Remarkable Disk and Off-Nuclear Starburst Activity in the Tadpole Galaxy as Revealed by the Spitzer Space Telescope

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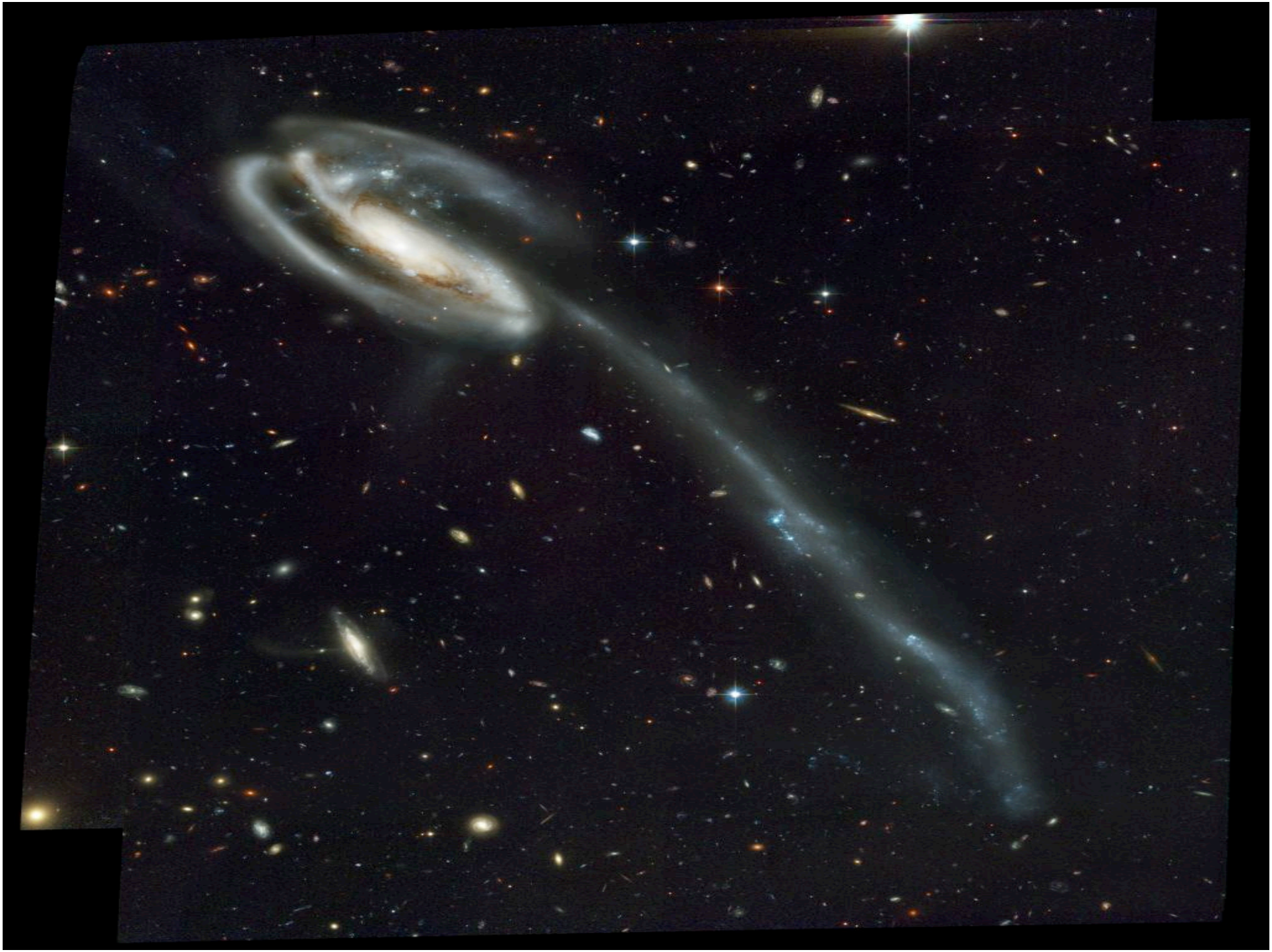
The Tadpole

- Designation: UGC 10214 = VV 29 = Arp 188
- z = 0.0310
- Distance = 129 Mpc (H_0=72 km s^{-1} Mpc^{-1})
- Gas rich main disk and tidal tail
- HST ACS images show newly forming, massive clusters in the spiral arms.
  - Some are SSC 'Super star clusters'
    - Total masses and stellar densities that rival globular clusters and dwarf galaxies ($M > 10^5 M_\odot$)

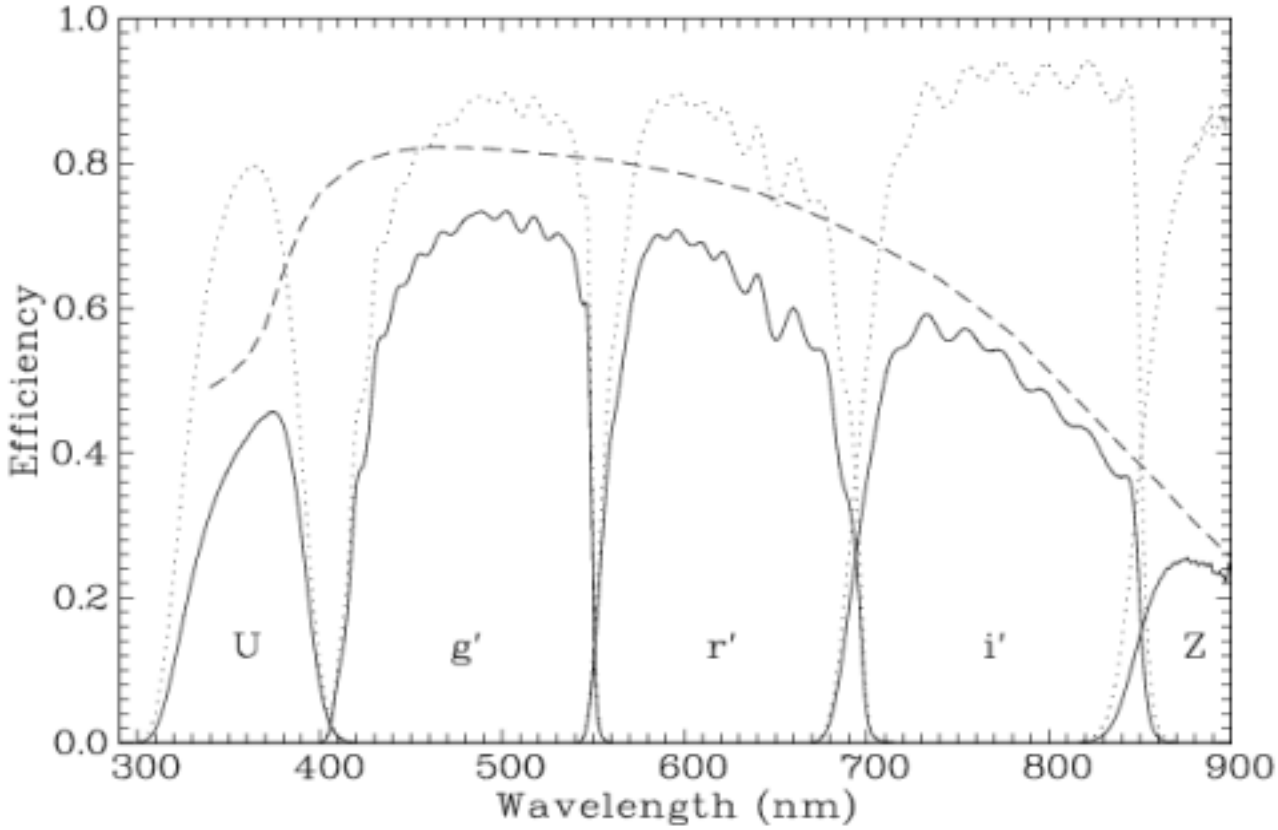


A Note on Mergers

- Boost level of star formation in disk galaxies
- Distortion of spiral arms
  - Violent star formation
    - Large-scale alterations to the underlying gas and stellar populations
    - ISM can collapse and form giant molecular clouds, spots for massive star formation
- Outer spiral arms
  - Atomic hydrogen stretched into filamentary tails
  - Will either dissipate into IGM or collapse back on merger remnant
    - Forms streams or ring-like structures
- But:
  - Not all tidally interacting galaxies show this remarkable star formation

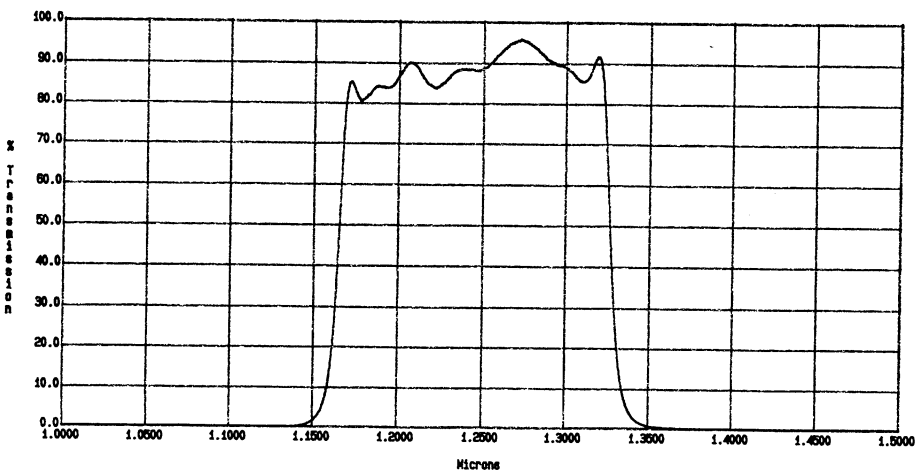
The Data

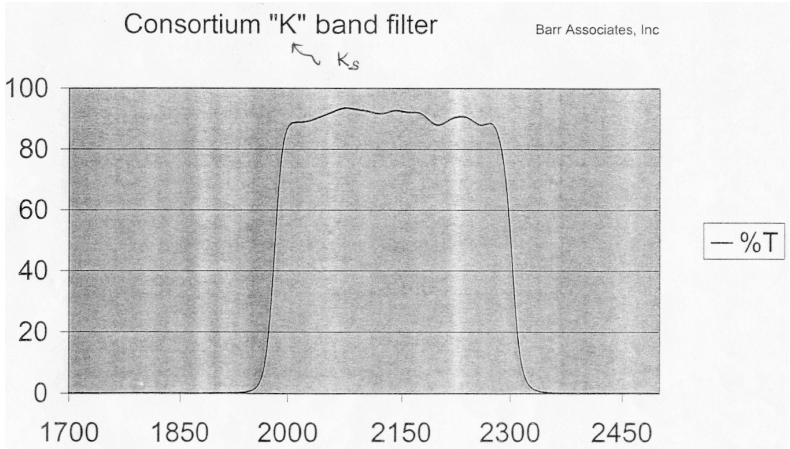
- Optical Images
  - U-band (0.358 um), g'-band (0.485 um), r'-band (0.624 um), and i'-band (0.774 um)
  - Gathered using the Issac Newton Telescope of the La Palma Observatory
  - Also employ HST ACS g-band (F475W) and V (F606W)



The Data II

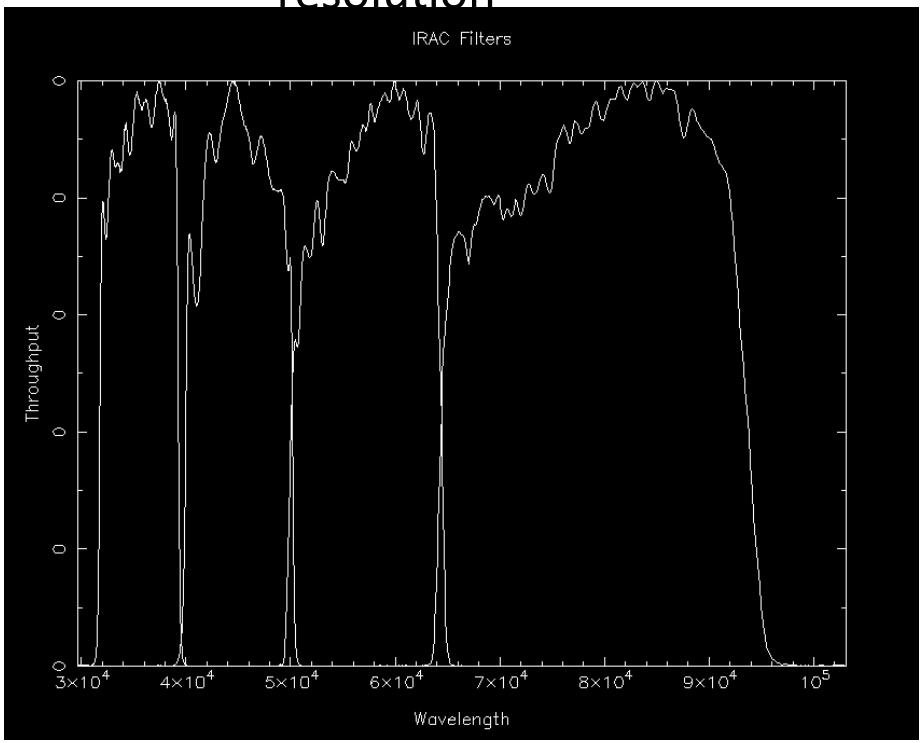
- Optical Spectroscopy
  - Tadpole Nucleus
  - The brightest tidal tail SSC – J160616.85+552640.6
    - Using the COSMIC camera on the Hale 200 inch (5m) at the Palomar Observatory
- NIR Images
  - J-band (1.2 um) and K_s-band (2.2 um)

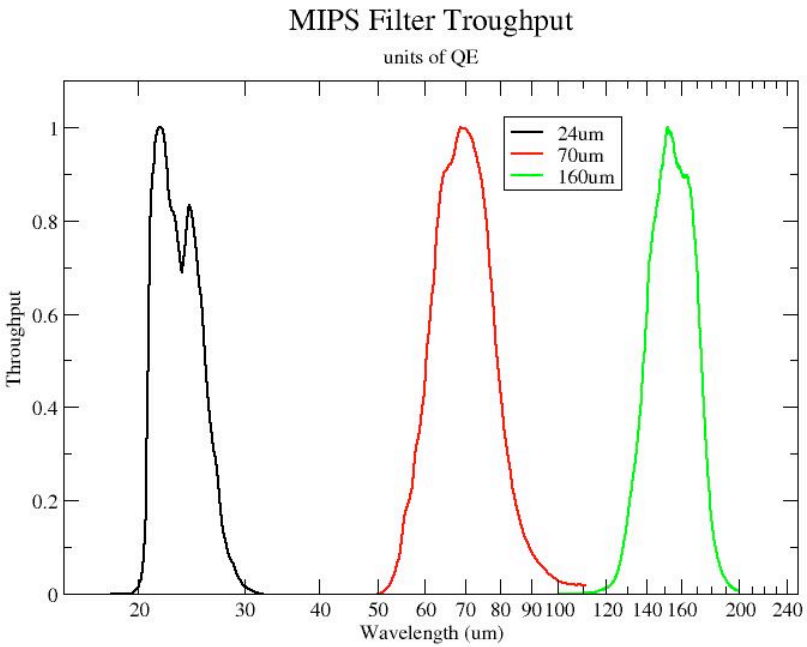




The Data III

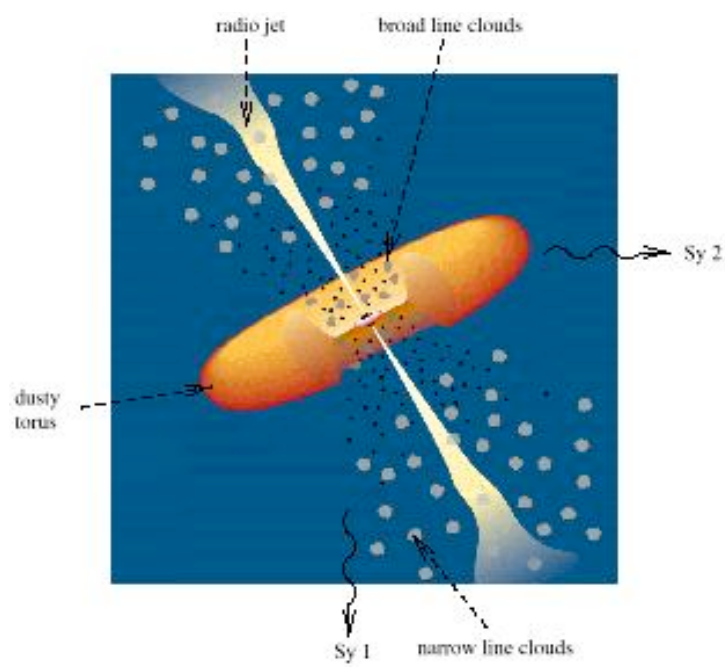
- Mid Infrared (MIR) – Spitzer Space Telescope
  - Four IRAC Bands
    - 3.6,4.5,5.8,8.0 um
  - Two MIPS Bands
    - 24, 70 um
- Resolution
  - All IRAC, NIR, and Optical data were reprojected and resampled onto a common grid and were Gaussian-convolved to match the 8 um image resolution

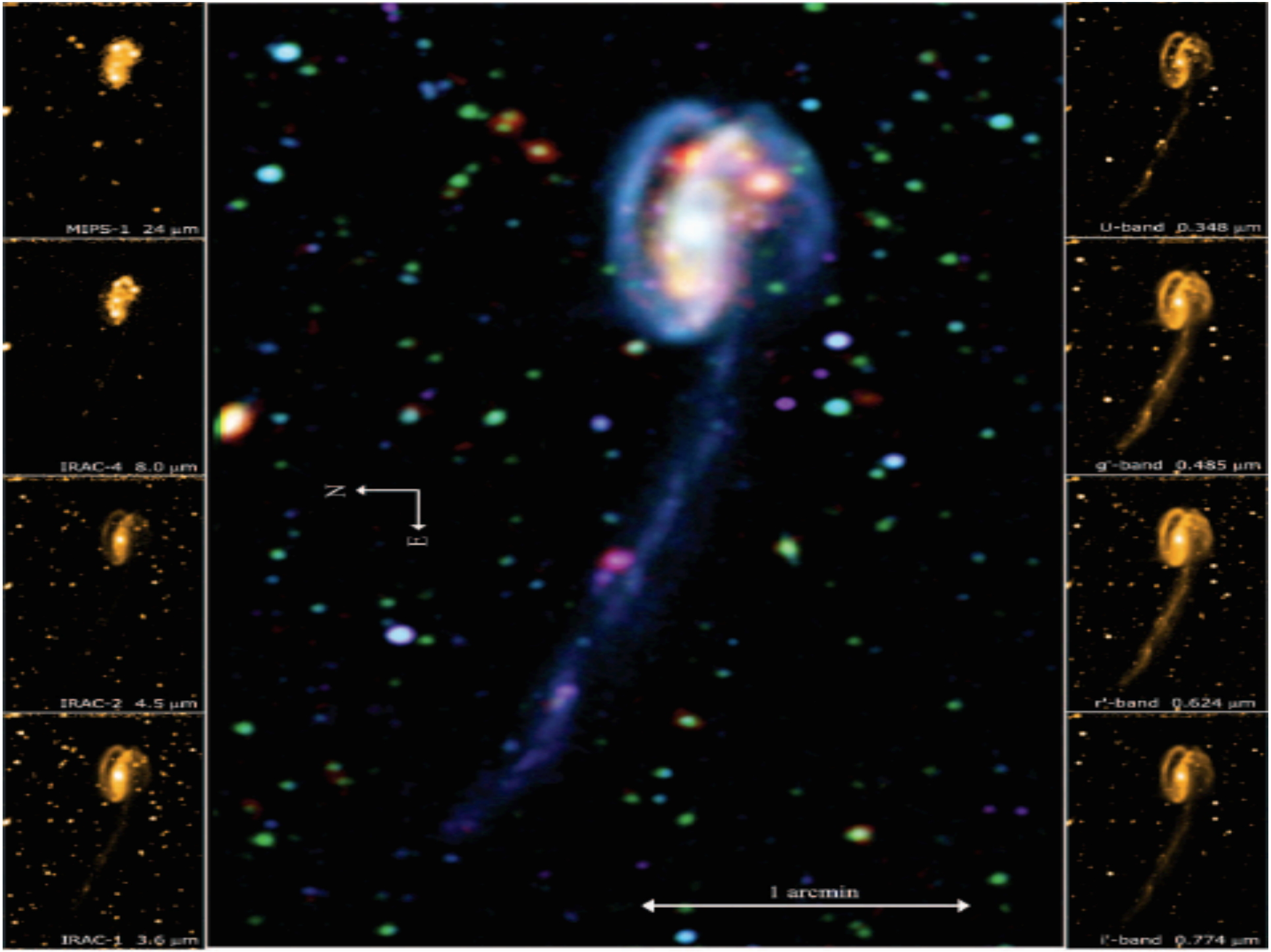




SED Templates

- SEDs from Tadpole are compared to representative galaxy types
  - 13 Gyr elliptical galaxies
    - The underlying (old) stellar components, dust free
  - S0/Sa Galaxies
    - Early-type disk galaxies
  - Sc disk galaxies
    - More active disk galaxies
  - IR-bright galaxies
    - Prototype starburst galaxy M82, with steeply rising SED from dust emission
  - Active, dust-absorbed nuclei
    - Seyfert 2 template




MIPS-1 24 μm
IRAC-4 8.0 μm
IRAC-2 4.5 μm
IRAC-1 3.6 μm
N
E
1 arcmin
U-band 0.348 μm
g'-band 0.485 μm
r'-band 0.624 μm
i'-band 0.774 μm

Global Measurements

TABLE 1

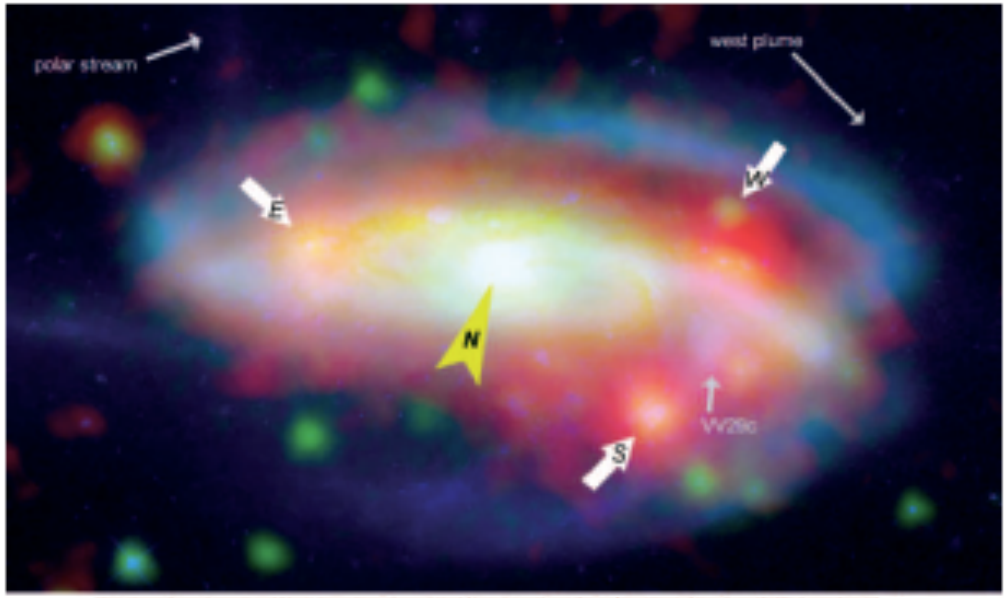
UGC 10214 Global Flux Density and Luminosity per Filter

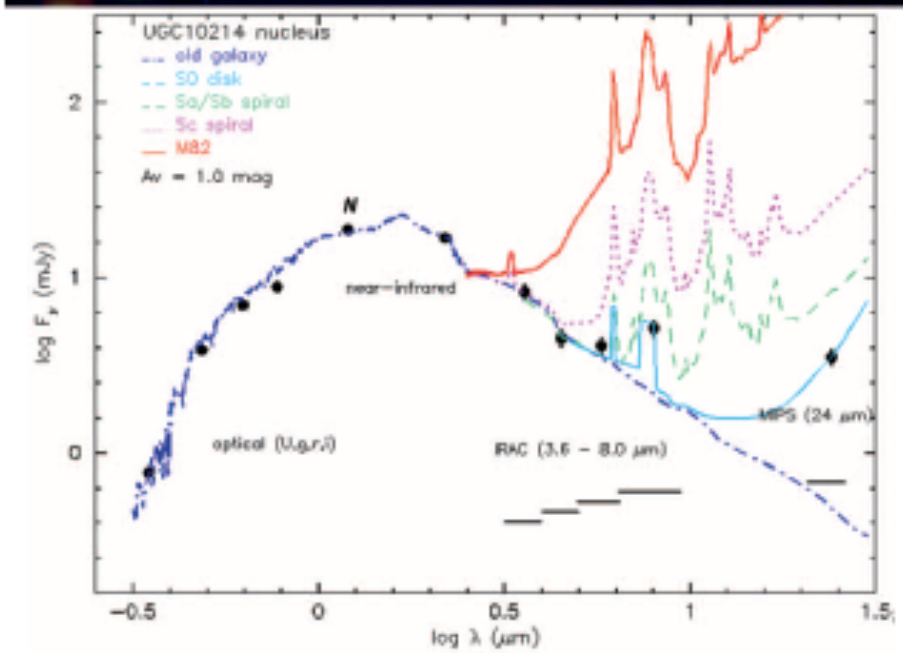
Band	λ_0 (μm)	$\Delta\lambda$ (μm)	F_ν (mJy)[a]	νL_ν ($10^9\ L_\odot$)[b]
U	0.3580	0.0638	2.132	8.89
g'	0.4846	0.1285	9.035	27.8
r'	0.6240	0.1347	15.292	36.6
I	0.7743	0.1519	19.848	38.3
J	1.250	0.162	47.181	56.4
K_s	2.150	0.397	43.020	29.9
IRAC-1	3.600	0.750	23.674	10.2
IRAC-2	4.500	1.020	13.816	4.58
IRAC-3	5.800	1.414	15.762	4.06
IRAC-4	8.000	2.974	28.253	5.27
MIPS-24	24.00	5.35	27.093	1.69
MIPS-70	71	19	207.5	4.36

[a] No reddening corrections are applied here; flux uncertainties are ~5% for the optical and NIR measurements and ~10%–20% for the IRAC and MIPS measurements.

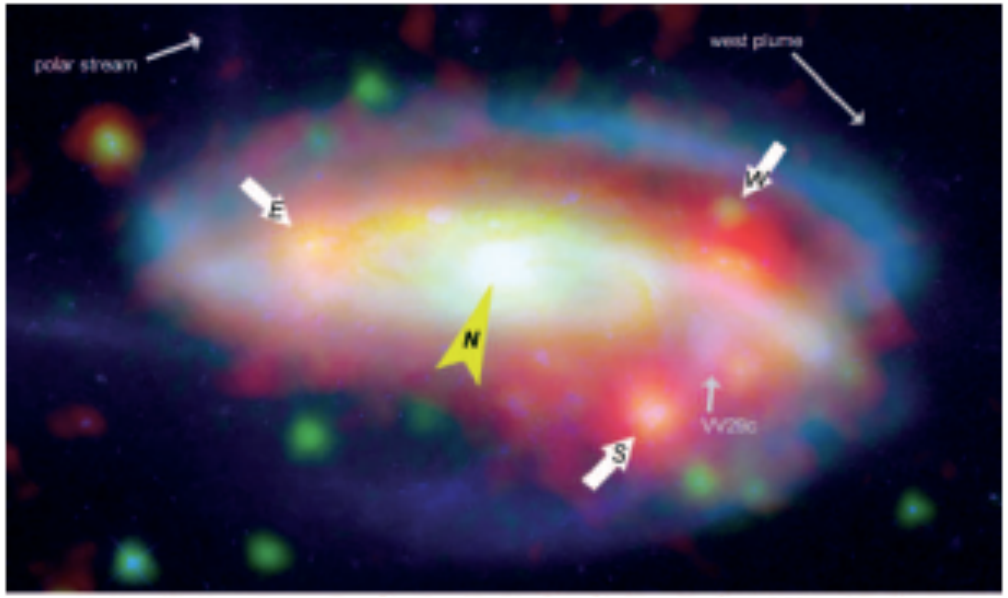
[b] Assuming a distance to UGC 10214 of 129 Mpc.

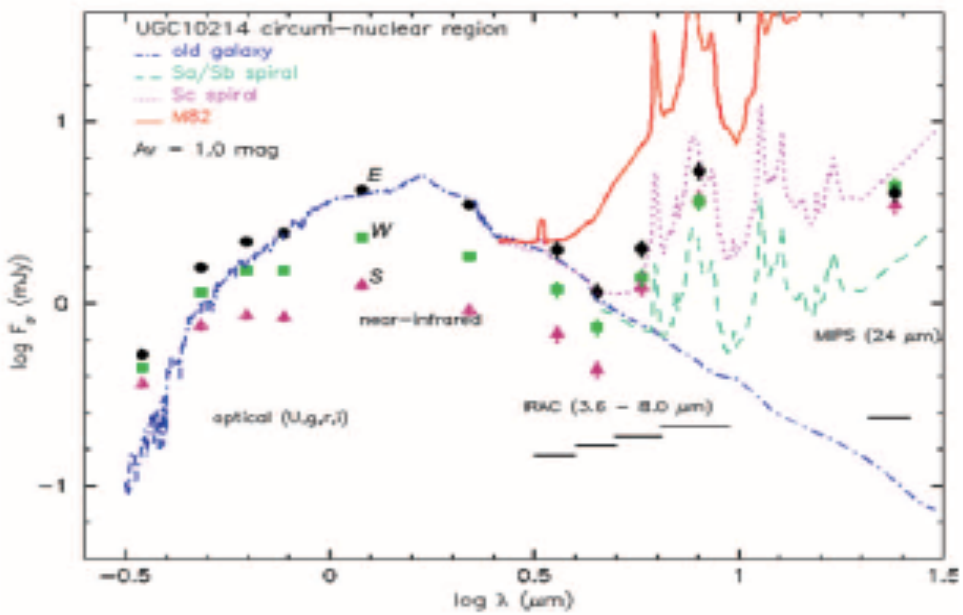
The Nucleus


polar stream
west plume
E
W
N
S
W2Sc

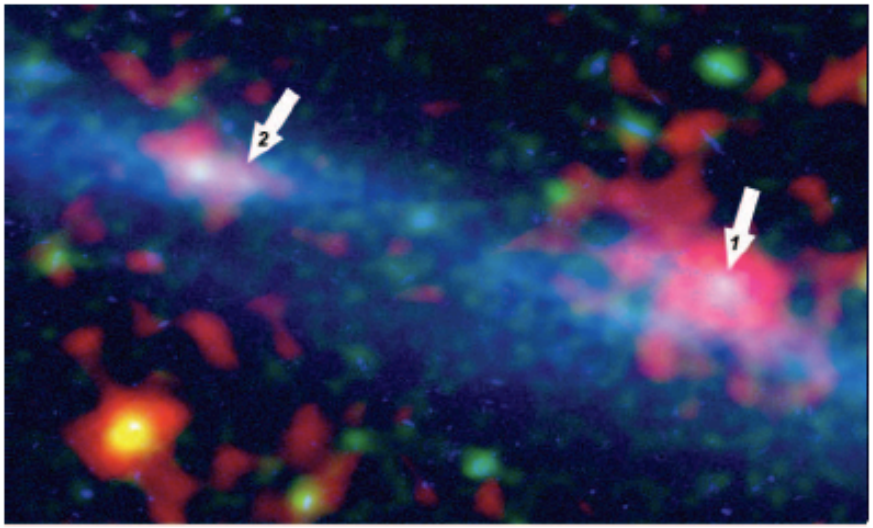

UGC10214 nucleus
old galaxy
S0 disk
Sa/Sb spiral
Sc spiral
M82
Av = 1.0 mag
N
near-infrared
optical (U,g,r,i)
IRAC (3.6 – 8.0 μm)
MIPS (24 μm)
log F_ν (mJy)
log λ (μm)
−0.5
0
0.5
1
1.5
2

Disk and Extranuclear Regions





The Tidal Tail



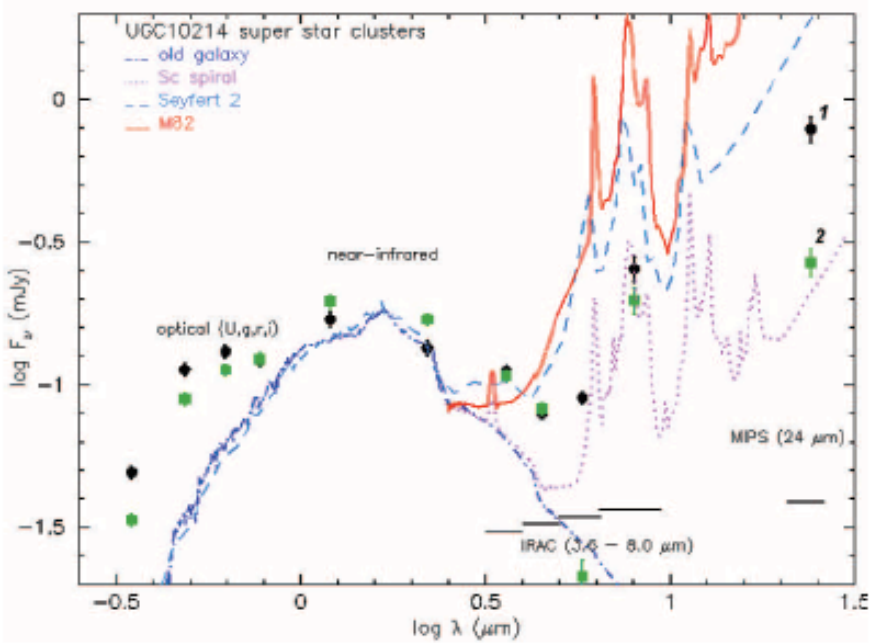


TABLE 2

Flux Density and Luminosity per Band for Super Star Cluster J160616.85+552640.6

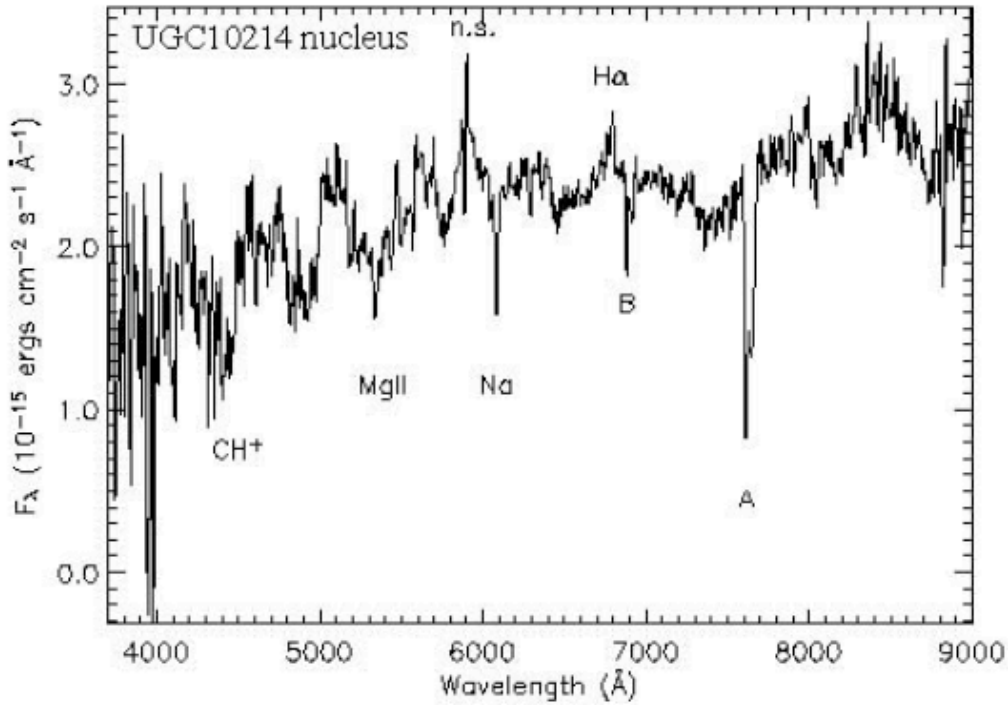
Band	λ_0 (μm)	$\Delta\lambda$ (μm)	F_ν (mJy)[a]	νL_ν ($10^7\ L_\odot$)[b]
U	0.3580	0.0638	0.049	20.4
g'	0.4846	0.1285	0.113	34.8
r'	0.6240	0.1347	0.131	31.4
i'	0.7743	0.1519	0.122	23.5
J	1.250	0.162	0.170	20.3
K_s	2.150	0.397	0.135	9.38
IRAC-1	3.600	0.750	0.112	4.65
IRAC-2	4.500	1.020	0.0800	2.65
IRAC-3	5.800	1.414	0.0900	2.32
IRAC-4	8.000	2.974	0.255	4.76
MIPS-24	24.00	5.35	0.789	4.91
MIPS-70[c]	71	19	<0.13	<0.27

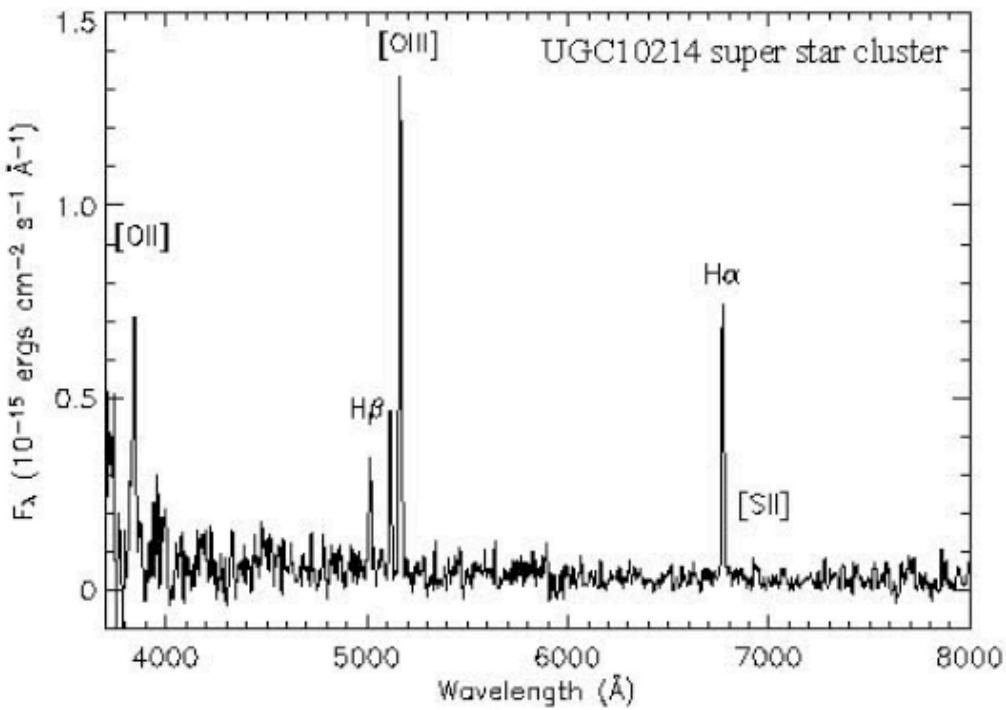
TABLE 3

Optical Integrated Line Fluxes for Super Star Cluster J160616.85+552640.6

Line (Å)	λ_0 (Å)	Flux (10^{-15} ergs cm^2 s^{-1})	FWHM (Å)
[O II] 3737	3840.8	18.9 ± 0.7	21.5
Hβ 4861	5015.2	5.7 ± 0.3	11.6
[O III] 4959	5115.6	0.8 ± 0.1	11.1
[O III] 5007	5165.3	25.8 ± 1.0	12.0
Hα 6563	6770.2	14.6 ± 0.5	12.4
[S II] 6718	6925.7	0.10 ± 0.01	12.4
[S II] 6733	6944.2	0.07 ± 0.01	12.4

Optical Spectra





Star Formation Rates

- Tracers of SF
  - Directly measure UV emission
    - Good only is there is no dust
  - FIR – Reprocessed starlight
    - Spatial Resolution of IRAS allows only for Global SFR
  - MIR – Kitchen sink
    - Starlight, ionized ISM, dust and PAHs, thermal radiation from dust grains, synchrotron radiation

TABLE 4

CURRENT STAR FORMATION RATES

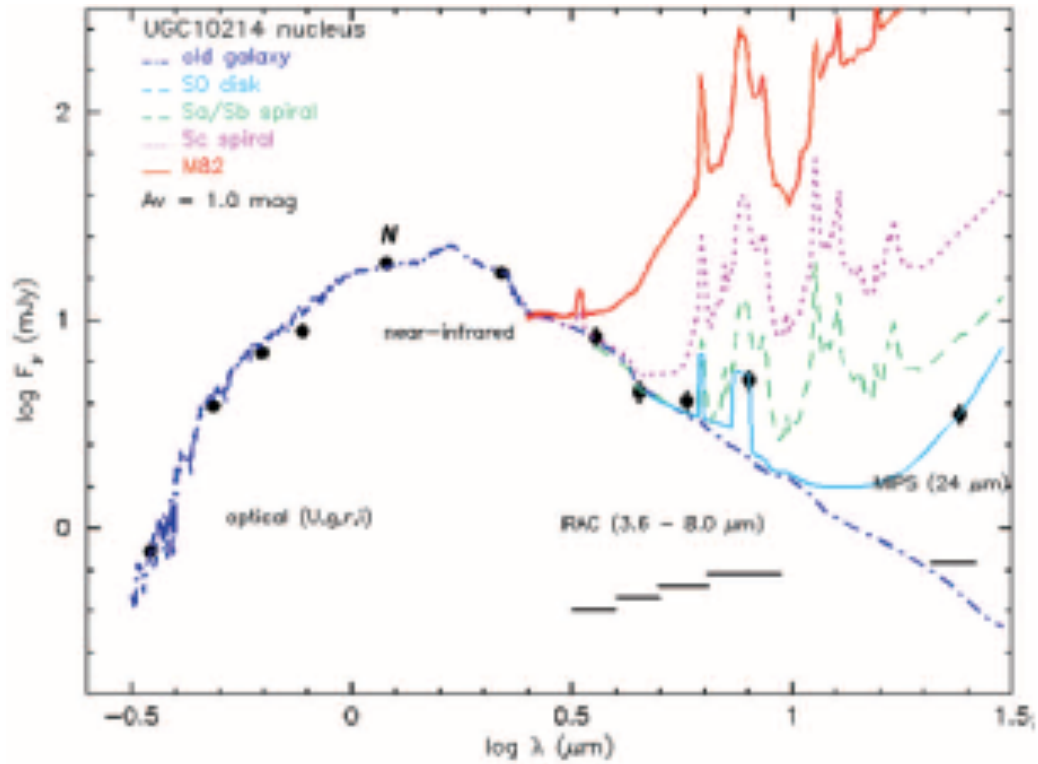
SFR Indicator[a]	Global SFR[b] ($M_\odot$ yr^{-1})	Disk Hot Spot SFR[c] ($M_\odot$ yr^{-1})	Super Star Cluster SFR[d] ($M_\odot$ yr^{-1})
FIR[e]	2.37	...	...
MIPS 70 μm[f]	4.5	...	...
MIPS 24 μm	3.26	0.51	0.11
Hα	...	...	0.23
[O III] + Hβ	...	...	0.39

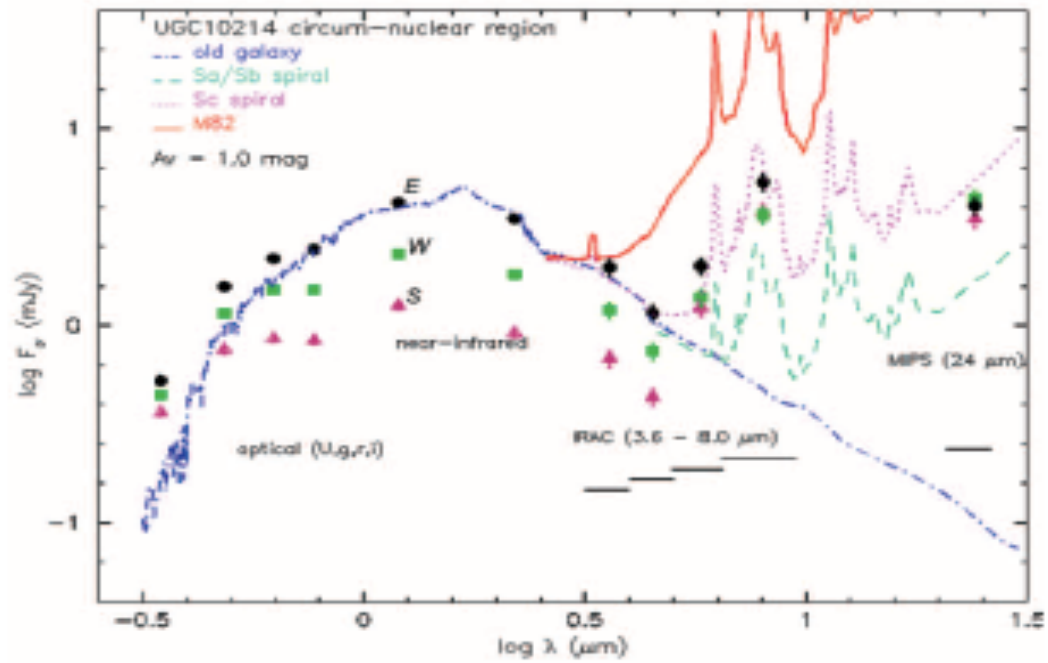
[a] For $M > 5\ M_\odot$.
[b] Total area = 2.97 arcmin^2 (see § 3.1).
[c] J160605.90+552532.5.
[d] J160616.85+552640.6.
[e] Using *IRAS* 60 and 100 μm emission.
[f] Derived for $M > 0.1\ M_\odot$.

PAH Emission

- Prominent Bands
  - 6.2,7.7,11.2 um.
  - Weaker bands: 3.3 and 8.6 um
- Demonstrated to be effective tracers of ongoing star formation activity from early-type stars in dust-rich galaxies
- Spitzer IRAC bands are sensitive to this emission
- Comparing 5.8 and 8.0 um bands to optical or NIR produces contrast between star formation regions and starlight from older populations

PAH: Nucleus & IR-Bright Spot



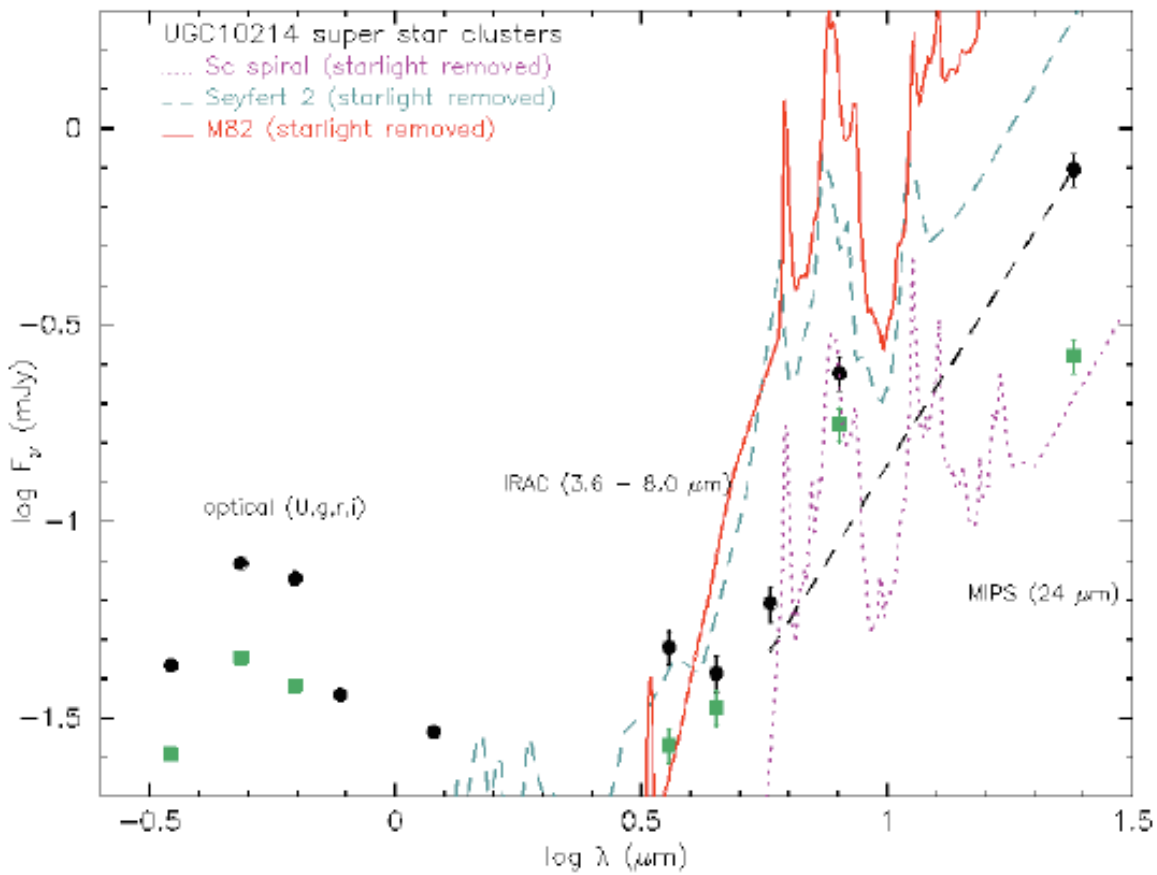


PAH: SSCs

Need to uncover PAH bands:

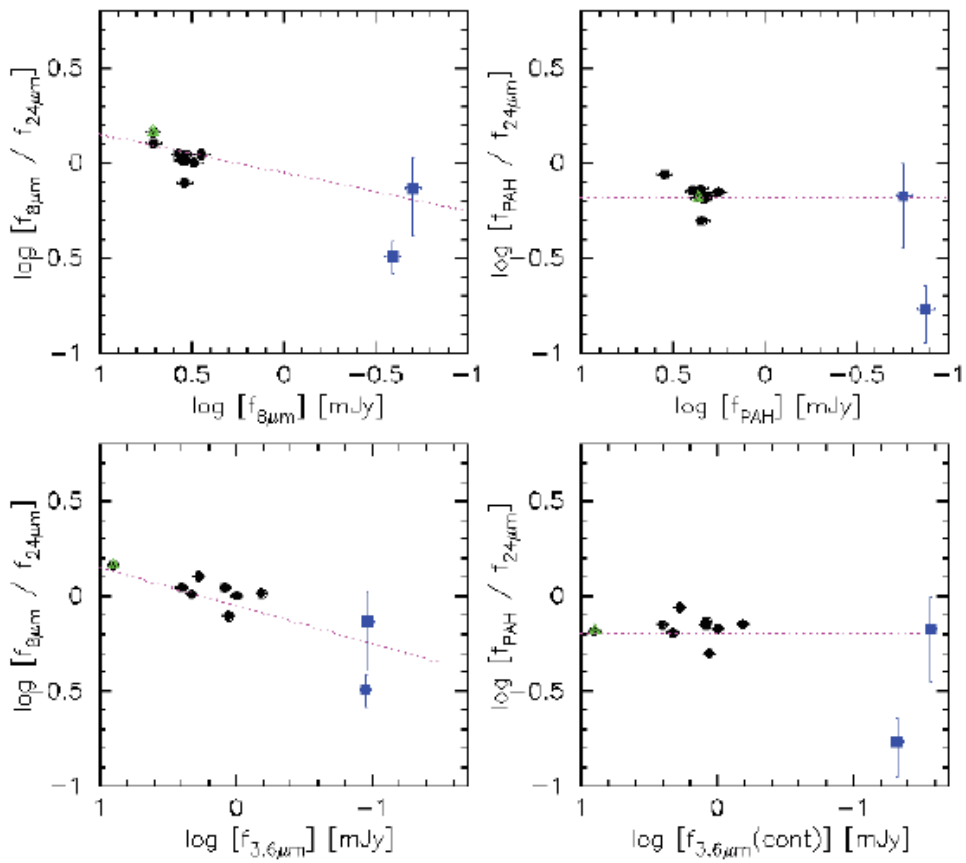
Remove all starlight from all bands

Remove the dust continuum from IRAC 8 um

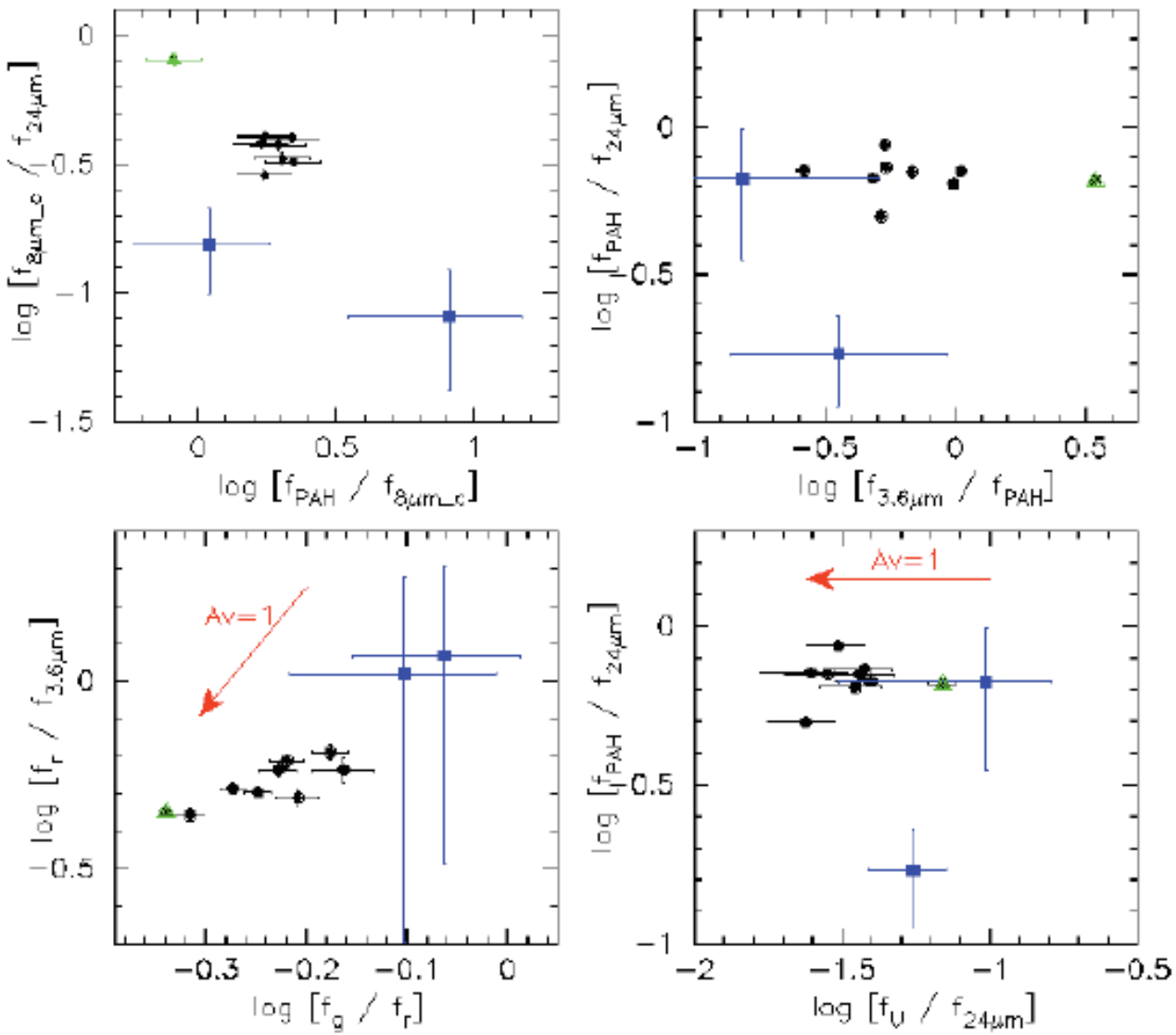


Quiescent or Active Star Formation

- Compare PAH strength to 24 um emission
  - F_{8um}/F_{24um} = const for normal disk galaxies
  - Decreases when SF activity and FIR continuum increases



PAH Equivalent Width



Poised for Nuclear Starburst?

- Must remove angular momentum from gas in spiral arms
  - Tadpole nucleus shows little SF activity
  - Spitzer: No bar
- 100-200 Myr old
- N-body sims show that tidal tail regions reform with nucleus over Gyr timescales
- Don't know: May be to early to tell.
  - Molecular gas may hold key

Off-Center Collision?

- Classic Spiral-Spiral Collision
  - Unwrapping of spiral arms (tidal tails)
  - Plumes
  - Counter-tails
- Tadpole has vigorous SF in disk. Ring?
  - Is this ring real? If so, could be formed by the merger
    - Off axis collision of 2 similar massed objects
  - Arguments for:
    - NIR & MIR
    - Ringlike structure of both old and new stars
    - Outer spiral arms
    - Distorted tidal tail
    - Companion that is directly behind the primary
    - Ring systems have little nuclear SF

Tidal Tail Stellar Cluster Masses

- SSCs
  - Emerging globular cluster systems?
  - Self-gravitating dwarf galaxies?
  - Do these remain bound or do they disperse
    - Must know: Mass, size, environment
      - IMF
    - Tran et al: $(0.5\text{-}1.0)\times10^6\ M_\odot$
      - Very high gas pressure and SF efficiency.
    - Compared to GCs SSCs cover much more area
      - Vulnerable to disruption
    - Mass estimates
      - g'-band: $5.0\times10^6\ M_\odot$ for 12" aperture
      - NIR: $7.0\times10^6\ M_\odot$ for 12" aperture
      - g'-band: $1.4\times10^6\ M_\odot$ for 4.5" aperture
      - NIR: $1.6\times10^6\ M_\odot$ for 4.5" aperture

Summary

- IR Morphology
  - Nucleus, disk with SF hot spots, spiral arms, plumes, tidal tails. No large-scale bar
- Active SF
  - Disk, spiral arms, tidal tail.
- Nucleus
  - Old stellar population.
  - No SF
- IR Bright Spots
  - Strong PAH emission tracing locations where gas has merged into massive star forming regions
- Ring-like structure has bright IR emission → Massive SF.
  - Ring may be from off-center collision with lower mass companion

Summary II

- Outer Spiral arm is VERY blue.
- Tidal Tail
  - Very blue. Lined with supermassive star clusters
- SCC J160616.85+552640.6
  - IR bright Tidal tail SSC, low metallicity
  - Strong 24 um. Suppressed PAH. SF.
- Mass of SSC
  - 1.4-1.6 x $M_{\odot}$ based on g' and NIR
    - Comparable to largest Globular Clusters in Milky Way or tidal dwarf galaxies

Outstanding Results

- Nucleus is not undergoing a starburst or even modest star formation
- Main disk is forming stars in a distorted spiral arm
- In the tidal tail, a massive cluster has formed after only a few megayears from a metal-poor gas reserve.

The End.

- Questions
- Comments