GOALS: The Great Observatories All-sky LIRG Survey

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Collaborators

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- **D. B. Sanders**, J. Barnes, L. Chien (IfA, Hawaii)
- K. Iwasawa (MPG, Garching)
- … and others

Luminous Infrared Galaxies

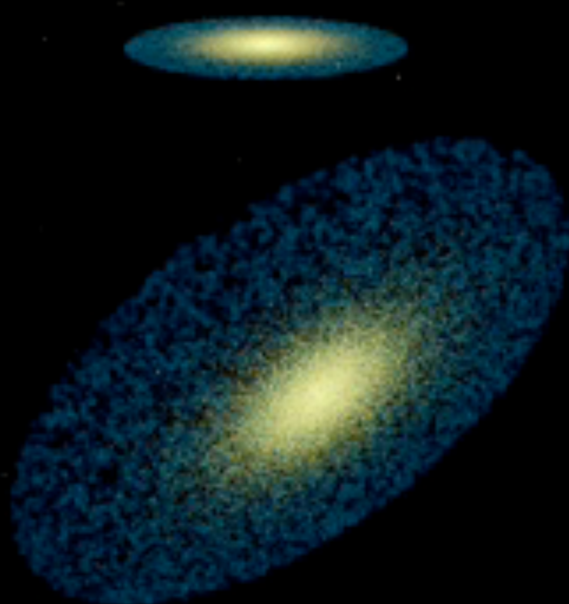
(LIRGs: L_{IR}[8-1000 μm] ≥ 10^{11} L_{sun})

- Spiral galaxies which show an increasing tendency to be involved in interactions or mergers with increasing luminosity
- Rich ISMs - dust and star-forming molecular gas
- Rich in optically-visible star clusters
- Optical evidence of active galactic nuclei in a substantial fraction

Why do we care about them?

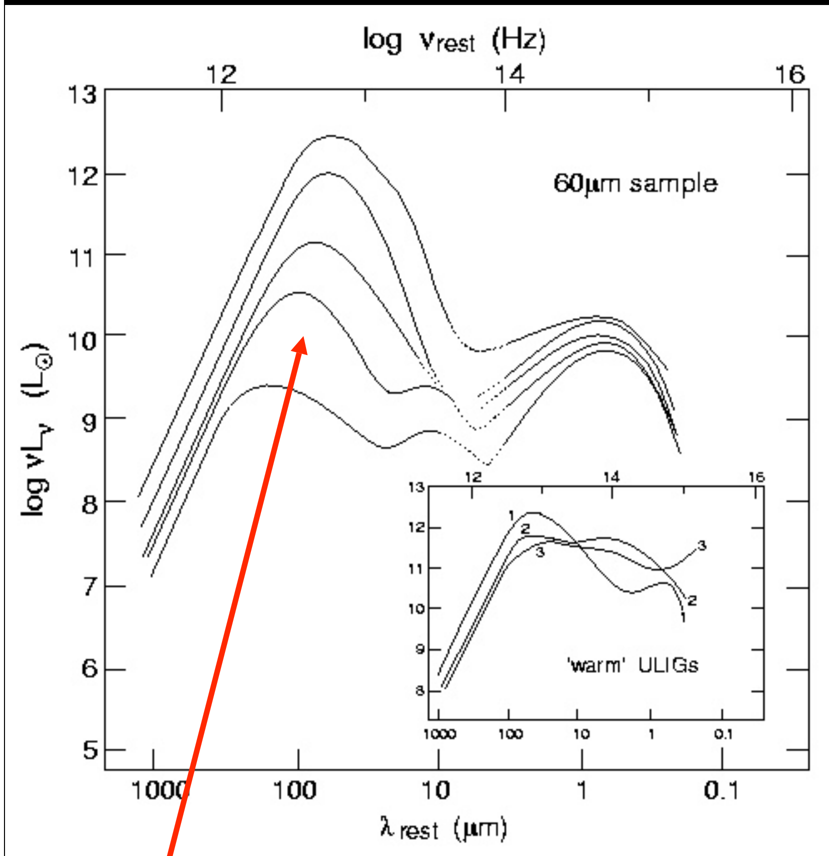
- Sites of enhanced star formation & (sometimes) AGN activity, making them ideal for studying the evolution of both phenomena & the interplay between them
- Method of building up massive galaxies
- More common in the early universe than in the present epoch, with space densities comparable to nearby, normal massive galaxies

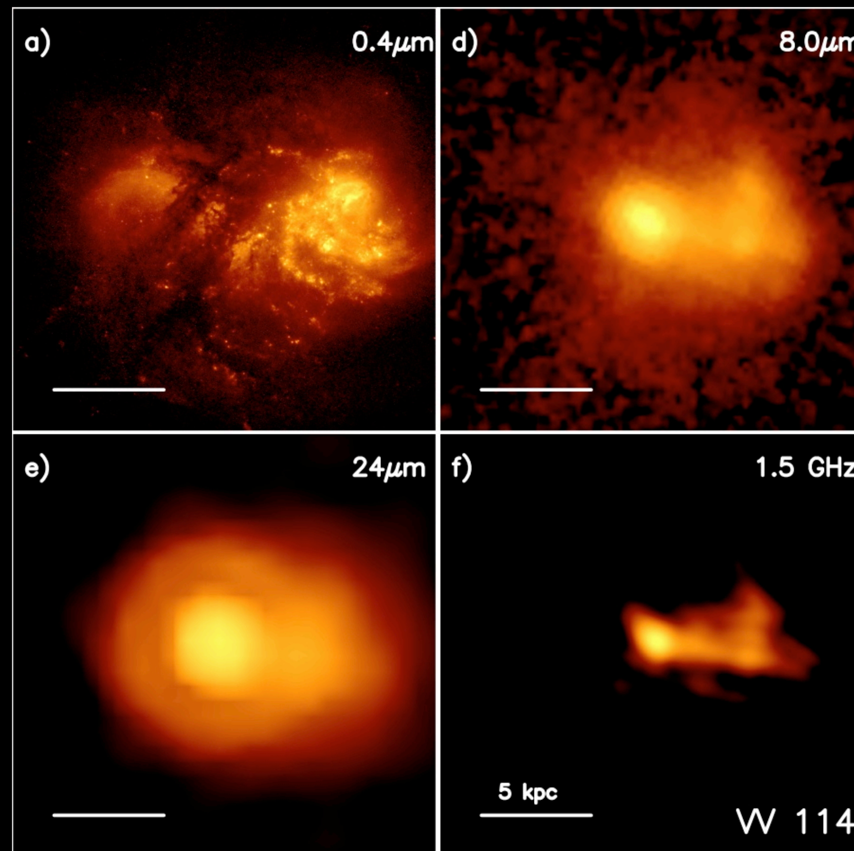
Issue 1: Mergers take ~ few x 10^8 years to evolve.



(C. Mihos)

Issue 2: Dust obscuration affects our perception of what is occurring



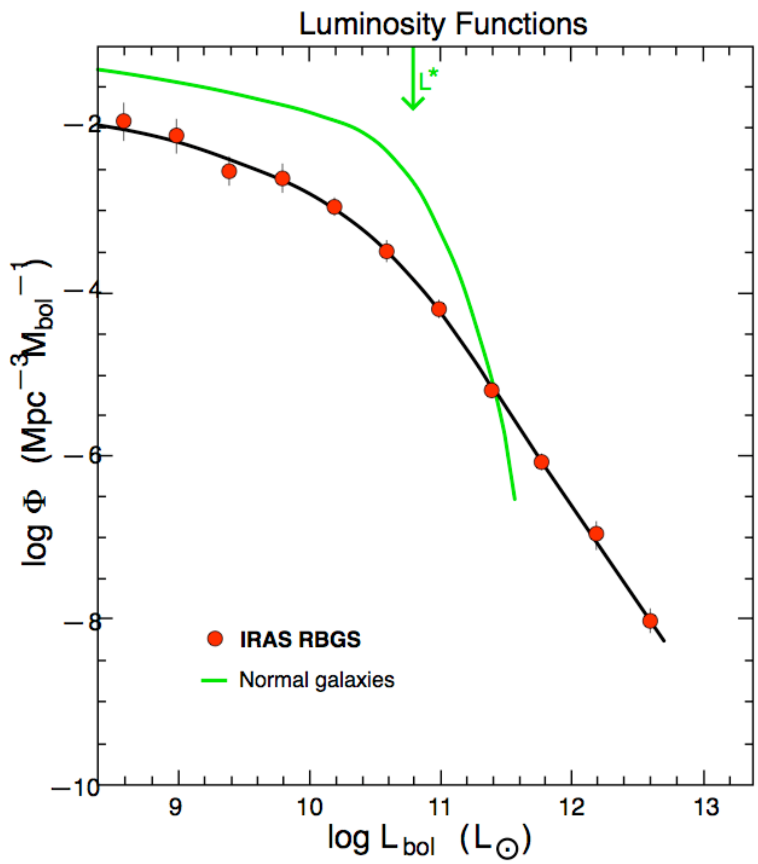


Thermal emission from dust heated by massive stars & putative AGN

(SED - Sanders & Mirabel 1996; Galaxy - Vavilkin et al. 2007)

The IRAS Revised Bright Galaxy Sample (RBGS)

- IRAS-detected galaxies with $f_{60\mu m}$ > 5.24 Jy & |b| > 5°
- 629 objects with z_{median} ~ 0.008 & $z_{maximum}$ ~ 0.08
- **200 with $L_{IR} \geq 10^{11.0}$ L_{sun}**
- Increasing signs of interaction & merger with increasing L_{IR}



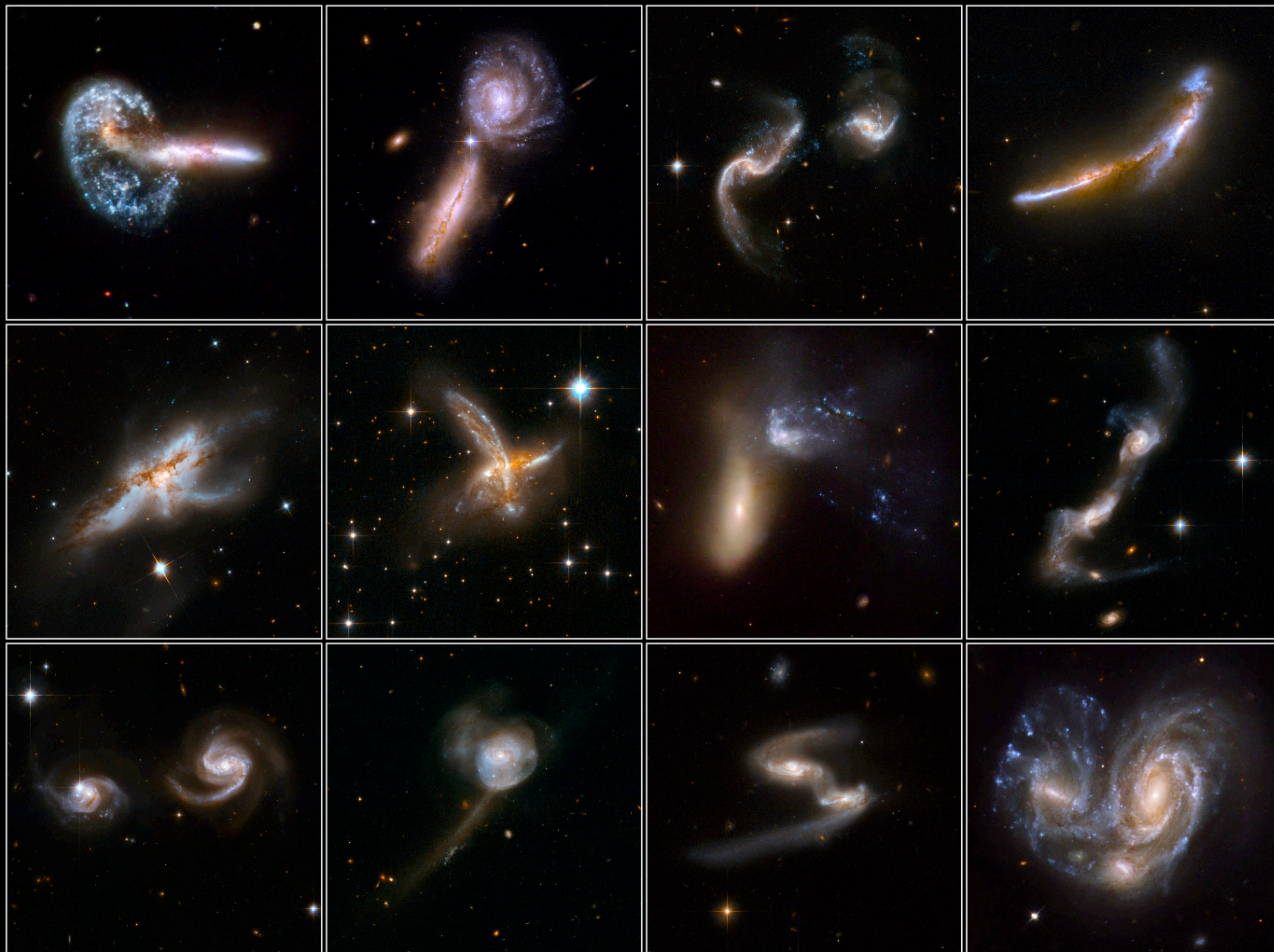
(Sanders et al. 2003)

GOALS Campaigns

- *Spitzer Space Telescope* IRAC and MIPS Imaging, and IRS Spectroscopy ($L_{IR} \geq 10^{11.0}$ L_{sun})
- *GALEX* UV imaging ($L_{IR} > 10^{11.5}$ L_{sun})
- *HST B, I*, and *H*-band Imaging ($L_{IR} > 10^{11.4}$ L_{sun}), and UV-band imaging of a subset of cluster-rich LIRGs
- *Chandra X-ray Observatory* data (most of *HST* sample)

Interacting Galaxies

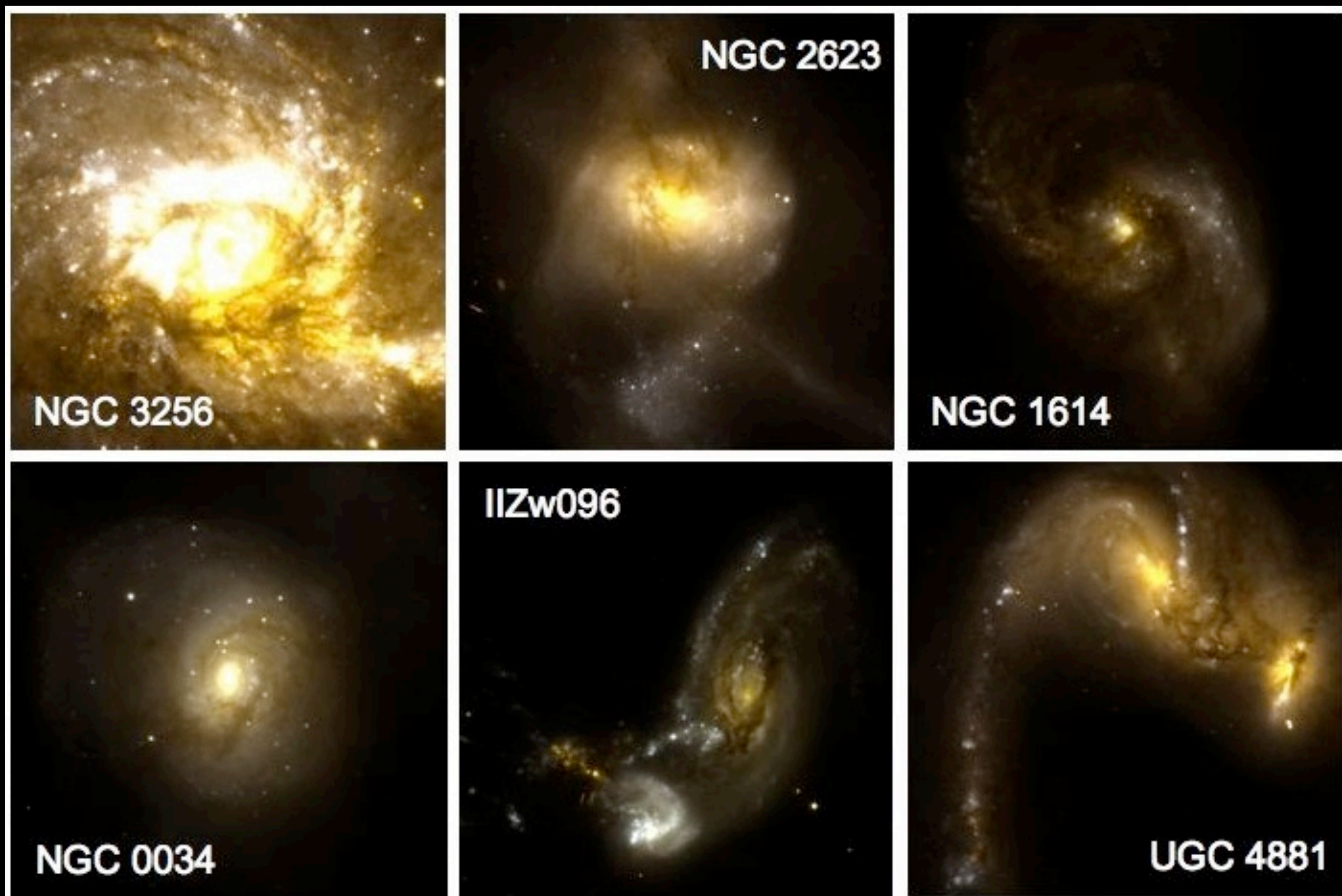
Hubble Space Telescope • ACS/WFC • WFPC2



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

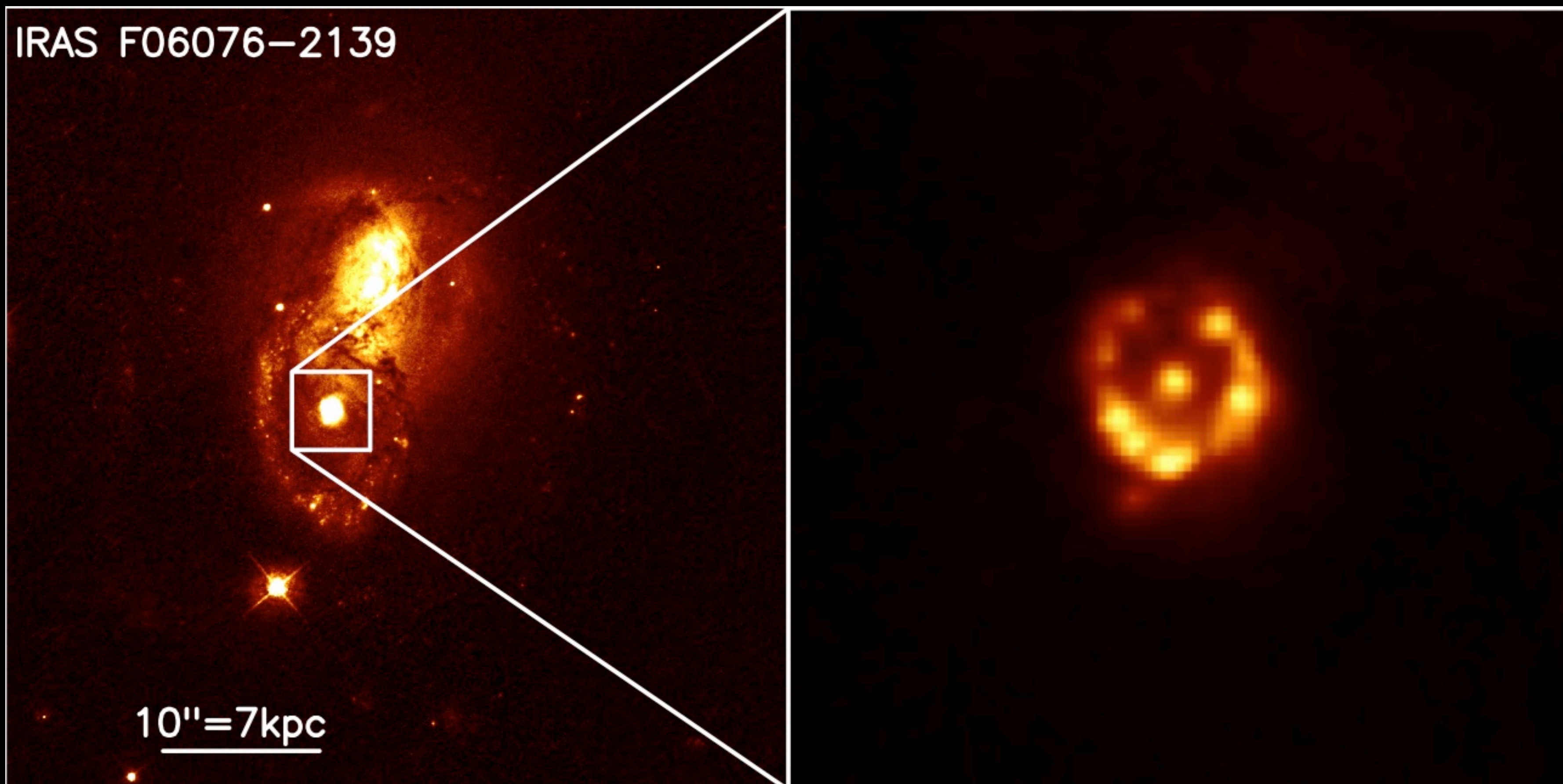
STScI-PRC08-16a

Blue star-forming knots around nuclei & in extended tails

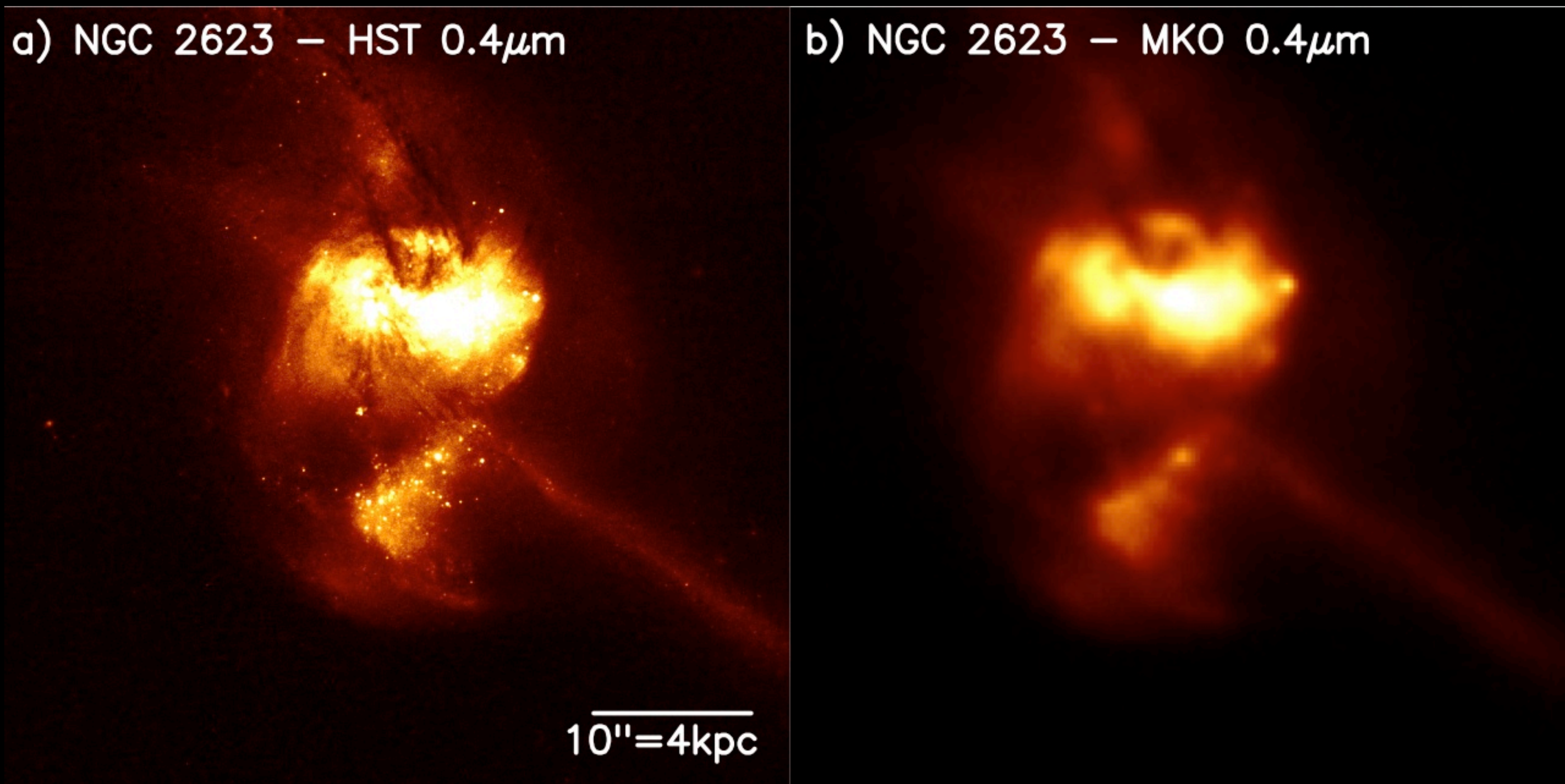


(Evans et al. 2007)

ACS survey - cluster ID benefits from HST resolution

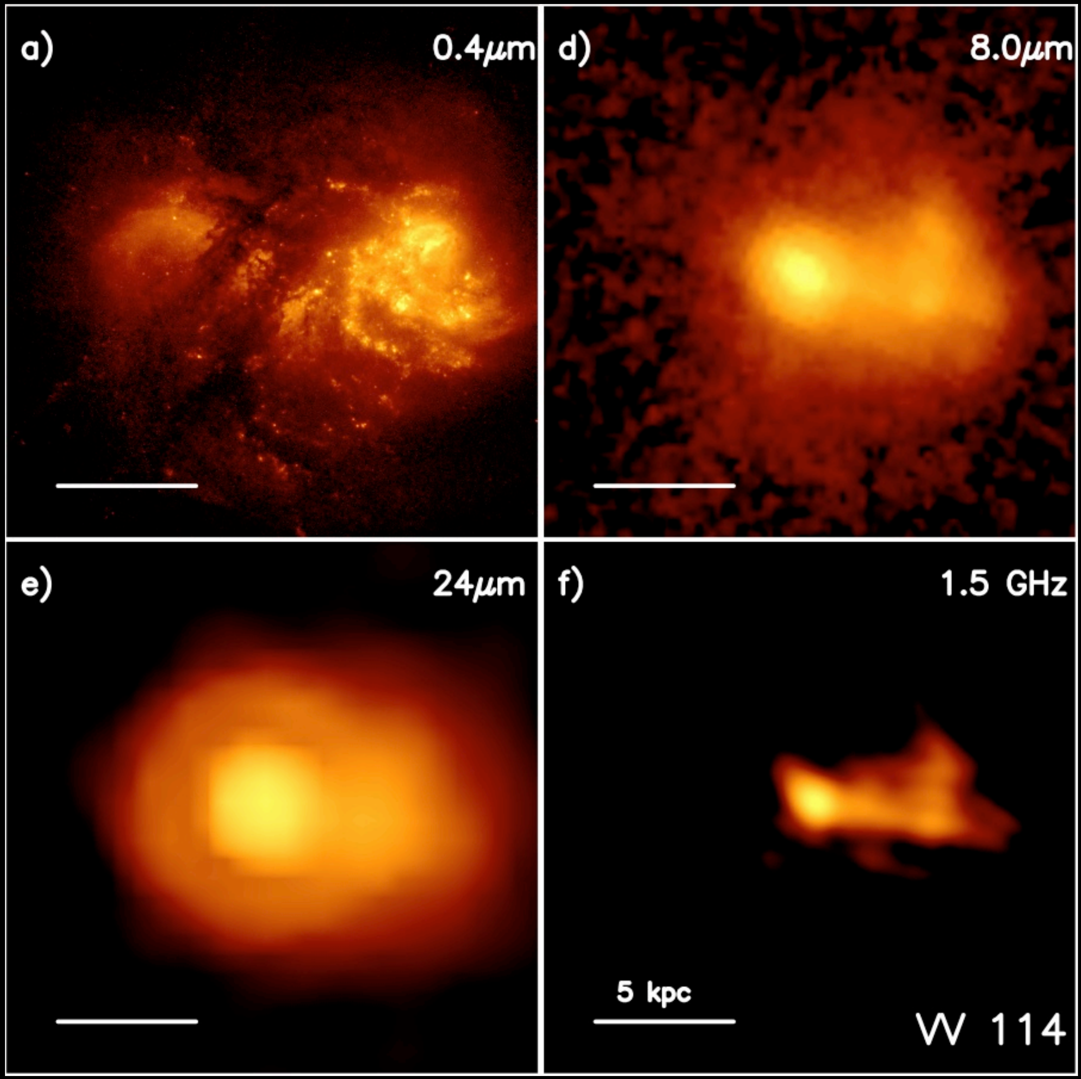


HST ACS vs. ground-based telescopes @ 0.4μm - a comparison



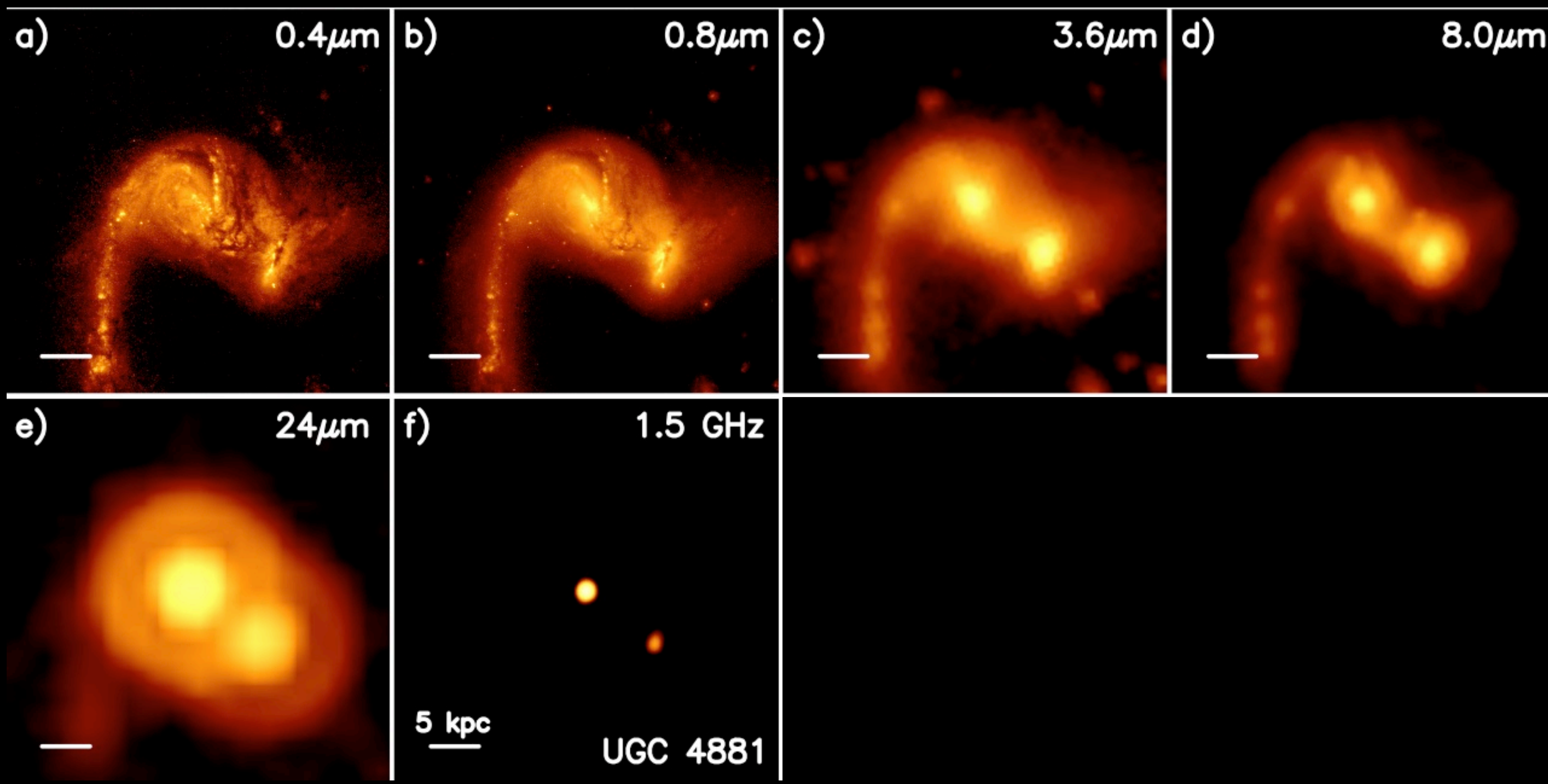
Ground-based telescope image - (Ishida 2004)

GOALS multi-wavelength dataset



(Evans 2007)

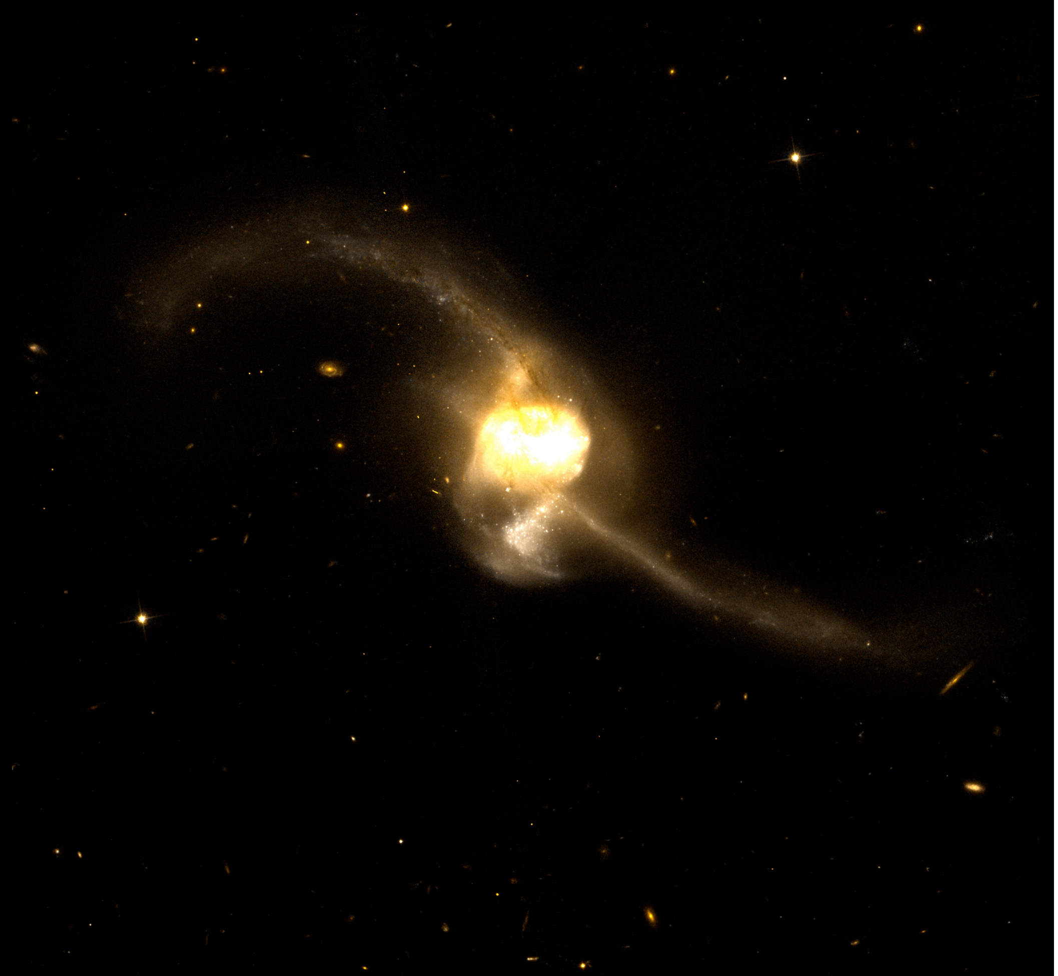
GOALS multi-wavelength dataset



(Vavilkin et al. 2008)

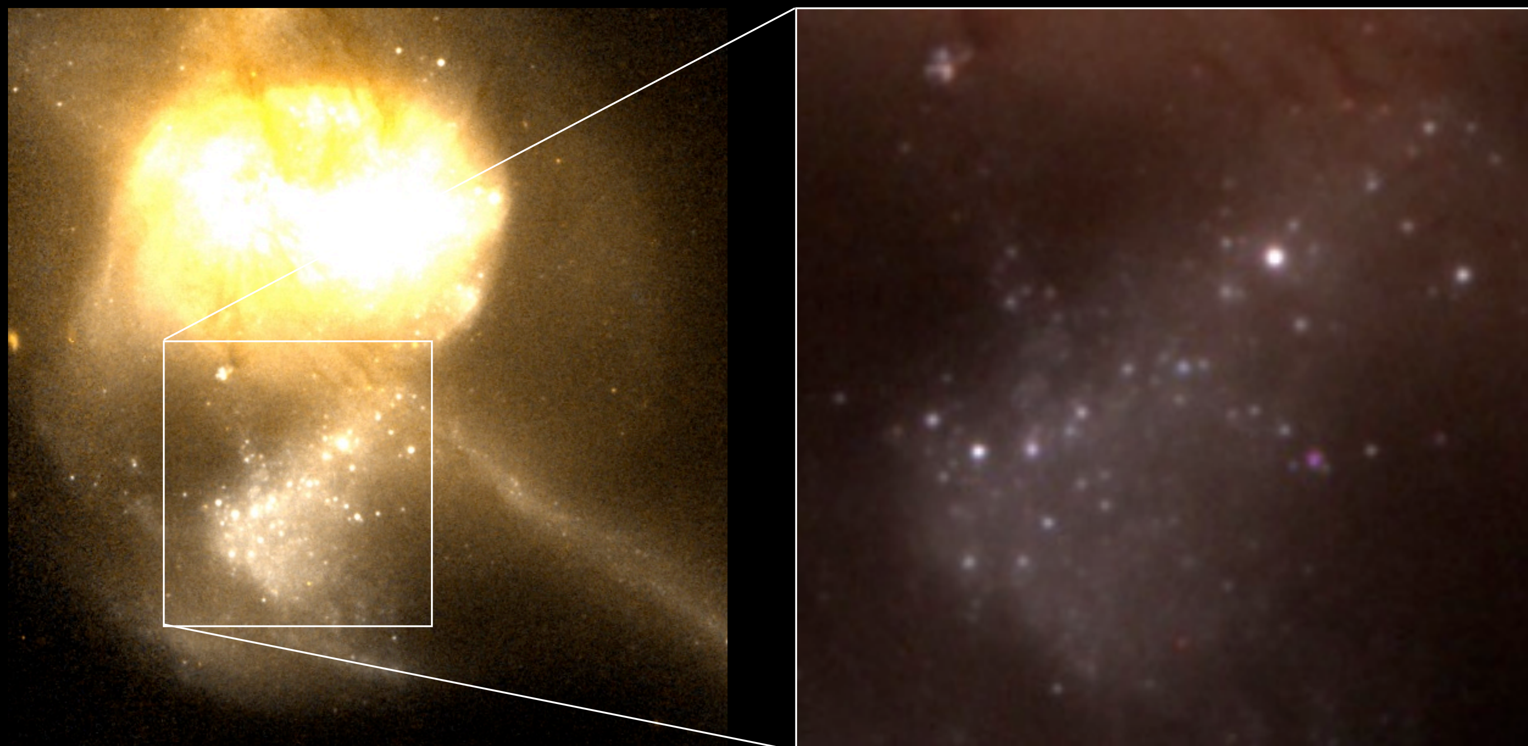
GOALS case study: NGC 2623

- Late-stage, Toomre sequence merger
- $L_{IR}(8\text{–}1000\mu m) \sim 3.3\times10^{11}$ L_{sun}
- $M(H_2) \sim 8\times10^9$ M_{sun} (Sanders et al. 1991; Bryant & Scoville 1999)
- Optical classification ambiguous due to Hβ non-detection (Kim et al. 1995)



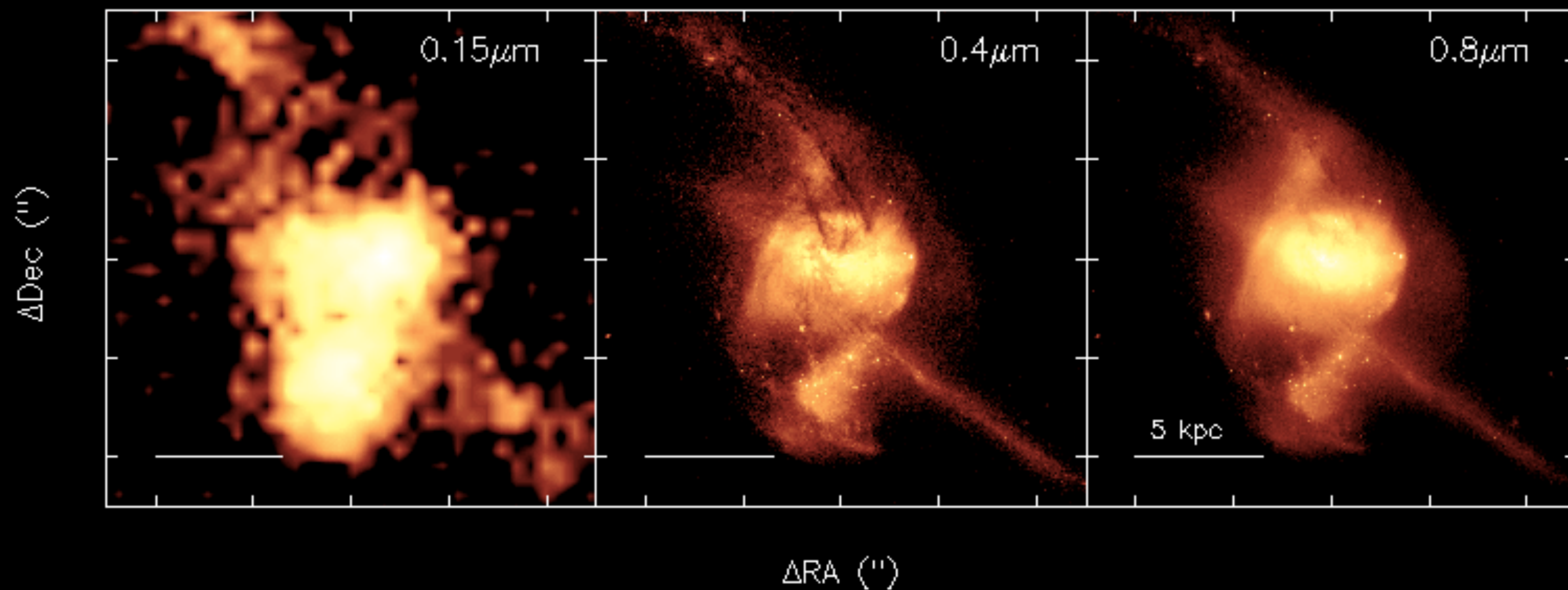
(Evans et al. 2008)

B & I-band off-nuclear star formation



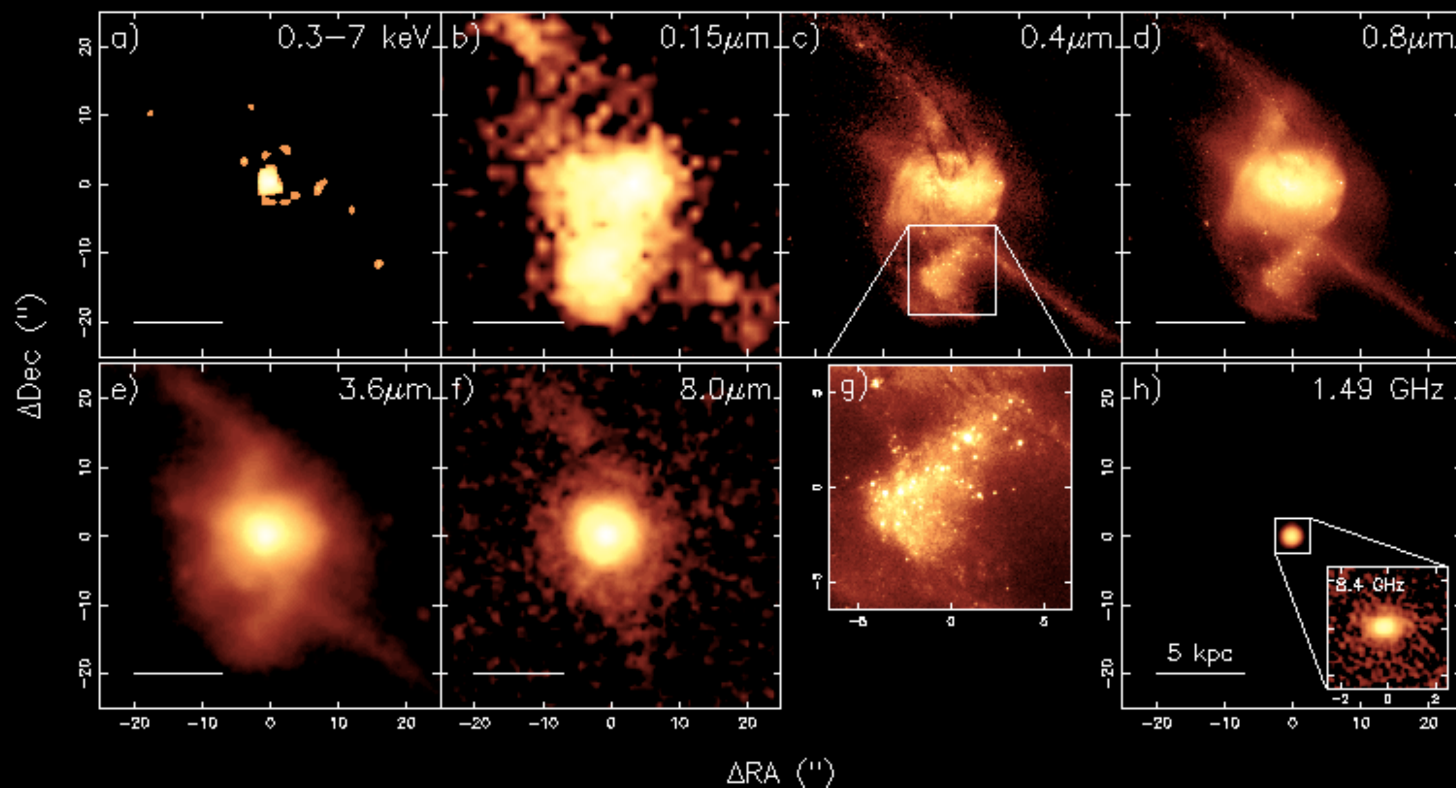
- About 100 clusters with M_V ~ -6.6 to -12.6 (within range of M_V for Antennae Galaxy)
- Age range ~ 10^{6-7} yr (A_V ~ 1) or few x 10^8 yrs with A_V ~ 0). Keck spectroscopy and HST UV data of the brightest clusters should constrain this.

The far-UV



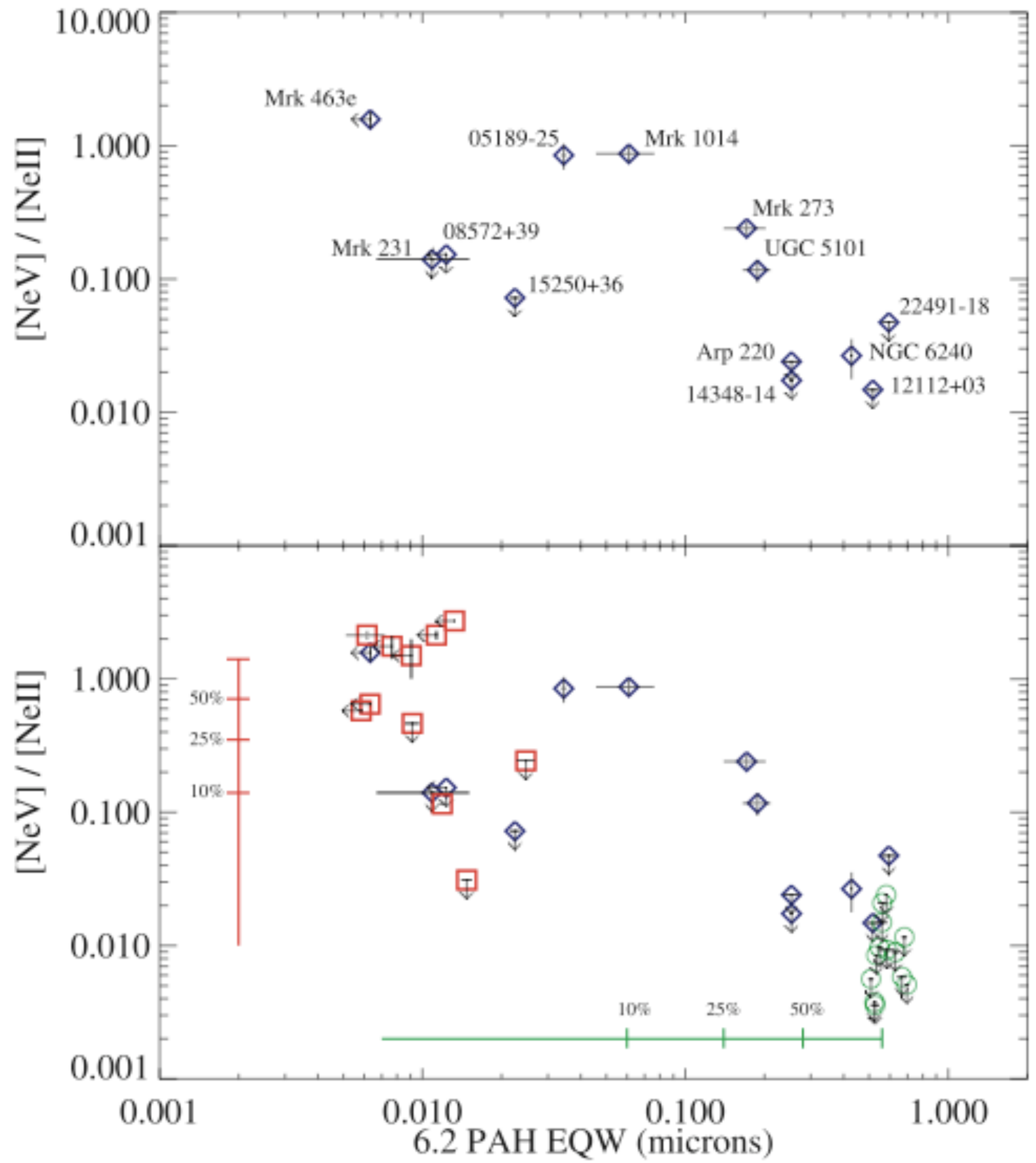
- In the Far-UV, the off-nuclear region (ONR) & nuclear region are nearly comparable in luminosity
- The UV-derived star formation rate (SFR) of the ONR is ~ 0.1 - 0.2 M_{sun} yr^{-1}
- The SFR rate is comparable to that of the LMC, which is twice the size and half as bright as the ONR

A multi-wavelength view of NGC 2623



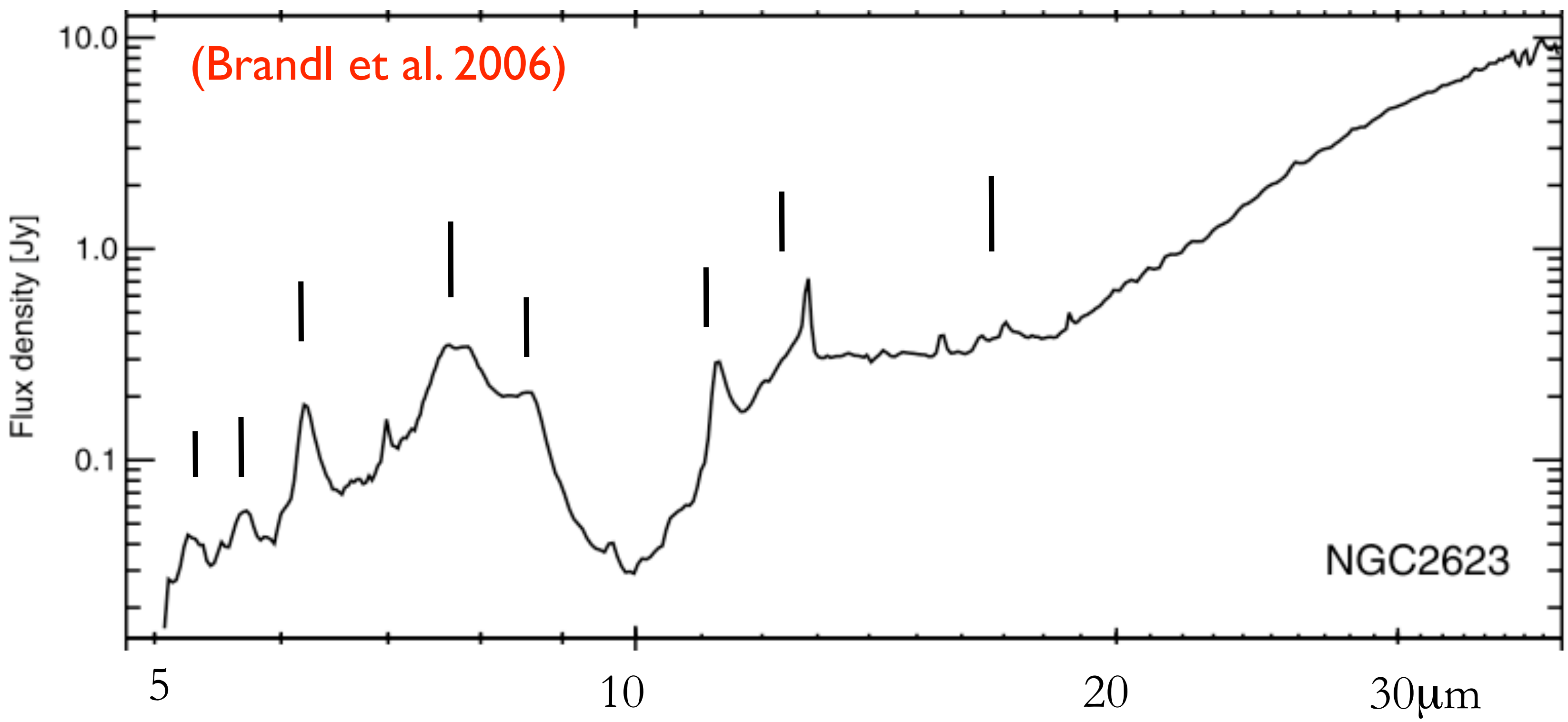
- The ONR contributes significantly less energy relative to the nuclear region at longer wavelengths
- The inner 600 - 700 pc produce almost all of the luminosity of NGC 2623

Mid-IR diagnostic diagram



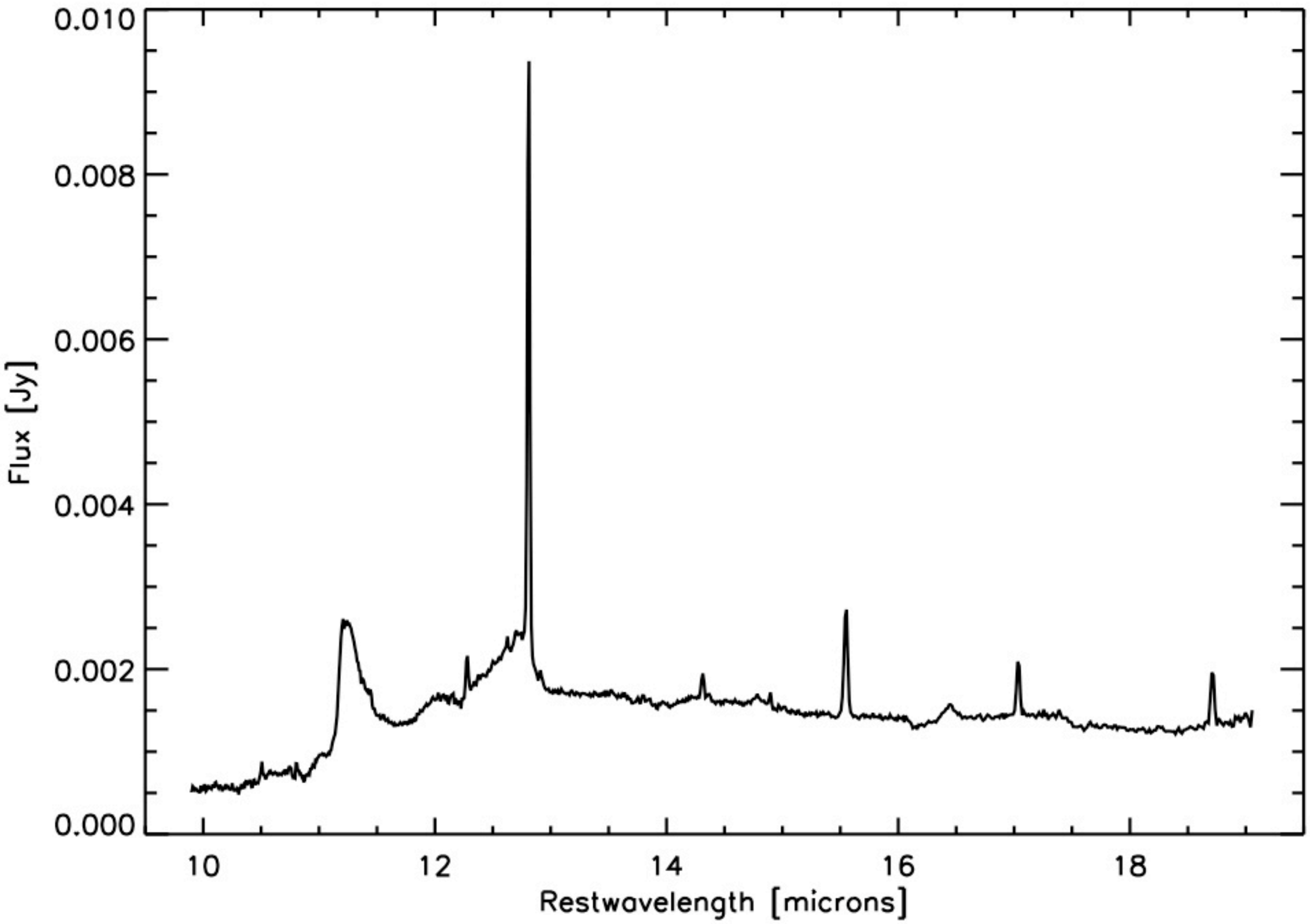
(Armus et al. 2007)

Nuclear energy source(s)?



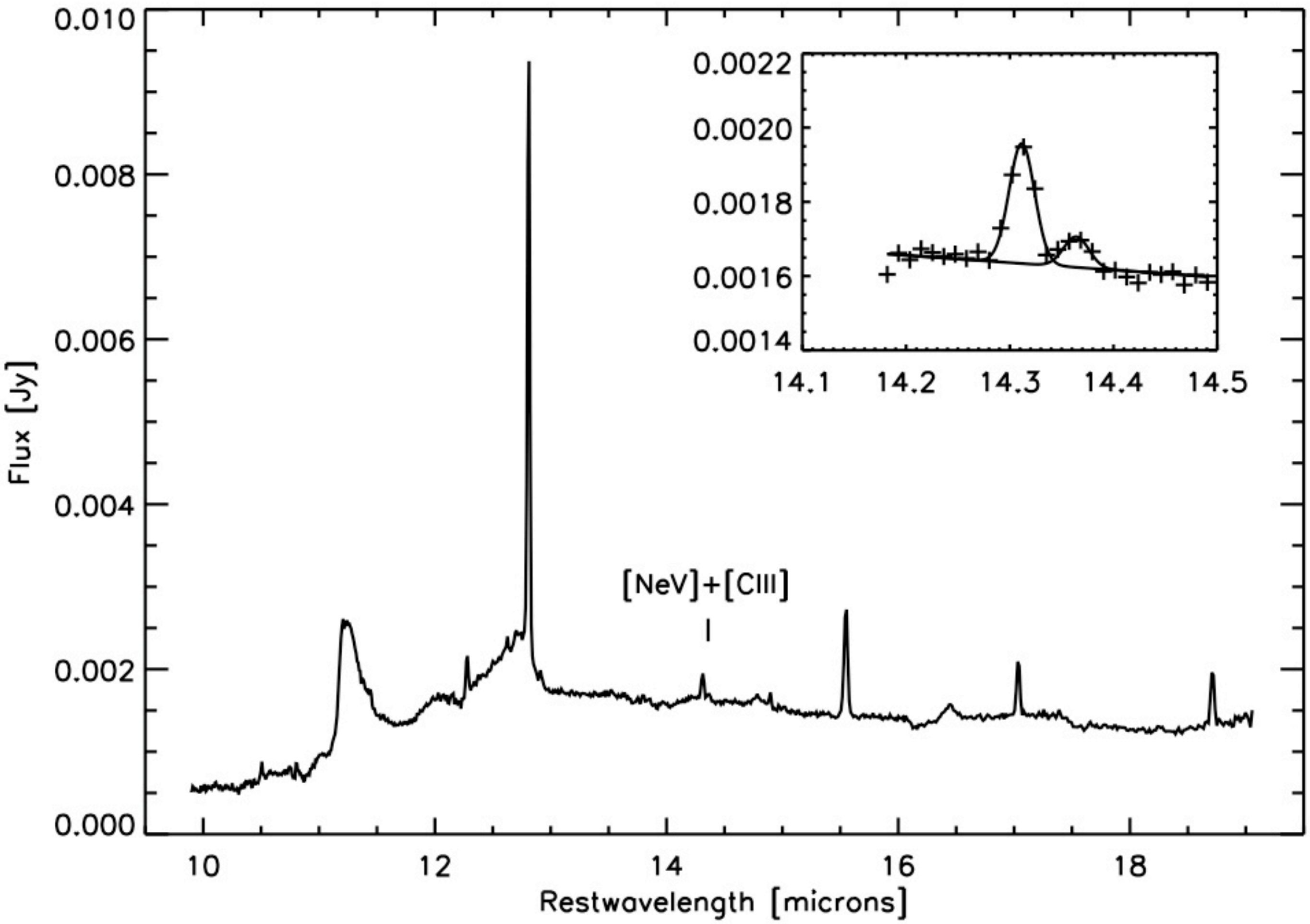
- The general appearance of the low-resolution IRS spectrum of NGC 2623 is that of a starburst galaxy
- 6.2μm PAH equivalent width (= 0.6μm) consistent with star formation
- **Stand-out feature**: 10μm silicate absorption ($\tau_{9.8}$ ~ 1.5)

Nuclear energy source(s)



- Spitzer short high-resolution IRS spectrum

Nuclear energy source(s)



- Faint high-ionization [Ne V] 14.32μm line detected. It is only seen in AGN hosts.

Nuclear energy source(s)

- The [Ne V] / [Ne II] 12.8μm ratio is low (~ 0.05)
- The IRS AGN evidence is consistent with the X-ray evidence of an AGN based on the hardness of the X-ray spectrum & the derived intrinsic X-ray luminosity (Maiolino et al. 2003; Evans et al. 2008)
- Evidence that the AGN is weak is consistent with the VLBI observation. It has a high brightness temperature core, but the core only accounts for 5% of the total radio emission (Lonsdale et al. 1993)

Star formation

- The IR and radio-derived SFR of the nuclear region ~ 50 M_{sun} yr^{-1}. The actual value depends ultimately on what fraction of the IR & radio are associated with the AGN.
- The UV-derived SFR of the ONR ~ 0.1 - 0.2 M_{sun} yr^{-1}.
- The optically-visible star formation, which prompted this case study, comprises < 1% of the total star formation in NGC 2623

Ground-based follow-up to GOALS

- Millimeter-line (CO, HCN) and continuum (dust) interferometric observations for tracing star forming molecular gas and the distribution of dust
- VLA Radio continuum for tracing star formation and AGN
- HI observations, which will aid and constraining dynamical models (e.g., J. Barnes Identakit program)
- and many others...