The Dual AGN System Mrk 266 Revealed in Hard X-rays to Radio Frequencies and Implications for Surveys of Dual and Binary AGN

Joseph M. Mazzarella (Caltech, IPAC)

Collaborators:
Kazushi Iwasawa (Universitat de Barcelona);
Tatjana Vivilkin (Stony Brook);
Lee Armus (Caltech, SSC);
Dong-Chan Kim (NRAO);
Greg Bothun (U. Oregon);
Aaron S. Evans (UVa & NRAO);
Henrik Spoon (Cornell);
Sabastian Haan (CSIRO);
Justin H. Howell (Caltech, IPAC);
Steven Lord (Caltech, NHSC);
Jason Marshall (Caltech, SSC);
Cathy Ishida (Subaru);
Kevin Xu (Caltech, NHSC);
Andreea Petric (Caltech, Astronomy Dept.);
David B. Sanders (U. Hawaii, IfA);
Jason A. Surace (Caltech, SSC);
Phil Appleton (Caltech, NHSC);
Ben Chan (Caltech, IPAC);
David T. Frayer (NRAO);
Hanai Inami (NOAO);
Edward Khachikian (Byurakan Observatory);
Barry F. Madore (Carnegie Observatories & Caltech/IPAC);
George C. Privon (UVa);
Eckhard Sturm (MPE);
Vivian U (UC, Riverside);
Sylvain Veilleux (U. Maryland).

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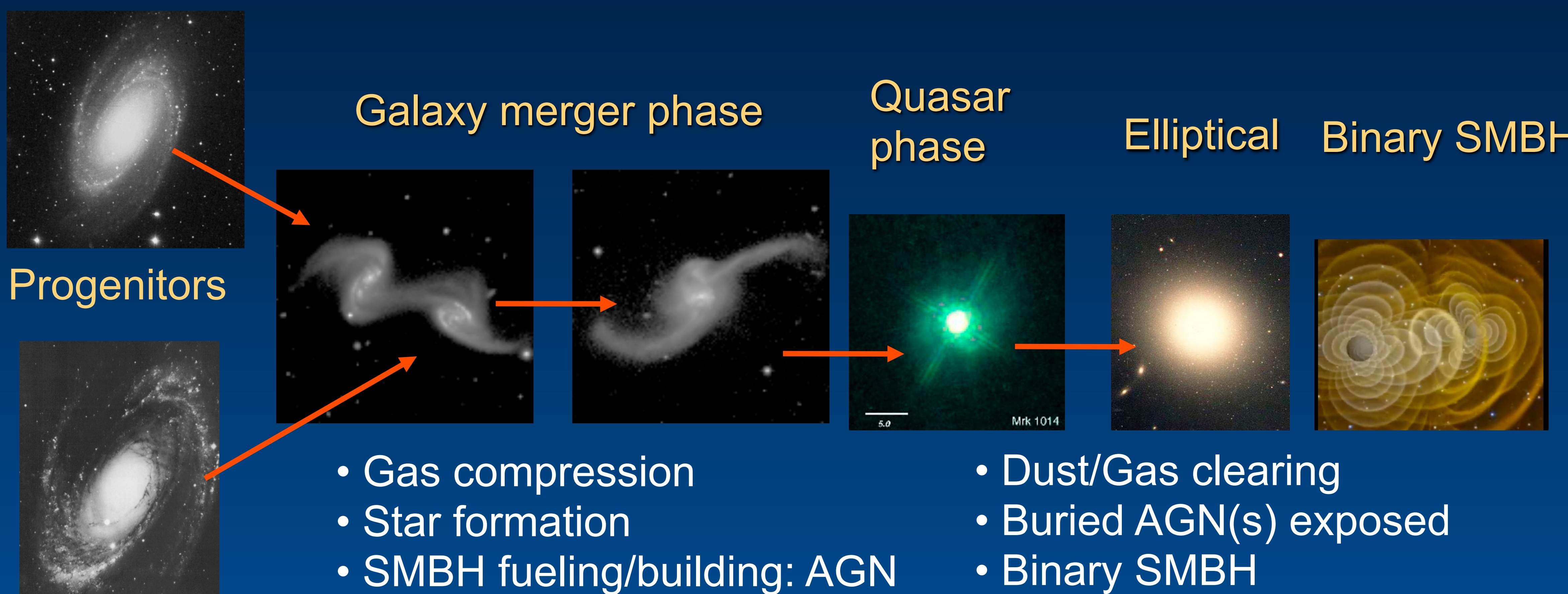
Outline

- ✦ Motivation: Questions in (U)LIRG ➔ Dual/Binary AGN Evolution
- ✦ In-depth study of Mrk 266 across the EM spectrum
- ✦ Wider Implications for (U)LIRGs and Dual/Binary AGN
- ✦ Recent NED services facilitating research

The Paradigm

- ✦ Luminous Infrared Galaxies = LIRGs: $10^{11}\,L_\odot \leq L_{ir} < 10^{12}\,L_\odot$
- ✦ Ultraluminous Infrared Galaxies = ULIRGs: $L_{ir} \geq 10^{12}\,L_\odot$
  - ❖ Along with QSOs, they are among the most luminous galaxies in the Universe
  - ❖ Intriguing objects with evolutionary connections to QSOs, powerful radio galaxies, and elliptical galaxy formation via tidal dissipation and violent relaxation in merging galaxies
  - ❖ Bolometric luminosities dominated by combo of dust-obscured AGNs and high star formation rates (SFRs)

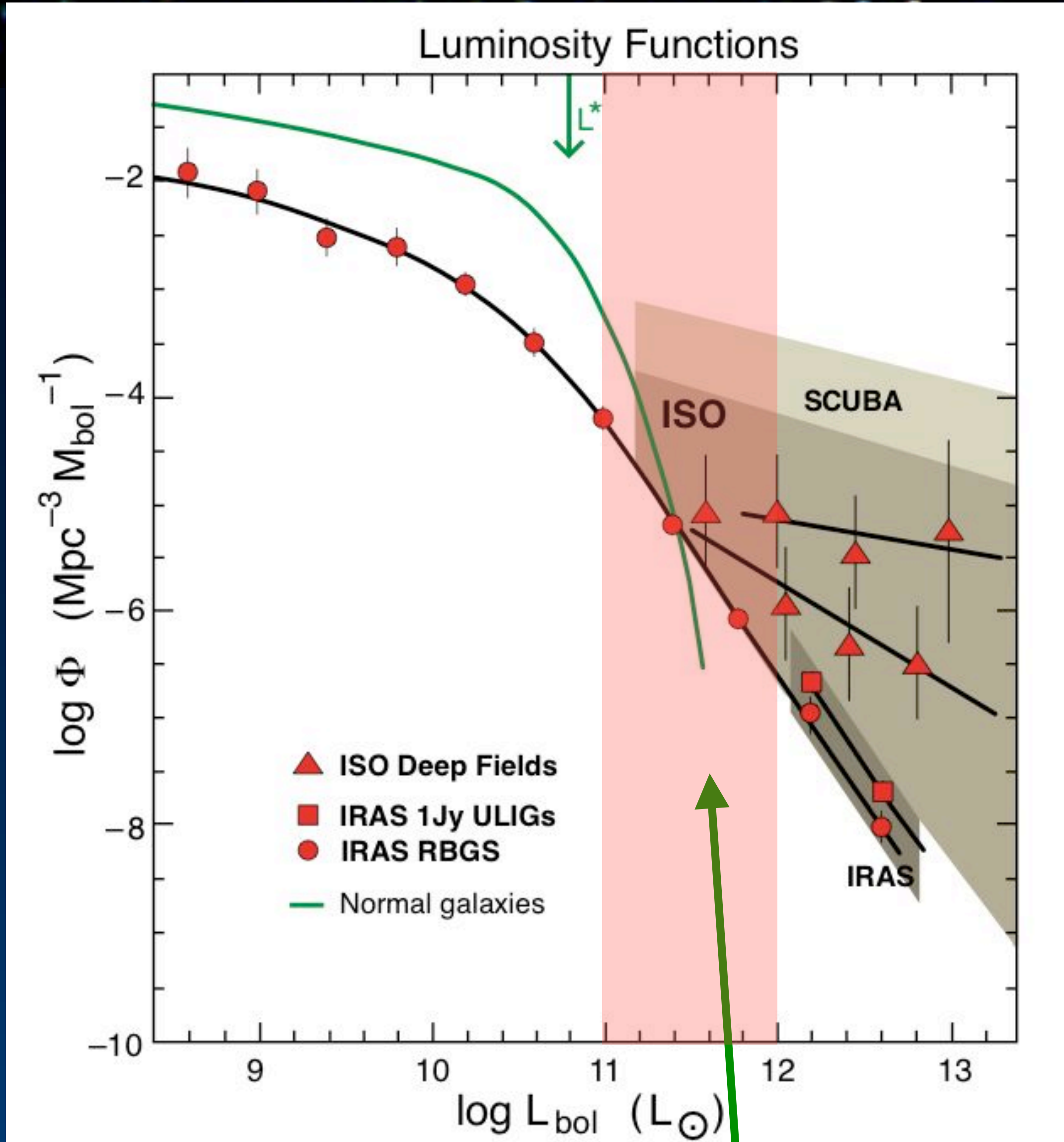


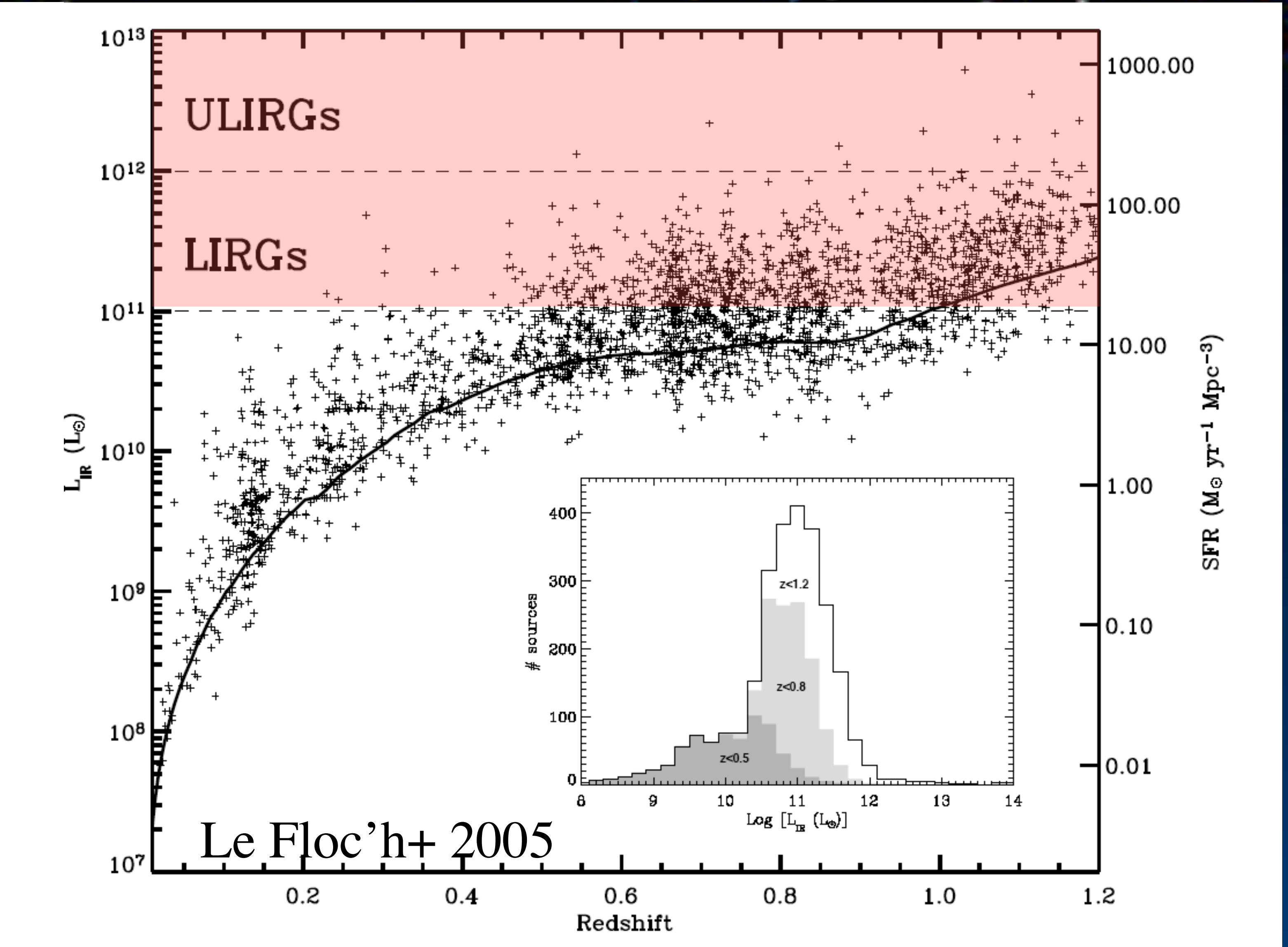
- Gas compression
- Star formation
- SMBH fueling/building: AGN

- Dust/Gas clearing
- Buried AGN(s) exposed
- Binary SMBH

Better understanding of the origin and demographics of binary AGN requires a more thorough understanding of their progenitors: dual AGN and their merging host galaxies

The Significance of (U)LIRGs



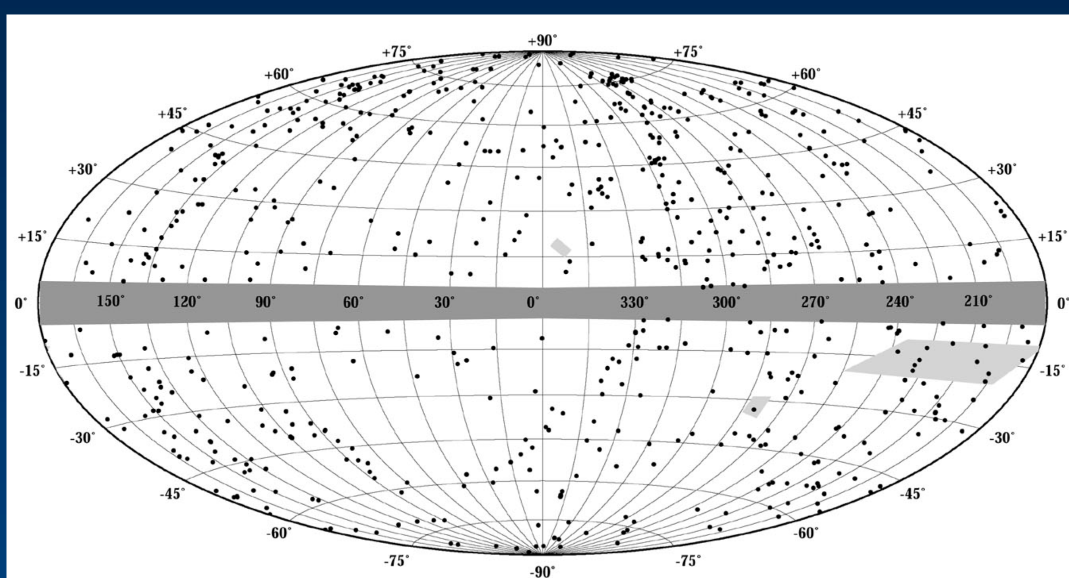


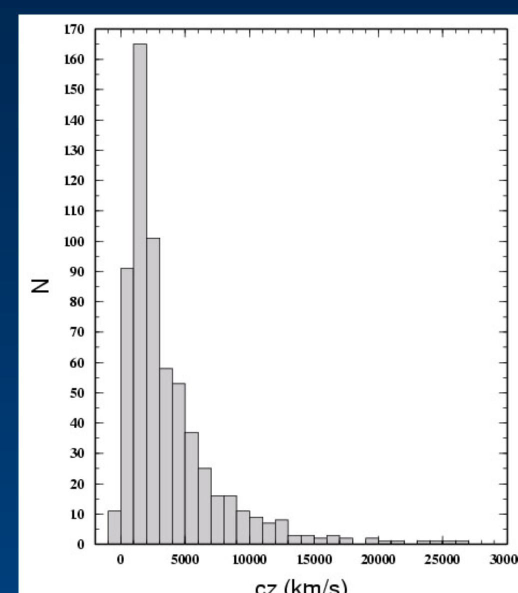
- Important to sample Φ_{ir} where it crosses the rapidly declining high luminosity tail of $\Phi_{optical}$ (Schechter function)
- IR-enhanced galaxy mergers dominate over largest single disk galaxies
- Cosmic star formation density is dominated by an increasing fraction of LIRGS and ULIRGs from z=0 to z~1.2
- In the total SF density at z < 1.2, LIRGs are more important than ULIRGs

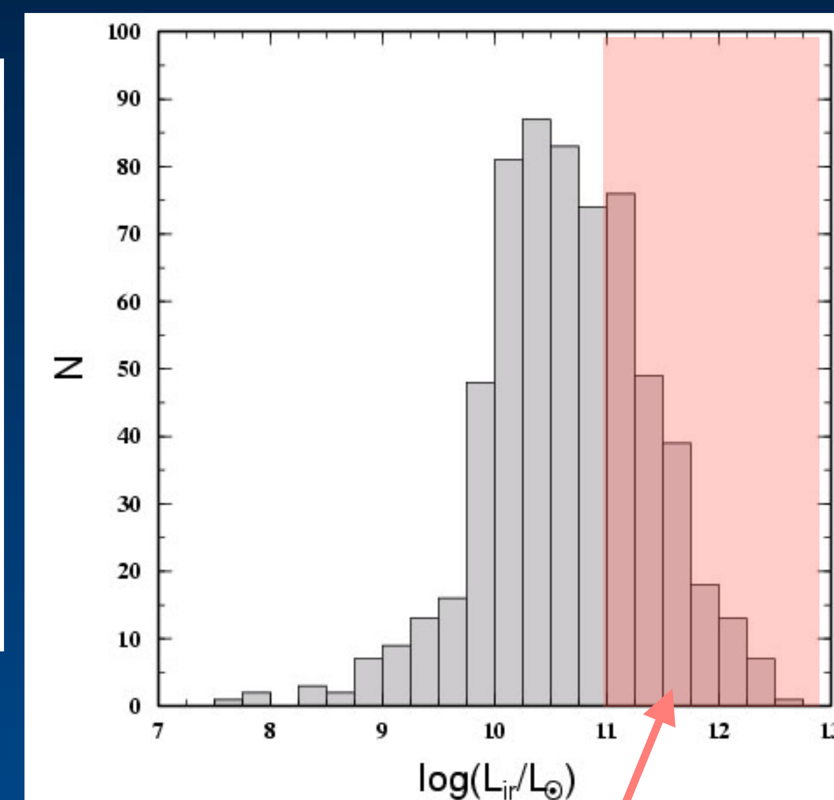
Since LIRGs and ULIRGs were much more common at earlier epochs, they are fundamental in understanding star formation, SMBH growth, and galaxy evolution

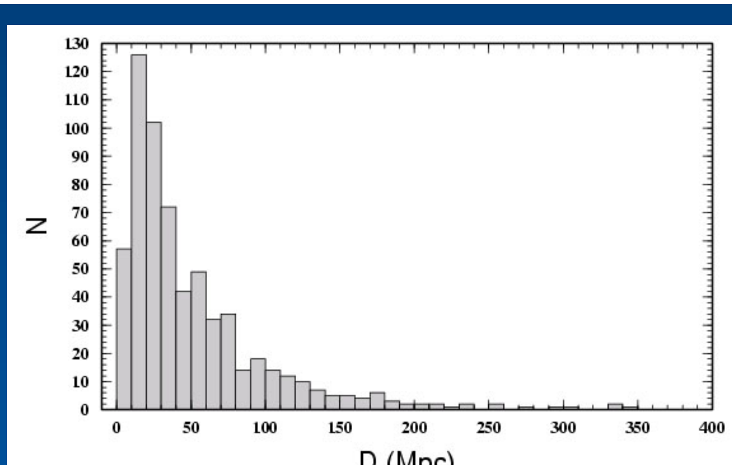
Great Observatories All-Sky LIRG Survey (GOALS)

- Parent population: IRAS Revised Bright Galaxy Sample (RBGS), a complete flux-limited survey of all *638 extragalactic objects* with total f(60μm) > 5.24 Jy, covering the entire sky surveyed by IRAS at Galactic latitudes |b| > 5° (Sanders, Mazzarella, Kim, Surace & Soifer 2003, AJ, 126, 1607).
  - ❖ Complete flux-limited sample of the brightest extragalactic FIR sources in the sky
  - ❖ Far-IR counterpart to the RSA (optically selected) or 3C (radio selected)
  - ❖ Offers ideal sources for detailed, close-up study of IR emission processes, and for multi-wavelength investigations with high spatial resolution









GOALS Sample:
203 LIRGs and ULIRGs

GOALS - The Data

Combining imaging and spectroscopic data from NASA & ESA space-borne observatories with ground-based observations for a comprehensive survey of the most luminous infrared-selected galaxies in the local Universe

Mid- and Far-Infrared: all ~200 LIRGs and ULIRGs in the IRAS RBGS
Cycle 1 GO imaging; 92 hr; 3.6, 4.5, 5.8, 8.0 (IRAC), 24, 70 & 160 μm (MIPS)
2 - 40” resolution; FOV ~ 5’x5’ (PI Joe Mazzarella; Caltech, IPAC)
Cycle 3 Legacy Program: 150 hr; IRS spectroscopy
(PI Lee Armus; Caltech, SSC)

Optical & Near-Infrared: 88 objects with $L_{ir} >= 10^{11.4} L_\odot$
Cycle 14 ACS imaging (PI Aaron Evans, Stony Brook); 0.4 & 0.9 μm; FOV ~ 3.4’x3.4’
Cycle 16 WFPC2/HRC NUV imaging, 81 orbit; 35 cluster-rich systems (PI Aaron Evans)
Cycle 16 NICMOS imaging: 76 orbits + archival; 1.6 μm (PI Jason Surace; Caltech, SSC)
@0.04 - 0.09” resolution

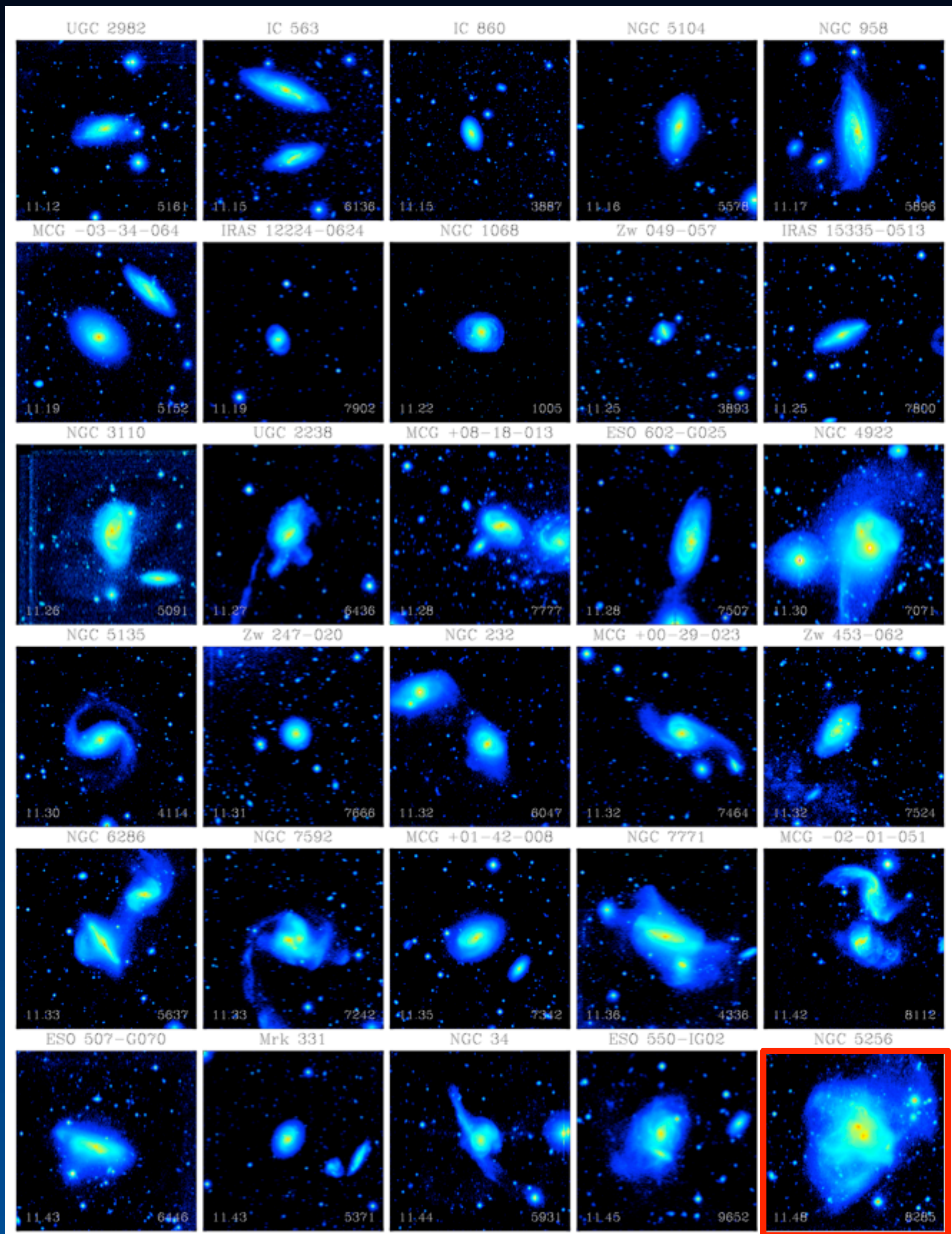
Ultraviolet: ~135 objects
FUV (0.15 μm) & NUV (0.23 μm); 5-7” resolution
Cycle 1 (PI J. Mazzarella)
Cycle 5 (PI J. Howell)
Nearby Galaxy Survey and All Sky Survey

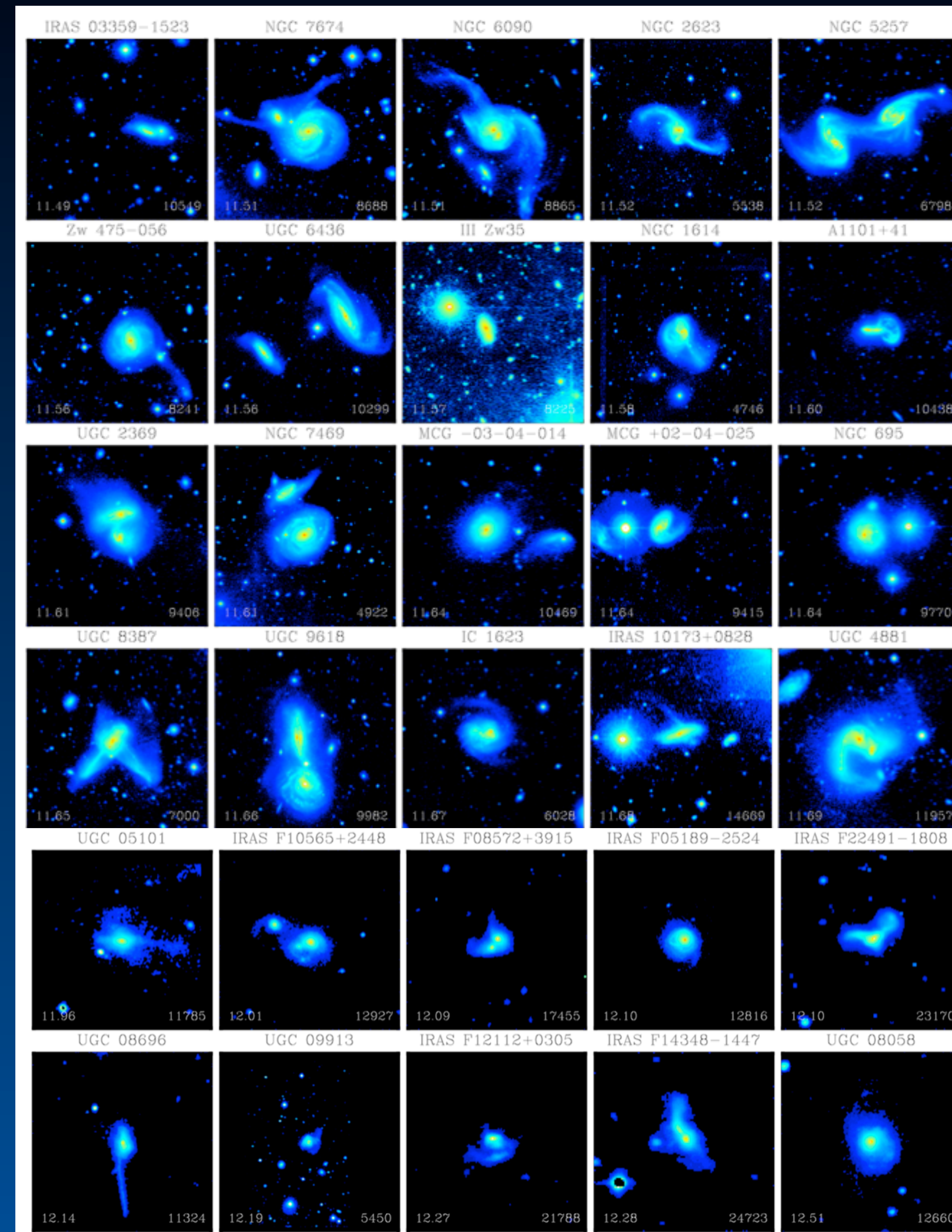
X-rays: Cycle 8; 15 ksec observations of 26 objects not previously observed with $L_{ir} >= 10^{11.67} L_\odot$
plus archival data (PI Dave Sanders; IfA, U. Hawaii)

Plus: ❖ XMM-Newton ❖ Herschel ❖ EVLA, GBT, WSRT ❖ Etc.

GOALS Sample: Ground-based Images

- Ishida (2007) BVI images for ~40% of GOALS objects (UH 88")
- 100 kpc x 100 kpc





- In order of ↑ L_{ir}
- Single galaxies ⇨ wide pairs ⇨ close pairs ⇨ double nuclei ⇨ merger remnants

Selected GOALS Publications

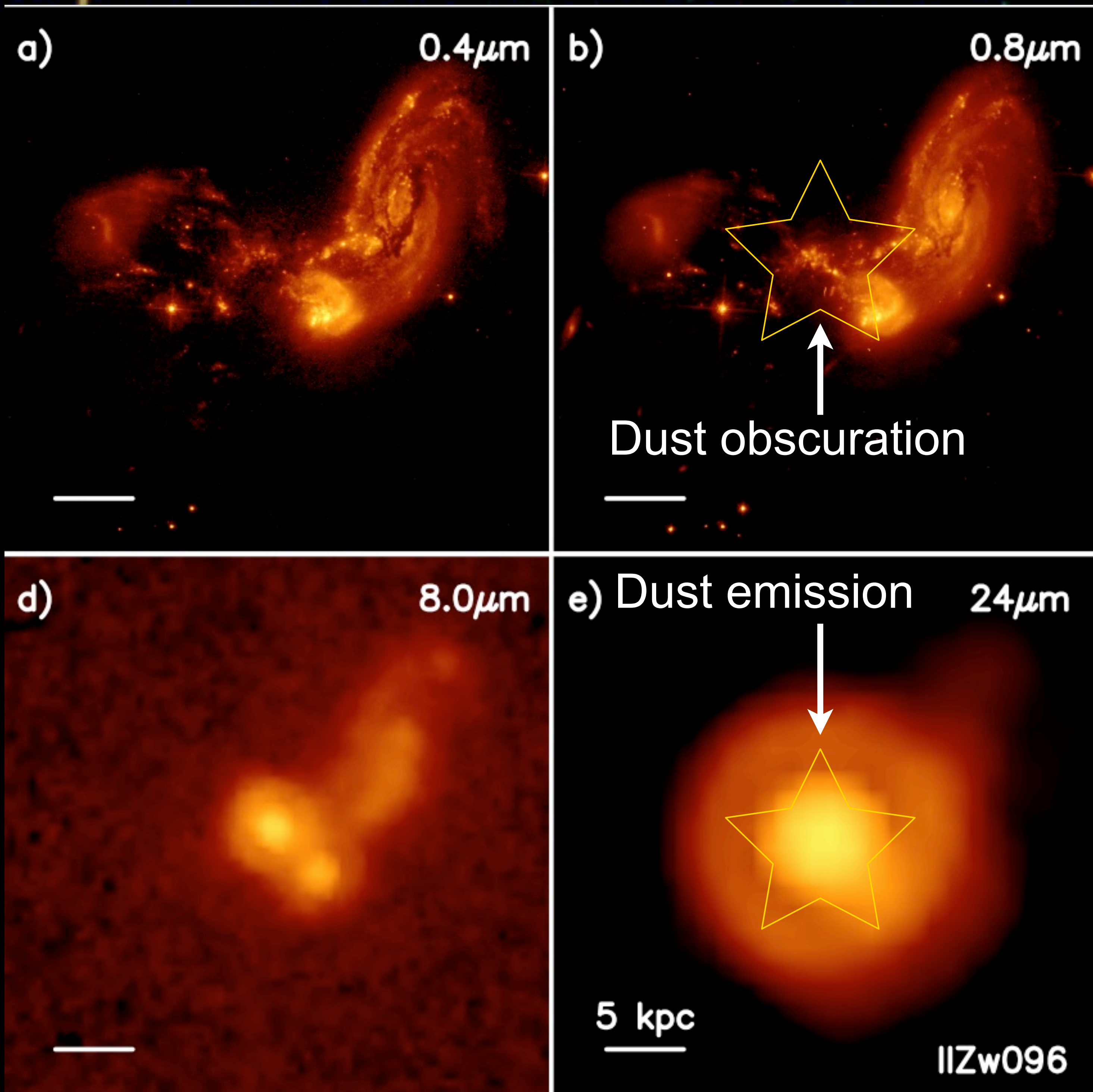
Survey studies

- "GOALS: The Great Observatories All-Sky Survey," Armus+ 2009, PASP
- "High-Ionization Fe K Emission from LIRGs," Iwasawa+ 2009, ApJL
- "The Great Observatories All-Sky LIRG Survey: Comparison of Ultraviolet and Far-Infrared Properties," Howell+ 2010, ApJ
- "The Spatial Extent of (U)LIRGs in the Mid-Infrared I: The Continuum Emission," Diaz-Santos+ 2010, ApJ
- "Mid-Infrared Spectral Diagnostics of LIRGs," A. Petric+ 2010, ApJ
- "Complex Radio Spectral Energy Distributions in (U)LIRGs," Leroy+ 2011, ApJ
- "The Nuclear Structure in Nearby LIRGs: HST NICMOS Imaging of the GOALS Sample," Haan+ 2011, AJ
- "Spectral Energy Distributions of Local (U)LIRGs," Vivian U+ 2013 (in press), ApJS

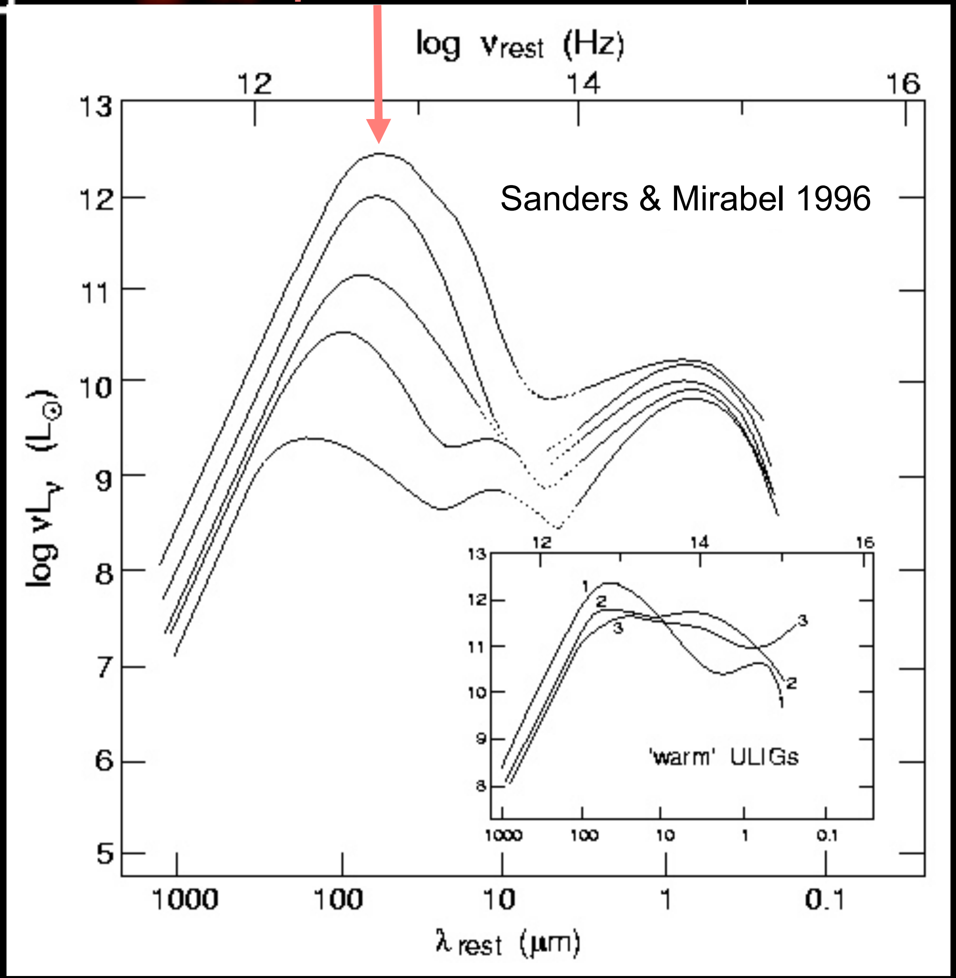
Individual systems

- "Tracing PAHs and Warm Dust Emission in the Seyfert Galaxy NGC 1068," Howell+ 2007, AJ
- "Off-Nuclear Star Formation and Obscured Activity in the LIRG NGC 2623," Evans+ 2008, ApJL
- "The Buried Starburst in the Interacting Galaxy II Zw 96 as Revealed by the Spitzer Space Telescope," Inami+ 2010, AJ
- "Multi-wavelength GOALS Observations of Star Formation and AGN Activity in the LIRG IC 883," F. Modica+ 2012, AJ
- "The location of an active nucleus and a shadow of a tidal tail in the ULIRG Mrk 273," Iwasawa+ 2011, A&A
- "Everything you ever wanted to know about Mrk 266 but were afraid to ask," Mazzarella+ 2012, AJ

The Appearance of (U)LIRGs Is Strongly Dependent on Wavelength

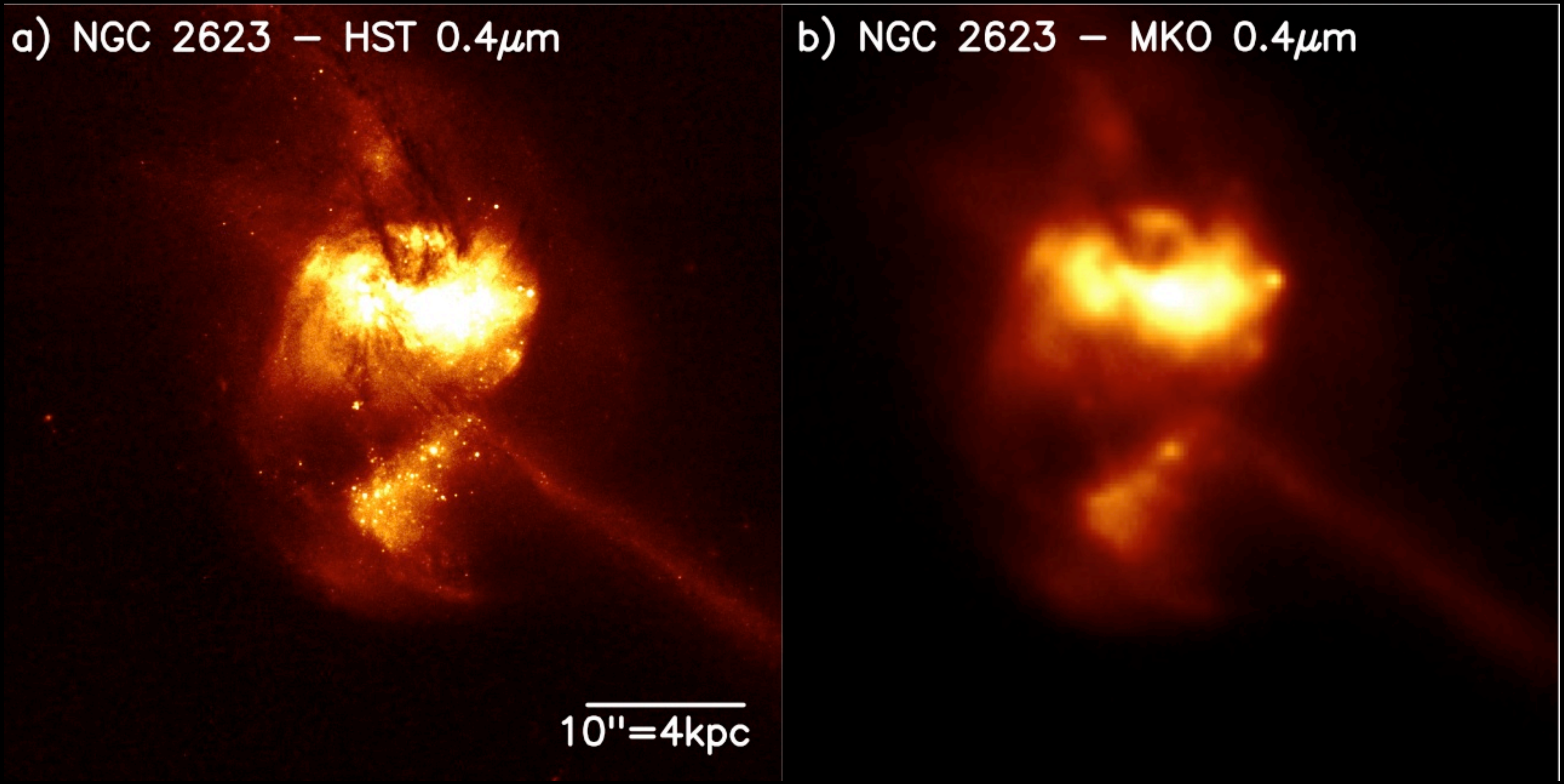


Thermal emission from dust heated by massive stars & putative AGN



- ✦ Log($L_{ir}/L_\odot$) = 11.9
- ✦ Off-nuclear starburst ~100X more luminous than the Antennae; SFR ~ 120 $M_\odot$/yr (Inami+ 2010, AJ, 140, 63)

HST ACS vs. Ground-based Obs @ 0.4μm



Over 100 star clusters (Evans+ 2008)

Ground-based image (Ishida 2004)

Dual AGNs in Major Mergers: Questions (1)

- What are the relative timescales and energetics of active star formation and AGN phenomena during different phases of the merger sequence?

- While at Kpc separations, how common is it for both SMBHs to have accretion rates high enough to produce luminous dual AGNs, rather than one or both nuclei being powered predominantly by star formation?

- How do AGN characteristics (AGN+AGN or AGN+SB) depend on properties of the host galaxies and dynamics of the encounter?

Dual AGNs in Major Mergers: Questions (2)

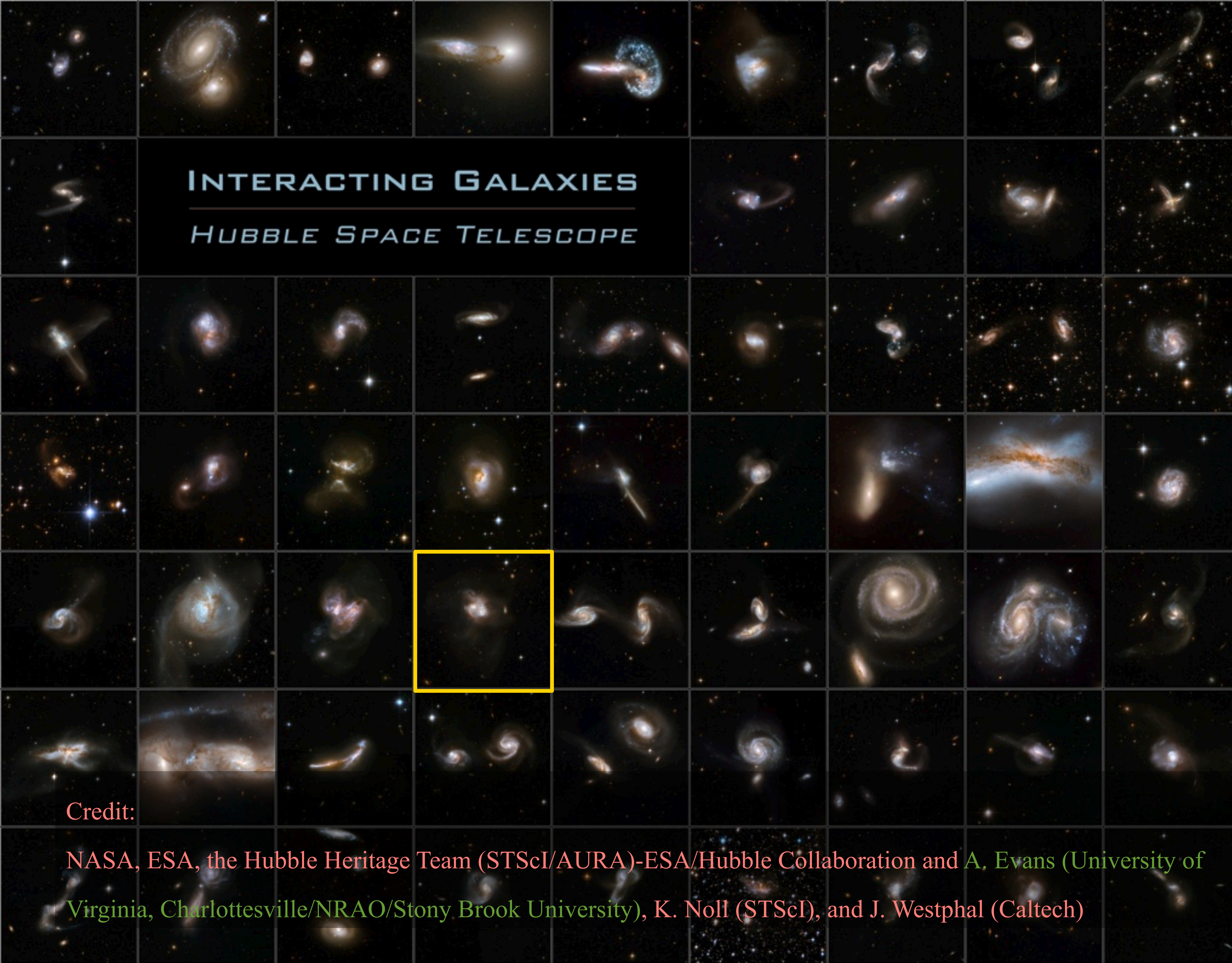
- ✦ Can fuel supplies and accretion rates sustain two luminous AGNs well into a true binary stage (e.g., binary QSOs), when the SMBHs are closely bound ($r < 100$ pc) in Keplerian orbits inside a dynamically relaxed (elliptical) merger remnant?

- ✦ What is the relative importance of AGNs and star formation in the energetics of the “superwind” phenomenon that appears to be ubiquitous in (U)LIRGs?

- ✦ Why have few dual AGNs been confirmed among local (U)LIRGs (e.g., NGC 6240 [Komossa+ 2003], Arp 299 [Ballo+ 2004], Mrk 463 [Bianchi+ 2008], Mrk 739 [Koss+ 2011], Mrk 266 [Mazz+ 2012])?
  - ❖ Dust obscuration, even in the mid-IR (Laurent+ 2000; Spoon+ 2004)?
  - ❖ Are the many LINERs (~30-40%) confusing the issue (photoionization from AGN, very hot stars, or shock heating)?

Outline

- Motivation: Questions in (U)LIRG → Dual/Binary AGN Evolution
- In-depth study of Mrk 266 across the EM spectrum
  - Why?
  - System overview
  - The galaxies revealed
  - Kpc-scale outflow/superwind(s)
  - NLR outflow in NE
  - Shock region b/w nuclei
  - SEDs & power sources
  - Star clusters
  - Mol gas
- Wider Implications for (U)LIRGs and Dual/Binary AGN
- Recent NED services facilitating research



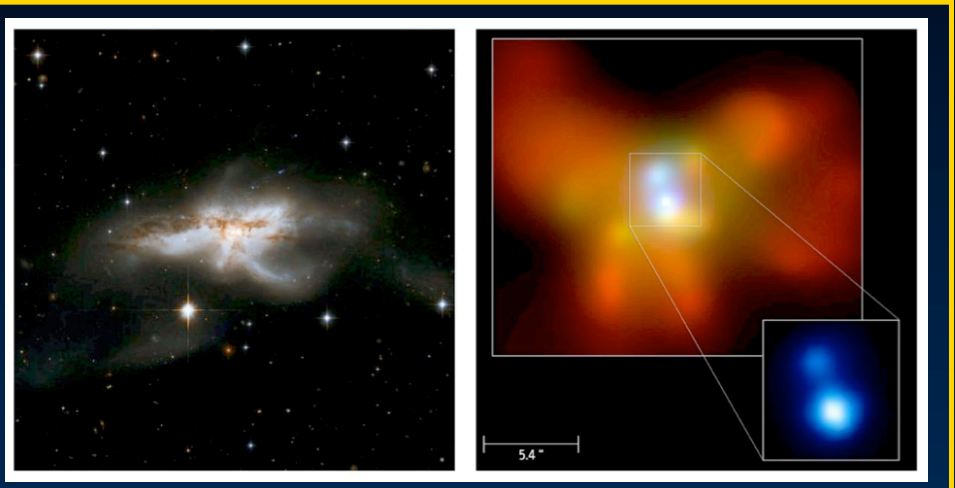
Credit:

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

Why an in-depth study of Mrk 266?

Among merging (U)LIRGs...

- ✦ **Confirmed dual AGNs** remain rare. Are many more lurking behind dust and/or in LINERs?
- ✦ **Molecular gas between merging nuclei** is relatively rare. Is it a time-scale issue?
- ✦ **Luminous radio-continuum emission between galaxies** is very rare. What is responsible?
- ✦ Galactic-scale **superwinds** are ubiquitous and thought to play an important role in sweeping out the dust to reveal hidden AGNs, and in quenching SF. But yet to date dust emission has been detected directly only in M82 (a sub-LIRG). **Can we detect dust in (U)LIRG outflows with Spitzer?**
- ✦ **Young star clusters** are also ubiquitous. Do their properties correlate with host galaxies or merger configuration?

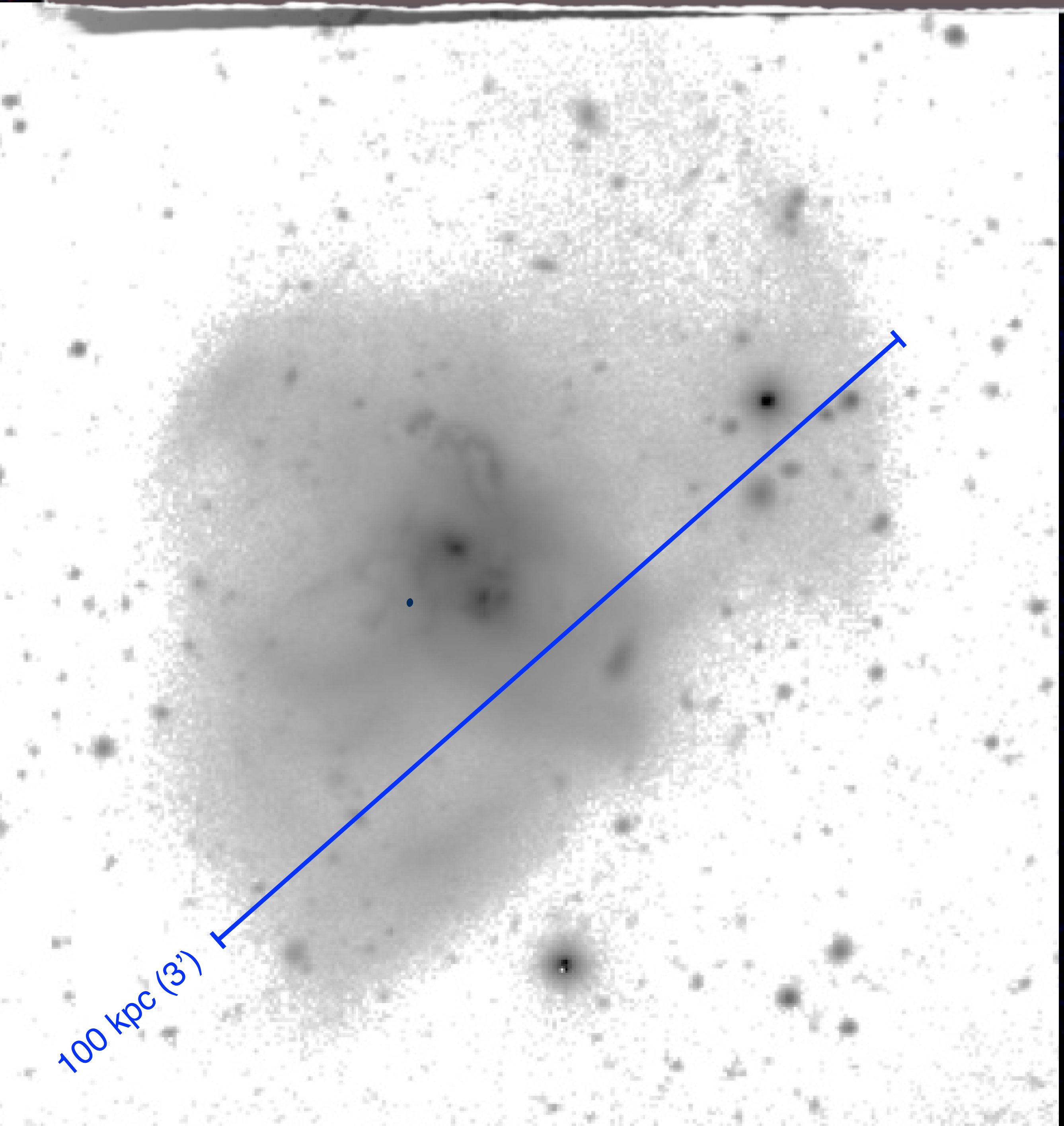


NGC 6240: dual AGNs with
Sep = 700 pc and
BH masses [2.4 + 0.7] x 10^9 $M_\odot$
(Kamossa+ 2003)

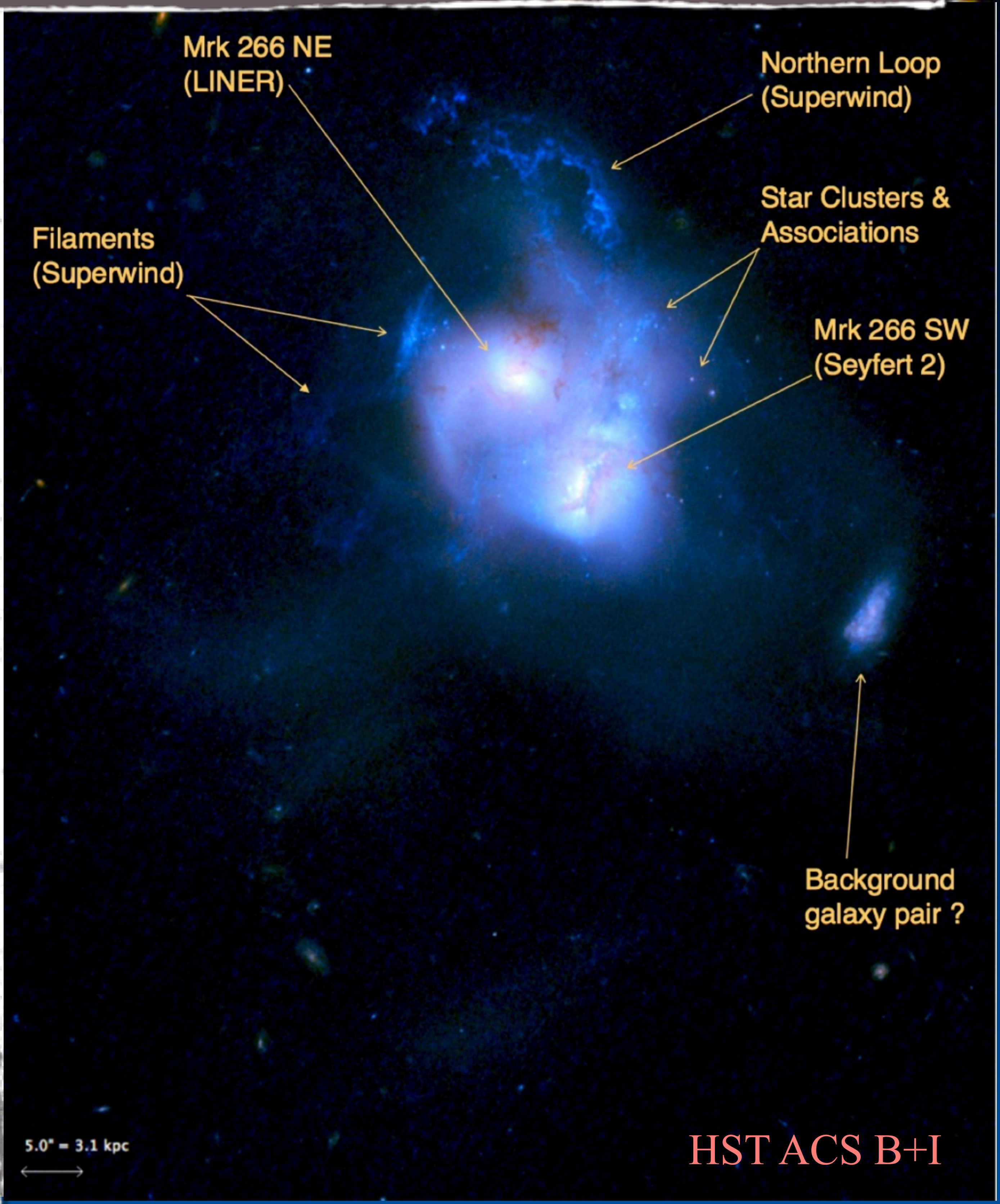
Mrk 266 is an important laboratory for matching observations with theory because it is one of very few local (U)LIRGs known to exhibit all five of these phenomena simultaneously.

System Overview (visual bands)

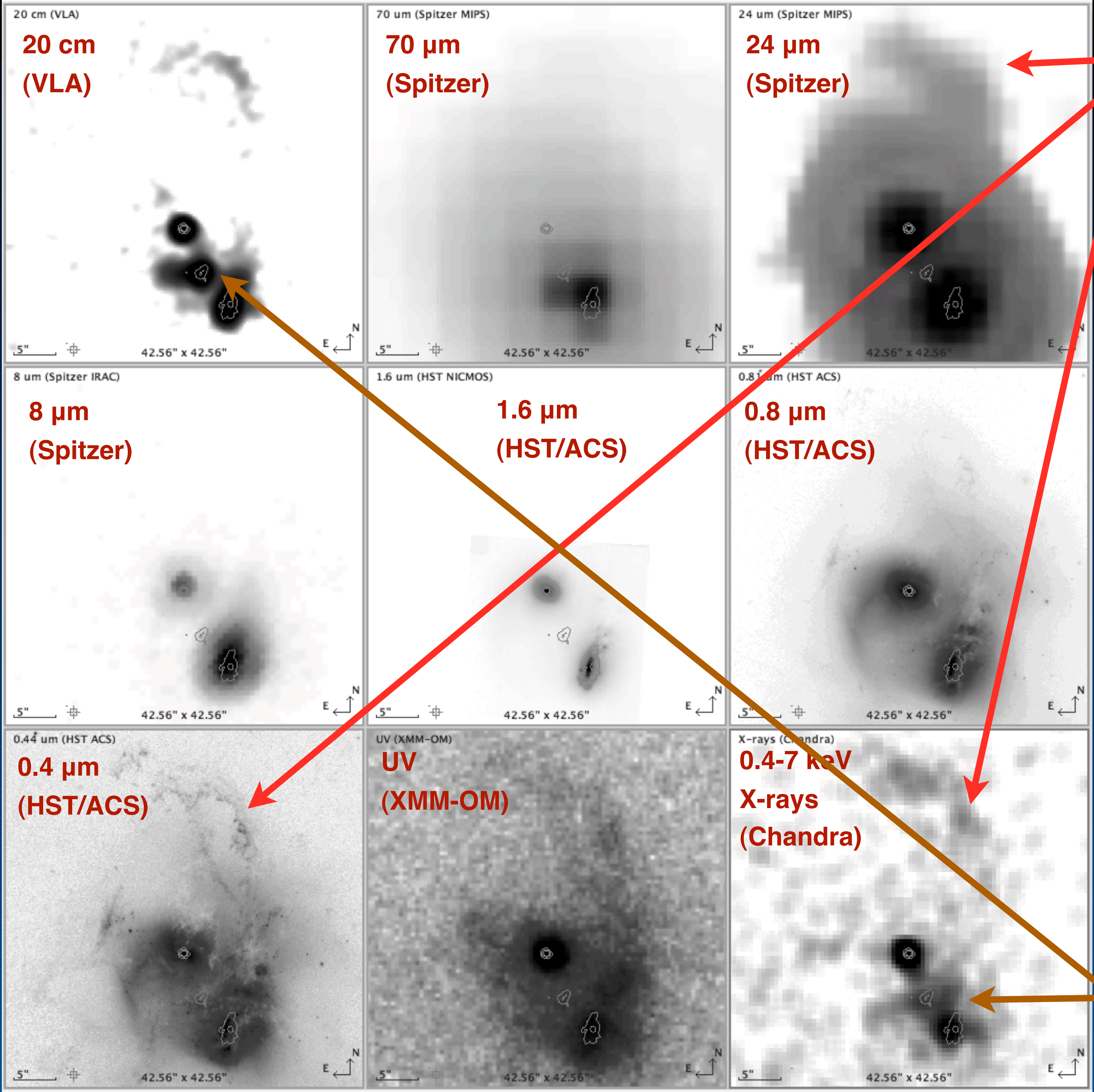
"Double-nucleus galaxy" @ ~1" resolution is resolved by HST into two merging galaxies



Deep B+I+V (2.5 hr, UH 88" telescope) image reveals a tidal debris halo as large as the span of the Antennae tidal tails



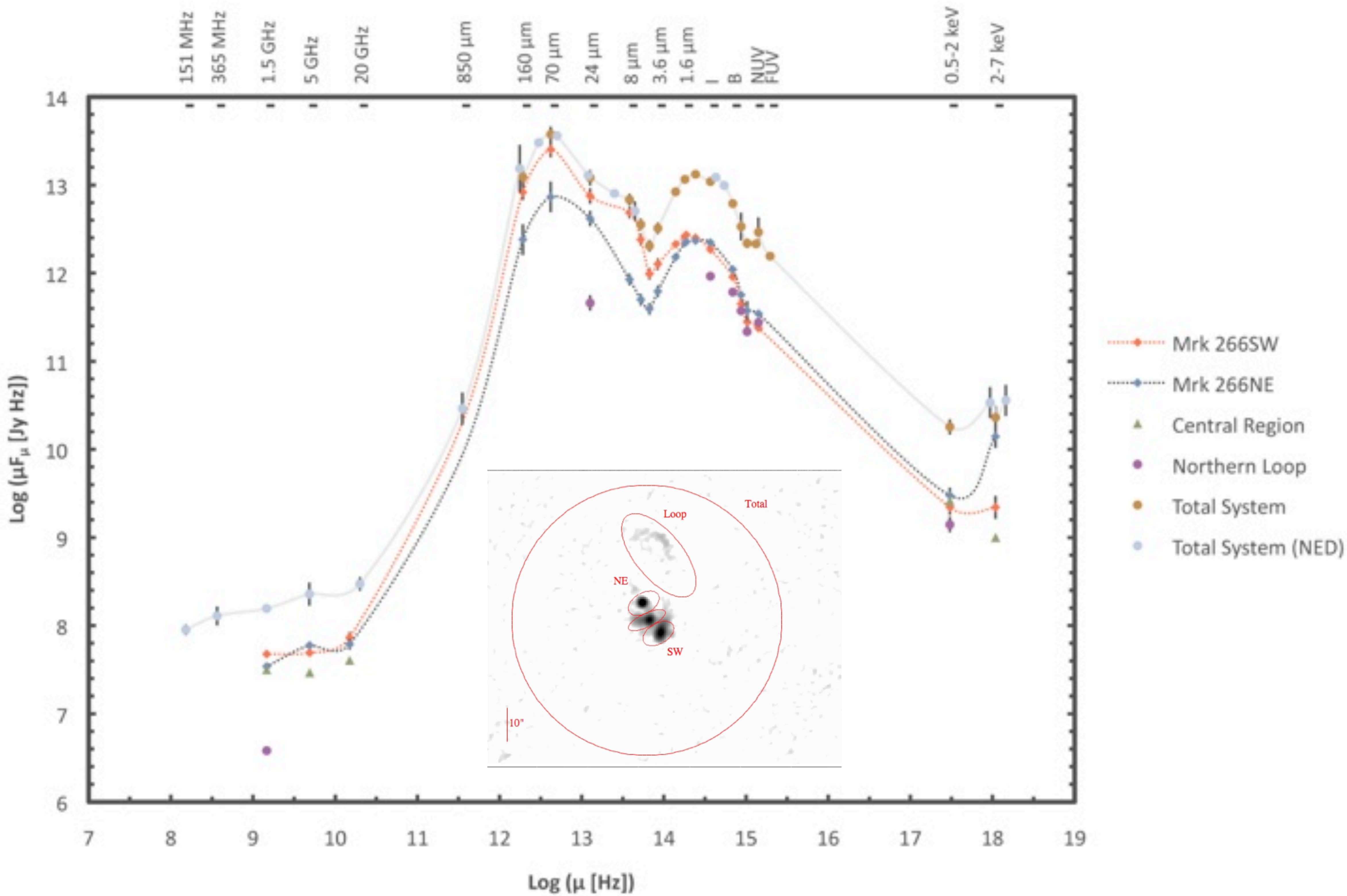
Mrk 266 in Radio Continuum to X-Rays



Note this correspondance

Bright radio continuum source between the nuclei has no counterpart in far-IR (not dust emission), mid-IR and visual (not starlight), or hard X-rays (no a third AGN). nucleus); only other region detected is soft X-rays.

Radio Continuum to X-rays



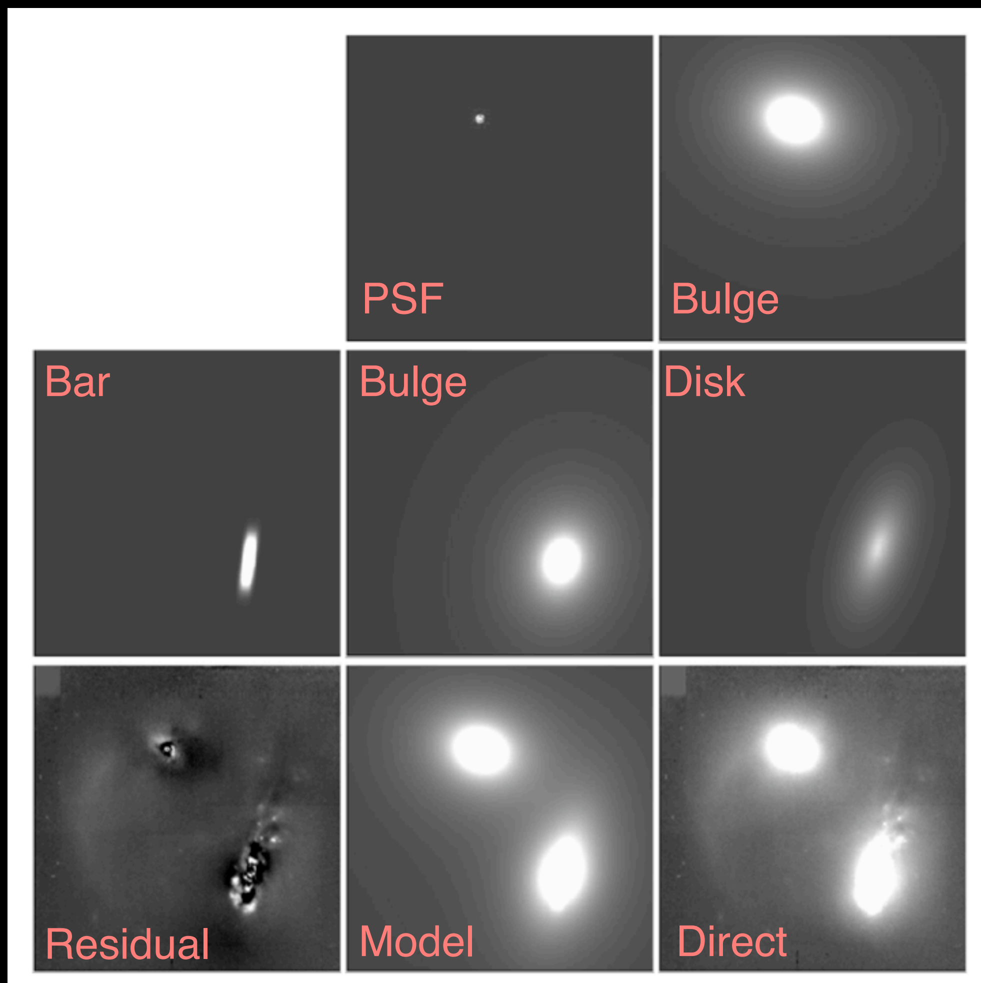
Using $\log(L_{ir}) = \log(L_{24}) + 0.87(\pm 0.03) + 0.56(\pm 0.09) \times \log(L_8/L_{24})$ (Xu+ 2010)

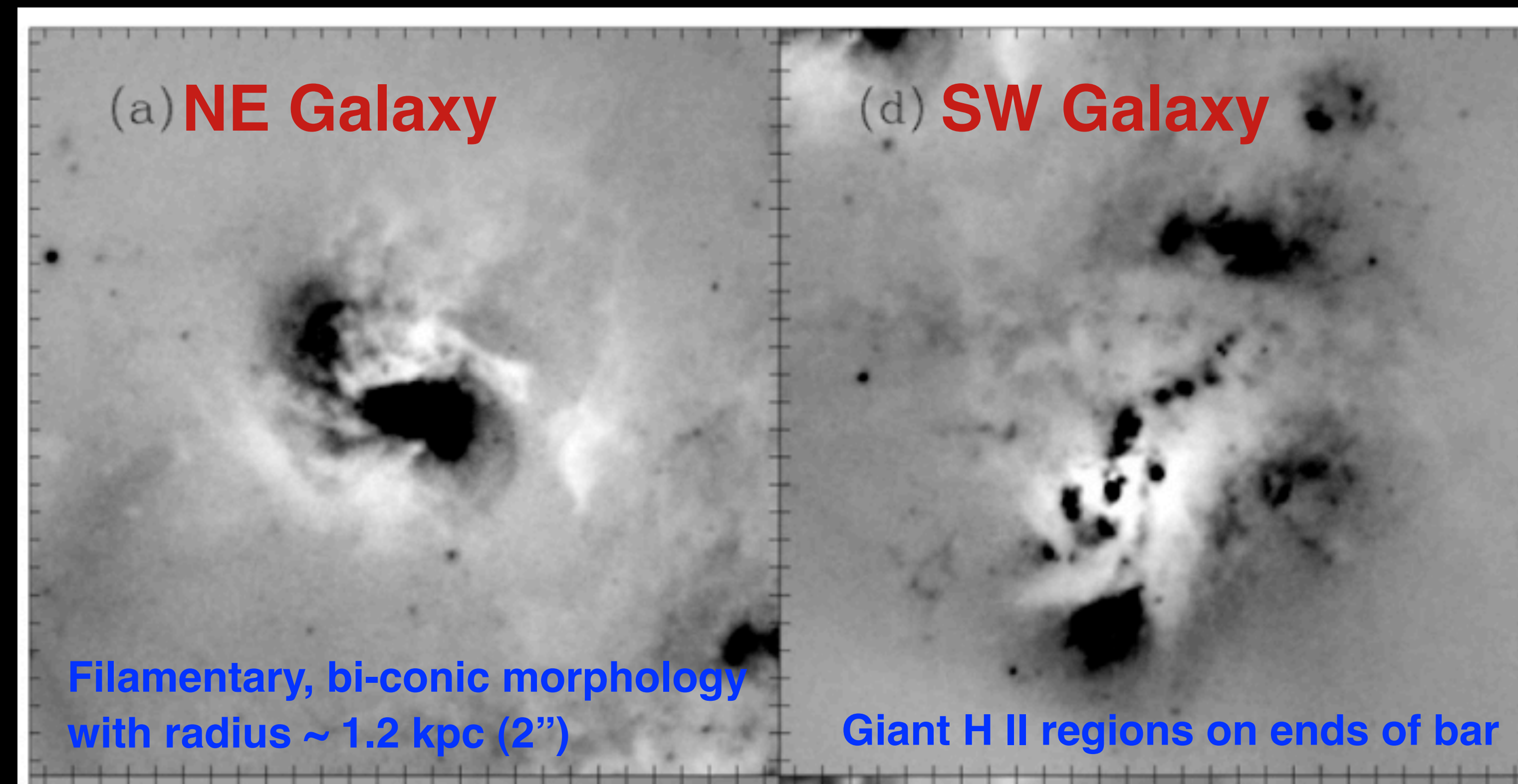
L_{ir} (SW) = 2.3×10^{11} $L_\odot$ L_{ir} (NE) = 0.7×10^{11} $L_\odot$

Disk/Bulge/Bar/Nucleus Decomposition

1.6 µm (H) results

(Direct - GALFIT model) residuals





B

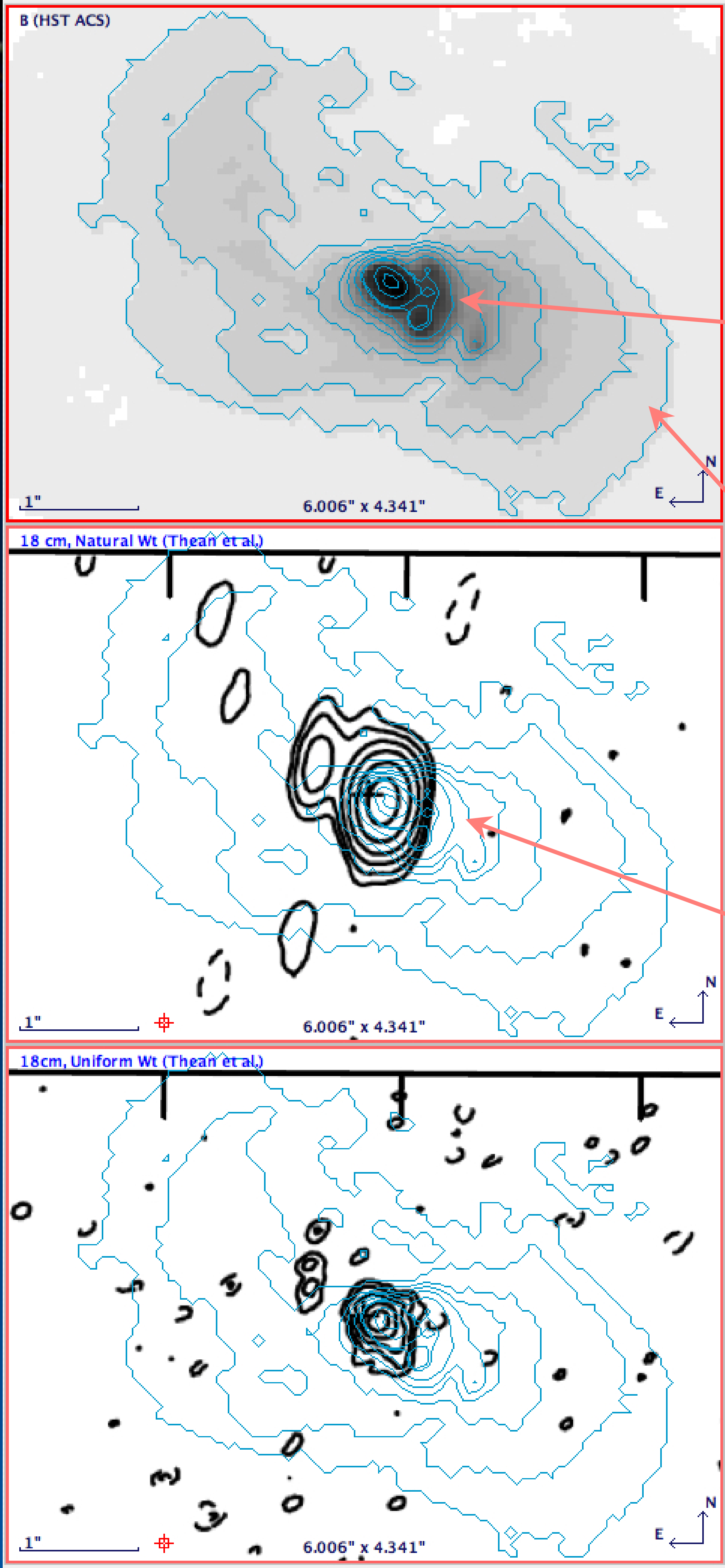
GALFIT

$L_{bulge} \Rightarrow M_{BH}$ (Marconi & Hunt 2003)

SW: $M(H)_{bulge} \Rightarrow M_{BH} = 2.0 \times 10^8\ M_\odot$

NE: $M(H)_{bulge} \Rightarrow M_{BH} = 2.2 \times 10^8\ M_\odot$

Radiative Bow Shock in Mrk 266 NE



Arc 300 pc (0.5”) long with three compact knots located 240 pc (0.4”) west of Mrk 266 NE; Lb ≈ substantially higher than SCs in Mrk 266

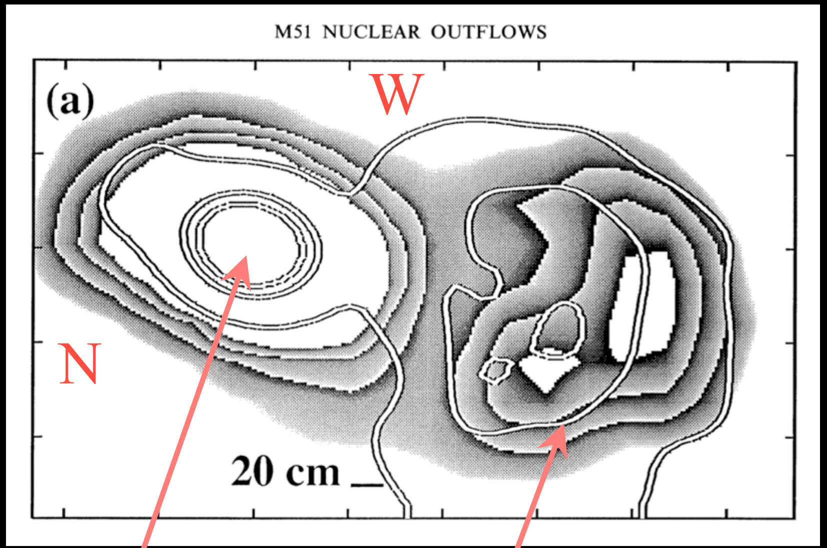
Filamentary, bi-conic morphology with radius ~ 1.2 kpc (2”) indicative of a classic AGN ionization cone; common in Seyferts, less so in LINERs. Axis roughly orthogonal to dust lane.

Knots located on outer boundary of radio continuum emission

Alignment of optical knots with axis of radio continuum suggests collimated outflow (two-sided jet), with plasma running into dense ISM constraining its flow and producing a bow shock.

Nuclear Outflow in M51

Collisionally excited [N II] λ6583 (grayscale) line emission concentrated on outer boundary of radio continuum arc (contour)
⇒ 4000 $M_\odot$ of ionized gas expanding at ~ 500 km/s (Cecil 1988)



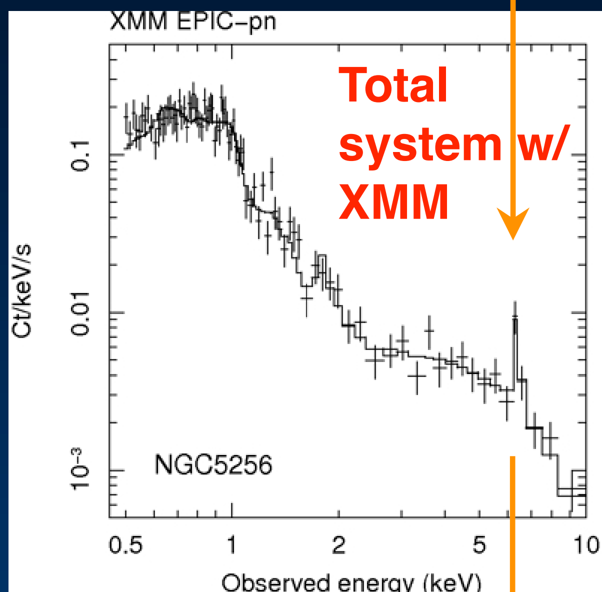
Nucleus (LINER)

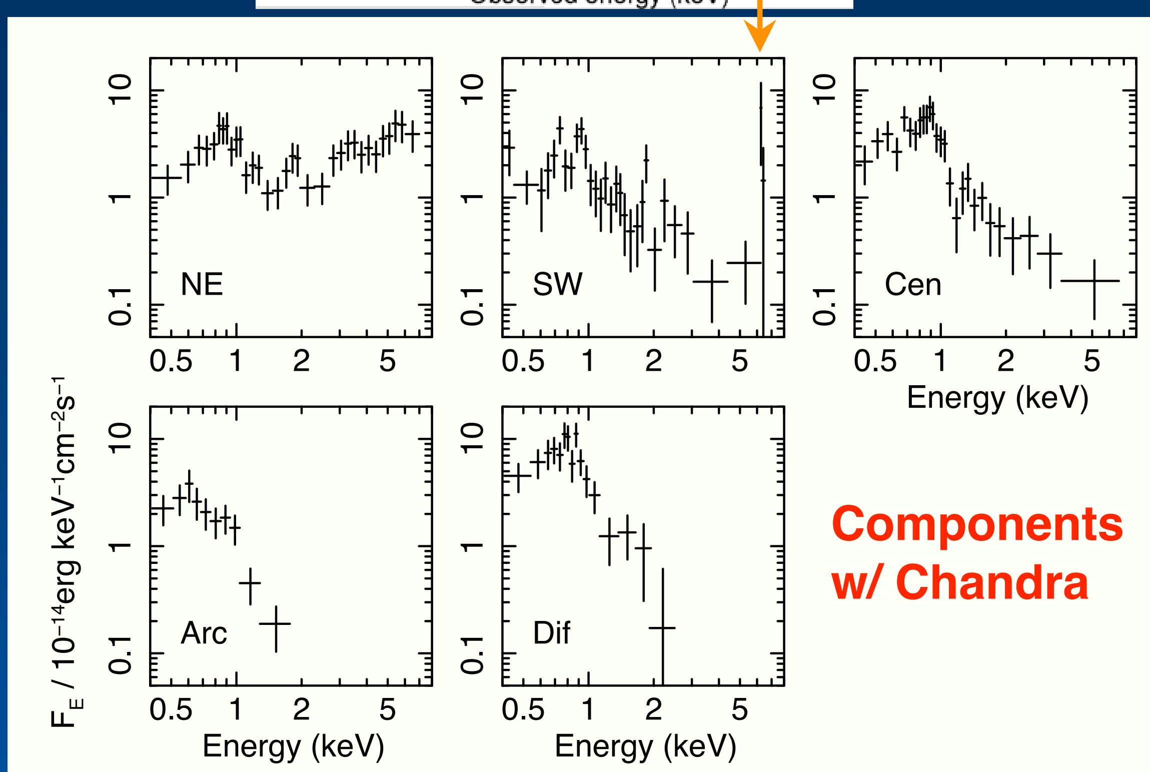
Radiative bow shock 180 pc (4”) from nucleus, within NLR radius ~ 400 pc (9”)

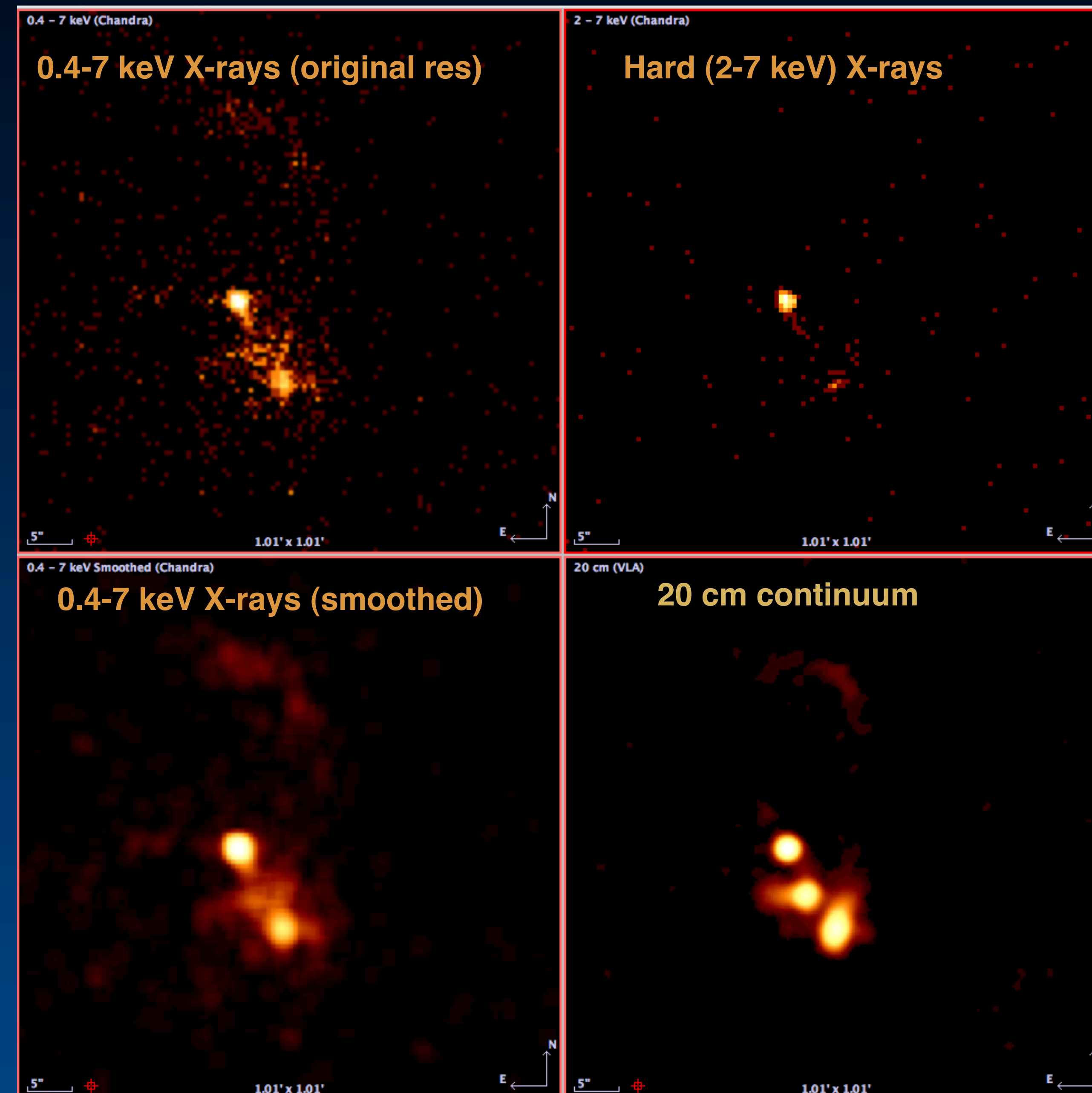
Mrk 266 NE has a remarkable resemblance to the LINER in M51

Two Obscured Hard X-Ray Sources

Fe Kα (6.4 keV) => fluorescence in cold material illuminated by a hard continuum spectrum is dominated by Mrk 266 SW (Sy 2)

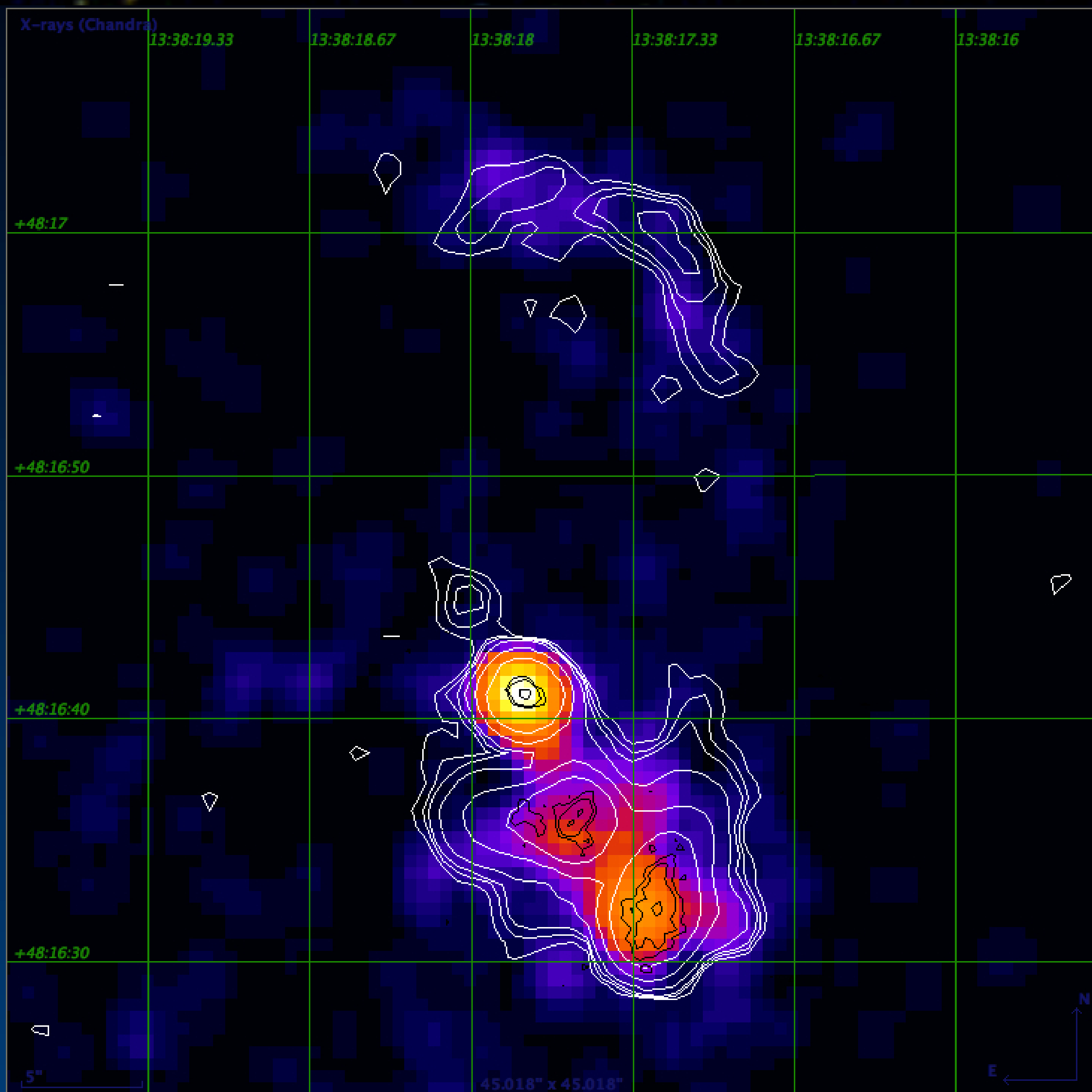






Mrk 266 SW is a strong candidate for a Compton-thick X-ray source, but confirmation requires high res @ E > 7 keV

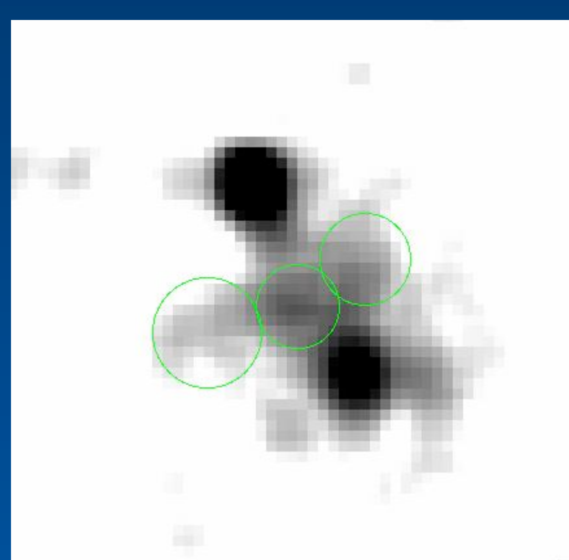
Soft X-rays & Radio Continuum Between the Nuclei



- First found in radio continuum; interpreted as shock-induced synchrotron emission (contours; Mazz+ 1988)
- Detected in X-rays with Chandra (Brassington+ 07)
- Modeled in greater detail here (Mazz+ 2012)
- Not detected in any waveband dominated by starlight or dust emission => plasma

TABLE 10
SPECTRAL ANALYSIS OF X-RAYS BETWEEN THE NUCLEI

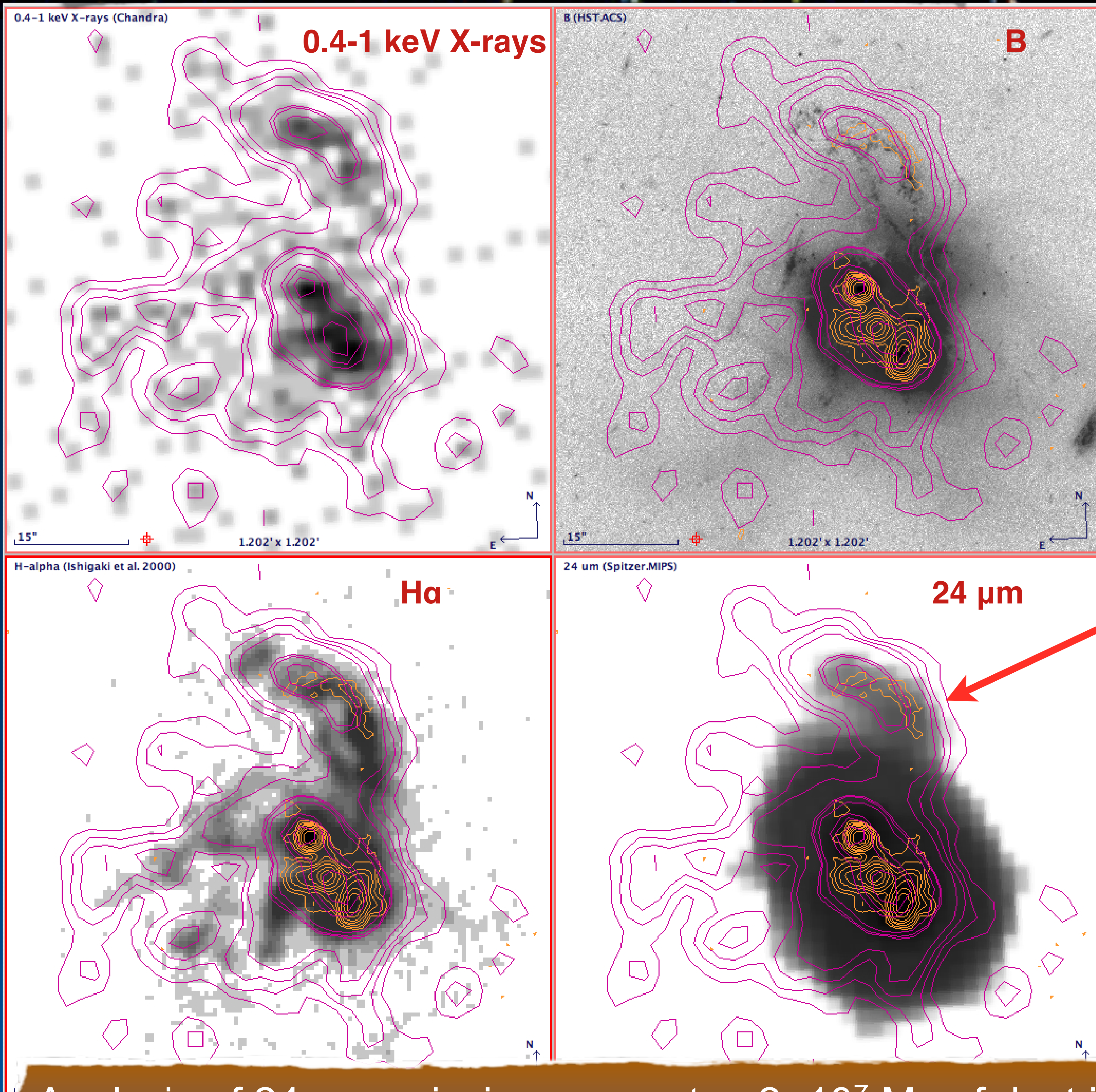
Parameter (1)	Value (2)	Units (3)
0.5-2 keV Flux	$2.7\text{x}10^{-14}$	erg s^{-1} cm^{-2}
Temperature (kT)	$0.72^{+0.11}_{-0.09}$	keV
Luminosity[a]	$1.1\text{x}10^{41}$	erg s^{-1}
Volume	$6.6\text{x}10^{65}$	cm^3
Electron Density	$1.1\text{x}10^{-2}$	cm^{-3}
Thermal Energy	$1.4\text{x}10^{55}$	erg
Gas Mass	$9.0\text{x}10^{6}$	$M_\odot$
Cooling Time	$4\text{x}10^{6}$	yr



Shocked gas from colliding galaxies/ISMs (ΔV~ 300 km/s) or due to colliding starburst/AGN-driven outflows (ΔV~1000 km/s)

Dust in the Wind

Strong correspondence b/w soft X-rays, Hα, and [O III] line emission filaments



24 µm MIPS image detects an arc spatially coincident with X-rays, 20 cm, Hα, [O III].

=> Direct evidence for dust entrained in a LIRG superwind (M 82 is a sub-LIRG)

F(24 µm) = 12 mJy => $M_d = 2 \times 10^7\ M_\odot$

Assumptions:

(1) F([O IV] 25.9 µm) < 10% F(MIPS 24 µm) as in planetary nebula NGC 2346 (Su+ 2004)

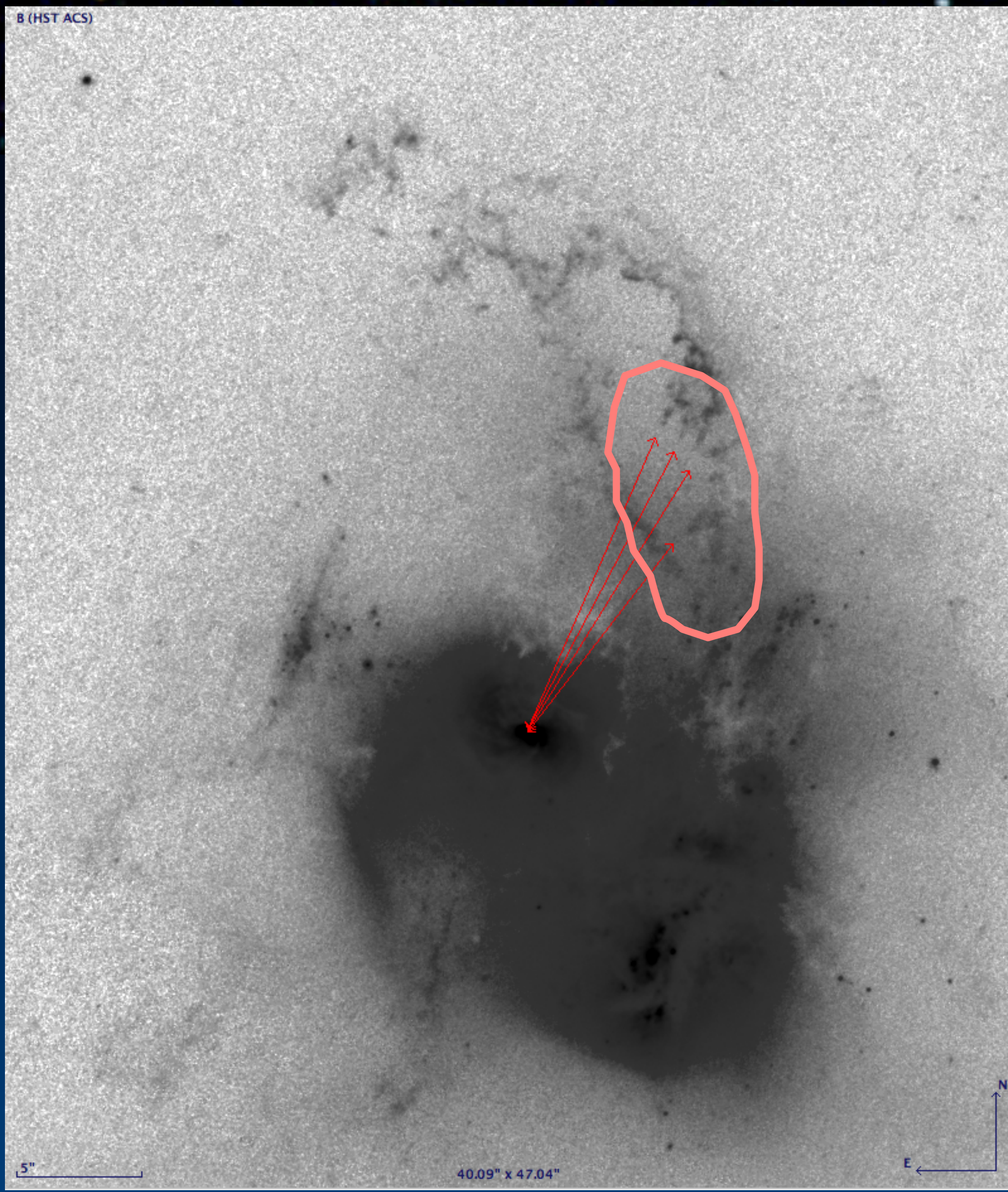
(2) $T_{dust} \approx 37$ K as in M82 (Alton+ 1999)

(3) Single-Temp dust model (Hildebrand 1983)

Scaling from M82 (18x lower Lir than Mrk 266) implies the northern arc contains 10% to the majorty of the dust in the wind

Analysis of 24µm emission suggests ~$2 \times 10^7\ M_\odot$ of dust is entrained in the superwind

Structure in the Superwind



Evidence for Rayleigh-Taylor fingers or bow shocks due to radiation pressure of the AGN

NOTE: [O III]/Hβ indicates photoionization by AGN dominates over starlight in the wind (Wang+ 1997)

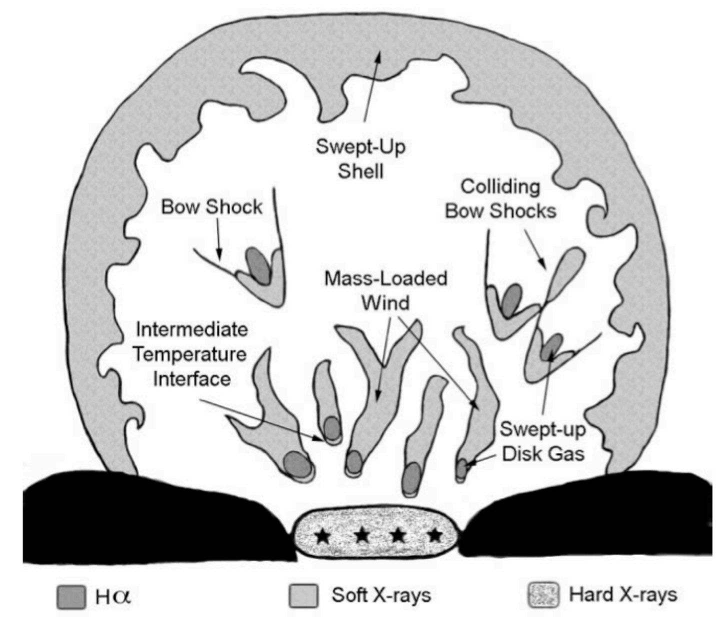


Fig. 15.—Schematic of the Hα and X-ray emission arising in a starburst wind and their spatial relationship.

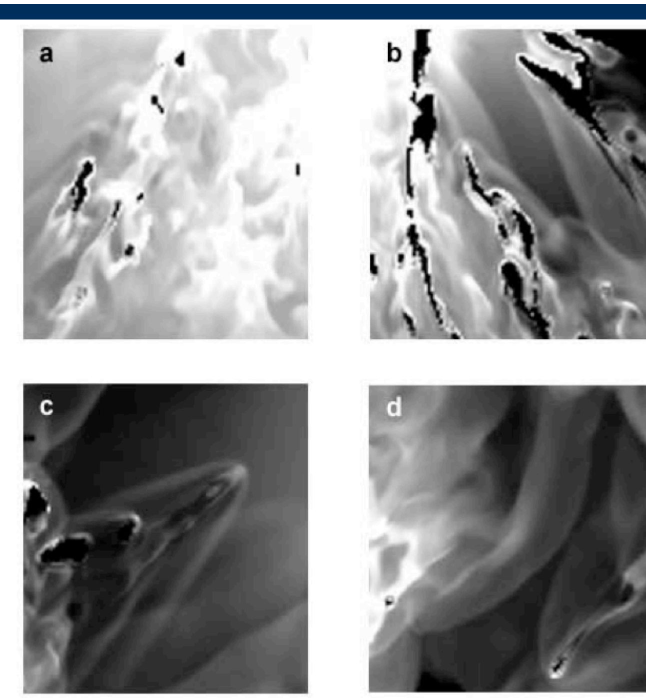


Fig. 14.—Highlighted soft X-ray emissivity from the wind in M01. Soft X-rays arise from (*a*) the cooling mass-loaded wind, (*b*) the intermediate-temperature interface between hot and cold gas, (*c*) bow shocks, and (*d*) the interaction between bow shocks. The size and location of each panel are indicated in Fig. 13. [*See the electronic edition of the Journal for a color version of this figure.*]

Structures in the HST ACS B-band image (containing [O II] λ3727) resemble 3-D simulations of galactic scale winds (Cooper et al. 2008).

E ~$10^{38\text{-}41}$ erg/s (SNe)

t ~ 2 Myr

T ~ 10^6 K gas

Bow shocks: Disk gas accelerated into the flow by ram pressure of hot wind; T ~ 10^7 K gas

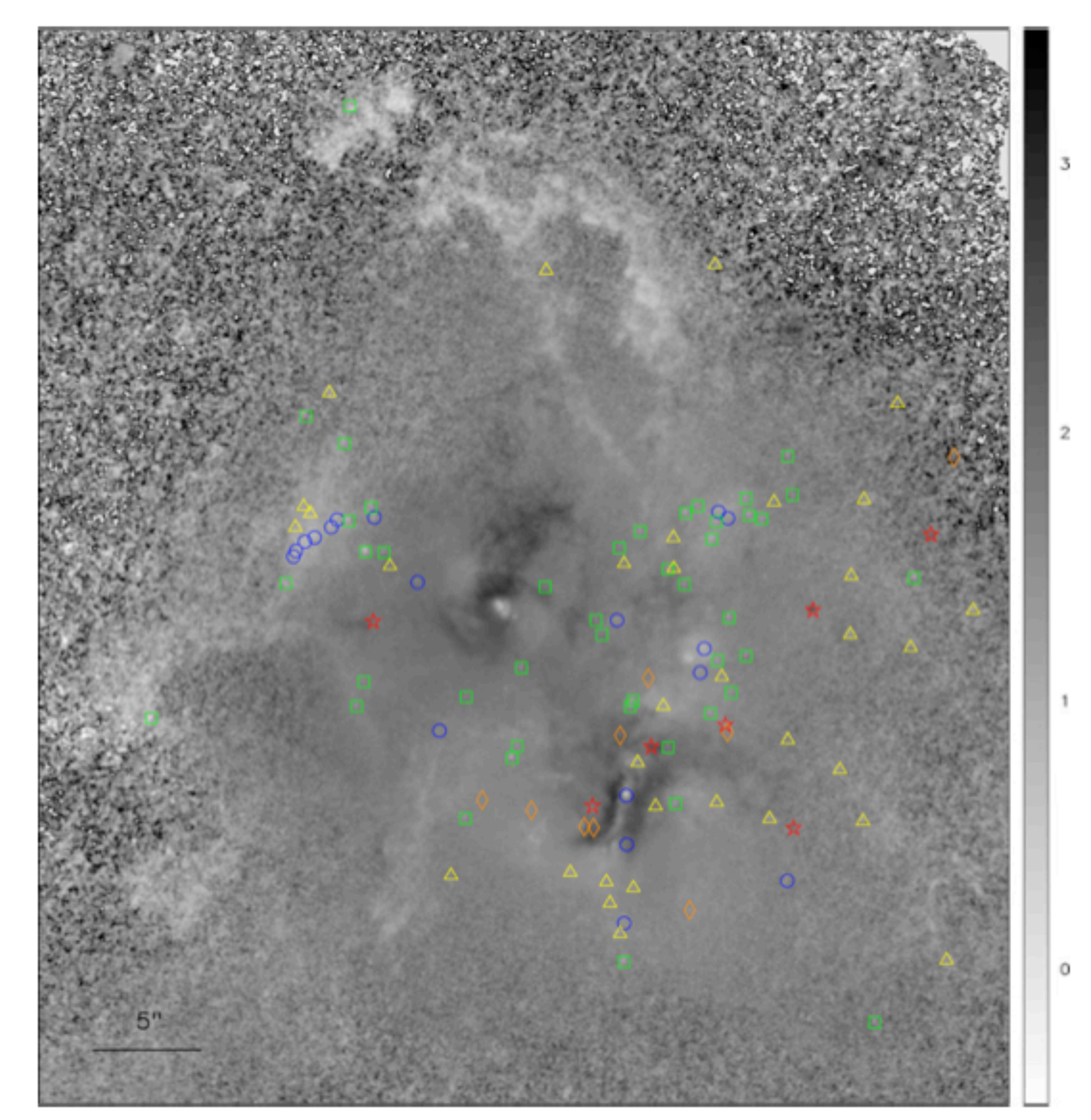
Star cluster analysis: Distribution & Colors

120 star clusters/associations detected, predominantly concentrated in SW galaxy and at base of the Northern Loop

Cluster luminosity function similar to other systems (e.g., Antennae, IC 883)

Total luminosity of 120 optically-detected star clusters is only 0.1% of Lir.

Ratios of cluster surface densities, L_{CO}, and L_{ir} within 3 kpc of each nucleus are similar: L(SW)/L(NW) ≈ 4.5



Star clusters superposed on HST/ACS F435W–F814W (B − I) color map

(B-I) colors: 0 - 0.5 mag (blue), 0.5 - 1 mag (green),1-1.5 (orange), 1-1.5 mag (yellow), and >1.5 mag (red).

Star cluster analysis: Age-Dating

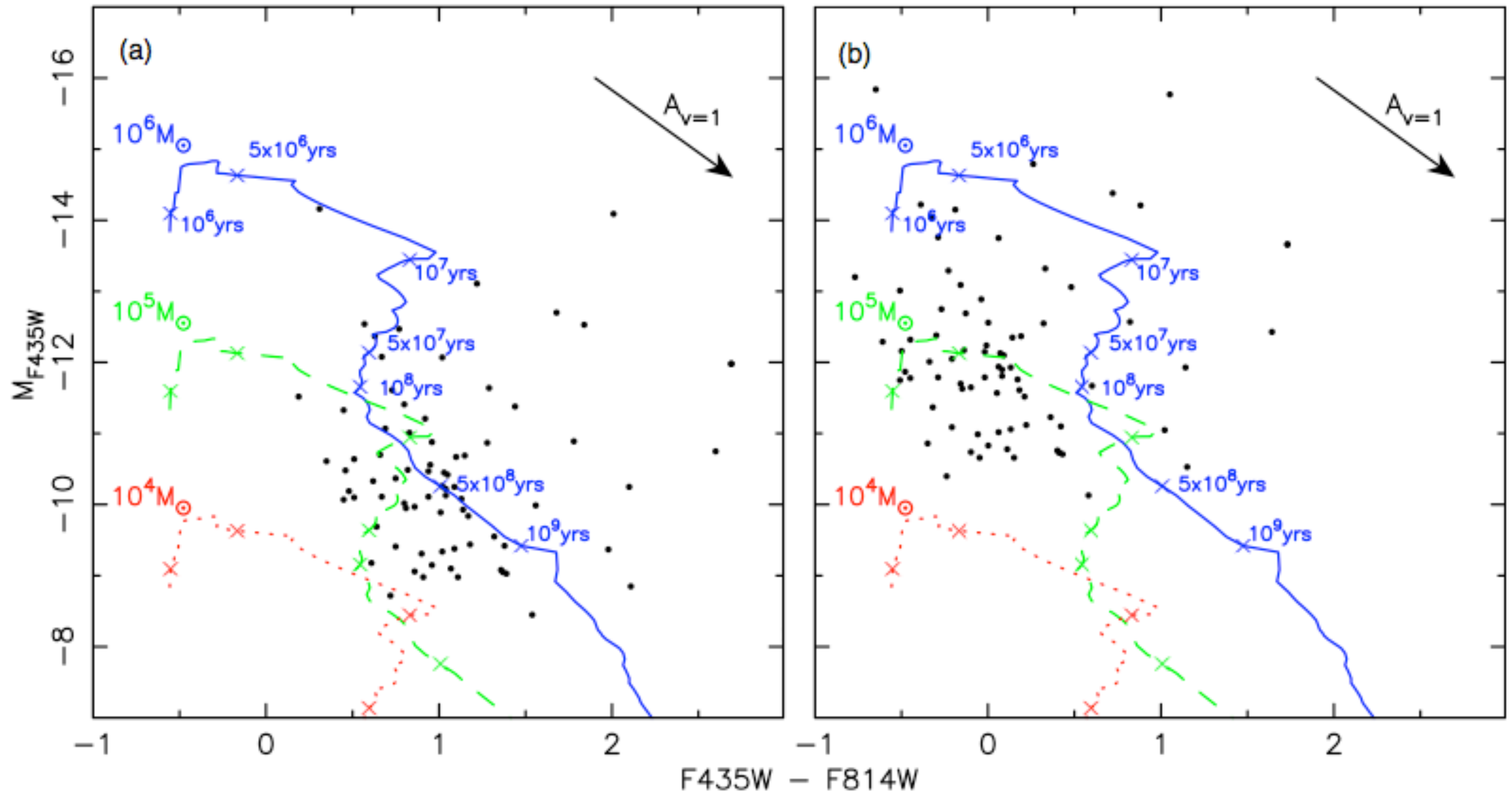


Figure 27. M_B vs. $B-I$ color–magnitude diagram for SCs detected in Mrk 266. Evolutionary tracks computed using population synthesis models (Bruzual & Charlot 2003) assuming an instantaneous starburst and solar metallicity for cluster masses of 10^4 (red), 10^5 (green), and 10^6 (blue) $M_\odot$ are shown. Marks on the 10^6 $M_\odot$ track indicate the age of the starburst. The data are plotted (a) with no extinction correction, and (b) with a mean extinction correction of $A_V = 1.2$ mag estimated from various measurements as described in the text. The vector represents 1 mag extinction in the V band. Only SCs with uncertainties in $B-I$ less than 0.2 mag are shown.

(A color version of this figure is available in the online journal.)

(B-I) vs. M_B color-magnitude diagram with Bruzual Charlot population synthesis models

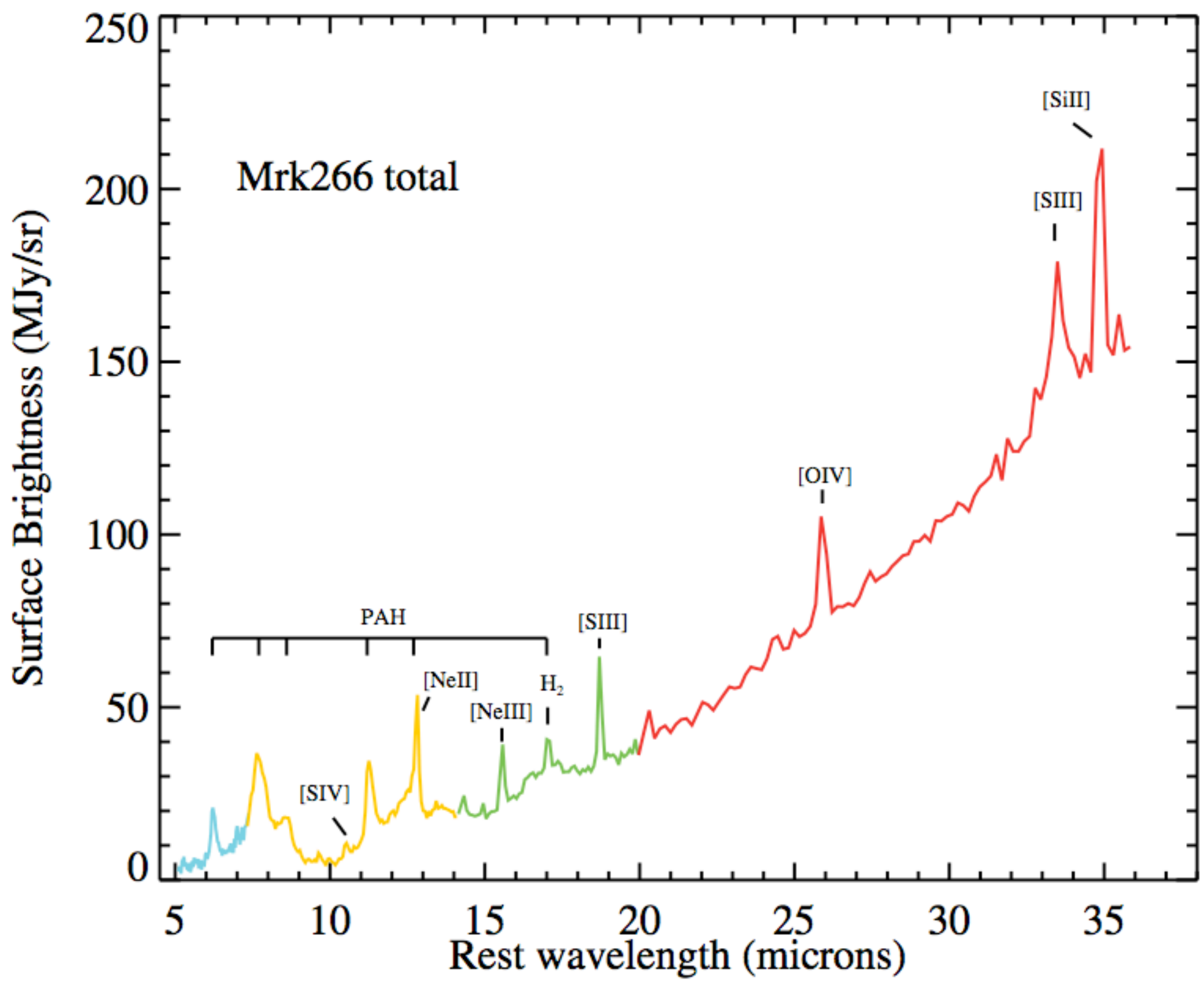
With mean extinction correction of $A_V \sim 1.2$ mag:

$\langle M_B \rangle \approx -12$ mag

$\langle M^* \rangle \approx 10^5\ M_\odot$; some reach $10^6\ M_\odot$

$\langle Age \rangle \approx 5$ Myr

Spitzer IRS Spectrum for Total System

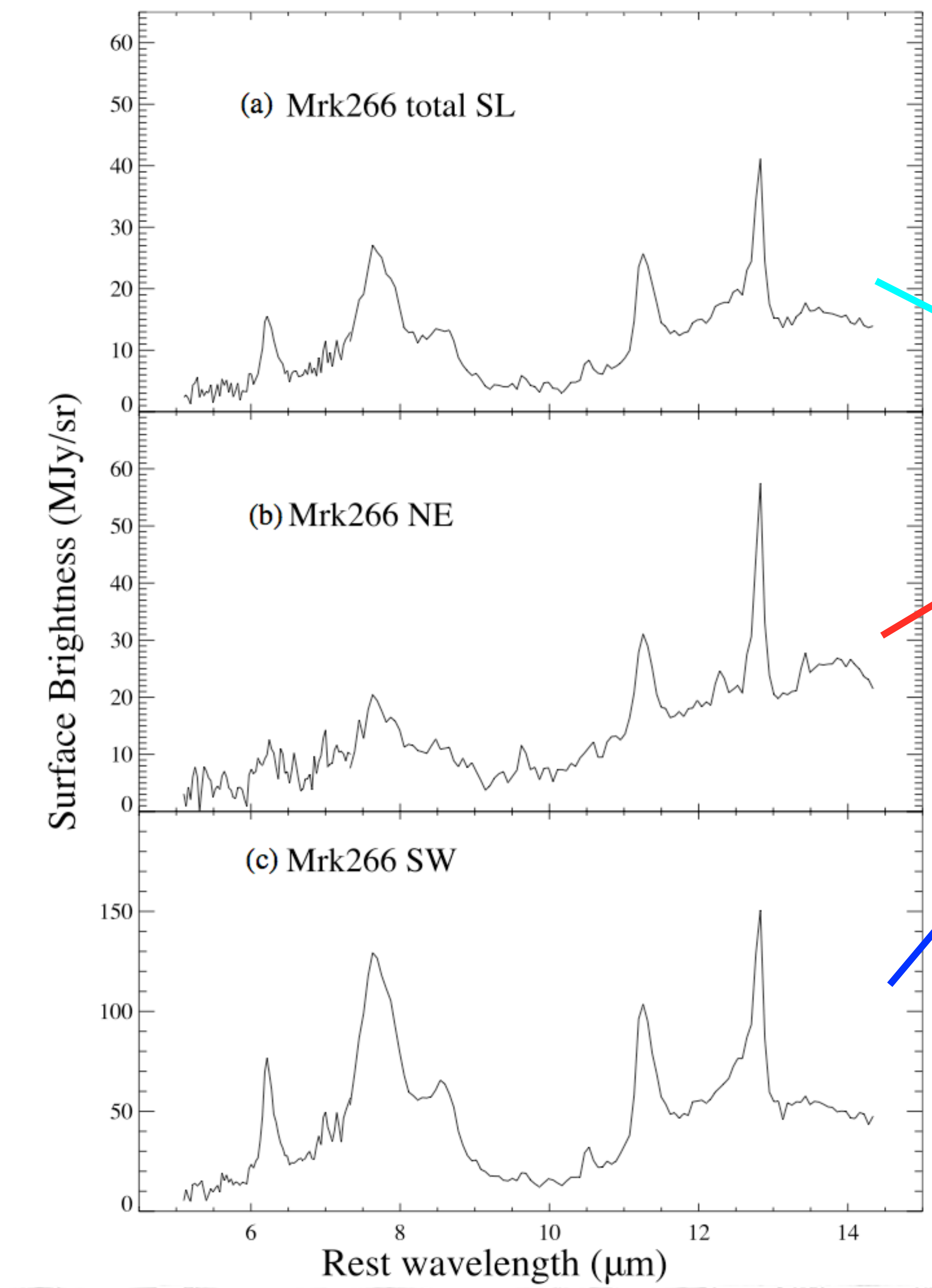


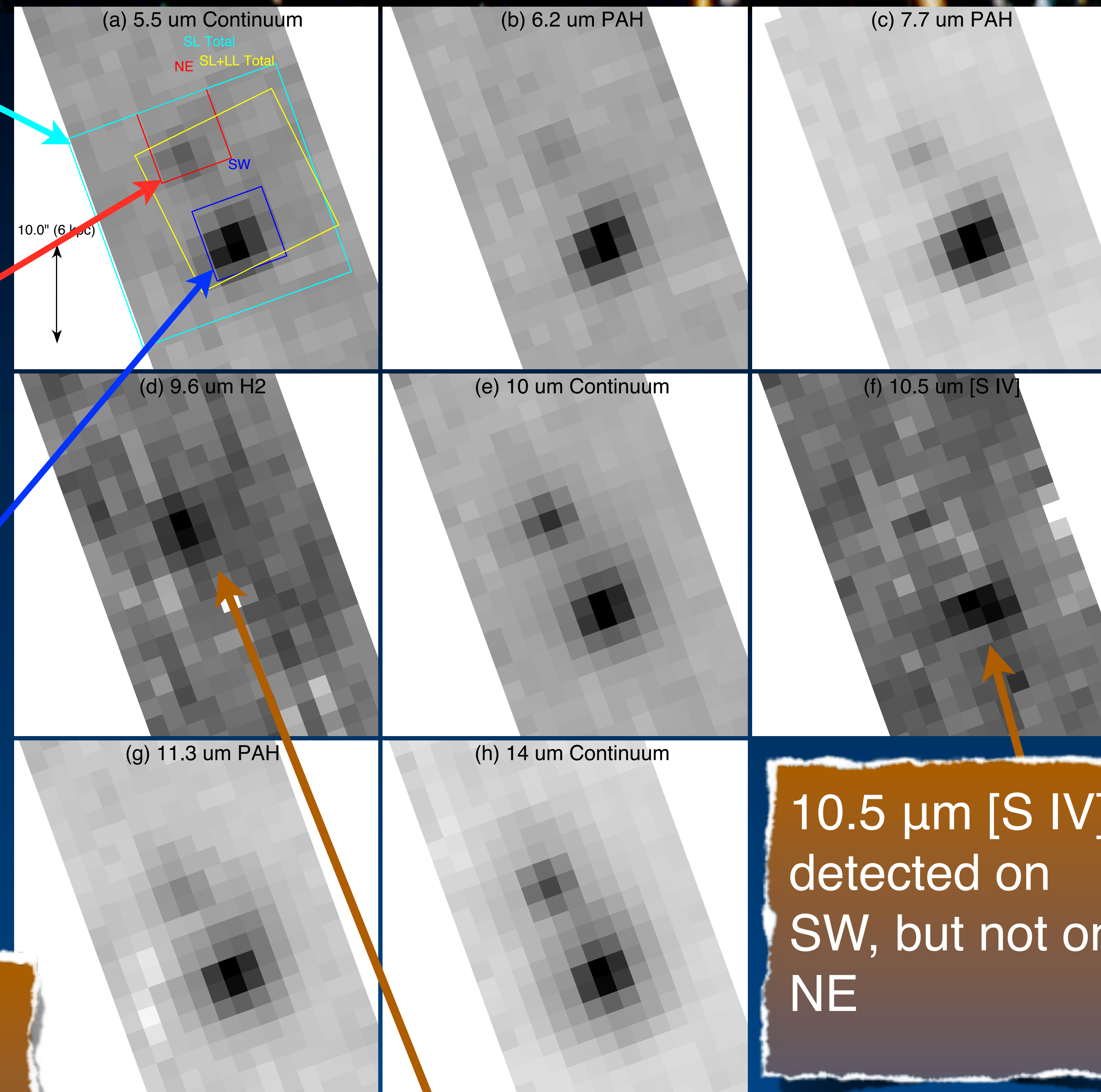
Mid-IR spectral diagnostics (Armus+ 2007; Veilleux+ 2009) give mixed results, but on average ≈ 50% AGN and 50% star formation powers L_{bol}

Table 5
Estimated AGN Contributions to the Mid-infrared and Bolometric Luminosity

Diagnostic	SW Galaxy			NE Galaxy			Total System		
	Value	$\frac{L_{AGN}}{L_{Diag}}$	$\frac{L_{AGN}}{L_{Bol}}$	Value	$\frac{L_{AGN}}{L_{Diag}}$	$\frac{L_{AGN}}{L_{Bol}}$	Value	$\frac{L_{AGN}}{L_{Diag}}$	$\frac{L_{AGN}}{L_{Bol}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) [O IV] 25.89 μm/[Ne II] 12.81 μm[a]	0.93	23%	73%	...	...	...	0.67	17%	64%
(2) [Ne V] 14.32 μm/[Ne II] 12.81 μm[a]	0.14	11%	53%	...	...	...	...	...	...
(3) PAH 6.2 μm EQW [μm][b]	0.67	0%	...	0.4	30%	...	0.47	10%	...
(4) PAH 7.7 μm EQW [μm][b]	0.54	69%	43%	0.25	79%	56%	0.46	71%	46%
(5) f(PAH 6.2 μm)/$f_{5.5\,\mu m}$ vs. f(15 μm)/$f_{5.5\,\mu m}$[b]	1.6,8.6	47%	9%	0.56,6.4	81%	33%	2.0,2.9	52%	11%
(6) $f_\nu(30)/f_\nu(15)$[c]	3.9	89%	82%	3.3	92%	87%	4.8	85%	76%
Mean[d]		40%	52%		71%	59%		47%	49%
Std. Dev.		35%	29%		28%	27%		33%	28%

Spitzer IRS Spectral Map





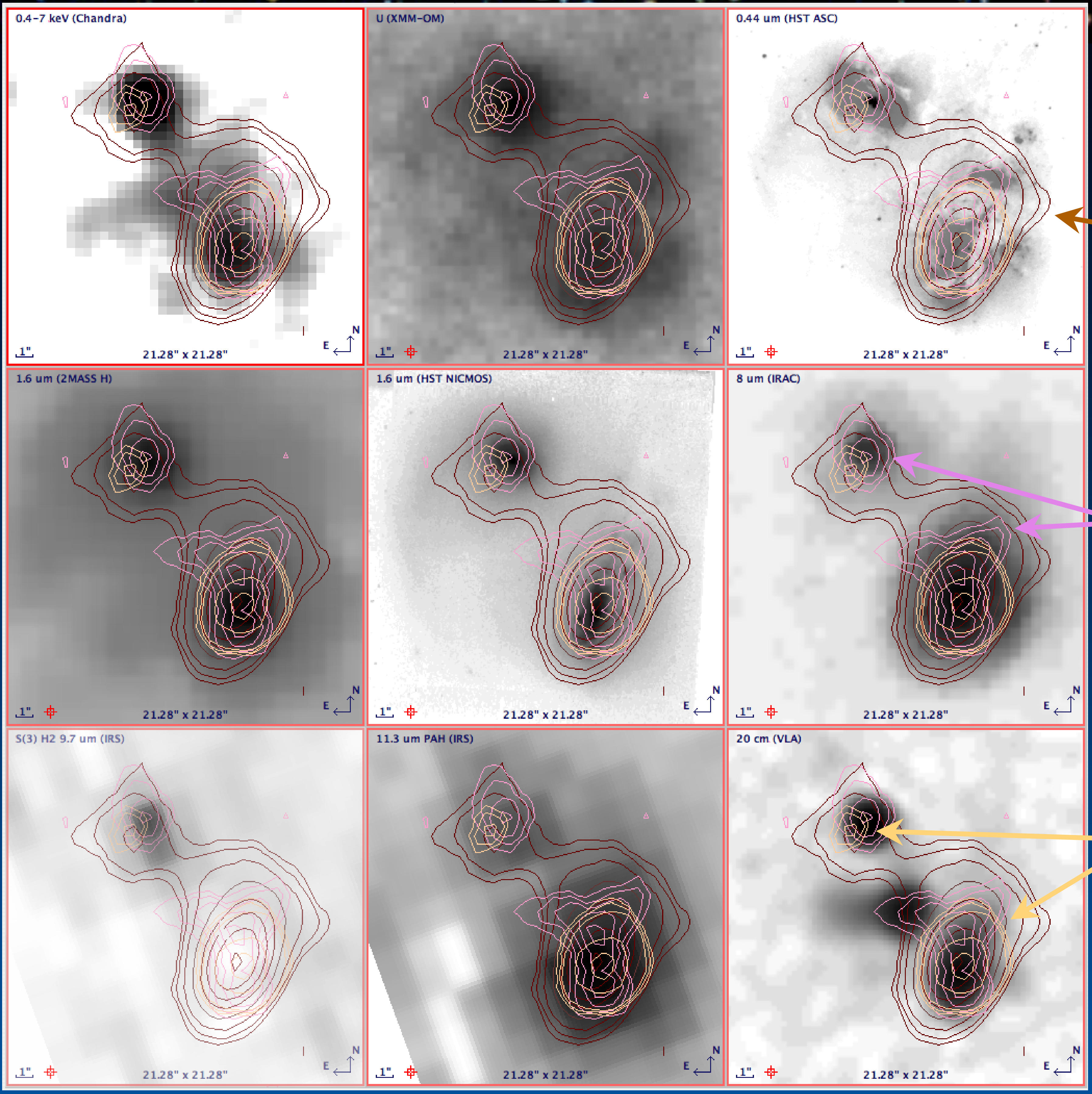
10.5 μm [S IV] detected on SW, but not on NE

PAH fluxes and EQWs higher in SW (higher SFR + heavily obscured AGN) than in NE (lower SFR + less obscured AGN)

11.3/7.7 PAH ratios indicate warm, ionized medium in SW and relatively cool, neutral medium in NE

9.6 μm H_2 S(3) detected on NE, but not on SW or between the galaxies
⇒ Strong shock here

Cold Molecular Gas Properties



- ✦ Nobeyama mm Array CO (1-0) channel map: Imanishi+ 2009
- ✦ Derived physical properties: Mazz+ 2012

CO (1-0)

SW: Aligned with disk

NE: Offset ~1 kpc SE of nucleus

Bridge between galaxies

HCN (1-0)

SW: partaking in outflow?

NE: Nuclear

HCO^+ (1-0):

SW & NE: Same centroid as CO (1-0)

CO (1-0) Channel Map Overlay on 1.6 µm

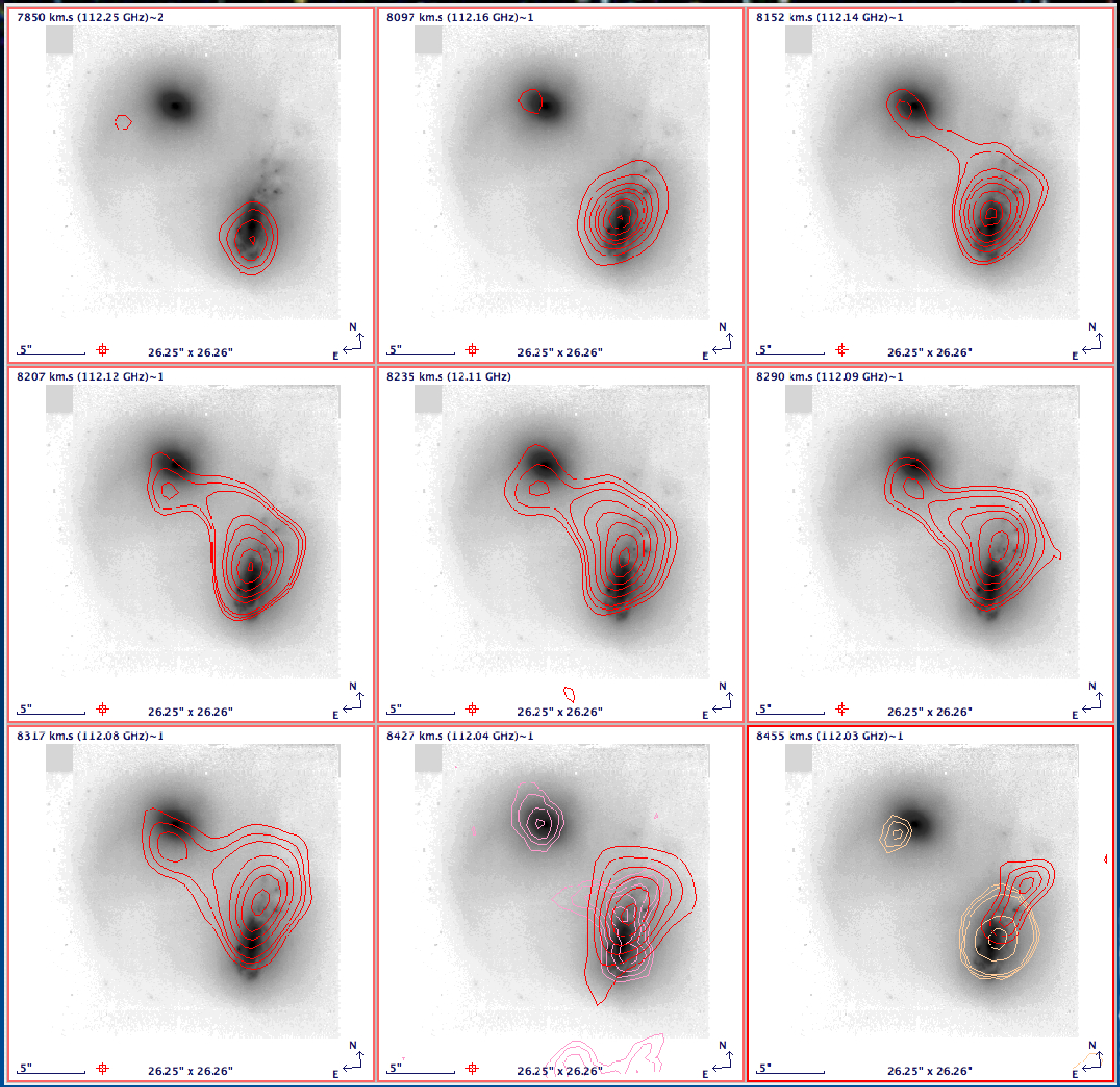


TABLE 11
MOLECULAR GAS PROPERTIES OF MRK 266

Parameter (1)	SW (2)	NE (3)	Total (4)
CO (1-0) flux [Jy km s^{-1}][a]	88	18	180
CO (1-0) FWHM [$km\ s^{-1}$][a]	500	250	...
L'_{CO} [K km s^{-1} pc^2]	3.4×10^9	7.0×10^8	7.0×10^9
$M(H_2)$] [$M_\odot$]	3.4×10^9	7.0×10^8	7.0×10^9
R(CO) [pc]	208	134	...
$M_{Dynamical}$ [$M_\odot$]	1.2×10^{10}	1.9×10^9	...
$M(H_2)/M_{Dynamical}$	0.28	0.37	...
Column Density [cm^{-2}]	1.6×10^{24}	7.9×10^{23}	...

NOTE. — Column (1): Observed or derived parameter. Columns (2)-(4): For the SW galaxy, NE galaxy, and the total system, respectively—the value of the parameter in Column (1).

[a] The CO (1-0) line fluxes and line widths are from data presented by Imanishi et al. (2009); all other parameters are derived and presented here for the first time.

SW: Rotating with NW side receeding, SW side approaching

NE: Peak offset ~1 kpc (1.5”) SE of nucleus

~40% of CO is bridging the galaxies

Dynamically younger than VV 114 and NGC 6090, which have larger fractions of their CO located between the nuclei

Mrk 266 Primary Conclusions (1)

The Galaxies

- ✦ SW is SBb (pec) and NE is S0/a (pec)
- ✦ Stellar tidal tail (H band) extending ~6 kpc south from NE galaxy
- ✦ Diffuse, asymmetric morphology and ~100 kpc extent of tidal debris suggests 2nd or 3rd encounter
- ✦ At 1.6 μm, SW and NE are both more luminous than local L* galaxies
- ✦ Mid-IR spectral diagnostics indicate, on average ≈ 50% AGN and 50% star-formation powers L_{bol}

The Nuclei

- ✦ SMBH masses of ~2.5×10^8 $M_\odot$ inferred in each nucleus
- ✦ Both nuclei have luminous hard X-ray sources, with L_{hx}(NE) = 6.4 x L_{hx}(SW)
- ✦ SW (Sy 2) is primary source of Fe Kα line => reflection-dominated, heavily obscured AGN. Fx/F[O III] ratio also indicates SW is a candidate for Compton-thick X-ray source.
- ✦ Warm molecular gas H_2 S(3) 9.7 μm provides evidence for shock excitation around NE AGN
- ✦ B band emission inside R ~2'' (1.2 kpc) around NE nucleus has a filamentary, bi-conic morphology indicative of an AGN ionization cone
- ✦ Radio continuum emission aligned along the same axis as the optical knots and bow structure suggests that jets from the AGN are interacting with the ISM in Mrk 266 NE: outflow
- ✦ NE (LINER) confirmed AGN from 4 lines of evidence: (1) L_{hx}; (2) M51-like row shock; (3) small PAH EQWs and deficiency of 6.2 μm & 7.7 μm PAH wrt 11.3 μm PAH; (4) high H2(1-0) S(1) to Br γ ratio

Mrk 266 Primary Conclusions (2)

Between the Galaxies

- Soft X-rays from $T \sim 10^7$ K shock-heated gas
- Lack of IR and CO (1-0) rules out 3rd galaxy or off-nuclear star formation and suggests the radio continuum and soft X-rays are short-lived ($t_{cool} \sim$ few Myr) and related to shocking of ISM
- Lack of detected 9.7 µm H_2 S(3) line supports suggestion of Davies+ (2000) [no H_2 1-0 S(1)]: $V_s \sim 1000$ km/s at interface of colliding superwinds can generate the non-thermal radio continuum emission and heat the gas far above the dissociation temperature of H_2
- $\approx$ 40% of the CO (1-0) is bridging between the galaxies, suggesting gas transfer or infall toward the CM well before the stellar systems merge

The Superwind

- Northern Loop extending ~34'' (20 kpc) north has morphology suggestive of Rayleigh-Taylor instabilities and bow shocks matching simulations of superwinds (not a tidal tail or a "jet")
- 24 µm emission co-spatial with Northern Loop suggests $\geq 2\times10^7\ M_\odot$ of dust is entrained in the wind

Star Clusters

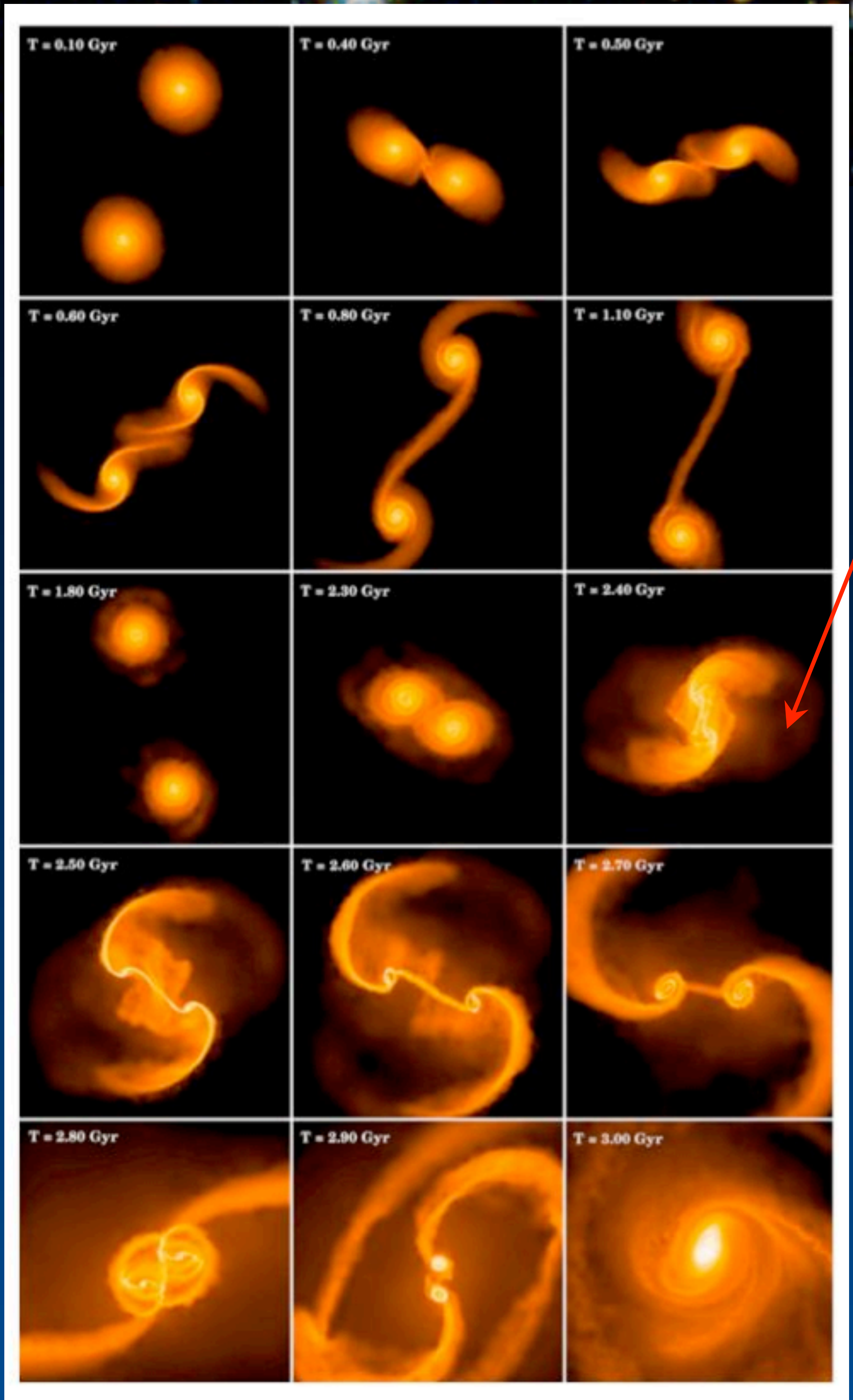
- Over 120 star clusters detected, predominantly concentrated in SW galaxy and at the base of the northern loop. Most have estimated ages < 50 Myr. SC and CO surface density match.
- Luminosity function and specific frequency of similar to young clusters in other galaxies
- Total luminosity of detected (unobscured) clusters is only 0.1% of Lir

Mazz+ 2012 (November, AJ)

Outline

- Motivation: Questions in (U)LIRG → Dual/Binary AGN Evolution
- In-depth study of Mrk 266 across the EM spectrum
- Wider Implications for (U)LIRGs and Dual/Binary AGN
  - LIRG → ULIRG
  - L_x/L_{ir} SMBH merger sequence
  - Why are binary AGNs so rare?
  - LINERs are AGNs too
- Recent NED services facilitating extragalactic research

Implications: LIRGs → ULIRGs



Major merger sim w/ dark matter, stars, gas, and SMBHs; gas component shown here (Mayer et al. 2007)

- In context of merger simulations
  - The galaxies lie within an asymmetric, low surface brightness tidal debris halo spanning ≈100 kpc
  - Nuclei have projected Sep = 6 kpc and relative velocity of only 135 km s^{-1}
  - Likely undergoing their second or third encounter with only 50 - 250 Myr remaining until they merge via tidal dissipation
- Total cold molecular gas mass of ≈7 × 10^9 M⊙
  - Similar to local and high-redshift ULIRGs
  - Since ≈40% of the total CO (1–0) emission is located between the galaxies, this reservoir is available to form more stars and to fuel the AGNs as the stellar systems and nuclei inexorably coalesce

Two lines of evidence suggest Mrk 266 is in a short-lived stage when the nuclei are about to enter the final phase of coalescence characteristic of ULIRGs

Implications: A proposed merger sequence

Table 10
Dual to Binary AGN Evolution Based on L_{hx}/L_{ir}

Object (1)	z (2)	D_L (Mpc) (3)	Sep ($''$) (4)	Sep (kpc) (5)	$\log(\frac{L_{ir}}{L_\odot})$ (6)	$\log(\frac{L_{hx}}{L_{ir}})$ (7)	Notes (8)	References (9)
Mrk 171 (NGC 3690 + IC 694)	0.01041	51.1	3.8	0.9	11.88	−4.1	...	1
Mrk 266 (NGC 5256)	0.02786	129	10	6.0	11.53	−3.5	...	2
NGC 6240	0.02448	116	1.8	0.9	11.93	−3.1	...	3
Mrk 463	0.05036	233	3.8	3.8	11.77	−2.8	Young radio jet?	4
3C 75	0.02315	97.9	14	6.4	...	...	Twin radio jets	5
COSMOS J100043.15+020637.2	0.36060	1944	0.5	2.5	11.59	−1.7	Recoiling SMBH?	6
4C +37.11	0.05500	242	0.0073	0.008	...	...	Binary AGN	7
SDSS J153636.22+044127.0	0.38930	2133	1.0?	10^{-4} or 5.1	...	...	Binary or dual AGN?	8,9

Notes. Basic parameters for confirmed dual AGNs and putative binary AGNs. Column 1: object name. Column 2: heliocentric redshift from NED (see citations therein). Column 3: luminosity distance computed by NED. Column 4: projected nuclear separation in arcseconds. Column 5: projected separation in kpc. Column 6: log of the infrared luminosity in Solar units. Column 7: log of the ratio of observed hard X-ray luminosity (2–10 keV from *XMM*, otherwise 2–7 keV from *Chandra*, uncorrected for absorption) to infrared luminosity. Column 8: Notes. Column 9: references for the redshift in Column 2, the hard X-ray flux used to compute the ratio in Column 7, or the Notes in Column 8; the codes are as follows—1: Ballo et al. (2004); 2: this article; 3: Komossa et al. (2003); 4: Bianchi et al. (2008); 5: Owen et al. (1985); 6: Civano et al. (2010); 7: Rodriguez et al. (2006); 8: Boroson & Lauer (2009); 9: Wrobel & Laor (2009). Measurements taken from the literature have been adjusted to $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$, $\Omega_V = 0.73$. For COSMOS J100043.15+020637.2, L_{ir} was estimated from the *Spitzer* IRAC 8 μm and MIPS 24 μm measurements in Civano et al. (2010) utilizing Equation (1) of the current study.

- The global L_{hx}/L_{ir} ratio increases by >100 as obscuring material is expelled by outflows to gradually expose previously obscured AGNs
- Mrk 266 is in an intermediate phase between Mrk 171 and NGC 6240

We propose that Mrk 266 belongs to an evolutionary sequence in which dual AGNs with Kpc separations represent precursors to putative binary AGNs with parsec-scale orbital radii.

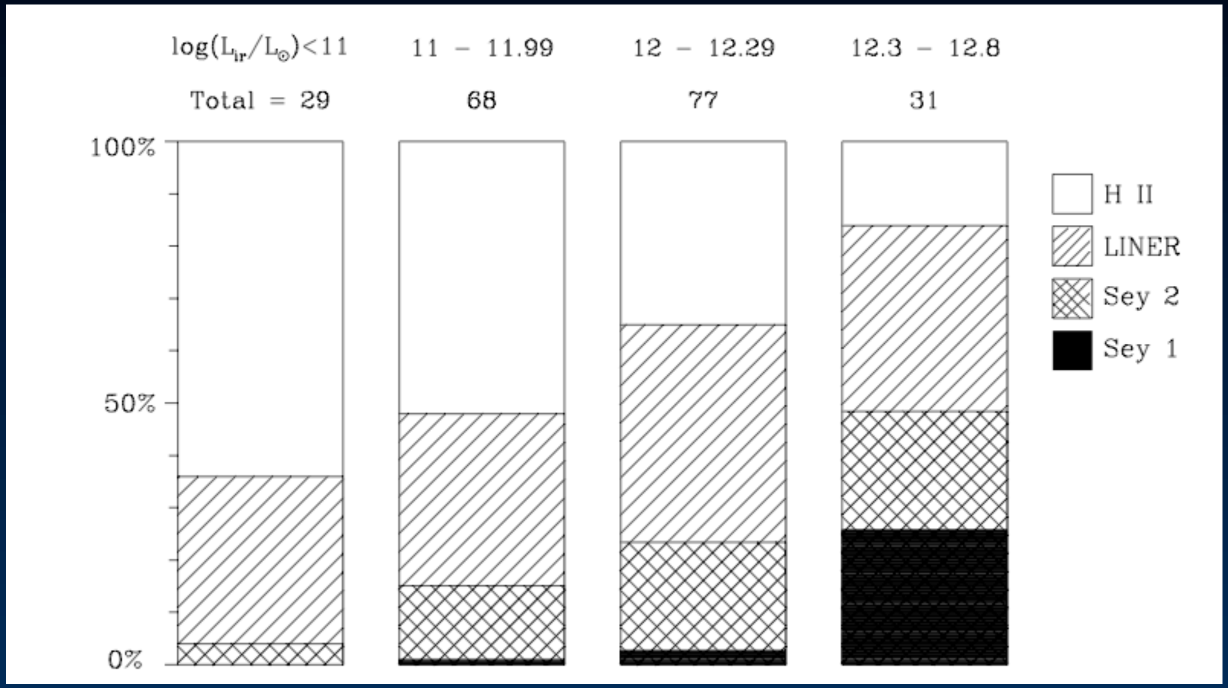
Implications: Why are binary AGNs so rare?

- Since major mergers provide a natural process to form SMBH/AGN pairs, the scarcity of confirmed and candidate binary AGNs (Sep < few pc) in large surveys is unexpected
  - ~1 among 18,000 candidates in a SDSS spectroscopic survey (Lauer & Boroson 2009)
  - ~1 (previously known 4C +37.11) among 3100 radio-loud AGNs (Burke-Spolaor 2011)
- Two possibilities (e.g., Gaskell 2010)
  - The SMBHs inspiral very rapidly
  - Fueling of the accretion disks is quenched during the binary phase
- We raise a third hypothesis...
  - Consider that the lifetimes of AGNs inferred from gas depletion rates in (U)LIRGs is only 10^{7-8} yr (Solomon & Vanden Bout 2005)
  - Similarly, the estimated lifetime of powerful radio galaxies is only ~10^7 yr (Bird+ 2008)

Since the gas depletion lifetime of ULIRGs and LIRGs is 10–100 times shorter than the timescale for creation of a binary SMBH (~1 Gyr), it is possible that, in most instances, the gas will be consumed by star formation and accretion during a dual AGN phase long before the SMBHs inspiral to a sub-parsec binary scale orbit.

Implications: Most LINERs are AGN too!?

- **The AGN fraction in (U)LIRGs increases dramatically with Lir and ~40% of local ULIRGs and 30% of local LIRGs are optical LINERs** (e.g., Veilleux+ 1999)
- Traditionally difficult to distinguish photoionization from AGN, very hot stars, or shock heating
- But recent results indicate most LINERs are AGNs w/ lower accretion rates that Seyferts (Kewley+ 2006; Ho 2008)
- Mrk 266 NE and NGC 6240 show that a LINER can be a mixture of AGN and shock heated gas
- **Many more dual AGNs may be discovered via X-ray observations of LINERs**



Outline

- Motivation: Questions in (U)LIRG → Dual/Binary AGN Evolution
- In-depth study of Mrk 266 across the EM spectrum
- Wider Implications for (U)LIRGs and Dual/Binary AGN
- Recent NED services facilitating extragalactic research
  - My interactions with Dave De Young were primarily from his interest in science archives and the Virtual Observatory (NVO, VAO, IVOA)
  - Dave was intrigued by some of NED's capabilities and we had various discussions about galaxy SEDs (complexities and modeling) and AGNs

NED features released in 2010-12...

NASA/IPAC EXTRAGALACTIC DATABASE
Date and Time of the Query: Wed Nov 28 14:59:58 2012 PDT
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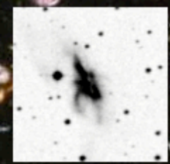
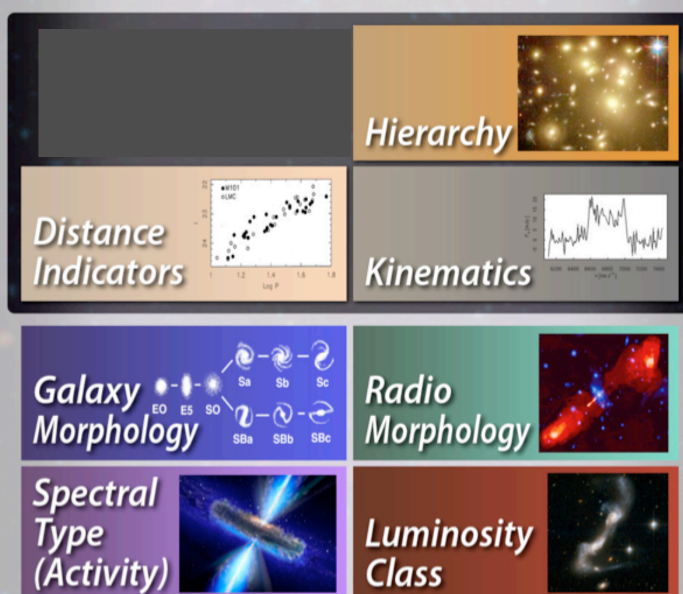
Classifications for NGC 6240

10 Classifications found in NED



Published		NED Homogenized					Find Similar Objects / Reset
Classification	Reference Code	Classification	Flag	Bandpass	Region	Notes	
Kinematics							
HI line width	1987ApJ...322...88G	HI line width	...	Radio	Galaxy	From HyperLEDA (Sept. 2010): log(w) = 2.238; [w = 172 km/s] 5: HI line width measured at 50% of maximum	○
HI line width	1994AJ....107...99R	HI line width	...	Radio	Galaxy	From HyperLEDA (Sept. 2010): log(w) = 2.790; [w = 616 km/s] 1: HI line width measured at 20% of maximum	○
Luminosity Class							
LIRG	2003AJ....126.1607S	LIRG	...	Infrared	Galaxy	$\log(L_{IR}/L_\odot) = 11.85$; $H_0 = 75\ kms^{-1}Mpc^{-1}$,	
ULIRG	2009ApJS..182..628V	ULIRG	...	Optical	Nucleus	...	
LIRG	2009PASP..121..559A	LIRG	...	Optical	Nucleus	...	
Galaxy Morphology							
I0: pec	1991RC3.9.C...0000d	I0? pec	...	Optical	Galaxy	Code: [.I.0.*P]	
PECULR	1973UGC...C...0000N	pec	...	Optical	Galaxy	...	
S0/a	1994AJ....107.1629T	S0/a	...	Optical	Galaxy	...	
multiple collision	1961CGCG1.C...0000Z	multiple collision	...	Optical	Galaxy	...	
Activity Type							
S3	2006A&A...455..773V	LINER	...	Optical	Nucleus	Low-ionization emissi Relevant reference: 19	

Detailed classifications in 7 domains for individual objects and for building samples



Example queries:

- Barred spirals of any sub-type
- Galaxies with Morphological Type S0 and nuclear Spectral Type Seyfert 2
- Galaxies with Luminosity Class ULIRG and Spectral Type AGN (any subclass)
- Galaxies with Cepheid distance indicators
- Galaxies with available H I (21 cm) line widths

Build user-customized data tables

- Combine photometric and diameter measurements from major surveys, along with Classifications and basic data, into a single table
- Vastly simplifies analysis of multiwavelength data for galaxy samples
- Accessible via new forms that search input object lists *By Name* and *Near Name/Position*, and also via queries for objects *By Classification*
- Options to choose what data columns to include

Derived kinematic V_{LSR}

Derived physical diameters

Derived luminosities (νL_ν)

Input a source list and find positional cross-matches with objects in NED

Coming soon...

Hierarchy in the Universe: NED is delivering a unique science service that enables exploration of environments of galaxies with available redshifts.

- Color coded shells around the target object
- Color coded approaching and receding ΔV
- Traverse the environment (recenter or translate)
- References for redshift measurements
- Available on the NED Proto site **Jan 2013**
- Talk and demos at AAS meeting in Long Beach, CA Jan 2013 (Madore et al.)
- Future: Survey selection and dynamic plot/table interactions

NASA/IPAC EXTRAGALACTIC DATABASE
Date and Time of the Query: Mon Oct 29 16:07:38 2012 PDT
Help | Comment | NED Home

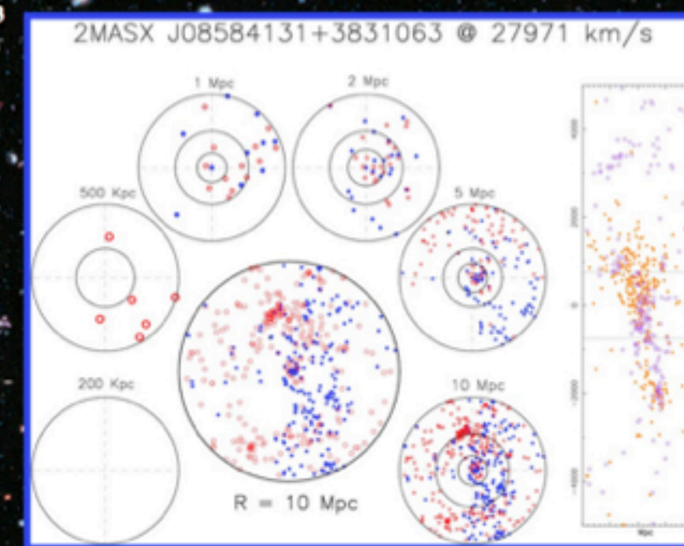
Environment search around 2MASX J08584131+3831063 at user defined cz = 27971 km/s

Cosmology Parameters Applied: H_o= 73; Ω_{matter} = 0.27; Ω_{vacuum} = 0.73
Note: Published redshifts used without any reference frame corrections

Angular-Size Distance = 343.7 Mpc
Search Radius of 10 Mpc = 1.667 deg

Projected Distance	0.5 Mpc	1 Mpc	2 Mpc	5 Mpc	10 Mpc
max($\lvert\Delta_{cz}\rvert$) [km/s]	250	500	1000	2500	5000
Object Counts	6	23	47	166	486

z-Reference	No.
2004SDSS3.C...0000:	459
1998ApJS..115....1S	16
2004SDSS2.C...0000:	10
1995ApJS..100...69F	1



Recenter	Translate	Name	RA Dec (J2000)	Object Type	cz [km/s]	z-flag	z-Reference	PA [°]	Sep. [Mpc]	Δ_{cz} [km/s]
⇒	⇒	2MASX J08583205+3829353	08h58m32.02s +38d29m35.6s	G	27990		2004SDSS3.C...0000:	-129.8	0.2358	19
⇒	⇒	2MASX J08583994+3833533	08h58m39.94s +38d33m53.2s	G	28065		2004SDSS3.C...0000:	-5.4	0.2796	94
⇒	⇒	SDSS J085843.12+382817.2	08h58m43.13s +38d28m17.3s	G	28183		2004SDSS3.C...0000:	172.7	0.2837	213
⇒	⇒	2MASX J08582719+3827564	08h58m27.17s +38d27m56.1s	G	28099		2004SDSS3.C...0000:	-138.9	0.4202	128
⇒	⇒	SDSS J085829.34+382704.1	08h58m29.34s +38d27m04.2s	G	28190		2004SDSS3.C...0000:	-149.9	0.4661	219
⇒	⇒	SDSS J085816.94+382946.5	08h58m16.95s +38d29m46.5s	G	28192		2004SDSS3.C...0000:	-105.5	0.4943	222
⇒	⇒	2MASX J08584131+3831063	08h58m41.29s +38d31m06.2s	G	27549		2004SDSS3.C...0000:	0.0	0.0000	-422
⇒	⇒	2MASX J08584541+3831213	08h58m45.42s +38d31m21.1s	G	28470		2004SDSS3.C...0000:	72.9	0.0846	500
⇒	⇒	2MASXi J0858202+383121	08h58m20.32s +38d31m21.7s	G	28423		2004SDSS3.C...0000:	-86.4	0.4108	453

Use case: Astronomer queries a 2MASS source and learns that it is a member of galaxy cluster Abell 724

THE END!