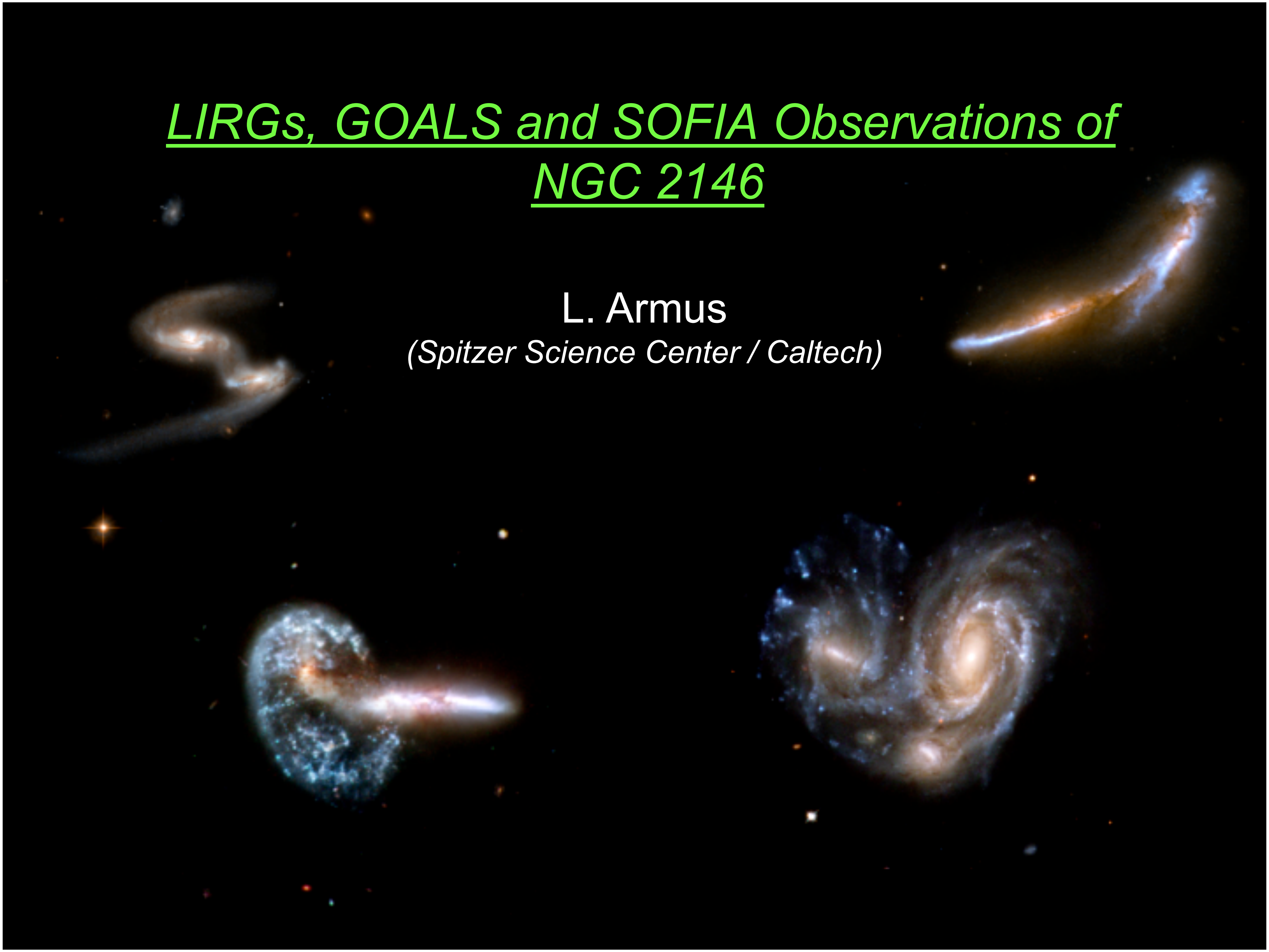
LIRGs, GOALS and SOFIA Observations of NGC 2146

L. Armus

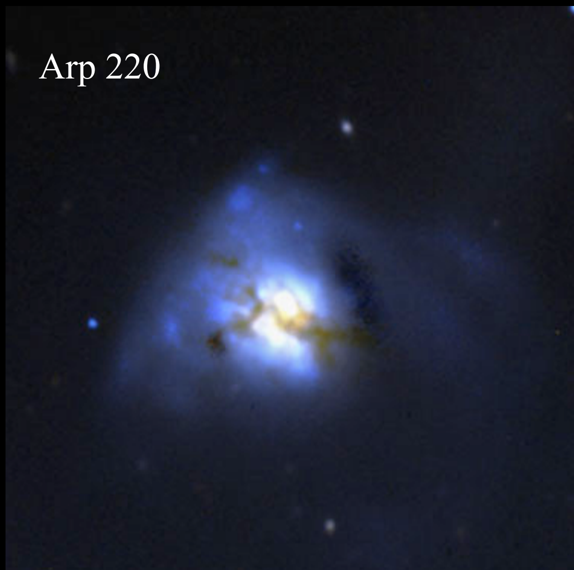
(Spitzer Science Center / Caltech)



Outline

1. ULIRG basics and Spitzer/IRS results
2. GOALS – The Great Observatories All-sky LIRG Survey
3. NGC 2146 and observations with FORCAST on SOFIA

Local ULIRGs



- Galaxies with QSO-like power output: $L_{bol} \geq 10^{12} L_\odot$
  $\Rightarrow L_{IR} \sim L_{bol}$ and $L_{opt} < 0.1 L_{IR}$
- 90 – 95% are interacting, or in merging systems
- Very strong emission lines (H^+, [OI,] [OIII], [NII], [SII]…)
- Large, compact reservoirs of cold molecular gas
  $\Rightarrow$ more than 10^9 - 10^{10} $M_\odot$ over $R \leq$ 1-few Kpc.
- Drive "superwinds" of hot, enriched gas (into the halo/IGM)

Huge MIR/FIR excess from dust (re-)radiation of UV light

ULIRG Evolutionary Model

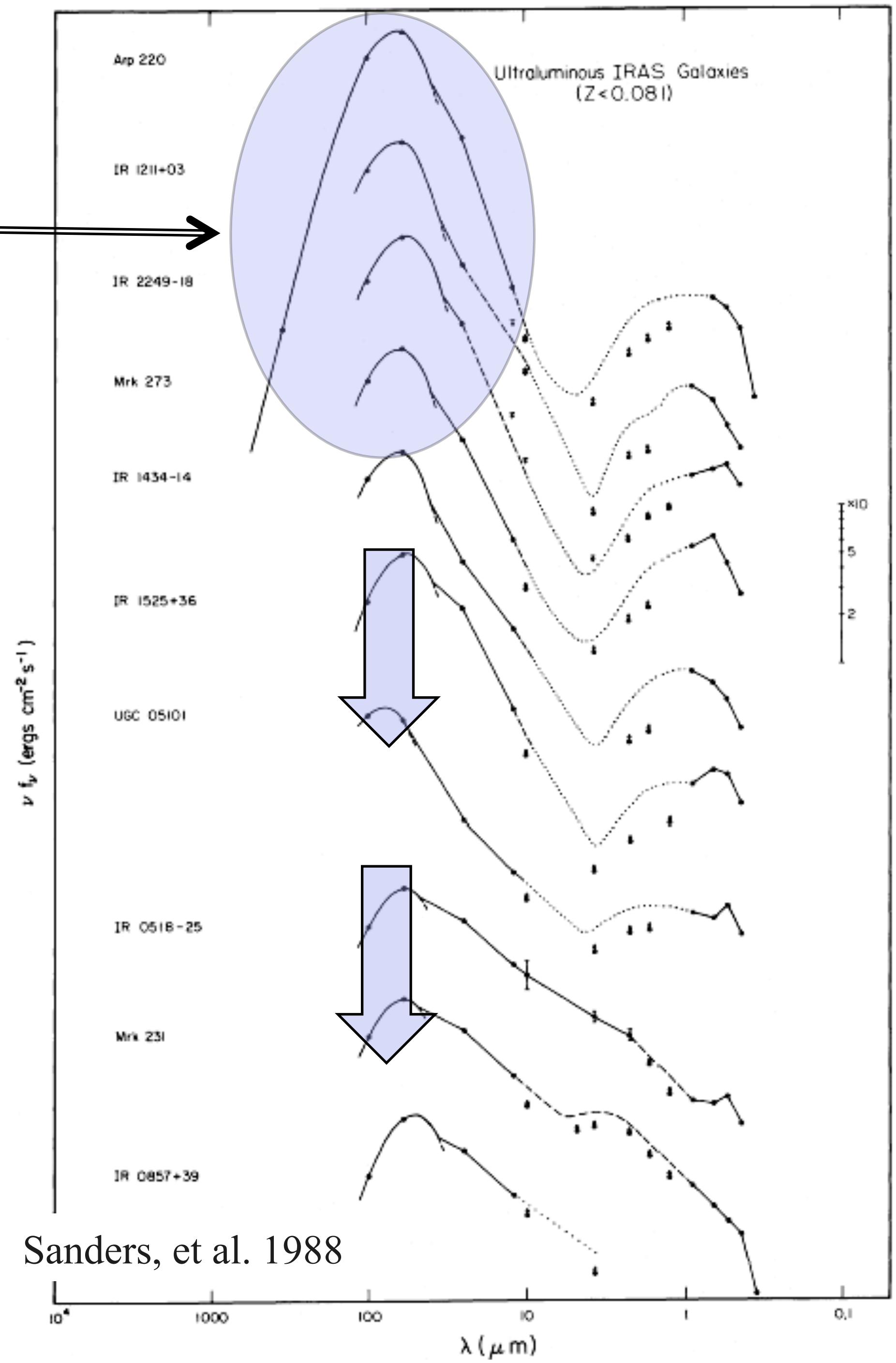
"cold" SB-dominated

↓

Warm SB + AGN

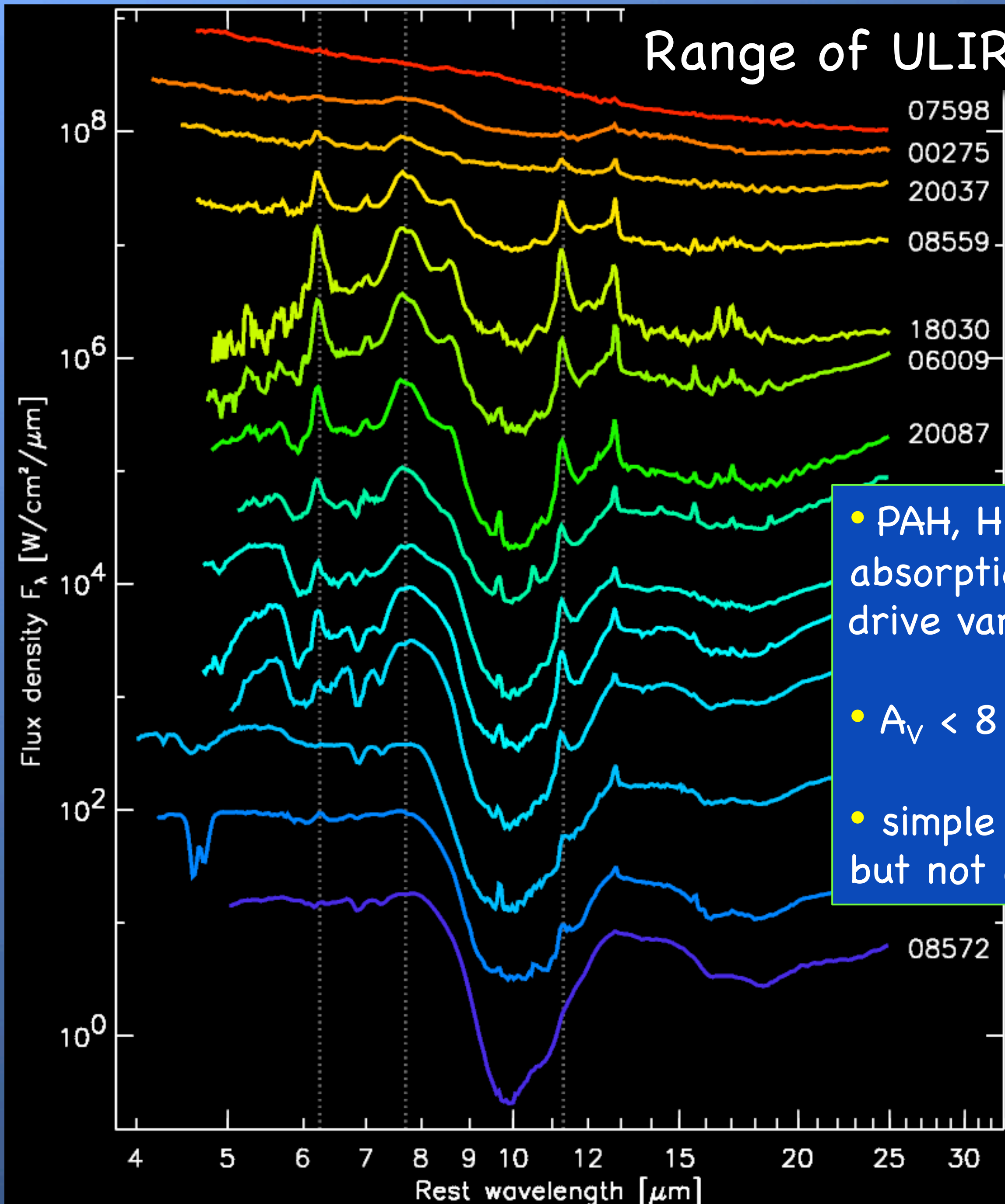
↓

Optical QSO



Sanders, et al. 1988

Range of ULIRG spectra



AGN-dominated

Starburst-dominated

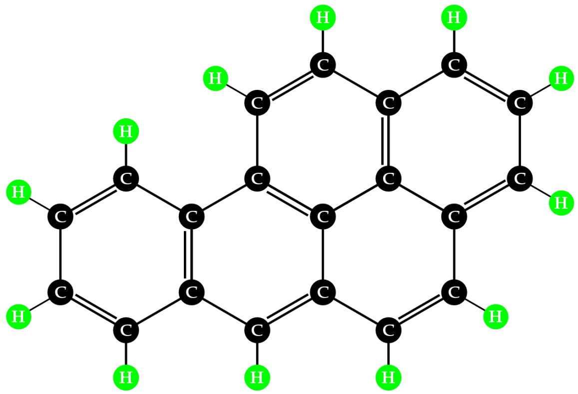
Absorption-dominated

- PAH, H_2O ice, hydrocarbon & silicate absorption, & range of dust temps drive variation in SEDs
- A_V < 8 to > 80 mag to nuclei
- simple dust geometries explain many but not all ULIRG spectra

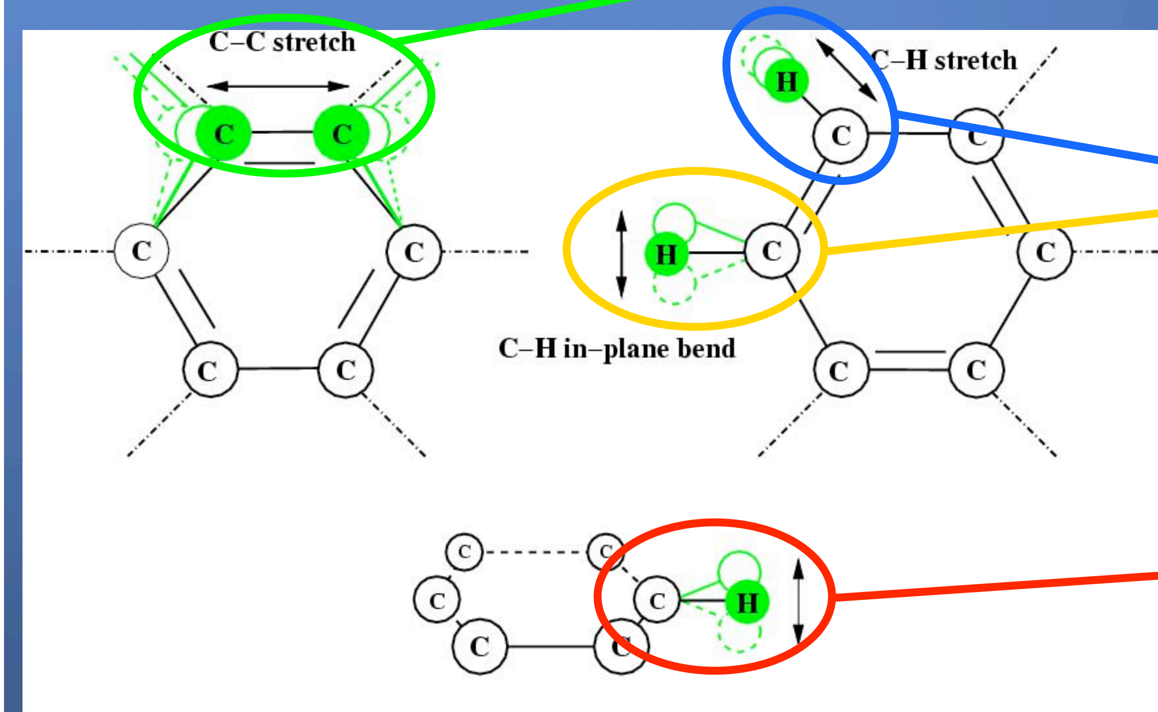
Spoon et al. (2007), Armus et al. (2006,2007), Hao et al. (2007), Imanishi et al. (2007), Levenson et al. (2007), Sirocki et al. (2008)

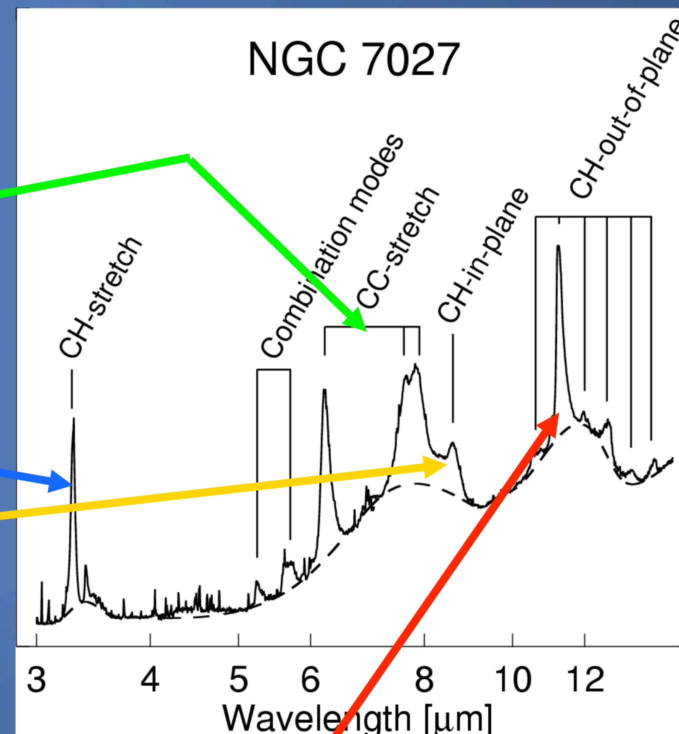
PAH Normal Modes

- Tens to hundreds of C atoms
- Bending, stretching modes ⇒ IR features
- flux ratios ⇒ ionized or neutral; sizes

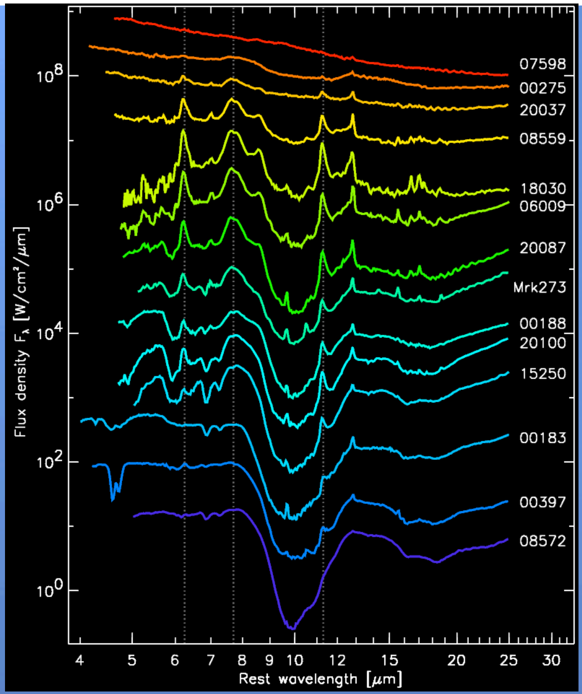


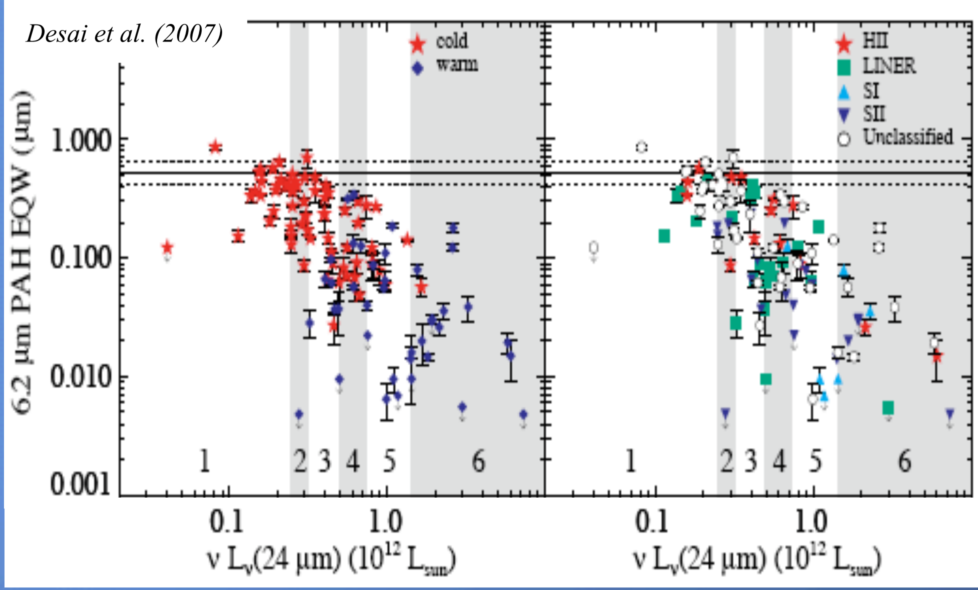
PAH molecule

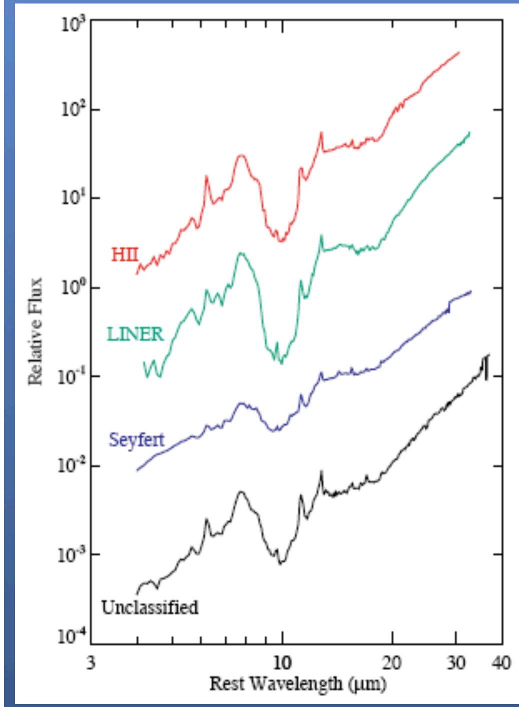




Leger & Puget (1984)
Sellgren (1984)
Desert, et al. (1990)
Draine & Li, (2001)
Peeters, et al. (2004)







- Large variation in MIR spectra driven by PAH, H_2O ice, hydrocarbon & silicate absorption

- 30-40% of the power of a typical ULIRG comes from an AGN. This rises with luminosity, dust temp, merger stage, etc.

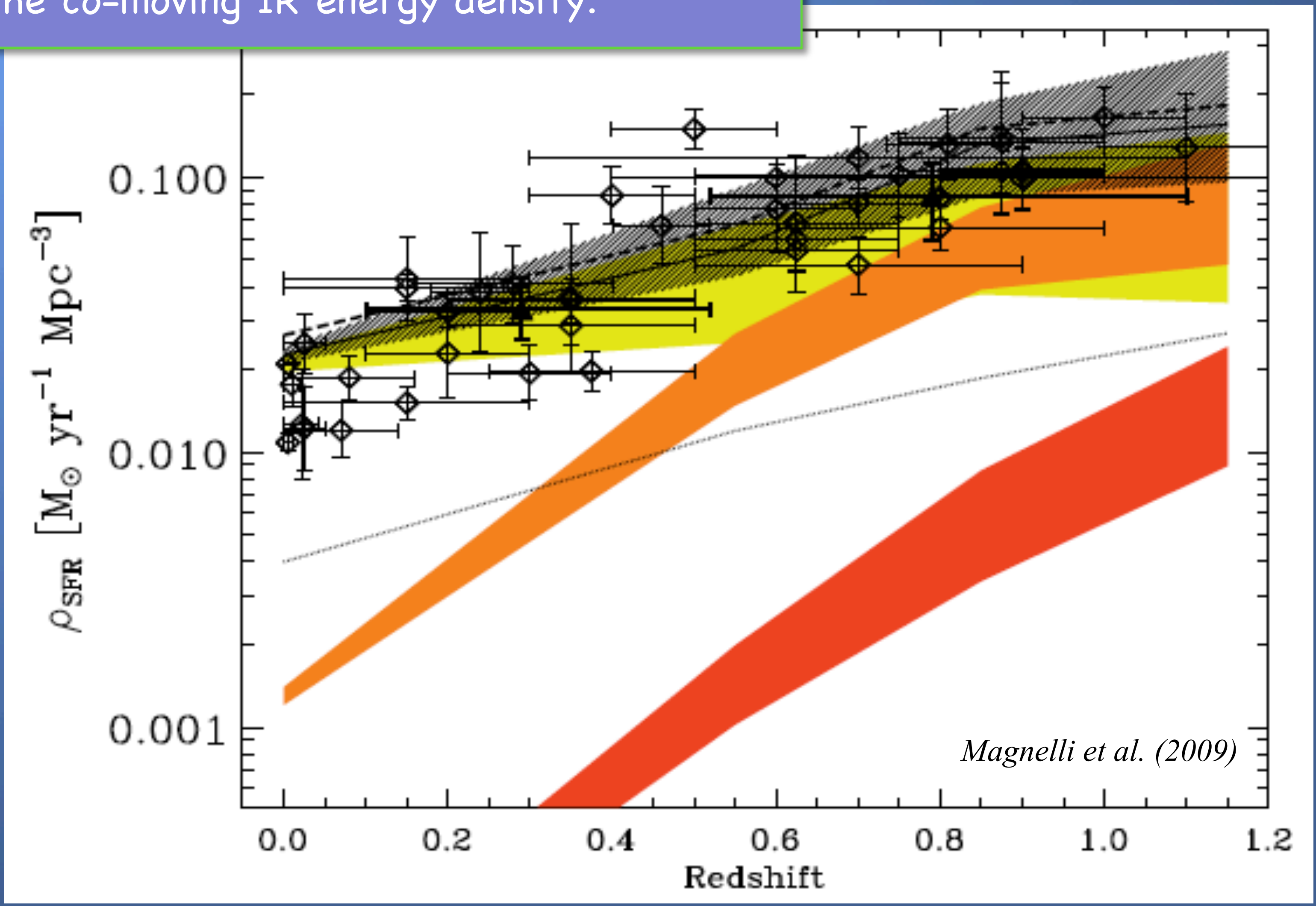
- detection of SB signatures (PAH + cold dust) in QSOs strengthened evidence for rapid BH and bulge growth in dusty, merging galaxies.

Spoon +(2007), Armus +(2006,2007), Desai +(2007), Hao +(2007), Imanishi +(2007), Schweitzer +(2008), Lutz +(2008), Veilleux +(2009)

Why study LIRGs ?

- All interaction stages are represented.
- Disentangle nuclear and disk properties. Compare to merger models. Resolve MIR, UV, gas emission.
- Detailed study of a population that has undergone rapid evolution since z=1.

At z=1, IR-luminous galaxies represent ≥ 50% of the co-moving IR energy density.



From ULIRGs to LIRGs

Expand multi-λ studies, and IR spectra of LIRGs from $0 < z < 1$

- Cover SB and AGN co-evolution in dusty galaxies over a greatly expanded luminosity range, range of merger states, AGN/SB fractions, etc.

- Combine MIR and FIR diagnostics to fully understand heating and cooling over a wide range in phase space (luminosity, density, morphology, SB/AGN fraction).

>> Spitzer Legacy projects (GOALS, 5MUSES, etc.)

>> Herschel GTO, OTKP and GO programs (HERCULES, SHINING, KINGFISH, GOALS)

A comprehensive study of 202 LIRGs in the local Universe drawn from the IRAS RBGS (629 with |b| > 5°, S_{60} > 5.24 Jy) http://goals.ipac.caltech.edu

Spitzer: IRAC, MIPS, images of complete sample. IRS spectra of all nuclei. IRS maps of representative subset.

HST: ACS B, I and NICMOS H-band images of those with log $L_{IR} > 11.4\ L_{\odot}$ and ACS FUV (F140 LP) imaging of 25.

GALEX: FUV & NUV images of about 70% of the sample.

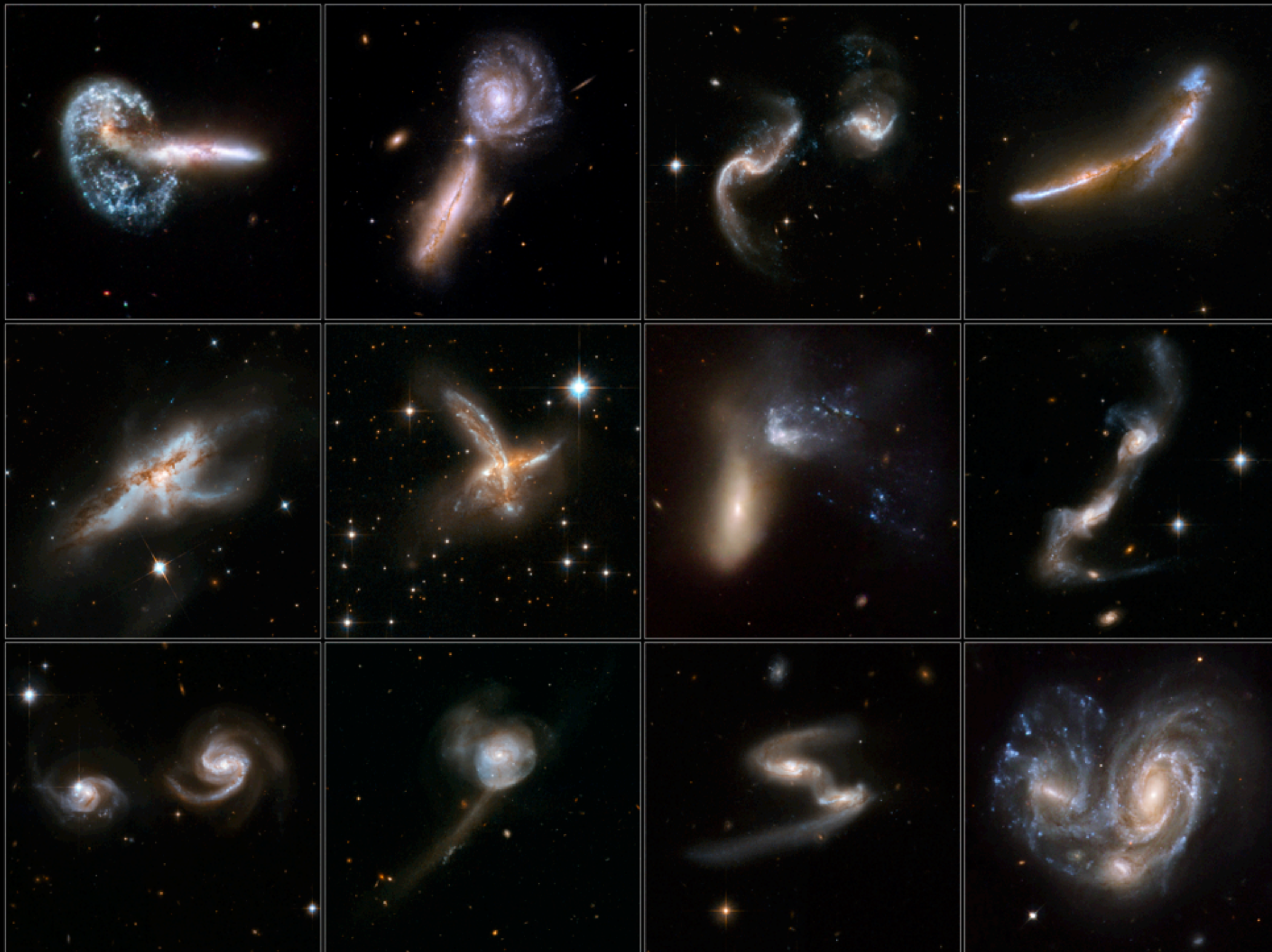
Chandra: X-ray images of about 1/2 of HST sample.

...also includes observations with CARMA & Nobeyama (CO), Palomar (NIR), Keck OSIRIS (NIR), and Herschel (OTKP and GO1)

Team: J. Mazzarella, D. Sanders, J. Surace, A. Evans, K. Iwasawa, J. Howell, B. Chan, T. Vavilkin, A. Petric, H. Inami, V. U, S. Haan, S. Stierwalt, P. Appleton, S. Lord, S. Veilleux, L. Kewley, H. Spoon, T. Diaz-Santos, V. Charmandaris, J. Marshall, B. Madore, B. Schulz, K. Xu, D. Frayer, D.C. Kim, G. Bothun

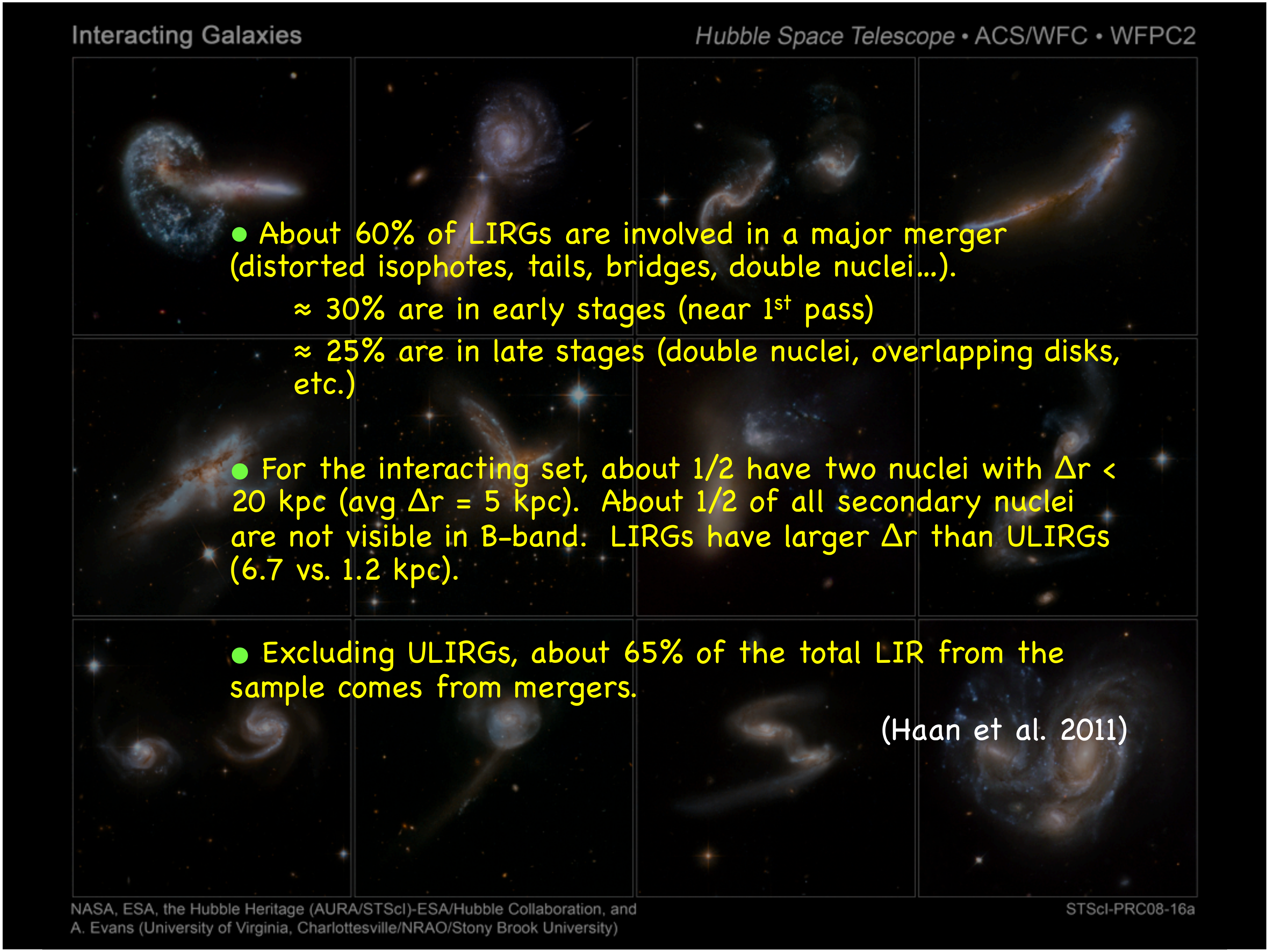
Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2



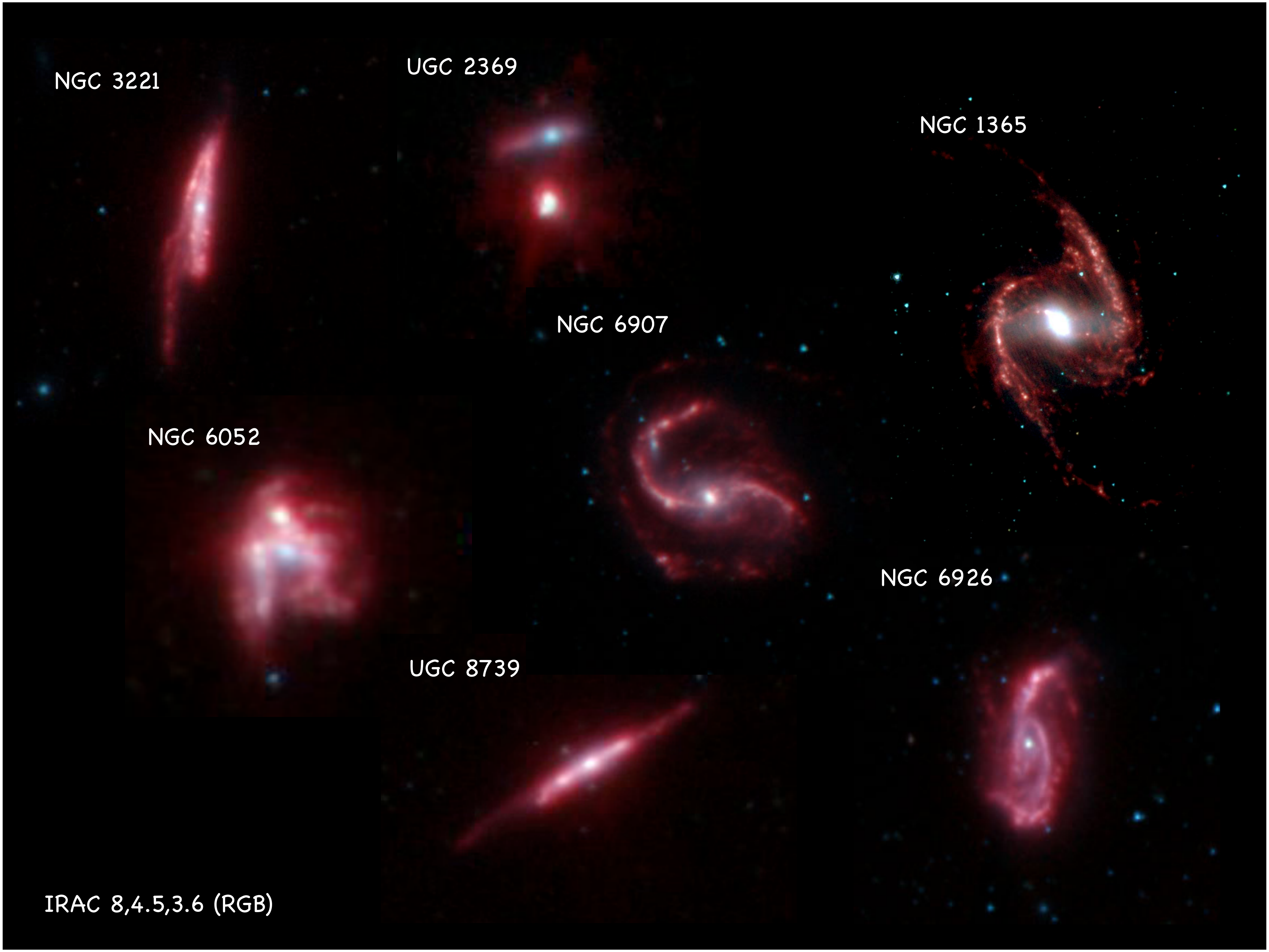
NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and
A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

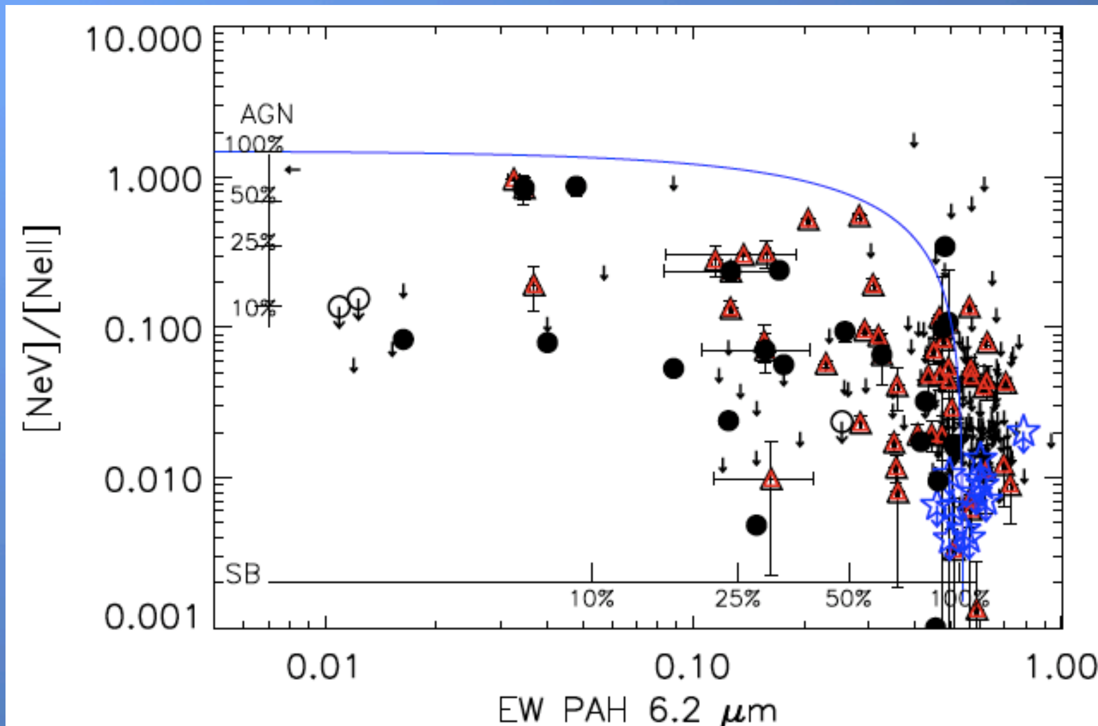
STScI-PRC08-16a



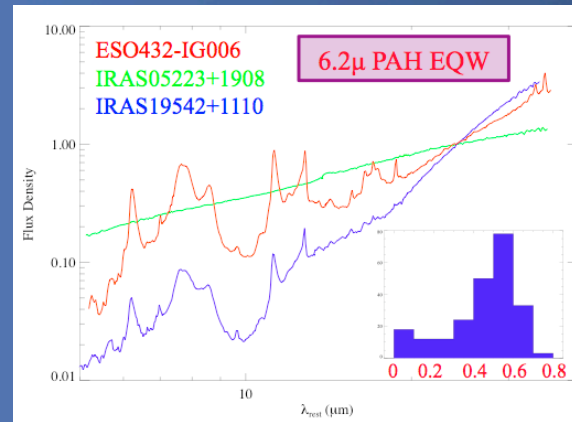
- About 60% of LIRGs are involved in a major merger (distorted isophotes, tails, bridges, double nuclei…).
  - ≈ 30% are in early stages (near 1st pass)
  - ≈ 25% are in late stages (double nuclei, overlapping disks, etc.)
- For the interacting set, about 1/2 have two nuclei with Δr < 20 kpc (avg Δr = 5 kpc). About 1/2 of all secondary nuclei are not visible in B-band. LIRGs have larger Δr than ULIRGs (6.7 vs. 1.2 kpc).
- Excluding ULIRGs, about 65% of the total LIR from the sample comes from mergers.

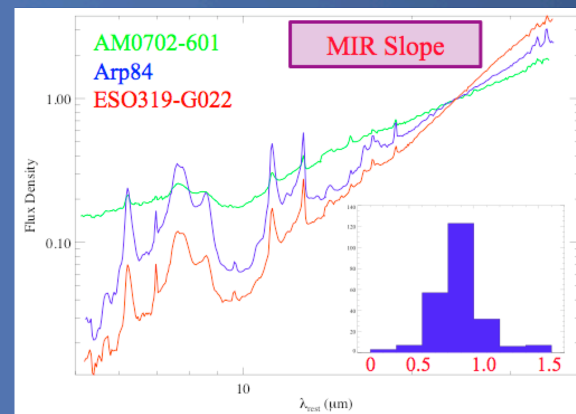
(Haan et al. 2011)

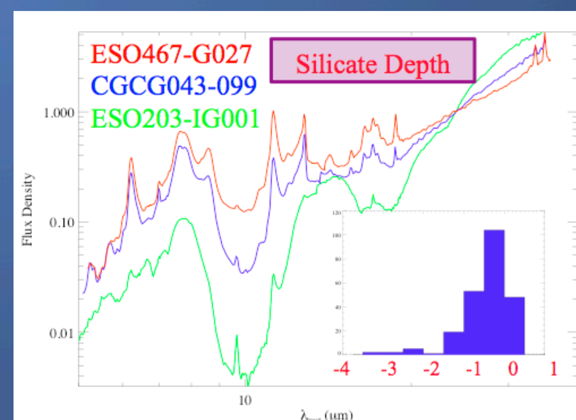

NGC 3221
UGC 2369
NGC 1365
NGC 6907
NGC 6052
NGC 6926
UGC 8739
IRAC 8,4.5,3.6 (RGB)



Petric et al. (2011)



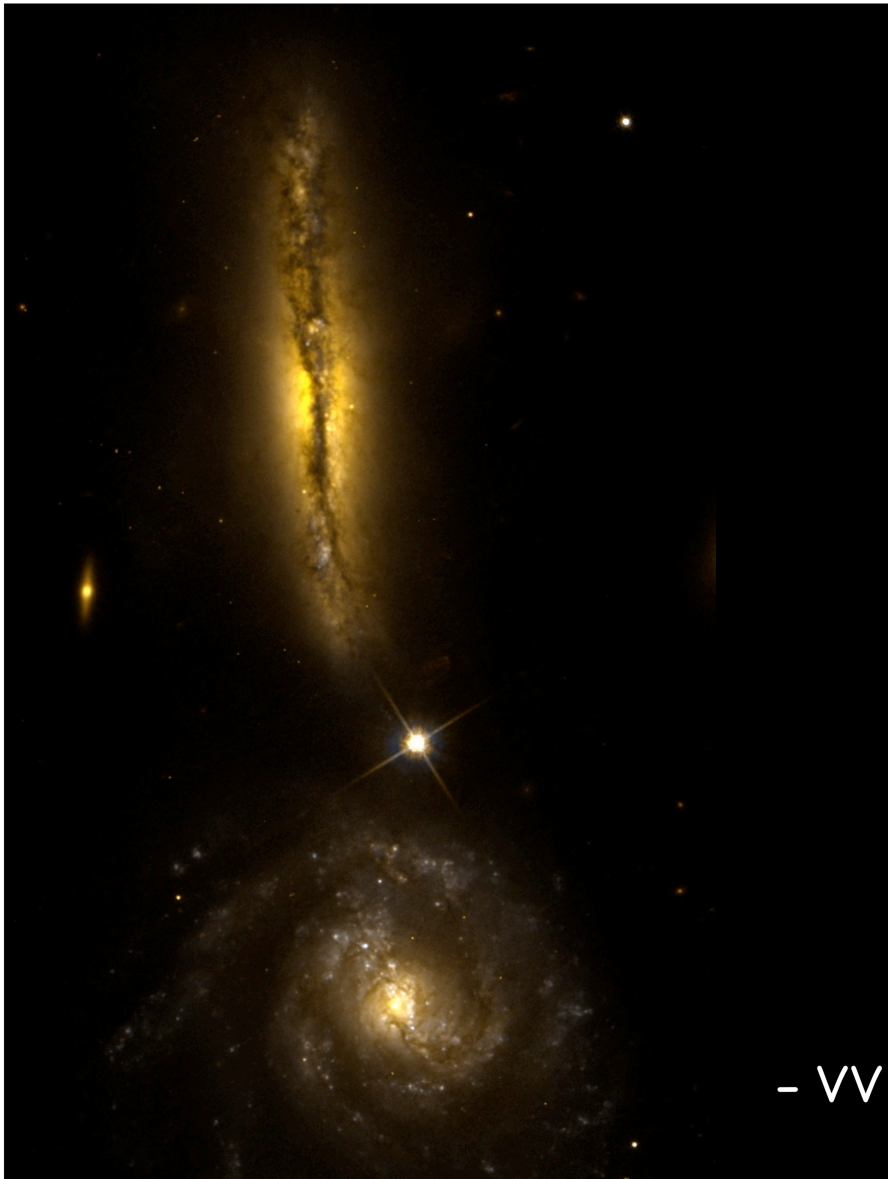


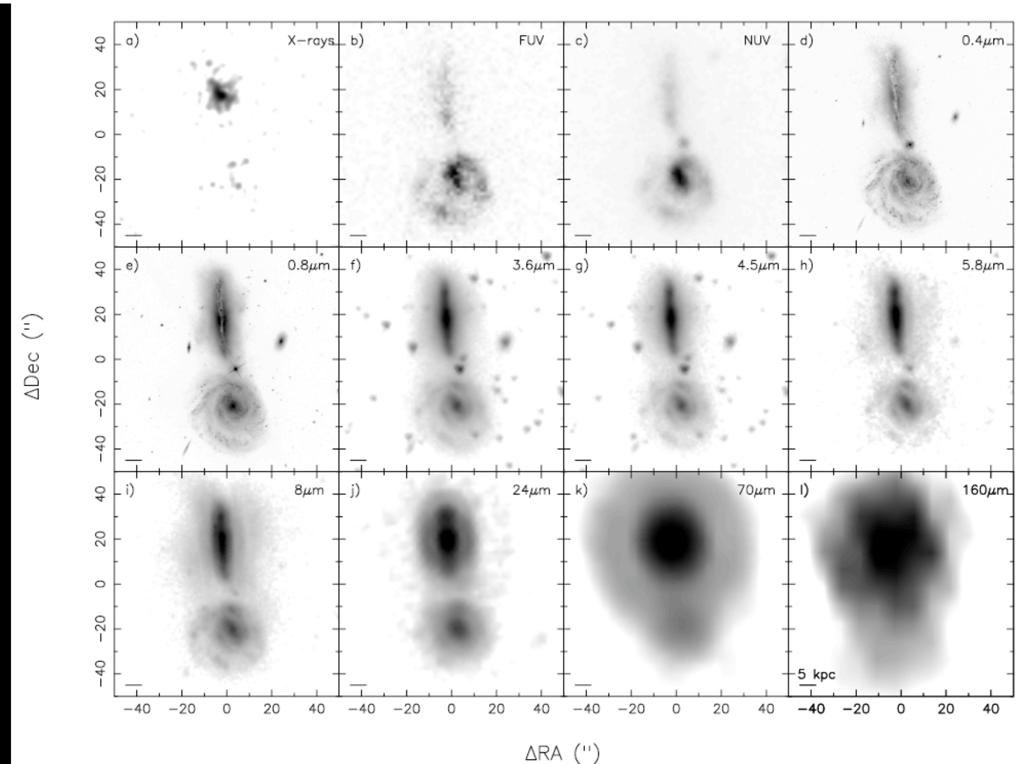


Stierwalt et al. (in prep)

Spectral shape and AGN power

- A large range in spectral shapes among LIRGs.
- While [NeV] is seen in 21% of LIRGs, the vast majority (90%) are SB dominated. The AGN fraction rises toward the latest merger stages.
- The integrated AGN contribution to the IR in LIRGs alone is 10-15% - about 1/4 - 1/3 that of ULIRGs.





VV 340
$L_{IR} = 5.5x10^{11}\ L_{\odot}$
$z = 0.034$

- VV 340N Emits more than 90% of LIR

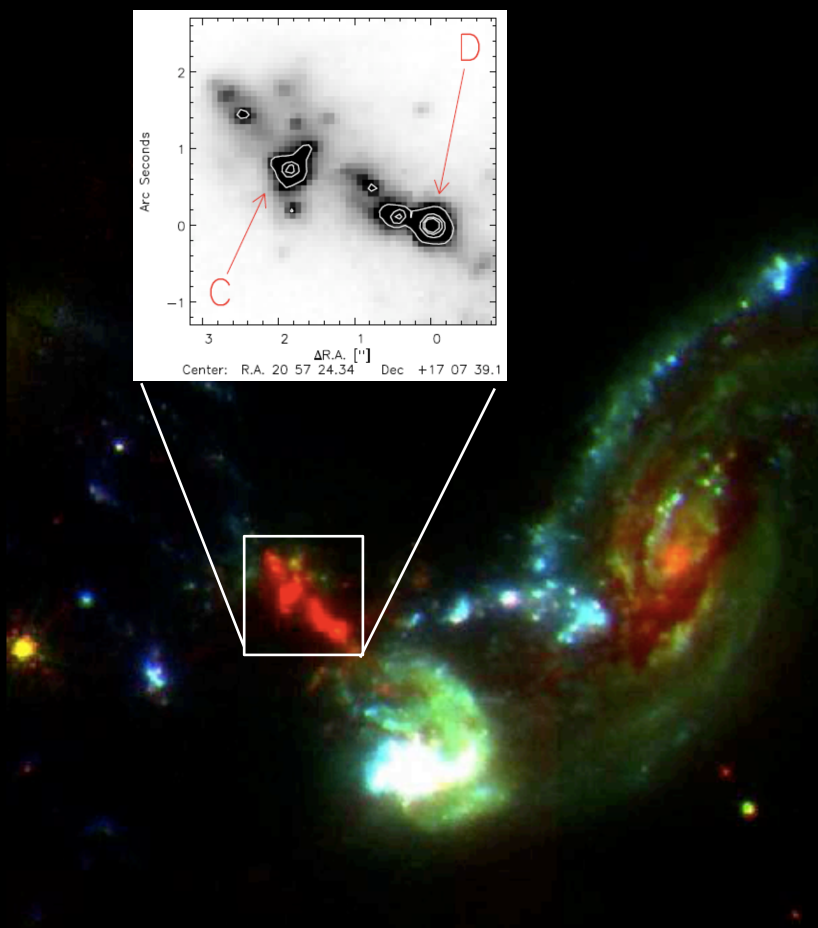
- IRS spectra, hard X-rays indicate a buried AGN in VV 340N contributing 10-15% of LIR

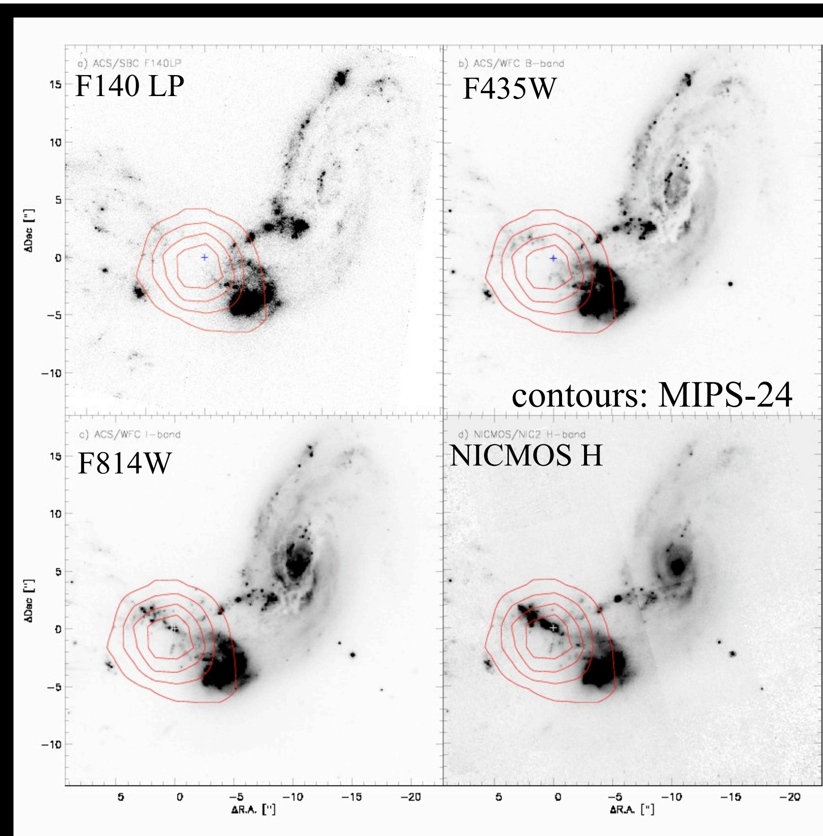
II Zw 096

Inami et al. (2010)

z = 0.036

$L_{IR} = 8 \times 10^{11}\ L_{\odot}$



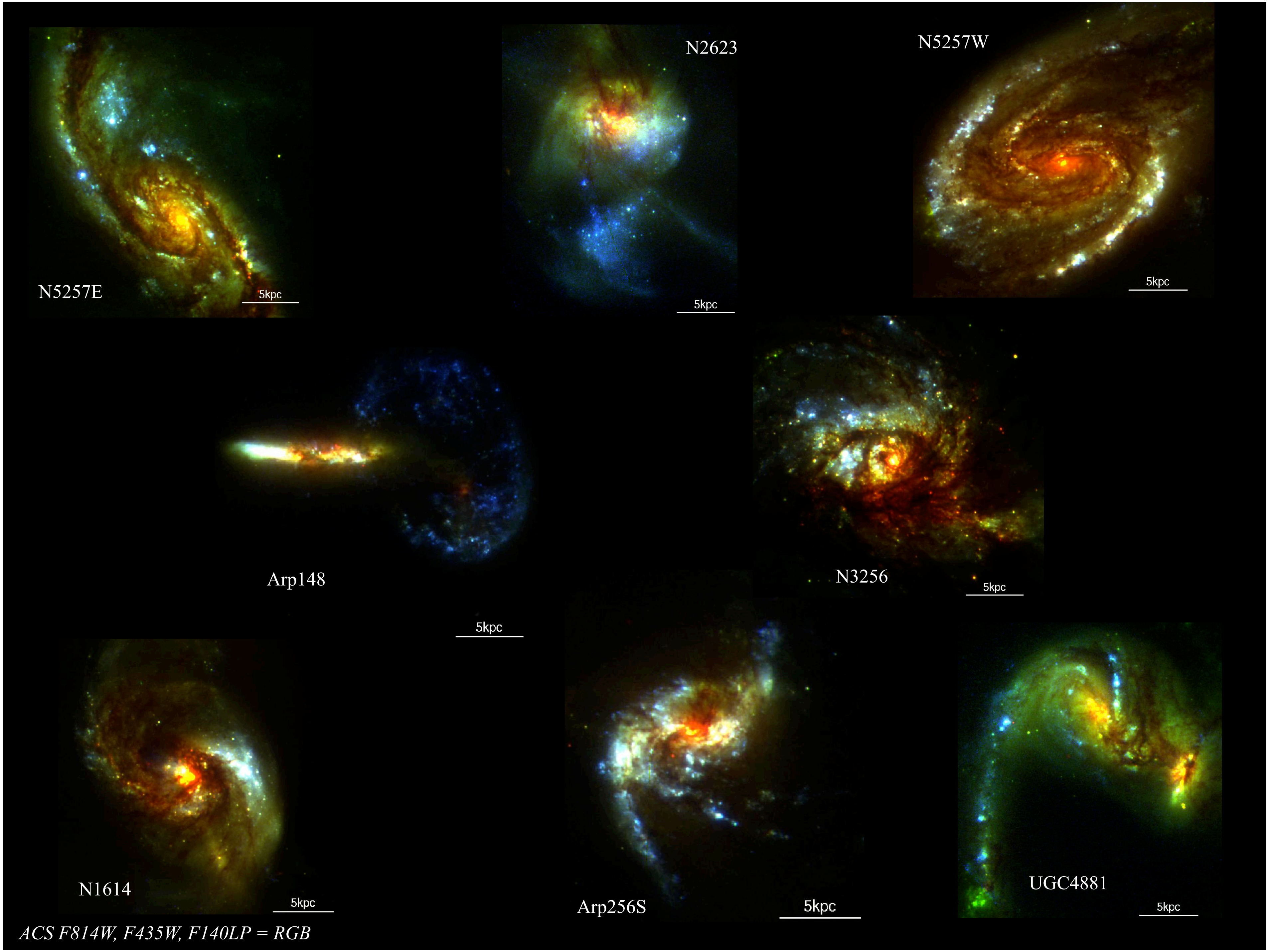


- At least 80% of FIR emission comes from source D, with a SFR = 120 $M_{\odot} yr^{-1}$. More than 10x buried SB in the Antennae *(Mirabel et al. 1998; Brandl et al. 2009)*

- Luminosity density = 4-5x10^{12} $L_{\odot}$ kpc^{-2} if NICMOS size (220 pc radius) is used.

>> A young (5 Myr), deeply buried (A_V > 20 mag) starburst

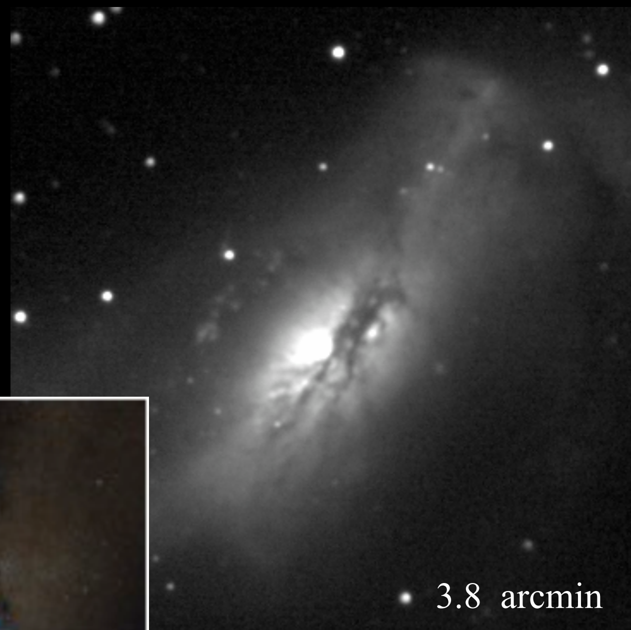
RGB = NICMOS H, ACS F435W, SBC F140LP

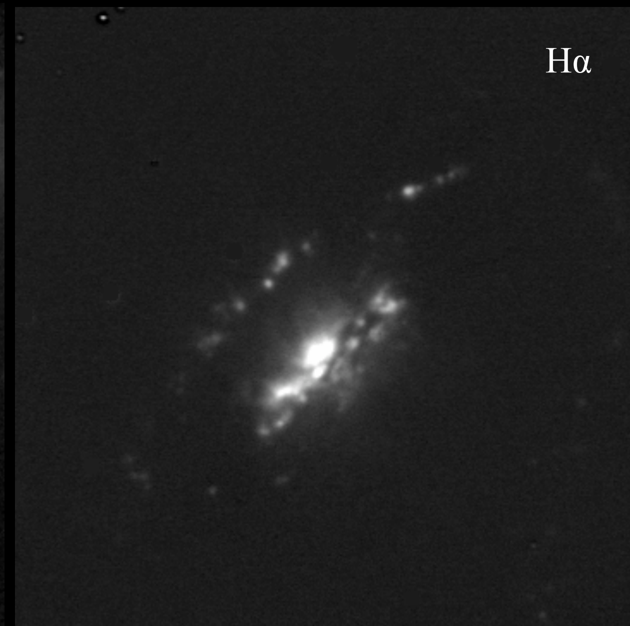

N5257E
5kpc
N2623
5kpc
N5257W
5kpc
Arp148
5kpc
N3256
5kpc
N1614
5kpc
Arp256S
5kpc
UGC4881
5kpc
ACS F814W, F435W, F140LP = RGB

NGC 2146

UGC 3429
IRAS 06106+7822
$z = 0.003$
$D = 17.5$ Mpc
$L_{IR} = 1.3\times10^{11}\ L_{\odot}$

R-band APO 3.5m



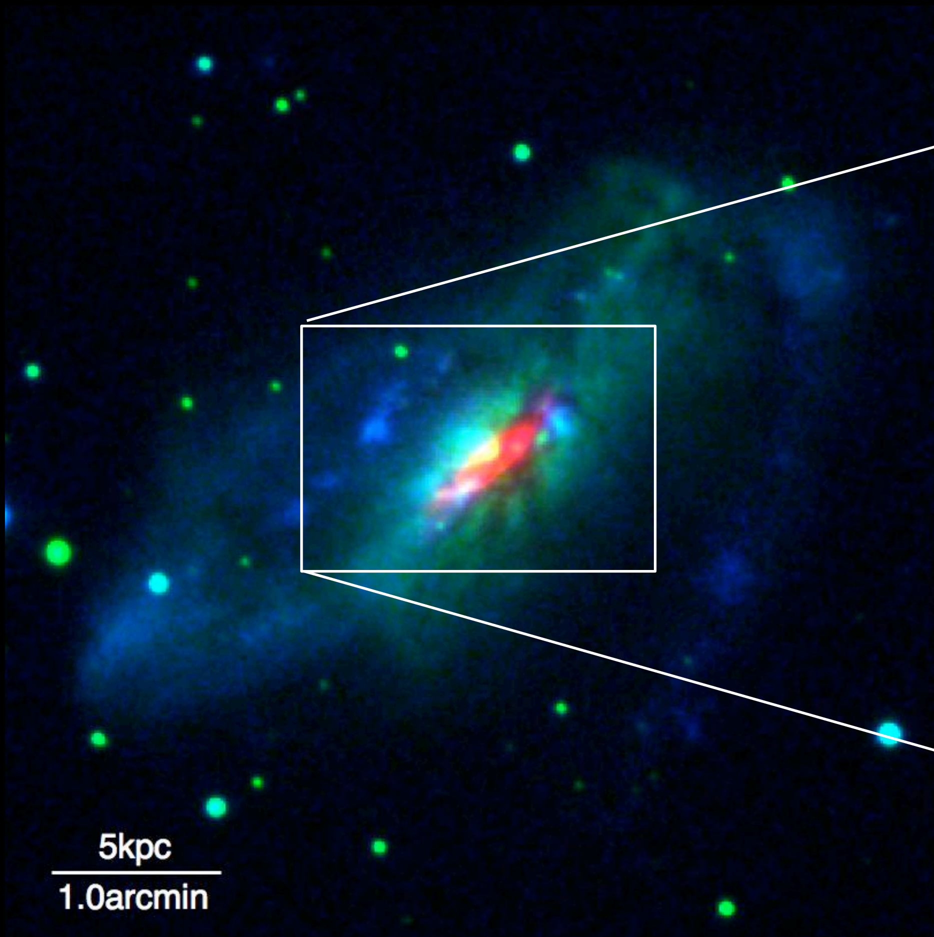


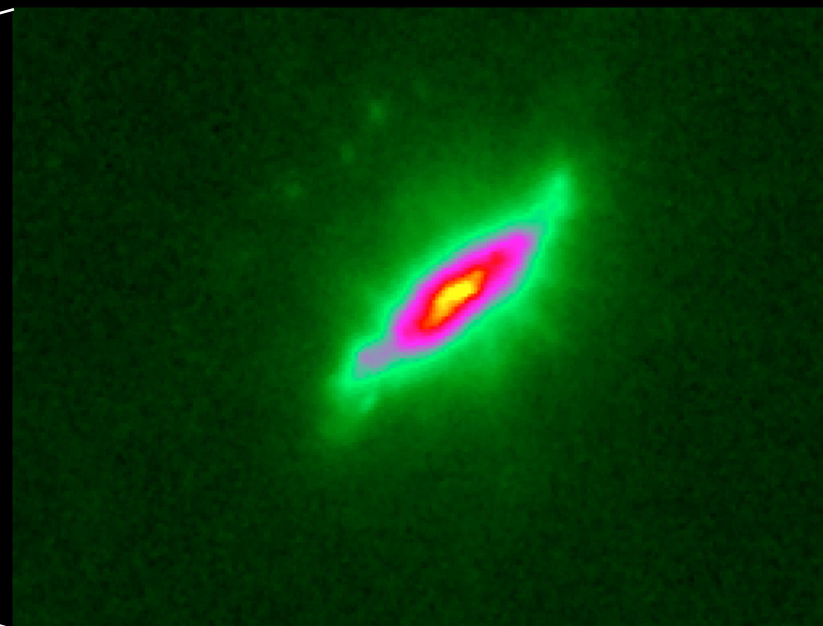
Hameed & Devereux (1999)

- One of the nearest and brightest GOALS targets (S_{60} = 147 Jy)
- DEC > -36 (met basic science restriction)
- SB pec spiral with a prominent dust lane and powerful nuclear starburst (Armus et al. 1989; Hameed & Devereux 1999)

NGC 2146

$z = 0.003$
$L_{IR} = 1.3 \times 10^{11} L_{\odot}$





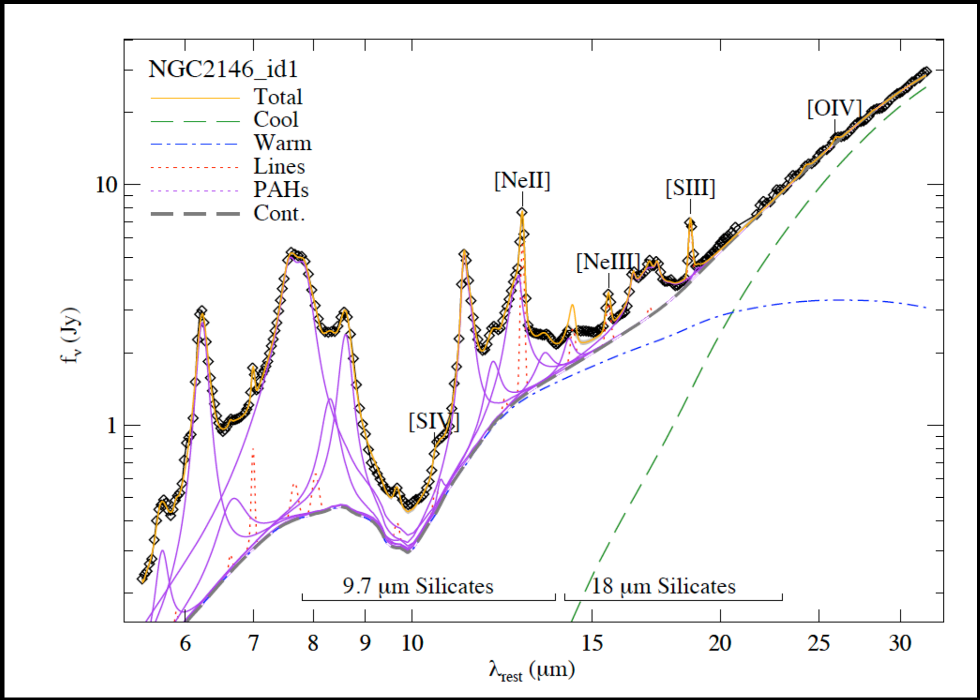
IRAC-8

RGB = IRAC-3.6, ACS F435W, GALEX NUV

NGC 2146

UGC 3429
IRAS 06106+7822
z = 0.003
D = 17.5 Mpc
$L_{IR} = 1.3 \times 10^{11} L_{\odot}$

- 6.2 PAH EQW = 0.67 μm
- S10 = -0.40
- f30/f15 = 10.76



NGC 2146

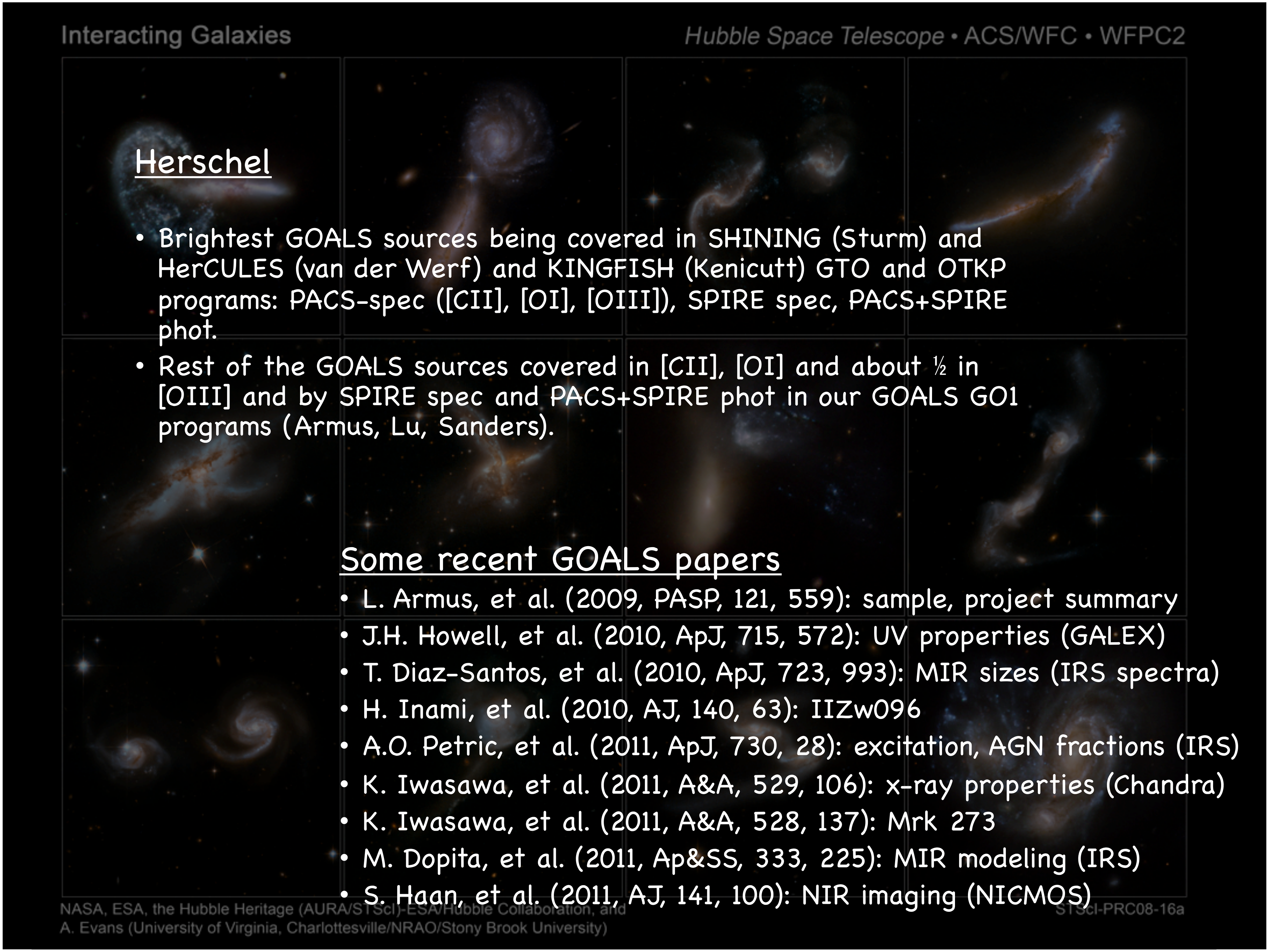
<u>SOFIA Observations</u>

- Image with FORCAST in the 11.3, 19.7, and 37.1 μm filters, broken up into 11.3 + 37.1 (1.5 hrs) and 19.7 + 37.1 (1 hr).

<u>Goals</u>

- Measure the strength and properties of the PAH emission across the SB (FORCAST + IRAC). Map the 11.3/7.7 ratio, which is sensitive to the ionization state of the small grains and the ionization field.

- Construct spatially resolved SEDs. Look for changes in the fraction of hot and warm dust in the SB disk. Fill in missing SED points (8-24-70) on much larger scales than IRS slit, and with high spatial resolution (300 pc). Fit SEDs to derive grain properties, Q_{PAH}, M_D, etc. (Draine et al. 2007).



Herschel

- Brightest GOALS sources being covered in SHINING (Sturm) and HerCULES (van der Werf) and KINGFISH (Kenicutt) GTO and OTKP programs: PACS-spec ([CII], [OI], [OIII]), SPIRE spec, PACS+SPIRE phot.
- Rest of the GOALS sources covered in [CII], [OI] and about ½ in [OIII] and by SPIRE spec and PACS+SPIRE phot in our GOALS GO1 programs (Armus, Lu, Sanders).

Some recent GOALS papers

- L. Armus, et al. (2009, PASP, 121, 559): sample, project summary
- J.H. Howell, et al. (2010, ApJ, 715, 572): UV properties (GALEX)
- T. Diaz-Santos, et al. (2010, ApJ, 723, 993): MIR sizes (IRS spectra)
- H. Inami, et al. (2010, AJ, 140, 63): IIZw096
- A.O. Petric, et al. (2011, ApJ, 730, 28): excitation, AGN fractions (IRS)
- K. Iwasawa, et al. (2011, A&A, 529, 106): x-ray properties (Chandra)
- K. Iwasawa, et al. (2011, A&A, 528, 137): Mrk 273
- M. Dopita, et al. (2011, Ap&SS, 333, 225): MIR modeling (IRS)
- S. Haan, et al. (2011, AJ, 141, 100): NIR imaging (NICMOS)