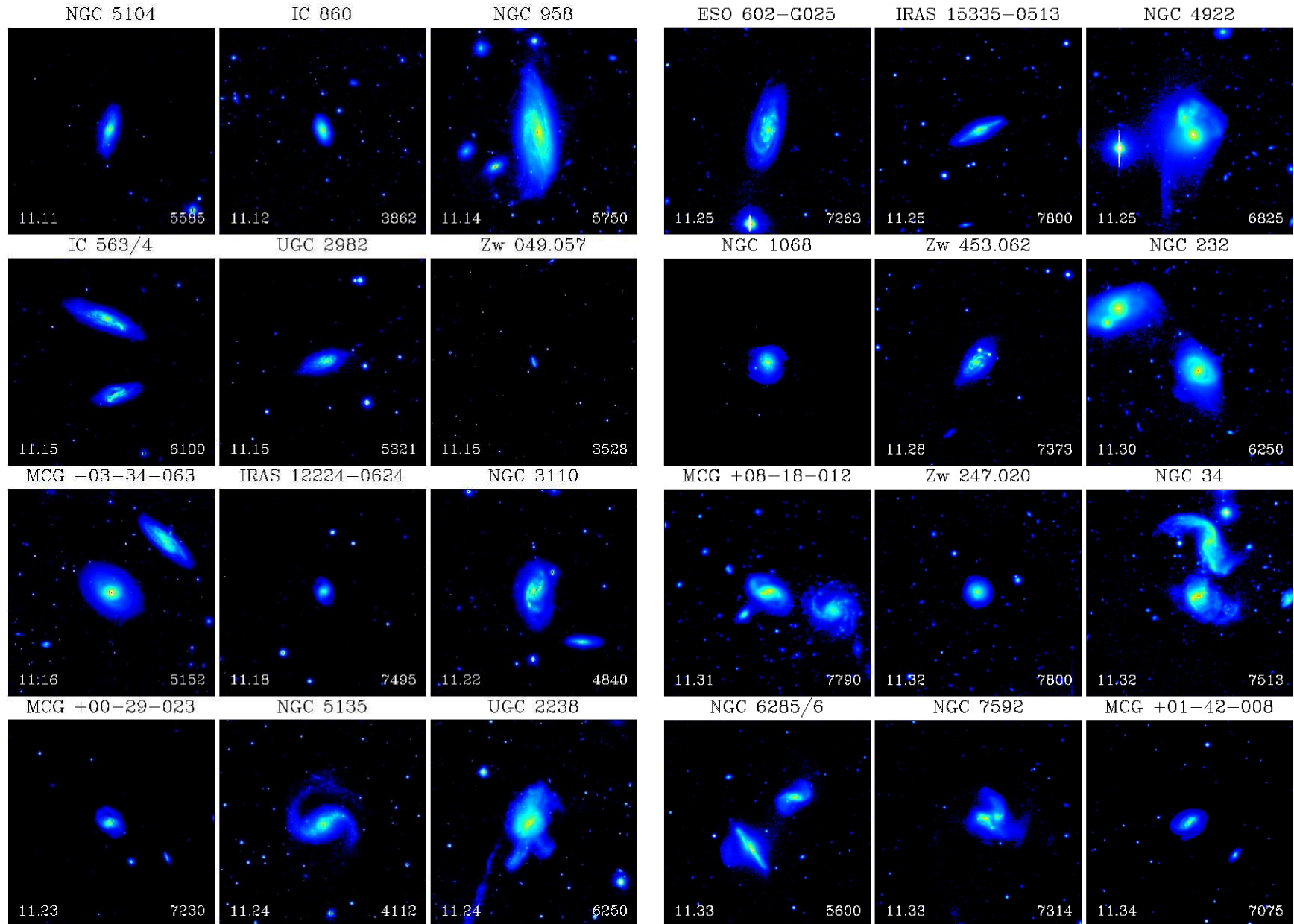
LIGs: 11.35 to 11.66 (50kpc Square)



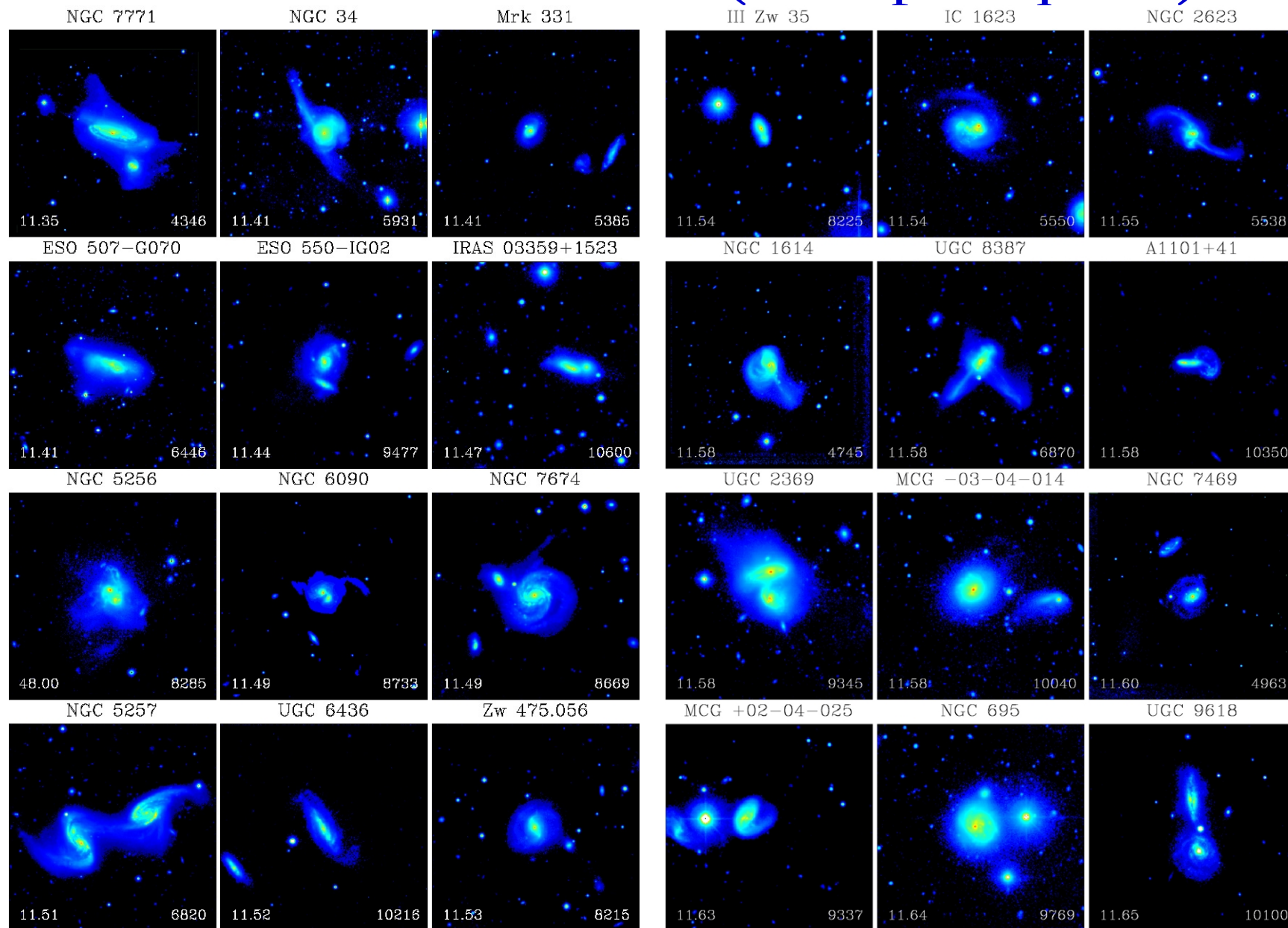
LIGs: 11.67 to 11.99 (50kpc Square)



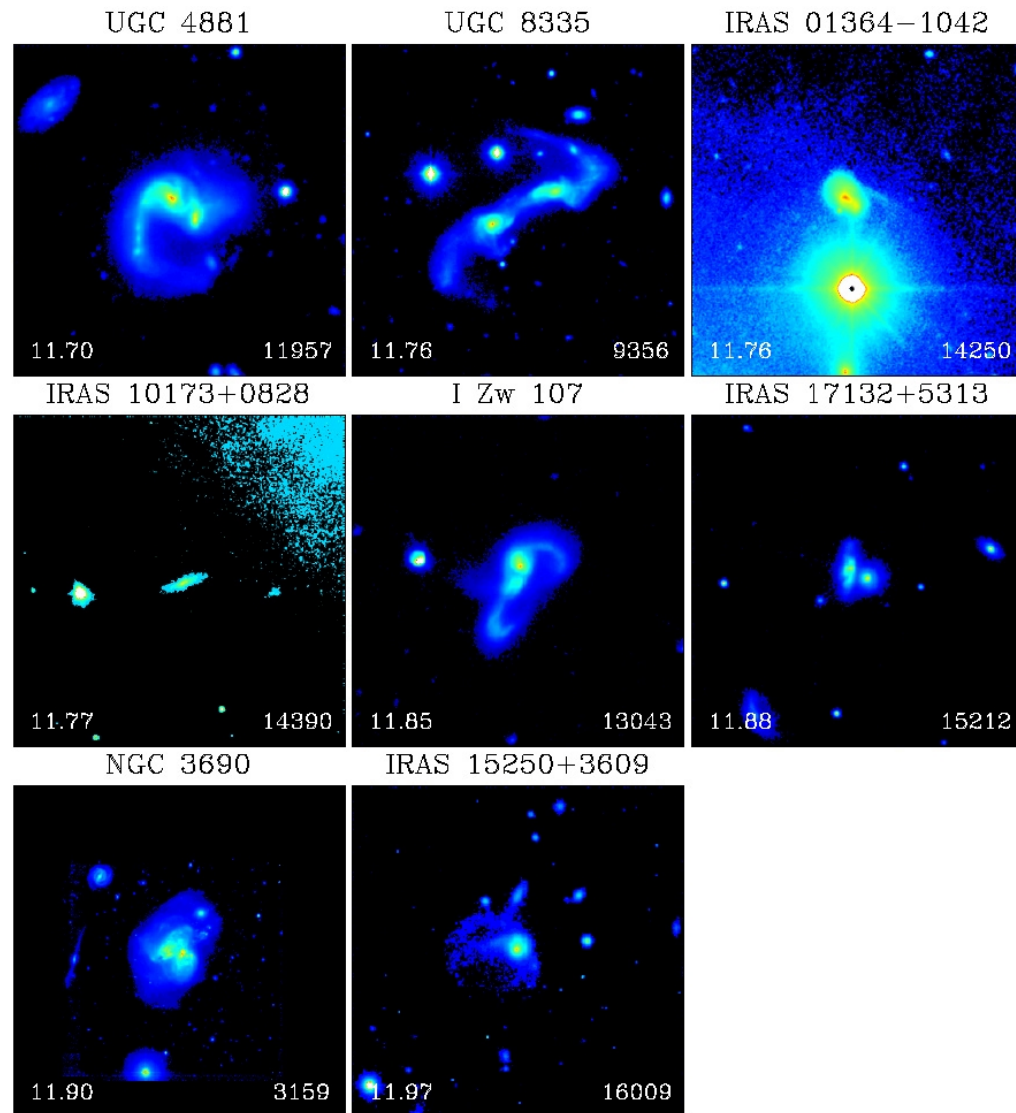
LIGs: 11.10 to 11.34 (100kpc Square)



LIGs: 11.35 to 11.66 (100kpc Square)

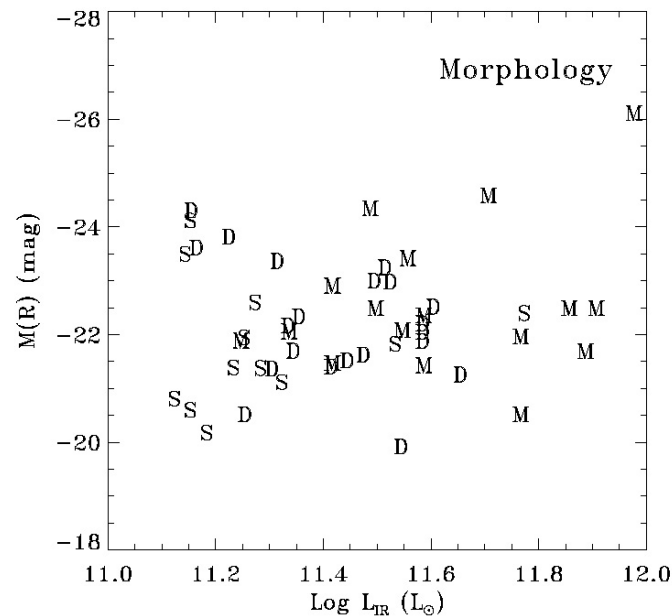


LIGs: 11.67 to 11.99 (100kpc Square)



With increasing L_{IR} , interactions involving equal mass spirals dominate

- Above $\log L_{\text{IR}} 11.33$, strong interactions of approximately equal size spirals dominate.
- Below $\log L_{\text{IR}} 11.33$, single objects and well separated but approximately equal size pairs of spirals dominate.

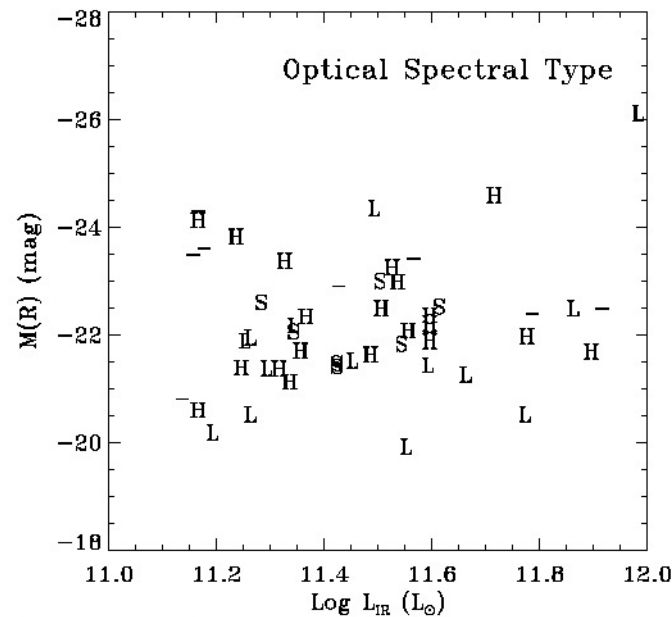


S = Single 26%

D = Interacting Double 41%

M = Advanced Merger 33%

Optical spectral types have no obvious trends with L_{IR}



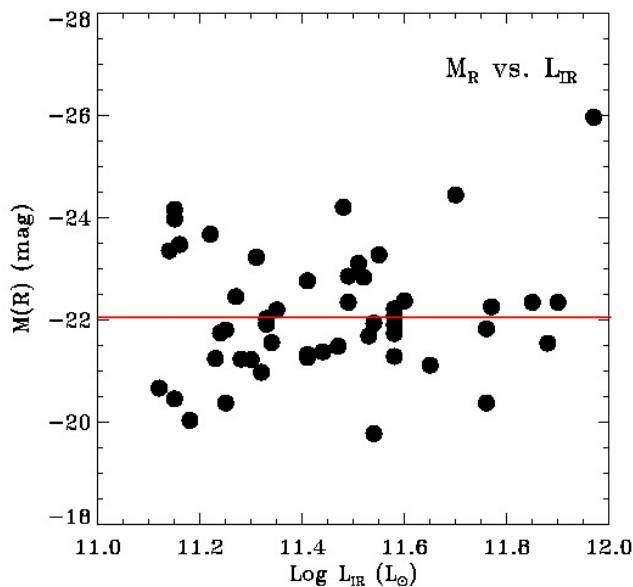
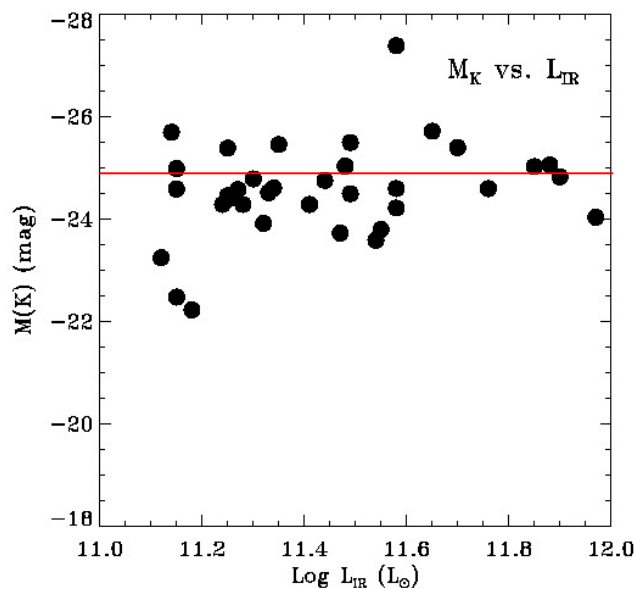
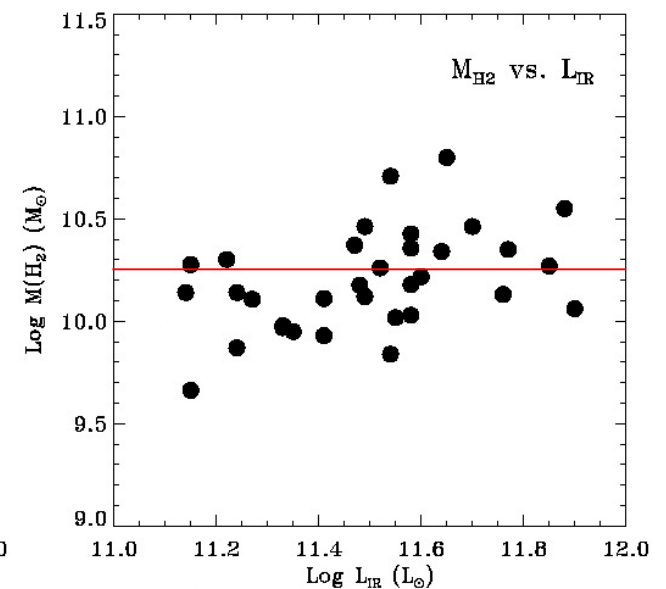
H = HII 49%

L = LINER 17%

S = Seyfert 34%

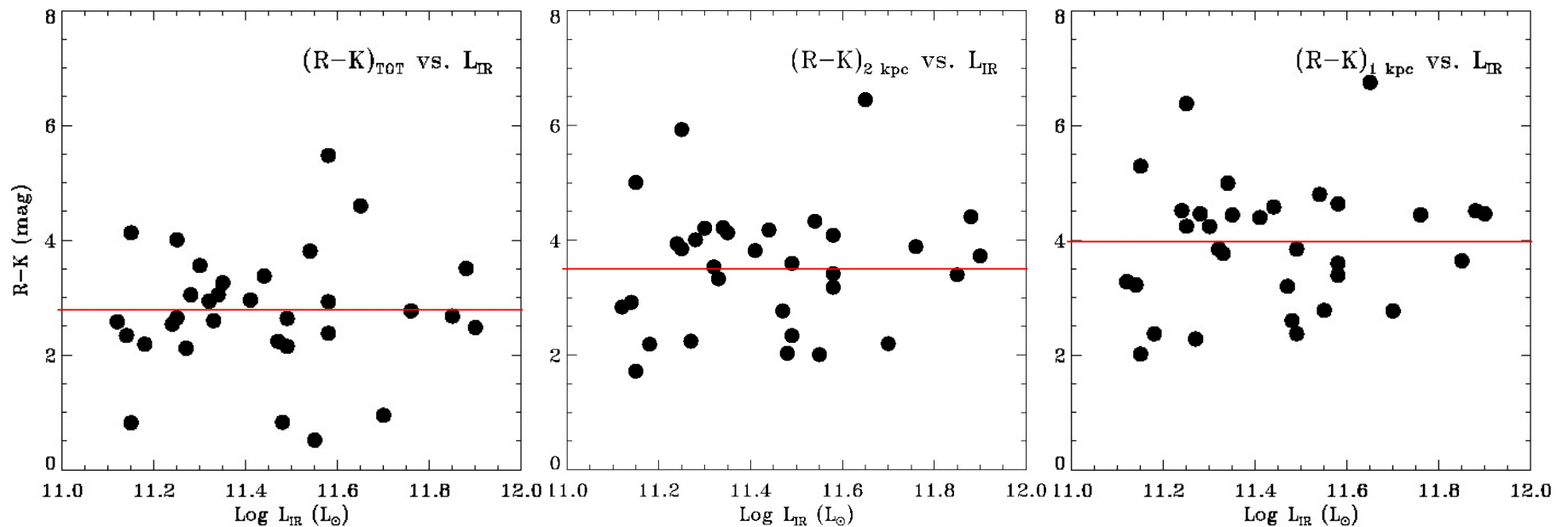
Total luminosities on the order of $2 L^*$ and greater

- Average r-band Magnitude = -22.1 ($M^*_r \sim -20.5$)
- Average Kp-band Magnitude = -24.6 ($M^*_{Kp} \sim -24.2$)
- Average H_2 Mass = $18.6 \times 10^9 M_{\text{sol}}$

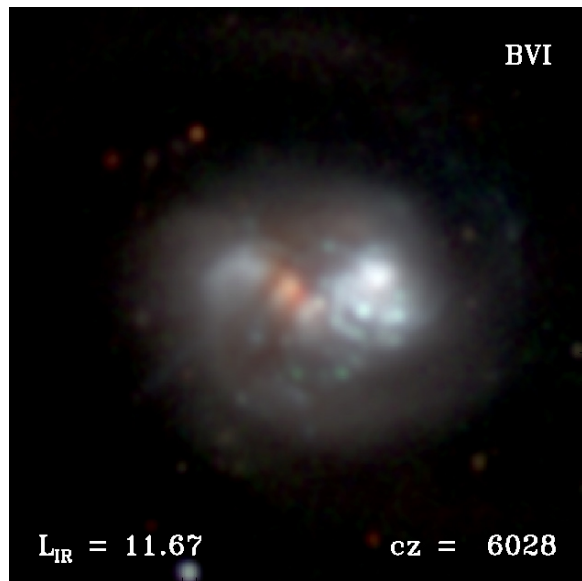
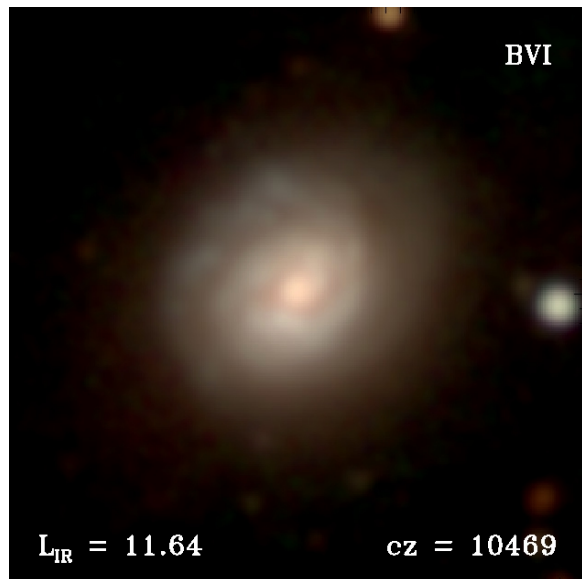
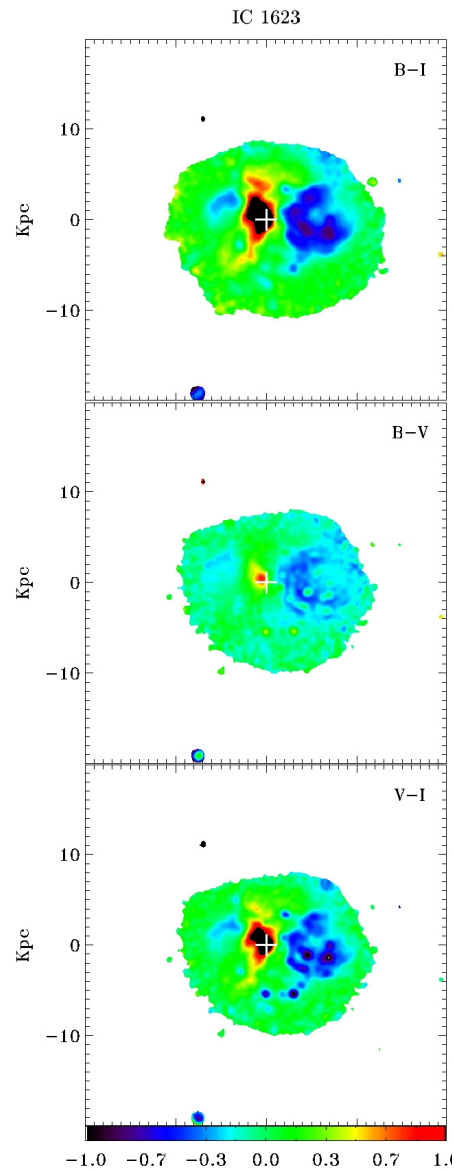
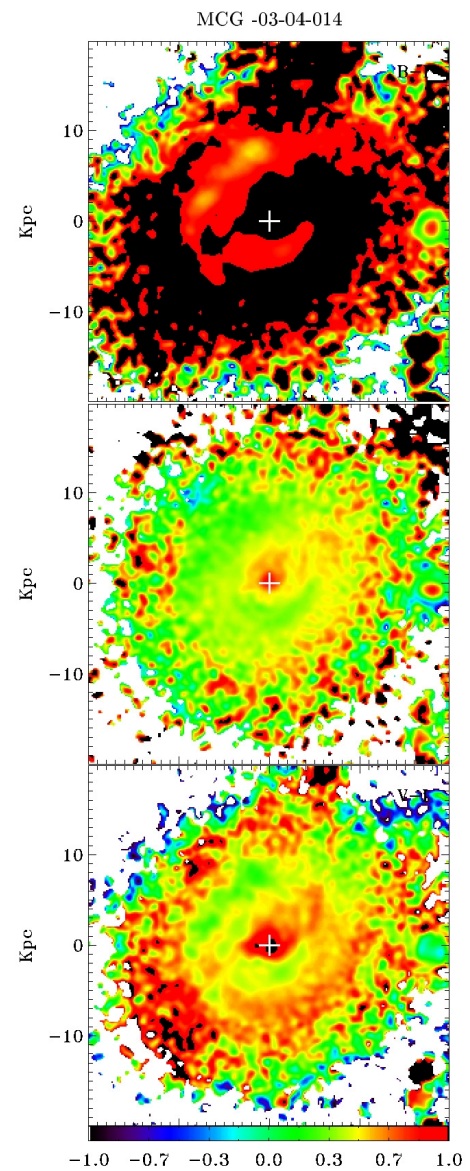


Colors indicate heavy extinction in centers, but extensive star formation, and blue tidal tails.

- Average total R-Kp color = 2.75
- Average R-Kp color within 2 kpc = 3.56
- Average R-Kp color within 1 kpc = 3.94



IC 1623 and MCG-03-04-014



Global optical colors are flat

- Early results indicate that...
 - Average $M_B \sim 22.3$ ($M^*_B = -19.7$)
 - Average $M_V \sim 22.6$
 - (Average $M_r \sim -22.1$ ($M^*_r = -20.5$))
 - Average $M_I \sim -22.7$
- On average A-star like but significant local variation

LIGs and ULIGs probably draw from the same underlying population

- Optical, NIR and CO properties of LIGs are comparable to ULIGs, although LIGs have bluer global colors
 - Average ULIG $M_B = -20.2$ (Armus 1990)
 - Average ULIG $M_r = -22.0$ (Murphy et al 1996)
 - Average ULIG $M_{Kp} = -24.8$ (Kim 1995)
 - Average ULIG $M(H_2) > 10^{10} M_{\text{sol}}$ (Sanders et al 1988)
- ULIG phase not sustainable $\rightarrow$ ULIGs must pass through a LIG phase twice: on the way up and on the way down
- Hypothesis: ULIGs represent mergers of 2 gas rich disk galaxies which feed an AGN/QSOs and form an elliptical via dissipative collapse. (Kormendy and Sanders 1992)
- Is there a merger sequence?

LIGs: Pre-ULIG? Post ULIG?

- No clear diagnostic yet
- Best candidates for a “Post-ULIG” sample are LIGs with $\log L_{\text{IR}}$ 11.33 to 11.66 with Liner or Seyfert optical spectra with little or no nuclear separation.
- Best candidates for a “Pre-ULIG” sample are LIGS with $\log L_{\text{IR}}$ 11.33 to 11.66 with HII region like spectra and clearly distinguishable separate nuclei ($\sim$ one galaxy radius)
- Some evidence for $S + S \rightarrow E$ in radial profiles

Post ULIG candidates: UGC 2238 and NGC 34

