Our Own Starburst

In this article we present the first results from a near-infrared campaign to characterize our Galaxy's own starburst event, W49A, a prodigious factory of massive stars at a distance of about 12 kpc and concealed from observations at visible wavelengths by more than 25 magnitudes of intervening dust extinction. Our results so far reveal the presence of previously unknown massive stellar clusters containing more than 100 OB stars, some as massive as 120 $M_\odot$, most still embedded in their parental molecular cloud and with ages as young as 10^{4-5} yr. We argue that this ongoing starburst appears to have been multi-seeded instead of resulting from a coherent trigger.

João Alves[1] and Nicole Homeier[1,2]

[1]European Southern Observatory, Garching, Germany
[2]John Hopkins University, Baltimore, USA

Stars with mass above 8 $M_\odot$ are the main suppliers of heavy elements in the Universe, the same elements that make up your body and the Messenger article you are reading. Massive stars also inject energy into a galaxy's interstellar medium (ISM) playing a critical role in regulating star formation and driving galaxy evolution. It is not clear today if massive stars are destroyers of embryonic planetary systems or if they act, under some conditions, as triggers to planet formation. Finally, because they die in spectacularly bright fashion as supernovae/gamma-ray bursts, their death can be seen across the Universe providing unique information to observational cosmology.

Despite their fundamental role in shaping our Universe, our knowledge of how Nature forms massive stars is rather primitive, in part because objects for study are rare due to the combination of small number statistics and the rapidity with which they pass through their early stages. With this in mind, the abundance of embedded massive stars in the Galactic star-forming region W49A marks it as a scientific gem.

Well known to radio astronomers, W49A (Mezger et al. 1967, Shaver et al. 1970) is one of the brightest Galactic giant radio H II regions (~10^7 $L_\odot$), powered by the equivalent of about 100 O7 V stars. It is embedded in the densest region of a ~10^6 $M_\odot$ Giant Molecular Cloud (GMC) extending more than ~100 pc in size (Simon 2001) and is the best Galactic analogue to the starburst phenomenon seen in other galaxies. W49A lies essentially on the Galactic plane (l = 43.17°, b = +0.00°) at a distance of 11.4±1.2 kpc (Gwinn 1992), has ~40 well studied ultra-compact (UC) HII regions (e.g., De Pree et al. 1997), each associated with at least one stars earlier than approximately B3. About 12 of these radio sources are arranged in the well known Welch "ring" (Welch et al. 1987). A few other young Galactic clusters have a large number of massive stars, e.g., η Carinae, NGC 3603, the Arches cluster, but no other known region has a high number of massive stars in such a highly embedded and early evolutionary state. For this reason W49A is unique in our Galaxy.

In an attempt to uncover and characterize the embedded stellar population in W49A we performed an unbiased 5′×5′ (16 pc × 16 pc), deep *J, H,* and K_s-band imaging survey with the SOFI camera on ESO's New Technology Telescope (NTT), centred on the densest region of the W49 Giant Molecular Cloud (Simon 2001) (see Figure 1).

The first results

The observations were taken in June 2001, with the SOFI near-infrared camera on the ESO 3.5 m New Technology Telescope (NTT) on La Silla, Chile, during a spell of good weather and exceptional seeing (FWHM ~ 0.5″) (see Alves & Homeier 2003). Follow-up Adaptive Optics observations of an embedded compact HII region powered by a newborn 80 $M_\odot$ candidate star were taken with NACO on the Very Large Telescope (VLT) during September 2003.

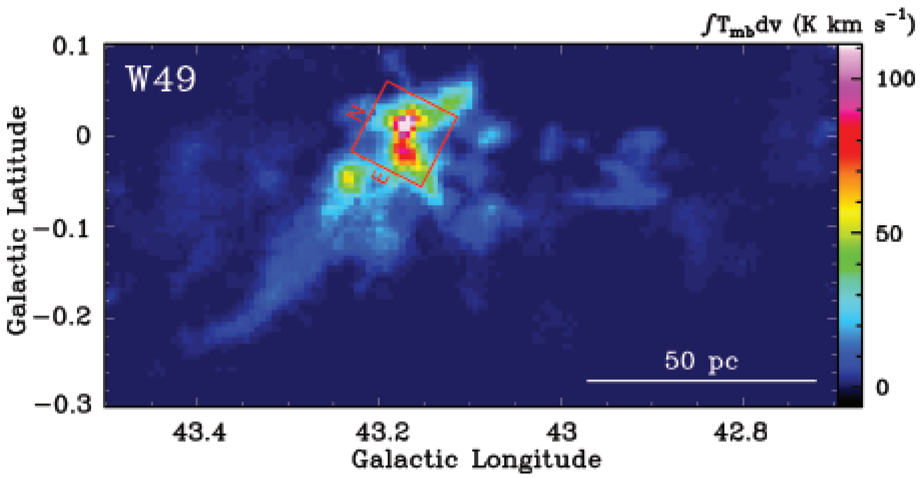

Figure 1: ^{13}CO Map of W49 giant molecular cloud. Our NTT-SOFI survey, marked as a red box, targeted the densest regions of this 10^6 $M_\odot$ giant molecular cloud. The survey covers an area of 16 × 16 pc at the distance to the complex (11.4 ± 1.2 kpc). ^{13}CO data taken from Simon et al. (2001).

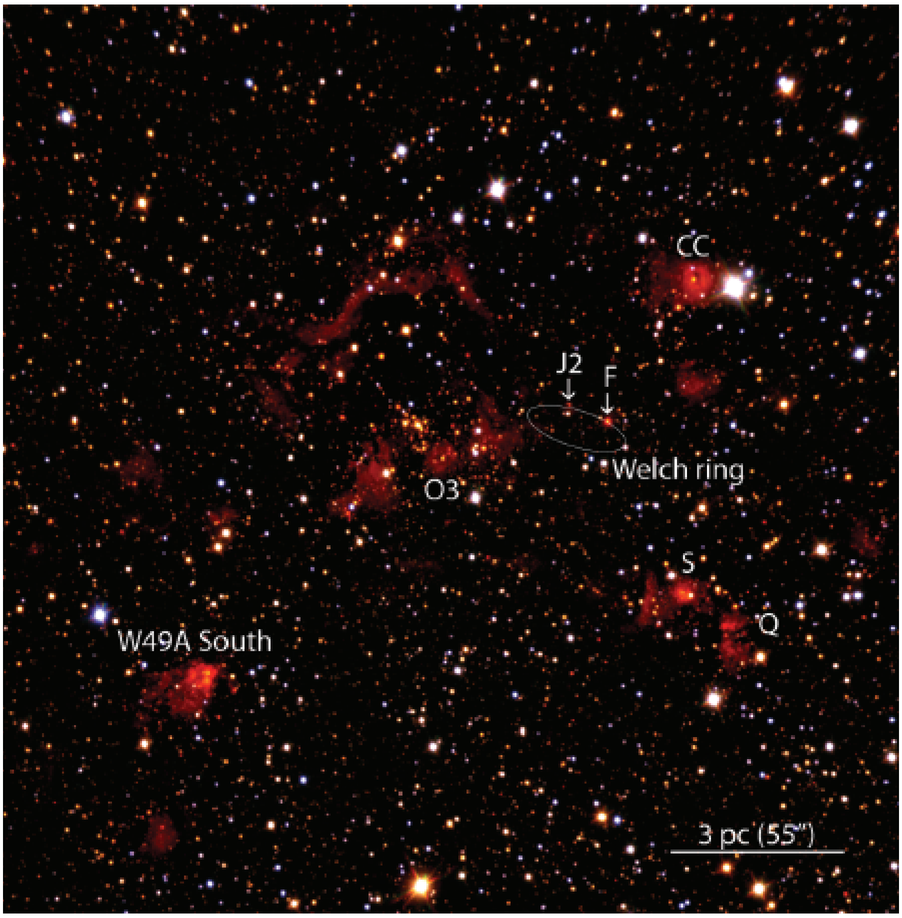

Figure 2: 5′× 5′ JHK_s colour composite of our survey. North is up and East is to the left. The red, green, and blue channels are mapped logarithmically to the K_s, H, and J-band respectively. The labels identify known radio continuum sources (De Pree et al., 1997). Sources F and J2 are UC HII regions in the Welch ring. The main cluster (Cluster 1) is seen NE of O3. Several candidate exciting sources of compact HII regions are visible (e.g., the sources at the centre of the CC, O3, W49A South HII regions). Dark pillars of molecular material are seen associated with radio sources Q and W49A South. None of W49A sources are optically visible. The coordinates of the image centre are: 19:10:16.724; +09:06:11.16 (J2000).

In Figure 2 we present the composite JHK_s colour image for our NTT-SOFI survey. The image covers an area of 5′×5′ on the sky and the red, green, and blue channels are mapped logarithmically to the K_s, H, and J-band respectively. Because most field stars are essentially colourless in the near-infrared one expects the colour of a star in this image to be, to first order, a qualitative measure of the amount of extinction towards this star. For this reason, all blue stars in this Figure are foreground sources to the star forming region.

In Figure 3 we present a 3.6 cm radio continuum (red), K_s (green), and J (blue) colour composite of the central regions of the survey. The radio continuum data is taken from De Pree et al. (1997) and has a spatial resolution of 0.8″, close to the spatial resolution of the NTT images. The red-only features in this image represent regions of ionised hydrogen so deeply embedded in the W49A molecular cloud that they cannot be detected in our K_s-band image, e.g., the Welch ring of UC HII regions with the exception of sources F and J2 (that appear in yellow in the image). Several HII regions and UC HII regions detected at radio continuum wavelengths are clearly detected on the K_s-band, suggesting that the K_s extended emission is dominated by hydrogen lines. The most prominent are identified in Figure 2 following De Pree (1997) nomenclature. Several point sources lie prominently in the centre of some of these regions (e.g., CC, O3, W49A south), are extincted by A_V > 24 mags of visual extinction (see below), and are excellent candidates to be the exciting sources powering these regions (Homeier & Alves, 2004).

The main feature in Figures 2 and 3 is the central 6 pc diameter region E of the ring of radio sources, with a stellar cluster at its projected centre. From here on we will refer to this cluster as Cluster 1. Note that only the North part of this 6 pc region is visible in the JHK_s colour composite, suggesting that there is a larger optical depth towards the South of Cluster 1, perhaps due to chance alignment of the embedded compact regions (e.g., JJ, O3) in front of it.

We present in Figure 4 the spatial distribution of the detected sources as a function of (H-K_s) colour. In Figure 5 we present the H-K_s vs. K_s Colour–Magnitude diagram for our survey. The solid line represents a 1 Myr old population taken from the Geneva tracks (Lejeune & Schaerer, 2001) and the slanted dotted lines represent a reddening in this diagram of A_V = 48 mag. The filled circles represent sources likely associated with the new clusters (see Figure 4).

Uncovering the beast

Since the W49A star forming region is at a distance of 11.4 kpc, virtually on the Galactic plane, one expects a large amount of unrelated line-of-sight dust extinction to W49A, as well as dust associated with the star forming region. We will take advantage of the large amounts of dust extinction to isolate a reliable stellar population associated with the W49A giant molecular cloud. We present in Figure 4 the spatial distribution of the detected sources as a function of (H-K_s)

Figure 3: J (blue), K_s (green), and 3.6 cm radio continuum (red) colour composite of W49A star forming region. Red only features represent radio HII regions too embedded to be detected in our deep K_s image (e.g., most of the Welch ring of UC HII regions). Yellow represents features seen in both the radio continuum and K_s-band, green-only sources are K_s sources too reddened to be detected at the J-band (essentially all of W49A young stellar population), while blue sources are foreground stars unrelated to the star forming region.

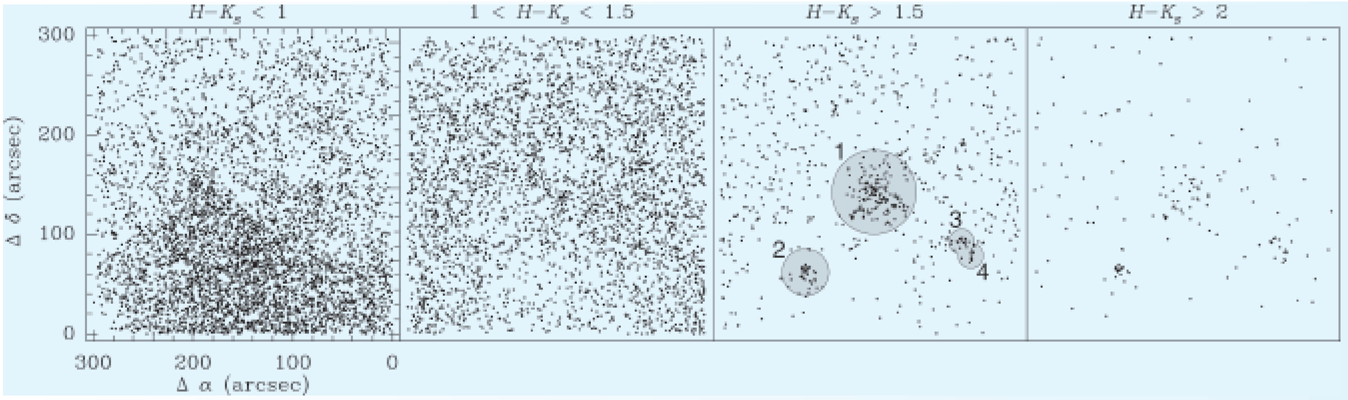

Figure 4: Spatial distribution of detected sources as a function of (H-K_s) colour. The clusters (labeled 1, 2, 3, and 4) become apparent in the third panel (where A_V ~ 20 mag). The non-uniform distribution of sources in panel 1 and 2 could be due to the intervening cloud GRSMC 43.30-0.33 located at a distance of ~3 kpc. The field shown is the same as in Figure 1.

colour. Starting with the bluer sources, (H-K_s < 1 mag) we find a non-uniform distribution in which about two third of the sources are found on the southern half of the field. Sources in this first bin are mainly foreground sources to the W49A star forming region, extincted by less than about 14 magnitudes of visual extinction, and the non-uniform distribution is likely caused by an intervening cloud at a distance of about 3 kpc (cloud GRSMC 43.30–0.33, Simon et al. 2001). The second panel (1 < H-K_s < 1.5 mag; 14 < A_V < 24 mag) further suggests this interpretation. We see the opposite spatial distribution with an increase in extinction and the region that in the first bin seemed under-populated is now over-populated. The majority of these stars are likely to be highly reddeneded stars in the background of GRSMC 43.30-0.33 but further work would have to be done to confirm this. In the third panel we clearly detect 4 clusterings of reddened sources. These make up the stellar population of W49A and some are still visible in the fourth panel where we find sources extincted by over 32 magnitudes of visual extinction, more than half associated with the newly found clusters. The positions of these 4 clusters are given in Table 1.

The Product of the W49A Starburst

Based on H-K_s colour and K_s magnitude, we preliminarily identify more than 100 O-stars candidates associated with the W49A region. We should bear in mind that due to the very high values of foreground and local (inhomogeneous) extinction *we are not complete even for the most luminous stars in W49A*. Nevertheless, this number compares already surprisingly well with the luminosity of the entire region (about 10^{51} Lyman continuum photons emitted per second). We can now say that the census of massive stars in W49A agrees with the number of Lyman continuum photons derived from radio observations. In fact, photon leakage or absorption by dust could be operating in the W49A region, as our count of candidate O-stars (incomplete due to severe inhomogeneous extinction), added to the number of known UC HII regions, gives ~140 stars with masses greater than 15–20 $M_{\odot}$, suggestive perhaps of a slight overabundance of ionizing stars. An estimate of the Initial Mass Function (IMF) in the main cluster suggests a Salpeter IMF down to ~ 2–3 $M_{\odot}$.

It is remarkable that the Welch ring of UC HII regions is seen in projection against the edge of the giant region powered by Cluster 1 (Figure 3). It necessarily invokes the classical triggering scenario of Elmegreen & Lada (1977) as one can easily imagine that, chronologically, the densest part of the W49A GMC collapsed to form Cluster 1, and the combined action of stellar winds and UV radiation compressed the abundant nearby gas to the West, triggering its collapse into the Welch ring. Recent theoretical calculations suggest timescales for massive star formation of the order of ~10^5 yr which for a typical sound speed of ~10 km/s agrees well with the crossing time in the Welch ring. However, we argue that the formation of the three smaller clusters to the South, undoubtedly associated with the burst of star formation in W49A, is unlikely to have been triggered by Cluster 1. The minimum distance (because of projection) between these less massive clusters and Cluster 1 is ~6 pc, which is larger than the bubble of ionised gas surround-

Table 1: W49 Stellar Clusters

Cluster	R.A. (J2000)	Decl.	Associated Radio Source
1	$19^h\ 10^m\ 17.5^s$	+9° 06′ 21″	Extended
2	$19^h\ 10^m\ 21.9^s$	+9° 05′ 04″	W49 A south
3	$19^h\ 10^m\ 11.9^s$	+9° 05′ 28″	S
4	$19^h\ 10^m\ 10.8^s$	+9° 05′ 14″	Q

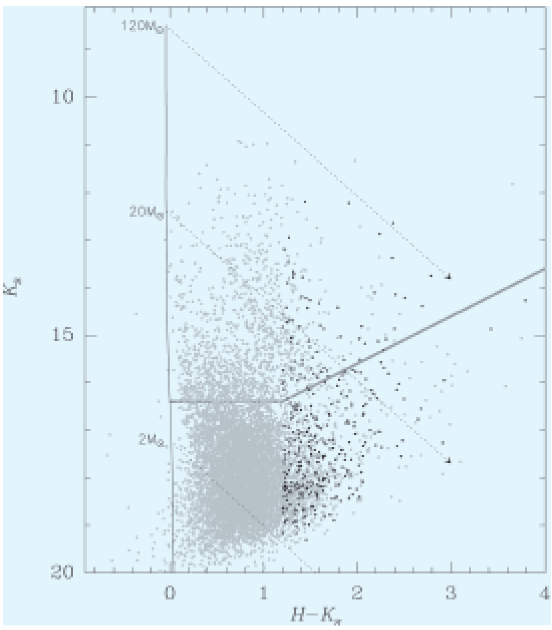

Figure 5: (H-K_s) vs. K_s Colour-Magnitude diagram for our survey. The solid line represents a 1 Myr old population taken from the Geneva tracks (Lejeune & Schaerer, 2001) and the slanted lines represent a reddening of A_V = 48 mag. The black circles identify stars likely associated with the W49A clusters. The 90% completeness limit for a star with errors less than 15% is marked as a bold grey line.

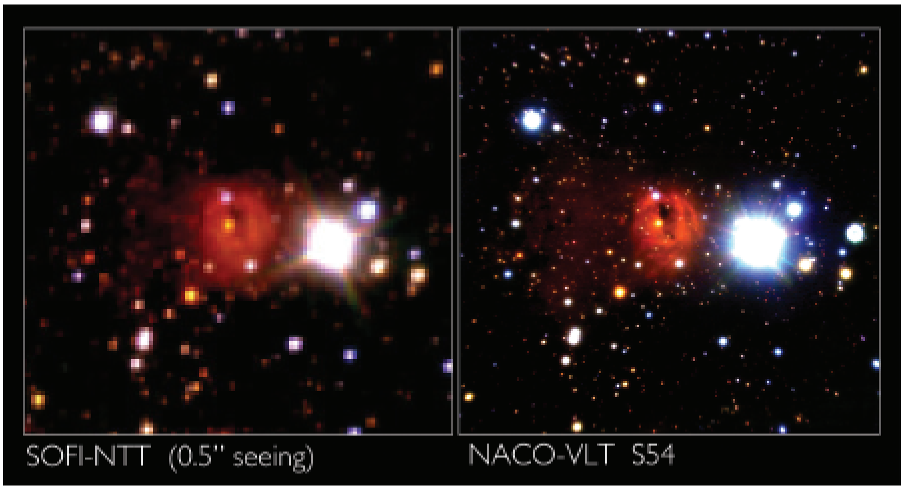

Figure 6: SOFI and NACO JHK_s colour composites of the only compact HII region that is accessible to NACO using natural guide stars. The object in the centre of the compact HII region is a newborn ~80 $M_\odot$ star candidate. Through comparison with models (Freyer et al. 2003) we estimate the age of the HII region to be remarkably young: 4 • 10^4 yr. This is a very young massive star caught in the rare act of passing from the ultracompact to compact HII region stage.

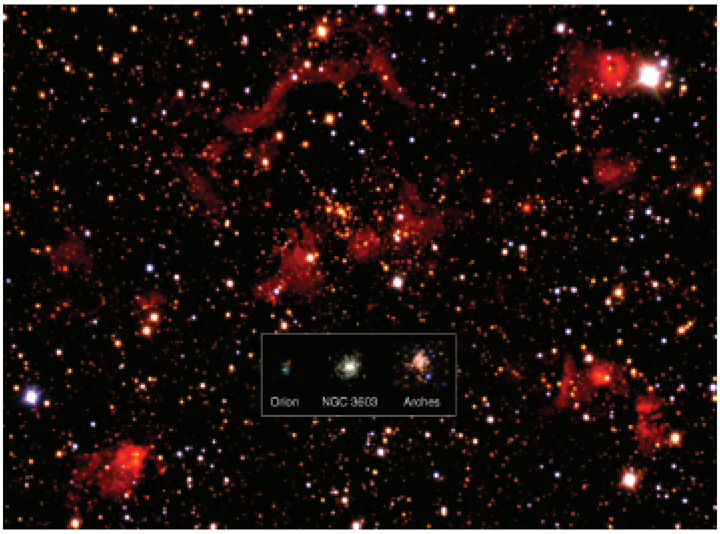

Figure 7: Size comparison between W49A and 1) Orion, 2) NGC 3603, and 3) the Arches cluster seen in the near-infrared as if they were located at the same distance and observed with the same instrument (SOFI on the NTT).

ing it, the giant central H II region in Figure 3. Also, given the short lifetimes of compact regions and the fact that they can be found almost over the entire surveyed region (e.g., the projected distance between source CC and W49A South is ~11 pc) suggests a multi-seeded, largely coeval, star formation episode in the W49A.

In Figure 6 we present preliminary results of a diffraction limited imaging follow-up on the only compact region that is accessible to NACO using natural guide stars. The object in the centre of the compact region is a newborn ~80 $M_\odot$ star candidate. We find that the source is unresolved down to the resolution of the image (600 AU at the distance of W49A) and through comparison with models (Freyer et al. 2003) we estimate the age of the region to be 4 • 10^4 yr.

Our first results suggests that W49A is indeed the most massive and youngest known star forming region in the Galaxy and that it extends over a larger area than previously thought (see Figure 7 for a visual comparison with well known young Galactic clusters). Moreover, star formation in W49A is still ongoing (the GMC is not exhausted yet) as 6 hot cores (the precursors of UC HII regions) were recently found in the vicinity of the Welch ring (Wilner et al., 2001). Although W49A is clearly of the class of 30 Dor in the Large Magellanic Cloud (LMC), a size comparison with the most luminous cluster in the Antennae galaxy (Figure 8), makes clear that the star forming conditions in the LMC and our Galaxy have to be radically different. Most important, our results show that a considerable part of the stellar population of W49A is accessible in the 2 µm window. Further characterization of the embedded population (via *H* and *K*-band spectra and adaptive optics techniques) is called for and will surely provide much needed information on the starburst phenomenon seen across the Universe.

Acknowledgements

We are pleased to acknowledge Miguel Moreira for discussions and assistance with the observations, Robert Simon for providing molecular line data from the BU-FCRAO Galactic Ring Survey on W49 giant molecular cloud and Chris De Pree for providing radio continuum data of the HII regions associated with W49A.

References

Alves, J., & Homeier, N. 2003, *ApJ*, 589, 45
De Pree, C.G., Mehringer, D.M., Goss, W. M. 1997, *ApJ*, 482, 307
Elmegreen, B. G., & Lada, C. J. 1977, *ApJ*, 214, 725
Gwinn, C. R., Moran, J. M., & Reid, M. J. 1992, *ApJ*, 393, 149
Homeier, N., & Alves, J. 2004, *A&A* in prep.
Lejeune, T., & Schaerer, D. 2001, *A&A*, 366, 538
Mezger, P. G., Schraml, J., & Terzian, Y. 1967, *ApJ*, 150, 807
Shaver, P.A., & Goss, W.M. 1970, *AuJPA*, 14, 133
Simon, R., Jackson, J.M., Clemens, D.P., Bania, T. M., & Heyer, M. H. 2001, *ApJ*, 551, 747
Welch, W. J., Dreher, J. W., Jackson, J. M., Terebey, S., & Vogel, S. N. 1987, *Science*, 238, 1550
Wilner, D. J., De Pree, C. G., Welch, W. J., & Goss, W. M. 2001, *ApJLet*, 550, L81

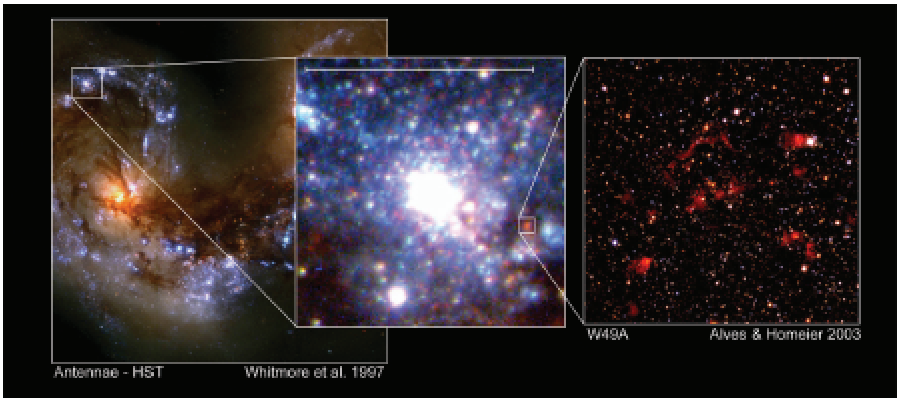

Figure 8: Size comparison between W49A and the most luminous cluster in the Antennae (starburst) galaxy. W49A is approximately an order of magnitude smaller. The luminosity comparison is not fair as the wavelengths of the two images are different (visible and near-infrared). Also, while the Antennae cluster is essentially extinction free, W49A is seen behind a wall of more than 30 mags of dust extinction.