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The Close AGN Reference Survey (CARS)

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The role of active galactic nuclei (AGN) in the evolution of galaxies remains a mystery. The energy released by these accreting supermassive black holes can vastly exceed the entire binding energy of their host galaxies, yet it remains unclear how this energy is dissipated throughout the galaxy, and how that might couple to the galaxy's evolution. The Close AGN Reference Survey (CARS) is a multi-wavelength survey of a representative sample of luminous Type I AGN at redshifts 0.01 < *z* < 0.06 to help unravel this intimate connection. These AGN are more luminous than very nearby AGN but are still close enough for spatially resolved mapping at sub-kpc scales with various state-of-the art facilities and instruments, such as VLT-MUSE, ALMA, JVLA, Chandra, SOFIA, and many more. In this article we showcase the power of CARS with examples of a multi-phase AGN outflow, diverse views on star formation activity and a unique changing-look AGN. CARS will provide an essential low-redshift reference sample for ongoing and forthcoming AGN surveys at high redshift.

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Science drivers

The powerful engines of AGN are known to drive very fast winds with speeds of more than 10 000 km s^{-1} based on the detection of very broad absorption lines at rest-frame X-ray and UV wavelengths. Furthermore, systematically blue-shifted wings in high ionisation lines, for example the [O III] 5007 Å emission and Na I D absorption lines, support the notion that those outflows are quite common in AGN and may significantly affect their host galaxies. These gas outflows were resolved with the Hubble Space Telescope (HST) for very nearby AGN host galaxies, and were shown to reach several hundreds of pc in size with a (hollow) biconical geometry (Fischer et al., 2013). It is expected that those outflows become more extended with increasing AGN luminosities and thereby influence the evolution of the entire host galaxies.

Since the interstellar medium (ISM) consists of different gas phases with a large range in temperature (10–10^6 K) and density (0.1–1000 cm^{-3}), it has been difficult to infer the total mass outflow rates and energetics as a function of radius. In particular, the cold molecular gas phase may carry the bulk mass in the outflow (Cicone et al., 2014), despite the ionised gas phase being easier to detect. Hence, multi-wavelength observations are crucial for characterising AGN-driven outflows and to verify whether the winds are either energy- or momentum-driven. In addition, not only the intense and hard radiation field of the AGN may accelerate the gas; radio jets can also directly impact and drive gas far away from the galaxy nucleus. High-resolution radio continuum images are needed to confirm or exclude the presence of extended radio jets in individual objects to discriminate between the different driving mechanisms.

Theorists mainly invoke AGN feedback to suppress star formation during galaxy evolution in order to reproduce the distribution of observed galaxy properties in the present-day Universe. However, a clear causal connection between AGN outflows and the suppression of star formation has not yet been observationally confirmed. Obvious issues that must be overcome to solve this puzzle include the very short timescales of AGN phases with respect to the large dynamical time of the host galaxy, the different timescales probed by star formation indicators, and sample selection effects of AGN and non-AGN control samples (see review by Harrison, 2017).

Many of the current AGN surveys, like the KMOS AGN Survey at High redshift (KASHz; Harrison et al., 2016), the SINFONI Survey for Unveiling the Physics and the Effect of Radiative feedback (SUPER; PI: V. Mainieri) and the WISE/SDSS-selected hyper-luminous quasar survey (WISSH; Bischetti et al., 2017), are focused on luminous AGN at redshifts between 1 and 3 where the peak in cosmic star formation occurs. However, the drawback is a large physical scale of > 7 kpc per arcsecond, which significantly limits the achievable spatial resolution (see Figure 1). For CARS we decided to target a representative sample of the most luminous AGN in the nearby Universe, with redshifts of 0.01 < *z* < 0.06. This approach allows us to dissect their host galaxies easily at sub-kpc scales, while still probing an important part of the AGN luminosity function. Thereby, CARS provides a unique reference data set for all high-redshift AGN and bridges the gap between low-luminosity AGN and the rare ultra-luminous AGN.

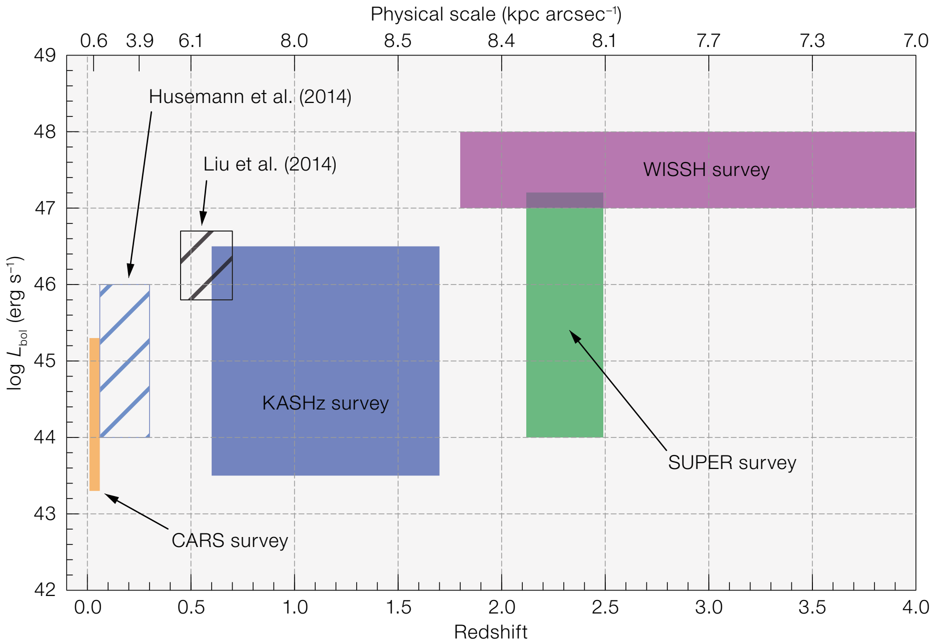


Figure 1. Redshift and AGN luminosity range of various existing and ongoing spatially resolved spectroscopic AGN surveys compared to CARS.

CARS sample and data

CARS is focused on Type I AGN, where the central engine is not blocked by obscuring material. Therefore, the black hole masses can be constrained from the optical spectra, and the point-spread function (PSF) of individual observations can be reconstructed by mapping the intensity of the broad lines from the unresolved nucleus (Jahnke et al., 2004). The largest catalogue of luminous Type I AGN in the southern hemisphere is the Hamburg-ESO Survey (HES; Wisotzki et al., 2000), where objects were selected through *B*-band imaging and slitless spectroscopy. A sub-sample of 99 Type I AGN with $z < 0.06$ has been intensively studied by the group of Andreas Eckart in Cologne (for example, Busch et al., 2014). From this sample, 41 galaxies have already been targeted with single-dish submillimetre telescopes to obtain cold molecular gas masses via the CO(1–0) emission line (Bertram et al., 2007). Since molecular gas content is the prime fuel for star formation in galaxies and an important quantity to study the feedback process in galaxies, the sub-sample of Bertram et al. (2007) serves as the parent sample for CARS.

Our spatially resolved multi-wavelength observations for CARS rely primarily on a snapshot survey with the Multi-Unit Spectroscopic Explorer (MUSE) on the Very Large Telescope (VLT) taken in Periods 94 and 95. Only 15- to 30-minute on-source exposure times are needed, thanks to the unique sensitivity of MUSE and its large field of view that captures the entire AGN host galaxy in one shot. Each MUSE observation obtains 90 000 spectra across a 1 × 1 arcminute field of view, which provides a wealth of physical information at a physical resolution of about ~ 600 pc at 0.8-arcsecond seeing. This is essential to separate the AGN and host galaxy emission and study the stellar and ionised gas components, their respective kinematic fields, ionisation conditions and the distribution of star-forming H II region complexes. The high quality and power of MUSE are shown in Figure 2, where we compare broad-band with pseudo-narrow-band colour images, which already reveal different ISM ionisation conditions in different kinds of host galaxies.

Since the ionised gas represents just one particular phase of the ISM, a large effort has been made by the CARS team to obtain spatially resolved observations of all other important gas phases of the ISM, i.e. atomic, molecular, warm-ionised and hot gas. The cold gas phases are traced by deep Jansky Very Large Array (JVLA) observations of H I at ~ 15-arcsecond resolution and ALMA observations of CO(1–0) at 0.8-arcsecond resolution. Furthermore, we have successfully obtained [C II] observations with the Far-Infrared Field-Imaging Line Spectrometer (FIFI-LS) on board the Stratospheric Observatory For Infrared Astronomy (SOFIA) for eight galaxies, and deep X-ray observations with the Chandra satellite to map the hot gas for two targets as a pilot study. Radio continuum images at C (4–8 GHz) and X (8–12 GHz) bands with 1-arcsecond resolution were also obtained for nearly the entire sample with the JVLA to detect extended radio jets and characterise their luminosity, size and orientation if present. Our follow-up observations do not yet cover the entire AGN sample because of sensitivity constraints and availability of observing time, but the first exciting results are coming out of the survey. Below we highlight some of our ongoing work that demonstrates the power of CARS to recover the individual characteristics of AGN host galaxies.

Tracing the impact of AGN outflows

HE 1353–1917 is fairly unique among the CARS targets because it is an edge-on disc galaxy with a bright unobscured AGN. This means that the usual obscuring torus of the AGN is not lined up with the disc and the ionisation cone of the AGN light directly intercepts the disc of its host galaxy. Indeed, the ionisation cones of the AGN are nicely recovered with MUSE as ionised gas filaments nearly parallel on both sides of the galaxy's disc with a projected extension of 30 kpc (Figure 3). The gas-phase metallicity in the ionisation cones exhibits a radial dependence similar to that of the gas in the disc, indicating that the material was likely lifted off the disc by continuous supernova explosions resulting from ongoing star formation, rather than being blown out by the AGN.

However, looking closer at the heart of the galaxy, the MUSE data reveal a distinct region of ionised gas with very

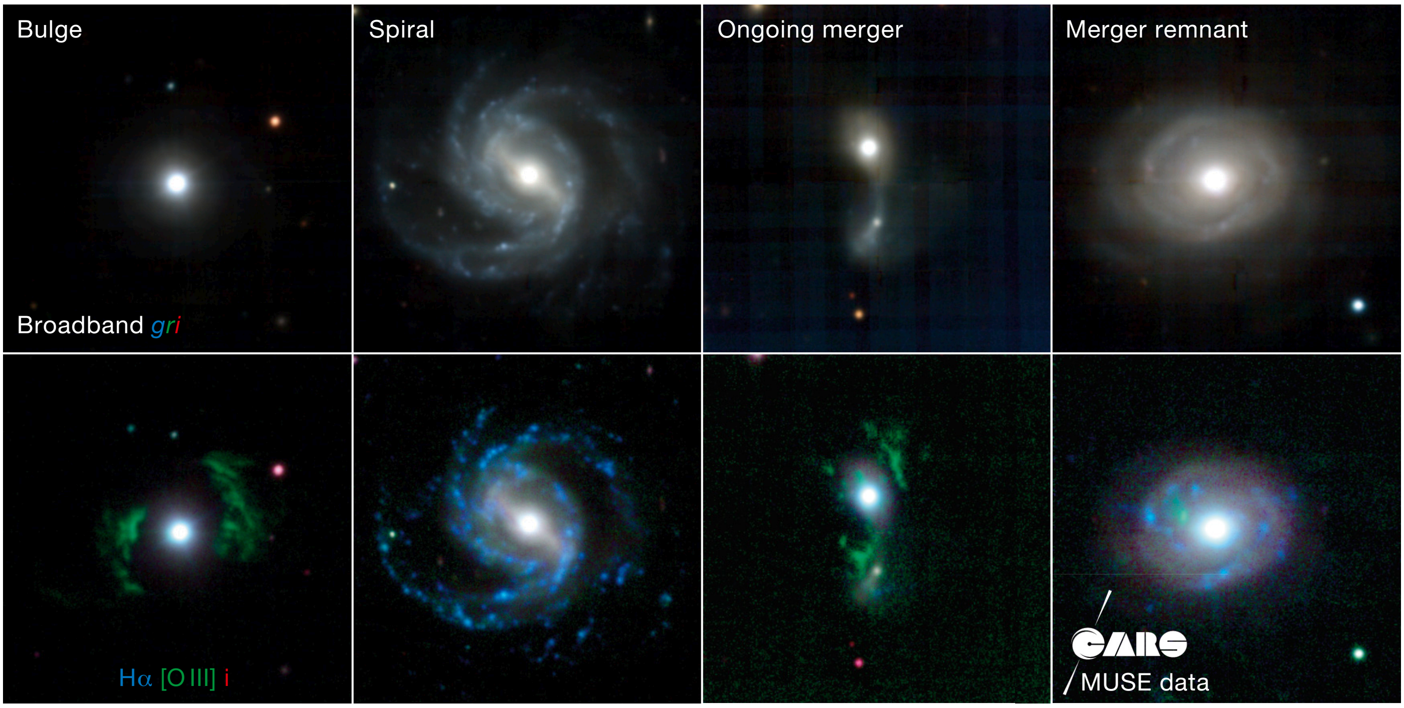
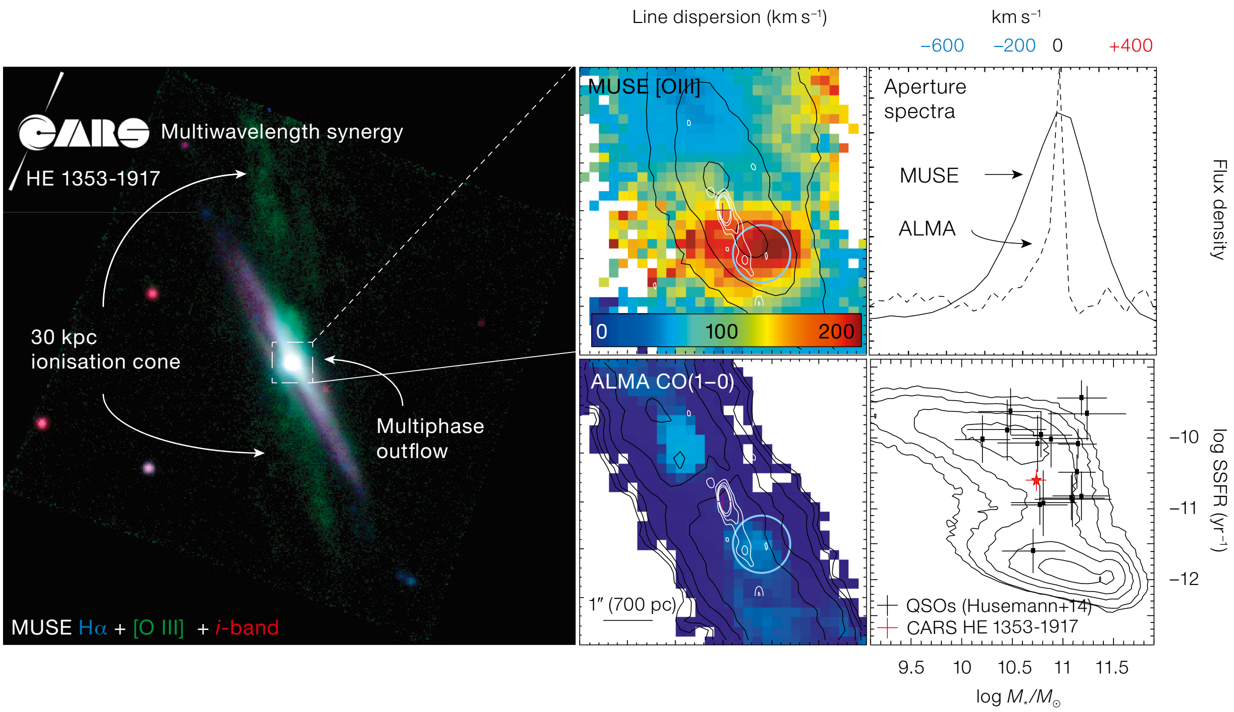


Figure 2 (Above). Broad-band (upper row) and narrow-band (lower row) colour images reconstructed from the MUSE data for four CARS galaxies as examples. Narrow-band images centred on important emission lines reveal very different ISM ionisation states (blue — ongoing star formation, green — AGN photoionisation) and ionised gas distributions on kpc scales reaching beyond the host galaxies in some cases.

Figure 3 (Below). CARS discovers a spectacular 30 kpc-long ionisation cone (left panel) and a bipolar multi-phase outflow from high velocity dispersion regions (centre panels) in the edge-on CARS galaxy HE 1353–1917. Extended radio emission obtained with the JVLA (white contours, middle panels) is indicative of a low-luminosity radio jet. The different line shapes in the ionised ([O III] from MUSE) and molecular (CO(1–0) from ALMA) gas shown in the upper right panel may be a consequence of the mass and outflow momentum carried in the different gas phases. This galaxy is located in the so-called "green valley" of galaxies with lower specific star formation compared to normal disc galaxies (contours in lower right panel), potentially as a consequence of the outflow's clearing the central kpc of gas.



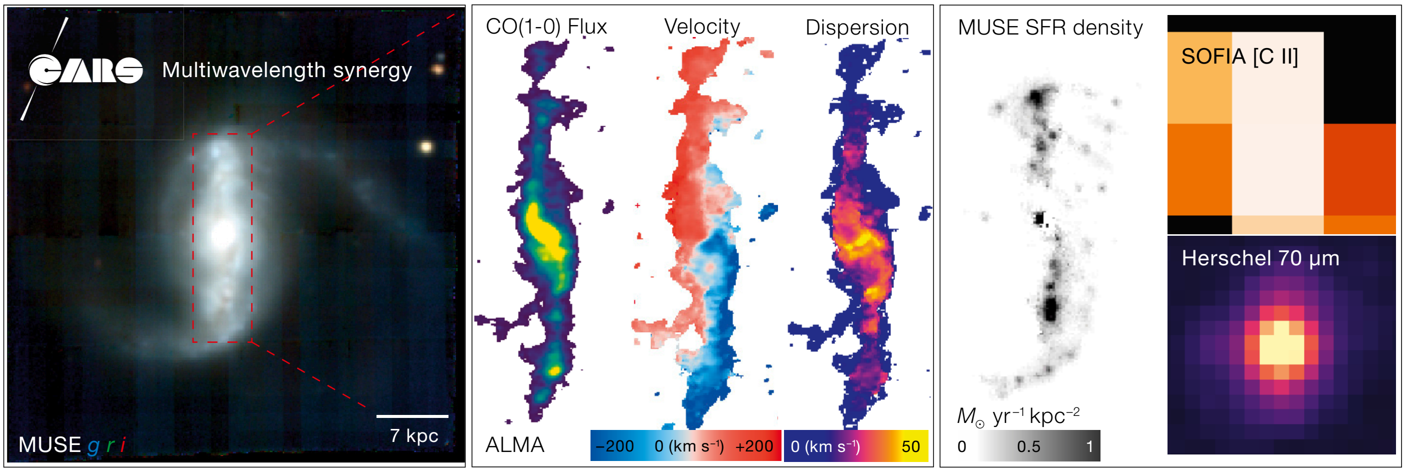


Figure 4. Images of various star formation tracers for the strongly barred CARS galaxy HE 0433–1028 with a luminous AGN at its centre. The left panel shows the *gri*-band composite image from MUSE. The centre panel shows the CO(1–0) emission from the bar, with flux, radial velocity (with a signature of radial motions along the bar), and velocity dispersion. The right panel shows the star formation rate derived from MUSE (Hα) compared to the infrared line ([C II]) and continuum (Herschel 70 μm) appearance.

high velocity dispersion about 1 kpc away from the nucleus. A broad wing in the ionised gas emission lines with an excess in blue-shifted velocities of a few 100 km s^{-1} (Figure 3, upper panels) confirms the presence of a powerful outflow. The JVLA continuum image reveals an extended radio structure terminating at this "hot spot", providing evidence for a possible radio jet. ALMA follow-up observations tracing the molecular gas with the CO(1–0) line also show elevated line dispersion at the same location (Figure 3, lower middle panel), which also occurs on the opposite side of the nucleus at the same distance. The outflow velocities are significantly lower than in the ionised gas, but the wings on the approaching and receding sides are detected as well. Since the molecular gas mass in the outflow is a factor of over 10 more than the ionised gas mass, the lower velocities can be understood in terms of a common momentum carried by the different gas phases, and the changing phase structure of the gas as it flows outwards. Such multi-gas-phase kinematic classifications are therefore important to understanding the physics of AGN-driven outflows. A systematic investigation of AGN-driven outflows in CARS is on the way and will help to understand the incidence, timescales, energetics and driving mechanisms.

One of the big questions for feedback is whether AGN-driven outflows actually cause a suppression of star formation. From the reconstructed broad-band spectral energy distribution of HE 1353–1917 spanning the ultraviolet to the far-infrared, we obtained the stellar mass and specific star formation rate (SSFR). When comparing this to the distribution of galaxies from the Sloan Digital Sky Survey (SDSS), we indeed find a suppression of star formation in HE 1353–1917 compared to that expected for a star-forming disc galaxy at a given stellar mass (lower right panel of Figure 3). This may be explained by a reduced cold gas content and we confirm this for the central circular region of the galaxy with a radius roughly matching the location of the detected shock front. It is tempting to argue for a causal connection between the AGN, the development of an extended outflow in the disc, and the suppressed star formation. However, secular evolution of the galaxy, a bar for example, could lead to a similar reduction of gas and star formation around the centre. Hence, we will have to employ the statistical power of CARS to verify those causal connections in the future.

Star formation in AGN host galaxies

Understanding how star formation and AGN are linked is one of the key aspects of understanding the feedback processes. However, it is notoriously difficult to measure the current SFR in AGN hosts cleanly as the tracers are usually contaminated by the bright AGN light. With CARS we do not want to focus on one measurement, but actually compare various star formation tracers, in order to understand the systematic effects in previous studies and guide future observations at low and high redshift.

An example of how our exquisite multiwavelength data set can shed light on this issue can be seen in HE 0433–1028, also known as Mrk 618. This galaxy is strongly barred, with intense star formation occurring along the bar. This is already unusual, as star formation is often suppressed along a bar by the high-shear environment. The molecular gas kinematics from ALMA reveal that the gas is apparently funneled inwards, along x_1 orbits at the leading edge of the bar, towards the inner regions where the black hole is being fueled (Figure 4). Gas clouds that are travelling along the x_1 orbits of the bar are subject to a velocity gradient perpendicular to the bar major axis. The resulting shear can disrupt the clouds and prevent them from collapsing and forming stars, which is not the case for HE 0433–1028.

In terms of SFR, we can use MUSE to map the Hα line, which we can verify is dominated by star formation ionisation by employing various emission-line ratio diagnostics, and also correction for dust attenuation as measured from the Balmer decrement. In order to subtract the bright nucleus we employ dedicated PSF-subtraction schemes optimised for integral field unit (IFU) data (QDeblend^{3D}; Husemann et al., 2014). Archival far-infrared (FIR) observations are available from the Herschel satellite mission and we also mapped the bright [C II] 158 μm emission line with SOFIA, the only operating FIR observatory in the current post-Herschel era (Figure 4, right panels). Despite the low spatial resolution of SOFIA in the FIR, we can degrade the SFR maps inferred from the MUSE Hα map to test how well all the emission relates to each other in a spatially resolved manner. This has not been done before, but provides important clues for the use of [C II] as a tracer for star formation and/or AGN outflows for high-redshift AGN observed with ALMA.

Mrk 1018 — A unique changing-look AGN

A problem with linking AGN and their host galaxies is the timescale of AGN variability. The CARS team discovered an extreme AGN variability event, which the team is currently monitoring in detail across the electromagnetic spectrum from X-ray to radio. Upon examining the MUSE data for Mrk 1018, we were surprised to find that the typical broad emission lines and continuum emission of a Type I AGN had almost completely disappeared (McElroy et al., 2016). Checking the literature we realised that this was not the first time Mrk 1018 had undergone a dramatic change, as this source also experienced something similar three decades ago. In the 1970s its spectrum also showed weak broad emission lines that then significantly brightened, appearing as a luminous Type I AGN a few years later. The MUSE observation taken by CARS clearly shows that the nucleus has faded significantly. The reconstructed AGN light curve reveals that the dimming started just a few years ago, between 2011 and 2013 (Figure 5).

Although AGN are known to be variable sources at all wavelengths, such dramatic changes in luminosity on short timescales are very unusual. The CARS team obtained rapid follow-up observations with Chandra at X-ray and with HST at far-ultraviolet (FUV) wavelengths. The X-ray spectra do not show any evidence for an increased column density of gas along our line of sight to the AGN, which rules out a temporary obscuration event as an explanation for the dimming (Husemann et al., 2016). A tidal disruption event (TDE) is also excluded because the bright AGN phase was too stable over a long period, which is not predicted by current TDE models. The FUV, which directly probes the accretion disc emission, also fell by a factor of 10–25 in 2016 compared to 2010. This leaves changes in the physical properties of the accretion disc itself as the only option. However, this is difficult to explain with standard accretion disc theory. The viscous timescale of an accretion disc around a black hole of $10^8 M_\odot$ (as in Mrk 1018) is several thousand years. We therefore speculated

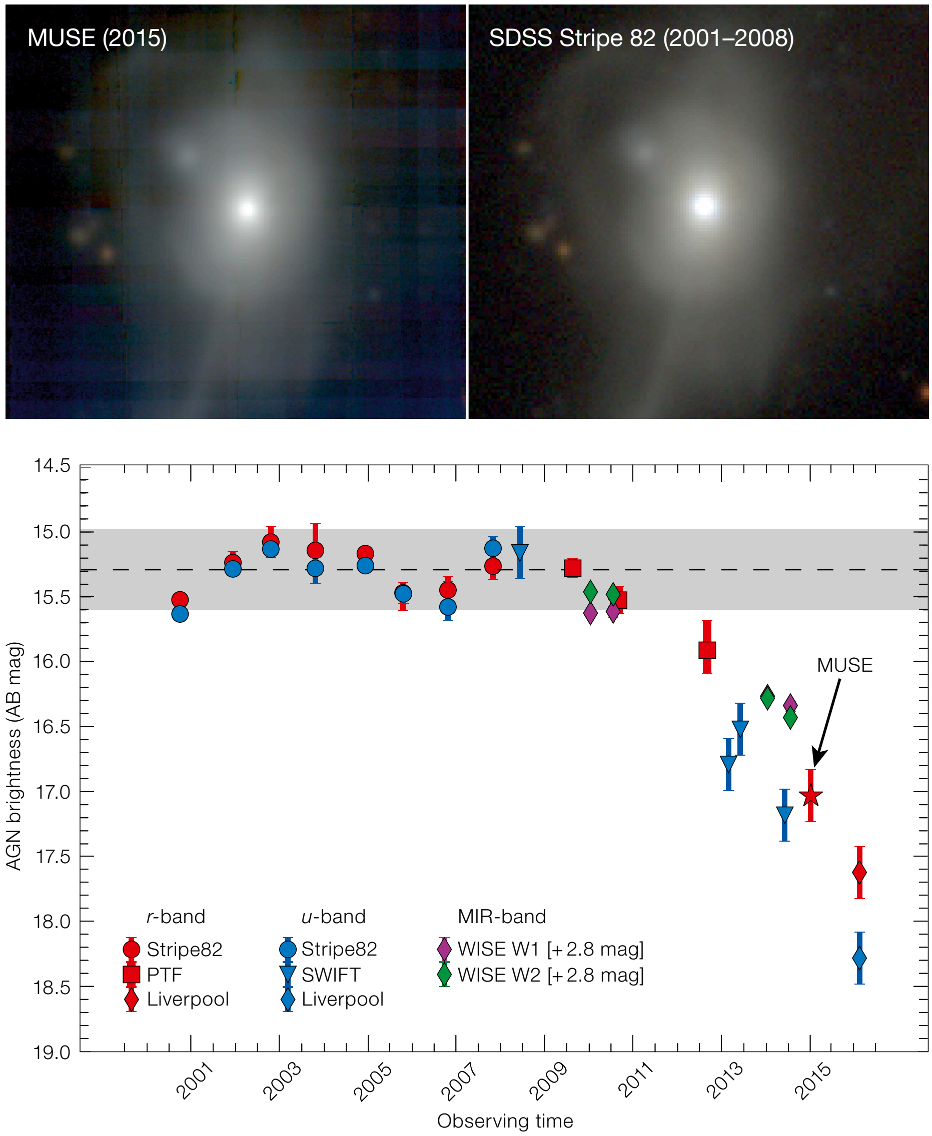


Figure 5. CARS serendipitously discovered an extreme "changing-look" AGN event in Mrk 1018. Upper panels: comparison of reconstructed *r*-band MUSE image with co-added broad-band SDSS Stripe 82 image, revealing a fading nucleus. Lower panel: a 16-year optical lightcurve of the nucleus, highlighting its rapid luminosity drop in recent years and the point of our MUSE discovery.

that the accretion disc is perturbed via an accretion disc outflow or an interaction with a nearby companion black hole, as highlighted in a recent ESO press release (eso1613).

It is exciting to witness how the accretion disc around a very massive black hole is undergoing a major reconfiguration over just a few years. The CARS team has triggered various ongoing monitoring campaigns in the optical with the VLT VIsible Multi Object Spectrograph (VIMOS), in the FUV with Hubble and in X-rays with Chandra and the X-ray Multi Mirror satellite (XMM-Newton). This will be crucial in understanding the underlying physical mechanism(s) behind the dramatic changes in this archetypical changing-look AGN. More exciting results may therefore be expected from Mrk 1018; stay tuned!

Outlook

The Close AGN Reference Survey (CARS) combines data from several state-of-the-art facilities to establish a spatially resolved multi-wavelength sample and convenes a diverse team with varied expertise. CARS offers a dataset covering a large wavelength range with additional data for selected objects. The combination of such a multi-wavelength dataset for nearby AGN host galaxies with such relatively high AGN luminosities at low redshifts is unique. It opens up a new window to study the link between AGN and their host galaxies via the exchange of energy and baryons.

Even more observations will be taken for CARS in the next year by ALMA to compare molecular and optical emission line diagnostics over the entire host galaxies, spectroscopy with VIMOS IFU in the optical blue wavelength range not covered by MUSE, and wide-field optical and near-infrared imaging to characterise the environment of all CARS AGN host galaxies. In addition, ongoing monitoring of the unique changing-look AGN Mrk 1018 will likely lead to new discoveries that provide important insights into the physics of accretion.

While a first series of CARS papers is currently being prepared by the team, it will clearly be a long-term effort to build up statistical AGN samples. Only with such systematic approaches can the physics of outflows, feedback, fuelling and quenching in AGN host galaxies be revealed. The ultimate aim of CARS is to establish a unique low-redshift reference point for ongoing AGN surveys at high redshift, such as KASHz, SUPER and WISSH, with a long-lasting legacy value.

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Links

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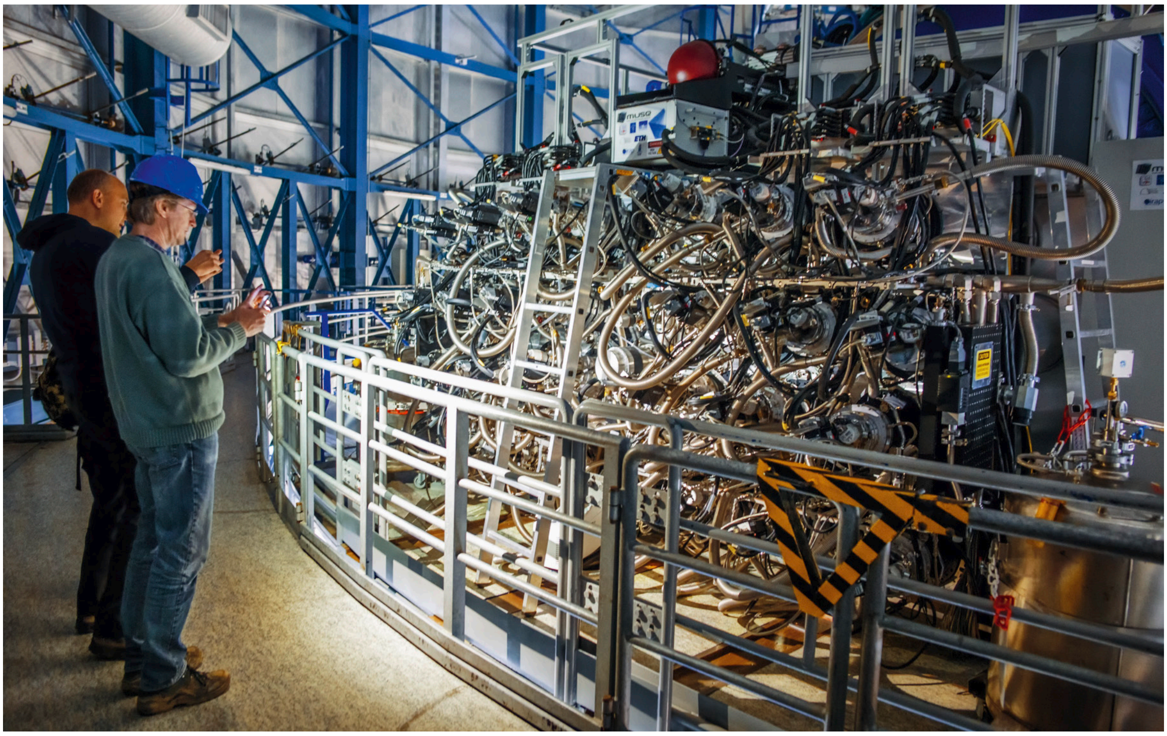

The MUSE instrument, showing the intricate network of pipes surrounding its 24 spectrographs.